

Search for Mixing and Charge Parity Violation in Neutral Charm Mesons through Semileptonic B Meson Decay

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Abstract

We present the measurement of mixing and Charge Parity violation parameters in the D^0 meson system using the decay

$$\overline{B} \rightarrow \mu^- D^{*+} X$$

$$D^{*+} \rightarrow D^0 \pi^+$$

$$D^0 \rightarrow K \pi$$

and charge conjugate decays using the full Run I dataset collected by the LHCb Collaboration at the LHC at CERN from 2011 to 2012. By fitting the time dependent ratio of “Wrong Sign” D^0 decays to “Right Sign” D^0 decays, we extract the parameters sensitive to mixing and charge parity violation. The resulting mixing fit yields

$$R_D = (3.48 \pm 0.11 \pm 0.01) \times 10^{-3}$$

$$y' = (4.60 \pm 3.50 \pm 0.18) \times 10^{-3}$$

$$x'^2 = (0.28 \pm 3.10 \pm 0.11) \times 10^{-4}.$$

The results for the no Direct CP Violation fits are

$$R_D = (3.48 \pm 0.11 \pm 0.01) \times 10^{-3}$$

$$y'^+ = (2.79 \pm 3.99 \pm 1.17) \times 10^{-3}$$

$$x'^{2+} = (1.94 \pm 3.47 \pm 0.98) \times 10^{-4}$$

$$y'^- = (6.51 \pm 4.17 \pm 1.66) \times 10^{-3}$$

$$x'^{2-} = (-1.53 \pm 4.26 \pm 1.68) \times 10^{-4}.$$

The results for the All CP Violation allowed fit are

$$\begin{aligned}
R_D^+ &= (3.38 \pm 0.15 \pm 0.06) \times 10^{-3} \\
y'^+ &= (5.81 \pm 5.02 \pm 0.32) \times 10^{-3} \\
x'^{2+} &= (-0.19 \pm 4.44 \pm 0.31) \times 10^{-4} \\
R_D^- &= (3.60 \pm 0.15 \pm 0.07) \times 10^{-3} \\
y'^- &= (3.32 \pm 4.87 \pm 0.40) \times 10^{-3} \\
x'^{2-} &= (0.79 \pm 4.33 \pm 0.38) \times 10^{-4}.
\end{aligned}$$

13 The results are consistent with CP symmetry. We provide the LHCb average of WS searches,
14 and predictions of the world averages of the underlying physics parameters with the inclusion
15 of this result.

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Chapter 1

Introduction

The standard model (SM) of particle physics has become one of the tried and true theories of modern physics. It has been able to give accurate predictions over the vast majority of high energy physics, from bubble chamber experiments to the high energy collisions of the LHC. However, the SM lacks a precise explanation of several phenomena, including the observed matter-antimatter asymmetry of the universe. Nor does it offer any clues about what Dark Matter is, or how this mysterious form of matter interacts with any of the other particles of the SM. It also does not provide any explanation of Dark Energy, which is thought to make up the vast majority of the mass of the universe and provide the mechanism to explain the increasing rate of expansion of the universe. Worse yet, the SM does not seem to hold up to the Planck Scale, does not explain the quantum nature of gravity, and cannot give an adequate explanation of the unification of gravity, the strong and weak force and electromagnetis. It is for this reason that many believe the SM to simply be an effective theory which seems to work at the energies which we are probing now. The answer to all of the unsolved phenomena listed above requires physics beyond the SM. Indeed, the fact that the neutrino has mass at all already points to physics beyond the SM.

It is the goal of current experiments, such as the LHCb experiment, to search for evidence of new physics, be it through direct detection of new forms of matter, variations from precision predictions from the standard model, or even new forces all together. By searching high

and low, physicists will eventually find something unexpected which cannot be adequately explained by the standard model. This door into the new unknown is what we search for, and is a major part of this thesis.

The D^0 system is, and has been for the past 30 years, an ideal testbed for looking for new physics contributions. As the system is neutral, it can oscillate between its particle and antiparticle, similar to the K^0 , B^0 and B_s^0 systems. This leaves open the possibility for Charge Parity (CP) violation in the oscillation from particle to antiparticle or vice versa. However, due to the high level of suppression in the possible short range contributions from Feynman diagrams which could describe the transition, and the possibility of non-perturbative long range contributions overwhelming these so called short range interactions, the D^0 system has a wide variety of predictions of rates of mixing and CP violation in the system. Mixing in the system was only first observed with a significance of greater than 5 standard deviations in the late 2000s in global combinations [1], and in 2012 by a single experiment. Violation of CP is still only constrained. If we see large variations in the form of a CP asymmetry, or the mixing rates of the decay are larger or smaller than the value calculated from the Standard Model, including estimates for non-perturbative effects, this would represent indirect evidence for new interactions. It would be a “smoking gun”. Looking for such an effect is the motivation of this thesis.

Chapter 2

The Standard Model of Particle Physics

The Standard Model of Particle Physics is built on the symmetry groups

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

where the term $SU(3)_C$ is responsible for the strong interactions, and is mediated by 8 massless gluons responsible for the transition of the three quark colors. The term $SU(2)_L \times U(1)_Y$ is responsible for the electroweak interactions. The physical W and Z bosons, as well as the photon γ , arise from the spontaneous symmetry breaking of the $SU(2)_L \times U(1)_Y$ to $U(1)_{EM}$ when the Higgs field acquires a vacuum expectation value. The masses of the fundamental particles of the SM come from their interactions with the Higgs field. The final unbroken $U(1)_{EM}$ symmetry is electromagnetism.

The $SU(2)_L$ group is responsible for the coupling of the weak gauge bosons to only left

handed fermion species. These species are given as

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \quad (2.2)$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}, \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}. \quad (2.3)$$

These fermion species not only include quarks, but also leptons, given in the second row of the equation above. The leptons include the electron, muon(μ) and the tau(τ), as well as the corresponding neutrinos, ν_e, ν_μ and ν_τ . The leptons are not charged under the $SU(3)_C$ symmetry of the standard model, and therefore do not take part in strong interactions.

2.1 The CKM Matrix

This section follows very closely the presentation of Ref. [2].

The CKM Matrix is responsible for the mixing of the quark generations and also for any CP violation found in the standard model. The CKM matrix arises from the Yukawa interactions of the quark fields with the Higgs field.

$$\mathcal{L}_{\text{Yukawa}} = -Y_{ij}^d \overline{Q_{Li}^I} \phi d_{Rj}^I - Y_{ij}^u \overline{Q_{Li}^I} \epsilon \phi^* u_{Rj}^I \quad (2.4)$$

Here, the terms $Y_{ij}^{u,d}$ represent the Yukawa couplings, which are 3×3 complex matrices, the terms Q_L^I are left handed quark doublets in the $SU(2)_L \times U(1)_Y$ representation before Electroweak Symmetry Breaking (EWSB), u_R^I and d_R^I are the right handed quark singlets in the same representation, ϵ is the 2×2 antisymmetric tensor, and ϕ is the doublet of Higgs fields before EWSB. When the Higgs field acquires a vacuum expectation value, and the Yukawa matrices are diagonalized such that the quark fields are rotated to be aligned with

the mass eigenstates by the following transformation

$$Q_L^I \rightarrow V_L^f Q_R^f \quad (2.5)$$

$$Q_R^I \rightarrow V_R^f Q_R^f, \quad (2.6)$$

904 where $f = u, d$, the langrangian above describes the quark masses. When all fields are
 905 rotated in this way, the kinetic term of the left handed quarks gives the following interaction
 906 with the charged W boson

$$-\frac{g}{\sqrt{2}} \begin{pmatrix} \overline{u}_L & \overline{c}_L & \overline{t}_L \end{pmatrix} \gamma^\mu W_\mu^+ V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.} \quad (2.7)$$

907 The matrix $V_{CKM} = V_L^u V_L^{d\dagger}$ is the Cabibbo-Kobayashi-Maskawa matrix. This matrix is
 908 unitary, and is in general represented by three real phases and one complex phase. This
 909 complex phase is responsible for all CP violation in the standard model. The CKM matrix
 910 can be represented as

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (2.8)$$

911 where we use the terminology $s_{ij} = \sin(\theta_{ij})$, $c_{ij} = \cos(\theta_{ij})$, and θ_{ij} are the three real phases
 912 defined above and δ is the one CP violating phase. The matrix is often reparameterized in
 913 the Wolfenstein parameterization [3]

$$\begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ \lambda^3 A(1 - \rho - i\eta) & -\lambda^2 A & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \quad (2.9)$$

914 In this parameterization, the expansion parameter $\lambda = 0.22 = s_{12}$, $A\lambda^2 = s_{23}$, and $s_{13}e^{i\delta} =$
915 $A\lambda^3(\rho + i\eta)$. This expansion holds unitarity of the CKM matrix up to λ^3 . The CKM matrix
916 can be thought of as the rotation matrix to bring the quark eigenstates from the physical
917 eigenstates, and this matrix defines all flavour changing processes and CP violation in the
918 standard model. If CP violation were seen beyond the level expected from calculations using
919 this matrix, it would be a tell-tale sign of new physics.

The unitarity of the CKM matrix implies that $\sum_i V_{ij}V_{ik}^* = \delta_{jk}$ and $\sum_j V_{ij}V_{kj}^* = \delta_{ik}$,
where δ_{ij} is the Dirac delta function. Those indeces which fail the Dirac delta function can
therefore be represented by triangles in the complex plane, with sides corresponding to the
individual elements from the delta function definitions. The most well used of these triangles
has

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb} = 0, \quad (2.10)$$

920 and is generally normalized by $V_{cd}V_{cb}^*$, as these are the best measured CKM matrix elements.
921 The normalization by this quantity puts bars on ρ and η . The theoretical distribution of
922 this Unitarity Triangle and the current world average [4] is given in Figure 2.1. Double the
923 area of this triangle is given as the Jarlskog invariant $J = (3.06_{-0.20}^{+0.21}) \times 10^{-5}$.

924 2.2 The Baryon Asymmetry of the Universe

925 This section is based in part on Refs. [5, 6].

926 The Universe as we know it today is made up of a small amount of matter, photons, dark

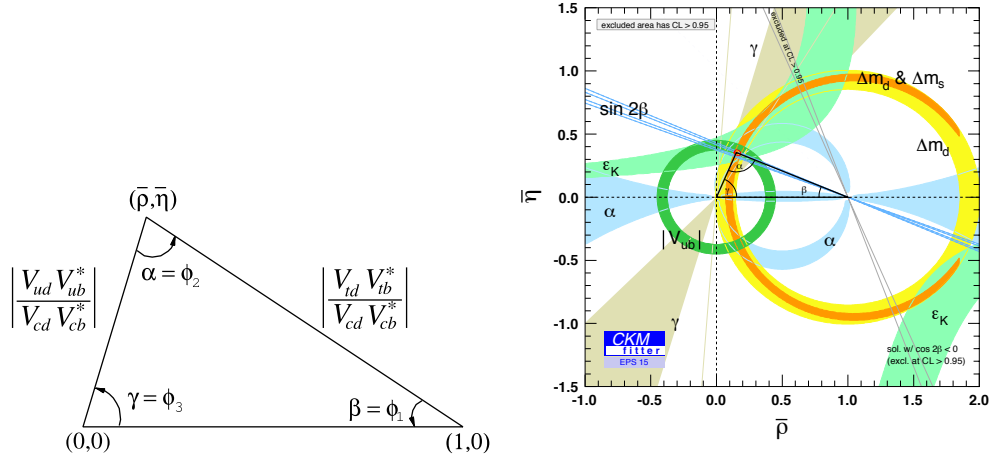


Figure 2.1: CKM Unitarity triangles. Left: Theoretical formation of the Unitarity triangle. Right: Current World Average provided by CKM Fitter.

matter and dark energy. Cosmological measurements point strongly to the fact that the big bang was very energetic, and given such, would have been radiation dominated, and that the Universe is homogeneous in this measure. Yet today, we see an asymmetry of baryons with respect to antibaryons, in that there are no areas in space filled with antiprotons or the like. Therefore, there must be some process which has created the matter-antimatter asymmetry we see today.

Measurements and fitted values [7] of the parameters related to the standard theory of cosmology, which come primarily from measurements of the Cosmic Microwave Background, in combination with a myriad of other measurements, place the baryon to photon ratio at current times at

$$\begin{aligned}
 \eta &= \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \\
 &\simeq (\Omega_B h^2) 2.68 \times 10^{-8} \\
 &= (5.97 \pm 0.05) \times 10^{-10} (68\% \text{C.I.})
 \end{aligned}
 \tag{2.11}$$

One of the best tests of the understanding of the cosmology of our universe comes from Big Bang Nucleosynthesis (BBN). From the measured values of the abundances of Deuterium,

Helium 3 and 4 and Lithium, it is possible to measure η and project to times just before BBN. These constraints, omitting the “lithium problem” [8] which may or may not be solved by unaccounted for systematic errors, gives

$$5.8 \times 10^{-10} \leq \eta \leq 6.6 \times 10^{-10} \quad (2.12)$$

The agreement between these two calculations of η (Eq 2.11 and 2.12) is considered to be one of the biggest successes of the standard cosmological model. With the agreement of these numbers comes the knowledge that any baryon asymmetry must have been present prior to nucleosynthesis. The generation of such an asymmetry requires the fulfillment of three conditions

1. Baryon or Lepton Number Violation,
2. C and CP violation, and
3. Departure from thermal equilibrium.

These conditions are called the Sakharov conditions [9]. The standard model of particle physics has a way to fulfill these conditions. The first condition is fulfilled by the fact that in the SM, the baryon minus lepton number $B - L$ is a conserved quantity, but the individual numbers are not conserved. The second is provided by the CP violating phase in the CKM matrix. For the third condition, one would assume that the electroweak phase transition would give an adequate departure from equilibrium. Due to the mass of the Higgs $m_H \simeq 126 \text{ GeV}/c^2$, the phase transition would only be weakly first order and not provide a strong enough departure from thermal equilibrium [10]. This is independent of any CP violation caused by the CKM matrix. Even more strongly, even if we neglect this problem and ask if the KM phase δ can account for the baryon asymmetry we see today, the answer is a strong no, as the Jarlskog invariant divided by the critical temperature of the electroweak phase transition [6], which gives a measure of CP violation at the transition gives a value of $\sim 10^{-18}$, thus failing to reproduce the baryon asymmetry by 8 orders of magnitude. It is for

954 this reason that we know there must be some physics beyond the standard model which can
955 explain the asymmetry we see today. As pointed out before, any larger CP violation would
956 be a “smoking gun” for new physics and may help to explain the baryon asymmetry of the
957 universe.

Chapter 3

CERN, The Large Hadron Collider and LHCb

3.1 CERN and the LHC

The “Conseil Européen pour la Recherche Nucléaire”¹ is a scientific laboratory situated between France and Switzerland between Geneva and the foot of the Jura mountains. The laboratory, since its founding in 1954, has been the home of many particle accelerators and detectors, and is funded, staffed, and used by researchers from all around the world. [11]. CERN is most recently host to the Large Hadron Collider (LHC), which collides protons at near the speed of light to study collisions between particles at energies only accessible shortly after the Big Bang. The LHC is a circular superconducting accelerator 26.7km in circumference, and is connected to the rest of the CERN accelerator complex by two transfer tunnels. The LHC has 4 large detectors at its collision points, ATLAS, CMS, ALICE and LHCb. The design energy of the LHC is 14 TeV², and is built to deliver a peak luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, and is accomplished by colliding 2808 bunches of 1.1×10^{11} protons per bunch at a bunch crossing rate of 40MHz. A complete description is given in Ref. [12].

¹European Council for Nuclear Research

²Throughout this thesis, units are such that $\hbar = c = 1$.

3.2 The LHCb Detector at the LHC

The LHCb detector is a single arm detector designed for the purpose of reconstructing the decays of beauty hadrons. Its unique shape and coverage is motivated by the production of b hadrons and $\bar{b}$ hadrons at high energies, which tend to be produced in the same forward or backward cone. A cartoon of the LHCb Detector is shown in Figure 3.1 [13].

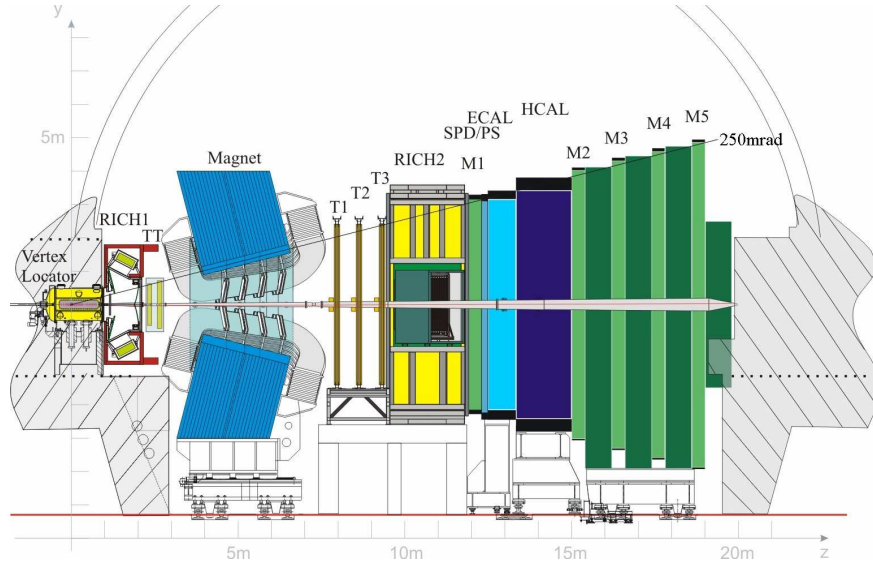


Figure 3.1: A cartoon of the LHCb Detector at CERN. From [13].

The detector consists of a tracking system comprised of a silicon strip Vertex Locator (VELO), the silicon strip tracker turicensis (TT) stations and the combination silicion strip and gas drift tube detectors comprising the T stations. On either side of the reversible dipole magnet sit two ring imaging Cherenkov detectors (RICH 1 and 2) for particle identification, followed by the calorimetry system and muon stations. The calorimetry system is comprised of a scintillating pad detector (SPD) and preshower (PS), followed by the electromagnetic calorimeter and the hadronic calorimeter. Just before the PS and SPD, and just after the HCAL are 5 muon stations. The entire detector has a two trigger system. The system consists of a Level 0 (L0) hardware trigger which operates synchronously with the 40 MHz bunch crossing rate of the LHC and the High Level Trigger (HLT), which runs concurrently with datataking on a processing farm and is asynchronous with the datataking itself. During

the Run I datataking period, the L0 trigger output was at 1 MHz; the HLT varied from 3.5 kHz output in 2011 to 5 kHz output in 2012. The L0 trigger searches for high transverse momentum or transverse energy (E_T)³ photons, hadrons, muons and electrons which characteristic of B meson decay. The HLT is responsible for reconstructing the rest of the event and triggering on events which specifically meet the criteria of the trigger selections.

3.2.1 Vertex Locator

The VELO is a tracking detector comprised of 42 half moon shaped silicon microstrip detectors. Each half moon shaped sensor has strips on one side in the r direction and in ϕ on the opposite side. This means that each plane can give a 2D spacial point, and when combined with the z position of the sensor gives a 3D spacepoint when a charged particle passes through the detector. The technology used is an n -type strip detector on n -type bulk material [14]. The detectors are organized into two halves which close around the beam to a distance of 8mm for the active area. As the sensors are so close to the beam, they are housed inside of the vacuum of the LHC beampipe within two vacuum chambers. The first vacuum chamber encloses all supports and cooling for the VELO, and the second separates the LHC vacuum from the VELO. The second chamber is corrugated to additionally suppress wakefields from the proton beams and RF interference. Additionally, to protect against unstable beam conditions, the halves are retracted to a distance of 6 cm until stable beams are declared, and then the VELO is inserted into position. The VELO provides coverage in a range from 1.6 to 4.5 in pseudorapidity⁴ η . The pitch for R strips varies from $38\mu\text{m}$ at the center for r sensors, linearly to $101.6\mu\text{m}$ at the largest radius. The ϕ sensors are split into two regions with the boundary between regions at a radius of 17.25mm; the inner region has pitch $78.3\mu\text{m}$, and the outer with a pitch of $38.3\mu\text{m}$. As the nominal choice of simple radial segmentation would result in unacceptable strip occupancy and strip pitch too large at the edge of the sensor, after which point the pitch is approximately halved to $39.3\mu\text{m}$. Strips

³Generally, $E_T = \sqrt{(m^2 + p_T^2)}$ for mass m and transverse momentum p_T

⁴ $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle.

1015 for ϕ sensors are oriented with two stereo angles, such that one strip will emerge at a stereo
 1016 angle of 20 degrees to radial, and at the second region change to a stereo angle of 10 degrees
 1017 to radial. Sensors are mounted such that from one side of the VELO to the other, the sensor
 1018 layout is $r\phi$, ϕr , $r\phi$, etc. The individual hit resolution is at best $7\mu\text{m}$, and varies according
 1019 to pitch and angle of track.

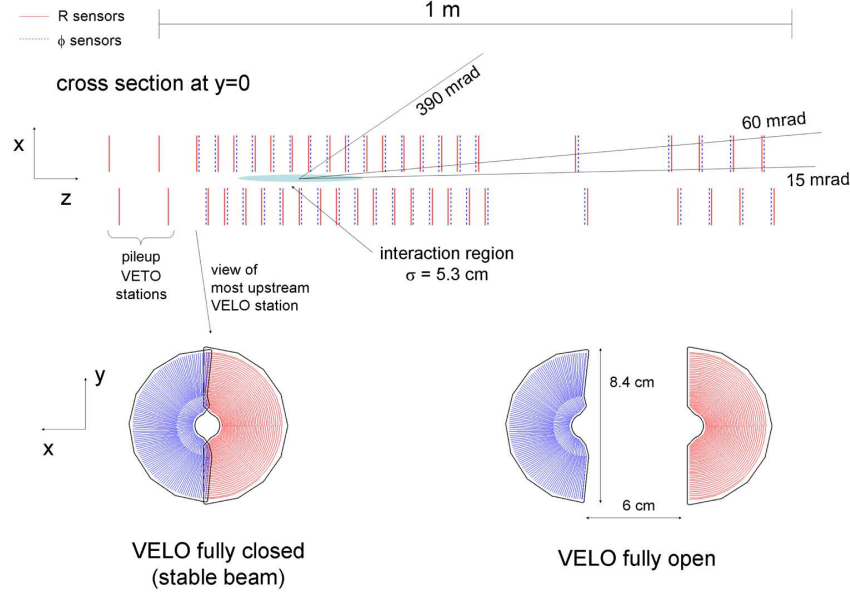


Figure 3.2: Cartoon of the VELO detector of the LHCb. The top part of the figure shows the length of the VELO detector, with the arrangement of each sensor about the interaction region. The bottom part of the figure shows the position of the two halves for the closed position on the left and the open position on the right. From Ref. [13].

1020 3.2.2 TT Station

1021 The TT station is comprised of 4 planes in an $x - u - v - x$ configuration of silicon microstrip
 1022 detectors. The u and v planes are rotated by ± 5 degrees, respectively. The pitch of the strips
 1023 of the TT station is $200\mu\text{m}$. The tracker covers an area of 150 cm in width and 130 cm in
 1024 height, covering the full pseudorapidity range of LHCb, $2 < \eta < 5$. Each plane in the TT
 1025 is comprised of many half modules. Each half module consists of a row of seven silicon
 1026 microstrip sensors with a stacked readout system at the far end. Half modules are joined

1027 together to form full modules which cover the left and right sides of the beampipe, and
 1028 above and below have one half module each. Modules are overlapped in the x direction to
 1029 fully cover the acceptance. All readout and cooling are above and below the active area of
 1030 the detector, minimizing material traversed by charged particles. These modules then make
 1031 up one plane. The technology for the silicon strips is $500\mu\text{m}$ thick $p^+ - \text{in} - n$ sensors. One
 1032 full plane as well as each module is shown in Figure 3.3. The TT station provides a $50\mu\text{m}$
 1033 single hit resolution. The entire TT is enclosed in a light tight box which is kept at 5 C and
 1034 constantly flushed with nitrogen to reduce leakage currents and prevent condensation on the
 1035 sensors.

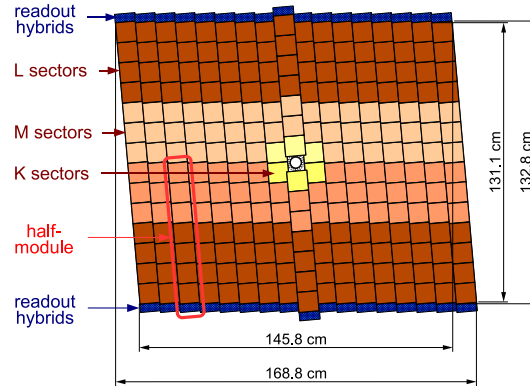


Figure 3.3: The v plane of the TT station. Shown are the active area of the detector plane, as well as the readout sectors, the placement of the readout sensors and the arrangement of the modules, both full and half, around the beam pipe. From Ref. [13].

1036 3.2.3 T stations

1037 The T stations are the final detector used in track reconstruction. These stations are made
 1038 up of two technologies: The inner region is a silicon microstrip detector in the central region,
 1039 and the outer region is a gas drift tube detector. These regions are called the Inner Tracker
 1040 (IT) and the outer tracker (OT). Each detection plane has an IT and OT part. One station
 1041 is made of 4 detection planes. The total T stations have 3 of these stations. The IT has the
 1042 same $x - u - v - x$ configuration, and has a strip pitch of roughly $200\mu\text{m}$, similar to the TT

stations. The IT is oriented around the beampipe and the detector covers a cross-shaped area of 40cm in the vertical direction and 120cm in the horizontal. The hit resolution is also roughly $50\mu\text{m}$. Each sensor is made of p^+ -on- n silicon, is single sided, and is either $320\mu\text{m}$ or $410\mu\text{m}$ thick depending on if the sensor will be part of a one or two sensor module. The sensors are biased from the back side of the sensor itself using n doped implants.

The OT consists of many straw drift tube detectors, which are oriented with two overlapping monolayers of straw tubes per module. With 4 modules per station arranged in an $x - u - v - x$ fashion, similar to the TT and IT. This is the same for each of 3 stations, giving a total active area of $5971 \times 4850 \text{mm}^2$ and an angular coverage of 300mrad horizontally and 250mrad vertically, corresponding to the bending and non-bending planes of the dipole magnet, respectively. Each straw has an inner diameter of 4.9mm. Straws are filled with a mixture of Argon, CO_2 and O_2 is used as the counting gas, which gives a drift time below 50ns. The inner foil anode of each straw is made of a $40\mu\text{m}$ thick wound foil of Kapton-XC and the outer cathode foil is a $25\mu\text{m}$ thick Kapton-aluminum, wound together. The spacial resolution achieved by the OT is $200\mu\text{m}$. The IT arrangement around the beampipe is shown in Figure 3.4 and the OT monolayer design is shown in Figure 3.5.

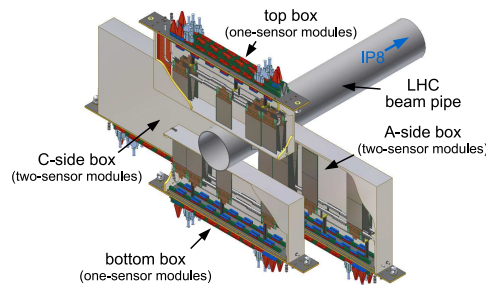


Figure 3.4: Left: The arrangement of the IT around the beampipe. From Ref. [13].

3.2.4 RICH Detectors

There are two Ring Imaging Cherenkov (RICH) Detectors just before the TT and just after the T stations. The RICH station before the magnet is called RICH1, and the one after

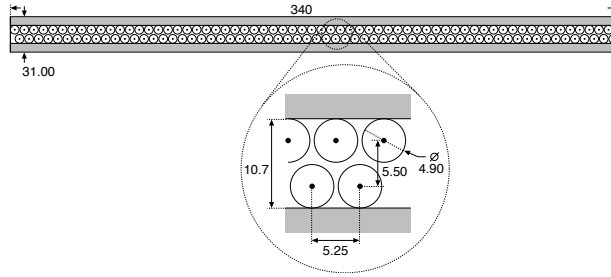


Figure 3.5: OT monolayer design. From Ref. [13].

the magnet is called RICH2. These detectors are used to aid in particle identification and separation between pions and kaons. The RICH1 detector provides particle identification over the range $\sim 1 - 60 \text{ GeV}/c$, and RICH2 from ~ 15 to beyond $100 \text{ GeV}/c$ in particle momentum. Each is based on the basic principle of Cherenkov radiation and uses a gaseous radiator, and sometimes also an aerogel radiator, to produce Cherenkov photons which are then reflected via a combination of spherical and flat mirrors to hybrid photon detectors (HPDs) in the wavelength range of 200-600nm. The characteristic angle is related to the velocity of the charged particle by $\cos \theta = 1/(n\beta)$, where β is the velocity of the particle divided by the speed of light. The HPDs are surrounded by iron shielding and placed in MuMetal cylinders, an alloy used for magnetic field shielding, to allow for operation in magnetic fields of up to 50mT. RICH1 is oriented so that the HPDs are vertical, and RICH 2 oriented horizontally. The cutaway of the RICH detectors is shown in Figure 3.6.

RICH1 uses both aerogel and C_4F_{10} radiators, and is positioned directly against the exit window of the VELO vacuum tank. For Run II of the LHC, the aerogel layer was removed. The minimum range is defined by the LHCb beampipe, which is made of beryllium and extends through the length of the LHCb detector, resulting in a minimum angular coverage in RICH1 of 25mrad. Photons are first reflected via spherical mirrors made of carbon fiber reinforced polymer substrate, chosen to keep the radiation length lower than that of glass. Photons are then reflected to flat glass substrate mirrors outside of the LHCb acceptance, then to the HPDs.

RICH2 covers a reduced angular acceptance of $\pm 120 \text{ mrad}$ in the horizontal plane and

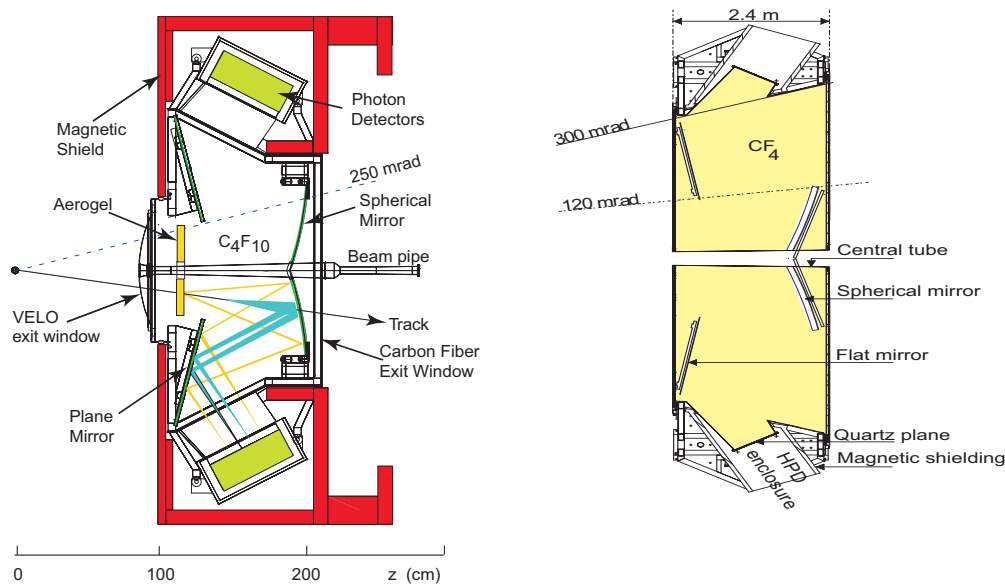


Figure 3.6: Cartoons of the RICH detectors. Left is RICH1, right is RICH2. Note that RICH1 is drawn in the yz plane and RICH2 is drawn in the xz plane, perpendicular to RICH1. From Ref. [13].

$\pm 100 \text{ mrad}$ in the vertical. This angular coverage is chosen to provide information in the region where high momentum particles will traverse. The minimum angular coverage is again limited by the beampipe and is 15 mrad in RICH2, and uses CF_4 as the radiator gas. Similar to RICH1, the HPDs are surrounded by magnetic shielding.

3.2.5 Magnet

The magnet used in the LHCb experiment is a reversible warm dipole magnet. The magnet is constructed out of saddle shaped coils, mirrored exactly across the yolk of the magnet. The yolk is designed to be compatible with the acceptance of the LHCb detector, and covers a range of $\pm 250 \text{ mrad}$ in the vertical direction and $\pm 300 \text{ mrad}$ in the horizontal. The magnet is shown in Figure 3.7, as well as the strength of the magnetic field as a function of the z position.

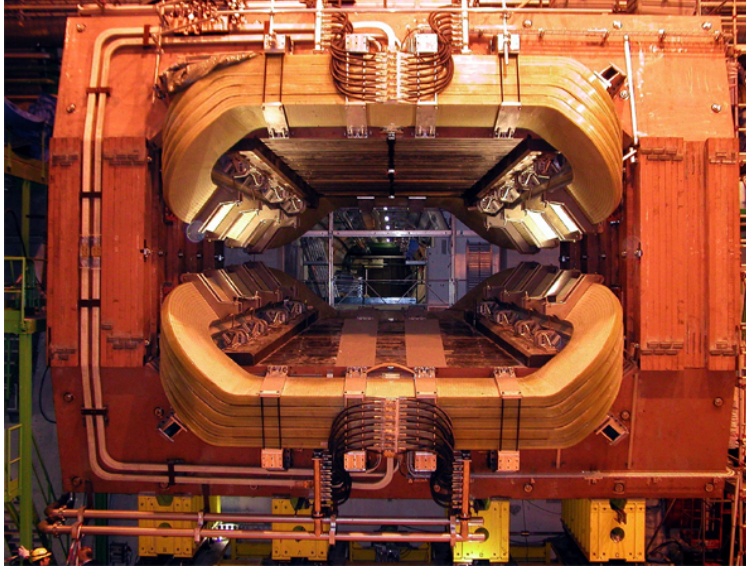


Figure 3.7: Photo of the LHCb magnet from 2004 after completion. The view is towards the VELO detector, before other subdetectors have been installed. Visible are the yoke (redish) and the coils (yellowish). From [15].

3.2.6 Calorimetry

The calorimetry system in LHCb is multitiered: the system starts with a scintillating pad detector (SPD), followed by a preshower(PS) detector, then the electromagnetic calorimeter(ECAL) and finally the hadronic calorimeter(HCAL). The purpose of the SPD and PS is to aid in the separation of high transverse energy electrons and backgrounds such as charged and neutral pions. The ECAL then provides separation between photons and electrons, and the HCAL between events which are hadronic in nature. All elements of the calorimetry share the same common design, a readout of light from wavelength shifting scintillating fiber read out by photomultipliers. All detectors have variable segmentation to cope with the range of occupancies expected over the acceptance. The SPD and PS cover an area of 7.6m by 6.2m, and consist of a 15mm thick piece of lead, corresponding to 2.5 radiation lengths, X_0 , between two planes of scintillating fibers arranged into pads. The ECAL is designed as a shashlik type, or of alternating led then scintillator planes, with scintillating fibres running along the beam axis which read out the signal. The size of the individual modules which build the ECAL ranges from about $4 \times 4 \text{cm}^2$ to about $12 \times 12 \text{cm}^2$ and of length 42cm. Each module

consists of alternating layers of lead, reflecting paper and scintillating tiles. The HCAL is alternating iron and scintillating square tiles, ranging in side length size from 131.3mm to 262.6mm.

3.2.7 Muon stations

The muon system is composed of 5 stations, one just before the calorimeters and 4 following. The stations are composed of multiwire proportional chambers far from the beampipe and triple gas electron multiplier (GEM) detectors in the central region, interleaved with 80cm thick iron absorbers. The detectors give an x, y position in the muon stations and allow for stand-alone track reconstruction as well as p_T calculation to feed into the trigger. The station closer to the magnet and before the calorimeters is called M1, and those behind the calorimetry, away from the magnet, are called M2-5. Only the M2-5 detectors are interleaved with iron. The total active area is 435m^2 , and the minimum momentum to traverse all 5 muon stations is roughly 6 GeV/ c . Each station is split into quadrants, and each quadrant has 4 regions, moving from the central region (R1) closest to the beampipe outwards to R4. The segmentation of each region decreases as a function of distance from the beampipe. A cartoon of the muon stations in the non-bending plane (yz) is shown in Figure 3.8.

3.2.8 Trigger

The LHCb trigger is split into two parts, the first is the so called Level-0 (L0) hardware trigger, followed by two High Level Triggers (HLT). The task of the L0 trigger is to reduce the rate from the 40 MHz bunch crossing rate to a level of 1 MHz, and takes input from the calorimetry, pile-up systems of the VELO, SPD and muon stations. The L0 trigger first reconstructs the highest E_T hadron, photon and electron, and the two highest p_T muons and triggers (or fires) on events which contain one of these events. The whole process is done in time with the 40 MHz LHC bunch crossing rate on custom electronics. The HLT then validates the decisions from L0 with full event info by reconstructing the full event, and finally triggers on events consistent with a large array of selection criteria. As the HLT is run

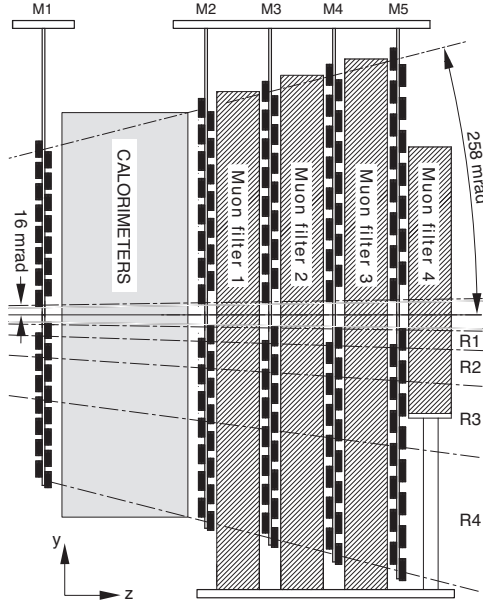


Figure 3.8: Cartoons of the muon stations in the non-bending plane. From Ref. [13].

1135 on a separate farm and separate from the 40 MHz bunch crossing rate, events from collision
 1136 are put to disk, then processed by a large computing farm. The HLT reduces the rate to
 1137 3.5 kHz in 2011 and 5 kHz in 2012. The main differences in the 2011 and 2012 trigger come
 1138 from the rates of topological trigger requirements and those linked to hadrons involving a
 1139 charm quark increased, as well as the number of processing cores in the event farm. The
 1140 schematic view of the triggering scheme is shown in Figure 3.9 [16].

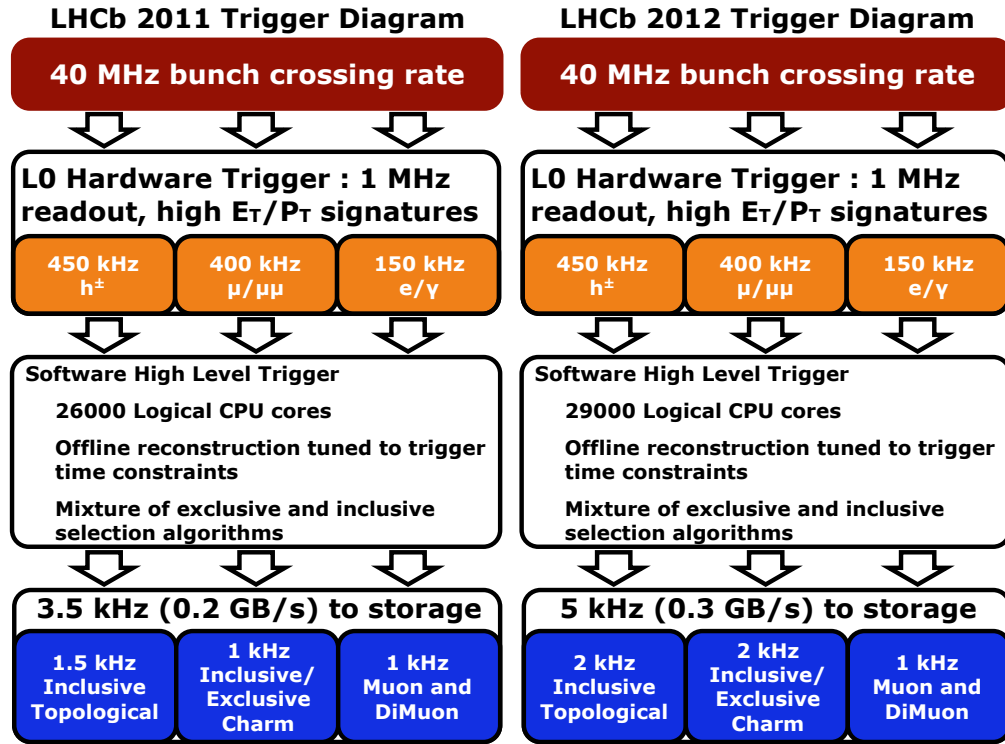


Figure 3.9: Trigger criterion for the 2011 (left) and 2012 (right) L0 and HLT triggers. From [16].

Chapter 4

Phenomenological Model of Neutral Meson Mixing and CPV

Here, we derive the phenomenology of the D^0 meson system. This chapter is based heavily on the paper by Kagan and Sokoloff [17].

There are two neutral D mesons, the D^0 and the $\bar{D}^0$. We can write the states describing these two mesons as $|D^0\rangle$ and $|\bar{D}^0\rangle$. The same can be said of the K^0 system, the B^0 system and the B_s^0 system. The non-hermitian Hamiltonian describing any neutral meson system can be written as:

$$\mathcal{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} \quad (4.1)$$

where $\mathbf{M}$ and $\mathbf{\Gamma}$ are the mass and the width matrices, respectively, defined as

$$\mathbf{M} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{11} \end{pmatrix}, \mathbf{\Gamma} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{11} \end{pmatrix}. \quad (4.2)$$

Non-hermiticity ensures that the neutral meson in question will eventually decay. Each matrix $\mathbf{M}$ and $\mathbf{\Gamma}$ are hermitian, with the on-diagonal elements forced to be the same by CPT invariance.

The eigenstates which diagonalize the above Hamiltonian are $|P_1\rangle$ and $|P_2\rangle$ ¹. As this thesis focuses only on the decays of the D^0 and $\bar{D}^0$ mesons, we write $|D_1\rangle$ and $|D_2\rangle$. These states are called the weak or mass eigenstates. The states $|D^0\rangle$ and $|\bar{D}^0\rangle$ are referred to as the flavor eigenstates, and are the states which are measured at production and decay. Re-expression of the mass eigenstates in terms of the flavor eigenstates gives

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle \quad (4.3)$$

$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle. \quad (4.4)$$

In this expression, p and q are complex numbers satisfying the normalization condition $|p|^2 + |q|^2 = 1$. The eigenvalues of the above Hamiltonian are easily solved for and given by the expression

$$\lambda_{1,2} = m_{1,2} - \frac{i}{2}\Gamma_{1,2} = \left(M_{11} - \frac{i}{2}\Gamma_{11}\right) \pm \frac{q}{p} \left(M_{12} - \frac{i}{2}\Gamma_{12}\right), \quad (4.5)$$

We have explicitly introduced the equalities

$$m_1 - \frac{i}{2}\Gamma_1 = \left(M_{11} - \frac{i}{2}\Gamma_{11}\right) + \frac{q}{p} \left(M_{12} - \frac{i}{2}\Gamma_{12}\right) \quad (4.6)$$

$$m_2 - \frac{i}{2}\Gamma_2 = \left(M_{11} - \frac{i}{2}\Gamma_{11}\right) - \frac{q}{p} \left(M_{12} - \frac{i}{2}\Gamma_{12}\right). \quad (4.7)$$

¹¹⁴⁹ These equalities relate the masses and widths of the weak eigenstates in terms of the matrix
¹¹⁵⁰ elements of the Hamiltonian directly.

With the eigenvalue problem solved, it is then possible to write the time evolution of the states produced purely in the $|D^0\rangle$ or $|\bar{D}^0\rangle$ states using the time dependent Schrödinger equation. For convenience, throughout the rest of this thesis, we set $\hbar = c = 1$. The time

¹The letter P is used to denote that all neutral mesons which have been studied (K^0, D^0, B^0 , and B_s^0) are pseudoscalars, meaning their total angular momentum is $J = 0$ and their parity is negative, $P = -1$

evolution of the mass eigenstates is given by

$$i \frac{\partial}{\partial t} |D_{1,2}(t)\rangle = (m_{1,2} - \frac{i}{2} \Gamma_{1,2}) |D_{1,2}(t)\rangle, \quad (4.8)$$

which immediately leaves

$$|D_{1,2}(t)\rangle = e^{-i(m_{1,2} - \frac{i}{2} \Gamma_{1,2})t} |D_{1,2}(0)\rangle. \quad (4.9)$$

Writing the mass eigenstates in favor of the flavor eigenstates gives

$$|D^0(t)\rangle = \frac{1}{2} \left(\left(e^{-i(m_1 - \frac{i}{2} \Gamma_1)t} + e^{-i(m_2 - \frac{i}{2} \Gamma_2)t} \right) |D^0\rangle + \frac{q}{p} \left(e^{-i(m_1 - \frac{i}{2} \Gamma_1)t} - e^{-i(m_2 - \frac{i}{2} \Gamma_2)t} \right) |\bar{D}^0\rangle \right), \quad (4.10)$$

$$|\bar{D}^0(t)\rangle = \frac{1}{2} \left(\frac{p}{q} \left(e^{-i(m_1 - \frac{i}{2} \Gamma_1)t} - e^{-i(m_2 - \frac{i}{2} \Gamma_2)t} \right) |D^0\rangle + \left(e^{-i(m_1 - \frac{i}{2} \Gamma_1)t} + e^{-i(m_2 - \frac{i}{2} \Gamma_2)t} \right) |\bar{D}^0\rangle \right). \quad (4.11)$$

1151 This qualitatively gives the correct behavior at $t = 0$, and as t moves forward, we see that
 1152 these states evolve, and have a time dependent probability of being measured as a D^0 or $\bar{D}^0$,
 1153 regardless of the flavor at production.

The next goal will be to write the time dependent decay rate of the D^0 and $\bar{D}^0$ mesons given a certain final state f . From Fermi's golden rule, we can write this decay rate as

$$\Gamma = |\mathcal{M}|^2 \Phi \quad (4.12)$$

where Φ is the Lorentz-invariant phase space integral. The part of importance to this discussion is the matrix element squared $|\mathcal{M}|^2$, as soon we will take a ratio of final states with equal phase space, thus the phenomenological discussion will focus on the matrix elements

squared. The particular matrix elements can then be written as

$$\langle f|\mathcal{H}|D^0(t)\rangle = \frac{1}{2} \left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} + e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \right) \langle f|\mathcal{H}|D^0\rangle + \frac{1}{2} \frac{q}{p} \left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} - e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \right) \langle f|\mathcal{H}|\bar{D}^0\rangle, \quad (4.13)$$

$$\langle f|\mathcal{H}|\bar{D}^0(t)\rangle = \frac{1}{2} \frac{p}{q} \left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} - e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \right) \langle f|\mathcal{H}|D^0\rangle + \frac{1}{2} \left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} + e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \right) \langle f|\mathcal{H}|\bar{D}^0\rangle. \quad (4.14)$$

It is constructive to introduce the shorthand for the amplitudes

$$\mathcal{A}_f = \langle f|\mathcal{H}|D^0\rangle, \quad (4.15)$$

$$\bar{\mathcal{A}}_f = \langle f|\mathcal{H}|\bar{D}^0\rangle, \quad (4.16)$$

$$\mathcal{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|D^0\rangle, \quad (4.17)$$

$$\bar{\mathcal{A}}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\bar{D}^0\rangle, \quad (4.18)$$

where $\bar{f}$ represents the CP conjugate of f . Equations 4.13 and 4.14 then become

$$\langle f|\mathcal{H}|D^0(t)\rangle = \frac{1}{2} \left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} + e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \right) \mathcal{A}_f + \frac{1}{2} \frac{q}{p} \left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} - e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \right) \bar{\mathcal{A}}_f, \quad (4.19)$$

$$\langle f|\mathcal{H}|\bar{D}^0(t)\rangle = \frac{1}{2} \frac{p}{q} \left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} - e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \right) \mathcal{A}_f + \frac{1}{2} \left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} + e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \right) \bar{\mathcal{A}}_f. \quad (4.20)$$

It is helpful to now introduce the notation

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}, \quad (4.21)$$

$$x = \frac{m_2 - m_1}{\Gamma}, \quad (4.22)$$

$$y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}. \quad (4.23)$$

The multiplication of the exponential factors in terms of the mixing parameters given in

Equations 4.21-4.23 can be written as

$$\left| e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} \right|^2 = e^{-\Gamma t} e^{y\Gamma t}, \quad (4.24)$$

$$\left| e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \right|^2 = e^{-\Gamma t} e^{-y\Gamma t}, \quad (4.25)$$

$$\left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} \right) (e^{-i(m_2 - \frac{i}{2}\Gamma_2)t})^* = e^{-\Gamma t} e^{-ix\Gamma t}, \quad (4.26)$$

$$\left(e^{-i(m_1 - \frac{i}{2}\Gamma_1)t} \right)^* (e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}) = e^{-\Gamma t} e^{+ix\Gamma t}. \quad (4.27)$$

Using these definitions, the matrix elements squared become

$$\begin{aligned} |\langle f | \mathcal{H} | D^0(t) \rangle|^2 &= \frac{e^{-\Gamma t}}{2} |A_f|^2 \left[\left(1 + \left| \frac{q}{p} \right|^2 \left| \frac{\bar{A}_f}{A_f} \right|^2 \right) \cosh(y\Gamma t) + \left(1 - \left| \frac{q}{p} \right|^2 \left| \frac{\bar{A}_f}{A_f} \right|^2 \right) \cos(x\Gamma t) \right. \\ &\quad + \left(\left(\frac{q\bar{A}_f}{pA_f} \right)^* + \left(\frac{q\bar{A}_f}{pA_f} \right) \right) \sinh(y\Gamma t) \\ &\quad \left. + \left(\left(\frac{q\bar{A}_f}{pA_f} \right)^* - \left(\frac{q\bar{A}_f}{pA_f} \right) \right) i \sin(x\Gamma t) \right] \end{aligned} \quad (4.28)$$

$$\begin{aligned} |\langle f | \mathcal{H} | \bar{D}^0(t) \rangle|^2 &= \frac{e^{-\Gamma t}}{2} |\bar{A}_f|^2 \left[\left(1 + \left| \frac{p}{q} \right|^2 \left| \frac{A_f}{\bar{A}_f} \right|^2 \right) \cosh(y\Gamma t) + \left(1 - \left| \frac{p}{q} \right|^2 \left| \frac{A_f}{\bar{A}_f} \right|^2 \right) \cos(x\Gamma t) \right. \\ &\quad + \left(\left(\frac{pA_f}{q\bar{A}_f} \right)^* + \left(\frac{pA_f}{q\bar{A}_f} \right) \right) \sinh(y\Gamma t) \\ &\quad \left. + \left(\left(\frac{pA_f}{q\bar{A}_f} \right)^* - \left(\frac{pA_f}{q\bar{A}_f} \right) \right) i \sin(x\Gamma t) \right] \end{aligned} \quad (4.29)$$

Now, we restrict ourselves to the case of the Right Sign (RS) $D^0 \rightarrow K^- \pi^+$ decay and its charge conjugate, and the Wrong Sign (WS) $D^0 \rightarrow K^+ \pi^-$ decay and its charge conjugate. The RS decay is named as such as it proceeds via Cabibbo favored decay, and the amplitude goes as $e^{-\Gamma t}$. The WS decay, however, has two viable decay routes: the decay can proceed either via direct Doubly-Cabibbo suppressed decay, or first via oscillation into the antiparticle (D^0 oscillates to $\bar{D}^0$ or vice versa), followed by Cabibbo favored decay. This is phenomenologically what we see in Equations 4.28 and 4.29.

1161

To move forward, we explicitly make the substitutions

$$\lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f} = - \left| \frac{q}{p} \right| R_f e^{i(\phi+\delta)}, \quad (4.30)$$

$$\lambda_{\bar{f}} \equiv \frac{q}{p} \frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}} = - \left| \frac{q}{p} \right| R_{\bar{f}} e^{i(\phi-\delta)}. \quad (4.31)$$

1162

Here, δ is the difference in strong phase between f and $\bar{f}$. We explicitly make the substitu-

1163

tions in the square braces of Equations 4.28 and 4.29:

$$\begin{aligned} |\langle f | \mathcal{H} | D^0(t) \rangle|^2 &= \frac{e^{-\Gamma t}}{2} |A_f|^2 \left[(1 + |\lambda_f|^2) \cosh(y\Gamma t) + (1 - |\lambda_f|^2) \cos(x\Gamma t) \right. \\ &\quad \left. + 2\text{Re}(\lambda_f) \sinh(y\Gamma t) - 2\text{Im}(\lambda_f) \sin(x\Gamma t) \right] \end{aligned} \quad (4.32)$$

$$\begin{aligned} |\langle f | \mathcal{H} | \bar{D}^0(t) \rangle|^2 &= \frac{e^{-\Gamma t}}{2} |\bar{A}_f|^2 \left[(1 + |\lambda_f^{-1}|^2) \cosh(y\Gamma t) + (1 - |\lambda_f^{-1}|^2) \cos(x\Gamma t) \right. \\ &\quad \left. + 2\text{Re}(\lambda_f^{-1}) \sinh(y\Gamma t) - 2\text{Im}(\lambda_f^{-1}) \sin(x\Gamma t) \right] \end{aligned} \quad (4.33)$$

1164

It is instructive to note that the term $2\text{Re}(\lambda_f) \sinh(y\Gamma t) - 2\text{Im}(\lambda_f) \sin(x\Gamma t)$ reduces to

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$2R_f y'^+ \Gamma t$ when expanding the sin and sinh to first order. The other terms, expanded to

1166

second order, leave one term which is the difference of the squares of x and y times $\Gamma^2 t^2$,

1167

which is small and neglected, and another term which reduces to $2 + R_f^2 \frac{x'^+ + y'^+}{2}$. Taking

1168

everything together, and factoring out the R_f , we are left with the quadratic forms

$$|\langle K^+ \pi^- | \mathcal{H} | D^0(t) \rangle|^2 \simeq e^{-\Gamma t} |A_{K^+ \pi^-}|^2 \left[R^+ + \sqrt{R^+} y'^+ \Gamma t + \frac{x'^+ + y'^+}{4} (\Gamma t)^2 \right], \quad (4.34)$$

$$|\langle K^- \pi^+ | \mathcal{H} | \bar{D}^0(t) \rangle|^2 \simeq e^{-\Gamma t} |A_{K^- \pi^+}|^2 \left[R^- + \sqrt{R^-} y'^- \Gamma t + \frac{x'^- + y'^-}{4} (\Gamma t)^2 \right], \quad (4.35)$$

1169

where we have noted that $|\bar{A}_{\bar{f}}| = |A_f|$, in accordance with no direct CPV in the RS decays.

1170

The explicit substitution for R_f in favor of $R^+ = \frac{|A_{K^+ \pi^-}|}{|A_{K^- \pi^+}|}$ and $R^- = \frac{|\bar{A}_{K^- \pi^+}|}{|\bar{A}_{K^+ \pi^-}|}$ yields the form

¹¹⁷¹ we will fit to.

Chapter 5

Overview of Analysis

This analysis is focused on measuring the mixing and CP violation parameters in the neutral meson system. As mentioned in Chapter 4, the goal is to fit the time dependent WS to RS ratio by the form

$$R^+(t) = R_D^+ + \sqrt{R_D^+} y'^+(t/\tau) + \frac{x'^{+2} + y'^{+2}}{4} (t/\tau)^2, \quad (5.1)$$

$$R^-(t) = R_D^- + \sqrt{R_D^-} y'^-(t/\tau) + \frac{x'^{-2} + y'^{-2}}{4} (t/\tau)^2. \quad (5.2)$$

All parameters corresponding to the “+” sign are for decays tagged as a D^0 at production, and those with a “-” are tagged as $\bar{D}^0$ at production. We consider three possibilities for the fit:

1. Mixing Only Fit: $R_D^+ = R_D^- = R_D$, $y'^+ = y'^- = y'$, and $x'^{2+} = x'^{2-} = x'^2$
2. No Direct CPV allowed: $R_D^+ = R_D^- = R_D$
3. All CPV allowed: all parameters are free to float.

We will measure these parameters using the events which follow the decay chain

$$\bar{B} \rightarrow \mu^- D^{*+} X$$

followed by

$$D^{*+} \rightarrow D^0 \pi_S^+$$

and finally

$$D^0 \rightarrow K \pi$$

This sample is referred to as the Doubly Tagged (DT) sample, as the flavor of the D^0 is tagged twice at production, once by the charge of the muon, and a second time by the oppositely charged characteristic lower momentum pion from the strong D^{*+} decay. Due to the characteristic low momentum, the tagging pion is called the “slow” pion, and is distinguished from all other pions by the subscript S .

There are two goals of the analysis:

1. Measure the mixing and CPV parameters of the D^0 system with the DT sample alone
2. Repeat the measurement combining the DT dataset with that of the 2013 measurement using prompt $D^{*+} \rightarrow D^0 \pi_S^+$ decays, followed by RS or WS D^0 decay [18].

The first goal is justified by the fact that the DT analysis on its own has roughly the same size as the older Belle [19], BaBar [20] and CDF [21] results. The second goal is justified by the fact that both the 2013 analysis, henceforth referred to as the “prompt” analysis, and the DT analysis come from the same dataset, common systematics can be taken into account and an LHCb wide average can be given.

The analysis has the additional benefit of providing an anchor in decay times which were inaccessible to the 2013 analysis due to stringent selection criteria which biased the decay time distributions of the sample. This is visualized in Figure 5.1, which shows the distribution of D^0 decay time for the prompt sample in black and for the DT sample in red. The strong turn off of the prompt sample at low decay times is caused by the trigger requirements, which are not present in the DT sample.

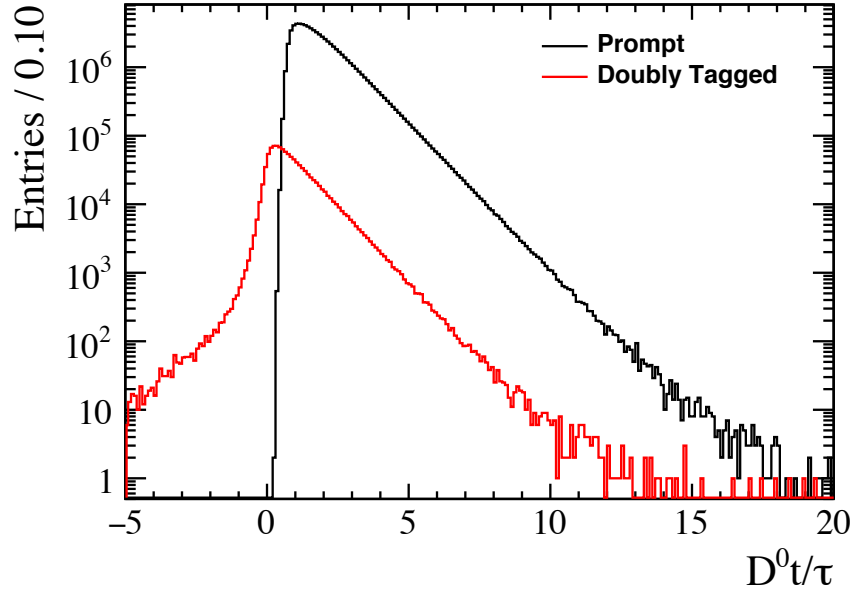


Figure 5.1: Decay time distribution of the prompt $D^* \rightarrow D^0 \pi_S$, $D^0 \rightarrow K^- \pi^+$ in black and the DT $\bar{B}^0 \rightarrow \mu^- D^{*+} X$, $D^{*+} \rightarrow D^0 \pi_s^+$, and Cabibbo favored $D^0 \rightarrow K^- \pi^+$ in red. In the lowest regions of D^0 decay time, the prompt sample cuts off, whereas the DT continues.

We study the combined fit of the DT and prompt analysis in Chapter 6.

Experimentally, we measure the observed yields of WS and RS decays. By dividing the data into bins of D^0 decay time, then extracting the WS and RS yields in each bin of decay time, we extract the WS/RS ratio as a function of decay time. These are the data which we will fit the form of of Equations 5.1 and 5.2. These extracted yields necessarily depend on detector effects such as differing reconstruction efficiencies for $K^+ \pi^-$ and $K^- \pi^+$ final states. Under the assumption that the efficiency of reconstructing the soft pion, the muon, and the efficiency of detecting the $K\pi$ final state are factorizable, the observed yields for each decay are

$$N_{RS+}^{\text{obs}} = N_{D^{*+}} \mathcal{B}(D^{*+} \rightarrow D^0 \pi_s^+) \mathcal{B}(D^0 \rightarrow K^- \pi^+) \epsilon(\mu^-) \epsilon(\pi_s^+) \epsilon(K^- \pi^+) \quad (5.3)$$

$$N_{WS+}^{\text{obs}} = N_{D^{*+}} \mathcal{B}(D^{*+} \rightarrow D^0 \pi_s^+) \mathcal{B}(D^0 \rightarrow K^+ \pi^-) \epsilon(\mu^-) \epsilon(\pi_s^+) \epsilon(K^+ \pi^-) \quad (5.4)$$

$$N_{RS-}^{\text{obs}} = N_{D^{*-}} \mathcal{B}(D^{*-} \rightarrow \bar{D}^0 \pi_s^-) \mathcal{B}(\bar{D}^0 \rightarrow K^+ \pi^-) \epsilon(\mu^+) \epsilon(\pi_s^-) \epsilon(K^+ \pi^-) \quad (5.5)$$

$$N_{WS-}^{\text{obs}} = N_{D^{*-}} \mathcal{B}(D^{*-} \rightarrow \bar{D}^0 \pi_s^-) \mathcal{B}(\bar{D}^0 \rightarrow K^- \pi^+) \epsilon(\mu^+) \epsilon(\pi_s^-) \epsilon(K^- \pi^+). \quad (5.6)$$

In these equations, N is the number of events, $\mathcal{B}$ is the branching fraction, and ϵ is the efficiency. As before, assuming negligible direct CPV in the Cabibbo favored RS decay, the ratio of WS to RS decays becomes

$$R^{\text{obs}+}(t) = \frac{N_{WS+}^{\text{obs}}(t)}{N_{RS+}^{\text{obs}}(t)} = R^+(t) \frac{\epsilon(K^+ \pi^-)}{\epsilon(K^- \pi^+)} \quad (5.7)$$

$$R^{\text{obs}-}(t) = \frac{N_{WS-}^{\text{obs}}(t)}{N_{RS-}^{\text{obs}}(t)} = R^-(t) \frac{\epsilon(K^- \pi^+)}{\epsilon(K^+ \pi^-)}. \quad (5.8)$$

In the case of possible peaking backgrounds which are not adequately accounted for, for instance true D^* decays which do not originate from $\bar{B} \rightarrow \mu D^* X$ decays, we can expand the Equations 5.7 and 5.8 to give the observed WS/RS ratio to be

$$R^{\text{obs}+} = \frac{N_{WS+}^{\text{obs}}}{N_{RS+}^{\text{obs}}} = R^+(1 - \Delta_{\text{peaking}}^+) \frac{\epsilon(K^+ \pi^-)}{\epsilon(K^- \pi^+)} \quad (5.9)$$

$$R^{\text{obs}-} = \frac{N_{WS-}^{\text{obs}}}{N_{RS-}^{\text{obs}}} = R^-(1 - \Delta_{\text{peaking}}^-) \frac{\epsilon(K^- \pi^+)}{\epsilon(K^+ \pi^-)}. \quad (5.10)$$

In these equations, we have defined the terms

$$\begin{aligned} \Delta_{\text{peaking}} &= f_{\text{peaking}} \left(1 - \frac{R_{\text{peaking}}(t)}{R(t)} \right) \\ &= f_{\text{peaking}} \left(1 - \frac{N_{WS,\text{peaking}}(t)/N_{RS,\text{peaking}}(t)}{N_{WS}(t)/N_{RS}(t)} \right) \end{aligned}$$

and $f_{\text{peaking}} \equiv \frac{N_{RS,\text{peaking}}}{N_{RS} + N_{RS,\text{peaking}}}$. A full derivation of this form is given in Appendix A.2. We finally also allow for backgrounds due to events which do not come from sources which

contribute to both WS and RS decays, which adds a final term to the end.

$$\begin{aligned}
R^{\text{obs}+} &= R^+(1 - \Delta_{\text{peaking}}^+) \frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} + p_{\text{other}}^+ \\
R^{\text{obs}-} &= R^-(1 - \Delta_{\text{peaking}}^-) \frac{\epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-)} + p_{\text{other}}^-.
\end{aligned}
\tag{5.11}$$

1209 For future convenience, we define $\epsilon_r^\pm \equiv \left(\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} \right)^{\pm 1}$. The analysis is performed blindly for
1210 the DT sample. Only after unblinding is the combination between prompt and DT samples
1211 performed.

Chapter 6

Expectations from Toy Monte Carlo

A series of pseudo-experiments were performed to understand the expected physics reach of the DT and prompt combination. In each of these so called toy Monte Carlo experiments, Right Sign $D^0 \rightarrow K^- \pi^+$ and Wrong Sign $D^0 \rightarrow K^+ \pi^-$, and their charge conjugate events are generated. The prompt sample is generated with 56 million events, roughly the same size as the published sample [18]. The doubly tagged sample is generated with 1.8 million $B \rightarrow \mu D^* X$ events, which is approximately the yield that is reported in Chapter 8. RS decays are generated using the approximation that there is no direct CPV in the Cabibbo favored decay, and the number of events is generated as $N_{D_{RS}^0} = N_{\bar{D}_{RS}^0} \propto e^{-t/\tau}$, where τ is the nominal D^0 decay time $\tau = 410.1$ ps [2]. Poisson fluctuations around this central value are then used. Events are generated in steps of 0.01 times the appropriate bin size for each sample. WS decays are then generated using

$$N_{D_{WS}^0} = e^{-t/\tau} \left(R_D + \sqrt{R_D} y' (\langle t \rangle / \tau) + \frac{x'^2 + y'^2}{4} \langle t^2 \rangle / (\tau)^2 \right), \quad (6.1)$$

where $\langle t \rangle$ is the average decay time in a bin. Samples are generated for both no CPV allowed and all CPV allowed. For these studies, the values of the D^0 mixing parameters are given in Table 6.1, and are drawn from the original prompt analysis.

To correctly account for the expected statistical errors in each bin of decay time, the WS

Table 6.1: Mixing parameters used in Monte Carlo pseudo-experiments drawn from the prompt analysis.

Parameter	Value
No CPV	
R_D	3.55×10^{-3}
x'^2	5.48×10^{-5}
y'	4.81×10^{-3}
CPV Allowed	
R_D^+	3.545×10^{-3}
x'^2+	4.9×10^{-5}
y'^+	4.78×10^{-3}
R_D^-	3.591×10^{-3}
x'^2-	5.99×10^{-5}
y'^-	4.83×10^{-3}

sample is altered by adding the expected background per bin,

$$\text{Expected Background}(\text{time bin } i) = B_i = \sigma^2(N_{WS}^i) - N_{WS}^i. \quad (6.2)$$

1228 The observed background is modeled as poisson noise around the expected background, b_i .

1229 The generated WS yields and statistical errors are then given by

$$\text{WS Yield} = N_{WS}^i + b_i - B_i, \quad (6.3)$$

$$\text{WS Error} = \sqrt{N_{WS}^i + b_i}. \quad (6.4)$$

1230 The error on the ratio of WS to RS is then given by

$$\delta(WS/RS) = \sqrt{\frac{n(WS)}{n(RS)^2} + \frac{n(WS)^2}{n(RS)^3}}. \quad (6.5)$$

1231 The same is done for both prompt and DT samples. The expected number of background
1232 events for the prompt sample is taken from the prompt analysis. As the DT sample is
1233 blind at the time of this study, the assumption is made that background distributions for

1234 RS and WS are the same with differing statistics. The WS background is given by the RS
 1235 background which is scaled by a factor of 0.0435838 to account for the different number
 1236 of events in each sample, which is determined from data. An example WS/RS ratio as a
 1237 function of decay time is given in Figure 6.1.

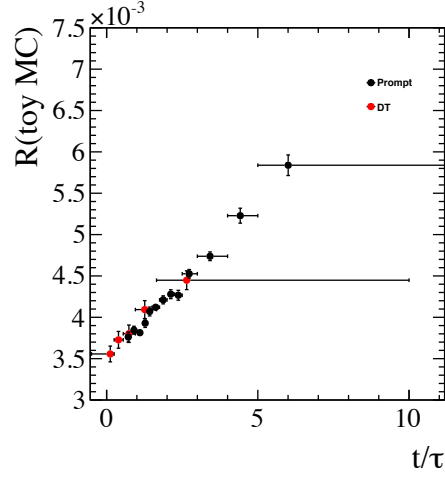


Figure 6.1: WS/RS ratio as a function of decay time for one pseudo-experiment with both the prompt (black) and the doubly tagged (red) $D^0 \rightarrow K\pi$.

The prompt sample also uses an empirical decay time acceptance function

$$1 - p_0 e^{(-p_1 t)} \quad (6.6)$$

1238 defined for $t > 0.6\tau$, to model the actual decay time acceptance of the LHCb detector for
 1239 $D^{*\pm}$ produced directly from the pp collision. No such acceptance is used for the DT sample,
 1240 as the B flight distance allows for triggering without such a decay time acceptance applied.
 1241 The samples are then fit using the form in Equations 5.1 and 5.2, the parameters extracted,
 1242 and the distributions of the residual between the input and extracted events, normalized
 1243 by the error in the event, or the pull, for each parameter is calculated. Additionally the
 1244 correlations are approximated for all parameters. This process is repeated one thousand
 1245 times. The results for the no CPV toys are given in Section 6.1, and for all CPV allowed are
 1246 given in Section 6.2

6.1 No CPV allowed

Figure 6.2 shows the pull distributions for the prompt only and prompt+DT samples, and Figure 6.3 shows the resulting central values and errors for the 1000 generated pseudo-experiments. These pseudo-experiments are unbiased and show a 17% improvement in the error on R_D and 14% improvement on the error of y' compared to the prompt sample alone fit. This is equivalent to adding 30-40% more prompt data to the existing 2011+2012 prompt analysis. Additionally, the correlations between parameters are given in Figures 6.4 and 6.5.

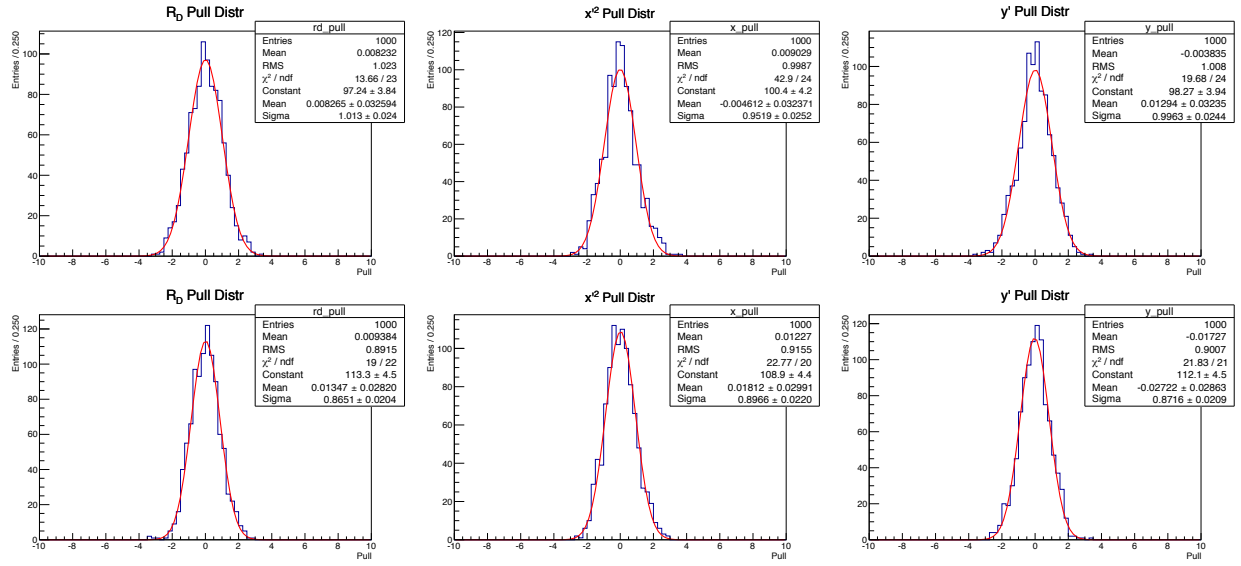


Figure 6.2: Pull distributions for Prompt only (top) and prompt+DT pseudo-experiments not allowing any CPV. Each of the prompt and prompt+DT samples have 1000 generated pseudo-experiments.

6.2 All CPV allowed

6.2.1 Without Statistical Dilution

To first check that the same gains are made in the all CPV allowed case, 1000 pseudo-experiments are generated without the statistical dilution of the WS background. The pulls remain unbiased, and the resulting errors are improved by 20% for $R_D^\pm$ and 16% for $y'^{\pm}$. The

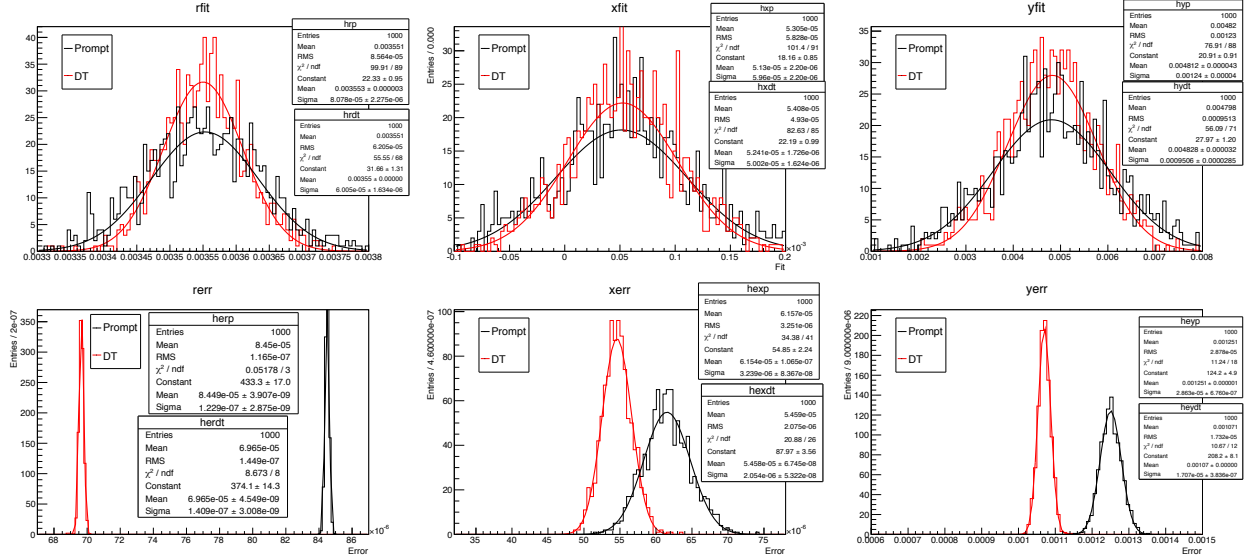


Figure 6.3: Mean values (top row) and errors (bottom row) of R_D (first column), x^2 (middle column) and y' (right column) from 1000 pseudoexperiments generated and fit. Red lines are the Prompt + DT sample, black lines indicate only using the prompt sample. A clear improvement in errors is seen with the addition of the DT sample.

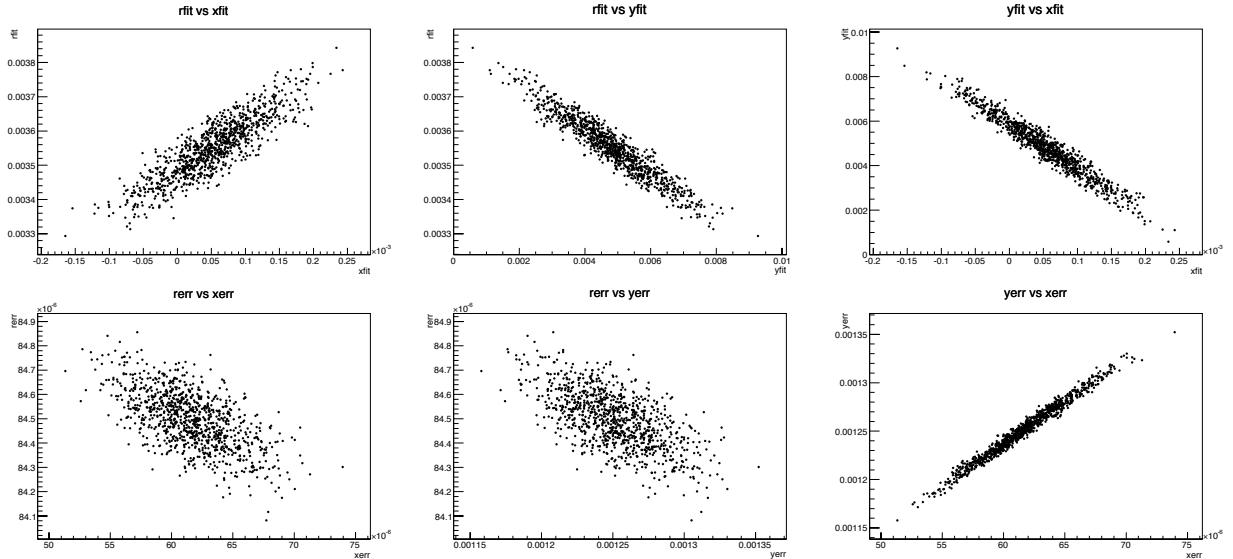


Figure 6.4: Correlation between variables of the 1000 pseudo-experiments fitting only with the prompt generated sample. Correlations between the fitted values are given on the top row, and the errors on the bottom.

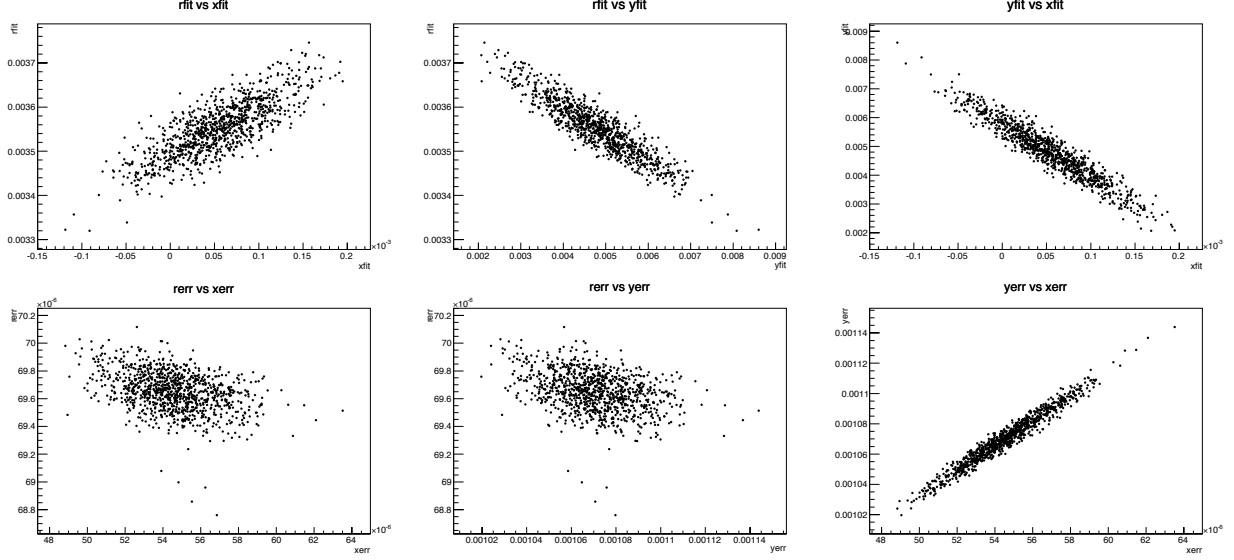


Figure 6.5: Correlation between variables of the 1000 pseudo-experiments fitting with the prompt+DT generated sample. Correlations between the fitted values are given on the top row, and the errors on the bottom.

pull distributions are given in Figure 6.6 and the resulting errors are given in Figure 6.7.

6.2.2 With Statistical Dilution

Allowing statistical dilution of the WS background in the all CPV allowed case, the pull width increases from unity for both the prompt and the prompt+DT samples, indicating that the extracted errors for this sample should be regarded as preliminary. These results are that the errors on $R_D^\pm$ increase by 11% and $y^\pm$ by 9%. The pull distributions are given in Figure 6.8, and the errors are shown in Figure 6.9.

6.2.3 Toy studies of combinations of Prompt and DT results

To understand the best way of combining the DT and prompt results, we test two possibilities: fitting both the prompt and DT simultaneously, as in the previous sections of this chapter, versus the possibility of fitting each sample independently, then combining in a global fit combination, using the tools described in Appendix A.8. We use the all CPV allowed toy MC without statistical dilution to gauge this effect. The process is done in the following

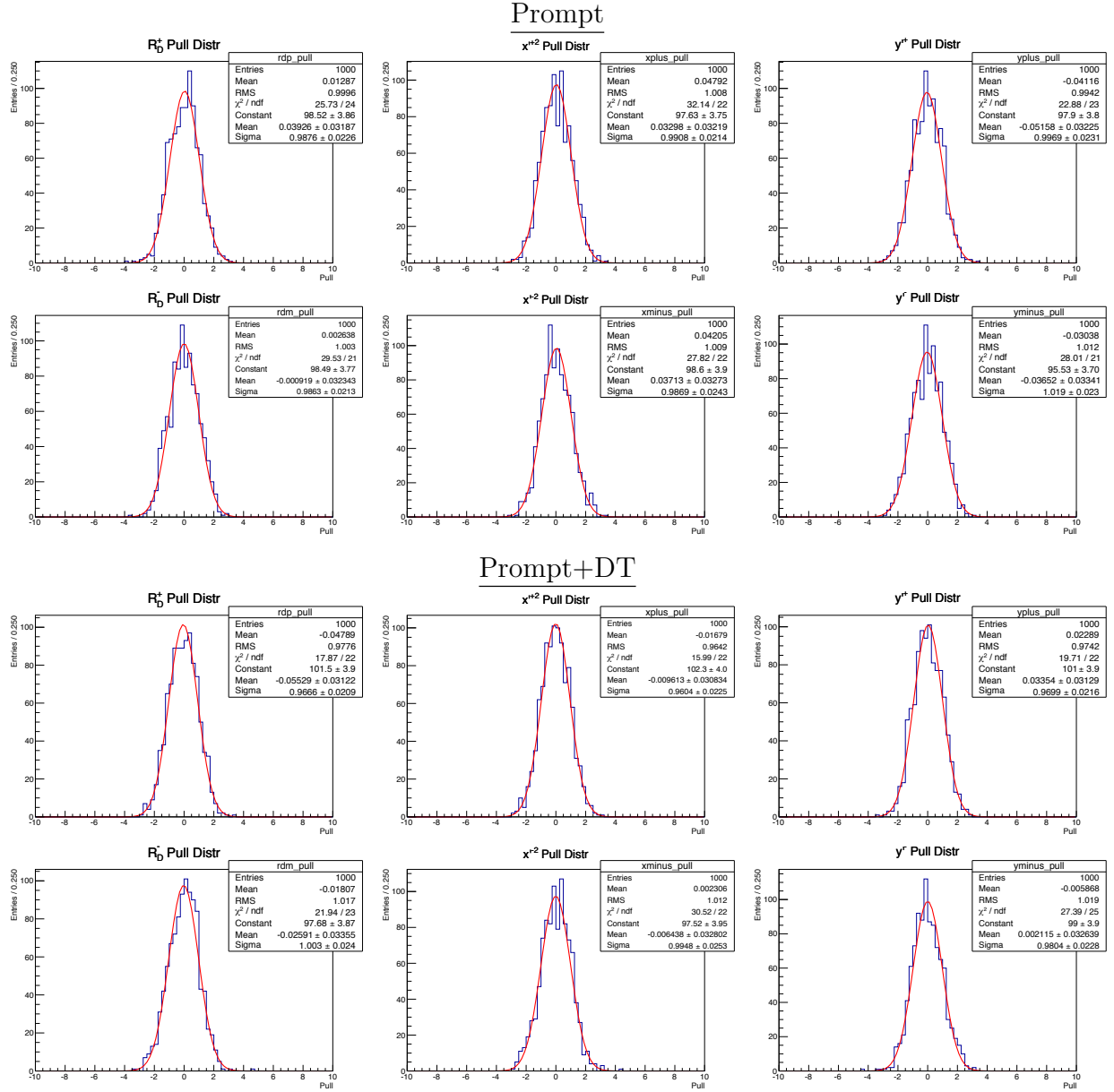


Figure 6.6: Pull distributions of the all CPV allowed fit without statistical dilution of the WS errors. The first six are for the prompt only sample, with the latter six containing the combined prompt and DT samples.

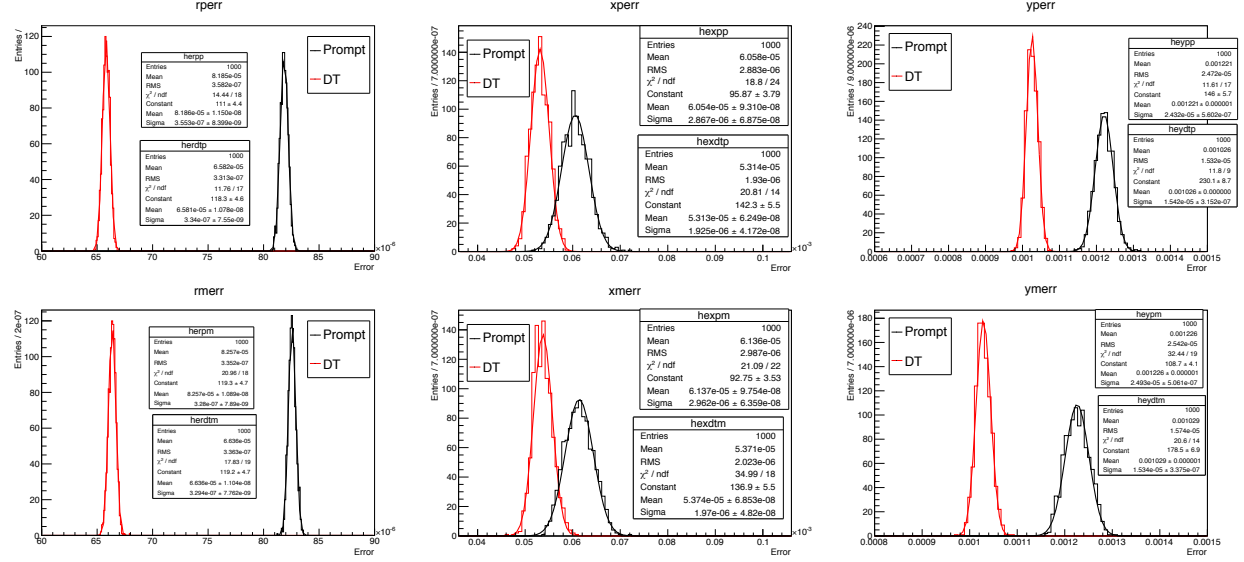


Figure 6.7: Error values from the fits of 1000 pseudo-experiments allowing all CPV, excluding statistical dilution of the WS sample.

manner:

1. Generate the Prompt and DT datasets as above.
2. Fit Prompt alone, extract its covariance matrix.
3. Fit DT alone, extract its covariance matrix.
4. Fit DT and Prompt in combination, as above.
5. Fit DT and Prompt in combination using the form in Appendix A.8, using the extracted covariance matrices.

The results are then analyzed with the generated values to understand the contributions to the pulls and errors of the above fits. These are summarized in Figures 6.10 and 6.11.

What is observed is that the global fit creates a bias on the observed mixing parameters that is not present in the prompt only fit or the fit to prompt and DT simultaneously. Additionally, the fits themselves can produce a lower error, but with a result which varies more from the nominal parameters, which then bias the measurement. This behavior is expected because the statistical power of the combined sample is larger than that of the two

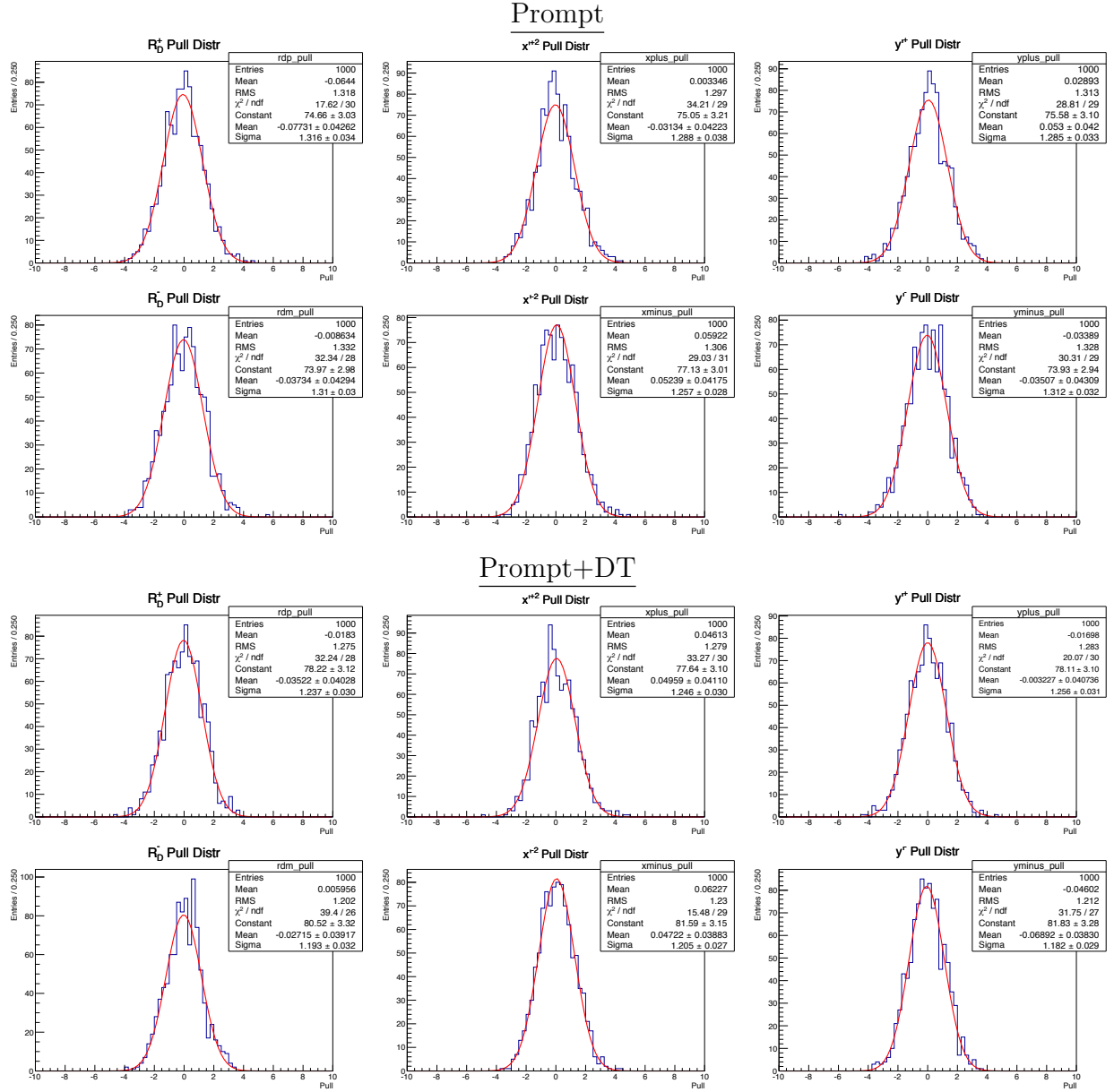


Figure 6.8: Pull distributions of the all CPV allowed fit with statistical dilution of the WS errors. The first six are for the Prompt only $R_D^\pm$, $x^{*2\pm}$ and $y^\pm$, with the latter six containing the prompt+DT samples.

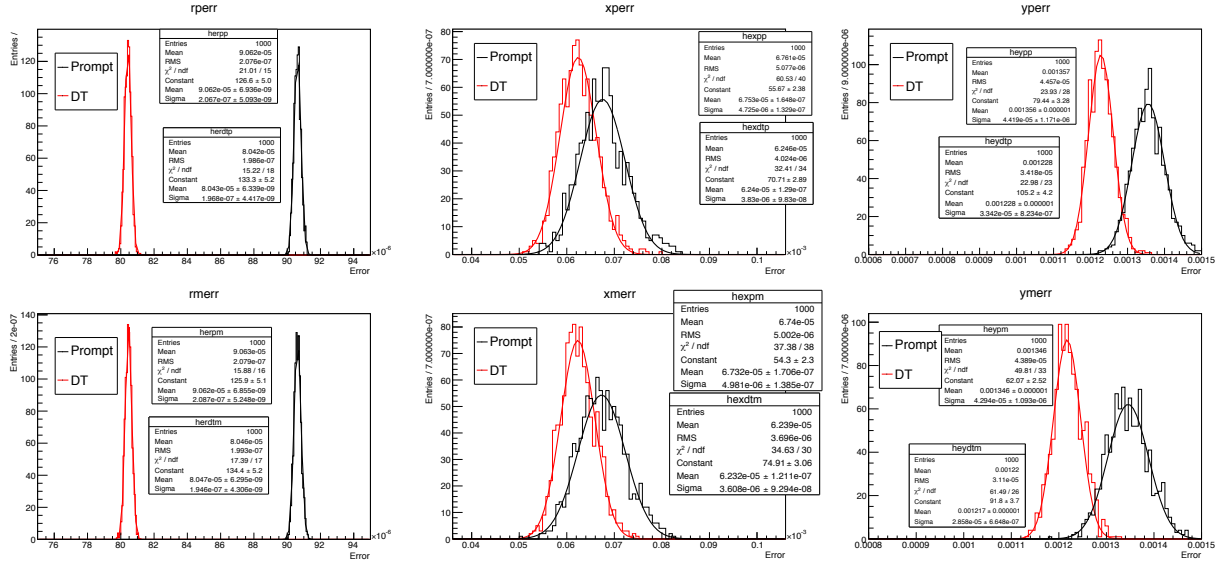


Figure 6.9: Error values from the fits of 1000 pseudo-experiments allowing all CPV, including statistical dilution of the WS sample.

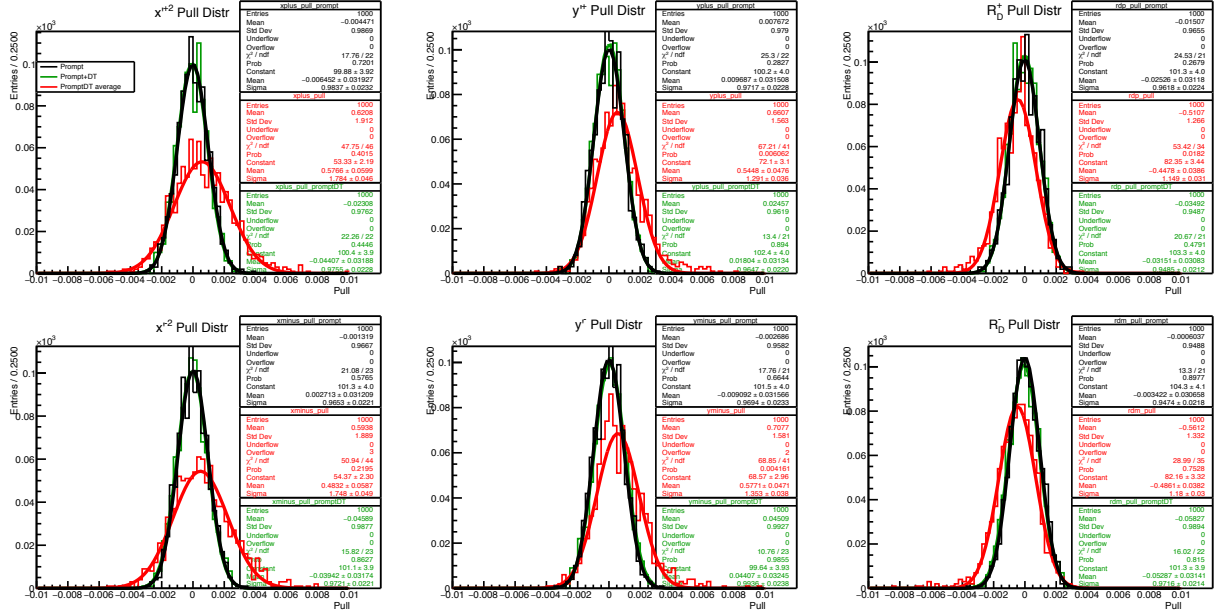


Figure 6.10: Pull distributions of toy MC with fits using different ways of combining the prompt and DT datasets. The black fits and histograms correspond to the prompt only dataset, the green histograms correspond to the combined fit to mixing parameters of the prompt and DT datasets, and the red corresponds to the fits of the prompt and DT datasets individually, then combined using an HFAG like fit.

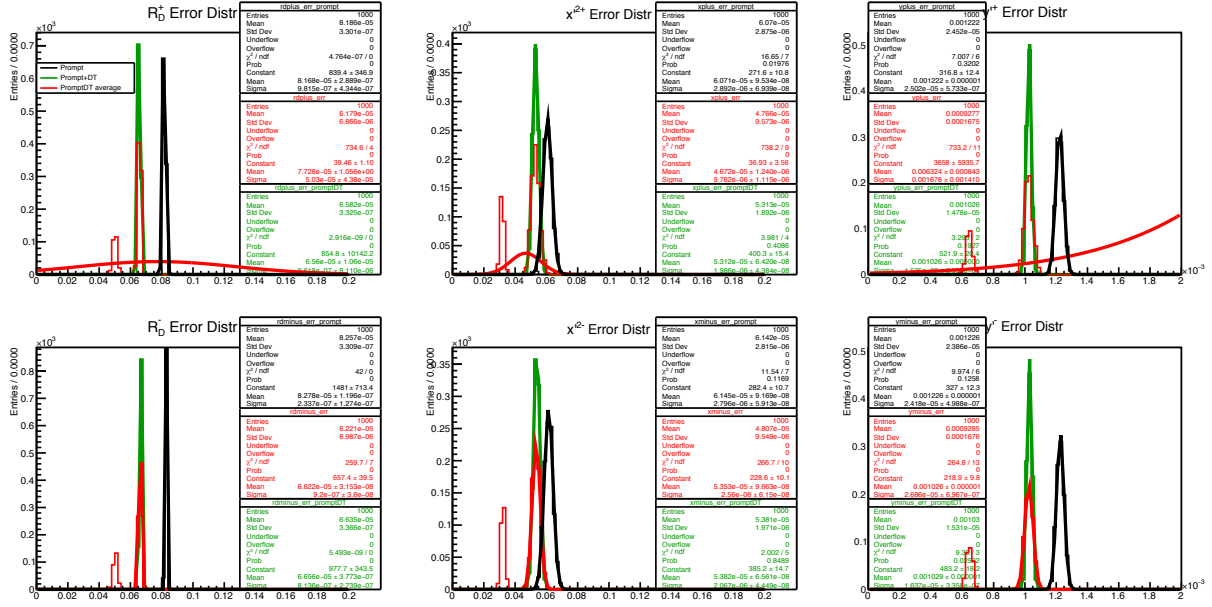


Figure 6.11: Error distributions of toy MC with fits using different ways of combining the prompt and DT datasets. The black fits and histograms correspond to the prompt only dataset, the green histograms correspond to the combined fit to mixing parameters of the prompt and DT datasets, and the red corresponds to the fits of the prompt and DT datasets individually, then combined using an HFAG like fit.

1286 datasets split, and a naive weighted average will not adequately reproduce the errors of the
1287 combined sample. It is for this reason that when providing the LHCb mixing average, we
1288 only use the combined fit of prompt and DT, not the combination of the individual results.
1289 Additionally, the combined fit has the advantage of accounting for correlated systematic
1290 uncertainties in the fit itself, whereas the procedure would be quite complex for the global
1291 combination fit.

Chapter 7

Event Selection

Events corresponding to the DT sample are first selected from a reduced, or *stripped*, dataset. Stripping is a process which filters interesting events from the huge LHCb dataset and places these events into smaller files, allowing for faster processing and analysis. The selection criteria of the stripping of interest for this analysis are listed in Table 7.1.

In this table, the direction angle is defined as the angle between the momentum vector of a particle and a line connecting the origin and decay vertices. The vertex χ^2 , χ_{vertex}^2 , comes from a kinematic fit of daughter tracks to a common point. This point is the decay vertex of the mother particle. The PV displacement is the displacement of any vertex described above from the primary vertex (PV) of the pp interaction region. The corresponding displacement χ^2 comes from the fit to this distance. The requirement on $z_{D^0} - z_B$ is only a safety check that the D^0 candidate is reconstructed. The variable $\Delta\log(\mathcal{L}_{x-y})$ contains information about particle identification. It incorporates information from the RICH detectors, muon systems and calorimeters into a likelihood of a particle being of type x (more positive) or of type y (more negative). The Ghost probability is a variable which quantifies the probability of a track being misreconstructed, otherwise known as a ghost. The variable χ_{track}^2 gives the quality of the track fit. The χ_{IP}^2 variable, or minimum Impact Parameter χ^2 , is the difference between the PV reconstructed with and without a track in question. Finally the variable Δm is the difference in mass between the $K\pi\pi_S$ combination and the $K\pi$ combination.

Table 7.1: Cuts from the stripping selection of the DT sample.

Variable	Stripping Selection Criteria
$m(\mu D^*)$	$[2.5, 6.0]$ GeV
Cosine of B Direction Angle	> 0.999
$z_{D^0} - z_B$	> -9999 mm
$\chi^2_{\text{vertex}}/\text{DoF}(B)$	< 6.0
$m(K\pi)$	$ m(K\pi) - m_{\text{PDG}}(D^0) < 80$ MeV
$\chi^2_{\text{vertex}}/\text{DoF}(D^0)$	< 6.0
D^0 PV Displacement χ^2	> 100
Cosine of D^0 Direction Angle	> 0.99
$p_T(\mu)$	> 1.2 GeV
$p(\mu)$	> 3 GeV
μ Ghost Probability	< 0.5
$\chi^2_{\text{track}}(\mu)$	< 4.0
Minimum Impact Parameter $\chi^2_{\text{Primary}}(\mu)$	> 9.0
Muon $\Delta \log(\mathcal{L}_{\mu-\pi})$	> -0.0
$\chi^2_{\text{track}}(K)$	< 4
$p(K)$	> 2 GeV
$p_T(K)$	> 300 MeV
K Ghost Probability	< 0.5
Minimum Impact Parameter $\chi^2_{\text{Primary}}(K)$	> 9
Kaon $\Delta \log(\mathcal{L}_{K-\pi})$	> 4.0
$\chi^2_{\text{track}}(\pi)$	< 4
Daughter pion $\Delta \log(\mathcal{L}_{K-\pi})$	< 4.0
$p(\pi)$	> 2 GeV
$p_T(\pi)$	> 300 MeV
Ghost Probability π	< 0.5
Minimum Impact Parameter $\chi^2_{\text{Primary}}(\pi)$	> 9
$p_T(K) + p_T(\pi)$	> 1.4 GeV
Distance of Closest Approach (K, π)	< 20 mm
Δm	$0 < \Delta m < 170$ MeV
$\chi^2_{\text{vertex}}/\text{DoF}(D^*)$	< 8.0

7.1 Decay Chain Refitting

When creating the final data file before analysis, the decay chain is refit using kinematic constraints [22]. In this framework, K and π are constrained to come from a common vertex (the D vertex); The D , slow π and the μ are constrained to come from the same vertex (the B vertex). No constraints on the mass of any of the mother or intermediate particles is applied, nor is a constraint for the mother to come from the primary vertex.¹ The effect of the application of this algorithm is most readily seen in the improvement of the resolution of the mass difference between the $D^{*\pm}$ and D^0 candidates (Δm). The RS and WS Δm distribution before and after this constraint is shown in Figure 7.1. The resolution is improved by about a factor of 2.

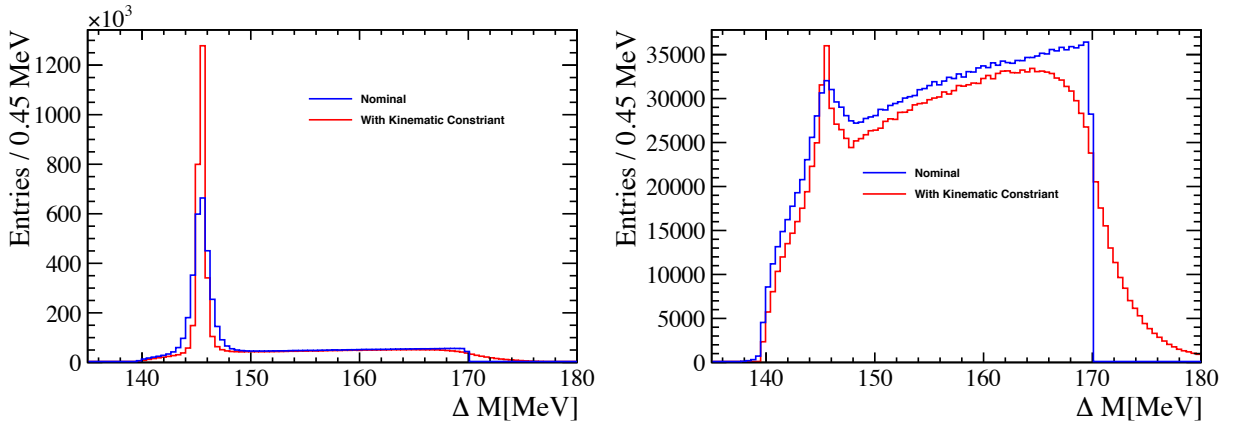


Figure 7.1: Comparison of the Δm distribution of the DT decay before and after applying kinematic constraints to the decay chain. The full dataset is shown. RS decays are shown on the left, and WS on the right. Blue corresponds to the nominal stripping level cuts, red corresponds to the distribution after applying the constraints.

7.2 Overlap of Prompt and Doubly Tagged Datasets

Candidates which appear in both the prompt and DT sample are vetoed from the DT dataset. This procedure is used to make the sample corresponding to the 2013 analysis of prompt

¹As there is an undetected neutrino in the event, the decay does not fulfill the kinematic conditions for the momentum vector of the B candidate to point to the primary vertex.

$D^{*\pm}$ [18] and DT samples are statistically independent, and also to remove at least part of the background associated to prompt D^* decay combined with a wrong muon. The vetoing procedure is accomplished by matching the unique run and event number for data taken in 2011, and in the 2012 sample the run number, event number, momentum components of the K , π and the transverse momentum of the π_S for data taken in 2012. The only reason for separated matching for different years is that the prompt analysis was performed with a different reconstruction than is used in the DT analysis for 2011 data. Therefore, if events enter both samples, the unique run and event number is enough to veto the event. In this vein, the kinematic vetos on the 2012 dataset are simply added as an extra precaution.

To understand the effect on the DT sample, we examine the distribution of the impact parameter χ^2 distribution with respect to the PV. As stated above, this variable is defined as the difference in χ^2 of the fit of the primary vertex of the event when reconstructed involving the track or particle in question. For this reason, tracks or particles which emerge from a secondary vertex are expected to have a larger χ_{IP}^2 than those of tracks which emerge from the primary vertex. The distributions for the complete DT sample in blue and the subset of events which are matched to the Prompt sample in red are shown in Figure 7.2 as a function of natural logarithm of the $D^0 \chi_{\text{IP}}^2$. The sample is not background subtracted. What is seen is that the subset of events matched to the prompt sample all fall below $\chi_{\text{IP}}^2 \leq 9$, and the DT distribution extends well into the high χ_{IP}^2 range, as expected. The total number of matched RS events is 12000. When running over the WS sample, we find 211 matches. The reduction in RS signal after rejecting matched candidates is 8 per mille and for the WS a reduction of 10 per mille. The integral of the sample matched to prompt over the total sample integral is 1.1%. We estimate a systematic uncertainty for this choice in section 13.3.4.

7.3 Final Candidate Selection

A number of offline selection criteria are applied to further separate signal and background. These so-called “cuts” are based largely on the selection criteria from the prompt $D^* \rightarrow D^0 \pi_S$

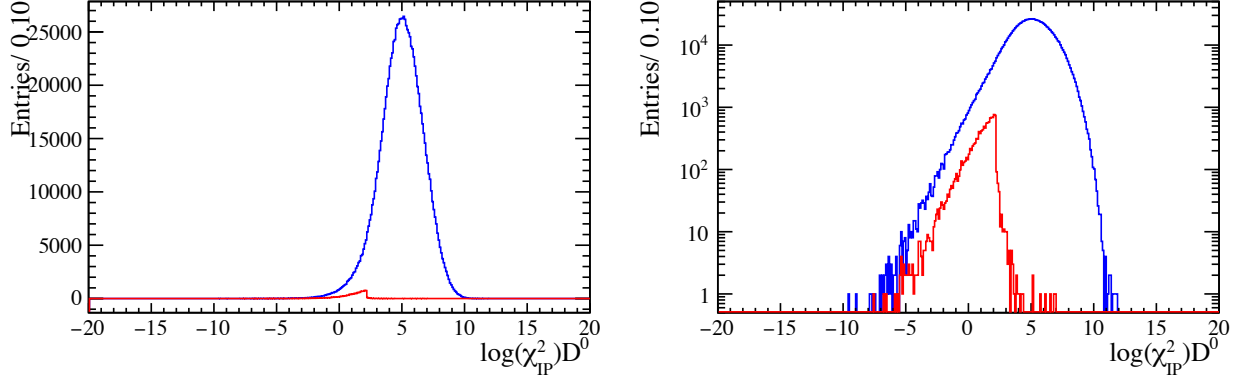


Figure 7.2: Distribution of the natural logarithm of χ^2_{IP} of the D^0 candidates which pass the nominal selection criteria (blue) and those which are matched to the prompt sample (red). Linear scale is on the left, and semilog y on the right.

1351 analysis of 2011 and 2012 data [18], though also include specific cuts for use in the DT sample.
 1352 These cuts are listed in Table 7.2. In the table, $m(D^0)_{\text{Decay Chain Refit}}$ corresponds to the cut
 1353 on the D^0 invariant mass after the refit of the decay chain using kinematic constraints.

Table 7.2: Offline selection criteria for DT sample.

Variable	Cut Value
$m(\mu D^*)$	$3.1 < m(\mu D^*) < 5.1$ GeV
K_PIDK	> 8
π _PIDK	< -5
$\Delta \log(\mathcal{L}_{e-\pi})(\pi_S)$	< 1
π_S _ProbNNghost	< 0.35
$ m(D^0)_{\text{Decay Chain Refit}} - 1864.86 $	< 24 MeV
$ m(D^0 \rightarrow KK \text{ as } D^0 \rightarrow K\pi) - 1864.84 $	> 40 MeV
$ m(D^0 \rightarrow \pi\pi \text{ as } D^0 \rightarrow K\pi) - 1864.84 $	> 40 MeV
π_S isMuon	False
μ isMuon	True
μ ProbNNmu	> 0.4
Decay Chain Refit χ^2/NDF	< 100

1354 In this table, the variable isMuon is a simple boolean which states whether or not a track
 1355 has hits in the muon station and is consistent with being a muon candidate. The variable
 1356 ProbNNmu is a probability based on the input variables from the RICH, muon stations,

calorimeters and tracking subdetectors. Finally, Decay Chain Refit χ^2 relates to the χ^2 of the kinematic constraints defined in Section 7.1.

The DT candidates are required to pass both hardware and software level trigger requirements on the muon candidate in the event. The muon is a common thread between RS and WS decays, therefore any bias induced on the muon will cancel to first order in the ratio of WS to RS decays. The candidates are specifically required to have been selected by the muon criteria in the hardware trigger. For the software level trigger, first a single high p_T muon detached from the PV is required, and afterwards required to pass a bonsai boosted decision tree selection of 2, 3 or 4 tracks in the final state, with one of the tracks being the muon candidate. These selections are the same for both RS and WS samples. The final selection on the muon candidate is discussed in the following section.

7.4 Muon Selection Criteria

To suppress random muon backgrounds and to ensure good muon selection, a so-called “tag and probe” analysis is performed on the sample $B \rightarrow J/\psi K_S$, with $J/\psi \rightarrow \mu^+\mu^-$ and $K_S \rightarrow \pi^+\pi^-$. The reason that we call this a “tag and probe” analysis is that the sample taken specifically has two similar particles in the final state; in our case, these are the muons from the J/ψ decay. We then take one of the muons as a “tag” muon, to which we apply a certain selection criteria on, then use the other as a probe of the variable to be studied. In our case, the goal is to tune the neural network probability that the track is actually a muon. This variable is called ProbNNmu.

The initial selection criteria of the sample are listed in Table 7.3, where the decay length significance is calculated by the projection of the momentum of a particle onto a line connecting the PV and the particle, divided by the error on the length of flight. This criteria simply ensures that the K_S^0 candidate has a significant flight distance. The same vertex and kinematic constraints which are applied to the $B \rightarrow \mu D^* X$ sample described above are used, and only tracks which are reconstructed in all tracking substations are considered;

Table 7.3: Selection criteria for $B \rightarrow J/\psi K_S$ sample.

Variable	Stripping Cut	Offline Selection
$p(\pi^\pm)$	$> 2 \text{ GeV}$	-
$ m(K_S) - m(K^0)_{PDG} $	$< 35 \text{ MeV}$	$490 < m(K_S) < 507 \text{ MeV}$
$\chi^2_{\text{vertex}}(K_S)$	< 20	-
$\chi^2_{ip}(\text{PV})(K_S)$	> 9	-
K_S PV Decay Length Significance	> 5	
$\pi^\pm$ ProbNNghost	-	< 0.5
$\mu^\pm$ PIDmu	> 0	-
$p_T(\mu^\pm)$	$> 500 \text{ MeV}$	-
$p(\mu^\pm)$	-	$> 5 \text{ GeV}$
$\chi^2_{\text{vertex}}(J/\psi)$	< 16	-
$m(J/\psi)$	$3020 < m(J/\psi) < 3180 \text{ MeV}$	$3070 < m(J/\psi) < 3130 \text{ MeV}$
$\mu^\pm$ ProbNNghost	-	< 0.5
$m(B)$	$5100 < m(B) < 5500 \text{ MeV}$	-
$\chi^2_{\text{vertex}}(B)/ndf$	< 10	-
$\tau(B)$	$> 0.2\text{ps}$	-

this is done in order to mimic the DT sample as closely as possible. To avoid events which cannot be reconstructed by the kinematic constraints, the fit to these constraints is required to converge. The result applied to 2012, magnet down data is shown in Figure 7.3. The fit models are double gaussian + exponential for the dimuon invariant mass, double gaussian + second order polynomial for the dipion invariant mass, and single gaussian plus exponential background for the $J/\psi K_S$ invariant mass. The extracted yields are $(54.55 \pm 2.07) \times 10^3$ J/ψ candidates, $(52.12 \pm 0.89) \times 10^3$ K_S candidates and, after selection criteria, $(10.75 \pm 0.17) \times 10^3$ B candidates.

To evaluate the tag and probe method, one muon is chosen, say the μ^+ . The ProbNNmu value of this muon is then constrained to be greater than a given value. This is referred to as the tagging muon. The analysis is performed for tags of 0.3, 0.4, 0.5, 0.6 and 0.9, as the probability ranges from 0 to 1. The other muon is then referred to as the probe muon. The value of ProbNNmu for that muon is then varied from being greater than 0.1 to greater than 0.9. The tag and probe definitions are performed for each muon. The signal fit model described above for the B candidates is fixed from the above fit and applied to each

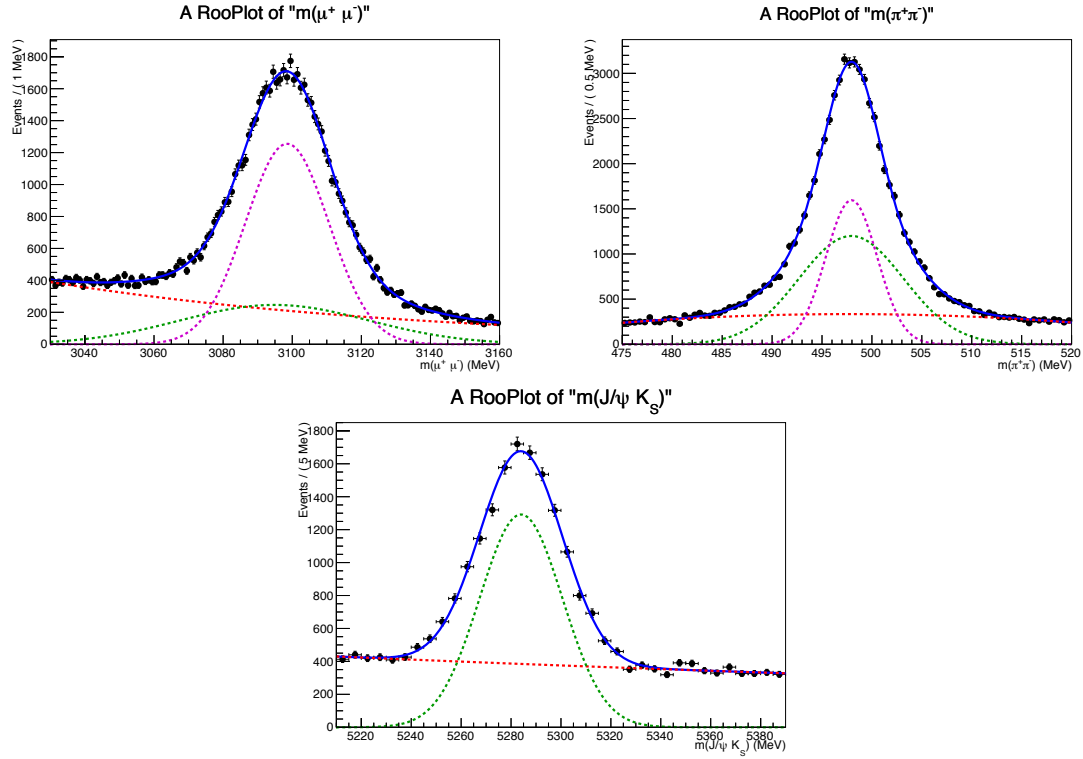


Figure 7.3: Invariant mass distributions of the $B \rightarrow J/\psi K_S$ sample. The top left plot shows the dimuon invariant mass, the top right the dipion invariant mass, and the bottom the $J/\psi K_S$ invariant mass.

individual sample. To ensure that the sample is unbiased by trigger selections, the event is required to be triggered by something other than the muons in both the hardware and software triggers. The effectiveness of the cut on ProbNNmu is defined by the efficiency of a cut and the background rejection of the cut. The quantities are defined as

$$\text{Efficiency} = \frac{n_{\text{sig},\text{pass}}}{n_{\text{sig},\text{pass}} + n_{\text{sig},\text{fail}}} \quad (7.1)$$

$$\text{Background Rejection} = 1 - \frac{n_{\text{bkg},\text{pass}}}{n_{\text{bkg},\text{pass}} + n_{\text{bkg},\text{fail}}}, \quad (7.2)$$

where $n_{\text{sig},\text{pass}}$ define the number of signal candidates which pass the cut, $n_{\text{sig},\text{fail}}$ are signal events which fail the cut, and $n_{\text{bkg},\text{pass}}, n_{\text{bkg},\text{fail}}$ are the same quantities for the number of background events in the region of interest. The pass and fail quantities are given to make the datasets statistically independent. The efficiency and background rejection distributions are shown in Figure 7.4

From the values reported in Figure 7.4, a cut at ProbNNmu > 0.4 gives roughly 90% efficiency with a background rejection of 70% which is consistent over all tag values and charge. In addition, the curves for different charges of tagging muon move together, indicating that there will not be an induced charge asymmetry by applying the cut.

The sample is also divided into 5 bins of approximately equal population of probe muon momentum to search for possible biases. The values of momentum used for the cuts are shown in Figure 7.5 and are given numerically in Table 7.4. Each bin is fit as described above. The results are shown in Figures 7.6-7.8 for tag values of 0.3, 0.4 and 0.5.

While there is a clear momentum dependence, the lack of charge dependence ensures that we will not introduce a bias with this cut. We choose a cut of ProbNNmu > 0.4 . For bookkeeping, we list the efficiency of the cut per tag value in Table 7.5 and plot these values in Figure 7.9.

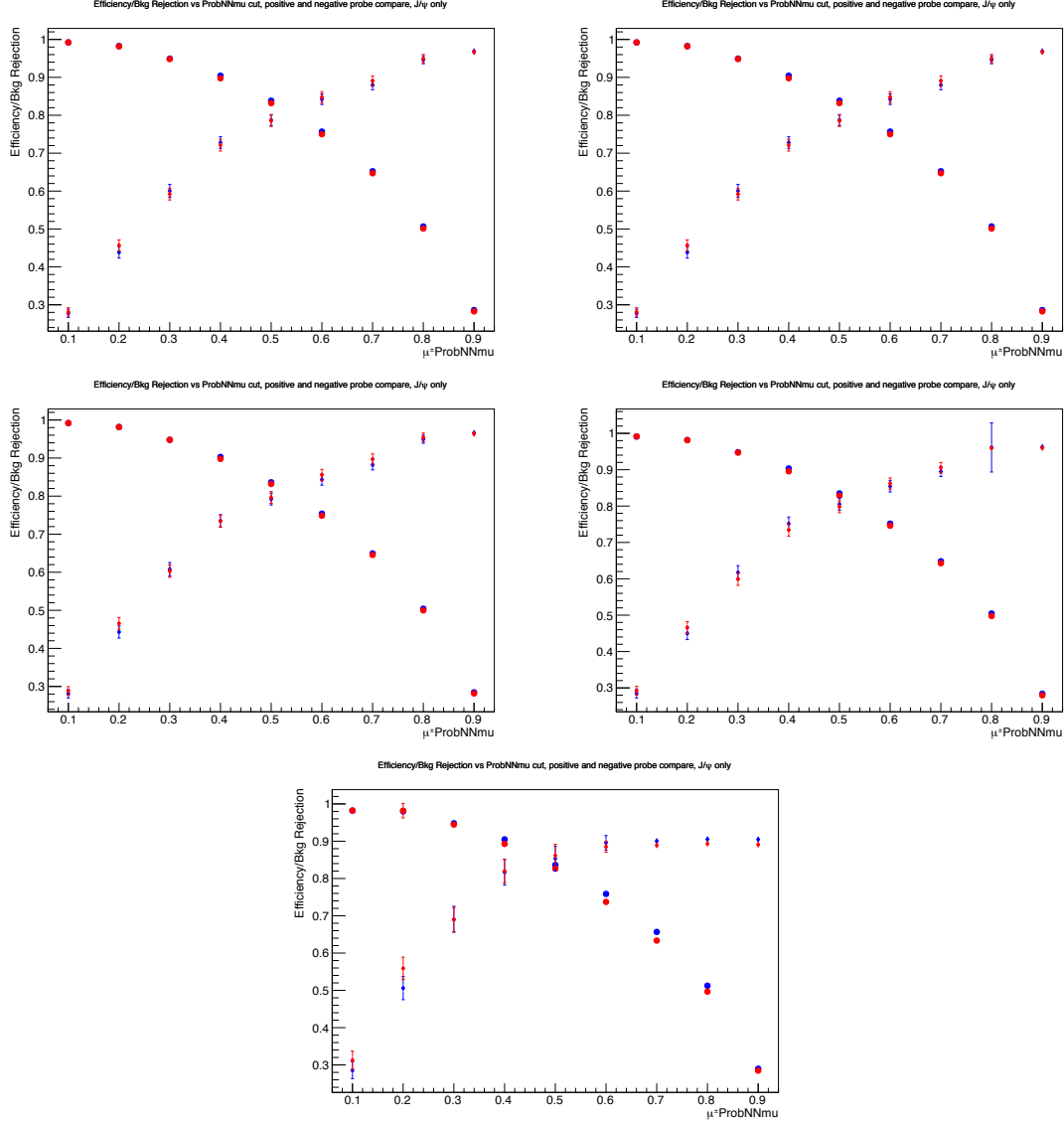


Figure 7.4: Signal efficiency and background rejection curves for the ProbNNmu variable. The blue points indicate the sample using the μ^+ as the probe, the red with the μ^- as the probe. Circles represent efficiency and diamonds represent background rejection. Top left represents a tag value of 0.3, top right 0.4, center left 0.5, center right 0.6 and bottom 0.9.

Table 7.4: Numeric values for bin boundaries of muon momentum for Tag and Probe analysis.

Bin Number	Cut Range
1	< 10750
2	$10750 \leq p < 16750$
3	$16750 \leq p < 26750$
4	$26750 \leq p < 48250$
5	≥ 48250

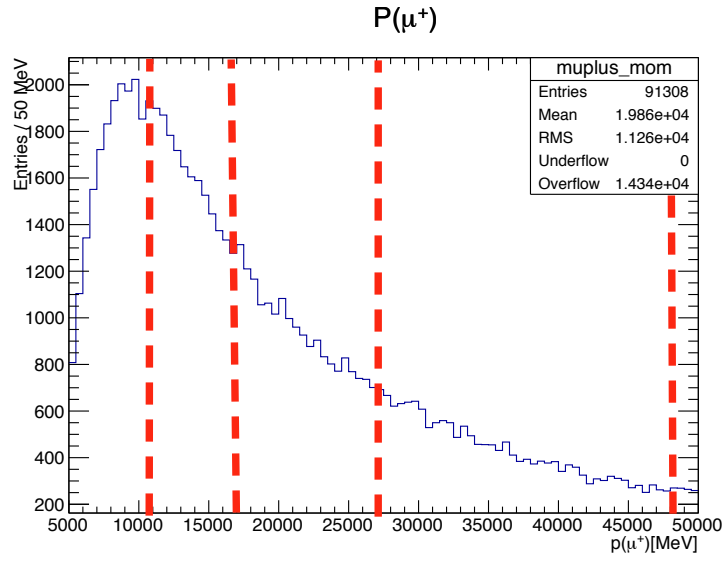


Figure 7.5: Definition of bin boundaries of muon momentum.

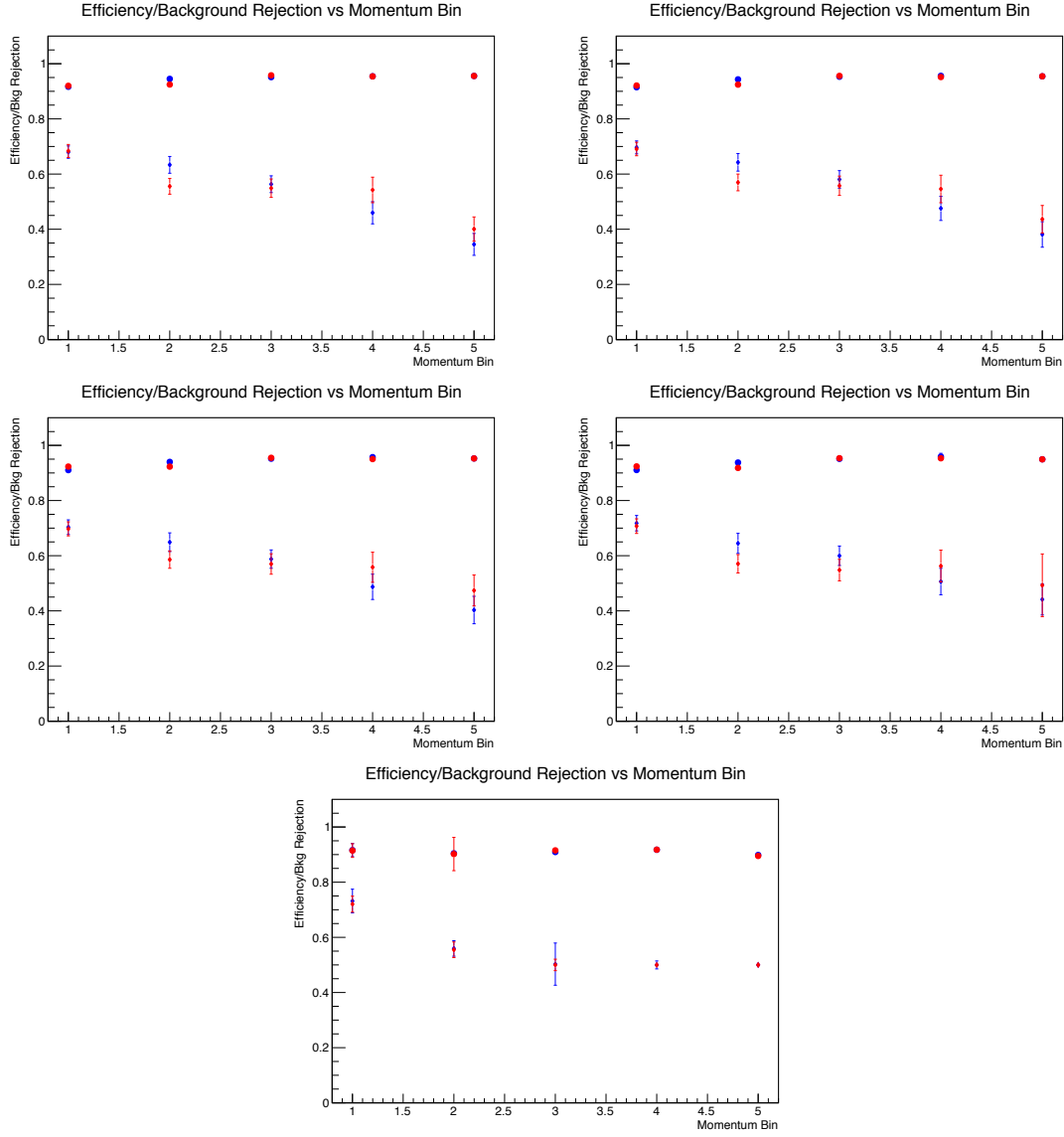


Figure 7.6: Efficiency (circles) and background rejection (diamonds) of the muon tag and probe method, with a probe value of ProbNNmu of 0.3, as a function of probe muon momentum bin. The differing tag values are shown on individual graphs: Top left is a tag value of 0.3; top right is 0.4; center left is 0.5; center right is 0.6; bottom is 0.9. Positive probe muons are shown in blue, and negative are shown in red.

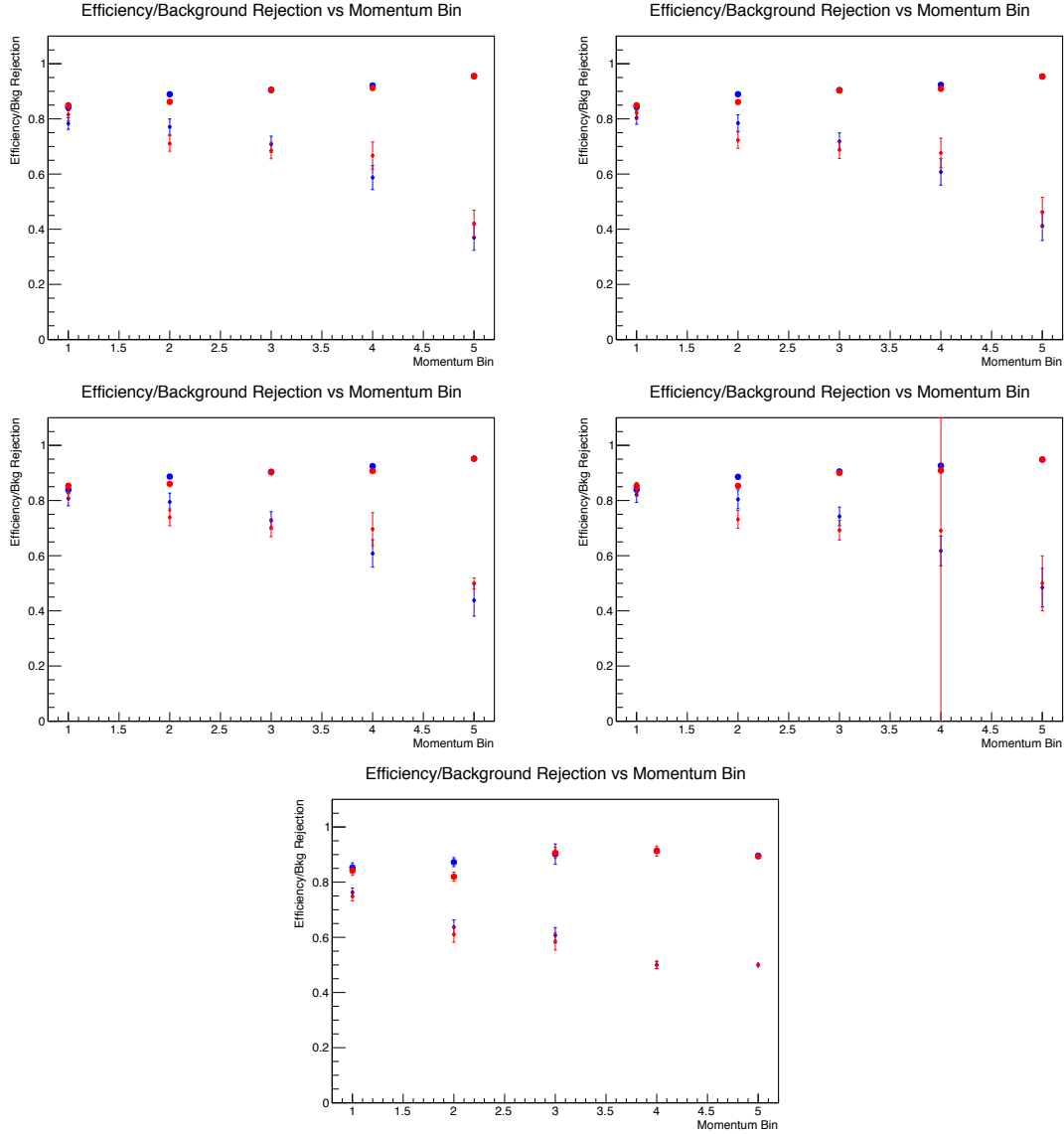


Figure 7.7: Efficiency (circles) and background rejection (diamonds) of the muon tag and probe method, with a probe value of ProbNNmu of 0.4, as a function of prob muon momentum bin. The differing tag values are shown on individual graphs: Top left is a tag value of 0.3; top right is 0.4; center left is 0.5; center right is 0.6; bottom is 0.9. Positive probe muons are shown in blue, and negative are shown in red.

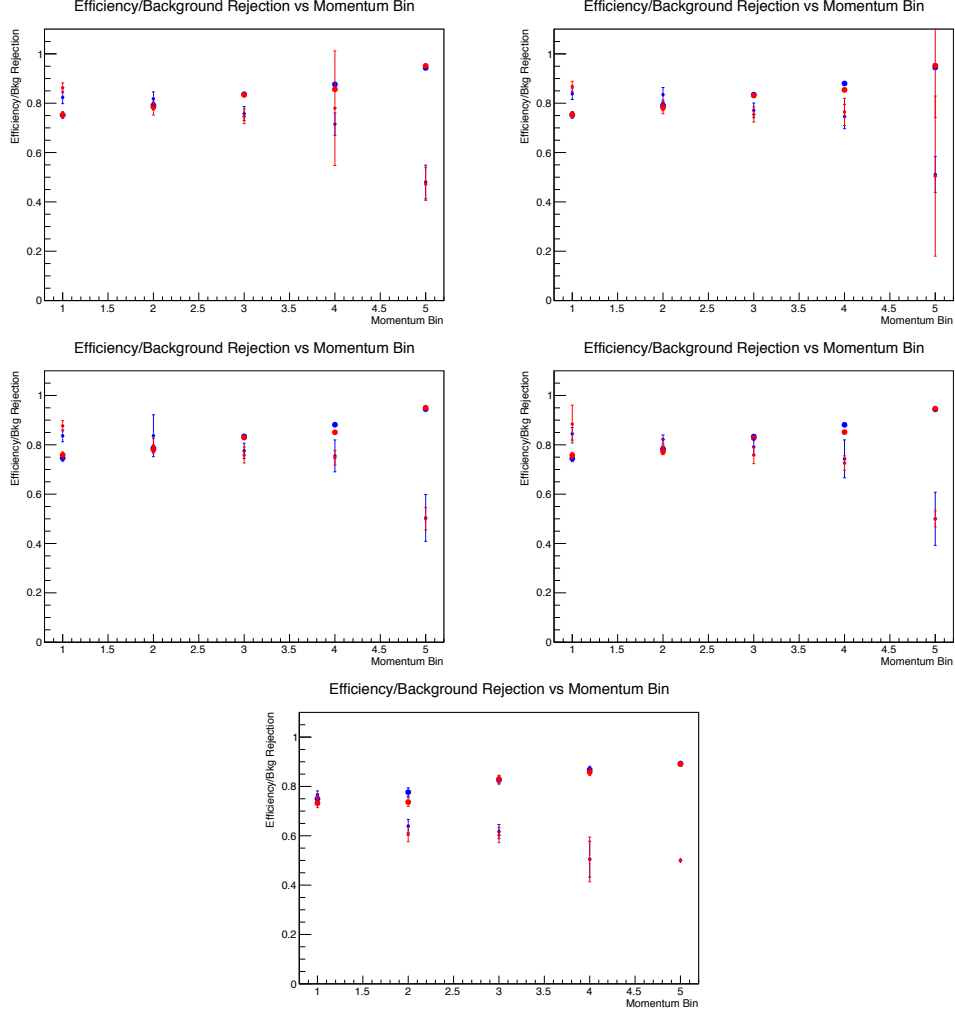


Figure 7.8: Efficiency (circles) and background rejection (diamonds) of the muon tag and probe method, with a probe value of ProbNNmu of 0.5, as a function of prob muon momentum bin. The differing tag values are shown on individual graphs: Top left is a tag value of 0.3; top right is 0.4; center left is 0.5; center right is 0.6; bottom is 0.9. Positive probe muons are shown in blue, and negative are shown in red.

Table 7.5: Probe [efficiency](#) of the ProbNNmu > 0.4 cut, for each tag value.

Tag Value	Probe Efficiency, μ^+	μ^-
0.3	90.4 ± 0.4	89.8 ± 0.4
0.4	90.4 ± 0.4	89.8 ± 0.4
0.5	90.3 ± 0.4	89.8 ± 0.4
0.6	90.3 ± 0.5	89.6 ± 0.4
0.9	90.5 ± 0.6	89.3 ± 0.6

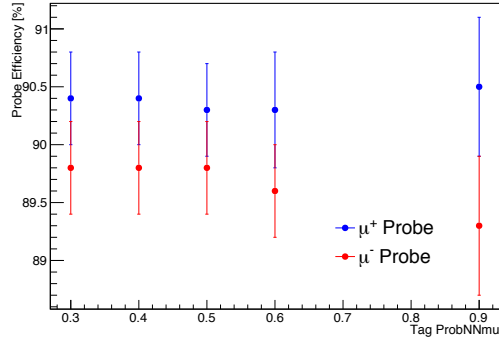


Figure 7.9: Plotted values of the Table 7.5

7.4.1 Effect on the DT analysis

To determine the effect of this cut on the measured quantities of the analysis, we explore the effect on the reconstructed B mass, $m(\mu D^*)$, the $D^{*\pm}$ mass and the D^0 decay time. The results are shown in Figures 7.10-7.11. As expected, the only major change seen in the cut is seen on the reconstructed B mass distribution.

Finally, the number of muons in each event which satisfy all selection criteria in the event is explored in Figure 7.12.

Each curve in Figure 7.12 has the same integral, as all events must fall into one of the bins. After the cut of μ ProbNNmu > 0.4 , 98.89% of all candidates have 0 extra muons in the event which satisfy the selection criteria, and 1.12% have one extra muon. The number of events with more falls off very rapidly. Since muons of both charges are considered here, the rate at which the wrong muon of the correct charge is chosen is 5.6 per mille. An effect at the per mille level will not effect the central value of the analysis significantly.

The physics cases where this could enter are two: first, there could be a true $B \rightarrow \mu D^* X$ decay, where the correct muon is not reconstructed, but instead a different muon is used. This case is combinatoric in nature and is treated in Section 7.5. The second case is a hadronic decay of the B meson, but where one of the tracks is misidentified as a muon. In the case that the charges are still correctly used to identify the decay, the flavor of the D at production is still unharmed, and would still be considered signal. There may be a slight

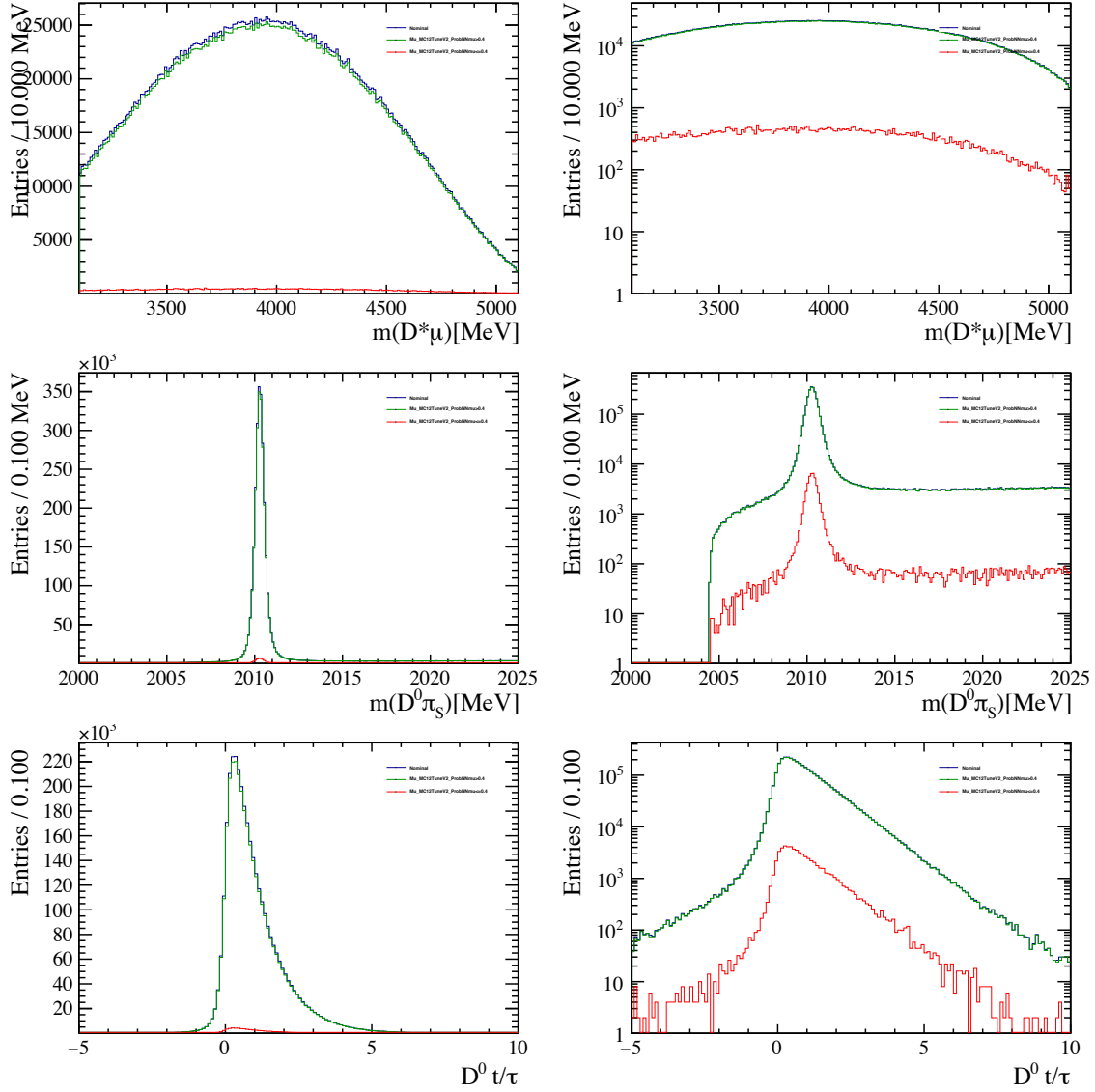


Figure 7.10: Effect of the cut on ProbNNmu on the tagging muon in the DT sample. The blue line represents the nominal values, the green after applying the cut, and the red those events which fail the cut. The left side is linear scale, and the right is log y. The top plots show the reconstructed B mass, the center is the D^* mass, and the bottom is the D^0 decay time. In all plots, the selection criteria discussed above, including the D^0 mass cut, have been applied.

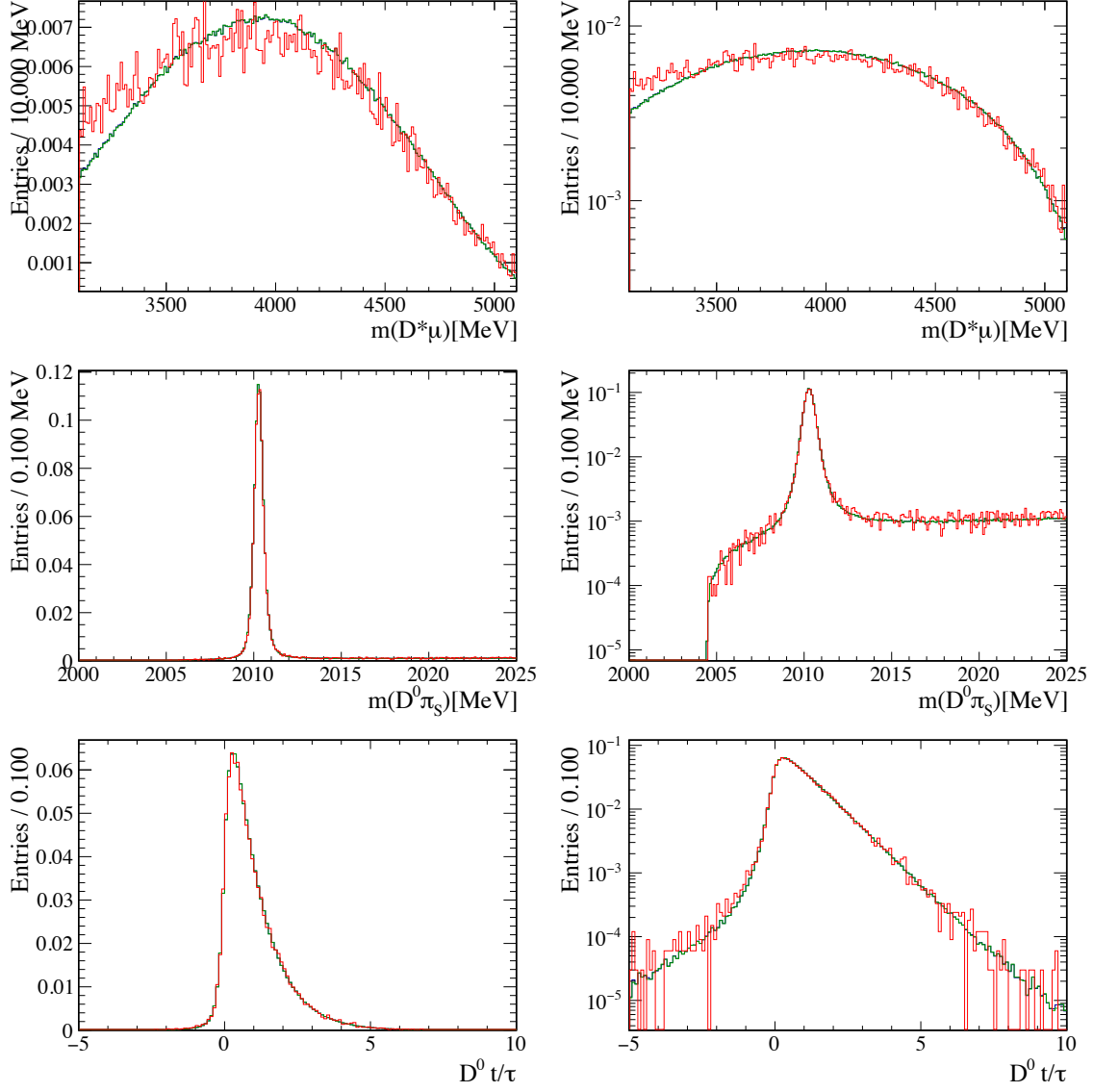


Figure 7.11: The same plots as Figure 7.10, but normalized to unit integral.

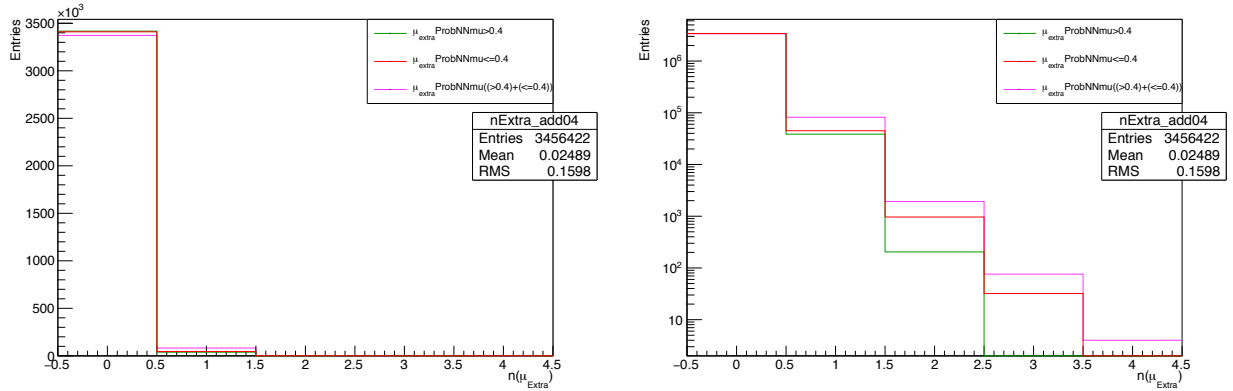


Figure 7.12: The number of extra muon candidates in one event satisfying all selection criteria with the effect of the ProbNNmu cut. On the left is linear scale, and the right is logy. Each curve has the same integral, meaning all the events which are considered are in the plot for each sample. The green line corresponds to μ ProbNNmu > 0.4 , the red corresponds to μ ProbNNmu ≥ 0.4 and the purple corresponds to the event by event sum of the two.

difference in muons of one sign to the other, which is accounted for, in the next section, by the scaling of the combinatoric subtraction. The effect of removing the wrong muon candidates is illustrated in the systematic uncertainties, Section 13.3.1, with the removal of muon mistags as described below.

7.5 Muon mistags and other wrong muons

To understand the muon mistag rate in the DT sample as well as to account for any possible association of a random or wrong muon to the decay, the same stripping and selection criteria are applied to a sample of events reconstructed as $\bar{B} \rightarrow \mu^+ D^{*+} X$ and charge conjugate decays. As this decay is not physical, the reconstruction probes not only how wrongly charged muons could possibly enter the sample but also gives a handle on the combination of true $D^* \rightarrow D^0 \pi_S$, $D^0 \rightarrow K \pi$ decays with a random muon attached. To distinguish the two samples, we refer to the unphysical sample, $\bar{B}^0 \rightarrow \mu^+ D^{*+} X$, as the Same Sign (SS) sample, and the signal decay $\bar{B}^0 \rightarrow \mu^- D^{*+} X$ as the Opposite Sign sample (OS). This is named from the charges of the muon and the slow pion candidates. Figure 7.13 shows the reconstructed

μD^* invariant mass separately for the signal, OS decay in blue and the wrongly charged muons reconstructed in the SS channel in red.

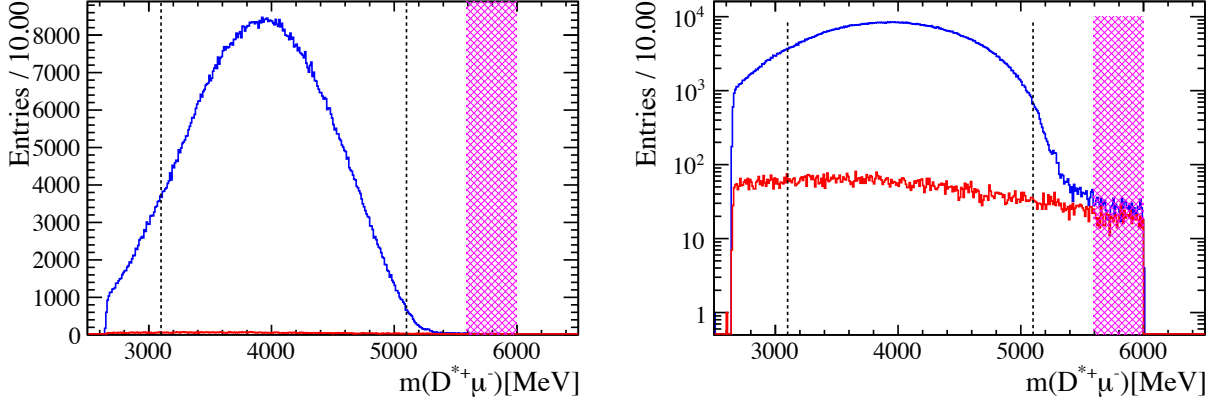


Figure 7.13: Reconstructed B mass for the SS (red) and (OS) samples overlaid. The vertical black lines indicate the nominal mass window, and the magenta hatched region shows the region over which the SS and OS samples are consistent. No scaling has been applied.

The high sideband of the reconstructed B mass distribution shows that the absolute rates of the SS and OS samples are in rough agreement, showing that this region is in fact due to wrongly associated muons. Explicitly, the number of events in the shaded region are 1097 for the OS sample and 788 for the SS sample. We interpret the SS sample as combinatoric muon background and by scaling the SS sample to the OS sample in the sideband between 5.6 and 6 GeV, obtain a shape in the signal region for said background. This also accounts for any possible asymmetry in charge of the combinatoric muon. The scaling factor to make the SS the same as the OS is about 1.4, though can vary with decay time. By integrating the shapes in the signal range of 3.1 and 5.1 GeV, we find that the total effect of the wrongly tagged muon is 0.6 to 1.4%, varying with decay time. This is illustrated by the same plots as Figure 7.13, but in bins of D^0 decay time in Figures 7.14 and 7.15.

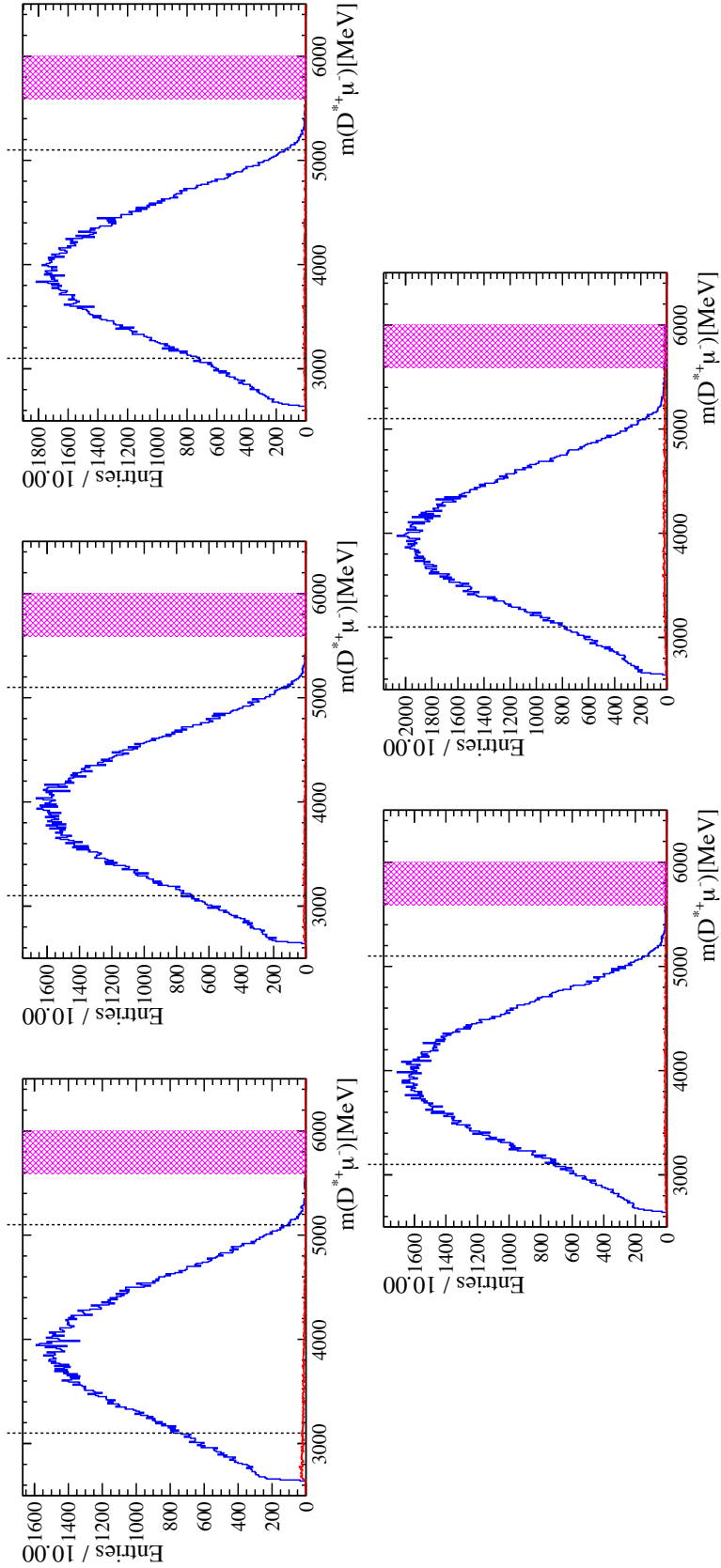


Figure 7.14: Decay time dependence of the SS shape. Linear scale in Y is shown. The first decay time bin represents on the top left, $-0.5 < t/\tau_{D^0} \leq 0.2$, then moving to the right $0.2 < t/\tau_{D^0} \leq 0.5$, $0.5 < t/\tau_{D^0} \leq 0.9$, then the bottom row is $0.9 < t/\tau_{D^0} \leq 1.5$, and $t/\tau_{D^0} \geq 1.5$.

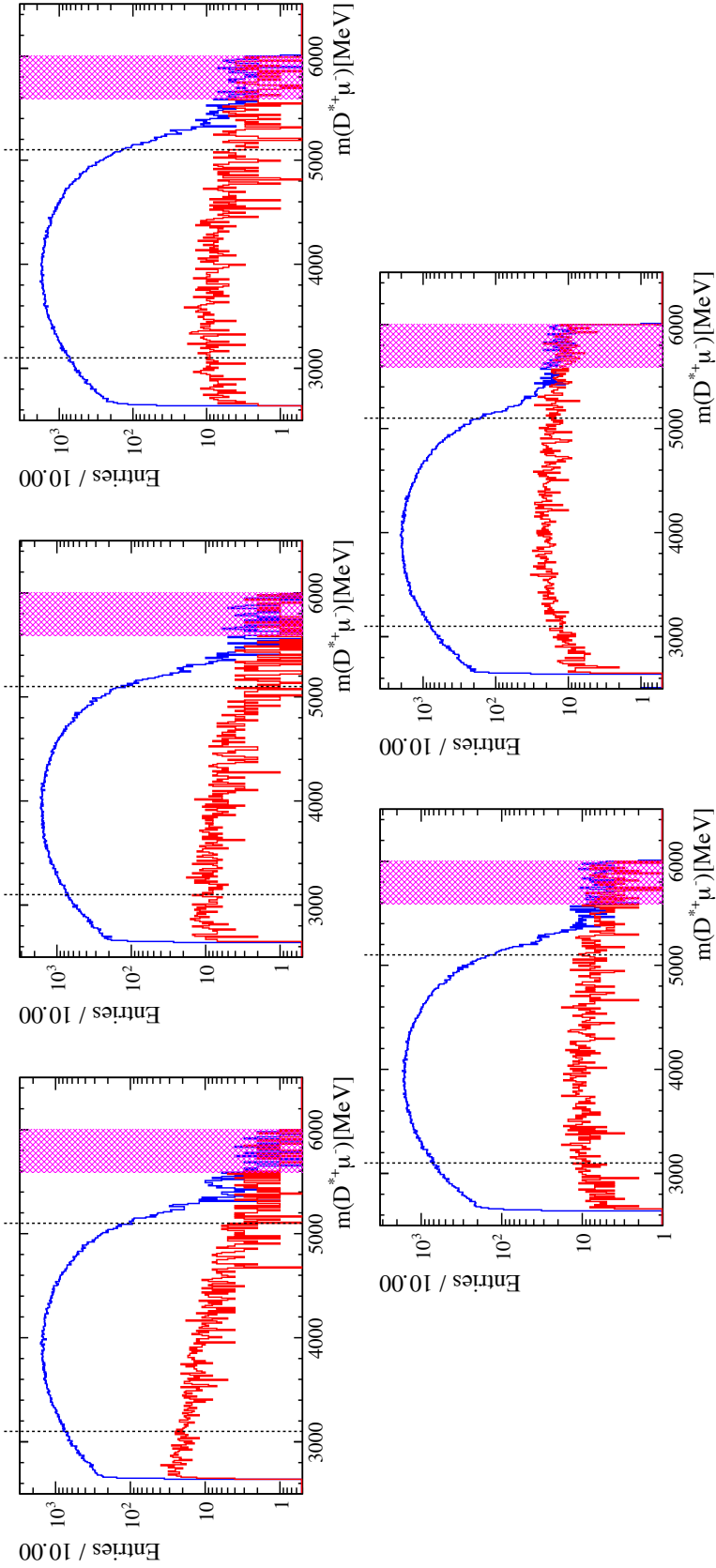


Figure 7.15: Decay time dependence of the SS shape. Semilog scale in Y is shown. The first decay time bin represents on the top left, $-0.5 < t/\tau_{D^0} \leq 0.2$, then moving to the right $0.2 < t/\tau_{D^0} \leq 0.5$, $0.5 < t/\tau_{D^0} \leq 0.9$, then the bottom row is $0.9 < t/\tau_{D^0} \leq 1.5$, and $t/\tau_{D^0} \geq 1.5$.

1465 To explore how the $D^{*\pm}$ mass depends on being tagged as SS or OS, we plot the normal-
1466 ized distributions of $m(D^{*\pm})$ for the SS and OS samples. These plots are shown for the time
1467 integrated sample in Figure 7.16 and separated by decay time in Figures 7.17 and 7.18.

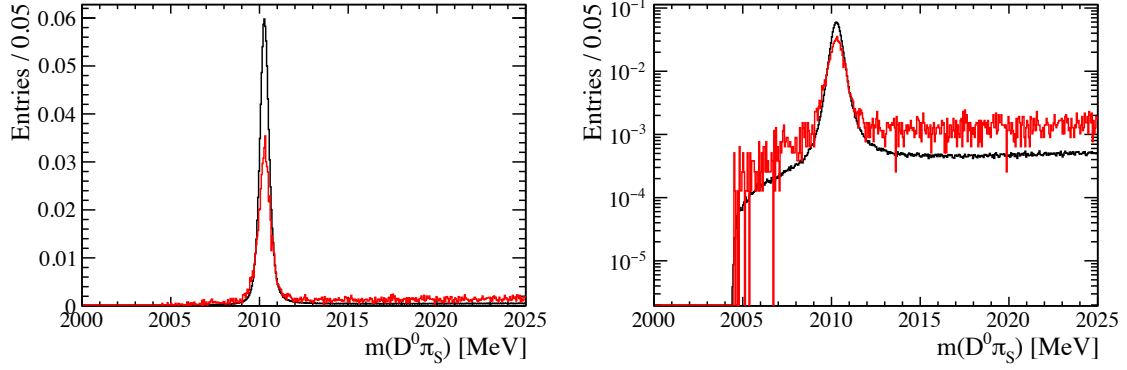


Figure 7.16: Normalized $D^{*\pm}$ distributions for the OS sample (black) and the SS sample (red), integrated over decay time. The left figure is linear Y scale, and the right log Y scale.

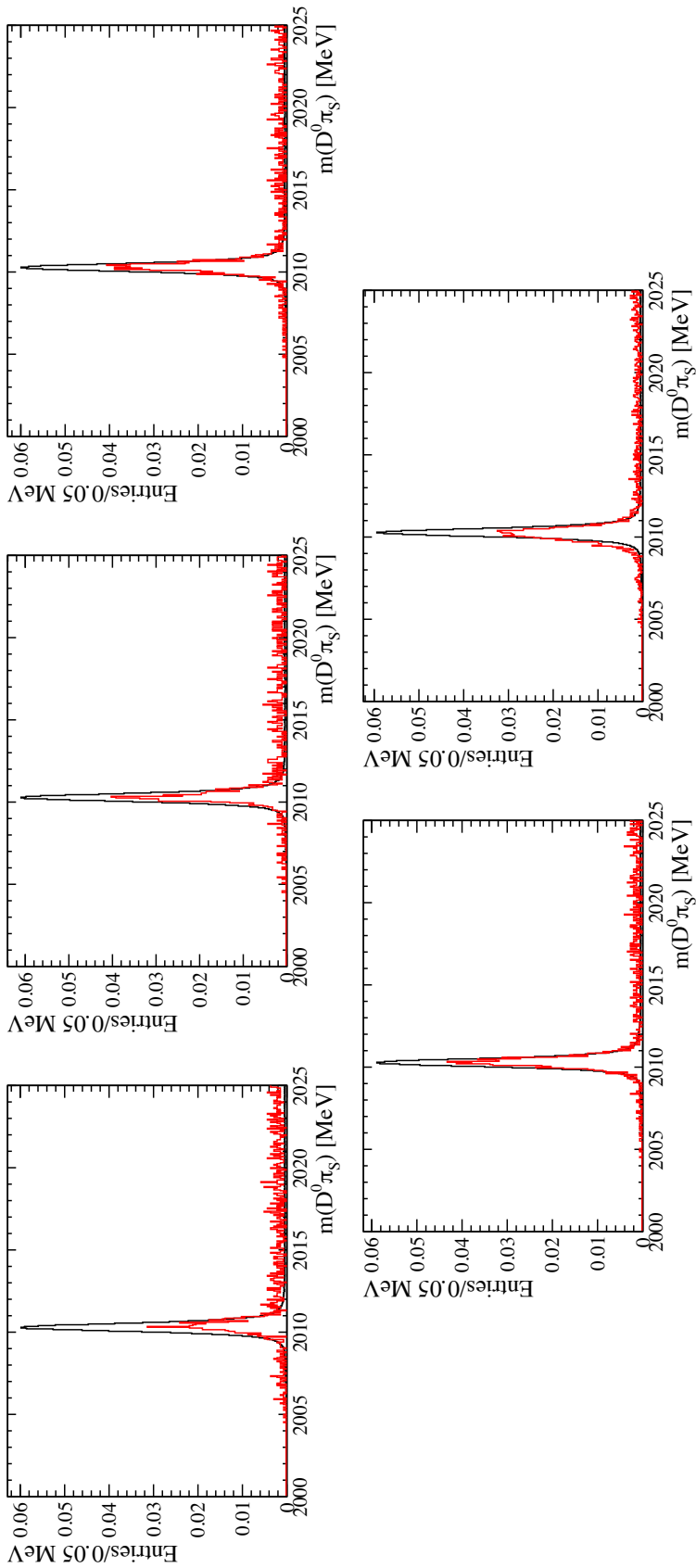


Figure 7.17: Normalized $D^{*\pm}$ distributions for the OS sample (black) and the SS sample (red), separated by decay time bin. Shown in this figure is linear Y scale. The first decay time bin represents on the top left, $-0.5 < t/\tau_{D^0} \leq 0.2$, then moving to the right $0.2 < t/\tau_{D^0} \leq 0.5$, $0.5 < t/\tau_{D^0} \leq 9$, and on the bottom $0.9 < t/\tau_{D^0} \leq 1.5$, and $t/\tau_{D^0} \geq 1.5$.

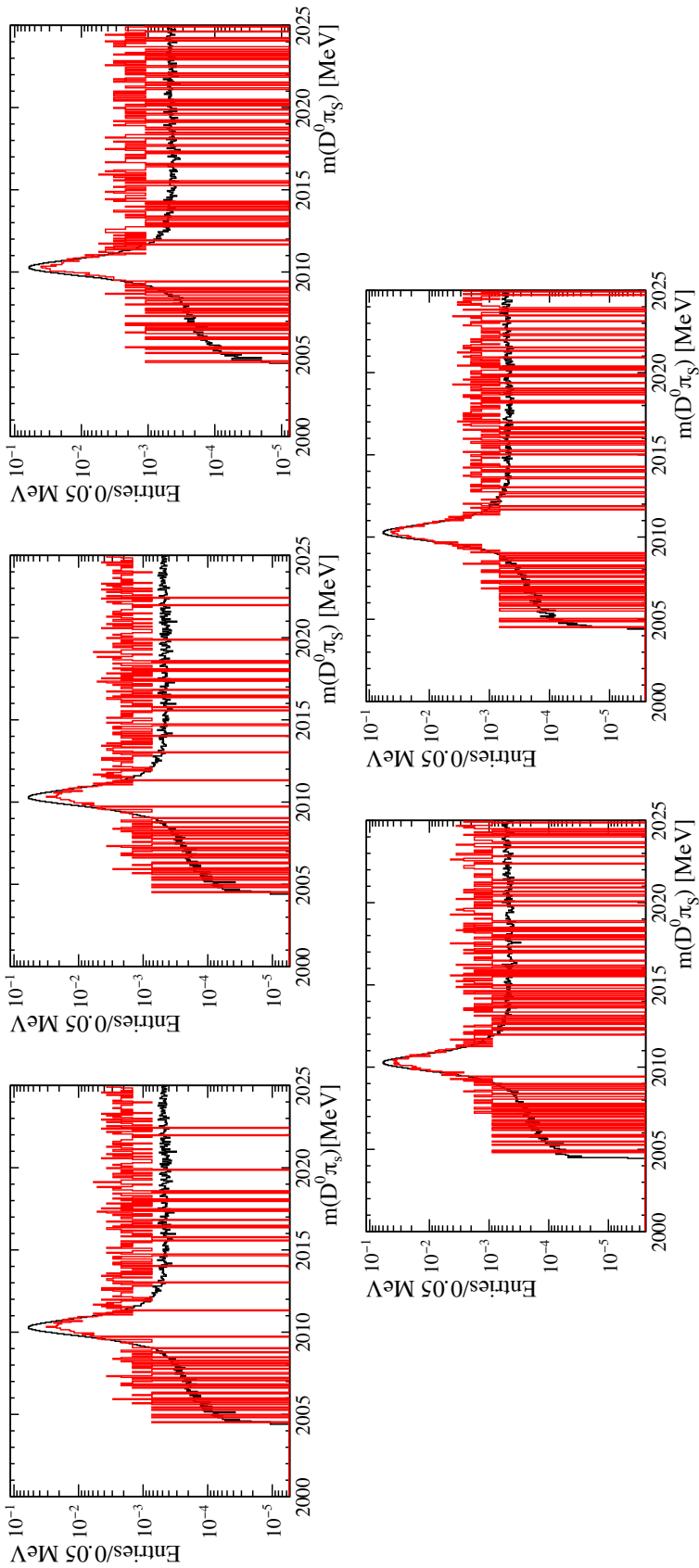


Figure 7.18: Normalized $D^{*\pm}$ distributions for the OS sample (black) and the SS sample (red), separated by decay time bin. Shown in this figure is semilog Y scale. The first decay time bin represents on the top left, $-0.5 < t/\tau_{D^0} \leq 0.2$, then moving to the right $0.2 < t/\tau_{D^0} \leq 0.5$, $0.5 < t/\tau_{D^0} \leq 0.9$, and on the bottom $0.9 < t/\tau_{D^0} \leq 1.5$, and $t/\tau_{D^0} \geq 1.5$.

The distributions themselves for SS and OS show similar combinatoric background shapes as well as the similar peaks, though the signal to background varies as a function of decay time for the SS sample more strongly than for the OS.

To take account for all these effects, we subtract the D^* mass distribution from the SS sample from that of the OS sample. Explicitly in each of the 5 decay time bins, we scale the SS to the OS sample in the region of 5.6 to 6 GeV. The scaling factor obtained is then applied to the distributions of interest, namely the $D^{*\pm}$ mass and anything else studied, and the SS sample is subtracted from the OS. To evaluate systematics based on this background subtraction, the scaling factor of the SS background to the OS sideband for each decay time bin is set to unity and the change in the WS/RS ratio is taken as the systematic.

7.6 Multiple Candidates

It is possible that in each event, there is more than one candidate that satisfies all the selection criteria. To explore this possibility, we search for events in sequence, with the same unique run and event number as the first event in the sequence, all of which pass the nominal selection criteria. These events represent multiple candidates per event. After identification of multiple candidates is performed, we analyze the source of the multiple candidates. To do this, we explicitly record the momentum of the daughter particles before any kinematic constraints on the decay, then match each case by hand. Namely:

- A different π_s , where all other daughter momenta match
- A different μ in the event, all other daughter momenta match
- A different daughter K , all other daughter momenta match
- A different daughter pion, all other momenta match
- A different D^0 candidate, where only the daughter K and π momenta are different
- A different μ and π_s candidate, where the D^0 is common

- Anything else, split by whether or not the B end vertex position is the same or not.

The results of this study are shown in Figure 7.19. The distribution is shown normalized to unity, as well.

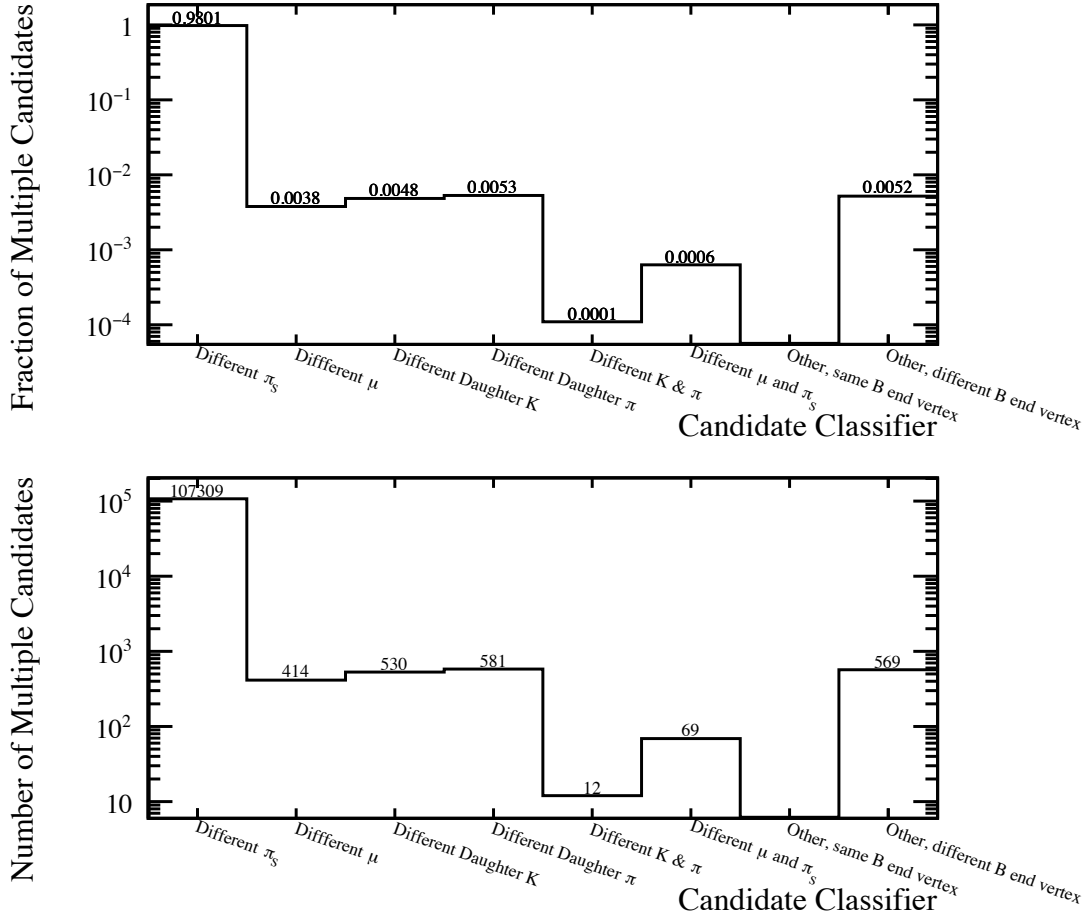


Figure 7.19: Distribution of multiple candidates of the DT sample. The histogram on top is normalized to unit integral and the numbers above the histogram represent the fraction of candidates falling into the given category. The bottom histogram is the distribution plotted with the number of entries on the Y axis. For the second to last bin, the content is zero.

What we find is that there are in total 109,484 multiple candidates, or about 12.5% of the RS sample. Of these multiple candidates, we find that 98% of candidates considered are simply due to the same decay with a different π_s associated to the event. As only the correct combination will peak in the $D^{*\pm}$ mass spectrum, which is fit to extract the signal yields,

these candidates do not need to be chosen between as they are considered background in the mass fit. 4 per mille of the multiple candidates is associated with a different muon, which is also subtracted in the SS subtraction. The different daughter kaon will also not peak in the correct $m(D^0)$ and Δm region, so this cannot contribute. The same must be true of the daughter π considered, as well as of the candidates which also have a different D^0 , because while they may peak in $m(D^0)$, they cannot peak in the $m(D^{*\pm})$ signal, and are thus subtracted away. The same is also true of the different μ and π_s candidates. Therefore, the only region of interest is the 5 per mille associated to all daughter particles being different. In this case alone, we have genuine decays which cannot be disentangled. These events, however, are entirely from the other b in the event, as the B decay vertices are not the same. As these decays may also be signal, so we explicitly do not choose to subtract them.

We explore just a bit deeper to understand if any of these candidates originate from clones which were not removed in previous steps. First, we explore the slow pion candidates of the RS sample to see how many of these multiple candidates fall 0.7 or 1.4 MeV of the $D^{*\pm}$ mass peak. The result of this search is shown in Figure 7.20.

Immediately it is noted that the majority of the time, there is either no or 1 candidate which could enter the signal region, thus supporting the understanding from the previous paragraph. Then, to check the possibility of being a clone, we take the first candidate in the sequence of candidates in the event and ask if the subsequent candidates have a momentum vector which lies within 0.6mrad of the original candidate momentum vector. We note that for the majority of events, there is only one additional multiple candidate which could be a clone. This is found by inspection. The distribution of the angle of the multiple candidates momentum vectors is shown in Figures 7.21 and 7.22.

Anything which lies above 0.6 mrad, we consider all candidates without vetoing. Below this, however, we adopt a strategy to veto these candidates. The fraction of these clones is small, so we do not expect there to be a large effect on the DT analysis result. Regardless, we choose one candidate to enter the sample as a precaution. As we do not know which of the clones is the correct one, we consider two possible ways of dealing with these clones: first,

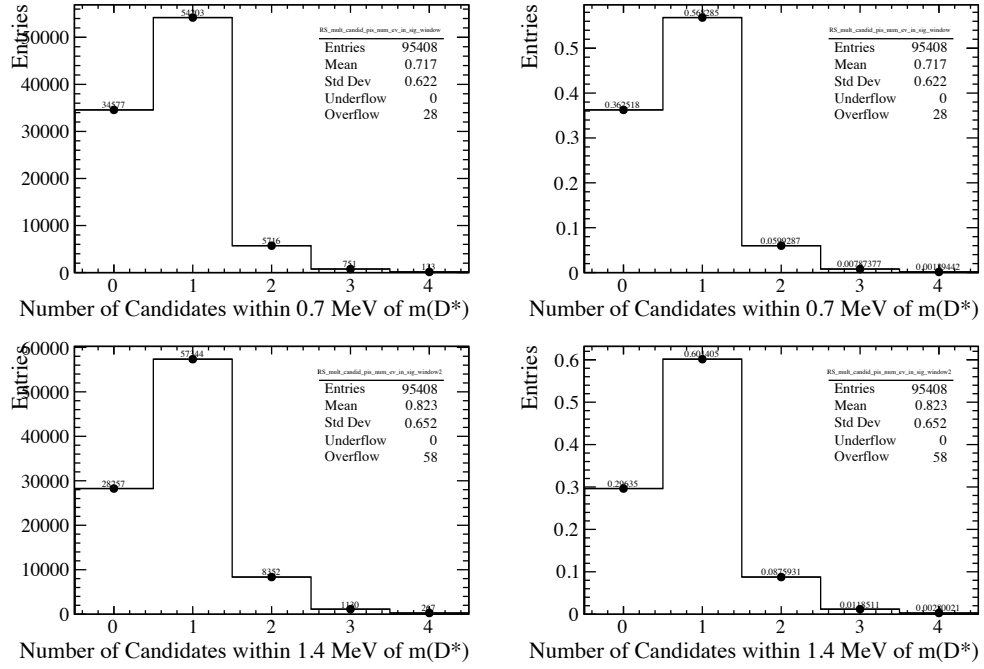


Figure 7.20: Left: Number of multiple candidates with different slow pions which enter the signal region of the $D^{*\pm}$ mass distribution. Right: Same as left, but divided by the total integral of the histogram, thus giving a rate. The top plots are those for the window of 0.7 MeV around the nominal $D^{*\pm}$ mass, and bottom are for 1.4 MeV around the nominal $D^{*\pm}$ mass.

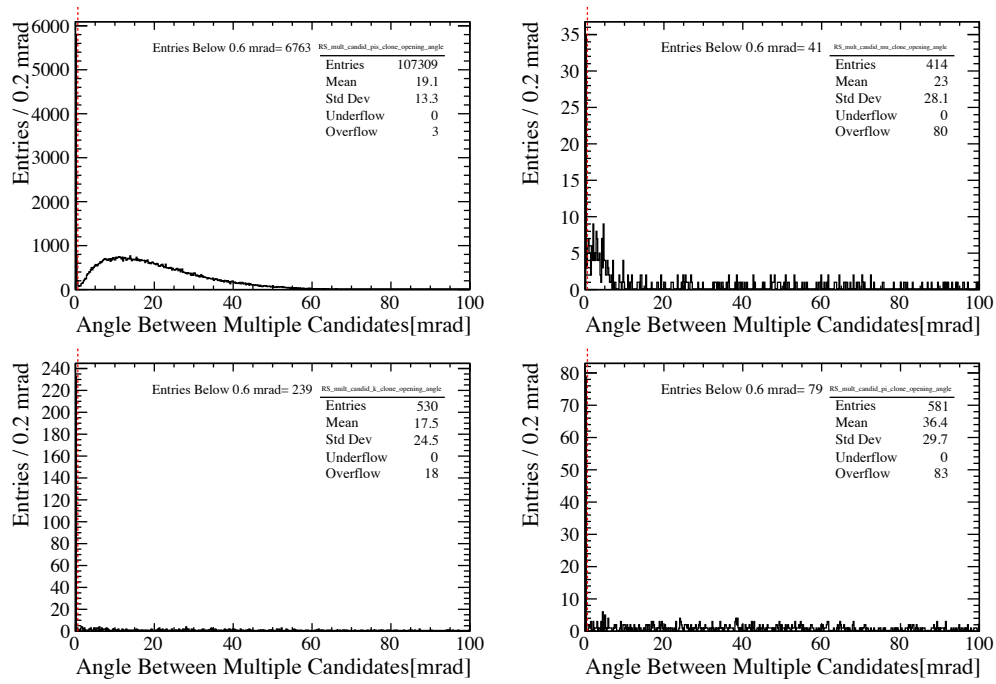


Figure 7.21: Angle of momentum vector of multiple candidates with respect to the first candidate considered for all daughter particles. On the top left is the distribution for slow pion candidates, the top right is for muon candidates, bottom left is for kaons, and bottom right is for pions. There is a red line at 0.6 mrad, and the inlaid number shows the number of entries below this line.

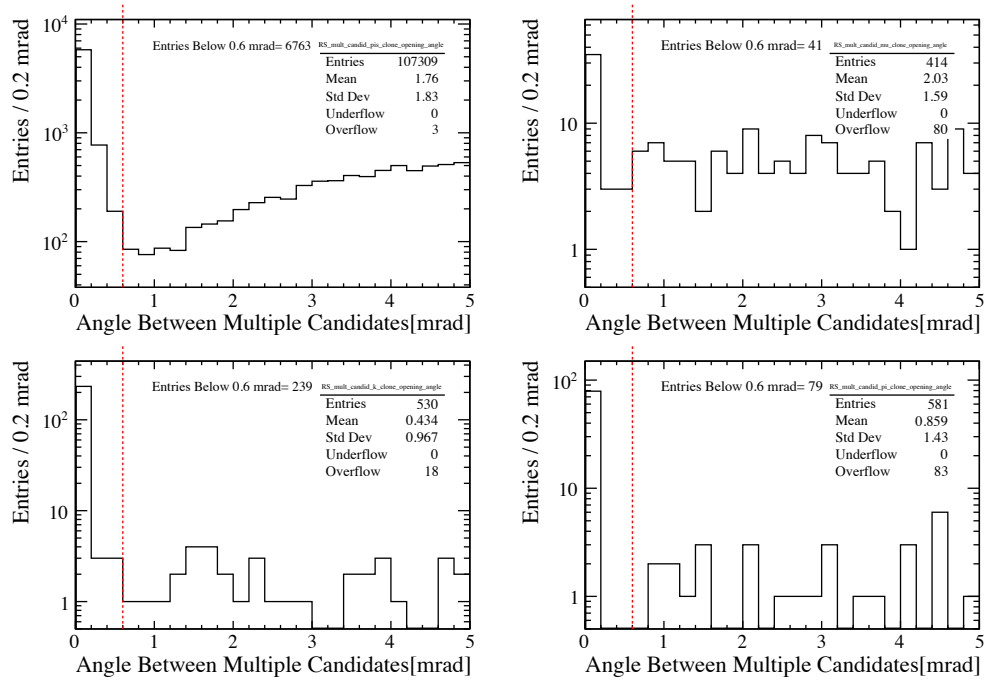


Figure 7.22: Angle of momentum vector of multiple candidates with respect to the first candidate considered for all daughter particles, zoomed into the region from 0 to 5 mrad. Scale is now semilog y. On the top left is the distribution for slow pion candidates, the top right is for muon candidates, bottom left is for kaons, and bottom right is for pions. The red line shows the cutoff point for being considered a clone. Inlaid is the number of entries below this line.

1527 we choose randomly, and second we choose the one with the best B end vertex χ^2 . Both
1528 procedures give little change with respect to the original procedure of taking all multiple
1529 candidates. We choose to sample at random, however, because choosing the best χ^2 will bias
1530 to lower momentum slow pions, as the error ellipse for these candidates is larger.

Chapter 8

Yield Extraction and Fit Model

In order to deduce the observed yields which enter Equations 5.7 and 5.8, the number of signal events must be extracted. The signal yields are extracted from a binned maximum likelihood fit to the D^* mass distributions. From the variables which are calculated after the kinematic constraints of the vertices of the decay, we reconstruct the D^* mass distribution by first combining the K and π candidates and constrain to the D^0 mass, then combine this with the slow pion candidate. To this distribution we fit a probability density function (PDF), which gives directly the signal yields.

8.0.1 Fit Model

The signal PDF for the extraction of the yields from the $m(D^*)$ distribution is composed of one Johnson S_U function [23],

$$\mathcal{J}(x|\mu, \sigma, \delta, \gamma) = \frac{e^{-\frac{1}{2}[\gamma + \delta \sinh^{-1}(\frac{x-\mu}{\sigma})]^2}}{\sqrt{1 + (\frac{x-\mu}{\sigma})^2}}, \quad (8.1)$$

which helps to account for the asymmetric tail, and three individual gaussians which account for the core of the distribution. The model is of the same form used in the previous analysis of prompt $D^{*\pm}$ [18]. This model is used in place of a relativistic Breit-Wigner (RBW) convolved with resolution functions, due to the limited signal Monte Carlo statistics compared to the

1547 statistics of the RS signal. An attempt was made to model the signal with the aforementioned
 1548 RBW, but showed poor performance. The signal PDF is constructed as

$$\mathcal{P}_{\text{sig}}(x|\theta_{\text{sig}}) = f_J \mathcal{J}(x|\mu_J, \sigma_J, \delta_J, \gamma_J) + (1 - f_J)[f_{G1} \mathcal{G}(x|\mu_{G1}, \sigma_{G1}) \quad (8.2)$$

$$+ (1 - f_{G1})f_{G2} \mathcal{G}(x|\mu_{G2}, \sigma_{G2}) + (1 - f_{G1})(1 - f_{G2})\mathcal{G}(x|\mu_{G3}, \sigma_{G3})], \quad (8.3)$$

1549 where θ_{sig} are the nuisance parameters of the fit from the signal PDF.

1550 The background PDF is described by an empirical function which describes events with
 1551 a random slow pion, or which are purely combinatoric in origin. The background PDF is
 1552 given by

$$\mathcal{P}_b(x|m_0, c, p) = x((x/m_0)^2 - 1)^p e^{c((x/m_0)^2 - 1)}. \quad (8.4)$$

Finally, the total fit is a combination of the signal and background PDFs, each of which carries as a normalization the number of signal or background events.

$$PDF = N_{\text{sig}} \mathcal{P}_{\text{sig}} + N_{\text{bkg}} \mathcal{P}_{\text{bkg}}. \quad (8.5)$$

1553 The fit strategy is to fit the total RS sample alone, then fix the signal shape and use this to
 1554 fit all subsequent datasets, be it WS or anything in bins. To list this entire process, we have

- 1555 1. Fit the time integrated RS sample. Fix the signal shape
- 1556 2. With fixed signal shape, fit WS sample
- 1557 3. With fixed signal shape, fit RS in bins of D^0 decay time
- 1558 4. With fixed signal shape, fit WS in bins of D^0 decay time

1559 Fits of the PDF to DT data are shown in Figure 8.1, with the residual distribution
 1560 normalized by the error, or pull, shown below. The number of signal events extracted from

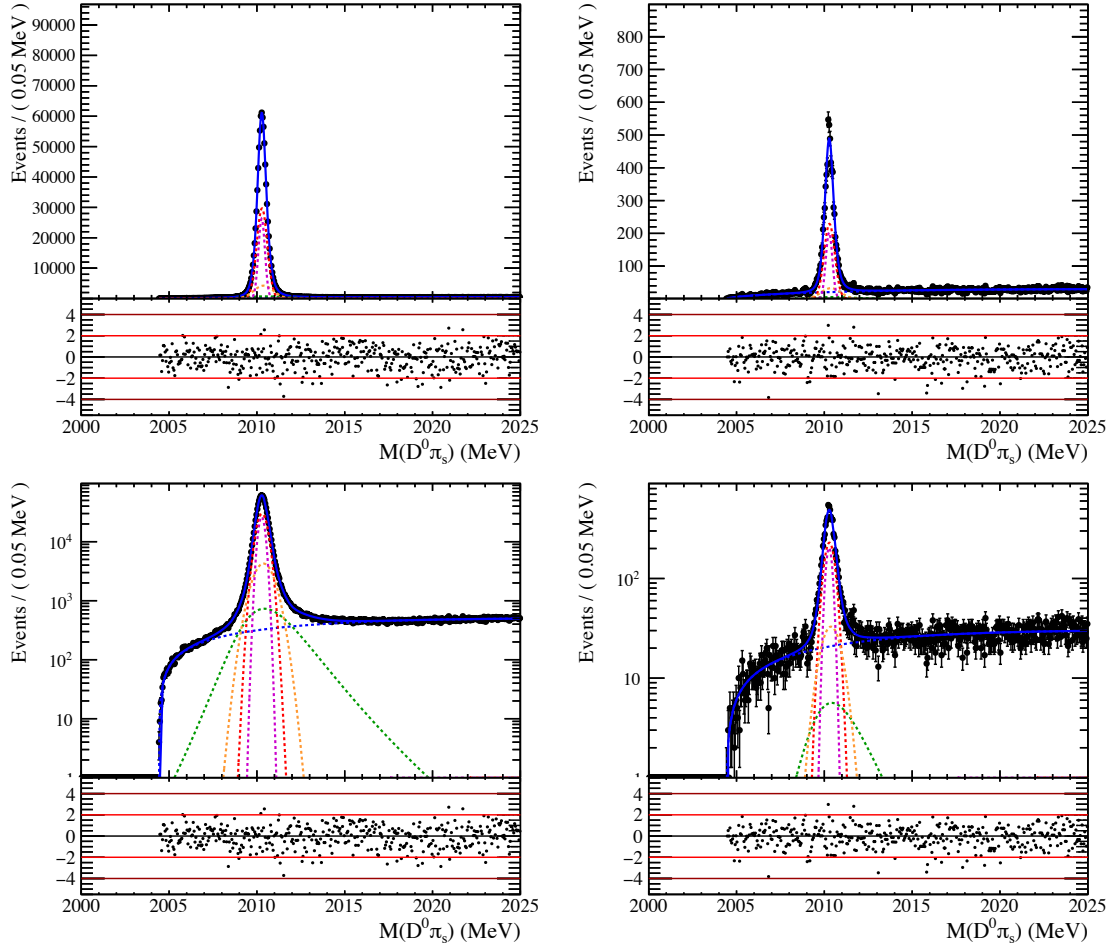


Figure 8.1: Fits of the total PDF to the DT data sample. Left column shows the fits for the RS sample, and right shows fits for the WS sample. Top row is linear scale, bottom semilog y.

1561 this distribution are 1726880 ± 1908 events for RS. This number is two times the number
1562 of observed events in the dataset itself, which is due to a trigger requirement that only half
1563 the observed events are written to disk. The yield for the WS is 6660 ± 89 events, and does
1564 not have this requirement. For comparison, the total yields of the sample used from prompt
1565 $D^{*\pm}$ [18] sample are approximately 54×10^6 RS signal events and 228×10^3 WS events.

Chapter 9

Fit Validation

9.1 Time Integrated Checks

To ensure that the yield extraction of the number of signal $D^{*\pm}$ is not biased, we test the fit model by splitting the sample into 5 bins of approximately equal population of a variable, integrated over D^0 decay time, fit separately, then recombined by adding the extracted number of signal events and adding the extracted errors in quadrature. The result is then compared to the original fit yield. This is done for the high statistics RS sample only. The variables chosen for binning are the momentum and transverse momentum of the D^* , the momentum and transverse momentum of the muon, the natural log of the impact parameter of the muon, the $\Delta \log(\mathcal{L}(K - \pi))$ of the daughter kaon and pion, where $\mathcal{L}(x - y)$ is the likelihood from the RICH detectors of either being identified as particle x or y , and the charge of the slow pion. We adopt the shorthand $XPIDY$ to signify $\Delta \log(\mathcal{L}(Y - \pi))$ of the particle X . To gauge if there is a correlation between the variable and the mean and width of the signal, the mean and width of the signal PDF are allowed to transform as $\mu \rightarrow \mu + \delta\mu$ and $\sigma \rightarrow \sigma(1 + \delta\sigma)$. We note that while μ of the Johnson does not correspond to the mean, allowing this variable to float with the means of the other gaussians allows the mean of the total distribution to shift accordingly. The definitions of bins for all variables are given in Figure 9.1, and are summarized in Table 9.1. The fits to the signal distribution in each bin

¹⁵⁸⁵ are given in Appendix A.3.

Table 9.1: Boundaries of bins for Time Integrated Fit Validation.

Variable	Bin 1 Range	Bin 2 Range	Bin 3 Range	Bin 4 Range	Bin 5 Range
$p(D^*)[\text{MeV}]$	$< 35700.$	$35700 \leq p < 45900.$	$45900 \leq p < 58700.$	$58700. \leq p < 79900.$	$\geq 79900.$
$p_T(D^*)[\text{MeV}]$	< 2130	$2130 \leq p_T < 2950$	$2950 \leq p_T < 3910$	$3910 \leq p_T < 5470$	≥ 5470
$p(\mu)[\text{MeV}]$	< 19700	$19700 \leq p < 29900$	$29900 \leq p < 43100$	$43100 \leq p < 65100$	≥ 65100
$p_T(\mu)[\text{MeV}]$	< 2070	$2070 \leq p_T < 2630$	$2630 \leq p_T < 3310$	$3310 \leq p_T < 4450$	≥ 4450
$\ln \text{IP}(\mu)$	< -1.6	$-1.6 \leq \ln \text{IP}(\mu) < -1.1$	$-1.1 \leq \ln \text{IP}(\mu) < -0.7$	$-0.7 \leq \ln \text{IP}(\mu) < -0.2$	≥ -0.2
K PID K	< 12.5	$12.5 \leq K\Delta \log \mathcal{L}(K - \pi) < 20.5$	$20.5 \leq K\Delta \log \mathcal{L}(K - \pi) < 27.5$	$27.5 \leq K\Delta \log \mathcal{L}(K - \pi) < 38.5$	≥ 38.5
π PID K	< -40.5	$-40.5 \leq \pi\Delta \log \mathcal{L}(K - \pi) < -25.5$	$-25.5 \leq \pi\Delta \log \mathcal{L}(K - \pi) < -14.5$	$-14.5 \leq \pi\Delta \log \mathcal{L}(K - \pi) < -5.5$	≥ -5.5

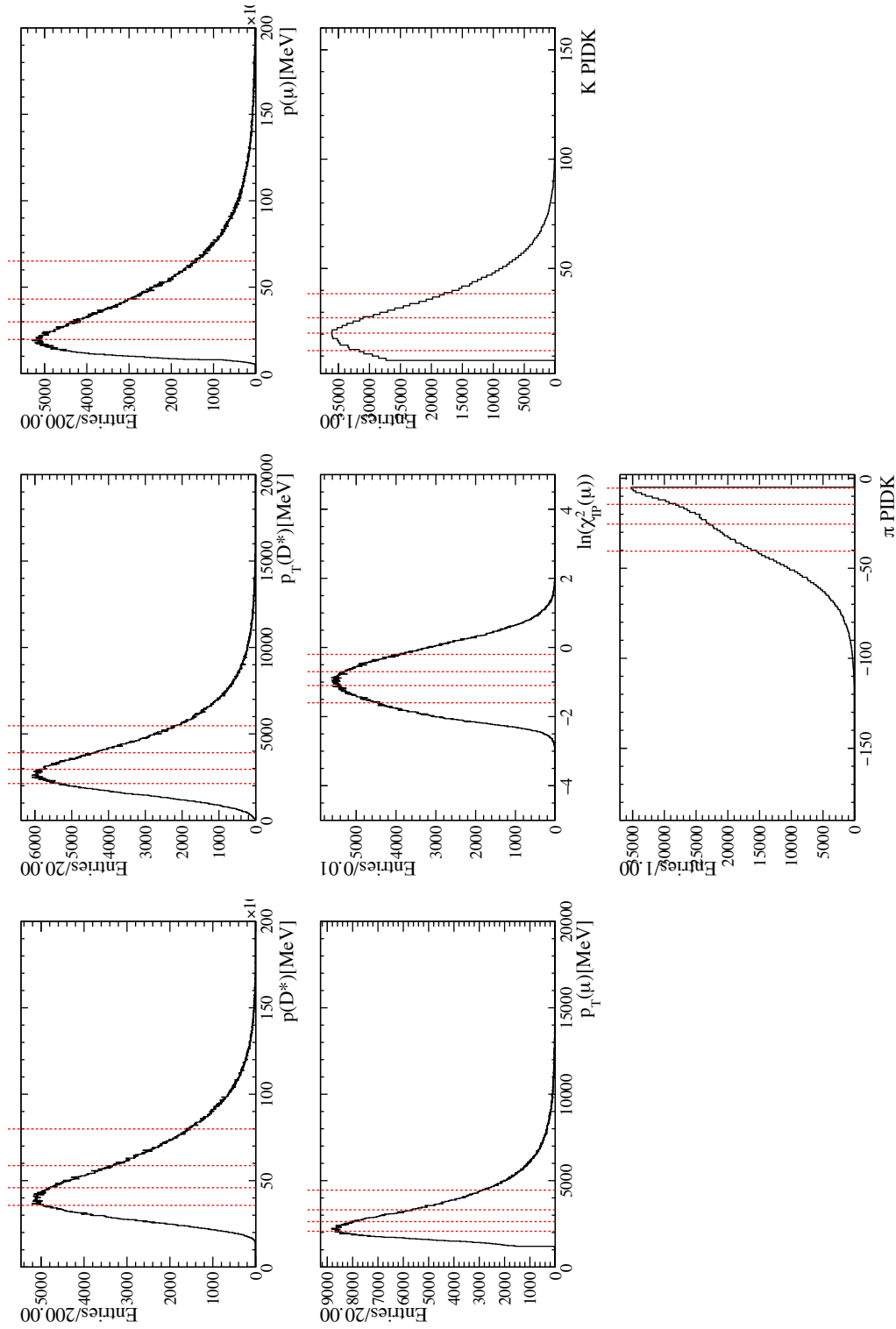


Figure 9.1: Definitions of bins of variables for validation of the fit model. The red dashed lines represent the bin boundaries. The graphs are the momentum of the D^* on the top left, transverse momentum of the D^* on the top middle, top right is the momentum of the muon, middle left is the transverse momentum of the muon, middle center is the log of the impact parameter of the muon, middle right gives the $\Delta \log(\mathcal{L}(K - \pi))$ for the daughter kaon of the D^0 , and the bottom right gives the $\Delta \log(\mathcal{L}(K - \pi))$ of the daughter pion.

1586 The trends for the change in mean position of the signal PDF as a function of variable
1587 are shown in Figure 9.2, and the change in width is shown in Figure 9.3. The maximum
1588 variation in mean position for all bins is 6 keV, and the maximum variation in the width is
1589 15% of the original fitted value. To understand the variation in width, the distributions of
1590 the invariant mass of the D^* candidate are plotted all atop one another in Figure 9.4. To
1591 compare background levels, the same distributions, normalized to the peak value, are shown
1592 in Figure 9.5. The largest variations are seen from the D^* momentum ranges. While the
1593 background levels in the highest range are lower than the other bins, the resolution is also
1594 worse.

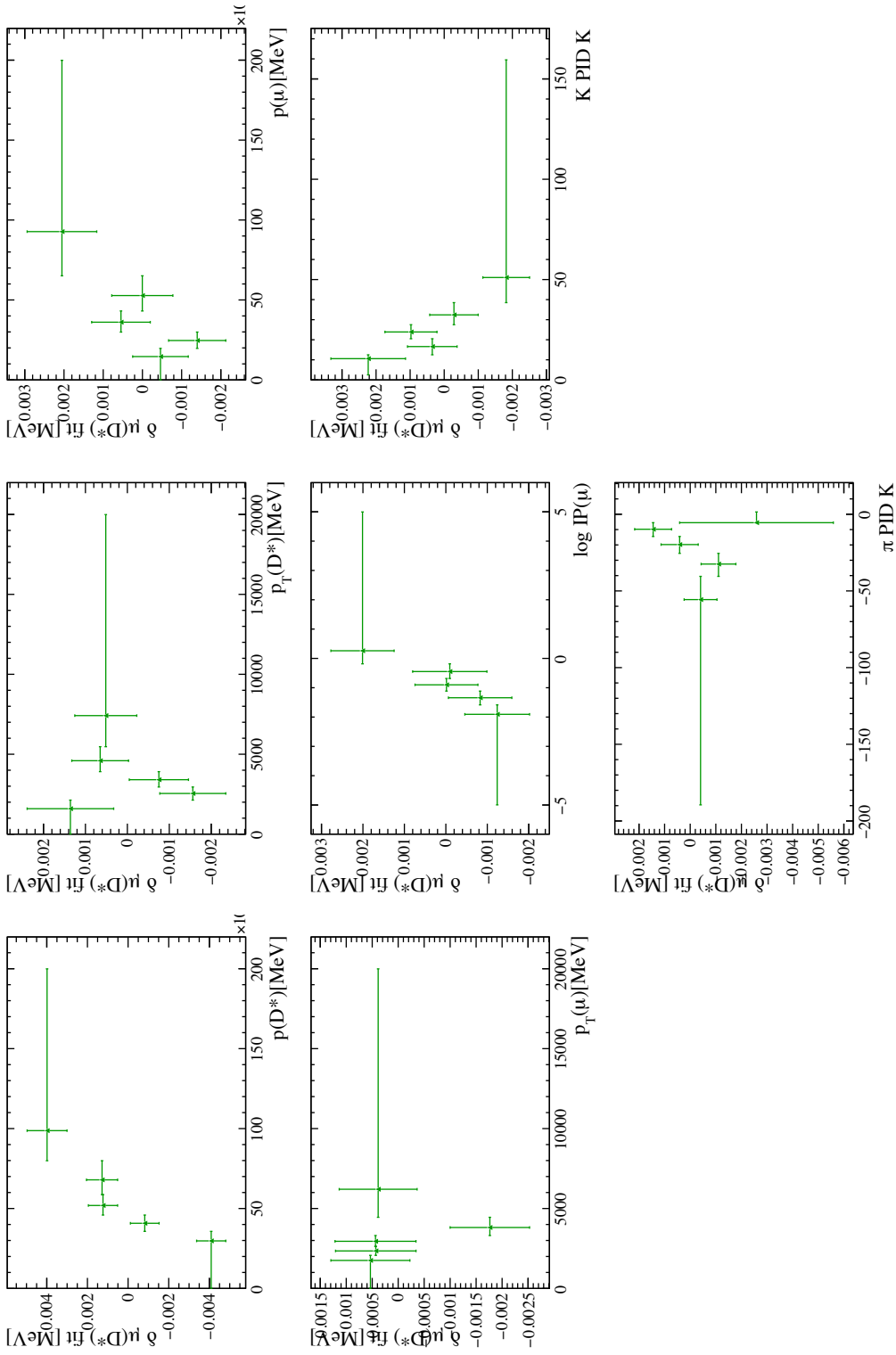


Figure 9.2: The change in mean position of the signal PDF as a function of variable studied. The distribution for the D^* momentum on the top left, D^* transverse momentum on the top middle, muon momentum on the top right, muon transverse momentum are on the middle left, muon $\ln IP$ on the middle center, kaon $\Delta \log(\mathcal{L}(K - \pi))$ on the middle right, and pion $\Delta \log(\mathcal{L}(K - \pi))$ on the bottom.

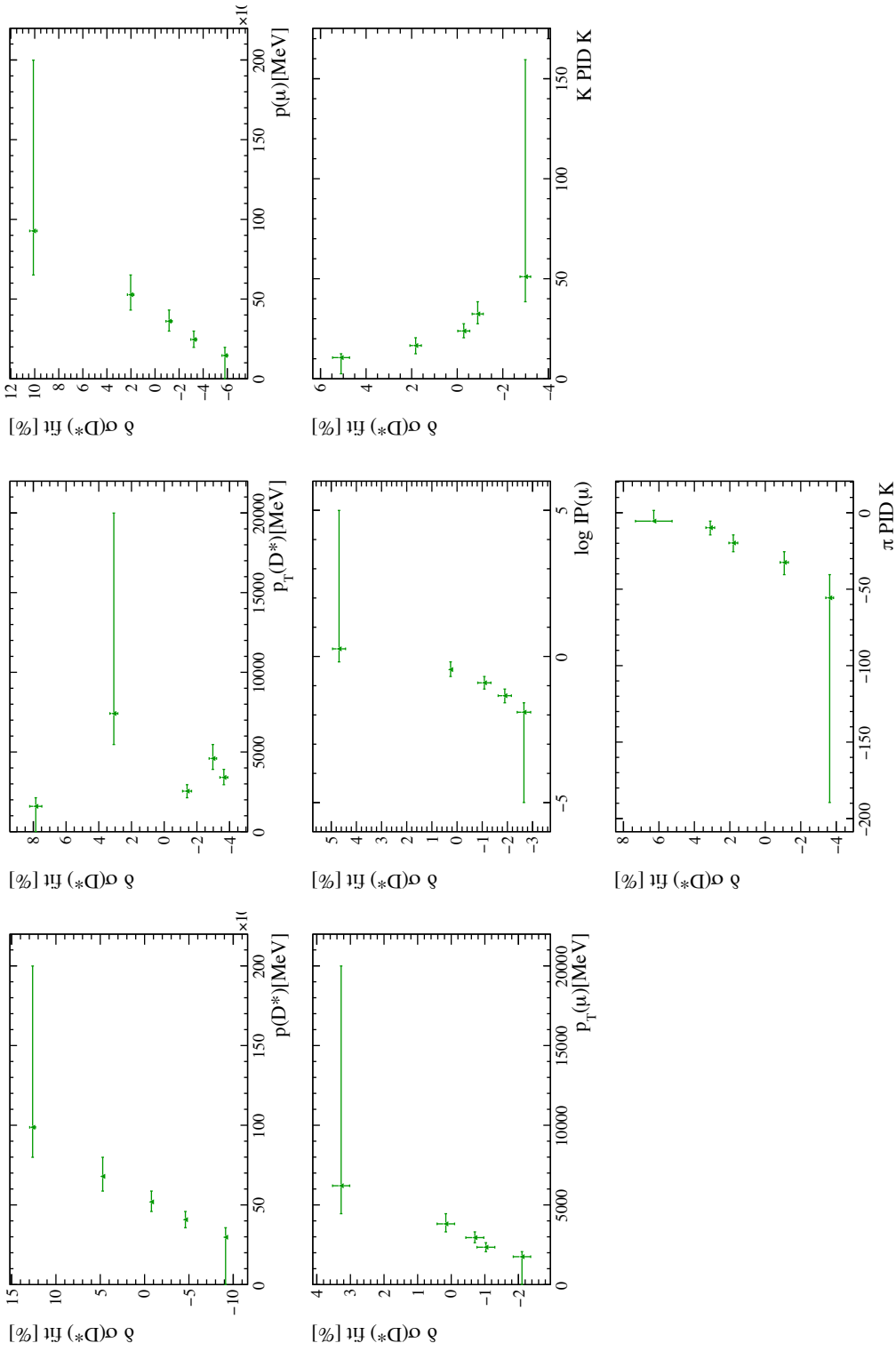


Figure 9.3: The change in the width of the signal PDF as a function of variable studied. The distribution for the D^* momentum on the top left, D^* transverse momentum on the top middle, muon momentum on the top right, muon transverse momentum on the middle left, muon $\ln IP$ on the middle center, kaon $\Delta\log(\mathcal{L}(K-\pi))$ on the middle right, and pion $\Delta\log(\mathcal{L}(K-\pi))$ on the bottom.

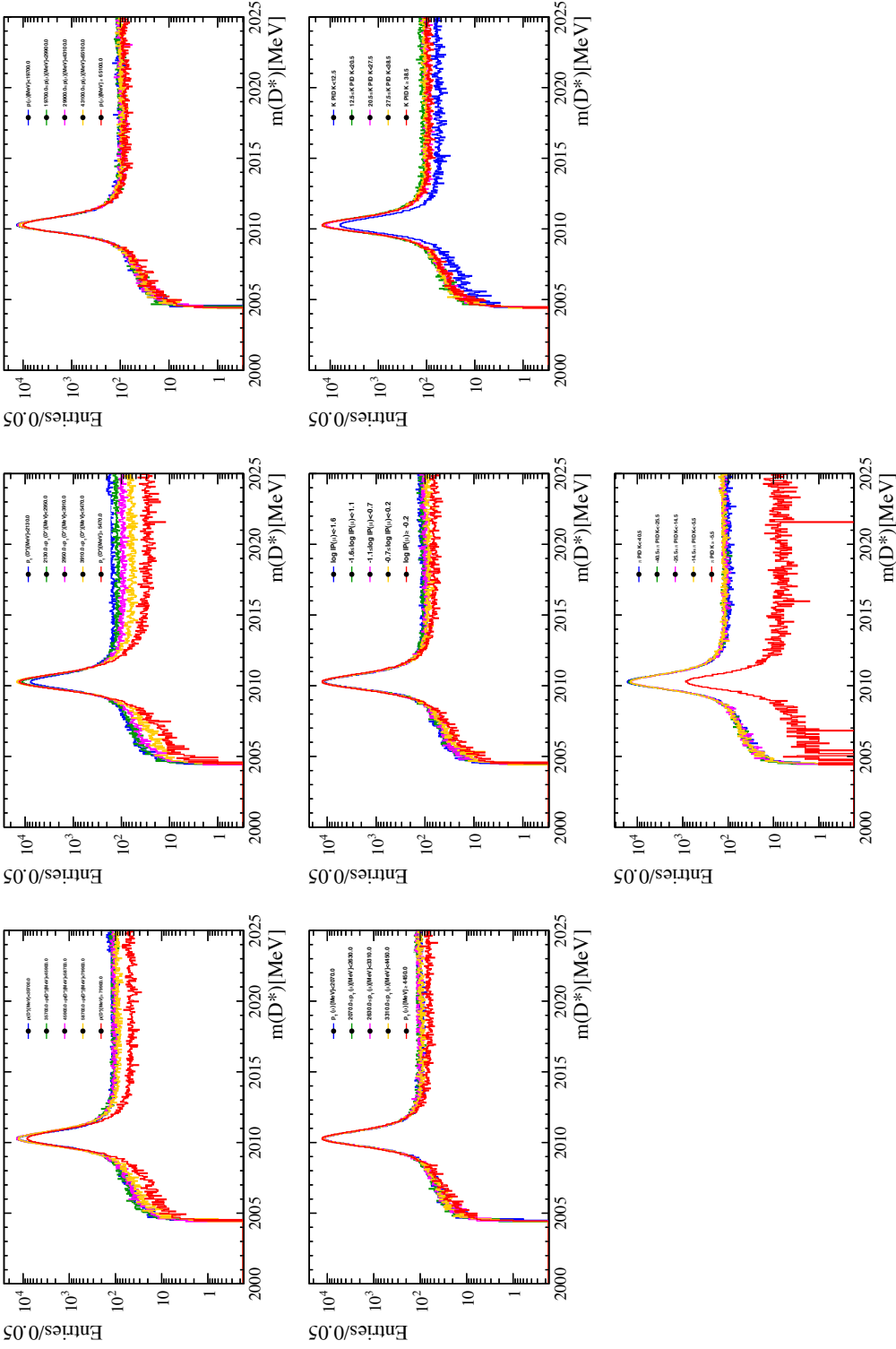


Figure 9.4: Comparison of the D^* invariant mass distribution for bins of variables. Top left is the D^* momentum; top middle is D^* transverse momentum; top right is muon momentum; middle left is muon transverse momentum; middle center is muon IP; middle right is $K \Delta \log(\mathcal{L}(K - \pi))$; bottom is π DLL ($K - \pi$). Cut ranges are shown in the legends.

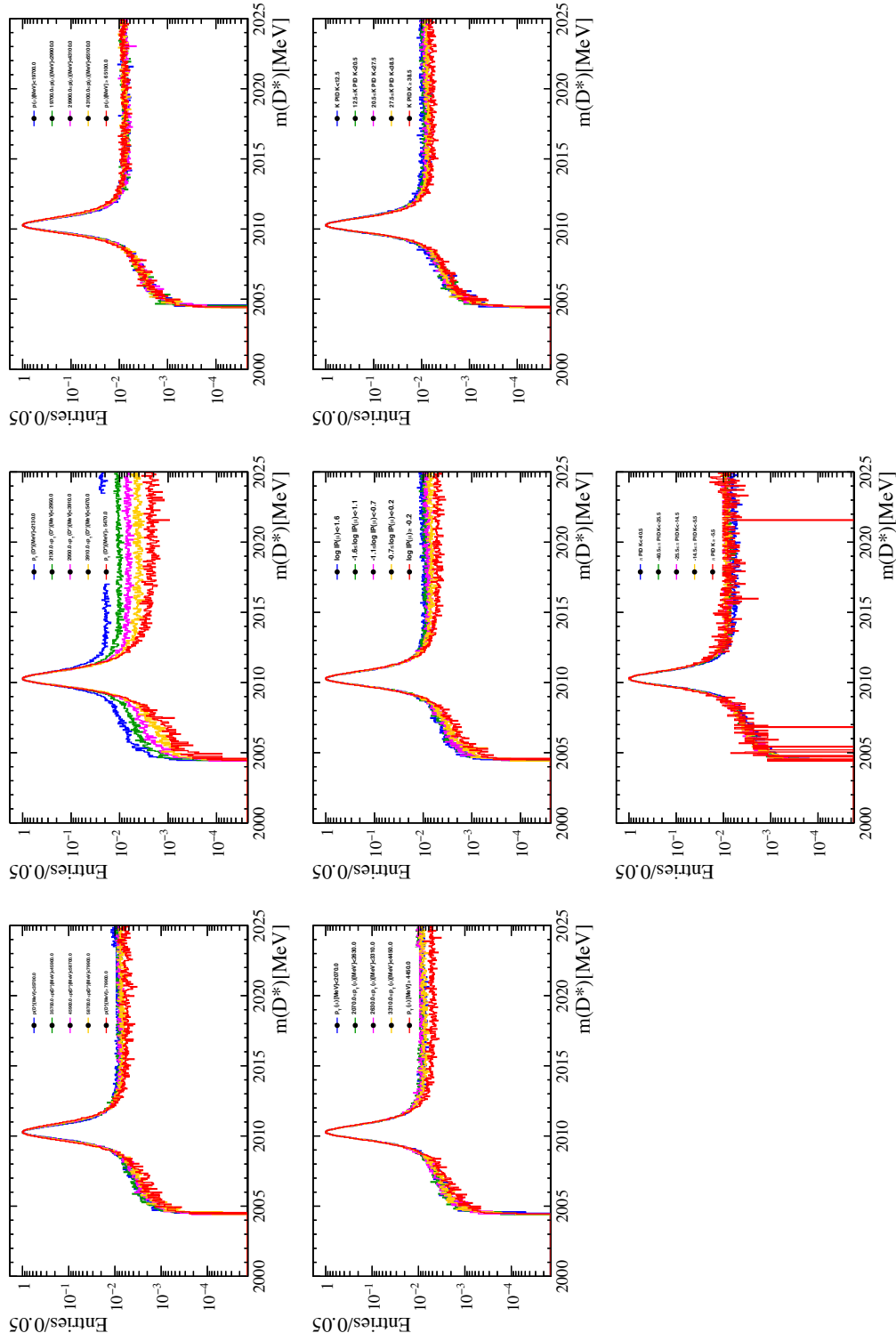


Figure 9.5: Comparison of the D^* invariant mass distribution for bins of variables, normalized to the maximum value. Top left is the D^* momentum; top center is D^* transverse momentum; top right is muon momentum; middle left is muon transverse momentum; middle center is muon $\ln$ IP; middle right is $K \Delta \log(\mathcal{L}(K - \pi))$; bottom is π DLL ($K - \pi$). Cut ranges are shown in the legends.

The resulting yields from each binning and from the original fit are shown in Figure 9.6, and are all statistically consistent with the fit to the total model. Thus the fit model is robust against all of these binnings.

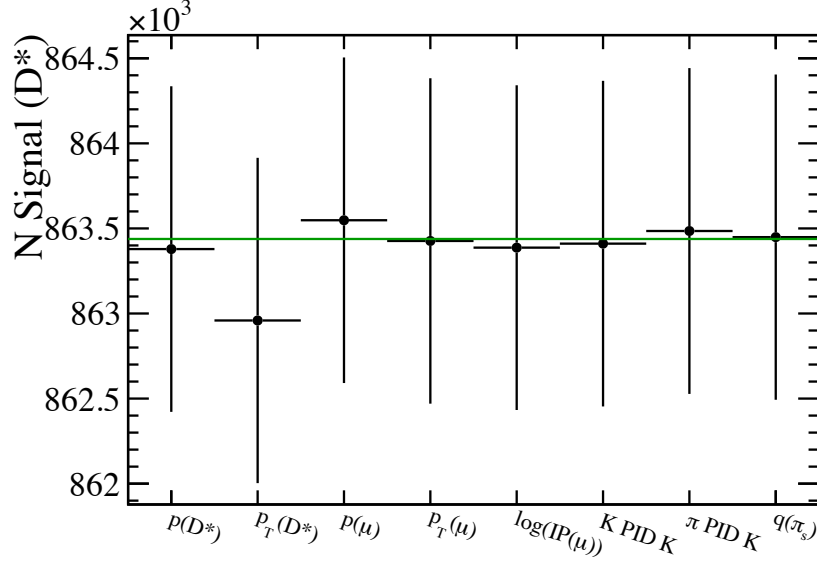


Figure 9.6: Right sign $D^0 \rightarrow K\pi$ signal yields for validation bins. The green line represents the extracted yield from the total sample, and the individual points represent the extracted yields from the bins of the variable on the x axis.

9.2 Validation of CPV fit

To validate that the CPV fit is indeed possible, the ratio of RS $\bar{D}^0 \rightarrow K^+\pi^-$ to RS $D^0 \rightarrow K^-\pi^+$ as a function of D^0 decay time is analyzed. This is shown as the fraction of RS $D^{*-}/\text{RS } D^{*+}$ signal events as a function of decay time. Any variation as a function of decay time represents either a production or detection asymmetry that is not previously understood. Using all analysis cuts defined before, the ratio is shown in Figure 9.7.

What is seen is that the data are consistent with a flat line at a p -value of 7%. This represents a consistency at the 1.7 standard deviation level. To test whether or not this is a statistical fluctuation or simply an artifact from fitting, we extract the same ratio by cutting 0.7 MeV around the nominal $D^{*\pm}$ mass. As we are dealing with RS decays, the expectation

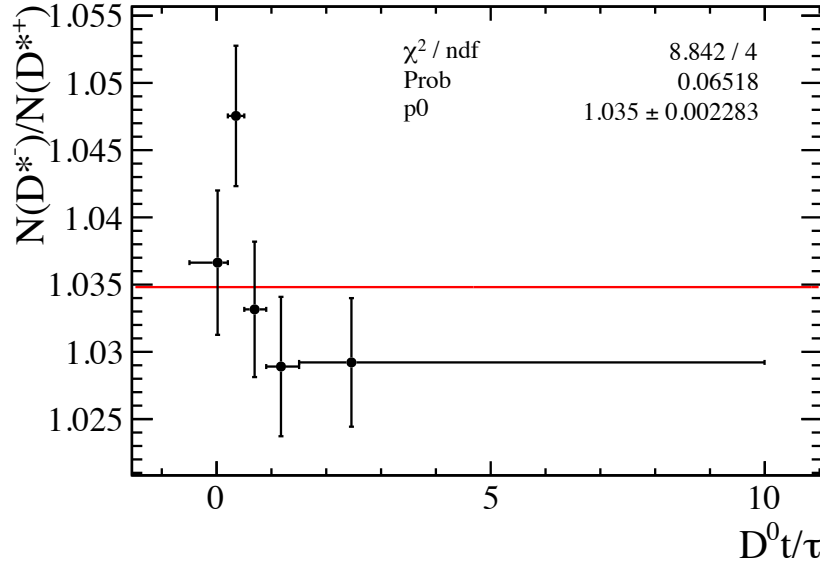


Figure 9.7: Number of Signal Right Sign D^{*-} to Right Sign D^{*+} decays as a function of D^0 decay time. The errors in x represent the size of the bins, and the errors in y represent the propagated statistical error. The points are placed at the mean value of the bin. The red line is a fit to a flat line.

is that this method will be equivalent to fitting the peak itself, therefore, comparing the two datasets allows for complete factorization of the fit model from the process. The result of this procedure is shown in Figure 9.8, and shows consistency with the fitted result, shown in Figure 9.8.

Previously, we searched also for effects from the trigger decisions, mass cuts, cuts on the transverse momentum of the slow pion candidate, and all searches showed no effect on this ratio. Therefore, we must assume one of the following hypotheses

1. The effect is due to some problem due to the muon.
2. The effect is due to non-cancellation of the slow pion detection asymmetry.
3. The effect is due to the D^0 daughters and an effect in their detection efficiency.
4. The effect is a statistical fluctuation.
5. The effect is something that we do not understand.

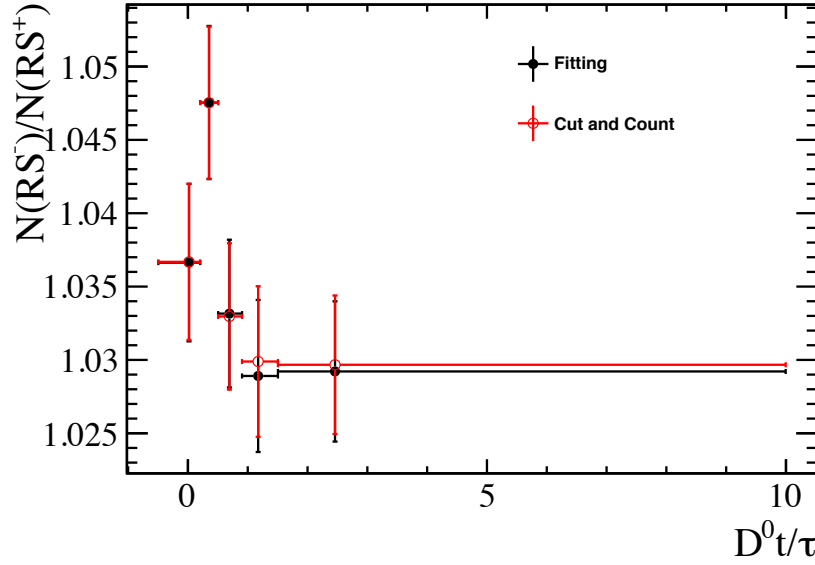


Figure 9.8: Comparison of original RS- over RS+ ratio with fitting (black) vs cutting and counting (red). The points are consistent with one another, and do not show improvement compared to the straight line fit with the original dataset.

The first effect is shown in Section 7.4, and also in the explicit calculation of the $K\pi$ asymmetry to be small, much less than 1% deviation. The second case is also considered in the prompt analysis [18], which shows that over a much larger decay time region, the result itself is consistent with being flat as a function of decay time. Regardless, we double check that there is no problem with the slow pion by plotting the distributions of the slow pion p_x vs p_z and p_y vs p_z both integrated over decay time and in each bin of decay time, along with the associated asymmetry $\left(= \frac{N(\pi_S^+) - N(\pi_S^-)}{N(\pi_S^+) + N(\pi_S^-)}\right)$ due to the slow pion, without SS subtraction. To separate signal from background, we cut within 0.7 MeV of the nominal D^* mass. The time integrated plots are shown in Figure 9.9. Immediately we note that the areas with the largest slow pion asymmetry are also those regions with the lowest statistics. We expect that removing these regions will therefore not have a large effect. For completeness, we also include the same plots in each independent decay time bin in Figures 9.10-9.11.

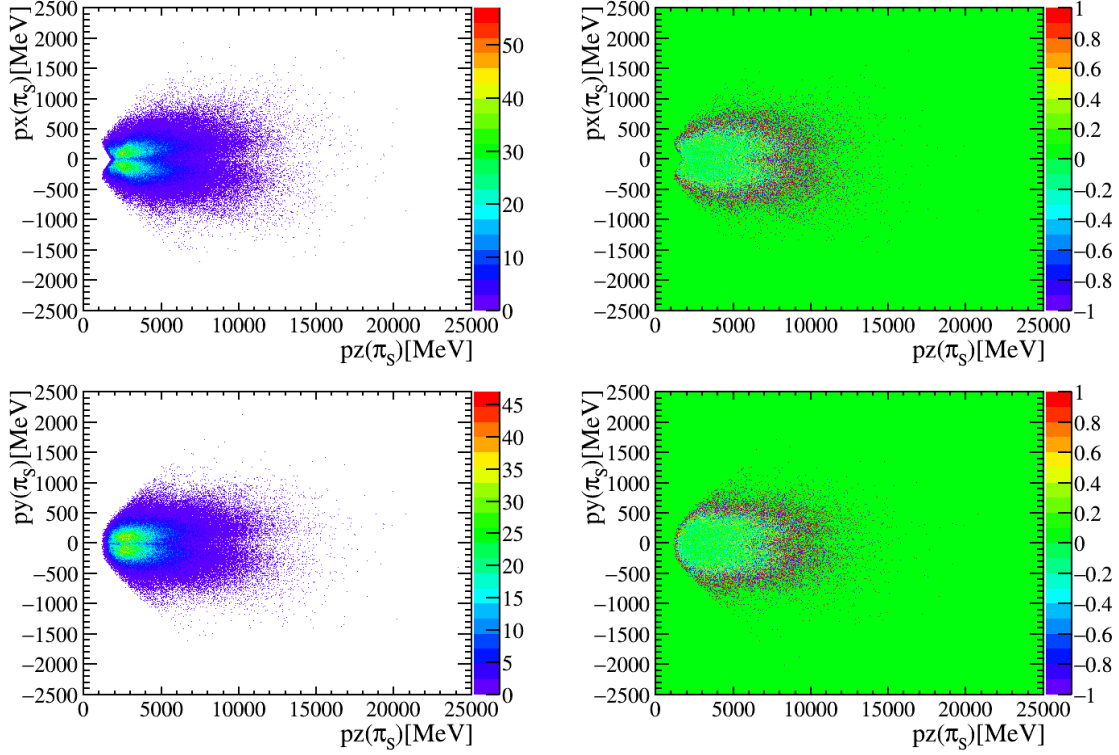


Figure 9.9: Top Left: The distribution of slow pion p_x vs p_z for decays tagged with a π_S^+ . Top Right: Asymmetry of the slow pion in the p_x vs p_z plane. The z-axis represents the asymmetry in the bin. Areas with the highest asymmetry are also those areas with the lowest population. Bottom: Same plots, but for p_y vs p_z . The same conclusion is reached.

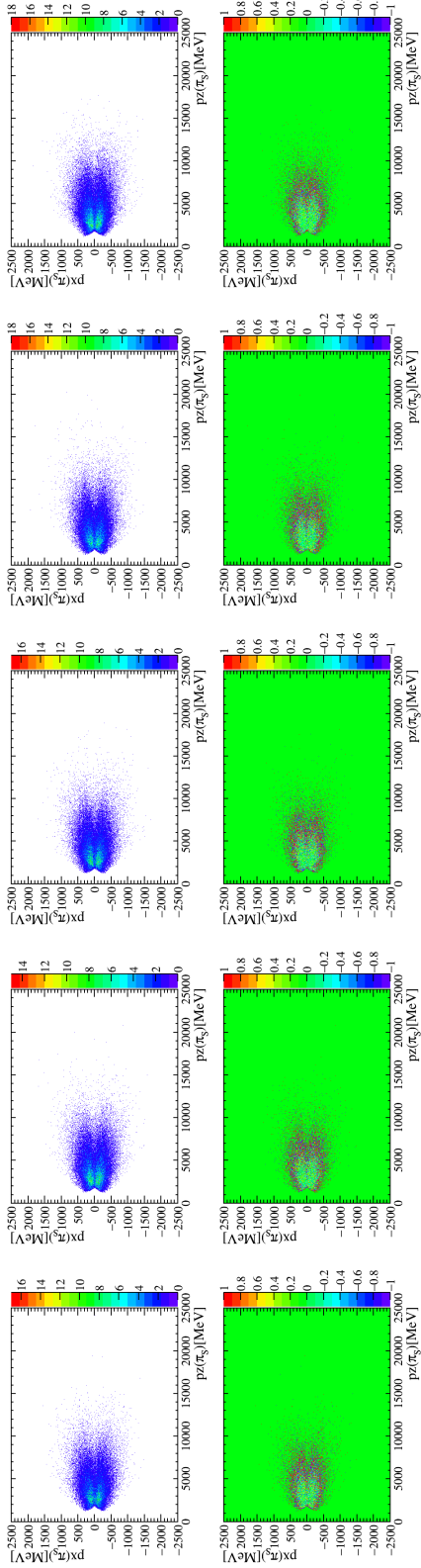


Figure 9.10: Top Row: Distribution of slow pion p_x vs p_z in bins of D^0 decay time. Bottom Row: Asymmetry of the π_s in the p_x vs p_z plane. The first column is $-0.5 < D^0 t / \tau \leq 0.2$, the second $0.2 < D^0 t / \tau \leq 0.5$, the third $0.5 < D^0 t / \tau \leq 0.9$, the fourth $0.9 < D^0 t / \tau \leq 1.5$, and the final column as $D^0 t / \tau > 1.5$.

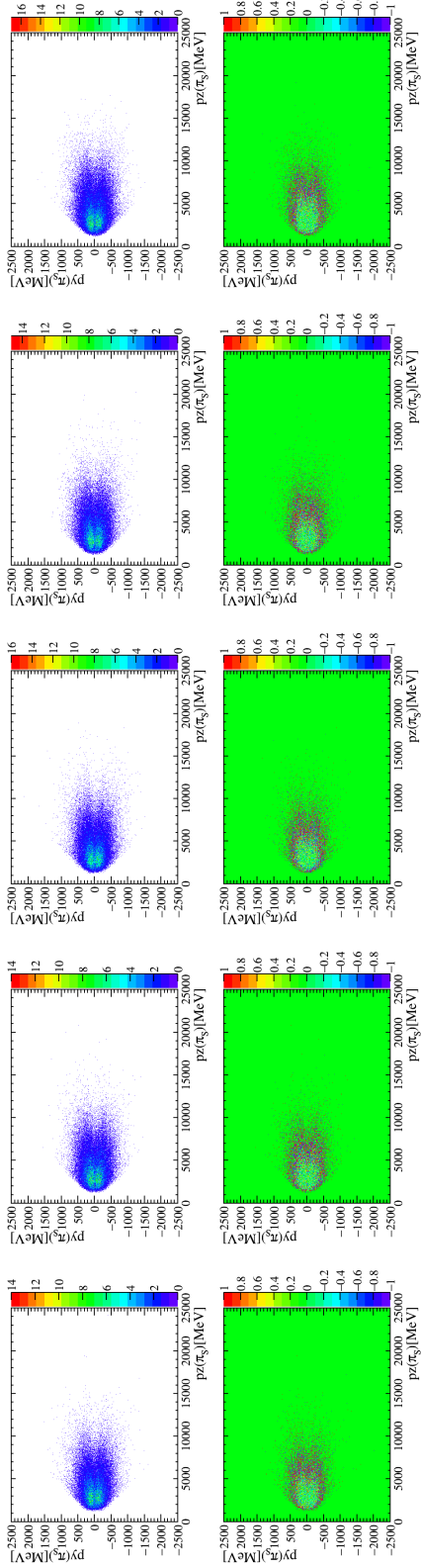


Figure 9.11: Top Row: Distribution of slow pion p_y vs p_z in bins of D^0 decay time. Bottom Row: Asymmetry of the π_S in the p_y vs p_z plane. The first column is $-0.5 < D^0 t/\tau \leq 0.2$, the second $0.2 < D^0 t/\tau \leq 0.5$, the third $0.5 < D^0 t/\tau \leq 0.9$, the fourth $0.9 < D^0 t/\tau \leq 1.5$, and the final column as $D^0 t/\tau > 1.5$.

Regardless of the size of the expected effect, we define the following fiducial cuts to the

π_S :

- $p_z(\pi_S) < 8 \text{ GeV}$
- $|p_x(\pi_S)| < 400 \text{ MeV}$
- $|p_y(\pi_S)| < 400 \text{ MeV}$
- $p_z(\pi_S) > (-2000 - 2 * |p_x(\pi_S)|) \text{ MeV}$
- $p_z(\pi_S) > (2000 + 4/3 * |p_y(\pi_S)|) \text{ MeV}$

These cuts are visualized in Figure 9.12.

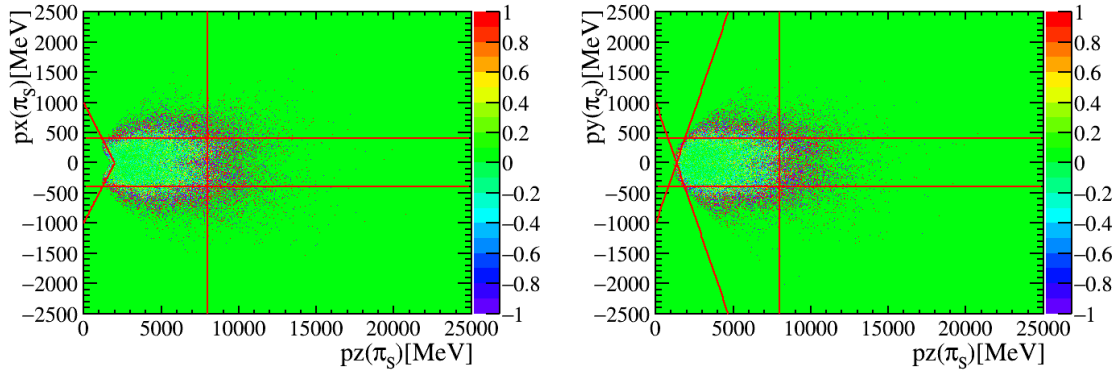


Figure 9.12: Fiducial cuts to the slow pion asymmetry in the p_x vs p_z plane (left) and the p_y vs p_z plane (right).

After applying these cuts, we look at the same D^{*-} over D^{*+} ratio for RS decays. This is shown in Figure 9.13. We see that these cuts do not improve the problem.

To check that the third possibility is not the answer, we explicitly check the $K\pi$ asymmetry as a function of D^0 decay time. We calculate the $K\pi$ asymmetry in Section 11.1 and find that there is no lifetime dependence of the $K\pi$ asymmetry. We choose to represent the possible variation then as a possible subleading effect, and treat the time variation as a systematic uncertainty applied to $A(K\pi)$ in Section 13.3.2.

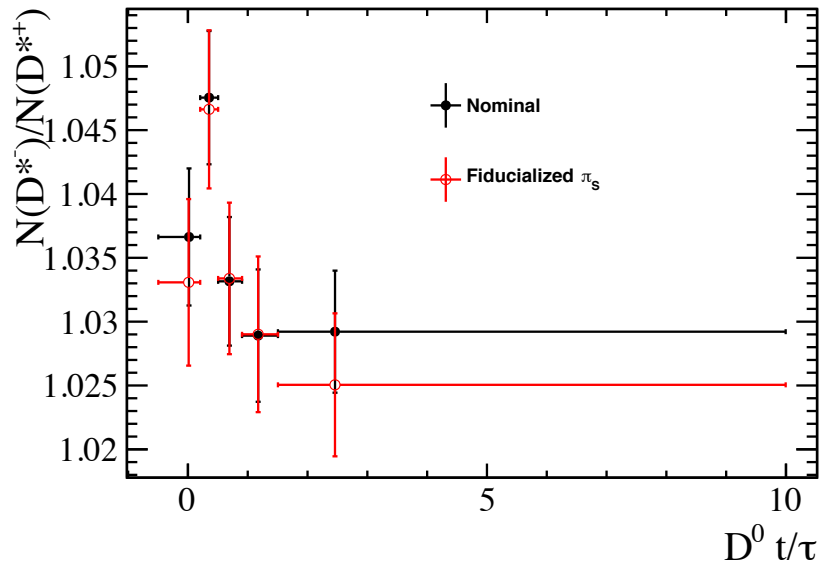


Figure 9.13: Overlay of the D^{*-} over D^{*+} ratio as a function of decay time for the nominal selection in black and the selection after the fiducial cuts to the slow pion in red.

Chapter 10

Peaking Backgrounds

10.1 Peaking Backgrounds from D^0

We search for events which are identified as $D^0 \rightarrow K\pi$, but are actually $D^0 \rightarrow KK$, $D^0 \rightarrow \pi\pi$ or $D^0 \rightarrow \pi K$, where this means that both the kaon and pion in the final state, or possibly both particles, are misidentified. Such backgrounds are potentially hazardous because they can dilute the signatures of mixing and CP violation in the sample. The effect is most dangerous to the WS sample. We analyze the individual contributions of each of these decays by defining sideband regions of the $D^0 \rightarrow K\pi$ region, namely $|m(K\pi) - m_{D^0,PDG}| > 40$ MeV. In these sideband regions, we then further restrict to events which are consistent with being in the signal region of one of the misidentification, e.g. consistency with $D^0 \rightarrow KK$ is defined by events falling within $|m(KK) - m_{D^0,PDG}| < 24$ MeV; similarly $D^0 \rightarrow \pi\pi$ fulfills $|m(\pi\pi) - m_{D^0,PDG}| < 24$ MeV. This is done by changing the mass assumption of the daughter particle in question, the daughter K or π , then recomputing the invariant mass of the D^0 candidate. The invariant mass of the $D^{*\pm}$ candidate for events satisfying these criteria are shown in Figure 10.1 for RS decays and Figure 10.2 for WS decays. The inlaid number represents the number of peaking events in the fit. For the first fit, the number of events is the extracted signal without accounting for the trigger acceptance of 50% of events.

By fitting the total sideband region and each subset corresponding to regions of particular

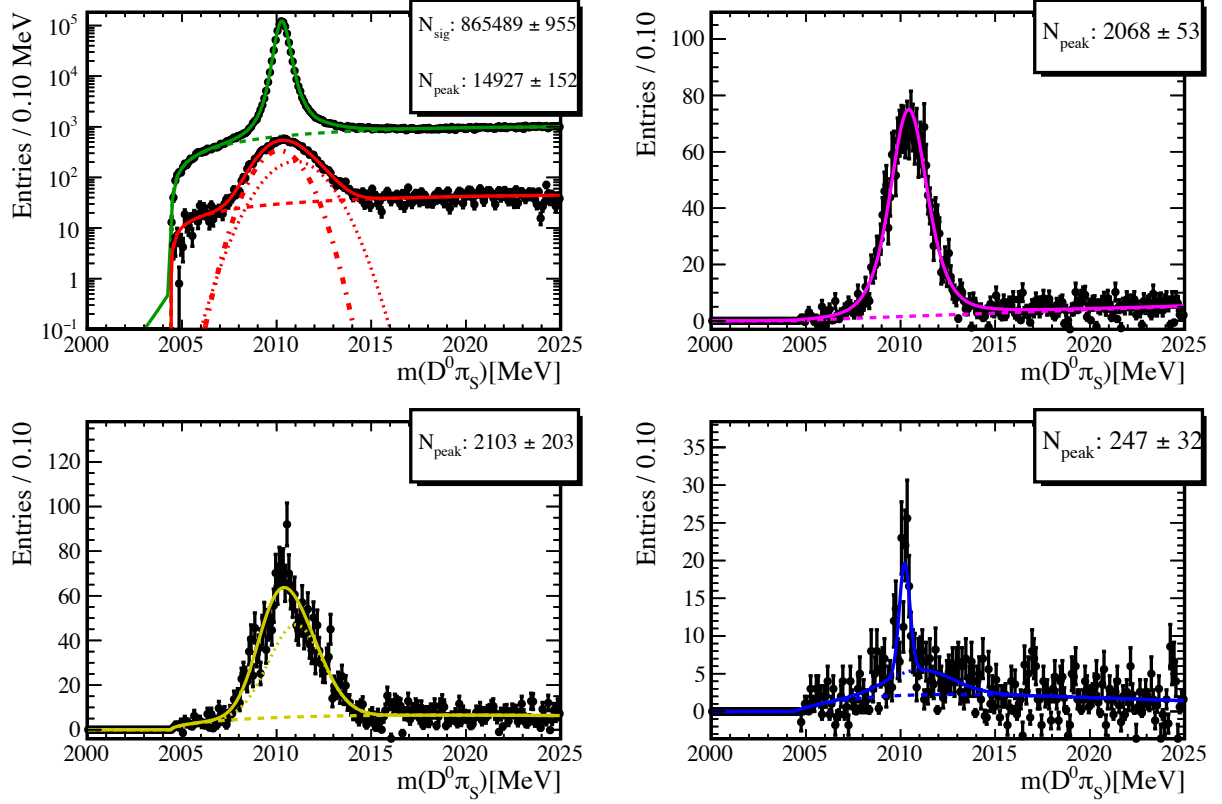


Figure 10.1: Reconstructed invariant mass distributions of the RS $D^{*\pm}$ candidates with fits overlaid for Signal $|m(K\pi) - m_{D^0,PDG}| < 24$ MeV (Top Left, green), events in the background region, $|m(K\pi) - m_{D^0,PDG}| > 40$ MeV (Top Left, Red), events consistent with double misidentification $|m(\pi K) - m_{D^0,PDG}| < 24$ MeV (Top Right, Magenta), background with $|m(KK) - m_{D^0,PDG}| < 24$ MeV (Bottom Left, yellow), and background with $|m(\pi\pi) - m_{D^0,PDG}| < 24$ MeV (Bottom Right, blue). The boxes inlaid show the number of peaking events extracted from a fit to data.

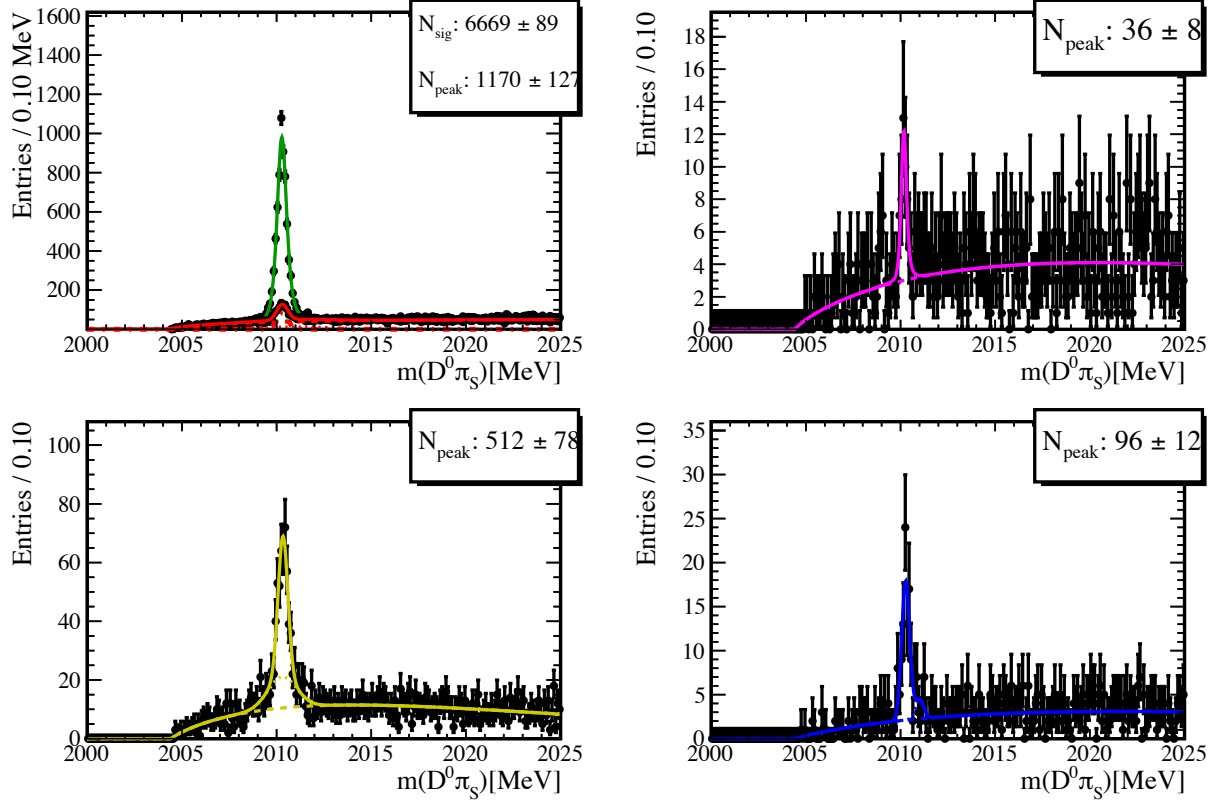


Figure 10.2: Reconstructed invariant mass distributions of the WS $D^{*\pm}$ candidates with fits overlaid for Signal $|m(K\pi) - m_{D^0,PDG}| < 24$ MeV (Top Left, green), events in the background region, $|m(K\pi) - m_{D^0,PDG}| > 40$ MeV (Top Left, Red), events consistent with double misidentification $|m(\pi K) - m_{D^0,PDG}| < 24$ MeV (Top Right, Magenta), background with $|m(KK) - m_{D^0,PDG}| < 24$ MeV (Bottom Left, yellow), and background with $|m(\pi\pi) - m_{D^0,PDG}| < 24$ MeV (Bottom Right, blue). The boxes inlaid show the number of peaking events extracted from a fit to data.

interest, we decompose the sideband composition. For RS decays, 14% of the total sideband has some peaking structure in $m(D^{*\pm})$ in the region corresponding to doubly misidentified D^0 decays, 14% for those events entering the vetoed $D^0 \rightarrow KK$ sideband region, and 2% events from the vetoed $D^0 \rightarrow \pi\pi$ sideband. For WS decays, 3% of the sideband is composed from events in the doubly misidentified sideband region, 43% come from the vetoed $D^0 \rightarrow KK$ sideband region, and 8% enter from the vetoed $D^0 \rightarrow \pi\pi$ region. These sidebands correspond to 30% of the total sideband in the RS, and 55% of the WS total sideband. In the RS, the ranges of the sidebands are roughly double that of the signal region, thus the maximum contribution of peaking background in the RS decay is at the level of 8 per mille, and there will be negligible contribution from WS misidentified as RS. However, for all cases, the $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$ decays are eliminated by enforcing that the allowed events satisfy $|m(KK) - m_{D^0,PDG}| > 40 \text{ MeV}$ and $|m(\pi\pi) - m_{D^0,PDG}| > 40 \text{ MeV}$.

In the WS, the possibility of swapped RS $D^0 \rightarrow \pi K$ being called WS $D^0 \rightarrow K\pi$ is a potentially hazardous peaking background. As the total of the three sidebands added together makes up only 55% of the total peaking contribution, modeling of only the doubly misidentified $D^0 \rightarrow \pi K$ component alone does not accurately assess the total peaking background contribution. For this reason, we choose instead to divide the D^0 sidebands into six lower sideband bins and six higher sideband bins, given in Table 10.1 and shown graphically in Figure 10.3. These bins enforce the condition that the $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$ are excluded, i.e. lie $> 40 \text{ MeV}$ from the nominal D^0 mass.

Table 10.1: Definition of Sideband Bins

Bin Number	Low Sideband Value	High Sideband Value
1	[1790, 1795.8]	[1904.84, 1911.]
2	[1795.8, 1801.6]	[1911., 1916.8]
3	[1801.6, 1807.4]	[1916.8, 1922.6]
4	[1807.4, 1813.2]	[1922.6, 1928.4]
5	[1813.2, 1819]	[1928.4, 1934.2]
6	[1819, 1824.84]	[1934.2, 1940]

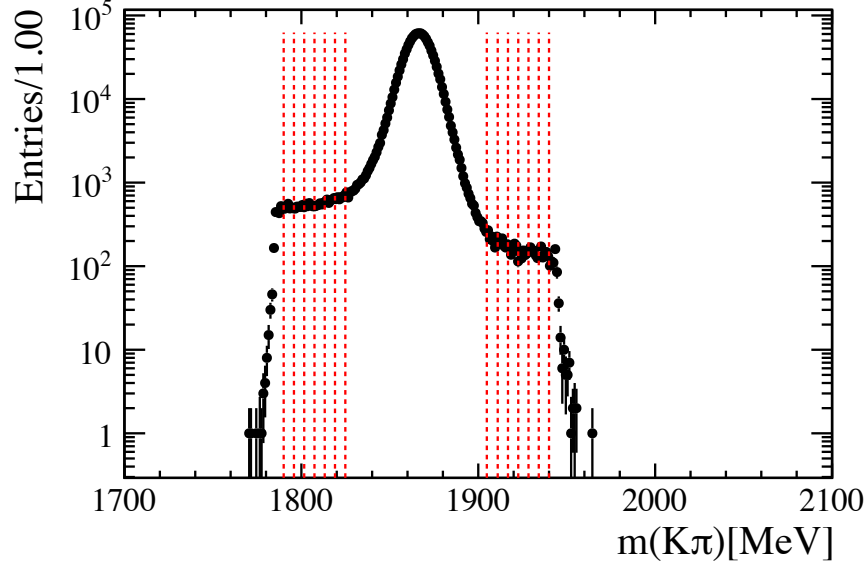


Figure 10.3: Definitions of the D^0 sidebands overlaid on the RS sample for the peaking background estimation in the WS sample.

Using these sideband definitions, we fit the $D^{*\pm}$ mass distribution in each subrange with a fit model taken from all bins added together. From the fit, we extract the total number of peaking events in each bin. We then fit the number of events in both sidebands and extract the number of peaking events in the D^0 signal region. The fits are shown in Figure 10.4 for the charge integrated sample, and split into D^{*+} and D^{*-} in Figure 10.5.

From this extraction, we find that there are 128 ± 31 peaking background events in the signal region. This accounts for $(1.9 \pm 0.7)\%$ of the WS yield, or a fraction of $(7.4 \pm 1.8) \times 10^{-5}$ when compared to the RS signal. This fraction compared to RS signal is the quantity p_{other} which enters into Equation 5.11. Split by charge, the D^{*+} sample contains 91 ± 16 events, and the D^{*-} sample contains 79 ± 32 events. As there is not enough statistics to extract the time dependence of this ratio, we incorporate an upper limit of events that could enter each time bin by taking the total RS peaking background over the total RS signal, multiplied by the RS yield in each bin. These numbers are reported in Table 10.2.

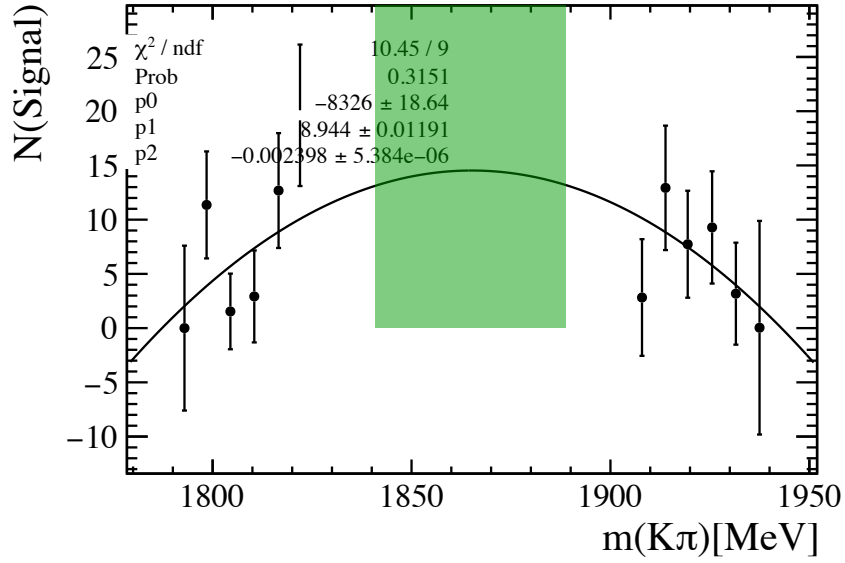


Figure 10.4: Fitted number of peaking background events in the D^0 sidebands, extrapolated into the signal region. The fit model is a second order polynomial.

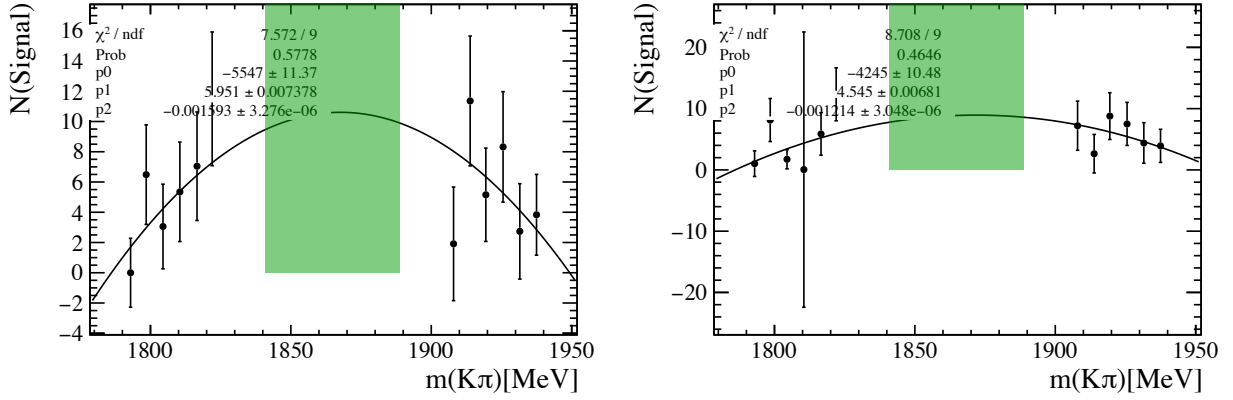


Figure 10.5: Fitted number of peaking background events in the D^0 sidebands, extrapolated into the signal region for the D^{*+} sample on the left and D^{*-} sample on the right. The fit model is a second order polynomial.

Table 10.2: Extracted number of peaking background events for the D^{*+} and D^{*-} samples.

Time bin	D^{*+} Peaking Background	D^{*-} Peaking Background
1	16.496 ± 2.95929	14.3955 ± 5.6747
2	17.6923 ± 3.17386	15.6051 ± 6.15153
3	18.6816 ± 3.3513	16.2512 ± 6.40622
4	17.5783 ± 3.15342	15.2268 ± 6.00239
5	20.6982 ± 3.71299	17.9365 ± 7.07051

10.2 Backgrounds from B Mesons

There are two possible combinations of background which could be misidentified as the signal B meson decay: First, there could be truly prompt decays which have a random muon associated. Second, there are decays which are not truly originating from a semileptonic B meson decay. Any contribution from the prompt $D^{*\pm}$ must be a very small amount. The rationale for this thinking is as follows: the only way that prompt decays could enter the DT sample is by having a genuine $D^{*\pm} \rightarrow D^0 \pi_s^\pm$ decay with $D^0 \rightarrow K\pi$ and have a false muon. This represents a combinatoric background which would enter into the scaled SS background. This contribution is subtracted away as indicated in Chapter 7.5. In addition, we veto any possible feed-through from the prompt sample into the DT sample by rejecting common events, as in Chapter 7.2. For these reasons we set the prompt feed-through to zero in the DT sample. We assess a systematic uncertainty for this choice by extracting the change in the final result with a change in scaling factor of the SS subtraction in each decay time bin to unity.

Chapter 11

Instrumental Asymmetries

It is well known that charged particles have differing interactions in matter depending on the sign of the charge. The charged kaon cross section in matter is one example of such an effect. In this analysis, it is necessary to quantify the asymmetries due to the charged D^0 daughters detection, as illustrated in Equation 5.11. This is accomplished by using the same technique as the prompt mixing analysis, but cannot yield the same result, as the momentum spectra of the D^0 daughters is expected to be different.

The calculation of this detection asymmetry uses the relation

$$\frac{\epsilon_{K^+\pi^-}}{\epsilon_{K^-\pi^+}} = \frac{N(D^- \rightarrow K^+\pi^-\pi^-)}{N(D^+ \rightarrow K^-\pi^+\pi^+)} \frac{N(D^+ \rightarrow K_s^0\pi^+)}{N(D^- \rightarrow K_s^0\pi^-)}. \quad (11.1)$$

This equation (Equation 11.1) becomes approximately

$$A_{K\pi} = A(K_s^0\pi) - A(K\pi\pi) - A_{K^0} + A_{L0}. \quad (11.2)$$

This expansion relies on the fact that each asymmetry above is $\mathcal{O}(1\%)$, and the second order terms in the expansion enter at the level of 10^{-6} . The expansion is derived in Appendix A.6. Each of these asymmetries can be extracted from individual samples, namely Cabibbo favored $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+ \rightarrow K_s^0\pi^+$. We explicitly only use the sample of K_s^0 mesons which have hits in all tracking detectors to more accurately mimic the signal decay, which

only contains such tracks. The caveat is that in order to completely cancel the production asymmetry, the events must be reweighted. The reweighting strategy is as follows:

1. The K^- from the three body D^+ sample and the π^+ from the same sample which did not originally trigger the event are reweighted in η, p_T of the kaon and p_T of the pion to match the kaon and pion from the DT signal sample
2. The D^+ and the π^+ of the $D^+ \rightarrow K_S^0 \pi^+$ are reweighted to the pion which triggered the D^+ event in p_T and the p_T and η of the D^+ three body decay.

Therefore, the final reweighting takes place in 3 dimensions in each step: $K(p_T), K(\eta)$ and $\pi(p_T)$ for the first and $D^+(p_T), D^+(\eta)$, and $\pi(p_T)$ for the second. The reweighting scheme used relies on the `hep_ml` framework [24] based on Scikit-learn [25], and is implemented by using a gradient boosted reweighter which reweights in the three dimensions for each step simultaneously. Reweighting in bins using a TH3 does not change the central value.

The results of the reweighting procedure for 2011 MD data are given in Figures 11.1-11.2, and plots for 2011 MD, 2011 MU, 2012 MD and 2012 MU are shown in Appendix A.7.

After the reweighting, the raw asymmetry of the $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^+ \rightarrow K_S^0 \pi^+$ is extracted by a simultaneous fit to the D^+ and D^- mass distributions with the asymmetry as a fitted parameter. The plots of the fits are shown in Figure 11.3.

Finally, the L0 asymmetry is due to the enforcement that the event pass the L0 muon trigger. We measure this asymmetry in data using Equation 11.1 and defining the L0 muon asymmetry as

$$\epsilon_{L0\mu} = \frac{N_{RS}(L0_{\text{Muon}})TIS\&\&TOS}{N_{RS}(L0_{\text{Muon}})TIS}. \quad (11.3)$$

The efficiency for L0 muon varies from 75% to 84%, with the higher efficiencies coming in 2011. As for the $K^0/\bar{K}^0$ asymmetries, they are taken from LHCb-PAPER-2012-052 [26], and is $A_{K^0} = -(0.05 \pm 0.01)\%$. The results of the procedure for all samples is given in Table 11.1. Note, we assess a systematic uncertainty on the reweighting in the next section. The total $K\pi$ asymmetry is calculated as the weighted average of the $K\pi$ asymmetry for each data sample.

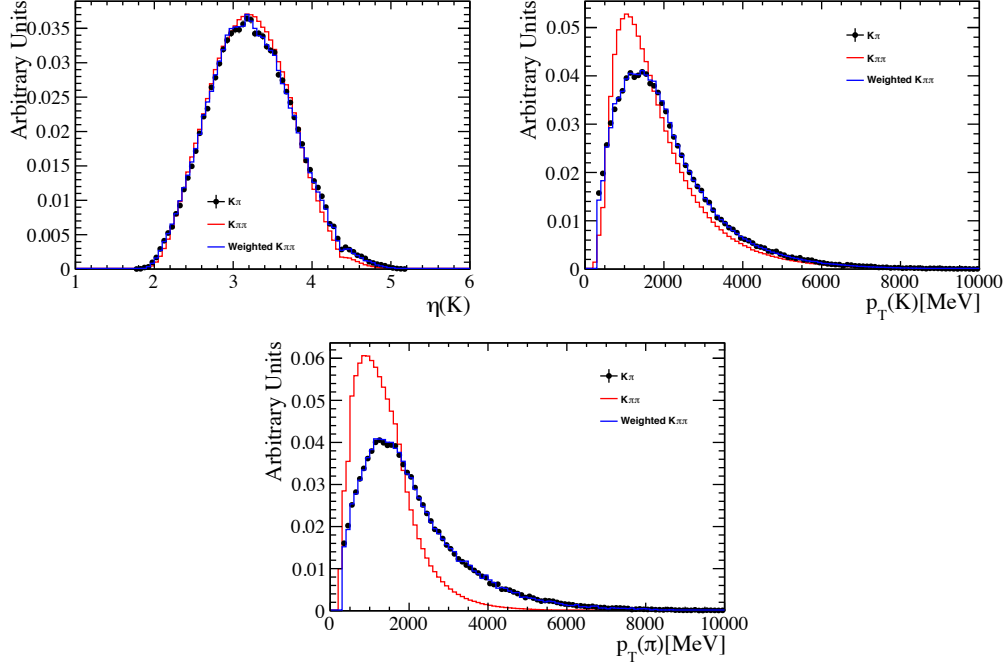


Figure 11.1: Reweighting plots for the first reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2011. The top left is the distribution for the pseudorapidity η of the kaon, the top right is that for the transverse momentum of the kaon, and the bottom plot is the distribution for the transverse momentum of the pion. In each plot, the red line represents the original $D^+ \rightarrow K^- \pi^+ \pi^+$ sample, the blue the reweighted $D^+ \rightarrow K^- \pi^+ \pi^+$ sample, and the points are the $D^0 \rightarrow K^- \pi^+$ sample.

Table 11.1: Measurement of the $K\pi$ detection asymmetry for the DT sample. The total selection is split by magnet polarity and year.

Sample	$A(K\pi\pi)[\%]$	$A(K_S^0\pi)[\%]$	$A_{L0muon}[\%]$	$A(K\pi)[\%]$
2011 Mag Down	-1.31 ± 0.27	-0.85 ± 0.31	-0.01 ± 0.01	0.50 ± 0.41
2011 Mag Up	-1.43 ± 0.28	-0.794 ± 0.36	0.02 ± 0.01	0.71 ± 0.45
2012 Mag Down	-1.81 ± 0.17	-0.647 ± 0.27	0.00 ± 0.01	1.22 ± 0.32
2012 Mag Up	-1.79 ± 0.21	-0.929 ± 0.25	0.00 ± 0.01	0.91 ± 0.33
Total	-1.67 ± 0.11	-0.81 ± 0.14	0.00 ± 0.01	0.90 ± 0.18

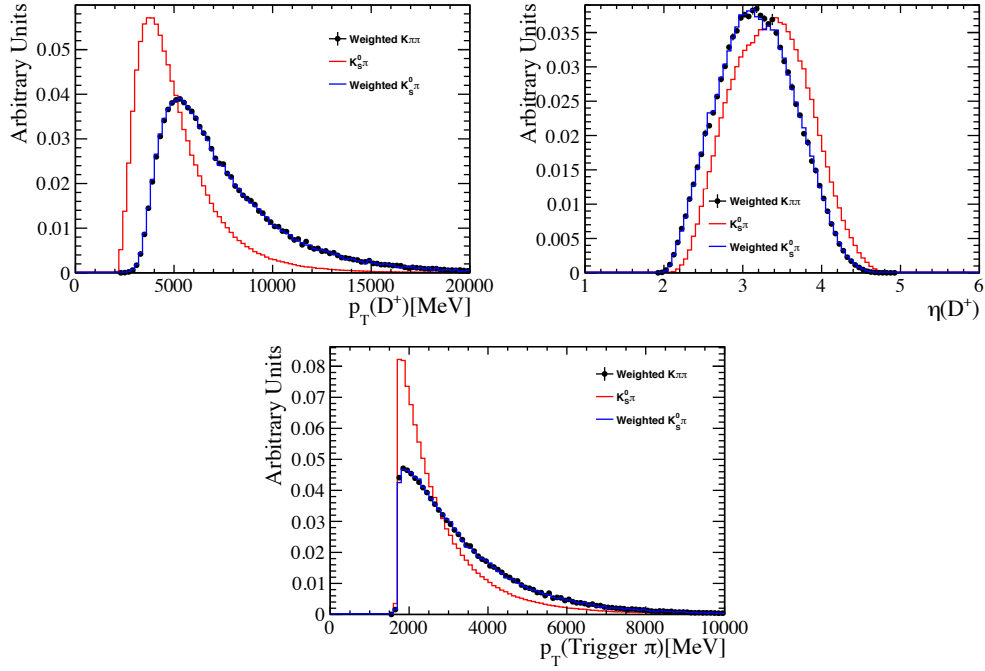


Figure 11.2: Reweighting plots for the second reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2011. The top left plot shows the D^+ transverse momentum distribution, the top right the D^+ pseudorapidity, and the bottom plot shows the trigger pion transverse momentum. In all plots, the red line represents the original $D^+ \rightarrow K_S^0 \pi^+$ sample, the blue line represents the reweighted $D^+ \rightarrow K_S^0 \pi^+$ sample, and the points are the previously weighted $D^+ \rightarrow K^- \pi^+ \pi^+$ sample.

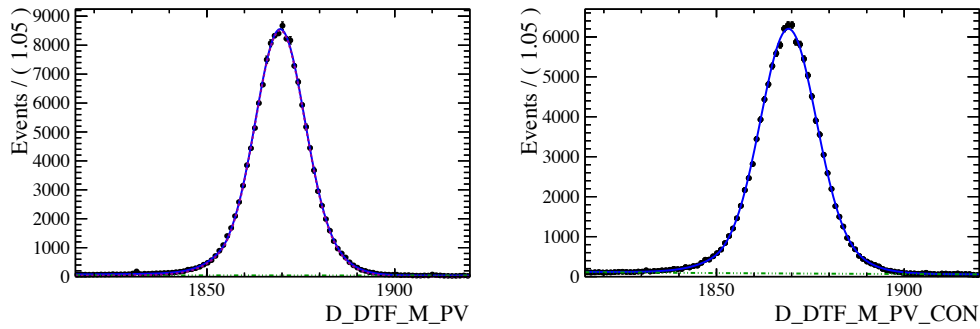


Figure 11.3: Fits to the D^+ mass distribution for the $D^+ \rightarrow K^- \pi^+ \pi^+$ on the left and $D^+ \rightarrow K_S^0 \pi^+$ on the right.

11.1 $A(K\pi)$ variation with D^0 decay time

To search for any decay time dependence of the $K\pi$ asymmetry, we first look at the distributions of kaon and pion momentum in each of the different bins of decay time. The normalized distributions are shown in Figure 11.4.

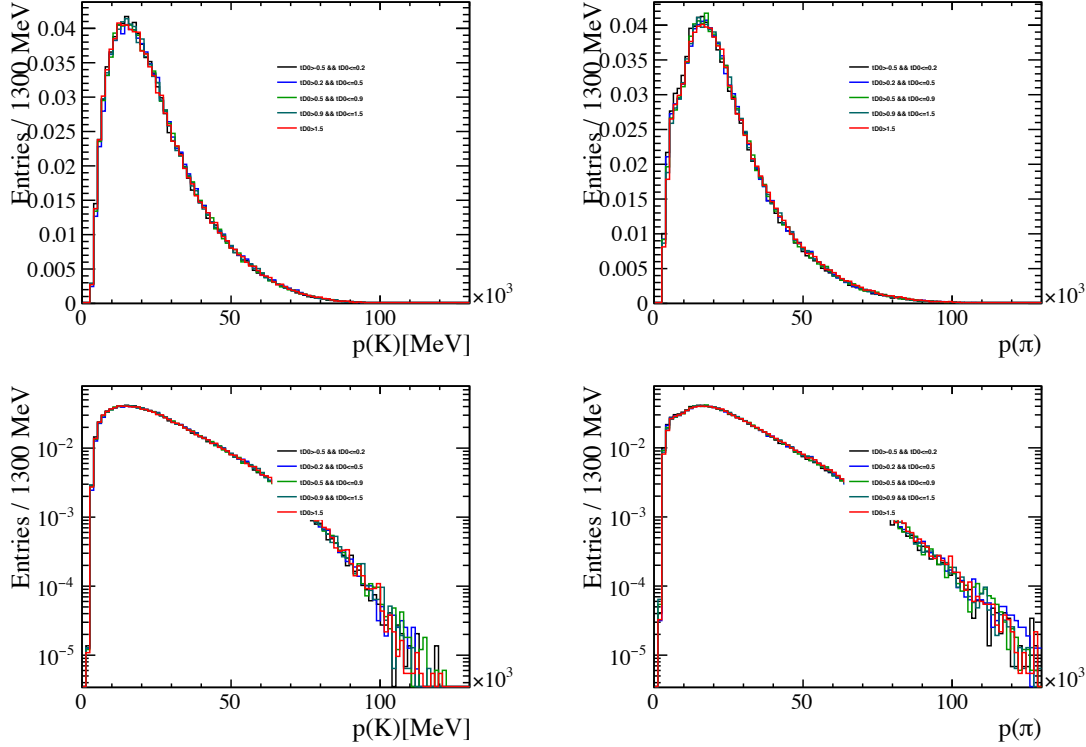


Figure 11.4: Normalized momentum distributions of the kaon (left) and pion (right) of the D^0 in bins of D^0 decay time. Top plots are linear scale, bottom are semilog y.

While these distributions look quite similar, we take one step further and look at the p -value of the χ^2 compatibility of each histogram with each other and also compare the similarities of the unbinned datasets by looking at the Kolmogorov-Smirnov (KS) probability that the datasets are from the same mother sample. The results of these studies are in Figure 11.5.

We therefore repeat the same procedure as above for each bin of decay time, then extract the $K\pi$ asymmetry. Each individual asymmetry per decay time bin is given in Figure 11.6 and is visualized in Figure 11.7. Here the points are the $K\pi$ asymmetry and the green line

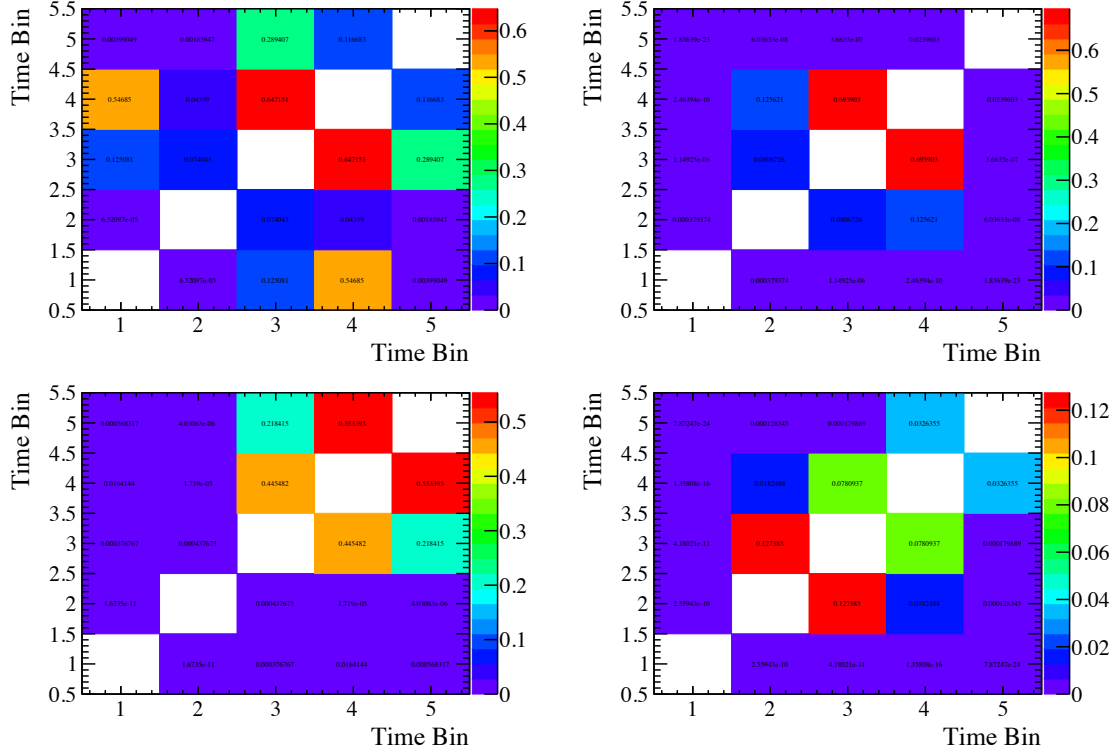


Figure 11.5: Top: Distribution of the p -values of compatibility between the kaon (left) and pion (right) momentum distributions in bins of decay time. Bottom: The KS probability for the unbinned datasets to be compatible between the kaon (left) and pion(right) momentum distributions.

corresponds to the value attained when fitting all decay time regions concurrently, with its error visualized as the purple band around the line. The red line is the average value over each decay time. The plot shows no significant variation as a function of D^0 decay time. It is important to note, though, that while the error bars are listed on the plot, the reweighting for each sample are done using the same D^+ samples, so each point is correlated. It is for this reason that we take the difference between the average over decay time bins and the time integrated sample as the systematic error associated with the reweighting procedure.

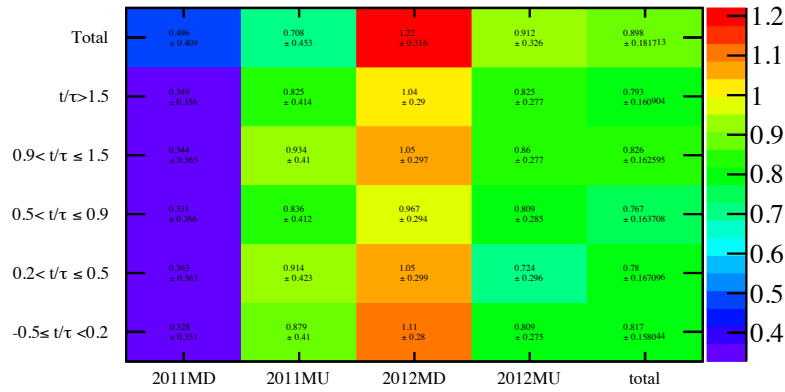


Figure 11.6: $K\pi$ asymmetry extracted in bins of D^0 decay time for each individual sample. The original total sample is also given as reference.

Therefore, the value of $A(K\pi)$ which is used in the final fit is

$$A(K\pi) = [0.90 \pm 0.18 \pm 0.10]\% \quad (11.4)$$

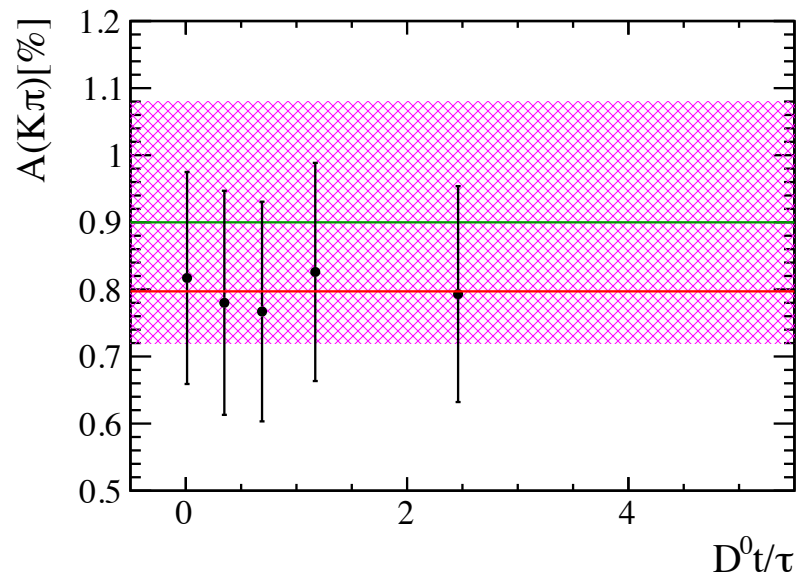


Figure 11.7: $K\pi$ asymmetry in bins of D^0 decay time. The overlaid green line is the central value from the fit to the integrated decay time distribution. The hatched region is the error on the central value, and the red line is the average value of the individual decay time bins.

Chapter 12

Blinding of the Doubly Tagged

Analysis

To blind the DT data when splitting into D^0 and $\bar{D}^0$ categories, we adopt the following strategy. In each bin of decay time, we calculate the value

$$R_{\text{shifted}}^{\pm}(t) = (R_D^{\pm} + \delta_1^{\pm}) + \sqrt{R_D^{\pm} + \delta_1^{\pm}} (y'^{\pm} + \delta_2^{\pm}) \left\langle \frac{t}{\tau} \right\rangle + \frac{(y'^{\pm} + \delta_2^{\pm})^2 + (x'^{2\pm} + \delta_3^{\pm})}{4} \mu_2' \left(\frac{t}{\tau} \right), \quad (12.1)$$

where $\delta_1^{\pm}$, $\delta_2^{\pm}$, $\delta_3^{\pm}$ are random values which are chosen from a Gaussian distribution of mean zero and widths

$$\sigma_{\delta_1} = 0.00035 \quad (12.2)$$

$$\sigma_{\delta_2} = 0.00015 \quad (12.3)$$

$$\sigma_{\delta_3} = 0.00008. \quad (12.4)$$

These values were chosen by hand to shift the mixing fit outside of the true value by about 1-2 standard deviations, as shown in Figure 12.1. Each of the D^{*+} and D^{*-} are generated

1777 to have a different blinding, so that any sum or difference of the data remains blinded.

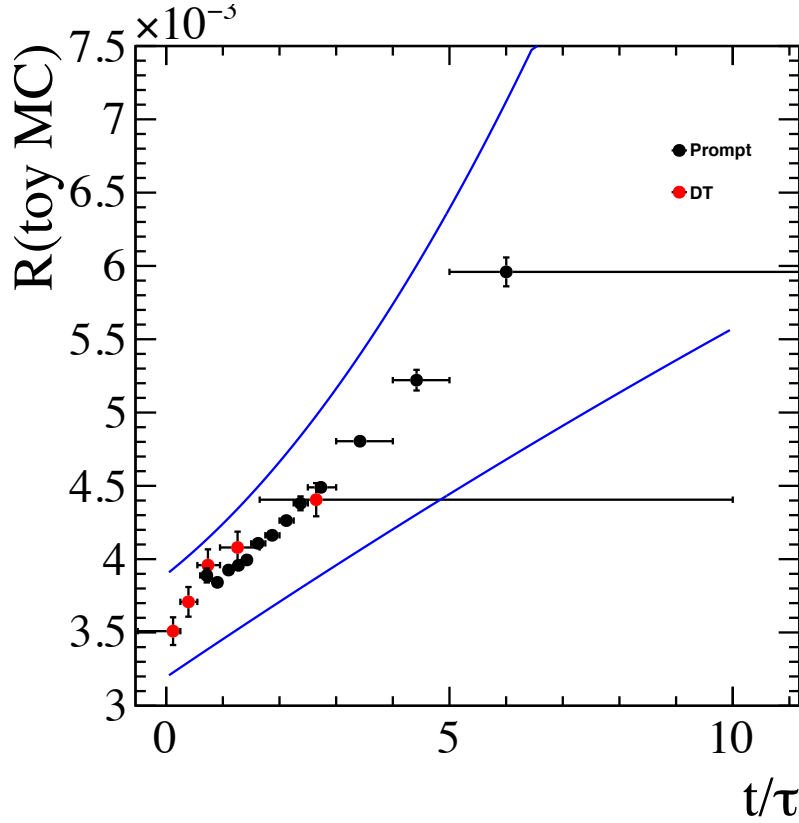


Figure 12.1: Toy MC generated sample showing the blinding envelope for the blinding procedure of the DT analysis. The black points are the pseudo prompt data, the red are the pseudo DT data and the blue lines represent R_{Shifted} with the shift being $\pm\delta_i$. The blue lines represent this blinding envelope, which is approximately 1 standard deviation of the possible blinding.

1778 The blue lines on the above graph represent the approximate 1 standard deviation enve-
1779 lope of the blinding of the DT data.

1780 To validate the blinding procedure, the blinding was applied to 1000 pseudo experiments
1781 using the nominal toy Monte Carlo inputs, as well as 11 points around the current 2σ band
1782 of the allowed x and y values from HFAG. The fits are done for all CPV allowed MC, and
1783 the values of x and y are propagated to $x'^{\pm 2}$ and $y'^{\pm}$ by using the relations from Ref. [17].
1784 From this, we extract the biases on the parameters of interest, namely $R_D^{\pm}$, $x'^{2\pm}$ and $y'^{\pm}$.
1785 This is summarized in Table 12.1. No bias is observed.

Table 12.1: Mean and width of pull distributions from 1000 toys for each different starting point for $x'^{\pm}$ and $y'^{\pm}$.

Point $(x, y)[\%]$	x'^{2+} Mean	x'^{2+} Width	x'^{2-} Mean	x'^{2-} Width	y'^{+} Mean	y'^{+} Width	y'^{-} Mean	y'^{-} Width
(0.6, 0.4)	0.1199	1.043	0.1017	1.02	-0.05708	0.9923	-0.02212	0.9873
(0.75, 0.5)	0.09077	1.101	0.1436	1.073	-0.009328	1.042	-0.07028	1.032
(0.7, 0.6)	0.07632	1.043	0.07903	1.021	-0.01555	1.011	-0.007558	0.9827
(0.6, 0.7)	0.06858	1.016	0.1101	1.054	-0.0008385	0.9886	-0.03737	1.009
(0.5, 0.8)	0.1379	1.094	0.06772	1.024	-0.06804	1.047	-0.02262	0.9901
(0.4, 0.85)	0.07238	1.002	0.06109	1.016	-0.02899	0.9751	-0.01023	0.9776
(0.2, 0.8)	0.1546	1.058	0.09059	1.016	-0.0879	0.9909	-0.03711	0.9894
(0.1, 0.7)	0.1279	1.017	0.05624	1.031	-0.08304	0.9681	0.006601	0.9984
(-0.05, 0.65)	0.0644	0.9838	0.1114	0.9976	-0.007809	0.9556	-0.06306	0.9732
(0.2, 0.55)	0.1499	1.024	0.1335	1.056	-0.07275	0.9856	-0.07875	1.018
(0.4, 0.5)	0.08581	1.03	0.0877	1.002	-0.01831	1.005	-0.03505	0.9678

12.0.1 Blinded Result on DT Data Only

The blinded results with statistical uncertainties only on the DT fit are given in Table 12.2.

The fits themselves are shown in Figure 12.2, and the contours for $x'^{2\pm}$ and $y'^{\pm}$ are shown

in Figure 12.3

Table 12.2: Central Value from the Blinded fit to DT only data.

Parameter[10^{-3}]	Central Value	Error
No CPV		
R_D	3.89	0.11
x'^{2-}	-0.027	0.31
y'	4.88	3.48
$\chi^2/\text{NDF} = 15.055/7$		
No Direct CPV		
R_D	3.89	0.11
x'^{2+}	0.34	0.34
y'^{+}	0.36	3.99
x'^{2-}	-0.48	0.43
y'^{-}	9.78	4.17
$\chi^2/\text{NDF} = 8.803/5$		
All CPV Allowed		
R_D^{+}	3.68	0.15
x'^{2+}	-0.05	0.44
y'^{+}	5.82	4.99
R_D^{-}	4.11	0.15
x'^{2-}	-0.01	0.44
y'^{-}	3.97	4.88
$\chi^2/\text{NDF} = 4.657/4$		

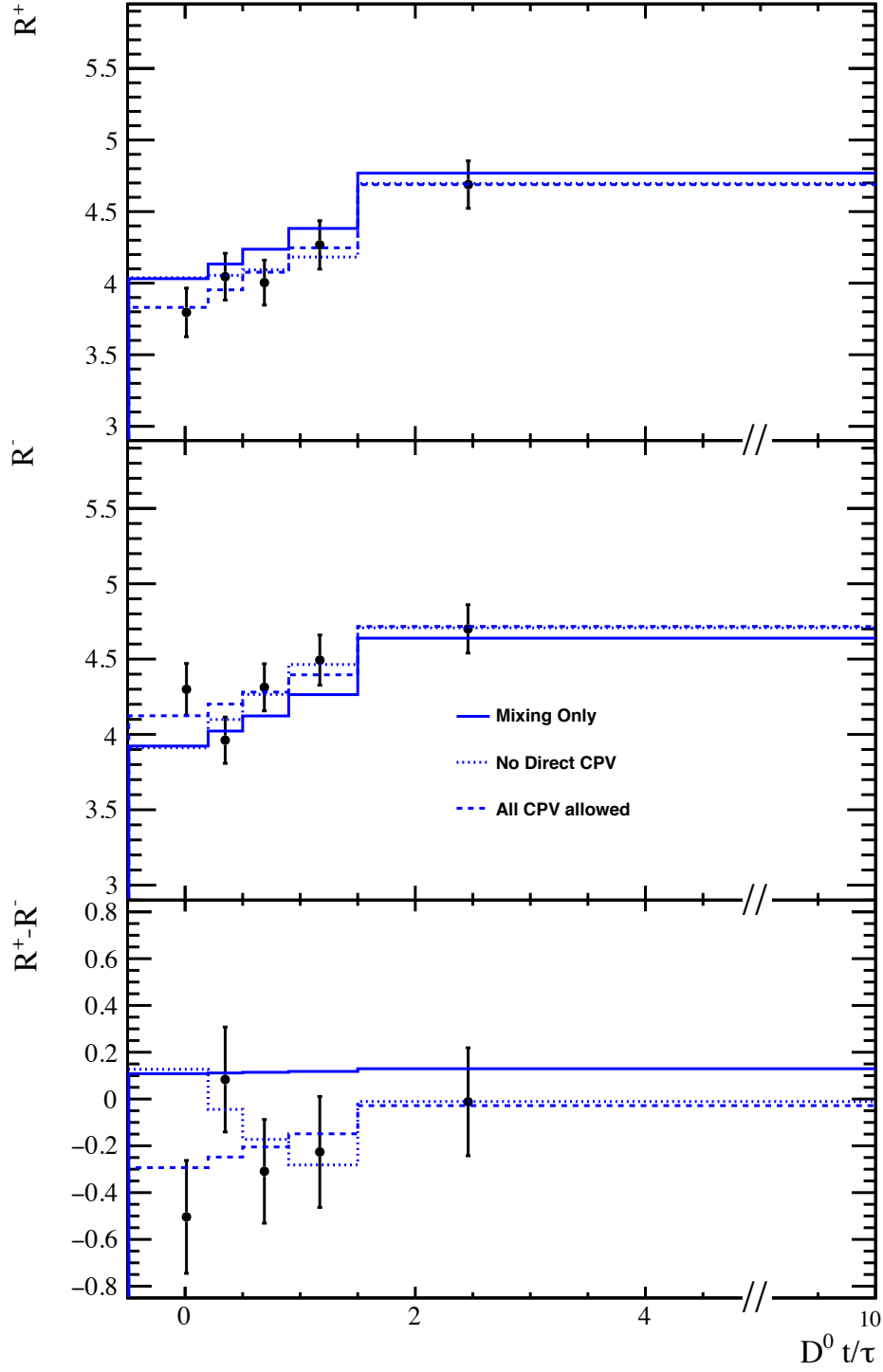


Figure 12.2: Individual fits to the time dependent WS over RS ratio for D^{*+} (top) and D^{*-} (bottom). In each plot, there are three fits, the solid line representing mixing only fit, the dotted line representing the no direct CPV fit, and the dashed line representing the all CPV allowed fit.

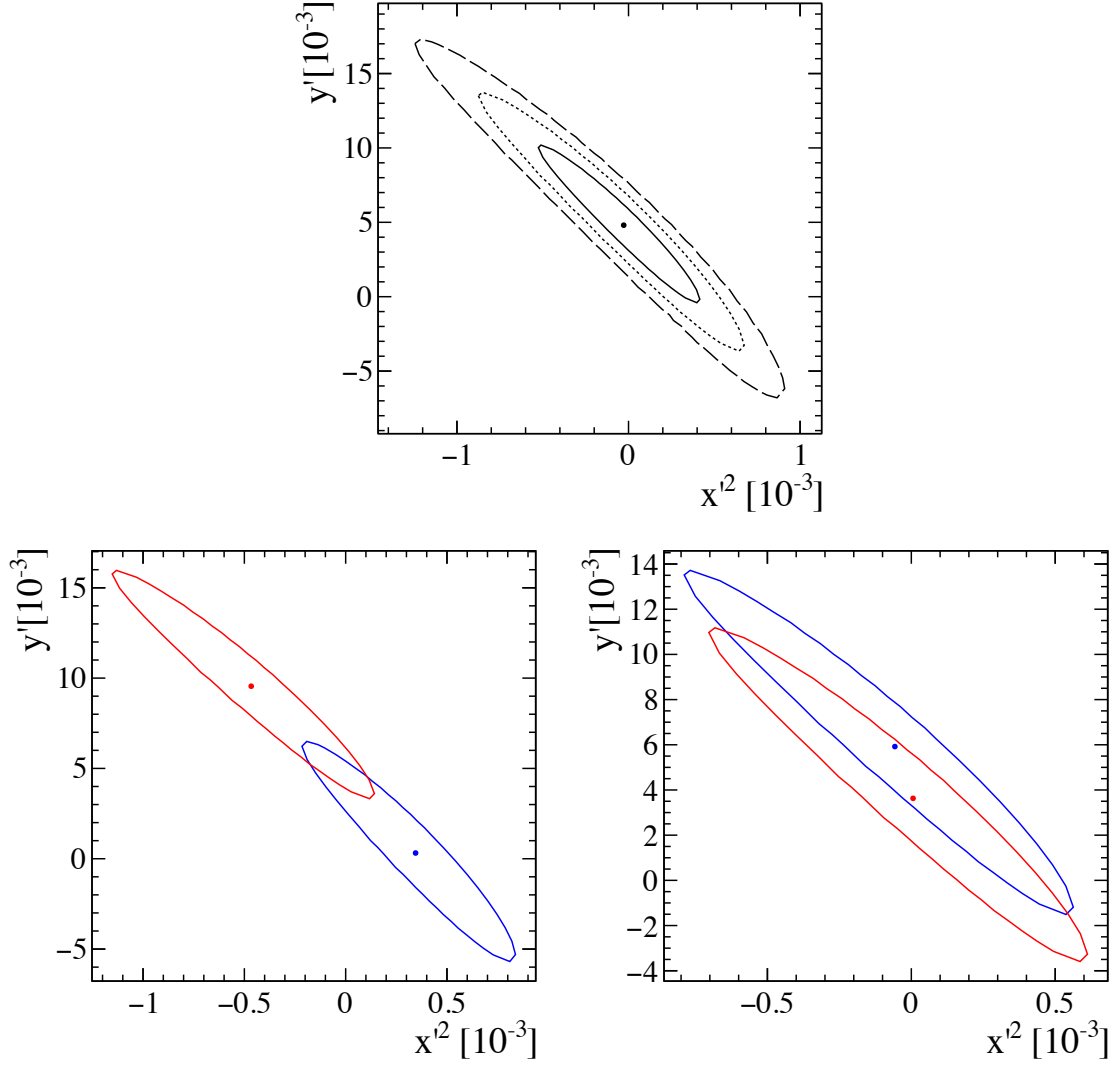


Figure 12.3: Blinded (x'^2, y') contours of the Mixing only fit (top), no Direct CPV fit (bottom left) and all CPV allowed fit (bottom right). The mixing plot shows the 1,2 and 3 σ contours, and the bottom plots show the 1 σ contours. In the no Direct CPV and all CPV allowed plots, the blue lines correspond to x'^{2+}, y'^+ and the red lines correspond to x'^{2-}, y'^- .

Chapter 13

Systematic Uncertainties

13.1 Systematic Uncertainties and Cross Checks

To check for possible variations as well as to assess systematic uncertainties on the analysis, we perform the analysis again in different binnings and on different datasets, then compare the results. All systematic uncertainties and cross checks are performed before unblinding. The cross checks we perform are

- Split by magnet polarity,
- Split by datataking year,
- Split by polarity and year,
- Split by kaon momentum,
- Split by slow pion p_T ,
- Split by muon p_T .

The systematic shifts we consider are

- No scaling of the unphysical $\mu^+ D^{*+}$, or Same Sign (SS) background,
- Variation of the $K\pi$ asymmetry as a function of decay time,

- Allowing the RS fit model to be different for each decay time bin.

The cross checks are given in Section 13.2, and the systematic uncertainties assessed in Section 13.3. For all variations described above, we compare results as outlined in Appendix A.8, which either compares the compatibility of two results directly, or fits more than two datasets and takes the p -value as the figure of merit to determine the consistency between the datasets. We explicitly do not associate a systematic due to multiple candidates, as keep all candidates.

13.2 Cross Checks

13.2.1 MagUp vs MagDown

Here, we run the full analysis, but split by magnet polarity. The results are consistent with the nominal value. The fits themselves are found in Figure 13.1 and the result of the fit is given in Table 13.1. The datapoints are highly consistent, as seen in the top right of Figure 13.1, as well as the contours for (x', y') and the fits themselves. The p -value reported in Table 13.1 for all fits further confirms this.

13.2.2 Split by Year

Here we repeat the analysis once on 2011 data and again on 2012 data. The individual fits and fit projections are shown in Figure 13.2, and the fit results are reported in Table 13.2. Again, the two results are consistent.

13.2.3 Split by Magnet Polarity and Year

With the split between polarity and year, we again find consistency between the two datasets. The fits are shown in Figures 13.3 and 13.4, and the fit results are reported in Table 13.3.

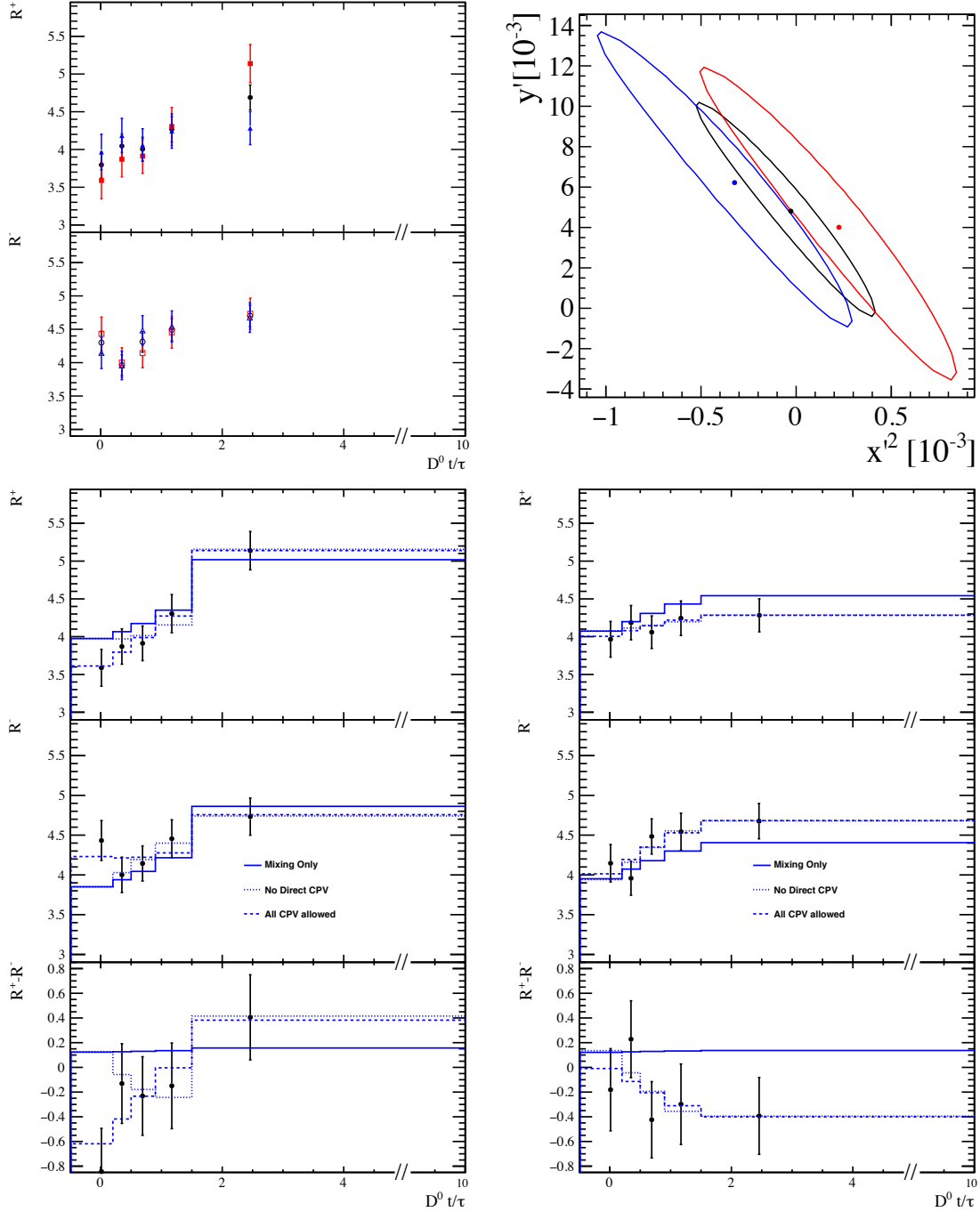


Figure 13.1: Comparison of blinded magnet polarities vs nominal fit results. Top right is the comparison of the datasets as a function of $D^0 t/\tau$. Red is the Mag Up, blue is Mag Down, and black is the nominal fit. The top left shows (x'^2, y') contours for Mag up and Mag Down. The coloring scheme is the same. The individual fit results are shown on the bottom, with bottom left being Mag Up and bottom right being Mag Down. The solid blue line represents the mixing only fit, the dashed blue line the no DCPV allowed fit, and the dotted blue line is the all CPV allowed fit.

Table 13.1: Comparison of Magnet Polarities

Parameter	Central Value $\pm$ Error		Largest Difference From Nominal
	Mag Up	Mag Down	
No CPV			
$R_D[10^{-3}]$	3.84 ± 0.15	3.94 ± 0.15	0.07
$x'^2[10^{-4}]$	2.25 ± 4.43	-3.24 ± 4.40	2.96
$y'[10^{-3}]$	4.01 ± 5.11	6.22 ± 4.82	1.41
Fit χ^2	11.967/7	9.464/7	-
Compatibility of Samples $\chi^2/\text{NDF}=4.985606/3$ (p=0.172854)			
No Direct CPV			
$R_D[10^{-3}]$	3.84 ± 0.15	3.93 ± 0.15	0.06
$x'^{2+}[10^{-4}]$	7.77 ± 4.94	-0.48 ± 4.86	4.32
$y'^+[10^{-3}]$	-1.28 ± 5.91	1.83 ± 5.47	1.60
$x'^{2-}[10^{-4}]$	-3.57 ± 6.05	-6.85 ± 6.13	2.19
$y'^-[10^{-3}]$	9.12 ± 6.01	11.22 ± 5.79	1.66
Fit χ^2	8.903/5	2.604/5	-
Compatibility of Samples $\chi^2/\text{NDF}=7.873881/5$ (p=0.163325)			
All CPV Allowed			
$R_D^+[10^{-3}]$	3.47 ± 0.21	3.86 ± 0.20	0.22
$x'^{2+}[10^{-4}]$	0.46 ± 7.00	-1.84 ± 5.75	1.27
$y'^+[10^{-3}]$	8.89 ± 7.64	3.74 ± 6.68	2.97
$R_D^-[10^{-3}]$	4.23 ± 0.22	4.01 ± 0.21	0.11
$x'^{2-}[10^{-4}]$	4.30 ± 5.55	-5.07 ± 6.78	5.13
$y'^-[10^{-3}]$	-1.35 ± 6.83	9.14 ± 6.97	5.51
Fit χ^2	2.487/4	2.338/4	-
Compatibility of Samples $\chi^2/\text{NDF}=9.998345/6$ (p=0.124722)			

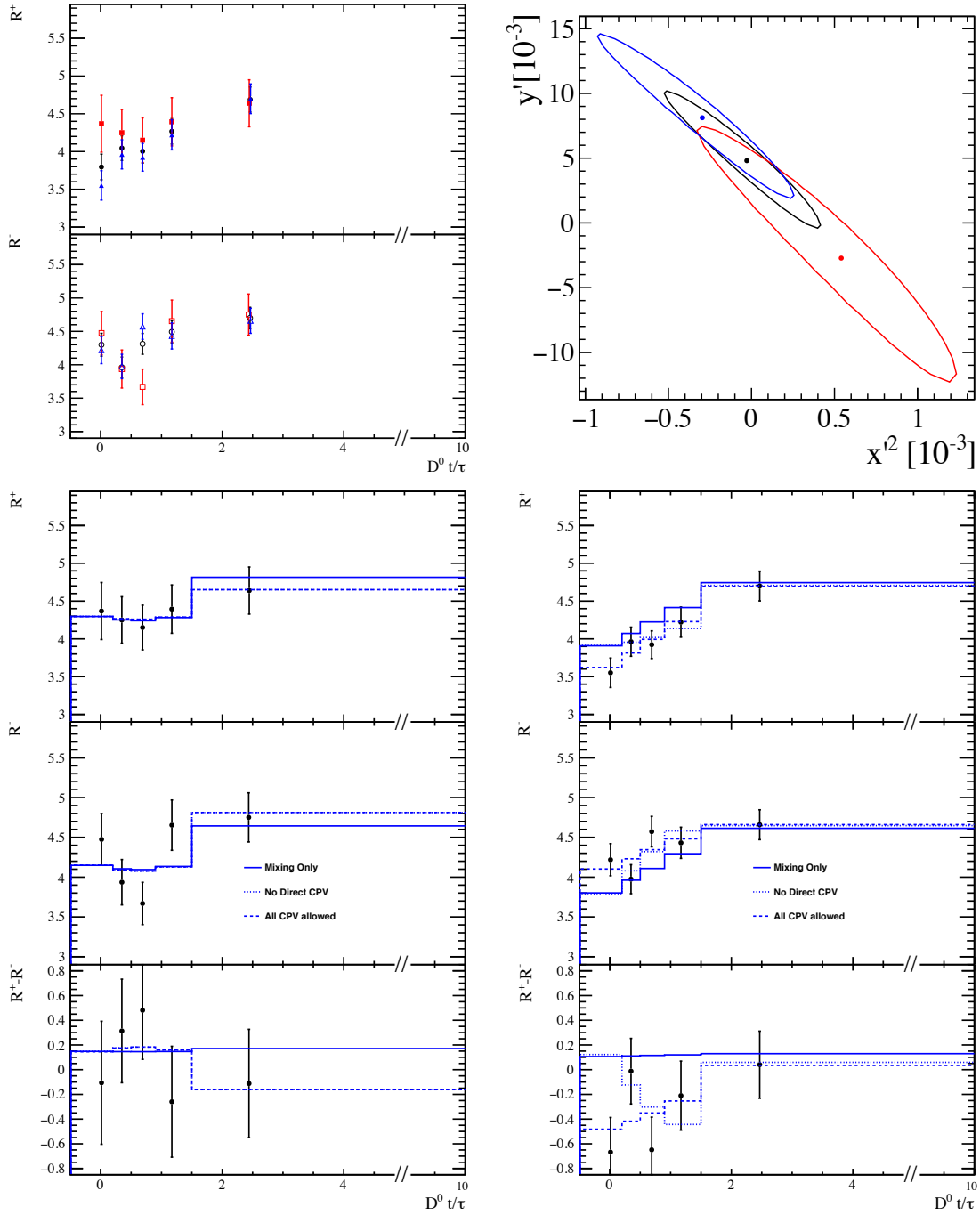


Figure 13.2: Comparisons of the blinded 2011 and 2012 datasets to the nominal fits. On the top left is the comparison of the datasets themselves. Black is nominal, red is 2011, and blue is 2012. Top right is the comparison of (x'^2, y') contours, with the same coloring scheme. The individual fit results are shown on the bottom, with bottom left being 2011 and bottom right being 2012. The solid lines are the mixing only fits, the dashed lines are no DCPV allowed, and dotted are all CPV allowed.

Table 13.2: Comparison of 2011 and 2012

Parameter	Central Value $\pm$ Error		Largest Difference From Nominal
	2011	2012	
	No CPV		
$R_D[10^{-3}]$	4.15 ± 0.21	3.78 ± 0.12	0.25
$x'^2[10^{-4}]$	5.41 ± 5.12	-2.96 ± 3.90	5.69
$y'[10^{-3}]$	-2.72 ± 6.51	8.12 ± 4.20	7.53
Fit χ^2	7.318/7	18.960/7	-
Compatibility of Samples $\chi^2/\text{NDF}=2.513467/3$ (p=0.472862)			
	No Direct CPV		
$R_D[10^{-3}]$	4.15 ± 0.21	3.78 ± 0.12	0.25
$x'^{2+}[10^{-4}]$	3.71 ± 6.43	3.07 ± 4.16	0.38
$y'^+[10^{-3}]$	-1.87 ± 7.53	1.58 ± 4.78	2.18
$x'^{2-}[10^{-4}]$	7.23 ± 6.22	-10.45 ± 5.57	11.90
$y'^-[10^{-3}]$	-3.68 ± 7.52	15.19 ± 5.04	13.23
Fit χ^2	6.725/5	11.160/5	-
Compatibility of Samples $\chi^2/\text{NDF}=5.598333/5$ (p=0.347284)			
	All CPV Allowed		
$R_D^+[10^{-3}]$	4.15 ± 0.31	3.48 ± 0.17	0.46
$x'^{2+}[10^{-4}]$	3.67 ± 7.49	-3.01 ± 5.64	4.24
$y'^+[10^{-3}]$	-1.81 ± 9.45	9.76 ± 6.08	7.73
$R_D^-[10^{-3}]$	4.15 ± 0.28	4.10 ± 0.18	0.03
$x'^{2-}[10^{-4}]$	7.27 ± 6.99	-2.85 ± 5.38	7.21
$y'^-[10^{-3}]$	-3.73 ± 8.99	6.33 ± 5.79	7.36
Fit χ^2	6.725/4	4.668/4	-
Compatibility of Samples $\chi^2/\text{NDF}=6.501753/6$ (p=0.369387)			

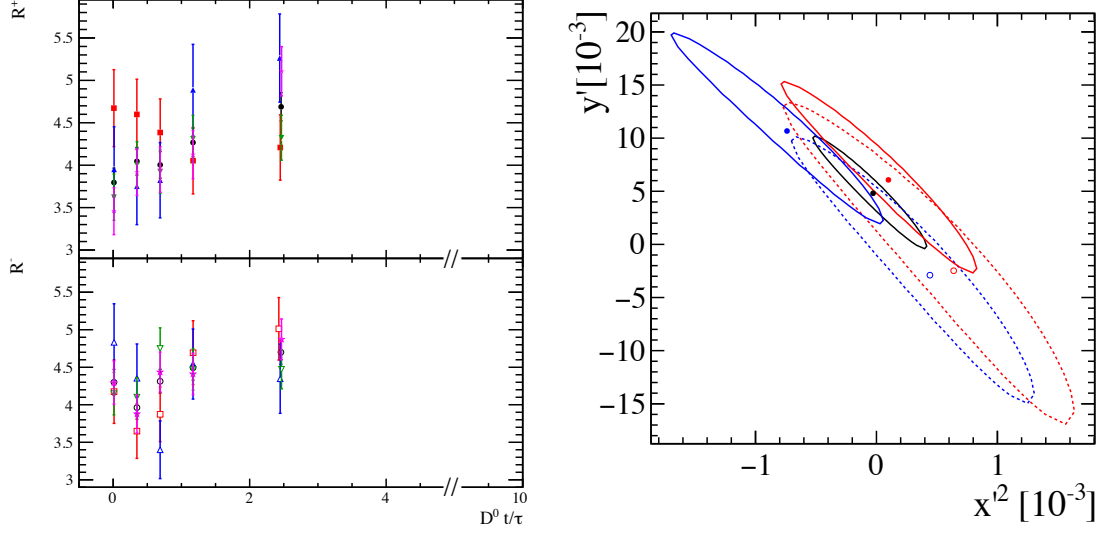


Figure 13.3: Comparisons of the blinded datasets and fits split by magnet polarity and year. Left shows the comparison of the datasets. Black is the nominal fit, Red is 2011 MD, Blue is 2011 MU, green is 2012 MD, and magenta is 2012 MU. Comparison of (x^2, y') contours is shown on the right. Here, 2011 is dashed and 2012 is solid, red is the Mag Up and blue is Mag Down.

Table 13.3: Comparison of Magnet Polarities split by year

Parameter	Central Value $\pm$ Error				Largest Difference From Nominal
	Mag Down 2011	Mag Up 2011	Mag Down 2012	Mag Up 2012	
No CPV					
$R_D[10^{-3}]$	4.19 ± 0.26	4.03 ± 0.31	3.80 ± 0.17	3.76 ± 0.17	0.29
$x'^2[10^{-4}]$	4.42 ± 6.55	6.38 ± 7.81	-7.40 ± 5.76	0.99 ± 5.31	7.12
$y'^+[10^{-3}]$	-2.90 ± 8.26	-2.48 ± 9.97	10.67 ± 5.92	6.07 ± 5.94	7.70
Fit χ^2	8.509/7	10.737/7	11.145/7	10.238/7	-
Compatibility of Samples $\chi^2/\text{NDF}=7.619374/9$ (p=0.572911)					
No Direct CPV					
$R_D[10^{-3}]$	4.20 ± 0.26	4.04 ± 0.31	3.79 ± 0.17	3.75 ± 0.17	0.30
$x'^{2+}[10^{-4}]$	0.56 ± 8.09	9.61 ± 9.91	-1.03 ± 6.06	7.14 ± 5.71	6.16
$y'^+[10^{-3}]$	-1.68 ± 9.40	-3.36 ± 11.92	3.65 ± 6.69	-0.40 ± 6.80	3.67
$x'^{2-}[10^{-4}]$	9.84 ± 8.09	3.81 ± 9.44	-15.84 ± 8.33	-6.23 ± 7.53	14.51
$y'^-[10^{-3}]$	-5.09 ± 9.84	-1.91 ± 11.23	18.62 ± 7.13	12.77 ± 7.08	14.64
Fit χ^2	4.891/5	9.451/5	5.493/5	6.825/5	-
Compatibility of Samples $\chi^2/\text{NDF}=15.836729/15$ (p=0.392985)					
All CPV Allowed					
$R_D^+[10^{-3}]$	4.61 ± 0.38	3.55 ± 0.43	3.52 ± 0.24	3.43 ± 0.24	0.92
$x'^{2+}[10^{-4}]$	6.32 ± 7.34	-0.55 ± 15.24	-7.04 ± 8.13	0.72 ± 7.87	6.89
$y'^+[10^{-3}]$	-11.14 ± 10.69	10.35 ± 15.89	11.38 ± 8.49	8.61 ± 8.70	17.06
$R_D^-[10^{-3}]$	3.82 ± 0.37	4.56 ± 0.44	4.10 ± 0.25	4.11 ± 0.25	0.44
$x'^{2-}[10^{-4}]$	2.58 ± 11.55	11.16 ± 7.92	-7.98 ± 8.19	1.65 ± 7.10	11.10
$y'^-[10^{-3}]$	5.21 ± 12.81	-14.66 ± 12.64	10.07 ± 8.26	3.05 ± 8.12	18.29
Fit χ^2	2.672/4	6.780/4	2.554/4	2.915/4	-
Compatibility of Samples $\chi^2/\text{NDF}=20.027198/18$ (p=0.331291)					

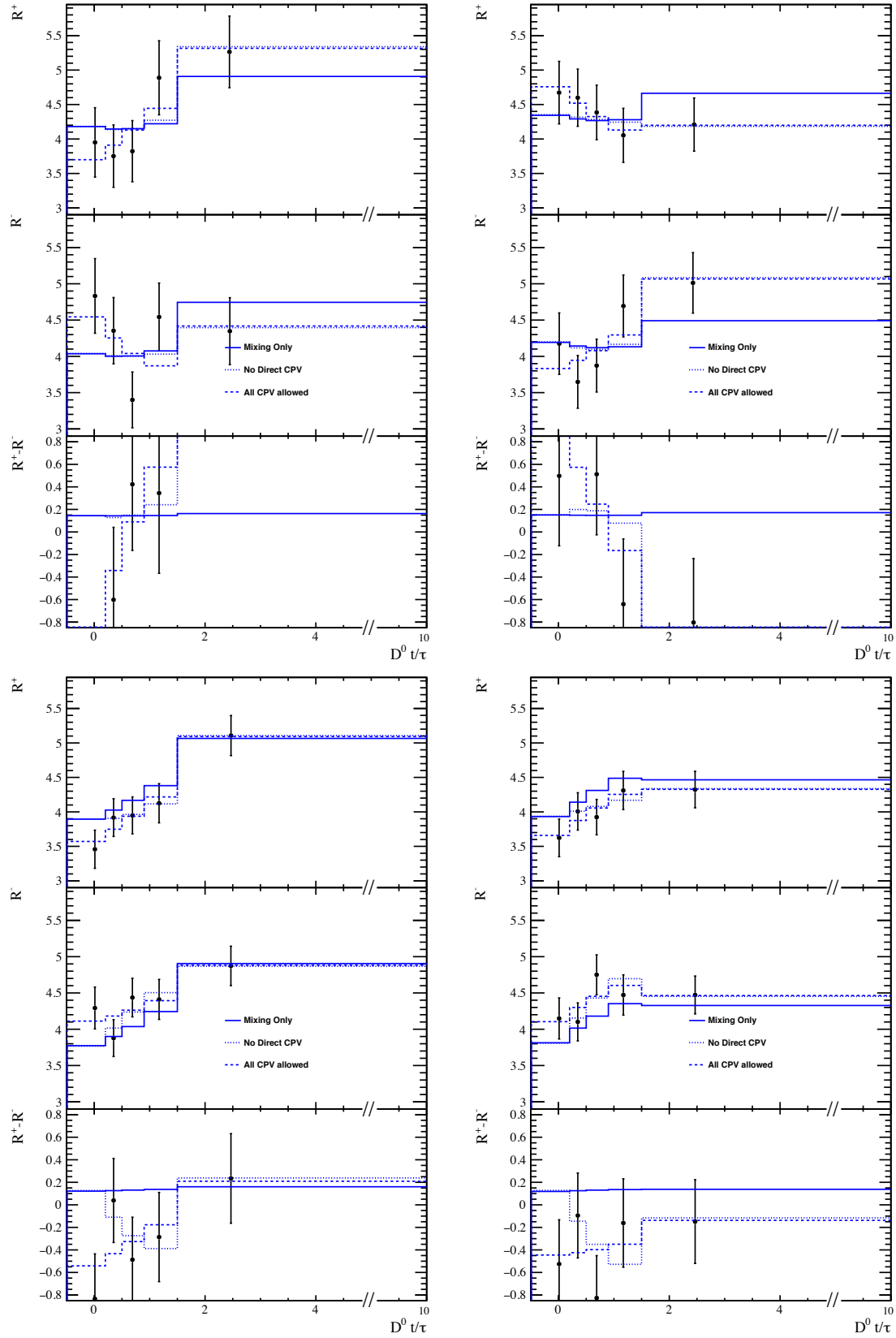


Figure 13.4: The blinded individual fit results for each individual magnet polarity and year. Top left plot is 2011 Mag Up, top right is 2011 mag down, bottom left is 2012 mag up, and bottom right being 2012 mag down.

13.2.4 Binned in Kaon Momentum

To judge whether or not the result is a function of kaon momentum, we repeat the analysis in three disjoint bins of $p(K)$, given by $p(K) < 16080$ MeV, $16080 \leq p(K) < 28140$ MeV, and $p(K) \geq 28140$ MeV. The bins are chosen to have roughly the same number of events. The results of the individual fits are summarized in Figure 13.6, and the total compatibility given in Table 13.4. The results are all compatible.

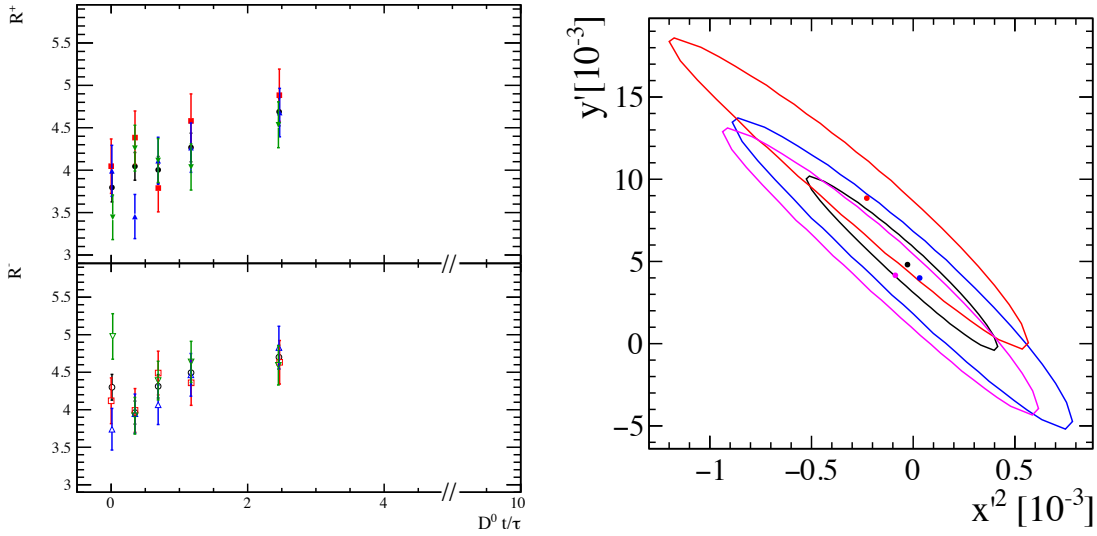


Figure 13.5: Comparison of blinded datasets and fit results as a function of kaon momentum. Left is the comparison of the datasets themselves to the nominal fit. Nominal is given in black, bin 1 ($p(K) < 16080$ MeV) is Red, bin 2 ($16080 \leq p(K) < 28140$ MeV) is blue and bin 3 ($p(K) \geq 28140$ MeV) is green. The 1σ contours for the (x'^2, y') are shown on the right. The blue contour corresponds to the first bin of $p(K)$, the red to the second bin and the magenta to the third.

We note explicitly that the blinded χ^2 for the all CPV fit is consistent with the fit at a p-value of 2%. We check to see if the poor fit quality is due to an unknown effect explicitly. We note by eye that the lowest decay time point for the highest kaon momentum bin is higher than all the rest. To understand if there is a systematic effect across this decay time bin at highest momentum, we further subdivide the kaon momentum in the bin into 4 subsamples, then compare the lowest decay time after the fit. More explicitly, we plot the lowest decay time bin as a function of kaon momentum, but only for events with $p(K) > 28140$ MeV.

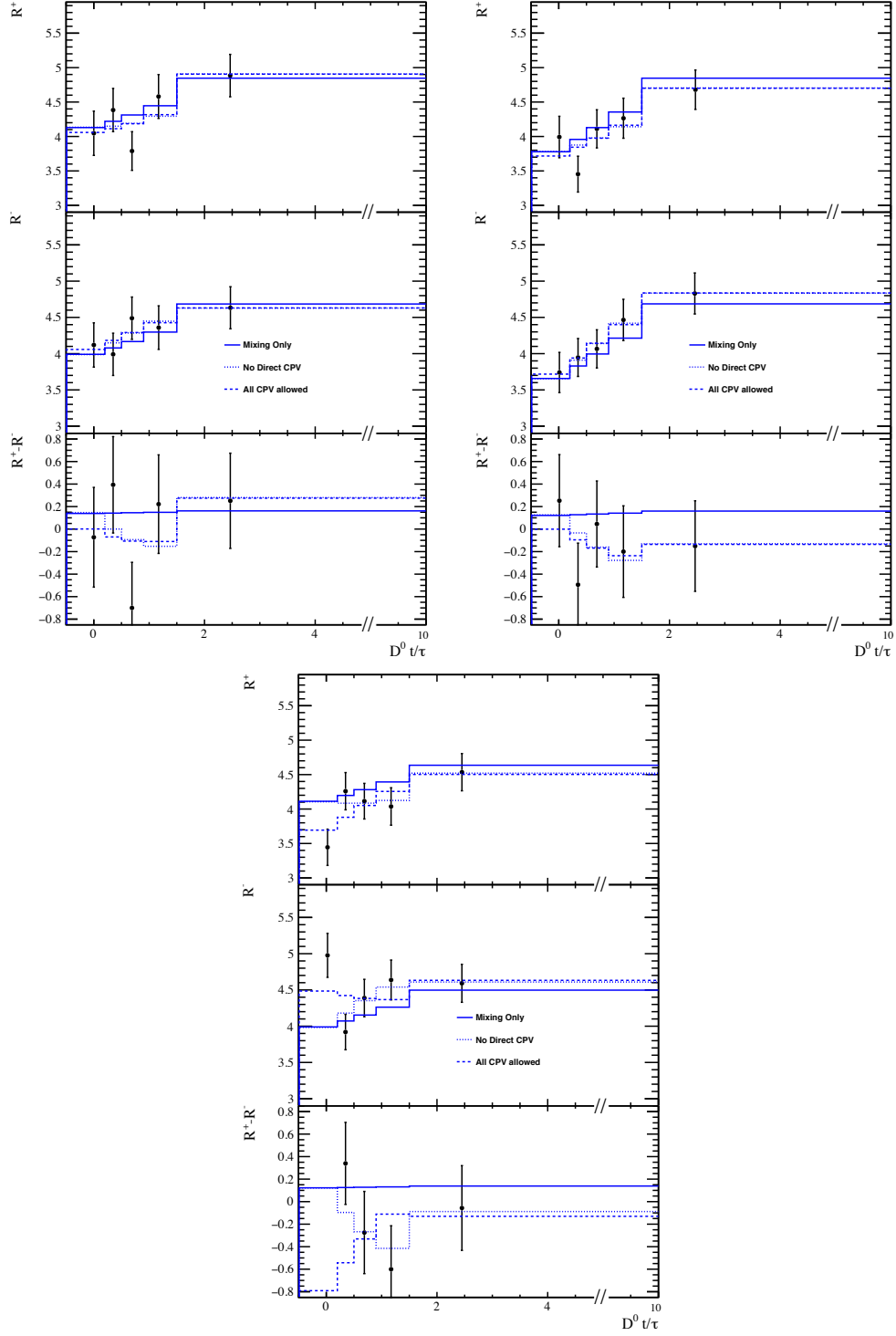


Figure 13.6: Blinded fit results as a function of kaon momentum. The first bin is on the top left, the second on the top right, and the bottom is the third bin of K momentum.

Table 13.4: Result split into three bins of Kaon momentum

Parameter	Central Value $\pm$ Error			Largest Difference From Nominal
	$p(K) < 16080$ MeV	$16080 \leq p(K) < 28140$ MeV	$p(K) \geq 28140$ MeV	
No CPV				
$R_D[10^{-3}]$	3.99 ± 0.19	3.64 ± 0.18	3.97 ± 0.17	0.26
$x'^2[10^{-4}]$	0.32 ± 5.49	-2.28 ± 5.79	-0.88 ± 5.10	2.00
$y'[10^{-3}]$	3.99 ± 6.24	8.85 ± 6.24	4.16 ± 5.76	4.04
Fit χ^2	5.591/7	6.190/7	22.981/7	-
Compatibility of Samples $\chi^2/\text{NDF}=4.103635/6$ (p=0.662654)				
No Direct CPV				
$R_D[10^{-3}]$	3.99 ± 0.19	3.64 ± 0.18	3.97 ± 0.17	0.26
$x'^{2+}[10^{-4}]$	4.23 ± 6.32	1.35 ± 6.44	3.71 ± 5.51	2.10
$y'^+[10^{-3}]$	0.16 ± 7.24	4.29 ± 7.15	-1.53 ± 6.53	3.97
$x'^{2-}[10^{-4}]$	-3.86 ± 7.37	-6.19 ± 7.84	-6.77 ± 7.23	2.10
$y'^-[10^{-3}]$	7.83 ± 7.38	13.31 ± 7.35	10.51 ± 6.89	3.76
Fit χ^2	4.565/5	3.750/5	18.950/5	-
Compatibility of Samples $\chi^2/\text{NDF}=4.888605/10$ (p=0.898494)				
All CPV Allowed				
$R_D^+[10^{-3}]$	3.91 ± 0.27	3.58 ± 0.25	3.55 ± 0.23	0.23
$x'^{2+}[10^{-4}]$	2.89 ± 7.50	-0.03 ± 7.72	-4.78 ± 7.94	4.21
$y'^+[10^{-3}]$	2.08 ± 8.92	6.16 ± 8.87	9.98 ± 8.38	4.06
$R_D^-[10^{-3}]$	4.06 ± 0.27	3.71 ± 0.25	4.50 ± 0.26	0.42
$x'^{2-}[10^{-4}]$	-2.38 ± 8.03	-4.59 ± 8.66	3.98 ± 6.33	4.65
$y'^-[10^{-3}]$	5.96 ± 8.74	11.47 ± 8.78	-3.39 ± 7.89	7.84
Fit χ^2	4.418/4	3.612/4	11.467/4	-
Compatibility of Samples $\chi^2/\text{NDF}=8.524798/12$ (p=0.742893)				

1840 The bin definitions are $28140 < p(K) \leq 32800$ MeV, $32800 < p(K) \leq 39200$ MeV, $39200 <$
1841 $p(K) \leq 49100$ MeV, and $p(K) > 49100$ MeV. This is shown graphically in Figure 13.7. This
1842 comparison is given in Figure 13.8.

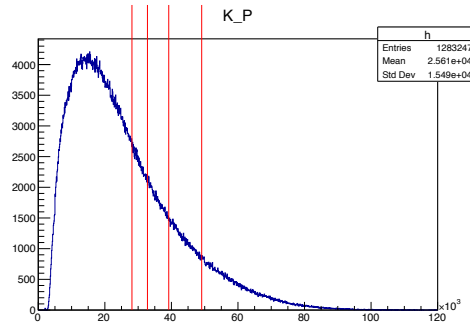


Figure 13.7: Bin definitions of further kaon momentum cuts.

1843 As we see no variation with kaon momentum in this bin, we refit the 5 decay time bins
1844 time 3 kaon momentum bins simultaneously and extract the pull and χ^2 contribution of each

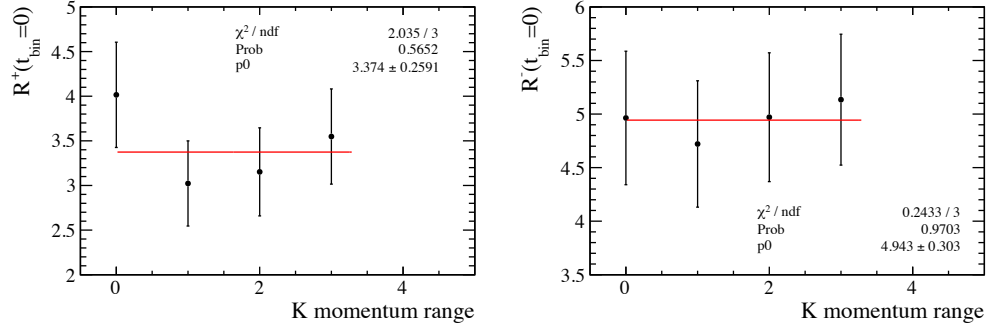


Figure 13.8: Variation of the lowest decay time bin of blinded WS/RS ratio as a function of kaon momentum, but only for events with $p(K) > 28140$ MeV. The bin definitions are $28140 < p(K) \leq 32800$ MeV, $32800 < p(K) \leq 39200$ MeV, $39200 < p(K) \leq 49100$ MeV, and $p(K) > 49100$ MeV. Left plot shows the blinded ratio for D^0 tagged at production and right shows $\bar{D}^0$. Overlaid is a fit to a flat line with no slope.

1845 point. The projection of the fit is shown in Figure 13.9. The individual contributions are
 1846 shown in Table 13.5, and the pull distributions are shown in Figure 13.10. What we see
 1847 is that the pull distribution is roughly gaussian, indicating that the p-value distribution of
 1848 these points with respect to the fit is roughly flat. The point in the highest momentum bin
 1849 at the lowest decay time contributes to the fit at roughly 3σ .

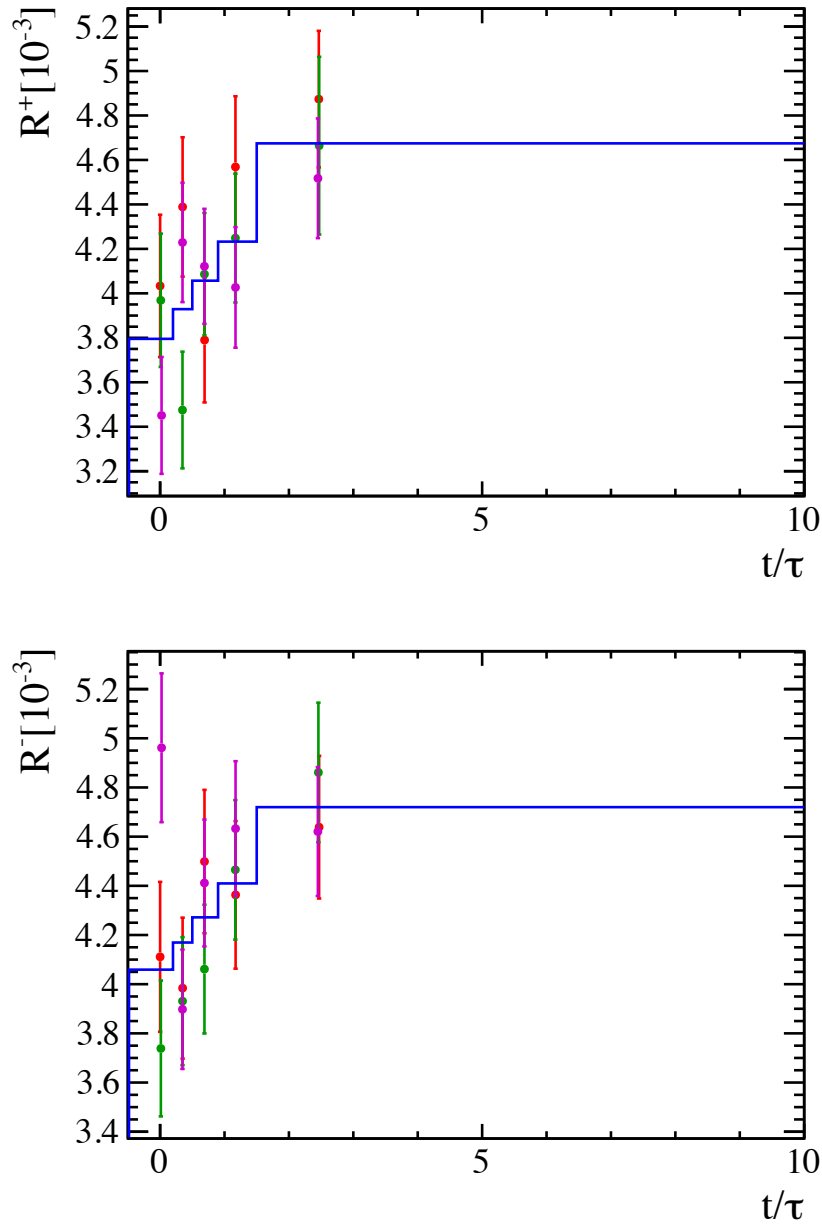


Figure 13.9: Fit to all blinded kaon bins at once for the AllCPV fit. Top plot is for R^+ , bottom is for R^- , and red is the lowest momentum bin, green is the center and magenta is the highest.

1850 The overall conclusion is that this is what we expect from statistical fluctuation around
1851 the fit projection, even with the underestimated errors produced by ignoring the fluctuations
1852 induced by blinding. Given also that the fitted mixing parameters for the highest momentum

Table 13.5: Individual χ^2 contributions of each bin of each point in each bin of Kaon Momentum to the total all CPV allowed fit to the WS/RS ratio. p values are calculated using the χ^2 with 1 degree of freedom.

Decay Time Bin	χ^2	p value for 1 DoF
$R^+, p(K) < 16080 \text{ MeV}$		
1	0.553682	0.456817
2	2.152593	0.142329
3	0.907363	0.340815
4	1.118804	0.290176
5	0.420335	0.516770
$R^+, 16080 \leq p(K) < 28140 \text{ MeV}$		
1	0.334611	0.562956
2	2.987792	0.083895
3	0.011366	0.915098
4	0.003031	0.956095
5	0.000668	0.979378
$R^+, p(K) \geq 28140 \text{ MeV}$		
1	1.719740	0.189726
2	1.250061	0.263541
3	0.062716	0.802253
4	0.577152	0.447431
5	0.340492	0.559546
$R^-, p(K) < 16080 \text{ MeV}$		
1	0.029194	0.864332
2	0.419008	0.517432
3	0.605172	0.436612
4	0.024163	0.876472
5	0.078813	0.778913
$R^-, 16080 \leq p(K) < 28140 \text{ MeV}$		
1	1.346424	0.245904
2	0.837186	0.360203
3	0.646698	0.421296
4	0.037971	0.845501
5	0.247628	0.618750
$R^-, p(K) \geq 28140 \text{ MeV}$		
1	8.895173	0.002859
2	1.252027	0.263166
3	0.293438	0.588026
4	0.661604	0.415994
5	0.143183	0.705137

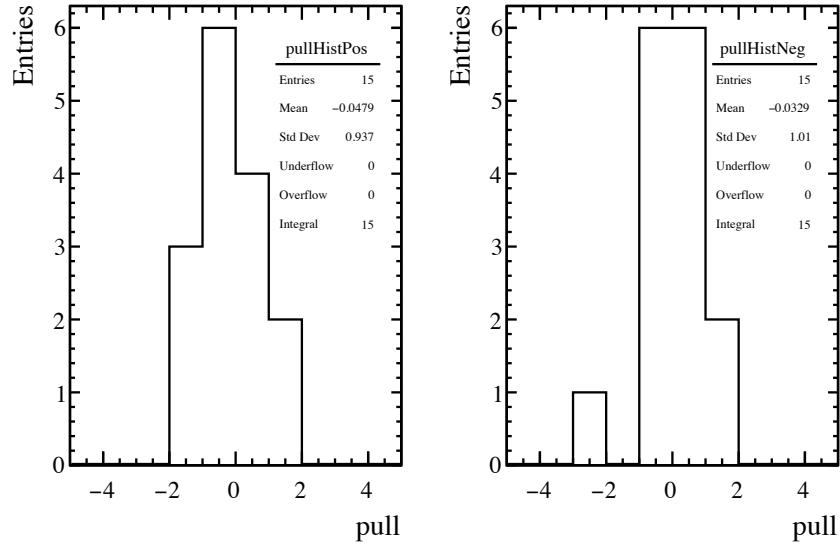


Figure 13.10: Pull distribution of fit to WS/RS ratio for all kaon momentum bins simultaneously. Left is for R^+ and right is for R^- .

dataset are consistent with those from the other subsets, and the nominal in Figure 13.6, our conclusion is that there is no evidence for a problem.

13.2.5 Muon p_T

We also divide the sample into three disjoint bins of muon transverse momentum, given by $p_T(\mu) < 2125$ MeV, $2125 \leq p_T(\mu) < 3400$ MeV and $p_T(\mu) \geq 3400$ MeV. The individual fits, as well as contours in (x'^2, y') are shown in Figures 13.11 and 13.12, and the results are summarized in Table 13.6.

13.2.6 Slow pion p_T

We also divide the sample into three disjoint bins of slow pion transverse momentum, given by $p_T(\pi_s) < 178.5$ MeV, $178.5 \leq p_T(\pi_s) < 306$ MeV, and $p_T(\pi_s) \geq 306$ MeV. The individual fits, as well as contours in (x'^2, y') are shown in Figure 13.13 and Figure 13.14, and the results are summarized in Table 13.7.

Table 13.6: Result split into three bins of muon transverse momentum.

Parameter	Central Value $\pm$ Error			Largest Difference From Nominal
	$p_T(\mu) < 2125$ MeV	$2125 \leq p_T(\mu) < 3400$ MeV	$p_T \geq 3400$ MeV	
	No CPV			
$R_D[10^{-3}]$	4.02 ± 0.23	3.83 ± 0.17	3.92 ± 0.16	0.12
$x'^2[10^{-4}]$	7.66 ± 6.02	-6.87 ± 5.72	1.18 ± 4.51	7.94
$y'[10^{-3}]$	-2.09 ± 7.51	11.07 ± 5.79	2.49 ± 5.38	6.89
Fit χ^2	4.213/7	9.773/7	13.183/7	-
Compatibility of Samples $\chi^2/\text{NDF}=5.655873/6$ (p=0.462821)				
No Direct CPV				
$R_D[10^{-3}]$	4.02 ± 0.23	3.83 ± 0.17	3.91 ± 0.16	0.12
$x'^{2+}[10^{-4}]$	13.74 ± 6.32	-7.79 ± 6.90	7.45 ± 4.73	11.24
$y'^+[10^{-3}]$	-9.26 ± 8.54	10.21 ± 6.71	-4.34 ± 6.11	9.89
$x'^{2-}[10^{-4}]$	0.08 ± 8.87	-5.78 ± 7.21	-6.58 ± 6.57	4.74
$y'^-[10^{-3}]$	5.58 ± 8.99	11.94 ± 6.80	9.85 ± 6.45	3.97
Fit χ^2	1.477/5	6.099/5	8.362/5	-
Compatibility of Samples $\chi^2/\text{NDF}=8.882067/10$ (p=0.543331)				
All CPV Allowed				
$R_D^+[10^{-3}]$	3.99 ± 0.33	3.59 ± 0.23	3.64 ± 0.23	0.30
$x'^{2+}[10^{-4}]$	13.41 ± 7.17	-13.66 ± 8.98	2.75 ± 6.37	13.98
$y'^+[10^{-3}]$	-8.66 ± 10.36	16.85 ± 8.44	2.93 ± 7.80	14.58
$R_D^-[10^{-3}]$	4.04 ± 0.33	4.09 ± 0.24	4.20 ± 0.23	0.08
$x'^{2-}[10^{-4}]$	0.59 ± 10.04	0.02 ± 7.21	-0.69 ± 6.42	0.75
$y'^-[10^{-3}]$	4.93 ± 10.91	4.89 ± 7.95	2.36 ± 7.43	1.30
Fit χ^2	1.466/4	3.917/4	5.409/4	-
Compatibility of Samples $\chi^2/\text{NDF}=9.973521/12$ (p=0.618284)				

Table 13.7: Result split into three bins of slow pion transverse momentum.

Parameter	Central Value $\pm$ Error			Largest Difference From Nominal
	$p_T(\pi_s) < 178.5$ MeV	$178.5 \leq p_T(\pi_s) < 306$ MeV	$p_T(\pi_s) \geq 306$ MeV	
No CPV				
$R_D[10^{-3}]$	3.86 ± 0.24	4.02 ± 0.17	3.77 ± 0.16	0.13
$x'^2[10^{-4}]$	-7.91 ± 8.16	3.11 ± 4.53	-0.37 ± 4.91	7.63
$y'[10^{-3}]$	12.25 ± 8.07	0.92 ± 5.42	5.40 ± 5.59	7.44
Fit χ^2	8.946/7	7.662/7	13.550/7	-
Compatibility of Samples $\chi^2/\text{NDF}=4.148325/6$ (p=0.656612)				
No Direct CPV				
$R_D[10^{-3}]$	3.86 ± 0.24	4.02 ± 0.17	3.76 ± 0.16	0.14
$x'^{2+}[10^{-4}]$	-7.70 ± 10.06	6.54 ± 5.11	5.31 ± 5.04	11.15
$y'^+[10^{-3}]$	11.17 ± 9.57	-3.25 ± 6.26	-1.62 ± 6.22	10.86
$x'^{2-}[10^{-4}]$	-7.99 ± 10.20	-0.80 ± 6.23	-8.61 ± 7.29	3.95
$y'^-[10^{-3}]$	13.18 ± 9.39	5.22 ± 6.45	13.99 ± 6.75	4.43
Fit χ^2	8.436/5	5.826/5	6.339/5	-
Compatibility of Samples $\chi^2/\text{NDF}=5.605308/10$ (p=0.847262)				
All CPV Allowed				
$R_D^+[10^{-3}]$	3.35 ± 0.32	3.92 ± 0.24	3.67 ± 0.23	0.34
$x'^{2+}[10^{-4}]$	-22.04 ± 15.20	4.83 ± 6.13	3.74 ± 6.09	21.47
$y'^+[10^{-3}]$	26.18 ± 12.62	-0.61 ± 7.69	0.75 ± 7.71	20.26
$R_D^-[10^{-3}]$	4.47 ± 0.35	4.13 ± 0.24	3.85 ± 0.23	0.35
$x'^{2-}[10^{-4}]$	3.93 ± 8.49	1.25 ± 6.69	-6.25 ± 8.08	6.31
$y'^-[10^{-3}]$	-2.22 ± 10.34	2.50 ± 7.66	11.34 ± 8.18	7.71
Fit χ^2	2.707/4	5.437/4	6.039/4	-
Compatibility of Samples $\chi^2/\text{NDF}=9.546697/12$ (p=0.655661)				

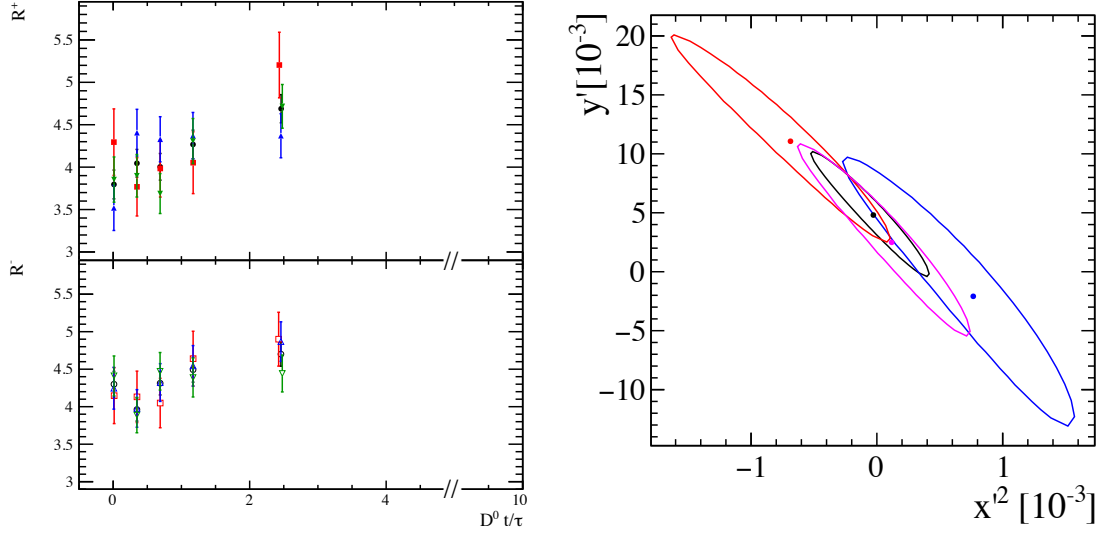


Figure 13.11: Comparisons of blinded datasets and fits for binning in muon p_T . Top left shows the datasets themselves, with black being the nominal dataset, bin 1 of muon momentum ($p_T(\mu) < 2125 \text{ MeV}$) is in red, bin 2 ($2125 \leq p_T(\mu) < 3400 \text{ MeV}$) in blue and bin 3 ($p_T(\mu) \geq 3400 \text{ MeV}$) in green. 1σ contours for the (x'^2, y') plane split by muon transverse momentum are shown on the top right. The blue contour corresponds to the first bin of $p_T(\mu)$, the red to the second bin and the magenta to the third.

13.3 Systematic Uncertainties

13.3.1 No SS Scaling

Here, we apply a scaling factor of 1 for all time bins of the SS sample to show the difference in the final fit results. The fits are shown in Figure 13.15, and the result of the fit, as well as the offset from the nominal fit is given in Table 13.8.

We assign the difference from the central value as the systematic uncertainty associated, and propagate the uncertainties via covariance matrices.

13.3.2 Accounting for asymmetry in RS D^{*-} vs RS D^{*+}

To account for the effect shown in Section 9.2, we adjust the $K\pi$ asymmetry by allowing a time dependence. While we note that we have shown that the $A(K\pi)$ extracted from data does not have a time dependence, the fact that the D^{*-}/D^{*+} ratio for RS does indicates that

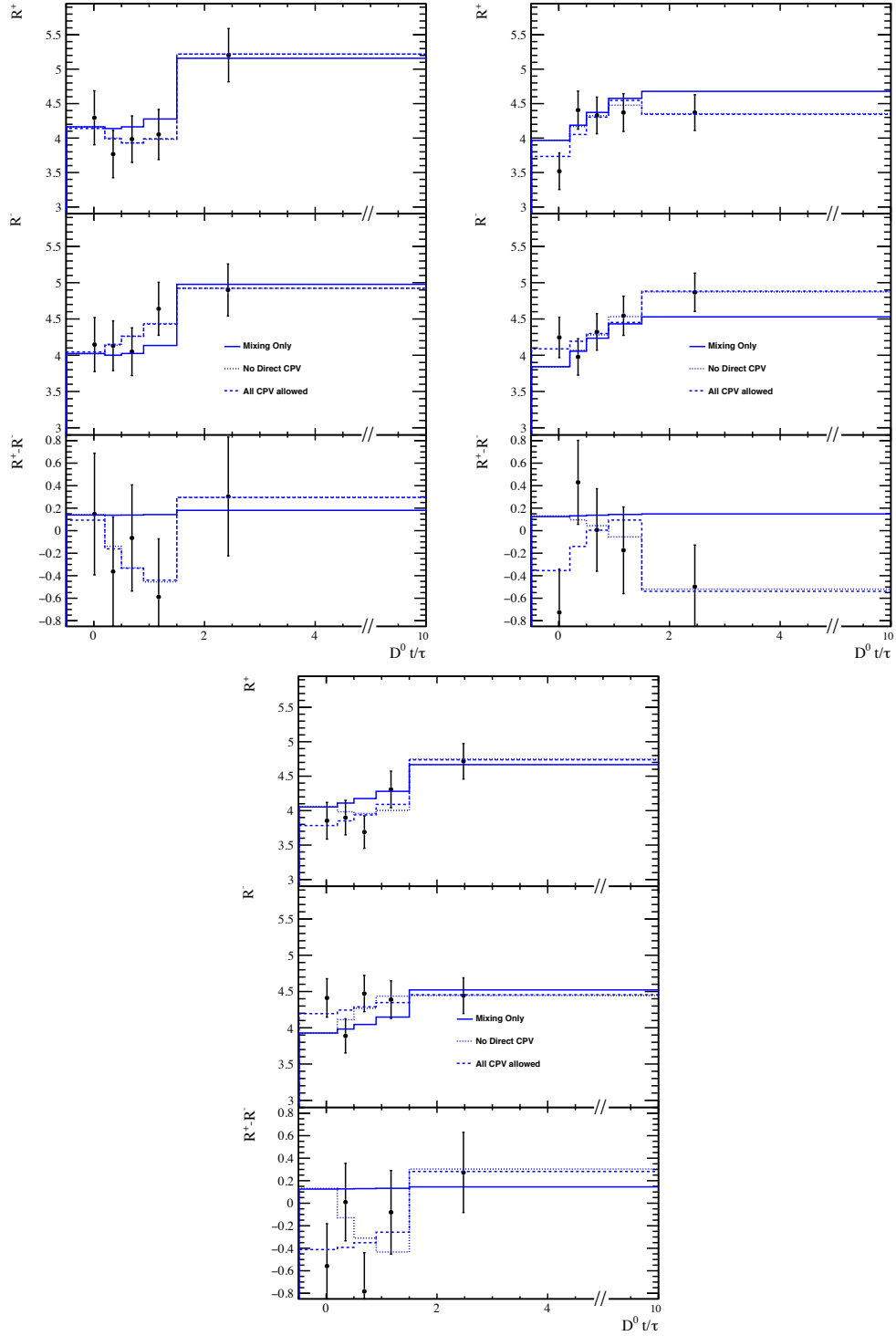


Figure 13.12: Plots of blinded fits to data in bins of muon transverse momentum. The lowest p_T bin, $p_T(\mu) < 2125$ MeV, is shown on the top left, the next, $2125 \leq p_T(\mu) < 3400$ MeV is shown on the top right, and the final bin, $p_T(\mu) \geq 3400$ MeV is shown on the bottom.

Table 13.8: Result of not using the SS scaling

Parameter	Central Value $\pm$ Error	Largest Difference From Nominal
No SS Scaling		
No CPV		
$R_D[10^{-3}]$	3.89 ± 0.11	0.01
$x'^2[10^{-4}]$	-0.24 ± 3.09	0.04
$y'[10^{-3}]$	4.77 ± 3.49	0.04
Fit χ^2	14.641/7	-
No Direct CPV		
$R_D[10^{-3}]$	3.89 ± 0.11	0.01
$x'^{2+}[10^{-4}]$	3.49 ± 3.46	0.04
$y'^+[10^{-3}]$	0.27 ± 4.02	0.04
$x'^{2-}[10^{-4}]$	-4.63 ± 4.25	0.04
$y'^-[10^{-3}]$	9.52 ± 4.17	0.03
Fit χ^2	8.813/5	-
All CPV Allowed		
$R_D^+[10^{-3}]$	3.68 ± 0.15	0.01
$x'^{2+}[10^{-4}]$	-0.53 ± 4.43	0.04
$y'^+[10^{-3}]$	5.89 ± 5.02	0.03
$R_D^-[10^{-3}]$	4.11 ± 0.15	0.01
$x'^{2-}[10^{-4}]$	0.10 ± 4.31	0.04
$y'^-[10^{-3}]$	3.59 ± 4.87	0.04
Fit χ^2	4.476/4	-

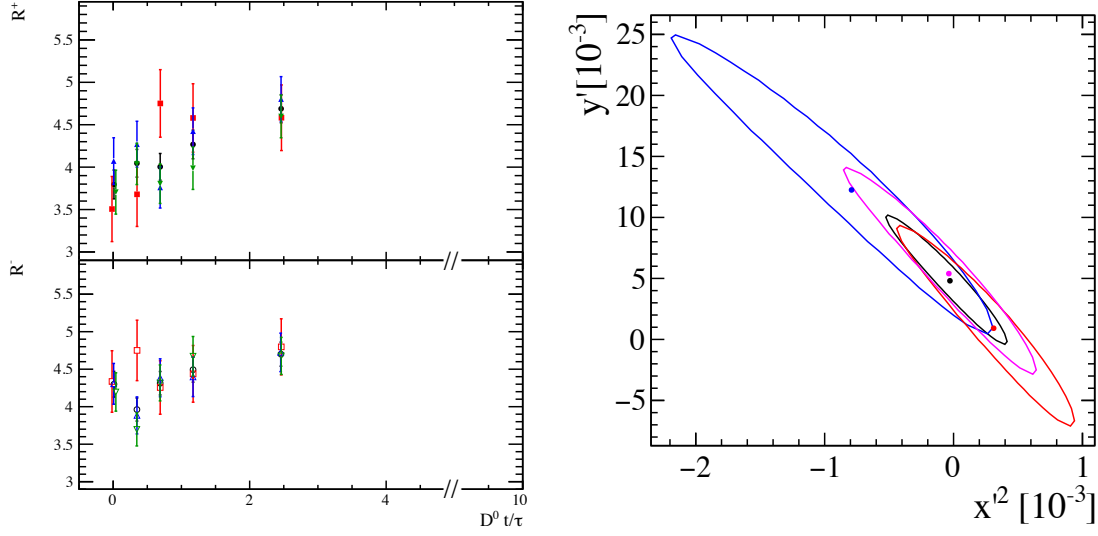


Figure 13.13: Comparisons of blinded datasets and fits for binning in slow pion p_T . Top left shows the datasets themselves, with black being the nominal dataset, bin 1 of slow pion momentum ($p_T(\pi_s) < 178.5$ MeV) is in red, bin 2 ($178.5 \leq p_T(\pi_s) < 306$ MeV) in blue and bin 3 ($p_T(\pi_s) \geq 306$ MeV) in green. 1σ contours for the (x'^2, y') plane split by slow pion transverse momentum are shown on the top right. The blue contour corresponds to the first bin of $p_T(\mu)$, the red to the second bin and the magenta to the third.

1876 there may be a residual production or detection asymmetry which is not properly accounted
 1877 for. The only place that this could contribute is in the overall detection asymmetry. This
 1878 time dependence goes as

$$A(t) = A(K\pi) + \delta(A_{K\pi}) + \alpha + \beta t. \quad (13.1)$$

1879 We take the factors α and β as a fit to the asymmetry of the RS D^{*-} and D^{*+} samples. The
 1880 factor $\delta(A_{K\pi})$ is a shift which allows for the average value of the $K\pi$ asymmetry over the
 1881 decay time range considered to be that of the measured $K\pi$ asymmetry. This fit is shown
 1882 in Figure 13.16. The derived value for $\delta(A_{K\pi})$ is -0.0110 .

1883 After allowing the $K\pi$ asymmetry to vary as a function of decay time and adding the
 1884 gaussian constraint on the slope, the changes we find in the fit are summarized in Table 13.9,
 1885 and shown in Figure 13.17.

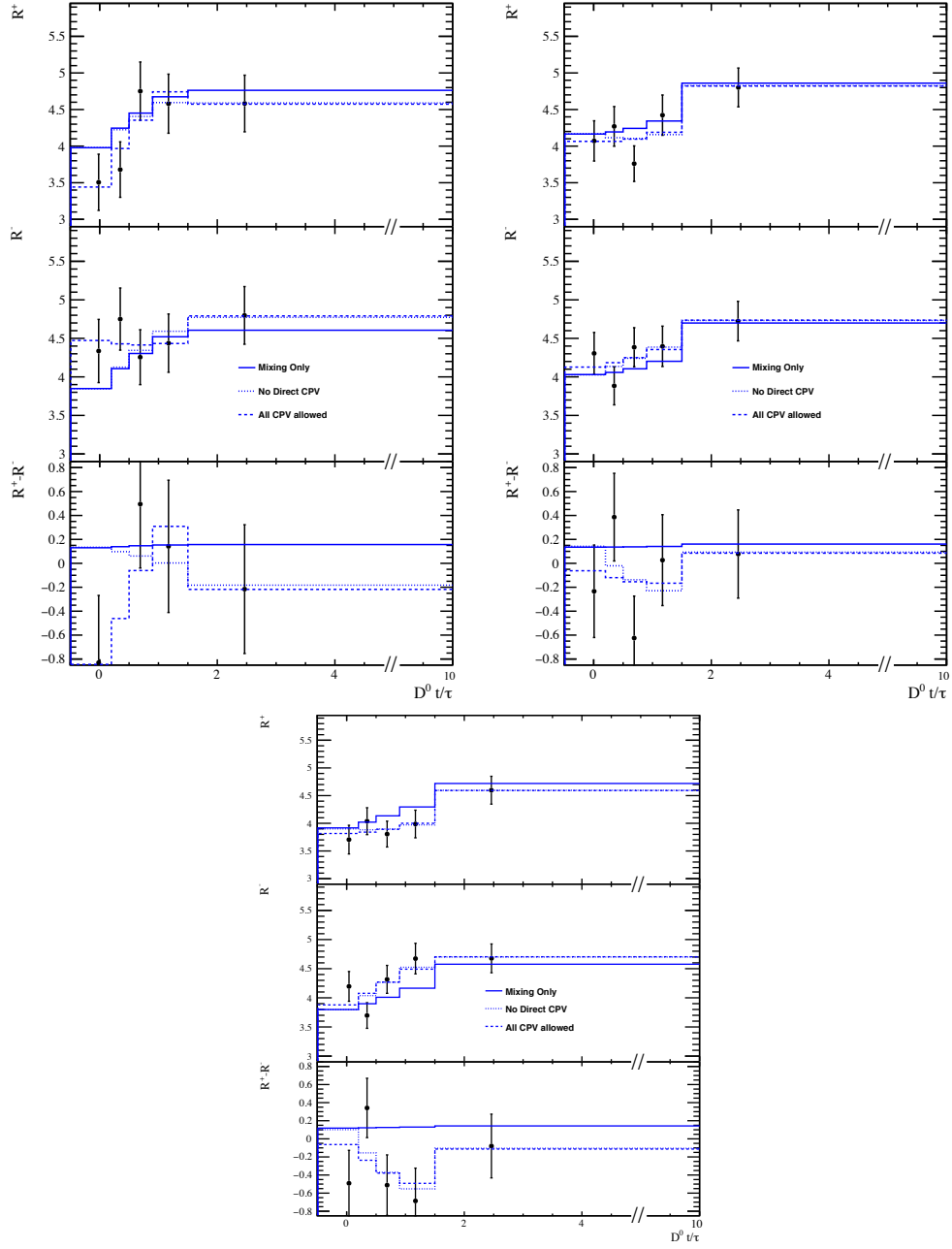


Figure 13.14: Blinded fits to data for the first bin ($p_T(\pi_s) < 178.5$ MeV, top left), the second ($178.5 \leq p_T(\pi_s) < 306$ MeV, top right) and third bin ($p_T(\pi_s) \geq 306$ MeV, bottom) of slow pion transverse momentum.

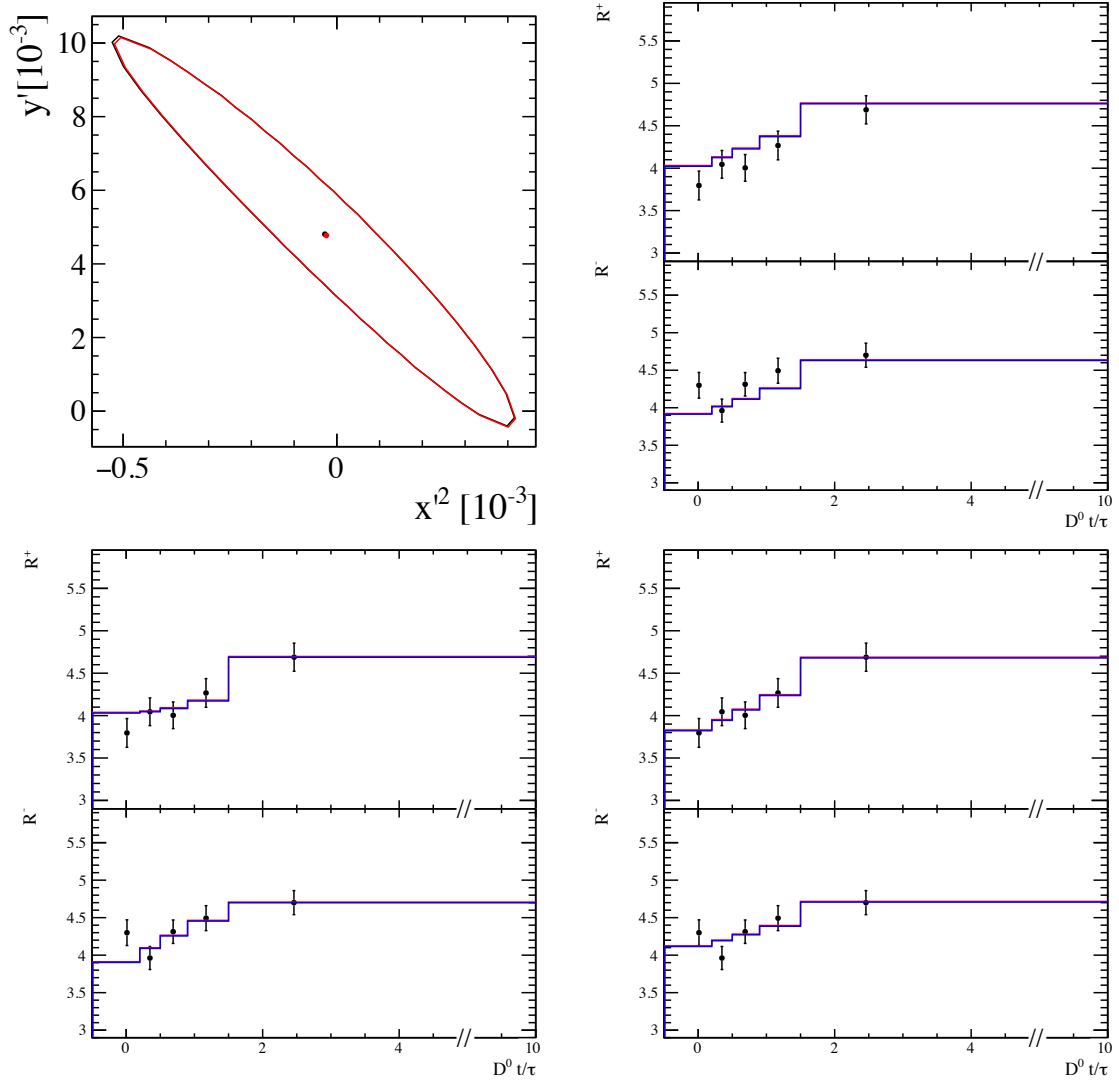


Figure 13.15: Blinded fit result after not scaling the SS sideband. The left top plot is the mixing only comparison of the nominal result (black) and the no scaling result (red). On the top right is the comparison of the mixing only fit on the data, with the blue being the nominal fit and the red being the fit with no SS scaling applied. The bottom left plot is the same figure, but for the no DCPV fit, and the bottom right for the all CPV fit.

Table 13.9: Result allowing for the $K\pi$ asymmetry to take on a time dependence.

Parameter	Central Value $\pm$ Error	Largest Difference From Nominal
$A(K\pi)$ with slope		
No CPV		
$R_D[10^{-3}]$	3.90 ± 0.11	0.01
$x'^2[10^{-4}]$	-0.32 ± 3.11	0.04
$y'[10^{-3}]$	4.88 ± 3.50	0.07
Fit χ^2	20.680/7	-
No Direct CPV		
$R_D[10^{-3}]$	3.89 ± 0.11	0.01
$x'^{2+}[10^{-4}]$	4.43 ± 3.36	0.98
$y'^+[10^{-3}]$	-0.85 ± 4.00	1.17
$x'^{2-}[10^{-4}]$	-6.33 ± 4.44	1.67
$y'^-[10^{-3}]$	11.20 ± 4.24	1.64
Fit χ^2	11.734/5	-
All CPV Allowed		
$R_D^+[10^{-3}]$	3.62 ± 0.15	0.06
$x'^{2+}[10^{-4}]$	-0.55 ± 4.42	0.03
$y'^+[10^{-3}]$	6.17 ± 5.00	0.25
$R_D^-[10^{-3}]$	4.19 ± 0.15	0.07
$x'^{2-}[10^{-4}]$	0.03 ± 4.35	0.03
$y'^-[10^{-3}]$	3.35 ± 4.90	0.28
Fit χ^2	4.464/4	-

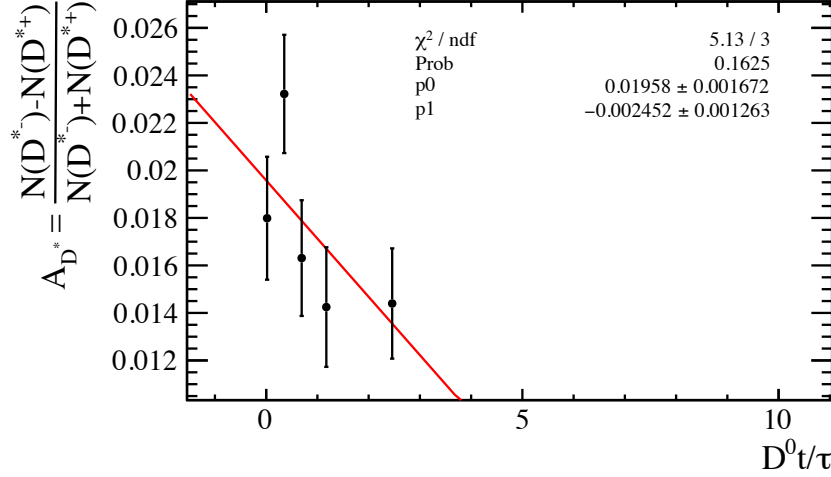


Figure 13.16: Fit to the time dependent asymmetry between the RS D^{*-} and D^{*+} samples. The black points are the data and the red line is the fit to a first order polynomial. The parameter p_0 corresponds to the α parameter in the parameterization of $A(t)$ and p_1 corresponds to the β parameter

We again take the offsets as systematic uncertainties from the fit. In the mixing only fit, the variations are below the level of accuracy of the result.

13.3.3 Variation of RS fit model as a function of bin of decay time

It is assumed that the RS fit model taken from the total fit with the largest statistics is accurate for all subsets of the data, be it decay time or otherwise. We proved this to be a good assumption in Section 9.1 for all the subsets we considered. As far as decay time, it is true that the pull distributions are not fantastic for the lowest decay time bin, highlighted in Figures A.11-A.12. To assess a systematic uncertainty with this choice, we allow the mean and width of the signal component to float in the RS fit in each decay time independently, then use the modified fit model in each bin with the new signal components fixed to fit the WS samples. The change in the mean positions and widths of the distributions are summarized in Figure 13.18. The overall variation is maximally 16 keV and 1% in the mean position and the width, respectively.

The systematic uncertainty is analyzed by performing the analysis again with these in-

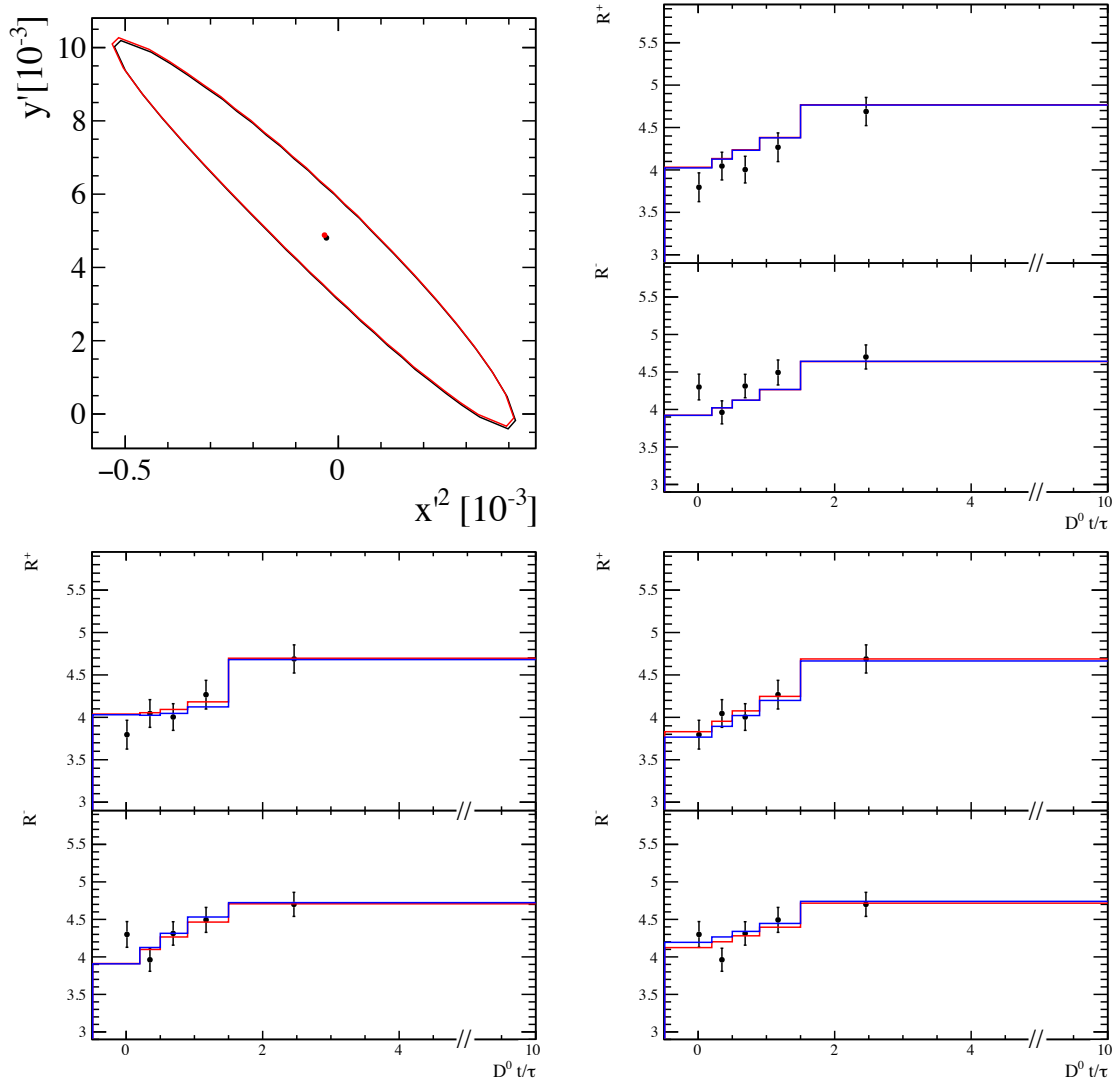


Figure 13.17: Blinded fit projections after allowing for a time dependent $K\pi$ asymmetry. The top left plot shows the (x'^2, y') mixing only contours for the nominal fit (black) and the modified fit (red). The top right shows the mixing only fit with the blue line as the nominal fit and the red line with a time dependent $K\pi$ asymmetry. The bottom left is the same, but for the no DCPV allowed fit and the bottom right is the same for the all CPV allowed fit.

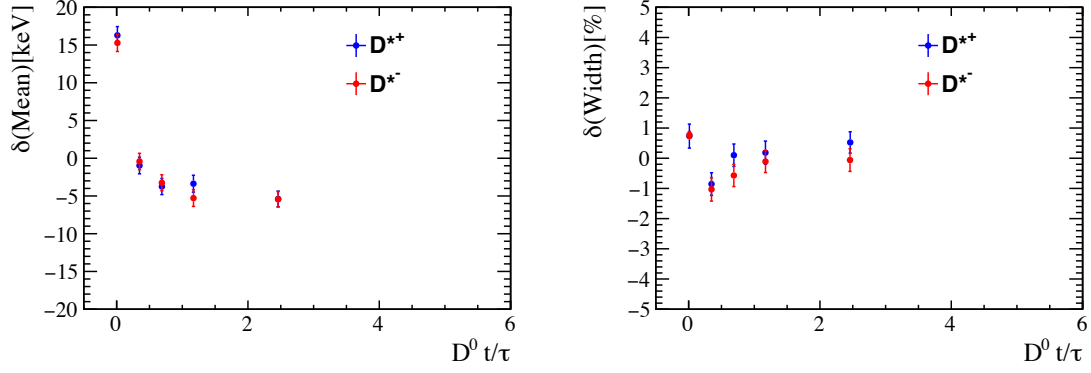


Figure 13.18: Left: Variation in keV of the mean position of the $D^{*\pm}$ signal PDF peak in decay time bins. Blue is the D^{*+} and red is D^{*-} sample. Right: Variation in percent of the width of the $D^{*\pm}$ signal PDF in decay time bins. Same coloring scheme applies.

1900 dependent fit models. The results are given in Table 13.10, and the fits are shown in Fig-
 1901 ures 13.20 and 13.21.

Table 13.10: Result allowing a different RS fit model for each decay time bin.

Parameter	Central Value $\pm$ Error	Largest Difference From Nominal
Different RS Fit Model in each Decay Time Bin		
No CPV		
$R_D[10^{-3}]$	3.90 ± 0.11	0.00
$x'^2[10^{-4}]$	-0.25 ± 3.10	0.03
$y'[10^{-3}]$	4.79 ± 3.50	0.01
Fit χ^2	14.717/7	-
No Direct CPV		
$R_D[10^{-3}]$	3.90 ± 0.11	0.00
$x'^{2+}[10^{-4}]$	3.48 ± 3.47	0.03
$y'^+[10^{-3}]$	0.30 ± 4.02	0.02
$x'^{2-}[10^{-4}]$	-4.64 ± 4.26	0.03
$y'^-[10^{-3}]$	9.55 ± 4.17	0.01
Fit χ^2	8.891/5	-
All CPV Allowed		
$R_D^+[10^{-3}]$	3.69 ± 0.15	0.00
$x'^{2+}[10^{-4}]$	-0.56 ± 4.44	0.01
$y'^+[10^{-3}]$	5.93 ± 5.02	0.01
$R_D^-[10^{-3}]$	4.12 ± 0.15	0.00
$x'^{2-}[10^{-4}]$	0.11 ± 4.32	0.05
$y'^-[10^{-3}]$	3.59 ± 4.87	0.04
Fit χ^2	4.529/4	-

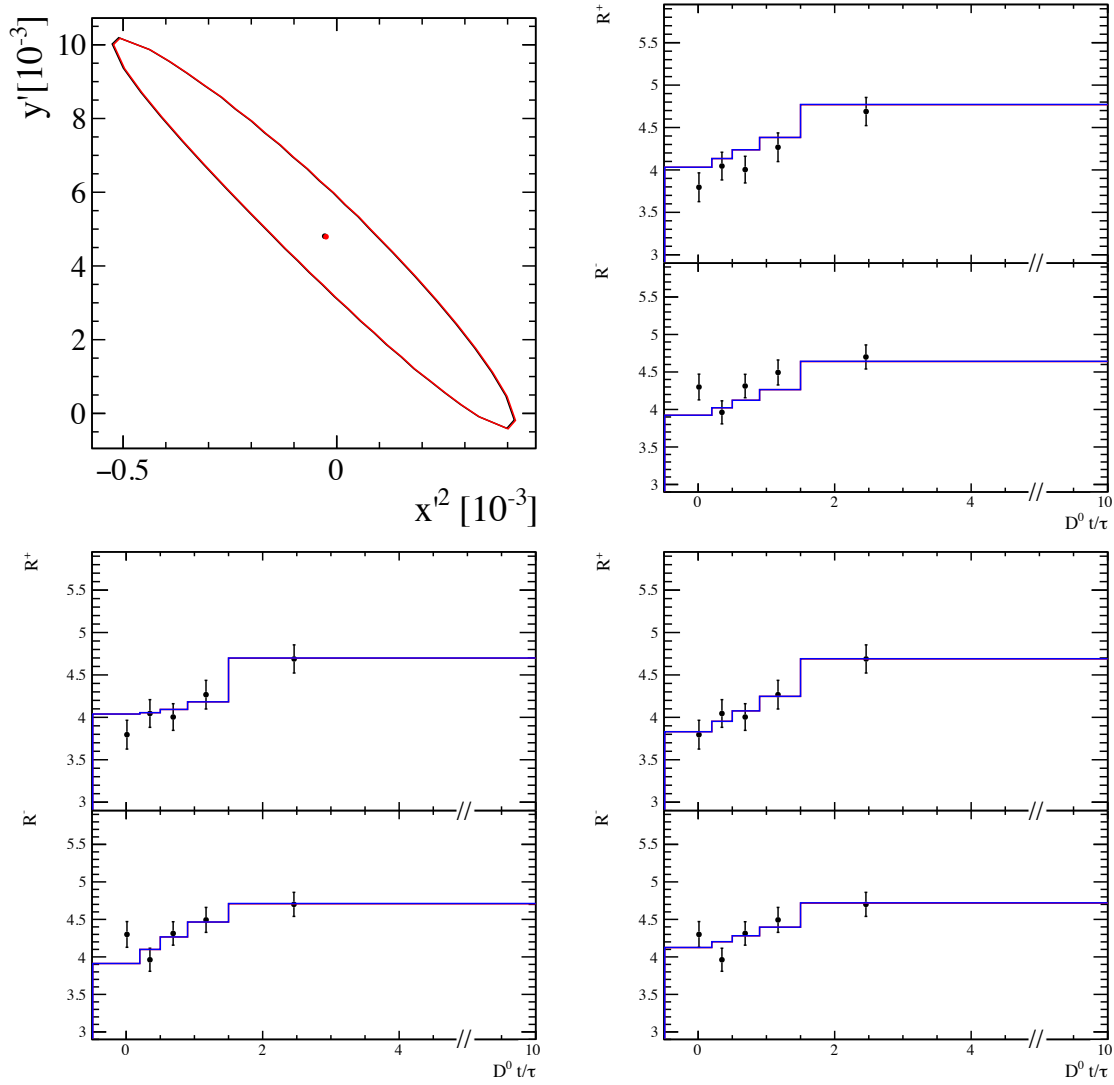


Figure 13.19: Comparison of blinded results allowing RS fit model to vary as a function of decay time bin. The top left plot shows the (x'^2, y') contours, with black being nominal and red allowing for this change. Top right shows the comparison of the mixing results with the blue line being the nominal fit, and the red being the fit to the distribution with the new models. The points are those from the nominal analysis. Bottom right is the same for the no DCPV fit, and bottom left is the same for All CPV allowed.

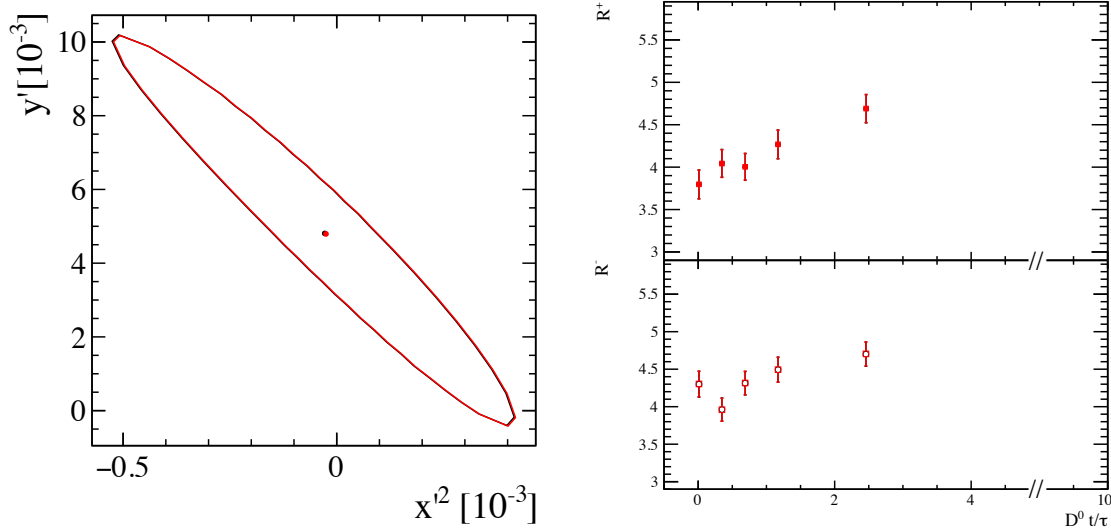


Figure 13.20: Comparison of blinded results allowing RS fit model to vary as a function of decay time bin. Left plot shows the (x'^2, y') contours, with black being nominal and red allowing for this change. Right is the comparison of the nominal dataset to that of the changed fit model.

13.3.4 Accounting for choice of Prompt Veto

To assess the impact on the DT sample to veto the prompt contributions, we perform the analysis again, but without the prompt veto taken into account. We see that the application of the veto does not change the result appreciably, but we still assign a systematic uncertainty for the change. The fits are shown in Figure 13.22, and the comparison of datasets is shown in Figure 13.23. Finally, the maximum difference from the nominal fit is reported in Table 13.11.

13.3.5 Fit Coverage Systematic

To account for the biases seen in the coverage of the blinding in Section 12, we fit together all 11,000 toy samples for all points considered around the allowed (x, y) contour considered, i.e. from Table 12.1, then fit the pull distribution for each variable from the total sample. We take the mean offset of the pull distribution multiplied by the extracted error from the blinded fit to get our systematic uncertainty, i.e. Table 12.2, and get the correlation coefficients from plotting each pull against each other pull. We obtain the results in Table 13.12.

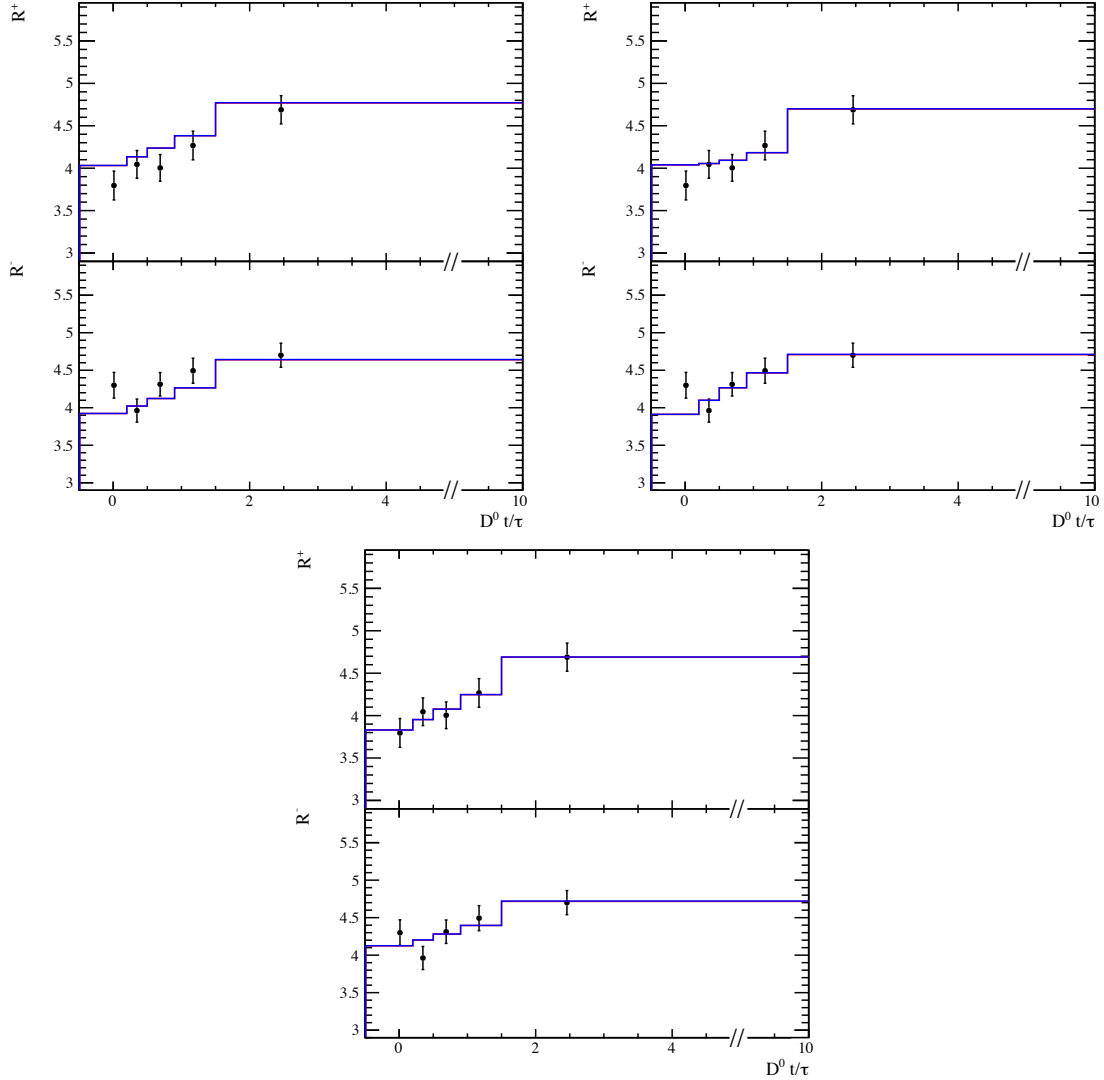


Figure 13.21: Comparison of the blinded fit results of the nominal fit with the fit allowing RS model time dependence. Top Left shows the comparison of the mixing results with the blue line being the nominal fit, and the red being the fit to the distribution with the new models. The points are those from the nominal analysis. Top right is the same for the no DCPV fit, and bottom is the same for All CPV allowed.

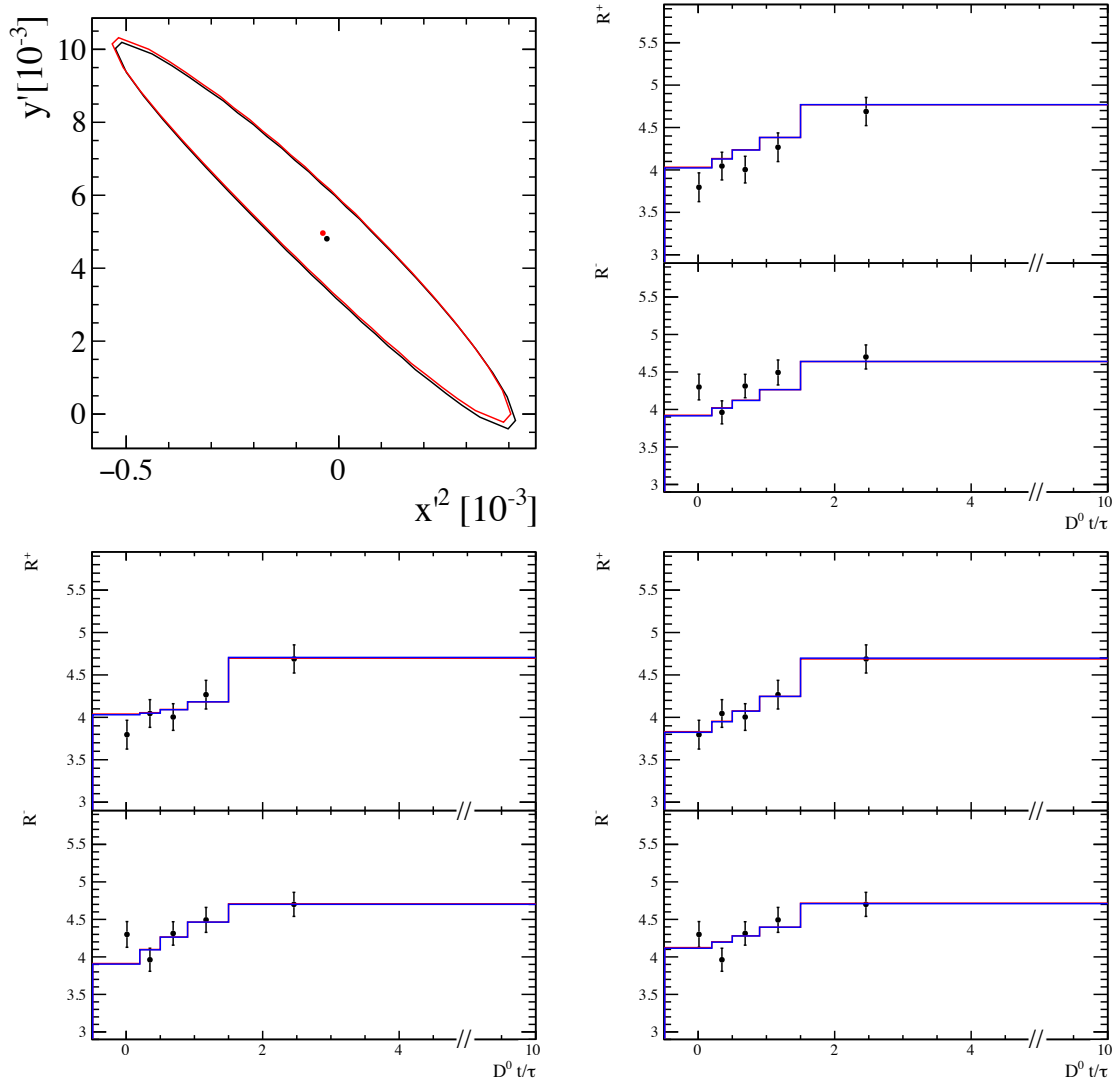


Figure 13.22: Blinded fit projections with no application of a veto for prompt overlap. The top left plot shows the (x'^2, y') mixing only contours for the nominal fit (black) and the modified fit (red). The top right shows the mixing only fit with the blue line as the nominal fit and the red line without the application of the prompt veto. The bottom left is the same, but for the no DCPV allowed fit and the bottom right is the same for the all CPV allowed fit.

Table 13.11: Result compared with not vetoing prompt candidates.

Parameter	Central Value $\pm$ Error	Largest Difference From Nominal
No Prompt Veto		
No CPV		
$R_D[10^{-3}]$	3.89 ± 0.11	0.01
$x'^2[10^{-4}]$	-0.37 ± 3.09	0.09
$y'[10^{-3}]$	4.96 ± 3.48	0.16
Fit χ^2	14.264/7	-
No Direct CPV		
$R_D[10^{-3}]$	3.89 ± 0.11	0.01
$x'^{2+}[10^{-4}]$	3.45 ± 3.46	0.00
$y'^+[10^{-3}]$	0.43 ± 4.00	0.11
$x'^{2-}[10^{-4}]$	-4.85 ± 4.25	0.19
$y'^-[10^{-3}]$	9.74 ± 4.15	0.19
Fit χ^2	8.449/5	-
All CPV Allowed		
$R_D^+[10^{-3}]$	3.68 ± 0.15	0.01
$x'^{2+}[10^{-4}]$	-0.56 ± 4.42	0.01
$y'^+[10^{-3}]$	6.01 ± 5.00	0.09
$R_D^-[10^{-3}]$	4.11 ± 0.15	0.01
$x'^{2-}[10^{-4}]$	-0.13 ± 4.31	0.19
$y'^-[10^{-3}]$	3.84 ± 4.85	0.21
Fit χ^2	4.131/4	-

Table 13.12: Systematic Uncertainty due to biases in coverage of blinding.

Parameter	Systematic Uncertainty $[10^{-3}]$
All CPV allowed	
R_D^+	0.00
y'^+	0.17
x'^{2+}	0.03
R_D^-	0.00
y'^-	0.18
x'^{2-}	0.03

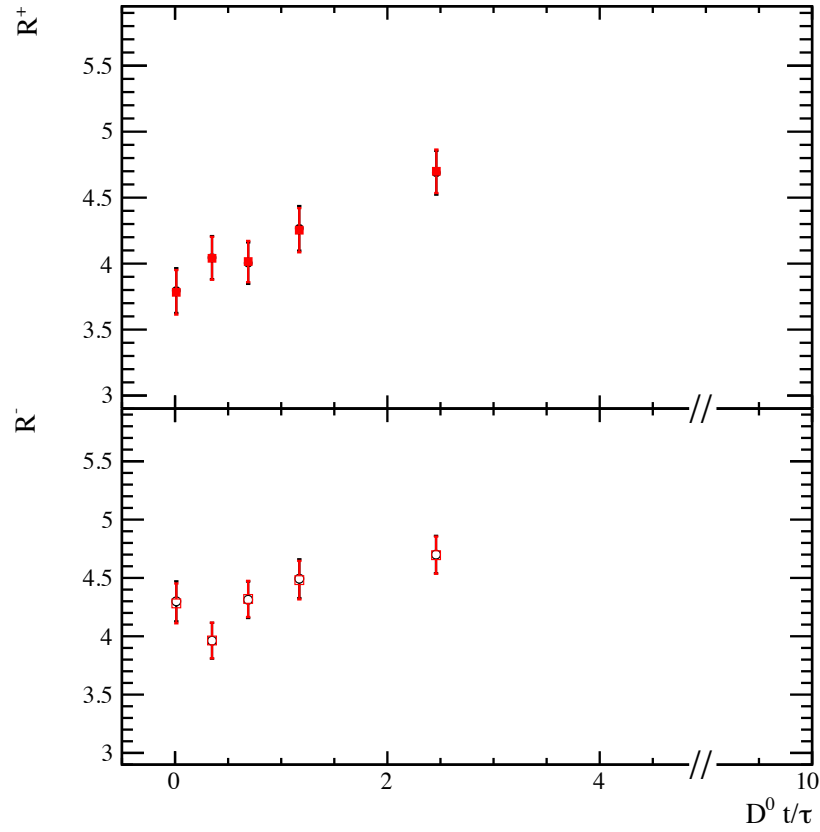


Figure 13.23: Comparison of the blinded datasets of the nominal sample (black) and the sample with no prompt veto (red). The top plots show the blinded $R^+(t)$ and bottom show the blinded $R^-(t)$. The filling simply helps to distinguish the two plots.

13.4 Summary of Systematic Uncertainties

We summarize the systematic uncertainties listed above in the following tables.

Table 13.13: Systematic Uncertainties for the mixing fit of the DT analysis

Systematic Uncertainty	Mixing Fit		
	$R_D[10^{-3}]$	$y'[10^{-3}]$	$x'^2[10^{-4}]$
No Scaling	0.01	0.04	0.04
$A(K\pi)$ Time Dependence	0.01	0.07	0.04
RS Fit Model Time Variation	0.00	0.01	0.03
No Prompt Veto	0.01	0.16	0.09
Total	0.01	0.18	0.11

Table 13.14: Systematic Uncertainties for the no DCPV fit of the DT analysis

Systematic Uncertainty	No DCPV Fit				
	$R_D[10^{-3}]$	$y'^+[10^{-3}]$	$x'^{2+}[10^{-4}]$	$y'^-[10^{-3}]$	$x'^{2-}[10^{-4}]$
No Scaling	0.01	0.04	0.04	0.03	0.04
$A(K\pi)$ Time Dependence	0.01	1.17	0.98	1.64	1.67
RS Fit Model Time Variation	0.00	0.02	0.03	0.01	0.03
No Prompt Veto	0.01	0.11	0.00	0.19	0.19
Total	0.01	1.17	0.98	1.66	1.68

Table 13.15: Systematic Uncertainties for the all CPV fit of the DT analysis

Systematic Uncertainty	All CPV Fit					
	$R_D^+[10^{-3}]$	$y'^+[10^{-3}]$	$x'^{2+}[10^{-4}]$	$R_D^-[10^{-3}]$	$y'^-[10^{-3}]$	$x'^{2-}[10^{-4}]$
No Scaling	0.01	0.03	0.04	0.01	0.04	0.04
$A(K\pi)$ Time Dependence	0.06	0.25	0.03	0.07	0.28	0.03
RS Fit Model Time Variation	0.00	0.01	0.01	0.00	0.04	0.05
No Prompt Veto	0.01	0.09	0.01	0.01	0.21	0.19
Toy MC Coverage	0.00	0.18	0.30	0.00	0.18	0.33
Total	0.06	0.32	0.31	0.07	0.40	0.38

13.4.1 Check of Systematic Uncertainties after Unblinding

As a follow up, we double check the systematic uncertainties on unblinded data. The results are summarized in Tables 13.16-13.18. We find that the systematics for the mixing only and all CPV allowed are unchanged within rounding error of the result. The no direct CPV allowed fit fluctuates slightly from the values expected before unblinding.

Table 13.16: Systematic Uncertainties for the mixing fit of the DT analysis after unblinding.

	$R_D[10^{-3}]$	$y'[10^{-3}]$	$x'^2[10^{-4}]$
No Scaling	0.01	0.04	0.04
$A(K\pi)$ Time Dependence	0.00	0.06	0.04
RS Fit Model Time Variation	0.00	0.02	0.03
No Prompt Veto	0.01	0.16	0.09
Total	0.01	0.18	0.11

Table 13.17: Systematic Uncertainties for the no DCPV fit of the DT analysis after unblinding.

	$R_D[10^{-3}]$	$y'^+[10^{-3}]$	$x'^{2+}[10^{-4}]$	$y'^-[10^{-3}]$	$x'^{2-}[10^{-4}]$
No Scaling	0.01	0.04	0.04	0.03	0.04
$A(K\pi)$ Time Dependence	0.00	1.21	1.00	1.56	1.41
RS Fit Model Time Variation	0.00	0.02	0.03	0.01	0.03
No Prompt Veto	0.01	0.12	0.00	0.20	0.18
Total	0.01	1.22	1.00	1.58	1.43

Table 13.18: Systematic Uncertainties for the all CPV fit of the DT analysis after unblinding.

	$R_D^+[10^{-3}]$	$y'^+[10^{-3}]$	$x'^{2+}[10^{-4}]$	$R_D^-[10^{-3}]$	$y'^-[10^{-3}]$	$x'^{2-}[10^{-4}]$
No Scaling	0.01	0.04	0.04	0.01	0.04	0.04
$A(K\pi)$ Time Dependence	0.06	0.24	0.02	0.06	0.25	0.02
RS Fit Model Time Variation	0.00	0.01	0.01	0.00	0.04	0.05
No Prompt Veto	0.01	0.09	0.01	0.01	0.23	0.19
Toy MC Coverage	0.00	0.18	0.30	0.00	0.18	0.33
Total	0.06	0.32	0.31	0.06	0.39	0.38

Chapter 14

Results

14.1 Unblinded Central Value

The unblinded central value of the DT only fit is given in Table 14.1, and the projection of the DT only fit is given in Figure 14.1. The individual contours for the mixing only, no direct CPV, and all CPV allowed given in the (x'^2, y') plane are shown in Figure 14.2

14.2 Discussion of DT only result

What we see from the central value is that the DT only data are consistent with the mixing only hypothesis with a p -value of 51%, calculated directly from the χ^2 value of the fit. We also fit using the hypothesis of no mixing ($x'^2 = y' = 0$) and find a χ^2 of 31.953. The difference in χ^2 is then 25.66 for 2 degrees of freedom, which gives a p -value of approximately 2.68×10^{-6} . This disfavors the no mixing hypothesis at approximately 4.6 standard deviations. The fits for the no mixing hypothesis are reported in Appendix A.12. The p -values of the no DCPV fit and all CPV allowed fit are both 0.35. As the DT data are well described by the mixing only fit, the conclusion is that these data are consistent with CP symmetry. We do not constrain the value of x'^2 to lie in the positive values on purpose, as we allow the fit itself to float freely for better constraints. We also note that the difference plot of Figure 14.1, is

Table 14.1: Central Value from the fit to DT only data. (Unblind)

Parameter	Central Value	Error
No CPV		
$R_D[10^{-3}]$	3.48	0.10
$x'^2[10^{-4}]$	0.28	3.10
$y'[10^{-3}]$	4.60	3.70
$\chi^2/\text{NDF} = 6.293/7$		
No Direct CPV		
$R_D[10^{-3}]$	3.48	0.10
$x'^{2+}[10^{-4}]$	1.94	3.67
$y'^+[10^{-3}]$	2.79	4.27
$x'^{2-}[10^{-4}]$	-1.53	4.04
$y'^-[10^{-3}]$	6.51	4.38
$\chi^2/\text{NDF} = 5.589/5$		
All CPV Allowed		
$R_D^+[10^{-3}]$	3.38	0.15
$x'^{2+}[10^{-4}]$	-0.19	4.46
$y'^+[10^{-3}]$	5.81	5.25
$R_D^-[10^{-3}]$	3.60	0.15
$x'^{2-}[10^{-4}]$	0.79	4.31
$y'^-[10^{-3}]$	3.32	5.21
$\chi^2/\text{NDF} = 4.473/4$		

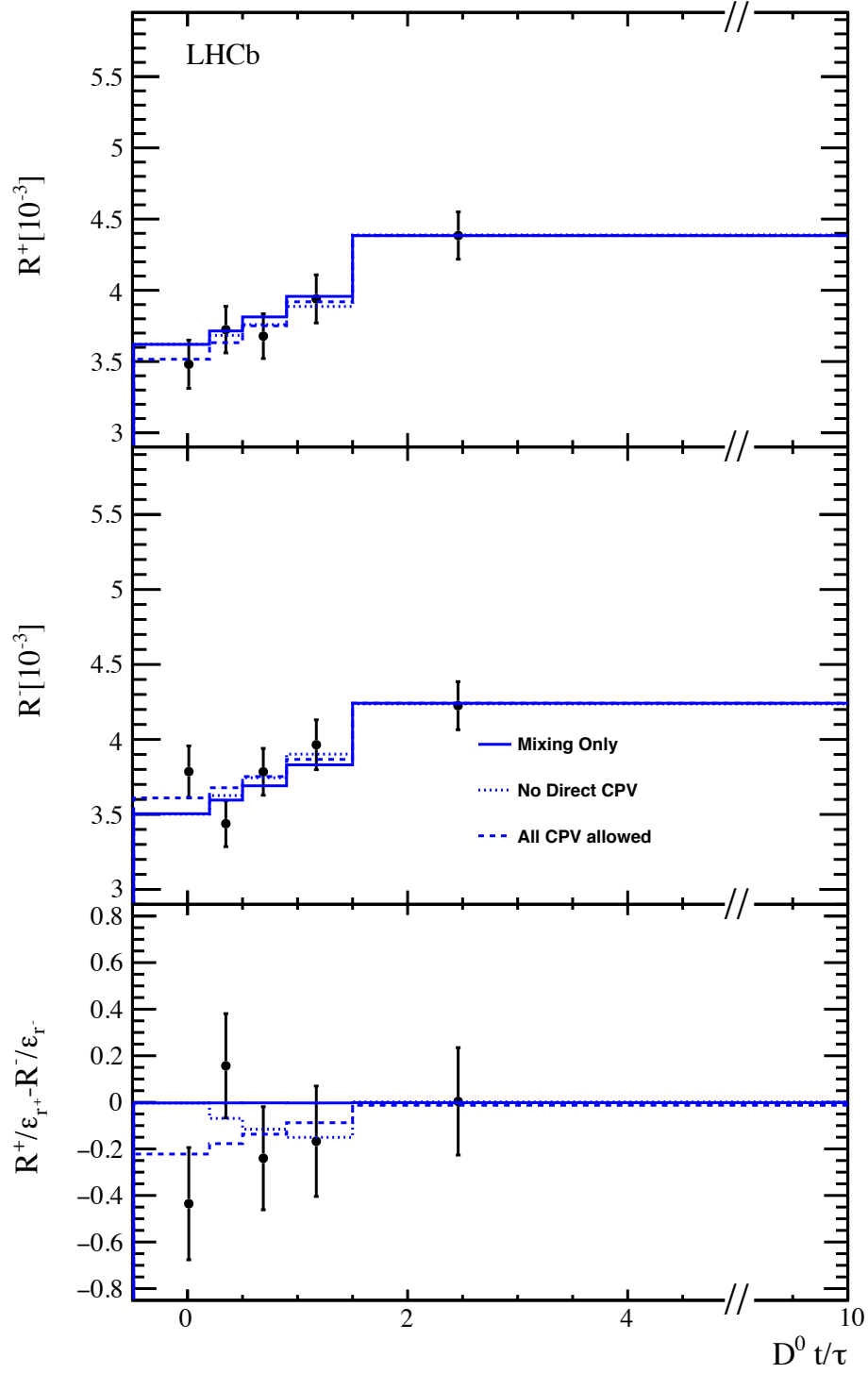


Figure 14.1: Unblind fit of the DT only sample. Top plot shows the fit to R^+ as a function of D^0 decay time, middle shows R^- , and the bottom shows the efficiency corrected difference. Inlaid are the fits to no CPV allowed (solid blue), no Direct CPV allowed (dotted blue) and all CPV allowed (dashed blue).

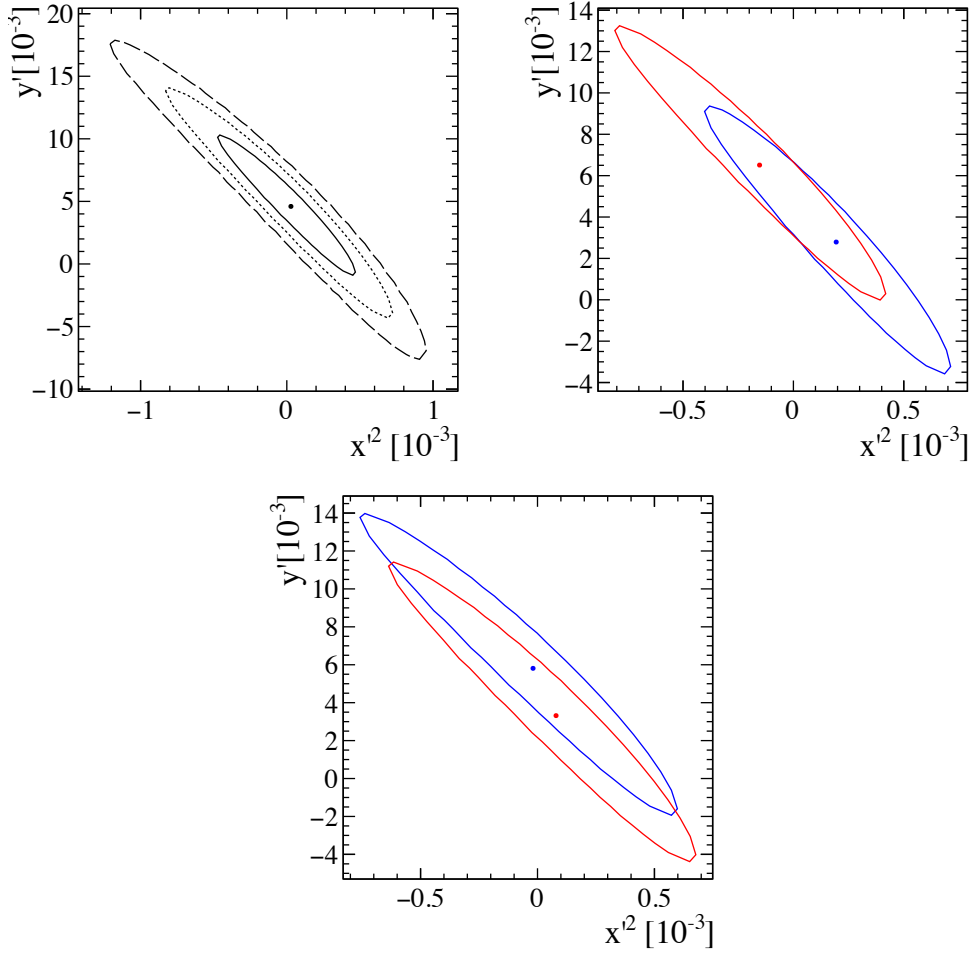


Figure 14.2: Projections onto the (x'^2, y') plane of the mixing only fit (left top), the no direct CPV fit (top left) and the all CPV allowed fit (bottom). For the mixing only contours, the $1, 2$ and 3σ contours are shown, and for the no direct CPV and all CPV allowed fits, the 1σ contours are shown. For the no direct CPV and all CPV fits, the blue corresponds to (x'^{+2}, y'^{+}) , and the red to (x'^{-2}, y'^{-}) .

sensitive to CPV in mixing, which would manifest itself as a slope in this graph. Again, the data are consistent with a flat line on this graph, indicating consistency with CP symmetry. The difference between the χ^2 for the mixing and no DCPV fits for the blind and unblind samples are due to the blinding procedure used, which generated a CP asymmetry in both mixing and direct CPV.

14.3 Combination with Previous LHCb $D^0 \rightarrow K\pi$ Result

As discussed in Section 6.2.3, we also fit the combination of the DT and prompt results simultaneously. The published result of the Prompt analysis [18] are listed in Table 14.2.

Table 14.2: Results from the prompt published paper [18].

Parameter	Value
All CPV allowed	
$R_D^+[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
$y'^+[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
$x'^{2+}[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
$R_D^-[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
$y'^-[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
$x'^{2-}[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf	85.9/98
No direct CP violation	
$R_D[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
$y'^+[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
$x'^{2+}[10^{-5}]$	$6.4 \pm 4.7 \pm 3.0$
$y'^-[10^{-3}]$	$4.8 \pm 0.9 \pm 0.6$
$x'^{2-}[10^{-5}]$	$4.6 \pm 4.6 \pm 3.0$
χ^2/ndf	86.0/99
No CP violation	
$R_D[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
$y'[10^{-3}]$	$4.8 \pm 0.8 \pm 0.5$
$x'^{2}[10^{-5}]$	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf	86.4/101

We now take the original prompt dataset, which results in the above fit result, and combine with the DT dataset and extract the final fit parameters. This combination is accomplished by resumming the χ^2 to include both datasets:

$$\chi^2 = \sum_{\text{DT, Prompt}} \sum_{i \in \text{Time Bins}} \left(\frac{f_i^+ - r_i^+}{\sigma_i^+} \right)^2 + \left(\frac{f_i^- - r_i^-}{\sigma_i^-} \right)^2 + \left(\frac{a_{K\pi} - A(K\pi)}{\sigma_{A(K\pi)}} \right)^2 + \left(\frac{p_i + P_i}{\sigma_{P_i}} \right)^2 + \left(\frac{f_{b/p,i} - F_{b/p,i}}{\sigma_{F_{b/p,i}}} \right)^2. \quad (14.1)$$

The final fit results for the combined DT and prompt analysis are given in Table 14.3, and the fit projections are shown in Figure 14.3. In the plots, the data are efficiency corrected, which means that we divide by $\epsilon_r^\pm$ for each sample.

The values for the prompt sample are those which were used in [18]. As the samples are disjoint, there is no cross-correlation term for either sample. While the data themselves are uncorrelated, the same is not necessarily true of the detection asymmetry $A(K\pi)$. The same data samples for the $D^\pm$ decays are used for both prompt and DT samples. While calculation of the correlation is possible using the bootstrap method, the data are not readily available for the calculation of the $K\pi$ asymmetry of the prompt sample. We have considered the case where the data have 100% correlation and 80% correlation, first considering only the correlation between the DT sample and both the prompt samples independently, and finally allowing for the same correlation coefficient between the prompt datasets used. The results of this study are shown in Tables 14.4 and 14.5.

As the central values for the mixing only fit do not show a sensitivity to any of these changes, and we lack the data to perform the bootstrapping to correctly account for the correlations, which show wild variation between the mixing and noDCPV results, we choose the more conservative approach of letting all asymmetries vary independently.

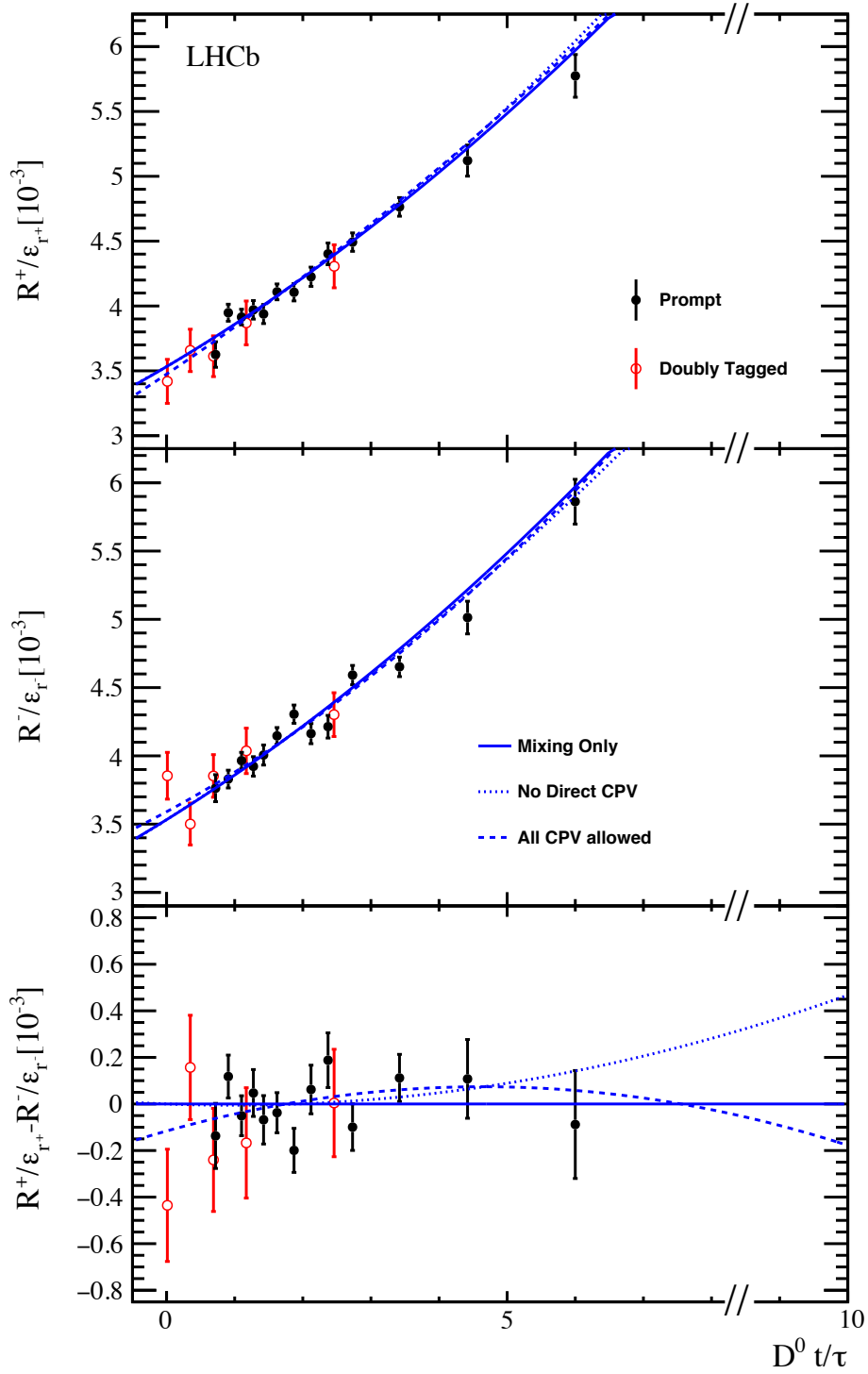


Figure 14.3: Efficiency corrected combined fit of the DT and prompt analysis. Top plot is R^+ versus D^0 decay time, middle is R^- , and the bottom is the difference between R^+ and R^- . Inlaid are the fit projections, with the solid blue line being for Mixing Only, the dotted blue line for no direct CPV allowed, and the dashed blue line is for all CPV allowed.

Table 14.3: Central Value from the fit to DT + Prompt data. (Unblind))

Parameter	Central Value	Error
No CPV		
$R_D[10^{-3}]$	3.5325	0.0533
$x'^2[10^{-4}]$	0.3635	0.4326
$y'[10^{-3}]$	5.2308	0.8393
$\chi^2/\text{NDF} = 96.594/111$		
No Direct CPV		
$R_D[10^{-3}]$	3.5325	0.0533
$x'^{2+}[10^{-4}]$	0.4900	0.5009
$y'^+[10^{-3}]$	5.1363	0.9118
$x'^{2-}[10^{-4}]$	0.2389	0.5026
$y'^-[10^{-3}]$	5.3235	0.9115
$\chi^2/\text{NDF} = 96.147/109$		
All CPV Allowed		
$R_D^+[10^{-3}]$	3.4745	0.0753
$x'^{2+}[10^{-4}]$	0.1065	0.6294
$y'^+[10^{-3}]$	5.9659	1.2032
$R_D^-[10^{-3}]$	3.5907	0.0755
$x'^{2-}[10^{-4}]$	0.6114	0.5919
$y'^-[10^{-3}]$	4.5035	1.1686
$\chi^2/\text{NDF} = 94.960/108$		

Table 14.4: Comparison of the central value of the DT+Prompt fit with no correlation added (left), 100% correlation between the DT and each prompt dataset (Center) and 100% correlation between all datasets(right)

Parameter	No Correlation	DT:Prompt correlation($\rho = 1$)	All Correlation($\rho = 1$)
Mixing Only			
$R_D[10^{-3}]$	3.532466 ± 0.053257	3.532535 ± 0.053240	3.532535 ± 0.053246
$y'[10^{-3}]$	5.230825 ± 0.839258	5.227818 ± 0.838973	5.227818 ± 0.839079
$x'^2[10^{-4}]$	0.36348 ± 0.43262	0.36488 ± 0.43246	0.36488 ± 0.43251
No DCPV			
$R_D[10^{-3}]$	3.532484 ± 0.053268	3.532505 ± 0.053247	3.532505 ± 0.053256
$y'^+[10^{-3}]$	5.136262 ± 0.911772	5.300764 ± 0.912803	5.300764 ± 0.912934
$x'^{2+}[10^{-4}]$	0.48999 ± 0.50088	0.40540 ± 0.50390	0.40540 ± 0.50395
$y'^-[10^{-3}]$	5.323453 ± 0.911453	5.156081 ± 0.909792	5.156081 ± 0.909923
$x'^{2-}[10^{-4}]$	0.23892 ± 0.50263	0.32530 ± 0.49932	0.32530 ± 0.49937
All CPV			
$R_D^+[10^{-3}]$	3.474528 ± 0.075286	3.524992 ± 0.076089	3.524992 ± 0.076102
$y'^+[10^{-3}]$	5.965900 ± 1.203154	5.407690 ± 1.198499	5.407690 ± 1.198717
$x'^{2+}[10^{-4}]$	0.10652 ± 0.62936	0.35621 ± 0.61912	0.35621 ± 0.61922
$R_D^-[10^{-3}]$	3.590716 ± 0.075532	3.539740 ± 0.074671	3.539740 ± 0.074683
$y'^-[10^{-3}]$	4.503502 ± 1.168552	5.053625 ± 1.171894	5.053625 ± 1.172100
$x'^{2-}[10^{-4}]$	0.61140 ± 0.59195	0.37206 ± 0.60115	0.37206 ± 0.60125

Table 14.5: Comparison of the central value of the DT+Prompt fit with no correlation added (left), 80% correlation between the DT and each prompt dataset (Center) and 80% correlation between all datasets(right)

Parameter	No Correlation	DT:Prompt correlation($\rho = 0.8$)	All Correlation($\rho = 0.8$)
Mixing Only			
$R_D[10^{-3}]$	3.532466 ± 0.053257	3.531971 ± 0.053226	3.531971 ± 0.053237
$y'[10^{-3}]$	5.230825 ± 0.839258	5.234386 ± 0.838875	5.234386 ± 0.839052
$x'^2[10^{-4}]$	0.36348 ± 0.43262	0.36204 ± 0.43248	0.36204 ± 0.43256
No DCPV			
$R_D[10^{-3}]$	3.532484 ± 0.053268	3.531938 ± 0.053231	3.531938 ± 0.053245
$y'^+[10^{-3}]$	5.136262 ± 0.911772	5.349319 ± 0.913009	5.349319 ± 0.913228
$x'^{2+}[10^{-4}]$	0.48999 ± 0.50088	0.38090 ± 0.50472	0.38090 ± 0.50481
$y'^-[10^{-3}]$	5.323453 ± 0.911453	5.121588 ± 0.909326	5.121588 ± 0.909544
$x'^{2-}[10^{-4}]$	0.23892 ± 0.50263	0.34359 ± 0.49855	0.34359 ± 0.49865
All CPV			
$R_D^+[10^{-3}]$	3.474528 ± 0.075286	3.537371 ± 0.076277	3.537371 ± 0.076298
$y'^+[10^{-3}]$	5.965900 ± 1.203154	5.272096 ± 1.197205	5.272096 ± 1.197565
$x'^{2+}[10^{-4}]$	0.10652 ± 0.62936	0.41638 ± 0.61657	0.41638 ± 0.61674
$R_D^-[10^{-3}]$	3.590716 ± 0.075532	3.526762 ± 0.074443	3.526762 ± 0.074463
$y'^-[10^{-3}]$	4.503502 ± 1.168552	5.195008 ± 1.172604	5.195008 ± 1.172947
$x'^{2-}[10^{-4}]$	0.61140 ± 0.59195	0.31005 ± 0.60346	0.31005 ± 0.60362

14.4 Systematic Uncertainties for the Prompt + DT analysis

The prompt analysis contains all systematic uncertainties in the fit itself, whereas the DT analysis has a host of extra systematic uncertainties aside from those included in the fit. To accurately account for the additional systematic uncertainties from the DT sample, we use the datasets which were used to calculate the systematic uncertainties for the DT analysis alone in Section 13.4, and fit in combination with the prompt data. The difference between the final results and those of these datasets is taken as a systematic uncertainty. All uncertainties are propagated to the final results by combination of their covariance matrices.

The summary of the systematic uncertainties for the DT + Prompt combination are given in Table 14.6-14.8.

Table 14.6: Systematic Uncertainties for the mixing only fit of the combined DT and prompt datasets.

Systematic Uncertainty	Mixing Fit		
	$R_D[10^{-3}]$	$y'[10^{-3}]$	$x'^2[10^{-4}]$
No Scaling	0.00	0.05	0.02
$A(K\pi)$ Time Dependence	0.00	0.02	0.01
RS Fit Model Time Variation	0.00	0.00	0.00
No Prompt Veto	0.00	0.04	0.02
Total	0.01	0.07	0.03

14.5 Comparison to Prompt only Result

In Table 14.9, we report the errors combined in quadrature, as the original prompt analysis calculated the statistical and systematic uncertainties differently than what is reported here. We see that the errors on R_D decrease by 19% and y' by 11% for the mixing only fit. For the no Direct CPV fit, we find that the errors decrease by 19% for R_D and roughly 16% for each of $y' \pm$. For the all CPV allowed fit, the errors reduce by 15 and 10% on $R_D^\pm$, and 9 and

Table 14.7: Systematic Uncertainties for the no direct CPV allowed fit of the combined DT and prompt datasets.

Systematic Uncertainty	No DCPV Fit				
	$R_D[10^{-3}]$	$y'^+[10^{-3}]$	$x'^{2+}[10^{-4}]$	$y'^-[10^{-3}]$	$x'^{2-}[10^{-4}]$
No Scaling	0.00	0.05	0.02	0.05	0.02
$A(K\pi)$ Time Dependence	0.00	0.02	0.02	0.06	0.03
RS Fit Model Time Variation	0.00	0.00	0.00	0.00	0.00
No Prompt Veto	0.00	0.04	0.02	0.04	0.02
Total	0.01	0.07	0.03	0.09	0.05

Table 14.8: Systematic uncertainties for the all CPV allowed fit of the combined DT and prompt datasets.

Systematic Uncertainty	All CPV Fit					
	$R_D^+[10^{-3}]$	$y'^+[10^{-3}]$	$x'^{2+}[10^{-4}]$	$R_D^-[10^{-3}]$	$y'^-[10^{-3}]$	$x'^{2-}[10^{-4}]$
No Scaling	0.00	0.06	0.02	0.00	0.05	0.02
$A(K\pi)$ Time Dependence	0.03	0.33	0.15	0.03	0.31	0.13
RS Fit Model Time Variation	0.00	0.00	0.00	0.00	0.01	0.00
No Prompt Veto	0.00	0.05	0.02	0.00	0.03	0.01
Total	0.03	0.34	0.15	0.03	0.31	0.13

Table 14.9: Central Value from the fit to DT + Prompt data, unblind. The center left column gives the combined result, the center column gives the original prompt result, and the right column gives the percentage reduction of error compared to original prompt analysis.

Parameter	DT+prompt combination	Prompt alone	% Error Improvement
No CPV			
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19
$x'^2[10^{-5}]$	3.6 ± 4.3	5.5 ± 4.9	12
$y'[10^{-3}]$	5.23 ± 0.84	4.80 ± 0.94	11
χ^2/NDF	96.594/111		
No Direct CPV			
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067	19
$x'^2+[10^{-5}]$	4.9 ± 5.0	6.4 ± 5.6	11
$y'^+[10^{-3}]$	5.14 ± 0.91	4.80 ± 1.08	16
$x'^2-[10^{-5}]$	2.4 ± 5.0	4.6 ± 5.5	9
$y'^-[10^{-3}]$	5.32 ± 0.91	4.8 ± 1.08	16
χ^2/NDF	96.147/109		
All CPV Allowed			
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095	15
$x'^2+[10^{-5}]$	1.1 ± 6.5	4.9 ± 7.0	7
$y'^+[10^{-3}]$	5.97 ± 1.25	5.10 ± 1.38	9
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090	10
$x'^2-[10^{-5}]$	6.1 ± 6.1	6.0 ± 6.8	10
$y'^-[10^{-3}]$	4.50 ± 1.21	4.50 ± 1.39	13
χ^2/NDF	94.960/108		

Chapter 15

Impact of Result on Global Fits

Using the result of the DT and prompt combination fit, we analyze the impact of the combination using external inputs on the underlying mixing parameters by performing an HFAG like global combination. We execute this process by combining results into a fit for mixing and CPV parameters using a global χ^2 defined as

$$\chi^2 = \vec{\epsilon}^T \sigma^{-1} \vec{\epsilon}. \quad (15.1)$$

In Equation 15.1, the elements of $\vec{\epsilon}$ are given by $\epsilon_i = m_i - p_i$, where m_i the measured values from each experiment, and p_i are the projected values to be extracted. This generalizes to the definitions that $\vec{m}$ is the list of measured values from experiments, and $\vec{p}$ is the proposed total set of parameters. We use MINUIT to vary $\vec{p}$ to find the final set which minimizes the χ^2 given in Equation 15.1. Finally, σ is an $N \times N$ matrix where N is the number of measurements, with $\sigma_{ij} = e_i c_{ij} e_j$. Here e_i is the reported error on measurement i , and c_{ij} is the correlation coefficient between measurements i and j .

We use Ref [17], noting the errata in equations 14 and 15 to perform the translations between the measurements of observables and mixing parameters. We fit for 3 different scenarios:

1. No Direct CP Violation,

2. No Direct CP Violation imposing the superweak constraint, and

3. All CPV allowed.

The mixing only fit is ignored as the global significance for mixing is greater than 10σ . Specifically, the superweak constraint is that which allows $\tan \phi = (1 - |q/p|)x/y$.

The external inputs we use for the fit are the HFAG COMBOS world average of A_Γ and y_{CP} [1], the mixing and CPV search of Belle using $D^0 \rightarrow K_S^0 \pi \pi$ [27], the BaBar $K_S^0 \pi \pi$ search [28], and the CLEO measurement of the strong phase difference [29]. These results are tabulated in Table 15.1.

Table 15.1: Values of the inputs for the sensitivity of the DT + Prompt analysis.

Measurement	Value
HFAG COMBOS y_{CP}	$(8.35 \pm 1.55) \times 10^{-3}$
HFAG COMBOS A_Γ	$(-5.9 \pm 4.0) \times 10^{-4}$
Belle $K_S \pi \pi$ x All CPV	$(5.8 \pm 1.9 \pm 0.96) \times 10^{-3}$
y All CPV	$(2.7 \pm 1.6 \pm 1.4) \times 10^{-3}$
$ q/p $ All CPV	$0.82 \pm 0.19 \pm 0.07$
ϕ All CPV	$-0.23 \pm 0.22 \pm 0.08$
BaBar $K_S \pi \pi$ x	$(1.6 \pm 2.3 \pm 1.2 \pm 0.8) \times 10^{-3}$
y	$(5.7 \pm 2.0 \pm 1.3 \pm 0.7) \times 10^{-3}$
CLEO $\cos \delta_{K\pi}$	$0.81 \pm 0.2 \pm 0.06$
$\sin \delta_{K\pi}$	$-0.01 \pm 0.4 \pm 0.04$

We also include the correlation matrices between the measurements, given in Table 15.2.

Table 15.2: Correlation coefficients for measurements in Table 15.1.

	x	y	$ q/p $	ϕ
Belle $K_S^0 \pi \pi$	1	0.054	-0.074	-0.031
		1	0.034	-0.019
			1	0.044
				1
BaBar $K_S^0 \pi \pi$			0.0615	
CLEO			0.040	

15.1 All CPV Allowed

Using these inputs, we calculate the parameters $x, y, \delta_{K\pi}, \phi, R_D^\pm$, and $|q/p|$ with the prompt only dataset and the prompt + DT combination. The result of the global fits for all CPV allowed are given in Table 15.3.

Table 15.3: Results of global fit for all CPV allowed using external inputs with the prompt dataset alone and the prompt + DT combination. The center column is the result with the prompt only $D^0 \rightarrow K\pi$ dataset included, and the right is the result with the prompt + DT result.

Parameter	Prompt Only	Prompt + DT
$x[10^{-3}]$	3.708 ± 1.449	3.518 ± 1.394
$y[10^{-3}]$	7.250 ± 0.733	7.335 ± 0.694
$\delta_{K\pi}[\text{rad}]$	0.380 ± 0.141	0.376 ± 0.135
$\phi[\text{rad}]$	-0.280 ± 0.161	-0.306 ± 0.156
$R_D^+[10^{-3}]$	3.519 ± 0.051	3.490 ± 0.048
$R_D^-[10^{-3}]$	3.606 ± 0.073	3.603 ± 0.068
$ q/p $	0.826 ± 0.085	0.823 ± 0.079
χ^2	9.033	9.021

From the projections onto the $(|q/p|, \phi)$ plane, we see immediately that the result of the DT and prompt moves the one standard deviation contour from the point (1,0), which is the no CPV point. Also, the relative error on x and y decreases by about 4-5%, 5% on ϕ and 8% on $|q/p|$.

15.2 No Direct CPV

We perform the same fit for the underlying physics parameters in the no direct CP violation allowed case by enforcing $R_D^+ = R_D^- = R_D$. We also fit in the two cases outlined above. In the case of the superweak constraint applied, we first fix $|q/p|$ and allow ϕ to float, deriving $|q/p|$ from the superweak constraint itself. We then reverse this requirement allowing for errors on both parameters to be calculated. In the case without the superweak constraint,

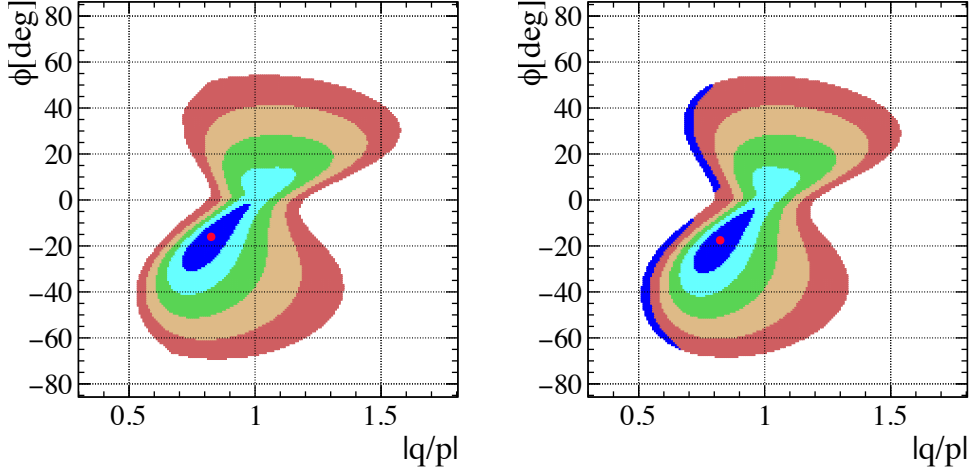


Figure 15.1: One through Five standard deviation contours in the $(|q/p|, \phi)$ plane for the fit with external inputs and the prompt $D^0 \rightarrow K\pi$ dataset on the left, and the prompt+DT dataset on the right. The central value is indicated with the magenta point, the one standard deviation contour is given by the blue shape, the two S.D. contour given by the cyan, three by green, four by orange and 5 by off red.

the parameters of interest are x_{12} , y_{12} and ϕ_{12} . These parameters are related to x and y by

$$x = \frac{1}{\sqrt{2}} \text{sign}(\cos \phi_{12}) \left(x_{12} - y_{12} + \sqrt{(x_{12}^2 + y_{12}^2)^2 - 4x_{12}^2 y_{12}^2 \sin^2 \phi_{12}} \right)^{1/2} \quad (15.2)$$

$$y = \frac{1}{\sqrt{2}} \left(y_{12} - x_{12} + \sqrt{(x_{12}^2 + y_{12}^2)^2 - 4x_{12}^2 y_{12}^2 \sin^2 \phi_{12}} \right)^{1/2} \quad (15.3)$$

The result to the fit of x_{12} , y_{12} and ϕ_{12} is given in Table 15.4, with the fit projections with 1-5 standard deviation contours shown in Figure 15.2.

What we see is that the 1-5 standard deviation contours actually appear to get larger, even though the errors decrease. This behavior is possibly explained by to changes in the correlation coefficients of the individual parameters between the prompt and prompt + DT fits. A follow up of with toy Monte Carlo is possible, but outside the time constraints of this thesis.

Finally, we do the same procedure with the superweak constraint applied. The resulting parameters are given in Table 15.5.

Again, the increase in errors for some parameters could be driven by the change in

Table 15.4: Results of global fit for no direct CPV allowed using external inputs with the prompt dataset alone and the prompt + DT combination. The center column is the result with the prompt only $D^0 \rightarrow K\pi$ dataset included, and the right is the result with the prompt + DT result.

Parameter	Prompt Only	Prompt + DT
$x_{12}[10^{-3}]$	4.506 ± 1.594	4.298 ± 1.558
$y_{12}[10^{-3}]$	6.325 ± 0.998	6.224 ± 0.984
$\delta_{K\pi}[\text{rad}]$	0.212 ± 0.229	0.178 ± 0.237
$\phi_{12}[10^{-2}][\text{rad}]$	0.530 ± 3.165	-0.847 ± 3.736
$R_D[10^{-3}]$	3.542 ± 0.045	3.528 ± 0.042
χ^2	11.742	11.2031

Table 15.5: Results of global fit for no direct CPV allowed using external inputs with the prompt dataset alone and the prompt + DT combination, and with the application of the superweak constraint. The center column is the result with the prompt only $D^0 \rightarrow K\pi$ dataset included, and the right is the result with the prompt + DT result.

Parameter	Prompt Only	Prompt + DT
$x[10^{-3}]$	4.505 ± 1.594	4.295 ± 1.558
$y[10^{-3}]$	6.325 ± 0.997	6.222 ± 0.986
$\delta_{K\pi}[\text{rad}]$	0.212 ± 0.229	0.178 ± 0.238
$\phi[10^{-2}][\text{rad}]$	-0.178 ± 1.067	0.273 ± 1.199
$ q/p $	1.003 ± 0.015	0.996 ± 0.017
$R_D[10^{-3}]$	3.542 ± 0.045	3.528 ± 0.042
χ^2	11.742	11.203

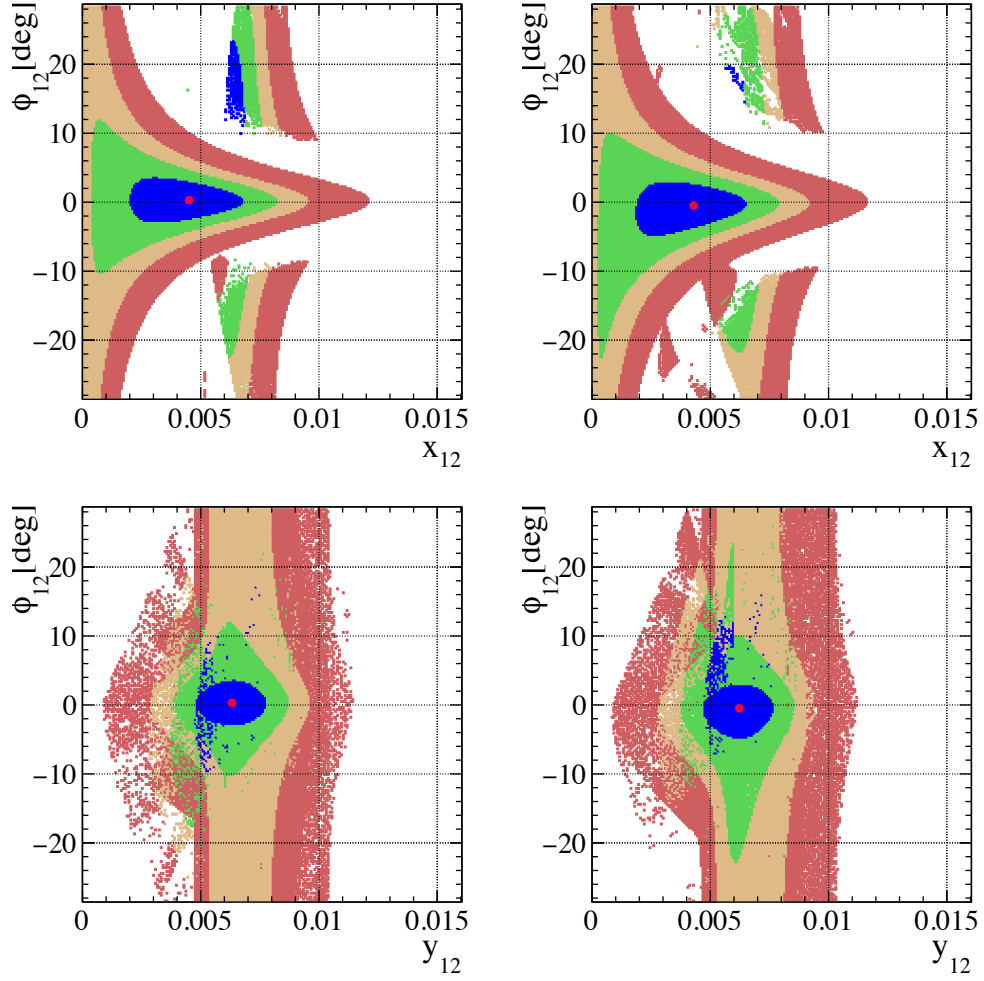


Figure 15.2: Projection of no direct CPV fit without superweak constraint onto the (x_{12}, ϕ_{12}) and (x_{12}, ϕ_{12}) planes (top and bottom). The left column is the result with the prompt only sample and the right is the prompt+ DT sample.

correlation coefficients, but a full toy Monte Carlo study is outside the time period of this thesis. If the correlation coefficient is in fact the cause, it would be simple to assume that the change is due to the uncertainties caused by the $A(K\pi)$ time dependence. In any case, in all fits, the results are consistent with CP symmetry.

Chapter 16

Conclusion

We have measured the D^0 mixing and CPV parameters using the doubly-tagged decay $B \rightarrow \mu D^* X$, $D^* \rightarrow D^0 \pi_S$, and $D^0 \rightarrow K \pi$. We find that the DT sample alone is inconsistent the no mixing hypothesis at a level of 4.6 standard deviations. We find also that the results are consistent with CP symmetry in fits of the doubly-tagged dataset alone as well as the combination of the doubly-tagged and prompt decays. We find that the inclusion of the doubly tagged dataset with the prompt dataset reduces the error by 8% in R_D and 11% in y' in the mixing only fit. For the no direct CPV allowed fit, the error on R_D reduces by 18%, and $y'^{\pm}$ each decrease by 16%. For the all CPV allowed fit, the error reduces by 14% for $R_D^{\pm}$, and by 10 and 12% for y'^+ and y'^- , respectively. While in all cases, the inclusion of the DT dataset reduces the error on each fitted parameter, the impact on the underlying parameters of the neutral D system decrease by less than 10% in global fits, and in the case of the no direct CP violation allowed fit, the errors on some of the underlying parameters increase.

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Appendix A

Appendices

A.1 Statistical Tools

In this section, we describe the statistical tools to compare the multitude of correlated results. The combination of n measurements is accomplished by performing a simultaneous fit to all disjoint datasets. This fit utilizes a χ^2 minimization, with the χ^2 given by

$$\chi^2 = \sum_{i=1}^n \sum_{\alpha,\beta=1}^m (p_{\alpha}^i - \hat{p}) V_{\alpha\beta,i}^{-1} (p_{\beta}^i - \hat{p}), \quad (\text{A.1})$$

where i denotes an index running over all measurements 1 to n , p^i is the vector of parameters measured in a subset i , which has m components, and V_i is the covariance matrix corresponding to the vector of measurements p^i . The extracted parameters $\hat{p}$ are those for the combined dataset, and the χ^2 is given by the above form, with $n(m-1)$ degrees of freedom.

In the case of two disjoint measurements only, we can reduce the χ^2 calculation to the compatibility of the two measurements between one another:

$$\chi^2_{2 \text{ measurements}} = \sum_{\alpha, \beta} (p_\alpha^1 - p_\alpha^2)(V_1 + V_2)^{-1}(p_\beta^1 - p_\beta^2). \quad (\text{A.2})$$

2119 A.2 Derivation of peaking background form of $R^\pm$

In order to spare some discussion in the main body of the text, we go through the derivation of the modification of the peaking background contributions to the WS/RS ratio here. We start with the extension

$$N_{RS}^{\text{obs}} \rightarrow N_{RS}^{\text{obs}} + N_{RS}^{\text{peak}} \quad (\text{A.3})$$

$$N_{WS}^{\text{obs}} \rightarrow N_{WS}^{\text{obs}} + N_{WS}^{\text{peak}}. \quad (\text{A.4})$$

We explicitly note that each of these yields depends on the decay time bin. The ratios of WS/RS then become

$$R_{\text{measured}}(t) = \frac{N_{WS} + N_{WS, \text{peaking}}}{N_{RS} + N_{RS, \text{peaking}}} \quad (\text{A.5})$$

$$= \frac{N_{RS, \text{peaking}} \left(\frac{N_{WS}}{N_{RS, \text{peaking}}} + \frac{N_{WS, \text{peaking}}}{N_{RS, \text{peaking}}} \right)}{N_{RS} + N_{RS, \text{peaking}}} \quad (\text{A.6})$$

$$= \frac{N_{RS, \text{peaking}} \left(\frac{N_{RS} N_{WS}}{N_{RS} N_{RS, \text{peaking}}} + \frac{N_{WS, \text{peaking}}}{N_{RS, \text{peaking}}} \right)}{N_{RS} + N_{RS, \text{peaking}}} \quad (\text{A.7})$$

$$= f_{\text{peaking}} \left[R(t) \frac{N_{RS}}{N_{RS, \text{peaking}}} + R_{\text{peaking}}(t) \right] \quad (\text{A.8})$$

We have defined $f_{\text{peaking}} \equiv \frac{N_{RS,\text{peaking}}}{N_{RS} + N_{RS,\text{peaking}}}$. Moving forward, we have

$$= R(t) \left(\frac{f_{\text{peaking}}(R_{\text{peaking}}(t))}{R(t)} + \frac{N_{RS} + N_{RS,\text{peaking}} - N_{RS,\text{peaking}}}{N_{RS} + N_{RS,\text{peaking}}} \right) \quad (\text{A.9})$$

$$= R(t) \left(\frac{f_{\text{peaking}}(R_{\text{peaking}}(t))}{R(t)} - f_{\text{peaking}} + 1 \right) \quad (\text{A.10})$$

$$= R(t) \left(1 - f_{\text{peaking}} \left(1 - \frac{R_{\text{peaking}}(t)}{R(t)} \right) \right) \quad (\text{A.11})$$

$$= R(t) (1 - \Delta_{\text{peaking}}) \quad (\text{A.12})$$

Where we explicitly note that

$$\Delta_{\text{peaking}} = f_{\text{peaking}} \left(1 - \frac{R_{\text{peaking}}(t)}{R(t)} \right) \quad (\text{A.13})$$

$$= f_{\text{peaking}} \left(1 - \frac{N_{WS,\text{peaking}}(t)/N_{RS,\text{peaking}}(t)}{N_{WS}(t)/N_{RS}(t)} \right) \quad (\text{A.14})$$

2120 **A.3 Mass fits for Time Integrated Checks**

2121 Mass fits for all the checks listed in Section 9.1.

2122 **A.4 Fits for Time Dependent CPV fit validation**

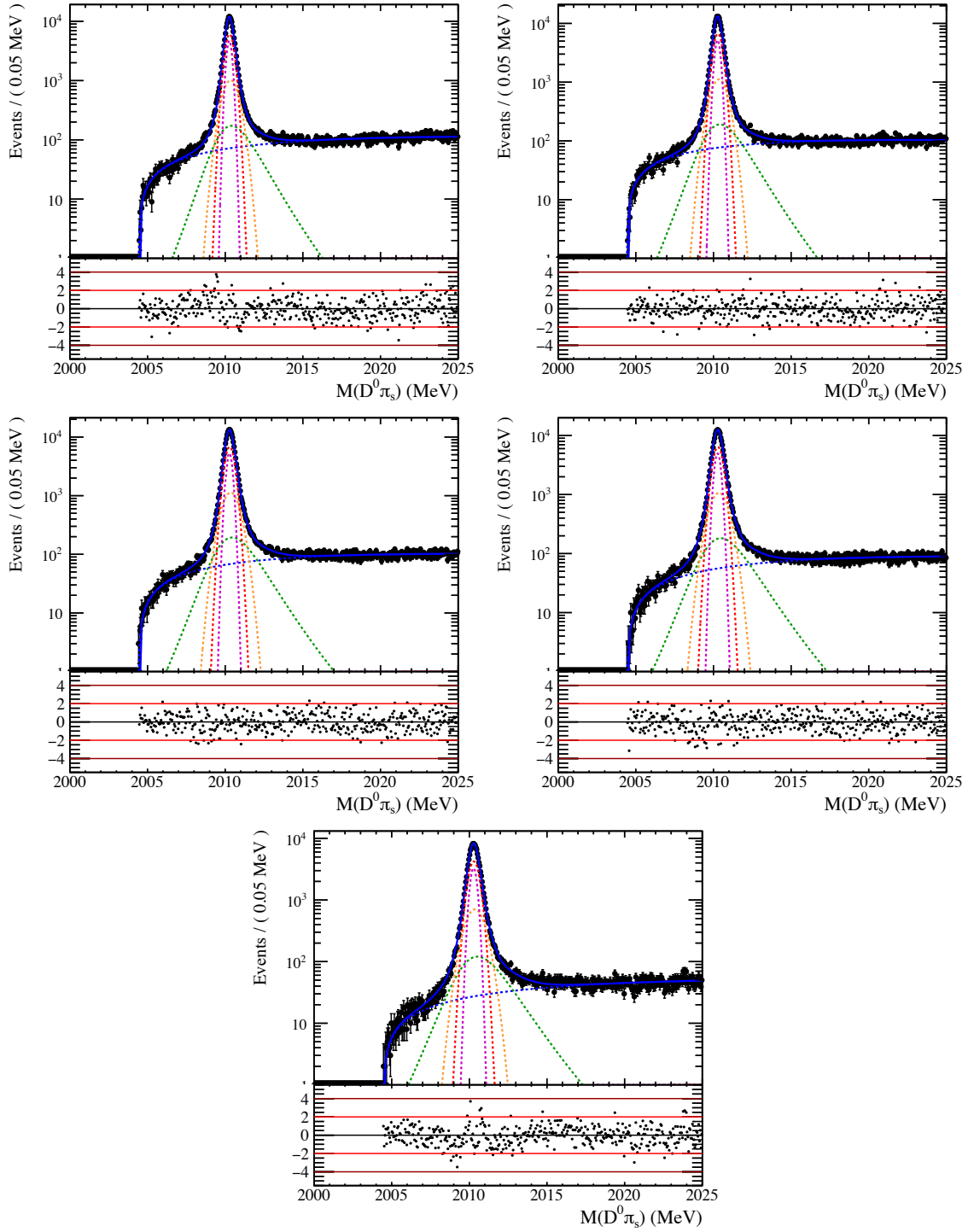


Figure A.1: Fits to the invariant mass of the D^* in bins of D^* momentum. The bins are labeled 1 on the top left, 2 on the top right, 3 in the center left, 4 on the center right, and 5 on the bottom. These bins correspond to $p < 35700.$, $35700 \leq p < 45900.$, $45900 \leq p < 58700.$, $58700. \leq p < 79900.$, and $p \geq 79900$ MeV.

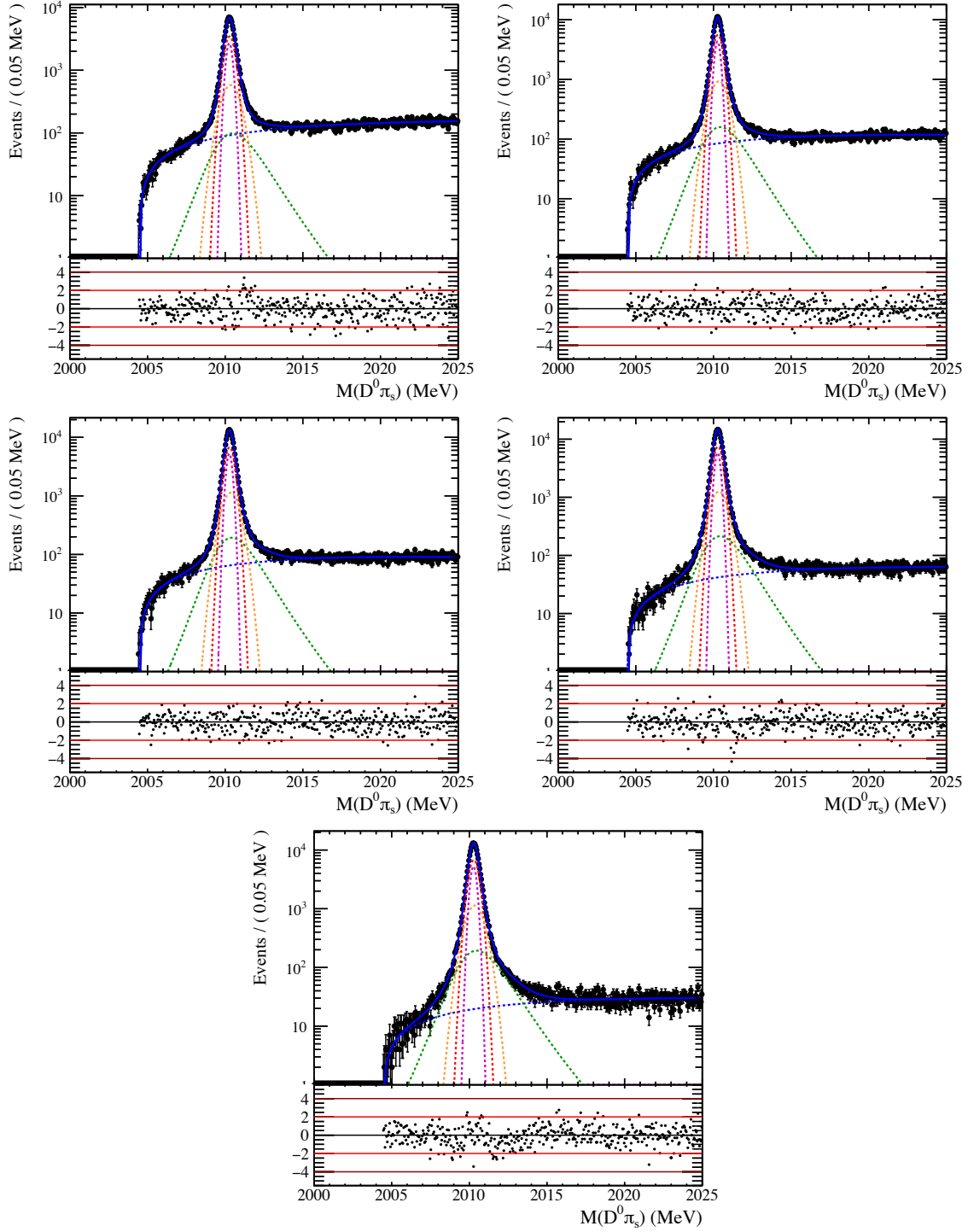


Figure A.2: Fits to the D^* invariant mass in bins of D^* transverse momentum. The bins are labeled 1 on the top left, 2 on the top right, 3 in the center left, 4 on the center right, and 5 on the bottom. These bins correspond to $p_T < 2130$, $2130 \leq p_T < 2950$, $2950 \leq p_T < 3910$, $3910 \leq p_T < 5470$, and $p_T \geq 5470$ MeV

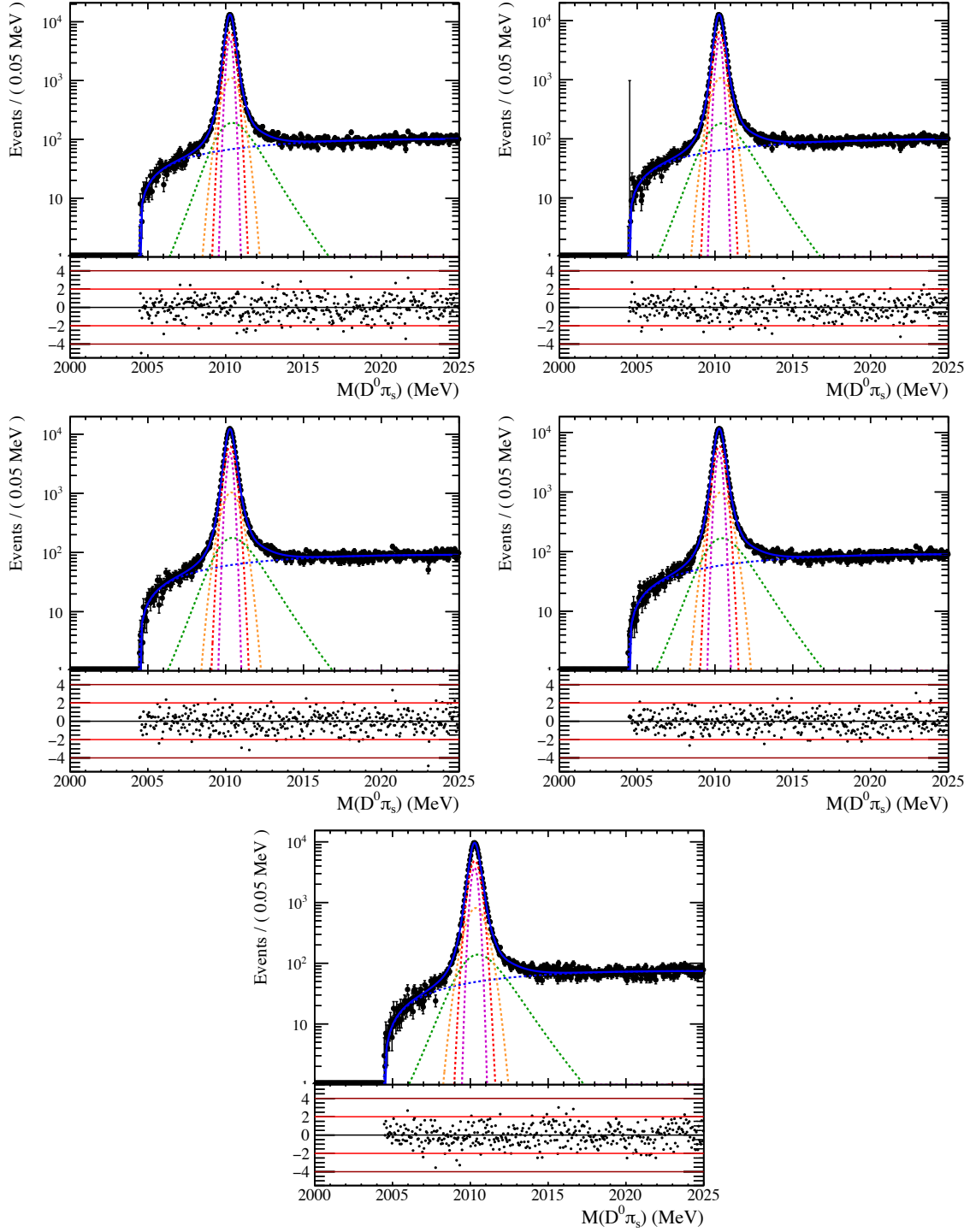


Figure A.3: Fits to the D^* invariant mass in bins of muon momentum. The bins are labeled 1 on the top left, 2 on the top right, 3 in the center left, 4 on the center right, and 5 on the bottom. These bins correspond to $p < 19700$, $19700 \leq p < 29900$, $29900 \leq p < 43100$, $43100 \leq p < 65100$, and $p \geq 65100$ MeV.

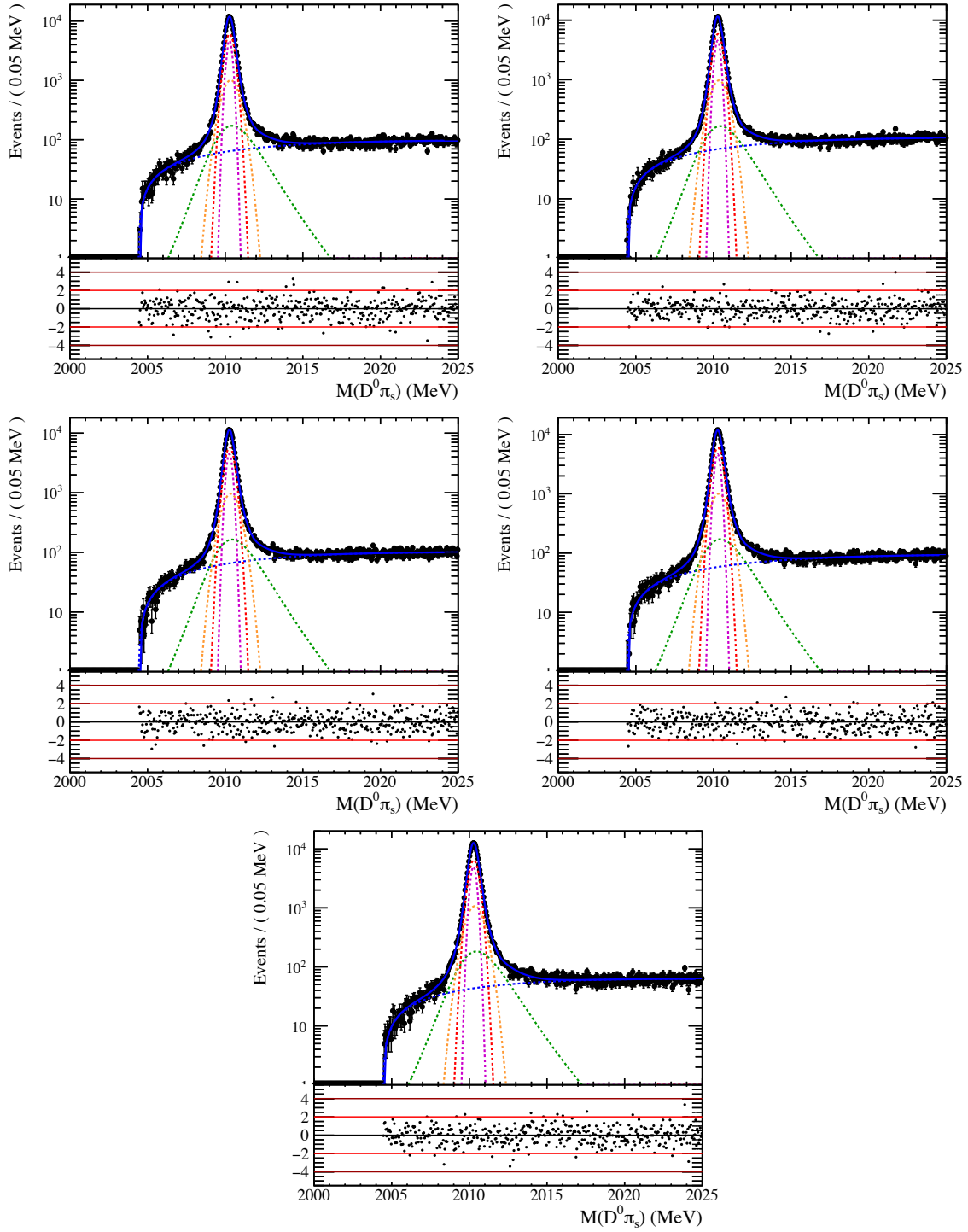


Figure A.4: Fits to the D^* invariant mass in bins of muon transverse momentum. The bins are labeled 1 on the top left, 2 on the top right, 3 in the center left, 4 on the center right, and 5 on the bottom. These bins correspond to $p_T < 2070$, $2070 \leq p_T < 2630$, $2630 \leq p_T < 3310$, $3310 \leq p_T < 4450$, and $p_T \geq 4450$ MeV.

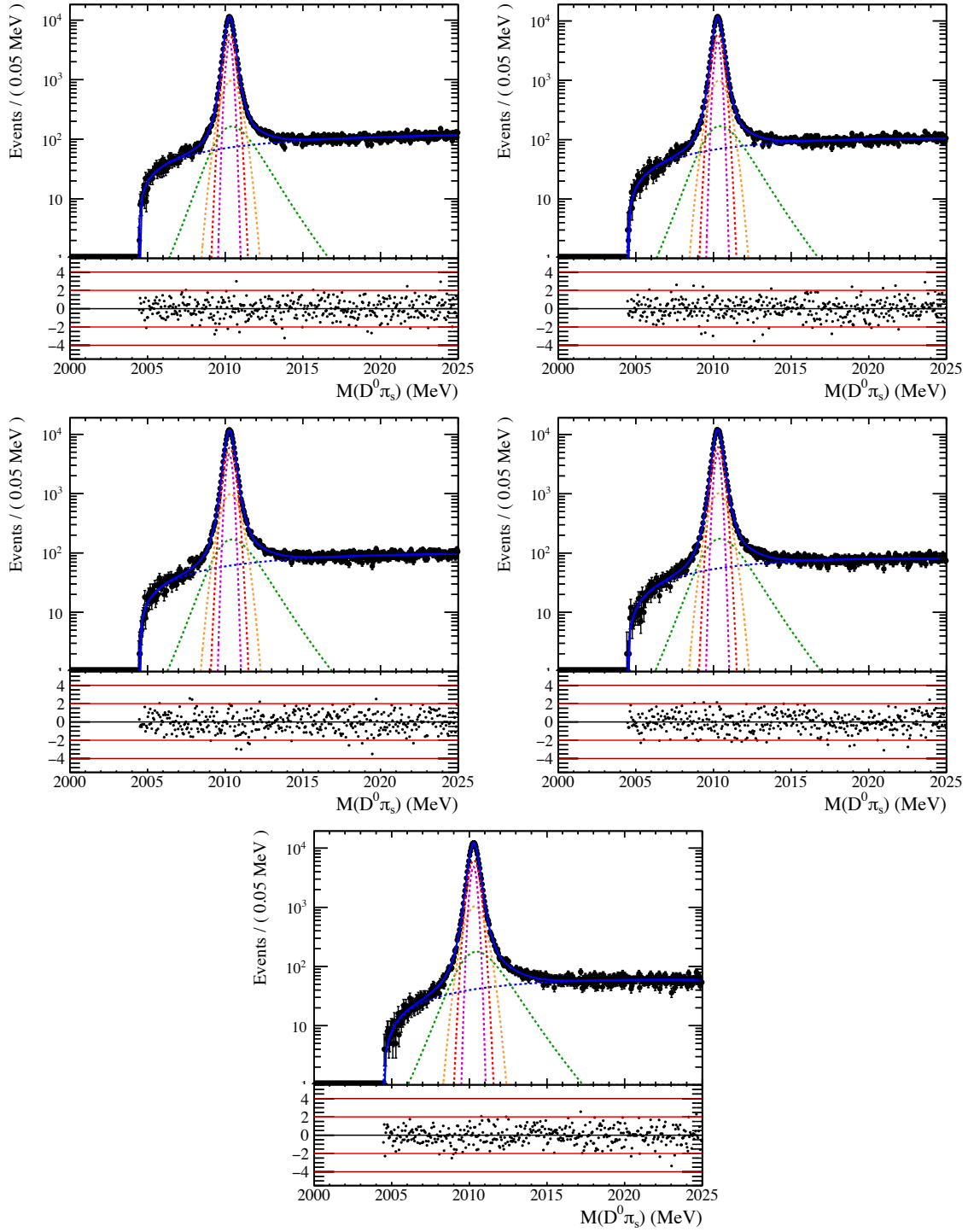


Figure A.5: Fits to the D^* invariant mass distribution in bins of the natural log of the muon IP. The bins are labeled 1 on the top left, 2 on the top right, 3 in the center left, 4 on the center right, and 5 on the bottom. These bins correspond to $\ln \text{IP}(\mu) < -1.6$, $-1.6 \leq \ln \text{IP}(\mu) < -1.1$, $-1.1 \leq \ln \text{IP}(\mu) < -0.7$, $-0.7 \leq \ln \text{IP}(\mu) < -0.2$, and $\ln \text{IP}(\mu) \geq -0.2$.

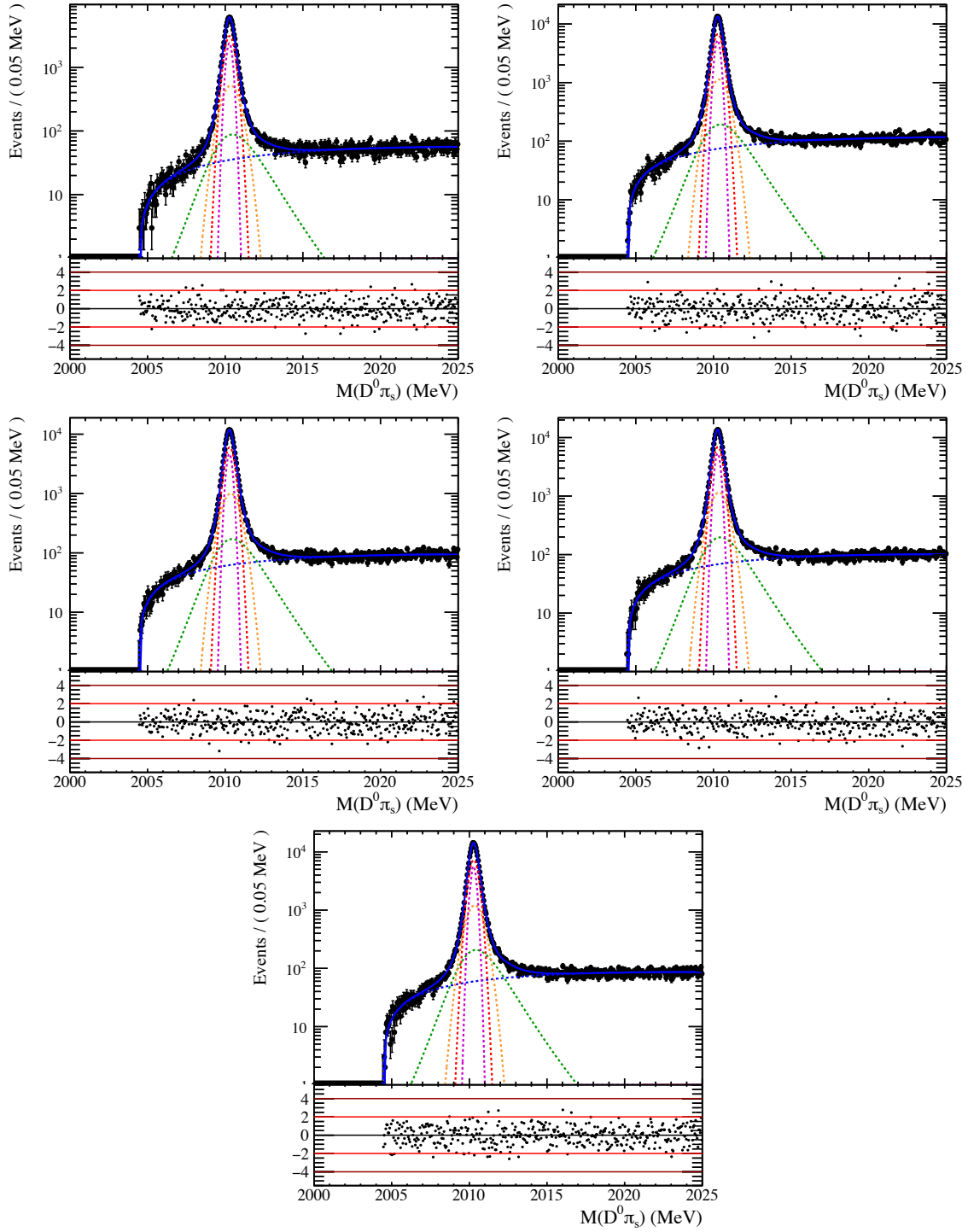


Figure A.6: Fits to the D^* invariant mass distribution in bins of $DLL(K-\pi)$ of the K from the D^0 . The bins are labeled 1 on the top left, 2 on the top right, 3 in the center left, 4 on the center right, and 5 on the bottom. These bins correspond to $KPIDK < 12.5$, $12.5 \leq KPIDK < 20.5$, $20.5 \leq KPIDK < 27.5$, $27.5 \leq KPIDK < 38.5$, and $KPIDK \geq 38.5$.

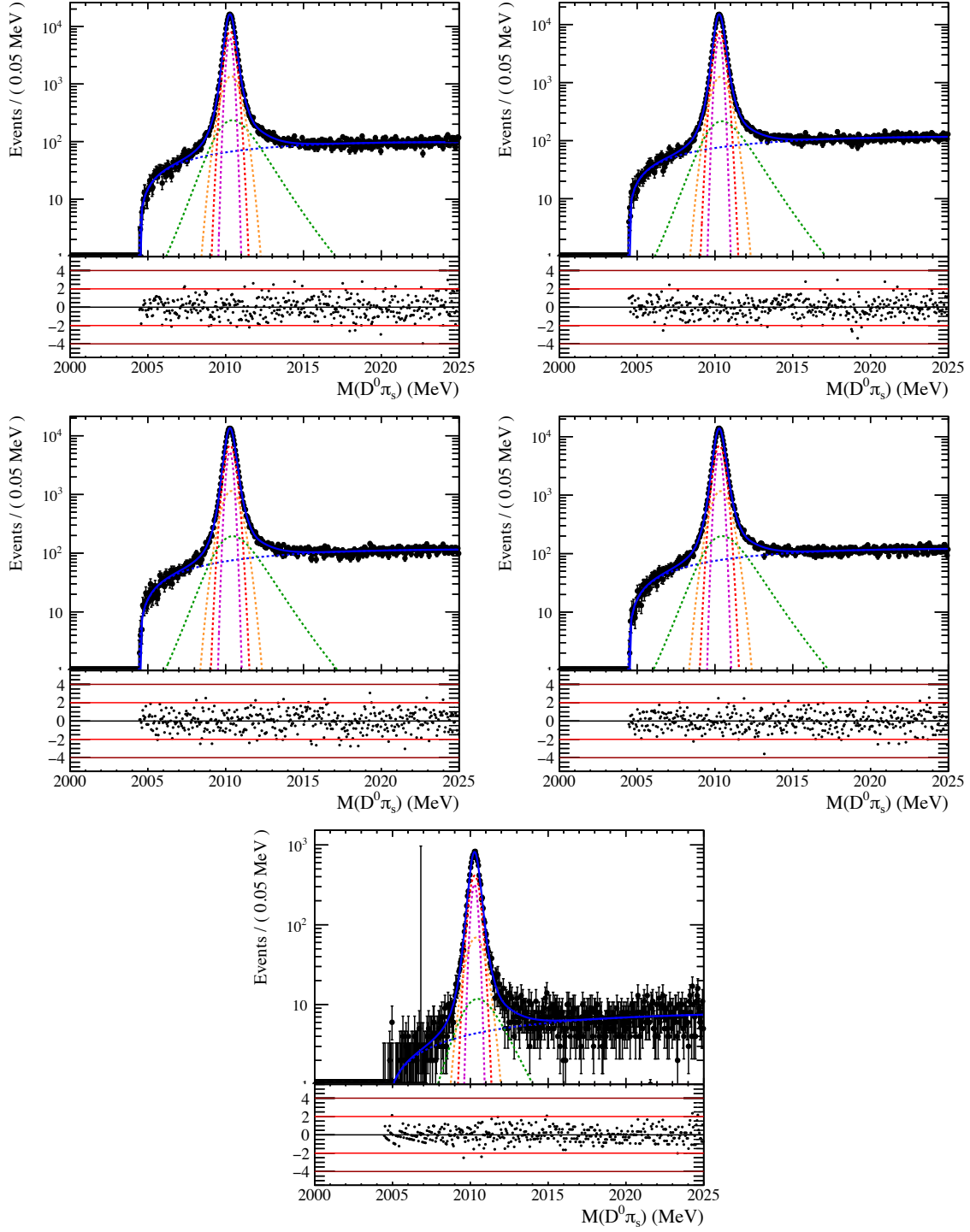


Figure A.7: Fits to the D^* invariant mass distribution in bins of $DLL(K-\pi)$ of the pion from the D^0 . The bins are labeled 1 on the top left, 2 on the top right, 3 in the center left, 4 on the center right, and 5 on the bottom. These bins correspond to $KPIDK < -40.5$, $-40.5 \leq \pi PIDK < -25.5$, $-25.5 \leq \pi PIDK < -14.5$, $-14.5 \leq \pi PIDK < -5.5$, and $KPIDK \geq -5.5$.

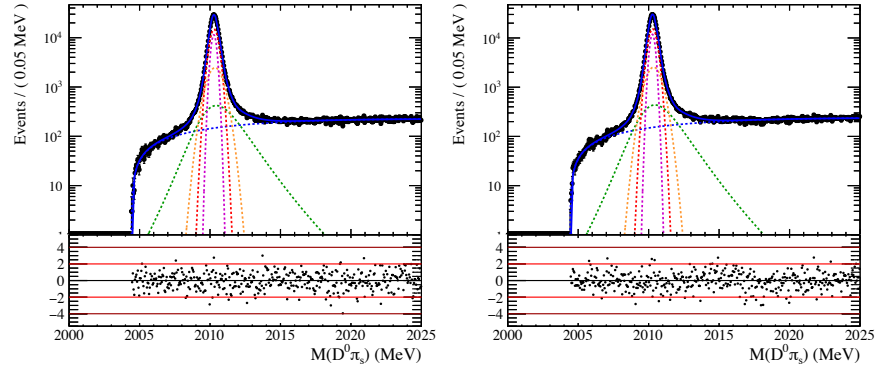


Figure A.8: Fits to the separate D^{*+} (left) and D^{*-} (right) samples, integrated over decay time.

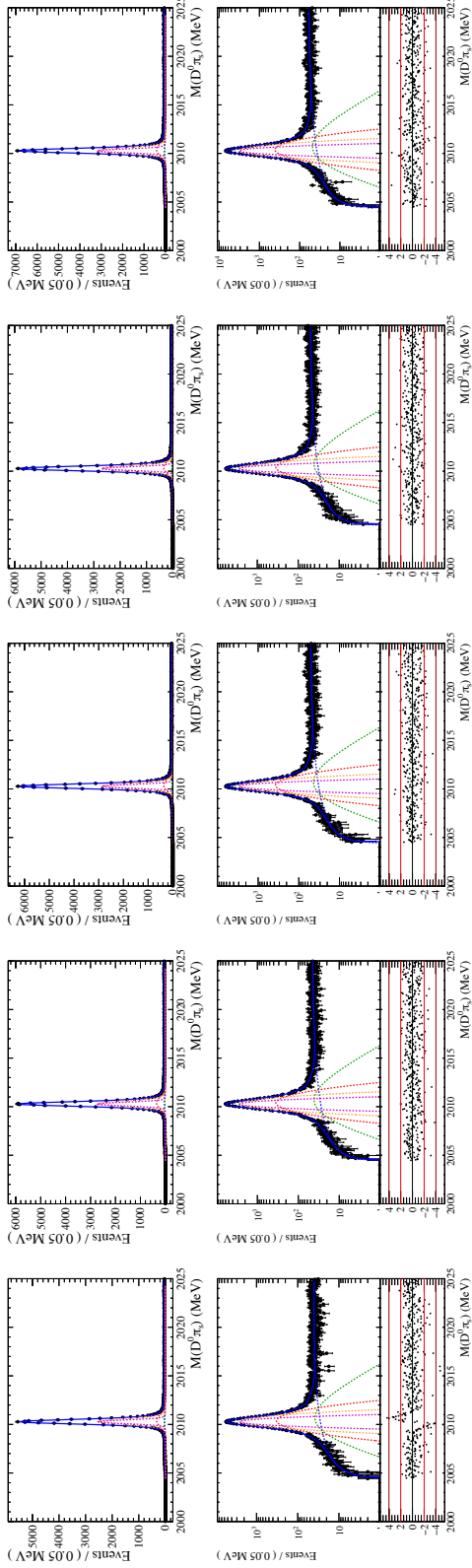


Figure A.9: Fits to the RS D^{*+} mass distribution in bins of D^0 decay time for the nominal PID sample corresponding to the selection by the Prompt Analysis. the top row is linear Y and the bottom is Semilog Y. The fits are ordered in D^0 decay time bin, from bin 1 on the left, to bin 5 on the right. The semilog plots include pull distributions below. The bin definitions for the time bins are $-0.5 \leq t/\tau < 0.2$, $0.2 \leq t/\tau < 0.5$, $0.5 \leq t/\tau < 0.9$, $0.9 \leq t/\tau < 1.5$, and $t/\tau > 1.5$.

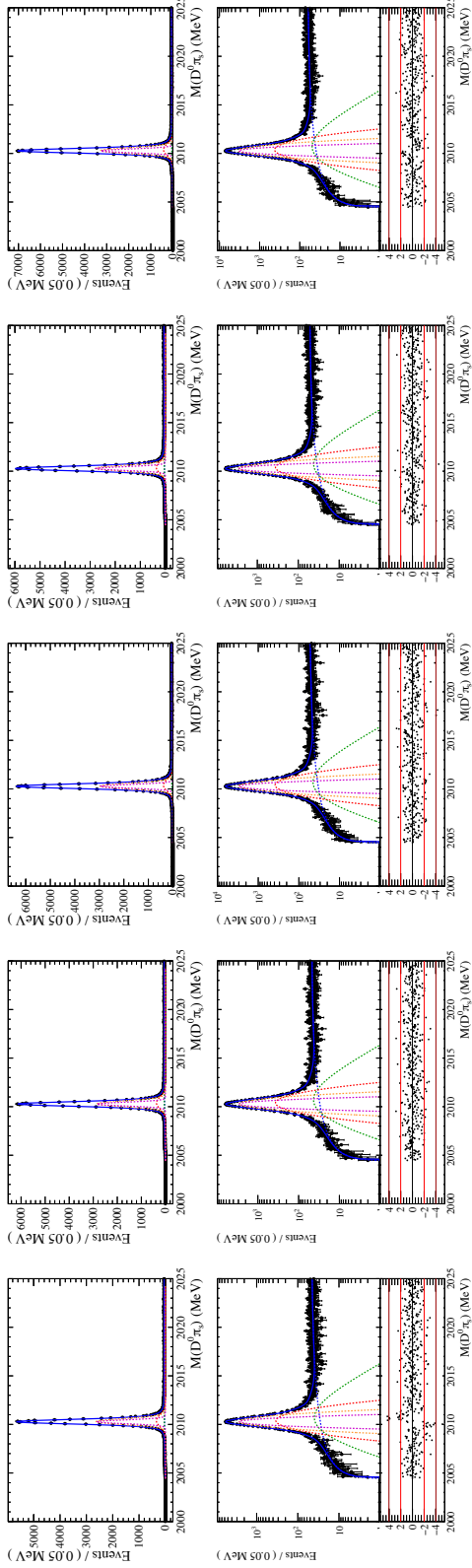


Figure A.10: Fits to the RS D^{*-} mass distribution in bins of D^0 decay time for the nominal PID sample corresponding to the selection by the Prompt Analysis. the top row is linear Y and the bottom is Semilog Y. The fits are ordered in D^0 decay time bin, from bin 1 on the left, to bin 5 on the right. The semilog plots include pull distributions below. The bin definitions for the time bins are $-0.5 \leq t/\tau < 0.2$, $0.2 \leq t/\tau < 0.5$, $0.5 \leq t/\tau < 0.9$, $0.9 \leq t/\tau < 1.5$, and $t/\tau > 1.5$.

2123 **A.5 Unblind WS fits in decay time bins**

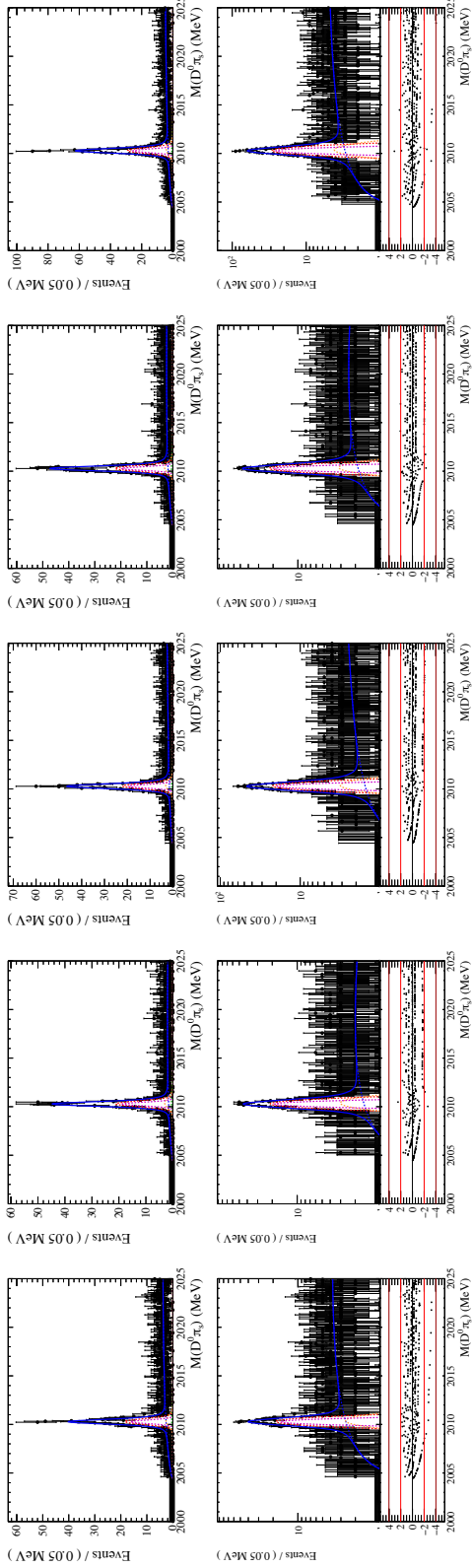


Figure A.11: Fits to the RS D^{*+} mass distribution in bins of D^0 decay time for the nominal PID sample corresponding to the selection by the Prompt Analysis. the top row is linear Y and the bottom is Semilog Y . The fits are ordered in D^0 decay time bin, from bin 1 on the left, to bin 5 on the right. The semilog plots include pull distributions below. The bin definitions for the time bins are $-0.5 \leq t/\tau < 0.2$, $0.2 \leq t/\tau < 0.5$, $0.5 \leq t/\tau < 0.9$, $0.9 \leq t/\tau < 1.5$, and $t/\tau > 1.5$.

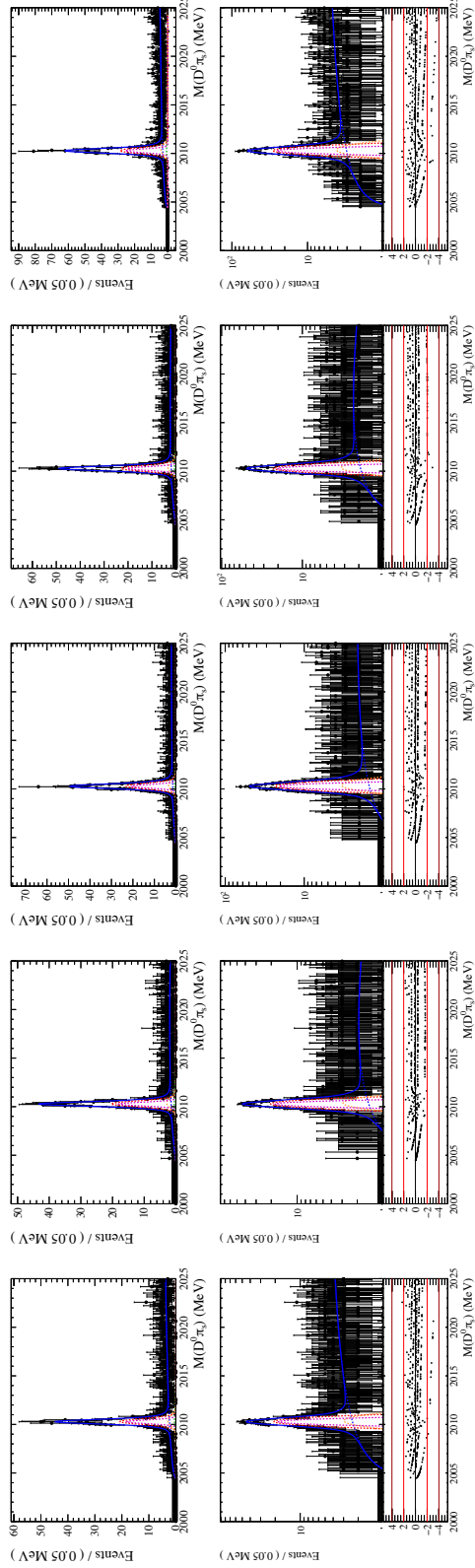


Figure A.12: Fits to the RS D^{*-} mass distribution in bins of D^0 decay time for the nominal PID sample corresponding to the selection by the Prompt Analysis. the top row is linear Y and the bottom is Semilog Y. The fits are ordered in D^0 decay time bin, from bin 1 on the left, to bin 5 on the right. The semilog plots include pull distributions below. The bin definitions for the time bins are $-0.5 \leq t/\tau < 0.2$, $0.2 \leq t/\tau < 0.5$, $0.5 \leq t/\tau < 0.9$, $0.9 \leq t/\tau < 1.5$, and $t/\tau > 1.5$.

A.6 Derivation of the $K\pi$ detection asymmetry

In this section, we derive the equation for the $K\pi$ detection asymmetry. As a start, let us define any detection asymmetry as of a charged particle p as

$$A_p = \frac{\epsilon_{p^+} - \epsilon_{p^-}}{\epsilon_{p^+} + \epsilon_{p^-}} \quad (\text{A.15})$$

Note that for the $K\pi$ asymmetry, this turns out to be -1 times the asymmetry used in the prompt analysis and in the analysis above, as we explicitly define

$$A_{K\pi} = A_D(K^-\pi^+) = \frac{\epsilon_{K^-\pi^+} - \epsilon_{K^+\pi^-}}{\epsilon_{K^-\pi^+} + \epsilon_{K^+\pi^-}}. \quad (\text{A.16})$$

For completeness, we also define

$$A_\pi = \frac{\epsilon_{\pi^+} - \epsilon_{\pi^-}}{\epsilon_{\pi^+} + \epsilon_{\pi^-}} \quad (\text{A.17})$$

To start, we assume that there is non-perfect factorization of detection efficiencies. To

this point, let us assume that

$$\epsilon(D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm) = (\epsilon_{K^\mp \pi^\pm} \epsilon_{\pi^\pm})(1 + \alpha^\pm), \quad (\text{A.18})$$

where $\alpha^\pm$ accounts for non-zero correlation between $\epsilon_{K^\mp \pi^\pm}$ and $\epsilon_{\pi^\pm}$, and can be different

for different charges.

Then, we can write the detection asymmetry for the channel $D^+ \rightarrow K^-\pi^+\pi^+$ as

$$A_{K\pi\pi} = \frac{\epsilon_{D^+ \rightarrow K^-\pi^+\pi^+} - \epsilon_{D^- \rightarrow K^+\pi^-\pi^-}}{\epsilon_{D^+ \rightarrow K^-\pi^+\pi^+} + \epsilon_{D^- \rightarrow K^+\pi^-\pi^-}} \quad (\text{A.19})$$

$$= \frac{\epsilon_{K^-\pi^+\pi^+} - \epsilon_{K^+\pi^-\pi^-}}{\epsilon_{K^-\pi^+\pi^+} + \epsilon_{K^+\pi^-\pi^-}} \quad (\text{A.20})$$

$$= \frac{\epsilon_{K^-\pi^+} \epsilon_{\pi^+} (1 + \alpha^+) - \epsilon_{K^+\pi^-} \epsilon_{\pi^-} (1 + \alpha^-)}{\epsilon_{K^-\pi^+} \epsilon_{\pi^+} (1 + \alpha^+) + \epsilon_{K^+\pi^-} \epsilon_{\pi^-} (1 + \alpha^-)}. \quad (\text{A.21})$$

Now, we employ the trick that any one detection efficiency can be written as

$$\epsilon^\pm = \frac{1}{2}(\epsilon^+ + \epsilon^-)(1 \pm A) \quad (\text{A.22})$$

2130 Where A is the detection asymmetry. Substituting Equation A.22 into Equation A.21,
2131 we have

$$A_{K\pi\pi} = \frac{(1 + A_{K\pi})(1 + A_\pi)(1 + \alpha^+) - (1 - A_{K\pi})(1 - A_\pi)(1 + \alpha^-)}{(1 + A_{K\pi})(1 + A_\pi)(1 + \alpha^+) + (1 - A_{K\pi})(1 - A_\pi)(1 + \alpha^-)}. \quad (\text{A.23})$$

2132 Expanding everything and factoring, we are left with

$$= \frac{(A_{K\pi} + A_\pi)(2 + \alpha^+ + \alpha^-) + (\alpha^+ - \alpha^-)(1 + A_{K\pi}A_\pi)}{(1 + A_{K\pi}A_\pi)(2 + \alpha^+ + \alpha^-) + (\alpha^+ - \alpha^-)(A_{K\pi} + A_\pi)}. \quad (\text{A.24})$$

2133 Changing variables from $\alpha^\pm$, we can define

$$\bar{\alpha} = \frac{1}{2}(\alpha^+ + \alpha^-), \quad (\text{A.25})$$

$$\delta\alpha = \frac{1}{2}(\alpha^+ - \alpha^-). \quad (\text{A.26})$$

2134 Substituting these definitions yields

$$A_{K\pi\pi} = \frac{(A_{K\pi} + A_\pi)(1 + \bar{\alpha}) + \delta\alpha(1 + A_{K\pi}A_\pi)}{(1 + A_{K\pi}A_\pi)(1 + \bar{\alpha}) + \delta\alpha(A_{K\pi} + A_\pi)} \quad (\text{A.27})$$

2135 For $\delta\alpha = 0$, we are left with

$$A_{K\pi\pi} = \frac{(A_{K\pi} + A_\pi)}{(1 + A_{K\pi}A_\pi)} \quad (\text{A.28})$$

For uncertainties of order 1%, the term in the denominator will be small. Expanding

$$\frac{1}{1+\epsilon} \approx 1 - \epsilon \text{ leaves}$$

$$A_{K\pi\pi} \approx (A_{K\pi} + A_{\pi})(1 - A_{K\pi}A_{\pi}) \quad (\text{A.29})$$

Thus, with the same argument, the second order terms contributing to the asymmetry can only enter at $(\mathcal{O}(1\%))^3 = 10^{-6}$, which is well below the statistical precision of the measurement.

A.7 Reweighting plots for $A_{K\pi}$

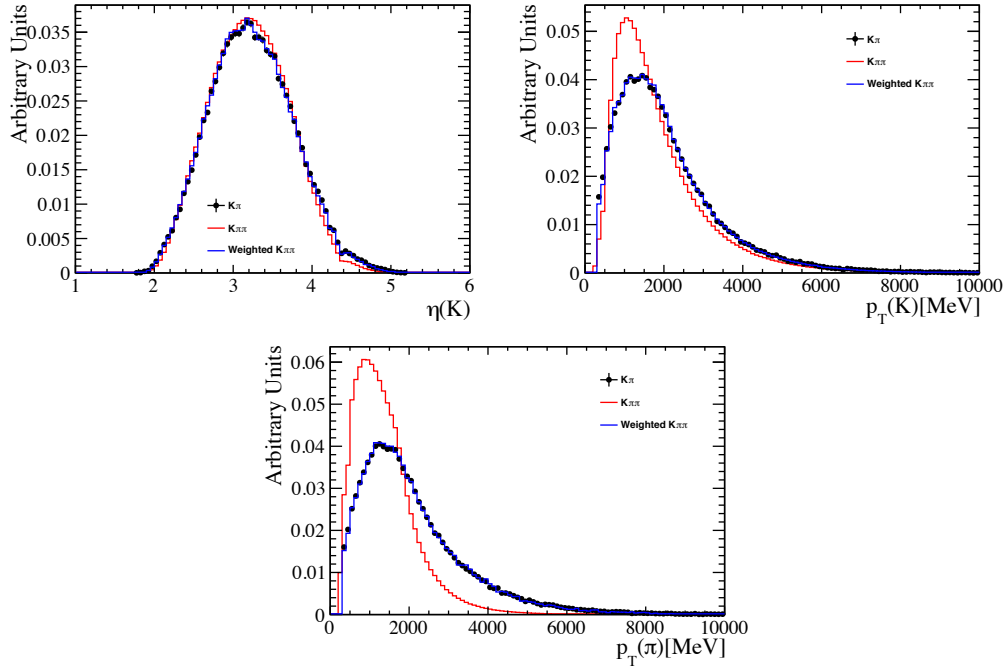


Figure A.13: Reweighting plots for the first reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2011. The top left is the distribution for the pseudorapidity η of the kaon, the top right is that for the transverse momentum of the Kaon, and the bottom plot is the distribution for the transverse momentum of the pion. In each plot, the red line represents the original $D^+ \rightarrow K^-\pi^+\pi^+$ sample, the blue the reweighted $D^+ \rightarrow K^-\pi^+\pi^+$ sample, and the points are the $D^0 \rightarrow K^-\pi^+$ sample.

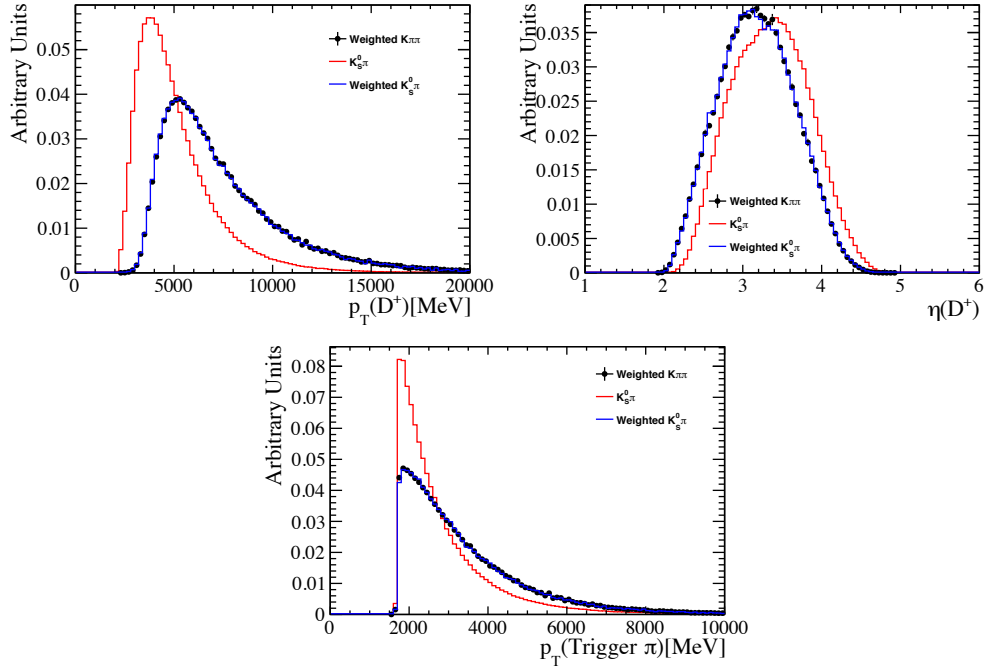


Figure A.14: Reweighting plots for the second reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2011. The top left plot shows the D^+ transverse momentum distribution, the top right the D^+ pseudorapidity, and the bottom plot shows the trigger pion transverse momentum. In all plots, the red line represents the original $D^+ \rightarrow K_S^0 \pi^+$ sample, the blue line represents the reweighted $D^+ \rightarrow K_S^0 \pi^+$ sample, and the points are the previously weighted $D^+ \rightarrow K^- \pi^+ \pi^+$ sample.

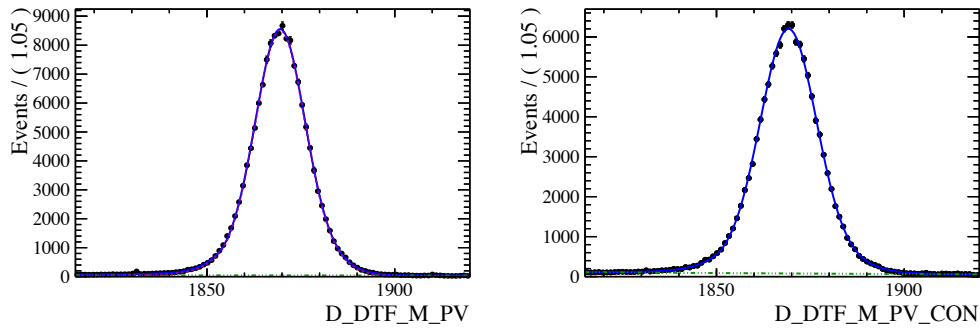


Figure A.15: Fits to the D^+ mass distribution for the $D^+ \rightarrow K^- \pi^+ \pi^+$ on the left and $D^+ \rightarrow K_S^0 \pi^+$ on the right. Sample is 2011 MD

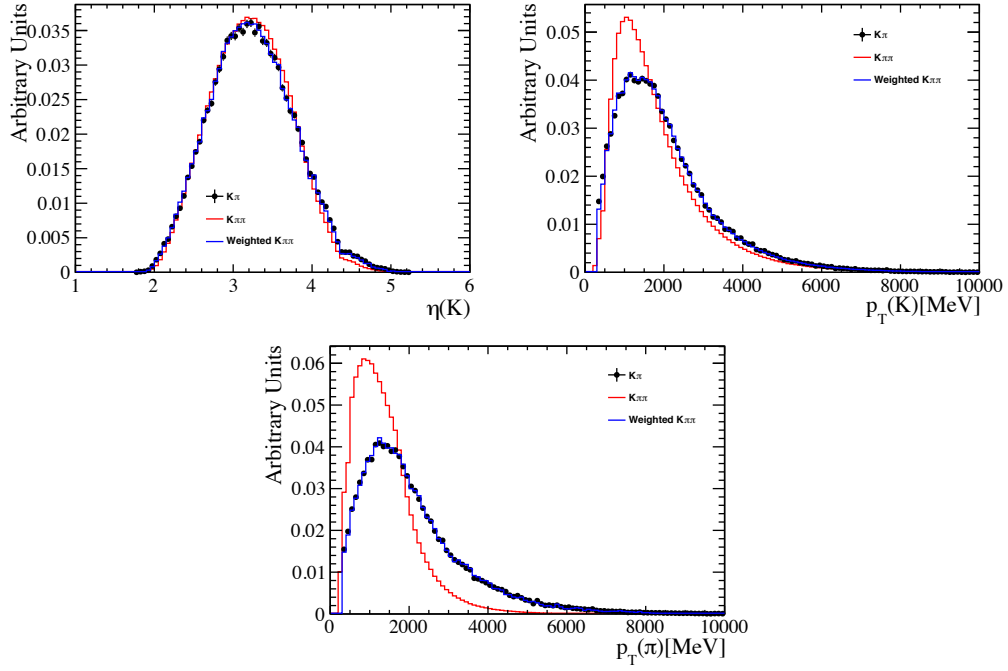


Figure A.16: Reweighting plots for the first reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2011. The top left is the distribution for the pseudorapidity η of the kaon, the top right is that for the transverse momentum of the Kaon, and the bottom plot is the distribution for the transverse momentum of the pion. In each plot, the red line represents the original $D^+ \rightarrow K^- \pi^+ \pi^+$ sample, the blue the reweighted $D^+ \rightarrow K^- \pi^+ \pi^+$ sample, and the points are the $D^0 \rightarrow K^- \pi^+$ sample.

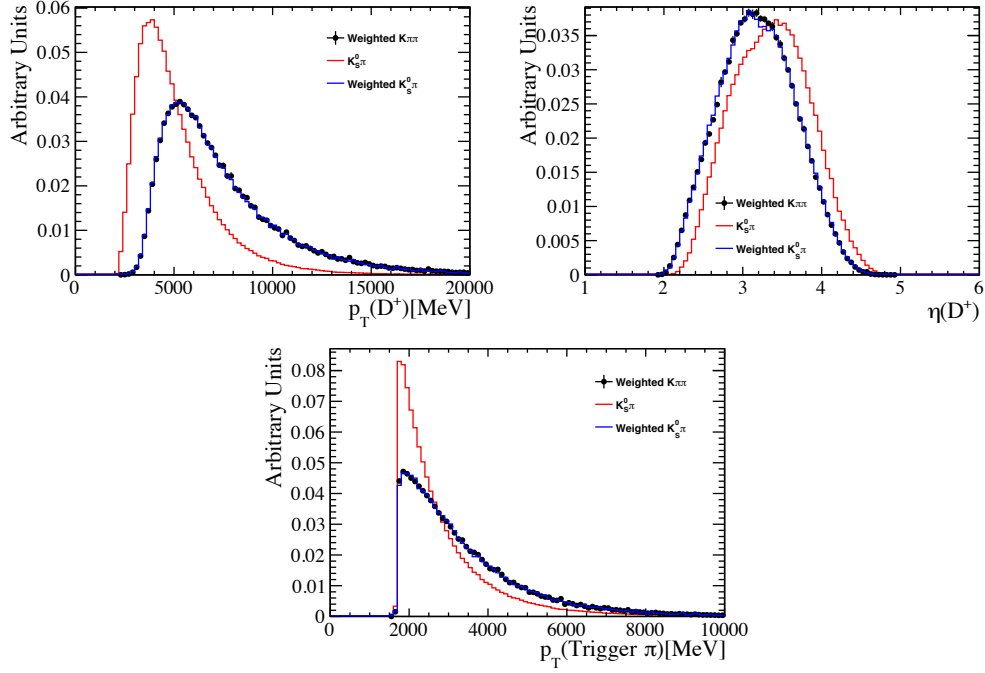


Figure A.17: Reweighting plots for the second reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2011. The top left plot shows the D^+ transverse momentum distribution, the top right the D^+ pseudorapidity, and the bottom plot shows the trigger pion transverse momentum. In all plots, the red line represents the original $D^+ \rightarrow K_S^0 \pi^+$ sample, the blue line represents the reweighted $D^+ \rightarrow K_S^0 \pi^+$ sample, and the points are the previously weighted $D^+ \rightarrow K^- \pi^+ \pi^+$ sample.

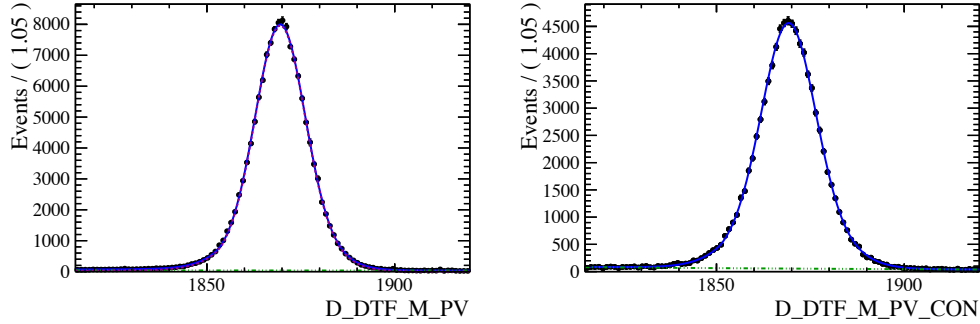


Figure A.18: Fits to the D^+ mass distribution for the $D^+ \rightarrow K^- \pi^+ \pi^+$ on the left and $D^+ \rightarrow K_S^0 \pi^+$ on the right. Sample is 2011 MU

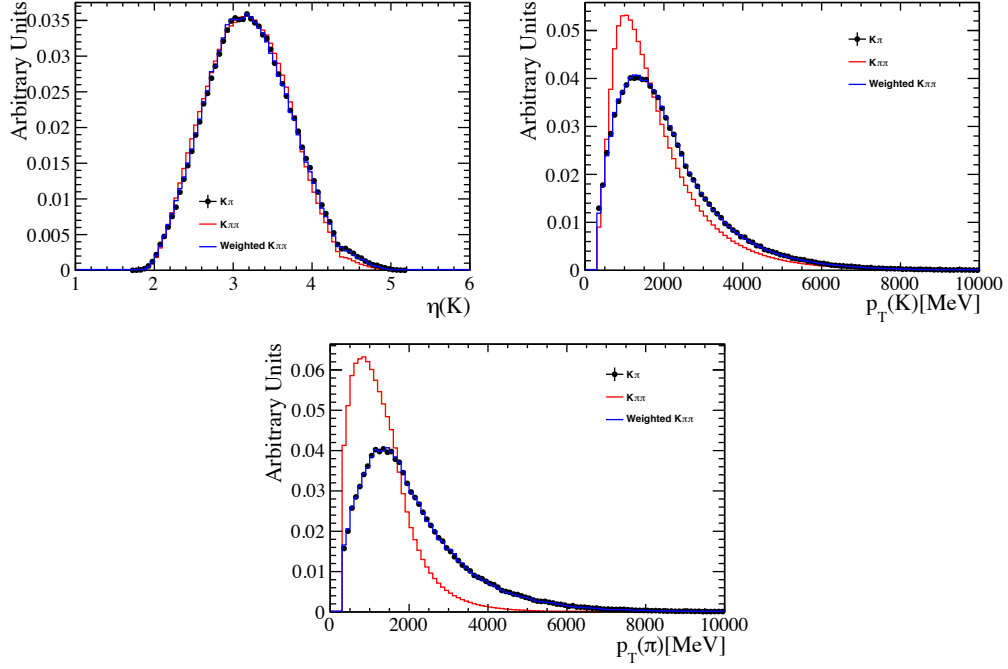


Figure A.19: Reweighting plots for the first reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2012. The top left is the distribution for the pseudorapidity η of the kaon, the top right is that for the transverse momentum of the Kaon, and the bottom plot is the distribution for the transverse momentum of the pion. In each plot, the red line represents the original $D^+ \rightarrow K^- \pi^+ \pi^+$ sample, the blue the reweighted $D^+ \rightarrow K^- \pi^+ \pi^+$ sample, and the points are the $D^0 \rightarrow K^- \pi^+$ sample.

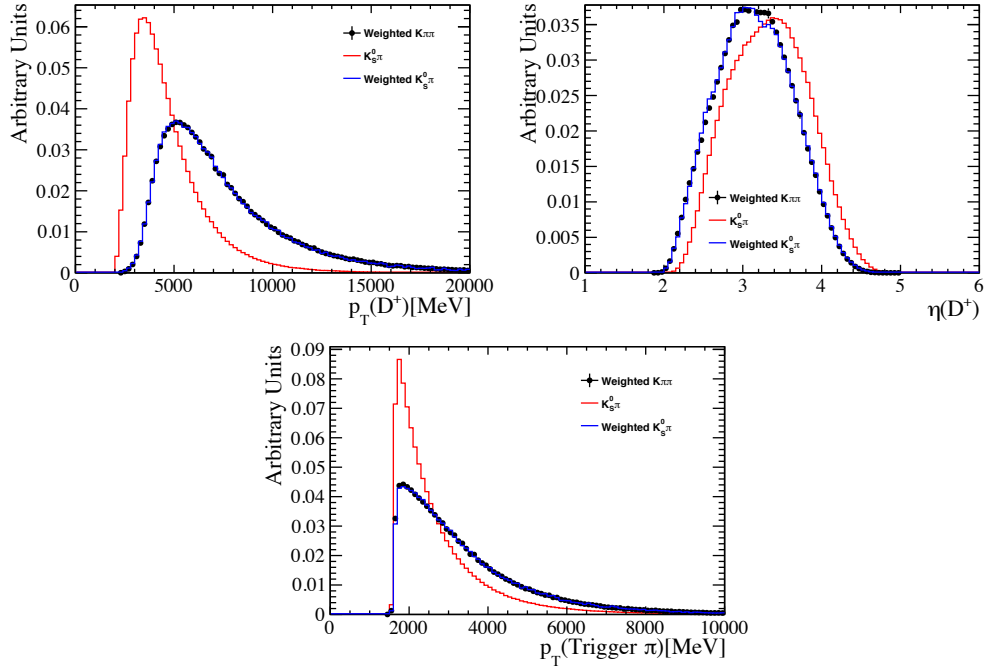


Figure A.20: Reweighting plots for the second reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2012. The top left plot shows the D^+ transverse momentum distribution, the top right the D^+ pseudorapidity, and the bottom plot shows the trigger pion transverse momentum. In all plots, the red line represents the original $D^+ \rightarrow K_S^0 \pi^+$ sample, the blue line represents the reweighted $D^+ \rightarrow K_S^0 \pi^+$ sample, and the points are the previously weighted $D^+ \rightarrow K^- \pi^+ \pi^+$ sample.

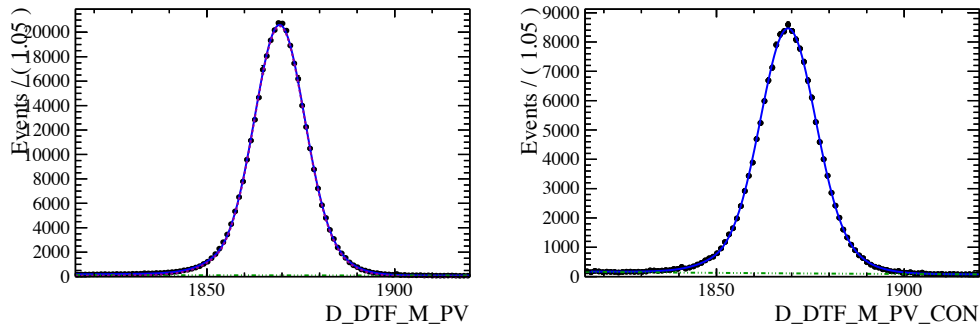


Figure A.21: Fits to the D^+ mass distribution for the $D^+ \rightarrow K^- \pi^+ \pi^+$ on the left and $D^+ \rightarrow K_S^0 \pi^+$ on the right. Sample is 2012 MD

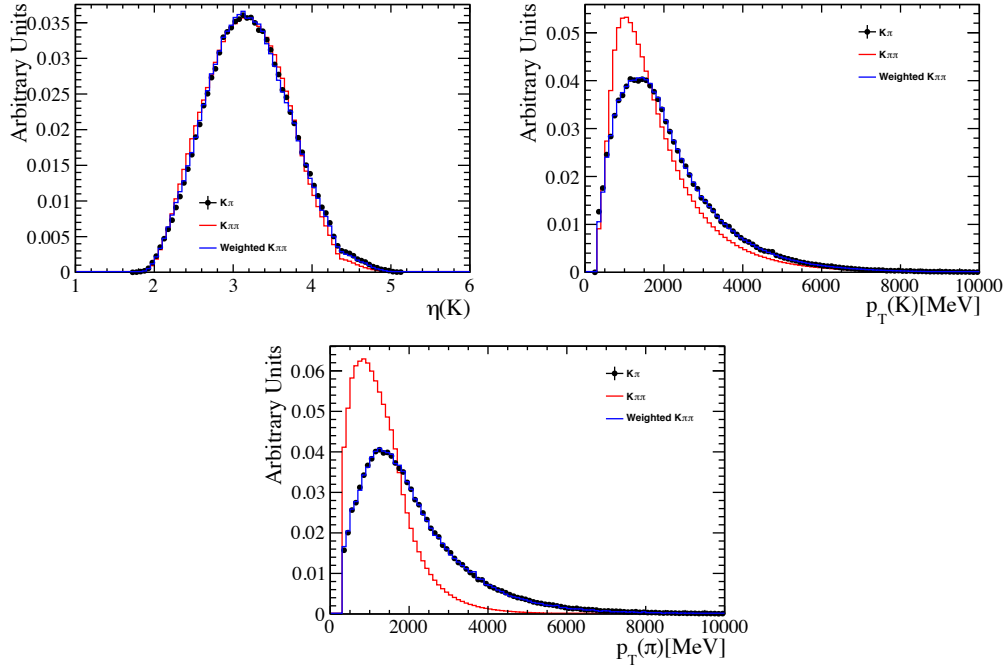


Figure A.22: Reweighting plots for the first reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2012. The top left is the distribution for the pseudorapidity η of the kaon, the top right is that for the transverse momentum of the Kaon, and the bottom plot is the distribution for the transverse momentum of the pion. In each plot, the red line represents the original $D^+ \rightarrow K^- \pi^+ \pi^+$ sample, the blue the reweighted $D^+ \rightarrow K^- \pi^+ \pi^+$ sample, and the points are the $D^0 \rightarrow K^- \pi^+$ sample.

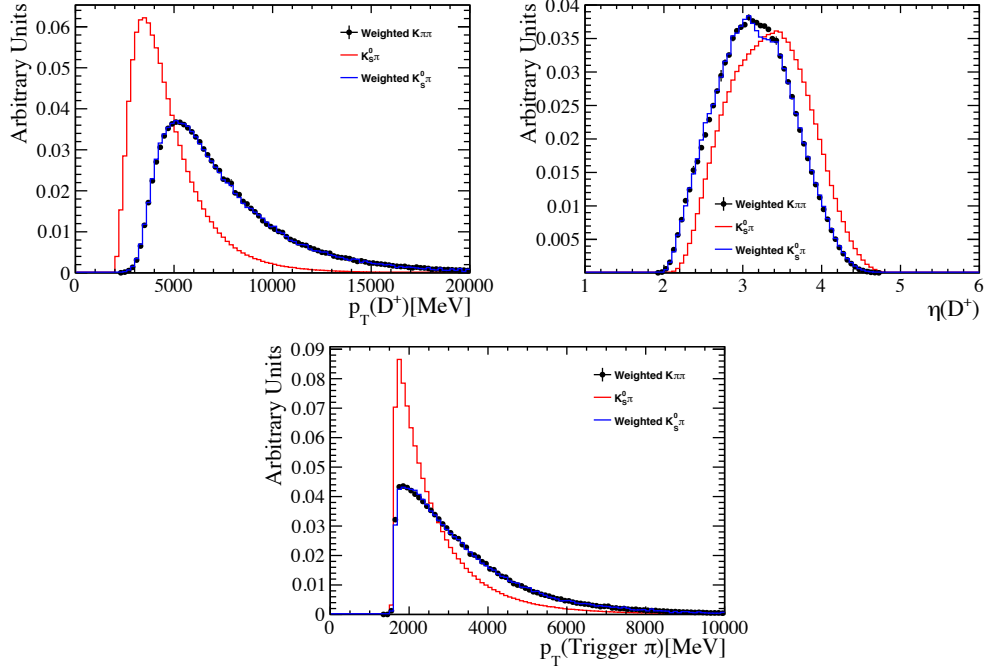


Figure A.23: Reweighting plots for the second reweighting step in the $A_{K\pi}$ calculation. The samples shown are for MD 2012. The top left plot shows the D^+ transverse momentum distribution, the top right the D^+ pseudorapidity, and the bottom plot shows the trigger pion transverse momentum. In all plots, the red line represents the original $D^+ \rightarrow K_S^0 \pi^+$ sample, the blue line represents the reweighted $D^+ \rightarrow K_S^0 \pi^+$ sample, and the points are the previously weighted $D^+ \rightarrow K^- \pi^+ \pi^+$ sample.

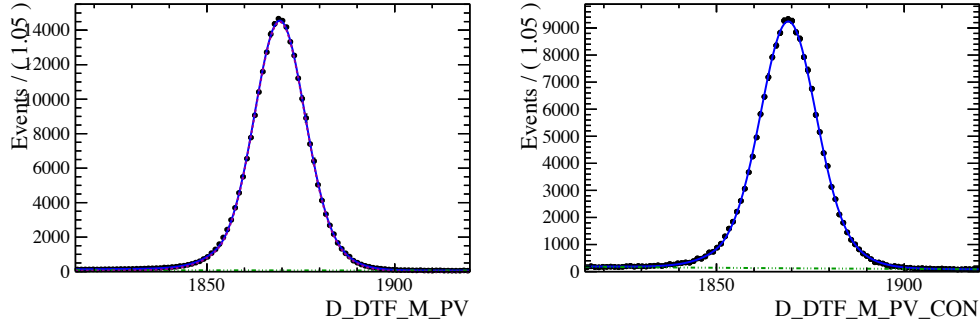


Figure A.24: Fits to the D^+ mass distribution for the $D^+ \rightarrow K^- \pi^+ \pi^+$ on the left and $D^+ \rightarrow K_S^0 \pi^+$ on the right. Sample is 2012 MU

A.8 Statistical Tools

In this appendix, we describe the statistical tools to compare the multitude of correlated results. The combination of n measurements is obtained by performing a simultaneous fit to all disjoint datasets. This fit utilizes a χ^2 minimization of the form

$$\chi^2 = \sum_{i=1}^n \sum_{\alpha,\beta=1}^m (p_\alpha^i - \hat{p}) V_{\alpha\beta,i}^{-1} (p_\beta^i - \hat{p}), \quad (\text{A.30})$$

where i denotes an index running over all measurements 1 to n , p^i is the vector of parameters measured in a subset i , which has m components, and V_i is the covariance matrix corresponding to the vector of measurements p^i . The extracted parameters $\hat{p}$ are those for the combined dataset, and the χ^2 is given by the above form, with $n(m-1)$ degrees of freedom. In the case of two disjoint measurements only, we can reduce the χ^2 calculation to the compatibility of the two measurements:

$$\chi_{2 \text{ measurements}}^2 = \sum_{\alpha,\beta} (p_\alpha^1 - p_\alpha^2) (V_1 + V_2)^{-1} (p_\beta^1 - p_\beta^2). \quad (\text{A.31})$$

A.9 Correlation matrices of final fit

We report the final correlation matrices, including all systematic uncertainties, here.

Table A.1: Final Correlation Matrix for Mixing only fit

	R_D	y'	x'^2
R_D	1.000000	-0.678408	0.607000
y'		1.000000	-0.940966
x'^2			1.000000

Table A.2: Final correlation matrix for no DCPV allowed fit

	R_D	y'^{+}	x'^{2+}	y'^{-}	x'^{2-}
R_D	1.000000	-0.368514	0.261308	-0.374346	0.309218
y'^{+}		1.000000	-0.943765	0.447934	-0.370002
x'^{2+}			1.000000	-0.351505	0.290119
y'^{-}				1.000000	-0.966900
x'^{2-}					1.000000

Table A.3: Final correlation matrix for All CPV allowed fit.

	R_D^{+}	y'^{+}	x'^{2+}	R_D^{-}	y'^{-}	x'^{2-}
R_D^{+}	1.000000	-0.658408	0.042787	-0.004753	0.000006	0.000148
y'^{+}		1.000000	0.437984	-0.000871	-0.000167	-0.000914
x'^{2+}			1.000000	-0.000036	-0.000053	-0.001802
R_D^{-}				1.000000	-0.621349	0.073845
y'^{-}					1.000000	0.050070
x'^{2-}						1.000000

A.10 Correlation matrices for the Prompt + DT combination

Table A.4: Correlation matrix for the Mixing Only fit of the Prompt + DT combination

	R_D	y'	x'^2
R_D	1.000000	-0.931827	0.825991
y'		1.000000	-0.958912
x'^2			1.000000

A.11 Mass fits for all cross checks

A.11.1 Magnet Up Vs Magnet Down

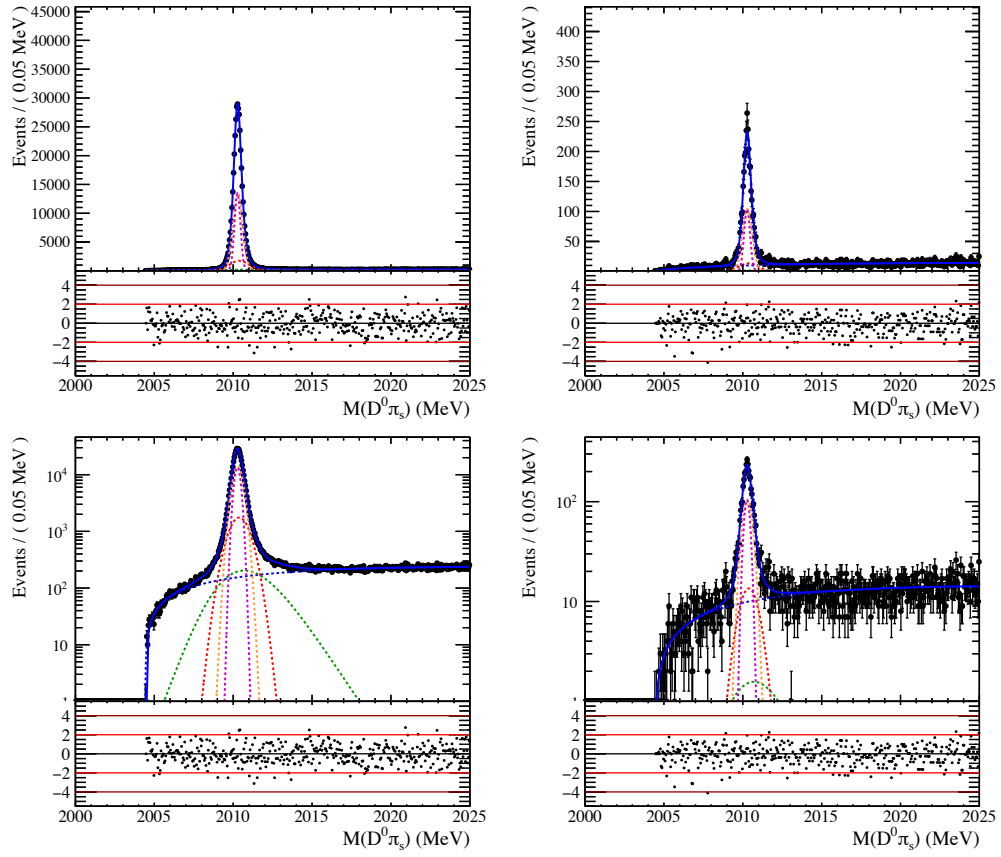


Figure A.25: Fits to the time integrated MU sample. Left: RS, Right: WS, Top: Linear, Bottom: Semilog

Table A.5: Correlation matrix for the no Direct CPV allowed fit of the Prompt + DT combination

	R_D	y'^{+}	x'^{2+}	y'^{-}	x'^{2-}
R_D	1.000000	-0.853676	0.685938	-0.751211	0.586106
y'^{+}		1.000000	-0.924859	0.631140	-0.501181
x'^{2+}			1.000000	-0.562726	0.458219
y'^{-}				1.000000	-0.937001
x'^{2-}					1.000000

Table A.6: Correlation matrix for the all CPV allowed fit of the Prompt + DT combination

	R_D^{+}	y'^{+}	x'^{2+}	R_D^{-}	y'^{-}	x'^{2-}
R_D^{+}	1.000000	-0.919736	0.822734	-0.006815	-0.010145	0.008110
y'^{+}		1.000000	-0.961948	-0.011139	0.000120	-0.002079
x'^{2+}			1.000000	0.009102	-0.002076	0.004076
R_D^{-}				1.000000	-0.917987	0.812006
y'^{-}					1.000000	-0.956019
x'^{2-}						1.000000

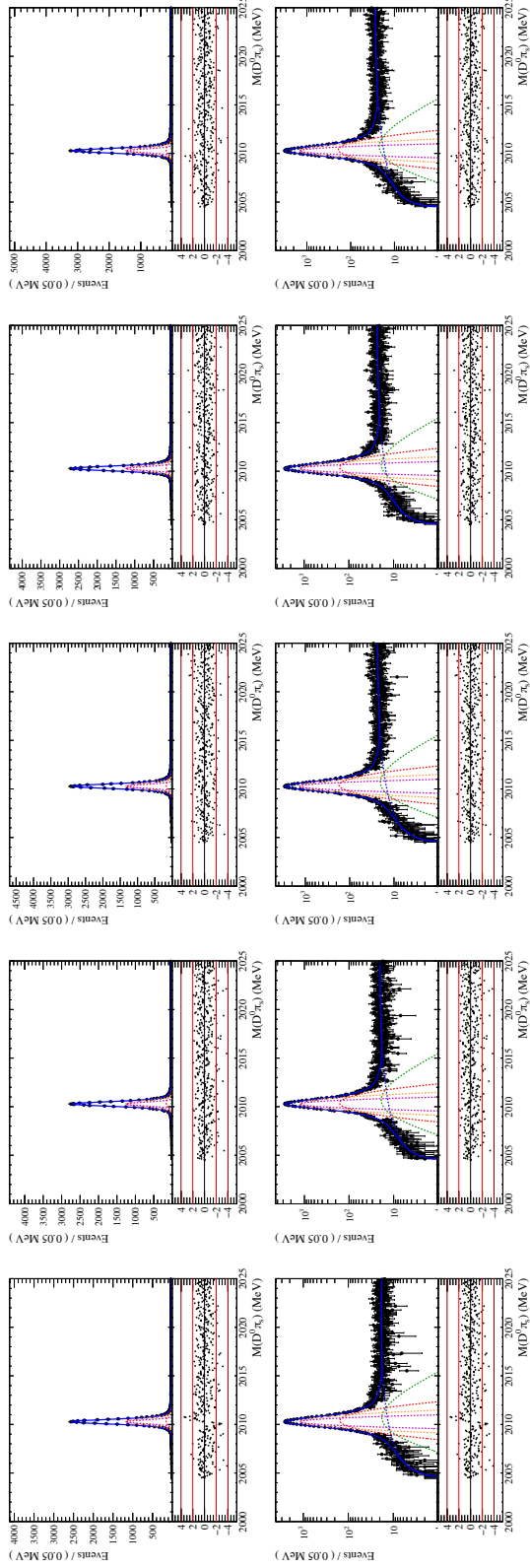


Figure A.26: MU RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

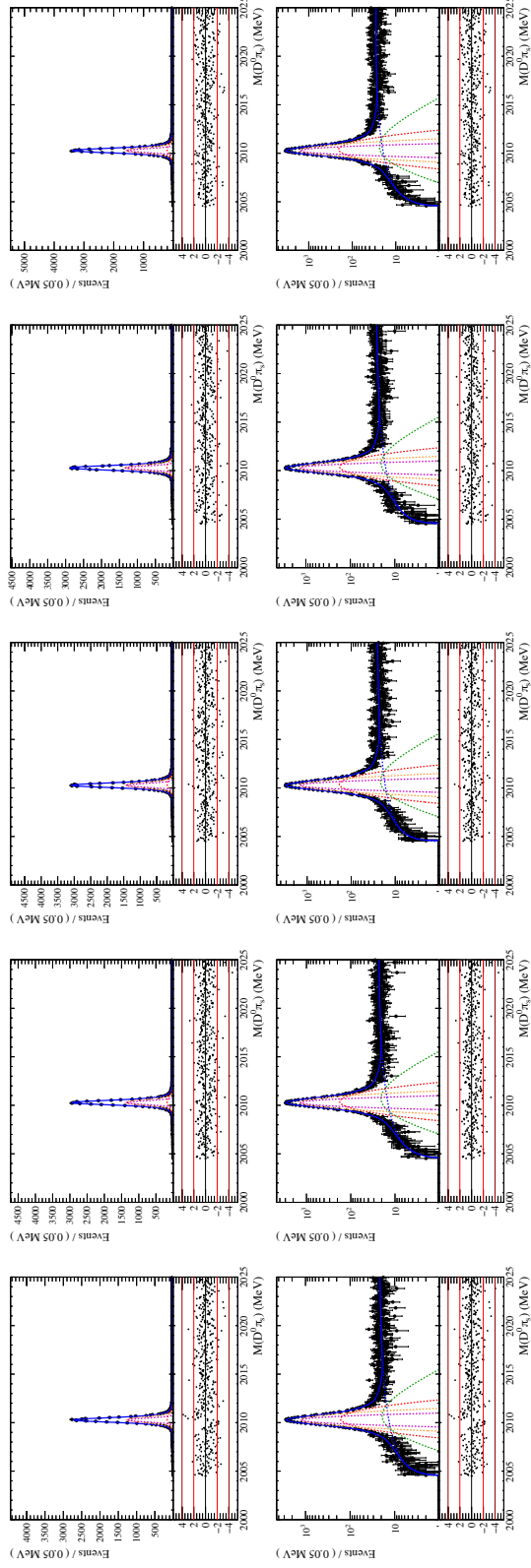


Figure A.27: MU RS- fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

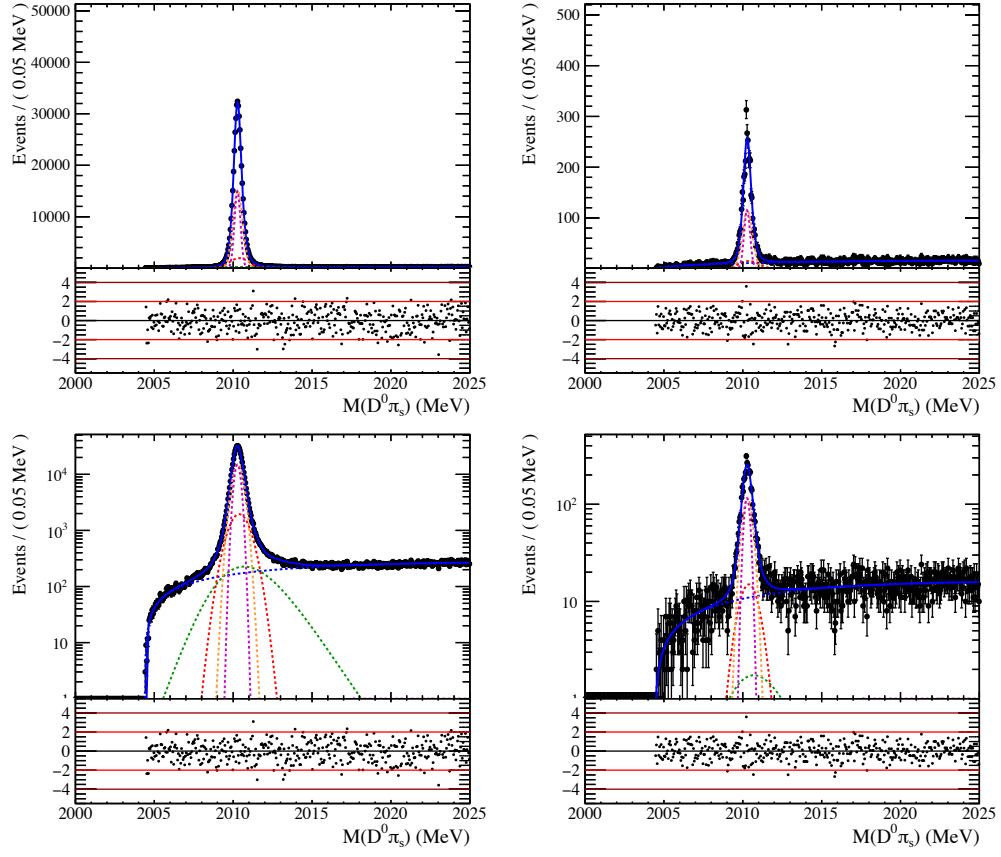


Figure A.28: Fits to the time integrated MD sample. Left: RS, Right: WS, Top: Linear, Bottom: Semilog

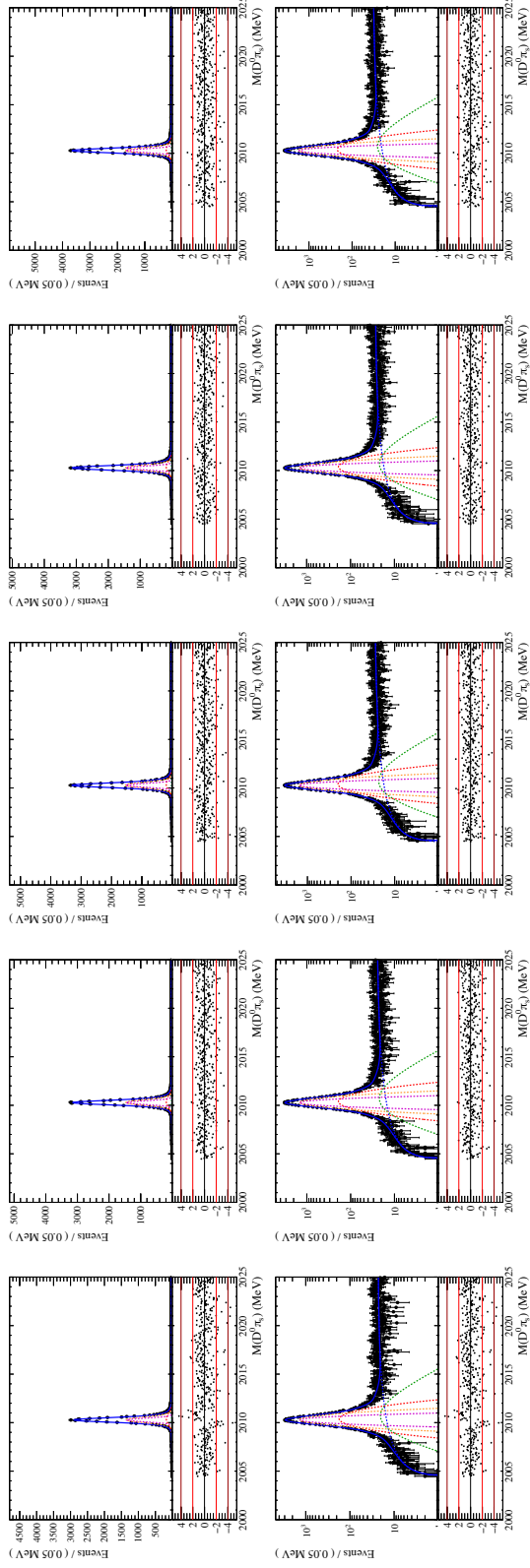


Figure A.29: MD RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

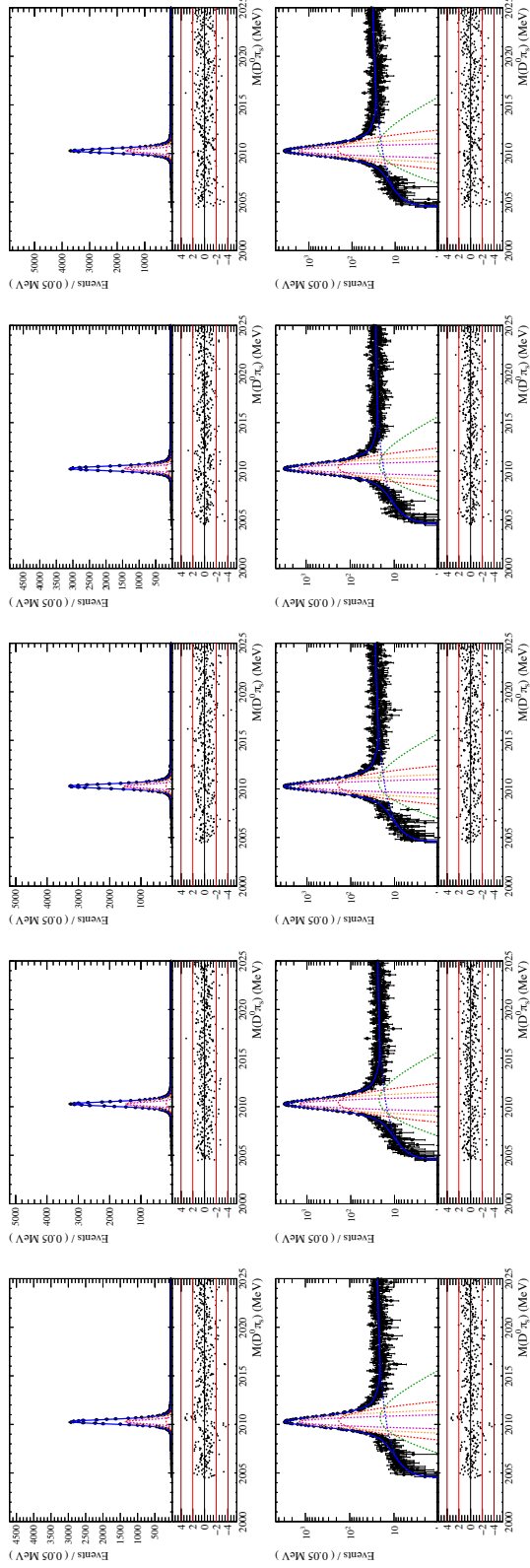


Figure A.30: MD RS- fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

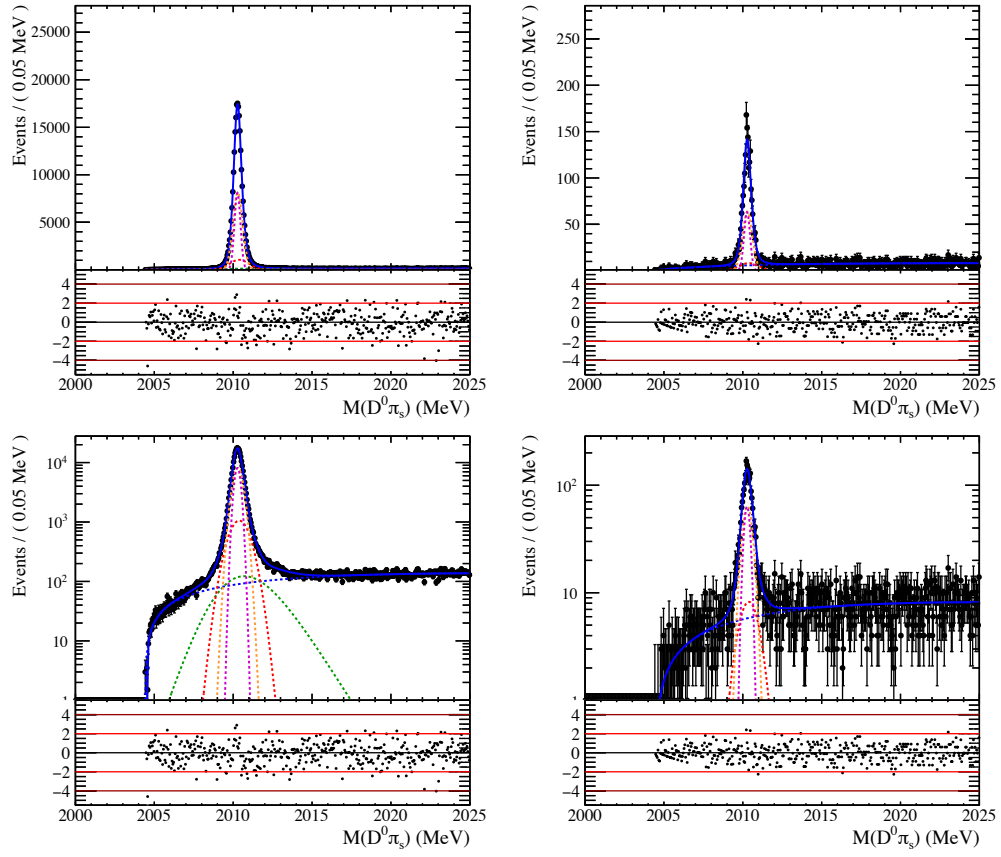


Figure A.31: Fits to the time integrated 2011 sample. Left:RS, Right:WS, Top:Linear, Bottom:Semilog

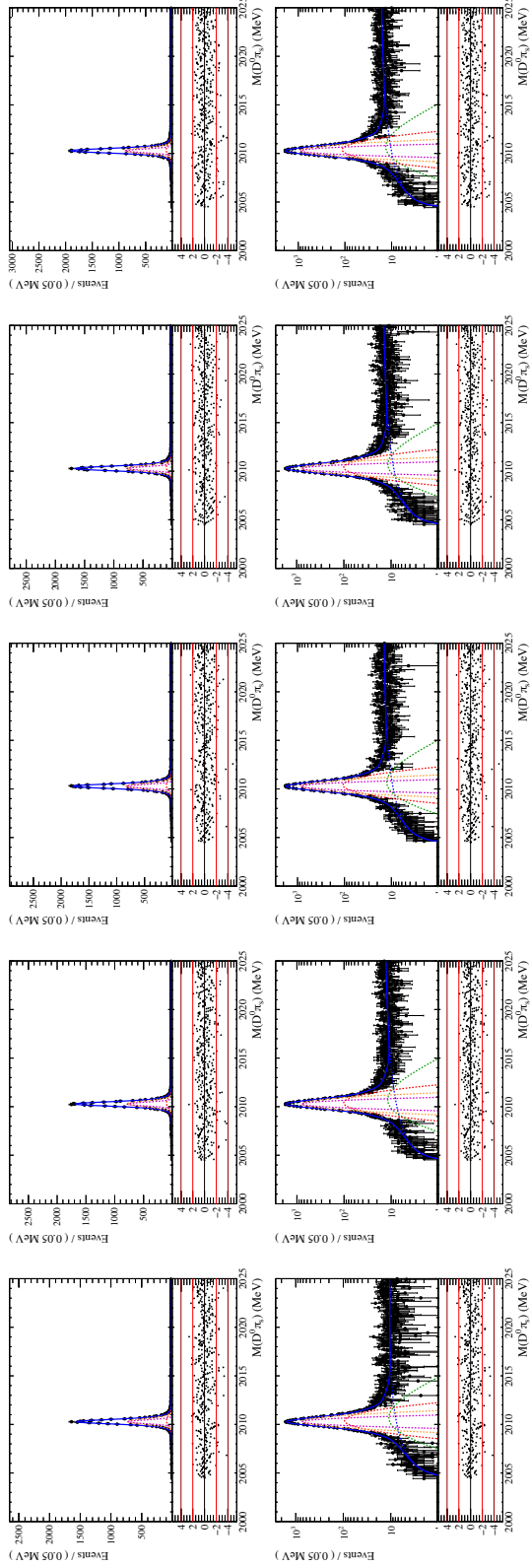


Figure A.32: 2011 RS+ fits vs decay time. Top: linear, bottom: logy. Left to right is decay time bin.

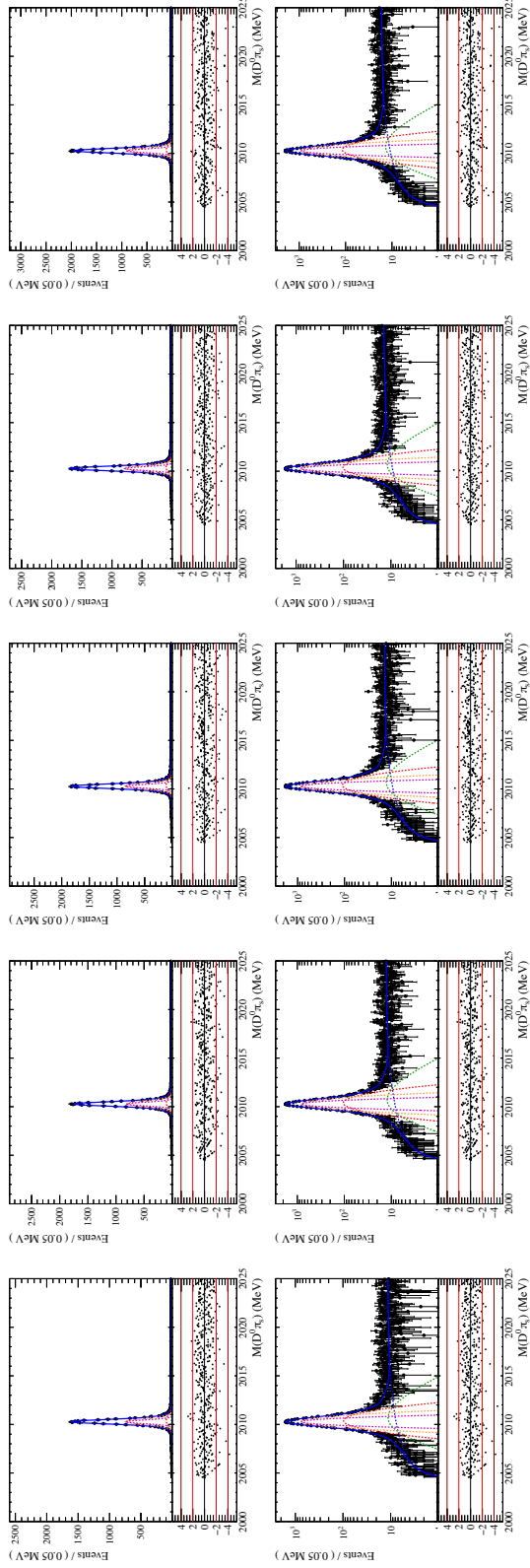


Figure A.33: 2011 RS- fits vs decay time. Top: linear, bottom: logy. Left to right is decay time bin.

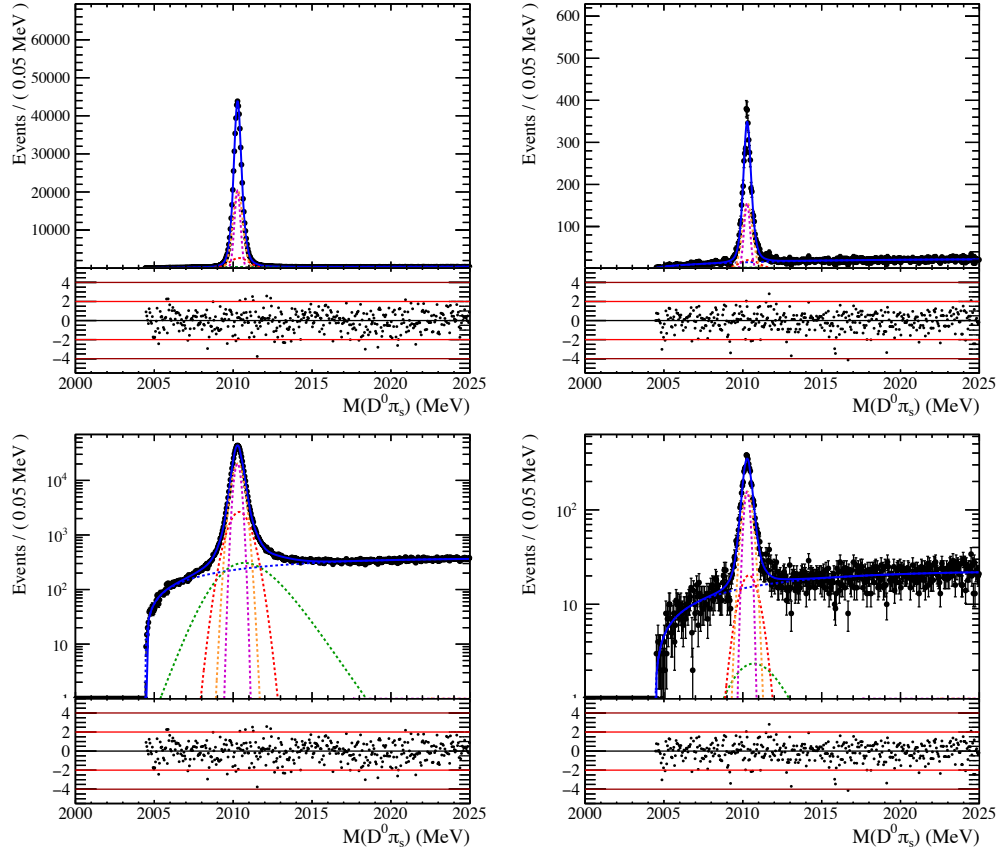


Figure A.34: Fits to the time integrated 2012 sample. Left:RS, Right:WS, Top:Linear, Bottom:Semilog

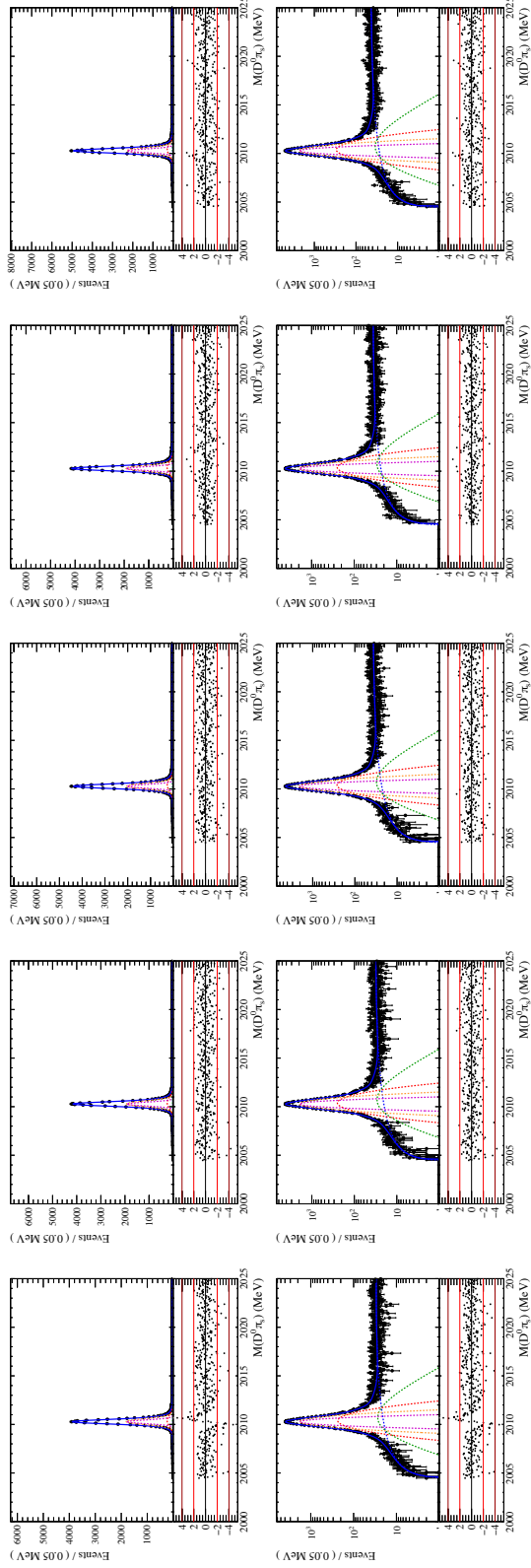


Figure A.35: 2012 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

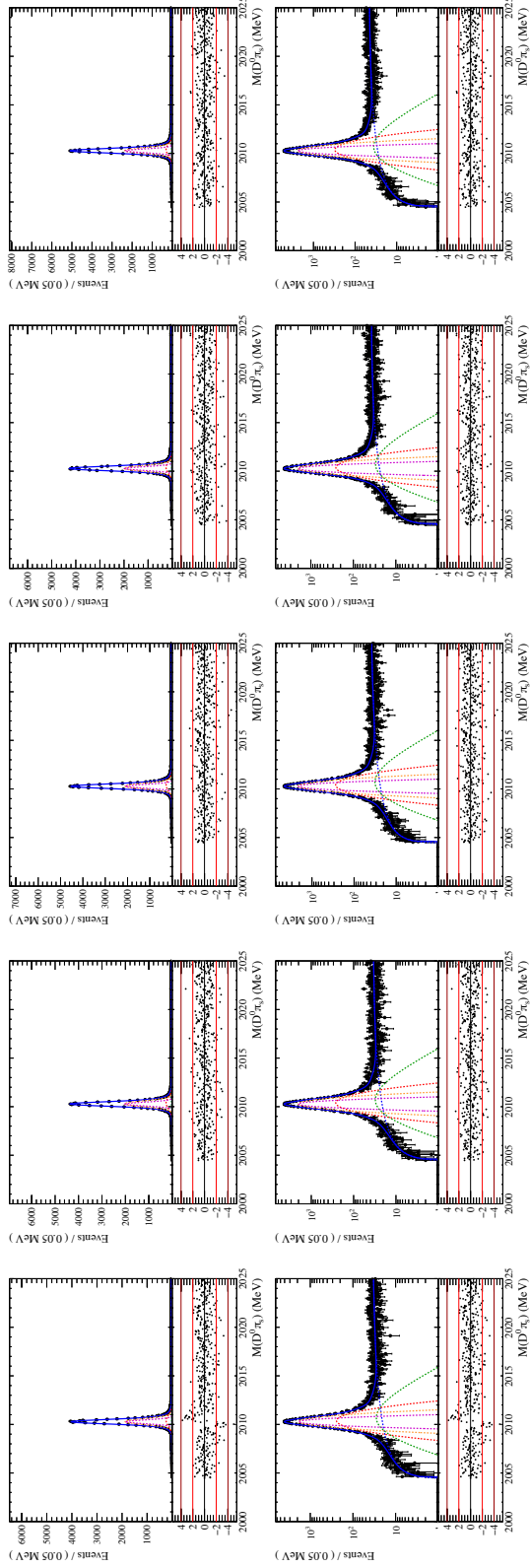


Figure A.36: 2012 RS- fits vs decay time. Top: linear, bottom: logy. Left to right is decay time bin.

A.11.3 MD2012 vs MU2012 vs MD2011 vs MU2011

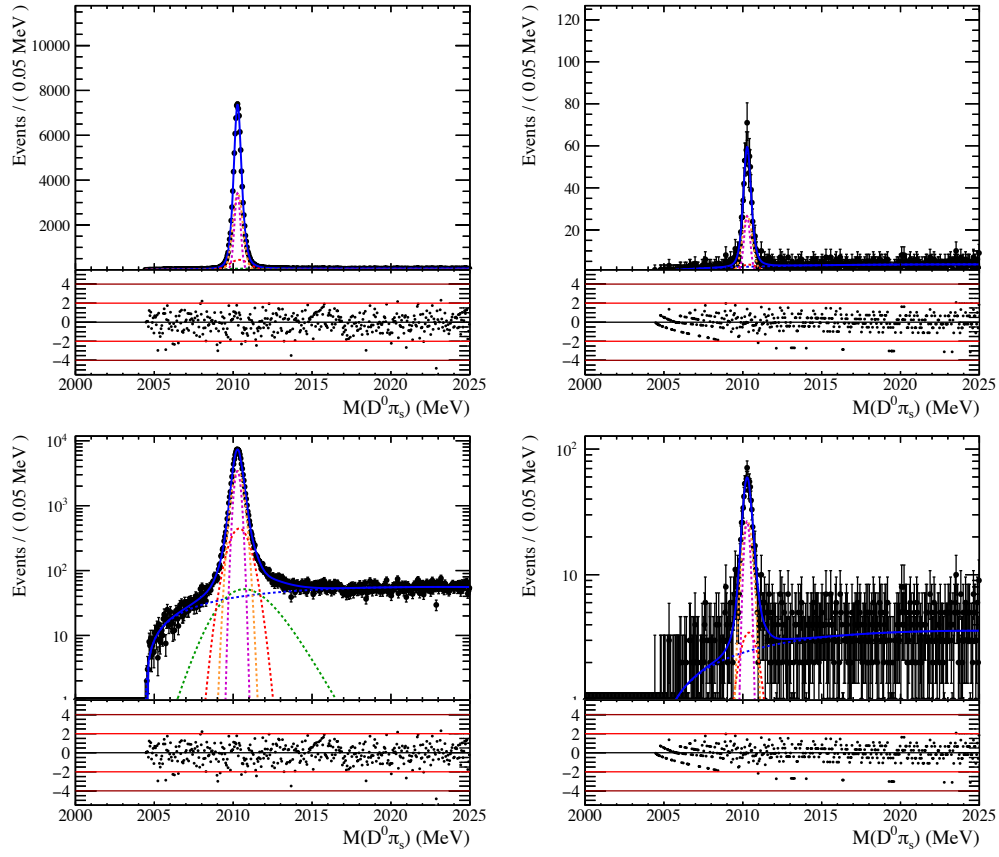


Figure A.37: Fits to the time integrated MU2011 sample. Left:RS, Right:WS, Top:Linear, Bottom:Semilog

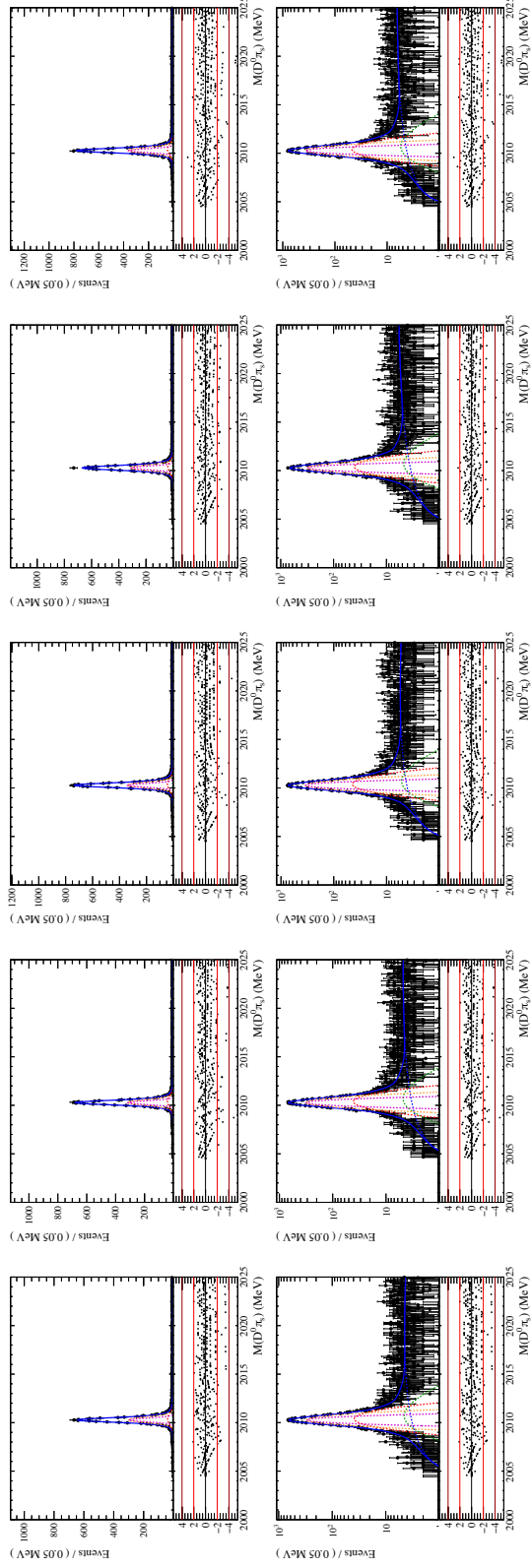


Figure A.38: MU2011 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

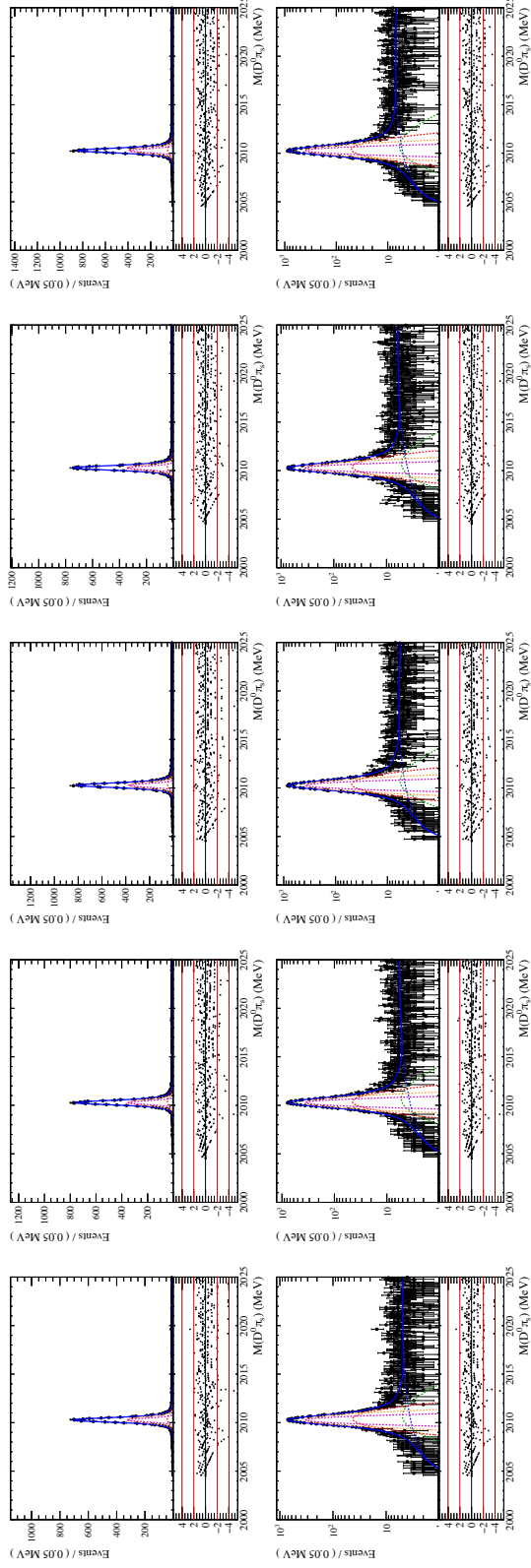


Figure A.39: MU2011 RS- fits vs decay time. Top: linear, bottom: logy. Left to right is decay time bin.

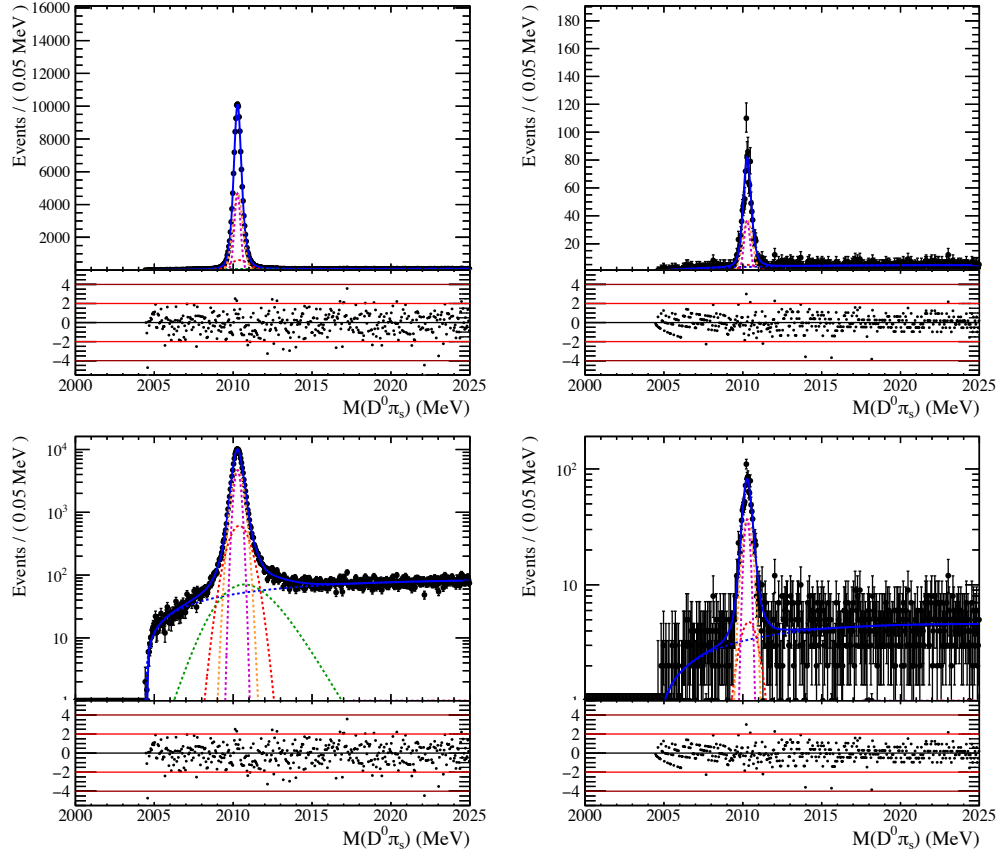


Figure A.40: Fits to the time integrated MD2011 sample. Left:RS, Right:WS, Top:Linear, Bottom:Semilog

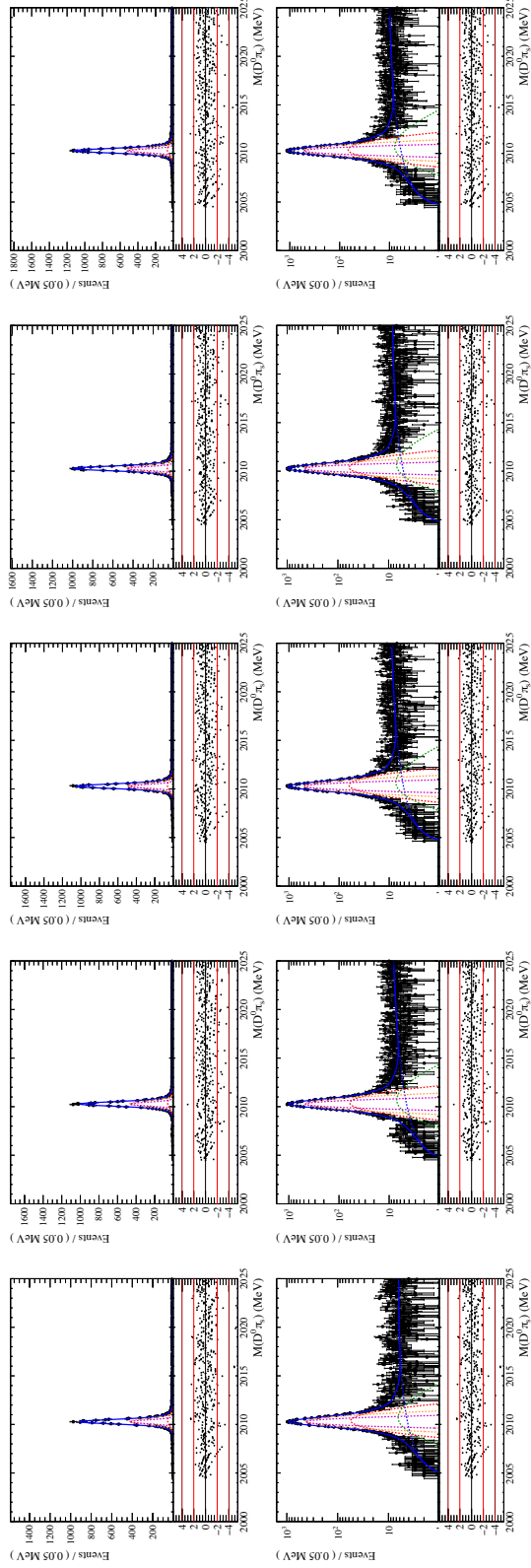


Figure A.41: MD2011 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

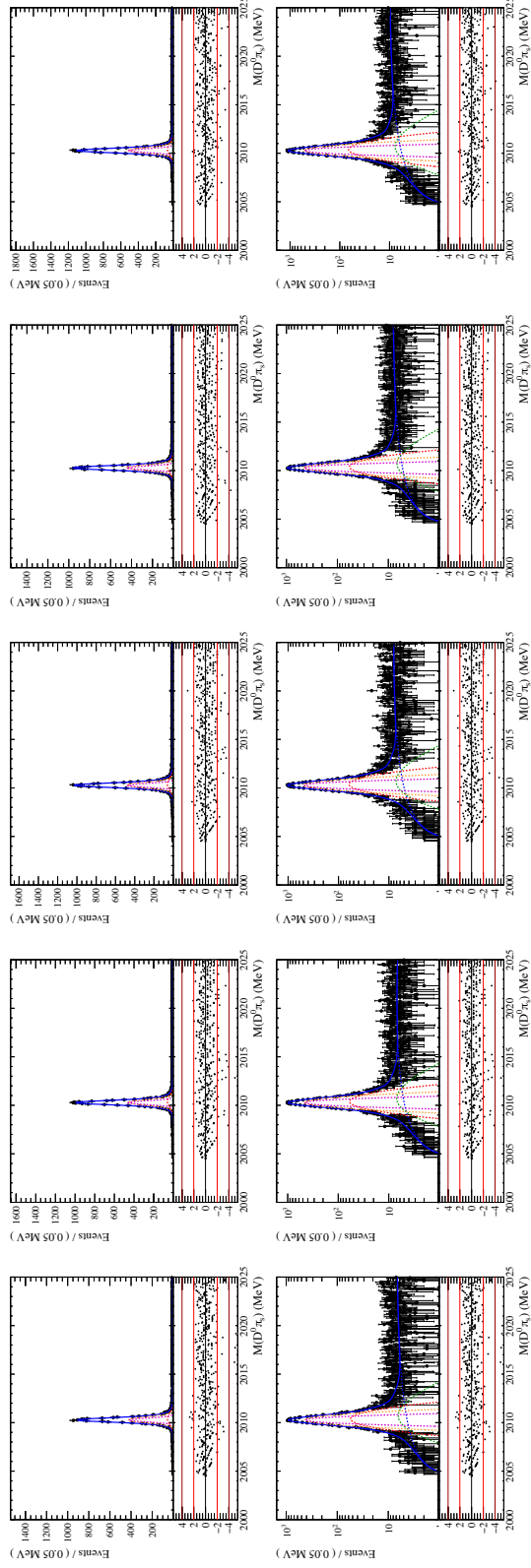


Figure A.42: MD2011 RS- fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

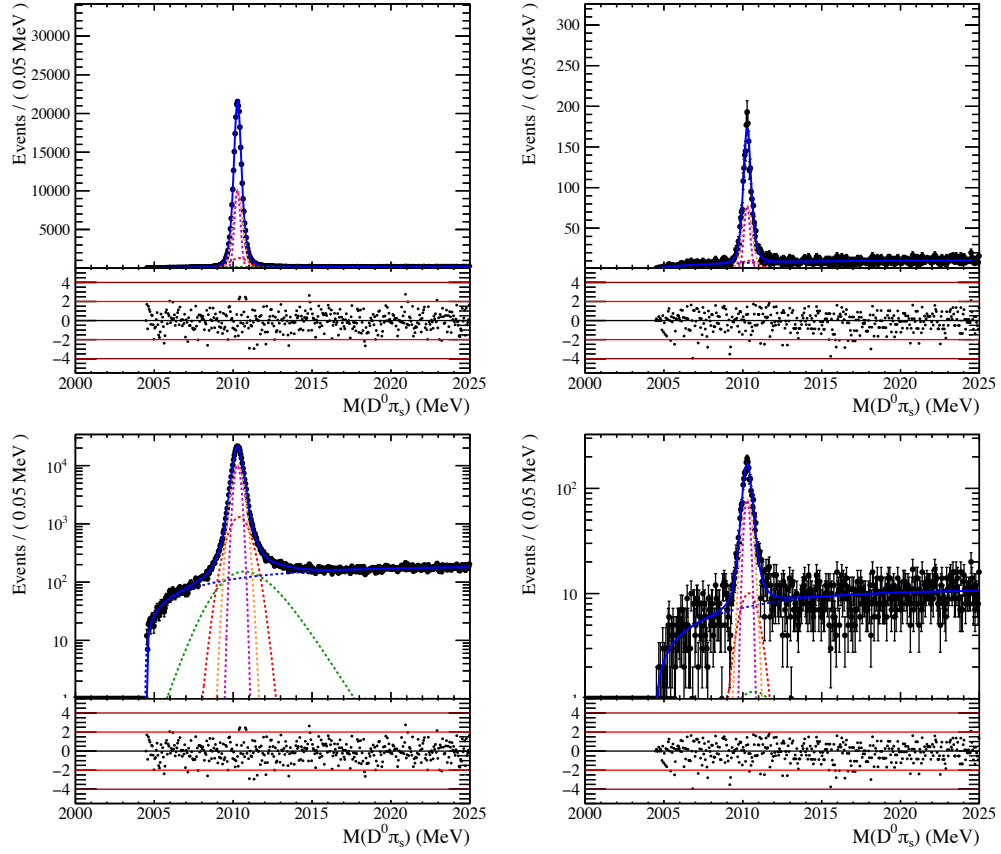


Figure A.43: Fits to the time integrated MU2012 sample. Left: RS, Right: WS, Top: Linear, Bottom: Semilog

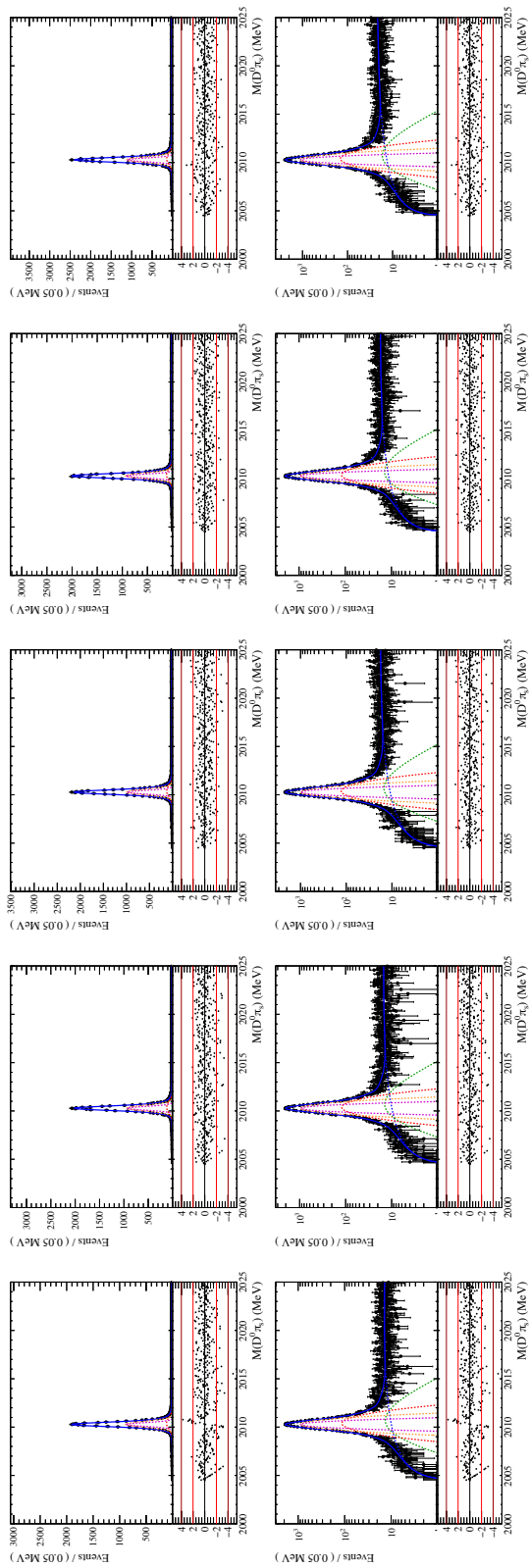


Figure A.44: MU2012 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

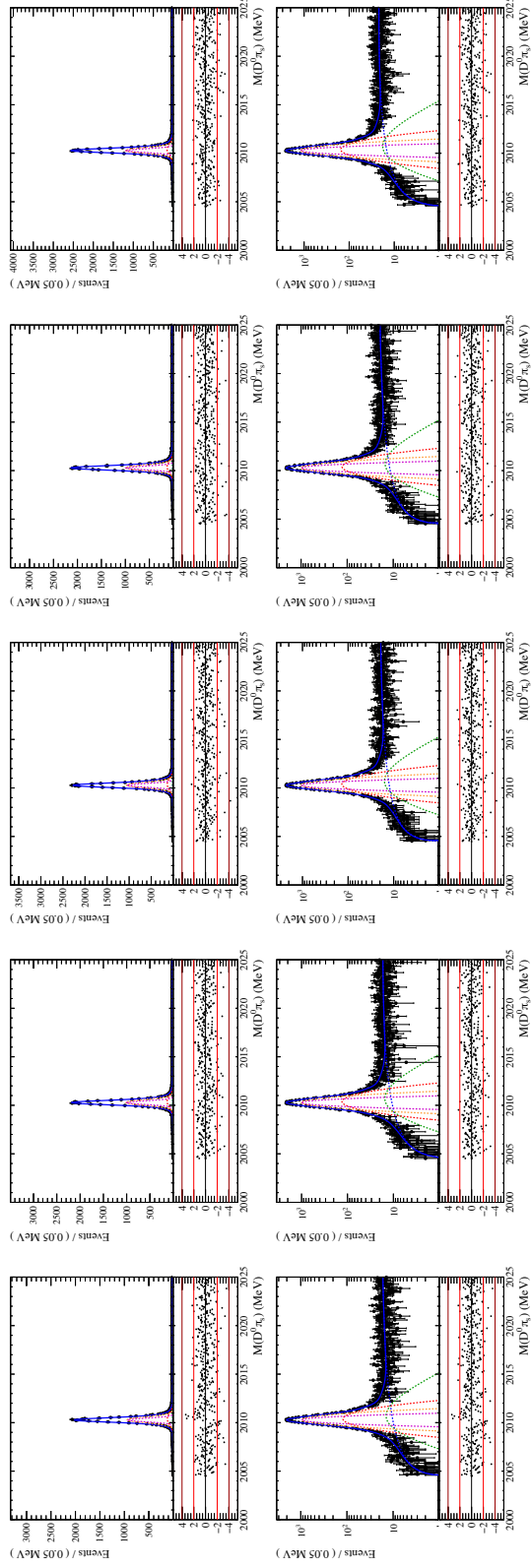


Figure A.45: MU2012 RS- fits vs decay time. Top: linear, bottom: log. Left to right is decay time bin.

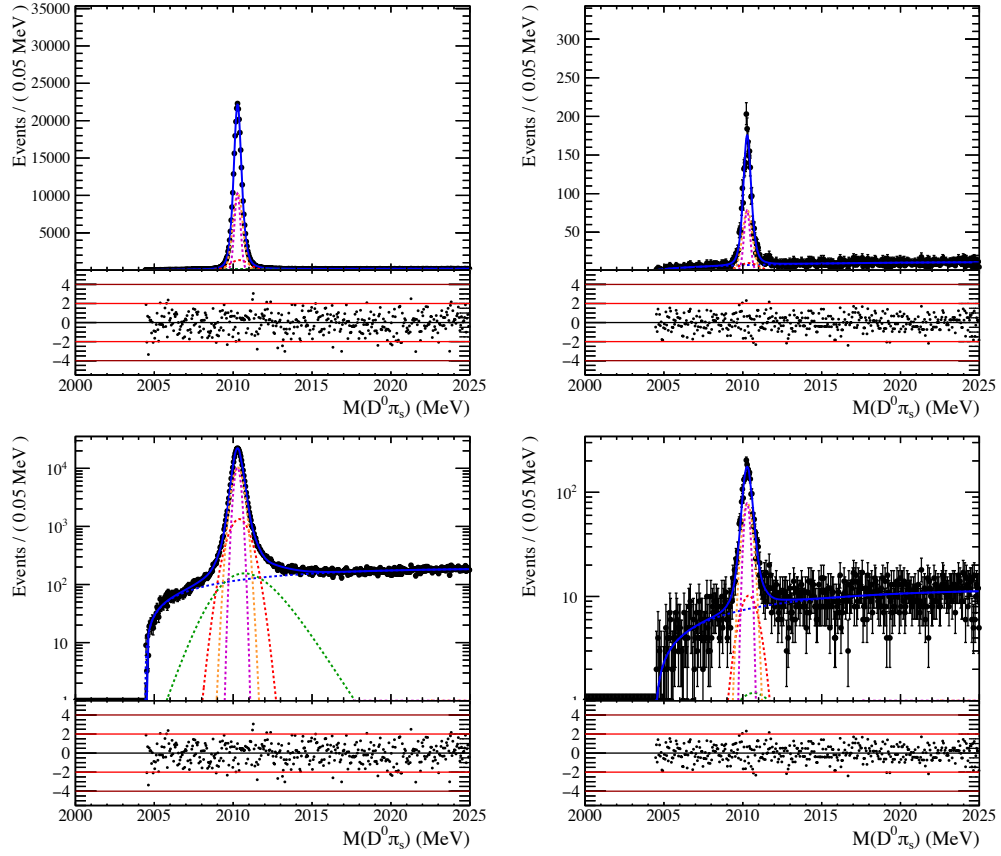


Figure A.46: Fits to the time integrated MD2012 sample. Left:RS, Right:WS, Top:Linear, Bottom:Semilog

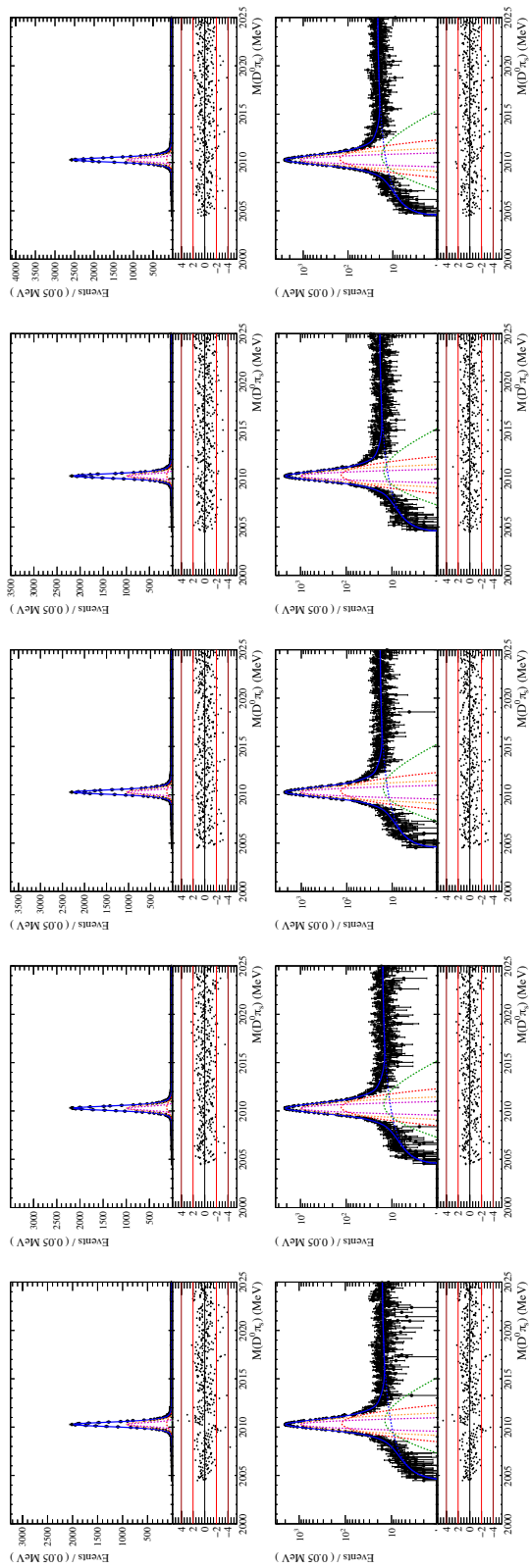


Figure A.47: MD2012 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

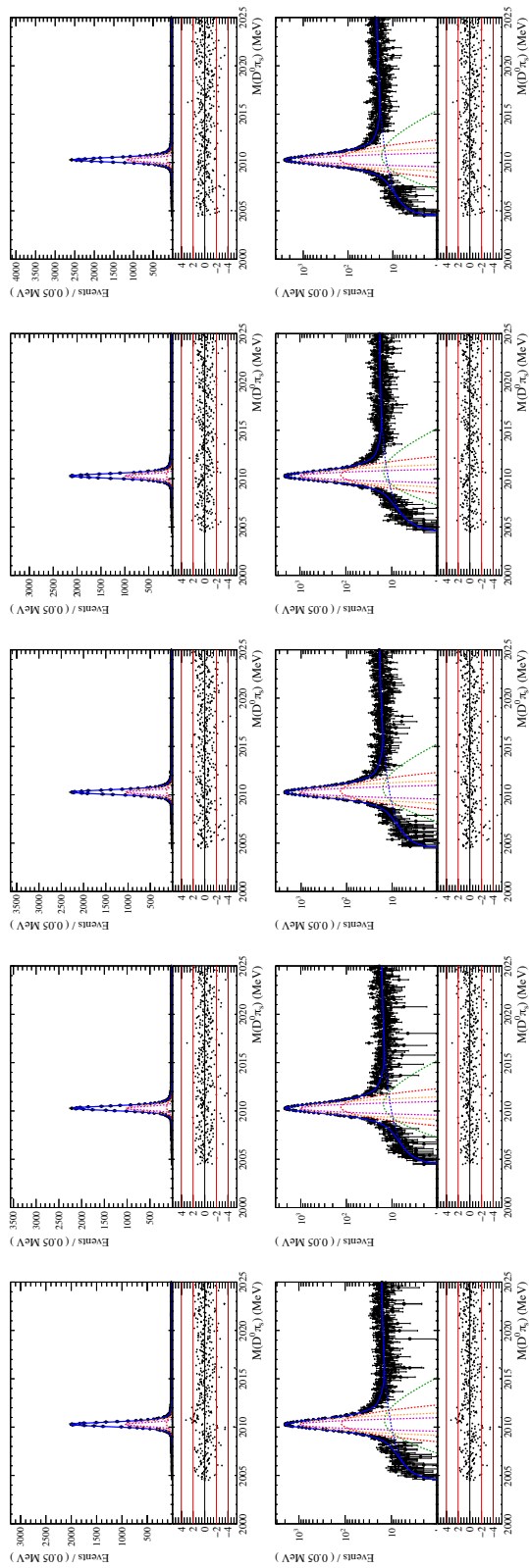


Figure A.48: MD2012 RS- fits vs decay time. Top: linear, bottom: logy. Left to right is decay time bin.

A.11.4 Kaon Momentum Bins

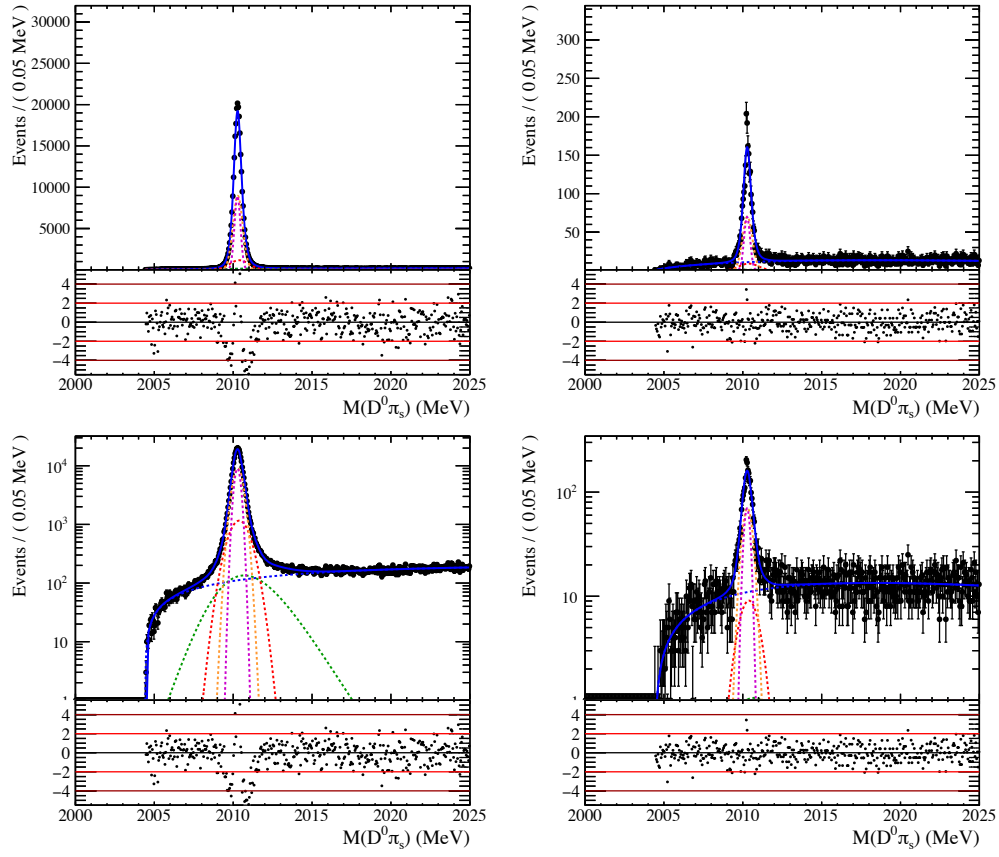


Figure A.49: Fits to the time integrated KAONP/BIN1 sample. Left: RS, Right: WS, Top: Linear, Bottom: Semilog

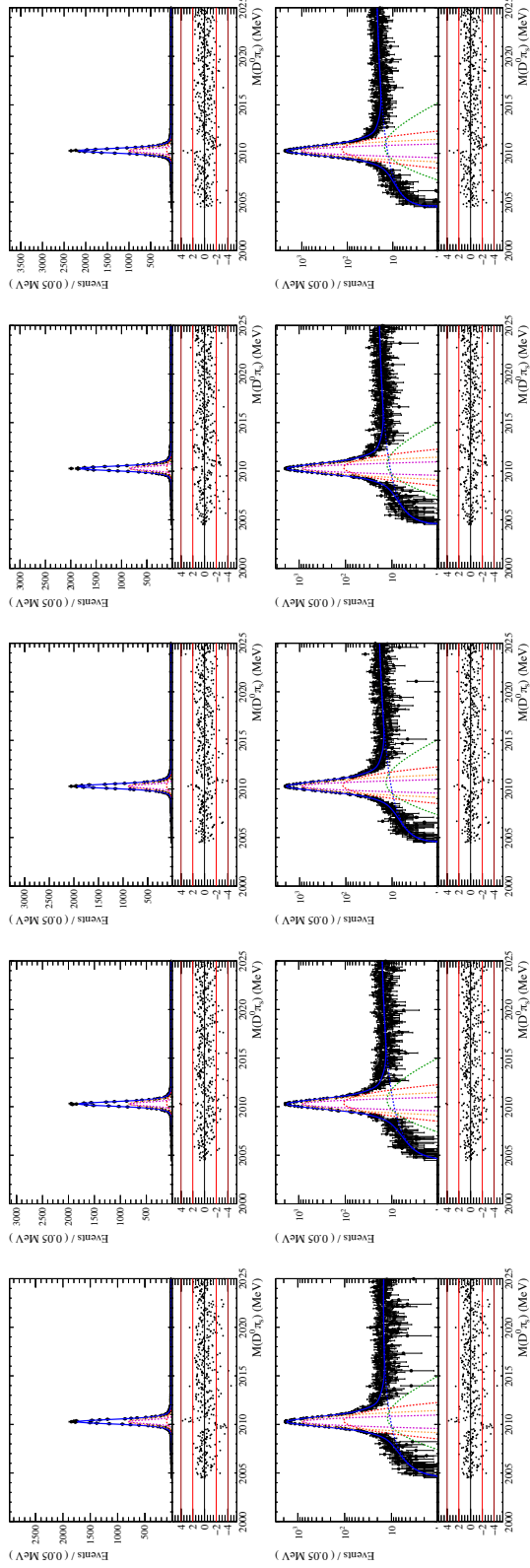


Figure A.50: KAONP/BIN1 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

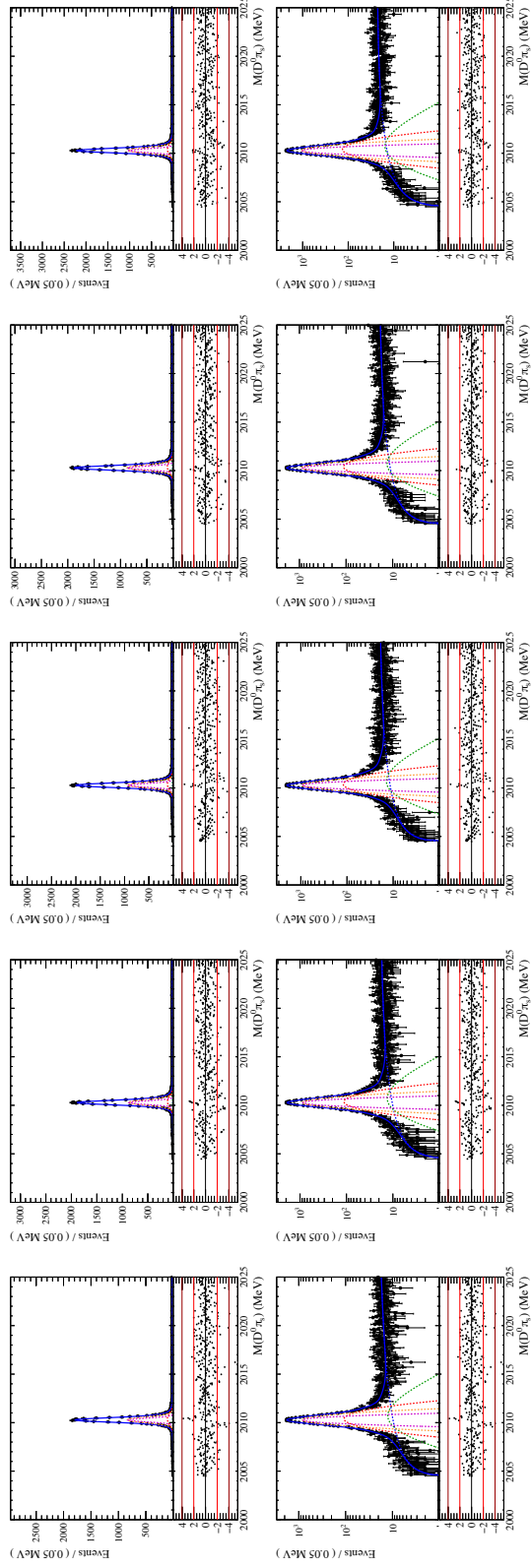


Figure A.51: KAONP/BIN1 RS-fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

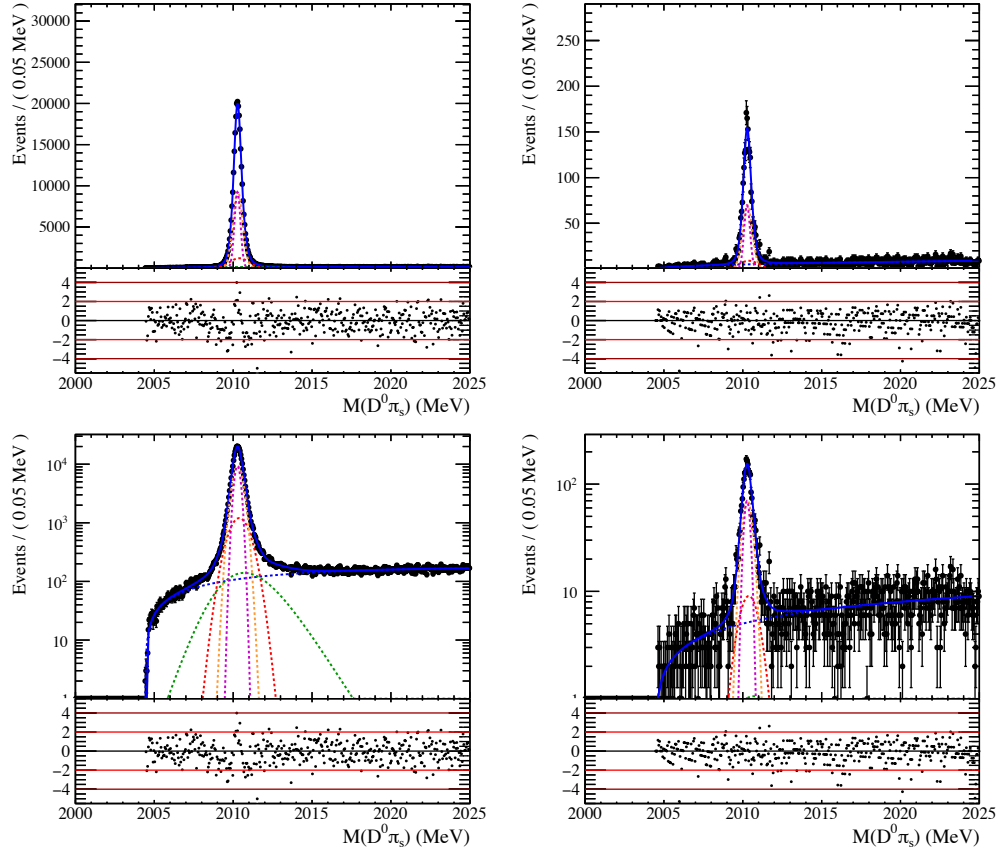


Figure A.52: Fits to the time integrated KAONP/BIN2 sample. Left:RS, Right:WS, Top:Linear, Bottom:Semilog

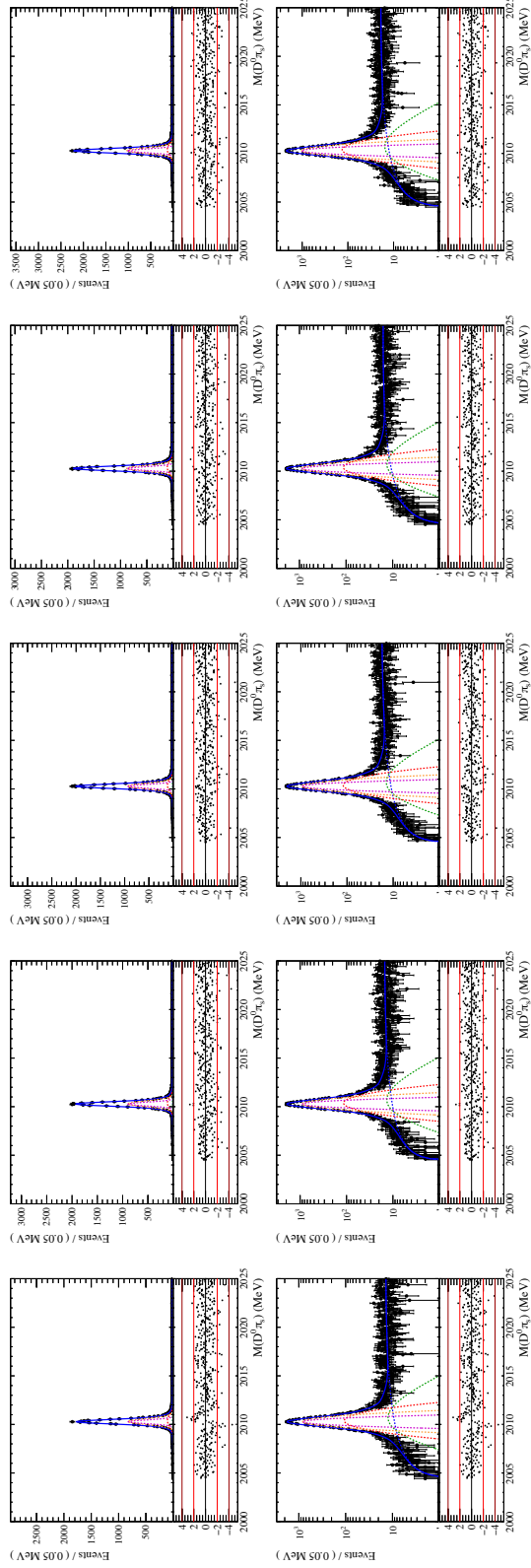


Figure A.53: KAONp/BIN2 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

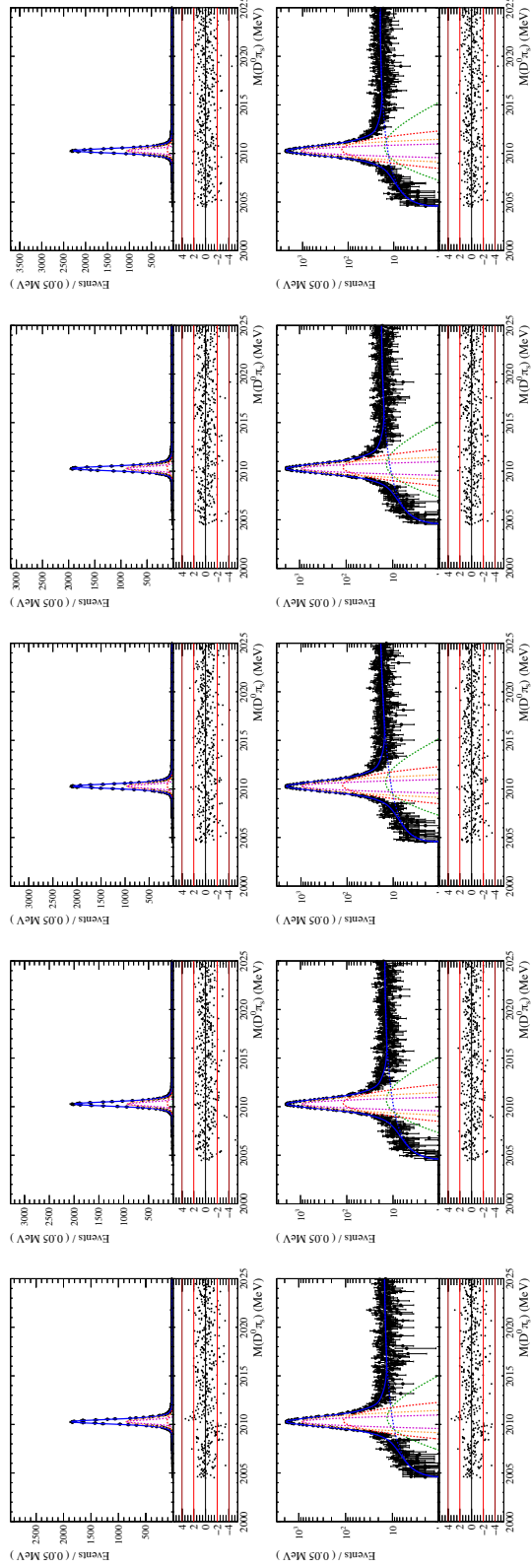


Figure A.54: KAONP/BIN2 RS-fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

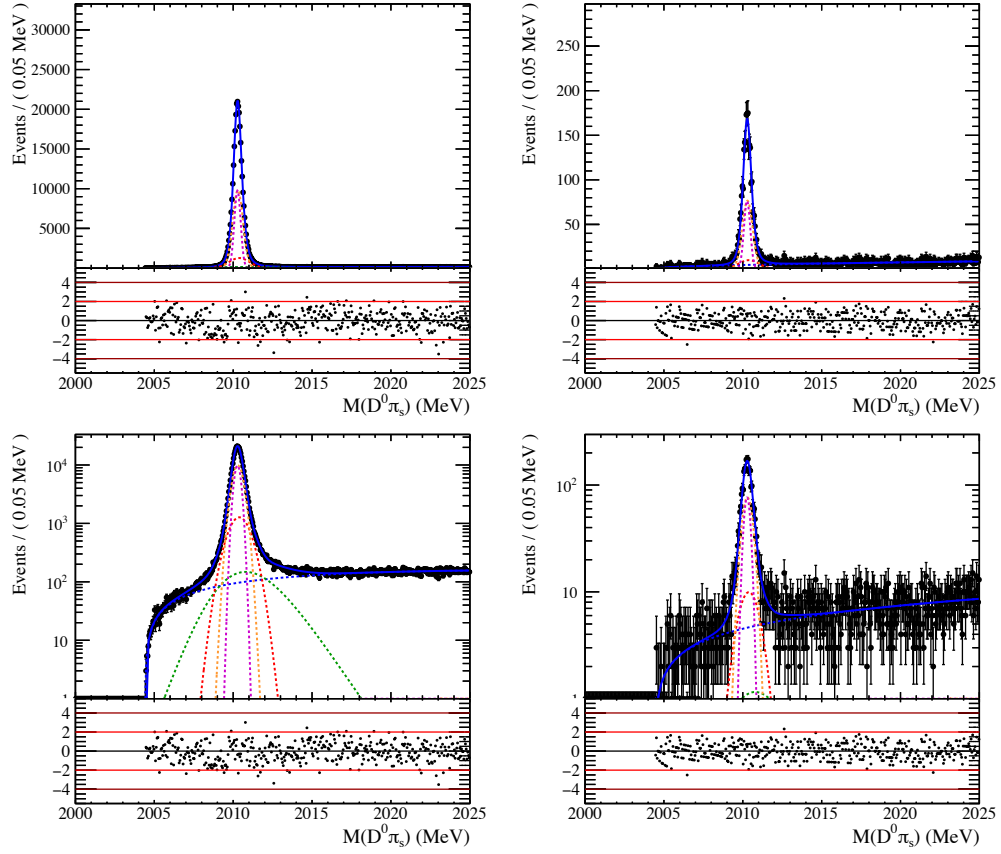


Figure A.55: Fits to the time integrated KAONP/BIN3 sample. Left: RS, Right: WS, Top: Linear, Bottom: Semilog

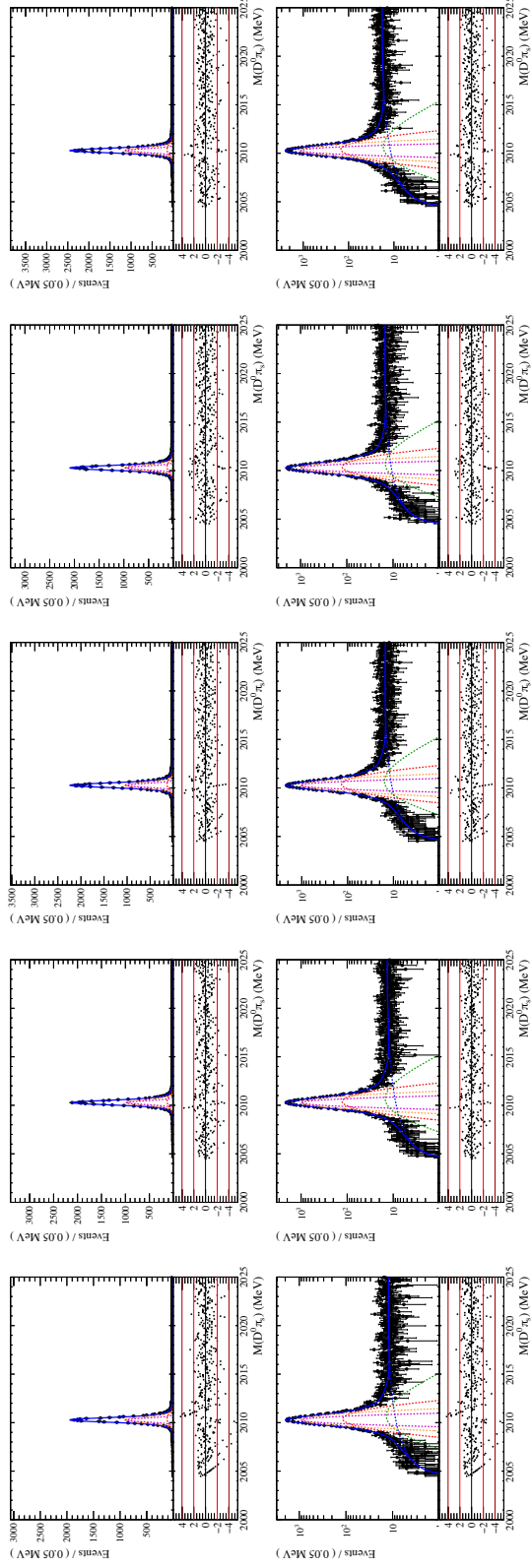


Figure A.56: KAONp/BIN3 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

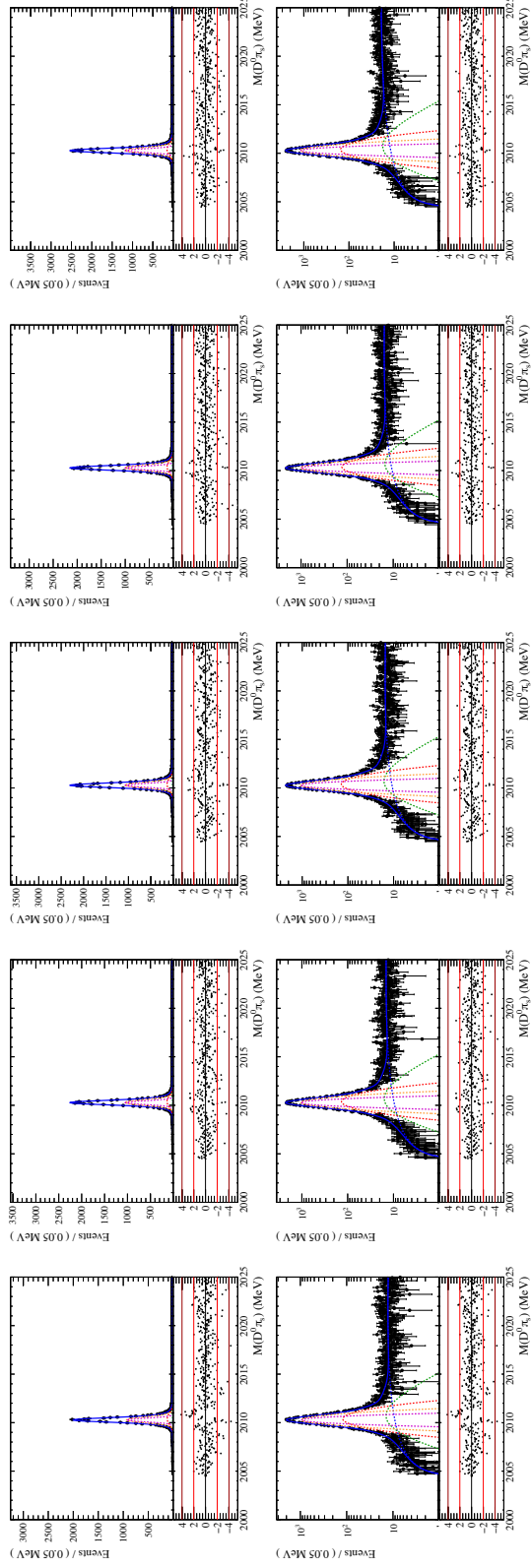


Figure A.57: KAONP/BIN3 RS-fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

A.11.5 Slow Pion p_T

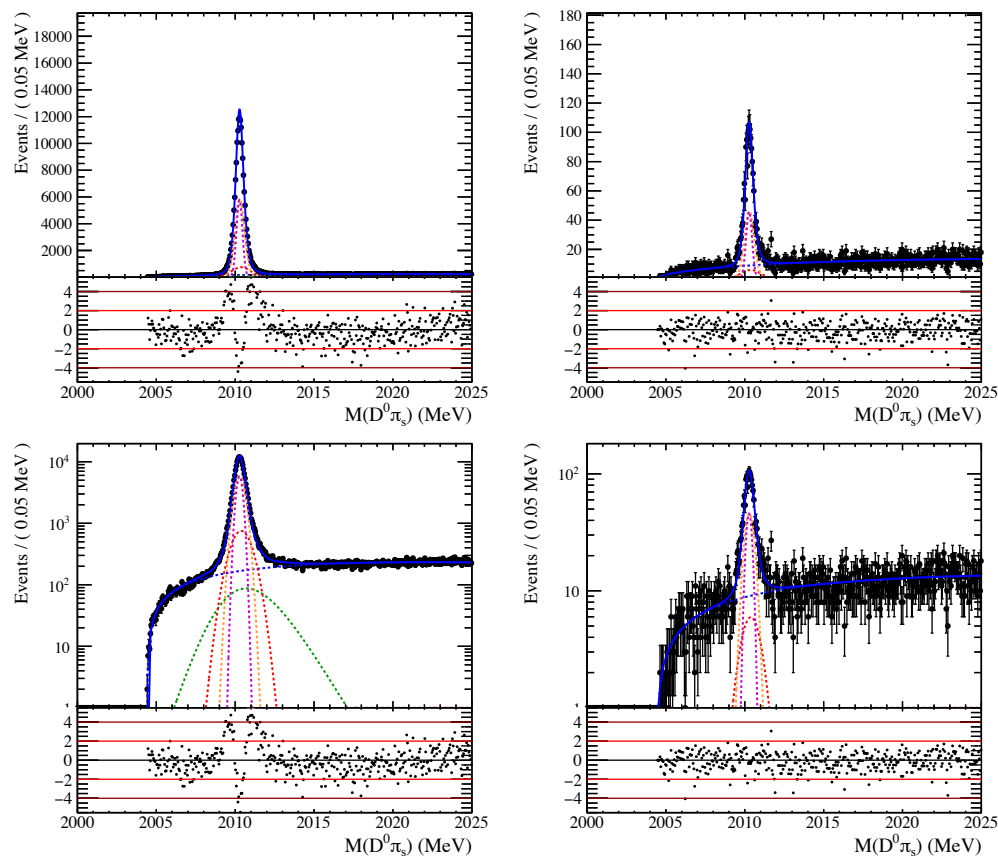


Figure A.58: Fits to the time integrated PISPT/BIN1 sample. Left:RS, Right:WS, Top:Linear, Bottom:Semilog

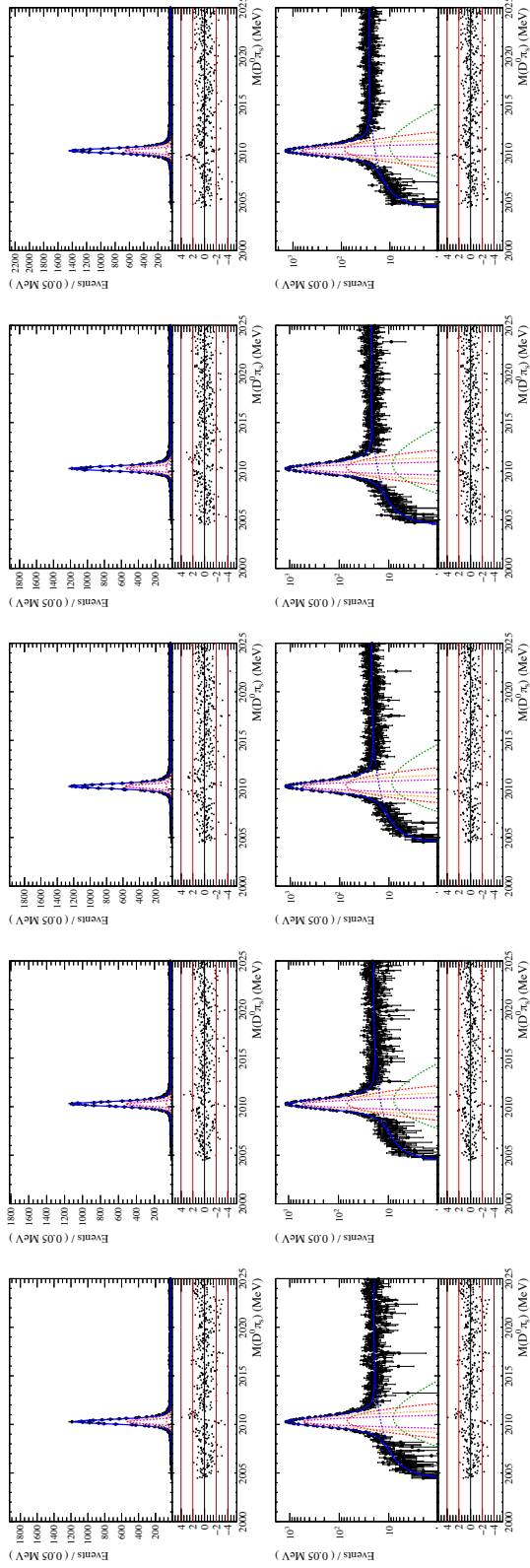


Figure A.59: PISPT/BIN1 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

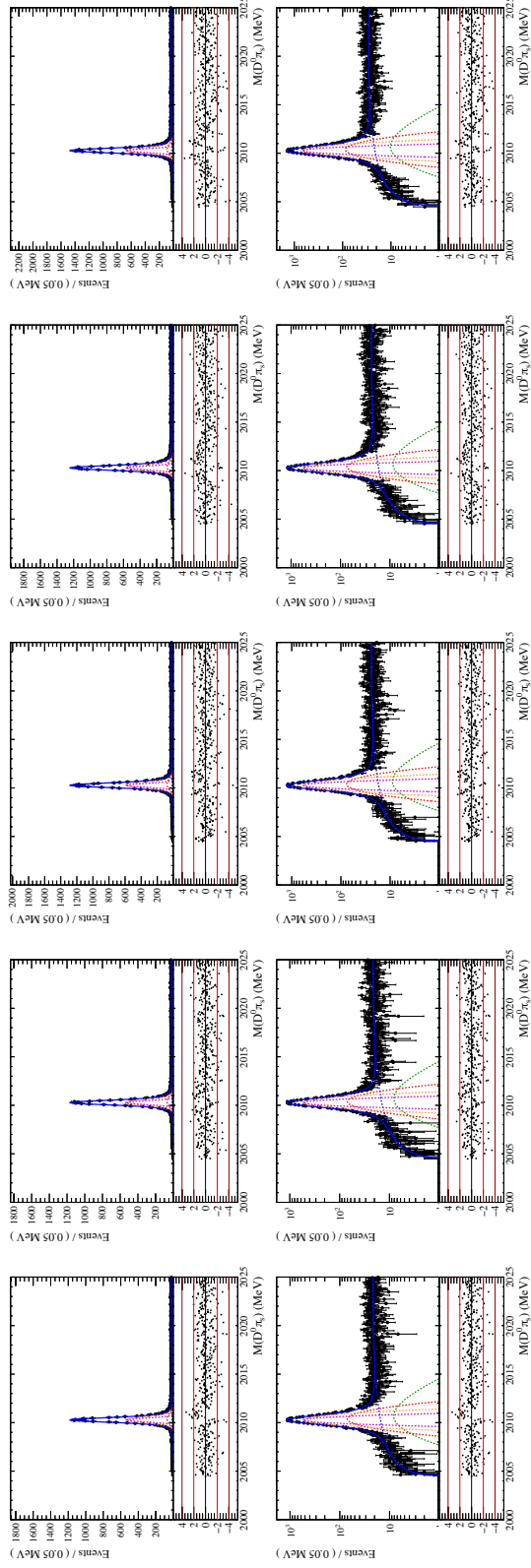


Figure A.60: PISPT/BIN1 RS- fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

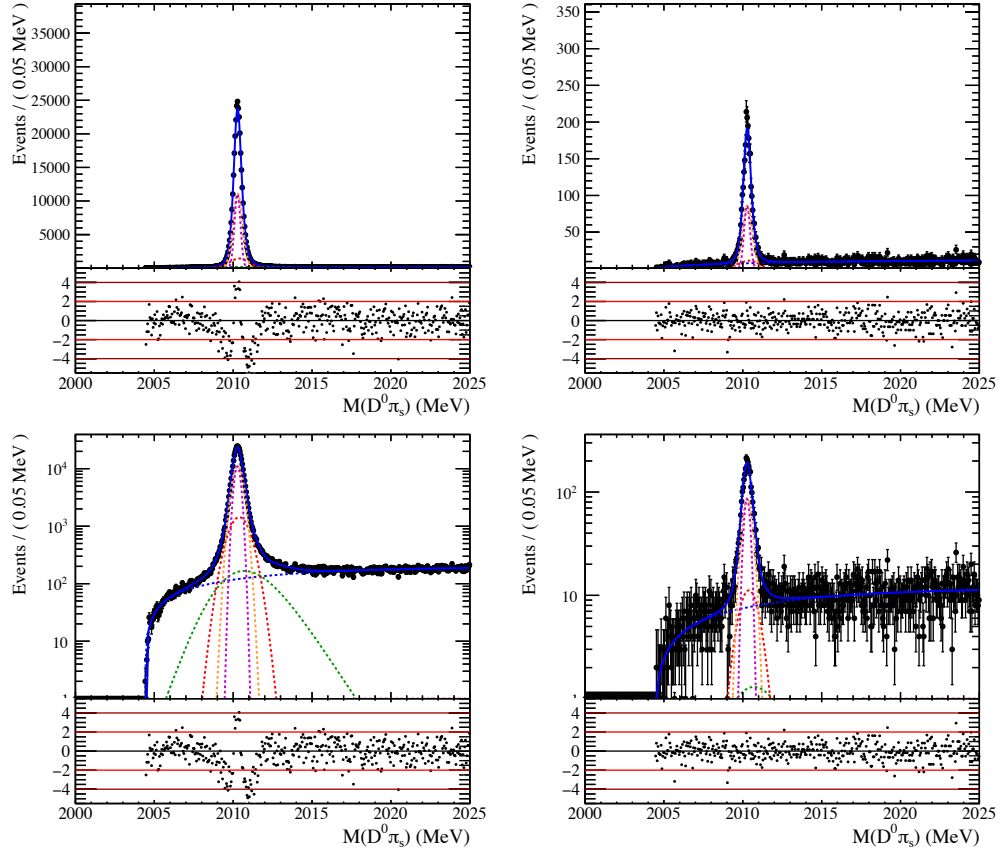


Figure A.61: Fits to the time integrated PISPT/BIN2 sample. Left:RS, Right:WS, Top:Linear, Bottom:Semilog

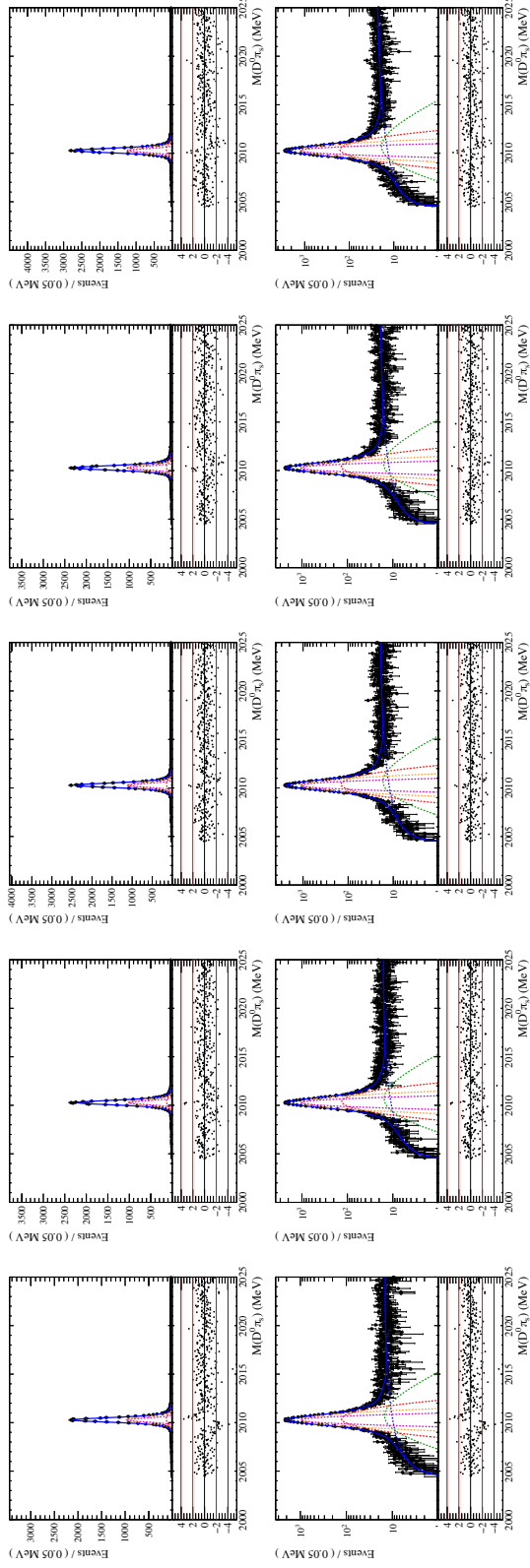


Figure A.62: PISPT/BIN2 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

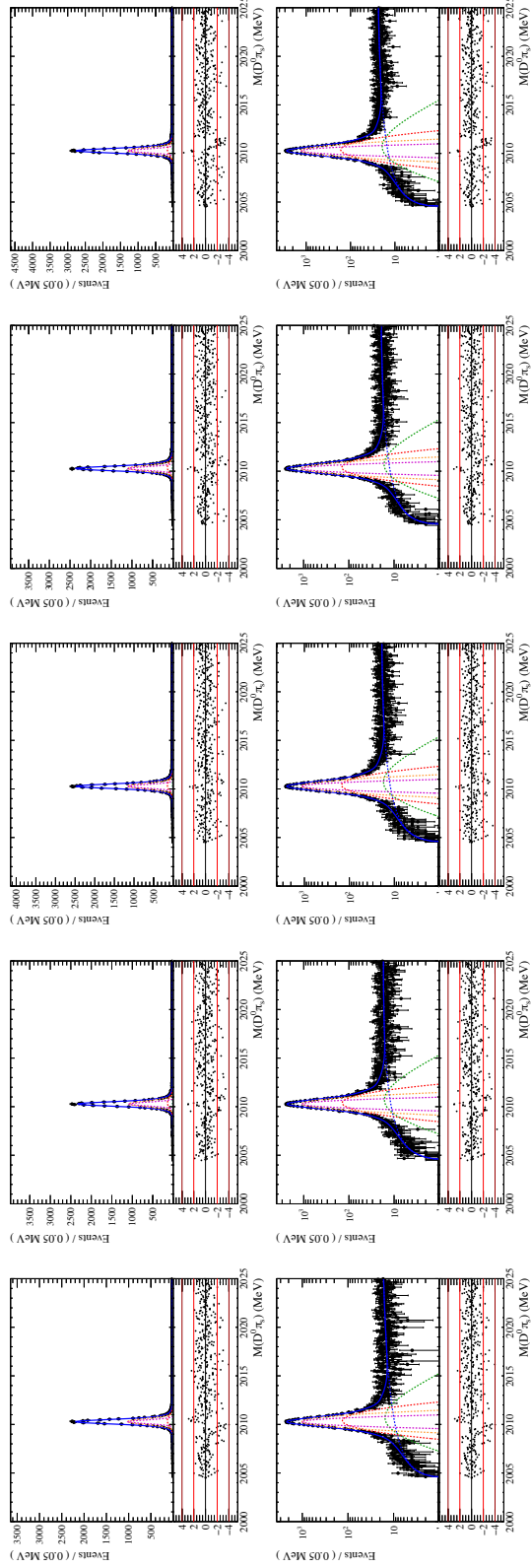


Figure A.63: PISPT/BIN2 RS- fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

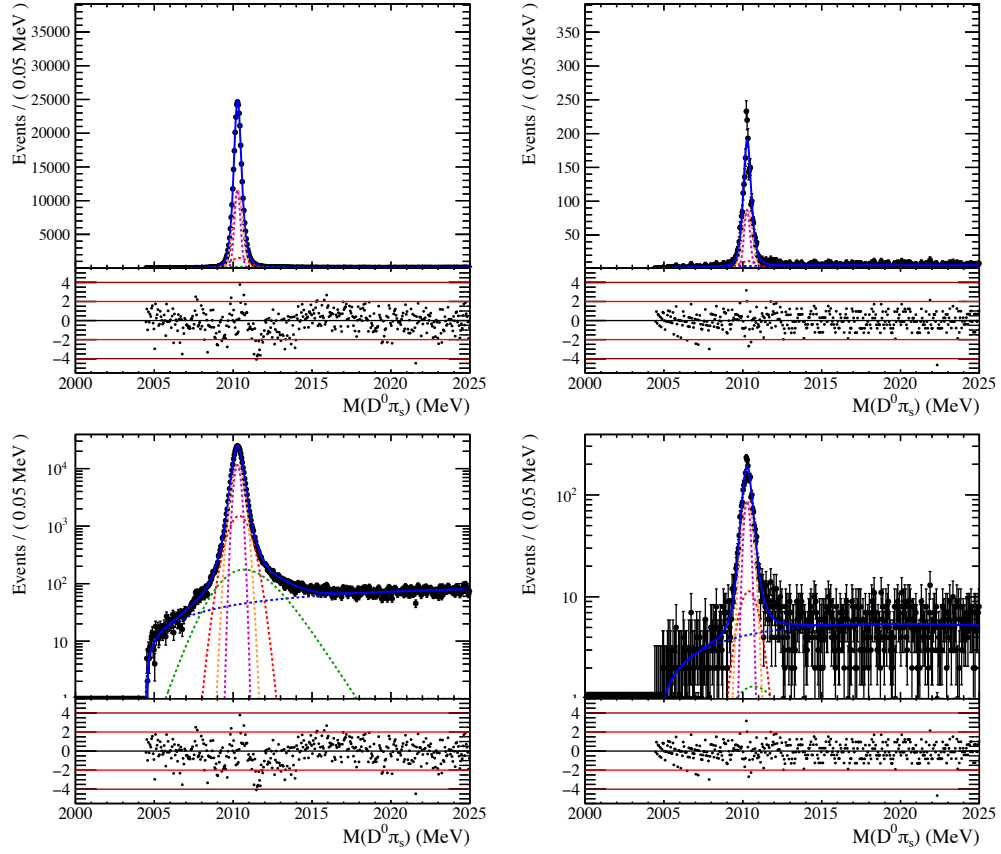


Figure A.64: Fits to the time integrated PISPT/BIN3 sample. Left: RS, Right: WS, Top: Linear, Bottom: Semilog

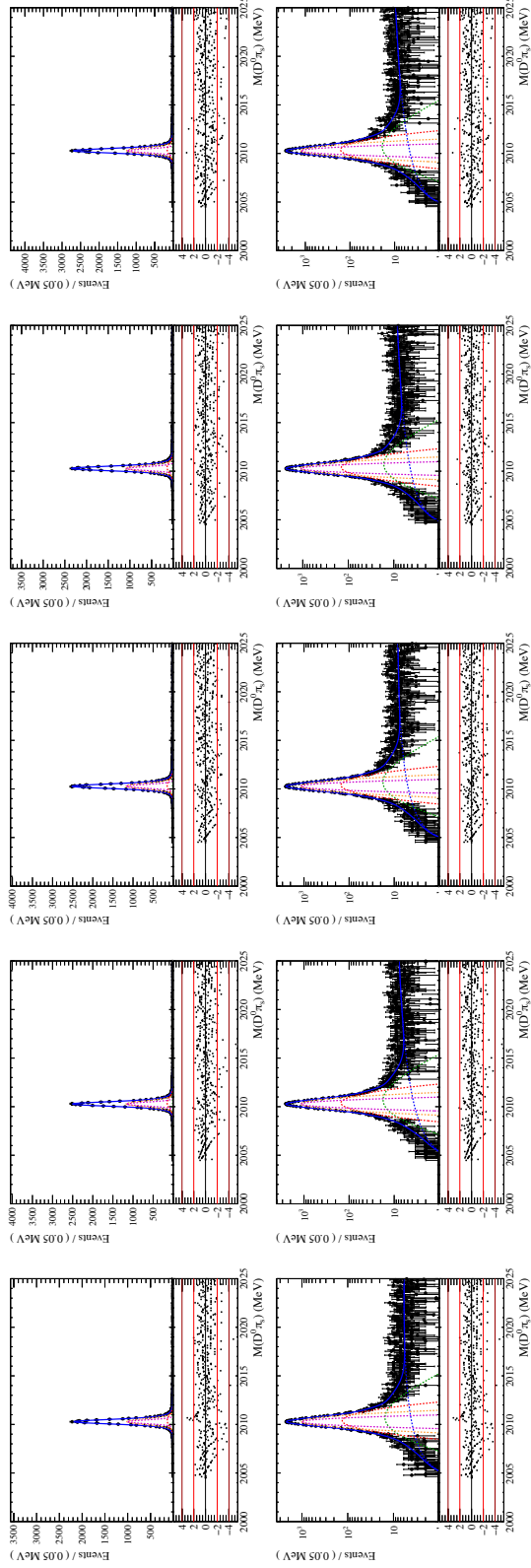


Figure A.65: PISPT/BIN3 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

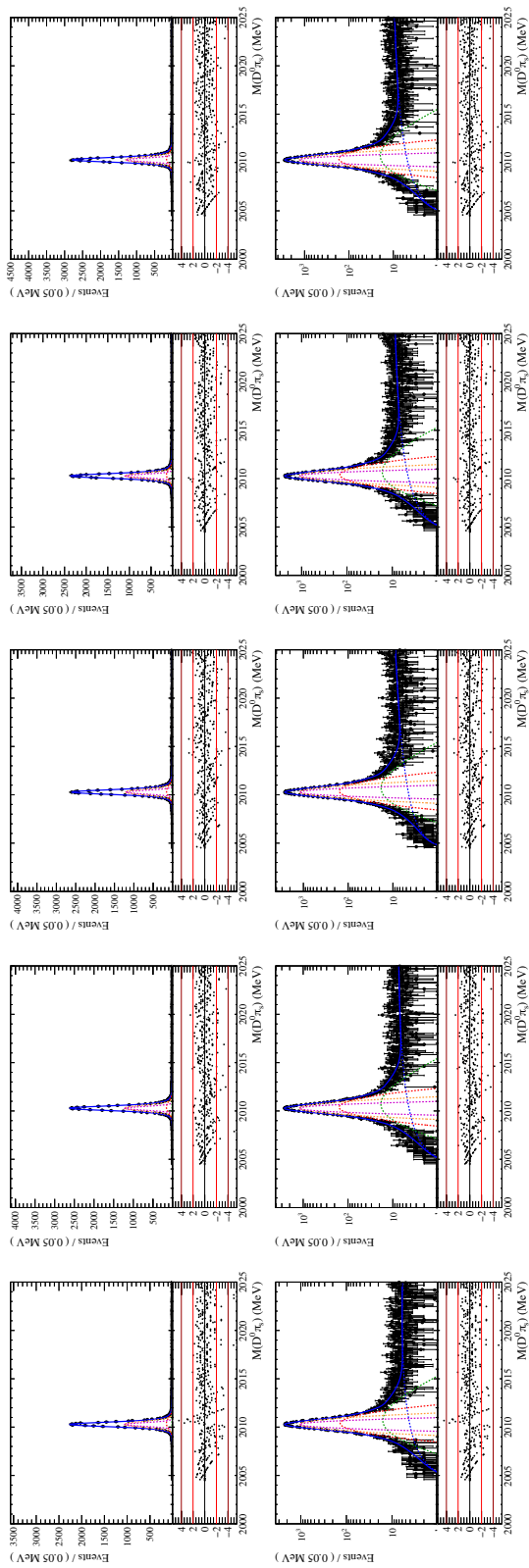


Figure A.66: PISPT/BIN3 RS- fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

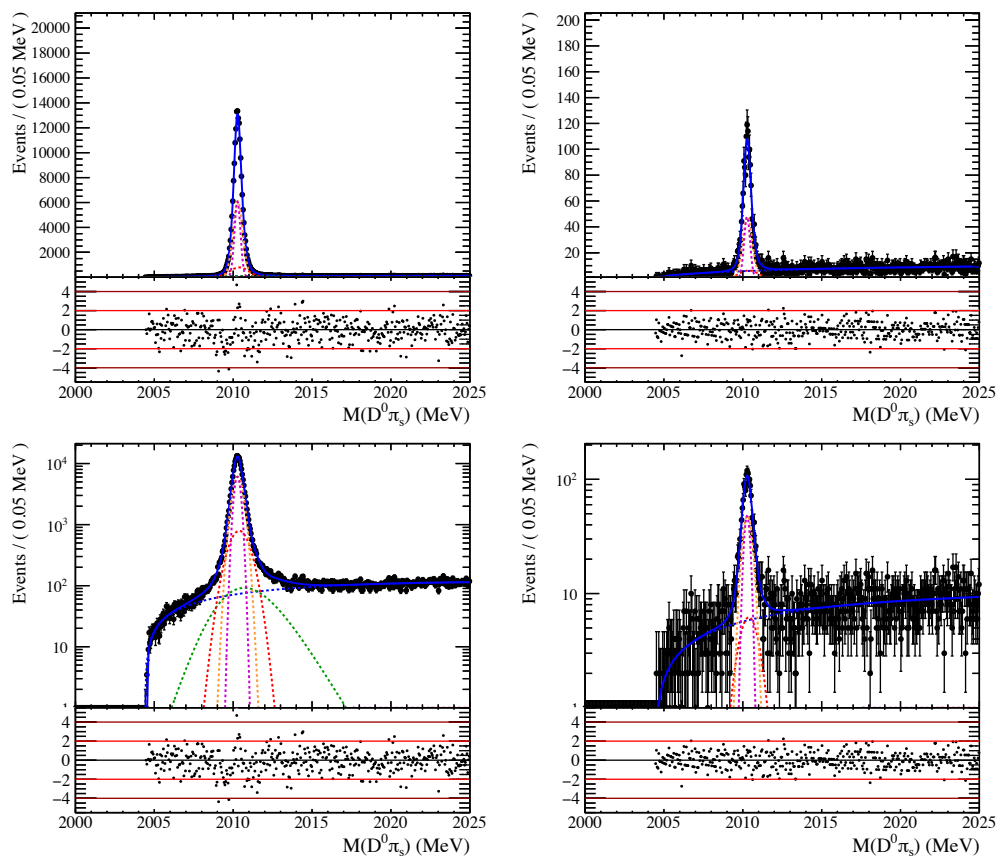


Figure A.67: Fits to the time integrated MUONPT/BIN1 sample. Left: RS, Right: WS, Top: Linear, Bottom: Semilog

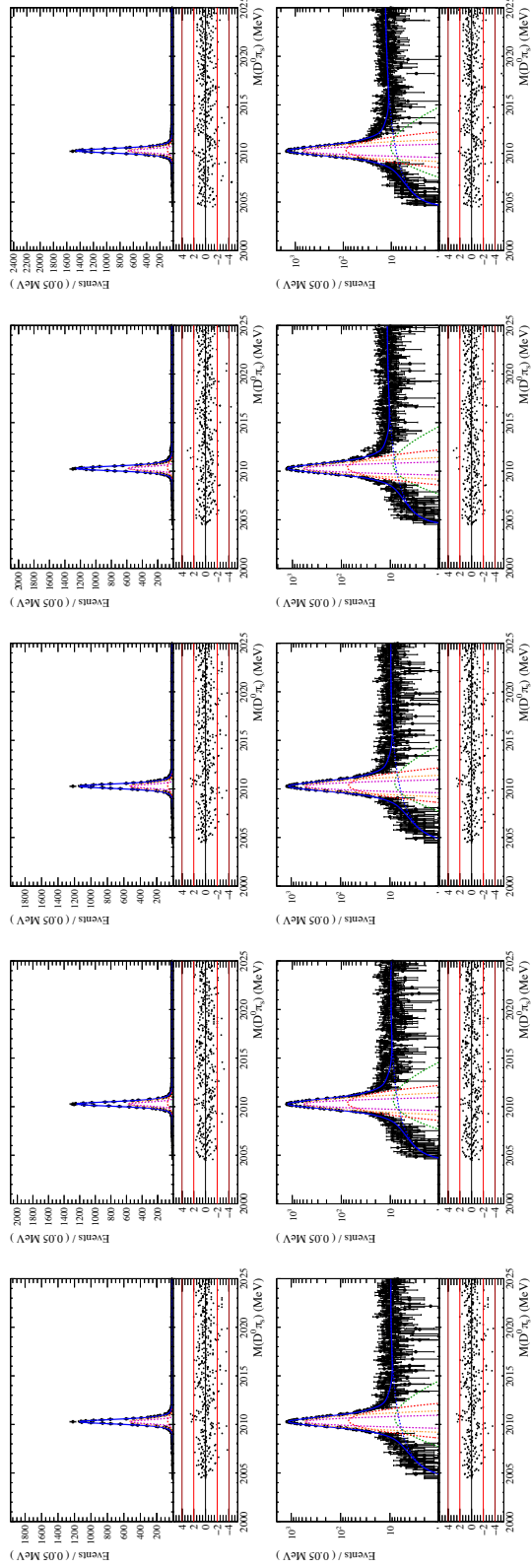


Figure A.68: MUONPT/BIN1 RS+ fits vs decay time. Top: linear, bottom: logy. Left to right is decay time bin.

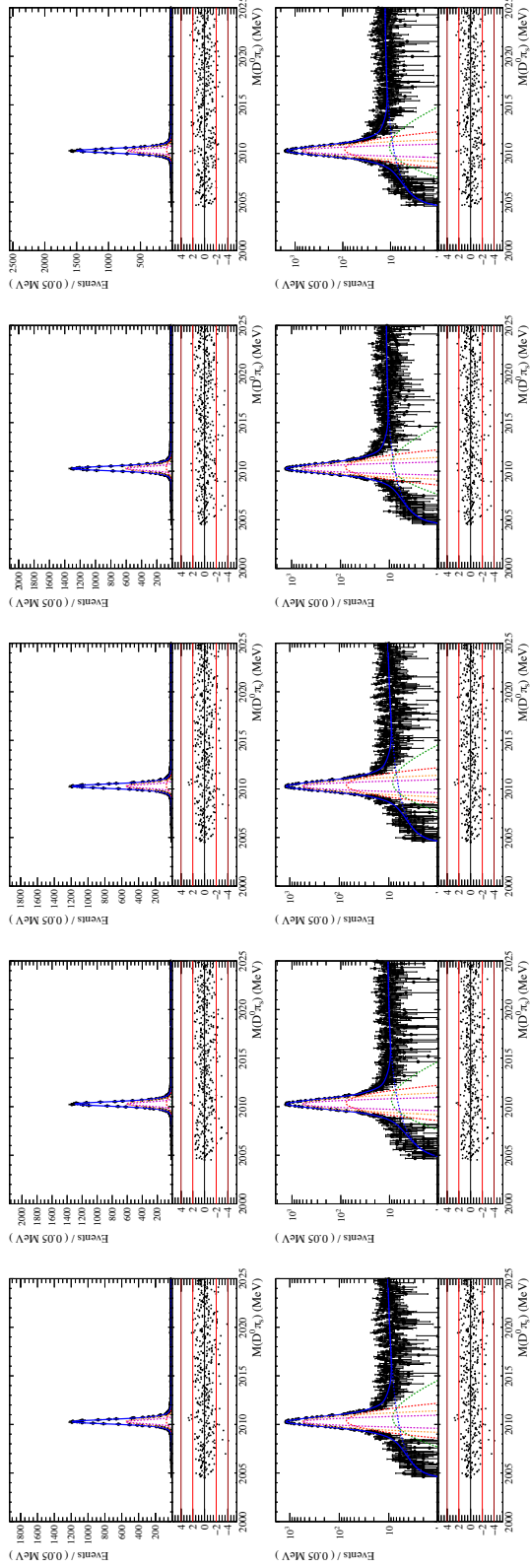


Figure A.69: MUONPT/BIN1 RS- fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

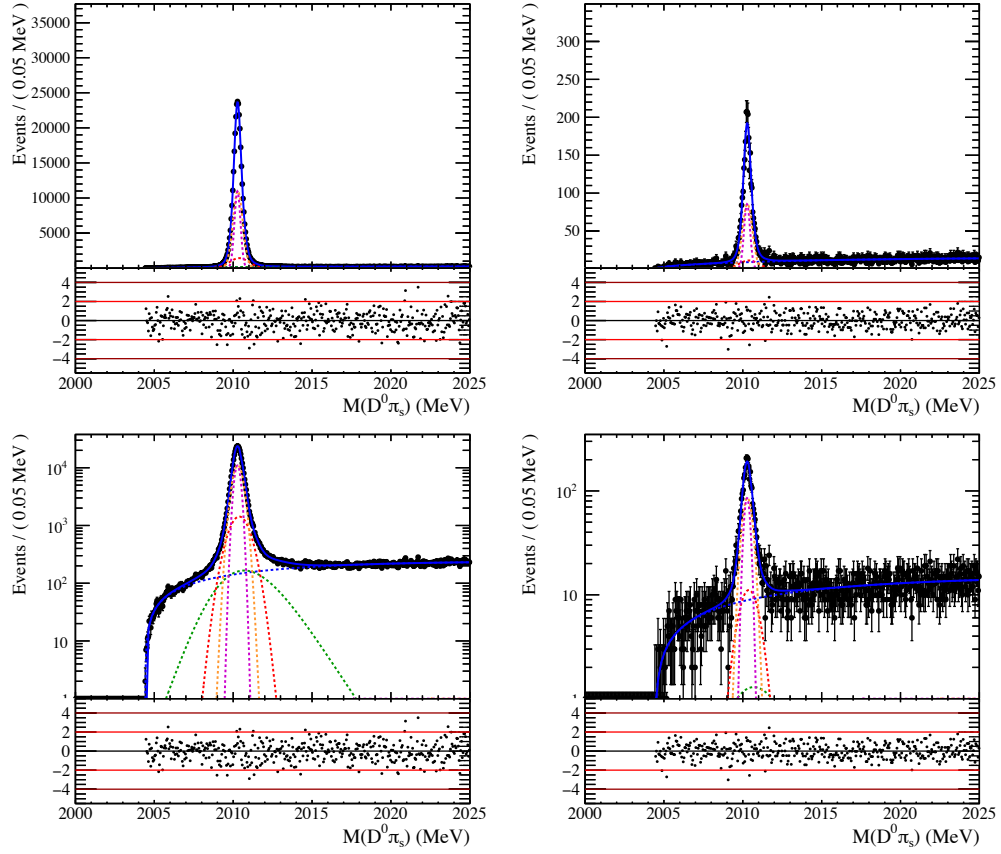


Figure A.70: Fits to the time integrated MUONPT/BIN2 sample. Left: RS, Right: WS, Top: Linear, Bottom: Semilog

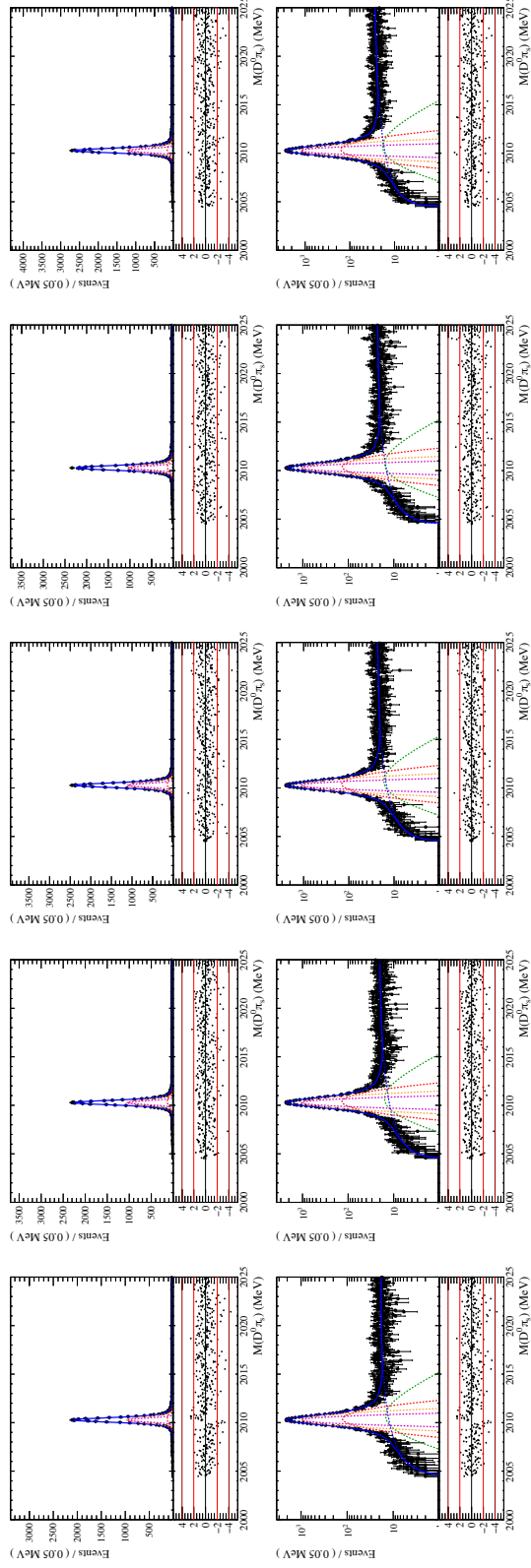


Figure A.71: MUONPT/BIN2 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

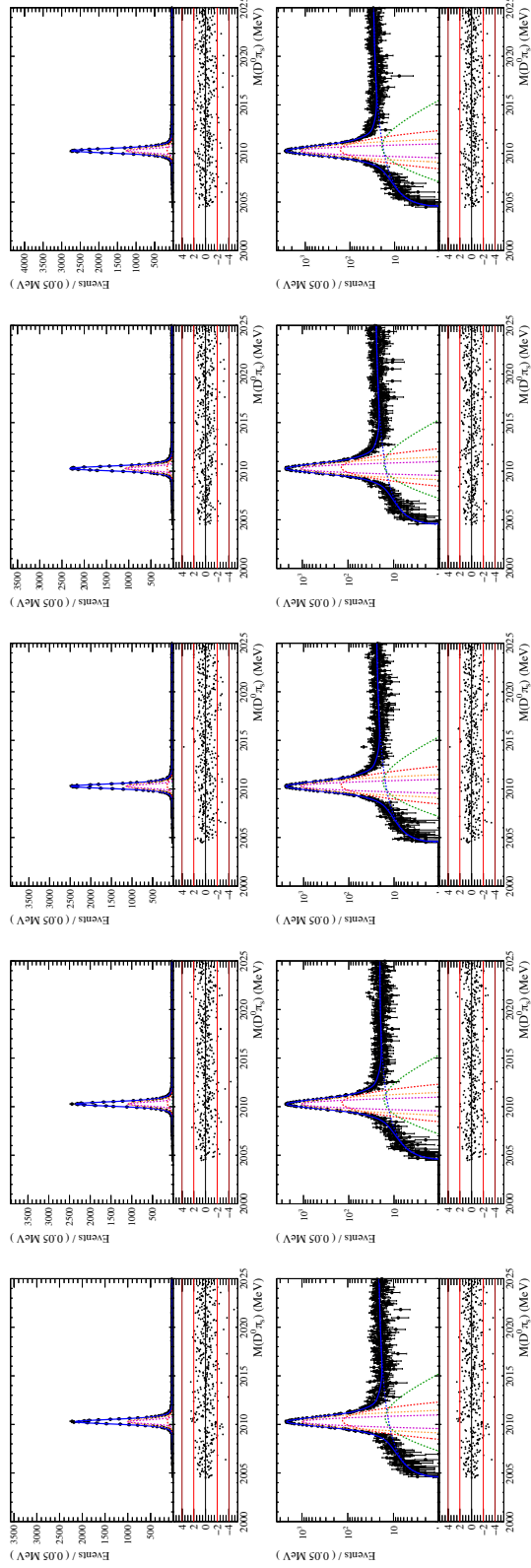


Figure A.72: MUONPT/BIN2 RS-fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

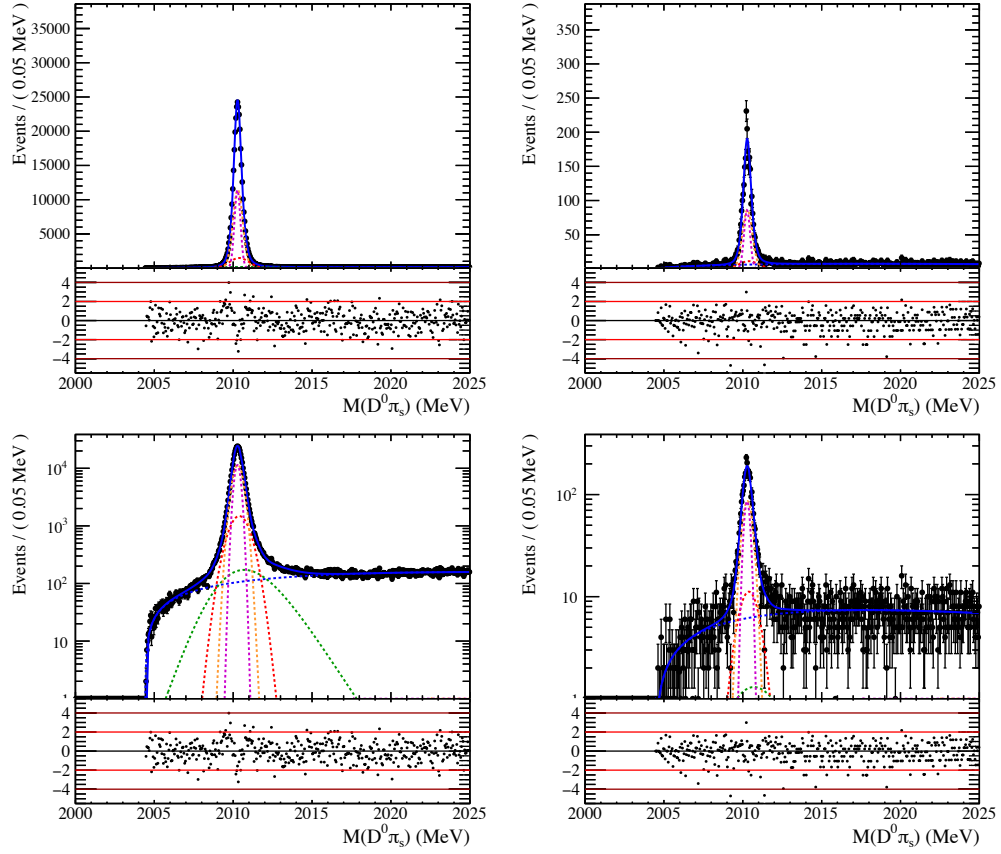


Figure A.73: Fits to the time integrated MUONPT/BIN3 sample. Left: RS, Right: WS, Top: Linear, Bottom: Semilog

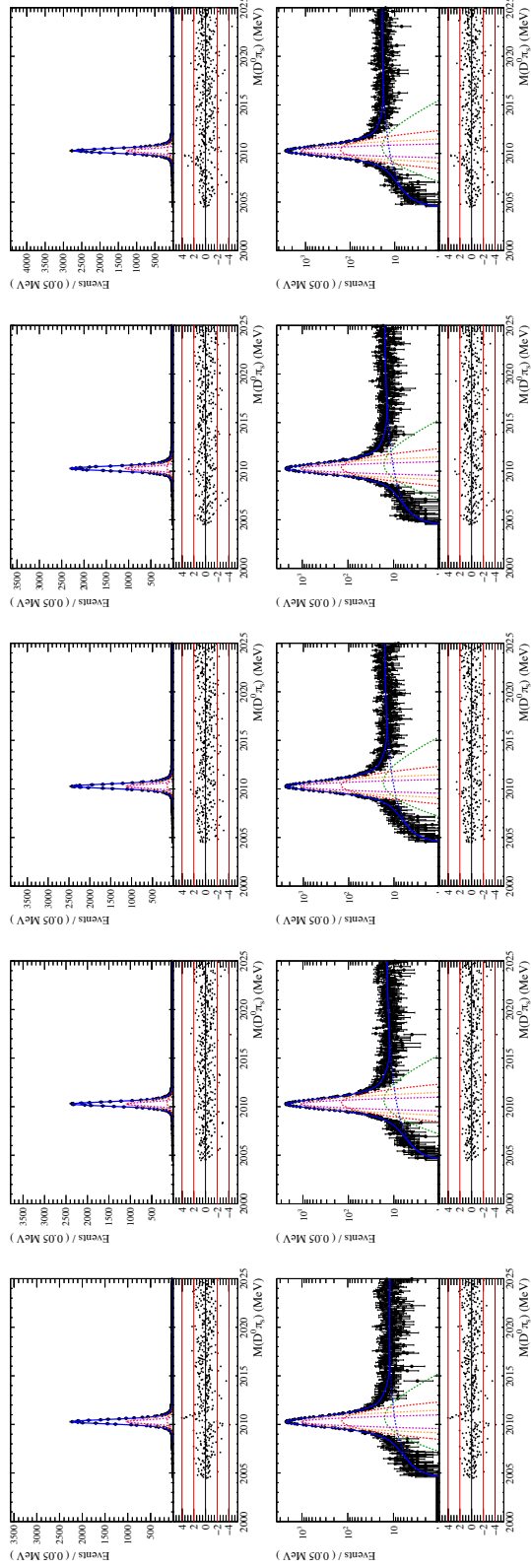


Figure A.74: MUONPT/BIN3 RS+ fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

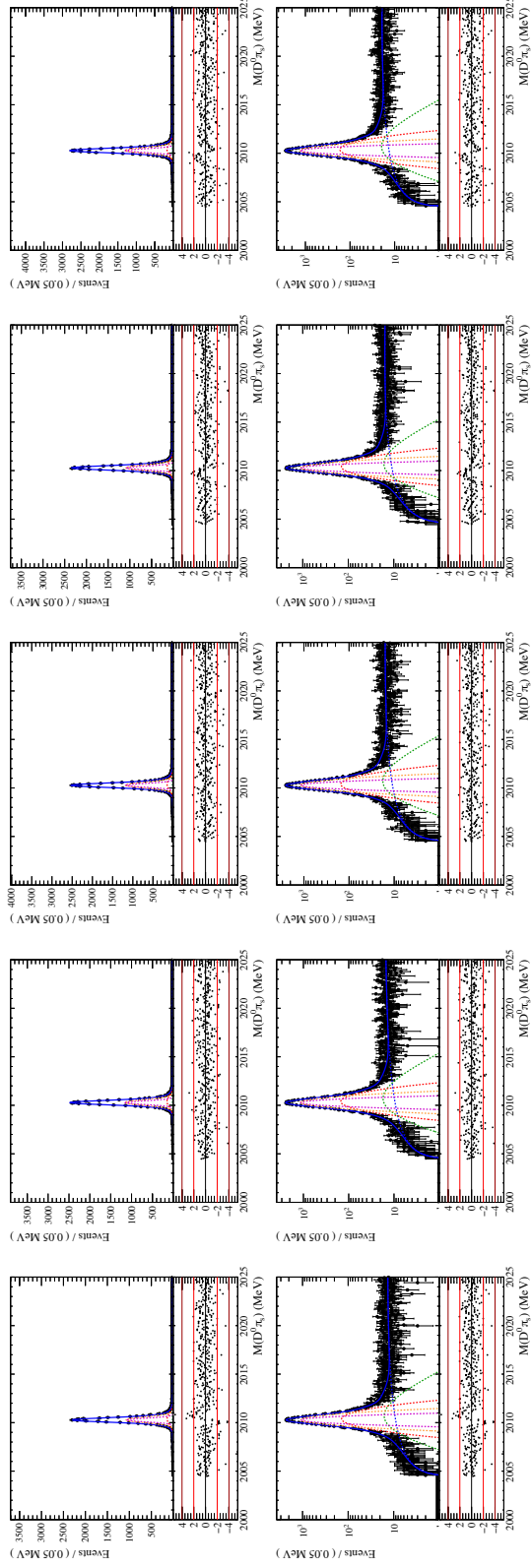


Figure A.75: MUONPT/BIN3 RS-fits vs decay time. Top:linear, bottom: logy. Left to right is decay time bin.

A.12 Fit for no mixing hypothesis

In this section, we adapt the fit to the DT data alone for a no-mixing hypothesis. In this hypothesis, both x'^2 and y' are set equal to zero, and the only parameter allowed to float is R_D . The same formalism for including the gaussian constraint is applied. The fits to the data are shown in Figure A.76. The data are not well described by this fit. The value of the

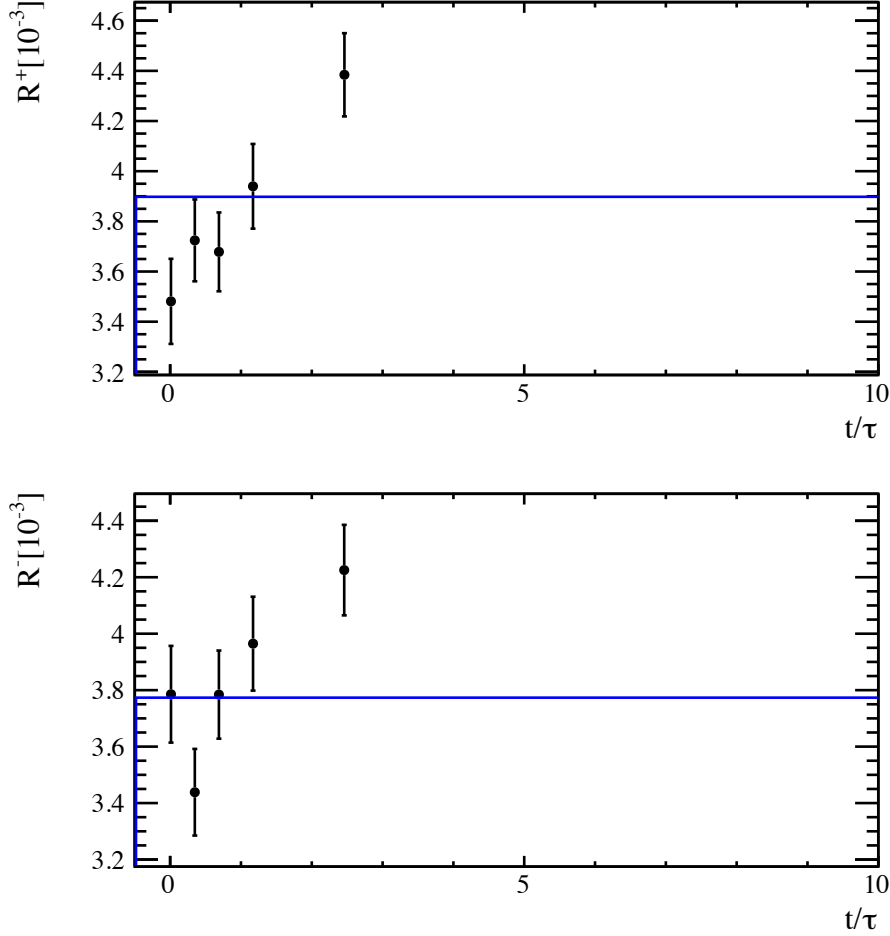


Figure A.76: Fit to the DT data with the no mixing hypothesis. The data are not well described by the fit.

fit is $R_D = (3.761116 \pm 0.054592) \times 10^{-3}$ with a χ^2/ndf of 31.953/9.

2169 **A.13 Comparison of Decay Time of DT Monte Carlo**
 2170 **to RD**

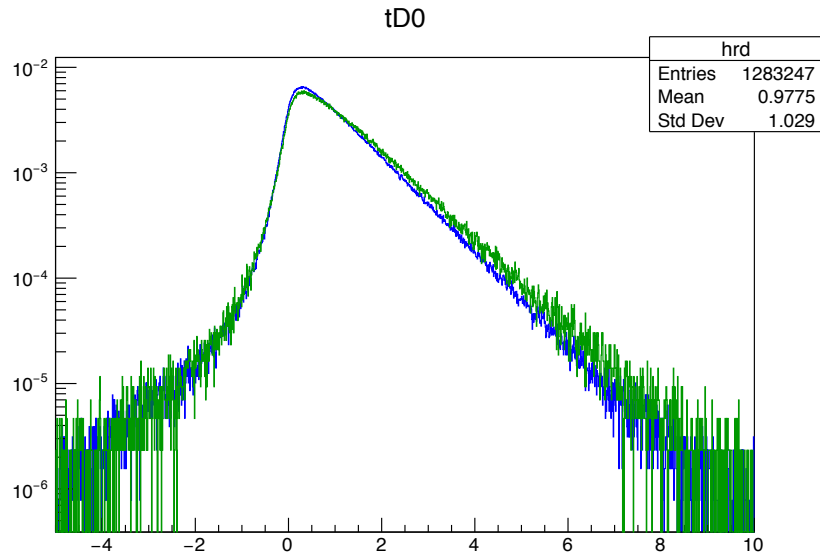


Figure A.77: Comparison of full MC (green) to Data (blue) of the D^0 decay time distribution. The curves are normalized to unit integral.