Measurement of π/K Production Ratio in Proton Carbon Interactions

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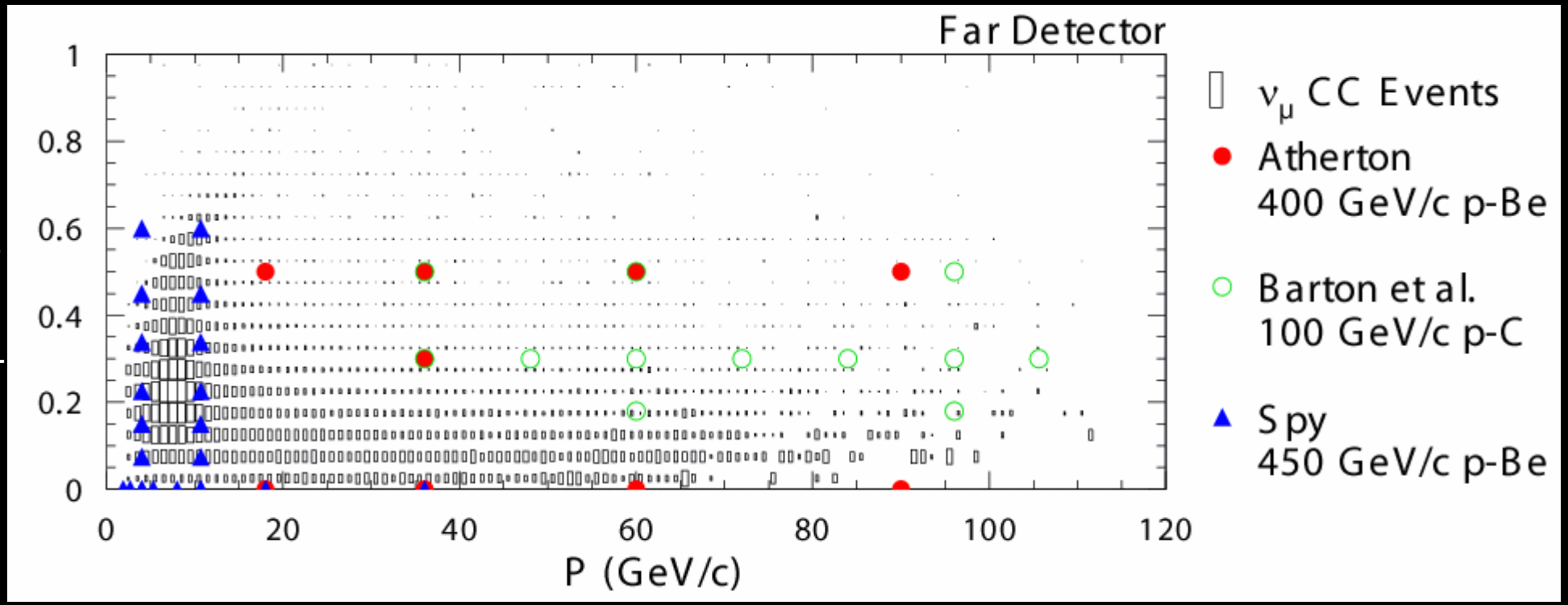
Outline

- Introduction
- MIPP Spectrometer
- Event reconstruction
- Detector Calibration
- Analysis
- Results & Conclusion

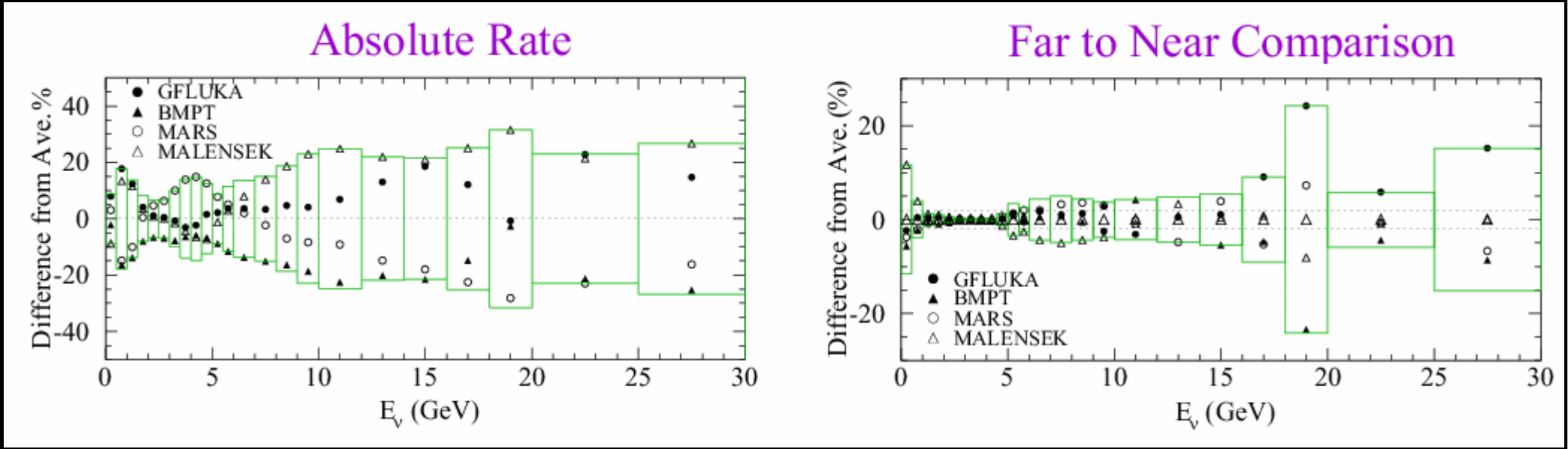
Why Measure Particle Production?

- There is very little data of inclusive particle production
  - Much of it taken with single-arm spectrometers



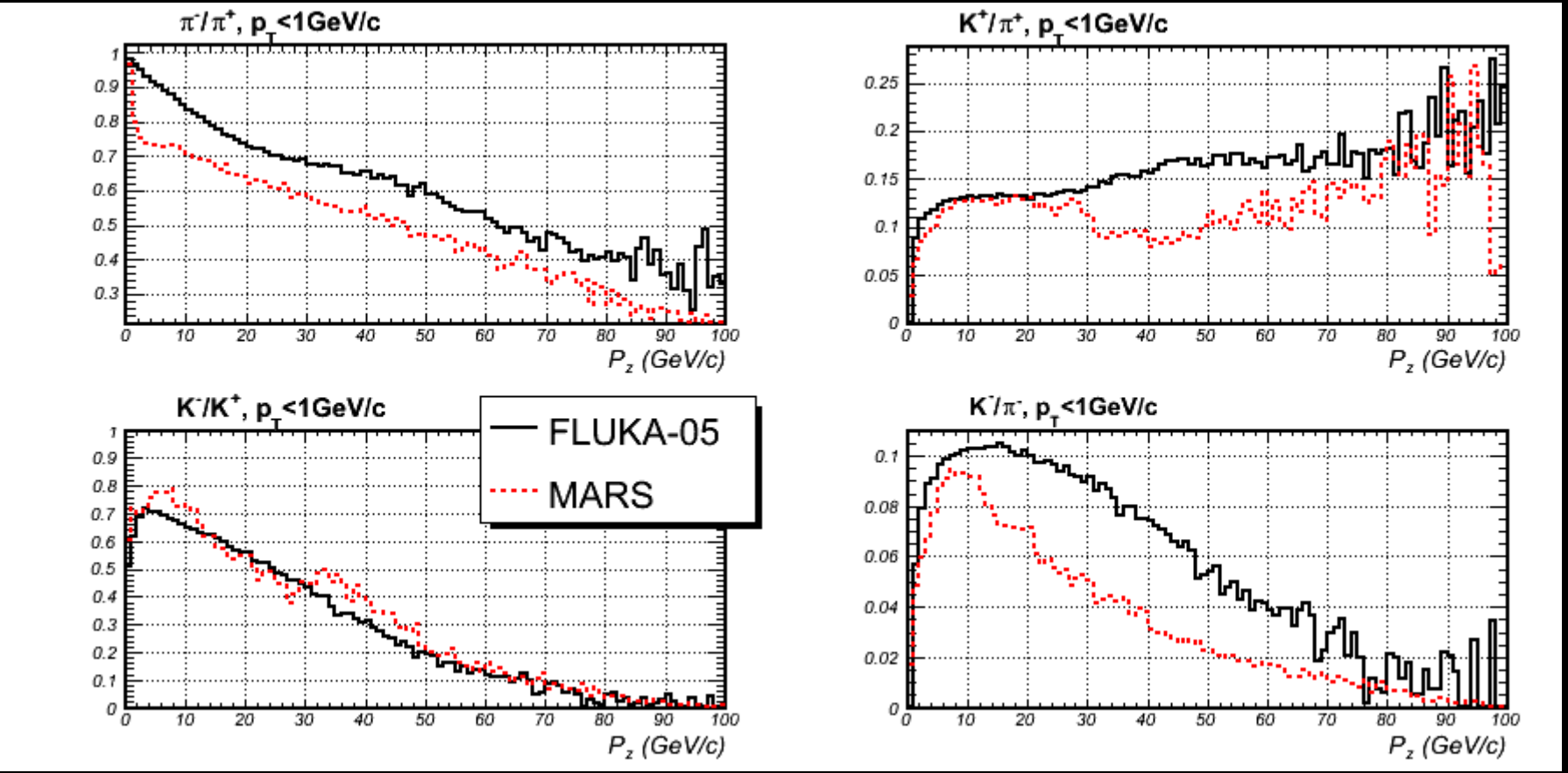
- In 2006, NA49 published $\pi^{\pm}$ production from pC at 158GeV/c

Modeled MINOS Neutrino Flux



- Predictions from different Monte Carlo models differ by up to 30%
- Differences do not cancel completely in near/far comparison

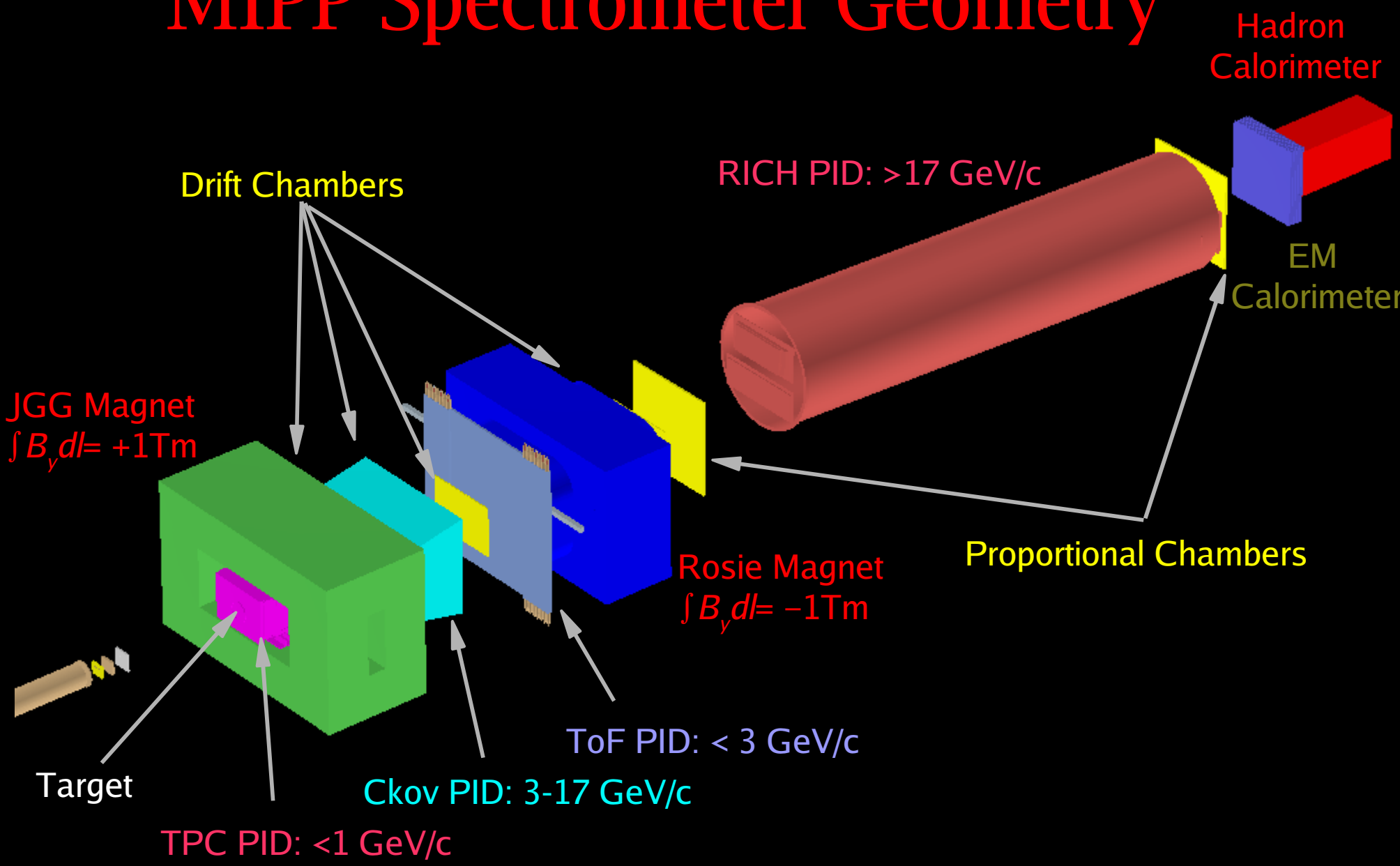
Predicted Production Ratios



- Predicted production ratios are not much better
- For MINOS, kaons matter because they produce ν_μ and ν_e

MIPP Spectrometer

MIPP Spectrometer Geometry



Beamline

Beam Cherenkov on a stand in MC7

- 3 wire chambers
  - Find incoming track
  - 1 mm wire spacing
- 3 scintillator counters
  - Form beam trigger
  - Measure time of flight
- 2 beam Cherenkovs
  - π/K <95 GeV/c
  - K/p <120 GeV/c

Tracking Detectors

TPC on the rails in front of the JGG magnet

- TPC
  - 120×128 pads in xz-plane each 0.8×1.2 cm
  - ~0.5 cm sampling in y
  - Multiplicities up to 200
  - Sits inside the JGG
- 4 drift chambers
  - 3.1-3.4 mm wire spacing
  - 1 ns time measurement
- 2 proportional chambers
  - 3.0 mm wire spacing

Particle Identification

View at the RICH from the far downstream end of MC7

- Energy loss in the TPC
  - <1 GeV/c
- Time of flight wall (TOF)
  - <3 GeV/c
- Segmented Cherenkov (Ckov)
  - <17 GeV/c
- Ring Imaging Cherenkov (RICH)
  - <100 GeV/c

MIPP Data Set

Number of triggers, x 10^6										
	Momentum (GeV/c)									*Total*
Target	**5**	**20**	**35**	**40**	**55**	**60**	**65**	**85**	**120**	
Empty		0.1	0.14			0.52			0.25	**1.01**
K^+ Mass				5.48	0.5	7.39	0.96			**14.33**
Empty LH1		0.3				0.61		0.31		**1.22**
LH	0.21	1.94				1.98		1.73		**5.65**
Be			0.1			0.56			1.08	**1.75**
C						0.21				**1.33**
C 2%		0.39				0.26			0.47	
NuMI									1.78	**1.78**
Bi			0.52			1.26			1.05	**2.83**
U						1.18				**1.18**
Total	**0.21**	**2.73**	**0.86**	**5.48**	**0.5**	**13.97**	**0.96**	**2.04**	**4.63**	**31.38**

This measurement

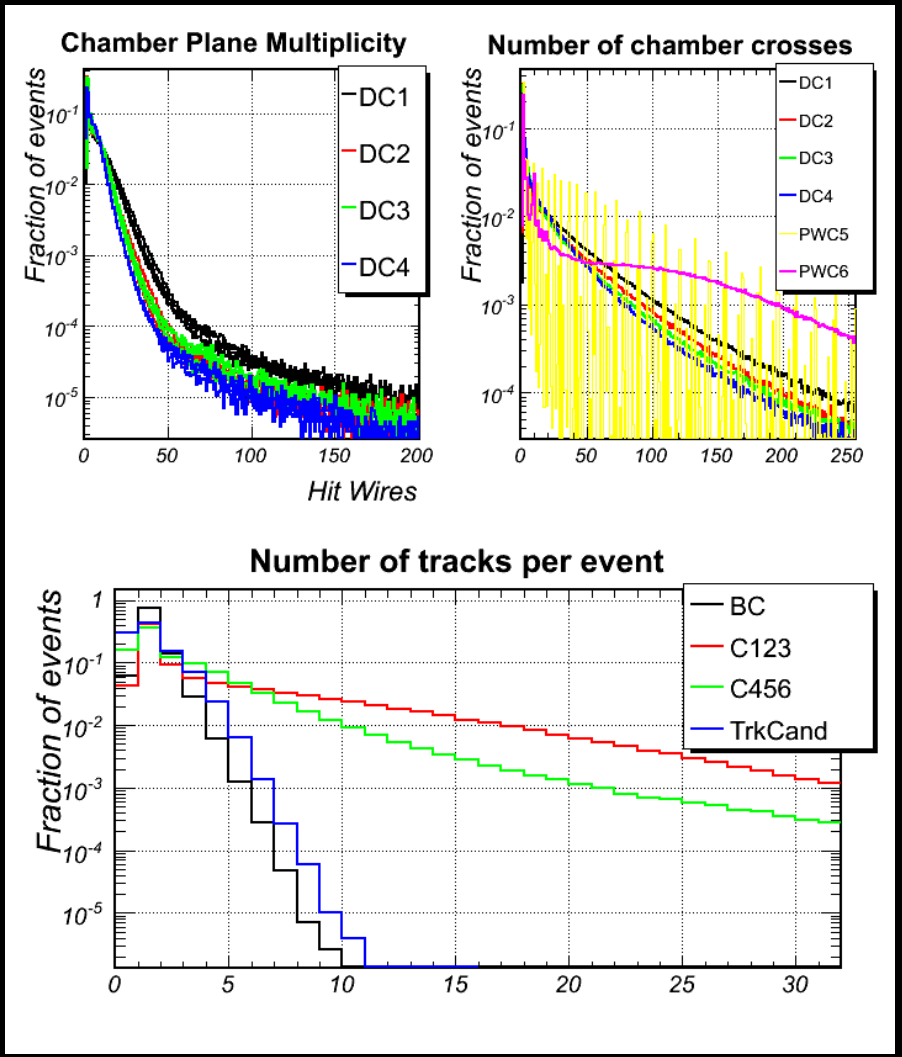
Event Reconstruction

Event Reconstruction Overview

- Find tracks using wire chamber hits
  - BC123, DC123, DC4+PWC56, and C1-6
- TPC track reconstruction
- Global tracks (TPC+chambers)
- Form and fit vertices
- Identify tracks
  - Incident particle identification using beam Cherenkovs
  - Secondary particle identification using TPC dE/dx, TOF time, Ckov light, RICH rings
- Find calorimeter showers

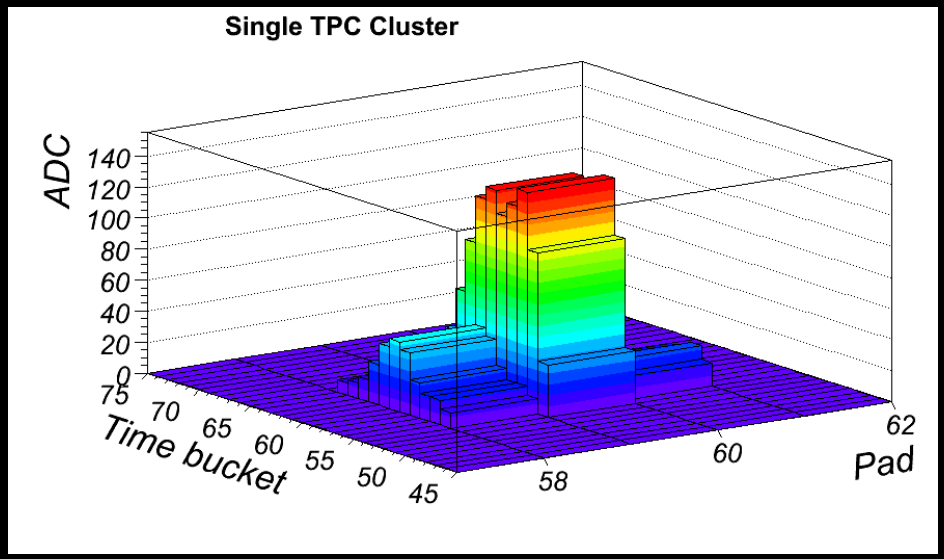
Chamber Tracks

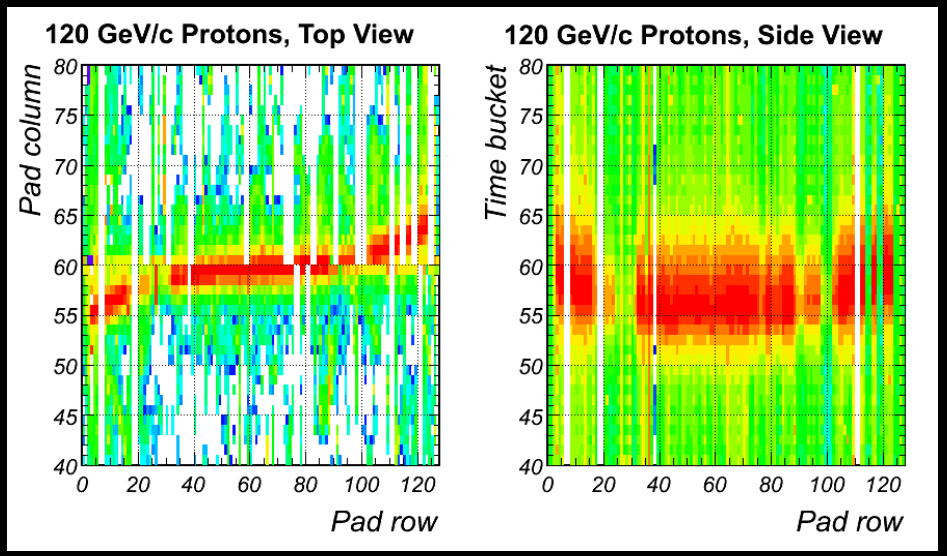
- Wire chamber track segments are found by going through "interesting" combinations of hits
  - Wires→wire clusters
  - Clusters→wire crosses
  - Crosses→track segments
  - Segments→track candidates
- Allows basic tracking without the TPC



TPC Hits

- TPC voxels are clustered into hits
  - Fit 1D time distributions to Gamma function
  - Compute *x* by fitting a Gaussian or weighted mean
- JGG magnetic field causes significant distortions of hit positions





TPC Distortion Corrections

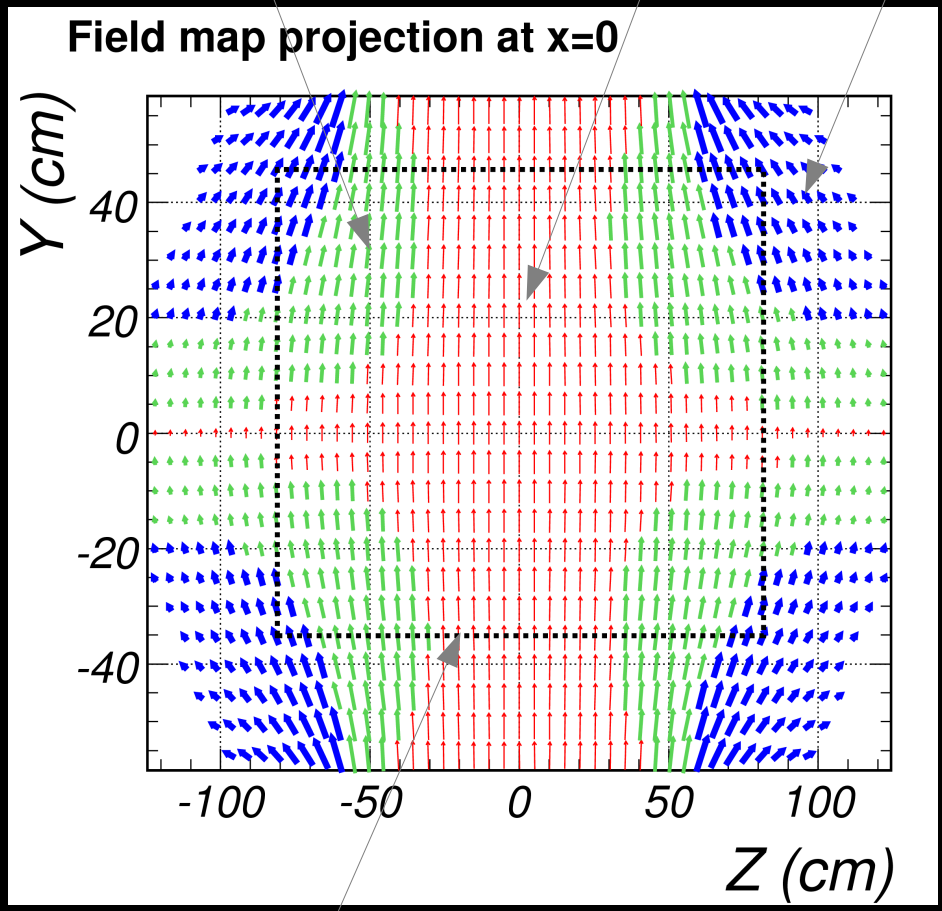
- Distortions result from electron drift in non-uniform magnetic field
- Simplest linear model

$$m\frac{d\vec{v}}{dt} = e\vec{E} + e\vec{v}\times\vec{B} - \frac{1}{\tau}\vec{v}$$

has a solution

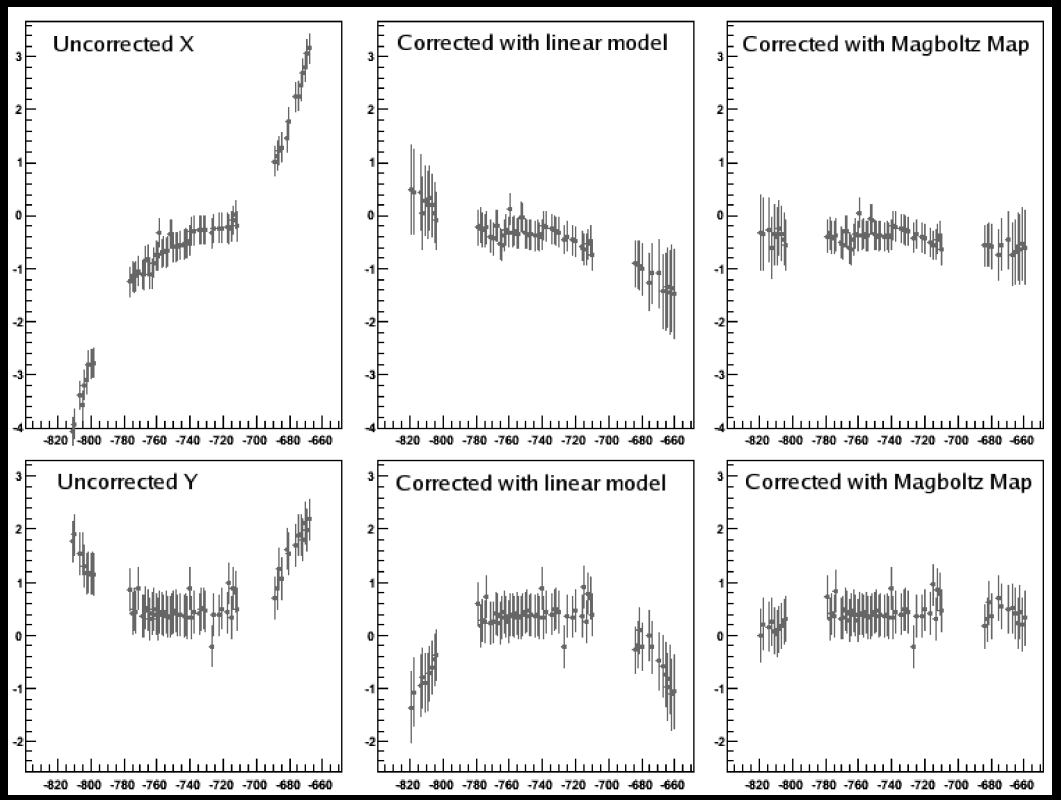
$$\vec{v} = \frac{v_0}{1+\omega^2\tau^2}\left[\vec{E} + \omega\tau\,\hat{E}\times\hat{B} + \omega^2\tau^2(\hat{E}\cdot\hat{B})\,\hat{B}\right]$$

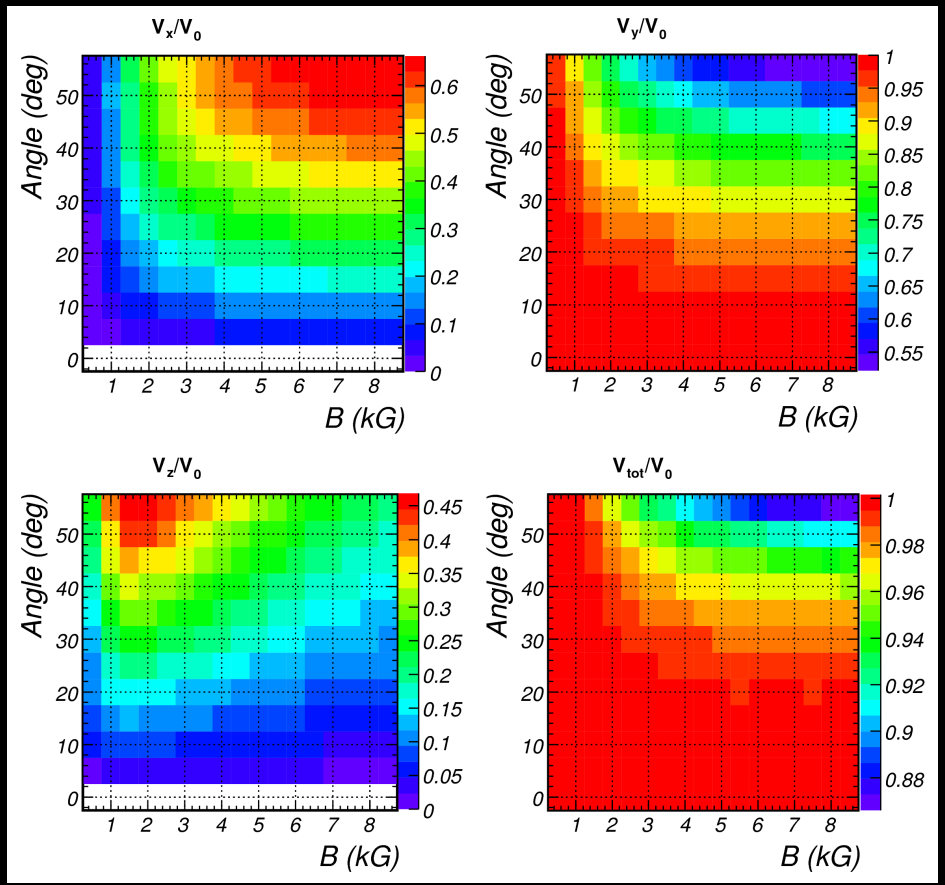
- This model worked well for BNL E910, but does not describe drift in JGG field



Distortion Corrections (cont.)

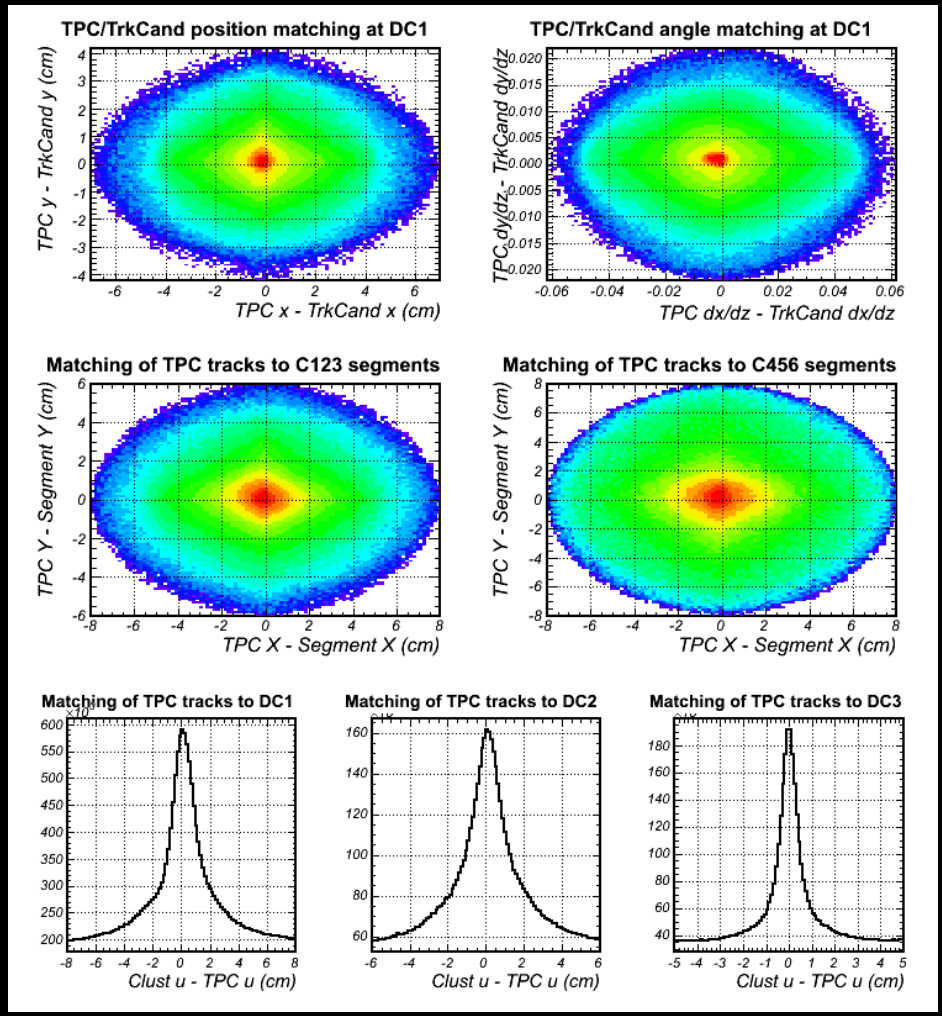
- We use Magboltz MC program to simulate electron drift given **E** and **B** vectors





Tracks Reconstruction

- Start TPC tracks with nearest neighbor hits on adjacent pad rows
- Fit to helix and continue to include good hits
- Refit the track using magnetic field map
- Connect TPC tracks to chamber track candidates, segments, or wire clusters

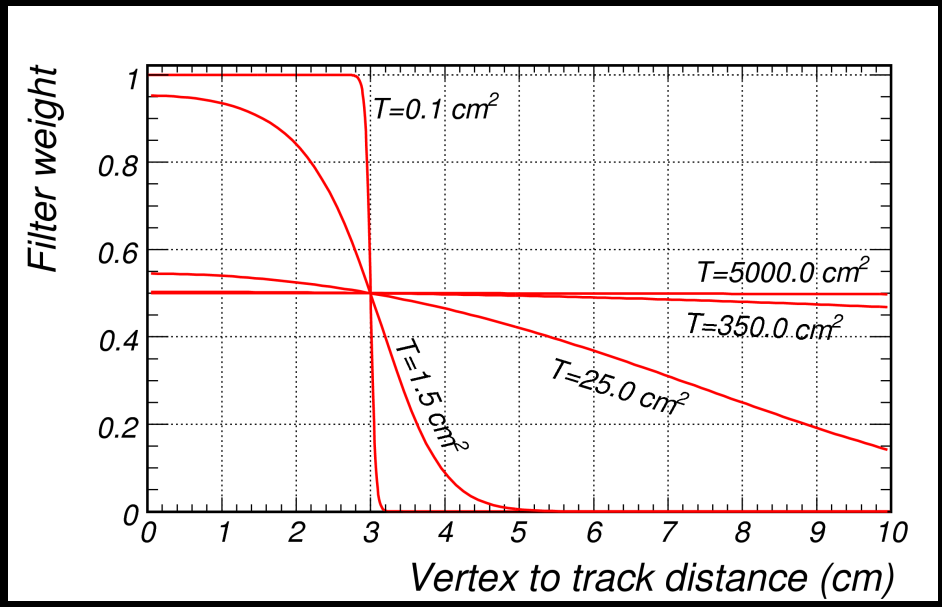


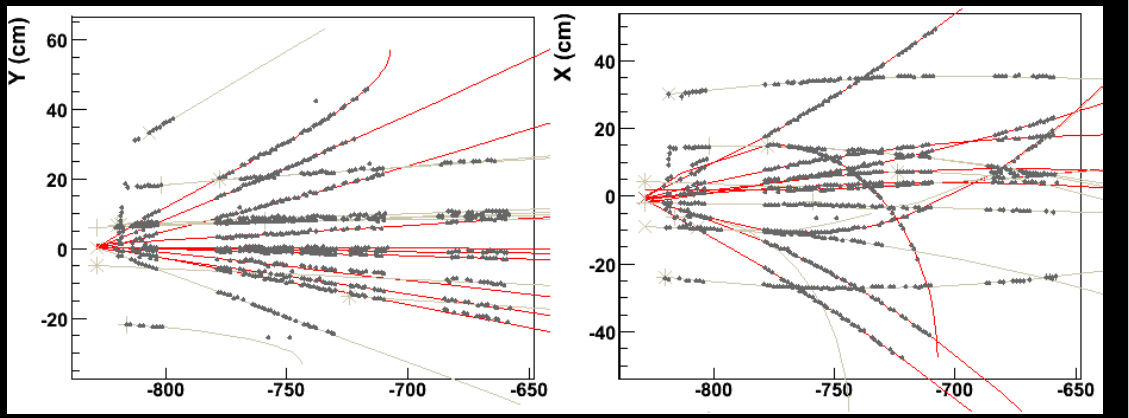
Vertex Finding

- Deterministic annealing filter used to find vertices
- Minimize sum of distance squared to tracks
  - Track weight is set to

$$w = \left[1 + \exp\left(\frac{D_{trk}^2 - D_c^2}{2 T_{DAF}} \right) \right]^{-1}$$

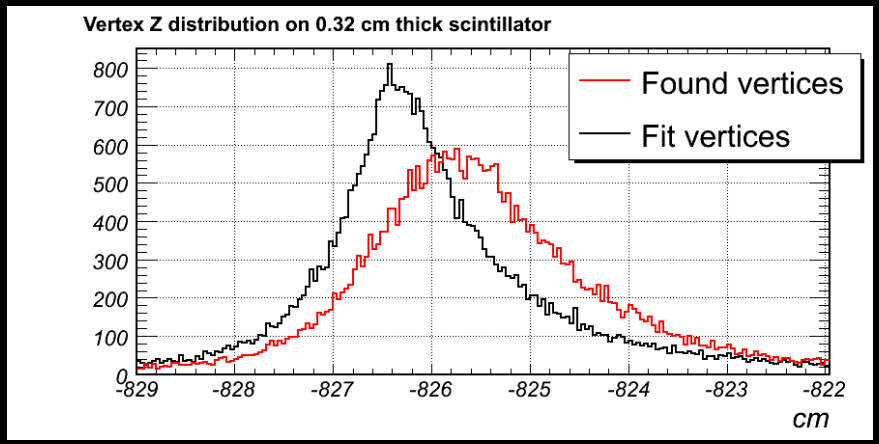
- Start with large T_{DAF} and reduce it slowly to 0 to "freeze out" noise

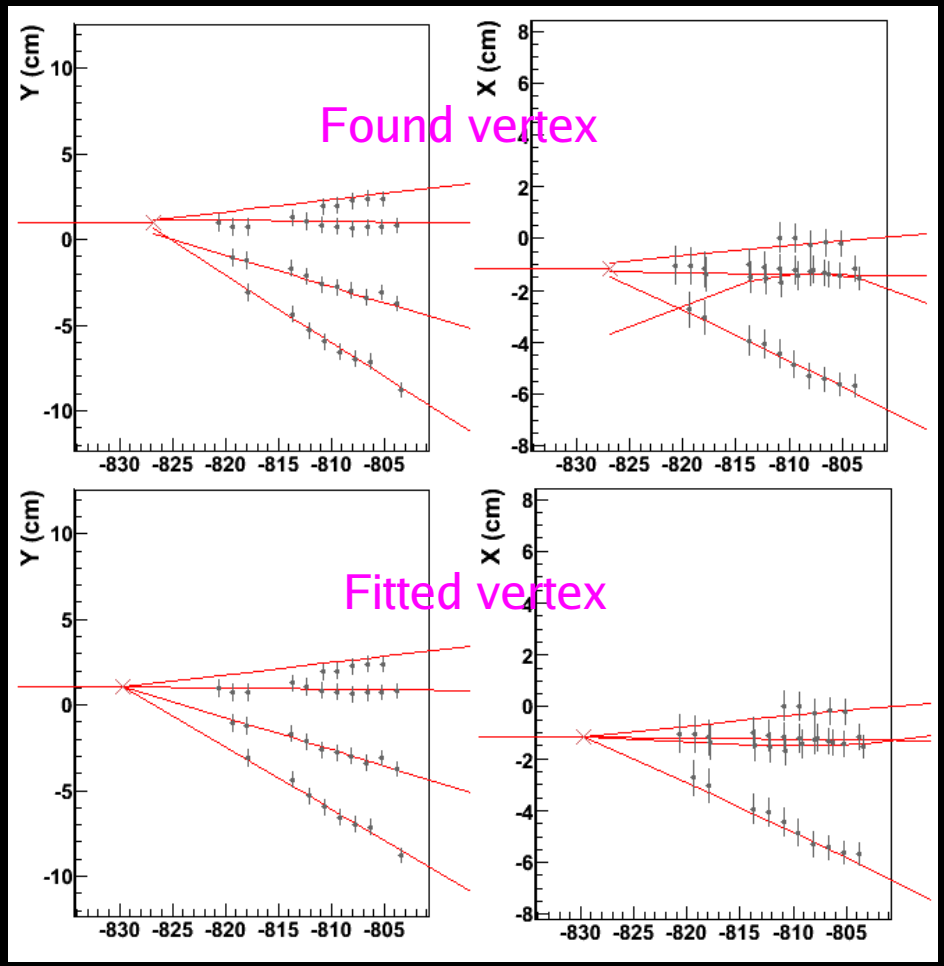




Vertex Constrained Fit

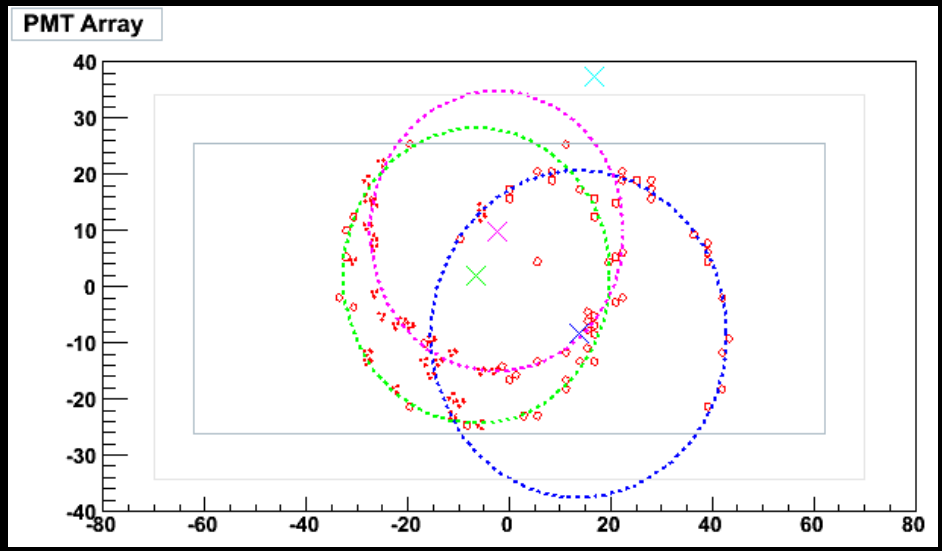
- The problem is linearized for track momenta and angles, and vertex (x,y)
  - Scan z to find the answer
- Improves reconstructed vertex z resolution from 2.1 cm to 1.3 cm FWHM

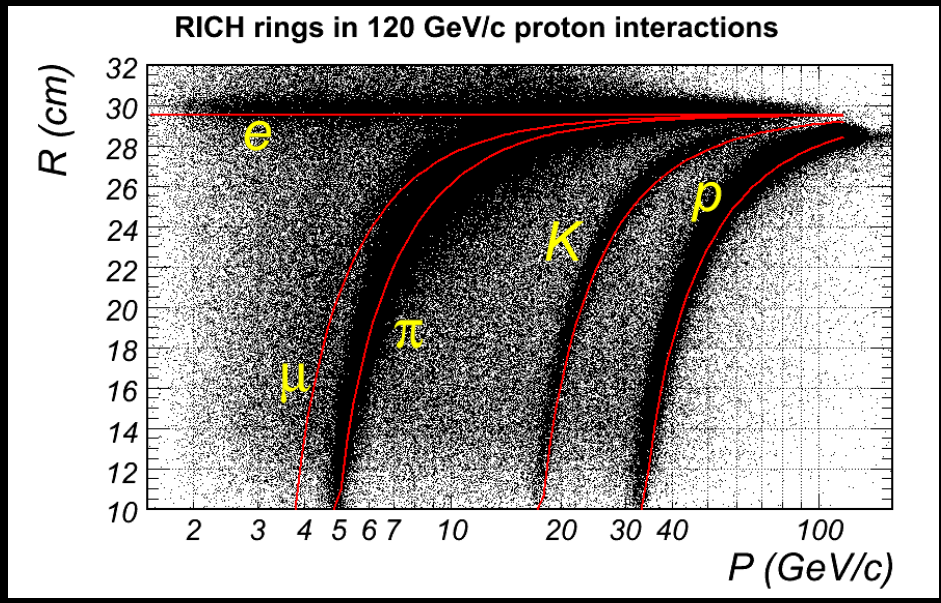




RICH Ring Fits

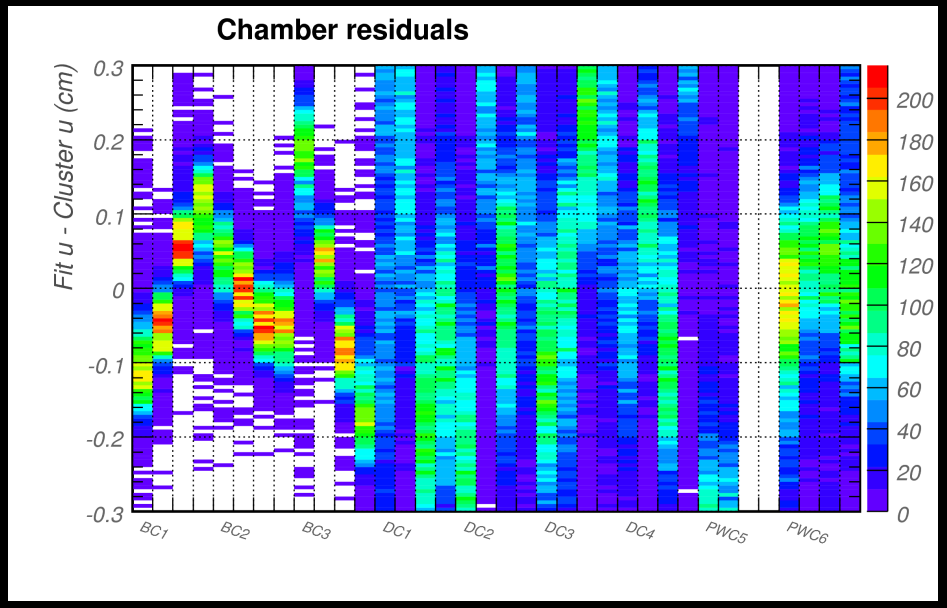
- Select tracks which
  - Go through CO_2 gas
  - Have projected center within 35cm of PMT array
- Fit for ring radius
  - Use DAF to reject noise
  - Share hits among rings: hit weight is proportional to the number of hits with similar distance from ring center

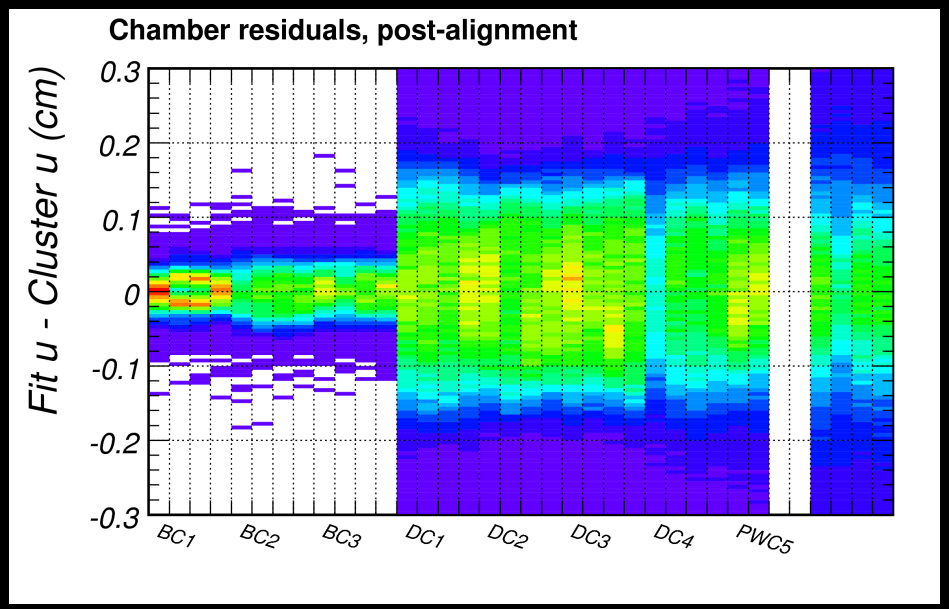




Calibration

Chamber Alignment

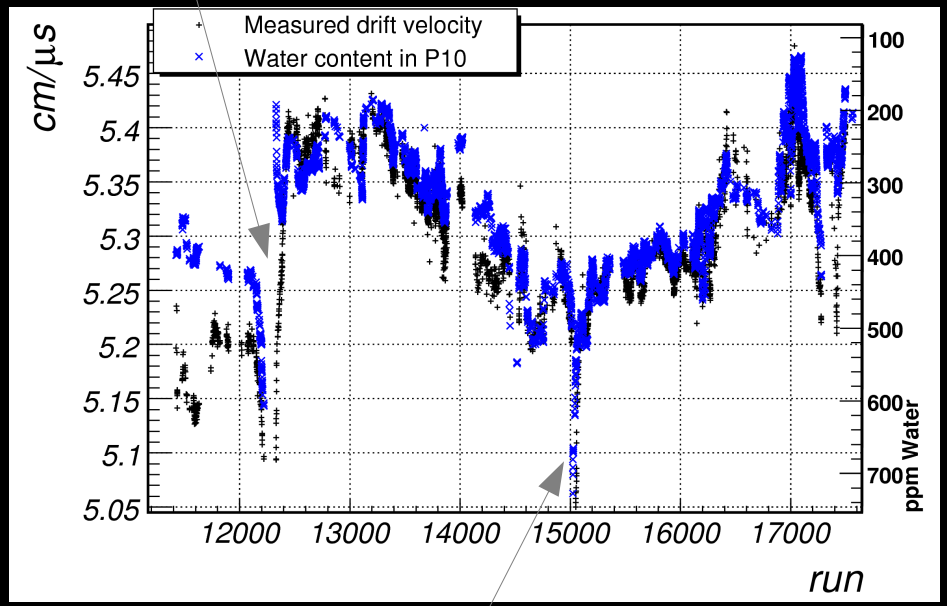




- Wire chamber alignment was possible with reconstructed chamber tracks
  - Found errors in geometry description
  - Corrected magnetic field maps
- Uncertainty in alignment 2-20% of wire spacing (30-600 micron)

TPC Drift Velocity

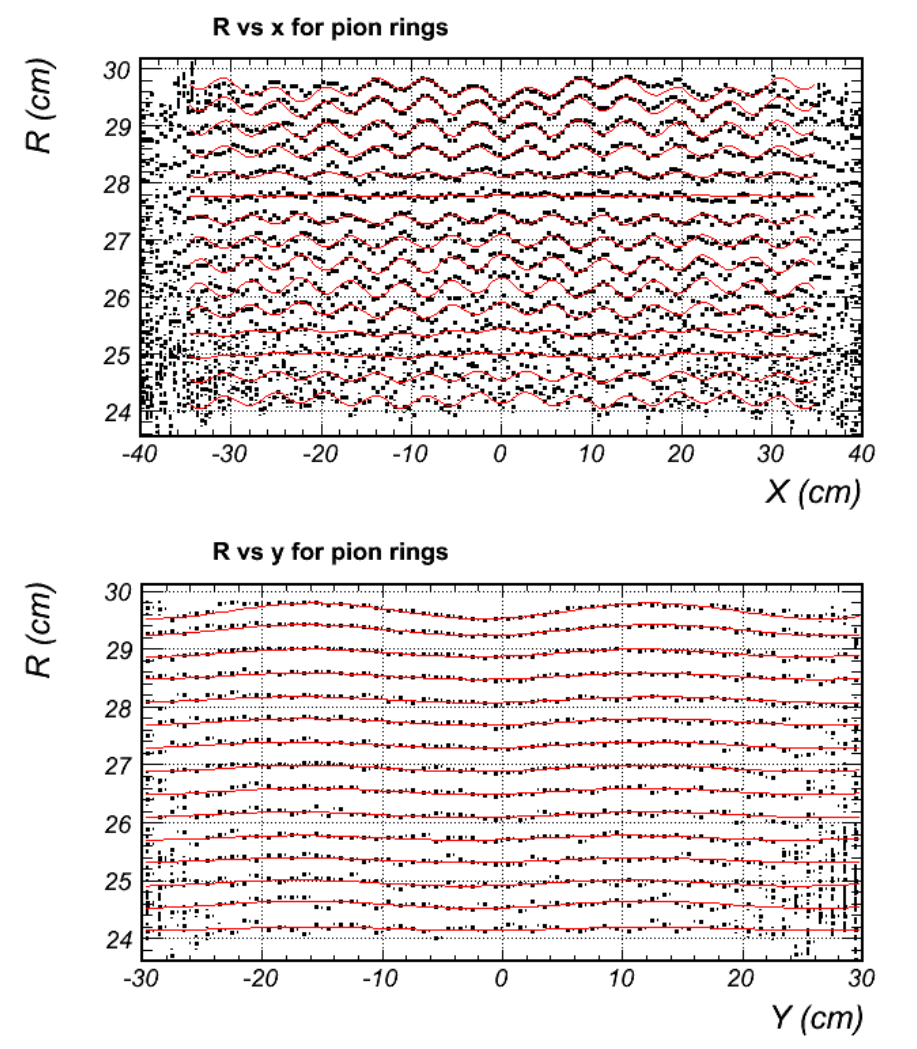
Double the flow of gas



Operator error: shut off exhaust valve prevented proper gas flow

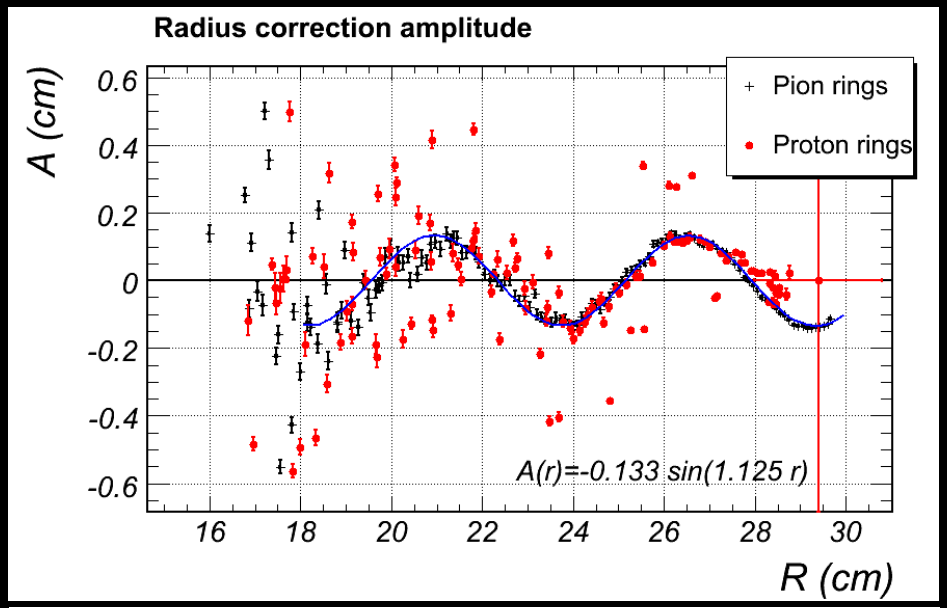
- Drift velocity in the TPC is a strong function of water and oxygen contamination
  - Effects of temperature and atmospheric pressure are much smaller
- We use the center of the TPC volume to measure drift velocity
  - Minimize effect from distortions due to JGG field

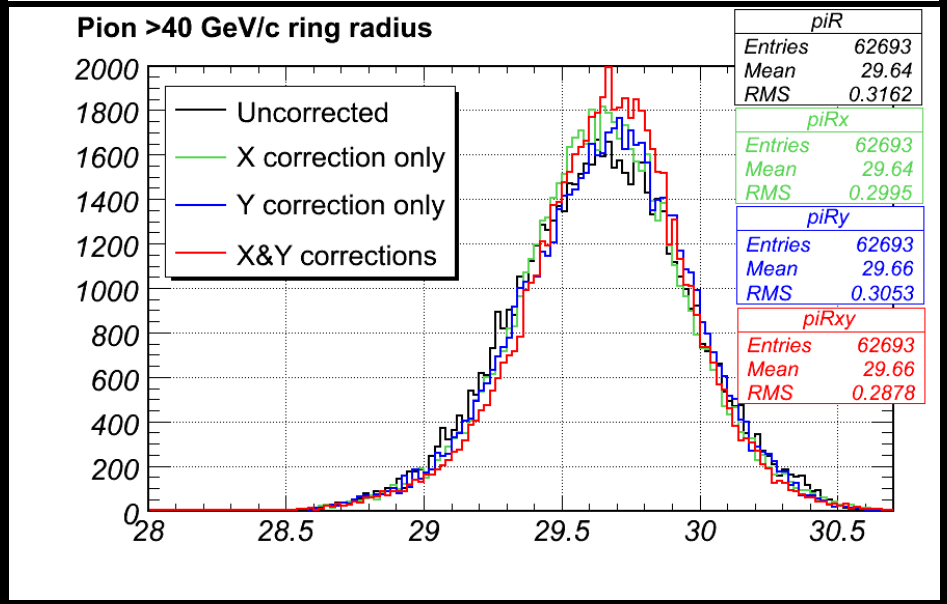
Corrections to RICH Ring Radius



- In March 2004, RICH PMTs caught on fire
- Repaired detector has every fourth column empty
  - 69 of 89 columns are now populated with PMTs
- Result is aliasing in fitted RICH ring radii
  - Fitted radius is a function of true (x, y, R)
  - Corrections are up to 1.3mm

Corrections to RICH Rings (cont.)





- Scan ring radius selecting pions within a small range momenta
  - Scan proton rings for sanity check
- Dominant ripples in x are well described by

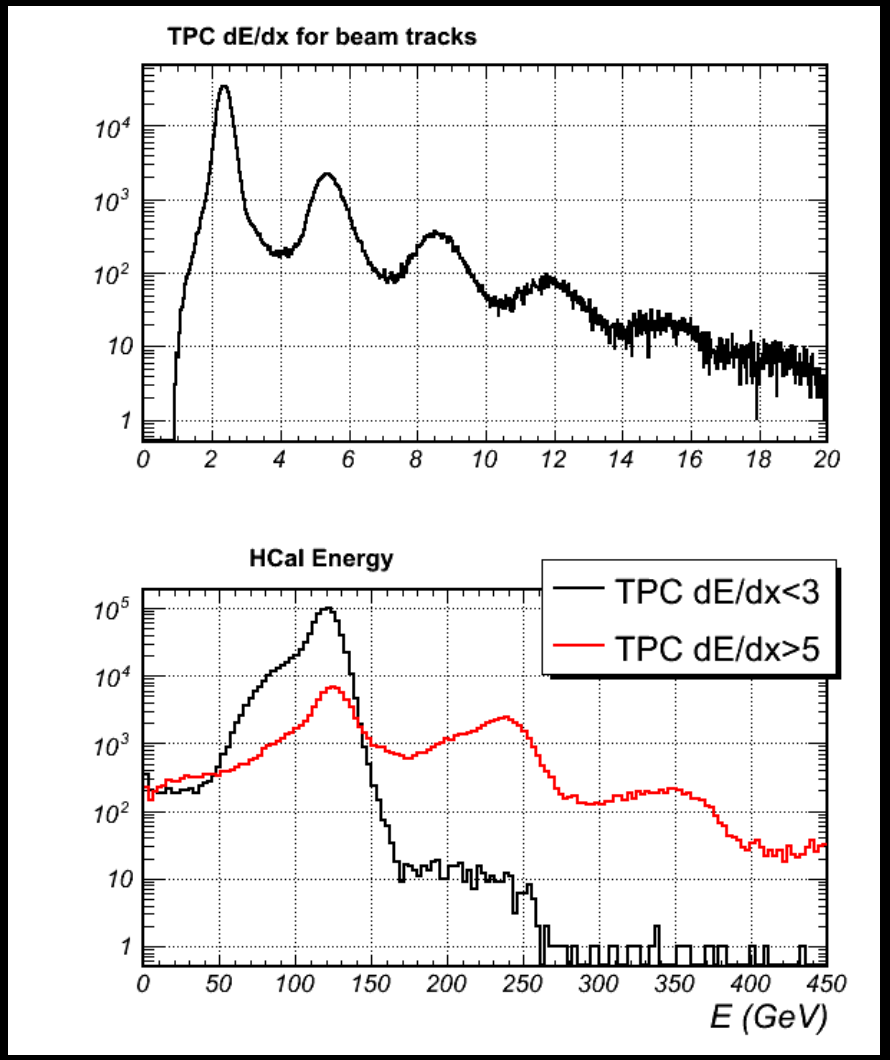
$$A(x, R) = A_0 \sin(2\pi r / D_4) \cos(2\pi x / D_4)$$

- Seen in Monte Carlo
- Correction makes peaks 10% narrower

Production Ratios Analysis

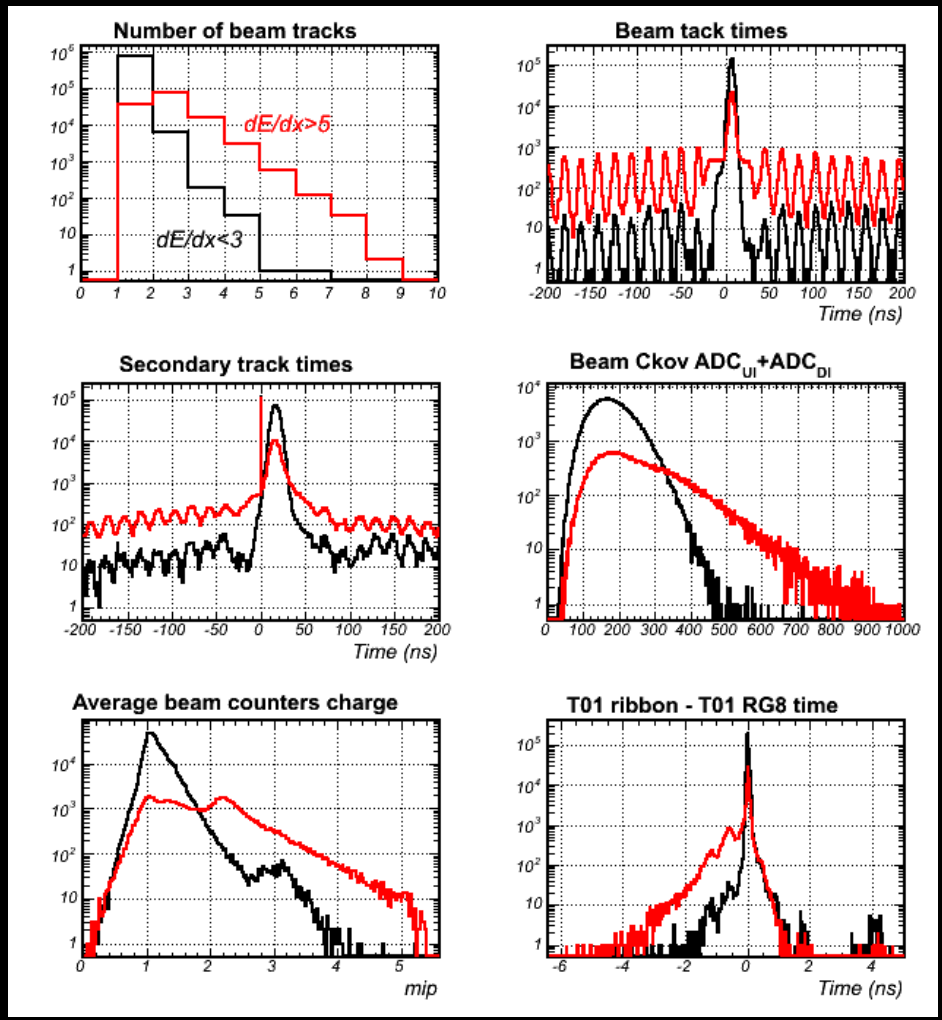
Pileup Removal

- Pileup is two or more incident protons in the same event
- Needs to be removed
  - Not modeled in MC
  - Can interfere with vertex finding and fitting
- Do as much as possible with beamline detectors
- TPC *dE/dx* in single-proton events identifies pileup



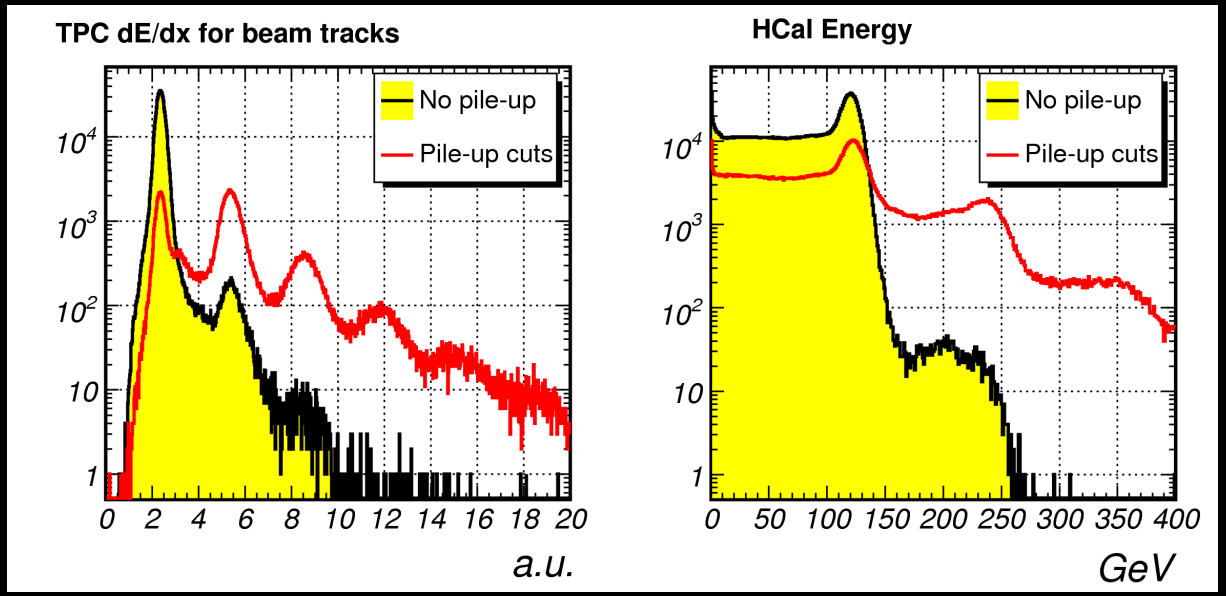
Pileup (cont.)

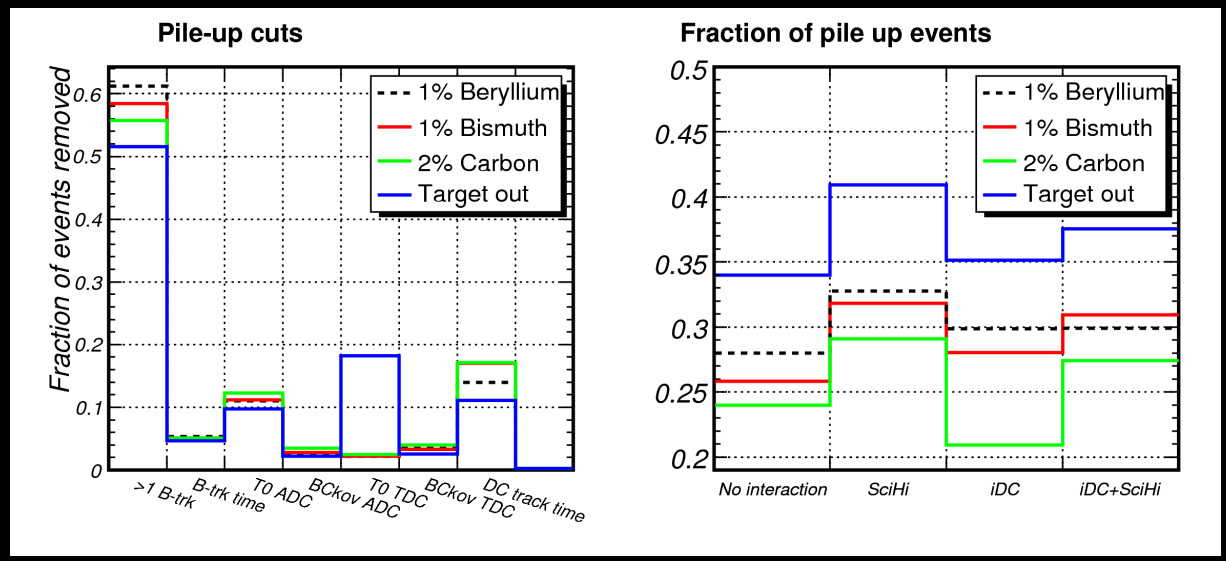
- A number of variables is used to reject pileup events
  - Number of beam tracks
  - Time of beam track
  - Time of secondary tracks
  - Total charge in beam Cherenkov PMTs
  - Total charge in scintillator beam counters
  - Time differences of beam counters



Pileup (cont.)

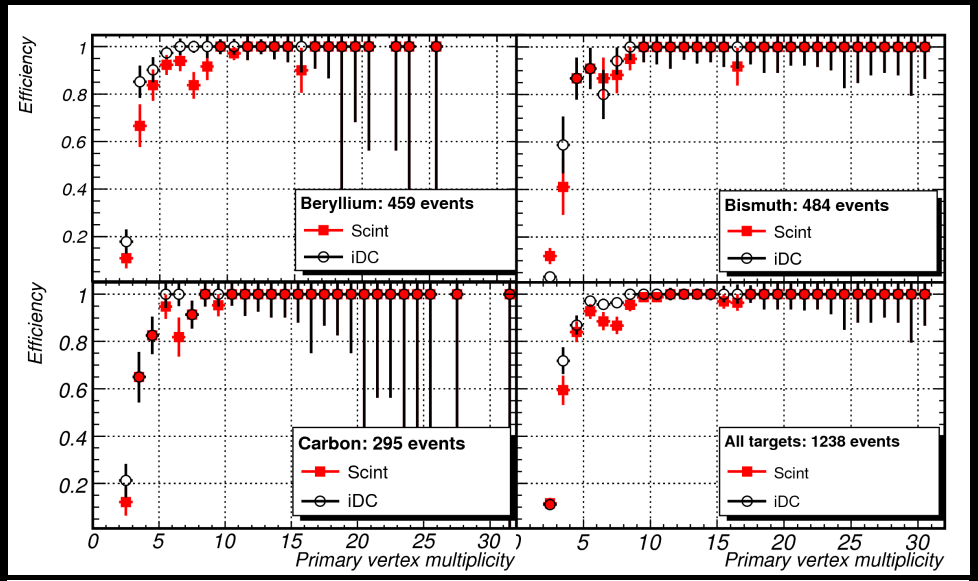
- When all the cuts are made
  - 20-40% of events are rejected
  - ~1% of pileup events remain in the sample

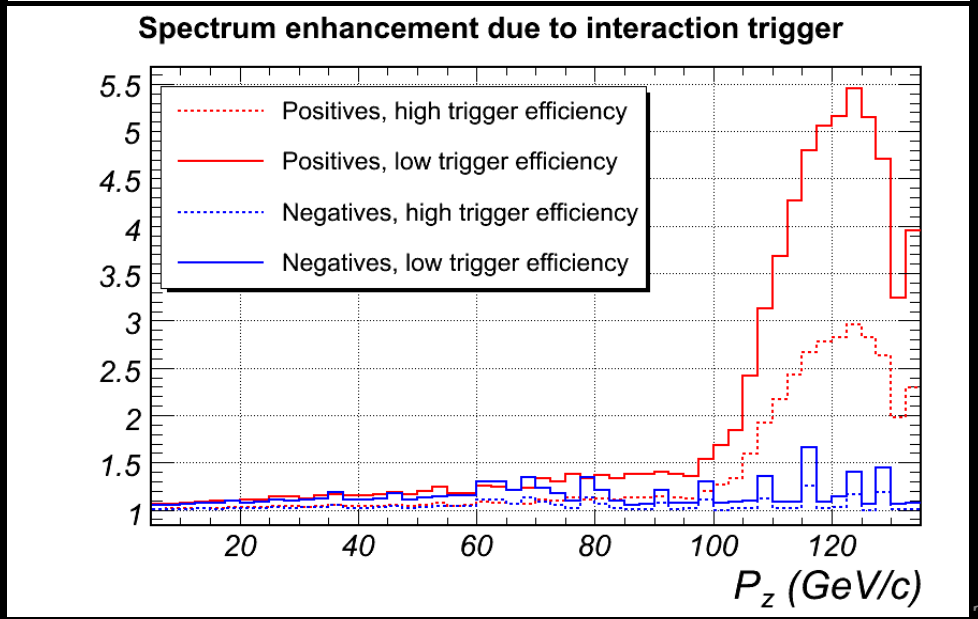




Interaction Trigger Efficiency

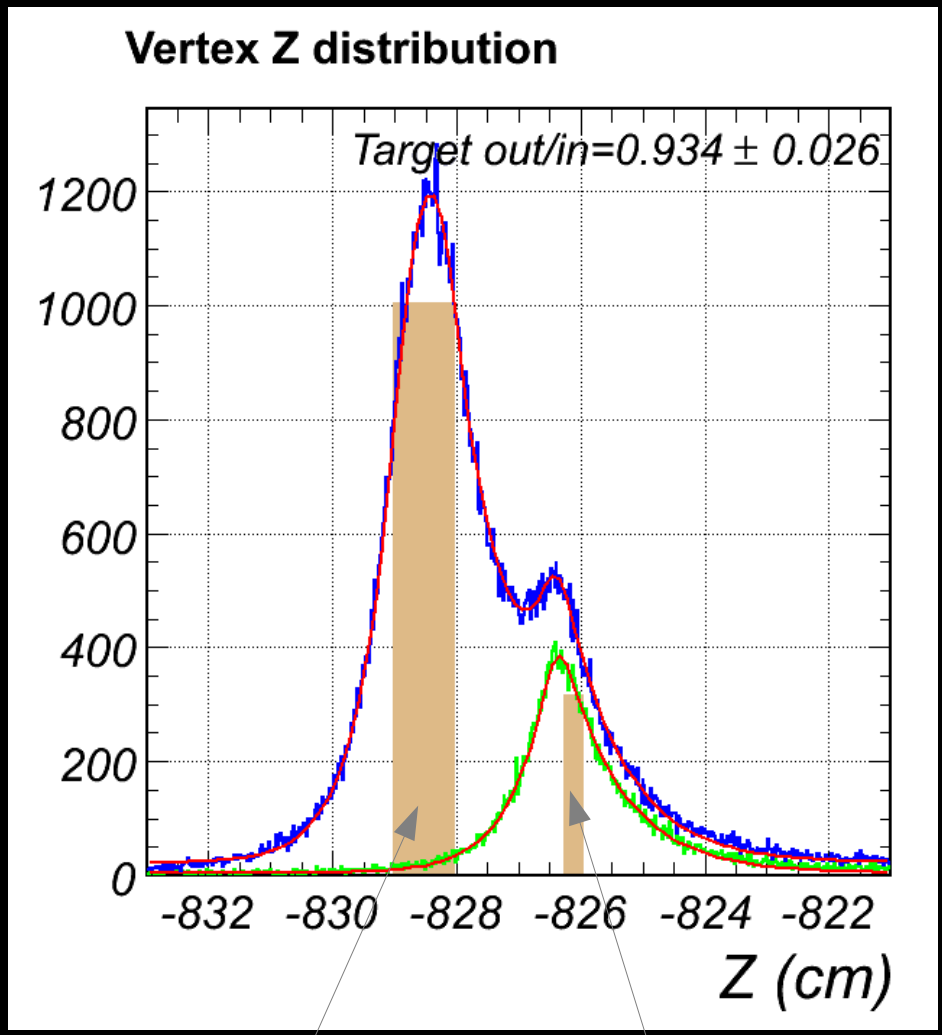
- Interaction trigger efficiency is measured from minimum bias trigger
  - Statistics are quite low: 295 carbon+459 beryllium
- Uncertainty in spectrum enhancement up to 30% for momenta of interest
  - Small systematic error on the ratios





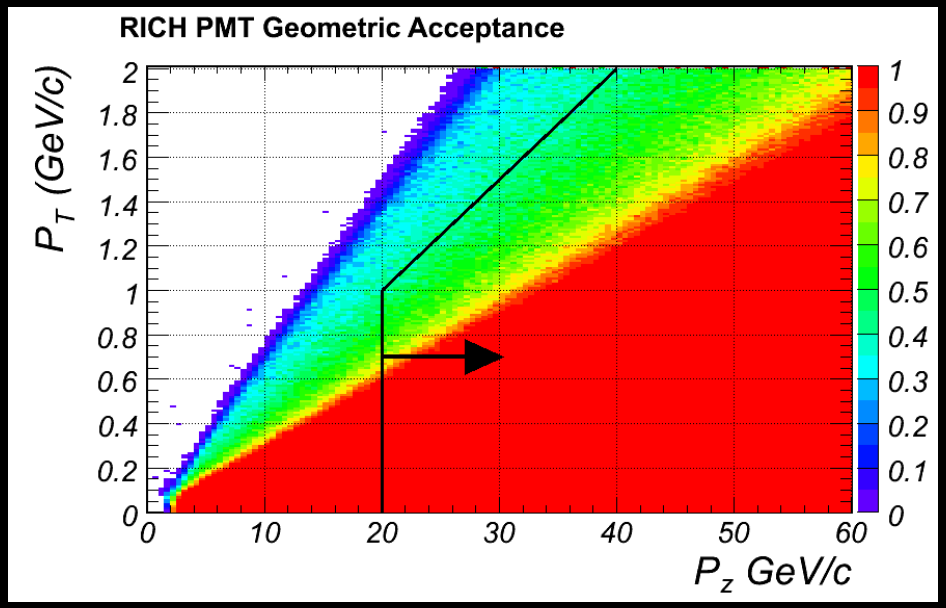
Empty Target Subtraction

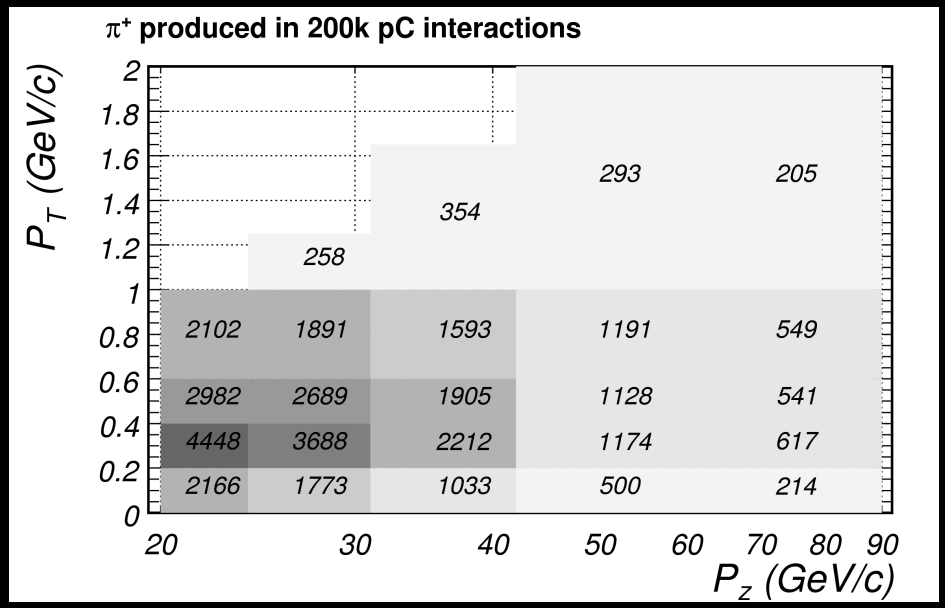
- We have to subtract target-out data
- Distribution in *z* is modeled well by Gaussian with exponential tails
- Fit target-out spectrum
- Fit target-in spectrum by holding the shape of Scint counter constant



Data Binning

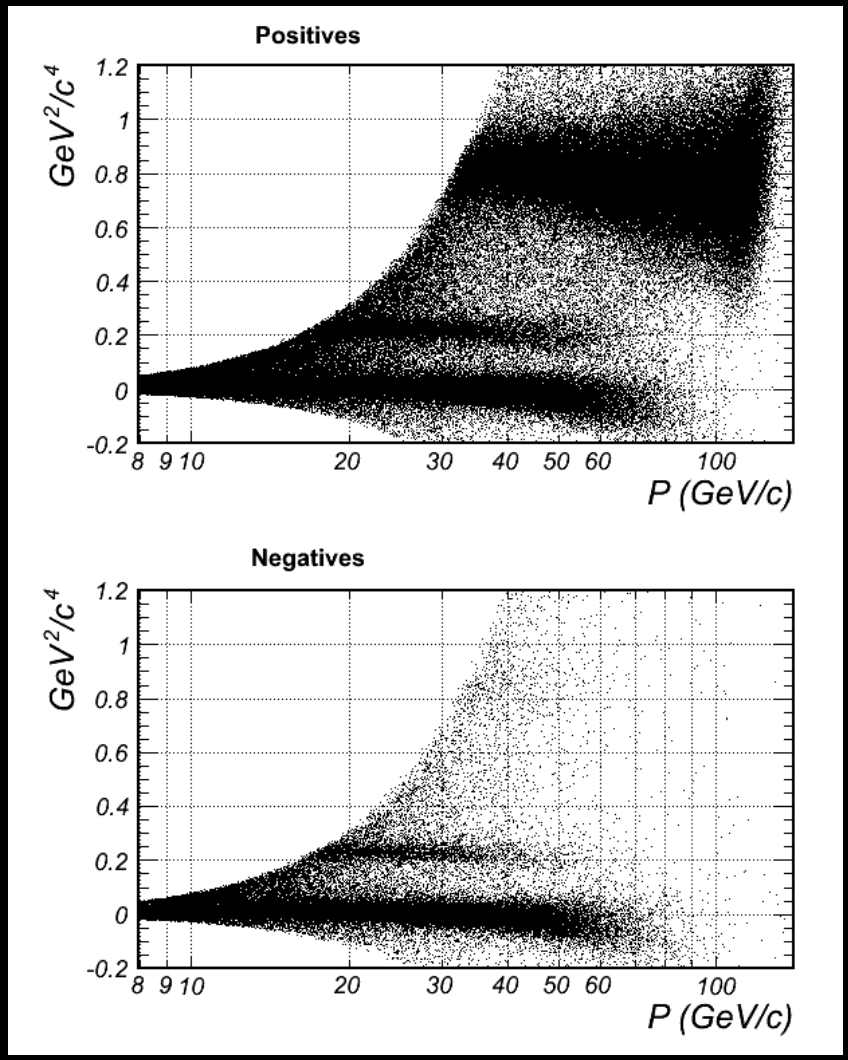
- Factors on bin selections
  - Geometric acceptance of RICH PMTs
  - RICH kaon threshold
  - Statistics
- 20 GeV/c is well above 17 GeV/c kaon threshold
- Make rectangular (p_z, p_T) bins, avoid regions with <50% acceptance
- Use FLUKA-06 π^+ flux to set bin sizes





Particle ID Variable

- RICH ring radii are converted to mass squared
- Mass squared depends on particle p_z and p_T
  - Not observed in MC
- Define particle ID variable
  - $0 \equiv \pi$, $1 \equiv p$, puts K=0.265
- Stretch and shift mass squared distributions in each (p_z, p_T) bin in data and MC

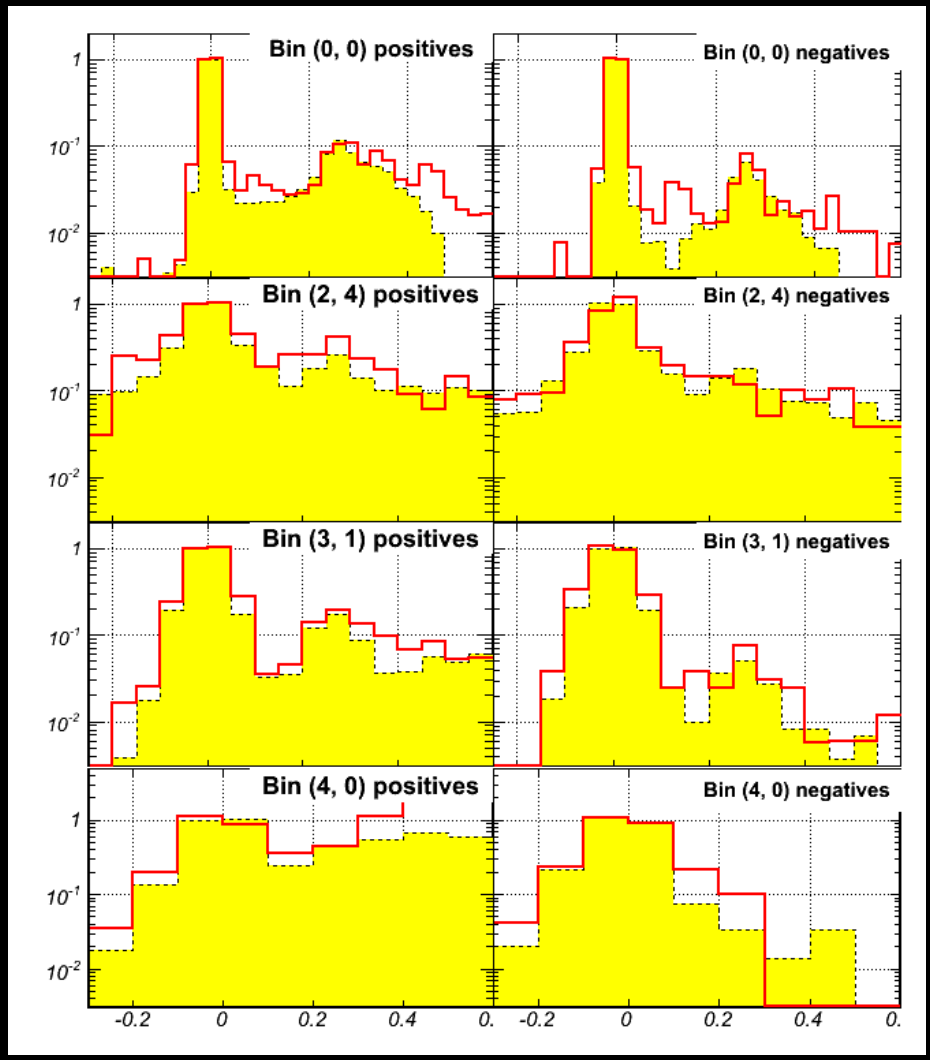


Need For Background Modeling

- Important effects
  - Interactions in the spectrometer
    - ~10% of particles interact before the RICH
    - ~10% more interact if they do not pass through the RICH window
  - Decay in flight
    - 10% of 20 GeV/c kaons decay before the RICH
  - Large angle multiple scattering
    - >100 GeV/c protons can be reconstructed with p<70 GeV/c
- Depend on
  - FLUKA-06 for proton carbon interactions
  - GEANT 3.21 for particle transport

Data – Monte Carlo Comparison

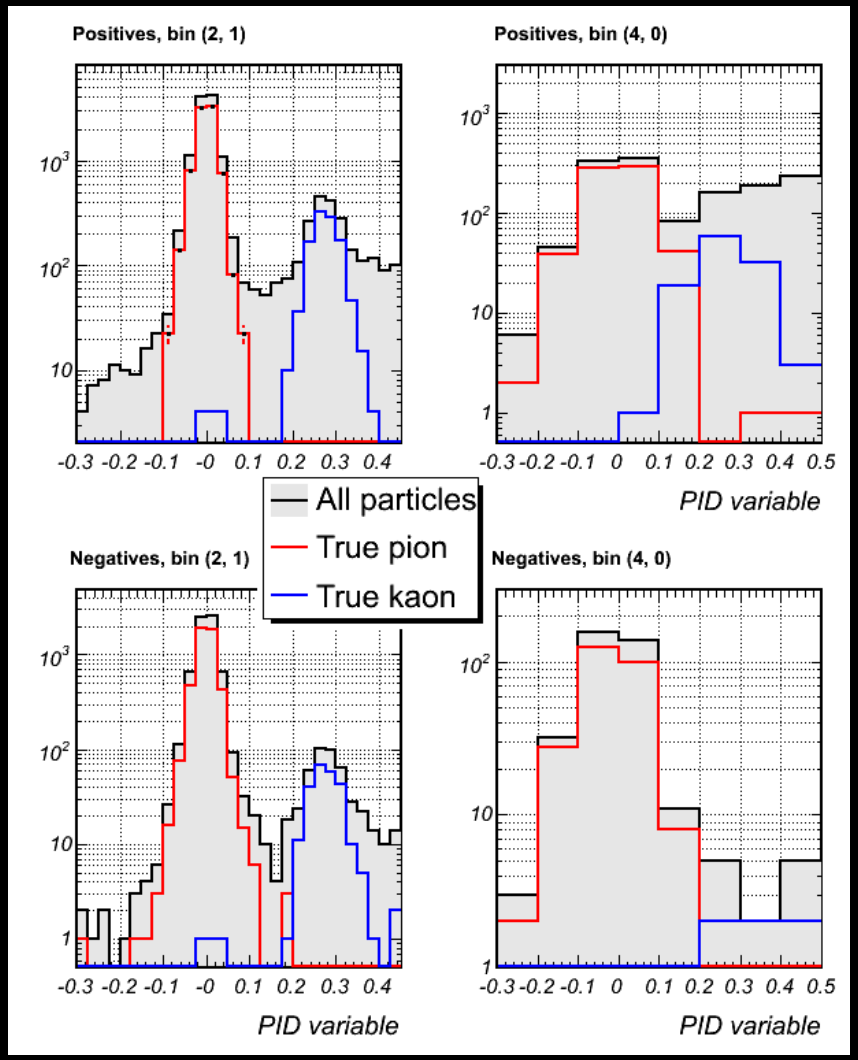
- Particle ID variable distributions in data and MC agree reasonably well
- More background in data
- Data peaks are wider
- High momentum positive bins look differently in data and MC



Data: red line; MC: yellow area

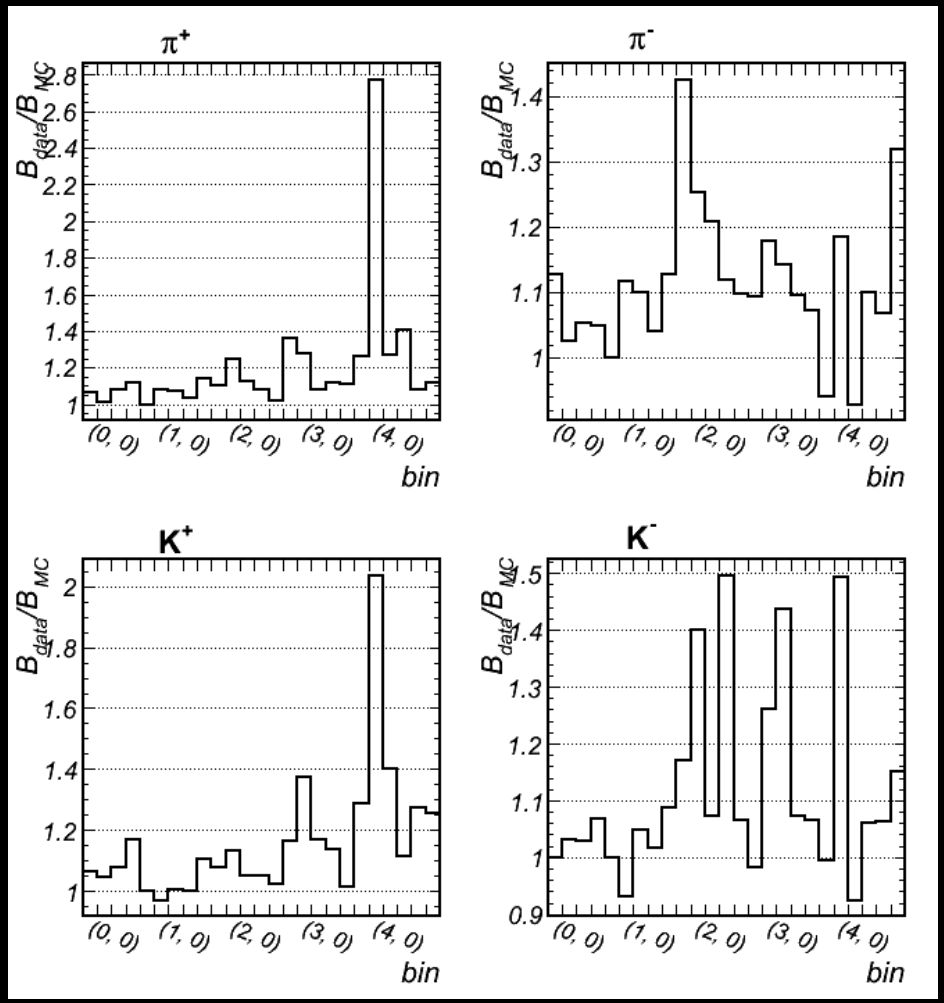
True Particle Occupancy

- Define occupancy *o* as the fraction of true pion/kaon with fit momentum within 4σ of true momentum
  - Ratio of red/blue histogram and shaded histogram
- At lower momenta, the peaks are well separated
- At higher momenta we depend on FLUKA+GEANT



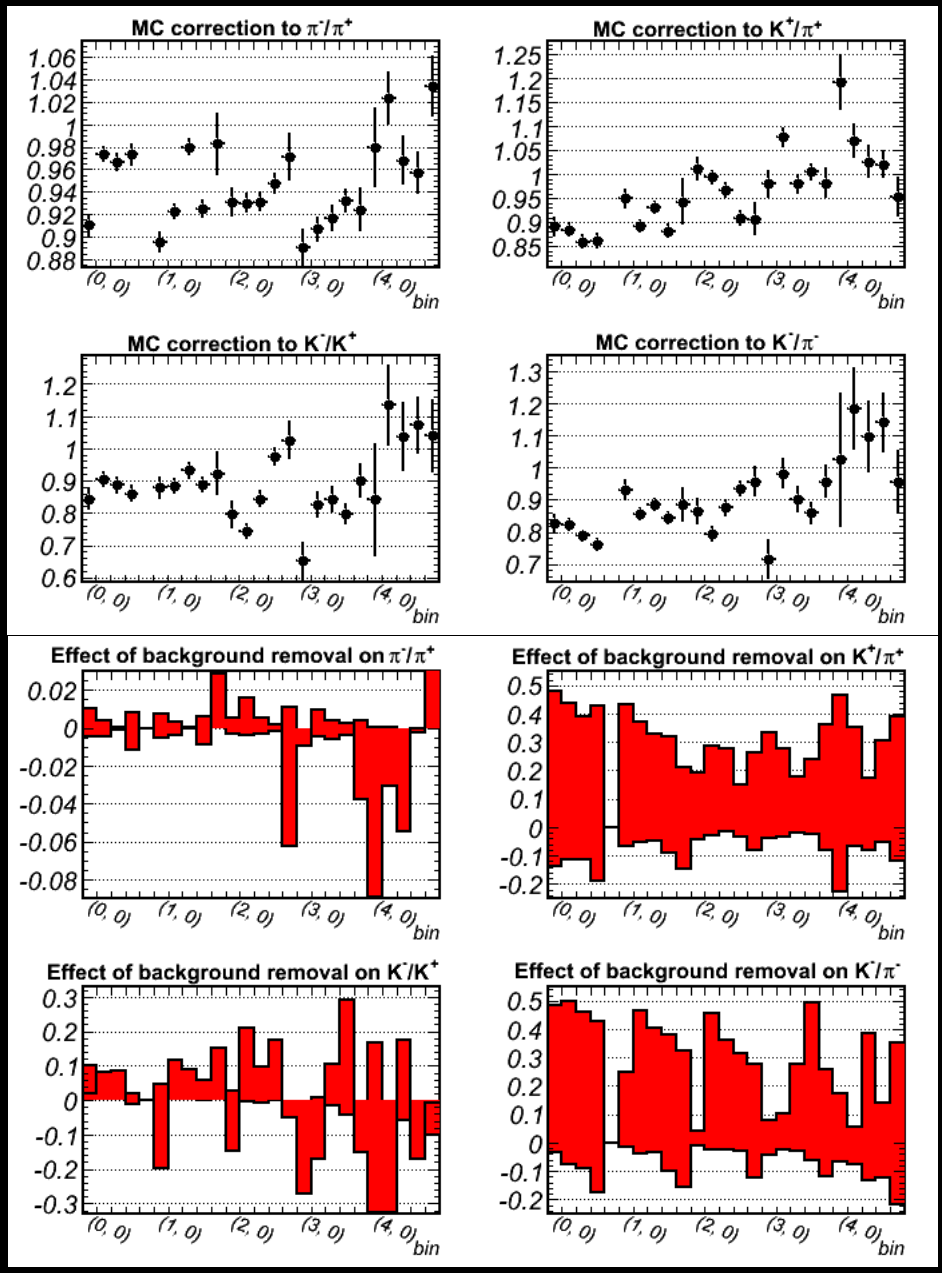
Data vs Monte Carlo Background

- To compare data/MC, compute the ratio of data and MC background
- Average of the ratio over all bins is 1.1
- Systematic error due to background removal
  - Scale (1-*o*) by at least 1.1 or by the ratio from the data/MC background comparison



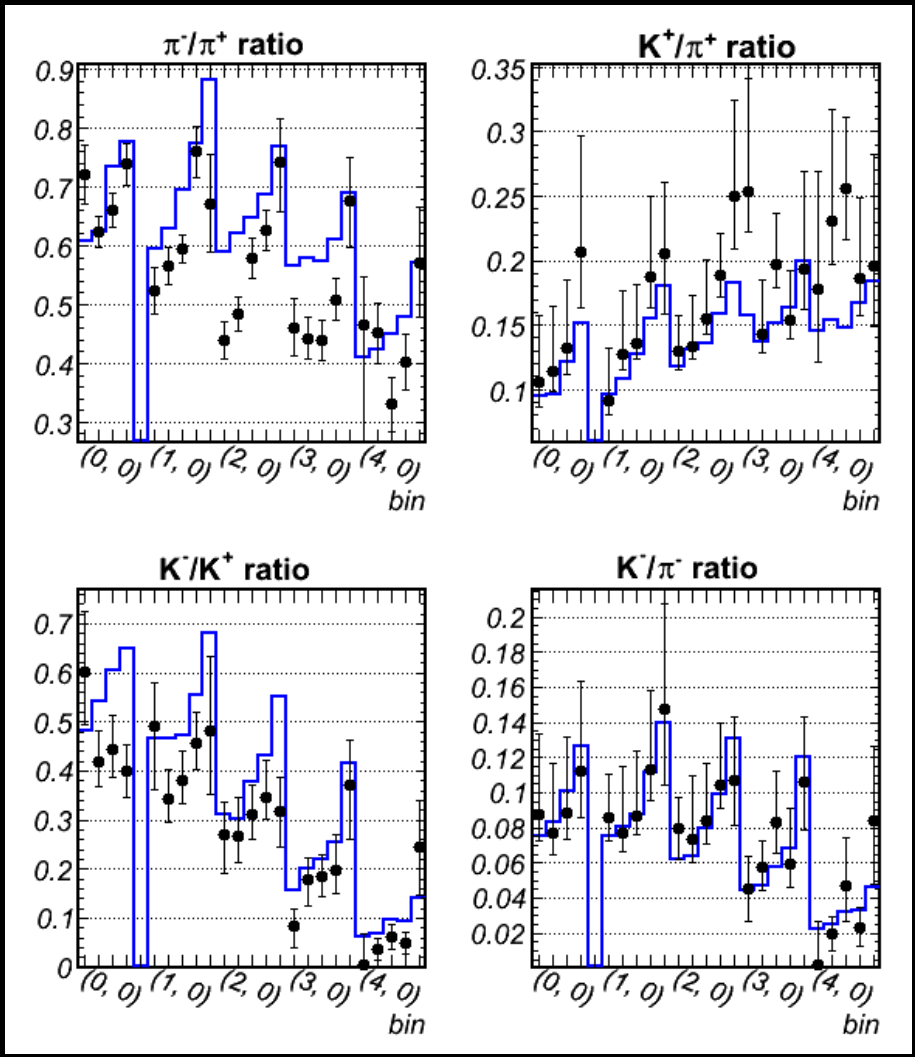
Monte Carlo Corrections and Error

- Assume 50% uncertainty on MC correction
  - Corrections are motivated by physics, but are not very well understood yet
- Error due to background modeling measured with data
- Errors are asymmetric where background is large



Results

Measurement vs FLUKA-06

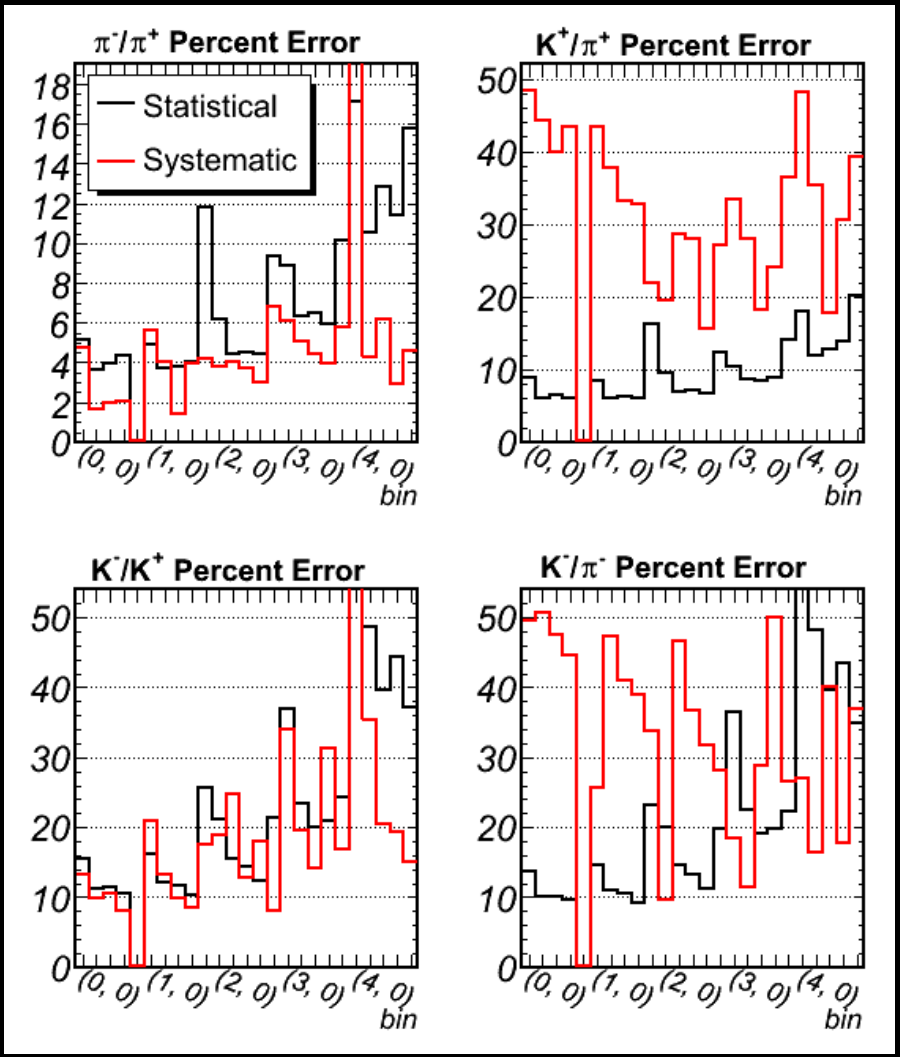


- The measurement agrees with FLUKA in π/K ratios quite well
- Predicted π^-/π^+ and K^-/K^+ ratios are different by up to 50%

Bin mapping in (p_z, p_T) space

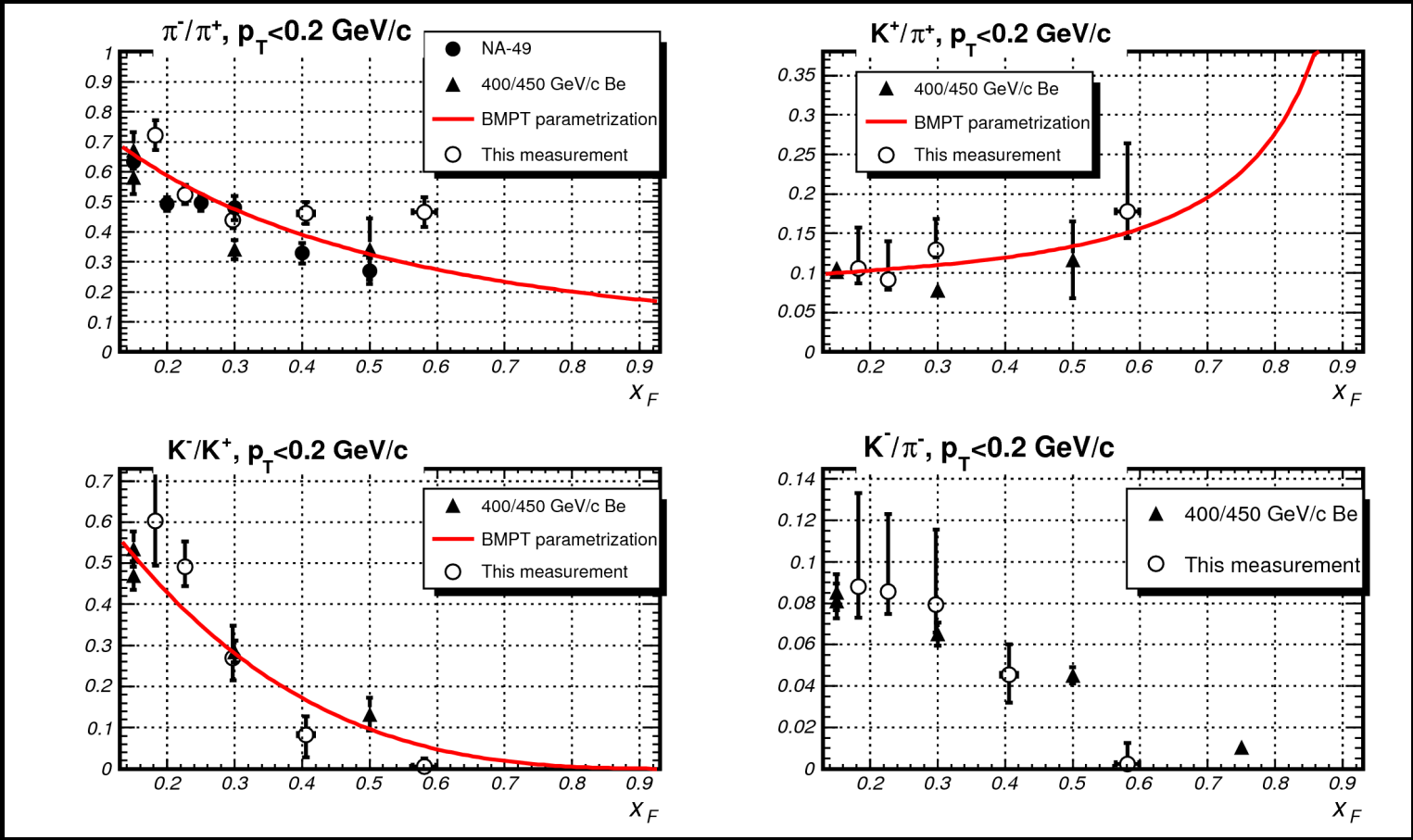
p_T (GeV/c)	p_z (GeV/c) 20-24	24-31	31-42	42-60	60-90
0-0.2	(0,0)	(1,0)	(2,0)	(3,0)	(4,0)
0.2-0.4	(0,1)	(1,1)	(2,1)	(3,1)	(4,1)
0.4-0.6	(0,2)	(1,2)	(2,2)	(3,2)	(4,2)
0.6-1	(0,3)	(1,3)	(2,3)	(3,3)	(4,3)
>1		(1,4)	(2,4)	(3,4)	(4,4)

Sources of Error

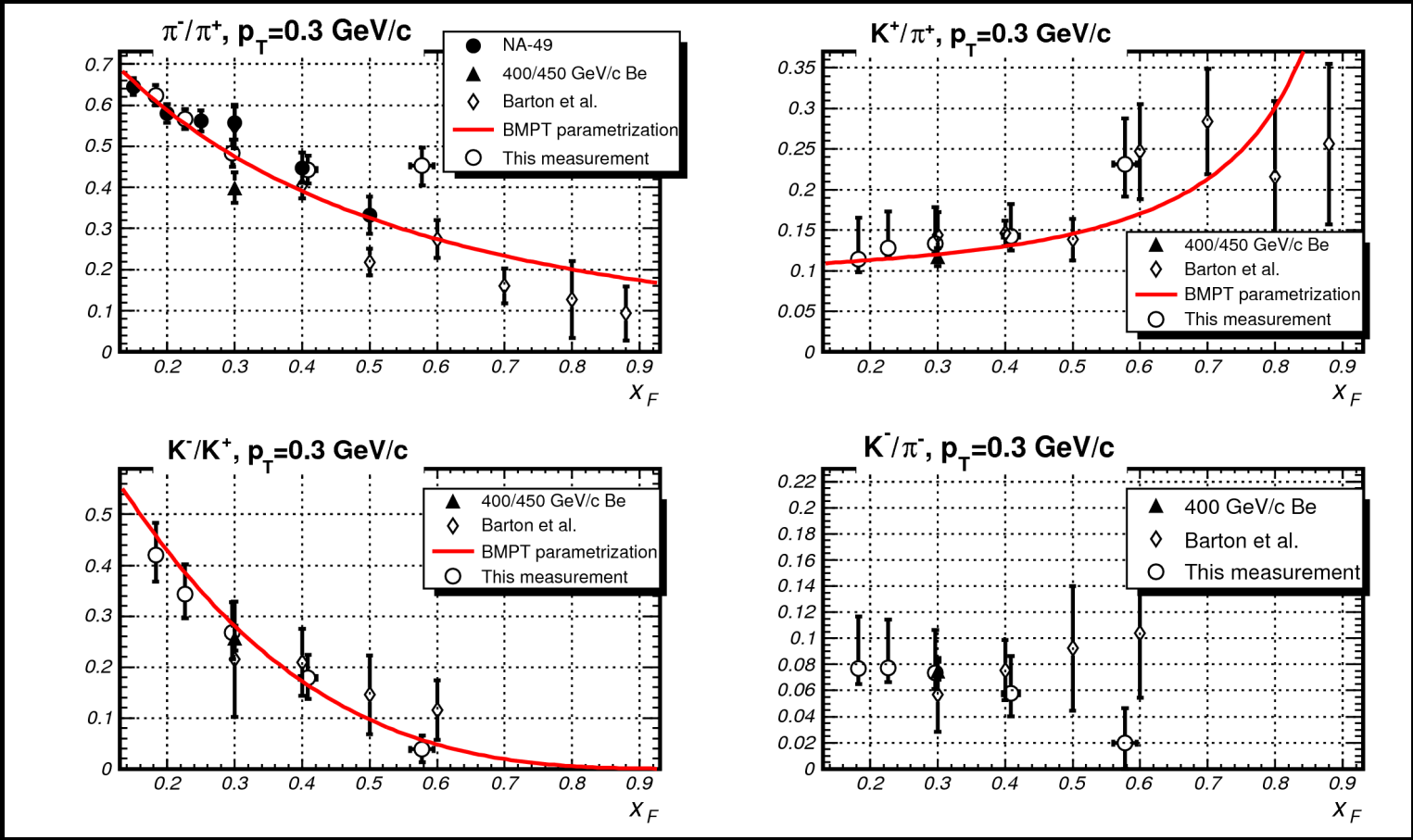


- Statistical errors on π^-/π^+ ratios are already at or below systematic
  - Need better understanding of background in high p_z bins
- Errors on π/K ratios are dominated by understanding of background
  - Can be reduced with better tuned Monte Carlo

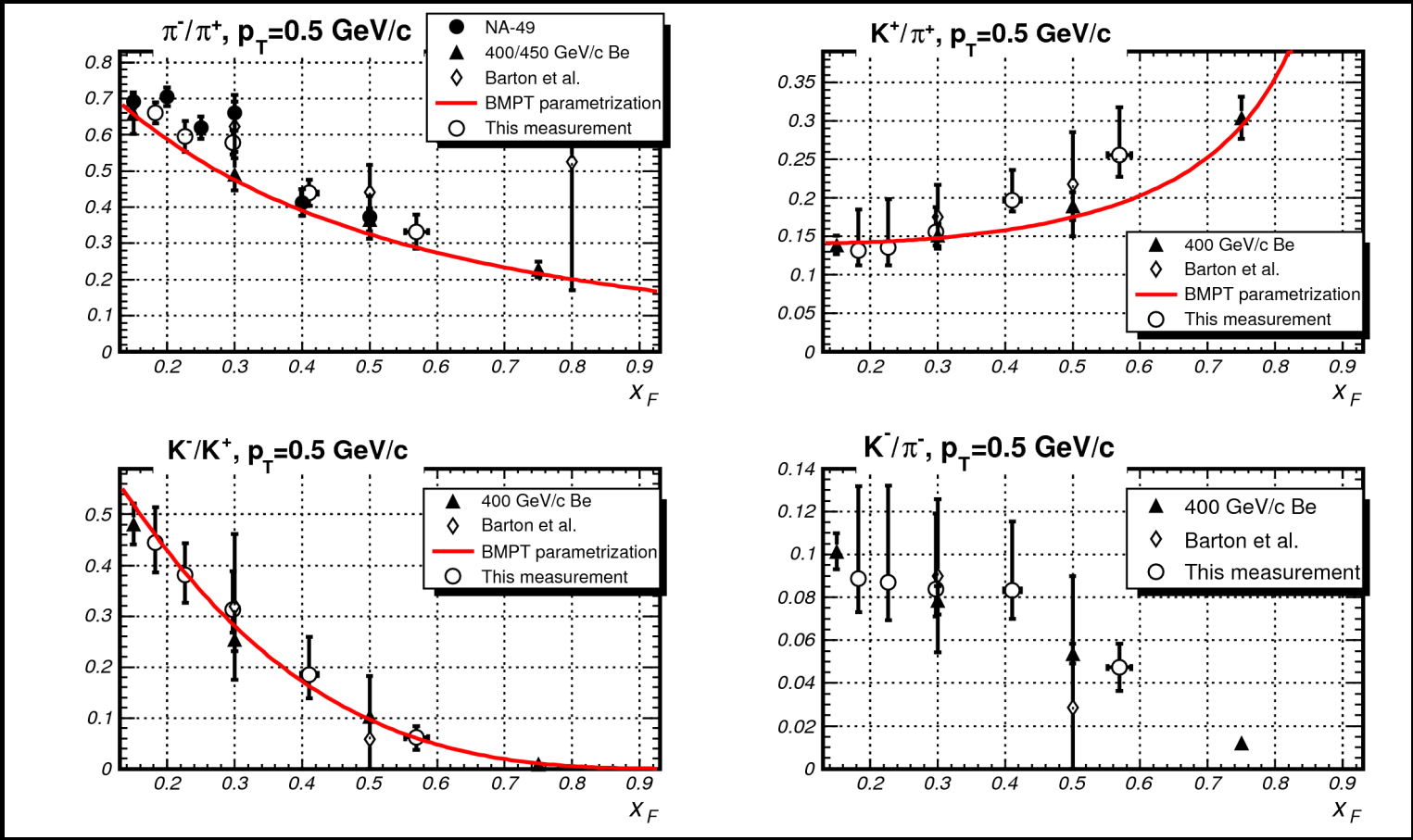
Comparison to Existing Data



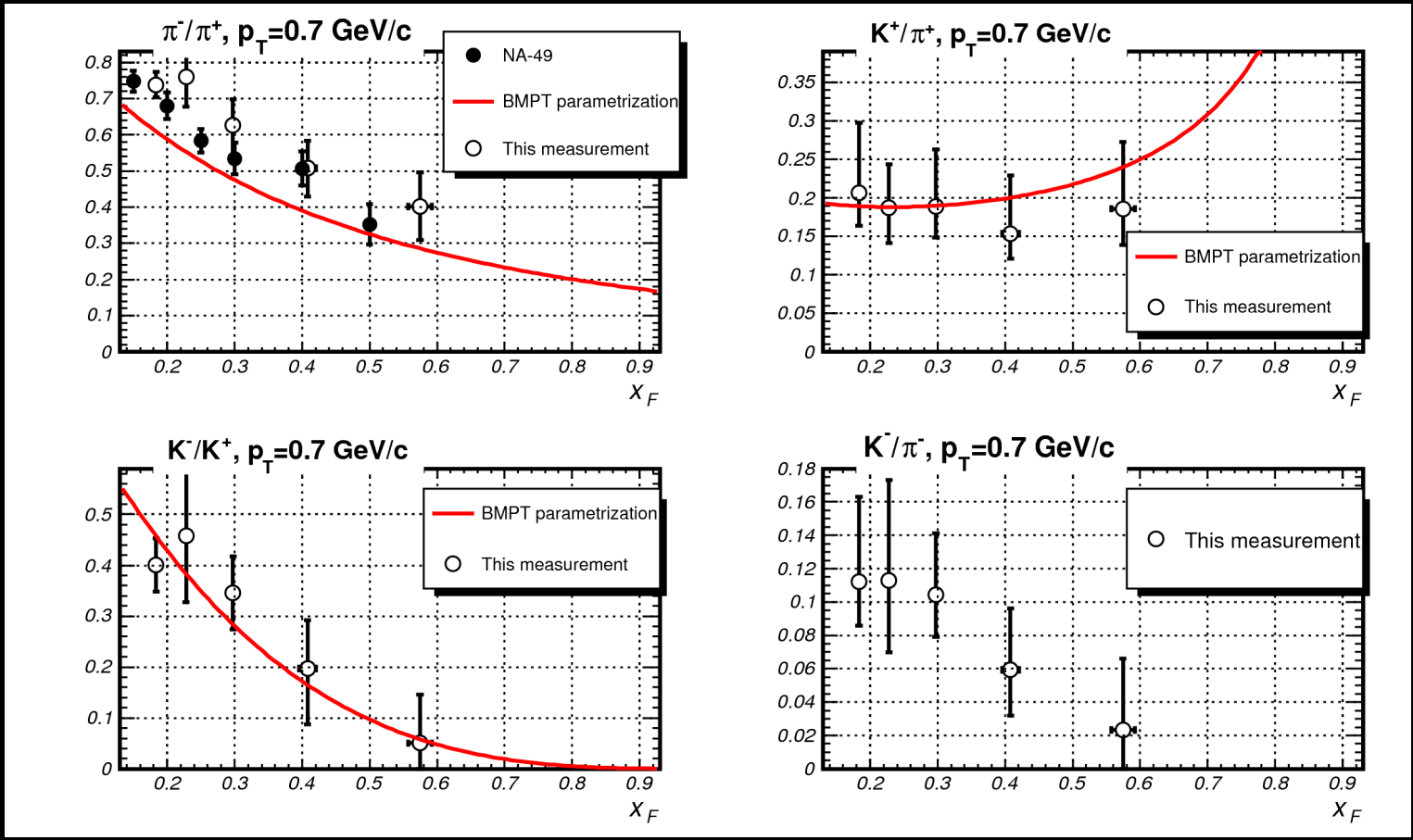
Comparison to Existing Data (cont.)



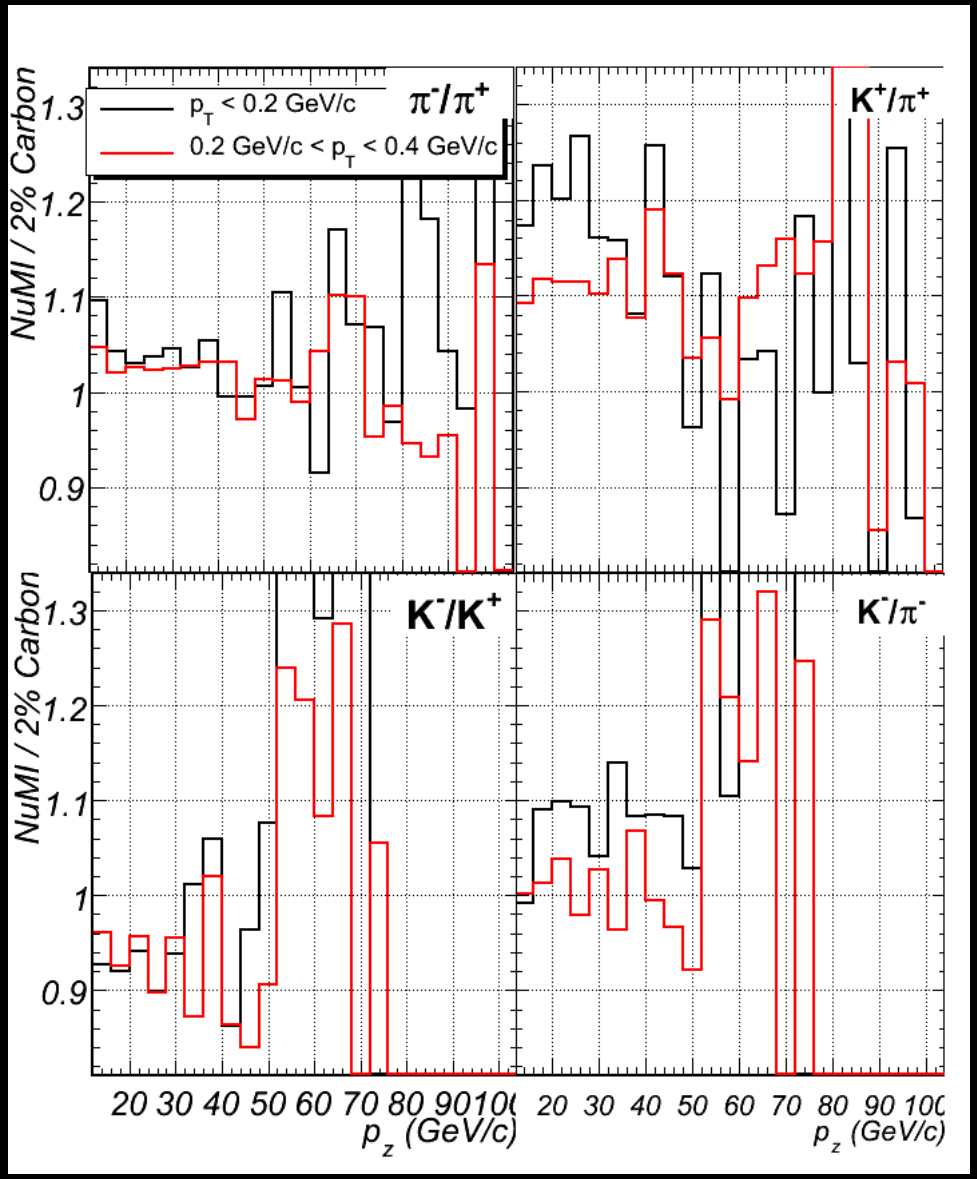
Comparison to Existing Data (cont.)



Comparison to Existing Data (cont.)

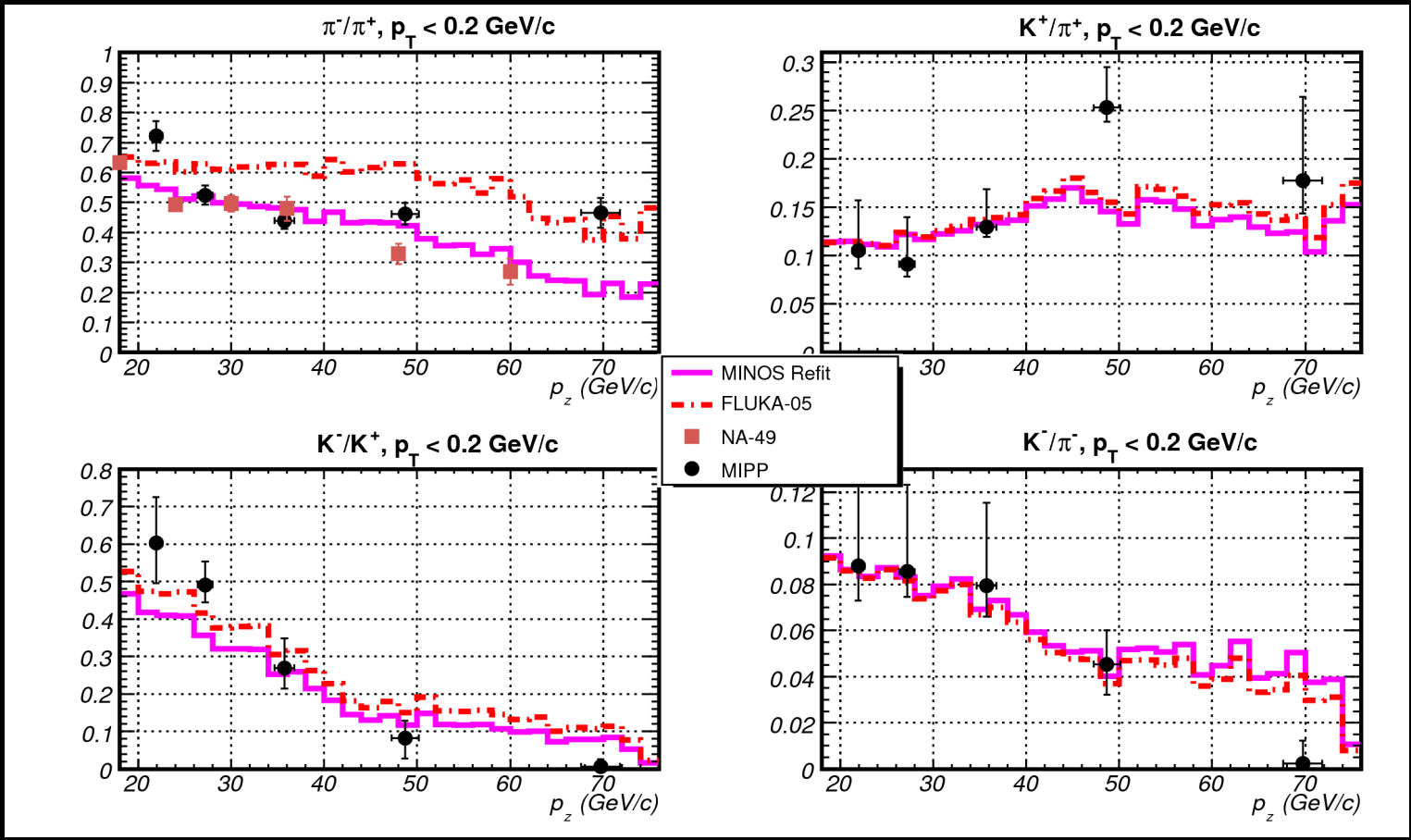


Comparison with NuMI Target Ratios



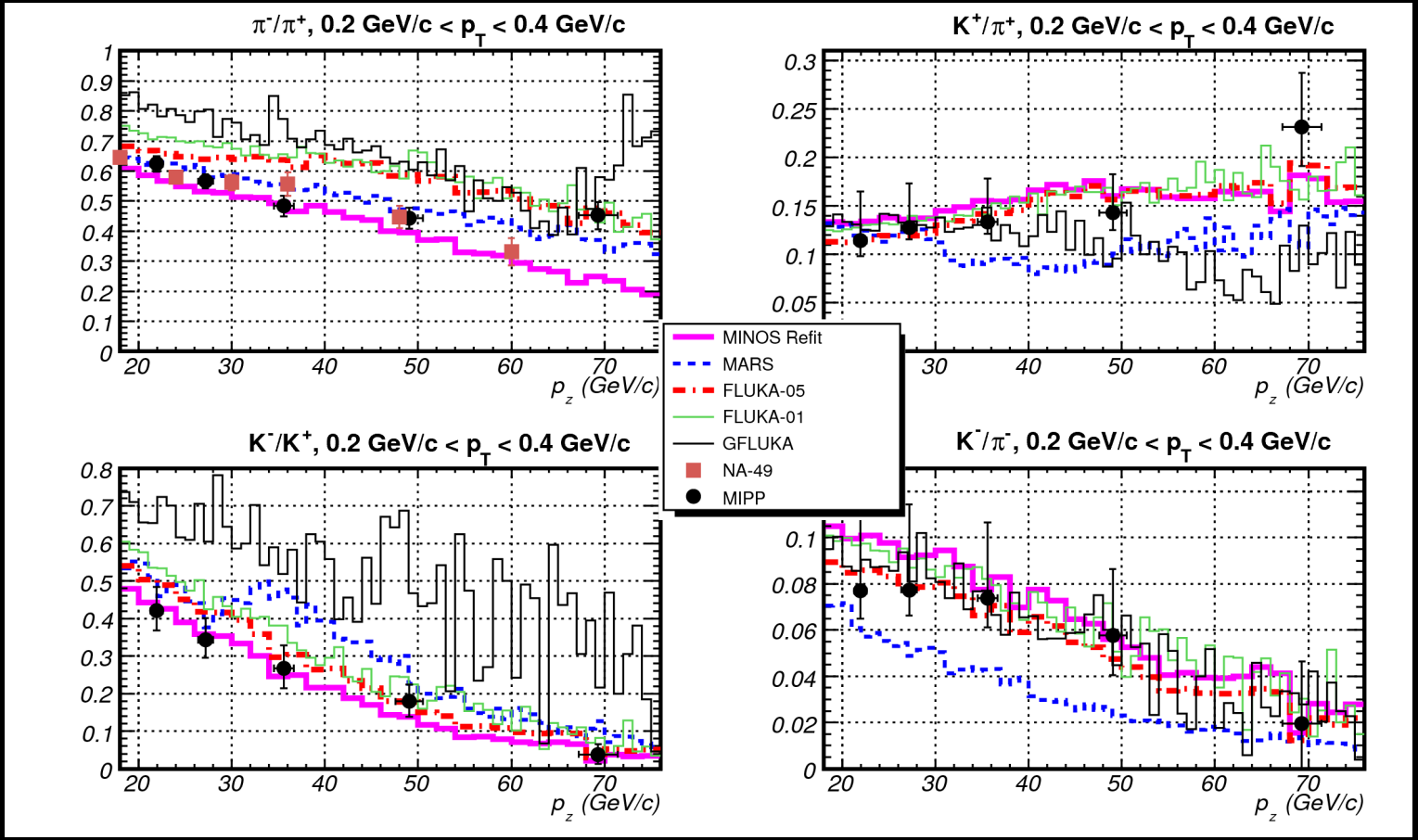
- At high momenta production is dominated by primary interactions, so comparison of ratios from NuMI target is valid
- MINOS beam systematics group fits π/K production spectrum
  - Target position selects hadron p_z
  - Horn currents change hadron p_T

Comparison to Fitted MINOS Ratios



- Prior to this measurement, MINOS found that their fits favor NA49 π^-/π^+ ratio over FLUKA-05

Comparison to Fitted MINOS Ratios



- Good agreement is found between MINOS fits and this measurement
- Higher statistics NuMI target data set is being analyzed

Summary

- The first physics analysis using MIPP data!
- The measurement agrees with the existing data and covers hereto unexplored (p_z, p_T) space of kaon production
- Good cross check of fit results from MINOS beam systematics group
  - NuMI target analysis will further help the group
- Better tuned Monte Carlo simulation and understanding of background are needed to reduce systematic error below statistical