Hadron production results from the Harp experiment

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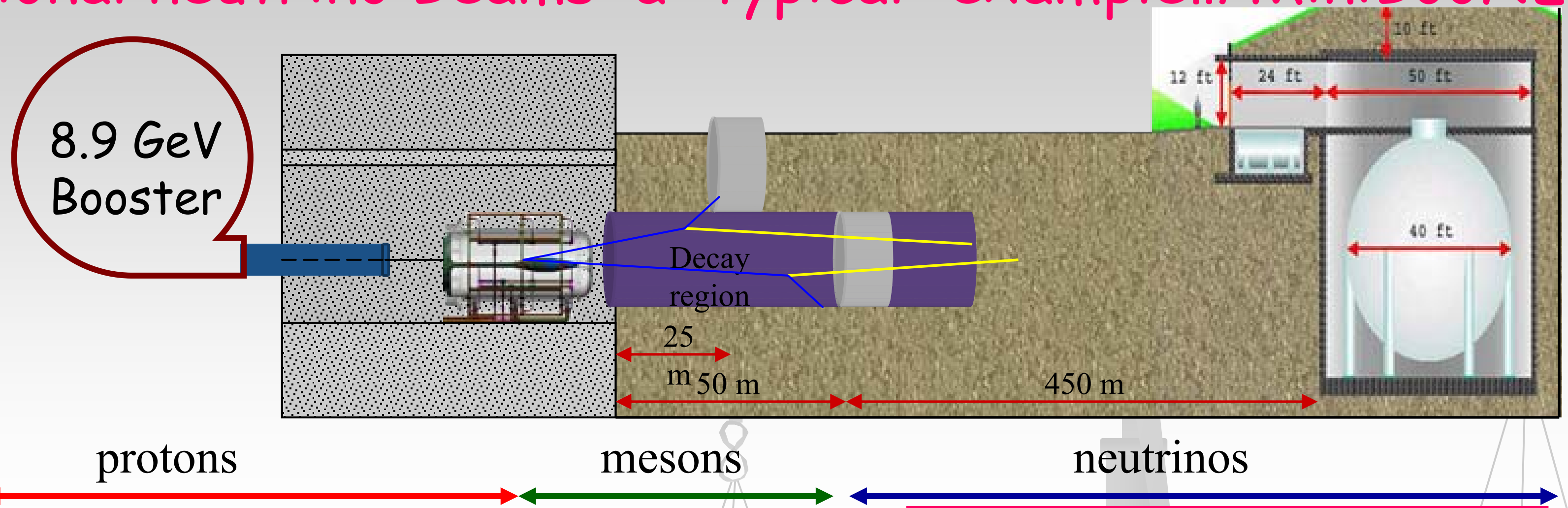
NOW Workshop

9-16 September 2006

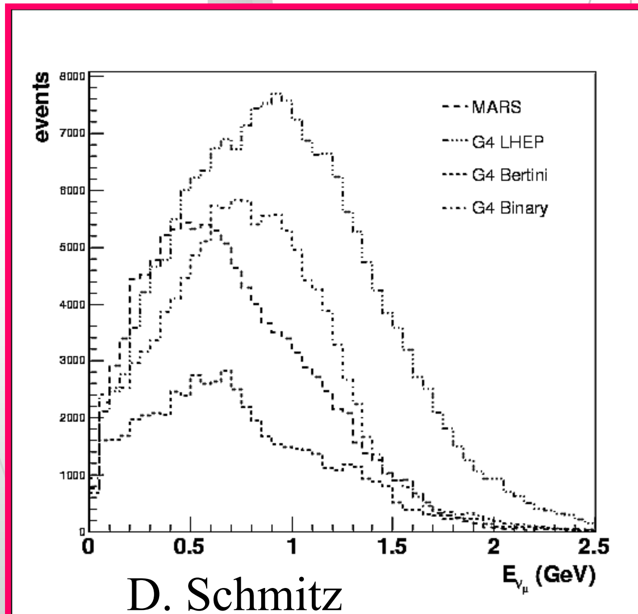
Outline

- Motivations
- *Harp* measurements
  - K2K & MiniBoone flux predictions
    - Al 12.9 GeV/c & Be 8.9 GeV/c
  - Inputs for Super Beams & Neutrino Factory Design
    - Tantalum 3-5-8-12 GeV/c
  - Atmospheric fluxes
    - Carbon 12 GeV/c
- Coming results

Conventional neutrino Beams: a "typical" example… MiniBooNE



- Energy, composition, geometry of the neutrino beam is determined by the development of the hadron interaction and cascade
- It's hard to make this kind of measurements in situ. Normally MC generators are used for this scope
- Various models are known to have large differences in neutrino rate predictions

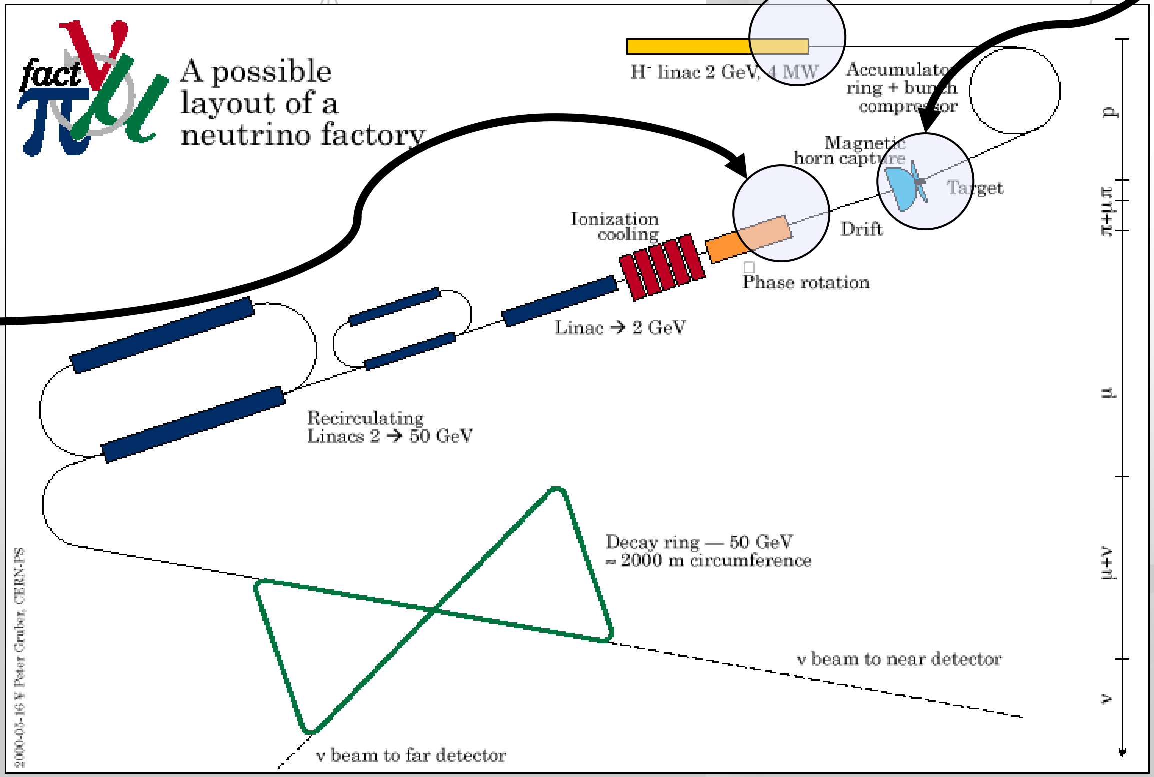


It is vital to calibrate neutrino production targets in a proton beam !

Design of future projects

Primary energy, target material and geometry, collection scheme
• maximizing the π^+, π^- production rate /proton /GeV
• knowing with high precision (<5%) the P_T distribution
CERN scenario: 2.2-5 GeV/c proton linac.

Phase rotation
• *longitudinally freeze* the beam: slow down earlier particles, accelerate later ones
• need good knowledge also of P_L distribution



Atmospheric neutrino fluxes: motivations for measurements

Initial reaction – well above the highest energy accelerator available.

Shower develops – a large number of lower energy interactions – accelerator measurements are helpful.

- Energy region: from few GeV

  → 200 GeV (contained)

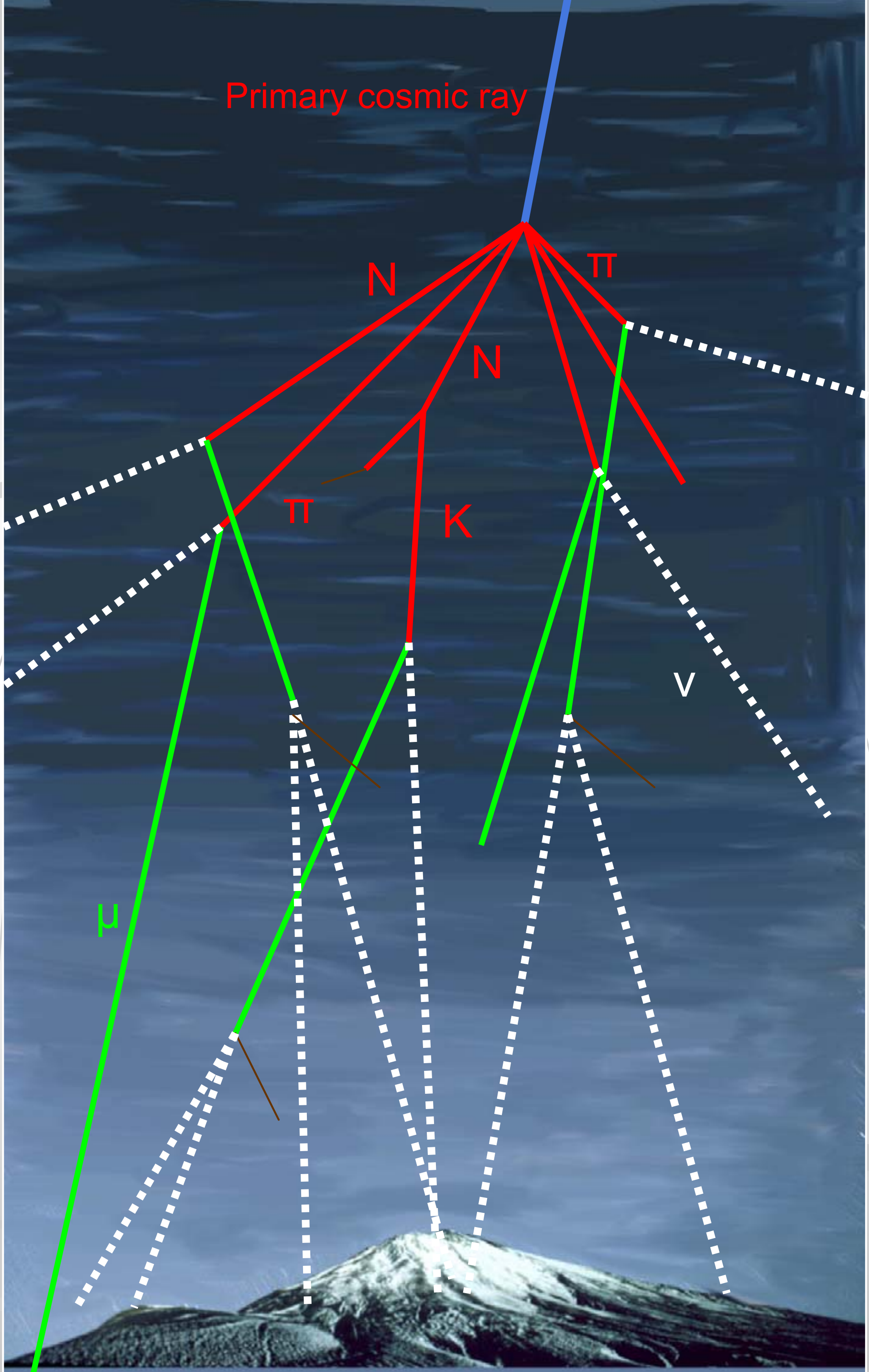
  → 2 TeV (through going)

Accelerator measurements are very sparse.

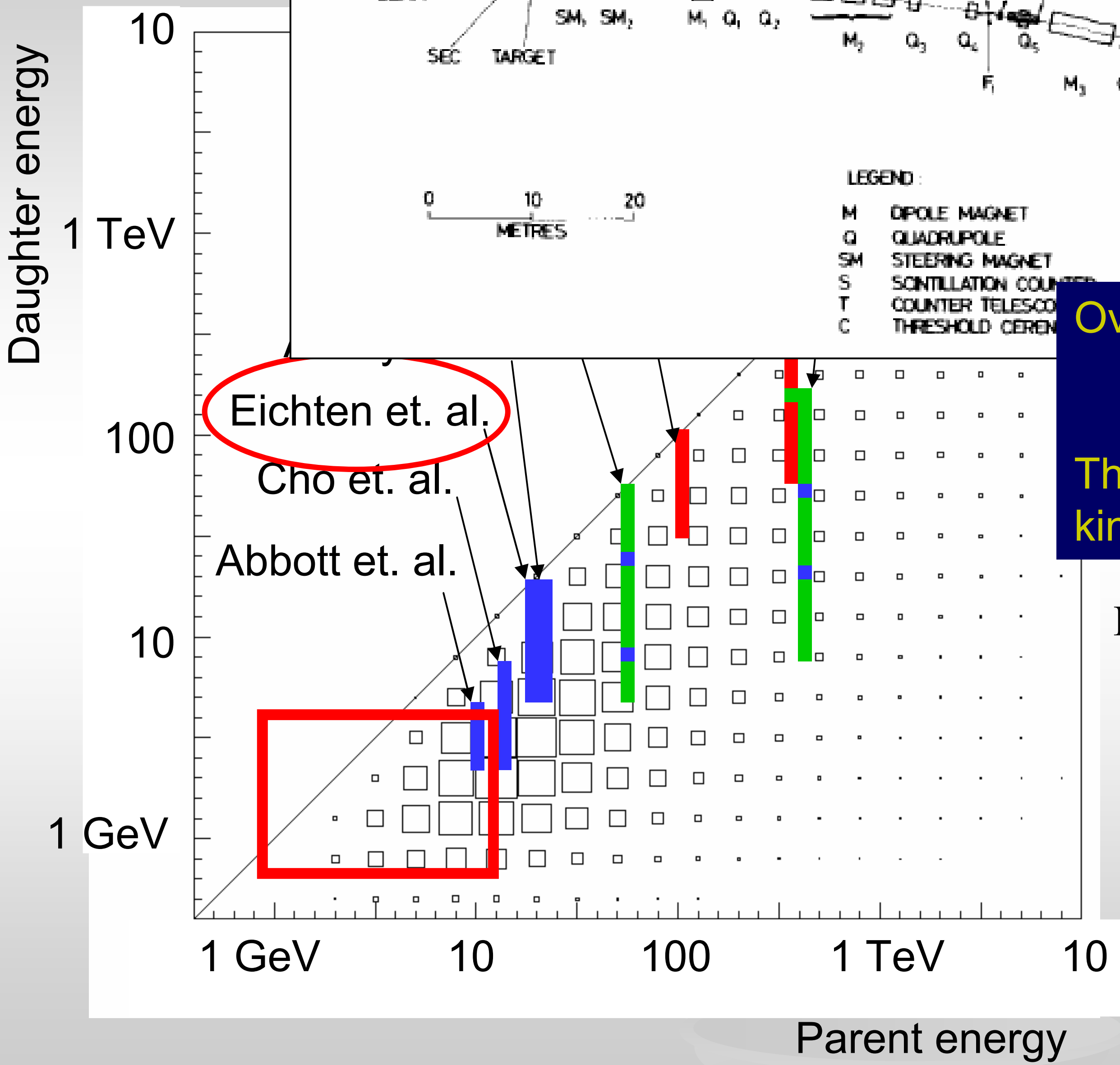
- Colliders: most particles close to beam and don't enter the detector.

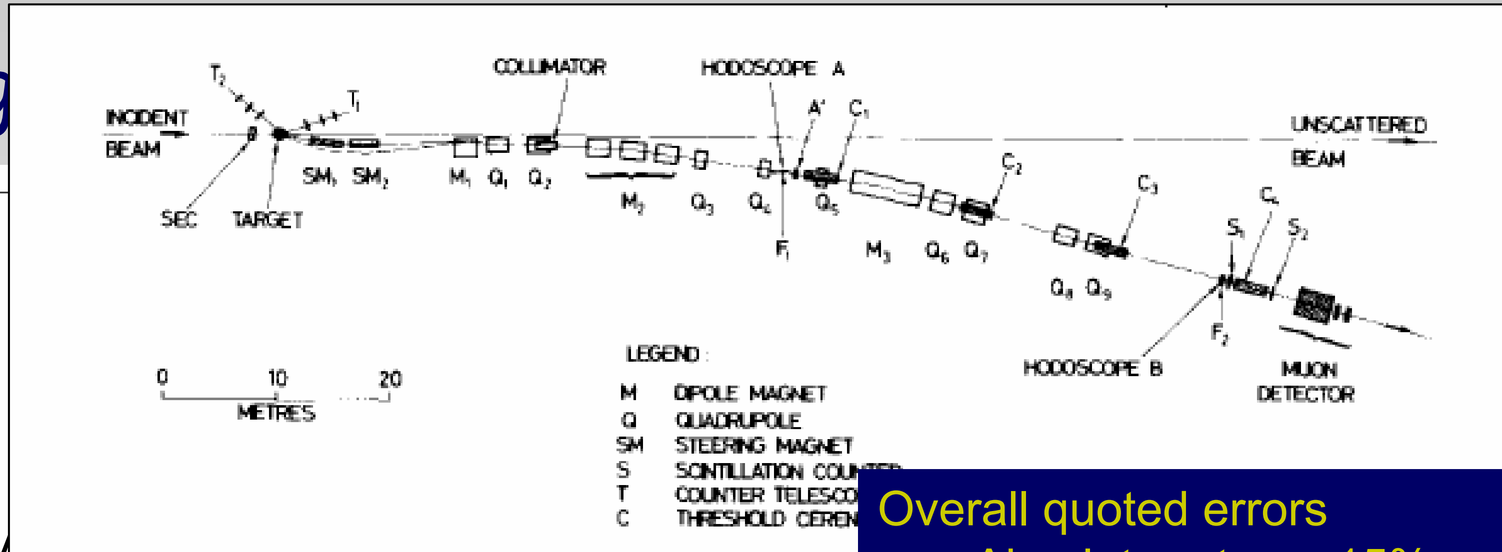
- Fixed target: The energies are much lower and few experiments have published.

- No data available on O_2 & N_2



Existing





Overall quoted errors

Absolute rates: ~15%

Ratios: ~5%

These figures are typical of this kind of detector setup

Measurements.

- 1-2 p_T points
- 3-5 p_T points
- >5 p_T points

How to overcome the problems

- **Event-by-event experiments, not particle-by-particle**
- **Modern design**
  - Open-geometry spectrometers
  - Full solid angle and P.Id.
  - Design inherited from Heavy Ions experiments (multiplicity, correlations, pion interferometry, …)
- **Full momentum acceptance, scan on incident proton momenta**
- **High event rate**
  - Heavy ions experiments are designed for very high track density per event, not for high rate of relatively simple events

Harp

- Inaugurates a new era in Hadron Production for Neutrino Physics:
- Based on a design born for Heavy Ions physics studies
  - Full acceptance with P.Id.
  - High event rate capability (3KHz on TPC)
- Built on purpose
- Collaboration includes members of Neutrino Oscillation & Cosmic rays experiments
- **HARP use T9 secondary beam line on the CERN PS that allows to explore the 2→15 GeV energy range**

HARP's recipe

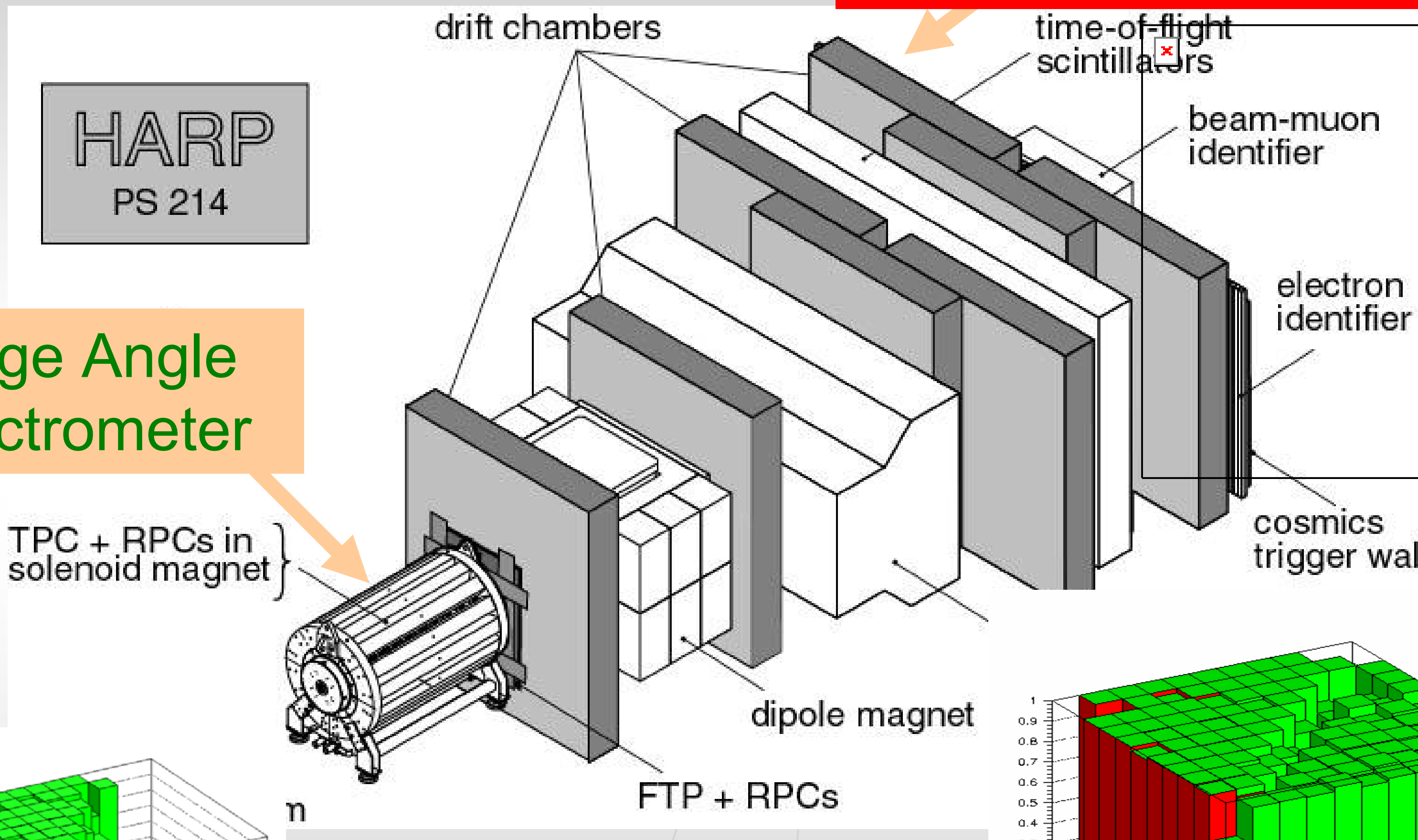
- **secondary hadron yields**
  - for different beam momenta
  - as a function of momentum and angle of daughter particles
  - for different daughter particles
- **as close as possible to full acceptance**
- **thin, thick and cryogenic targets**
- **T9 secondary beam line on the CERN PS allows a 1.5→15 GeV energy range**
- **O(10^6) events per setting**
  - a setting is defined by a combination of target type and material, beam energy and polarity
- **Fast readout**
  - aim at ~10^3 events/PS spill, one spill=400ms. Event rate ~ 2.5KHz
  - corresponds to some 10^6 events/day
  - ➔ very demanding (unprecedented!) for the TPC.

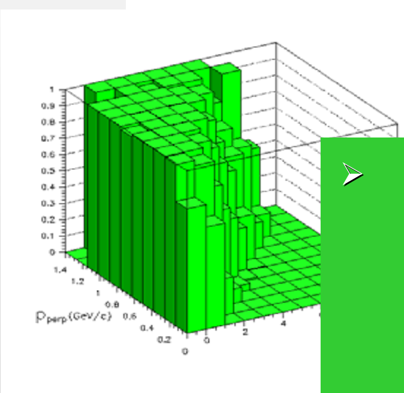
Detector

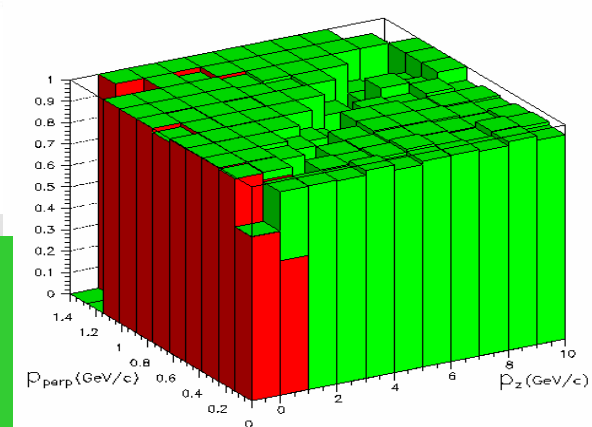
- Forward Spectrometer:
  - 30 mrad < θ < 210 mrad.
  - 750 MeV/c < p < 6.5 GeV/c

HARP
PS 214

Large Angle spectrometer







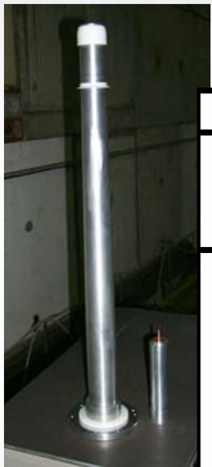
- Large Angle Spectrometer:
  - 0.35 rad < θ < 2.15 rad
  - 100 MeV/c < p < 700 MeV/c

More details in the NIM paper “The Harp Detector @ the CERN PS”

Data taking summary

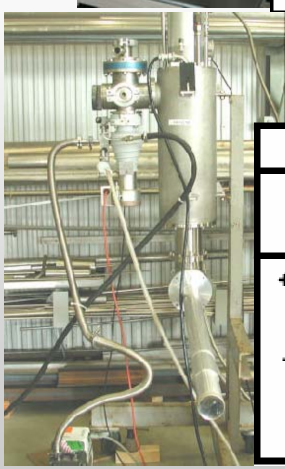
HARP took data at the CERN PS T9 beamline in 2001-2002

Total: 420 M events, ~300 settings



SOLID:

Be	C	Al	Cu	Sn	Ta	Pb	H_2O	Empty
2% 5% 100%	2% 5% 100%	2% 5% 100%	2% 5% 100%	2% 5% 100%	2% 5% 100%	2% 5% 100%	10% 100%	0%
+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8 -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+1.5, +3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+1.5, +3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+1.5,+8 GeV/c	+1.5, +3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c



CRYOGENIC:

H	D	N	O	Empty
0.8% 2.4%	2.1%	5.5%	7.5%	0%
+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c

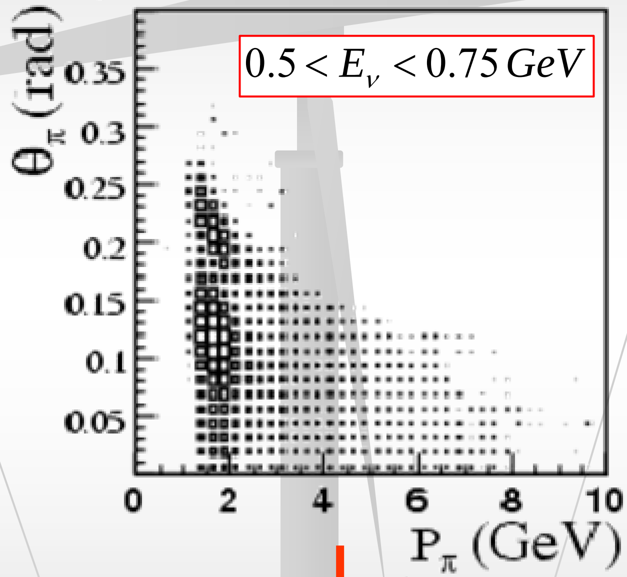
ν EXP:

K2K: Al	MiniBoone: Be	LSND: H_2O
5% 50% 100% Replica	5% 50% 100% Replica	10% 100%
+12.9 GeV/c	+8.9 GeV/c	+1.5 GeV/c

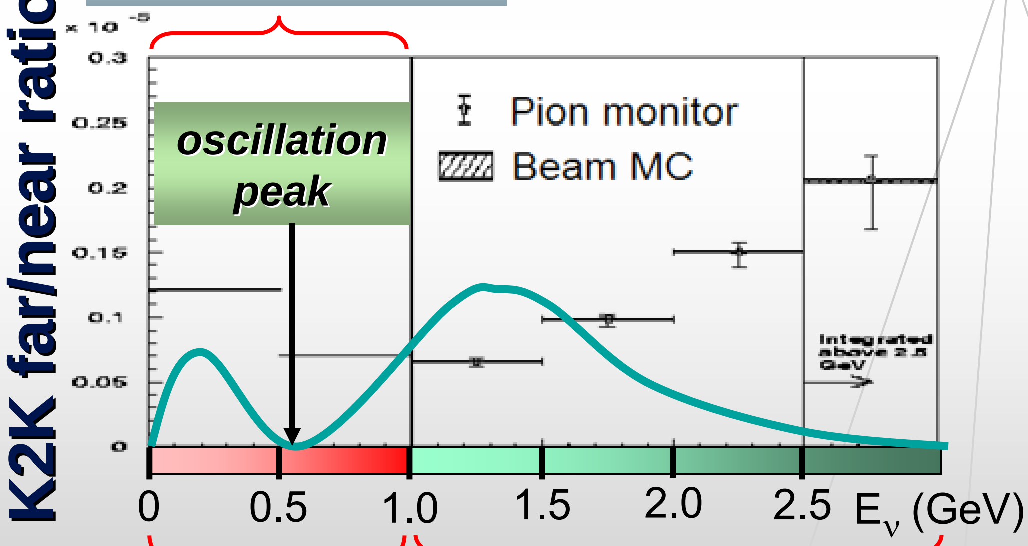
Relevance of HARP for K2K neutrino beam

One of the largest K2K systematic errors comes from the uncertainty of the far/near ratio

pions producing neutrinos in the oscillation peak



To be measured by HARP



Beam MC

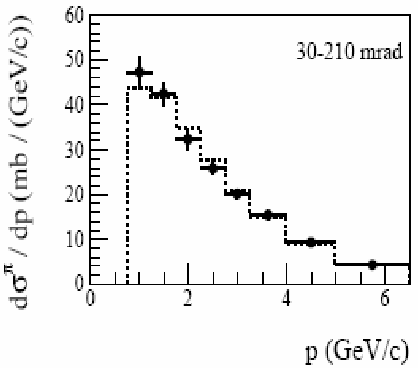
Beam MC confirmed by Pion Monitor

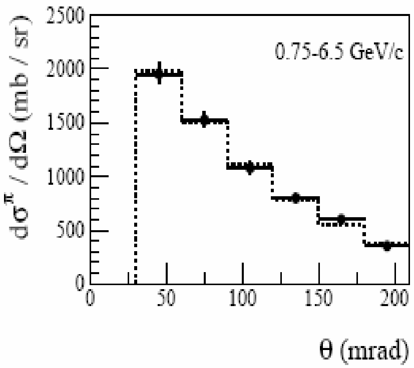
See also I.Kato talk

K2K interest

$$\begin{cases} P_\pi > 1\,GeV \\ \theta_\pi < 250\,mrad \end{cases}$$

Al 5% 12.9 GeV/c Results





Error Evaluation

- Thorough systematics error evaluation performed, to quantify errors on both:
- $d^2\sigma^{\pi}/(dp d\Omega)\ (p,\theta)$

Typical error: **8.7%**

- $\sigma^{\pi}(0.75<p<6.5\ GeV/c, 30<\theta<210\ mrad)$

Error on total cross-section: **4.7%**

Error Source	δ_{diff} (%)	δ_{int} (%)
Overall normalization	4.0	4.0
Momentum scale	3.6	0.3
Al target statistics	3.2	0.6
Acceptance correction	2.6	0.7
(π, p) PID	2.5	0.5
Empty target statistics	2.2	0.4
Electron PID	2.1	0.5
Momentum resolution (smearing)	1.3	1.6
Empty target normalization	1.2	1.1
Momentum resolution (model dep.)	1.0	1.1
Reconstruction efficiency	0.8	0.2
Kaon PID	0.3	0.1
Secondary interactions	0.2	0.1
PID probability cut	0.2	0.1
Total	8.7	4.7

Dominant error contributions:

- Overall normalization
- Momentum scale
- Statistics

Parametrization of HARP Data

- HARP data on inclusive pion production fitted to Sanford-Wang parametrization:

$$\frac{d^2\sigma(p+Al\to\pi^+ + X)}{dp\,d\Omega}(p,\theta)=c_1 p^{c_2}\left(1-\frac{p}{p_{beam}}\right)\exp\left[-c_3\frac{p^{c_4}}{p_{beam}^{c_5}}-c_6\theta(p-c_7 p_{beam}\cos^{c_8}\theta)\right]$$

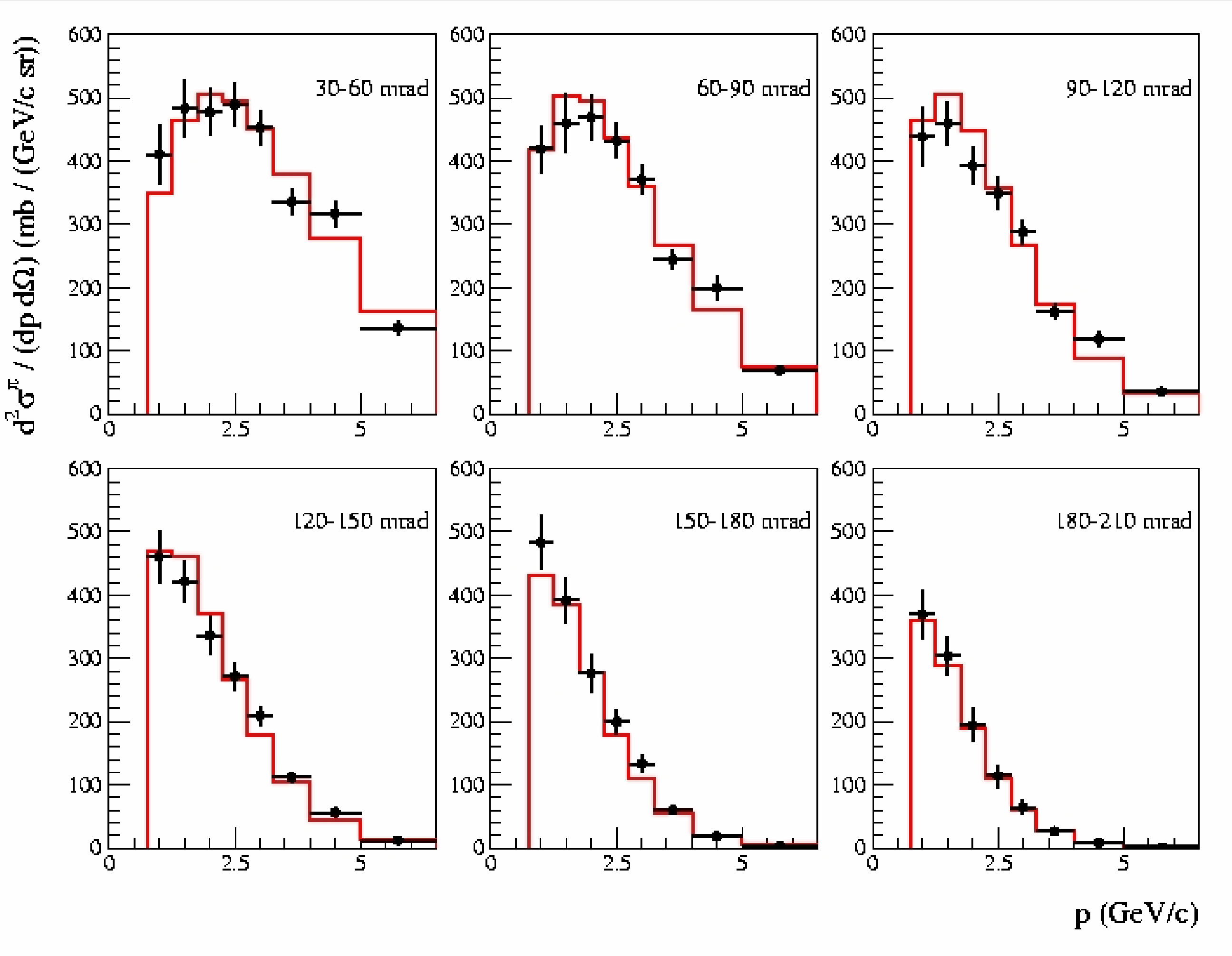
where:

- X: any other final state particle
- $p_{beam}=12.9$: proton beam momentum (GeV/c)
- p, θ: π^+ momentum(GeV/c), angle(rad)
- $d^2\sigma/(dp\,d\Omega)$ units: $mb/(GeV/c\ sr)$, where $d\Omega\equiv 2\pi\, d(\cos\theta)$
- $c_1, \ldots, c_8$: emprical fit parameters

Sanford-Wang parametrization used to:

- Use HARP data in K2K beam MC
- Translate HARP pion production uncertainties into flux uncertainties
- Compare HARP results with previous results in similar beam momentum, pion phase space range

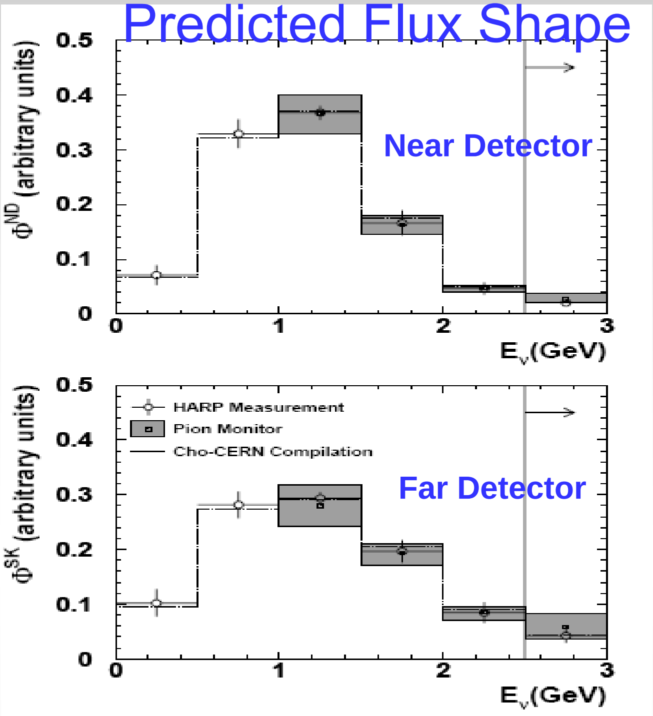
Al 5% 12.9 GeV/c Results



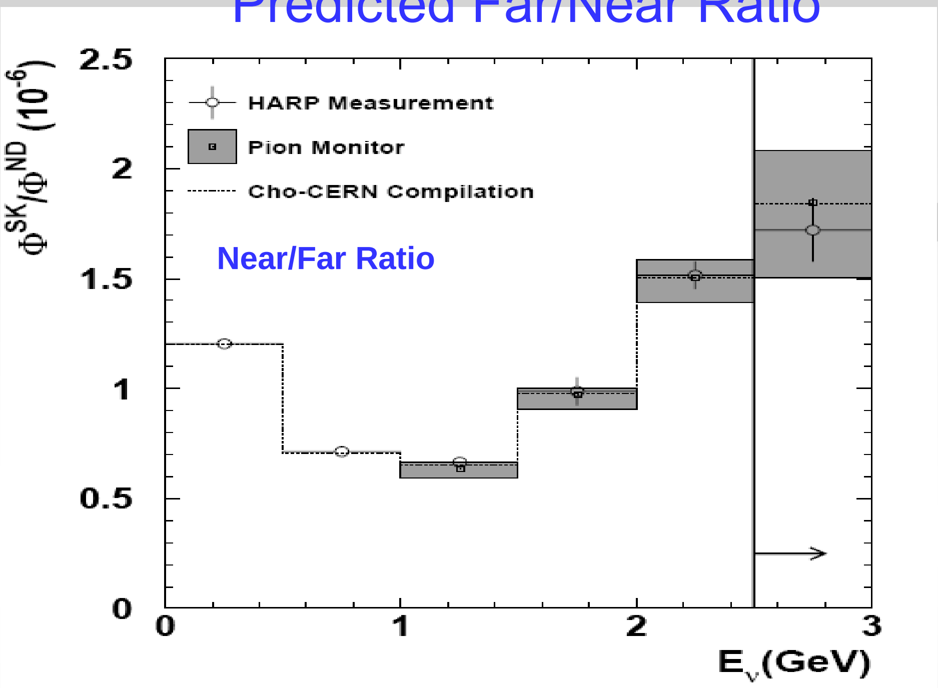
HARP results in black, Sanford-Wang parametrization of HARP results in red

Far/Near Ratio in K2K

Predicted Flux Shape

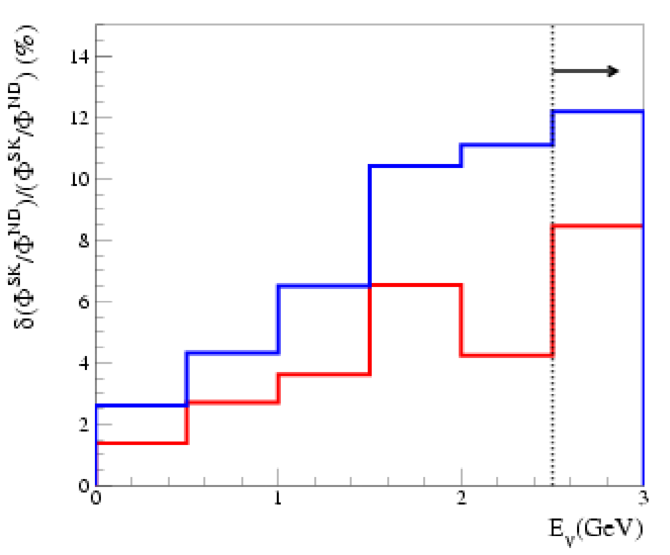


Predicted Far/Near Ratio

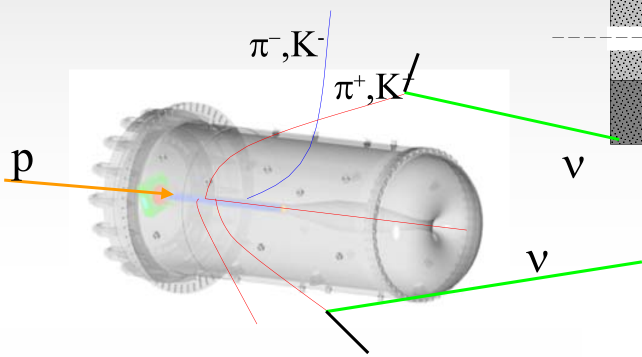


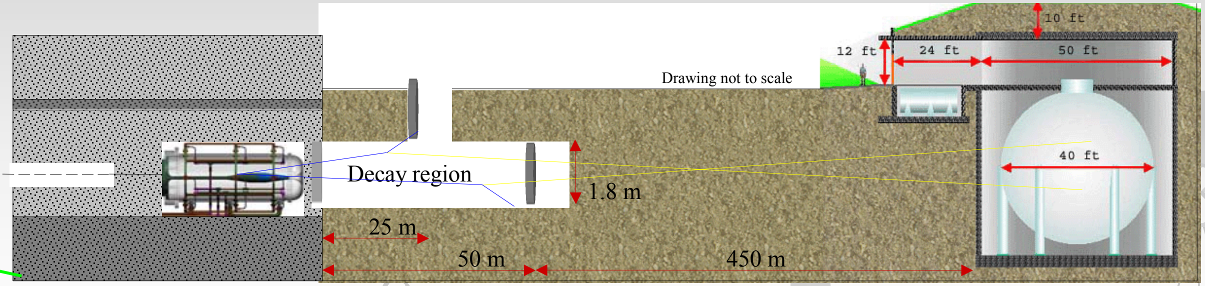
HARP gives ~ factor 2 error reduction across all energies

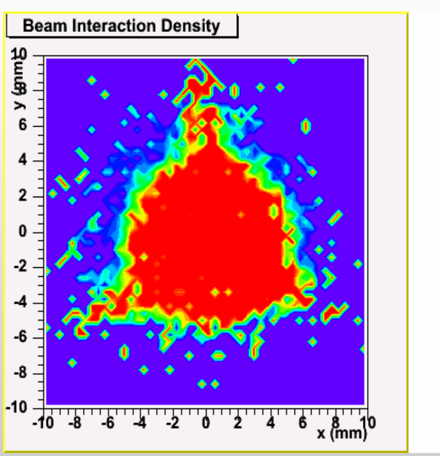
Nucl.Phys.B732:1-45,2006
hep-ex/0510039



Miniboone: 8.9 GeV p beam hitting a berillium target





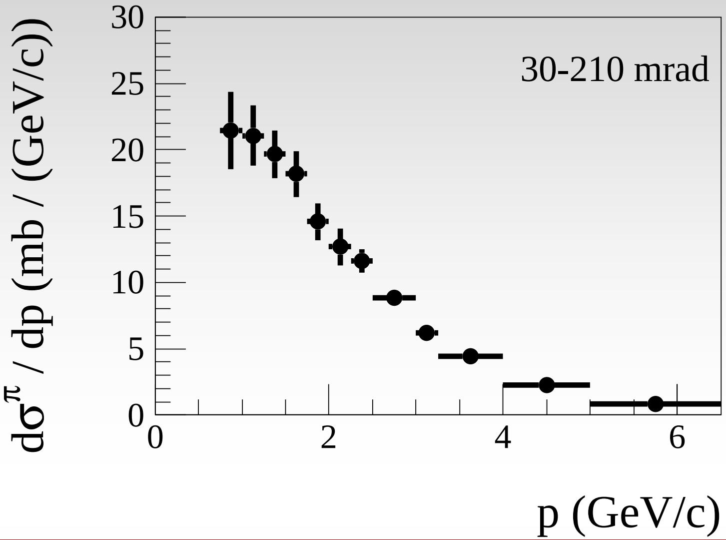


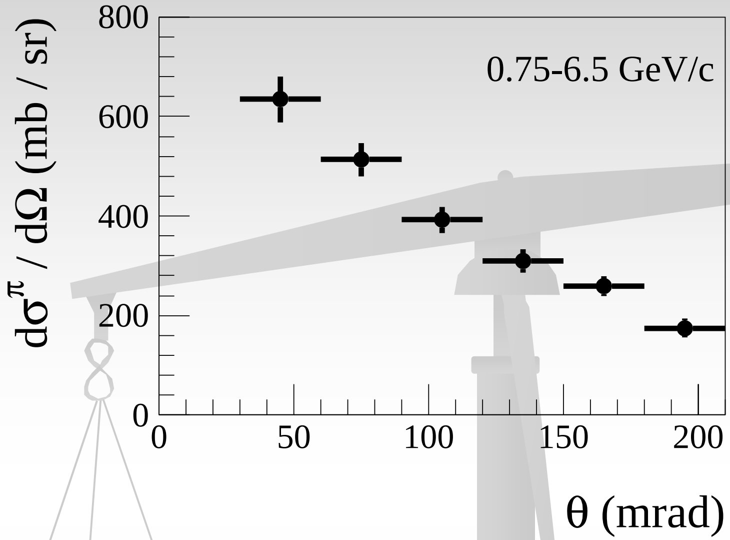
MiniBooNE $\nu_\mu \rightarrow \nu_e$ Analysis

- Goal: confirm or refute the LSND $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ result in a definitive and independent way
- Method: combined fit to ν_e CCQE and ν_μ CCQE samples in bins of reconstructed neutrino energy

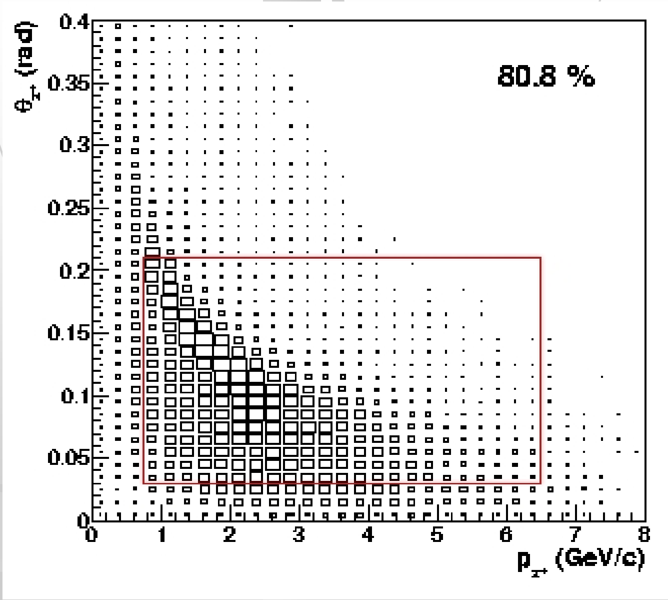
See also Z.Djurcic talk

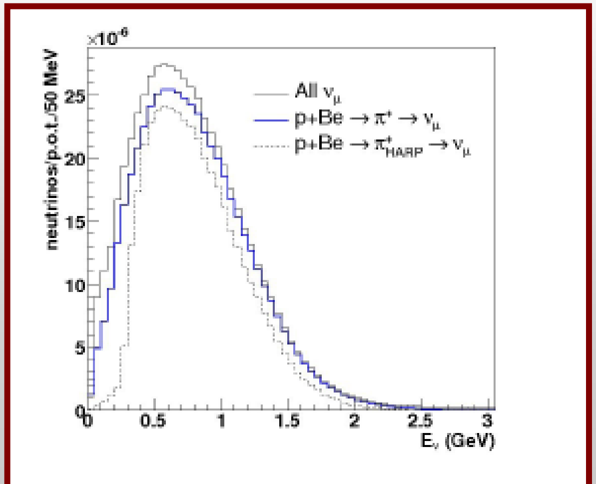
HARP Be 8.9 GeV 5% Target Results π^+



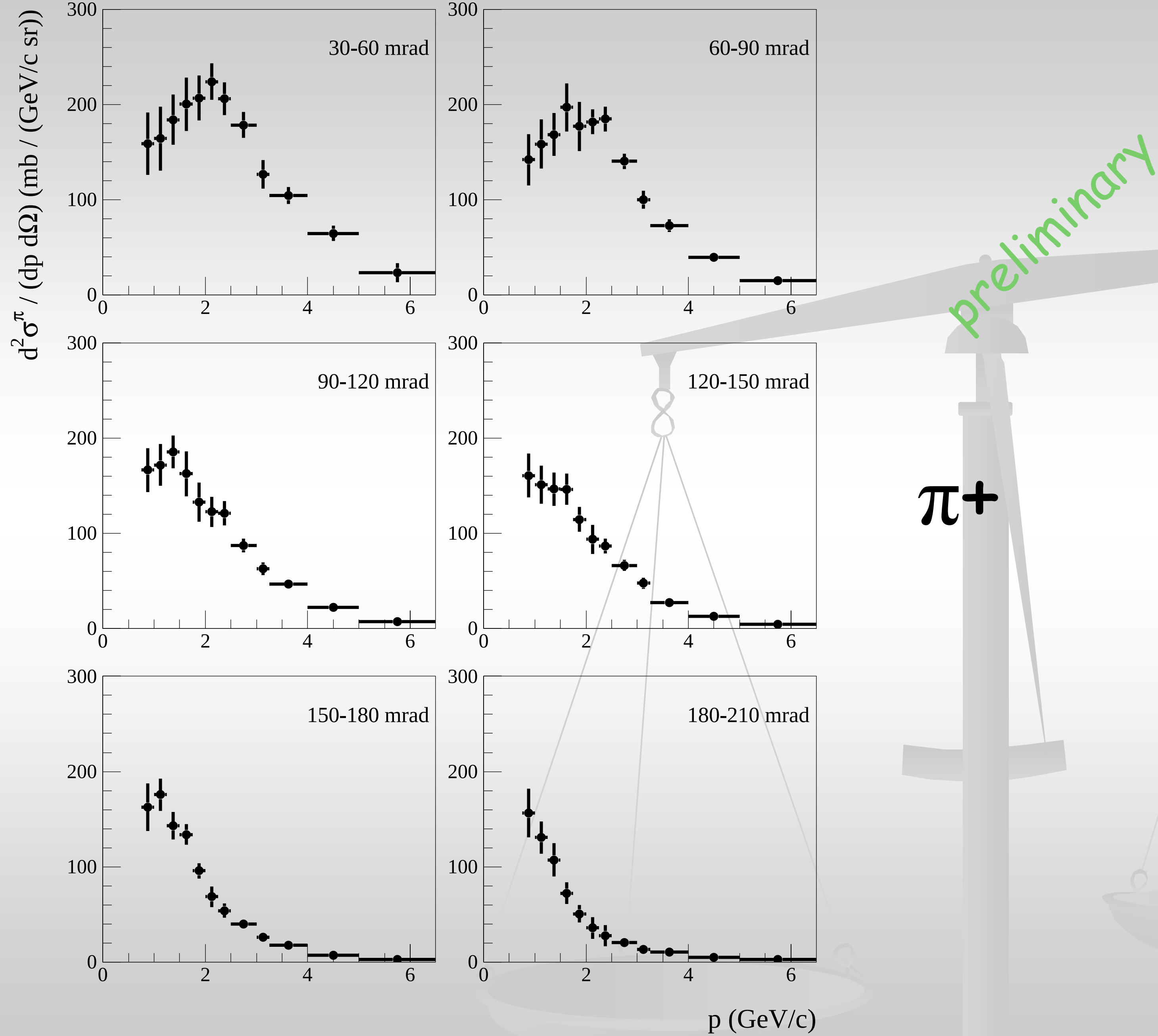


Harp Forward Spectrometer Acceptance





Berillium 8.9 GeV/C Results



- More HARP data for accurate flux prediction coming:

K± production data

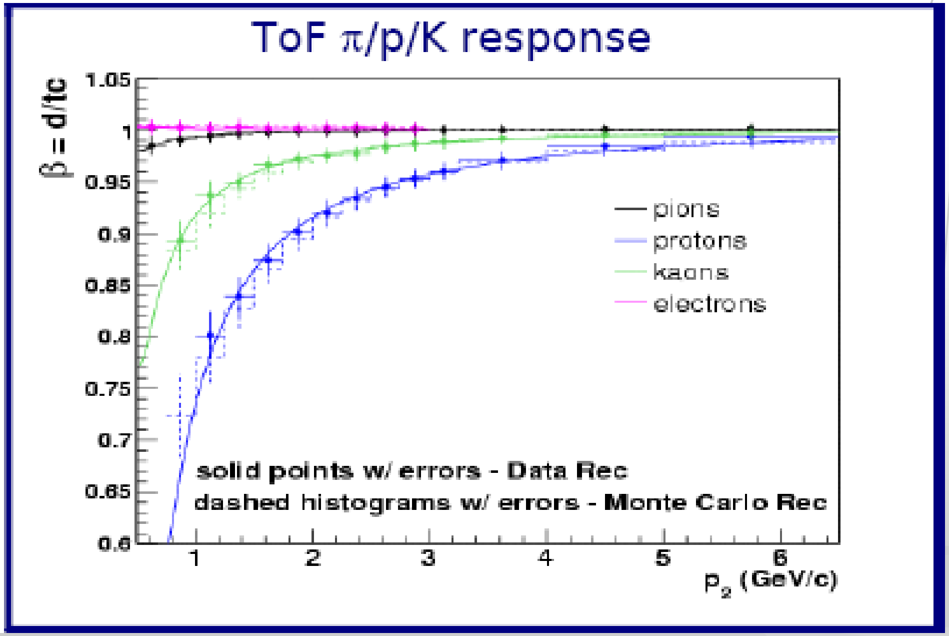
p π interaction in thick target

π- production data

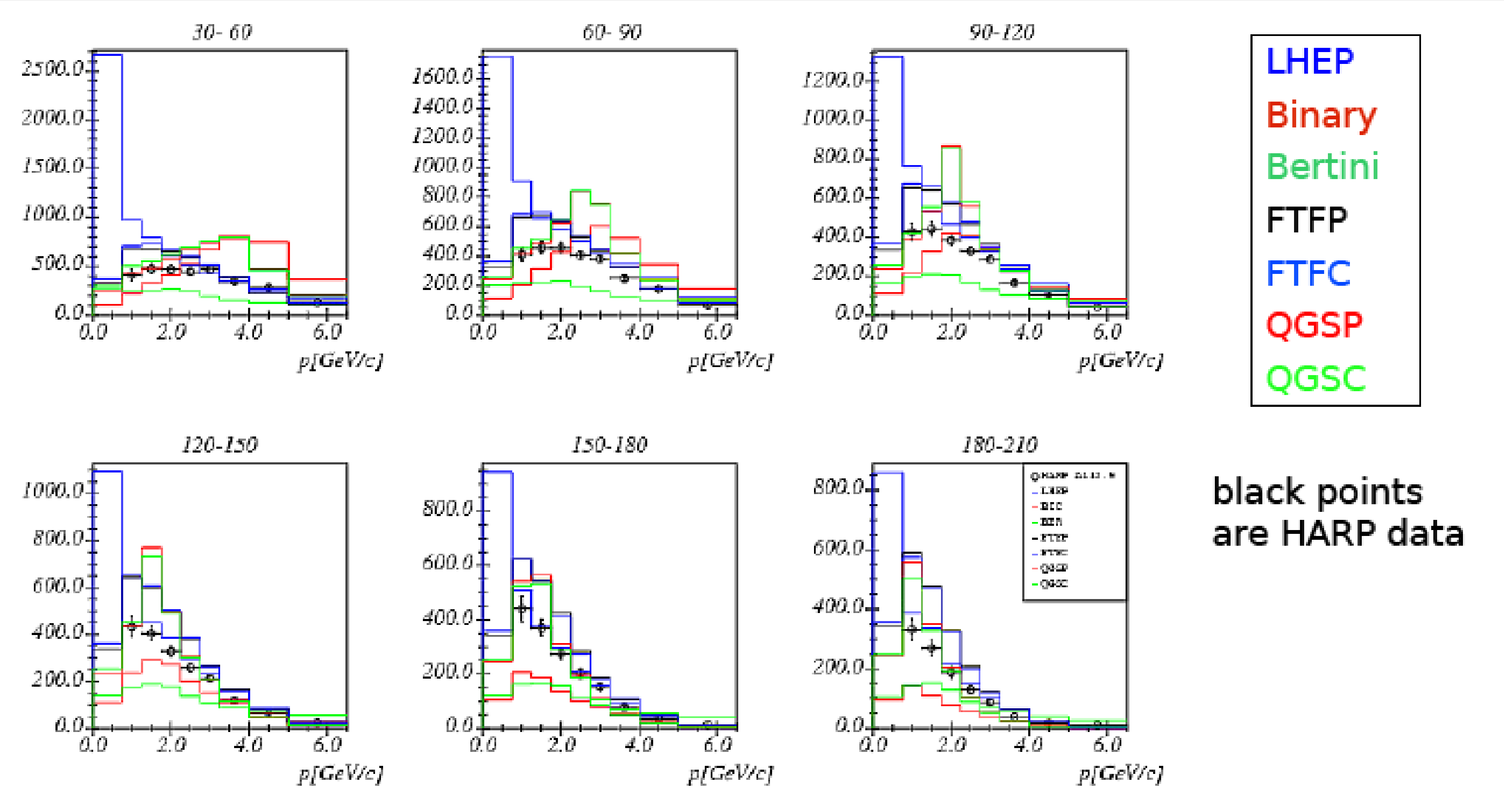
Direct measurement of the main source of the νe background

Direct measurement of the rescattering

Anti-neutrino flux measurement

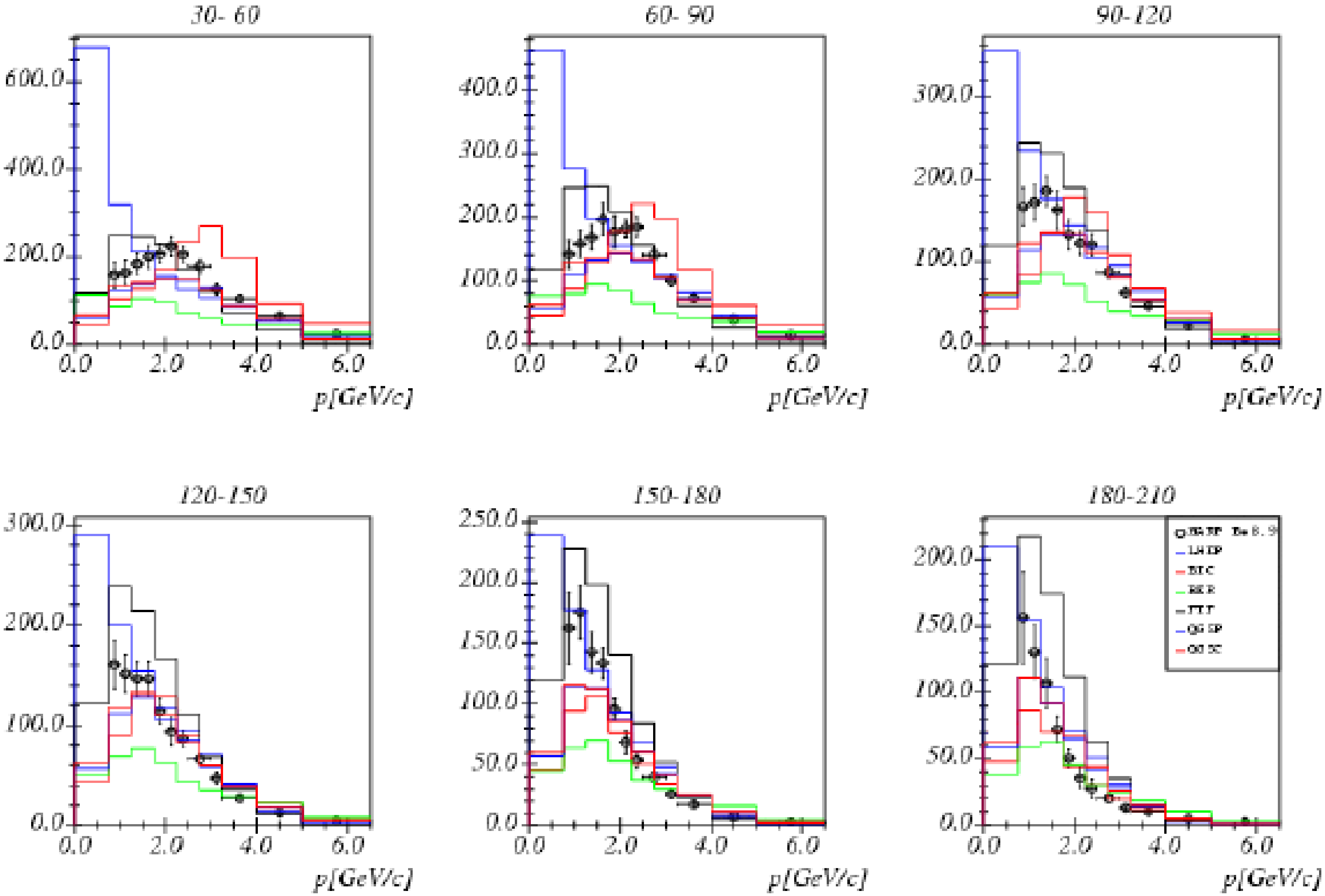


Al 12 GeV/c : a first (raw) comparison with some geant4 hadronic generators:



black points are HARP data

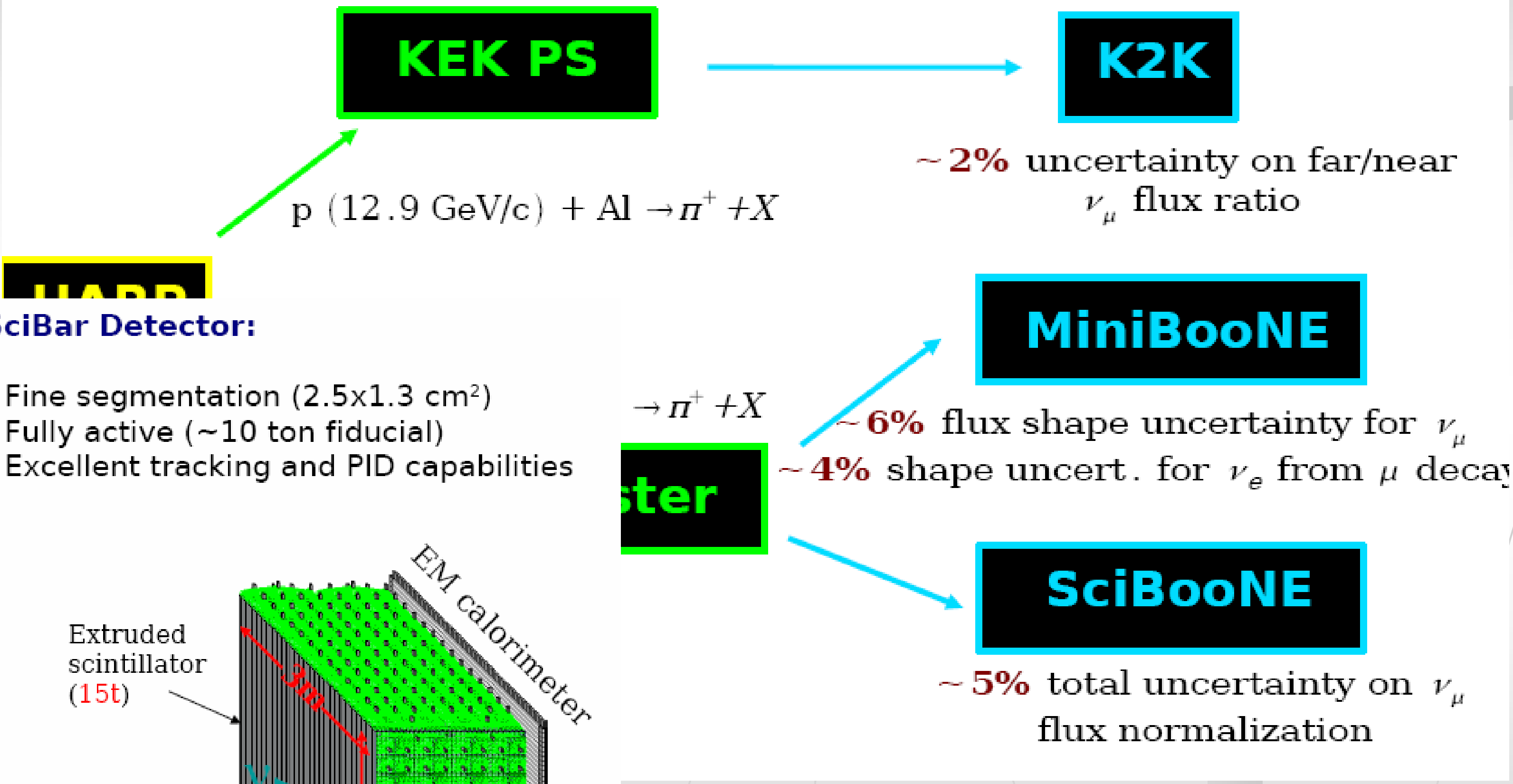
Be 8.9 GeV/c : a first comparison with geant4 hadronic generators:



LHEP
Binary
Bertini
FTF
QGSP
QGSC

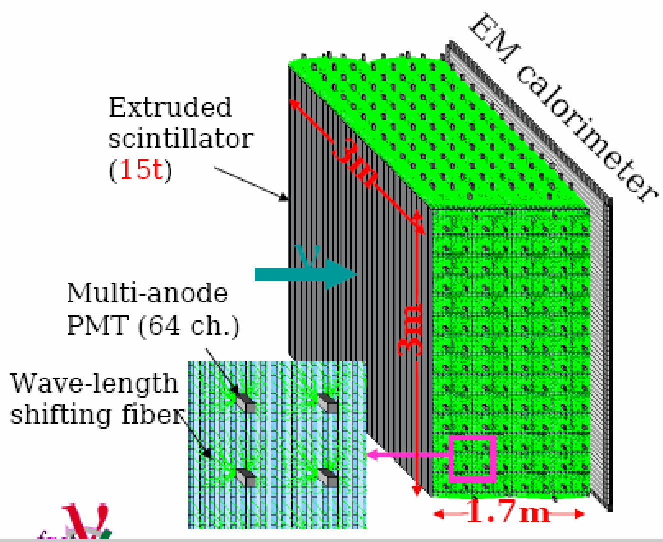
black points are HARP data

Flux Uncertainties With New HARP Data



SciBar Detector:

- Fine segmentation (2.5x1.3 cm²)
- Fully active (~10 ton fiducial)
- Excellent tracking and PID capabilities

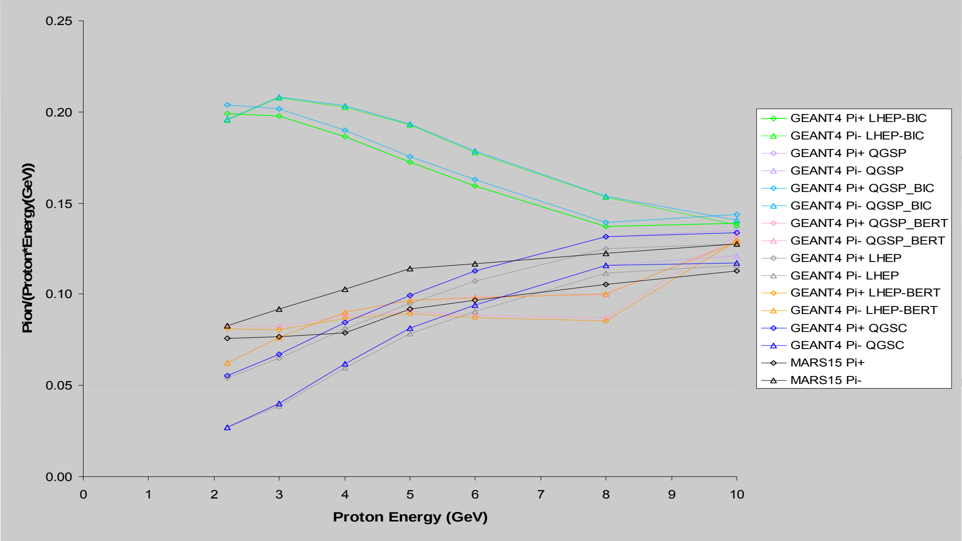


M.Sorel Nufact06

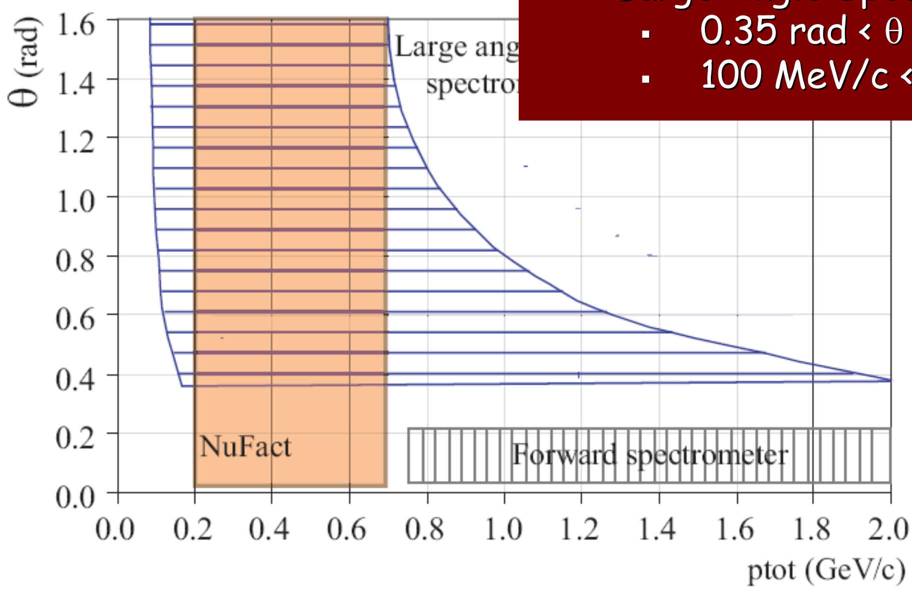
See also F.Sanchez talk

Possible proton-driver energies for neutrino factory & super beams

Proton Driver	GeV
Old SPL energy (2.2 GeV)	2.2
[New SPL energy 3.5GeV]	3.5
FNAL linac (driver study 2)	8
[FNAL driver study 1, 16GeV]	16
[BNL/AGS upgrade, 24GeV]	24



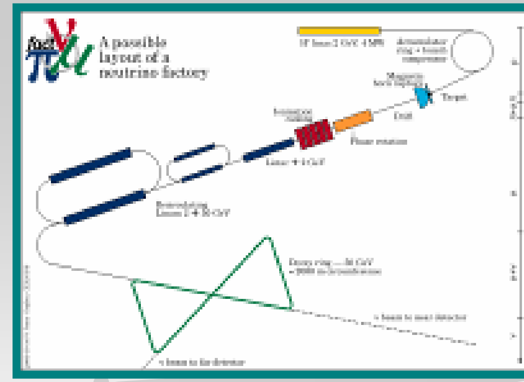
Harp Acceptance

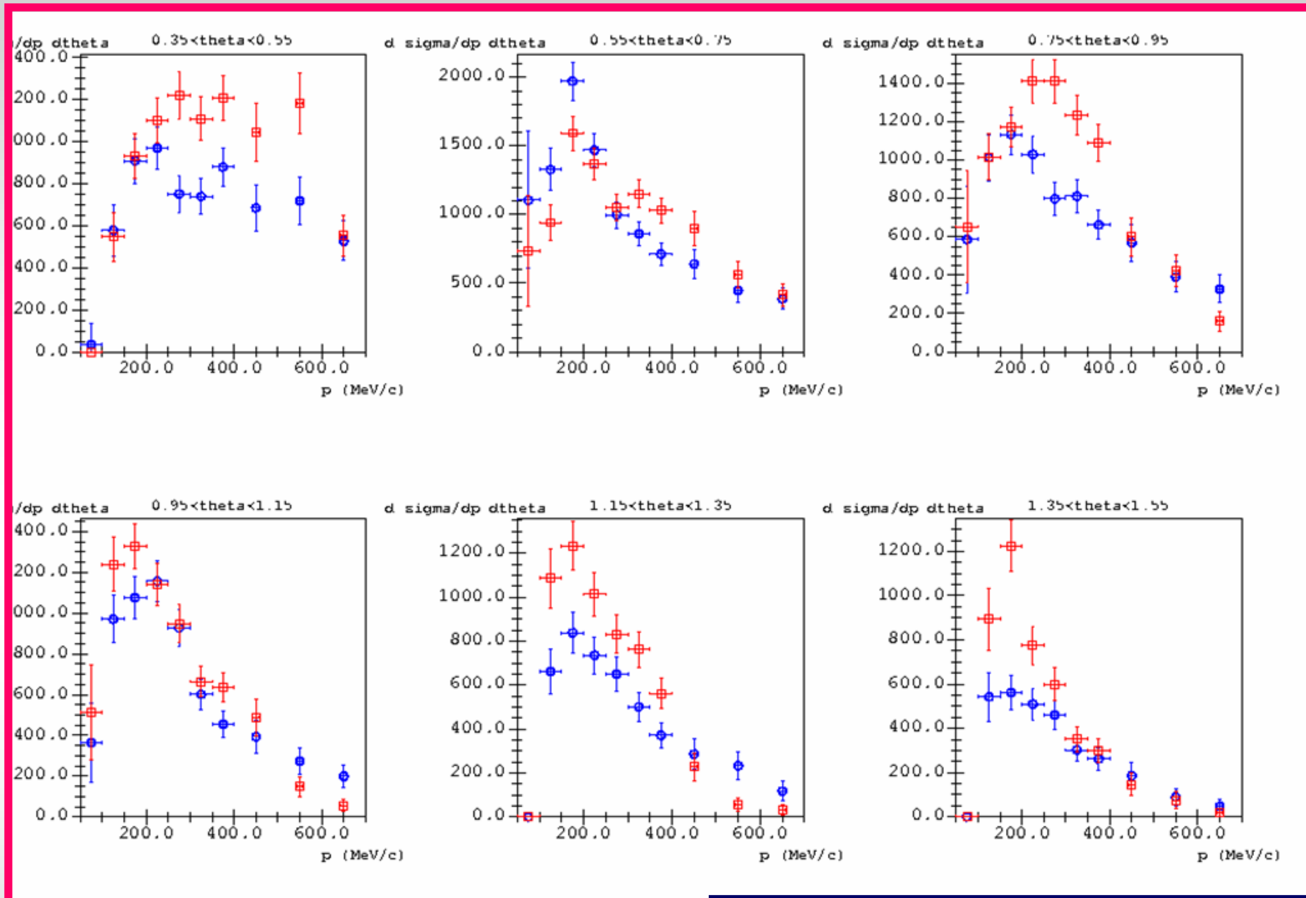


- Large Angle Spectrometer:
  - $0.35 \text{ rad} < \theta < 2.15 \text{ rad}$
  - $100 \text{ MeV/c} < p < 700 \text{ MeV/c}$

- Geant/Mars comparison
- Obvious discrepancies in
  - Total yields
  - Relative abundance +/-
- Larger discrepancies at low proton energy

5 GeV/c p-Ta Results

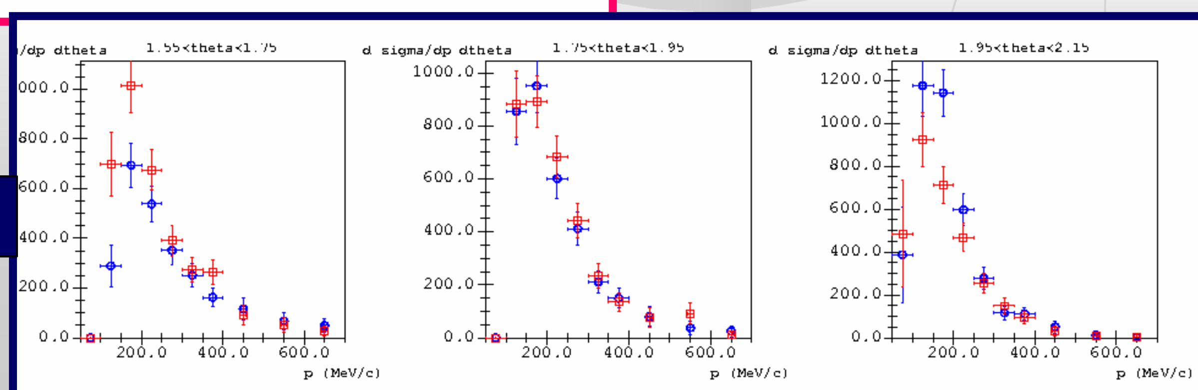




π+π-

Forward :

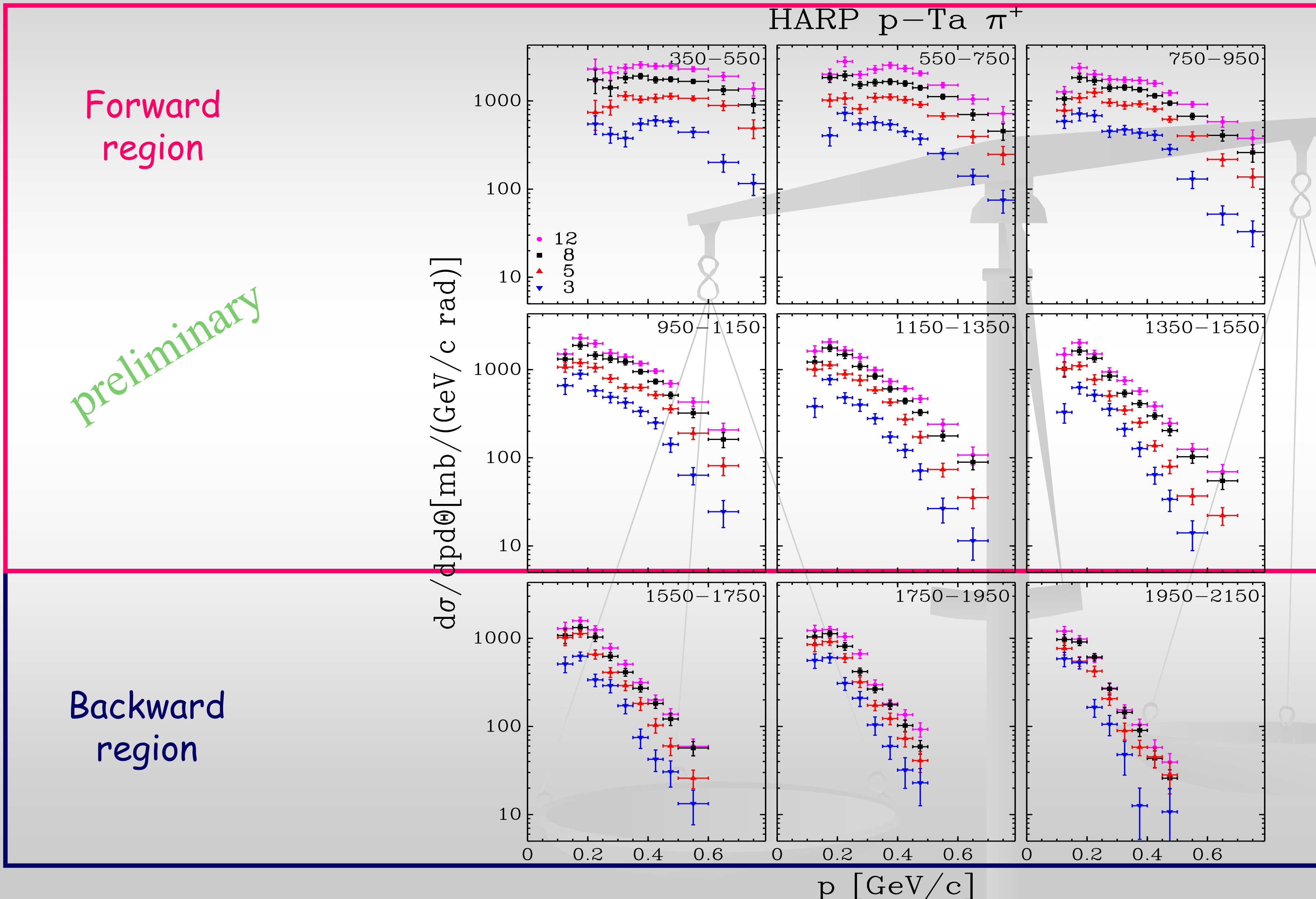
20° < θ < 90°



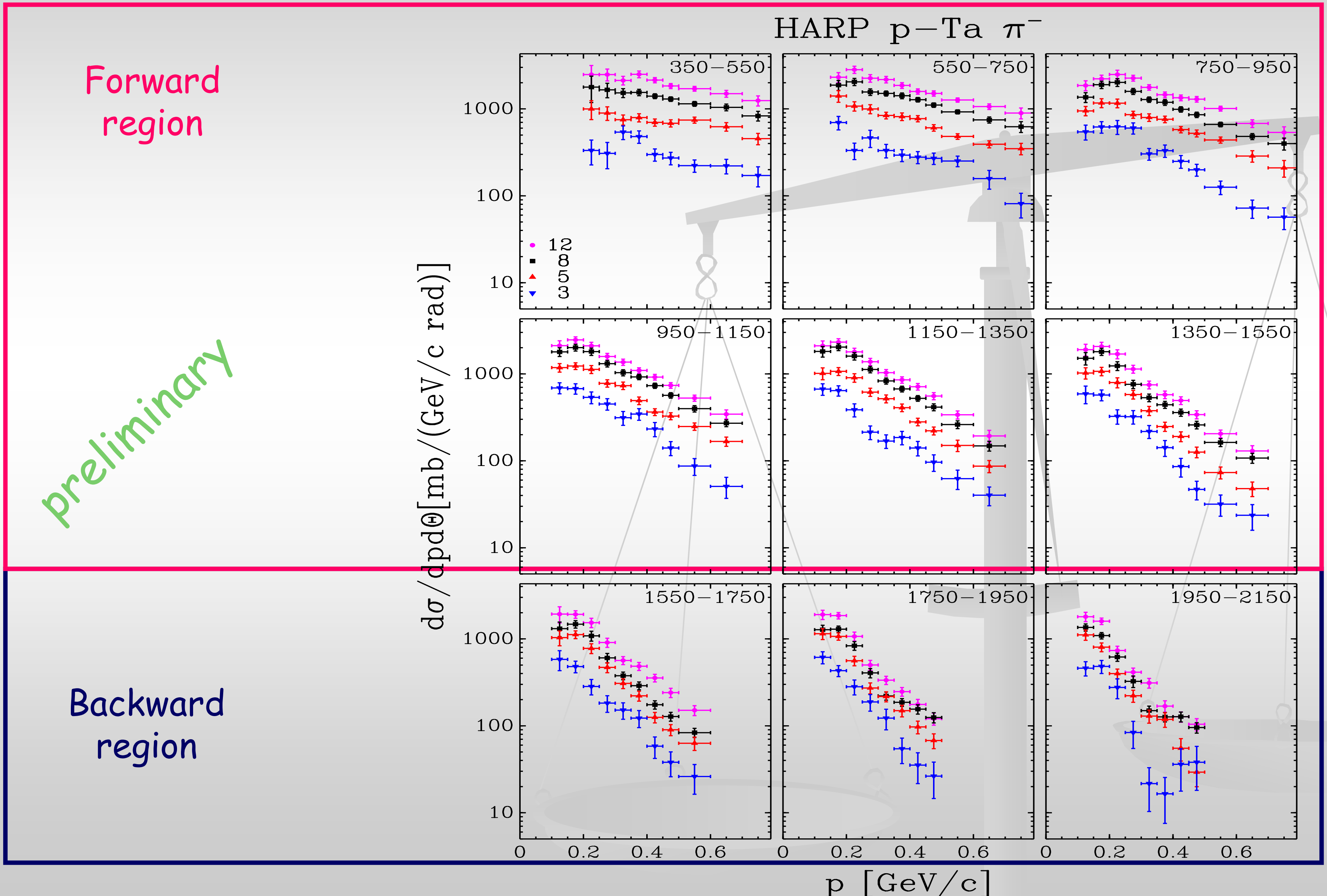
Backward:

90° < θ < 135°

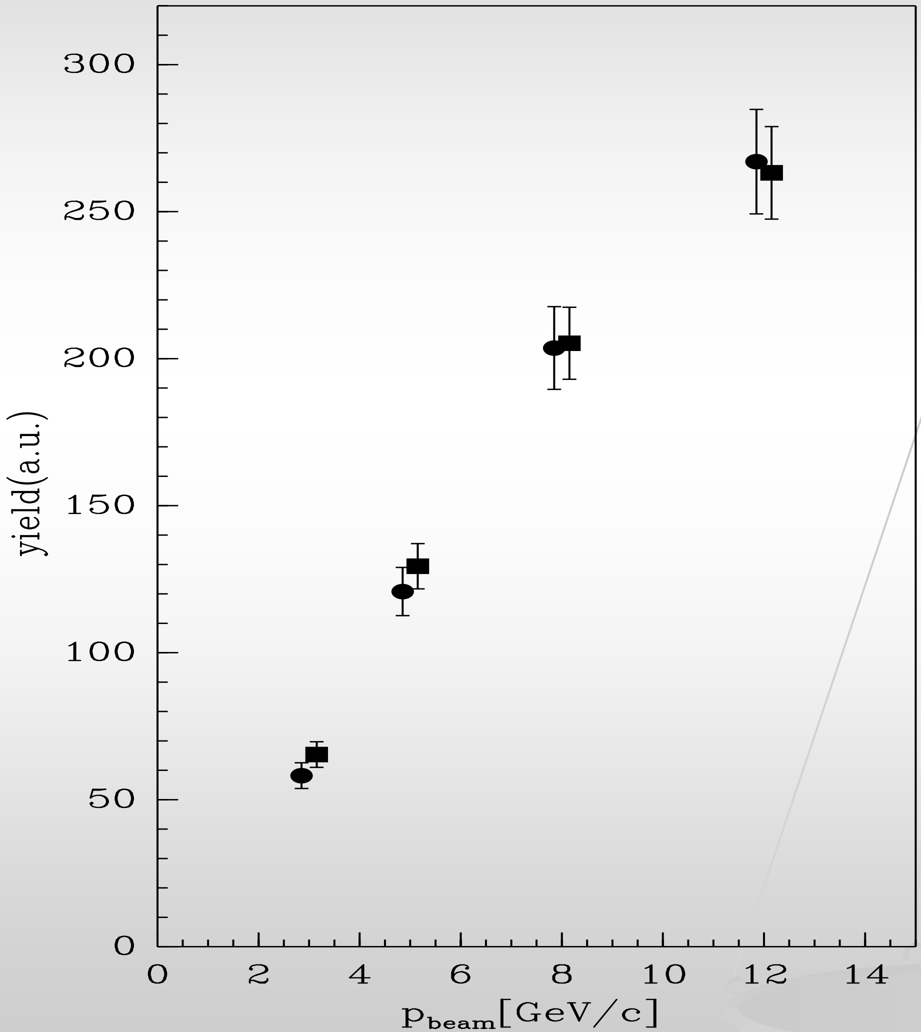
3-5-8-12 GeV/c p-Ta Results → π+



3-5-8-12 GeV/c p-Ta Results → π-



π+ π- vs beam momentum



● π+

■ π-

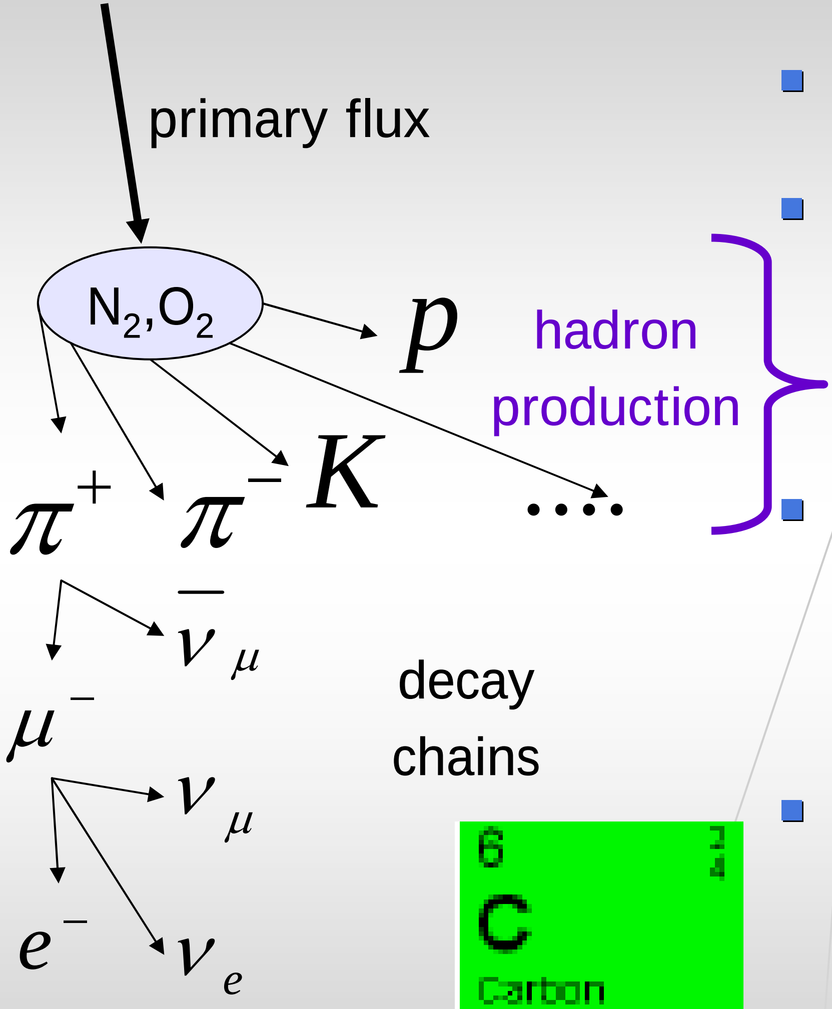
Statistical & Systematic errors included

Ongoing analysis :

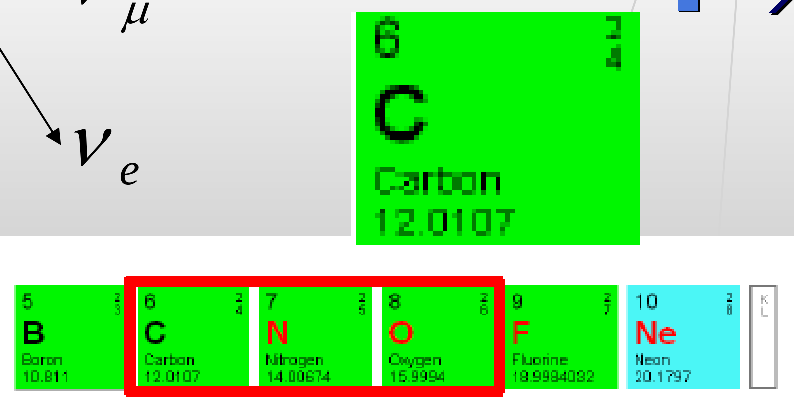
3-5-8-12 GeV/c on heavy targets

Sn Pb Cu C and Al

Atmospheric neutrino fluxes

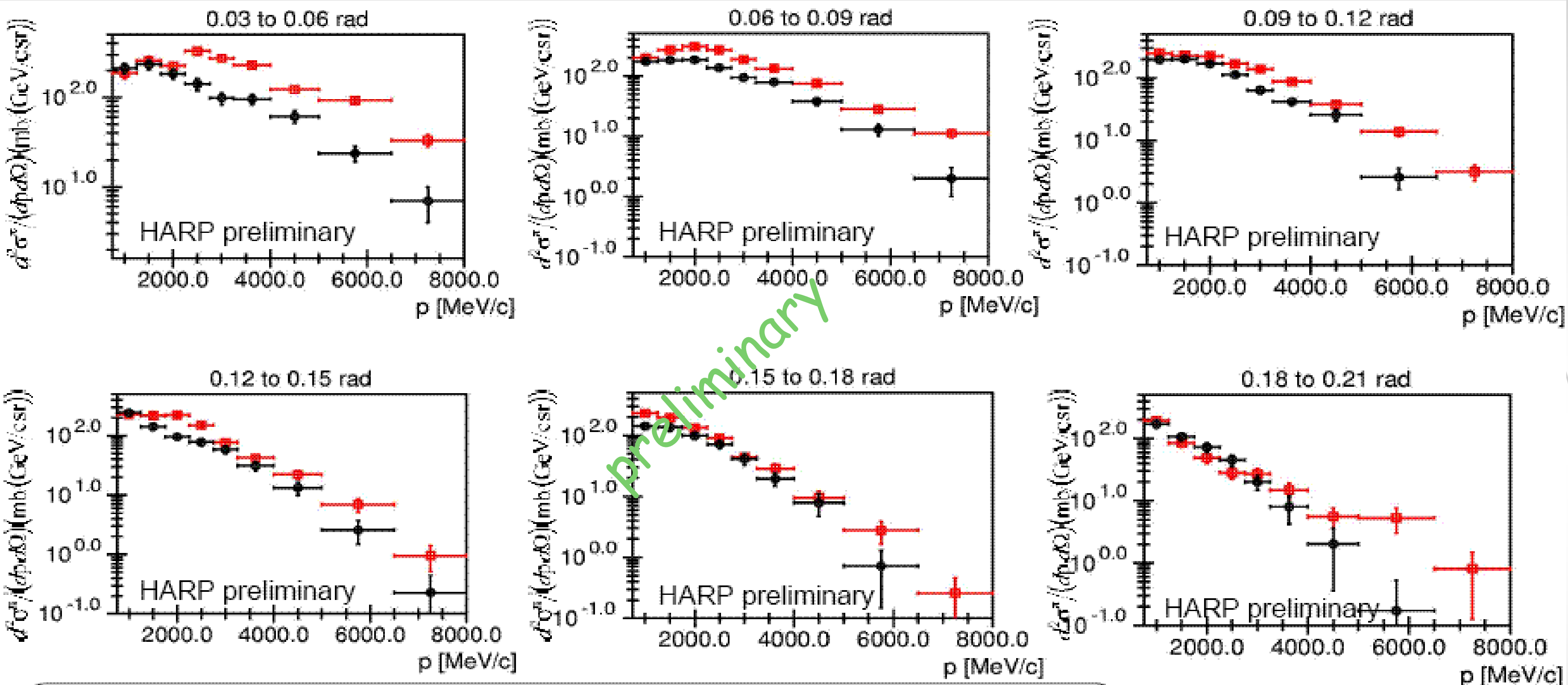


- Primary flux is now considered to be known to better than 10%
- Most of the uncertainty comes from the lack of data to construct and calibrate a reliable hadron interaction model.
- Model-dependent extrapolations from the limited set of data leads to about 30% uncertainty in atmospheric fluxes
- → cryogenic targets



78% nitrogen
21% oxygen

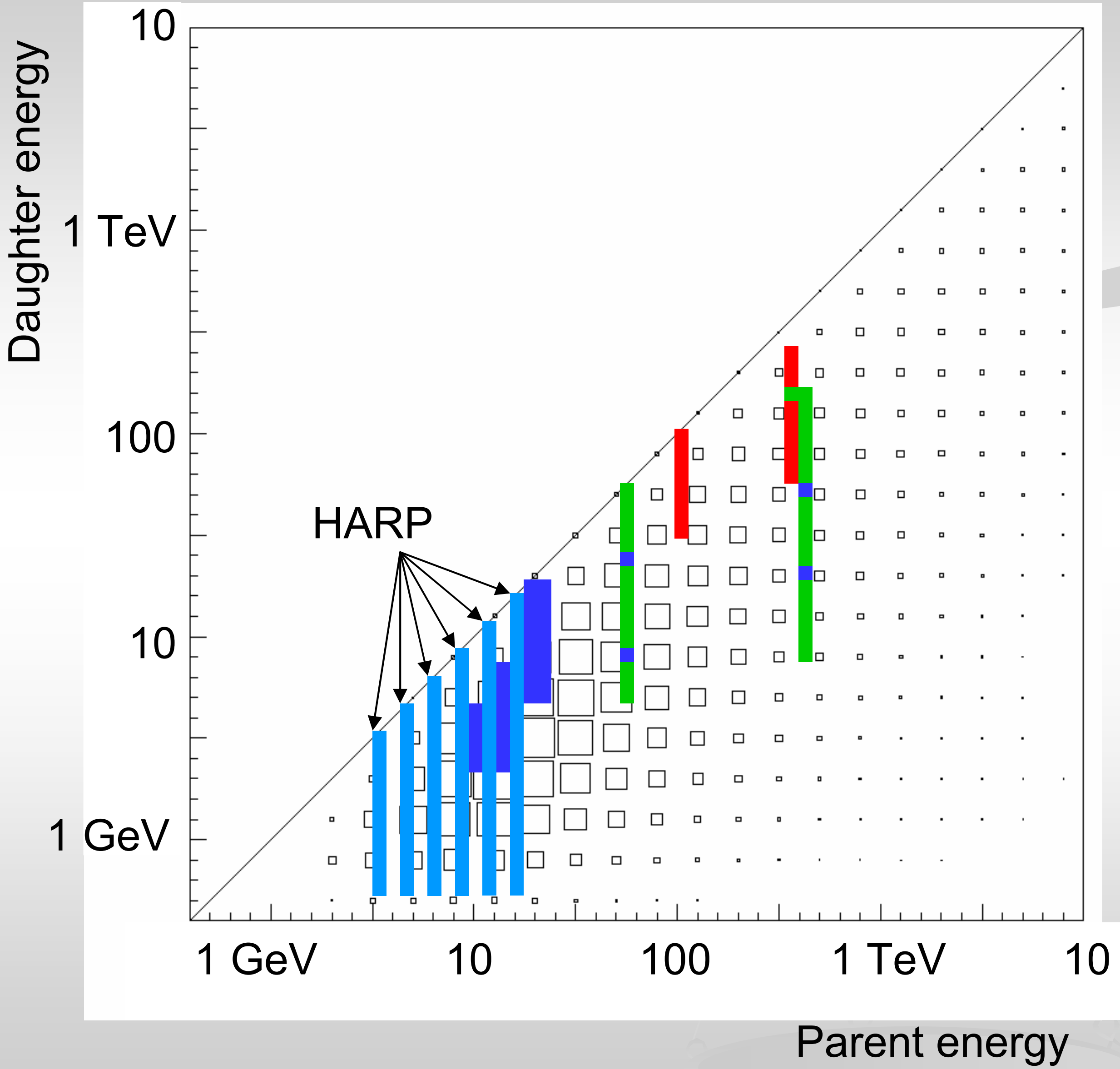
$p+C \rightarrow \pi^{\pm}+X$, p_{beam}=12 GeV/c



- π^+: leading particle effect
- Comparison with models in preparation
- Error: stat. and syst. error
  → syst. error: kaon subtraction in progress

π^-, π^+

New Harp measurements



Conclusions

- Precision n studies require a precise knowledge of ν production and HARP measurements fill an important gap in ν flux predictions
- HARP Al results have been published and incorporated into K2K final oscillation analysis giving a factor of 2 reduction in errors on F/N ratio predictions
- HARP Be results are ready .These results are used in MiniBooNE oscillation analyses
- Harp Ta results at large angle from 3 to 12 GeV/c are also ready. The work to integrated them in the design studies of the facilities for the next ν beam generations is under way.
- Preliminary results from with Carbon target @12 GeV/c are now available
- Many new data will be available in the future

Just in case

Why we still need hadron production measurements ?

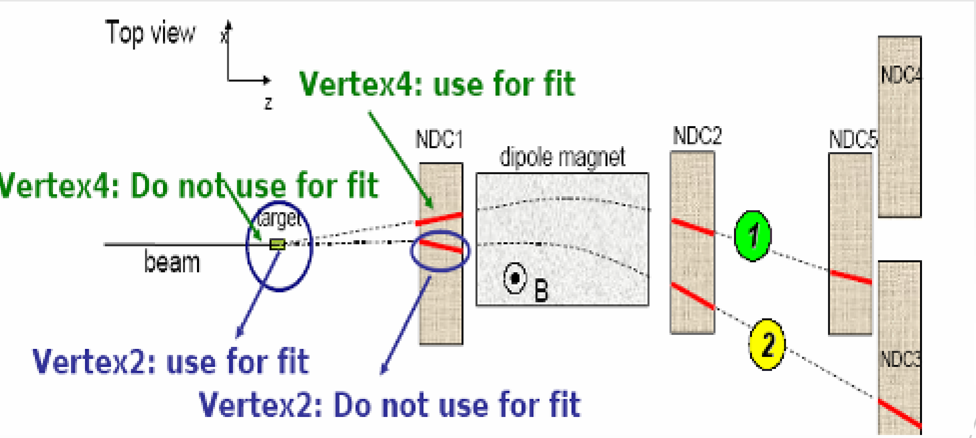
Contains everything interesting: oscillation physics, exotic event rates etc.

(observed event rate) = (X-section) (neutrino flux) (detection efficiency)

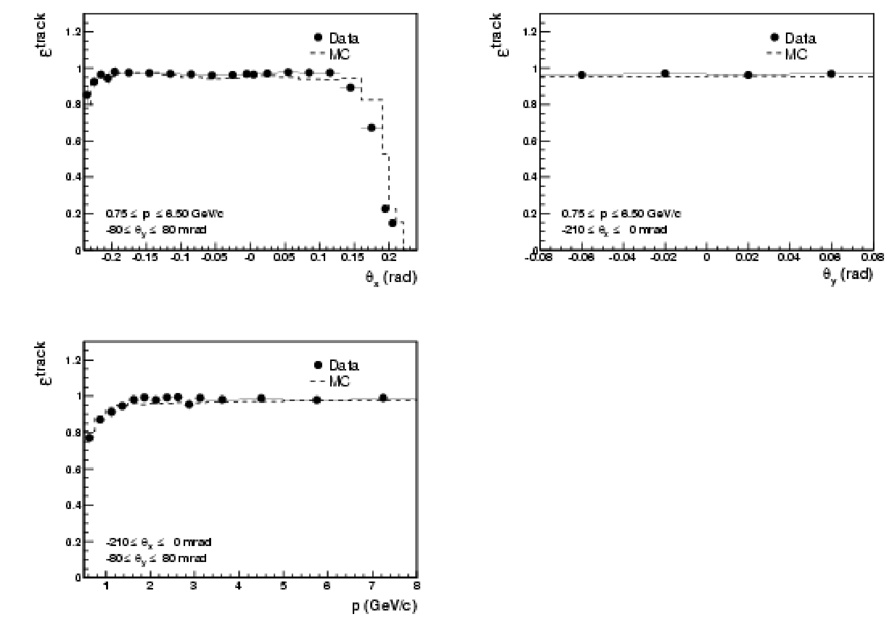
The subject of this talk

- The task to make a reliable prediction of the neutrino flux at the experiment is difficult.
  - You need a precise knowledge of the relative population of the different kind of particles and energy spectrum .
- To avoid one of the main source of systematic error the neutrino experiments community was always committed to measure in ancillary experiments the hadron production

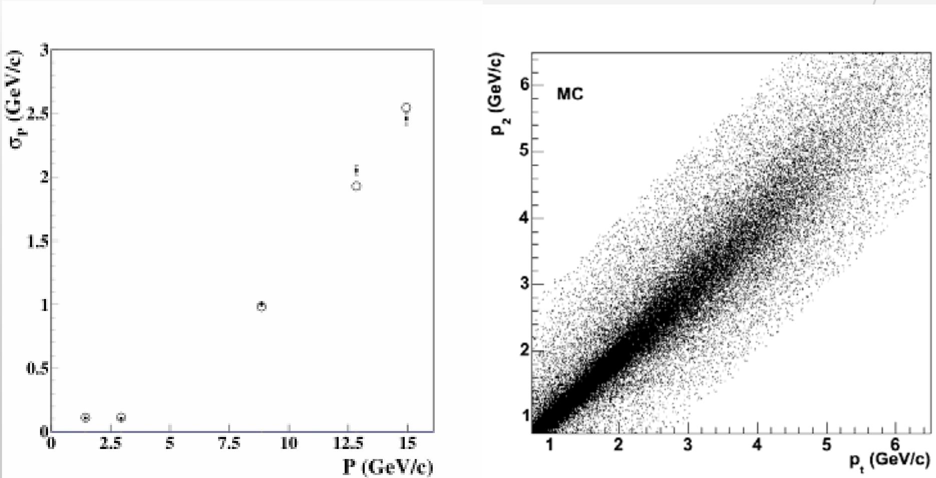
Forward Region :Tracking



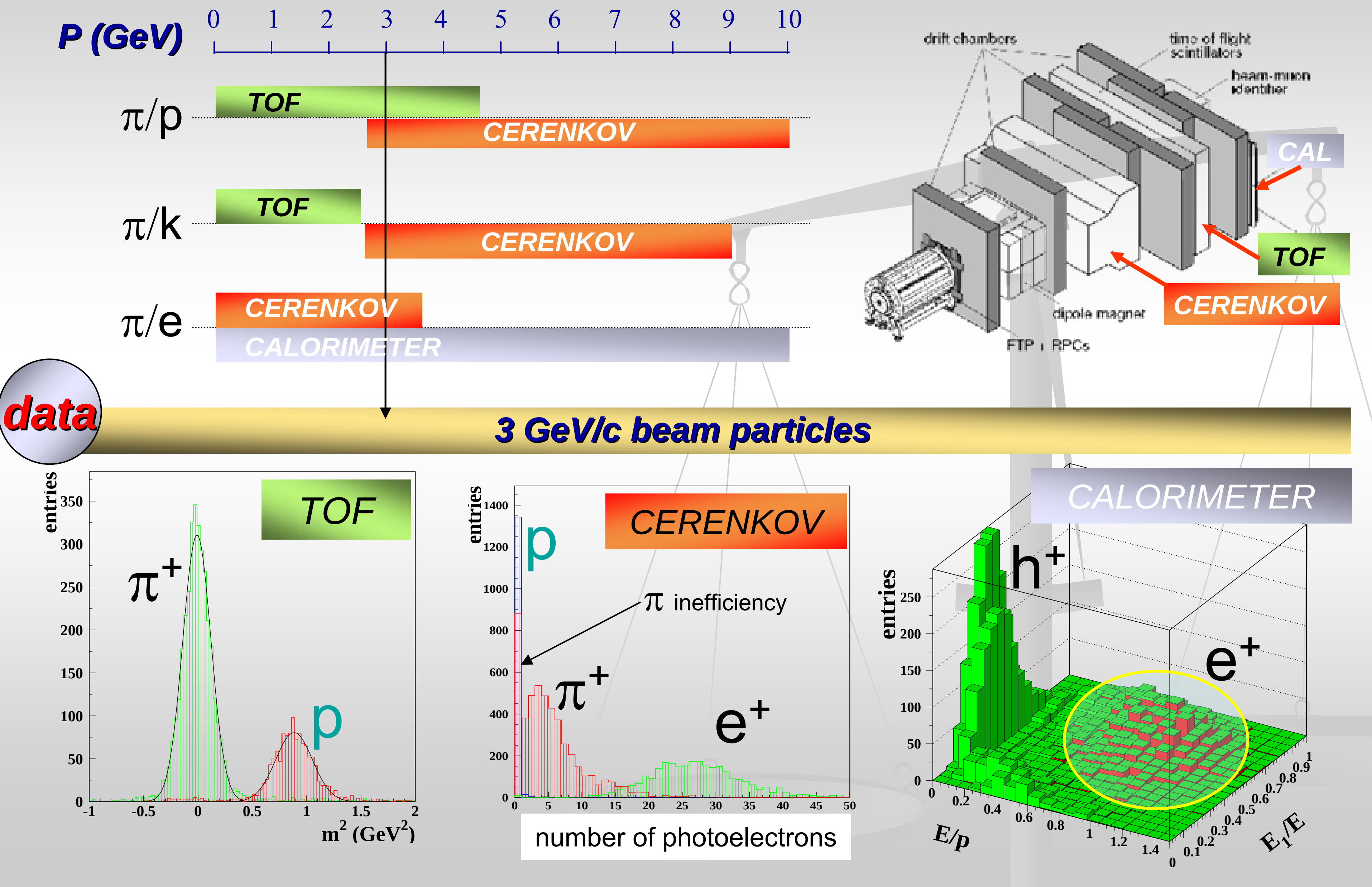
Tracking Efficiency



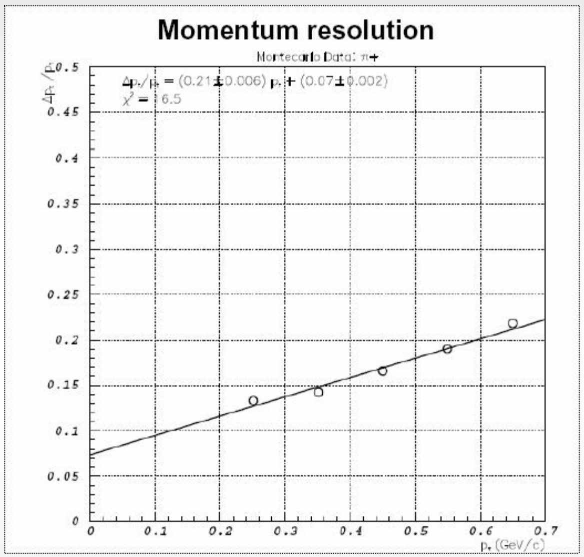
Tracking Resolution



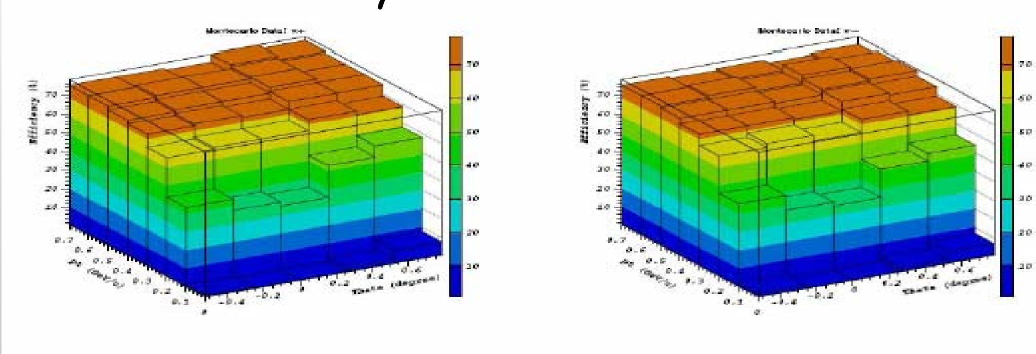
PId FW region:

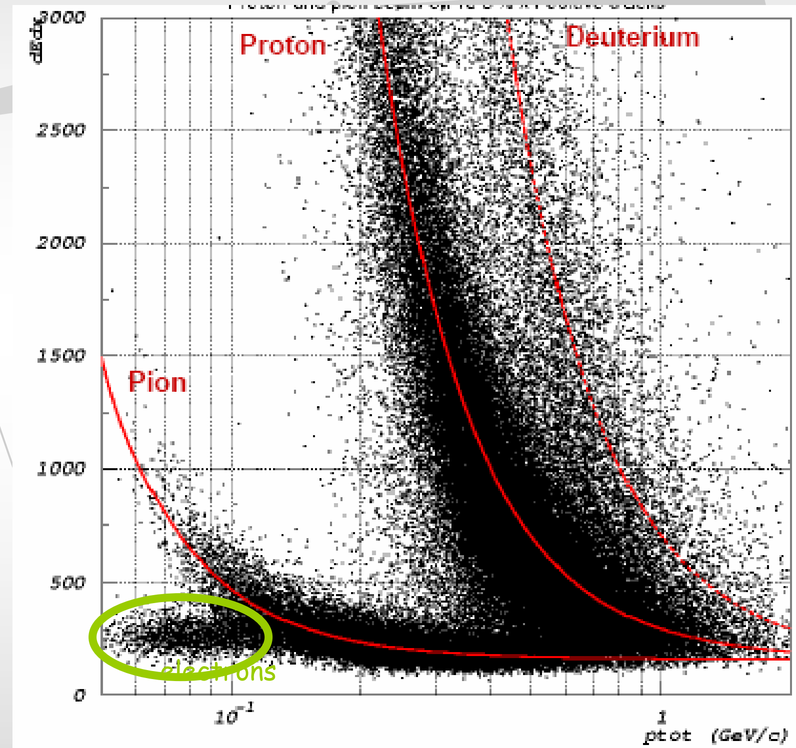


Large Angle Region (TPC)



π+π- efficiency





dE/dx: Ta data 3,5,8 GeV/c

Al 12.9 GeV/c: Comparison with older data