The Main Injector Particle Production Experiment at Fermilab

Physics Motivation and First Results

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Fermilab

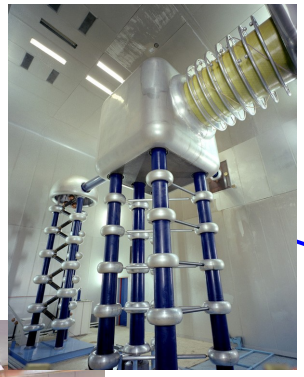
Particle Physics Seminar
Brookhaven National Laboratory
Thursday, 8 May 2008

MIPP

Fermilab Particle Accelerators

MIPP

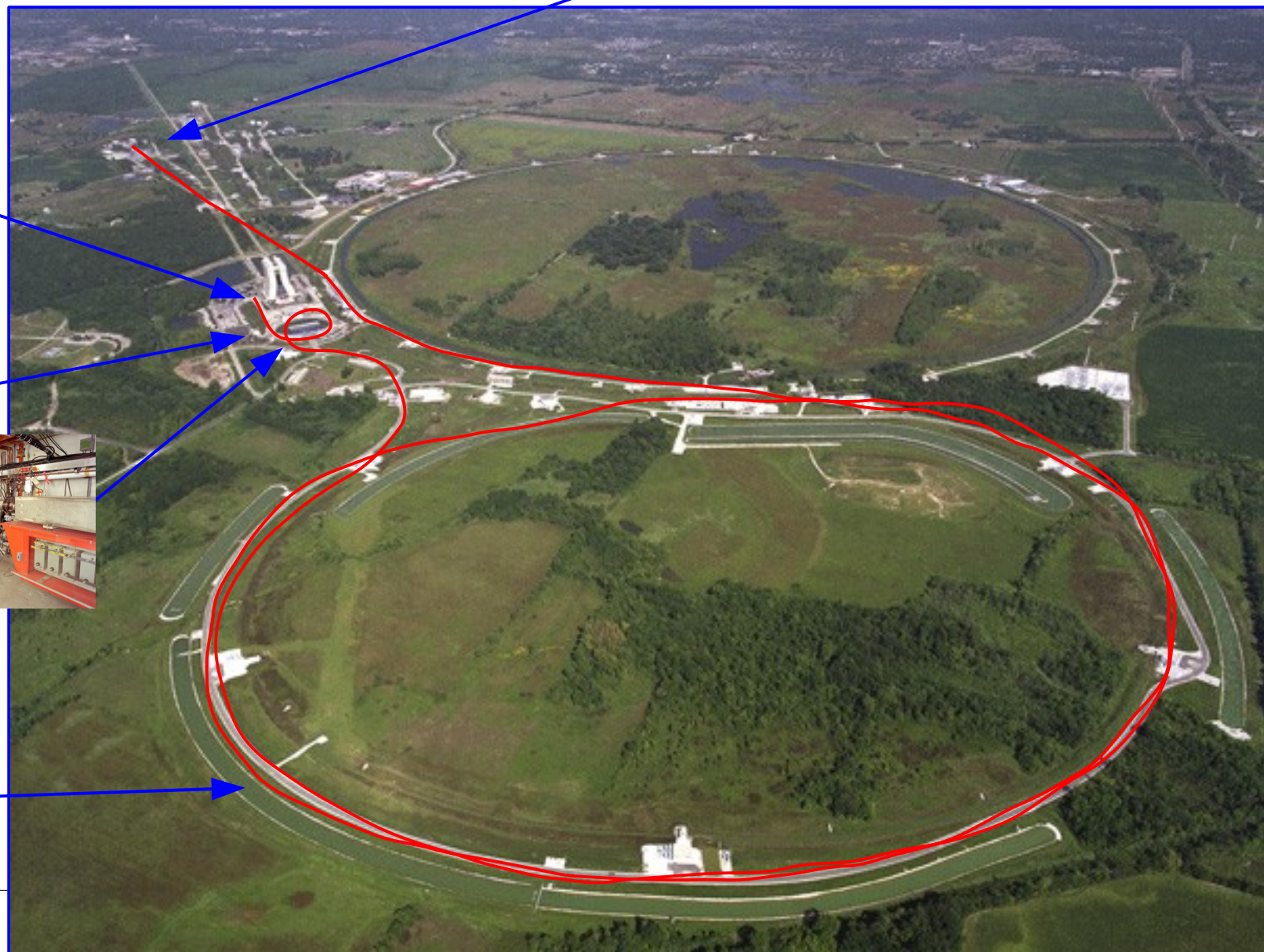
Cockroft-Walton



Linac

Booster

Main Injector



The MIPP Collaboration

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E907 Installation at MC7
Upstream
MC7
JGG
Rosie
Downstream
MC7
5/31/2002

The MIPP Experiment

- **Approved in November 2001, installed in Meson Center MC7,**
  14 months physics run ended in Februrary 2006 – 18 million events
- **Use 120 GeV/c Main Injector protons to produce**
  – secondary beams of $\pi^{\pm}$, $K^{\pm}$, and $p^{\pm}$ from 5 GeV/c to 90 GeV/c
  – 120 GeV/c proton beam

6 beam species

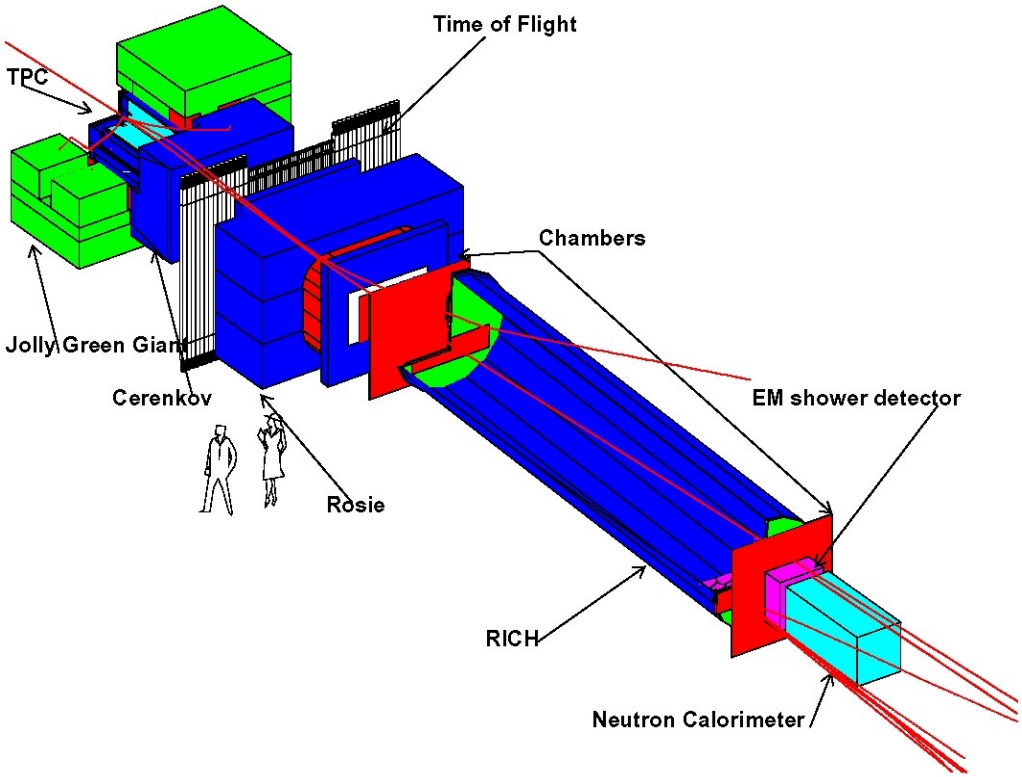
Large range of energies

- **Measure particle production cross sections on fixed targets**
  – various nuclei including hydrogen and the NuMI target

Many targets

- **Momenta of ~all charged particles measured with TPC and tracking chambers.**
  Particle identification with dE/dx, ToF, differential Cherenkov, and RICH technologies.
- **Open Geometry – Lower systematics & Higher statistics than existing data – what Bubble chamber experiments in 70's and 80's wanted to, but could not do.**
- **A proposal FNAL-P960 to upgrade MIPP is under consideration**

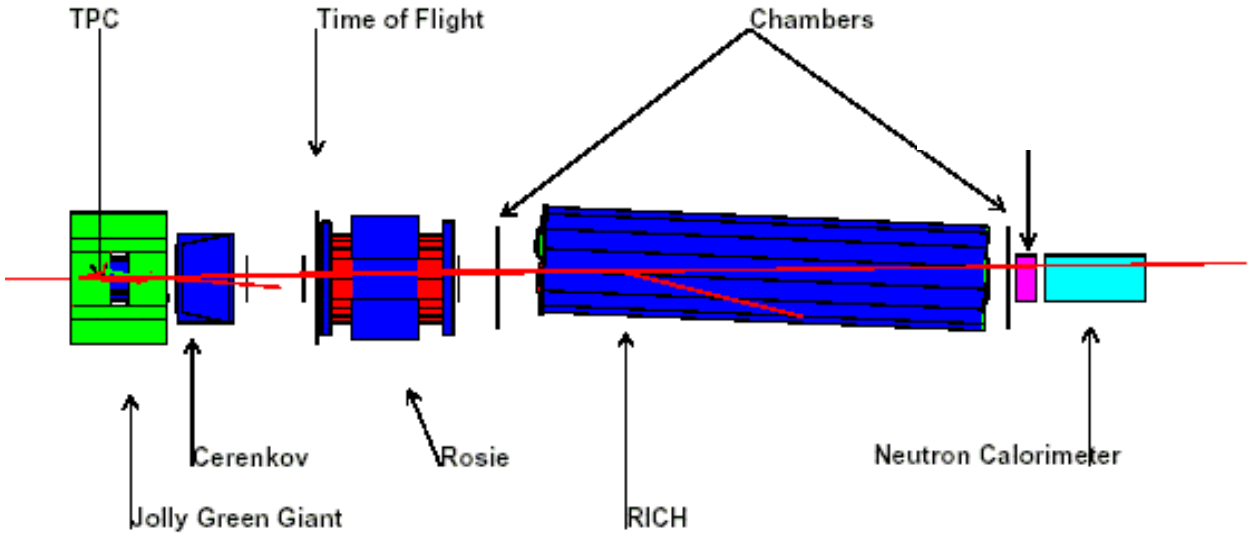
The MIPP Detector



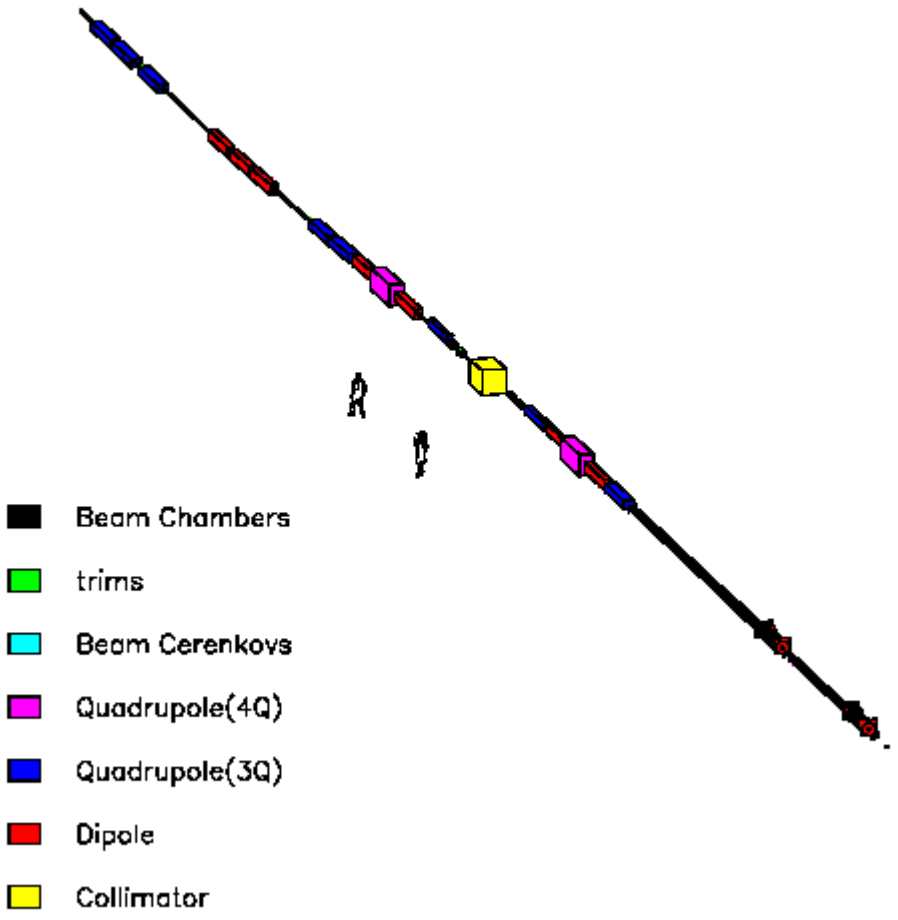
MIPP

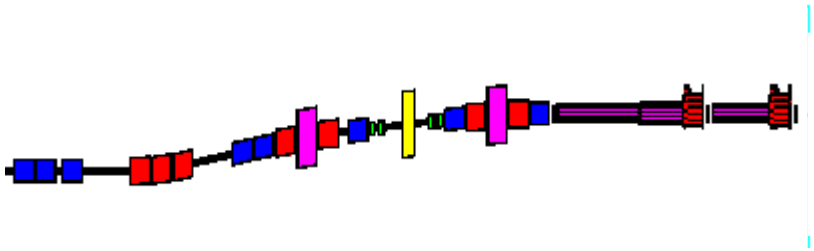
Main Injector Particle Production Experiment

Vertical cut plane



The MIPP Beam





- Excellent performance.
- Ran it successfully in MIPP from 5-85 GeV/c secondaries and 120 GeV/c primary protons.
- Excellent particle ID capabilities using 2 Beam Cherenkovs. For low momenta (<~10 GeV/c) ToF is also used for pid.
- Design principles and lessons learned used in M-test upgrade at Fermilab.

MIPP Physics - Overview

- Particle Physics – To acquire unbiased high statistics data with complete particle id coverage for hadron interactions.
  - Study non-perturbative QCD hadron dynamics, scaling laws of particle fragmentation
  - Investigate light meson spectroscopy, missing baryon resonances
  - Charged Kaon mass measurement
- Nuclear Physics
  - Investigate strangeness production in nuclei
  - Nuclear y-scaling
  - Propagation of flavor through nuclei
- Service Measurements
  - Improve shower models in MARS, Geant4 and Calorimetry (e.g. for ILC)
  - Proton Radiography – Stockpile Stewardship- National Security
  - MINOS target – pion production measurements to control the near/far systematics

Theory of strong interaction - QCD

- We do not know how to calculate a single cross section in non-perturbative QCD! This is >99% of the total QCD cross section.
  - Perturbative QCD has made impressive progress. But it relies on structure functions for its calculations, which are non-perturbative and derived from data.
- Feynman scaling, KNO scaling, rapidity plateaus are all violated. We cannot predict elastic cross sections, diffractive cross sections, let alone inclusive or semi-inclusive processes. Regge “theory” is in fact a phenomenology whose predictions are flexible and can be easily altered by adding more trajectories.
- QCD theorist states- We have a theory of the strong interaction and it is quantum chromodynamics.
  Experimentalist asks– what does QCD predict? One finds that we can only use the theory where the strong interaction becomes weak!
- We have declared this physics as “uninteresting” for ~ 30 years and hence our problems with systematics in every experiment where the strong interaction is either the signal or the background.
- To make progress we need high quality data to test new theories and find patterns in the cross sections.

Hadronic shower simulation

- Programs like Geant4, MARS, Fluka, etc. model hadronic interactions based on available data.
  - No first principles, QCD does not give answers
  - Most existing data are old, low statistics, with poor particle id, sometimes contractory
- All neutrino flux problems (NuMI, MiniBoone, K2K, T2K, Nova, Minerva), all Calorimeter design problems, and all Jet energy scale systematics (not including jet definition ambiguities here) can be reduced to one problem: the current state of hadronic shower simulators.
- MIPP has high statistics, low systematics data with 6 beam species on IH2
  - Missing neutral channels available from constrained kinematic fit
- A library of MIPP events can be used in the simulation packages.

General scaling law of particle fragmentation

- States that the ratio of a semi-inclusive cross section to an inclusive cross section is a function of the missing mass only:

$$\frac{\sigma\left(a+b\rightarrow c+X_{subset}\right)}{\sigma\left(a+b\rightarrow c+X\right)}\equiv\frac{\sigma_{subset}\left(M^2,s,t\right)}{\sigma\left(M^2,s,t\right)}=\beta_{subset}\left(M^2\right)$$

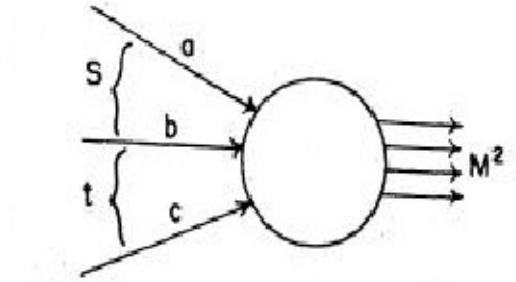
  - where M^2, s, and t are the Mandelstam variables for the missing mass squared, CMS energy squared and the momentum transfer squared between the particles a and c. PRD18(1978)204.

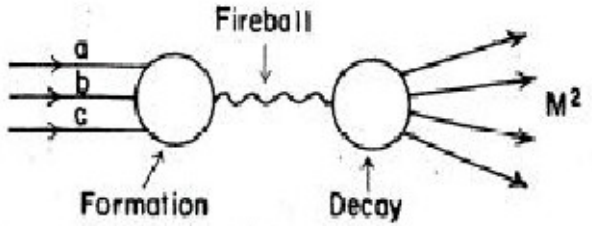
- EHS data confirms this scaling in 12 reactions, but only at fixed s
  - Y. Fisyak, R. Raja, Proceedings of DPF1992
- MIPP data on LH_2 will test this in 36 reactions as a function of both s and t for various particle types a, b, and c.

Scaling law (continued)

- Scaling Law follows naturally if the reaction factorizes into a two step process:
  - Formation of a pseudo-resonance
  - Decay into final state

$$\frac{\sigma\left(a+b+c\to X_{subset}\right)}{\sigma\left(a+b+c\to X\right)}\equiv\frac{F\left(M^2,s,t\right)D_{subset}\left(M^2\right)}{F\left(M^2,s,t\right)D\left(M^2\right)}=\beta_{subset}\left(M^2\right)$$





- Fast equilibrium after scattering

- Reactions related by symmetry relations should have same scaling behavior:
  - 15 crossing symmetry and 3 charge symmetry relations can be tested with the 36 reactions in MIPP
  - For example: $\pi^+p\to\pi^+X$ and $\pi^-p\to\pi^-X$ should have same $\beta(M^2)$ for all subsets of X
  - Or $p^-p\to\pi^+X$ and $\pi^-p\to pX$
    Central production diffractive

Other physics interests

- Nuclear y-scaling
  - Verified in ep scattering and with low energy hadron beams (KEK E352)

$$\frac{d\sigma}{d\Omega\, dE} = \sigma_{beam\,N} F(y)$$

  - Probe transition from quasielastic scattering to DIS
  - Extract cross sections inside the nuclear medium, compare to cross sections in vacuum
- Missing Baryon resonanaces
  - Partial wave analyses of πN scattering have yielded some of the most reliable information of masses, total widths and πN branching fractions. In order to determine couplings to other channels, it is necessary to study in elastics such as

$$\pi^- p \to \eta n; \pi^- p \to \pi^+ \pi^- n; \pi^- p \to K^0 \Lambda$$

  - All of the known baryon resonances can be described by quark-diquark states. Quark models predict a much richer spectrum. Where are the missing resonances? F.Wilczek, A. Selem
  - "..this could form the quantitative foundation for an effective theory of hadrons based on flux tubes"– F.Wilczek

Charged Kaon mass in MIPP

- RICH ring radius of tagged π, K, p beam particles measures K mass relative to well know masses of π, p.
  - Measure K^+ and K^- mass (test CPT)
  - With higher statistics this could resolve the disagreement between existing measurements, see PDG.
    - Important for determination of V_{US} in the CKM mixing matrix

The main disagreement is between the two most recent and precise results,

$$m_{K^\pm} = 493.696 \pm 0.007 \text{ MeV} \quad \text{DENISOV 91}$$

$$m_{K^\pm} = 493.636 \pm 0.011 \text{ MeV (S = 1.5)} \quad \text{GALL 88}$$

$$\text{Average} = 493.679 \pm 0.006 \text{ MeV}$$

$$\chi^2 = 21.2 \text{ for 1 D.F., Prob. } = 0.0004\% , \quad (3)$$

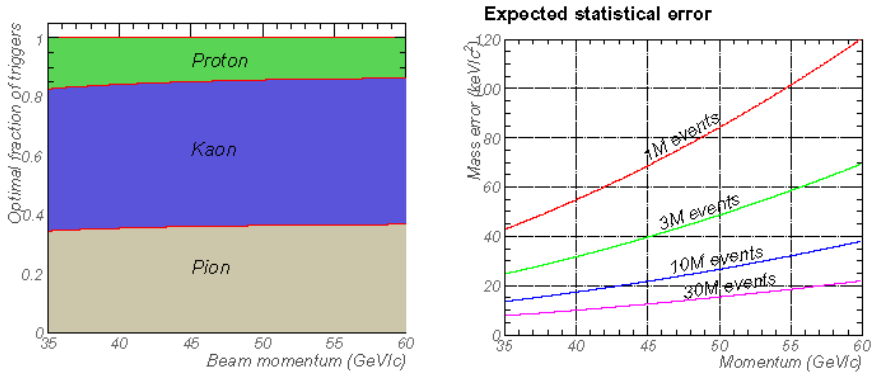


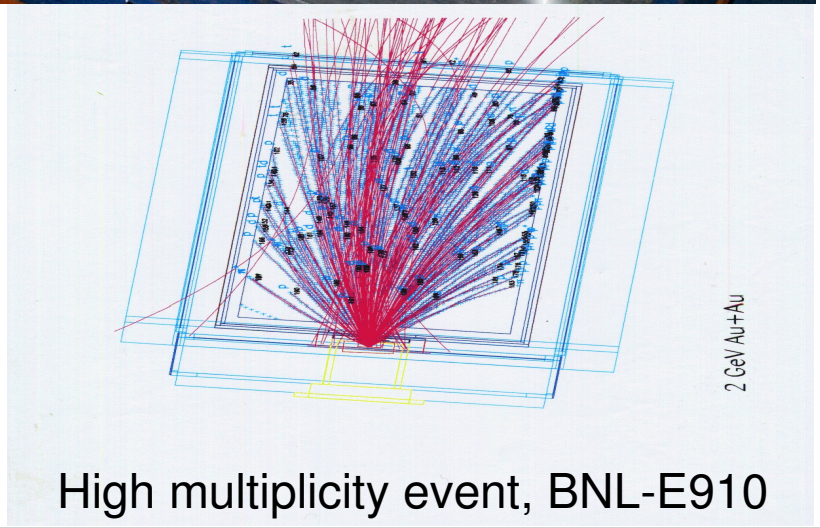
Figure 1: Optimal fraction of pion, kaon, and proton triggers (left), and expected statistical error for different total number of triggers, assuming optimal distribution of events in the sample (right).

Data taken for Kaon mass

Momentum	Magnets	Number of beam spills	Number of events
-60	Off	3203	2701458
37.5	Off	1114	1687073
40	Off	2146	2884920
42.5	Off	618	911701
56	On	460	497633
59	Off	2017	2735482
59	On	673	738983

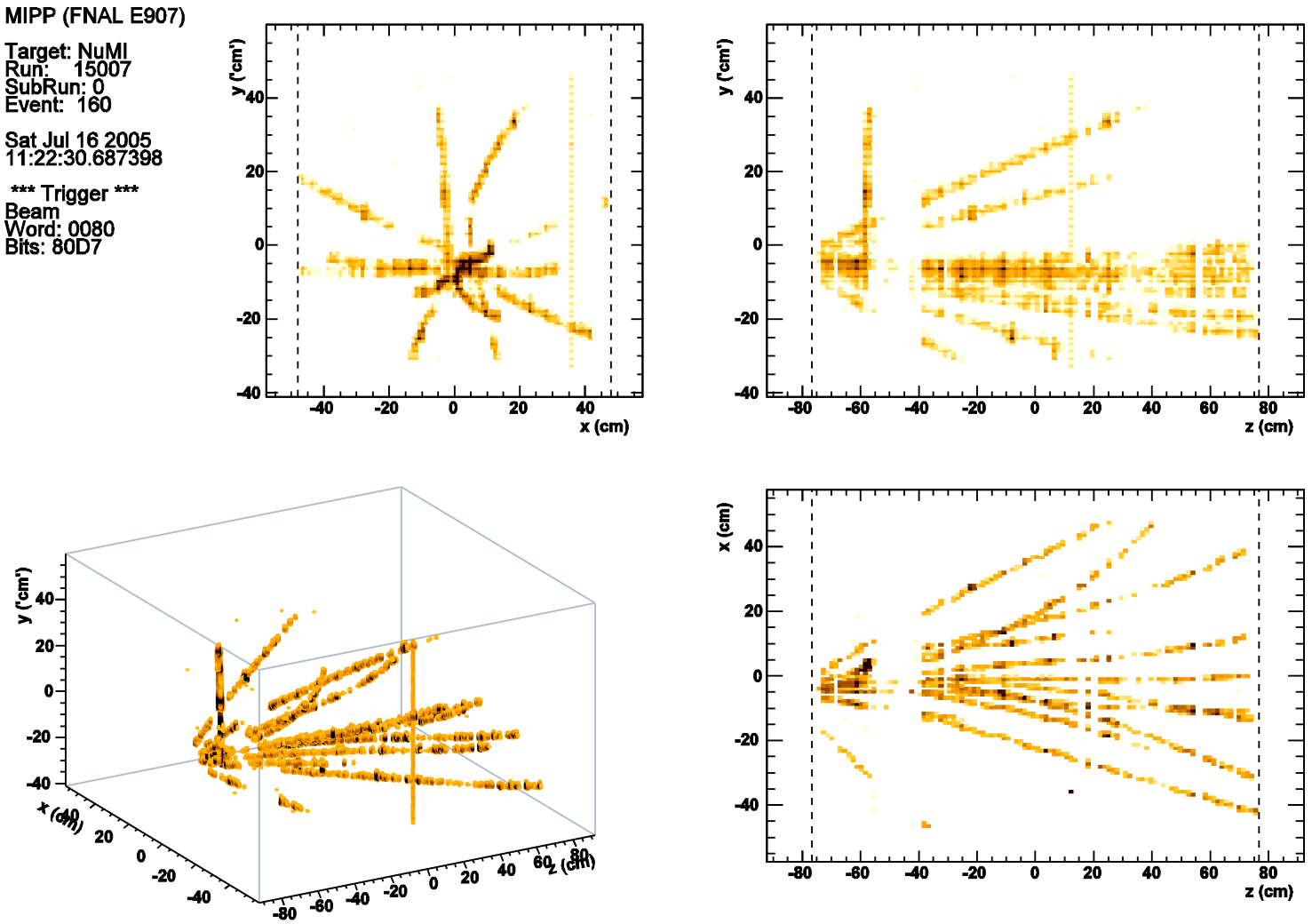
MIPP TPC

- Time Projection Chamber, previously used at the Bevalac and BNL-E910
  - Particle tracks ionize P10 gas (10% Methane in Argon), electrons drift in 10kV electric field
    - The amount of ionization per path length, dE/dx, depends on the particle type
  - 120×128 readout pads of 8×12 mm^2 area on bottom give position in x and z
  - Drift time measurement gives y coordinate at each point along the track
  - Track curvature in 0.7 T magnetic field of the JGG gives particle momentum

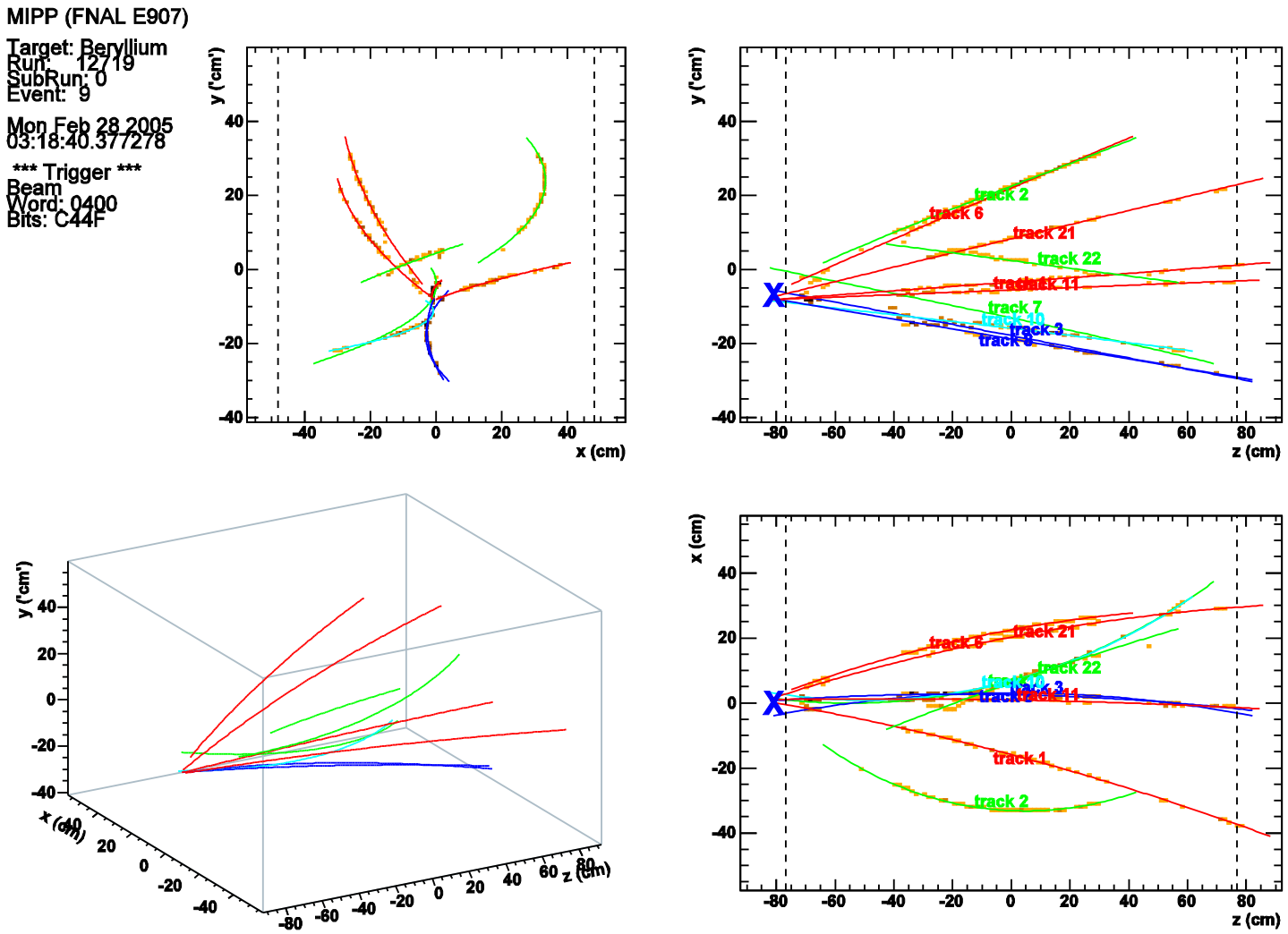


High multiplicity event, BNL-E910

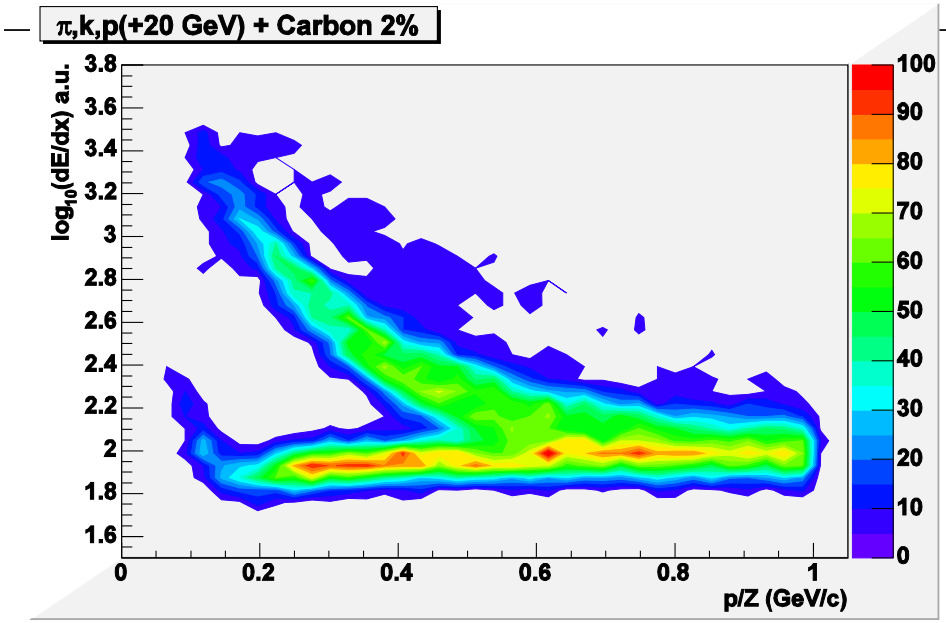
MIPP TPC – Raw data

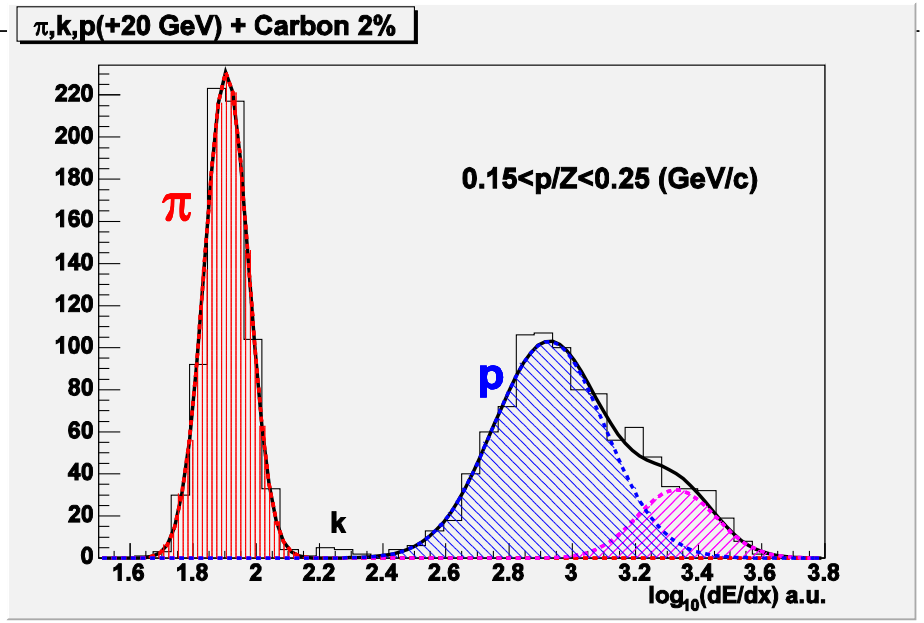


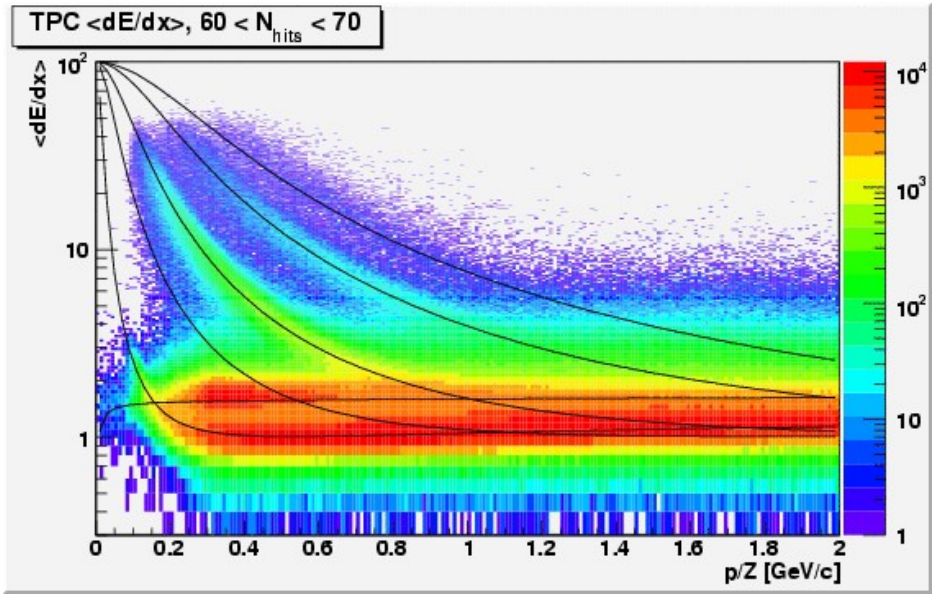
MIPP TPC – Reconstructed tracks

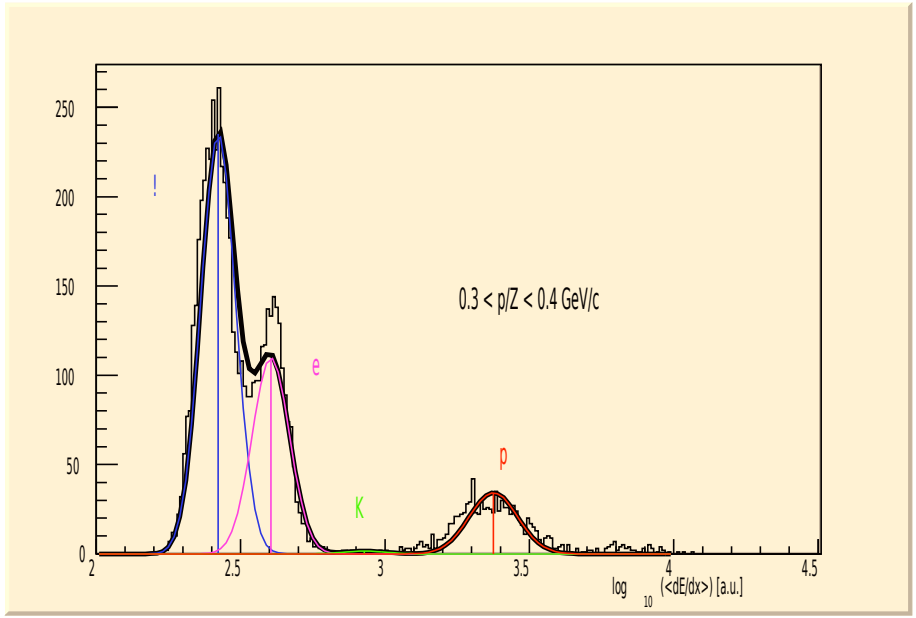


dE/dx in the TPC



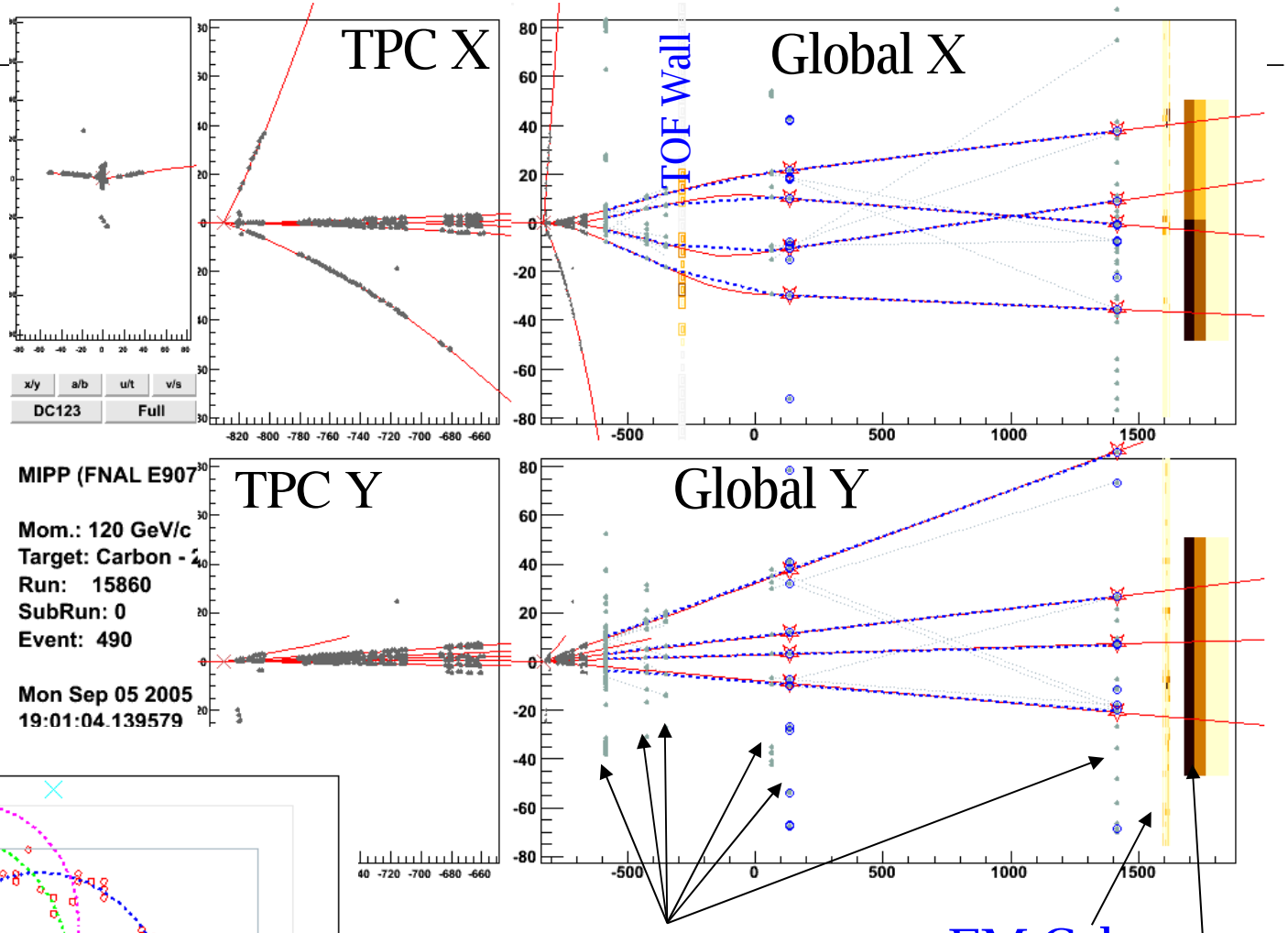


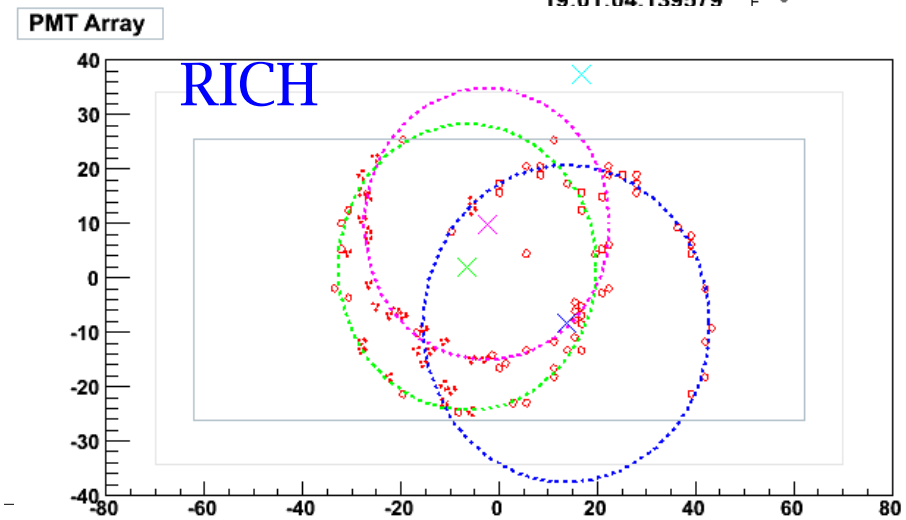




Reconstructed p-C 120GeV/c event

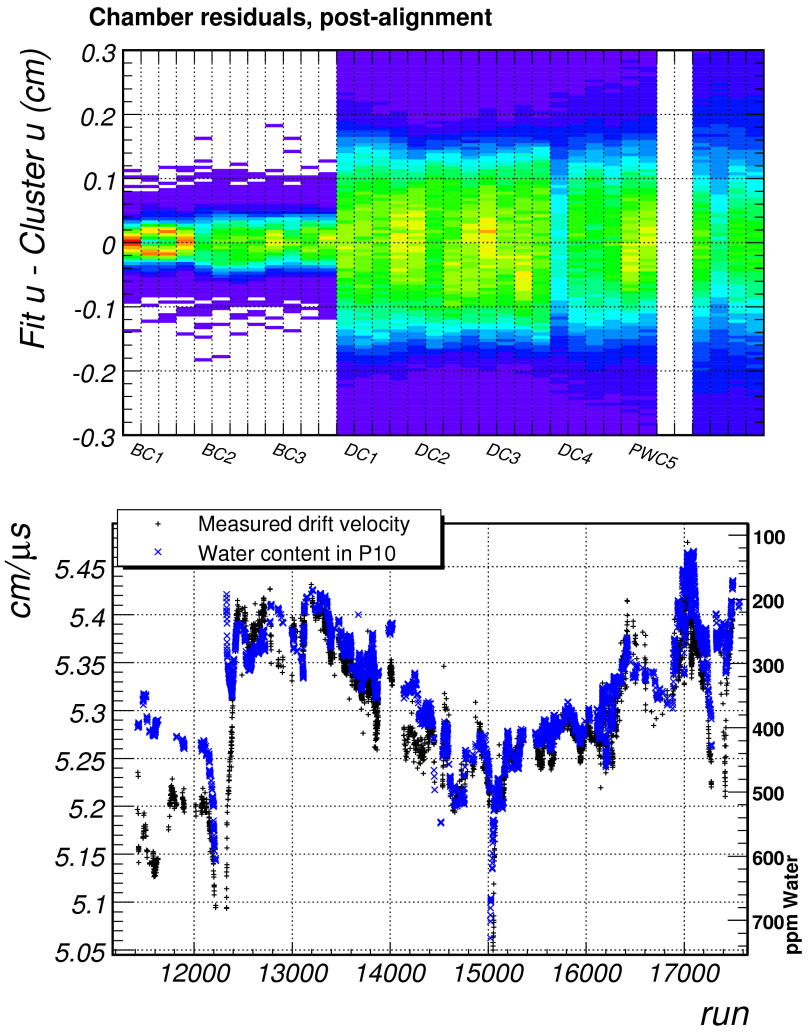
Tracking and
RICH displays





Spectrometer Calibration

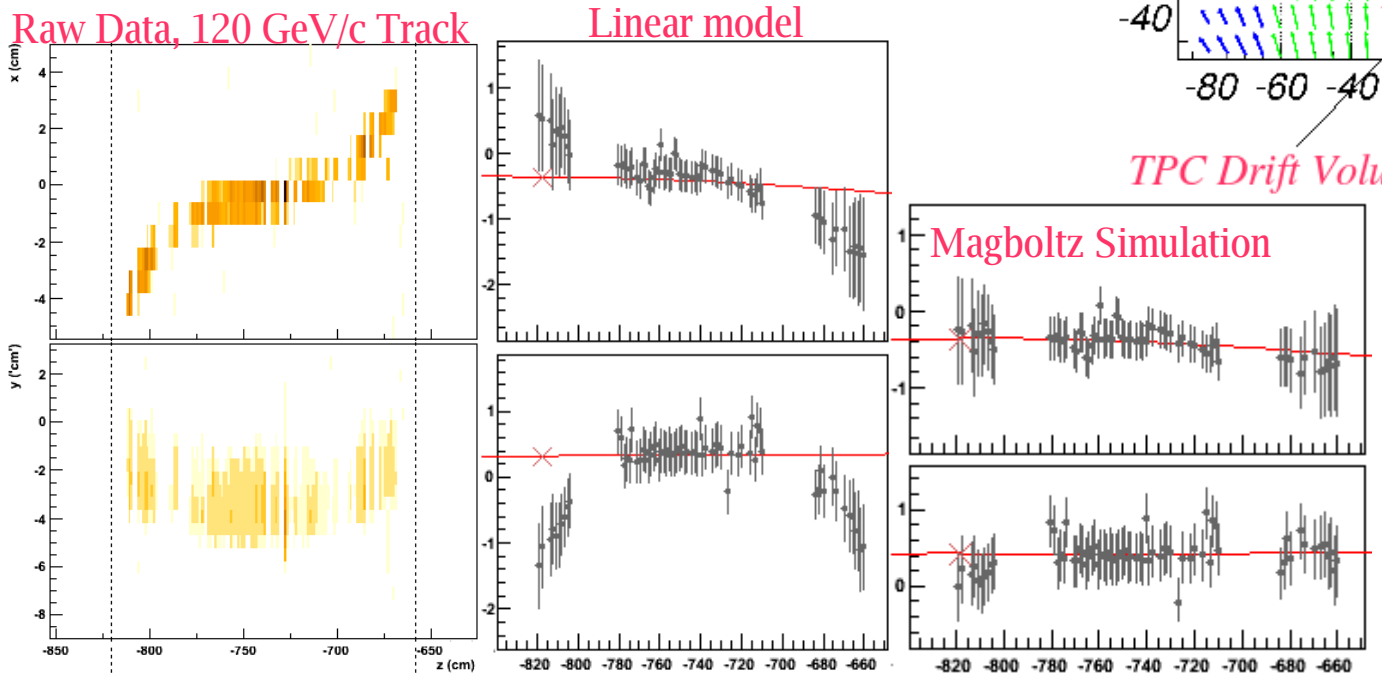
- Chamber alignment done for every run
  - Helped to find bugs in geometry description and refine magnetic field maps
- TPC electron drift velocity measured for every run
  - Strong correlation with water vapor contamination in Ar/CH_4

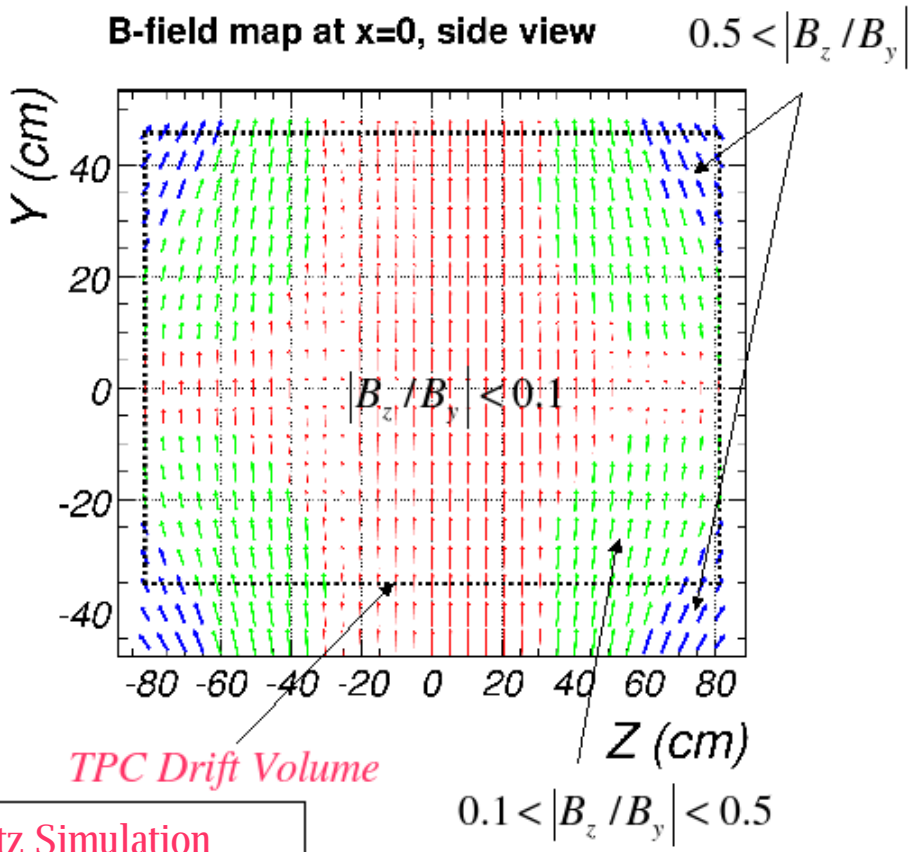


TPC Hit Reconstruction

- JGG field is non-uniform
  - Huge ExB effect on electron drift in TPC
- Previous experiments applied corrections based on steady state solution to linear model

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



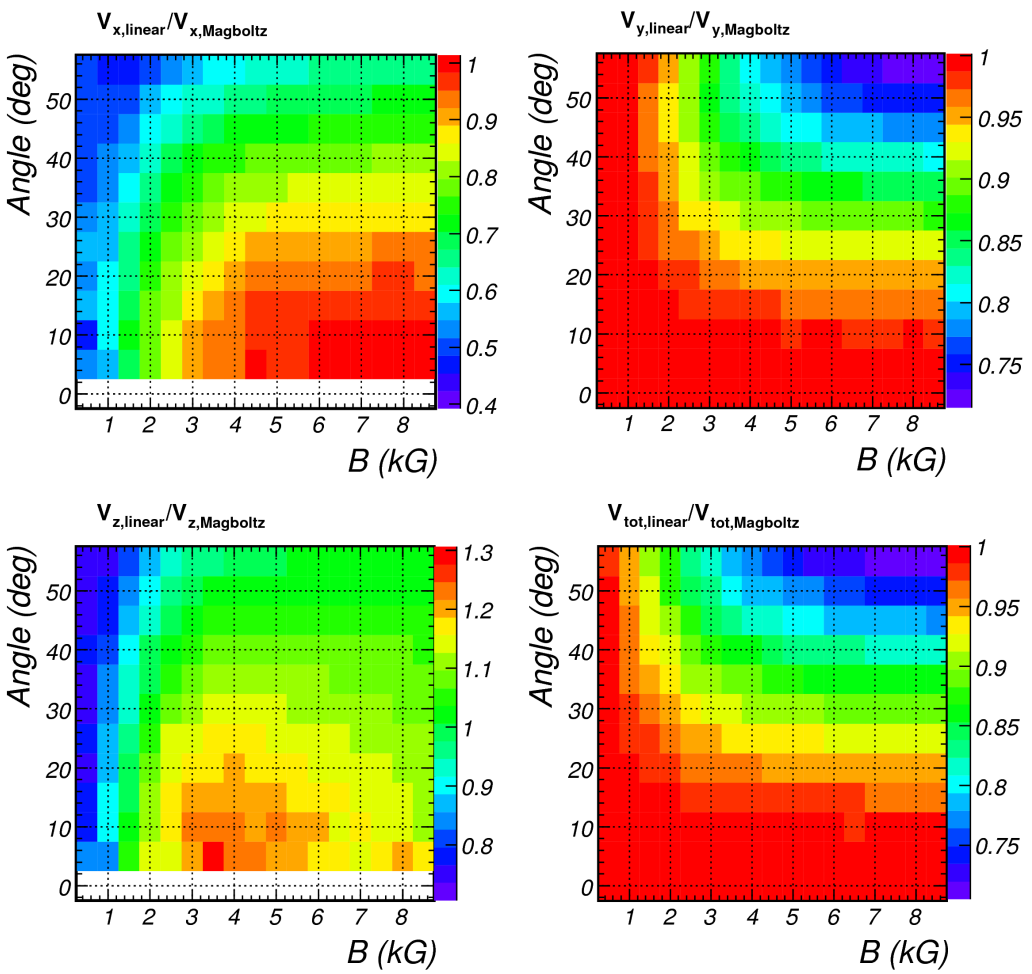


Magboltz simulation to map out drift velocity components as a function of v_0, B-field strength, and angle between E and B-fields.

Good agreement with TPC data.

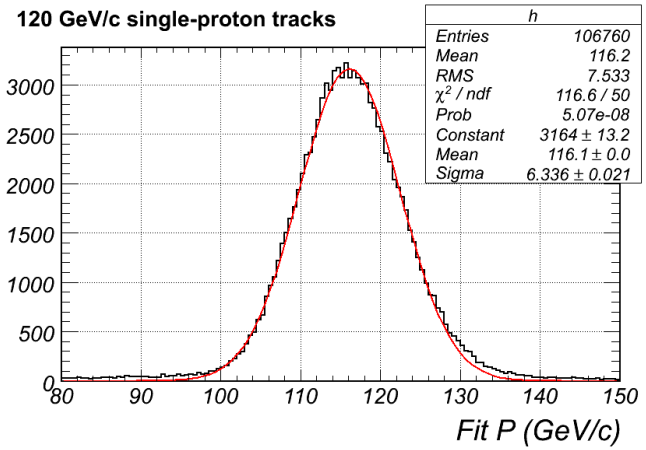
Linear Drift Model vs. Magboltz

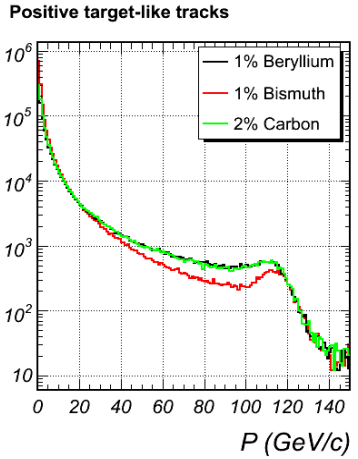
- Magboltz (by Stephen Biagi, http://consult.cern.ch/writeup/magboltz/) solves the Boltzmann transport equations for electrons in gas mixtures under the influence of electric and magnetic fields.
- Magnetic field inside the TPC varies from 3.5 to 8 kG
- The angle between E and B fields goes up to 50 degrees
- Difference in drift velocity components reaches 30%

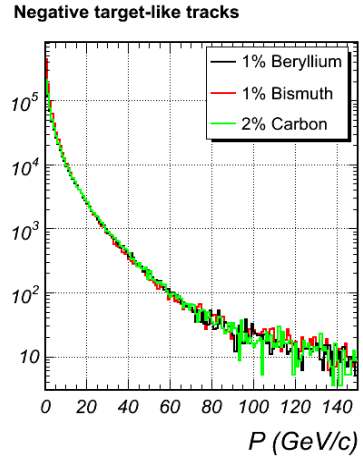


Track Reconstruction

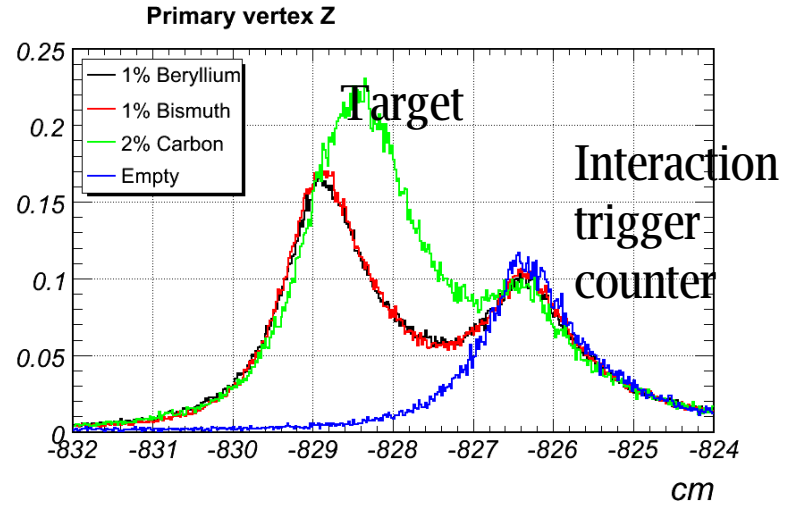
- TPC tracks are fitted to helices
  - Non-uniform B-field complicates the task
- Matched to chamber wires to form global tracks
  - Fit using track templates
- Momentum resolution 5.5% at 120 GeV/c
  - Drift times are not yet used

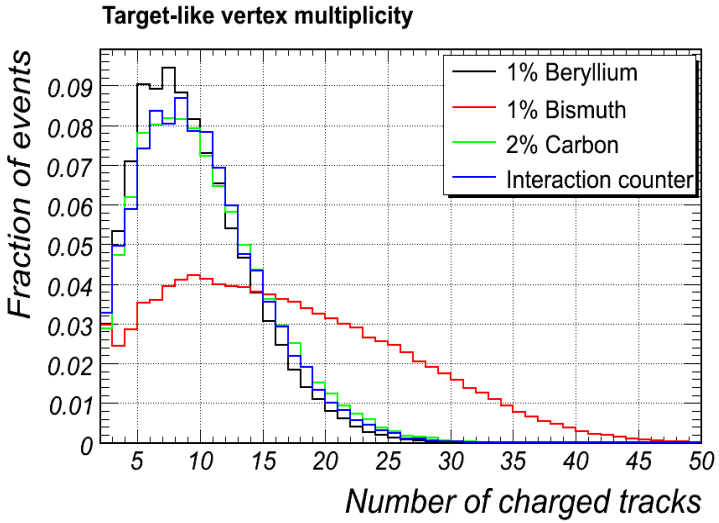






Vertex Reconstruction

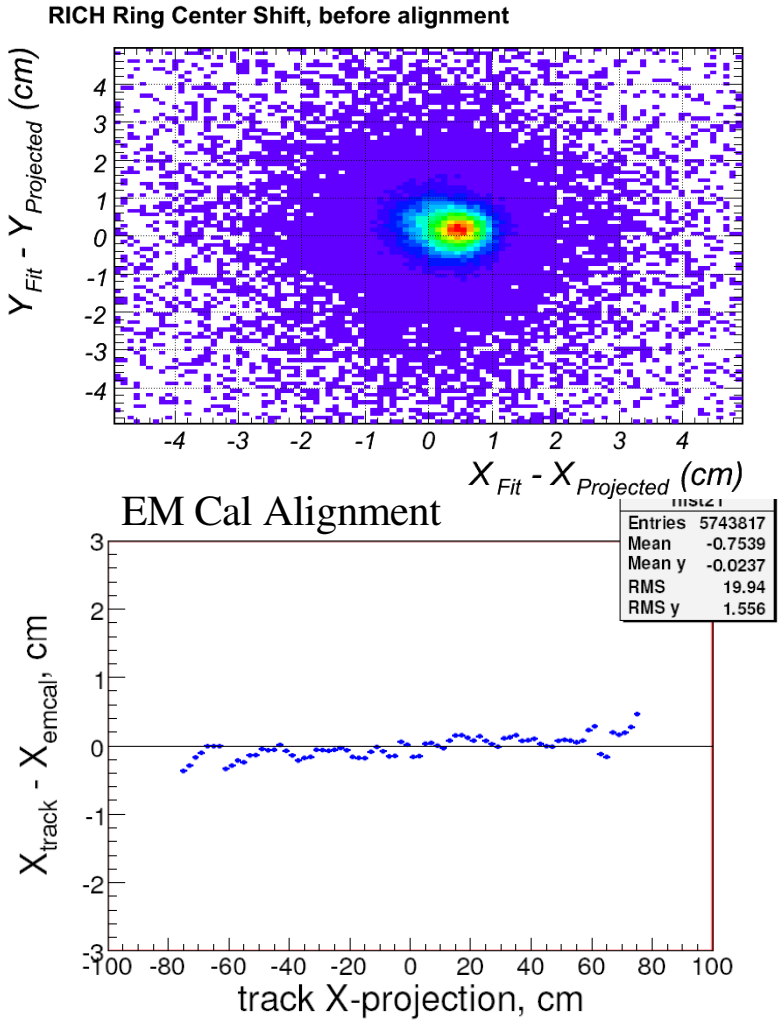




- Two steps to vertexing:
  - Vertex finding is done with deterministic annealing filter.
  - All tracks of each vertex are refit with the constraint of originating at the vertex. Uses track templates.
- Vertex resolution:
  - 6mm vertex Z resolution
  - X,Y resolution < 1mm
- Good separation of target interactions from background

Calibration (continued)

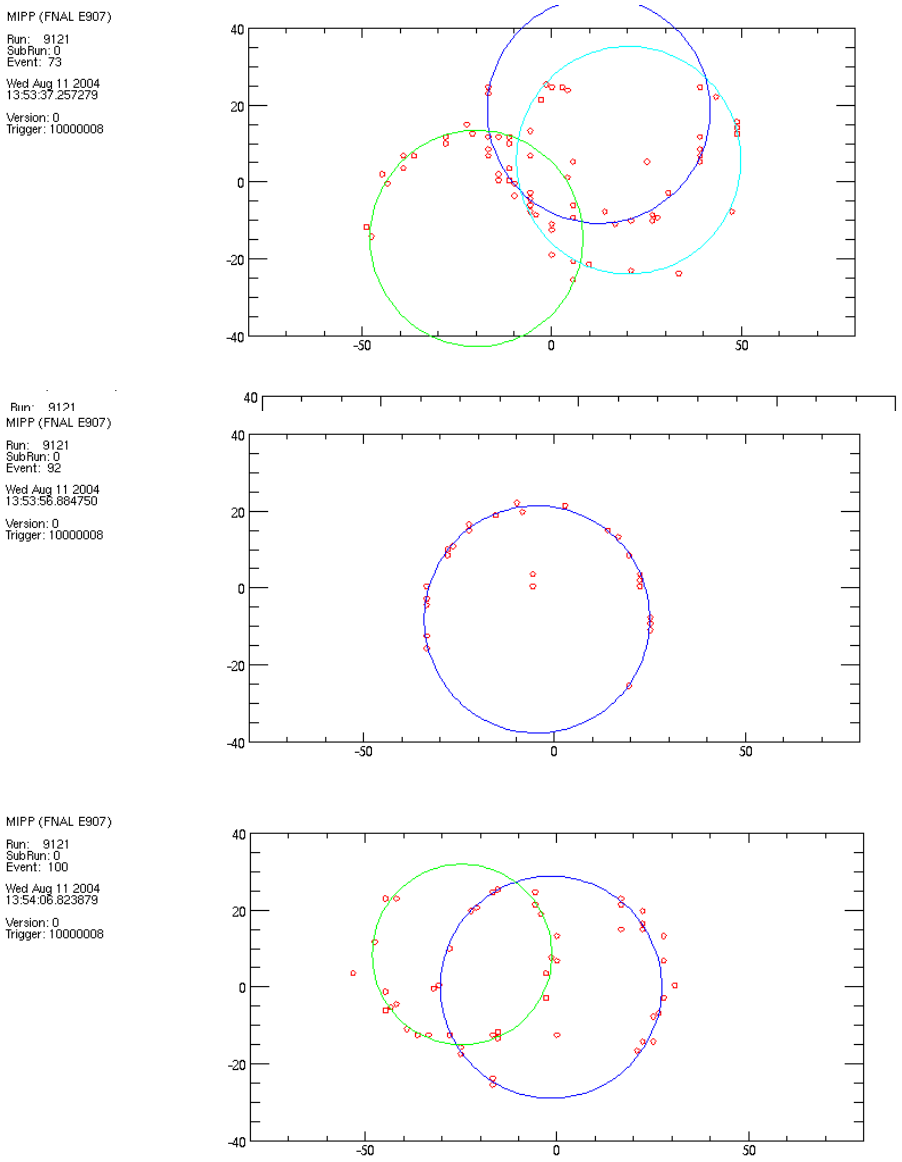
- Global tracking is used to
  - Align the RICH
  - Align EM calorimeter
  - Compute drift attenuation in the TPC
  - Compute ToF cable delays
  - Calibrate Ckov light output
  - Calibrate RICH index of refraction
- Calibration is complete



Event Reconstruction Summary

- Track reconstruction
  - Form hits in TPC, find tracks and fit to helices
  - Match TPC tracks to chamber hits, fit using track template method
- Vertex reconstruction
  - Find vertices using Deterministic Annealing Filter (DAF)
  - Make vertex constrained fits using track templates
- Particle identification
  - Compute TPC dE/dX, track ToF, Cherenkov likelihood
  - Match tracks to RICH rings and compute likelihoods
  - Match tracks to calorimeter showers

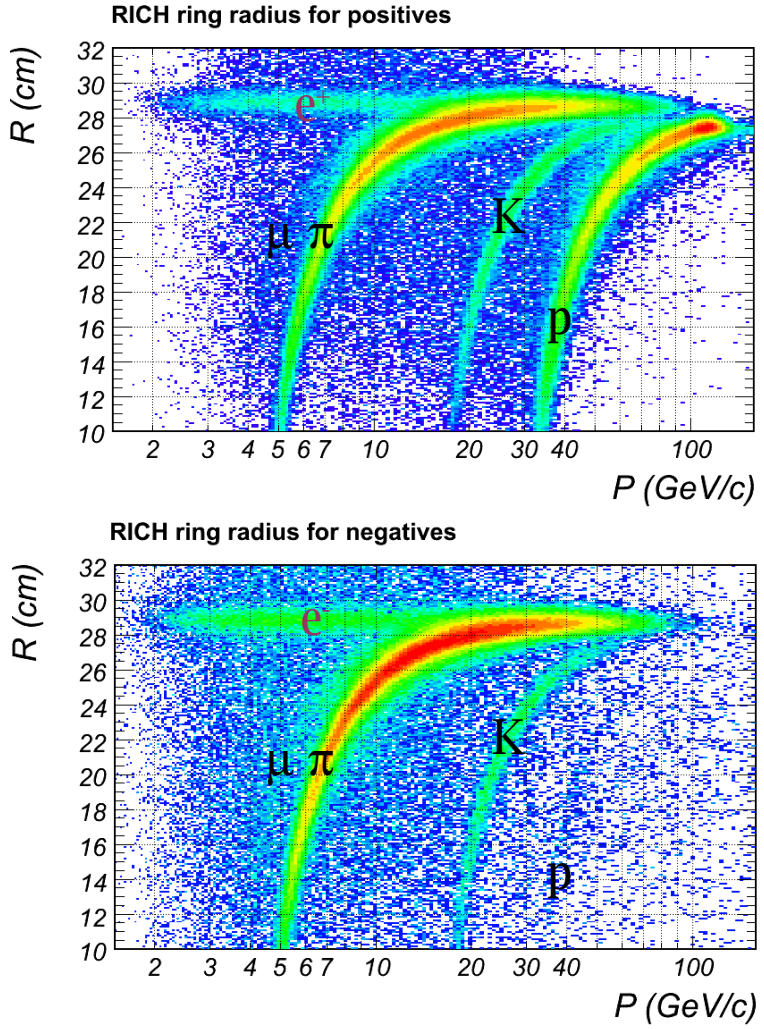
RICH rings



- The MIPP **R**ing **I**maging **CH**erenkov detector captures Cherenkov light on an array of 3000 pmts of 0.5" diameter.
- Inherited from Selex
- Gives lots of hits for MIPP momentum range.
  - easy to fit good circles

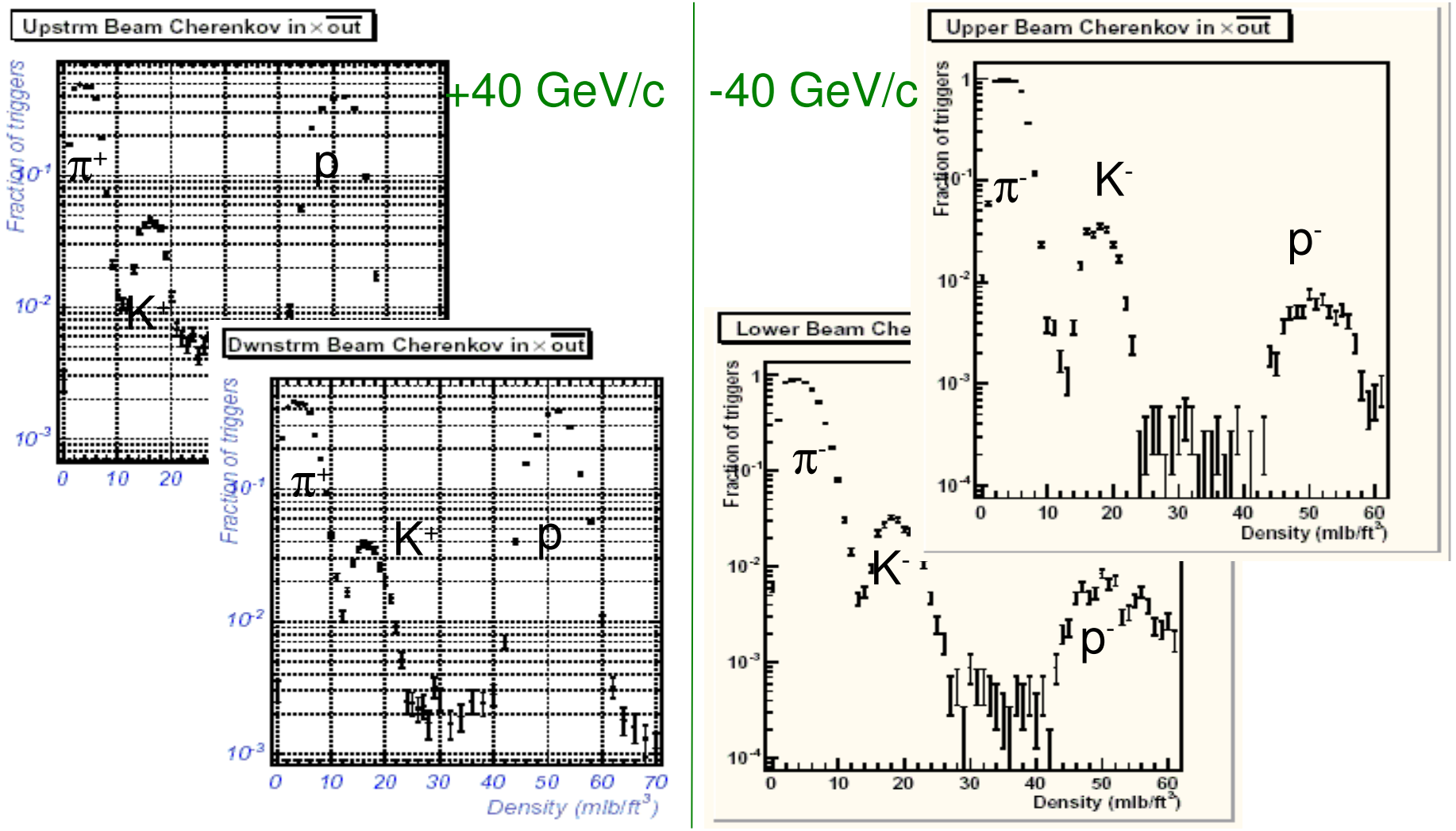
RICH particle id

- RICH ring radius gives very good particle ID within acceptance
  - e/μ/π up to 12 GeV/c
  - π/K/p to 100 GeV/c
- Detector is calibrated and well understood



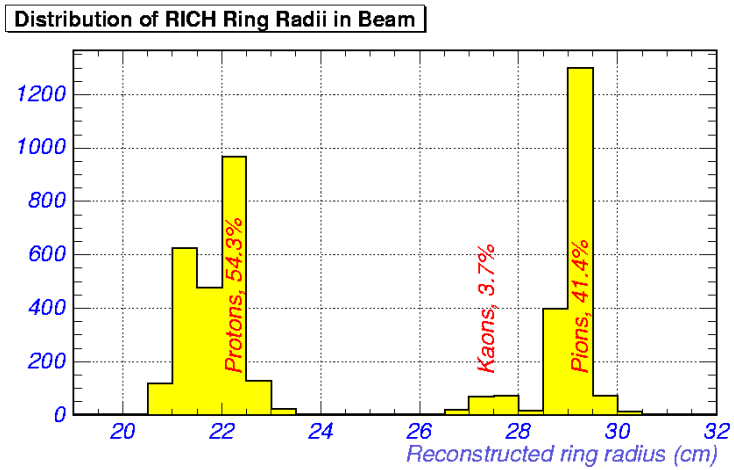
Beam Cherenkov Pressure Curve

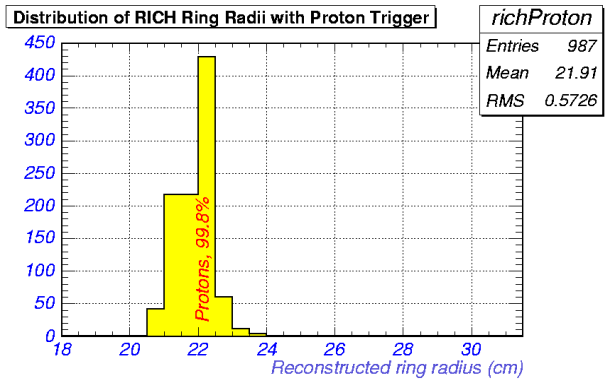
- Two differential Ckovs separate π/K or K/p depending on N_2 radiator pressure

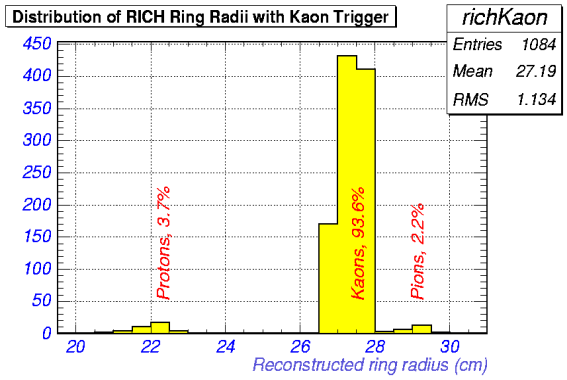


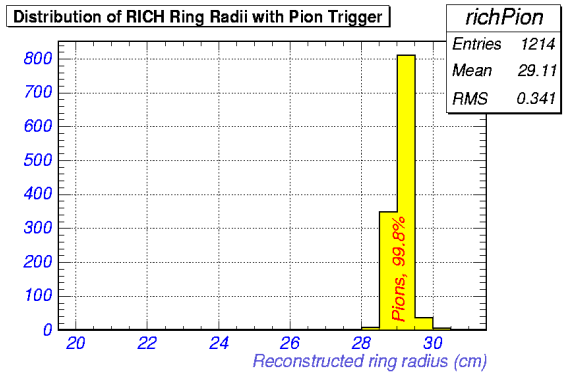
Beam Cherenkov performance

- Uninteracted beam particles are identified in both beam and RICH
  - Comparison for +40 GeV/c beam – No additional cuts!

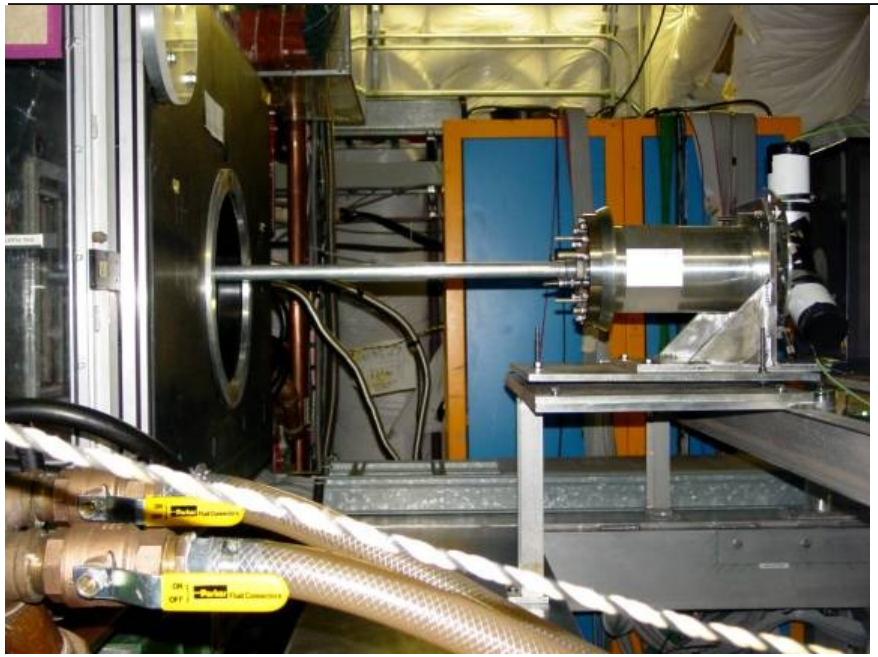


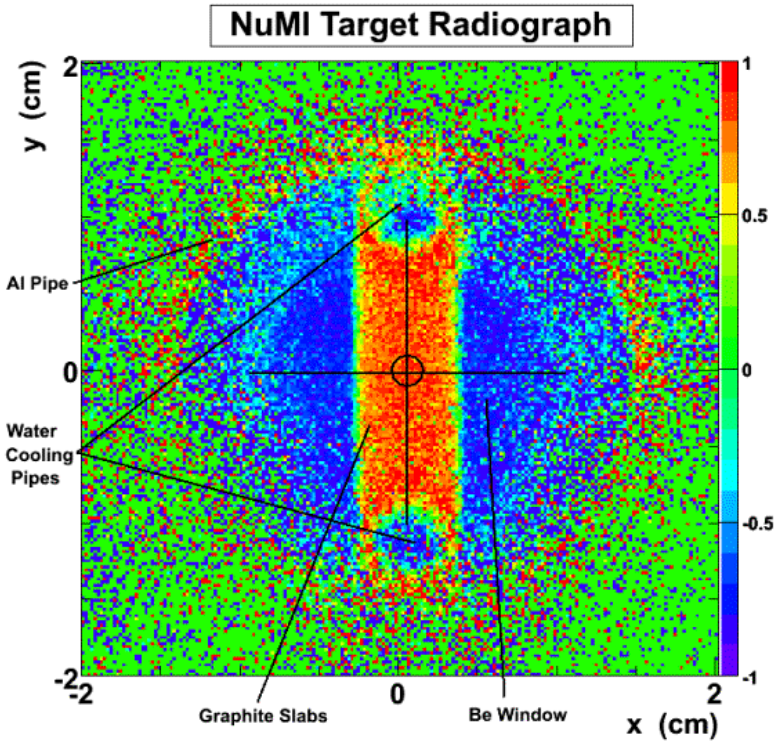


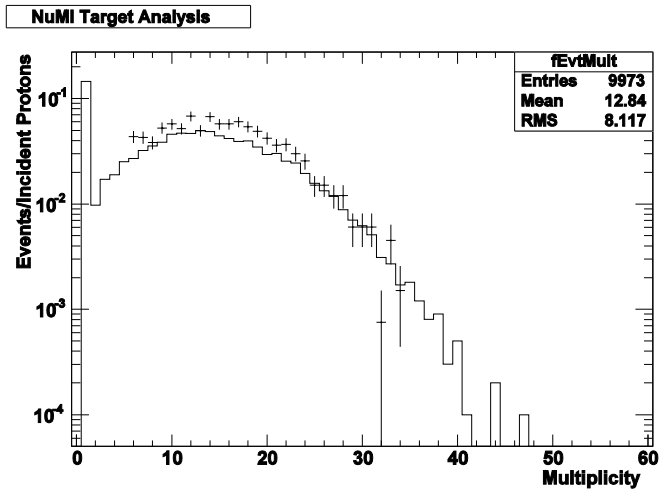


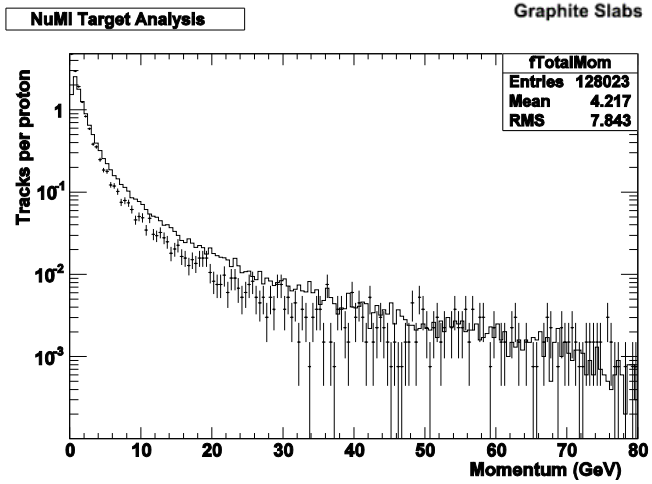


The NuMI target measurement





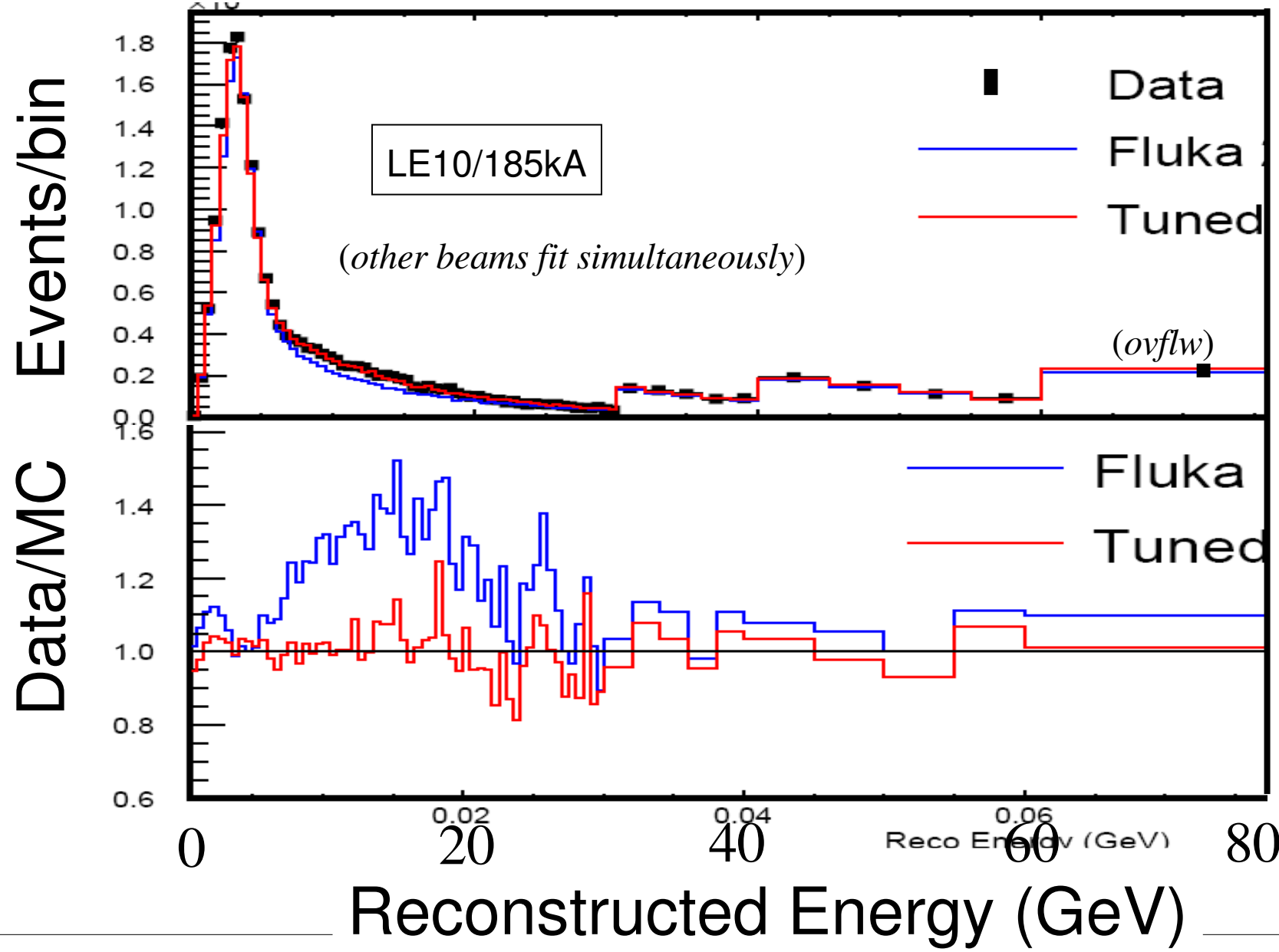




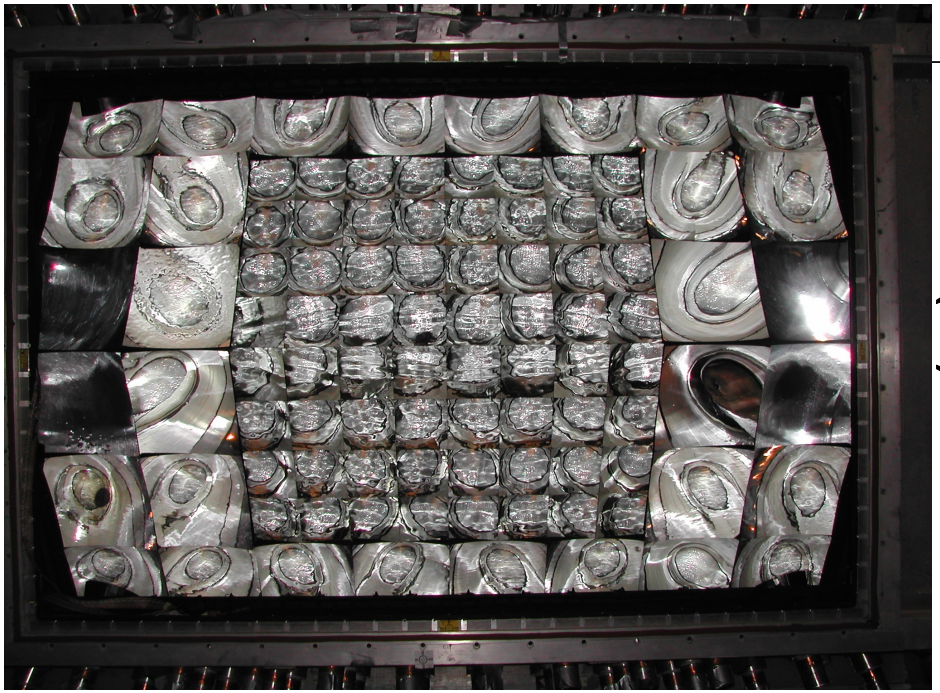
Preliminary Comparison of NUMI target to FLUKA predictions

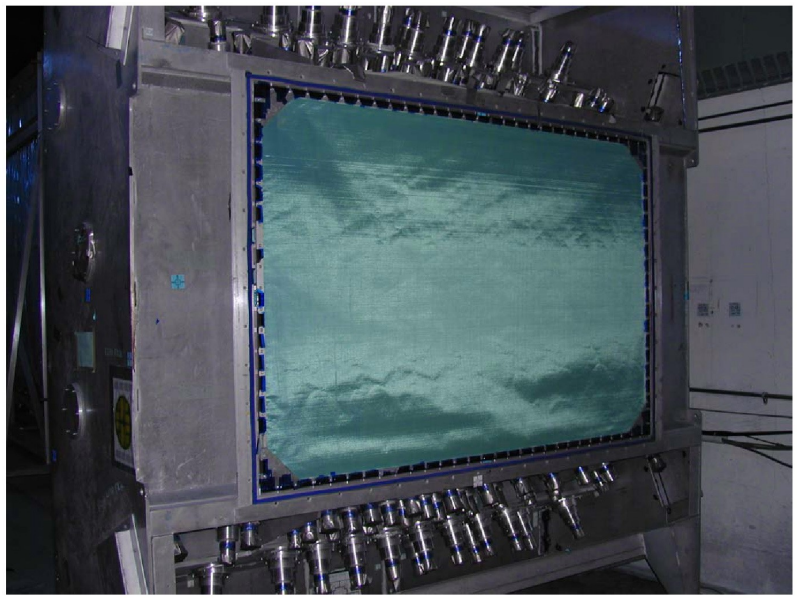
MINOS beam problem

(from S. Kopp)

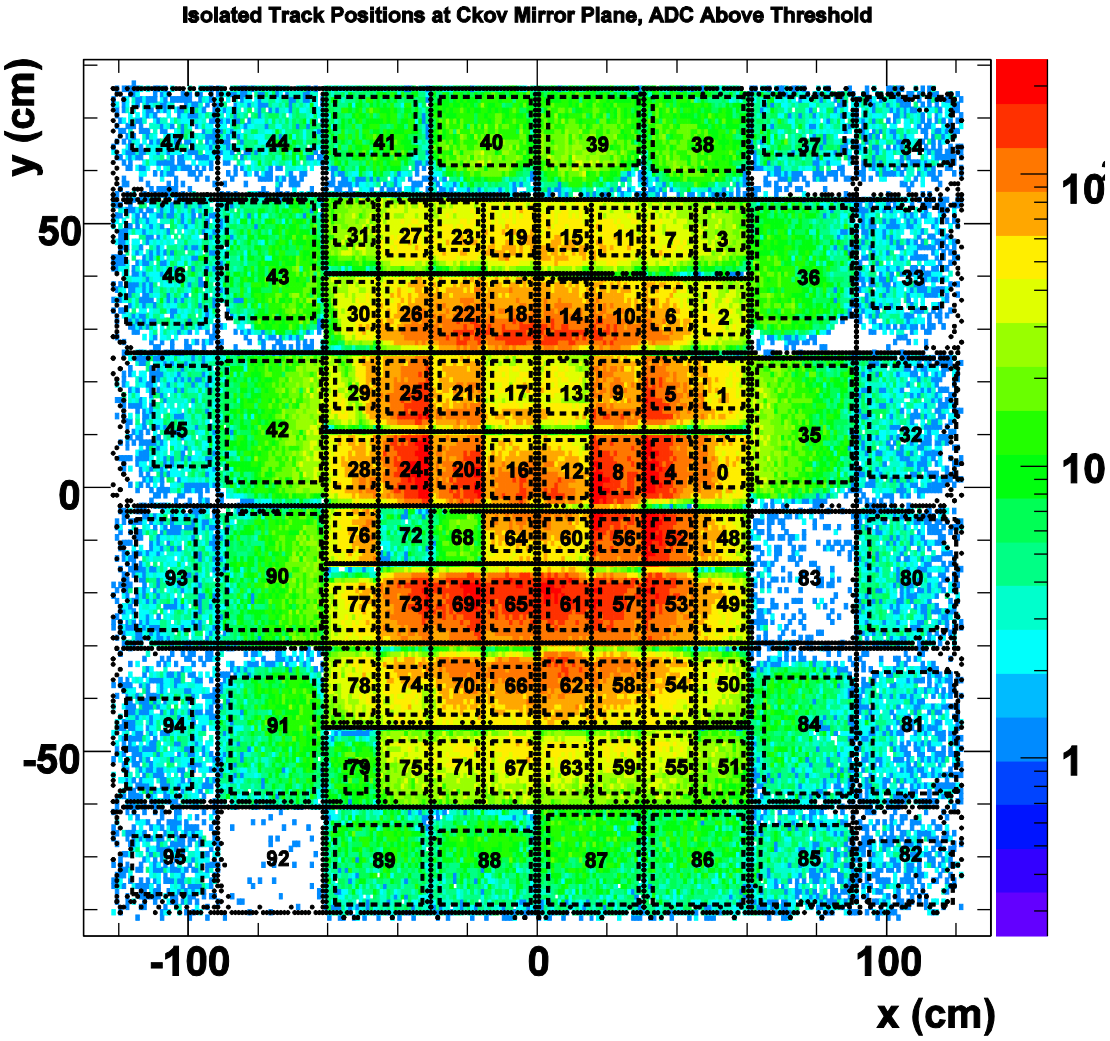


Multicell threshold Cherenkov



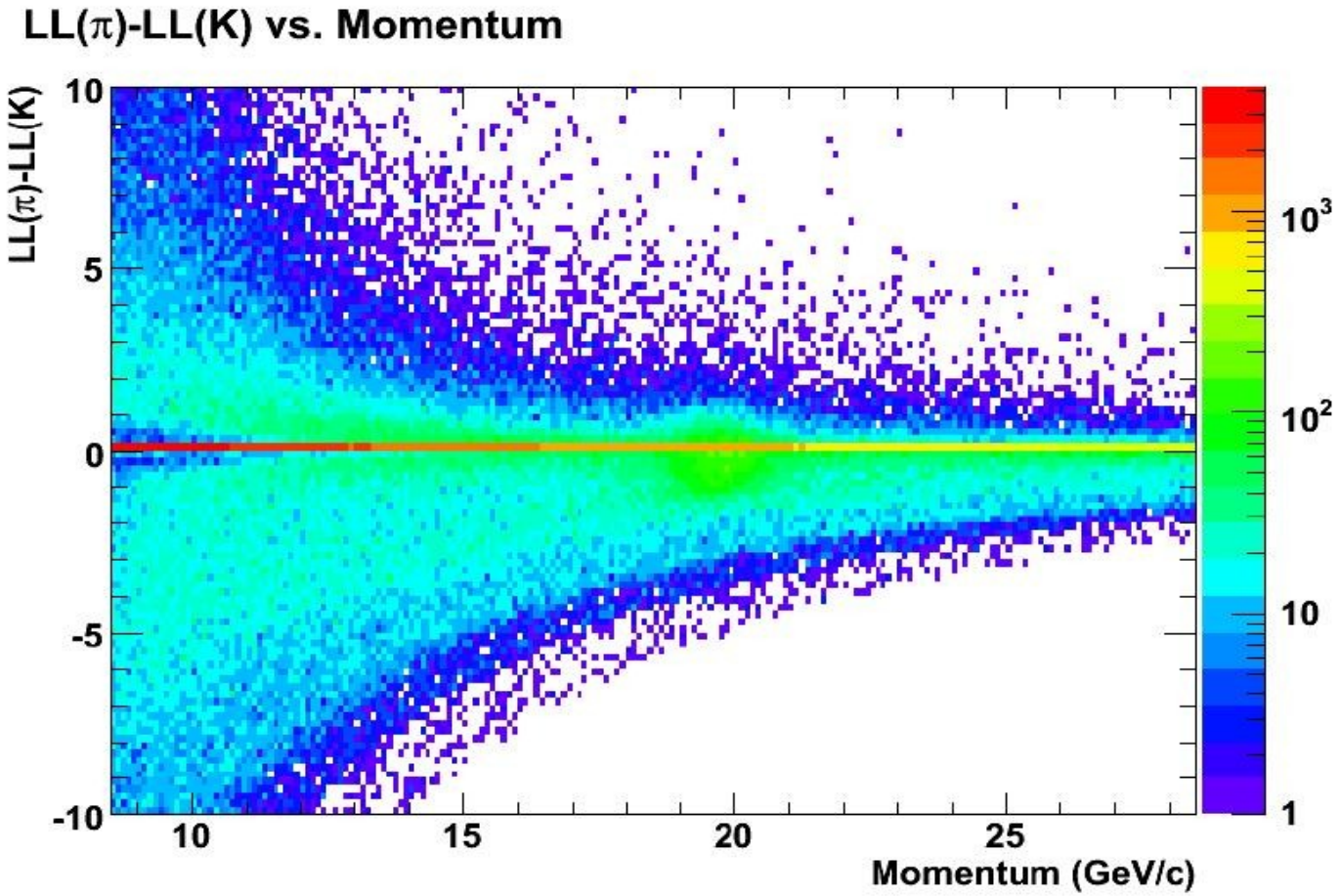


- C4F10 gas, Thresholds: π = 2.5 GeV/c,
  K = 8.9 GeV/c, p = 17.5 GeV/c



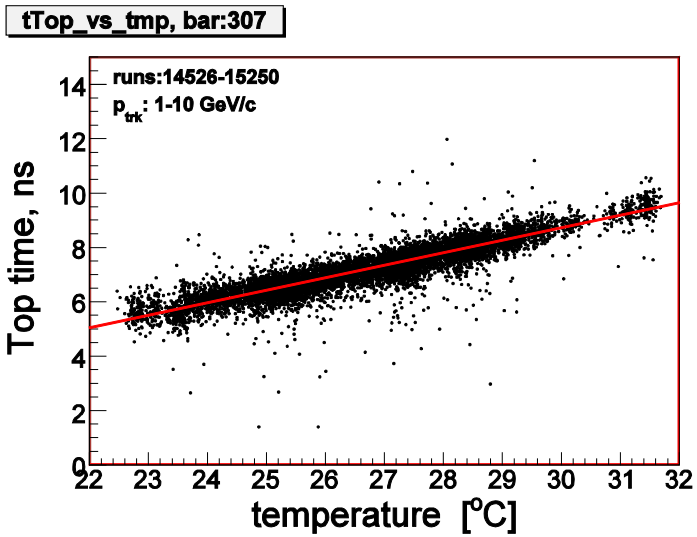
Cherenkov particle ID

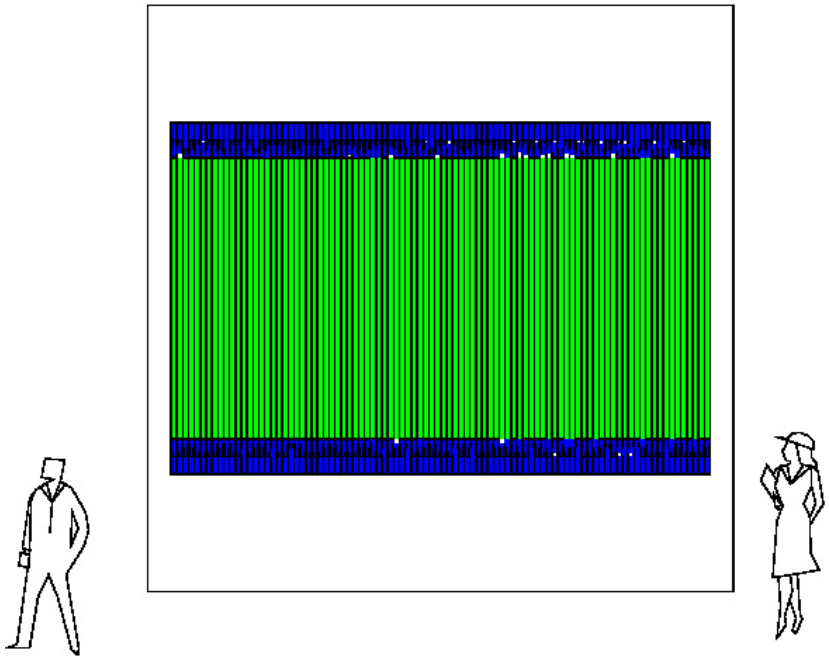
- Every mirror calibrated with data assuming pions and Poisson statistics.
  - Light yield lower than expected.



Time of Flight Wall

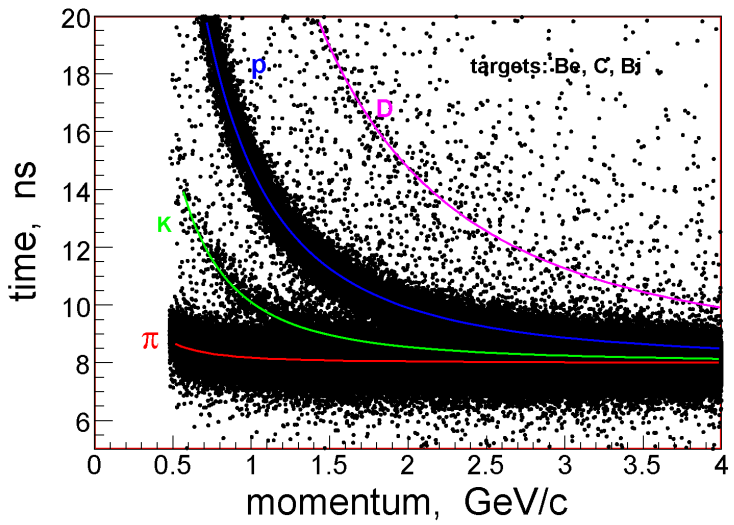
- Designed and built by MIPP
  - 5cmx 5cm square scintillator bars in Rosie aperture, 10cmx10cm outside. ~ 200ps resolution.
- Calibration:
  - Temperature dependence in delay cables
  - Cross talk when neighboring bars are hit

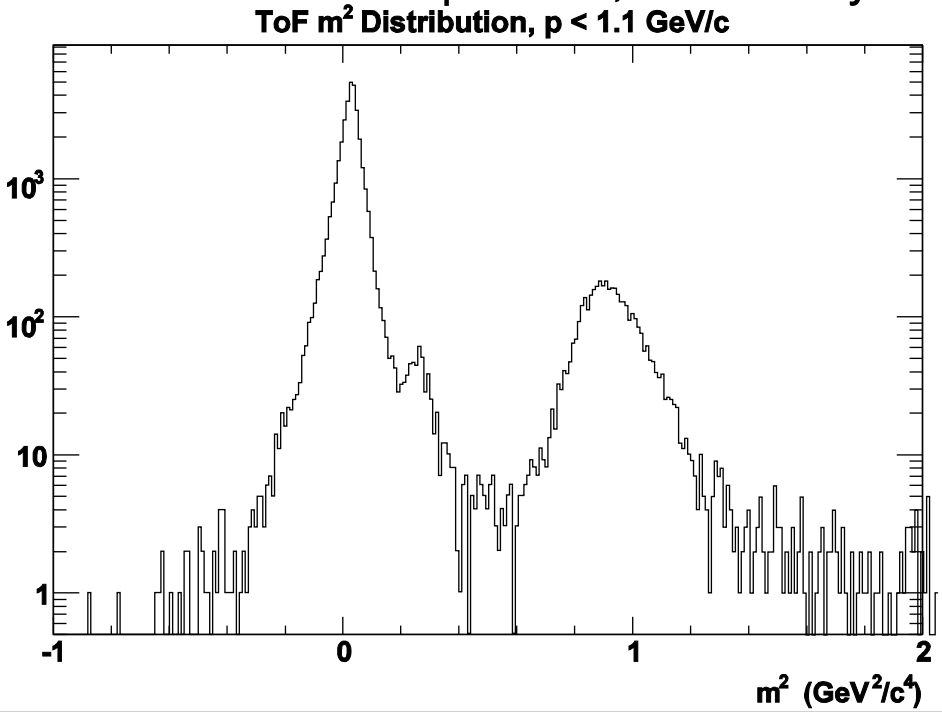


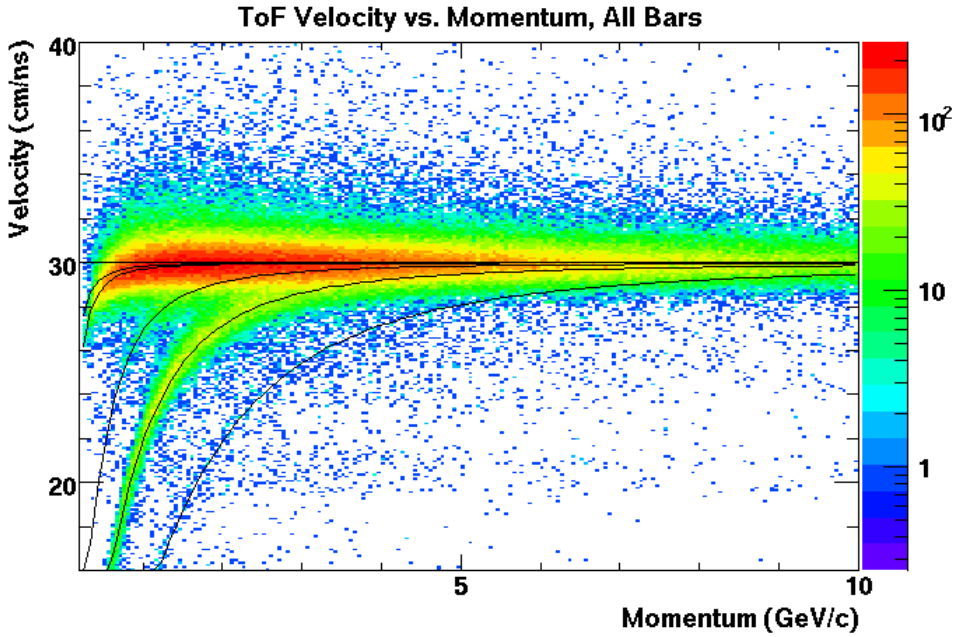


TOF particle ID

- The pathlength of the track to the TOF wall divided by the measured time of arrival at the TOF wall is the particle velocity β.
- Comparing β and momentum p gives the mass of the particle, its identity.

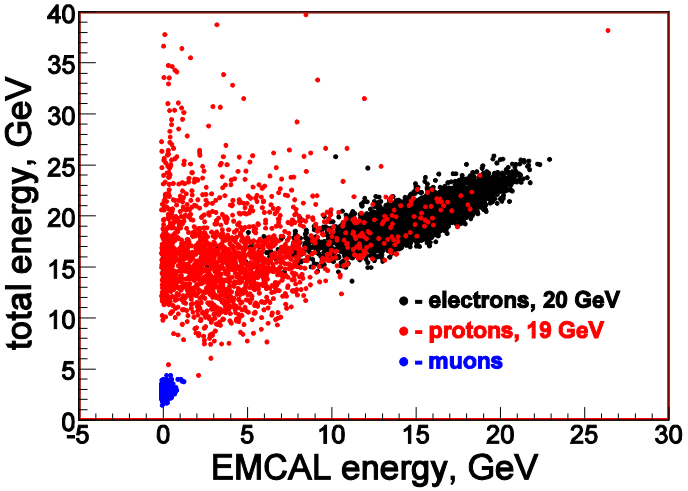


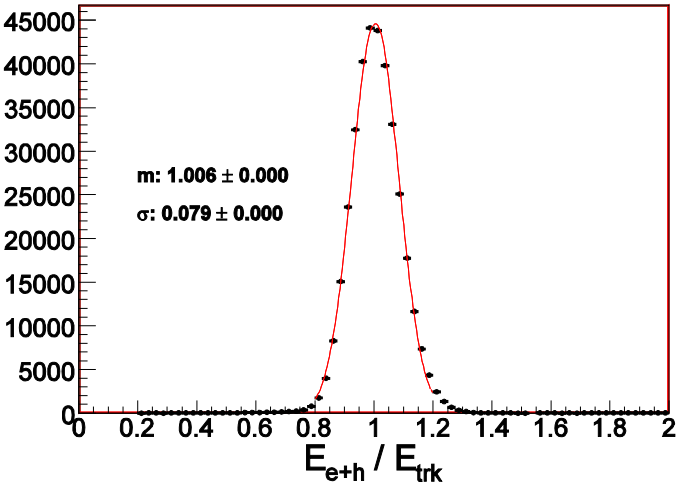




Calorimeters

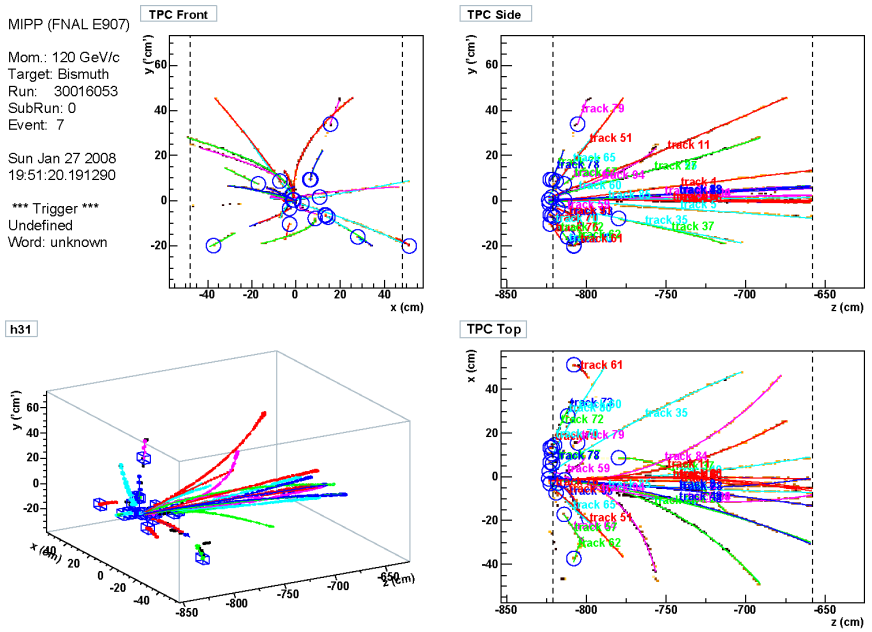
- EM calorimeter followed by hadronic calorimeter

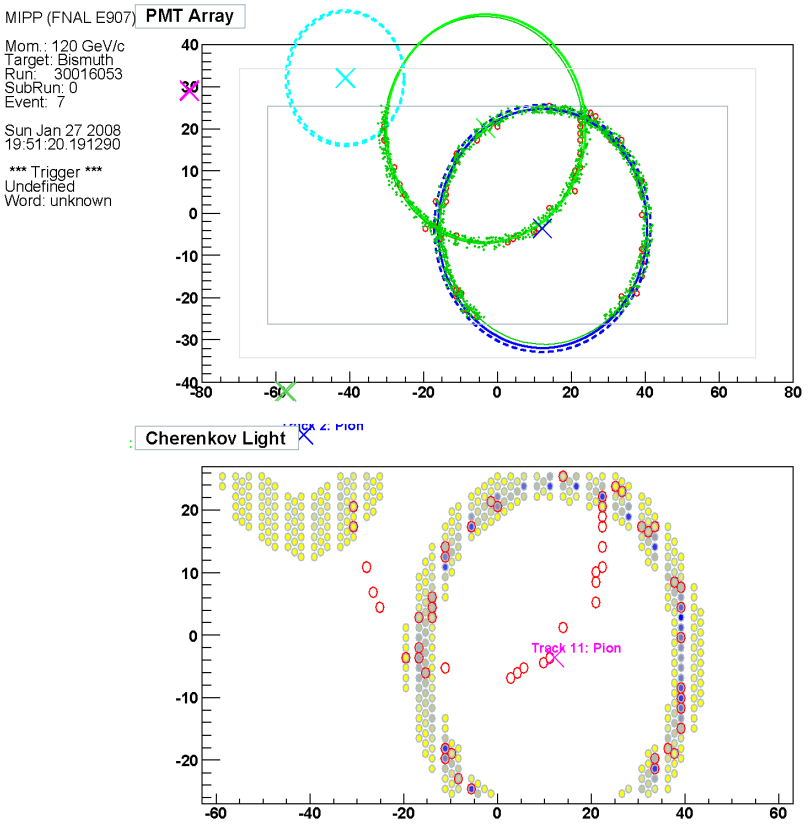




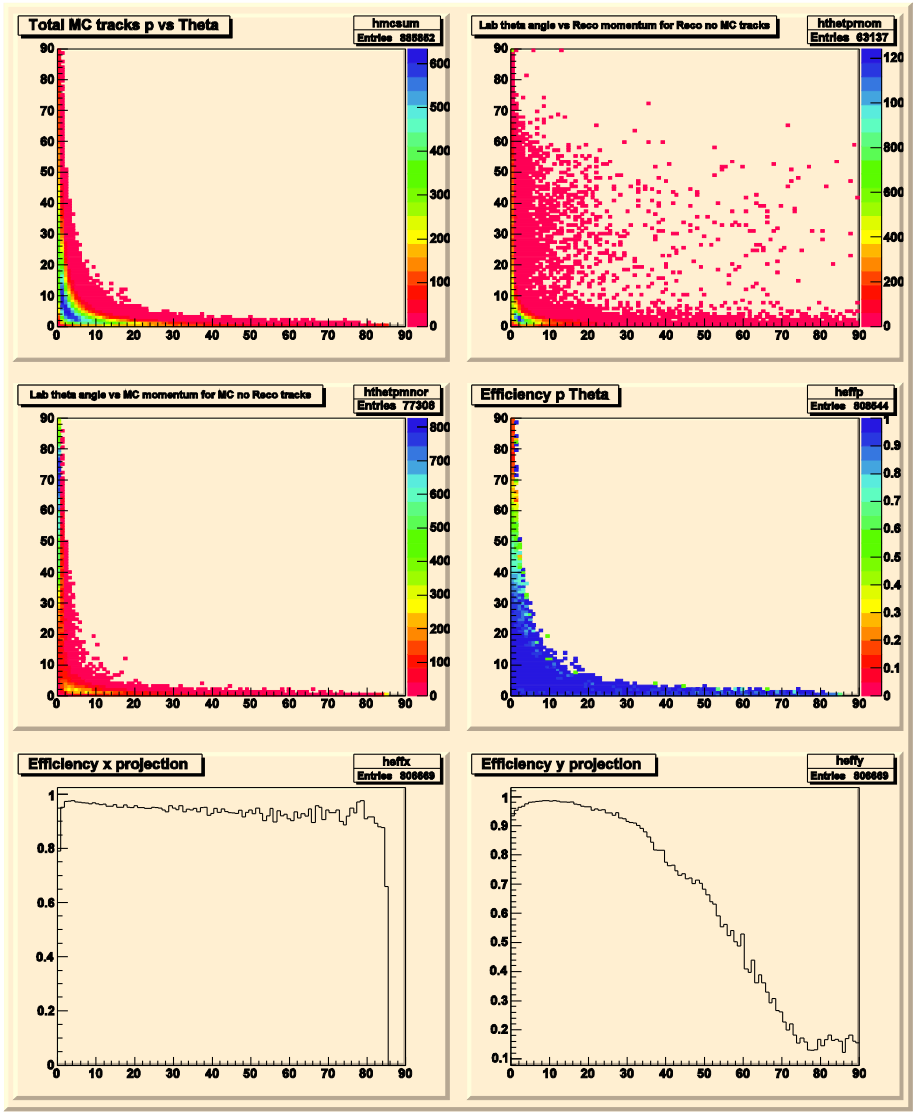
Resolutions and Acceptances

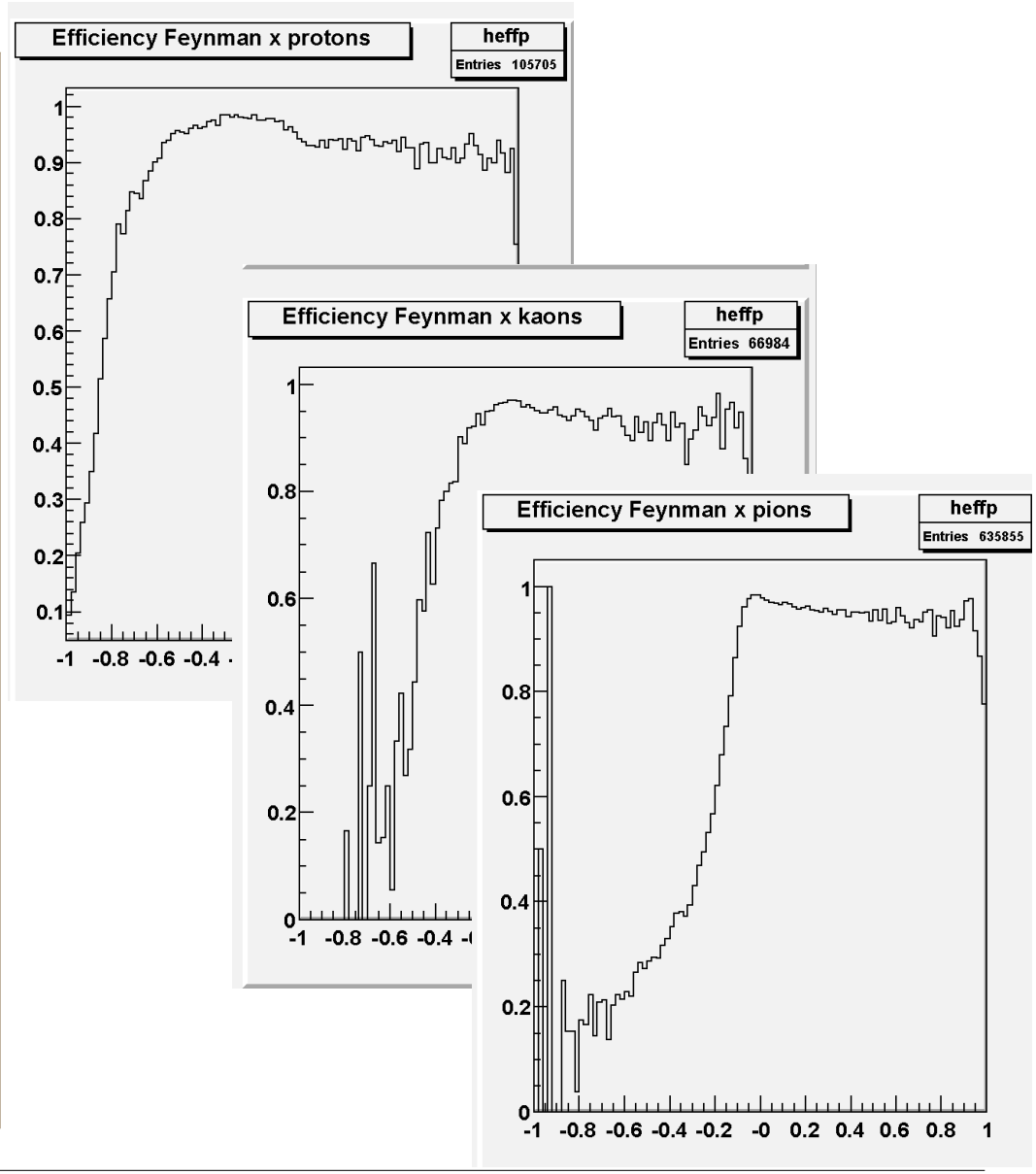
- Full Geant3 based Monte Carlo simulation of the detector response. Use known tracks and match them to found tracks to determine acceptance*tracking efficiency and momentum resolution.
- MC event display





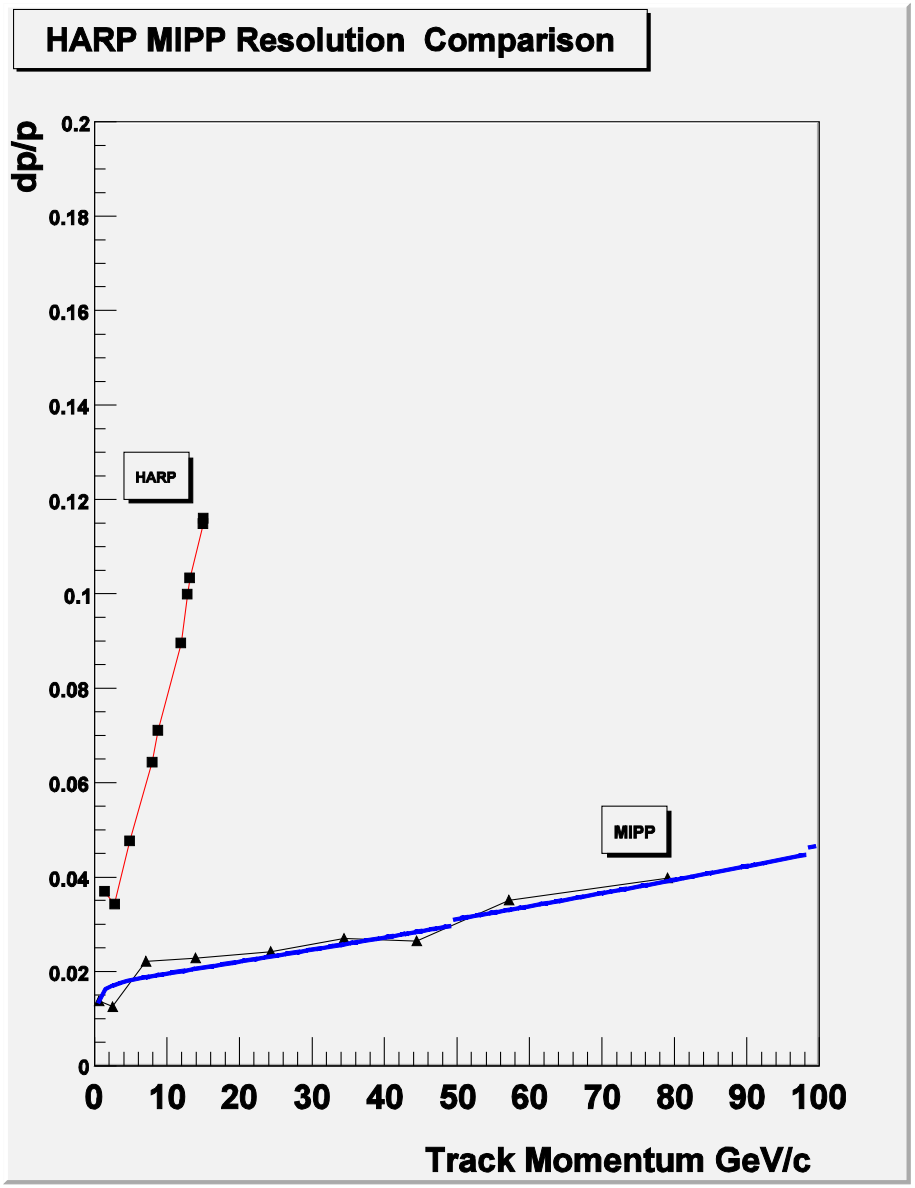
Detector efficiency





Momentum resolution compared to HARP at CERN

- MIPP momentum resolution is excellent
  - TPC with JGG field at low momenta
  - Rosie magnet and Drift Chambers at higher momenta
  - Redundancy
    - 128 TPC hits
    - 24 wire chamber planes

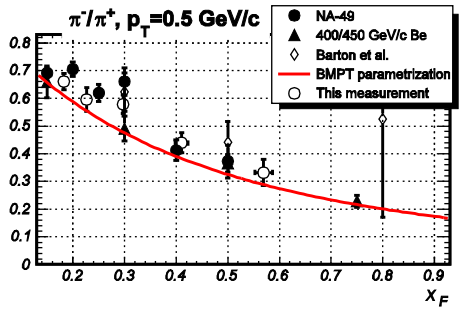


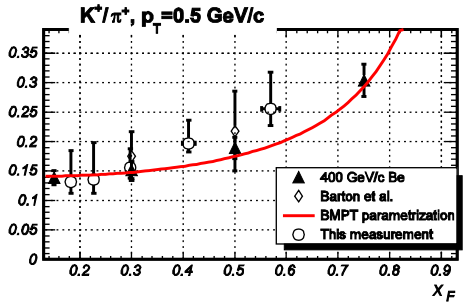
MIPP Data set

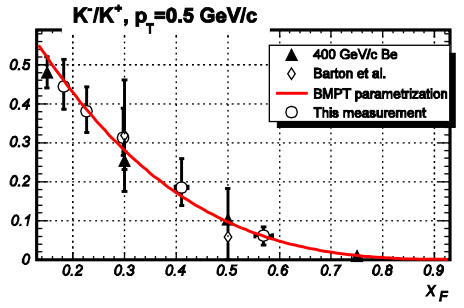
Data Summary 27 February 2006			Acquired Data by Target and Beam Energy Number of events, x 10^6								
Target			E								Total
Z	Element	Trigger Mix	5	20	35	40	55	60	65	85	120	
0	Empty[1]	Normal		*0.10*	*0.14*			*0.52*			*0.25*	***1.01***
	K Mass[2]	No Int.				*5.48*	*0.50*	*7.39*	*0.96*			***14.33***
	Empty LH[1]	Normal		*0.30*				*0.61*		*0.31*		**7.08**
1	LH	Normal	0.21	**1.94**				**1.98**		**1.73**		
4	Be	*p* only									1.08	**1.75**
		Normal			0.10			0.56				
6	C	Mixed						**0.21**				**1.33**
	C 2%	Mixed		**0.39**				**0.26**			**0.47**	
	NuMI	*p* only									**1.78**	**1.78**
13	Al	Normal			*0.10*							***0.10***
83	Bi	*p* only									1.05	**2.83**
		Normal			0.52			1.26				
92	U	Normal						1.18				**1.18**
Total			**0.21**	**2.73**	**0.86**	**5.48**	**0.50**	**13.97**	**0.96**	**2.04**	**4.63**	**31.38**

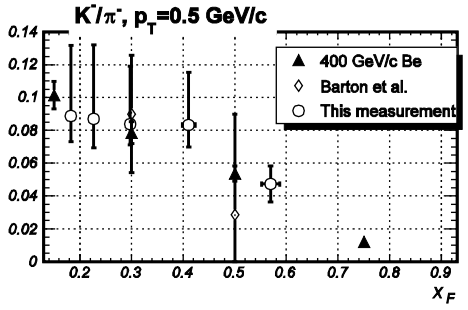
MIPP Results

- Two PhD theses finished
  - Ratio of Pion Kaon Production in Proton Carbon Interactions (Andre Lebedev)
  - Measurement of Pi-K Ratios from the NuMI Target (S. Seun)
  - 120 GeV/c proton beam
- Several other preliminary Results
  - Multiplicities
  - Cross Sections
- More and final results will become available this spring and summer!



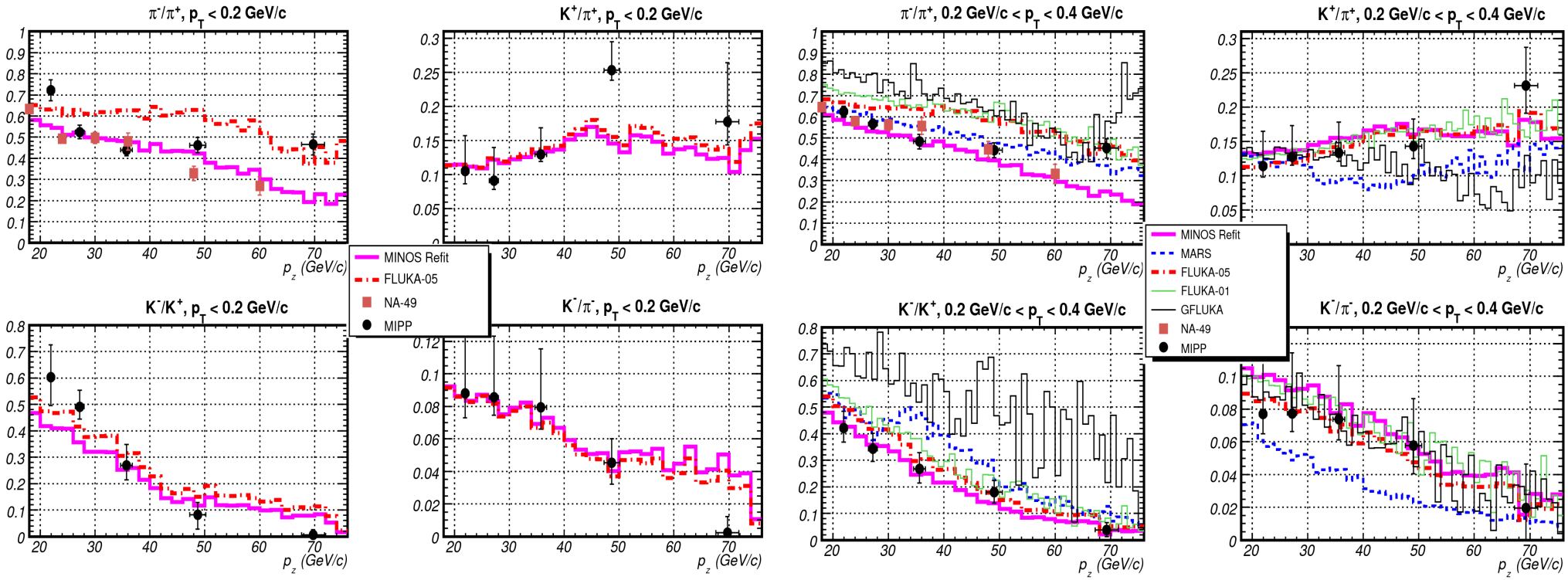






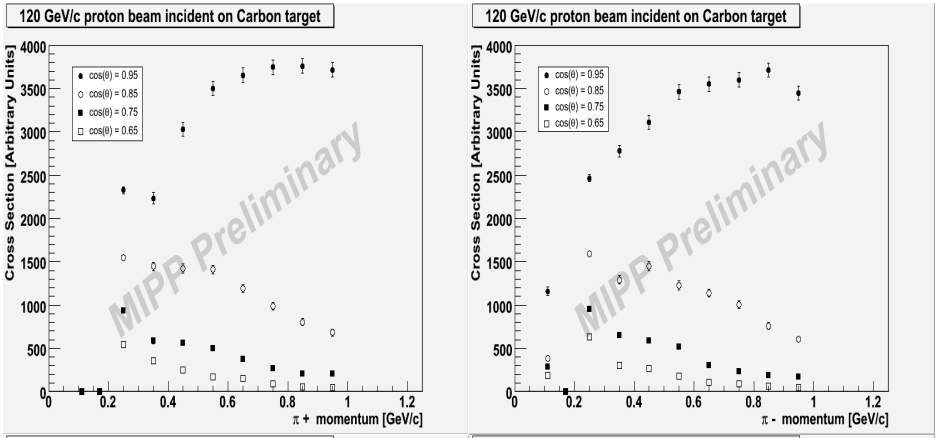
MIPP 120 GeV/c proton on Carbon

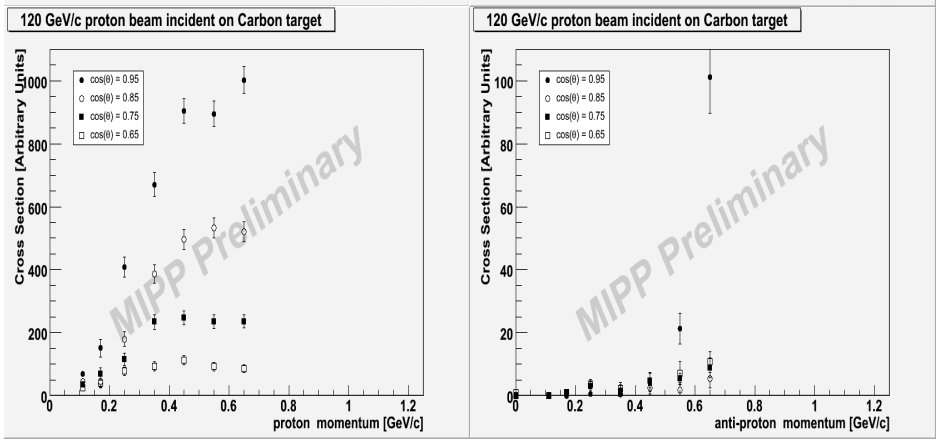
- MIPP data for ratios of π and K produced by p on thin-Carbon – A. Lebedev
  - MIPP data is needed to constrain models and fits to other data

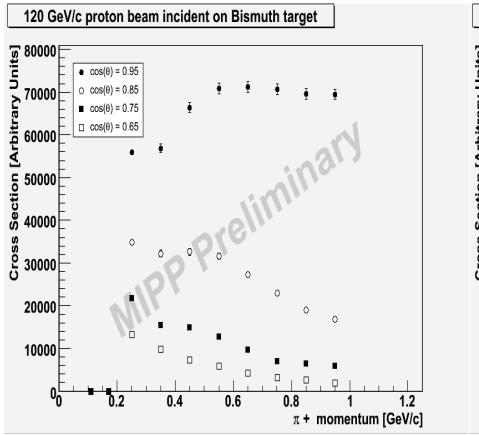


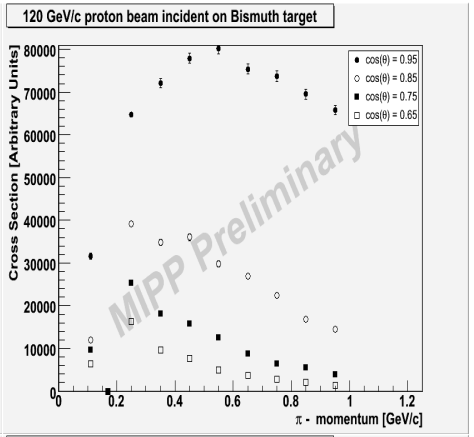
Preliminary Cross Sections

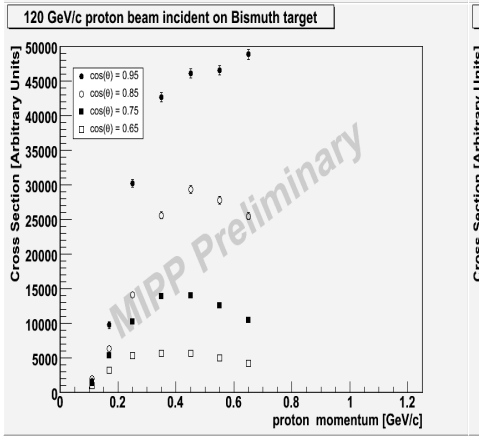
- Reasonable first results, using PID in the TPC
  - needs work on normalization, some other improvements

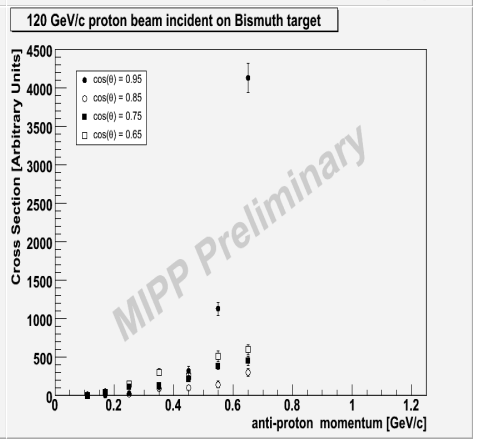






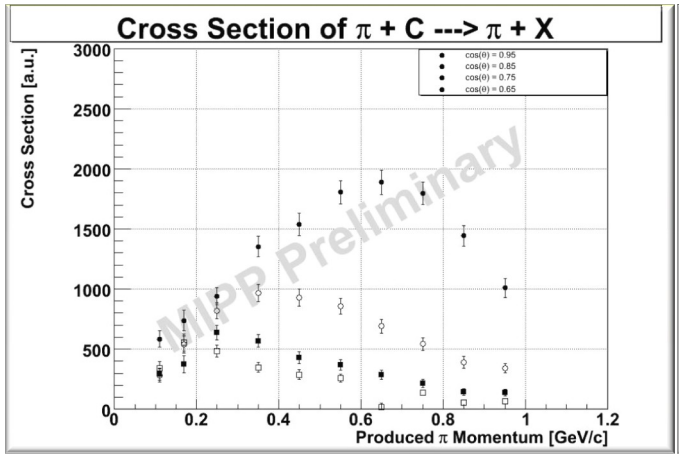


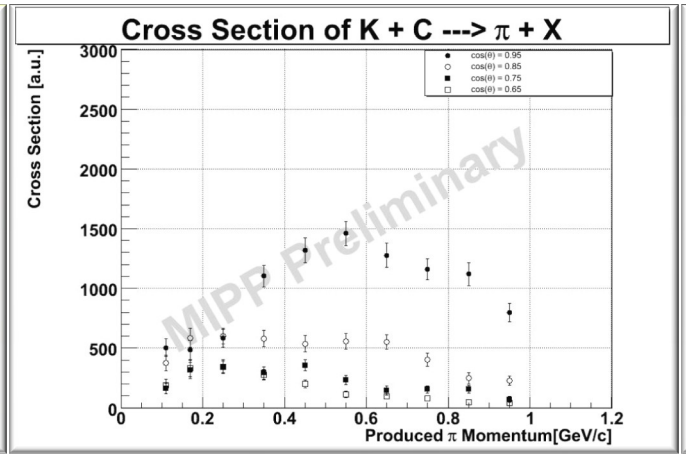


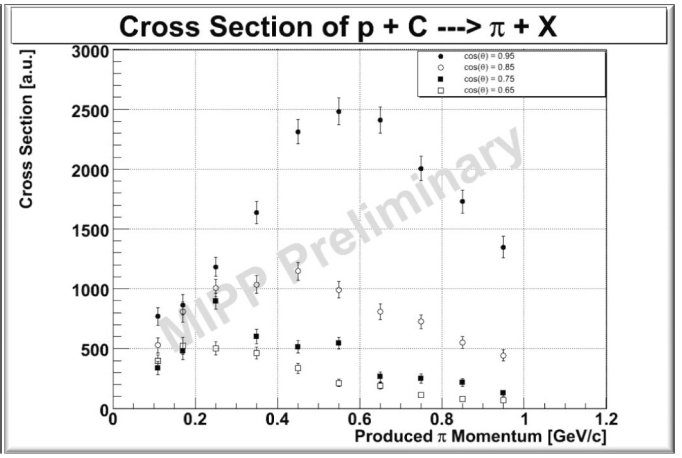


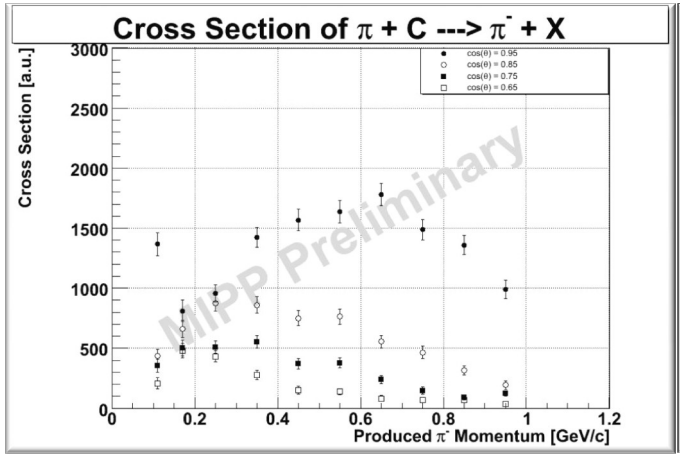
Preliminary Cross Sections at 58 GeV/c

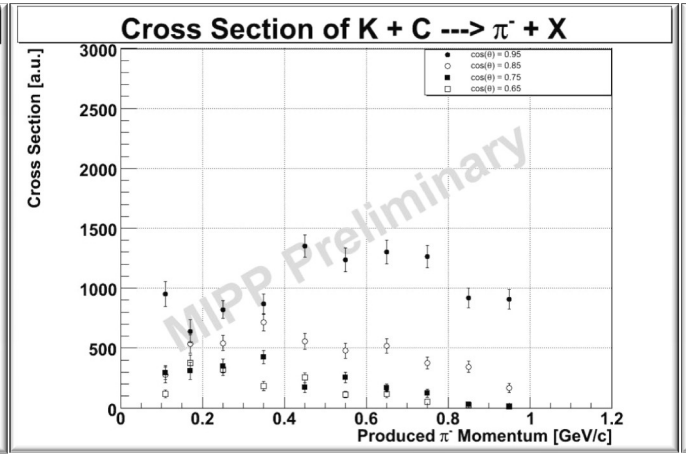
- Same systematics in all these reaction:

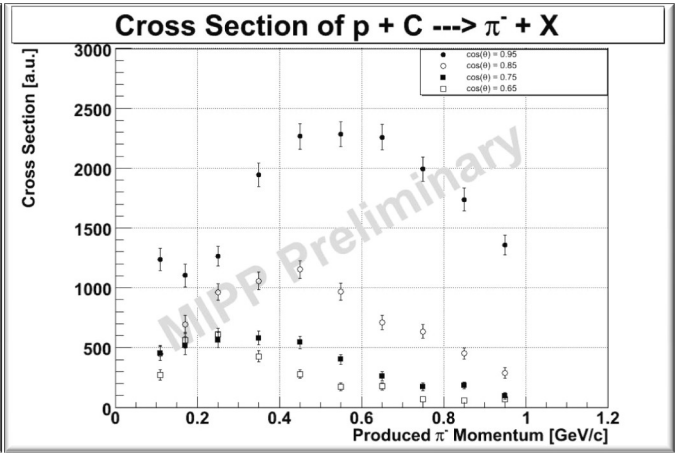










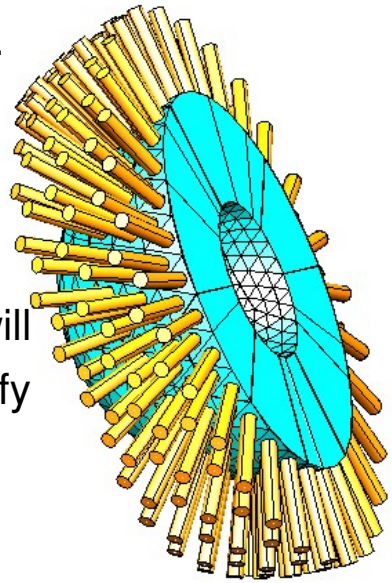


MIPP Upgrade proposal

- DAQ speed – TPC readout upgrade
  - The data rate in MIPP is limited to 30 Hz by the 1990s TPC electronics. Using the ALTRO/PASA chips developed for the ALICE experiment we can speed it up to ~3kHz. 1100 ALTRO/PASA chips have been delivered from CERN ($80k).
- 5 million events per day with the same beam delivery rate
  - We assume the delivery of a single 4 second spill every two minutes from the Main Injector. We assume a 42% downtime of the Main Injector for beam manipulation etc. This is conservative. Using these figures, we can acquire 5 million events per day.
- Jolly Green Giant Coil Replacement
  - Towards the end of our run, the bottom two coils of the JGG burned out. We have decided to replace both the top and bottom coils with newly designed aluminum coils that have better field characteristics for the TPC drift. The coils have been delivered ($200K).

MIPP Upgrade proposal (cont.)

- Other upgrades
  - The MIPP secondary **beamline** ran satisfactorily from 5GeV/c to 85GeV/c. We plan to run it from ~1 GeV/c to 85 GeV/c. The low momentum running will be performed using low current power supplies that regulate better. Hall probes in magnets will control hysteresis effects.
  - **Recoil detector** - GSI- Darmstadt / KVI Groningen have joined us. They will bring the plastic ball detector (a hemisphere of it) which will serve to identify recoil (wide angle) neutrons, protons and gammas from our targets. We may also add a recoil cluster counting chamber.



  - **Triggering system** - We propose to replace the MIPP interaction trigger (scintillator/wire chamber) with 3 planes of silicon pixels based on the B-TeV design. Will enable us to trigger more efficiently on low multiplicity events. Trigger information will be processed in a new Master Trigger Board.
  - Drift Chamber/PWC **readout electronics** - These electronics (E690/RMH) worked well for the first run. They are old (1990's). RMH will not do 3kHz. We will replace both systems with a new design that utilizes some of the infrastructure we developed for the RICH readout.

The MIPP Upgrade Collaboration

- D. Isenhower, M. Sadler, R. Towell, S. Watson; Abilene Christian University
- R. J. Peterson; University of Colorado, Boulder
- W. Baker, B. Baldin,D. Carey, D. Christian, M. Demarteau, D. Jensen, C. Johnstone, H. Meyer, R. Raja, A. Ronzhin, W. Wester, J.-Y. Wu; Fermi National Accelerator Laboratory
- W. Briscoe, I. Strakovsky, R. Workman; George Washington University, Washington D.C
- H. Gutbrod, B. Kolb, K. Peters; GSI, Darmstadt, Germany
- G. Feldman; Harvard University, Y. Torun; Illinois Institute of Technology
- M.D. Messier, J. Paley; Indiana University
- U. Akgun, G. Aydin, F. Duru, E. Gülmez, Y. Gunaydin, Y. Onel, A. Penzo; University of Iowa
- V. Avdeichikov, P. Filip, R. Leitner, J. Manjavidze, V. Nikitin, I. Rufanov, A. Sissakian, T. Topuria, A. Zinchenko; Joint Institute of Nuclear Research, Dubna, Russia
- D. M. Manley; Kent State University
- H. Löhner, J. Messchendorp; KVI, Groningen, Netherlands
- H. R. Gustafson, M. Longo, T. Nigmanov, D. Rajaram; University of Michigan
- S. P. Kruglov, I. V. Lopatin, N. G. Kozlenko, A. A. Kulbardis, D. V. Nowinsky, A. K. Radkov, V. V. Sumachev; Petersburg Nuclear Physics Institute, Gatchina, Russia
- A. Bujak, L. Gutay; Purdue University, D. Bergman, G. Thomson; Rutgers University, New Jersey
- A. Godley, S. R. Mishra, C. Rosenfeld; University of South Carolina
- C. Dukes, C. Materniak, K. Nelson, A. Norman; University of Virginia
- P. Desiati, F. Halzen, T. Montaruli; University of Wisconsin, Madison
- P. Sokolsky, W. Springer; University of Utah, N. Solomey,; Wichita State University

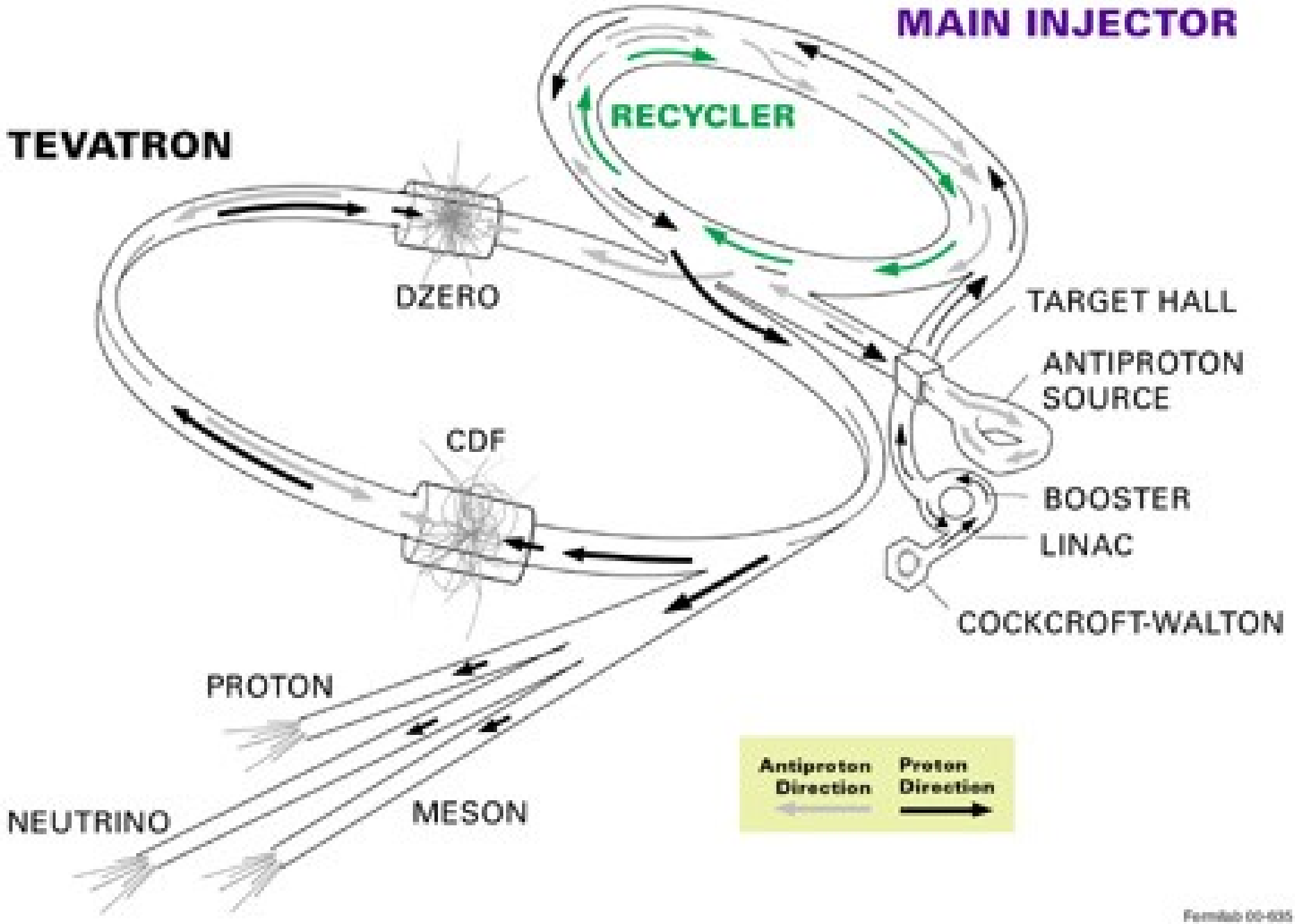
Conclusions

- Data analysis from the MIPP run in 2005/2006 is in progress
  - Looking forward to a lot of results from MIPP this year.
- MIPP is a very versatile experiment.
  - Interesting physics on its own
  - MIPP data is an important input for many other experiments
    - Atmospheric Neutrinos & Cosmic Rays: PIERRE AUGER, ICE CUBE
    - MINOS/MINERνA/NOνA, Super K/Hyper K (neutrino spectra)
    - CMS/Atlas (hadronic energy scale)
    - ILC calorimetry (hadronic energy scale/resolutions)
- A future run (if approved) will improve statistics and physics reach further.
  - The MIPP Upgrade Collaboration has proposed a cost effective way to upgrade the experiment to speed up the DAQ by a factor of 100.

Backup slides

Backup slides

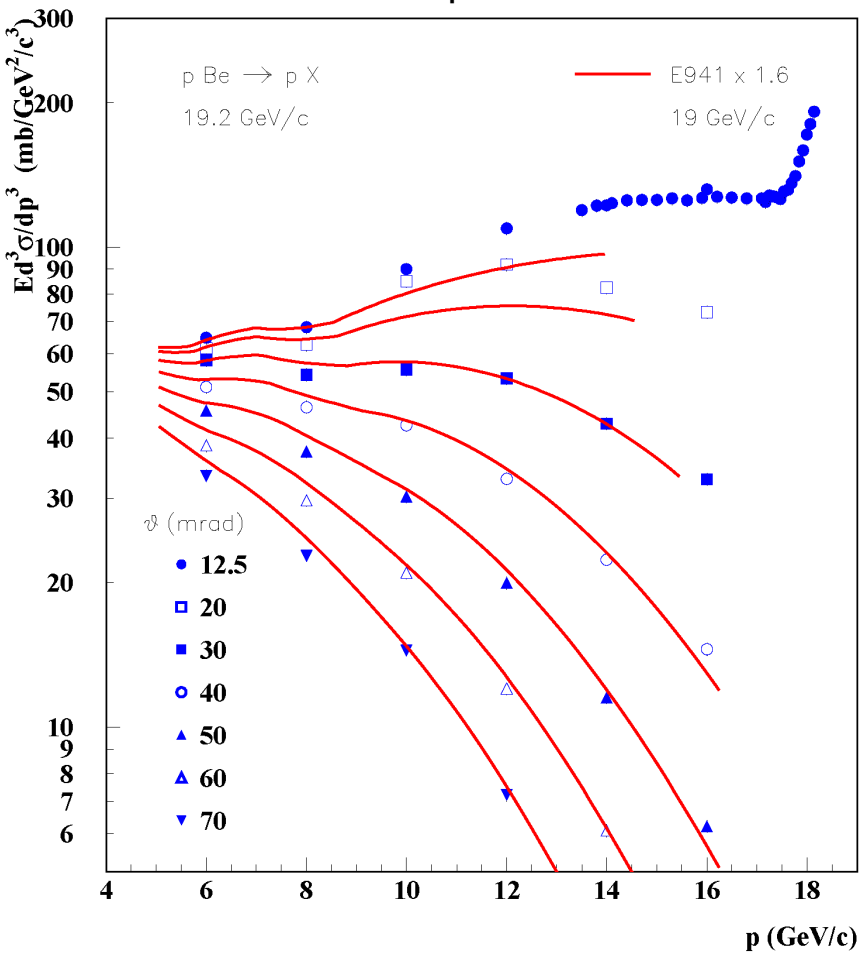
FERMILAB'S ACCELERATOR CHAIN

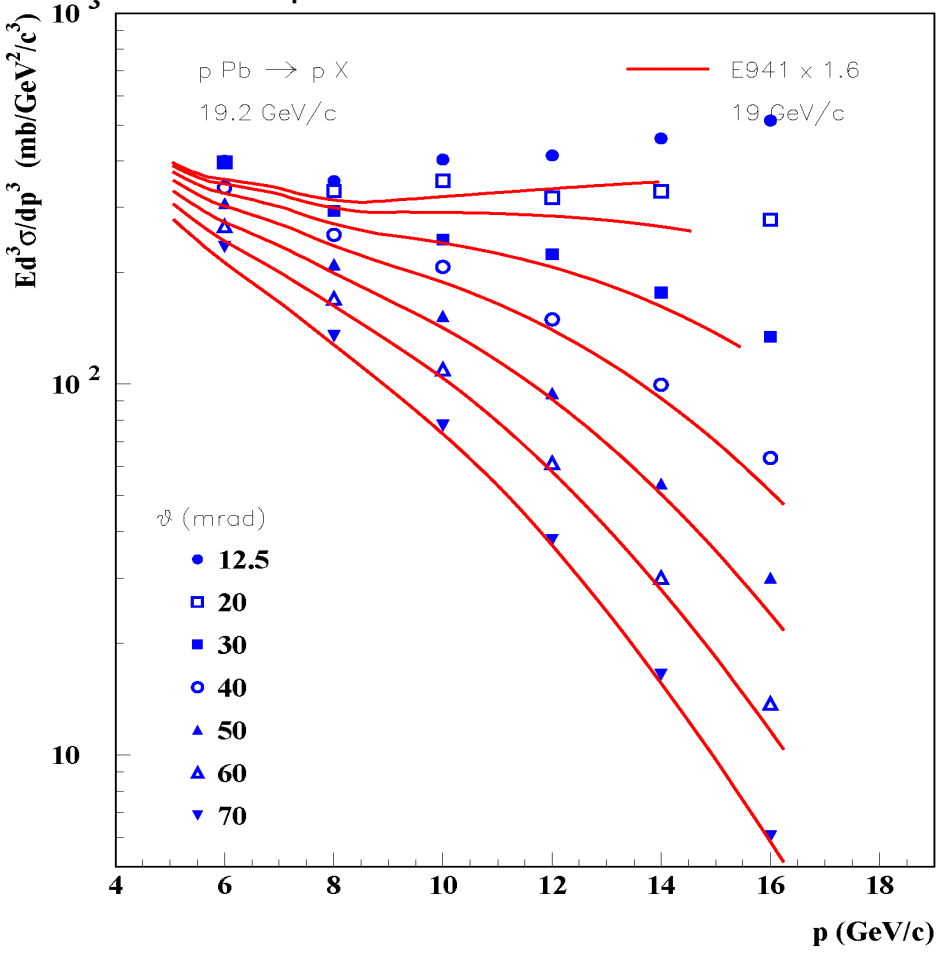


Fermilab 00-605

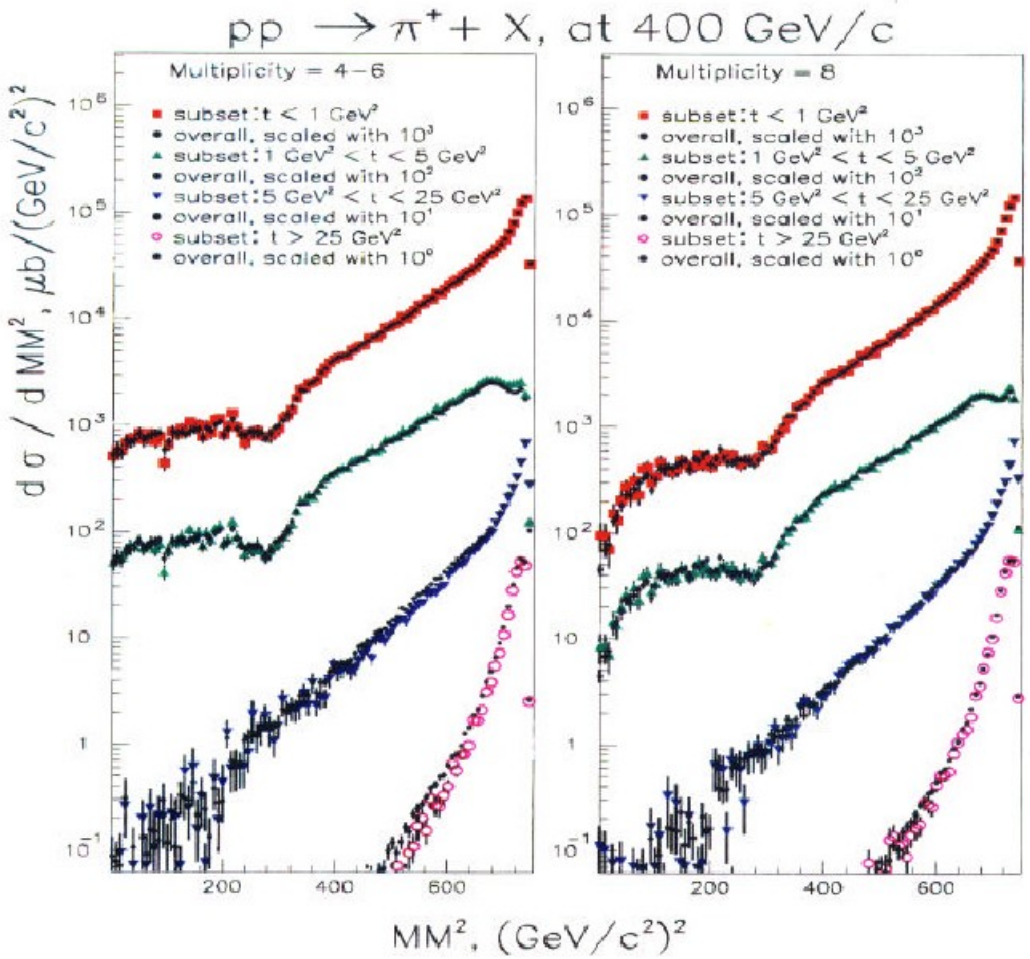
Status of available data

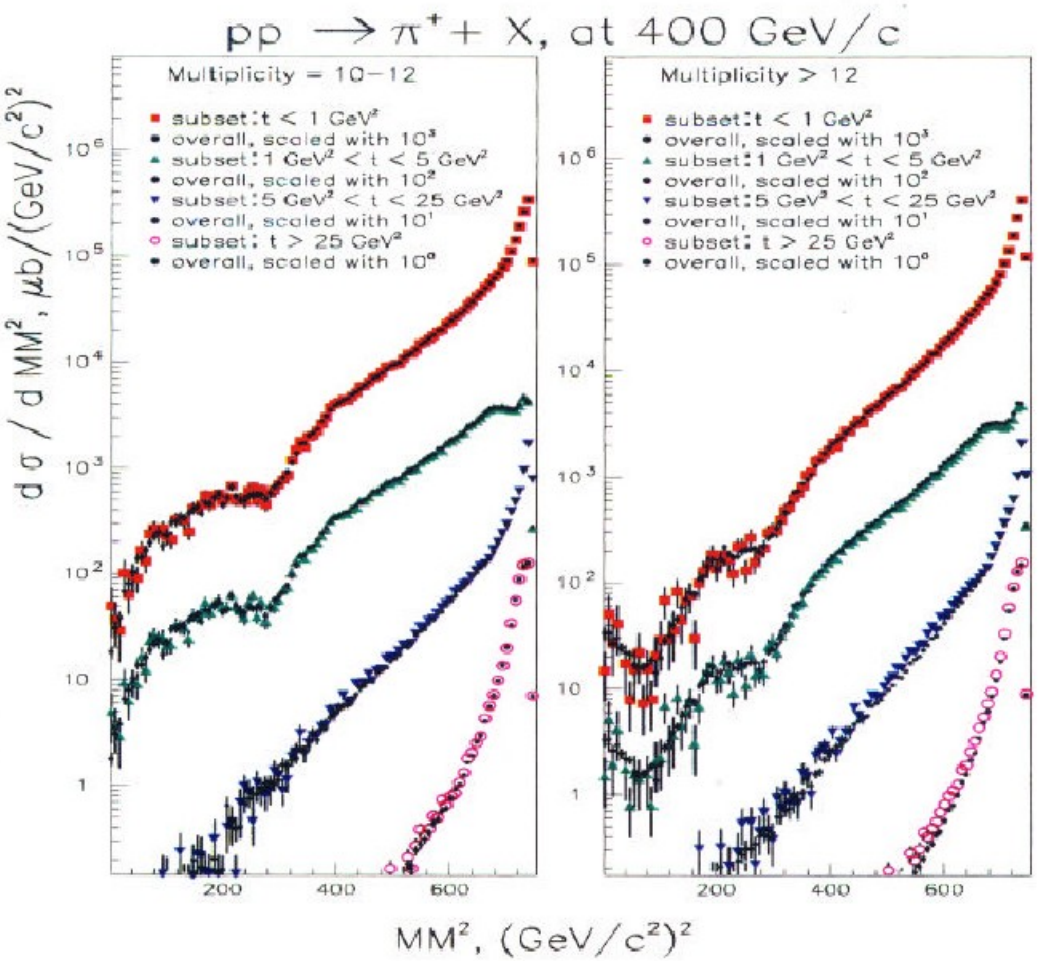
- Model Input data unreliable
  - a recent example: 60% normalization error between 2 experiments.





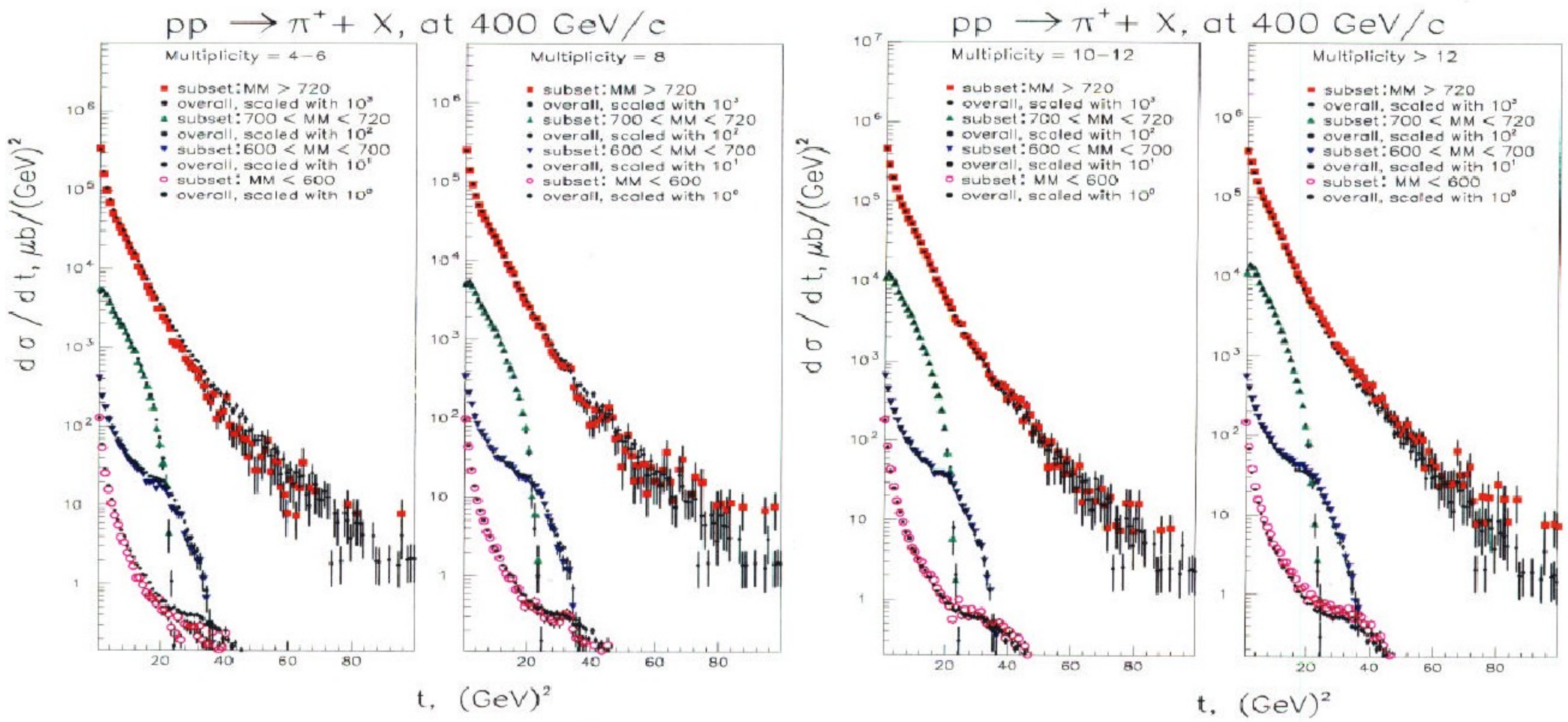
Scaling Law - EHS Data





- European Hybrid Spectrometer Data
  - pp->p++X at 400 GeV/c
  - as a function of missing mass squared for various multiplicities

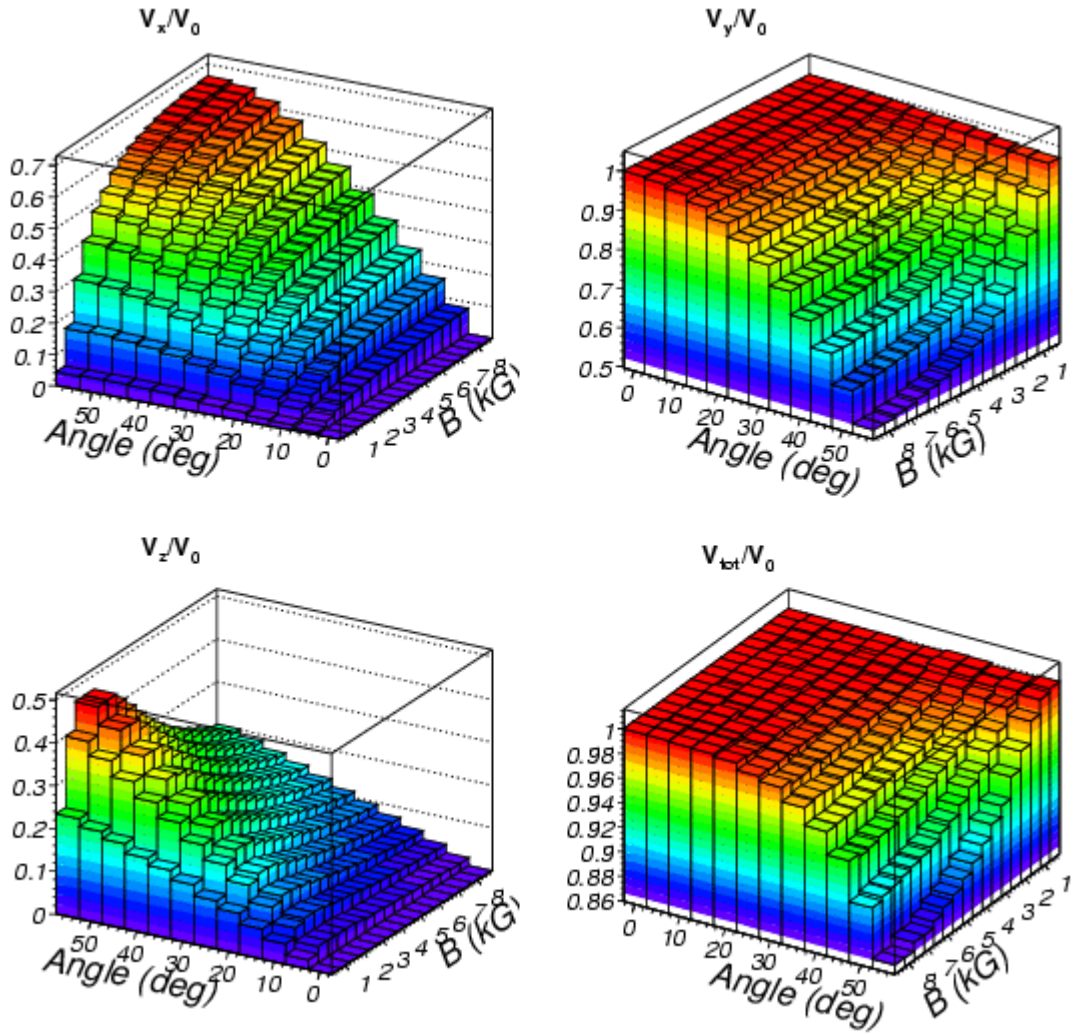
Scaling Law - EHS Data



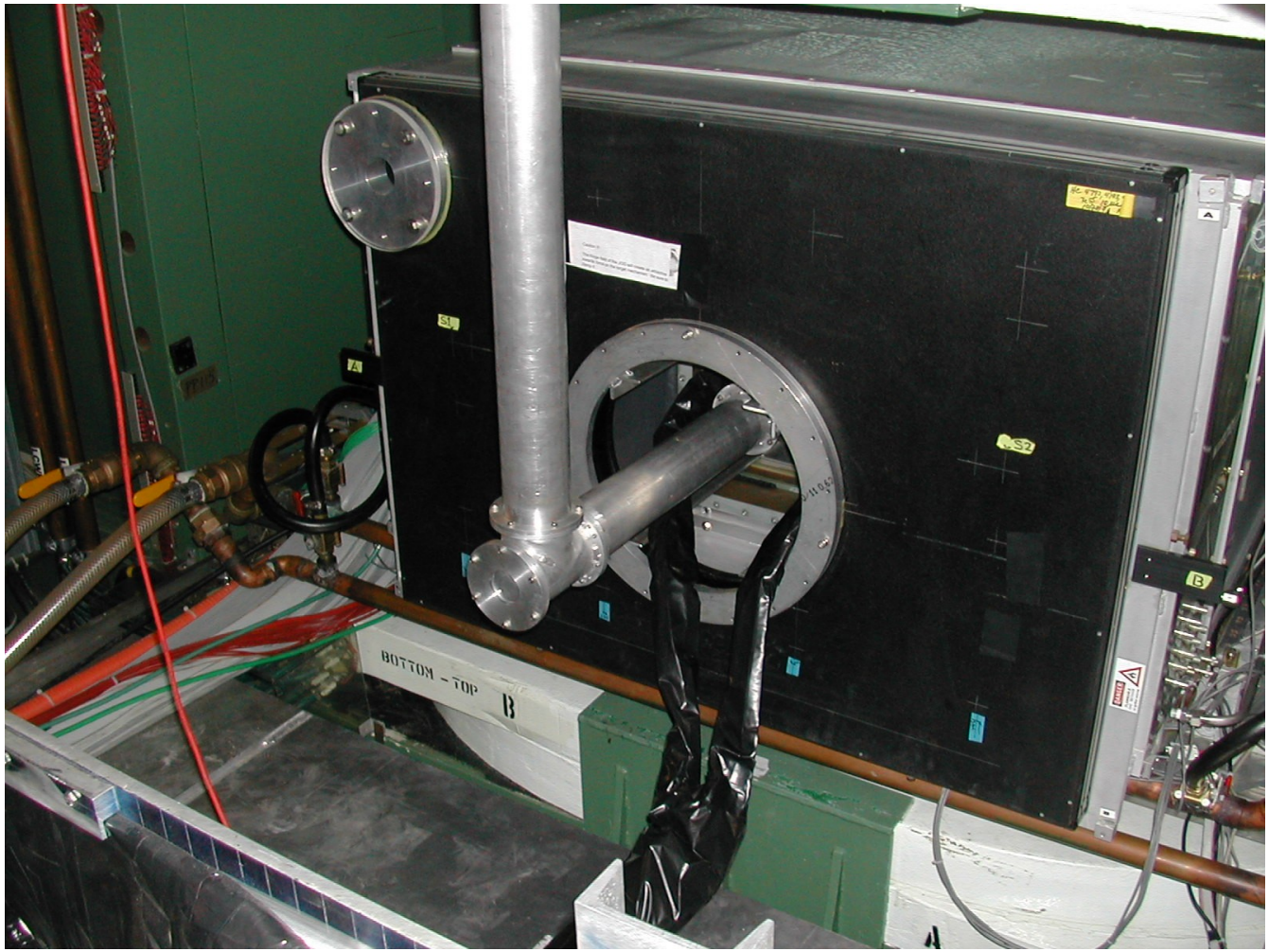
- European Hybrid Spectrometer Data
  - pp->p++X at 400 GeV/c
  - as a function of squared momentum transfer t for various multiplicities

TPC distortion corrections

- Drift velocity components vs Angle and magnetic field strength
- The effects are large in the field of the JGG



Cryogenic target mounted in TPC



Cosmic Ray shower simulation – existing data is insufficient

MIPP

C. Meurer et al.

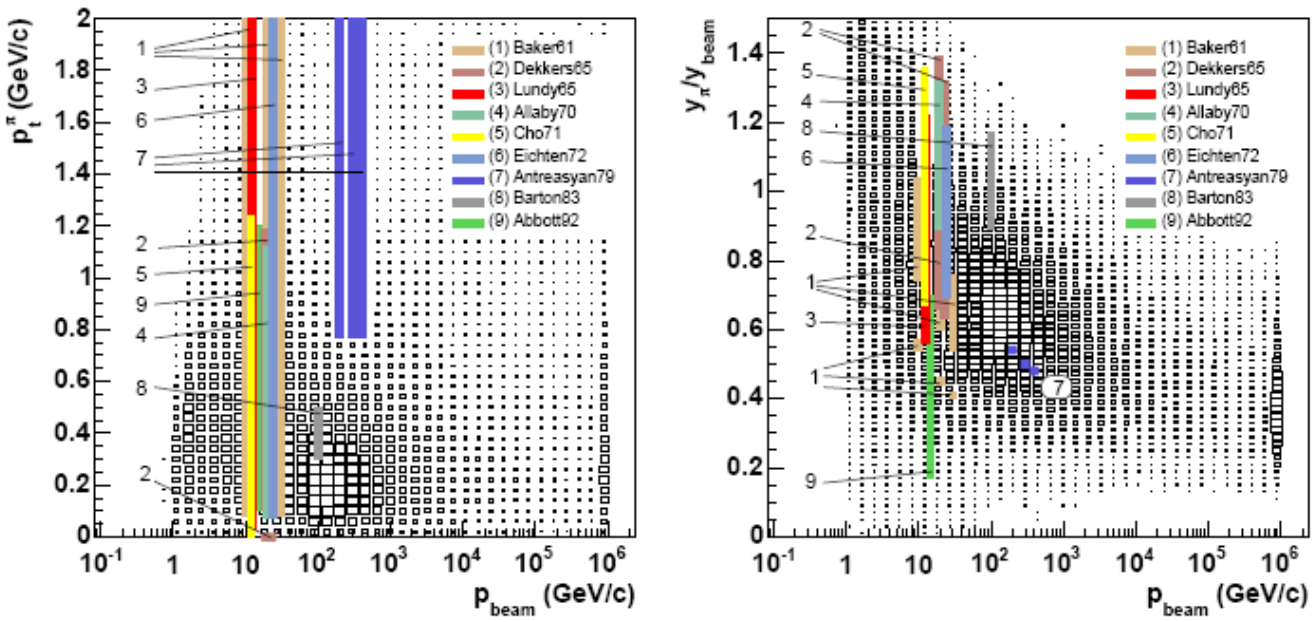
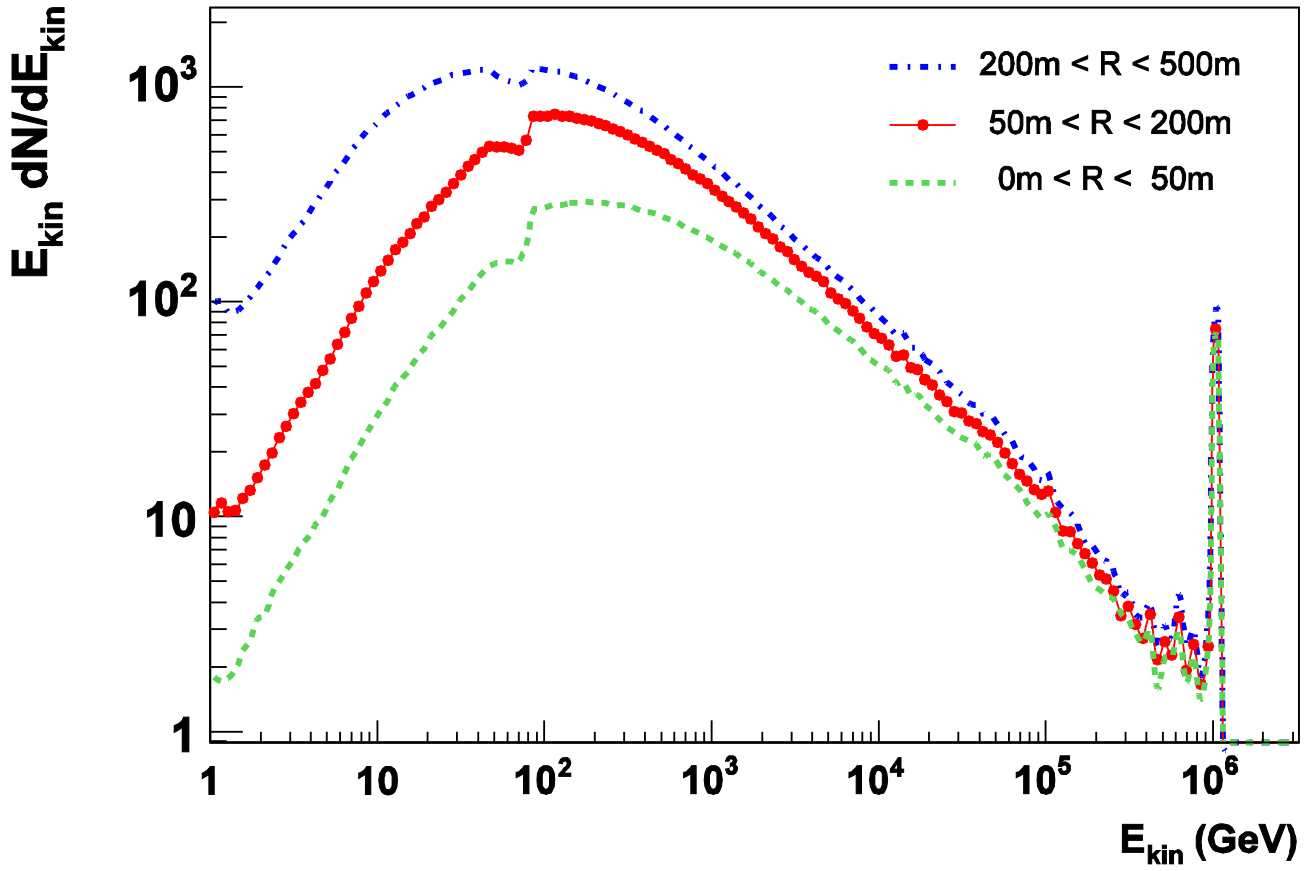


Fig. 9. Compilation of the phase space regions covered by fixed target data given in transverse momentum and rapidity of secondary particles and the phase space regions covered by the $\theta - p_{sec}$ data (see Fig. 8), whereas an approximate conversion of the covered phase space has been done. Left panel: transverse momentum of secondary pions vs. total momentum of proton projectiles. Right panel: rapidity of secondary pions normalized by the beam rapidity vs. beam momentum.

Simulation of Cosmic Ray air showers

- Meurer et al – Cosmic ray showers discontinuity
  - Gheisha at low energies and QGSJET at higher energies