
Experimentelle Physik

Di-hadron correlations of identified particles at
high p_T in pp collisions at the LHC

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1 Introduction

Collisions of protons at high energy play an important role in the study of the fundamental principles of our Universe. In order to provide precise measurements with high statistics, the Large Hadron Collider (LHC) was built at the European Organization for Nuclear Research (CERN)¹. One of the biggest achievements of the experiments located at the LHC so far is the discovery of the Higgs boson, the last missing piece of the Standard Model (SM). Ahead of that, they have also provided many precise measurements of the SM quantities, making the SM the most precisely tested theory in physics, describing the elementary particles and their interactions.

Besides proton–proton (pp) collisions, also heavy nuclei can be accelerated with the LHC and collided at the experiments. Such heavy-ion collisions are in the main focus of the ALICE (A Large Ion Collider Experiment) experiment. In these collisions, the Quark–Gluon Plasma (QGP) is created: a state of matter where quarks and gluons do not belong to any specific hadrons, but they can freely exist within the QGP volume. It is theoretically predicted that our Universe consisted of it a few microseconds after the Big Bang. The QGP is a strongly interacting state of matter where a traversing quark or gluon will lose energy by interacting with the color charges of the QGP. It is predicted that heavy quarks should lose less energy than light quarks and the highest energy loss should experience gluons due to the highest Casimir colour factor. Heavy quarks can be identified with the hadrons including them, but, so far, there is no straightforward way how to distinguish between the hadronised light quark or gluon. One of the possible methods is using the di-hadron correlations with neutral strange trigger particles. This approach is tested within this thesis in pp collisions at 13 TeV.

Moreover, the results of current measurements reveal some of the features associated with the QGP formation in heavy-ion collisions also in pp and proton–lead (p–Pb) collisions with high particle multiplicity. One of them is the increase of relative strangeness production with the collision multiplicity. Thus, in the second part of this thesis, the neutral strange hadrons are used as associated particles in the di-hadron correlation

¹The acronym stood originally for Conseil Européen pour la Recherche Nucléaire.

method as a tool to study whether the jet fragmentation plays an important role in the strangeness enhancement in small collision systems with high multiplicity.

The thesis is structured as follows: Chapter 2 provides basic theoretical concepts important for the thesis as well as the description of the Monte Carlo (MC) models used for comparison with the results and current results in the field. In Chapter 3, the ALICE experiment, the functionality of its sub-detectors and the analysis software are introduced. All the measurement steps, corrections, and consistency checks are described in detail in Chapter 4. Next, Chapter 5 describes the systematic uncertainty study. The final results are presented, discussed and compared with MC generator predictions in Chapter 6.

2 Theoretical Background

2.1 Standard Model

The Standard Model (SM) is the current theory of particle physics whose first key elements were developed already in early 1970s. It is based on the principles of special relativity, quantum field theory and gauge invariance. The SM describes the elementary particles and the interactions between them and it is composed of three distinct sectors: gauge, fermionic and scalar sector.

The gauge sector describes spin-one bosons mediating the strong and electroweak interaction. The symmetry groups of the gauge sector can be written as:

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

$SU(3)_C$ is the symmetry group of the strong interaction, representing Quantum Chromodynamics (QCD) and the subscript C is pointing out that the gauge bosons of QCD, gluons, couple only to coloured objects. The symmetry group requires 8 generators which are manifested in the terms of eight gluons. These are massless, electrically neutral and carry colour charge, meaning that they can interact with each other [1]. The symmetry group of the unified electroweak interaction is written as $SU(2)_L \times U(1)_Y$, where the subscripts L and Y reflect the fact that the $SU(2)$ group couples only to left-handed and $U(1)$ only to weakly hypercharged particles, respectively. The massless bosons resulting from these symmetry group mix and three of them become massive as a consequence of the spontaneous symmetry breaking of the Higgs mechanism [2, 3, 4]. After the symmetry breaking, there is one massless, neutral photon γ , intermediating the electromagnetic interaction, and three weak bosons: $W^\pm$ and Z . The latter three are massive and while Z is electrically neutral, the $W^\pm$ bosons carry an electrical charge $Q = \pm 1$, respectively.

The fermionic sector contains spin-one-half particles, quarks and leptons, which are organised into three families, also called generations. These families are identical in every

property except for the mass. The SM contains 45 fermions and their antiparticles, which can be ordered into multiplets (summarised in Tab. 2.1) within each family according to how they transform under the gauge symmetries [5]. The fermions can be transformed into other fermions only within these multiplets. Nevertheless, quarks can never occur as free particles but are bound into hadrons due to the confinement, described in Sec. 2.1.1.

Table 2.1: Summary of the SM fermionic multiplets.

Family	Multiplets				
	Left-handed quarks	Right-handed up quarks	Right-handed down quarks	Left-handed leptons	Right-handed leptons
1 st family	$\begin{pmatrix} u_L^r & u_L^g & u_L^b \\ d_L^r & d_L^g & d_L^b \end{pmatrix}$	$\begin{pmatrix} u_R^r & u_R^g & u_R^b \end{pmatrix}$	$\begin{pmatrix} d_R^r & d_R^g & d_R^b \end{pmatrix}$	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{pmatrix} e_R \end{pmatrix}$
2 nd family	$\begin{pmatrix} c_L^r & c_L^g & c_L^b \\ s_L^r & s_L^g & s_L^b \end{pmatrix}$	$\begin{pmatrix} c_R^r & c_R^g & c_R^b \end{pmatrix}$	$\begin{pmatrix} s_R^r & s_R^g & s_R^b \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \mu_R \end{pmatrix}$
3 rd family	$\begin{pmatrix} t_L^r & t_L^g & t_L^b \\ b_L^r & b_L^g & b_L^b \end{pmatrix}$	$\begin{pmatrix} t_R^r & t_R^g & t_R^b \end{pmatrix}$	$\begin{pmatrix} b_R^r & b_R^g & b_R^b \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$\begin{pmatrix} \tau_R \end{pmatrix}$

The scalar sector contains only one spin-zero boson, the Higgs boson, which was added to the SM as a consequence of the Higgs mechanism. This boson was discovered by the Compact Muon Solenoid (CMS) and A Toroidal LHC Apparatus (ATLAS) collaborations [6, 7] in 2012 and it was the final particle of the SM that was searched for.

The SM has been widely tested over past 30 years and its predictions were confirmed with highest precision. This makes from the SM the most precise theory the mankind ever had. Nevertheless, it has its limitations. There are many free parameters, as e.g. the masses of the fermions and bosons, that cannot be calculated from the first principles, but which only can be measured as an input for the model. Moreover, the SM does not incorporate gravity and has no explanation for e.g. dark matter. Thus, there are still searches for theories beyond the SM that would be able to include gravity and describe all missing phenomena with a smaller number of free parameters [5, 8]

2.1.1 Asymptotic freedom and confinement

In deep inelastic scattering experiments, it was measured that the strong force between the quarks inside protons is weak, if the transferred momentum is high. Nevertheless, there were never free quarks observed, suggesting that the force between them must be strong on long distances. On short distances, quantum-mechanical effects in the terms of vacuum polarisation need to be taken into account. These are quantum-mechanical

fluctuations where an electron-positron pair can be created from a photon and immediately annihilates back or a quark-antiquark pair exists shortly from a gluon. In this picture, every quark is enveloped by a sea of virtual gluons and quark-antiquark pairs. The presence of these virtual gluons, which is possible due to the gluon self-interaction, gives rise to a larger effective colour charge than the original charge of the quark. The amount of the virtual gluons increases with the distance from the bare quark and so does the charge [9]. As a consequence, the effective colour charge decreases with the decreasing distance. This effect is called asymptotic freedom. The change of the effective charge also means that the coupling constant is actually not a constant, but runs with the distance, respectively with the transferred momentum what was experimentally confirmed (Fig. 2.1). This can be explained by the non-Abelian (see Ref. [10]) nature of the SU(3) group, describing the QCD [1].

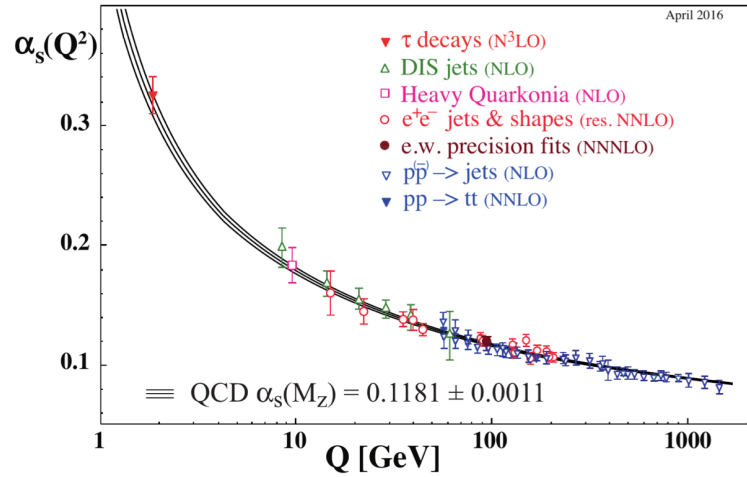


Figure 2.1: Coupling constant of the strong interaction measured as a function of the energy Q [11].

However, the non-existence of free colour charges, also called quark confinement in hadrons, is observed in nature, it cannot be directly explained by perturbative QCD calculations because these work only for small coupling constants. From the observations, it is clear that the force between two quarks is large at big distances. As two quarks are being stretched from each other, the force between them increases and the field lines are pulled together due to the gluon self-interaction. As is illustrated in Fig. 2.2, the field lines build a tube between quarks, in contrast to the lines of an electric field, which are

drawn further apart with increased distance between charges. These tubes are described as strings in the Lund model [12] with potential:

$$V(r) \approx -\frac{4}{3} \frac{\alpha_S}{r} + \kappa r \quad (2.2)$$

where κ is the string tension.

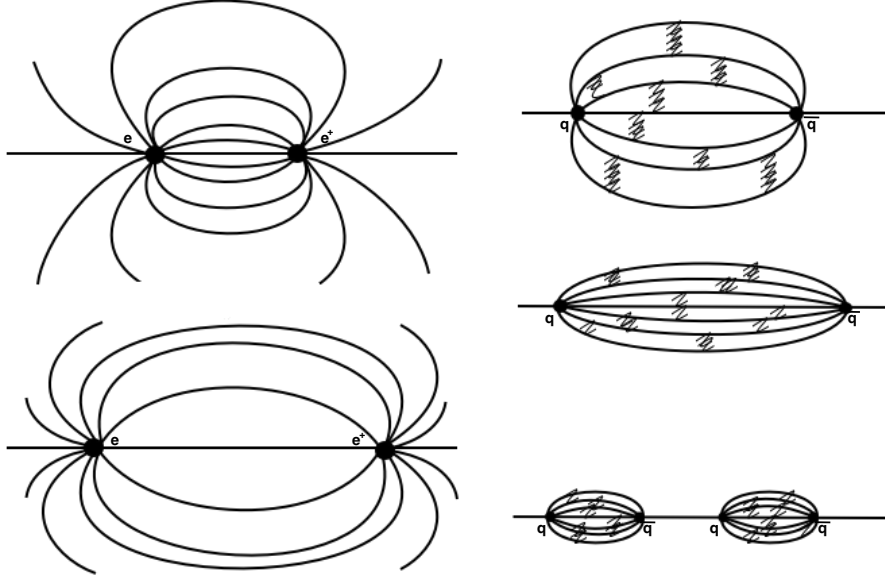


Figure 2.2: Schematic view of electric field lines (left) and colour force field lines (right).

2.2 Jets

Jets are collimated hadron showers in one direction that are generated in high energy particle collisions. It is actually the partons colliding and not the protons as whole by a proton–proton (pp) collision. By these hard processes quarks or gluons are scattered sideways from the colliding hadrons. As the colour charged objects are moving from each other and the force between them increases, there is enough energy that a new quark–antiquark pair can be created (as shown in the bottom right part of Fig. 2.2). This process continues as long as there is energy for the pair creation. But due to the confinement phenomenon (Sec. 2.1.1), no free colour charged objects can be observed in nature. And so at the end, the new quarks build hadrons, which are observed in the detectors. This process of fragmentation and hadronisation is described as string breaking together with other features, e.g. tunnelling or mass dependent baryon production, in the Lund model [12, 13]. With the help of jets, the properties of the original parton can be studied.

The cross section of the hadron production X within a jet in a pp collision is a convolution of a Parton Distribution Function (PDF), which demonstrate the probability to find the colliding parton with a given momentum fraction within the proton, the hard process cross section and a Fragmentation Function (FF), which gives the probability of having a given hadron in the final state from the parton created in the hard process. This cross-section can be written as:

$$\sigma_{p+p \rightarrow X}(p_T) = \sum_{a,b,c,d=q,\bar{q},g} \int_{x_1^{min}}^1 dx_1 \int_{x_2^{min}}^1 dx_2 f_{a/p}(x_1, \mu^2) f_{b/p}(x_2, \mu^2) \times \hat{\sigma}_{a+b \rightarrow c+d}(Q^2, \mu^2) F_{c,d \rightarrow X}(p_T), \quad (2.3)$$

where $f_{a/p}$ and $f_{b/p}$ are the PDFs, $\hat{\sigma}$ is the cross section of the hard process and $F_{c,d \rightarrow X}$ is the FF. With jet measurements, the FF is mostly studied.

2.2.1 Quark and gluon jets

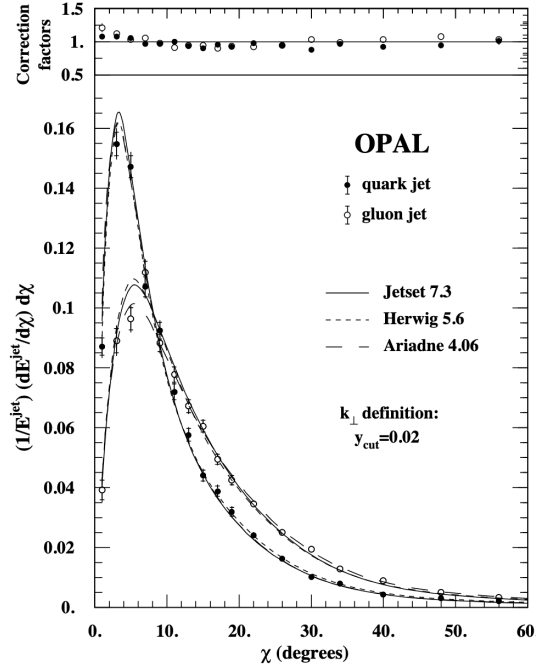


Figure 2.3: Normalised distribution of the jet energy as a function of the angle between the particles and the jet axis in gluon and quark jets using the $k_{\perp}$ jet finder measured by the OPAL collaboration and compared with model predictions [14]. The detector correction factors are shown in the small figure above the data distributions.

Jets have different properties based on the original parton. Already in measurements of the Large Electron-Positron Collider (LEP) experiments, different features of quark and gluon jets were discovered. The first one is the jet width. It was theoretically expected, gluon jets to be wider [15, 16]. In the OPAL (Omni-Purpose Apparatus for LEP) study [14], three jet events selected with the $k_{\perp}$ jet finder [17] in $e^+ + e^-$ collisions were studied, where it was assumed that the jet with the highest energy is a quark jet. The second quark jet was required to have a secondary vertex, associated with heavy quark decay. Such jet with heavy quark is likely to be a quark jet [18]. The last jet was stated as gluon jet. After this "anti-tagging" of the gluon jets, the normalised energy distribution around the jet axis was measured, as shown in Fig. 2.3. It is visible that the energy of particles from quark jets is more collimated around the jet axis. This observation is in agreement with the expectation that gluon jets are broader.

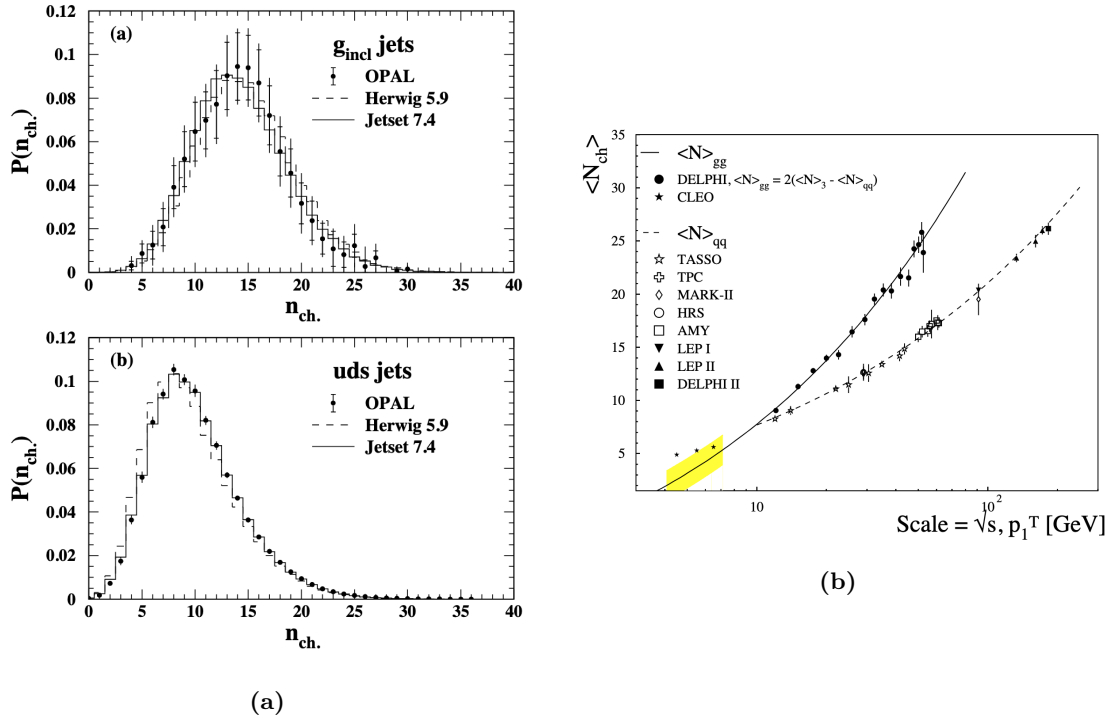


Figure 2.4: (a) Charged particle multiplicity distribution of gluon (top) and quark (bottom) jets compared with model predictions measured by OPAL [19]. (b) Average charged particle multiplicity in quark and gluon jets as a function of the scale measured by DELPHI [20].

Another interesting feature studied at both OPAL and DELPHI (DEtector with Lepton, Photon and Hadron Identification) experiments is the multiplicity of charged particles produced within jets. In the OPAL data analysis, a similar technique as described above was used to tag the quark and gluon jets. Afterwards, the charged particle distribution was measured in both jet samples and as shown in Fig. 2.4a, gluon jets have higher

probability to produce more charged particles as quark jets [19]. At the DELPHI experiment, the average charged particle multiplicity was measured as a function of the scale of the collision energy (Fig. 2.4b). The scale here was defined as the energy of the $q\bar{q}$ pair and the transverse momentum of the gluon, which were calculated directly from the jet angle. The $q\bar{q}$ multiplicity was defined as the multiplicity of e^+e^- annihilation events corrected for the $b\bar{b}$ contribution. The gg multiplicity represents twice the difference between the three-jet events and the $q\bar{q}$ multiplicity. From the distributions in Fig. 2.4b, it is visible that gluon jets have higher multiplicity of charged particles, which increases with the scale around twice as fast as the multiplicity of quark jets [20].

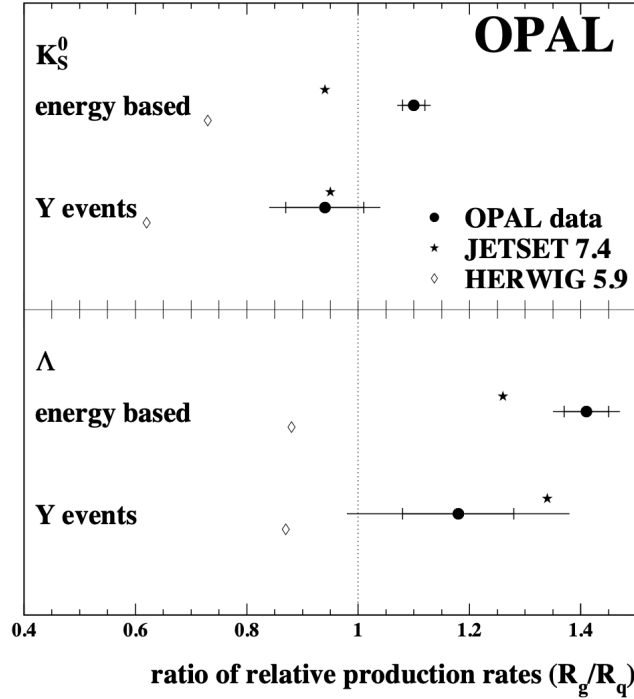


Figure 2.5: Ratios of relative production of K_S^0 mesons and Λ baryons in quark and gluon jets measured by OPAL in e^+e^- collisions and compared with model predictions and among the used methods. The experimental statistical errors are delimited by the small vertical bars [21].

The OPAL experiment has also measured the relative production of strange particles in terms of K_S^0 mesons and Λ hyperons in quark and gluon jets. Two complementary methods of jet tagging were used. The energy based method used the secondary vertices in the three-jet events to tag the heavy quark(anti-quark) jets, while the Y-event method used the symmetric three-jet events to tag quark jets based on the collimation of their energy flow [21]. The relative production of K_S^0 and Λ to charged particles was measured separately in quark and gluon jets and afterwards, the ratios $R_g^{K_S^0}/R_q^{K_S^0}$ and R_g^Λ/R_q^Λ of relative K_S^0 and Λ production rates in pure gluon and quark jets were calculated. These

are shown in Fig. 2.5. An enhanced relative Λ baryon production in gluon jets with respect to quark jets of 41% and 18% with the energy based and Y-event method, respectively, was observed, while the relative K_S^0 production shows only a small enhancement [21].

2.3 Quark-Gluon Plasma

From the asymptotic freedom feature of the QCD described above follows that on very short distances, the strong force between partons becomes weak. Thus, under extreme conditions, like very high temperature and pressure, partons become deconfined and a new state of matter, the so-called Quark-Gluon Plasma (QGP) [22], is created. It is likely that our Universe consisted of this state of matter a few microseconds after the Big Bang [23]. It was already confirmed that the pressure and temperature in the middle of neutron stars can be sufficiently high for the QGP creation [24], but these conditions can also be reached in a controlled way in Ion-Ion (AA) collisions, where the properties of this state of matter can be studied (eg. [25, 26]). This is very challenging because the QGP expands extremely quickly and the temperature decreases down to a critical value when hadrons are formed and the quarks and gluons become confined again. This point is called the chemical freeze-out and one of the estimates of the critical temperature at the Large Hadron Collider (LHC), $T_{CF} = 156.5 \pm 1.5$ MeV, comes from the fit of particle multiplicities from the Statistical Hadronisation Model on the data [27]. Around the temperature of the freeze-out, the perturbative calculations cannot be used any more due to the big value of α_S , but the phase transition between hadron gas and QGP can be calculated with the lattice QCD [28].

The phase diagram of the QGP, shown in Fig. 2.6, is characterised by temperature T and baryon chemical potential μ_B . Several distinct areas can be defined there:

- at low temperature and low baryon density - the hadron phase
- at high temperature and relatively low baryon density - deconfined QGP as created at the LHC and the Relativistic Heavy Ion Collider (RHIC)
- at relatively low temperature and high baryon density - compressed baryonic matter (the future Facility for Antiproton and Ion Research (FAIR)), possible core of neutron stars

The transition at low baryon chemical potential should be a cross-over and at high baryon densities a first-order phase transition, as predicted by lattice QCD calculations. Thus, a critical point should be present, but it has never been observed so far [29].

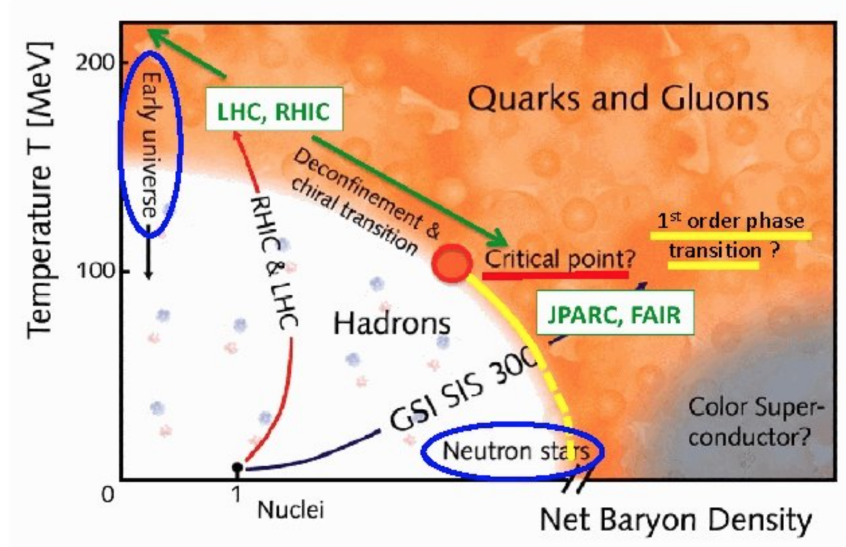


Figure 2.6: Phase diagram of the QGP [30].

2.3.1 Characteristic features

As the QGP cannot be observed directly, there are some characteristic features in the final state after the AA collisions that can be measured and confirm the QGP formation. One of these is jet quenching. Due to the momentum conservation in the transverse plane, at least two jets need to be created. In the case that the QGP is created, one jet fragments almost only in vacuum, while the recoil parton travels through the QGP first and hadronises, afterwards. It loses energy via interaction with the quark-gluon medium. Thus, the recoil jet is observed as suppressed or not at all. This happens when the parton is fully stopped by the medium and the jet is fully quenched [31]. Due to the energy loss in the QGP, particles with initial high transverse momentum (p_T) are measured with lower p_T . To quantify this effect, the nuclear modification factor is calculated. This is defined as a ratio $R_{AA} = \frac{N_{AA}^{particles}}{\langle T_{AA} \rangle N_{pp}^{particles}}$, where $N_{pp}^{particles}$ is a spectrum of specific particle species in pp collisions, $\langle T_{AA} \rangle$ is the average number of elementary collisions in one AA collision and $N_{AA}^{particles}$ is a spectrum of the same particle species in AA collisions. Suppression of this ratio was measured for various particle species, e.g. [32, 33, 34], confirming the energy loss in the medium.

The QGP consists of deconfined quarks and gluons that undergo collective effects, like expansion, due to pressure gradients present in the medium and the strong coupling of the QGP. The final state hadrons are also affected by this collective behaviour. The measurable quantities describing this phenomenon are the collective flow coefficients. They are defined as harmonic coefficients in a Fourier decomposition of the azimuthal

distribution of particles with respect to the collision symmetry plane [35]. The second coefficient v_2 represents the magnitude of the elliptic flow, which is caused by the pressure coming from the almond shape of the overlapping region of the two colliding nuclei as shown in Fig. 2.7. This was measured in various collision systems at different energies [36]. Another consequence of the collective behaviour is the double-ridge structure in the two-particle correlation function [37, 38].

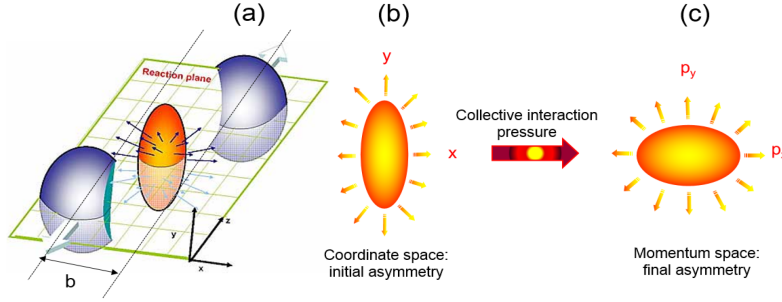


Figure 2.7: Left: Schematic view of the collision zone between two incoming nuclei where x-z is the reaction plane. Right: Initial-state anisotropy in the collision zone converting into final-state elliptic flow, measured as anisotropy in particle momentum [39].

The increased production of strange hadrons in nuclear collisions with respect to pp collisions was proposed to be a consequence of the QGP formation [40, 41] as well, because the strangeness formation via $g + g \rightarrow s + \bar{s}$ is more probable in the QGP. This enhanced production was observed in many experiments [42, 43, 44].

2.3.2 Nuclear PDFs

For the theoretical predictions of the QGP and the AA collisions, the knowledge of the initial conditions of the collisions plays an important role. To constrain that, the PDFs are used that are crucial for the final state cross-section calculation as visible in Eq. 2.3. Nevertheless, the PDF of a free proton (neutron) is not the same as the one of a proton (neutron) bound inside a nucleus. The difference is caused by the interactions between the nucleons. Thus, Nuclear Parton Distribution Functions (nPDFs) need to be constrained to predict AA collisions. While the PDFs of a free proton are already precisely known from fits to data [45], the nPDFs still have big uncertainties [46, 47, 48]. Particularly problematic is the gluon nPDF, because the data (Deep Inelastic Scattering (DIS) and Drell-Yan (DY) data) used in the previous nPDFs fits are not sensitive to the gluon nPDF at the leading order, because of the electroweak nature of these processes.

During her PhD, the author participated in a theory project within the nuclear CTEQ (nCTEQ) collaboration with the objective to use new data on the R_{pA} ratio and estimate new nPDF fits. These ratios are sensitive to the gluon nPDF, as the hadronic cross-section at the LHC and RHIC energies is dominated by the gluon nPDF of the lead nucleus, as shown in Fig. 2.8. Thus, all published R_{pA} ratios of identified hadrons from A Large Ion Collider Experiment (ALICE), Solenoidal Tracker At RHIC (STAR) and Pioneering High Energy Nuclear Interaction eXperiment (PHENIX) were collected with 251 data points. Whereas, the ratio cannot be calculated perturbatively for low p_T , all points below 3 GeV/ c were excluded leaving 109 data points for the fits.

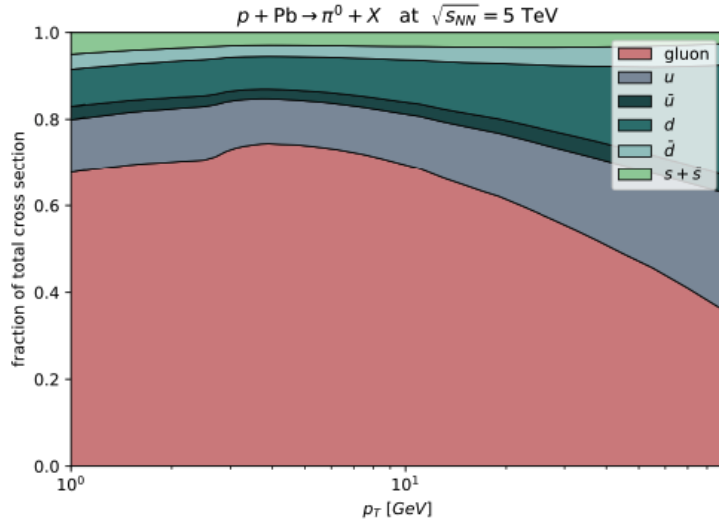


Figure 2.8: Fractional contributions of the total $p + \text{Pb} \rightarrow \pi^0 + X$ cross section initiated by each PDF flavor $f_i^{\text{Pb}}(x, Q)$ of the lead nucleus [49].

The FF, which describes the hadronisation of a partonic constituent into a final-state hadron, plays an important role in the observable calculation. Recently, a few FFs became available for different charged hadrons. In principle, all of them could provide slightly different predictions for the hadron spectra, so their predictions were compared and concluded as consistent within the provided uncertainty for $p_T > 3$ GeV/ c . In the final calculation, the DSS [50, 51] FFs were used.

The final results of the fits are shown in Fig. 2.9. It is visible that the gluon nPDF is estimated more precisely than it was before, while the up, down and strange quark nPDFs stayed rather unchanged, as the previously used data were sufficiently sensitive to their nPDFs.

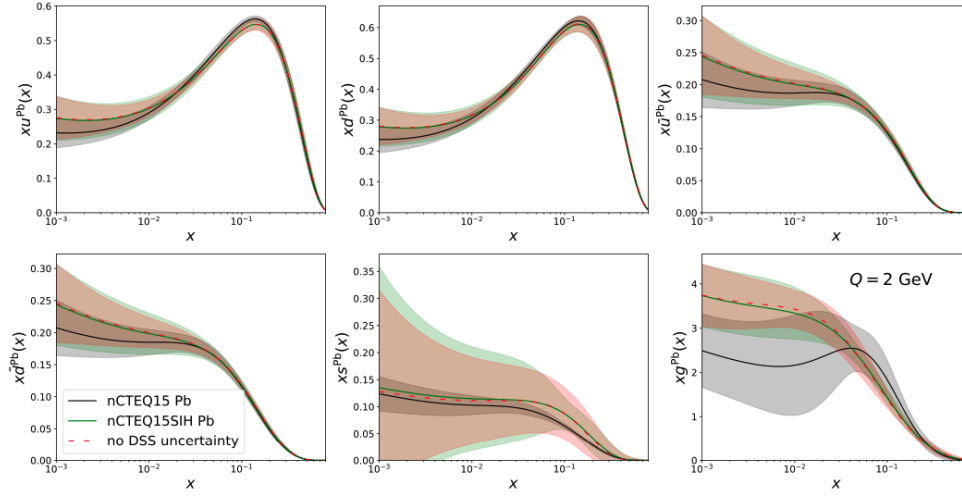


Figure 2.9: Lead PDFs from fits to the nCTEQ15 data + single inclusive hadron production data [49], baseline nCTEQ15 [46] (black), the fit with unmodified data (red) and the fit where the uncertainties from the DSS FFs were added as a systematic uncertainty (green).

2.4 Recent measurements of collective behaviour in high-multiplicity pp collisions

Recent measurements show that some of the above described characteristic features of the QGP are also present in high-multiplicity pp and proton–lead (p–Pb) collisions, where no QGP should be present. One of these is the relative strangeness production measurement as a function of multiplicity in different collision systems performed with ALICE [52]. As shown in the left plot of Fig. 2.10, there is a smooth increase of the relative production of strange hadrons over pions with multiplicity from small to large collision systems. Moreover, as it is visible from the right plot in the same figure, the production of particles consisting of more strange quarks increases more steeply, which is in agreement with the strangeness enhancement in the QGP assumption.

Another observation of the QGP-like features in small collision systems is the measurement of the non-zero anisotropic flow coefficients [53] and the ridge-like structure in long-range correlations [54], which are pointing out the presence of some collective behaviour in small systems. However, no signs of the jet quenching have been observed in small systems so far [55]. Thus, an open question remains what is the origin of these observations in pp collisions, whether there is a small droplet of QGP produced, as proposed in the model presented in Ref. [56], or whether there is another similar mechanism of particle production in small and large systems.

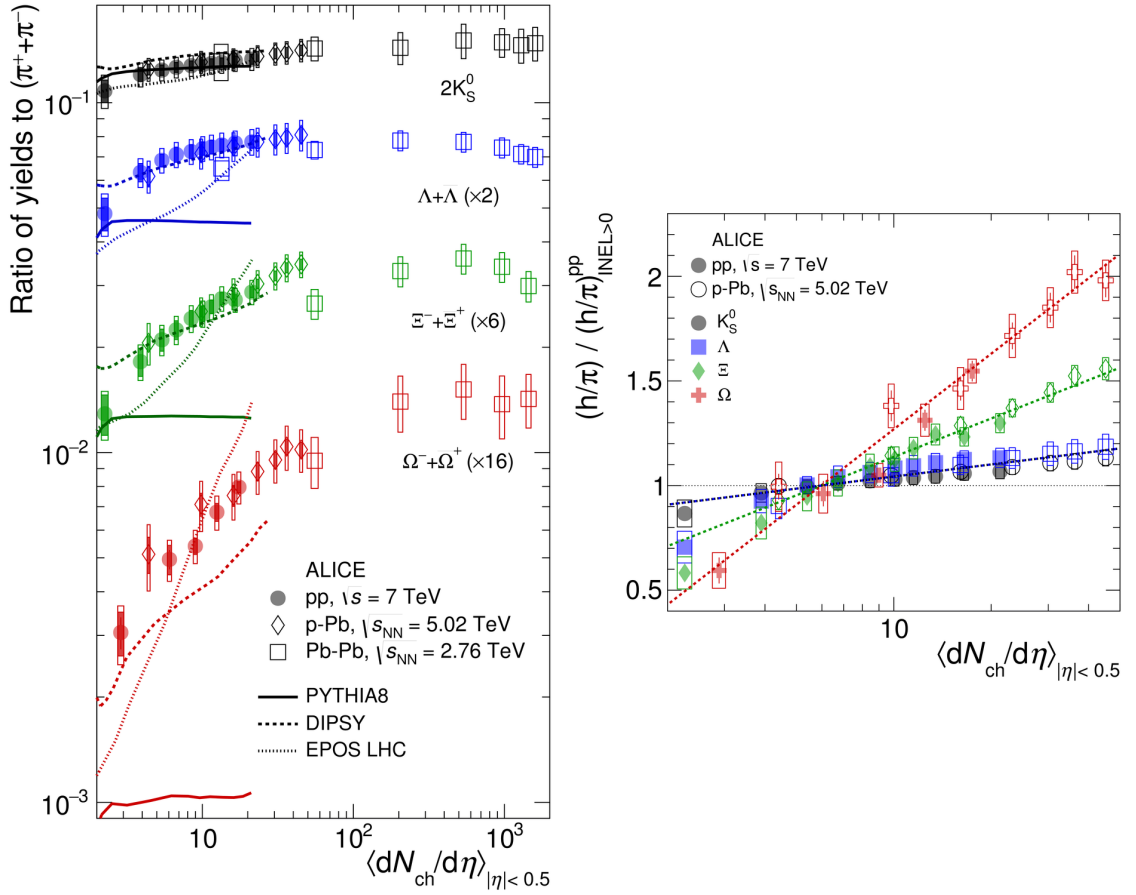


Figure 2.10: Left: p_T -integrated yield ratios of strange hadrons to pions ($\pi^+ + \pi^-$) as a function of $\langle dN_{ch}/d\eta \rangle$ measured at $|y| < 0.5$. Right: Particle yield ratios to pions normalised to the values measured in the inclusive pp sample [52].

2.5 Pythia

One of the recently most used event generators in the High-Energy Physics (HEP) community is PYTHIA [57]. This is a leading-order Monte Carlo (MC) collision generator based largely on the Lund string fragmentation model, but it also incorporates other models. Many different collision types can be simulated, from $e^+ + e^-$ and $p + \bar{p}$ in various combinations and at various energies up to AA collisions with the Angantyr [58] extension. The development was started in 1978 by the Lund theory group [59]. The original JETSET model and its extensions were merged into one program, called PYTHIA. The Fortran 77 based main version PYTHIA6.4 [60] was rewritten to C++ and extended to a new standard version PYTHIA8.3 released in 2019.

PYTHIA model predictions are dependent on the input parameters that are tuned on the data. The current standard tune is the Monash 2013 tune [61], which was tuned including the data from the first run at the LHC.

2.5.1 Shoving model

As described above in Sec. 2.4, collectivity and strangeness enhancement is observed in high-multiplicity pp collisions. The standard PYTHIA is not able to describe such observations and it is difficult to add new dynamic that is present only at the soft scales, because it would break the jet universality¹. But, this is achieved with a new model of overlapping strings, "rope hadronisation", that was originally implemented into the DIPSY generator [62]. This model was improved with the shoving model within PYTHIA, where the increased string tension can generate a flow-like effect in small systems [63]. The principle of the model is shown in Fig. 2.11, which represents one slice in rapidity. At $t = t_1$, the strings are fully overlapped with high density in the center that is causing a pressure gradient. The p_T of the strings is increased due to this gradient. As they are moving apart, the gradient decreases and so the strings pick up less p_T . At $t = t_4$, there is no overlap present anymore and the strings only move apart and hadronise.

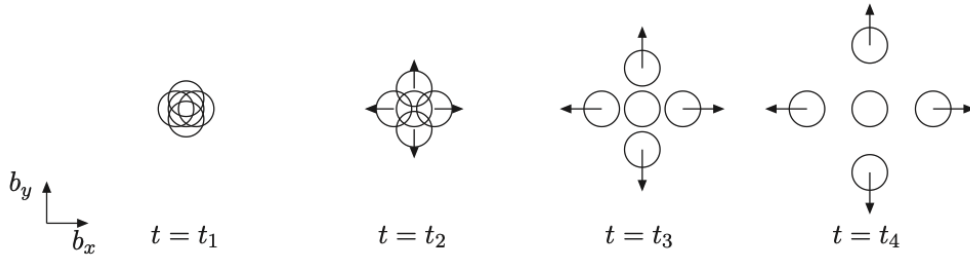


Figure 2.11: Schematic presentation of overlapped strings in the impact parameter space and their time evolution ($t_1 < t_2 < t_3 < t_4$) in the Shoving model. The increasing p_T is represented by the arrows [63].

2.6 EPOS LHC

In the EPOS LHC [64] model, the initial conditions are represented by strings, not partons, and the evolution of each collision type is divided into two parts: "core" and "corona". The core represent areas with high string densities while in the corona, there

¹The assumption that jets fragment in the same way in vacuum without any dependencies on the original collision system

is lower density and the strings fragment unmodified as in other models like PYTHIA. The core appears only, if the local string density is high enough, which is easily reachable in heavy ion collisions. Nevertheless, also in pp collisions at the LHC energies, it is possible to create more than 10 strings close to each other building the core, which leads to high-multiplicity in the final state [64]. As the core hadronises collectively, the collective-flow effect in pp collisions is naturally simulated by the EPOS LHC model.

2.7 Di-hadron correlation method

Due to the confinement, physicists are not able to measure quarks or gluons directly in the experiments. Only jets, the hadron showers in one direction as the result of fragmentation and hadronisation of the original parton, can be detected. One simple way how to study jets would be to use a pre-defined jet-finding algorithm. These are widely used for small systems, but they do not perform well in AA collisions, where too many particles are produced and other effects of the QGP are present, as for example jet quenching.

For this reason, one can use an indirect method - di-hadron correlations. In this approach, the particles are not clustered into jets directly, but the whole collision is taken into account. As the name is already suggesting, always two hadrons are correlated and their selection is based on the motivation of the study. The first selected group of particles are the so called triggers. In general, they should have high momentum and they serve as a proxy of the jet-axis coming from the initial parton. The second group are particles associated with the trigger particles, having in general lower transverse momentum.

The way of association is the building of a correlation function in a way of calculating differences of azimuthal angle and pseudorapidity of the trigger and associated particles:

$$\Delta\varphi = \varphi^{trigg} - \varphi^{assoc}, \quad (2.4)$$

$$\Delta\eta = \eta^{trigg} - \eta^{assoc}. \quad (2.5)$$

With these differences, one can construct a two-dimensional correlation function, schematically written as:

$$\frac{d^2 N_{\text{pair}}}{d\Delta\varphi d\Delta\eta}(\Delta\varphi, \Delta\eta) = \frac{1}{N_{\text{trigg}}} \frac{1}{\varepsilon_{\text{trigg}}} \frac{1}{\varepsilon_{\text{assoc}}} \frac{d^2 N_{\text{pair}}^{\text{raw}}}{d\Delta\varphi d\Delta\eta}(\Delta\varphi, \Delta\eta) \frac{1}{\varepsilon_{\text{pair}}} \quad (2.6)$$

where N_{trigg} is the number of trigger particles corrected for the reconstruction efficiency and contamination and $\varepsilon_{\text{pair}}, \varepsilon_{\text{trigg}}$ and $\varepsilon_{\text{assoc}}$ are corrections described in Sec. 4.2.1. As the example plot in Fig. 2.12 is showing, around the (0,0) bin, one can observe the so called near-side peak, which originates of the pairs of particles that fragmented within the same jet. Due to the momentum conservation, the jets are produced back-to-back in the transverse plane. Thus, a second peak around π in the $\Delta\varphi$ direction can be observed. This one is smeared in $\Delta\eta$, because the partons can have in principal any longitudinal momentum. With the selection of the trigger particle, the near-side jet is fully reconstructed in the longitudinal direction, but the away-side jet is not necessarily within the detector acceptance as well.

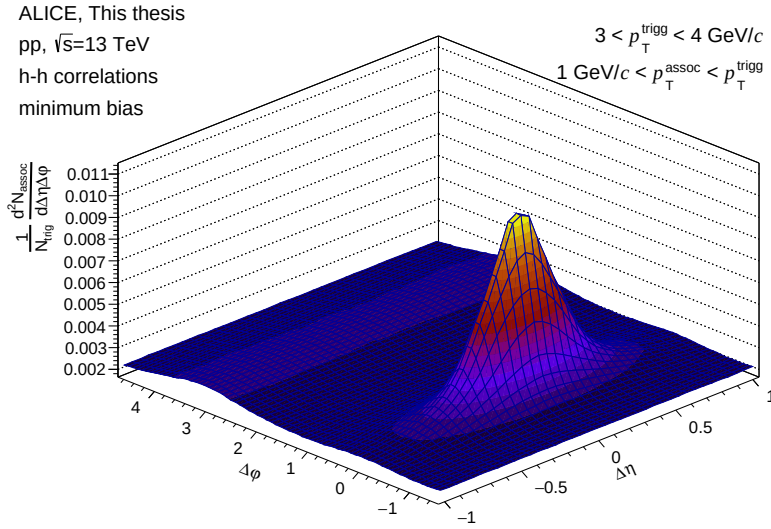


Figure 2.12: An example of a two-dimensional correlation of two unidentified hadrons.

From the correlation function, the $\Delta\varphi$ projections are produced and the per-trigger associated particle yield is calculated for the near-side and away-side jet peak, which is defined as:

$$Y_J^{\Delta\varphi} = \int_{\Delta\varphi_1}^{\Delta\varphi_2} \frac{dN}{d\Delta\varphi} d\Delta\varphi \quad (2.7)$$

2.8 Historical result on the di-hadron correlations

As described in Sec. 2.3.1, the suppression of high energy hadrons in the AA collisions is connected to the energy loss in the QGP. The disappearance of the recoil-jet in the most central Au+Au collisions was firstly observed by the STAR collaboration using the di-hadron correlations approach [65]. Within this study was concluded that the away-side jet is consistent with the background modified by the collective flow and thus fully quenched.

2.9 Recent results on the di-hadron correlations at RHIC and LHC

In lead-lead (Pb-Pb) collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, the correlation functions between two primary charged hadrons were measured with the ALICE experiment [66]. The extracted per-trigger jet-like yields were compared with the ones from pp collisions by calculating the I_{AA} ratio, defined as a ratio of yields in Pb-Pb collisions to the same quantity measured in pp collisions, in order to study the influence of the QGP on jets. In the case of no present medium, the ratio should be around unity and, otherwise, a modulation should be visible. This was also observed, as shown in Fig. 2.13, where the ratio is compatible with unity for peripheral collisions where no significant medium effects are predicted. On the other hand, the ratio for central collisions shows enhancement for the near- and suppression for the away-side, respectively. The suppression was expected and it can be explained by the energy loss of the jet particles in the medium. The near-side enhancement was observed for the first time and it is suggesting that the near-side parton is affected by the QGP as well. Three possible effects were suggested as explanation for the enhancement: a change of the FF, change of the quark/gluon jet ratio in the final state due to the different coupling to the medium and a bias on the parton p_{T} spectrum after energy loss due to the trigger particle selection [66].

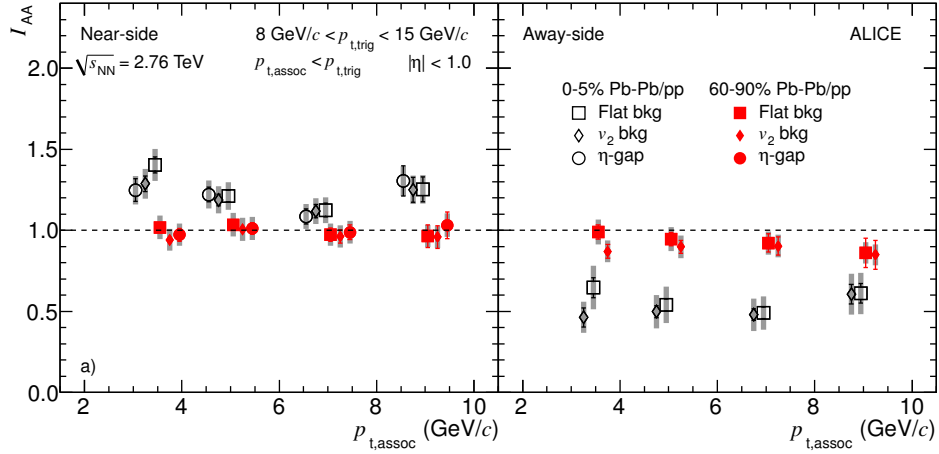


Figure 2.13: I_{AA} for central and peripheral collisions with different background subtraction methods [66].

The correlation functions with primary charged and neutral strange hadrons were studied by the STAR collaboration [67]. In this study, the near-side peak yields from five correlation functions (K_{S}^0 -h, $(\Lambda + \bar{\Lambda})$ -h, h-h, h- K_{S}^0 , h- $(\Lambda + \bar{\Lambda})$) were measured in

three collision systems (d+Au, Cu+Cu, Au+Au). From the h- K_S^0 and h- $(\Lambda + \bar{\Lambda})$ yields, the baryon over meson ratio $((\Lambda + \bar{\Lambda})/2K_S^0)$ was calculated in Cu+Cu collisions and it was concluded as consistent with the inclusive measurement in pp collisions. This was explained as a consequence of the system independent jet fragmentation, as the particle production is dominated by this effect in pp collisions. It was also implied that the jet-like correlations are not affected by the recombination production of Λ hyperons, as is the underlying event in heavy-ion collisions. The near-side yields from K_S^0 -h and $(\Lambda + \bar{\Lambda})$ -h correlation were studied as a function of p_T^{trigg} , p_T^{assoc} and collision systems. The results show no dependence on the collision system and only a hint of a dependence on the trigger particle type due to the large statistical uncertainties.

This work continues in these correlation studies in pp collisions at $\sqrt{s} = 13$ TeV measured with ALICE. The large statistics of the LHC Run2 data makes it possible to increase the p_T^{trigg} up to 20 GeV/c and study the yields more differential in p_T^{trigg} , p_T^{assoc} and multiplicity. The V^0 -h and h-h correlations are used to prove the possibility to distinguish between quark and gluon jets, which can be further used in Pb-Pb collisions to study the effect of the quark/gluon jet ratio on the near-side I_{AA} . Moreover, with h- V^0 correlations the contribution to $(\Lambda + \bar{\Lambda})/2K_S^0$ from jet and underlying event will be studied as well as the jet and underlying event contribution to the strangeness enhancement in high multiplicity collisions.

3 Experimental set-up and analysis software

3.1 Large Hadron Collider

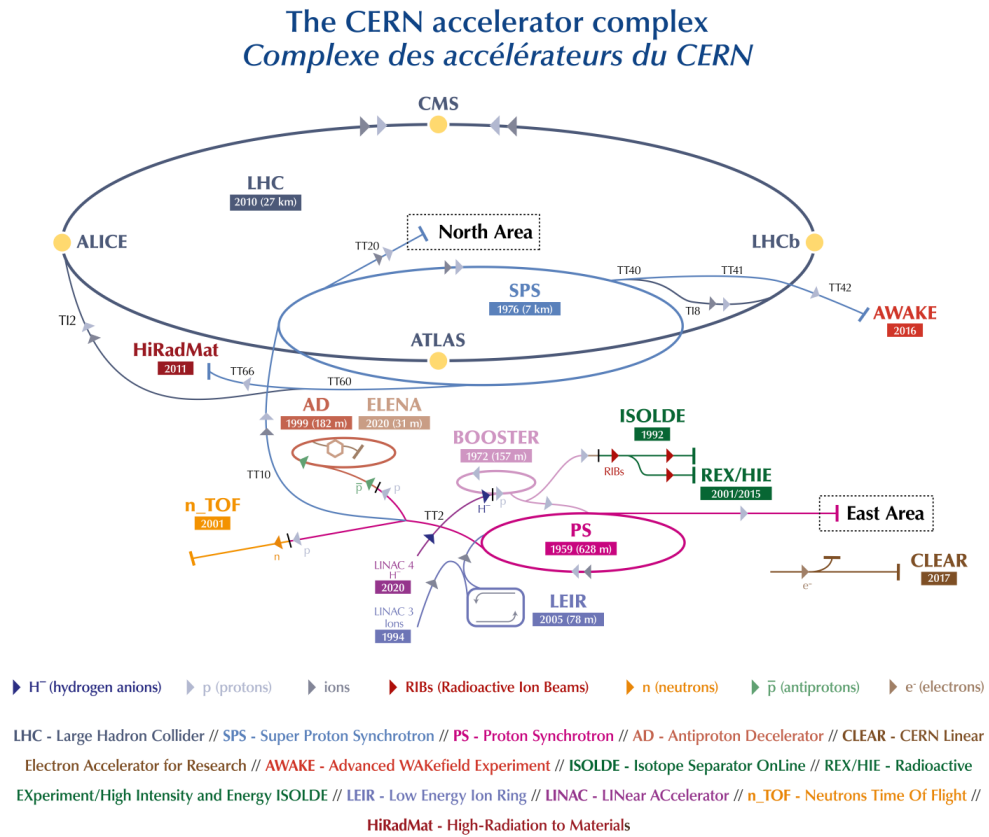


Figure 3.1: The acceleration complex at CERN [68].

The Large Hadron Collider (LHC) [69] is a part of the biggest particle acceleration complex (Fig. 3.1) in the world at European Organization for Nuclear Research (CERN) and it is the biggest particle collider ever built. It is located inside a tunnel, built originally for the Large Electron-Positron Collider (LEP) [70], which has a circumference of 27 km and is buried about 45 to 170 m below ground level. The LHC is able to accelerate protons up to the energy of 7 TeV and lead ions up to 2,51 TeV per nucleon. The acceleration

begins in Linac 2 (in Run 2) for protons and in Linac 3 for lead nuclei where both of them are linear accelerators. The protons continue the acceleration process in the booster, while the nuclei go into the Low Energy Ion Ring (LEIR) [71]. From this step on, both protons and nuclei undergo the same way into the Proton Synchrotron (PS) [72] and the Super Proton Synchrotron (SPS) [73] for further pre-acceleration. From there, they are injected into the LHC up to the maximal capacity of 2556 (600) bunches of 1.15×10^{11} (7×10^7) protons (lead nuclei) in each direction [69]. The circular trajectory is created by superconducting dipole magnets, producing a field of circa 8T and operating at a temperature of 1.9K [74]. The bunches are furthermore focused with sets of quadrupole and sextupole magnets.

At the LHC, four big experiments are positioned: A Toroidal LHC Apparatus (ATLAS) [75], A Large Ion Collider Experiment (ALICE) [76], Compact Muon Solenoid (CMS) [77] and Large Hadron Collider beauty (LHCb) [78]. This analysis was performed within the ALICE collaboration, thus this experiment will be described in the next sections in more details.

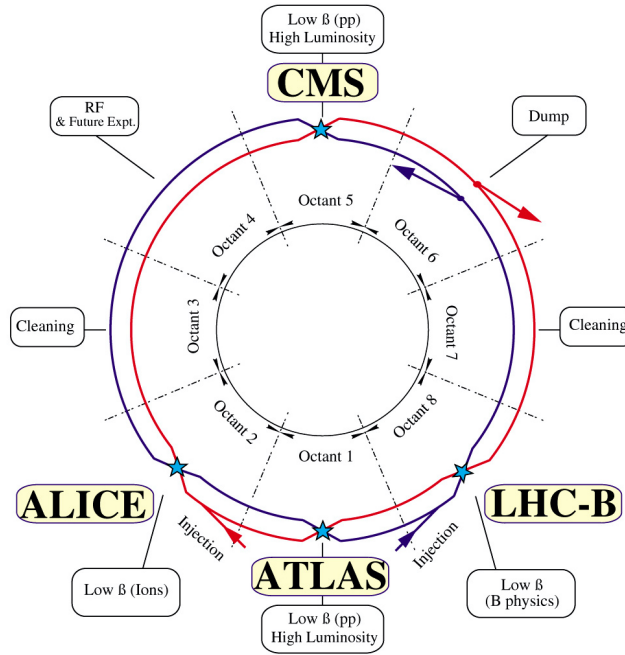


Figure 3.2: Schematic view of LHC division [79].

The LHC ring can be divided into eight sectors as is schematically shown in Fig. 3.2, where each of these Octants has an access-point from the surface. Following components can be found within the sectors:

- The four main experiments at the access-points: P1: ATLAS, P2: ALICE, P5: CMS and P8: LHCb
- Radiofrequency cavities [74] in sector 4 which are increasing the beam energy
- A cleaning system in sectors 3 and 7
- The beam dump [74] in Octant 6
- Injection points from the SPS in sector 2 and 8, just before the ALICE and the LHCb experiments

3.2 ALICE experiment

The ALICE experiment is one of the four big LHC experiments located at the access point 2, 60m underground of Saint-Genis, France. The whole experiment is 16m tall, 16m wide and 26m long and weighs around 10 000 tons [76]. The experiment, as it was operating during the Run2 data-taking period, is shown in Fig 3.3.

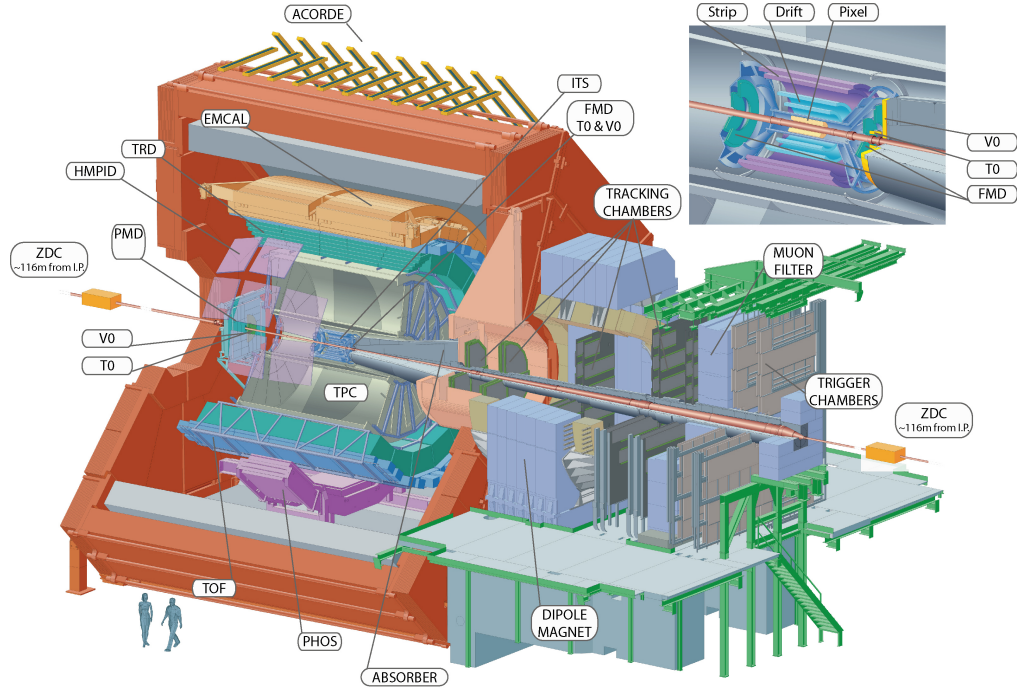


Figure 3.3: Schematic picture of the ALICE experiment during Run2 with sub-detector names [80].

The name is an acronym for “A Large Ion Collider Experiment” and as this name is suggesting, the main focus of this experiment is the study of heavy-ion collisions and the matter under extreme conditions that are occurring in these collisions. Thus,

all the sub-detectors are adjusted to be able to detect a large multiplicity of particles coming from the Quark–Gluon Plasma (QGP) fragmentation. Nevertheless, interesting measurement can be done also in proton–proton (pp) collisions, thanks to the Minimum-Bias (MB) and High Multiplicity (HM) trigger system, the good resolution down to zero- p_T and the good Particle Identification (PID) which distinguish ALICE from the other LHC experiments.

The particle detection is based on the interaction with matter where different particle species interact differently. The difference is based on their mass, charge and energy, but also on the used detection material. Thus, it is necessary to use different interaction processes to detect all possible particles created during the collisions. For this reason, the whole experiment is divided into many sub-detectors with specialised purpose, which are surrounded by a huge solenoid magnet producing a magnetic field of 0.5 T. These individual interactions in all sub-detectors produce in general electric signals, which are read out and stored in the LHC Computing Grid (LCG) (See Sec. 3.4) around the world. The signals are afterwards reconstructed and combined to form tracks - trajectories of the particles. Because of the present magnetic field, the tracks are curved and from the curvature, charge and transverse momentum can be calculated. For the energy measurement, calorimeters are used. These detectors consist of high density material which causes that the particles deposit the whole energy in the small area of the detector, so it can be estimated.

Another important feature of the ALICE experiment is the PID based on various techniques. Each particle is losing energy while traversing matter. This energy loss depends on the particle energy, its mass and the traversing material and can be estimated from the Bethe-Bloch formula :

$$-\frac{dE}{dx} = \frac{4\pi n z^2}{m_e c^2 \beta^2} \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \left[\ln \left(\frac{2m_e c^2 \beta^2}{I(1 - \beta^2)} \right) - \beta^2 \right] \quad (3.1)$$

where c is the speed of light, ϵ_0 the vacuum permittivity, $\beta = v/c$, e the electron charge, m_e electron mass and n the electron density of the traversing material defined as:

$$n = \frac{N_A Z \rho}{A M_u} \quad (3.2)$$

with N_A and M_u being the Avogadro number and the Molar mass constant, Z , ρ and A being the atomic number, density and the relative atomic mass, respectively. From the Bethe-Bloch formula is visible that each particle species has a special energy loss as

different particle species with the same momentum have different β depending on their mass. Thus, the energy loss can be calculated for each species and then compared with the measured one. Based on this match, the particle can be identified. This technique is mostly used for low momenta particles, where they can be satisfyingly distinguishable as is shown in Fig. 3.4. For intermediate and high momenta particles the time-of-flight method is used, where mass of a particle with momentum p_i can be estimated by measuring the time t_i needed to travel the length l :

$$m_i = \frac{p_i^2}{l^2} [ct_i - l][ct_i + l] \quad (3.3)$$

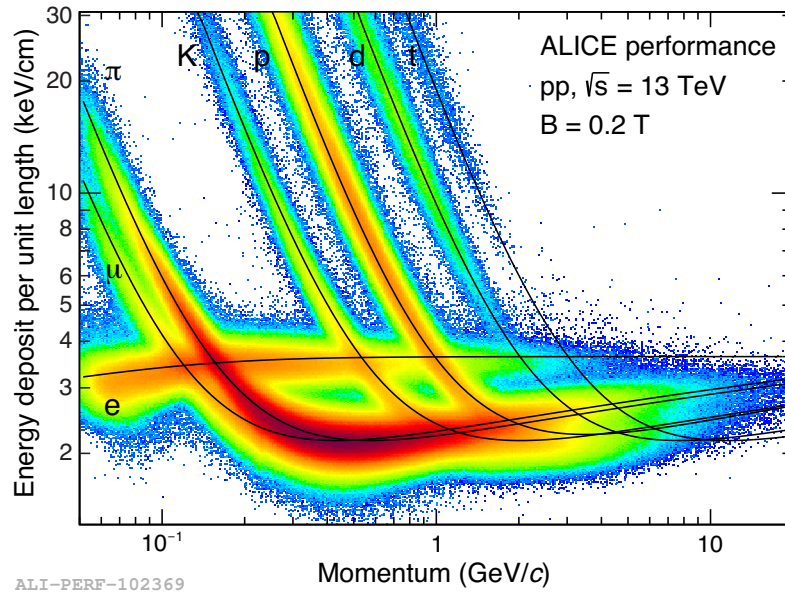


Figure 3.4: Specific energy loss measured by the ALICE TPC [81].

Moreover, the Transition Radiation (TR) is used to distinguish electrons from pions, the deposited energy in calorimeters measures photon and electron energies (Electromagnetic Calorimeter (EMCal), Di-jet Calorimeter (DCal), Photon Spectrometer (PHOS)) and hits in the trigger detectors in the muon arm provide information about muons.

In order to implement all the above described functionality around 20 sub-detectors surround the beam-pipe in an onion-like structure. The nearest ones to the collision point are tracking and triggering detectors (Inner Tracking System (ITS), Time Projection Chamber (TPC), Triggering and Centrality Detector (V0) and Timing and Trigger detector at ALICE (T0)), further away, the Time Of Flight (TOF) and Transition Radiation Detector (TRD) are placed and the last part within the main magnet is filled with electromagnetic calorimeters (EMCal, DCal, PHOS). Moreover, the muon arm is

located in the forward direction, which consist of an absorber, homogenous magnetic field created by dipole magnets and trigger chambers.

In further sections, the sub-detectors crucial for this analysis are discussed in more detail.

3.2.1 Inner Tracking System

The main tasks of the Inner Tracking System (ITS) are the determination of the Primary Vertex (PV) position¹, Secondary Vertex (SV) position of weakly decaying particles, estimation of the charged-particle multiplicity at mid-rapidity, identification of pile-up events (more than one collision takes place during one bunch-crossing) and tracking of all charged particles. The ITS surrounds the beam pipe and covers pseudorapidity range of $|\eta| < 0.9$ for all collisions taken place within ± 5.3 cm from the geometrical centre of the whole experiment (Interaction Point (IP)). The whole system is optimised for lowest possible material budget to minimise the scattering on the detector material. The detector must exempt high spatial resolution to distinguish individual tracks, because it is placed in an area with high particle densities (up to 50 tracks per cm^2 in lead–lead (Pb–Pb) collisions). Thus, it consist of 6 coaxial layers with radius 4–43.6 cm using 3 different technologies of semi-conductive detectors:

- **Silicon Pixel Detector (SPD)** It is located innermost at the beam pipe in the area with the highest particle densities and radiation. For this reason, it is based on hybrid silicon pixels forming a set of matrices with area of $12.8 \text{ mm} \times 70.7 \text{ mm}$ consisting of 256×32 detector cells [76].
- **Silicon Drift Detector (SDD)** The SDD constitutes two intermediate layers of the ITS. It has the capability to provide two samples of dE/dx for low momentum PID within the ITS.
- **Silicon Strip Detector (SSD)** Two outer layers of the ITS are built up of SSDs, which provide two-dimensional information about track position and 2 other samples of dE/dx . This information is necessary for track matching between the ITS and the TPC signals.

With this set-up, the momentum resolution of 2% can be reached for pions with momentum up to 3 GeV/c [76].

¹The place a collision.

3.2.2 Time Projection Chamber

The Time Projection Chamber (TPC) [82] is the main tracking detector of the central barrel. Besides tracking with a good momentum and spatial resolution, it contributes to the particle identification via the dE/dx measurement as shown in Fig. 3.4. It operates in high particle density (up to 20 000 tracks in central Pb–Pb collisions), thus everything was adjusted in order to separate all of them. The TPC has a cylindrical shape with inner radius of 85 cm, outer radius of 250 cm and length of 500 cm. With this measures, it covers the full azimuth and pseudorapidity of $|\eta| < 0.9$ for full length tracks matching to the ITS and the TOF and up to $|\eta| < 1.5$ for short tracks with lower momentum resolution. The inner volume is filled with a gas-mixture of Ar/CO₂ (88/12, in 2016 and 2018) or Ne/CO₂/N₂ (90/10/5 in 2017) [82] which was optimised for stability, low multiple scattering and small space-charge effects.

The whole cylinder is divided into two sections with the central electrode as is shown in Fig. 3.5. This anode together with two end-caps cathodes creates a homogeneous electric field of strength: 400 V/cm [76]. A particle passing the active volume of the TPC ionises the gas and the created electrons are drifting towards cathodes at the end caps. For the signal read-out, the Multi-Wire Proportional Chambers (MWPC) with cathode pad read-out are used. These are mounted to 18 trapezoidal sectors at each side. Each sector is divided into two smaller sectors, which are further divided into pad-rows for better spacial resolution.

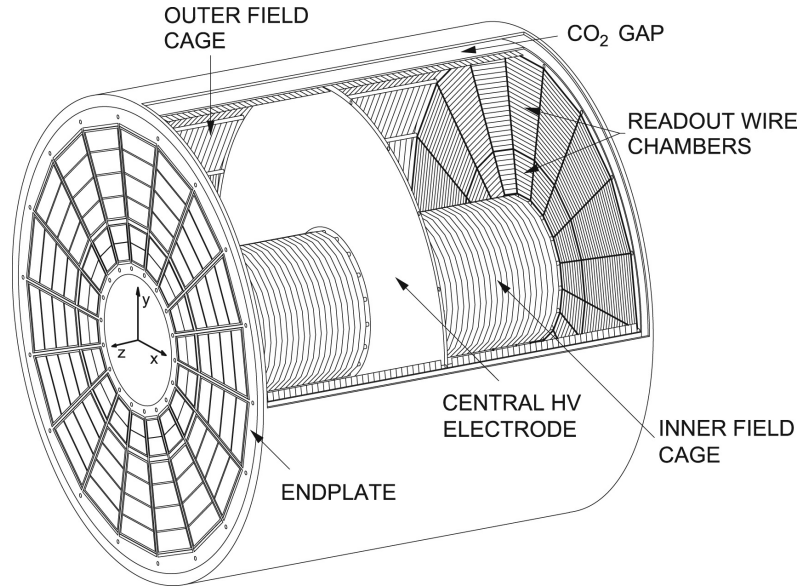


Figure 3.5: Schematic drawing of the TPC [83].

3.2.3 Transition Radiation Detector

The ALICE Transition Radiation Detector (TRD) [84] is the next detector after the TPC in the from inside of the barrel part. It consists of 18 supermodules, as shown in Fig. 3.6, which are covering the full azimuth and pseudorapidity range of $-0.848 < \eta < 0.84$. Each supermodule is divided into 30 chambers organised in 5 longitudinal stacks and 6 layers at a radial distance from 2.90 m to 3.68 m from the beam axis. Each chamber consist of foam/fibre radiator and a MWPC filled with a gas mixture of Xe and CO₂. The drift region between the radiator and MWPC is 3 cm. Particles with Lorenz factor $\gamma \approx 1000$ passing the radiator will emit additional TR photons with energies of 1–30 keV. The TR photons are absorbed in the drift region close to the absorber leading to a characteristic peak (TR peak) at large drift times. Since at the LHC energies, only electrons can produce the TR, the presence of the TR peak can distinguish electrons from other particles.

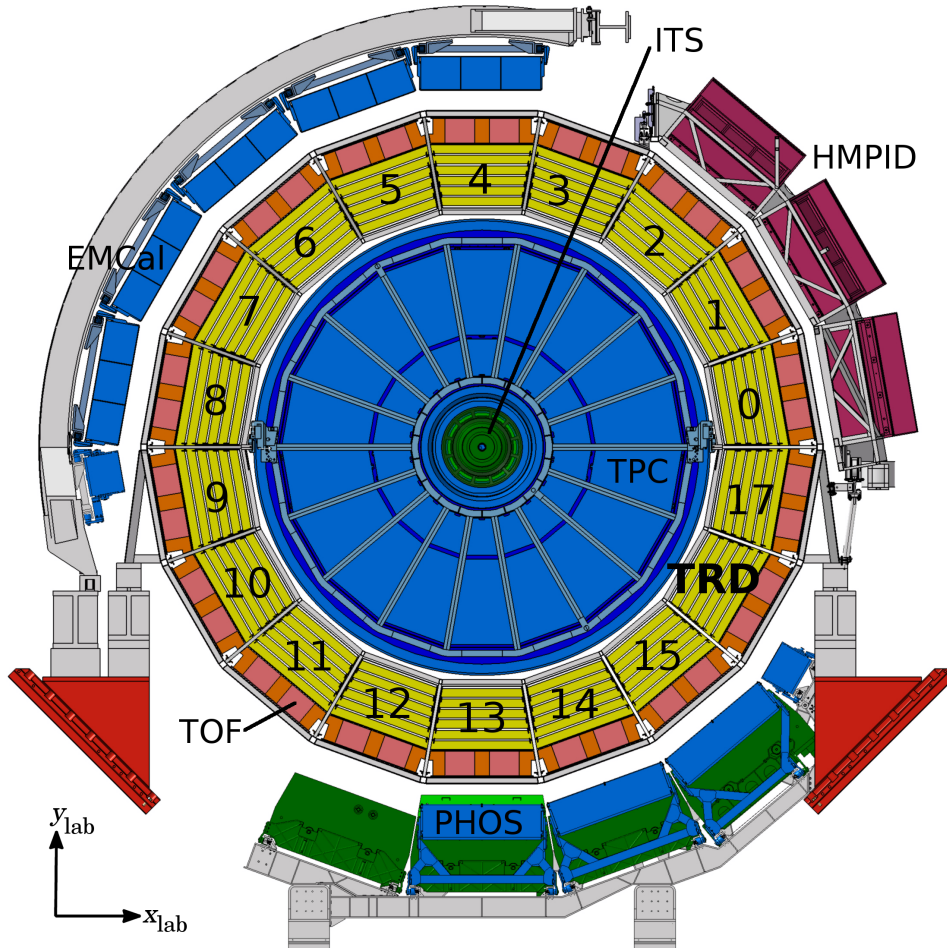


Figure 3.6: Schematic cross-section of the ALICE detector perpendicular to the LHC beam direction [84].

TRD repair

As a part of her service task, the author participated by the TRD repair during the 2nd Long Shutdown (LS2).

During the Run2 data-taking period, many of the TRD chambers stopped to work and the cause was assigned to the failure of capacitors in the High Voltage (HV) filter box. This supplies the HV to the drift cathode and six anode segments. It was decided that the capacitors can be removed without a big impact on the TRD performance. Nine of the supermodules (0,1,2,6,7,8,10,12,16 as marked in Fig. 3.6) with the highest amount of not working chambers were selected, where the capacitors were removed.

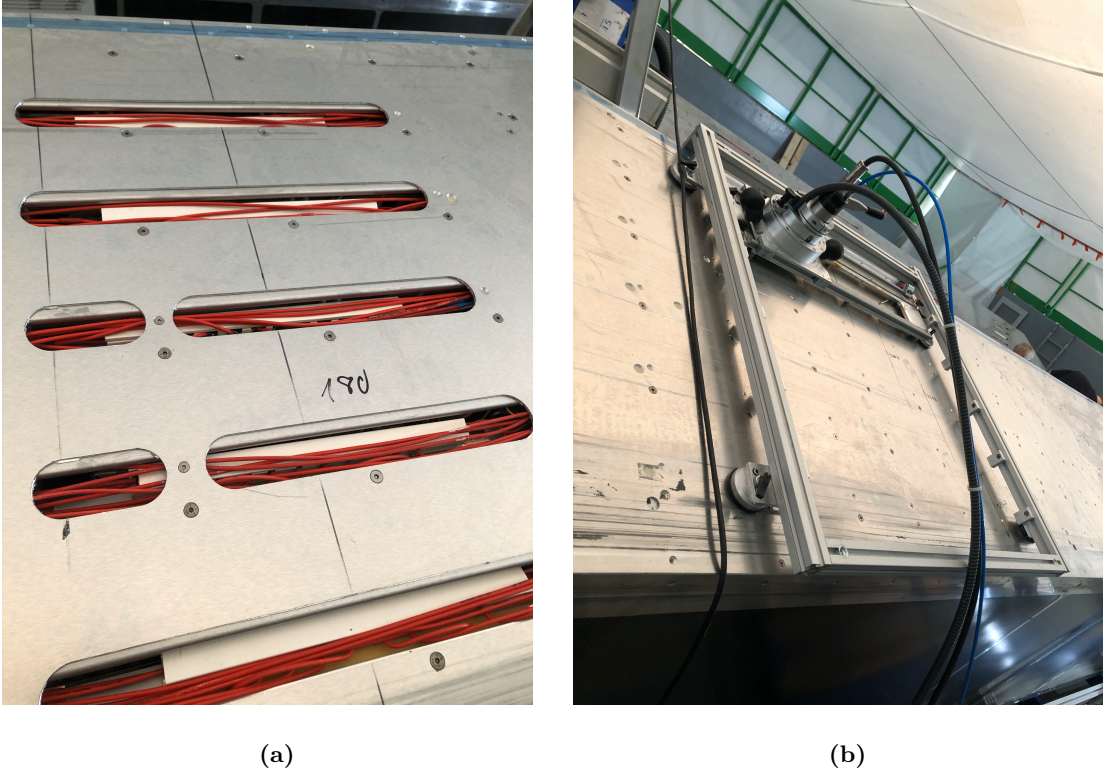


Figure 3.7: (a) Milled holes with visible HV filter boxes. (b) The milling frame.

Each of the selected supermodules was extracted from the space-frame and transported from the cavern to the repair hall. Instead of the complete disassembly of the module to remove the capacitors, holes were milled into the aluminium coverage of the module as shown in Fig. 3.7a. For this purpose a special milling frame for the boring drill was manufactured to help drilling only the wanted area (Fig. 3.7b). Afterwards, the HV filter box was opened and the capacitors were removed. The holes were finally covered with kapton foil and taped with kapton tape (Fig. 3.8). The HV filter boxes of the uppermost

layer are covered by the main frame of the supermodules, thus no holes could be milled there. The full upper aluminium coverage was removed as well as the cooling pipe to get access to the capacitors of this layer. After the successful tests of the HV, Low Voltage (LV) supplies and vacuum tightness of the cooling, the supermodules were closed, transported to the cavern and injected back to the space frame. Thanks to the repairing campaign, the number of not working chambers was decreased from 93 and 12 to 23 and 4 for the drift and anode channels, respectively. Moreover, the working chambers were stabilised for further operation.

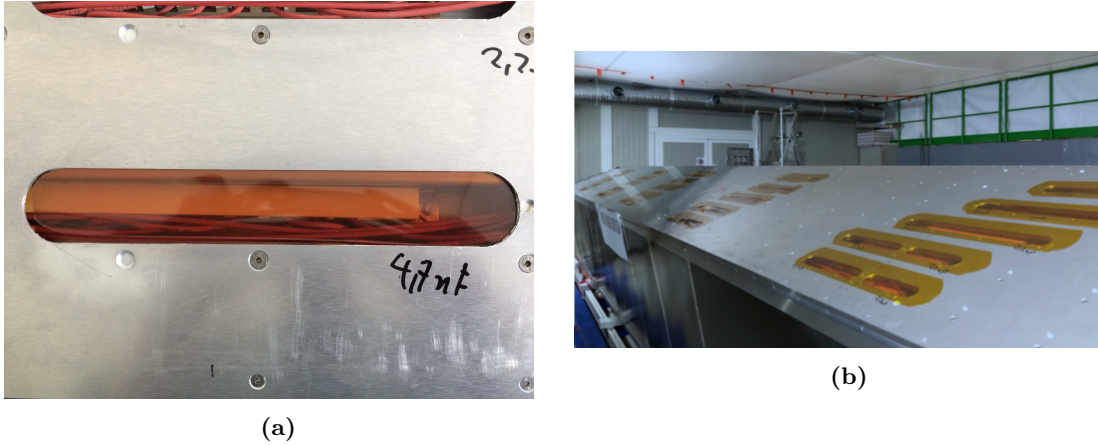


Figure 3.8: (a) The hole covered with kapton foil. (b) All holes in a supermodule taped with kapton tape.

3.2.4 Time-Of-Flight detector

The Time-Of-Flight (TOF) detector [85] covers the whole azimuth and pseudorapidity range of $|\eta| < 0.9$ and contributes to the tracking capability, the PV reconstruction, pile-up rejection and PID with $\pi^\pm/K^\pm$ and K/p separation better than 3σ as visible in Fig. 3.9. The detector consists of 10^5 independent channels of Multi-gap Resistive-Plate Chambers (MRPC). These are organised into 18 azimuthal sectors (Fig. 3.6), each further divided into 5 longitudinal segments. The main advantage of this gaseous detector is an immediate avalanche after passing of a particle which generates signals on the electrodes. This gives TOF great time resolution of 40 ps and efficiency close to 100% [76].

3.2.5 V0

The Triggering and Centrality Detector (V0) [86] consist of two rings of scintillating detectors (V0A and V0C) placed on both sides of the ITS covering pseudorapidity

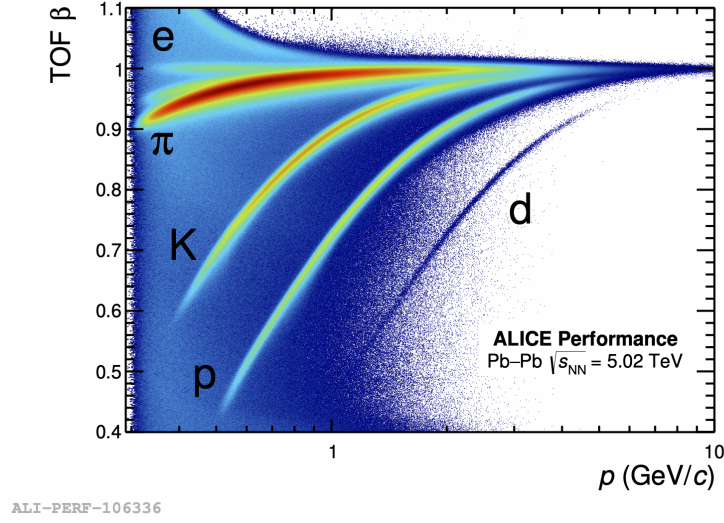


Figure 3.9: Velocity of different particle species measured by ALICE TOF [81].

intervals of $2.8 < \eta < 5.1$ (V0A) and $-3.1 < \eta < -1.7$ (V0C). In pp collisions, it serves mainly as a part of the MB trigger system². In Pb–Pb collisions, the monotonic dependence of detected tracks in V0 on the primary created particles is used for the determination of the centrality of collisions. The same feature is used in pp collisions to determine the event multiplicity. Each of the detectors consists of 32 segments organised in 4 rings produced from scintillating material.

3.3 Root and AliRoot framework

ROOT is an analysis framework based on C++ [87] and developed at CERN [88]. It was adjusted to be able to work with huge amounts of data that can be saved in special compressed binary ROOT files with a tree object. These trees can be chained for assessing a huge amount of such ROOT files e.g. in the LCG (Sec. 3.4). Moreover ROOT offers wide range of mathematical and statistical tools, plotting, and visualisation options for publishing of the analysed data. ROOT can be used as a stand-alone framework or it can be linked to other program languages or frameworks such as Python, Ruby or R.

AliROOT [89] and AliPhysics [90] are extensions of the ROOT framework with specially adjusted classes and functions necessary for the analyses of the data measured by ALICE. Within this extended framework basic selection criteria, e.g for events or tracks, are set.

²electronics, which online decides whether an event is interesting enough to be stored for later analyses

Thus, each analysis can access them. Within AliROOT two data formats can be analysed (both of them were used in the following analysis):

- **Event Summary Data (ESD)** - processed raw data³ without filtering. All objects are already reconstructed as charged particle tracks or weak decays with all attributes (charge, momentum, decay position, ...).
- **Analysis Object Data (AOD)** - data after filtration, where only necessary information suitable for general analyses is left in order to decrease the CPU time for the processing.

Besides the data analysis, AliRoot is linked with Monte Carlo (MC) event generators as PYTHIA [57], Hijing [91] or AMPT (A Multi-Phase Transport Model) [92] and detector response simulation framework GEANT4, which are used for simulating the collisions under the same conditions, as were present at the data taking (simulation are anchored to specific data). The simulated events contain the full information about the generated particles as well as about the remaining particles after the interactions with the detector material. The reconstructed tracks can be directly connected with the generated ones. Hence, these simulations are an important tool for calculating the detection efficiencies and amount of misidentified particles and thus are further used for corrections in the analyses. In the following analysis, all MC based corrections were performed with PYTHIA8 Monash tune [61] simulation anchored to the used data.

3.4 LEGO trains on grid

ALICE produces a huge amount of data with recording rate of 100 MB/s each data-taking period [93]. Such amounts can not be stored and analysed on local computers, thus the LCG [94, 95] is used. This is a loosely coupled distributed computing and storage infrastructure used by the entire High-Energy Physics (HEP) community at the LHC. A special interface called ALICE Environment (AliEn) [96] was developed by the ALICE collaboration in order to access the computing resources of LCG. Each user can submit jobs separately or use the Lightweight Environment for Grid Operations (LEGO) train system. This system increases the CPU efficiency such that more analysis tasks, which would otherwise run separately on the same data set, are merged into one single job. In this way, the analysed data set needs to be read only once [97, 98].

³Pure detector signals assigned to each collision

4 Measurement method

In this analysis, the di-hadron correlation method is used, which is described in detail in Sec. 2.7. The K_S^0 mesons, Λ ($\bar{\Lambda}$) hyperons and unidentified charged primary hadrons are used as trigger as well as associated particles with $3 < p_T^{\text{trigg}} < 20$ GeV/ c and $1 \text{ GeV}/c < p_T^{\text{assoc}} < p_T^{\text{trigg}}$ kinematic restrictions.

By this trigger and associated particle selection, several autocorrelation can occur which need to be removed using following criteria: The invariant mass of two charged hadrons is checked and if it is close to the mass of a fast decaying particle (K_S^0 , Λ , $\bar{\Lambda}$, photon, ρ , ϕ , K^* , Δ^{++}), such a pair is removed, the associated tracks to V^0 are checked to be their daughter tracks and the pairs are rejected in such a case, Λ and $\bar{\Lambda}$ are not correlated with tracks in a case that their total invariant mass is close to the cascade (Ξ, Ω) mass.

The yields are calculated with the bin counting method from the $\Delta\varphi$ projection within the intervals $[-0.9, 0.9]$ and $[\pi - 1.4, \pi + 1.4]$ for the near- and away-side peak, respectively.

4.1 Selection criteria

4.1.1 Event selection

This analysis is performed on the pp collisions measured at 13 TeV, which were collected during the Run 2 data-taking period between 2015 and 2018 with the ALICE apparatus. The events are selected with kINT7 MB trigger, which uses the coincident signal in the V0A and V0C detectors. The total number analysed pp collisions is 1.58×10^9 corresponding to the integrated luminosity of 27.3 nb^{-1} .

Moreover, PV position is required to be within 10 cm away from the IP along the z-axis, to guarantee that the most of all produced tracks are within the detector acceptance. In addition, other specific event-selection criteria are applied with the help of AliEventCuts class, where the criteria for the Run2 pp collision are required, e.g. rejection of the in-bunch pile-up.

The events are divided into several multiplicity classes based on percentiles of the summed signal in the two V0 detectors (V0M), for instance the 0-1% and 50-100% classes are the events with the highest and the lowest range of the V0M signal, respectively.

4.1.2 Primary track selection

In order to perform the analysis only on particles originated from the PV, several selection criteria are applied on the tracks. First, the pseudorapidity in absolute value was required to be less than 0.8. Moreover, hybrid global cuts are used, which are pre-defined as the Filter Bit (FB)256. This set requires from the tracks to have:

- minimal number of crossed TPC pad rows: 70
- minimal ratio of the number of the crossed rows to the number of findable clusters (geometrically possible assignable clusters to a track): 0.8
- maximal fraction of shared clusters with other tracks: 0.4
- maximal Distance of Closets Approach (DCA) to the PV in xy-plane: 2.4 cm
- maximal DCA to the PV in y-direction: 3.2 cm
- the DCA has to be inside an ellipsoid around the PV defined by the two previous parameters as semi-axes
- the TPC and the ITS refit
- maximal fitting χ^2 per cluster in the TPC: 4
- maximal fitting χ^2 per cluster in the ITS: 36
- global refit with maximal fitting χ^2 per cluster: 36
- no kink decays (after a kink decay one daughter particle continues almost in the same direction as the mother particle and the second one is neutral and thus invisible for the detector)
- minimal 1 hit in the SPD

Due to the problems with the MC closure test described below in Sec. 4.4 a special set of criteria has been created for charged primary hadrons for h-($\Lambda + \bar{\Lambda}$) and ($\Lambda + \bar{\Lambda}$)-h analysis, which includes following criteria:

- maximal fitting χ^2 per cluster in TPC: 4
- no kink decays
- the DCA does not need to be inside a specific ellipsoid around the PV

- maximal DCA to PV in xy-plane: 0.9 cm
- maximal DCA to PV in y-direction: 2 cm
- the TPC and the ITS refit
- minimal 1 hit in the SDD
- minimal number of crossed TPC pad rows: 70
- minimal ratio to the number of findable clusters: 0.8

4.1.3 V^0 selection criteria

The strange hadrons of interest in this analysis are the K_S^0 mesons and Λ resp. $\bar{\Lambda}$ baryons, which decay topology has a V shape (Fig. 4.1). For this reason, they are named V^0 particles. All of them are neutral particles that means that they cannot be tracked directly. They are reconstructed in their most frequent decay channels [11]:

$$K_S^0 \rightarrow \pi^+ + \pi^- (69, 2\%)$$

$$\Lambda \rightarrow p + \pi^- (63, 9\%)$$

$$\bar{\Lambda} \rightarrow \bar{p} + \pi^+ (63, 9\%)$$

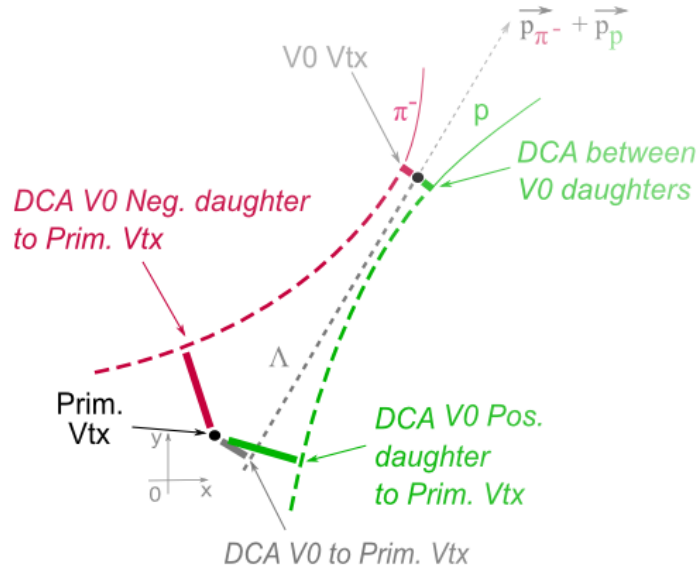


Figure 4.1: Scheme of the V^0 decay [99].

The decay daughter tracks are identified in the TPC based on the energy loss information and some more quality criteria are required:

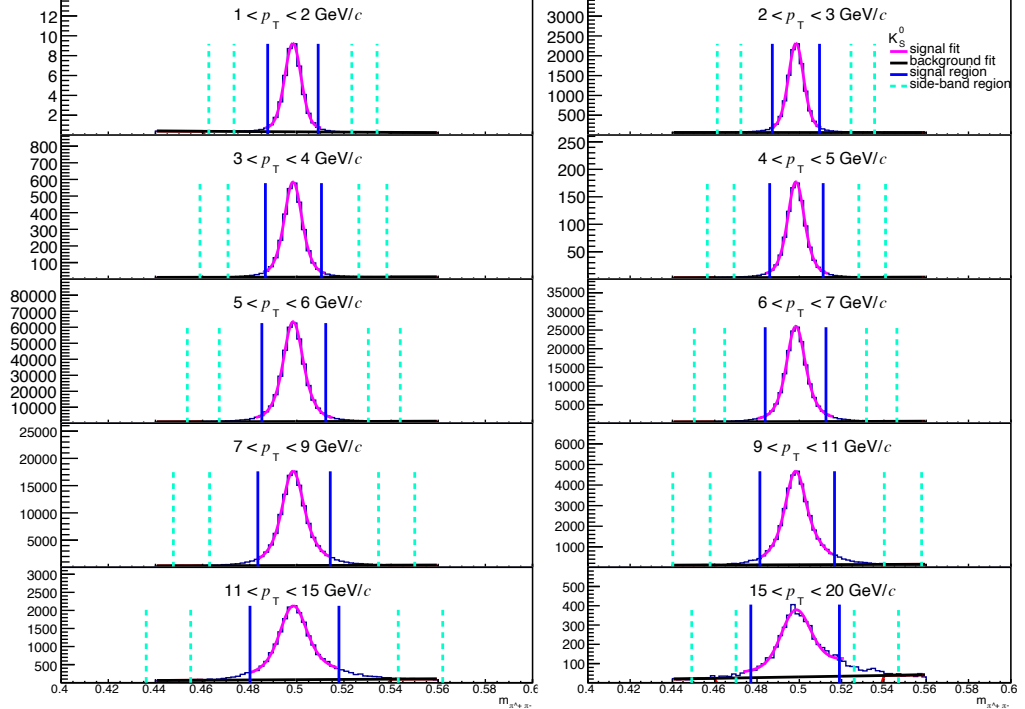
- $|\eta| < 0.8$
- minimal number of crossed TPC pad rows: 70
- minimal ratio to the number of findable clusters: 0.8
- the TPC refit

Pairs of such identified tracks are combined and the invariant mass of each pair is calculated. In order to suppress the combinatorial background even more, additional selection criteria are required, which are based on the V-shaped decay topology. These are listed in Tab. 4.1. Here, the V^0 decay radius is the distance between the SV and the PV. The DCA Neg. to PV and DCA Pos. to the PV are the distances of closest approach between the negative and positive daughter track (or the prolonged track fit), respectively, and the PV. The θ_{PA} refers to the pointing angle that is the angle between the full-momentum vector of the V^0 candidate and the line connecting the PV and the SV. The reconstructed proper lifetime of an individual particle is defined as mL/p , where m is the particle mass, L is the distance between the PV and the SV and p is the particle momentum. The mean life $c\tau$ is listed in Ref. [11] and its value is 2.68 cm and 7.89 cm for K_S^0 and Λ ($\bar{\Lambda}$), respectively. It can happen that a certain pair of daughter tracks can give an invariant mass value of K_S^0 for the $\pi^+\pi^-$ assumption and the one of Λ ($\bar{\Lambda}$) in the case of $p\pi$ assumption. Such pairs are not accepted based on the competing rejection requirement.

The V^0 candidates are accepted in the case that they pass all the selection criteria and if their invariant mass is within the interval $\pm 3\sigma$ from the mean value of the invariant mass spectrum (μ). In order to estimate this invariant mass acceptance region, the invariant mass spectrum of each pair of daughter tracks is fitted with a double-Gaussian function with 1st order polynomial background, where the bigger of the two σ in the double-Gaussian fit is taken for the acceptance range. The invariant mass spectra together with fits and side-band regions (necessary for the misidentified V^0 correction explained in Sec. 4.2.5) are shown in Fig. 4.2 and Fig. 4.3 for K_S^0 and $(\Lambda + \bar{\Lambda})$, respectively. The purity is defined as $1 - \frac{back}{full}$ where *back* is the integral of the background function in the $\mu \pm 3\sigma$ interval and *full* is the sum of bins within the same range. These purities are shown in Fig. 4.12.

Table 4.1: Selection criteria for V^0 candidates

Selection	Value
Online or On-The-fly	only offline
Rapidity $ y $	<0.5
V^0 decay radius (cm)	>0.5
DCA Neg to PV (cm)	>0.06
DCA Pos to PV (cm)	>0.06
DCA V^0 daughters (σ)	<1
$V^0 \cos(\theta_{PA})(K_S^0)$	>0.97
$V^0 \cos(\theta_{PA})(\Lambda)$	>0.995
Proper lifetime K_S^0 (cm)	<20
Proper lifetime Λ (cm)	<30
Competing V^0 rejection K_S^0 (GeV/c^2)	<0.005
Competing V^0 rejection Λ (GeV/c^2)	<0.01
dE/dx ($N\sigma$)	<3

**Figure 4.2:** Invariant mass distributions of K_S^0 candidates. Note that the y-axis of the plots in the first two rows is multiplied by 10^3 .

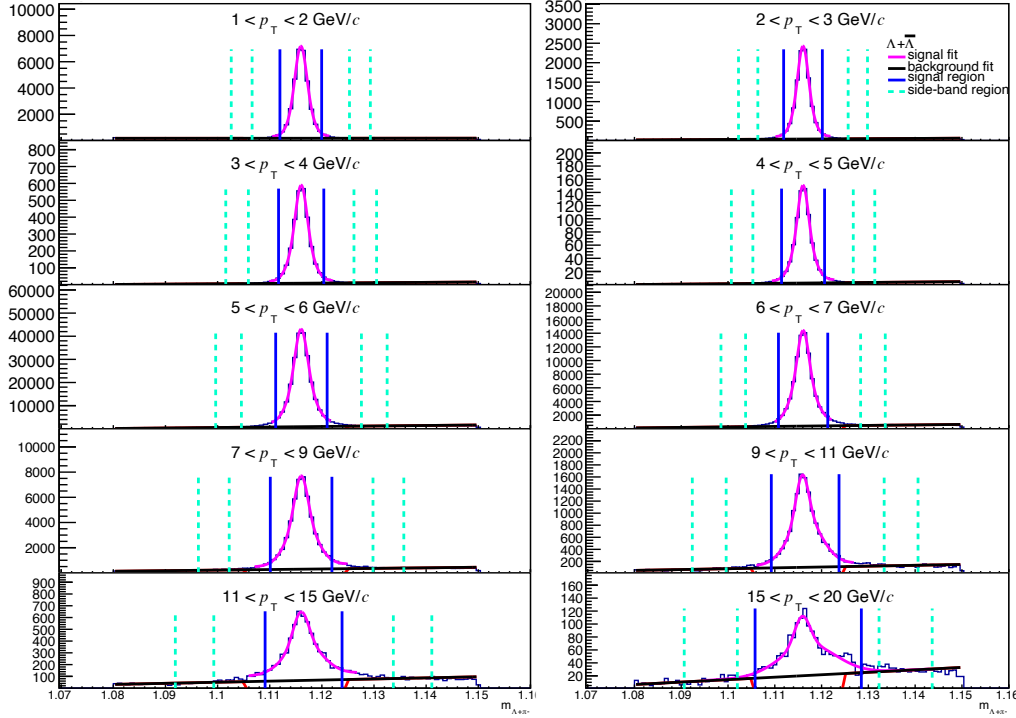


Figure 4.3: Invariant mass distributions of Λ and $\bar{\Lambda}$ candidates. Note that the y-axis of the plots in the first two rows is multiplied by 10^3 .

To suppress the out-of-bunch pileup¹, two additional selections are applied, which are used also in other types of analyses, eg. [100]. At least one of them needs to be fulfilled:

- at least one daughter track is reconstructed both in the ITS and TPC
- at least one daughter track has the TOF signal

The extracted and corrected signal for V^0 is compared with published data [101] and this comparison is shown in Fig. 4.4. The spectra agrees within the uncertainties.

4.2 Corrections

4.2.1 Detector acceptance correction

Because of the finite acceptance of the detector, the correlation function exhibits a characteristic triangular shape. To correct for this geometrical correlation, the event-mixing method is used, where particles from different events are used to calculate the correlation function. In this case, no physical correlation should occur, because

¹A situation when some of particles from previous collisions were still not read out from the TPC and particles from new collision are already present.

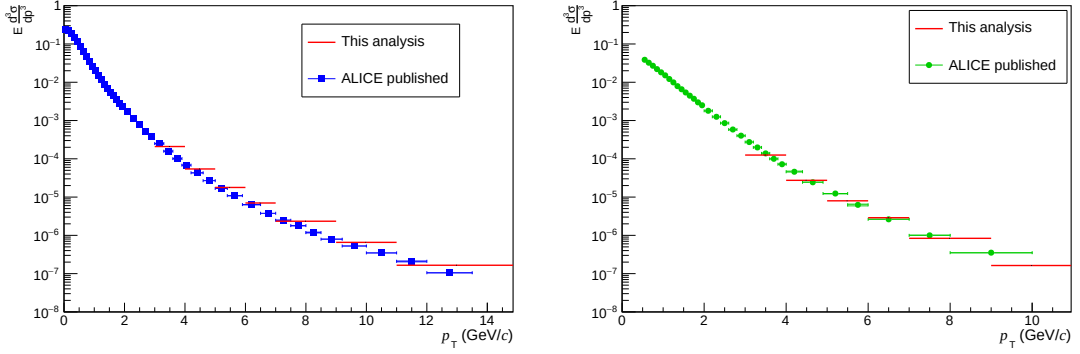


Figure 4.4: Comparison of K_S^0 and Λ invariant p_T spectra with published results [101].

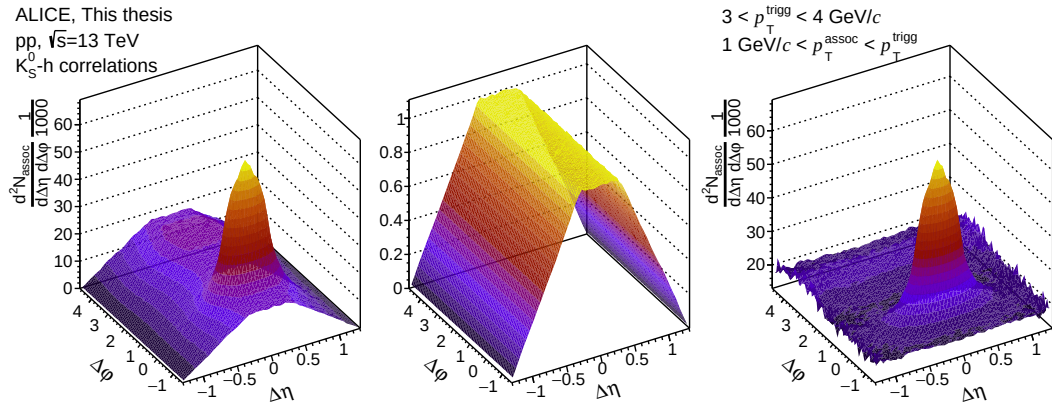


Figure 4.5: Example of the mixing procedure applied on the K_S^0 -h correlation function: left: uncorrected correlation function with the triangular shape, middle: mixed correlation function normalised to unity, right: K_S^0 -h correlation function corrected for the detector acceptance.

the particles come from independent events. However, these events should be similar: the PV position is within the same 1 cm range as the original event and the multiplicities are within the same percentile bin with width of 10%. This method allows for evaluating correlations coming from detector effects as a function of p_T and PV position (example of the procedure in Fig. 4.5). Afterwards, the true correlation function can be obtained as:

$$\frac{d^2N_{pair}}{d\Delta\varphi, d\Delta\eta}(\Delta\varphi, \Delta\eta) = \sum_i \frac{S_i(\Delta\varphi, \Delta\eta)}{\frac{1}{\alpha_i} M_i(\Delta\varphi, \Delta\eta)} \quad (4.1)$$

where the sum goes over PV position bins, α_i is a scaling factor (in this analysis, it is the average over bins with $\Delta\eta = 0$), $S_i(\Delta\varphi, \Delta\eta)$ is the correlation function from the same events and $M_i(\Delta\varphi, \Delta\eta)$ is the mixed correlation function. In Eq. 4.1, this correction is schematically written as ε_{pair} .

4.2.2 Wing correction for h-h correlations

In the case of h-h correlation function, the mixed background does not describe the shape of the acceptance-related correlation function completely (left part of Fig. 4.6a). As visible in the ratio plot in the same figure, after the division, small "wings" are present. To account for this fact, a dedicated wing - correction is applied. Such very similar wings were present also in another analyses (e.g. [102]), where the same correction was applied. It is assumed that the $\Delta\eta$ projection of the away-side peak is completely flat, thus the range of $\pi/2 < \Delta\varphi < 3\pi/2$ is projected on $\Delta\eta$ and normalised by number of bins in that $\Delta\varphi$ range (Fig. 4.6b top panel). From this a two dimensional distribution is derived (Fig. 4.6b bottom panel), over which the correlation function is divided. This correction is done as the mixing correction for each PV and multiplicity bin separately.

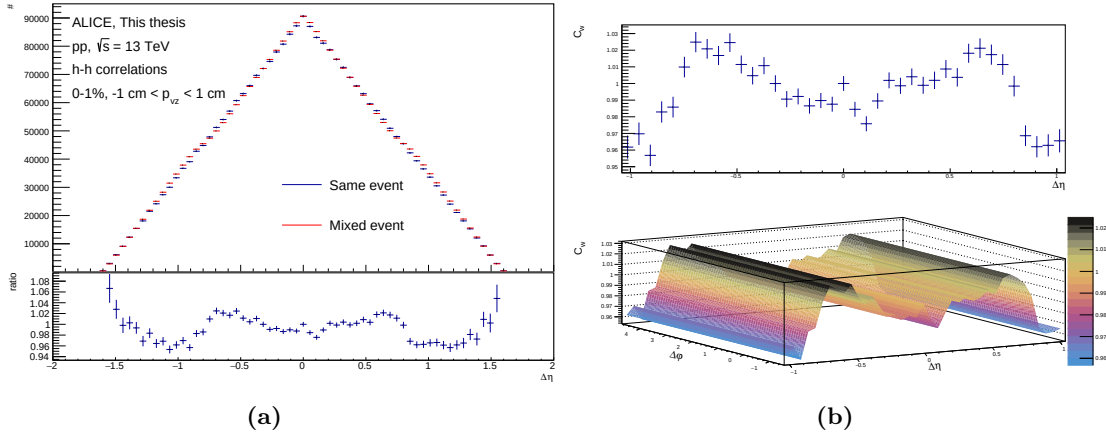


Figure 4.6: (a) $\Delta\eta$ projection of the same event and mixed event distribution of the h-h correlation function for $1 < \Delta\varphi < 1.5$ and their ratio. (b) 1-dimensional wing correction factor (top), 2-dimensional wing correction factor (bottom).

4.2.3 Single particle efficiency

Due to the detector effects, it is not possible to reconstruct all particles with an efficiency of 100%. To correct for this fact, a single particle efficiency is calculated based on the MC information. The same selection criteria are applied for tracks reconstructed both in real and MC data. For the MC data, it is also checked whether a selected track is associated with a primary particle. The reconstruction efficiency is calculated for primary tracks within the pseudorapidity acceptance $|\eta| < 0.8$. The efficiency is then defined as:

$$\varepsilon = \frac{N_{reconstructed}^{primary}}{N_{generated}^{primary}} \quad (4.2)$$

where $N_{reconstructed}^{primary}$ is the number of reconstructed primary hadrons and $N_{generated}^{primary}$ is the number of generated primary hadrons. This efficiency correction is applied as a function of p_T , η , PV position and φ in this analysis. This correction is applied on-the-fly and for each data taking year separately, because the correction factors differ across different years (Fig. 4.7). The similarity of the correction factor across different data taking periods within each year has been checked. From this check follows that the efficiency correction factors from the different periods are compatible and can be merged in order to decrease the statistical fluctuations mostly for high p_T particles. The same procedure is applied also to the V^0 candidates. For all of the reconstructed candidates that satisfied the selection criteria, it is checked whether they are true primary V^0 particles. The correction factors for different data taking years are shown in Fig. 4.8, 4.9 and 4.10.

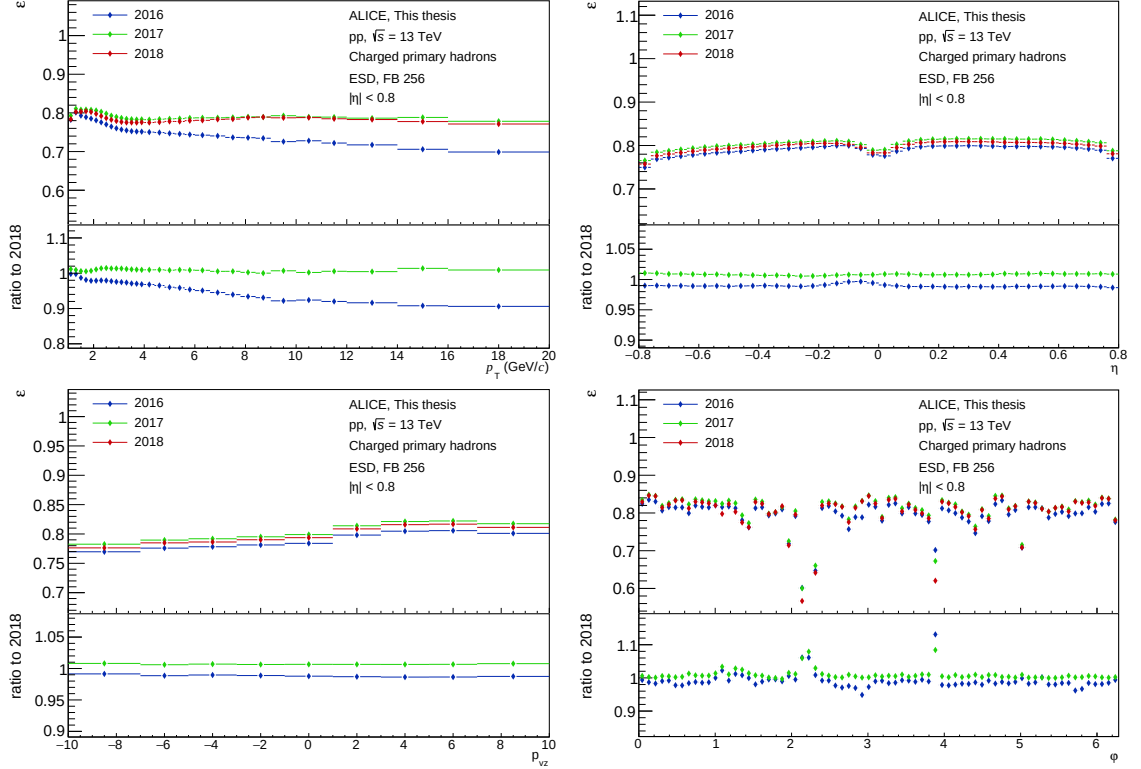


Figure 4.7: Efficiency factors for primary hadrons for different data taking years and their ratio.

4 Measurement method

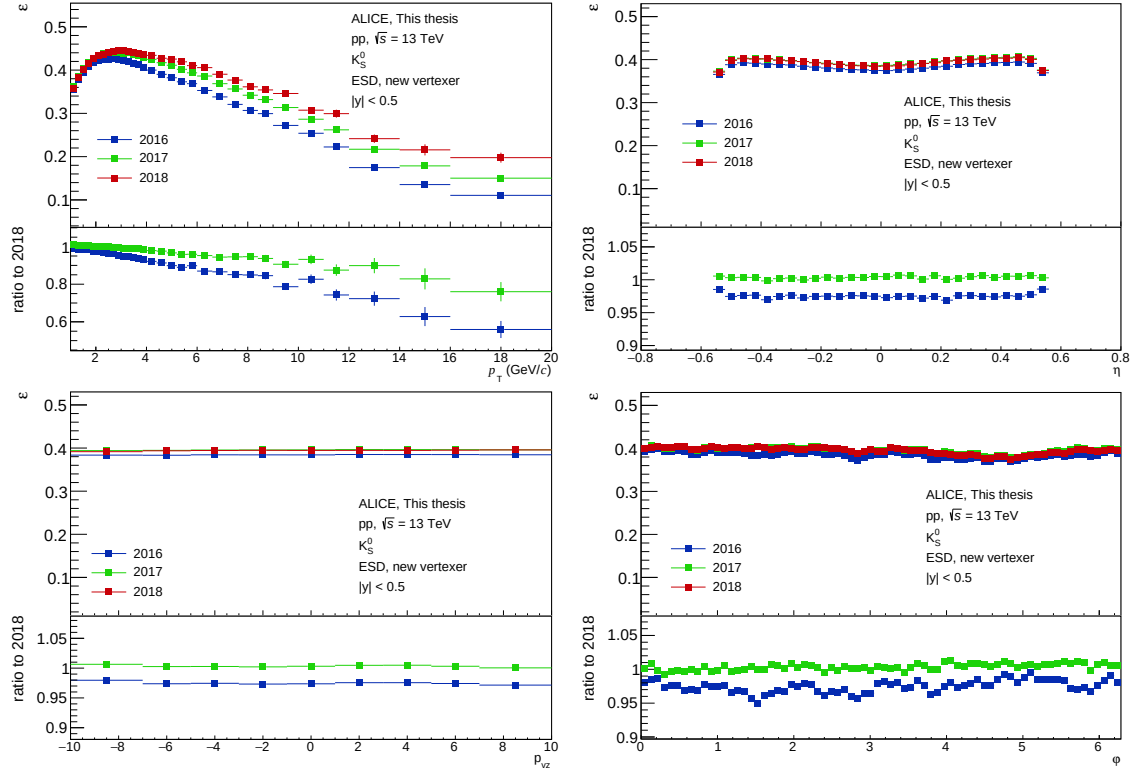


Figure 4.8: Efficiency factors for K_S^0 for different data taking years and their ratio.

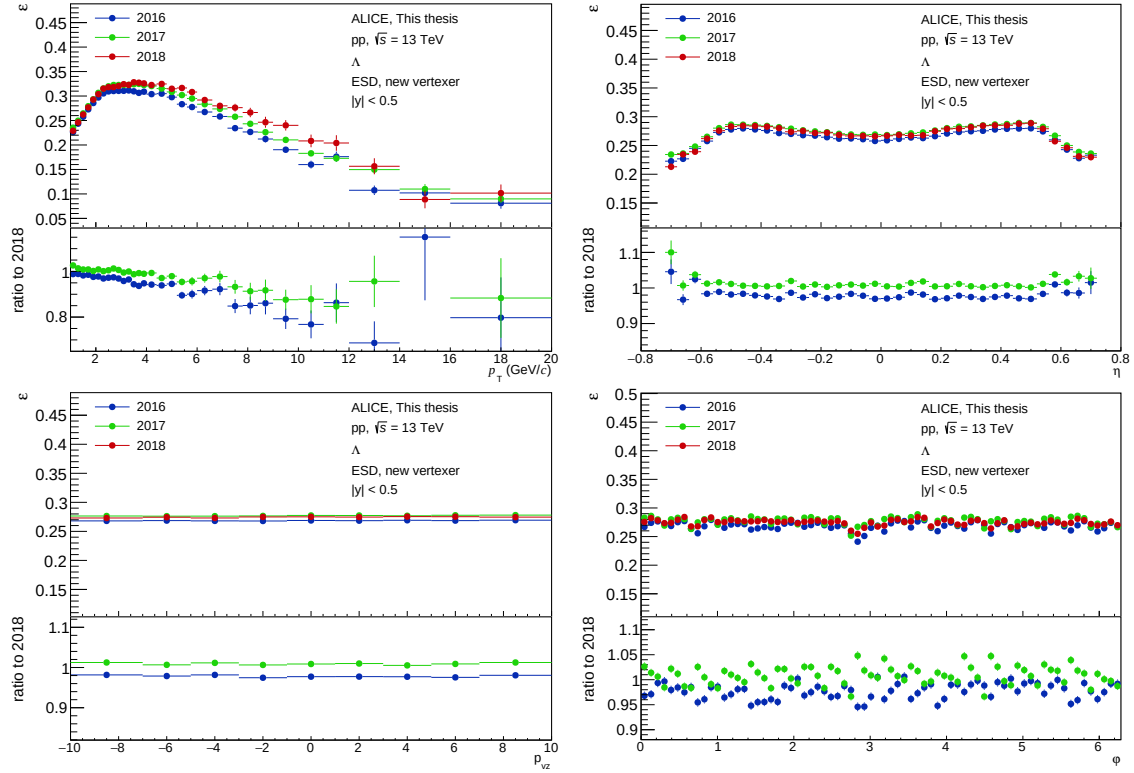


Figure 4.9: Efficiency factors for Λ for different data taking years and their ratio.

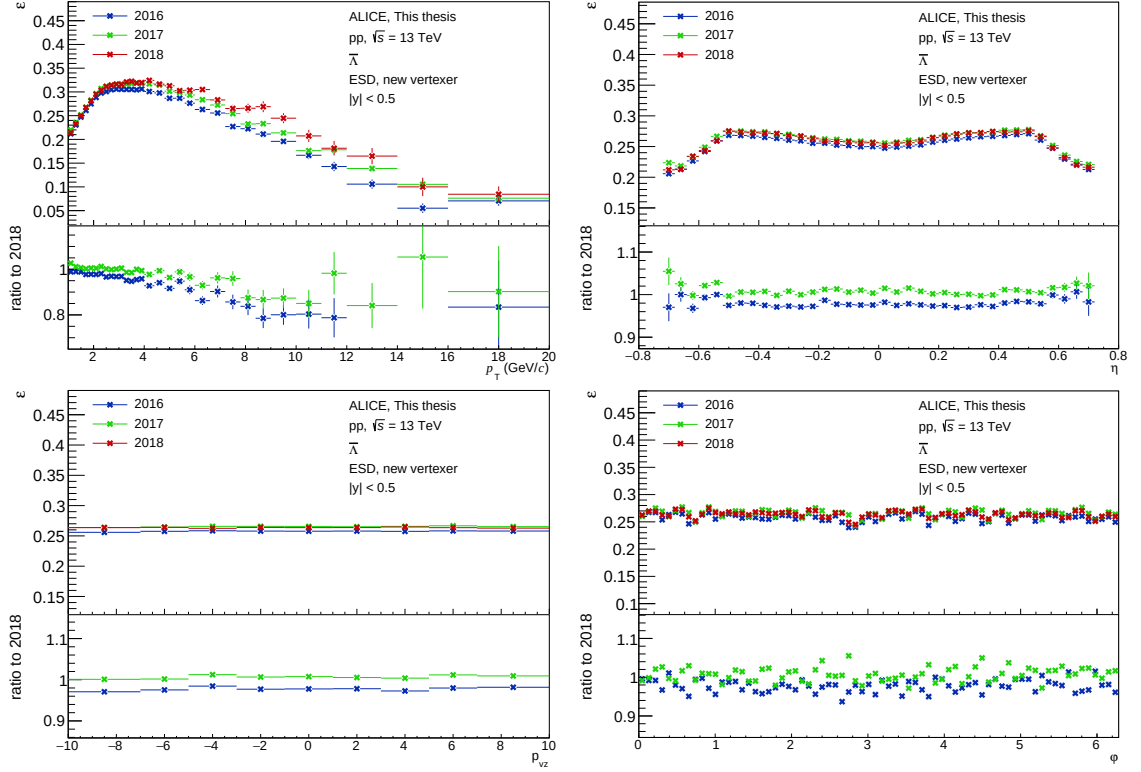


Figure 4.10: Efficiency factors for $\bar{\Lambda}$ for different data taking years and their ratio.

4.2.4 Secondary contamination correction

Not all charged-particle tracks that satisfy the selection criteria are in reality primary. In order to correct for this fact, a correction factor C is defined as $C = N_{\text{secondaries}}/N_{\text{hadrons}}$. With this, the corrected number of charged-particle tracks is defined as:

$$N^{\text{corrected}} = \frac{1 - C}{\varepsilon} N^{\text{raw}} \quad (4.3)$$

where ε is the single-particle efficiency described above in Sec 4.2.3 and N^{raw} is the number of reconstructed hadrons. It has been also checked whether all data periods have the same contamination factor and it has been confirmed that all of them within one year are compatible, thus the contamination factor is calculated from merged data for each year. The comparison across different years is shown in Fig. 4.11. In this analysis, only the p_T dependence of this contamination correction factor is used.

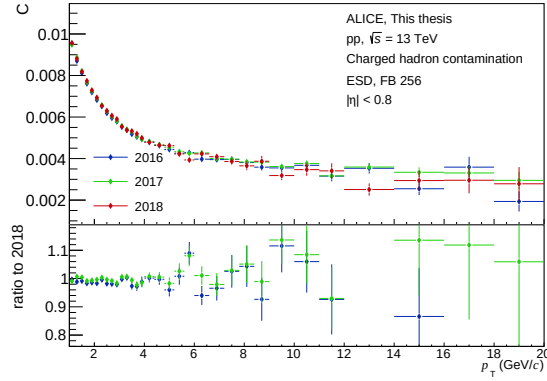


Figure 4.11: Correction factor for the secondary hadrons.

4.2.5 Correction for the contribution of misidentified V^0

Not all V^0 candidates, which satisfied the selection criteria, are real V^0 and some of them are misidentified. The shape of the correlation function calculated with such a misidentified V^0 candidate can be in general different from the one calculated with a real V^0 . This means that the correlation function should be corrected for this contribution. Thus, a second correlation function is calculated, where the V^0 candidates are taken from side-band regions, $[\mu \pm 7\sigma, \mu \pm 10\sigma]$, of the invariant mass spectrum (the area marked with cyan lines in the Fig. 4.2). The actual correction is done after all previous corrections and looks like follows:

$$\begin{aligned} \frac{d^2 N_{pair}^{fully\ corrected}}{d\Delta\varphi d\Delta\eta}(\Delta\varphi, \Delta\eta, p_T^{trigg}) &= \frac{1}{N_{trigg}^{fully\ corrected}(p_T^{trigg})} \times \\ &\left(\frac{d^2 N_{pair\ sig}^{corr}}{d\Delta\varphi d\Delta\eta}(\Delta\varphi, \Delta\eta, p_T^{trigg}) - \frac{d^2 N_{pair\ side}^{corr}}{d\Delta\varphi d\Delta\eta}(\Delta\varphi, \Delta\eta, p_T^{trigg}) \right), \end{aligned} \quad (4.4)$$

where the side-band region is composed of left and right part and together has the same width in the invariant mass spectrum as the signal region. It was checked that the shape of the left and right parts of the side-band correlation function is the same and they can be summed together. In the case of V^0 -h correlations, the number of trigger particles should be also corrected for the misidentification with the purity factor. The corrected number of V^0 trigger particles is:

$$N_{trigg}^{fully\ corrected} = \frac{signal}{signal + background} N_{trigg}^{corr} \quad (4.5)$$

where the purity factor $\frac{signal}{signal+background}$ is shown in Fig. 4.12.

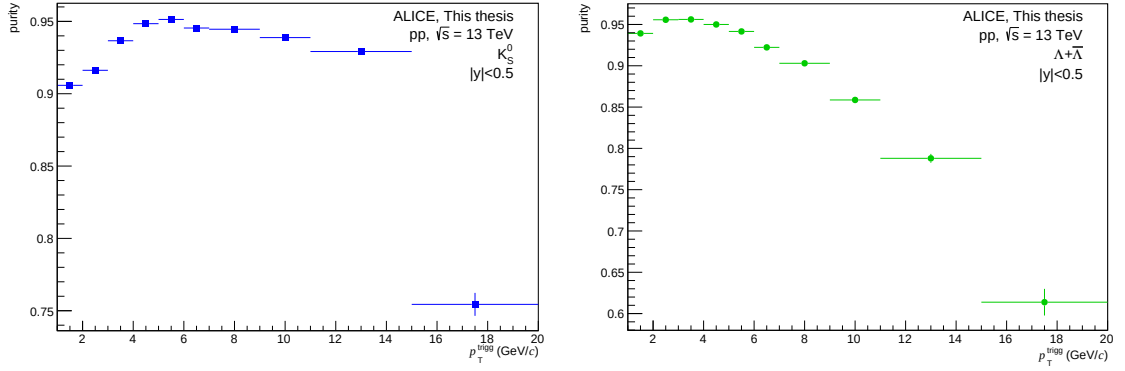


Figure 4.12: Purity of K_S^0 mesons (left) and $(\Lambda + \bar{\Lambda})$ hyperons (right).

4.2.6 Feed-down correction

A non-negligible amount of the measured Λ and $\bar{\Lambda}$ candidates is not created in the collision, but is a product of mostly Ξ baryon decays. In general, the shape of the correlation function, either Λ being the trigger or associated particle, does not need to be the same in case that this Λ is primary or secondary. To correct for this fact, a dedicated feed-down subtraction is performed. The amount of uncorrected measured Λ ($\bar{\Lambda}$) can be written in general as:

$$\Lambda_{measured}^{raw} = \Lambda_{primary}^{raw} + \Lambda_{secondary}^{raw} \quad (4.6)$$

The number of secondary Λ hyperons can be calculated with help of a feed-down matrix (Fig. 4.13), which is calculated in MC, as follows:

$$\Lambda_{sec}(p_{T,i}) = F_{ij} \int_{p_{T,i}} \frac{dN}{dp_T}(\Xi) dp_T \quad (4.7)$$

where the integral stands for the corrected amount of reconstructed Ξ baryons in a p_T bin j and the F_{ij} is the feed-down matrix element. The feed-down matrix is shown in Fig. 4.13 and each its element is defined as:

$$F_{ij} = \frac{N_{rec}(\Lambda)_{from \Xi^{\pm,0}}^{in \ bin \ i}}{N_{gen}(\Xi^{\pm})_{in \ bin \ j}} \quad (4.8)$$

where the Λ baryons are the decay product from both charged and neutral Ξ baryons, but the denominator is the number of only charged Ξ baryons primary generated in the collision. This approach is used, because the Ξ^0 and $\bar{\Xi}^0$ cannot be reconstructed in the data. This means that the $\Xi^0/\Xi^{\pm}$ ratio is fixed by the MC.

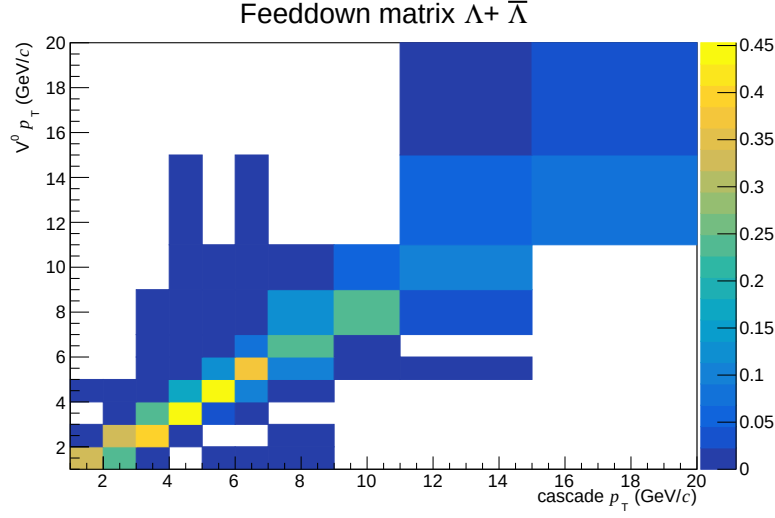


Figure 4.13: Feed-down matrix.

Within this correction, both number of trigger particles and correlation function need to be corrected. In order to do so, the $(\Xi^+ + \Xi^-)$ -h and h- $(\Xi^+ + \Xi^-)$ correlation functions must be calculated. The Ξ^+ and Ξ^- candidates are reconstructed in their most probable cascade decay channels [11]:

$$\Xi^+ \rightarrow \bar{\Lambda} + \pi^+ (99.8\%), \bar{\Lambda} \rightarrow \bar{p} + \pi^+ (63.9\%)$$

$$\Xi^- \rightarrow \Lambda + \pi^- (99.8\%), \Lambda \rightarrow p + \pi^- (63.9\%)$$

The identification is based on the topological selection criteria listed in Tab. 4.2. The invariant mass acceptance range is estimated with double-Gaussian fit as $\mu \pm 3\sigma$ (the σ comes from the broader Gauss function and μ is the common mean value). The invariant mass spectra of the Ξ candidates are shown in Fig. 4.14 together with fits and side-band ranges.

The $(\Xi^+ + \Xi^-)$ -h and h- $(\Xi^+ + \Xi^-)$ correlation functions are corrected on all above mentioned corrections. The efficiency corrections for different data taking years are shown in Fig. 4.15. The feed-down contribution is after all corrections subtracted in the following way:

$$N_{trigg}^{final}(p_{T,i}) = C_{purity}^{\Lambda}(p_{T,i}) * (N_{\Lambda}^{measured}(p_{T,i}) - \frac{1}{\varepsilon_{\Lambda}}(p_{T,i}) \times \sum_j F_{ij} * C_{purity}^{\Xi}(p_{T,j}) * N_{\Xi}^{measured}(p_{T,j})) \quad (4.9)$$

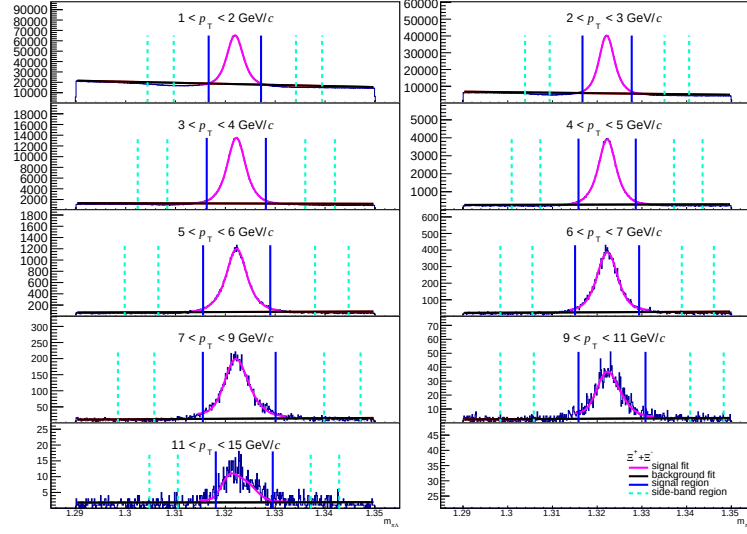


Figure 4.14: Invariant mass spectra of $\Xi^\pm$ candidates.

Table 4.2: Selection criteria for charged Ξ candidates

Topological Variable	Value
Cascade transv. decay radius R_{2D} (cm)	> 0.6
V^0 transv. decay radius (cm)	> 1.2
DCA bachelor to PV (cm)	> 0.04
DCA V^0 to PV (cm)	> 0.06
DCA meson V^0 track to PV (cm)	> 0.04
DCA baryon V^0 track to PV (cm)	> 0.03
DCA V^0 daughters (σ)	< 1.5
DCA bachelor to PV (cm)	< 1.3
Cascade $\cos(\theta_{PA})$	> 0.97
$V^0 \cos(\theta_{PA})$	> 0.97
Proper lifetime V^0 (cm)	< 20
V^0 invariant mass window (GeV/c^2)	± 0.008
Maximum DCAz bachelor to PV (cm)	< 4
Selection	Value
Rapidity $ y $	< 0.5
dE/dx ($N\sigma$)	< 5
Proper lifetime mL/p	$< 3 \times c\tau$
Tracking flags for daughters	kTPCrefit
Daughter Track $N_{TPC \text{ clusters}}$	> 70

$$N_{\Lambda-h}^{final}(p_{T,i}) = N_{\Lambda-h}^{measured}(p_{T,i}) - \frac{1}{\varepsilon_{\Lambda}}(p_{T,i}) \times$$

$$\sum_j F_{ij} * (N_{\Xi-h}^{measured}(p_{T,j}) - N_{\Xi-h}^{side-band}(p_{T,j})) - N_{\Lambda-h}^{side-band}(p_{T,j}) \quad (4.10)$$

$$N_{h-\Lambda}^{final}(p_{T,i}) = N_{h-\Lambda}^{measured}(p_{T,i}) - \frac{1}{\varepsilon_{\Lambda}}(p_{T,i}) \times$$

$$\sum_j F_{ij} * (N_{h-\Xi}^{measured}(p_{T,j}) - N_{h-\Xi}^{side-band}(p_{T,j})) - N_{h-\Lambda}^{side-band}(p_{T,j}) \quad (4.11)$$

The feed-down contribution is multiplied with the Λ efficiency factor, because the $N_{\Lambda}^{measured}$ and $N_{\Lambda-h}^{measured}$ are corrected on efficiency on-the-fly and the equation 4.6 is valid only for uncorrected amounts.

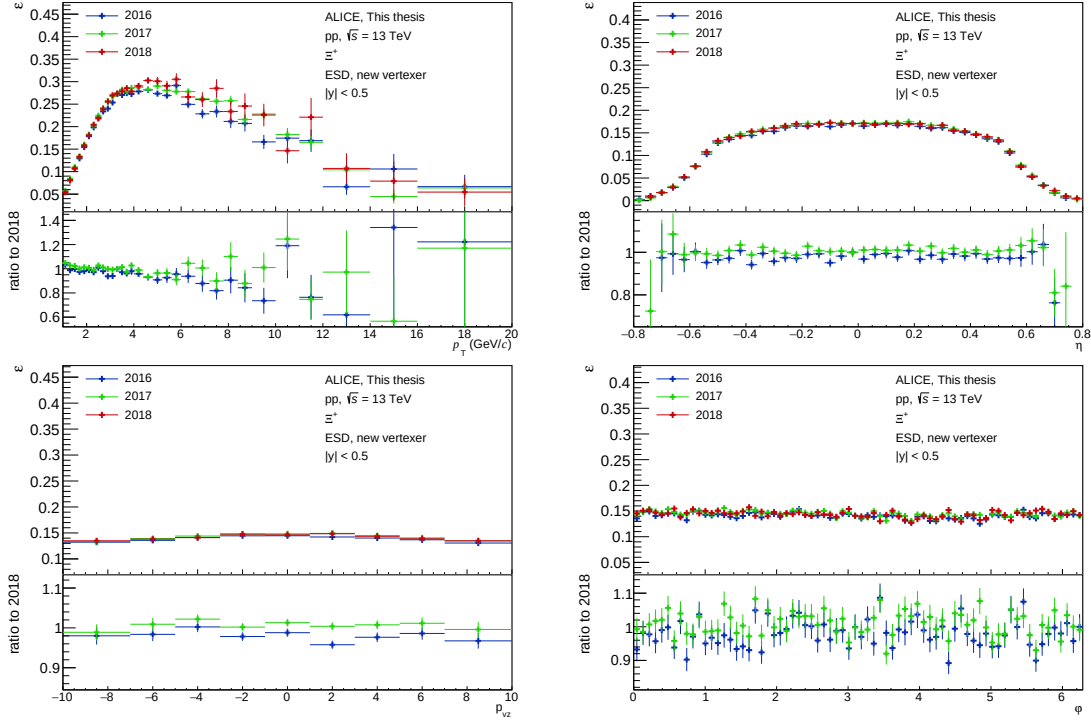


Figure 4.15: Efficiency factors for Ξ baryons for different data taking years and their ratio.

4.2.7 Background subtraction

After the corrections mentioned above and normalisation on the number of trigger particles, one obtains a corrected two-dimensional correlation function, which can be projected on the $\Delta\varphi$ axis. Because of the presence of some uncorrelated particle pairs from

the underlying event, the minimum of these projections never reach zero. This background is estimated as the average of values from 6 bins within the area outside of the correlation peaks. The bins are in intervals $[-1.35, 1.15]$ and $[1.5, 1.7]$. The average method is chosen instead of taking only the minimum bin to reduce the statistical fluctuation effects. Afterwards, this constant function is subtracted from the $\Delta\varphi$ projection.

4.3 Additional checks

Consistency between different data taking years in data

The data used in this analysis are merged over three data-taking years. Before the merging process, it has been first checked whether the results coming from the different years are compatible. Thus, the ratios of $\Delta\varphi$ projections of the correlation functions with different trigger and associated particles from 2016, 2017 and 2018 data taking years over the merged sample are fitted with a constant function. The values of this fit for the h-h correlation function are shown in Fig. 4.16 and the other fit results can be found in Appendix A. The fit values are fluctuating around unity only up to 2 %. The highest p_T bin of $(\Lambda + \bar{\Lambda})$ -h correlations assigns a deviation of 5 % with a high statistical uncertainty, thus it is assumed that this is only a statistical fluctuation. Thanks to the consistency of the three data sets, they are merged to increase the statistical significance of this analysis.

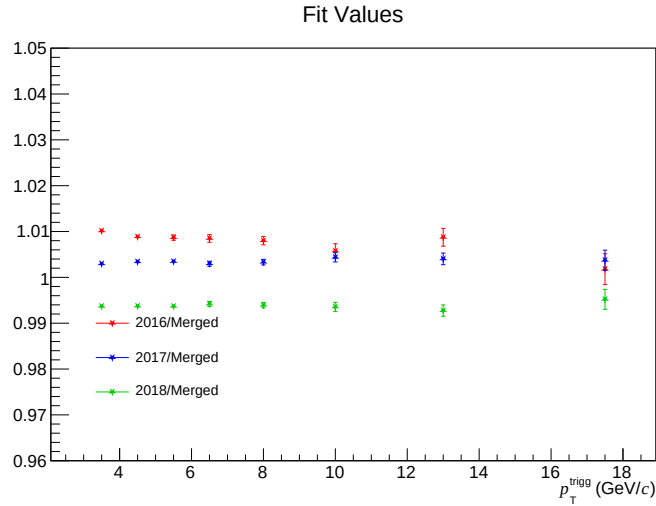


Figure 4.16: The fit values of the ratio of the $\Delta\varphi$ projections from different data-taking years over the merged sample for the h-h correlation function as a function of p_T^{trigg} .

Consistency between different data taking years in MC

The same check as described in previous section has been performed also for the MC sample. The generated and reconstructed $\Delta\varphi$ projections of correlation functions has been compared for all trigger and associated particle types for different p_T^{trigg} bins. The ratios to the merged sample of $\Delta\varphi$ projections are fitted with a constant function and the fit values are fluctuating only within a few % from unity, which means that the results are compatible and can be merged. These fit values are shown in Fig. 4.17 for the h-h correlation function and in Appendix A for the other combination of trigger and associated particles.

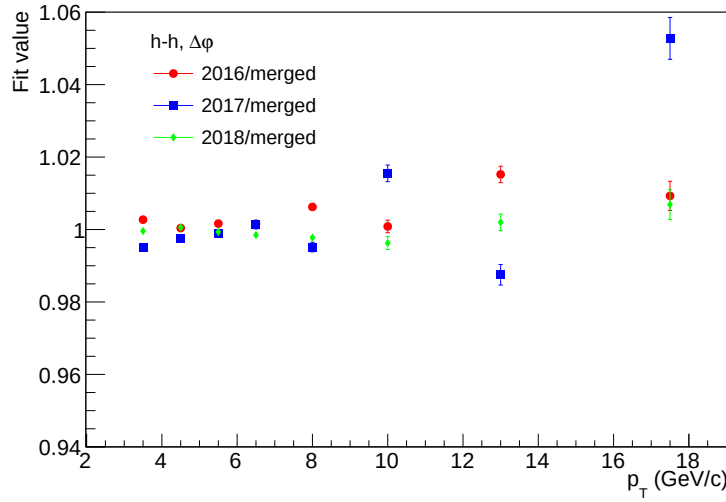


Figure 4.17: The fit values of the ratio of the $\Delta\varphi$ projections from MC anchored to different data-taking years over the merged sample for the h-h correlation function as a function of p_T^{trigg} .

Λ -h (h- Λ) and $\bar{\Lambda}$ -h (h- $\bar{\Lambda}$) consistency check

In the case that the Λ -h(h- Λ) and $\bar{\Lambda}$ -h (h- $\bar{\Lambda}$) correlations turn out to be similar, they can be merged into a common correlation function in order to decrease the statistical fluctuations. Such a comparison has been done both for MC and data on the $\Delta\varphi$ projections. Afterwards, the $\bar{\Lambda}$ -h (h- $\bar{\Lambda}$) projection is divided by the Λ -h(h- Λ) projection. This ratio is fitted with a constant function and the results from these fits are shown in Fig. 4.18 both for MC and data. Following from the plots, one can conclude that the Λ -h (h- Λ) and $\bar{\Lambda}$ -h (h- $\bar{\Lambda}$) are consistent both in data and MC and thus can be merged.

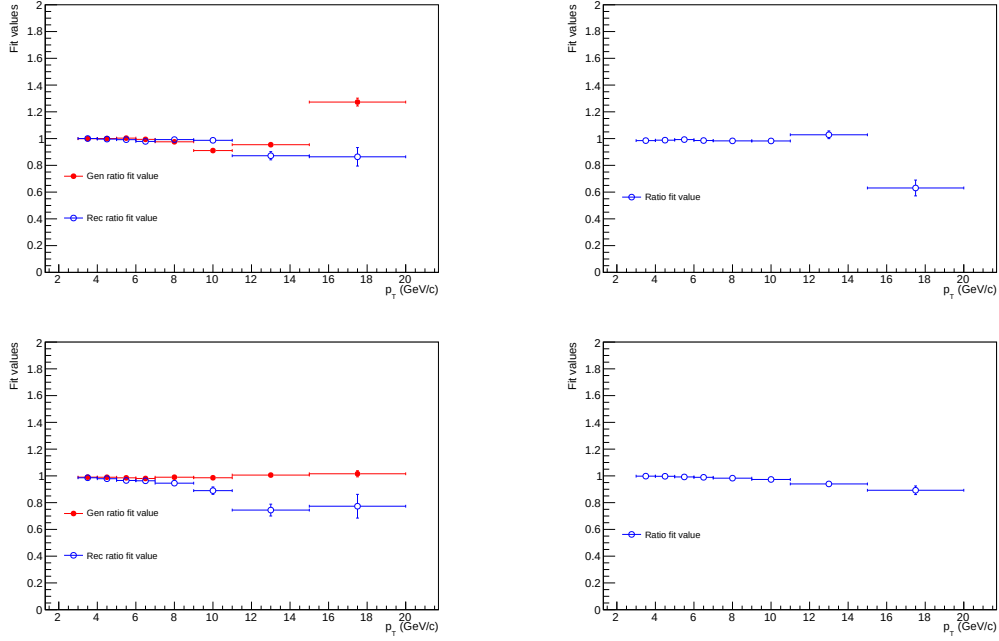


Figure 4.18: The fit values for the Λ -h and $\bar{\Lambda}$ -h (top row) and the h- Λ and h- $\bar{\Lambda}$ (bottom row) comparison, MC based (left), data-based (right).

Effect of the feed-down correction on the correlation function in MC

The effect of the feed-down correction on the final correlation function and on the near-side yields has been tested in MC. In the top left panel of Fig. 4.19, the $\Delta\varphi$ projection of the $(\Lambda + \bar{\Lambda})$ -h normalised on the number of trigger particles is shown both with and without applying the feed-down subtraction. One can clearly see, that the shape did not change by the application of the feed-down correction. This means that the shape of the correlation function triggered with primary and secondary Λ hyperons is the same in MC. Also the effect on the yields is checked, which is plotted in the bottom panels of Fig. 4.19. From the ratio plot, we can conclude that no effect is observed.

The effect of the feed-down subtraction has been also studied for the h- $(\Lambda + \bar{\Lambda})$ correlation function. The $\Delta\varphi$ projection of h- $(\Lambda + \bar{\Lambda})$ correlation function with and without feed-down correction as well as the ratio of these two distributions are shown in the top panels of Fig. 4.20. A modulation of both peaks of about 5% is visible. The difference in near-side integrated yields increases with p_T^{trigg} (bottom panels of Fig. 4.20).

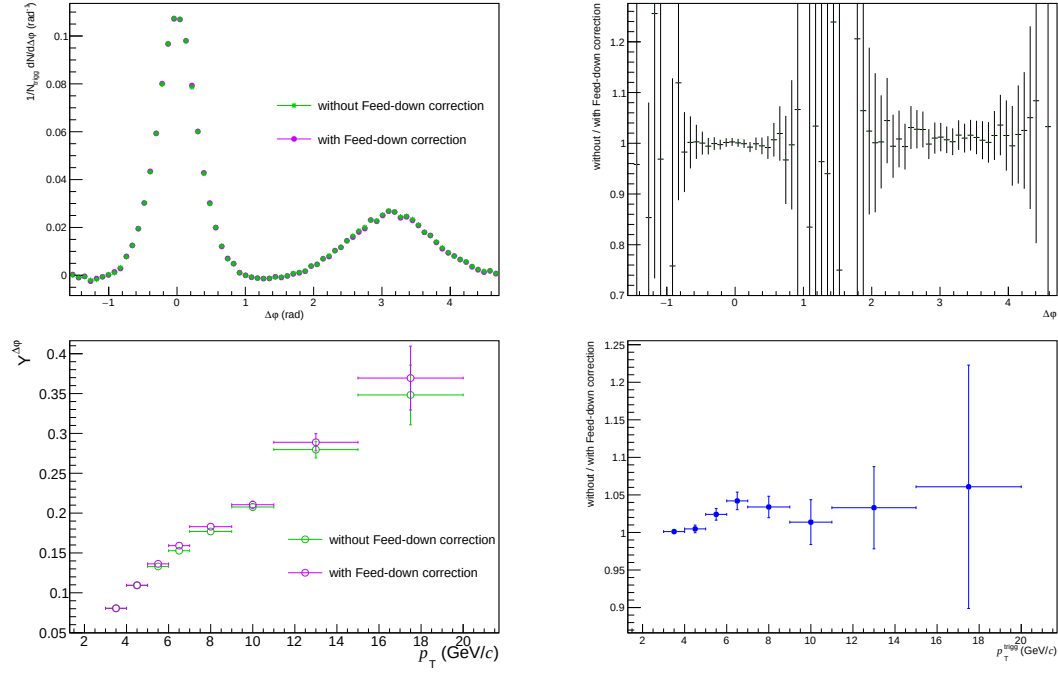


Figure 4.19: Comparison of the $\Delta\varphi$ projection of $(\Lambda + \bar{\Lambda})$ -h without, green markers, and with feed-down correction, violet markers, (top row) and of the per-trigger yields (bottom row) in MC (left) and their ratio (right).

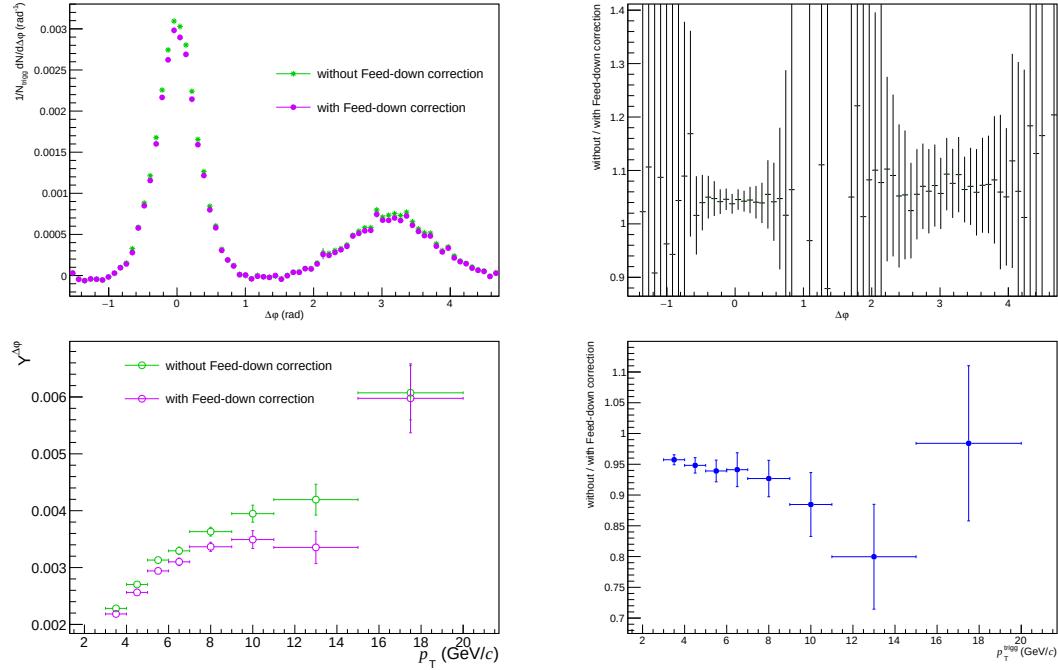


Figure 4.20: Comparison of the $\Delta\varphi$ projection of $h-(\Lambda + \bar{\Lambda})$ without, green markers, and with feed-down correction, violet markers, (top row) and of the per-trigger yields (bottom row) in MC (left) and their ratio (right).

Effect of the feed-down correction on the correlation function in Data

The same cross-check has been performed also in data. In Fig. 4.21, the $\Delta\varphi$ projections and yields are compared for the $(\Lambda + \bar{\Lambda})$ -h correlation function. A visible difference can be seen both in yields and $\Delta\varphi$ comparison, from which follows that the shape of the correlation function triggered with primary and secondary Λ is not the same and it is necessary to perform the feed-down subtraction to get the correct result. Even more prominent effect is visible in the case of h- $(\Lambda + \bar{\Lambda})$ correlation function, where the difference is bigger than 10% for both near- and away-side peaks as shown in Fig. 4.22. In both cases, the influence is more prominent in data than in MC.

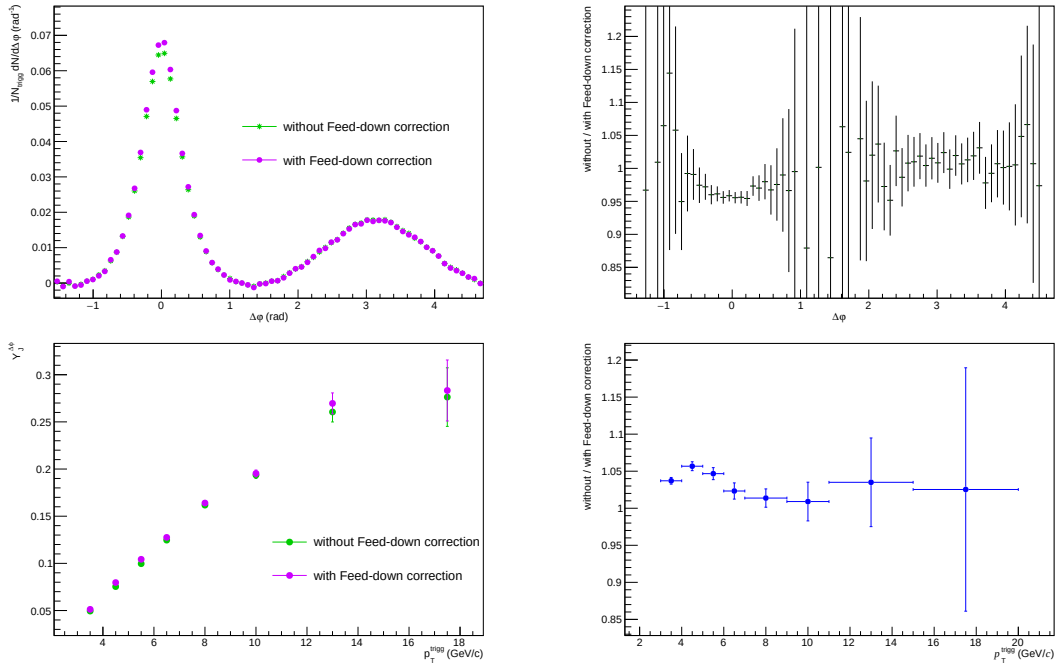


Figure 4.21: Comparison of the $\Delta\varphi$ projection of $(\Lambda + \bar{\Lambda})$ -h without, green markers, and with feed-down correction, violet markers, (top row) and of the per-trigger yields (bottom row) in data (left) and their ratio (right).

4 Measurement method

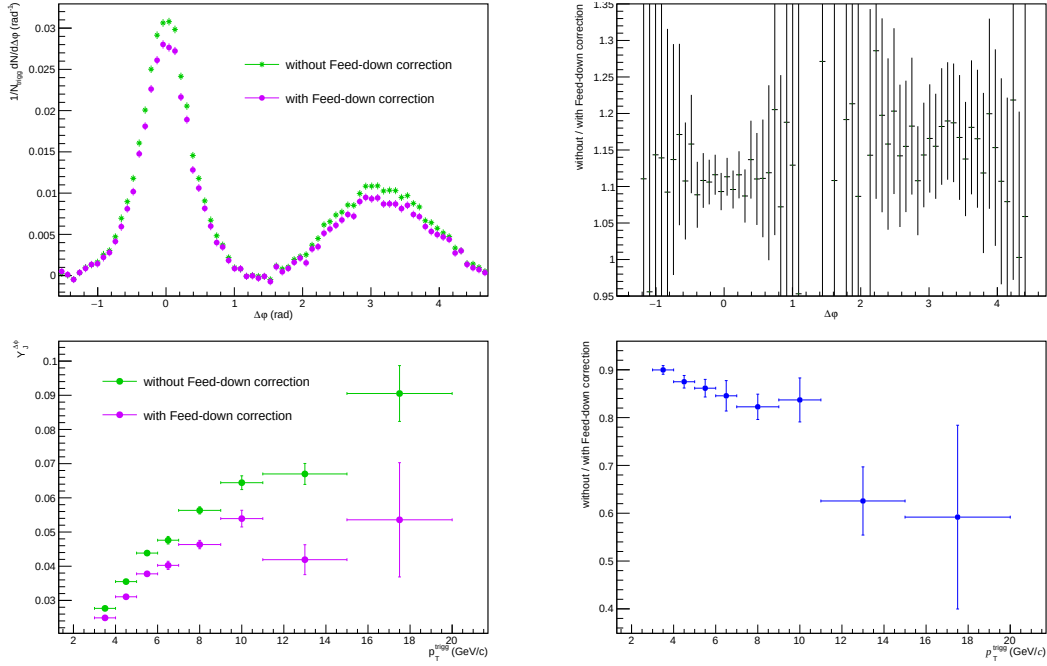


Figure 4.22: Comparison of the $\Delta\varphi$ projection after background subtraction of $h-(\Lambda+\bar{\Lambda})$ without, green markers, and with feed-down correction, violet markers, (top row) and of the per-trigger yields (bottom row) in data (left) and their ratio (right).

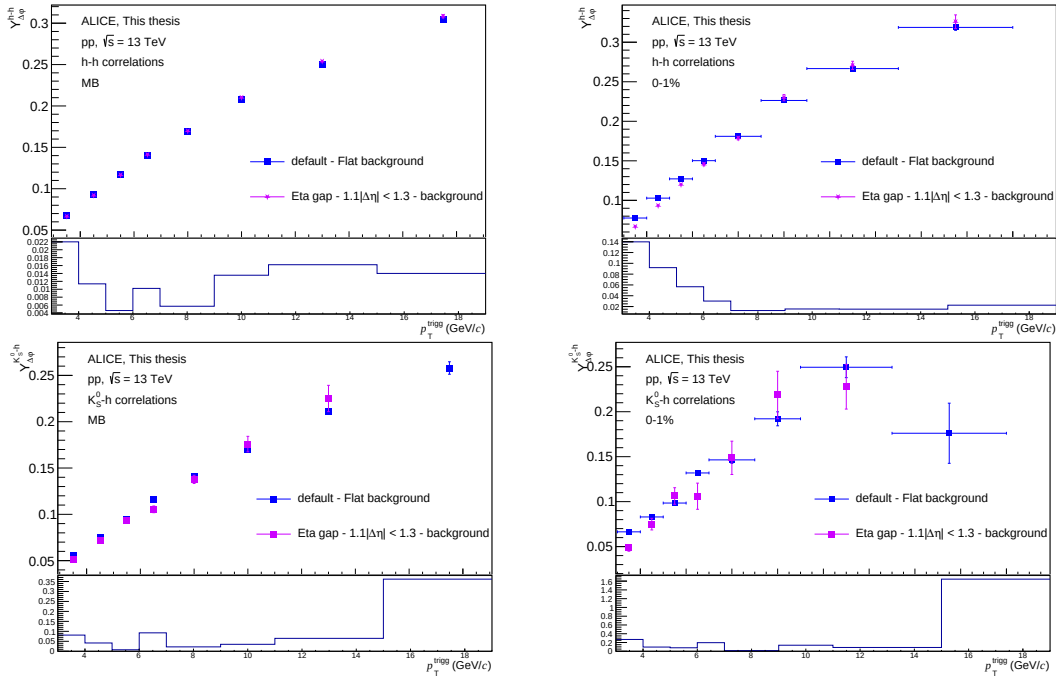


Figure 4.23: Comparison of the per-trigger yields of h-h (top) and K_S^0 -h (bottom) correlation function calculated with flat background and long-range background in minimum-bias sample (left) and 0-1% multiplicity class (right). The bottom panels show their ratio.

η -gap check for the background subtraction

In order to check the long-range correlation influence on the yield calculation, the yields are calculated also from $\Delta\varphi$ projection, where the background is estimated with the so called η -gap method. In this method, besides of the $\Delta\varphi$ projection in the default range $|\Delta\eta| < 1$ also $\Delta\varphi$ projections for range $1.1 < |\Delta\eta| < 1.3$ are done. After proper scaling of the long-range projection, this is taken as the underlying event background. Yields calculated with the long-range background subtraction are compared with the ones calculated with a flat background for h-h and K_S^0 -h correlations in the MB sample and 0-1% multiplicity class, shown in Fig. 4.23. From these plots, a strong dependence on the choice of trigger particle is seen. As the effect of the long-range correlations in pp collisions was observed only in much higher multiplicity class (0-0.001% [54]), thus no strong effect is awaited in MB. Also no trigger particle dependence can be explained with the previous observation. Hence, it is concluded that the observed effect is in this case caused by the jet tail and a flat background is taken as default procedure in this analysis.

4.4 MC closure test

The quality of the applied corrections can be examined by performing a MC closure test. In this test, a correlation function from generated particles in the MC sample is calculated. The generated tracks are selected on pseudorapidity and p_T in the same way as the measured tracks and only primary charged tracks are accepted. The V^0 particles are selected on rapidity, daughter-tracks pseudorapidity and p_T and it is checked whether they are physical primary. The second correlation function necessary for this test is the one calculated from reconstructed MC particles, on which exactly the same selection criteria are applied as on data (except for the dE/dx in the TPC). After all corrections applied on this reconstructed correlation function, the $\Delta\varphi$ projections of both functions are compared. The ratio of the projections should fluctuate around unity, if all corrections are performed correctly. The $\Delta\varphi$ projections for generated and reconstructed MC sample and their ratios are plotted for different p_T^{trigg} bins and for $1 \text{ GeV}/c < p_T^{\text{assoc}} < p_T^{\text{trigg}}$ in Fig. 4.24-4.28 for K_S^0 -h, $(\Lambda + \bar{\Lambda})$ -h, h-h, h- K_S^0 and h- $(\Lambda + \bar{\Lambda})$ correlations, respectively.

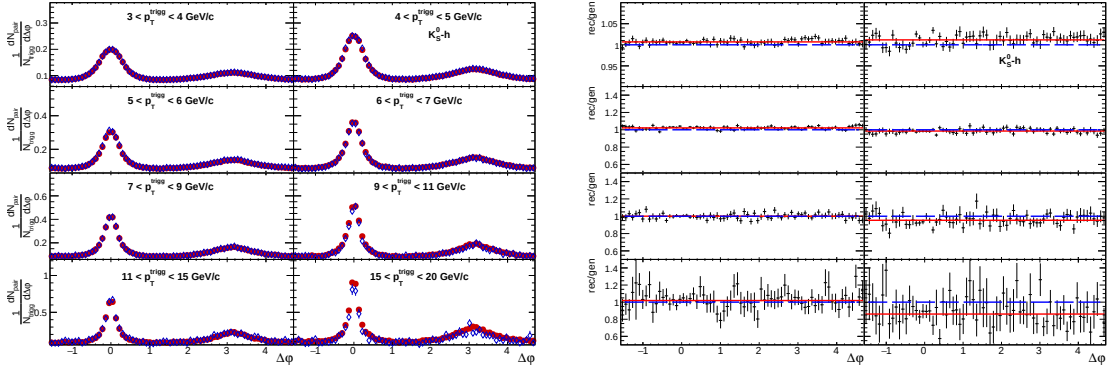


Figure 4.24: MC closure test for K_S^0 -h correlations. Comparison of generated and reconstructed $\Delta\varphi$ projection (left) and their ratio fitted with red constant function and compared with blue line at unity (right).

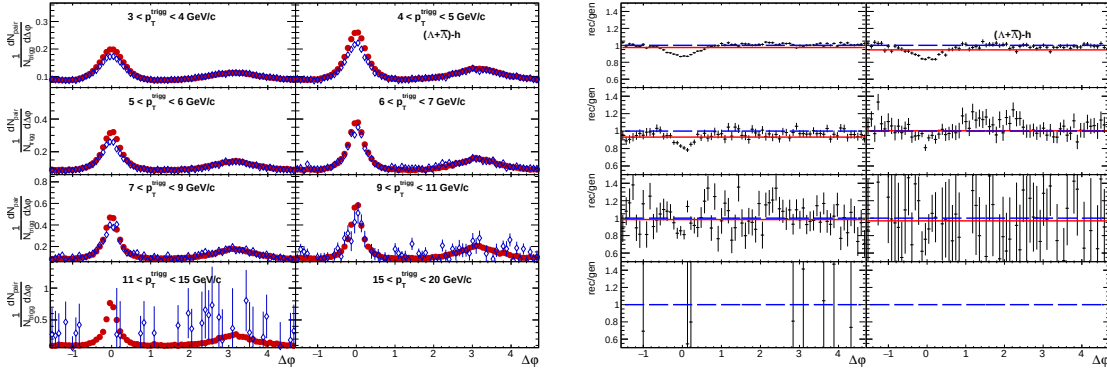


Figure 4.25: MC closure test for $(\Lambda + \bar{\Lambda})$ -h correlations. Comparison of generated and reconstructed $\Delta\varphi$ projection (left) and their ratio fitted with red constant function and compared with blue line at unity (right).

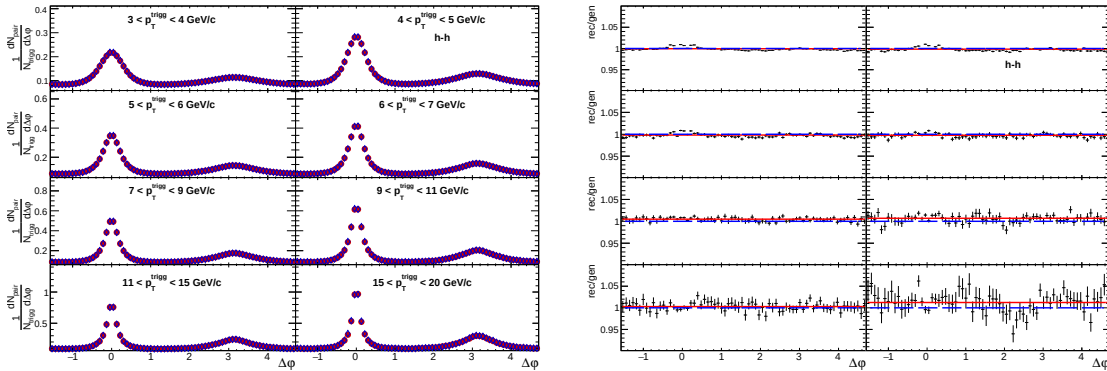


Figure 4.26: MC closure test for h-h correlations. Comparison of generated and reconstructed $\Delta\varphi$ projection (left) and their ratio fitted with red constant function and compared with blue line at unity (right).

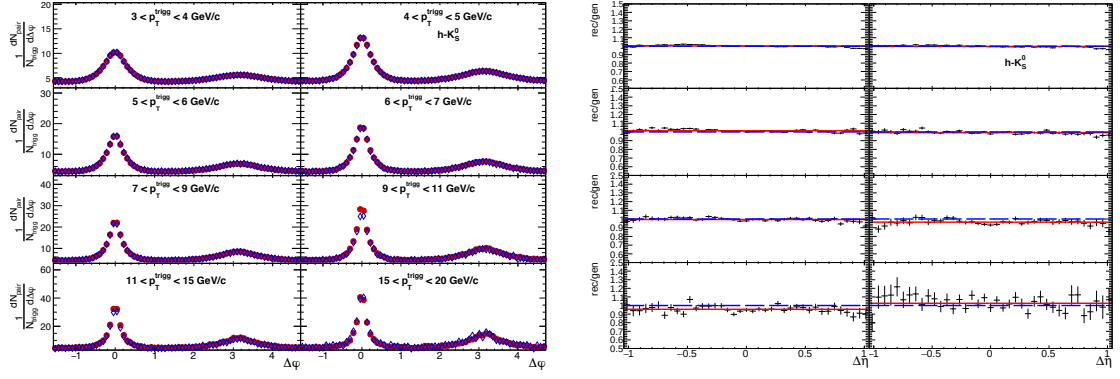


Figure 4.27: MC closure test for $h\text{-}K_S^0$ correlations. Comparison of generated and reconstructed $\Delta\varphi$ projection, the y-axis multiplied by 10^{-3} , (left) and their ratio fitted with red constant function and compared with blue line at unity (right).

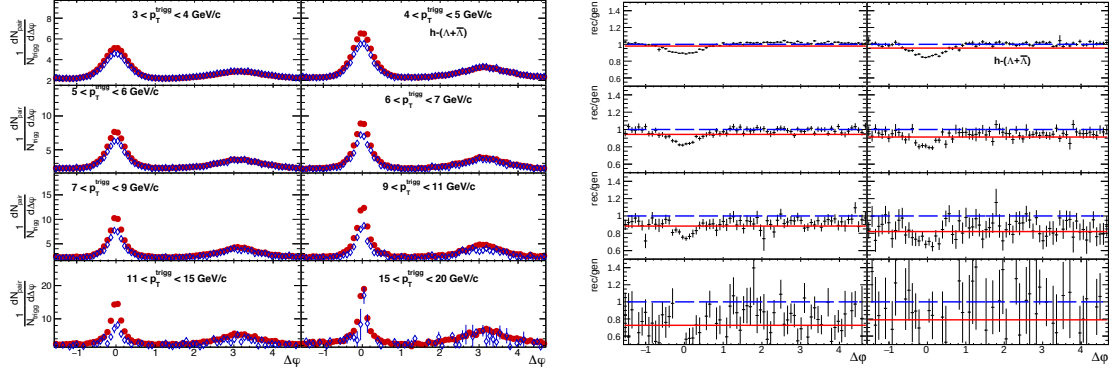


Figure 4.28: MC closure test for $h\text{-(}\Lambda + \bar{\Lambda}\text{)}$ correlations. Comparison of generated and reconstructed $\Delta\varphi$ projection, the y-axis multiplied by 10^{-3} , (left) and their ratio fitted with red constant function and compared with blue line at unity (right).

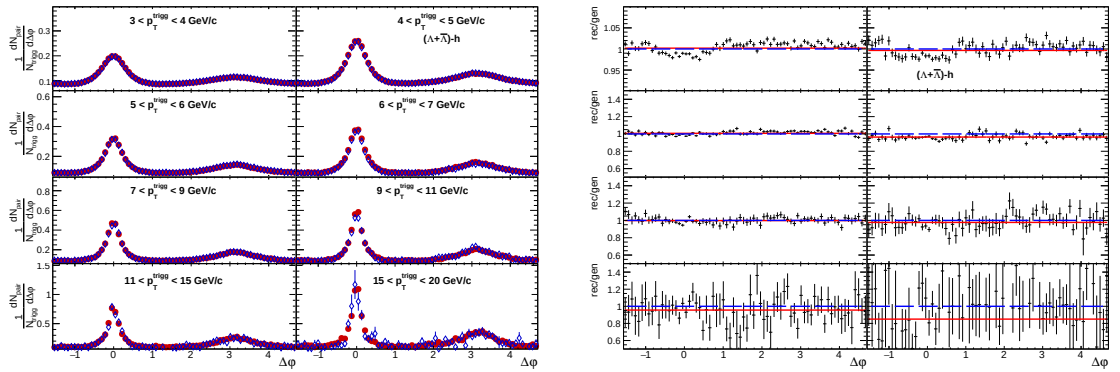


Figure 4.29: MC closure test for $(\Lambda + \bar{\Lambda})\text{-}h$ correlations. Comparison of generated and reconstructed $\Delta\varphi$ projection (left) and their ratio fitted with red constant function and compared with blue line at unity (right).

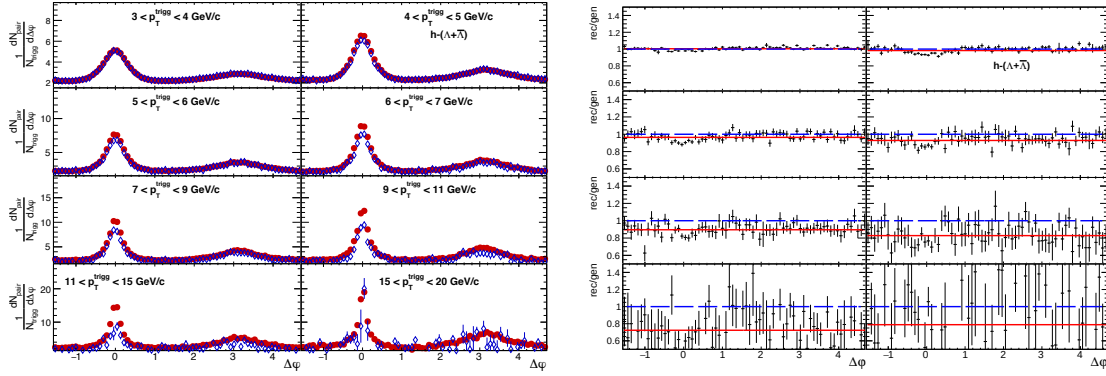


Figure 4.30: MC closure test for $h-(\Lambda + \bar{\Lambda})$ correlations where $h^- - \Lambda$ and $h^+ - \bar{\Lambda}$ pairs were merged. Comparison of generated and reconstructed $\Delta\varphi$ projection, the y-axis multiplied by 10^{-3} , (left) and their ratio fitted with red constant function and compared with blue line at unity (right).

It is visible in Fig. 4.25 that there is a non-closure for the $(\Lambda + \bar{\Lambda})$ - h correlation function around the near-side peak reaching up to 10%. The original source of the non-closure has not been found, but it has been shown that with different selection criteria of the charged primary hadrons, the non-closure becomes smaller, only around 2%, as is visible in Fig. 4.29. This another set of selection criteria is described in Sec. 4.1.2 and it has been tuned in order to leave the secondary contamination minimal by the minimal residual non-closure.

In the ratio plots of the $h-(\Lambda + \bar{\Lambda})$ correlation function in Fig. 4.28, it is clearly visible that there is still big non-closure around the near-side peak which reaches up to 15%. This is pointing out that some pairs close to each other in the angular space are not detected. This fact cannot be corrected via the single particle efficiency. The effect has been studied in more details and it has been found out that in the case of using the same selection criteria for primary hadrons as for the $(\Lambda + \bar{\Lambda})$ - h correlation function and of using charge dependent pairs, where only negative charged hadrons are correlated with Λ and positive charged hadrons with $\bar{\Lambda}$, the merged result is showing a smaller non-closure as shown in Fig 4.30. In this case, all charged hadrons are correlated with Λ and $\bar{\Lambda}$ in the generated level and reconstructed correlation function is constructed as follows:

$$h - (\Lambda + \bar{\Lambda}) = \frac{2 \times (N_{pair}^{h^- - \Lambda} + N_{pair}^{h^+ - \bar{\Lambda}})}{N_{trigg}} \quad (4.12)$$

The sum is multiplied by 2, because approximately the same amount of positive and negative hadrons is produced at the LHC energies. This has been checked both in MC, in terms of efficiency, and in data, both are shown in Appendix A. The side-band

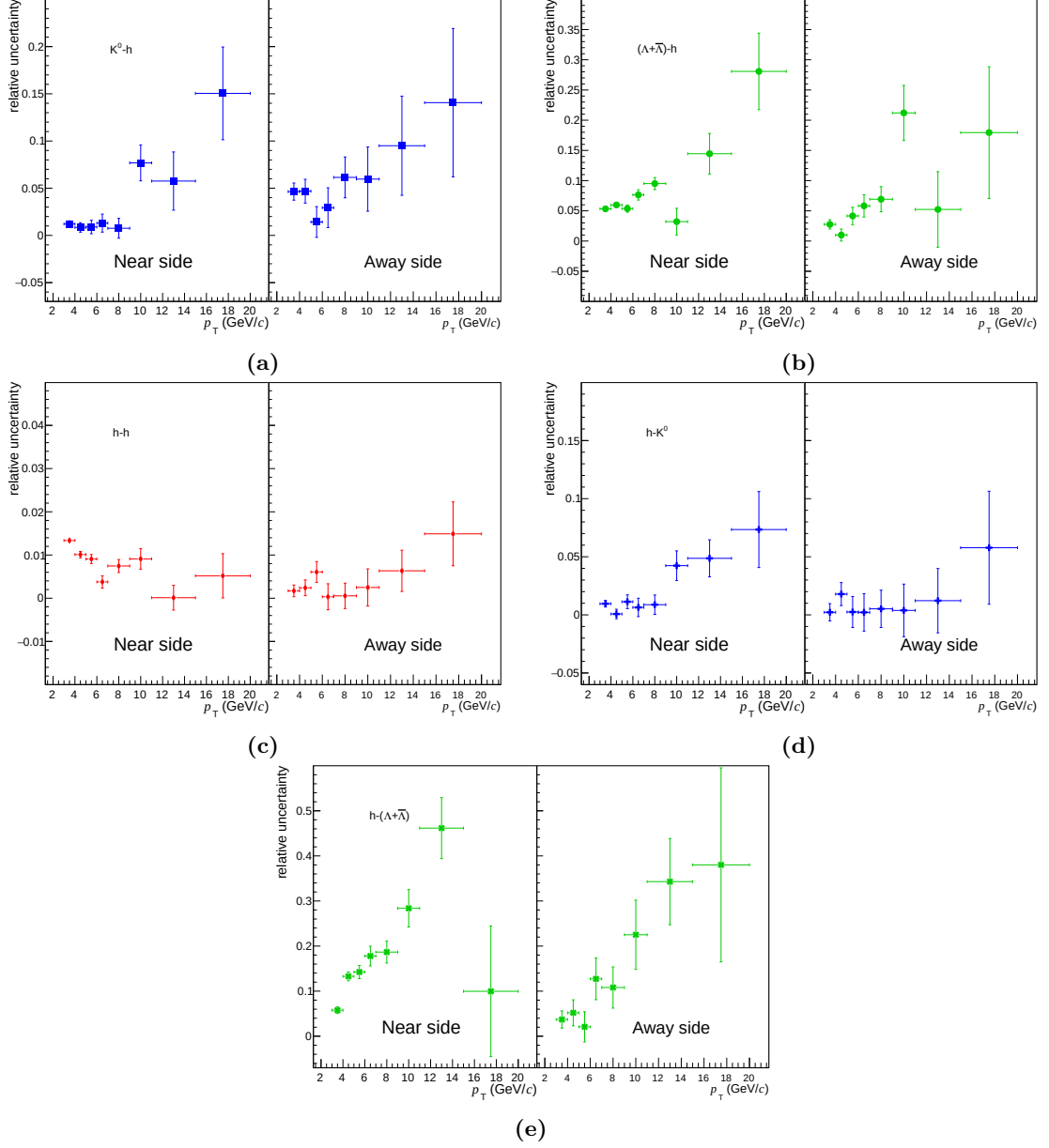


Figure 4.31: Relative uncertainty from MC closure test on yields for different trigger and associated particle combinations: K_S^0 -h (a), $(\Lambda + \bar{\Lambda})$ -h (b), h-h (c), h- K_S^0 (d) and h- $(\Lambda + \bar{\Lambda})$ (e).

correction is also calculated only from $h^- - \Lambda$ and $h^+ - \bar{\Lambda}$ pairs, however the feed-down correction is calculated disregarding the hadron charge. The most plausible explanation for the observation of better closure test with this approach is that the daughter protons (anti-protons) are merged in the detector with primary positive (negative) track and are reconstructed as a single track. A possible solution to the problem would be a suitable track merging cut, since, the existing one assumes that the merged tracks are produced in the same vertex, which is not the case here. The development of such a cut should be followed up. In this analysis, the $h^- - \Lambda$ and $h^+ - \bar{\Lambda}$ pairs are used and a residual non-closure uncertainty is assigned as a part of systematic uncertainty.

In the second step of this test, the uncertainty on yields is estimated. This uncertainty is defined as:

$$\frac{|Y_{gen} - Y_{rec}|}{Y_{gen}}, \quad (4.13)$$

where the Y_{gen} and Y_{rec} are the $\Delta\varphi$ yields extracted from the generated and the reconstructed correlation function, respectively. This uncertainty is shown in Fig. 4.31. The visible residual non-closure is assigned as a part of systematic uncertainty of 2.5% and 4% for the $(\Lambda + \bar{\Lambda})$ -h and h- $(\Lambda + \bar{\Lambda})$ near-side yields, respectively.

The closure test was performed also as a function of the p_T^{assoc} and it is presented in the Appendix B.

Effect of the trigger particle selections set on the h- $(\Lambda + \bar{\Lambda})$ correlation function in data

It is important to check the effect of selecting only positive (negative) trigger particles in the h- $\bar{\Lambda}$ (h- Λ) correlation functions also in the data in order to be sure whether it is not only an effect observed in MC. This approach is checked with two separate selection criteria sets: FB256 which is used also for K_S^0 -h, h-h and h- K_S^0 correlations and specially tuned set used for $(\Lambda + \bar{\Lambda})$ -h marked as FB1. The results are shown in Fig. 4.32. An obvious effect is visible, where the highest near-side yield has the FB1 with merged $h^- - \Lambda$ and $h^+ - \bar{\Lambda}$ pairs. As this set of selection also shows the smallest residual non-closure, it is used as default for the analysis. Moreover, the underlying event and the away-side peak are consistent for the different selections, pointing out that all the corrections are done properly and really only the near-side yield is affected.

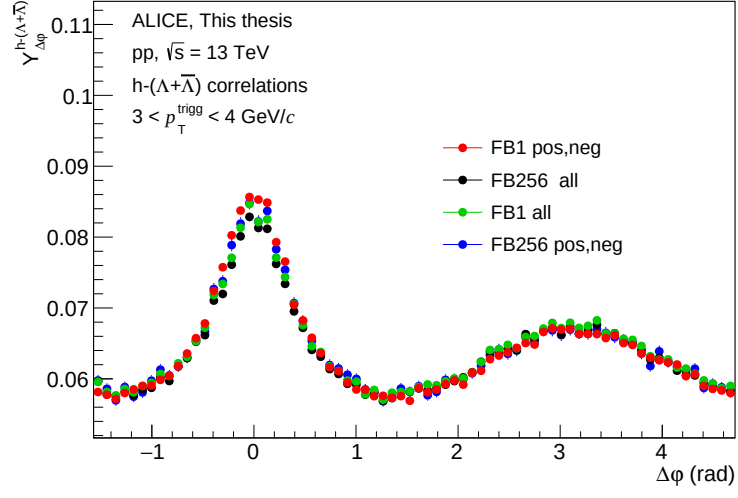


Figure 4.32: $\Delta\varphi$ projection of $h-(\Lambda + \bar{\Lambda})$ correlation function for $3 < p_T^{\text{trigg}} < 4 \text{ GeV}/c$ with different trigger particle selections.

5 Systematic uncertainty study

The sources of systematic uncertainty connected to the measurement are discussed in this chapter. Nine of them are taken into account for the h-h correlations, ten for the K_S^0 -h (h- K_S^0) and thirteen for the $(\Lambda + \bar{\Lambda})$ -h (h- $(\Lambda + \bar{\Lambda})$) correlations. In all cases, the relative uncertainty is defined as:

$$u = \frac{|Y_{var} - Y_{def}|}{Y_{def}} \quad (5.1)$$

where the Y_{var} is the yield value after a variation and Y_{def} is the yield calculated with the default settings. If there are two variations for one source of systematic uncertainty, the maximum of the two uncertainties is taken into account. Only one parameter is varied at the time.

Following variations are common for all three correlations:

- **mixing scaling factor estimation:** The default scaling factor for mixing is defined as the average over all bin values with the coordinate $\Delta\eta = 0$. For the systematic estimation, the bin with coordinates $\Delta\varphi = \pi, \Delta\eta = 0$ is taken to be the scaling factor.
- **constant background estimation:** The default technique is described in Sec. 4.2.7. To calculate the uncertainty, the background is fitted with a constant function defined in intervals $[-\frac{\pi}{2}, -1]$ and $[\frac{\pi}{2} - 0.55, \frac{\pi}{2} + 0.25]$, where no peaks occur.
- **integration window width:** The default intervals are set to $[-0.9, 0.9]$ and $[\pi - 1.4, \pi + 1.4]$ for the near-side and away-side peak, respectively. For this source two variations are taken into account, which correspond to one bin change:
 - wider windows: $[-1, 1]$ and $[\pi - 1.6, \pi + 1.6]$
 - narrower windows: $[-0.8, 0.8]$ and $[\pi - 1.32, \pi + 1.32]$
- **selection criteria for primary charged hadrons:**
 - h-h and K_S^0 -h (h- K_S^0): The default criterion is the pre-defined FB 256 described in Sec. 4.1.2 and the varied one is FB32 which differs in the following criteria:
 - * maximal fraction of shared clusters with other tracks: not required

- * maximal DCA to the PV in xy-plane is p_T dependent: $0.0105 + 0.0350/p_T^{1.1}$
- * maximal DCA to the PV in y-direction: 2 cm
- * the DCA does not need to be inside a specific ellipsoid around the PV
- $(\Lambda + \bar{\Lambda})$ -h ($h(\Lambda + \bar{\Lambda})$): The default set is described in Sec. 4.1.2 and the DCA cuts are varied in two ways:
 - * maximal DCA to the PV in the xy plane is 0.6 cm and maximal DCA to the PV in the z direction is 1.8 cm
 - * maximal DCA to the PV in the xy plane is 1.3 cm and maximal DCA to the PV in the z direction is 2.4 cm
- **PV acceptance region:** The default one is within 10 cm from the IP and the varied one is within 7 cm from the IP.
- **binning in the distance from IP:** The default one includes 9 bins unequally wide: -10,-7,-5,-3, -1,1,3,5,7,10 and the variation has 7 equally wide bins. An example of this variation in $\Delta\varphi$ projection of $h(\Lambda + \bar{\Lambda})$ correlation function is shown in Fig. 5.1.
- **$\Delta\eta$ region for the $\Delta\varphi$ projection:** Default interval is $|\Delta\eta| < 1$. This variation is valid only for the near-side yield calculation. Two variations were used:
 - $|\Delta\eta| < 1.1$
 - $|\Delta\eta| < 0.9$
- **yield calculation method:** Default procedure is the bin-counting method where all bin contents in defined region are added. As a variation, the peaks are fitted and the yield is calculated as an integral of the fit function in the same region as the bin counting method is performed.

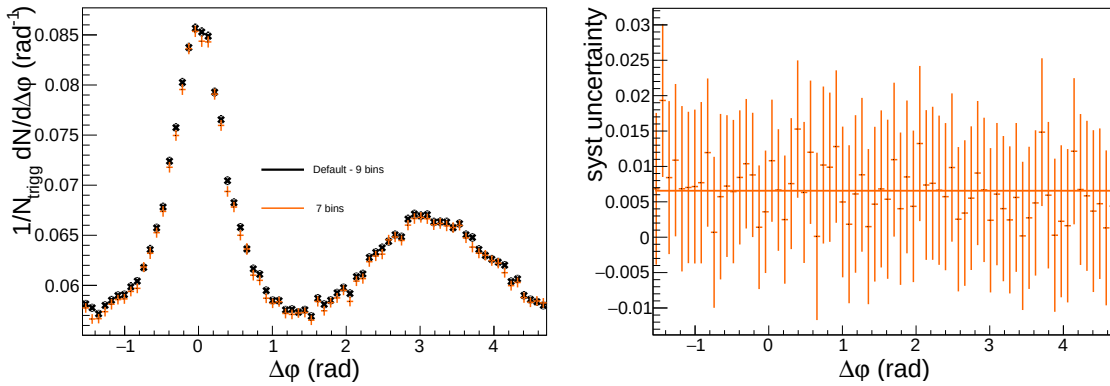


Figure 5.1: The variation of number of PV bins in $\Delta\varphi$ projection of $h(\Lambda + \bar{\Lambda})$ correlation function (left) and the following uncertainty (right).

Following variations are common for K_S^0 -h (h- K_S^0) and $(\Lambda + \bar{\Lambda})$ -h (h- $(\Lambda + \bar{\Lambda})$) correlations:

- **topological selections:** The variations of topological variables are taken from a V^0 specified analysis [103], which were tuned in order to modify the signal in 10%. Two variations sets are used - tight and loose set - listed in Tab. 5.1. The efficiency correction is calculated and applied for each set separately.
- **invariant mass acceptance:** The default acceptance in the invariant mass spectrum for the signal and side-bad region is $\mu \pm 3\sigma$ and $\mu \pm 7\sigma - \mu \pm 10\sigma$, respectively. Two variations are used to estimate the systematic uncertainty where the efficiency correction is calculated and applied for each variation separately:
 - $\mu \pm 2\sigma$ and $\mu \pm 8\sigma - \mu \pm 10\sigma$,
 - $\mu \pm 4\sigma$ and $\mu \pm 6\sigma - \mu \pm 10\sigma$,

Table 5.1: Variation of the selection criteria for V^0 candidates

Selection	Loose	Default	Tight
V^0 decay radius (cm)	> 0.4	>0.5	>0.6
DCA Neg to PV (cm)	>0.05	>0.06	>0.07
DCA Pos to PV (cm)	>0.05	>0.06	>0.07
DCA V^0 daughters (σ)	<1.25	<1	<0.75
$V^0 \cos(\theta_{PA})(K_S^0)$	>0.96	>0.97	>0.98
$V^0 \cos(\theta_{PA})(\Lambda)$	>0.994	>0.995	>0.994
Proper lifetime K_S^0 (cm)	<30	<20	<12
Proper lifetime Λ (cm)	<35	<30	<25
Competing V^0 rejection K_S^0 (GeV/c^2)	<0.001	<0.005	<0.01
Competing V^0 rejection Λ (GeV/c^2)	<0.005	<0.01	<0.015
dE/dx ($N\sigma$)	<4	<3	<3
Number of crossed rows	70	70	75

Additional variations are taken into account for $(\Lambda + \bar{\Lambda})$ -h (h- $(\Lambda + \bar{\Lambda})$) correlations:

- **Ξ topological selections:** The variations of topological variables are taken from a Ξ specified analysis [104], which were tuned in order to modify the signal in 10%. Two variations sets are used - tight and loose set - listed in Tab. 5.2. The efficiency correction is calculated and applied for each set separately.
- **MC closure:** Because of the unexplained non-closure, an uncertainty of 2.5% and 4% is assigned in the case of near-side yields from $(\Lambda + \bar{\Lambda})$ -h and h- $(\Lambda + \bar{\Lambda})$ correlation functions, respectively.

Table 5.2: Variation of the selection criteria for Ξ candidates

Selection	Loose	Default	Tight
Ξ transv. decay radius (cm)	> 0.5	>0.6	>0.8
V^0 transv decay radius (cm)	> 1.1	> 1.2	> 2.5
DCA Bachelor to PV (cm)	>0.03	>0.04	>0.1
DCA V^0 to PV (cm)	>0.05	>0.06	>0.1
DCA meson V^0 track to PV (cm)	>0.03	>0.04	>0.15
DCA baryon V^0 track to PV (cm)	>0.02	>0.03	>0.09
DCA V^0 daughters (σ)	<1.8	<1.5	<1.2
DCA Bachelor to V^0 (cm)	<1.8	<1.3	<1.1
$\Xi \cos(\theta_{PA})$	>0.96	>0.97	>0.98
$V^0 \cos(\theta_{PA})$	>0.96	>0.97	>0.98
V^0 invariant mass window (MeV/c^2)	± 0.009	± 0.008	± 0.007
dE/dx ($N\sigma$)	<5	<5	<3
Proper lifetime (mL/p)	$< 4 \times c\tau$	$< 3 \times c\tau$	$< 2.5 \times c\tau$
Number of crossed rows	70	70	75

The **wing correction variation** is performed for the h-h correlation, where the $\Delta\varphi$ range for the correction distribution is set in the region between the peaks. In the case of $(\Lambda + \bar{\Lambda})$ -h the discrepancy in mixing description is smaller, thus the wing correction is taken only as systematic check.

The total systematic uncertainty is calculated as a sum of quadratures of all contributions and then a square root is taken.

The systematic uncertainty is calculated separately for the $\Delta\varphi$ projections and the yields in each multiplicity class. The uncertainty for the yield ratios is also calculated separately (the yield-ratio for each variation is calculated and from this the uncertainty is estimated). With this approach all correlated uncertainties should cancel out. For the yield uncertainty, no p_T dependence is awaited, thus the uncertainties for each source are smoothed in the way, that an average of all p_T bins is calculated except for large fluctuating bins and bins rejected by the Barlow test (Sec. 5.1). The final uncertainties for the yields in the MB sample and contributions from different variations are shown in Fig 5.2. The uncertainty ranges for the yields calculated in multiplicity classes and yield ratios are listed in the Appendix C.

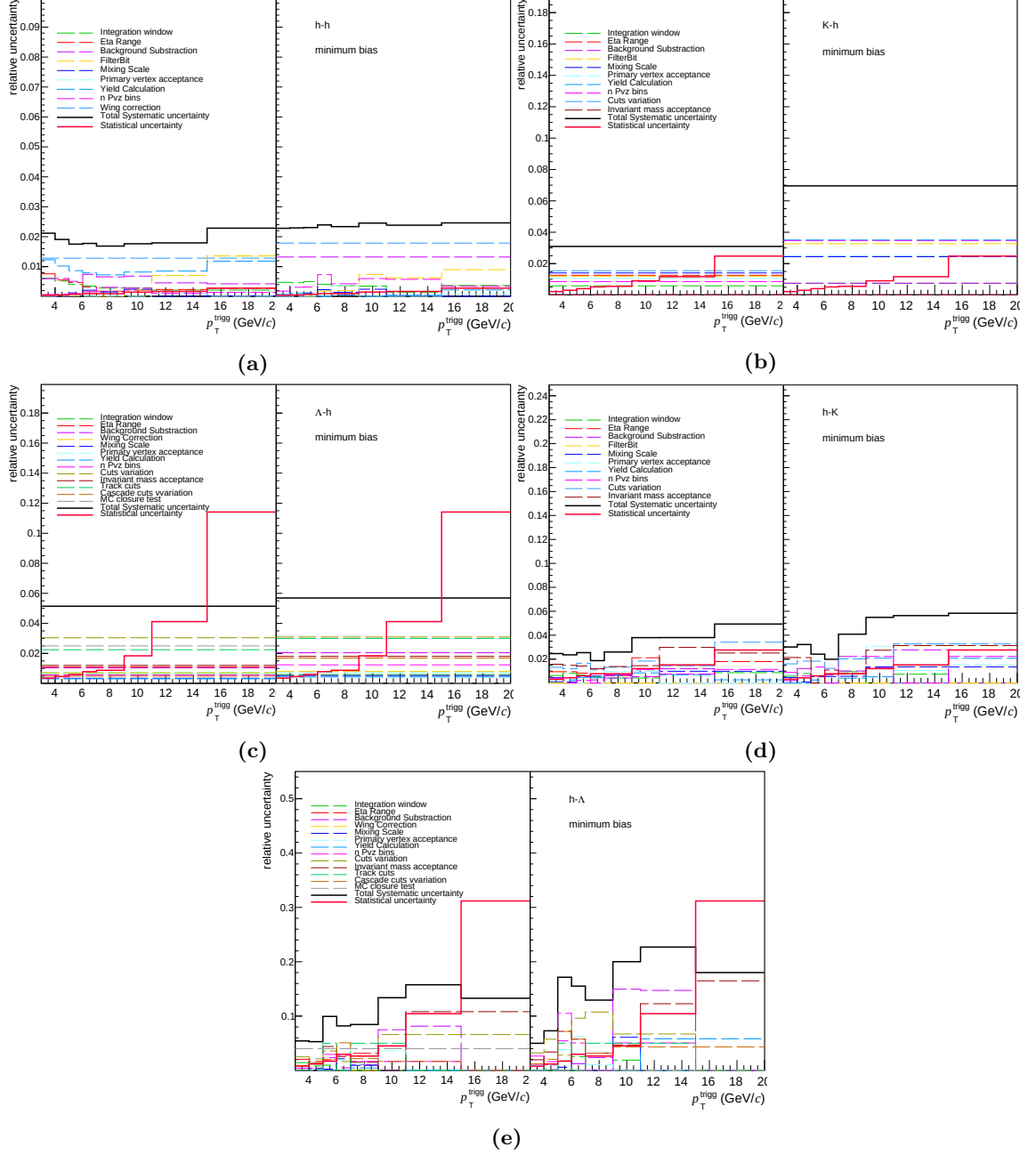


Figure 5.2: Total systematic uncertainty and different its contributions after the Barlow check for the near-side (each left part) and away-side (each right part) per-trigger yield of h-h(a), K_S^0 -h (b), $(\Lambda + \bar{\Lambda})$ -h (c), h- K_S^0 (d) and h- $(\Lambda + \bar{\Lambda})$ (e) correlations as a function of p_T^{trigg} for minimum bias.

5.1 Barlow check

Due to the lack of statistics, particularly of Λ baryons at high p_T , it can happen that some of the differences in yields after the variations described above are still within the statistical uncertainty. In such a case, this source should not be taken into account for the total systematic uncertainty. For this purpose, the Barlow check [105] was done. Let assume that the default measurement is $y_d \pm \sigma_d$ and the measurement after each variation is $y_i \pm \sigma_i$. Let us define Δy_i , $\Delta \sigma_i$ and n_i as:

$$\Delta y_i = y_d - y_i \quad (5.2)$$

$$\Delta \sigma_i = \sqrt{|\sigma_d^2 - \sigma_i^2|} \quad (5.3)$$

$$n_i = \frac{\Delta y_i}{\Delta \sigma_i} \quad (5.4)$$

The n_i is afterwards calculated for each p_T ($\Delta\varphi^1$) bin. The mean value and standard deviation along $\Delta\varphi$ bins are computed from n_i distribution for each systematic source and if the mean is close to 0 and at the same time the standard deviation is smaller than 1, this result is consistent with the default one within the statistical uncertainty and this source is excluded from the total systematic uncertainty. As there is a small number of p_T bins in the integrated yield analysis, the sources in bins where n_i is smaller than 1 are rejected.

¹for the calculation of the systematics in the $\Delta\varphi$ projections

6 Results

In the following chapter, the correlation functions, the yields and their ratios are presented. In this context, the event multiplicity influence on the jet and underlying event fragmentation will be discussed. Moreover, the role of the trigger particle selection in the quark or gluon jet-tagging will be explored.

6.1 Two dimensional per-trigger yields

Examples of two-dimensional (2D) h-h correlation functions are shown in Fig. 6.1 for different p_T^{trigg} and p_T^{assoc} intervals. In the first row, correlation functions for the same interval of p_T of associated particles and three different p_T^{trigg} intervals are shown. It is visible that the near-side peaks becomes slightly narrower with increasing p_T^{trigg} that is caused by a bigger relativistic boost of the original parton. Further, if the p_T of the trigger particle stays constant, as shown in the middle row of Fig. 6.1, the near-side peak becomes smaller as the p_T^{assoc} increases, because of the smaller probability of production many high- p_T associated particles inside a jet. The peak becomes narrower for higher p_T^{assoc} as a consequence of a smaller value of α_S by radiating a high p_T particle under a small angle. This is causing a smaller probability of radiating a high p_T particle under bigger angles. On the other hand, softer particles, low p_T^{assoc} , can be also radiated under bigger angles, making the jet-peak wider. In the bottom row of Fig. 6.1, correlation functions for different p_T^{trigg} intervals with integrated p_T^{assoc} are presented. It is visible that the near-side peak becomes narrower and higher with increasing p_T^{trigg} . This is caused by the fact that a trigger particle with higher p_T is a proxy for a more energetic jet where more associated particles can be created. However, such jets are more collimated around the jet axis, which is caused by an interplay of the both previously explained effects, relativistic boost and α_S value.

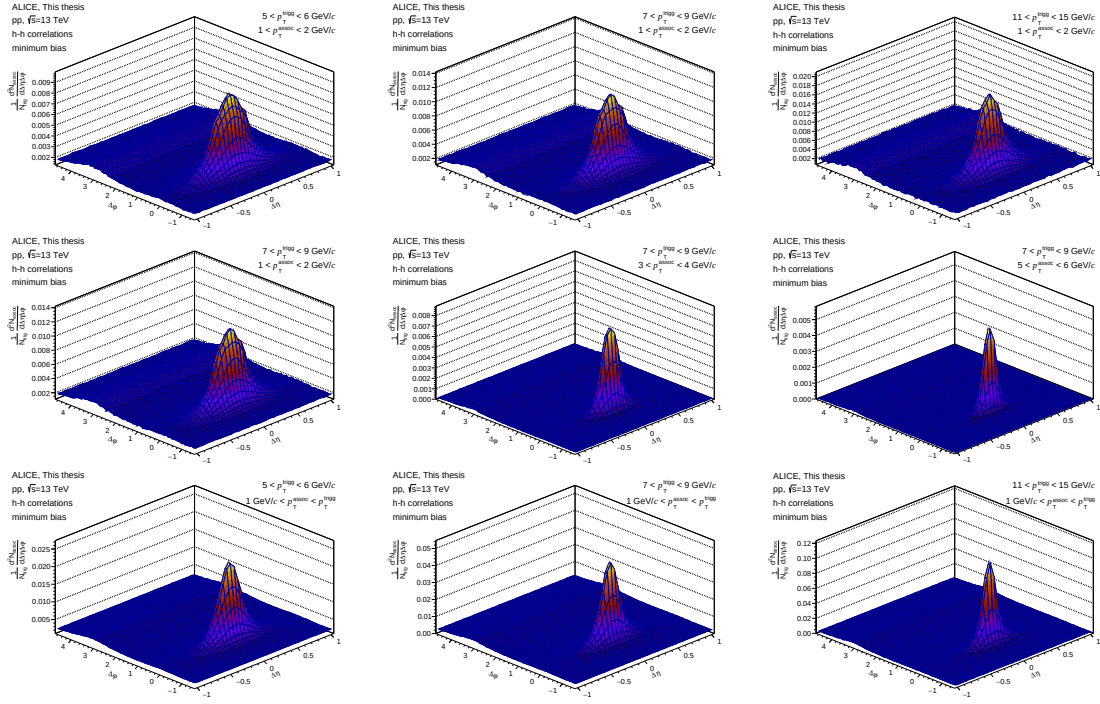


Figure 6.1: Two-dimensional h-h correlation functions for different p_T^{trigg} intervals by a constant p_T^{assoc} interval in the top row, different p_T^{assoc} intervals by a constant p_T^{trigg} interval in the middle row and for different p_T^{trigg} intervals with integrated p_T^{assoc} in the bottom row.

6.2 $\Delta\varphi$ projections

In Fig. 6.2 and 6.3, the $\Delta\varphi$ projections of the correlation functions for two p_T^{trigg} ranges (3-4 GeV/c, 9-11 GeV/c) are shown together with the MC model predictions. The first figure presents the projections of V^0 -h and h-h correlation functions after the background subtraction, as the underlying event stand not in the focus of this part of the study, while the h- V^0 and h-h projections are plotted with the underlying event in the second figure. It is visible that none of the used models can describe the shape of all the correlation functions.

From Fig. 6.2, it is visible that both PYTHIA models similarly overestimate the absolute size of both, near- and away-side, peaks for low p_T of the trigger particle, while the Shoving model underestimates the size of the peaks for higher p_T^{trigg} . The EPOS LHC model underestimates the size and overestimates the width of the near-side peak for all trigger particles in both p_T^{trigg} intervals except for K_S^0 , where the peak is described reasonably well.

Comparing the h-h projections before and after the underlying event subtraction (the left panels of Fig. 6.2 and Fig. 6.3), the differences in the model description of the hard

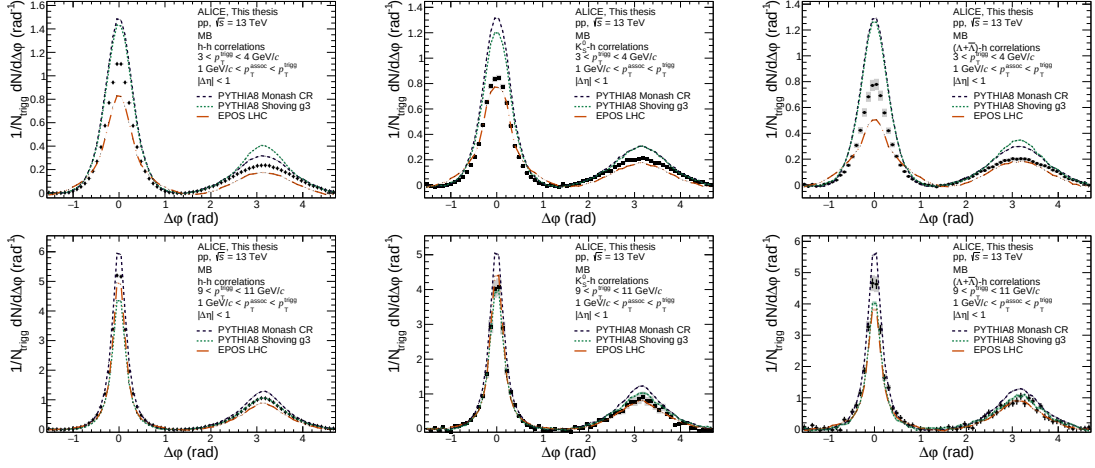


Figure 6.2: $\Delta\varphi$ projections of h-h(left), K_S^0 -h (middle) and $(\Lambda + \bar{\Lambda})$ -h (right) correlation function after background subtraction compared with MC generator predictions. The data points are published in Ref. [106].

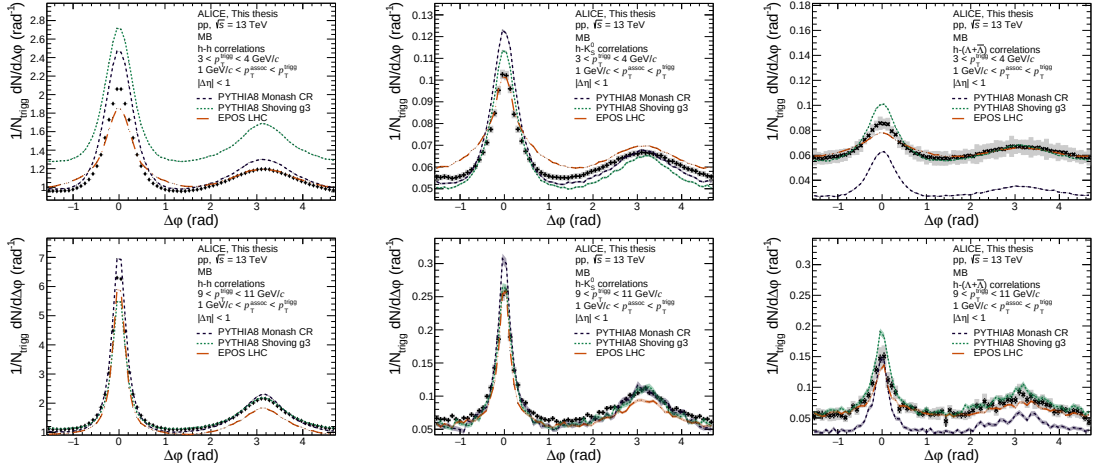


Figure 6.3: $\Delta\varphi$ projections of h-h (left), h- K_S^0 (middle) and h- $(\Lambda + \bar{\Lambda})$ (right) correlation function before underlying event subtraction compared with MC generator predictions.

processes (the peaks) and of the soft processes (the underlying event) is clearly visible. While the standard Monash tune and the Shoving model predict similar size of the peaks, their prediction for the underlying event differs for low p_T of the trigger particle. The Monash tune fits the underlying event well thanks to the proper tuning on the inclusive pion p_T spectra. However, the additional Shoving mechanism in PYTHIA leads to an overestimated prediction of the underlying pions (the charged hadron sample is dominated by pions). Nevertheless, this model improves the description of h- $(\Lambda + \bar{\Lambda})$ underlying event by a lot. This is suggesting that thanks to the Shoving model, more strange baryons can be produced in the underlying event than in the standard fragmentation model, both for low and high p_T^{trigg} . Thus, it can be concluded that

the baryon production mechanism is not driven by the simple string breaking. The EPOS LHC overestimates the width of the near-side peaks also for h - V^0 correlations with low- p_T trigger particle and can describe the underlying event and away-side peak of Λ hyperons, but overestimates the K_S^0 production associated with low- p_T trigger particle and underestimates it in the case of the higher p_T^{trigg} .

6.3 Per-trigger yields as a function of p_T^{trigg} and event multiplicity

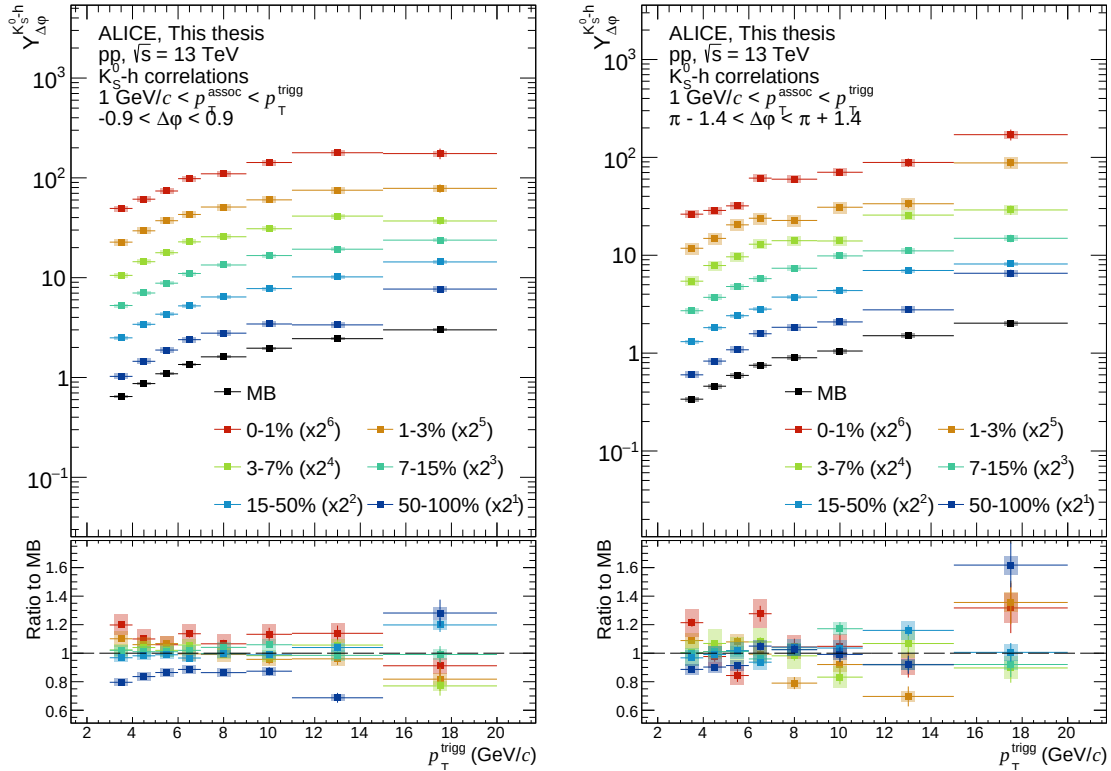


Figure 6.4: Per-trigger yields of the near-side (left) and away-side (right) peak from K_S^0 - h correlation function as a function of p_T^{trigg} and multiplicity class. Bottom panels show the ratio over the yields from MB sample. The data points are published in Ref. [106].

In Figs. 6.4-6.8, the per-trigger yields as a function of p_T^{trigg} are presented for all combinations of trigger and associated particles of interest. For the h -($\Lambda + \bar{\Lambda}$) correlation function, the last two p_T^{trigg} bins are excluded due to the lack of statistics. An increasing trend of yields on both, near- and away-side is visible, which is caused by more available energy in harder processes (higher p_T^{trigg}) to produce more associated particles in jets.

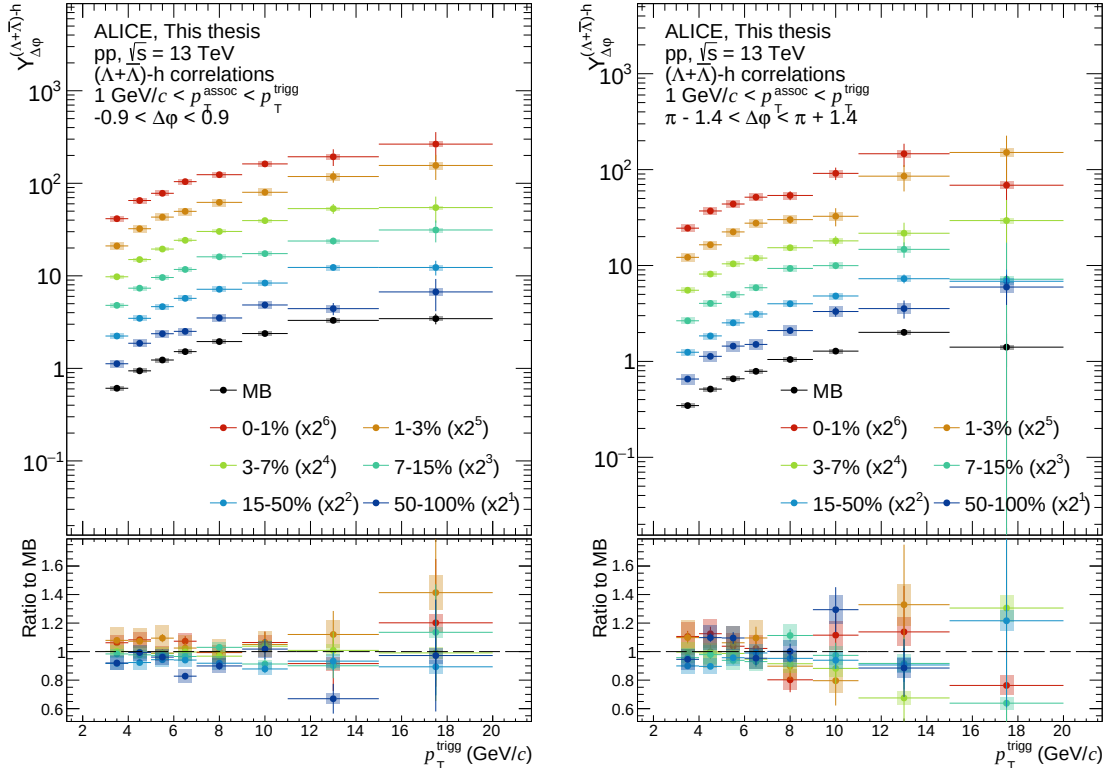


Figure 6.5: Per-trigger yields of the near-side (left) and away-side (right) peak from $(\Lambda + \bar{\Lambda})$ -h correlation function as a function of p_T^{trigg} and multiplicity class. Bottom panels show the ratio over the yields from MB sample. The data points are published in Ref. [106].

In order to provide a more quantitative study of the event activity dependence, a ratio between yields from different multiplicity classes over the ones from the MB sample is calculated, which is shown in the bottom panels of Figs. 6.4-6.8. A clear difference in the trends is visible for the near- and away-side peaks. The near-side ordering is similar for all combination of trigger and associated particles, but it is pronounced the most for the h-h case. The events with the highest multiplicity of charged particles exhibit the highest near-side jet-like yields, while the smallest yields are calculated in the events with the lowest multiplicity. The enhancement and suppression are mostly pronounced for the low p_T of the trigger particle and become smaller with increasing p_T^{trigg} . One of the possible causes could be the collective ridge, which is not accounted for in this analysis. Nevertheless, the expected effect is not that big, as the ridge was measured only in the highest multiplicity class 0–0.01% [54]. Hence, this result could point out that the jet fragmentation is not universal.

On the away-side, there is a difference between the yield ratios from correlation functions with primary charged hadrons and V^0 as associated particles. For the h- V^0 yields, the ordering seems to be the same as on the near-side, however, there are big fluctuations,

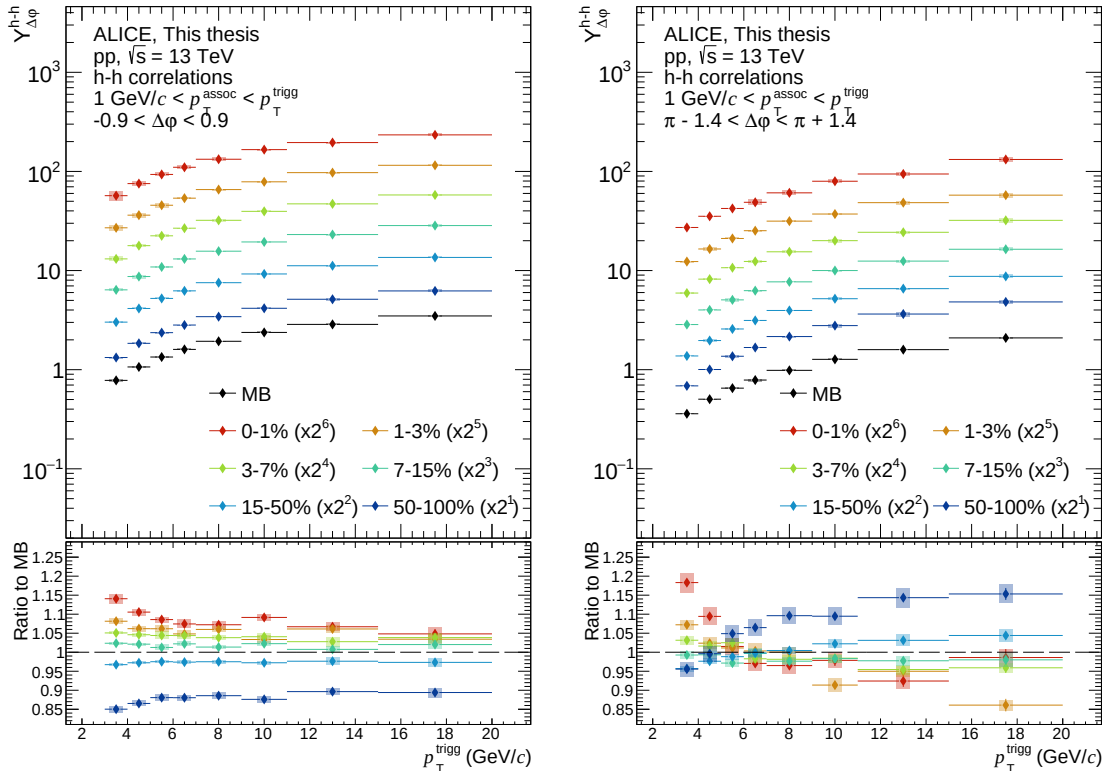


Figure 6.6: Per-trigger yields of the near-side (left) and away-side (right) peak from h-h correlation function as a function of p_T^{trigg} and multiplicity class. Bottom panels show the ratio over the yields from MB sample. The data points are published in Ref. [106].

preventing from a strong conclusion. On the other hand, a reverted ordering is observed for the ratios in the h-h correlations at intermediate and high p_T^{trigg} . This trend is less significant for the V^0 -h correlations due to the large uncertainties. The away-side reverted ordering can be understood as a bias due to the event multiplicity selection with the V0 detectors. By the definition of the correlation function, the near-side peak is necessarily fully reconstructed in the central barrel detectors, but the η location of the away-side peak is not fixed and thus can possibly be within the acceptance of the V0 detectors. This means that the selection of high (low) multiplicity class is affected by more (less) away-side jets in the V0 acceptance causing less (more) reconstructed away-side jets in the central barrel detectors and thus smaller (bigger) calculated away-side yields. The yields on the away-side from the h- V^0 correlation functions cannot be affected by this, as V^0 hadrons are neutral and do not contribute to the V0 signal. This is also visible in the results in Figs. 6.7 and 6.8.

By looking on the different associated particles, it is also interesting to study the production of the associated particles in the underlying event as a function of the hardness of the process and event multiplicity as well. Thus, the underlying event yields are

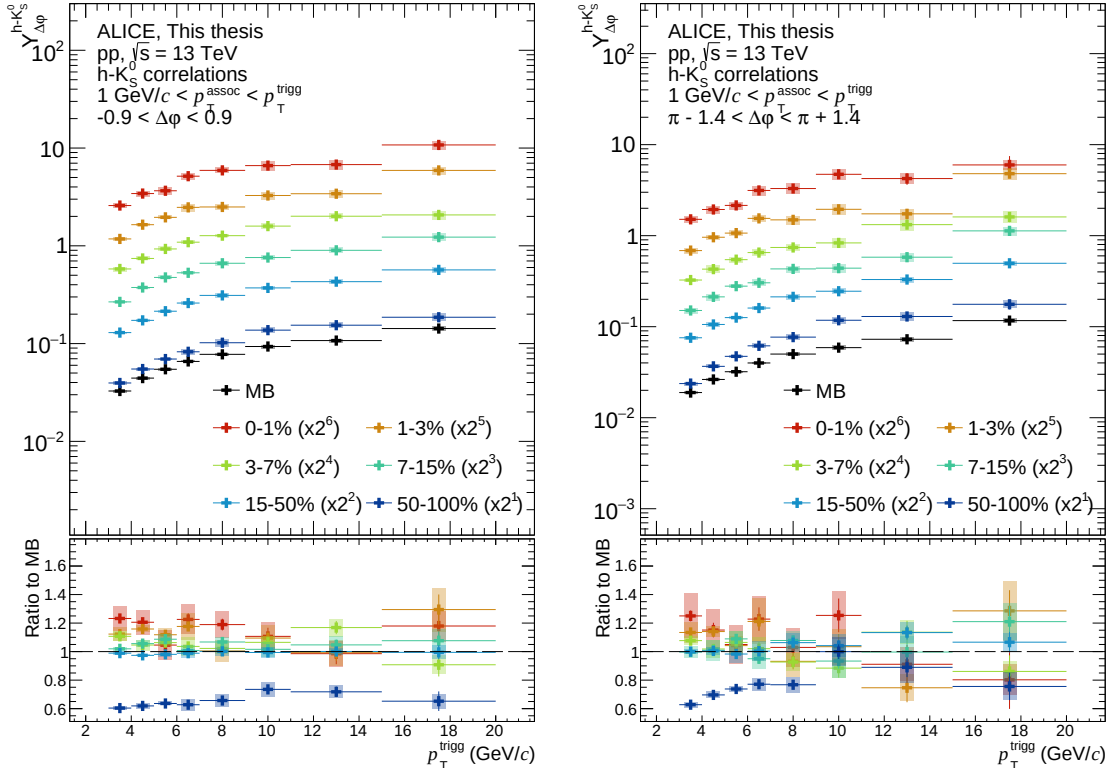


Figure 6.7: Per-trigger yields of the near-side (left) and away-side (right) peak from $h\text{-}K_S^0$ correlation function as a function of p_T^{trigg} and multiplicity class. Bottom panels show the ratio over the yields from MB sample.

shown as a function of p_T^{trigg} for $h\text{-}h$ and $h\text{-}V^0$ correlation functions in Fig. 6.9. It can be observed that there is almost no dependence on the p_T^{trigg} in all the considered multiplicity classes except for the lowest one where a slight increase is observed. Although, there is an approximately 2 orders of magnitude difference between the primary charged hadrons and the neutral strange hadron yields in the underlying event, the ratios to the yields from the MB sample are similar (bottom panels of Fig. 6.9). This is suggesting that the amount of particles of each type is only determined by the overall event multiplicity.

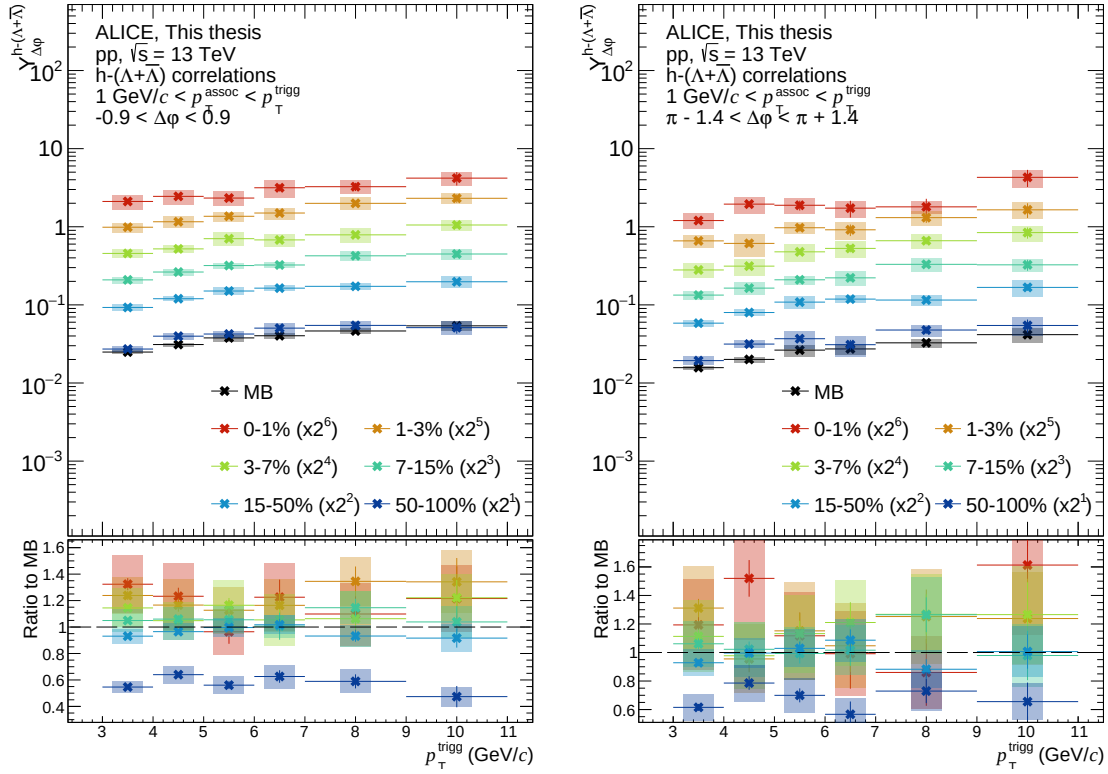


Figure 6.8: Per-trigger yields of the near-side (left) and away-side (right) peak from $h-(\Lambda + \bar{\Lambda})$ correlation function as a function of p_T^{trigg} and multiplicity class. Bottom panels show the ratio over the yields from MB sample.

6.3 Per-trigger yields as a function of p_T^{trigg} and event multiplicity

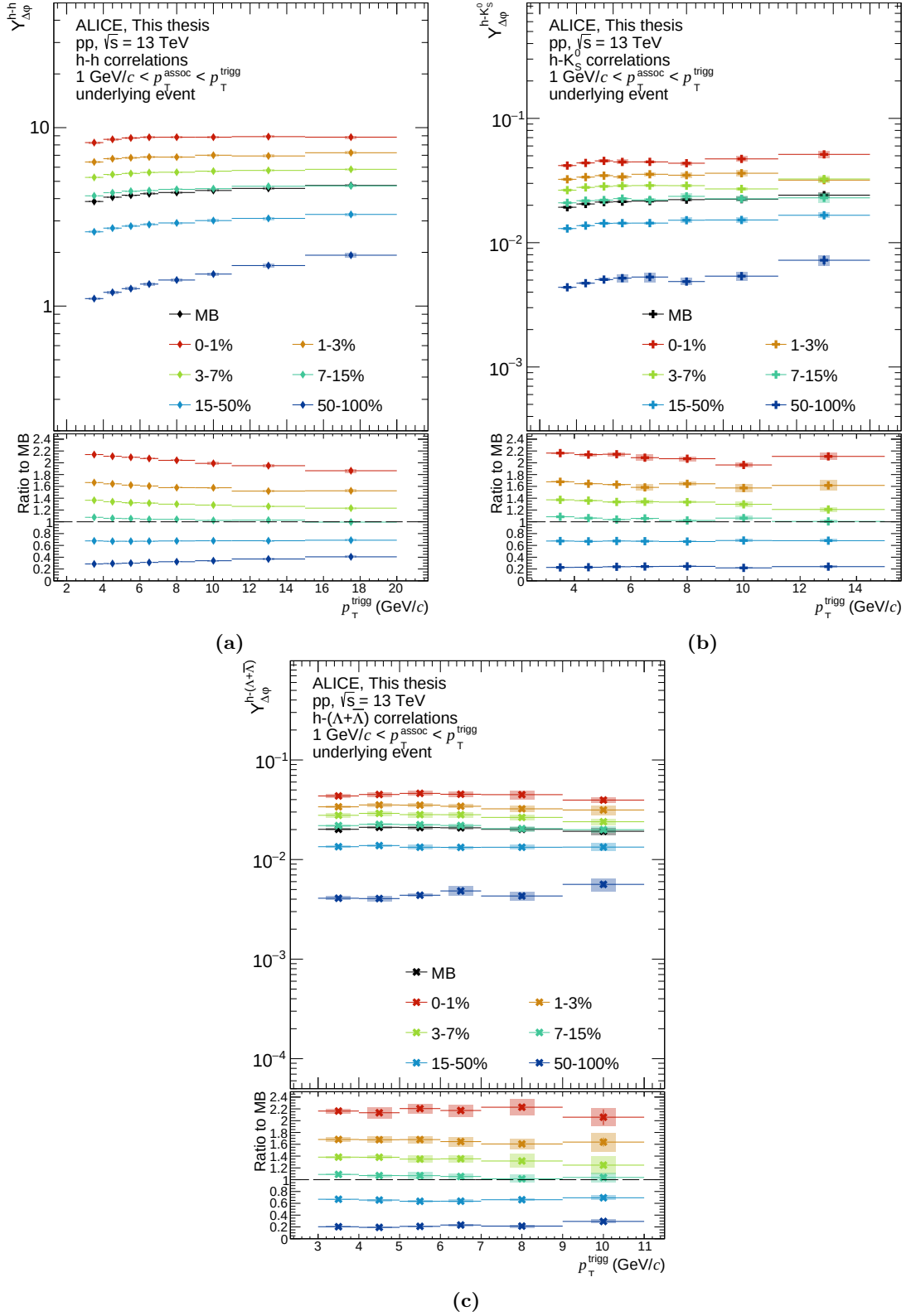


Figure 6.9: Per-trigger underlying event yields from h-h (a), h- K_S^0 (b) and h-($\Lambda + \bar{\Lambda}$) (c) correlation function as a function of p_T^{trigg} and multiplicity class. Bottom panels show the ratio over the yields from MB sample.

6.4 Per-trigger yields as a function of p_T^{assoc}

The per-trigger yields for the near- and away-side peaks as a function of the p_T of the associated particle for various p_T^{trigg} intervals are presented in Figs. 6.10-6.14 for all studied combinations of trigger and associated particles. The decreasing trend with p_T^{assoc} is connected with the smaller probability for high- p_T associated particles to be created. Not the full p_T range is covered by all p_T^{trigg} intervals due to the $p_T^{\text{assoc}} < p_T^{\text{trigg}}$ kinematic restriction. Moreover, some points are not presented for the $(\Lambda + \bar{\Lambda})$ -h and h- $(\Lambda + \bar{\Lambda})$ yields because of the lack of statistics at high- p_T .

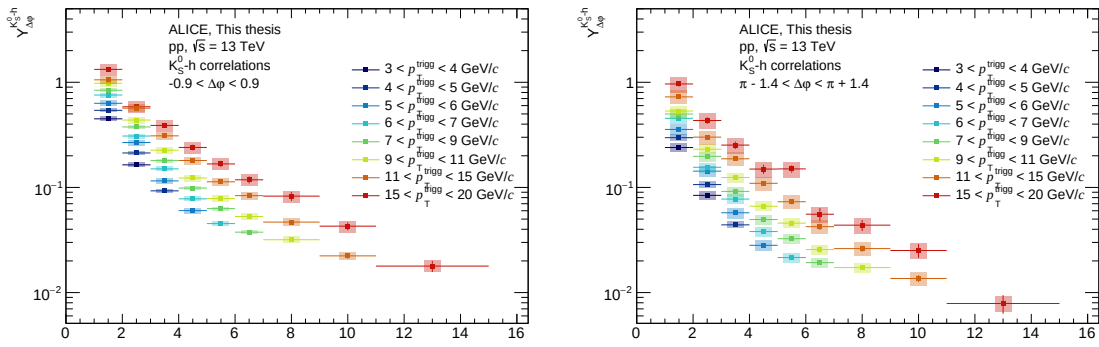


Figure 6.10: Per-trigger yields of the near-side (left) and away-side (right) peak from K_S^0 -h correlation function as a function of p_T^{assoc} . The data points are published in Ref. [106].

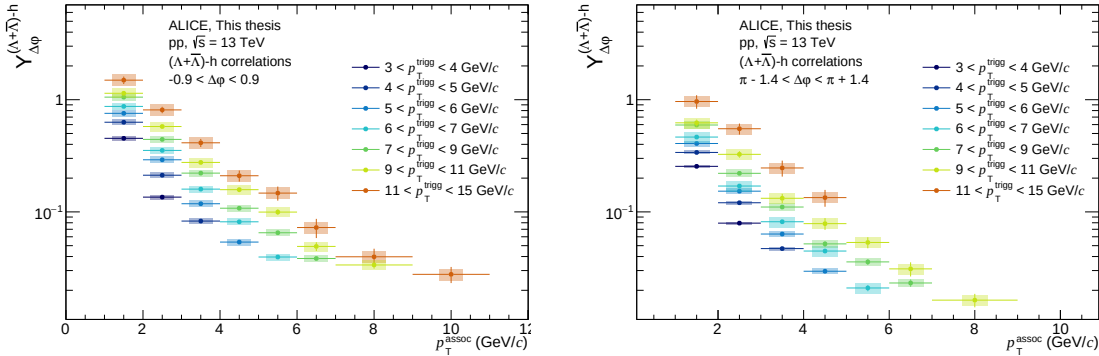


Figure 6.11: Per-trigger yields of the near-side (left) and away-side (right) peak from $(\Lambda + \bar{\Lambda})$ -h correlation function as a function of p_T^{assoc} . The data points are published in Ref. [106].

In Fig. 6.15, the underlying event yields of h-h and h- V^0 correlation functions are shown. The absent dependence on the hardness of the process is pronounced in these plots, where the points for different p_T^{trigg} intervals overlap each other at the same p_T^{assoc} . The decreasing trend with p_T is visible also here, as explained above, the probability of particle creation decreases with p_T .

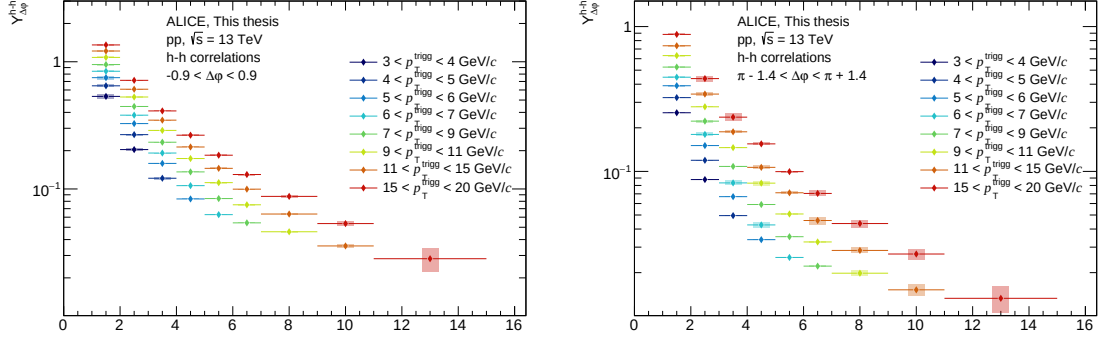


Figure 6.12: Per-trigger yields of the near-side (left) and away-side (right) peak from h-h correlation function as a function of p_T^{assoc} . The data points are published in Ref. [106].

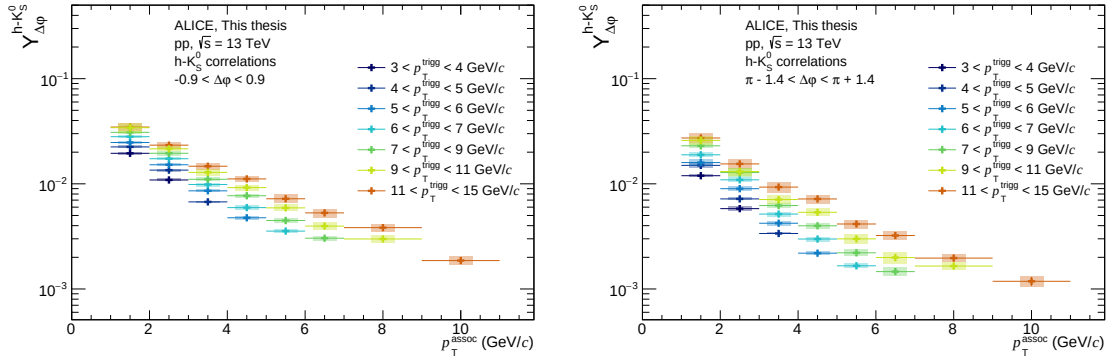


Figure 6.13: Per-trigger yields of the near-side (left) and away-side (right) peak from h- K_S^0 correlation function as a function of p_T^{assoc} .

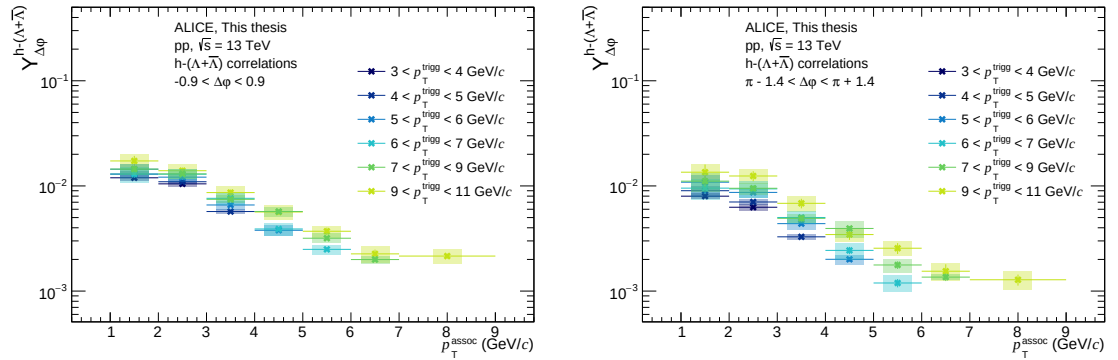


Figure 6.14: Per-trigger yields of the near-side (left) and away-side (right) peak from h- $(\Lambda + \bar{\Lambda})$ correlation function as a function of p_T^{assoc} .

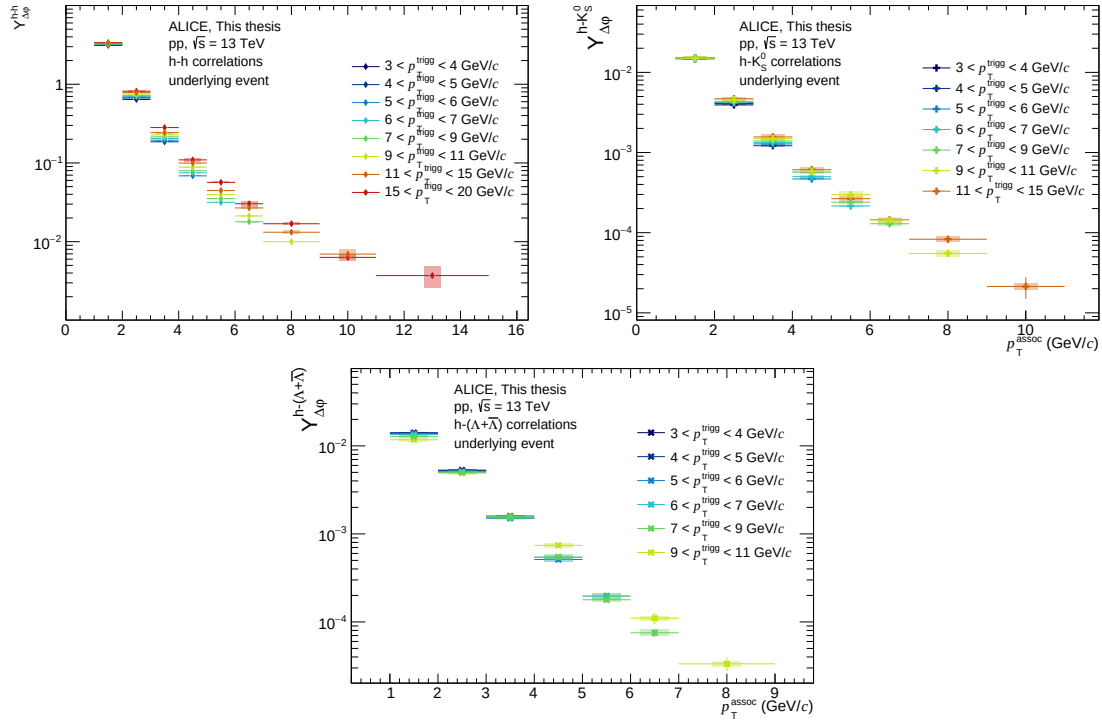


Figure 6.15: Per-trigger underlying event yields from h-h (top left), h- K_S^0 (top right) and h- $(\Lambda + \bar{\Lambda})$ (bottom) correlation function as a function of p_T^{assoc} .

6.5 Comparison with MC generators

For the model comparison, the ratio of the MC predictions to data is calculated, which is shown in Fig. 6.16 for all combination of trigger and associated particles for the near- and away-side per-trigger yields as a function of p_T^{trigg} for the MB sample as well as the event classes selected on their multiplicity. The model description is rather similar for all trigger particles.

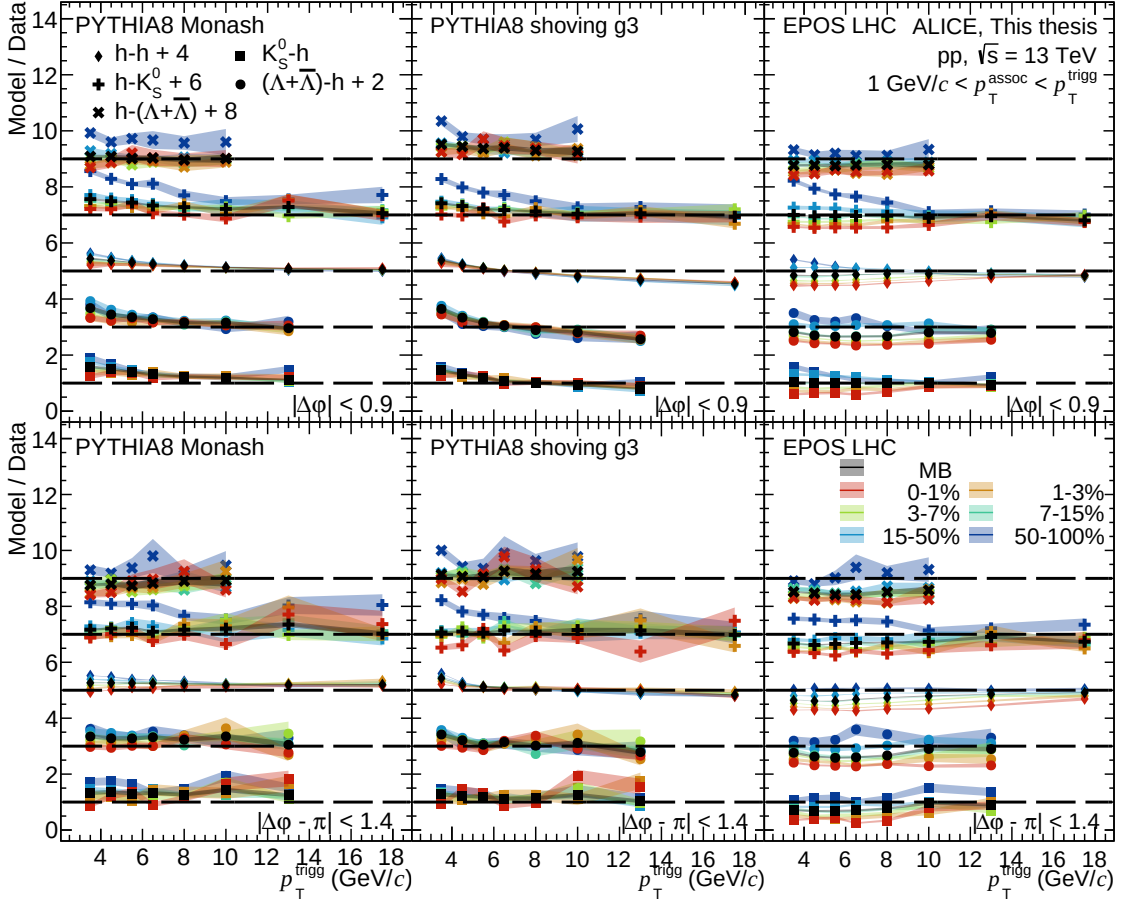


Figure 6.16: Data to model ratio of per-trigger yields as a function of p_T^{trigg} for different combinations of trigger and associated particles. The data points for V^0 -h and h-h yields are published in Ref. [106].

On the near-side, the standard Monash Tune of PYTHIA8 with colour re-connection can describe the yields of primary charged hadrons triggered with high- p_T hadron, while it overestimates these yields for low- p_T^{trigg} . The description is only weakly dependent on the multiplicity class selection or the trigger particle selection. This is a consequence of the good description of the hard QCD processes in PYTHIA8, which does not depend on the event multiplicity. Similar agreement between PYTHIA8 and data is visible also

for h - K_S^0 near-side yields, where only the lowest multiplicity class is showing bigger discrepancies. Surprisingly, PYTHIA8 describes the near-side yields of associated Λ ($\bar{\Lambda}$) hyperons in the MB events through the whole p_T^{trigg} range reasonably well. This good agreement holds for all multiplicity classes except for the lowest one, where the yields are overestimated. On the away-side, the Monash tune overestimates the yields from the h - h and the V^0 - h correlation functions slightly through the whole p_T^{trigg} range, but fits well the yields of K_S^0 and Λ ($\bar{\Lambda}$).

The Shoving model improves the description of charged hadron per-trigger yields at intermediate p_T on the near-side at the price of degrading the harder sector, where the yields are underestimated. From this follows that allowing the Shoving mechanism without a p_T cut, as done in this simulation, is not truly physical. But there is no improvement or worsening by description of K_S^0 yields in the Shoving model in comparison with the standard Monash tune. Nevertheless, the $(\Lambda + \bar{\Lambda})$ per-trigger yields get slightly overestimated for all multiplicity classes by the Shoving model. For the away-side, PYTHIA8 with Shoving provides moderately better description for all combinations of trigger and associated particles than the Monash tune.

In the core-corona model implemented in the EPOS LHC, the multiplicity dependence of the jet-like yields on both sides and all combinations is not reproducing the data well. In the model, a milder event-activity dependence is observed, which leads to under-predicting the data for high multiplicities and over-predicting them for low multiplicities at the near-side and fitting them well at the away-side. However, the discrepancies converge for high- p_T^{trigg} towards the data, suggesting that the hard processes are described well also within the EPOS LHC model.

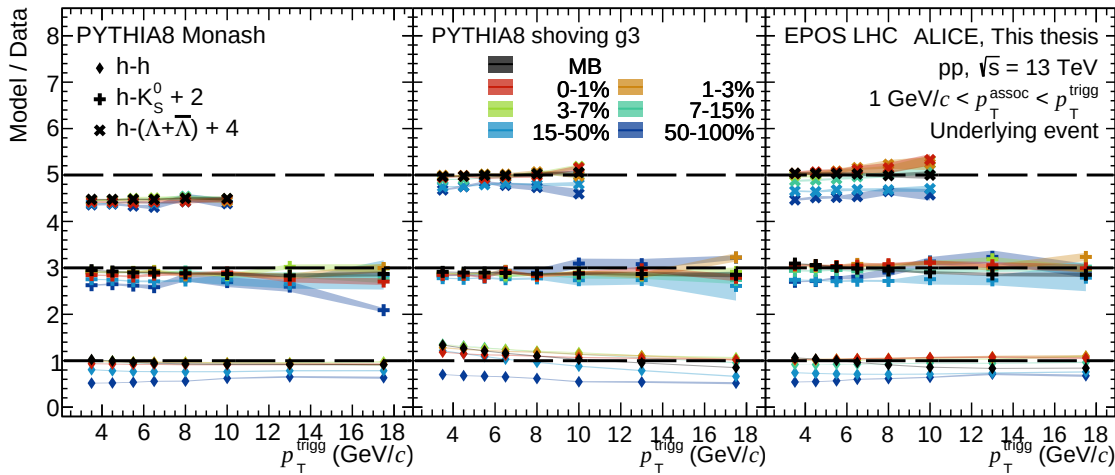


Figure 6.17: Data to model ratio of per-trigger yields from the underlying event as a function of p_T^{trigg} for different combinations of trigger and associated particles.

The comparison with models of the underlying event yields of different associated particles as a function of p_T^{trigg} and event-activity class is presented in Fig. 6.17. The model description of the underlying event yield differs a lot from the jet-like yield one.

In the Monash tune of PYTHIA8, there is no dependence on the multiplicity class by the description of the Λ ($\bar{\Lambda}$) hyperon production in the underlying event, which is underestimated by nearly 50%. On the other hand, the yields of primary charged hadrons and K_S^0 mesons are predicted rather well in the MB and higher multiplicity classes and getting under-predicted in the classes with the lowest multiplicity.

The description of the $(\Lambda + \bar{\Lambda})$ in the underlying event is improved in the Shoving model for the MB sample and the highest multiplicity classes. However, the the lowest multiplicity classes are still under-estimated by this model. The Shoving extension of the PYTHIA8 model also predicts the K_S^0 yields in the underlying event better than the Monash tune, where the yields are only slightly underestimated for all multiplicity classes through the whole p_T^{trigg} region. The yields of primary charged hadrons are well described for the intermediate p_T of the trigger particle and overestimated (underestimated) for low (high) p_T^{trigg} for all multiplicity classes except for the lowest one, where the yields are under-predicted for each p_T^{trigg} bin.

In the EPOS LHC model, the dependence on the multiplicity class is visible for all associated particle species. The MB and high multiplicity predictions fit the data while the events with lower activity are strongly under-predicted.

The model to data ratio of near- and away-side yields as a function of p_T^{assoc} is shown in Fig 6.18. In the comparison with both PYTHIA8 models, a dependence on the hardness of the process is visible for the V^0 -h and h-h yields on the near-side. While the Monash tune describes the hardest ($11 < p_T^{\text{trigg}} < 15$ GeV/c) processes well and the other p_T^{trigg} intervals over-predicts, the Shoving model fits the data in the intermediate p_T^{trigg} sector and overestimates and underestimates the lower and the higher p_T^{trigg} intervals, respectively. The h- V^0 near-side yields are well described by both PYTHIA8 models independent on the p_T^{trigg} interval in the full p_T^{assoc} range except for the first bin ($1 < p_T^{\text{assoc}} < 2$ GeV/c), where the data are overestimated. The EPOS LHC event generator predicts exact results for the K_S^0 -h yields on the near-side and slightly under-predicts the yields from other correlation functions independently on p_T^{trigg} or p_T^{assoc} . On the away-side, PYTHIA8, both the Monash tune and the Shoving model, provide a good data description within the uncertainty for all combination of trigger and associated particles while the EPOS LHC tends to under-estimate the yields.

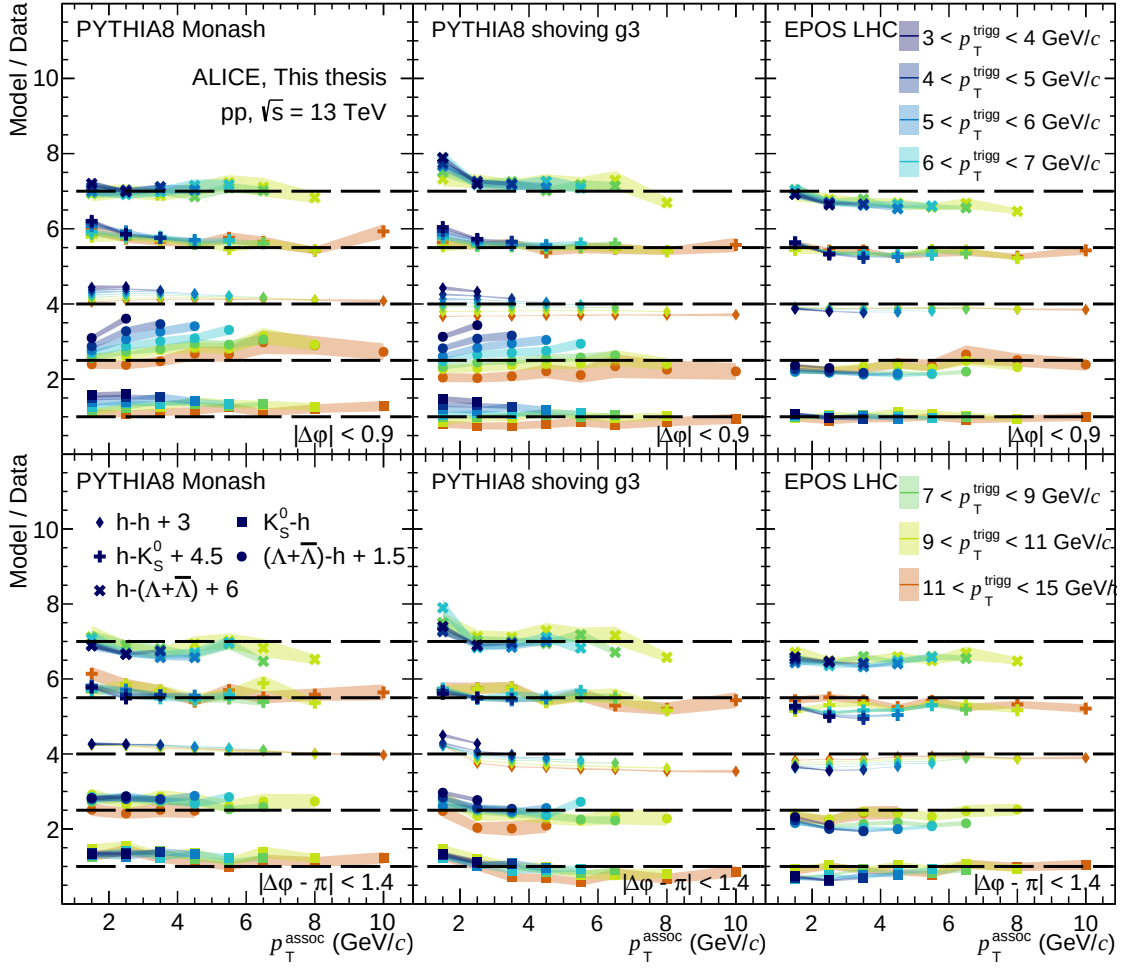


Figure 6.18: Data to model ratio of per-trigger yields as a function of p_T^{assoc} for different combinations of trigger and associated particles. The data points for V^0 -h and h-h yields are published in Ref. [106].

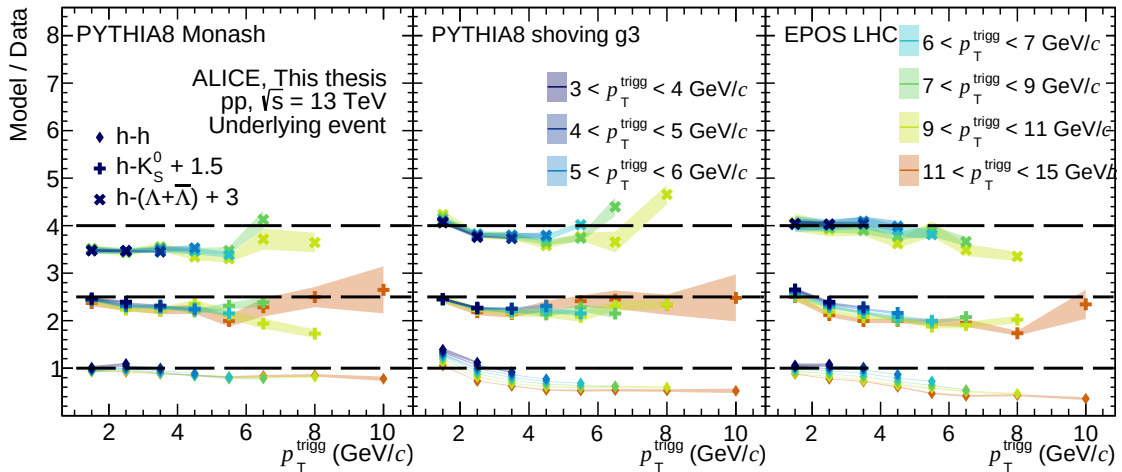


Figure 6.19: Data to model ratio of per-trigger yields from the underlying event as a function of p_T^{trigg} for different combinations of trigger and associated particles.

The comparison with models of the underlying event yields is shown in Fig. 6.19 for the h-h and h- V^0 correlations. The Monash tune provides a good description of the h-h underlying event yields through the whole p_T^{assoc} region, which could be a consequence of the good tuning on the single pion spectra. However, the yields of the strange hadrons are underestimated in the case of the yields Λ ($\bar{\Lambda}$) hyperons up to 50%. This follows from the wrong modelling of the strange baryon production within the string breaking model. This is improved in the Shoving model at the price of degrading the yields description of the primary charged hadrons, which is strongly underestimated for $p_T^{\text{assoc}} > 3$ GeV/c. This could be caused by allowing the Shoving mechanism also for high p_T processes, which shows as not entirely physical. The EPOS LHC fits the data for the lowest p_T^{assoc} interval for all associated particles species (in the case of Λ hyperons even up to 5 GeV/c), but underestimates it with increasing p_T of associated particle, suggesting that in the core-corona model, there is a smaller probability to create a high p_T particle outside the jet than in the data.

6.6 Ratio to h-h yields

In order to compare different trigger and associated particles with each other, yield ratios to the yields from h-h correlations are calculated. These are presented in the following sections.

6.6.1 V^0 -h to h-h ratios

The yields of the V^0 -h correlation function to the ones from h-h are presented in Fig. 6.20 as a function of p_T^{trigg} and event multiplicity class. The data indicate that the differences between charged-hadron triggered yields and either K_S^0 or $(\Lambda + \bar{\Lambda})$ triggered yields are small and have a weak dependence on the event-activity class. The data points are compared with the three considered models. Both PYTHIA8 settings provide very similar description better fitting the ratios than the yields. This is a consequence of the earlier finding that the model-data disagreements are very similar for the three trigger-particle species. On the other hand, the EPOS LHC predicts a dependence on the multiplicity class for both ratios on the near-side, an enhancement of the K_S^0 -h over h-h yield-ratio and suppression of the $(\Lambda + \bar{\Lambda})$ -h over h-h yield-ratio for the highest multiplicity classes. This could suggest that within the core-corona model, the yields in the high multiplicity events are rather initiated by mesons than by baryons.

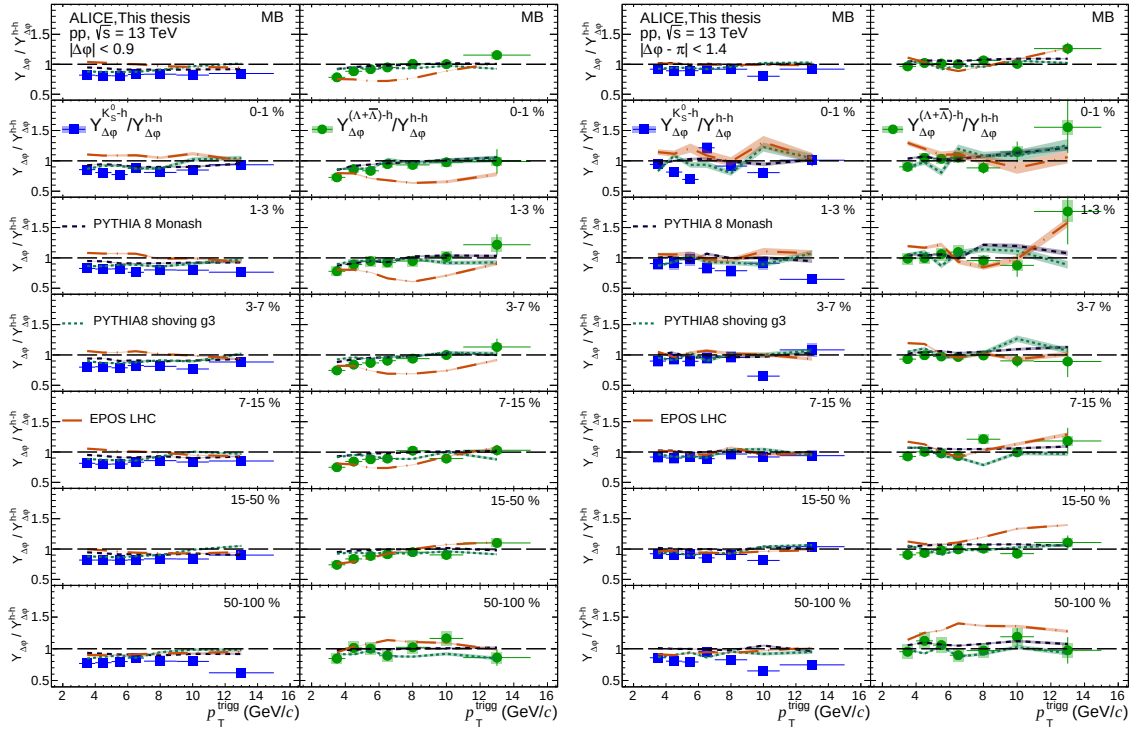


Figure 6.20: Ratios of integrated per-trigger yield of K_S^0 -h (left column) or $(\Lambda + \bar{\Lambda})$ -h (right column) to h-h as a function of p_T^{trigg} , for the near-side in the left plot and for the away-side in the right plot, for different event multiplicity classes. The data points are published in Ref [106].

On the away side, all models are in agreement with the data that are compatible with unity within the uncertainties, thus no dependence on the trigger particle species is seen. Even-though, deviations in some bins from unity are visible, these are caused by the fluctuations of the underlying event estimation. This fits to the expectation that there is no trigger particle bias in the away-side jet. The agreement with the models is confirming this assumption.

At closer examination of the near-side yield ratios, a difference between different trigger particle species can be observed. The ratios of yields triggered with K_S^0 mesons are flat through the whole p_T^{trigg} region and smaller than unity. This indicates that jets triggered with K_S^0 contain less associated particles than the jets triggered with primary charged hadron (inclusive jets). This feature does not depend on the hardness of the process (p_T^{trigg}) or the underlying event-activity. In contrast to that, there is an increasing trend of the $Y_{\Delta\phi}^{(\Lambda+\bar{\Lambda})-h}/Y_{\Delta\phi}^{h-h}$ ratio with p_T^{trigg} . Potentially, this could be explained with a bias towards gluon jets, which contain more particles [20, 19] and have enhanced relative production of Λ hyperons [21]. From Fig. 6.21, where the same ratios are shown as a function of p_T^{assoc} , it is visible that this effect is pronounced in the low p_T^{assoc} region for high p_T^{trigg} (the soft part of harder jets). Moreover, a decreasing trend with the p_T^{assoc} is

observed in the both ratios on the near-side suggesting that the jets triggered with a V^0 particle produce a smaller amount of associated particles with higher p_T than charged particle triggered jets. This trend is well reproduced by all three considered models. The away-side yield ratio dependence on the p_T^{assoc} is flat and compatible with unity confirming the away-side yield universality observed in the ratio plots as a function of p_T^{trigg} .

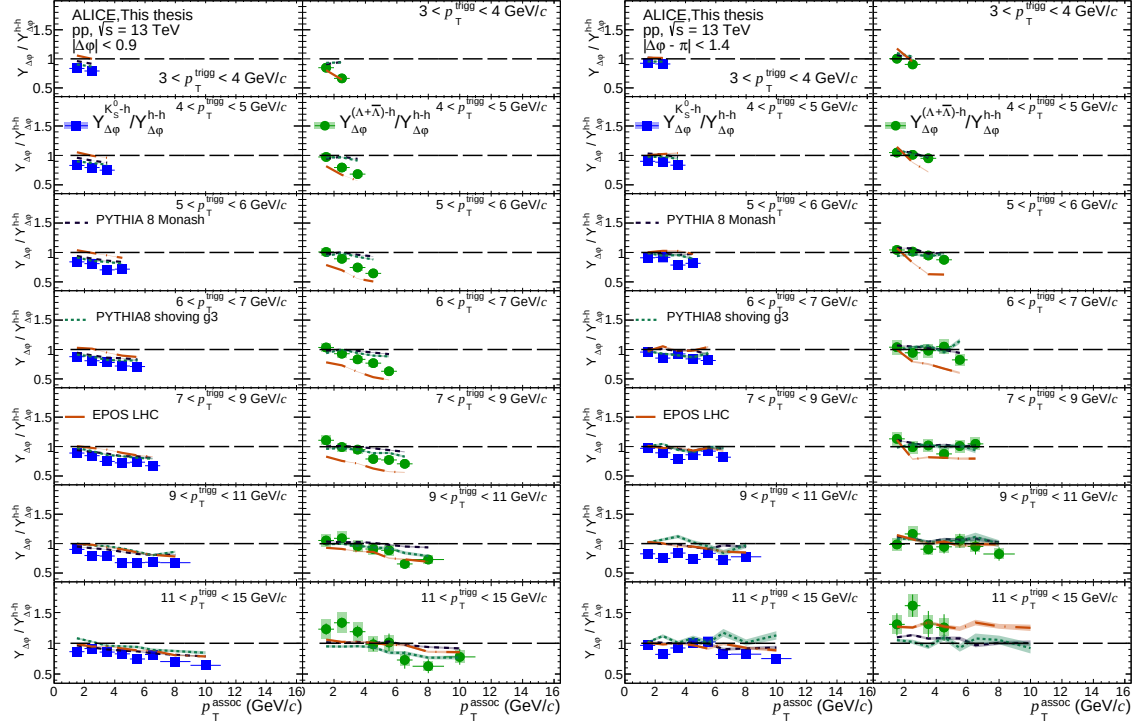


Figure 6.21: Ratios of integrated per-trigger yield of K_S^0 -h (left column) or $(\Lambda + \bar{\Lambda})$ -h (right column) to h-h as a function of p_T^{assoc} , for the near-side in the left plot and for the away-side in the right plot, for different p_T^{trigg} intervals. The data points are published in Ref. [106].

6.6.2 PYTHIA8 simulation of hard processes

In order to prove the assumption that the difference in ratios triggered with K_S^0 or $(\Lambda + \bar{\Lambda})$ is caused by the bias towards gluon jets, when triggering with a high p_T Λ or $\bar{\Lambda}$ hyperon, a separate PYTHIA8 study is performed. In this simulation, only hard processes are considered that either contain only gluons or only quarks in the final state, here using the $g + g \rightarrow g + g$ and $q + \bar{q} \rightarrow q + \bar{q}$ channels, respectively. In the first step, it is necessary to check whether the enhancement of the relative Λ production in gluon jets is implemented in the PYTHIA8 model. Thus, the ratio R_g/R_q is calculated for both, K_S^0 mesons and Λ ($\bar{\Lambda}$) hyperons. Here, R_g is the relative production of K_S^0 or $(\Lambda + \bar{\Lambda})$

to primary charged particles in the gluon jet sample and R_q is the same quantity in the quark jet sample. This ratio is shown in Fig. 6.22 and it is visible that the difference in the relative production of K_S^0 mesons and Λ ($\bar{\Lambda}$) baryons in quark and gluon jets is a part of the PYTHIA8 model.

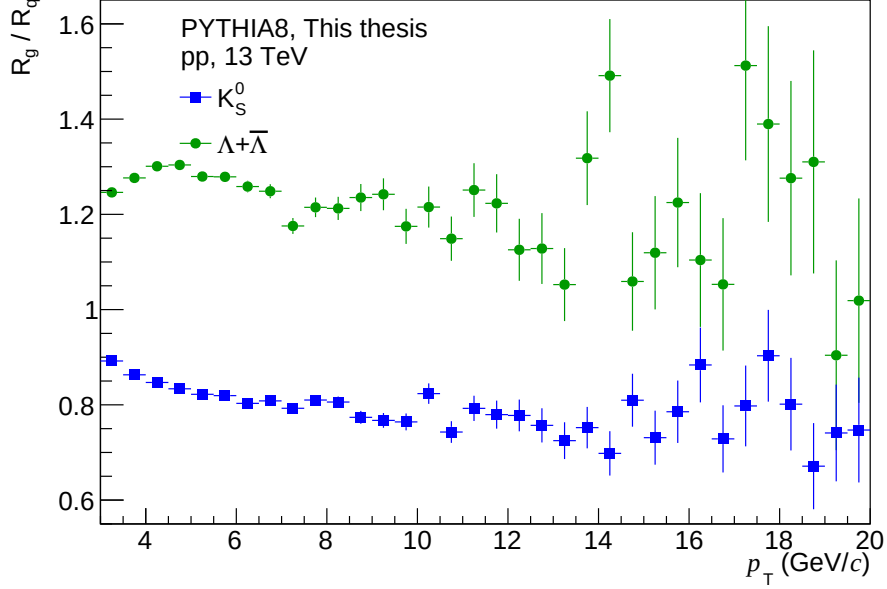


Figure 6.22: PYTHIA8 simulation of ratio of relative production of K_S^0 mesons and Λ ($\bar{\Lambda}$) baryons in gluon jets to the one in quark jets.

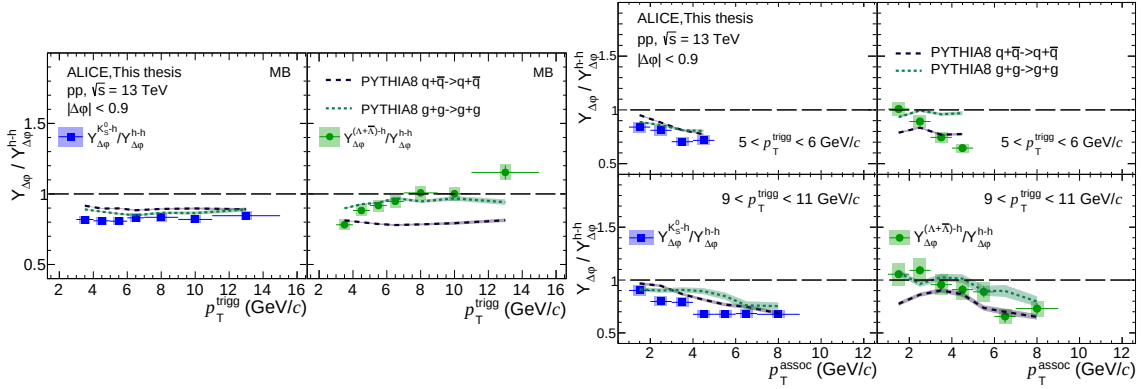


Figure 6.23: Ratios of integrated per-trigger yield of K_S^0 -h (left column) or $(\Lambda + \bar{\Lambda})$ -h (right column) to h-h as a function of p_T^{trigg} (left) and p_T^{assoc} (right) compared with PYTHIA8 simulation with only quarks or gluons in the final state. The simulation is published in Ref. [106].

Afterwards, the K_S^0 -h, $(\Lambda + \bar{\Lambda})$ -h and h-h correlation functions are constructed in both samples and from the near-side yields, the ratio over the one from h-h correlation function is calculated. The results in comparison with the data are shown in Fig. 6.23 as a function of p_T^{trigg} and p_T^{assoc} . There is a clear difference visible between the gluon and quark sample,

predicting the ratios triggered with different strange hadron. For the ratios triggered with K_S^0 , both samples give compatible results, which are also describing the data well, both as a function of p_T^{trigg} and p_T^{assoc} . In contrast to that, the gluon jet simulation provides an enhanced $Y_{\Delta\varphi}^{(\Lambda+\bar{\Lambda})-h}/Y_{\Delta\varphi}^{h-h}$ ratio in comparison with the quark jet simulation. Moreover, there is a visible hint of the increasing trend with p_T^{trigg} as also observed in data. Although, the p_T distributions of hadrons in the simulated exclusive processes may be different than in MB collisions, it is expected that the observed difference is generic and explains at least some of the trends seen in the data.

6.6.3 h- V^0 to h-h ratios

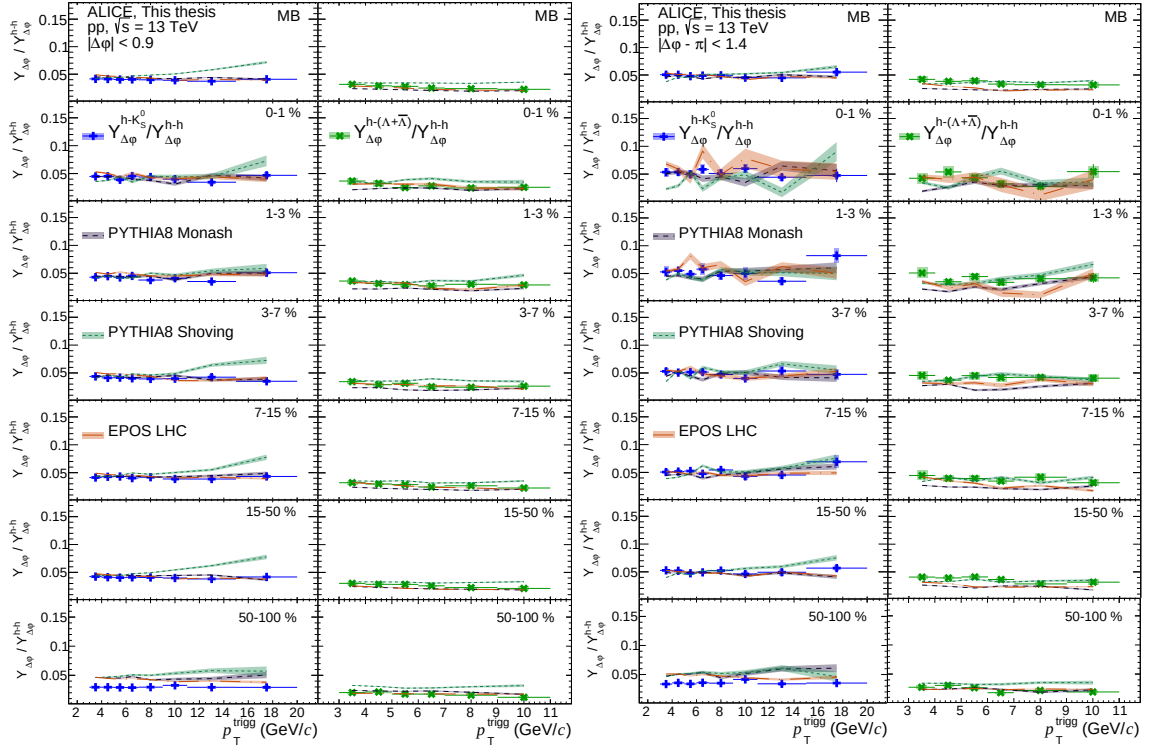


Figure 6.24: Ratios of integrated per-trigger yield of h- K_S^0 (left column) or h- $(\Lambda + \bar{\Lambda})$ (right column) to h-h as a function of p_T^{trigg} , for the near-side in the left plot and for the away-side in the right plot, for different event multiplicity classes.

The $Y_{\Delta\varphi}^{h-V^0}/Y_{\Delta\varphi}^{h-h}$ yield-ratios are presented in Fig. 6.24 as a function of p_T^{trigg} and event multiplicity class for the near- and away-side peak. The ratios are showing no clear dependence neither on the p_T of the trigger particle nor on the multiplicity class, suggesting that the relative production of K_S^0 mesons and Λ ($\bar{\Lambda}$) hyperons in jets does not depend on the hard scale of the process. The ratios are compared with the MC predictions showing a good agreement with all three models except for the Shoving model that

predicts an increasing trend with p_T^{trigg} of the relative production of K_S^0 in the near-side peak.

The ratios as a function of p_T of associated particles are shown in Fig. 6.25. They are increasing with p_T on both near- and away-side and for both associated particle species. The increase is steeper for lower p_T of the trigger particle where the ratio has also a slightly higher value. These trends are well described by all three MC models.

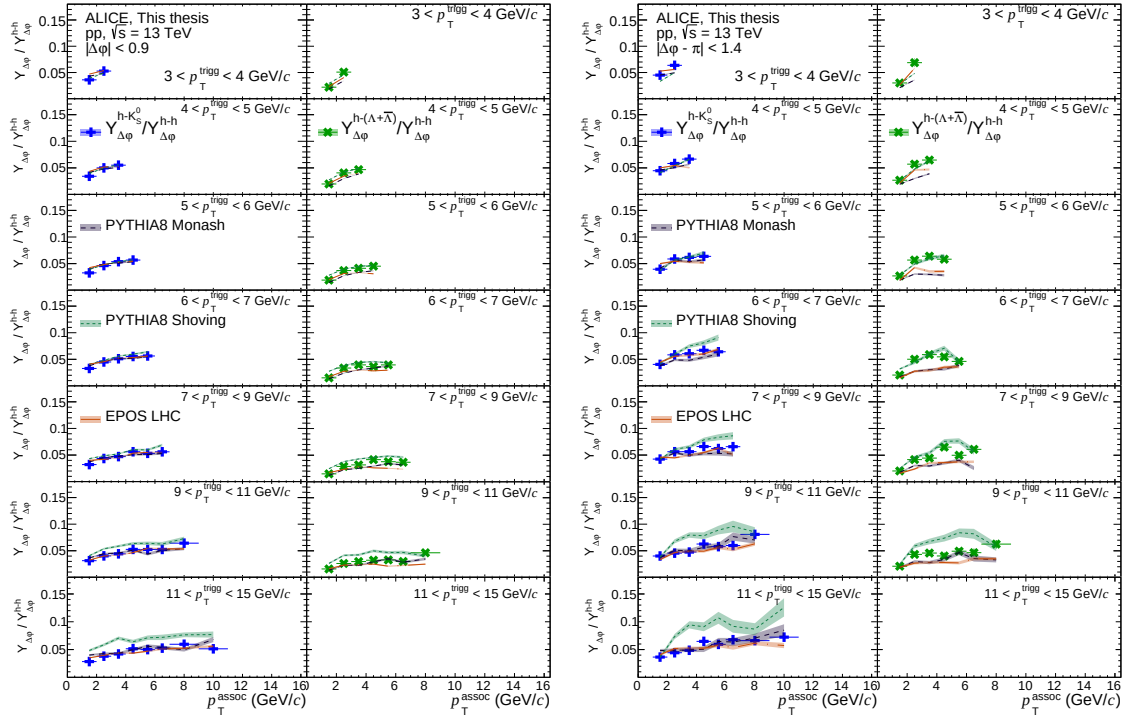


Figure 6.25: Ratios of integrated per-trigger yield of $h-K_S^0$ (left column) or $h-(\Lambda + \bar{\Lambda})$ (right column) to $h-h$ as a function of p_T^{assoc} , for the near-side in the left plot and for the away-side in the right plot, for different p_T^{trigg} intervals.

The $Y_{\Delta\phi}^{h-V^0}/Y_{\Delta\phi}^{h-h}$ yield-ratios are also studied in the underlying event region, which are shown in Fig. 6.26 both as a function of p_T^{trigg} and p_T^{assoc} . The relative production of K_S^0 mesons show no strong dependence neither on the multiplicity class nor on the p_T of the trigger particle and is well described by all assumed MC models, while the relative production of Λ ($\bar{\Lambda}$) baryons shows a hint of decreasing trend with increasing p_T^{trigg} . The ratio of associated Λ hyperons are also strongly underestimated by the Monash tune of PYTHIA8, which is caused by the underestimated inclusive Λ production. The $Y_{\Delta\phi}^{h-K_S^0}/Y_{\Delta\phi}^{h-h}$ yield-ratio is continuously increasing with p_T of the associated particle, while the $Y_{\Delta\phi}^{h-(\Lambda+\bar{\Lambda})}/Y_{\Delta\phi}^{h-h}$ yield-ratio has a maximum around 4 GeV/c, suggesting higher probability of creating a baryon in this p_T region.

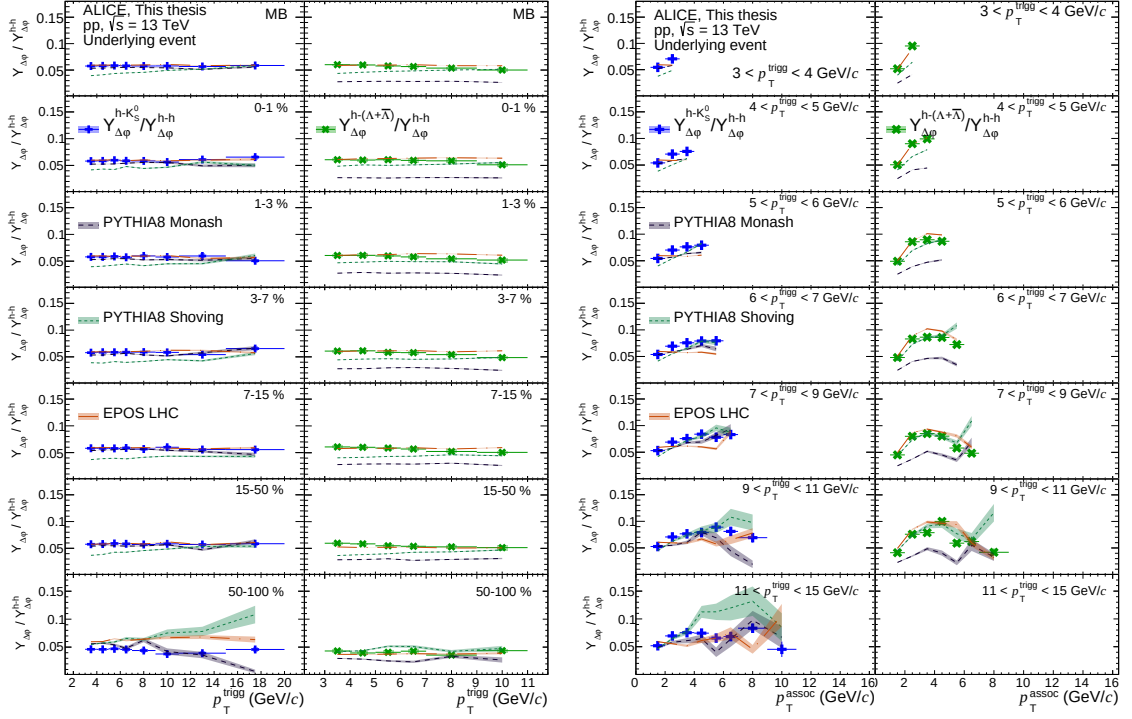


Figure 6.26: Ratios of integrated per-trigger yield of $h\text{-}K_S^0$ (left column) or $h\text{-}(\Lambda + \bar{\Lambda})$ (right column) to h-h from the underlying event as a function of p_T^{trigg} (left) and p_T^{assoc} (right).

In order to study the multiplicity dependence of the strangeness production and the soft- and hard-fragmentation contribution to the strangeness enhancement in high multiplicity collisions [52], the $Y_{\Delta\phi}^{h-V^0}/Y_{\Delta\phi}^{h-h}$ yield-ratios are plotted as a function of multiplicity in Fig. 6.27. A hint of an increase with multiplicity is visible in all regions, but the highest increase is visible between the lowest and intermediate multiplicity class. The 0-0.01% multiplicity class triggered with the HM trigger could help by drawing better conclusion. The ratio is the highest for the underlying event, suggesting that this region contributes the most to the inclusive enhancement. But since a hint of increase is visible also in the jet yield ratios, the contribution of hard processes can not be fully excluded. Moreover, the primary charged hadron sample consists not only from pions, even it is dominated by them. For this reason, our results cannot be directly compared with the measurements showing the enhancement published in Ref. [52].

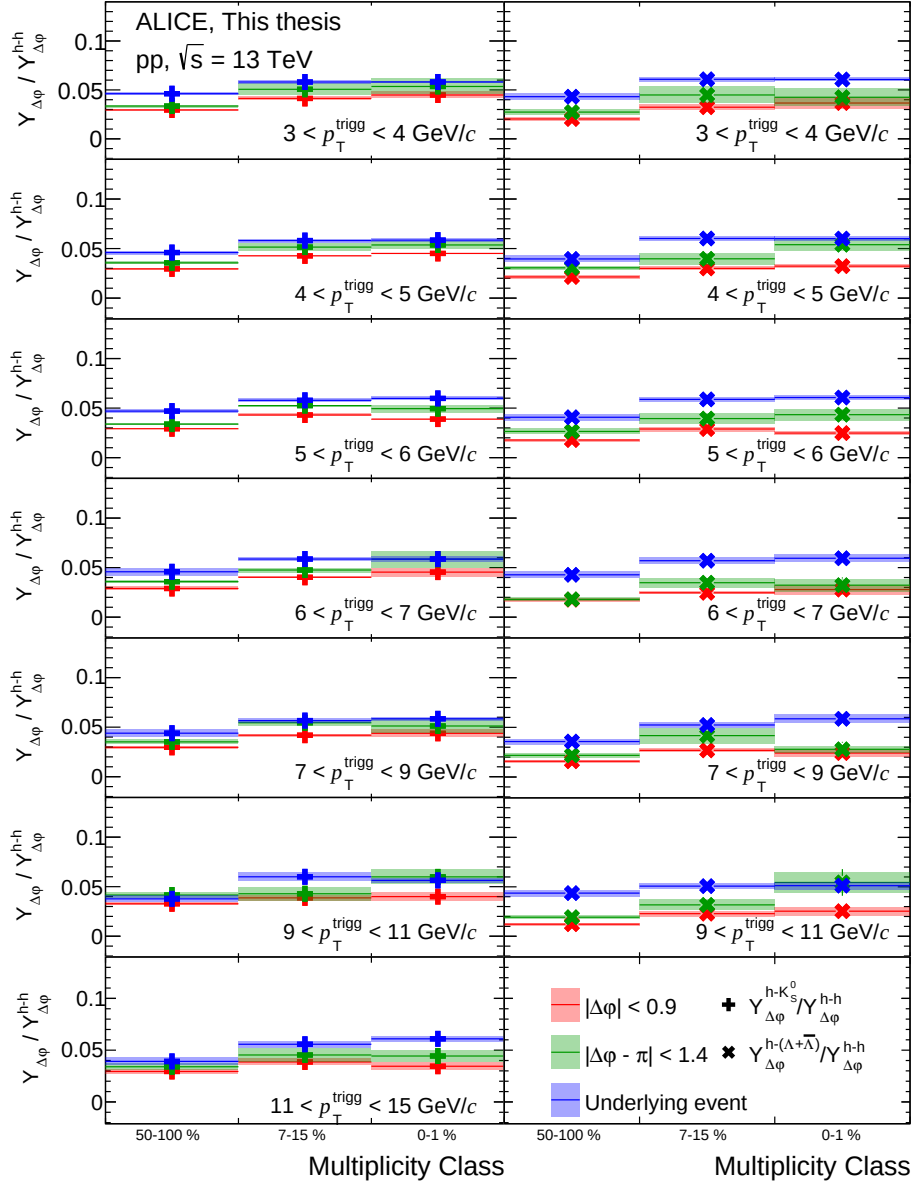


Figure 6.27: Ratios of integrated per-trigger yield of h-K_S⁰ (left column) or h-(Λ + Λ̄) (right column) to h-h as a function of the multiplicity class for the near-, away-side peak and underlying event.

6.7 Baryon to meson ratio

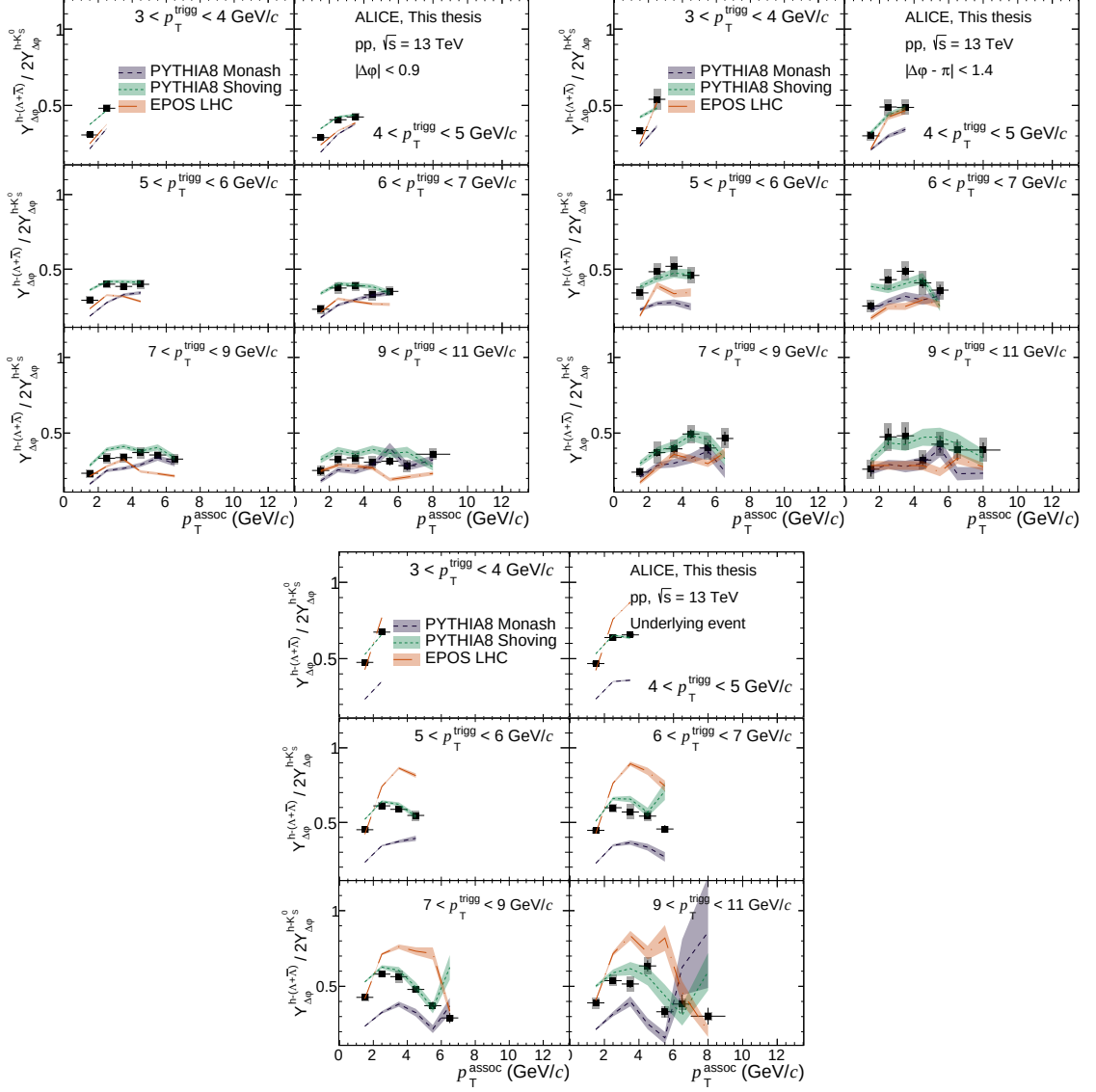


Figure 6.28: $(\Lambda + \bar{\Lambda})$ over $2 K_S^0$ ratio as a function of V^0 p_T for different p_T^{trigg} intervals for the near- (top left), away-side peak (top right) and underlying event (bottom).

In order to study the differences in meson and baryon production, the baryon to meson ratio is commonly calculated. In our case, this is: $Y_{\Delta\phi}^{h-(\Lambda+\bar{\Lambda})}/2Y_{\Delta\phi}^{h-K_S^0}$. These ratios are shown in Fig. 6.28 as a function of p_T of associated particle for near-side and away-side peak and underlying event. The ratios are compared also with MC generator results. All three considered models describe the data quite well for the near- and away-side, but PYTHIA8 with the Shoving model provides the overall best description by fitting

the data also in the underlying event region. In this region, the data are overestimated by the EPOS LHC model and underestimated by the Monash tune of PYTHIA8.

The shape of the ratio evolves with increasing p_T of the trigger particle for the near- and away-side peak, while it stays rather unchanged in the underlying event region. For the near-side peak, the ratio increases with p_T for $p_T^{\text{trigg}} < 5 \text{ GeV}/c$, while it is rather flat for $p_T^{\text{trigg}} > 7 \text{ GeV}/c$. For high p_T of the trigger particle, hard fragmentation dominates, which means higher probability for mesons to be created causing the smaller ratio. The increase for low p_T of the trigger particle suggest that in this p_T region, the soft fragmentation is still dominant with higher probability of the baryon production. In the ratio in the underlying event region, a typical maximum is visible around $3 \text{ GeV}/c$, which is observed also in the inclusive measurement [101].

The comparison with this inclusive measurement from Ref. [101] is shown in Fig. 6.29. One can see that our measurement of the $(\Lambda + \bar{\Lambda})/2K_S^0$ ratio in the underlying event is consistent within the uncertainties with the inclusive measurement, suggesting that the soft baryon production dominates in the unbiased sample. For p_T bigger than $5 \text{ GeV}/c$, the ratio for the near-side peak, underlying event and inclusive sample is consistent, pointing out that in this p_T region, the jet fragmentation is dominant.

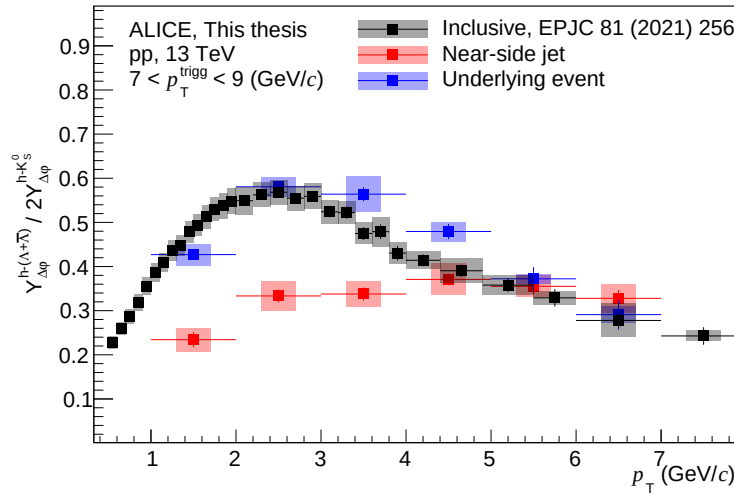


Figure 6.29: $(\Lambda + \bar{\Lambda})$ over $2 K_S^0$ ratio as a function of $V^0 p_T$ for $7 < p_T^{\text{trigg}} < 9 \text{ GeV}/c$ for the near-side peak and underlying event compared with the inclusive measurement [101].

Our measurement of the baryon to meson ratio in and outside of jets with the di-hadron correlation method is compared with the same ratio where the jets are identified with the anti- k_T jet finder algorithm [107]. This measurement is still ongoing within the ALICE collaboration. As is visible from Fig. 6.30, the trends, shape, and difference

between the in jet and the out-off jet region are compatible within the two measurement approaches. It is important to note that the points are not fully compatible with each other. This inconsistency is caused by the different kinematic selection criteria of the V^0 candidates in these two analyses. While in our measurement, the $|y| < 0.5$ selection is used, in the measurement using the jet-finding algorithm, $|\eta| < 0.75$ cut is applied. This difference is causing a selection of more K_S^0 in the jet analysis which decreases the ratio. Nevertheless, the good agreement in the shapes of the ratio shows that the di-hadron correlation approach can be used in Ion–Ion (AA) collisions where usage of the jet-finding algorithms is problematic due to the big amount of particles in the underlying event.

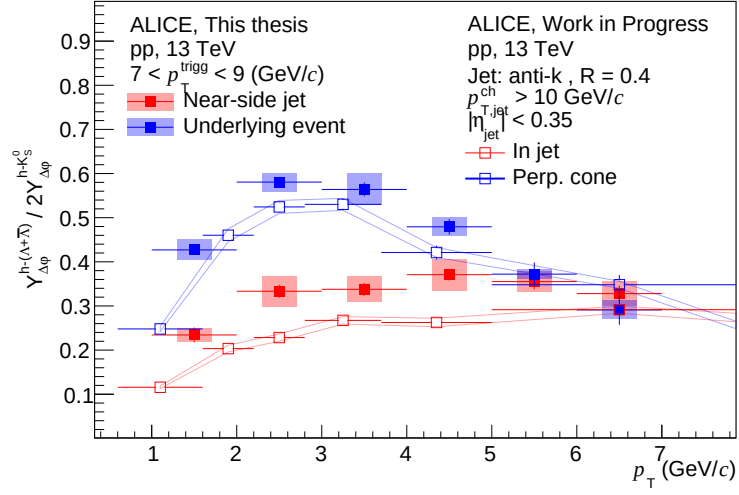


Figure 6.30: $(\Lambda + \bar{\Lambda})$ over $2 K_S^0$ ratio as a function of $V^0 p_T$ for $7 < p_T^{\text{trigg}} < 9$ GeV/c for the near-side peak and underlying event compared with the measurement using jet finding algorithm.

7 Summary

The measurement of the correlation functions triggered with different strange neutral hadrons (V^0) and their yields allows for the study of the differences in the jet fragmentation depending on the original parton. Moreover, the study of yields of different associated particles brings knowledge about the meson and baryon production in and outside of jets.

In this thesis, the first measurements of V^0 -h and h- V^0 correlations in proton–proton (pp) collisions at 13 TeV within the ALICE (A Large Ion Collider Experiment) collaboration are presented. The per-trigger yields are extracted for the near- and away-side peak as well as for the underlying event. These are studied as a function of p_T of trigger and associated particle and event-multiplicity class, compared among the different trigger and associated particle species and with Monte Carlo (MC) generator predictions.

A dependence on the event-multiplicity of the per-trigger yields from all studied correlation functions is observed. On the near-side, it may be explained by an interplay of different fragmentation and collective effects in the terms of the long-range ridge that is not accounted for in the background subtraction. The reverse multiplicity ordering observed on the away-side for h-h and V^0 -h yields is caused by a selection bias, where the away-side jet is within the Triggering and Centrality Detector (V0) detector acceptance causing smaller away-side yields for the high-multiplicity classes. The multiplicity dependence of the underlying event yield is expected, as this is mainly determining the multiplicity class. Nevertheless, it was observed that the soft fragmentation of the underlying event particles is not influenced by the hard process in the event.

In order to overcome the multiplicity bias and compare among the different particle species, the ratios of yields to the ones from h-h correlation function are presented. In the comparison of different trigger particles, a different dependence on the p_T^{trigg} and p_T^{assoc} was found for K_S^0 or Λ ($\bar{\Lambda}$) being the trigger particle. While the $Y_{\Delta\varphi}^{K_S^0-h}/Y_{\Delta\varphi}^{h-h}$ is flat, the $Y_{\Delta\varphi}^{(\Lambda+\bar{\Lambda})-h}/Y_{\Delta\varphi}^{h-h}$ increases with p_T^{trigg} and this difference is mostly pronounced for the softer part (low p_T^{assoc}) of hard processes (high p_T^{trigg}). A PYTHIA8 study of

the respective exclusive processes reveals that the difference is caused by the bias towards gluon jets by triggering with high- p_T Λ or $\bar{\Lambda}$ hyperon due to the higher relative production of Λ baryons in gluon jets [21].

Otherwise, in the case of the h - V^0 correlations, the multiplicity dependence of the ratio to the yields from h - h correlations is in the main interest in order to constrain the contribution from hard and soft processes to the strangeness enhancement observed in the high-multiplicity collisions [52]. Only a hint of an increase of this ratio as a function of event-multiplicity is observed in all studied regions (near-side peak, away-side peak, underlying event). For better conclusions, the 0-0.01% multiplicity class should be included to the study. Nevertheless, the ratio of the underlying event-yields is the highest one, suggesting that the softer processes are contributing the most to the strangeness production.

The $(\Lambda + \bar{\Lambda})/2K_S^0$ ratio is calculated in order to compare the production of baryons and mesons in and outside a jet. The enhancement of the ratio at intermediate p_T , observed in the inclusive measurement [101], is also present in our measurement of the ratio in the underlying event region. This is also consistent within uncertainties with the inclusive measurement. The absence of the maximum in the near-side peak region is suggesting that the enhanced baryon production at intermediate p_T is caused by the parton recombination in the soft particle production processes. At high p_T , the ratio in the inclusive measurement is consistent with the ratio in the near-side region, proving that the production of high- p_T particles is dominated by hard processes (jet fragmentation).

The $(\Lambda + \bar{\Lambda})/2K_S^0$ ratio in and out of jet is compared to the same quantity measured with the help of the anti- k_T jet-finding algorithm. The compatibility of the results is showing that the di-hadron correlation approach can be used to calculate the soft and hard process contribution to the ratio also in Ion-Ion (AA) collisions where the usage of jet-finding algorithms is problematic due to the huge amount of produced particles.

Moreover, all the measured quantities are compared with model predictions revealing that none of the used models, PYTHIA8 with the Monash tune, PYTHIA8 with the Shoving extension and the EPOS LHC, can reproduce all of the presented results. While the Monash tune can reproduce well the primary charged hadron production in the underlying event and the yields in the near-side peak triggered with high- p_T hadrons, it underestimates strongly the Λ and $\bar{\Lambda}$ production in the underlying event. This is improved in the Shoving model at the price of degrading the description of the jet-like yields for

the highest p_T of the trigger particle. EPOS LHC fails in describing the jet-like yields as a function of event-multiplicity.

Overall, a detailed study of the fragmentation patterns has been performed and a part of it has been published in Ref. [106]. Hence, the knowledge about the bias towards gluon jets by triggering with a high- p_T Λ hyperon can be used in AA collisions to study the differences of the quark and gluon energy loss in the Quark–Gluon Plasma (QGP). While higher statistics is needed for more conclusive statement about the jet fragmentation contribution to the strangeness enhancement in high multiplicity pp collisions, the discrepancies between the model predictions and data can serve as an input for an improvement of the models.

8 Zusammenfassung

Die Messung der Korrelationsfunktionen, die mit verschiedenen neutralen Strange-Hadronen (V^0) getriggert werden, und ihrer Yields ermöglicht die Untersuchung der Unterschiede in der Jet-Fragmentierung in Abhängigkeit vom ursprünglichen Parton. Darüber hinaus liefert die Untersuchung der Yields verschiedener assoziierter Teilchen Erkenntnisse über die Mesonen- und Baryonenproduktion in und außerhalb von Jets.

In dieser Arbeit werden die ersten Messungen von V^0 -h und h- V^0 -Korrelationen in pp-Kollisionen bei 13 TeV im Rahmen der ALICE-Kollaboration vorgestellt. Die per-trigger Yields werden sowohl für den Near-side und Away-side Peak als auch für das zugrunde liegende Ereignis extrahiert. Diese werden als Funktion des p_T des Trigger- und des assoziierten Teilchens sowie der Ereignismultiplizitätsklasse untersucht und mit den verschiedenen Trigger- und assoziierten Teilchenspezies sowie mit den Vorhersagen der MC-Ereignisgeneratoren verglichen.

Bei allen untersuchten Korrelationsfunktionen wird eine Abhängigkeit der Yields pro Triggerteilchen von der Ereignismultiplizitätsklasse beobachtet. Auf der Near-Seite kann sie durch ein Zusammenspiel verschiedener Fragmentierungs- und kollektiver Effekte in Bezug auf die langreichweite Gipfelstruktur erklärt werden, die bei der Hintergrundsubtraktion nicht berücksichtigt wird. Die auf der Away-Seite beobachtete umgekehrte Multiplizitätsordnung für h-h- und V^0 -h Yields ist auf eine Selektionsverzerrung zurückzuführen, bei der der Jet auf der Away-Seite innerhalb der V0-Detektorakzeptanz liegt, was zu kleineren Yields auf der Away-Seite für die Klassen mit hoher Multiplizität führt. Die Abhängigkeit der zugrundeliegenden Yields von der Multiplizität ist zu erwarten, da diese hauptsächlich die Multiplizitätsklasse bestimmt. Es wurde jedoch beobachtet, dass die weiche Fragmentierung der zugrundeliegenden Ereignisteilchen nicht durch den harten Prozess im Ereignis beeinflusst wird.

Um den Multiplizitätsbias zu überwinden und die verschiedenen Teilchenspezies zu vergleichen, werden die Verhältnisse der Yields zu denen der h-h-Korrelationsfunktion dargestellt. Beim Vergleich verschiedener Triggerteilchen wurden unterschiedliche Abhängigkeiten von p_T^{trigg} und p_T^{assoc} für K_S^0 oder Λ ($\bar{\Lambda}$) als Triggerteilchen festgestellt.

Während der $Y_{\Delta\varphi}^{K_S^0-h}/Y_{\Delta\varphi}^{h-h}$ flach ist, nimmt der $Y_{\Delta\varphi}^{(\Lambda+\bar{\Lambda})-h}/Y_{\Delta\varphi}^{h-h}$ mit p_T^{trigg} zu, und dieser Unterschied ist für den weichen Teil (niedriges p_T^{assoc}) von harten Prozessen (hohes p_T^{trigg}) am stärksten ausgeprägt. Eine PYTHIA8-Untersuchung der jeweiligen exklusiven Prozesse zeigt, dass der Unterschied durch die Verzerrung in Richtung Gluonenjets durch das Triggern mit hoch- p_T Λ oder $\bar{\Lambda}$ -Hyperon aufgrund der höheren relativen Produktion von Λ -Baryonen in Gluonenjets [21] verursacht wird.

Im Falle der h - V^0 -Korrelationen ist die Multiplizitätsabhängigkeit des Verhältnisses zu den Yields aus h - h -Korrelationen von größtem Interesse, um den Beitrag harter und weicher Prozesse zur Strangeness-Erhöhung, die bei Kollisionen mit hoher Multiplizität beobachtet wird, einzugrenzen. In allen untersuchten Regionen (Near-side Peak, Away-side Peak, zugrunde liegendes Ereignis) wird nur ein Hinweis auf einen Anstieg dieses Verhältnisses in Abhängigkeit von der Multiplizität beobachtet. Für bessere Schlussfolgerungen sollte die 0-0,01%-Multiplizitätsklasse in die Untersuchung einbezogen werden. Nichtsdestotrotz ist das Verhältnis der Yields aus dem zugrundeliegenden Ereignis am höchsten, was darauf hindeutet, dass die weichen Prozesse den größten Beitrag zur Strangeness-Produktion leisten.

Für den Vergleich der Baryonen- und Mesonenproduktion innerhalb und außerhalb eines Jets wird das $(\Lambda + \bar{\Lambda})/2K_S^0$ -Verhältnis berechnet. Die bei der inklusiven Messung beobachtete Erhöhung des Verhältnisses bei mittlerem p_T ist auch bei unserer Messung des Verhältnisses in der zugrunde liegenden Ereignisregion vorhanden. Dies ist ebenfalls innerhalb der Unsicherheiten mit der inklusiven Messung konsistent. Das Fehlen des Maximums im Bereich des Near-side Peaks deutet darauf hin, dass die verstärkte Baryonenproduktion bei mittlerem p_T durch die Partonenrekombination bei der Produktion weicher Teilchen verursacht wird. Bei hohem p_T stimmt das Verhältnis in der inklusiven Messung mit dem Verhältnis im Near-side Bereich überein, was beweist, dass die Produktion von Teilchen bei hohem p_T von harten Prozessen (Jet-Fragmentierung) dominiert wird.

Das $(\Lambda + \bar{\Lambda})/2K_S^0$ -Verhältnis innerhalb und außerhalb des Jets wurde mit der gleichen Größe verglichen, die mit Hilfe des Jet-Finding-Algorithmus gemessen wurde. Die Kompatibilität der Ergebnisse zeigt, dass die Di-Hadron-Korrelationsmethode verwendet werden kann, um den Beitrag weicher und harter Prozesse zum Verhältnis auch bei AA-Kollisionen zu berechnen, bei denen die Verwendung von Jet-Finding-Algorithmen aufgrund der riesigen Menge an produzierten Teilchen problematisch ist.

Darüber hinaus werden alle gemessenen Größen mit Modellvorhersagen verglichen. Dabei zeigt sich, dass keines der verwendeten Modelle - PYTHIA8 mit dem Monash-Tune,

PYTHIA8 mit der Shoving-Erweiterung und EPOS LHC - alle vorgestellten Ergebnisse reproduzieren kann. Während die Monash-Einstellung die primäre Produktion geladener Hadronen im zugrundeliegenden Ereignis und die Yields im Near-side Peak, der durch die Hadronen mit hohem p_T getriggert wird, gut wiedergeben kann, unterschätzt sie die Λ - und $\bar{\Lambda}$ -Produktion im zugrundeliegenden Ereignis stark. Dies wird im Shoving-Modell um den Preis einer Verschlechterung der Beschreibung der jet-like Yields für den höchsten p_T des Triggerteilchens verbessert. EPOS LHC versagt bei der Beschreibung der jet-like Yields als Funktion der Ereignismultiplizität.

Insgesamt wurde eine detaillierte Studie der Fragmentierungsmuster durchgeführt, von der ein Teil in Ref. [106] veröffentlicht wurde. Daher kann das Wissen über die Bevorzugung der Gluonenjets durch das Triggern mit einem Λ -Hyperon mit hohem Transversalimpuls in AA-Kollisionen genutzt werden, um die Unterschiede zwischen dem Quark- und Gluonenenergieverlust im QGP zu untersuchen. Während für eine schlüssigere Aussage über den Beitrag der Jet-Fragmentierung zur Strangeness-Erhöhung in pp-Kollisionen mit hoher Multiplizität eine höhere Statistik erforderlich ist, können die Diskrepanzen zwischen den Modellvorhersagen und den Daten als Anregung für eine Verbesserung der Modelle dienen.

Appendices

A Consistency checks

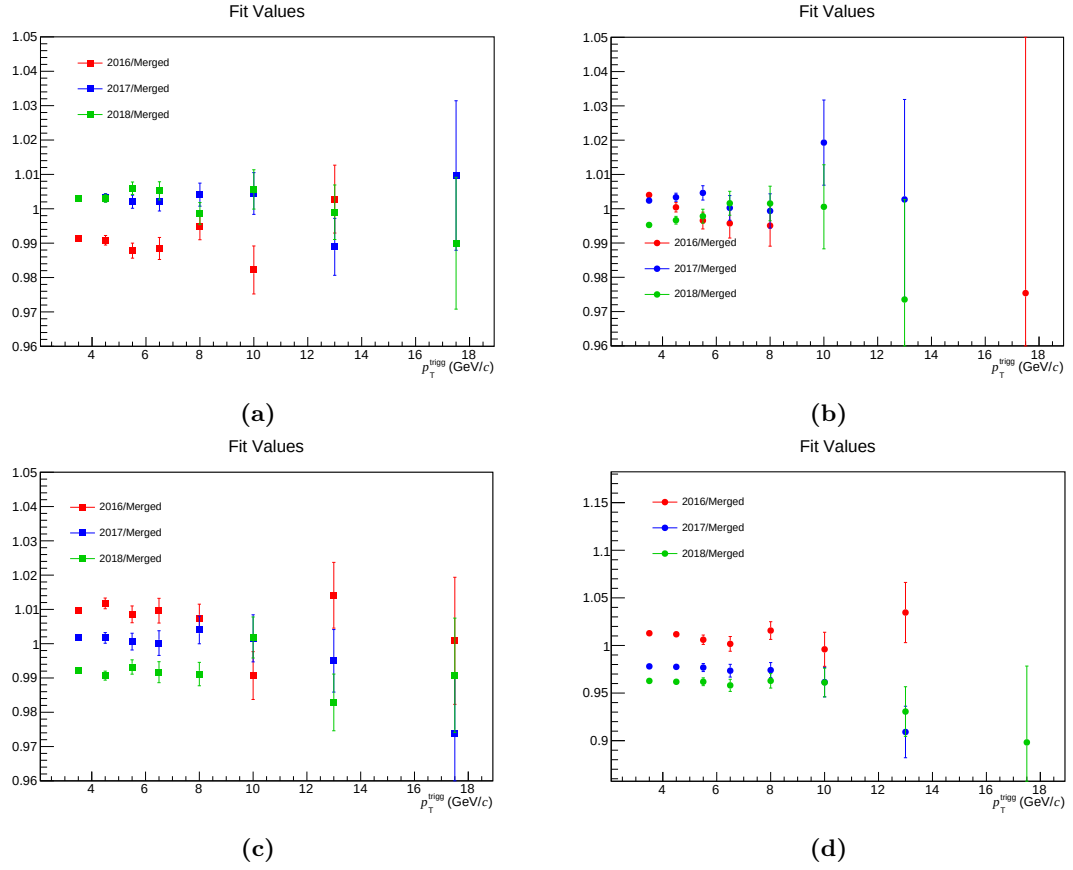


Figure A.1: The fit values of the ratio of the $\Delta\varphi$ projections from different data-taking years over the merged sample for different trigger and associated particles, K_S^0 (a), $(\Lambda + \bar{\Lambda})$ (b), $h\text{-}K_S^0$ (c) and $h\text{-}(\Lambda + \bar{\Lambda})$ (d), as a function of p_T^{trigg} .

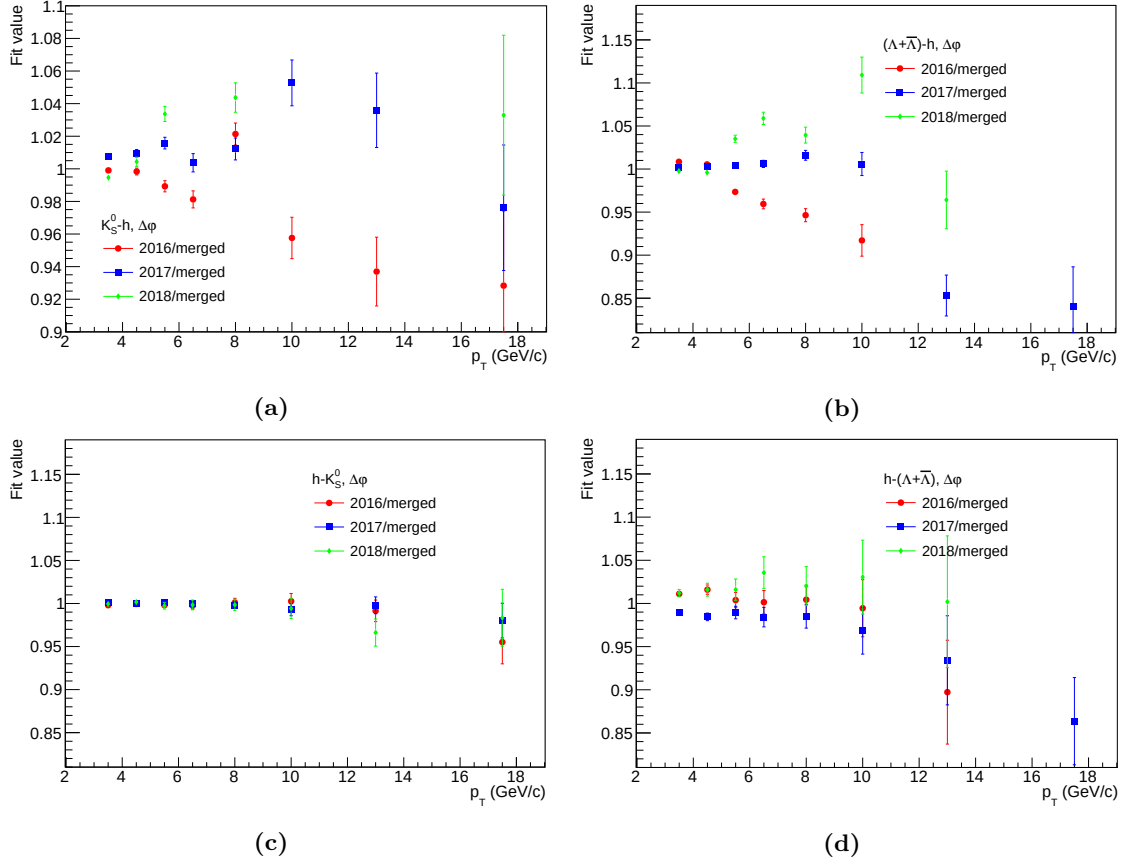


Figure A.2: The fit values of the ratio of the $\Delta\phi$ projections from MC anchored to different data-taking years over the merged sample for different trigger and associated particles, K_S^0 (a), $(\Lambda + \bar{\Lambda})$ (b), h- K_S^0 (c) and h- $(\Lambda + \bar{\Lambda})$ (d), as a function of p_T^{trigg} .

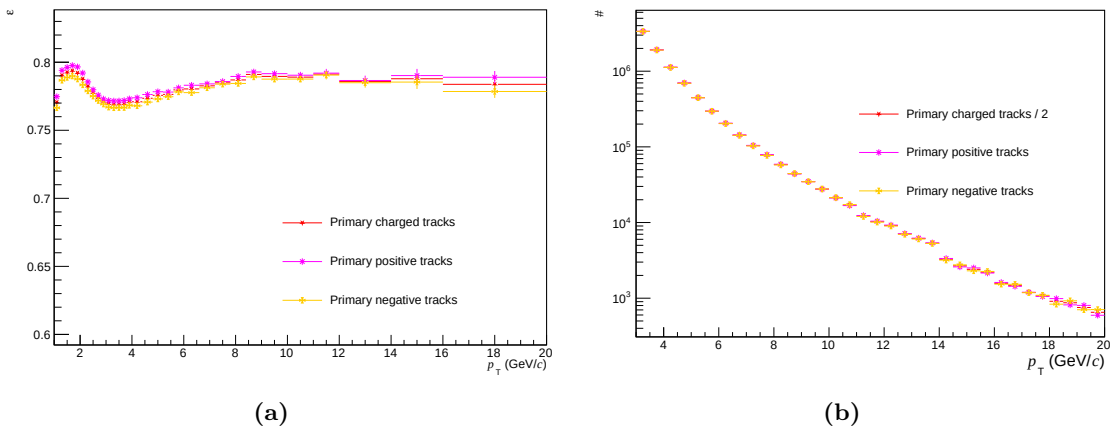


Figure A.3: (a) Efficiency of all primary charged particles compared with the one of positive and negative sample. (b) Number of primary charged hadrons divided by 2 compared with number of positive respectively negative charged hadrons.

B MC closure test as a function of p_T^{assoc}

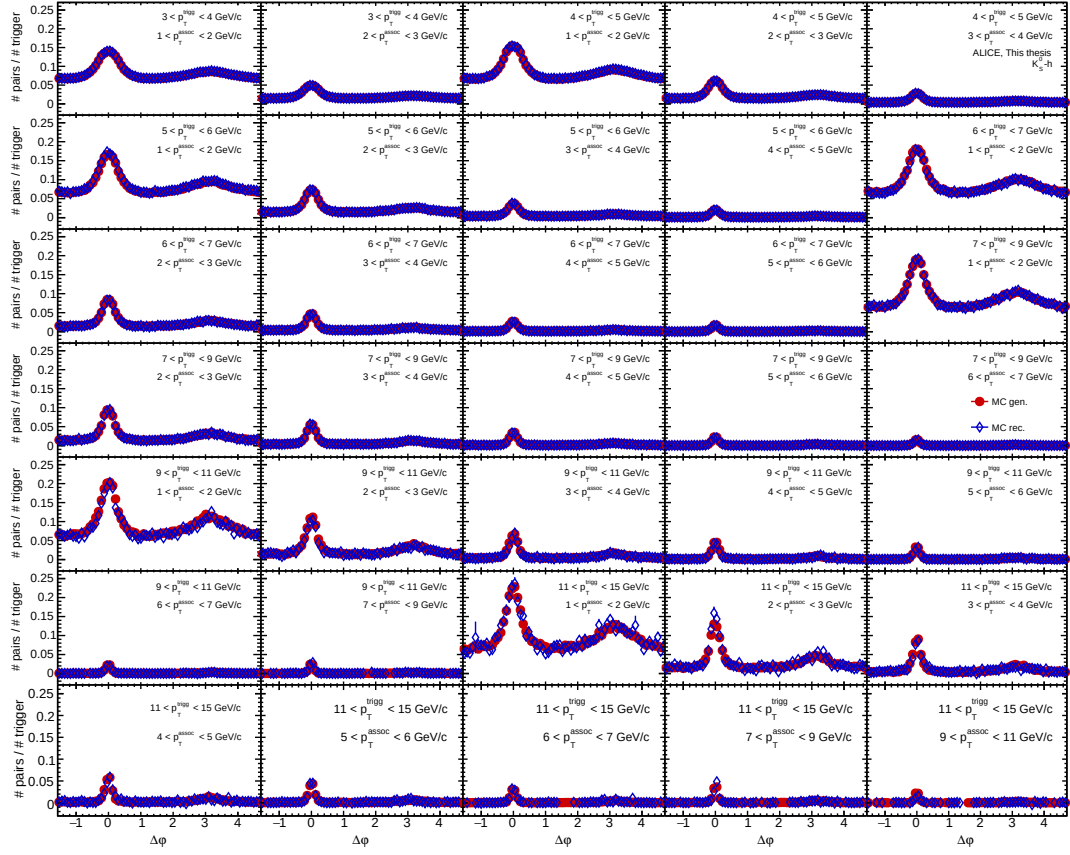


Figure B.1: Comparison of generated correlation function (full red markers) and MC reconstructed correlation function (open blue markers) for the K_S^0 -h combination as a function of $\Delta\phi$ for different p_T^{trig} and p_T^{assoc} intervals.

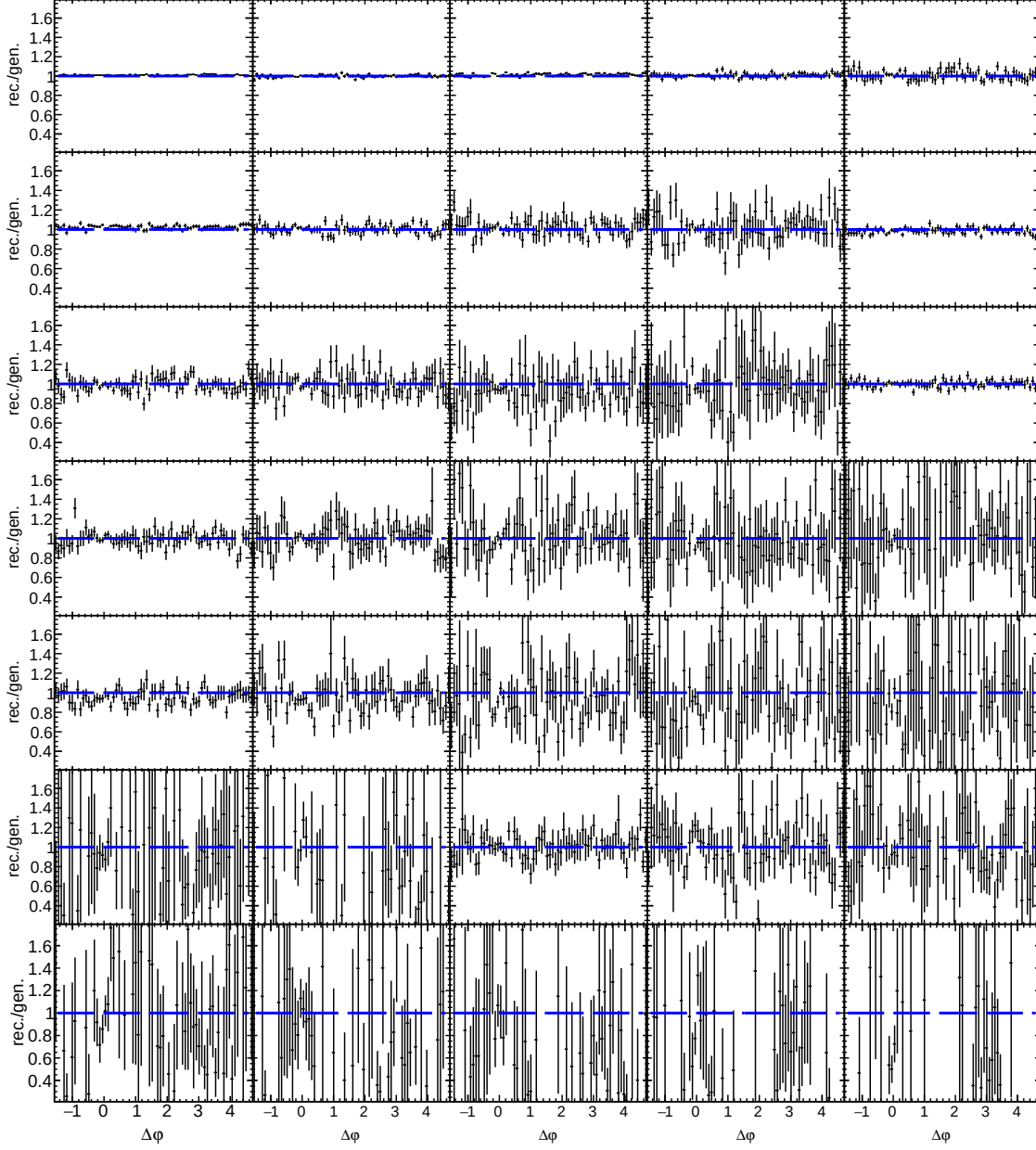


Figure B.2: Ratio of the reconstructed over generated K_S^0 -h correlation function as a function of $\Delta\varphi$ for the same p_T^{trigg} and p_T^{assoc} intervals as in previous Figure plotted with constant function (blue line) at unity.

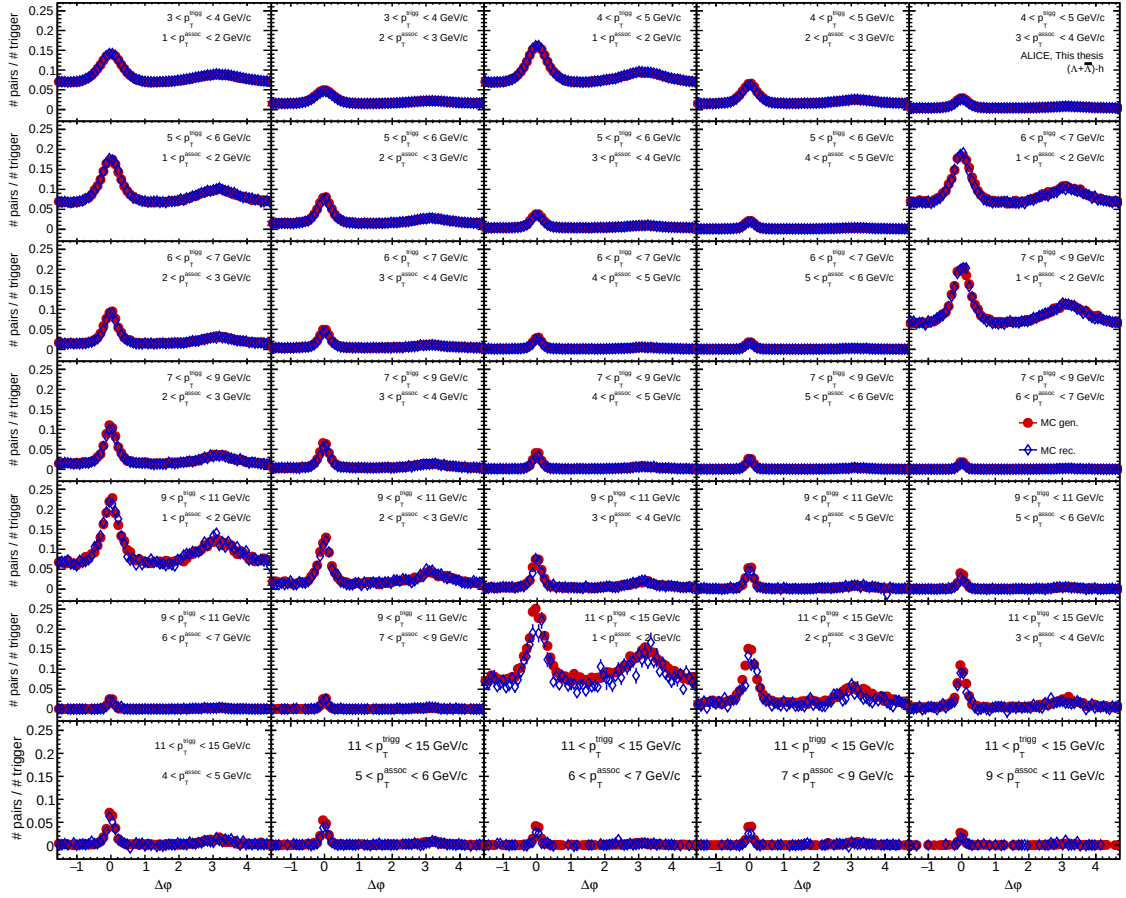


Figure B.3: Comparison of generated correlation function (full red markers) and MC reconstructed correlation function (open blue markers) for the $(\Lambda+\Lambda)$ -h combination as a function of $\Delta\varphi$ for different p_T^{trigg} and p_T^{assoc} intervals.

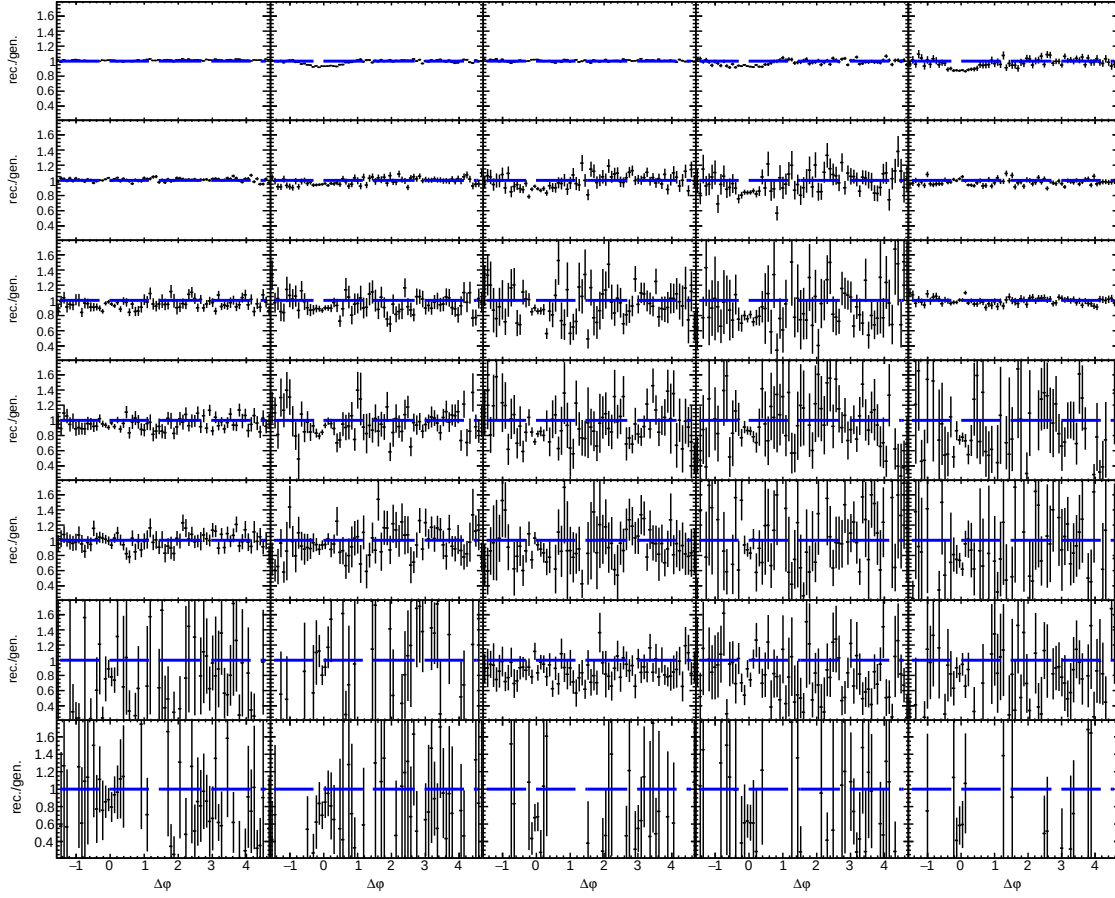


Figure B.4: Ratio of the reconstructed over generated $(\Lambda+\bar{\Lambda})$ -h correlation function as a function of $\Delta\varphi$ for the same p_T^{trigg} and p_T^{assoc} intervals as in previous Figure plotted with constant function (blue line) at unity.

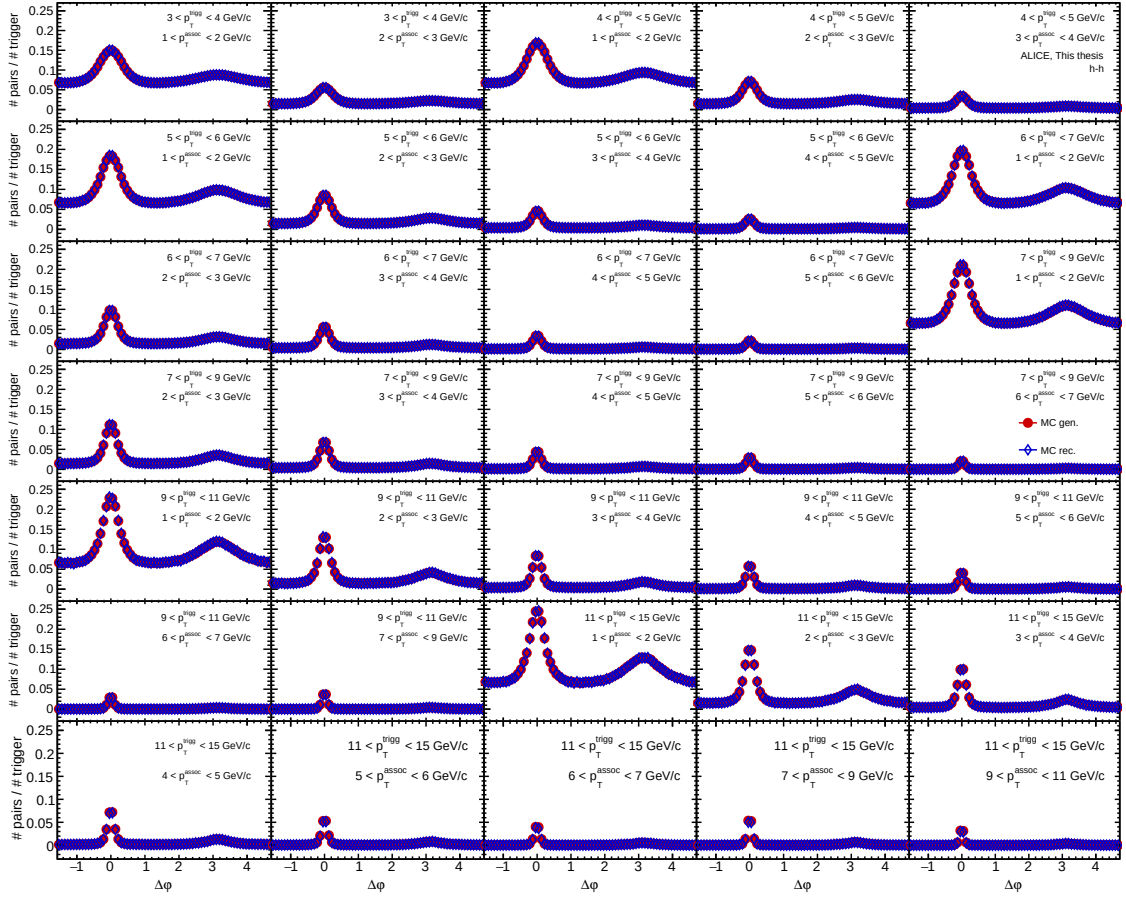


Figure B.5: Comparison of generated correlation function (full red markers) and MC reconstructed correlation function (open blue markers) for the h-h combination as a function of $\Delta\varphi$ for different p_T^{trigg} and p_T^{assoc} intervals.

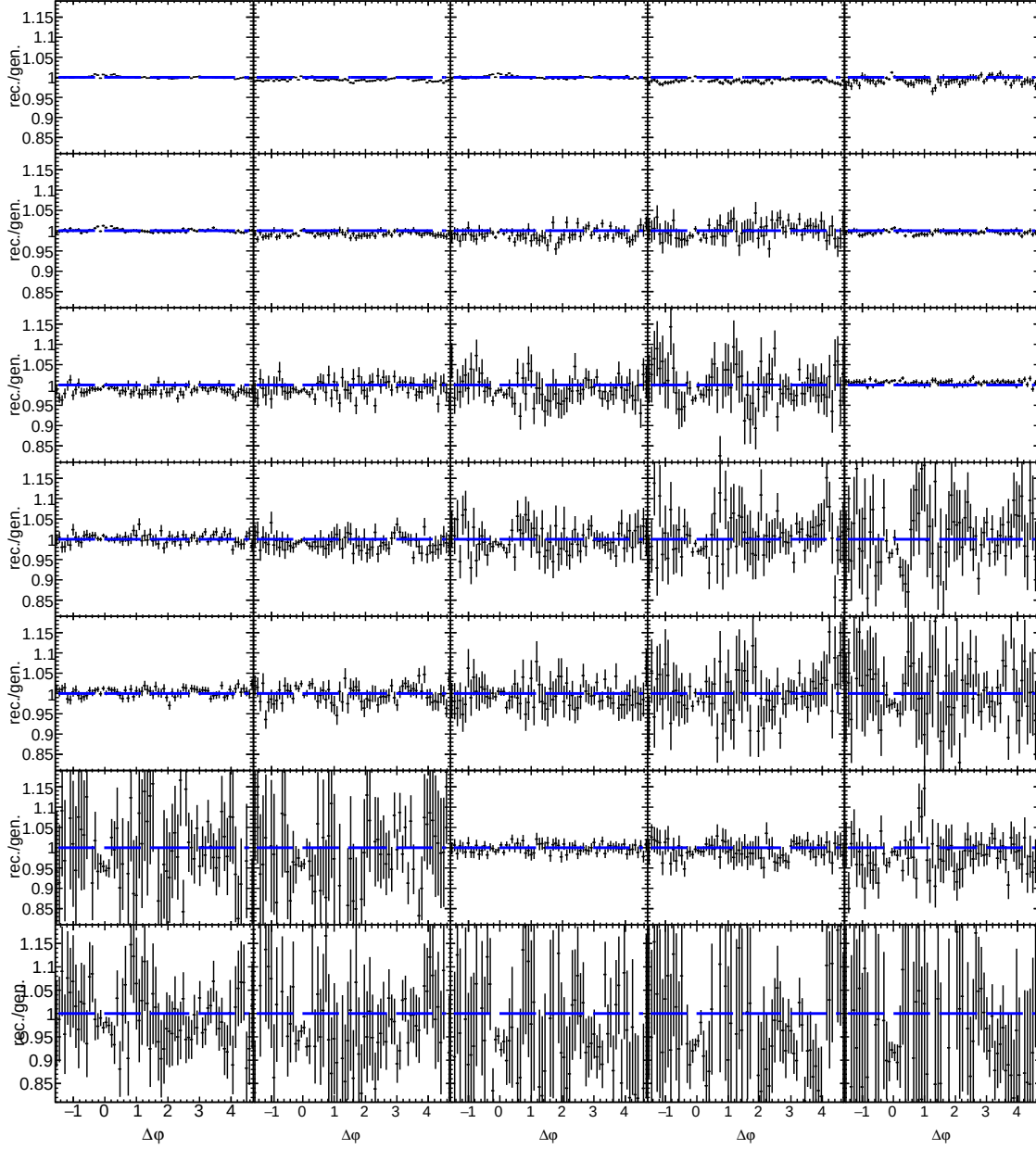


Figure B.6: Ratio of the reconstructed over generated h-h correlation function as a function of $\Delta\phi$ for the same p_T^{trigg} and p_T^{assoc} intervals as in previous Figure plotted with constant function (blue line) at unity.

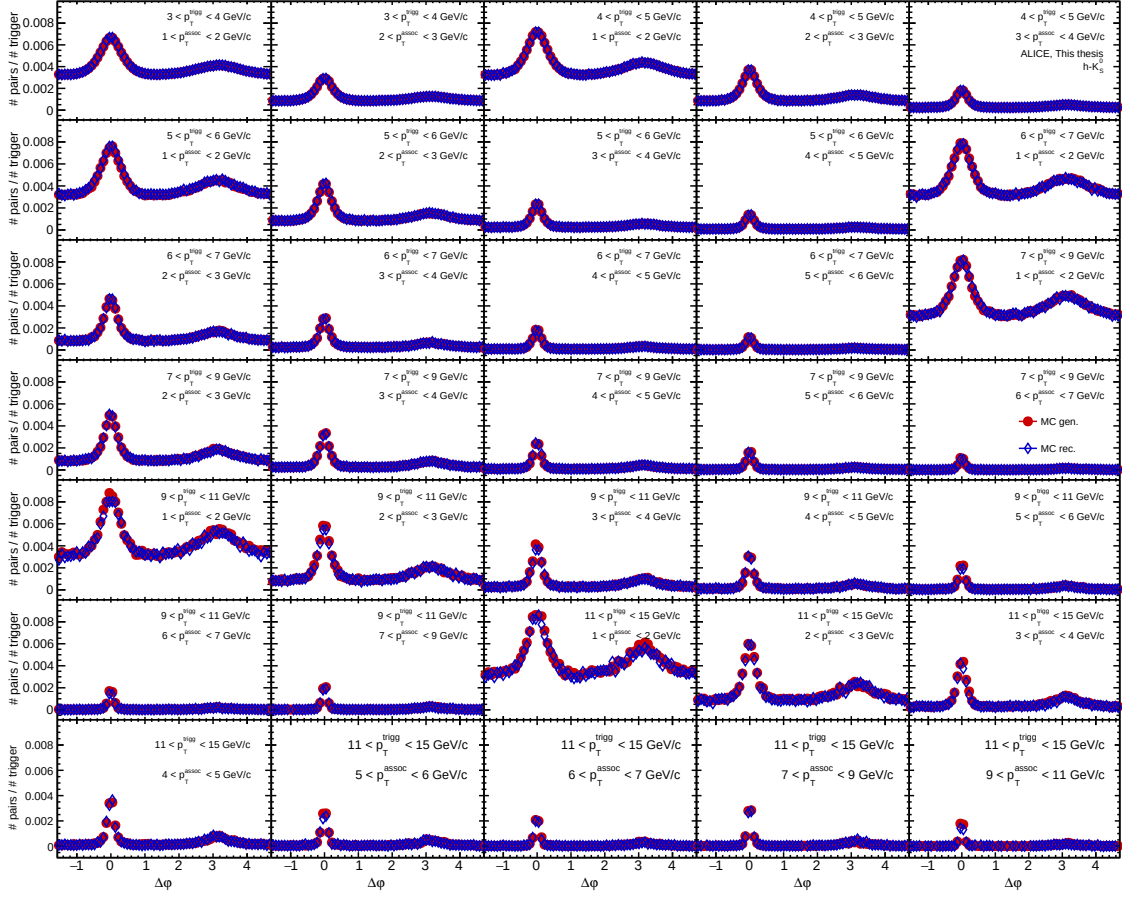


Figure B.7: Comparison of generated correlation function (full red markers) and MC reconstructed correlation function (open blue markers) for the h-K_S⁰ combination as a function of $\Delta\phi$ for different p_T^{trigg} and p_T^{assoc} intervals.

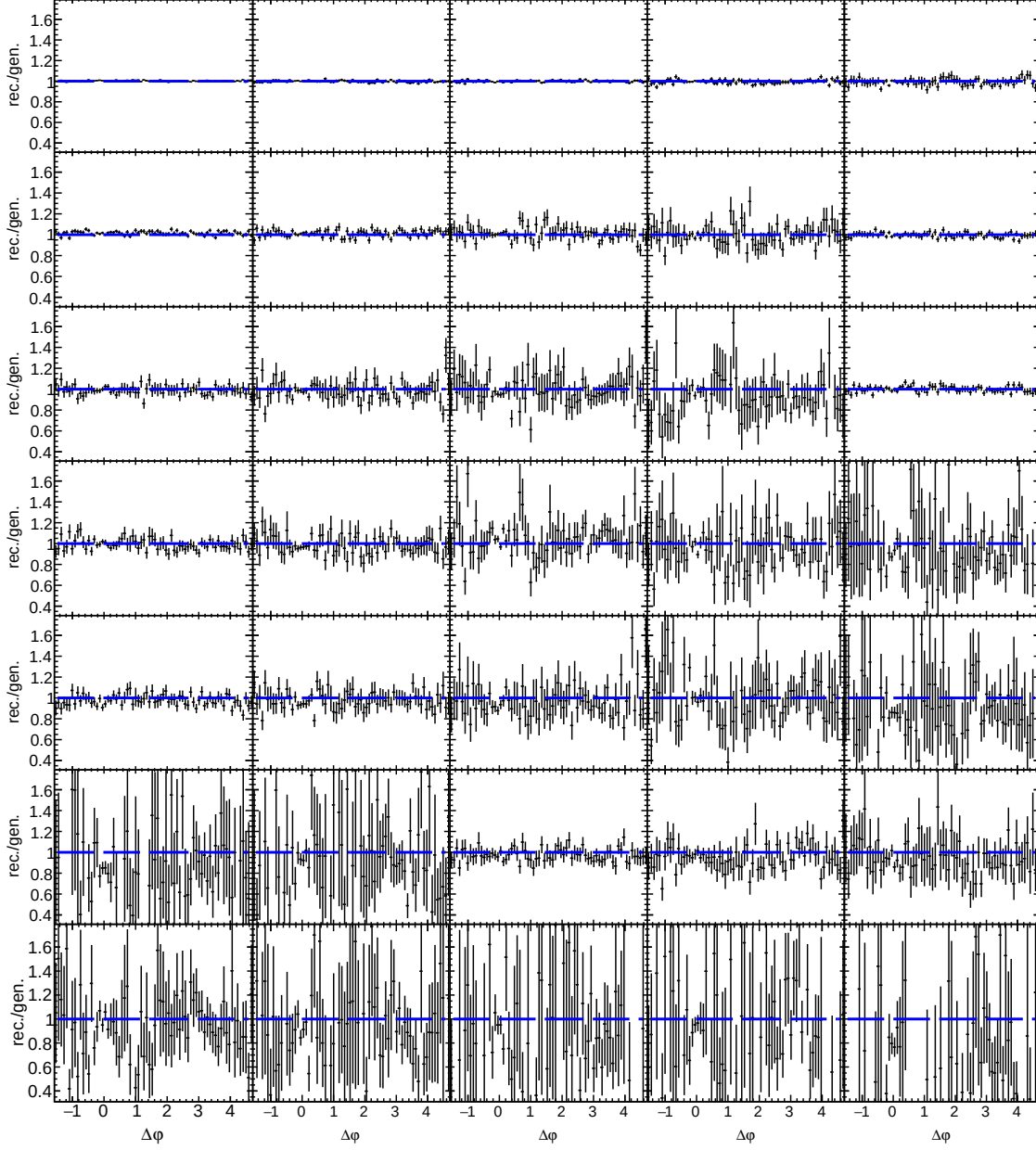


Figure B.8: Ratio of the reconstructed over generated h - K_S^0 correlation function as a function of $\Delta\phi$ for the same p_T^{trigg} and p_T^{assoc} intervals as in previous Figure plotted with constant function (blue line) at unity.

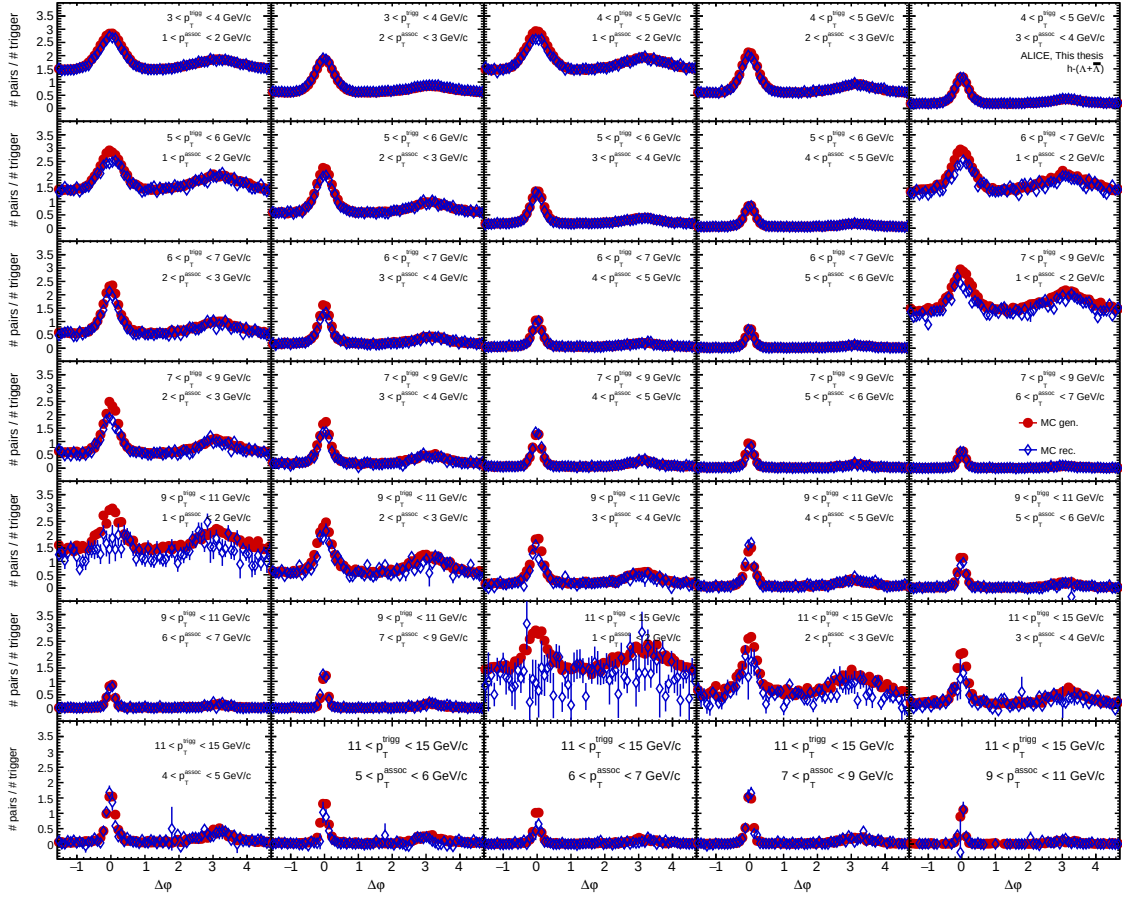


Figure B.9: Comparison of generated correlation function (full red markers) and MC reconstructed correlation function (open blue markers) for the h-($\Lambda+\bar{\Lambda}$) combination as a function of $\Delta\phi$ for different p_T^{trigg} and p_T^{assoc} intervals. The y-axis is multiplied by 10^{-3} .

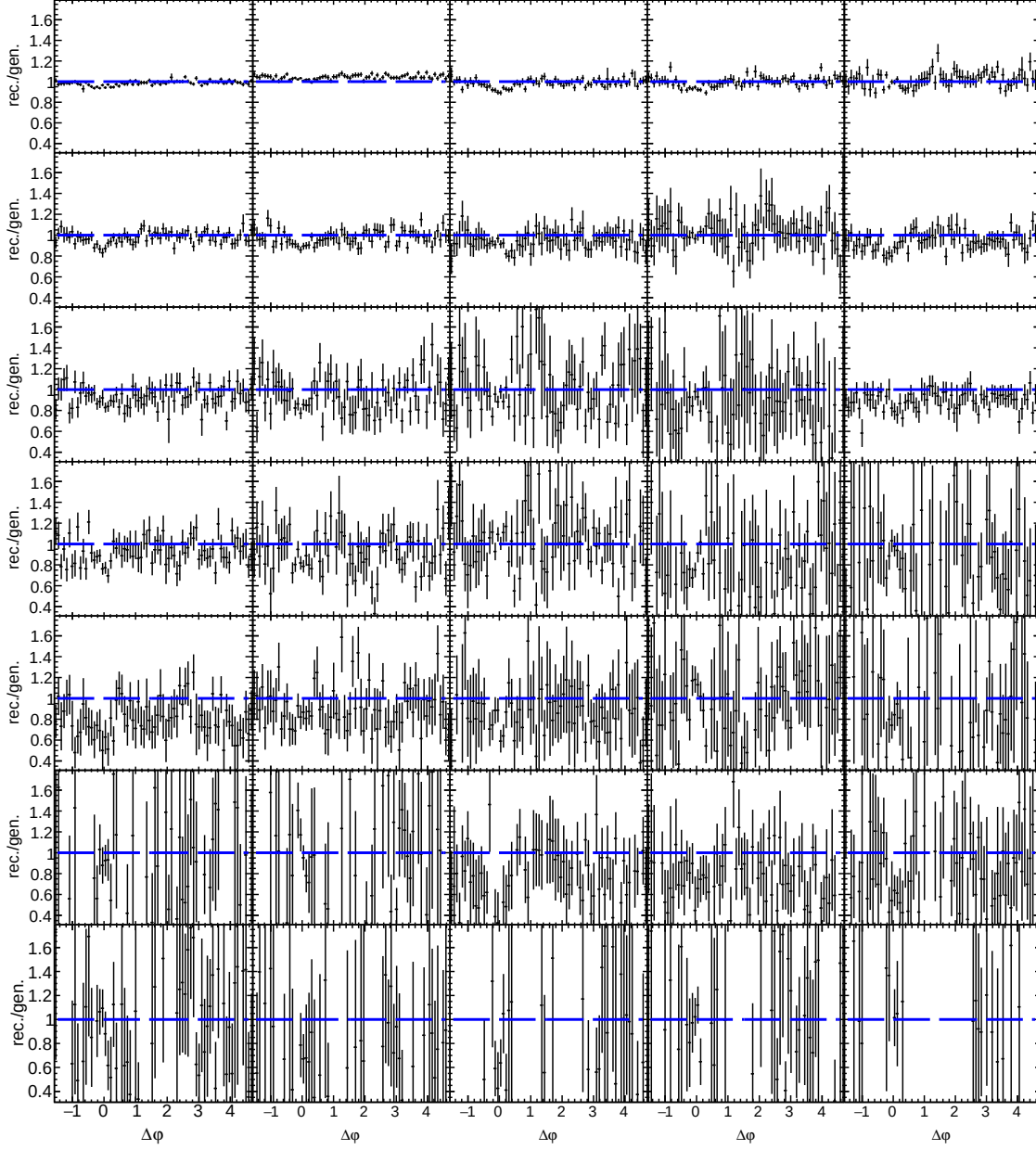


Figure B.10: Ratio of the reconstructed over generated $h-(\Lambda + \bar{\Lambda})$ correlation function as a function of $\Delta\varphi$ for the same p_T^{trigg} and p_T^{assoc} intervals as in previous Figure plotted with constant function (blue line) at unity.

C Systematic uncertainty

Table C.1: The minimal and maximal value of systematic uncertainty expressed in % for each source for the near side yield for multiplicity differential analysis. The abbreviation negl. stands for negligible and rej. for rejected based on the Barlow test. – means that this source does not contribute to the total uncertainty in that case.

Source	h-h	K_S^0 -h	$(\Lambda + \bar{\Lambda})$ -h	h- K_S^0	h- $(\Lambda + \bar{\Lambda})$
Mixing scale	negl.	0.7–1.5	0.2–0.4	0.5–3.8	<3.4
Pedestal subtraction	≈ 0.6	≈ 2	≈ 1.8	<3.1	1–7.5
$\Delta\varphi$ window	≈ 0.4	0.4–2	0.4–2	0.5–3.2	1–8
Primary track selection	<0.7	0.9–2.4	1.3–3.9	rej.	4–10
PV along the z-axis (z_{vtx})	<0.3	0.7–2.3	0.7–2.7	0.3–4.3	0.8–9
Binning in z_{vtx}	<0.5	0.5–2.7	0.4–1.5	0.5–5.6	1.4–7.2
$\Delta\eta$ range	0.3–0.9	0.6–1.9	0.4–2.4	0.8–5.2	1.5–12
Yield calculation	≈ 1	1.1	0.3–0.8	<3.1	1–6
Topological variables	–	1.5–5.8	2.2–7.5	1–8.1	1.2–16
Invariant mass range	–	rej.	0.5–3.9	0.4–7.2	1–10
Wing correction	1.2	–	0.7	–	–
Ξ topological variables	–	–	0.2–4	–	1–8.8
MC closure	negl.	negl.	2.5	negl.	4
Total	1–6.5	3.5–7.2	4.2–9.9	3–7	6.5–21

Table C.2: The minimal and maximal value of systematic uncertainty expressed in % for each source for the away-side yield for multiplicity differential analysis. The abbreviation negl. stands for negligible and rej. for rejected based on the Barlow test. – means that this source does not contribute to the total uncertainty in that case..

Source	K_S^0 -h	$(\Lambda + \bar{\Lambda})$ -h	h-h	h- K_S^0	h- $(\Lambda + \bar{\Lambda})$
Mixing scale	0.9-2	0.2-0.5	negl.	<4.1	1-9
Pedestal subtraction	≈ 2.2	≈ 4.5	≈ 1.5	0.5-6	2.5-18
$\Delta\varphi$ window	0.4-2	0.4-2	≈ 0.4	0.8-6.1	1.5-10
Primary track selection	1.3-3.9	0.2-3.1	<0.7	rej.	5.5-11
PV along the z-axis (z_{vtx})	1.7-4.5	0.7-4.9	<0.3	0.8-5.9	2-15
Binning in z_{vtx}	1.2-5.2	0.8-2.8	<0.5	0.3-6	5-12.5
Yield calculation	≈ 0.7	0.2-3.4	<0.2	0.2-6.7	1-13
Topological variables	2.2-7.5	2-5.5	–	1.4-10.7	2-20
Invariant mass range	rej.	1.1-4.3	–	1.2-7.1	2.5-13
Wing correction	–	≈ 0.8	≈ 1.8	–	–
Ξ topological variables	–	0.2-3.9	–	–	2.5-15
Total	4.5-13.2	6.8-12.6	0.5-4.5	4-14	10-33

Table C.3: The minimal and maximal value of systematic uncertainty expressed in % for each source for the underlying event yield for multiplicity differential analysis. The abbreviation negl. stands for negligible and rej. for rejected based on the Barlow test. – means that this source does not contribute to the total uncertainty in that case.

Source	h-h	h- K_S^0	h- $(\Lambda + \bar{\Lambda})$
Mixing scale	<2	<3.5	<2.3
Pedestal subtraction	<2.1	<2.5	0.2-5.4
Primary track selection	<2.2	rej.	1-6.4
PV along the z-axis (z_{vtx})	<0.5	0.2-4.5	<2.5
Binning in z_{vtx}	<1.5	0.2-7.5	1-8
Topological variables	–	0.6-4.6	1.5-12
Invariant mass range	–	0.5-6	0.5-7
Wing correction	<2.2	–	–
Ξ topological variables	–	–	0.8-5.5
Total	0.5-3.4	1-9	2-14

Table C.4: The minimal and maximal value of systematic uncertainty expressed in % for each source for the near-side yield ratio to Minimum-Bias (MB). The abbreviation negl. stands for negligible and rej. for rejected based on the Barlow test. – means that this source does not contribute to the total uncertainty in that case.

Source	K_S^0 -h	$(\Lambda + \bar{\Lambda})$ -h	h-h	h- K_S^0	h- $(\Lambda + \bar{\Lambda})$
Mixing scale	0.6-1.2	≈ 3.5	negl.	< 2.5	< 2.2
Pedestal subtraction	0.7-2.1	0.8-2.3	negl.	0.5-4.5	0.5-7.2
$\Delta\varphi$ window	0.6-1.2	negl.	0.4-1.4	< 3	0.3-8
Primary track selection	0.6-1.1	0.5-3.1	negl.	rej.	2.5-9.4
PV along the z-axis (z_{vtx})	0.7-1.9	0.7-1.9	negl.	0.1-3.5	0.4-5.4
Binning in z_{vtx}	0.7-1	0.5-2.3	negl.	0.5-4.5	2-8.4
$\Delta\eta$ range	0.9-2	0.8-2.7	0.5-1.9	0.5-6	0.5-11
Yield calculation	0.5-1.2	negl.	0.5-2.5	< 2.5	0.4-8.5
Topological variables	2-4.5	1.5-4.6	–	0.5-5.9	1-14
Invariant mass range	rej.	1.1-3.2	–	1-7	1-10.5
Wing correction	–	negl.	≈ 0.4	–	–
Ξ topological variables	-	0.2-2.1	–	–	0.9-8.1
Total	2.7-6	3.2-8.6	1.2-3.5	1-11.5	6-22

Table C.5: The minimal and maximal value of systematic uncertainty expressed in % for each source for the away-side yield ratio to MB. The abbreviation negl. stands for negligible and rej. for rejected based on the Barlow test. – means that this source does not contribute to the total uncertainty in that case.

Source	K_S^0 -h	$(\Lambda + \bar{\Lambda})$ -h	h-h	h- K_S^0	h- $(\Lambda + \bar{\Lambda})$
Mixing scale	0.4-3.4	0.2-4.6	< 1	< 2	< 4
Pedestal subtraction	0.9-3.4	2.1-4.8	< 1.3	0.5-7	2-15
$\Delta\varphi$ window	0.6-2	0.2-1.5	0.6-4.4	0.2-4	0.35-9.8
Primary track selection	0.5-3.8	0.5-3.5	< 1.1	rej.	8.2-15.8
PV along the z-axis (z_{vtx})	1.7-3	1.1-4.4	< 1.4	0.5-4.7	0.8-7.6
Binning in z_{vtx}	0.8-3.5	1.5-4.2	< 1	0.4-6.8	1-12
Yield calculation	< 1	0.2-1.8	1.1-4.1	< 3.5	2-14
Topological variables	1.2-5.5	1.9-5.3	–	1-9	4-13
Invariant mass range	rej.	1.4-4.7	–	1-8	1-12
Wing correction	–	≈ 0.6	0.4-1.8	–	–
Ξ topological variables	-	0.26-1.7	–	–	1-10
Total	3.8-9	6-10.9	1.8-6.4	2.5-16	10-30

Table C.6: The minimal and maximal value of systematic uncertainty expressed in % for each source for the underlying event yield ratio to MB. The abbreviation negl. stands for negligible and rej. for rejected based on the Barlow test. – means that this source does not contribute to the total uncertainty in that case.

Source	h-h	h-K _S ⁰	h-(Λ + $\bar{\Lambda}$)
Mixing scale	<1.9	<1.8	<3
Pedestal subtraction	<4	<3	0.2-5.5
Primary track selection	<1.8	rej.	1.5-8
PV along the z-axis (z_{vtx})	negl.	<2	<4
Binning in z_{vtx}	<1.6	0.2-5	1-7.5
Topological variables	–	<3	0.2-6.4
Invariant mass range	–	<4.1	0.1-8
Wing correction	negl.	–	–
Ξ topological variables	–	–	<3.8
Total	0.1-2.1	0.5-5.5	1.5-12

Table C.7: The minimal and maximal values of systematic uncertainty expressed in % for each source for V⁰-h /h-h yield ratio as a function of p_T^{trigg} for the near-, away-side and underlying event covering all multiplicity classes. The abbreviation negl. stands for negligible and rej. for rejected based on the Barlow test. – means that this source does not contribute to the total uncertainty in that case.

Source	K _S ⁰ -h / h-h		(Λ + $\bar{\Lambda}$)-h / h-h	
	near-side	away-side	near-side	away-side
Mixing scale	0.8-1.9	1.5-4.3	<2.3	0.3-2.4
Pedestal subtraction	negl.	0.6-4.9	0.8-1.7	1.2-4.9
Δφ window	negl.	negl.	negl.	negl.
Primary track selection	0.7-2.8	1.6-4.2	0.5-3.5	0.2-3.8
PV along the z-axis (z_{vtx})	0.7-2.7	1.9-5.6	0.8-2.6	0.9-2.5
Binning in z_{vtx}	0.6-2.4	1.4-5.6	0.5-1.4	0.6-2.7
Δη range	0.4-2.2	–	1.4-2.5	–
Yield calculation	negl.	negl.	≈0.7	<1.6
Topological variables	1.3-3.6	1.6-5.5	1.8-6.5	2-8.9
Invariant mass range	rej.	rej.	0.5-3.9	1.1-4.3
Wing correction	negl.	<1.2	negl.	0.2-1.3
Ξ topological variables	–	–	0.2-4.8	0.3-3.8
MC closure	negl.	negl.	2.5	negl.
Total	2.4-6.2	4-11.8	4.7-10.1	4.6-11.8

Table C.8: The minimal and maximal values of systematic uncertainty expressed in % for each source for h-V⁰/h-h yield-ratio as a function of p_T^{trigg} for the near-, away-side and underlying event covering all multiplicity classes. The abbreviation negl. stands for negligible, rej. for rejected based on the Barlow test and under. for underlying event. – means that this source does not contribute to the total uncertainty in that case.

Source	h-K _S ⁰ / h-h			h-(Λ + $\bar{\Lambda}$)/ h-h		
	near-side	away-side	under.	near-side	away-side	under.
Mixing scale	0.1-5.7	2-7.5	0.2-4.5	≈1.5	≈5	0.1-3.7
Pedestal subtraction	0.2-3.2	1-9	0.1-3.5	0.5-8	3-12	0.2-5.3
Δφ window	0.2-4	0.5-7.3	–	1-6	1-8	–
Primary track selection	rej.	rej.	rej.	rej.	rej.	rej.
PV along the z-axis (z_{vtx})	0.8-5	2-8	0.5-6	1.3-6.2	3.4-6.8	0.2-3
Binning in z_{vtx}	0.5-4.6	1.4-7.8	0.1-6	1-8	6.5-8.5	0.5-4.5
Δη range	0.1-5.5	–	–	1-5.8	–	–
Yield calculation	0.1-2.8	1-5.8	–	1.5-3.2	3.5-7	–
Topological variables	1-6.3	1.8-10.5	0.5-4.8	2-11	2-12	1-6
Invariant mass range	0.8-7.4	0.5-12	0.3-5.2	1-6.9	2-9	0.5-4.5
Wing correction	0.3-4.8	2-6.2	0.1-3.5	1-2.5	2-10	0.1-2.4
Ξ topological variables	–	–	–	1-6	2-9.5	0.5-3.8
MC closure	negl.	negl.	negl.	4	negl.	negl.
Total	2-11	2-17	1.5-9	6-18	6-20	2.5-10

Table C.9: The maximal value of systematic uncertainty expressed in % for each source for baryon to meson ratio for the near-, away-side and underlying event covering all p_T^{trigg} intervals. The abbreviation negl. stands for negligible and rej. for rejected based on the Barlow test. – means that this source does not contribute to the total uncertainty in that case.

Source	near-side	away-side	underlying
Mixing scale	6	9	7
Pedestal subtraction	6	8	10.5
$\Delta\varphi$ window	0.8	3.5	–
Primary track selection	rej.	rej.	rej.
PV along the z-axis (z_{vtx})	5.5	10.5	7.5
Binning in z_{vtx}	7	9.5	4
$\Delta\eta$ range	6	–	–
Yield calculation	5.5	10	–
Topological variables	9.8	12	7
Invariant mass range	9.4	7.8	5.1
Ξ topological variables	6.4	8.8	6.8
MC closure	4	negl.	negl.
Total	4.5 - 18	1- 22	1.7 - 17

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Acronyms

2D	two-dimensional
AA	Ion–Ion
ALICE	A Large Ion Collider Experiment
AliEn	ALICE Environment
AMPT	A Multi-Phase Transport Model
AOD	Analysis Object Data
ATLAS	A Toroidal LHC Apparatus
CERN	European Organization for Nuclear Research
CMS	Compact Muon Solenoid
CTEQ	The Coordinated Theoretical-Experimental Project on QCD
DCA	Distance of Closets Approach
DCal	Di-jet Calorimeter
DELPHI	DEtector with Lepton, Photon and Hadron Identification
DIS	Deep Inelastic Scattering
DY	Drell-Yan
EMCal	Electromagnetic Calorimeter
ESD	Event Summary Data
FAIR	Facility for Antiproton and Ion Research
FB	Filter Bit
FF	Fragmentation Function
GEANT	Detector Description and Simulation Tool
HEP	High-Energy Physics
HM	High Multiplicity

HV	High Voltage
IP	Interaction Point
ITS	Inner Tracking System
LCG	LHC Computing Grid
LEIR	Low Energy Ion Ring
LEGO	Lightweight Environment for Grid Operations
LEP	Large Electron-Positron Collider
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty
LV	Low Voltage
LS2	2nd Long Shutdown
MB	Minimum-Bias
MC	Monte Carlo
MWPC	Multi-Wire Proportional Chamber
MRPC	Multi-gap Resistive-Plate Chamber
nCTEQ	nuclear CTEQ
nPDF	Nuclear Parton Distribution Function
OPAL	Omni-Purpose Apparatus for LEP
pp	proton–proton
p–Pb	proton–lead
Pb–Pb	lead–lead
PDF	Parton Distribution Function
PID	Particle Identification
PHOS	Photon Spectrometer
PHENIX	Pioneering High Energy Nuclear Interaction eXperiment
PS	Proton Synchrotron
PV	Primary Vertex
QCD	Quantum Chromodynamics
QGP	Quark–Gluon Plasma

RHIC	Relativistic Heavy Ion Collider
SDD	Silicon Drift Detector
SM	Standard Model
SPD	Silicon Pixel Detector
SPS	Super Proton Synchrotron
SSD	Silicon Strip Detector
STAR	Solenoidal Tracker At RHIC
SV	Secondary Vertex
T0	Timing and Trigger detector at ALICE
TOF	Time Of Flight
TPC	Time Projection Chamber
TR	Transition Radiation
TRD	Transition Radiation Detector
V0	Triggering and Centrality Detector
V0A	V0 sub-detector on A-side
V0C	V0 sub-detector on C-side

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6. 2021, La Thuile 2021 (online, 09.–11. March): "Study of K_S^0 production via high- p_T dihadron correlations in pp collisions with ALICE"
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3. 2019, SQM (Bari, 9.–15. Jun): "Two-particle correlations with high- p_T K_S⁰ mesons in pp collisions at ALICE"