Conservative Estimates of PID systematics

Milind Purohit, Ryan White, Hongxuan Liu
(Univ. of South Carolina)

Abstract

In this note we present conservative estimates of systematic errors for the most commonly used PID selectors. We also present the techniques used so others may obtain systematic errors in a similar fashion for their analyses.

Contents

1 Introduction

We outline how estimates of systematic errors on PID efficiencies may be obtained and present results for the simplest cases.

First, we outline possible sources of systematic error on the PID efficiency of a signal yield:

1. Flaws in simulation of PID-related aspects of detectors, e.g., incorrect simulation of dE/dx, DIRC photons, incorrect simulation of material interactions.

2. MC may not simulate all runs equally well (time dependence).

3. Dependence on event environment, such as the track multiplicity, may be somewhat different in the signal mode (analysis sample) and the PID control sample mode on which PID tables are based.

4. Dependence on Λ, K_S^0 flight length, if any, could be different in the signal mode (analysis sample) and the PID control sample mode on which PID tables are based.

5. Possibly incorrect p, θ spectra of final state particles because the true signal PDF is not completely known, (e.g., polarization in decay).

6. Bin-centering corrections due to differences between signal and PID sample spectra within bins.

7. Problems intrinsic to the PID tweaking procedure.

Items 1, 2 should be covered by errors in the PID tweaking / weighting procedures. Items 3, 4 can be examined using data if signal is copious, from similar copious decay modes in data, or from MC.

In this note, we focus on items 1-4. Items 5, 6 must necessarily be handled by the analyst by varying the true pdf. Item 7 can be addressed by adjusting the PID tweaking procedure: this could be a project for someone eager to improve existing PID selectors.

2 Alternative PID tables

In this section we describe how alternative PID tables are obtained for the various particle types.

1. e and μ: We use leptonic decays of the J/Ψ in $B \to J/\Psi K^{(*)}$ decays. The statistical precision of these tables is far poorer than the standard PID tables.

2. π and K: We use the copious charm decay $D^+ \to K^-\pi^+\pi^+$. The statistical precision of these tables is comparable to the standard PID tables derived from $D^0 \to K^-\pi^+$ decays where the D^0 arises from D^{*+} decays.

3. p: We use $\Lambda_c^+ \to pK^*$ and $\Lambda_c^+ \to pK_S^0$ decays. [Yet to be implemented].

3 Procedures for estimating Systematic Errors

We will describe the procedures by referring to one or more of the tables that constitute the results of this note. Consider Table 1. The table lists estimates of systematic errors for the PID efficiency for a given selector, typically LH for the hadrons, NN for muons and Micro for electrons, at different tightness levels indicated by the column heading. The table is derived for a given sample of tracks. Currently we use electrons and muons from J/Ψ decay in the $B \rightarrow J/\Psi K^{(*)}$ mode, and kaons and pions from D^0 decay in the $B \rightarrow D^0\pi$ mode.

Note that we refer to one or more of three distinct samples in this note. The "PID control sample" (or "fine" binned sample) is the standard control sample used by the PID group. The "alternative PID sample" (or "coarse" binned sample) is the alternative PID sample mentioned in the section above. Finally, we pretend to be analysts finding an average PID efficiency and use an "analysis sample" (typically from signal MC) to define the (p, θ, ϕ) spectrum of the particles being studied.

The first row of errors is simply the statistical error due to the PID table statistics. Even with an infinitely large sample, the PID efficiency errors will make a finite contribution.

The second row reflects the statistics of the analysis sample.

The third row is an estimate of the error due to the statistics of the PID tweaking procedure.

The remaining rows are all derived from the difference in efficiency obtained from the standard PID table and from an alternative PID table. For leptons, the alternative PID table is obtained from a data sample of $B \rightarrow J/\Psi K^{(*)}$ decays. Since this has limited statistics, the binning of these tables is necessarily coarse. For this reason, in the following, we shall often refer to the alternative PID table as the "coarse binned" table, and the regular PID table as the "fine binned" table (even though for K and π the binning is the same). For K and π the alternative PID table is derived from $D^+ \rightarrow K^-\pi^+\pi^+$ decays.

Rows 4 through 6 are estimated from the slope of the (coarse - fine) difference vs. momentum, theta and time respectively. For time, we use the integrated luminosity, normalized to 1.

Row 7 lists the difference of average efficiencies. In all cases, we only use bins where the coarse-binned table has non-zero entries for comparison.

Adding all rows in quadrature implies double counting. Therefore, we take only the largest of the last 4 rows in quadrature with the first three to form the total error.

The expressions used for the various errors are as follows. The average efficiency is defined by

$$\langle \epsilon \rangle = \sum_i f_i \epsilon_i \tag{1}$$

where f_i is the fraction of events in bin i and ϵ_i is the efficiency in that bin. Note that the index i runs over all bins and is "multi-dimensional" in that sense. We chose not to use separate indices for p, θ and ϕ. Of course, since there are many runs, labeled by $j = 1 \ldots n_R$, we should write

$$\langle \epsilon \rangle = \sum_j l_j \sum_i f_{ji} \epsilon_{ji} \tag{2}$$

where l_j is the fractional integrated luminosity in each run: $\sum_j l_j = 1$. In actual practice, the efficiency is only averaged over bins in which both the "fine" and "coarse" binning values exist; such bins are labeled by i' to distinguish them from all bins.

The error on this average efficiency is defined by

$$\Delta\langle\epsilon\rangle = \sqrt{\sum_j l_j^2 \sum_{i'}[(\Delta f_{ji'})^2\epsilon_{ji'}^2 + f_{ji'}^2(\Delta\epsilon_{ji'})^2]} \tag{3}$$

Similarly, the error on the difference between average efficiencies $\delta\epsilon \equiv \epsilon_1 - \epsilon_2$ based on two different PID tables (1 and 2) is given by

$$(\Delta(\delta\epsilon))^2 = \sum_j l_j^2 \sum_{i'}[(\Delta f_{ji'})^2(\delta\epsilon_{ji'})^2 + f_{ji'}^2(\Delta(\delta\epsilon_{ji'}))^2] \tag{4}$$

The error due to the tweaking procedure is defined by

$$(\Delta\epsilon_{tw})^2 = \sum_j l_j^2 \sum_{i'}[(f_{ji'}\epsilon_{ji'}^{MC})^2\Delta r_{i'}^2] \tag{5}$$

where $\epsilon_{ji'}^{MC}$ is the MC efficiency in a bin and $\Delta r_{ji'}$ is the error on the ratio $\epsilon_{ji'}^{MC}/\epsilon_{ji'}$. For purposes of error estimation, we replace $\epsilon_{ji'}^{MC}$ in equation (5) above with $\epsilon_{ji'}$.

For the momentum, angle and time dependence, we plot the difference defined above vs. the relevant quantity and fit a straight line to this plot. The probability p_{sl} for the slope to be non-zero is defined as the χ^2-derived probability, using $\chi^2 = (a/\Delta a)^2$, where a is the slope and 1 degree of freedom. Then, the error is defined as

$$\Delta\epsilon = (1 - p_{sl})a\sigma \tag{6}$$

where σ is the rms of the independent variable (momentum, angle or time).

Why use this formula and where did it come from? Initially, we chose to examine the χ^2/DF for the constant difference hypothesis (no dependence) and assign a systematic error when the χ^2/DF exceeded unity. However, this caused the errors to jump from being zero to significantly non-zero values for selectors of different tightness. The formula above seeks to avoid such behavior.

This formula was our best guess. We knew that a low probability implied we should assign a systematic error, and a high probability meant we shouldn't, but didn't know how to smoothly go from one extreme to the other. This formula is something we just invented. We're still looking for a better one, so if you have a better argument, we can change it.

4 Conclusions and Remaining Issues

We find that the **electron** (and positron) errors are $\sim$1%. Considering all the problems the other particles display, this may be considered surprisingly good. In any case, it assures us that the code, which is essentially the same for all particle types, does not automatically create large systematic errors.

The **muon** alternative tables do not agree with the standard tables to better than 5%. The effect seems real since it can be reproduced by an independent program. Perhaps there is a magical cut one can apply to bring the numbers closer. Our search for a significant hadronic peaking background did not yield a positive result.

We have checked that the difference in muon efficiencies is not a simple programming error. First, one of us doing the analysis wrote separate programs to check the difference in the average efficiency for the full sample of μ^+ using the VeryLoose selector. They gave exactly the same result. Then, we had different people repeat the efficiency calculation for this same sample using yet other programs, one each for the "fine" and "coarse" binned samples. Once again, they obtained exactly the same numerical values for the PID efficiencies.

Pions and **Kaons** agree very well for the usual selectors (VL, L, T, VT) but not for the GLH Tight selector. It seems that the GLH Tight selector standard PID tables are a lot different from those for the usual Tight selector, so perhaps the problem lies with the GLH Tight selector. One remaining issue with the pions is why the momentum dependence is peculiar above 1.5 GeV.

Proton statistics are poor, and the alternative tables are $\sim$10% different from the standard tables. The only cut which gives a clear mass peak for the $\Lambda_c^+ \to pK_S^0$ channel is the proton PID cut, so fits without this cut tend to exhibit all the ills of poor statistics. Perhaps we should switch to the $\Lambda_c^+ \to pK^-\pi^+$ mode where PID cuts on the charged kaon can be made.

5 Acknowledgements

We would like to acknowledge all those who have done similar studies in the past, since we learned so much from them. For example, the idea behind eqn. (1) is from Mike Roney et al. (see the PID systematics web page for a more complete list of prior analyses). We also got good comments from many people inside and outside the PID group, including David Aston, Kevin Flood, Riccardo Faccini, Ilya Narsky and Roger Barlow. We also got much help for the lepton ntuples and associated code from Jonathan Hollar, and from Kevin Flood.

Finally, we would like to end with a reminder from Mike Sokoloff: each analyst should estimate systematic errors for their analysis on their own, because there are many differences between analyses. For instance, an analysis may use ChargedTracks in place of GoodTracksVeryLoose, or may have different vertexing cuts. Track and vertexing quality can affect ones choice of tracks and therefore of PID efficiencies. Similarly, background shapes can affect yields and PID efficiencies based on such yields.

6 Appendix I: Tables

Table 1: Summary of systematic errors in % for e^-.

	PidLH	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.00	0.00	0.00	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00	0.00
Momentum dependence	0.11	0.26	0.39	0.12	0.33
Theta dependence	1.03	0.32	0.12	1.08	0.41
Run dependence	0.85	0.78	1.26	0.27	0.26
Other PID table	0.84	1.35	2.51	2.27	2.46
Total	1.03	1.35	2.51	2.27	2.46

Table 2: Summary of systematic errors in % for e^+.

	PidLH	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.00	0.00	0.00	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00	0.00
Momentum dependence	0.18	0.15	0.08	0.02	0.01
Theta dependence	0.00	0.18	0.01	0.29	0.11
Run dependence	0.18	0.37	0.44	0.37	0.07
Other PID table	0.69	0.07	0.08	0.34	0.37
Total	0.69	0.37	0.44	0.37	0.37

Table 3: Summary of asymmetries and errors in % for e.

	PidLH	VLoose	Loose	Tight	VTight
Fine Asymmetry	0.31 ± 0.02	2.44 ± 0.03	0.20 ± 0.03	0.05 ± 0.03	0.12 ± 0.03
Coarse Asymmetry	0.21 ± 0.12	2.88 ± 0.06	0.93 ± 3.15	0.41 ± 0.47	0.72 ± 0.15
CrsAsym - FineAsym	-0.09 ± 0.12	0.43 ± 0.07	0.73 ± 3.15	0.36 ± 0.47	0.61 ± 0.15

Table 4: Summary of systematic errors in % for μ^-.

	MinIon	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.00	0.00	0.00	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00	0.00
Momentum dependence	0.20	0.35	0.12	0.30	0.00
Theta dependence	1.14	0.01	0.00	0.66	1.25
Run dependence	0.05	1.52	1.80	0.20	0.08
Other PID table	2.45	4.61	5.20	4.53	5.11
Total	2.45	4.61	5.20	4.53	5.11

Table 5: Summary of systematic errors in % for μ^+.

	MinIon	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.00	0.00	0.00	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00	0.00
Momentum dependence	0.04	0.01	0.05	0.03	2.24
Theta dependence	0.85	0.42	0.94	2.89	0.83
Run dependence	0.02	0.05	2.21	0.94	0.06
Other PID table	0.59	3.68	5.08	3.99	3.17
Total	0.85	3.68	5.08	3.99	3.17

Table 6: Summary of asymmetries and errors in % for μ.

	MinIon	VLoose	Loose	Tight	VTight
Fine Asymmetry	0.02 ± 0.03	1.25 ± 0.02	1.24 ± 0.02	1.50 ± 0.03	1.56 ± 0.03
Coarse Asymmetry	1.36 ± 0.05	1.87 ± 0.17	1.40 ± 1.71	2.00 ± 1.21	3.15 ± 0.18
CrsAsym - FineAsym	1.35 ± 0.06	0.62 ± 0.17	0.16 ± 1.71	0.51 ± 1.21	1.60 ± 0.18

Table 7: Summary of systematic errors in % for π^-.

	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.01	0.01	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00
Momentum dependence	1.11	0.47	0.48	0.78
Theta dependence	0.53	0.37	0.00	0.24
Run dependence	0.03	0.00	0.20	0.03
Other PID table	0.27	0.05	0.01	0.00
Total	1.11	0.47	0.48	0.78

Table 8: Summary of systematic errors in % for π^+.

	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.01	0.01	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00
Momentum dependence	0.94	0.45	0.52	0.87
Theta dependence	0.44	0.25	0.30	0.32
Run dependence	0.19	0.01	0.26	0.25
Other PID table	0.02	0.00	0.00	0.00
Total	0.94	0.45	0.52	0.87

Table 9: Summary of asymmetries and errors in % for π.

	VLoose	Loose	Tight	VTight
Fine Asymmetry	-0.03 ± 0.04	0.13 ± 0.04	0.05 ± 0.03	-0.34 ± 0.03
Coarse Asymmetry	0.02 ± 0.01	0.39 ± 0.00	0.25 ± 0.00	-0.20 ± 0.00
CrsAsym - FineAsym	0.05 ± 0.04	0.26 ± 0.04	0.20 ± 0.03	0.14 ± 0.03

Table 10: Summary of systematic errors in % for K^-.

	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.00	0.00	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00
Momentum dependence	0.62	0.15	0.18	0.30
Theta dependence	0.41	0.52	0.68	0.73
Run dependence	0.02	0.07	0.00	0.00
Other PID table	0.00	0.55	1.98	2.05
Total	0.62	0.55	1.98	2.05

Table 11: Summary of systematic errors in % for K^+.

	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.00	0.00	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00
Momentum dependence	0.48	0.15	0.01	0.11
Theta dependence	0.19	0.83	0.87	0.91
Run dependence	0.15	0.04	0.00	0.00
Other PID table	0.00	0.26	1.46	1.56
Total	0.48	0.83	1.46	1.56

Table 12: Summary of asymmetries and errors in % for K.

	VLoose	Loose	Tight	VTight
Fine Asymmetry	0.32 ± 0.04	0.22 ± 0.04	0.31 ± 0.04	0.29 ± 0.04
Coarse Asymmetry	0.11 ± 0.00	0.21 ± 0.00	0.39 ± 0.00	0.39 ± 0.00
CrsAsym - FineAsym	-0.20 ± 0.04	-0.01 ± 0.04	0.08 ± 0.04	0.10 ± 0.04

Table 13: Summary of systematic errors in % for p^-.

	GLHT	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.00	0.00	0.00	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00	0.00
Momentum dependence	0.01	0.89	4.05	4.74	0.67
Theta dependence	4.63	0.00	0.55	0.14	0.85
Run dependence	4.94	7.59	9.42	7.53	6.37
Other PID table	1.10	5.30	10.93	10.13	7.77
Total	4.94	7.59	10.93	10.13	7.77

Table 14: Summary of systematic errors in % for p^+.

	GLHT	VLoose	Loose	Tight	VTight
PID Efficiency Statistics	0.00	0.00	0.00	0.00	0.00
Analysis Sample Statistics	0.00	0.00	0.00	0.00	0.00
Data/MC Effy. Ratio statistics	0.00	0.00	0.00	0.00	0.00
Momentum dependence	0.01	1.42	0.28	0.01	1.14
Theta dependence	0.03	3.00	4.15	4.82	4.64
Run dependence	8.85	0.59	2.39	3.39	0.86
Other PID table	3.29	15.75	12.57	9.37	8.32
Total	8.85	15.75	12.57	9.37	8.32

Table 15: Summary of asymmetries and errors in % for p.

	GLHT	VLoose	Loose	Tight	VTight
Fine Asymmetry	2.20 ± 0.01	2.75 ± 0.02	2.03 ± 0.01	1.66 ± 0.01	0.82 ± 0.01
Coarse Asymmetry	0.91 ± 0.07	-3.65 ± 0.11	1.25 ± 0.09	2.40 ± 0.06	0.50 ± 0.07
CrsAsym - FineAsym	-1.29 ± 0.07	-6.40 ± 0.11	-0.78 ± 0.09	0.73 ± 0.07	-0.33 ± 0.07

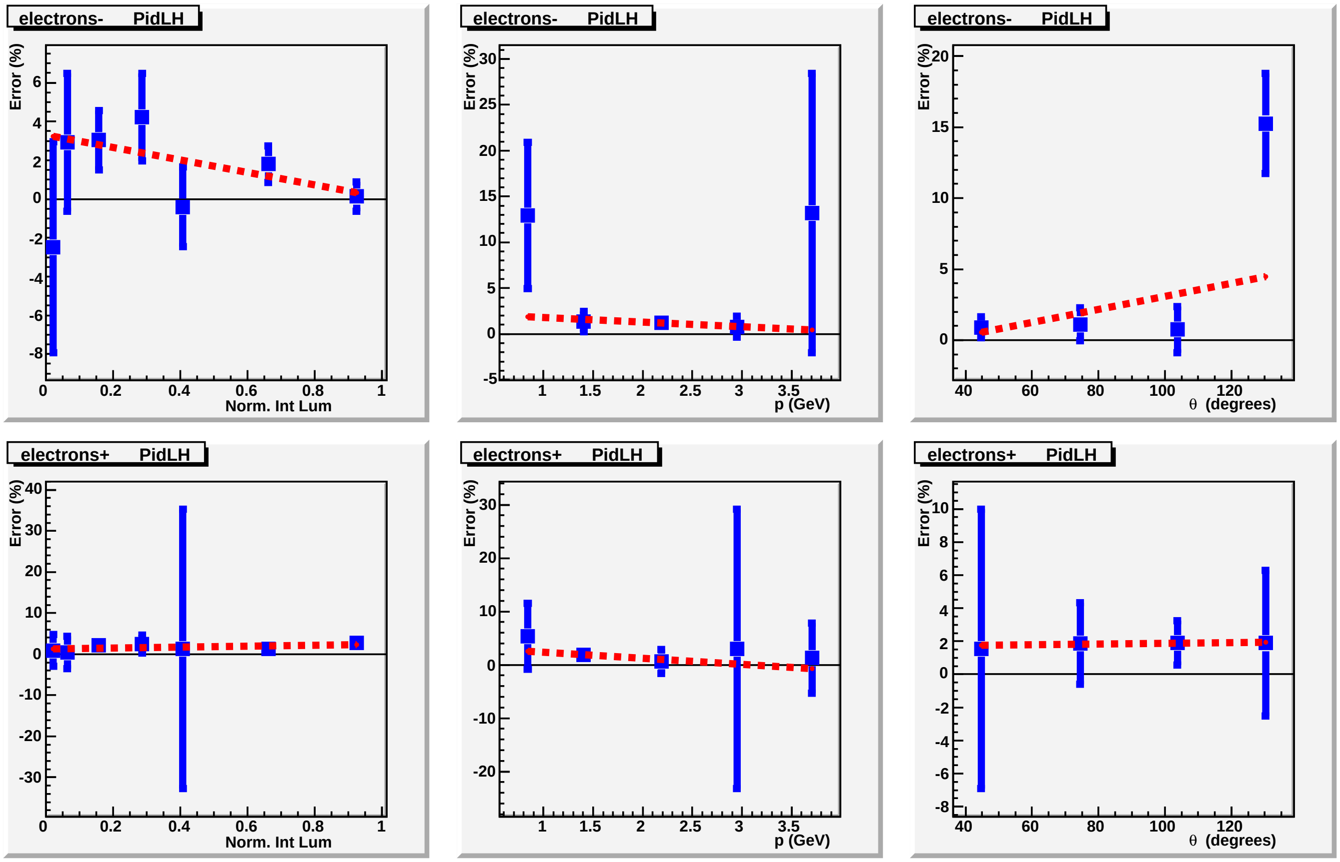

Figure 1: p, θ and run dependence of differences in PID efficiencies for electrons (NotPi).

7 Appendix II: Figures

We include here all the figures showing the momentum, angle and time dependence of differences between PID efficiencies obtained using two different control samples. In all cases the quantity plotted is the standard PID efficiency minus the alternative PID efficiency, in %. Only point-to-point statistical errors are shown and used in the linear fit, with the correlated errors removed.

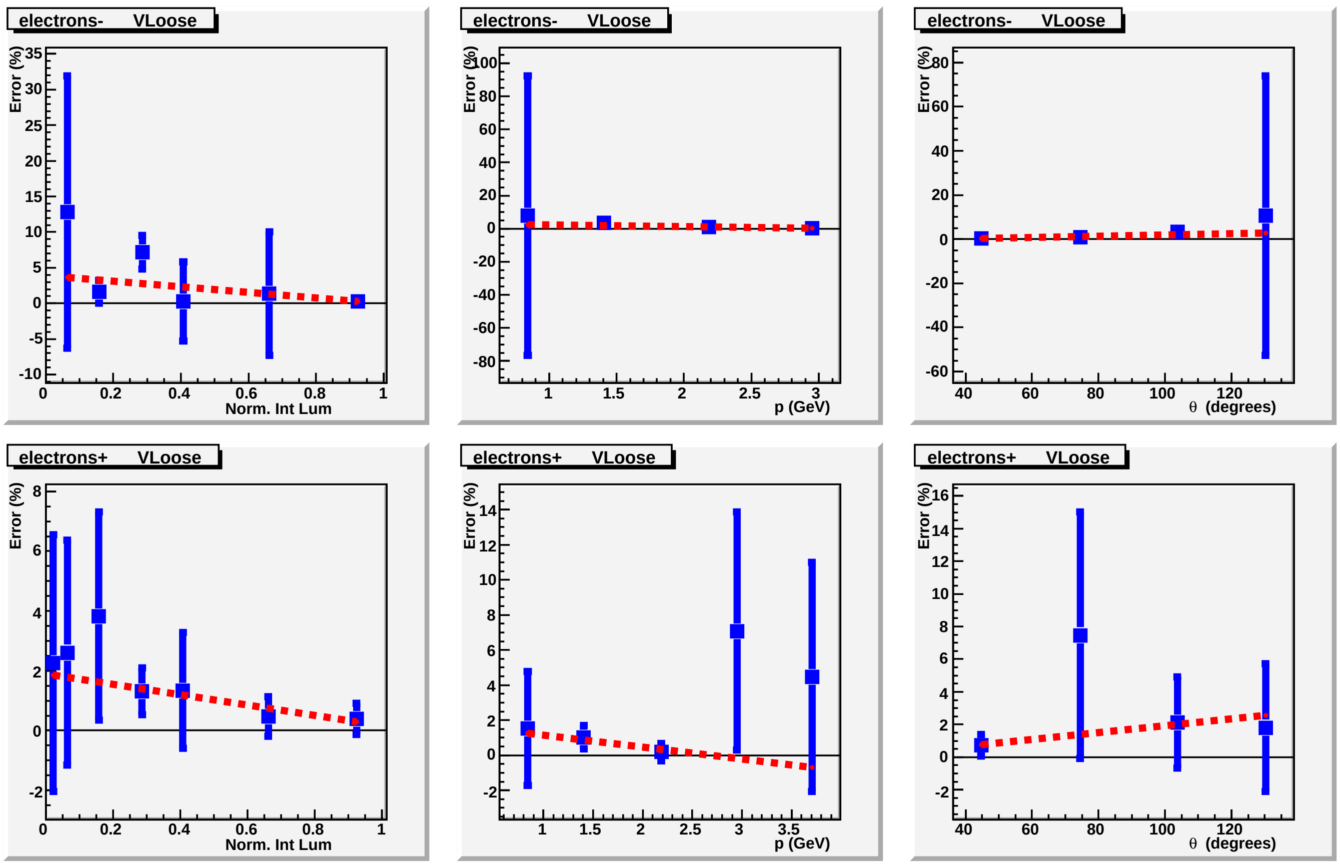

Figure 2: p, θ and run dependence of differences in PID efficiencies for electrons (VLoose).

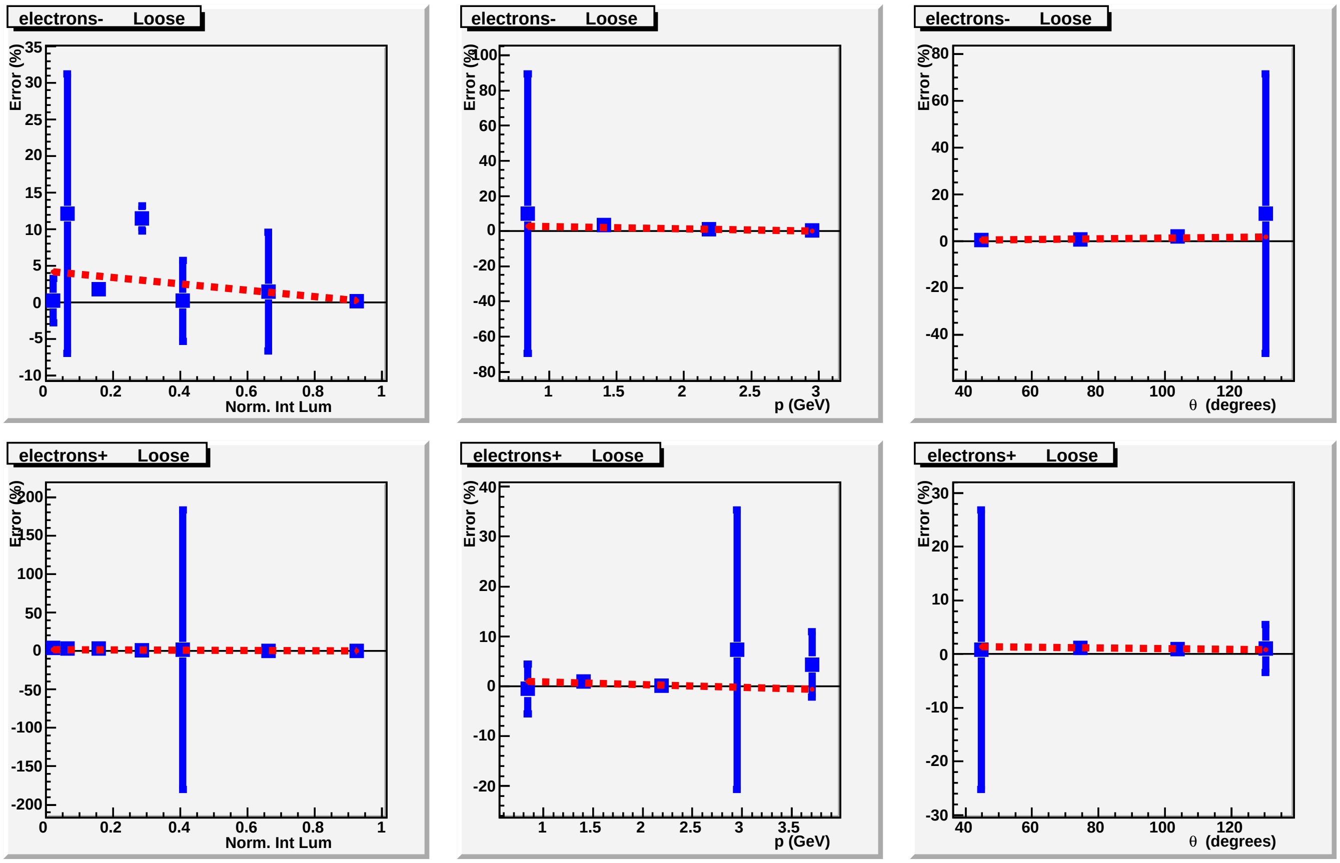

Figure 3: p, θ and run dependence of differences in PID efficiencies for electrons (Loose).

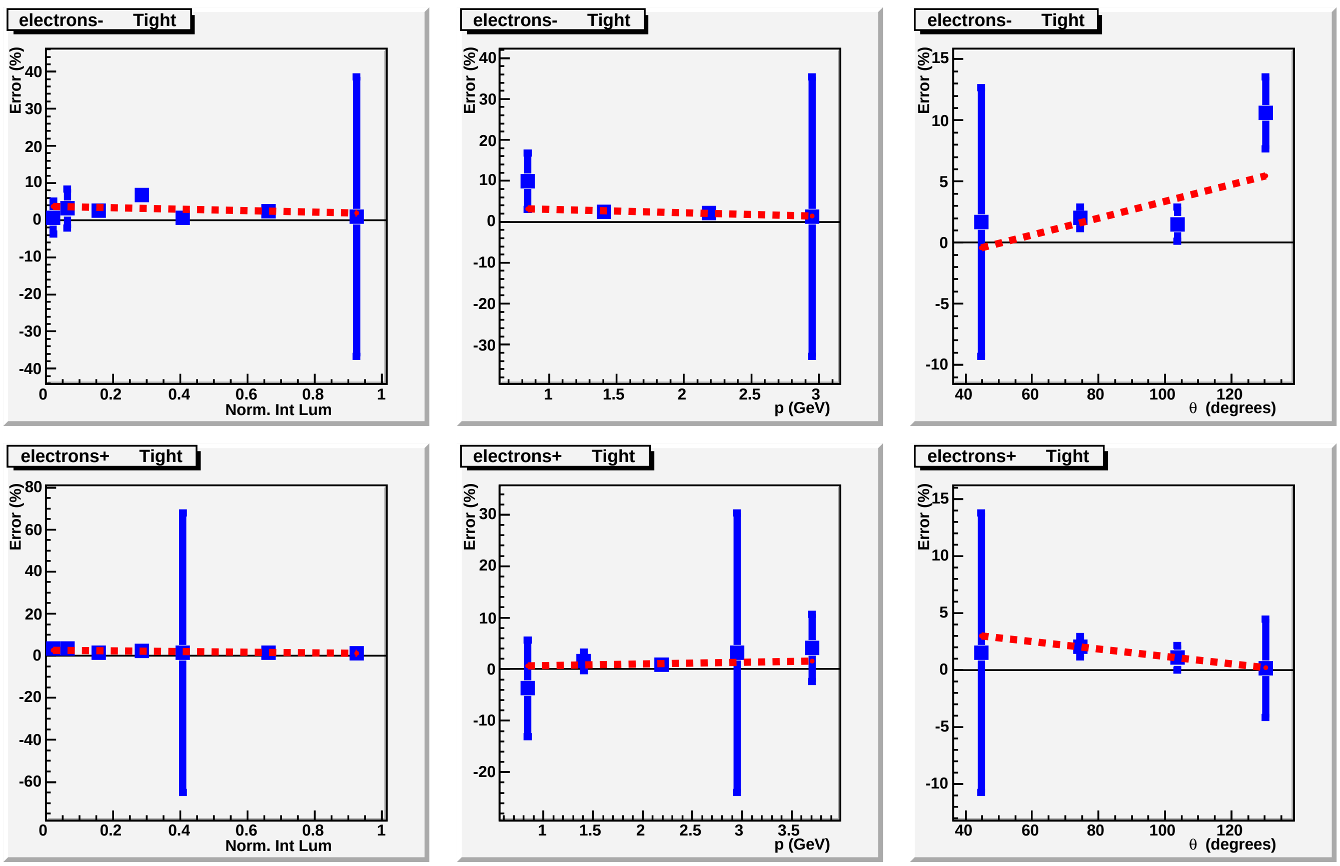

Figure 4: p, θ and run dependence of differences in PID efficiencies for electrons (Tight).

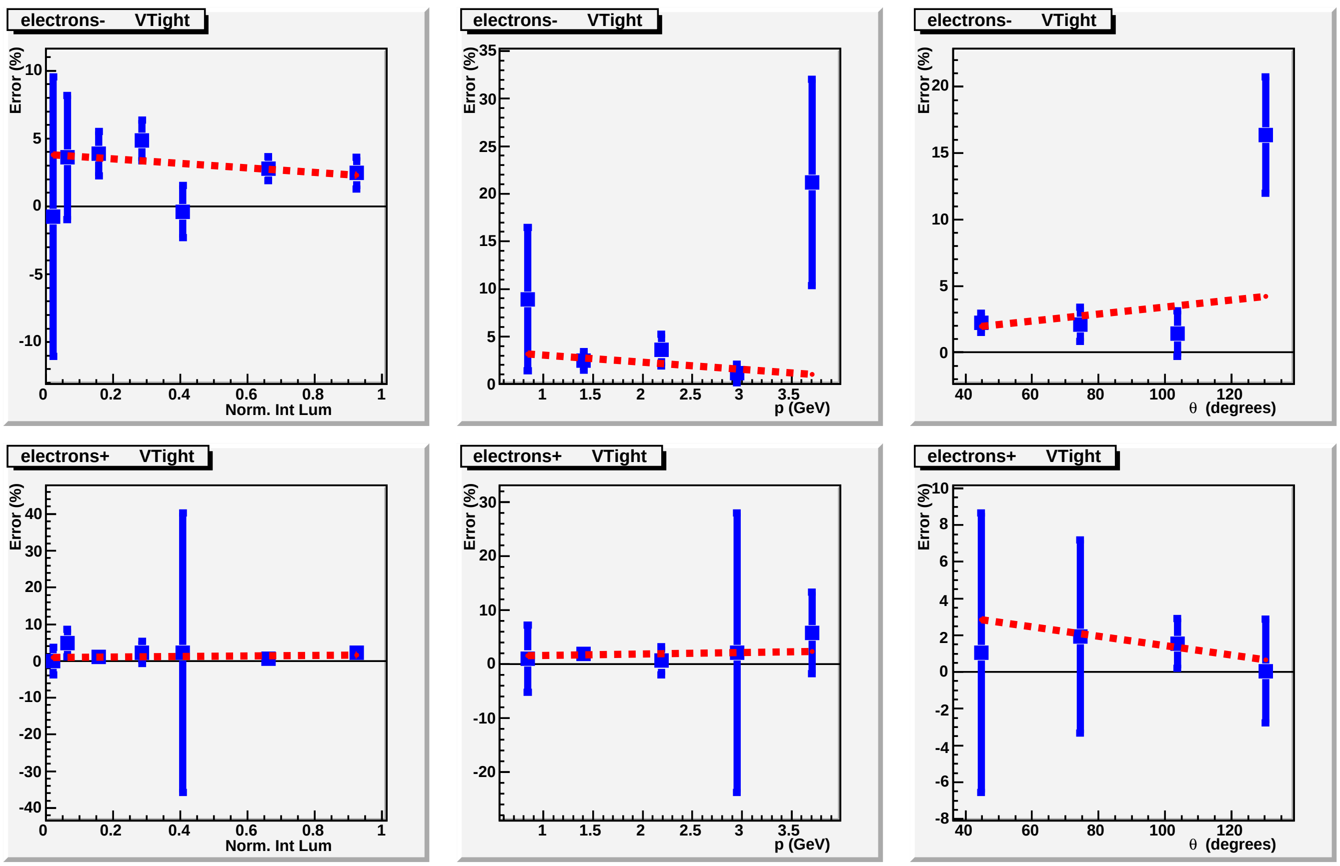

Figure 5: p, θ and run dependence of differences in PID efficiencies for electrons (VTight).

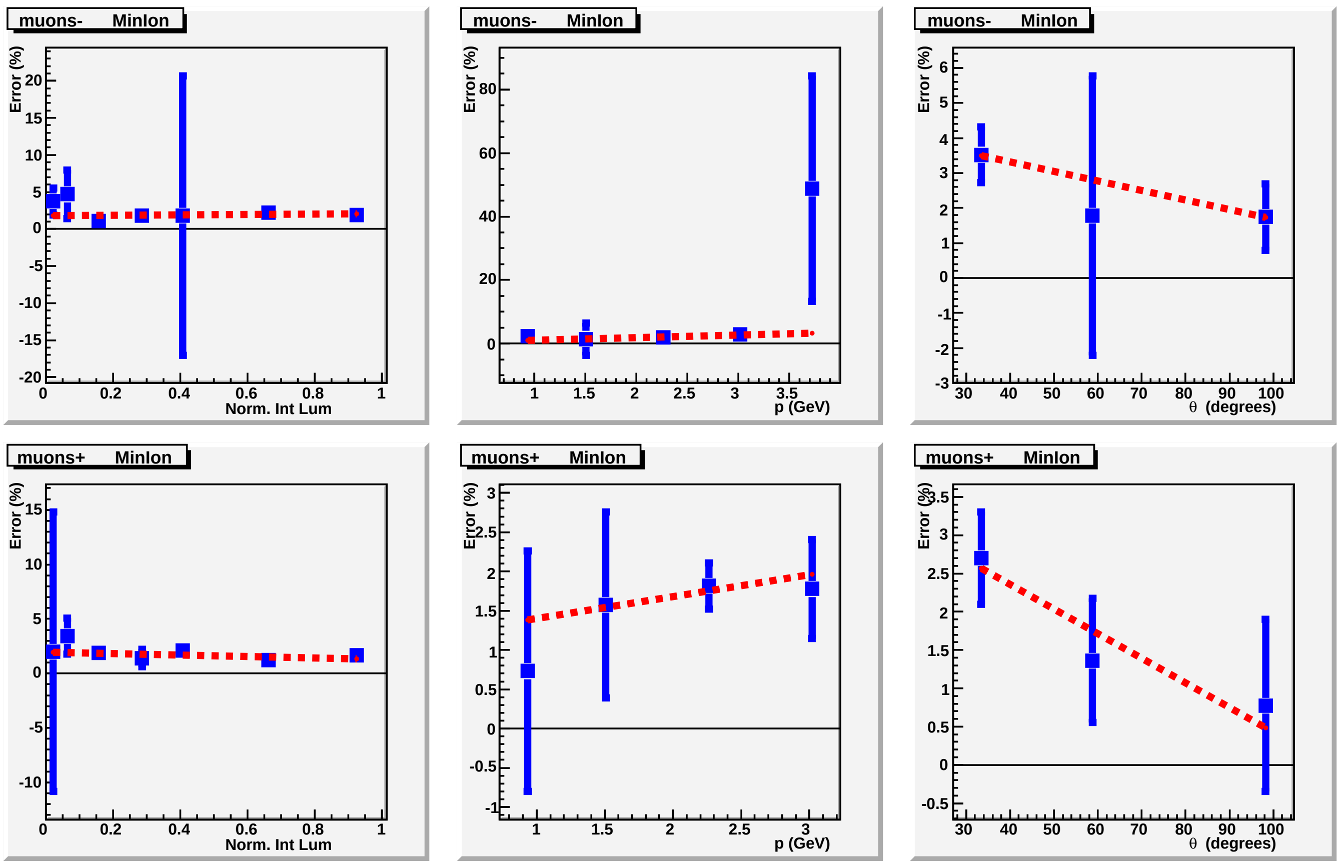

Figure 6: p, θ and run dependence of differences in PID efficiencies for muons (MinIon).

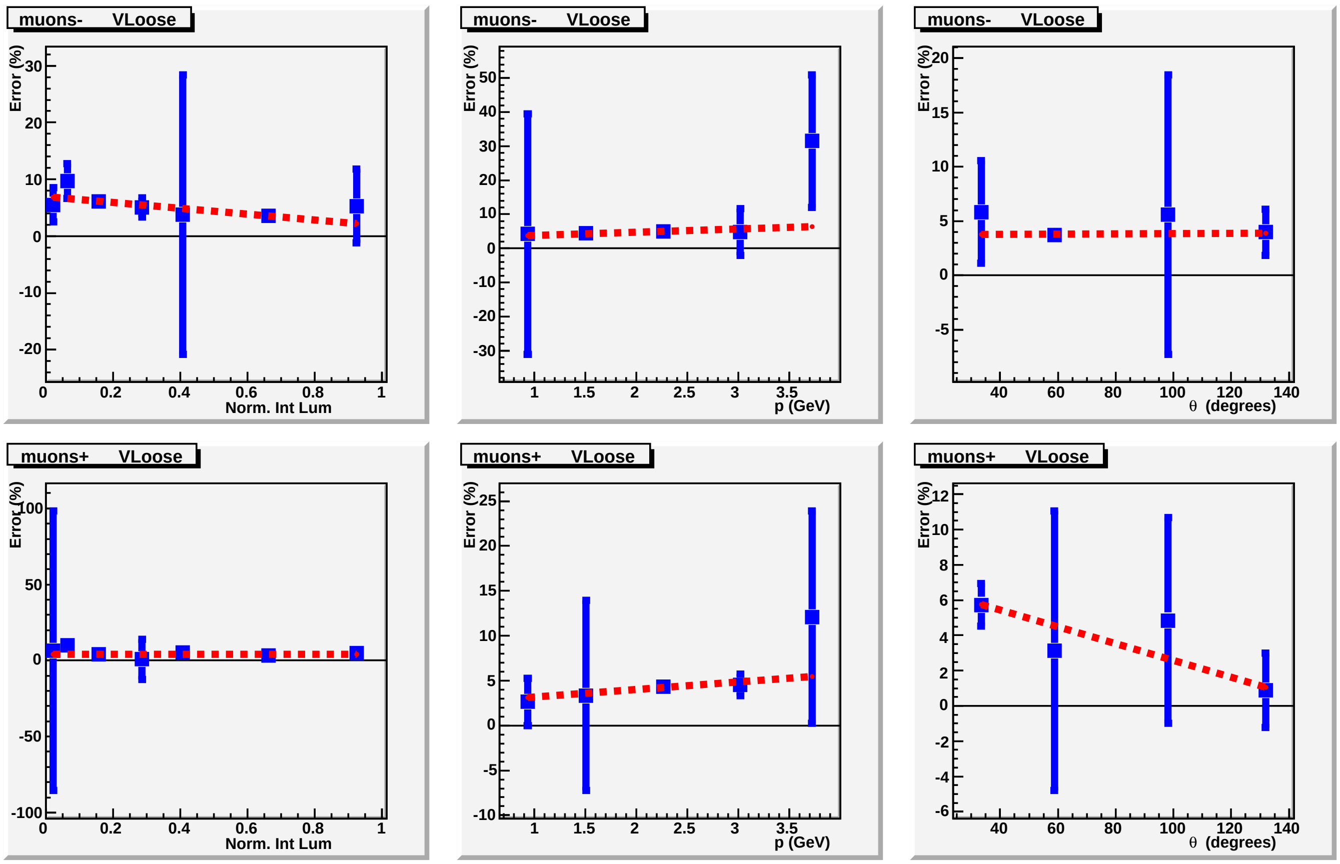

Figure 7: p, θ and run dependence of differences in PID efficiencies for muons (VLoose).

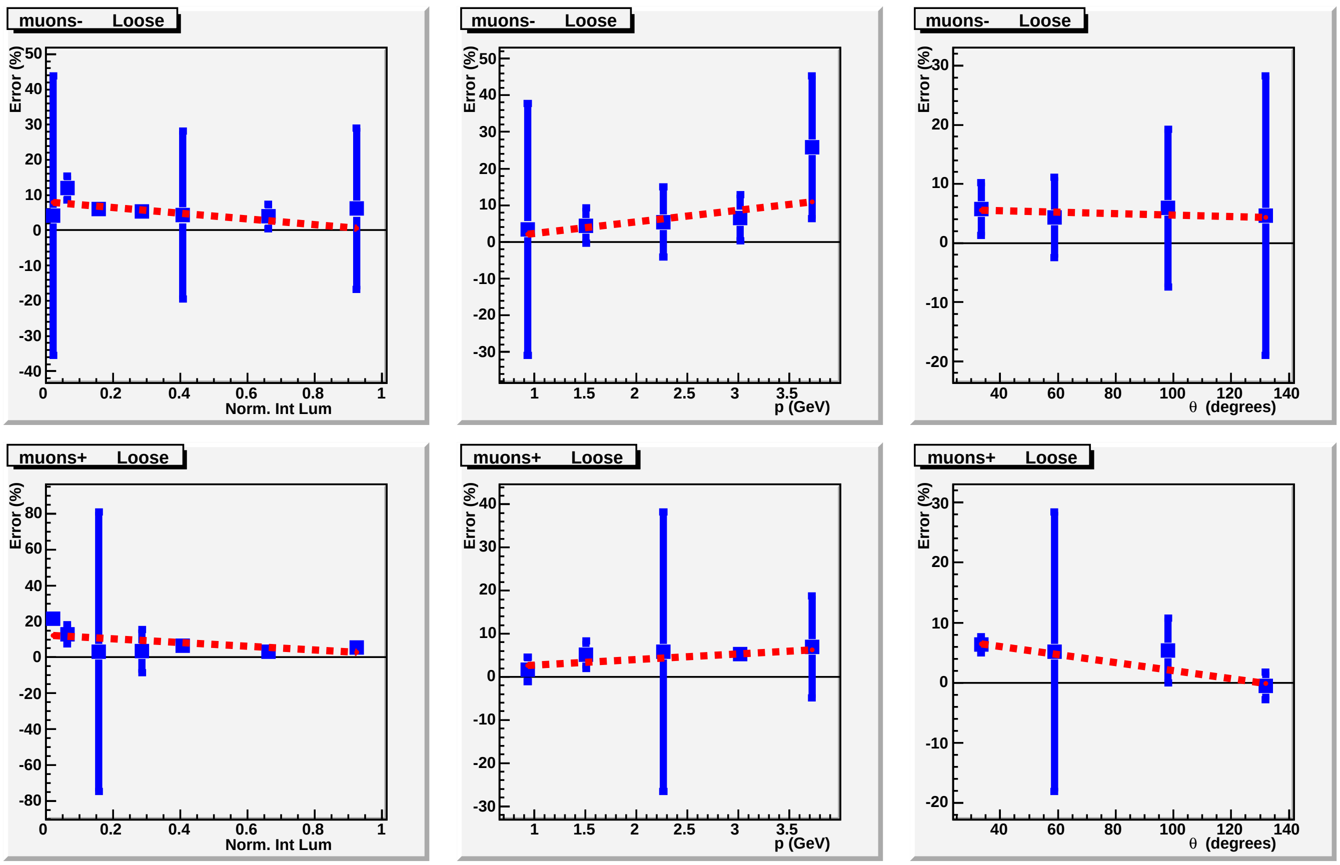

Figure 8: p, θ and run dependence of differences in PID efficiencies for muons (Loose).

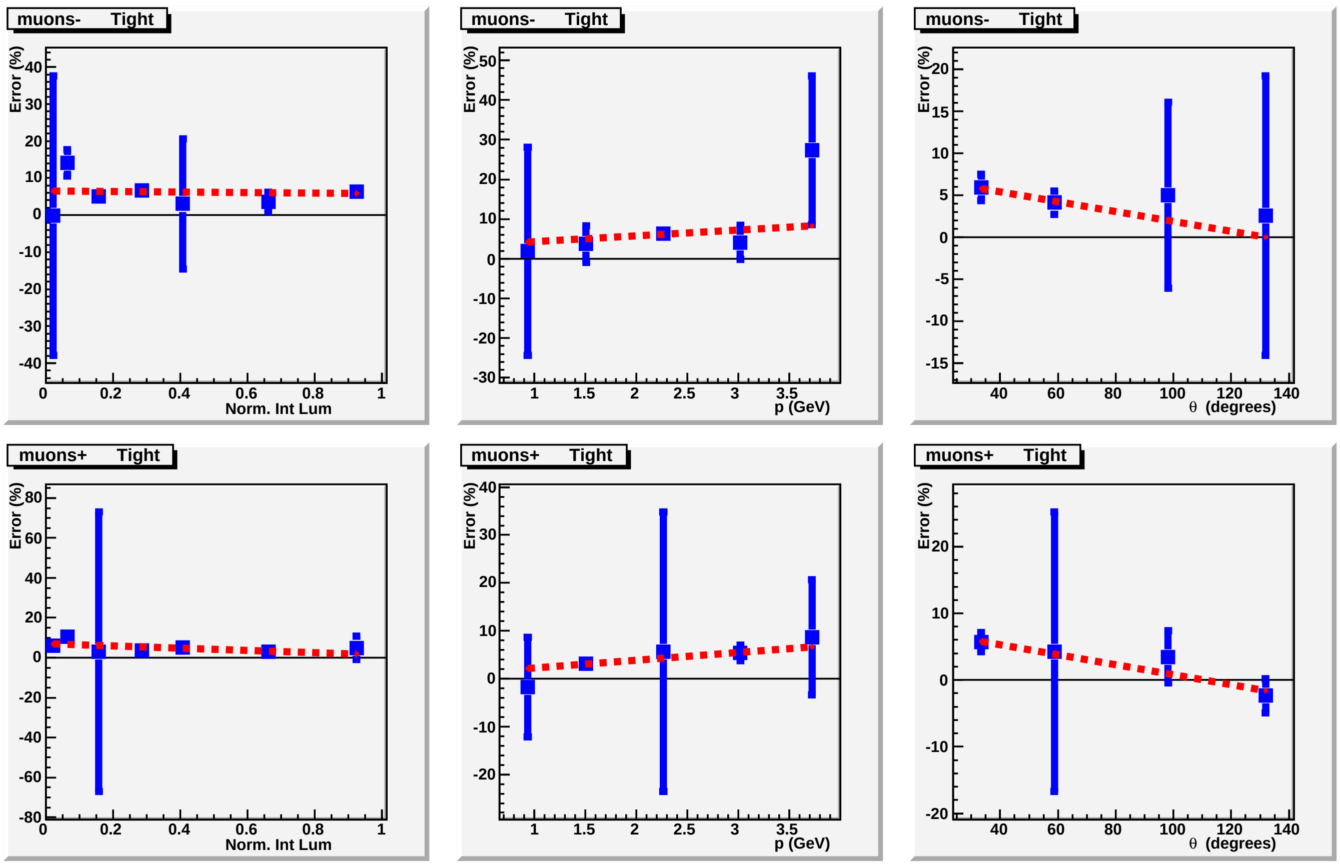

Figure 9: p, θ and run dependence of differences in PID efficiencies for muons (Tight).

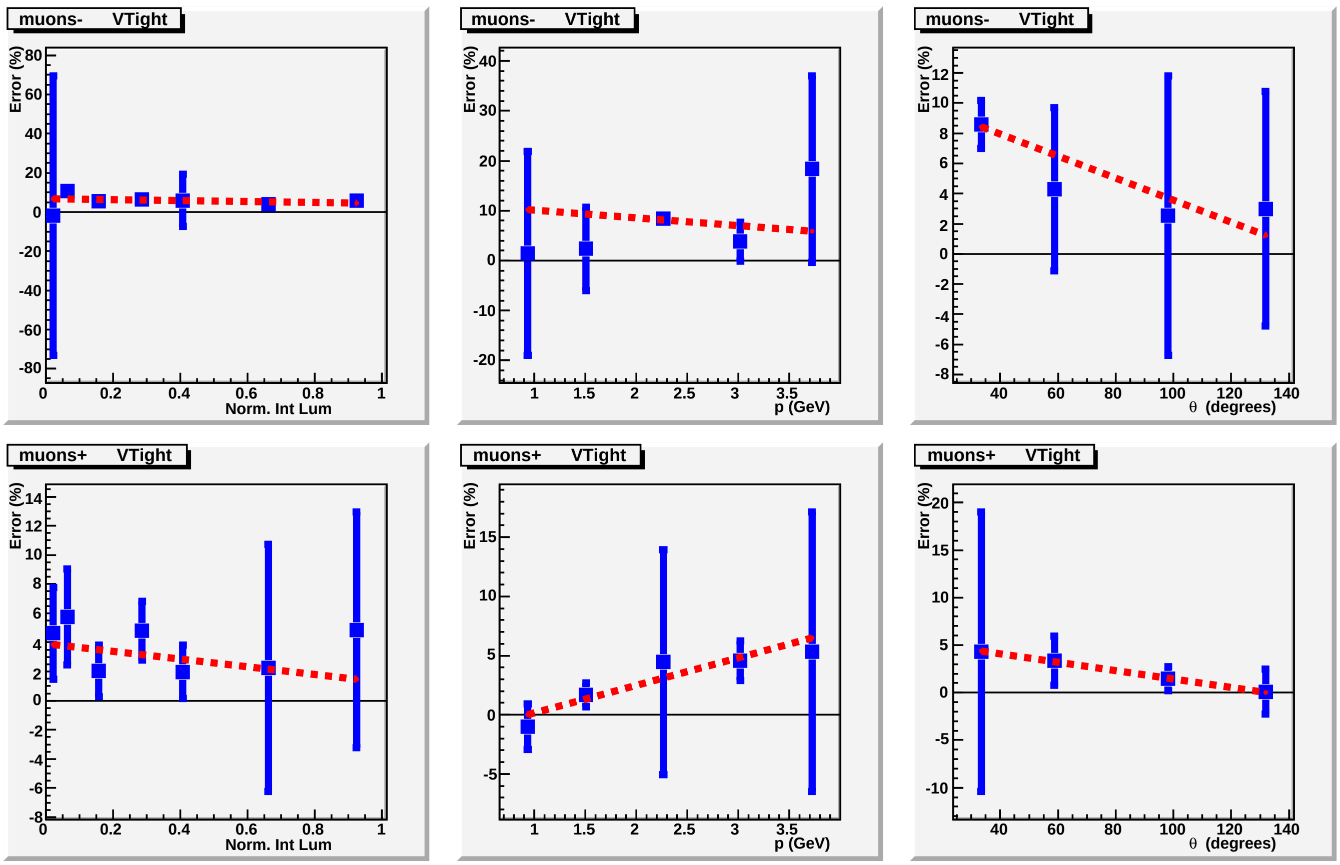

Figure 10: p, θ and run dependence of differences in PID efficiencies for muons (VTight).

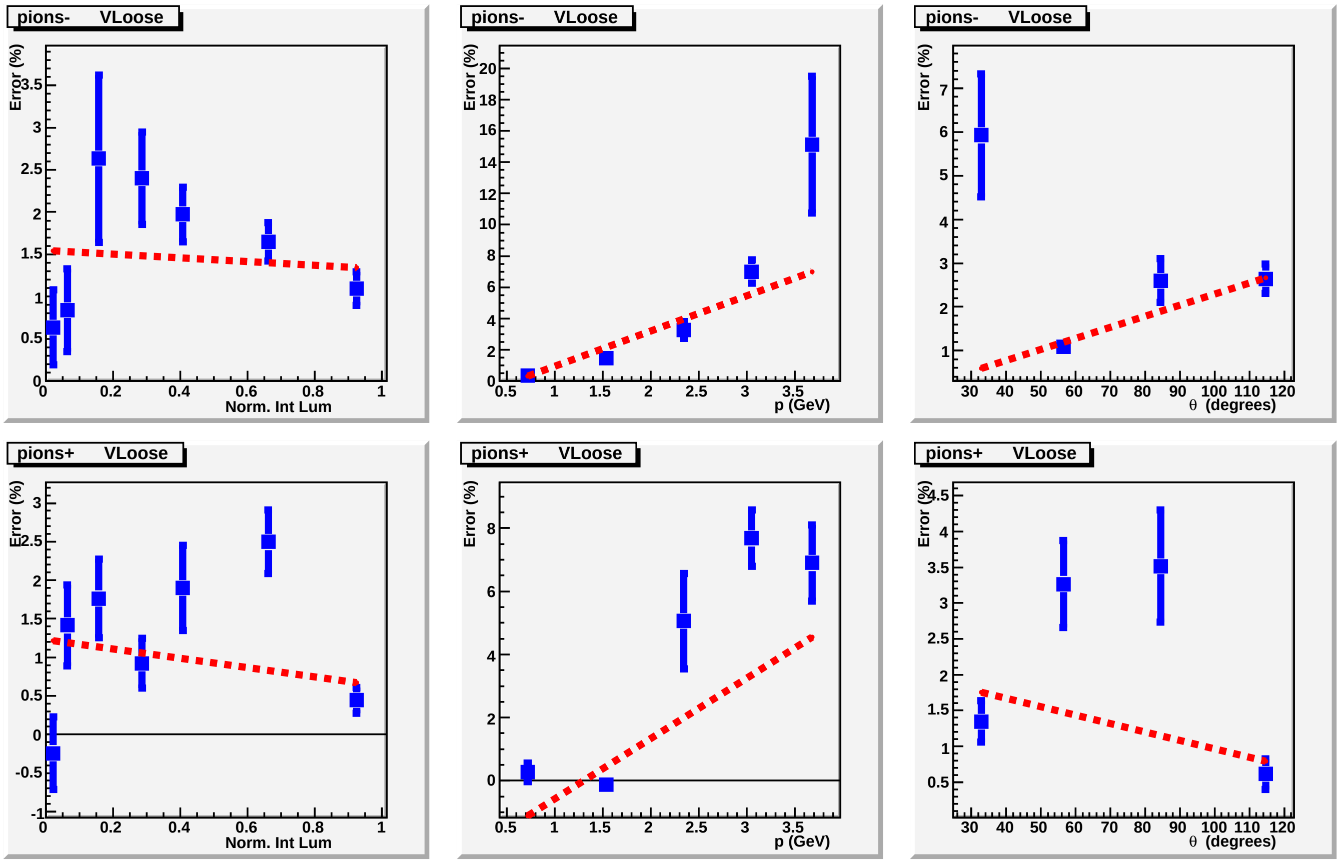

Figure 11: p, θ and run dependence of differences in PID efficiencies for pions (VLoose).

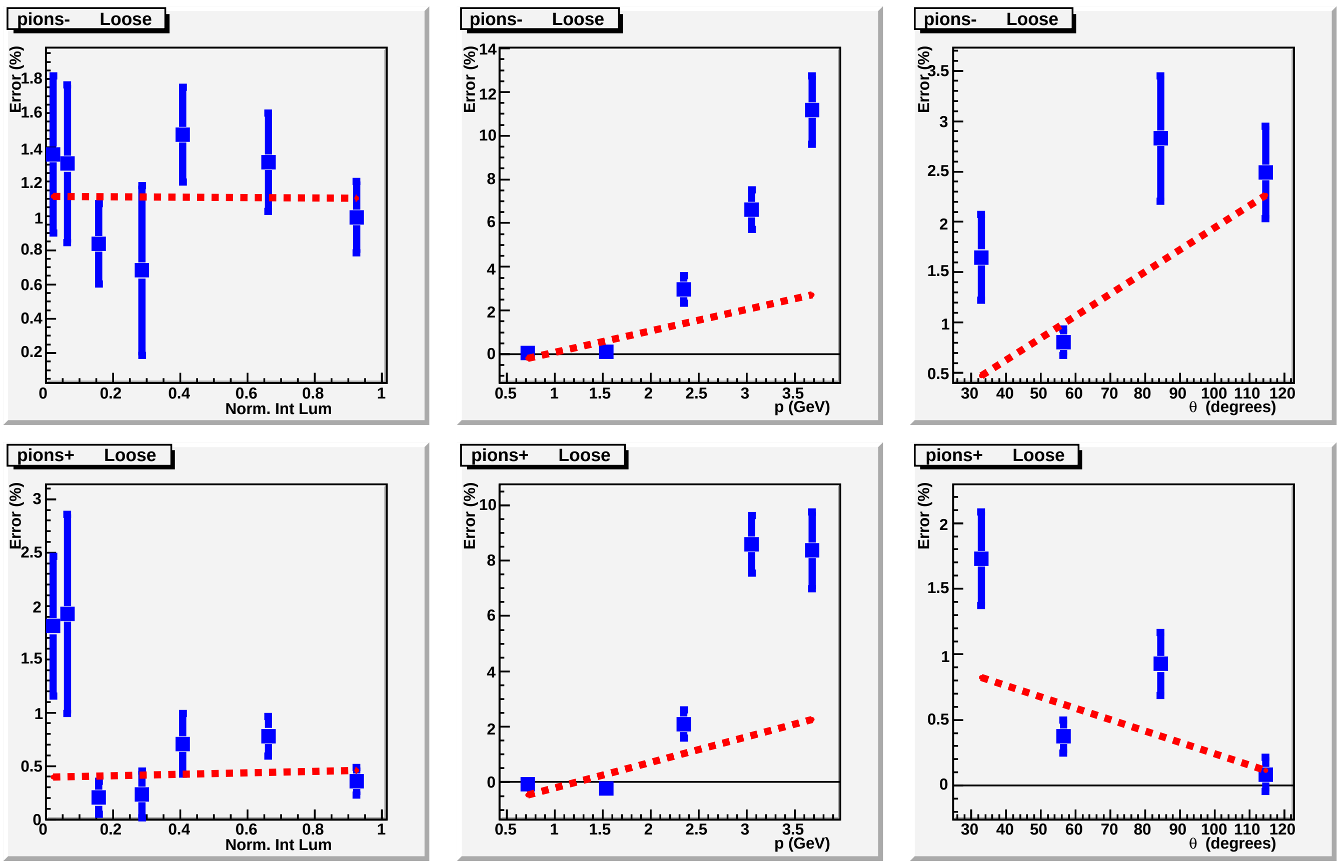

Figure 12: p, θ and run dependence of differences in PID efficiencies for pions (Loose).

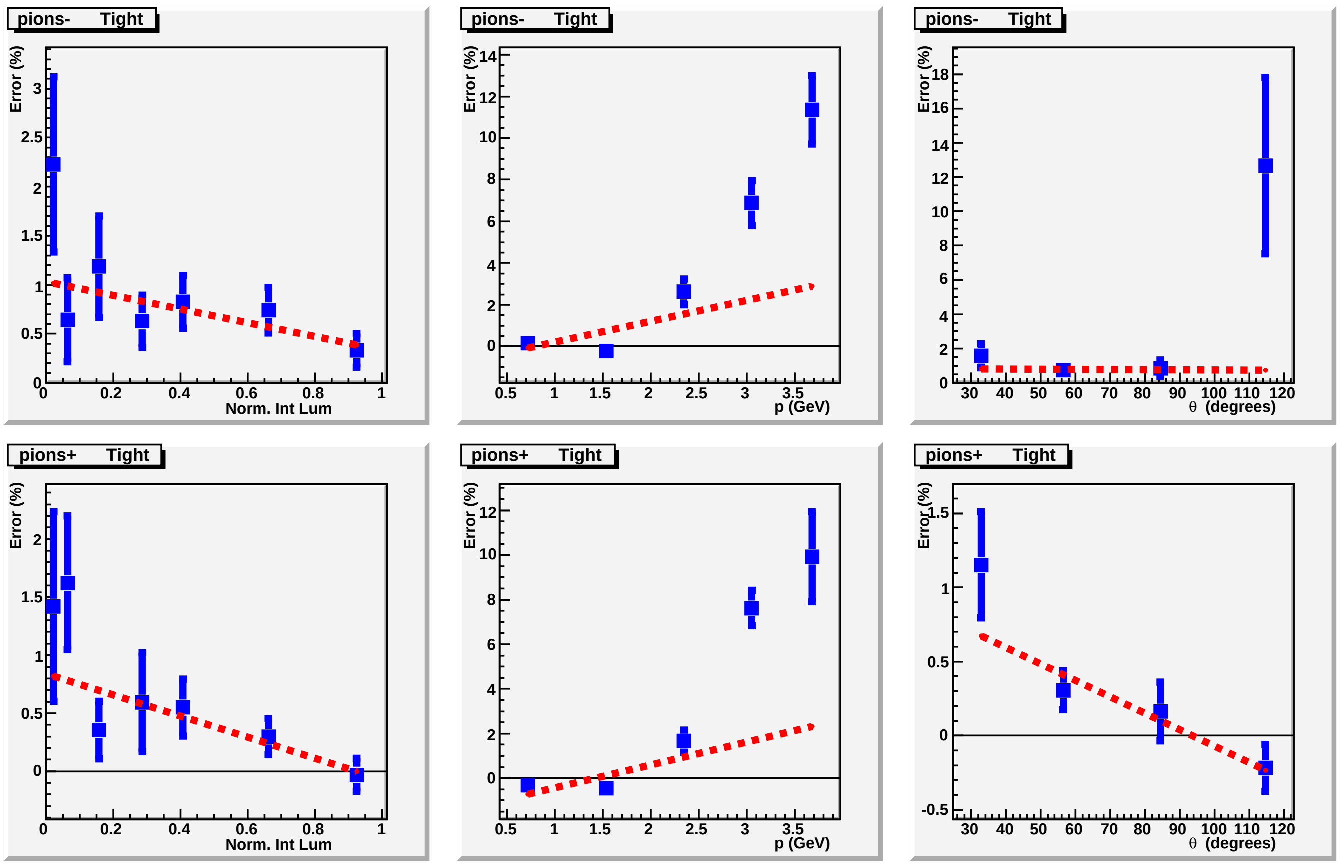

Figure 13: p, θ and run dependence of differences in PID efficiencies for pions (Tight).

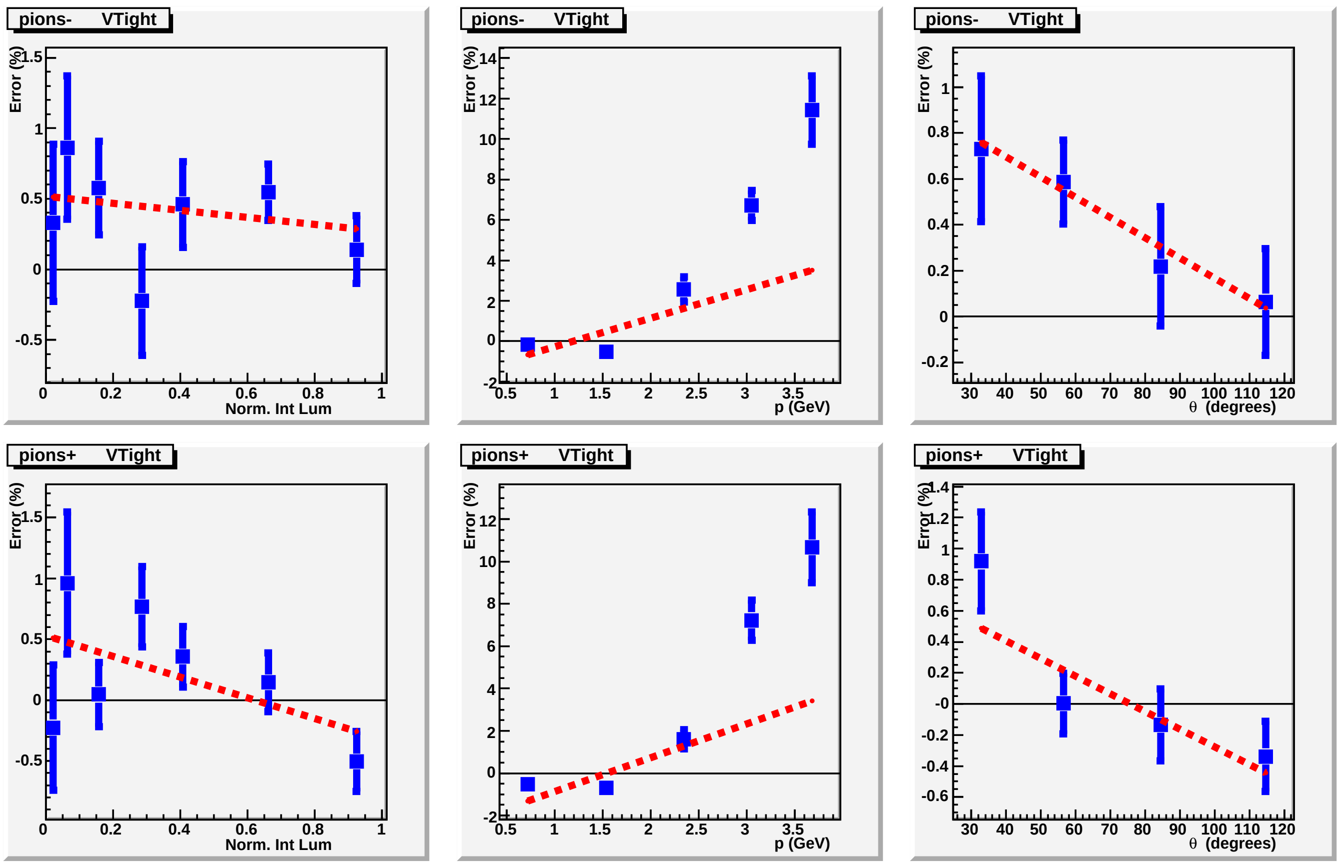

Figure 14: p, θ and run dependence of differences in PID efficiencies for pions (VTight).

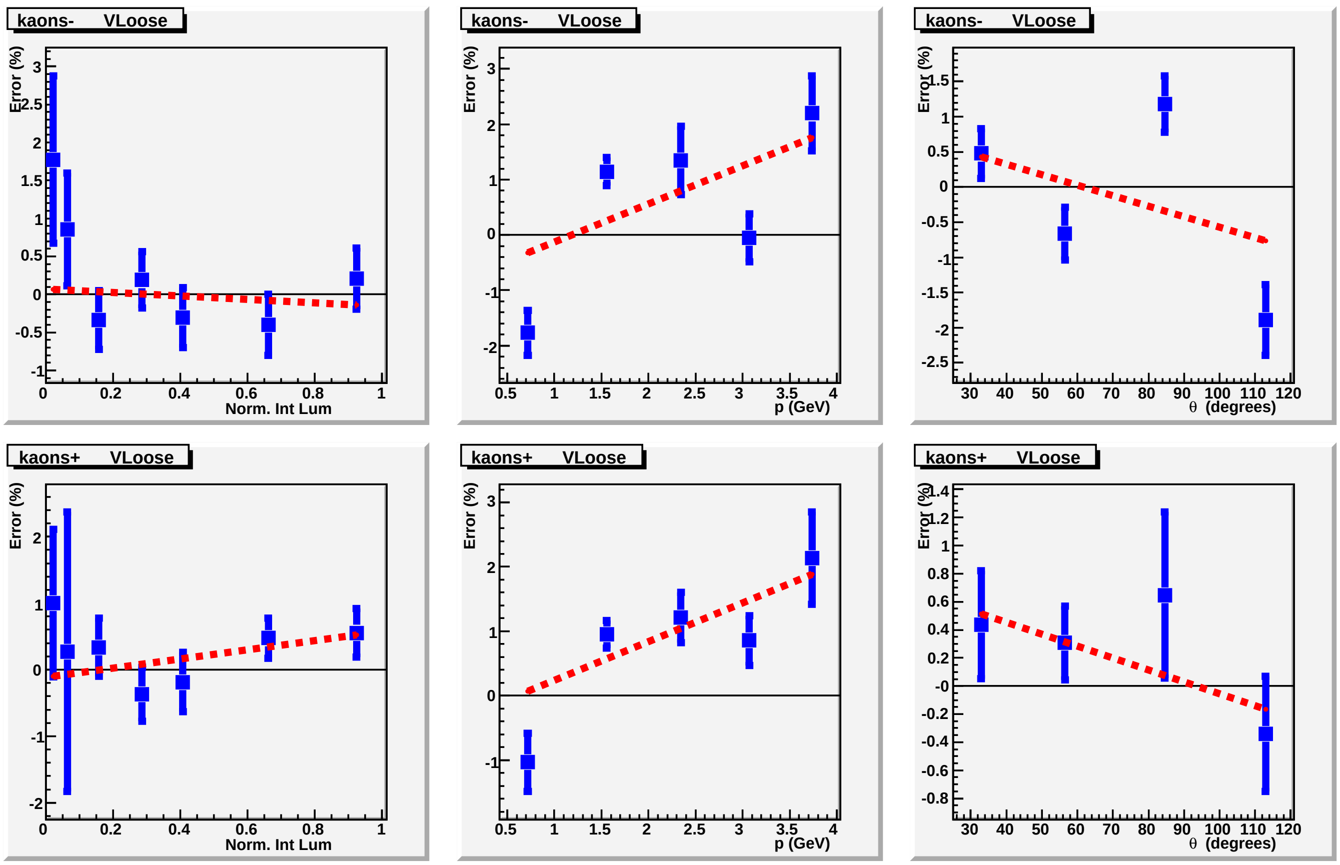

Figure 15: p, θ and run dependence of differences in PID efficiencies for kaons (VLoose).

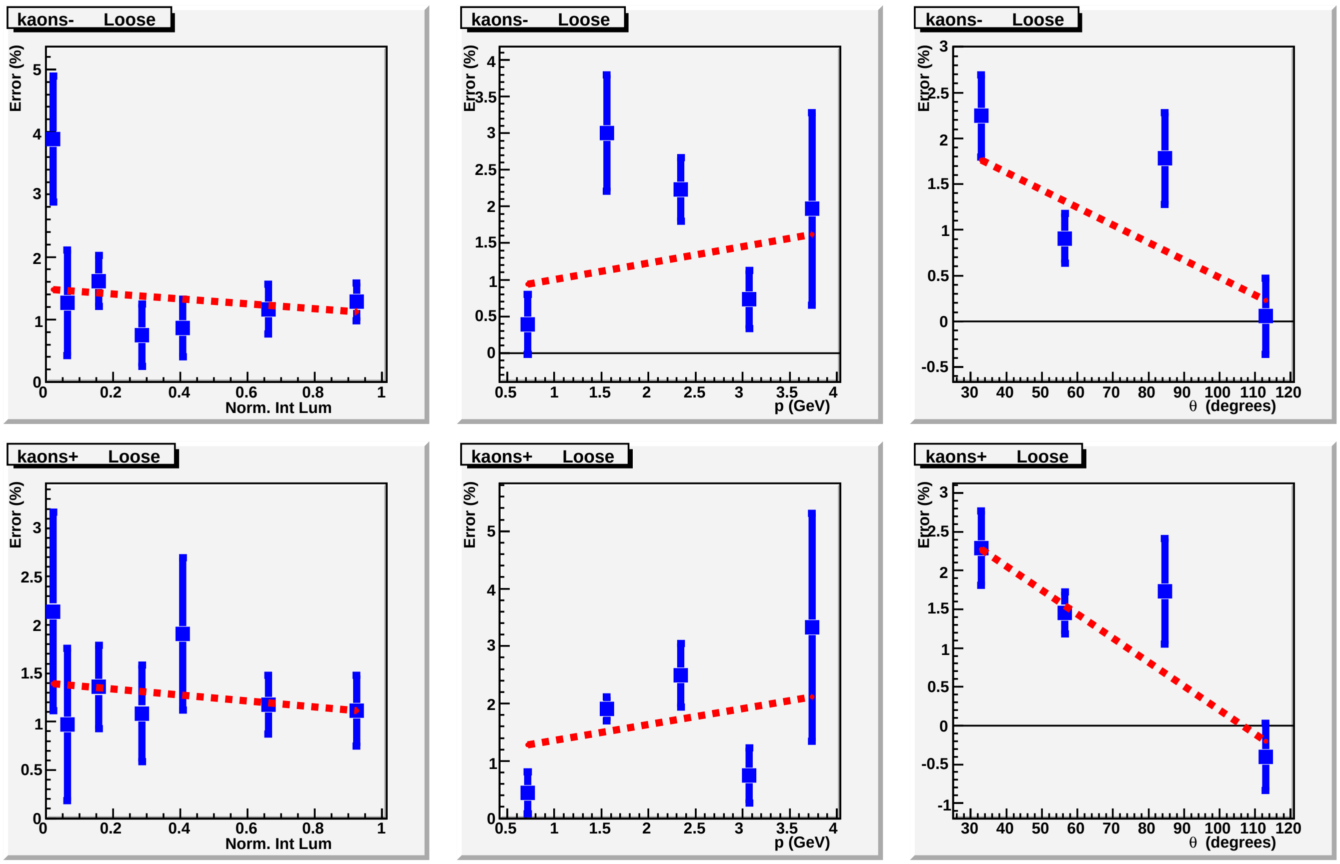

Figure 16: p, θ and run dependence of differences in PID efficiencies for kaons (Loose).

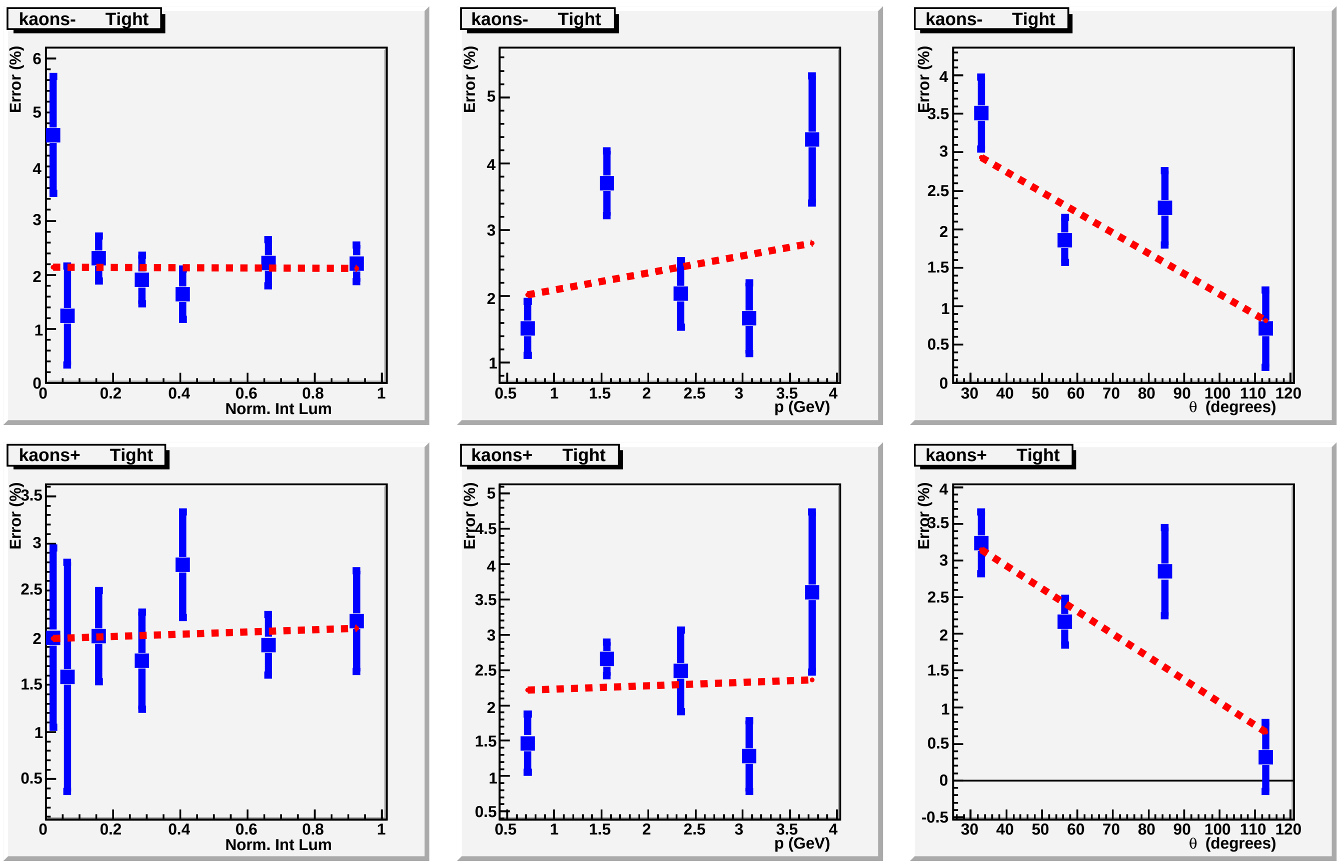

Figure 17: p, θ and run dependence of differences in PID efficiencies for kaons (Tight).

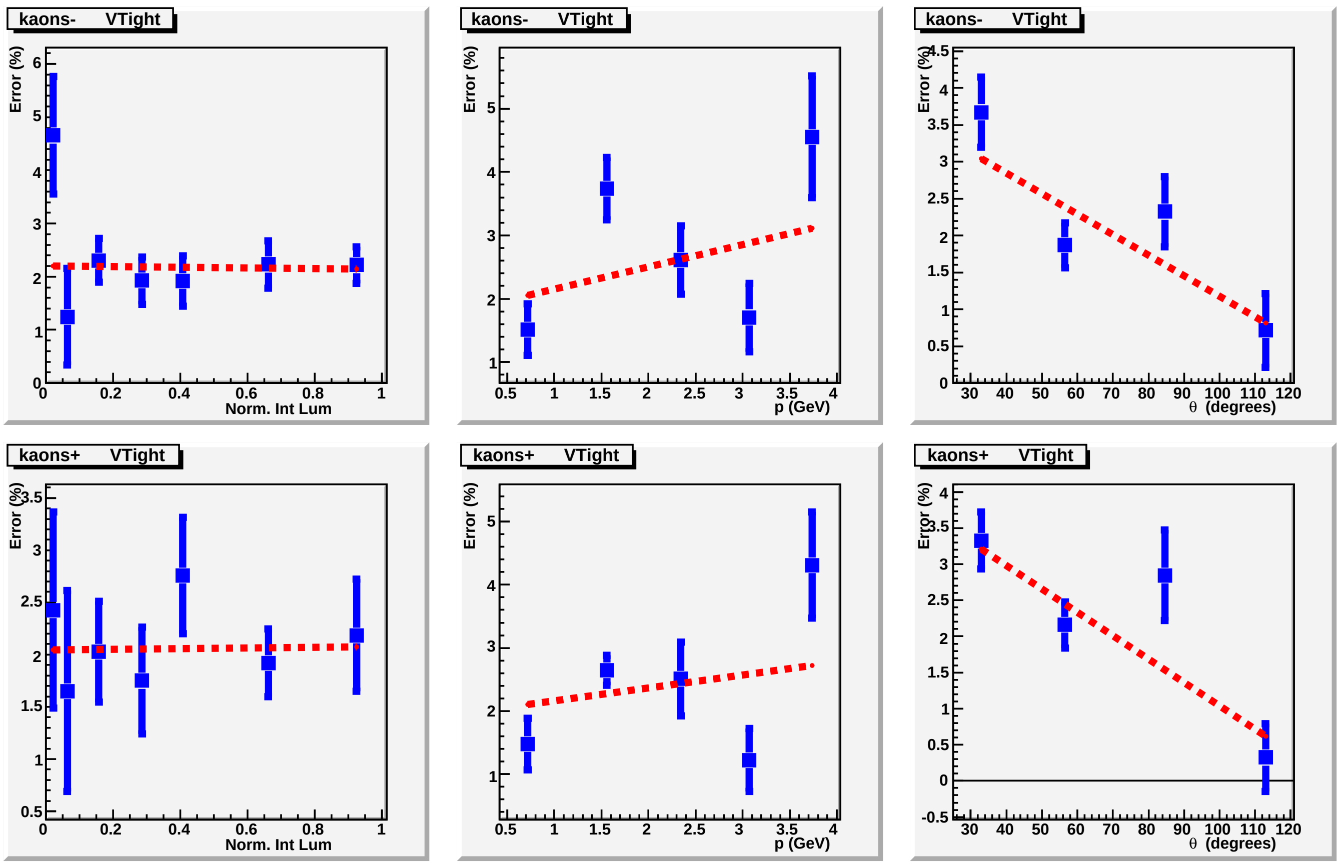

Figure 18: p, θ and run dependence of differences in PID efficiencies for kaons (VTight).

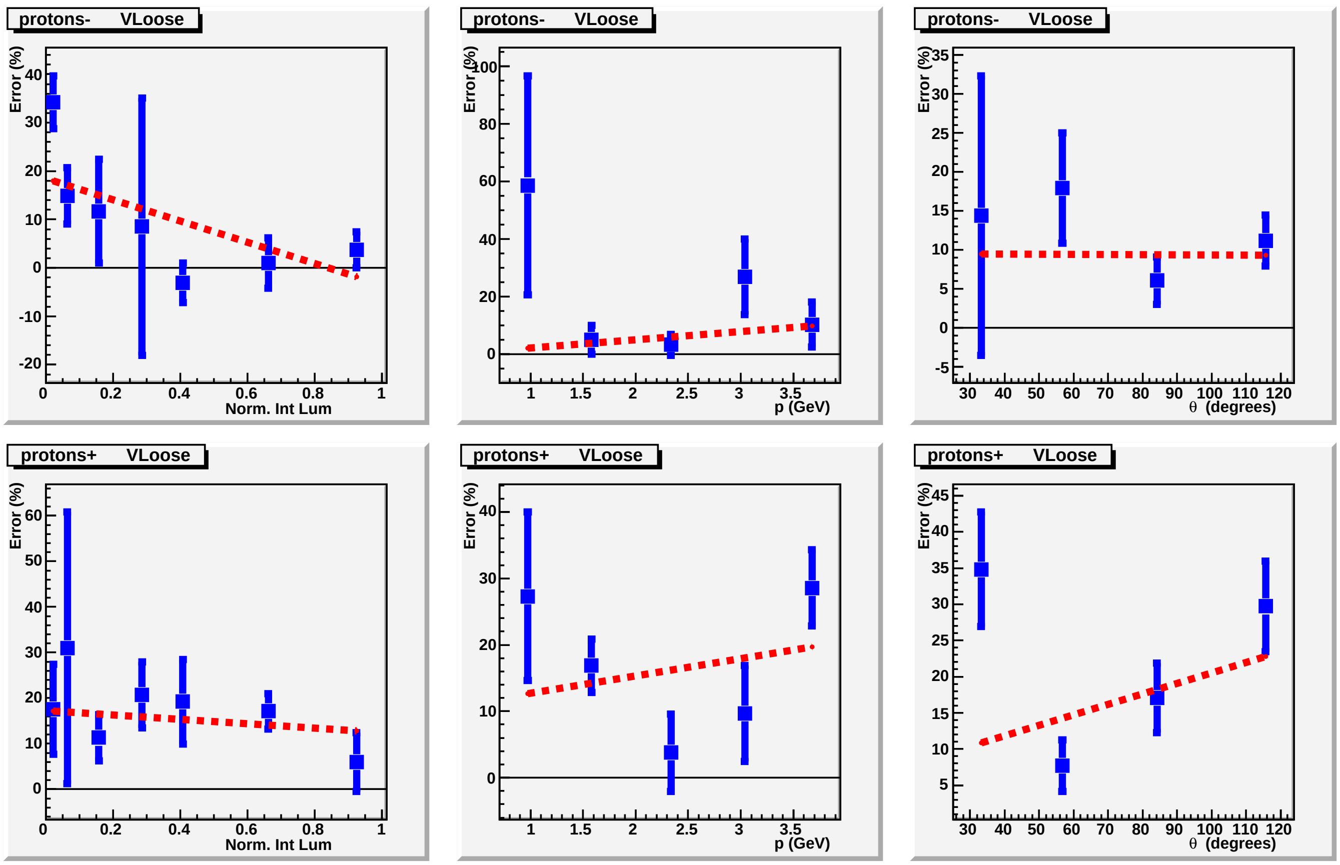

Figure 19: p, θ and run dependence of differences in PID efficiencies for protons (VLoose).

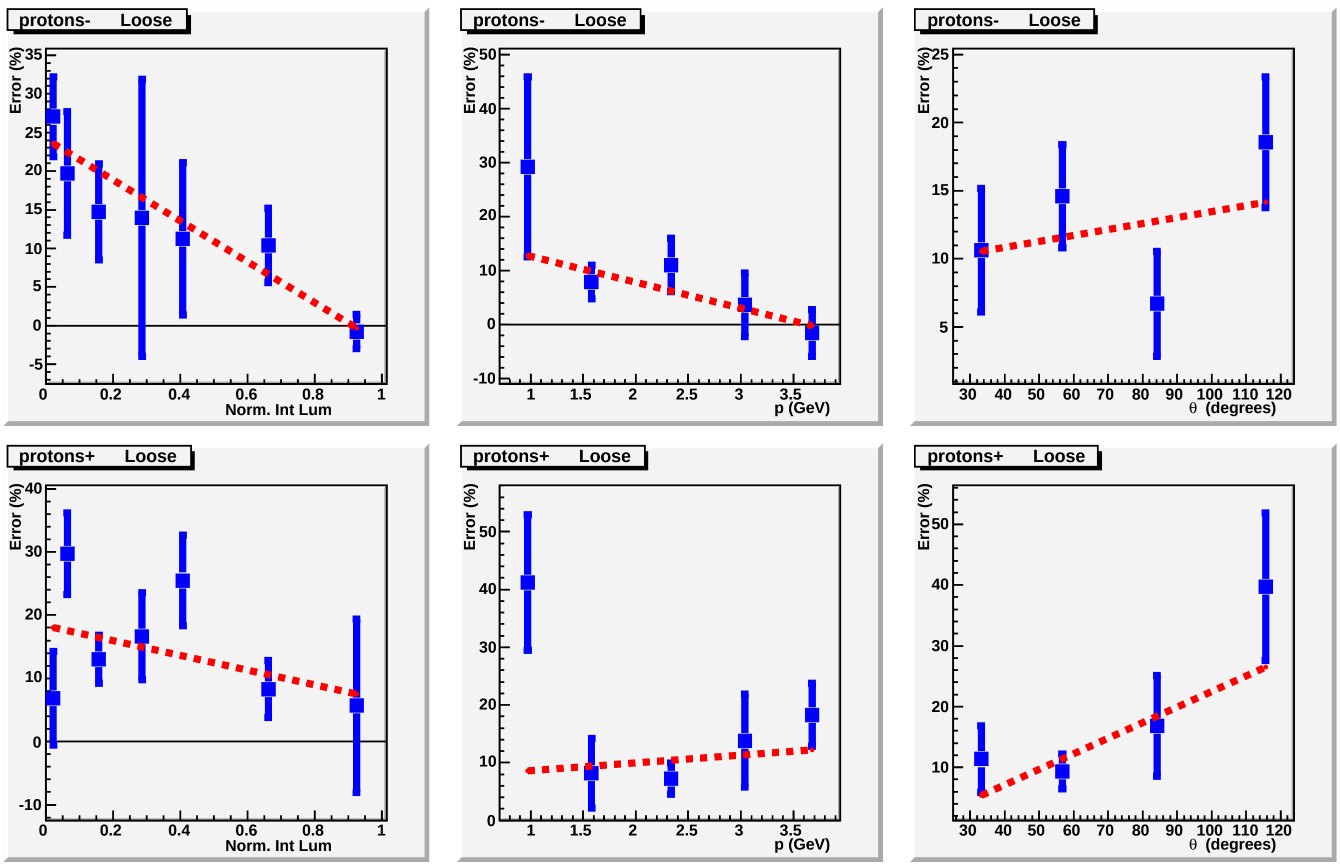

Figure 20: p, θ and run dependence of differences in PID efficiencies for protons (Loose).

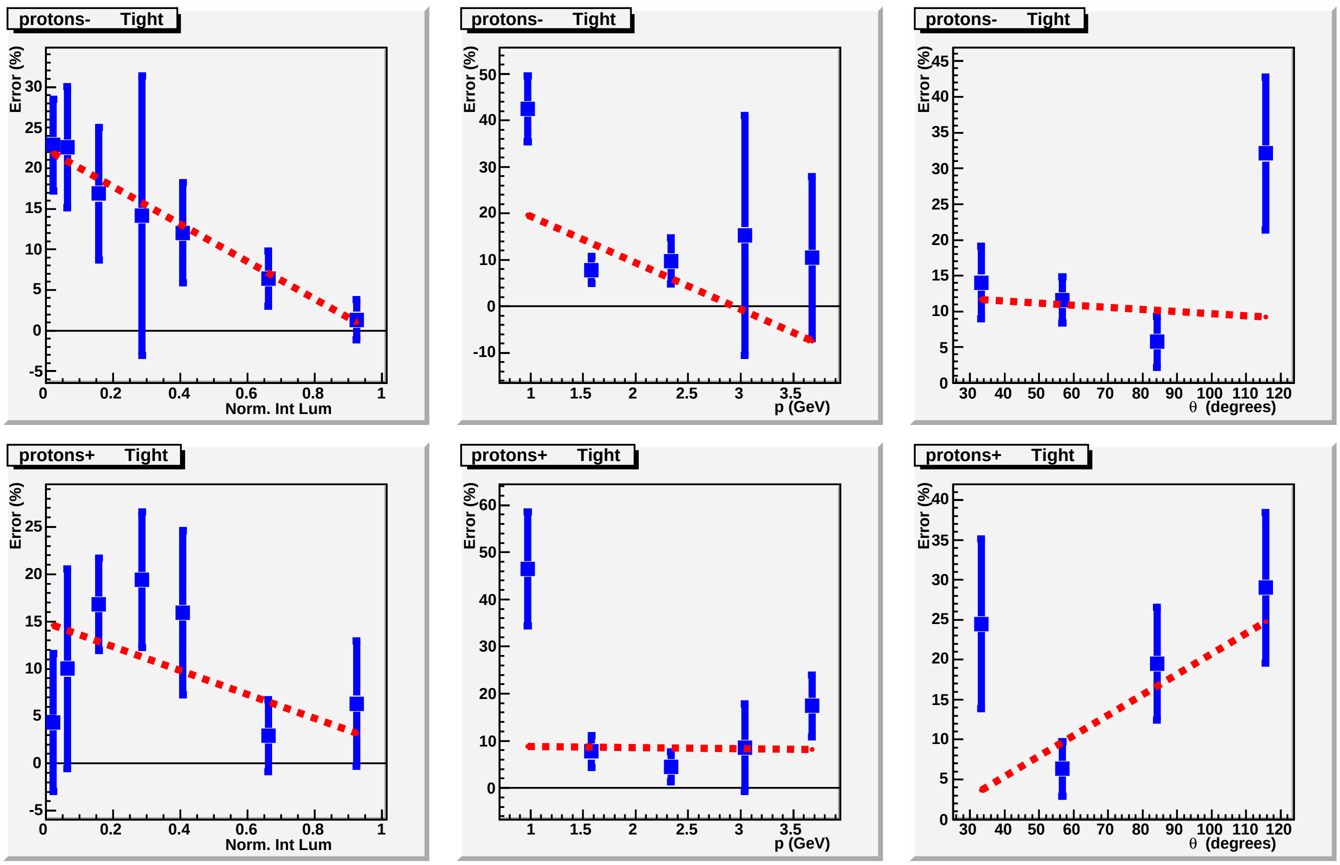

Figure 21: p, θ and run dependence of differences in PID efficiencies for protons (Tight).

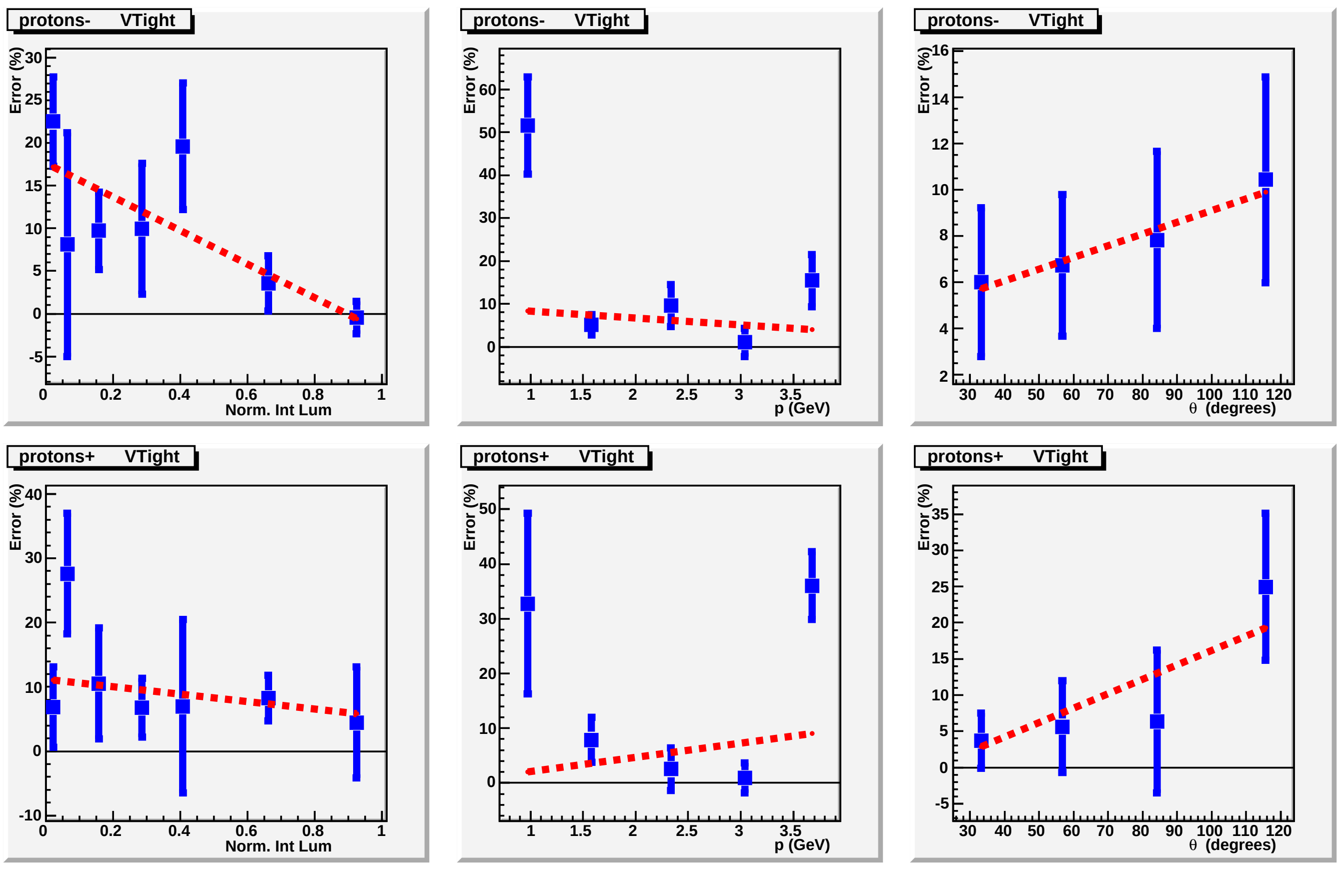

Figure 22: p, θ and run dependence of differences in PID efficiencies for protons (VTight).

8 Appendix III: Alternative Control Samples

The following section describes the event selection for the skims, cuts used to produce the control samples, and the additional cuts used to produce the efficiency tables. Variables stored in the ntuple that are not previously documented in BAD 1056 are described as well.

8.1 Lepton Control Sample

We use the already existing BaBar skim Jpsitoll. Refer to the FilterTools sequence in JpsitollPath.tcl. The skim provides us with one lepton track identified with PID, while the other track does not have PID requirements.

The lepton control sample comes from decays of J/Ψ, where the J/Ψ originates from various B decays:

•$B^+ \to J/\Psi K^+$
•$B \to J/\Psi K_s$
•$B \to J/\Psi K^*$

The selection criteria for the sample is as follows:

•Electron from eBremRecoELNC
•Muon from muNNVeryLoose
•Other lepton from GoodTracksLoose
•K^+ from KLHLoose
•K_s from KsDefault
•K^* from KstarKPiDefaultPID
•BGFMultiHadron
•ntracks > 4
•R2 < 0.7
•2.9 $GeV/c^2 < m(J/\Psi) < 3.2$ GeV/c^2
•5.2 $GeV/c^2 < mES < 5.3$ GeV/c^2
•-0.15 $GeV/c^2 < \Delta E < 0.15$ GeV/c^2

To increase the purity of the control samples before the efficiency tables are made, tighter requirements are placed on the pid identified lepton track, the mass of the J/Ψ, and the event helicity.

The following cuts required for the electron sample:

•Prob(vertex χ^2) > 0.02
•2.95 $GeV/c^2 < m(J/\Psi) < 3.14$ GeV/c^2
•-0.05 $GeV/c^2 < \Delta E < 0.05$ GeV/c^2
•Require the identified electron to be PidLHElectron
•-0.7 $<$ cos(Helicity Angle) < 0.7

The following cuts required for the muon sample:

•Prob(vertex χ^2) > 0.02
•3.06 $GeV/c^2 < m(J/\Psi) < 3.14$ GeV/c^2
•-0.05 $GeV/c^2 < \Delta E < 0.05$ GeV/c^2
•Require the identified muon to be MuNNTight
•-0.7 $<$ cos(Helicity Angle)< 0.7

Below are the variables stored in the ntuple tress for $B \to J/\Psi K$ decays.

The tree associated with the electron is identified as ntp901. The tree associated with the muon is identified as ntp902.

•otherp: Pid identified lepton track's momentum

•othertheta: Pid identified lepton track's polar angle

•otherphi: Pid identified lepton track's azimuthal angle

•othercharge: Pid identified lepton track's charge

•otheriselh: Pid identified electron also passes PidLHElectron selector

•otherismunnt: Pid identified muon also passes MuNNTight selector

•kmass: Kaon mass

•kmode: Decay type, K^+ decay = 1, $K_s = 2$, K^* decay = 3

•kp: Kaon track's momentum

•mPsi: Mass of J/Ψ candidate

•mES: Beam-energy substituted mass

•deltaE: Difference between the reconstructed energy of the B candidate and the beam energy

•R2: Second to zeroth Fox-Wolfram moment

•nTrk: Number of charged tracks in the event

•helicity: Angle between one of the lepton daughters and the $K_{(s)}^{(+,*)}$ in the J/Ψ rest frame

8.2 $D^+ \to K^-\pi^+\pi^+$ Control Sample

In order to obtain a high statistics sample of kaons and pions, which do not come from D^0 decays, the most copius mode available are charged D meson decays. There was no existing charm skim for such a decay. In FilterTools, the skim is defined in DcToKPiPiPromptNoPidPath.tcl and the selection criteria for the skim is described here:

•GoodTracksVeryLoose for all tracks

•Cascade vertexer

•Geometric constraint

•$p^* > 2.7\ GeV/c$

•$1.7\ GeV/c^2 < m(D^+) < 2.1\ GeV/c^2$

•Prob(vertex χ^2) > 0.005

The decays of charmed D mesons provide a relatively high statistics control sample for kaons and pions. With the use of DTaggingTools, we are able to provide a high purity sample. We require at least 3 charged tracks in the event along with the following requirements:

•BGFMultiHadron

•R2 > 0.2

•Sphericity < 0.5

•Thrust > 0.7

We obtain the likelihood from DTaggingTools for the Beam fit and the Dalitz fit. Both likelihoods are stored in the ntuple, but we only cut on the Beam fit likelihood which is required to be greater than 1.

To further increase the purity of the sample before creating the efficiency tables, we impose an additional cut using the Dalitz likelihood cut from DTaggingTools.

•likelihdDalitz > 3.5

Below are the variables stored in the $D^+ \to K^-\pi^+\pi^+$ trees

The tree associated with the kaon track is identified as ntp401.

•dpcms: D center of mass momentum

•likelihdDalitz: Value of likelihood from Dalitz fit in DTaggingTools

•likelihdBeam: Value of likelihood from Beam fit in DTaggingTools

•nTrk: Number of charged tracks in the event

•kpi1Mass: kaon and first pion daughters' pair mass

•kpi2Mass: kaon and second pion daughters' pair mass

•pi1pi2Mass: pion daughters' pair mass

The tree associated with the first pion daughter is identified as ntp402, and the second pion daughter tree is identified as ntp403.

8.3 Proton Control Sample

We use protons from $\Lambda_c^+ \to pK^-\pi^+$, however, in an effort to achieve a pure sample we require that the Λ_c candidates come from decays of $\Sigma_c^{++,0} \to \Lambda_c^+\pi^{+,-}$. The skim defined in SigmaCToLambdaCNoPidProtonPath.tcl includes the $pK\pi$ decay mode along with the pK_s decay mode. The latter is not used as part of the control sample due to such low statistics.

•K_s default list

•$0.455\ GeV/c^2 < m(K_s) < 0.54\ GeV/c^2$

•GoodTracksVeryLoose for proton track

•Kaon and pion tracks from LHTight lists

•Cascade vertexer for Λ_c

•Geometric constraint

•$p^*(\Lambda_c) > 2.7\ GeV/c$

•$2.18\ GeV/c^2 < m(\Lambda_c) < 2.38\ GeV/c^2$

•Add4 Λ_c and pion

•$p^*(\Sigma_c) > 2.7\ GeV/c$

•$m(\Sigma_c) - m(\Lambda_c) < 300\ MeV/c^2$

The Σ_c candidate is formed by simply adding the four vectors of the Λ_c candidate, which has the same requirements as the skim, with a pion from a tight Pid list. To remove Λ_c candidates that do not come from Σ_c we place cuts on the p^* of the Σ_c candidate and the mass difference between the Σ_c and the Λ_c:

•$p^*(\Sigma_c) > 3.2\ GeV/c$

•$160\ MeV/c^2 < m(\Sigma_c) - m(\Lambda_c) < 175\ MeV/c^2$

The Λ_c candidates may contain reflections from charm mesons D^+, D_s, or D^* which may affect proton efficiency. To look for reflections we recalculate the proton track's energy either with a kaon or pion hypothesis (denoted as K_p or π_p) and form either a D^+ or D_s. A D^0 may be formed using the kaon track with the proton track as a pion(π_p), we can then find the q value of the D^* decay. Efficiency tables were produced with and without removing the reflections. The reflections can be removed using the following cuts:

•$1.859\ GeV/c^2 < m(K\pi\pi_p) < 1.879\ GeV/c^2$

•$4\ MeV/c^2 < m(K\pi\pi_p) - m(K\pi_p) - m(\pi) < 8\ MeV/c^2$

•$1.959\ GeV/c^2 < m(K\pi K_p) < 1.979\ GeV/c^2$

Below are the variables stored in the ntuples for the $\Lambda_c \rightarrow pK\pi$ tree. This control sample contains just one tree for the proton track, identified as ntp501.

•LambdaCpcms: Λ_c center of mass momentum

•SigmaCpcms: Σ_c center of mass momentum

•massDiff: m(Σ_c) - m(Λ_c)

•KKpiMass: Recalculated mass of Λ_c daughters using a kaon hypothesis for the proton track

•KpipiMass: Recalculated mass of Λ_c daughters using a pion hypothesis for the proton track

•Qvalue: $m(K\pi\pi_p) - m(K\pi_p) - m(\pi)$

8.4 Mass Distributions

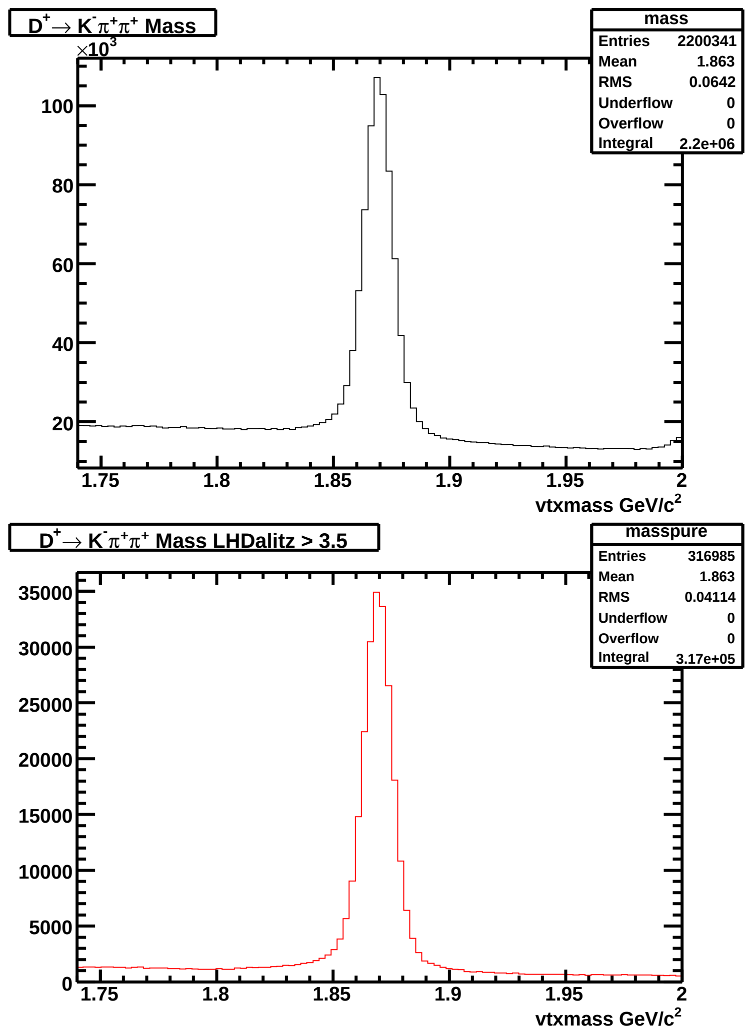

Figure 23: **Top: D^+ mass distribution at the ntuple level; Bottom: D^+ mass distribution with Dalitz likelihood cut imposed for producing efficiency tables; taken from Run4 OnPeak data ˜68 fb^{-1}.**

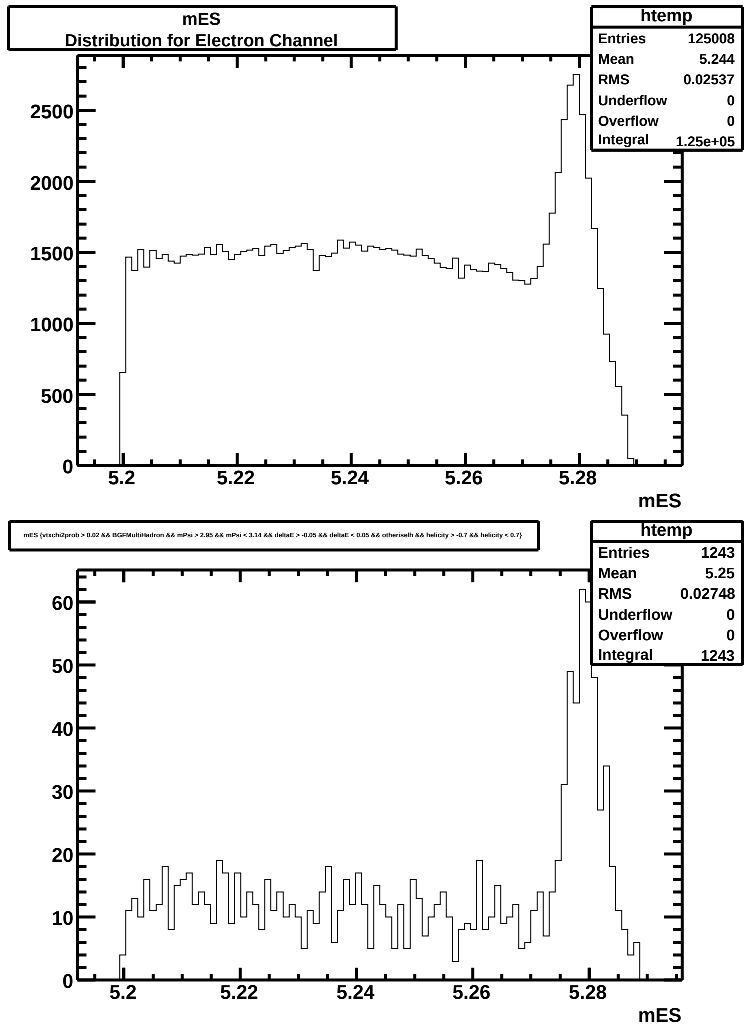

Figure 24: **Top: mES Distribution for $J/\Psi \rightarrow e^+e^-$ Bottom: mES Distribution with further cuts imposed for producing efficiency tables; taken from Run4 OnPeak data ˜68 fb^{-1}.**

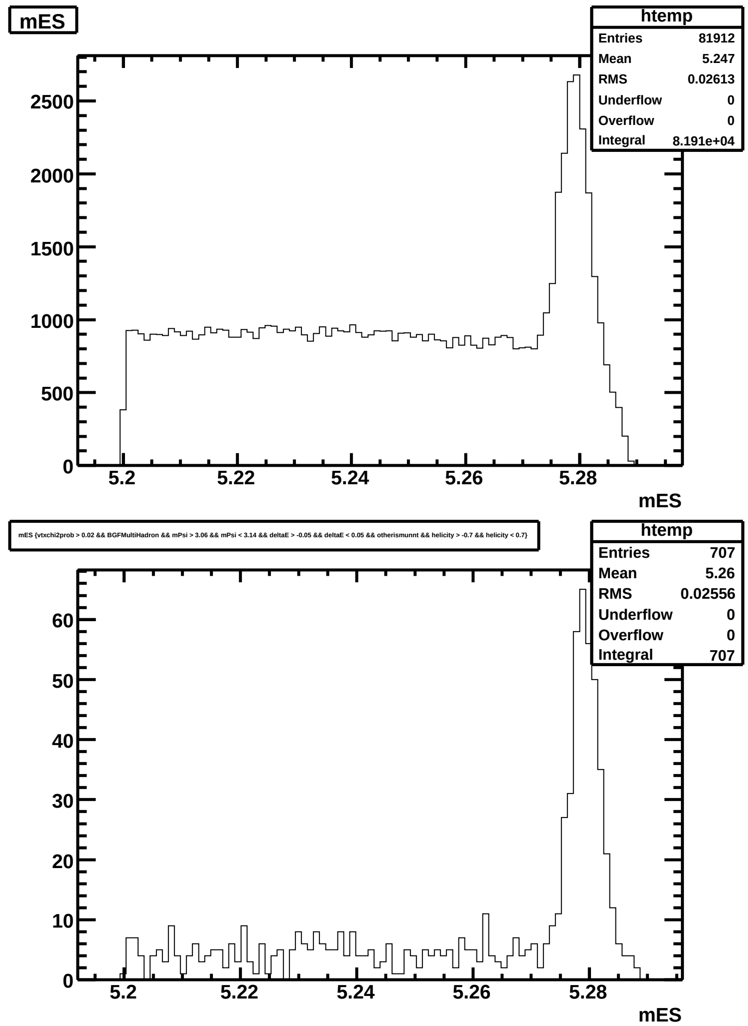

Figure 25: **Top: mES Distribution for $J/\Psi \rightarrow \mu^+\mu^-$ Bottom: mES Distribution with further cuts imposed for producing efficiency tables; taken from Run4 On-Peak data ˜68 fb^{-1}.**

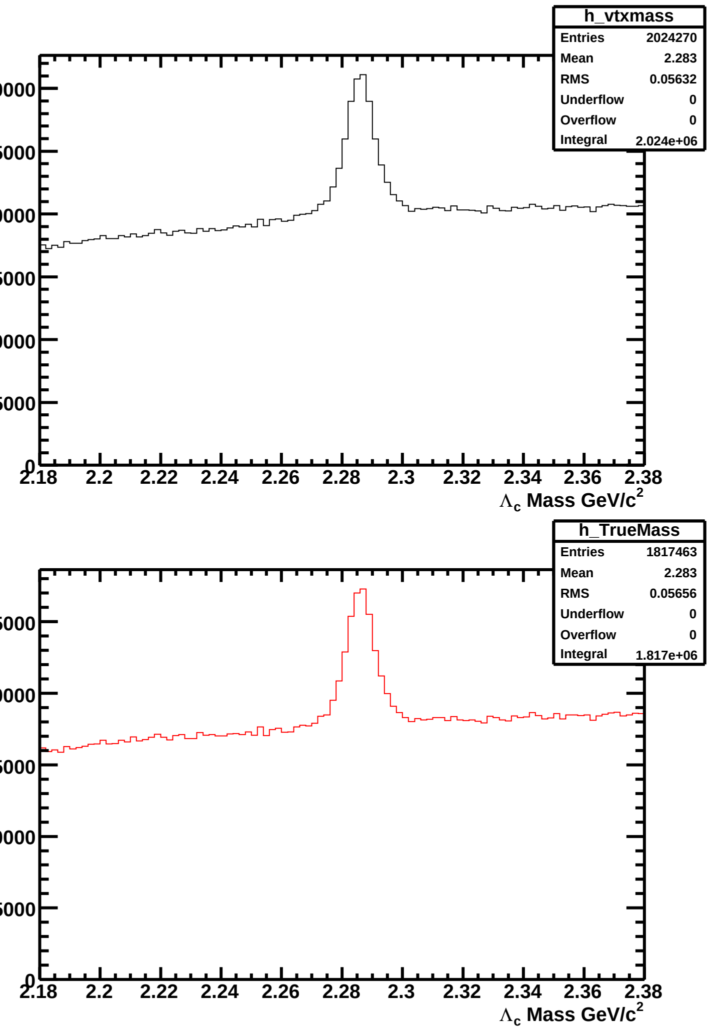

Figure 26: **Top: Mass distribution of Λ_c candidate Bottom: Λ_c mass distribution after cutting out the reflections; taken from the entire dataset ˜246 fb^{-1}.**

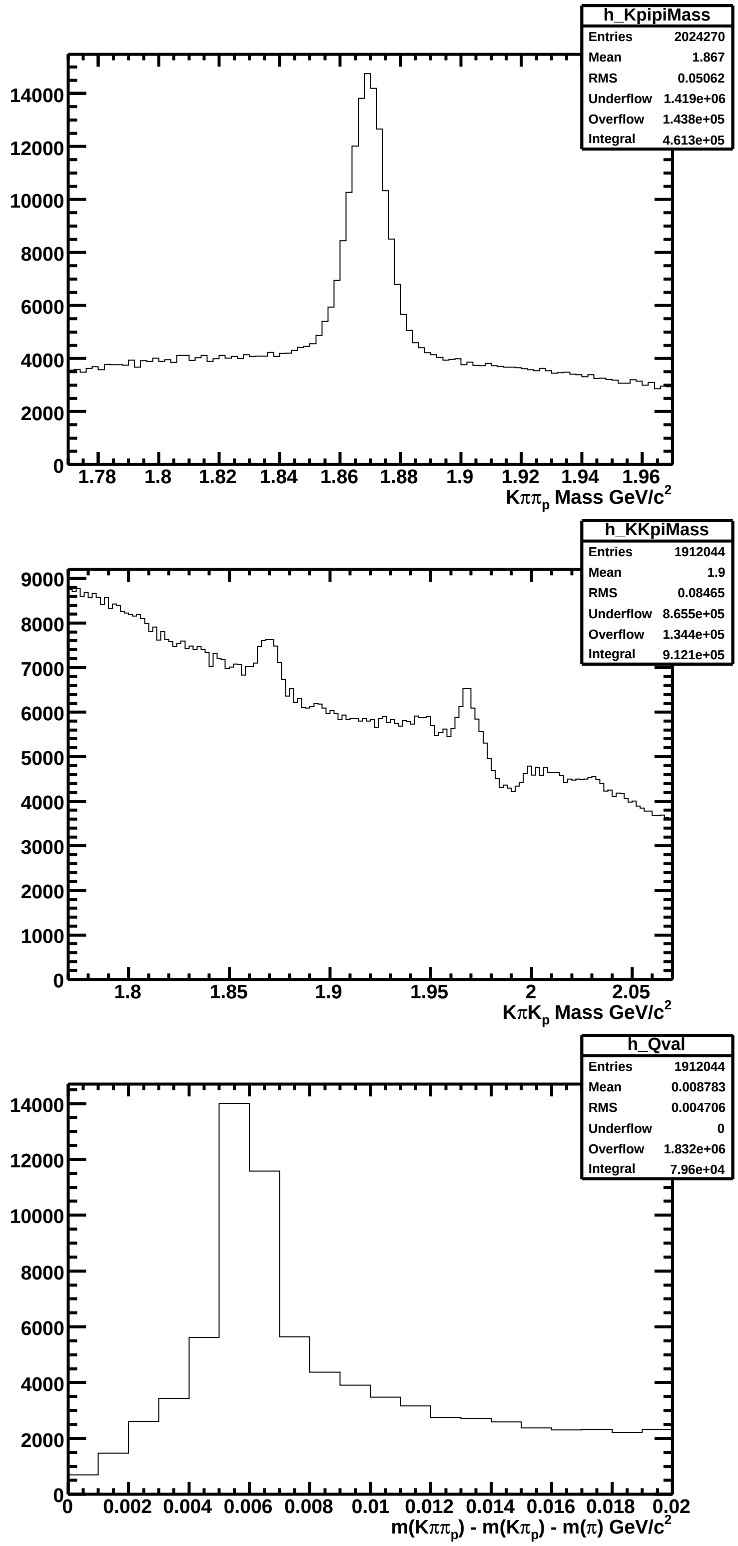

Figure 27: **Recalculated mass of Λ_c daughters using either kaon or pion hypothesis for the proton track. The $K\pi K_p$ and Q value are plotted after a cut around the D^+ mass peak from $K\pi\pi_p$.**