Measurement of Charged Pion Yields off the NuMI Target in the MIPP Experiment

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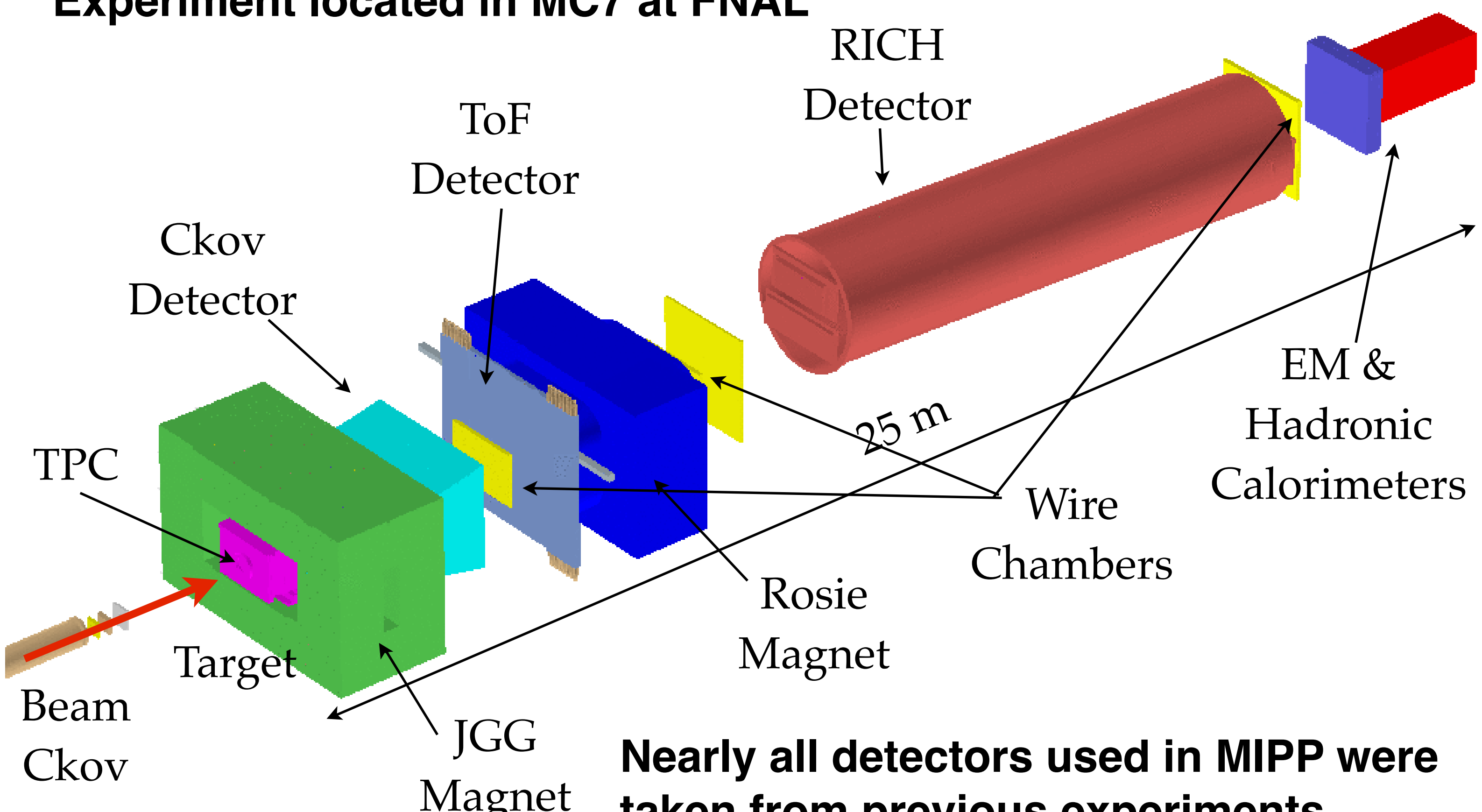
Neutrino Flux Prediction Discussion
September 22, 2014

Outline

- Overview of the MIPP spectrometer and particle id detectors
- Extraction of pion yields from particle id distributions in ~125 bins of (p_z,p_T)
- Systematics
- Final results (J. Paley, et al., PRD 90, 032001) and preliminary comparison to existing simulations

Main Injector Particle Production (MIPP) Experiment

Experiment located in MC7 at FNAL

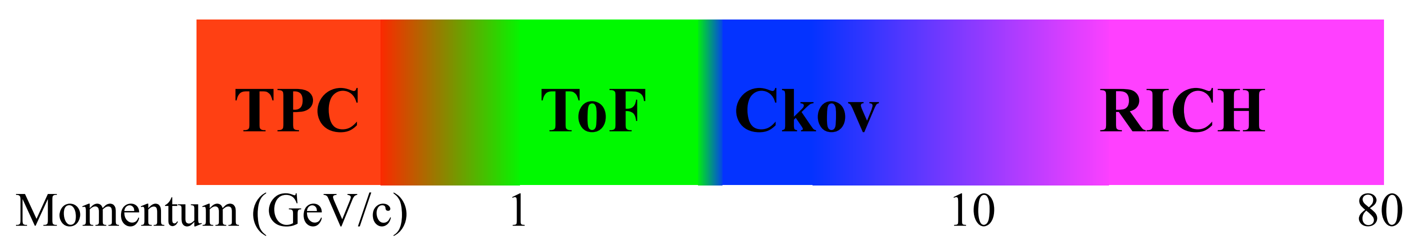


Nearly all detectors used in MIPP were taken from previous experiments.

- Goal: collect comprehensive hadron production cross-section data set with particle id using various beams and targets (thick and thin).
- These data may then be used to tune / validate MC event generators.

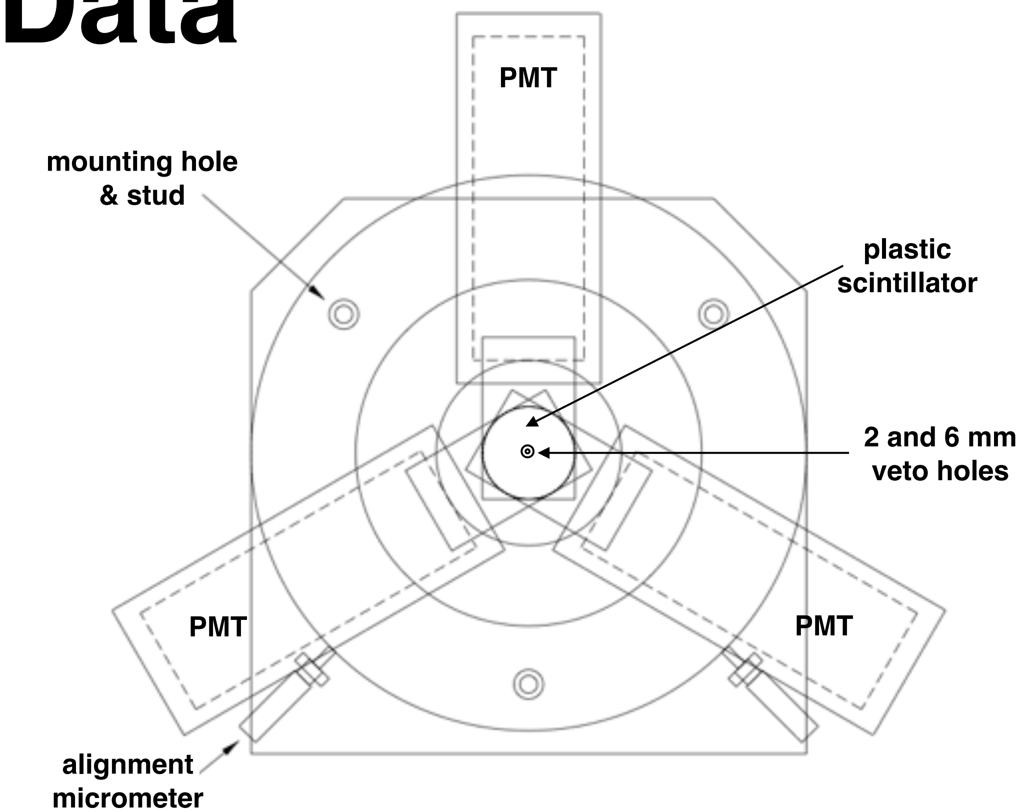
- Full acceptance spectrometer
  - Two analysis magnets deflect in opposite directions
  - TPC + 4 Drift Chambers + 2 PWCs

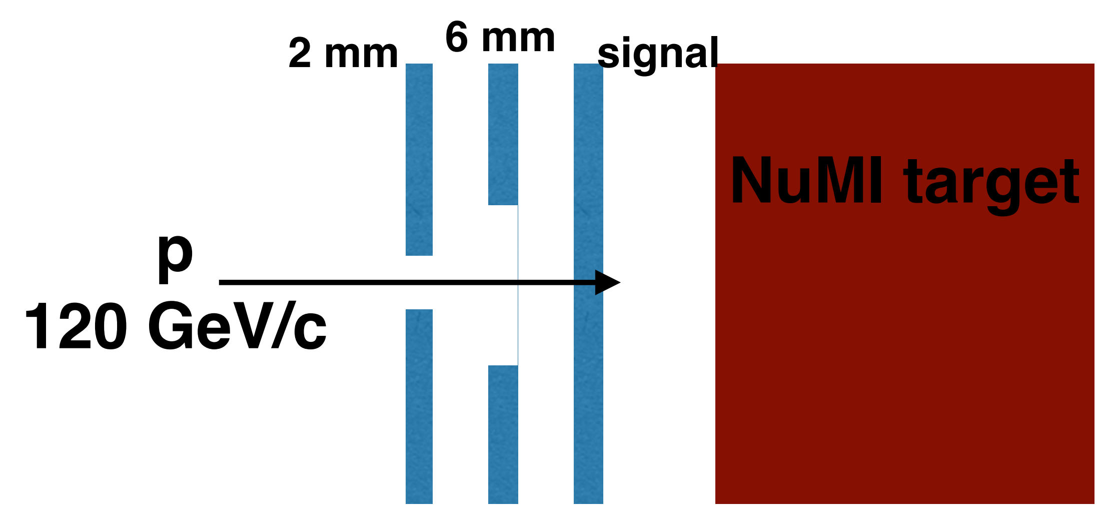
- Designed for excellent particle ID (PID) separation (2-3σ)

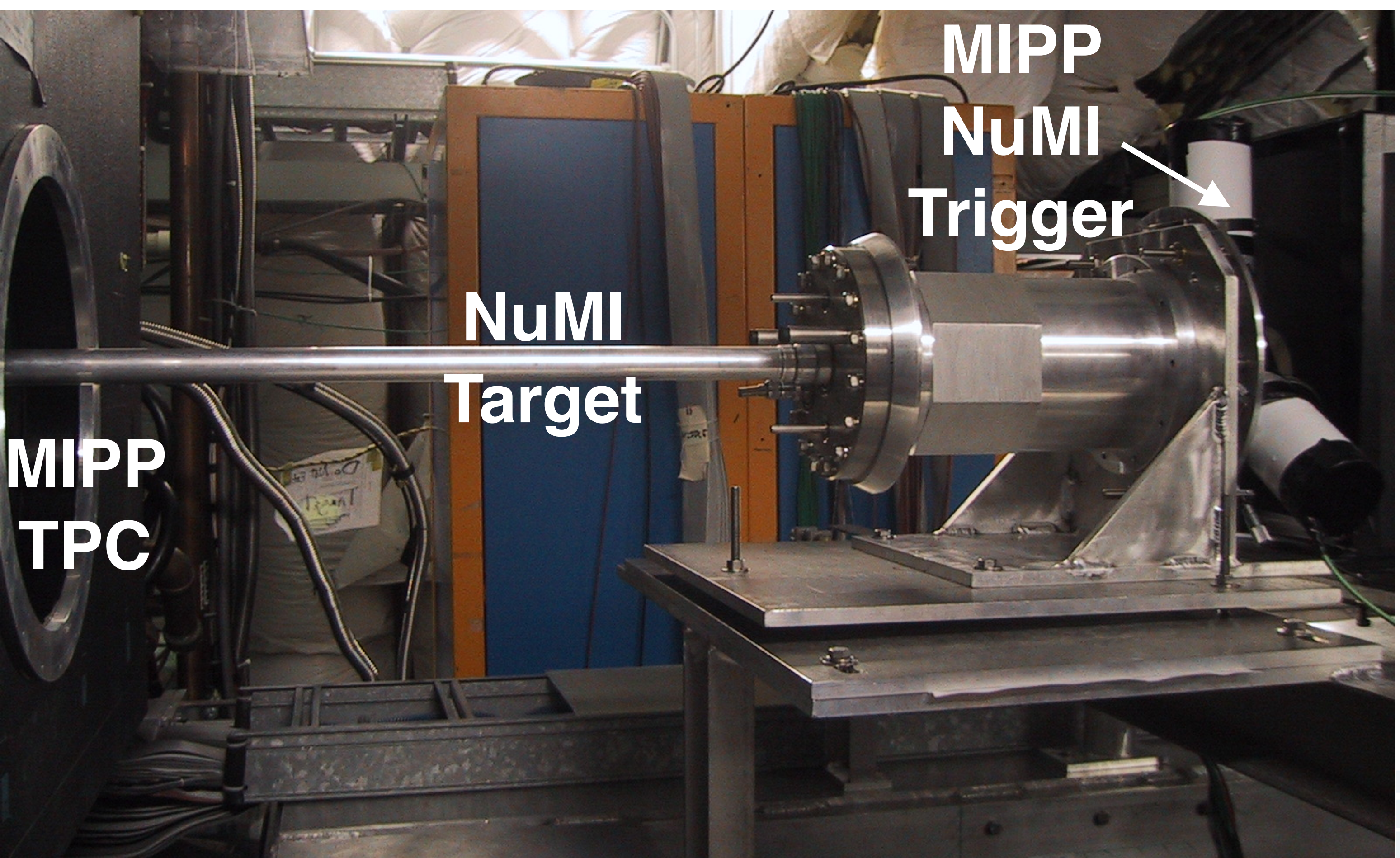


NuMI Target Data

- Collected 1.43 x 10^6 events of Main Injector 120 GeV/c protons on a ***spare*** NuMI target (T2).
- Two interaction length target consists of 47 2-cm thick graphite slabs contained in a 90-cm long, 3 cm diameter aluminum vacuum can.
- MI beam was slow extracted into SY120.
- Pinhole collimator reduce MI proton flux by 10^{-8}

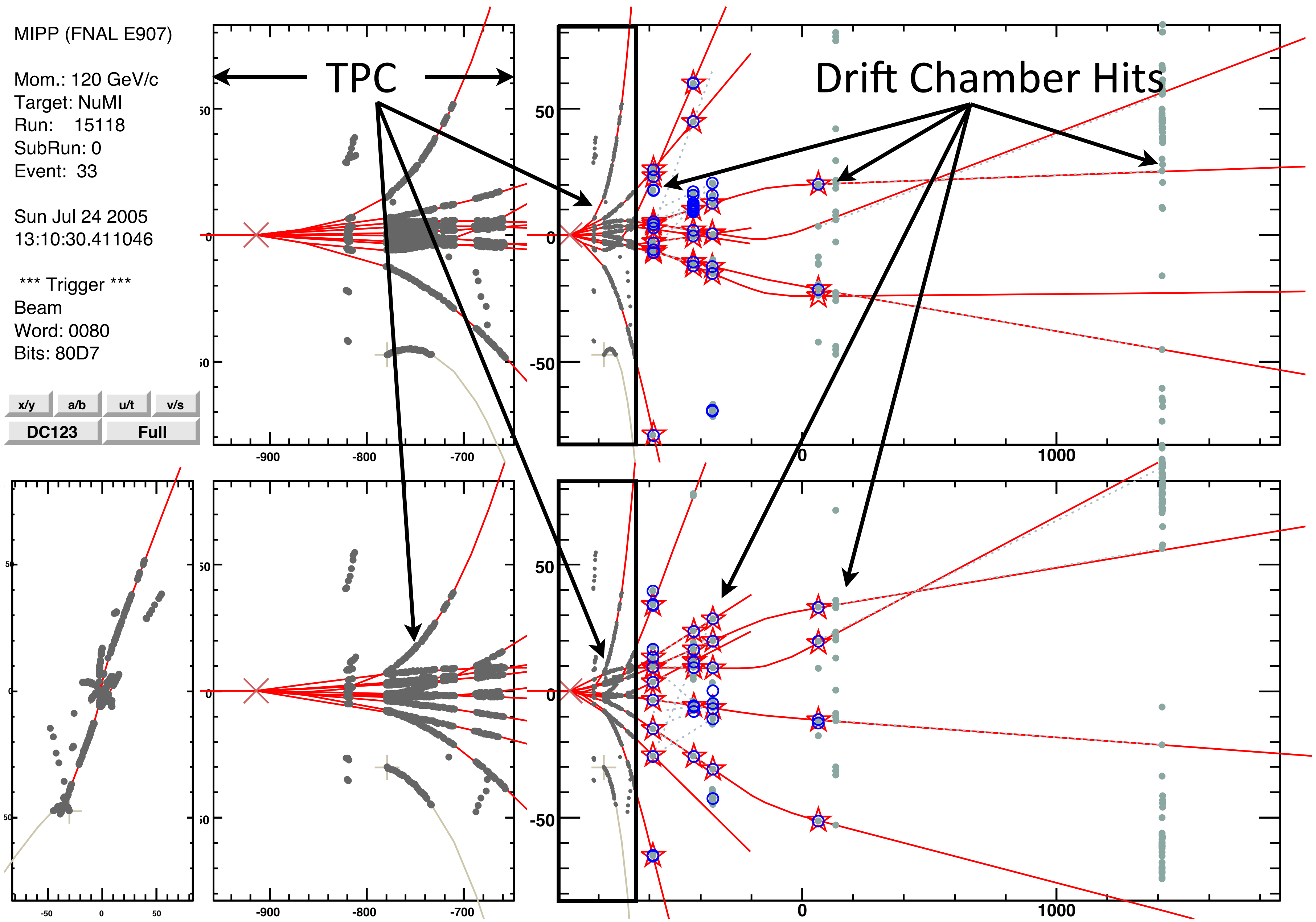


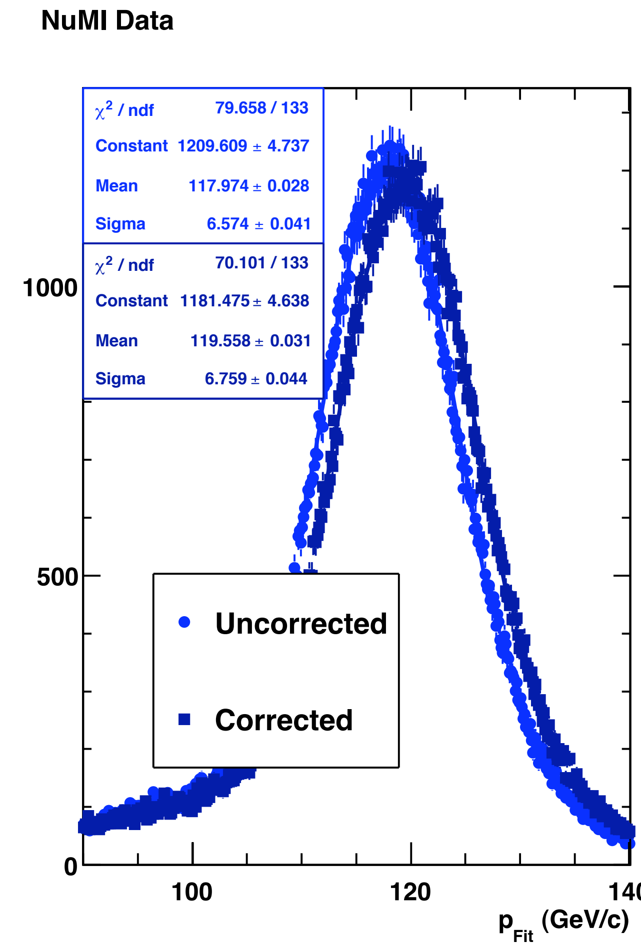




- Trigger detector used to guarantee that beam was centered on target, and to reproduce ~1 mm^2 beam spot size seen in NuMI facility

Track Reconstruction



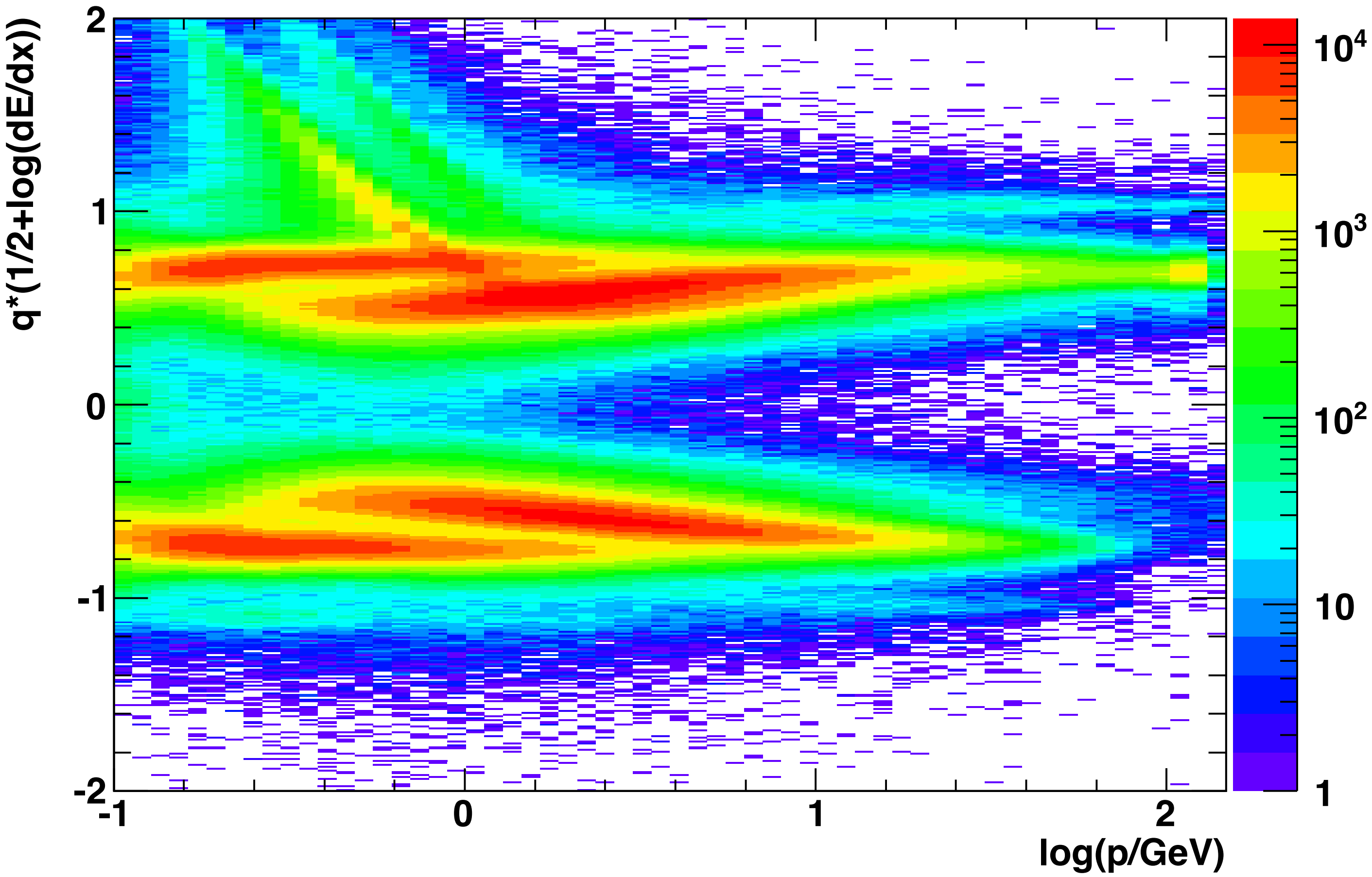


TPC track segments are matched to downstream drift chamber hits, momentum is determined from bend in both magnets.

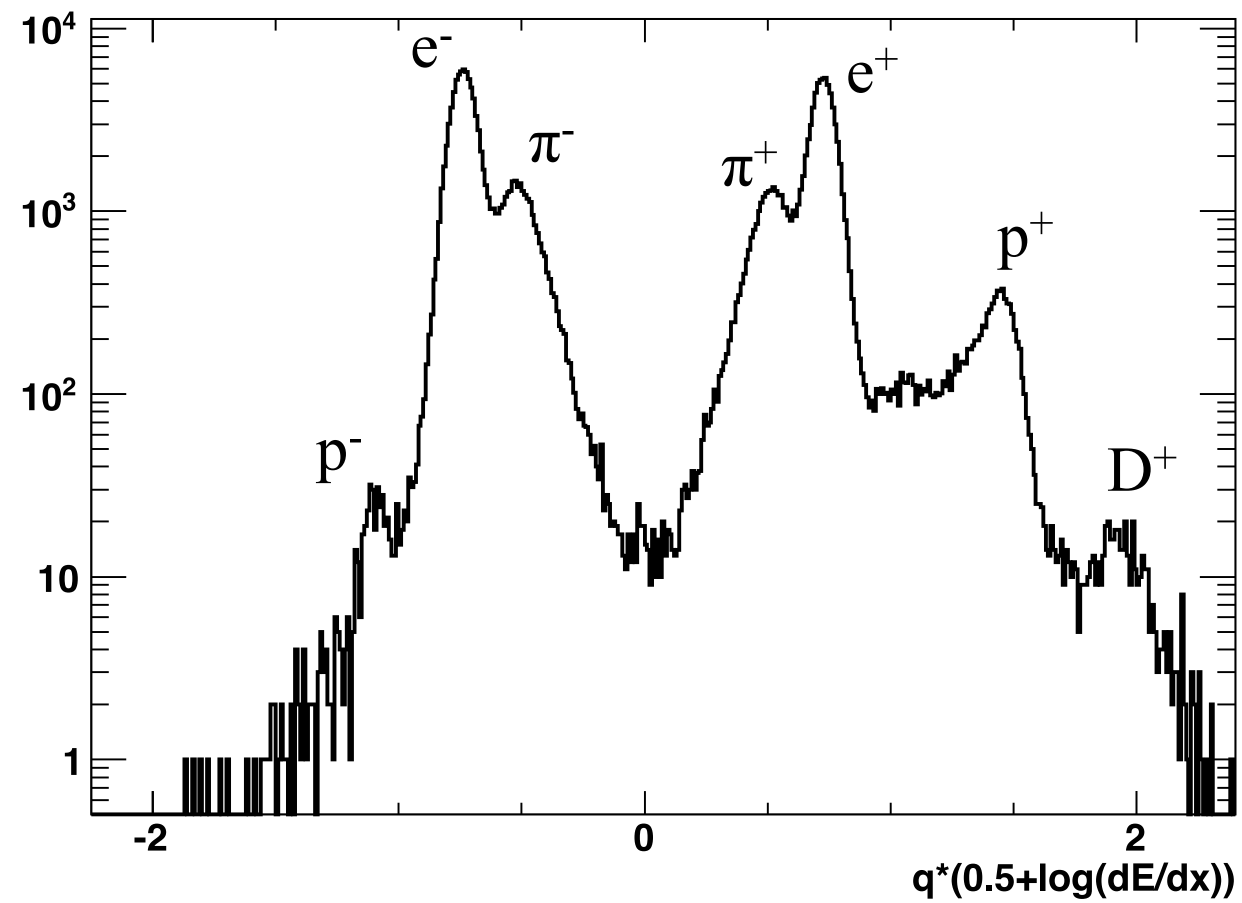
- Momentum resolution is < ~5%
- p_T resolution < 20 MeV/c
- Absolute momentum scale known to ~1%

TPC PID Performance

TPC <dE/dx> vs. P, Full NuMI Data Set

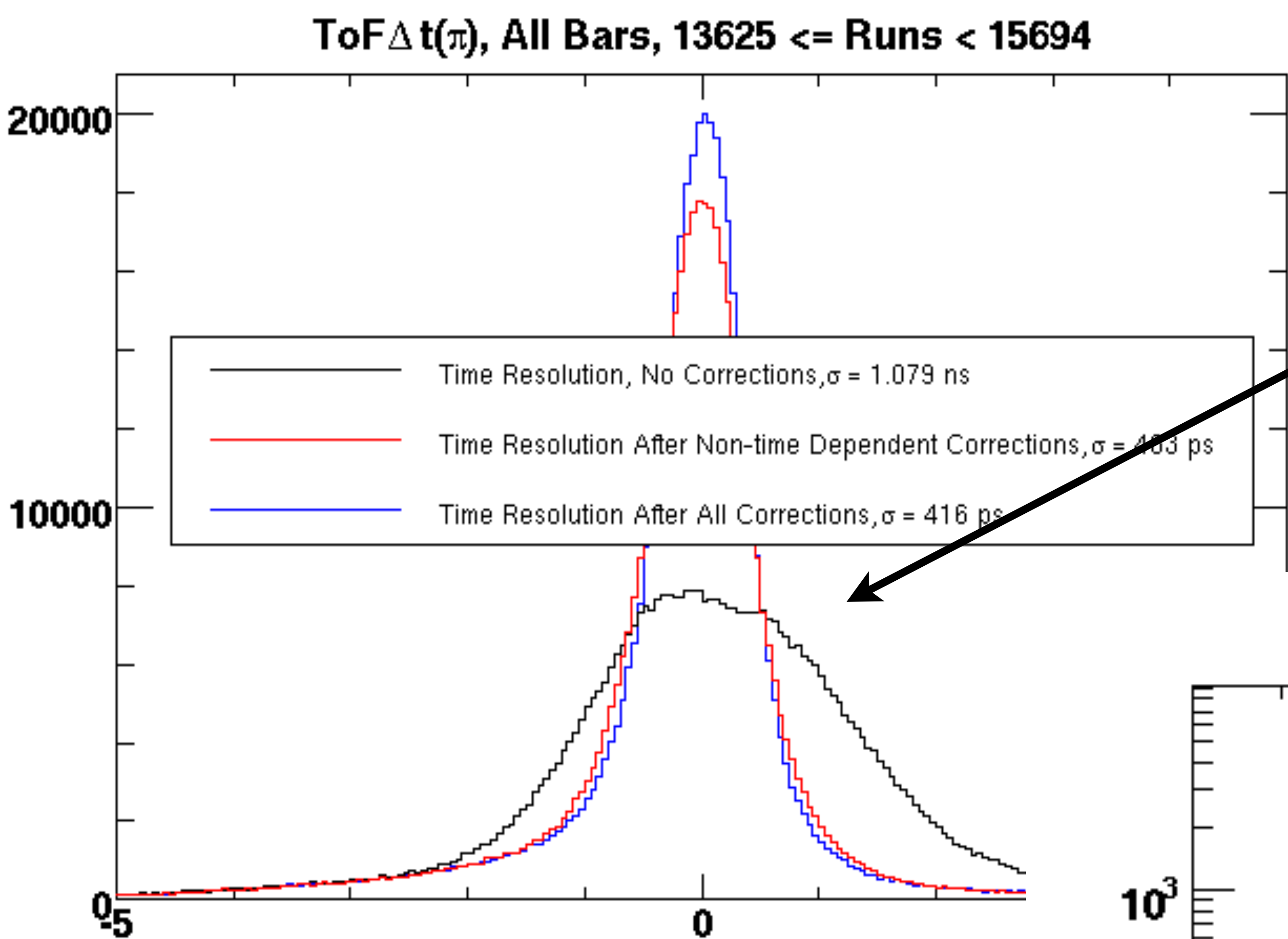


TPC <dE/dx> for 0.30 < P < 0.33 GeV/c



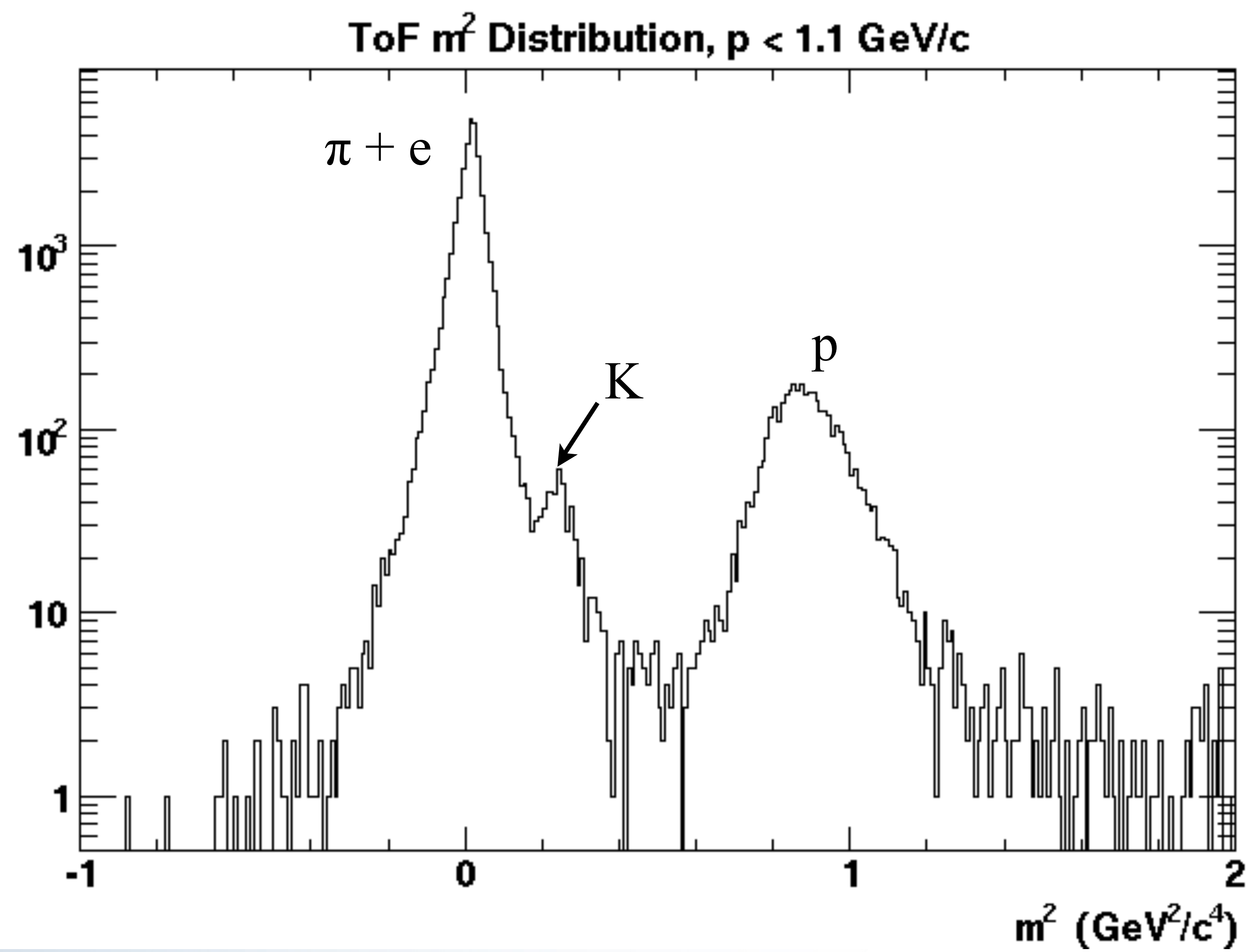
- TPC data are calibrated such that <dE/dx>(π) is 1 for p = 0.4 GeV/c and give expected Bethe-Bloch functional form.
- <dE/dx> resolution ~10%.
- Clean π, p separation between 0.2 and 1.2 GeV/c.

ToF PID Performance

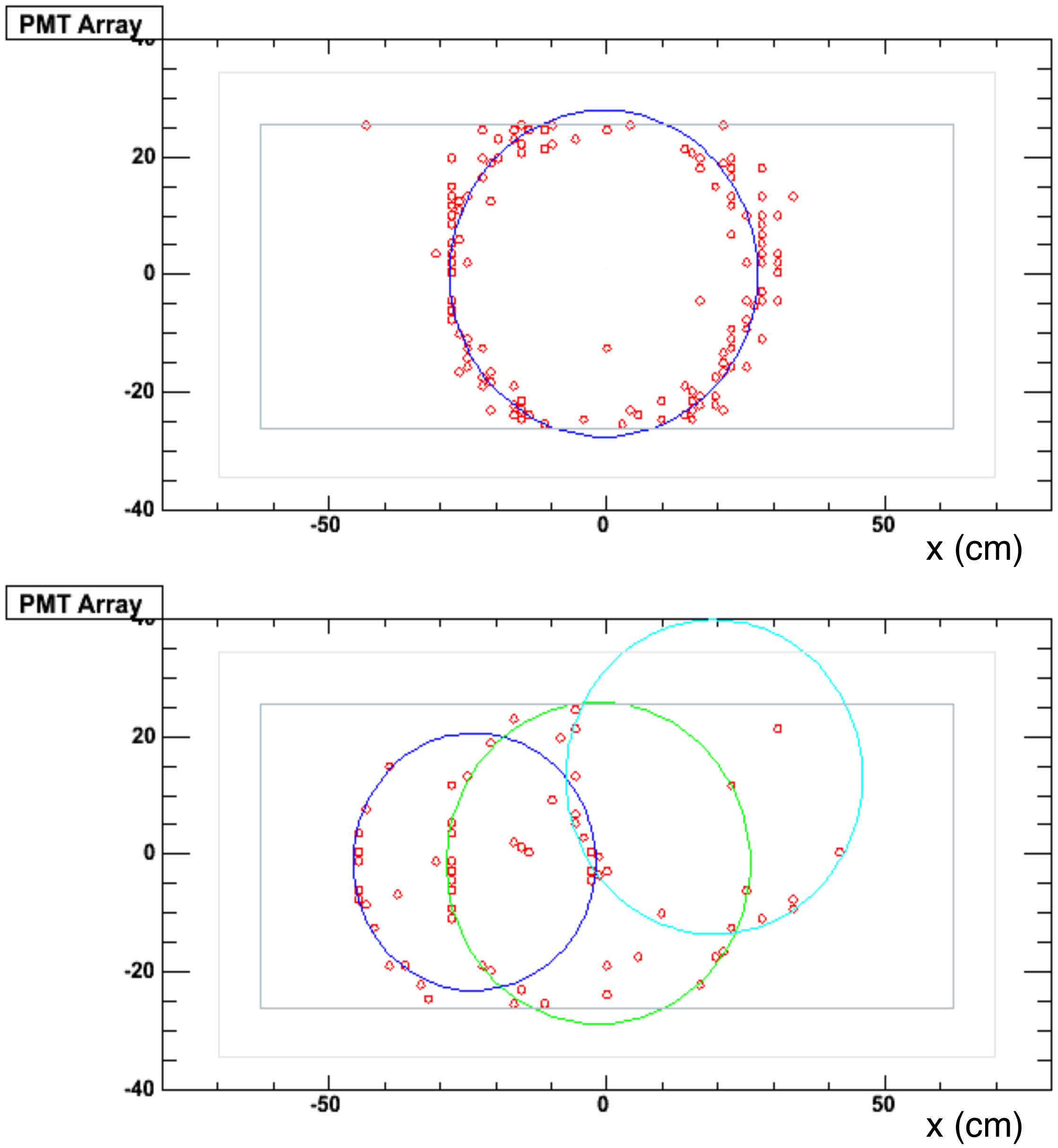


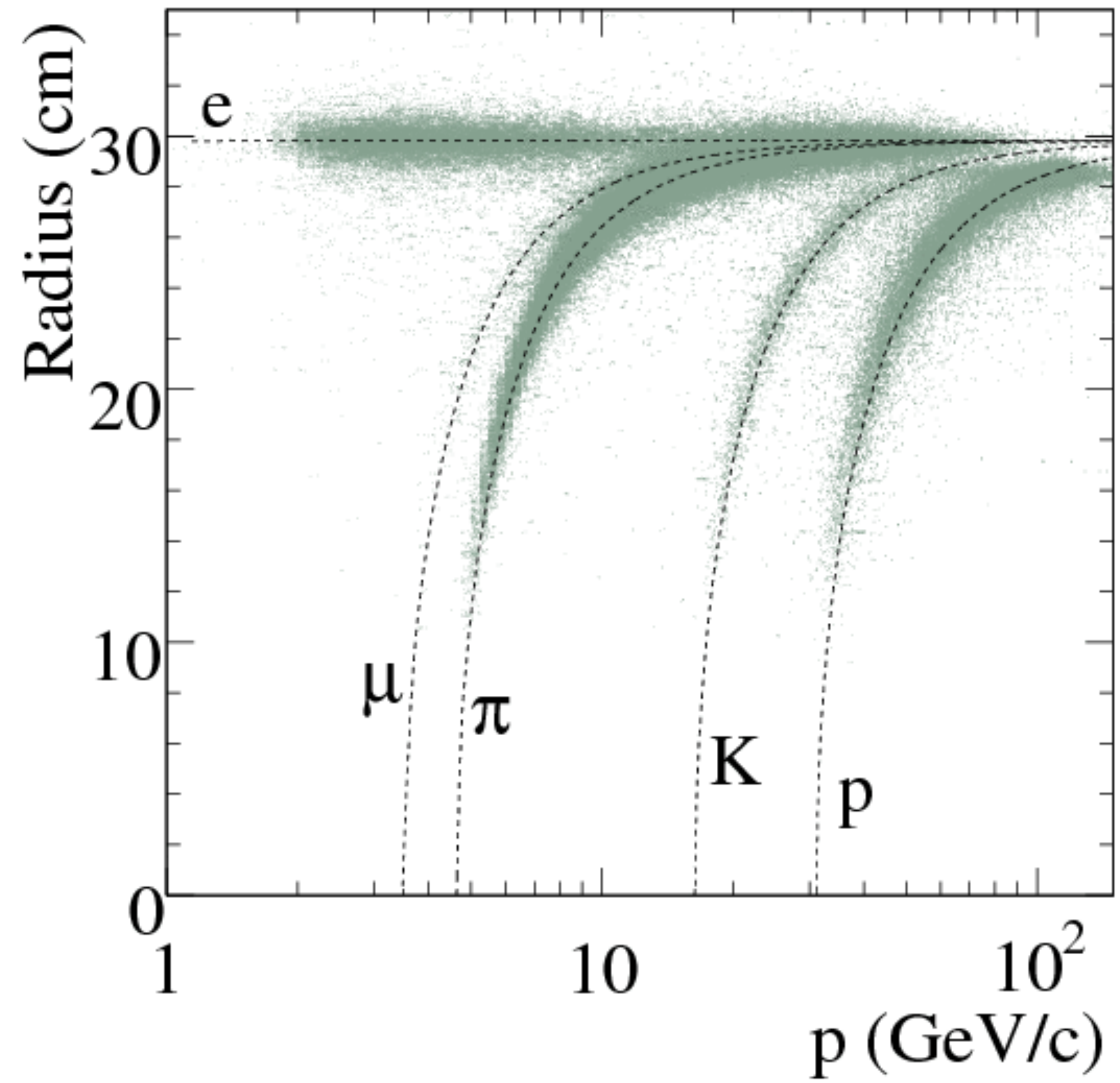
- 54 5-cm thick, 5-m tall scintillator bars, read out on both top and bottom.
- Data-driven corrections improved timing resolution by about a factor of 2.5
- Allows for proton-tagging up to a few GeV/c

$$m^2 = p^2\left(\frac{c^2\Delta t^2}{\Delta L^2} - 1\right)$$



RICH PID Performance





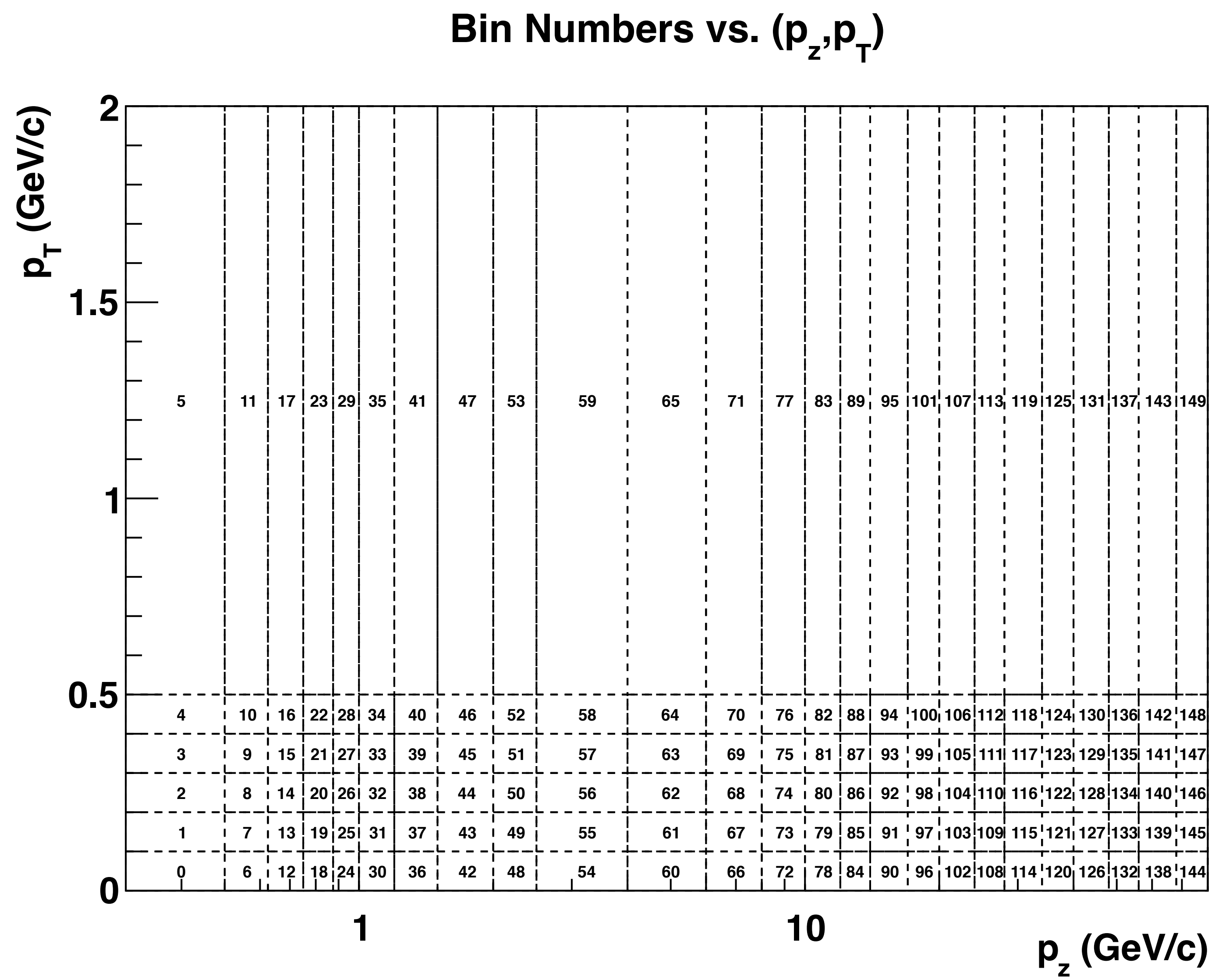
- Ckov light ring formed on array of ~2300 1/2” PMTs.
- Ring radius ~ Ckov angle ~ velocity.
- Excellent π/K and p/K separation up to 80 GeV/c

$$m^2 \simeq p^2 n^2 \left(1 - \left(\frac{r}{L}\right)^2\right) - p^2$$

The Analysis

NuMI Target Analysis

- Measure pion yield off surface of NuMI target (120 GeV/c p + NuMI).
- $N(\pi^{\pm})$/POT binned in (p_z, p_T), 150 bins *defined*, yields reported for ~125 bins.
- Bin widths chosen such that uncertainty on $N(\pi)$ ~ 5% but still much larger than resolution of spectrometer
- Yields are extracted from TPC, ToF and RICH PID distributions.
- Several acceptance and efficiency corrections must be applied to get the final yield.
- POT is defined as the number of proton interactions (events) that pass event selection.



$$N_\pi(p_z, p_T) = \frac{N_\pi^{\mathrm{meas}}(p_z, p_T)}{\epsilon_{\mathrm{accept}}^{\mathrm{spect}} \times \epsilon_{\mathrm{eff}}^{\mathrm{reco}} \times \epsilon_{\mathrm{accept}}^{\mathrm{PID}} \times \epsilon_{\mathrm{eff}}^{\mathrm{PID}}}$$

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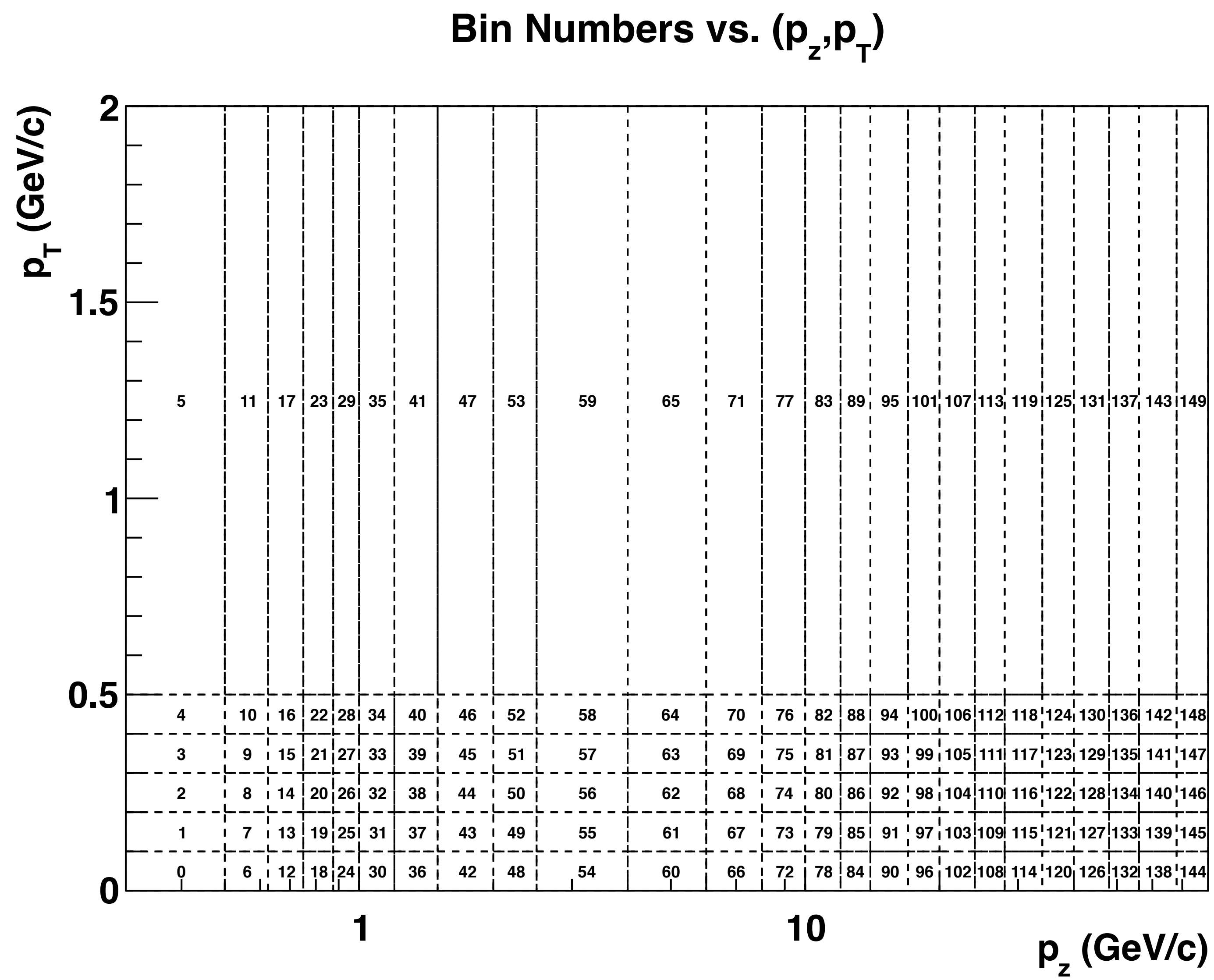

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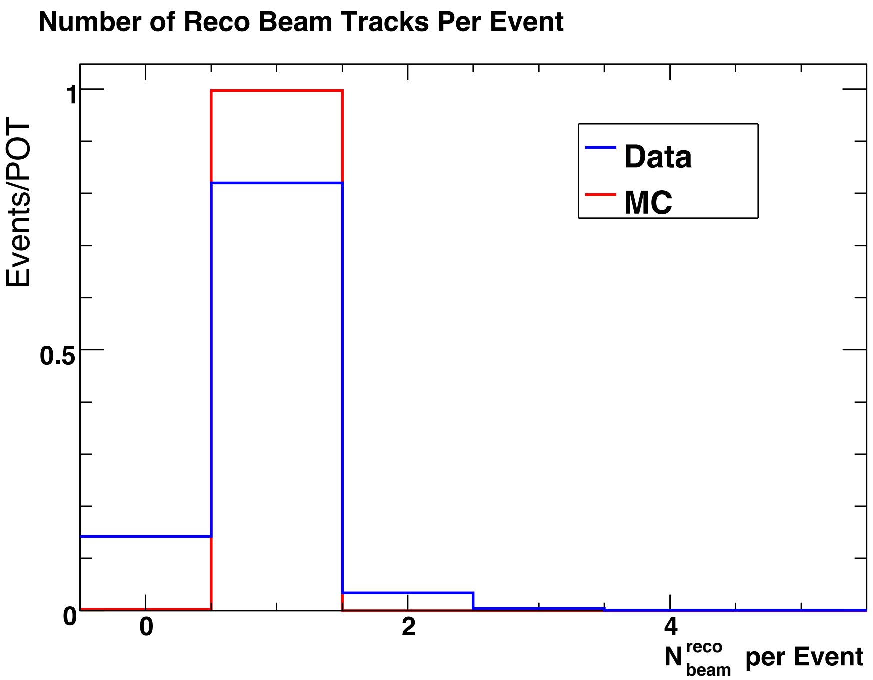
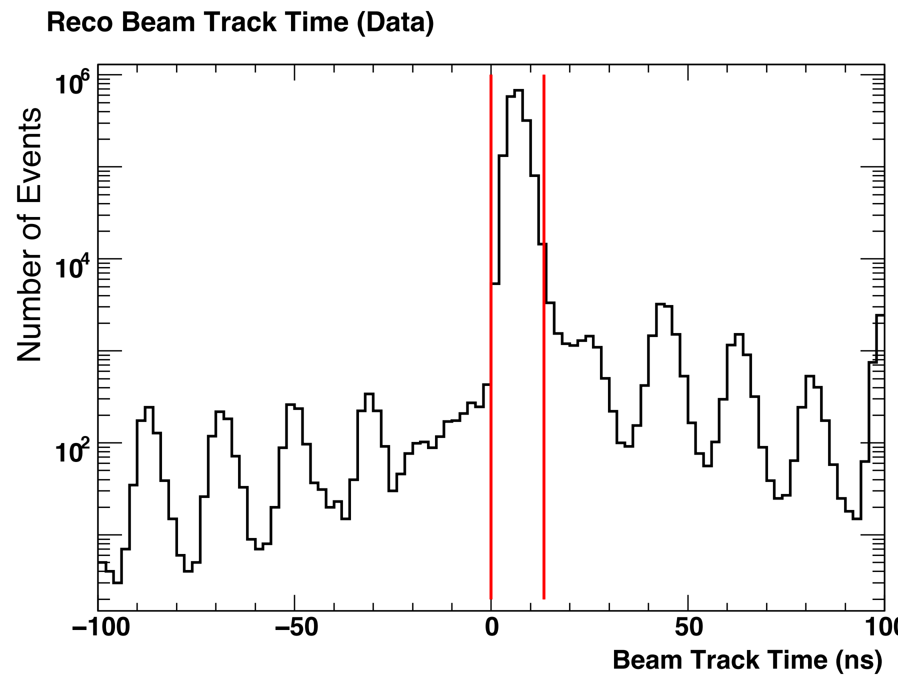
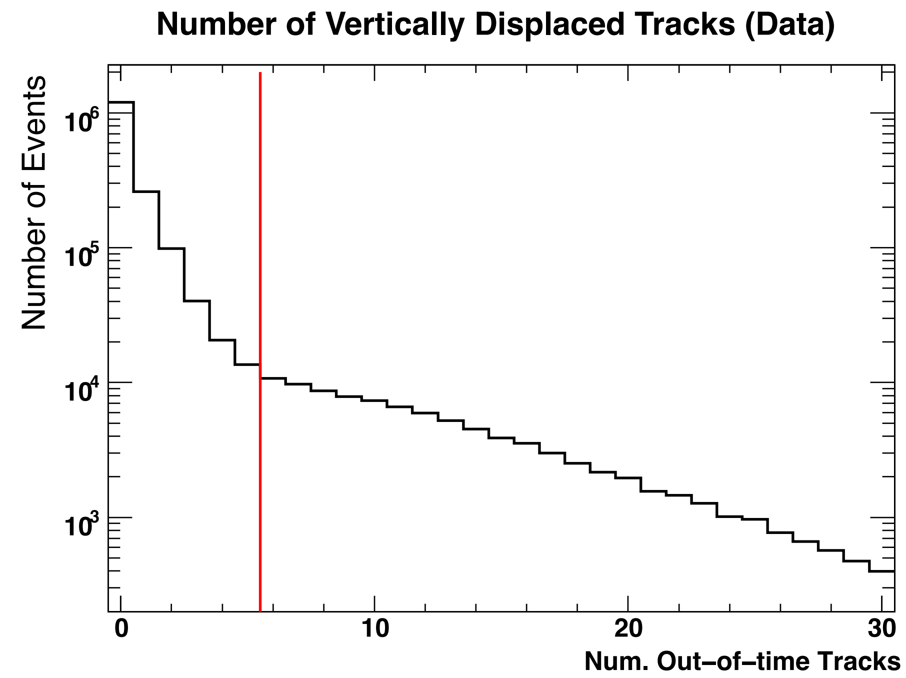
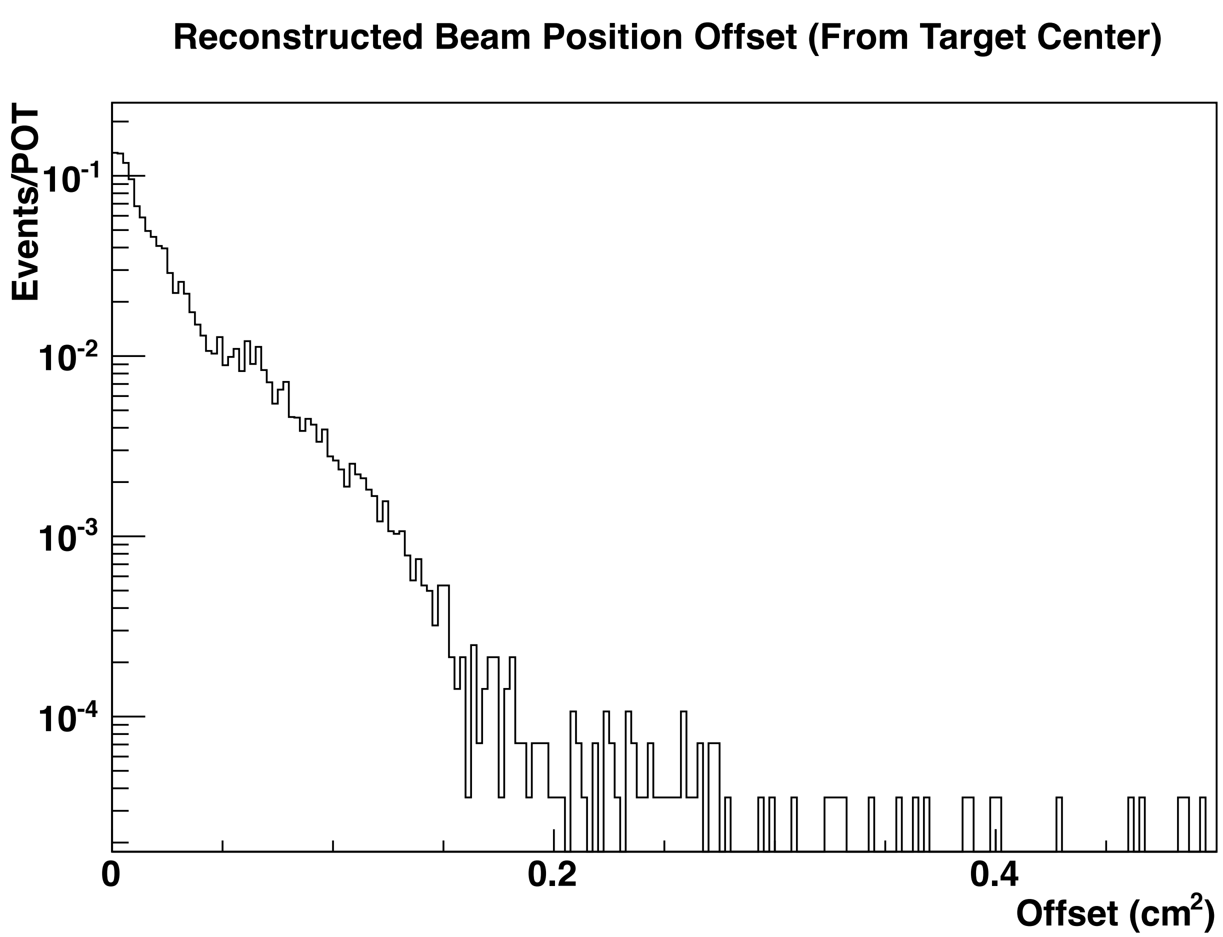
Determined from MC (Fluka v2005 + GEANT3)

Event Selection









- Require only one reconstructed beam track
- Reject events with multiple incident beam protons
- Ensure beam is centered on the NuMI target

TPC PID Measurements

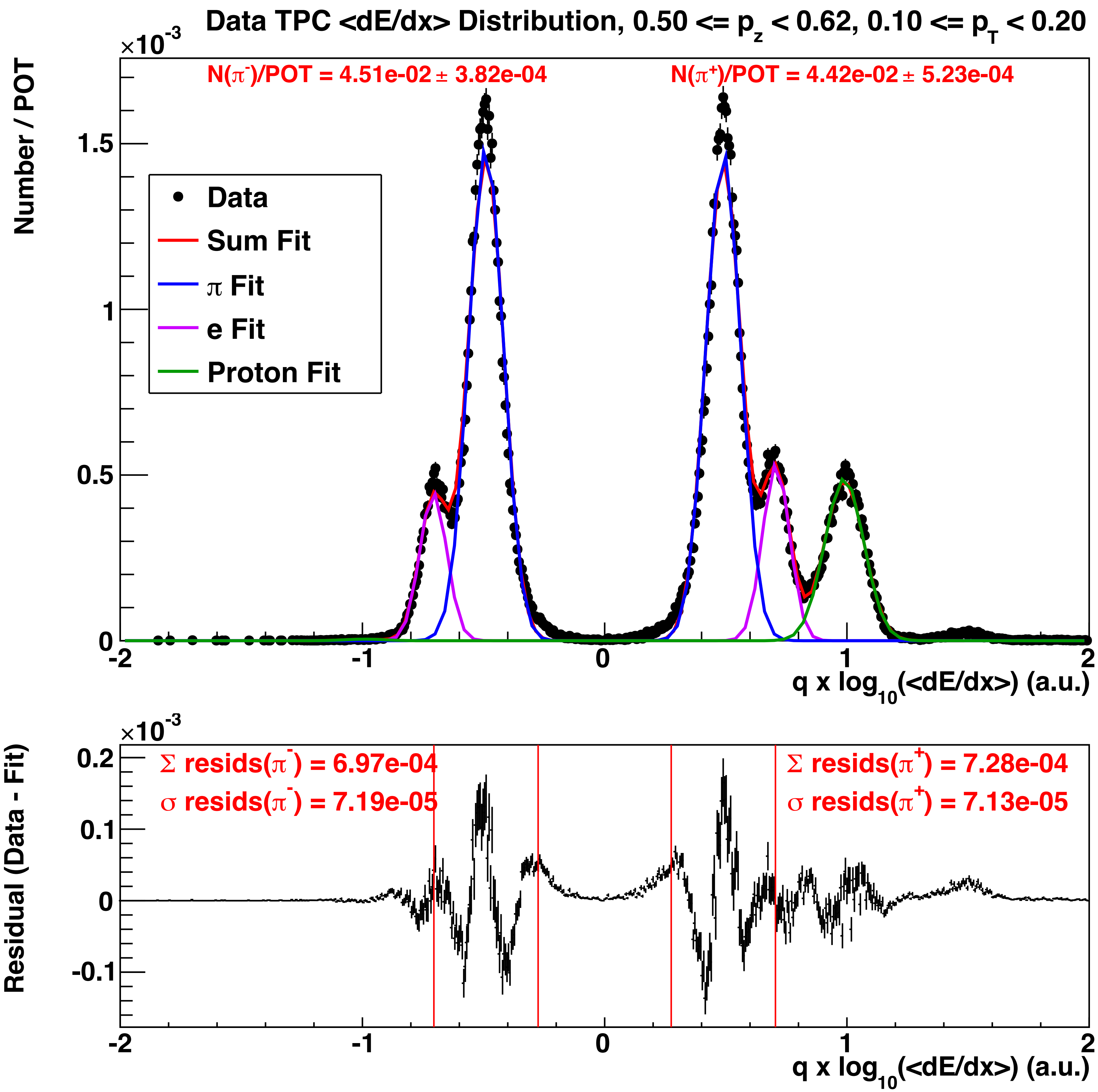
- *log(<dE/dx>)* distributions are nearly Gaussian in bins of p_{TOT}, and very nearly Gaussian in most (p_z,p_T) bins.
- Approach is to fit these distributions to sum of 3 Gaussians
- TPC fits: function is 3-Gaussian sum, kaons are negligible

$$\begin{aligned} N(y) = & A_{\pi^+}\left[f^+_{e\pi}G^+_e(y) + G^+_\pi(y) + f^+_{p\pi}G^+_p(y)\right] + \\ & A_{\pi^-}\left[f^-_{e\pi}G^-_e(y) + G^-_\pi(y) + f^-_{p\pi}G^-_p(y)\right] \end{aligned}$$

, where $G^{\pm}_i = \exp\left(\frac{(y \mp y_i)^2}{2\sigma_i^2}\right)$

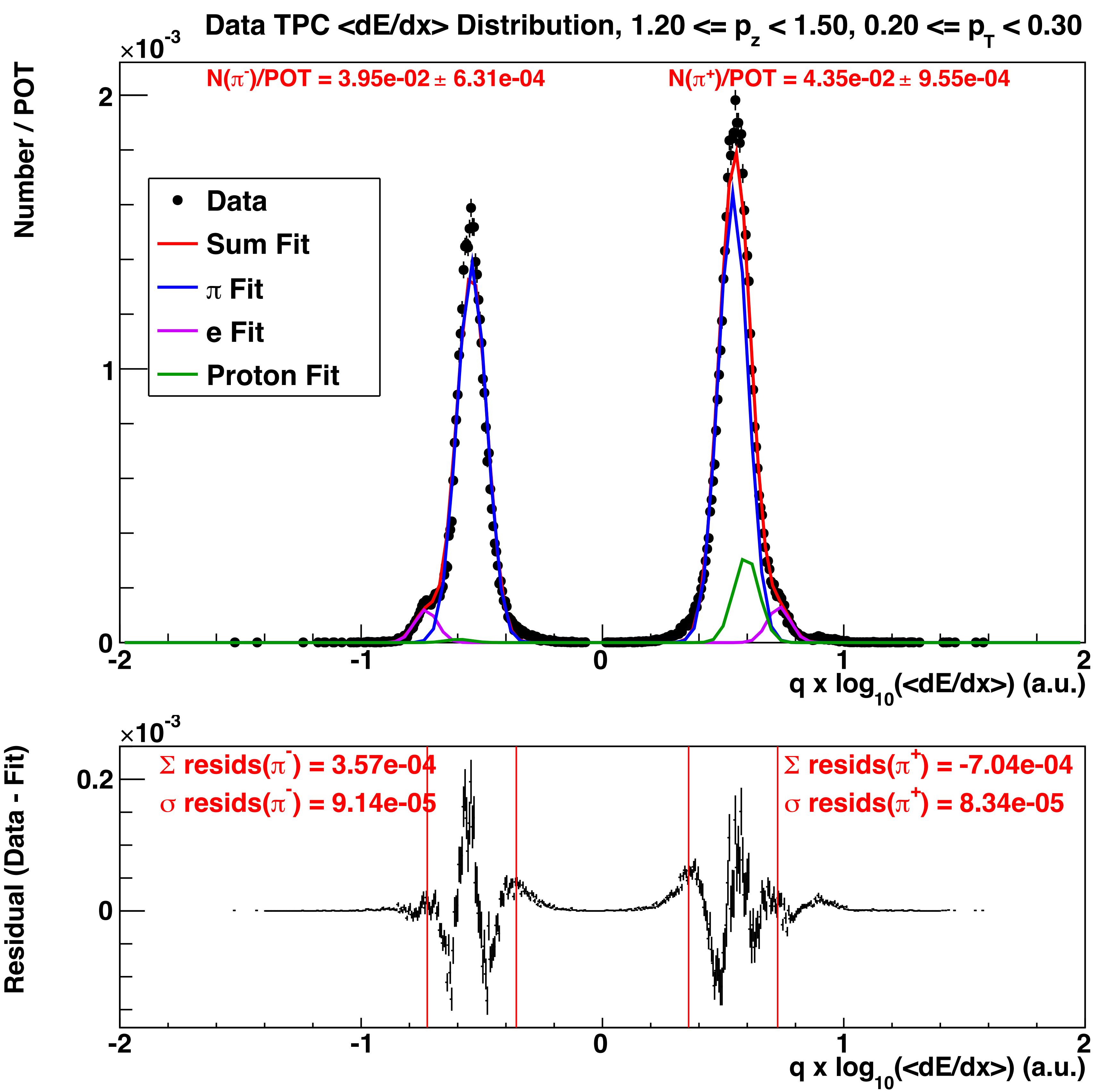
  - y = log(<dE/dx>)
  - $f_{e\pi} = A_e/A_\pi$, $f_{p\pi} = A_p/A_\pi$
  - widths are constrained to be "physical", means are constrained to be close to expected values from MC

TPC PID Measurements



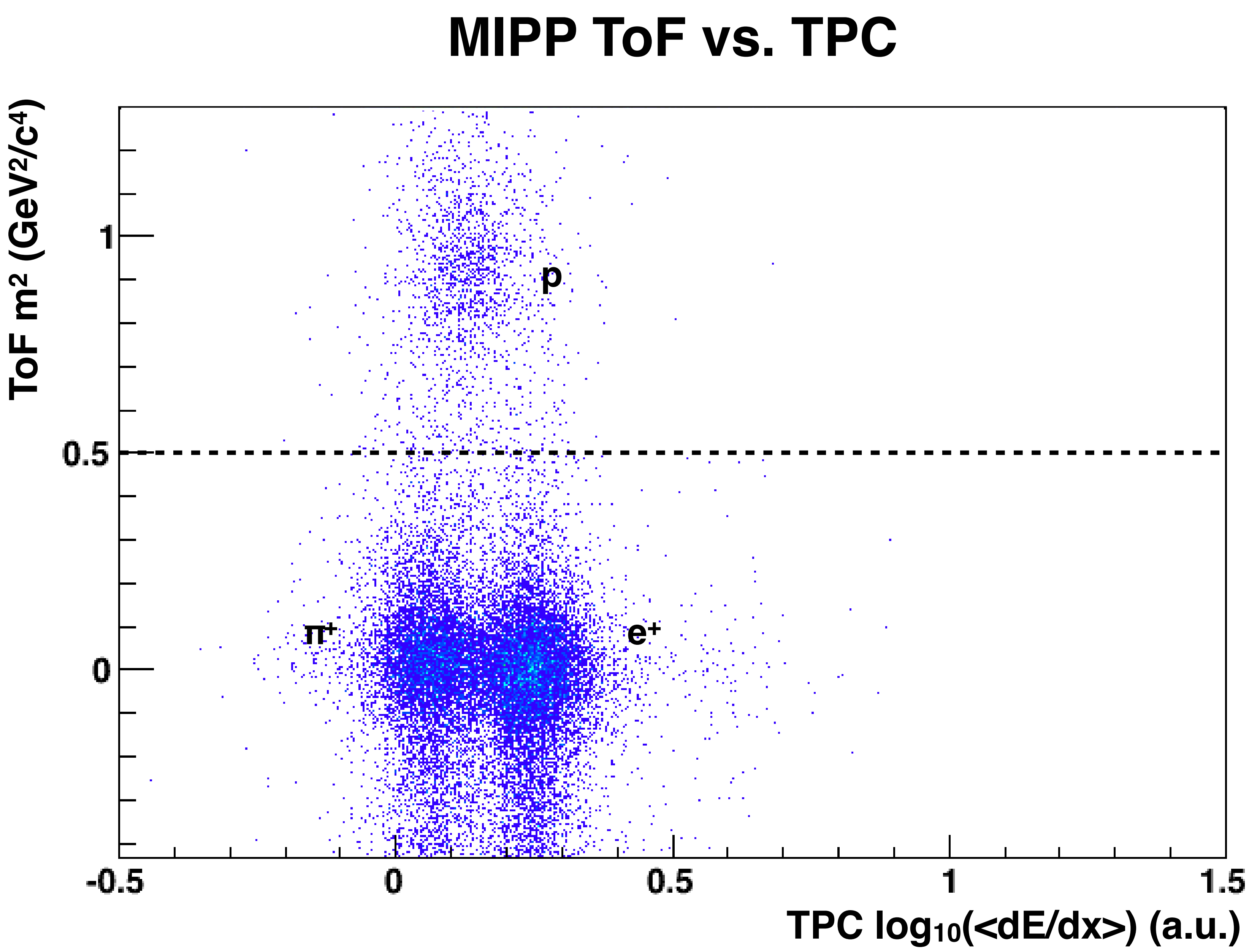
- $N(\pi)$ = integral of Gaussian corresponding to pion peak. Uncertainty derived from fit parameter uncertainties.
- The extent to which any non-Gaussian feature(s) of the distribution effects the $N(\pi)$ can be estimated by looking at the integral of the residuals over the range of the pion peak. Very small effect observed.

TPC PID Measurements



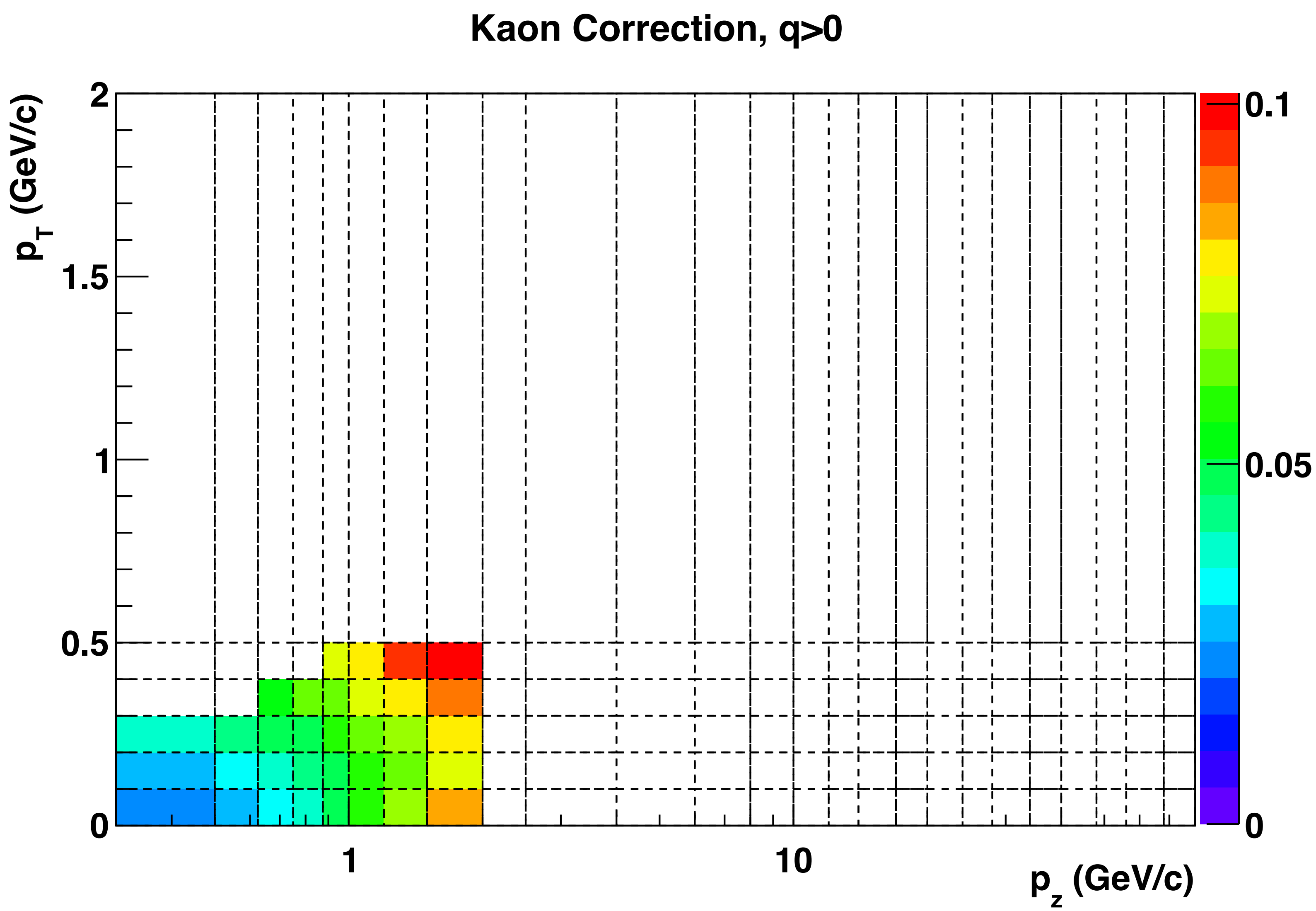
- In some bins, the proton peak sits right the pion peak.

TPC PID Measurements



- In some bins, the proton peak sits right the pion peak.
- We use the ToF data where no other reconstructed track traverses the ToF scintillator bar.
- Fit <dE/dx> data with $m^2_{ToF} < 0.5$ to 4 Gaussian peak function.
- "Count" protons ($m^2_{ToF} > 0.5$)
- Use count and fit to estimate the p/π fraction.

What About the Kaons?



- We've ignored the kaons in the fit because we can't see them. But they're there.
- Use MC to estimate the K/π fraction in each bin, which is then subtracted from the pion yield.
- Assume a 30% uncertainty from MC.

RICH PID Measurements

- m^2 distributions are not very Gaussian. But peaks are generally well separated.
- Approach is to "cut and count". Split m^2 distribution in each (p_z,p_T) bin into three regions: 1 "mostly" signal + 2 "mostly background" sidebands.

$$N_\pi = \sum_i N_{\pi_i} \qquad \sigma^2_\pi = \sum_i \sigma^2_{\pi_i}$$

Data

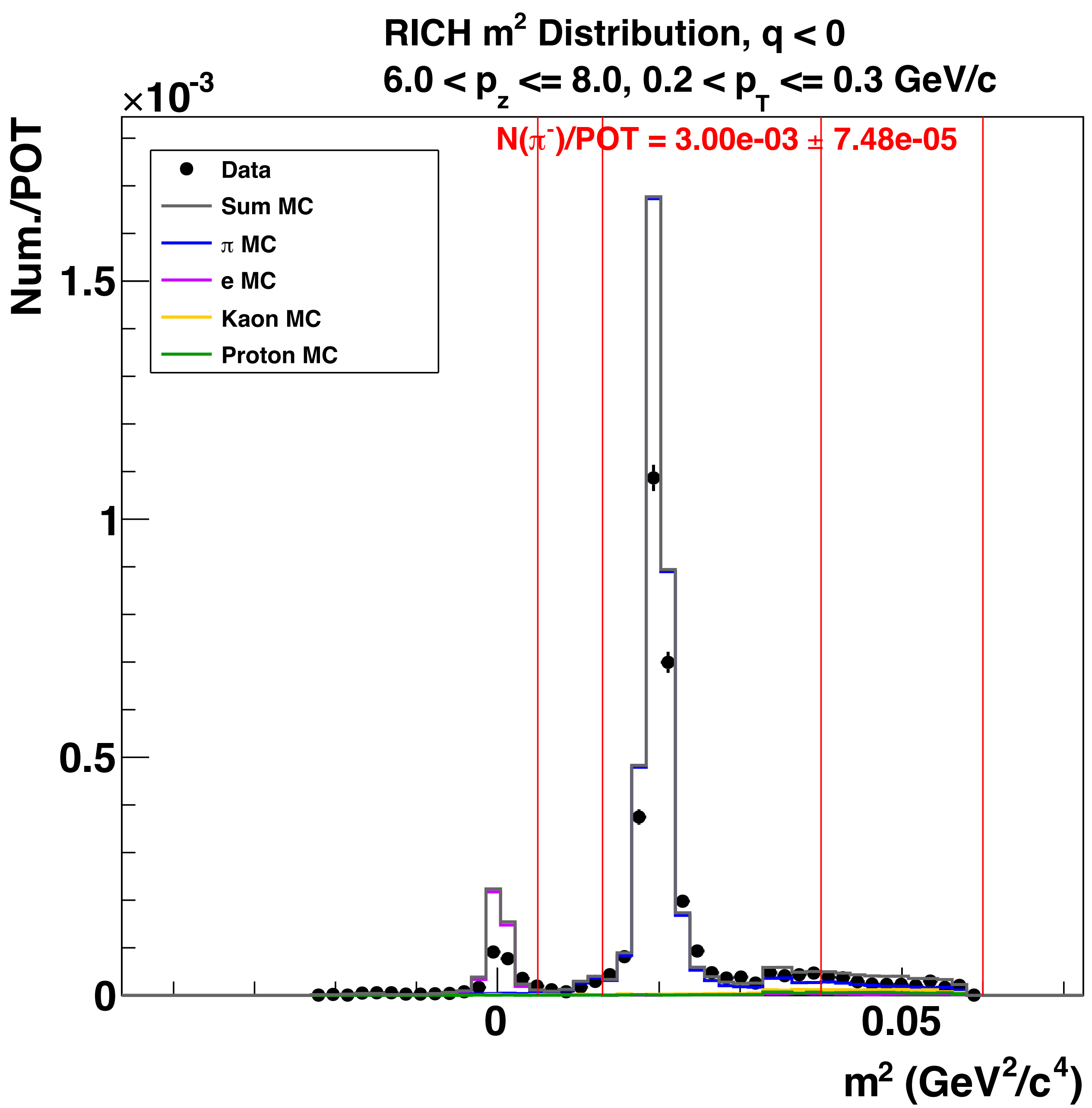
$$N_{\pi_i} = N_i - b_i \bar{N}_i \qquad b_i = \frac{B_i}{\bar{S}_i + \bar{B}_i}$$

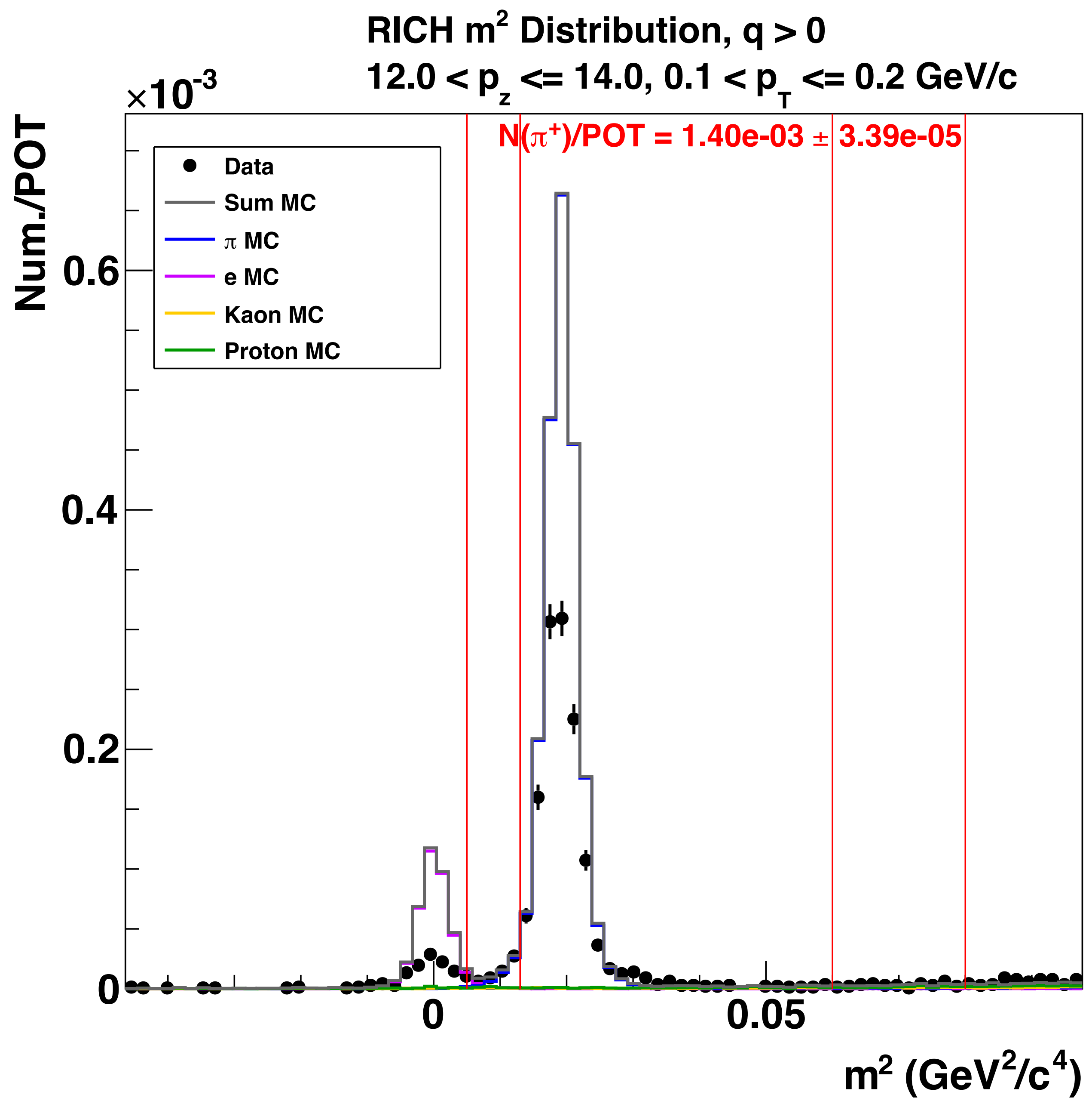
MC

$$\sigma^2_{N_{\pi_i}} = N_i + \bar{N}_i b_i^2 (1 + \bar{N}_i \delta b_i)$$

- Set δb_i = 30%

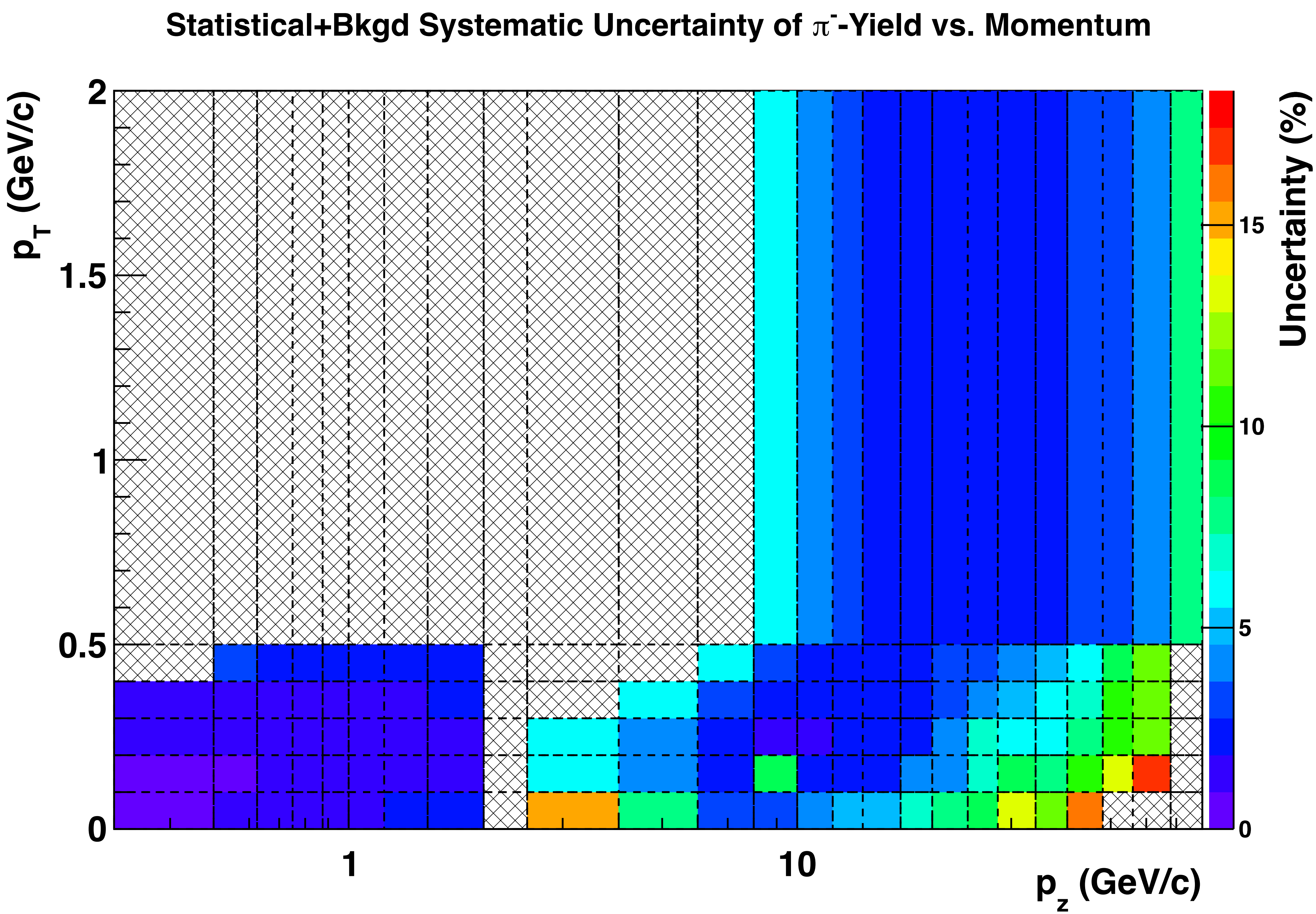
RICH PID Measurements





- MC is used to determine ranges for cut-and-count approach, as well as to estimate backgrounds in the 3 regions defined by the red lines.
- Error shown here is combined statistical and systematic (background subtraction).

Statistical ⊕ Background Systematic Uncertainties



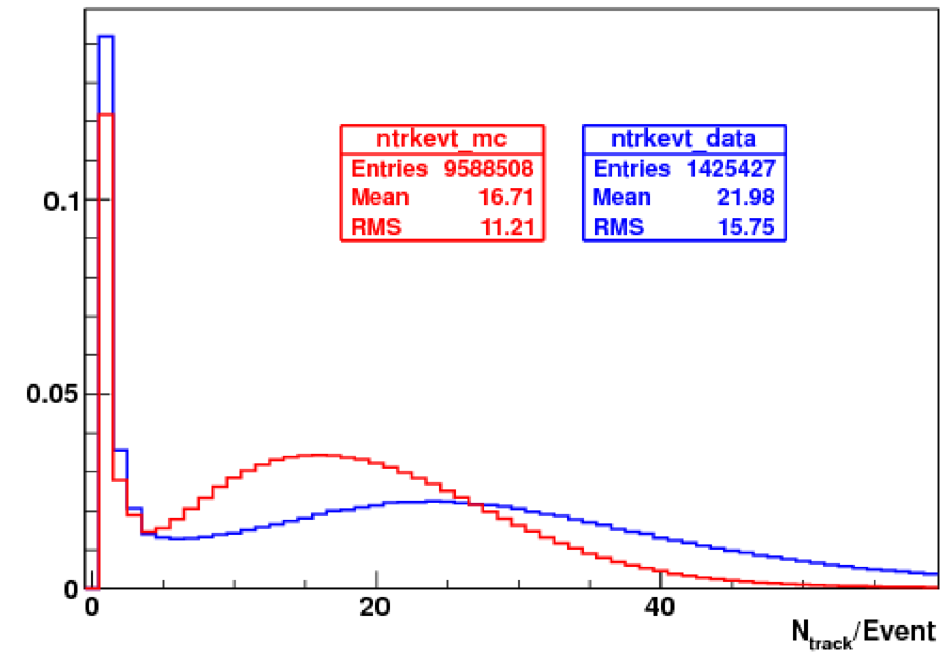
Other Systematics

- Momentum Bias Correction (~< 2%)
- Absolute Momentum Scale (~< 2%)
- Resolution and Reconstruction Failures (~4%)
- **Acceptance and Efficiency Corrections**

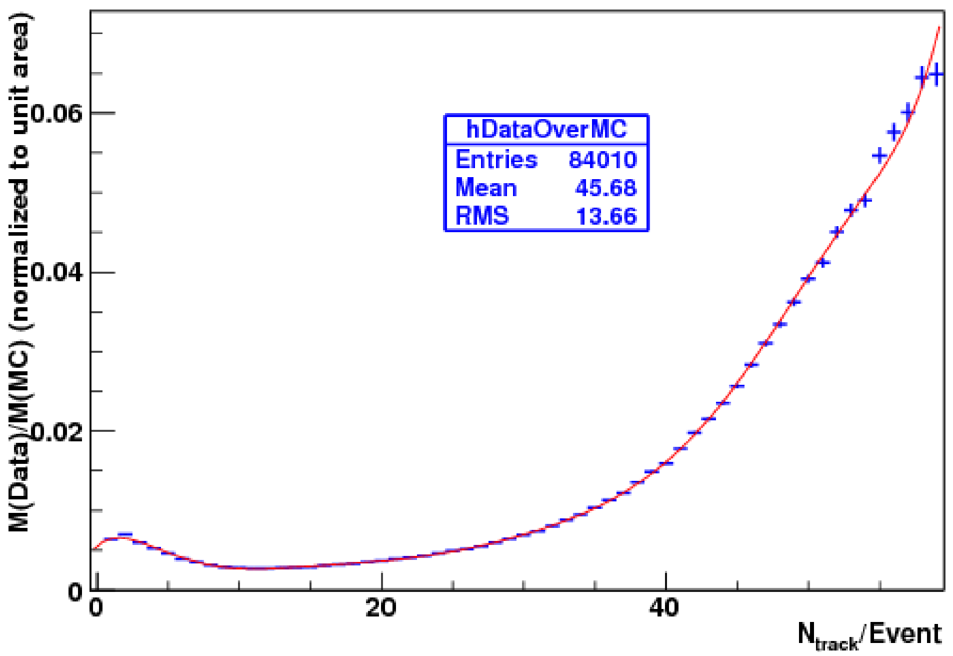
Efficiency and Acceptance Corrections

- imperfections in the geometry model of the spectrometer (negligible)
- imperfections in the modeling of the performance of the tracking and PID detectors (2%)
- incorrect modeling of the particle yields in the MC
  - we know this is true since we see large discrepancies in the number of e-/e+ pairs at low momenta in the data than we do in the MC
  - data shows higher multiplicities; high multiplicity events have higher rates of track reconstruction inefficiencies
  - to get a handle on this, we re-weight MC events such that the MC multiplicity distribution matches that of the data and calculate all efficiency corrections

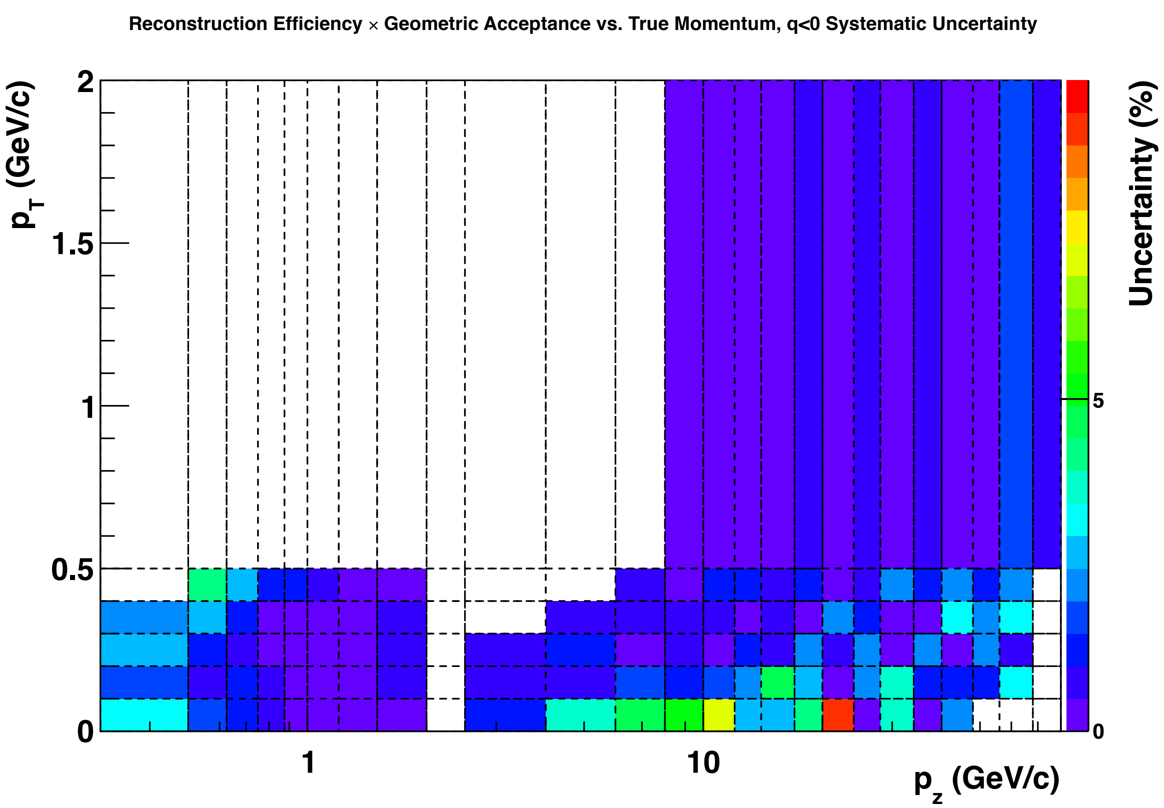
Track Multiplicity Distribution

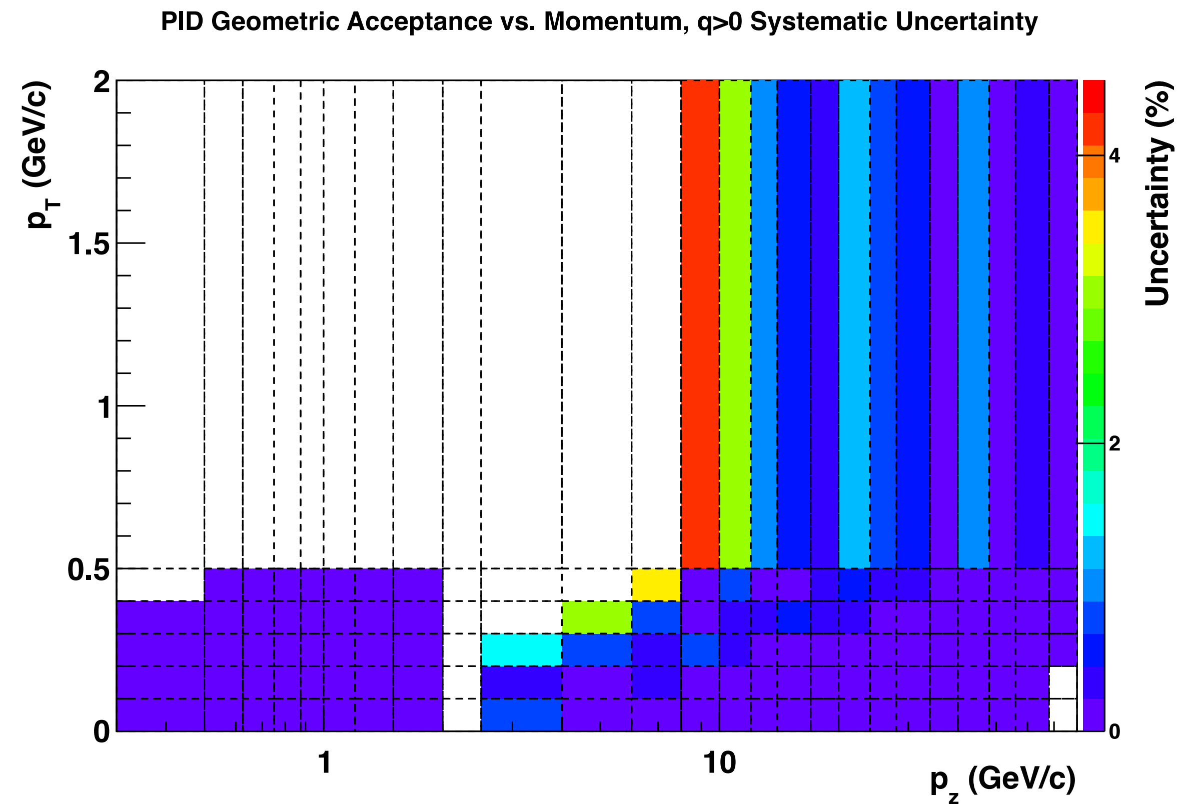


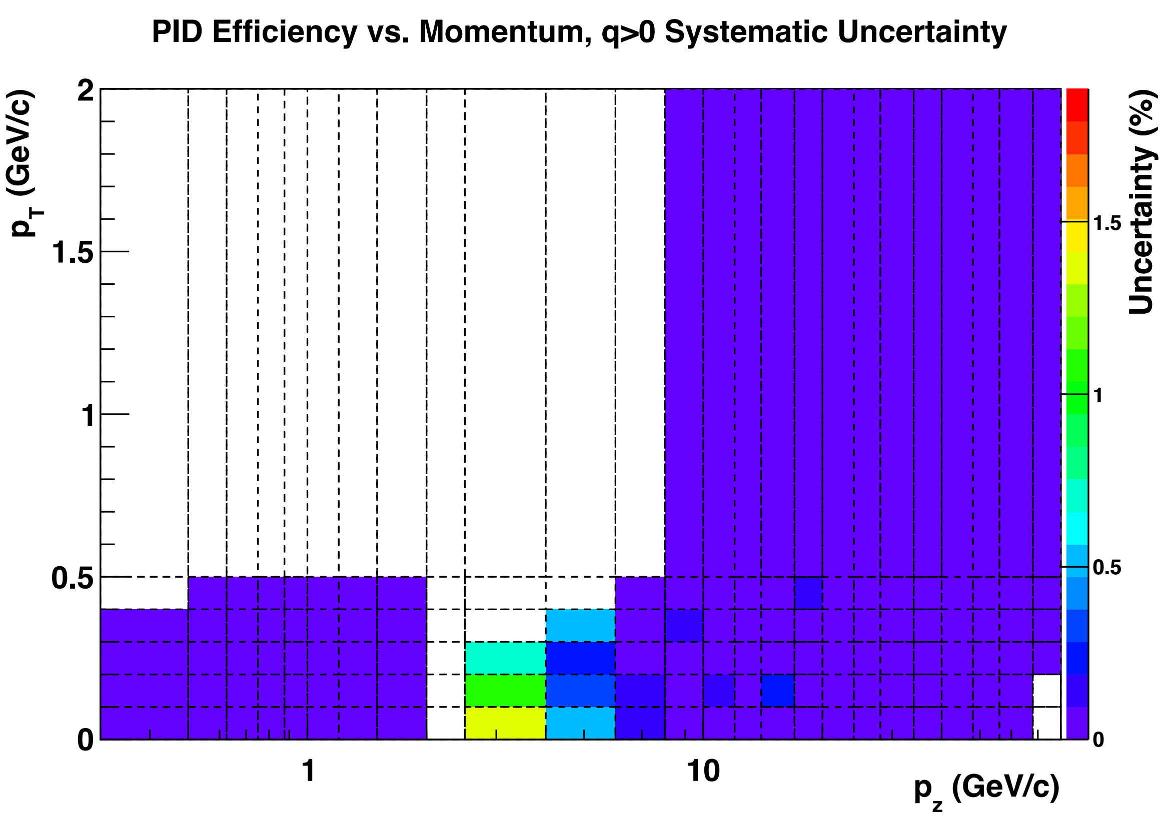
Data/MC Multiplicity Ratio



Efficiency and Acceptance Correction Systematics



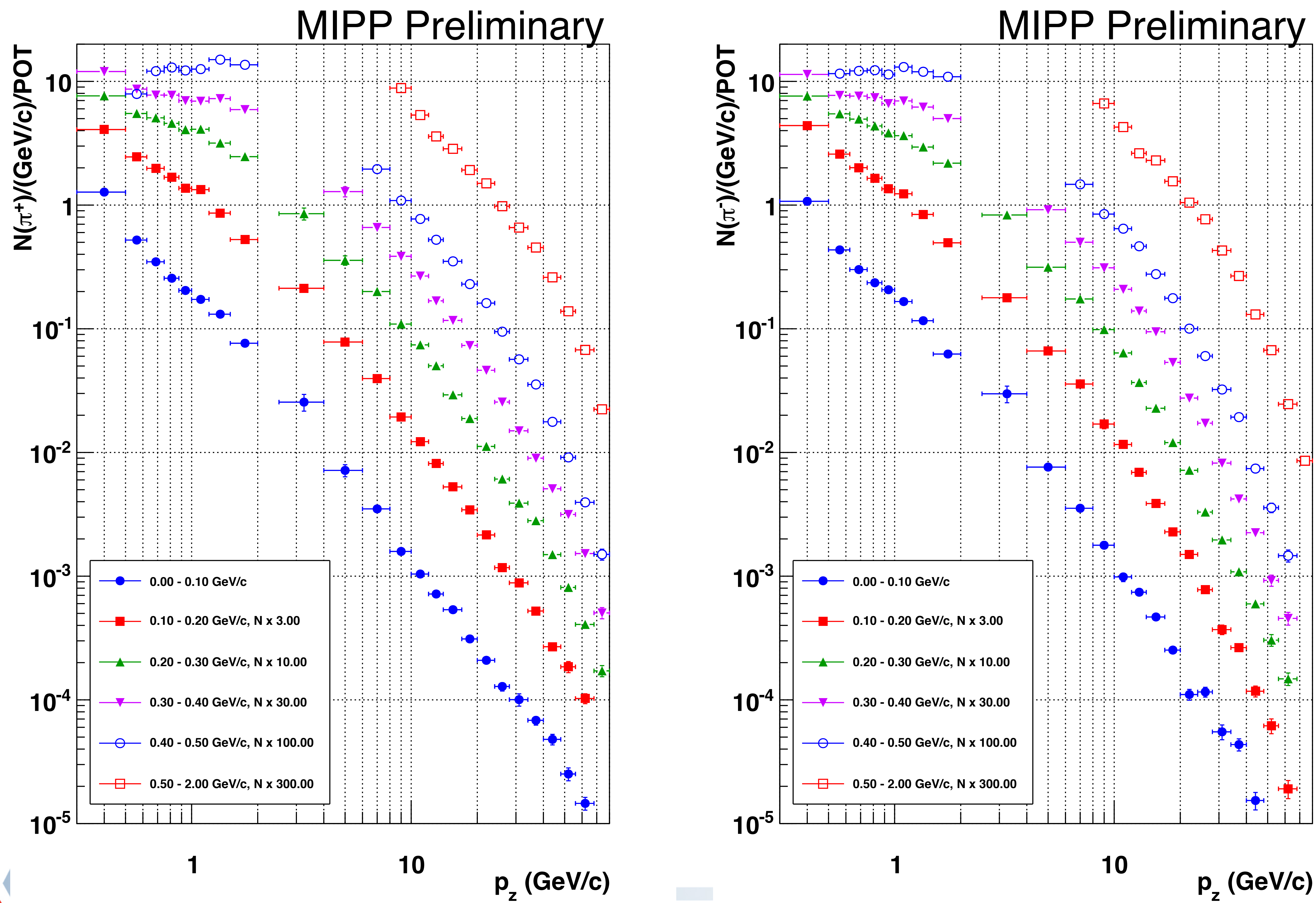




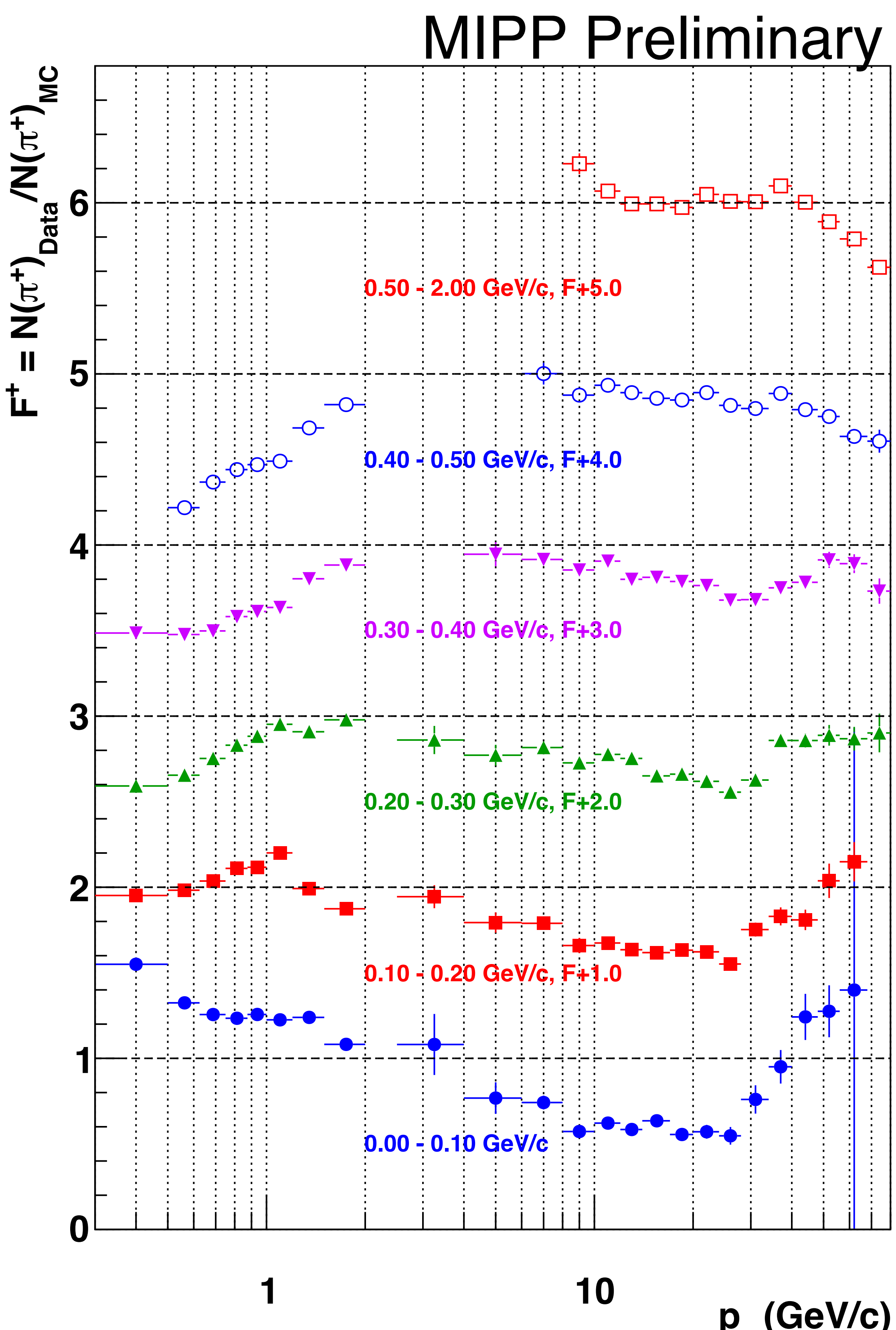
- Uncertainty on the measurement of the multiplicity of an event is < 20%
- Take 20% of the difference between efficiencies determined from nominal and re-weighted MC as an estimate of the systematic uncertainty due to incorrectly modeling the particle yields

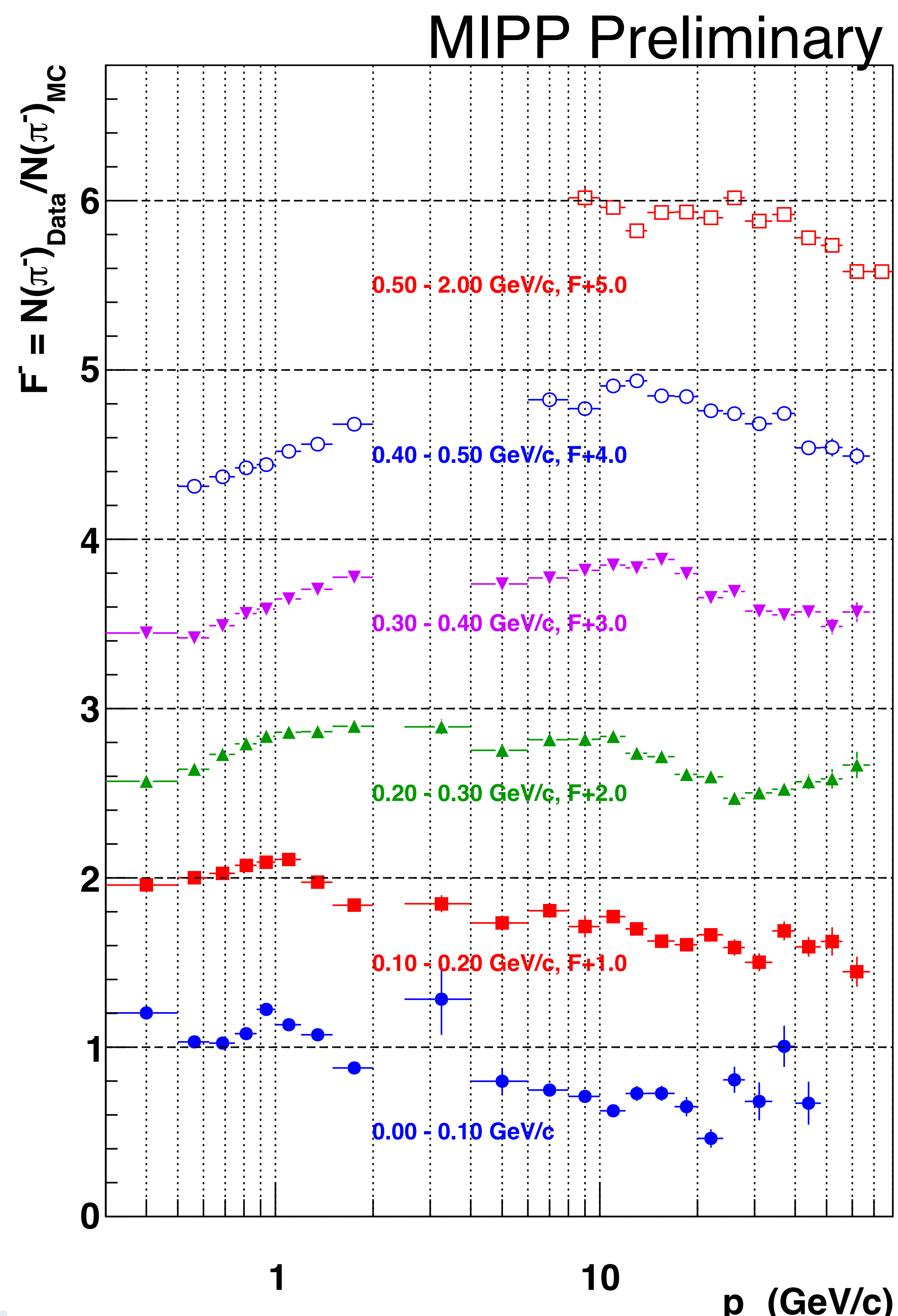
Final Results and MC Comparisons

π Yields


MIPP Preliminary
$N(\pi^+)/(GeV/c)/POT$
MIPP Preliminary
$N(\pi^-)/(GeV/c)/POT$
0.00 - 0.10 GeV/c
0.10 - 0.20 GeV/c, N x 3.00
0.20 - 0.30 GeV/c, N x 10.00
0.30 - 0.40 GeV/c, N x 30.00
0.40 - 0.50 GeV/c, N x 100.00
0.50 - 2.00 GeV/c, N x 300.00
p_z (GeV/c)

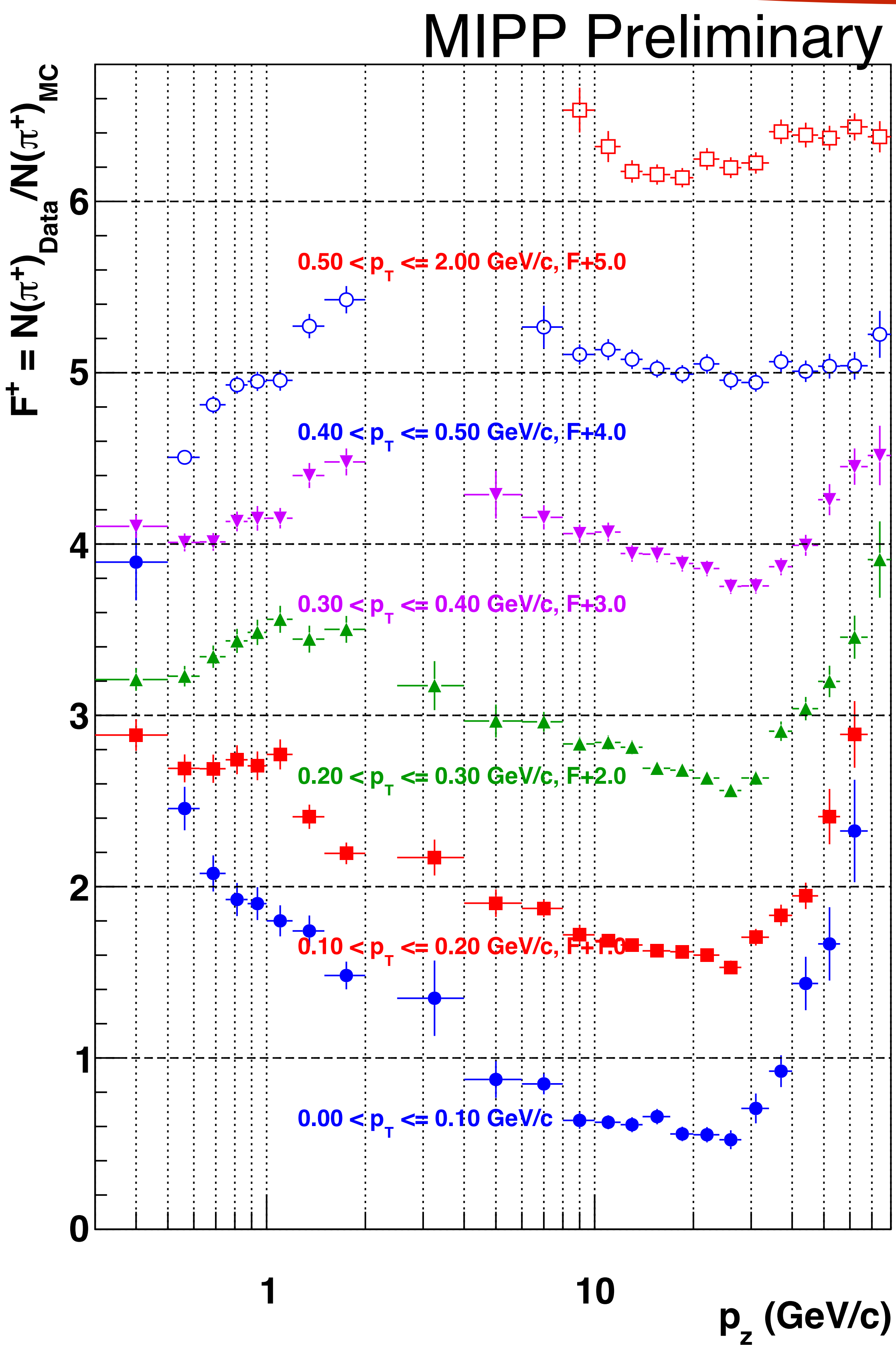
Data/Fluka MC Yield Ratios

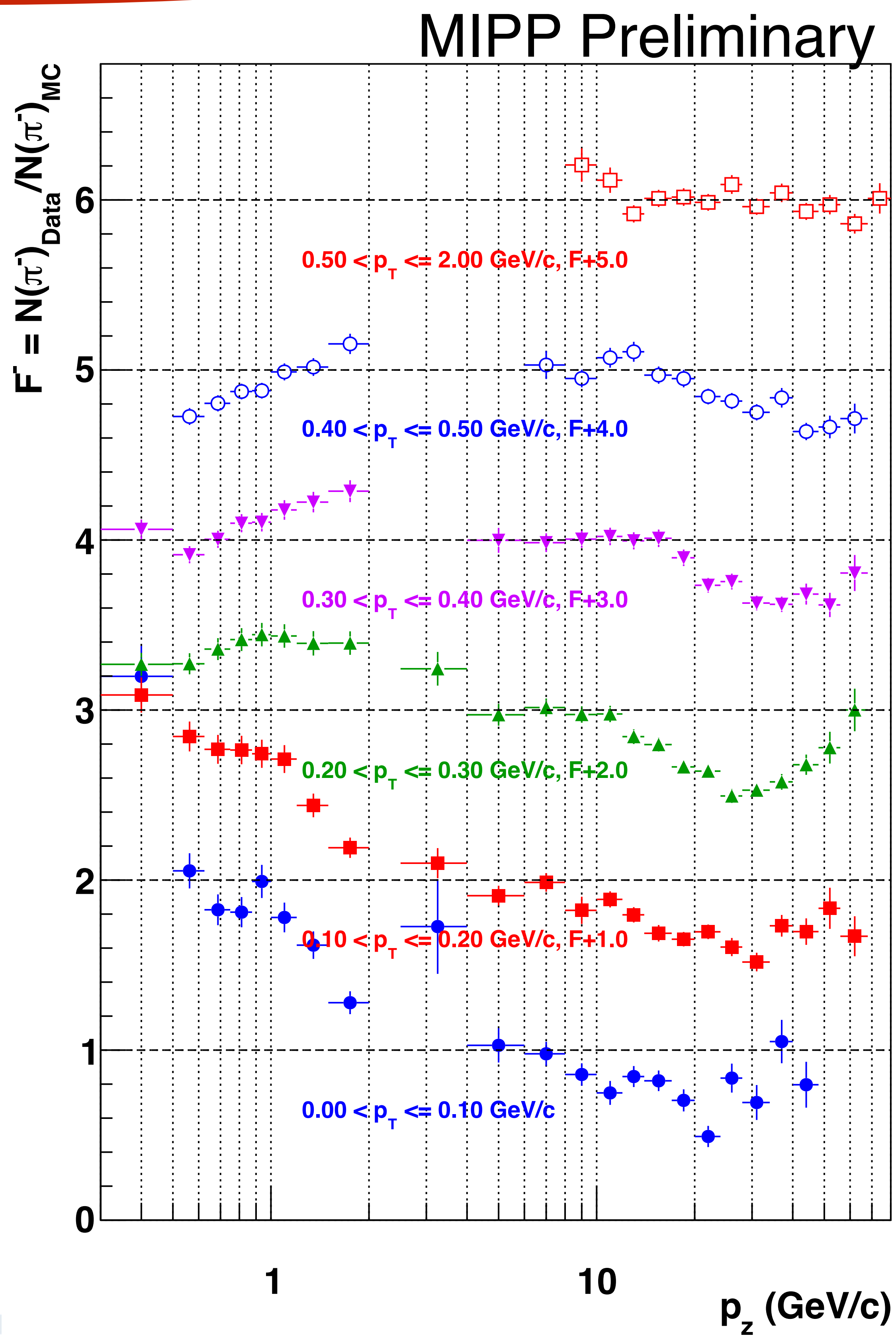




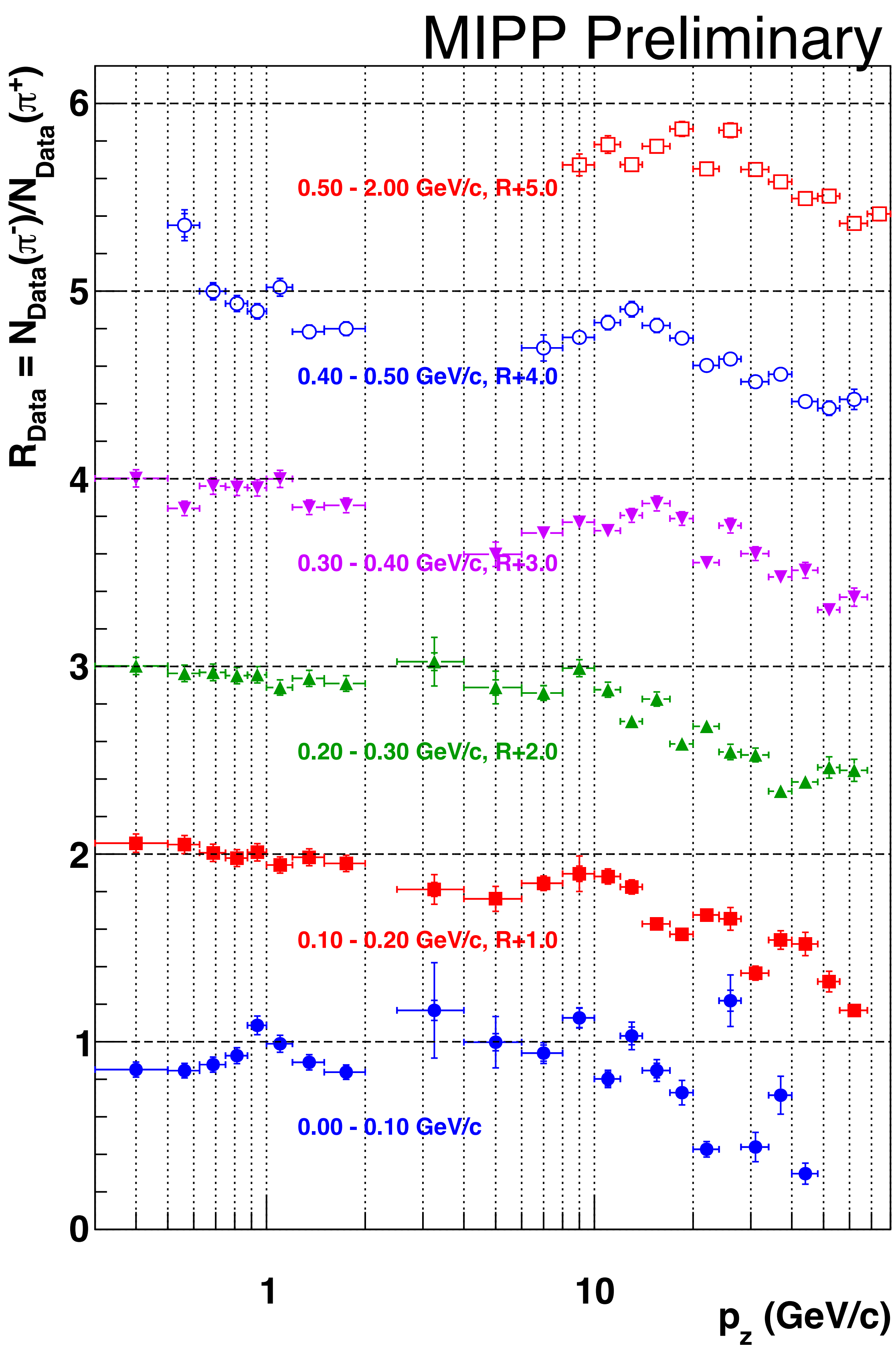
Data/g4NuMI MC Yield Ratios

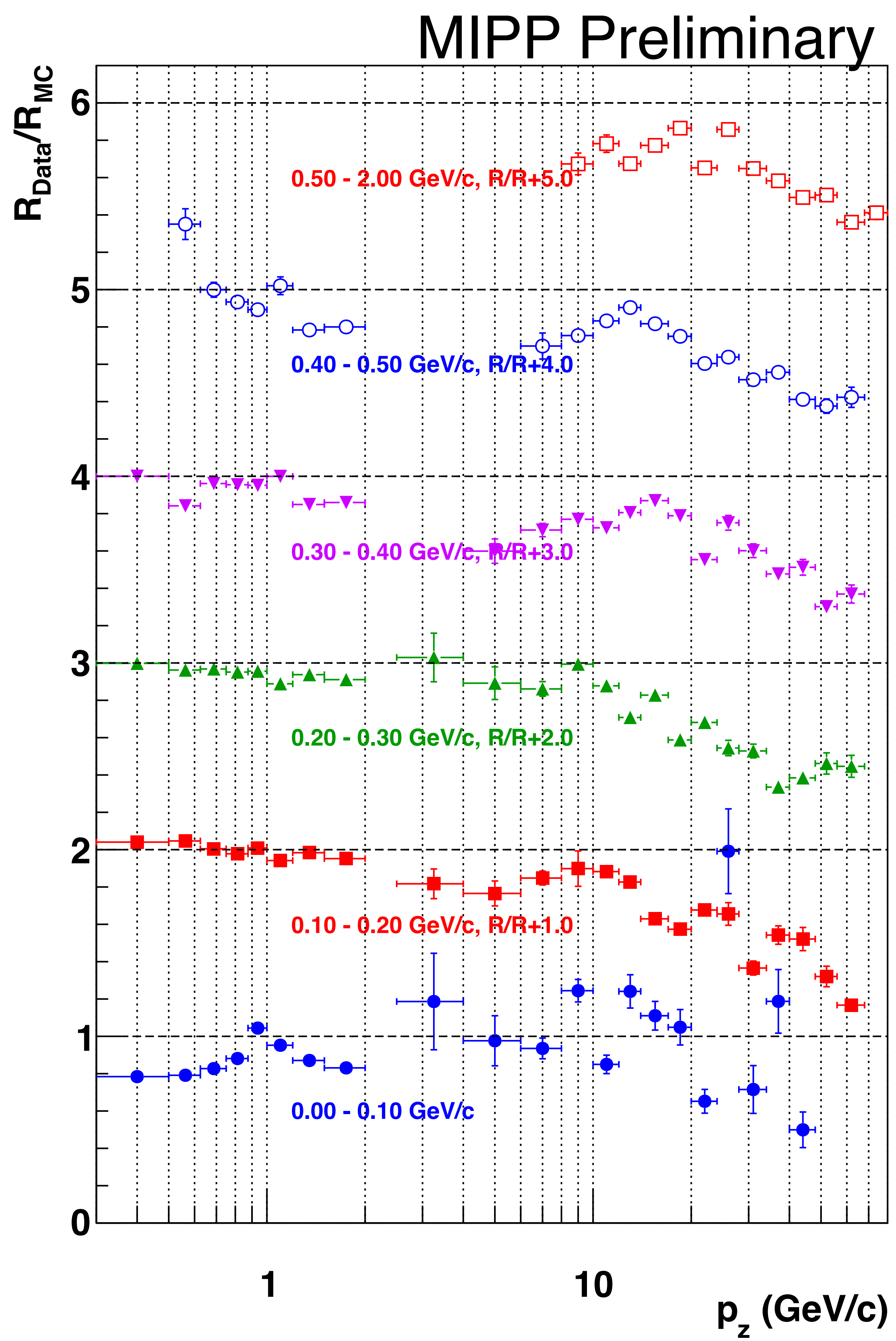
Many thanks to Leo Soplin!





π-/π+ Ratios


MIPP Preliminary
$R_{Data} = N_{Data}(\pi^-)/N_{Data}(\pi^+)$
0.50 - 2.00 GeV/c, R+5.0
0.40 - 0.50 GeV/c, R+4.0
0.30 - 0.40 GeV/c, R+3.0
0.20 - 0.30 GeV/c, R+2.0
0.10 - 0.20 GeV/c, R+1.0
0.00 - 0.10 GeV/c
0
1
2
3
4
5
6
1
10
p_z (GeV/c)

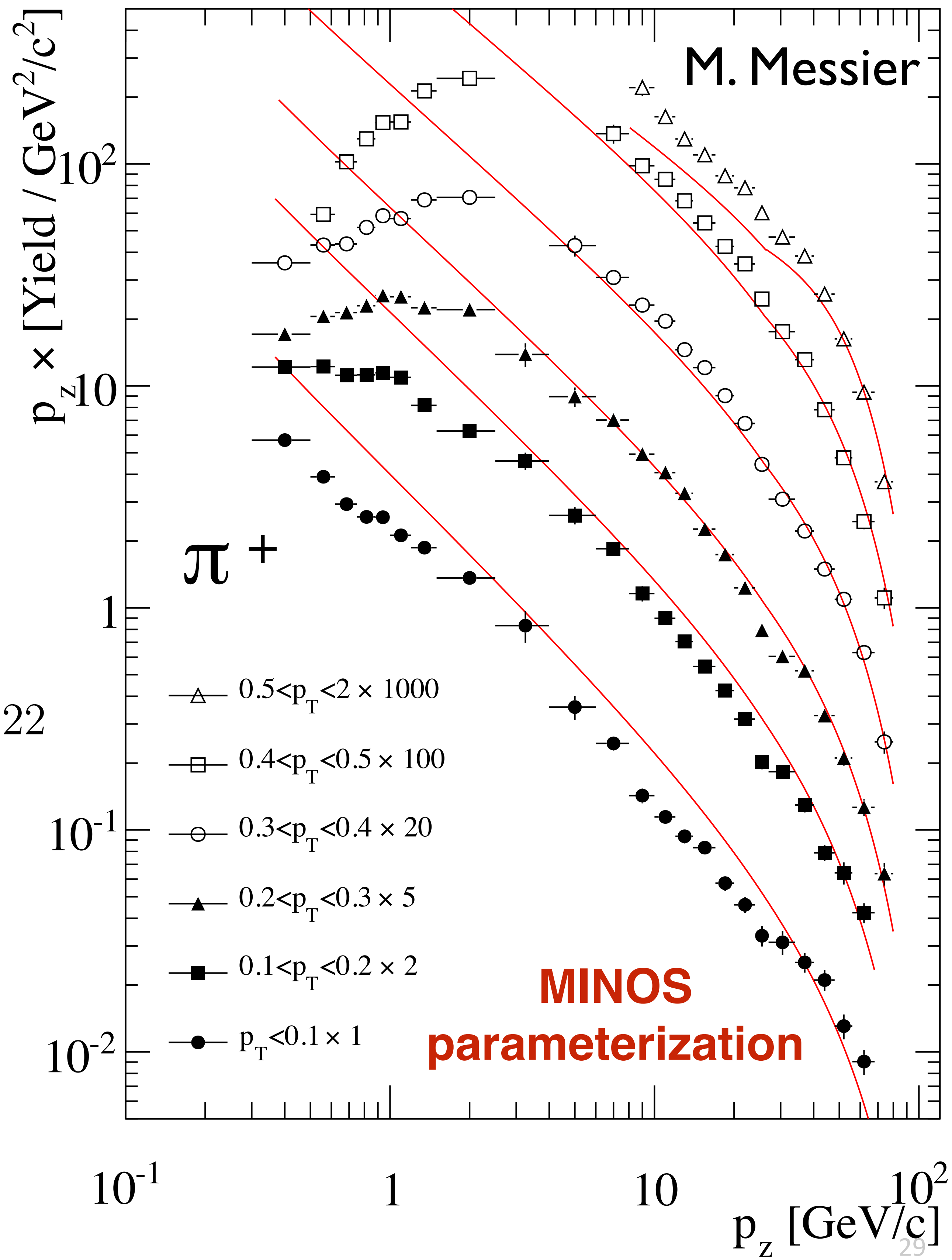

MIPP Preliminary
R_{Data}/R_{MC}
0.50 - 2.00 GeV/c, R/R+5.0
0.40 - 0.50 GeV/c, R/R+4.0
0.30 - 0.40 GeV/c, R/R+3.0
0.20 - 0.30 GeV/c, R/R+2.0
0.10 - 0.20 GeV/c, R/R+1.0
0.00 - 0.10 GeV/c
0
1
2
3
4
5
6
1
10
p_z (GeV/c)

Parameterizing the Yield

- Comparison to MINOS's parameterization of the hadron production off the NuMI target (aka SKZP):

$$\frac{d^2N}{dp_Z dp_T} = \frac{1}{p_{\rm inc}}(A + Bp_{\rm T})e^{-Cp_{\rm T}^{3/2}}$$
$$A = a_1(1-x)^{a_2}(1+a_3x)x^{-a_4}$$
$$B = b_1(1-x)^{b_2}(1+b_3x)x^{-b_4}$$
$$C = -c_1/x^{c_2} + c_3 \quad \text{for} \quad x < 0.22$$
$$C = c_1^*/e^{(x+c_2^*)c_3^*} + c_4^*x + c_5^* \quad \text{for} \quad x > 0.22$$

- MINOS parameters from fit to MC data above a few GeV/c
- Many thanks to Anna Holin and Mike Kordosky!



Preliminary Fits to Parameterization Function

- Our own (very preliminary!) fits to the MIPP results, starting at $p_z = 1$ GeV/c

$$
\begin{aligned}
\frac{d^2N}{dp_Z dp_T} &= \frac{1}{p_{\rm inc}}(A + Bp_T)e^{-Cp_T^{3/2}} \\
A &= a_1(1-x)^{a_2}(1+a_3x)x^{-a_4} \\
B &= b_1(1-x)^{b_2}(1+b_3x)x^{-b_4} \\
C &= -c_1/x^{c_2} + c_3 \quad \text{for} \quad x < 0.22 \\
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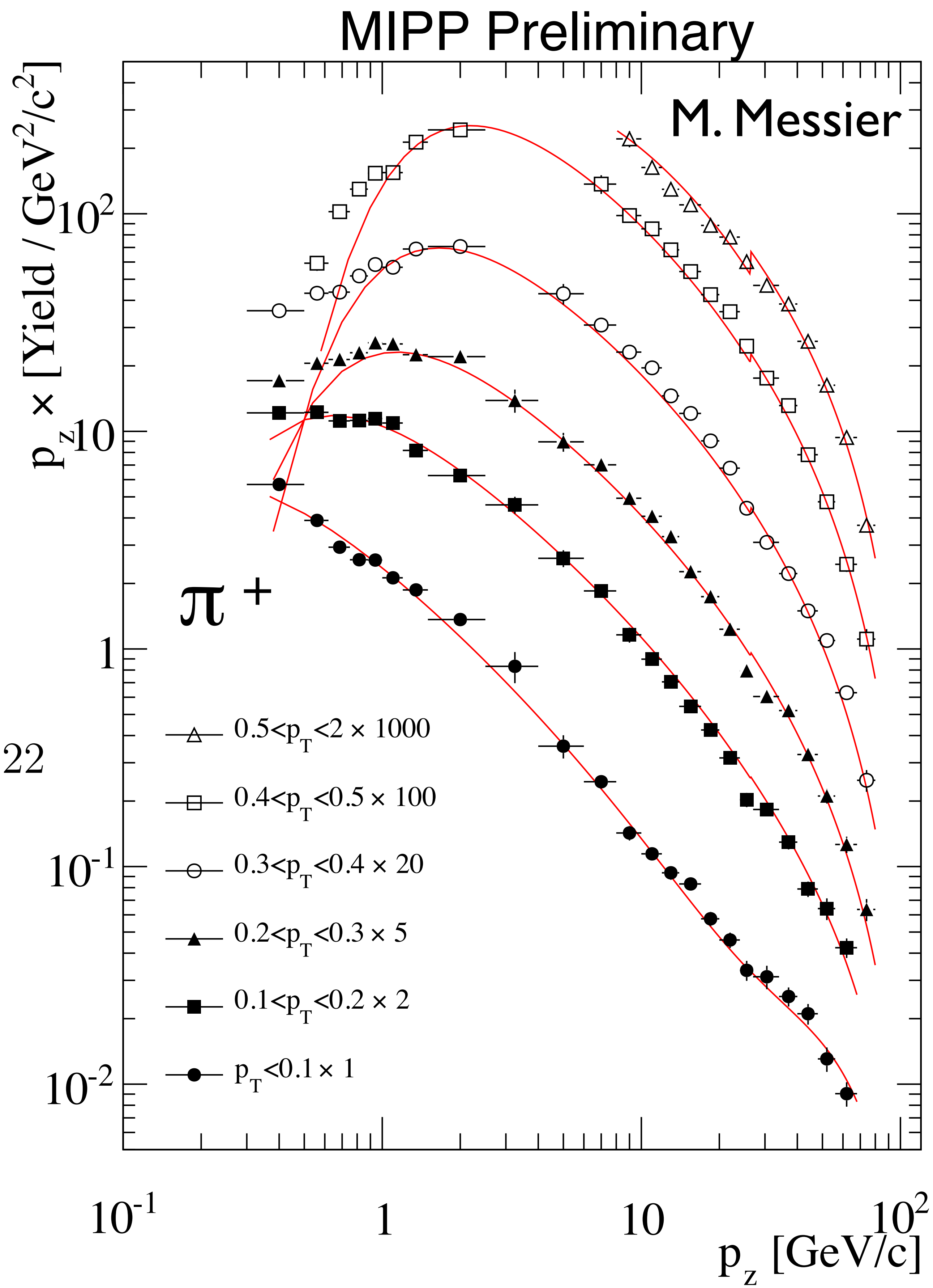
\end{aligned}
$$



- Gives quite reasonable fit results

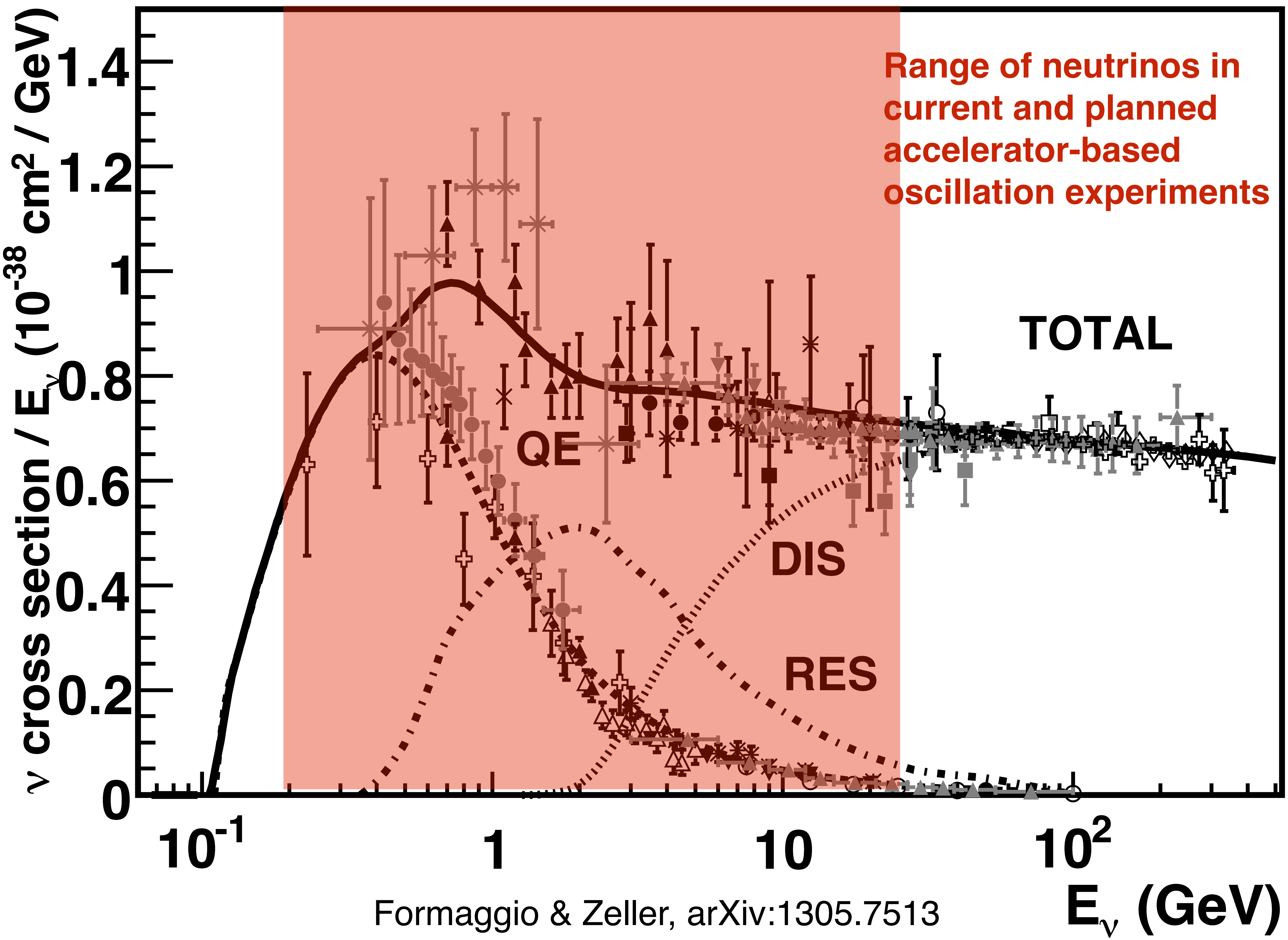
Summary

- MIPP collected 1.43 x 10^6 120 GeV protons on an actual NuMI target.
- We have measured the pion yield in ~125 bins of (p_z,p_T) across 2 orders of magnitude in momentum using data from the tracking detectors and PID data from the TPC and RICH detectors.
- Combined statistical and systematic uncertainties are < 10% in nearly all bins
- Data imply that MCs tend to:
  - over-estimate pion yields at high momentum.
  - slightly over-estimate pion yields in momentum region that contributes most to the NuMI beam spectrum
- Preliminary fits of empirical function used by NuMI experiments to parameterize hadron production off the target seem to give reasonable results.
- These data may be used to re-weight MC predictions of the NuMI flux and reduce the overall systematic uncertainty on the neutrino flux
- Kaon production analysis is underway (p > 20 GeV/c)

BACKUP

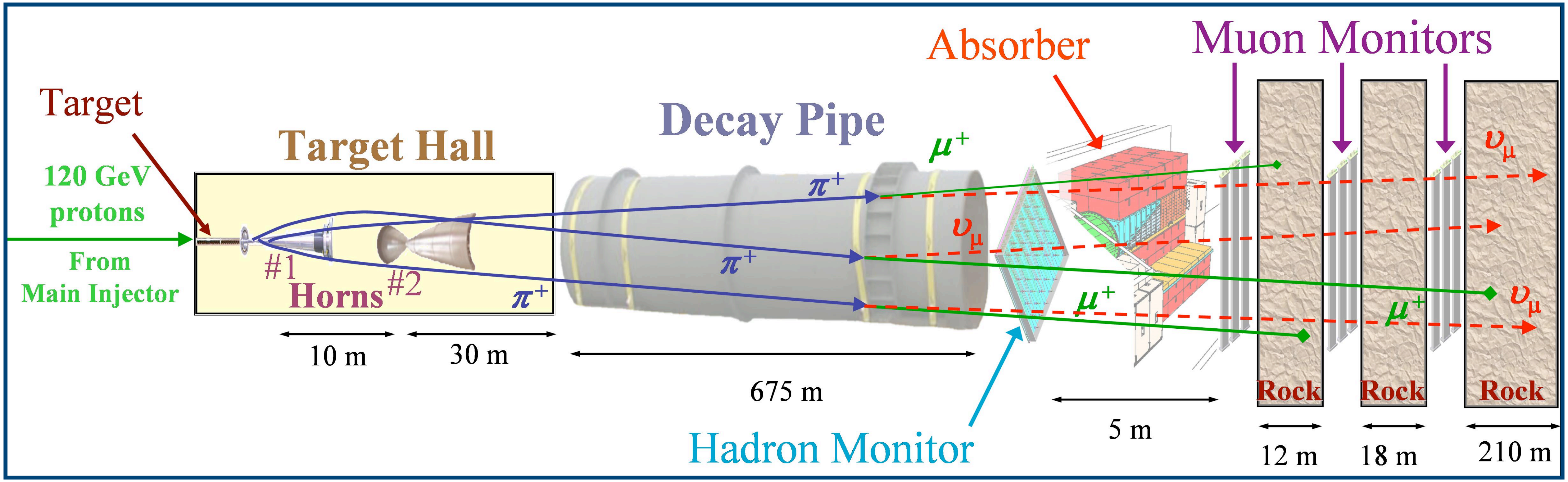
Large Uncertainties in Neutrino Cross Sections

(useful/necessary for some oscillation experiments)



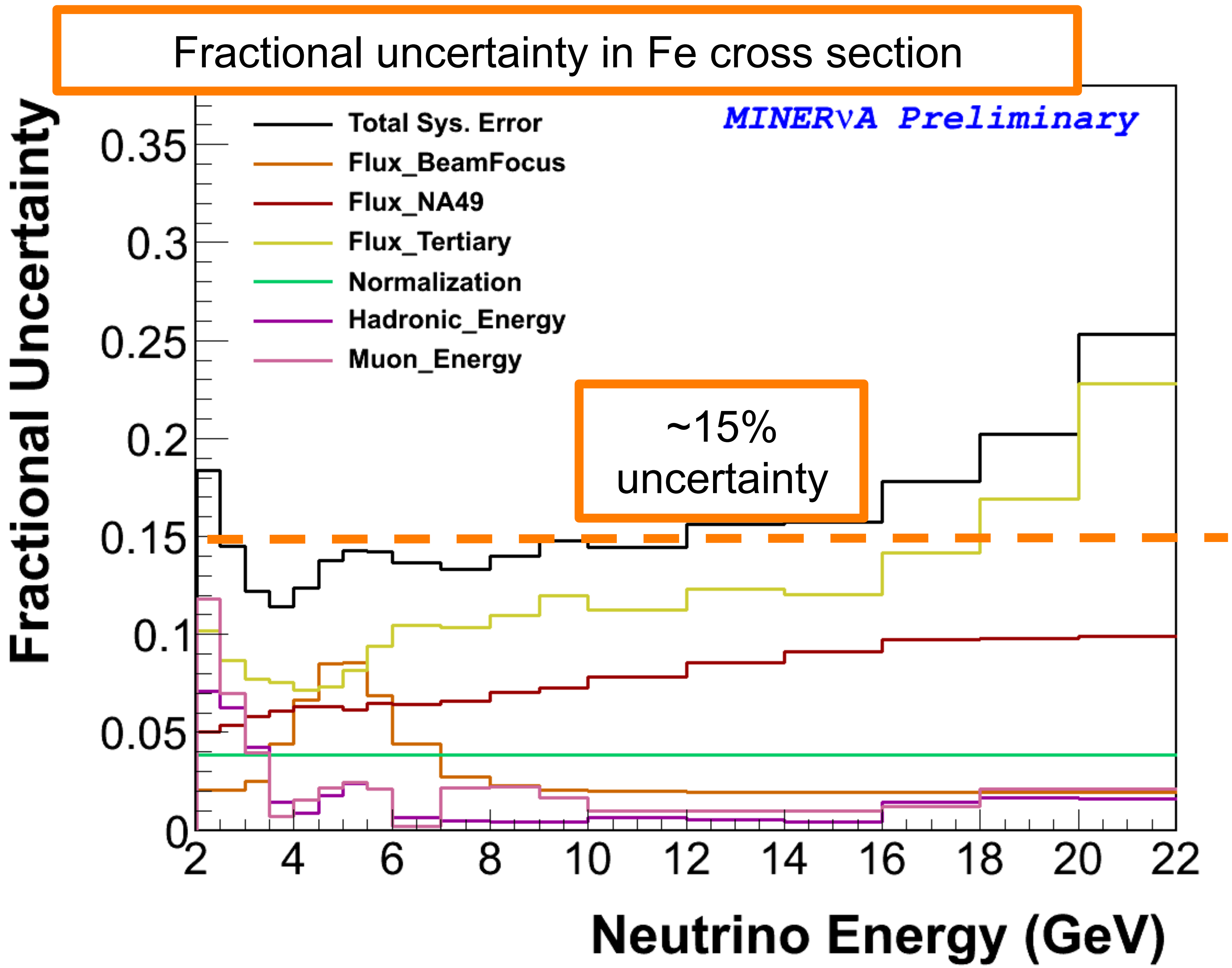
Formaggio & Zeller, arXiv:1305.7513

Neutrino Source



- Neutrinos come from meson decays in flight
- Mesons come from interactions of protons on thick carbon/beryllium targets
- Sparse measurements of cross sections across the broad range of momenta and particles that contribute to secondary and tertiary interactions in the target

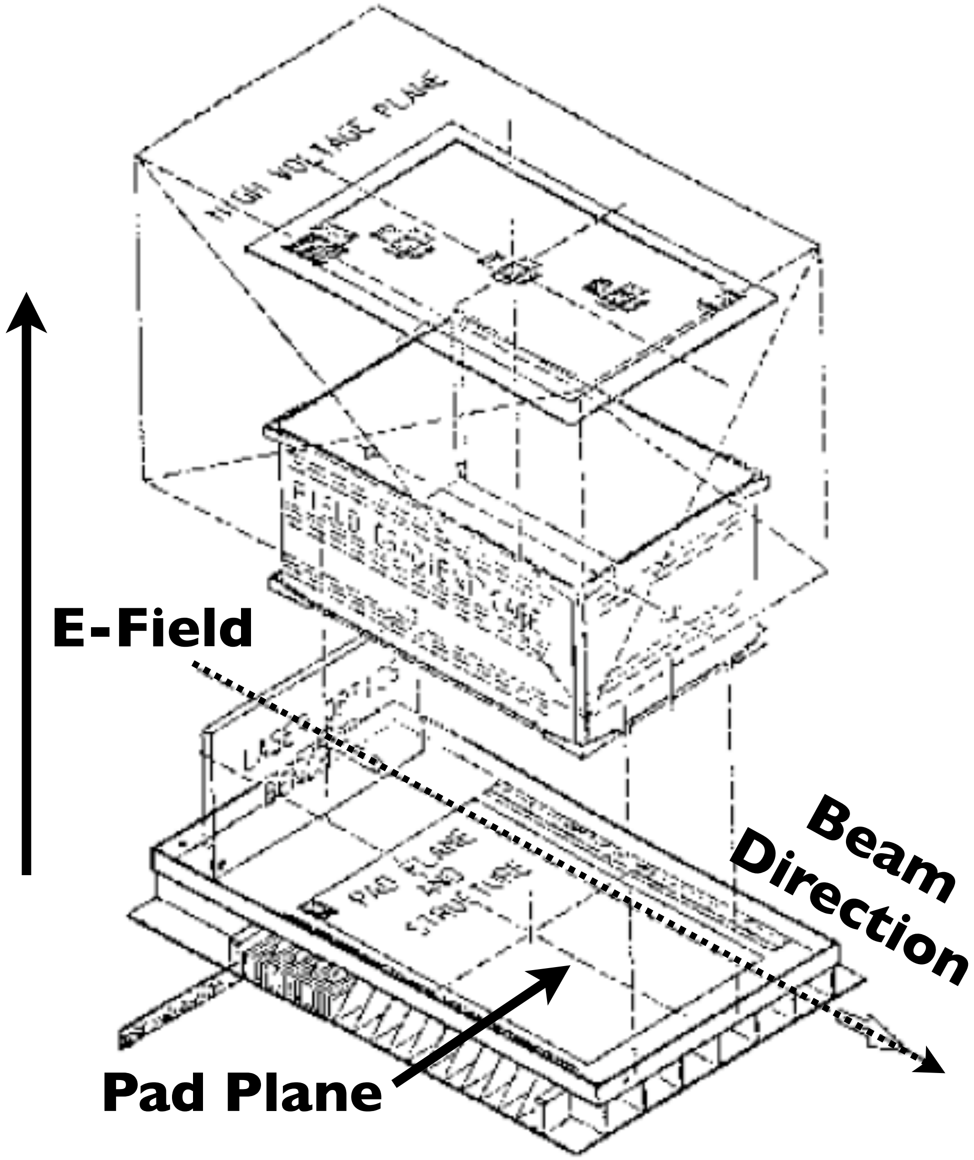
Some Motivation...



Steven Manly's NuFact 2013 MINERνA presentation

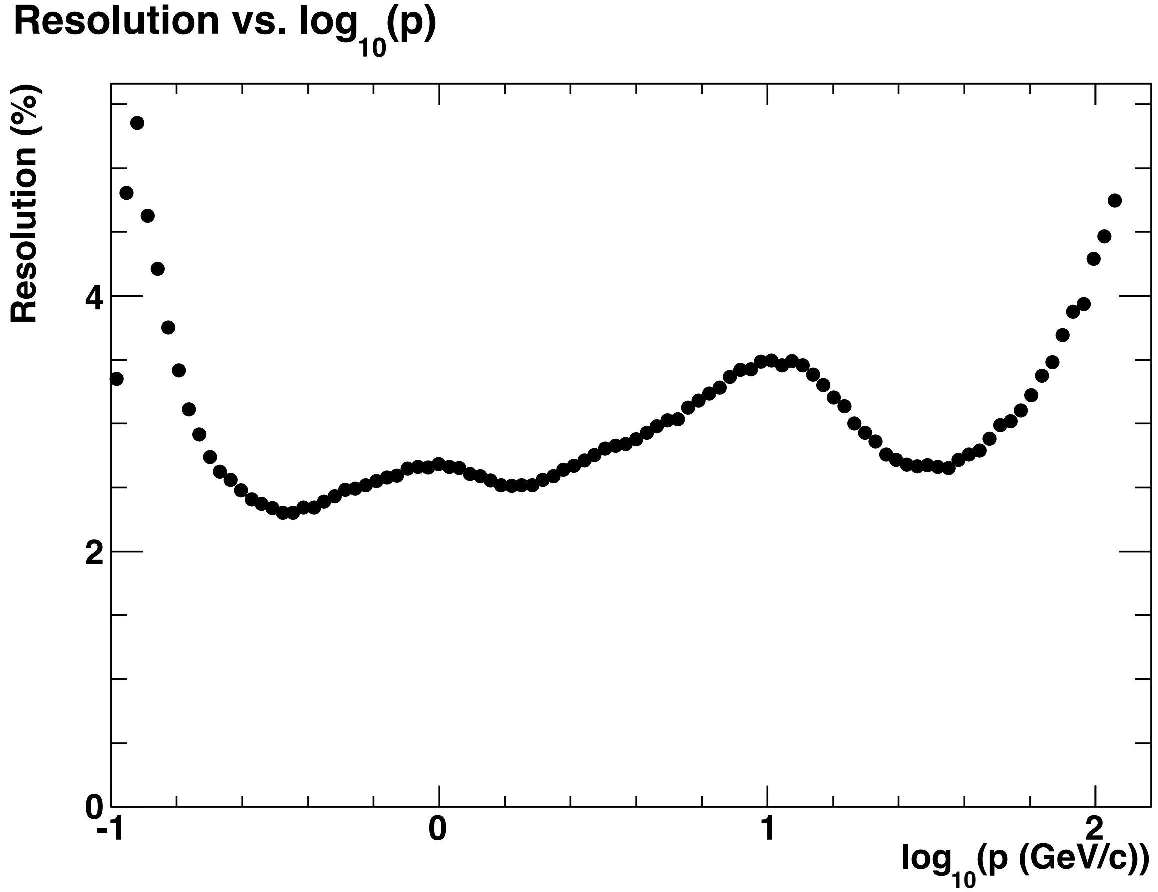
- Despite recent progress and measurements from hadron production experiments over the past 10+ years, we're *still* talking about 10-20% uncertainties in the hadron production off the NuMI target

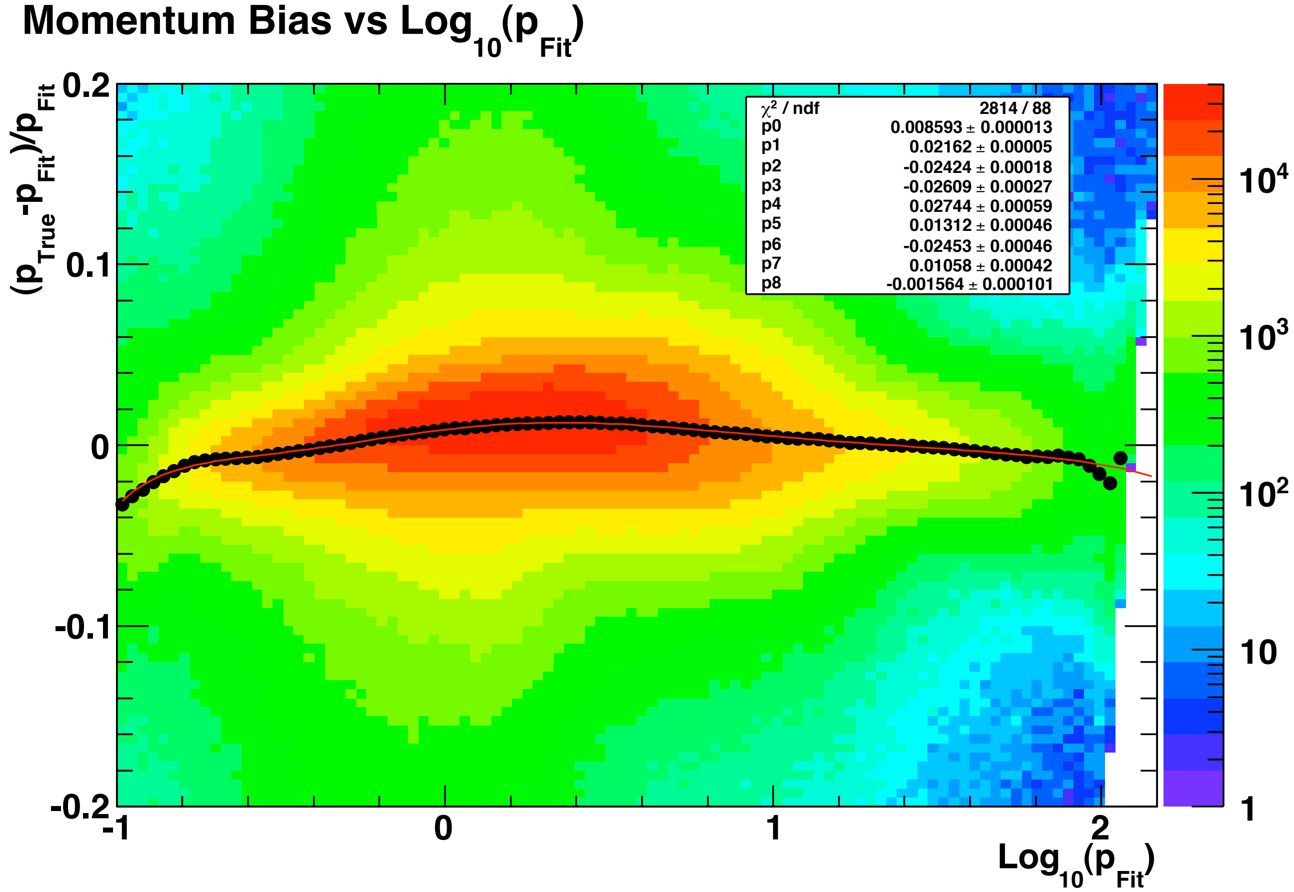
Time Projection Chamber



- Centerpiece of MIPP, originally built for the EOS experiment and used in several other prior experiments.
- Measures track trajectory in 3D: (x,z) position → pad locations, y position → drift time
- Active volume of ~1 m^3 and a resolution of ~0.5 cm^3
- PID via <dE/dx> below ~1.5 GeV/c

Momentum Resolution and Bias

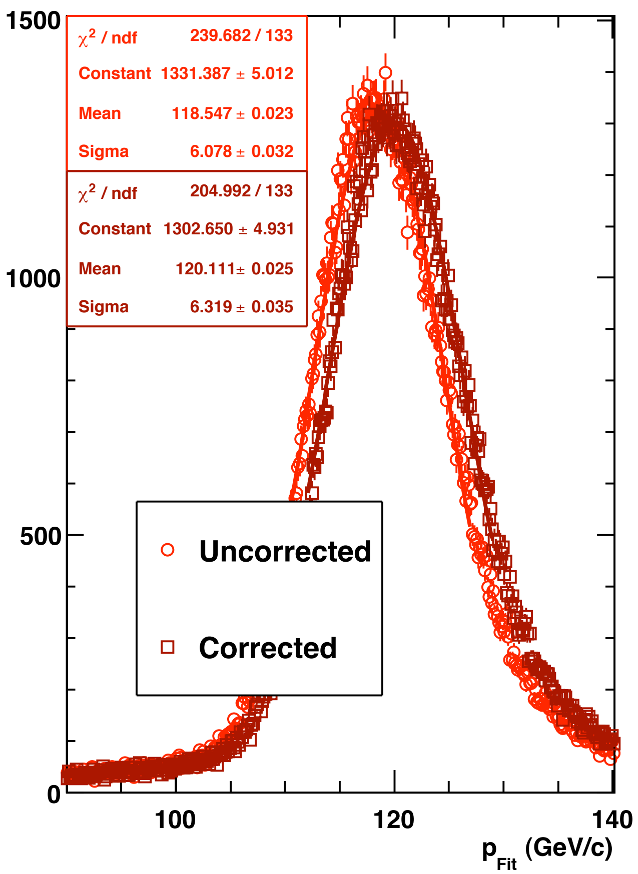




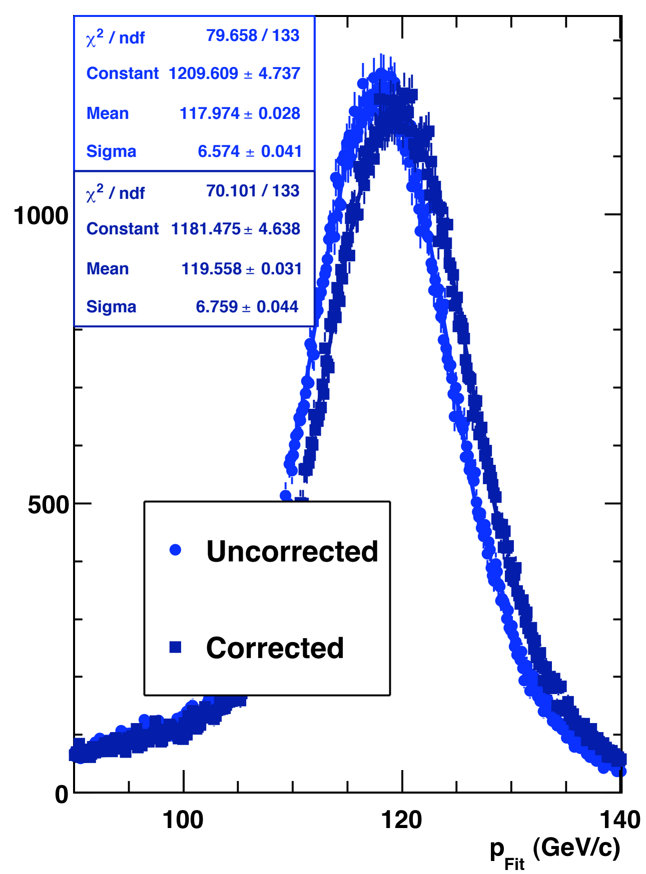
- Momentum resolution is < ~5%
- Bias < ~2%. Correction is applied and has a very small uncertainty.
- Transverse momentum resolution is < 0.02 GeV

Absolute Momentum Scale

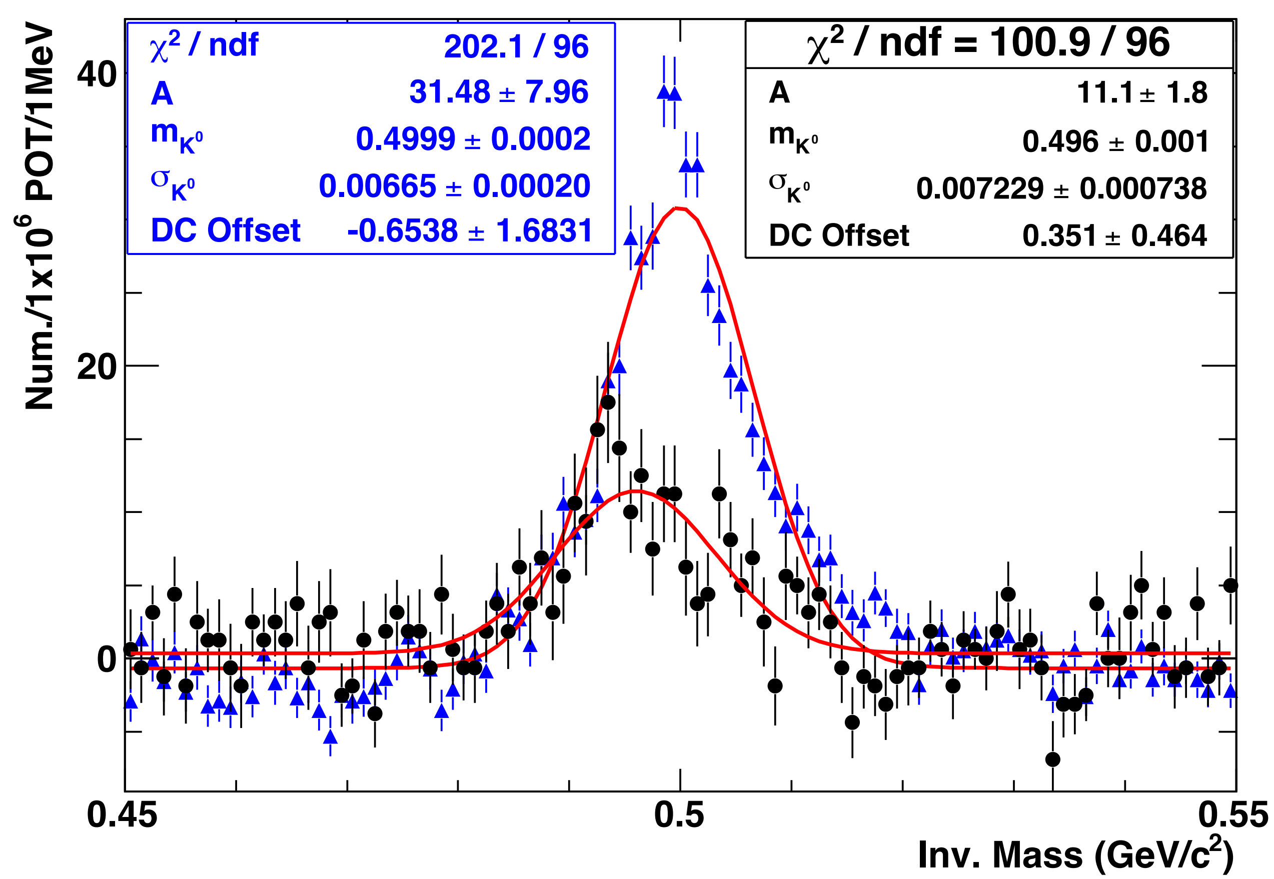
NuMI MC



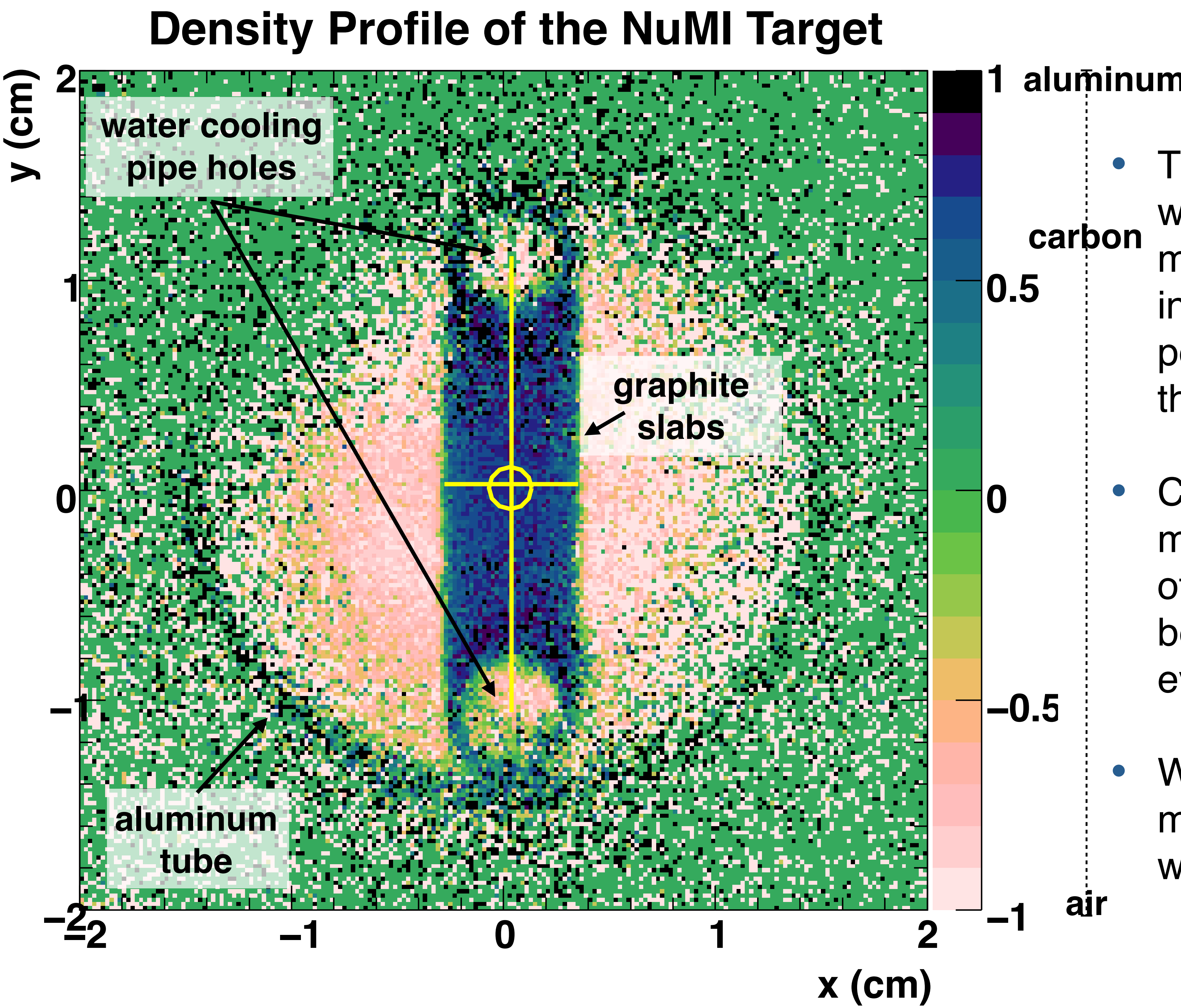
NuMI Data



Bkg-Subtracted Inv. Mass Distribution, NuMI MC, dz Cut

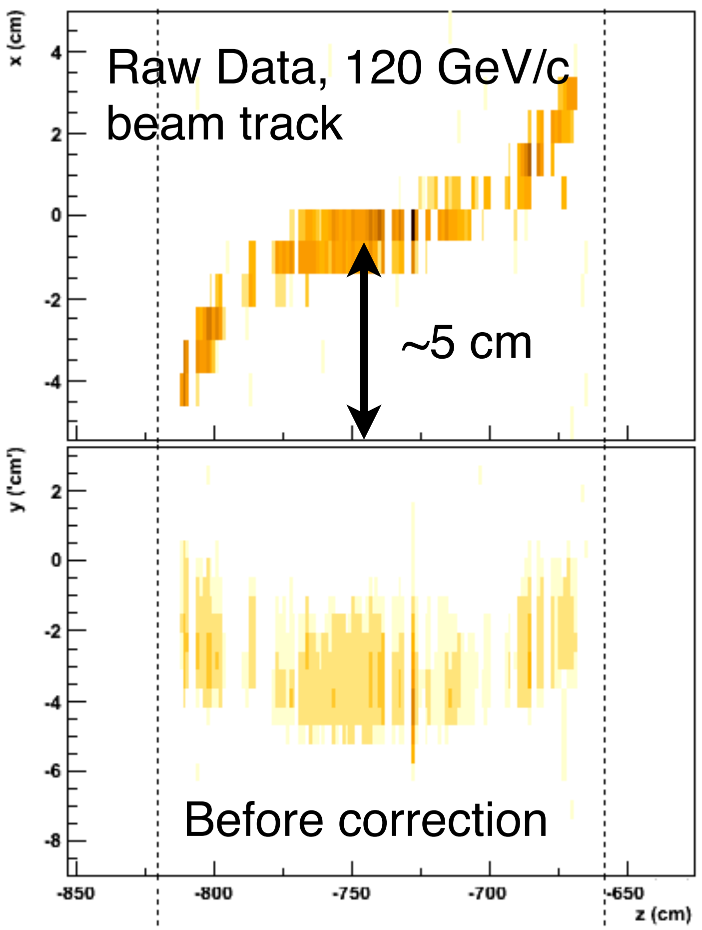


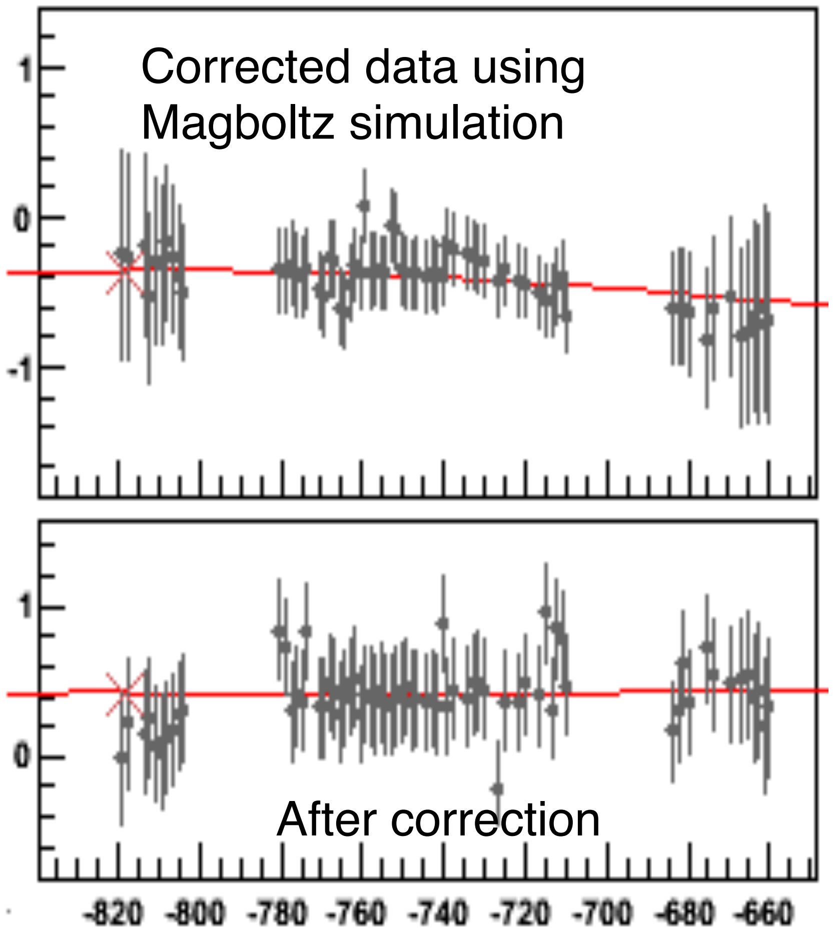
- After momentum bias correction, single proton beam data and MC agree.
- Reconstructed K^0 invariant mass using tracks with p < 2 GeV/c indicates systematic offset of ~-1%.

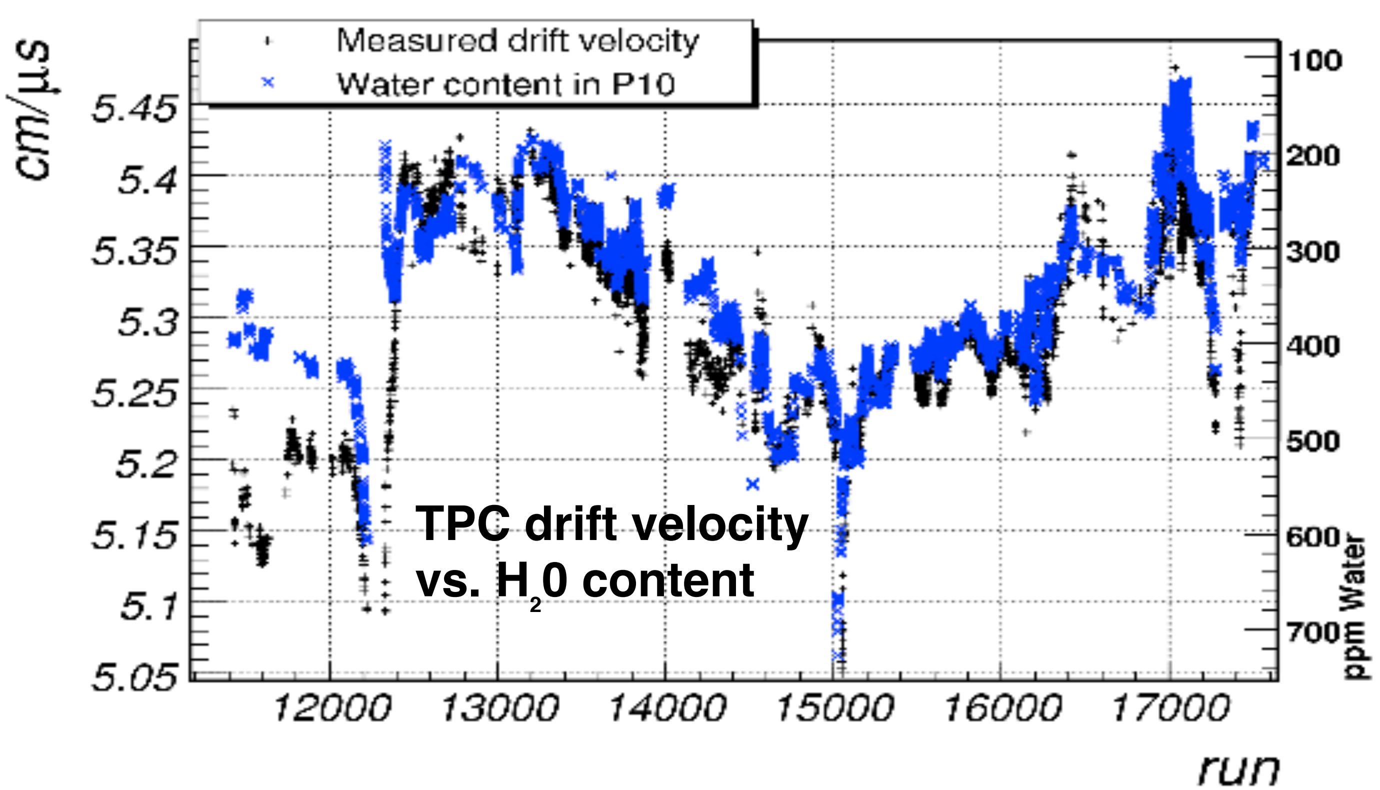


- Three upstream beam wire chambers give 0.2 mm resolution of the incident beam track position at the front face of the target.
- Center of circle represents measured mean position of reconstructed incident beam particles in selected events
- Width of circle represents measured 1mm^2 beam width

TPC Calibrations

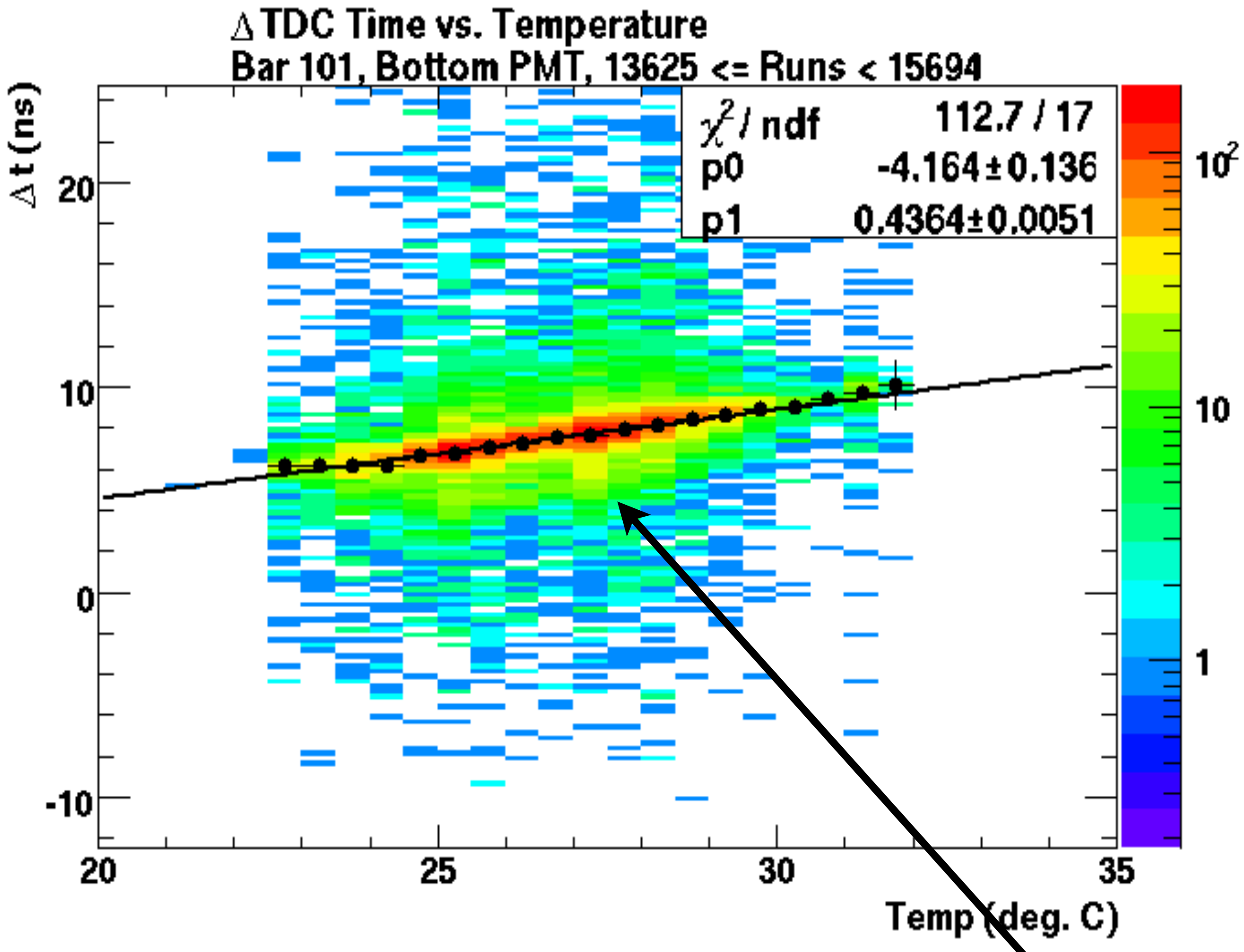


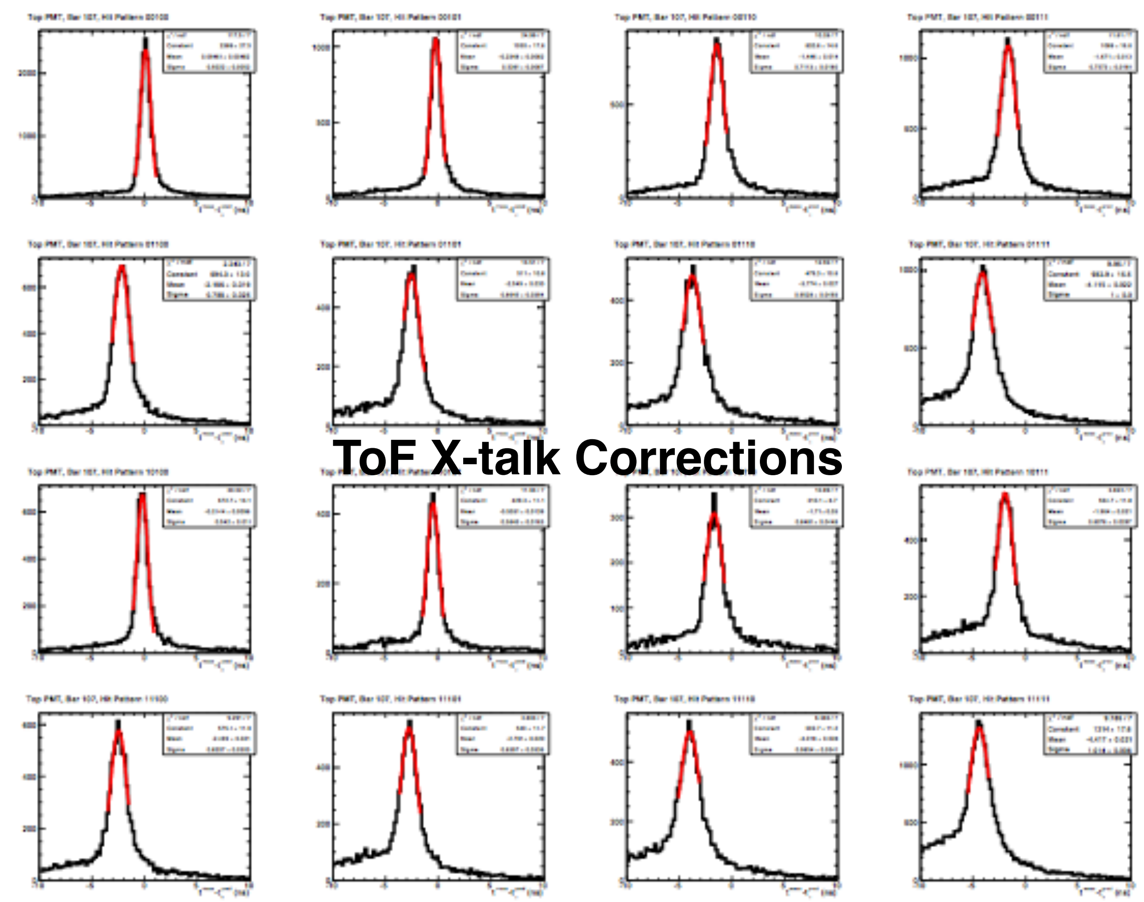




- Inhomogeneous magnetic field causes drift electrons to deviate from straight-line path to the pad plane on the bottom of the TPC. Deviations of up to 5 cm were observed!
- Using a map of the magnetic field and the Magboltz simulation, were were able to correct these ExB drift effects to the level of of 90% (~2 mm worst case)
- Furthermore, the electron drift velocity was time dependent: sensitive to the water contamination in the P10 gas.
- Time-dependent corrections to the drift velocity are made. Drift velocity known to better than 1%.

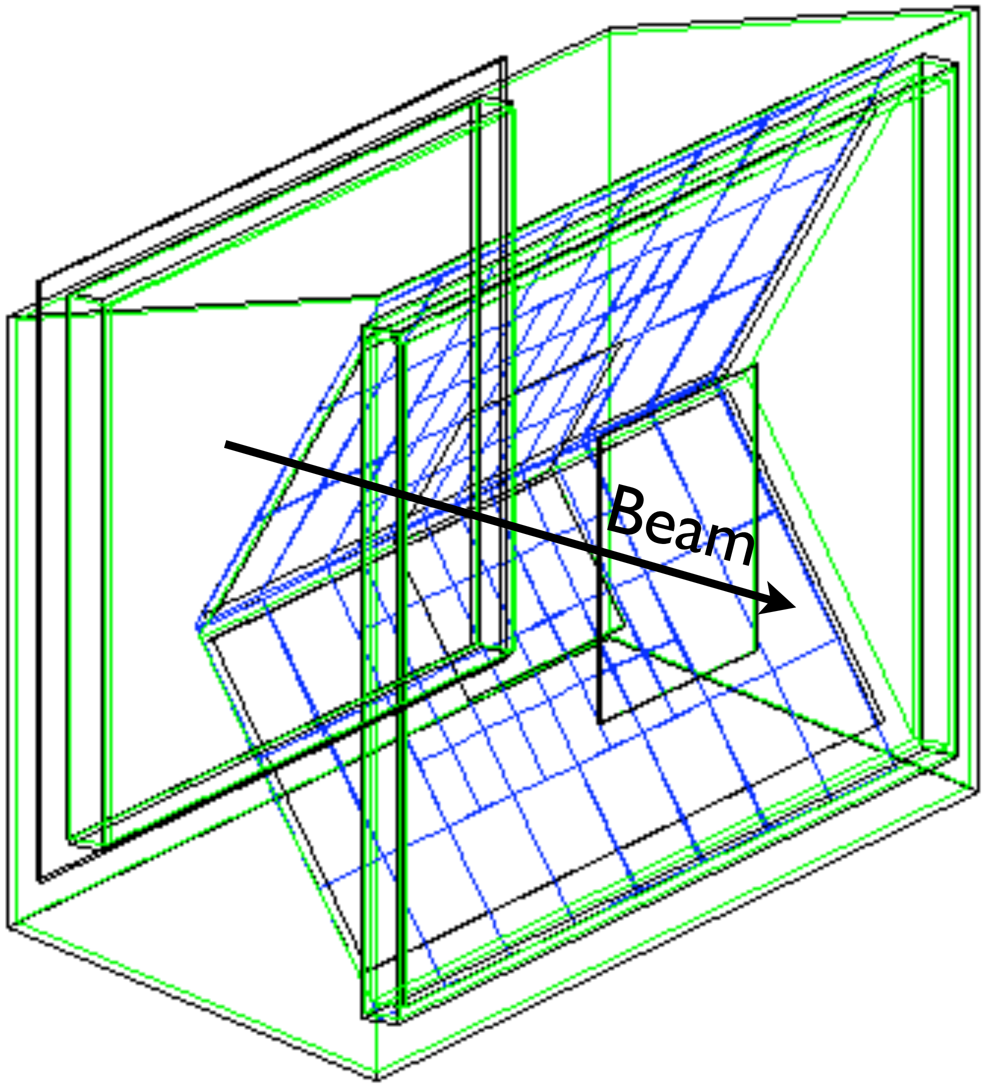
ToF PID Performance

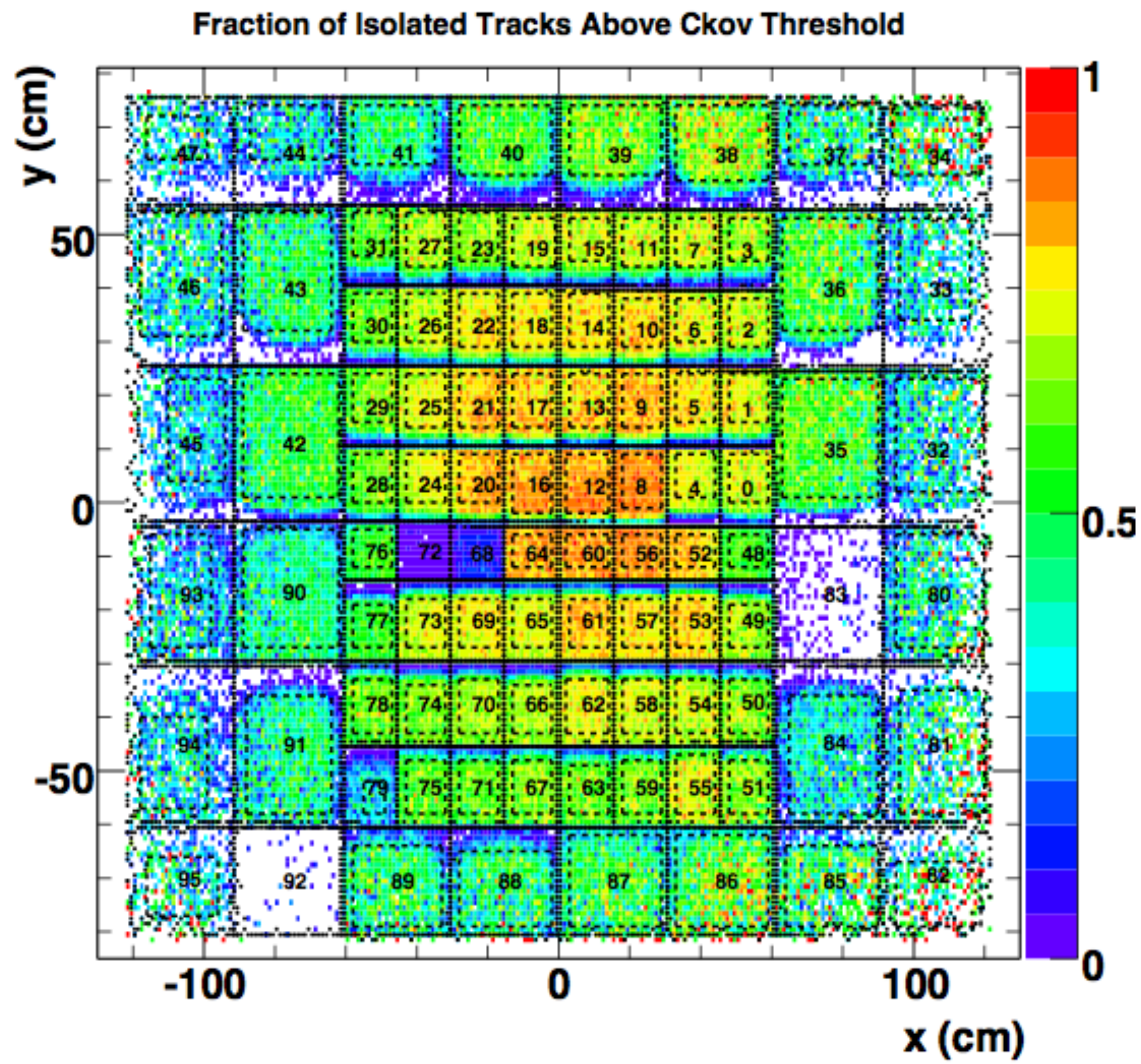




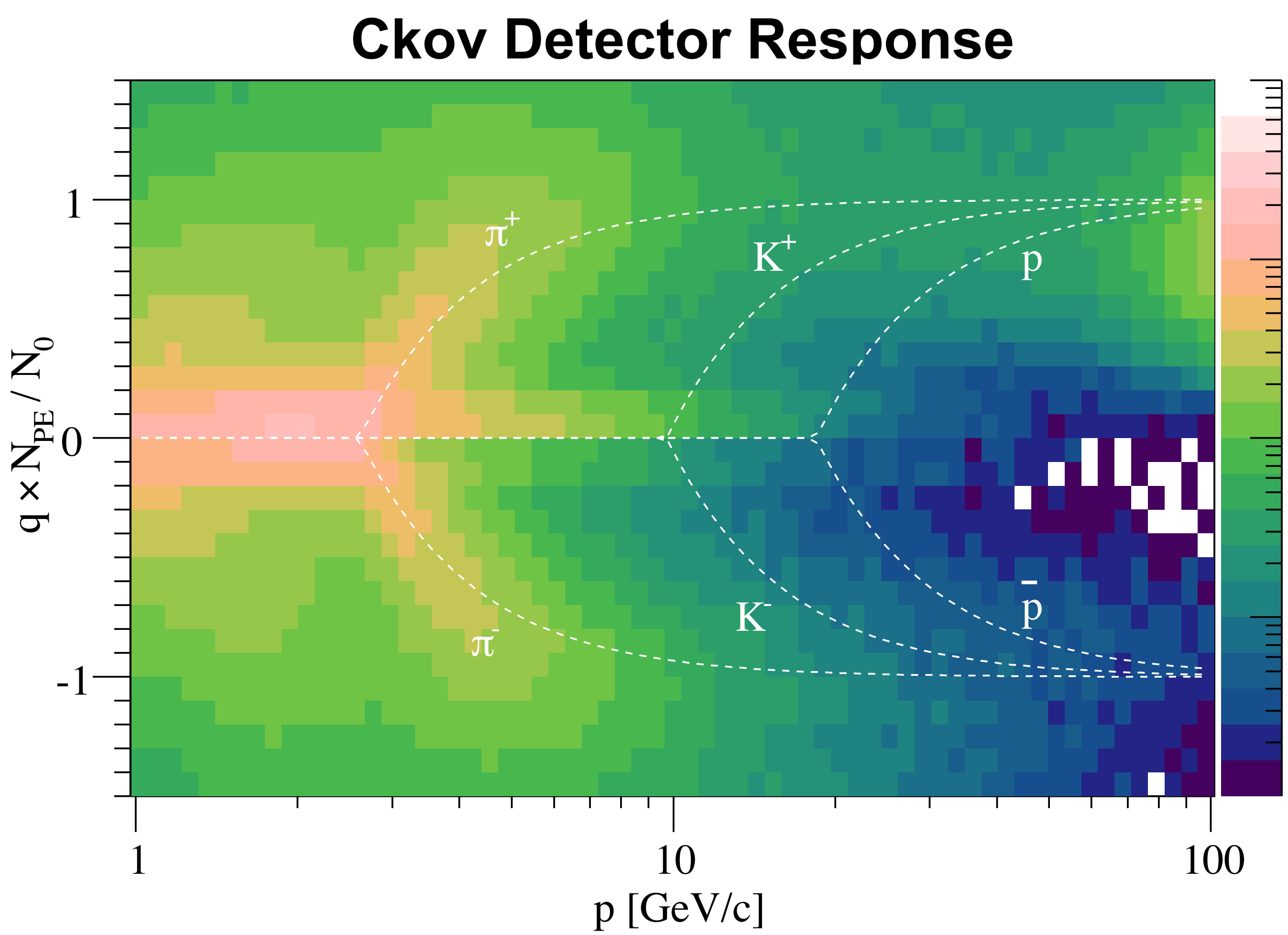
- Measured time affected by temperature fluctuations (Δt ~ 500 ps/ºC) and amplitude of the signal (Δt ~ 10 ps/ADC)
- Capacitive cross-talk in all 108 channels shifts measured time
- Data-driven methods to correct for all effects

Cherenkov (Ckov) Detector

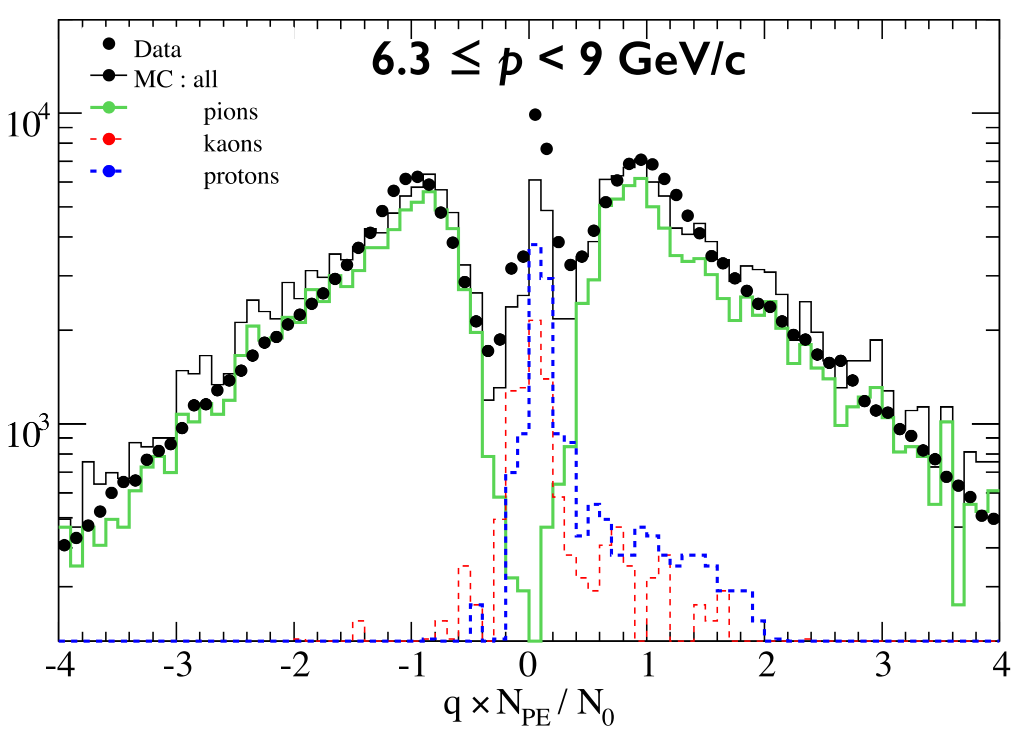


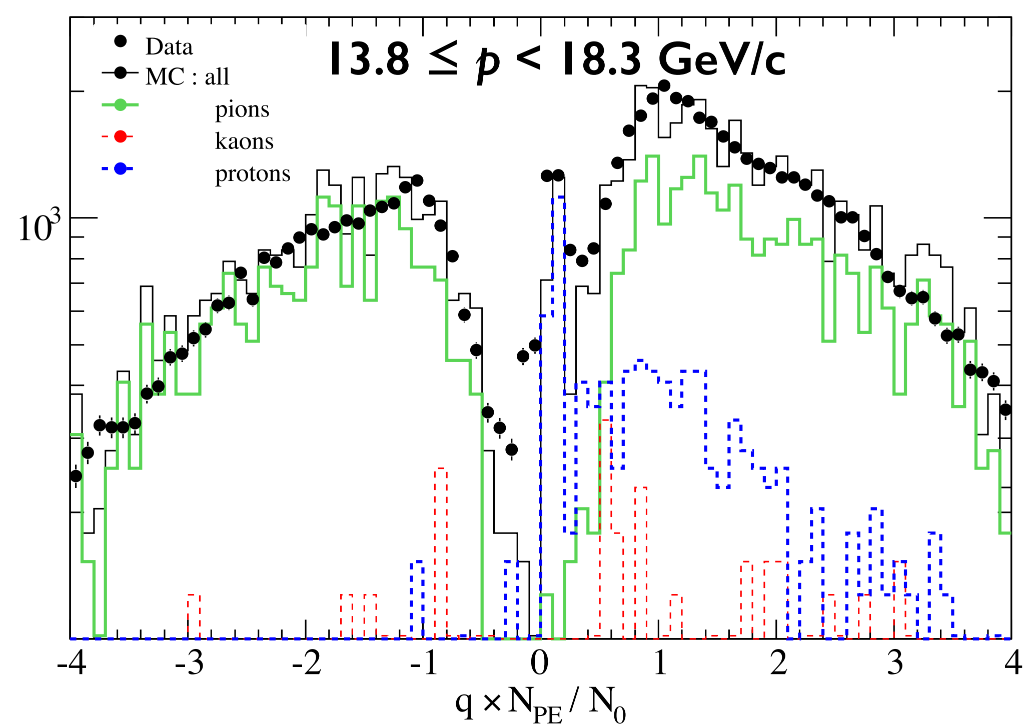


Ckov PID Performance



- Since all mirrors have a different response, each measurement of Npe is normalized to that of a β=1 particle.
- Pion "turn-on" clearly visible; proton "turn-on" also visible in slices of momentum.
- Shape of normalized response dist. in MC agrees very well with data.
- Data-driven calibration of 96 mirrors found detector response gives <10 pe/β=1 track.



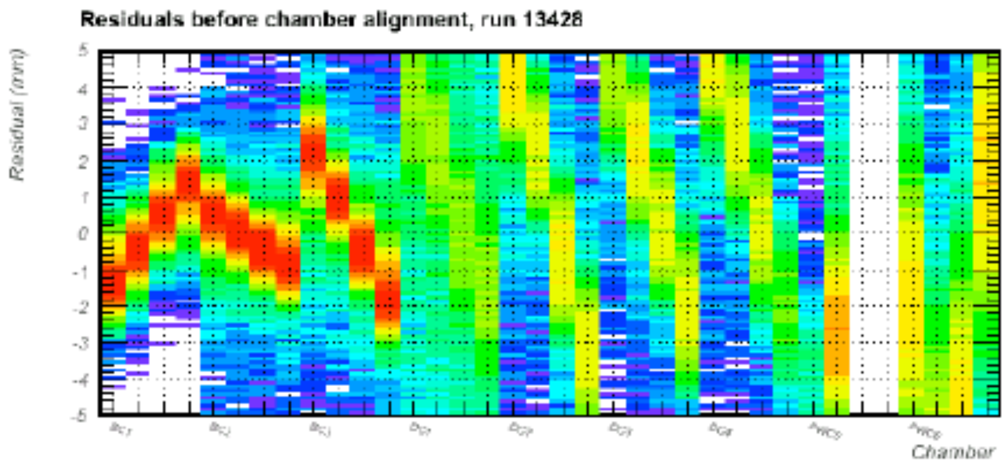


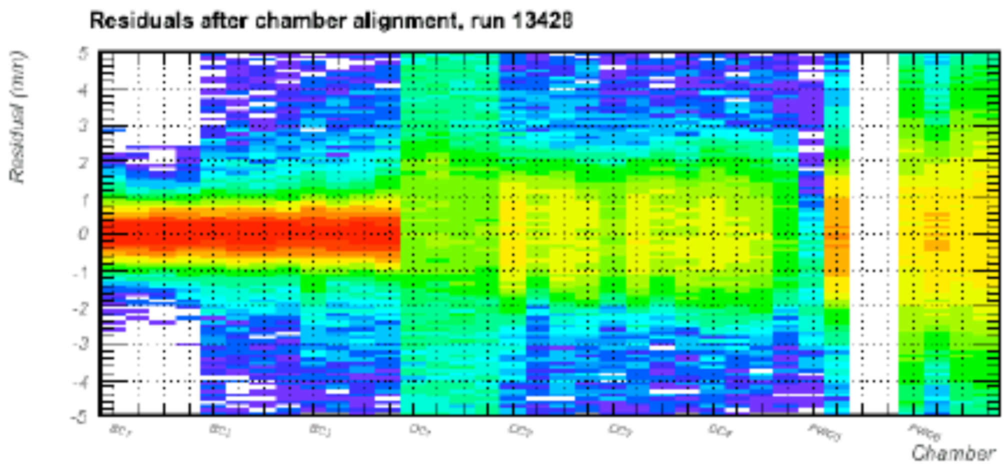
- Must only consider "isolated" tracks passing through mirrors; reject ~50% of Ckov PID data.

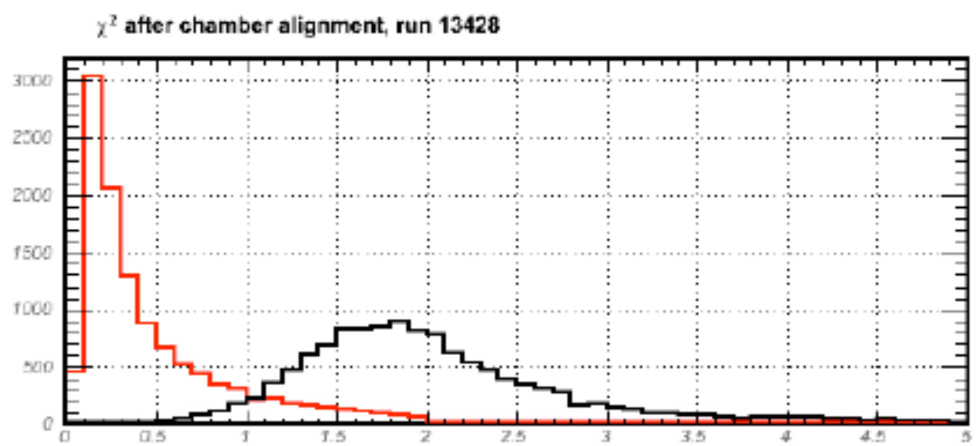
Particle Identification Detectors

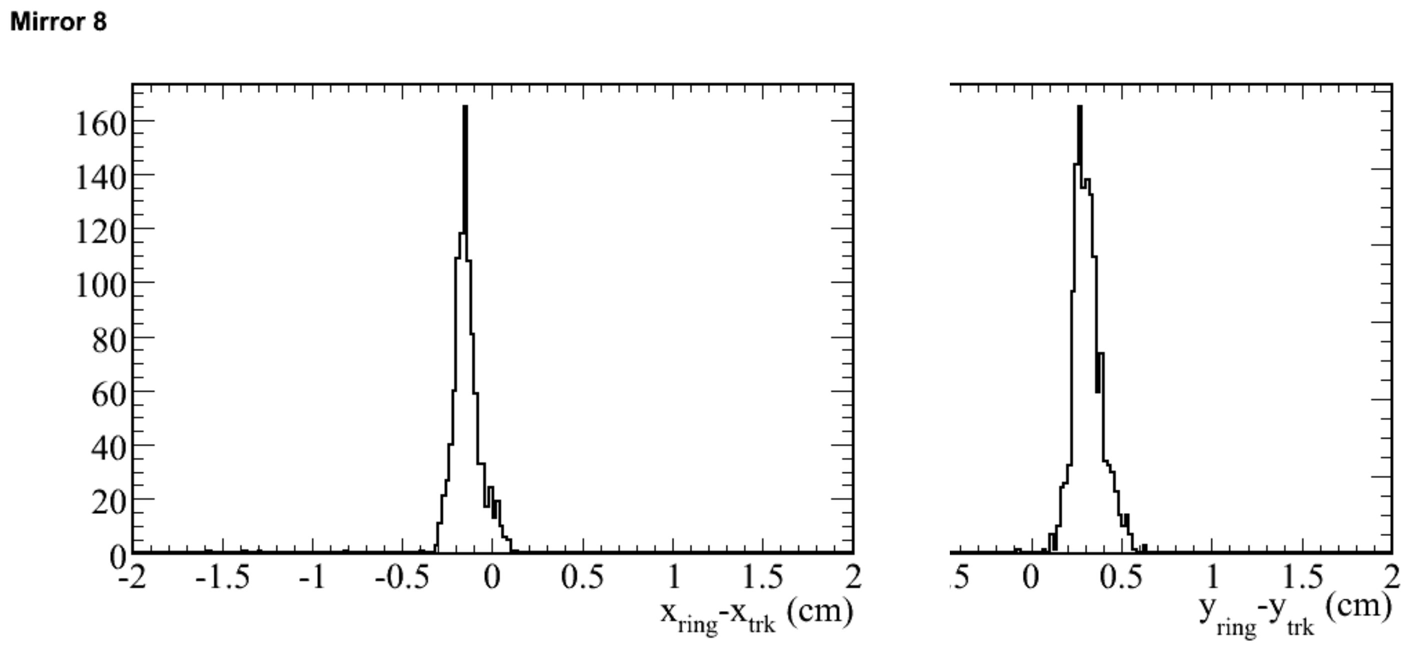
- High segmentation in the TPC and RICH detectors allow for PID measurements in the high multiplicity environment of these data
- ToF:
  - two or more particles traversing the same scintillator bar channel cannot be untangled
  - ~50% of all tracks at lower momenta passing through a ToF bar have another track passing through the same bar
- Cherenkov:
  - similar issue: cannot distinguish light from two or more particles traversing the same central mirror
  - Again, ~50% of all tracks passing through this detector have a partner-in-crime
- For these reasons, the ToF data are used only in conjunction with TPC <dE/dx> measurements, and the Cherenkov data are ignored altogether.

Detector Alignment





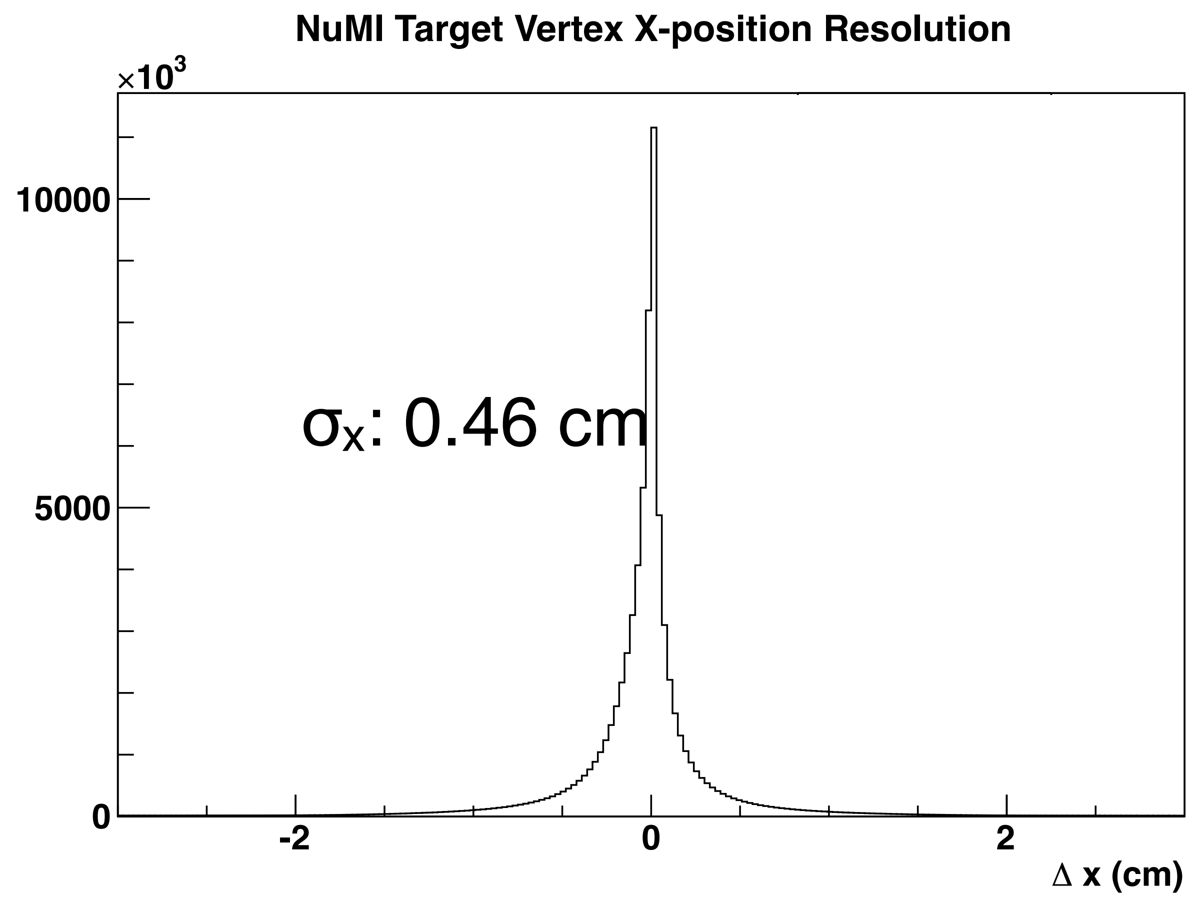


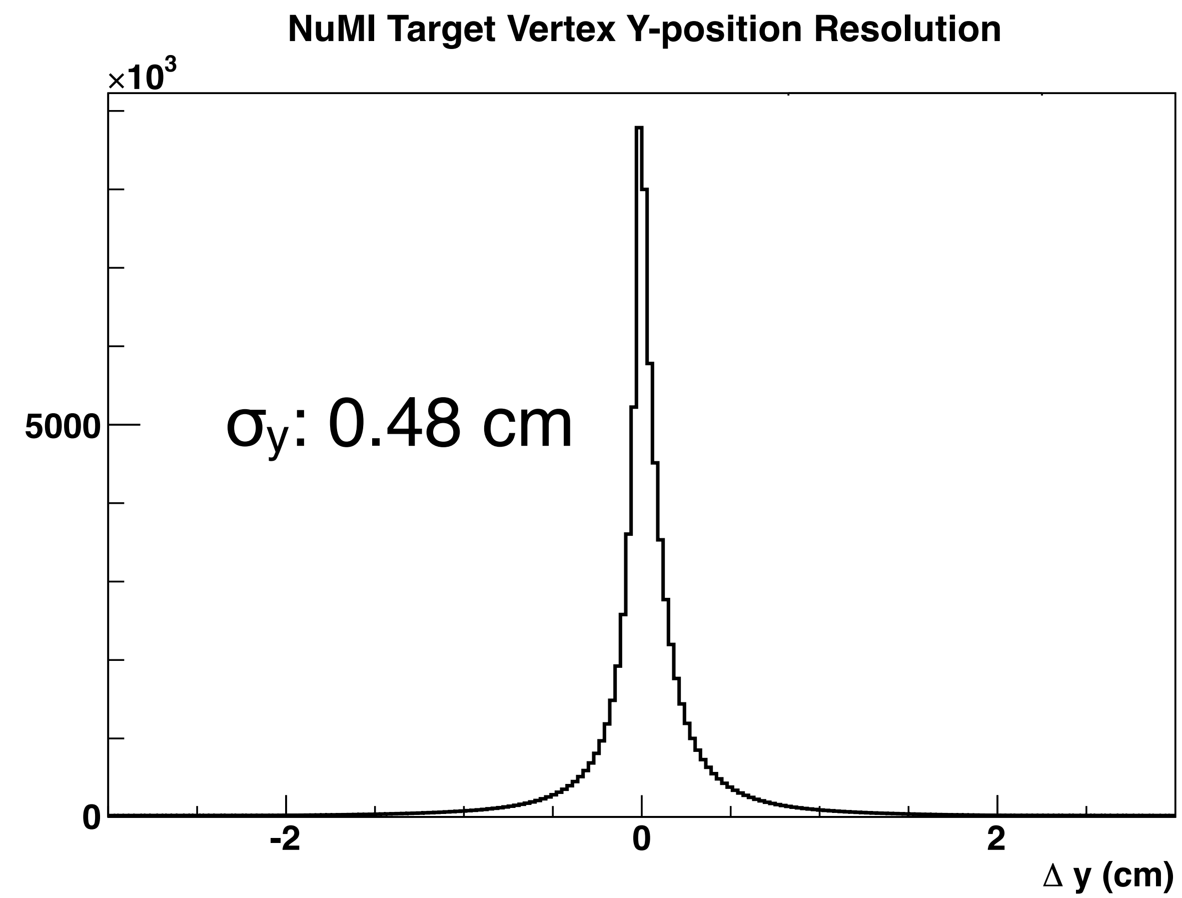


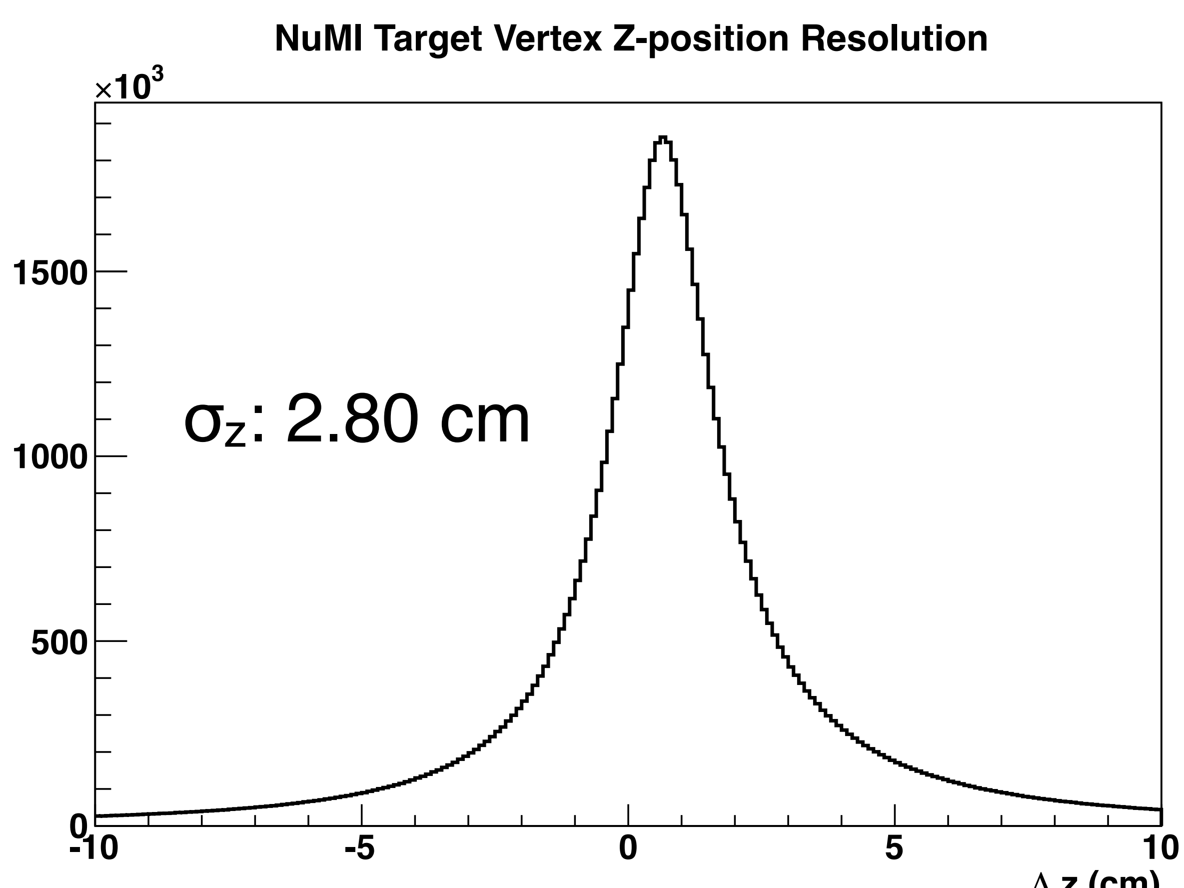
RICH alignment – mirrors aligned to within a few mm

Drift chamber alignment – wire chambers to within 0.2 wire-spacing.

Vertex Resolutions

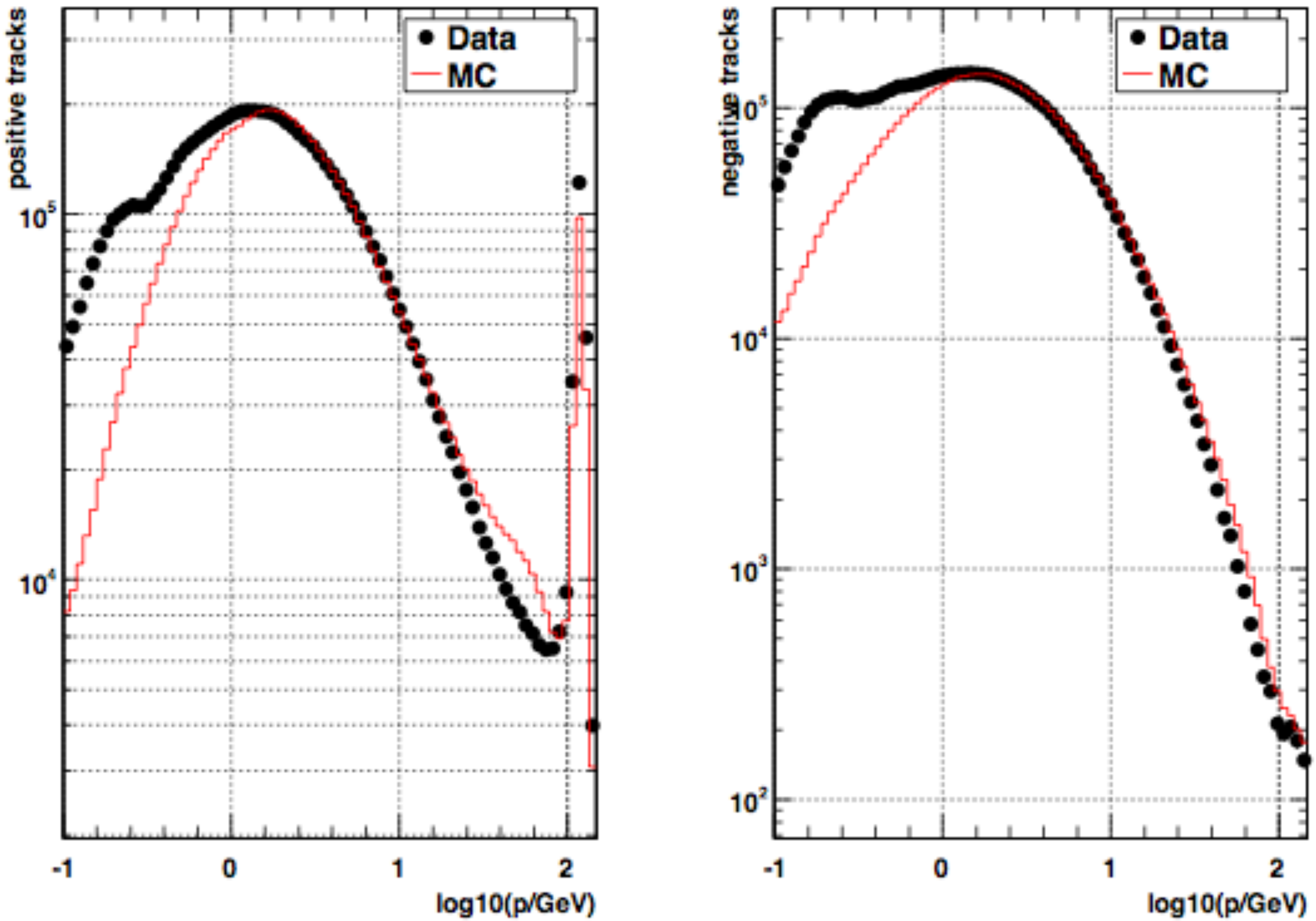




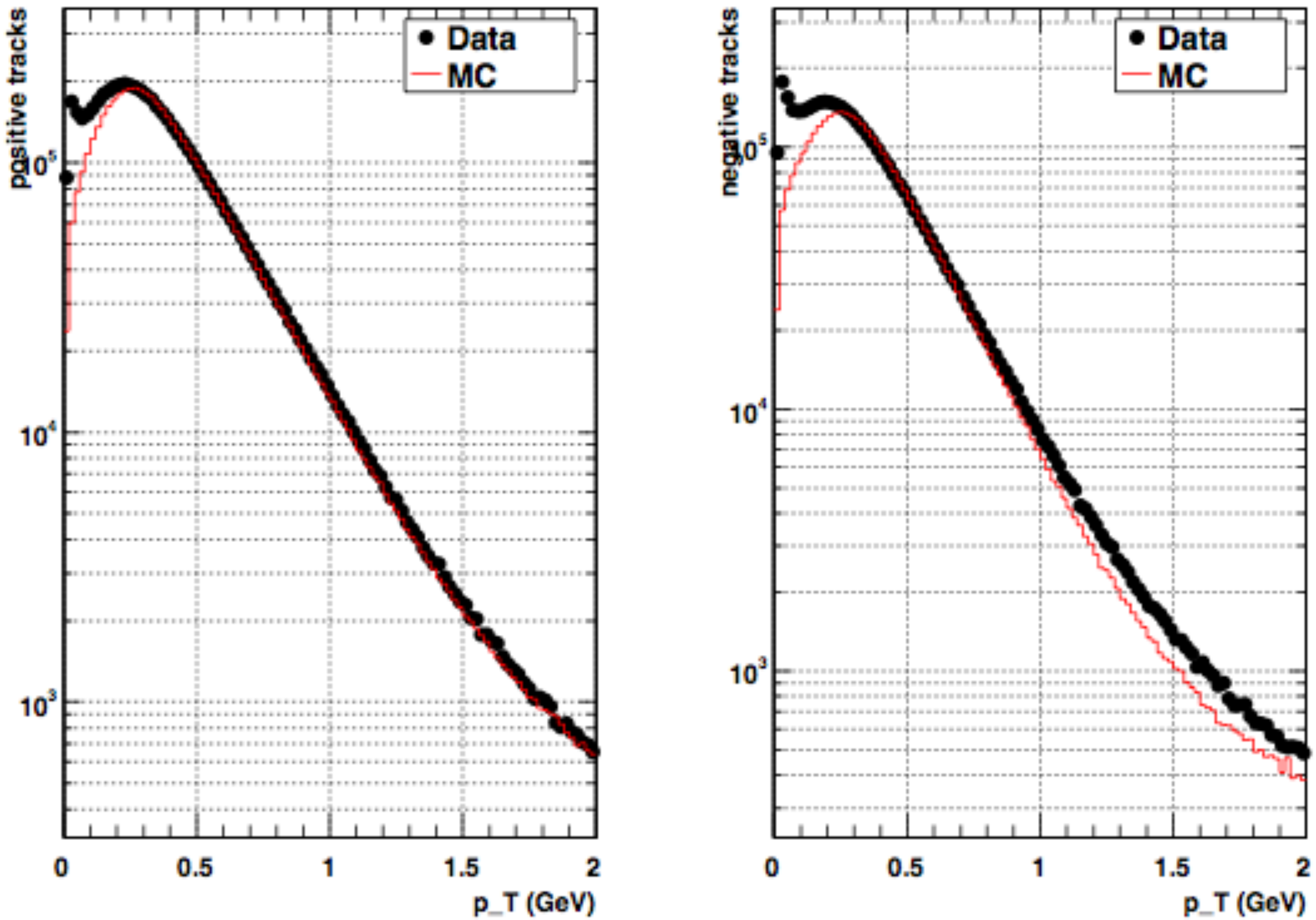


- Simulation “vertex” is position at outer surface of target
- Reconstructed “vertex” is reconstructed trajectory extrapolated to the outer surface of the target

Simulation

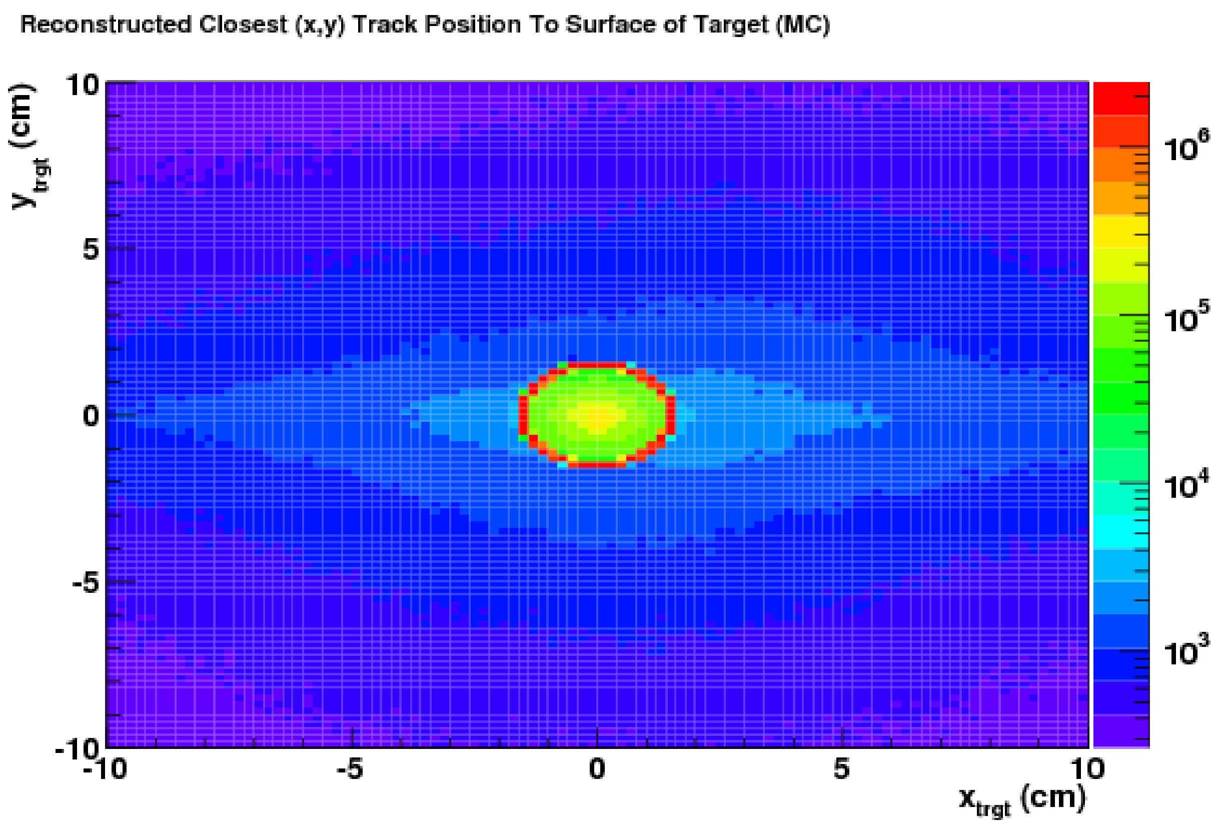

positive tracks
10^5
10^4
Data
MC
-1
0
1
2
log10(p/GeV)
negative tracks
10^5
10^4
10^3
10^2
Data
MC
-1
0
1
2
log10(p/GeV)

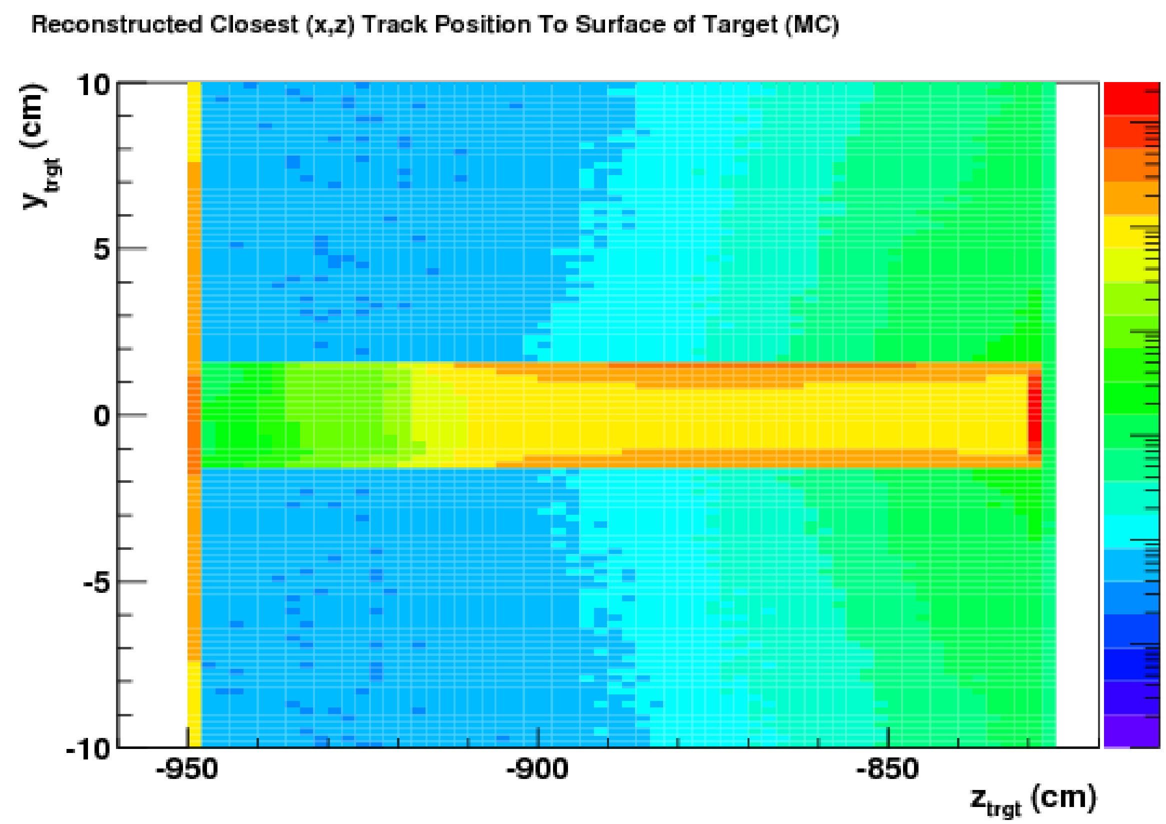
Simulation

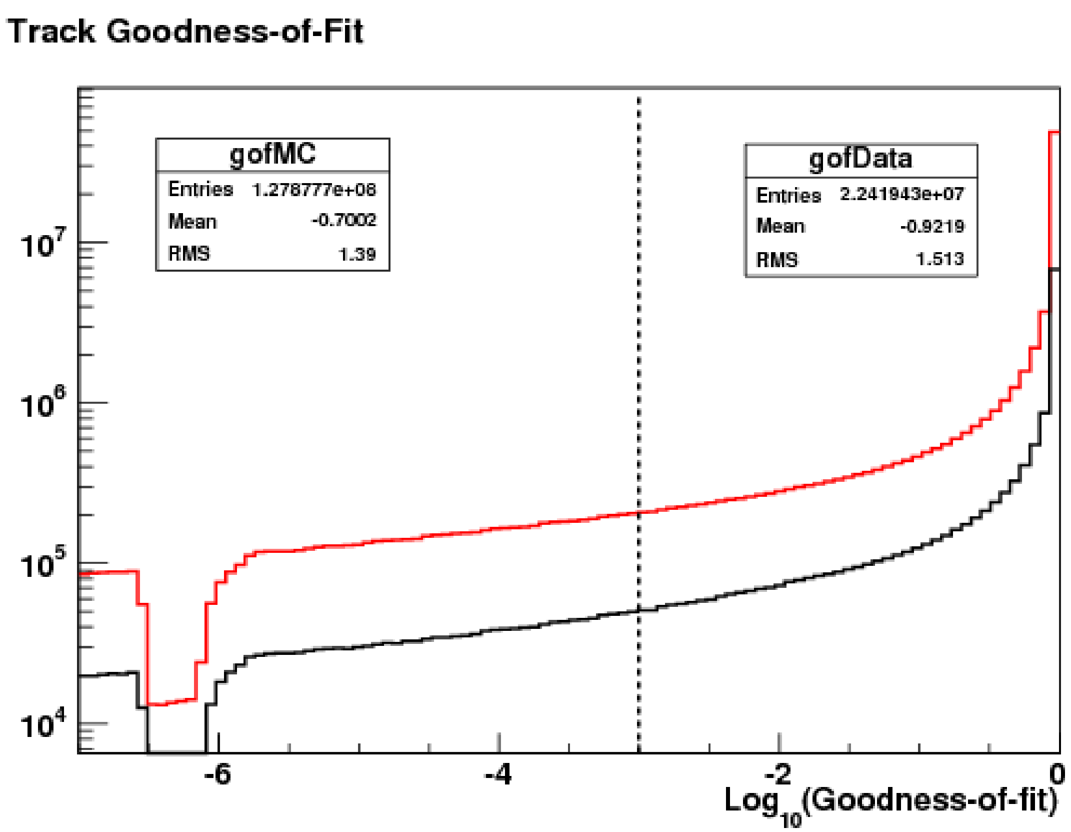


positive tracks
Data
MC
10^5
10^4
10^3
0
0.5
1
1.5
2
p_T (GeV)
negative tracks
Data
MC
10^5
10^4
10^3
0
0.5
1
1.5
2
p_T (GeV)

Track Selection

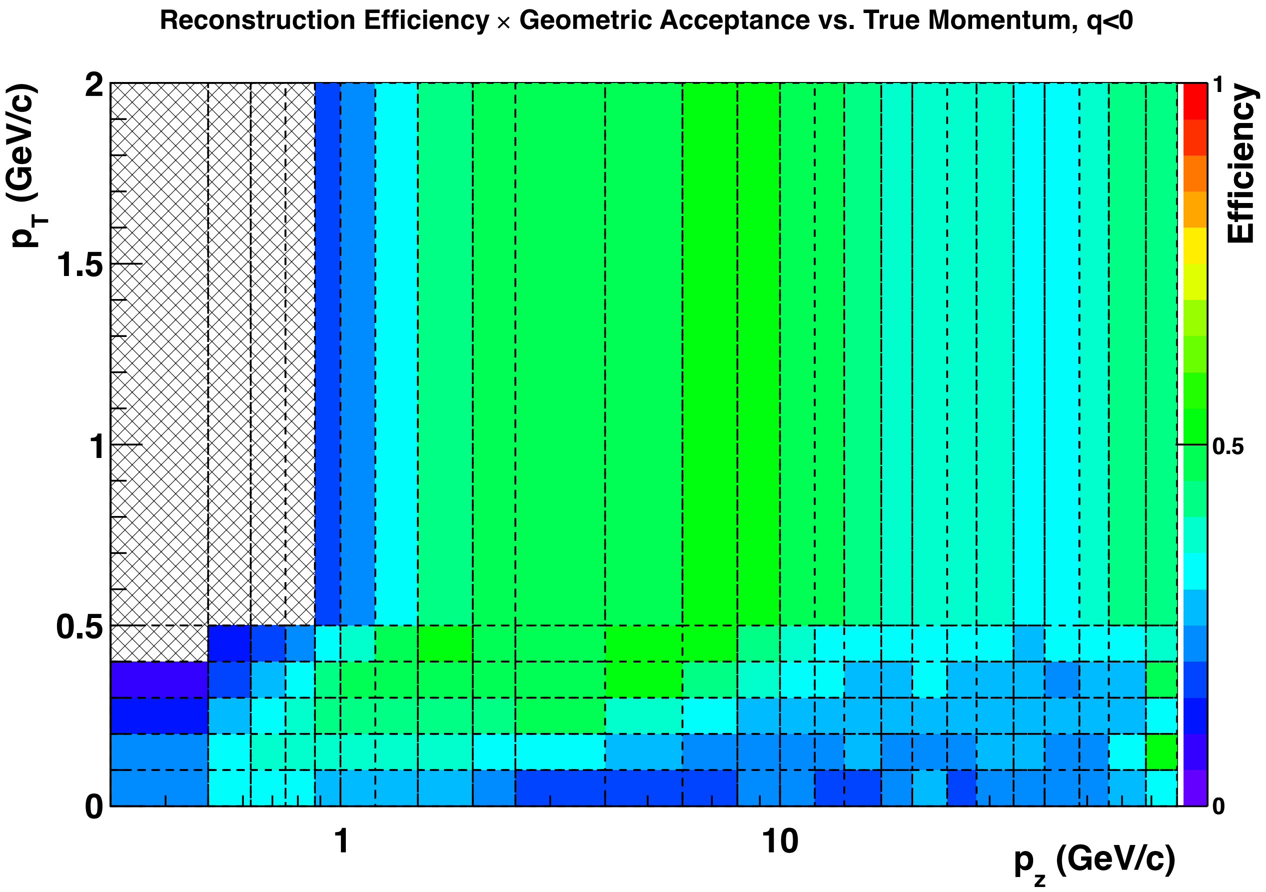


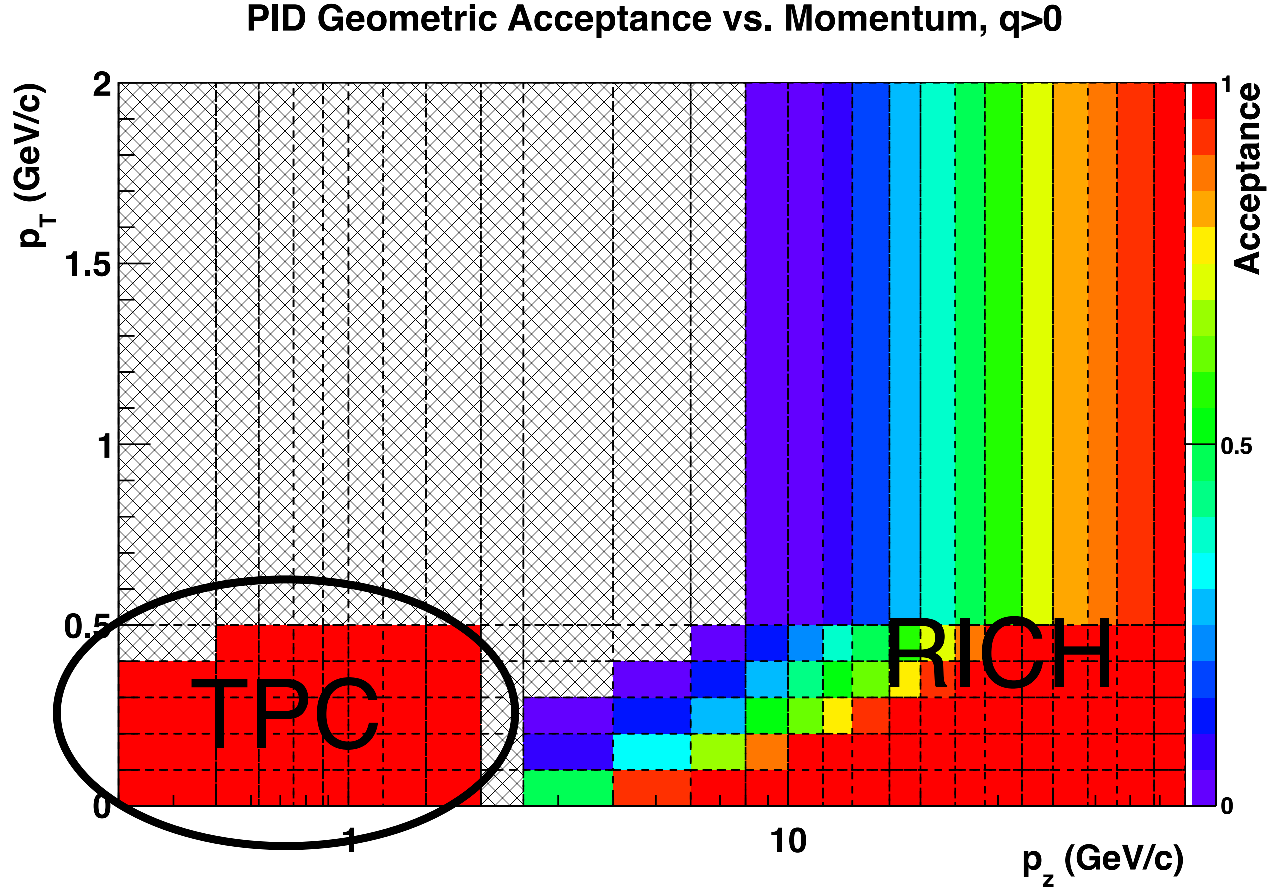




- Reject tracks that do not originate from the target
- Reject tracks that are very poorly reconstructed
  - momentum < 150 GeV/c
  - “goodness-of-fit” > $1x10^{-3}$

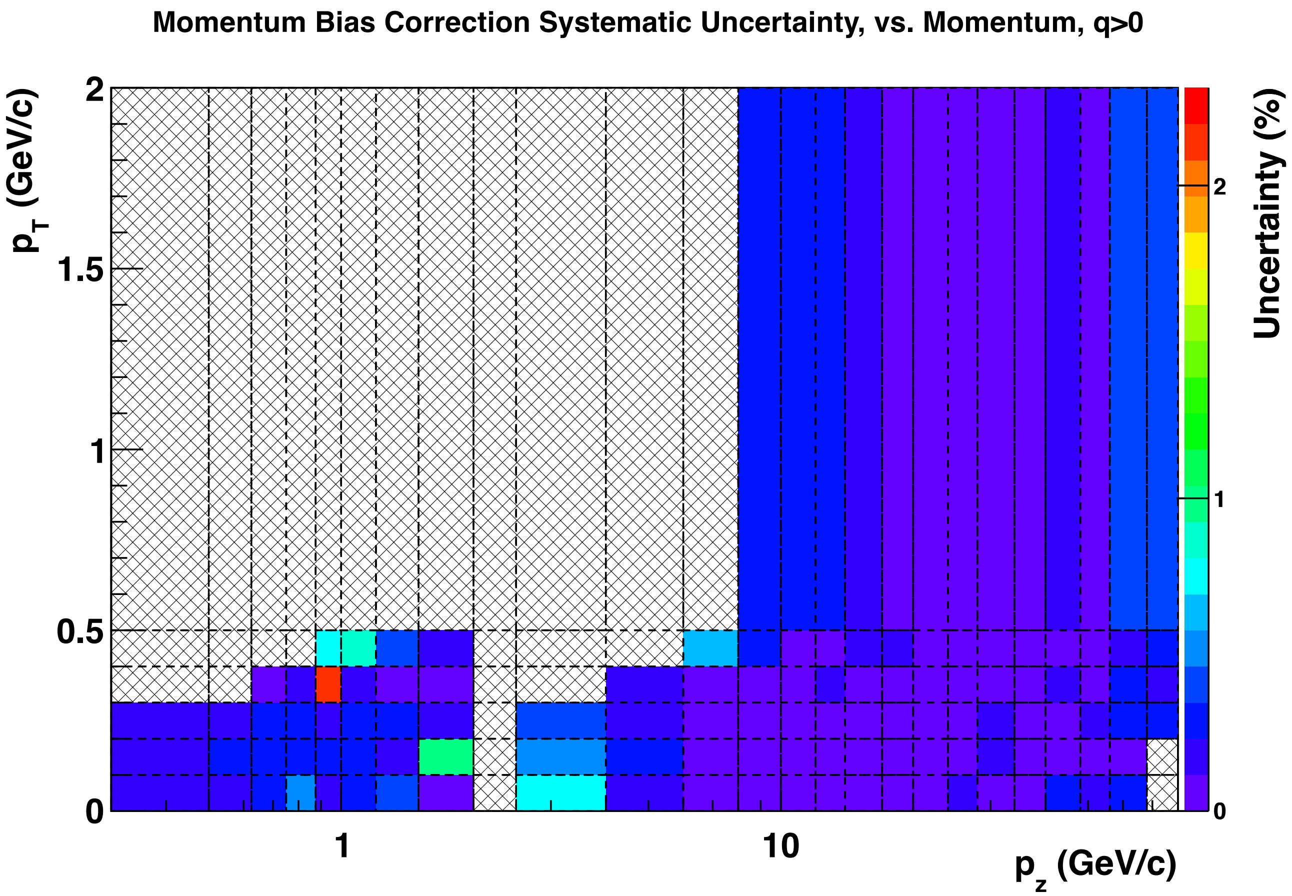
Efficiency and Acceptance Corrections

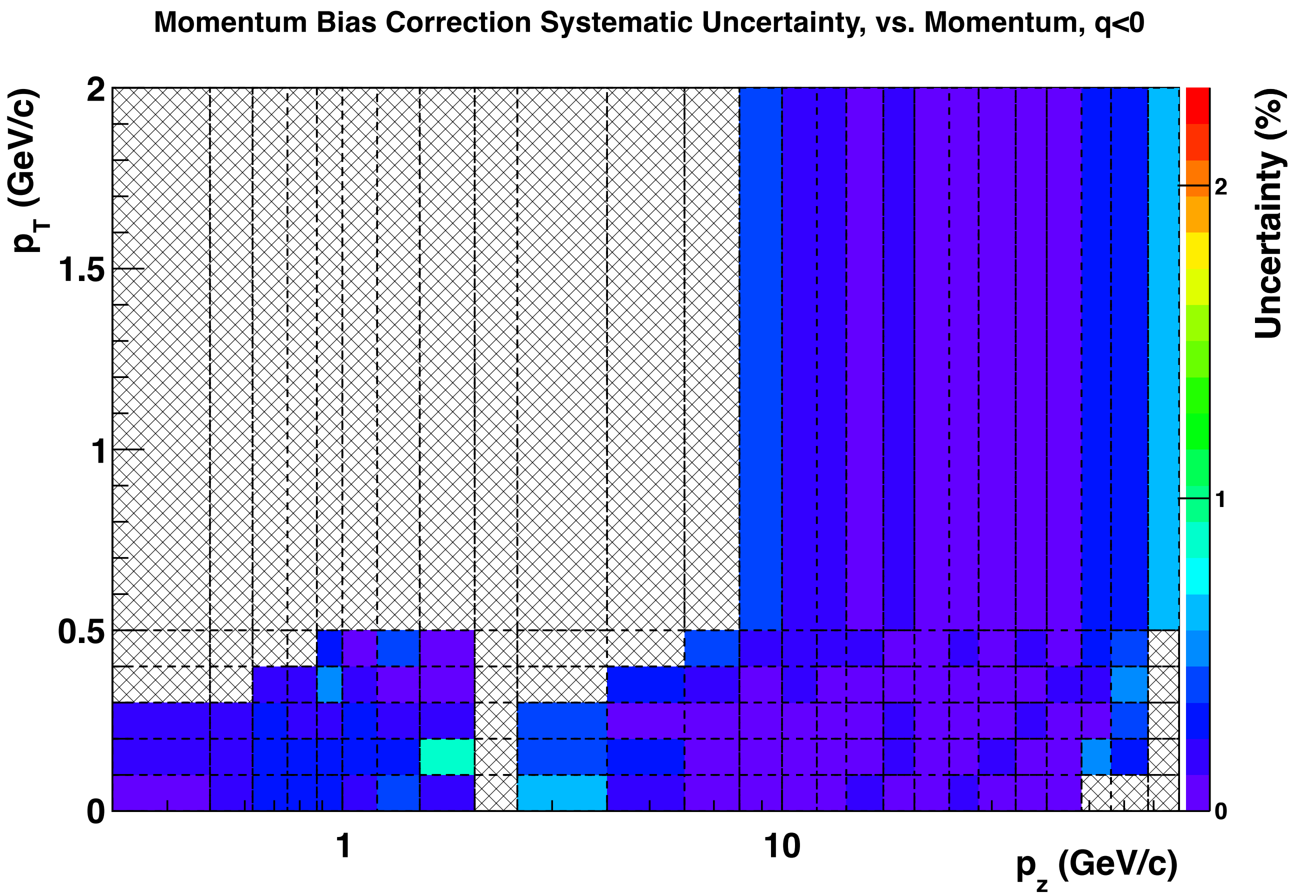




- Track selection efficiency (fraction of tracks that pass all track selection criteria) is ~60%.
- PID acceptance is the fraction of reconstructed tracks that made it into a PID detector.
  - All selected tracks are required to have TPC hits, so acceptance for TPC PID is 100%.
  - RICH acceptance requires particles to traverse length of spectrometer, so lower acceptance at lower momenta and higher (relative) p_T.

Momentum Bias Correction Systematic

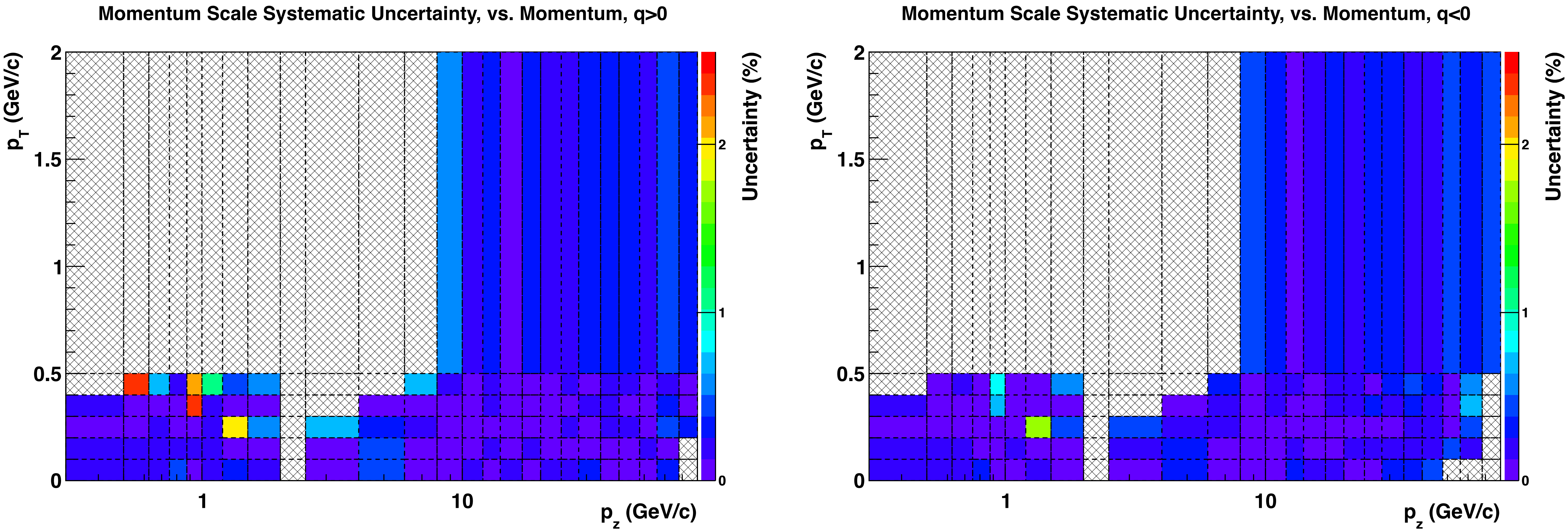




$$\sigma_{\mathrm{p-bias}} = 10\% \left(\frac{N(\pi)^{2\times\mathrm{bias}} - N(\pi)^{-1\times\mathrm{bias}}}{2} \right)$$

- Apply 200% and -100% of the correction to the data.
- Conservative uncertainty of 10% on the correction itself.

Momentum Scale Systematic

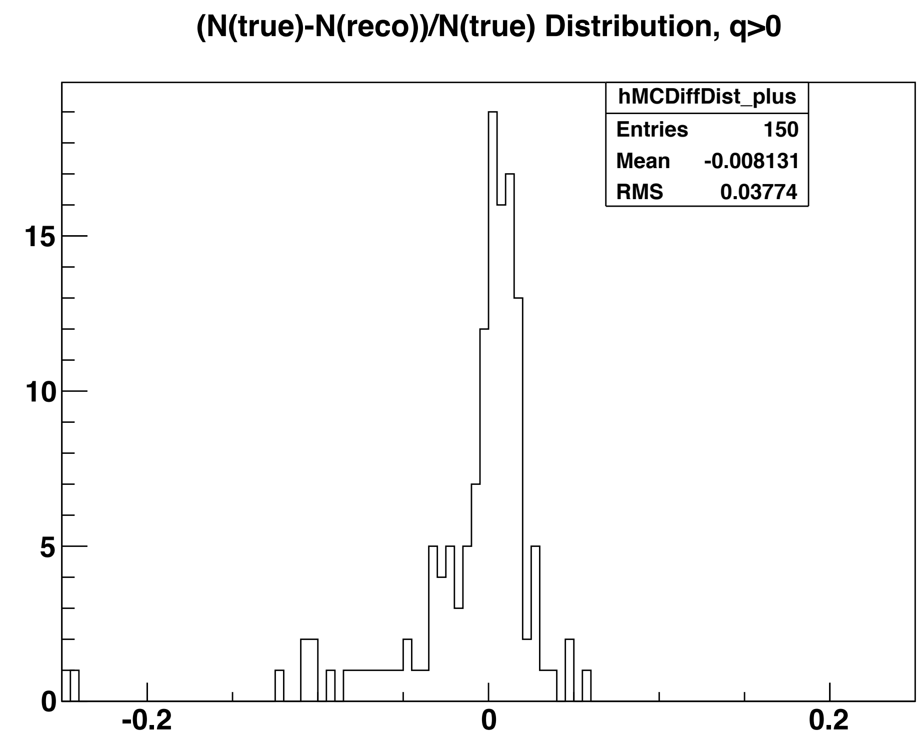


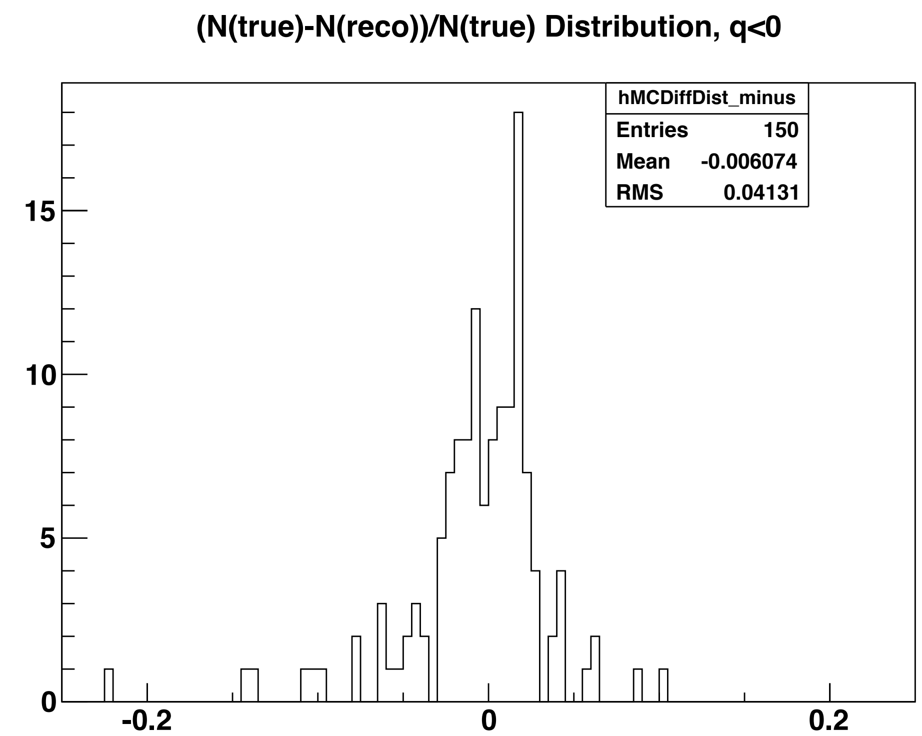
$$\sigma_{\mathrm{p-scale}} = 10\% \left(\frac{N(\pi)^{2\times\mathrm{scale}} - N(\pi)^{-1\times\mathrm{scale}}}{2} \right)$$

- Apply 200% and -100% of the correction to the data.
- Conservative uncertainty of 10% on the correction itself.

Resolution and Reconstruction Failures

- Momentum resolution and reconstruction failures result in migrations across bins of (p_z,p_T).
- Distribution of fractional difference between number of reconstructed pions and true pions in each bin has a width ~4%
- 1% uncertainty estimated due to mis-modeling of detector noise





Preliminary Fits to Parameterization Function

- Our own (very preliminary!) fits to the MIPP results, starting at $p_Z = 1$ GeV/c

$$\frac{d^2N}{dp_Z dp_T} = \frac{1}{p_{\rm inc}}(A + Bp_T)e^{-Cp_T^{3/2}}$$
$$A = a_1(1-x)^{a_2}(1+a_3x)x^{-a_4}$$
$$B = b_1(1-x)^{b_2}(1+b_3x)x^{-b_4}$$
$$C = -c_1/x^{c_2} + c_3 \quad \text{for} \quad x < 0.22$$
$$C = c_1^*/e^{(x+c_2^*)c_3^*} + c_4^*x + c_5^* \quad \text{for} \quad x > 0.22$$

- Gives quite reasonable fit results