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Μελέτη πολυ-λεπτονικών καταστάσεων για την αναζήτηση Νέας Φυσικής με το πείραμα ATLAS στον LHC στο CERN

Τσοπούλου Μαρία-Ευανθία

Διατριβή που υποβλήθηκε για την απόκτηση του διδακτορικού διπλώματος

στο Τμήμα Φυσικής της Σχολής Θετικών Επιστημών

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Δεκέμβριος, 2022



Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο

Επιχειρησιακό Πρόγραμμα
Ανάπτυξη Ανθρώπινου Δυναμικού,
Εκπαίδευση και Διά Βίου Μάθηση

Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης



«Το έργο συγχρηματοδοτείται από την Ελλάδα και την Ευρωπαϊκή Ένωση (Ευρωπαϊκό Κοινωνικό Ταμείο) μέσω του Επιχειρησιακού Προγράμματος «Ανάπτυξη Ανθρώπινου Δυναμικού, Εκπαίδευση και Διά Βίου Μάθηση», στο πλαίσιο της Πράξης «Ενίσχυση του ανθρώπινου ερευνητικού δυναμικού μέσω της υλοποίησης διδακτορικής έρευνας» (MIS-5000432), που υλοποιεί το Ίδρυμα Κρατικών Υποτροφιών (ΙΚΥ)»



Περίληψη

Από τους πρώτους προ-Χριστιανικούς αιώνες, η “Ατομική” θεωρία εμφανίστηκε ως έννοια τόσο στα ελληνικά (Δημόκριτος, Λεύκιππος) όσο και σε ινδικά φιλοσοφικά ρεύματα. Η αντίληψη ότι το Σύμπαν αποτελείται από στοιχειώδη σωματίδια επανήλθε τον 16ο αιώνα από τον Γαλιλαίο, ο οποίος ισχυριζόταν ότι όλα τα φυσικά φαινόμενα (εκτός του ήχου) παράγονται από “ύλη σε κίνηση”. Η ιδέα ότι η ύλη αποτελείται από άτομα επικυρώθηκε το 1930 όπου τα υποατομικά σωματίδια (ηλεκτρόνιο, πρωτόνιο και φωτόνιο) ταυτοποιήθηκαν πλήρως με την συμβολή της θεωρίας της Κβαντομηχανικής. Αργότερα, στα μέσα του 1970, τελειοποιήθηκε η θεωρία του Καθιερωμένου Προτύπου μέσω της πειραματικής επιβεβαίωσης της ύπαρξης των κουάρκ: πρόκειται για μια θεωρία που περιγράφει τα στοιχειώδη σωματίδια της ύλης καθώς και τις αλληλεπιδράσεις που αναπτύσσονται μεταξύ τους. Παρά το γεγονός ότι η παρατήρηση των W και Z διανυσματικών μποζονίων, του κορυφαίου (top) κουάρκ, του t -νετρίνο και ειδικότερα του μποζονίου Higgs προσέδωσαν υψηλή αξιοπιστία στο Καθιερωμένο Πρότυπο, η ύπαρξη αρκετών ανεξήγητων φαινομένων όπως η βαρυονική ασυμμετρία της ύλης, η ενσωμάτωση της βαρυτικής δύναμης και η ύπαρξη Σκοτεινής Ύλης – Ενέργειας οδήγησαν στην ανάπτυξη θεωριών πέραν του Καθιερωμένου Προτύπου. Ως αποτέλεσμα, η τρέχουσα επιστημονική πρόκληση είναι η εύρεση τρόπων πειραματικής επιβεβαίωσης αυτών των θεωριών (όποτε αυτό είναι δυνατό) και η διερεύνηση μιας πιθανής επέκτασης ή τροποποίησης του Καθιερωμένου Προτύπου με στόχο την διαμόρφωση μιας πιο γενικής “Θεωρίας των Πάντων”.

Η αναζήτηση για διμποζονικούς συντονισμούς αποτελεί μια βασική διερεύνηση στα πλαίσια της κατανόησης του σπασίματος της ηλεκτρασθενούς συμμετρίας. Στο Καθιερωμένο Πρότυπο η ισχύς της σύζευξης του βαθμωτού πεδίου Higgs με τα διανυσματικά μποζόνια περιγράφεται σε ικανοποιητικό βαθμό, ωστόσο είναι ευρέως γνωστό ότι η χαμηλή μάζα του μποζονίου Higgs οδηγεί σε προβλήματα ιεράρχησης των μαζών γεγονός που υποδηλώνει ότι το Καθιερωμένο Πρότυπο αποτελεί μια προσεγγιστική θεωρία που περιγράφει πολύ ικανοποιητικά τις χαμηλές περιοχές ενέργειας στο κέντρο μάζας. Ως αποτέλεσμα προκύπτει η ανάγκη για εισαγωγή Νέας Φυσικής που να περιγράφει περιοχές υψηλότερης ενέργειας στο κέντρο μάζας. Η παρούσα διδακτορική διατριβή εστιάζει σε πολυ-λεπτονικές τελικές καταστάσεις οι οποίες μας παρέχουν καθαρές ενδείξεις γεγονότων σήματος. Η παρούσα διατριβή στοχεύει στην αναζήτηση συντονισμών οι οποίοι προβλέπονται από δύο διακριτές υποθέσεις θεωριών σήματος: ένα μοντέλο που περιλαμβάνει ένα μποζόνιο W' με σπιν 1 που προκύπτει από την παραμετροποίηση της Λαγκραζιανής που περιγράφει μια τριπλέτα διανυσματικών μποζονίων με μεγάλη μάζα (Heavy Vector Triplet ή HVT) και ένα μοντέλο που προβλέπει την ύπαρξη ενός φορτισμένου μποζονίου Higgs $H^\pm$ με σπιν 0 (Georgi-Machacek ή GM Model). Ειδικότερα, μελετήσαμε την παραγωγή συντονισμών που διασπώνται σε μποζόνια W και Z χρησιμοποιώντας δεδομένα που αντιστοιχούν σε συγκρούσεις πρωτονίων που έχουν συλλεχθεί από τον ανιχνευτή ATLAS στον μεγάλο αδρονικό επιταχυντή (LHC), τα οποία αντιστοιχούν σε ολοκληρωμένη φωτεινότητα ίση με 139 fb^{-1} και ενέργεια κέντρου μάζας ίση με 13 TeV ; για τις διασπάσεις των W και Z μποζονίων λαμβάνουμε υπ' όψιν μόνο τα λεπτονικά κανάλια διάσπασης που περιλαμβάνουν ηλεκτρόνια ή μύονια. Δεν παρατηρήθηκαν αποκλίσεις από το Καθιερωμένο Πρότυπο οπότε ορίστηκαν όρια στην ενεργό διατομή παραγωγής (cross section) πολλαπλασιασμένη με τον λόγο του επιμέρους πλάτους διάσπασης του συγκεκριμένου συντονισμού ως προς το ολικό πλάτος διάσπασης (branching ratio) σαν συνάρτηση της μάζας συντονισμών που προκύπτουν από δύο διαφορετικά θεωρητικά μοντέλα, το Heavy Vector Triplet και το Georgi-Machacek. Στην μελέτη μας λάβαμε υπ' όψιν δύο διαφορετικά κανάλια παραγωγής των νέων συντονισμών: παραγωγή είτε μέσω σύντηξης διανυσματικών μποζονίων (Vector Boson Fusion) είτε μέσω διαδικασιών Drell-Yan (εξαύλωση κουάρκ – αντικουάρκ), στις οποίες θέσαμε ανεξάρτητα όρια. Παρά το γεγονός ότι η ευρέως χρησιμοποιούμενη μεταβλητή διαχωρισμού σήματος από υπόβαθρο είναι η αναλλοίωτη

μάζα του συστήματος των W και Z μποζονίων, εξετάσαμε αναλλακτικές επιλογές και θέσαμε όρια χρησιμοποιώντας εναλλακτικές κινηματικές μεταβλητές. Γενικότερα, η αναλλοίωτη μάζα του συστήματος των W και Z μποζονίων δίνει αυστηρά όρια ωστόσο σε ορισμένες περιοχές μαζών πετύχαμε πιο χαμηλές τιμές με την χρήση εναλλακτικών μεταβλητών ως παράμετρο για τον υπολογισμό των ορίων με την Μέθοδο της Μέγιστης Πιθανοφάνειας.

Η δομή της παρούσας διατριβής περιγράφεται συνοπτικά παρακάτω. Στο Κεφάλαιο 2 πραγματοποιείται μια σύντομη εισαγωγή στην θεωρία του Καθιερωμένου Προτύπου, συνοδευόμενη από την παρουσίαση δύο θεωριών πέραν του Καθιερωμένου Προτύπου (Μοντέλα των Heavy Vector Triplet and Georgi-Machacek) οι οποίες θα μελετηθούν στην συνέχεια πειραματικά. Στο Κεφάλαιο 3 περιγράφουμε τα κύρια χαρακτηριστικά του Μεγάλου Επιταχυντή Αδρονίων (LHC) καθώς και τεχνικά χαρακτηριστικά και βασικές λειτουργίες του ανιχνευτή ATLAS. Επίσης, παρουσιάζεται το πρόγραμμα αναβάθμισης του New Small Wheel δίνοντας ιδιαίτερη σημασία στον ανιχνευτή Micromegas όπου η συγγραφέας είχε σημαντική συμβολή όσον αφορά την κατασκευή των LM2 θαλάμων ολίσθησης (Drift Panels) ως μέλος της ομάδας ATLAS του Αριστοτελείου Πανεπιστημίου Θεσσαλονίκης, την πραγματοποίηση ελέγχων ποιότητας και σωστής λειτουργίας (QA/QC) και την διατήρηση της βάσης δεδομένων της ομάδας. Στο Κεφάλαιο 4 περιγράφουμε τα δείγματα δεδομένων και προσομοιώσεων Monte Carlo που χρησιμοποιήθηκαν (γεγονότα σήματος και διαφορετικών υποβάθρων). Στο Κεφάλαιο 5 περιγράφουμε αναλυτικά την ανακατασκευή των προς μελέτη αντικειμένων που χρησιμοποιήθηκαν στην ανάλυση δεδομένων (ηλεκτρόνια, μύονια και πίδακες σωματιδίων), όπου η συγγραφέας συνέβαλε στην διαδικασία του βέλτιστου ορισμού της παραμέτρου της “απομόνωσης” (isolation) των μιονίων αλλά και στην σύγκριση των αποτελεσμάτων της ανάλυσης μεταξύ δύο διαφορετικών προγραμματιστικών πλαισίων (analysis frameworks). Συγκεκριμένα, έγινε σύγκριση του πλήθους των γεγονότων μετά την εφαρμογή των κριτηρίων επιλογής σε κάθε προγραμματιστικό πλαίσιο. Στο Κεφάλαιο 6 ορίζουμε ορισμένες βασικές κινηματικές μεταβλητές οι οποίες θα χρησιμοποιηθούν στην παρούσα εργασία καθώς και αναφέρουμε τα κριτήρια επιλογής που εφαρμόζουμε με σκοπό τον καθορισμό των περιοχών γεγονότων σήματος (Drell-Yan και VBF) και των αντίστοιχων περιοχών ελέγχου (signal and control regions) της ανάλυσης. Στο Κεφάλαιο 7 ορίζουμε τις πηγές υποβάθρου για συντονισμούς που διασπώνται σε W και Z μποζόνια και μελετάμε το σχήμα των κατανομών των αντίστοιχων περιοχών ελέγχου. Στο Κεφάλαιο 8 η συγγραφέας εξέτασε την περίπτωση ύπαρξης νέων ευαίσθητων μεταβλητών στα πλαίσια της αναζήτησης Νέας Φυσικής εκτός της αναλλοίωτης μάζας του συστήματος των W και Z μποζονίων η οποία χρησιμοποιήθηκε στο Run I, ενώ στο Κεφάλαιο 9 συνοψίζουμε τις πηγές των πειραματικών αβεβαιοτήτων. Οι θεωρητικές αβεβαιότητες στα γεγονότα σήματος αλλά και στα κύρια υπόβαθρα της ανάλυσης επισημαίνονται στο Κεφάλαιο 10, όπου συμβάλλαμε στον υπολογισμό των αβεβαιοτήτων λόγω της επιλογής συνάρτησης πυκνότητας πιθανότητας των συγκρουόμενων πρωτονίων (particle density function pdf), λόγω του σχήματος της κατανομής των παρτονίων στο πρωτόνιο της εν λόγω συνάρτησης λόγω διαφορετικής επιλογής των παραμέτρων κανονικοποίησης και παραγοντοποίησης (renormalization scale μ_R / factorization scale μ_F) και λόγω διαφορετικού μοντέλου καταγισμού παρτονίων (parton – shower). Στο Κεφάλαιο 11 πραγματοποιείται μια εισαγωγή στην στατιστική θεωρία η οποία αφορά τις μεθόδους που εφαρμόζονται στις μελέτες του LHC. Στο Κεφάλαιο 12 παρουσιάζουμε το πρότυπο της Μεθόδου Πιθανοφάνειας, τις παραμέτρους που περιλαμβάνονται σε αυτήν όπως και τις στατιστικές μεθόδους που εφαρμόσαμε στην αναζήτηση του καναλιού $X \rightarrow W Z \rightarrow l\nu l l$. Στο ίδιο κεφάλαιο παρουσιάζουμε βελτιστοποίηση του διαχωρισμού του εύρους των ιστογραμμάτων σε κατάλληλα επιλεγμένα διαστήματα (binning optimization) και την εξαγωγή ορίων χρησιμοποιώντας την αναλλοίωτη μάζα του συστήματος των W και Z μποζονίων όπως και τις υπό μελέτη εναλλακτικές μεταβλητές, για διαφορετικές κατηγορίες σήματος (HVT / GM) και περιοχών γεγονότων σήματος (Drell-Yan/ VBF). Στην τελευταία ενότητα του ίδιου κεφαλαίου παραθέτουμε ορισμένες συγκριτικές γραφικές παραστάσεις μεταξύ των θεωρητικά αναμενόμενων (expected) και των

πειραματικά παρατηρούμενων (observed) ορίων για τις Drell-Yan και VBF κατηγορίες, όπου παρατηρούμε ότι παρά το γεγονός ότι η αναλλοίωτη μάζα των W και Z μποζονίων δίνει αυστηρά όρια, υπάρχουν εναλλακτικές κινηματικές μεταβλητές όπως η εγκάρσια μάζα του συστήματος των W και Z μποζονίων οι οποίες δίνουν αυστηρότερα όρια σε ορισμένες περιοχές μαζών των υπό μελέτη συντονισμών.



ARISTOTLE UNIVERSITY OF THESSALONIKI

Search for New Physics with the Study of Multi-lepton Final States with the ATLAS Experiment at the LHC at CERN

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A thesis submitted in the fulfillment for the PhD degree

in the
Faculty of Sciences,
School of Physics

Supervising Professor : Chara Petridou

December, 2022



Operational Programme
Human Resources Development,
Education and Lifelong Learning
Co-financed by Greece and the European Union



“This research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Program “Human Resources Development, Education and Lifelong Learning” in the context of the project “Strengthening Human Resources Research Potential via Doctorate Research” (MIS-5000432), implemented by the State Scholarships Foundation (IKY)”

*‘ Τον αριστοτέχνην τών σοφώς και εντέχνως γενομένων δοξάσωμεν,
και εκ τού κάλλους τών ορωμένων τον υπέρκαλον εννοώμεθα,
και εκ τού μεγέθους τών αισθητών τούτων και περιγραπτών σωμάτων
αναλογιζώμεθα τον άπειρον και υπερμεγέθη και πάσαν διάνοιαν
εν τω πλήθει τής εαυτού δυνάμεως υπερβαίνοντα.’*

(Μέγας Βασίλειος, Ομιλία εις την Εξαήμερον)

Abstract

The search for diboson resonances is an essential probe for understanding the source of electroweak symmetry breaking (EWSB). In the Standard Model (SM), the strength of the coupling of the Higgs scalar to vector boson pairs is well predicted, but it is well known that the low mass of the Higgs boson leads to hierarchy and naturalness problems suggesting that the SM is only an effective theory at low masses. As a result, there is need for New Physics to be introduced for higher masses, focusing on multi-lepton final states which provide us with clear signal signatures. The present thesis targets on the search for resonances predicted by two distinct signal hypothesis: a spin-1 W' from the Parametrization of heavy vector triplet (HVT) Lagrangians and a spin-0 charged higgs $H^\pm$, predicted by Georgi-Machacek (GM) model. More specifically, we study the resonant WZ diboson production using 139 fb^{-1} data collected at 13 TeV center of mass energy by the ATLAS detector at the LHC, where only the leptonic final states (e or μ) are considered for the W and Z boson decays. Limits on the production cross-section times branching ratio are obtained as a function of the resonance mass for resonances arising from two different models, Heavy Vector Triplet and Georgi-Machacek model. Two different production modes are considered, the vector boson fusion and the Drell-Yan process (quark-anti quark fusion), on which independent limits are set. Although the nominal discriminating variable for the limits setting procedure is the invariant mass of the WZ system, different options are examined too and limits are obtained using alternative variables which in some cases result in stricter limits.

Acknowledgements

Finalizing my doctoral thesis, I would like to express my gratitude to those who supported, taught and guided me on this long and demanding journey.

First of all, it has been a great privilege to be part of the ATLAS Collaboration; it provided me with an inspiring and highly-motivating environment which allowed me to participate in the exploring of the smallest constituents of matter and the forces acting between them. Being part of the collaboration since my graduate years, I had the chance to directly observe the bridging attempt between numerous theoretical models and experimental data; a really demanding, precise and detailed procedure. I would like to thank my supervisor Chara Petridou for her constant support, guidance and encouragement during my undergraduate, master and PhD academic years; our discussions have always been fruitful, enlightening and provided me with a fresh look and inspiration to move on and further explore new ideas. I would also like to thank professors Spyros Tzamarias and Kostas Kordas for their guidance, their sharing of knowledge and their help to understand even the most complex theoretical or experimental issues; also for the useful comments and for the nice conversations on various topics. I could not have missed to express my gratitude to professor Dimitrios Sampsonidis for giving me the chance to be part of the construction team of the LM2 drift chambers for the ATLAS NSW project; it has been a great opportunity to participate in the technical construction giving me a whole new perspective in the experimental procedures and demands but also it was very nice to work in a pleasant and highly-educational environment. Many thanks to Dinos Bachas, Joany Manjarres-Ramos, Samira Hassani, Spyros Tzamarias and Kostas Kordas for the useful comments on my PhD work. I especially thank Joany for her guidance and mentoring through the WZ resonance analysis team and the really inspiring team spirit. I could not have skipped the rest of the WZ resonance analysis team members and especially Miaoran Lu and Abhishek Nag; thanks for the nice cooperation, the fruitful comments, the guidance and for helping me understand all the major/minor technical and physical aspects of the analysis. Many thanks to the ATLAS Dresden group and especially to Abhishek Nag, Tim Herrmann and Carsten Bittrich for all the time they have spent supporting and for patiently helping me to understand and use the analysis framework. Very special thanks to the whole ATLAS Thessaloniki group but especially to Ioannis Manthos, Ioannis Maniatis, Ioannis Karkanias, Alexandra Kalitsopoulou, Lily Maragkou, Eirini Kassimi, Christos Lampoudis, Panos Paschalias and Aggelos Tsiamis; it has been a great pleasure to work with all of you and thanks for the sharing of your knowledge and expertise.

I own gratitude to my mother Eleni, my father Marios and my sisters Chrisi and Eirini for their constant practical support and help with the care-taking of my children; this achievement could not have been done without your contribution. Finally, I would like to thank my husband

Nikos for the constant support and encouragement; thanks for always been there to listen my concerns and empowering me to accomplish my academic goals. I have trust in myself my because you have never stopped believing in me. But most of all thanks for the beautiful family we have made together; this accomplishment is dedicated to you and our sons.

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Chapter 1

Introduction

Since ancient times, people have tried to understand and tame the laws that overrule Nature; the establishment of physical laws was formed in order to explain the physical observation with terms that were familiar to the human perception. The perpetual search for explanations of Nature's complexity has resulted in numerous theoretical models; the reliability of the latter is certified by conducting experiments. Theoretical models boost the technological upgrade by demanding the development of cutting-edge laboratory facilities (f.e. Large Hadron Collider), while the technological growth spurt of the last century has given several theories high granularity (f.e. Standard Model).

Dating back to B.C. centuries, the natural theory of the "Atomism" appeared in both Greek (Democritus, Leucippus) and Indian philosophical currents. The perception that the Universe is composed of fundamental particles was further re-investigated in the 16th century by Galileo who suggested that all physical phenomena (except sound) are produced by "matter in motion". The idea that matter is composed of atoms was validated in 1930s when its subatomic constituents (electron, proton and photon) were fully identified with the assistance of Quantum Mechanics. Later, the Standard Model of particles that was finalized in mid-1970s with the experimental confirmation of the existence of quarks; it is a theory that describes the fundamental particles (elementary particles) of matter and their interactions. Although the observation of the W and Z bosons, the top quark, the tau neutrino and especially the Higgs boson attributed high credibility to the Standard Model, several unexplained phenomena like the baryon asymmetry, the incorporation of gravity and the existence of dark matter/energy have given rise to beyond Standard Model theoretical scenarios. As a result, the scientific challenge now is to test experimentally these theories (when possible) and investigate a possible extension or modification of the Standard Model targeting the formation of a more general "Theory of Everything".

Resonance searches are an independent probe to New Physics and particles, since they are included in various beyond Standard Model scenarios. In the present thesis we have performed a search for New Physics with the study of multi-lepton final states with the ATLAS Experiment at the LHC at CERN. More specifically, we have searched for the existence of a heavy resonance decaying into WZ in the fully leptonic channel (electrons and muons plus a neutrino) using the proton-proton collision data collected by the ATLAS experiment at the Large Hadron Collider at a center of mass energy of 13 TeV, corresponding to an integrated luminosity of 139 fb^{-1} . We have obtained limits on the production cross-section times branching ratio as a function of the resonance mass (and also of other alternative variables) for resonances that arise from two different models, the Heavy Vector Triplet (HVT) and Georgi-Machacek (GM) model, considering two different production modes - the Vector Boson Fusion and the Drell-Yan- on which independent limits are set.

The organization of the current thesis is briefly described below.

In Chapter 2 a short introduction of Standard Model is performed, accompanied by a presentation of the two beyond Standard Model theories (Heavy Vector Triplet and Georgi-Machacek Model) that are going to be later tested. In Chapter 3 we describe the main characteristics of the Large Hadron Collider and the ATLAS detector's technical aspects and functionalities; the New Small Wheel upgrade is presented giving special mention to the Micromegas detector (MM) where the author had significant contribution concerning the technical construction of the MM LM2 drift panels with the ATLAS team of the Aristotle University of Thessaloniki, performing the QA/QC measurements and tests and maintaining the team's logistic database. In Chapter 4 we describe the data and Monte Carlo samples (signals and backgrounds) used in the present analysis. In Chapter 5 the object reconstruction is described explicitly, where the author contributed to the optimization of the muon isolation working points and the outflow comparison of events between the two available analysis frameworks. In Chapter 6 we determine some basic kinematic variables that are going to be used in the present thesis and we refer to the event selection requirements for the establishment of the signal and control regions of interest (Drell-Yan and VBF). In Chapter 7 we determine the background sources of the WZ resonance search and we study the shape of corresponding control regions. In Chapter 8 the author has examined the existence of new sensitive variables in the search of New Physics phenomena besides the invariant mass of the WZ system that has been used in Run I, while Chapter 9 summarizes the sources of experimental systematic uncertainties. The theoretical uncertainties on the signals and the main backgrounds are separately mentioned in Chapter 10, where we have contributed with the calculation of the pdf, scale and parton shower uncertainties. A theoretical statistical introduction concerning the methods applied in LHC studies is done in Chapter 11. In Chapter 12 we present the likelihood template, the inputs to the fit and the statistical methods applied in the $X \rightarrow WZ \rightarrow l\nu ll$ search; we also present the binning optimization that we performed and the limits extraction using the invariant mass of the WZ

system but also the different new variables under investigation, for the different categories of signals (HVT and GM) and signal regions (Drell-Yan and VBF). In the last section of the same Chapter we have produced some comparison plots of the expected and observed limits for the Drell-Yan and VBF categories, as well as of the extracted normalization factors of the WZ-QCD and ZZ backgrounds given each time a 500 GeV signal mass point.

Chapter 2

Theoretical Introduction

2.1 The Standard Model : a brief introduction

The **Standard Model** (SM) of particle physics represents the heart of our understanding concerning the fundamental matter components of the Universe (elementary particles) and the interactions that are developed between them (forces). Developed in the early 1970s, it has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena [2], so it became established as a well-tested physics theory.

2.1.1 Fundamental Particles

The world around us seems to be formed from a few elementary particles that are the building blocks of matter; they are called so because they do not seem to be constructed of further smaller particles. These particles are categorized in two basic types called **quarks** and **leptons** (see p.1-4 in [3]). Each group consists of six particles that are organized in pairs that are called “generations”. The first generation consists of the lightest and most stable particles; for the quarks these are the “up” and the “down” quark, while for the leptons these are the “electron” and the “electron neutrino”. The second and the third generations consist of heavier particles that quickly decay to more stable ones; these are the “charm” and “strange” quark and then the “top” and “bottom (or beauty)” quark, while for the leptons these are “muon” and the “muon neutrino” and the “tau” and the “tau neutrino”.

The electron, the muon and the tau all have an electric charge and a sizeable mass, whereas the neutrinos are electrically neutral and have very little mass.

Quarks also carry an additional charge called “color” that is relevant to the strong interactions which binds them together into “colorless” particle states called hadrons ; every quark can appear in three different states called “red”, “green”, “blue”.

Quarks and leptons have a spin equal to $1/2$ and they obey to the Fermi-Dirac statistics and so they are called **fermions**.

2.1.2 Fundamental forces and their mediators

In nature, there are four fundamental forces : the strong, the weak, the electromagnetic and the gravitational force. They work over different ranges and have different strengths. More specifically, gravity is the weakest but it has an infinite range while the electromagnetic force also has infinite range but it is many times stronger than gravity. The weak and strong forces are effective only over a very short range and dominate only at the level of subatomic particles (see p.4-5 in [3]).

Particles of matter interact with each other by transferring discrete amounts of energy via exchanging **bosons** with each other; the latter have an integer spin and follow the Bose-Einstein statistics. So, each fundamental force has its own corresponding boson that acts like the mediator of the force : the strong force is carried by the “**gluon**”, the electromagnetic force is carried by the “**photon**”, the “**W**” and “**Z**” bosons are responsible for the weak force and the “**graviton**”, a spin-2 boson, should be the corresponding force-carrying particle of gravity (although not yet found). The Standard Model includes the electromagnetic, strong and weak forces and all their carrier particles, and explains well how these forces act on all of the matter particles. However, the most familiar force in our everyday lives, gravity, is not part of the Standard Model, as fitting gravity comfortably into this framework has proved to be a difficult challenge [2].

This happens because the quantum theory that is used to describe the micro world, and the general theory of relativity used to describe the macro world, are difficult to be incorporated into a single mathematical framework in the context of the Standard Model; but this does not downsize its credibility because for particle physics the effect of gravity at their scale is so weak , so it can be neglected.

Every particle is associated with an antiparticle of same mass and opposite charge, although some are their own antiparticle. A summary of the SM fermions and bosons is presented in figure 2.1.

Three Generations of Matter (Fermions)					
	I	II	III		
mass→	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0	±125 GeV/c ²
charge→	2/3	2/3	2/3	0	0
spin→	1/2	1/2	1/2	1	0
name→	u up	c charm	t top	γ photon	H Higgs- boson
Quarks	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	g gluon	
Leptons	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²	
	0	0	0	0	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z weak force	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²	
	-1	-1	-1	±1	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	W weak force	
					Bosons (Forces)

FIGURE 2.1: Standard Model elementary particles (fermions i.e. quarks and leptons) and force mediators (bosons) and their fundamental properties : mass, charge, spin.

2.1.3 Gauge Symmetries

Standard Model is a relativistic quantum field theory [4]; in this theory the laws that overrule particle physics phenomenology are a combination of quantum mechanics and relativity.

In physics, a **gauge theory** is a type of field theory in which the Lagrangian is invariant under local transformations according to certain smooth families of operations (Lie groups) [5]. In practical, there are transformations that are called **gauge symmetries** (and the corresponding fields are called **gauge fields**) that preserve some measurable physics properties.

When the Lagrangians [4, 6] are invariant under a transformation identically performed at every point in the space-time in which the physical processes occur, they are said to have a **global** symmetry [5], while **local** symmetries depend on the position. Each of the generators of the local gauge symmetry group is associated with a *massless* gauge boson.

Standard Model is a *renormalisable* [7] theory that relies on two basic concepts : the theory of the strong force, Quantum Chromodynamics (QCD) [8] and the Electroweak (EWK) theory

[9] that unifies the Quantum Electrodynamics (QED) of the electromagnetism with the weak force.

SM describes the electromagnetic, strong and weak interactions based on the following combination of local gauge symmetry groups :

$$U(1)_Y \times SU(2)_L \times SU(3)_C \quad (2.1)$$

where $U(1)_Y$ stands for the unitarity invariance of the electromagnetic field that describes the preservation of the weak hyper-charge (Y), $SU(2)_L$ stands for the conservation of the weak isospin, where only left-handed fields (L) are included and $SU(3)_C$ denotes the color (C) symmetry of QCD. The term $U(1)_Y \times SU(2)_L$ refers to the gauge symmetry of the electroweak force unification that was developed by Glashow, Salam and Weinberg in the 1960s [9, 10]; its spontaneous breaking down through the **Higgs mechanism** [11–13] gives rise to masses for the gauge bosons while maintaining the renormalisability of the theory.

From all the above it is obvious that the forces mediators described in subsection 2.1.2 are *gauge bosons*.

2.1.4 Standard Model weak sector and the Higgs mechanism

In the electro-weak unified theory developed by Glashow, Salam and Weinberg the $U(1)_Y \times SU(2)_L$ gauge group includes a massless iso-vector triplet $\vec{W}_\mu = W_\mu^{(1)}, W_\mu^{(2)}, W_\mu^{(3)}$ for the $SU(2)$ and a massless vector $\vec{B}_\mu$ for the $U(1)$.

The EWK interaction energy is described by the Lagrangian density; the latter includes the product of the fermion(quarks, leptons) currents with the $\vec{W}_\mu$ and $\vec{B}_\mu$ (see chapter 9.6 in [14]):

$$\mathcal{L}_{ewk}^{\vec{}} = g \vec{J}_\mu \cdot \vec{W}_\mu + g' J_\mu^Y \cdot B_\mu \quad (2.2)$$

where $\vec{J}_\mu$ and J_μ^Y represent the isospin and hyper-charge currents of the fermions and g/g' are the coupling constants with the $\vec{W}_\mu$ and $\vec{B}_\mu$ fields,

the hyper-charge is $Y = Q - I_3$ (Q : is the electric charge and I_3 : is the third component of the weak isospin vector)

and the hyper-charge current is $J_\mu^Y = J_\mu^{H/M} - J_\mu^{(3)}$, where $J_\mu^{H/M}$ is the electromagnetic current that conjugates with the charge Q and $J_\mu^{(3)}$ is the third component of the isospin current $\vec{J}_\mu$.

The physical gauge bosons consist of the charged particles $W_\mu^\pm$ and the electrically neutral Z_μ and A_μ (photon); the last one can be written as a linear combination of $W_\mu^{(3)}$ and B_μ :

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^{(1)} \mp iW_\mu^{(2)}), \quad (2.3)$$

$$W_\mu^{(3)} = \frac{gZ_\mu + g'A_\mu}{\sqrt{g^2 + g'^2}}, \quad (2.4)$$

$$B_\mu = \frac{-g'Z_\mu + gA_\mu}{\sqrt{g^2 + g'^2}} \quad (2.5)$$

If we define the weak mixing angle (or Weinberg angle) as :

$$\tan\theta_W = \frac{g'}{g} \quad (2.6)$$

the equations 2.4 and 2.5 gives us the two neutral bosons, the Z and the photon :

$$Z_\mu = W_\mu^{(3)}\cos\theta_W - B_\mu\sin\theta_W \quad (2.7)$$

$$A_\mu = W_\mu^{(3)}\sin\theta_W + B_\mu\cos\theta_W \quad (2.8)$$

Proven experimentally, the masses of the $W^\pm$, Z bosons and the fermions are non-zero, a fact that violates the gauge symmetry. In order to maintain the electroweak theory as gauge invariant and also introduce mass terms for the gauge bosons, we need to consider the case where a symmetry of the Lagrangian is not a symmetry of the vacuum, known as **Spontaneous Symmetry Breaking (SSB)**.

The **Higgs mechanism** stands for the SSB of the $SU(2)_L \times U(1)$ to a $U(1)$ subgroup; it is a process that describes how the particles gain their masses. According to the Nambu-Goldstone theorem [10, 15] the spontaneous breaking of a global symmetry results in the appearance of massless bosons. The Standard Model Higgs mechanism gives rise to three Goldstone bosons that will be required to provide the longitudinal degrees of freedom of the W^+ , W^- and Z bosons (see chapter 17.5.4 in [3]). In addition, after symmetry breaking, there will be (at least) one massive scalar particle corresponding to the field excitations in the direction picked out by the choice of the physical vacuum; this new degree of freedom is the complex $SU(2)$ doublet Higgs field.

As the Higgs mechanism is required to generate the masses of the electroweak gauge bosons, one of the scalar fields must be neutral, written as ϕ^0 and the other must be charged such that

ϕ^+ and $(\phi^+)^* = \phi^-$ give the longitudinal degrees of freedom of the W^+ and W^- . The minimal Higgs model consists of two complex scalar fields with four real components, placed in a weak isospin doublet (see chapter 17.5.4 in [3]) :

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2.9)$$

The corresponding Lagrangian is :

$$\mathcal{L}_{Higgs} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi) \quad (2.10)$$

where the last term stands for the Higgs potential :

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (2.11)$$

with μ being the mass parameter and λ being the Higgs self-coupling parameter.

The vacuum configurations are determined by minimizing the potential V and as a result for $\mu^2 < 0$, the potential has an infinite set of degenerate minima :

$$\phi^\dagger \phi = \frac{-\mu^2}{2\lambda} = \frac{v^2}{2} \quad (2.12)$$

After symmetry breaking ($\mu^2 < 0$), the neutral photon is required to remain massless, and therefore the minimum of the potential must correspond to a non-zero vacuum expectation value (v) only of the neutral scalar field ϕ^0 :

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}; v = \sqrt{\frac{-\mu^2}{\lambda}} \quad (2.13)$$

Perturbation theory can be constructed around this minimum by including the Higgs field ($h(x)$), which is zero when the system is at the lowest energy state :

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2.14)$$

After the SSB through the Higgs mechanism, three of the four gauge bosons (W^+ , W^- and Z boson) become massive, while the photon (γ) remains massless :

$$\begin{aligned}
M_\gamma &= 0 \\
M_W &= \frac{1}{2} \cdot g v \\
M_Z &= \frac{1}{2} v \cdot \sqrt{g^2 + g'^2} \\
M_{Higgs} &= \sqrt{2\lambda v^2}
\end{aligned} \tag{2.15}$$

where $v = (\sqrt{2}G_F)^{-1/2} = 246$ GeV, fixed by the Fermi coupling G_F .

Except from the gauge bosons, this mechanism gives masses to fermions as they couple to the Higgs field via Yukawa interactions. The Yukawa couplings of the fermions to the Higgs field are given by :

$$g_f = \sqrt{2} \frac{m_f}{v} \tag{2.16}$$

where m_f stands for the fermion mass. And the Feynman rule for the interaction vertex with a fermion is :

$$-i \frac{m_f}{v} \equiv -i \frac{m_f}{2M_W} g \tag{2.17}$$

More details on the fermions mass generation can be found here (see chapter 17.5.5 - 17.6 in [3]).

In Figure 2.2 we present the Feynman diagrams of the Higgs coupling to the gauge bosons, while on Figure 2.3 Feynman diagrams of the Higgs coupling to a fermion of mass m_f [16].

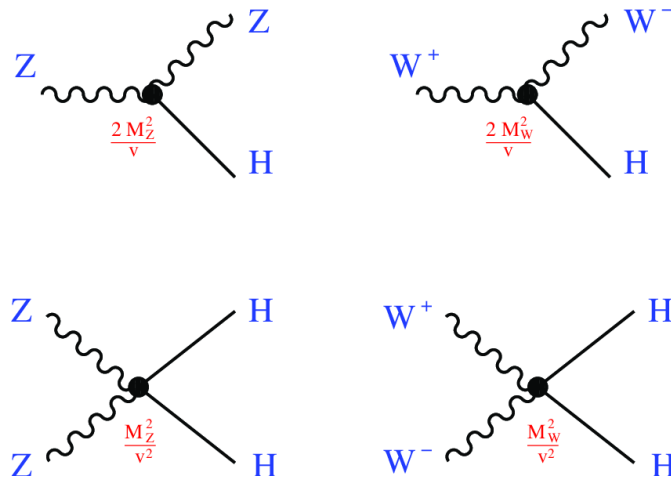


FIGURE 2.2: Feynman diagrams of the Higgs coupling to the gauge bosons.

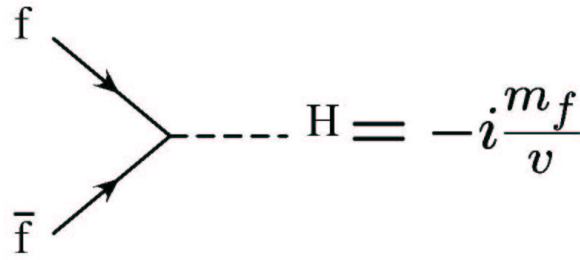


FIGURE 2.3: Feynman diagrams of the Higgs coupling to a fermion of mass m_f .

In 1973, physicists working with the Gargamelle bubble chamber at CERN presented the first direct evidence of the weak neutral current [17], which further led to the discovery of the W and Z bosons in 1983 [18].

The recent observation (2012) of a neutral, spin - 0 particle of mass $M_{Higgs} = 125.1$ GeV was compatible to the Standard Model Higgs boson ; this discovery was achieved by the combined efforts of the ATLAS [19] and CMS [20] experiments at the LHC and is an important validation of the Standard Model theory.

2.2 Models beyond the Standard Model

After the Higgs boson discovery, there is no particle with definite properties (spin, color, charge, mass) that we are still looking for. In other words, all features of the world around us can be derived, in principle, from the quarks, leptons and interactions of the SM.

But, there are observations and inefficiencies of the SM that lead us in the search for new physical theories beyond SM. For example, the SM predicts stable and massless neutrinos, contrary to the observation of solar neutrinos that oscillate between flavours, a fact that indicates the existence of non-zero mass [21, 22]. Furthermore, SM does not incorporate gravity and is able to describe only around 5 % of the energy content of the Universe, as dark matter and energy completely dominate it. Moreover, SM does not provide explanation of why there are three generations of fermions with large mass hierarchy and also it is unable to describe physics at high energies near the Planck Scale (10^{19} GeV).

In order to explain the deficiencies of the SM, we could assume that the SM is a low energy limit of a more fundamental higher energy theory. Several theoretical scenarios exist; here we are going to present the **Georgi-Machacek Model** (GM), which is a model that extends the SM Higgs sector, and the **Heavy Vector Triplet Model** (HVT) ,which includes new heavy vector resonances by using a parametrized SM Lagrangian ; these models are going to be later tested experimentally with data form the ATLAS detector as presented in Chapter 11.

2.2.1 Georgi-Machacek Model

2.2.1.1 Introduction

There are extensions of the SM Higgs sector that contain scalars in triplet or larger isospin representations and that preserve the custodial symmetry in the scalar sector; these generically contain fermiophobic scalars that transform as a fiveplet under the custodial symmetry. These custodial-fiveplet scalars play an essential role in the unitarity of vector boson scattering amplitudes [23–25]. The coupling strength of the custodial-fiveplet scalars to VV is proportional to the vacuum expectation value (vev) carried by the higher-isospin representation(s) (see p. 571[26]).

Experiments performed at LHC at CERN have sensitivity to the production and decay modes of the fermiophobic custodial-fiveplet states : H_5^{++} , H_5^+ , H_5^0 , H_5^- , H_5^{--} through their tree-level couplings to W and Z bosons pairs. In the present analysis we are going to study only the production of $H_5^\pm$ via vector boson fusion (VBF) decaying into $W^\pm Z$ pairs.

In the Georgi-Machacek (GM) model [27, 28] the SM Higgs sector is extended by two isospin triplets, while preserving the custodial SU(2) symmetry, avoiding stringent constraints from the ρ parameter. The latter is a measure of the relative strengths of the charged and neutral current interactions and is related at tree-level to the W and Z boson masses by the equation :

$$\rho = \frac{M_W^2}{\cos^2\theta_W M_Z^2} (=1 \text{ for SM}) \quad (2.18)$$

These GM higgs bosons are different from the one predicted by other BSM theories like two Higgs doublet models (2HDMs) or singlet extensions of the SM. First of all, they do not couple to fermions and as a result they cannot be produced in gluon fusion or in association with a top quark.

Secondly, the singly-charged higgs scalars $H_5^\pm$ couple to $W^\pm Z$ at tree level, while for the charged scalar of the 2HDM this coupling appears only at one loop. Moreover, the relative coupling strengths of H_5^0 to W^+W^- and ZZ are different than those of the SM Higgs boson, leading to $(H_5^0 \rightarrow W^+W^-)/(H_5^0 \rightarrow ZZ) \rightarrow 1/2$ in the high-mass region, contrary to the SM expectation of $(h_{SM} \rightarrow W^+W^-)/(h_{SM} \rightarrow ZZ) \rightarrow 2$. Finally, the presence of a doubly-charged Higgs boson with decays to like-sign W bosons is an important indication for the existence of isospin representations larger than doublets that contribute to electroweak symmetry breaking (see p.572 [26]).

In Figure 2.4 we present the Feynman diagram of the production of a heavy GM $H_5^\pm$ resonance via vector boson fusion (VBF) and its decay to W and Z bosons, that subsequently decay to $l^+l^-l^\pm\nu$ (decay channel of interest for the present analysis).

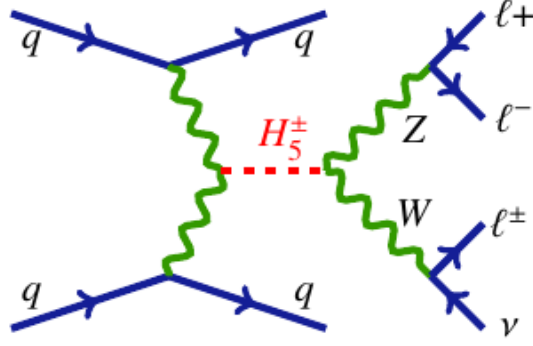


FIGURE 2.4: Feynman diagram of the production of a heavy GM $H_5^\pm$ resonance via vector boson fusion (VBF) and its decay to W and Z bosons, that subsequently decay to $l^+ l^- l^\pm \nu$.

2.2.1.2 Model parametrization

The scalar sector of the GM model includes the usual complex isospin doublet (ϕ^+, ϕ^0) (higgs bi-doublet) with hypercharge $Y=1$ (which is responsible for the SM fermion masses), a real triplet (ξ^+, ξ^0, ξ^-) with $Y=0$ and a complex triplet $(\chi^{++}, \chi^+, \chi^0)$ with $Y=2$.

The scalar potential is chosen (by hand) to preserve a global $SU(2)_L \times SU(2)_R$ symmetry in order to keep $\rho = 1$ at tree level. One can write the doublet in the form of a bi-doublet Φ and combine the triplets in order to form a bi-triplet X :

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^{+*} & \phi^0 \end{pmatrix}, X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix} \quad (2.19)$$

With the help of the Fermi constant G_F the vacuum expectation values' combination is given by (Eq. IV.4.18 [26], [27]):

$$v_\phi^2 + 8v_\chi^2 \equiv v^2 = \frac{1}{\sqrt{2}G_F} \approx (246 \text{ GeV})^2 \quad (2.20)$$

We decompose the neutral fields into into real and imaginary parts :

$$\phi^0 \rightarrow \frac{v_\phi}{\sqrt{2}} + \frac{\phi^{0,r} + i\phi^{0,i}}{\sqrt{2}}, \chi^0 \rightarrow v_\chi + \frac{\chi^{0,r} + i\chi^{0,i}}{\sqrt{2}}, \xi^0 \rightarrow v_\chi + \xi^{0,r} \quad (2.21)$$

After the symmetry breaking the physical fields can be organized into a fiveplet (H_5), a triplet (H_3) and two singlets (H_1 and H_1') (Eq. IV.4.23 in [26], [27]) :

$$H_5^{\pm\pm} = \chi^{\pm\pm}, H_5^\pm = \frac{(\chi^\pm - \xi^\pm)}{\sqrt{2}}, H_5^0 = \sqrt{\frac{2}{3}}\xi^{0,r} - \sqrt{\frac{1}{3}}\chi^{0,r} \quad (2.22)$$

$$H_3^\pm = -s_H\phi^\pm + c_H\frac{\chi^\pm + \xi^\pm}{\sqrt{2}}, H_3^0 = -s_H\phi^{0,i} + c_H\chi^{0,i} \quad (2.23)$$

$$H_1 = \sqrt{\frac{1}{2}}(\phi^0 + \phi^{0*}), H_1' = \sqrt{\frac{1}{3}}\xi^0 + \sqrt{\frac{2}{3}}\chi^{0,r} \quad (2.24)$$

where $\phi^- = \phi^{+*}$, $\chi^- = \chi^{+*}$, $\chi^{--} = \chi^{++*}$, $\xi^- = \xi^{+*}$ and the vacuum expectation values (vev) are parametrized using the mixing angle θ_H :

$$c_H \equiv \cos\theta_H = \frac{v_\phi}{v}, s_H \equiv \sin\theta_H = \frac{2\sqrt{2}v_\chi}{v} \quad (2.25)$$

The theoretical parameter s_H^2 represents the fraction of the gauge boson masses squared (M_W^2 and M_Z^2) that is generated by the vev of the triplets. On the other hand, the parameter c_H^2 represents the fraction generated by the usual Higgs doublet.

The states of the custodial fiveplet have a common mass m_5 and the states of the custodial triplet have a common mass m_3 as shown in Equations (IV.4.27 nad IV.4.28) in [26].

The two custodial singlets mix by an angle α and result in the following mass eigenstates :

$$h = \cos\alpha\phi^{0,r} - \sin\alpha H_1', H = \sin\alpha\phi^{0,r} + \cos\alpha H_1' \quad (2.26)$$

where we denote their masses by m_h and m_H respectively, with $m_h = 125$ GeV being the SM Higgs boson discovered at LHC [19, 20].

The fiveplet H_5 is fermiophobic and couples nearly exclusively to vector bosons and is therefore an ideal candidate for Vector Boson Fusion searches. All the $H_5 \rightarrow VV$ couplings are proportional to s_H (see Eq. IV.4.34 in [26]), so the VBF production cross sections and decay widths are expected to be proportional to s_H^2 . If the spectrum is such that decays of $H_5 \rightarrow H_3V$ or $H_5 \rightarrow H_3H_3V$ are forbidden, the total decay widths of the $H_5 \rightarrow VV$ depend only on m_5 and s_H .

2.2.1.3 H5plane benchmark for the Georgi-Machacek Model

The H5plane benchmark was developed to facilitate the H_5 searches over the $m_5 - s_H$ plane; these are treated as free parameters and can be varied. Other parameters are chosen so that $m_3 > m_5$ (in order to kinematically avoid the $H_5 \rightarrow H_3V$ or $H_5 \rightarrow H_3H_3V$ decays) and to

keep the largest possible parameters region for $200 \text{ GeV} < m_5 < 3000 \text{ GeV}$. For this H5plane benchmark we have used the spectrum calculator GMCALC [29]. More details about GMCALC input parameters can be found in section IV.4.4.b in [26].

One important constraint arises from the perturbative unitarity of $VV \rightarrow VV$ scattering amplitude :

$$s_H^2 \lesssim \left(\frac{667 \text{ GeV}}{m_5} \right)^2 \quad (2.27)$$

for $m_5 \gg m_W, m_Z, m_h$. This implies that $\Gamma(H_5 \rightarrow VV) \lesssim 0.10 m_5$ for each of the H_5 states, after taking into account the full set of perturbative unitarity constraints [30, 31].

The production cross-sections for different values of s_H are calculated by :

$$\sigma^{NNLO}(VBF \rightarrow H_5) = s_H^2 \sigma_1^{NNLO}(VBF \rightarrow H_5) \quad (2.28)$$

where σ_1^{NNLO} represents the NNLO cross section for $s_H = 1$. Similarly, the decay widths for different s_H values are estimated using the decay width Γ_1 calculated for $s_H = 1$.

$$\Gamma(H_5 \rightarrow VV) = s_H^2 \Gamma_1(H_5 \rightarrow VV) \quad (2.29)$$

2.2.2 Heavy Vector Triplet Model

Before developing the idea of the Heavy Vector Triplet (HVT) model it is necessary to introduce the general strategy behind it, which is the **Simplified Model** approach developed below.

In order to explore the possible existence of New Physics which consists of the production of narrow new particles, we should keep in mind that these resonance searches are only sensitive to parameters that are correlated to the mass of the resonance and to interactions involved in its production and decay. As a result, we can establish a *phenomenological* Lagrangian [32] in order to describe the new resonance, including only mass parameters and relevant couplings. The experimental results are going to be presented in terms of a likelihood function. We have to keep in mind though that the Simplified Model is not a complete theory as f.e. is the SM, so it should only be used in its region of validity which is the *on-shell* resonance production and decay. In conclusion, the Simplified Lagrangian connects the phenomenological parameters and the experimental data; the parameters of the model can predict experimental observations and inversely, the experimental measurements can introduce constraints on parameters of an explicit model that is studied.

As an example of a Simplified Lagrangian, we study the case of electroweak-charged spin-1 heavy resonances that are called Heavy Vector Triplets (HVT). In this model, in addition to the

known SM fields and interactions, a real vector V_μ^α , $\alpha = 1, 2, 3$ in the adjoint representation of $SU(2)_L$ is considered. It represents two charged and one electrically neutral heavy spin-1 particles, with charge eigenstate fields defined as :

$$V_\mu^\pm = \frac{V_\mu^1 \mp iV_\mu^2}{\sqrt{2}}, \quad V_\mu^0 = V_\mu^3 \quad (2.30)$$

Described in [32], the new vector boson dynamics is represented by a simple phenomenological Lagrangian :

$$\begin{aligned} \mathcal{L}_V = & -\frac{1}{4}D_{[\mu}V_{\nu]}^\alpha D^{[\mu}V^{\nu]\alpha} + \frac{m_V^2}{2}V_\mu^\alpha V^{\mu\alpha} \\ & + ig_V c_H V_\mu^\alpha H^\dagger \tau^\alpha \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^\alpha J_F^{\mu\alpha} \\ & + \frac{g_V}{2} c_{VVV} \epsilon_{abc} V_\mu^\alpha V_\nu^b D^{[\mu}V^{\nu]c} + g_V^2 c_{VVHH} V_\mu^\alpha V^{\mu\alpha} H^\dagger H - \frac{g}{2} c_{V VW} \epsilon_{abc} W^{\mu\nu\alpha} V_\mu^b V_\nu^c \end{aligned} \quad (2.31)$$

where g denotes the $SU(2)_L$ gauge coupling, $\tau^\alpha = \sigma^\alpha/2$ are the Pauli matrices and ϵ_{abc} is the structure constant of the particular gauge group.

The first line in the above equation presents the kinetic and mass term of the V boson and also trilinear and quadrilinear interactions with the vector bosons.

The second line includes the direct interactions of V with the Higgs current and with the SM left handed fermionic currents :

$$J_F^{\mu\alpha} = \sum_f \bar{f} \gamma^\mu \tau^\alpha f_L \quad (2.32)$$

In this line, the parameter c_H controls the interactions of the boson V with the physical Higgs field (more specifically its decays into SM bosons) and with the SM W and Z vector bosons. The parameter c_F presents the direct interaction of V with fermions, responsible for both its fermionic decays and its production via quark-antiquark annihilation (Drell-Yan) process. Actually as presented here it is generalization for different couplings to leptons, light quarks, and third-generation quarks taking into account the corresponding currents:

$$c_F V \cdot J_F \rightarrow c_l V \cdot J_l + c_q V \cdot J_q + c_3 V \cdot J_3 \quad (2.33)$$

The parameter c_F is of order one and c_H is of order one in the strongly-coupled scenario but can be lower in the weakly-coupled scenario.

The third line in the above equation inserts the parameters c_{VVV} , c_{VVHH} and $c_{V VW}$; these are disregarded since they do not contain vertices of one V with light SM fields or of single

production processes so they are irrelevant with LHC searches. Actually they do affect the above processes only through the mixing of V with the W , but since the mixing is typically small their effect is marginal.

Finally, in the above equation we use the parameter g_V that represents the typical strength of V interactions and the dimensionless coefficients “ c ”parametrize the departure from the typical size; the parametrization of the fermion couplings is an exception to this rule, where we introduce an extra factor of g^2/g_V^2 . The parameter g_V can vary over one order of magnitude from a weakly-coupled scenario ($g_V \approx 1$) up to the extreme strong limit where $g_V \approx 4\pi$.

Taking into account all the above, the whole phenomenological model can be parametrized by using the c_H , the three c_F parameters plus the mass term of the new heavy vector m_V .

If we call W' (Z') the electrically charged (neutral) heavy resonance with mass $M_{\pm}$ (M_0) we obtain a generalized custodial relation among physical masses (sim. to Eq. 2.18 in [32]):

$$M_W^2 M_{\pm}^2 = \cos^2 \theta_W M_Z^2 M_0^2 \quad (2.34)$$

With this model, our goal is to describe new vectors at or above the TeV scale, but also be able to reproduce the SM $M_{W,Z} \approx 100$ GeV masses. This is possible via applying a hierarchy in the mass spectrum :

$$\frac{\hat{M}_{W,Z}}{\hat{M}_V} \sim \frac{M_{W,Z}}{M_{\pm,0}} \lesssim 10^{-1} \ll 1 \quad (2.35)$$

Also, it is found that the charged and neutral heavy vectors are degenerate and thus they have comparable production rates at the LHC.

Concerning the decay widths, the relevant decay channels are di-lepton, di-quark and di-boson. All the couplings to fermions are controlled by the parameter $g^2/c_F g_V$. The partial width to fermions is given by:

$$\Gamma_{V_{\pm} \rightarrow f \bar{f}'} \approx 2\Gamma_{V_0 \rightarrow f \bar{f}} \approx N_c[f] \left(\frac{g^2 c_F}{g_V} \right)^2 \frac{M_V}{48\pi} \quad (2.36)$$

where $N_c[f]$ stands for the number of colors thus is equal to 3 for the di-quark and to 1 for the di-lepton decays.

For the di-boson case, we take into account the “Equivalence Theorem”[33] where in the high energy regime, the longitudinal polarization will dominate and the coupling to the Higgs boson c_H , will be the same as to the SM gauge bosons W and Z . So the corresponding partial width is :

$$\Gamma_{V_0 \rightarrow W_L^+ W_L^-} \approx \Gamma_{V_{\pm} \rightarrow W_L^{\pm} Z_L} \approx \frac{g_V^2 c_H^2 M_V}{192\pi} \quad (2.37)$$

As far as the production rate is concerned, the cross section of both production mechanisms i.e. Drell-Yan and VBF is found to be proportional to the partial width $\Gamma_{V \rightarrow ij}$:

$$\sigma(pp \rightarrow V + X) \propto \sum_{i,j \in p} \frac{\Gamma_{V \rightarrow ij}}{M_V} \quad (2.38)$$

where with $i, j = \{q, \bar{q}, W, Z\}$ we denote the colliding partons in the two protons.

In Figure 2.5 we present the Feynman diagram of the production of a heavy W' resonance via Drell-Yan (left) and vector boson fusion (VBF) (right) modes and its decay to W and Z bosons, that subsequently decay to $l^+ l^- l^\pm \nu$ (decay channel of interest for the present analysis).

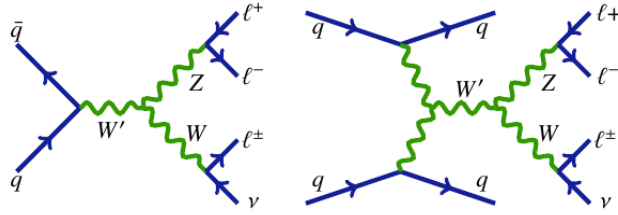


FIGURE 2.5: Feynman diagram of the production of a heavy W' resonance via Drell-Yan (left) and vector boson fusion (VBF) (right) modes and its decay to W and Z bosons, that subsequently decay to $l^+ l^- l^\pm \nu$

2.2.2.1 Explicit Models

We describe three explicit models, Model A, Model B and Model C of the Simplified Model that have been used as benchmark models for our analysis. **Model A** describes a vector triplet emerging from an underlying weakly-coupled extension of the SM gauge group [34]. **Model B** is about a vector triplet considered in the strongly coupled Composite Higgs scenario [35] and finally, **Model C** describes a vector triplet produced by vector boson fusion.

Model A In this model we consider the extended gauge theory $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ [34] and the SM fermions are charged under the $SU(2)_1$ and $U(1)_Y$, preserving their usual quantum numbers. An additional scalar field Φ is introduced that transforms as a real bi-doublet $(2,2)_0$. When Φ obtains a vacuum expectation value f :

$$\langle \Phi \rangle = \begin{pmatrix} f & 0 \\ 0 & f \end{pmatrix} \quad (2.39)$$

the $SU(2)_1 \times SU(2)_2$ symmetry is broken into the $SU(2)_L$ gauge group. After the field re-definition and the mass mixing, we identify the SM W boson field and the heavy vector triplet (V).

The coupling are of the order :

$$c_H \sim -g^2/g_V^2 \quad c_F \sim 1 \quad (2.40)$$

which leads to the partial width of the $V_{\pm}$ to fermions, Eq. 2.36, being comparable to the one of the gauge bosons in Eq. 2.37.

Model B This model relies on the Minimal Composite Higgs Model [36] where the Higgs doublet emerges from the spontaneous breaking of the global $SO(5)$ symmetry to an $SO(4)$ subgroup. More specifically, this Higgs “light” state is a result of an underlying strong dynamics that predicts the existence of heavy vector resonances with electroweak quantum numbers that strongly couple to gauge bosons. Here the couplings to bosons and fermions both are comparable of the order one :

$$c_H \sim c_F \sim 1 \quad (2.41)$$

As a result, the partial width Γ to gauge bosons in Eq. 2.37 , will dominate over to that of fermions Eq. 2.36.

Model C This is a new model defined to examine a scenario where there is no coupling of the heavy vectors to fermions. It is required that $c_F = 0$, so it couples exclusively to vector bosons, making it an ideal candidate for VBF searches. In this analysis, the HVT masses are excluded for this model with $g_V \cdot c_H$ parameters product set to 1.0, 1.5 and 2.0 respectively.

Chapter 3

The Large Hadron Collider and the ATLAS Experiment

3.1 The Large Hadron Collider (LHC)

The **Large Hadron Collider** (LHC) is the most powerful particle accelerator; it is a particle accelerator that pushes protons or ions (hadrons) to near the speed of light and collides them after organizing them in two beams travelling in opposite directions. It consists of a 27-kilometre ring of superconducting magnets with a number of accelerating structures that boost the energy of the particles along the way, located in a tunnel 100 metres underground at the European Organization for Nuclear Research (CERN), on the Franco-Swiss border near Geneva, Switzerland [37].

3.1.1 The LHC accelerating complex and detectors

The LHC is the last element of the CERN accelerator complex chain (Figure 3.1); the latter is a group of machines with increasingly higher acceleration energies (each machine accelerates a beam of particles to a given energy before injecting the beam into the next machine in the chain), making the beams to reach their highest energy at the LHC ring [37].

Inside the LHC, two particle beams travel at opposite directions in separate beam pipes (two tubes kept at ultrahigh vacuum) close to the speed of light before they are made to collide, guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. The first collisions were achieved in 2010 at an energy of 3.5 TeV and later 4 TeV per beam (Run 1); after upgrades it reached 6.5 TeV per beam ($\sqrt{s} = 13$ TeV collision energy at the center of mass system, called Run 2). At the end of 2018, the last shutdown for

maintenance and upgrade reasons took place, aiming to reach the $\sqrt{s} = 14$ TeV energy at the center of mass system by restarting for Run 3 in 2022. The corresponding integrated luminosity for these energies was 6.1 fb^{-1} for $\sqrt{s} = 7$ TeV, 23 fb^{-1} for $\sqrt{s} = 8$ TeV and 139 fb^{-1} for $\sqrt{s} = 13$ TeV (years from 2015-2018). Such an unprecedented high energy and luminosity 3.1.2 environment enables the LHC to extend the frontiers and answer unresolved questions of particle physics.

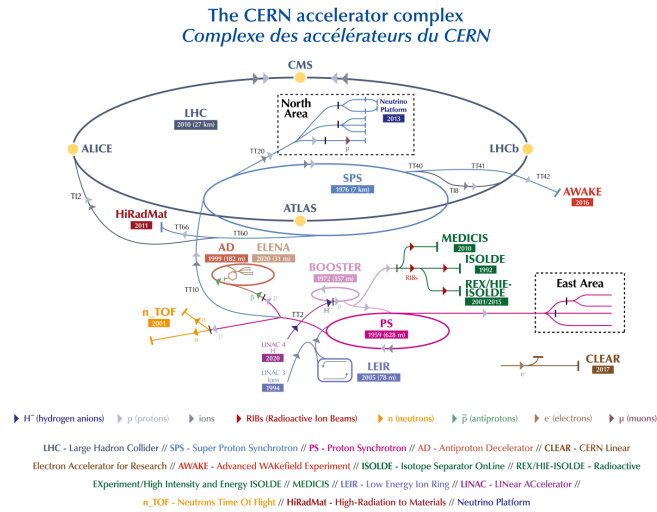


FIGURE 3.1: Presentation of the LHC accelerating complex.

At the collision points of the accelerated particles, eight detector systems are established, with four of them being the main experiments of LHC :

- **ATLAS (A Torroidal LHC ApparatuS)**: a general purpose detector that focuses on High-Energy Physics studies [38] .
- **CMS (Compact Muon Solenoid)**: same as ATLAS, a general purpose detector that contributes to general research in the field of High-Energy Physics [39].
- **ALICE (A Large Ion Collider Experiment)** : a detector for heavy-ion collisions, that aims to study the physics of strong interactions and the quark-gluon plasma at extreme values of energy density and temperature [40].
- **LHC-b**: a detector designed for b-quark physics studies [41].

that are accompanied with four smaller systems performing a more specialized research :

- **TOTEM (TOTal Elastic and diffractive cross-section Measurement)** that focuses on total proton-proton cross section and diffraction measurements [42].

- **MoEDAL** (**Monopole and Exotics Detector At the LHC**) that focuses on specialized particle searches [43].
- **LHCf** (**Large Hadron Collider forward**) that studies especially forward particles [44].
- **FASER** (**ForwArd SEarch ExpeRiment**) that searches for exotic weak-interacting and high-energy neutrinos [45].

3.1.2 The LHC luminosity

In pp collisions, a crucial parameter is the **instantaneous luminosity** $\mathcal{L}$, which associate the event production rate R and cross section under study σ :

$$R = \mathcal{L} \times \sigma \quad (3.1)$$

This parameter $\mathcal{L}$ can be calculated from the knowledge of the parameters of the colliding beams. More specifically, the particles in an accelerator are grouped into bunches that are brought into collision at one or more interaction points (IP) where the detectors are located; for the LHC, the bunches are separated by 25 ns (for $\sqrt{s} = 13$ TeV), corresponding to a collision frequency of $f = 40$ MHz. Assuming that the beams have a Gaussian profile and collide head-on and if we consider that the number of particles in the colliding bunches are n_1 and n_2 , f is the revolution frequency, n_b is the number of bunches colliding at the interaction point and Σ_x and Σ_y are the horizontal and vertical beam profiles, the instantaneous luminosity is given by [46]:

$$\mathcal{L} = f \frac{n_1 n_2 n_b}{2\pi \Sigma_x \Sigma_y} \quad (3.2)$$

The **integrated luminosity** is obtained, by integrating the instantaneous luminosity over the accelerator active time, and it associates the total number of produced events N_{tot} to the pp cross-section :

$$N_{tot} = \sigma \cdot \int \mathcal{L} dt \quad (3.3)$$

3.2 The ATLAS detector

The ATLAS detector is a general purpose experimental facility which means that it is not designed to focus only on a specific physics procedure; with its assistance we can validate the expectations of the Standard Model but also search for new physics signals. It is designed in a way to be able to detect the particles produced in pp collisions at the LHC. ATLAS is the biggest detector of this kind, having a cylindrical shape with diameter of 25 m, length of 46 m, weight

over 7000 t and solid angle coverage of almost 4π . ATLAS consists of different sub-detectors piled up from inside to outside, to keep track of the momentum, trajectory and power of particles in order to identify and reconstruct them properly. Also, it includes a large magnet system that curves the trajectories of the particles, so their momenta can be estimated and evaluated precisely. The particles that emerge due to the collisions in the transverse plane to the beam direction can be identified in the barrel part, while particles close to the beam are detected by so-called end-caps. In this section we are presenting a very brief introduction on the basic operational structures of the ATLAS detector.

The main components of the ATLAS detector that are going to be later presented with more details in following sub-sections are :

- the **Inner detector**
- the **Caloreimeters** (hadronic and electromagnetic)
- the **Muon spectrometer**
- the **Magnet system**

In Figure 3.2 we can view the ATLAS detector with its main components and sub-detector systems.

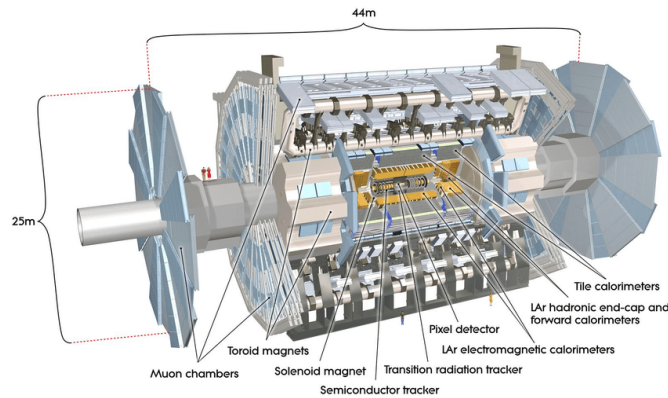


FIGURE 3.2: ATLAS detector with its main components and sub-detector systems.

3.2.1 ATLAS coordinate system

As the origin of the coordinate system in the ATLAS detector, we define the nominal interaction point (IP); the beam direction defines the z -axis and the x - y plane is transverse to the beam direction. The positive x -axis is defined as pointing from the interaction point to the centre

of the LHC ring while the positive y -axis is defined as pointing upwards. The side-A of the detector is defined as that with positive z and side-C is that with negative z (see p. 1 [38]). The azimuthal angle ϕ is measured around the beam axis and the polar angle θ is the angle from the beam axis 3.3 from Fig. 3.2 in [47].

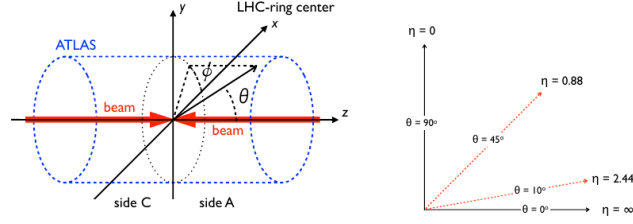


FIGURE 3.3: The coordinate system used in ATLAS detector (left) and the correspondence between the pseudorapidity η and the polar angle θ for some values (right.)

Pseudorapidity is defined as :

$$\eta = -\ln \tan(\theta/2) \quad (3.4)$$

In the case of massive objects such as jets, the **rapidity** is used :

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (3.5)$$

where E is the energy and p_z is the component of particle's momentum along the beam axis. Finally, the distance ΔR in the pseudorapidity-azimuthal angle space is defined as :

$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \quad (3.6)$$

3.2.2 Inner Detector

First of all, the Inner Detector (ID) is designed to provide excellent pattern recognition, momentum resolution and primary and secondary vertex measurements for charged tracks above a given p_T threshold (usually 0.5 GeV, but can be 0.1 GeV in some studies of initial measurements with minimum-bias events) and within the pseudorapidity range $|\eta| < 2.5$. Also, it provides electron identification over $|\eta| < 2$ and a wide range of energies (between 0.5 GeV and 150 GeV). The information of the momentum and the charge of the collision produced particles is obtained via their interaction with the detector material and the curvature of their tracks provoked by a 2T solenoidal magnetic field that surrounds the ID. A schematic representation of the ID is shown in Figure 3.4.

The main components of the Inner Detector as shown in Figure 3.5 are ([48] and Chapter 4 in [38]):

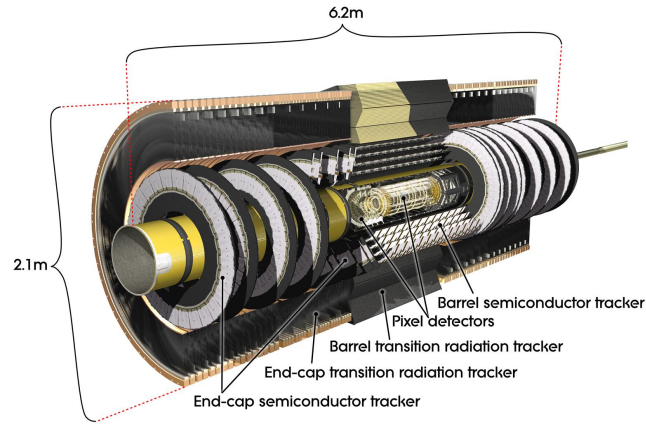


FIGURE 3.4: A schematic representation of Inner Detector (ID).

- **Pixel Detector** : It is located 3.3 cm from the LHC beam line; as a result, it is the first point of detection in the ATLAS experiment. It consists of four layers of silicon pixels. The low energy deposits left from the collision-produced charged particles are recorded in the Pixel Detector; these signals are measured with a precision of almost $10\mu m$ to determine the origin and momentum of the particle.
- **Semiconductor Tracker (SCT)** : It surrounds the Pixel Detector and is used to detect and reconstruct the tracks of charged collision-produced particles. It has over 4,000 modules of 6 million “micro-strips” of silicon sensors and it is designed so that each particle crosses at least four layers of silicon, allowing to measure particle tracks with a precision of up to $25\mu m$.
- **Transition Radiation Tracker (TRT)** : It is made up of 300,000 thin-walled drift tubes (called “straws”); each of them has a $4mm$ diameter, with a $30\mu m$ gold-plated tungsten wire in its centre. All these straws are filled with a gas mixture (70% Xe , 27% CO_2 , and 3% O_2) and as charged particles cross through them, they ionise the gas to create a detectable electric signal. The latter is useful for the reconstruction of the particle tracks and for the identification of the particle type that flew through the detector. More specifically, the drift time of electrons originating from the ionization and collected at the wire, provides discrimination between tracking hits and hits from *transition radiation* (radiation emitted by charged particles in the X-ray regime when traversing the between two materials that have different dielectric properties), an important feature for the electrons identification and their discrimination against pions.

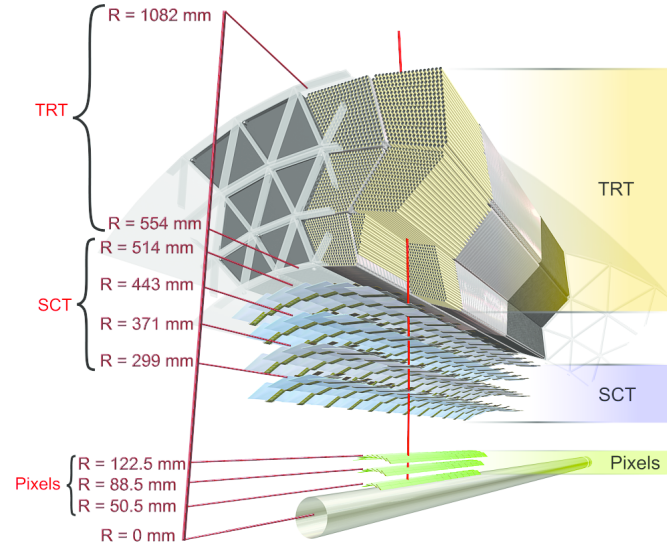


FIGURE 3.5: A representation of the Inner Detector with its main components and their distances from the Interaction Point (IP).

3.2.3 Calorimeters

The ATLAS calorimeter system is designed to absorb most of the particles coming from a collision, by forcing them to deposit all of their energy (by using an “active” medium that measures their energy) and by stopping them within the detector (by using “absorbing” high-density material layers). Particles like electrons and photons that interact with matter deposit their energy to the **electromagnetic calorimeter**, while **hadronic calorimeters** measure the energy of hadrons (particles that contain quarks) as they interact with atomic nuclei. The only particles that can escape from the calorimeters are the muons and the neutrinos.

The ATLAS calorimeters consist of a number of sampling detectors with full ϕ -symmetry and coverage around the beam axis. The calorimeters closest to the beam-line are housed in three cryostats, one barrel and two end-caps (p. 110 in [38]). The barrel cryostat includes the electromagnetic barrel calorimeter and each of the two end-cap cryostats contains an **electromagnetic end-cap calorimeter (EMEC)**, a **hadronic end-cap calorimeter (HEC)**, located behind the EMEC, and a **forward calorimeter (FCal)** (in order to cover the region closest to the beam). The active detector medium for the above is liquid argon, which presents stable response over time and intrinsic radiation-hardness.

This *Liquid Argon (LAr) Calorimeter* surrounds the ATLAS ID and measures the energy of electrons, photons and hadrons with the following procedure: layers of metal (either tungsten, copper or lead) absorb incoming particles, converting them into a new lower energy particle shower (via Bremsstrahlung irradiation as well as electron-positron pair). These subsequent particles ionise liquid argon that exists between the layers, resulting in a measurable electric

current. Then the energy of the original particle is determined by combining all of the detected currents.

For the electromagnetic calorimeter, the barrel region covers the range $|\eta| < 1.475$ and the two end-cap regions cover the range $1.375 < |\eta| < 3.2$. Also, this subsystem is the most precise on spatial and energy information measurements.

On the other hand, the hadronic is a *Tile Calorimeter* that surrounds the LAr calorimeter and measures the energy of hadronic particles, which do not deposit all of their energy in the LAr Calorimeter. Here the sampling medium consists of scintillator tiles and the absorber medium is steel. When particles hit the layers of steel, they generate a shower of new particles and then the plastic scintillators in turn produce photons, which are converted into an electric current whose intensity is proportional to the original particle's energy. Moreover, the tile calorimeter is composed of three parts, one central barrel and two extended barrels covering the range of $0 < |\eta| < 1.7$. Also, the hadronic calorimetry is extended to larger pseudorapidities by the HEC and the FCal reaching a coverage over $|\eta| < 4.9$. The hadronic calorimeter plays crucial role in jet identification and also missing transverse energy (E_T^{miss}) determination.

Figure 3.6 shows the ATLAS calorimeter and its subsystems.

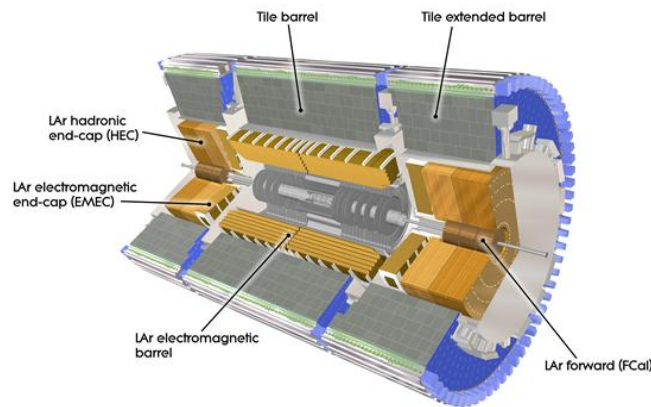


FIGURE 3.6: The ATLAS calorimeter and its subsystems.

3.2.4 Muon Spectrometer

As we know, muons are particles that usually pass through the ID and Calorimeter undetected. The muon spectrometer forms the outer part of the ATLAS detector and is designed to detect charged particles exiting the barrel and end-cap calorimeters and to measure their momentum in the pseudorapidity range $|\eta| < 2.7$ (p. 164 [38]) with full ϕ coverage. Also, it is designed to trigger on these particles in the region of $|\eta| < 2.4$. There are precision-tracking chambers in the barrel region that are located between and on the eight coils of the superconducting

barrel toroid magnet, while the end-cap chambers are in front and behind the two end-cap toroid magnets. Also, the chambers in the barrel are arranged in three concentric cylindrical shells around the beam axis at radii of approximately 5 m, 7.5 m, and 10 m; muon chambers from large wheels in the two end-cap regions are perpendicular to the z-axis and located at distances of $|z| \approx 7.4$ m, 10.8 m, 14 m, and 21.5 m from the interaction point (IP).

Subsections of the muon spectrometer system are : the **Thin Gap Chambers (TGCs)**, the **Resistive Plate Chambers (RPCs)**, the **Monitored Drift Tubes (MDTs)** and the **Cathode Strip Chambers (CSCs)**. Figure 3.7 demonstrates the ATLAS muon spectrometer and its subsystems.

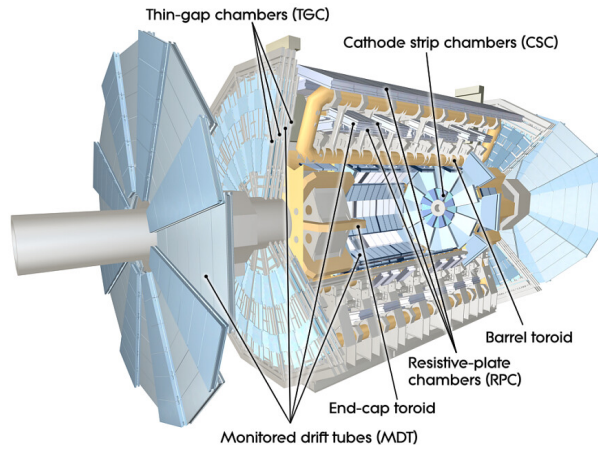


FIGURE 3.7: The ATLAS muon spectrometer and its subsystems.

The **Monitored Drift Tubes (MDTs)** combine high measurement accuracy and predictability of mechanical deformation so they provide an accurate track reconstruction and momentum measurement. They cover the pseudorapidity range $|\eta| < 2.7$ (except in the innermost end-cap layer where $|\eta| < 2.0$). These chambers consist of three to eight layers of *drift* tubes, with the inner chambers having more detecting layers for better granularity. These drift tubes are made of aluminium and have a 30mm diameter, $400\mu m$ thickness and are filled with a gas mixture of $Ar/CO_2(93\% : 7\%)$ at 3 bar absolute pressure.

The **Cathode Strip Chamber (CSC)** system combines high spatial, time and double track resolution with high-rate capability and low neutron sensitivity. It is located at a distance of about 7 m from the IP and 16 CSCs are placed on each end-cap. They are mounted together with the MDTs and TGCs on the shielding disk forming the so-called **Small Wheel** and they cover the pseudorapidity range of $|\eta| 2 - 2.7$. The CSCs are multiwire proportional chambers that have segmented cathode readout where the anode wires have a radial orientation and are spaced by 2.5 mm, while the cathode strips are placed perpendicular and parallel to them. Each CSC consists of four identical layers and it is filled with a gas mixture consisting of 80% Ar and 20% CO_2 .

The **Resistive Plate Chambers (RPCs)** are gaseous parallel electrode-plate (no wire) detectors; the gas used is a mixture of 94.7% $C_2H_2F_4$, 5% C_4H_{10} and 0.3% SF_6 . They achieve a time resolution of up to 1 ns and a moderate spatial resolution of 1 cm. The RPCs cover the range of $|\eta| < 1.05$ and they provide measurements for the trigger and the coordinate measurement also in the ϕ direction (while the MDTs only provide the η coordinate).

Finally, the **Thin Gap Chambers (TGCs)** are used in the end-cap region, covering the range $1.05 < |\eta| < 1.92$ for triggering and for spatial measurement of the azimuthal coordinate to complement the measurement of the MDTs in the bending (radial) direction. They are multi-wire proportional chambers that consist of two cathode plates forming a 2.8 mm gas gap, where the anode wires are located in the middle of the two plates (having a distance between them of 1.8 mm). They are filled with a gas mixture 45% n- C_5H_{12} and 55% CO_2 and the optimal performed HV supply is 3200 V.

3.2.5 Magnet System

In the ATLAS detector, we can measure their momentum and charge by bending the trajectories of charged particles. The magnetic field is generated by the ATLAS superconducting **Magnet System** 3.8; this consists of one *solenoid* and three *toroids* (one barrel and two end-caps) and is 22 m in diameter and 26 m in length, with a stored energy of 1.6 GJ. The *solenoid* is aligned on the beam axis and provides a 2 T axial magnetic field for the ID, while it minimises the radiative thickness in front of the barrel electromagnetic calorimeter. The *barrel toroid* and two *end-cap toroids* produce a toroidal magnetic field of approximately 3.5 T (Chapter 2 in [38], [49]). The end-cap toroids extend the magnetic field to particles that travel across the beam pipe direction. Also, the toroidal magnetic field at the muon spectrometer is parallel to the ϕ direction, while implying a curvature at η direction. Finally, all magnetic systems are cooled to about 4.5 K in order to provide the necessary strong magnetic fields.

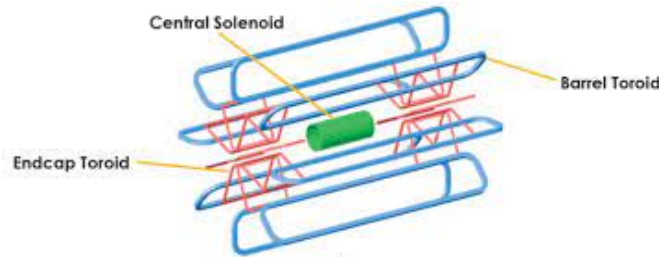


FIGURE 3.8: The ATLAS magnet system.

3.3 The New Small Wheel Upgrade

As we have mentioned before, luminosity is an important indicator of the performance of an accelerator as it is proportional to the number of collisions that occur in a specific time. Higher luminosity means higher particle rates which subsequently means greater opportunities for rare processes observation. But this new high luminosity environment demands extended technical upgrades to maintain a high level detector performance, carried out at detector shutdown periods. The achieved *nominal* luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ is aimed to be increased to $2 - 3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ after the second long shutdown period (LS2) in 2019-2021, allowing the ATLAS detector to collect up to $100 \text{ fb}^{-1}/\text{year}$ data. The above shutdown period called Phase-1 upgrade for the ATLAS and CMS detectors, will be followed by the Phase-2 stage taking place in 2026-2028 (LS3) where the installation of the High-Luminosity LHC (HL-LHC) will be performed, aiming to reach the luminosity of $5 - 7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Figure 3.9 gives a timeline presentation of the LHC and HL-LHC run and shutdown periods as well as the corresponding achieved center-of-mass energies and luminosity.

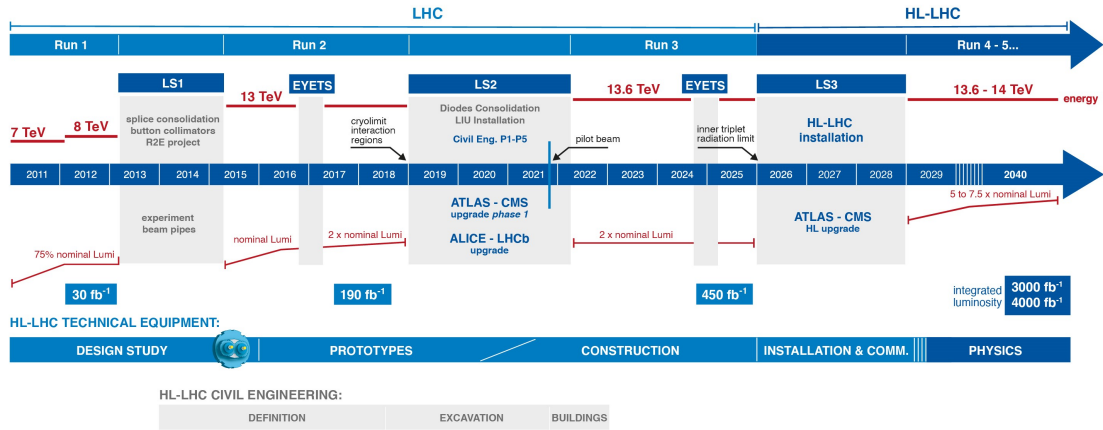


FIGURE 3.9: Timeline for the LHC and HL-LHC run and shutdown periods.

The **Small Wheel** is the region with highest background rates in the present ATLAS Muon Spectrometer. As we have mentioned before, the present system consists of Cathode Strip Chambers (CSCs), Monitored Drift Tubes (MDTs), the Thin Gap Chambers (TGCs) and the Resistive Plate Chambers (RPCs). With the high expected particle rates that are now produced in Run 3 (and the more demanding high luminosity environment expected at the HL-LHC), the existing infrastructure performance would be severely affected in multiple ways, especially in the first forward station (Small Wheel).

More specifically, after the LS2 luminosity increase the Small Wheel will be inadequate for muon tracking and efficiency determination; the TGCs, MDTs and CSCs are not designed to manipulate with this extremely high p_T particle flow in the forward region and simultaneously

the increased background rate, resulting in limited spatial resolution and efficiency drop. Moreover, in the previous setup the L1 trigger in the muon end-caps was performed from the TGC chambers of the Big wheel; this trigger rate was dominated by a high number of fake events produced by low energy particles that were attributed to muons with $|\eta| > 1.0$, not being detected in the Inner Detector (ID). The above problems could be moderated if we introduced upgraded detectors that present good spatial and fast time resolution, efficient trigger decision and preserving high efficiency rates in the HL-LHC conditions, while being compatible with the existing tracking detectors and end-cap alignment system; all these performed by the **New Small Wheel (NSW)** project.

3.3.1 New Small Wheel detector systems and technical infrastructure

The NSW is the largest Phase-1 upgrade project of ATLAS; it consists of two wheels (10 m in diameter) that replaced the first muon stations in the high-rapidity regions of ATLAS ($1.3 < |\eta| < 2.7$) and are equipped with multiple layers of two new detector technologies : the **small-strips Thin Gap Chambers (sTGCs)** and the **Micromegas (MM)** [50]. The sTGCs are devoted to the L1-trigger at background rates up to $15 \text{ kHz}/\text{cm}^2$ with an angular resolution of approximately 1 mrad; the MM detectors are built for precision tracking of muons, due to their small gap (5 mm) and strip pitch ($450 \text{ }\mu\text{m}$), succeeding in spatial resolution of about $100 \text{ }\mu\text{m}$ per detector layer while forming a total active area of more than 1200 m^2 . Both sTGC and MM are gas-filled detectors, measuring the effects related to the drifting of electrons and ions separated by muons ionizing the gas.

The sTGCs have two cathode boards with a gas gap that contains gold-coated tungsten wires between the cathode boards filled with 55 % CO_2 + 45% n-Pentane [50], while the MM consist of a planar electrode structure with a thin metal micro-mesh that electrically divides the gas volume (93 % Ar / 5 % CO_2 / 2% Isobutane) in the conversion gap (5 mm) and a thin amplification gap ($120 \text{ }\mu\text{m}$).

Each one of the two wheels has eight large and eight small sectors (wedges) that partially overlap and are fixed on a *spacer frame* which is a metallic circular structure. A single sector has two MM wedges attached on both sides of the spacer frame and sandwiched by two sTGC wedges; MM and sTGC chambers in wedges have four active detector layers that form *quadruplets*. As a result, the NSW has eight layers of MM and eight of sTGCs detectors. Each MM wedge is segmented in two trapezoids of different size that cover different η regions, resulting in four types of MM : **SM1** and **SM2** as Small Sector Modules and **LM1** and **LM2** as the Large Sector Modules, having 2 m^2 and 3 m^2 chamber size respectively. INFN Laboratory in Italy was responsible for the SM1 modules construction, German laboratories for the SM2, Sanclay Laboratory in France for the LM1, while the LM2 construction was shared among the ATLAS

team of Thessaloniki in Greece, Russia and CERN. In Figure 3.11 the different modules and in Figure 3.10 the different sectors of the NSW are shown. More technical details about the NSW project can be found in [51].

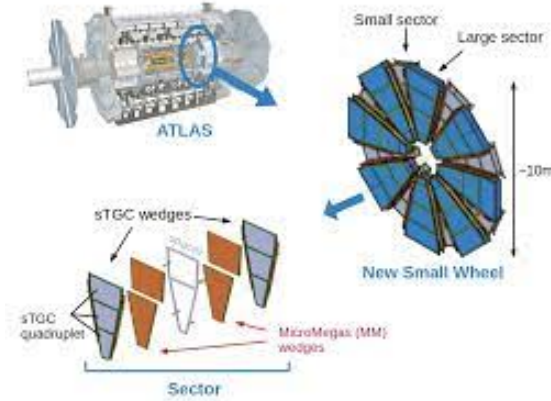


FIGURE 3.10: Position inside the ATLAS detector and different sectors of the NSW.

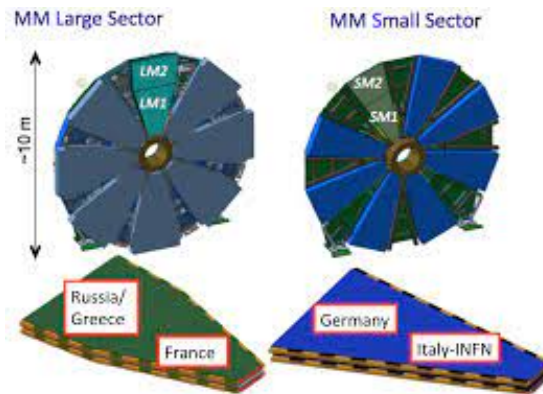


FIGURE 3.11: Large and small modules and corresponding construction sites for the NSW.

3.3.2 The Micromegas Detector

The Micromegas (MICROMesh Gaseous Structure) is a gaseous particle detector first developed at Sanclay [52]. It consists of a two-stage parallel-plate avalanche chamber that has a small amplification gap ($128 \mu\text{m}$) and also includes a conversion-drift space. During the collection of the electron avalanche on the anode microstrip plane, we obtain fast signals (≤ 1 ns). With the Micromegas we have achieved a gas gain of up to 10^4 due to the fast evacuation of the produced positive ions and the high granularity of the detector.

3.3.2.1 Basic operation principles

The basic operation principles of a MM setector are described below. The MM is a position sensitive gaseous detector with planar parallel electrodes and consists of three planes : the cathode (drift), the anode (readout) and the micro-mesh [53]. As a typical gaseous detector, the detection of the muons is done by amplifying the charges that originate from ionizations in the gas volume.

First of all, the micro-mesh separates the conversion space (5 mm gap), from the amplification gap (128 μm). The above infrastructure results in a very high electric field in the amplification region ($\sim 50 \text{ kV/cm}$) and a quite low electric field in the drift region ($\sim 100 \text{ V/cm}$) while applying reasonable voltages in the three electrodes. When an incident charged particle (here muon) passes through a MM, it causes ionizations in the gas volume inside the drift space, resulting in the creation of electron/ion pairs. Affected by the drift region's electric field applied, the electrons will drift towards the micro-mesh, while the ions get directed to the cathode. Then, when an electron gets close to the micro-mesh it gets accelerated by the intense electric field developed in the amplification gap ($\sim 50 \text{ kV/cm}$) leading to the *avalanche* development; the latter is a cascade formation of drop-like shape that includes ionised gas atoms and newly-freed electrons (caused by the transversing electron) that in turn create further ionizations.

Furthermore, because of the difference between the two applied electric fields, the micro-mesh is up to 95 % transparent for the drifting free electrons. The high electric field applied in the amplification gap plays a second role, too : due to its presence the ion cloud is quickly collected on the micro-mesh and only a small part of it escapes to the conversion region (which is inversely proportional to the electric field ratio), preventing possible ion discharges in the amplification region. The mechanism described above has as outcome the creation of a significant signal, whose amplitude and shape are read via the electronic system on the readout electrode, providing information on the time and the energy of the charged particle.

The anode plane consists of printed circuit boards (Readout PCBs), having copper strips on the surface of 300 μm width, and pitch of 425 or 450 μm (in small and large wedges respectively), produced photo-lithographically, having also a layer of resistive strips on a Kapton foil glued on top of the copper strips for the discharge protection with resistivity of 10 to 20 $M\Omega/\text{cm}$. The micro-mesh (called "mesh" from now on for simplicity) is a stainless steel grid (30 μm wire diameter, 70 μm wide opening and 100 μm wire pitch) which is stretched with a tension of 7-10 N/cm, that is supported by pillars of 128 μm height, 350 μm diameter and pitch of 0.4 mm. These pillars are placed on top of the resistive strips and guarantee the uniformity of the amplification gap. Finally, the cathode is also a PCB that has a thin layer copper on its surface. Figure 3.12 displays the operating principles of a MM detector.

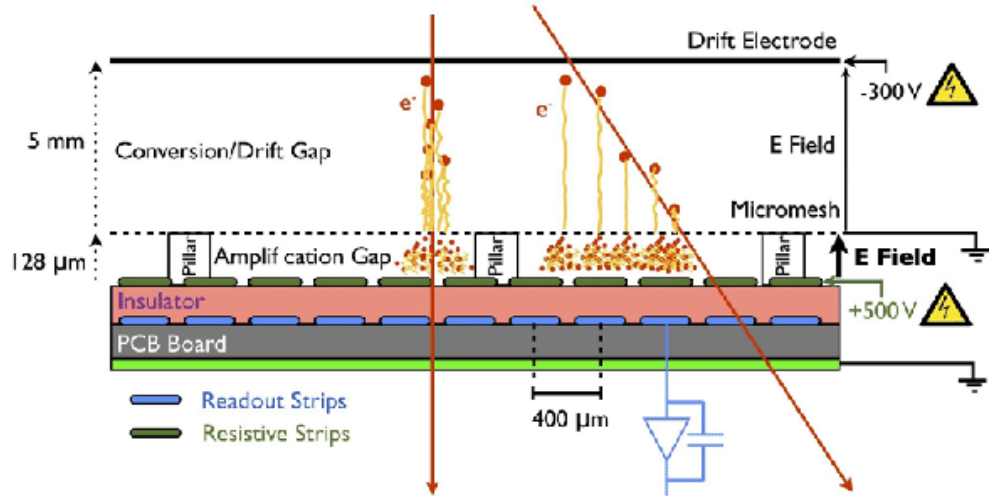


FIGURE 3.12: Operating principles of a MM detector.

The LM1 and SM1 detectors consist of five PCBs while the LM2 and SM2 have three, making each MM sector to be constructed by eight PCBs. Each MM Module (Quadruplet) in the NSW sector consists of four MM detectors that form four active MM gas gaps. The MM chambers need to fulfil specific mechanical requirements in order to be able to reconstruct a muon momentum track with a resolution of the order 15% at 1 TeV in ATLAS; this demands excellent quality of the construction materials, strict quality control measurements of the produced chambers, as well as specialized construction techniques. The precision for the strip position in η should be $30 \mu m$ and $80 \mu m$ for the strip position in Z (perpendicular to the detection plane). Each quadruplet consists of five trapezoidal panels forming the four active MM gaps and the sequence of its components is Drift-Readout-Drift-Readout-Drift panel. Each quadruplet has one “ η ” readout panel (two detection planes in η direction) having the strips parallel to the trapezoid bases in order to measure the η coordinate and one “stereo” panel (two stereo detection planes, where strips have an angle of $\pm 1.5^\circ$) to measure η coordinates but also reconstruct the second coordinate ϕ with few mm resolution (page 3 in [53]). Also, there are two drift panels that have one side covered with copper operating as cathodes (called *external* panels) and one *central* drift panel having both sides covered with copper. The mesh is glued on the drift panels via an appropriate mesh frame and attached to the pillars when the quadruplet is assembled. Figure 3.13 gives a schematic view of the five panels of MM quadruplet.

3.3.2.2 LM2 Drift panel production

A panel has a light and stiff structure that consists of an aluminium frame and an aluminium honeycomb of 10.1 mm thickness with 6 mm hexagonal cells that is sandwiched between two outer surfaces made by 0.5 mm FR4 material (PCBs). The frame consists of aluminum bars having 10.0 mm thickness, perimetric and cross as reinforcement bars with four special aluminum

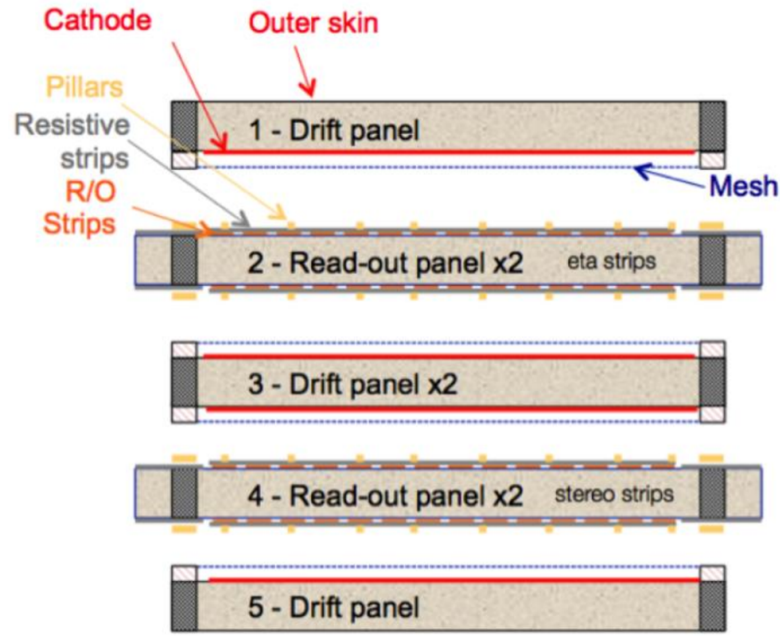


FIGURE 3.13: Schematic view of the five panels of MM quadruplet.

corners which implement the gas inlet and outlet to the MM gap; it is prepared in advance by gluing all the parts on a precise assembly table using special dowel pins to align the parts properly. The above described structure is called *bare panel*; when the aluminium mesh - frame, the mesh, the interconnections, the high voltage connectors and the gas-pipes are placed then the panel is considered as *complete*.

The ATLAS group of the Aristotle University of Thessaloniki produced 35 LM2 Modules, consisting of two external and one central drift panels for each quadruplet. The preparation and the assembly of all the drift panels was performed in a class D pressurized clean room in the AUTH MicroMegas construction laboratory. The nominal tolerances for the panel planarity are $37 \mu m$ in r.m.s., equivalent to $\pm 110 \mu m$ mechanical tolerance. The panel construction is done using two ultra flat *vacuum tables* made from carbon fiber and perforated aluminium honeycomb; one of them had permanent fixed position (Table I) and the other was movable and able to rotate along its long axis (Table II). The first step in the panel production is the assembly of the aluminium frame which is a process done at two steps : first, the gluing of top and bottom bars with the corner parts is done on a special high precision holes table called *assembly tool* using dowel pins and then all bars are indexed on Table I using dowels and glued together forming a three sub-areas trapezoidal frame. A layer of silver paste is also applied on the glued elements in order to ensure the electrical conductivity. Using this void aluminium frame as reference, three aluminium honeycomb pieces are cut in the proper size to avoid possible mechanical constraints.

Afterwards, the PCBs are indexed on the vacuum tables via precision holes on the tables using 5 mm dowel pins and consequently sucked at an under-pressure of 100 mbar taking advantage of the planarity of the tables ($\pm 30 \mu m$). Then, a kapton tape having $70 \mu m$ thickness is applied along the PCB junctions (for sealing purposes) and the interconnections are glued on the PCBs on Table I. The interconnections are important for avoiding a possible increase in the drift gap size due to gas over-pressure which in turn could impact the drift region's electric field and subsequently the uniformity of the final collected charge.

Before the gluing procedure, a simulation of the process is performed called “dry-run” where after placing the PCBs on both tables, the aluminium frame (which is indexed using special pins on the four corners) and the honeycomb pieces on Table I, Table II is rotated and placed on top of Table I standing on 10 high precision spacers that are in the perimeter of Table I and ensure that the panel's thickness will not exceed the construction specifications. The glue is distributed on the PCBs as well as on the aluminum frame. Then, after positioning the honeycomb pieces, Table II is placed on top of Table I standing on the ten precision spacers, maintaining the under-pressure for ~ 20 h during glue curing. Next day, the upper table is removed and some minor fixing of the panels is performed (like removing the PCB in excess and the remaining glue, glue insertion in the space between the PCBs' junctions for preventing gas-leaks). After the above procedures the bare panel is considered as complete.

The mesh aluminium frames are then screwed (ensuring electrical continuity between the mesh and the panel frames) and glued on the drift plane with the required accuracy of $\pm 200 \mu m$ in the plane and $\pm 25 \mu m$ in height; gluing is performed very carefully in order to avoid possible gas leaks that could affect the chambers operation. Next the interconnection drift spacers are glued with $\pm 25 \mu m$ precision in height using a special designed tool. After that step, the gas pipes are mounted and glued in contact with the inner side of the mesh frame long and short sides. Then, the HV connectors are glued in the outer side of the aluminum frame of the panel and soldered in the copper of the PCB. For the central panels all the procedures mentioned before have to be performed twice, for both copper sides.

The mesh is an important element of the MM detector; to ensure the homogeneity of the amplification gap and avoid sags between the pillars, the mesh must be stretched at a specific tension and glued on the drift panel. For the large MM construction we have used the *floating mesh* technique which ensures that the quadruplet can be re-opened since the mesh is not glued to the readout PCB : the positioning of the mesh at the right distance from the anode is guaranteed by stretching the mesh along the edges at a specific tension and by the precise pillars height. Using a special stretching table, the mesh is stretched to the desired tension and in order to move it while keeping it at the achieved tension, the mesh is glued on a reusable heavy iron transfer frame. The nominal mesh tension is in the range of $7 - 10$ N/cm with a uniformity of $\pm 10\%$ after gluing on the drift panel. To achieve this measurement in the final

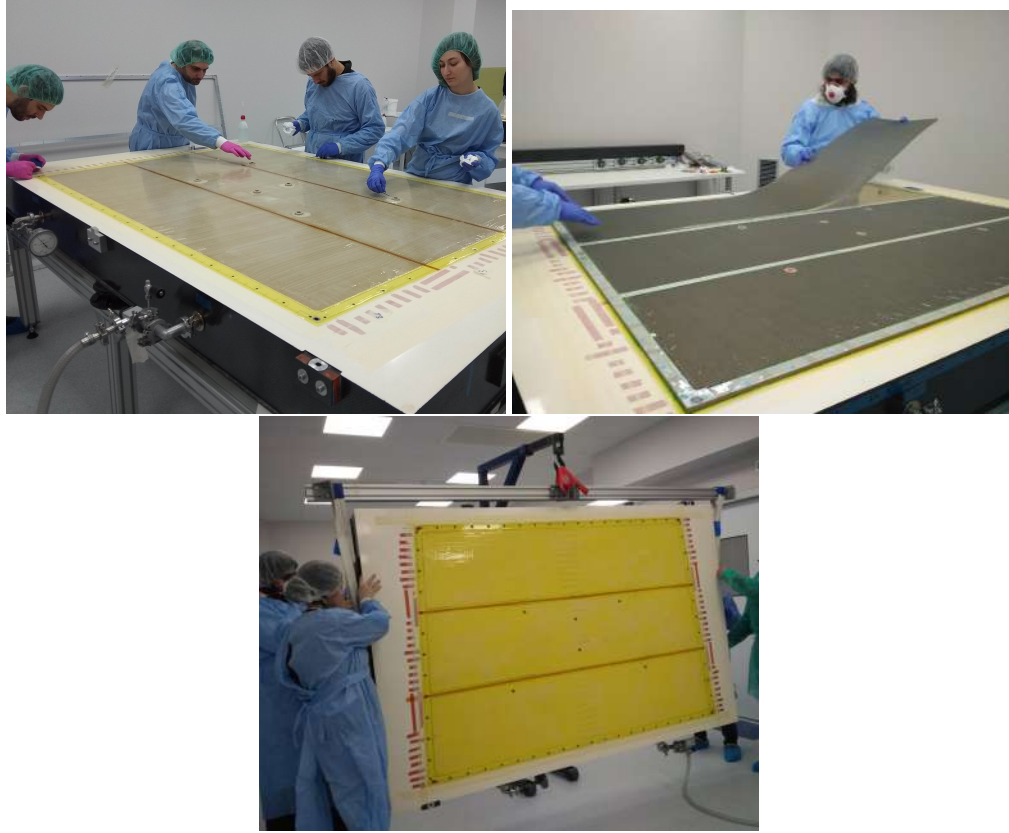


FIGURE 3.14: Application of glue on the PCBs of Table I (up left), insertion of honeycombs (up right) and rotation of Table II in order to be glued on top of Table I (bottom)

panel, the initial tension on the stretch table is adjusted to $\sim 9.5 - 10$ N/cm, taking into account that after cutting the glued mesh on the transfer frame to release it from the stretch table and after cutting the mesh on the mesh frame of the panel after gluing, we observe a decrease of 10 – 15%.

Before gluing on the panel, the mesh is cleaned with water and dried thoroughly. Afterwards, the mesh is perforated at the interconnections' positions with the special tool where glue is then applied to prevent from the mesh damage (a procedure called *passivation*); then the mesh is glued on the panel using a custom limbo tool that ensures that no glue bumps are created after curing. The glue is left to cure overnight and then the mesh gets cut (correcting possible excesses) and polished, so the *complete* panel is ready for the last certification controls (gas leak and high voltage test).

3.3.2.3 LM2 Drift panel QA/QC measurements

In the ATLAS NSW upgrade project the quality control performed is tight in order to fulfill the high standards and the small error tolerances specified by the ATLAS collaboration. These measurements are indicated by various parameters that could affect the successful detector



FIGURE 3.15: Mesh stretched on custom made table and tension measurement

operation. Quality control is performed before drift panel assembly - on all the separate parts that are going to be used for the panel composition- , during panel production to check the quality of the single production steps, but also after the drift panel's complete construction to ensure its proper function. In most cases of defects or malfunctions, there are specific processes that can repair certain kinds of equipment (like when observing gas leakage at some area of the panel, the construction team searches for any small rubbish that affects the measurement or rearranges the clamps); otherwise there is spare equipment (f.e. extra mesh sheets) or the faulty parts have to be sent back and replaced by the manufacturer.

The QA/QC controls performed are split into two categories : tests expecting specific numerical measurements (nominal mean value, tolerance and min/max value) of a parameter and tests concerning the acceptance or rejection ("pass" or "fail") of specific production equipment or processes. The first category mentioned above is done by tracking the measurements of interest in especially created Excel Templates that are later translated through python import scripts into .csv files and thus uploaded to the Central NSW muon database. These templates are necessary for Thessaloniki site since we are not equipped with machines that directly calculate the mean, min/max value and rms; they are well-defined so their use is straightforward for the shifter. The second category of measurements is handled by a Graphical User Interface (GUI) especially developed to handle visual or "pass" or "fail" tests. GUI is also used for registering an equipment and for the parenting, procedures that are going to be presented below. The results of all the above QA/QC tests are uploaded to the Central NSW muon database and are accessible by all sites participating in the project. This database holds all data related to material, tracking and logistics for the NSW series production.

The first step concerning the database logistics, is to declare the reception of all the material shipped to Thessaloniki site and obtaining a unique equipment identification number (EQ-ID) for all equipment; it is important to record this number in order to later use it for *parenting*, a procedure where the received equipment is going to be attached to a specific drift-panel. Also, when a bare panel is completed it is also registered to the database and is given a unique EQ-ID which is going to be used for parenting but also for the submission of any measurement (visual, “pass” or “fail” or numerical). An important information that also needs to be declared to the database is the manufacturing date (of bare / completed panel), the date when the mesh is placed on the panel and also dates of the performed measurements.

Any damaged/replaced equipment should be declared on the database by inserting the corresponding status (*damaged/replaced*) on the database. Also, a bare or completed drift panel is declared using the statuses *completed bare* and *completed* (after the mesh assembly); this step is important because the database gives the opportunity to track down the production status of the bare and the completed panels, by producing timeline production plots (Figure 3.16). All equipment placed on a panel have the *distributed* status, while drift panels assembled to a quadruplet together with readout panels, have the *assembled* status.

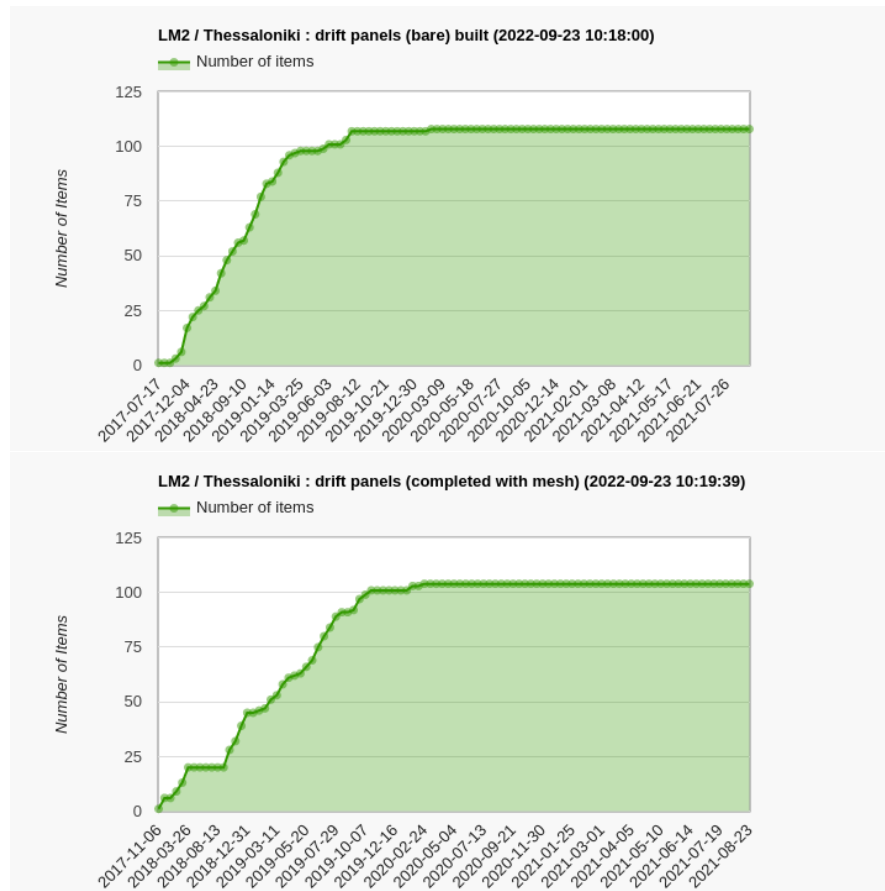


FIGURE 3.16: Timeline production plots of bare and completed LM2 drift-panels for Thessaloniki production site.

Besides receiving construction materials, the database user is responsible to declare any shipments from the Thessaloniki site to other locations, specifically Dubna (as the two groups cooperate on the LM2 production) accompanied by any documents of interest like gas leak and planarity measurements. Every equipment shipped is attached to a barcode sticker printed by the database with an MTF-ID that refers to the EQ-ID. The NSW database gives the possibility to construction sites to check anytime the received and sent material and also display information for any equipment declared using the unique EQ-ID.

Concerning the *parenting* procedure [54] as a *parent* we treat the “more composed” component like the drift-panel; the “more raw” components that are used for the panels construction are considered as *children* f.e. the mesh attached to a panel, the PCBs, the aluminium bars used for the frames production and the honeycomb pieces. Parenting is performed also for the honeycombs when the “raw” honeycomb (parent) is attached to three smaller honeycomb pieces (that are cut out of it), which are registered on the database by the user and as treated as its children. The parenting step is important because it gives the ability to track down out of which manufactured equipment a panel is built, a useful information for the explanation of any possible future dysfunctions or divergences from nominal measurements.

Finally, there is equipment that is declared as *batches* in the database like the aluminium frame or mesh-frame bars; this material is usually received in small groups of items by the manufacturer. These declared batches (children) are attached to the raw equipment’s EQ-ID (parent). In Figure 3.17 we present the database display of an LM2 external drift-panel, where the equipment ID, the status, the shipping history and the parenting is shown.

3.3.2.4 Visual or “pass” or “fail” tests

As we have already mentioned before there are quality control tests concerning the acceptance or rejection (“pass” or “fail”) of specific production equipment or processes or the visual inspection of production material. All these tests should be “pass” in order to proceed to the next production technique; otherwise there should be refinements/replacements. These tests are :

- Checking the bending, thickness and torsion of the aluminium frames used for the panel construction (Frames type 2.1 and 2.2) before their assembly, using an appropriate Limbo tool, by checking if the frame bars pass through it without being in contact with it.
- Mesh inspection and comparison with accompanying documents before gluing on transfer frame (visual check).
- Electrical continuity of Honeycomb pieces with frames.

Search for MTF - no. (20MN X XXXX # ####): Search for unique DB EQ ID: Search for EQ ALIAS:

20MNMDEL2000002 Drift Panel LM2 External		EQ ALIAS 	EQ SUB BATCH ID 	EQ ID 13755	(GOOD UNITS / UNITS IN BATCH) pcs / pcs
CURRENT STATUS assembled		STATUS SINCE / YYYY-MM-DD HH:MM:SS (USER) 2018-06-11 11:40:06 (dkhartch)		EQ REGISTERED / YYYY-MM-DD (USER) 2017-09-28 (mtsopoul)	
CURRENT LOCATION / SITE: (see parent)		BUILDING OR ROOM: 		LOCATION SINCE / YYYY-MM-DD HH:MM:SS (USER) 2018-06-11 11:40:06 (dkhartch)	
SUPPLIER: 		MANUFACTURING DATE / YYYY-MM-DD: 2017-07-12		DELIVERY DATE / YYYY-MM-DD: 	
CABLE LENGTH (METERS): 0.00	ORDERED BY: 	ORDER DATE / YYYY-MM-DD: 	ORDER REFERENCE (EDMS / DAI LINK): 		

HISTORY:

☒	SHIP ID	SENT TO SENT FROM	STATUS	LOCATION	DATE	AUTHOR
☒			assembled	(see parent)	2018-06-11 11:40:06	dkhartch
☐			delivered	Dubna	2017-12-11 12:00:00	dkhartch
☐	196	Dubna Thessaloniki	in transit	in transit	2017-11-10 13:48:00	mtsopoul
☐			completed		2017-11-03 22:15:37	mtsopoul
☐			assembling	Thessaloniki	2017-09-28 12:48:09	mtsopoul
☐			completed, bare	Thessaloniki	2017-07-13 14:16:11	mtsopoul

CHILDREN

☒	CHILD EQ ID	CHILD EQ MTF ID	CHILD OTHER ID	CHILD TYPE NAME	POSITION	#	ATTACHMENT DATE	BY
☐	464	20MNMDEL200026	Mesh_LM2_026	Mesh LM2		1	2017-10-25 14:39	ggiakous
☐	4988	20MNMDEL600001	outer_board_lm2_type6	Outer Skin Boards LM2_6		1	2017-10-25 14:33	ggiakous
☐	4989	20MNMDEL700001	outer_board_lm2_type7	Outer Skin Boards LM2_7		1	2017-10-25 14:35	ggiakous
☐	4990	20MNMDEL800001	outer_board_lm2_type8	Outer Skin Boards LM2_8		1	2017-10-25 14:35	ggiakous
☐	7019	20MNMDEL600028	dr_board_lm2_LD6_S05_008	Drift Boards Large 6		1	2017-10-25 14:31	ggiakous
☐	7063	20MNMDEL700032	dr_board_lm2_LD7_S05_012	Drift Boards Large 7		1	2017-10-25 14:32	ggiakous
☐	7110	20MNMDEL800039	dr_board_lm2_LD8_S05_019	Drift Boards Large 8		1	2017-10-25 14:33	ggiakous
☐	13756	20MNMHCL600001		Honeycomb Foils LM2_6		1	2017-10-25 14:36	ggiakous
☐	13757	20MNMHCL700001		Honeycomb Foils LM2_7		1	2017-10-25 14:37	ggiakous
☐	13758	20MNMHCL800001		Honeycomb Foils LM2_8		1	2017-10-25 14:38	ggiakous
☐	13759	20MNMFDRM000003		Frames type 2-1 machined - batch		1	2017-10-25 14:41	ggiakous
☐	13760	20MNMFDRM000004		Frames type 2-1 machined - batch		1	2017-10-25 14:41	ggiakous
☐	13761	20MNMFDRM000005		Frames type 2-1 machined - batch		1	2017-10-25 14:42	ggiakous
☐	13762	20MNMFDRM000006		Frames type 2-1 machined - batch		1	2017-10-25 14:42	ggiakous

FIGURE 3.17: Database display of an LM2 external drift-panel, where the equipment ID, the status, the shipping history and the parenting is shown.

- Electrical continuity between cathodes.
- HV Connector Connection to Cathodes.
- Quality of soldering (cleaning).
- Cathodes insulation from all other metallic parts.
- Mesh Frame Grounding
- Mesh quality of gluing on mesh frame (visual check).
- Electrical Continuity of the gas pipe with the mesh frame.
- Checking gas flow from all holes of gas pipes.
- Mesh inspection after hole punching at the interconnection points (visual check).

3.3.2.5 Drift panel thickness and planarity

All constructed panels have to be controlled concerning the planarity and thickness. For these measurements a limbo tool has been developed that consists of a rigid aluminum profile, equipped with four height gauges that are calibrated on a granite bar before every measurement (see left in Figure 3.18). The thickness and planarity are measured for both sides of a panel on vacuum Tables I and II; the thickness measurement is performed applying an under-pressure of about 100 mbar (indicated as vacuum ON measurement), while the measurement for the planarity is performed with no vacuum applied (vacuum off). Each panel's side surface (with position indicated as side 1 or side 2 related to the vacuum table on which it was constructed) is scanned by taking measurements at a grid of 152 points in total. Values are stored via USB to a PC on especially created excel templates as in top Figure 3.21. Then the excel templates are converted through python import scripts into .csv files that are appropriate for uploading on the database as in bottom in Figure 3.21. The uploaded values are the mean, minimum/maximum and rms measurements for each side's thickness and planarity as well as the excel template that includes measurements' map.

All data are recorded and analysed to produce the planarity and thickness mapping of a panel.

Results of a produced panel are shown on Figure 3.21 having an rms value of $17 \mu m$ which is within specifications. In Figure 3.19 we present the average thickness of some produced panels, a 2 dimensional contour plot of a single produced panel's thickness, the planarity rms and the difference between maximum and minimum measured values; from all above it is obvious that produced panels are well within specifications. In Figure 3.20 we present the planarity and thickness measurements of side 2 plots of all produced panels obtained from the



FIGURE 3.18: Measurement of thickness and planarity with limbo tool (left) and perimetrical thickness measurement with digital micrometer (right).

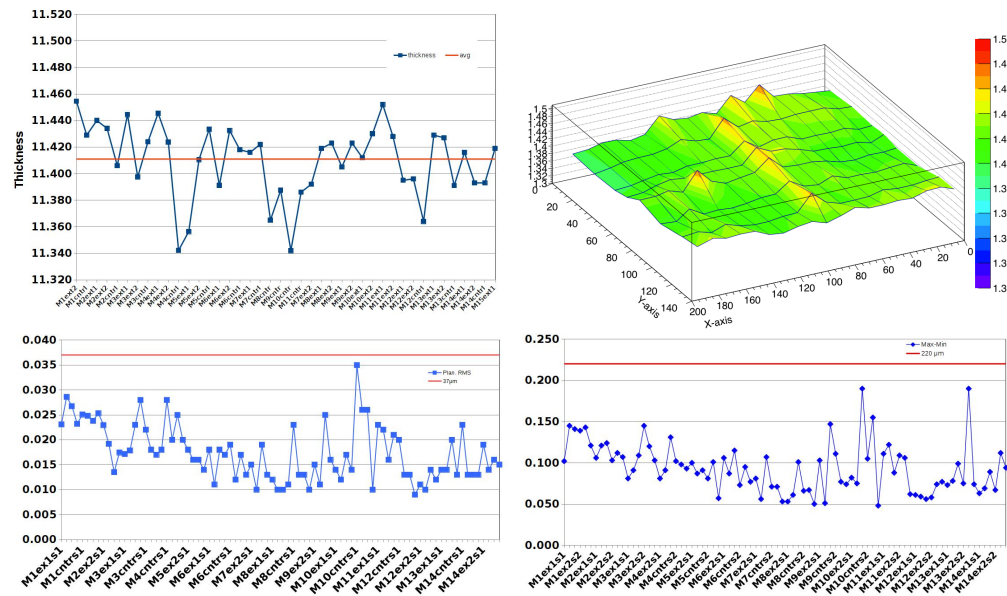


FIGURE 3.19: Average thickness of some produced panels (top left) , 2 dimensional contour plot of a single produced panel's thickness (top right), planarity rms (bottom left), difference between maximum and minimum measured values (bottom right). It is obvious that produced panels are within specifications.

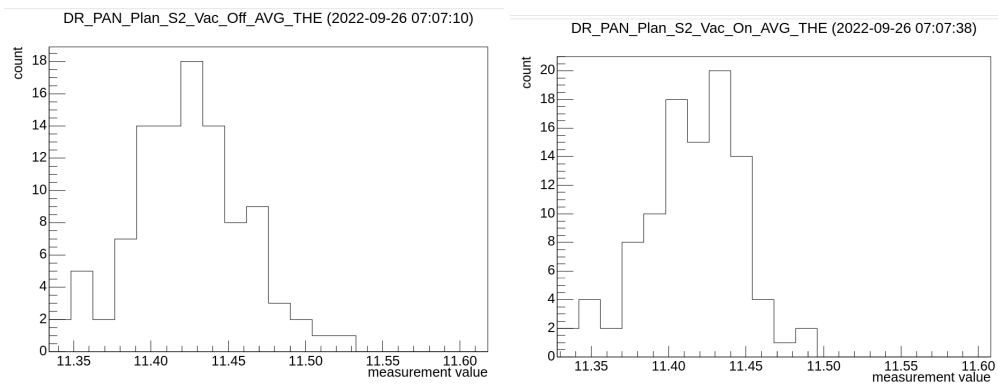


FIGURE 3.20: Planarity (left) and thickness (right) measurements of side 2 plots of all produced panels, obtained from the Central NSW database.

Central NSW database. Additional measurements of panel thickness outside the copper zone are performed, along the perimeter using a digital micrometer (caliper) in 62 points using an appropriate excel templates.

DRIFT PANEL - THICKNESS AND PLANARITY SIDE-1 VAC ON									
EQENTRYID	14843	4x19 + 4x19 measurements							
MEASUREMENT DATE (YYYY-MM-DD)	2017-11-30 00:00:00								
SHIFTER	marievi	right side							
POSITION	side 1								
		long side							
		short side							
		1.431	1.421	1.4	1.404	1.391	1.416	1.417	
		1.427	1.423	1.397	1.392	1.394	1.399	1.419	1.431
		1.422	1.425	1.394	1.384	1.38	1.394	1.41	1.416
		1.429	1.427	1.395	1.377	1.377	1.394	1.416	1.417
		1.429	1.423	1.391	1.38	1.376	1.392	1.414	1.417
		1.451	1.417	1.392	1.387	1.38	1.393	1.407	1.419
		1.431	1.418	1.403	1.397	1.393	1.4	1.411	1.419
		1.441	1.428	1.399	1.4	1.39	1.389	1.407	1.419
		1.41	1.415	1.392	1.404	1.395	1.394	1.413	1.413
		1.412	1.414	1.397	1.4	1.36	1.398	1.414	1.404
		1.407	1.398	1.383	1.395	1.396	1.389	1.403	1.412
		1.416	1.4	1.387	1.396	1.389	1.394	1.409	1.416
		1.421	1.4	1.378	1.39	1.398	1.389	1.405	1.407
		1.397	1.389	1.379	1.397	1.409	1.389	1.406	1.415
		1.391	1.387	1.375	1.4	1.434	1.388	1.416	1.433
		1.398	1.383	1.373	1.4	1.404	1.388	1.421	1.437
		1.399	1.39	1.37	1.39	1.425	1.404	1.412	1.434
		1.396	1.385	1.369	1.387	1.412	1.392	1.426	1.442
		1.411	1.408	1.373	1.393	1.415	1.392	1.421	1.427
		left side							
		MIN VALUE	MAX VALUE	AVERAGE VALUE	RMS VALUE				
		11.360	11.451	11.403	0.017				

EQENTRYID	CONTEXTNAME	MEASVALUE	MEASUREMENT TIME	SHIFTER	WEBSITEUSER	POSITION	MEASFILEPATH
14843	DR_PAN_Plan_S1_Vac_On_MIN_THE	11.36	2017-11-30	marievi	mtsopoul	side 1	
14843	DR_PAN_Plan_S1_Vac_On_MAX_THE	11.451	2017-11-30	marievi	mtsopoul	side 1	
14843	DR_PAN_Plan_S1_Vac_On_AVG_THE	11.403	2017-11-30	marievi	mtsopoul	side 1	
14843	DR_PAN_Plan_S1_Vac_On_RMS_THE	0.017	2017-11-30	marievi	mtsopoul	side 1	
14843	DR_PAN_Plan_S1_Vac_On_MAP_THE		2017-11-30	marievi	mtsopoul	side 1	/home/auth/Programs/Atlas_NSW_from_LXPLUS/ ATLAS_NSW_AUTH_IMPORT_SCRIPTS/ Excel_Measurements_Construction/Drift_Panels/Drift_Panel- Thickness_and_Planarity_Side-1_Vac_ON/DP_Thick_Side- 1_Vac_ON_M6cntrl.xls
14843	DR_PAN_Plan_S1_Vac_Off_MIN_THE	11.38	2017-11-30	marievi	mtsopoul	side 1	
14843	DR_PAN_Plan_S1_Vac_Off_MAX_THE	11.495	2017-11-30	marievi	mtsopoul	side 1	
14843	DR_PAN_Plan_S1_Vac_Off_AVG_THE	11.425	2017-11-30	marievi	mtsopoul	side 1	
14843	DR_PAN_Plan_S1_Vac_Off_RMS_THE	0.019	2017-11-30	marievi	mtsopoul	side 1	
14843	DR_PAN_Plan_S1_Vac_Off_MAP_THE		2017-11-30	marievi	mtsopoul	side 1	/home/auth/Programs/Atlas_NSW_from_LXPLUS/ ATLAS_NSW_AUTH_IMPORT_SCRIPTS/ Excel_Measurements_Construction/Drift_Panels/Drift_Panel- Thickness_and_Planarity_Side-1_Vac_OFF/DP_Plan_Side- 1_Vac_OFF_M6cntrl.xls
14843	DR_PAN_Plan_S2_Vac_On_MIN_THE	11.401	2017-11-30	marievi	mtsopoul	side 2	
14843	DR_PAN_Plan_S2_Vac_On_MAX_THE	11.459	2017-11-30	marievi	mtsopoul	side 2	
14843	DR_PAN_Plan_S2_Vac_On_AVG_THE	11.433	2017-11-30	marievi	mtsopoul	side 2	
14843	DR_PAN_Plan_S2_Vac_On_RMS_THE	0.01	2017-11-30	marievi	mtsopoul	side 2	
14843	DR_PAN_Plan_S2_Vac_On_MAP_THE		2017-11-30	marievi	mtsopoul	side 2	/home/auth/Programs/Atlas_NSW_from_LXPLUS/ ATLAS_NSW_AUTH_IMPORT_SCRIPTS/ Excel_Measurements_Construction/Drift_Panels/Drift_Panel- Thickness_and_Planarity_Side-2_Vac_ON/DP_Plan_Side- 2_Vac_ON_M6cntrl.xls
14843	DR_PAN_Plan_S2_Vac_Off_MIN_THE	11.395	2017-11-30	marievi	mtsopoul	side 2	
14843	DR_PAN_Plan_S2_Vac_Off_MAX_THE	11.468	2017-11-30	marievi	mtsopoul	side 2	
14843	DR_PAN_Plan_S2_Vac_Off_AVG_THE	11.44	2017-11-30	marievi	mtsopoul	side 2	
14843	DR_PAN_Plan_S2_Vac_Off_RMS_THE	0.012	2017-11-30	marievi	mtsopoul	side 2	
14843	DR_PAN_Plan_S2_Vac_Off_MAP_THE		2017-11-30	marievi	mtsopoul	side 2	/home/auth/Programs/Atlas_NSW_from_LXPLUS/ ATLAS_NSW_AUTH_IMPORT_SCRIPTS/ Excel_Measurements_Construction/Drift_Panels/Drift_Panel- Thickness_and_Planarity_Side-2_Vac_OFF/DP_Plan_Side-

FIGURE 3.21: Excel template for side 1 drift panel's thickness measurement (top) and example of a .csv file for uploading data on the NSW database (bottom).

3.3.2.6 Mesh frame and interconnections drift spacers height

The mesh frame height is a crucial parameter that needs to be measured in order to ensure the proper detector's operation; otherwise, in case f.e. of glue bumps or aluminium mesh frame bars anomalies, the height of the amplification region will not be determined by pillars and thus the electric field will not be uniform. The mesh frame height is measured using 66 points with an appropriate excel template, with a digital gauge that is mounted on a custom flat base 3.22. The nominal expected value is set to be 5.06 mm with a tolerance of 25 μm . Figure 3.22 displays the average mean value of the mesh frame height for some panels.

The interconnection spacers' height should also be controlled; it is measured using a digital gauge and each of the six interconnection spacers is measured in five spots (in the center and

in four points in the edges forming a cross) with an excel template. The nominal value for this height is 5 mm with a tolerance of $50\ \mu\text{m}$.

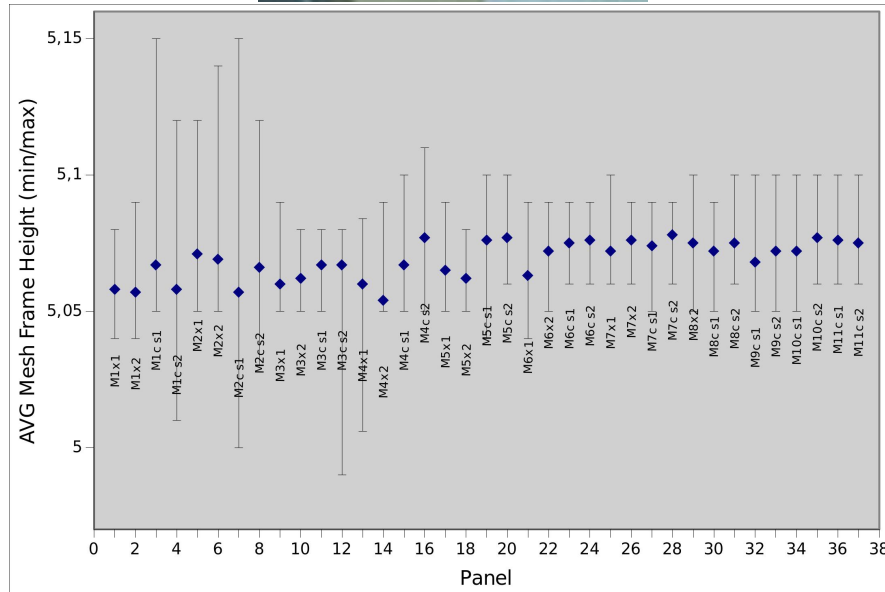


FIGURE 3.22: Mesh frame height measurement using a digital gauge (top) and average mesh frame heights for various panels (bottom).

3.3.2.7 Gas tightness certification

Before gluing the mesh on the drift panel, the gas leak test is performed. It is a crucial procedure that ensures the desired gas tightness of a single panel and consequently the tightness of the MM quadruplet in total; otherwise, a high gas leak rate could affect the ionization rate due to the contamination of the MM chamber with oxygen. For the external panels we check only the side that participates to MM detector in the quadruplet, while the central panels have to be checked for both sides. The first step is to clean the panel thoroughly in order to avoid any

rubbish that could affect the tightness procedure. Then the panel is mounted on a special tool designed for the panel holding/rotating and a 7 mm o-ring is placed on the periphery of the panel. One (two) “dummy” panel is placed on top (and bottom) of the external (central) panel creating the gas gap. After that, an extra aluminium frame outside the o-ring is placed sup-pressing the o-ring and sealing the gas gap between the two panels, that are further clamped. The six interconnection holes are further sealed with custom caps that are screwed on both their top and bottom side. Then the gas gap is filled with Ar at about 4 mbar over-pressure (while the pressure on the working NSW is expected to be 3 mbar) and the pressure drop is monitored typically for 24h. An exponential fit is performed to the pressure drop rate, after correcting data for temperature variations and for the ambient pressure. A drift panel is certified to successfully pass the gas leak test when the corresponding rate has a limit of 0.6 mbar/h at pressure of 3 mbar. For the determination of the gas leak rate we have used the **Pressure Drop Rate (PDR)** method (page 33-34 in[55]). If we determine the over-pressure as $p_{over} = 4\text{mbar}$, $V_0 \approx 15.5\text{ L}$ the active volume of the panel’s gap, $f_{in} \approx 6\text{ bar L/h}$ the constant flow rate for the incoming gas, p_{atm} the atmospheric pressure and neglecting the room temperature variations since they are low (at the range of 0.1° C), the gas leak rate is given by the following expression :

$$\text{Gas Leak} = \frac{\Delta p_{atm}}{p_0} + (k + 1) \frac{\Delta p_{over}}{p_0} \quad (3.7)$$

where the factor $\Delta p_{over}/p_0$ is the slope of the measured drop taken from exponential fit and k is the volume expansion factor defined by Equations (1) and (2) (in page 33 in[55]). In Figure 3.23 the monitoring of the pressure of an under study panel is presented, where the leakage rate is calculated by fitting the pressure and implementing corrections concerning the atmospheric pressure variations and the panel’s volume deformations.

3.3.2.8 Mesh tension on the transfer frame, during gluing and after gluing and cutting on panel

The mesh tension is susceptible to changes during the various production steps so it is controlled both on transfer frame (after gluing and being cut) and on drift panel (during the curing of glue and after being glued and cut on panel). It is measured using an analogue gauge in a 20 points grid for the x-coordinate (tensiometer parallel to the panel’s bases) and 20 points for the y-coordinate (tensiometer perpendicular to the bases); with the average value of each (x,y)-coordinate measurement we create a final 20 point mesh tension grid out of which we calculate the nominal average value, the minimum/maximum, rms and uniformity (ratio of rms over average) of mesh tension measurements. In Figure 3.24 the excel template for the mesh tension measurement after gluing on a drift panel is presented (a similar used for the case of tension during gluing and on transfer frame). In Figure 3.25 we present the average mesh

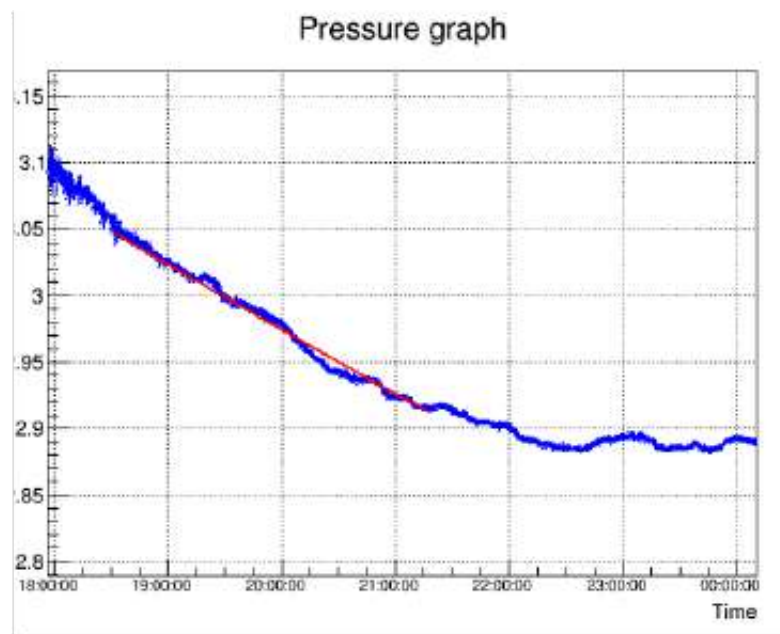


FIGURE 3.23: Monitoring of the pressure of an under study panel. The leakage rate is calculated by fitting the pressure and implementing corrections concerning the atmospheric pressure variations and the panel's volume deformations.

tension on transfer frame, during the curing of glue on the drift panel and after gluing and being cut from the drift panel (top) and the estimated uniformity for various panels (bottom).

DRIFT PANEL – MESH TENSION AFTER GLUING									
5x4 measurements									
X-coordinate (Tensionmeter Parallel to the bases)					Average Tension				
long side					10.65	10.6	9.85	10.2	10.75
10	10.4	10.2	10.7	11.2	10.1	9.4	8.8	9.7	10.05
9.3	9.1	8.7	9.8	10.2	10.65	10.25	9.25	9.25	9.25
9.8	9.8	9.2	9.8	9	9	9.1	8.65	8.85	8.7
8.2	8.9	8.4	8.7	8.3					
short side					MIN VALUE	MAX VALUE	AVERAGE VALUE		RMS VALUE
					8.7	10.8	9.7		0.71
Y-coordinate (Tensionmeter Perpendicular to the bases)					UNIFORMITY				
long side					0.07				
11.3	10.8	9.5	9.7	10.3					
10.9	9.7	8.9	9.6	9.9					
11.5	10.7	9.3	8.7	9.5					
9.8	9.3	8.9	9	9.1					
short side									

FIGURE 3.24: Excel template for the mesh tension measurement after gluing on a drift panel.

Additionally, there are some qualification measurements performed at 10 % sampling fraction of the corresponding equipment, before its assembly to the drift panel. First of all, there is the thickness of the drift boards on perimeter only and also on copper surface, as well as the thickness of the outer layer boards with nominal values of 0.518 ± 0.017 mm, 0.536 ± 0.017 mm and 0.518 ± 0.017 mm respectively. These measurements are performed using a digital micrometer(caliper) with appropriate excel templates.

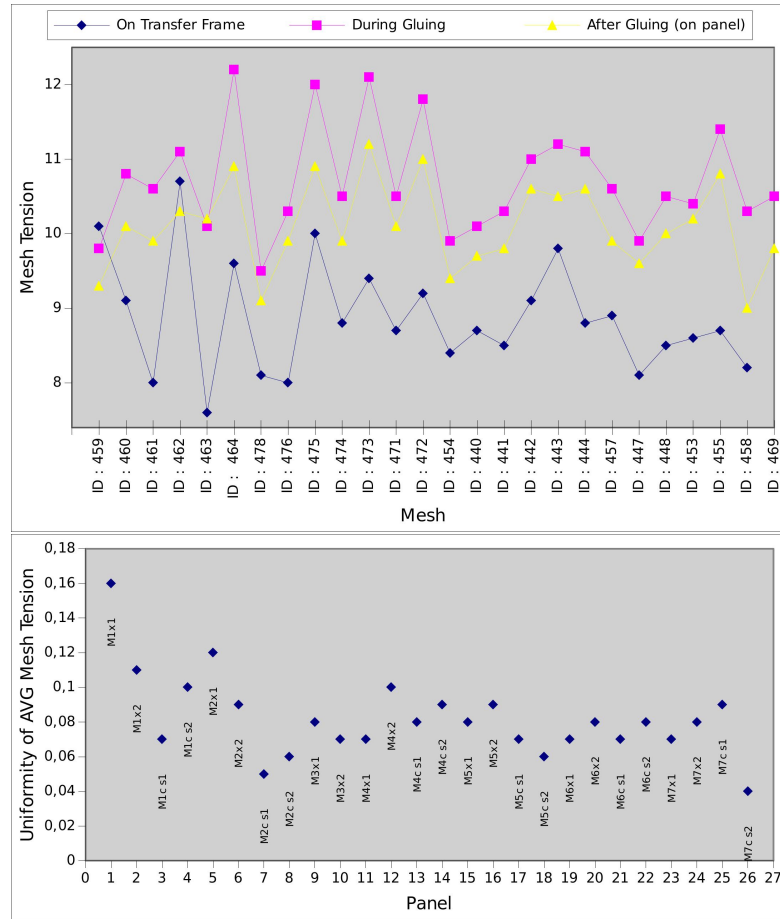


FIGURE 3.25: Mesh tension on transfer frame, during and after gluing on the drift panel (top) and the estimated uniformity for various panels (bottom).

Moreover, the thickness of the three honeycomb pieces after cutting them in order to fit the aluminium frame is measured with a digital depth-meter and with a nominal value of 10.10 mm and 0.017 mm tolerance. Finally we measure the thickness and the width of the aluminium frames used for the mesh frame (Frames type 3) using a caliper with nominal values of 5.06 ± 0.008 mm and 11 ± 0.033 mm respectively at 66 points in total.

Chapter 4

Data and Monte-Carlo samples

In this analysis, we use di-lepton filter samples DAOD_STDM5 derivations (derivation format 5 of the Standard Model physics group). These derivation formats in general, are designed to provide the minimal set of information necessary to apply all corrections by the combined performance groups for all reconstructed particle types and are thus widely usable. Especially the DAOD_STDM5 format applies a strong skimming to store only events with at least three identified leptons with $p_T > 6$ GeV. Samples with p-tag p4095, p4096 and p4097 are used in this study.

4.1 Data samples

The present analysis uses a data sample of proton-proton collisions collected at a center of mass energy of $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC. Events are selected based on data quality flags per luminosity block, using the Good Run List (GRL) definition [56] as will be later explained in more detail in section 6.2.

Data samples used have a combined integrated luminosity (as reported by the ATLAS luminosity calculation tool [57]) of 139 fb^{-1} with an uncertainty of 1.7 % and were collected from 2015 to 2018.

4.2 Monte-Carlo samples

Generated signal and background events are fully simulated by Monte-Carlo (MC) generators; the detector response was modelled using the *GEANT4* simulation within the ATLAS software

framework. *Pile-up* (i.e. the simulation of the multiple interactions in the same and neighbouring bunch crossings) is done in a separate step in the simulation chain, during digitization. During this procedure, the simulated hard-scattering event is superimposed on inelastic pp-collision events. The distribution of the number of pile-up events reproduces the bunch structure and the average number of interactions per - bunch crossing- of the run periods.

4.2.1 Monte-Carlo signal samples

First of all, simulated signal events are used to model the benchmark physics processes and optimize the selection cuts.

For the *Drell-Yan* case, the samples were generated at Leading Order (LO) in QCD with Madgraph 2.6.5 interfaced to Pythia8 (for parton-level hadronization), for masses of diboson resonances range from 250 GeV to 5 TeV. All lepton flavors were included in $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ decays and the nominal PDF set to create the samples was *NNPDF23_lo_as_0130_qed* with *A14* tune.

For the HVT production via the *Drell-Yan process* ($q\bar{q} \rightarrow W' \rightarrow WZ \rightarrow \ell\nu\ell\ell$) two benchmark models are used to interpret the results : *Model A* and *Model B*.

Model A describes weakly coupled vector resonances arising from an extension of the SM gauge group [34] with an additional SU(2) symmetry, and the branching ratios to fermions and gauge bosons are kept comparable. *Model B* accounts for an HVT produced in a strongly-coupled scenario, as in a Composite Higgs model [35] with suppressed fermionic couplings. For the Drell-Yan signals, the parameter g_V was set to 1 for Model A and to 3 for Model B, while for both models c_F is set to 1 and is assumed to be the same for all types of fermions.

Since intrinsic resonance width remains well below the experimental resolution and the angular distributions are the same for both models, in order to interpret the *Model B* we use the *Model A* simulation with scaled cross-sections.

Information about the Drell-Yan signal MC samples is summarised in table 4.1.

DSID	Mass	Events	Filter eff.	Cross-section [fb]	k-factor
307376	250	60000	1.00	4110	1.00
451943	275	20000	1.00	3083	1.00
307377	300	50000	1.00	2260	1.00
451944	325	20000	1.00	1666	1.00
451945	350	20000	1.00	1240	1.00
451946	375	20000	1.00	936	1.00
307378	400	60000	1.00	717	1.00
451947	425	20000	1.00	557.7	1.00
451948	450	20000	1.00	439.4	1.00
451949	475	20000	1.00	350.6	1.00
302266	500	30000	1.00	283.9	1.00
451950	525	20000	1.00	230.8	1.00
451951	550	20000	1.00	190	1.00
302267	600	30000	1.00	132.2	1.00
302268	700	18000	1.00	69.23	1.00
302269	800	25000	1.00	39.41	1.00
302270	900	30000	1.00	23.80	1.00
302271	1000	45000	1.00	15.09	1.00
302272	1100	18000	1.00	9.921	1.00
302273	1200	30000	1.00	6.751	1.00
302274	1300	10000	1.00	4.676	1.00
302275	1400	30000	1.00	3.313	1.00
302276	1500	29000	1.00	2.391	1.00
302277	1600	30000	1.00	1.749	1.00
302278	1700	28000	1.00	1.298	1.00
302279	1800	30000	1.00	0.9720	1.00
302280	1900	30000	1.00	0.7350	1.00
302281	2000	18000	1.00	0.5610	1.00
302282	2200	35000	1.00	0.3334	1.00
302283	2400	45000	1.00	0.2028	1.00
302284	2600	30000	1.00	0.1258	1.00
302285	2800	29000	1.00	0.07925	1.00
302286	3000	20000	1.00	0.05036	1.00
302287	3500	25000	1.00	0.01692	1.00
302288	4000	30000	1.00	0.00587	1.00
302289	4500	25000	1.00	0.00200	1.00
302290	5000	30000	1.00	0.00073	1.00

TABLE 4.1: Summary of the LO HVT signal MC simulation for the Drell-Yan analysis.

For the HVT production via the *VBF process* we use a benchmark model where the product of the coupling parameters $g_V \cdot c_H$ is set to 1.0, 1.5 and 2.0 and all other couplings of heavy triplet (c_F included) are set to 0 in order to maximize the VBF contribution. Signal samples were generated at Leading Order (LO) in QCD with Madgraph 2.6.5 interfaced to Pythia8, for masses of diboson resonances range from 250 GeV to 2 TeV. The nominal PDF set to create the samples was *NNPDF23_lo_as_0130_qed* with *A14* tune. Also, the W and Z decay to all three

lepton flavors (e, μ, τ) and no lepton filter is applied and a generator cut of $m_{jj} > 150$ GeV was applied on these samples.

Information about the VBF HVT signal MC samples is summarised in table 4.2.

DSID	Mass	Events	Filter eff.	Cross-section [fb]	k-factor
307730	250	200000	1.00	24.196	1.00
313538	275	200000	1.00	22.7	1.00
307731	300	200000	1.00	10.54	1.00
313539	325	200000	1.00	6.71	1.00
313540	350	200000	1.00	4.524	1.00
313541	375	200000	1.00	3.19	1.00
307732	400	200000	1.00	2.299	1.00
313542	425	200000	1.00	1.73	1.00
313543	450	200000	1.00	1.32	1.00
313544	475	200000	1.00	1.02	1.00
307733	500	200000	1.00	0.7975	1.00
313545	525	200000	1.00	0.639	1.00
313546	550	200000	1.00	0.515	1.00
307734	600	200000	1.00	0.3408	1.00
307735	700	200000	1.00	0.1663	1.00
307736	800	200000	1.00	0.0879	1.00
307737	900	200000	1.00	0.04988	1.00
307738	1000	200000	1.00	0.02961	1.00
307739	1100	200000	1.00	0.01814	1.00
307740	1200	200000	1.00	0.01171	1.00
307741	1300	200000	1.00	0.007621	1.00
307742	1400	200000	1.00	0.005078	1.00
307743	1500	200000	1.00	0.003449	1.00
307744	1600	200000	1.00	0.002391	1.00
307745	1700	200000	1.00	0.001673	1.00
307746	1800	200000	1.00	0.001192	1.00
307747	1900	200000	1.00	0.0008536	1.00
307748	2000	200000	1.00	0.0006183	1.00

TABLE 4.2: Summary of the LO HVT signal MC simulation for the VBF analysis.

The GM signal production with *VBF process* is described by $pp \rightarrow H_5^\pm jj \rightarrow W^\pm Z jj \rightarrow \ell^\pm \nu \ell^+ \ell^- jj$, vetoing W or Z bosons in the s-channel. These samples were produced with MADGRAPH 2.7.2 at next-to-leading order (NLO) in QCD. These simulated signals were produced for the mass range 200 GeV to 1 TeV in the H_5 -plane defined in Refs. [26, 58], using the tool GMCALC [29]. The theoretical parameter $\sin \theta_H$ was set to 0.5 for masses up to 800 GeV and 0.25 for higher masses to be compatible with present constraints [58]. NNPDF30NLO [59] PDF sets were used, interfaced to PYTHIA 8 for the modelling of the parton shower, hadronization, and underlying event, using the A14 tuning parameters [60]. Also, a minimum p_T of 15 GeV (10 GeV) for the jets (leptons) was required during event generation.

Information about the VBF GM signal MC samples is summarised in table 4.3.

DSID status	Mass	Events	$\sin(\theta_H)$	ptj	Filter eff.	Cross-section [fb]
450765	200	200000	0.5	10.	0.4444	23.8
502511	225	200000	0.5	10.	0.4466	20.31
450766	250	200000	0.5	10.	0.4490	17.54
502512	275	200000	0.5	10.	0.456	15.04
450767	300	200000	0.5	10.	0.4605	13.78
502513	325	200000	0.5	10.	0.469	11.33
450768	350	200000	0.5	10.	0.4782	10.54
502514	375	200000	0.5	10.	0.476	9.147
450769	400	200000	0.5	10.	0.4871	8.215
502515	425	200000	0.5	10.	0.483	7.116
450770	450	200000	0.5	10.	0.4926	6.342
502516	475	200000	0.5	10.	0.484	5.291
450771	500	200000	0.5	10.	0.5011	4.979
502517	525	200000	0.5	20.	0.492	3.902
502518	550	200000	0.5	20.	0.501	3.449
502519	600	200000	0.5	20.	0.502	2.782
502520	700	200000	0.5	20.	0.510	1.994
502521	800	200000	0.5	20.	0.514	1.327
502522	900	200000	0.25	20.	0.519	0.2495
502523	1000	200000	0.25	20.	0.522	0.1842

TABLE 4.3: Summary of GM NLO signal MC simulations for the VBF analysis.

4.2.2 Monte-Carlo background samples

The dominant background for this resonance search is the SM QCD mediated WZ process, here called WZ-QCD. This background includes processes up to order four in the electroweak coupling constant, α_{EW} , and is modelled using SHERPA 2.2.2 [61]. During this modelling procedure we include up to one jet calculated at NLO in QCD, while second and third jets were calculated at LO in QCD and merged with the parton shower. Targeting the estimation of the generator and parton shower modelling uncertainties, we produce an alternative NLO WZ-QCD sample using MADGRAPH 2.6.5 with FxFx merging [62] of up to two extra jets, using the PDF set NNPDF3.0nLOas118. In both samples, the hadronization was performed with PYTHIA 8.186 with the A14 tune.

We also use a sample of the purely electroweak process $WZjj \rightarrow \ell\nu \ell\ell jj$, including processes of order six in α_{EW} , called WZ-EWK; this was generated separately with MADGRAPH 2.7.3 together with PYTHIA 8.244 using the A14 tune [60] and the NNPDF3.0NLO[59] PDF set. Similarly, in order to estimate an uncertainty due to the parton shower modelling, we have produced an alternative sample using the same MADGRAPH 2.7.3 matrix element but HERWIG 7.2.1 for the parton shower.

Furthermore, the Standard Model predicts a small amount of interference between electroweak and QCD WZ production; the latter was modelled with MADGRAPH 2.7.3 + PYTHIA 8.244 using the A14 tune [60] and the NNPDF3.0NLO[59] PDF set and combined with the simulated WZ-EWK sample.

Background processes of $q\bar{q} \rightarrow ZZ \rightarrow 4\ell$, $q\bar{q} \rightarrow ZZ \rightarrow \ell\ell \nu\nu$ and triboson events were generated with SHERPA 2.2.2 [63] using matrix elements at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions, including off-shell effects and Higgs boson contributions. The purely electroweak process $q\bar{q} \rightarrow ZZjj \rightarrow 4\ell jj$ and the $gg \rightarrow ZZ$ process were also generated with SHERPA 2.2.2 [63]; here we have LO-accurate matrix elements that were matched to a parton shower based on Catani–Seymour dipole factorization [64, 65] using the MEPS@LO prescription [66–69], using the NNPDF3.0NNLO PDF set [59], and SHERPA parton-shower parameter values.

For the modelling of $t\bar{t}V$ background processes we have used the MADGRAPH 2.3.3 [70] generator at NLO in QCD with the NNPDF3.0NLO[59] PDF set, where the events were interfaced to PYTHIA[8.210] [71] using the A14 tune and the NNPDF2.3LO [59] PDF set.

SM backgrounds that include at least one misidentified or non-prompt lepton, including $Z\gamma$, $W\gamma$, Drell–Yan $Z \rightarrow \ell\ell$, $W \rightarrow \ell\nu$ as well as top-quark pairs and single top-quark have been generated to assist in estimating the fake/non-prompt lepton background. Events with

$V\gamma$ in the final state were simulated with the SHERPA[2.2.4] [63] generator, with matrix elements calculated at LO accuracy in QCD for up to three additional parton emissions; events were matched and merged with the SHERPA parton shower [64–69] and generated using the NNPDF3.0NNLO PDF set [59], along with the dedicated set of tuned parton-shower parameters developed by the SHERPA authors. Drell-Yan $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ were produced with POWHEGBox[v1] generator [72–75] at NLO accuracy for the hard-scattering processes of W and Z boson production and decay in the electron, muon, and τ -lepton channels. Events were interfaced to PYTHIA[8.186] [76] for the modelling of the parton shower, hadronization, and underlying event, with parameters set according to the AZNLO tune [77]. The CT10NNLO PDF set [78] was used for the hard-scattering processes, whereas the [6L1] PDF set [79] was used for the parton shower. Moreover, the effect of QED final-state radiation was simulated with PHOTOSpp[3.52] [80, 81].

For top-quark pairs and single top-quark productions the POWHEGBox[v2] [72–74, 82] generator was used at NLO with the NNPDF3.0NNLO [59] PDF set, interfacing events with PYTHIA [8.230] [71] using the A14 tune [60] and the NNPDF2.3LO PDF set.

Finally, SM backgrounds including Higgs bosons ($H, t\bar{t}H, VH$) are neglected in this study, because they are expected to contribute less than 0.1% of the total background because of the low cross-section and the requirement of a well-reconstructed leptonically decaying Z boson.

Chapter 5

Object Reconstruction

5.1 Electrons and Muons

Electrons candidates are reconstructed from energy deposits in the electromagnetic calorimeter which are matched to a well-reconstructed ID track [83]. To improve reconstruction for candidates, especially for electrons which undergo significant energy loss due to Bremsstrahlung, the track associated to a cluster, passing loose shower shape requirement, is refitted using a Gaussian-Sum Filter. To distinguish between isolated electrons and other objects such as hadronic jets faking electrons, a set of variables that provide good separation is used. In this direction, we consider only electrons with transverse energy $E_T > 7$ GeV and within the pseudorapidity range of $|\eta| < 2.47$, excluding the barrel-endcap transition region $1.37 < |\eta| < 1.52$.

Generally in ATLAS experiment, we have various algorithms to reconstruct muons by combining the information from the Muon Spectrometer(MS), the Inner Detector(ID) and the calorimeter detectors. This yields four different types of reconstructed muons:

- *Combined* (CB): Starting from tracks reconstructed in the MS and extrapolating to the interaction point (ME tracks), this algorithm searches for an ID track within a cone around the ME track. Then a combined fit using the hits of the inner detector track, the energy loss in the calorimeter and the hits of the track in the muon system is performed.
- *MuGirl*: This complementary algorithm starts from ID track with $p_T > 2$ GeV and projects outwards using a neural network to select reconstructed segments in the MS. Afterwards, a combined fit is performed using the same procedure as the combined muon reconstruction.

- *Segment tagged (ST)*: A track in the ID is identified as a muon if the trajectory extrapolated to the MS can be associated with track segments in the precision muon chambers. ST muons adopt the measured parameters of the associated ID track.
- *Calorimeter tagged (CT)*: A trajectory in the ID is identified as a muon if the associated energy depositions in the calorimeters are compatible with the hypothesis of a minimum ionizing particle. Their use in the analysis is to cover the region of $|\eta| < 0.1$ which is not equipped with muon chambers. The calorimeter muon identification algorithm is optimized for muons with $p_T > 15$ GeV.
- *StandAlone*: In the $2.5 < |\eta| < 2.7$ region, where the ID provides no coverage, tracks are reconstructed in the MS and are extrapolated back to the interaction point.

Muons are identified either by matching muon spectrometer tracks with tracks in the ID or by using the calorimeter-based muon identification [84]. A requirement of a transverse momentum $p_T > 5$ GeV ($p_T > 15$ GeV if calorimeter tagged) and pseudorapidity $|\eta| < 2.7$ is applied.

Identification and isolation criteria, either “loose”, “medium” or “tight” as described in [83, 84], are applied to electron and muon candidates. Identification criteria are based on shower shapes and track parameters for electrons, and on track parameters for muons. The isolation criteria use information about ID tracks and calorimeter energy deposits in a fixed cone of size $\Delta R = 0.2$ around each lepton. Four lepton categories are designed using the identification and isolation criteria: *Baseline* electrons and muons are required to satisfy “loose” identification and isolation criteria (for muons with $p_T > 300$ GeV the dedicated “High p_T identification” is required). The *Loose*, *Tight Z* and *Tight W* leptons are defined as subsets of the *Baseline* lepton selection with $p_T > 25$ GeV. For the *Tight Z* leptons the “medium” identification and “tight” isolation criteria are applied, while for *Tight W* leptons the “tight” identification and “tight” isolation criteria are applied.

Electron and muon candidates are required to originate from the primary vertex. The primary vertex is defined, using tracks with $p_T > 500$ MeV, as the vertex candidate with the highest $\sum p_T^2$ of its associated tracks. The transverse impact parameter of the track (d_0) is calculated relative to the beam line. For all four lepton categories, the longitudinal impact parameter, z_0 (the difference between the value of z at the point of the track where d_0 is defined and the longitudinal position of the primary vertex), is required to satisfy $|z_0 \cdot \sin\theta| < 0.5$ mm. Furthermore, for the *Loose*, *Tight Z* and *Tight W* leptons the significance of the transverse impact parameter of the track, $|d_0/\sigma_{d_0}|$, must be smaller than 3.0 for muons and less than 5.0 for electrons.

Applying all the above cuts, we have high quality tracks to allow for a robust 4-vector measurement both electrons and muons.

Electron and Muon object selection requirements used in this analysis are summarized in Tables 5.2 and 5.1.

Electron object selection				
Selection	<i>baseline</i>	<i>loose</i>	<i>tight(Z)</i>	<i>tight(W)</i>
$p_T > 7 \text{ GeV}$	✓	✓	✓	✓
$p_T > 25 \text{ GeV}$		✓	✓	✓
$ \eta^{\text{cluster}} < 2.47$	✓	✓	✓	✓
Exclude $1.37 < \eta^{\text{cluster}} < 1.52$		✓	✓	✓
Electron object quality	✓	✓	✓	✓
$ z_0 \sin \theta < 0.5 \text{ mm}$	✓	✓	✓	✓
$ d_0/\sigma(d_0) < 5^2$		✓	✓	✓
LooseLH+BLayer identification	✓	✓	✓	✓
FCLoose isolation	✓	✓	✓	✓
$e\text{-}\mu$ and $e\text{-}e$ overlap removal		✓	✓	✓
$e\text{-jets}$ overlap removal		✓	✓	✓
MediumLH identification			✓	
FCTight isolation			✓	
TightLH identification				✓
FCTight isolation				✓

TABLE 5.1: Electron object selection used in the analysis.

Muon object selection				
Selection	<i>baseline</i>	<i>loose</i>	<i>tight(Z)</i>	<i>tight(W)</i>
$p_T > 5 \text{ GeV}$ (15 GeV for CT muons)	✓	✓	✓	✓
$p_T > 25 \text{ GeV}$		✓	✓	✓
$ \eta < 2.7$	✓	✓	✓	✓
$ z_0 \sin \theta < 0.5 \text{ mm}$	✓	✓	✓	✓
cosmic cut ($ d_0 < 1 \text{ mm}$)	✓	✓	✓	✓
$ d_0/\sigma(d_0) < 3^2$		✓	✓	✓
Loose quality (if $p_T > 300 \text{ GeV}$ HighPt quality)	✓	✓	✓	✓
FCLoose isolation	✓	✓	✓	✓
$\mu\text{-jet}$ overlap removal		✓	✓	✓
Medium quality (if $p_T > 300 \text{ GeV}$ HighPt quality)			✓	
FCTight isolation			✓	
Tight quality (if $p_T > 300 \text{ GeV}$ HighPt quality)				✓
FCTight isolation				✓

TABLE 5.2: Muon object selection used in the analysis.

¹ $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

² not required for measuring fake rates

5.1.1 Optimisation of muon isolation working points

In the previous 36 fb^{-1} analysis [85] the *baseline* and Z-selected muon isolation working point was “LooseTrackOnly” while the W-selected muon was chosen to have “Gradient” isolation. These options are not supported anymore; new working points are “FCLoose”(which has tighter requirements compared to “LooseTrackOnly”) and “FCTight”[86].

So the *nominal* selection is defined as : no selection requirement for *baseline*, “FCLoose” for Z-selected and “FCTight” for W-selected muons. While, the alternative option that is investigated is : “FCLoose” for *baseline*, “FCLoose” for Z-selected and “FCTight” for W-selected muons. Here we have to note that the idea behind the application of tighter cuts to the W lepton candidates than for the Z lepton candidates is that the looser cuts on the Z leptons are to compensate the possible efficiency loss for the Z lepton candidates, when they are very close-by.

The aim of this study is to specify the most optimal baseline, W and Z muon isolation selection requirements, in order to reduce the background contamination including the non-prompt background, while maintaining the signal efficiency as high as possible.

Table 5.3 shows the recommended Working Points (WPs) used for this study and their definitions [87].

Isolation WPs	Calo-isolation	Track-isolation
FCLoose	$\text{topoetcone20/pT} < 0.3$	$\text{ptvarcone30_TightTTVA_pt1000/pT} < 0.15$
FCTight	$\text{topoetcone20/pT} < 0.15$	$\text{ptvarcone30_TightTTVA_pt1000/pT} < 0.04$

TABLE 5.3: Muon isolation working points

Signal and background MC samples of MC16a+MC16d+MC16e periods and $L = 139\text{ fb}^{-1}$ were used for this study and we have measured the signal efficiency separately for qqHVT(Drell-Yan) and vbfHVT signals for masses : 500 GeV, 700 GeV, 1000 GeV, 2000 GeV see Tables 4.1, 4.2.

Selected events have the invariant mass of the WZ system to be within 2 times the width (2σ) around the investigated signal mass point.

In order to estimate the change in background yield, two figures of merit have been used : the signal-to background ratio $\frac{S}{\sqrt{S+B}}$ and the significance $\frac{S}{\sqrt{S+B+0.1*B^2}}$. The S is the signal yield, B is the background yield and $\Delta B = 0.1$ takes into account the effect of systematics. The signal efficiency is defined as the ratio of the total number of *baseline* leptons passing the “FCLoose” isolation WP over the nominal selection (no isolation for *baseline*).

We present here the signal efficiency as a function of the signal-to-background ratio and the signal efficiency as a function of the significance for the $\mu\mu\mu$ channel only and including all lepton final states ($eee, ee\mu, \mu\mu e, \mu\mu\mu$) for the WZ Inclusive region and VBF (Drell-Yan) signal region using the vbfHVT(qqHVT) signals in Figures 5.1- 5.8.

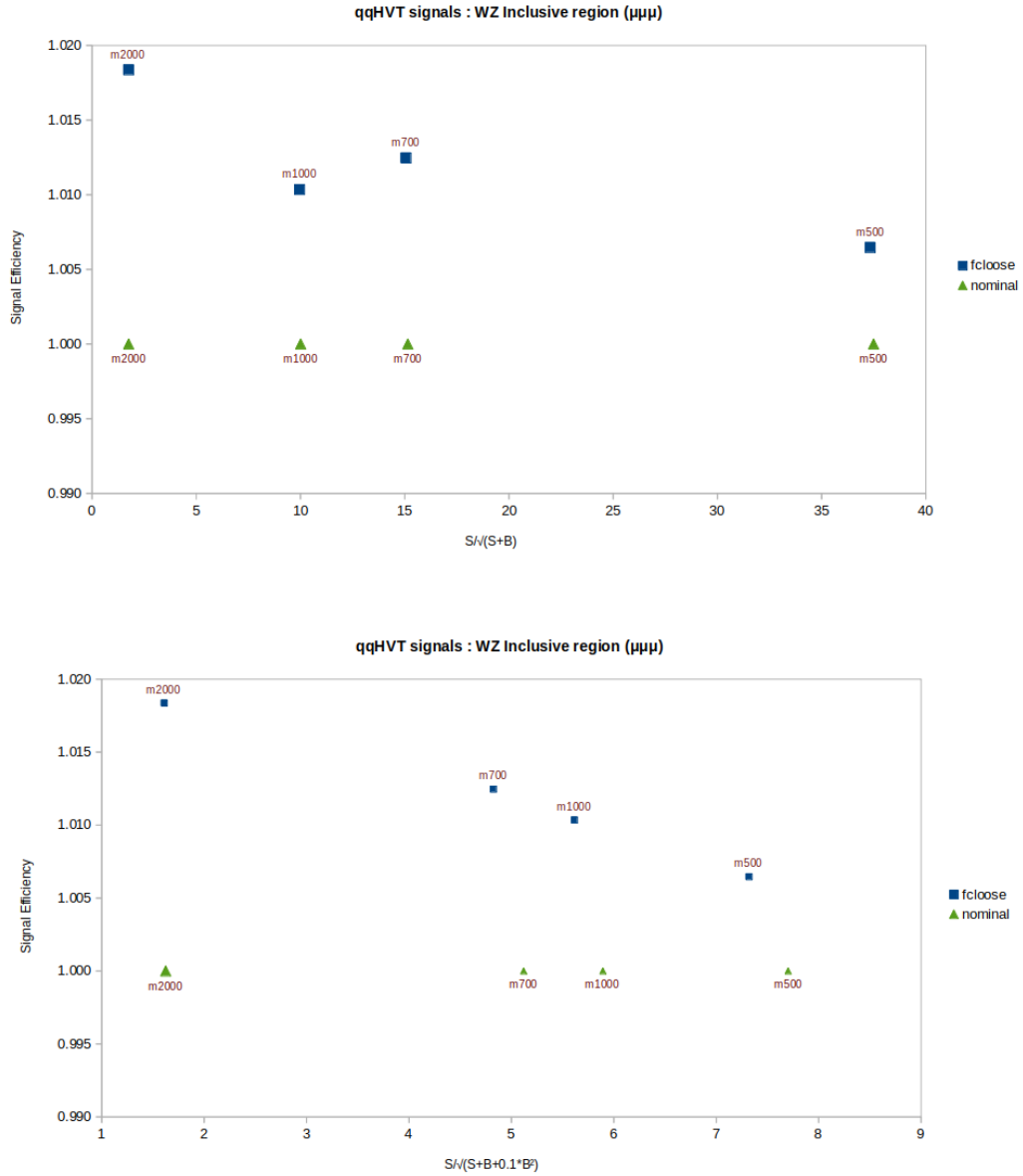


FIGURE 5.1: Signal efficiency with respect to the S/B ratio and to significance for $\mu\mu\mu$ channel for WZ Inclusive region for qqHVT signals.

From the above figures it is obvious that the “FCLoose” isolation WP for the *Baseline* leptons has better signal efficiency than using no isolation requirement, both in WZ Inclusive, Drell-Yan and VBF signal regions; thus, it is going to be used for *baseline* leptons in this analysis.

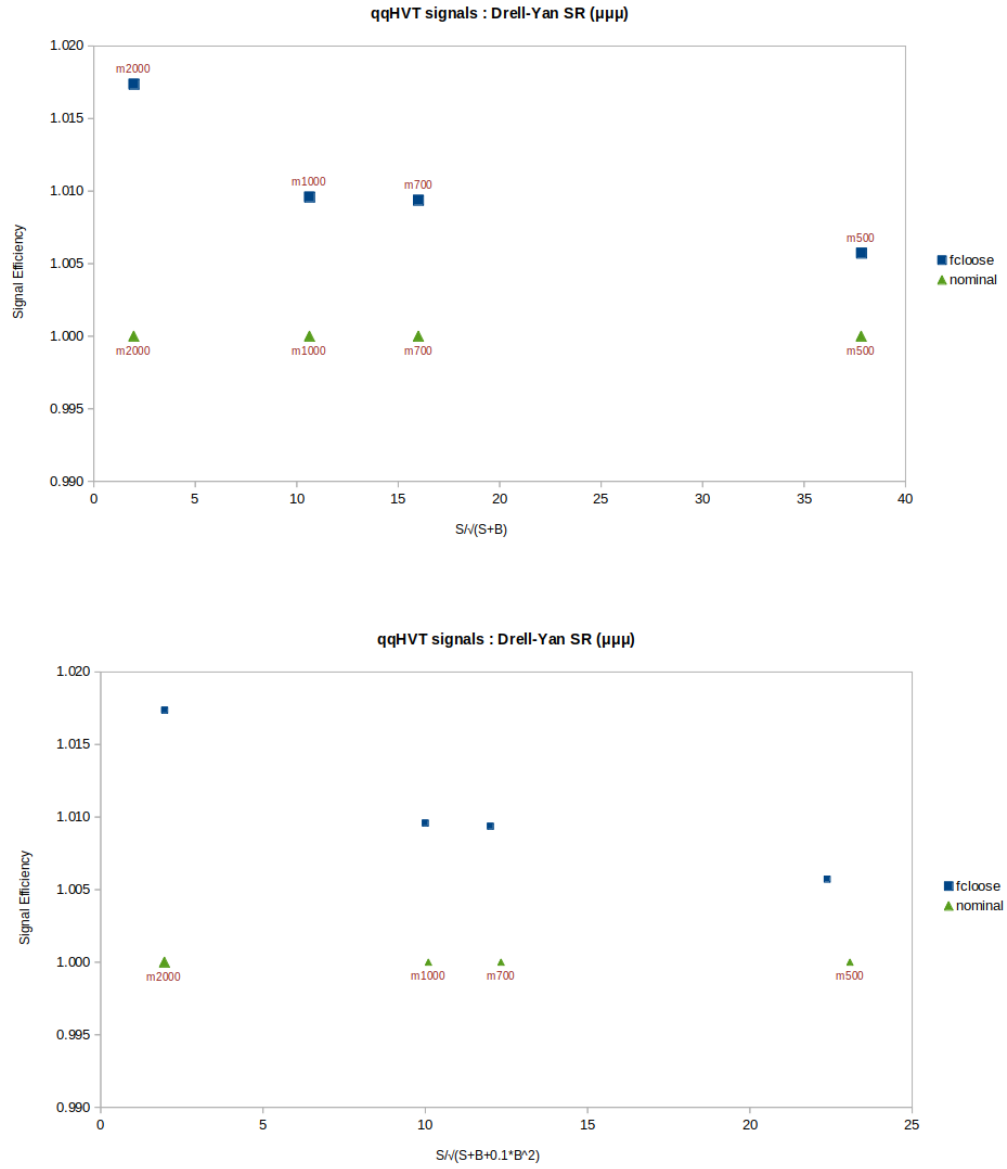


FIGURE 5.2: Signal efficiency with respect to the S/B ratio and to significance for $\mu\mu\mu$ channel for Drell-Yan signal region.

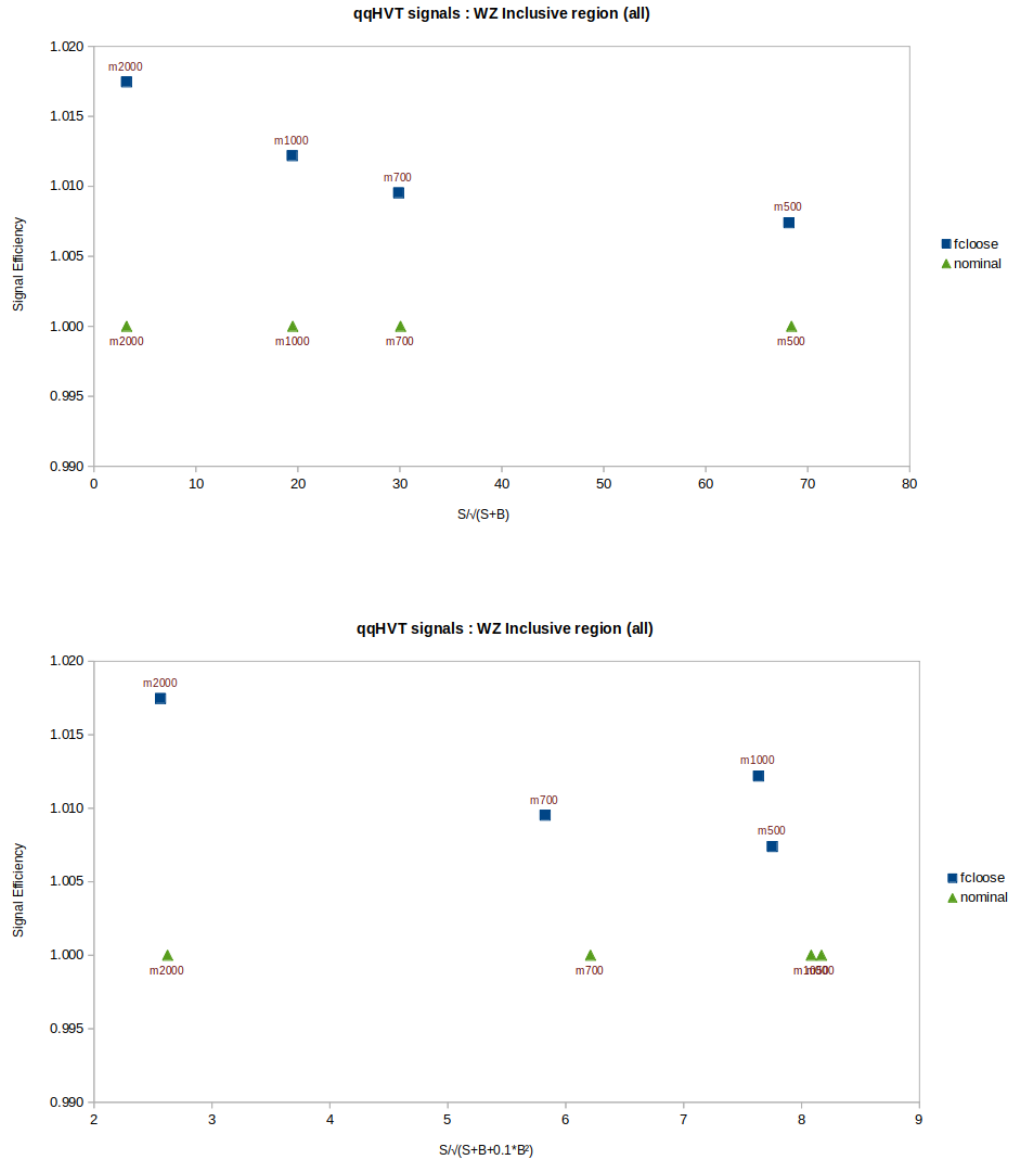


FIGURE 5.3: Signal efficiency with respect to the S/B ratio and to significance for all channels for WZ Inclusive region for qqHVT signals.

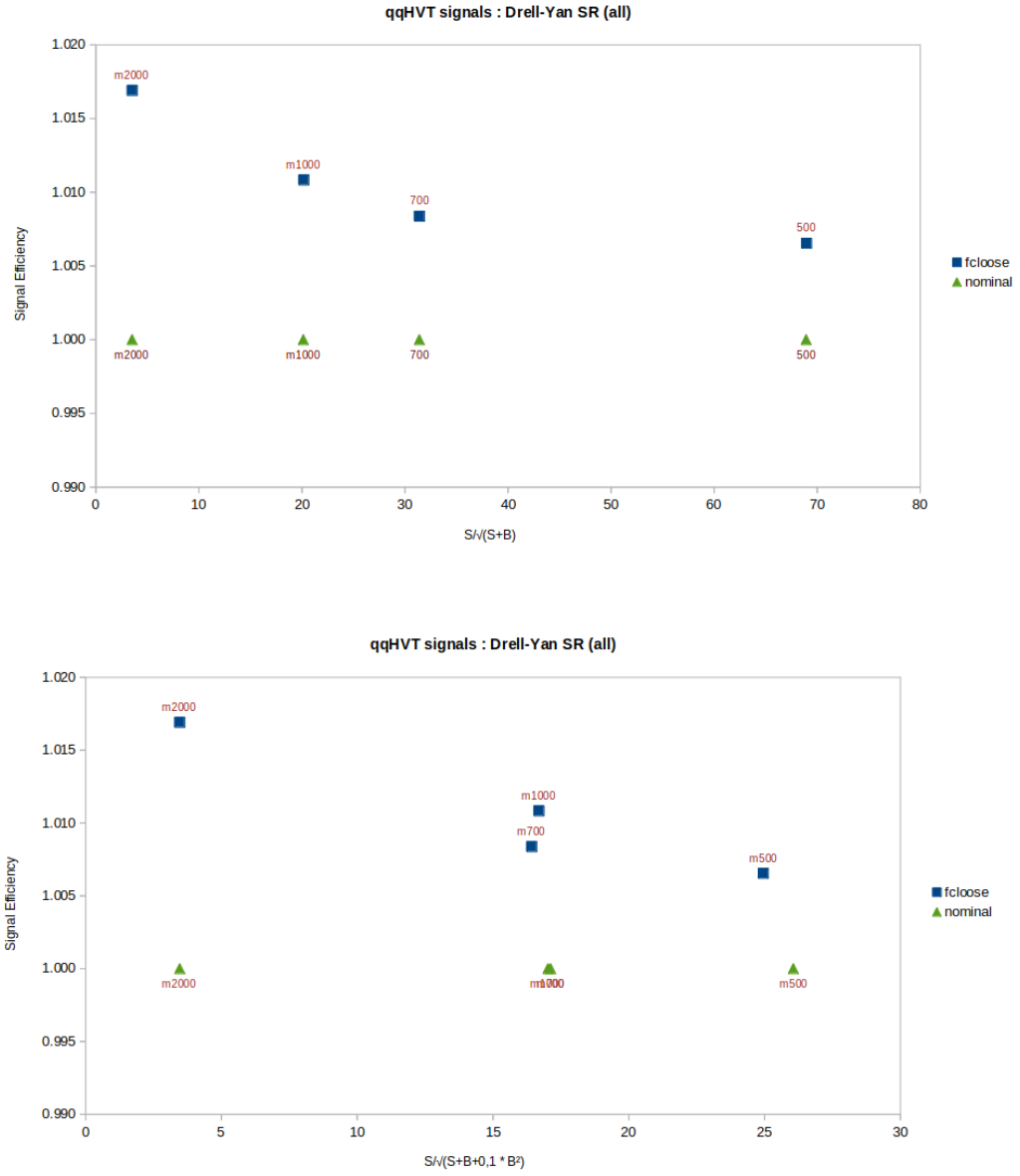


FIGURE 5.4: Signal efficiency with respect to the S/B ratio and to significance for all channels for Drell-Yan signal region.

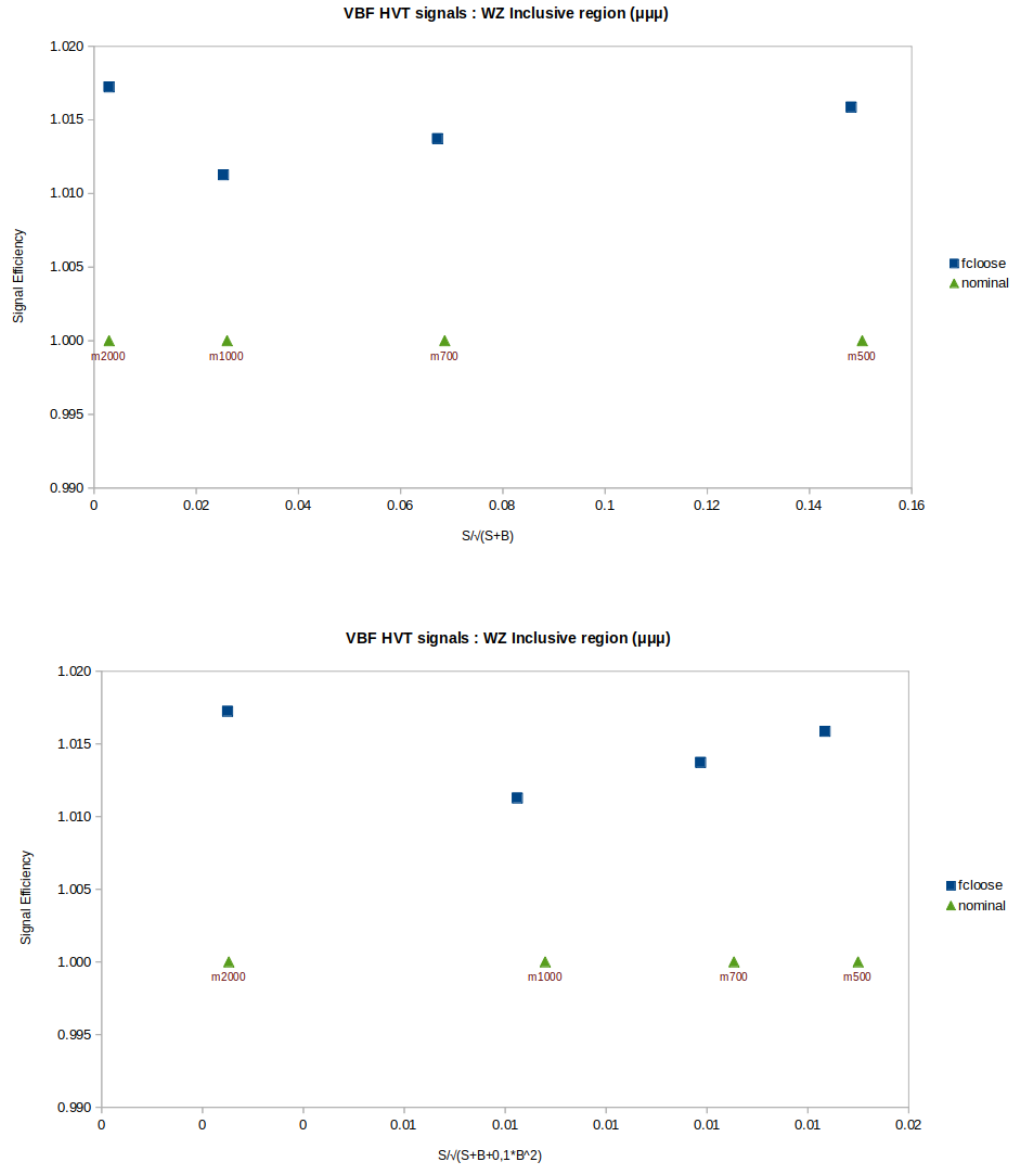


FIGURE 5.5: Signal efficiency with respect to the S/B ratio and to significance for $\mu\mu\mu$ channel for WZ Inclusive with vbfHVT signals.

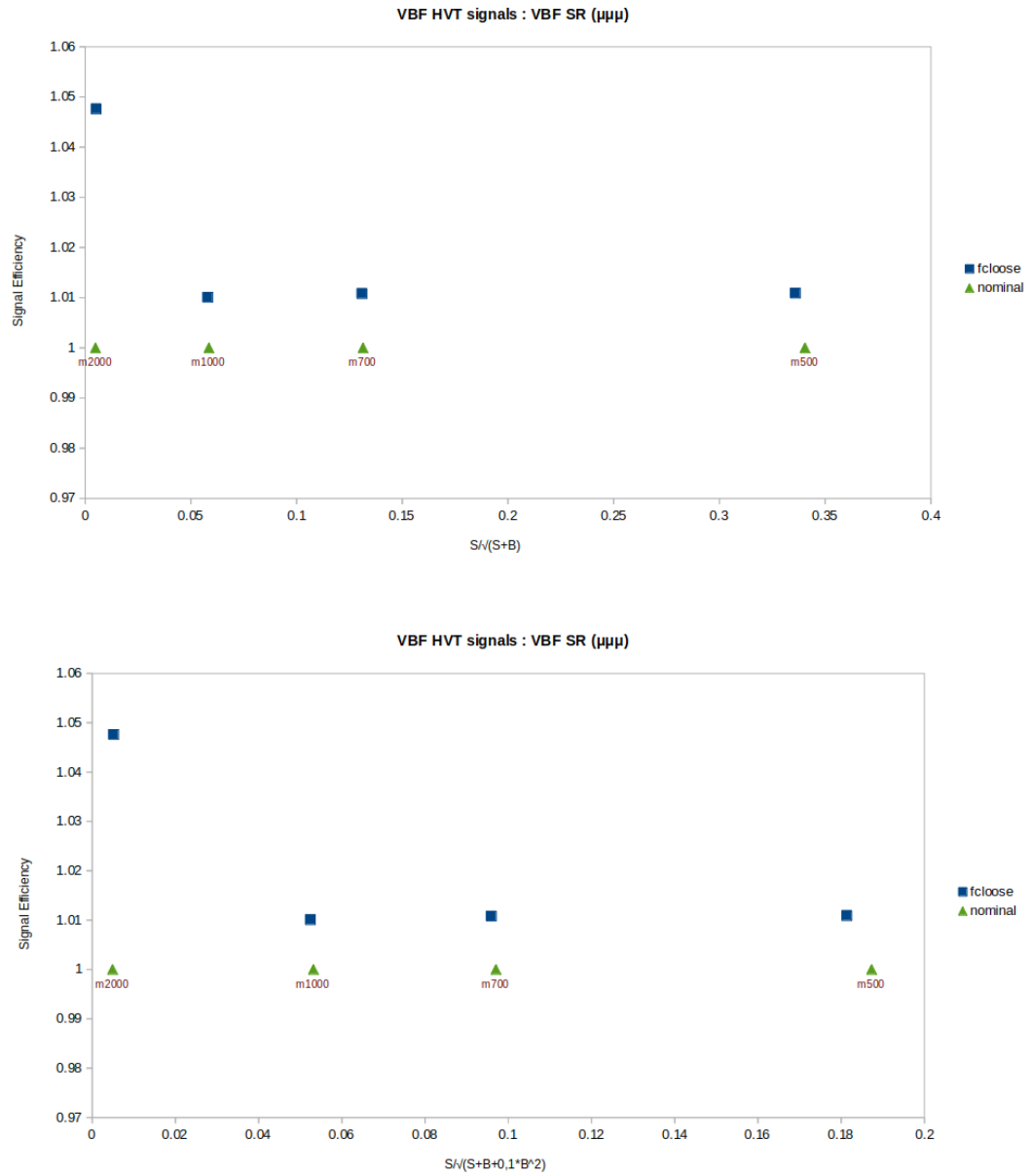


FIGURE 5.6: Signal efficiency with respect to the S/B ratio and to significance for $\mu\mu\mu$ channel for VBF signal regions.

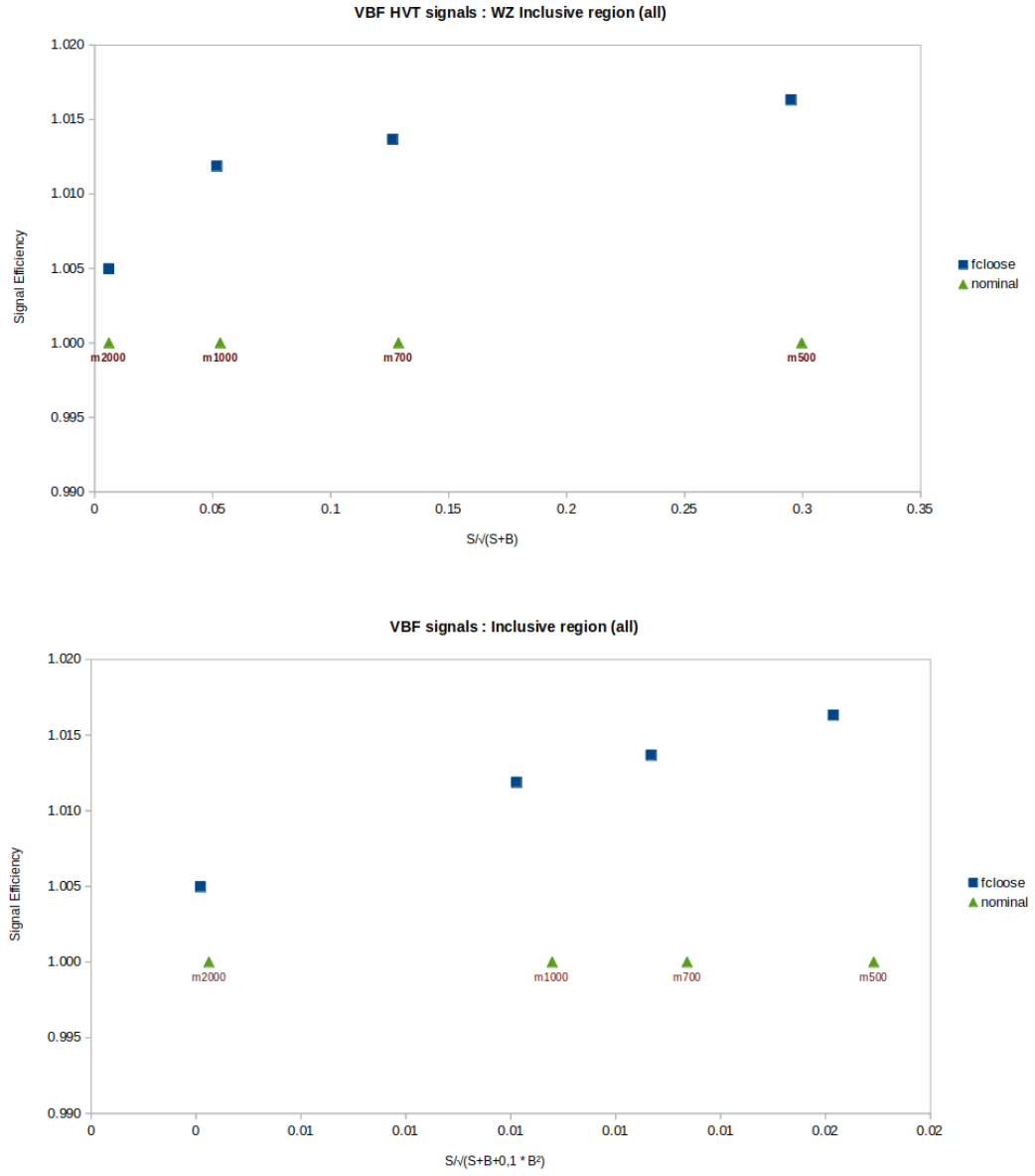


FIGURE 5.7: Signal efficiency with respect to the S/B ratio and to significance for all channels for WZ Inclusive region with vbfHVT signals.

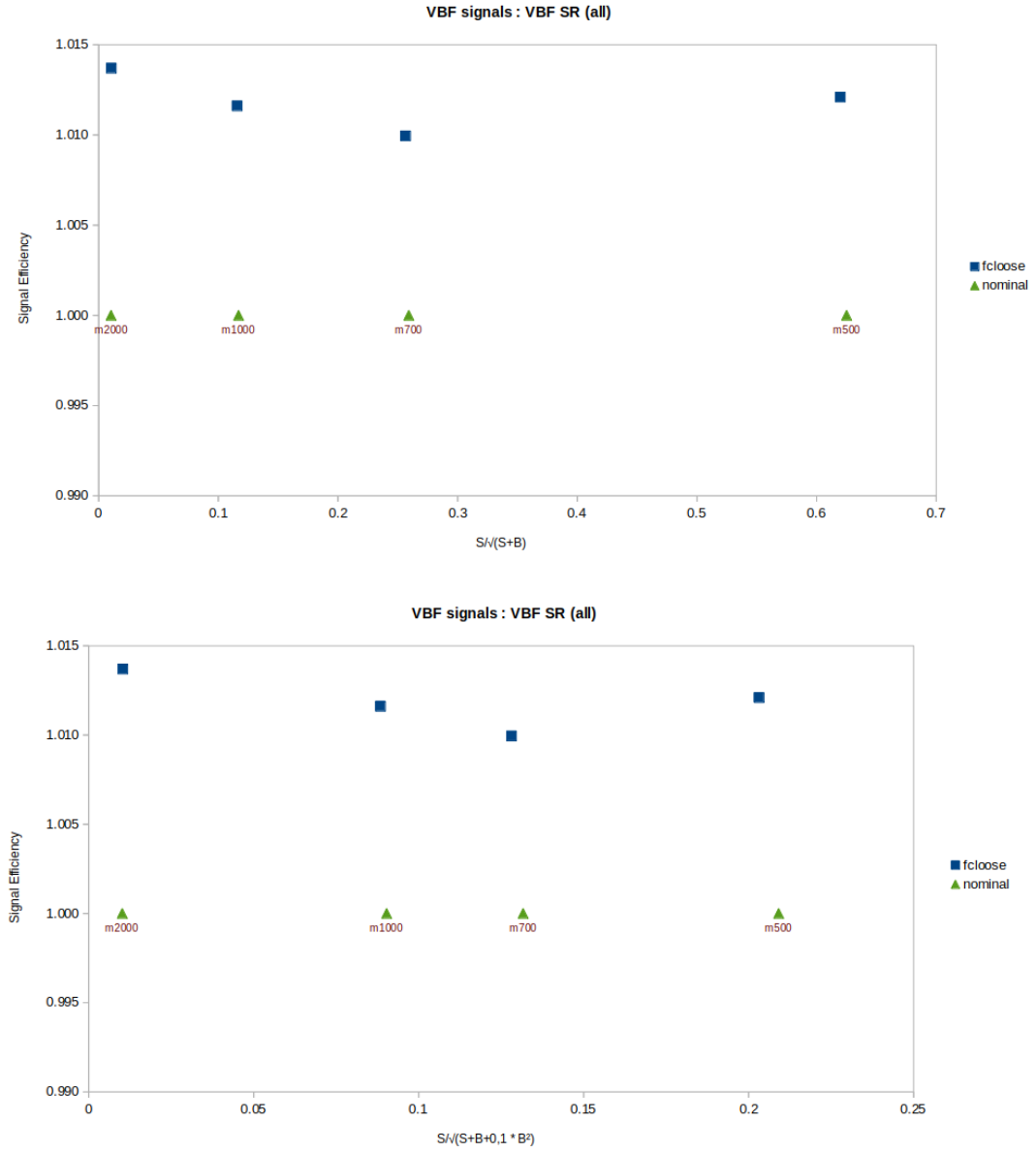


FIGURE 5.8: Signal efficiency with respect to the S/B ratio and to significance for all channels for VBF signal regions.

The WZ Standard Model analysis suggested that the fake rate is high for “FCLoose”; for this resonance analysis, we can see a reduction of about 30 % in fake backgrounds when using “FCTight” for Z-selected leptons in all the control regions while only a 6 % reduction in data and the irreducible backgrounds. As a result, we choose the “FCTight” isolation WP for both Z and W selected muons.

5.2 Jets

Jets are used to tag the VBS event topology, and to veto the b -quark-induced jets (b -jets) in the event. Jets are based on particle-flow objects built from noise-suppressed positive-energy topological clusters of cells in the calorimeter and reconstructed tracks [88]. The anti- k_t algorithm [89, 90] with a radius parameter of $R = 0.4$ is used.

For jets, the main backgrounds are either beam-induced, due to proton collisions upstream of the interaction point, from cosmic-ray showers or highly coherent calorimeter noise. In order to reject these, jets are required to fulfill the *Bad Loose* set of quality criteria [91]. Furthermore, to mitigate the pile-up contamination, jets with $p_T < 60$ and $\eta < 2.4$ should have a jet-vertex-tagger (JVT) score greater than 0.2 [92]. Jets with $p_T < 120$ and $2.5 < \eta < 4.5$ are required to have a forward jet-vertex-tagger (fJVT) score less than 0.5 and $|timing| < 10$ ns [92]; the JVT is a 2-dimensional likelihood method that uses the corrected jet-vertex fraction [92] and the ratio of the scalar sum of hard-vertex associated track p_T to the jet p_T [92] to discriminant against pile-up jets.

Jet energies are corrected [93] for detector in-homogeneities, the non-compensating nature of the calorimeter, and the impact of multiple overlapping pp interactions. Correction factors are derived using test beam, cosmic ray, pp collision data, and a detailed Geant4 detector simulation.

The ATLAS jet flavor tagging algorithm, DL1r [94], is used to suppress $t\bar{t}$ background in the signal region. Out of the possible working points corresponding to different b-tagging efficiencies, the 85 % working point (threshold value of 0.1758) is selected as the baseline tagger to achieve high $t\bar{t}$ reduction.

“Baseline” level jets are defined as $p_T > 30$ GeV and $|\eta| < 4.5$. The “baseline” jets will be used to calculate missing transverse momentum and carry out overlap removal, while “baseline” jets passing pile-up removal, b-jet veto and overlap removal will be considered as VBS jet candidates.

Table 5.4 summarizes the jets object reconstruction selection.

Jet object selection		
Selection	<i>baseline</i>	VBS
$p_T > 30 \text{ GeV}$	✓	✓
$ \eta < 4.5$	✓	✓
Pile-up Removal		✓
veto b-Tagging		✓
μ -jet overlap removal		✓
e -jets overlap removal		✓

TABLE 5.4: Object selection for jets

5.3 Overlap Removal

In order to avoid events where the detector response to a single physical object is reconstructed as two different final-state objects, an overlap-removal algorithm is applied to the *Baseline* selected leptons and jets.

For the electron objects, if two electrons share the same track then the lower- p_T electron is discarded. Also, electrons that share the same track as a selected muon with a muon spectrometer track are also discarded; but in the case of a calorimeter-tagged muon, it is the muon which is rejected. Furthermore, a jet is removed if its separation from an electron satisfies $\Delta R < 0.2$; the electron is removed if the separation satisfies $0.2 < \Delta R < 0.4$. For nearly collinear muons and jets, the jet is removed if it is separated from the muon by $\Delta R < 0.2$ and if it has less than three tracks, or if the energy and momentum differences between the muon and the jet are small; otherwise the muon is removed if the separation satisfies $\Delta R < 0.4$.

The overlap removal procedure is handled by the “OverlapRemovalTool” with the “Standard” working point as described in [95, 96].

5.4 Missing Transverse Energy Determination

The missing transverse momentum $\vec{p}_T^{miss}$ and its magnitude E_T^{miss} are the main physics quantities used to search for the presence of particles that leave no signal in the detector; these could be either SM neutrinos or particles predicted by BSM theories. These particles leave the detector without any energy deposition and as a result they create an imbalance in the sum of visible transverse momenta of reconstructed physics objects.

Here we have to mention that from a physics point of view, the conservation of momentum projected in the transverse plane of the colliding beams is really important because of the complex structure of hadrons; the initial momentum of the colliding partons along the beam axis is not known, so the transverse plane is the key for objects reconstruction.

The missing transverse momentum components are given by :

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,\tau} + E_{x(y)}^{miss,jets} + E_{x(y)}^{miss,\mu} + E_{x(y)}^{miss,soft} \quad (5.1)$$

where the terms for jets, charged leptons, and photons are the negative sum of the momenta for the respective calibrated objects. It is built from reconstructed baseline physics objects: electrons, muons, jets and soft term, which is reconstructed from tracks or calorimeter cell clusters not associated with the hard objects.

From the above, the observable E_T^{miss} can be constructed as :

$$E_T^{miss} = - \sum_{i=\text{all visible final state particles}} p_T^i \quad (5.2)$$

In this analysis, E_T^{miss} is reconstructed with the *METMakerTool*, using calibrated electrons and muons passing the baseline selection, and calibrated jets before any selection. The soft term used in the analysis is track-based soft term (TST). This term is built from ID tracks satisfying certain selection criteria but are not matched to any reconstructed hard object. Tracks close to the hard objects in $\eta - \phi$ space are also removed. Since tracks may be accurately matched to a primary vertex, the TST is relatively insensitive to pile-up effects. However, it does not include contributions from soft neutral particles and from forward regions ($|\eta| > 2.5$).

5.5 Cutflow comparison

We have performed a cutflow comparison for baseline electrons, baseline muons, Z-selected electrons, Z-selected muons, jets and events passing WZ Inclusive selection. The cutflow comparison was done between two different analysis frameworks that use DxAODs as inputs : the nominal (a framework migrated from the 36.1 fb^{-1} analysis called *AODNtupleUtility* [97]) used in the present analysis which was also used for the Run I results and one developed by the Dresden group called *ELCore* Framework [98] that uses *EventLoop* package [99] , used as a crosscheck.

Results are presented in Table 5.5. Both frameworks are in full agreement.

Object & Event Cutflow			
Analysis Release	21.2.72		
Twiki for selection	https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/HiggsZZlllPreparationFullRunII		
HIGG2D1 sample	mc16_13TeV.361601.PowhegPy8EG_CT10nloME_AZNLOCTEQ6L1_WZlvll_mll4.deriv.DAOD_HIGG2D1.e4475_s3126_r10201_p3652		
HIGG2D1 filename	DAOD_HIGG2D1.15650384..000021.pool.root.1		
	Abhishek	Miaoran	Marievi
Start	91726	91726	91726
GRL	91726	91726	91726
larError	91726	91726	91726
Vertex	91726	91726	91726
Trigger	56294	56294	56294
Baseline Electrons	334559	334559	334559
LooseLH+BLayer identification	57428	57428	57428
pT>7GeV	50696	50696	50696
eta<2.47	50696	50696	50696
Object quality	50532	50532	50532
$ z_0 \sin \theta < 0.5$	49513	49513	49513
Overlap	49361	49361	49361
Z selected Electrons			
pT>25GeV	40551		40551
Exclude $1.37 < \eta_{cluster} < 1.52$	38451	38451	38451
Likelihood Medium	37339	37339	37339
FCHighPtCaloOnly ³	35533	35533	35533
$d_0/\sigma(d_0) < 5$	35375	35375	35375
Baseline Muons	171951	171951	171951
Loose working point	71232	71232	71232
pT>5GeV	61982		61982
if xAOD::Muon::CaloTag == muauthor(): pT>15GeV	61914	61914	61914
d_0 (cosmics)	61618	61618	61618
$ z_0 \sin \theta < 0.5$	60575	60575	60575
Overlap	60574	60574	60574
Z selected Muons			
pT> 25GeV	46305	46305	46305
Likelihood Medium	45882	45882	45882
FixedCutHighPtTrackOnly ³	42299	42299	42299
$d_0/\sigma(d_0) < 3$	41632	41632	41632
Jets (AntiKt4TopoEM Jets)	7.41E+05	7.41E+05	740922
pT > 30 GeV and $ \eta < 4.5$	124953	124953	124953
Pile up removal			
Overlap	80317	80317	80317
JVT (central)	58874	58874	58874
fJVT	55367	55367	55367
Event selection			
Jet Cleaning	56003	56003	56003
min 3 baseline	5912		
trigger match	5903		
min 2 ZSel and 1 WSel leptons	4287		4286
ZZ veto: veto events with 4 or more baseline leptons	4207		4207
SFOS	4185	4185	4185
Z mass window	3885	3885	3885
$E_T^{miss} > 25\text{GeV}$	3112	3112	3112

TABLE 5.5: Cutflow comparisons

³ used only for cutflow comparison, not in analysis

Chapter 6

Event Selection

6.1 Basic kinematic variables determination

6.1.1 Invariant Mass of WZ system Reconstruction

The WZ invariant mass is a fundamental discriminant variable in this analysis. To reconstruct the four-vector of the W boson, an ambiguity exists due to the incomplete knowledge of the neutrino four-vector. Since we can only measure the missing transverse energy, the equation $E^2 = P^2 + M^2$ is solved using the x and y components of the missing transverse energy E_T^{miss} and the four-vector of the charged lepton assigned to the W boson in order to estimate the longitudinal momentum p_z^ν of the neutrino four-vector.

More explicitly, since the measured E_T^{miss} vector is assumed to be the neutrino p_T^ν , the x and y components of it can be written as :

$$p_x^\nu = p_T^\nu \times \cos\phi^\nu \quad \text{and} \quad p_y^\nu = p_T^\nu \times \sin\phi^\nu \quad (6.1)$$

Then the p_z^ν can be obtained by solving a quadratic equation and using the measured mass of the W boson m_W as defined by PDG [100] for a W boson produced at rest, when the $m_\nu = 0$ and the W lepton mass is considered as negligible ($m_l = 0$):

$$m_W^2 = (p_\nu + p_l)^2 = (E_\nu + E_l)^2 - (\vec{p}_\nu + \vec{p}_l)^2 = 80.4 \text{ GeV} \Rightarrow \frac{m_W^2}{2} = E_\nu E_l - \vec{p}_\nu \vec{p}_l \quad (6.2)$$

where $E_\nu = \sqrt{(p_T^\nu)^2 + (p_z^\nu)^2}$ and $\vec{p}_\nu \vec{p}_l = p_T^\nu \cdot p_T^l \cos(\phi^\nu - \phi^l) + p_z^\nu \cdot p_z^l$

with the above definitions, the equation 6.2 will take the form :

$$(p_z^\nu)^2 \cdot [E_l^2 - (p_z^l)^2] - 2B \cdot p_z^\nu p_z^l + [E_l^2 p_T^\nu)^2 - B^2] = 0 \quad (6.3)$$

where we have defined the constant term $B = \frac{m_W^2}{2} + p_T^\nu \cdot p_T^l \cos(\phi^\nu - \phi^l)$.

Solving this quadratic equation leads in two solutions, which are going to be either real or complex depending on the determinant :

$$p_z^\nu = \frac{B p_z^l \pm E_l \sqrt{B^2 + (p_T^\nu)^2 [(p_z^l)^2 - E_l^2]}}{E_l^2 - (p_z^l)^2} \quad (6.4)$$

As it is a priori arbitrary which solution is best, it has been studied which solution is closest to the truth invariant mass see section 5.6.2 in [47]. The option providing the better resolution was the following: if there are two real solutions, the one with the smaller magnitude is chosen. If there is no real solution, the real part of the solution with the smaller magnitude is chosen in this analysis. Using this reconstructed neutrino four-vector, the four-vector of the W boson can be reconstructed, as well as the invariant mass of the WZ system.

6.1.2 Transverse Mass of W and of WZ system

The W boson transverse mass is defined as :

$$m_T^W = \sqrt{(2p_T^l E_T^{miss}(1 - \cos\Delta\phi))} \quad (6.5)$$

where $\Delta\phi$ is the angle between the momenta of the neutrino and the W -lepton in the transverse plane.

The WZ transverse mass is reconstructed by taking the four-vectors of the final state leptons (associated to the W and Z bosons) projected on the transverse plane by neglecting their longitudinal component. Then the m_T^{WZ} is defined as :

$$m_T^{WZ} = \sqrt{\left(\sum_{l=1}^3 p_T^l + E_T^{miss}\right)^2 - \left(\sum_{l=1}^3 p_x^l + E_x^{miss}\right)^2 - \left(\sum_{l=1}^3 p_y^l + E_y^{miss}\right)^2} \quad (6.6)$$

6.2 Inclusive WZ analysis selection

Here we will present the event selection criteria for our analysis. In this search all final states with three charged leptons (electrons or muons) and missing transverse momentum from WZ

leptonic decays are considered ($\mu^+\mu^-\mu^\pm$ or $\mu^+\mu^-e^\pm$ or $e^+e^-\mu^\pm$ or $e^+e^-e^\pm + E_T^{miss}$). The first step for the event selection is the requirement of a WZ Inclusive phase space; this phase space plays the role of a baseline selection. The next step is two selections that are defined in order to build signal regions (SRs) targeting the Drell-Yan and VBF production modes, on top of this baseline selection. The specific WZ Inclusive event selection criteria are described in the following and are briefly summarized in Table 6.2 .

- **Event cleaning:** The first step in the event selection is accomplished by requiring a data quality flag that rejects Liquid Argon and Tile Calorimeter corrupted events, as well as incomplete events. The data and simulation event cleaning is done by rejecting events with at least one misidentified jet of non-collision background or detector problems origin [101], with respect to the high-efficiency *loose* working point of selecting jets [102]. Also, data events are selected based on data quality flags per luminosity block, using the Good Run List listed in 6.2.
 - data15.13TeV.periodAllYear.DetStatus-v89-pro21-02.Unknown.PHYS.StandardGRL.All.Good.25ns
 - data16.13TeV.periodAllYear.DetStatus-v89-pro21-01.DQDefects-00-02-04.PHYS.StandardGRL.All.Good.25ns
 - data17.13TeV.periodAllYear.DetStatus-v97-pro21-17.Unknown.PHYS.StandardGRL.All.Good.25ns.Triggerno17e33prim
 - data18.13TeV.periodAllYear.DetStatus-v102-pro22-04.Unknown.PHYS.StandardGRL.All.Good.25ns.Triggerno17e33prim
- **Trigger:** For this analysis, single electron or muon trigger has to fire during the entire run period , with logical OR between the single-lepton triggers summarized in table 6.1). We require that at least one of the analysis leptons is responsible for the trigger of the events by using the trigger matching tool. The name of each trigger in Table 6.1) provides information about the associated requirements that go along with it. The name consists of a combination of tags: the tag eXX requires electrons with a transverse momentum of at least XX GeV. The same naming scheme holds for muons, which are indicated by mu instead. The tags *iloose*, *ivarmedium*, *lhloose*, *lhmedium* and *lhtight* indicate isolation and identification requirements that are applied in the High Level Trigger (HLT). Finally, the tag *nod0* for the electron triggers simply indicates that d0 information is not used for reconstruction.
- **Primary vertex:** In order to make sure that the selected events correspond to a hard-scattering proton-proton collision, the vertex with the largest $\sum p_T^2$ (primary vertex) has to be reconstructed with at least two associated tracks with $p_T > 500$ MeV. Additionally, the three lepton tracks originating from a primary vertex must have distances $|z_0 \cdot \sin(\theta)| < 0.5$ mm from the primary vertex along the proton beam line . Also, in

	2015	2016-2018
Single muon	HLT_mu20_iloose_L1MU15 HLT_mu50	HLT_mu26_ivarmedium HLT_mu50
Single electron	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0

TABLE 6.1: Summary of the single lepton HLT triggers that are used in this analysis.

order to reduce the cosmic background, an additional cut on the muon transverse impact parameter is applied ($|d_0| < 1$ mm), as already described in 5.1.

- **Jet cleaning:** The presence of an unclean jet (i.e. a jet with badly measured energy and direction) in an event can affect the resolution of E_T^{miss} reconstruction. So a cleaning designed to veto events that have one or more unclean jets is applied; these jets can originate either from background events (cosmic and non-collision background) or from detector effects like noise spikes, coherent noise and dysfunctional calorimeter regions. The jets in each event should comply with the “DFCommonJetseventCleanLooseBad” criteria [103].
- **Exactly 3 leptons:** The event must have exactly 3 leptons originating from the primary vertex and passing the “loose[−]” selection criteria (defined as “loose” as in section 5.1 but without $d_0^{Significance}$ cut) in order to be able to estimate the reducible background estimation using matrix method. These leptons should also have $p_T > 25$ GeV. Furthermore, to ensure that the trigger efficiency is well determined, at least one of the three candidate leptons must be trigger-matched and is required to have $p_T > 27$ GeV.
- **W, Z lepton assignment:** Each event must have two leptons of the same flavor and opposite charge as the Z lepton candidates, with a dilepton invariant mass consistent with the Z mass : $|M_{ll} - 91.1876| < 20$ GeV. In the case of the existence of one extra pair of leptons that can form a Z candidate, the pair with invariant mass closest to the PDG mass is taken; this choice relies on the fact that the Z boson will more likely be found near the pole mass. Then, the third lepton is considered as the W lepton candidate that together with the E_T^{miss} build-up the W boson.

We end up with totally 4 possible combinations, namely $\mu^\pm \mu^\mp \mu^\mp$, $\mu^\pm \mu^\mp e^\mp$, $e^\pm e^\mp \mu^\mp$, and $e^\pm e^\mp e^\mp$; the first and second lepton means Z lepton candidates and the third lepton means the W lepton candidate and the Z lepton with the same charge as the W lepton is always placed at the second position.

- **W, Z lepton quality requirement:** The W and Z leptons are then required to satisfy the “tight(Z)” and “tight(W)” selection criteria as described in section 5.1.

- **ZZ veto:** In order to decrease background from ZZ , events with additional “baseline” leptons are vetoed.
- E_T^{miss} : Missing transverse energy in the event must be greater than 25 GeV.

Inclusive event selection	
Event cleaning	Reject LAr, Tile and SCT corrupted events and incomplete events
Primary vertex	Hard scattering vertex with at least two tracks
Trigger	Single lepton (electron or muon) trigger
Jet cleaning	pass <code>DFCommonJetseventCleanLooseBad</code>
ZZ veto	veto events with additional <i>Baseline</i> leptons
N leptons	Exactly three leptons passing the “loose-” lepton selection with $p_T > 25$ GeV ($p_T > 27$ GeV for the trigger-matched lepton)
Z candidate	built from Same-Flavor-Opposite-Sign (SFOS) lepton pair with $M_{\ell\ell}$ closest to Z PDG mass
W candidate	built from the third lepton and E_T^{miss}
W, Z selection	Z leptons passing “tight(Z)” lepton selection W leptons passing “tight(W)” lepton selection.
Mass window	$ M_{\ell\ell} - M_Z < 20$ GeV
Missing Energy	$E_T^{miss} > 25$ GeV

TABLE 6.2: Overview of the analysis event selection requirements.

6.3 Inclusive WZ control distributions

To verify the data and Monte Carlo agreement, we demonstrate here distributions of the WZ events after selection of W and Z reconstructed candidates, before the signal regions cuts.

Control distributions for the sum of all channels for the reconstructed Z and W bosons and of the WZ diboson system are presented in Figure 6.1 - Figure 6.5. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The Sherpa MC generator is used to model the WZ QCD and Madgraph for the WZ EWK SM expectation. Backgrounds from mis-identified leptons are estimated from MC and will be estimated using the Matrix Method, as described in section 7.1. Distributions show only statistical uncertainties. Theory uncertainties are expected to be of the order of 20% for the SM WZ. In general a fair agreement is observed in the shapes of the distributions between data and expected number of events.

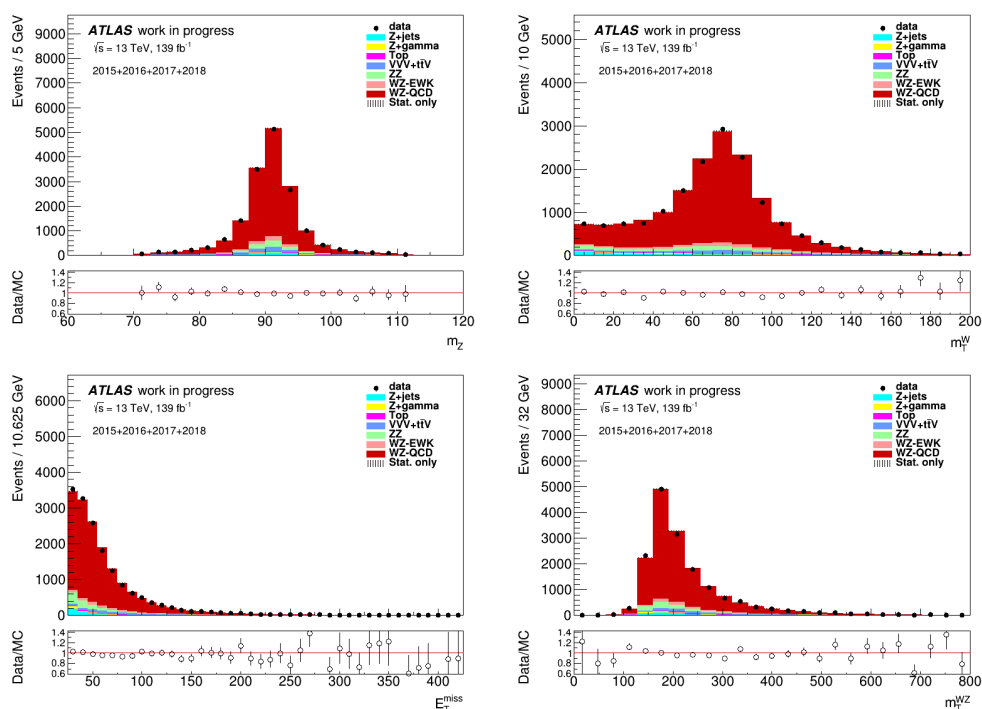


FIGURE 6.1: Control distributions for the sum of all channels, the Z boson invariant mass is shown on the top left, the W boson transverse mass on the top right, the E_T^{miss} on the bottom left, the transverse mass of the WZ system on the bottom right. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from ttbarV, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

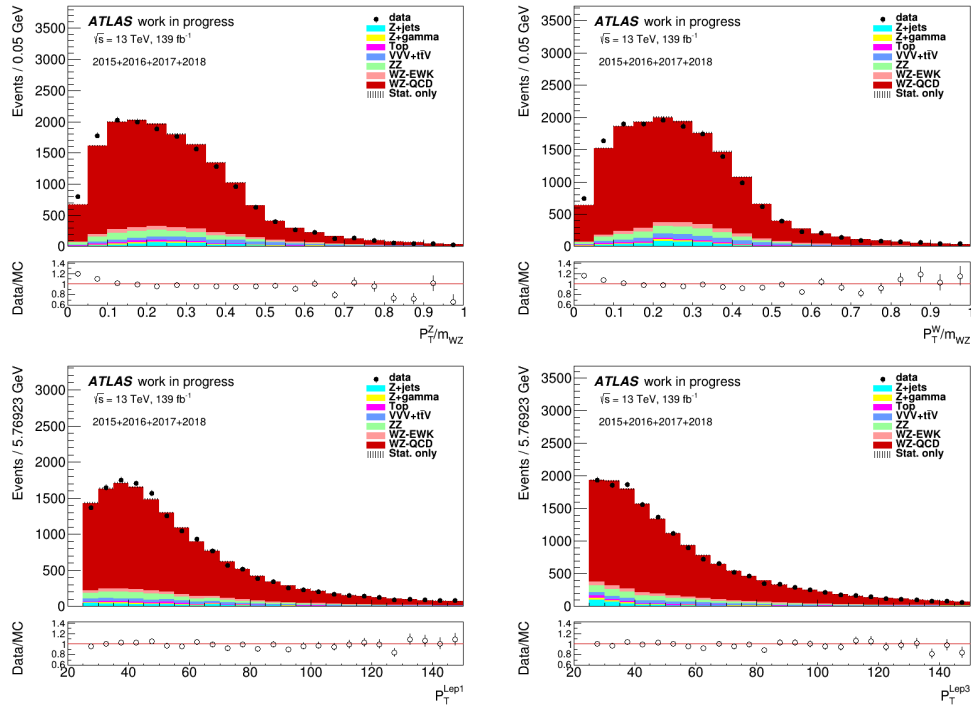


FIGURE 6.2: Control distributions for the sum of all channels. In the first row the $PtBalanceZ = p_T^Z / m_{WZ}$ is shown on the left and $PtBalanceW = p_T^W / m_{WZ}$ on the right. In the second row the Z lepton p_T is shown on the left, the W lepton p_T is shown on the right. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}b\bar{v}$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

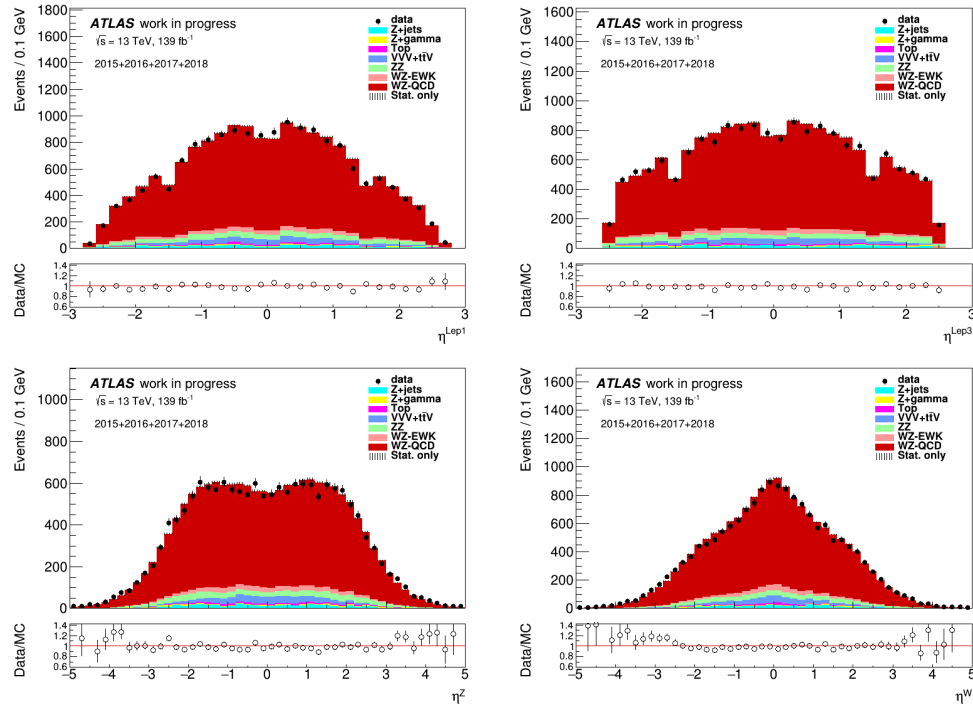


FIGURE 6.3: Control distributions for the sum of all channels. In the first row the Z lepton η is shown on the left, the W lepton η is shown on the right. In the second row we have the Z boson η on the left and the W boson η on the right. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}b\bar{b}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

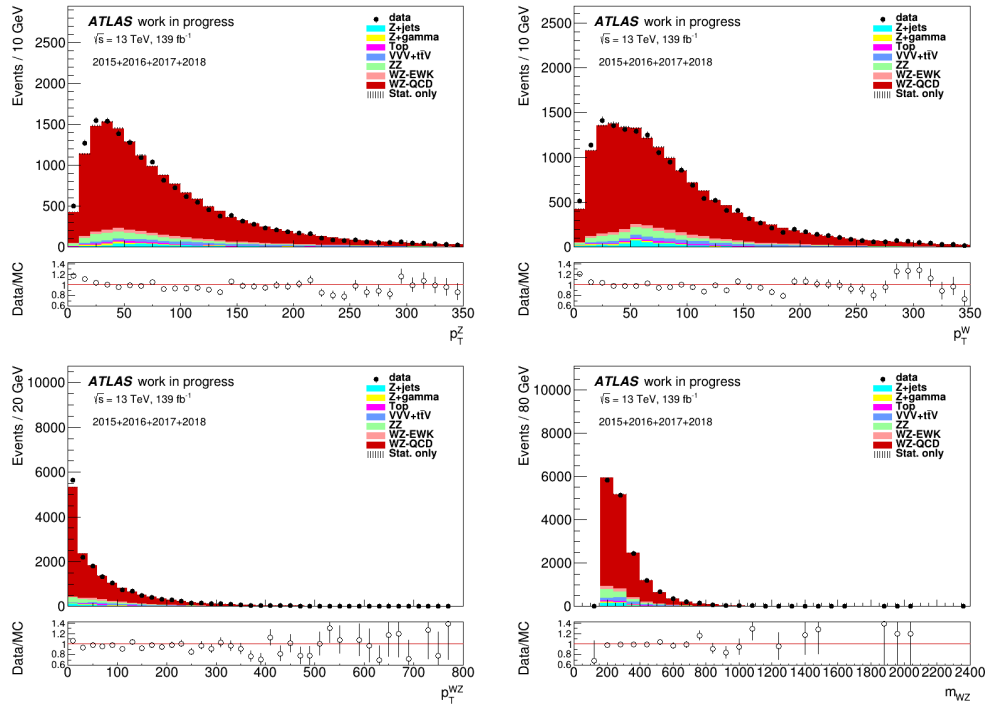


FIGURE 6.4: Control distributions for the sum of all channels. In the first row the transverse momentum of the Z boson is shown on the left, the transverse momentum of the W boson is shown on the right. In the second row we have the transverse momentum of the WZ system on the left and the invariant mass of the WZ system on the right. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}b\bar{b}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

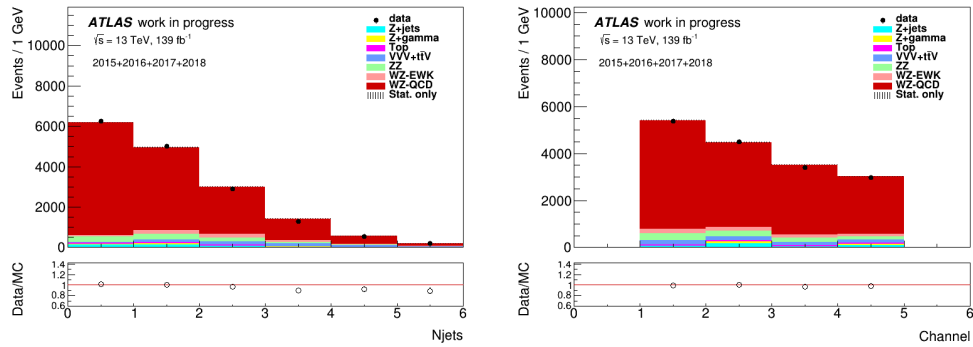


FIGURE 6.5: The jet multiplicity and the total event yields in both data and MC are given for WZ events after the inclusive selection of W and Z candidates. The bins on the figure on the right correspond to the different decay channels, reading from left to right $\mu^+\mu^-\mu^\pm\nu$, $\mu^+\mu^-e^\pm\nu$, $e^+e^-\mu^\pm\nu$, and $e^+e^-e^\pm\nu$. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}b\bar{b}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

6.4 Drell-Yan signal region definition and control distributions

The Drell-Yan signal region is built on top of the WZ Inclusive selection described above. Since the transverse momentum of W and Z bosons are strongly correlated with the HVT resonance mass (i.e. for a heavy resonance produced at rest in the s-channel we expect the selected W and Z bosons to have transverse momenta close to 50 % of the resonance mass), an interesting discriminating variable is the ratio of the $p_T^{Z/W}/m_{WZ}$, also called PtBalanceZ or PtBalanceW respectively. So to reduce the contribution of non-resonant WZ, events passing the WZ Inclusive selection are also required to have $p_T^Z/m_{WZ} > 0.35$ and $p_T^W/M_{WZ} > 0.35$; these two variables provide a clear separation between the signal and the WZ SM background as we can see in Figure 6.6. The cut value of 0.35 was the optimal for the 36 fb^{-1} publication and the same was kept for the full run-2 analysis. In Table 6.3 we present the total event yields in

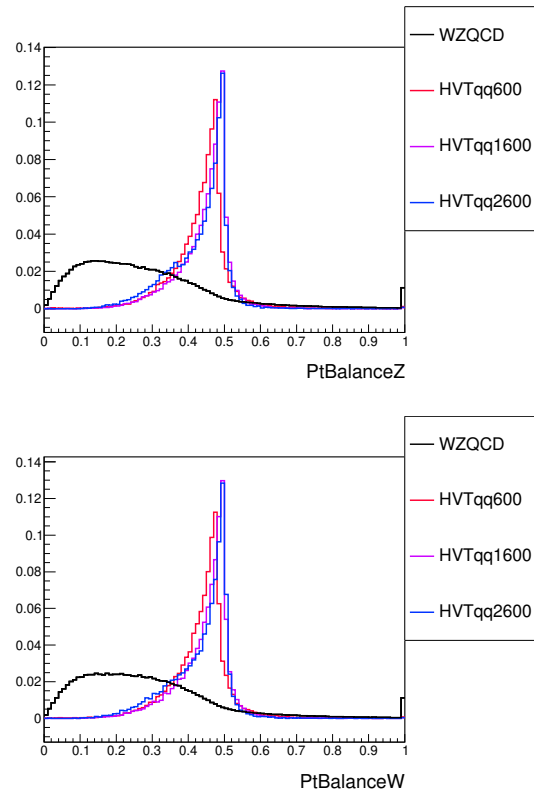


FIGURE 6.6: WZ QCD background and various Drell-Yan signals for the PtBalanceZ and PtBalanceW variables normalized to unit. (Fig. 7.1 in [1])

both data and MC for events after applying WZ Inclusive and Drell-Yan signal selection cuts ($p_T^Z/M_{WZ} > 0.35$ and $p_T^W/M_{WZ} > 0.35$). The uncertainties are only statistical and the backgrounds are directly taken from MC predictions, which underestimate the contribution from fake backgrounds. The last row in the Table stands for fractional difference between data and

MC yields and the overall data/MC ratio. After the Drell-Yan selection, we observe a total of 2155 events.

Process	all lepton final states combined
data	2155 ± 46.42
total MC	2358.03 ± 389.87
VVV	147.06 ± 3.75
Z+gamma	9.04 ± 1.79
Top	14.06 ± 2.42
ZZ	87.15 ± 12.85
Z+jet	26.98 ± 12.50
WZ EW	90.34 ± 9.77
WZ QCD	1983.39 ± 387.79
Data/MC	0.91 ± 0.15

TABLE 6.3: Summary of observed and expected yields for WZ events for inclusive channels after applying $p_T^Z/M_{WZ} > 0.35$ and $p_T^W/M_{WZ} > 0.35$. Uncertainties shown include only statistical uncertainties. WZ EW background also includes the contribution from interference between WZ QCD and WZ EW

The data/MC comparison of control distributions of kinematic variables in Drell-Yan signal region are shown in Figures 6.7 - 6.9.

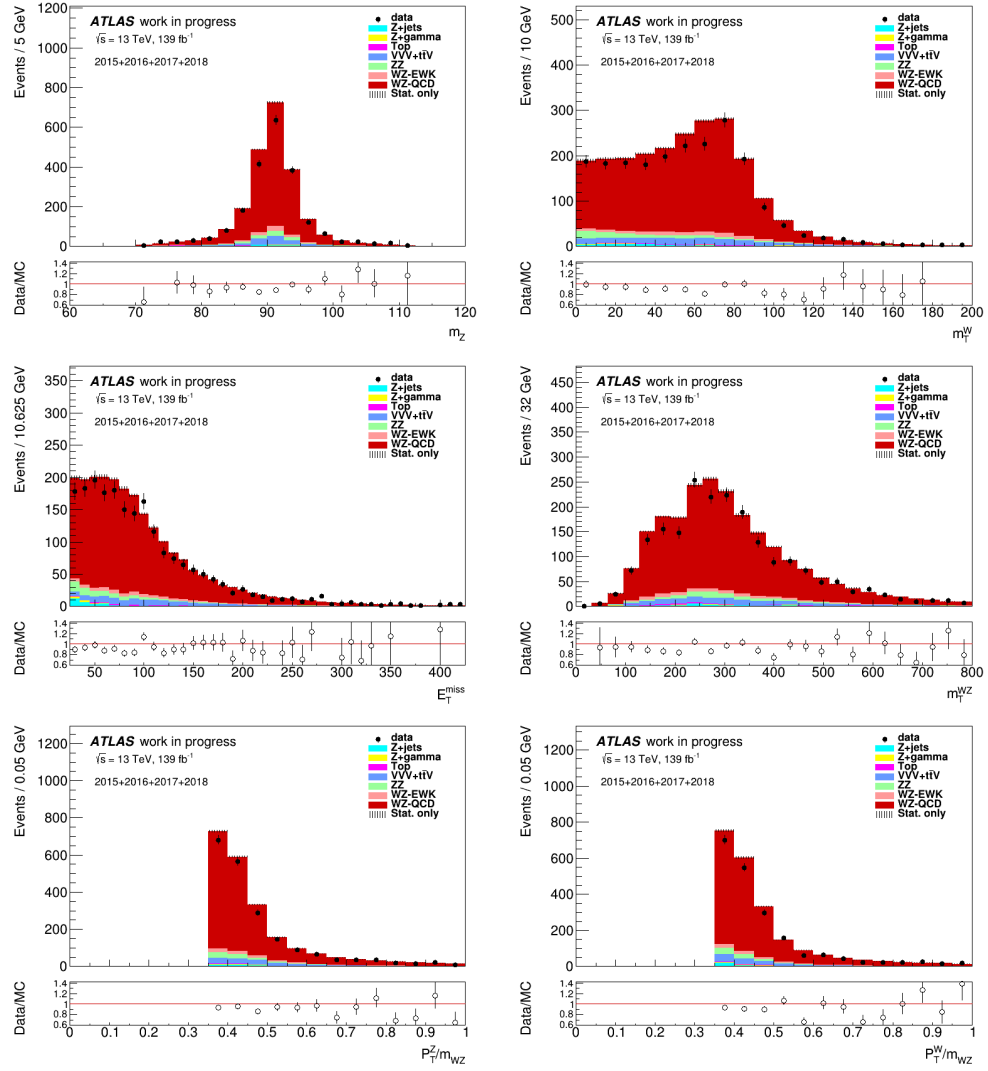


FIGURE 6.7: Data/Monte Carlo comparison plots in Drell-Yan signal region. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}b\bar{b}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

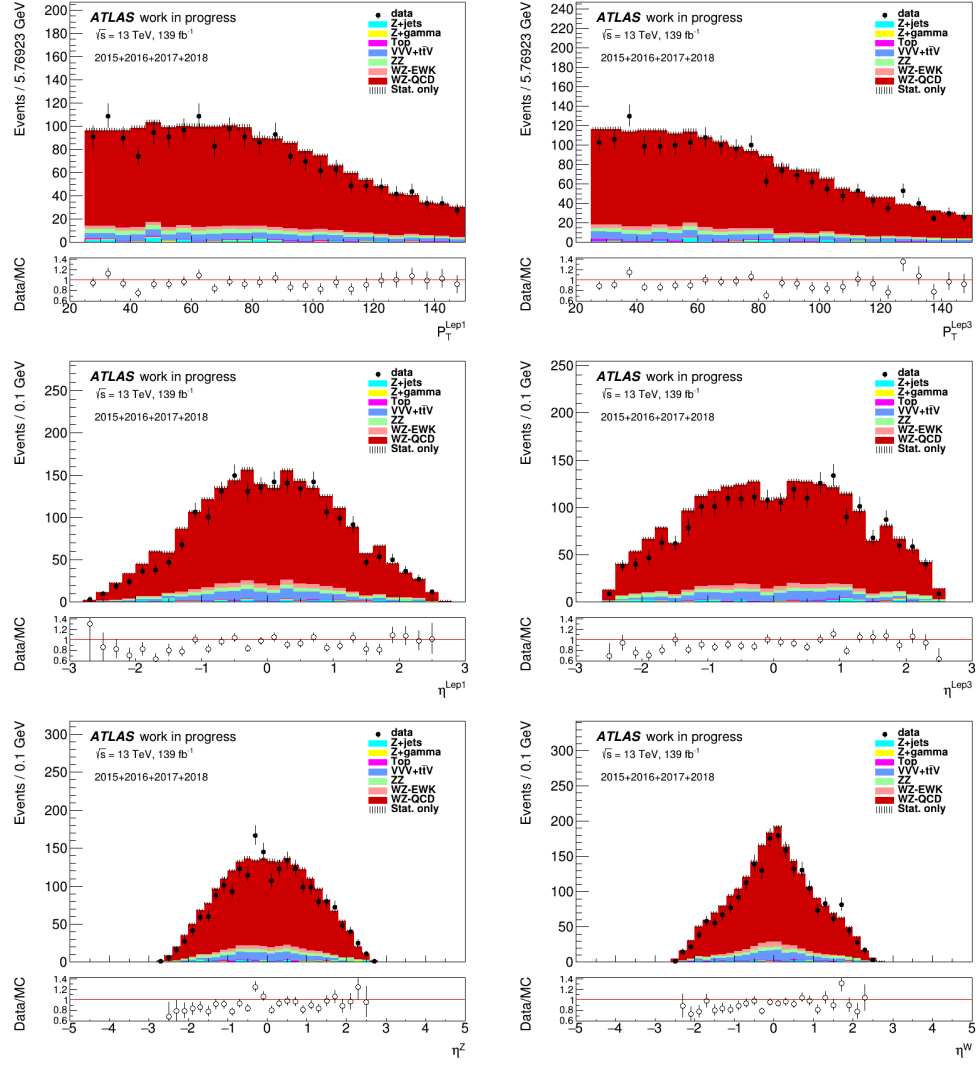


FIGURE 6.8: Data/Monte Carlo comparison plots in Drell-Yan signal region. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VV also includes contribution from $t\bar{t}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

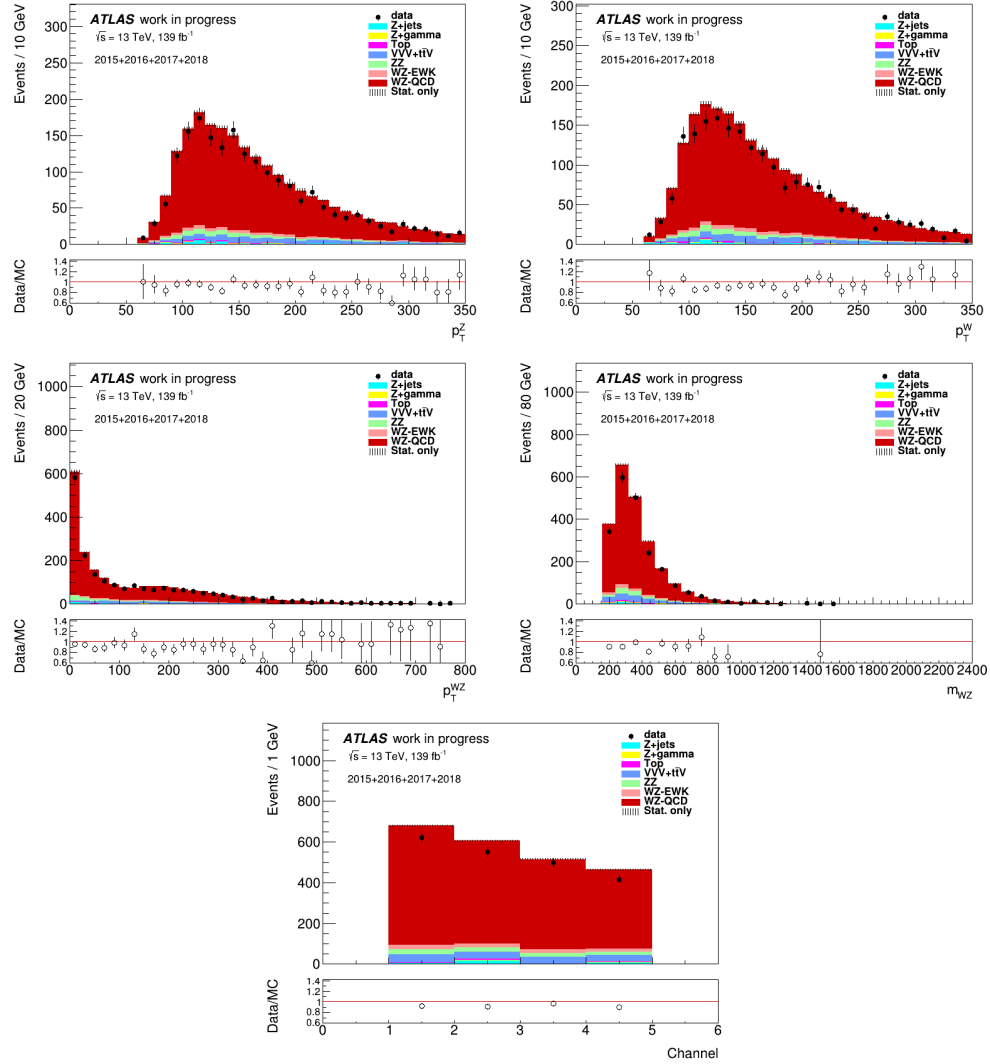


FIGURE 6.9: Data/Monte Carlo comparison plots in Drell-Yan signal region. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VV also includes contribution from $t\bar{t}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

6.5 VBF signal region definition and control distributions

The VBF process ($pp \rightarrow W'jj \rightarrow WZjj$) is characterized by the presence of two jets with a large rapidity gap resulting from quarks from which a vector boson has been radiated. To target this region we select events with two or more jets, with $p_T > 30$ GeV and $|\eta| < 4.5$, which have significant rapidity separation $|\Delta Y_{jj}| > 3.5$, and with a di-jet invariant mass above 500 GeV.

A b -jet veto is applied on the two p_T -leading jets, in order to further reject the top quark pair background, $t\bar{t} + V$ and tZ events. Out of the possible working points corresponding to different b -tagging efficiencies, the 85% working point (threshold value of 0.1758) is selected as the baseline; this cut rejects $\sim 50\%$ of these backgrounds.

In Table 6.4 the total event yields in both data and MC are given for WZ events after applying VBF signal selection cuts; after the full selection, 381 data events are observed. The uncertainties are only statistical and the backgrounds are directly taken from MC predictions. The last row in the table stands for fractional difference between data and MC yields and the overall data/MC ratio.

Process	all lepton final states combined
data	381 ± 19.52
total MC	470.12 ± 104.90
VVV	30.3 ± 2.37
Z+gamma	3.87 ± 2.12
Top	7.61 ± 2.77
ZZ	25.30 ± 6.64
Z+jet	6.05 ± 3.17
WZ EW	100.88 ± 13.87
WZ QCD	296.11 ± 95.56
Data/MC	0.81 ± 0.19

TABLE 6.4: Yields of selected events in 139 fb^{-1} of data at 13 TeV, together with the expected yields from various background processes in the VBF signal region. Uncertainties are statistical only.

The data/MC comparison of distributions of kinematic variables in VBF signal regions are shown in Figures 6.10 - 6.14 .

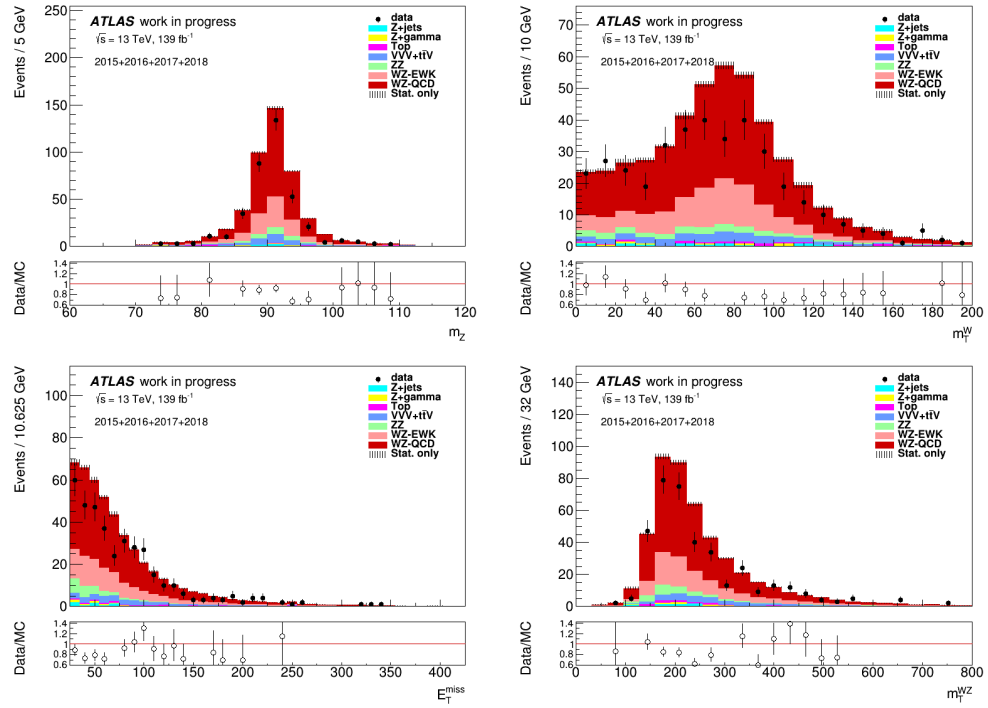


FIGURE 6.10: Data/Monte Carlo comparison plots in VBF signal region. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

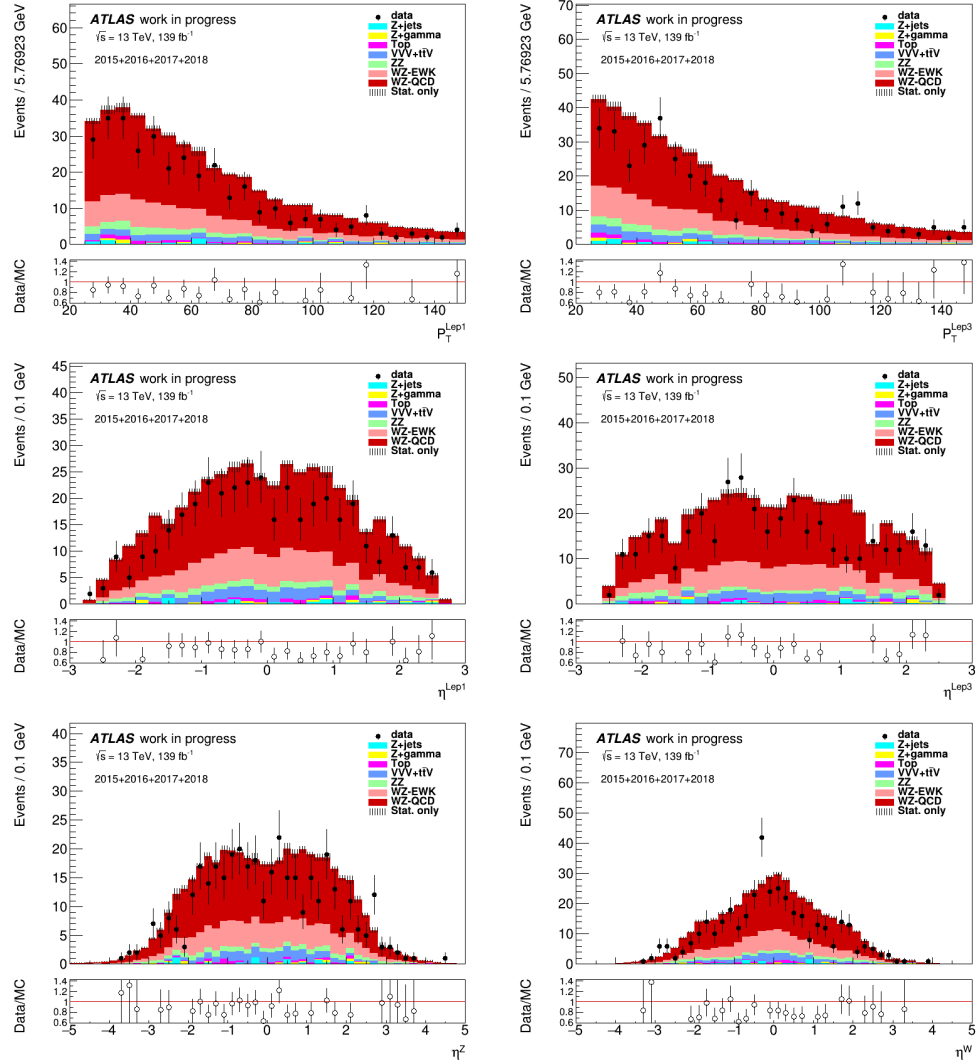


FIGURE 6.11: Data/Monte Carlo comparison plots in VBF signal region. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

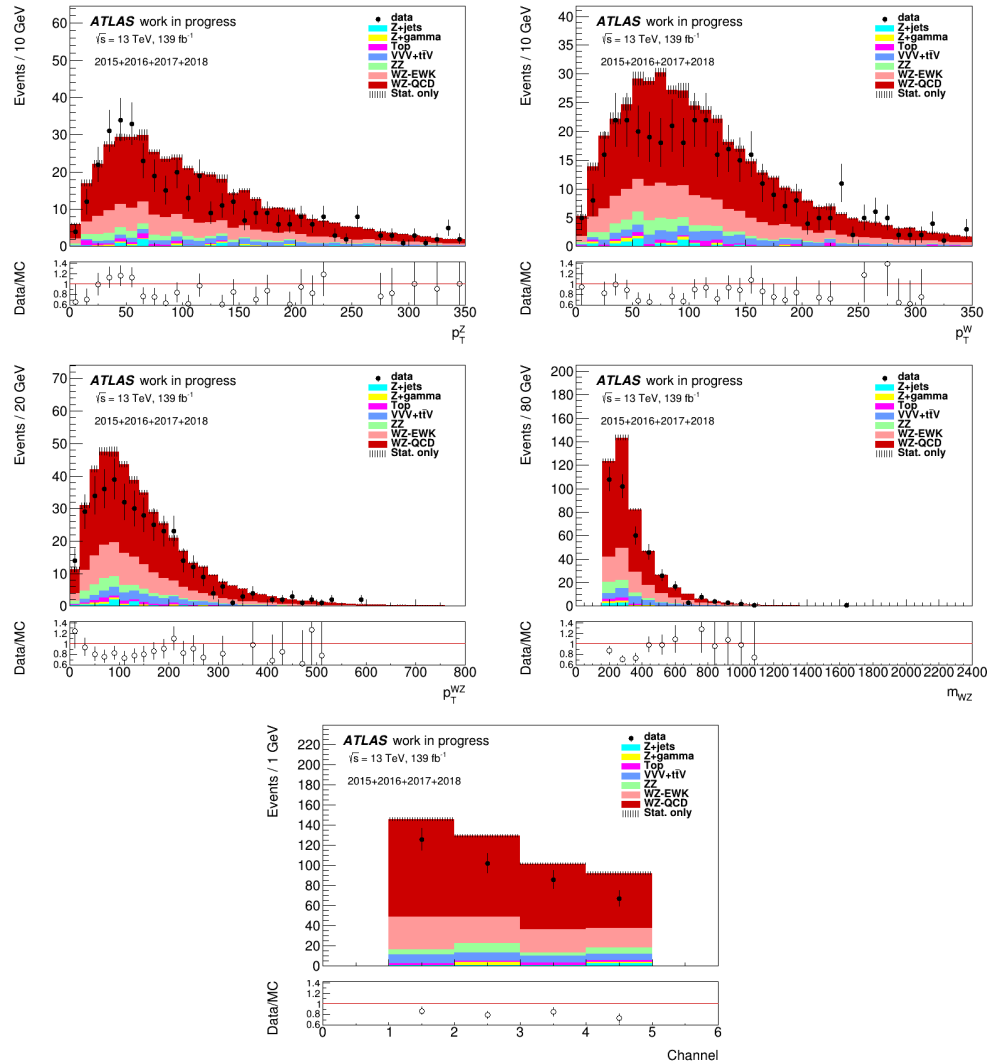


FIGURE 6.12: Data/Monte Carlo comparison plots in VBF signal region. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

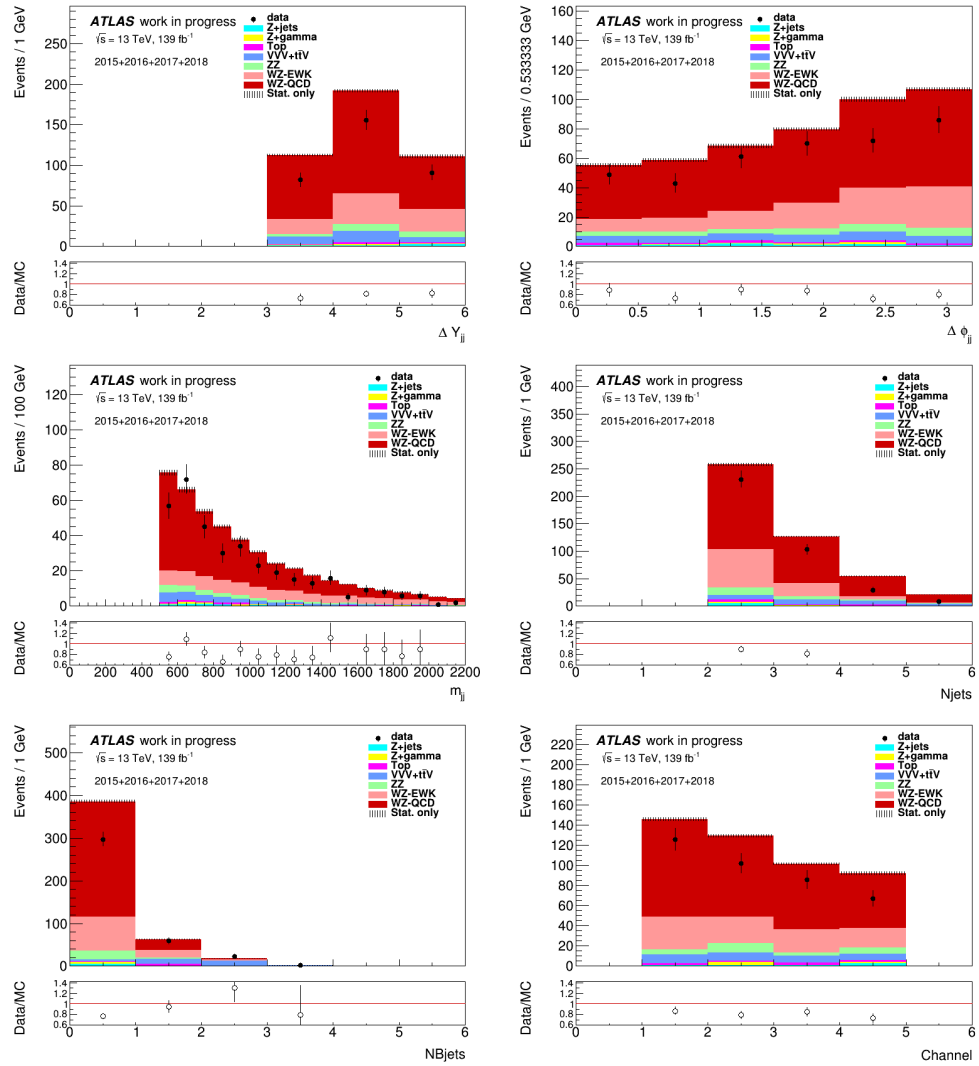


FIGURE 6.13: Data/Monte Carlo comparison plots in VBF signal region. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

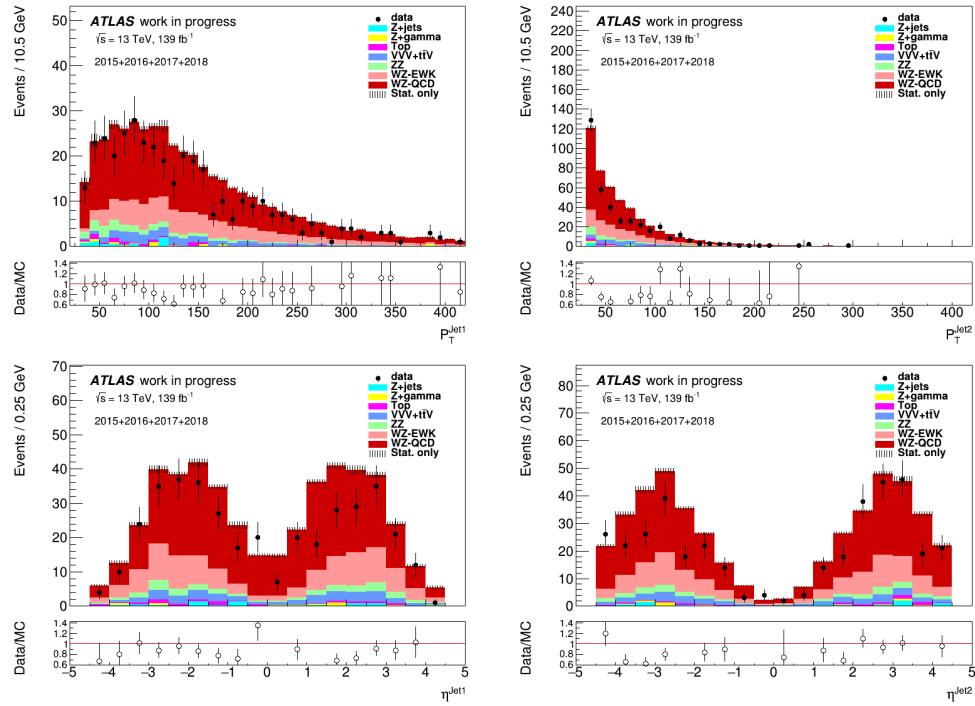


FIGURE 6.14: Data/Monte Carlo comparison plots in VBF signal region. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The dashed band represents the Monte Carlo statistical uncertainties only. In these figures, VVV also includes contribution from $t\bar{t}V$, and WZ EW also includes the contribution from interference between WZ EW and WZ QCD.

Chapter 7

Background Estimation

The background sources that can mimic the $W^\pm Z$ resonance signature, can be classified into two categories: the *irreducible* backgrounds where all reconstructed lepton candidates are prompt (arise from the primary process) and the *reducible* backgrounds where at least one of the lepton candidates is non-prompt (usually called “fake/non-prompt” leptons).

7.1 Reducible Background

The reducible background consists of SM processes that have one or two leptons originating from jets/ photons like :

- background due to fake leptons which include pion, kaon and heavy-quark decays to real leptons, in addition to jets misidentified as lepton. This background comes mainly from Z +jets, $t\bar{t}$, Wt , WW or QCD multijet processes where one or two jets are misreconstructed as leptons
- $Z + \gamma$ process where the photon is reconstructed as an electron

For both Drell-Yan and VBF signal regions, the reducible background normalizations are derived from a data-driven method that is based on a global matrix which exploits the differences in object characteristics between real and fake/non-prompt leptons on a statistical basis. More details about this method can be found in [104]. For the Drell-Yan region, the shape is also obtained from the data-driven method; for the VBF region, due to the lack of statistics, the shapes are taken from Monte-Carlo simulation.

7.2 Irreducible Background

Irreducible background consists of SM processes that produce events with three real leptons :

- WZ process which has exactly the same signature as the signal and where three leptons pass the event selection, the WZ background has two production modes QCD and EWK mediated; both production modes contribute, with the WZ-QCD being the dominant in all signal regions
- ZZ process where three leptons pass the event selection, while the fourth lepton is not reconstructed or identified
- $t\bar{t} + V$ process $V = W, Z$
- $t + Z$ process
- VVV process where V denotes any vector bosons
- double parton scattering (DPS) processes where the WZ signature comes mostly from collisions between two pairs of partons producing single W and Z/γ^* bosons.

Processes like $t\bar{t} + V$ and VVV are estimated using MC simulations. The background due to DPS was calculated to be 0.16% of the SM WZ QCD contribution and neglected in the rest of the analysis.

In this analysis, the dominant contribution comes from the WZ QCD and EWK mediated production and diboson ZZ ; for these background sources the shape is taken from Monte-Carlo simulation while the normalization of the WZ-QCD and ZZ is constrained by data in a simultaneous fit using the signal regions (Drell-Yan / VBF) and dedicated control regions as described in sections 12.5 and 12.6; the latter are chosen to be kinematically close to the signal regions but orthogonal to them.

Each signal region (Drell-Yan / VBF) is associated to two control regions (CRs) that are designed to have high purity, small statistical uncertainties in terms of the background process of interest and to contain only a small fraction of the potential signal. These CRs are defined in the following sub-sections, while an overview of the selection requirements of the WZ Inclusive region and the analysis signal and control regions is presented in Table 7.1.

Selection	Signal Regions				Control Regions	
	Drell-Yan	VBF	ZZ Drell-Yan	ZZ VBF	WZ-QCD Drell-Yan	WZ-QCD VBF
$E_T^{miss} > 25$ GeV	✓	✓	fail	fail	✓	✓
4 lepton veto	✓	✓	fail	fail	✓	✓
inclusive WZ	✓	✓			✓	✓
at least 2 VBS jets		✓		✓		✓
b-jet veto		✓				✓
$M_{jj} > 500$ GeV		✓				✓
$ \Delta Y_{jj} > 3.5$		✓				fail
p_T^Z/m_{WZ} and $p_T^W/m_{WZ} > 0.35$	✓				fail (but with $p_T^{Z/W}/m_{WZ} > 0.1$)	

TABLE 7.1: Summary of the control and signal regions in the analysis

7.2.1 WZ Control regions

7.2.1.1 WZ-QCD Drell-Yan CR

The WZ-QCD Drell-Yan CR is dedicated to the Drell-Yan analysis. More explicitly, it selects the WZ inclusive events that fail the PtBalance cut either by having $p_T^Z/m_{WZ} < 0.35$ or $p_T^W/m_{WZ} < 0.35$. For this CR we also have the minimum requirement of $p_T^V/m_{WZ} > 0.1$ in order to be close to the signal region. This CR is then by definition orthogonal the Drell-Yan signal region.

Figure 7.1 shows the invariant mass distribution in the WZ-QCD Drell-Yan CR. It can be seen that is clearly enriched in WZ with small contamination from ZZ and irreducible background processes. This region is included in the Drell-Yan signal region fits to constrain the WZ QCD normalization.

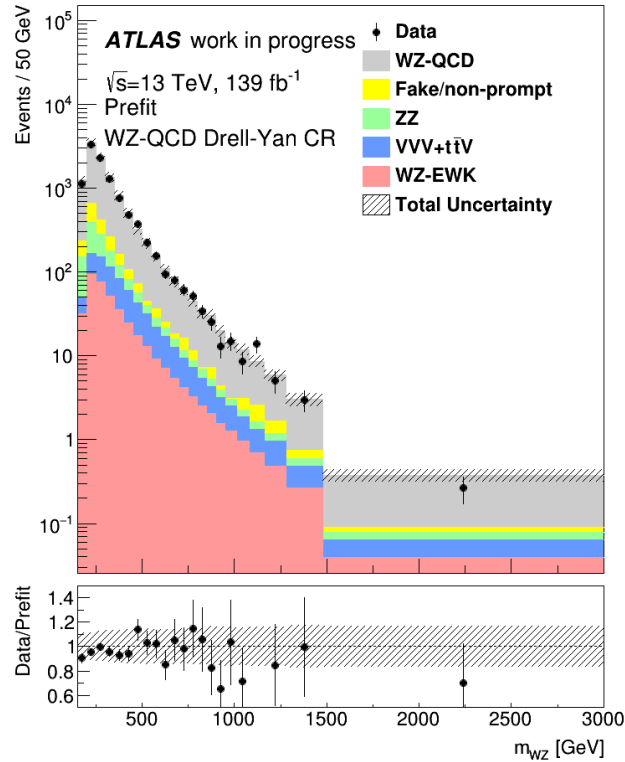


FIGURE 7.1: Pre-fit WZ invariant mass is shown in the WZ-QCD Drell-Yan CR control region. Here we have the optimized variable binning, explained later in section 12.5. The total uncertainty is shown by shaded band and it includes the statistical, theoretical and systematic uncertainties.

7.2.1.2 WZ-QCD VBF CR

The WZ-QCD VBF CR is dedicated to the VBF analysis. More explicitly, it selects the WZjj events that fail the $|\Delta Y_{jj}|$ cut; the high m_{jj} requirement is still applied in order to match the signal region event topology. This CR is then by definition orthogonal the VBF signal region.

Figure 7.2 shows the invariant mass distribution in the WZ-QCD VBF CR. It can be seen that is clearly enriched in WZ background processes. A WZ QCD mis-modelling is visible in this region and will be corrected in the limit setting fit and is fully covered by the theory systematic uncertainties that are of the order of 30% for the WZ QCD in this region, see details in Appendix B.

This region is included in the VBF signal region fits to constrain the WZ QCD normalization.

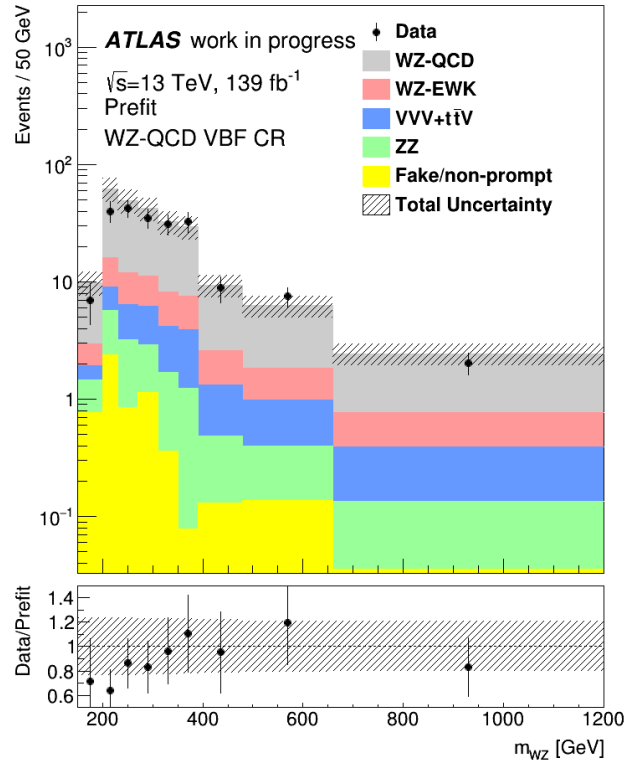


FIGURE 7.2: Pre-fit WZ invariant mass is shown in the WZ-QCD VBF CR control region. Here we have the optimized variable binning, explained later in section 12.5. The total uncertainty is shown by shaded band and it includes the statistical, theoretical and systematic uncertainties.

7.2.2 ZZ Control regions

7.2.2.1 ZZ Drell-Yan CR

The ZZ Drell-Yan CR is defined by requiring the presence of at least an additional fourth lepton that fulfills the “Baseline” identification criteria and no requirement on the missing transverse energy. Figure 7.3 shows the invariant mass distribution in the ZZ Drell-Yan CR. It can be seen that is clearly enriched in ZZ background processes. This region is included in the Drell-Yan signal region fits to constrain the ZZ normalization.

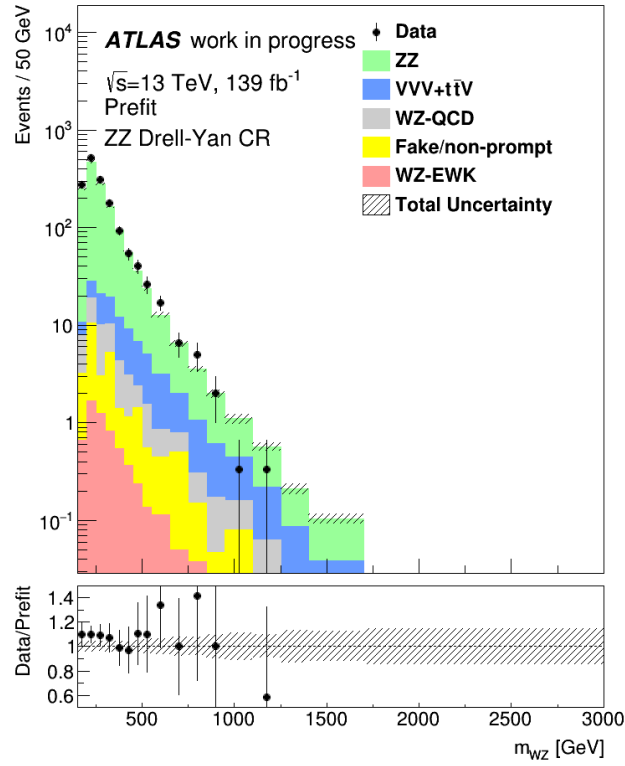


FIGURE 7.3: Pre-fit WZ invariant mass is shown in the ZZ Drell-Yan CR control region. Here we have the optimized variable binning, explained later in section 12.5. The total uncertainty is shown by shaded band and it includes the statistical, theoretical and systematic uncertainties.

7.2.2.2 ZZ VBF CR

The ZZ VBF CR is defined by requiring the presence of at least an additional fourth lepton that fulfills the “Baseline” identification criteria, no requirement on the missing transverse energy but also requiring at least two VBF-tagged jets. Figure 7.4 shows the invariant mass distribution in the ZZ VBF CR. It can be seen that is clearly enriched in ZZ background processes. This region is included in the VBF signal region fits to constrain the ZZ normalization.

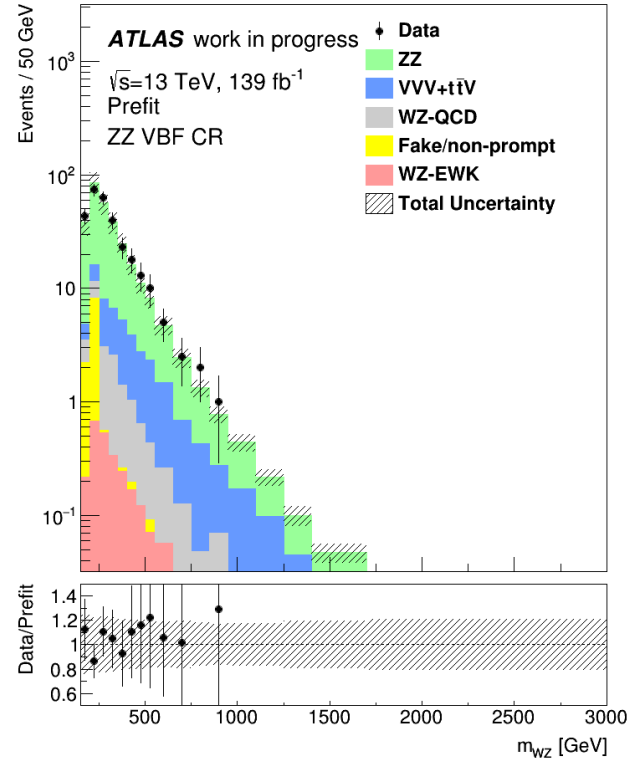


FIGURE 7.4: Pre-fit WZ invariant mass is shown in the ZZ VBF CR control region. Here we have the optimized variable binning, explained later in section 12.5. The total uncertainty is shown by shaded band and it includes the statistical, theoretical and systematic uncertainties.

Chapter 8

Sensitive variables in the search of new particles

8.0.1 VBF signal regions distributions

As we mentioned before, when computing the WZ invariant mass there is an ambiguity due to the incomplete knowledge of the neutrino. In that direction, we have performed a study concerning the search of sensitive variables - besides the invariant mass of the WZ system - that could be used in the limits setting procedure, in order to search for new particles in the direction of the extension of the Standard Model.

The alternative variables that have been tested are the delta phi angle between the two leptons of Z boson ($\Delta\phi(l^{Z_1}, l^{Z_2})$), the delta phi angle between the leading Z lepton and the W lepton ($\Delta\phi(l^{Z_{lead}}, l^W)$), the delta phi angle between the two VBS jets ($\Delta\phi_{jj}$), the rapidity separation of the two VBS jets (ΔY_{jj}), the invariant mass of the two jets (m_{jj}), the invariant mass of the three leptons (m_{3lep}), the missing transverse energy (E_T^{miss}), the transverse mass of the WZ system (m_T^{WZ}), the transverse momentum of the WZ system (p_T^{WZ}), the transverse momentum of the three leptons (p_{T3lep}) and the numerical sum of the transverse momenta of the three leptons ($Sum3Pt$). For all these variables we have compared the corresponding distributions for the WZ QCD background and various vbf signals, to check their shapes and discriminating power. All the above are included in the Figures 8.1 and 8.2 together with the corresponding m_{WZ} distributions.

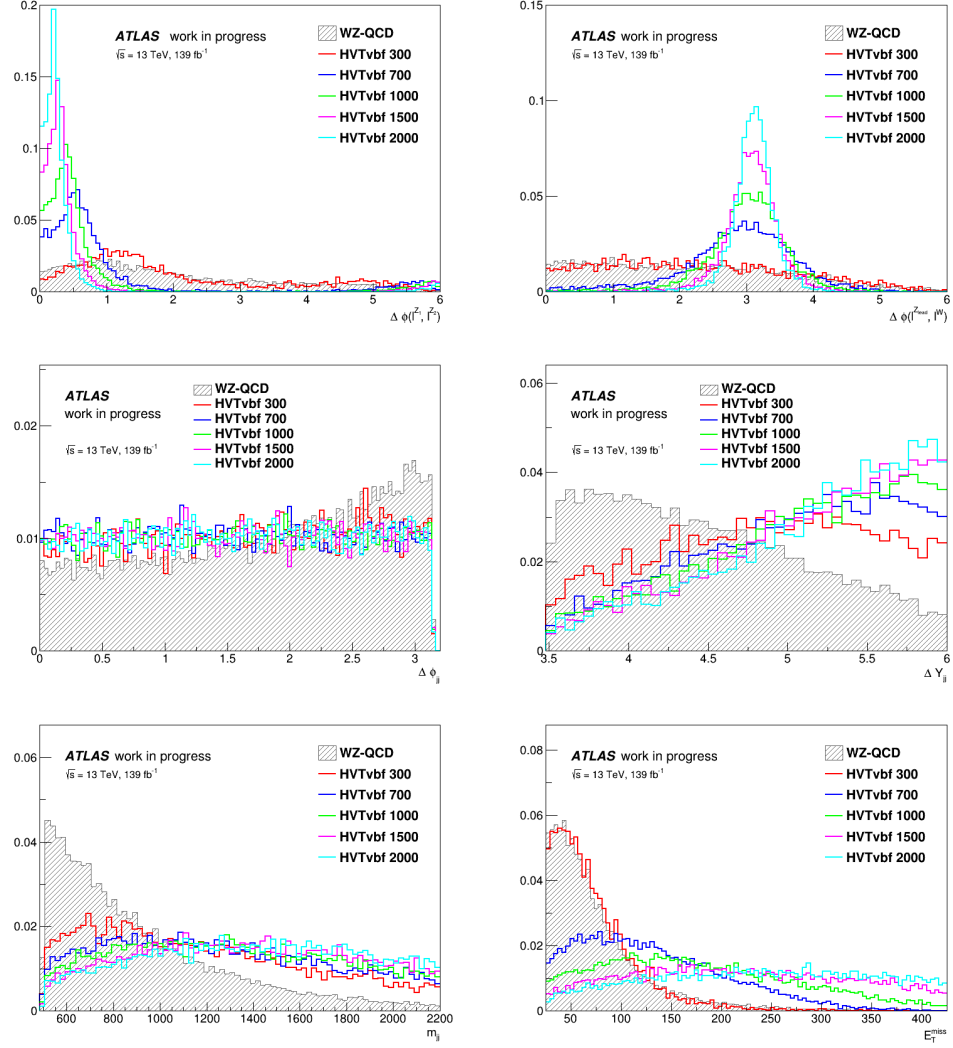


FIGURE 8.1: Alternative variables for limits setting in VBF SR

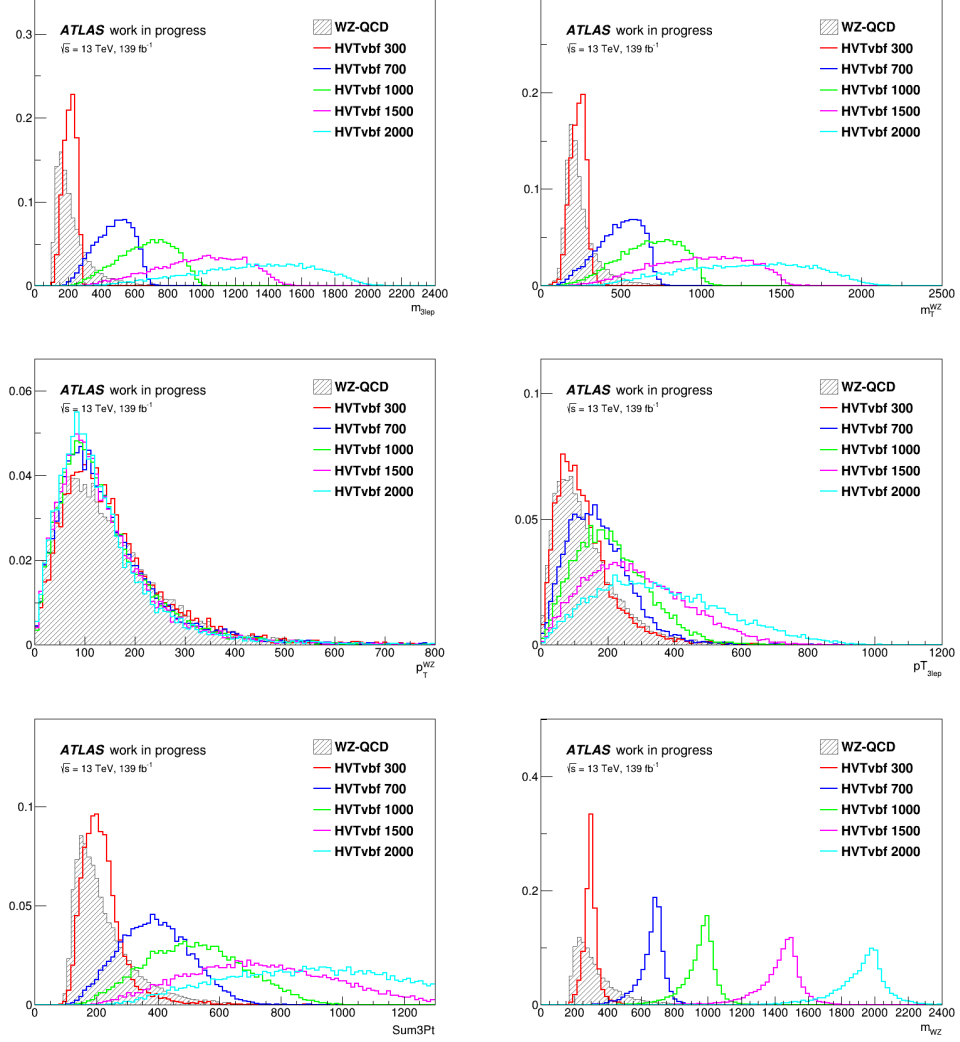


FIGURE 8.2: Alternative variables for limits setting in VBF SR

In the Figure 8.2 there are some variables that are interesting to be used in the limits since they give clear signal peaks and have also good discriminating power between different signal models. These variables that are going to be used as an alternative to the m_{WZ} in the procedure of setting limits, are the invariant mass of the three leptons (m_{3lep}), the transverse mass of the WZ system (m_T^{WZ}), the transverse momentum of the three leptons (pT_{3lep}) and the numerical sum of the transverse momenta of the three leptons ($Sum3Pt$).

8.0.2 Estimation of correlations of alternative variables for two dimensional limits setting

It would also be interesting to set limits with two variables simultaneously. Of course this would demand that they are low correlated. So, an estimation of the average correlation for different combinations of the above “interesting” variables are shown in Figures 8.3 and 8.4. As it is seen, a good combination that seems suitable to test is m_{jj} with m_T^{WZ} , as it has low correlation value. The invariant mass of the two jets (m_{jj}) is interesting because it is effective in discriminating between all non-VBS processes and the signal, since in VBS/VBF topologies we have large values for it. As a result, it would be nice to be used for setting limits in VBF topologies.

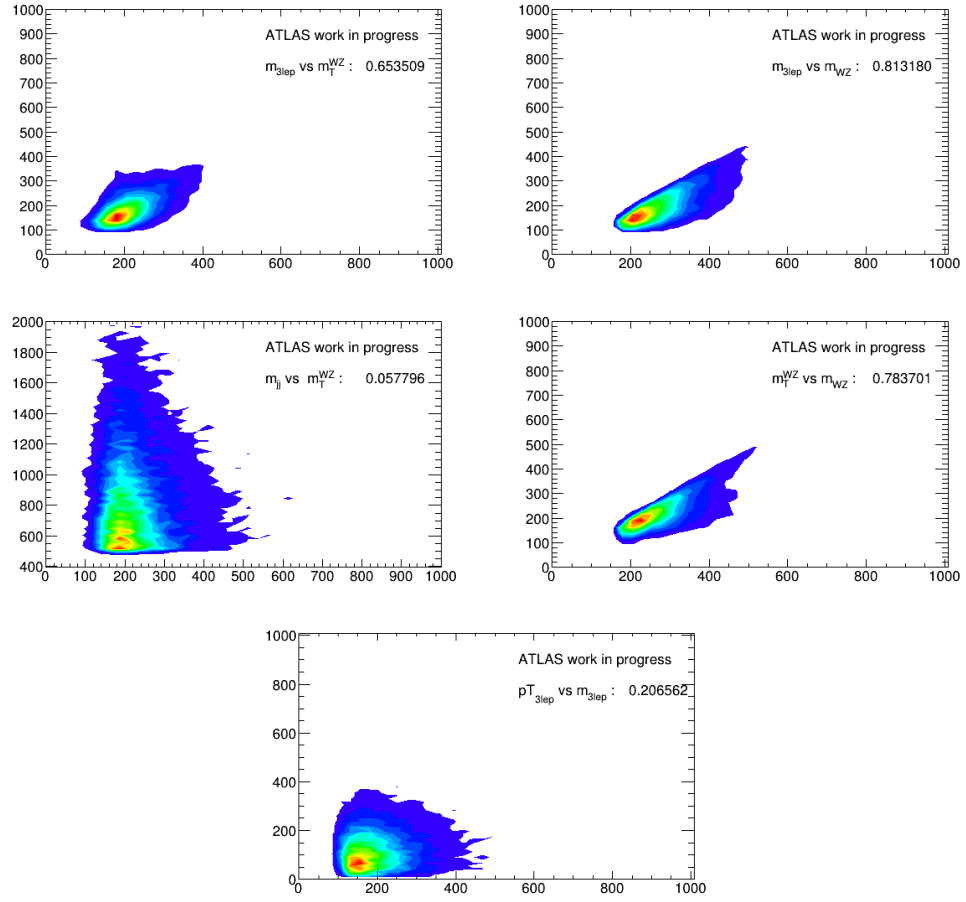


FIGURE 8.3: Estimation of correlations of alternative variables for limits setting in VBF SR

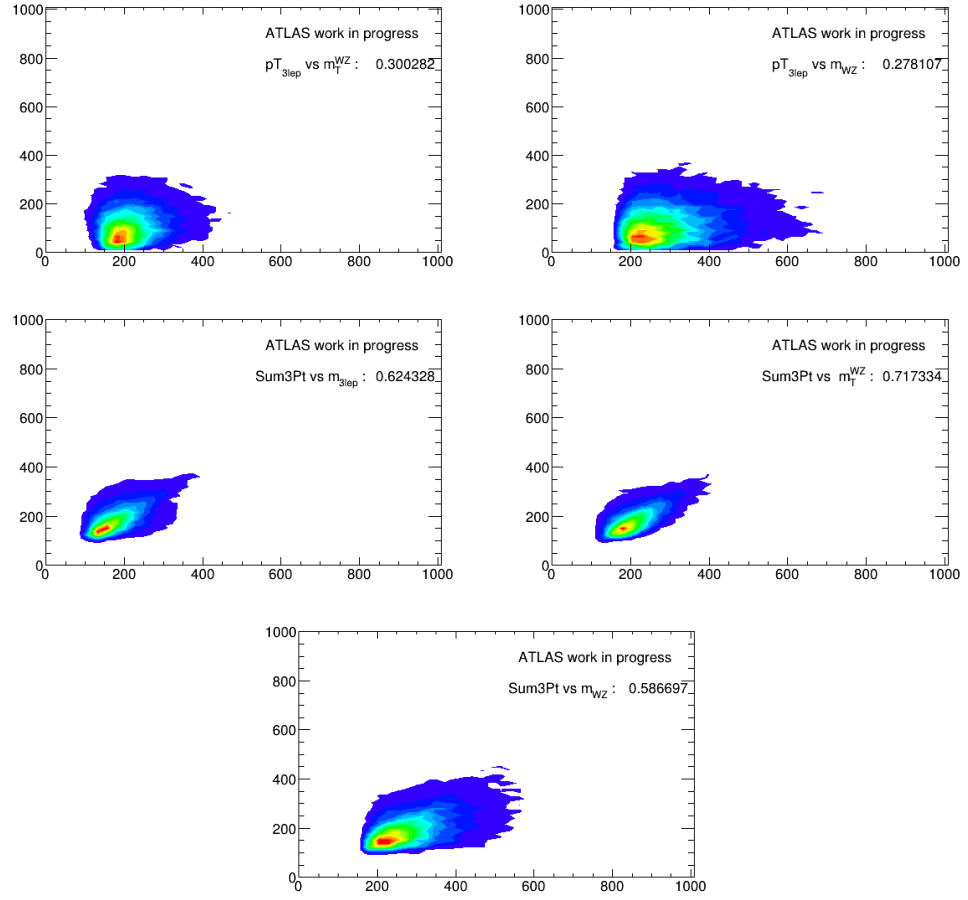


FIGURE 8.4: Estimation of correlations of alternative variables for limits setting in VBF SR

Chapter 9

Sources of Experimental Systematic Uncertainties

The experimental systematic uncertainties are related to the detector and reconstruction performance. They arise from the calculation of the integrated luminosity (which affects the Monte-Carlo normalization) and from the modelling of trigger, the reconstruction, isolation and resolution efficiency of physics objects as well as the missing transverse energy computation. Systematic uncertainties are calculated by taking the fractional difference between the nominal predicted number of events and the number of events predicted by the systematic variation (evaluated measurement at $\pm 1\sigma$ of some systematic uncertainty i.e. systematic up/down variation).

The normalization uncertainty related to the **integrated luminosity** of the data samples used in this analysis is estimated to be 1.7% [57]; this is also used for Monte-Carlo samples that are normalized to the calculated luminosity of data.

For the **muons**, the main sources of systematic uncertainties come from reconstruction and identification efficiency and transverse momentum resolution and scale; we also consider a systematic uncertainty on the muon isolation and the impact parameter cut efficiency [84].

The reconstruction and identification efficiencies are measured from data and simulation using tag-and-probe methods in $Z \rightarrow \mu\mu$ events; the differences between data and Monte-Carlo (MC) are included by scaling the simulation with scale factors (SF). More specifically, the scale factors are varied up and down following their corresponding source of systematics and they lead us to a varied shape of spectrums that results to an altered signal yield.

The transverse momentum resolution correction plays an important role in such analyses as the momentum resolution affects f.e. the muons selection efficiency, the Z boson mass reconstruction and the W lepton p_T determination. This uncertainty is estimated by comparing the

di-muon mass resolution between data and MC; the event yields are obtained by varying the p_T correction of the muons separately in the Inner Detector (ID) and Muon Spectrometer (MS), taking into account the uncertainties on p_T scale and resolution observed in data.

As far as the muon isolation and impact parameter efficiencies are concerned, they are also measured by calculating the differences between data and MC using again the Z tag-and-probe method.

For the **electrons**, the primary sources of systematic uncertainties come from reconstruction and identification efficiency and the electron energy resolution and scale; we also consider the energy scale and smearing uncertainty as well as the electron isolation and impact parameters systematics [83].

The differences observed in the reconstruction and identification efficiencies between data and MC are eliminated by weighting the simulation with scale factors (SF); these SF represent auxiliary measurements done in each of the different bins. Similarly to the muons, the isolation and impact parameter uncertainties are estimated by differences between data and MC using again the Z tag-and-probe method ($Z \rightarrow ee$).

The correction of the electron energy resolution is performed by correcting the MC in order to match the observed data. Moreover, the electron energy scale is checked and calibrated both in data and MC using $Z \rightarrow ee$ events; the dominant uncertainties on this energy scale come from the modelling of the ATLAS detector and the calibration of the EM calorimeter pre-sampler energy scale. For both electron resolution and energy scale, all physical effects are summed in quadrature and considered fully correlated in eta.

In general, the impact of the efficiency of the lepton triggers as well as the lepton uncertainties (as described above) on the expected number of events is found to be negligible (typically below 1 %).

As far as the **jets** are concerned, systematic uncertainties that affect the reconstruction and energy calibration of jets are propagated through this analysis and they are the dominant experimental uncertainties in the VBF category. The jet energy scale and resolution uncertainties are obtained from simulation and *in-situ* techniques [105]. Finally, as we have already mentioned in the event selection cuts, VBF jets are required to pass JVT cut and also fail the existence of b-jets; so there are the corresponding JVT and b-tagging efficiencies. In general, the effect of the jet uncertainties on the expected number of events is up to 17 % for the VBF category as we can see in Table A.6 in Appendix A.

The uncertainty for the **missing transverse energy** measurement is performed by propagating the uncertainties in the transverse momenta of the pre-selected leptons and jets that take part into its calculation, as well as those uncertainties contributing in the soft term [106].

The experimental uncertainty of **pile-up** reweighting derives from the DataScaleFactor; the latter scales the μ to improve the data/MC agreement. The nominal value of this scale factor is set to 1.0/1.09 and it is then varied to 1.0 and 1/1.18 to represent the systematic uncertainty [107].

We also consider an uncertainty in the prediction of the fake/non-prompt background as it affects the shape and the normalization of the background distributions. The total uncertainty is about 60 % (> 100 %) for the Drell-Yan (VBF) selections; it is larger for the second category as there are higher statistic uncertainties [104] .

In Appendix A in Tables A.1 to A.6 we provide a summary of all systematic uncertainties; there, we calculate the relative effect in percent on the number of reconstructed 3-lepton events in each of the four available channels of the different sources of systematic. The existence of some very large uncertainties is explained due to very low statistics of MC samples.

Chapter 10

Theoretical Uncertainties

10.1 Introduction

Whenever we try to measure a physical quantity or test hypothesized models, it is necessary to know the accuracy of our analysis result. *Statistical* uncertainties arise from the limited accuracy of any measurement, or from the Poisson fluctuations related with counting independent events; an important key-fact is that these uncertainties can be greatly constrained if we accomplish enough repeated measurements (f.e. by achieving higher luminosity).

On the other hand, *systematic* uncertainties arise from many sources; more often they do not cause a spread in results when repeating experiments, but merely shift them away from the true value. In that direction, executing more experiments usually does not reduce the impact of a systematic effect. From all the above it is obvious that systematics is an immense topic that requires more effort on its estimation.

Systematic uncertainties are present in all physics analyses where there are uncertainties in the predictions of the simulation steps. All uncertainties that are related to the ATLAS detector simulations are named as *experimental* uncertainties, while uncertainties that arise due to physical processes and their modelling (f.e. Parton Density Functions or PDFs, parton shower, perturbation theory, QED corrections) are called as *theoretical* uncertainties.

The estimation and the detection of the source of both theoretical and experimental uncertainties is important because they enter into the likelihood fit as nuisance parameters and as a result, they are significant in particular for discovery and exclusion limits.

The *PDF uncertainties* reflect the information available (or lack of it) in the underlying data and the way it constrains PDFs [108]; in other words the approximations that are made in theory that relate the PDFs to measureable quantities. In general, the examined PDF sets differ

: (a) in the choice of datasets (the PDF sets used here include data from electroproduction and hadroproduction, from both fixed-target and collider experiments), (b) in the statistical calculation of the pdf uncertainty and (c) in the parton parametrization [108] .

The *scale uncertainties* (Renormalization/Factorization) derive from the uncertainty due to uncalculated higher order terms of perturbative QCD, by varying μ_R / μ_F over some range (typically a factor of 2)¹.

The *parton shower* or *modelling* uncertainties derive from the comparison of different generators predictions in order to capture the showering MC systematic uncertainties; this kind of uncertainty is often described as “2-point systematics ” [109].

Theory uncertainties associated with the PDF sets used to generate the simulation, associated to the choice of the renormalization scale μ_R and factorization scale μ_F and the parton shower settings are estimated for signal and backgrounds. Table 10.1 shows a summary of the calculated theory uncertainties and their implementation on the fit. More details about the calculation and the values of each uncertainty is given in each corresponding section.

Process	Uncertainties	Fit implementation
WZ -QCD	pdf, scale and modelling (comparing generators with different ME and parton shower)	Shape only decorrelated from SR and CR
ZZ	pdf and scale	Shape only
WZ -EWK	pdf, scale and parton shower (comparing same ME events showered with Herwig and Pythia8)	Shape and normalization decorrelated from SR and CR
$t\bar{t}V + VVV$	pdf and scale	20% normalization
Signals	pdf and scale	Normalization only

TABLE 10.1: Summary of the theory uncertainties included in the analysis and the fit implementation

¹“...divergences arising from virtual corrections in the ultraviolet limit (i.e. for very large momenta) can be absorbed by renormalizing the theory, yielding finite terms with a dependence on the so-called renormalization scale μ_R . Similarly, divergences arising in the limit of highly collinear emissions can be regularized away by factorizing the calculation between parton densities and matrix element, giving rise to the so-called factorization scale μ_F . Any dependence of the resulting finite terms on these artificial scales would disappear if it were possible to calculate all orders of the perturbative series” [109]

10.2 Theoretical uncertainties on the Signal

For the pdf uncertainty estimation, the current recommendation for quark initiated processes [110] is to create an envelope using the maximum upwards and downwards deviations choosing among the standard deviation of the 100 replicas of the NNPDF set and the difference of the central PDF set (NNPDF) and the alternative (when they exist). For the scale uncertainties, the envelopes are created by taking the maximum upwards and downwards deviations of the different scale variations from the default value. The pdf and scale uncertainties are calculated for the reconstructed fiducial phase space, using exactly the same cuts as the corresponding signal and control region definitions (Drell-Yan /VBF).

10.2.1 Drell-Yan-Category PDF and Scale uncertainties on the Signal

The uncertainties associated with the PDF sets used in generating the signal MC samples on the signal acceptance are evaluated for the HVT signal samples.

Truth derivation samples are produced containing the PDF information and a PDF reweighting method is applied. The HVT signal samples are produced with NNPDF23loas0130qed NLO PDF set. For the pdf uncertainty calculation, the intrinsic uncertainties associated with NNPDF are evaluated by looking at the 100 MC replicas and the standard deviation is taken as the intrinsic uncertainty. The NNPDF set is also compared with the CT14llo and MMHT2014lo68cl and the difference is taken as extra uncertainty. Then, the total PDF uncertainty is computed by taking the difference of the lowermost and uppermost values of the estimations described above.

For the scale uncertainty, events are reweighted to seven variations (dropping $\mu_R=0.5$, $\mu_F=2$ and $\mu_R=2$, $\mu_F=0.5$ variations). The maximum upwards and downwards deviations from the default values-not coming necessarily from the same variation - with respect to the default choice $\mu_R = \mu_F$ is used to estimate the scale uncertainty.

The pdf and renormalization uncertainties are calculated for both Drell-Yan signal and control region. The pdf uncertainty is found to vary from 12.85% to 26.17% and the scale uncertainty from 1% to 14.36%. Results are shown in table 10.2.

10.2.2 VBF-Category PDF and Scale uncertainties on the Signal

The theory uncertainty of the VBF signal samples is evaluated in a similar way as for the quark fusion category. The HVT VBF signal samples are produced with NNPDF23loas0130qed NLO PDF set. For the pdf uncertainty calculation, the intrinsic uncertainties associated with NNPDF are evaluated by looking at the 100 MC replicas and the standard deviation is taken as the

mass [GeV]	pdf (%)	scale (%)
250	± 13.23	± 4.09
300	± 13.16	± 3.17
400	± 12.94	± 1.49
500	± 12.88	± 0.99
600	± 12.85	± 1.60
700	± 12.97	± 2.28
800	± 13.01	± 2.88
900	± 13.24	± 3.45
1000	± 13.49	± 3.97
1100	± 13.94	± 4.46
1200	± 14.46	± 4.91
1300	± 15.08	± 5.32
1400	± 15.74	± 5.73
1500	± 16.38	± 6.09
1600	± 17.00	± 6.46
1700	± 17.56	± 6.79
1800	± 18.14	± 7.10
1900	± 18.72	± 7.41
2000	± 19.16	± 7.72
2200	± 19.95	± 8.26
2400	± 20.66	± 8.83
2600	± 21.24	± 9.35
2800	± 21.85	± 9.86
3000	± 22.09	± 10.35
3500	± 22.75	± 11.50
4000	± 23.47	± 12.60
4500	± 24.64	± 13.56
5000	± 26.17	± 14.36

TABLE 10.2: The relative uncertainties due to PDF and scale for HVT WZ signal in Drell-Yan signal region.

intrinsic uncertainty . The NNPDF set is also compared with the CT14llo and MMHT2014lo68cl and the difference is taken as extra uncertainty. Then, the total PDF uncertainty is computed by taking the difference of the lowermost and uppermost values of the estimations described above.

The GM VBF signal samples are produced with NNPDF30nloas0119atlas NLO pdf set. The pdf uncertainty is calculated by taking the standard deviation of the 100 MC replicas.

For the scale uncertainties calculation, for both HVT and GM signals, events are reweighted to seven variations (dropping $\mu_R=0.5$, $\mu_F=2$ and $\mu_R=2$, $\mu_F=0.5$ variations) and by taking the maximum upwards and downwards deviations from the default values- not coming necessarily from the same variation - with respect to the default choice $\mu_R = \mu_F$.

The pdf and renormalization uncertainties are calculated for both HVT and GM VBF signals, using the corresponding signal and control regions definitions.

The relative uncertainty on pdf for the VBF GM signal samples is found to vary from 24.19% to 27.41% and the cut-based scale uncertainties from 13.11% to 15.38% ,as shown in table 10.3.

Likewise, the relative uncertainty on the pdf of the VBF HVT signal samples is found to vary from 15.72% to 16.8% and the scale is found to vary from 7.39% to 17.72% , as shown in table 10.4.

DSID	mass [GeV]	pdf (%)	scale (%)
450765	200	± 24.59	± 13.42
450766	250	± 24.74	± 13.49
450767	300	± 24.75	± 13.63
450768	350	± 25.62	± 13.54
450769	400	± 24.45	± 13.81
450770	450	± 25.63	± 14.17
450771	500	± 25.36	± 14.45
502511	225	± 24.44	± 13.11
502512	275	± 24.19	± 13.38
502513	325	± 25.49	± 13.62
502514	375	± 26.32	± 13.37
502515	425	± 25.11	± 13.89
502516	475	± 24.95	± 13.62
502517	525	± 26.08	± 13.78
502518	550	± 26.35	± 13.85
502519	600	± 26.87	± 13.89
502520	700	± 26.42	± 14.17
502521	800	± 27.41	± 14.60
502522	900	± 27.05	± 14.73
502523	1000	± 26.74	± 15.38

TABLE 10.3: The relative uncertainties due to PDF and scale for GM WZ signal in the VBF signal region.

mass [GeV]	pdf (%)	scale (%)
250	± 15.72	± 7.39
275	± 15.82	± 7.63
300	± 15.84	± 7.65
325	± 15.86	± 8.00
350	± 15.92	± 8.06
375	± 16.02	± 8.30
400	± 15.95	± 8.35
425	± 15.98	± 8.71
450	± 16.11	± 8.89
475	± 16.13	± 9.00
500	± 16.12	± 9.02
525	± 16.05	± 9.43
550	± 16.12	± 9.54
600	± 16.25	± 9.66
700	± 16.37	± 10.44
800	± 16.28	± 11.15
900	± 16.42	± 11.68
1000	± 16.39	± 12.33
1100	± 16.48	± 12.92
1200	± 16.53	± 13.52
1300	± 16.60	± 14.13
1400	± 16.53	± 14.63
1500	± 16.67	± 15.25
1600	± 16.60	± 15.66
1700	± 16.61	± 16.23
1800	± 16.73	± 16.76
1900	± 16.64	± 17.16
2000	± 16.80	± 17.72

TABLE 10.4: The relative uncertainties due to PDF and scale for HVT WZ signal in the VBF signal region.

10.3 Theoretical uncertainties on the Standard Model WZ background

10.3.1 PDF uncertainties on SM WZ background

The PDF uncertainties were estimated for the QCD background using two generators Madgraph and Sherpa QCD, and for the EWK mediated production using Madgraph (Madgraph+Pythia8) samples, technical details about the samples can be found in Chapter 4.

The uncertainty estimation is done using the reconstructed fiducial phase space, using exactly the same cuts as the cut-based analysis signal and control regions definitions in Sections 6.4 and 6.5. The EWK Sherpa sample shown also in this section is here for comparison purposes but is not used in the analysis due a known bug on the color flow modeling. Sherpa WZ samples were produced with NNPDF30nnloas0118 PDF set, while the Madgraph WZ QCD and EWK samples were produced with NNPDF30nnloas0118 PDF set. Uncertainties due to the PDFs are computed using the 100 MC replicas of the NNPDF PDF set. Following the PDF4LHC recommendations [111], the 68 % confidence level PDF uncertainty is calculated as the standard deviation of the distribution of MC replicas:

$$\delta\sigma^{NNPDF} = \sqrt{\frac{1}{(N_{mem} - 1)} \sum_{k=1}^{N_{mem}} (\sigma^k - \langle \sigma \rangle)^2} \quad (10.1)$$

where N_{mem} is the number of MC replicas and the mean value of the cross section, $\langle \sigma \rangle$, is computed as:

$$\langle \sigma \rangle = \frac{1}{N_{mem}} \sum_{k=1}^{N_{mem}} \sigma^k \quad (10.2)$$

Figure 10.1 shows the $\delta\sigma$ distributions for the Drell-Yan and VBF signal regions for Sherpa QCD and Sherpa EWK sample. For the Madgraph QCD sample the standard deviation is the only information that we can use for the creation of the envelope that contains the up and down variations. For the Sherpa QCD the NNPDF set is also compared with the CT14nnlo and MMHT2014nlo68cl sets. In this case, we take into account besides the standard deviation of the 100 MC replicas, the comparison with the other two sets, that are derived by comparing each time the nominal value of the NNPDF weight with the nominal values of CT14nnlo and MMHT2014nlo68cl weights. So we end up with a PDF uncertainty envelope that is created by the lowest and highest values of all above.

Finally, for the Madgraph EWK sample the PDF uncertainty envelope is created by taking the uppermost - lowermost values between the standard deviation of the 100 MC replicas and the Asymmetric Hessian Errors that are derived by using the 56 eigenvectors of CT14nlo set. The idea behind the Hessian method is that each PDF has N (uncorrelated) parameters and hence

each parameter can be varied independently by $\pm 1 \sigma$ to create a new (error) PDF [111]. Let consider X as any one of the physical quantities of interest that depends on the PDFs. It is considered as a function of the parameters that define the PDFs at the initial scale $X(\vec{a})$, where $\vec{a}$ forms a vector with an N -dimensional PDF parameter space. In the Hessian formalism for the uncertainty analysis, this parton parameter space is spanned by a set of orthonormal eigenvectors obtained by a self-consistent iterative procedure [112]. The uncertainty of the quantity $X(\vec{a})$ is characterized by $2N$ sets of published eigenvector PDF sets along with the central fit, 2 PDF sets for each of the N eigenvectors, along the $(\pm)$ directions and it is defined as in 10.3 :

$$\Delta X_+ = \sqrt{\sum_{i=1}^N \max(0, X_{i+} - X_0, X_{i-} - X_0)^2} \quad (10.3)$$

$$\Delta X_- = \sqrt{\sum_{i=1}^N \max(0, X_0 - X_{i+}, X_0 - X_{i-})^2}$$

where X_{i+} and X_{i-} are the values of X computed from the 2 sets of the PDFs along the $\pm$ direction of the i -th eigenvector and X_0 is the value of the observable using the central value PDF (nominal).

The relative uncertainties on the SM WZ QCD background shape due to PDF as function of the WZ invariant mass can be seen in Figure 10.2 for both Drell-Yan and VBF categories. The relative uncertainties on the SM EW WZ background shape due to PDF as function of the WZ invariant mass can be seen in Figure 10.3 for both Drell-Yan and VBF categories. The pdf uncertainties are also estimated for the corresponding Drell-Yan and VBF control regions as shown in Figures B.1 and B.2 in Appendix B.

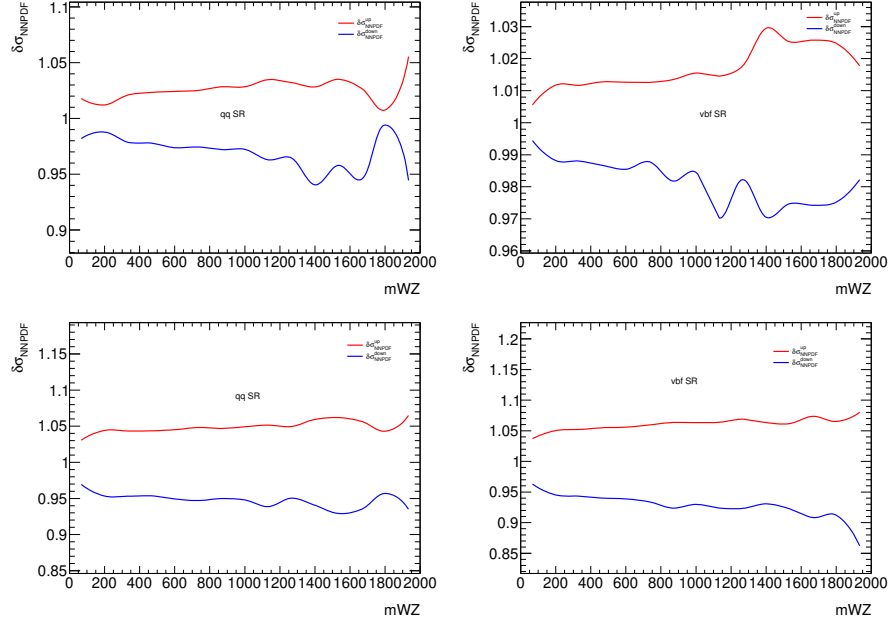


FIGURE 10.1: The $\delta\sigma$ envelopes for the Drell-Yan and VBF signal regions for Sherpa QCD (up plots) and Sherpa EWK (down plots) samples as function of the WZ invariant mass. Sherpa EWK sample is here for comparison but not used in the analysis due a known bug on the color flow modeling.

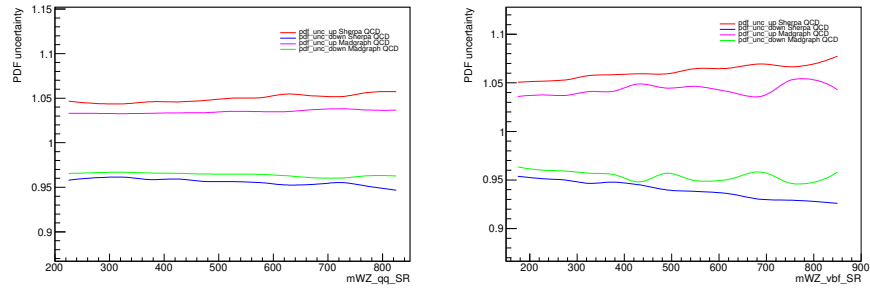


FIGURE 10.2: The relative uncertainties on the SM QCD WZ background shape due to PDF as function of the WZ invariant mass in the Drell-Yan fiducial volume (left) and on the VBF fiducial volume (right). Here is shown a comparison of the pdf envelopes between Madgraph and Sherpa QCD.

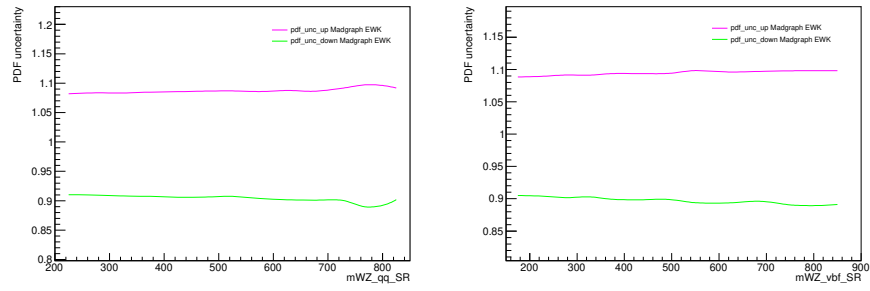


FIGURE 10.3: The relative uncertainties on the SM EWK WZ background shape due to PDF as function of the WZ invariant mass in the Drell-Yan fiducial volume (left) and on the VBF fiducial volume (right).

10.3.2 Scale uncertainties on SM WZ background

To estimate the uncertainty on SM QCD WZ shape deriving from the choice of the renormalization scale μ_R and factorization scale μ_F it is a common procedure to vary them independently and by a factor of 2 (or 1/2) up and down from the default production scale. This was done by setting the scales accordingly during the production of the Sherpa and Madgraph QCD samples. To estimate the scale uncertainties the events are reweighted to seven variations (dropping $\mu_R = 0.5$, $\mu_F = 2$ and $\mu_R = 2$, $\mu_F = 0.5$ variations). The maximum upwards and downwards deviations from the default values-not coming necessarily from the same variation - with respect to the default central value choice $\mu_0 = \mu_R = \mu_F = 1$ is used to estimate the scale uncertainty. For the Madgraph EWK we have 8 variations of renormalization scale μ_R and factorization scale μ_F ($[0.5, 2.0]$, $[1, 0.5]$, $[0.5, 1]$, $[1, 2]$, $[2, 0.5]$, $[2, 1]$, $[2, 2]$), which are used to estimate the scale uncertainty, taking as nominal $\mu_R = \mu_F = 1$ variation and creating the corresponding envelope, as described above. The variations and the envelope of the uncertainty as function of the QCD WZ invariant mass are presented in Figure 10.4 on the top Figure for the Drell-Yan and on the bottom for the VBF signal region selections respectively. The variations and the envelope of the uncertainty as function of the EW WZ invariant mass are presented in Figure 10.5 on the top for the Drell-Yan Signal region and on the bottom for the VBF selection.

The scale uncertainties are also estimated for the Drell-Yan and VBF control regions, as shown in Figures B.3 and B.4 in Appendix B.

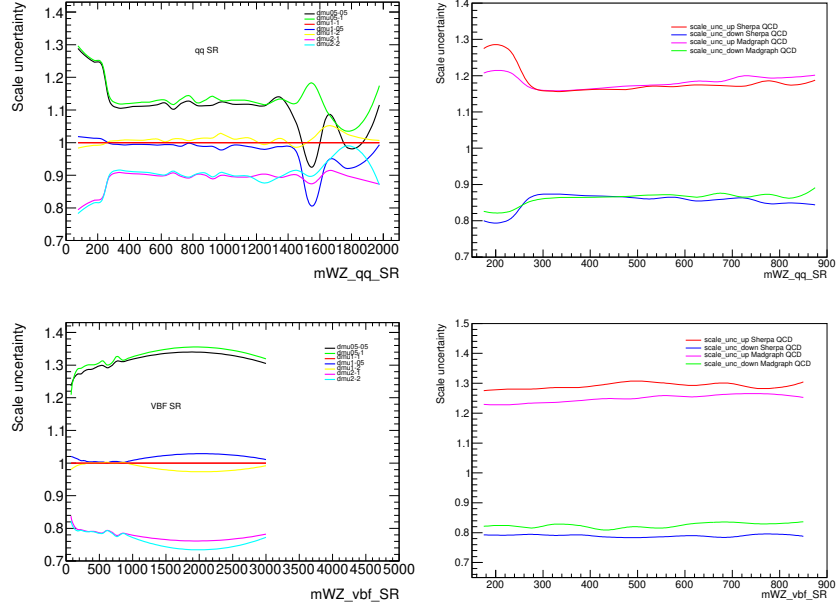


FIGURE 10.4: The uncertainties on the SM QCD WZ background shape caused by the choice of the scale as function of the WZ invariant mass. The plot on the left shows the uncertainty for each variation separately while the plot on the right displays the envelope in Drell-Yan (top) and VBF (bottom) reconstructed phase space.

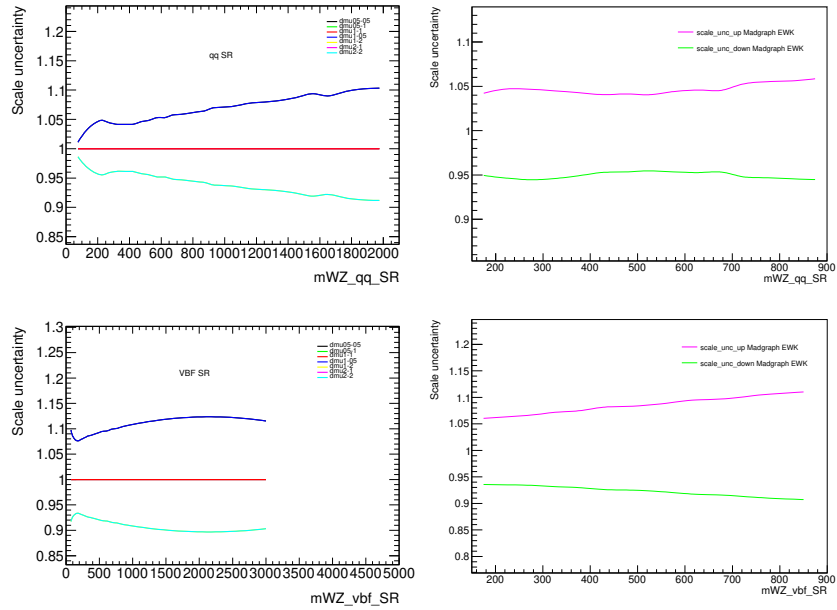


FIGURE 10.5: The uncertainties on the SM EW WZ background shape caused by the choice of the scale as function of the WZ invariant mass. The plot on the left shows the uncertainty for each variation separately while the plot on the right displays the envelope in Drell-Yan (top) and VBF (bottom) reconstructed phase space.

10.3.2.1 Different scales of Madgraph EWK samples comparison

Madgraph has the possibility to produce samples using different central value scales [113]. In the EWK sample we have stored 4 of those weights in order to have the possibility to use also different scales as nominal : $\text{sum}p_T$, hT , $hT2$, sqrts , as shown in Table 10.5. Each of them has 9 renormalization and factorization scales, while the nominal ($\mu_0 = -1$) that is used has 8.

μ_0	dynamical scale definition
-1 (nominal)	LO code: transverse mass (m_T) of the $2 \rightarrow 2$ system resulting of a k_T clustering NLO code: sum of the transverse mass divided by 2 : $h_T = \frac{1}{2} \sum_{i=1}^N \sqrt{m_i^2 + p_{T,i}^2}$
1	total transverse energy of the event $\text{sum}p_T = \sum_{i=1}^N \frac{E_i p_{T,i}}{\sqrt{p_{x,i}^2 + p_{y,i}^2 + p_{z,i}^2}}$
2	sum of the transverse mass $hT = \sum_{i=1}^N \sqrt{m_i^2 + p_{T,i}^2}$
3	sum of the transverse mass divided by 2 $hT2 = \frac{1}{2} \sum_{i=1}^N \sqrt{m_i^2 + p_{T,i}^2}$
4	partonic energy $\text{sqrts} = \sqrt{\hat{s}}$

TABLE 10.5: Central values supported and their corresponding functional form of the factorisation and renormalisation scale μ_R and μ_F , for both leading order and next to leading order computations for Madgraph EWK samples.

In the following plots (see Figure 10.6) we compare the invariant mass distribution of the WZ system for the different scales for the Madgraph+Pythia8 ewk sample with the nominal ($\mu_0 = -1$, $m_T^{2 \rightarrow 2, \text{sys}}$), for the Drell-Yan and VBF fiducial phase space.

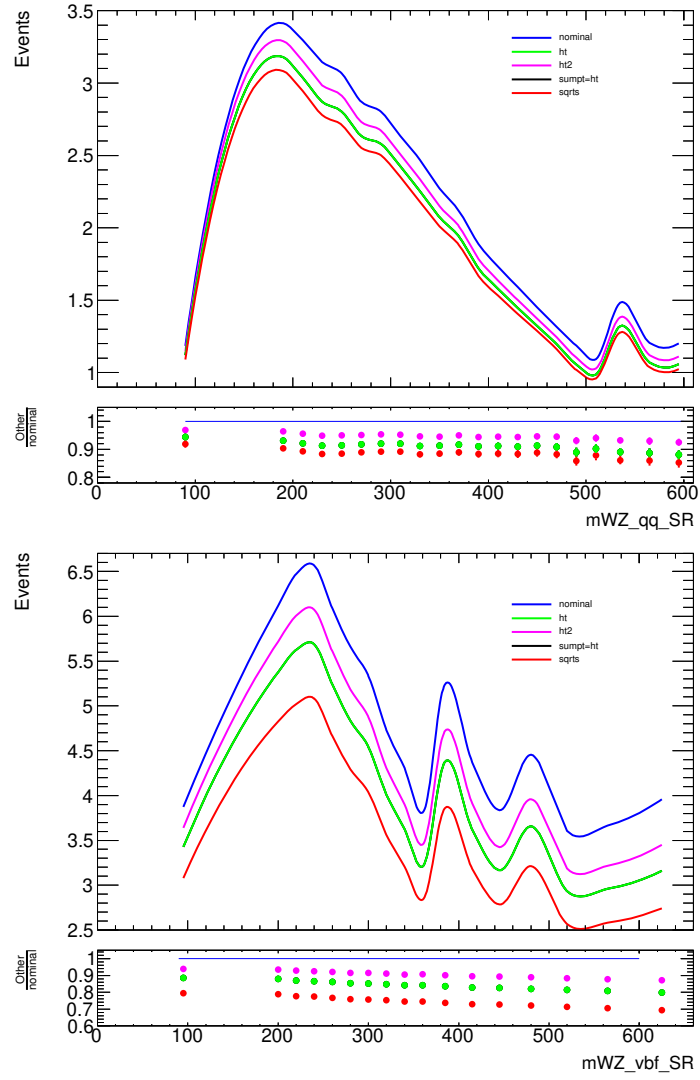


FIGURE 10.6: Comparison of the invariant mass of the WZ system for the different scales of the Madgraph+Pythia8 ewk sample in the Drell-Yan fiducial volume (top) and on the VBF fiducial volume (bottom) and their respective ratio to the nominal

10.3.3 Parton shower uncertainties on SM WZ background

The uncertainties associated with the parton shower modeling of the WZ SM backgrounds are computed by comparing different MC samples created using different parton shower models.

No built-in variations for the parton shower uncertainties are present in the Sherpa MC samples available. Therefore, for the WZ QCD background, the Madgraph+Pythia8 MC sample has been used to derive possible difference between different QCD parton shower and matrix element models implemented by the two generators.

Due to the absence of known parametric forms for this uncertainty, we need to investigate multiple plausible variants of parametric models and perform the final statistical analysis [109] in order to check if the fit is “healthy”.

First of all, in order to avoid the impact of the large difference normalization between the two MC samples on the calculation of the fragmentation uncertainty, the Madgraph distribution is normalized to the Sherpa. Then we calculate the difference between the distributions of Madgraph and Sherpa per bin and the obtained results are used to calculate the relative uncertainty associated with the parton shower and Matrix element generator.

There have been studied several options for the formula that calculates the parton shower+modelling relative uncertainty; they have been included in the fit in order to check how they affect the likelihood estimation.

The 1st option was to use $|Madgraph - Sherpa|/Madgraph$,

the 2nd to use $\frac{1}{2}|Madgraph - Sherpa|/Madgraph$ and

the 3rd $\frac{1}{\sqrt{12}}|Madgraph - Sherpa|/Madgraph$ (standard deviation of uniform distribution).

Comparisons of the obtained uncertainties for the QCD case are given in Appendix C.1. The last two formulas gave the best fit results (concerning the presence of pulls/overconstraints) in the fit and we choose to keep the 2nd formula as a more conservative estimate (and also consistent with the previous Run analysis).

As a result, the relative uncertainty divided by a factor of two is used to construct a symmetric fragmentation uncertainty band centred around the Sherpa distribution. The procedure is exemplified in the Figure 10.7, where the parton shower uncertainty band obtained is represented around the Sherpa prediction by shaded pink band. This uncertainty represents a conservative estimate of the parton shower and generator modelling differences between Madgraph+Pythia8 and Sherpa 2.2.2 QCD Monte Carlo samples. This uncertainty is calculated using the Drell-Yan and VBF reconstructed phase space, as described before.

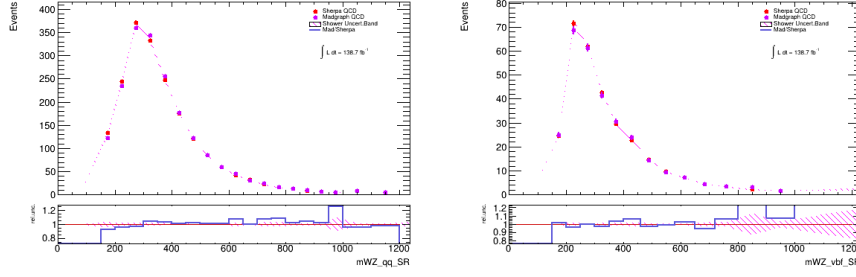


FIGURE 10.7: Comparison of the M_{WZ} distribution between Sherpa2.2.2 and Madgraph+Pythia8 event generators in Drell-Yan SR on the left and VBF SR in the right. The parton shower uncertainty is shown by shaded pink bands. In the down plot there is also an estimate of the ratio between the two QCD generators.

For WZ EW background, the estimation of the parton shower uncertainties is performed by comparing the WZ EW Madgraph+Pythia8 and Madgraph+Herwig generators. First of all, the Madgraph+Herwig distribution is normalized to the Madgraph+Pythia8.

Similarly with the procedure described above, we have tested different formulas for the estimation of the parton shower uncertainty :

the 1st option was to use $|MadPy8 - MadHerwig|/MadHerwig$,

the 2nd to use $\frac{1}{2}|MadPy8 - MadHerwig|/MadHerwig$ and

the 3rd $\frac{1}{\sqrt{12}}|MadPy8 - MadHerwig|/MadHerwig$ (standard deviation of uniform distribution).

Comparisons of the obtained uncertainties for the EWK case are given in Appendix C.2. The last two formulas gave the best fit results (concerning the presence of pulls/overconstraints) in the fit and we choose to keep the 2nd formula as a more conservative estimate (and also consistent with the previous Run analysis).

The difference between the distributions of Madgraph+Herwig and Madgraph+Pythia8 per bin is used to calculate the relative uncertainty that is related to the MadGraph+Herwig parton shower. This relative uncertainty divided by a factor of two is used to construct a symmetric fragmentation uncertainty band centred around the Madgraph+Pythia8 distribution, to build a parton shower uncertainty band (see Figure 10.8).

The envelopes that include the up and down variations for the parton shower uncertainties are given in Figure 10.9 for the QCD and in Figure 10.10 for the EWK case.

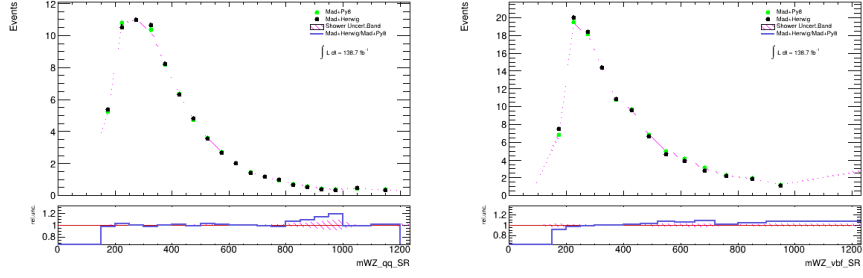


FIGURE 10.8: Comparison of the M_{WZ} distribution between Madgraph+Pythia8 and Madgraph+Herwig event generators in Drell-Yan SR on the left and VBF SR in the right. The parton shower uncertainty is shown by shaded pink bands. In the down plot there is also an estimate of the ratio between the two EWK generators.

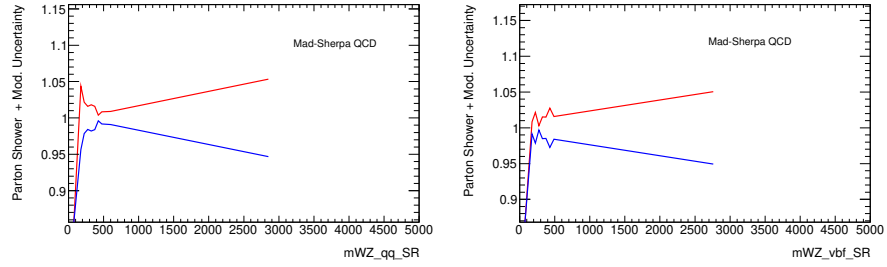


FIGURE 10.9: The relative uncertainties on the SM QCD WZ background shape due to the different parton shower and modelling of the QCD generators (Madgraph+Pythia8, Sherpa 2.2.2) as function of the WZ invariant mass in the Drell-Yan fiducial volume (left) and on the VBF fiducial volume (right).

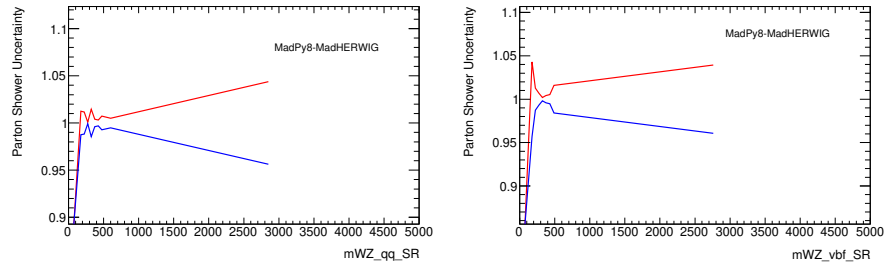


FIGURE 10.10: The relative uncertainties on the SM EWK WZ background shape due to the different parton shower of the EWK generators (Madgraph+Pythia8, Madgraph+Herwig) as function of the WZ invariant mass in the Drell-Yan fiducial volume (left) and on the VBF fiducial volume (right).

10.4 Theoretical uncertainties on Standard Model WZ background using alternative variables

As discussed in Section 8, alternative variables are going to be used as inputs to the fit. Here we have compared the pdf, scale and parton shower uncertainties when using m_T^{WZ} with the ones already calculated using the m_{WZ} variable. The relative difference is below 5-6 % for both Drell-Yan and VBF fiducial phase spaces, as we can see in figures D.1, D.2 in Appendix D.

So we perform the general approach that the theoretical uncertainties calculated using the m_{WZ} variable can be inserted in the fit when using alternative variables.

10.5 Theoretical uncertainties on the other Standard Model irreducible backgrounds

The uncertainties assigned to the cross sections of the other minor background sources taken from MC simulation consist of a contribution from PDF uncertainties and from QCD scale uncertainties. They are estimated to be 20% for VVV [114] and 13% for ttV [115] [116]. A validation region was built [104] to verify the modelling, even though the agreement is not perfect, the flat 13% uncertainty assigned is sufficient to cover the discrepancy in the invariant mass distribution. Also, the pdf and scale uncertainties have been calculated for the ZZ background for the Drell-Yan and vbf signal and control regions. The estimated uncertainties again are sufficient to cover the discrepancy in the invariant mass distribution.

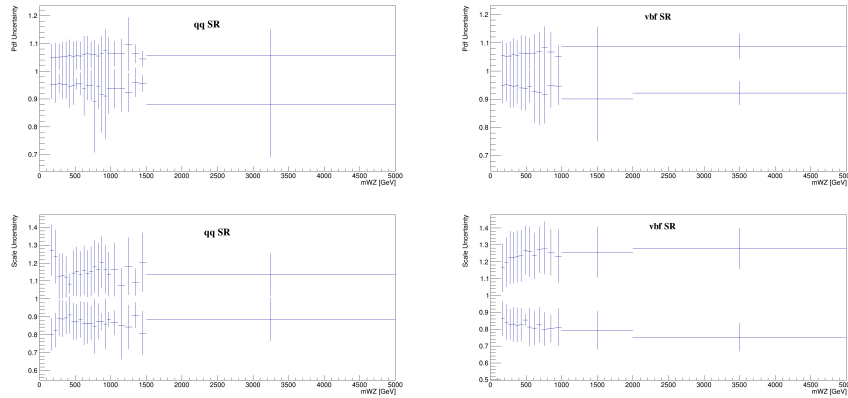


FIGURE 10.11: The pdf (up) and scale (down) envelopes for the ZZ background as function of the WZ invariant mass in the Drell-Yan fiducial volume (left) and on the VBF fiducial volume (right).

Chapter 11

Statistical Methods for LHC

11.1 Introduction

11.2 Search as a statistical test

11.2.1 Definition of test-statistic t_μ

In particle physics experiments one often searches for processes that have been predicted but not yet seen, such as production of a Higgs boson. The statistical significance of an observed signal can be quantified by means of a p-value or its equivalent Gaussian significance. Also, it is useful to characterize the sensitivity of an experiment by reporting the expected (e.g., mean or median) significance that one would obtain for a variety of signal hypotheses.

A common procedure is the search of a new phenomenon expressed in the formalism of a statistical test. Let us assume that one aims to discover a new signal process; then one defines the null hypothesis H_0 , as describing only known processes (here designated as background). This is to be tested against the alternative H_1 , which includes both background and signal. When setting limits, the model with signal plus background plays the role of H_0 , which is tested against the background-only hypothesis, H_1 . To quantify the level of agreement of the observed data with a given hypothesis H , we use the p-value i.e. the probability under the assumption of H , of finding data of equal or greater incompatibility with the predictions of H . Then, one can regard the hypothesis as excluded if its p-value is observed below a specified threshold.

In particle physics one usually converts the p-value into an equivalent significance, Z , defined such that a Gaussian distributed variable found Z standard deviations above its mean, has an

upper-tail probability equal to p .

$$Z = \Phi^{-1}(1 - p) \quad (11.1)$$

where Φ^{-1} is the quantile (inverse of the cumulative distribution) of the standard Gaussian. For a signal process such as the Higgs boson, we tend to reject the background hypothesis with a significance of at least $Z = 5$ as an appropriate level to constitute a discovery, which corresponds to $p = 2.87 \times 10^{-7}$. For purposes of excluding a signal hypothesis, a threshold p -value of 0.05 (95 % confidence level) is often used, which corresponds to $Z = 1.64$.

A widely used procedure to establish discovery (or exclusion) in particle physics is based on a frequentist significance test using a likelihood ratio as a test statistic; a test statistic aims to make a statement about how well the observed data stand in agreement with given predicted probabilities by hypothetical models. Except from the parameters of interest such as the rate (cross-section) of the signal process, the signal and background models will contain in general *nuisance parameters* whose values are not taken as known a priori but rather must be fitted from the data. Let us now to consider an experiment where for each selected event one measures the values of certain kinematic variables, and thus the resulting data can be represented as one or more histograms [117]. Suppose for each event in the signal sample one measures a variable x and uses these values to construct a histogram $\mathbf{n} = (n_1, \dots, n_N)$. The expectation value of n_i can be written as :

$$E[n_i] = \mu s_i + b_i \quad (11.2)$$

where the mean number of entries in the i -th bin from signal and background are :

$$\begin{aligned} s_i &= s_{tot} \int_{bin,i} f_s(x; \theta_s) dx \\ b_i &= b_{tot} \int_{bin,i} f_b(x; \theta_b) dx \end{aligned} \quad (11.3)$$

In equation 11.2, the parameter μ determines the strength of the signal process, with $\mu = 0$ corresponding to the background-only hypothesis and $\mu = 1$ being the nominal signal hypothesis. We often write $\mu = \sigma/\sigma_{SM}$, where σ_{SM} is the Standard Model production cross-section. In equation 11.3, s_{tot} and b_{tot} are the total mean number of signal and background events; the $f_s(x; \theta_s)$ and $f_b(x; \theta_b)$ are the probability density functions (pdfs) of the variable x for signal and background events; θ_s and θ_b represent parameters that characterize the shapes of pdfs (nuisance parameters) and the integrals represent the probabilities for an event to be found in bin i . In the analysis below, we will use $\theta = (\theta_s, \theta_b, b_{tot})$ to denote all of the nuisance parameters; the signal normalization s_{tot} is not, an adjustable parameter but rather is fixed to the value predicted by the nominal signal model.

In addition to the measured $\mathbf{n}$ histograms we might perform further subsidiary measurements that will help us to constrain the nuisance parameters. For example, one may select a control sample where one expects mainly background events and from them construct a histogram of some chosen kinematic variable. This gives a set of values $\mathbf{m} = (m_1, \dots, m_M)$, for the number of entries in each of the M bins. Then, the expectation value of m_i can be written as in the following equation where the u_i are calculable quantities depending on the parameters θ :

$$E[m_i] = u_i(\theta) \quad (11.4)$$

These subsidiary measurements are often used to provide information on the background normalization parameter and also on signal and background shape parameters.

If we consider that n_i follows a Poisson distribution with mean value $\mu s_i + b_i$, the binned likelihood function is written as the product of these Poisson probabilities to observe n_i events in a given bin i (and the same Poisson hypothesis to be valid also for the subsidiary measurements m_i), for all bins :

$$L(\mu, \theta) = \prod_{j=1}^N \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^M \frac{u_k^{m_k}}{m_k!} e^{-u_k} \quad (11.5)$$

In general, s and b are affected by systematic uncertainties (theoretical and experimental), that are treated as nuisance parameters θ so that signal and background expectations become functions of them $s(\theta)$ and $b(\theta)$.

Taking into account the nuisance parameters, the best one-dimensional test-statistic (in the sense of maximum power and due to its known asymptotic properties, as discussed later) for investigating a hypothesized value of μ is the profile likelihood ratio :

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\hat{\theta}})} \quad (11.6)$$

In the above equation, the $\hat{\hat{\theta}}$ denotes the value of θ that maximizes L for the specified μ , i.e., it is the conditional maximum-likelihood (CMLE) estimator of θ (also referred to as "profiled value" of θ). Also, the denominator is the maximized (unconditional) likelihood function, meaning that $\hat{\mu}$ and $\hat{\hat{\theta}}$ are fixed to the values of their maximum likelihood estimators (MLE).

The loss of information about μ due to the systematic uncertainties is reflected in the presence of the nuisance parameters that broaden the profile likelihood as a function of μ relative to what one would have if their values were fixed.

From equation 11.6 one can see that $0 \leq \lambda \leq 1$, with λ near 1 implying good agreement between the data and the hypothesized value of μ . As a basis of a statistical test, it is convenient to use the test-statistic :

$$t_\mu = -2\ln\lambda(\mu) \quad (11.7)$$

The t_μ stands as a measure of discrepancy between data and the given hypothesis, with higher values of t_μ indicating greater incompatibility between them.

To quantify the level of disagreement we calculate the p-value :

$$p_\mu = \int_{t_{\mu,obs}}^{\infty} f(t_\mu|\mu) dt_\mu \quad (11.8)$$

where $t_{\mu,obs}$ is the value of the statistic observed from the data and $f(t_\mu|\mu)$ denotes the pdf of t_μ under the assumption of the signal strength μ .

If one assumes that the presence of a new signal can only increase the mean event rate beyond what is expected from background alone, the signal process necessarily has $\hat{\mu} \geq 0$. When a model like this is valid, if we find data that have $\hat{\mu} < 0$ then the best level of agreement between the data and any physical value of μ occurs for $\mu = 0$. So we define a modified profile likelihood ratio as:

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}, & \hat{\mu} \geq 0 \\ \frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(0, \hat{\boldsymbol{\theta}}(0))}, & \hat{\mu} < 0 \end{cases} \quad (11.9)$$

where $\hat{\boldsymbol{\theta}}(0)$ and $\hat{\boldsymbol{\theta}}(\mu)$ stand for the conditional MLE of $\boldsymbol{\theta}$ given a strength parameter as 0 and μ respectively.

And as a result the test-statistic becomes :

$$\tilde{t}_\mu = -2\ln\tilde{\lambda}(\mu) = \begin{cases} -2\ln\frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}, & \hat{\mu} \geq 0 \\ -2\ln\frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(0, \hat{\boldsymbol{\theta}}(0))}, & \hat{\mu} < 0 \end{cases} \quad (11.10)$$

11.2.2 Test-Statistic for discovery

An special case of the statistic t_μ described above is used to test $\mu = 0$ in a model where we assume $\mu \geq 0$. In order to discover new signal, we have to reject the $\mu = 0$ hypothesis. For this important case we use the special notation $q_0 = t_0$ [117]. Using the equation 11.10 with $\mu = 0$ one finds :

$$q_0 = \begin{cases} -2\ln\lambda(0), & \hat{\mu} \geq 0 \\ 0, & \hat{\mu} < 0 \end{cases} \quad (11.11)$$

where $\lambda(0)$ is derived from equation 11.6. If $f(q_0|0)$ denotes the pdf of the statistic q_0 under assumption of the background-only ($\mu = 0$) hypothesis, the corresponding p-value is :

$$p_0 = \int_{q_{0,obs}}^{\infty} f(q_0|0)dq_0 \quad (11.12)$$

11.2.3 Test-Statistic for setting upper limits

In order to establish an upper limit on the strength parameter μ , we consider the test statistic [117]:

$$q_\mu = \begin{cases} -2\ln\lambda(\mu), & \hat{\mu} \leq \mu \\ 0, & \hat{\mu} > \mu \end{cases} \quad (11.13)$$

Data with $\hat{\mu} > \mu$ represent less compatibility with μ than the data obtained, and therefore this is not taken as part of the rejection region of the test (the test statistic becomes 0). Also, from the definition of the test statistic one sees that higher values of q_μ represent greater incompatibility between the data and the hypothesized value of μ .

If $f(q_\mu|\mu)$ is the pdf of q_μ assuming the hypothesis μ , the corresponding p-value for the case of setting upper limits becomes :

$$p_\mu = \int_{q_{\mu,obs}}^{\infty} f(q_\mu|\mu)dq_\mu \quad (11.14)$$

When one considers models for which $\mu \geq 0$, $\lambda(\mu)$ follows 11.9 and the alternative test-statistic becomes :

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu), & \hat{\mu} \leq \mu \\ 0, & \hat{\mu} > \mu \end{cases} = \begin{cases} -2\ln\frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(0, \hat{\boldsymbol{\theta}}(0))}, & \hat{\mu} < 0 \\ -2\ln\frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}, & 0 \leq \hat{\mu} \leq \mu \\ 0, & \hat{\mu} > \mu \end{cases} \quad (11.15)$$

11.2.4 χ^2 Approximation for the distribution of profile likelihood ratio

Let's now consider a statistical test of the strength parameter μ , which here can either be zero (for discovery) or nonzero (for an upper limit). If we suppose the data are distributed according to a strength parameter μ' , the distribution $f(q_\mu|\mu')$ is given by Wald [118], who showed that for the case of a single parameter of interest :

$$-2\ln\lambda(\mu) = \frac{(\mu - \hat{\mu})^2}{\sigma^2} + O(1/\sqrt{N}) \quad (11.16)$$

In the above equation $\hat{\mu}$ follows a Gaussian distribution with mean μ' and standard deviation σ ($\hat{\mu} \sim \text{Gaussian}(\mu', \sigma)$). A possible way to estimate σ is from the covariance matrix of the estimators for all the parameters, where here the θ_i represent both μ as well as the nuisance parameters. In the large-sample limit (where we neglect the $O(1/\sqrt{N})$), the bias of ML estimators in general tend to zero, so the standard deviation calculated by the inverse of the covariance matrix that is created from the nuisance parameters :

$$\sigma \approx V_{ij}^{-1} = \text{cov}^{-1}[\hat{\theta}_i, \hat{\theta}_j] \Big|_{\hat{\mu}=\mu'} = -E \left[\frac{\partial^2 \ln L}{\partial \theta_i \partial \theta_j} \right] \quad (11.17)$$

Taking into account that $\hat{\mu}$ is Gaussian distributed and the $O(1/N)$ term in 11.16 is neglected, then one can show that the statistic t_μ follows a *non-central chi-square* distribution for one degree of freedom [119] :

$$t_\mu = -2\ln\lambda(\mu) \sim f(t_\mu; \Lambda) = \frac{1}{2\sqrt{t_\mu}} \frac{1}{\sqrt{2\pi}} \left[e^{-\frac{1}{2}(\sqrt{t_\mu} + \sqrt{\Lambda})^2} + e^{-\frac{1}{2}(\sqrt{t_\mu} - \sqrt{\Lambda})^2} \right] \quad (11.18)$$

where Λ is the non-centrality parameter and is defined by :

$$\Lambda = \frac{(\mu - \mu')^2}{\sigma^2} \quad (11.19)$$

From equation 11.18 when replacing $\mu = \mu'$, the test-statistic t_μ is simply a chi-square distribution for one degree of freedom, according to the Wilks earlier result [120] :

$$f(t_\mu|\mu) = \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{t_\mu}} e^{-t_\mu/2} \quad (11.20)$$

The cumulative distribution of t_μ is :

$$F(t_\mu|\mu') = \Phi\left(\sqrt{t_\mu} + \frac{\mu - \mu'}{\sigma}\right) + \Phi\left(\sqrt{t_\mu} - \frac{\mu - \mu'}{\sigma}\right) - 1 \quad (11.21)$$

where Φ is the cumulative distribution of the standard Gaussian (zero mean, unit variance). So, the special case $\mu = \mu'$ is therefore :

$$F(t_\mu|\mu) = 2\Phi(\sqrt{t_\mu}) - 1 \quad (11.22)$$

The p-value of a hypothesized value of μ for an observed value t_μ is therefore :

$$p_\mu = 1 - F(t_\mu|\mu) = 2(1 - \Phi(\sqrt{t_\mu})) \quad (11.23)$$

and the corresponding significance is :

$$Z_\mu = \Phi^{-1}(1 - p_\mu) = \Phi^{-1}(2\Phi(\sqrt{t_\mu}) - 1) \quad (11.24)$$

If the p-value is found below a specified threshold α (often one takes $\alpha = 0.05$), then the value of μ is said to be excluded at a confidence level (CL) of $1 - \alpha$. Here the endpoints of the interval can be obtained simply by setting $p_\mu = \alpha$ and solving for μ . So, assuming the Wald approximation 11.16 and using Eq. 11.23 one finds :

$$\mu_{up/low} = \hat{\mu} \pm \sigma \Phi^{-1}(1 - \alpha/2) \quad (11.25)$$

11.2.4.1 Distribution of q_0 (discovery)

According to Eq. 11.16, the test-statistic from Eq. 11.11 becomes :

$$q_0 = \begin{cases} -2\ln\lambda(0) = \hat{\mu}^2/\sigma^2, & \hat{\mu} \geq 0 \\ 0, & \hat{\mu} < 0 \end{cases} \quad (11.26)$$

where $\hat{\mu}$ follows a Gaussian distribution with mean μ' and standard deviation σ . From this one can show that the pdf of q_0 for the case of $\mu' = 0$ has the form of a half chi-square distribution or $\frac{1}{2}\chi_1^2$, which is a mixture of a delta function at zero and a chi-square distribution for one degree of freedom, with each term having a weight of 1/2 :

$$f(q_0|0) = \frac{1}{2}\delta(q_0) + \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{q_0}} e^{-q_0/2} \quad (11.27)$$

and the corresponding cumulative distribution is :

$$F(q_0|0) = \Phi(\sqrt{q_0}) \quad (11.28)$$

So the p-value and the significance for the $\mu = 0$ hypothesis are :

$$p_0 = 1 - F(q_0|0),$$

$$Z_0 = \Phi^{-1}(1 - p_0) = \sqrt{q_0} \quad (11.29)$$

11.2.4.2 Distribution of q_μ and $\tilde{q}_\mu$ (upper limits)

Assuming the validity of the Wald approximation Eq. 11.16, we can write the test-statistic used for upper limits, using Eq. 11.13 as :

$$q_\mu = \begin{cases} \frac{(\mu - \hat{\mu})^2}{\sigma^2}, & \hat{\mu} < \mu \\ 0, & \hat{\mu} > \mu \end{cases} \quad (11.30)$$

where $\hat{\mu}$ as before follows a Gaussian distribution, centred about μ' with a standard deviation σ . The pdf $f(q_\mu|\mu')$ is found to be :

$$f(q_\mu|\mu') = \Phi\left(\frac{\mu - \mu'}{\sigma}\right) \delta(q_\mu) + \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{q_\mu}} e^{-\frac{1}{2}\left(\sqrt{q_\mu} - \frac{\mu - \mu'}{\sigma}\right)^2} \quad (11.31)$$

and the corresponding cumulative distribution is :

$$F(q_\mu|\mu') = \Phi\left(\sqrt{q_\mu} - \frac{\mu - \mu'}{\sigma}\right) \quad (11.32)$$

For the special case that $\mu = \mu'$, the pdf is a half-chi-square distribution :

$$f(q_\mu|\mu) = \frac{1}{2}\delta(q_\mu) + \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{q_\mu}} e^{-q_\mu/2} \quad (11.33)$$

And the corresponding cumulative is :

$$F(q_\mu|\mu) = \Phi(\sqrt{q_\mu}) \quad (11.34)$$

So the p-value and the significance for the $\mu = \mu'$ hypothesis are :

$$p_\mu = 1 - F(q_\mu|\mu) = 1 - \Phi(\sqrt{q_\mu}),$$

$$Z_\mu = \Phi^{-1}(1 - p_\mu) = \sqrt{q_\mu} \quad (11.35)$$

For a specified threshold α (often one takes $\alpha = 0.05$), then the value of μ is said to be excluded at a confidence level (CL) of $1 - \alpha$. The upper limit on μ is the largest μ with $p_\mu \leq \alpha$. Here this can be obtained simply by setting $p_\mu = \alpha$ and solving for μ :

$$\mu_{up} = \hat{\mu} + \sigma \Phi^{-1}(1 - \alpha) \quad (11.36)$$

If we now consider the case of the alternative test-statistic $\tilde{q}_\mu$ defined by Eq. 11.15 [117] and assuming the Wald approximation we find :

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu), & \hat{\mu} \leq \mu \\ 0, & \hat{\mu} > \mu \end{cases} = \begin{cases} \frac{\mu^2}{\sigma^2} - \frac{2\mu\hat{\mu}}{\sigma^2}, & \hat{\mu} < 0 \\ \frac{(\mu - \hat{\mu})^2}{\sigma^2}, & 0 \leq \hat{\mu} \leq \mu \\ 0, & \hat{\mu} > \mu \end{cases} \quad (11.37)$$

For the case that $\mu = \mu'$ the pdf and the cumulative distribution become :

$$f(\tilde{q}_\mu|\mu) = \frac{1}{2}\delta(\tilde{q}_\mu) + \begin{cases} \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{\tilde{q}_\mu}} e^{-\tilde{q}_\mu/2}, & 0 < \tilde{q}_\mu \leq \mu^2/\sigma^2 \\ \frac{1}{\sqrt{2\pi}(2\mu/\sigma)} e^{-\frac{1}{2} \frac{(\tilde{q}_\mu + \mu^2/\sigma^2)^2}{(2\mu/\sigma)^2}}, & \tilde{q}_\mu > \mu^2/\sigma^2 \end{cases} \quad (11.38)$$

$$F(\tilde{q}_\mu|\mu) = \begin{cases} \Phi(\sqrt{\tilde{q}_\mu}), & 0 < \tilde{q}_\mu \leq \mu^2/\sigma^2 \\ \Phi\left(\frac{\tilde{q}_\mu^2 + \mu^2/\sigma^2}{2\mu/\sigma}\right), & \tilde{q}_\mu > \mu^2/\sigma^2 \end{cases} \quad (11.39)$$

The p-value is :

$$p_\mu = 1 - F(\tilde{q}_\mu|\mu) \quad (11.40)$$

And therefore the significance is :

$$Z_\mu = \begin{cases} \sqrt{\tilde{q}_\mu}, & 0 < \tilde{q}_\mu \leq \mu^2/\sigma^2 \\ \frac{\tilde{q}_\mu^2 + \mu^2/\sigma^2}{2\mu/\sigma}, & \tilde{q}_\mu > \mu^2/\sigma^2 \end{cases} \quad (11.41)$$

The upper limit on μ at confidence level $1 - \alpha$ is found by setting $p_\mu = \alpha$ and solving for μ . To the extent that the Wald approximation holds, the two statistics q_μ and $\tilde{q}_\mu$ lead to *identical* upper limits :

$$\mu_{up} = \hat{\mu} + \sigma\Phi^{-1}(1 - \alpha) \quad (11.42)$$

The value given by Eq. 11.42 is also called the CL_{S+B} upper limit on the signal strength parameter μ .

11.2.5 Asymptotic approximation

11.2.5.1 Definition of Asimov dataset and basic concepts

In general, a crucial element of the statistical method involves the estimation of the median significance by replacing the simulated datasets by a single representative one, called the “**Asimov**” **dataset**. The latter is an artificial dataset where all the parameters are fixed to their expected values. This asymptotic approximation is really important because the generation of signal+background Monte Carlo pseudo-experiments under the assumption of the signal strength μ is not practical from a computational point of view due to high CPU demand; one should generate more than 10^7 pseudo-experiments to achieve a 5σ level of certainty, that corresponds to a p-value of 2.85×10^{-7} [121].

If we define the expected number of events (ν_i) in the i-th bin given a μ' signal strength value from 11.2:

$$\nu_i = \mu' s_i(\theta) + b_i(\theta) \quad (11.43)$$

We let $\theta_0 = \mu$ represent the strength parameter, so that here θ_i can stand for any of the parameters. The ML estimators for the parameters can be found by setting the first derivatives of $\ln L$ with respect to all of the parameters equal to zero. Using 11.5 this happens if the Asimov data, $n_{i,A}$ and $m_{i,A}$, are equal to their expectation values:

$$\frac{\partial \ln L}{\partial \theta_j} = \sum_{i=1}^N \left(\frac{n_i}{\nu_i} - 1 \right) \frac{\partial \nu_i}{\partial \theta_j} + \sum_{i=1}^M \left(\frac{m_i}{u_i} - 1 \right) \frac{\partial u_i}{\partial \theta_j} = 0 \quad \Rightarrow$$

$$n_{i,A} = E[n_i] = \nu_i = \mu' s_i(\theta) + b_i(\theta) \quad (11.44)$$

and

$$m_{i,A} = E[m_i] = u_i(\theta)$$

Using the Asimov dataset one can evaluate the “Asimov likelihood” L_A and the corresponding profile likelihood ratio λ_A [117]:

$$\lambda_A(\mu) = \frac{L_A(\mu, \hat{\theta})}{L_A(\hat{\mu}, \hat{\theta})} = \frac{L_A(\mu, \hat{\theta})}{L_A(\mu', \theta)} \quad (11.45)$$

where the estimators for the parameters are equal to their hypothesized values ($\hat{\mu} = \mu'$ and $\hat{\theta} = \theta$) when using an Asimov dataset.

One way of calculating the standard deviation σ , is by obtaining the inverse covariance matrix from equation 11.17 for the Asimov likelihood L_A .

Another method for estimating σ is by using equation 11.16, where setting $\hat{\mu} = \mu'$ for the Asimov dataset. Then the corresponding test-statistic $q_{\mu,A}$ becomes :

$$q_{\mu,A} = -2 \ln \lambda_A(\mu) \approx \frac{(\mu - \mu')^2}{\sigma_A^2} \quad (11.46)$$

And the the variance σ^2 which characterizes the distribution of $\hat{\mu}$ is given by :

$$\sigma_A^2 = \frac{(\mu - \mu')^2}{q_{\mu,A}} \quad (11.47)$$

For the case of discovery one tests $\mu = 0$ and the variance becomes :

$$\sigma_A^2 = \frac{\mu'^2}{q_{0,A}} \quad (11.48)$$

While in order to find the median exclusion significance for the hypothesis μ assuming that there is no signal, then one has $\mu' = 0$ and therefore :

$$\sigma_A^2 = \frac{\mu^2}{q_{\mu,A}} \quad (11.49)$$

11.2.5.2 Combination of multiple channels

In many analyses, there can be several search channels which need to be combined f.e. signal and control regions. For each channel i there is a likelihood function $L_i(\mu, \theta_i)$; the set of nuisance parameters for the i -th channel θ_i may be common between channels. If the strength parameter μ is assumed to be the same for all channels and the channels are statistically independent (as can usually be arranged) the full likelihood function is written as the product over all channels :

$$L(\mu, \boldsymbol{\theta}) = \prod_i L_i(\mu, \boldsymbol{\theta}_i) \quad (11.50)$$

The profile likelihood ratio is therefore :

$$\lambda(\mu) = \frac{\prod_i L_i(\mu, \hat{\boldsymbol{\theta}}_i)}{\prod_i L_i(\hat{\mu}, \hat{\boldsymbol{\theta}}_i)} \quad (11.51)$$

When using the Asimov data corresponding to a strength parameter μ' , since they contain no statistical fluctuations, one has $\hat{\mu} = \mu'$ for all channels. In this case, the Asimov profile likelihood can be written as the product of the corresponding profile likelihood of each channel :

$$\lambda_A(\mu) = \frac{\prod_i L_i(\mu, \hat{\boldsymbol{\theta}})}{\prod_i L_i(\mu', \boldsymbol{\theta})} = \prod_i \lambda_{A,i}(\mu) \quad (11.52)$$

11.2.5.3 Experimental Sensitivity

In general, we are not interested in the significance obtained from a single data set, but rather in the expected (median) significance in order to characterize the sensitivity of an experiment. With the latter we would be able to reject different values of μ . For example, for the case of discovery one would like to know the median significance, under the assumption of the nominal signal model ($\mu = 1$), with which one would reject the background-only ($\mu = 0$) hypothesis. And for the case of setting exclusion limits, the sensitivity is described by the median significance, assuming data generated using the $\mu = 0$ hypothesis, with which one rejects a nonzero value of μ (usually $\mu = 1$).

By using an Asimov dataset, in which all statistical fluctuations are suppressed, we obtain a direct estimate of the experimental sensitivity; median discovery or exclusion significance.

For the case of discovery using q_0 , one wants the median discovery significance assuming a strength parameter μ' and for the upper limits we are interested in the median exclusion significance assuming $\mu' = 0$. From Eq. 11.29 and 11.35 the median significance for an Asimov dataset for the two cases described above are [117] :

$$\begin{aligned} med[Z_0|\mu'] &= \sqrt{q_{0,A}} = \mu' / \sigma_A \quad , \quad \text{for discovery} \\ med[Z_\mu|0] &= \sqrt{q_{\mu,A}} = \mu / \sigma_A \quad , \quad \text{for exclusion limits} \end{aligned} \quad (11.53)$$

11.2.5.4 Error bands

By using the Asimov data set we can find the median significance (assuming a signal strength parameter μ') for rejecting a hypothesized value μ . Even if the hypothesized value μ' is correct, the actual data will contain statistical fluctuations and as a result the observed significance is not in general equal to the median. Also, it is useful to know by how much the significance is expected to vary, given the expected fluctuations in the data; thus to calculate error bands for the median significance.

A convenient method for this estimation is to calculate them as corresponding to the $\pm N\sigma$ variation of $\hat{\mu}$. As we have mentioned before, $\hat{\mu}$ is Gaussian distributed, so these error bands correspond to the variation of $\hat{\mu}$ of $\pm N\sigma$ about μ' (the + is for $N > 0$, while the – for $N < 0$) [122].

For the case of exclusion limits, when using both the statistic q_μ as well as $\tilde{q}_\mu$ we found the same expression for the upper limit at a confidence level of $1 - \alpha$, namely in Eq. 11.36, 11.42.

Therefore the median upper limit assuming a strength parameter μ' is found simply by substituting this for $\hat{\mu}$:

$$med[\mu_{up}|\mu'] = \mu' + \sigma \Phi^{-1}(1 - \alpha) \quad (11.54)$$

And the $\pm N\sigma$ error bands (also called CL_{S+B} error bands) are :

$$\begin{aligned} band_{N\sigma} &= med[\mu_{up}|\mu'] \pm N\sigma \Rightarrow \\ band_{N\sigma} &= \mu' + \sigma(\Phi^{-1}(1 - \alpha) \pm N) \end{aligned} \quad (11.55)$$

where the standard deviation σ of $\hat{\mu}$ can be obtained from the Asimov value of the test statistic q_μ using Eq. 11.47.

11.2.5.5 The CL_s Technique

In particle physics, CL_s represents a statistical method for setting upper limits (also called exclusion limits) on model parameters, a particular form of interval estimation used for parameters that can take only non-negative values. It was first introduced by physicists working at the LEP experiment at CERN and has since been used by many high energy physics experiments. It is a frequentist method in the sense that the properties of the limit are defined by means of error probabilities.

Suppose now that we define a statistical test that may be carried out for hypothesized values of μ , which may be done by computing a p-value, p_μ , for each hypothesized μ . Those values not rejected in a test of size α (for which one does not find $p_\mu < \alpha$), constitute a *confidence interval* with confidence level $1 - \alpha$.

In general for some regions in the parameter space of the signal model, the predictions from data are almost indistinguishable from those of the background-only model. This happens when μ is very small, as would occur, f.e. if one searches for a new heavy boson with a mass so high that its production rate in a given experiment is negligible. In that case when f.e. $\mu = 0$, $\alpha = 0.05$ means that 5% of experiments will end up excluding a signal of zero strength. Although the sensitivity to a model (or a point in a model's parameter space) might be very low, it should not be excluded. The CL_s method aims to mitigate the problem of excluding models to which one is not sensitive by effectively penalizing the p-value of a tested parameter by an amount that increases with decreasing sensitivity [123]. The procedure is based on a statistic called CL_s , which is defined as [121] :

$$CL_s = \frac{p_\mu}{1 - p_b} \equiv \frac{CL_{s+b}}{CL_b} \quad (11.56)$$

where p_b is the p-value of the background-only hypothesis. The CL_s upper limit from observed data is obtained by solving the equation :

$$\frac{p_{\mu,obs}}{1 - p_b} = a \quad (11.57)$$

where using Eq. 11.35 and Eq. 11.32 for $\mu' = 0$

$$CL_b = 1 - p_b = F(q_0|0) \Rightarrow$$

$$CL_b = \Phi\left(\frac{\mu}{\sigma} - \sqrt{q_{\mu,obs}}\right) \quad (11.58)$$

Using Eq 11.47 for the estimation of the variance using an Asimov dataset for the case $\mu' = 0$, we have :

$$CL_b = 1 - p_b = \Phi\left(\sqrt{q_{\mu,A}} - \sqrt{q_{\mu,obs}}\right) \quad (11.59)$$

Also

$$p_{\mu,obs} = 1 - F(q_{\mu,obs}|\mu) = 1 - \Phi(\sqrt{q_{\mu,obs}}) \quad (11.60)$$

Finally, we calculate the upper limit on the observed value $\mu_{up,obs}$ by solving Eq. 11.57, after substituting Eq. 11.59 and Eq. 11.60 :

$$\frac{1 - \Phi(\sqrt{q_{\mu,obs}})}{\Phi(\sqrt{q_{\mu,A}} - \sqrt{q_{\mu,obs}})} = \alpha \quad (11.61)$$

with $\sqrt{q_{\mu,obs}} = (\mu_{up,obs} - \hat{\mu})/\sigma$ and $\sqrt{q_{\mu,A}} = \mu_{up,obs}/\sigma$.

Similarly, the median or expected CL_S upper limit is obtained by solving :

$$\frac{p_{\mu,exp}}{1 - p_b} = a \quad (11.62)$$

Here $1 - p_b = 1/2$ and $p_{\mu,exp} = 1 - \Phi(\sqrt{q_{\mu,A}}) = 1 - \Phi(\mu_{up,exp}/\sigma)$. So the expected upper limit on the value of μ is :

$$\mu_{up,exp} = \sigma \Phi^{-1}(1 - 0.5\alpha) \quad (11.63)$$

and the $N\sigma$ CL_S (N : positive or negative) error bands as defined as :

$$band_{N\sigma} = \sigma(\Phi^{-1}(1 - \alpha\Phi(N)) + N) \quad (11.64)$$

since

$$CL_b = \Phi(\sqrt{q_{\mu,A}} - \sqrt{q_{\mu,obs}}) = \left(\frac{\mu}{\sigma} - \frac{\mu - \hat{\mu}}{\sigma}\right) = \Phi(N) \quad (11.65)$$

for $\hat{\mu} = N\sigma$.

Usually $\alpha = 0.05$ so we have the 95% CL bands.

Chapter 12

Statistical Framework & Methods for $X \rightarrow WZ \rightarrow l\nu ll$

In our analysis we implement the *ResonanceFinder* package [124]; this is based on the *HistFactory* tool [125], that was developed to build parametrized probability density functions (pdf) in the RooFit/ RooStats framework [126]. In order to further explain the statistical procedure followed by our analysis, let us now introduce a slightly different notation for the likelihood determination that was done in Chapter 11.

12.1 The Likelihood template

First of all, we consider the simple case where we have a single channel (which is a region of the data defined by a specific event selection) with one signal and one background contribution; for simplicity we will neglect now the effect of the systematics and we will denote the discriminating variable as x . We denote as S/B and $f_S(x)/f_B(x)$ the number of signal/background events and their corresponding pdfs that describe their “shape”. We also introduce the “signal strength” parameter μ which is otherwise called our “parameter of interest” (POI); $\mu = 0$ corresponds to the background-only hypothesis while $\mu = 1$ corresponds to the signal+background hypothesis.

We assume that we obtain n events in data where the discriminating variable for the event e has a value of x_e , thus the full dataset is denoted as $x_1, \dots, x_n$. If we include the Poisson probability of obtaining n events for $\mu S + B$ expected events and the probability density of obtaining x_e based on the relative mixture $f_S(x)$ and $f_B(x)$ for a given value of μ , we end up with a probability model known as “marked Poisson model” that is described by the binned

likelihood [125]:

$$L(x_1, \dots, x_n | \mu) = \text{Pois}(n | \mu S + B) \left[\prod_{e \in n} \frac{\mu S f_S(x_e) + B f_B(x_e)}{\mu S + B} \right] \quad (12.1)$$

In order to perform a binned analysis using histograms, we use the binned equivalent of the probability model above, and denote $\nu_b^{sig/bkg}$ as the expected number of events for signal/background in bin with index b . The latter is related to the shape functions $f_{S/B}(x)$ as:

$$f_S(x_e) = \frac{\nu_{be}^{sig}}{S \Delta_{be}} \quad \text{and} \quad f_B(x_e) = \frac{\nu_{be}^{bkg}}{B \Delta_{be}} \quad (12.2)$$

where b_e is the index of the bin containing x_e and Δ_{be} is the bin width. If we express the probability model in terms of individual bins, we have :

$$\begin{aligned} L(n_b | \mu) &= \text{Pois}(n_{tot} | \mu S + B) \left[\prod_{b \in bins} \frac{\mu \nu_b^{sig} + \nu_b^{bkg}}{\mu S + B} \right] \\ &= N_{comb} \prod_{b \in bins} \text{Pois}(n_b | \mu \nu_b^{sig} + \nu_b^{bkg}) \Rightarrow \\ L(n_b | \mu) &= \prod_{b=1}^N \frac{(\mu \nu_b^{sig} + \nu_b^{bkg})^{n_b}}{n_b!} e^{-(\mu \nu_b^{sig} + \nu_b^{bkg})} \end{aligned} \quad (12.3)$$

where :

n_b : the total number of observed events in data for each bin b , of N total number of bins that exist for each histogram

N_{comb} : combinatorial factor that can be neglected since is constant

$S = \sum_{b \in bins} \nu_b^{sig}$, $B = \sum_{b \in bins} \nu_b^{bkg}$: the total number of signal and background events in histogram.

12.2 Constraint terms and Interpolation

In order to incorporate the systematic and statistical uncertainties, the shape and normalization variations and also the ability to use multiple signal and background samples, the binned likelihood function needs to be modified. In that direction we will use the following notations [125]

e : stands for events,

b : for histogram bins,

c : for channel (a region of data defined by corresponding event selection i.e. our analysis signal and control regions),

s : for sample (a set of scattering processes that can be added together incoherently since they interfere quantum mechanically),

n_{cb} : for the observed number of events in each bin for each channel,

ν_{cb} : for the expected number of events in a given bin/channel, where $\nu_{cb} = \nu_{bc}^{bkg}(\theta) + \mu\nu_{bc}^{sig}(\theta)$,

λ : for the nuisance parameter related to luminosity (within a given channel this is a common luminosity parameter for all the samples that include luminosity uncertainty),

θ : for the nuisance parameters used in the model, with $\mathbf{N} = \{\phi_\theta\}$ being the unconstrained normalization factors (including the parameter of interest μ and in our analysis), $\mathbf{S} = \{\alpha_\theta\}$ the systematic uncertainties that have external constraints and $\mathbf{\Gamma} = \{\gamma_{cb}\}$ the bin-by-bin uncertainties with constraints (statistical errors, shape systematics and data driven shape extrapolations).

The modified likelihood is in the form:

$$L(n_{cb}|\mu, \theta) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}} Pois(n_{cb}|\nu_{cb}(\gamma_{cb}, \lambda, \alpha_\theta, \phi_\theta)) \cdot Constraints(\lambda, \gamma, \alpha) \quad [\theta = \lambda \cup \{\alpha_\theta\} \cup \{\gamma\} \cup \{\phi_\theta\}] \quad (12.4)$$

First of all, in Eq. 12.4 the constraint factor analyzes in the following terms :

$$Constraints(\lambda, \gamma, \alpha) = Constraint_\gamma(\gamma) \cdot Constraint_\lambda(\lambda) \cdot Constraint_\alpha(\alpha) \quad (12.5)$$

• The term

$$Constraint_\gamma(\gamma) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}} Pois(m_{cb}|\gamma_{cb} \cdot \tau_{cb}) \quad (12.6)$$

is a Poisson constraint term, where we treat the Monte Carlo as an auxiliary measurement : if we generated a new Monte Carlo sample, m_{cb} would fluctuate about $\gamma_{cb} \cdot \tau_{cb}$, where τ_{cb} is the “true” event rate $\tau_{cb} = (\nu_{cb}^{MC}/\delta_{cb})^2$ (δ the bin width or total MC statistical uncertainty, ν^{MC} the total number of Monte Carlo events in bin) and γ_{cb} is the nuisance parameter reflecting that the true rate may differ from the MC estimate ν_{cb}^{MC} by some amount. Since we have scaled γ ($\gamma_{cb} = \frac{m_{cb}}{\tau_{cb}}$) to be around 1 (since we assume to have large enough MC samples-that is not valid for MC toy generation), $m_{cb} = \tau_{cb} = (\nu_{cb}^{MC}/\delta_{cb})^2$ accounts for the relative MC statistical uncertainty.

• The term

$$Constraint_\lambda(\lambda) = Gauss(1|\lambda, \Delta\lambda) \quad (12.7)$$

is the luminosity constraint factor that is described by a Gaussian distribution with

$\lambda = L^{fitted}/L^{nominal}$ and $\Delta\lambda$ being the relative luminosity uncertainty (for our analysis set as 0.0001).

- And the term

$$Constraint_{\alpha}(\alpha) = \prod_{\alpha_{\theta} \in \mathbf{S} + \mathbf{\Gamma}} Gauss(0|\alpha_{\theta}, 1) \quad (12.8)$$

stands for the Gaussian constrain of the nuisance parameters α_{θ} (θ runs over the full set of systematic uncertainties). The constrain term acts as an idealized version of the auxiliary measurement, where the observed value should be zero, while the expected will have a mean value equal to the calculated nominal systematic value and a standard deviation equal to one ($\sigma = 1$) [127, 128].

Furthermore, in Eq. 12.4 for the expected number of events ν_{cb} that includes the effect of the systematic uncertainties, one has to apply an interpolation algorithm to quantify the effect of these “ $\pm 1\sigma$ ” variations about the nominal predictions.

First of all, in order to parametrize the variation in the *normalization* of any sample due to some systematic effect for a given channel c , we introduce the uncertainty $\eta_s(c)$ with $\eta_s^0 = 1$ representing the nominal and $\eta_{s\alpha_{\theta}}^{\pm}$ up/down (1σ) variations, respectively. Then, in order to parametrize the variation in the *normalization & shape* of any sample due to the influence of a systematic source, we introduce the binned uncertainty $\sigma_{sb}(c)$ with $\sigma_{sb}^0 = 1$ representing the nominal and $\sigma_{sb\alpha_{\theta}}^{\pm}$ up/down (1σ) variations, respectively.

Given the above, the expected number of events in each bin (b) in Eq. 12.4 can be written as :

$$\nu_{cb}(\gamma_{cb}, \lambda, \alpha_{\theta}, \phi_{\theta}) = \lambda \cdot \gamma_{cb} \cdot \phi_{cs}(c) \cdot \eta_{cs}(c) \cdot \sigma_{csb}(c) \quad (12.9)$$

where $\phi_{cs}(c) = \prod_{\theta \in \mathbf{N}} \phi_{\theta}$ and $\eta_{cs}(c) / \sigma_{csb}(c)$ the parametrized normalization/shape uncertainties for a given channel c . From the above it is clear that the effect of the systematic α_{θ} gets splitted into the normalization and shape part.

- For the normalization uncertainty $\eta_{cs}(c)$, HistFactory performs a piecewise exponential interpolation method. The normalization uncertainties then become :

$$\eta_{cs}(c) = \prod_{\alpha_{\theta} \in \mathbf{S} + \mathbf{\Gamma}} I_{exp}(\alpha_{\theta}; 1, \eta_{s\alpha_{\theta}}^+, \eta_{s\alpha_{\theta}}^-) \quad (12.10)$$

where

$$I_{exp} = \begin{cases} \left(\frac{\nu_{tot}^{up,\theta}}{\nu_{tot}^{nom,\theta}} \right)^{\alpha_\theta}, & \alpha_\theta \geq 0 \\ \left(\frac{\nu_{tot}^{down,\theta}}{\nu_{tot}^{nom,\theta}} \right)^{\alpha_\theta}, & \alpha_\theta < 0 \end{cases} \quad (12.11)$$

if we denote the total integral in the nominal variation as :

$$\nu_{tot}^{nom,\theta} = \sum_s \sum_c \sum_b \nu_b^{s,nom} \text{ (where } b \in \text{bins in a channel } c \text{ affected by systematic } \alpha_\theta \text{)}$$

and the corresponding total integral of up and down variation of systematic α_θ are :

$$\nu_{tot}^{\{up/down\},\theta} = \sum_s \sum_c \sum_b \nu_b^{s,\{up/down\},\theta}$$

- For the shape uncertainty $\sigma_{csb}(c)$, HistFactory performs a piecewise linear interpolation method. Then the shape uncertainties become :

$$\sigma_{csb}(c) = \sum_s \left(\sigma_{sb}^0 + \sum_{\alpha_\theta \in \mathbf{S} + \mathbf{\Gamma}} I_{lin}(\alpha_\theta; \sigma_{sb}^0, \sigma_{sb\alpha_\theta}^+, \sigma_{sb\alpha_\theta}^-) \right) \quad (12.12)$$

where the $\sigma_{sb}^0 \equiv \nu_b^{s,nom}$ stands for the expected yield if there are no variations from the nominal and

$$I_{lin} = \begin{cases} \alpha_\theta \cdot \left(\nu_b^{s,up_\theta,shape} - \nu_b^{s,nom} \right), & \alpha_\theta \geq 0 \\ \alpha_\theta \cdot \left(\nu_b^{s,nom} - \nu_b^{s,down_\theta,shape} \right), & \alpha_\theta < 0 \end{cases} \quad (12.13)$$

If we take into account that for each bin and sample which is affected by systematic α_θ there is an up fluctuation ν_b^{s,up_θ} and a down fluctuation $\nu_b^{s,down_\theta}$ in the yield, then the $\nu_b^{s,up_\theta,shape} / \nu_b^{s,down_\theta,shape}$ are the shape-only variations of α_θ in the b -th bin of channel c for sample s :

$$\begin{aligned} \nu_b^{s,up_\theta,shape} &= \nu_b^{s,up_\theta} \cdot \frac{\nu_{tot}^{nom,\theta}}{\nu_{tot}^{up,\theta}} \\ \nu_b^{s,down_\theta,shape} &= \nu_b^{s,down_\theta} \cdot \frac{\nu_{tot}^{nom,\theta}}{\nu_{tot}^{down,\theta}} \end{aligned} \quad (12.14)$$

To sum up, in order to insert the systematic effects as continuous nuisance parameters in the final likelihood, one must provide an interpolation algorithm in order to describe the up and down variations as well as incorporate constraint terms on the α_θ to account for the fact that the uncertainty parameter has been estimated with some uncertainty provided by an auxiliary measurement.

12.3 Estimated significance

As we can see from Eq. 12.4 and 12.6, our likelihood model is described as a product of Poisson distributions that incorporate the systematic uncertainties to the nominal distribution and also apply a constraint term on the Monte Carlo uncertainty (MC treated as an auxiliary measurement). This is the so called “Poisson-Poisson ”model.

If we consider $\mu = 1$ and focus now on a single bin b of a specific channel c and also neglect the nuisance parameter constraining terms, the full likelihood function that describes both the primary observed measurement n and the control measurement m is written in the simplified form of the product of the two corresponding Poisson distributions following 11.5 [129]:

$$L(s, b) = \frac{(s+b)^n}{n!} e^{-(s+b)} \frac{(\gamma b)^m}{m!} e^{-\gamma b} \quad (12.15)$$

In the above equation s is the expected number of signal events, b is the expected number of background events that are measured with some uncertainty, m is the expected number of background events in a data sample where signal events are believed to be absent and γ is a transfer factor relating m and b , where $\gamma = b/\sigma^2$. To find the profile likelihood ratio one needs the estimators for b and s as well as the conditional estimator for b given a value of s , which are calculated as [122] :

$$\begin{aligned} \hat{s} &= n - m/\gamma, \\ \hat{b} &= m/\gamma, \\ \hat{\hat{b}}(s) &= \frac{n + m - (1 + \gamma)s + \sqrt{(n + m - (1 + \gamma)s)^2 + 4(1 + \gamma)sm}}{2(1 + \gamma)} \end{aligned} \quad (12.16)$$

For the background only hypothesis the significance becomes :

$$Z = \sqrt{q_0} = \begin{cases} \sqrt{-2\ln\lambda(0)}, & \hat{s} \geq 0 \quad (n \geq \hat{b}) \\ 0, & \hat{s} < 0 \quad (n < \hat{b}) \end{cases} \quad (12.17)$$

If we replace in Eq. 12.17 the data values n and m by their expectation values $s + b$ and γb to give the “Asimov ”approximation for the median significance and also including the variance of $\hat{b}$ to be $\sigma^2 = b/\gamma$ we end up with the term :

$$Z_A = \sqrt{2 \left((s+b) \ln \left[\frac{(s+b)(b+\sigma^2)}{b^2 + (s+b)\sigma^2} \right] - \frac{b^2}{\sigma^2} \ln \left[1 + \frac{\sigma^2 s}{b(b+\sigma^2)} \right] \right)} \quad (12.18)$$

12.4 Pull distributions and impact parameters

In general the *pull* quantifies how far from its expected value we had to “pull” the parameter while finding the Maximum Likelihood Estimator (MLE) for it. A *healthy* fit is when the pull average is zero with a standard deviation close to 1; if this is not the case, further investigation is required. The expected value of a nuisance parameter and its assumed standard deviation will be based on an auxiliary measurement or MC studies.

If we have a random variable x that is generated with a Gaussian distribution of mean μ and width σ , then the pull [130] :

$$g = \frac{x - \mu}{\sigma} \quad (12.19)$$

will be distributed as a standard Gaussian with mean 0 and unit width. For hypothesis testing and parameter estimation, pulls provide evidence for possible existence of biases and allow the verification of the error coverage. So we calculate the pulls for the systematics (θ) of our analysis :

$$pull = \frac{\hat{\theta} - \theta_0}{\Delta\theta_0} \quad (12.20)$$

where $\hat{\theta}$ is the maximum likelihood estimated value of the systematic uncertainty, θ_0 is the nominal systematic value and $\Delta\theta_0$ is the width of the nominal systematic. The corresponding error of the pull is given by :

$$pull_{err} = \frac{\Delta\hat{\theta}}{\Delta\theta_0} \quad (12.21)$$

where $\Delta\hat{\theta}$ is the MLE error.

The *impact* of a nuisance parameter θ f.e. for the case of the μ parameter estimation is defined as [131]:

$$impact(\theta) = \Delta\mu^\pm = \hat{\mu}_{\theta_0 \pm \Delta\theta_0} - \hat{\mu} \quad (12.22)$$

where $\hat{\mu}_{\theta_0 \pm \Delta\theta_0}$ is the conditional maximum likelihood estimate of the signal strength parameter, when we profile every parameter except θ , and set the value of θ to its expectation value plus or minus one standard deviation and $\hat{\mu}$ is the initially calculated MLE of μ . The impact gives a measure of how much our parameter of interest varies as we change the nuisance parameter. This is especially helpful for simplifying the fitting procedure, because a nuisance parameter with low impact may be possibly discarded (or “pruned”).

12.5 Statistical Treatment of $X \rightarrow WZ \rightarrow l\nu ll$

12.5.1 Inputs to the fit

The strategy for the statistical analysis is using a combined profile likelihood fit to binned discriminant distributions in all categories simultaneously. A binned maximum-likelihood fit is performed using the reconstructed WZ invariant mass spectrum (m_{WZ}), the invariant mass of the three leptons (m_{3lep}), the transverse mass of the WZ system (m_T^{WZ}), the transverse momentum of the three leptons (pT_{3lep}), the numerical sum of the transverse momenta of the three leptons ($Sum3Pt$) and the two dimensional phase space defined by the invariant mass of the two jets (m_{jj}) and m_T^{WZ} .

Histogram templates of the signal and backgrounds are fitted using the standard package *RooStats* called within the *ResonanceFinder* package. All the decay channels (electron and muon) are merged together in a single distribution and additionally to the signal region, the control regions for the WZ QCD and the ZZ backgrounds are included. The fit is performed for the Drell-Yan ($q\bar{q}F$) and VBF signal regions for $qqHVT$, $vbfHVT$ and $vbfGM$ signals.

The inputs to the fit, for each of the signal regions, are the following:

1. The corresponding distribution in the signal region to fit (m_{WZ} , m_{3lep} , pT_{3lep} , m_T^{WZ} , $Sum3Pt$, m_{jj} and m_T^{WZ}).
2. The corresponding distribution in the respective $W^\pm Z$ and ZZ control regions (each SR has their respective $W^\pm Z$ and ZZ CRs). For the Drell-Yan category, the ZZ CR is defined by requiring an extra baseline(pass OLR) lepton and removing the E_T^{miss} cut, as already mentioned in Section 7.2.2.1. For the vbf category, we define the $ZZjj$ CR as the ZZ CR but also requiring the existence of two vbf jets 7.2.2.2. These control regions are build to be orthogonal to the signal regions and are used to constrain the main background contributions in SRs using data.
3. The corresponding distributions of the fake-lepton events in each region is obtained with the data-driven method and the other backgrounds $t\bar{t} + V$ and VVV are taken from MC simulations.

The numbers of observed and predicted events in each of these regions are described using Poisson probability density functions. There are two extra free parameters considered per signal region in the fit : one normalisation scale for the $W^\pm Z$ and one for the ZZ background; the other backgrounds from $t\bar{t} + V$ and VVV are allowed to vary in the fit within their respective uncertainties.

The experimental systematic uncertainties (Chapter A) and the MC statistical uncertainties on the expected values are included in the fit as nuisance parameters. They are constrained by a

Gaussian function and a Poissonian function, respectively as discussed in 12.2; correlations between these parameters are also taken into account.

In addition to the experimental uncertainties, the theory uncertainties are calculated directly from MC following PMG recommendations, see Section 10. Only the shape component of the theory uncertainty is considered for backgrounds that have free floating normalization. Also, pdf and scale uncertainties are not correlated among processes or control regions. Finally, the fake background is allowed to vary within the uncertainties estimated by the Matrix Method and the systematic uncertainties that induce changes of less than 1% in the nominal yields are removed by pruning. Table 10.1 summarizes how the theory uncertainties enter the fit.

The product of the various pdfs forms the likelihood function; the fit maximises it by adjusting the input parameters and the nuisance parameters described above.

Here we have to mention that the fit may introduce a negative correlation between the three normalisation scales and as a result the relative uncertainty on the individual contributions may increase. As a result, the sum of the total background relative uncertainty may then be smaller than the sum in quadrature of the individual components.

12.5.2 Binning optimization

While performing a statistical analysis, a stable fit template is important to allow for a reasonable uncertainty estimate and to mitigate the risk of strong fluctuations in the background template; in that case we could have numerical problems in the maximum likelihood estimation. To deal with the above, the analysis team has introduced a binning optimization algorithm in order to study the sensitivity of our fit to the different binning options.

First of all, we have started with a distribution of the different variables that had a bin width of 10 GeV and use this as an input to the binning optimization algorithm. The algorithm we have used takes the input histogram and merges the adjacent bin until the satisfaction of the conditions described below :

- For the asymptotic approximation to work properly, a minimum number of background events per bin (10 events) is required.
- In order to avoid bins with large MC uncertainties, the maximum relative background MC uncertainty to be 0.3 .

Applying the algorithm described above, the optimum binning that has been used for each of the distribution used in the fit is as it follows :

Variable	Binning
m_{WZ}	vbfHVT=[0,150,200,250,300,350,400,460,520,650,5000] vbfGM=[0,150,200,230,270,310,350,390,480,660,5000] Drell-Yan=[0,150,200,250,300,350,400,450,500,550,600,650,700,750,800,850,900,950,1010,1080,1160,1280,1480,5000]
m_T^{WZ}	vbf=[0, 120, 150, 170, 190, 210, 230, 250, 270, 290, 320, 350, 390, 440, 510, 640, 3000] Drell-Yan=[0, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 510, 540, 570, 610, 660, 720, 810, 1010, 3000]
$m_{jj} \text{ \& } m_T^{WZ}$	[500,1500] , medium m_T^{WZ} =[0, 130, 150, 170, 190, 210, 230, 250, 270, 300, 330, 370, 420, 490, 640,3000] [1500, ∞] , high m_T^{WZ} =[0, 160, 200, 240, 300, 400, 3000]
m_{3lep}	vbf=[0, 110, 130, 150, 170, 190, 210, 230, 250, 270, 300, 330, 370, 410, 470, 560, 790, 3000] Drell-Yan=[0, 110, 130, 150, 170, 190, 210, 230, 250, 270, 290, 310, 330, 350, 370, 390, 420,450, 490, 540, 610, 730, 3000]
pT_{3lep}	vbf=[0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 230, 260, 300, 360, 480, 3000] Drell-Yan=[0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 330, 360, 400, 450, 530, 740, 3000]
$Sum3Pt$	vbf=[0, 120, 140, 160, 180, 200, 220, 240, 260, 280, 310, 340, 380, 430, 500, 660, 3000] Drell-Yan=[0, 130, 150, 170, 190, 210, 230, 250, 270, 290, 310, 330, 350, 370, 390, 410, 440, 470, 500, 540, 590, 660, 800,3000]

TABLE 12.1: Summary of the binning used for each variable for the Drell-Yan and VBF regions

To avoid a possible double counting for the two-dimensional fit, we create two separate m_{jj} regions (denoted as *medium* and *high*) that each of them is fitted simultaneously with its corresponding m_T^{WZ} distribution, so that is the reason of having two different binnings in the above Table.

12.6 Limits and μ_{WZ}^{QCD} , μ_{ZZ} estimation

In order to extract the normalization scaling factors for WZ-QCD and ZZ backgrounds, the postfit yields and distributions, we perform a simultaneous fit with the signal and corresponding control regions with data for the background-only hypothesis ($\mu = 0$).

Constraints on the production of heavy resonances are derived by repeating the profile likelihood fit for the signal-plus-background hypothesis for different signal models, by fitting simultaneously the signal and their corresponding control regions. For all different variables, no significant deviations from the Standard Model predictions have been observed and thus upper limits on the production cross-section times branching ratio are obtained as a function of the resonant mass, for Heavy Vector Triplet (HVT) and Georgi-Machechek (GM) models.

Limits, pull, correlation and ranking plots as well as post-fit yields and plots are obtained for each of the variables of interest, using qqF HVT, vbfHVT and vbfGM signals are given in Sections 12.6.1, 12.6.2, 12.6.3, 12.6.4, 12.6.5, 12.6.6. The postfit distributions include the total postfit uncertainty (statistical + systematic).

12.6.1 m_{WZ}

12.6.1.1 Drell-Yan

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in Drell-Yan-enriched category, using the m_{WZ} distribution as input to the fit. Masses below 2400 GeV can be excluded for Model A and 2500 GeV for Model B.

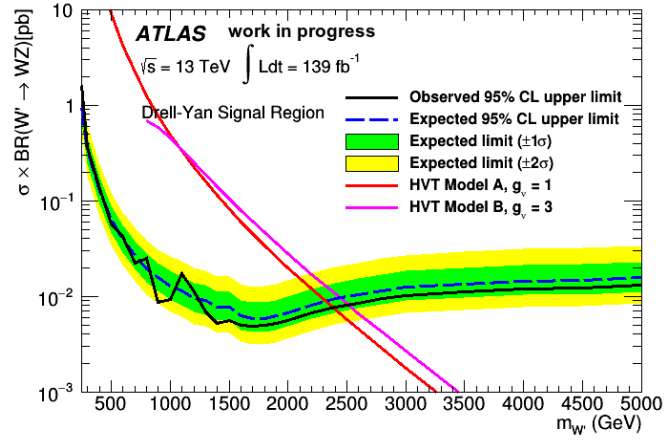


FIGURE 12.1: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in Drell-Yan-enriched category using the m_{WZ} distribution as input to the fit. Masses below 2400 GeV can be excluded for Model A and 2500 GeV for Model B.

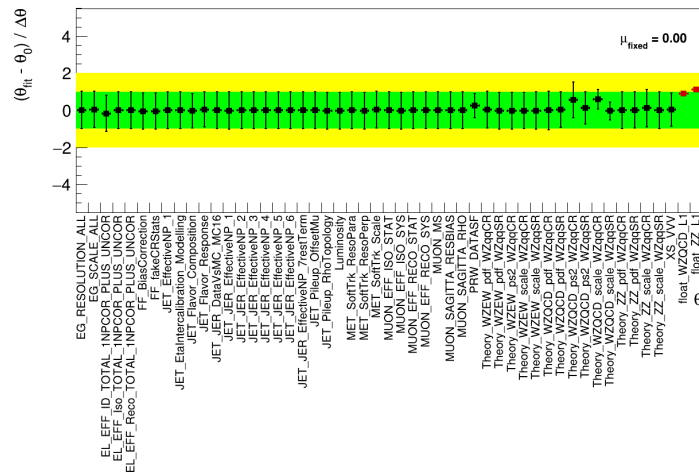


FIGURE 12.2: Nuisance parameter pulls for the SR+CR fit in the Drell-Yan category for 500 GeV mass point using the m_{WZ} distribution as input to the fit.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The cross-section of $VVV + t\bar{t}V$, the parton shower, pdf and scale uncertainty for WZQCD, some jet and fake systematics and μ_{WZ}^{QCD} have the highest impact on the calculation of the signal-strength parameter μ .

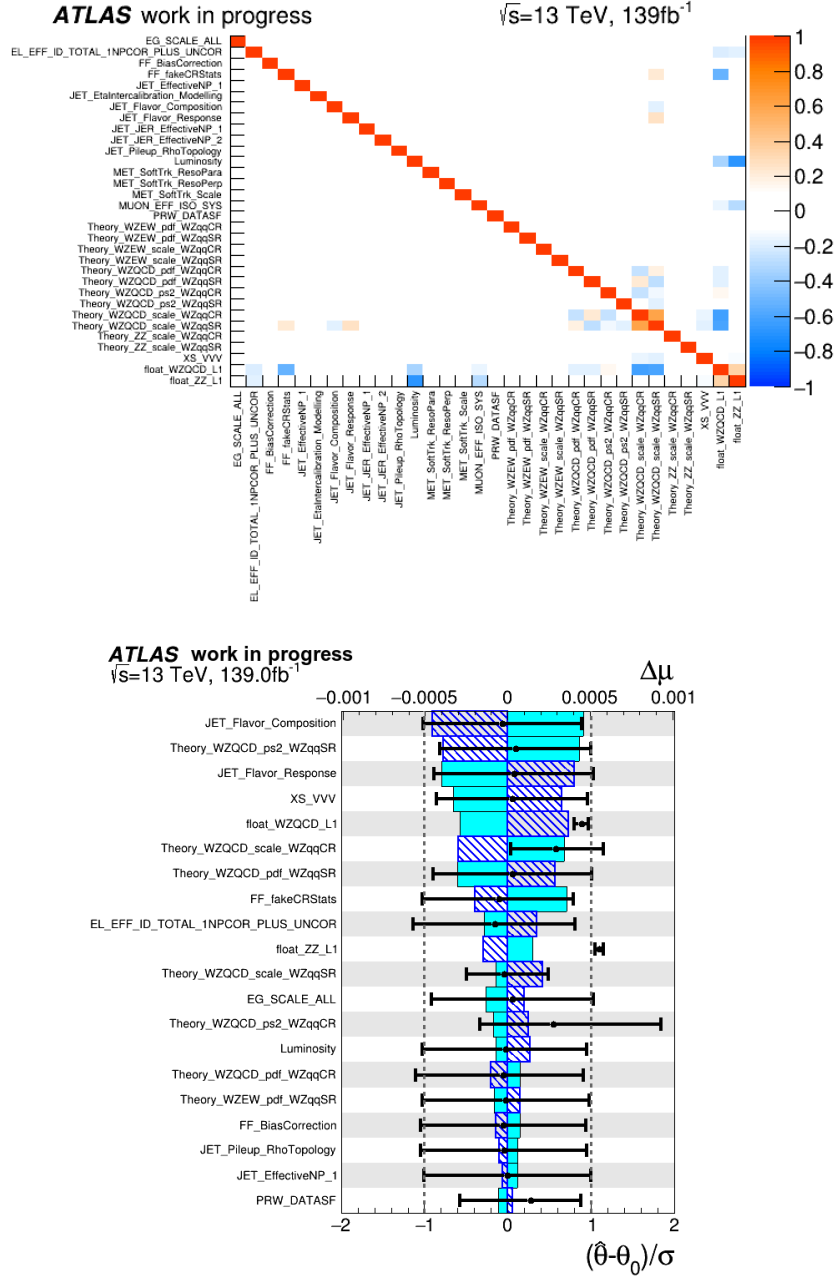


FIGURE 12.3: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized HVT signal production of mass 500 GeV in the Drell-Yan category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_{WZ} distribution used as input to the fit.

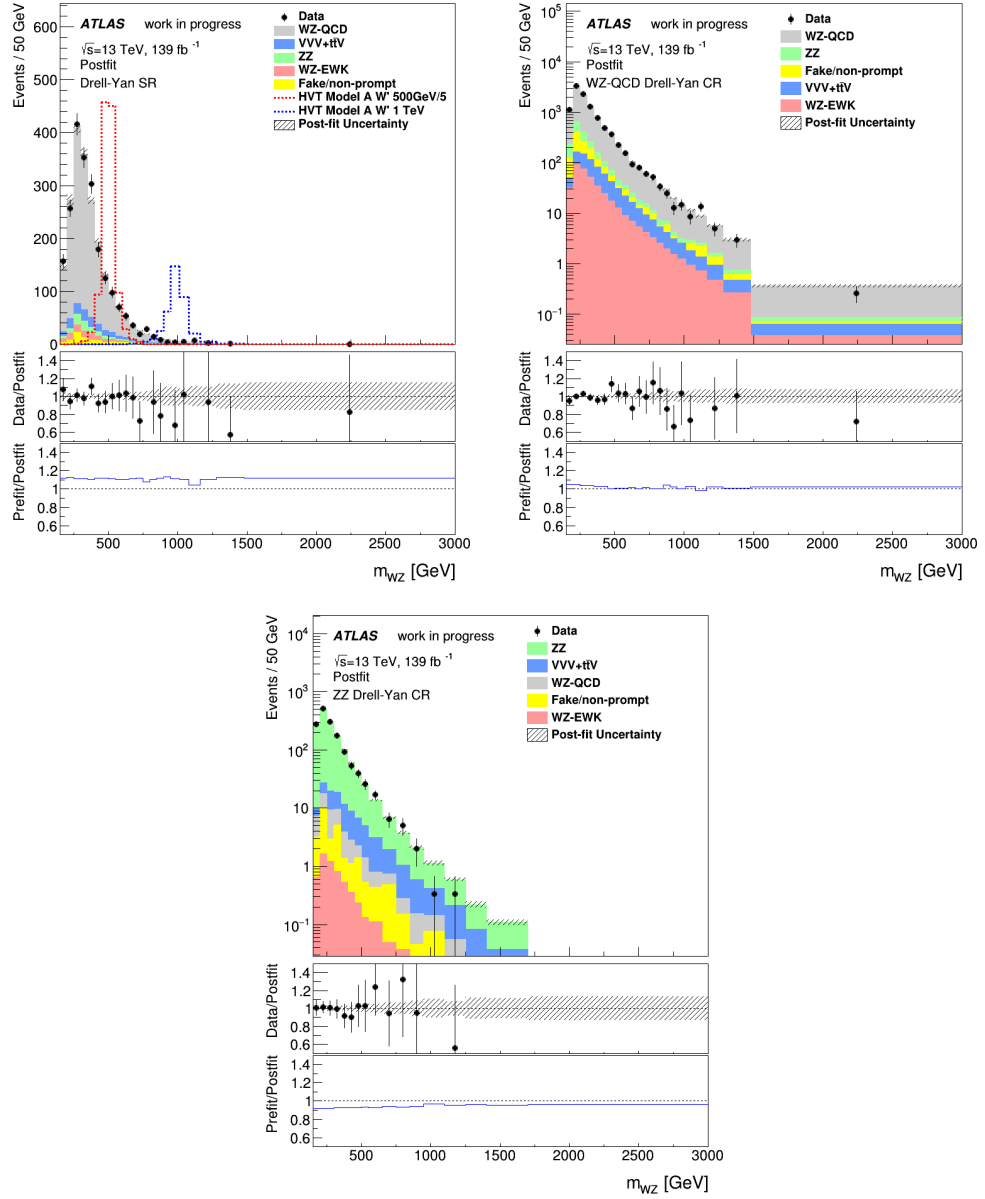


FIGURE 12.4: The postfit invariant mass distributions of the Drell-Yan SR +CR and ZZ CR are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.884 ± 0.084
μ_{ZZ}	1.102 ± 0.053

TABLE 12.2: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous Drell-Yan $W^\pm Z$ SR/CR and ZZ CR fit with data, using the m_{WZ} distribution as input to the fit for the 500 GeV mass point.

	Drell-Yan SR
WZEW	89.35 ± 9.77
WZQCD	1734.81 ± 77.09
ZZ	95.27 ± 5.2
Fakes	88.28 ± 49.3
VVV+ $t\bar{t}V$	146.94 ± 27.17
Total Expected Background	2154.66 ± 71.39
Observed	2155

TABLE 12.3: Expected and observed postfit yields in the Drell-Yan signal region, using the m_{WZ} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the Drell-Yan SR, WZ-QCD and ZZ Drell Yan CRs. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.1.2 vbfHVT

We have estimated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category, for vbfHVT signals using the m_{WZ} distribution as input to the fit. Masses below 370 GeV can be excluded for model with $g_V c_H = 1$ and 480 GeV can be excluded for model with $g_V c_H = 1.5$.

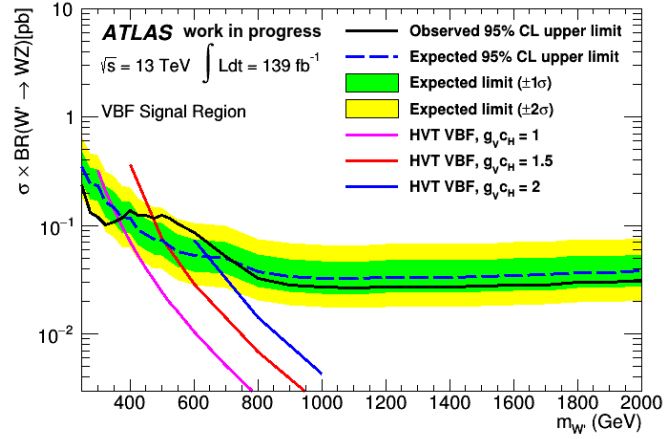


FIGURE 12.5: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for vbfHVT signals using the m_{WZ} distribution as input to the fit.

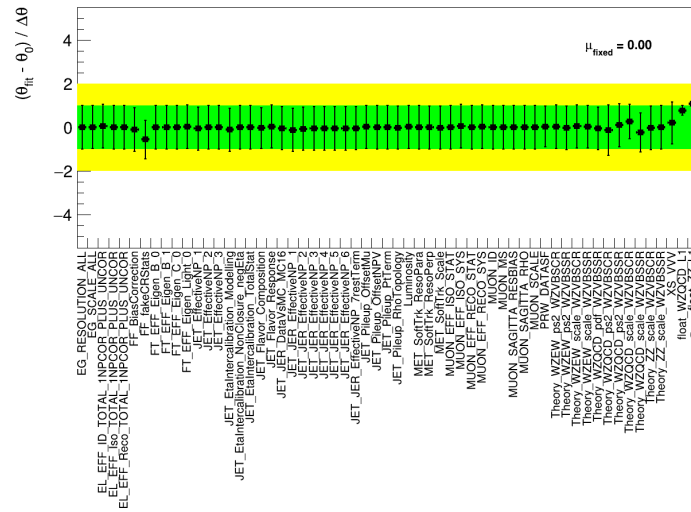


FIGURE 12.6: Nuisance parameter pulls for the SR+CR fit in the vbf category for 500 GeV vbfHVT mass point using the m_{WZ} distribution as input to the fit.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The μ_{ZZ} , cross-section of $VVV + t\bar{t}V$, some jet systematics, the WZ-EWK

scale uncertainty and the WZ-QCD parton shower and scale uncertainties have the highest impact on the calculation of the signal-strength parameter μ .

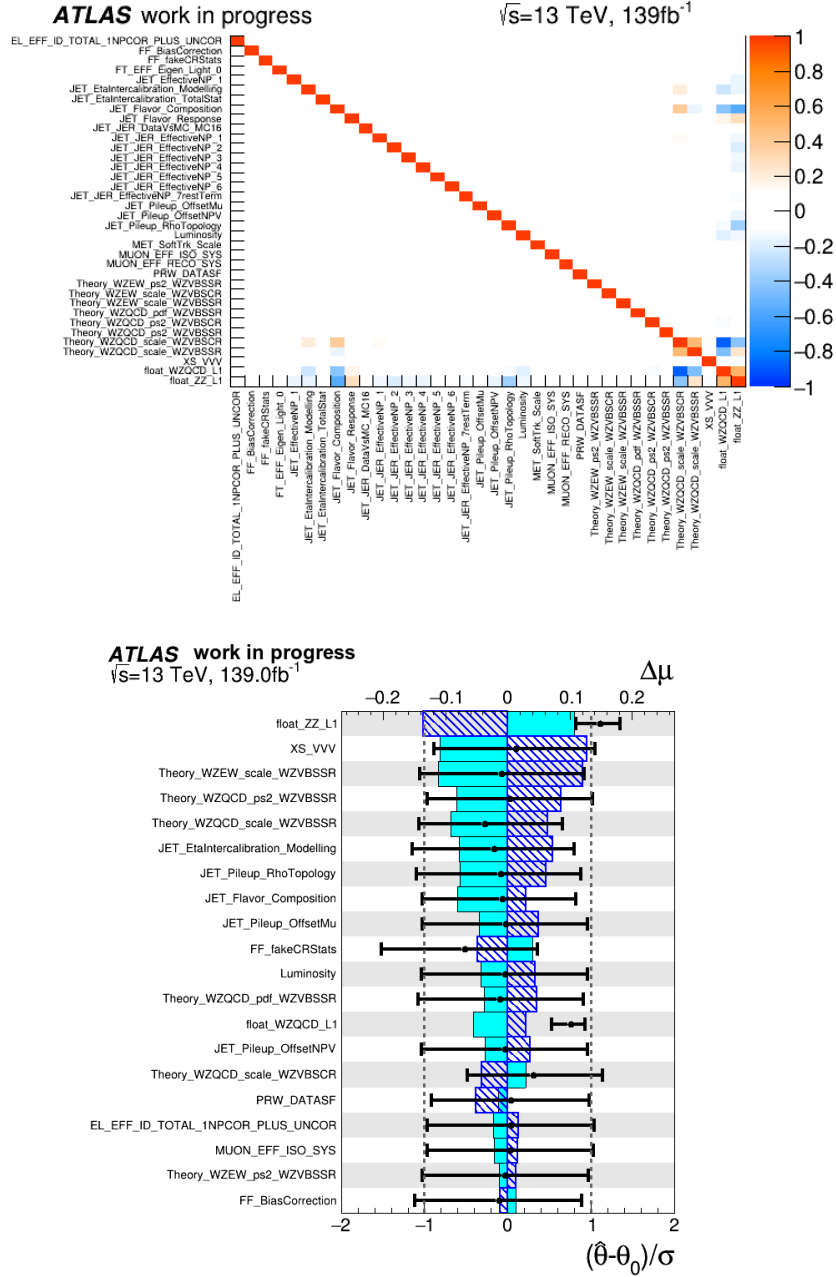


FIGURE 12.7: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized HVT signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_{WZ} distribution used as input to the fit.

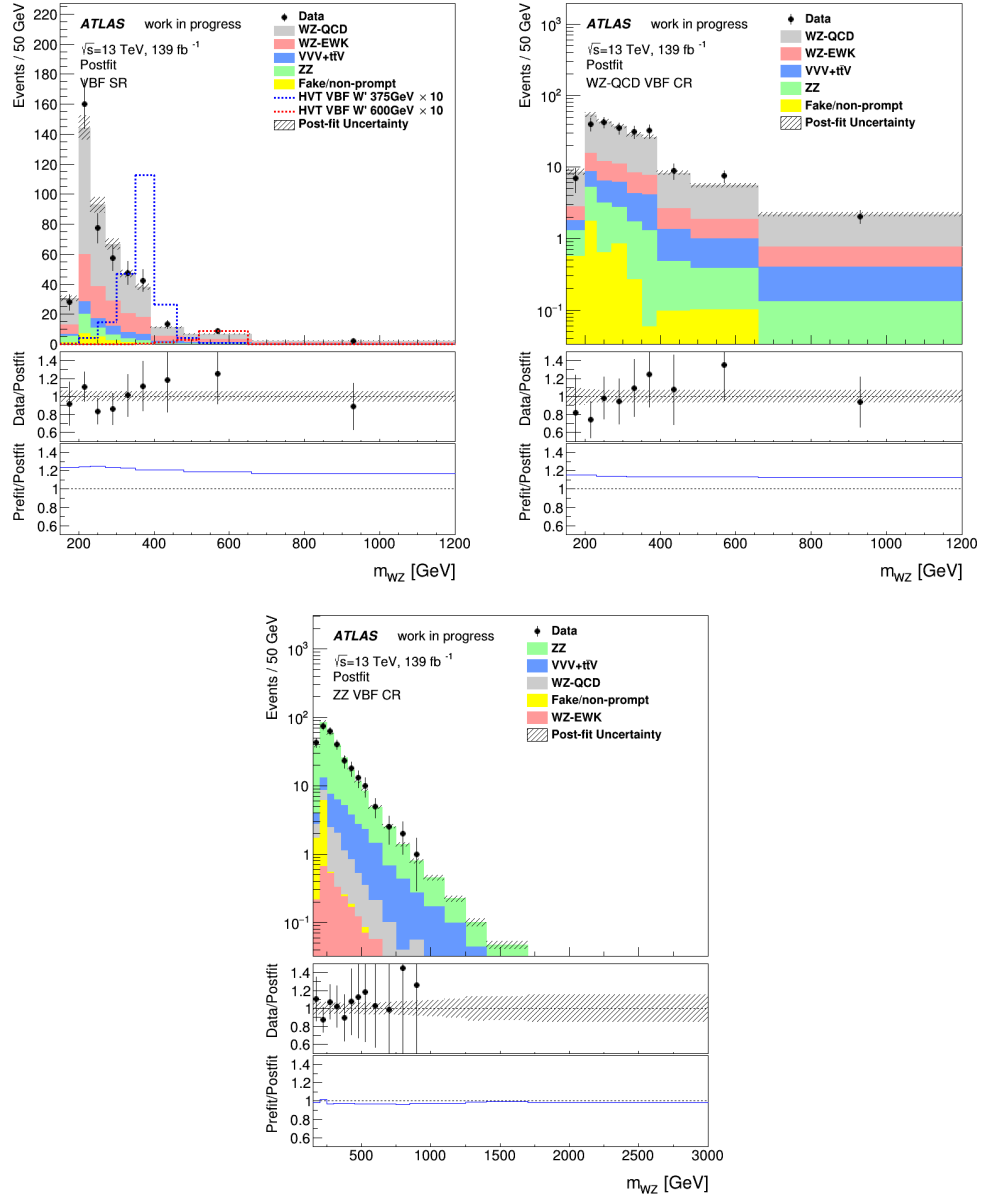


FIGURE 12.8: The postfit invariant mass distributions of the vbf SR + CR and ZZjj CR are shown for vbfHVT signals fit. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Pre-fit/Postfit ratio.

μ_{WZ}^{QCD}	0.774 ± 0.217
μ_{ZZ}	1.079 ± 0.267

TABLE 12.4: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for vbfHVT signals, using the m_{WZ} distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	100.46 ± 10.58
WZQCD	210.5 ± 24.23
ZZ	26.35 ± 4.41
Fakes	13.84 ± 4.56
VVV+ $t\bar{t}V$	31.13 ± 6.62
Total Expected Background	382.27 ± 22.01
Observed	381

TABLE 12.5: Expected and observed postfit yields in the vbf signal region for vbfHVT signals, using the m_{WZ} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.1.3 vbfGM

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the m_{WZ} distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

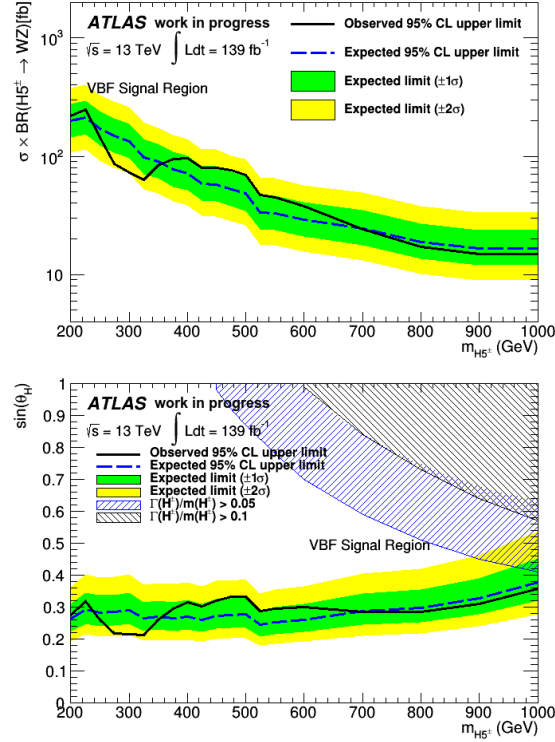


FIGURE 12.9: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the m_{WZ} distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The WZ-QCD pdf uncertainty, the μ_{ZZ} , the cross-section of $VVV + t\bar{t}V$, the WZ-EWK scale uncertainty and some jet systematics have the highest impact on the calculation of the signal-strength parameter μ .

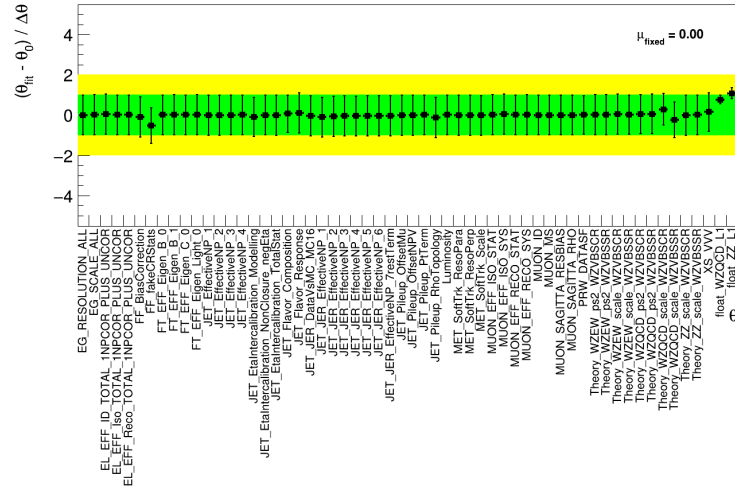


FIGURE 12.10: Nuisance parameter pulls for the SR+CR fit in the vbf signal and control regions for 500 GeV GM mass point using the m_{WZ} distribution as input to the fit.

FIGURE 12.11: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized GM signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_{WZ} distribution used as input to the fit.

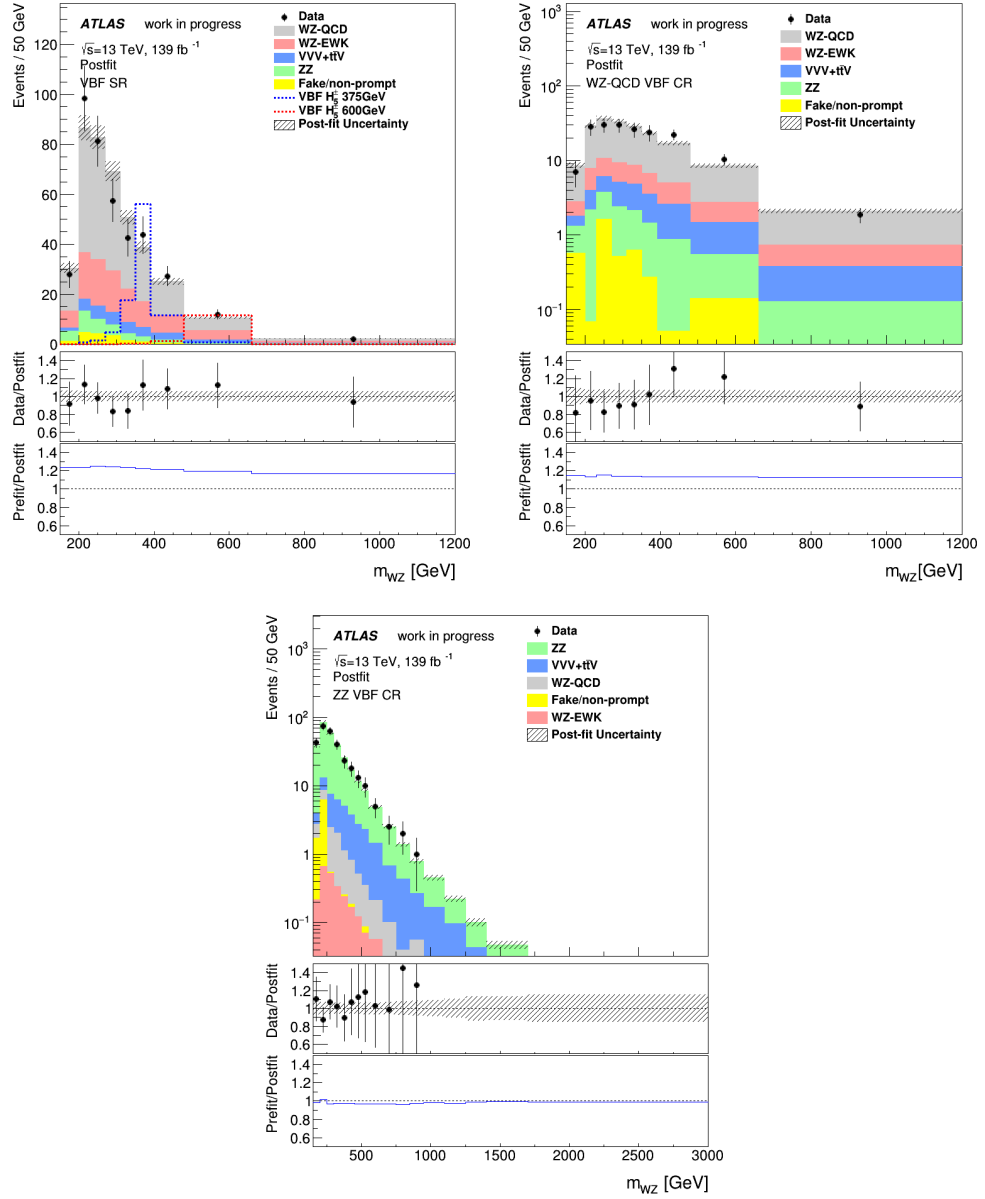


FIGURE 12.12: The postfit invariant mass distributions of the vbf SR +CR and ZZjj CR for GM signals fit are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Pre-fit/Postfit ratio.

μ_{WZ}^{QCD}	0.767 ± 0.209
μ_{ZZ}	1.078 ± 0.264

TABLE 12.6: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for GM signals, using the m_{WZ} distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	100.9 ± 10.48
WZQCD	210.19 ± 24
ZZ	26.52 ± 4.46
Fakes	13.91 ± 4.61
VVV+ $t\bar{t}V$	30.86 ± 6.65
Total Expected Background	382.38 ± 22.08
Observed	381

TABLE 12.7: Expected and observed postfit yields in the vbf signal region for GM signals, using the m_{WZ} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

FIGURE 12.14: Nuisance parameter pulls for the SR+CR fit in the Drell-Yan category for 500 GeV mass point using the m_T^{WZ} distribution as input to the fit.

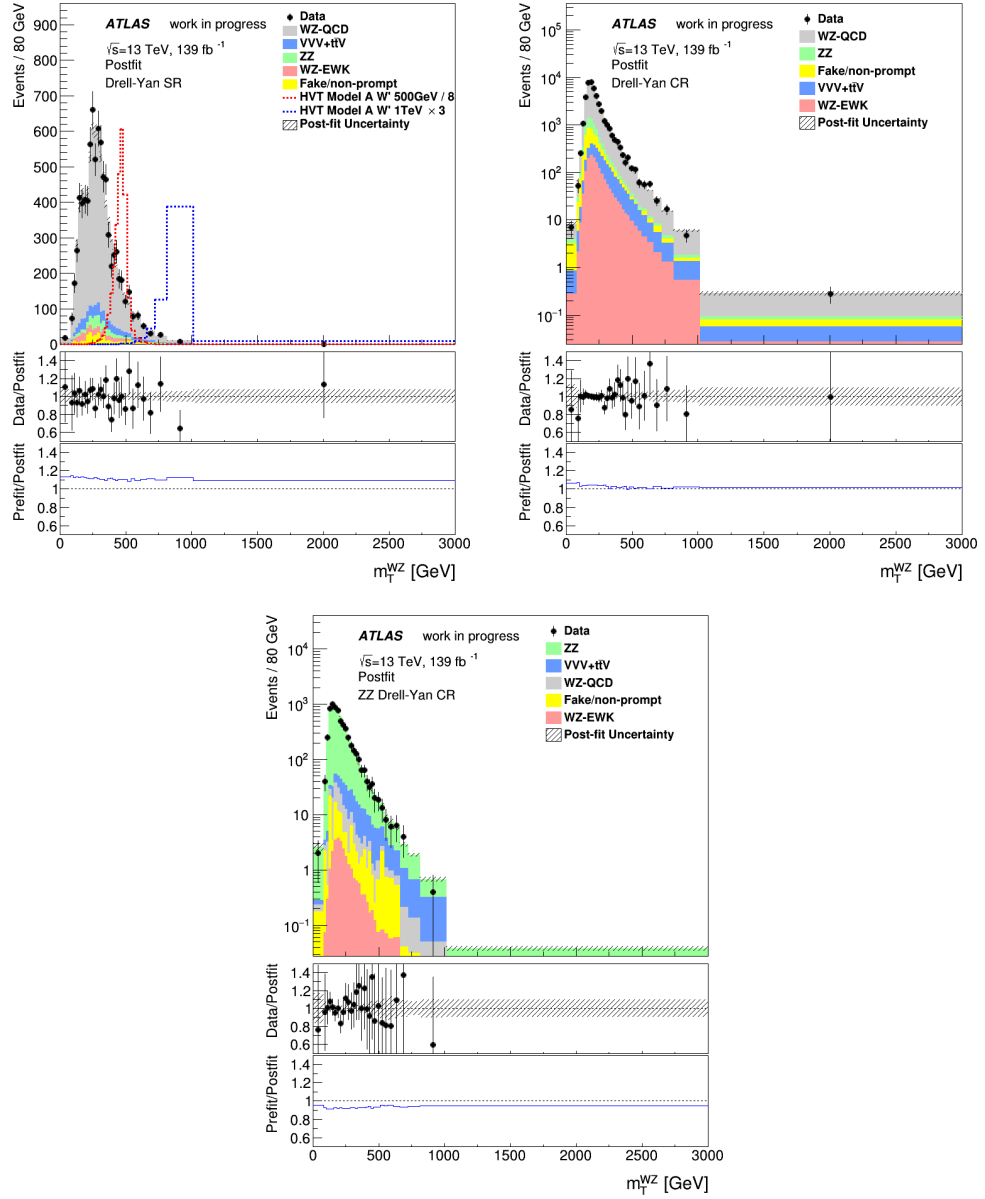


FIGURE 12.16: The postfit WZ transverse mass distributions of the Drell-Yan SR + CR and ZZ CR are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.933 ± 0.111
μ_{ZZ}	1.086 ± 0.066

TABLE 12.8: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous Drell-Yan $W^\pm Z$ SR/CR and ZZ CR fit with data, using the m_T^{WZ} distribution as input to the fit for the 500 GeV mass point.

	Drell-Yan SR
WZEW	89.89 ± 9.78
WZQCD	1732.74 ± 63.62
ZZ	94.62 ± 6.07
Fakes	85.16 ± 29.16
VVV+ $t\bar{t}V$	153.54 ± 25.55
Total Expected Background	2155.95 ± 80.32
Observed	2155

TABLE 12.9: Expected and observed postfit yields in the Drell-Yan signal region, using the m_T^{WZ} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the Drell-Yan SR, WZ Drell-YanCR and ZZ CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.2.2 vbfHVT

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for vbfHVT signals, using the m_T^{WZ} distribution as input to the fit. Masses below 380 GeV can be excluded for model with $g_V c_H = 1$, 480 GeV can be excluded for model with $g_V c_H = 1.5$ and 640 GeV can be excluded for model with $g_V c_H = 2$.

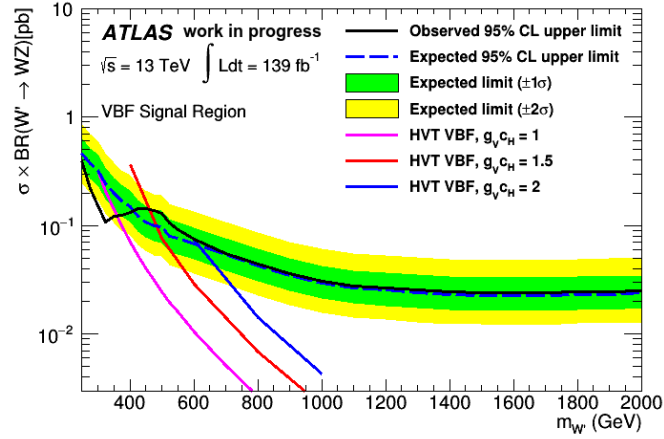


FIGURE 12.17: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for vbfHVT signals using the m_T^{WZ} distribution as input to the fit.

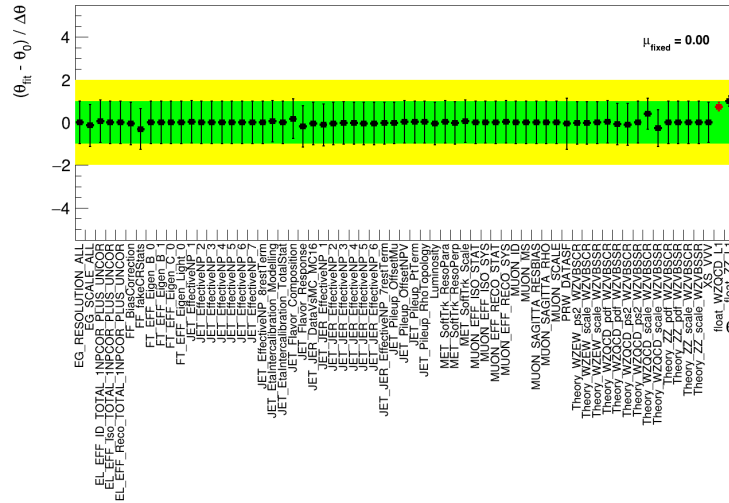


FIGURE 12.18: Nuisance parameter pulls for the SR+CR fit in the vbf category for 500 GeV vbfHVT mass point using the m_T^{WZ} distribution as input to the fit.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The μ_{ZZ} , μ_{WZ}^{QCD} , cross-section of $VVV + t\bar{t}V$, the WZ-QCD and the WZ-EWK scale uncertainty have the highest impact on the calculation of the signal-strength parameter μ .

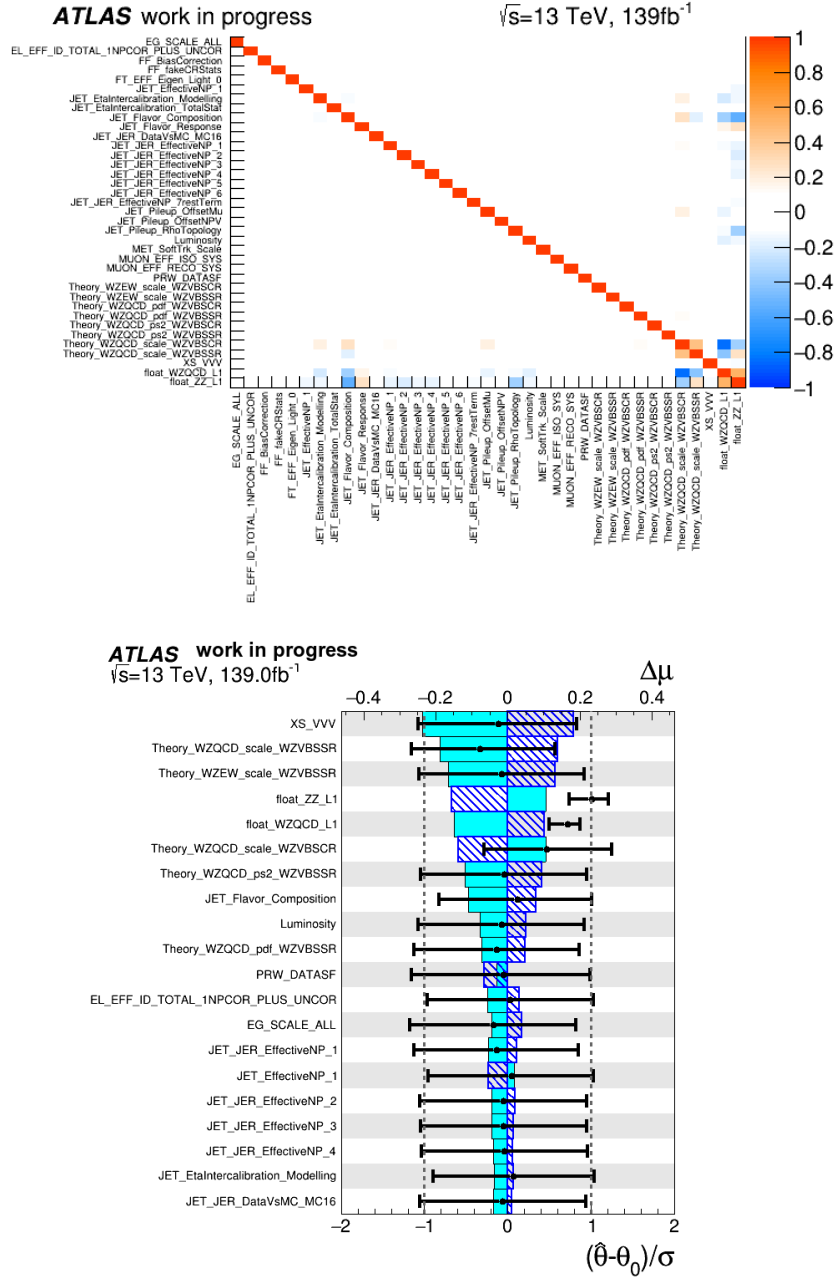


FIGURE 12.19: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized HVT signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_T^{WZ} distribution used as input to the fit.

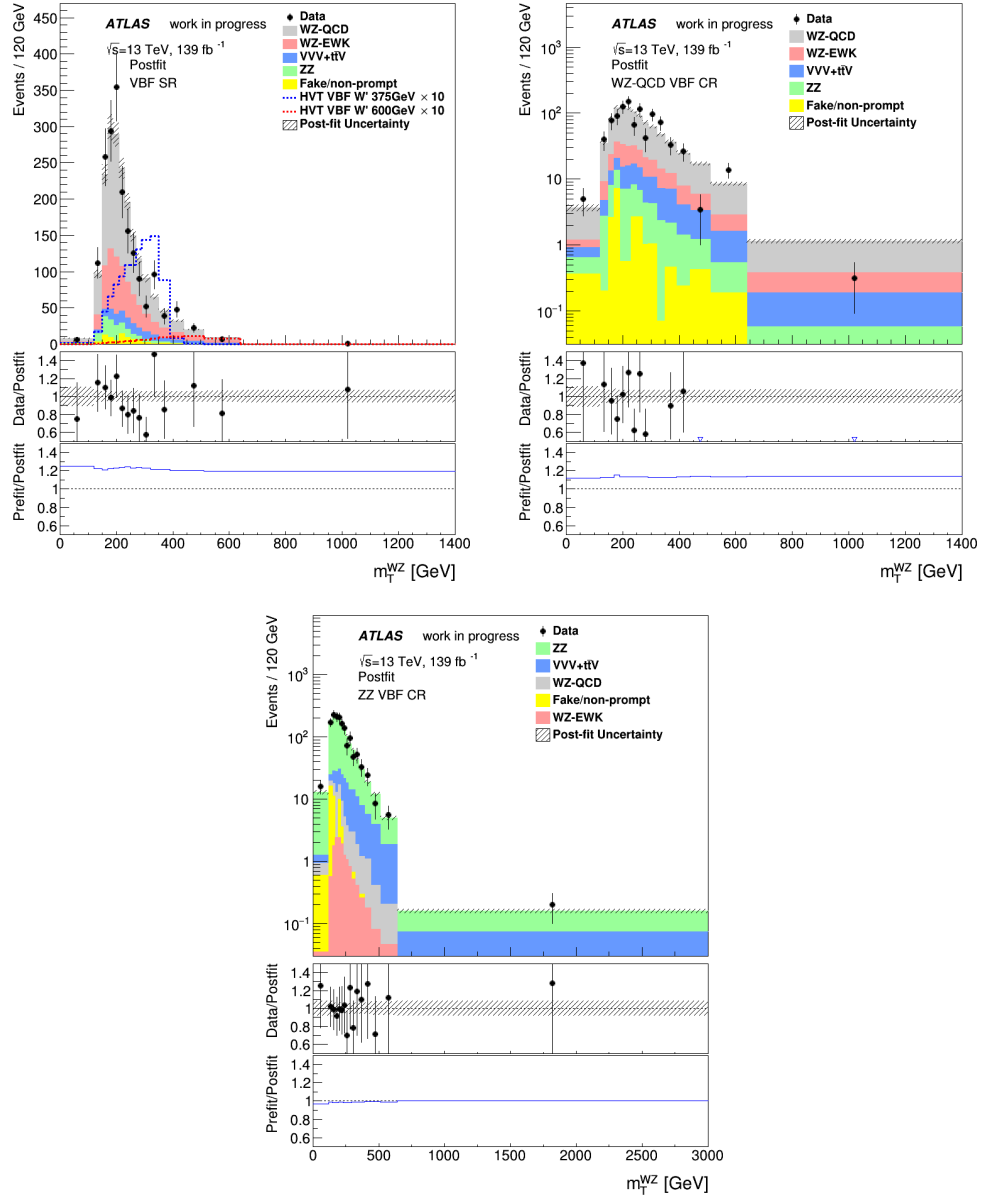


FIGURE 12.20: The postfit WZ transverse mass distributions of the vbf SR +CR and ZZjj CR are shown for vbfHVT signals fit. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.734 ± 0.197
μ_{ZZ}	1.002 ± 0.237

TABLE 12.10: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for vbfHVT signals, using the m_T^{WZ} distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	102.55 ± 11.1
WZQCD	209.39 ± 24.33
ZZ	26.45 ± 4.43
Fakes	14.24 ± 4.89
VVV+ $t\bar{t}V$	30.68 ± 6.62
Total Expected Background	383.3 ± 23.29
Observed	381

TABLE 12.11: Expected and observed postfit yields in the vbf signal region for vbfHVT signals, using the m_T^{WZ} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.2.3 vbfGM

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the m_T^{WZ} distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

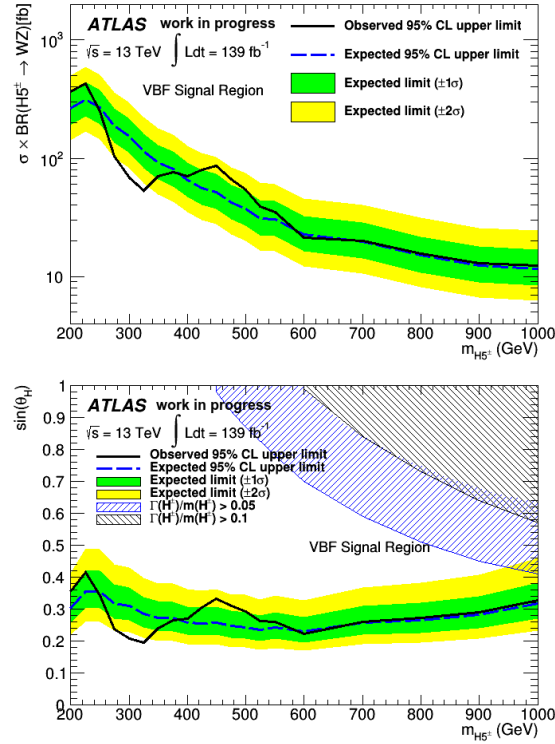


FIGURE 12.21: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the m_T^{WZ} distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The μ_{ZZ} , cross-section of $VVV + t\bar{t}V$, the WZ-QCD scale and parton shower uncertainty and the WZ-EWK scale uncertainty have the highest impact on the calculation of the signal-strength parameter μ .

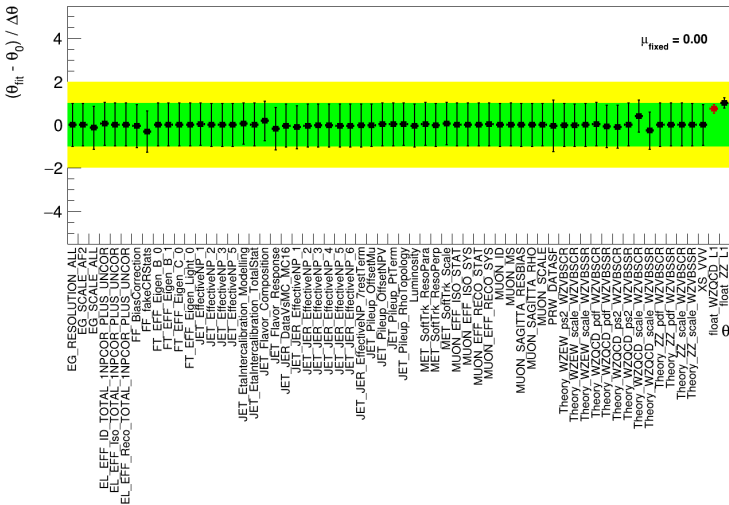


FIGURE 12.22: Nuisance parameter pulls for the SR+CR fit in the vbf cayegory for 500 GeV GM mass point using the m_T^{WZ} distribution as input to the fit.

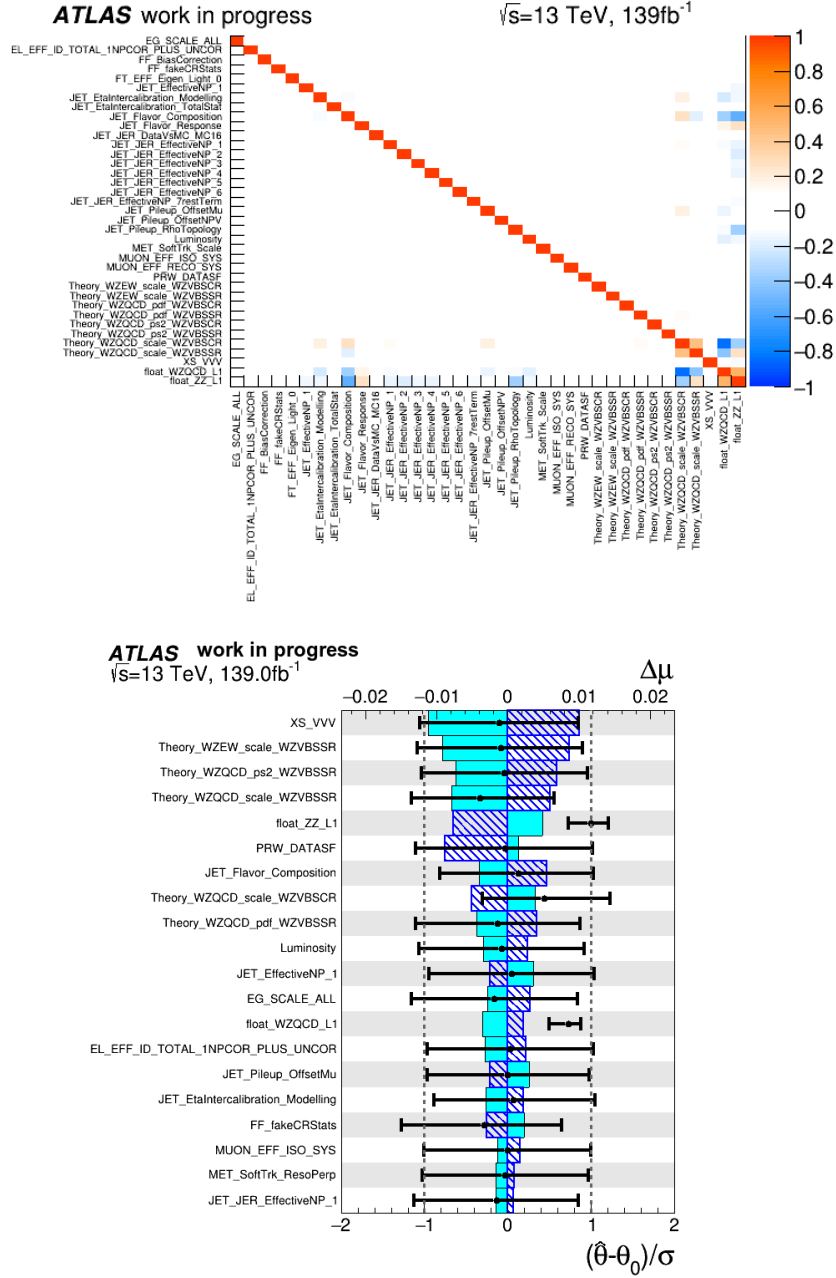


FIGURE 12.23: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized GM signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_T^{WZ} distribution used as input to the fit.

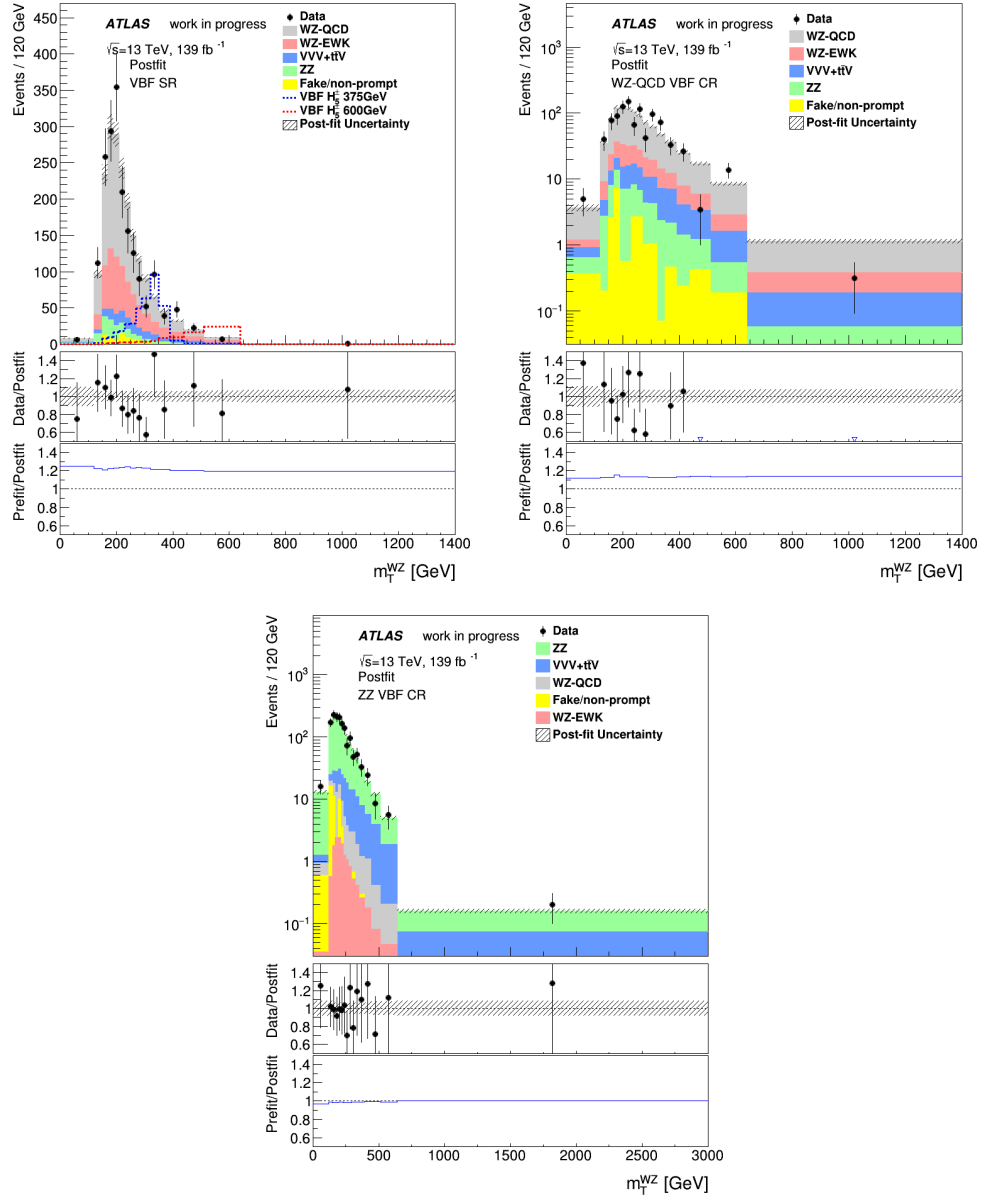


FIGURE 12.24: The postfit WZ transverse mass distributions of the vbf SR +CR and ZZjj CR for GM signals fit are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.734 ± 0.197
μ_{ZZ}	1.002 ± 0.237

TABLE 12.12: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for GM signals, using the m_T^{WZ} distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	102.55 ± 11.1
WZQCD	209.39 ± 24.33
ZZ	26.45 ± 4.43
Fakes	14.24 ± 4.89
VVV+ $t\bar{t}V$	30.68 ± 6.62
Total Expected Background	383.3 ± 23.29
Observed	381

TABLE 12.13: Expected and observed postfit yields in the vbf signal region for GM signals, using the m_T^{WZ} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.3 m_T^{WZ} & m_{JJ}

12.6.3.1 vbfHVT

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for vbfHVT signals using the m_T^{WZ} and m_{jj} distributions as inputs to the fit. Masses below 400 GeV can be excluded for model with $g_V c_H = 1$, 500 GeV can be excluded for model with $g_V c_H = 1.5$ and 650 GeV can be excluded for model with $g_V c_H = 2$.

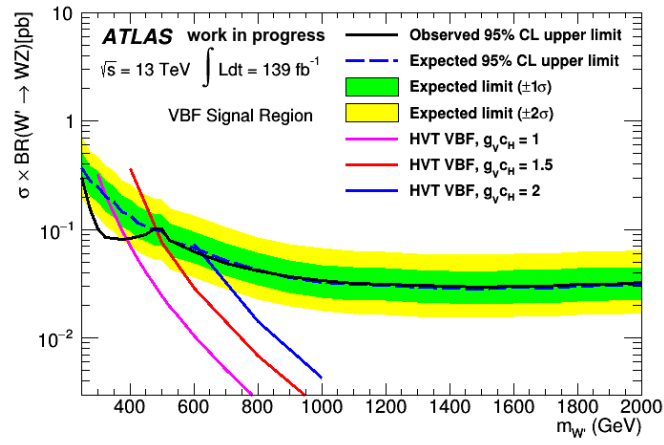


FIGURE 12.25: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for vbfHVT signals using the m_T^{WZ} and m_{jj} distributions as inputs to the fit.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The cross-section of $VVV + t\bar{t}V$, μ_{ZZ} , μ_{WZ}^{QCD} and the WZ-EWK and WZ-WCD scale uncertainties have the highest impact on the calculation of the signal-strength parameter μ .

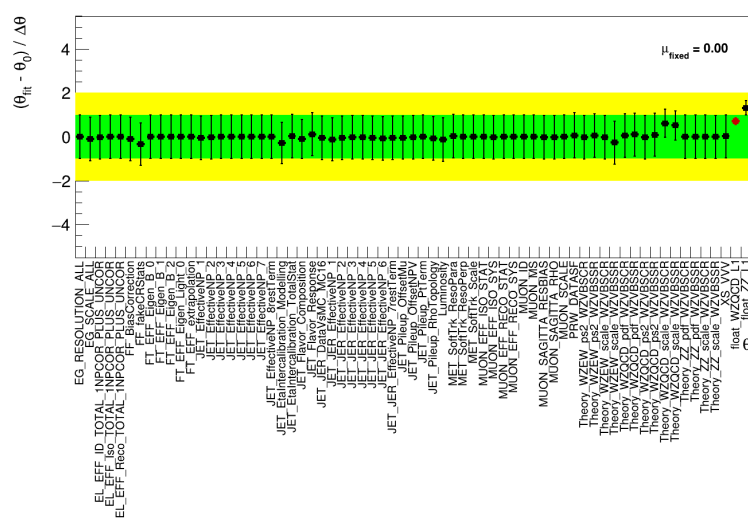


FIGURE 12.26: Nuisance parameter pulls for the SR+CR fit in the vbf category for 500 GeV vbfHVT mass point using the m_T^{WZ} and m_{jj} distributions as inputs to the fit.

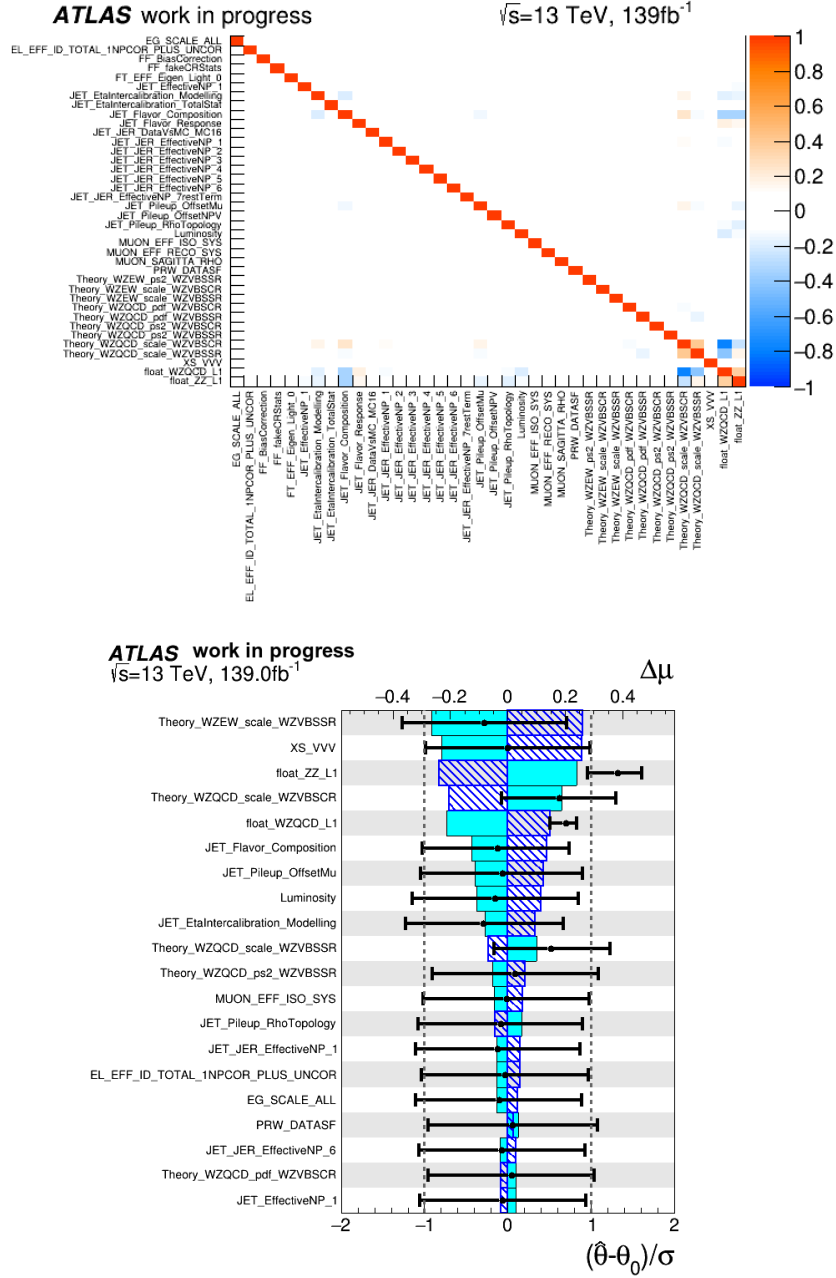


FIGURE 12.27: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized HVT signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_T^{WZ} and m_{jj} distributions are used as inputs to the fit.

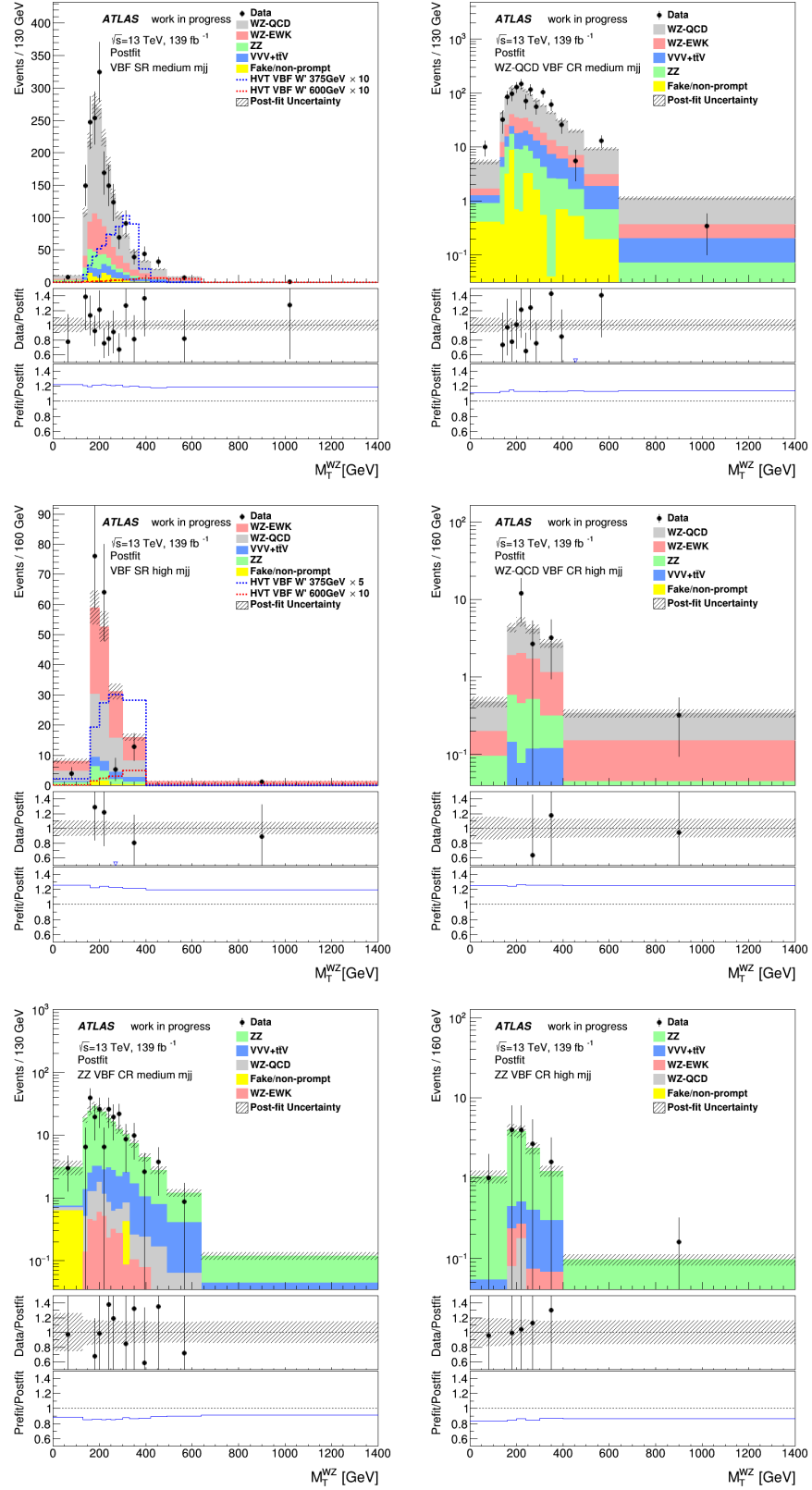


FIGURE 12.28: The postfit WZ transverse mass distributions of the vbf SR +CR and $ZZjj$ CR are shown for $vbfHVT$ signals fit; they correspond to the medium/high m_{jj} regions ($[500,1500]/[1500,\infty]$), as defined for the fit. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.698 ± 0.159
μ_{ZZ}	1.315 ± 0.322

TABLE 12.14: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for vbfHVT signals, using the m_T^{WZ} and m_{jj} distributions as inputs to the fit for the 500 GeV mass point.

	medium m_{jj} vbf SR	high m_{jj} vbf SR
WZEW	63.51 ± 5.97	32.18 ± 3.69
WZQCD	192.98 ± 19.86	24.09 ± 4.23
ZZ	25.66 ± 5.5	4.3 ± 0.96
Fakes	13.93 ± 4.42	1.31 ± 0.91
VVV+ $t\bar{t}V$	24.56 ± 5.33	4.72 ± 1
Total Expected Background	320.64 ± 20.17	66.61 ± 6.04
Observed	324	57

TABLE 12.15: Expected and observed postfit yields in the vbf signal region for vbfHVT signals, using the m_T^{WZ} and m_{jj} distributions as inputs to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.3.2 vbfGM

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for vbfGM signals using the m_T^{WZ} and m_{jj} distributions as inputs to the fit. Limits are also produced for the $\sin(\theta_H)$ parameter.

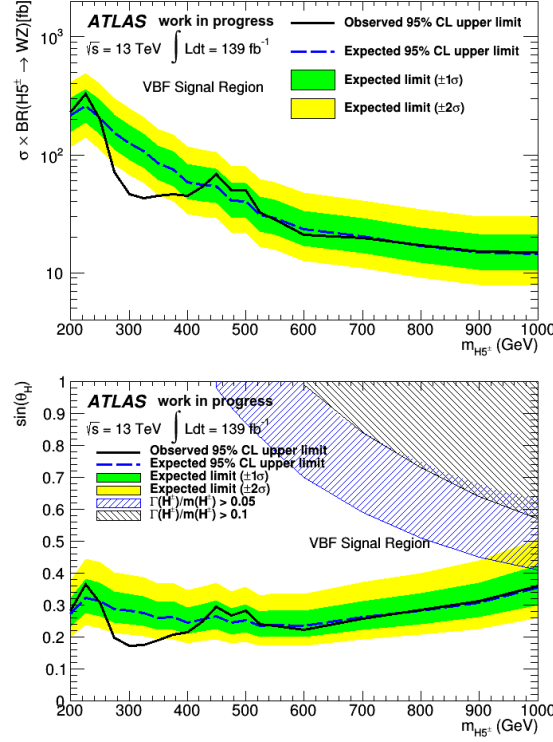


FIGURE 12.29: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for vbfGM signals using the m_T^{WZ} and m_{jj} distributions as inputs to the fit. Limits are also produced for the $\sin(\theta_H)$ parameter.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The μ_{ZZ} , the cross-section of $VVV + t\bar{t}V$, the WZ-EWK and WZ-QCD scale uncertainties and some jet systematics and have the highest impact on the calculation of the signal-strength parameter μ .

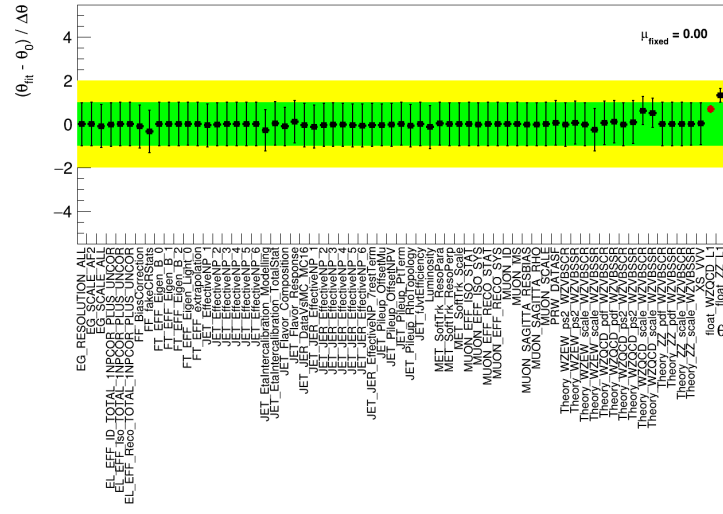


FIGURE 12.30: Nuisance parameter pulls for the SR+CR fit in the vbf category for 500 GeV vbfGM mass point using the m_T^{WZ} and m_{jj} distributions as inputs to the fit.

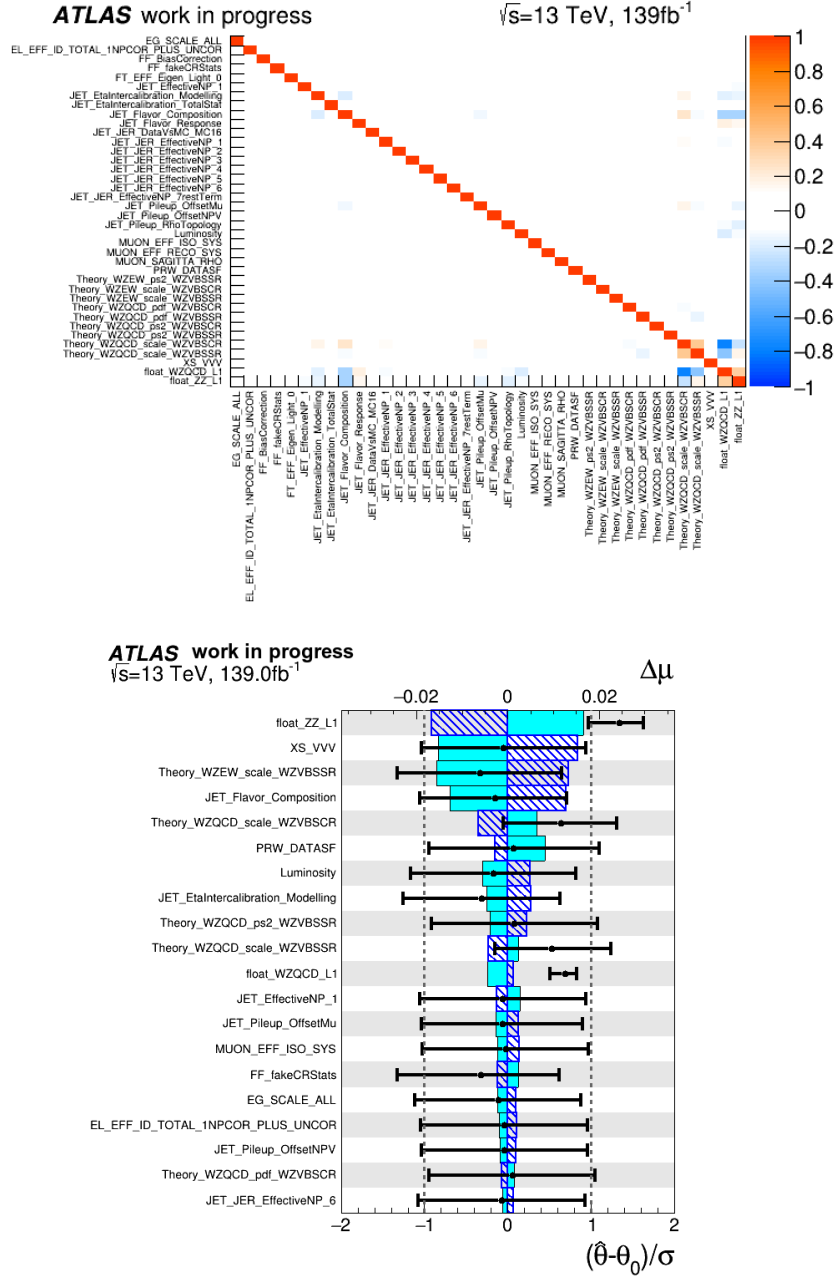


FIGURE 12.31: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized GM signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_T^{WZ} and m_{jj} distributions are used as inputs to the fit.

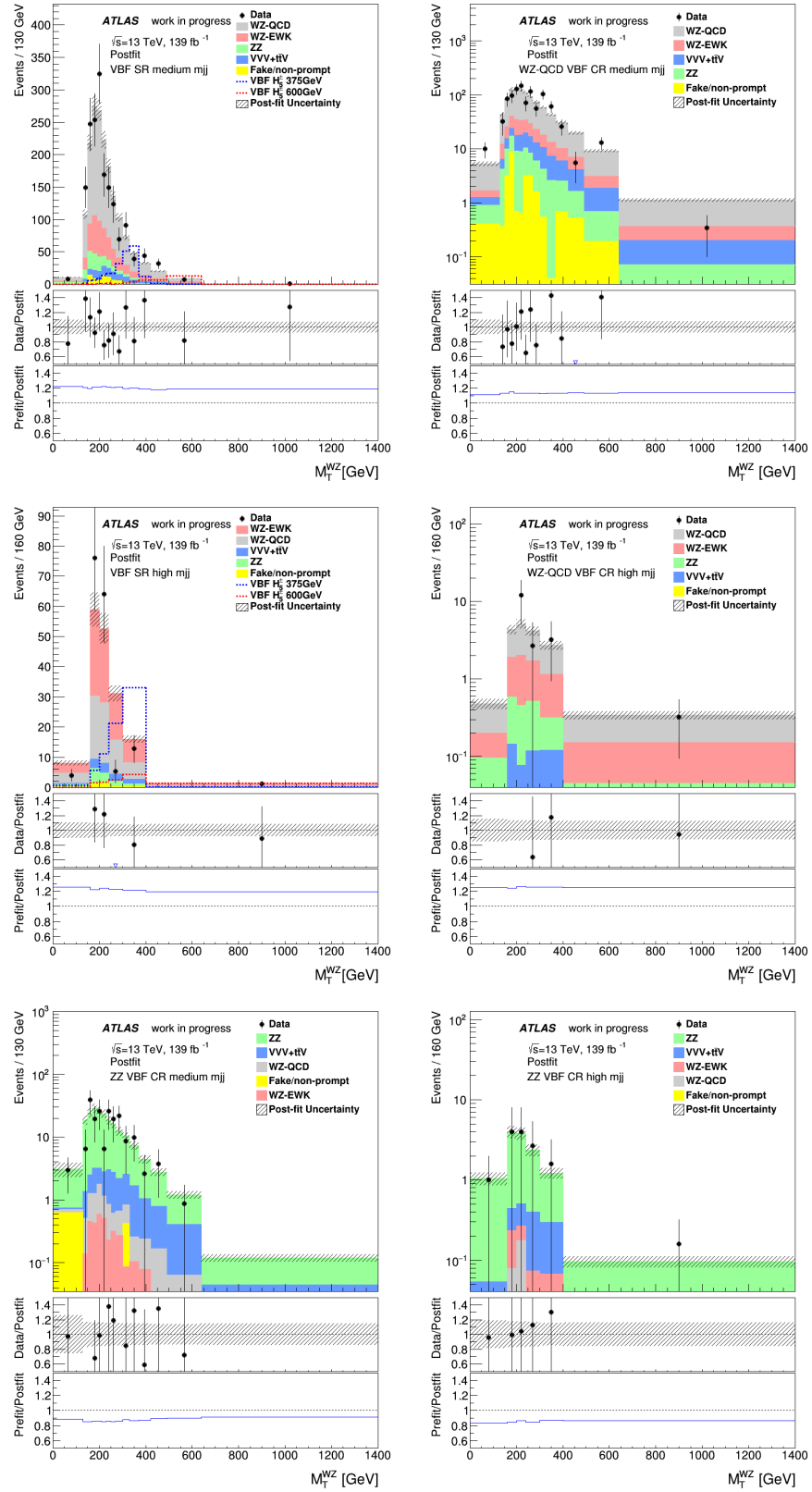


FIGURE 12.32: The postfit WZ transverse mass distributions of the vbf SR +CR and ZZjj CR are shown for vbfGM signals fit; they correspond to the medium/high m_{jj} regions ([500,1500]/[1500, ∞]), as defined for the fit. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.698 ± 0.159
μ_{ZZ}	1.315 ± 0.322

TABLE 12.16: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for vbfGM signals, using the m_T^{WZ} and m_{jj} distributions as inputs to the fit for the 500 GeV mass point.

	medium m_{jj} vbf SR	high m_{jj} vbf SR
WZEW	63.51 ± 5.97	32.18 ± 3.69
WZQCD	192.98 ± 19.86	24.09 ± 4.23
ZZ	25.66 ± 5.5	4.3 ± 0.96
Fakes	13.93 ± 4.42	1.31 ± 0.91
VVV+ $t\bar{t}V$	24.56 ± 5.33	4.72 ± 1
Total Expected Background	320.64 ± 20.17	66.61 ± 6.04
Observed	324	57

TABLE 12.17: Expected and observed postfit yields in the vbf signal region for vbfGM signals, using the m_T^{WZ} and m_{jj} distributions as inputs to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

FIGURE 12.34: Nuisance parameter pulls for the SR+CR fit in the Drell-Yan category for 500 GeV mass point using the m_{3lep} distribution as input to the fit.

No over-constraints are present; some systematics are pulled but within 1 or 2σ so the fit is considered as healthy. The WZ-QCD pdf and scale uncertainty, the cross-section of $VVV + t\bar{t}V$, the μ_{WZ}^{QCD} and the *Jet Flavor Response* systematic have the highest impact on the calculation of the signal-strength parameter μ .

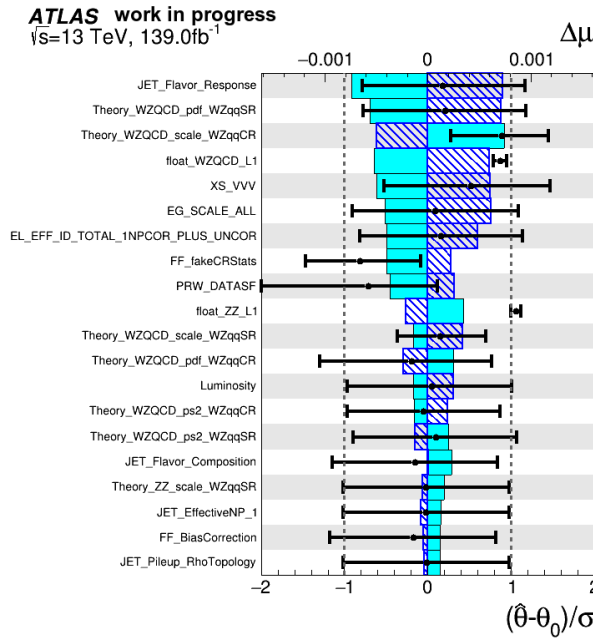
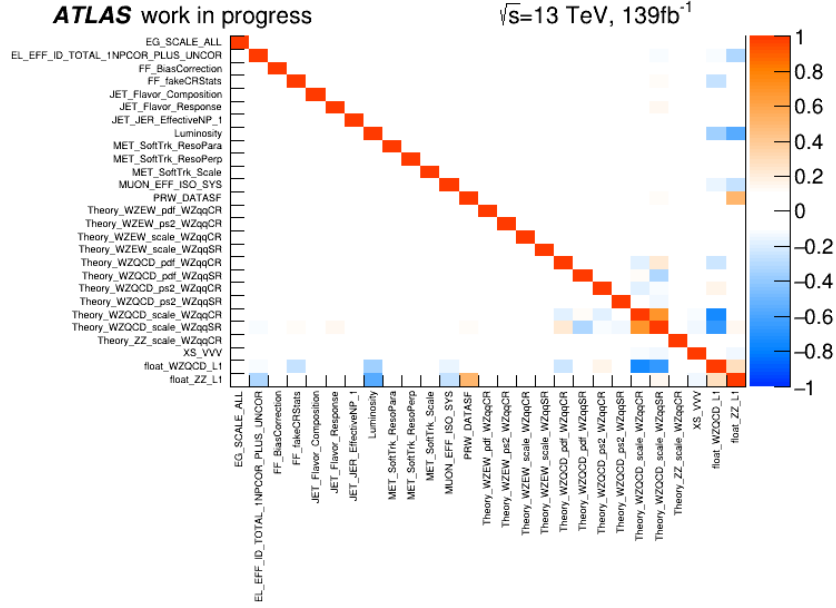


FIGURE 12.35: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized HVT signal production of mass 500 GeV in the Drell-Yan category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_{3lep} distribution used as input to the fit.

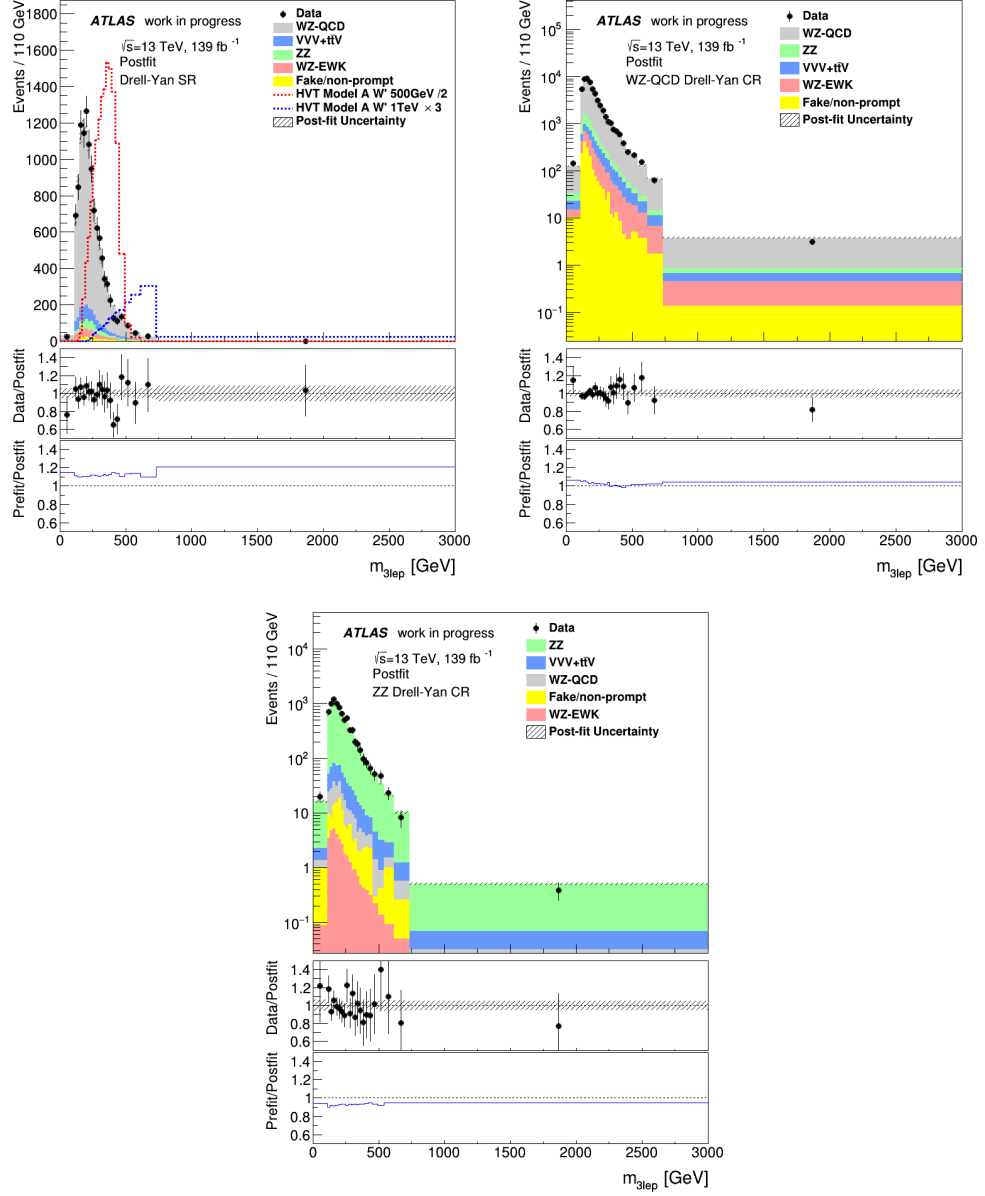


FIGURE 12.36: The postfit invariant mass of the three leptons of WZ decay distributions of the Drell-Yan SR/CR and ZZ CR are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.859 ± 0.078
μ_{ZZ}	1.066 ± 0.063

TABLE 12.18: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous Drell-Yan $W^\pm Z$ SR/CR and ZZ CR fit with data, using the m_{3lep} distribution as input to the fit for the 500 GeV mass point.

	Drell-Yan SR
WZEW	91.71 ± 6.2
WZQCD	1764.17 ± 59.86
ZZ	92.94 ± 5.79
Fakes	46.98 ± 27.35
VVV+ $t\bar{t}V$	158 ± 30.38
Total Expected Background	2153.8 ± 68.73
Observed	2155

TABLE 12.19: Expected and observed postfit yields in the Drell-Yan signal region, using the m_{3lep} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the Drell-Yan SR, WZ QCD Drell-Yan CR and ZZ CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.4.2 vbfHVT

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The μ_{ZZ} , WZ-EWK pdf and scale uncertainties, the WZ-QCD scale uncertainty, the cross-section of $VVV + t\bar{t}V$ and the $\mathcal{J}ET_Flavor_composition$ systematic have the highest impact on the calculation of the signal-strength parameter μ .

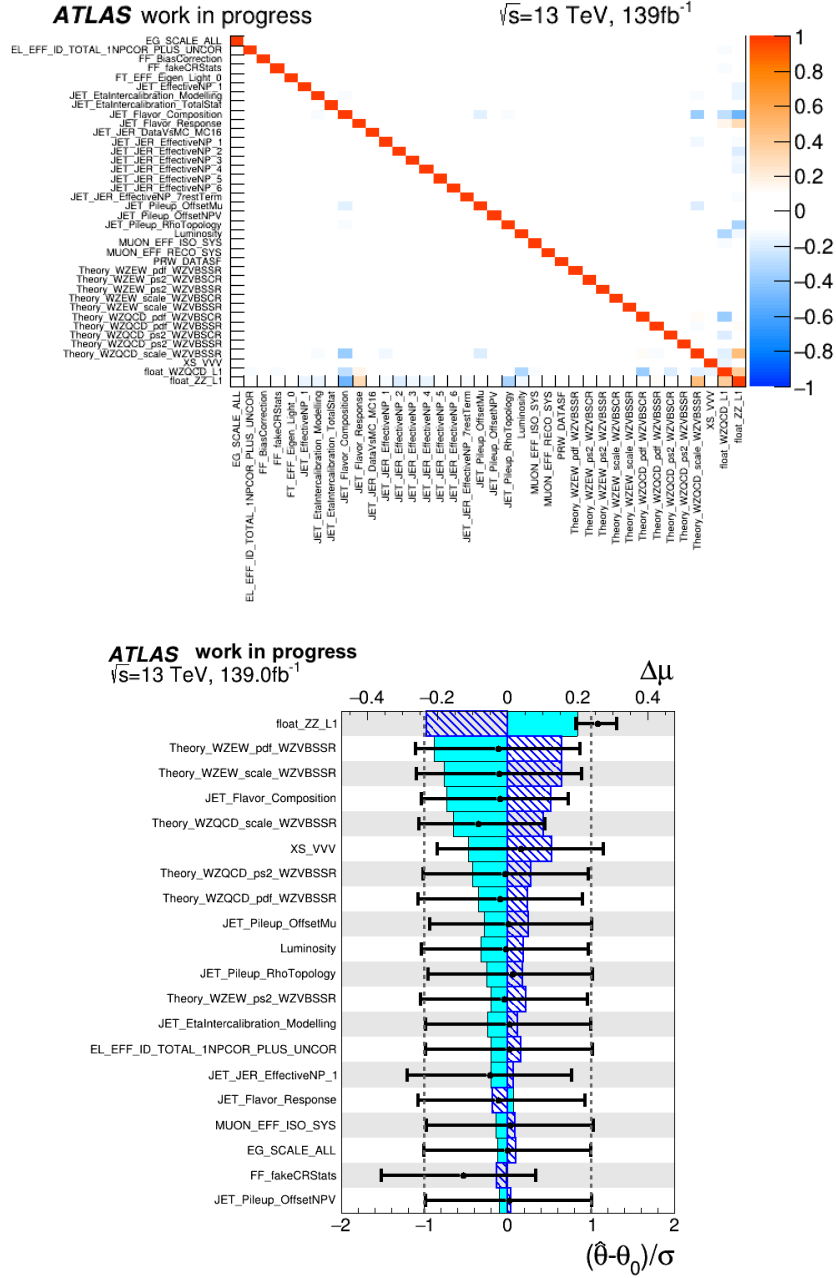


FIGURE 12.39: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized HVT signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_{3lep} distribution used as input to the fit.

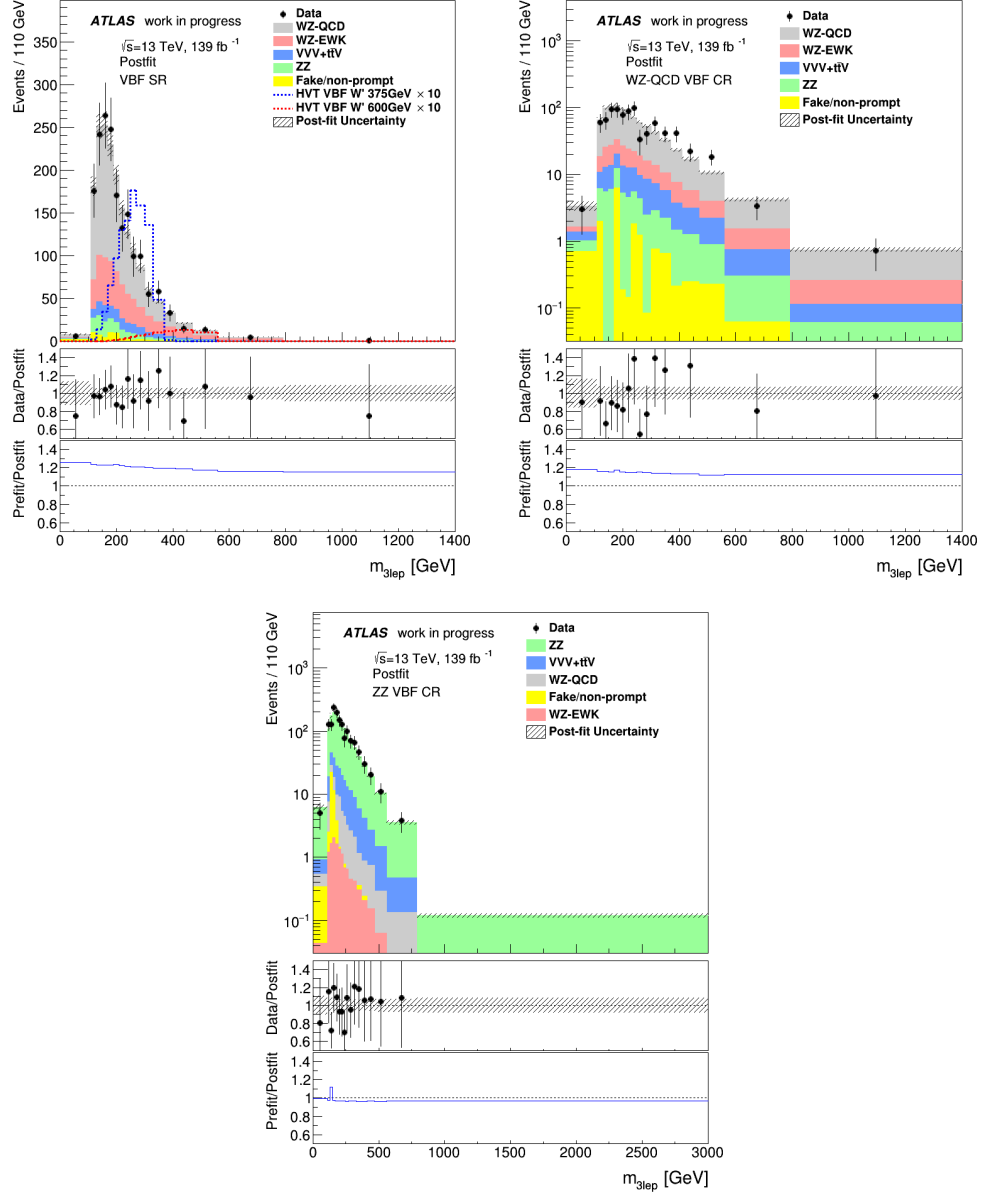


FIGURE 12.40: The postfit invariant mass of the three leptons of WZ decay distributions of the vbf SR +CR and ZZjj CR are shown for vbfHVT signals fit. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.804 ± 0.109
μ_{ZZ}	1.056 ± 0.24

TABLE 12.20: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for vbfHVT signals, using the m_{3lep} distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	98.98 ± 12.98
WZQCD	215.03 ± 24.5
ZZ	26.56 ± 4.24
Fakes	13.25 ± 4.07
VVV+ $t\bar{t}V$	31.07 ± 6.5
Total Expected Background	384.89 ± 23.78
Observed	381

TABLE 12.21: Expected and observed postfit yields in the vbf signal region for vbfHVT signals, using the m_{3lep} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.4.3 vbfGM

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the m_{3lep} distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

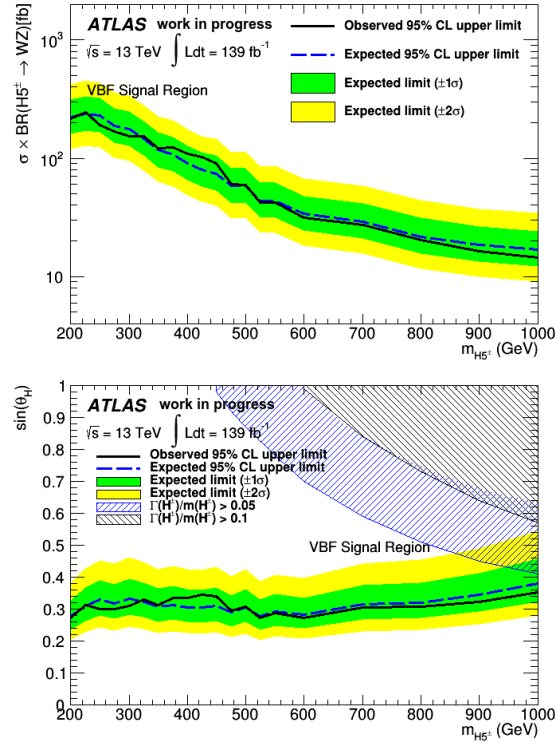


FIGURE 12.41: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the m_{3lep} distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The WZ-EWK pdf and scale uncertainties, the μ_{ZZ} , the $\text{JET_Flavor_Composition}$, the WZ-QCD scale uncertainty and the cross-section of $VVV + t\bar{t}V$ have the highest impact on the calculation of the signal-strength parameter μ .

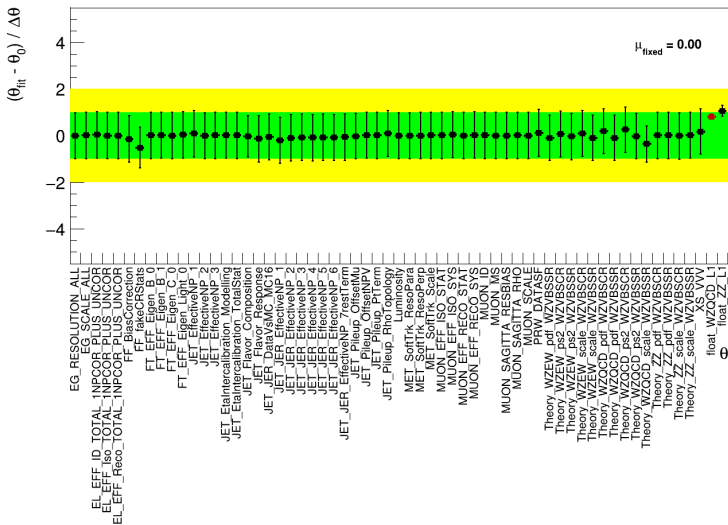


FIGURE 12.42: Nuisance parameter pulls for the SR+CR fit in the vbf category for 500 GeV GM mass point using the m_{3lep} distribution as input to the fit.

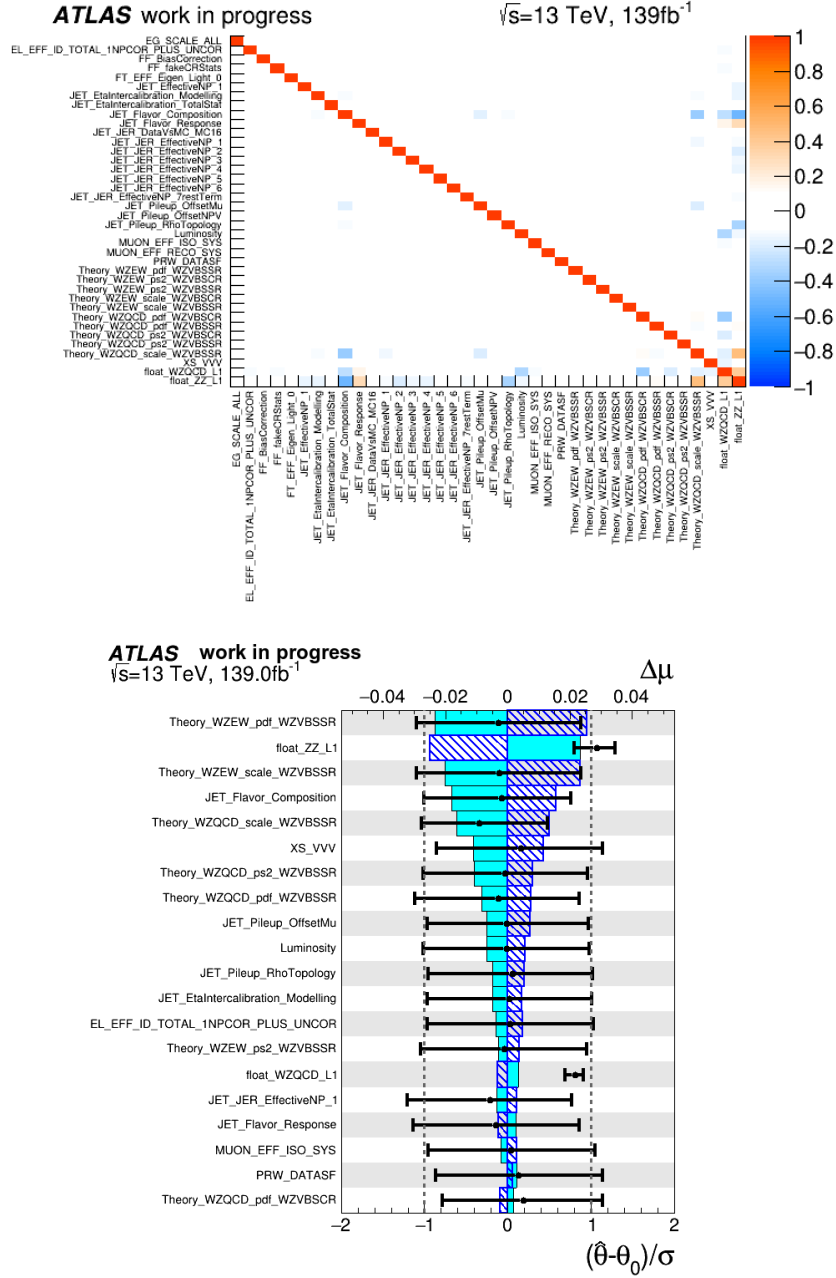


FIGURE 12.43: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized GM signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The m_{3lep} distribution used as input to the fit.

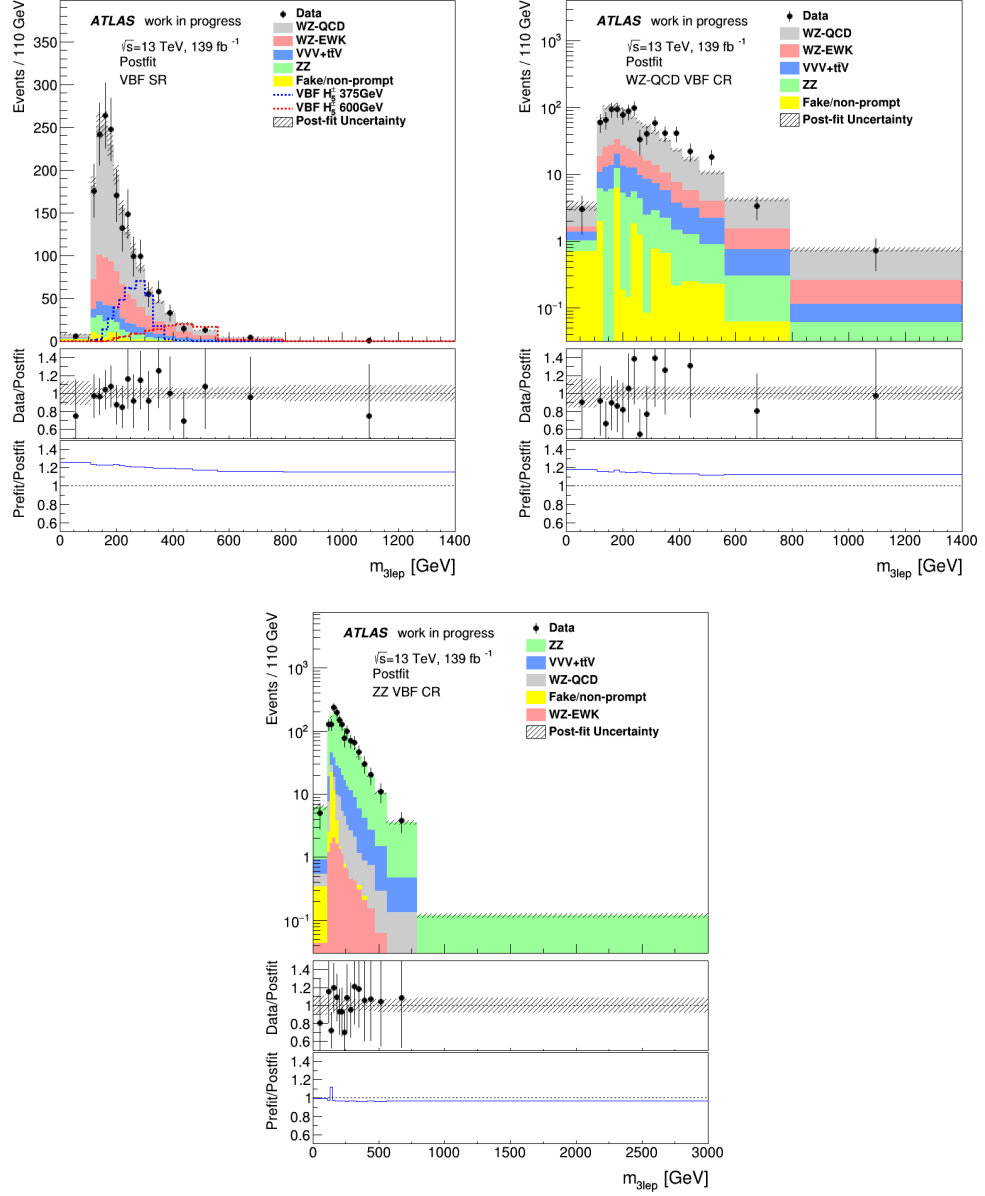


FIGURE 12.44: The postfit invariant mass of the three leptons from the WZ decay distributions of the vbf SR +CR and ZZjj CR for GM signals fit are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.804 ± 0.109
μ_{ZZ}	1.056 ± 0.24

TABLE 12.22: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for GM signals, using the m_{3lep} distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	98.98 ± 12.98
WZQCD	215.03 ± 24.5
ZZ	26.56 ± 4.24
Fakes	13.25 ± 4.07
VVV+ $t\bar{t}V$	31.07 ± 6.5
Total Expected Background	384.89 ± 23.78
Observed	381

TABLE 12.23: Expected and observed postfit yields in the vbf signal region for GM signals, using the m_{3lep} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

FIGURE 12.46: Nuisance parameter pulls for the SR+CR fit in the Drell-Yan category for 500 GeV mass point using the pT_{3lep} distribution as input to the fit.

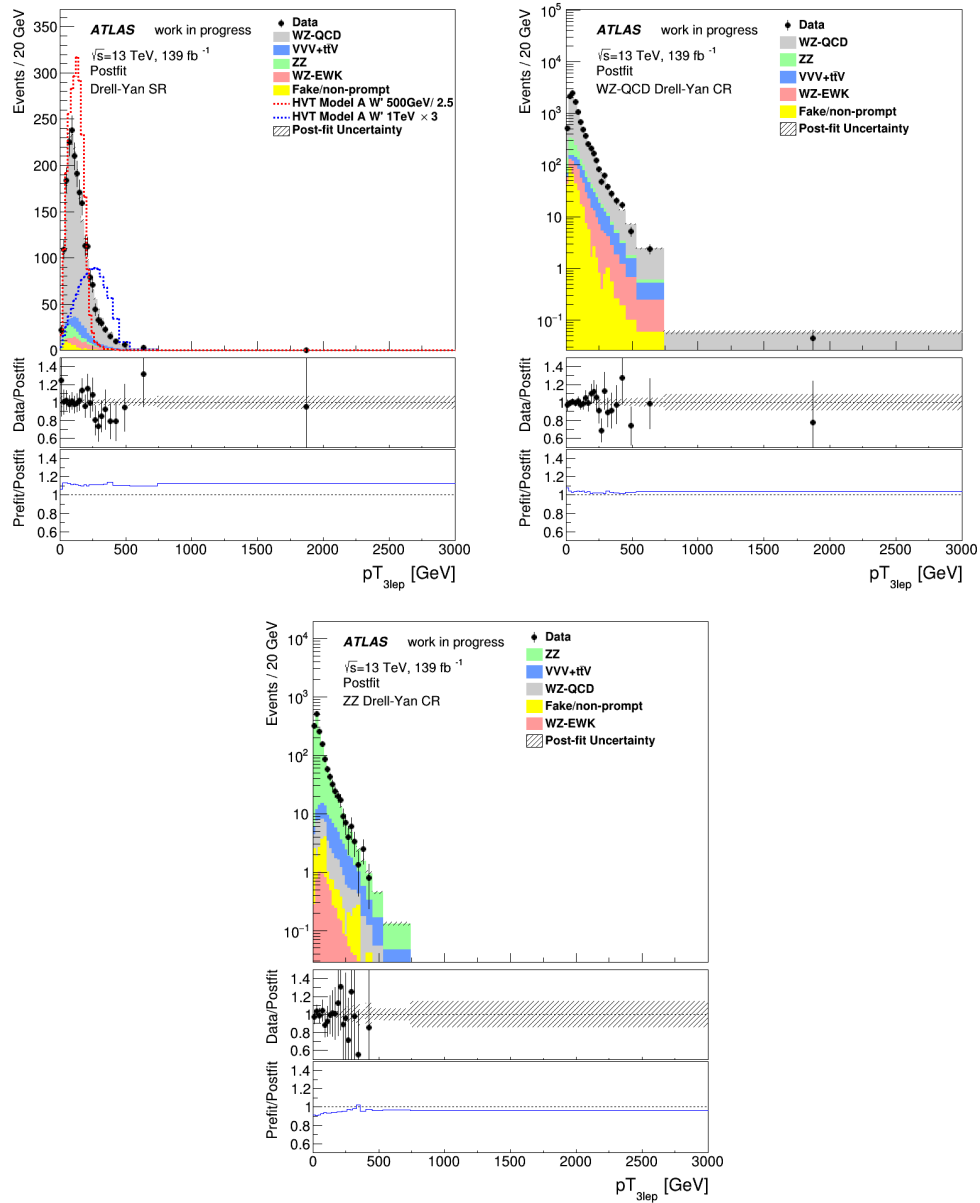


FIGURE 12.48: The postfit transverse momentum of the three leptons of WZ decay distributions of the Drell-Yan SR +CR and ZZ CR are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.95 ± 0.103
μ_{ZZ}	1.106 ± 0.061

TABLE 12.24: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous Drell-Yan $W^\pm Z$ SR/CR and ZZ CR fit with data, using the pT_{3lep} distribution as input to the fit for the 500 GeV mass point.

	Drell-Yan SR
WZEW	89.85 ± 4.26
WZQCD	1782.21 ± 60.42
ZZ	95.84 ± 5.72
Fakes	47.49 ± 24.91
VVV+ $t\bar{t}V$	140.59 ± 22.8
Total Expected Background	2155.98 ± 66.39
Observed	2155

TABLE 12.25: Expected and observed postfit yields in the Drell-Yan signal region, using the pT_{3lep} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the Drell-Yan SR/CR and ZZ CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.5.2 vbfHVT

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The μ_{ZZ} , μ_{WZ}^{QCD} and some jet systematic uncertainties have the highest impact on the calculation of the signal-strength parameter μ .

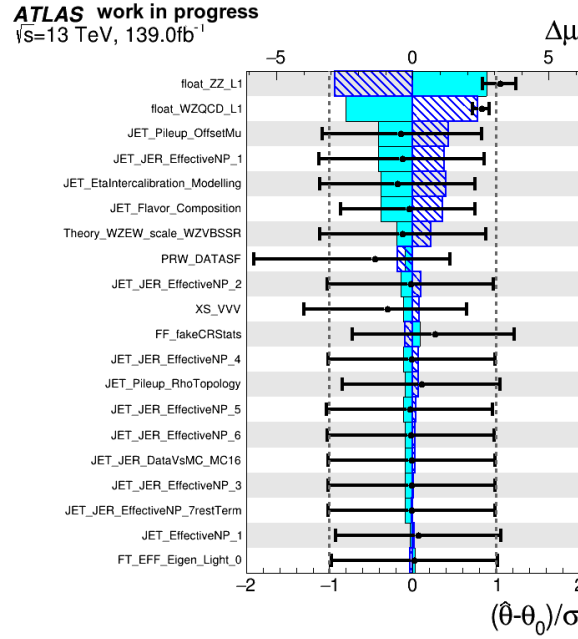
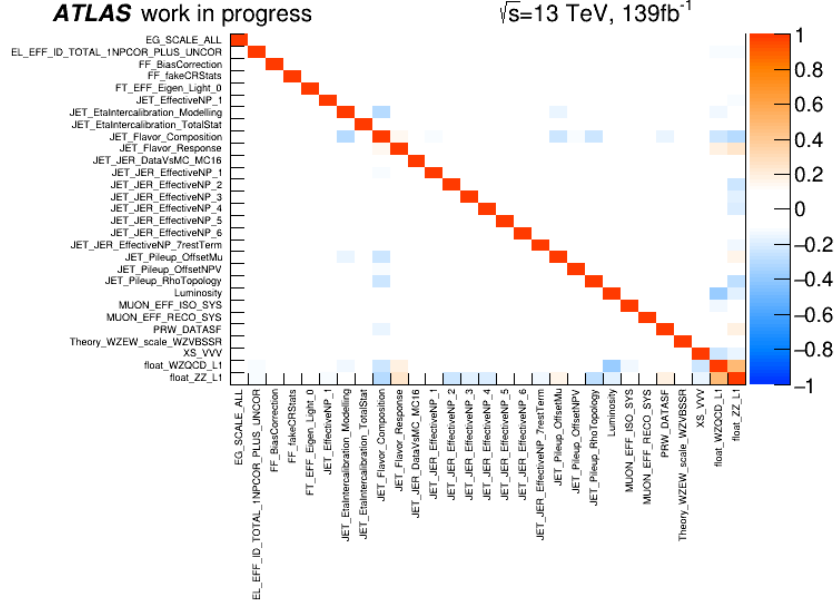


FIGURE 12.51: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized HVT signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The pT_{3lep} distribution used as input to the fit.

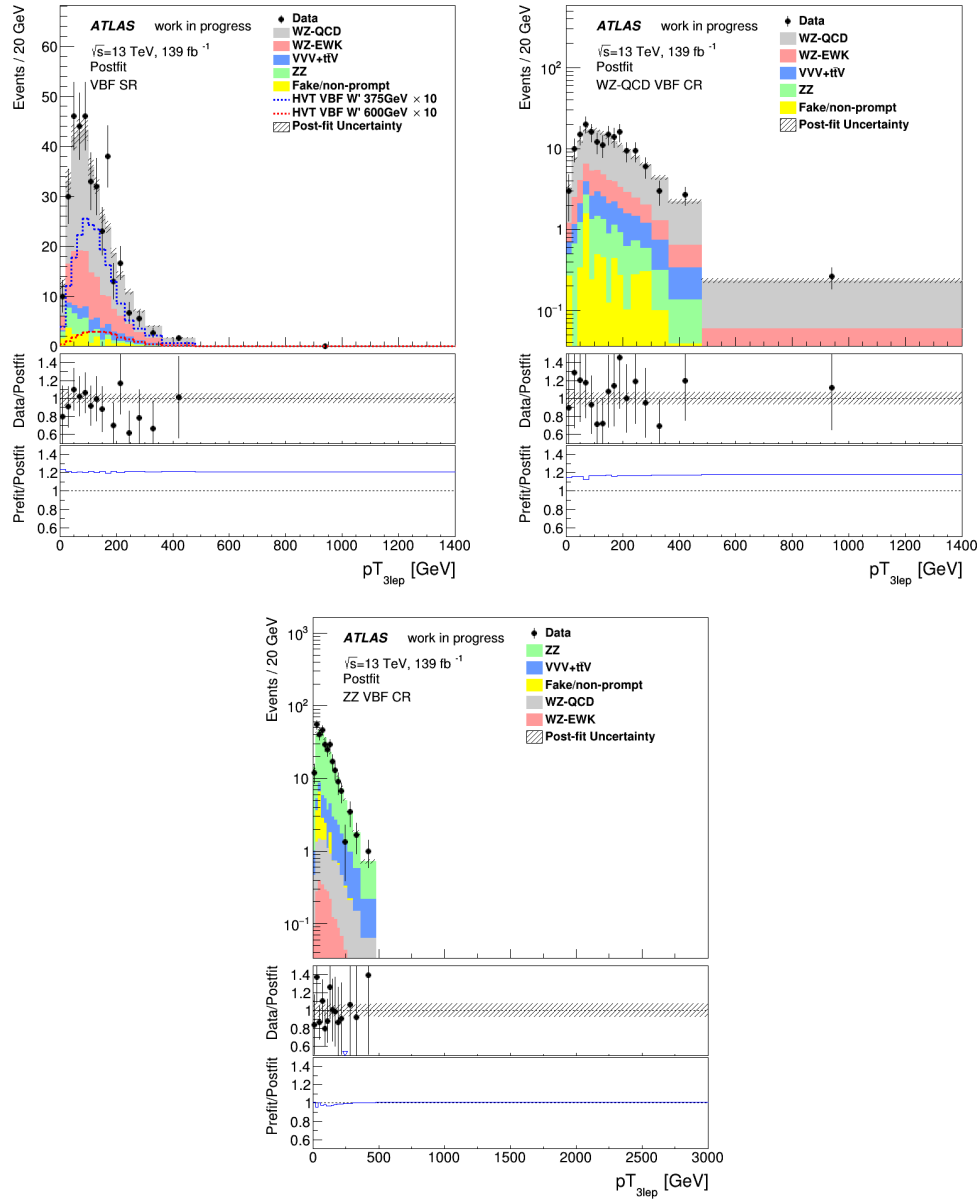


FIGURE 12.52: The postfit transverse momentum of the three leptons of WZ decay distributions of the vbf SR +CR and ZZjj CR are shown for vbfHVT signals fit. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.808 ± 0.094
μ_{ZZ}	1.099 ± 0.187

TABLE 12.26: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for vbfHVT signals, using the pT_{3lep} distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	97.68 ± 8.98
WZQCD	220.3 ± 18.77
ZZ	24.35 ± 3.86
Fakes	18.78 ± 6.06
VVV+ $t\bar{t}V$	26.98 ± 5.81
Total Expected Background	388.1 ± 21.75
Observed	381

TABLE 12.27: Expected and observed postfit yields in the vbf signal region for vbfHVT signals, using the pT_{3lep} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.5.3 vbfGM

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the pT_{3lep} distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

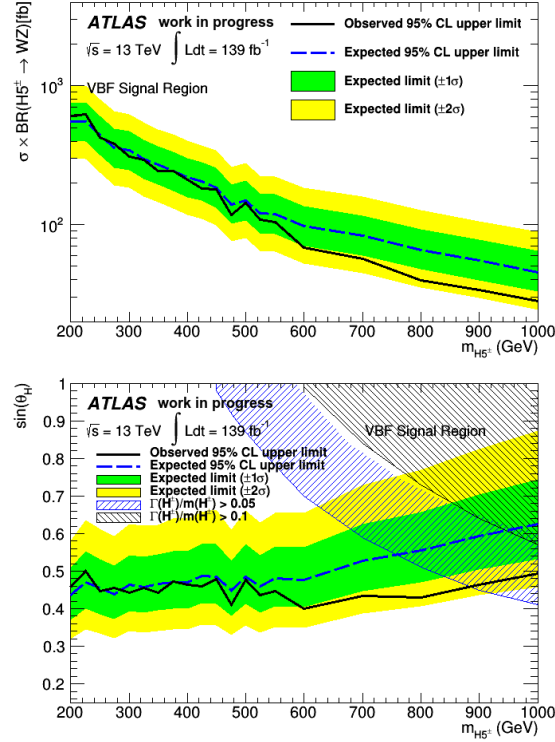


FIGURE 12.53: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the pT_{3lep} distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The μ_{ZZ} , μ_{WZ}^{QCD} and some jet systematic uncertainties have the highest impact on the calculation of the signal-strength parameter μ .

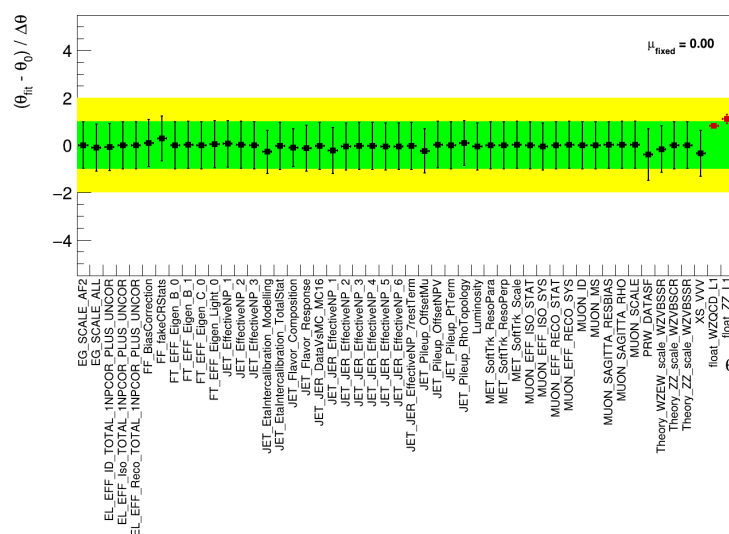


FIGURE 12.54: Nuisance parameter pulls for the SR+CR fit in the vbf category for 500 GeV GM mass point using the pT_{3lep} distribution as input to the fit.

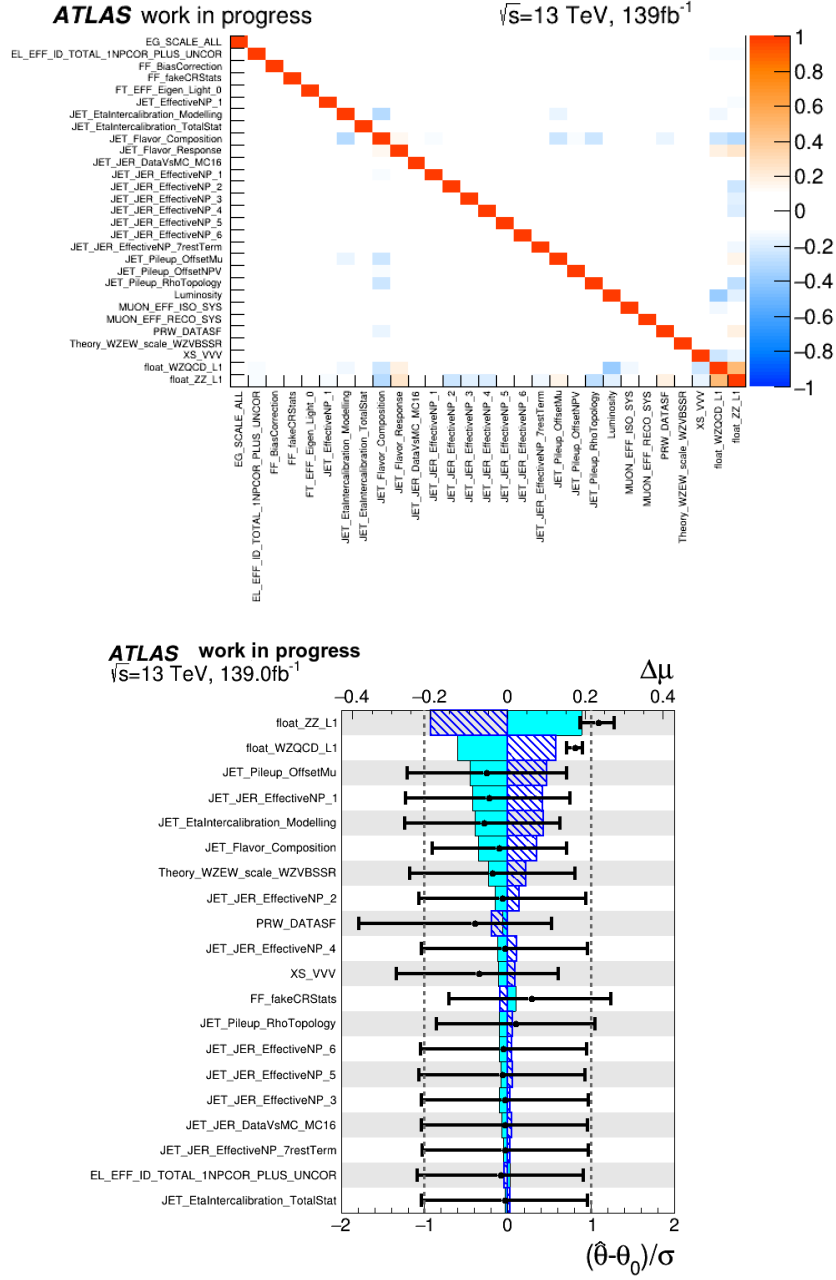


FIGURE 12.55: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized GM signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The pT_{3lep} distribution used as input to the fit.

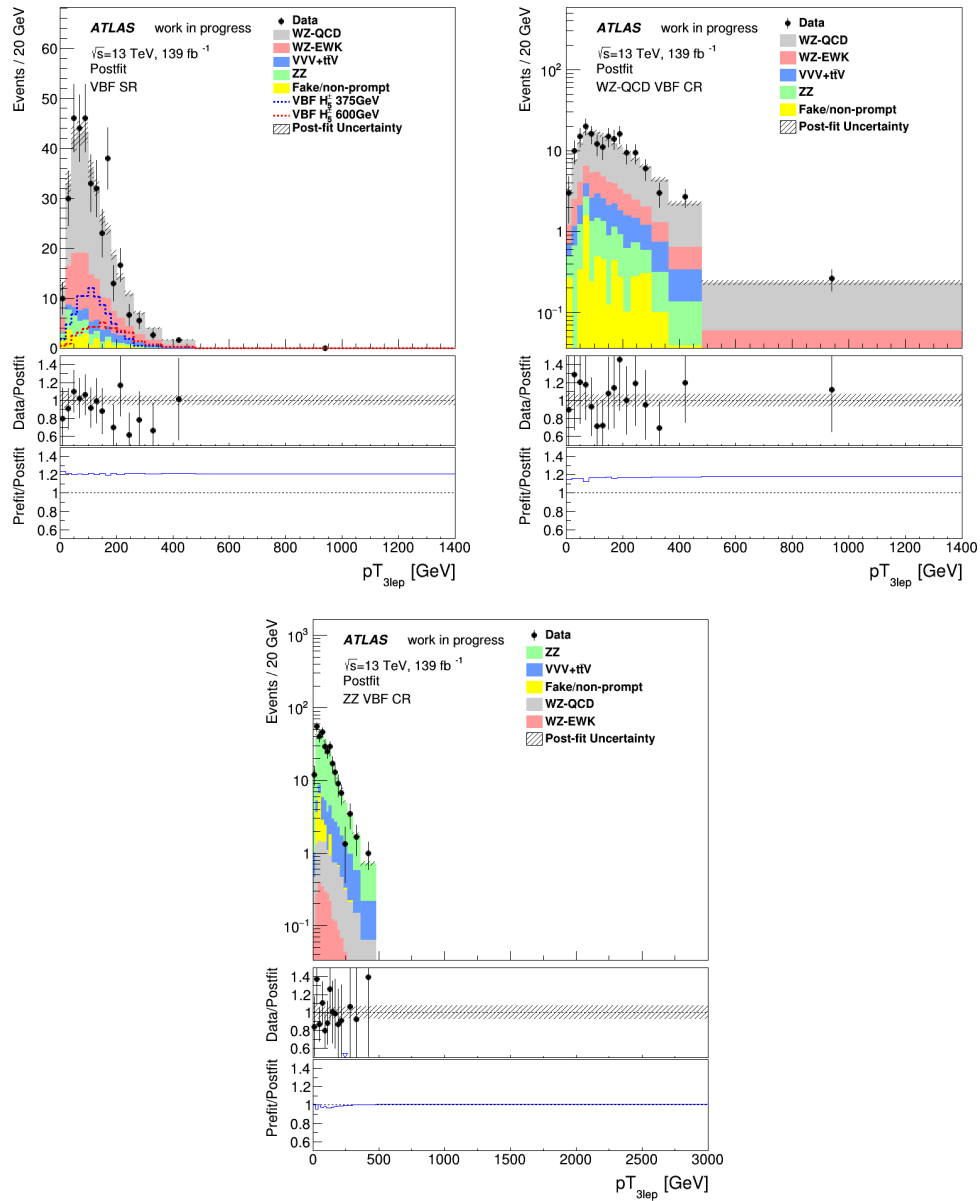


FIGURE 12.56: The postfit transverse momentum of the three leptons from the WZ decay distributions of the vbf SR +CR and ZZjj CR for GM signals fit are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.808 ± 0.094
μ_{ZZ}	1.099 ± 0.187

TABLE 12.28: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for GM signals, using the pT_{3lep} distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	97.68 ± 8.98
WZQCD	220.3 ± 18.77
ZZ	24.35 ± 3.86
Fakes	18.78 ± 6.06
VVV+ $t\bar{t}V$	26.98 ± 5.81
Total Expected Background	388.1 ± 21.75
Observed	381

TABLE 12.29: Expected and observed postfit yields in the vbf signal region for GM signals, using the pT_{3lep} distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and ZZjj CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.6 *Sum3Pt*

12.6.6.1 *Drell – Yan*

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in Drell-Yan-enriched category using the *Sum3Pt* distribution as input to the fit. Masses below 2200 GeV can be excluded for Model A and 2300 GeV for Model B.

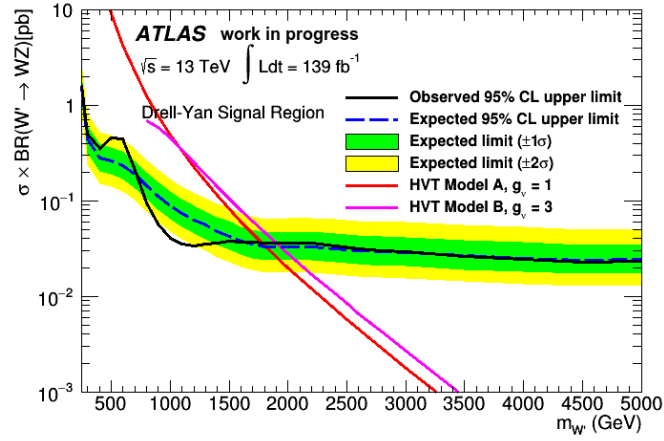


FIGURE 12.57: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in Drell-Yan-enriched category using the *Sum3Pt* distribution as input to the fit. Masses below 2200 GeV can be excluded for Model A and 2300 GeV for Model B.

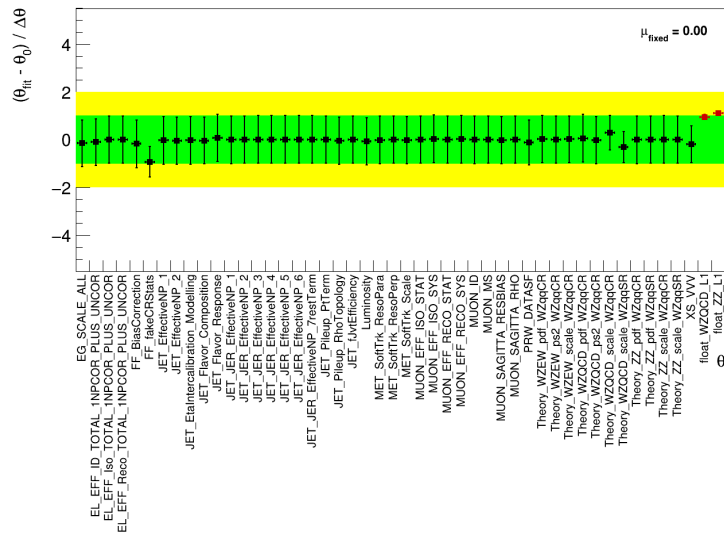


FIGURE 12.58: Nuisance parameter pulls for the SR+CR fit in the Drell-Yan category for 500 GeV mass point using the *Sum3Pt* distribution as input to the fit.

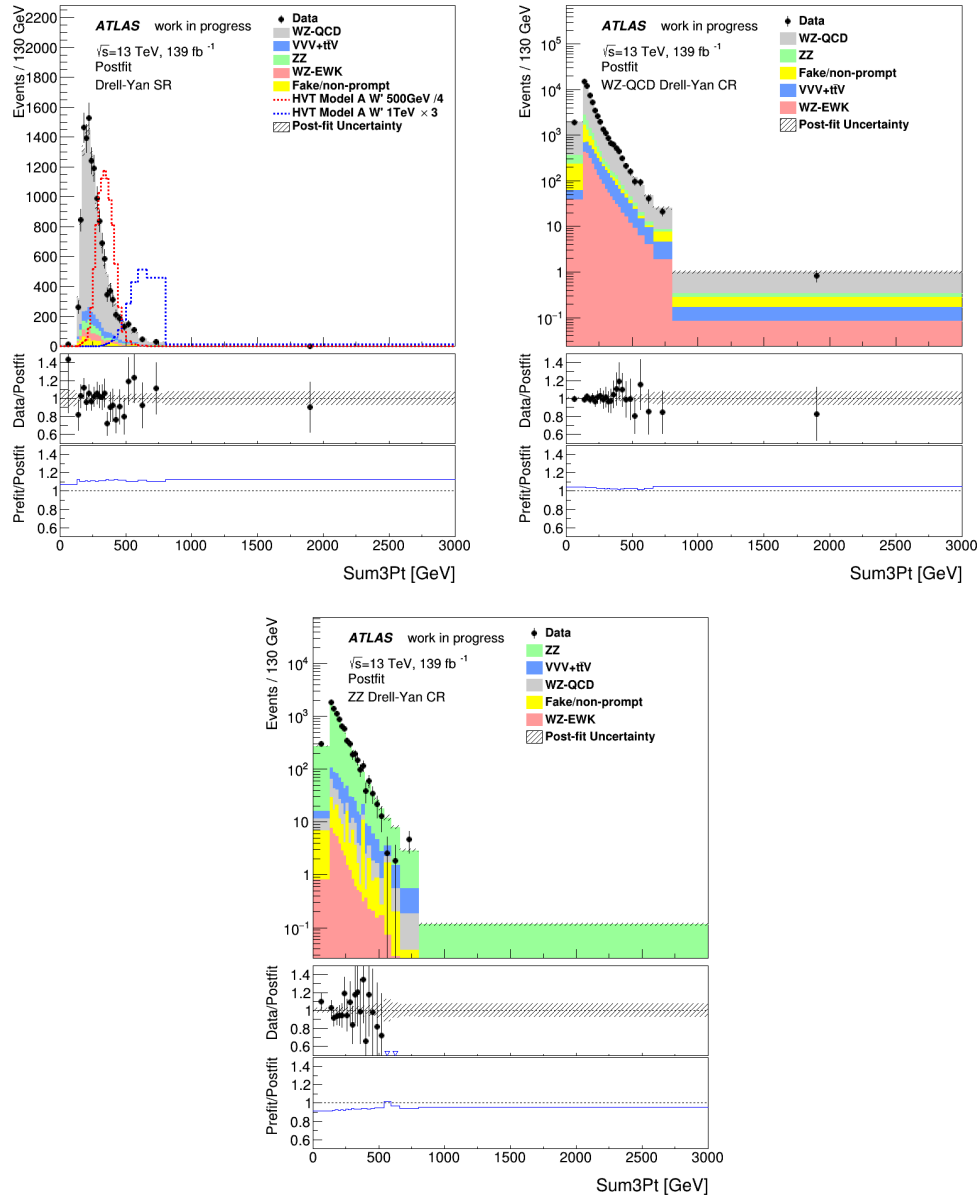


FIGURE 12.60: The postfit sum of the transverse momenta of the three leptons of WZ decay distributions of the Drell-Yan SR +CR and ZZ CR are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.885 ± 0.099
μ_{ZZ}	1.094 ± 0.066

TABLE 12.30: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous Drell-Yan $W^\pm Z$ SR/CR and ZZ CR fit with data, using the *Sum3Pt* distribution as input to the fit for the 500 GeV mass point.

	Drell-Yan SR
WZEW	90.12 ± 6.32
WZQCD	1749.14 ± 65.81
ZZ	94.8 ± 6.01
Fakes	80.94 ± 32.35
VVV+ $t\bar{t}V$	142.28 ± 26.33
Total Expected Background	2157.29 ± 68.5
Observed	2155

TABLE 12.31: Expected and observed postfit yields in the Drell-Yan signal region, using the *Sum3Pt* distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the Drell-Yan SR/CR and ZZ CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.6.2 vbfHVT

$VV + t\bar{t}V$ and some jet systematics have the highest impact on the calculation of the signal-strength parameter μ .

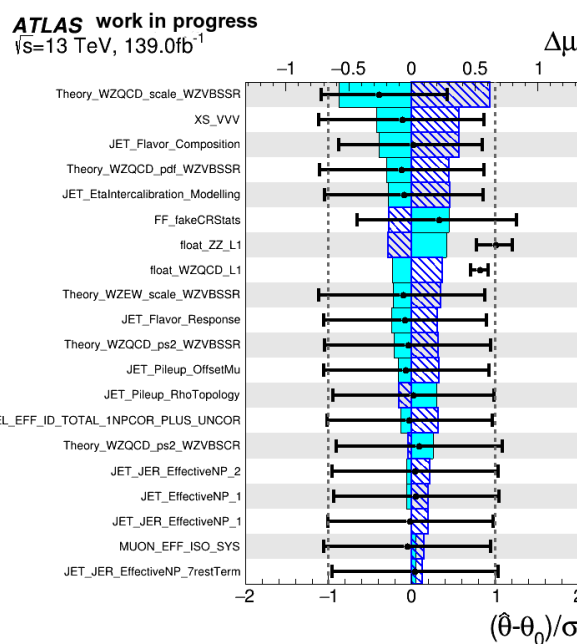
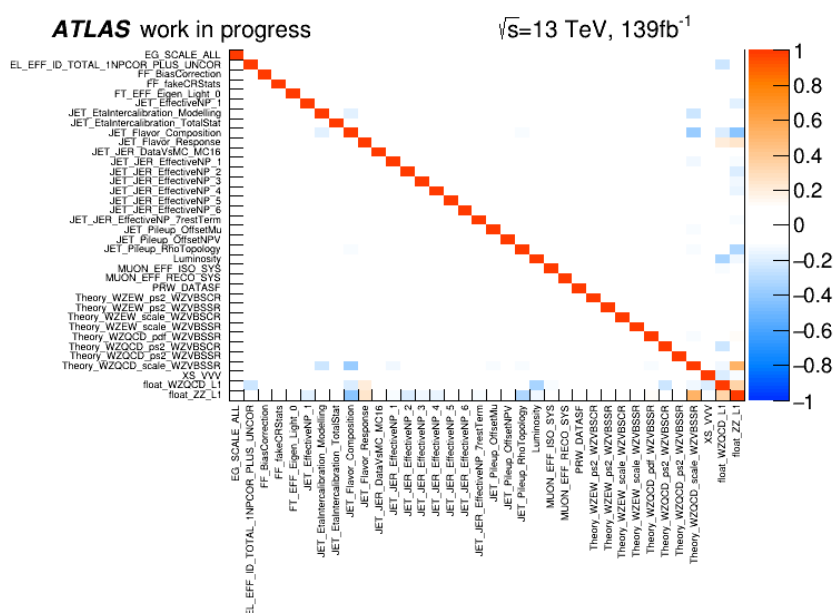


FIGURE 12.63: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized HVT signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The *Sum3Pt* distribution used as input to the fit.

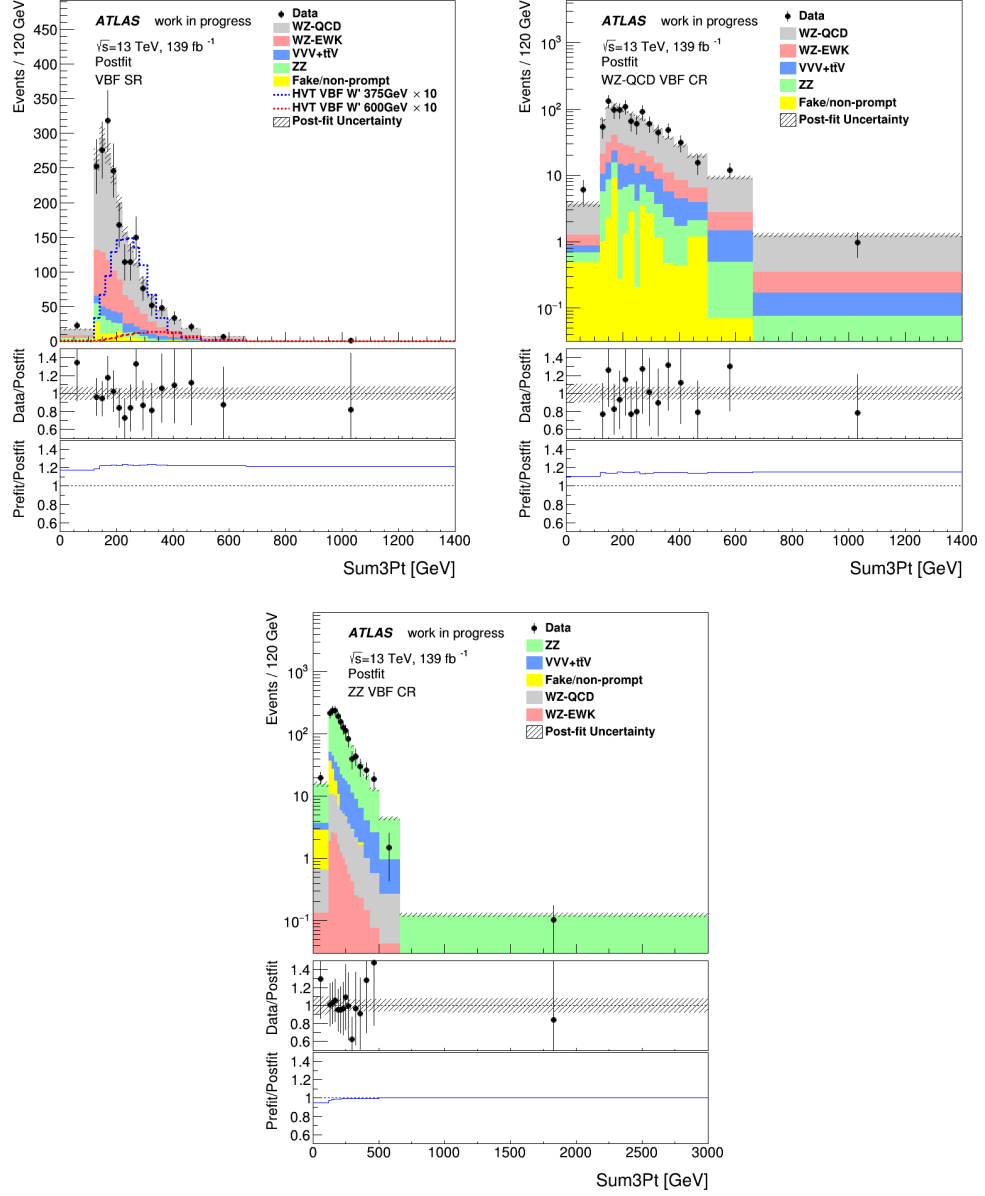


FIGURE 12.64: The postfit sum of the transverse momenta of the three leptons of WZ decay distributions of the vbf SR +CR and ZZjj CR are shown for vbfHVT signals fit. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.823 ± 0.104
μ_{ZZ}	1.022 ± 0.213

TABLE 12.32: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for vbfHVT signals, using the *Sum3Pt* distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	99.81 ± 10.18
WZQCD	212.06 ± 23.56
ZZ	25.3 ± 4.19
Fakes	18.53 ± 6.45
VVV+ $t\bar{t}V$	29 ± 6.41
Total Expected Background	384.7 ± 23.27
Observed	381

TABLE 12.33: Expected and observed postfit yields in the vbf signal region for vbfHVT signals, using the *Sum3Pt* distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and $ZZjj$ CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.6.6.3 vbfGM

We have calculated the observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the $Sum3Pt$ distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

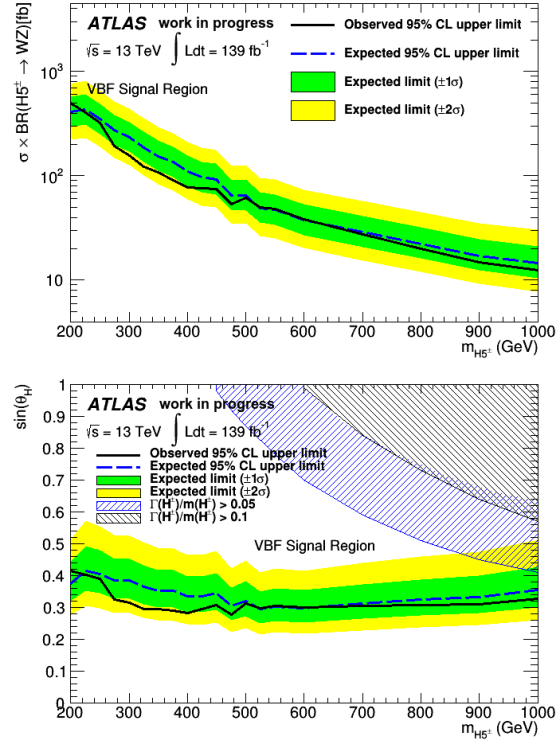


FIGURE 12.65: Observed and expected 95% C.L. exclusion upper limits with an integrated luminosity of 139 fb^{-1} on the production cross-section multiplied by the branching fraction for the signal selections in the in vbf-enriched category for GM signals using the $Sum3Pt$ distribution as input to the fit. Limits are also calculated for the theory parameter $\sin(\theta_H)$. The shaded region shows where the theoretical intrinsic width of the resonance would be larger than 5% or 10% of the mass.

No over-constraints are present; some systematics are pulled but within 1σ so the fit is considered as healthy. The WZ-QCD scale uncertainty, the cross-section of $VVV + t\bar{t}V$, $JET_Flavor_Composition$, the $FF_fakeCRStats$ and μ_{ZZ} have the highest impact on the calculation of the signal-strength parameter μ .

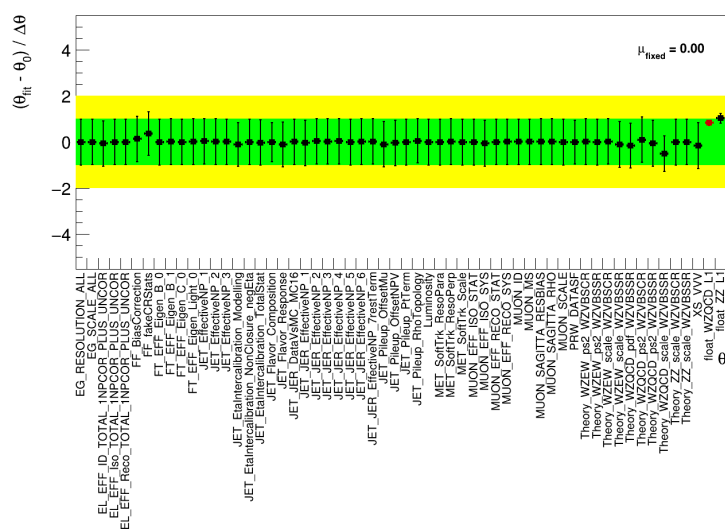


FIGURE 12.66: Nuisance parameter pulls for the SR+CR fit in the vbf category for 500 GeV GM mass point using the $Sum3Pt$ distribution as input to the fit.

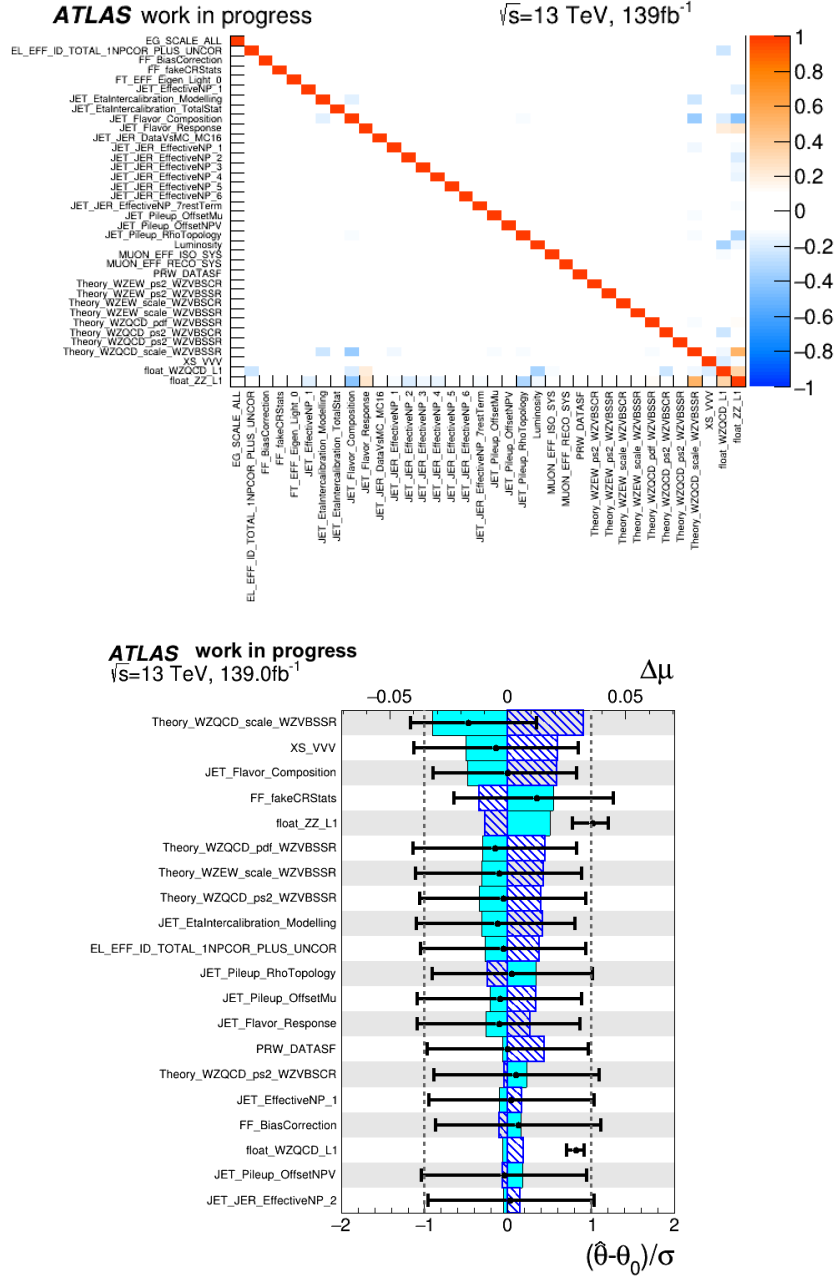


FIGURE 12.67: Nuisance parameters correlation plot and dominant relative uncertainties in the signal-strength parameter μ (ranking plot) of hypothesized GM signal production of mass 500 GeV in the vbf category, assuming that the production cross-sections equal the expected 95% CL upper limits. The *Sum3Pt* distribution used as input to the fit.

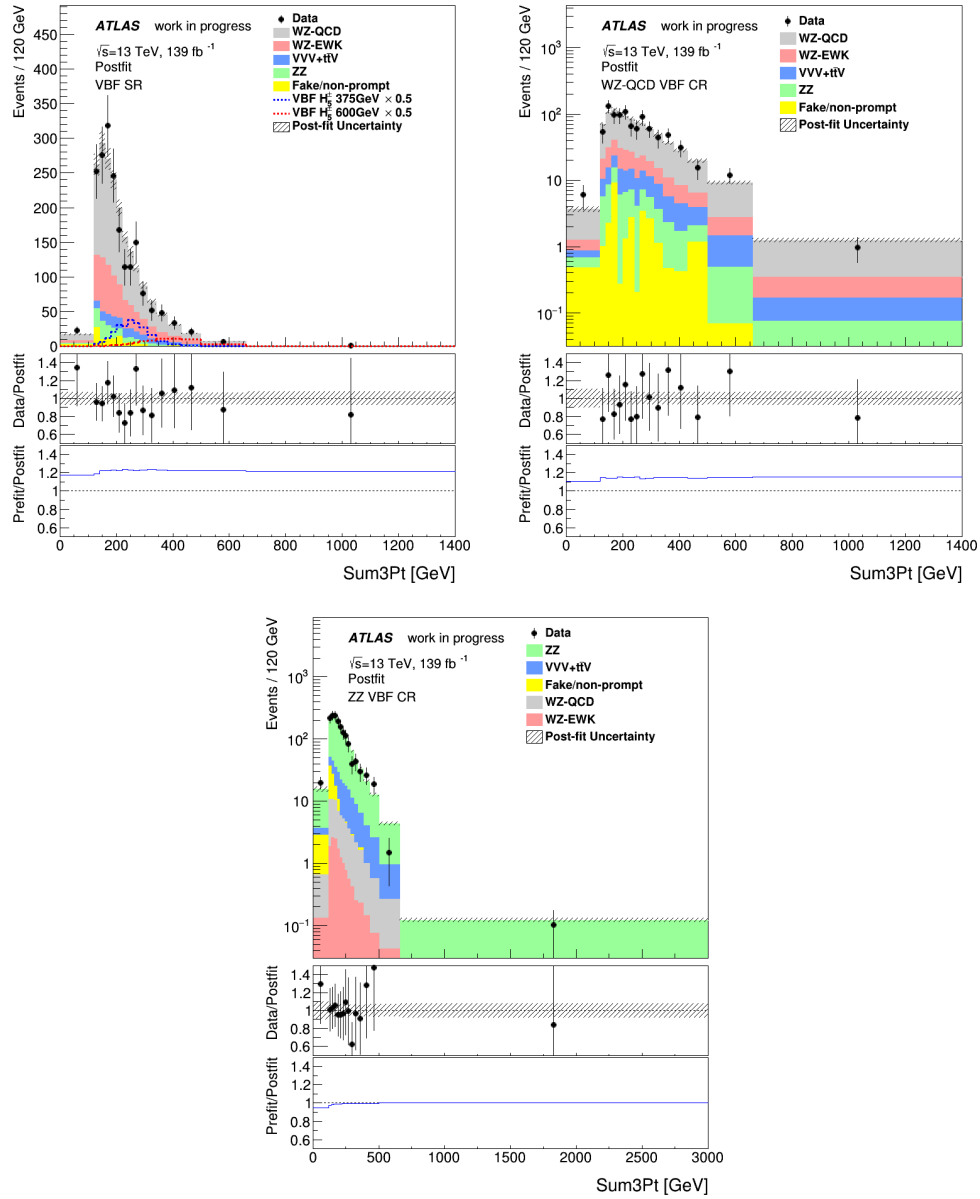


FIGURE 12.68: The postfit sum of the transverse momenta of the three leptons from the WZ decay distributions of the vbf SR +CR and ZZjj CR for GM signals fit are shown. The ratio panel in the middle shows the ratio Data/Postfit background, the postfit uncertainties are shown as shaded area. The panel on the bottom shows the Prefit/Postfit ratio.

μ_{WZ}^{QCD}	0.823 ± 0.104
μ_{ZZ}	1.022 ± 0.213

TABLE 12.34: Scaling factors for the floating normalization for WZQCD and ZZ in simultaneous vbf $W^\pm Z$ SR/CR and ZZjj CR fit with data for GM signals, using the *Sum3Pt* distribution as input to the fit for the 500 GeV mass point.

	vbf SR
WZEW	99.81 ± 10.19
WZQCD	212.06 ± 23.56
ZZ	25.3 ± 4.19
Fakes	18.53 ± 6.45
VVV+ $t\bar{t}V$	29 ± 6.41
Total Expected Background	384.7 ± 23.27
Observed	381

TABLE 12.35: Expected and observed postfit yields in the vbf signal region for GM signals, using the *Sum3Pt* distribution as input to the fit. Yields and uncertainties are evaluated after a background-only fit to the data using the simultaneous fit of the vbf SR, vbf CR and $ZZjj$ CR. The uncertainty on the total background estimate can be smaller than the quadratic sum of the individual background contributions due to anti-correlations between the estimates of different background sources.

12.7 Results

12.7.1 Drell-Yan expected and observed limits comparison

When we compare the limits obtained with different variables for the Drell-Yan category, although in general the invariant mass of the WZ system (m_{WZ}) seems to be the best for limits setting, for masses below around 1100 GeV (800 GeV) for the observed (expected) case the transverse mass of the WZ system (m_T^{WZ}) gives almost equivalent results. A more detailed comparison of the limits obtained using each variable is described in Tables E.1 and E.2 in Appendix E.

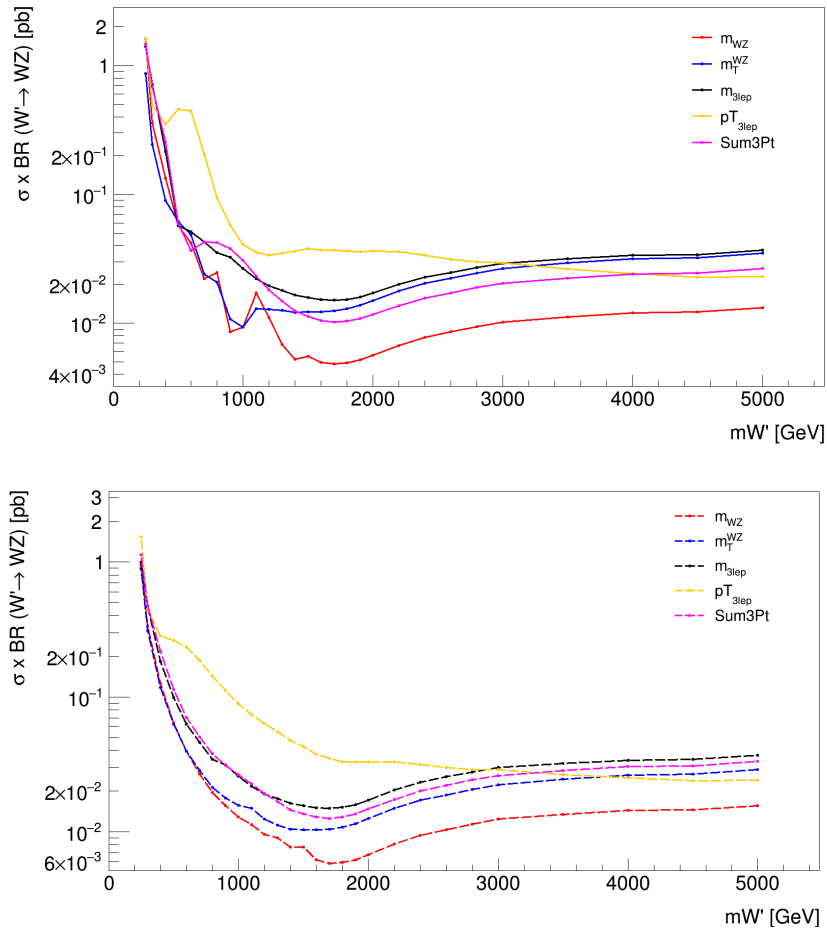


FIGURE 12.69: Observed (up) and expected (bottom) limits comparison using different variables as an input to the likelihood fit for the Drell-Yan category.

12.7.2 vbfHVT expected and observed limits comparison

When we compare the limits obtained with different variables for the *vbfHVT* category, the invariant mass of the WZ system (m_{WZ}) seems to be the best for limits setting, up to a mass of around 1000 GeV for the expected limits; above that mass the transverse mass of the WZ system (m_T^{WZ}), the invariant mass of the three leptons (m_{3lep}), the 2-dimensional fit with m_T^{WZ} & m_{jj} and the sum of the transverse momenta (*Sum3Pt*) of the three leptons (above 1150 GeV) give better limits for the expected limits case. For the observed limits, up to a mass of around 700 GeV the 2-dimensional fit with m_T^{WZ} & m_{jj} appear to give better results than the nominal m_{WZ} . On the other hand, for masses above 1200 GeV m_{3lep} , m_T^{WZ} and *Sum3Pt* provide better limits as well. A more detailed comparison of the limits obtained using each variable is described in Tables E.3 and E.4 in Appendix E.

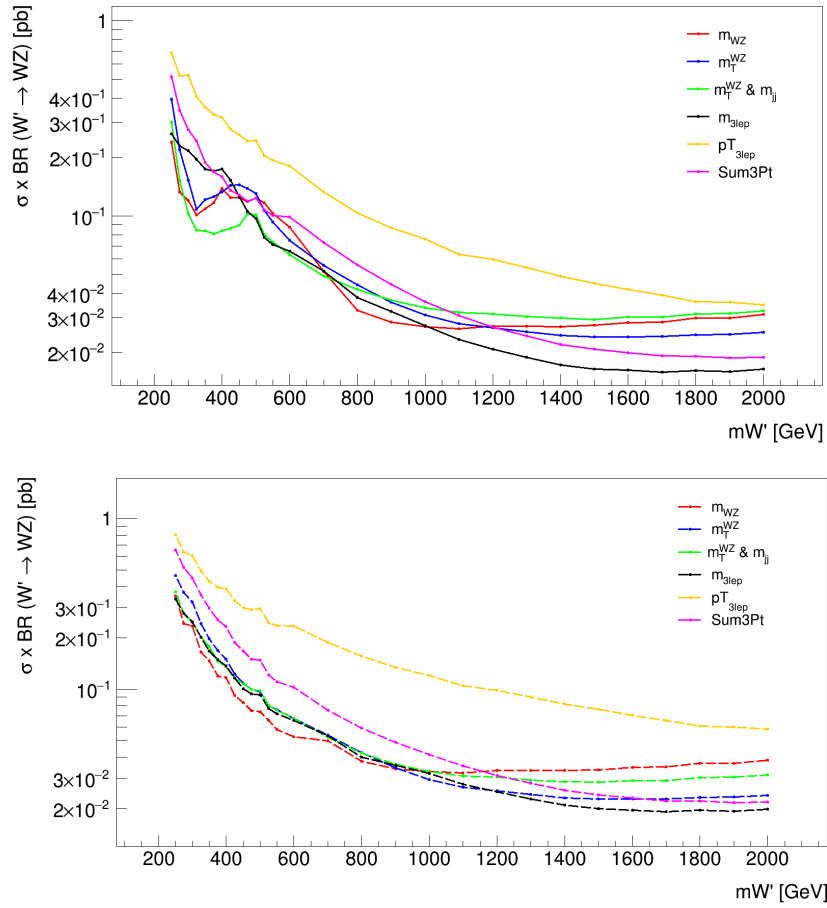


FIGURE 12.70: Observed (up) and expected (bottom) limits comparison using different variables as an input to the likelihood fit for the *vbfHVT* category.

12.7.3 vbfGM expected and observed limits comparison

When we compare the limits obtained with different variables for the *vbfGM* category, the invariant mass of the WZ system (m_{WZ}) seems to be best for limits setting up to a mass of around 280 GeV (360 GeV) for the observed (expected) limits case; above that mass point the transverse mass of the WZ system (m_T^{WZ}) in two dimensional fit with the invariant mass of the two jets (m_{jj}) and the transverse mass of the WZ system (m_T^{WZ}) provide better results. A more detailed comparison of the limits obtained using each variable is described in Tables E.5 and E.6 in Appendix E.

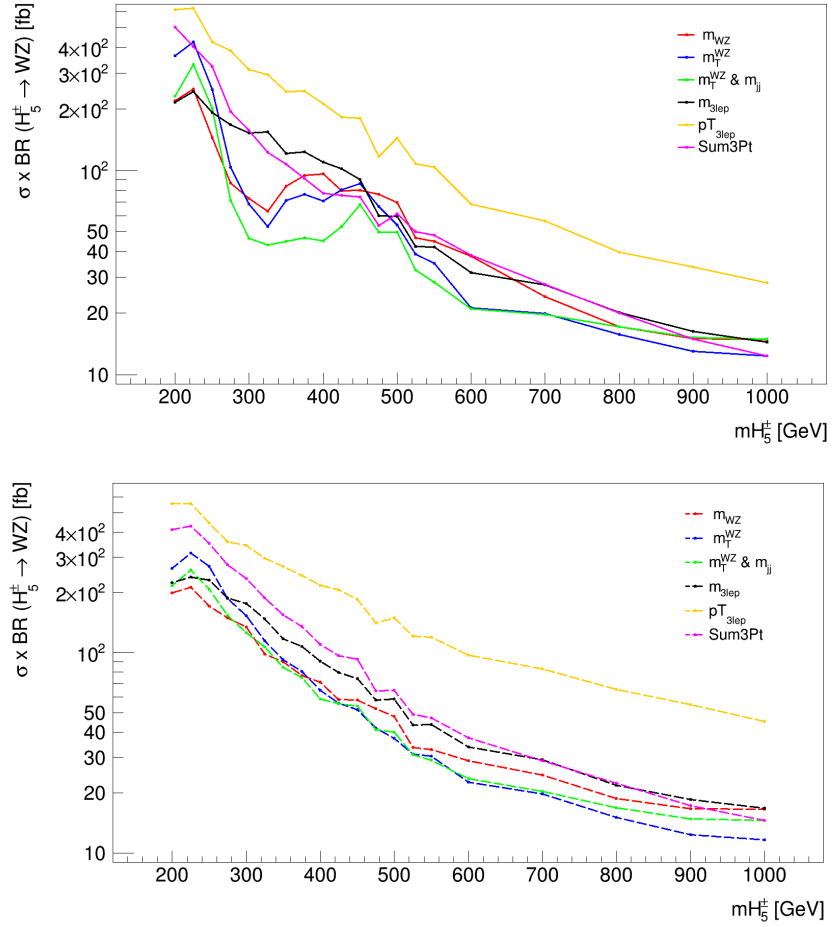


FIGURE 12.71: Observed (up) and expected (bottom) limits comparison using different variables as an input to the likelihood fit for the *vbfGM* category.

We also compare the limits obtained with different variables for the $vbfGM$ category for the $\sin\theta_H$ parameter. The invariant mass of the WZ system (m_{WZ}) seems to be best for limits setting up to a mass of around 300 GeV (360 GeV) for the observed (expected) limits case; above that mass point the transverse mass of the WZ system (m_T^{WZ}) in two dimensional fit with the invariant mass of the two jets (m_{jj}) and the transverse mass of the WZ system (m_T^{WZ}) provide better results.

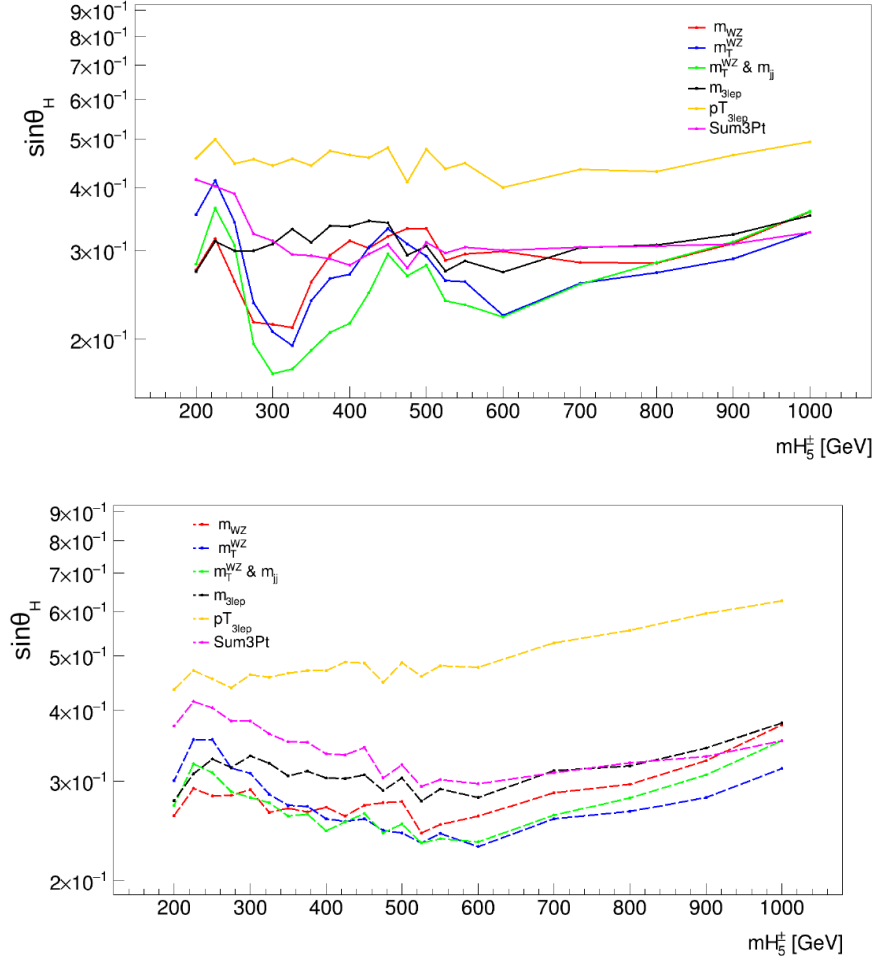


FIGURE 12.72: Observed (up) and expected (bottom) limits comparison using different variables as an input to the likelihood fit for the $vbfGM$ category for the $\sin\theta_H$ parameter.

12.7.4 Comparisons of $\mu_{WZ}^{QCD} / \mu_{ZZ}$ for the 500 GeV mass point

12.7.4.1 $\mu_{WZ}^{QCD} / \mu_{ZZ}$ comparison for Drell-Yan

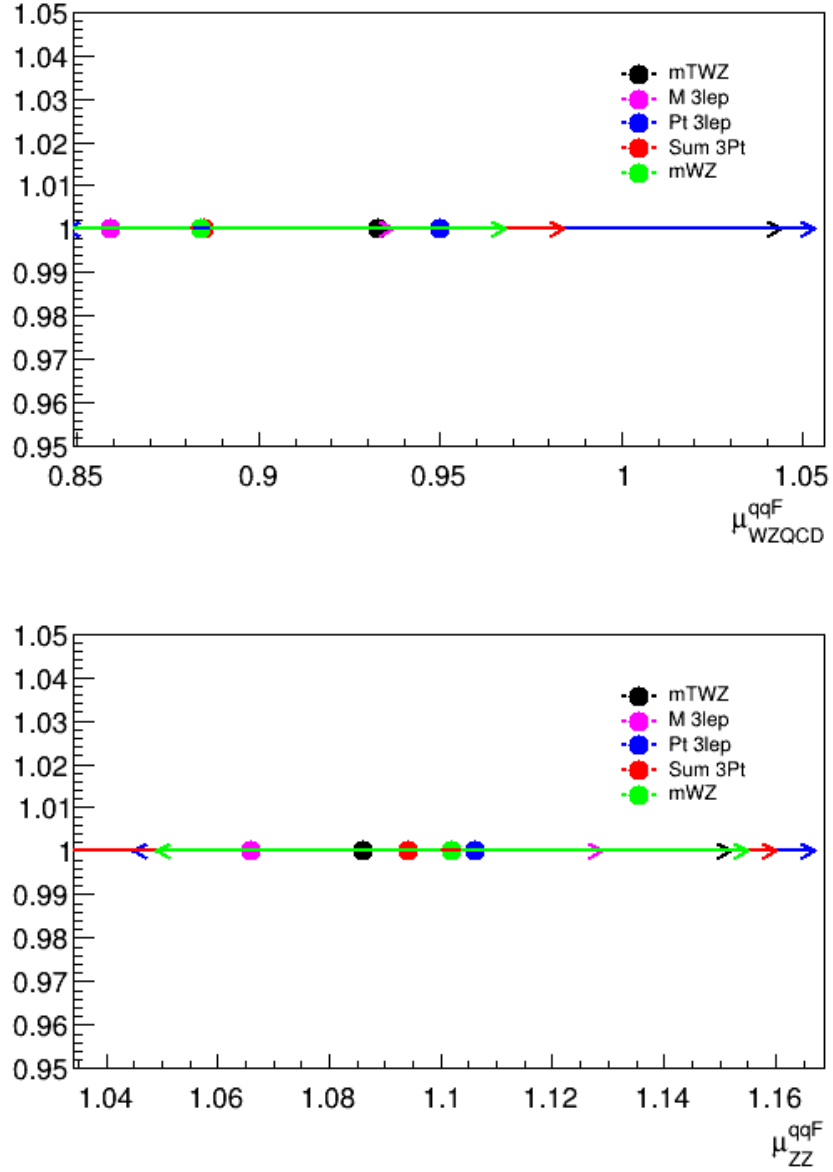


FIGURE 12.73: μ_{WZ}^{QCD} (up) and μ_{ZZ} (bottom) normalization factors comparison using different variables as an input to the likelihood fit for the Drell-Yan category.

12.7.4.2 $\mu_{WZ}^{QCD} / \mu_{ZZ}$ comparison for $vb fHVT$

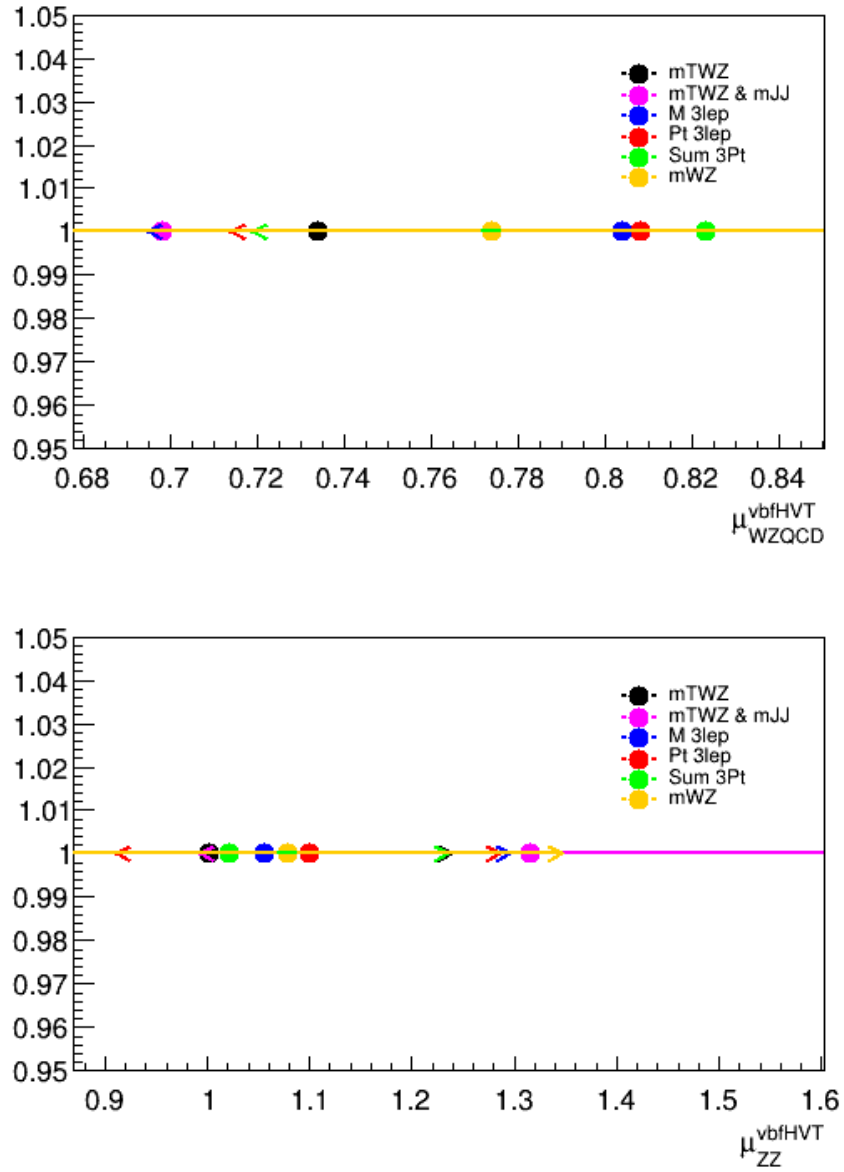


FIGURE 12.74: μ_{WZ}^{QCD} (up) and μ_{ZZ} (bottom) normalization factors comparison using different variables as an input to the likelihood fit for the $vb fHVT$ category.

12.7.4.3 $\mu_{WZ}^{QCD} / \mu_{ZZ}$ comparison for vbfGM

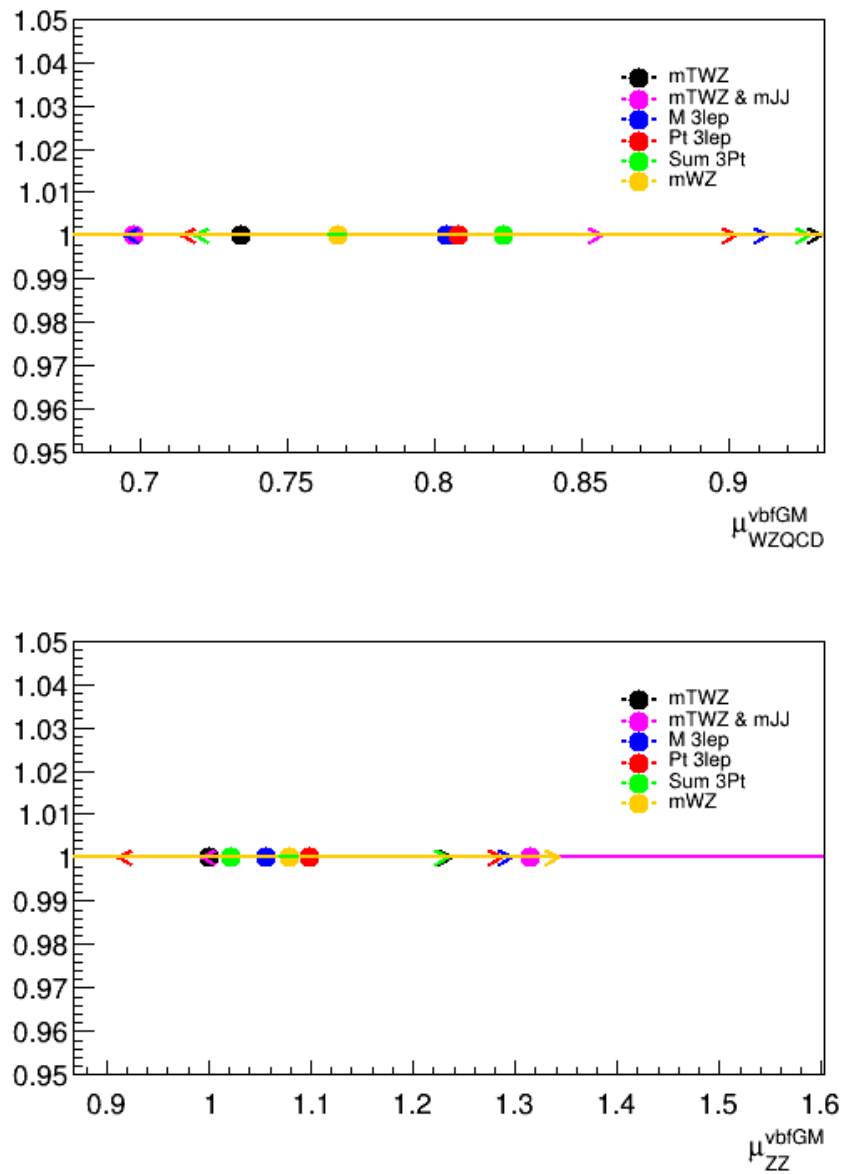


FIGURE 12.75: μ_{WZ}^{QCD} (up) and μ_{ZZ} (bottom) normalization factors comparison using different variables as an input to the likelihood fit for the $vbfGM$ category.

Chapter 13

Conclusions

Standard Model (SM) is a well-established physical theory that describes the fundamental particles (elementary particles) of matter and the interactions developed between them (forces). Although the observation of the W and Z bosons, the top quark, the tau neutrino and especially the Higgs boson attributed high credibility to the Standard Model, several unexplained phenomena like the baryon asymmetry, the incorporation of gravity and the existence of dark matter/energy have given rise to beyond Standard Model theoretical scenarios. So, the scientific challenge now is towards the direction of experimentally verifying these theories (when possible) and investigating a possible extension or modification of the Standard Model. As we know, the search for diboson resonances is an essential probe for understanding the source of electroweak symmetry breaking (EWSB). In the Standard Model (SM), the strength of the coupling of the Higgs scalar to vector boson pairs is well predicted, but it is well known that the low mass of the Higgs boson leads to hierarchy and naturalness problems suggesting that the SM is only an effective theory at low masses. As a result, there is need for New Physics to be introduced for higher masses, focusing on multi-lepton final states which provide us with clear signal signatures.

The analysis performed in this PhD thesis targeted on the search for resonances predicted by two distinct beyond SM signal hypothesis: a spin-1 W' from the parametrization of heavy vector triplet (HVT) Lagrangians and a spin-0 charged higgs $H^\pm$ boson, predicted by Georgi-Machacek (GM) model. More specifically, we study the resonant WZ diboson production using 139 fb^{-1} data collected at 13 TeV center of mass energy by the ATLAS detector at the LHC, where only the leptonic final states (e or μ) are considered for the W and Z boson decays. Being part of the corresponding $X \rightarrow WZ \rightarrow l\nu ll$ ($l = e$ or μ) ATLAS analysis team, the author took part in the cutflow comparison between two different available analysis frameworks, concerning the electron, muon and jet objects and finally the WZ region selected events; an important procedure because the crosscheck between different frameworks performing the same analysis

provides high credibility to the final results. Furthermore, we studied the optimization of the muon isolation working points aiming to select the most optimal configuration that reduces the background events, while maintaining the signal efficiency as high as possible. Moreover, the theoretical uncertainties (pdf, renormalization / factorization and parton shower) have been calculated for the different signals and for the analysis irreducible background (WZ and ZZ). Especially for the parton shower uncertainty, in the absence of known parameteric forms we examined three different formulas and took our final decision based on their impact on the final fit behaviour (checking for pulls / overconstraints).

Concerning the two available theoretical models (Heavy Vector Triplet and Georgi-Machacek) no significant deviations from SM were observed, so we set 95 % CL limits on the production cross-section times branching ratio as a function of the resonance mass. For the Georgi-Machechek model we also set limits on the theoretical parameter $\sin\theta_H$ as a function of the resonance mass. Two different production modes were considered, the vector boson fusion and the Drell-Yan process (quark- anti quark fusion), on which independent limits are set. Although the nominal discriminating variable for the limits setting procedure was the invariant mass of the WZ system (m_{WZ}), different options were examined too and limits were obtained using alternative variables : the invariant mass of the three leptons (m_{3lep}), the transverse mass of the WZ system (m_T^{WZ}), the transverse momentum of the three leptons (pT_{3lep}), the numerical sum of the transverse momenta of the three leptons ($Sum3Pt$) and a two-dimensional fit using the invariant mass of the two jets (m_{jj}) together with the m_T^{WZ} . For some mass ranges, the alternative discriminating variables provide us with stricter limits than the nominal m_{WZ} ; especially for the vbfGM signals above 280 GeV (360 GeV) for the observed (expected) limits, the m_T^{WZ} and the m_T^{WZ} in two dimensional fit with the m_{jj} provide better 95 % CL limits.

Taking into account the impressively improved limits in the $X \rightarrow WZ \rightarrow l\nu ll$ published results [104] - where an artificial neural network approach (ANN) was performed in order to define the VBF signal regions that resulted in around 50 % decrease in background events- an interesting idea in the future would be to set limits with alternative variables after creating the corresponding ANN signal regions. Furthermore, following the CMS strategy for the GM that produced combined limits of $W^\pm W^\pm + WZ$ (combining $H^{\pm\pm} + H^\pm$ models) for the $\sin\theta_H$ parameter, we could also produce combined limits as well [132]. Finally with more statistics in the future, we could probably derive a normalization scale factor for the WZ-EWK background as well.

The LHC now targets to achieve higher luminosity in order to increase the available statistics, but also increase the possibility of observing new “rare” or beyond SM physic processes. But the high particle rates request extended technical upgrades to maintain high level detector performance; in this direction the New Small Wheel (NSW) project took place in order to prevent

possible efficiency loss and limited spatial resolution in the end-caps of the Muon Spectrometer. During the first PhD academic years, it was a privilege to be part of the LM2 drift panels production by the ATLAS NSW Thessaloniki team. Taking part in the technical production of the LM2 drift panels, the performance of tight QA/QC measurements and the maintenance of the NSW database, we got a whole new perspective in the experimental procedures besides the physics analysis of the experimental data.

The LHC experiments have already validated many aspects of the Standard Model and especially the existence of the SM Higgs boson. The forthcoming increase in luminosity broadens the spectrum of the signals that may indicate the existence of New Physics beyond SM. As a result, we are excited about the future discoveries by the ATLAS detector that may lead our knowledge into a whole new perspective.

Appendix

Appendix A

Summary of experimental systematic uncertainties

A summary of all systematic uncertainties described in Section 9. The relative effect in percent on the number of events of the different source of systematic is presented. Some very large uncertainties are due to very low statistics.

	$VVV + t\bar{t}V$	ZZ	$WZEW$	$WZQCD$
EG_RESOLUTION_ALL	0.090%	0.062%	0.011%	0.087%
EG_SCALE_AF2	0.000%	0.000%	0.000%	0.000%
EG_SCALE_ALL	0.079%	0.098%	0.074%	0.091%
EL_EFF_ID_TOTAL_1NPCOR_PLUS_UNCOR	1.133%	1.181%	1.186%	1.128%
EL_EFF_Iso_TOTAL_1NPCOR_PLUS_UNCOR	0.171%	0.162%	0.175%	0.163%
EL_EFF_Reco_TOTAL_1NPCOR_PLUS_UNCOR	0.201%	0.199%	0.201%	0.199%
MUON_EFF_ISO_STAT	0.448%	0.446%	0.445%	0.441%
MUON_EFF_ISO_SYS	0.944%	1.092%	0.995%	1.029%
MUON_EFF_RECO_STAT	0.111%	0.126%	0.114%	0.120%
MUON_EFF_RECO_STAT_LOWPT	0.000%	0.000%	0.000%	0.000%
MUON_EFF_RECO_SYS	0.488%	0.519%	0.498%	0.489%
MUON_EFF_RECO_SYS_LOWPT	0.000%	0.000%	0.000%	0.000%
MUON_EFF_TTVA_STAT	0.069%	0.064%	0.069%	0.065%
MUON_EFF_TTVA_SYS	0.098%	0.089%	0.097%	0.091%
MUON_ID	0.105%	0.106%	0.034%	0.039%
MUON_MS	0.045%	0.029%	0.031%	0.037%
MUON_SAGITTA_RESBIAS	0.135%	0.367%	0.122%	0.071%
MUON_SAGITTA_RHO	0.241%	0.625%	0.027%	0.126%
MUON_SCALE	0.009%	0.023%	0.034%	0.041%
MET_SoftTrk_ResoPara	0.115%	1.377%	0.167%	0.290%
MET_SoftTrk_ResoPerp	0.277%	1.597%	0.079%	0.266%
MET_SoftTrk_Scale	0.109%	1.508%	0.109%	0.179%

TABLE A.1: Relative uncertainties for leptons of number of events for Drell-Yan category

	$VVV + t\bar{t}V$	ZZ	$WZEW$	$WZQCD$
FT_EFF_Eigen_B_0	0.119%	0.003%	0.022%	0.009%
FT_EFF_Eigen_B_1	0.063%	0.005%	0.019%	0.008%
FT_EFF_Eigen_B_2	0.025%	0.002%	0.012%	0.001%
FT_EFF_Eigen_B_3	0.004%	0.000%	0.002%	0.000%
FT_EFF_Eigen_B_4	0.000%	0.000%	0.001%	0.000%
FT_EFF_Eigen_B_5	0.000%	0.000%	0.000%	0.000%
FT_EFF_Eigen_B_6	0.000%	0.000%	0.000%	0.000%
FT_EFF_Eigen_B_7	0.000%	0.000%	0.000%	0.000%
FT_EFF_Eigen_B_8	0.000%	0.000%	0.000%	0.000%
FT_EFF_Eigen_C_0	0.003%	0.042%	0.004%	0.049%
FT_EFF_Eigen_C_1	0.009%	0.000%	0.006%	0.009%
FT_EFF_Eigen_C_2	0.001%	0.001%	0.001%	0.002%
FT_EFF_Eigen_C_3	0.000%	0.002%	0.000%	0.001%
FT_EFF_Eigen_Light_0	0.058%	0.020%	0.058%	0.022%
FT_EFF_Eigen_Light_1	0.001%	0.003%	0.005%	0.000%
FT_EFF_Eigen_Light_2	0.004%	0.003%	0.016%	0.008%
FT_EFF_Eigen_Light_3	0.001%	0.000%	0.002%	0.000%
FT_EFF_extrapolation	0.014%	0.000%	0.025%	0.003%
FT_EFF_extrapolation_from_charm	0.009%	0.009%	0.012%	0.014%

TABLE A.2: Relative uncertainties for flavor-tagging of number of events for Drell-Yan category

	$VVV + t\bar{t}V$	ZZ	$WZEW$	$WZQCD$
JET_BJES_Response	0.000%	0.000%	0.000%	0.000%
JET_EffectiveNP_1	0.445%	0.491%	0.377%	0.387%
JET_EffectiveNP_2	0.084%	0.084%	0.166%	0.134%
JET_EffectiveNP_3	0.125%	0.062%	0.097%	0.089%
JET_EffectiveNP_4	0.050%	0.028%	0.035%	0.018%
JET_EffectiveNP_5	0.009%	0.025%	0.032%	0.022%
JET_EffectiveNP_6	0.012%	0.029%	0.021%	0.013%
JET_EffectiveNP_7	0.017%	0.019%	0.006%	0.004%
JET_EffectiveNP_8restTerm	0.024%	0.008%	0.008%	0.011%
JET_EtaIntercalibration_Modelling	0.253%	0.423%	0.455%	0.182%
JET_EtaIntercalibration_NonClosure_2018data	0.147%	0.116%	0.143%	0.140%
JET_EtaIntercalibration_NonClosure_highE	0.000%	0.001%	0.004%	0.000%
JET_EtaIntercalibration_NonClosure_negEta	0.017%	0.036%	0.009%	0.008%
JET_EtaIntercalibration_NonClosure_posEta	0.024%	0.029%	0.005%	0.008%
JET_EtaIntercalibration_TotalStat	0.058%	0.080%	0.065%	0.048%
JET_Flavor_Composition	0.861%	1.271%	0.800%	0.420%
JET_Flavor_Response	0.863%	1.068%	0.723%	0.708%
JET_JER_DataVsMC_MC16	0.136%	0.280%	0.082%	0.020%
JET_JER_EffectiveNP_1	0.087%	0.807%	0.167%	0.026%
JET_JER_EffectiveNP_2	0.154%	1.111%	0.308%	0.168%
JET_JER_EffectiveNP_3	0.104%	0.681%	0.027%	0.042%
JET_JER_EffectiveNP_4	0.063%	0.810%	0.118%	0.075%
JET_JER_EffectiveNP_5	0.043%	0.577%	0.032%	0.040%
JET_JER_EffectiveNP_6	0.003%	0.589%	0.131%	0.032%
JET_JER_EffectiveNP_7restTerm	0.054%	0.636%	0.124%	0.068%
JET_JvtEfficiency	0.252%	0.630%	0.126%	0.054%
JET_Pileup_OffsetMu	0.170%	0.327%	0.103%	0.024%
JET_Pileup_OffsetNPV	0.270%	0.329%	0.094%	0.107%
JET_Pileup_PtTerm	0.076%	0.125%	0.147%	0.126%
JET_Pileup_RhoTopology	0.419%	0.669%	0.292%	0.272%
JET_PunchThrough_MC16	0.004%	0.002%	0.018%	0.007%
JET_SingleParticle_HighPt	0.000%	0.000%	0.000%	0.000%
JET_fJvtEfficiency	0.161%	0.340%	0.164%	0.132%
PRW_DATASF	0.968%	0.183%	1.804%	1.647%

TABLE A.3: Relative uncertainties for jets of number of events for Drell-Yan category

	$VVV + t\bar{t}V$	ZZ	$WZEW$	$WZQCD$
EG_RESOLUTION_ALL	0.733%	0.608%	0.103%	0.067%
EG_SCALE_AF2	0.000%	0.000%	0.000%	0.000%
EG_SCALE_ALL	0.975%	0.784%	0.178%	0.118%
EL_EFF_ID_TOTAL_1NPCOR_PLUS_UNCOR	1.162%	1.280%	1.082%	0.989%
EL_EFF_Iso_TOTAL_1NPCOR_PLUS_UNCOR	0.173%	0.162%	0.150%	0.137%
EL_EFF_Reco_TOTAL_1NPCOR_PLUS_UNCOR	0.220%	0.217%	0.190%	0.189%
MUON_EFF_ISO_STAT	0.286%	0.232%	0.353%	0.322%
MUON_EFF_ISO_SYS	0.992%	1.307%	1.286%	1.369%
MUON_EFF_RECO_STAT	0.096%	0.095%	0.111%	0.107%
MUON_EFF_RECO_STAT_LOWPT	0.000%	0.000%	0.000%	0.000%
MUON_EFF_RECO_SYS	0.361%	0.302%	0.408%	0.380%
MUON_EFF_RECO_SYS_LOWPT	0.000%	0.000%	0.000%	0.000%
MUON_EFF_TTVA_STAT	0.045%	0.038%	0.054%	0.049%
MUON_EFF_TTVA_SYS	0.067%	0.045%	0.072%	0.066%
MUON_ID	1.341%	0.117%	0.080%	0.057%
MUON_MS	0.844%	0.241%	0.023%	0.133%
MUON_SAGITTA_RESBIAS	1.926%	0.102%	0.019%	0.182%
MUON_SAGITTA_RHO	1.574%	0.262%	0.091%	0.136%
MUON_SCALE	0.020%	0.086%	0.071%	0.078%
MET_SoftTrk_ResoPara	0.200%	3.067%	0.270%	0.439%
MET_SoftTrk_ResoPerp	1.174%	1.335%	0.265%	0.201%
MET_SoftTrk_Scale	0.885%	1.886%	0.200%	0.608%

TABLE A.4: Relative uncertainties for leptons of number of events for VBF category

	$VVV + t\bar{t}V$	ZZ	$WZEW$	$WZQCD$
FT_EFF_Eigen_B_0	2.654%	0.048%	0.289%	0.033%
FT_EFF_Eigen_B_1	0.590%	0.005%	0.060%	0.007%
FT_EFF_Eigen_B_2	0.493%	0.006%	0.052%	0.005%
FT_EFF_Eigen_B_3	0.140%	0.003%	0.016%	0.002%
FT_EFF_Eigen_B_4	0.005%	0.000%	0.000%	0.000%
FT_EFF_Eigen_B_5	0.002%	0.000%	0.000%	0.000%
FT_EFF_Eigen_B_6	0.001%	0.000%	0.000%	0.000%
FT_EFF_Eigen_B_7	0.000%	0.000%	0.000%	0.000%
FT_EFF_Eigen_B_8	0.000%	0.000%	0.000%	0.000%
FT_EFF_Eigen_C_0	0.560%	0.172%	0.074%	0.177%
FT_EFF_Eigen_C_1	0.008%	0.004%	0.018%	0.012%
FT_EFF_Eigen_C_2	0.045%	0.007%	0.004%	0.012%
FT_EFF_Eigen_C_3	0.007%	0.003%	0.001%	0.002%
FT_EFF_Eigen_Light_0	0.541%	0.305%	0.305%	0.440%
FT_EFF_Eigen_Light_1	0.004%	0.006%	0.001%	0.008%
FT_EFF_Eigen_Light_2	0.004%	0.005%	0.010%	0.004%
FT_EFF_Eigen_Light_3	0.004%	0.002%	0.002%	0.003%
FT_EFF_extrapolation	0.001%	0.001%	0.007%	0.004%
FT_EFF_extrapolation_from_charm	0.412%	0.227%	0.008%	0.007%

TABLE A.5: Relative uncertainties for flavor-tagging of number of events for VBF category

	$VVV + t\bar{t}V$	ZZ	$WZEW$	$WZQCD$
JET_BJES_Response	0.000%	0.000%	0.000%	0.000%
JET_EffectiveNP_1	1.381%	4.783%	0.821%	1.912%
JET_EffectiveNP_2	0.254%	0.927%	0.079%	0.408%
JET_EffectiveNP_3	0.146%	0.600%	0.053%	0.260%
JET_EffectiveNP_4	0.491%	0.437%	0.035%	0.090%
JET_EffectiveNP_5	0.280%	0.045%	0.001%	0.059%
JET_EffectiveNP_6	0.225%	0.054%	0.010%	0.070%
JET_EffectiveNP_7	0.225%	0.091%	0.012%	0.093%
JET_EffectiveNP_8restTerm	0.225%	0.085%	0.007%	0.068%
JET_EtaIntercalibration_Modelling	3.855%	12.551%	2.187%	8.753%
JET_EtaIntercalibration_NonClosure_2018data	0.673%	0.404%	0.012%	0.126%
JET_EtaIntercalibration_NonClosure_highE	0.000%	0.010%	0.004%	0.000%
JET_EtaIntercalibration_NonClosure_negEta	0.302%	0.116%	0.038%	0.202%
JET_EtaIntercalibration_NonClosure_posEta	0.252%	0.546%	0.069%	0.392%
JET_EtaIntercalibration_TotalStat	0.659%	1.305%	0.295%	0.837%
JET_Flavor_Composition	3.877%	16.976%	3.347%	12.750%
JET_Flavor_Response	0.702%	6.612%	1.293%	3.259%
JET_JER_DataVsMC_MC16	0.909%	0.295%	0.449%	2.496%
JET_JER_EffectiveNP_1	3.172%	4.993%	1.048%	9.117%
JET_JER_EffectiveNP_2	2.004%	1.254%	0.428%	3.143%
JET_JER_EffectiveNP_3	2.250%	1.434%	0.382%	2.343%
JET_JER_EffectiveNP_4	0.919%	0.188%	0.381%	1.975%
JET_JER_EffectiveNP_5	0.687%	0.141%	0.467%	2.152%
JET_JER_EffectiveNP_6	3.041%	0.264%	0.397%	2.220%
JET_JER_EffectiveNP_7restTerm	0.261%	1.215%	0.225%	1.399%
JET_JvtEfficiency	0.478%	0.262%	0.156%	0.064%
JET_Pileup_OffsetMu	4.374%	10.361%	1.258%	10.504%
JET_Pileup_OffsetNPV	1.301%	5.604%	0.549%	3.161%
JET_Pileup_PtTerm	1.075%	0.491%	0.159%	0.726%
JET_Pileup_RhoTopology	1.015%	8.337%	1.138%	4.707%
JET_PunchThrough_MC16	0.000%	0.000%	0.000%	0.008%
JET_SingleParticle_HighPt	0.000%	0.000%	0.000%	0.000%
JET_fJvtEfficiency	0.955%	0.742%	0.414%	0.315%
PRW_DATASF	2.339%	7.177%	1.101%	7.186%

TABLE A.6: Relative uncertainties for jets of number of events for VBF category

Appendix B

PDF and Scale uncertainties for Drell-Yan and VBF Control Regions

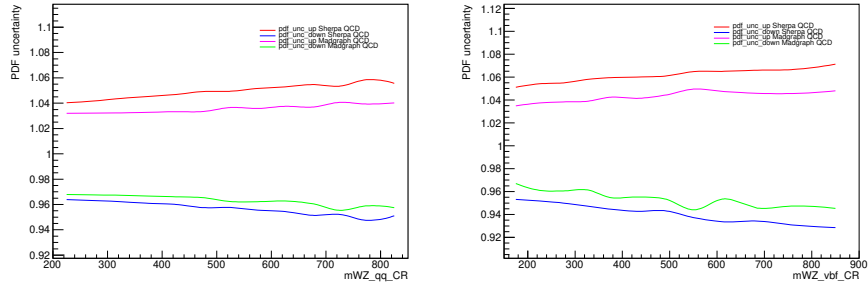


FIGURE B.1: The relative uncertainties on the SM QCD WZ background shape due to PDF as function of the WZ invariant mass in the Drell-Yan (left) and on the VBF control regions (right). Here is shown a comparison of the pdf envelopes between Madgraph and Sherpa QCD.

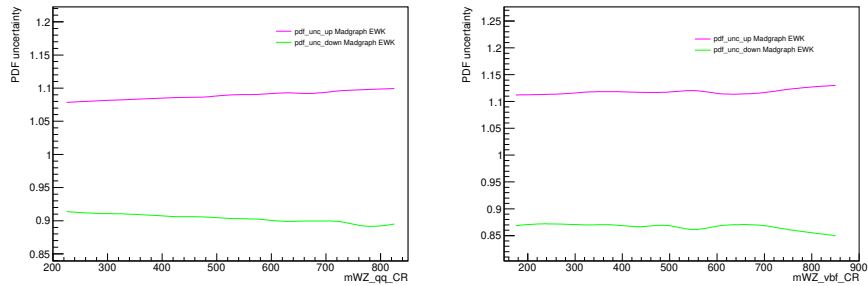


FIGURE B.2: The relative uncertainties on the SM EWK WZ background shape due to PDF as function of the WZ invariant mass in the Drell-Yan (left) and on the VBF control regions (right). Here is shown the pdf envelope of Madgraph EWK.

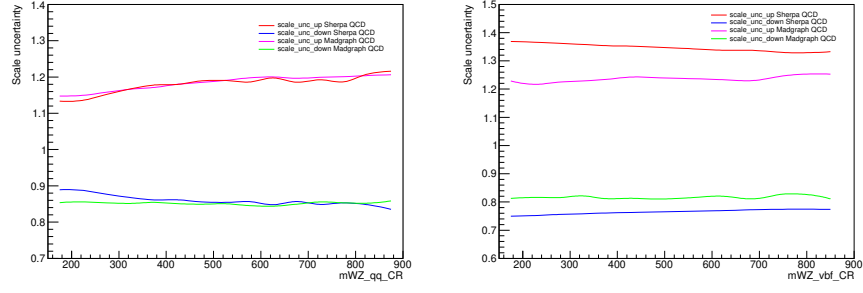


FIGURE B.3: The uncertainties on the SM QCD WZ background shape caused by the choice of the scale as function of the WZ invariant mass. The plot on the left shows the envelope in Drell-Yan and on the right in VBF control regions.

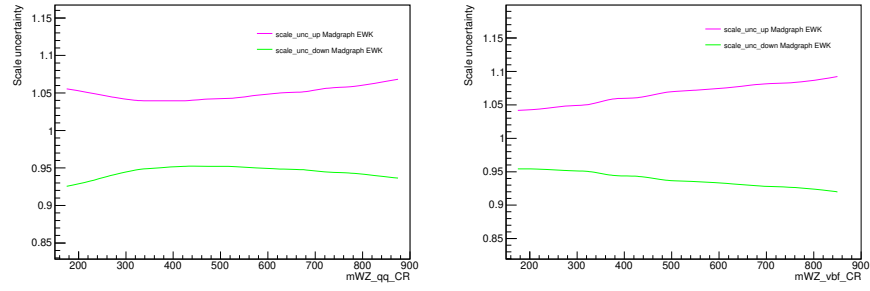


FIGURE B.4: The uncertainties on the SM EW WZ background shape caused by the choice of the scale as function of the WZ invariant mass. The plot on the left shows the envelope in Drell-Yan and on the right in VBF control regions.

Appendix C

Parton shower uncertainty estimation for different formulas

C.1 QCD

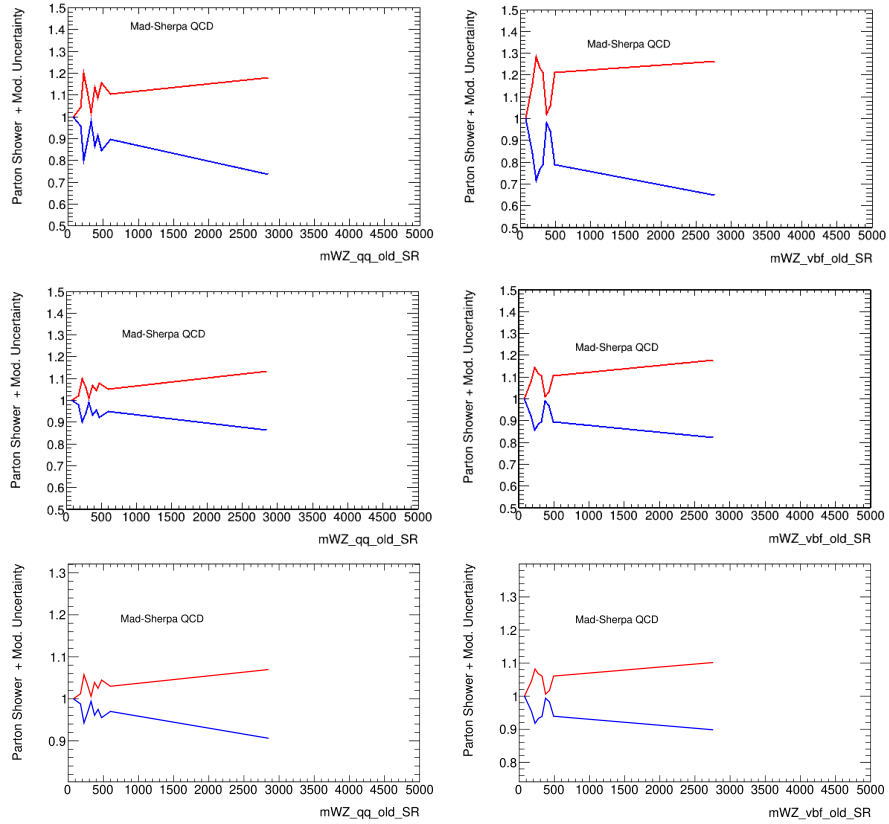


FIGURE C.1: Comparisons of different parton-shower/modelling uncertainty formulas for QCD case: 1st (up), 2nd (middle) and 3rd (bottom), for Drell-Yan (left) and VBF (right) fiducial signal regions.

C.2 EWK

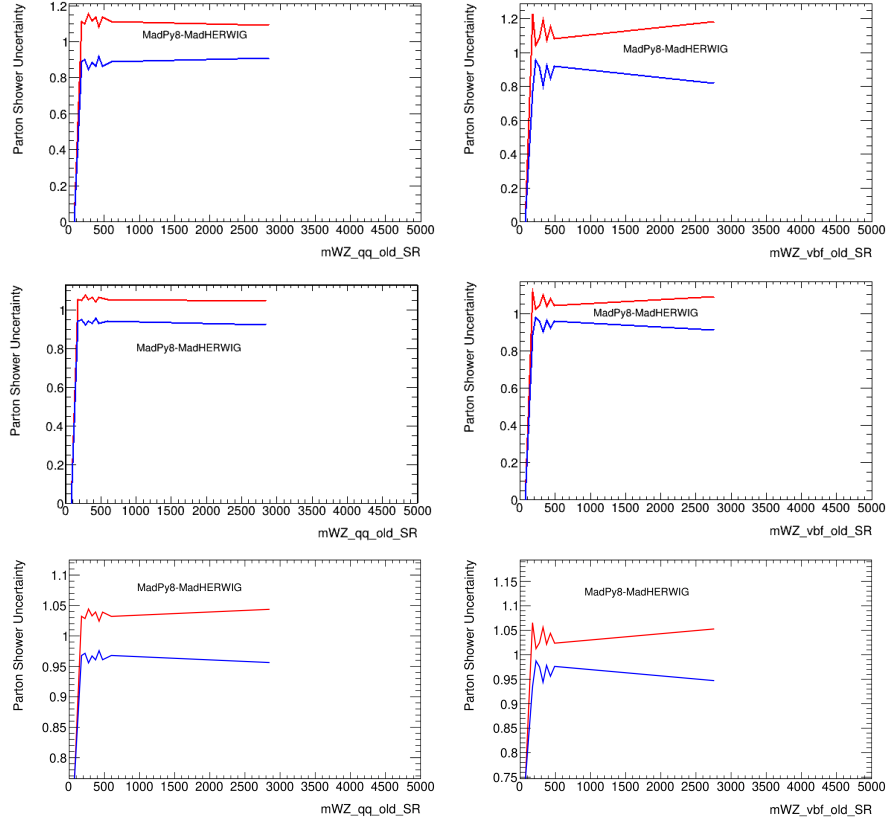


FIGURE C.2: Comparisons of different parton-shower uncertainty formulas for EWK case: 1st (up), 2nd (middle) and 3rd (bottom), for Drell-Yan (left) and VBF (right) fiducial signal regions.

Appendix D

Theoretical uncertainties on Standard Model WZ background using alternative variables

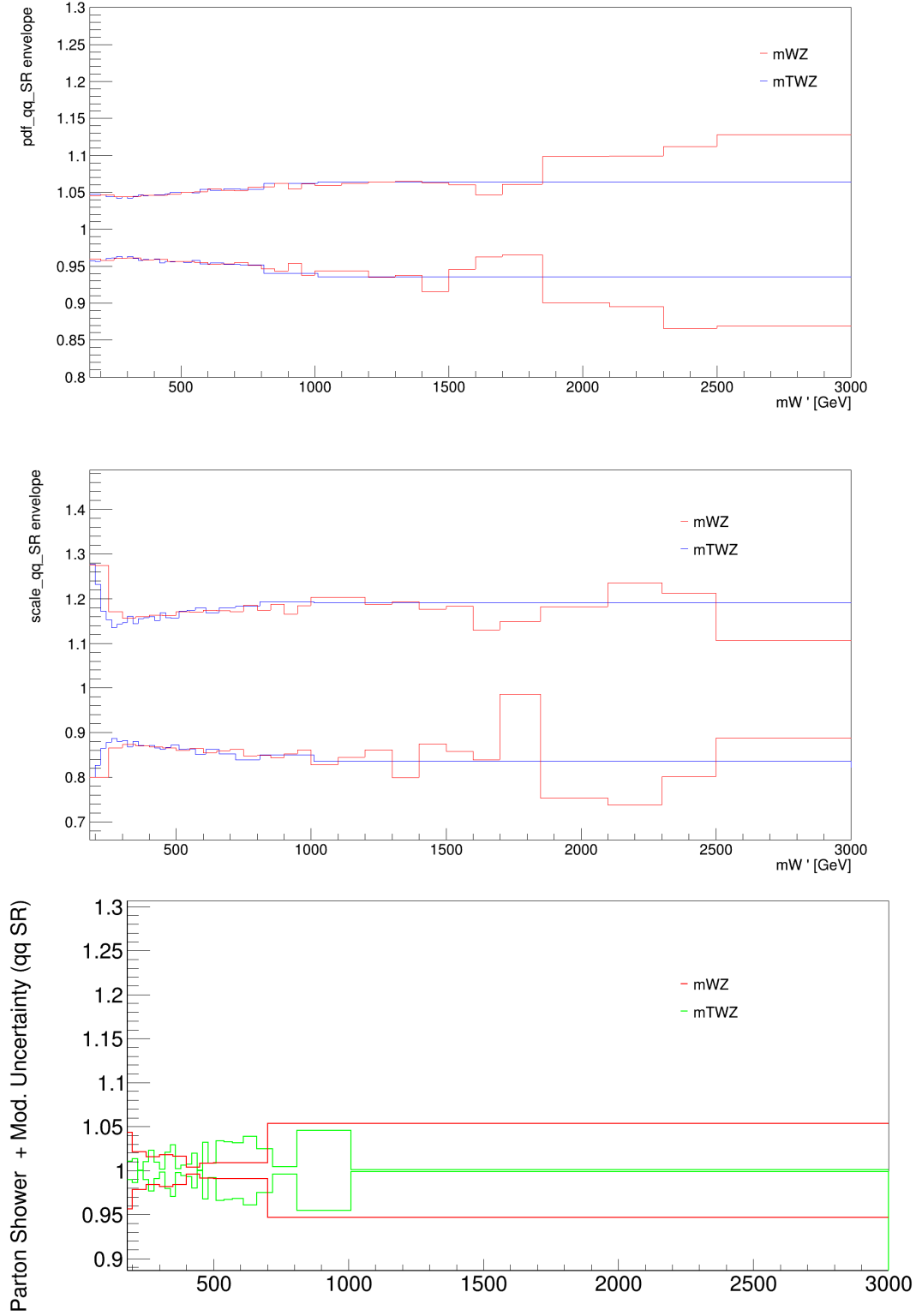


FIGURE D.1: The pdf (top), scale (middle) and parton-shower (bottom) envelopes comparisons for the WZ background for the invariant mass (m_{WZ}) and the transverse mass (m_T^{WZ}) of the WZ system in the Drell-Yan fiducial volume.

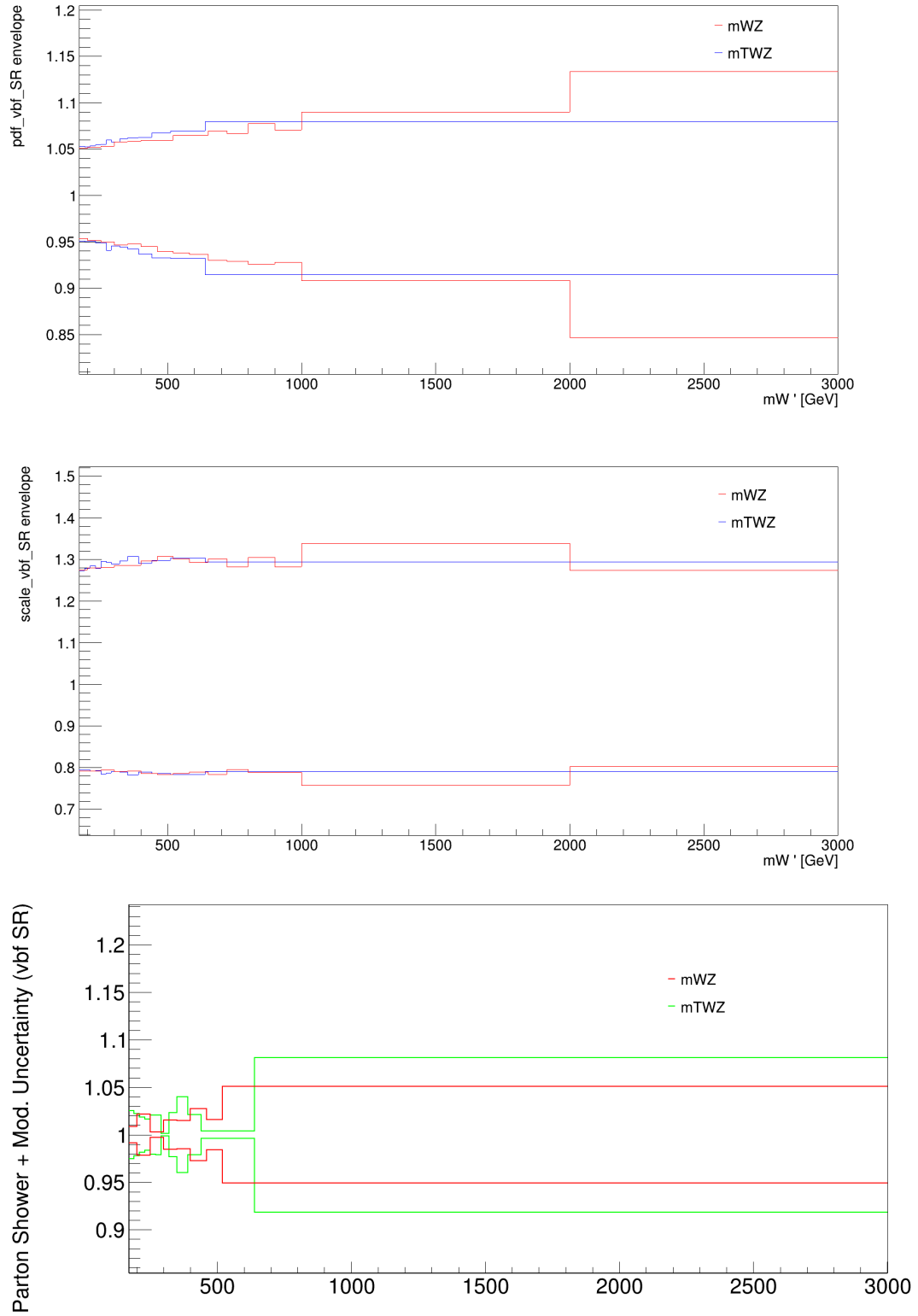


FIGURE D.2: The pdf (top), scale (middle) and parton-shower (bottom) envelopes comparisons for the WZ background for the invariant mass (m_{WZ}) and the transverse mass (m_T^{WZ}) of the WZ system in the VBF fiducial volume.

Appendix E

**Analytic tables with limits for
alternative variables and relative
difference with the m_{WZ} (nominal)**

E.1 Drell-Yan signals category

Variables mass [GeV]	m_{WZ}		m_T^{WZ}		n_{3lep}		p_T^{3lep}		$Sum3Pt$	
	obs limit(pb)	exp limit(pb)	obs limit(pb)	exp limit(pb)	obs limit(pb)	exp limit(pb)	obs limit(pb)	exp limit(pb)	obs limit(pb)	exp limit(pb)
250	1.6133	0.9395	0.8680	0.8918	1.3981	0.9916	1.6288	1.5344	1.4716	1.1289
300	0.3585	0.3356	0.2445	0.3090	0.7151	0.4673	0.4935	0.4409	0.6828	0.4758
400	0.1335	0.1255	0.0890	0.1176	0.2136	0.1835	0.3494	0.2827	0.2541	0.2182
500	0.0574	0.0638	0.0613	0.0627	0.0573	0.0989	0.4562	0.2616	0.0591	0.1140
600	0.0420	0.0395	0.0484	0.0396	0.0511	0.0629	0.4444	0.2347	0.0367	0.0706
700	0.0221	0.0268	0.0239	0.0284	0.0427	0.0458	0.2056	0.1873	0.0428	0.0504
800	0.0247	0.0195	0.0208	0.0214	0.0352	0.0345	0.0942	0.1429	0.0422	0.0379
900	0.0086	0.0156	0.0108	0.0178	0.0325	0.0314	0.0577	0.1116	0.0379	0.0310
1000	0.0093	0.0129	0.0093	0.0157	0.0266	0.0258	0.0408	0.0887	0.0308	0.0265
1100	0.0172	0.0113	0.0129	0.0150	0.0222	0.0216	0.0354	0.0742	0.0232	0.0227
1200	0.0111	0.0095	0.0128	0.0124	0.0195	0.0191	0.0337	0.0631	0.0181	0.0193
1300	0.0068	0.0090	0.0125	0.0112	0.0179	0.0177	0.0350	0.0552	0.0148	0.0167
1400	0.0052	0.0077	0.0122	0.0104	0.0165	0.0162	0.0360	0.0476	0.0124	0.0146
1500	0.0055	0.0077	0.0123	0.0104	0.0157	0.0156	0.0380	0.0428	0.0112	0.0136
1600	0.0050	0.0062	0.0123	0.0103	0.0152	0.0151	0.0369	0.0375	0.0105	0.0128
1700	0.0048	0.0058	0.0125	0.0104	0.0151	0.0149	0.0367	0.0350	0.0102	0.0126
1800	0.0049	0.0059	0.0129	0.0108	0.0153	0.0151	0.0362	0.0330	0.0103	0.0128
1900	0.0052	0.0062	0.0138	0.0115	0.0159	0.0158	0.0359	0.0330	0.0108	0.0136
2000	0.0056	0.0067	0.0149	0.0125	0.0171	0.0172	0.0361	0.0329	0.0117	0.0148
2200	0.0067	0.0081	0.0177	0.0149	0.0201	0.0204	0.0359	0.0329	0.0137	0.0174
2400	0.0078	0.0094	0.0204	0.0171	0.0227	0.0232	0.0338	0.0315	0.0157	0.0200
2600	0.0085	0.0104	0.0224	0.0188	0.0247	0.0255	0.0314	0.0299	0.0172	0.0221
2800	0.0094	0.0114	0.0245	0.0205	0.0269	0.0277	0.0298	0.0290	0.0190	0.0243
3000	0.0102	0.0124	0.0266	0.0223	0.0290	0.0299	0.0294	0.0288	0.0204	0.0261
3500	0.0111	0.0134	0.0294	0.0245	0.0317	0.0321	0.0262	0.0265	0.0224	0.0284
4000	0.0120	0.0144	0.0316	0.0264	0.0336	0.0339	0.0242	0.0251	0.0240	0.0304
4500	0.0122	0.0146	0.0322	0.0268	0.0341	0.0343	0.0228	0.0238	0.0244	0.0308
5000	0.0131	0.0156	0.0348	0.0289	0.0370	0.0370	0.0230	0.0242	0.0264	0.0331

TABLE E.1: Observed and expected limits for various variables for Drell-Yan signals.

Variables mass [GeV]	$m_T^{WZ} - m_{WZ}/m_{WZ}$ obs limit(%)	exp limit(%)	$m_{3lep} - m_{WZ}/m_{WZ}$ obs limit(%)	exp limit(%)	$pT_{3lep} - m_{WZ}/m_{WZ}$ obs limit(%)	exp limit(%)	$Sum3Pt - m_{WZ}/m_{WZ}$ obs limit(%)	exp limit(%)
250	-46.2	-5.08	-13.34	5.54	0.96	63.31	-8.78	20.15
300	-31.81	-7.95	99.45	39.23	37.63	31.35	90.44	41.76
400	-33.28	-6.33	60.03	46.13	161.82	125.20	90.36	73.84
500	6.80	-1.81	-0.09	54.88	695.25	309.86	3.01	78.57
600	15.39	0.29	21.77	59.40	959.23	494.64	-12.53	78.87
700	8.17	5.80	92.79	70.58	829.16	597.96	93.20	87.98
800	-15.89	9.33	42.46	76.36	281.71	631.03	70.87	93.98
900	25.43	13.71	278.35	100.64	571.60	613.82	340.84	98.63
1000	0.11	21.78	185.99	99.84	338.21	587.79	230.91	105.30
1100	-24.94	32.63	29.04	91.72	106.25	556.90	35.25	101.15
1200	15.90	29.99	76.58	100.53	204.75	561.82	63.18	102.16

TABLE E.2: Relative percent differences for observed and expected limits between alternative variables and m_{WZ} (nominal) for Drell-Yan signals. The case where the alternative variable provides stricter limits than the nominal (m_{WZ}) are indicated with red color.

E.2 vbfHVT signals category

Variables mass [GeV]	m_{WZ}		m_T^{WZ}		$m_{jj} \& m_T^{WZ}$		m_{3lep}		p_T^{3lep}		$Sum3Pt$	
	obs limit(pb)	exp limit(pb)	obs limit(pb)	exp limit(pb)	obs limit(pb)	exp limit(pb)	obs limit(pb)	exp limit(pb)	obs limit(pb)	exp limit(pb)	obs limit(pb)	exp limit(pb)
250	0.2384	0.3510	0.3960	0.4633	0.3030	0.3716	0.2632	0.3367	0.6845	0.8060	0.5171	0.6526
275	0.1327	0.2418	0.2180	0.3696	0.1521	0.2791	0.2273	0.2780	0.5224	0.6368	0.3471	0.5172
300	0.1198	0.2336	0.1520	0.3235	0.1022	0.2484	0.2162	0.2483	0.5253	0.6050	0.2757	0.4466
325	0.1009	0.1649	0.1078	0.2426	0.0842	0.2020	0.1943	0.2013	0.4077	0.4915	0.2416	0.3563
350	0.1087	0.1468	0.1208	0.1970	0.0836	0.1782	0.1731	0.1670	0.3592	0.4302	0.1877	0.2977
375	0.1167	0.1196	0.1257	0.1680	0.0807	0.1456	0.1694	0.1491	0.3308	0.3949	0.1679	0.2547
400	0.1382	0.1168	0.1325	0.1503	0.0837	0.1349	0.1741	0.1366	0.3184	0.3872	0.1583	0.2327
425	0.1239	0.0916	0.1435	0.1230	0.0863	0.1159	0.1525	0.1164	0.2772	0.3313	0.1345	0.1876
450	0.1236	0.0834	0.1444	0.1083	0.0895	0.1075	0.1256	0.1007	0.2593	0.3011	0.1277	0.1678
475	0.1179	0.0747	0.1379	0.0996	0.1024	0.0996	0.1055	0.0937	0.2415	0.2924	0.1189	0.1501
500	0.1232	0.0738	0.1302	0.0967	0.1012	0.0978	0.0966	0.0926	0.2426	0.2962	0.1234	0.1482
525	0.1170	0.0655	0.1066	0.0802	0.0802	0.0803	0.0774	0.0766	0.2031	0.2450	0.1072	0.1213
550	0.1028	0.0580	0.0927	0.0759	0.0735	0.0753	0.0712	0.0717	0.1928	0.2363	0.1001	0.1110
600	0.0872	0.0526	0.0748	0.0674	0.0629	0.0675	0.0660	0.0657	0.1800	0.2339	0.0985	0.1024
700	0.0518	0.0498	0.0555	0.0537	0.0491	0.0524	0.0520	0.0533	0.1323	0.1881	0.0729	0.0753
800	0.0327	0.0377	0.0441	0.0426	0.0418	0.0423	0.0381	0.0400	0.1033	0.1562	0.0559	0.0591
900	0.0284	0.0341	0.0361	0.0345	0.0368	0.0362	0.0323	0.0358	0.0870	0.1345	0.0444	0.0487
1000	0.0270	0.0329	0.0309	0.0295	0.0338	0.0329	0.0274	0.0320	0.0759	0.1200	0.0363	0.0412
1100	0.0264	0.0323	0.0280	0.0266	0.0319	0.0310	0.0232	0.0278	0.0634	0.1050	0.0309	0.0355
1200	0.0272	0.0333	0.0266	0.0254	0.0314	0.0305	0.0207	0.0250	0.0598	0.0988	0.0269	0.0312
1300	0.0272	0.0334	0.0254	0.0241	0.0304	0.0293	0.0187	0.0228	0.0543	0.0900	0.0242	0.0282
1400	0.0271	0.0333	0.0243	0.0231	0.0299	0.0288	0.0172	0.0209	0.0491	0.0815	0.0218	0.0255
1500	0.0275	0.0337	0.0240	0.0227	0.0293	0.0285	0.0164	0.0199	0.0449	0.0762	0.0207	0.0241
1600	0.0283	0.0347	0.0240	0.0227	0.0302	0.0292	0.0161	0.0196	0.0420	0.0704	0.0198	0.0231
1700	0.0285	0.0351	0.0241	0.0227	0.0302	0.0291	0.0158	0.0191	0.0393	0.0657	0.0191	0.0222
1800	0.0299	0.0368	0.0245	0.0232	0.0313	0.0303	0.0161	0.0196	0.0363	0.0609	0.0190	0.0220
1900	0.0300	0.0368	0.0246	0.0233	0.0316	0.0306	0.0158	0.0192	0.0360	0.0598	0.0187	0.0217
2000	0.0312	0.0383	0.0253	0.0239	0.0324	0.0315	0.0163	0.0198	0.0351	0.0582	0.0188	0.0218

TABLE E.3: Observed and expected limits for various variables for vbfHVT signals.

Variables mass [GeV]	$m_T^{WZ} - m_{WZ}/m_{WZ}$		$ m_{jj} - m_T^{WZ} - m_{WZ}/m_{WZ}$		exp limit(%)	$m_{3lep} - m_{WZ}/m_{WZ}$		exp limit(%)	$pT_{3lep} - m_{WZ}/m_{WZ}$		exp limit(%)	$Sum3Pt - m_{WZ}/m_{WZ}$		exp limit(%)
	obs	limit(%)	obs	limit(%)		obs	limit(%)		obs	limit(%)		obs	limit(%)	
250	66.10	31.99	27.11	5.89	-4.07	10.41	187.14	129.63	116.89	129.63	116.89	85.93		
275	64.35	52.90	14.66	15.43	15.00	71.33	293.77	163.40	161.66	163.40	161.66	113.94		
300	26.94	38.47	-14.67	6.33	6.29	80.49	338.58	158.95	130.16	158.95	130.16	91.15		
325	6.88	47.11	-16.47	22.52	22.05	92.63	304.24	198.05	139.59	198.05	139.59	116.05		
350	11.14	34.18	-23.1	21.41	13.79	59.20	230.37	193.08	72.61	193.08	72.61	102.78		
375	7.70	40.40	-30.83	21.70	24.62	45.12	183.43	230.06	43.86	230.06	43.86	112.92		
400	-4.10	28.72	-39.44	15.51	17.01	25.96	130.43	231.66	14.55	231.66	14.55	99.33		
425	15.84	34.28	-30.33	26.51	27.08	23.13	123.78	261.74	8.59	261.74	8.59	104.79		
450	16.87	29.91	-27.6	28.84	20.78	1.60	109.86	260.98	3.35	260.98	3.35	101.20		
475	16.96	33.39	-13.14	33.41	25.50	-10.49	104.84	291.53	0.85	291.53	0.85	101.03		
500	5.69	30.95	-17.89	32.38	25.44	-21.63	96.87	301.14	0.16	301.14	0.16	100.62		
525	-8.84	22.41	-31.46	22.67	17.03	-33.86	73.58	274.21	-8.39	274.21	-8.39	85.31		
550	-9.83	30.84	-28.51	29.89	23.69	-30.77	87.50	307.41	-2.63	307.41	-2.63	91.31		
600	-14.18	28.17	-27.79	28.21	24.83	-24.29	106.51	344.67	12.95	344.67	12.95	94.63		
700	7.20	7.82	-5.11	5.12	6.92	0.49	155.71	277.50	40.89	277.50	40.89	51.14		
800	34.71	12.81	27.72	12.00	5.97	16.37	215.58	313.81	70.67	313.81	70.67	56.65		
900	27.05	1.14	29.55	6.11	4.72	13.74	205.98	293.92	56.16	293.92	56.16	42.68		
1000	14.48	-10.19	25.25	0.11	-2.51	1.38	181.01	264.93	34.53	264.93	34.53	25.42		
1100	5.95	-17.74	20.98	-4.07	-14.06	-12.13	140.19	224.82	17.03	224.82	17.03	9.92		
1200	-1.9	-23.8	15.70	-8.52	-24.87	-23.88	120.31	196.46	-1.09	196.46	-1.09	-6.31		
1300	-6.7	-27.86	11.78	-12.23	-31.84	-31.1	99.62	169.35	-11.15	169.35	-11.15	-15.61		
1400	-10.05	-30.68	10.40	-13.57	-37.12	-36.35	81.30	144.65	-19.38	144.65	-19.38	-23.58		
1500	-12.61	-32.60	6.66	-15.61	-40.87	-40.21	63.60	125.76	-24.77	125.76	-24.77	-28.69		
1600	-15.25	-34.57	7.01	-15.92	-43.61	-42.92	48.57	102.76	-29.8	102.76	-29.8	-33.43		
1700	-15.67	-35.46	5.88	-17.04	-45.53	-44.75	37.81	87.11	-33.07	87.11	-33.07	-36.9		
1800	-17.91	-36.91	4.75	-17.55	-46.79	-46.06	21.43	65.63	-36.45	65.63	-36.45	-40.05		
1900	-17.98	-36.7	5.28	-16.99	-47.81	-47.16	20.06	62.48	-37.56	62.48	-37.56	-41.12		
2000	-18.87	-37.57	4.16	-17.88	-48.34	-47.57	12.58	51.88	-39.55	51.88	-39.55	-43.14		

TABLE E.4: Relative percent differences for observed and expected limits between alternative variables and m_{WZ} (nominal) for vbfHVT signals. The case where the alternative variable provides stricter limits than the nominal (m_{WZ}) are indicated with red color.

E.3 vbfGM signals category

Variables mass [GeV]	m_{WZ}		m_T^{WZ}		$m_{jj} \& m_T^{WZ}$		m_{3lep}		p_T^{3lep}		$Sum3Pt$	
	obs limit(fb)	exp limit(fb)	obs limit(fb)	exp limit(fb)	obs limit(fb)	exp limit(fb)	obs limit(fb)	exp limit(fb)	obs limit(fb)	exp limit(fb)	obs limit(fb)	exp limit(fb)
200	219.216	198.566	364.828	263.942	231.084	216.183	215.948	224.167	611.165	553.782	502.800	411.285
225	250.005	211.760	425.967	315.060	330.650	258.617	243.706	238.065	621.037	553.961	403.034	429.601
250	144.810	171.020	248.740	270.198	201.305	206.764	191.768	230.777	425.583	442.899	323.319	351.043
275	86.817	149.517	103.703	186.923	71.229	154.073	167.238	187.437	384.578	358.302	194.487	274.093
300	73.035	134.098	68.220	153.118	46.461	125.686	152.436	176.083	311.137	342.615	156.993	234.812
325	62.926	98.466	53.221	114.418	43.116	107.052	154.226	147.520	294.048	297.080	122.343	187.452
350	83.887	90.016	71.035	92.161	45.031	84.490	120.791	117.003	243.086	270.348	107.154	154.925
375	94.594	76.906	76.373	80.480	46.621	75.322	123.056	107.233	245.121	242.954	91.185	135.382
400	96.346	71.319	70.896	64.831	45.174	58.827	109.810	90.783	211.330	217.613	77.182	110.266
425	79.431	58.521	80.258	56.118	53.054	55.850	102.090	79.634	182.156	206.179	75.463	96.469
450	79.915	57.898	86.116	51.774	68.128	54.163	90.448	74.366	179.874	184.319	74.224	92.508
475	76.481	52.593	66.523	42.088	49.707	41.187	60.024	58.082	117.047	140.457	53.595	64.425
500	69.587	48.233	54.105	37.349	49.905	40.133	59.401	58.560	143.921	149.540	61.252	65.025
525	46.820	33.684	38.984	31.078	32.456	31.024	42.446	43.640	108.111	120.576	50.098	49.192
550	45.006	32.798	35.055	30.480	28.294	29.124	42.229	43.841	103.632	119.336	48.070	47.196
600	38.082	28.918	21.238	22.554	20.924	23.497	31.637	33.793	68.331	97.449	38.462	37.690
700	24.029	24.509	19.917	19.771	19.721	20.344	27.511	29.267	56.437	83.070	27.685	28.841
800	17.178	18.754	15.699	15.037	17.181	16.828	20.207	21.805	39.672	65.790	20.036	22.354
900	15.002	16.641	13.036	12.334	15.220	14.790	16.238	18.456	33.704	55.190	14.918	17.197
1000	14.857	16.521	12.340	11.602	14.946	14.540	14.387	16.774	28.216	45.444	12.354	14.504

TABLE E.5: Observed and expected limits for various variables for vbfGM signals.

Variables mass [GeV]	$m_T^{WZ} - m_{WZ}/m_{WZ}$		exp limit(%)	$[m_{jj}, m_T^{WZ}] - m_{WZ}/m_{WZ}$		exp limit(%)	$m_{3lep} - m_{WZ}/m_{WZ}$		exp limit(%)	$pT_{3lep} - m_{WZ}/m_{WZ}$		exp limit(%)	$Sum3Pt - m_{WZ}/m_{WZ}$		exp limit(%)
	obs	limit(%)		obs	limit(%)		obs	limit(%)		obs	limit(%)		obs	limit(%)	
200	66.42	32.92	5.41	8.87	-1.49	12.89	178.80	178.89	129.36	107.13	129.36	107.13	129.36	107.13	
225	70.38	48.78	32.26	22.13	-2.52	12.42	148.41	161.60	61.21	102.87	61.21	102.87	161.60	102.87	
250	71.77	57.99	39.01	20.90	32.43	34.94	193.89	158.97	123.27	105.26	123.27	105.26	158.97	105.26	
275	19.45	25.02	-17.96	3.05	92.63	25.36	342.98	139.64	124.02	83.32	124.02	83.32	139.64	83.32	
300	-6.59	14.18	-36.39	-6.27	108.72	31.31	326.01	155.50	75.10	114.96	75.10	114.96	155.50	75.10	
325	-15.42	16.20	-31.48	8.72	145.09	49.82	367.29	201.71	94.42	90.37	94.42	90.37	201.71	90.37	
350	-15.32	2.38	-46.32	-6.14	43.99	29.98	189.78	200.33	27.74	72.11	27.74	72.11	200.33	72.11	
375	-19.26	4.65	-50.71	-2.06	30.09	39.43	159.13	215.91	-3.60	76.04	-3.60	76.04	215.91	76.04	
400	-26.42	-9.10	-53.11	-17.52	27.29	27.29	119.35	205.12	-19.89	54.61	-19.89	54.61	205.12	54.61	
425	1.04	-4.11	-33.21	-4.56	28.53	36.08	129.33	252.32	-5	64.84	-5	64.84	252.32	64.84	
450	7.76	-10.58	-14.75	-6.45	13.18	28.44	125.08	218.35	-7.12	59.78	-7.12	59.78	218.35	59.78	
475	-13.02	-19.97	-35.01	-21.69	10.44	10.44	53.04	167.07	-29.92	22.50	-29.92	22.50	167.07	22.50	
500	-22.25	-22.57	-28.28	-16.79	21.41	21.41	106.82	210.04	-11.98	34.81	-11.98	34.81	210.04	34.81	
525	-16.74	-7.74	-30.68	-7.90	29.56	29.56	130.91	257.96	7	46.04	7	46.04	257.96	46.04	
550	-22.11	-7.07	-37.13	-11.2	33.67	33.67	130.26	263.86	6.81	43.90	6.81	43.90	263.86	43.90	
600	-44.23	-22.01	-45.05	-18.75	16.86	16.86	79.43	236.99	1.00	30.33	1.00	30.33	236.99	30.33	
700	-17.11	-19.33	-17.93	-16.99	19.41	19.41	134.87	238.93	15.22	17.67	15.22	17.67	238.93	17.67	
800	-8.61	-19.82	0.02	-10.27	17.63	16.27	130.95	250.80	16.64	19.19	16.64	19.19	250.80	19.19	
900	-13.11	-25.88	1.45	-11.13	8.24	10.91	124.66	231.65	-0.56	3.34	-0.56	3.34	231.65	3.34	
1000	-16.94	-29.77	0.60	-11.99	-3.17	1.53	89.92	175.07	-16.84	-12.21	-16.84	-12.21	175.07	-12.21	

TABLE E.6: Relative percent differences for observed and expected limits between alternative variables and m_{WZ} (nominal) for vbfGM signals. The case where the alternative variable provides stricter limits than the nominal (m_{WZ}) are indicated with red color.

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