Particle Production Results from the MIPP Experiment

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Joint Experimental-Theoretical Seminar
at Fermilab
Friday, 9 July 2010

Outline

- Introduction to the MIPP experiment
  - Physics motivation
  - Detector
  - Beamline
- Data analysis
  - Event reconstruction
    - Tracking
    - Particle identification
  - Results
    - NuMI target data analysis
    - Forward neutron cross sections
- MIPP Upgrade
  - Why?
  - How?

The MIPP collaboration

MIPP

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E. Swallow - Elmhurst College and EFI

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W. Baker, D. Carey, J. Hylen, C. Johnstone, M. Kostin, N. Mokhov, A. Para, R. Raja, S. Striganov - Fermi National Accelerator Laboratory

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P. Hanlet, O. Kamaev, D. Kaplan, H. Rubin, Y. Torun - Illinois Institute of Technology

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T. Bergfeld, A. Godley, S. R. Mishra, C. Rosenfeld, K. Wu - University of South Carolina

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The MIPP experiment

- Approved in November 2001, installed in Meson Center MC7,
  14 months physics run ended in February 2006 – 18 million events
- Use 120 GeV/c Main Injector protons to produce
  - secondary beams of $\pi^{\pm}$, $K^{\pm}$, and p, $\overline{p}$ from 5 GeV/c to 90 GeV/c
  - 120 GeV/c proton beam for NuMI and nuclear targets (A=1 to A=238)
- **Measure particle production cross sections** on fixed targets
  - various nuclei including hydrogen and the NuMI target
- Momenta of ~all charged particles measured with TPC and tracking chambers.
- Particle identification with dE/dx, ToF, multicell Cherenkov, and RICH detectors and calorimeter for neutrons.
- Open Geometry – Lower systematics than single arm spectrometers
- A proposal FNAL-P960 to **upgrade** MIPP was **deferred until publications**

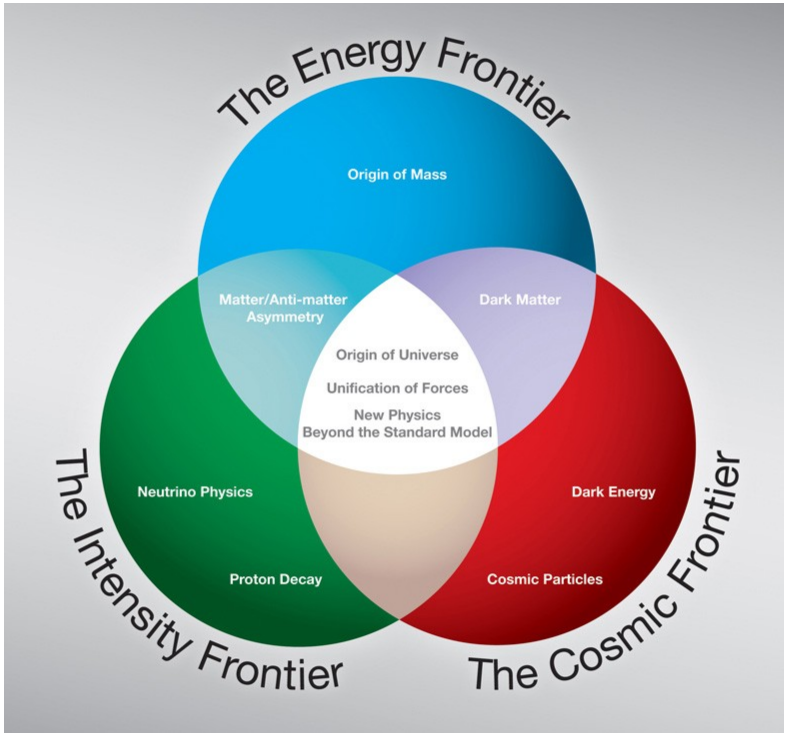
DAQ rate Increase x100

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 (NIM **A631**)
- 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
  - Proton Radiography – LLNL
  - NuMI target – pion and kaon production measurements to control the near/far systematics

MIPP physics and frontiers

- Intensity Frontier
  - Neutrino flux from MIPP measurements of Kaon and Pion production on NuMI targets.
  - Mu2e beam
- Cosmic Frontier
  - Cosmic Ray shower development in atmosphere from MIPP cross sections on Nitrogen target.
- Energy Frontier
  - Better understanding of hadronic showers in calorimeters, measure particle correlations
- Good Physics behind the frontier
  - Missing Baryon resonances
  - ....



Hadronic shower simulation

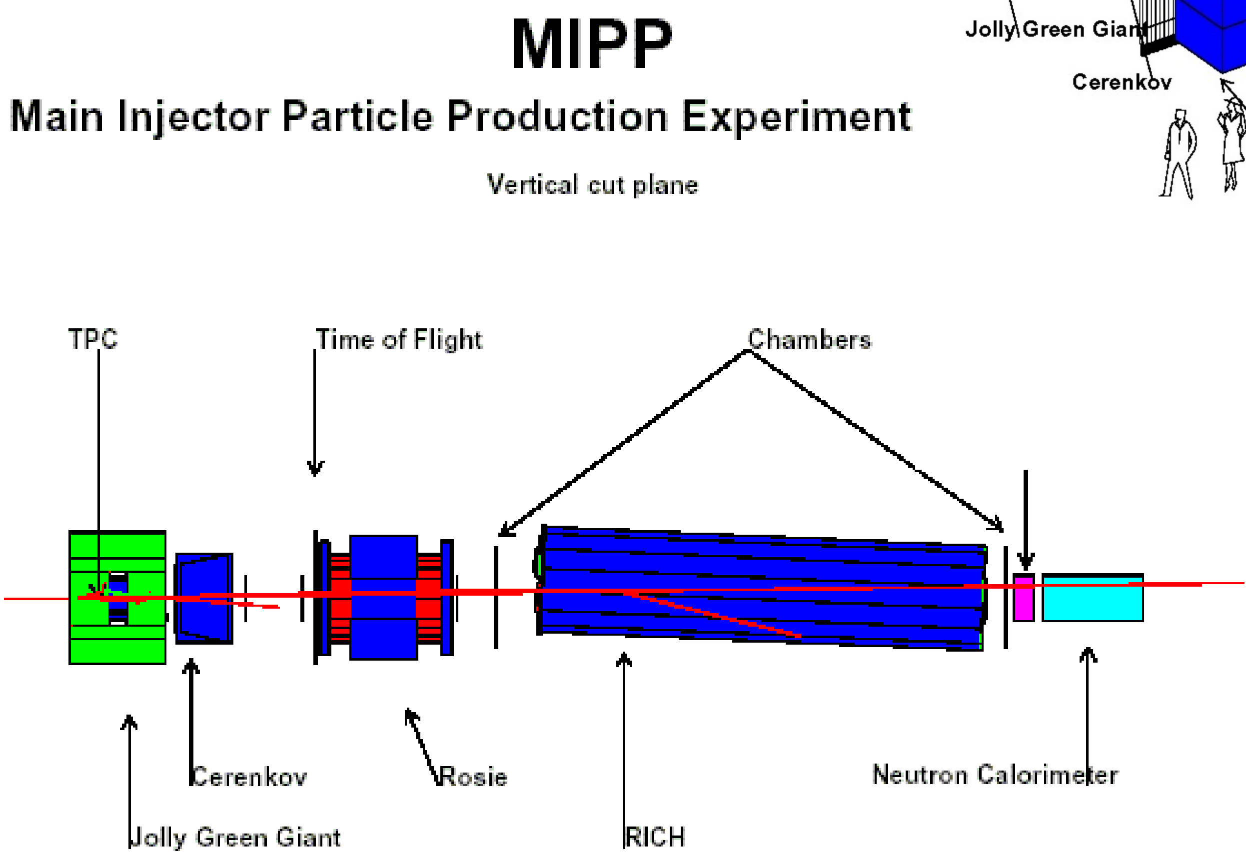
- Programs like Geant4, MARS, Fluka, etc. model hadronic interactions based on available data.
  - No first principles, non-perturbative QCD (strong interaction) calculations are possible
  - Most existing data are low statistics, with poor particle id, sometimes contradictory
- All neutrino flux problems (NuMI, MiniBoone, K2K, T2K, NOνA, Minerνa), all Calorimeter design problems, and all Jet energy scale systematics (not including jet definition ambiguities here) can be reduced to one problem: the current insufficient state of hadronic shower simulators.
- MIPP has high statistics, low systematics data with 6 beam species.
- A library of MIPP events can be used in the simulation packages.

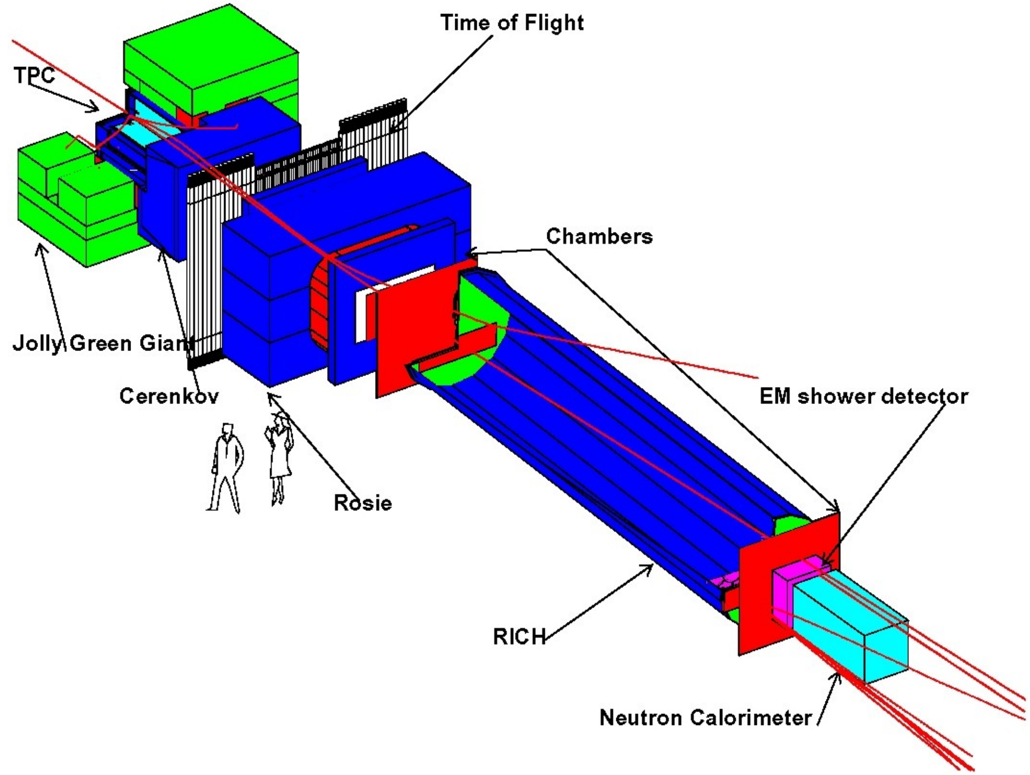
MIPP 'worm' on 5/31/2002

MIPP

The MIPP detector

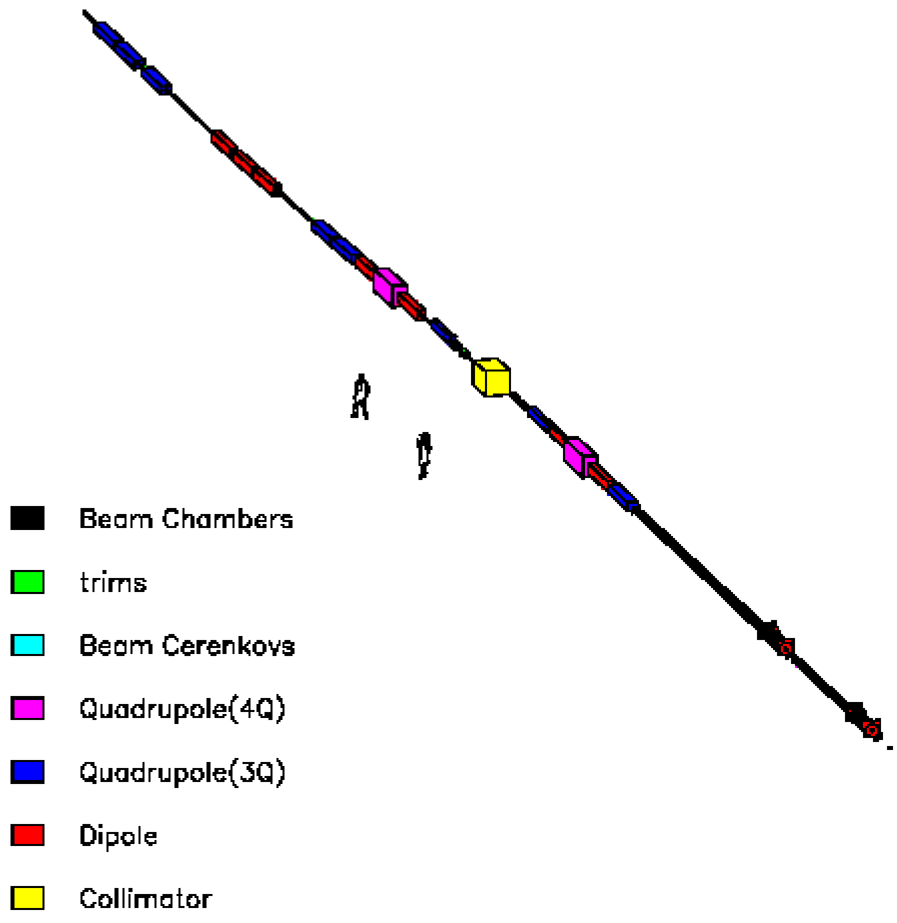
TPC and 6 Chambers for tracking

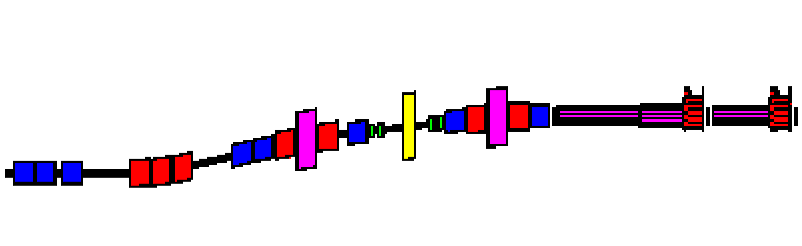




TPC dE/dx	0 to 1 GeV/c
ToF	to 2 GeV/c
Ckov	to 17 GeV/c
RICH	to 120 GeV/c

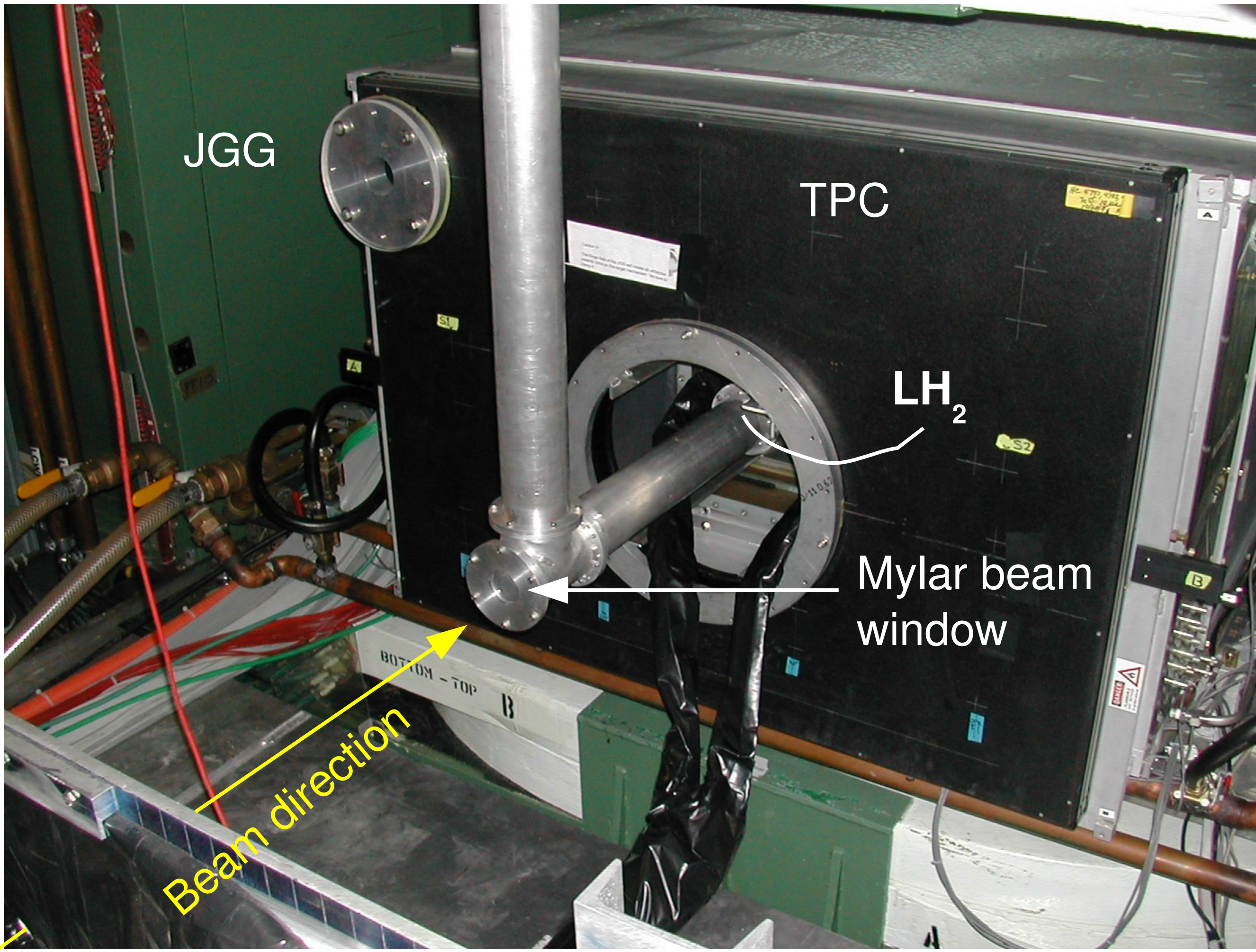
The MIPP beam

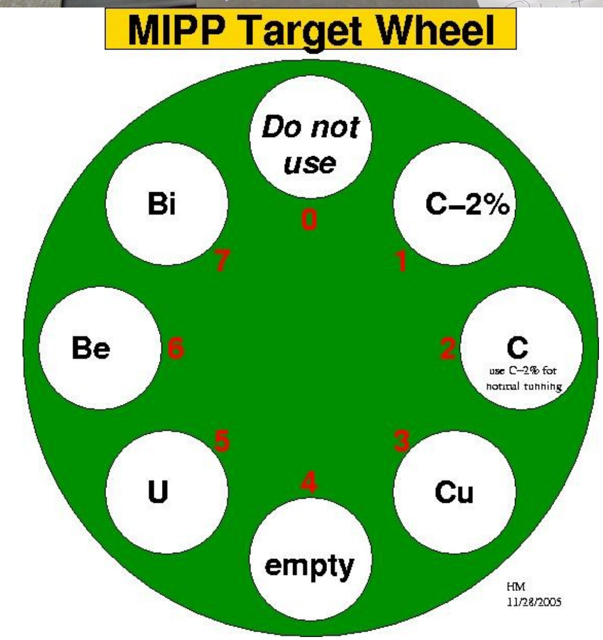




- MIPP design, very short from primary to secondary target (95 m)
- Excellent performance, kaons down to 3 GeV/c (in upgrade), enough kaons survive.
- Ran it successfully in MIPP from 5-85 GeV/c secondaries and 120 GeV/c primary protons.
- Excellent particle ID capabilities using 2 Beam Cherenkovs. For low momenta (<~10 GeV/c) Beam-ToF is also used for pid.
- Design principles and lessons learned used in M-test at Fermilab.

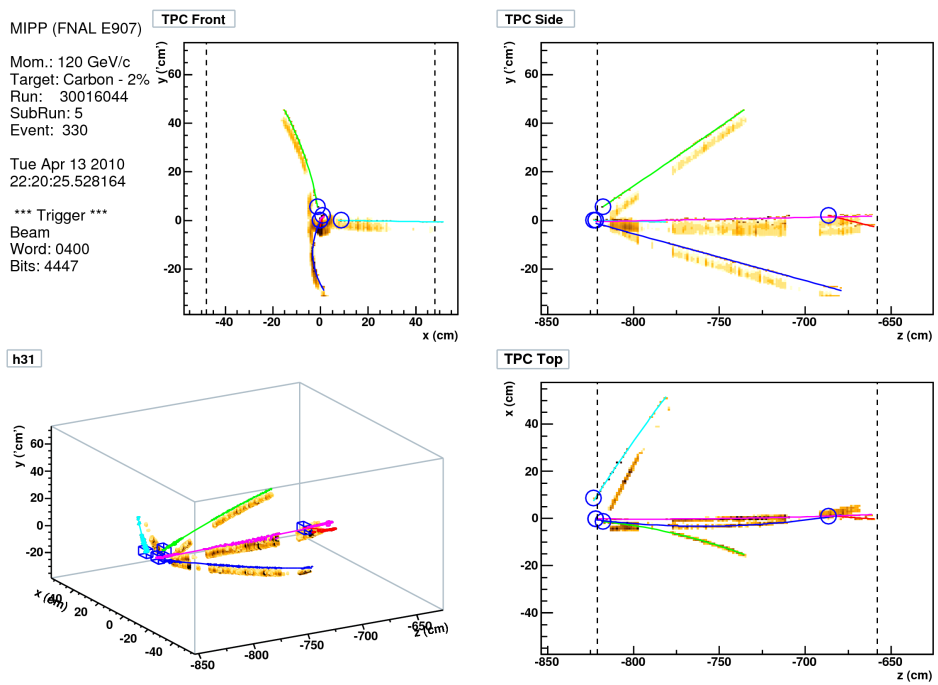
Cryogenic target mounted in TPC, NuMI target and target wheel

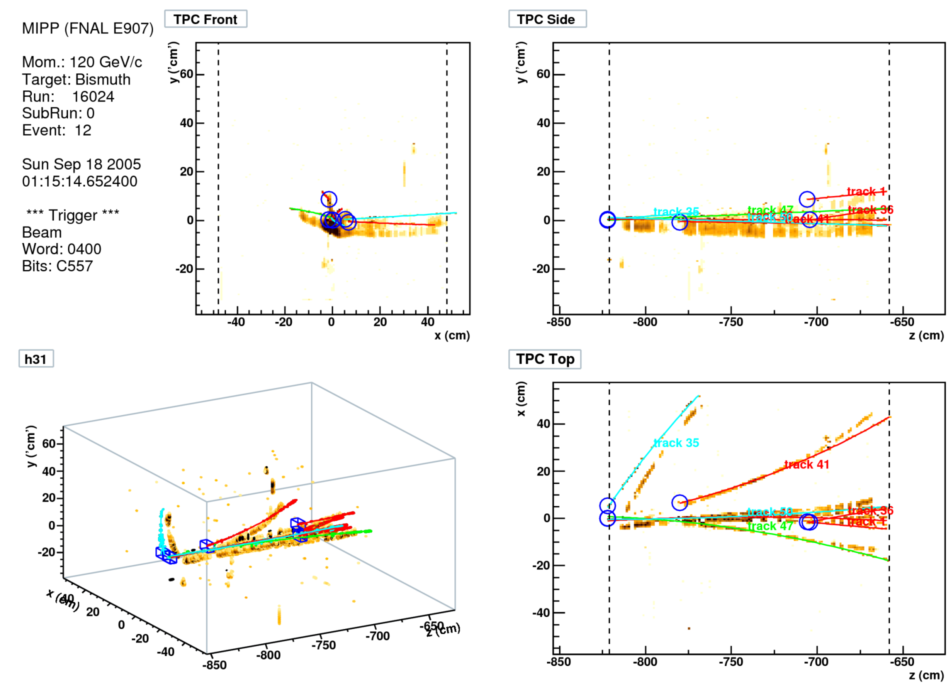




Event Display – Data and MC

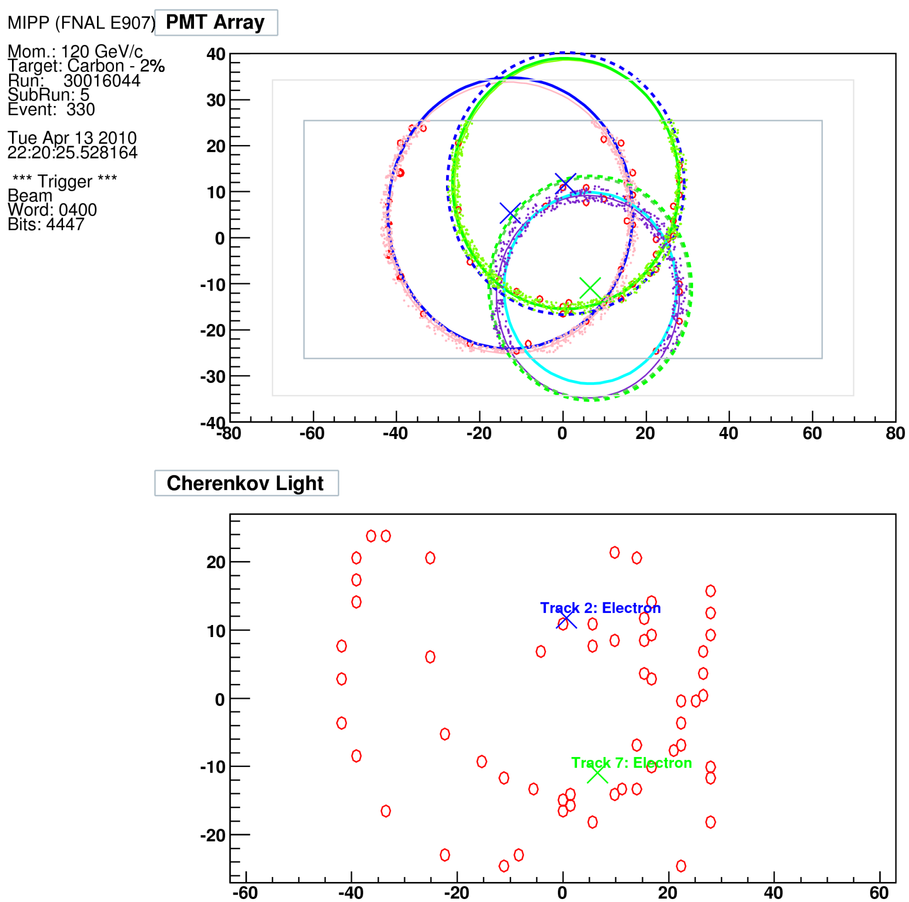
- TPC hits and reconstructed tracks

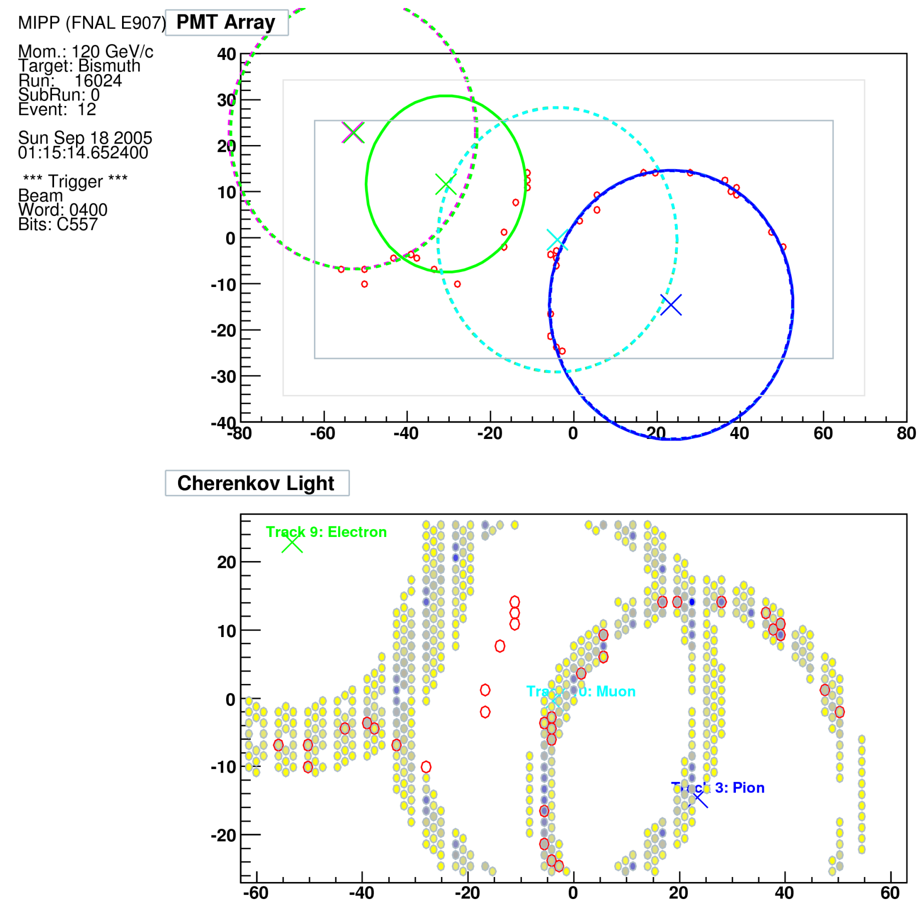




Event Display – Data and MC

- RICH hits and reconstructed rings





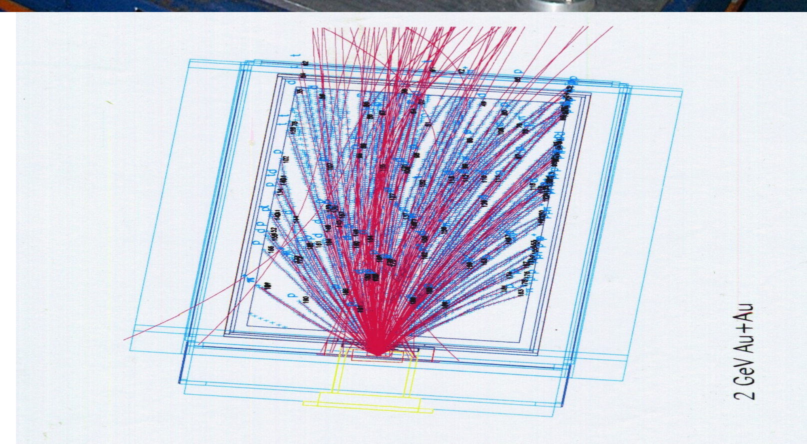
red: pmt hits

yellow/grey: hit probability from reconstruction

Track reconstruction

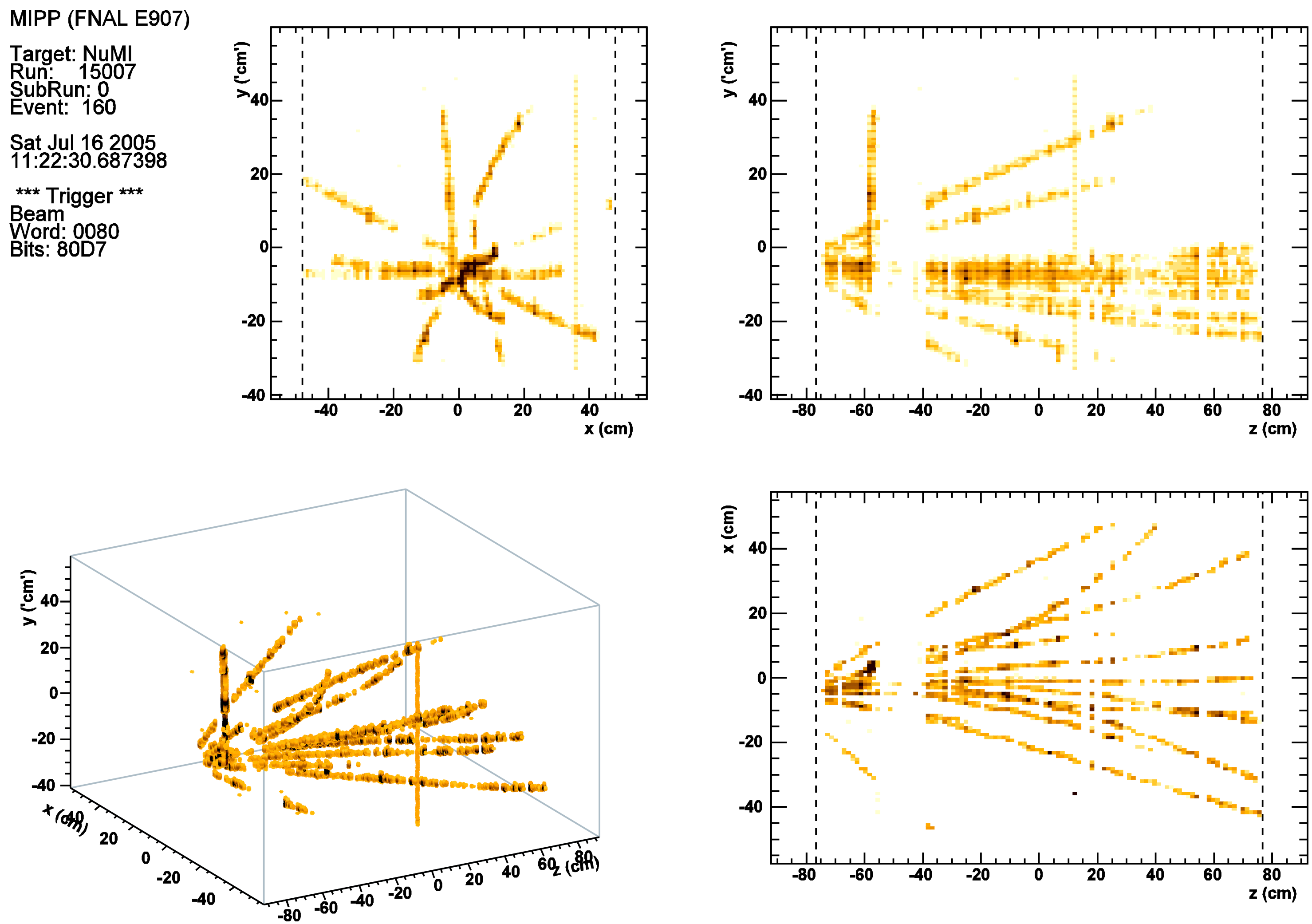
MIPP TPC

- 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
  - Can handle much larger multiplicities than we encounter in MIPP
    - No problem with overlapping tracks

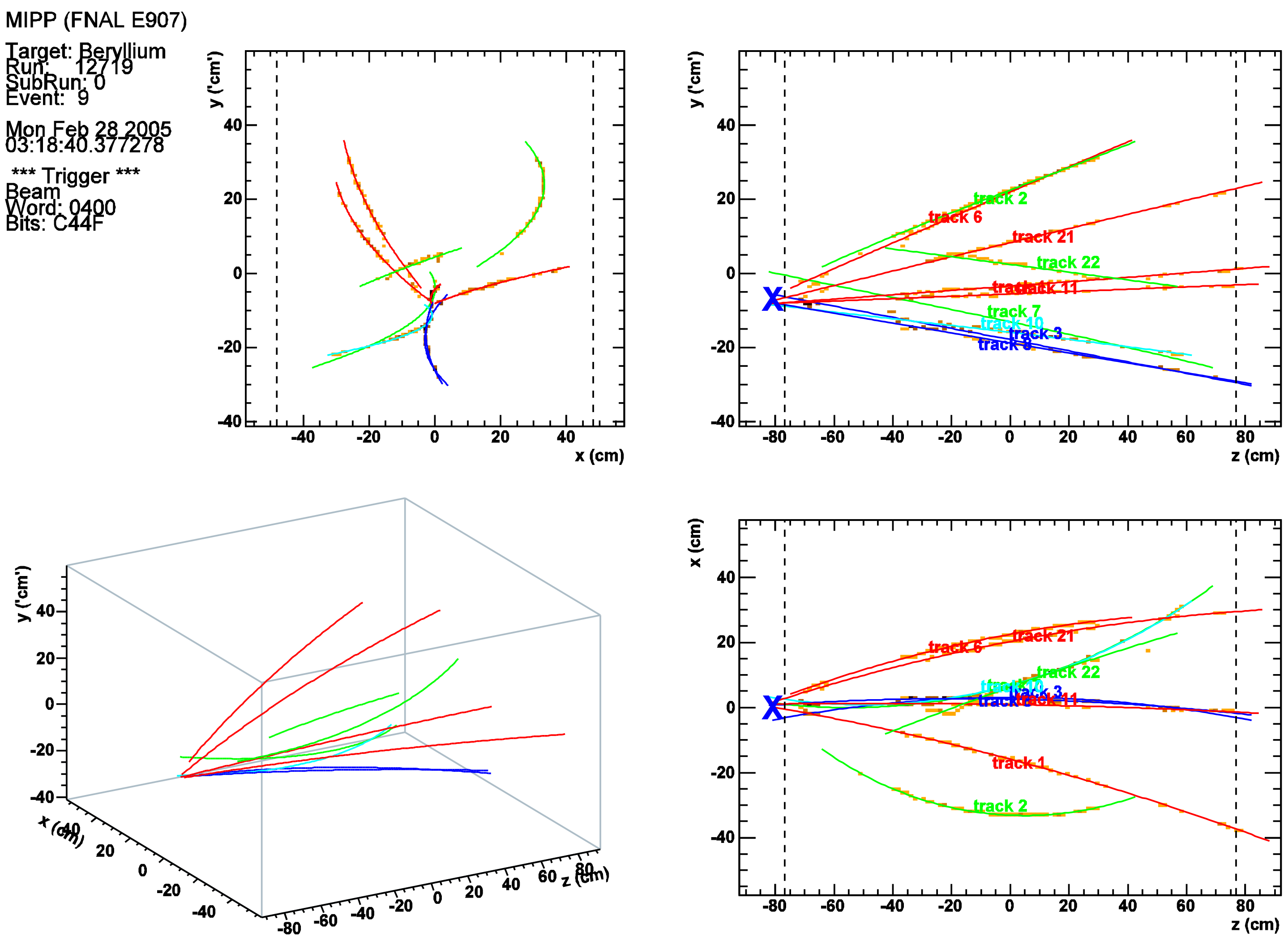


High multiplicity event, BNL-E910

MIPP TPC – Raw data

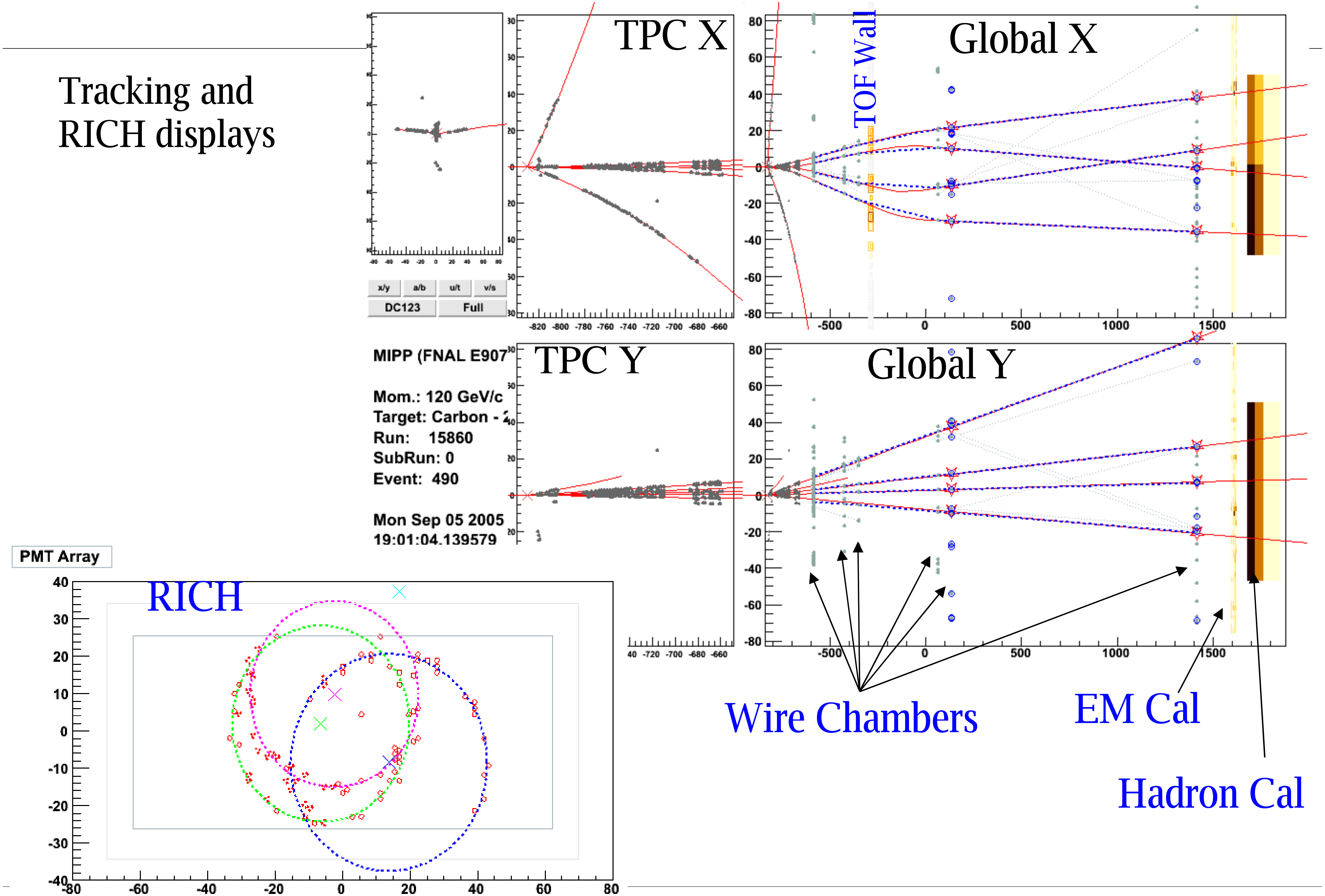


MIPP TPC – Reconstructed tracks



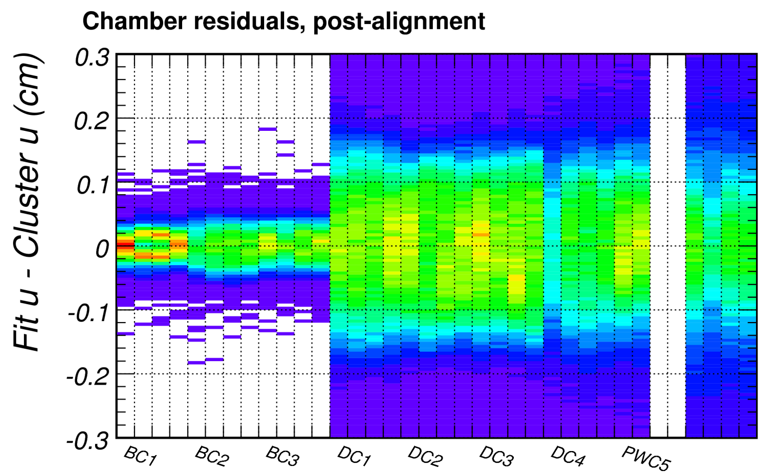
Reconstructed p-C 120GeV/c event

Tracking and RICH displays

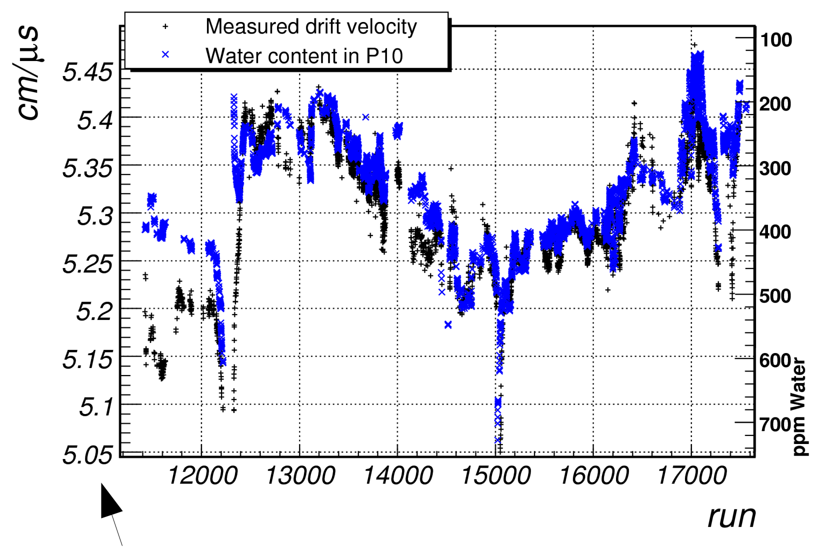


Spectrometer calibration

- Chamber alignment done for every run
  - Helped to refine magnetic field maps



- TPC electron drift velocity measured for every run
  - Strong correlation with water vapor contamination in Ar/CH_4

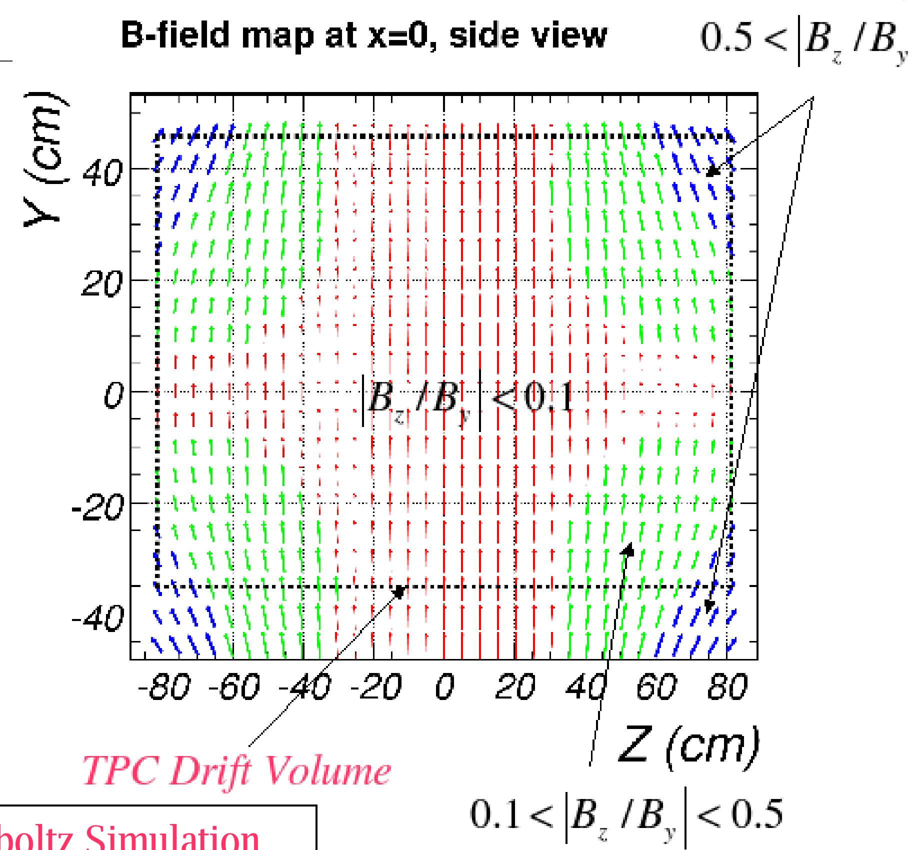


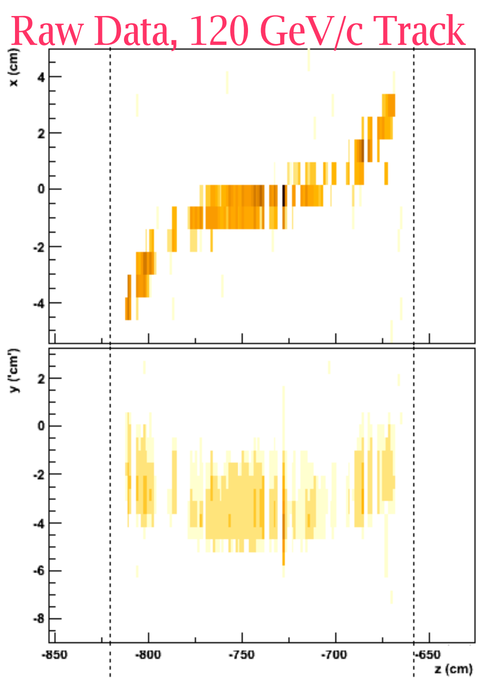
suppressed 0

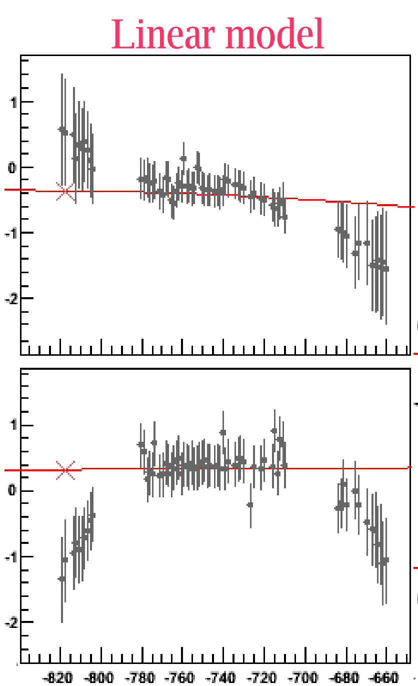
TPC hit reconstruction

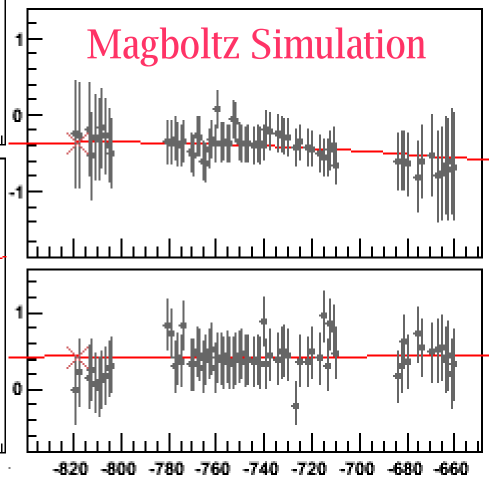
- JGG field is non-uniform
  - Huge ExB effect on electron drift in TPC
- Previous experiments applied corrections based on steady state solution to linear model

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







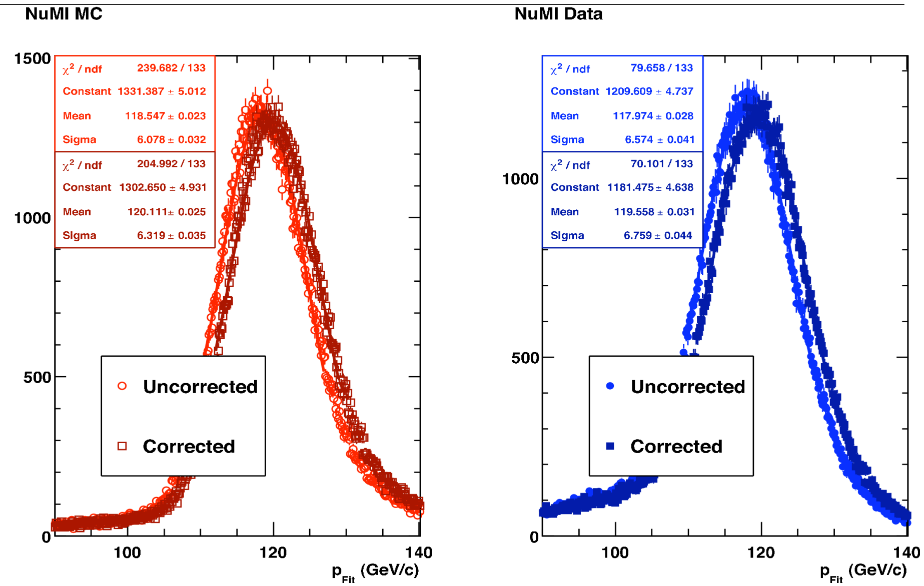


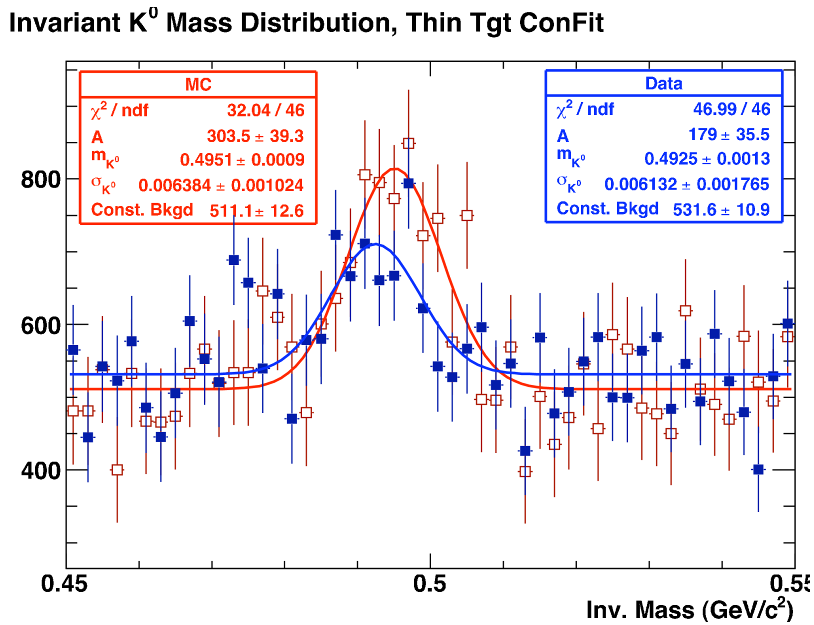
Magboltz simulation to map out drift velocity components as a function of v_0, B-field strength, and angle between E and B-fields.
Good agreement with TPC data.

Track reconstruction

MIPP

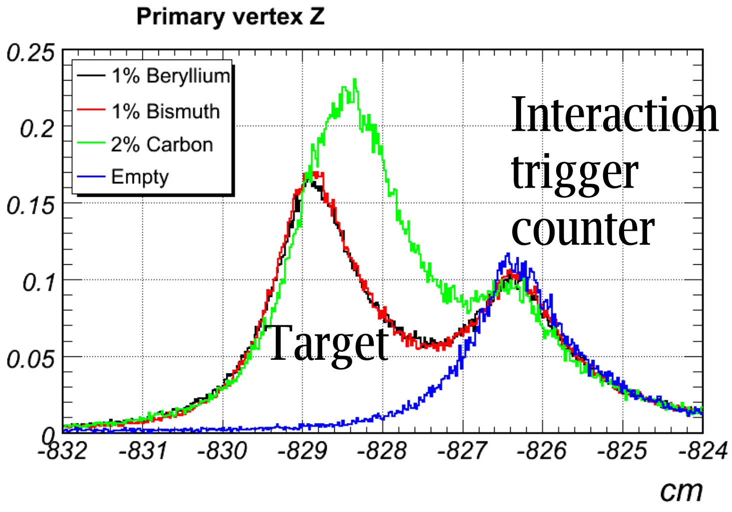
- TPC track determination (Runge-Kutta)
  - Non-uniform B-field complications solved, detailed Ziptrack B-field map was used
- Matched to wire chamber hits to form global tracks
  - Fit using track templates
- Momentum resolution 5.5% at 120 GeV/c
- Absolute energy scale from
  - 120 GeV protons
  - Low momentum K^0_S
  - 0.85% correction

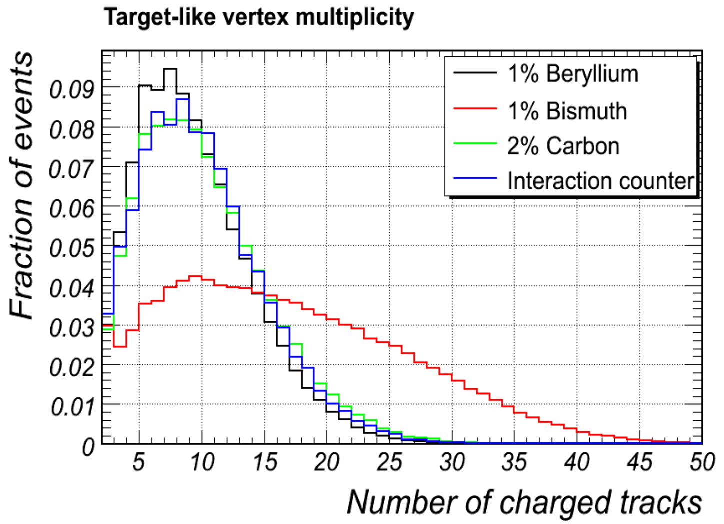




Vertex reconstruction

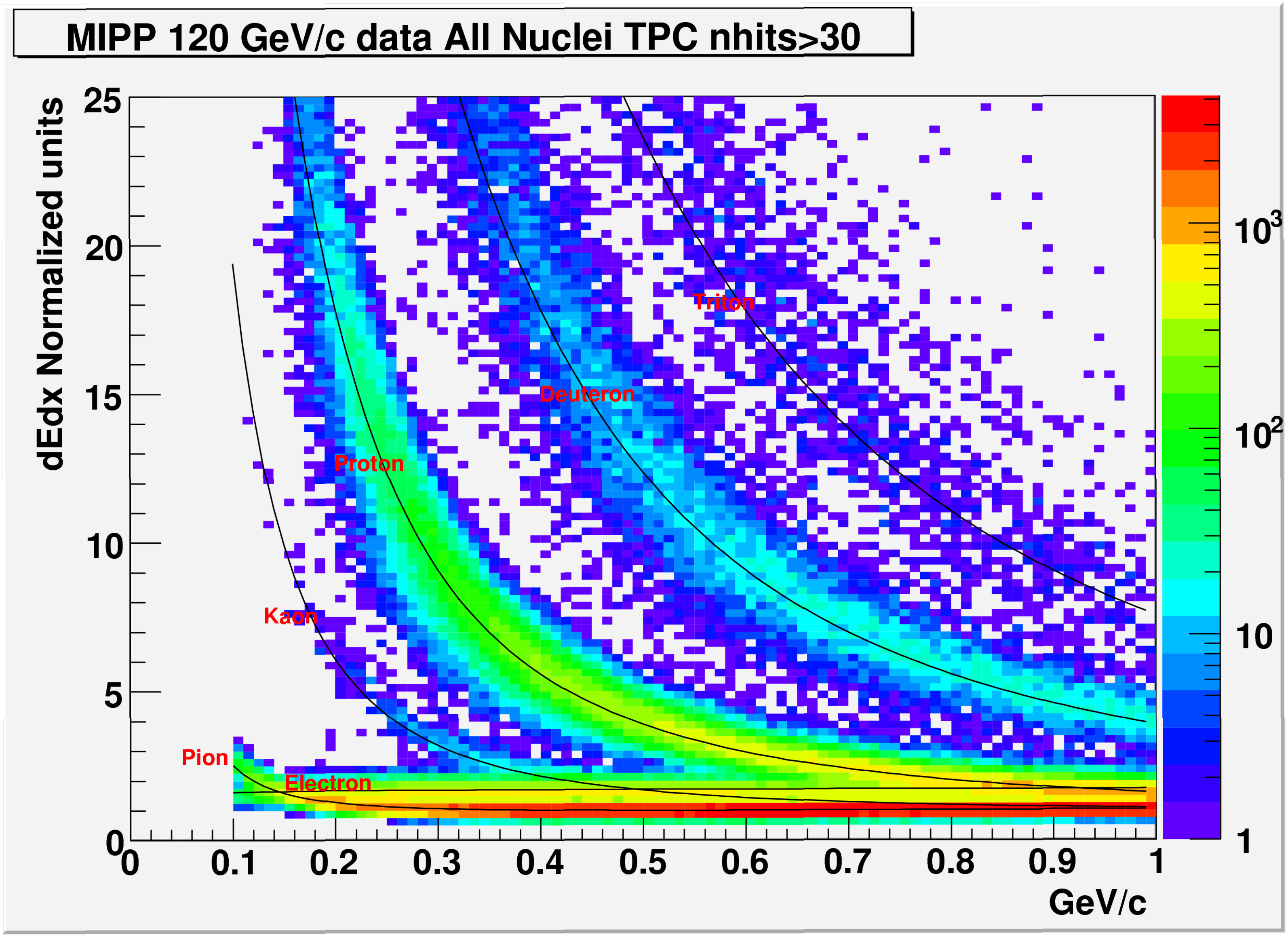
- Two steps to vertexing:
  - Vertex finding is done with iterative algorithm.
  - All tracks of each vertex are refit with the constraint of originating at the vertex. Uses track templates.
- Vertex resolution:
  - 6mm vertex Z resolution
  - X,Y resolution < 1mm
- Good separation of target interactions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





Particle Identification

dE/dx in the TPC - data

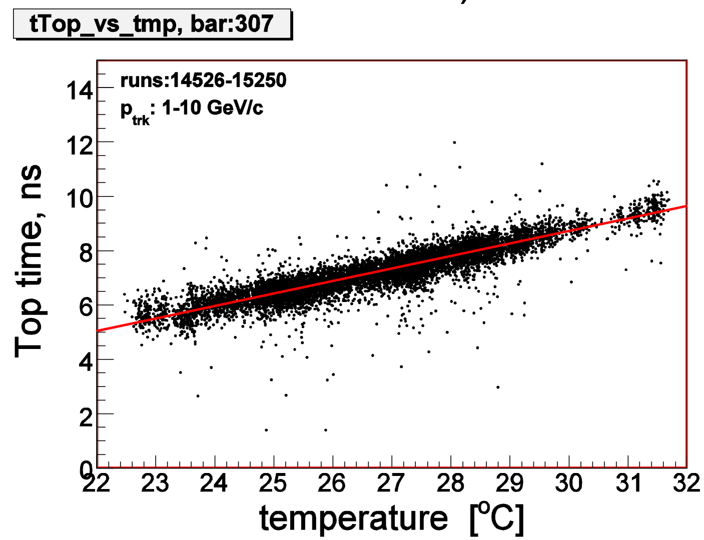


Time of Flight wall

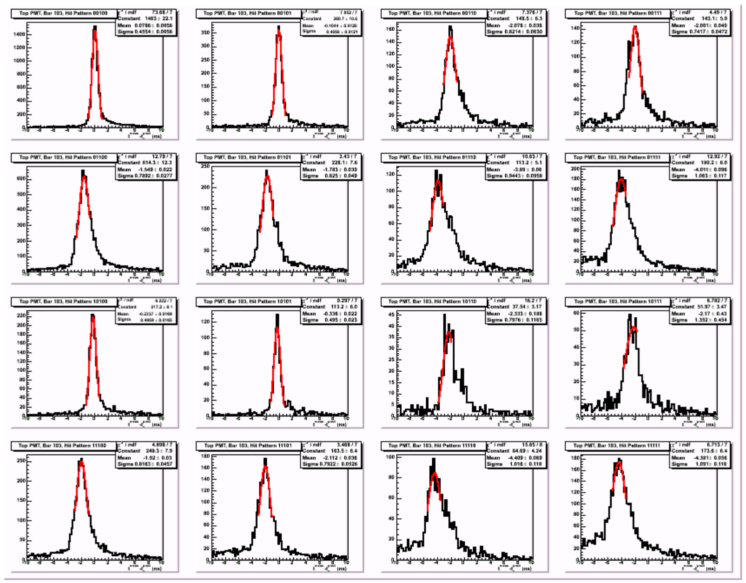
- Designed and built by MIPP
  - 5 cm x 5 cm square scintillator bars in Rosie aperture, 10 cm x 10 cm outside. ~200 ps resolution after all corrections.
  - ~200 ns of cable delay
    (needed for trigger formation and distribution)
    save cost: use Twist'N'Flat cables
  - CAMAC TDC and ADC readout

ToF wall calibration

- Pulse height correction (using adcs, corrects for discriminator slew)
- Temperature dependence in delay cables
  - up to 4000 ps effect

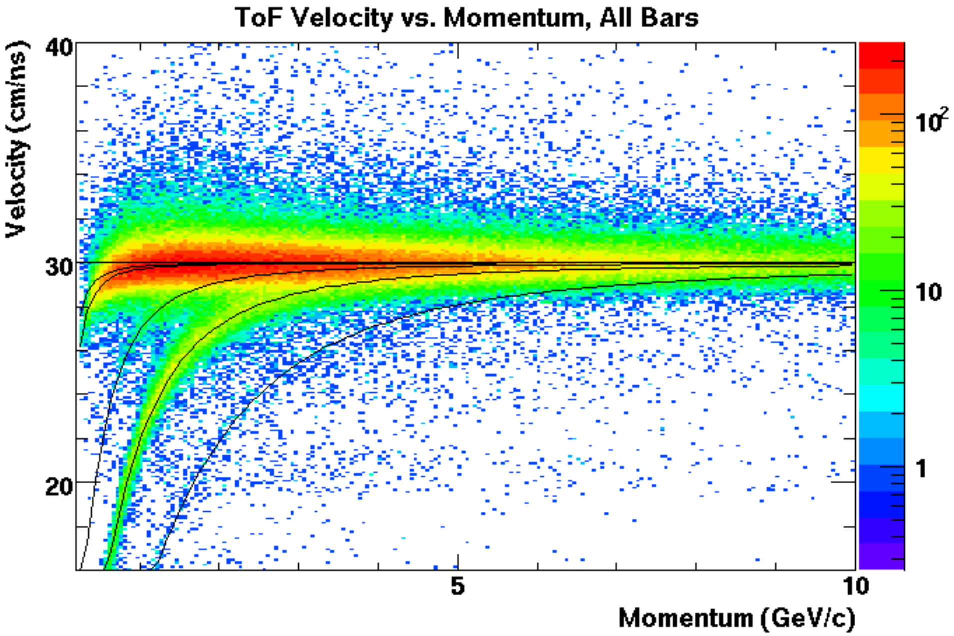


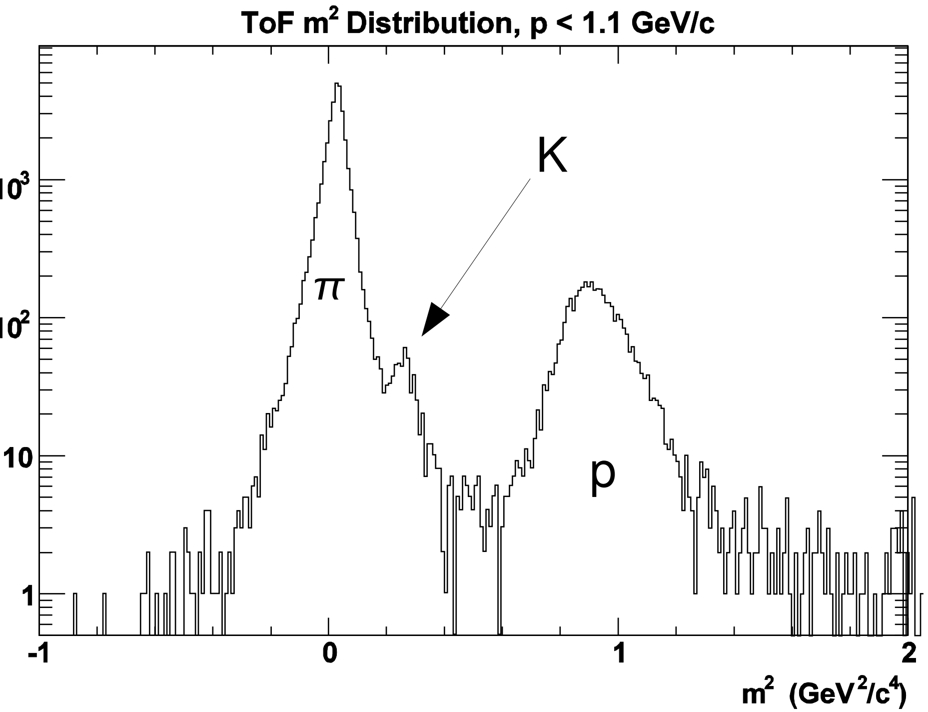
- Cross talk correction
  - Cross talk when neighboring bars are hit
  - Also next to neighboring channels
  - Due to capacitative coupling in delay cables
  - 2^4=16 time dependent correction constants per pmt



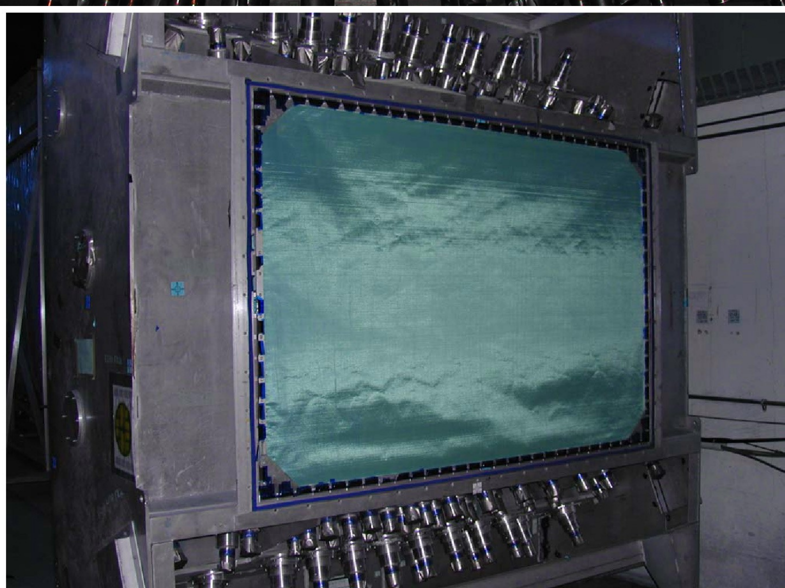
TOF particle ID

- TOF did not work as well as designed, but gives good PID over most of the momentum region it was supposed to cover after all corrections are applied carefully.

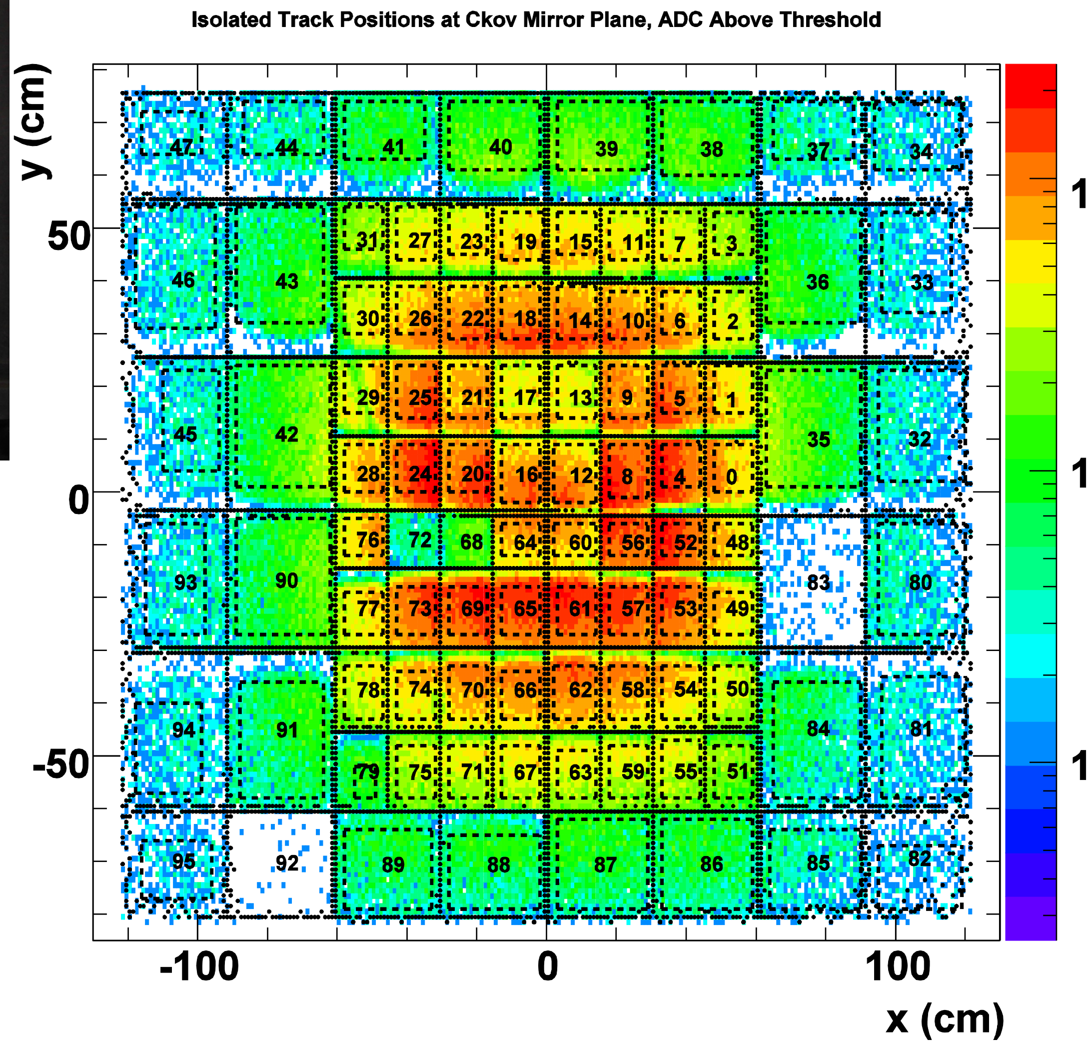




Multicell threshold Cherenkov

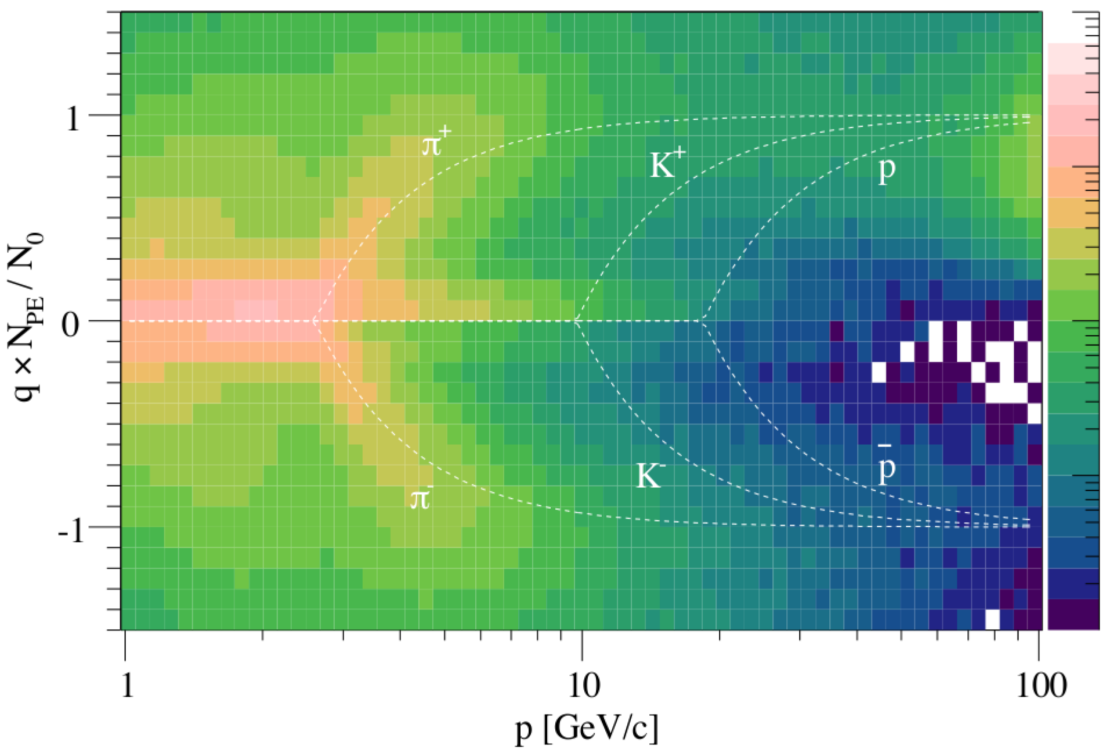


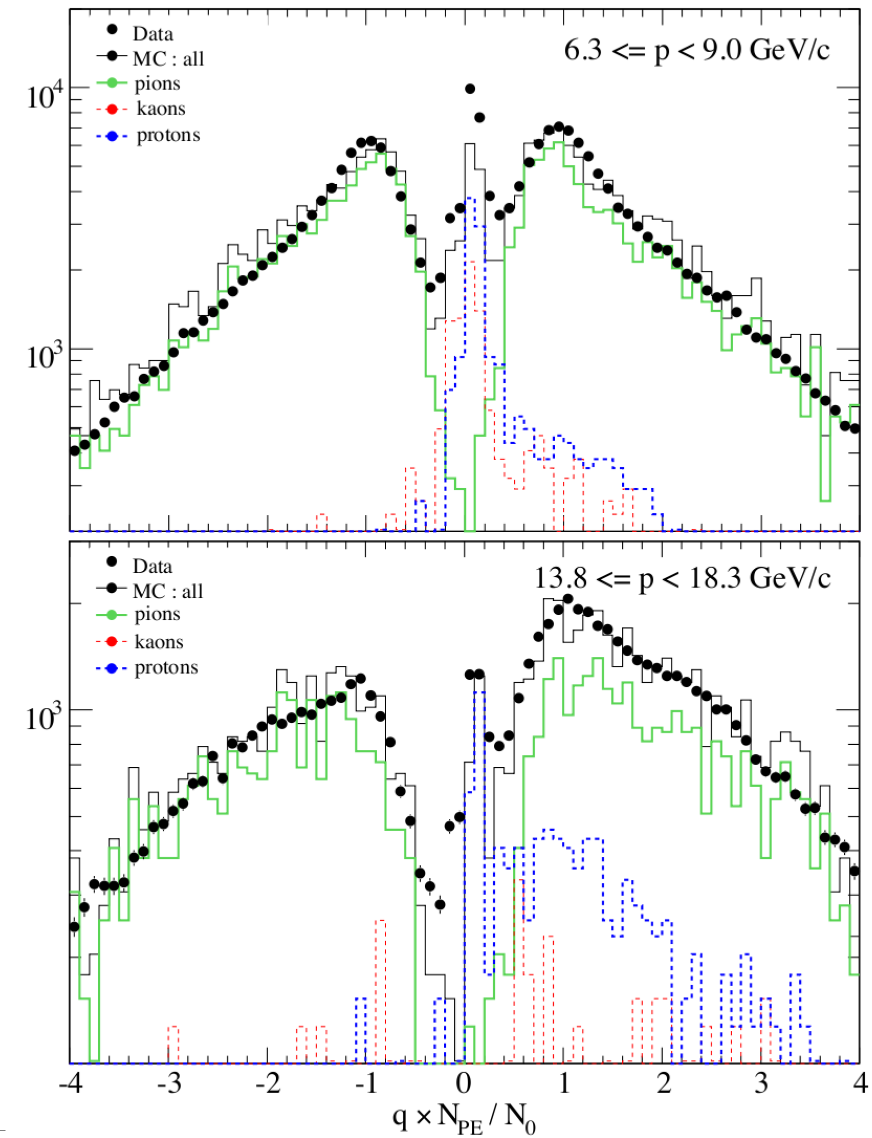
- C4F10 gas, Thresholds: π = 2.5 GeV/c, K = 8.9 GeV/c, p = 17.5 GeV/c



Cherenkov particle ID

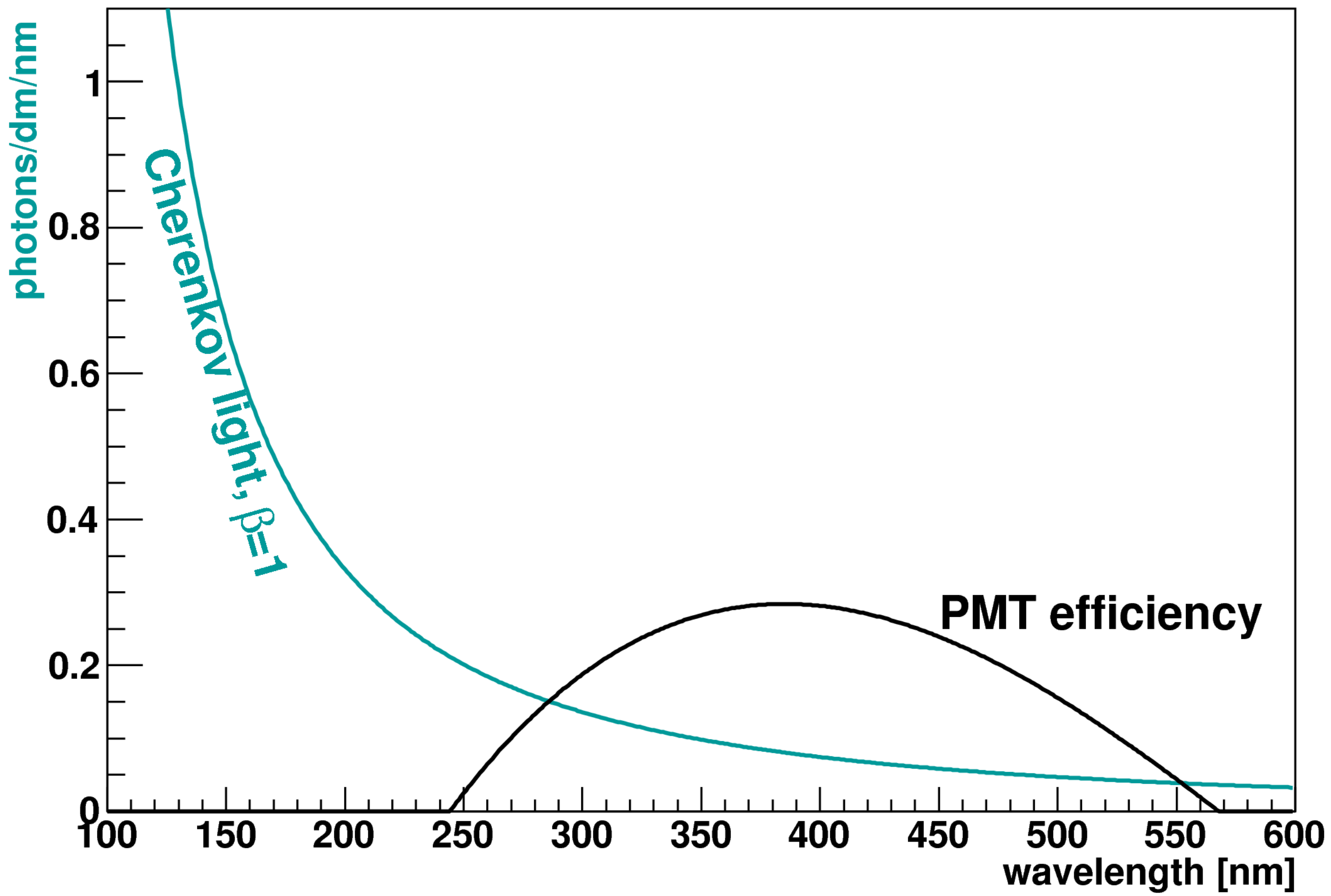
- Every mirror calibrated with data assuming pions and Poisson statistics.
  - Light yield lower than expected.
  - Normalized to β=1 to put all mirrors in same plot
  - NuMI target data and MC shown here





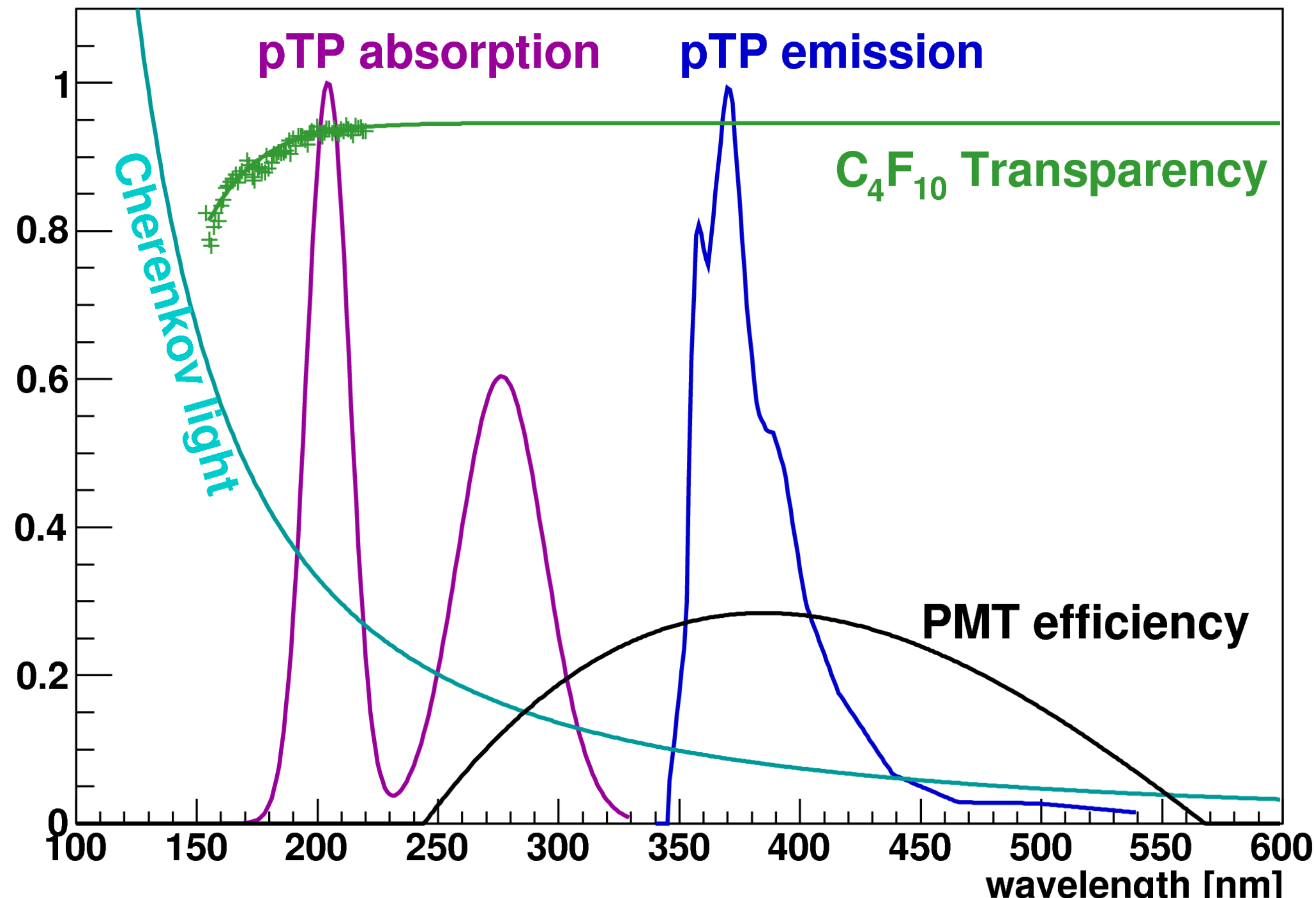
Cherenkov light yield

- Detect as much of the light produced through pmt glass window



Cherenkov light detection

- Use purified gas for good transparency
- Use wavelength shifting coating on pmts



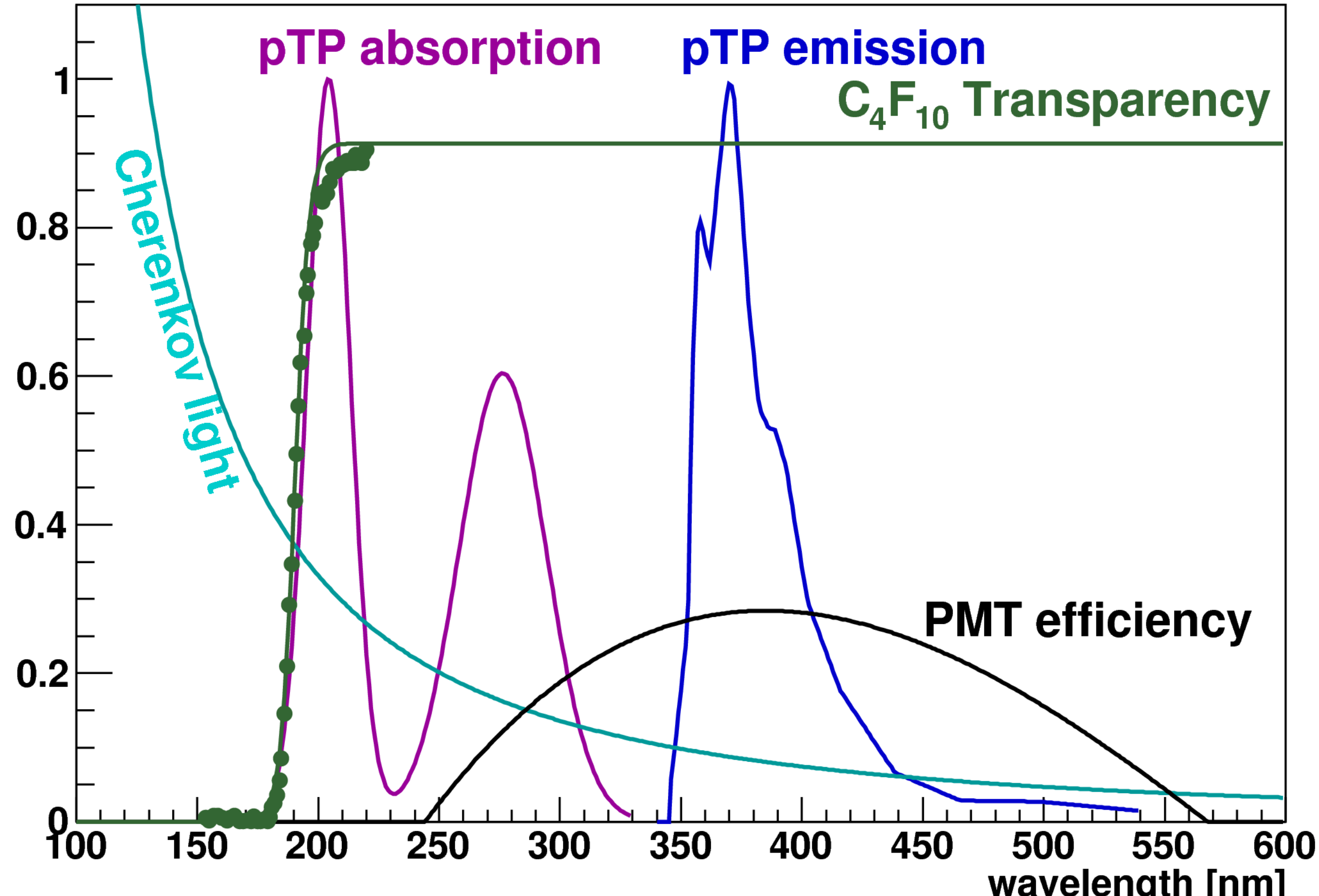
- This would produce a lot of photoelectrons, however...

  \+ Ullaland, NIM A553 (2005)

Cherenkov light detection

MIPP

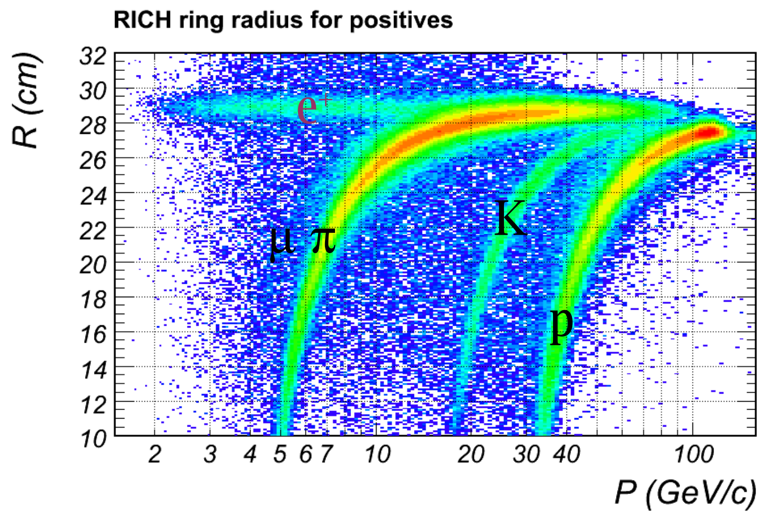
- MIPP gas was not purified and may have been more contaminated than the sample shown here. Transparency at low wavelengths was low. Molecular sieve and activated carbon to remove benzene, etc. from C4F10.

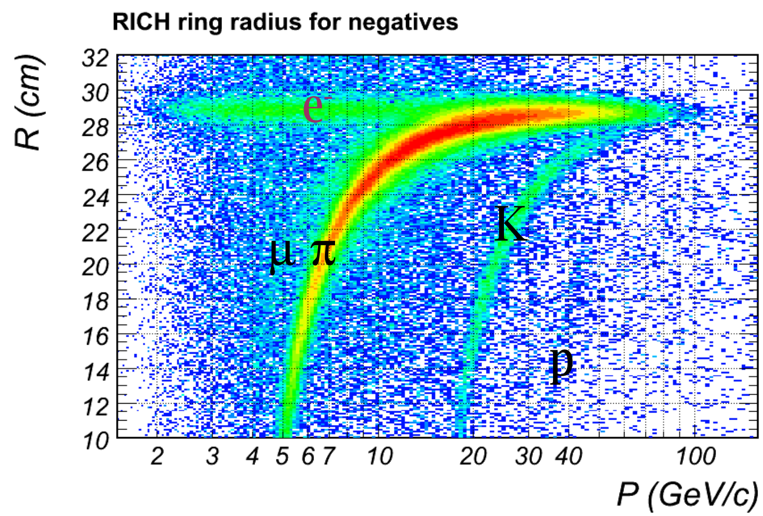


- Result: few photoelectrons
  - Ullaland, NIM A553 (2005), same gas before purification

RICH particle id

- From Selex, entirely new readout electronics and some PMTs replaced
- Radiator: CO_2 gas at STP
- Gives lots of hits for MIPP momentum range.
  - easy to fit good circles
- RICH ring radius gives very good particle ID
  - e/μ/π up to 12 GeV/c
  - π/K/p to 120 GeV/c

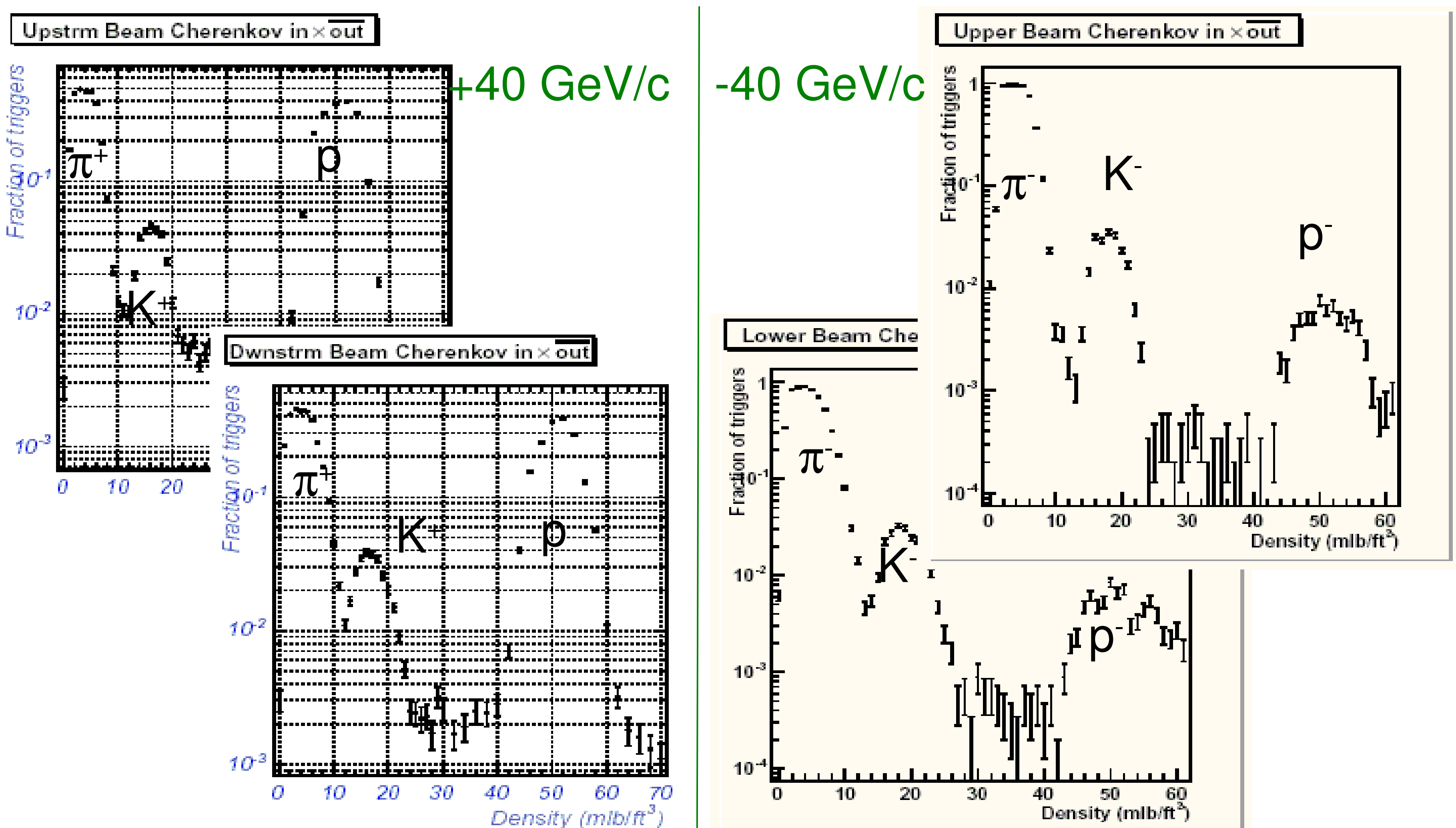




Beam Cherenkov Pressure Curve

MIPP

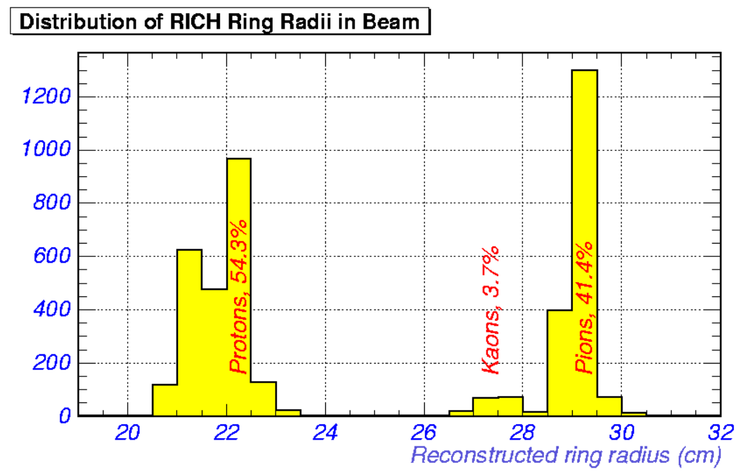
- Two differential Ckovs separate π/K or K/p depending on N_2 radiator pressure

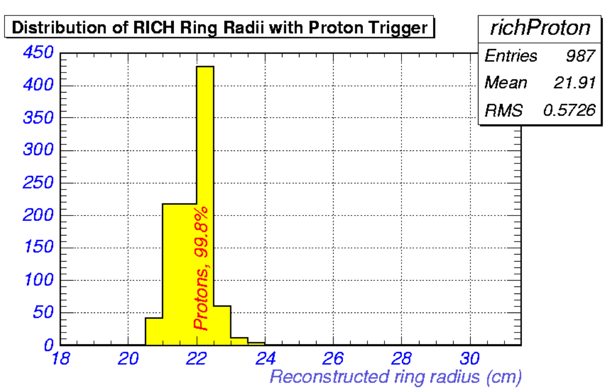


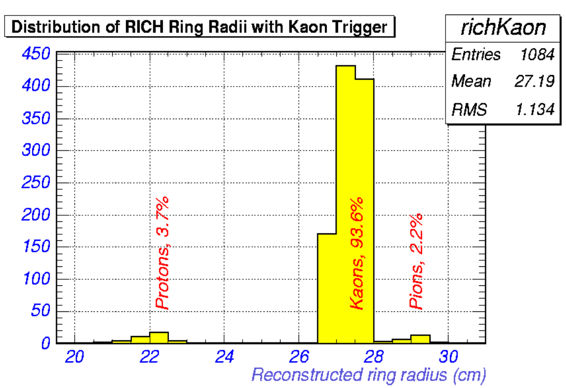
Beam Cherenkov performance

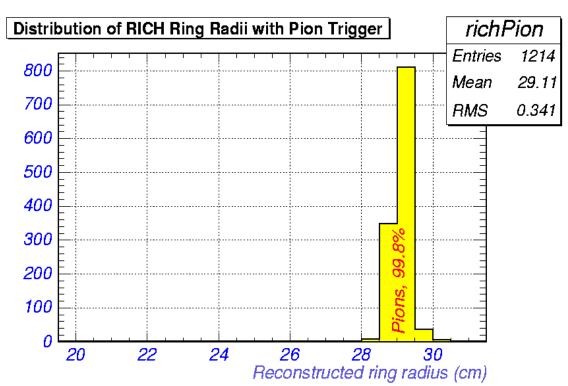
MIPP

- Uninteracted beam particles are identified in both beam and RICH
  - Comparison for +40 GeV/c beam – No additional cuts!
  - Offline cuts can clean up kaon beams further



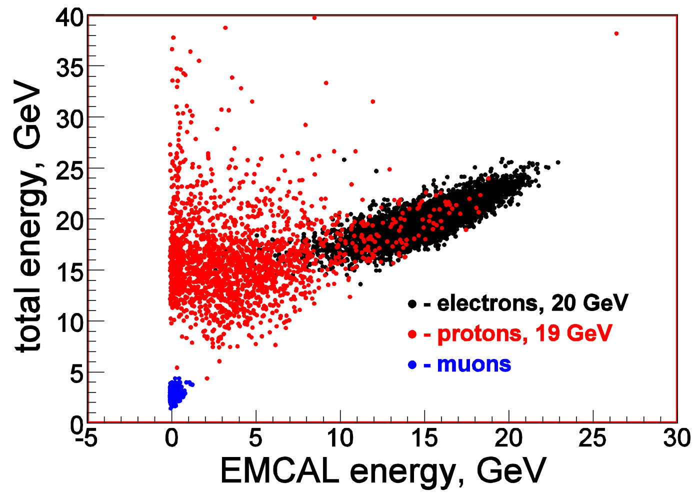


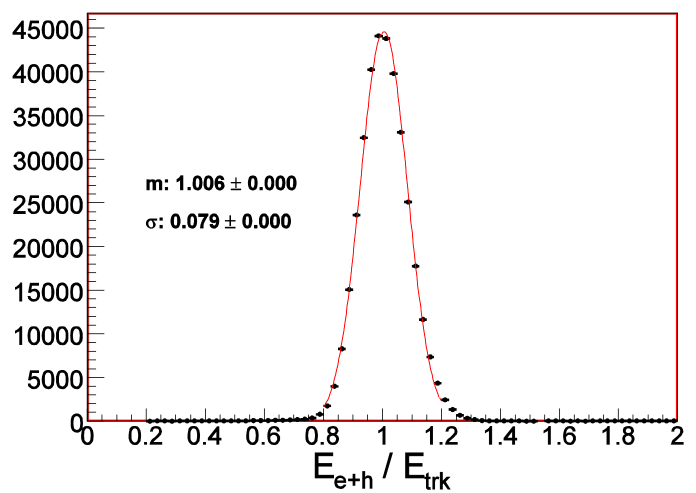




Calorimeters

- EM calorimeter followed by hadronic calorimeter
- NIM A598 (2009) 394-399

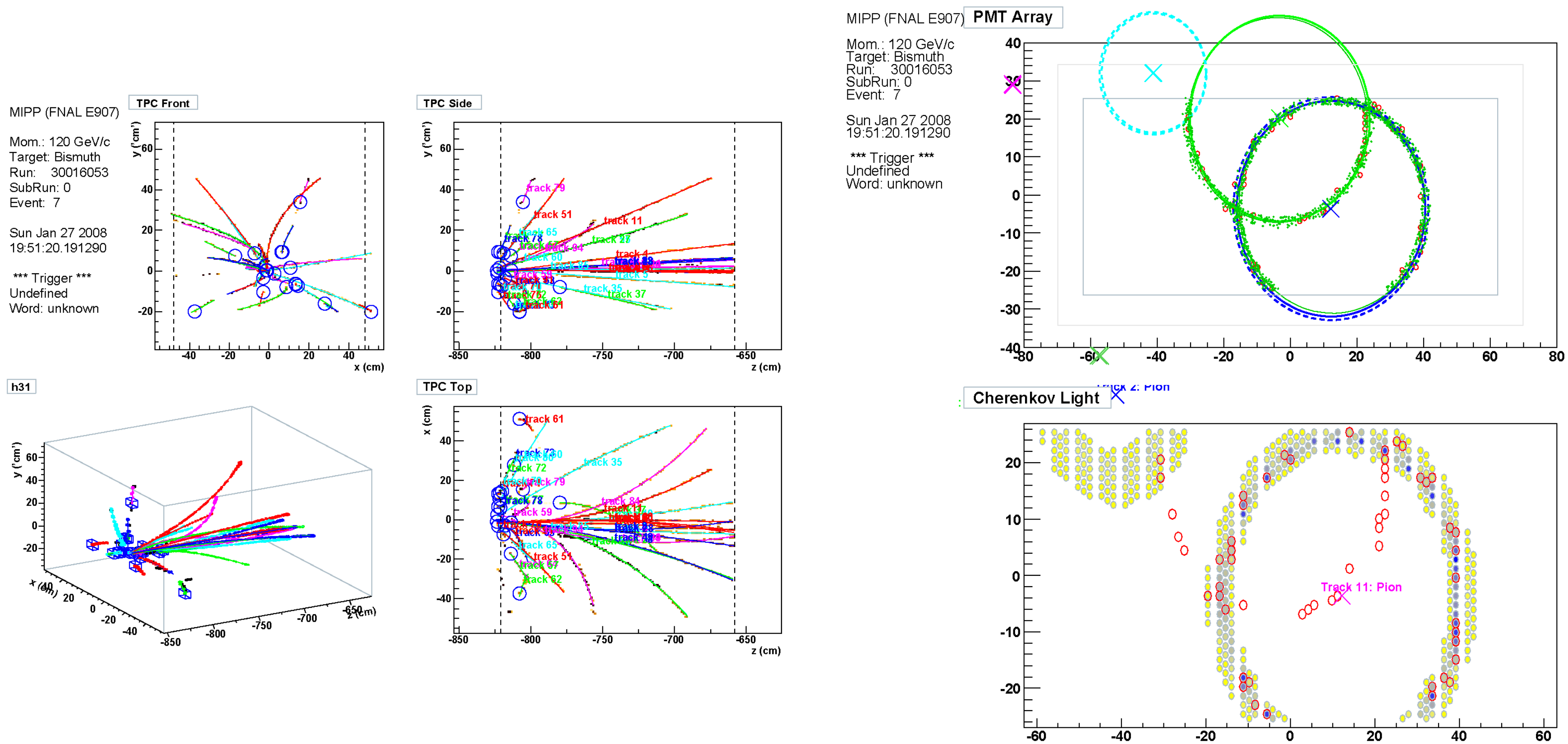




$$\frac{\sigma}{E} = \frac{0.554}{\sqrt{E}} \oplus 0.026$$

Resolutions and Acceptances

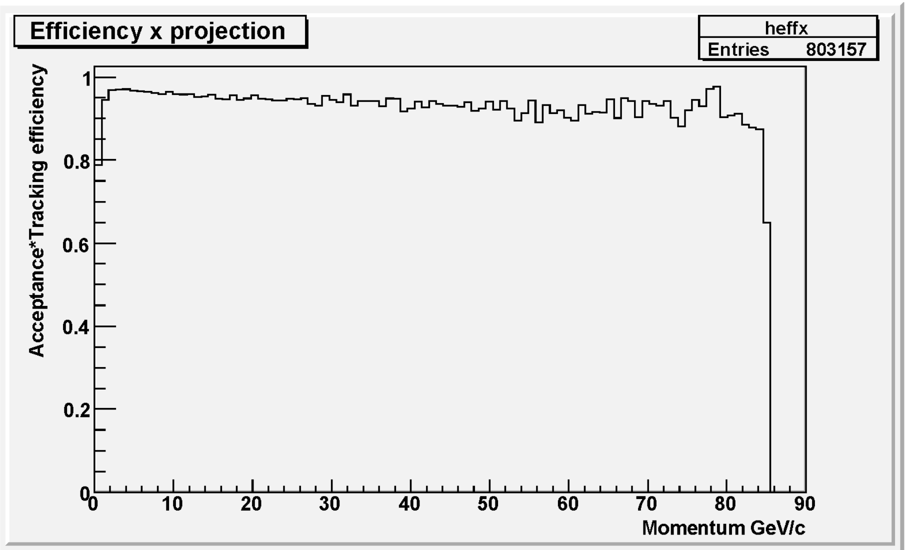
- Full Geant3 based Monte Carlo simulation of the detector response. Use known tracks and match them to found tracks to determine acceptance*tracking efficiency and momentum resolution.
- MC event display



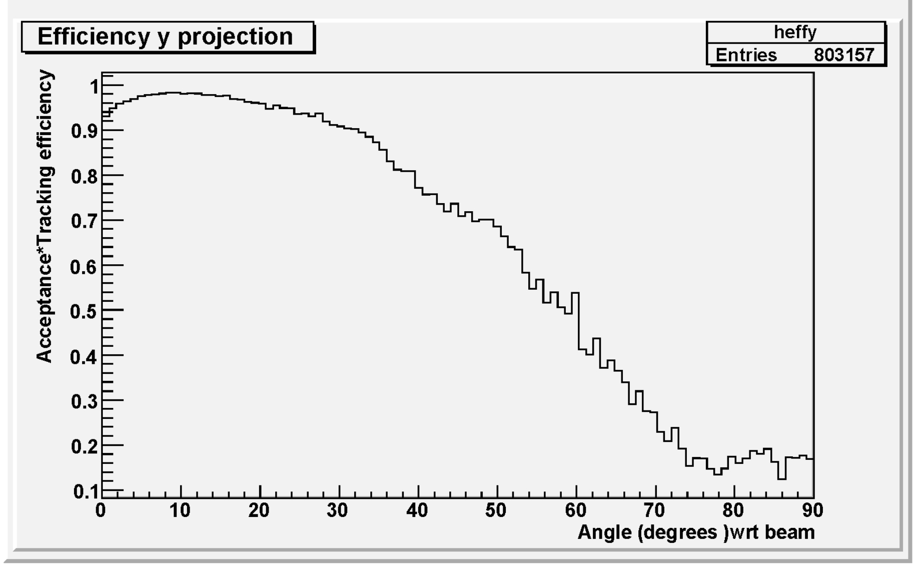
Detector acceptance

MIPP-I Acceptances
MIPP-II will have backward acceptances.

Efficiency vs. momentum

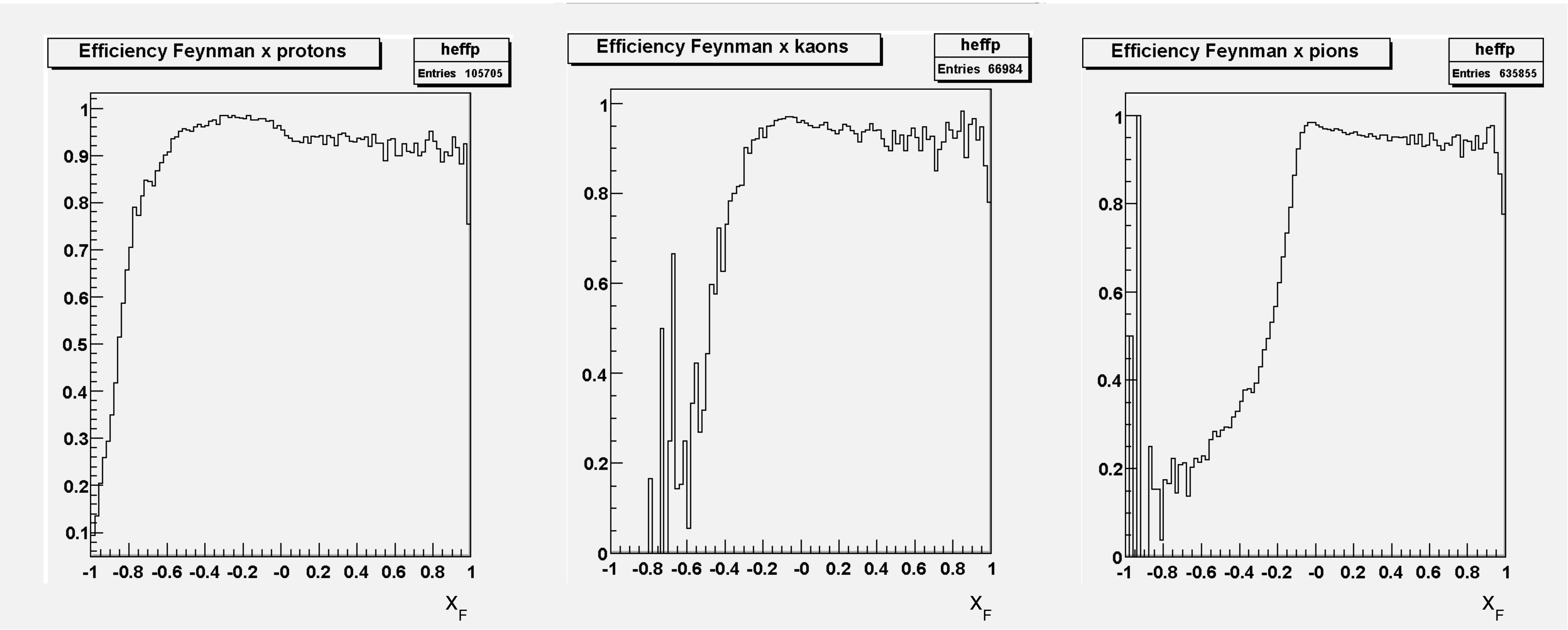


Efficiency vs. θ_{lab}



Detector acceptance

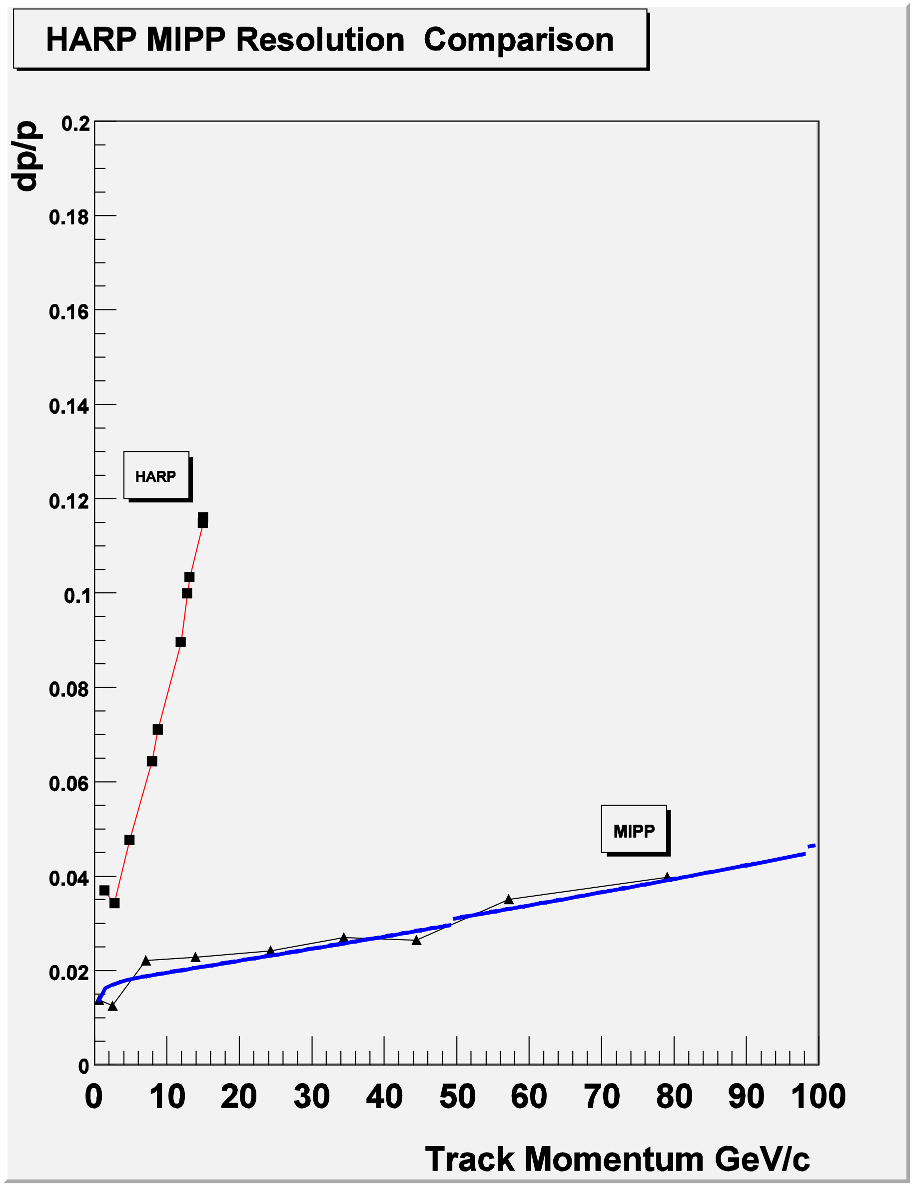
- Pions at low x_F move backward in the lab



- Plastic Ball detector in the upgrade will increase acceptance.

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

Final Data Summary, Number of events x 10^6												
Target			Beam momentum (GeV/c)									
Z	Element	Trigger Mix	5	20	35	40	55	60	65	85	120	Total
0	Empty thin	Normal		0.10	0.14			0.52			0.25	1.01
	Empty cryo	Normal		0.30				0.61		0.31		1.22
	K mass	No Int.				5.48	0.50	7.39	0.96			14.33
1	LH	Normal	0.21	1.94				1.98		1.73		5.86
4	Be	p only									1.08	1.74
		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	6.58 +7.39	0.96	2.04	4.63	17.05 +14.33

MIPP results

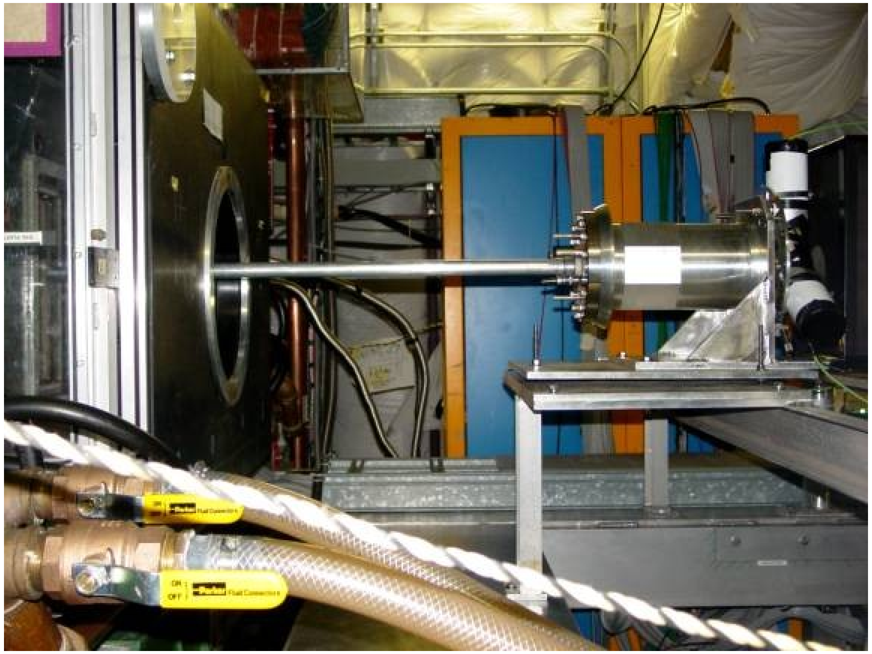
- Five PhD's awarded
  - Ratio of Pion Kaon Production in Proton Carbon Interactions (A. Lebedev, Harvard)
  - Measurement of Pi-K Ratios from the NuMI Target (S. Seun, Harvard)
  - Measurement of the Charged Kaon Mass with the MIPP RICH (N. Graf, Indiana) (published)
  - Charged pion production cross section using 120 GeV/c proton beam on carbon target (G. Aydin, Iowa)
  - Cross section measurements in the Main Injector Particle Production (FNAL-E907) experiment at 58 GeV/c (Y. Gunaydin, Iowa)
- Publications
  - Kaon mass: NIM A631 (Mar. 2010)
  - Calorimeter performance: NIM A598 (Jan. 2009)
- Today
  - NuMI target particle yields
  - Forward neutron production cross sections
- Soon
  - A lot more cross sections

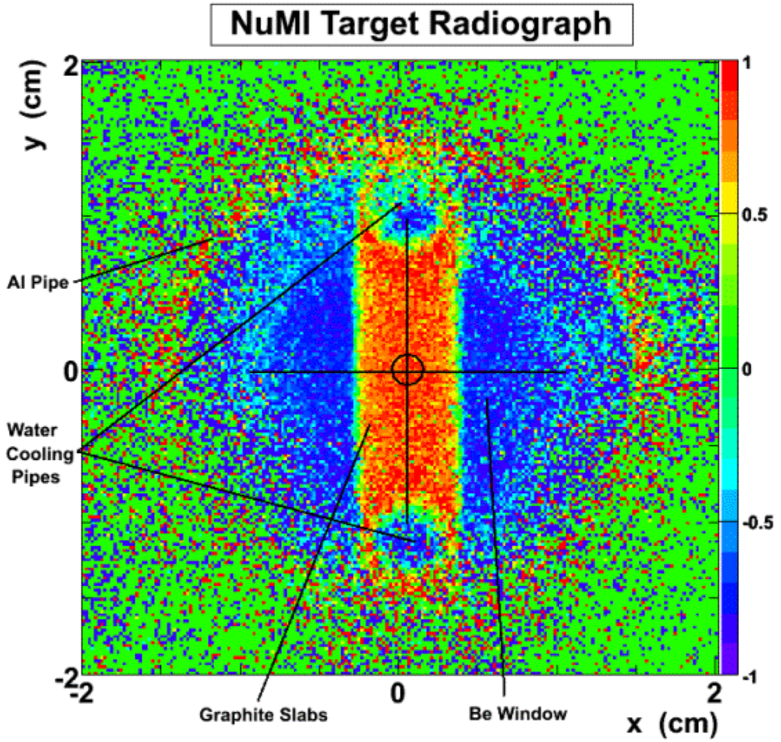
- Other analyses are progressing, even if I do not report on them today.

NuMI target data analysis

The NuMI target measurement

2 interaction length

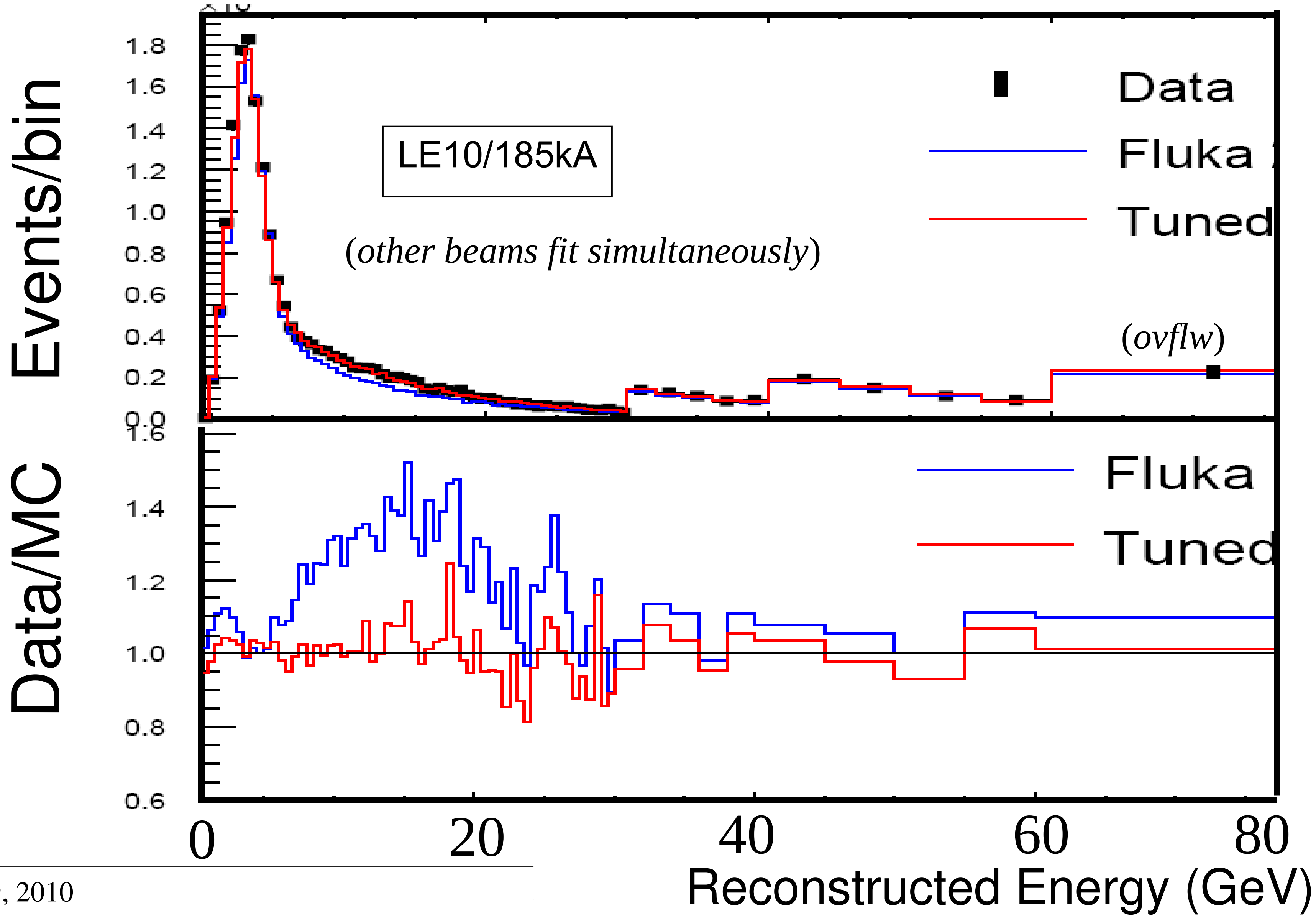




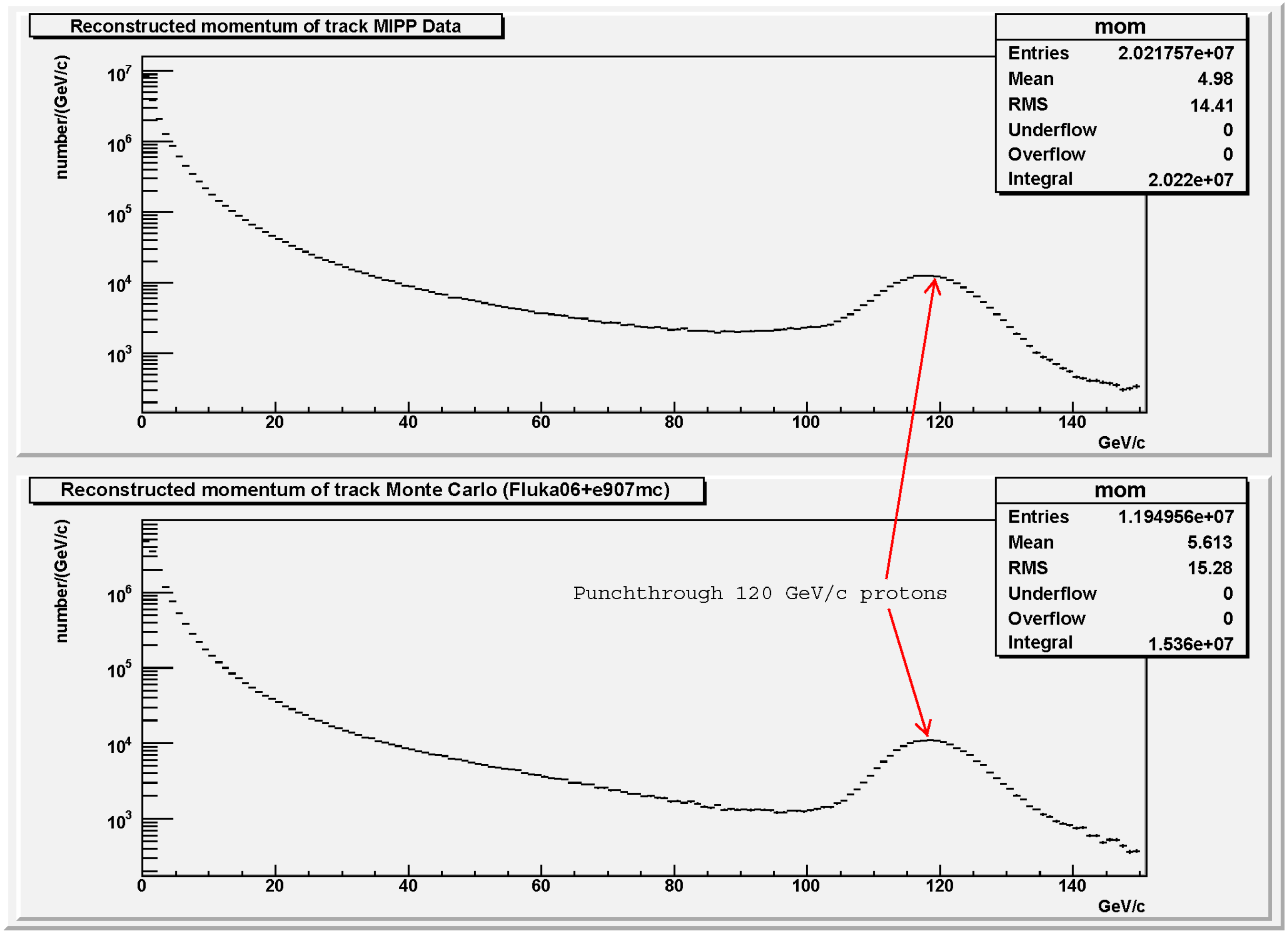
- NuMI analysis goal:
  - provide particle spectra from direct measurement to reduce systematic uncertainty in ND/FD ratio of neutrino spectra.

MINOS beam problem (from S. Kopp)

•To get red points, MINOS assumed they know the ν N cross section for E_ν<10 GeV. Somewhat circular argument. We need flux to measure ν N cross section, instead we use an assumed cross section to determine flux.
First principles flux measurement will get us out of this loop.



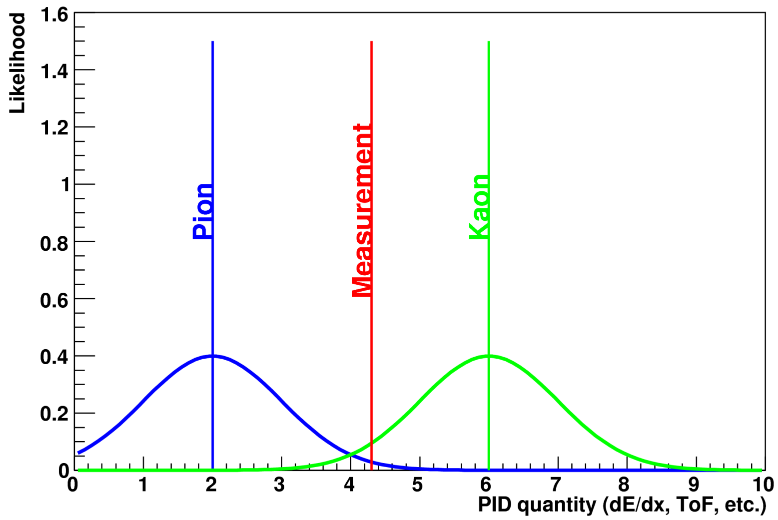
Momentum Spectra from NuMI target – Data and MC



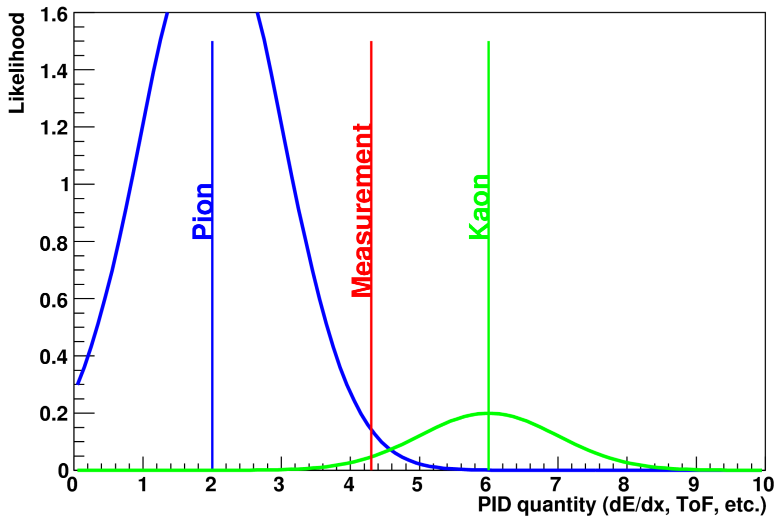
Global PID algorithm – Need for Priors

- We consider 4 hypotheses for particle id
  - Electron, pion, kaon, and proton (denoted by H)
  - Initially we do not distinguish by charge since none of the pid measurements (dE/dx, ToF, Ckov, RICH; denoted by x) depend on the charge of the particle.
- We employ the maximum likelihood technique to determine the spectra of each particle type in data. However, the likelihood that a measurement is that of (e.g.) a pion or kaon depends not only on the individual measurement but also on the total number of pions and kaons in the sample.

No Priors: Kaon hypothesis more likely than pion



Priors: Pions more abundant than kaons, hence pion more likely



Bayes' theorem – Global PID formalism

MIPP

- The joint probability P(H,x) can be written as (H = e,π,K,p; x = dE/dx, ToF, r_{RICH},...)

$$P(H,x)=P(x|H)P(H)$$

where P(H) is the probability of a particular hypothesis. This is what we are trying to determine. These equations are for a given momentum. We have suppressed the momentum dependence for simplicity.

- By Bayes' theorem

$$P(H,x)=P(H|x)P(x)$$

- This leads to

$$P(H|x)=\frac{P(x|H)P(H)}{\sum_H P(x|H)P(H)}$$

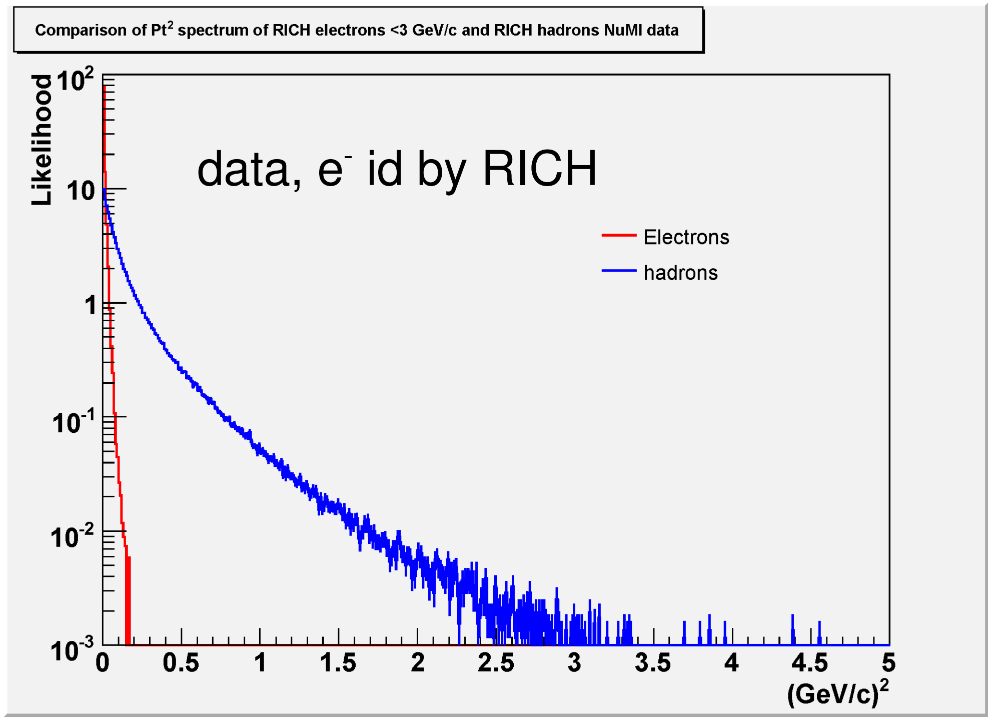
- We determine P(H) iteratively. Assume that all hypotheses are equally likely initially, i.e. P(H) = ¼ since there are 4 hypotheses (e/π/K/p). For each track, we then determine the posterior probability P(H|x) which is used to weight the track for each hypothesis.

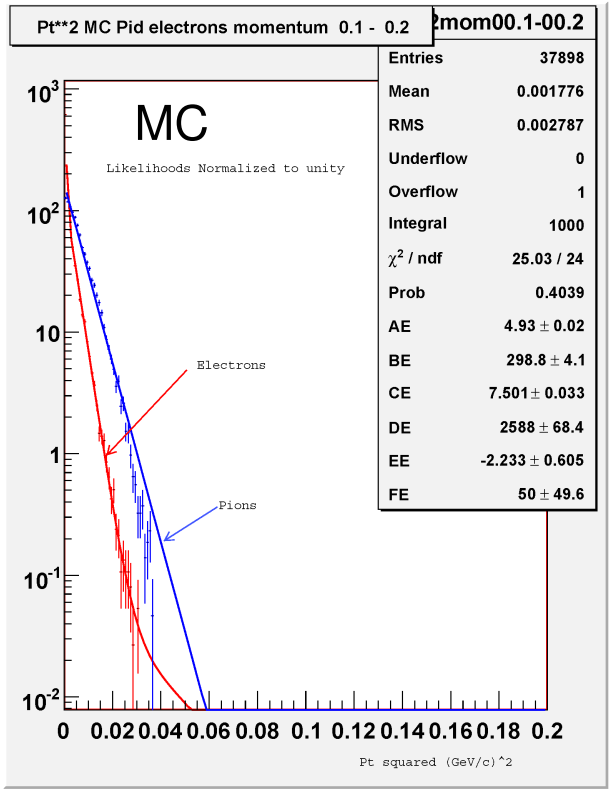
$$\sum_H P(H|x)=1$$ preserves unitarity

- The resulting P(H) is used for the next iteration, till convergence.
- The aim is not to determine whether each particle is definitely one type or the other but to determine the maximum likelihood momentum functions for each hypothesis. Each particle enters all hypotheses plots with its appropriate hypothesis dependent weight.
- We treat MC and data as two separate experiments, each with slightly different behavior. We test the algorithm on the MC, since we know the answer. – (Movie)

Separation of Electrons and Pions in MIPP – p_t^2 as a discriminant

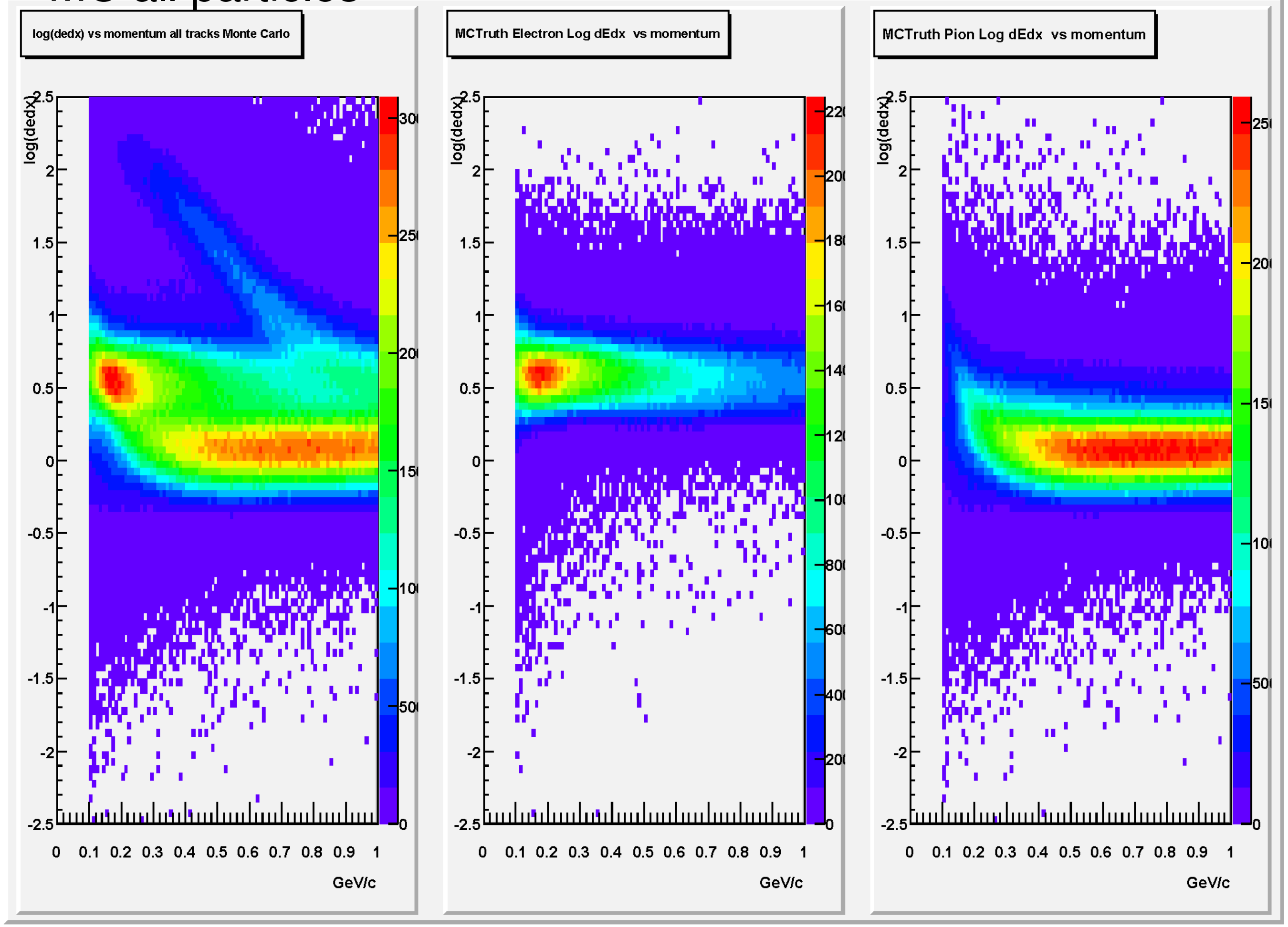
- There is some distinction between electrons and pions in the TPC dE/dx and in the RICH below the pion threshold at 4.6 GeV/c. Pretty much everywhere else they are indistinguishable since they are both β~1 particles.
- However, electrons arise from π^0 which decay to two photons which then convert again. At each stage the average p_t of the final state particle is lowered by ~ a factor of two. So for any given momentum an electron will have approximately a factor 4 less p_t than a charged pion. Verified in data and MC. Use p_t^2 likelihood as an added discriminant – R. Raja, MIPP-Doc 993





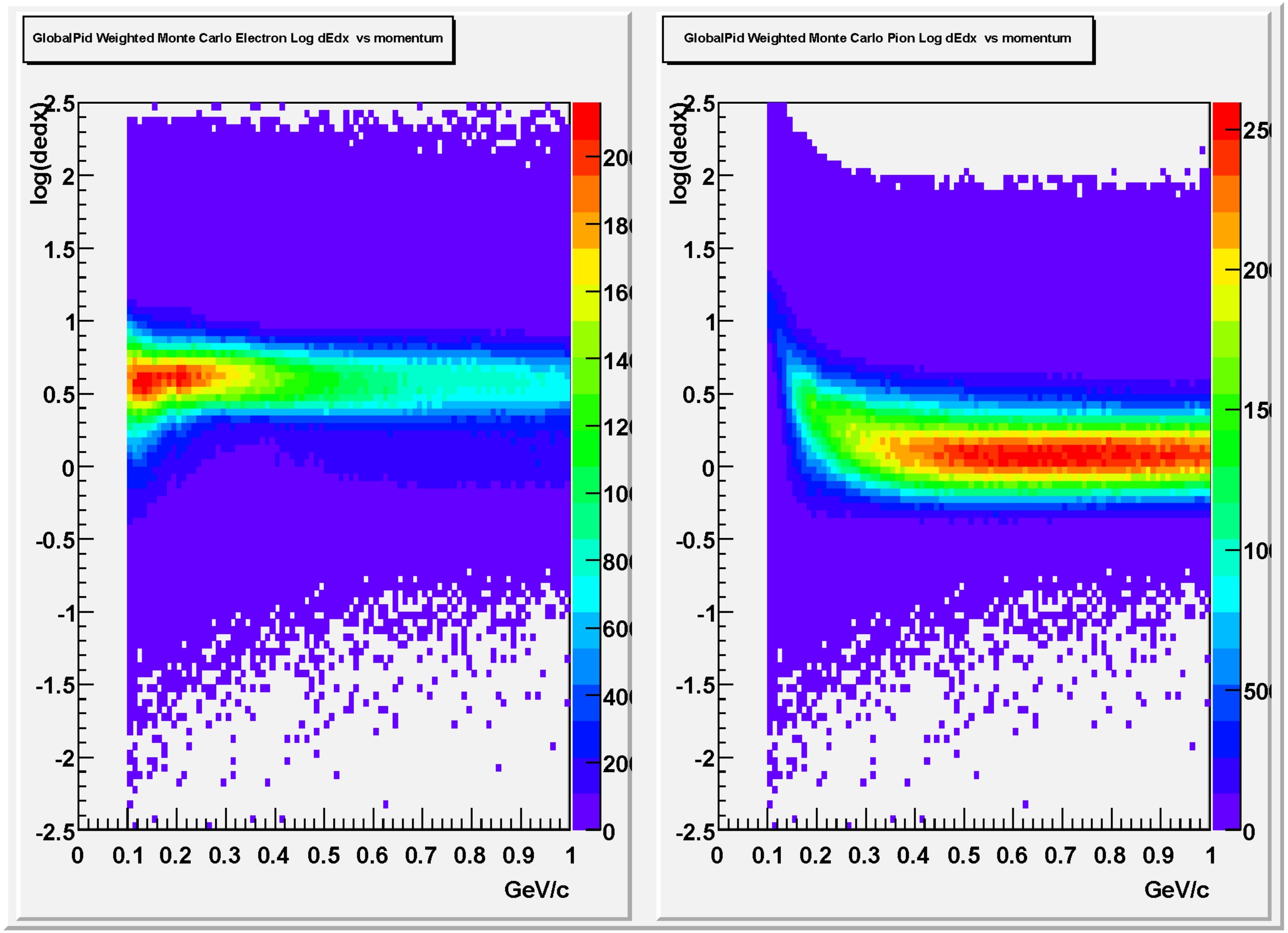
Monte Carlo Truth

MC all particles — Electrons — Pions



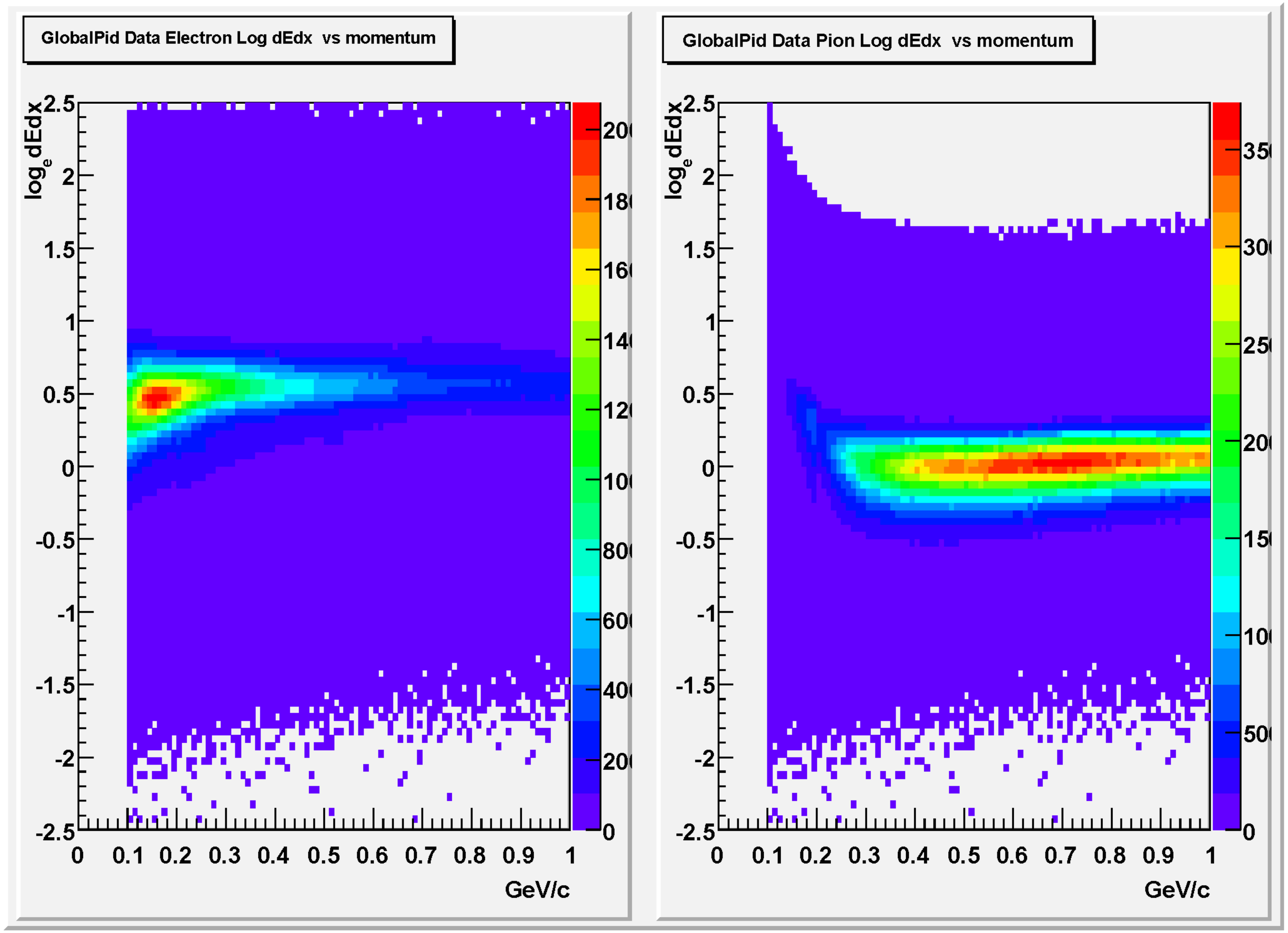
Global Pid result with p_t^2 likelihood Monte Carlo

MIPP

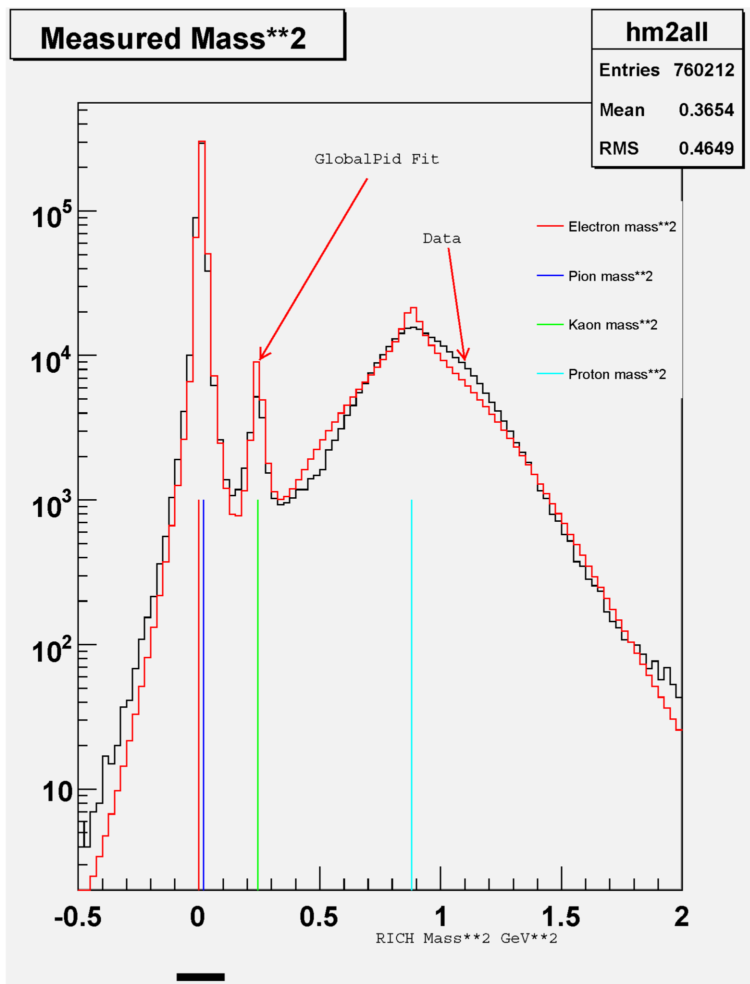


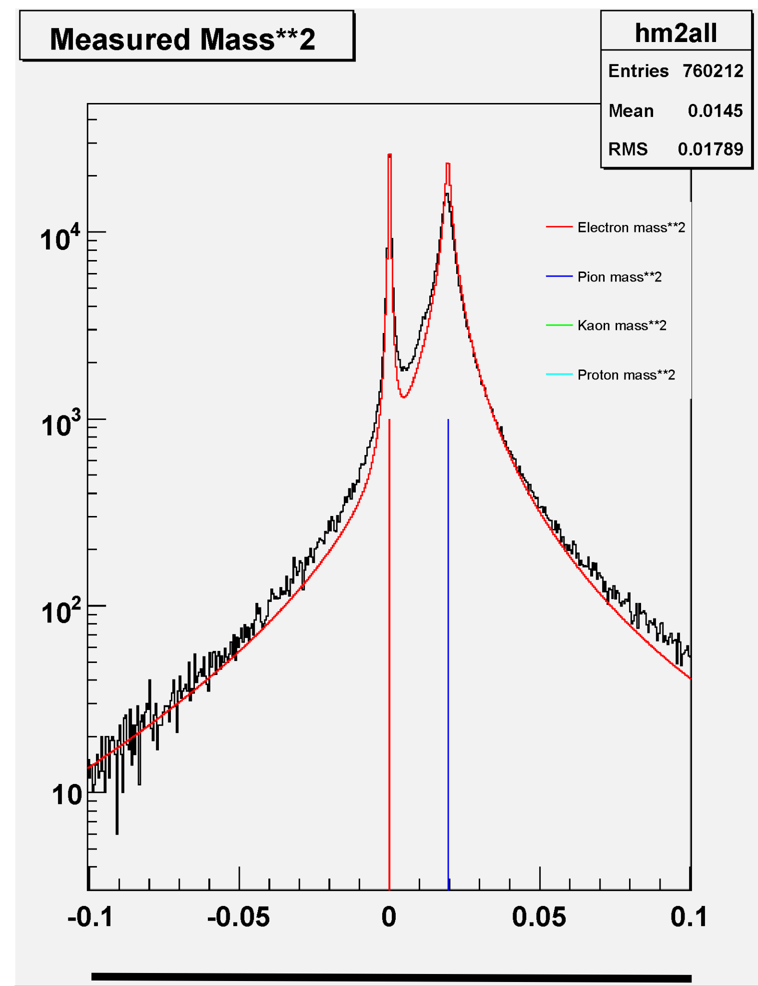
- Every track enters into all plots with its appropriate weight.
- Graphic cuts would have caused cut boundaries between the two.

Global Pid with NuMI target data



Comparing fits with data





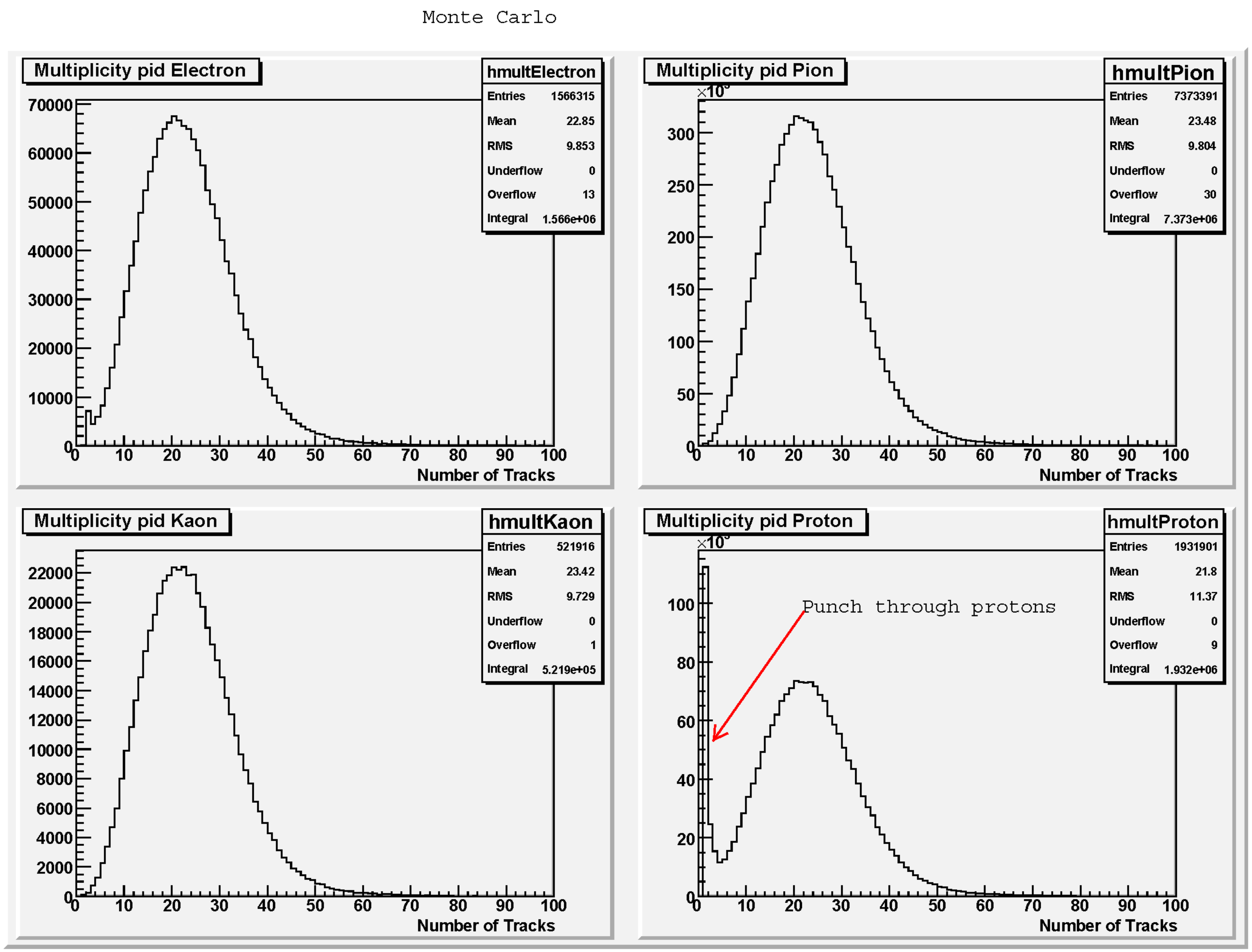
- Bayes theorem gives expression for theoretical fit $P(x) = \sum_H P(x|H)\,P(H)$

NuMI target Global PID

- We test the algorithm with Monte Carlo and compare the MC Truth against the output of the Global Pid.
- We add 2 more likelihoods to the RICH in addition to the one based on radius.
  - Punchthrough protons have low multiplicity.
    In the high momentum bins they overwhelm the pions. We use multiplicity based likelihood to aid the pattern recognition.
  - Below the proton threshold and above the kaon threshold if there is no ring, it is likely a proton.

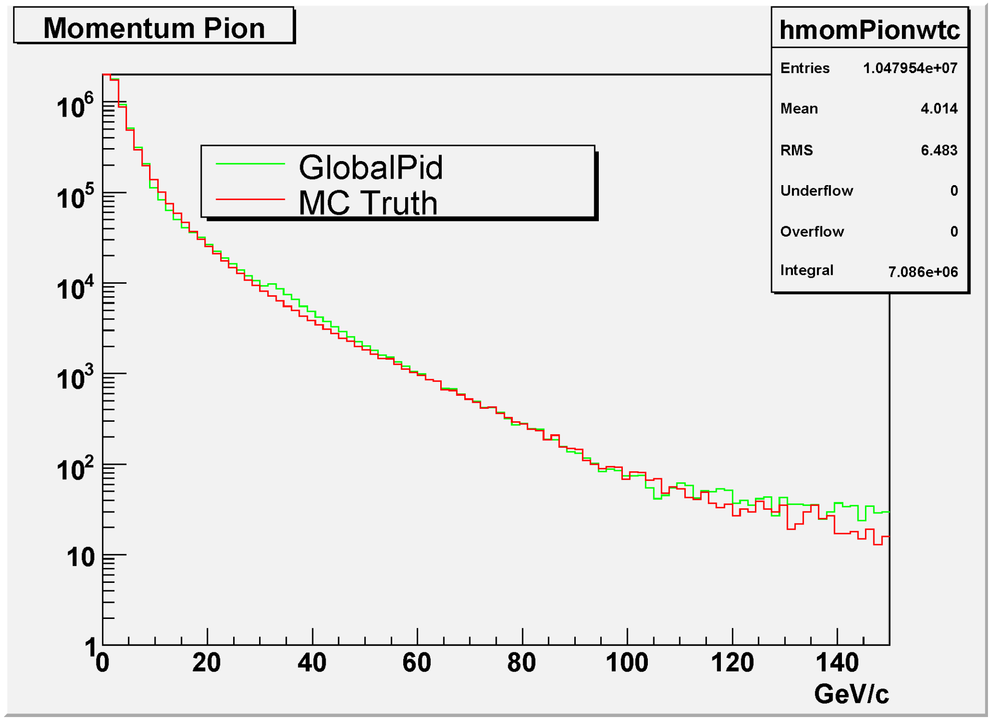
Multiplicity Distributions Monte Carlo

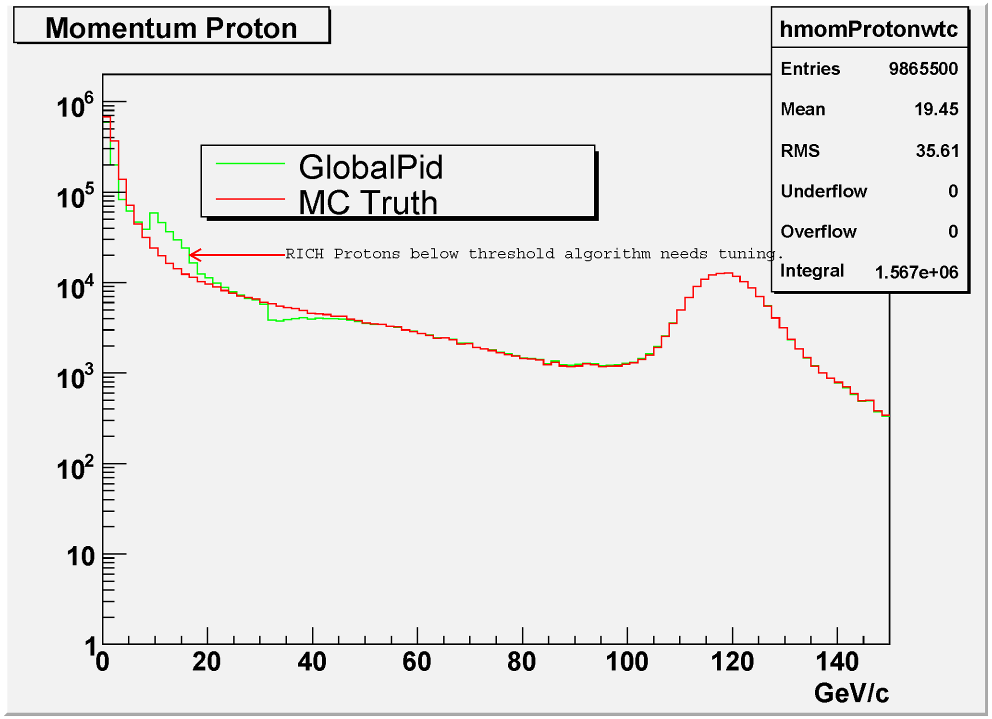
- Data shows similar low multiplicity excess.



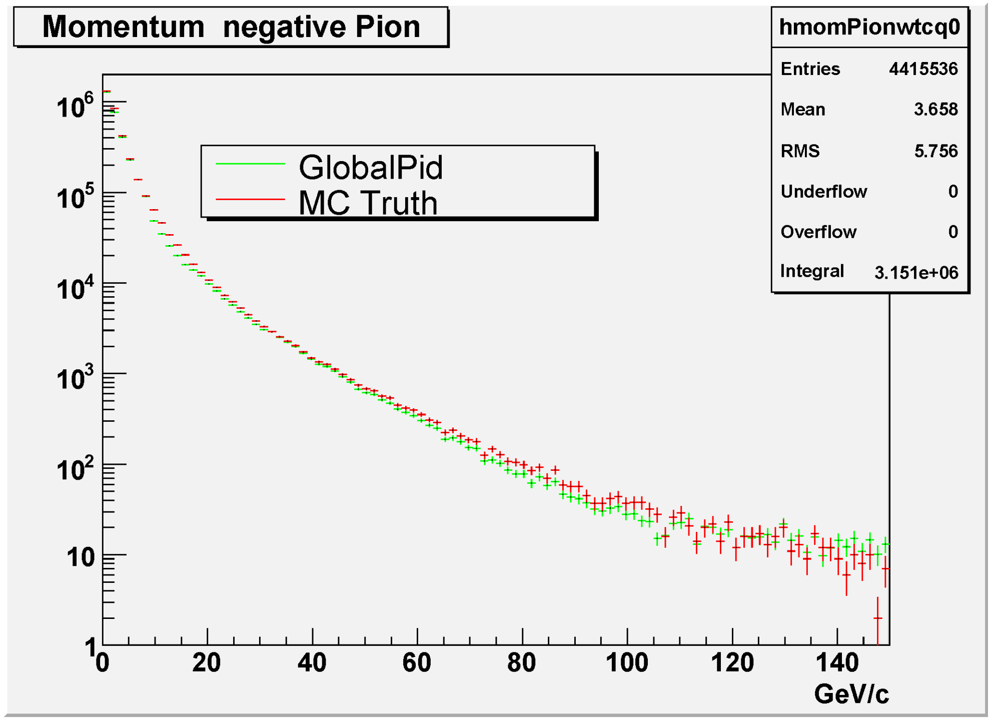
Monte Carlo Global Pid test

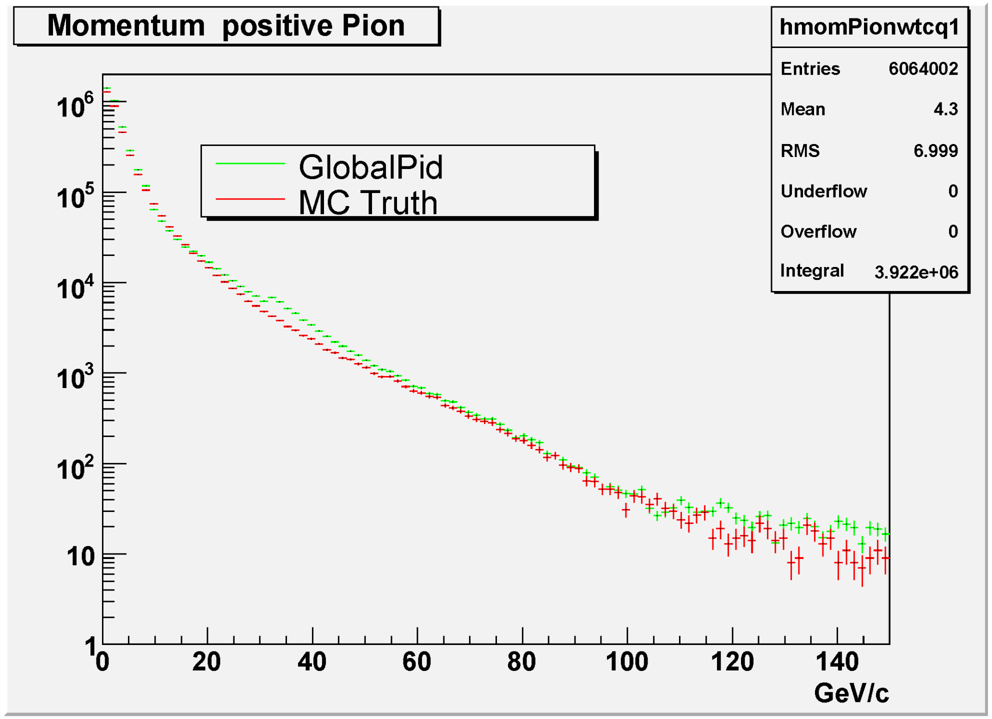
- Preliminary results. Lots of tuning to be done.



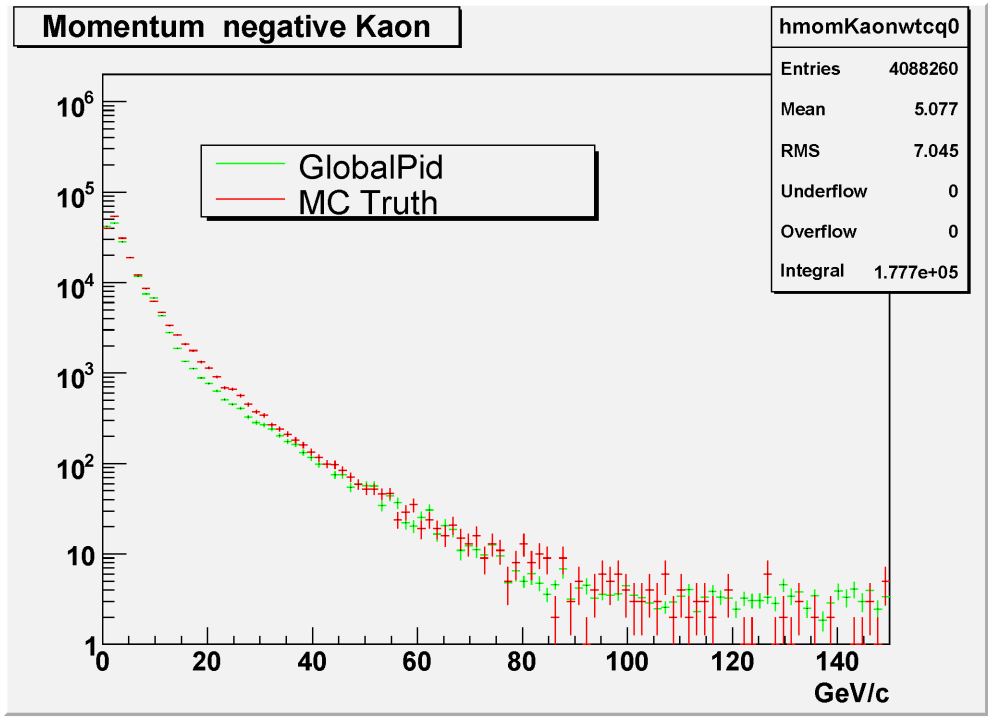


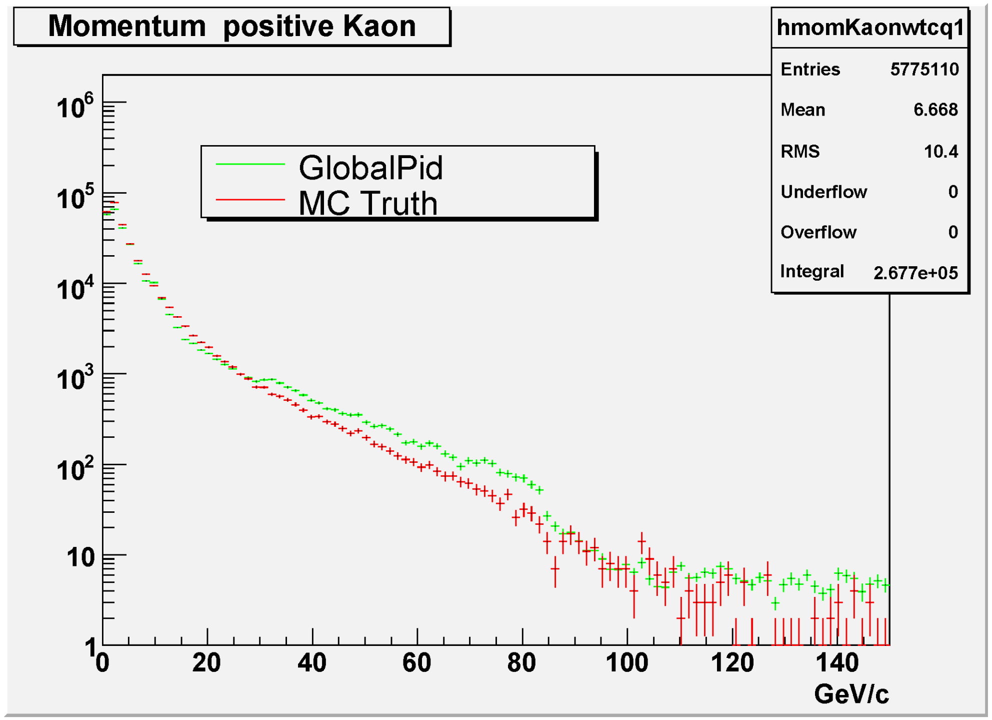
Separate positive and negative



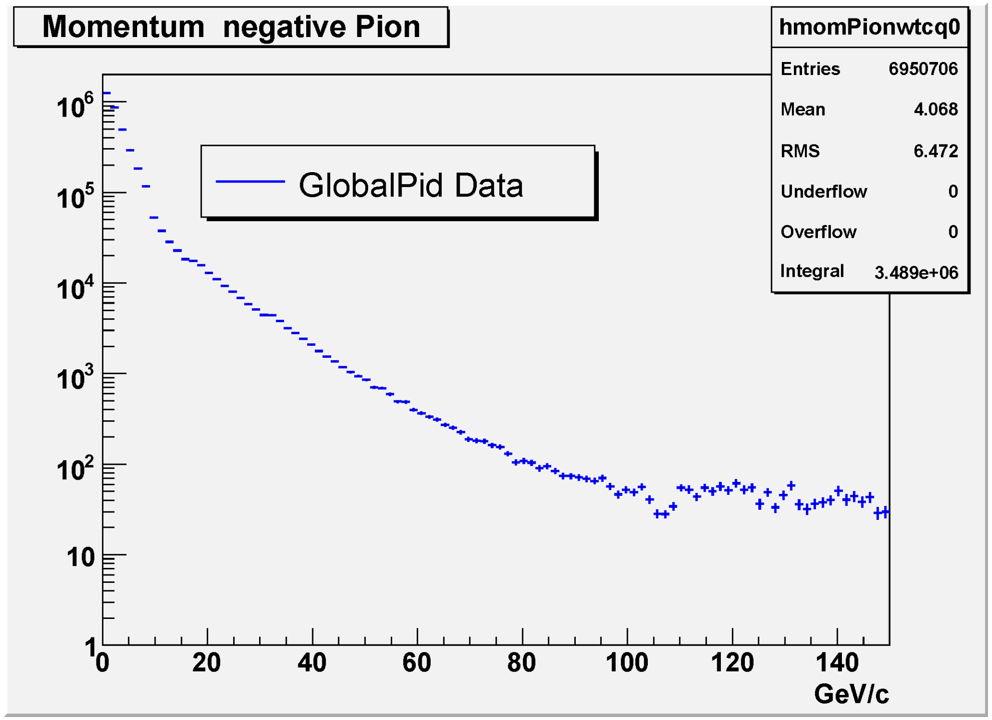


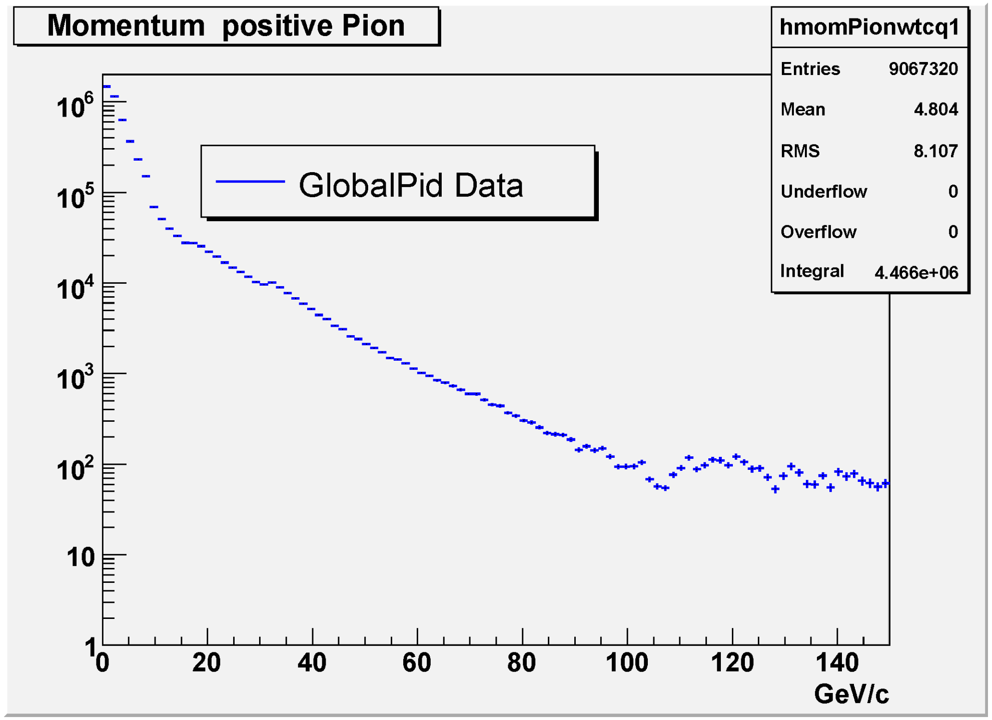
Kaons MC Global Pid comparison



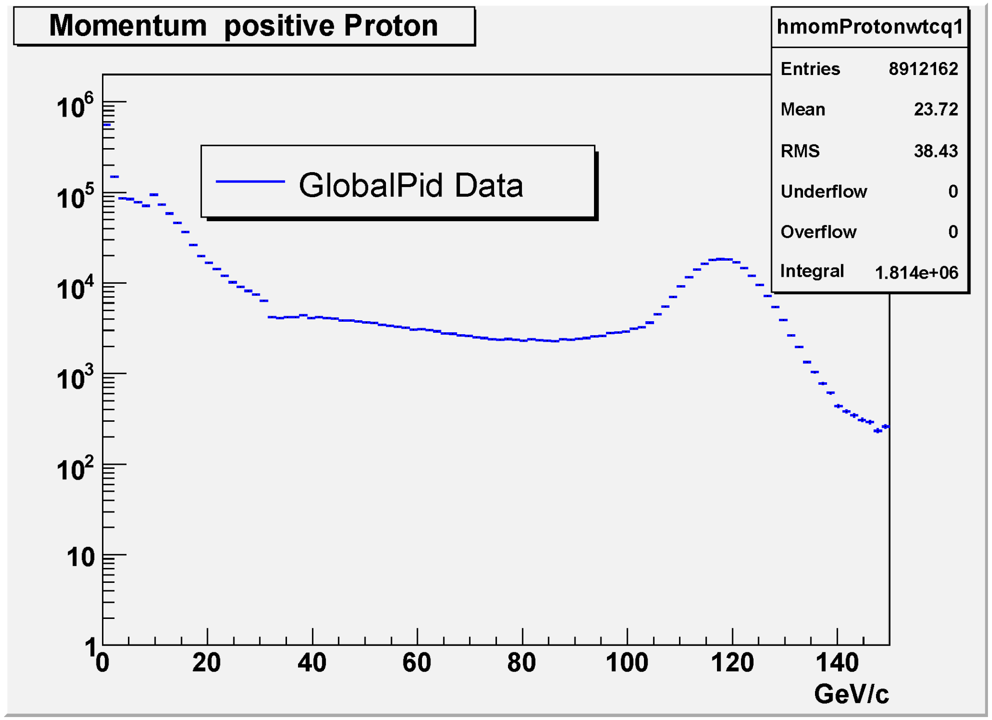


NuMI target analyzed by GlobalPid





NuMI target analyzed by GlobalPid

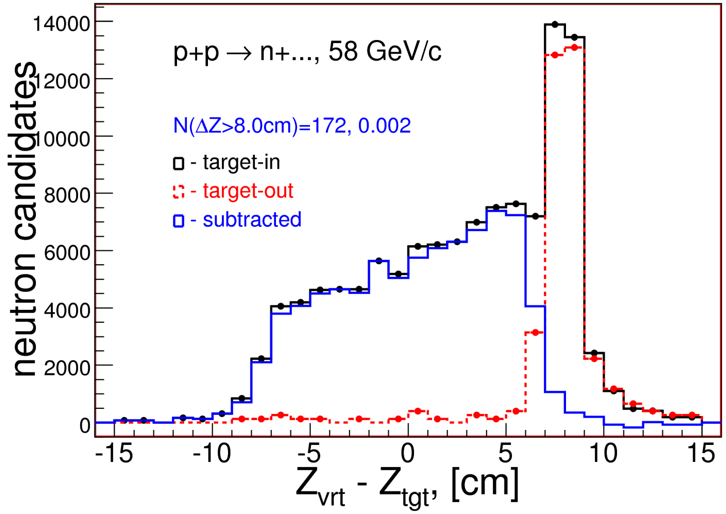


- Further work to be completed
  - Tweak various algorithms
  - As p_t increases, we lose acceptance. This results in a dilution of analysis power of algorithm. P_t dependence has to be studied before we make detailed MC data comparisons.
  - Estimate systematic errors
  - Do momentum smearing corrections
  - Minority particles (K, p-bar) after further study

Forward neutron inclusive cross sections

Forward neutron production cross sections

- Event quality cuts, neutron selection
- Target-out subtraction
- Acceptance, corrections
- Backgrounds
- Cross checks
- Results



- Status: Everything is very near final.
  Working on some systematic errors.

  Shown here: All results officially preliminary, but central values will not change and error bars will not grow.

  Another Wine&Cheese: Full details

Neutron cross sections

- Targets used: LH_2, Be, C, Bi, U
- Proton beam momenta used: 20, 58, 84, 120 GeV/c
- What we measure: inclusive neutron cross section p A → n + X

$$\sigma(p_n > p_{min}) = \frac{n_n(tgt-in) - n_n(tgt-out)}{N_{beam} \times \epsilon_{combined}} \times \frac{1}{n_t} \times 10^4 \, mb/(GeV/c)$$

- n_n(tgt-in) – neutron candidate events with target in place

  n_n(tgt-out) – neutron candidate events without target

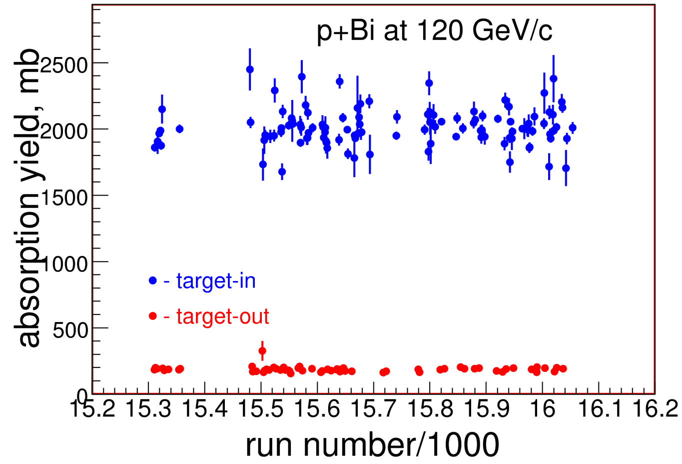
  N_{beam} – proton beam flux

  n_t – number of target nucleons per cm^2

  $\epsilon_{combined}$ – trigger-, cut-efficiencies, neutron losses and backgrounds

Neutron cross sections
Event and neutron selection

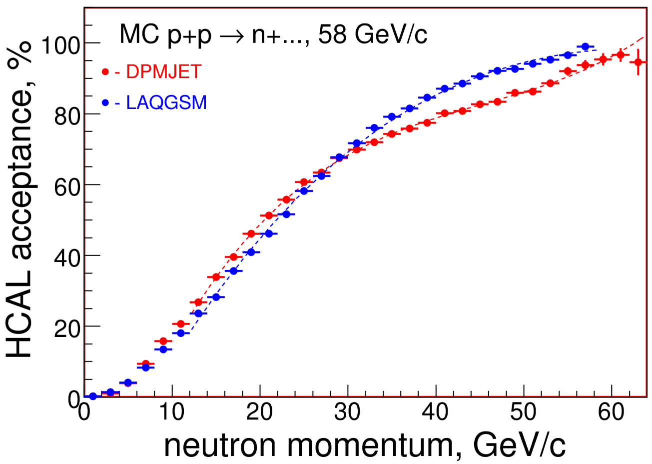
- Data quality cuts (fraction of event after cut, 120GeV/c thin targets)
  - Calorimeter worked well 100%
  - Trigger scintillator installed and working (removes some early data) 100%
  - Less than 30 tracks in event (removes beam backgrounds) 96.3%
  - Single beam track with good timing 81.4%
  - Primary vertex is in target 96.7%
  - Beam particle is proton 99.3%
- Reconstruction quality cuts
  - Sum of particle momenta < 1.1 beam-momentum 93.7%

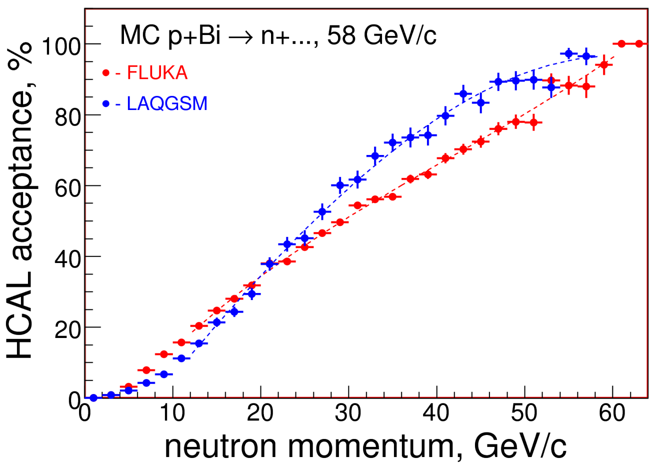


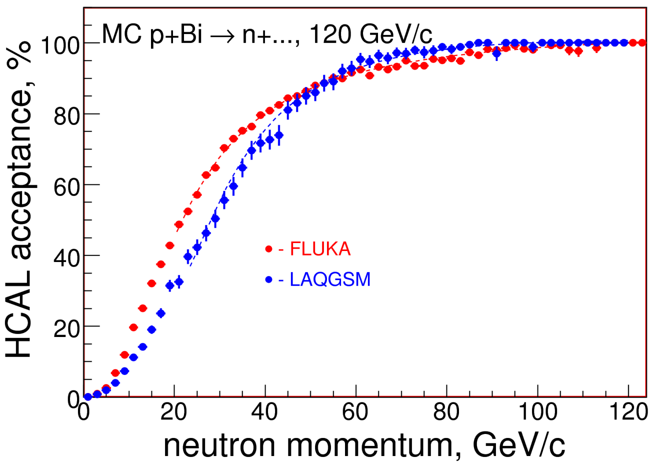
- Neutron candidates
  - Energy excess in calorimeter above threshold
  - Excess means larger energy deposit than charged tracks (if any) pointing to it.

Neutron cross sections Acceptance

- Different event generators result in different acceptance
  - Due to differences in p_T distribution
  - Enters as a systematic error in some of the results
  - Large differences between DPMJET/FLUKA and LAQGSM
  - Input to MC generators needs to improve – That's why we are doing MIPP

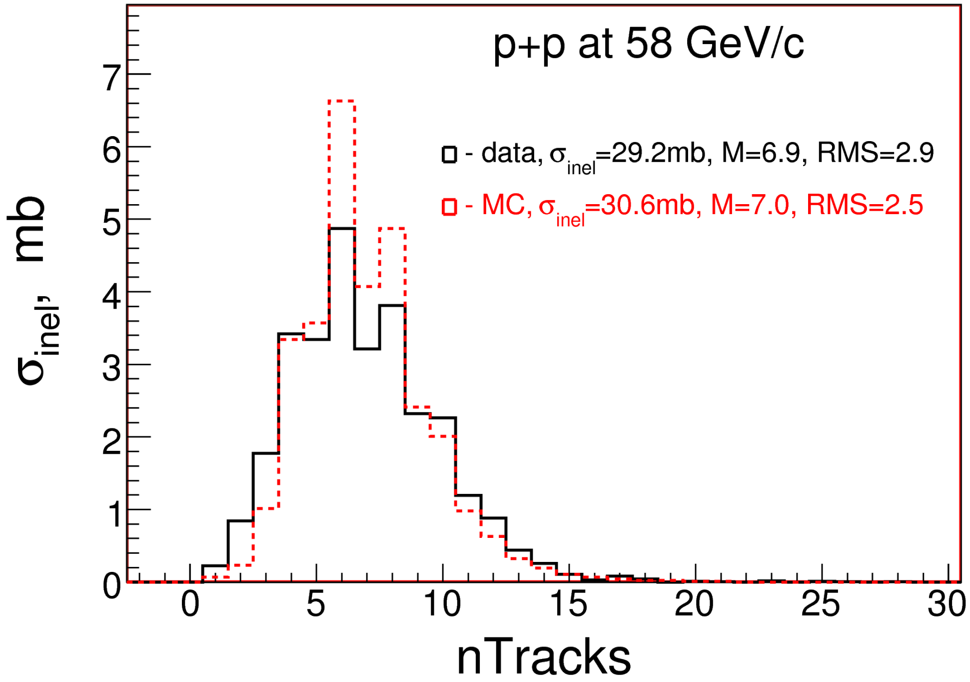


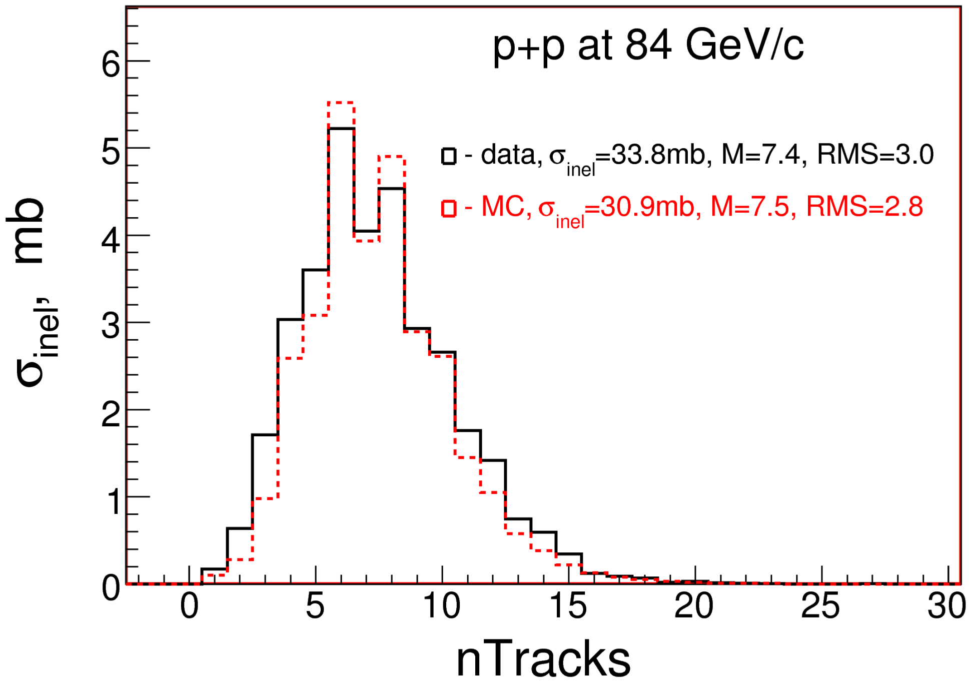




Neutron cross sections
Cross check

- Look at well known p-p cross sections and multiplicities to validate
  - Beam flux determination
  - Event reconstruction
  - Detector simulation

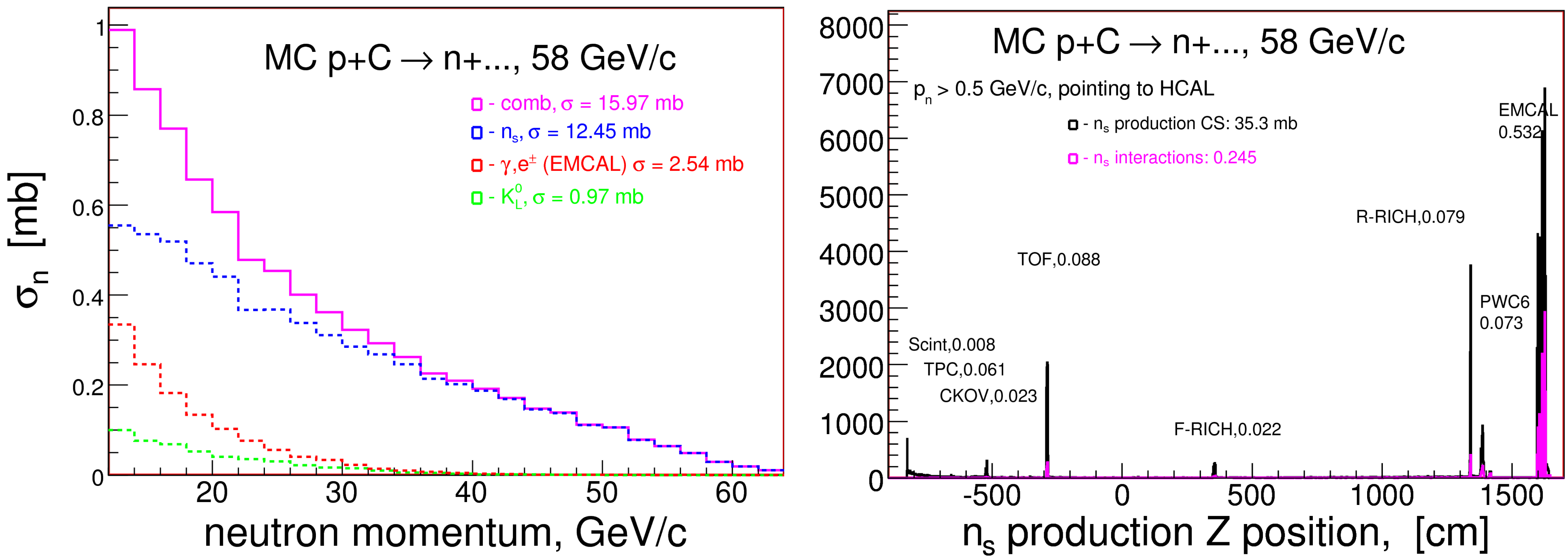




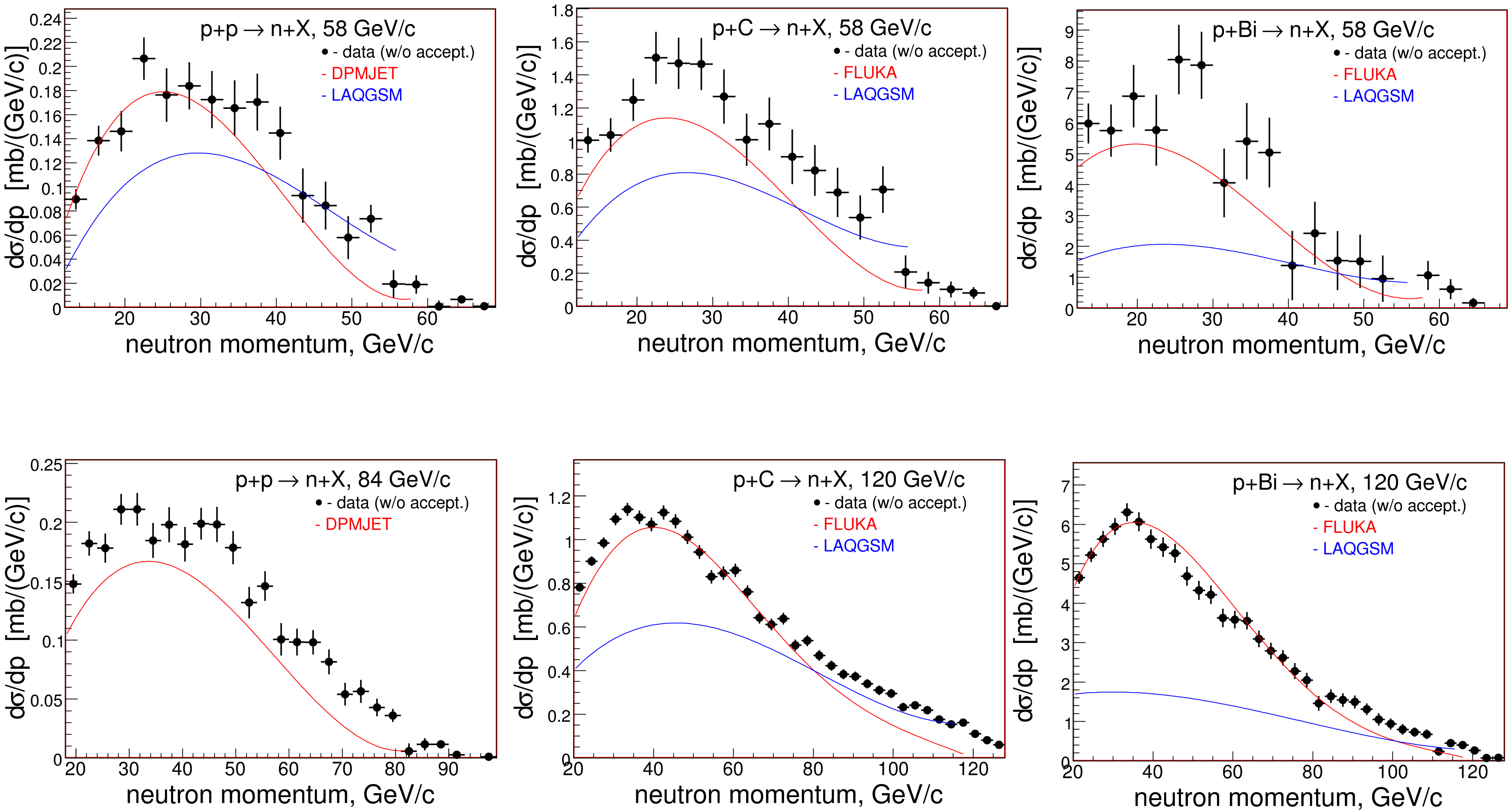
Neutron cross sections Backgrounds

MIPP

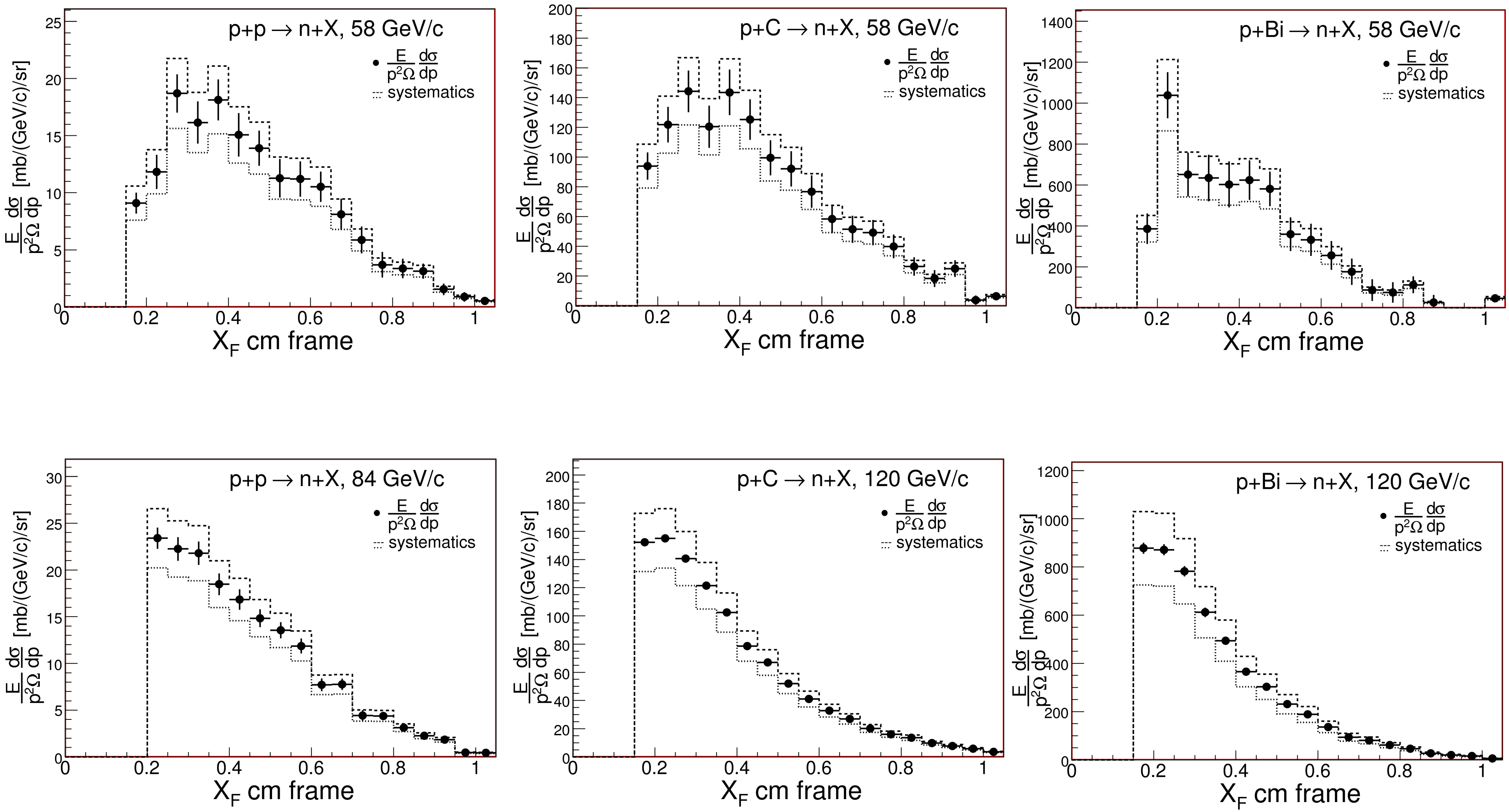
- Background composition for 58GeV/c on carbon (other momenta and targets are similar)
  - Secondary neutrons are largest background
  - Produced in ToF wall material and RICH
  - Also consider if these secondary neutrons interact before reaching the HCAL



Neutron cross sections
some cross section results

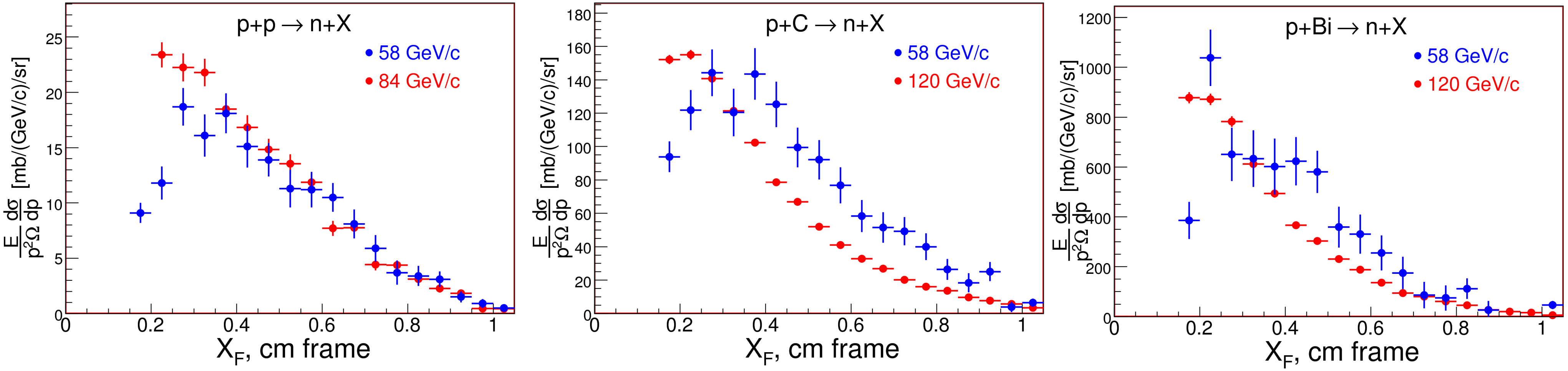


Neutron cross sections invariant cross section

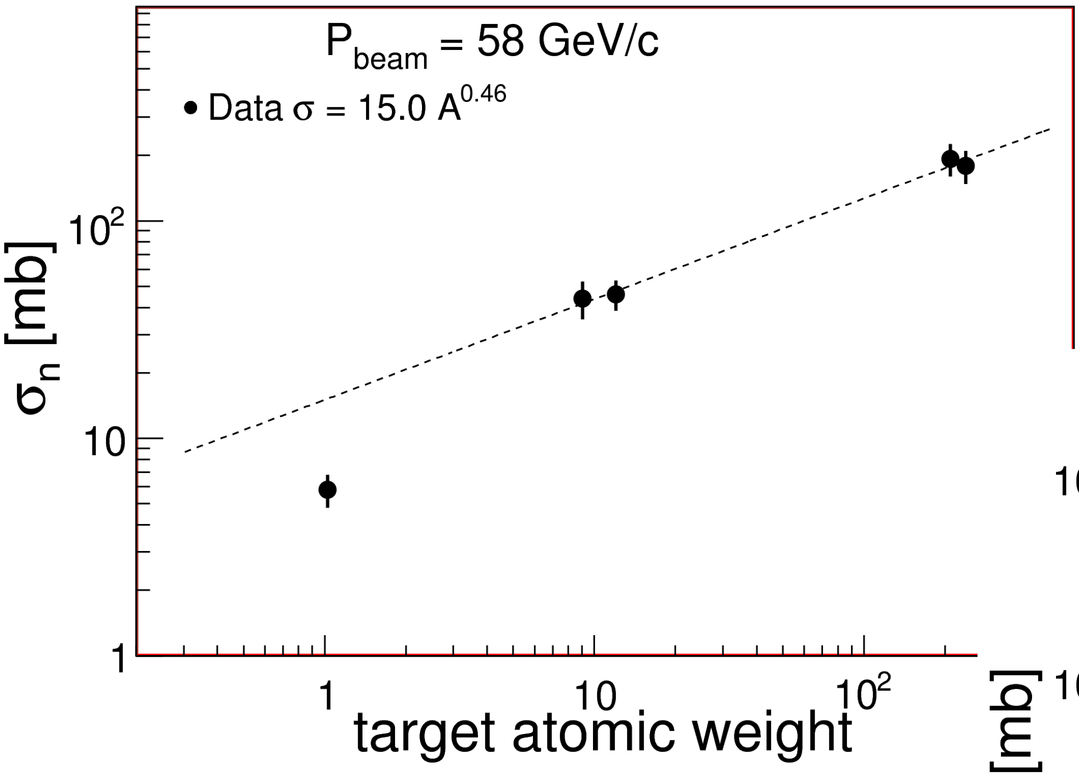


Neutron cross sections invariant cross section scaling

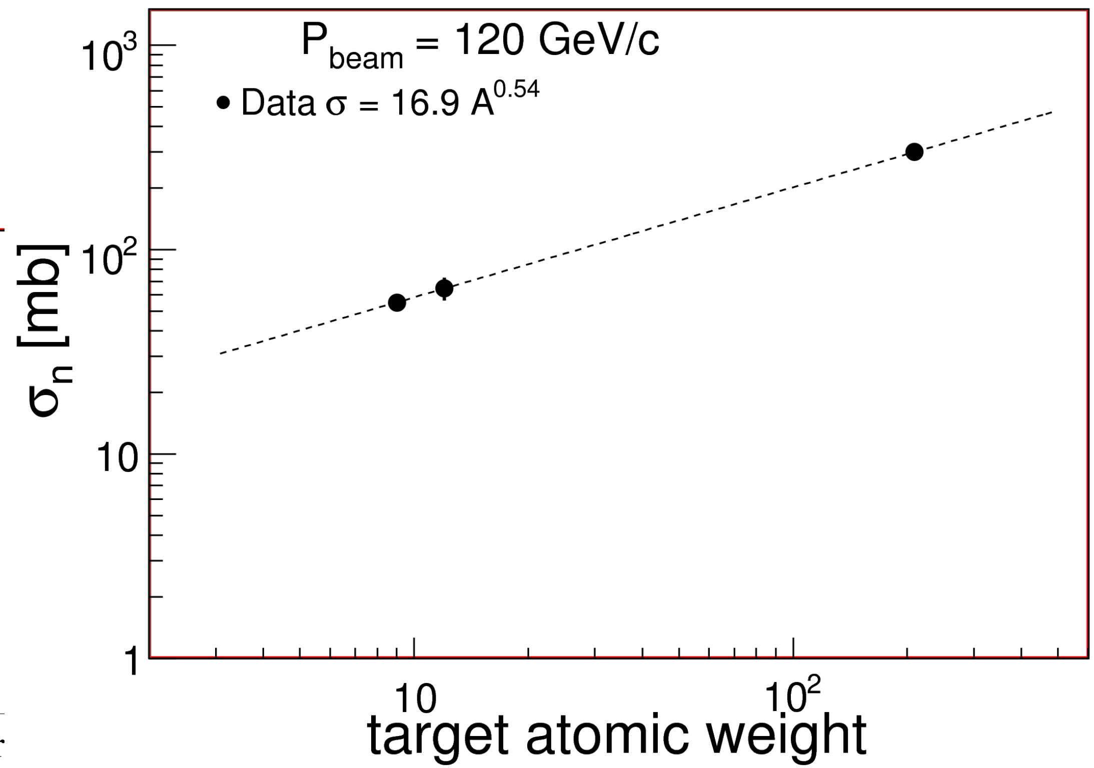
- Scaling of the Lorentz invariant cross section
  - Observed for p+p
  - Not observed for p+A



Neutron cross sections
Results as a function of A

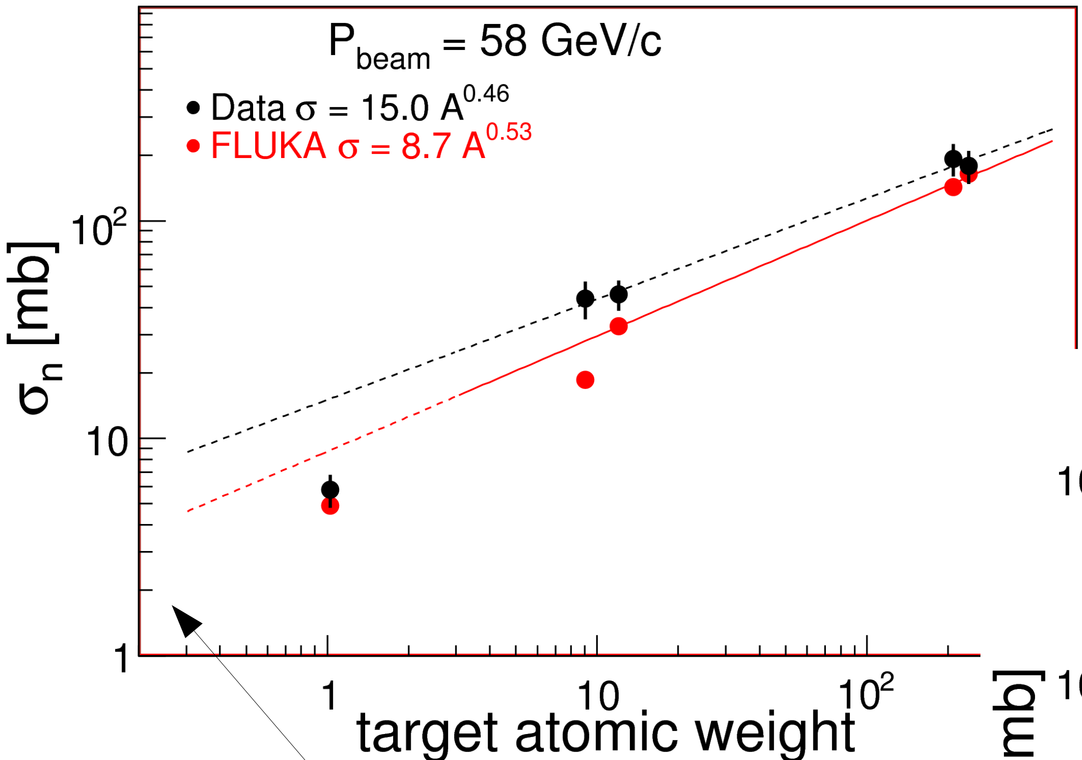


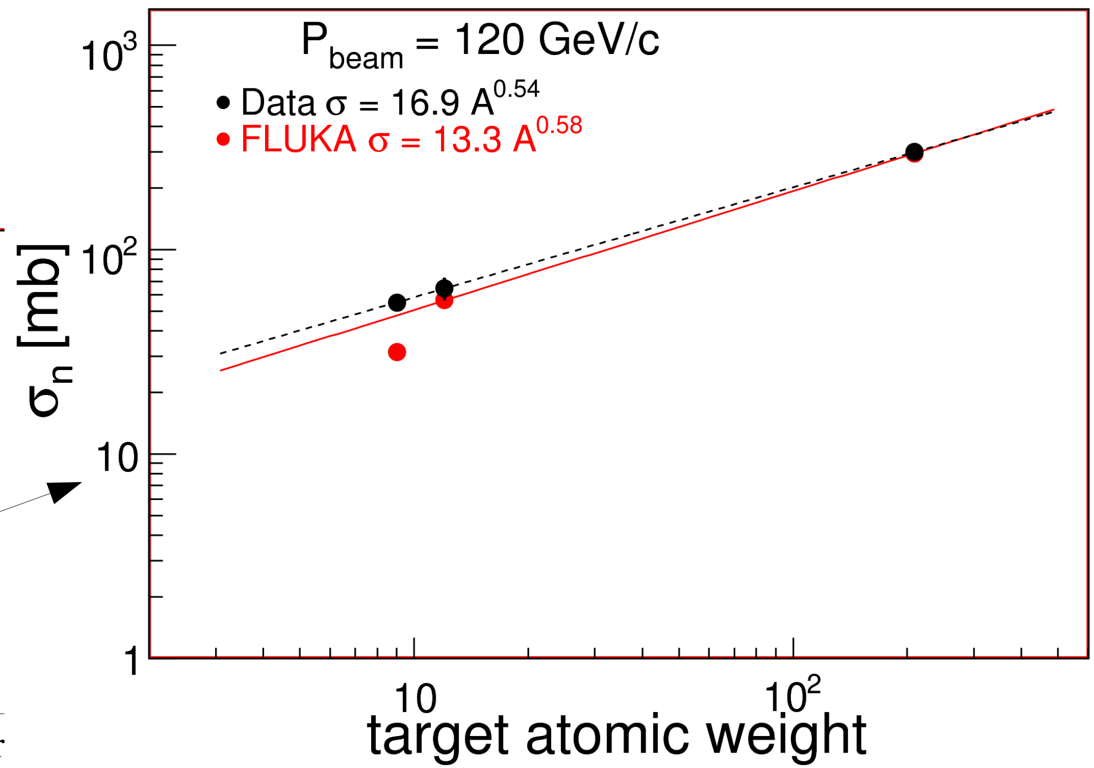
- MIPP neutron cross section measurements on nuclei show consistent behavior
  - $A^{0.5}$ dependence
  - LH_2 data point is lower



Neutron cross sections
Results as a function of A

- Fluka/DPMJET predictions
  - Be prediction is low, does not fall on line
  - Pion and kaon inclusive cross sections on Be are also low in Fluka, although total cross section is ok.

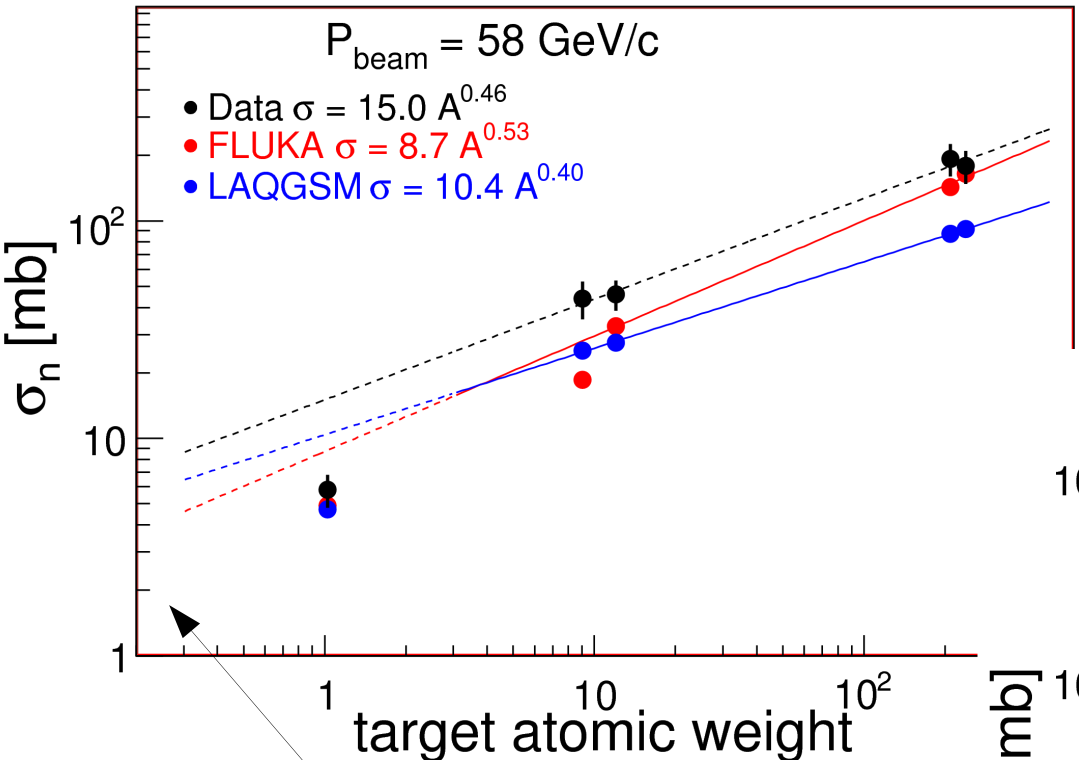




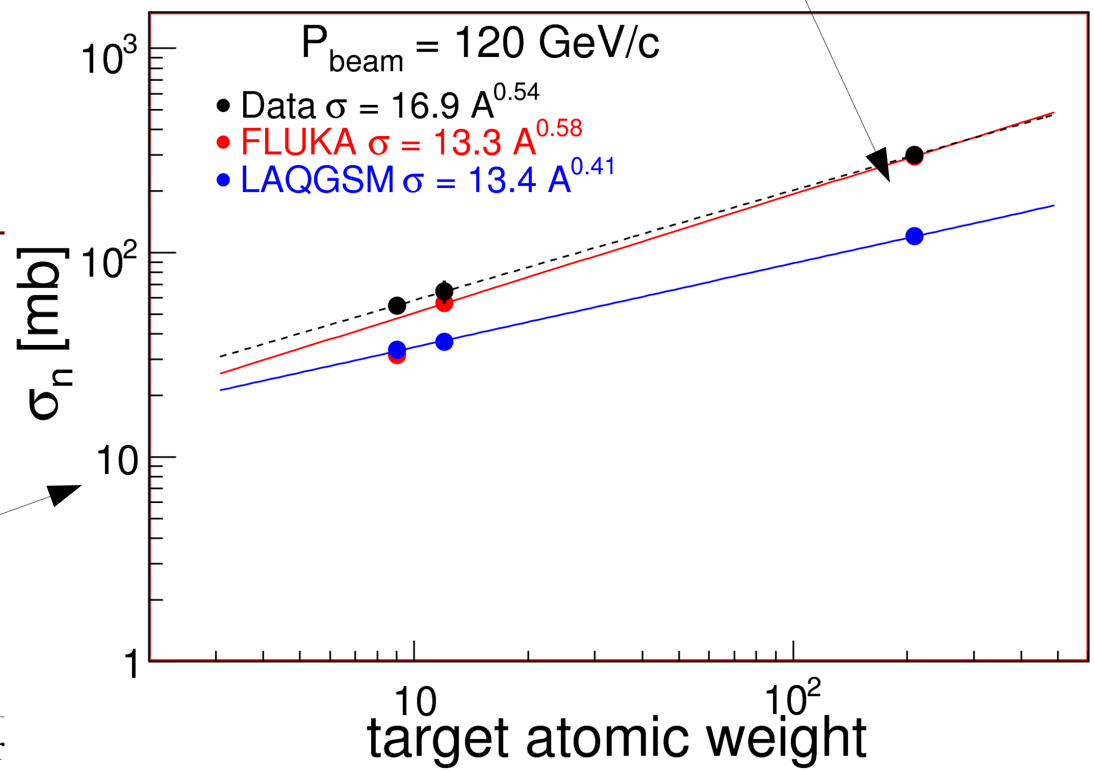
log scale

Neutron cross sections
Results as a function of A

MIPP



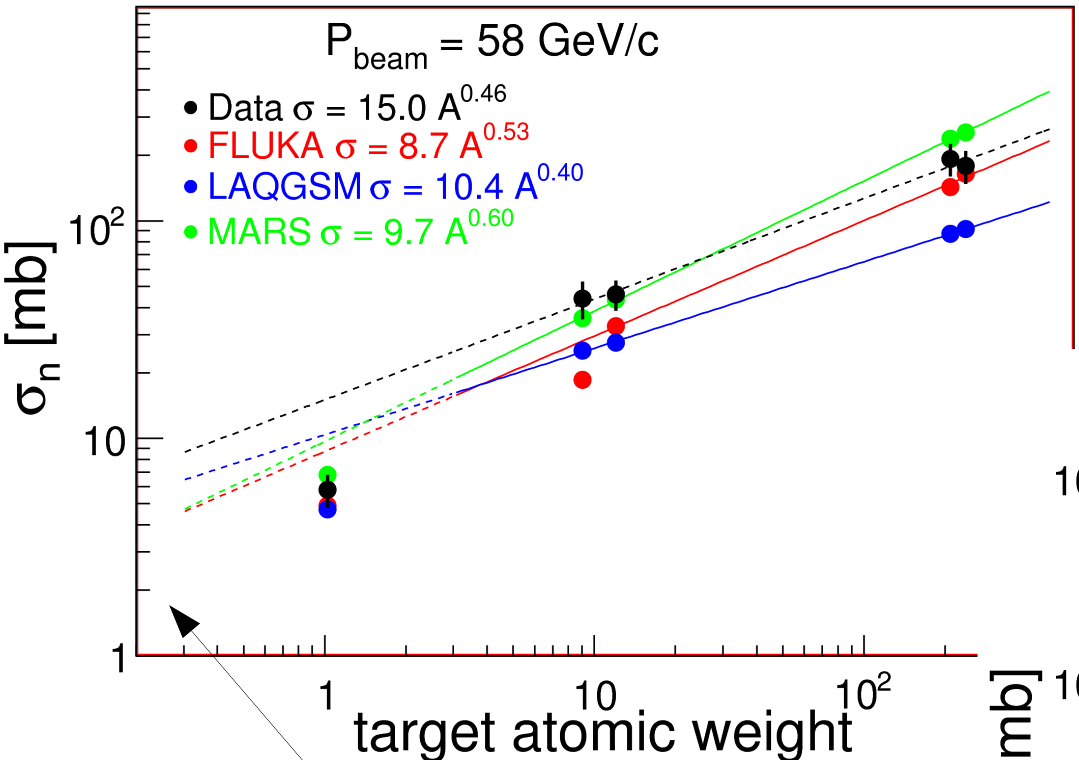
- LAQGSM predictions
  - Predictions are low
  - Discrepancy of x2.5 for Bi

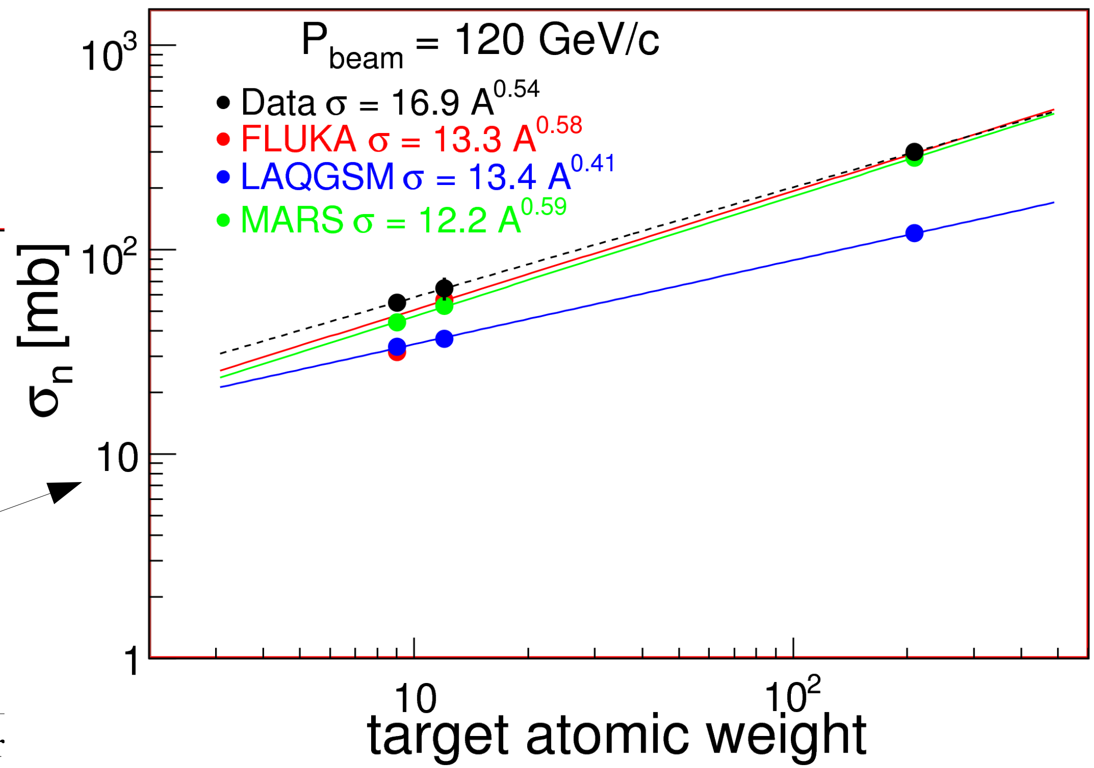


log scale

Neutron cross sections
Results as a function of A

- MARS predictions





log scale

Neutron cross sections
Results as a function of A

MIPP

- Results from previous page in table form:

Target	Beam momentum	data	Stat. error	Sys. error	DPMJET or FLUKA	LAQGSM	MARS
	GeV/c	mbarn	mbarn	mbarn	mbarn	mbarn	mbarn
H_2	20	1.5	0.1	0.3	0.9		
H_2	58	5.8	0.2	1.0	4.9	4.7	6.8
Be	58	44.0	4.4	8.3	18.6	25.3	35.7
C	58	45.9	1.5	7.2	32.7	27.5	43.5
Bi	58	193.2	10.4	32.5	143.4	87.3	238.0
U	58	178.8	7.7	30.8	165.0	91.5	256.0
H_2	84	8.8	0.2	1.2	6.4		
Be	120	55.0	0.4	8.2	31.6	33.4	44.0
C	120	64.5	0.4	8.8	56.5	36.6	53.1
Bi	120	300.2	3.1	52.0	296.1	120.1	281.1

MIPP upgrade

What could we do with 100 times the MIPP data?

MIPP

- Solve the hadronic shower simulation problem in a *model independent* way!
  - Record 5 million events a day on 30 nuclei → 1 Month!
  - The A-list:
  - **H_2, D_2, Li, Be, B, C, N_2, O_2, Mg, Al, Si, P, S, Ar, K, Ca, Fe, Ni, Cu, Zn, Nb, Ag, Sn, W, Pt, Au, Hg, Pb, Bi, U**
  - Feed this *library of events* into hadronic shower generator programs.
  - Beam momenta from 1 GeV/c to 90 GeV/c
  - Full acceptance over phase space, including info on nuclear fragmentation → Plastic Ball
  - Events contain correlations between final state particles!
- Look for unobserved baryon resonances
  - Only quark-diquark degrees of freedom or three quark model?
  - Simple beam upgrade to go down to 1 GeV/c
  - Complementary to programs at JLAB, MAMI (Mainz), ...
- Much more

Tagged neutral beams

MIPP

- Use LH_2 target → Initial state kinematics is known.
- Use diffractive reactions

$$p\,p \rightarrow p\,\pi^+\,n$$
$$K^+\,p \rightarrow p\,\pi^+\,\overline{K^0};\,\overline{K^0} \rightarrow K_L^0$$
$$K^-\,p \rightarrow p\,\pi^-\,K^0;\,K^0 \rightarrow K_L^0$$
$$\overline{p}\,p \rightarrow p\,\pi^-\,\overline{n}$$

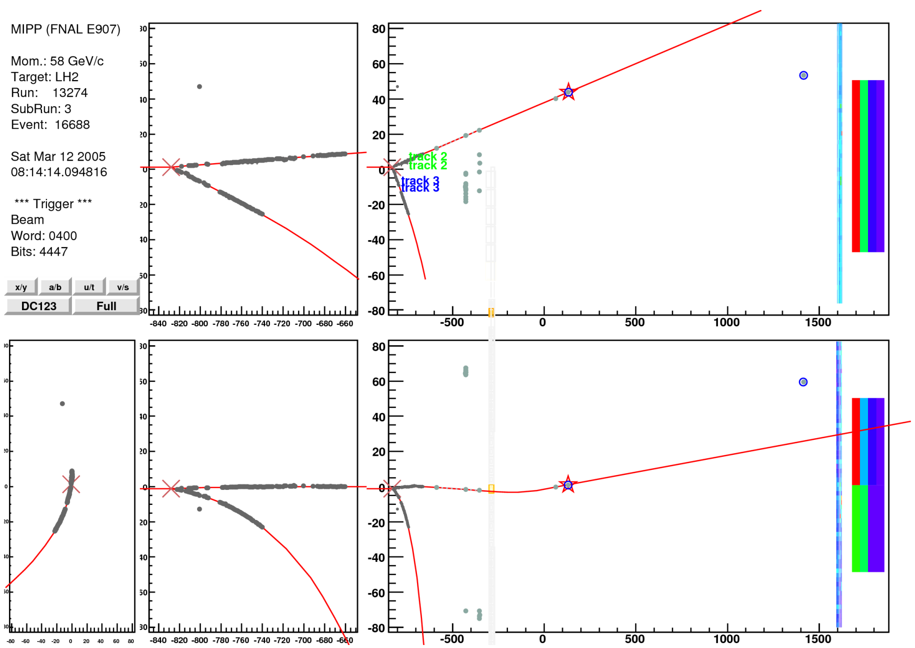
- Neutral particle momentum determined to ~2%
  - 1-C fit for one neutral particle (assuming neutral particle mass)
  - 3-C fit if direction of the neutral particle is known. → can reject events with additional π^0.
- Need to instrument backward hemisphere, upstream of LH_2 target
  - Plastic Ball detector
- Get few×10k events per day in 2m×2m area 25m downstream of target with upgrade, e.g. 66k tagged neutrons for 30 GeV/c proton beam.
(R. Raja, MIPP-doc130, arXiv:hep-ex/0701043)
- Useful for ILC PFA studies and tertiary target measurements

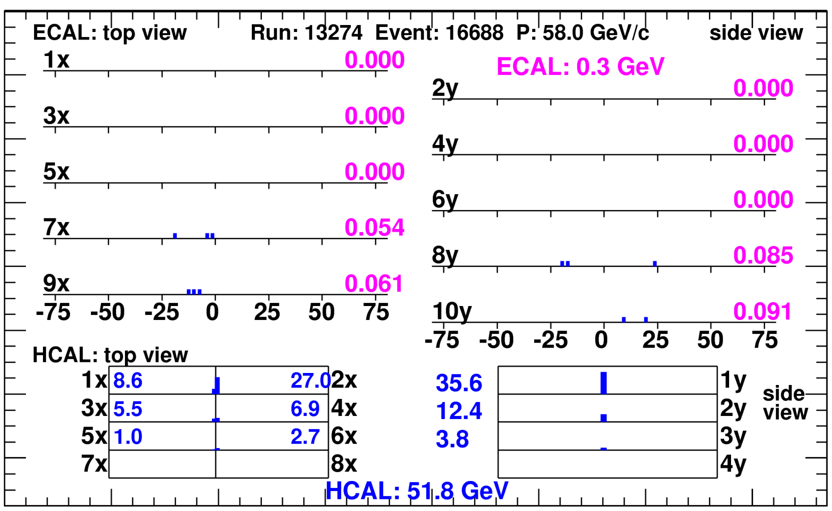
Tagged neutral beams

- Sometimes the proton moves into the TPC. Event recorded on 12 March 2005
- 58 GeV/c proton on proton
- Two charged tracks
  - (0.21 GeV/c, 0.52 GeV/c, 11.79 GeV/c)
  - (-0.04 GeV/c, -0.12 GeV/c, 0.42 GeV/c)

$$p\,p \rightarrow p\,\pi^{+}\,n$$

- Large energy in Calorimeter, no charged track pointing to it.





Other physics interests

MIPP

- 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 resonances
  - 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 inelastics such as

$$\pi^- p \rightarrow \eta n \qquad \pi^- p \rightarrow \pi^+ \pi^- n \qquad \pi^- p \rightarrow K^0 \Lambda$$

    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 needs the MIPP upgrade with improvements to the beam line to take data at ~1 GeV/c

Charged kaon mass in MIPP

MIPP

- RICH ring radius of tagged π, K, p beam particles measures K mass relative to well know masses of π, p. – NIM **A631** (March 2010)
  - 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,

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

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

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

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

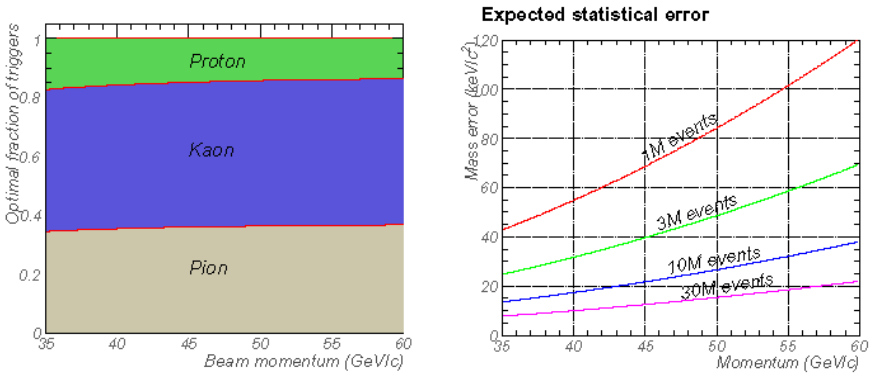


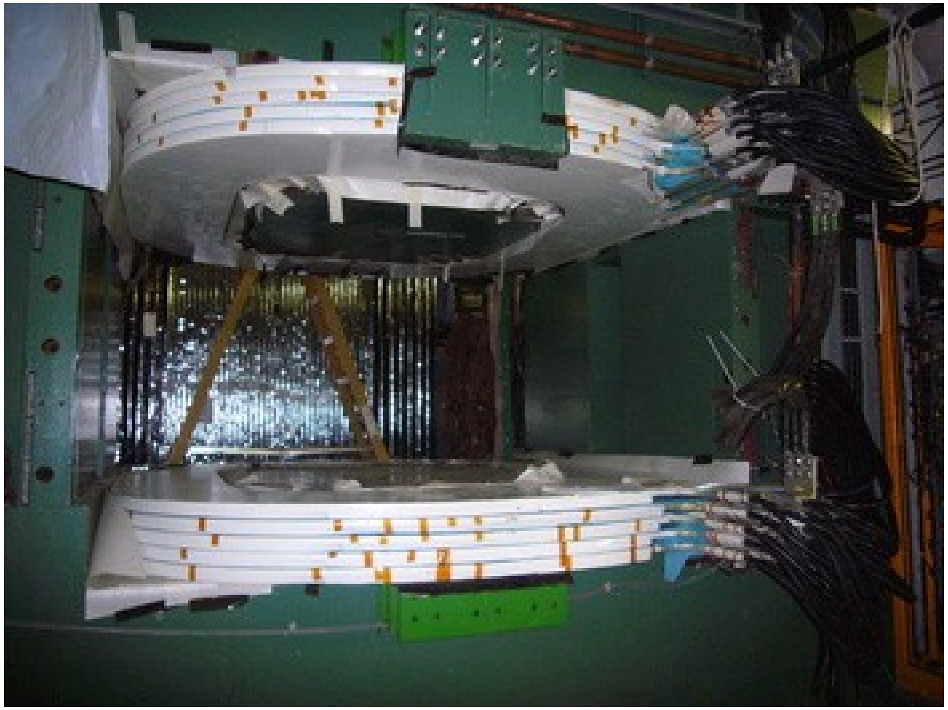
Figure 1: Optimal fraction of pion, kaon, and proton triggers (left), and expected statistical error for different total number of triggers, assuming optimal distribution of events in the sample (right).

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

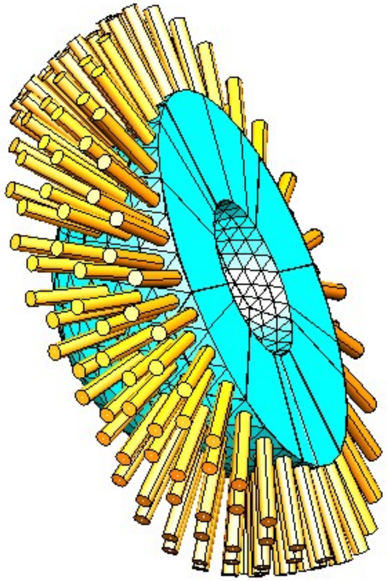
MIPP Upgrade proposal

- 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 ($100k).
- 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 replaced both the top and bottom coils with newly designed aluminum coils that have **better field characteristics** for the TPC drift.
    The new coils have been installed ($200K+labor).
- Other upgrades



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.
  - **Beam veto wall**: larger coverage to veto beam spray, assembled at FNAL, awaiting installation (ACU, Mike Sadler et al.)
  - **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.

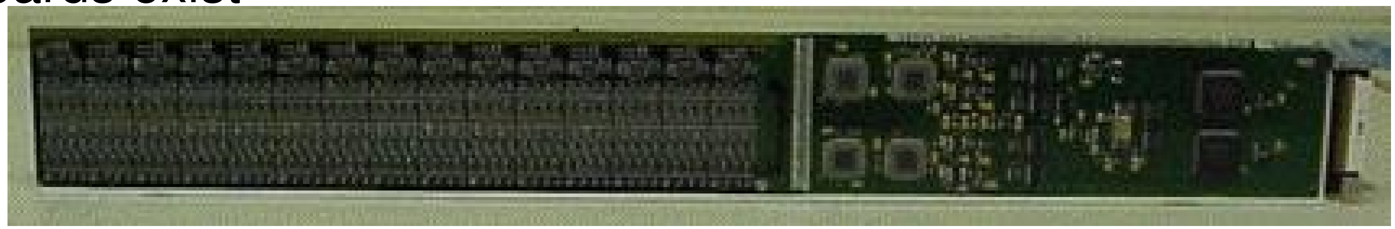


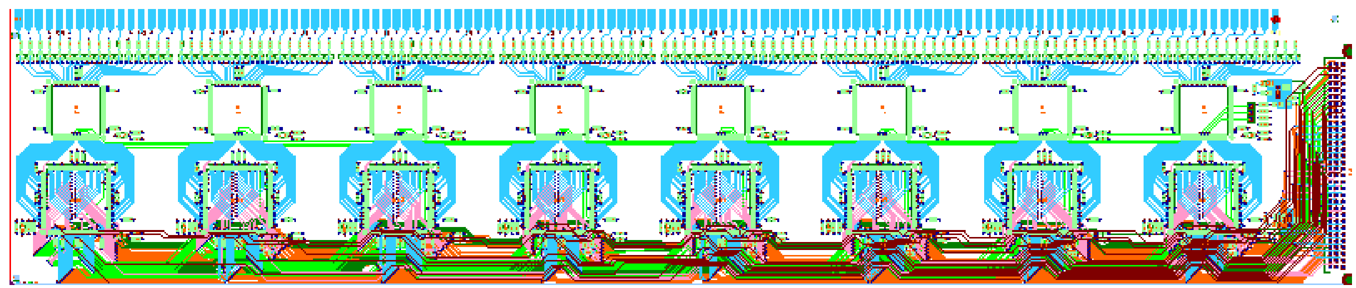
  - **Triggering system** - We propose to replace the MIPP interaction trigger (scintillator/wire chamber) with 3 planes of silicon pixels based on the B-TeV design. Will trigger more efficiently on low multiplicity events. New Master Trigger Board to form triggers.
  - Drift Chamber/PWC **readout electronics** - 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.
  - ToF/Ckov/Calo **readout electronics** – All readouts will be fully buffered: no more delay cables, common back-end for overall simpler DAQ system. Also more energy efficient.

MIPP Upgrade electronics

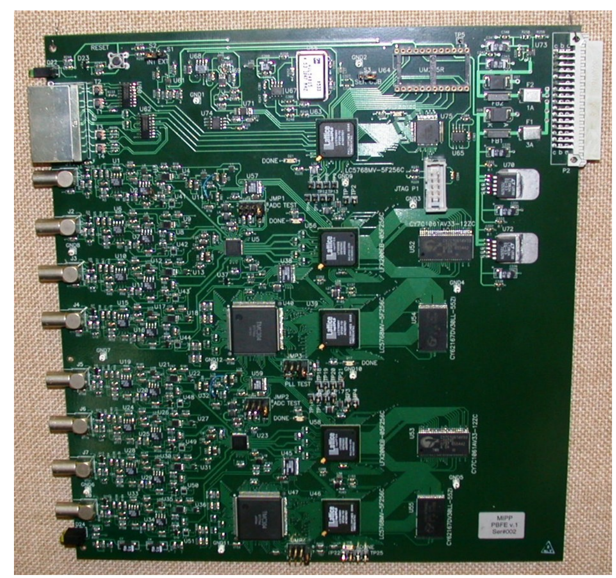
MIPP

- Several prototype boards exist
  - TPC stick prototype:
    - writing firmware
    - comparing two options





  - Plastic Ball readout
    - similar to calorimeter readout



  - DC, PWC preamp boards, discriminator & tdcs, common back-end, etc.

MIPP Upgrade summary

- MIPP can increase data rate to ~5 million events per day
  - High statistics data spanning the periodic table
  - Tagged neutral beams
  - Physics at 1 to 120 GeV/c
- Strong interest in current and future MIPP data
  - At ISVHECRI last week, peak of VHE CR energy deposit is in MIPP range
  - Hadronic shower simulation, ...
- Proposal is developed in detail
  - Full WBS: total cost ~$2 million (~$0.5 million has been spent)
  - Low risk: prototypes for key electronics exist
- Timeline
  - $\leq$1 year to build and commission upgrades
  - depends on manpower

The MIPP Upgrade Collaboration

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University of Wisconsin, Madison
P.Sokolsky, W.Springer
University of Utah
H.Meyer, N.Solomey
Wichita State University, Kansas

16 new institutions have joined. 6 from India.
New Collaborators in color cyan

Conclusions

- MIPP has produced a new technique for analyzing particle id data that employs Bayes' theorem iteratively. The GlobalPid algorithm can be applied to other analysis (pattern recognition) problems in HEP.
- We have proposed a new scheme for separating electrons and pions that employs transverse momentum as a particle id variable.
- We have used this algorithm (GlobalPid) to analyze particle production off the NuMI target.
- We have measured forward neutron cross sections on various nuclei. Significant disagreement is observed with two Monte Carlo models.
- We have observed tagged neutron events that will permit tagged neutral beams (n, n-bar, K^0_L) in the proposed MIPP upgrade.
- We have proposed a low cost upgrade to the apparatus that will significantly enhance its data gathering and physics abilities.
(Missing baryon resonance search, scaling laws, more nuclear physics)

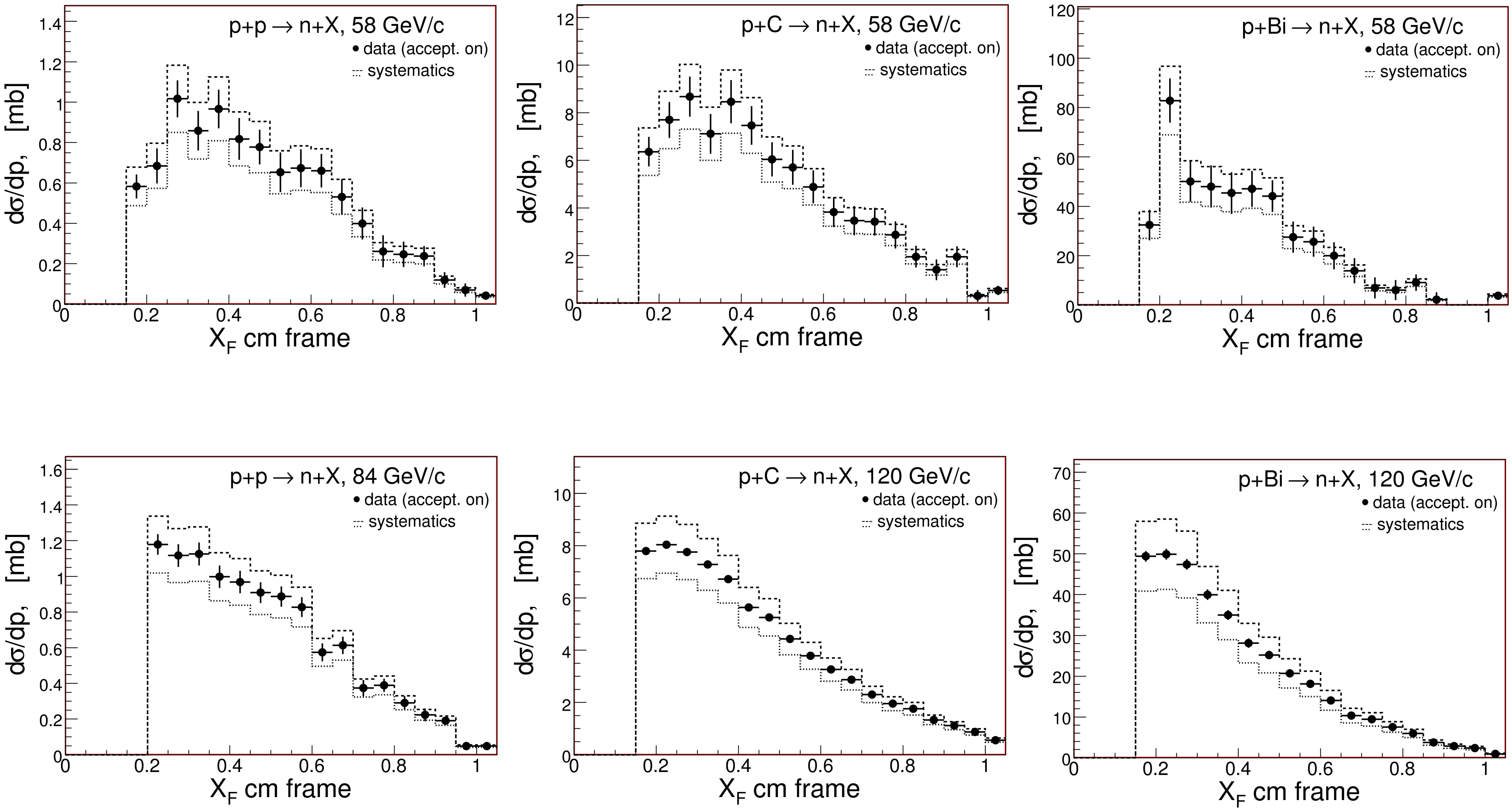
Backup slides

Backup slides

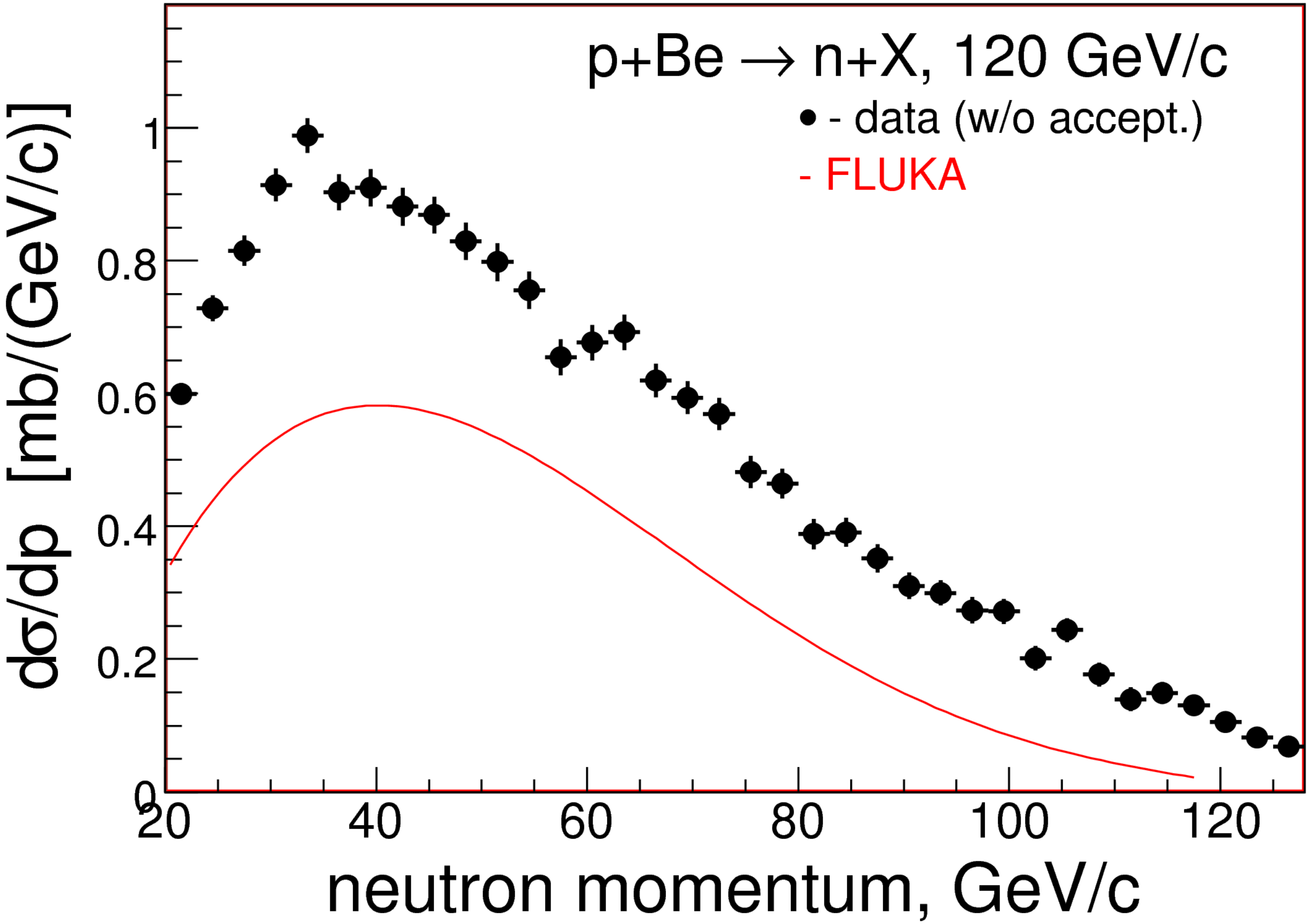
Why has MIPP data analysis taken so long?

- DoE (and NSF for U. of Colorado) decided NOT to fund MIPP specific graduate students and postdocs. Net result – University participants had to use their existing grants to fund student, postdocs (MINOS, others).
- As a result, Colorado, IIT, and Purdue could not participate.
- Livermore had to drop out (of MIPP and MINOS) because they lost stockpile stewardship program to LANL
- Finally DoE forced University of Virginia to leave MIPP and join D0!
- But we kept going. And we are near completion. MIPP data is now needed by all neutrino experiments, as well as mu2e, muon collider / neutrino factory, rare kaon decay experiments , as well as all experiments that require modeling of hadronic showers.

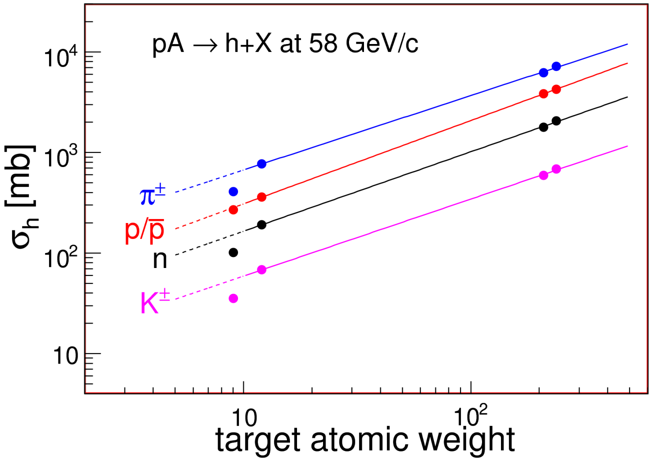
Neutron cross sections
some cross section results

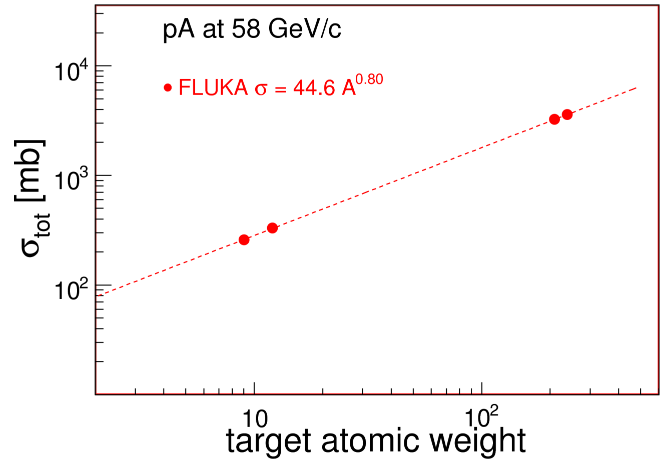


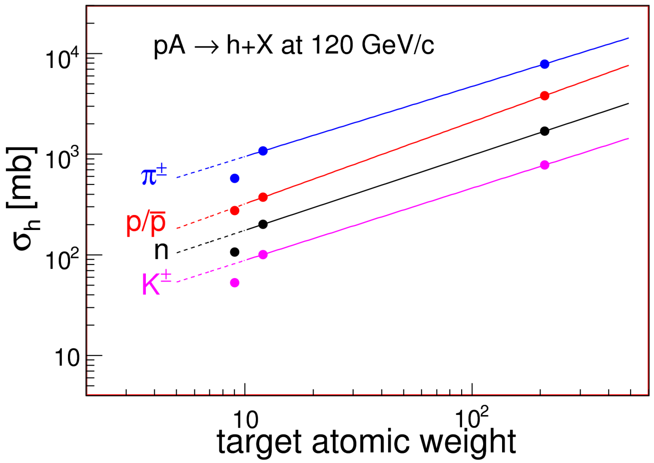
Neutron cross section on Be

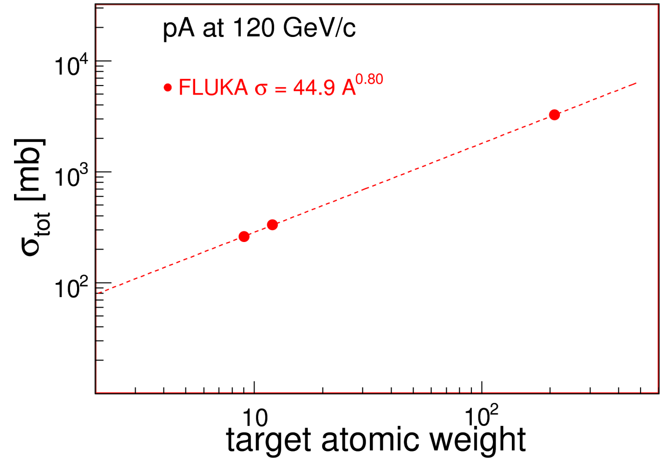


Fluka Be problem





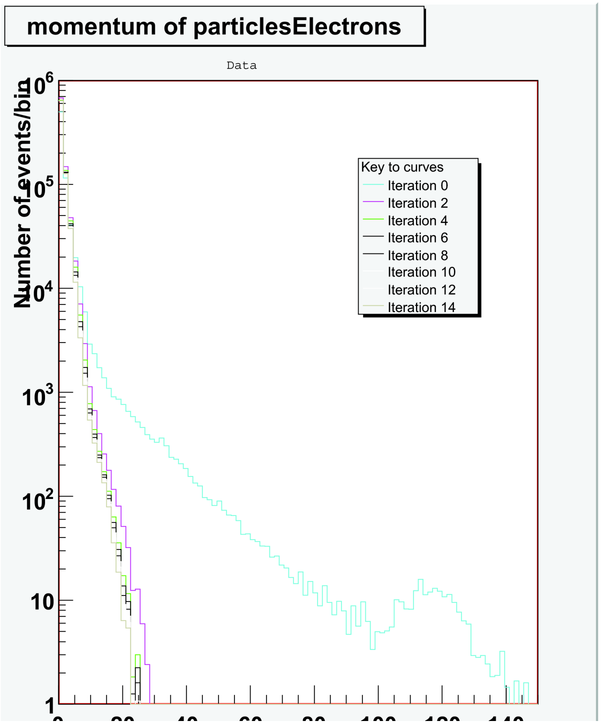




Global PID formalism

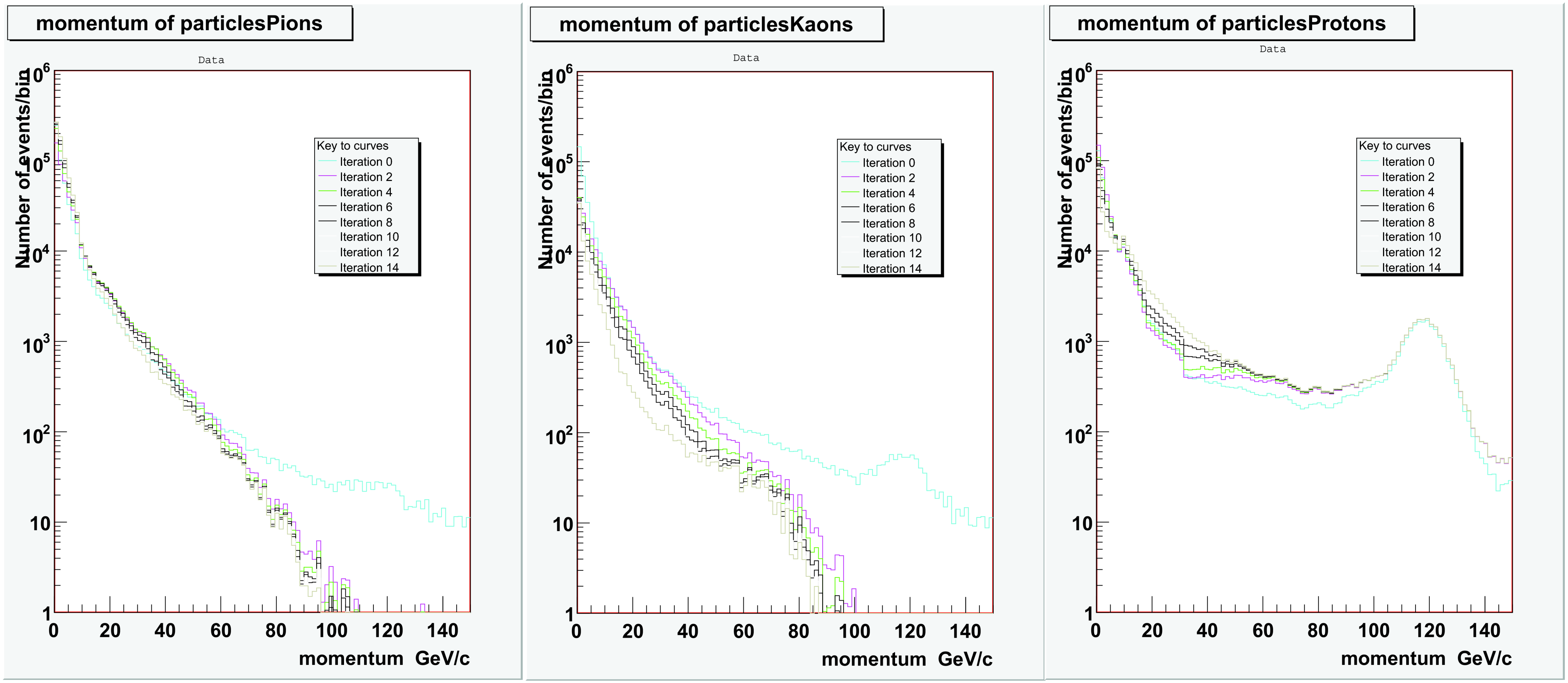
MIPP

- Bayes theorem gives posterior probability P(H|x) that track with observables x (dE/dx, ToF, r_{RICH},...) fits PID hypothesis H (e/π/K/p)
  - $$P(H|x)=\frac{P(H,x)}{P(x)}=\frac{P(x|H)P(H)}{P(x)}=\frac{P(x|H)P(H)}{\sum_H P(H|x)\times P(x)}=\frac{P(x|H)P(H)}{\sum_H P(x|H)P(H)}$$
- Iterative determination of priors P(H)
  - Start with equal weights (0.25 for each of e/π/K/p) at all momenta for first iteration
  - For each track determine $P(\vec{x}|H)=\prod_{i=1}^{ndet} P(x_i|H)$ using all PID detectors
  - Weigh each track with P(H|x) in second iteration
  - Repeat until values for P(H) converge ~15 iterations
  - P(H) yields momentum spectra



Global PID iterations

- Spectra for pions, kaons, and protons



Interest in MIPP upgrade

January 10, 2008

Dr. R. Raja
Fermilab

Re: Interest in data provided by the upgraded MIPP experiment at Fermilab

Dear Raja:

We would like to express our keen interest in utilizing the data provided by the upgraded MIPP experiment at Fermilab in improving the predictive power of hadronic shower simulation codes. The upgraded MIPP experiment will provide high quality data with final state particle identification on 30 nuclei using six beam species with momentum ranging from 1 to 90 GeV/c. The present codes use models that are tuned on single-particle inclusive data taken over many years and not always mutually consistent with each other. The MIPP upgrade data will eliminate a significant portion of the systematic uncertainties involved in hadronic shower simulations. Improved codes will benefit diverse fields within the HEP community, such as the fixed target neutrino and kaon programs, the atmospheric neutrino program, cosmic rays, calorimetry simulations in hadron collider experiments, as well as outside HEP such as studies to design radiation safe spacecraft environments. Improved codes will also help planning and calorimeter design studies for the International Linear Collider and a Muon Collider.

Sincerely,

John Apostolakis (CERN), Dennis Wright (SLAC), on behalf of the GEANT4 team

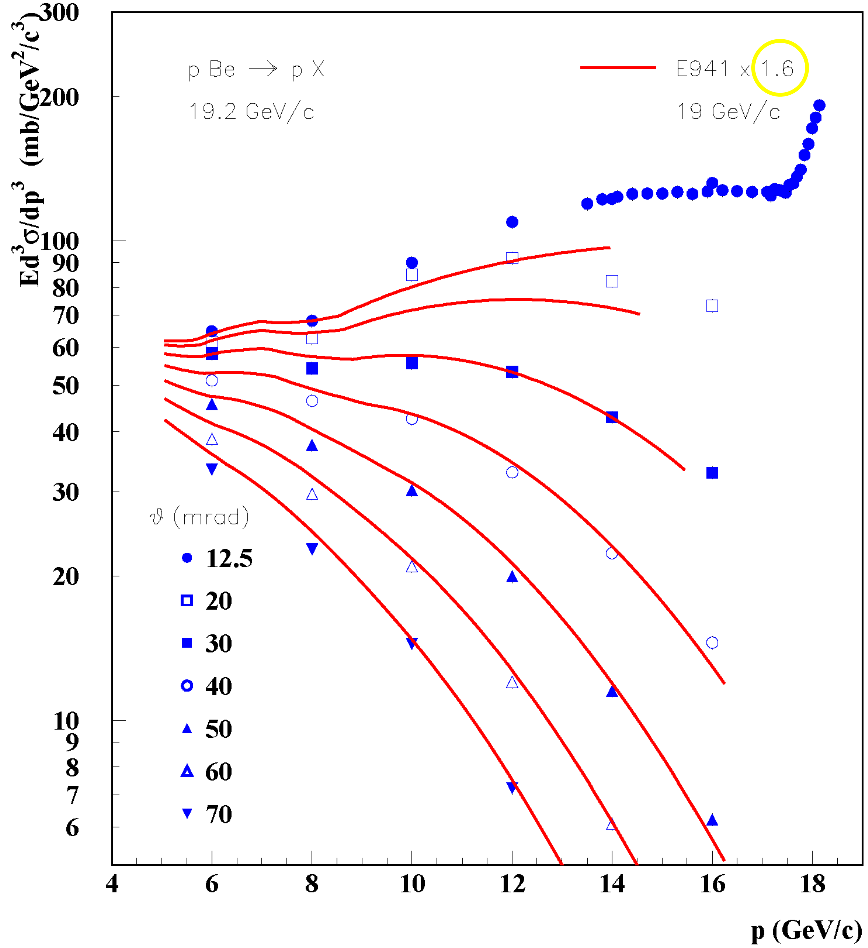
Nikolai Mokhov (Fermilab) on behalf of the MARS team

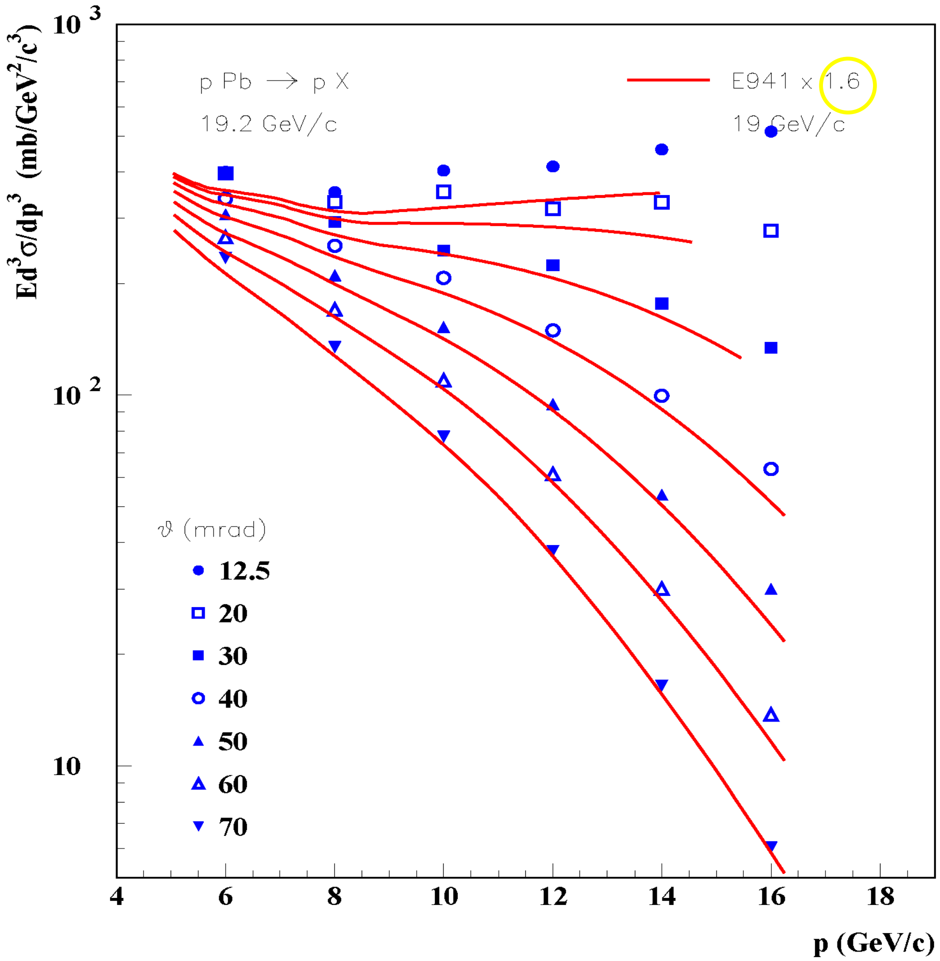
Koji Niita (RIST/JAEA) on behalf of the PHITS team

Laurie Waters (LANL) on behalf of the MCNPX team

Status of available data

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





Cosmic Ray shower simulation – existing data is insufficient

C. Meurer et al.

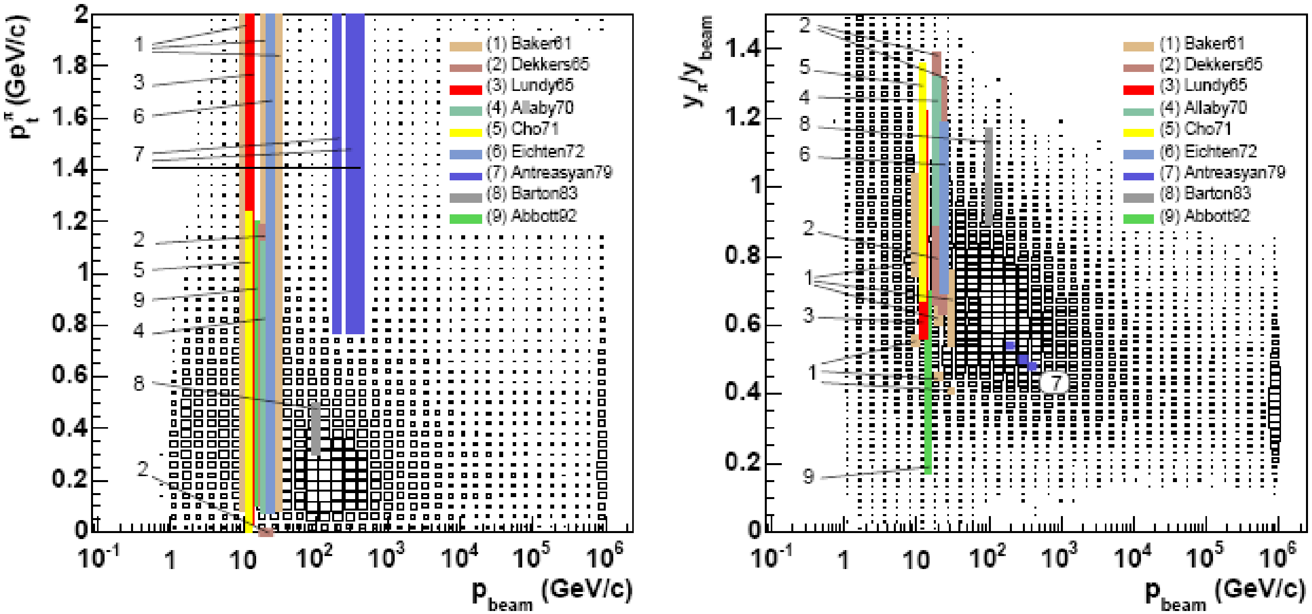
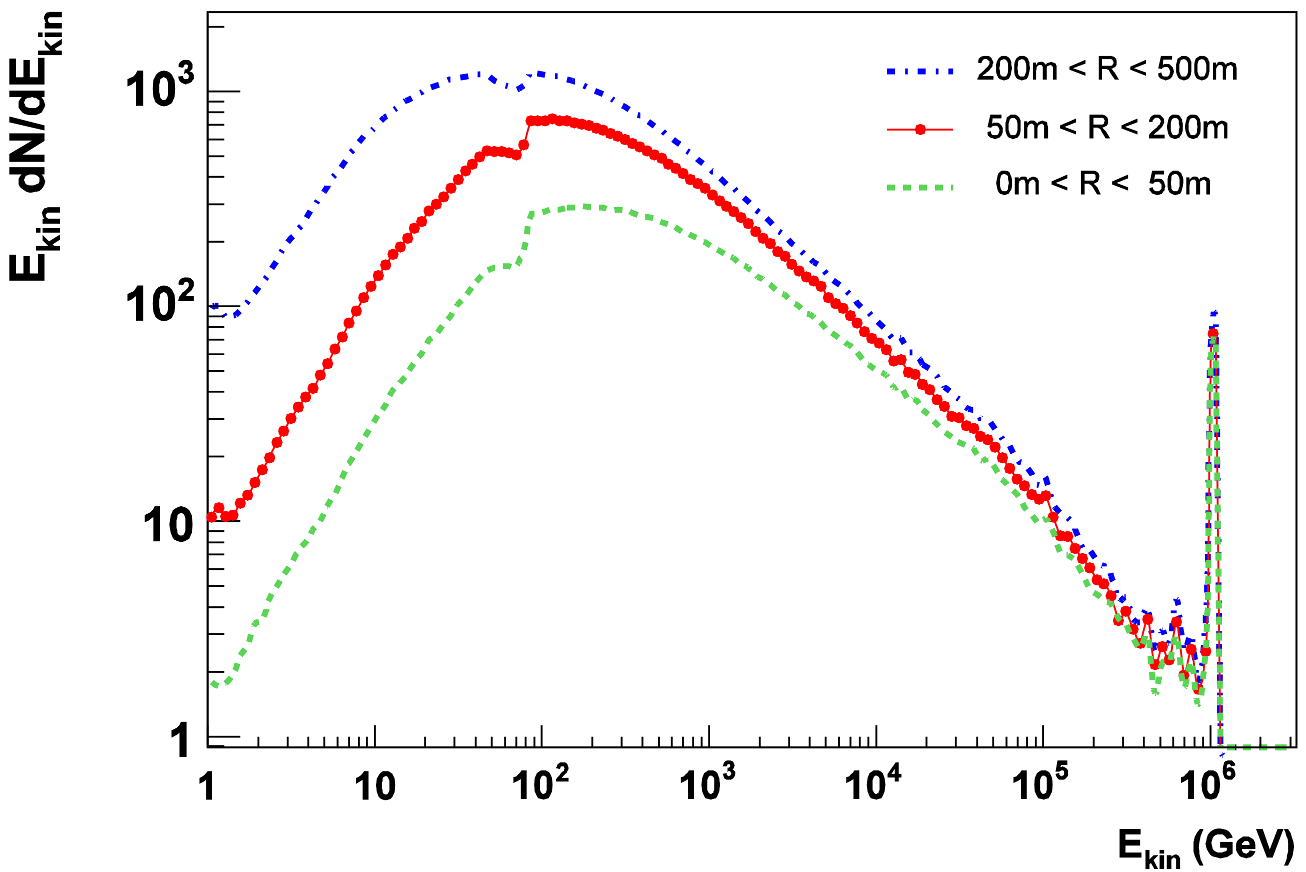


Fig. 9. Compilation of the phase space regions covered by fixed target data given in transverse momentum and rapidity of secondary particles and the phase space regions covered by the $\theta - p_{sec}$ data (see Fig. 8), whereas an approximate conversion of the covered phase space has been done. Left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



Theory of strong interaction - QCD

MIPP

- 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.

General scaling law of particle fragmentation

MIPP

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

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

  - 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.

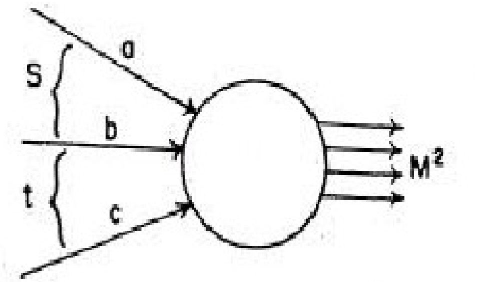
- EHS data confirms this scaling in 12 reactions, but only at fixed s
  - Y. Fisyak, R. Raja, Proceedings of DPF1992

- 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.

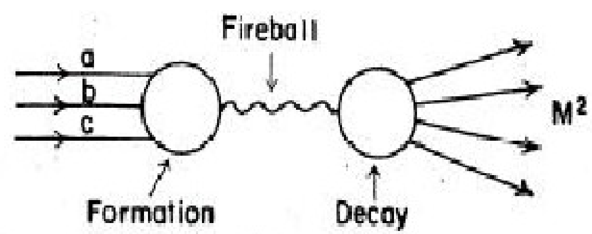
Scaling law (continued)

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

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



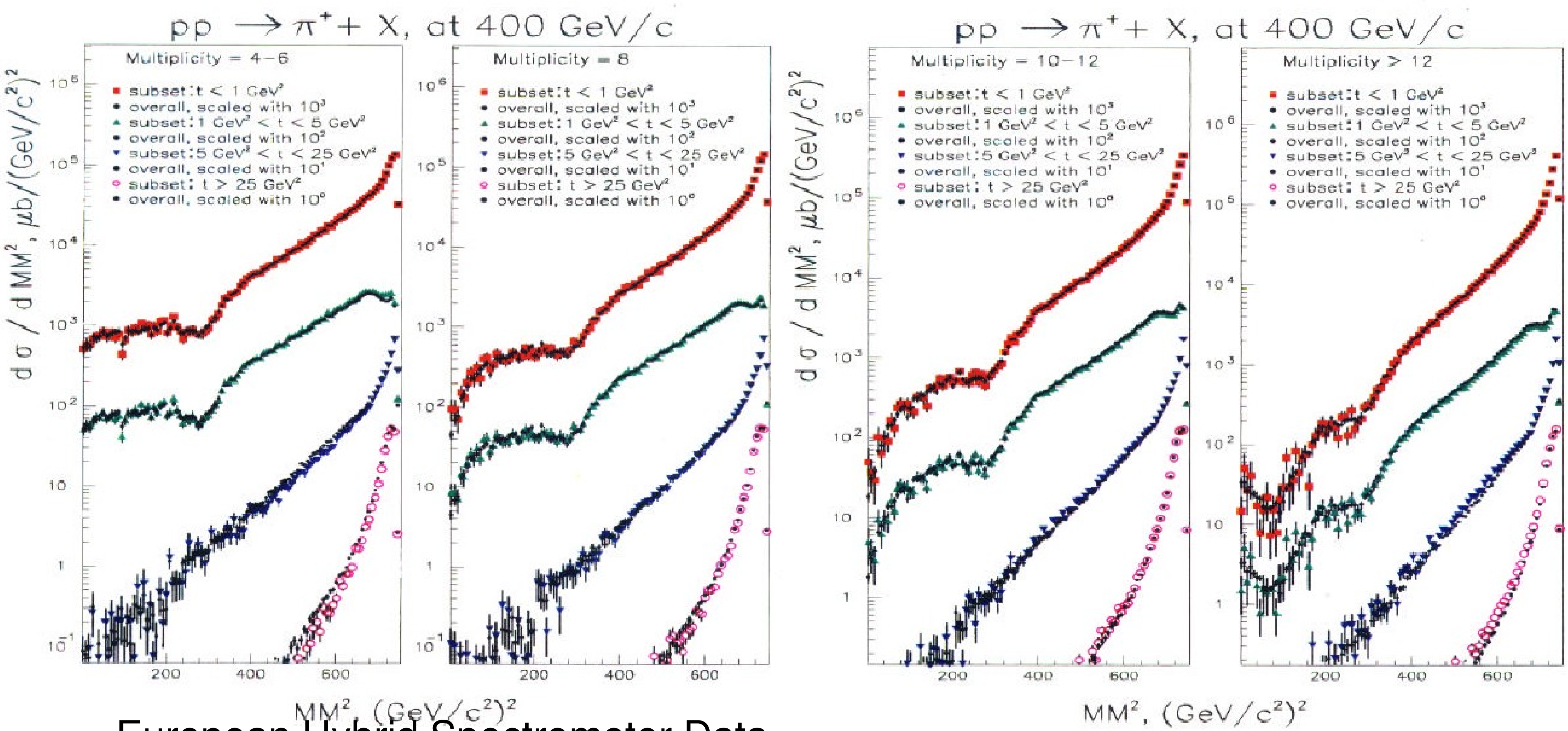
- Fast equilibrium after scattering



- 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: $\pi^+p\rightarrow\pi^+X$ and $\pi^-p\rightarrow\pi^-X$ should have same $\beta(M^2)$ for all subsets of X
  - Or $\bar{p}p\rightarrow\pi^+X$ and $\pi^-p\rightarrow pX$

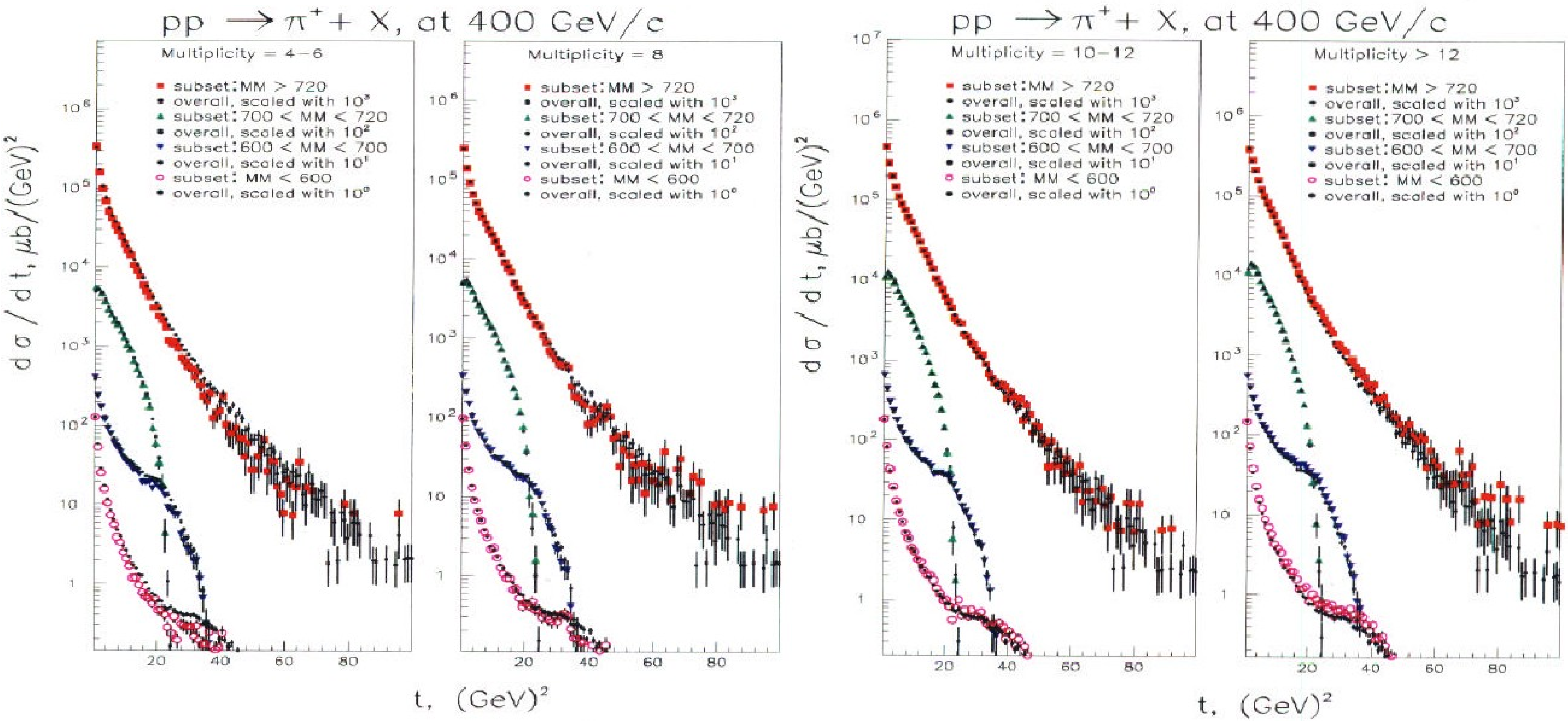
Central production diffractive

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

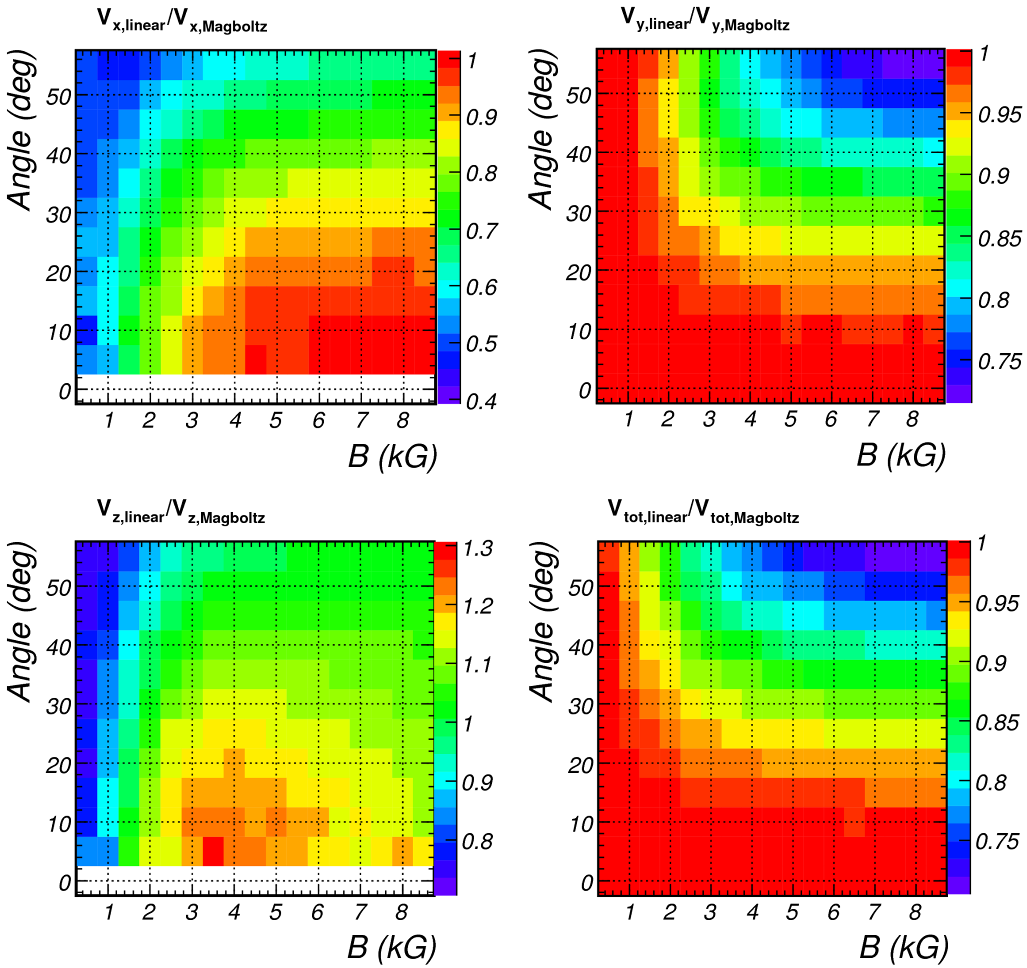
Scaling Law - EHS Data



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

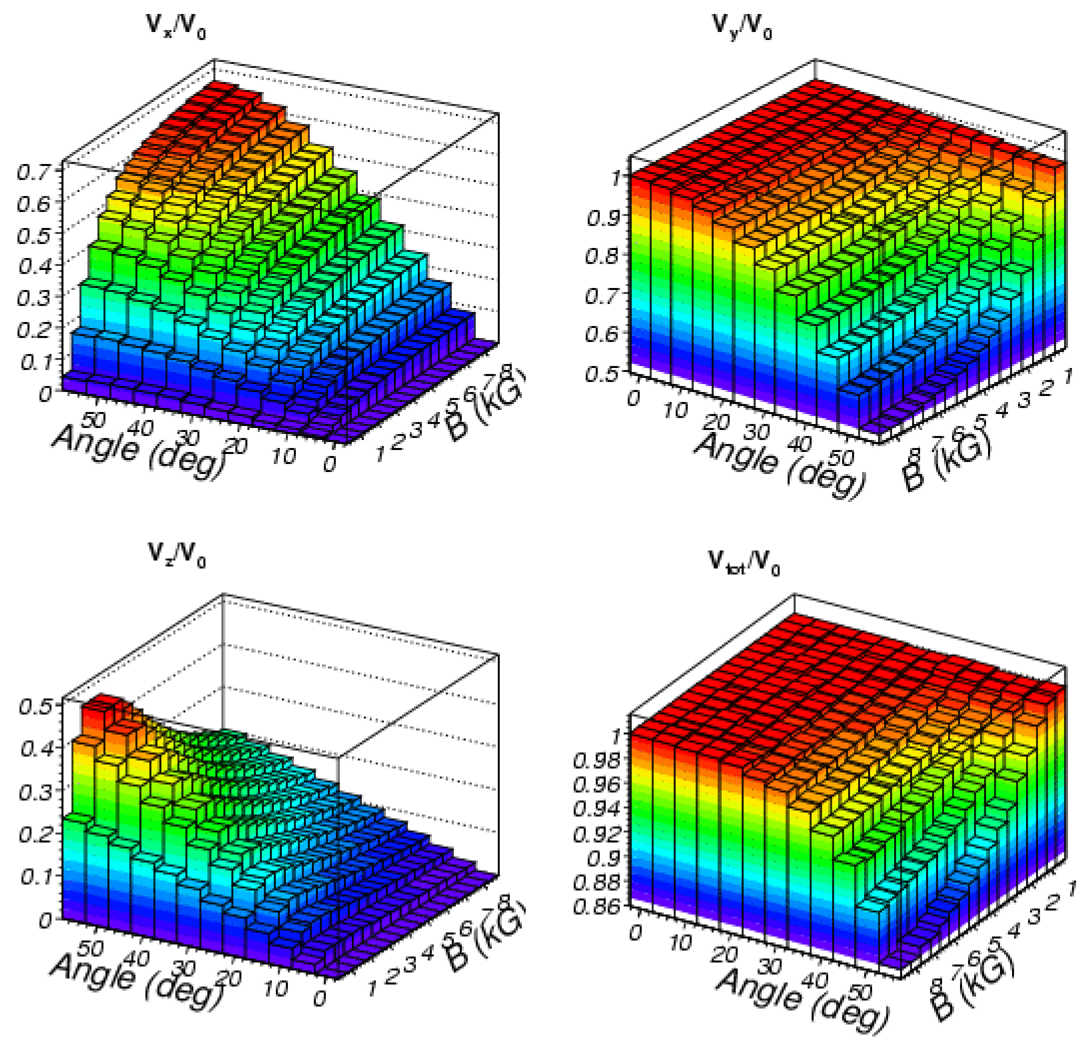
Linear Drift Model vs. Magboltz

- 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%

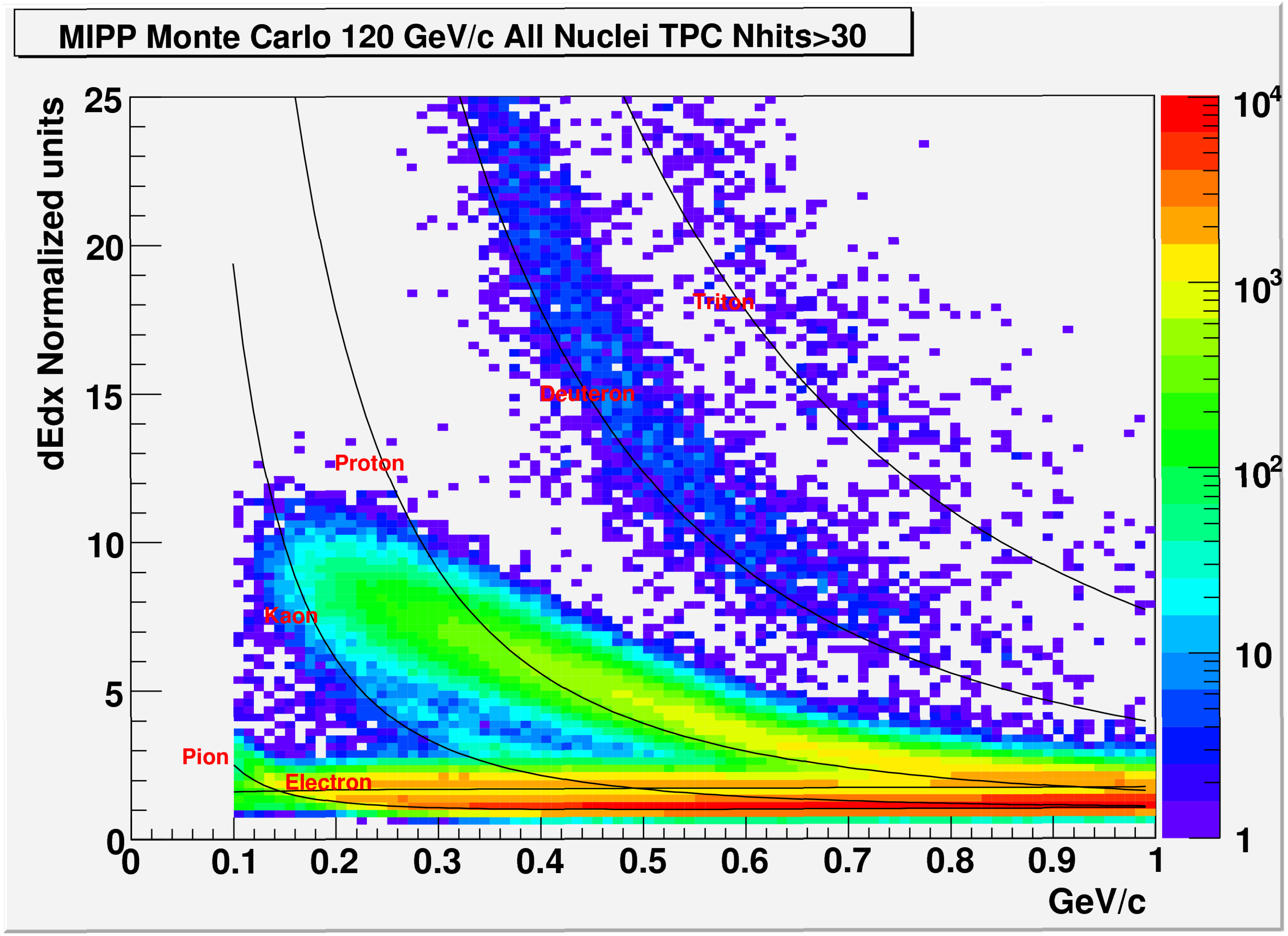


TPC distortion corrections

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

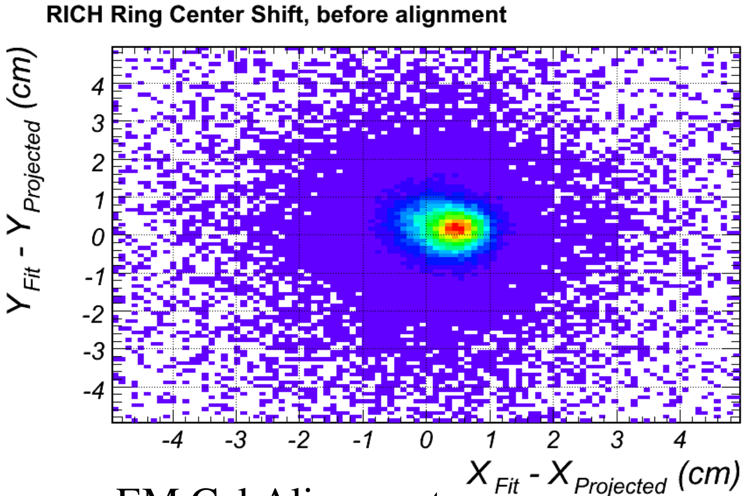


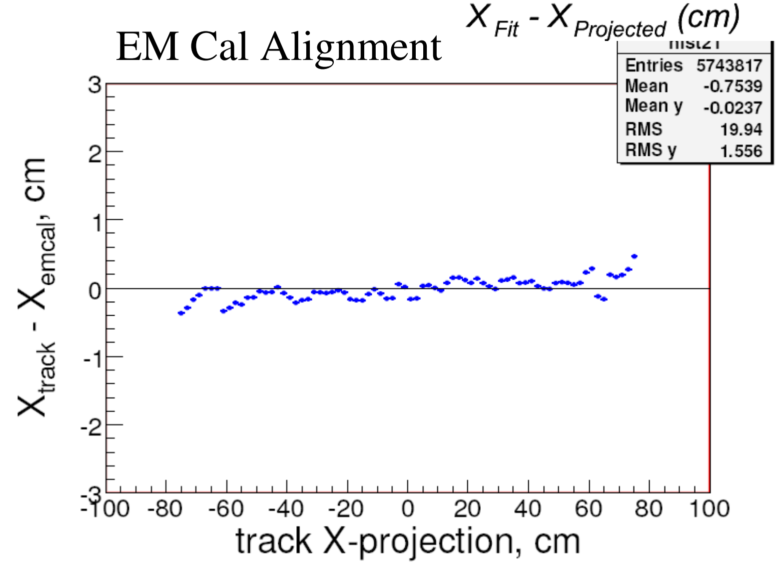
dE/dx in the TPC - MC



More calibration

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





Track direction uncertainty

- Track angles are known to better than ~1 mrad in θ and ~5 mrad in ϕ.
- Comparison of MC reconstructed to MC truth angles.