Particle production Experiments and their relevance to understanding Extensive Air showers

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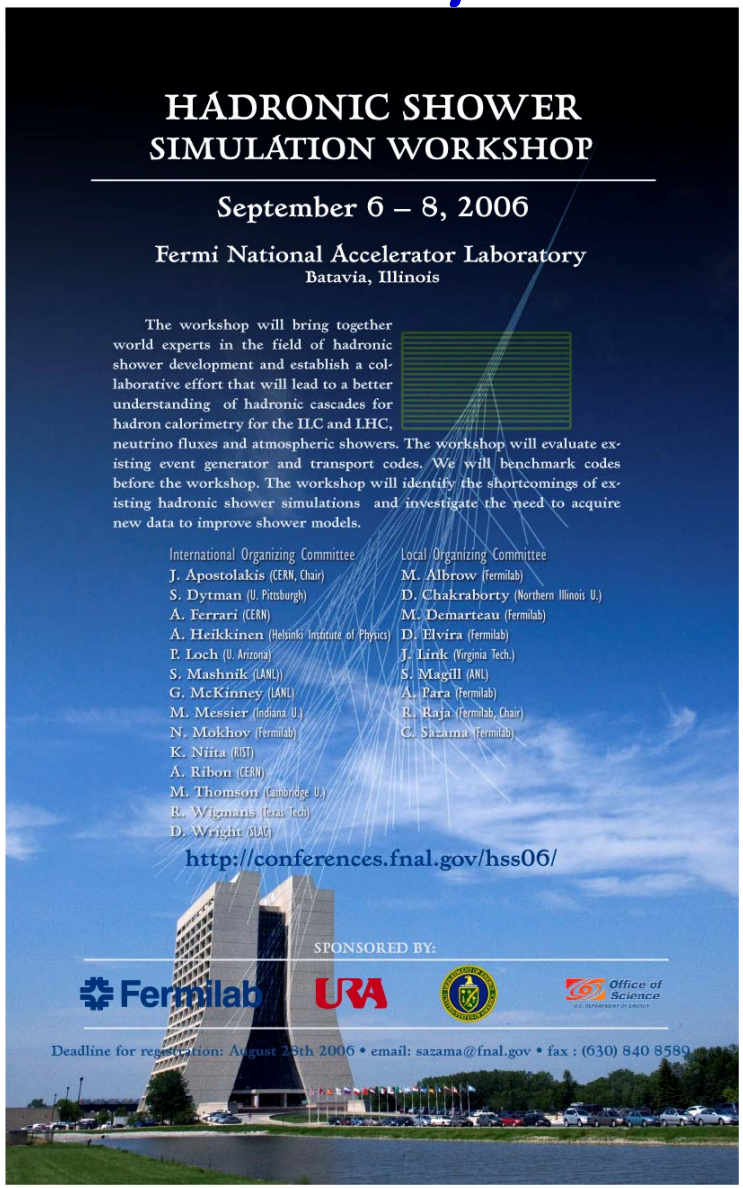
Fermilab

- Need to improve Hadronic Shower Simulators
  - » Need felt across a wide spectrum of experiments
  - » Fixed target neutrino experiments (Minos, MinerVa, LBNE, T2K)
  - » Atmospheric neutrino experiments (Hi-Res, IceCube, INO..)
  - » Project-X experiments (Kaon production, muon production in μ2e)
  - » Muon collider neutrino factory yields
- Hadronic Shower Simulator Workshop benchmarks
- NA49 and NA61 results
- MIPP results & MIPP upgrade

Hadronic Shower Simulation Workshop HSSW06

- Venue—Fermilab September 6-8, 2006
- Experts from GEANT4, FLUKA, MARS, MCNPX, and PHITS attended as well users from Neutrino, ILC, Atlas, CMS communities. Goal was to reduce systematics between various models and arrive at a suite of programs that can be relied on.
- Major conclusion—too many models-new particle production data on thin targets essential to improve models.
- Thick target data to verify new simulators



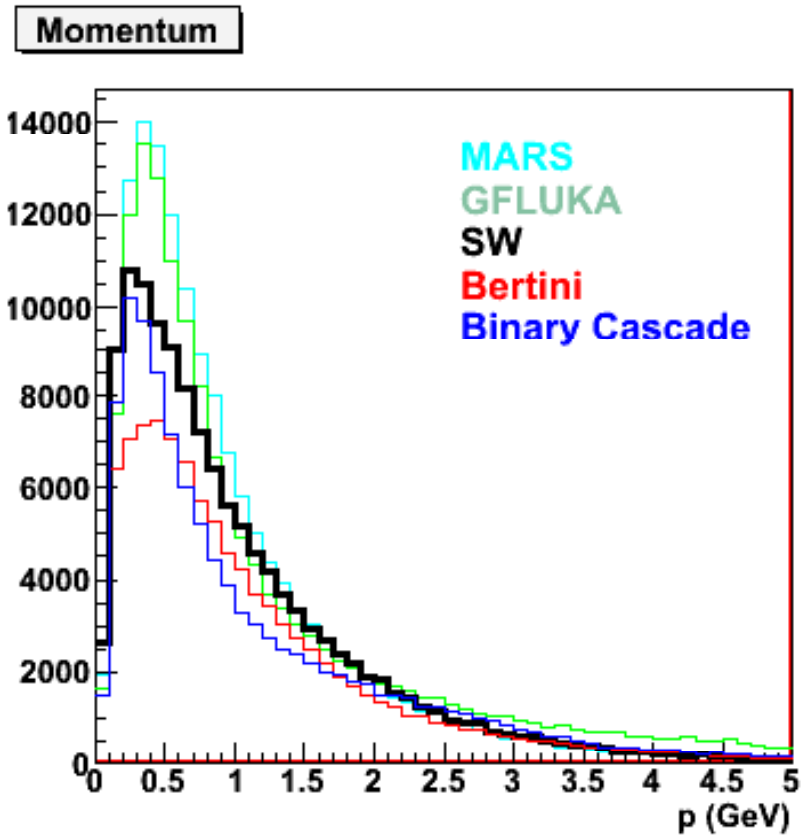
HSSW06 programs and models used by them

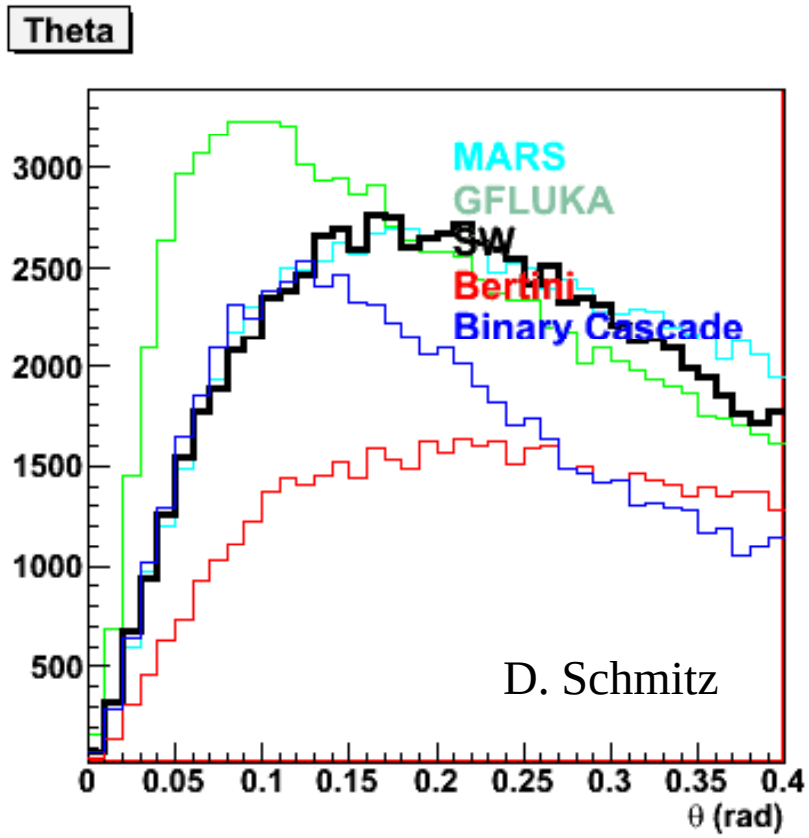
Program	Event Generator Models	Nuclear Break up models
Fluka05	Isobar model (below few GeV) own version of DPM + hadronization	PEANUT (Includes GINC) Generalized InterNuclear Cascade
Geant4	QGS + Fritiof String model $> 20GeV$ Bertini Cascade Model $< 10GeV$ Binary Cascade model Low Energy Parametrized Models & High Energy Parametrized Models (GHEISHA origin)	Geant4 Pre-compound model Bertini evaporation model Chiral Invariant Phase Space model (CHIPS) $< 20MeV$ Nuclear break-up libraries
MARS15	Inclusive event generator CEM03, LAQGSM03 Quark-Gluon String model	Generalized intra-nuclear cascade evaporation and fission models
PHITS	Jet AA Microscopic Transport Model (JAM) $> 20MeV$ Jaeri Quantum Molecular Dynamics model JQMD	Neutrons done as in MCNP JQMD
MCNPX	Fluka79 or LAQGSM	Intra Nuclear Cascade models Bertini, ISABEL, CEM, INCL4..

Models Fit to data where they have been tuned

- Tuning done in single inclusive variable –eg Feynman x or multiplicity.
- Errors in models multiply when applied to the calorimeter problem. Repeated showering causes systematics to be enlarged.
- In order to get longitudinal and transverse shapes correctly, one needs to not only single particle inclusive cross sections but also multiparticle correlations.
- To do this we need new data.
- To illustrate—Neutrino targets (many interaction lengths) and transverse size of target restricted.

Miniboone-Sanford-Wang (SW) parametrizaion of E910 and HARP compared to other models

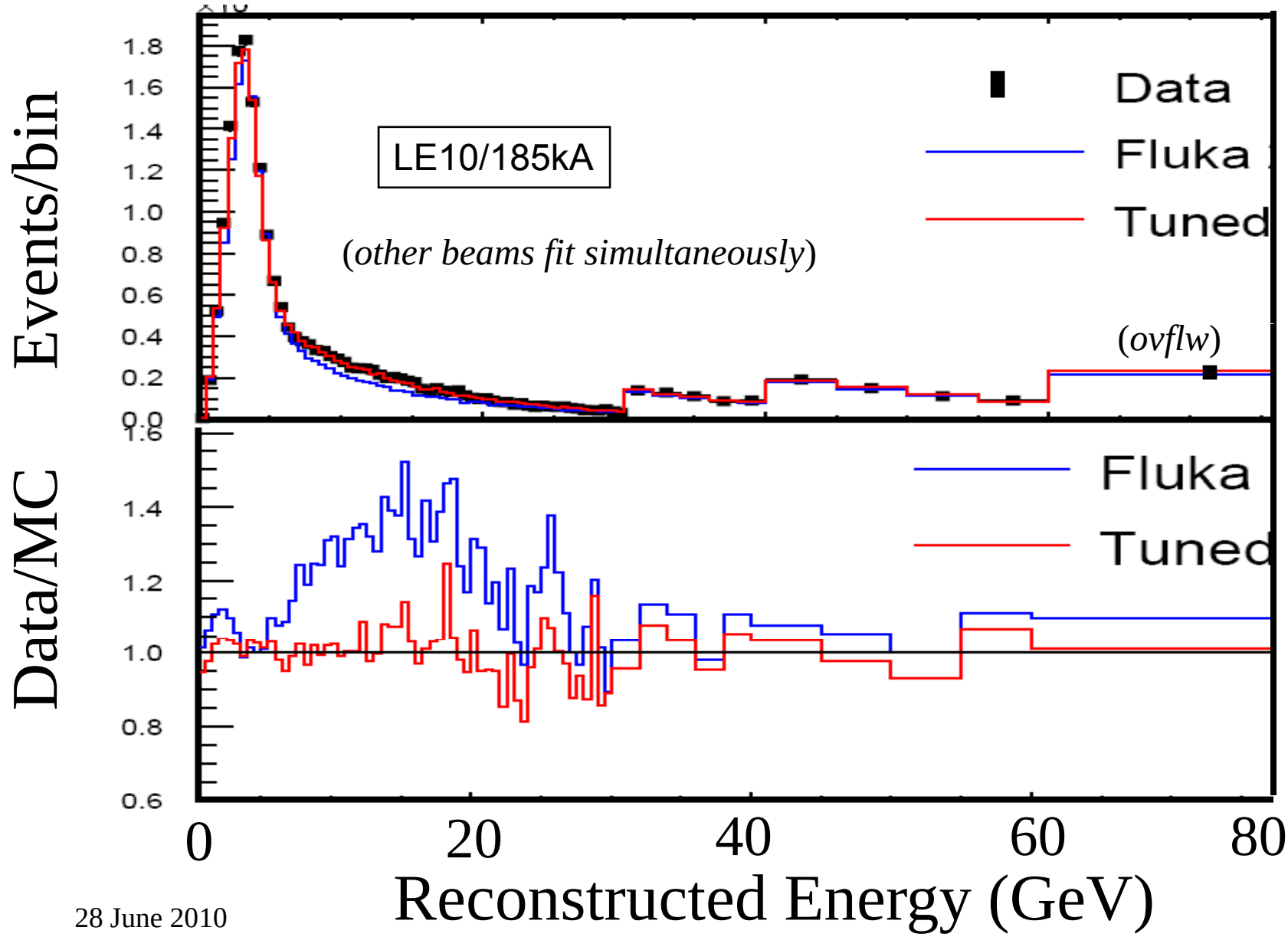




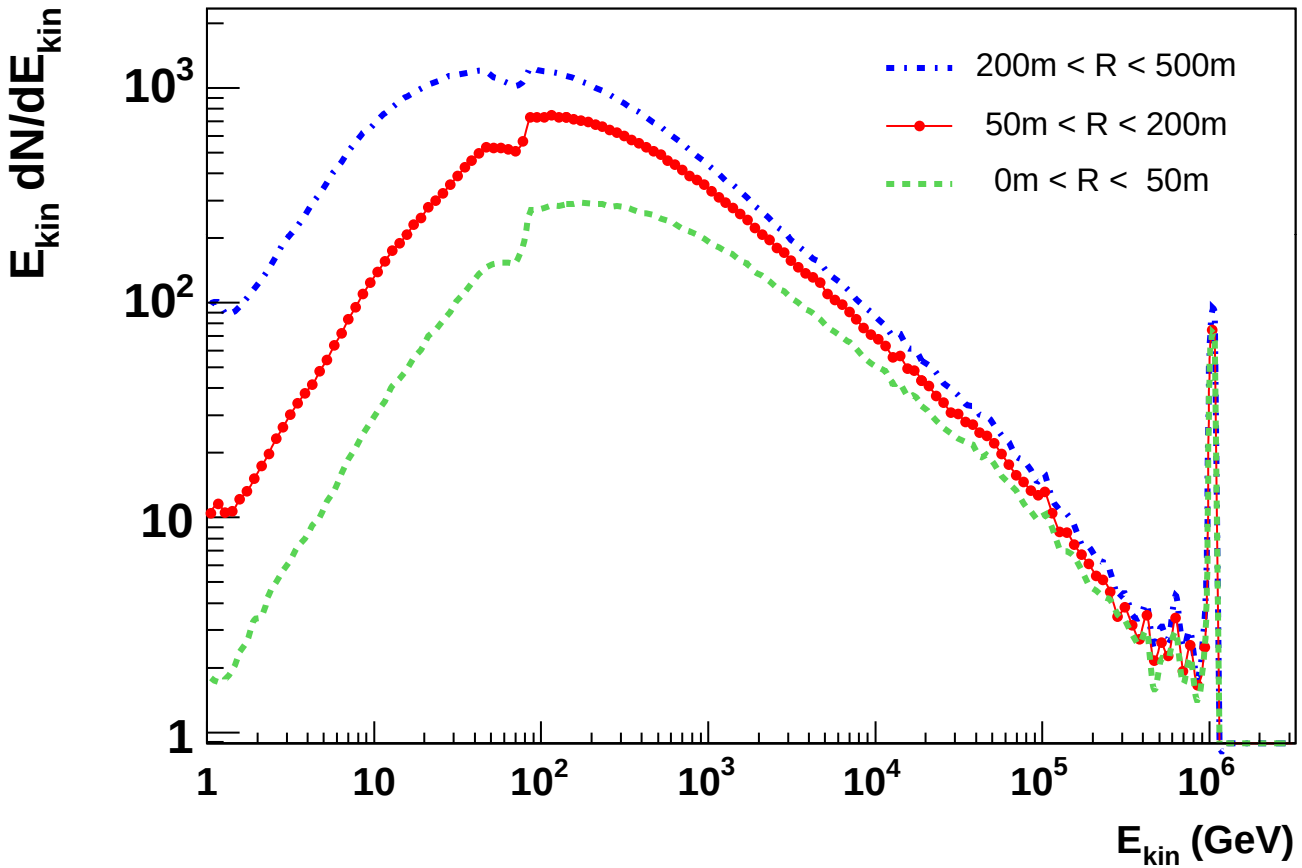
The differences are dramatic in the between models! But the E910 and HARP cross sections determine the correct model, which is very close to MARS.—Does this mean MARS is now the correct simulator to use?

MINOS problem– (from S.Kopp)

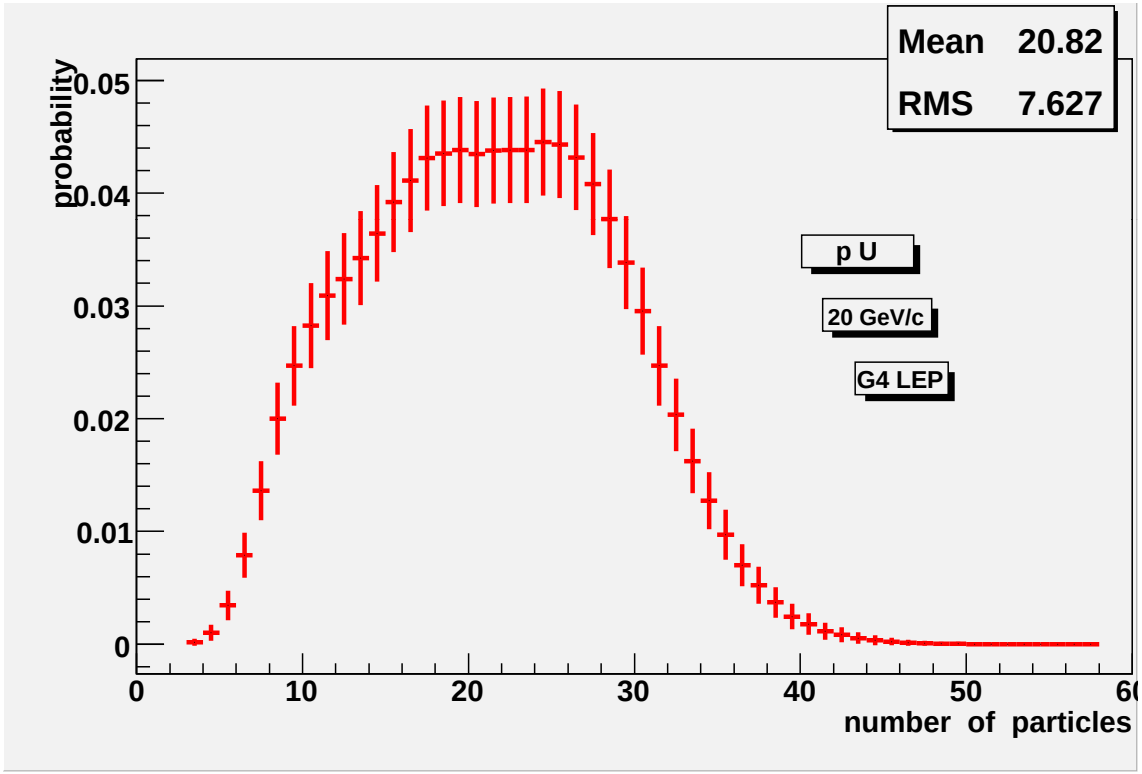
To get red points, MINOS assumed they know the νN cross section for E_ν<10 GeV. Somewhat circular argument. We need flux to measure νN cross section, instead we use an assumed cross section to determine flux. First principles flux measurement will get us out of this loop.

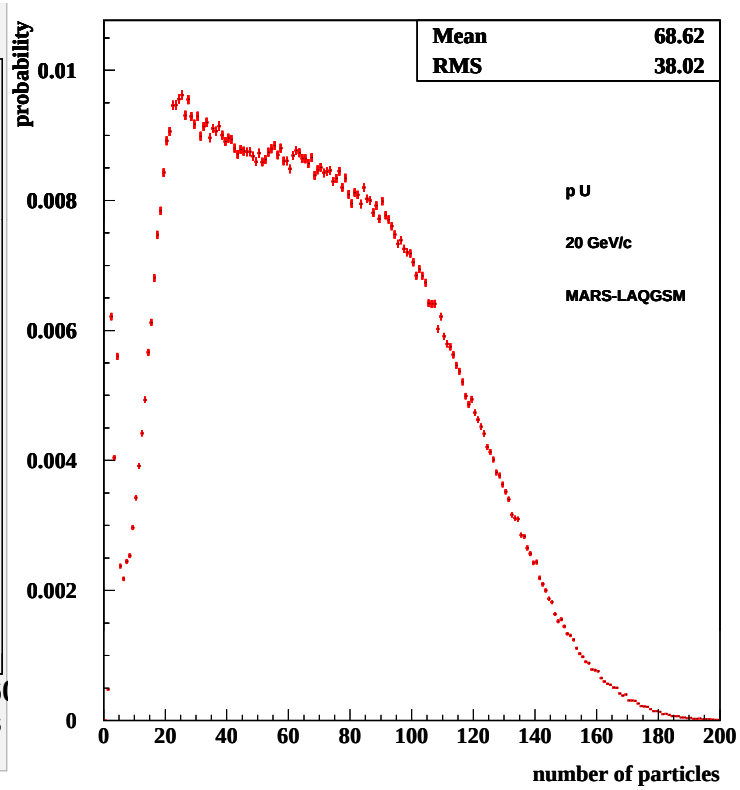


Meurer et al –Cosmic ray showers Discontinuity-Gheisha at low energies and QGSJET at higher energies-Simulation of air showers. This problem cannot be solved by measuring a nitrogen target at one or two energies.



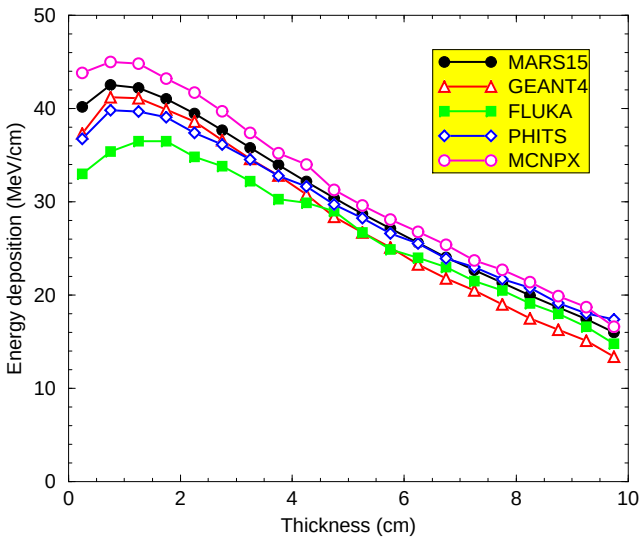
Thin target data model comparisons



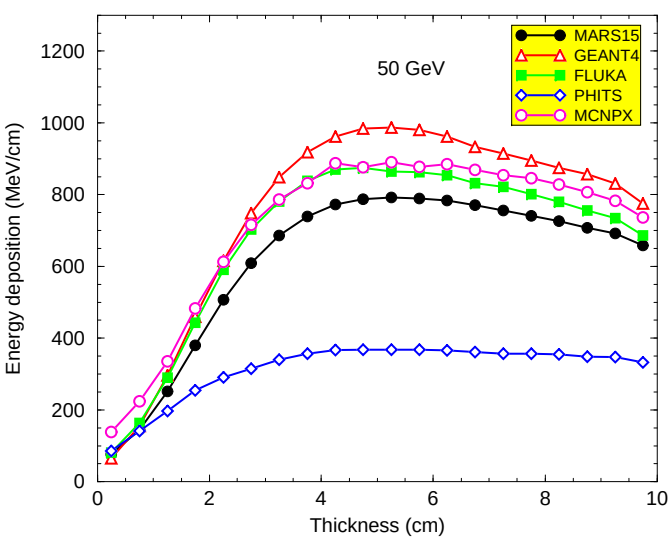


Benchmark example from HSSW06- (N.Mokhov,S.Striganov,D.Wright et al)

- Energy deposit profile as a function longitudinal depth in a tungsten rod of 1cm radius—Challenges to get longitudinal and transverse distributions correctly simultaneously.



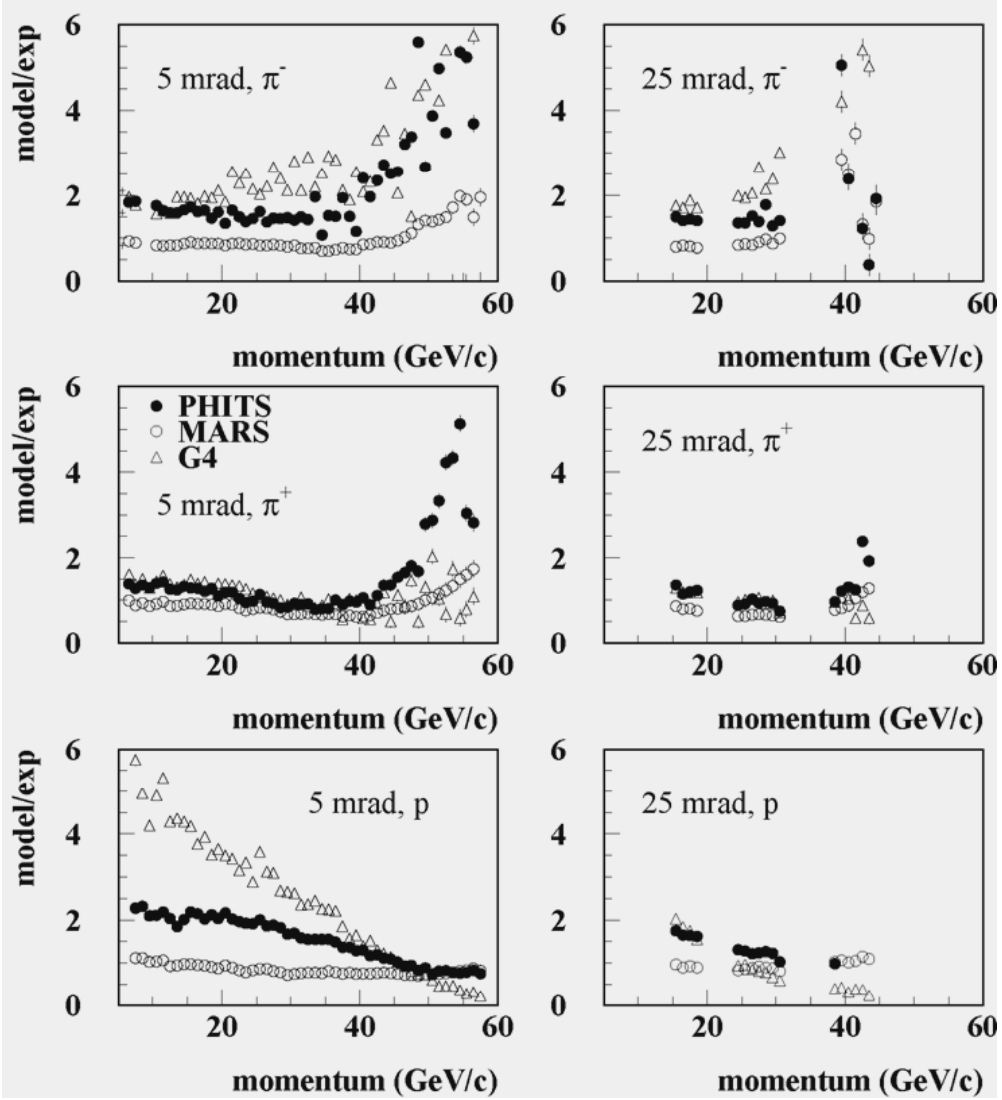
1 GeV/c protons



50 GeV/c protons

Models plotted as a function of ratio to data.

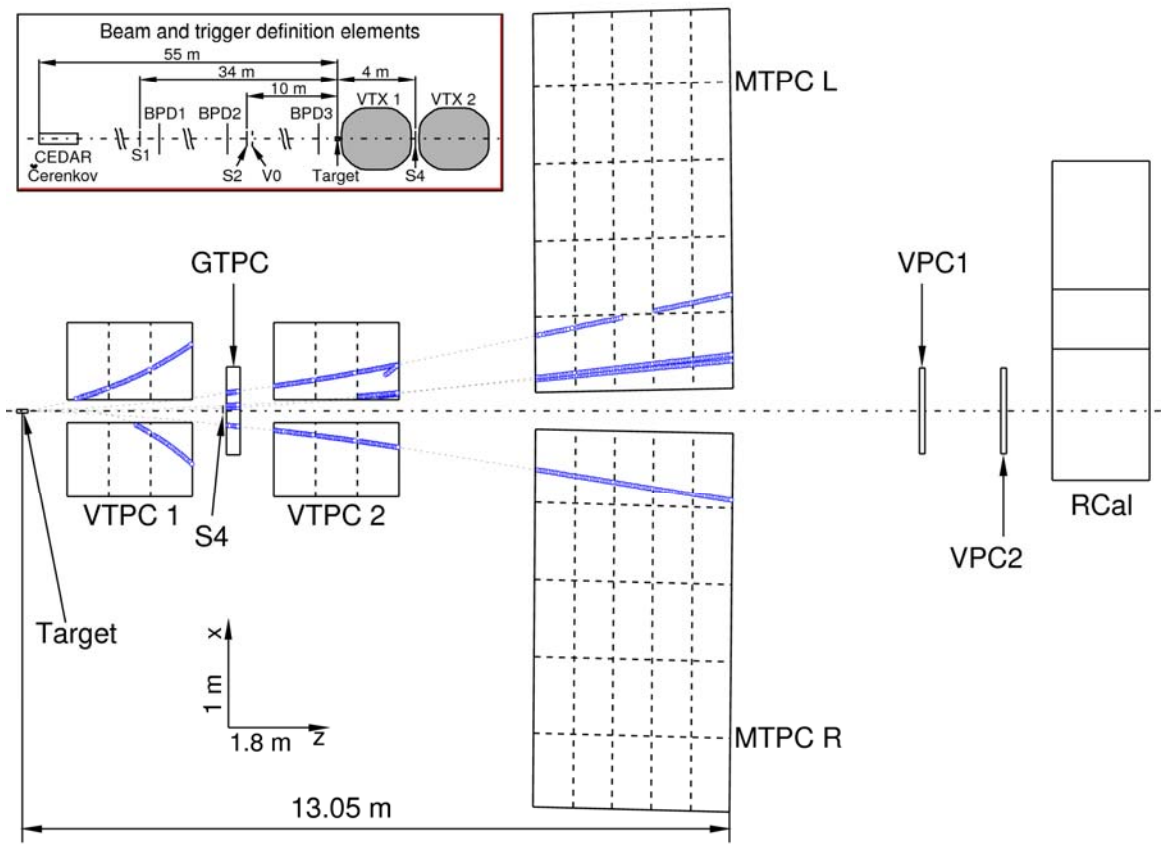
- Plotted on right are the ratios of model/data for various final state particles for 67 GeV/c protons on a thick aluminum target at Protvino. Discrepancies of order 5-6 are evident between model and data. Models disagree amongst themselves.



Summary of simulator problem

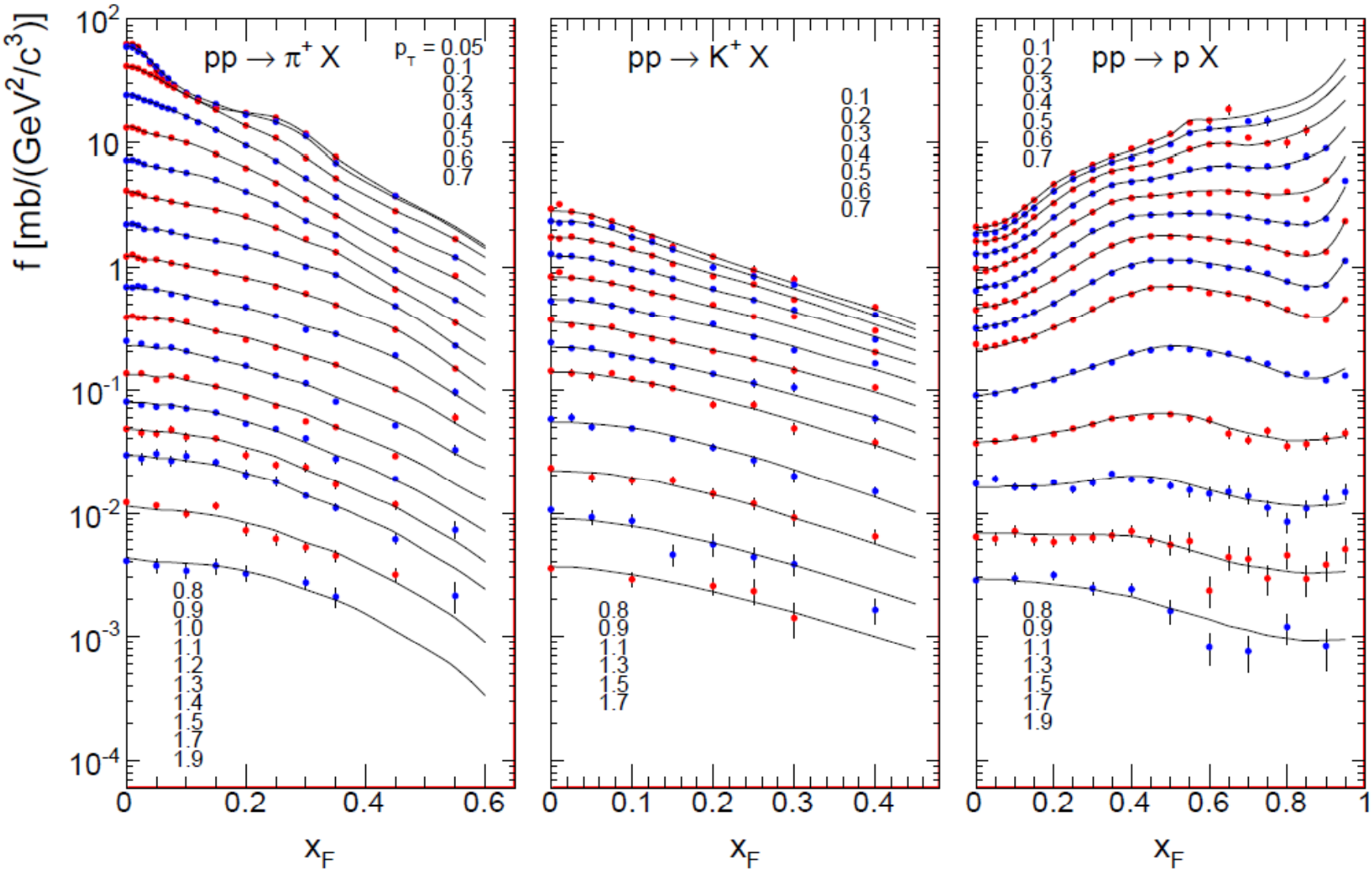
- Large variations in models predicting longitudinal energy deposition in thick targets.
- Models/data are off ~500% in 67-GeV p-Al (Thick target data) from Protvino.
- x_F-vs-p_T distribution of π/K production are 30 years old and are sparse.
- Thin target data (where avaliable) and models do not agree
- Particle correlations are important for transverse shapes (and thus also for neutrino spectra for thick targets whose transverse size is less than hadronic shower). Little correlation data available. So large model variations.

Hadron Production from the NA49 Experiment

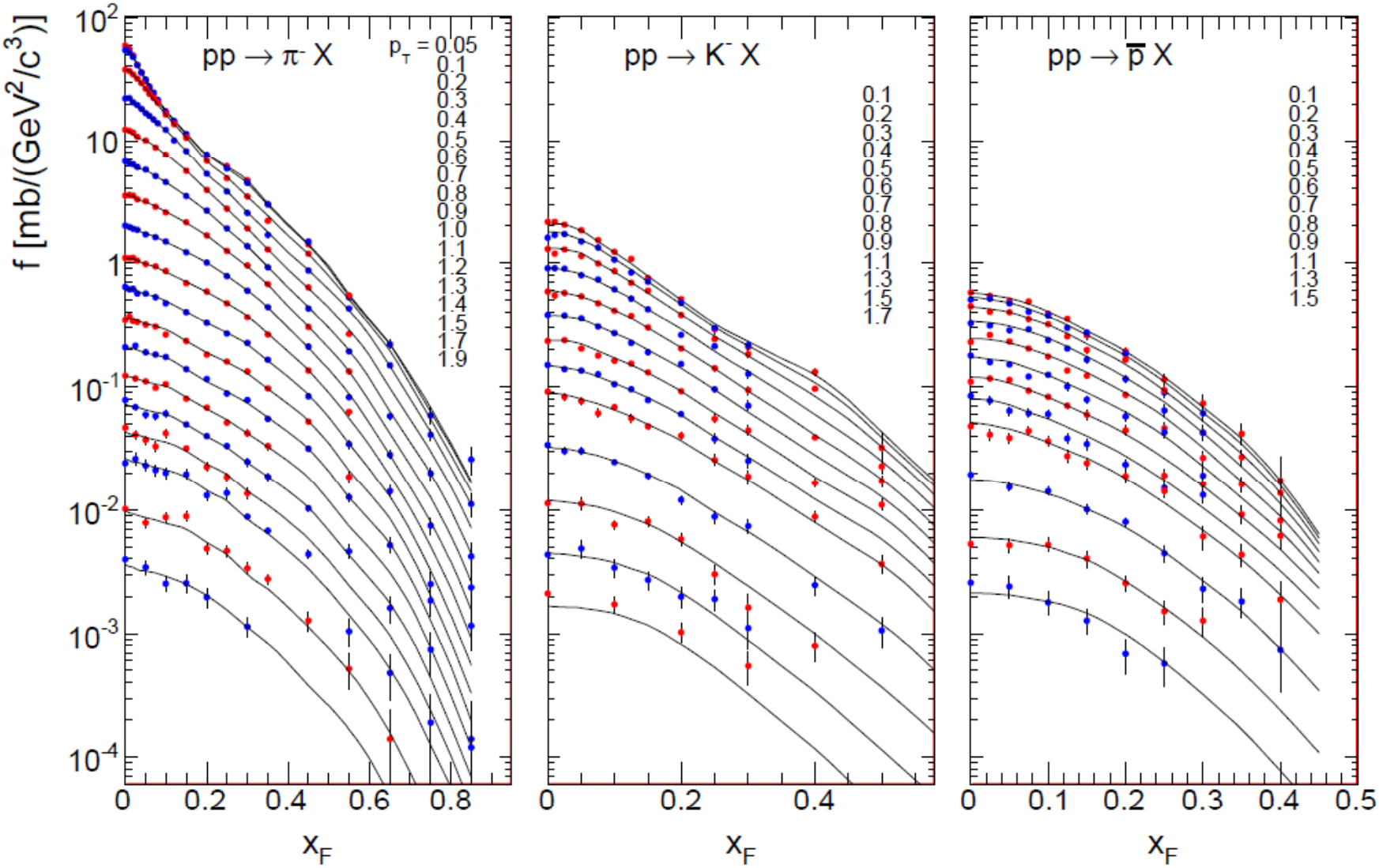


- 2 Superconducting Magnets
- 4 large Time Projection Chambers
- Systematic uncertainties on few % level
- Hadron + hadron collisions:
  - » p+p, n+p, pi+p
- Hadron+nucleus collisions:
  - » p+C, p+Pb, pi+Pb
- Nucleus+nucleus collisions:
  - » C+C, Pb+Pb
- DAQ speed ~ 7Hz.

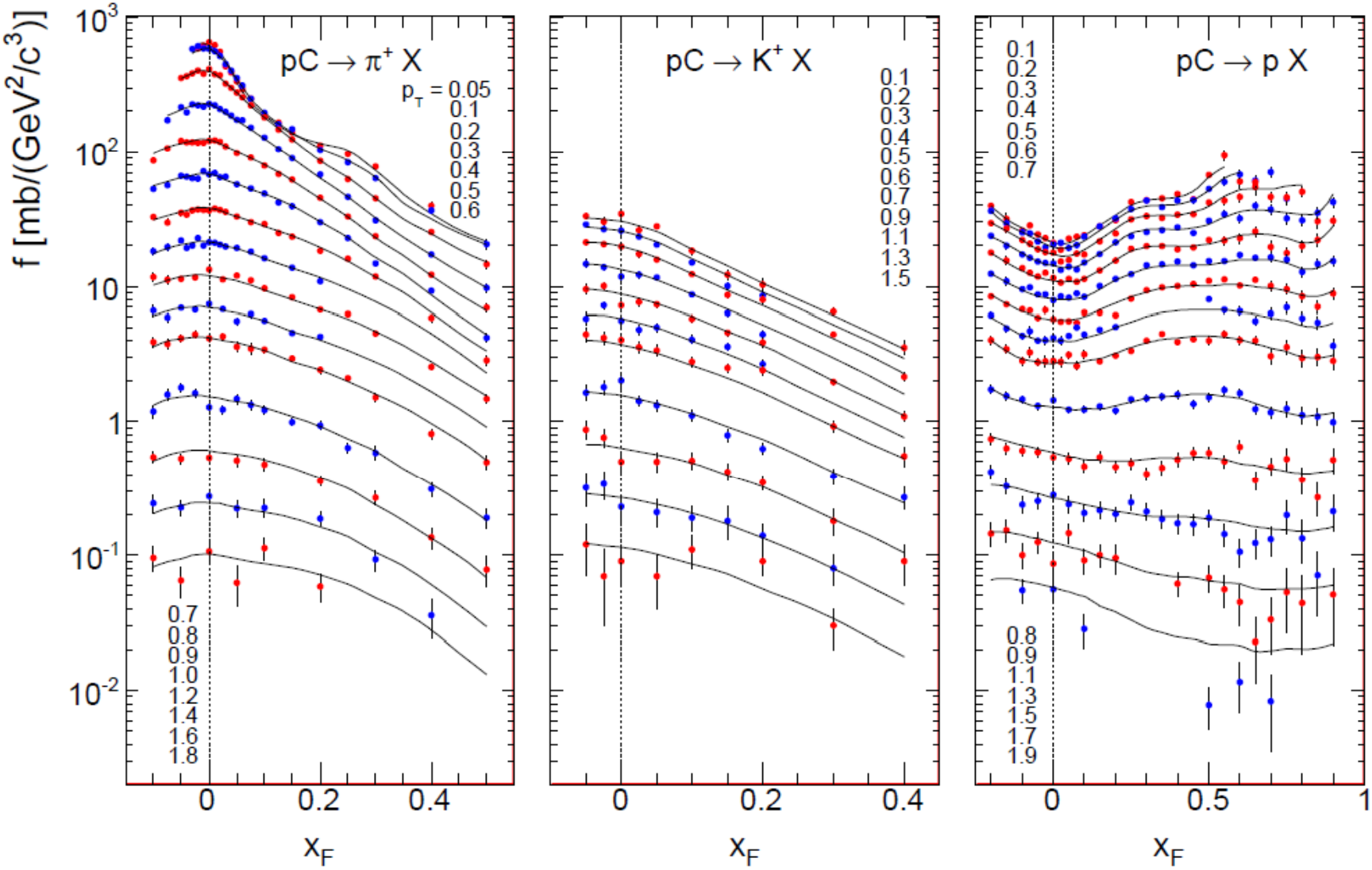
NA49 Positive Particle Production in 158 GeV/c p+p Interactions



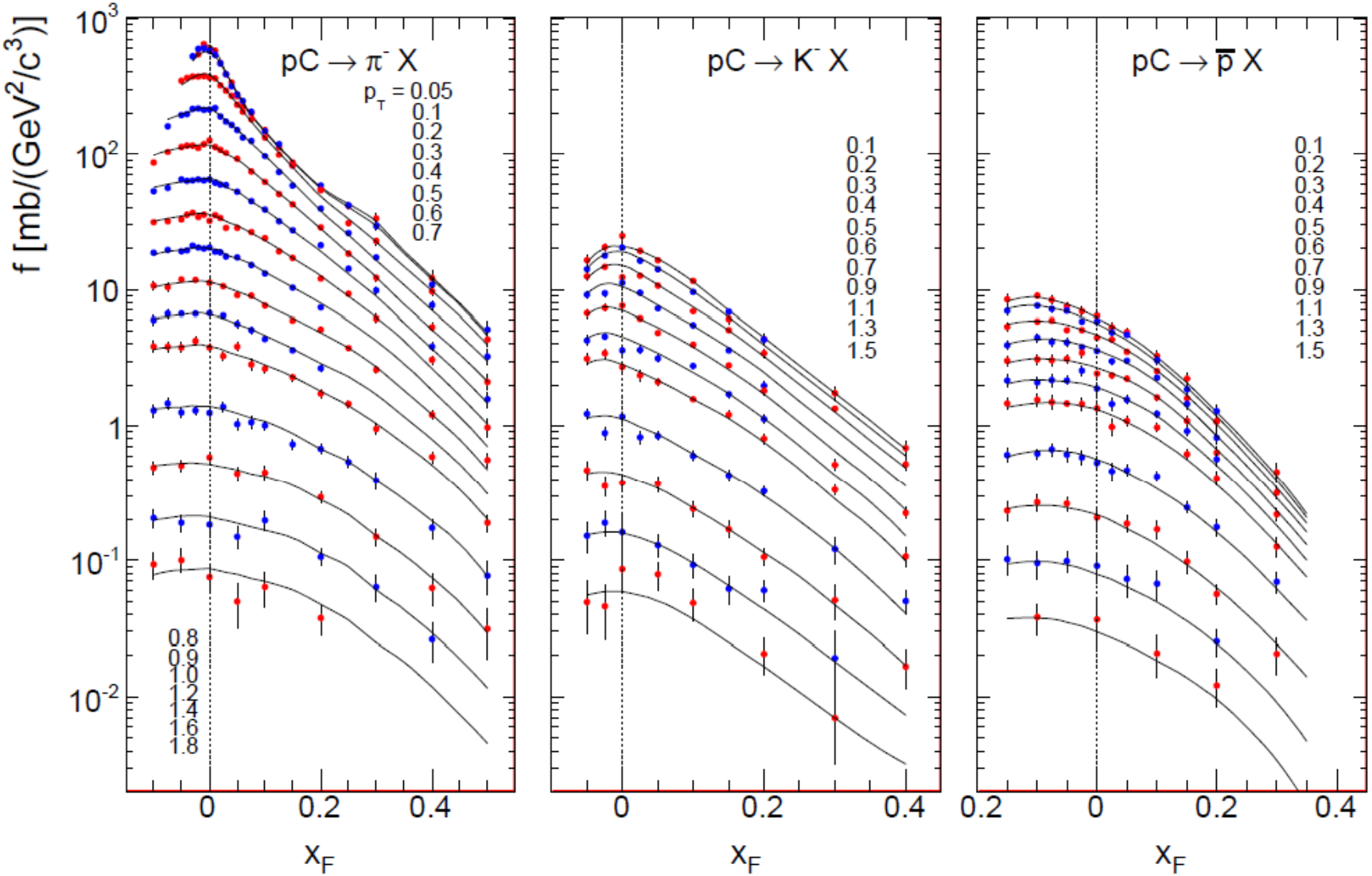
NA49-Negative Particle Production in 158GeV/cp+p Interactions



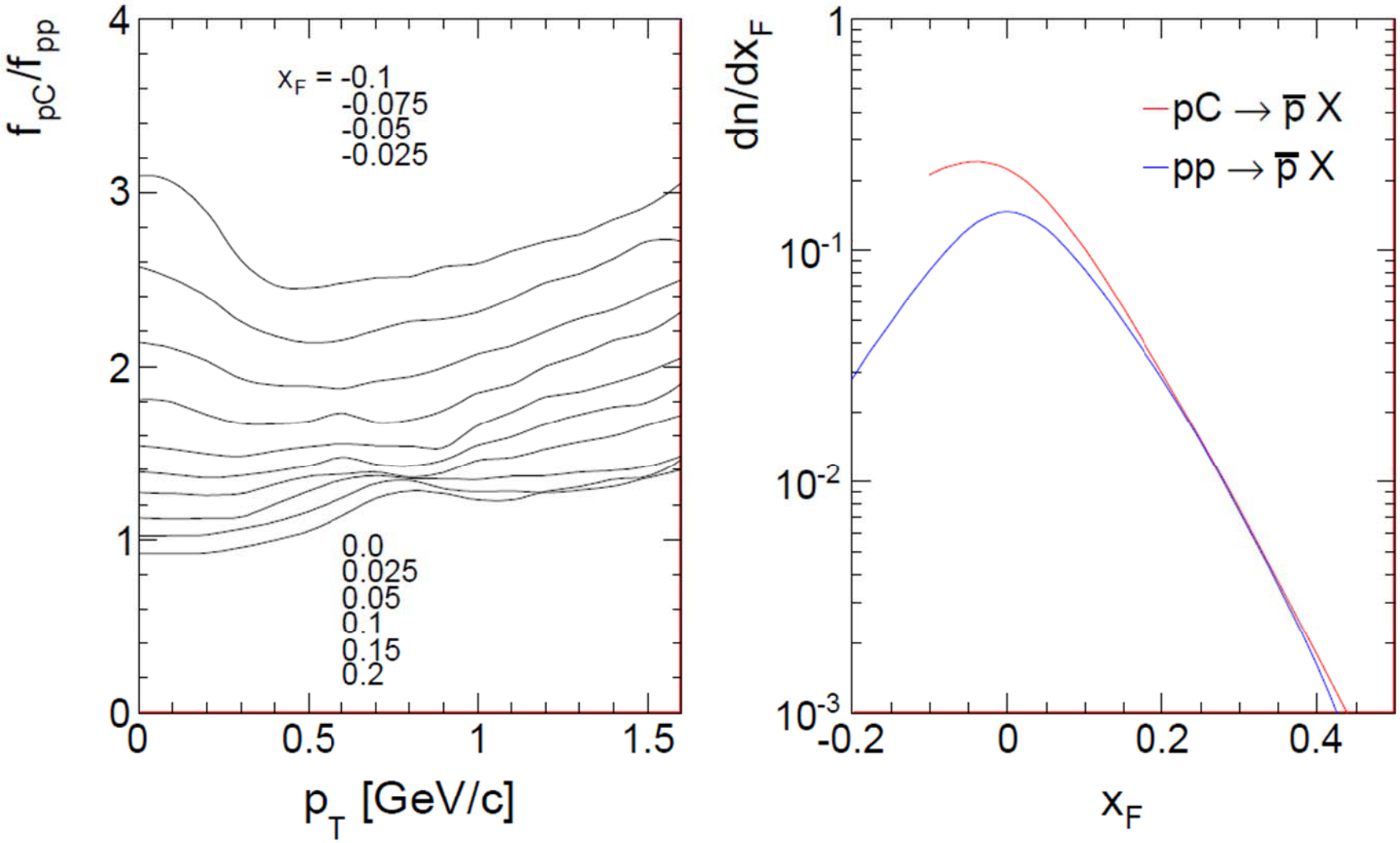
NA49- Positive Particle Production in 158GeV/c p+C Interactions



NA49-Negative Particle Production in 158 GeV/c p+C Interactions



NA49 Example of Detailed Comparison of pA and pp



NA49-Main Observations

- pC compatible with1.6 projectile collisions
- Importance of isospin effects (pions, kaons, anti-protons)
- Separation of
  - » Intra-nuclear cascading
  - » Target nucleon fragmentation
  - » Projectile fragmentation
- Model independent study of two-component mechanism of target and projectile hadronization

  see EPJC 49 (2007) 919
- More analyses in progress

NA61/SHINE at the CERN SPS

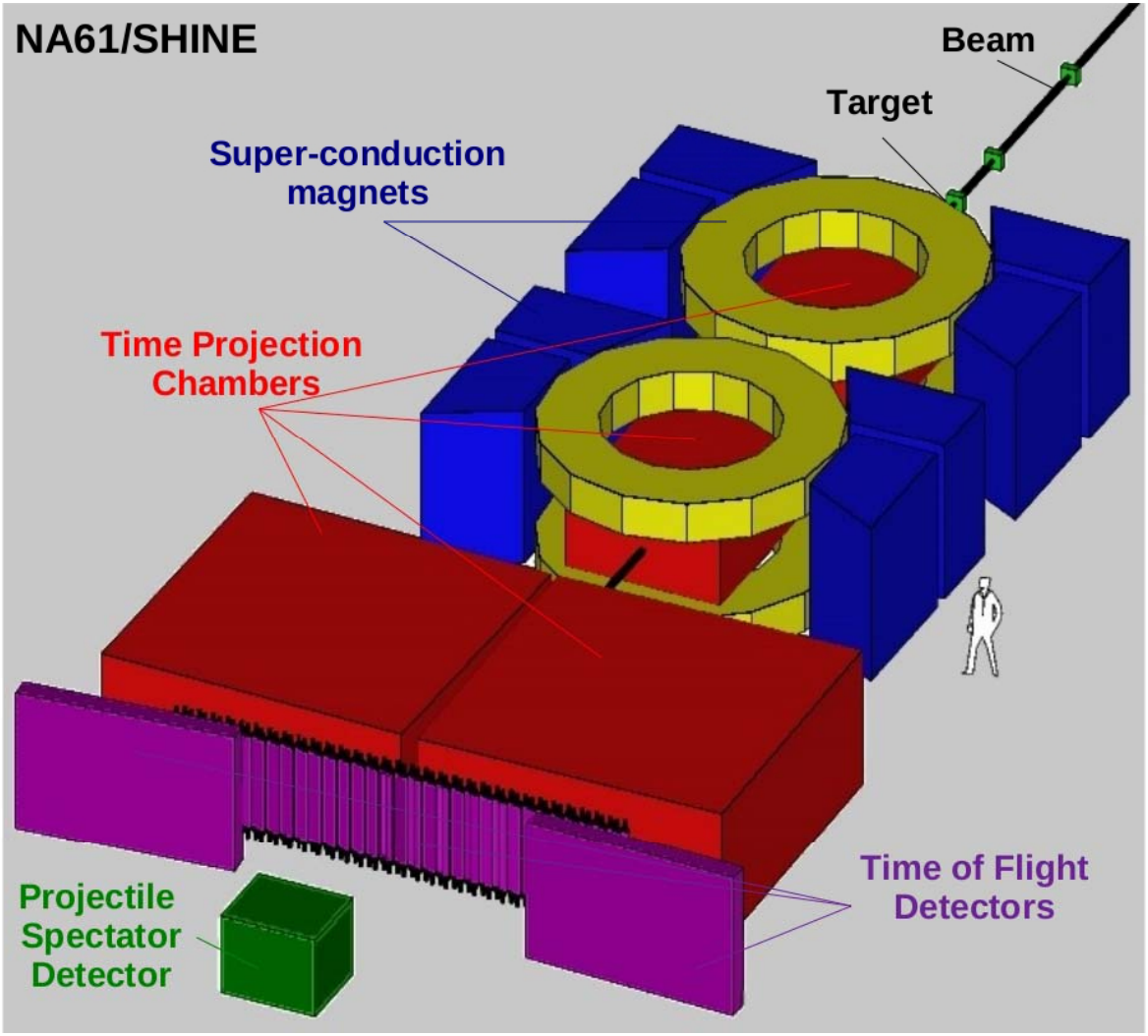
(**SHINE – SPS Heavy Ion and Neutrino Experiment**)

NA61/SHINE physics program:

-Critical Point and
Onset of Deconfinement,
-High p_T physics
-Neutrino physics,
-Cosmic-ray physics

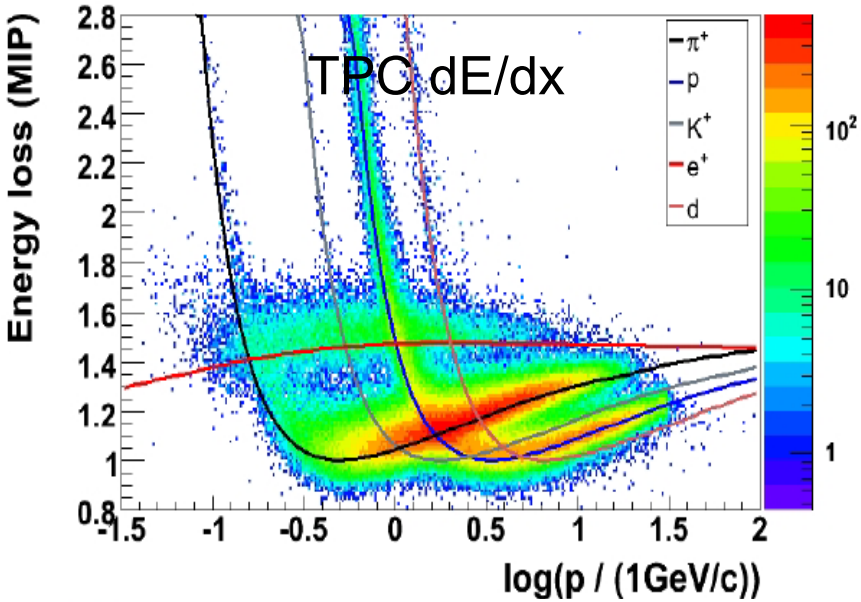
Proposal: *CERN-SPSC-2006-034, SPSC-P-330 (November 3, 2006)*
LoI: *CERN-SPSC-2006-001, SPSC-I-235 (January 6, 2006)*
EoI: *CERN-SPSC-2003-031, SPSC-EOI-001 (November 21, 2003)*

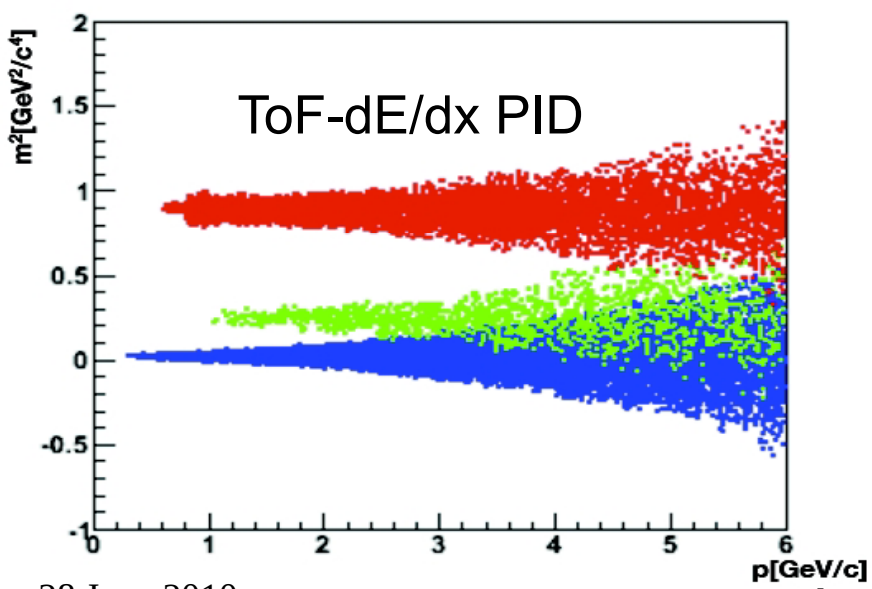
Detector



NA49: Nucl. Instrum. Meth. A430, 210 (1999)
NA61 upgrades: CERN-SPSC-2006-034, SPSC-P-330

Detector performance





Results of the 2007 run:

- Large acceptance: ≈50%
- High momentum resolution:

  $\Delta p / p^2 = 10^{-4} GeV / c^{-1}$

  at full magnetic field
- Good particle identification:

  $TOF \approx 100\, ps$

  $\Delta(dE/dx)/(dEdx) \approx 0.04$

  $m_{inv} = 5 MeV$
- High detector efficiency:

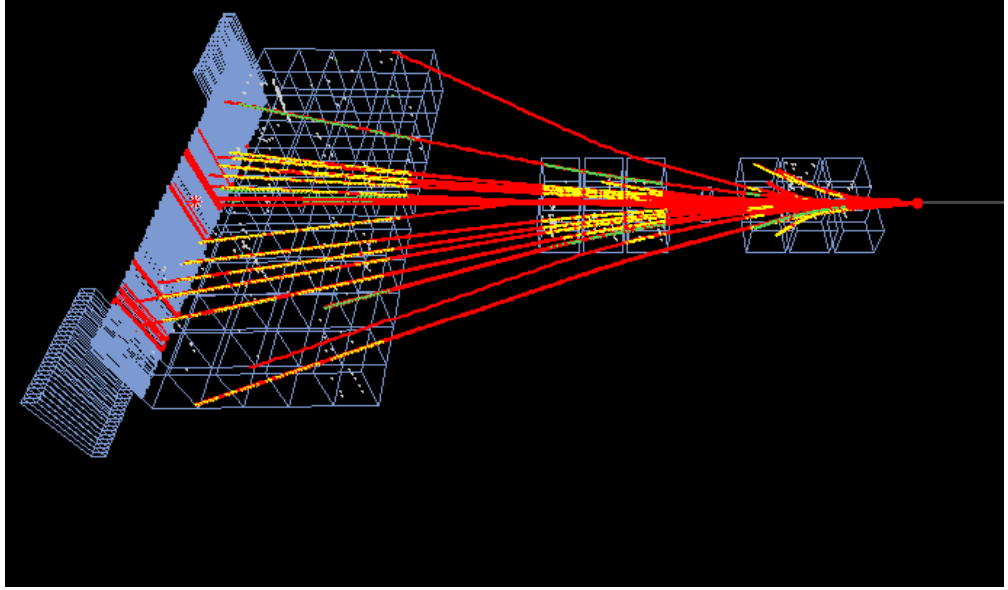
  > 95%
- Event rate:

  70 events/sec

NA61/SHINE achievements in 2009

Successful physics data taking period

9 reactions and 40M events registered in the 2009 run



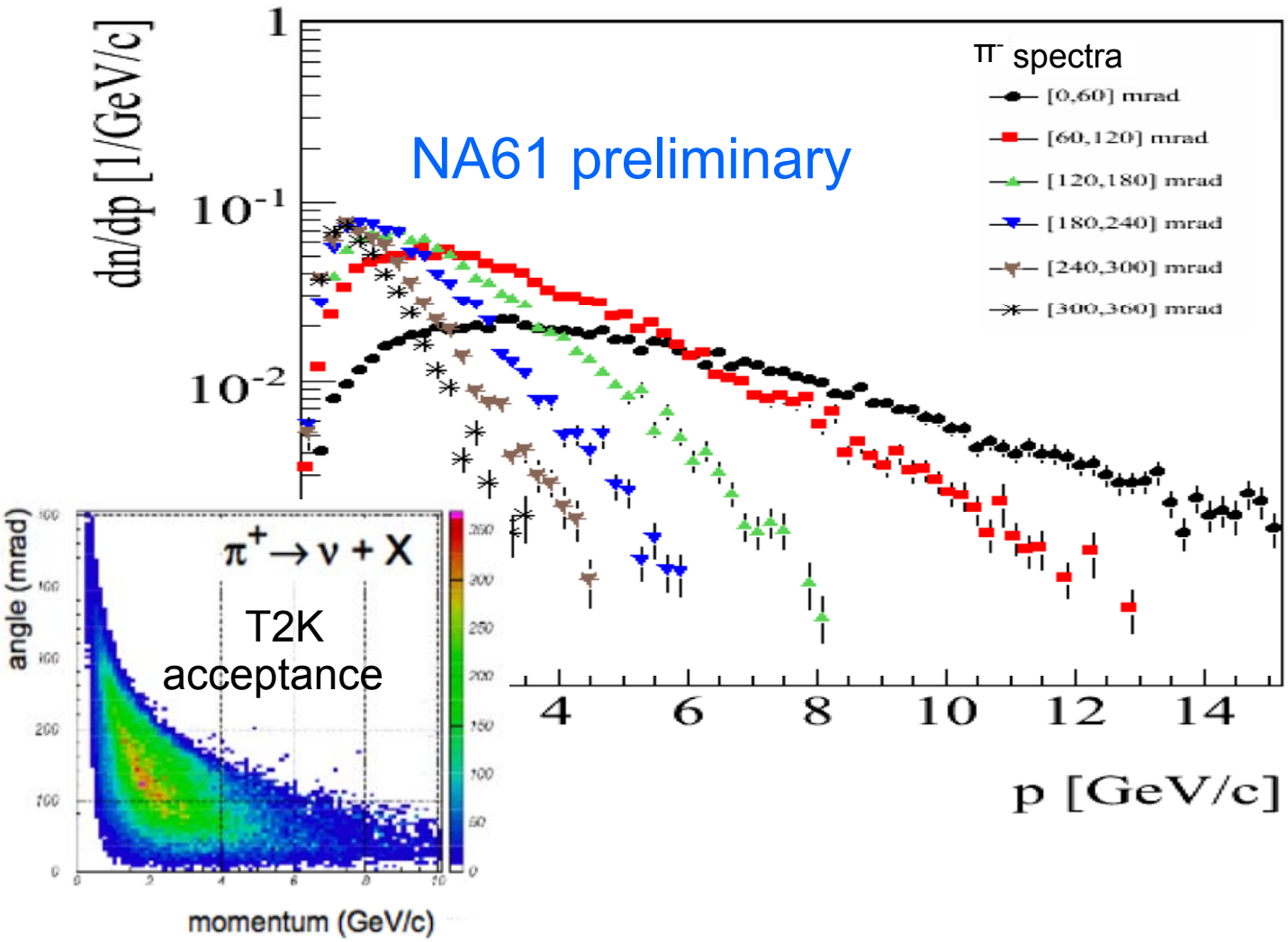
Registered in 2009:

for T2K
- p+C at 31 GeV/c
- p+(T2K RT) at 31 GeV/c

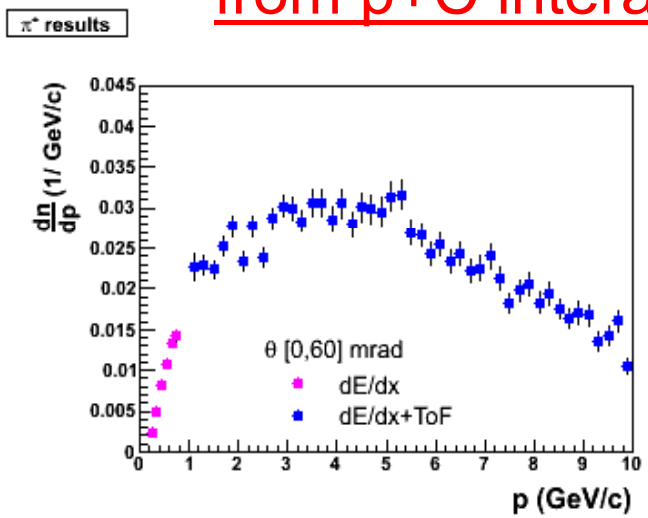
for Pierre Auger:
- pion+C at 158 GeV/c
- pion+C at 350 GeV/c

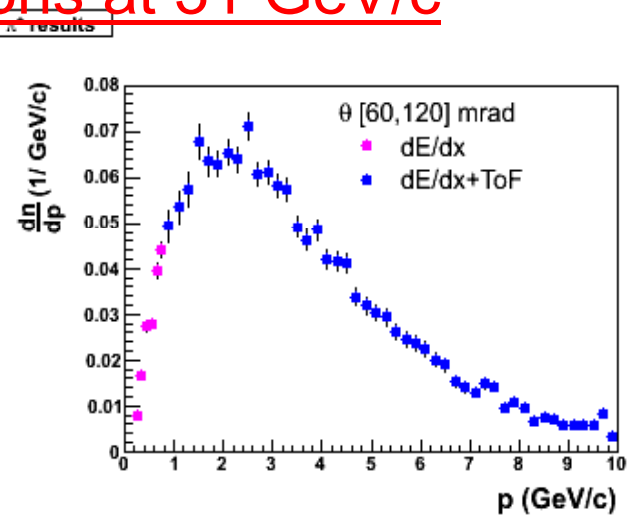
for critical point and onset of deconfinement:
- p+p at 20 GeV/c
- p+p at 31 GeV/c
- p+p at 40 GeV/c
- p+p at 80 GeV/c
- p+p at 158 GeV /c

2009: π^- spectra for T2K from p+C interactions at 31 GeV/c

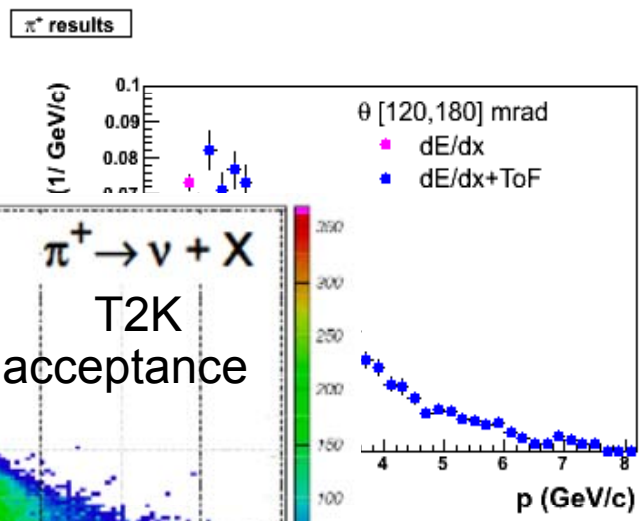


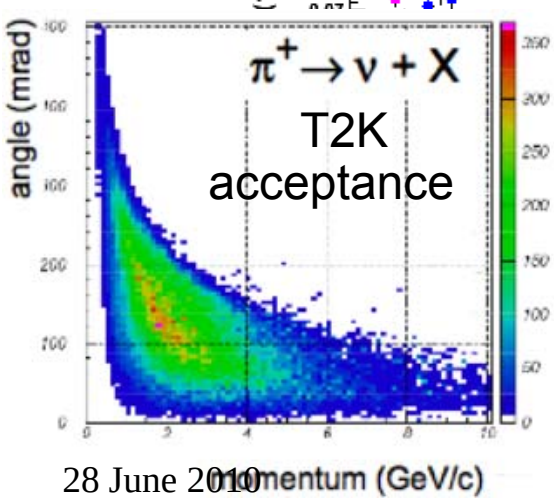
2009: π^+ spectra for T2K from p+C interactions at 31 GeV/c

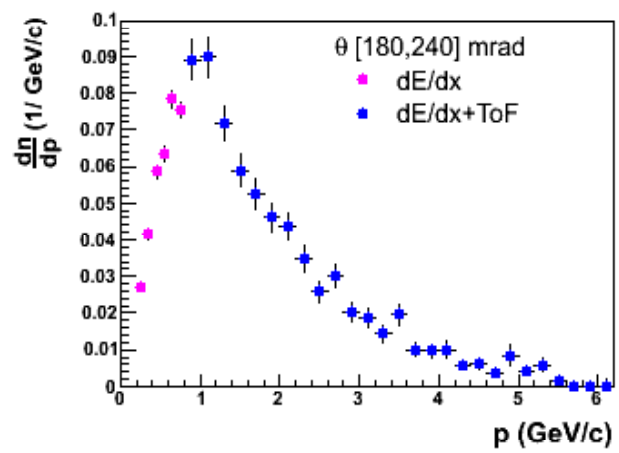




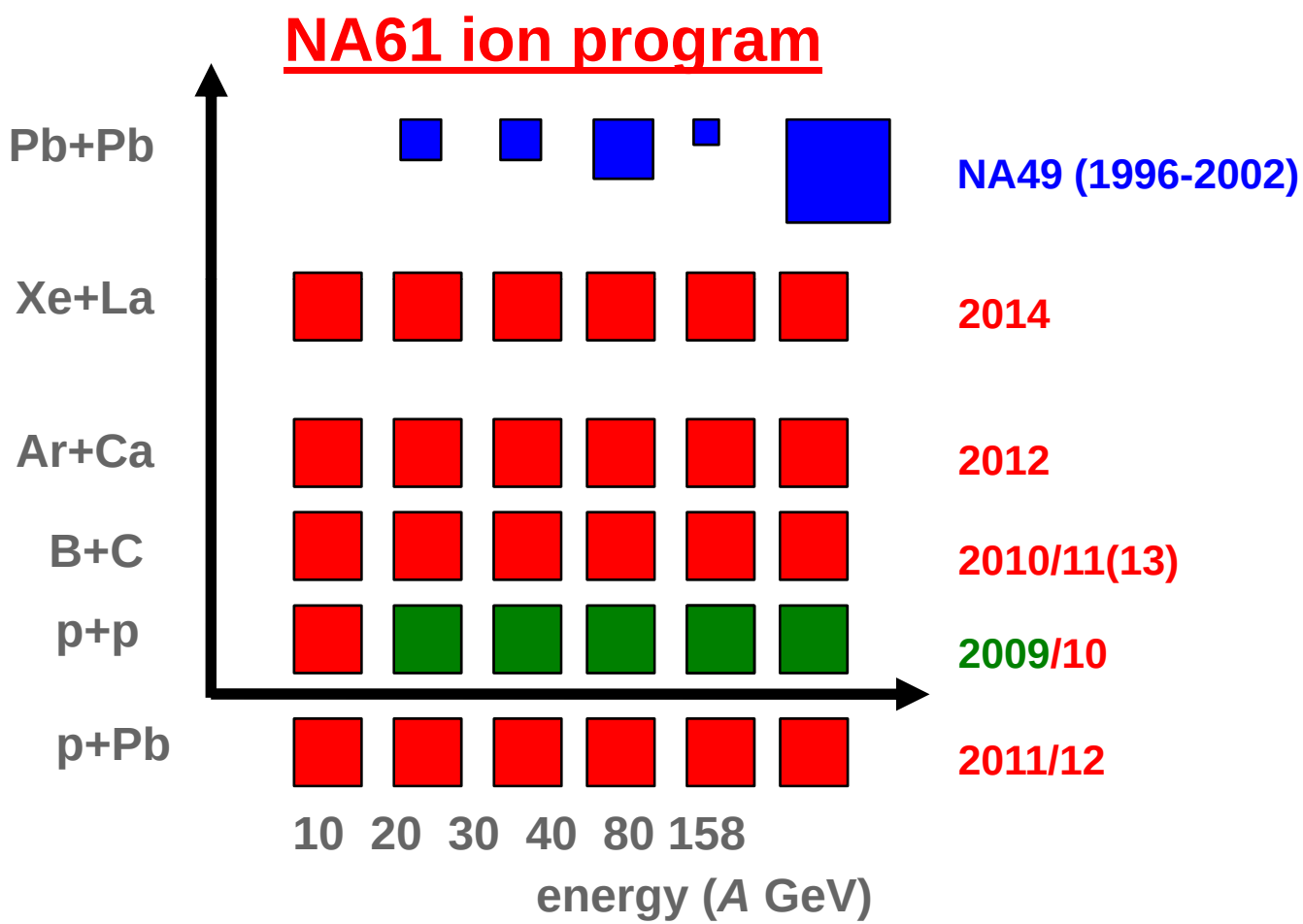
NA61 preliminary







2009: start of the 2D search for the critical point and the LHC compatible schedule of future runs

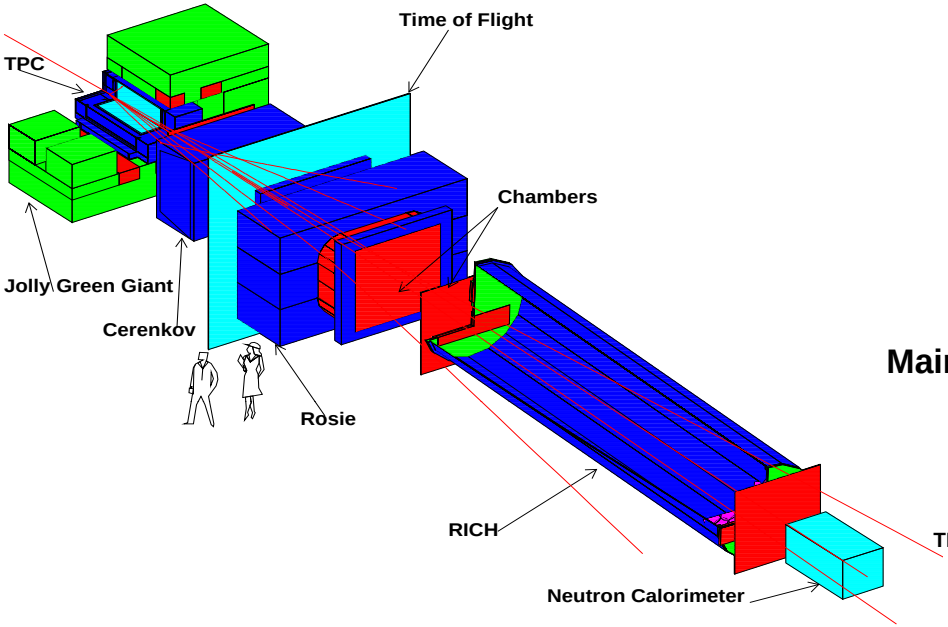


MIPP Experiment--Installation in progress-Collision Hall. Took data in 2006

MIPP

Main Injector Particle Production Experiment (FNAL-E907)

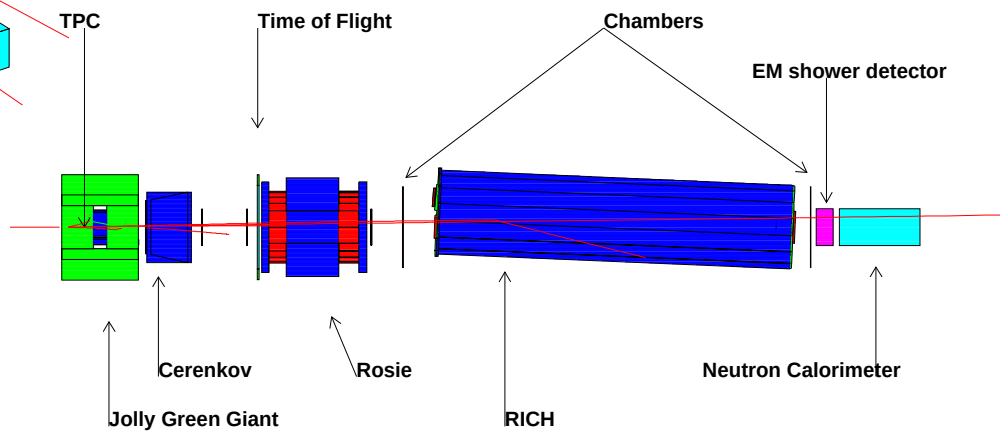
DAQ rate 30Hz



MIPP

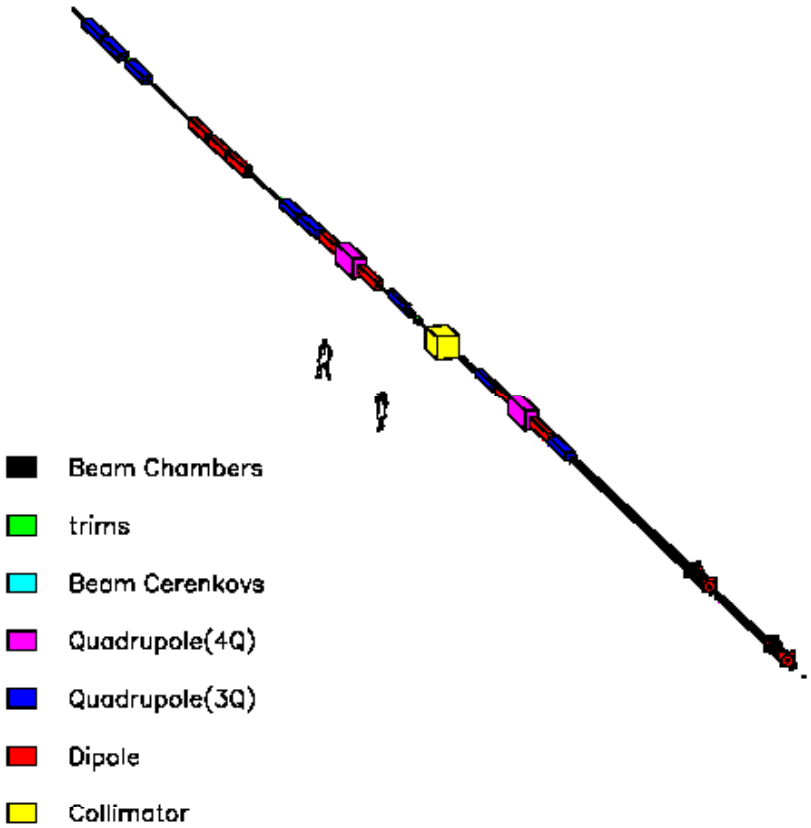
Main Injector Particle Production Experiment (FNAL-E907)

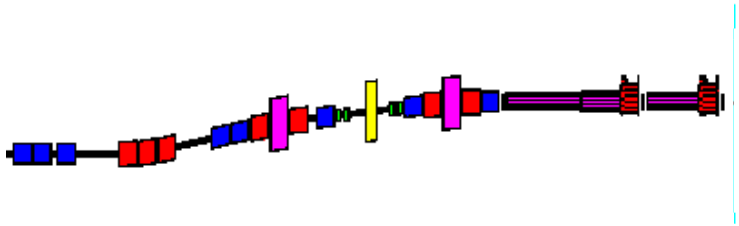
Vertical cut plane



- TPC dE/dx 0 to 1 GeV/c
  ToF 0 to 2 GeV/c
- Ckov to 14 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
- 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.

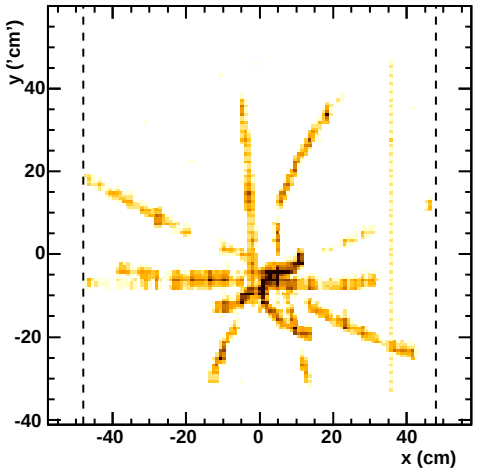
MIPP TPC raw data

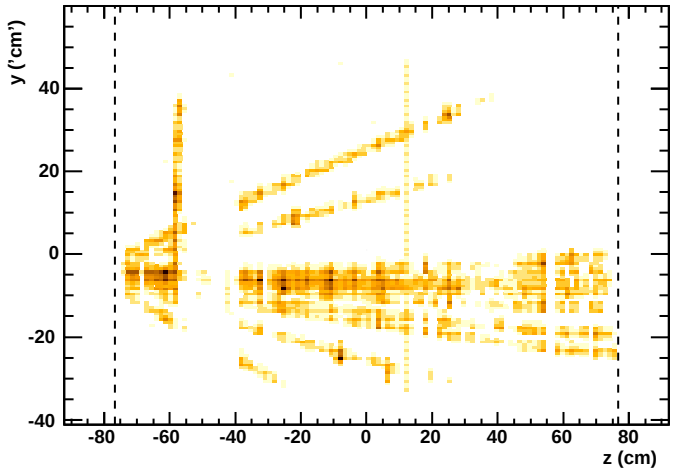
MIPP (FNAL E907)

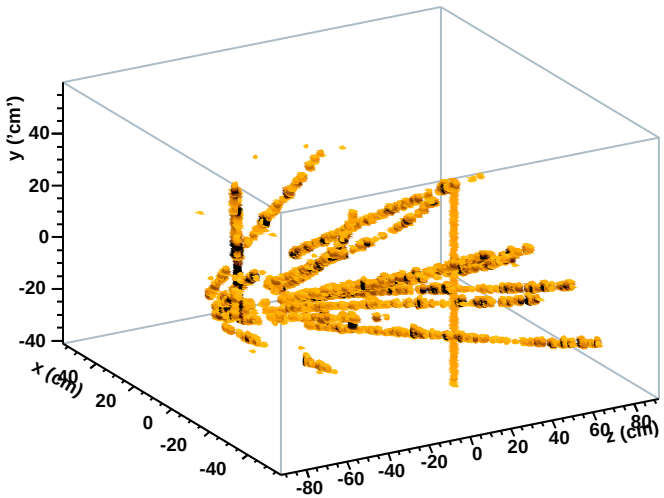
Target: NuMI
Run: 15007
SubRun: 0
Event: 160

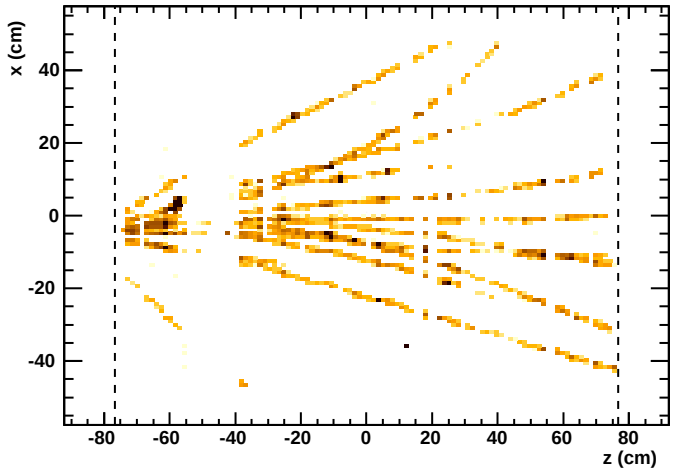
Sat Jul 16 2005
11:22:30.687398

*** Trigger ***
Beam
Word: 0080
Bits: 80D7

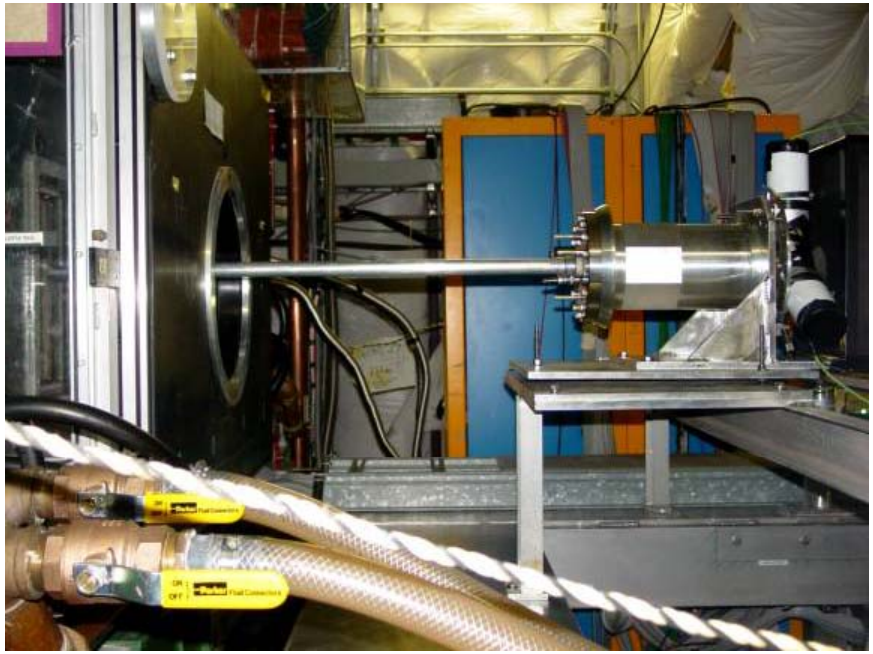


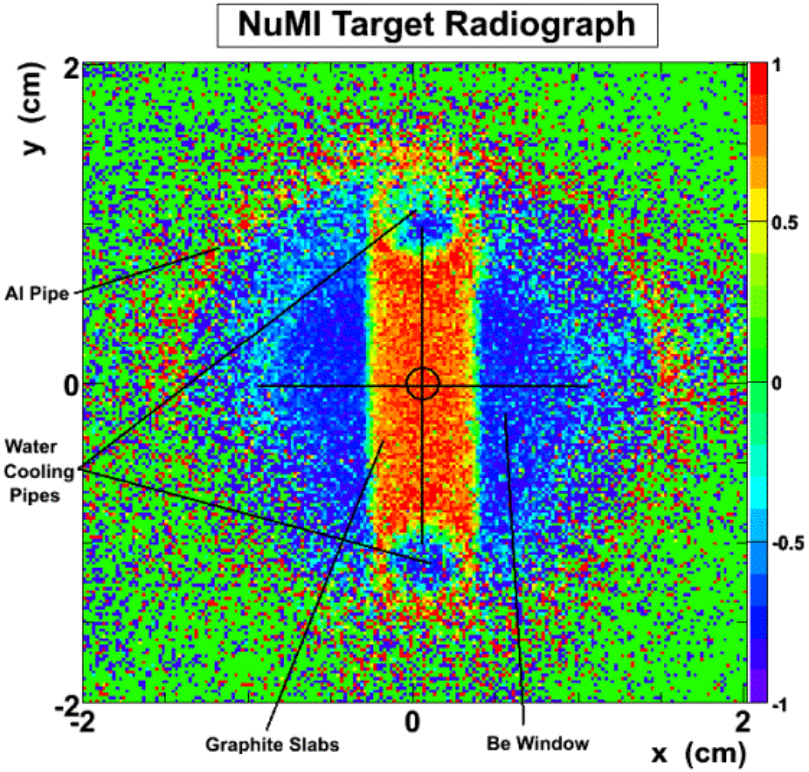




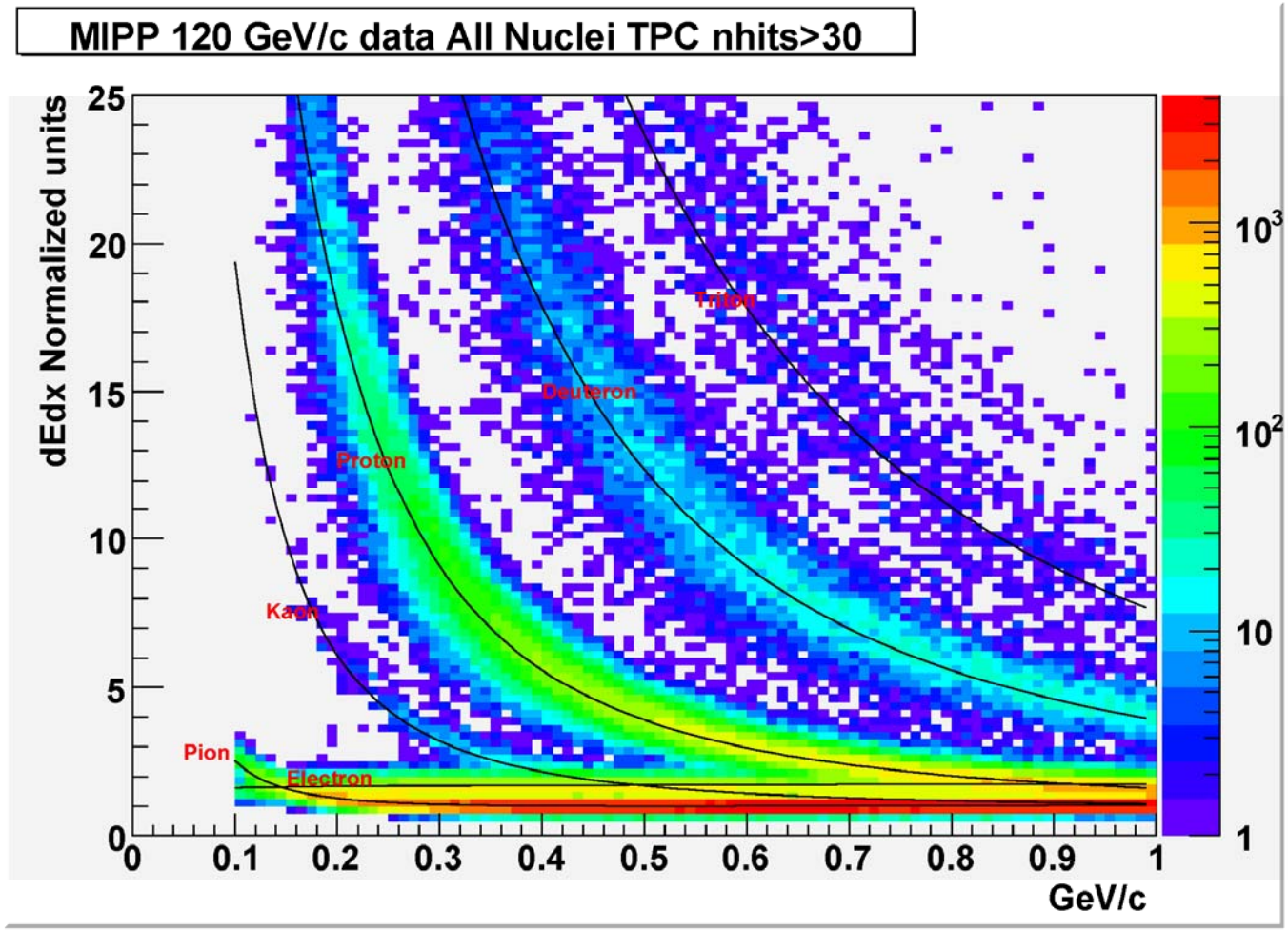


NUMI target pix



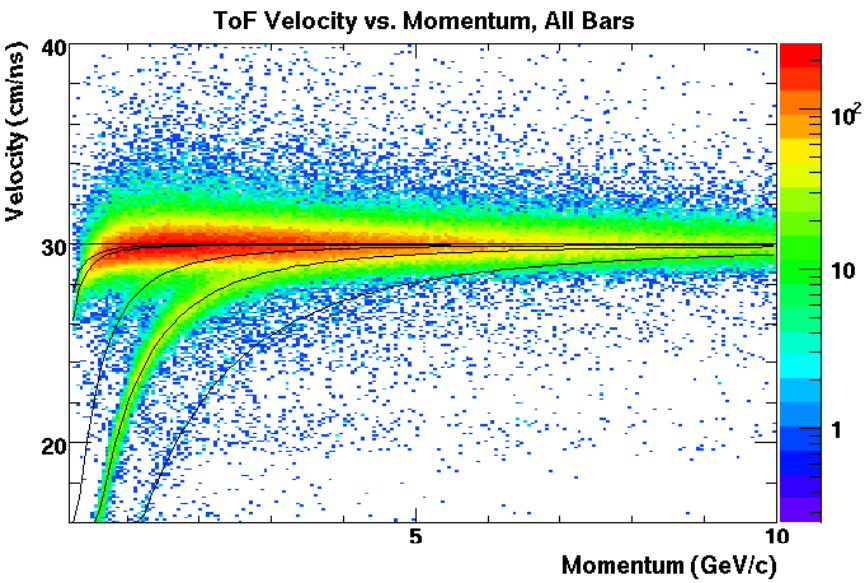


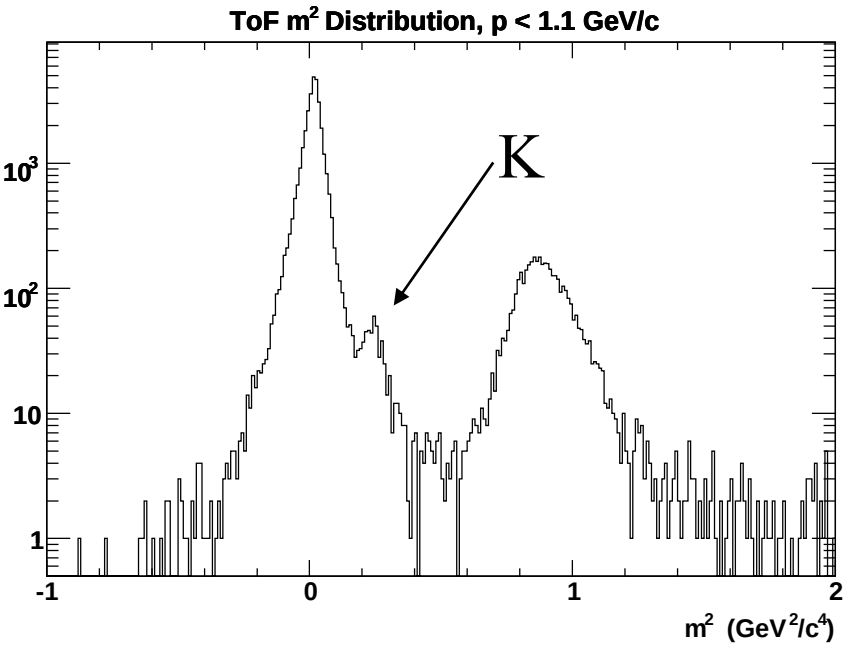
MIPP TPC dEdx



TOF particle ID

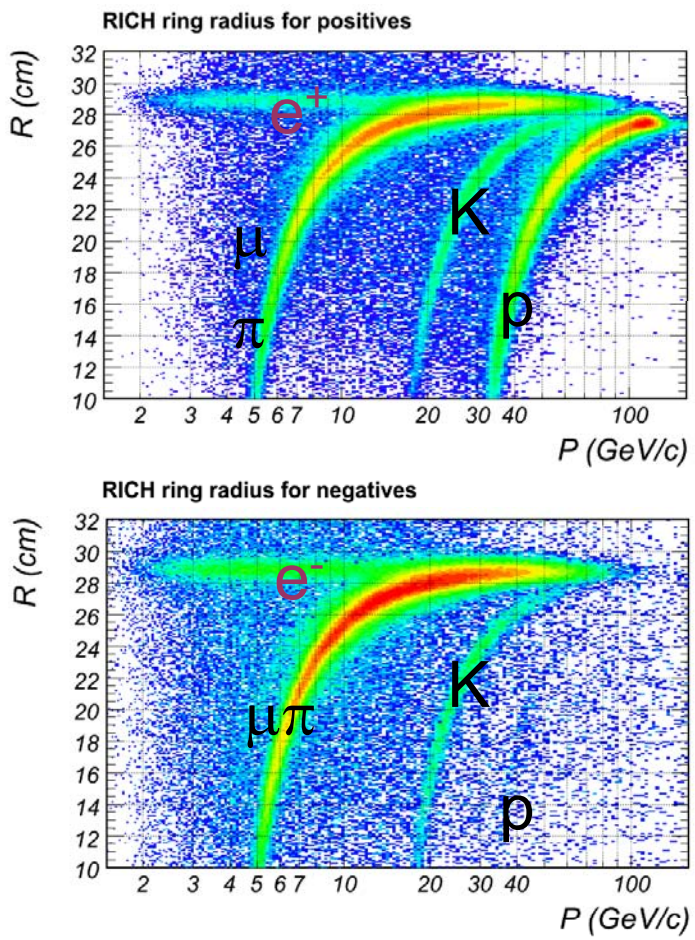
- TOF gives good PID over most of the momentum region it was supposed to cover after all corrections (temperature + cross talk) are applied carefully.





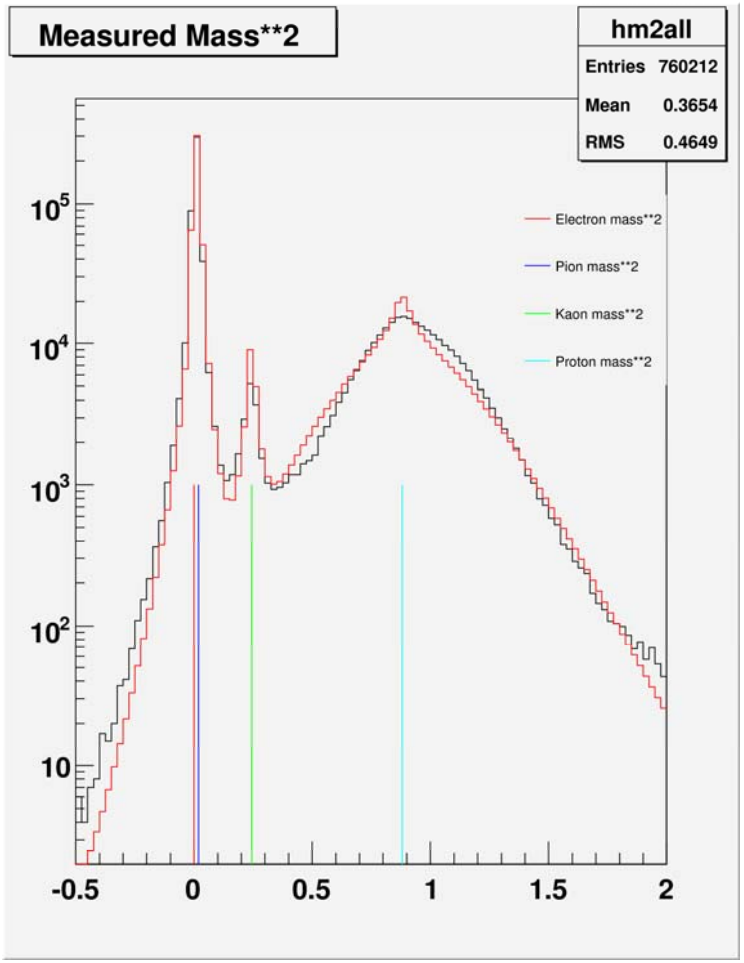
RICH particle id

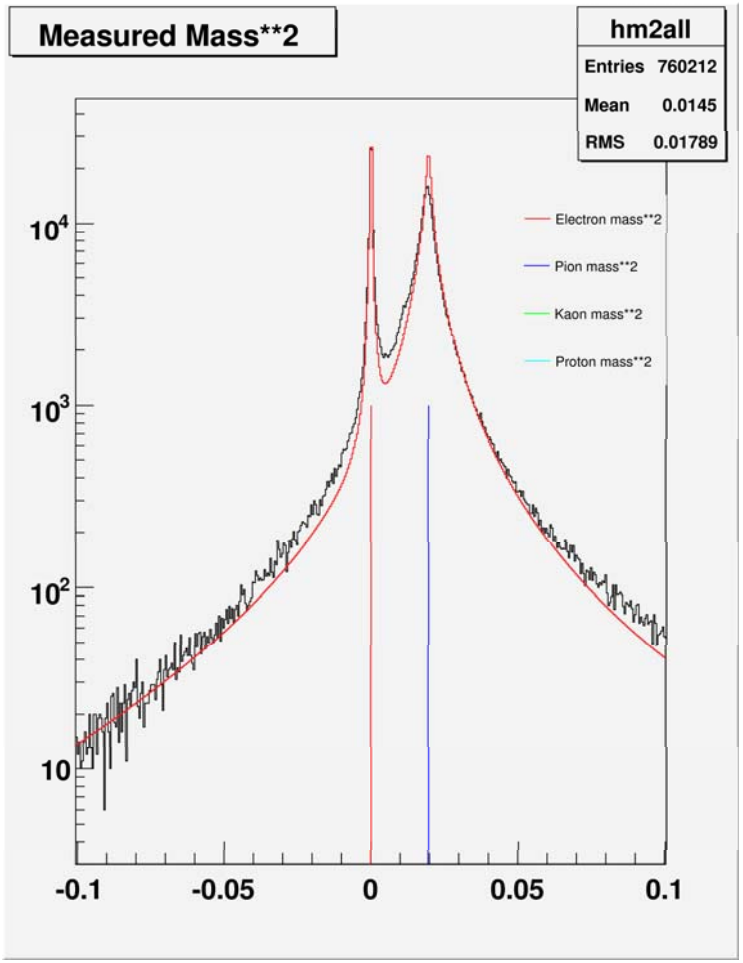
- From Selex, entirely new readout electronics and some PMTs replaced
- Radiator: CO_2 gas at STP
- Gives lots of hits for MIPP momentum range.
  - easy to fit good circles
- RICH ring radius gives very good particle ID within acceptance
  - e/μ/π up to 12 GeV/c
  - π/K/p to 120 GeV/c



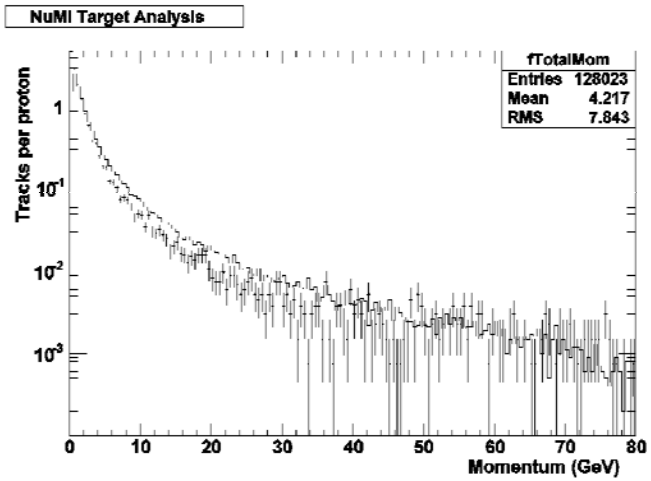
RICH mass-squared

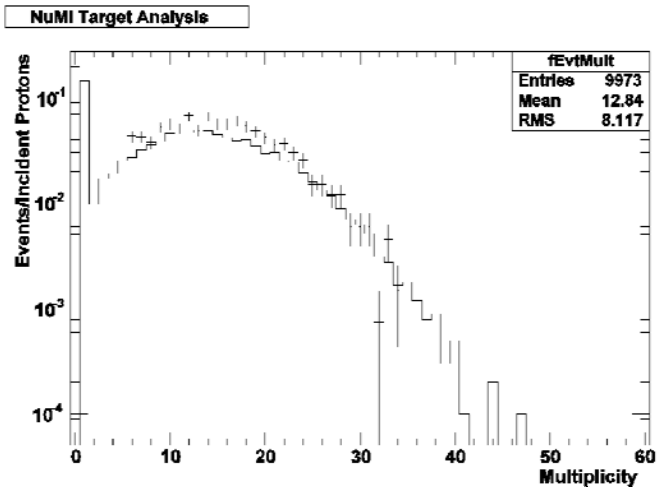
- **Global PID** describes **data** quite well.



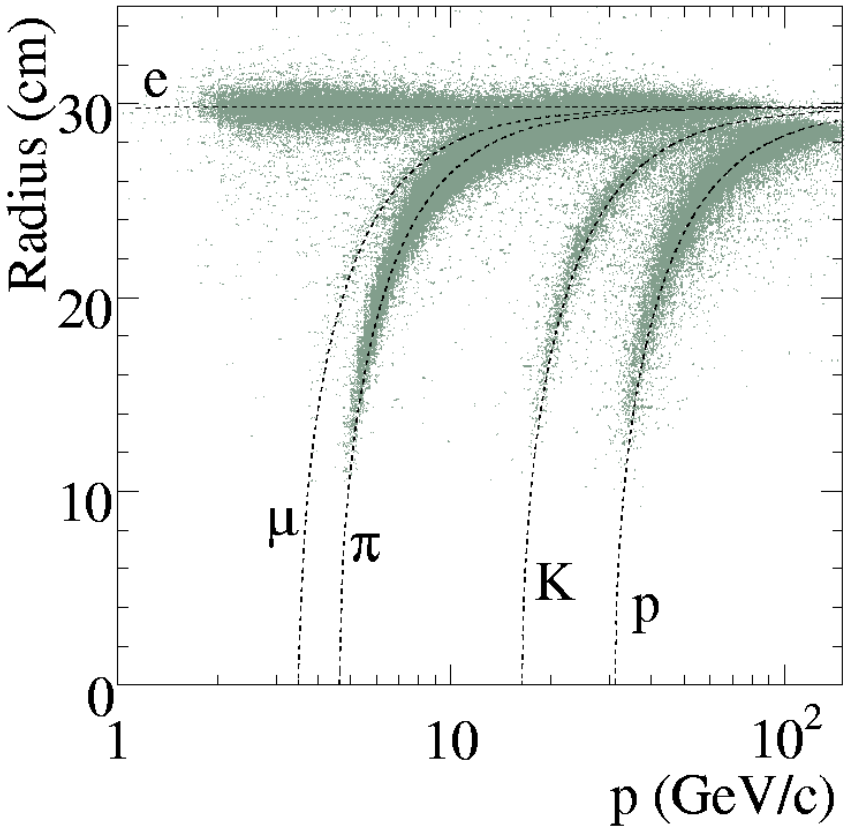


MIPP Wine and Cheese Talk on July 9th



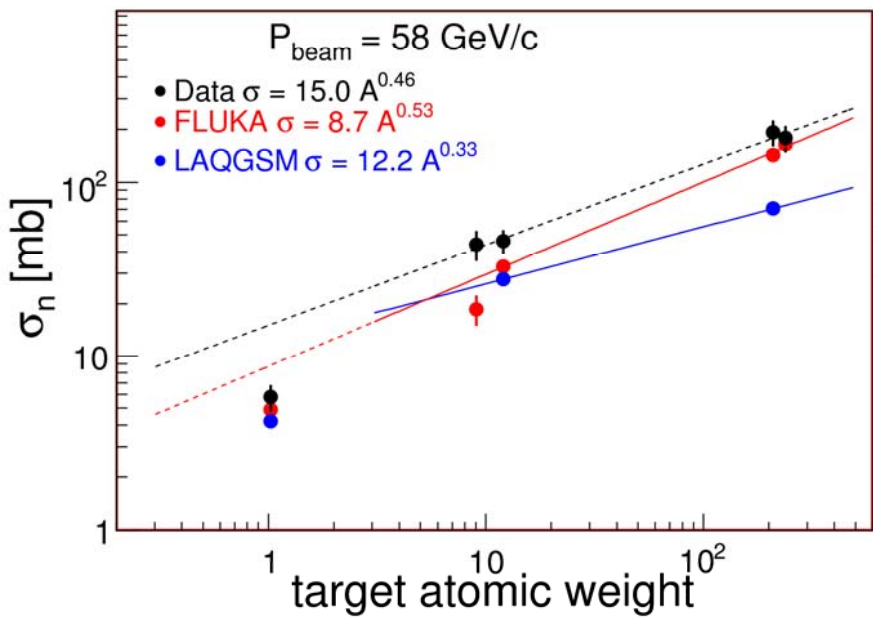


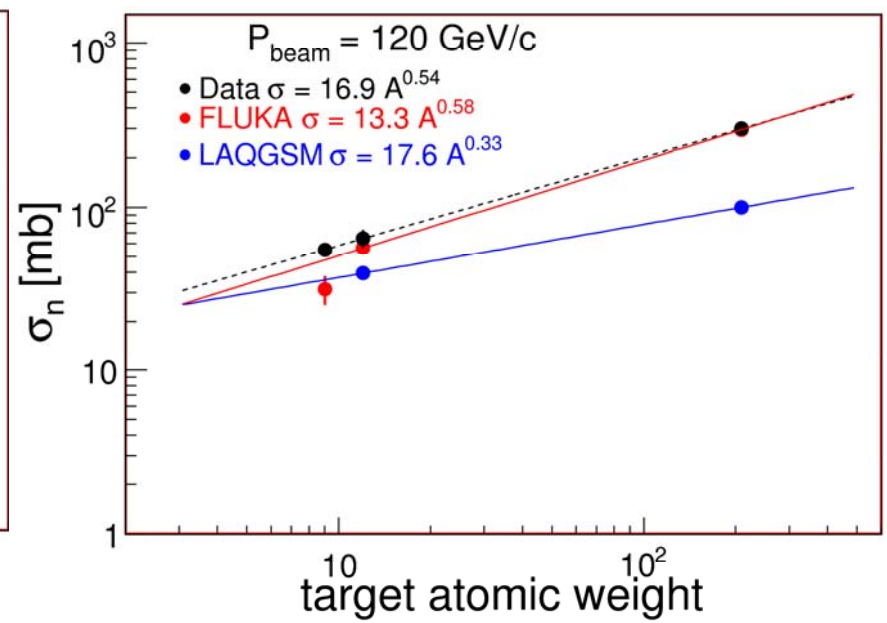
- Will have results on NuMI full target
- Forward neutron cross sections.



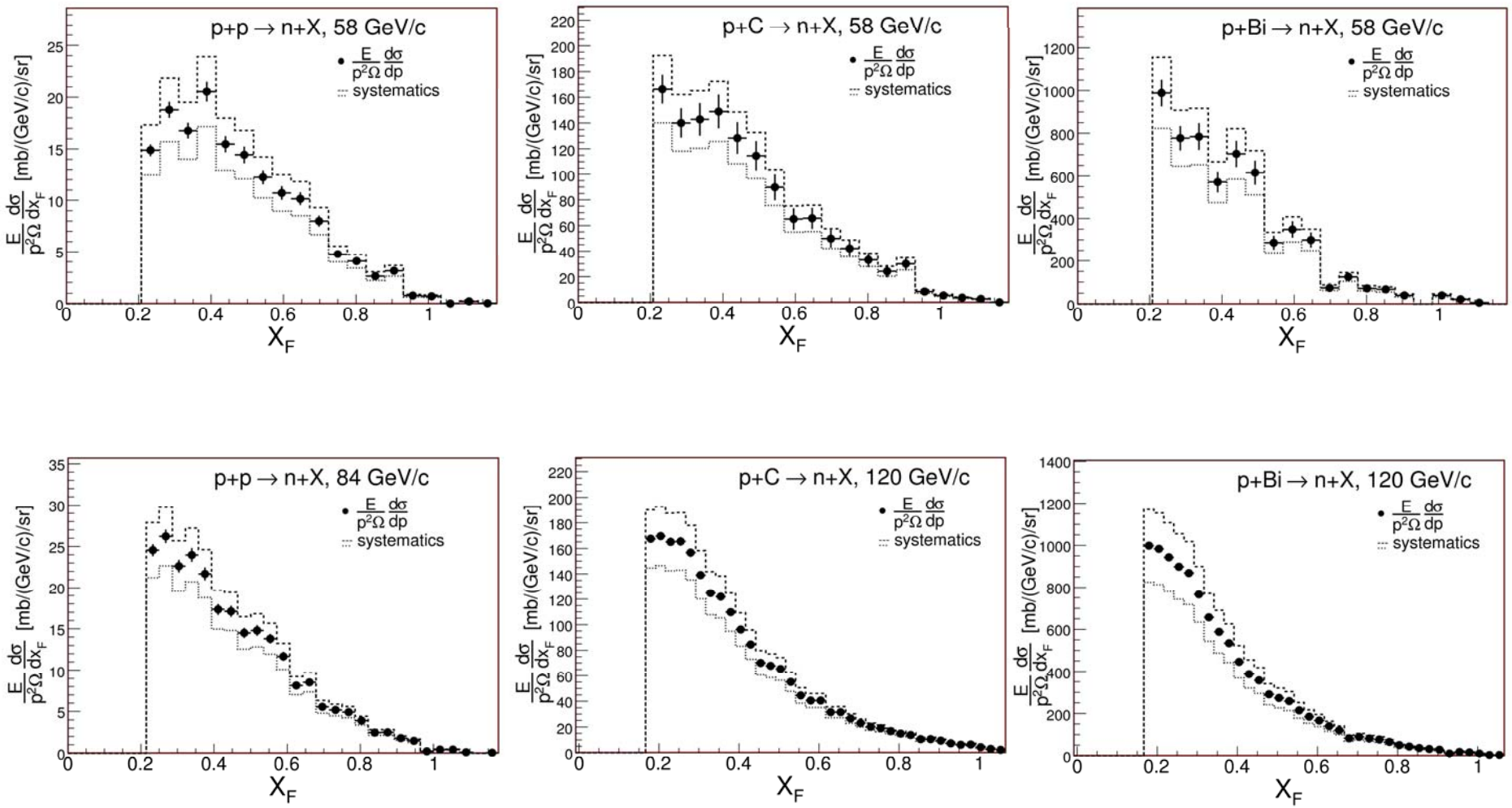
Neutron cross sections
Results as a function of A

- Data falls on a line in the log plot
- MCs differ from each other (by up to x5) and from data (by up to x5)!
  - Especially neutron cross section on Be is low in Fluka
  - Other channels are also under-predicted on Be by Fluka, although total cross section falls on the line .





Neutron cross sections
invariant cross section scales



The MIPP Upgrade Proposal in a nutshell DAQ rate 3000Hz

- MIPP -I took data at ~20Hz. The limitation was the TPC electronics which are 1990's vintage. We plan to speed this rate up to 3000Hz (~150 times faster) using ALTRO/PASA chips developed for the ALICE collaboration.
- 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 coil has been fabricated.
- Beamline upgrade- The MIPP secondary beamline ran satisfactorily from 5 5GeV/c-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 eliminate hysteresis effects.
- TPC Readout Upgrade-We have ordered 1100 ALTRO/PASA chips from CERN ($80K). Chips have been delivered and first prototype boards have been made.

Nuclei of interest- 1st pass list

- 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
-
- On each nucleus, we can acquire 5 million events/day with one 4sec beam spill every 2 mins and a 42% downtime.
- We plan to run several different momenta (1-85 geV/c) and both charges. For neutrinos we will also have p=120GeV on thick and thin targets.
- The libraries of events thus produced will be fed into shower generator programs which currently have 30 year old single arm spectrometer data with high systematics

The recoil detector-Important for calorimetric simulations and nuclear physics

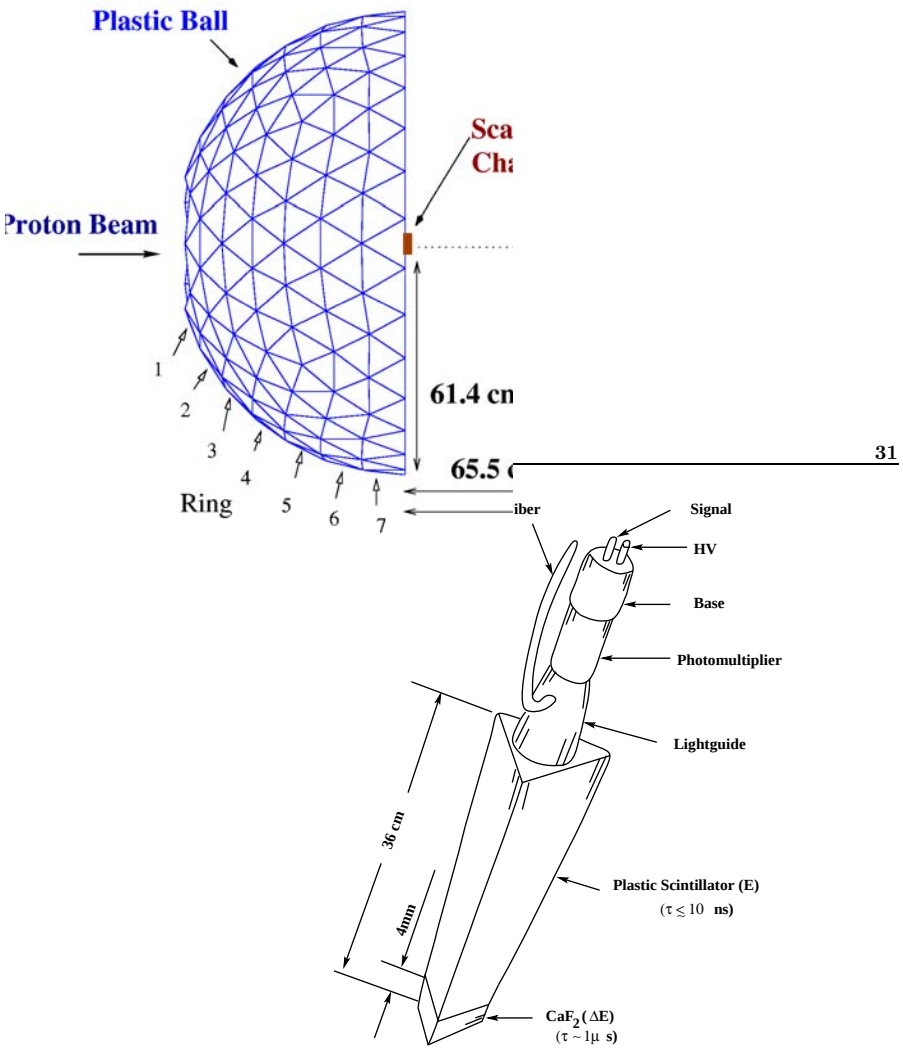
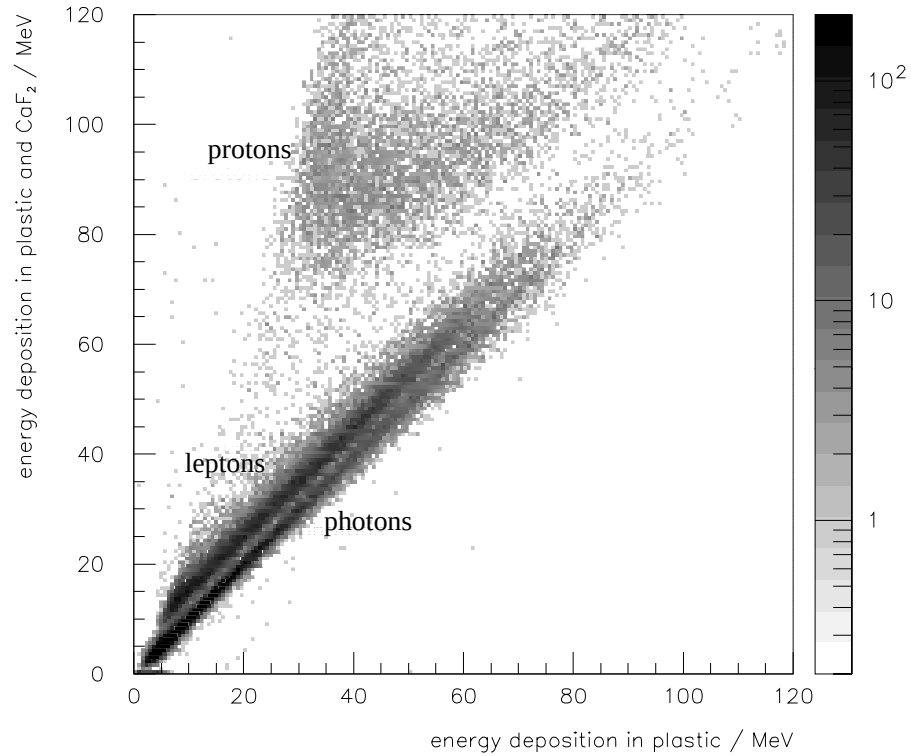


Figure 3.5: Schematic drawing of an individual Plastic-Ball detector.



Detect recoil protons, neutrons, pizeros and charged pions,kaons

Can we reduce our dependence on models?

- Answer- Yes- With the MIPP Upgrade experiment, one can acquire 5 million events per day on various nuclei with six beam species ($\pi^{\pm}$,$K^{\pm}$,$p^{\pm}$) with beam momenta ranging from 1 GeV/c-90 GeV/c. Full acceptance over phase space, including info on nuclear fragmentation
- This permits one to consider random access event libraries that can be used to generate the interactions in the shower.

Random Access Data Libraries

- Typical storage needed

Nuclei	beam species	momentum bins	events/bin	tracks/event	words/track
30	6	10	100000	10	5
	Number of events		1.80E+08	Number of days	36
	Total number of words		9.00E+09	to take data	
		Bytes	3.60E+10		

- Mean multiplicities and total and elastic cross section curves are parametrized as a function of s.
- Events contain correlations!

Conclusions

- It is necessary to measure particle production in an energy regime that encompasses the resonant region as well as the scaling region (~1 GeV/c to 200 GeV/c) beam energy to build up a library of events if one wants to improve the precision of the simulation of particle showers.
- A large number of experiments will benefit
- Such data will lay the foundation of our understanding of non-perturbative phenomena.