HARP
Hadron production experiments for neutrino physics

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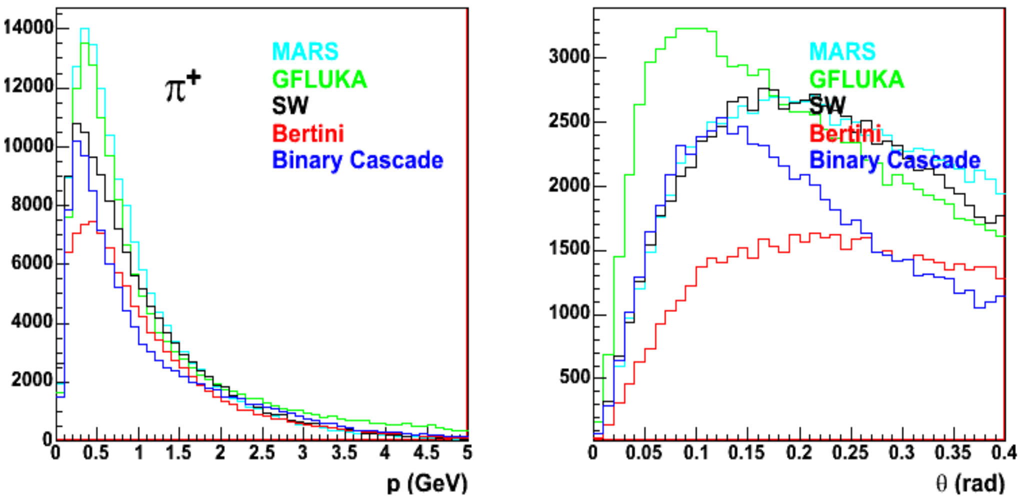
Hadron production for neutrino experiments:

- Neutrino fluxes in conventional beams
- Prediction of atmospheric neutrino flux
- Neutrino factory design
- Hadronic interaction generators

HARP measurements
- p-Al (K2K)
- p-Be (MiniBooNE)
- p-Ta (neutrino factory)
- p-C (atmospheric neutrinos)

Outlook
- MIPP
- NA49

Hadron yields for neutrino beams



Different generators applied to MiniBooNE beam

New measurements essential!

(Dave Schmitz -NBI05)

Past: single arm spectrometers

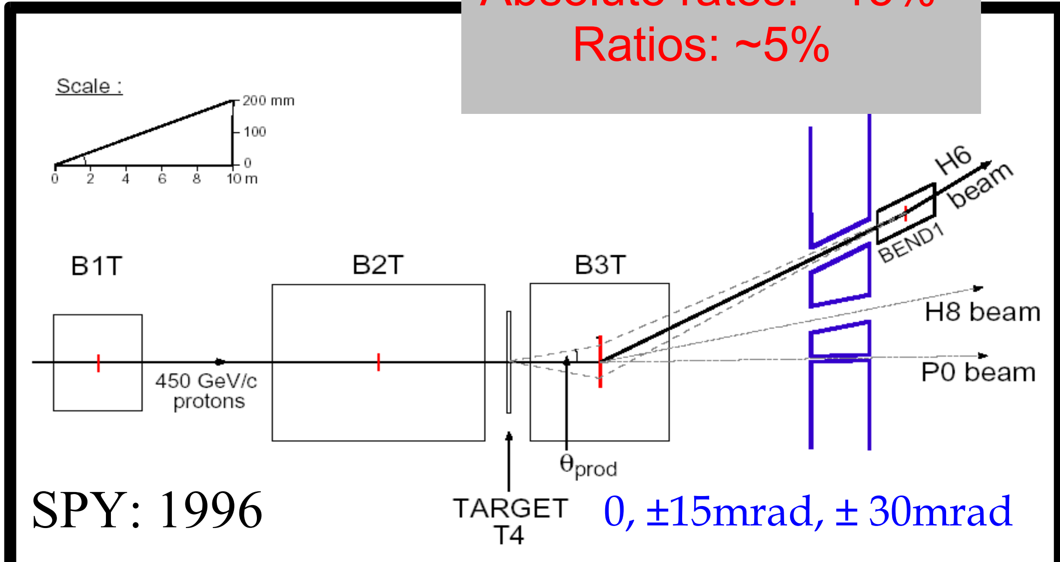
at CERN:

Eichten et al., Atherton et al., SPY

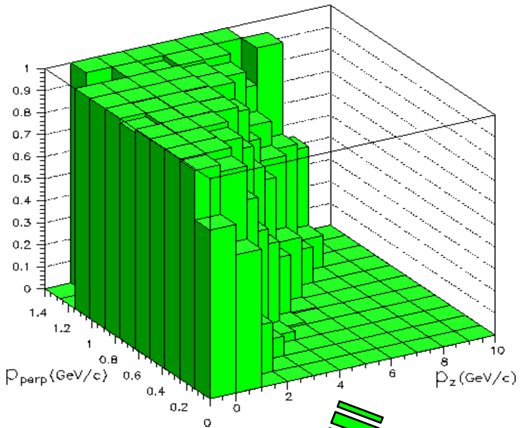
Present: Open geometry, heavy ion-like experiments

BNL-E910, HARP, NA49, MIPP

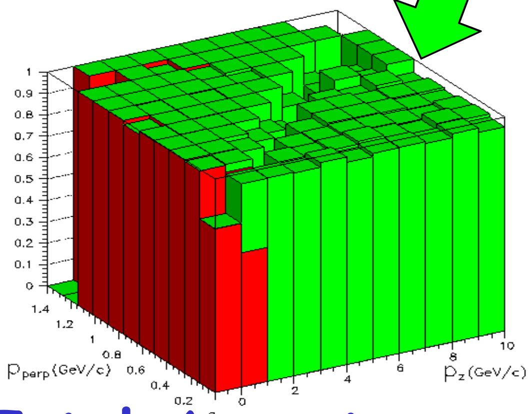
Typical errors
Absolute rates: ~15%
Ratios: ~5%



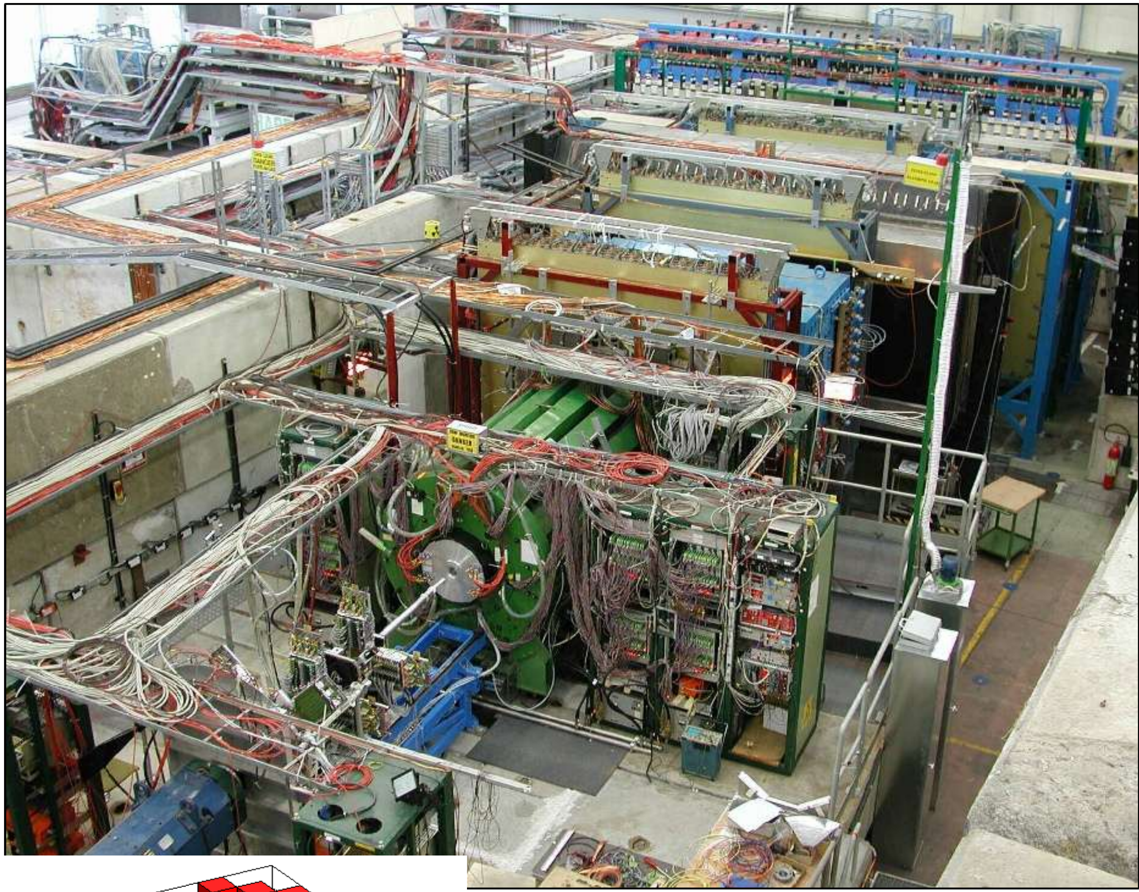
The HARP experiment

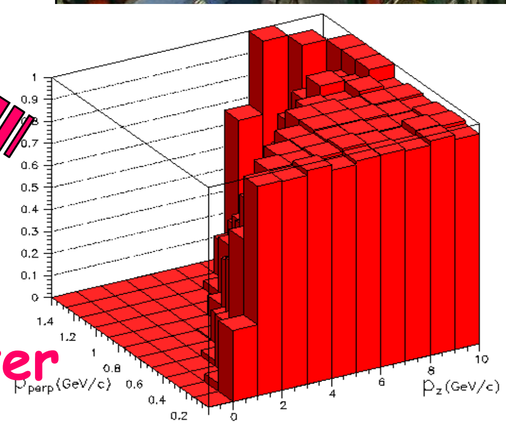


TPC



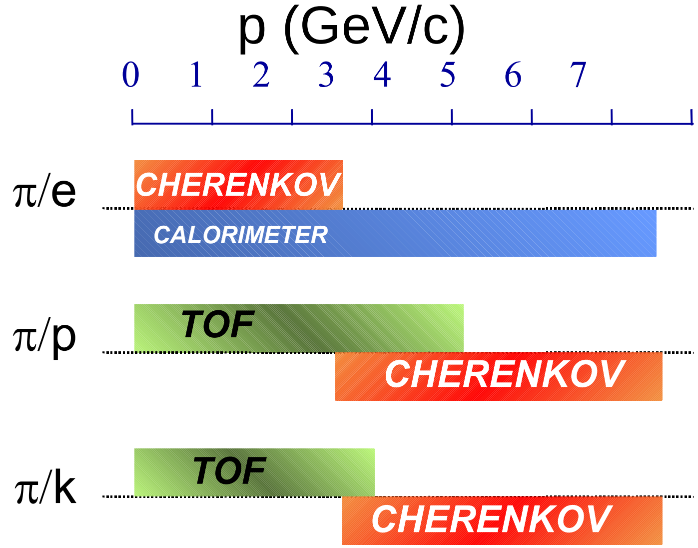
Total Acceptance

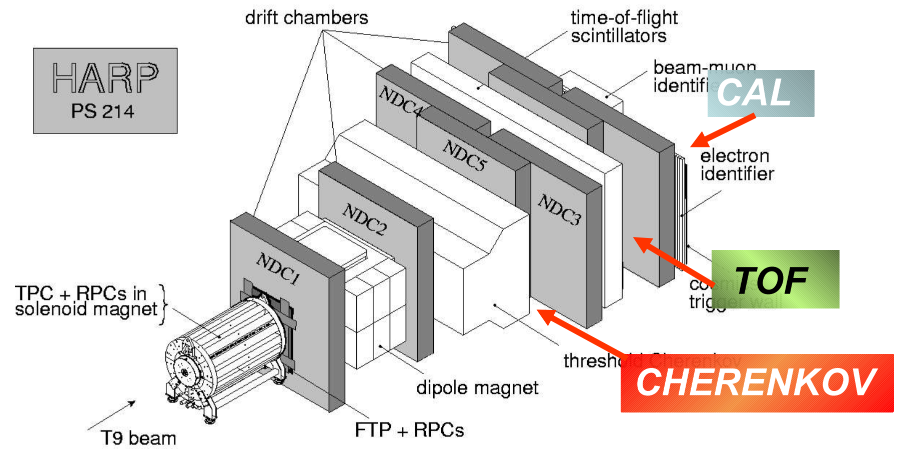




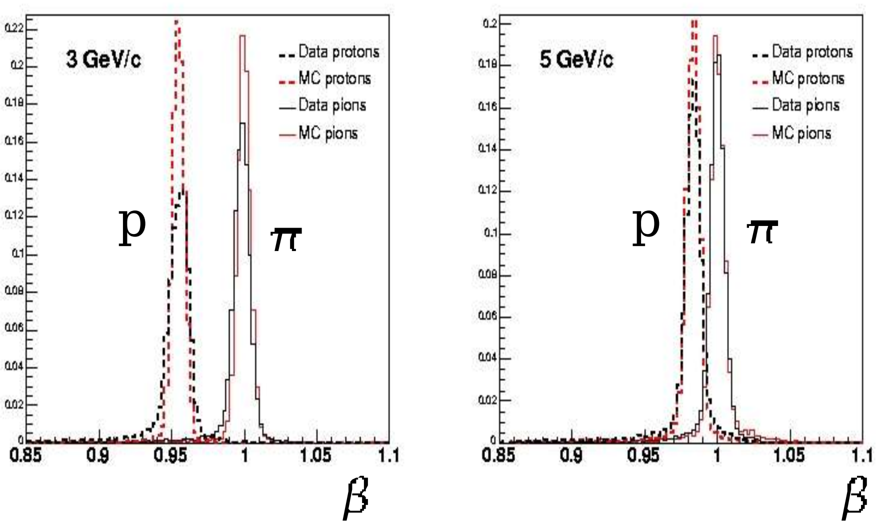
Forward Spectrometer

Pion Id. (forward spectrometer)





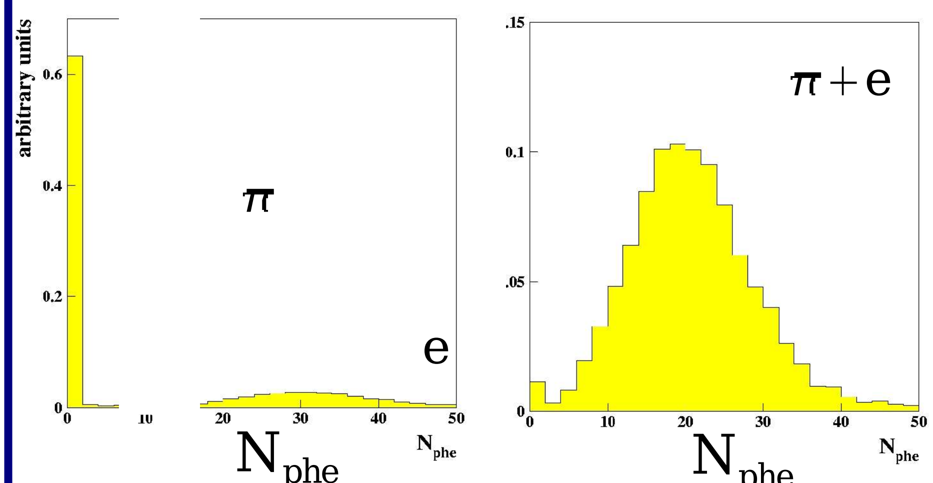
TOF pi/p response for beam particles



Cherenkov pi/e response for negative particles

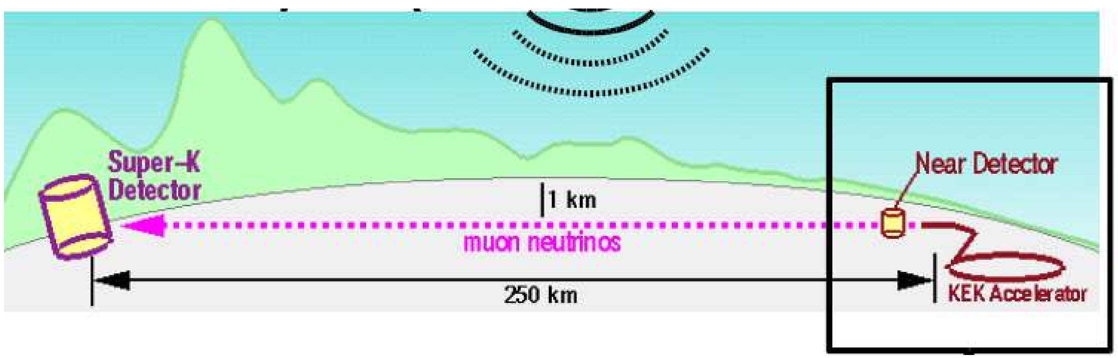
Below pion threshold

Above pion threshold

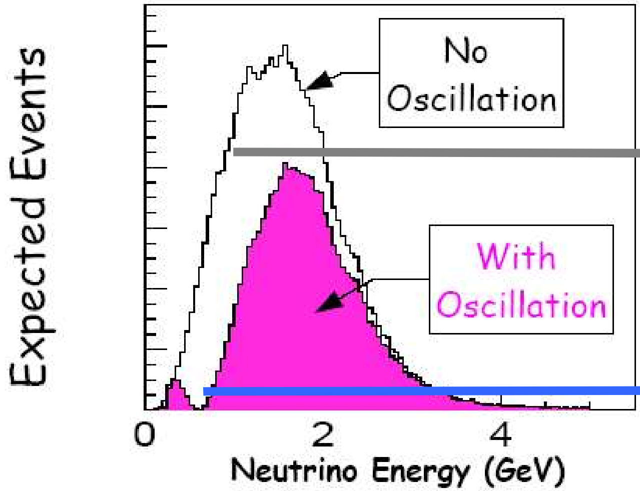


HARP measurement for K2K beam

K2K: Disappearance experiment to confirm atmospheric oscillation



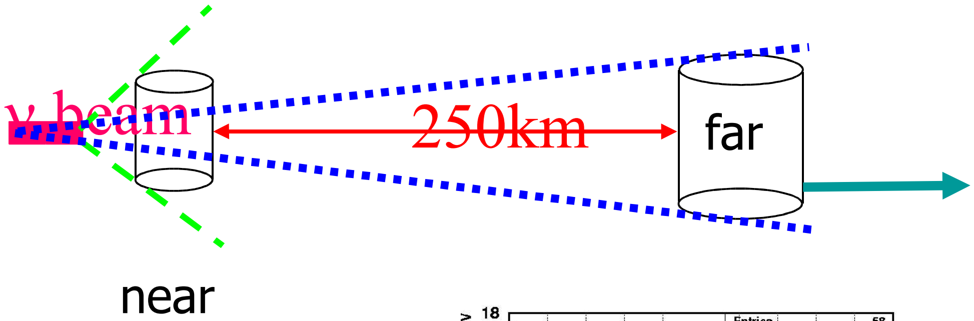
Oscillation probability at 250 km from the source for atmospheric parameters: maximum effect at ~1GeV



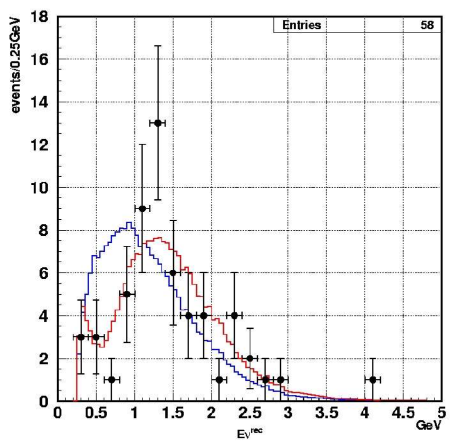
Non-oscillated spectrum must be measured near the neutrino source

oscillations: energy-dependent suppression of the spectrum

Far-Near flux ratio



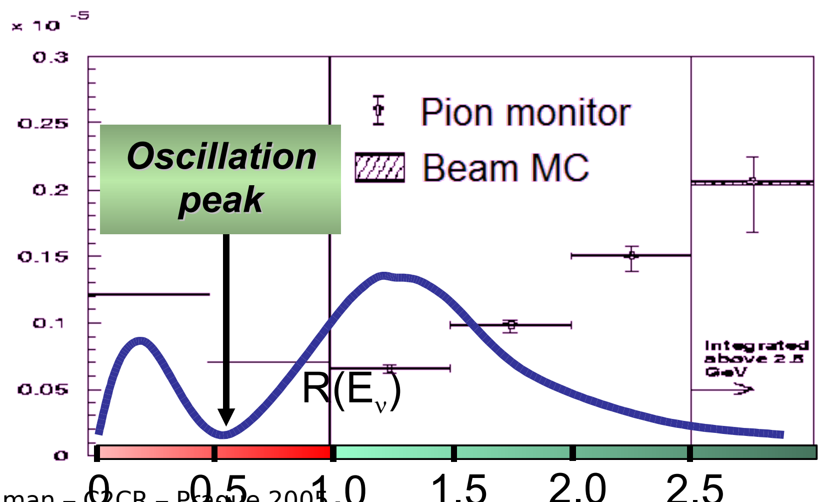
For a point-like source the flux, in the absence of oscillations scales like $1/R^2$



If the near detector does not see a point-like source it is necessary to multiply by a factor **$R(E_\nu)$** to obtain the predicted spectrum in the far detector.

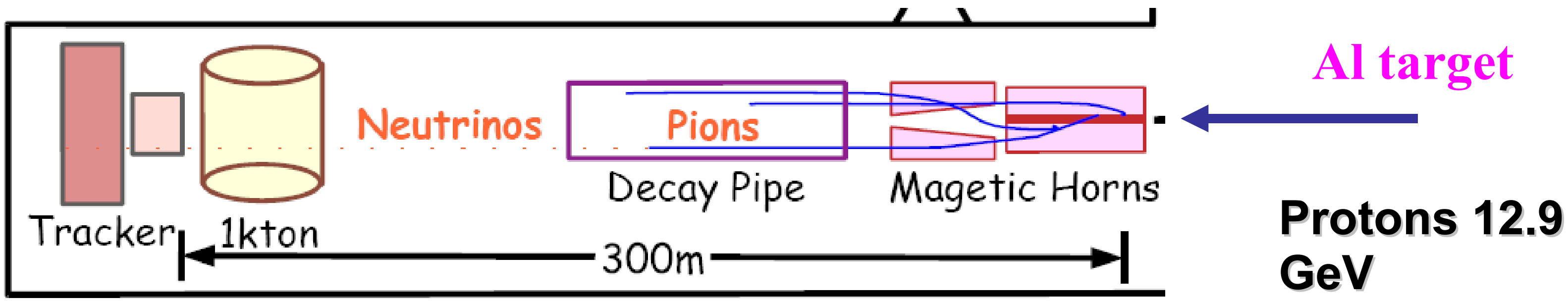
ν_μ flux: 99% from π^+ decay

$$\Phi(E_\nu)^{far} = R(E_\nu)\,\Phi(E_\nu)^{near}$$



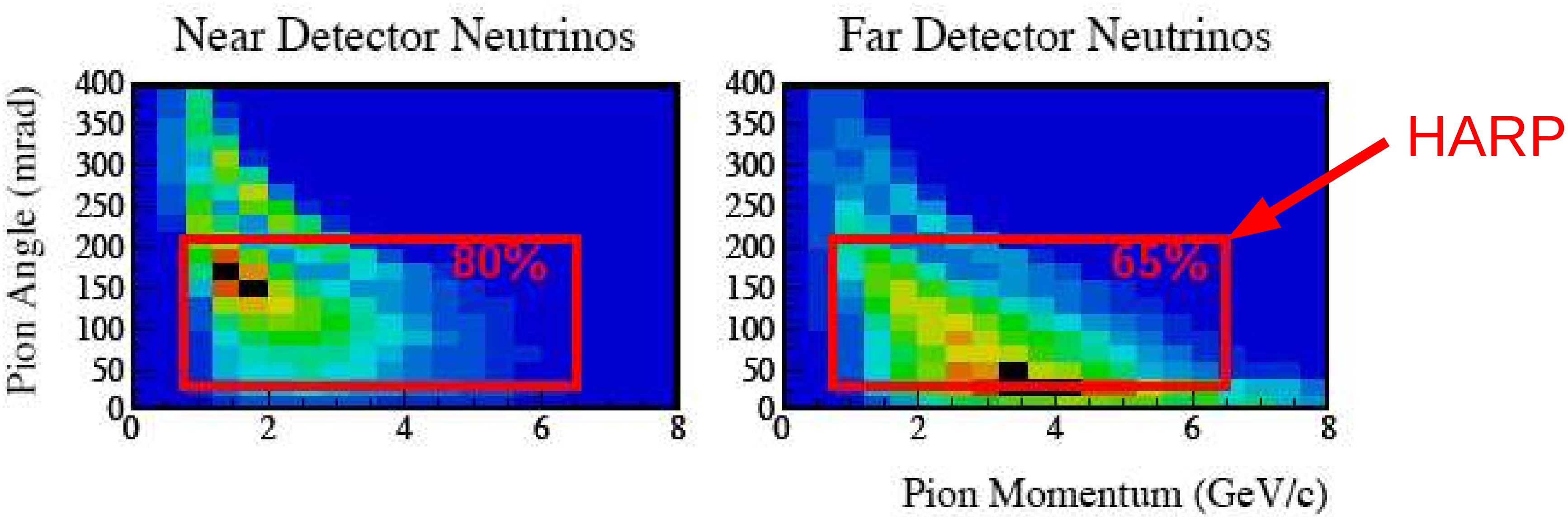
The determination of $R(E_\nu)$ is essential since the signal is a distortion of the energy spectrum (a wrongly determined $R(E_\nu)$ could "distort" oscillations)

HARP measurement for K2K



Protons 12.9 GeV

- Good coverage of phase space of relevance to K2K flux predictions:



Data taken with the parameters of the K2K beam **(p-Al at 12.9 GeV/c)**

("thin" 5% target)

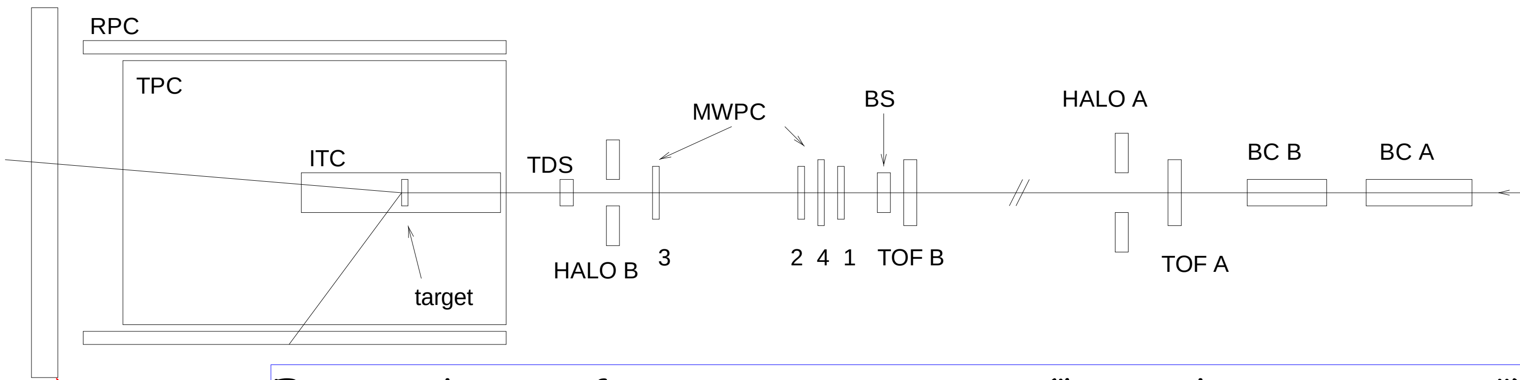
Cross-Section calculation

$$\frac{d^2\sigma^{\pi}}{dp\,d\Omega} \propto \frac{\Delta^2 N^{\pi}}{\Delta p\,\Delta\Omega}\;\frac{\text{correction factors}(p,\theta)}{N_{pot}}$$

CORRECTIONS:

Track reconstruction efficiency	**~ ☝ 10 % (Data)**
Geometrical correction	**~ ☝ 50-80% (Analytical)**
Absorption/decay in upstream detector	**~ ☝ 15 % (MC)**
Spectrometer acceptance	**~ ☝ 10-25 % (MC)**
Tertiary production in upstream materials	**~ ☟ 5 % (MC)**
Electron veto efficiency correction	**~ ☝ 5 % (Data)**
Kaon subtraction	**~ ☟ 1-3 % (Data)**
PID π efficiency	**~ ☝ < 5% (Data)**
PID p-π migration	**~ ☟ < 5% (Data)**

Event Selection



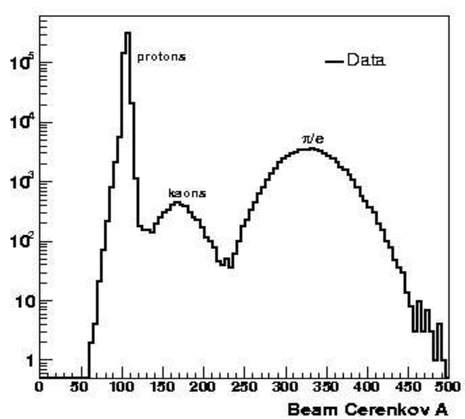
Event selection for **protons on target** (“normalization trigger”):

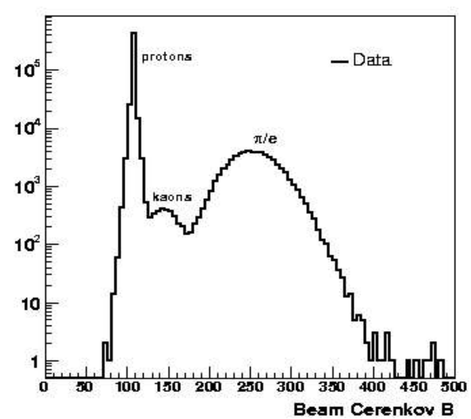
impact point and direction of primaries (BS, TDS, HALO A, HALO B)

protons: identified by TOF and Cherenkovs (TOF A, TOF B, BC A, BC B)

Event selection for proton **inelastic interactions** (“physics trigger”):

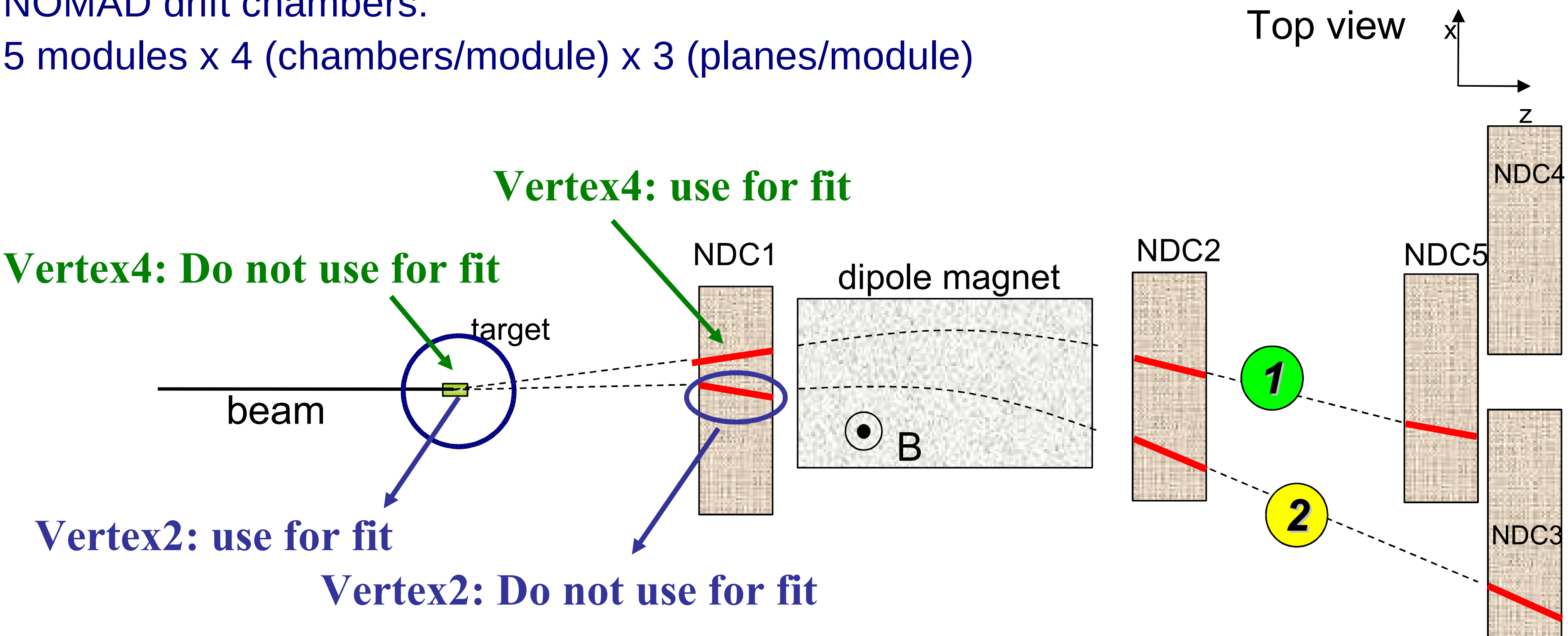
normalization trigger && forward trigger scintillator plane (FTP)





Track Reconstruction

NOMAD drift chambers:
5 modules x 4 (chambers/module) x 3 (planes/module)



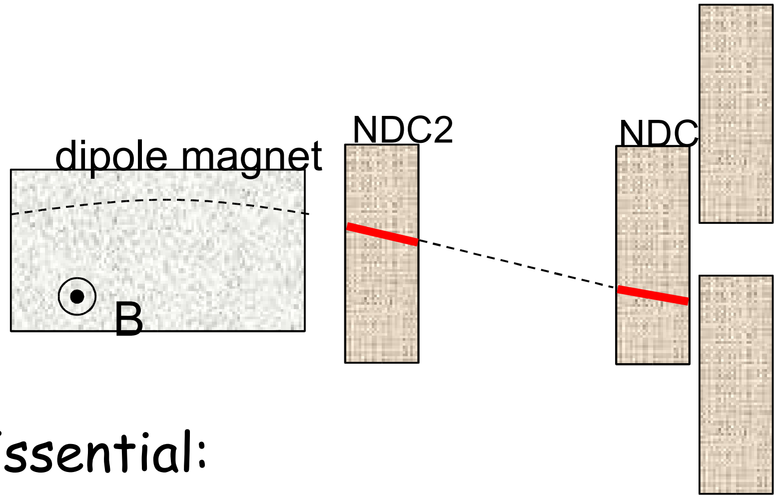
Two independent ways to reconstruct tracks:

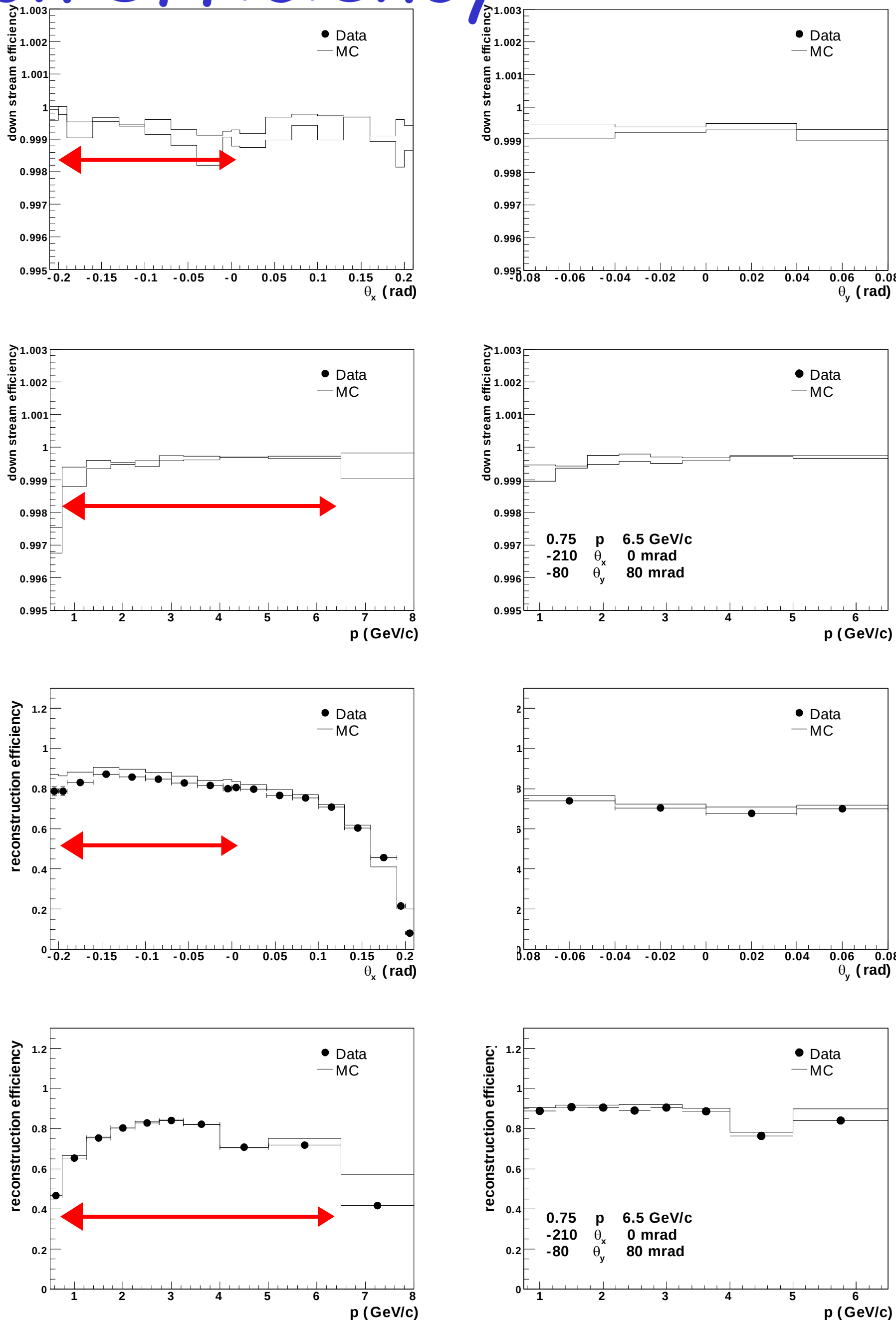
Vertex2 tracks: 3D track segment **downstream**, plus vertex match
used to measure pion yield

Vertex4 tracks: 3D track segment **downstream**, plus 3D segment in NDC1
used to measure track reconstruction efficiency in data

Number of reconstructed tracks in analysis: 210,000

Reconstruction efficiency





Essential:

downstream efficiency nearly 100%

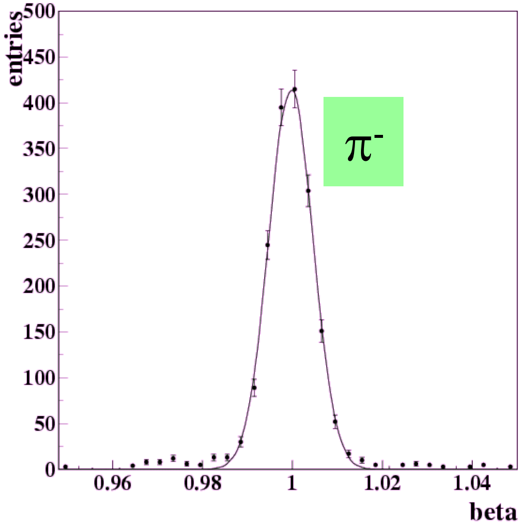
overall efficiency nearly constant and ~90% (in used phase space)

conditions:

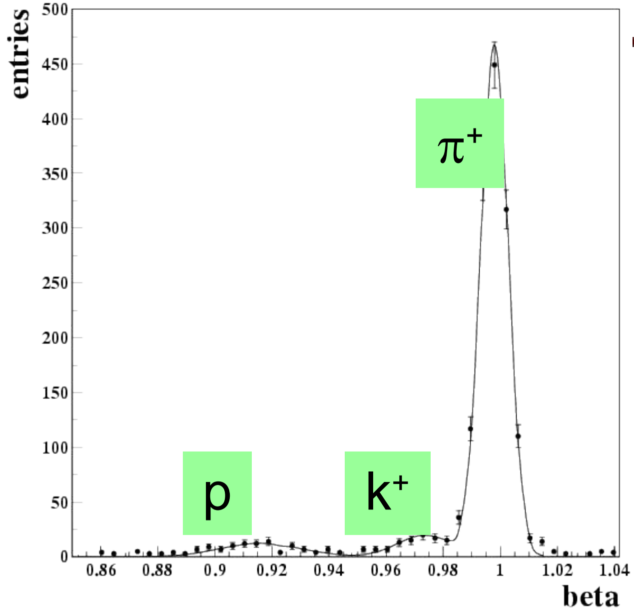
- Match downstream with vertex
- TOF measurement

Detector response measured from data

99% pions in a sample of negative particles with e-veto



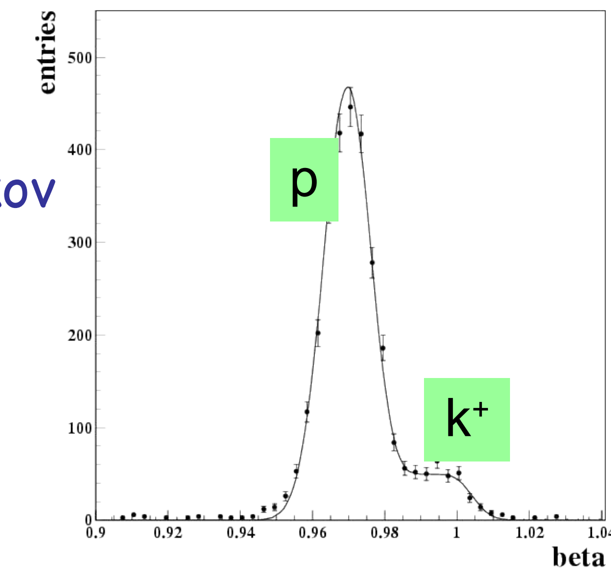
π^+ and π^- have the same behaviour



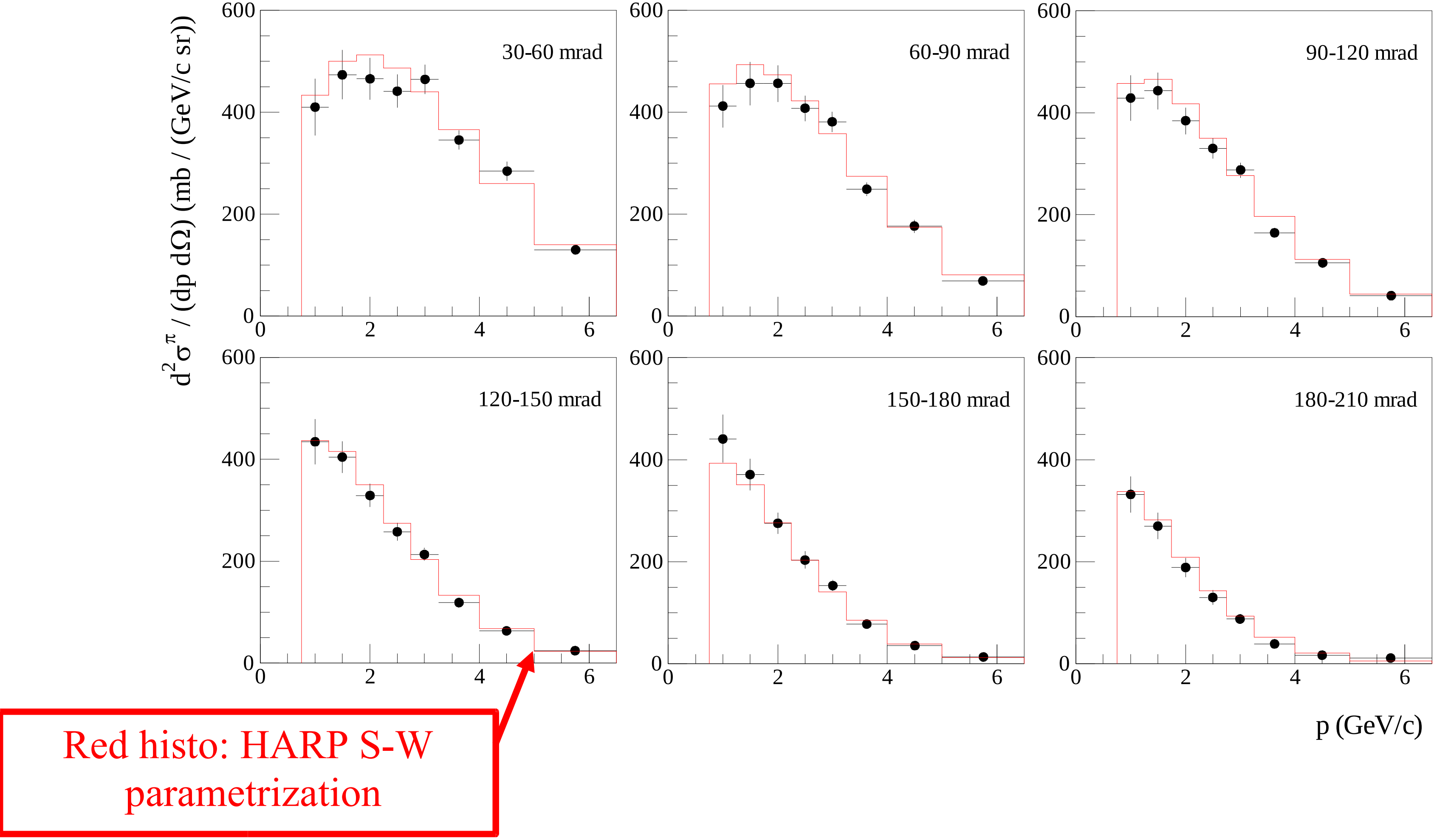
- π/p/k are clearly separated by the TOFW below 3 GeV

Fit the inclusive beta distribution to a triple Gaussian with fixed shapes and free normalization

- Above pion Cherenkov threshold pions are suppressed to less than 1% by N_{phe}<3



HARP Results (p-Al at 12.9 GeV/c)



HARP results in black, parametrization of HARP results in red

Error Evaluation

systematic error evaluation performed,
to quantify errors on:

$d^2\sigma^\pi/(dp d\Omega)\ (p,\theta)$

Typical error: 8.2%

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

Error on total cross-section: 5.8%

Error Category	Error Source	δ_{diff} (%)	δ_{int} (%)
Statistical	Al target statistics	1.6	0.3
	Empty target subtraction (stat.)	1.3	0.2
	Sub-total	**2.1**	**0.4**
Track yield corrections	Reconstruction efficiency	0.8	0.4
	Pion, proton absorption	2.4	2.6
	Tertiary subtraction	3.2	2.9
	Empty target subtraction (syst.)	1.2	1.1
	Sub-total	**4.5**	**4.1**
Particle identification	PID Probability cut	0.2	0.2
	Kaon subtraction	0.3	0.1
	Electron veto	2.1	0.5
	Pion, proton ID correction	2.5	0.4
	Sub-total	**3.5**	**0.7**
Momentum reconstruction	Momentum scale	3.0	0.3
	Momentum resolution	0.6	0.6
	Sub-total	**3.2**	**0.7**
Overall normalization	**Sub-total**	**4.0**	**4.0**
All	**Total**	**8.2**	**5.8**

Dominant error contributions:

- Overall normalization
- Tertiary subtraction
- 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 (similar beam momentum, phase space)

Comparing HARP With Previous Results

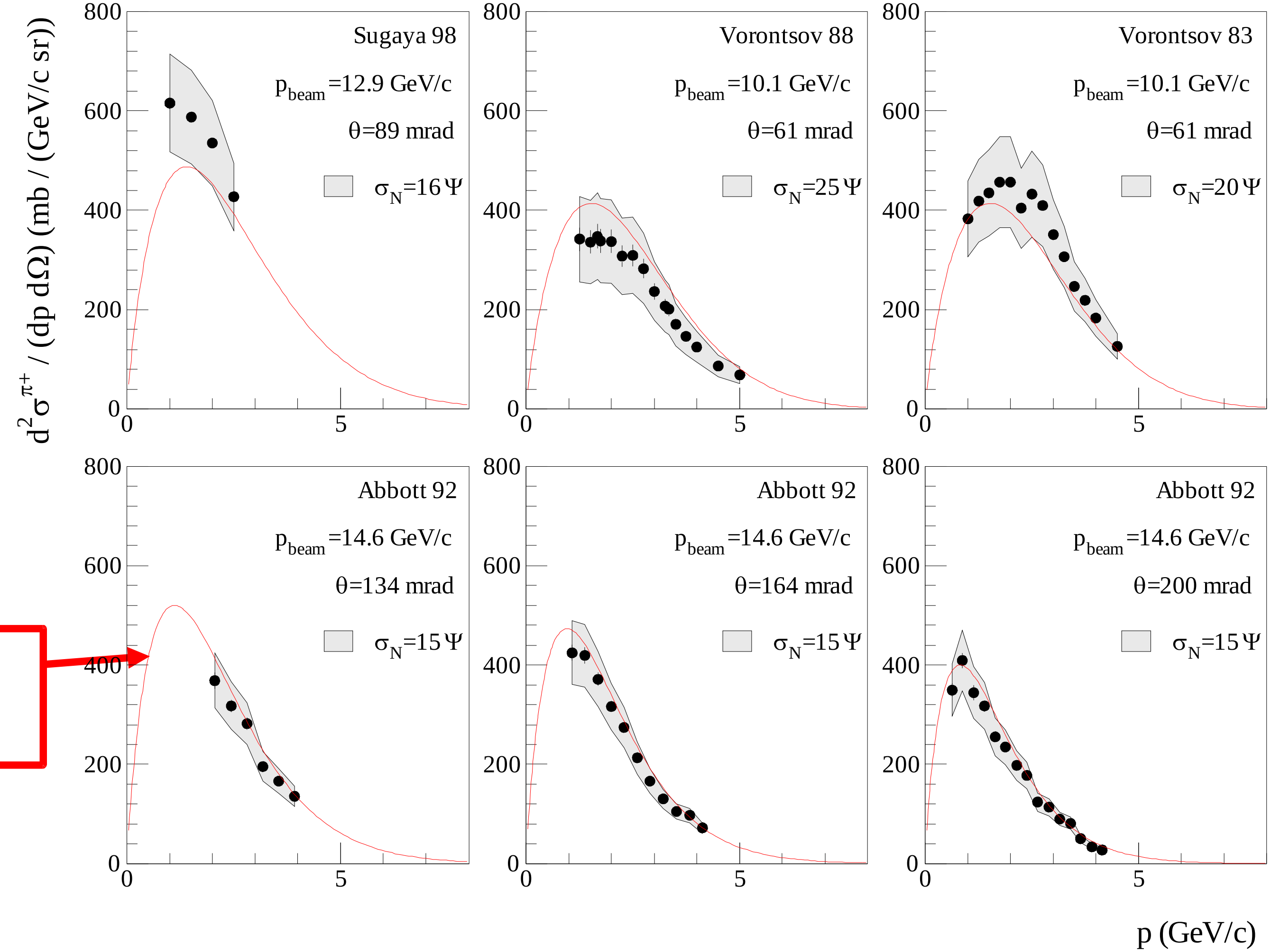
Reasonable agreement between HARP and previous results on $p + Al \rightarrow \pi^{+} + X$

Restrict comparison to:

Proton beam momentum between 10 and 15 GeV/c,

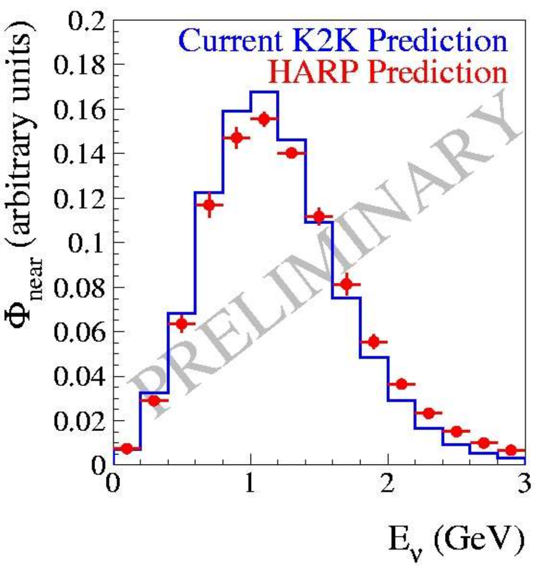
Forward pion production (<200 mrad).

Red curve: HARP S-W parametrization

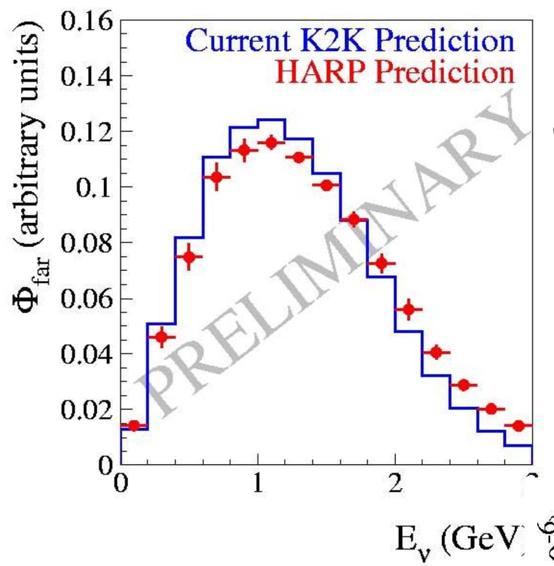


K2K Neutrino Flux Predictions

Relatively Norm. Near Flux

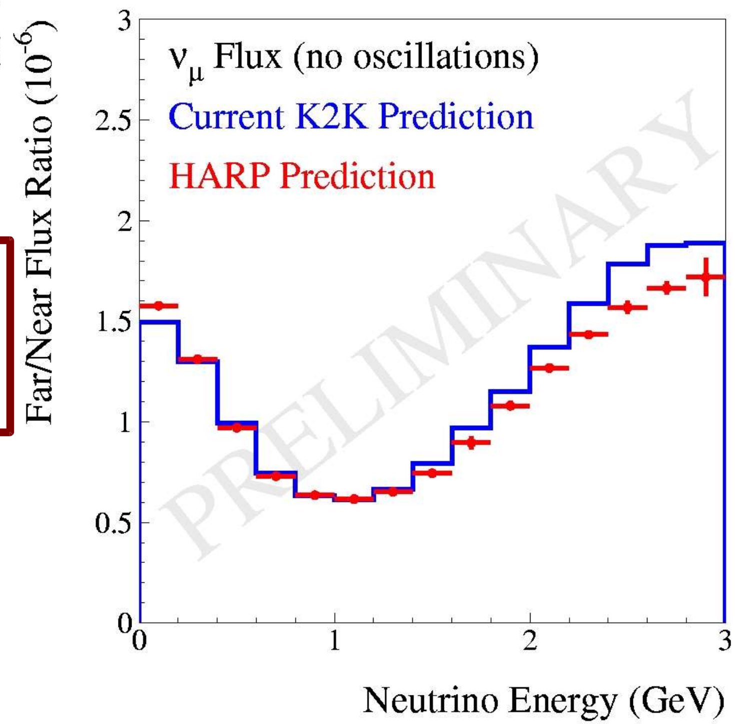


Relatively Norm. Far Flux



Similar neutrino energy shapes arising from K2K default and HARP pion production assumptions in K2K beam MC

Far/Near ratio



Neglecting neutrino cross-sections, efficiencies, etc.:

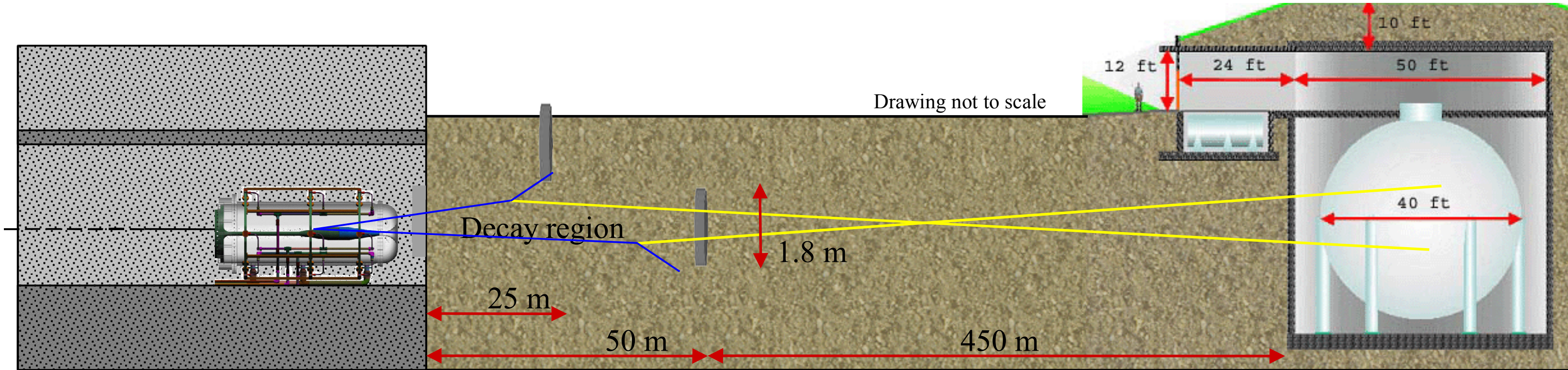
$$(F/N)_{\mathrm{K2K\,default}} = 0.8264 \cdot 10^{-6}$$
$$(F/N)_{\mathrm{HARP}} = 0.8246 \cdot 10^{-6} \quad (-2‰)$$

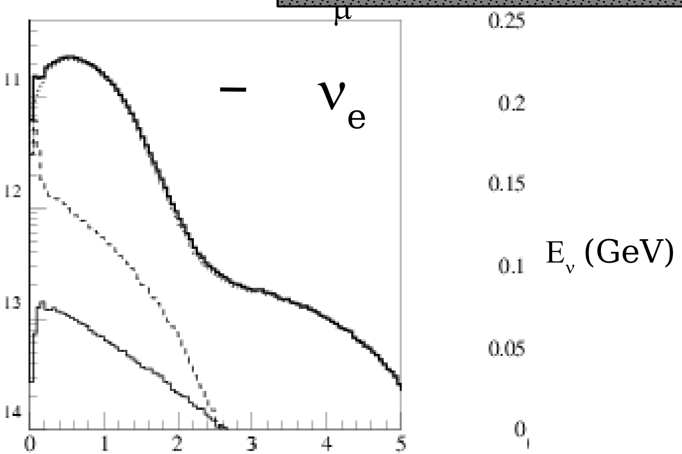
HARP pion production uncertainty:

<1% error on overall F/N flux ratio

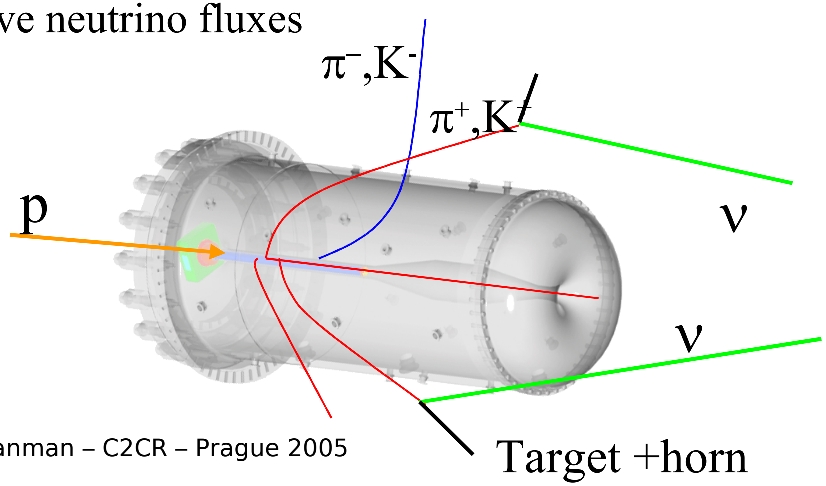
(but there are more error sources)

MiniBooNE Neutrino Beam





Relative neutrino fluxes



$$\pi^+ \to \mu^+ + \nu_\mu$$

~90% of all ν flux

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$K^+ \to \pi^0 + e^+ + \nu_e$$

$$K^0 \to \pi^{\pm} + e^{\mp} + \bar{\nu}_e$$

ν_e ~0.6% of all ν's

$$K^+ \to \mu^+ + \nu_\mu$$

$$K^+ \to \pi^0 + \mu^+ + \nu_\mu$$

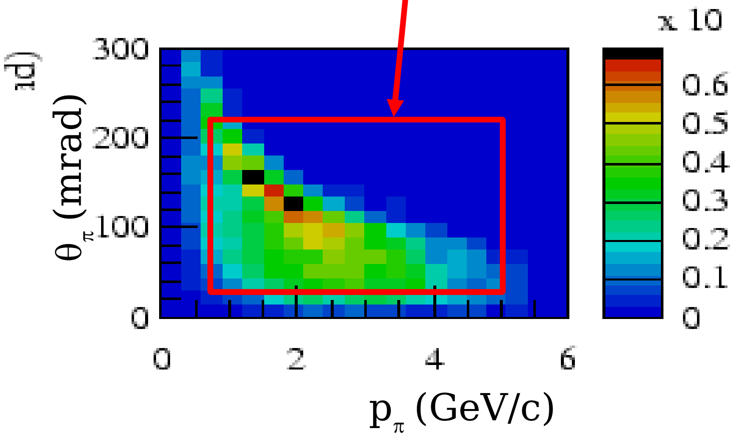
~3% of all ν's

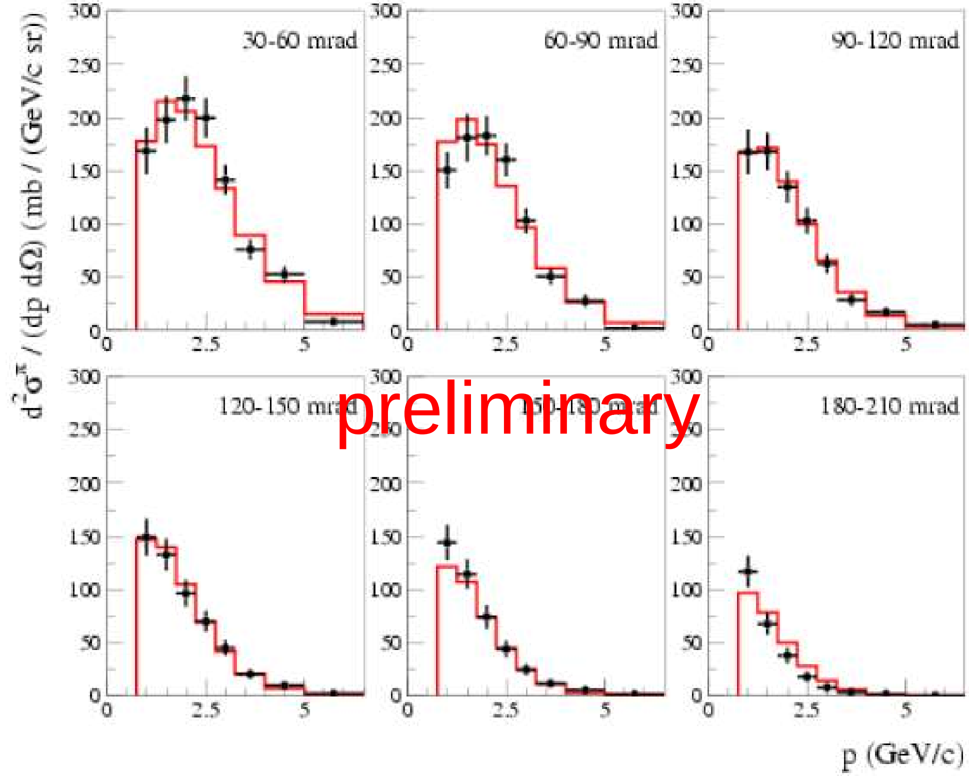
HARP Beryllium Thin Target Results

Preliminary double differential π^+ production cross sections from the Be 5% target are available

$0.75 < p_\pi < 5$ GeV/c

$30 < \theta_\pi < 210$ mrad



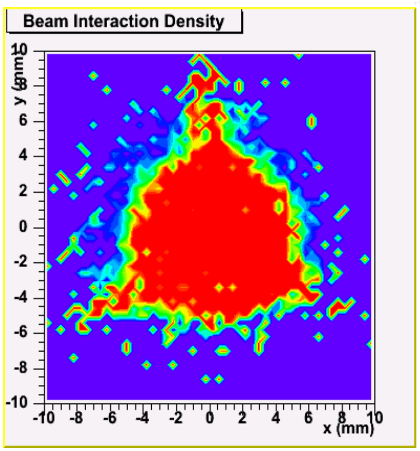


Momentum and Angular distribution of pions decaying to a neutrino that passes through the MB detector.

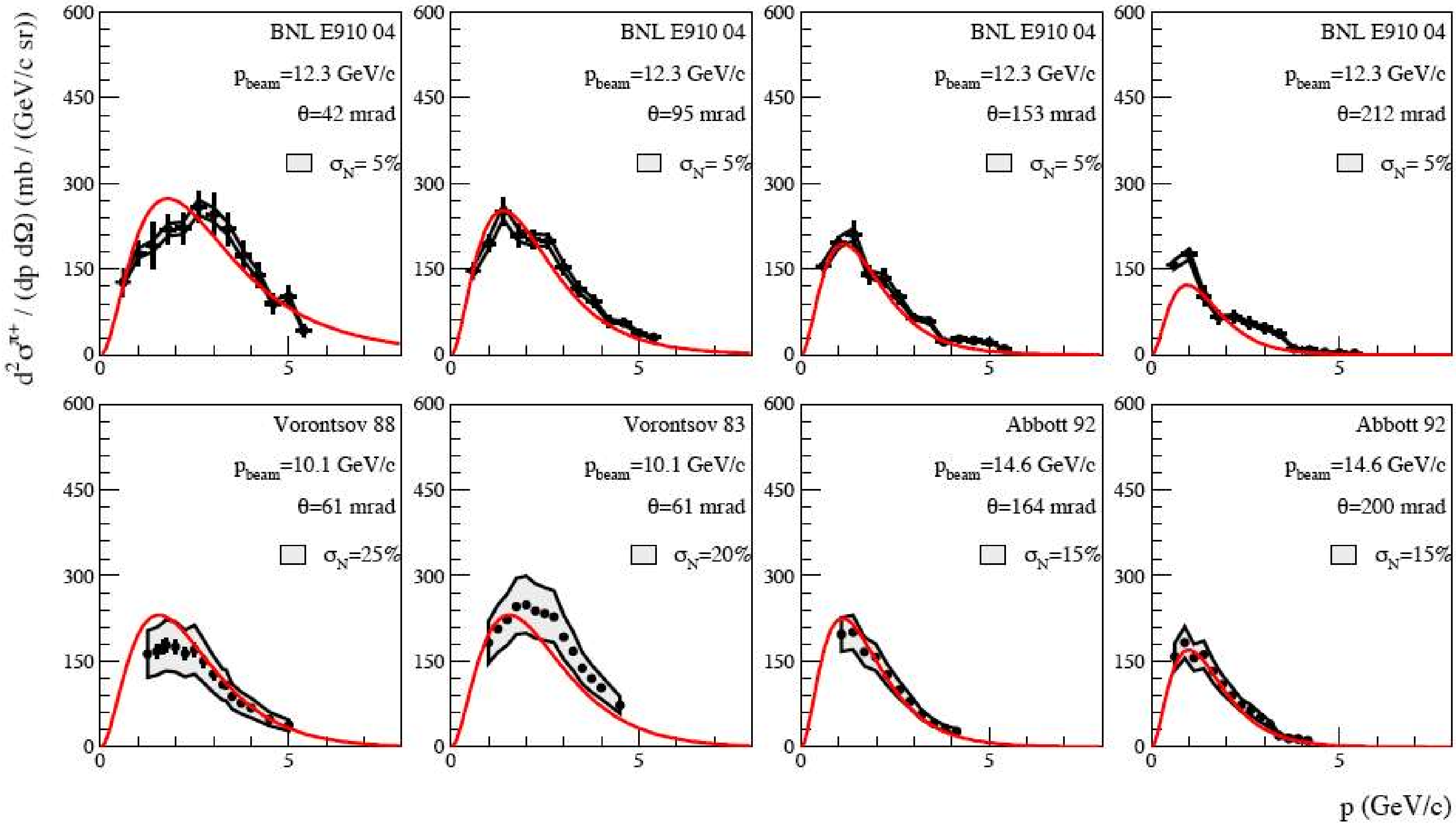
Data with target replica and

thick targets of different lengths

shape of target visible

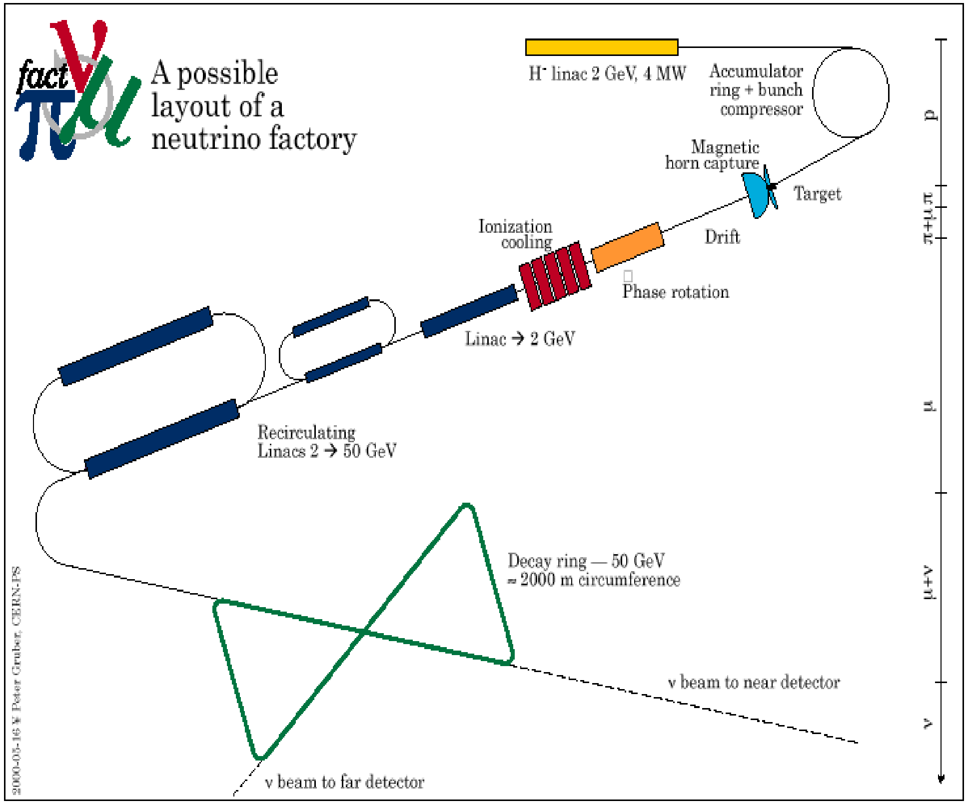


Comparison with older data: Be



Neutrino factory

maximize $\pi^{\pm}$ production rate



➢**Optimize:**

- target material and geometry
- primary beam energy
- collection scheme

➢Experimental data are poor (small acceptance, few materials) and old (Allaby et al.1970, Eichten et al. 1972)

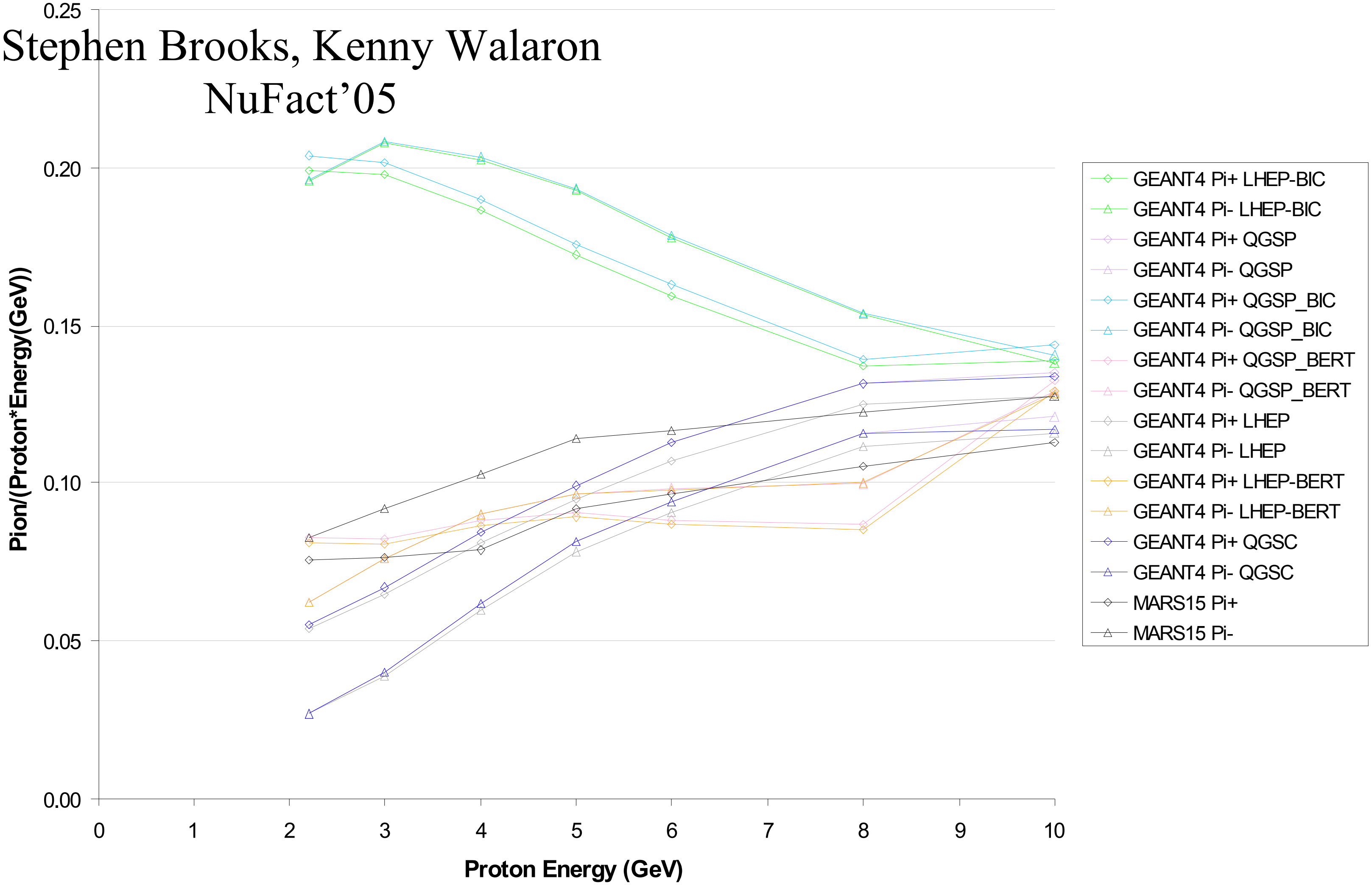
➢Existing simulation packages show large discrepancies on pion yields and distributions

Measure p_T distribution with high precision (<5%)

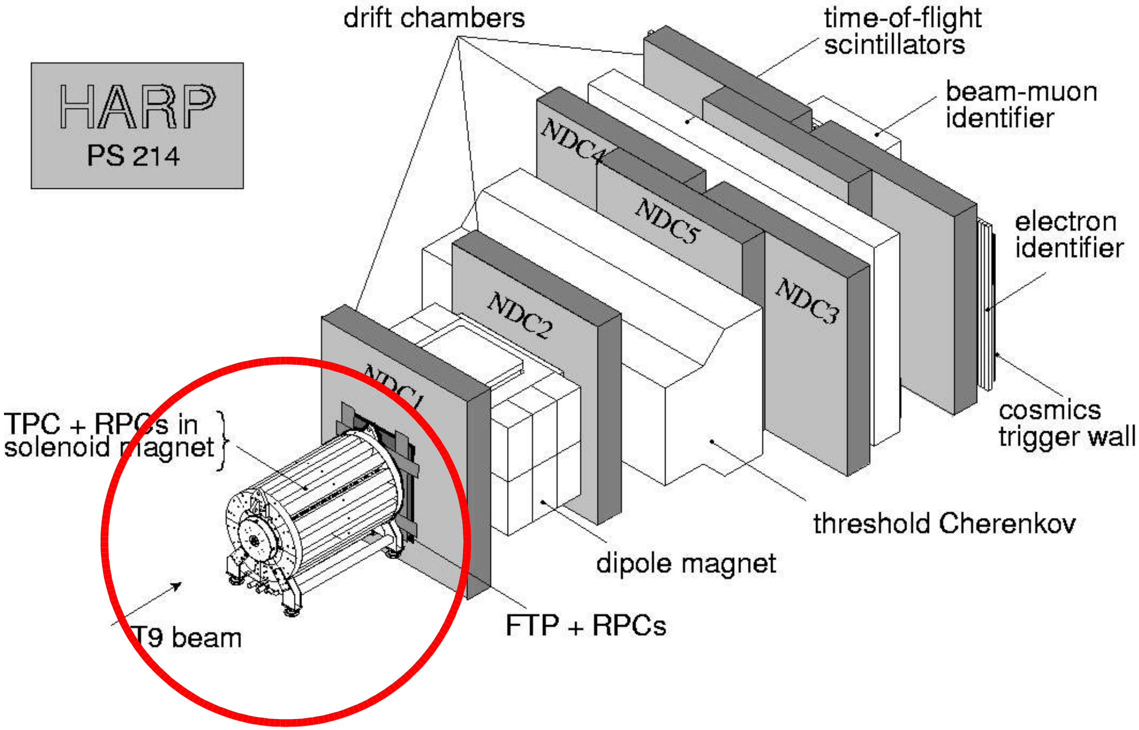
Why do we need measurements?

Total Yield of π^+ and π^-: +GEANT4

Stephen Brooks, Kenny Walaron
NuFact'05



HARP large angle analysis



Large angle detectors

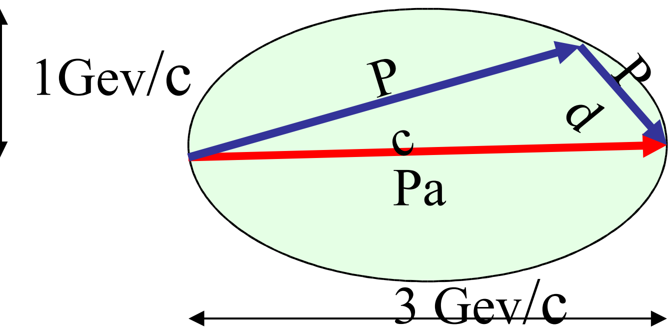
TPC

- Pattern recognition
- Momentum
- dE/dx

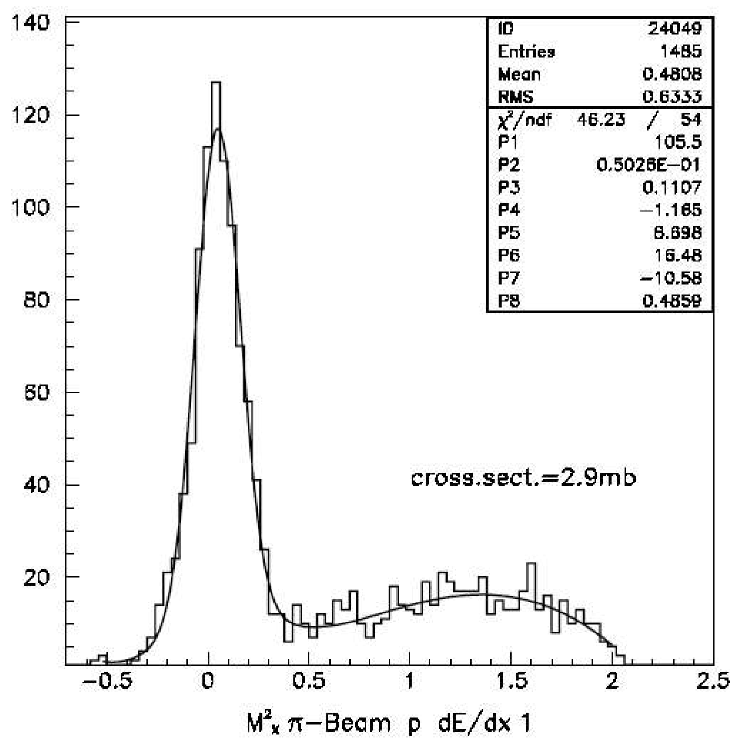
RPCs

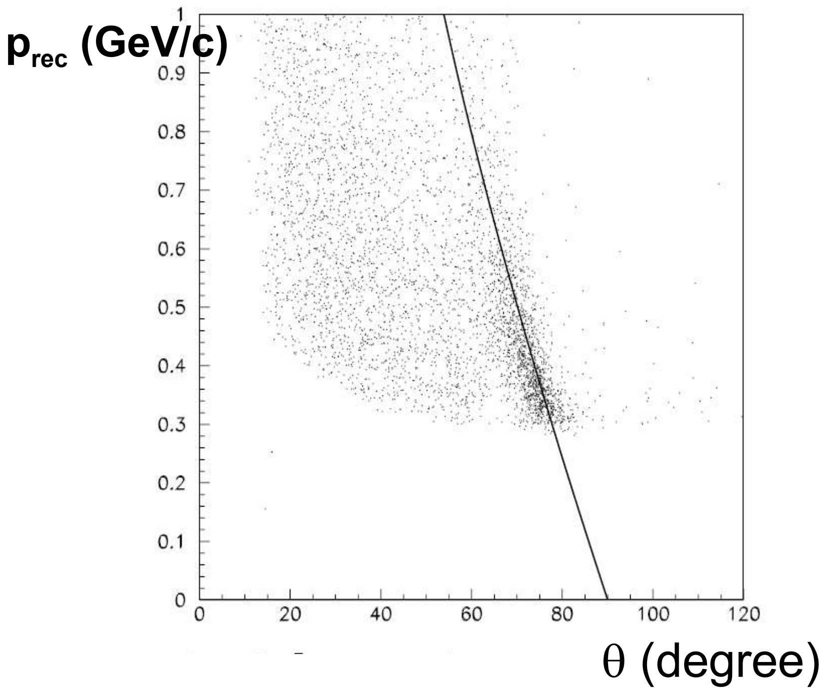
- TOF

Elastic scattering: TPC response

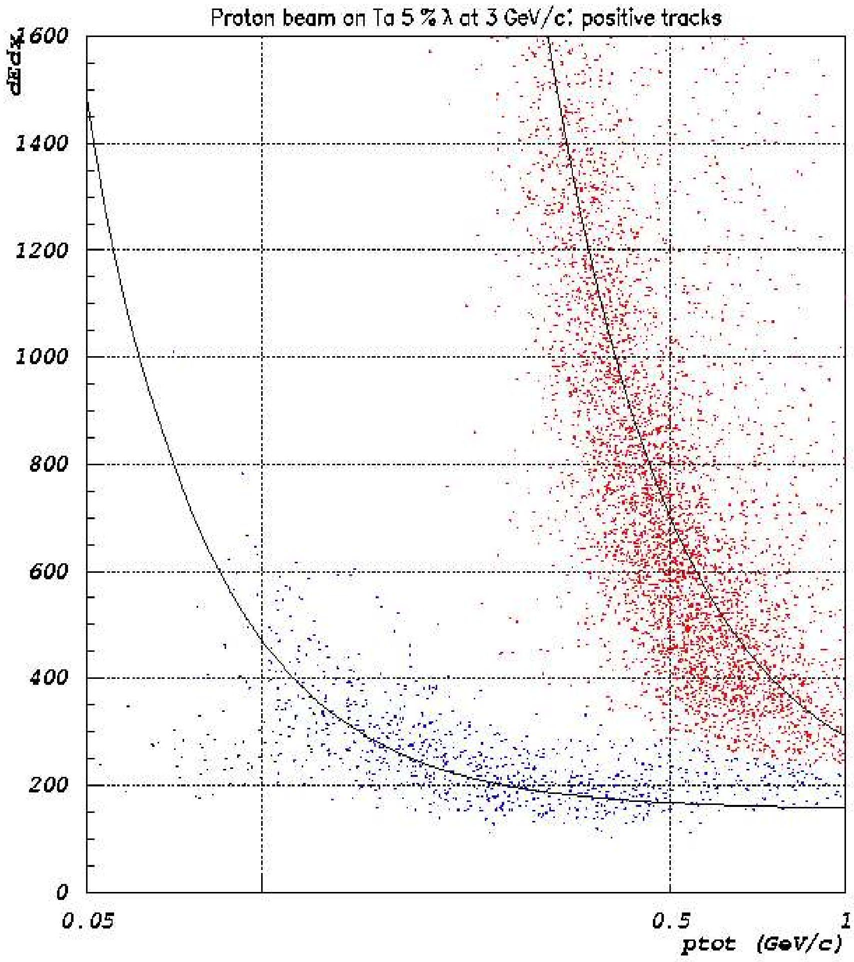


missing mass peak

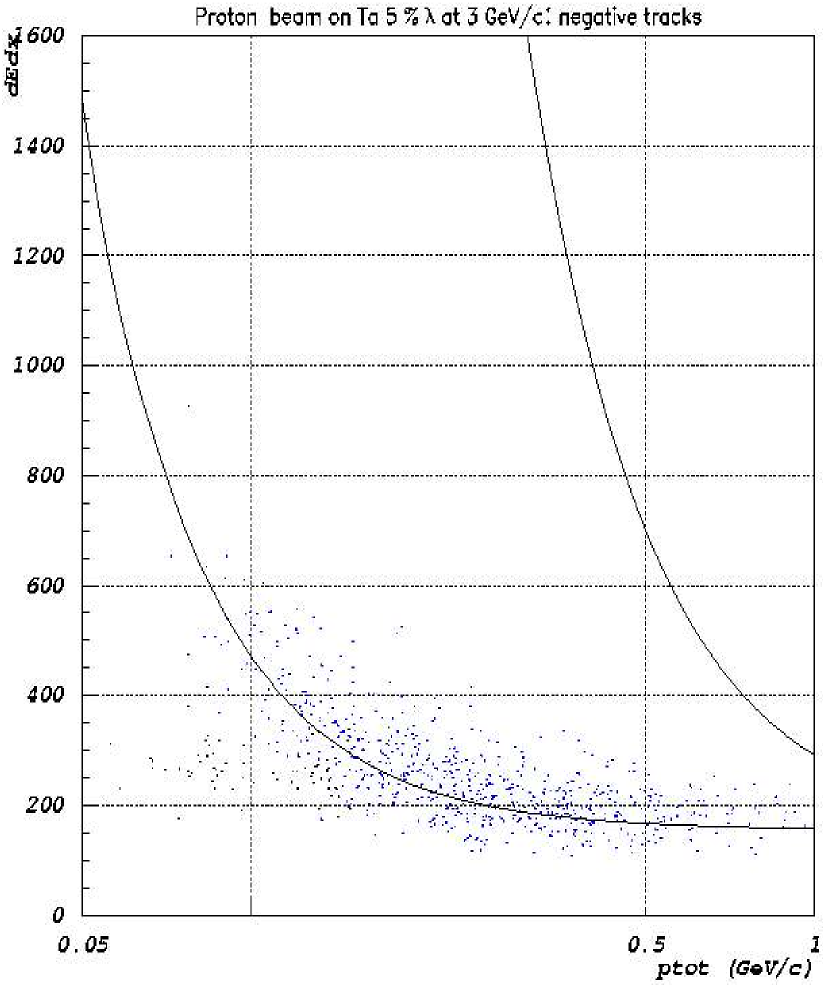




PID with dE/dx in TPC

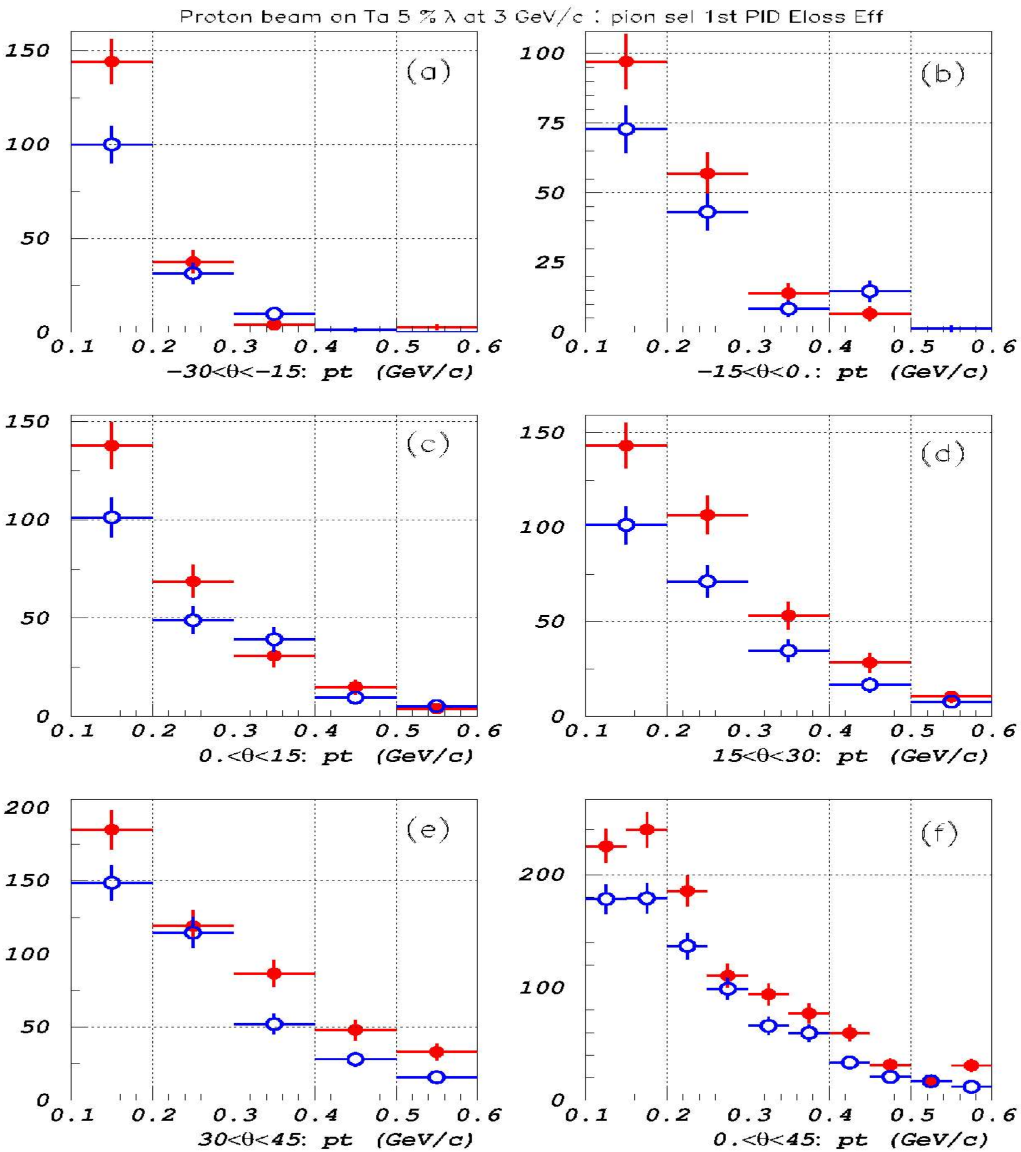


positives



negatives

Preliminary measurement of pion yields



3 GeV/c p-Ta data

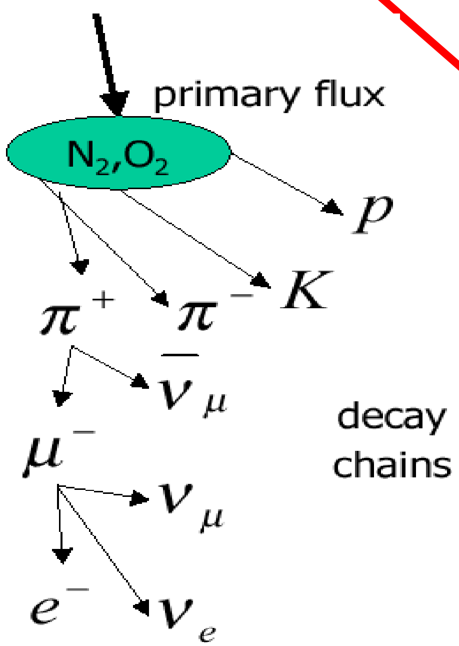
Backward production

π^+
π^-

Forward production

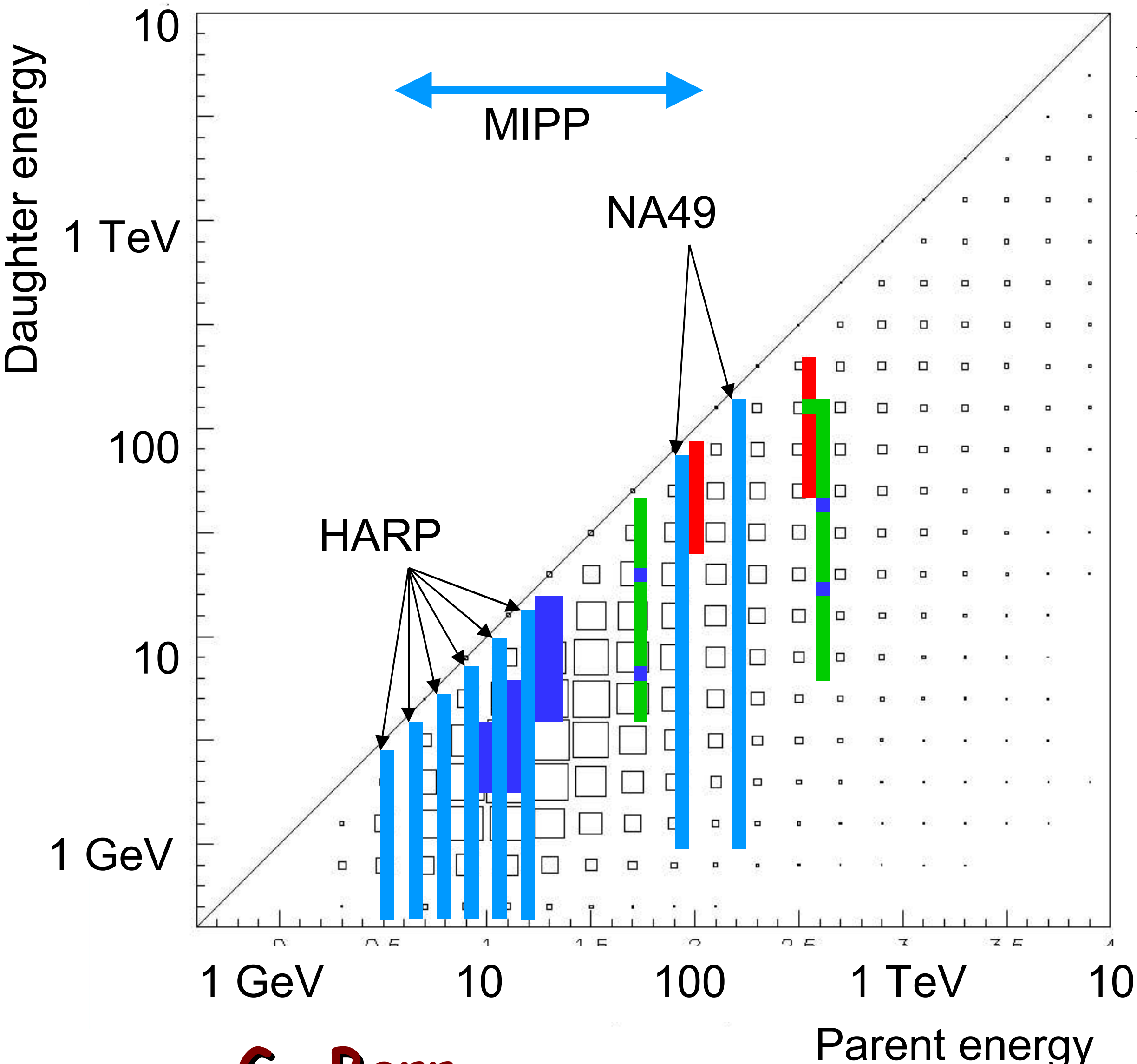
Hadron production for atmospheric neutrinos

- Input for precise calculation of the **atmospheric neutrino** flux (from yields of secondary π, K)
- Uncertainty now dominated by hadron interaction model
- About 30% uncertainty in extrapolations
- Cryogenic targets or **carbon**



	Target material	Target length (l%)	Beam Momentum (GeV)	#events (millions)
Solid targets	Be			
	C	2 (2001)	±3	
	Al		± 5	
	Cu	5	± 8	233.16
	Sn		± 12	
	Ta	100	± 15	
	Pb		Negative only 2% and 5%	
K2K	Al	5, 50, 100, replica	+12.9	15.27
MiniBooNE	Be		+8.9	22.56
Cu "button"	Cu		+12.9, +15	1.71
Cu "skew"	Cu	2	+12	1.69
Cryogenic targets	N_7	6 cm	±3	58.43
	O_8		± 5	
	D_1		± 8	
	H_1		± 12 ± 15	
	H_2	18 cm	±3, ±8, ±14.5	13.83
Water	H_2O	10, 100	+1.5, +8(10%)	9.6

Atmospheric neutrinos: range covered

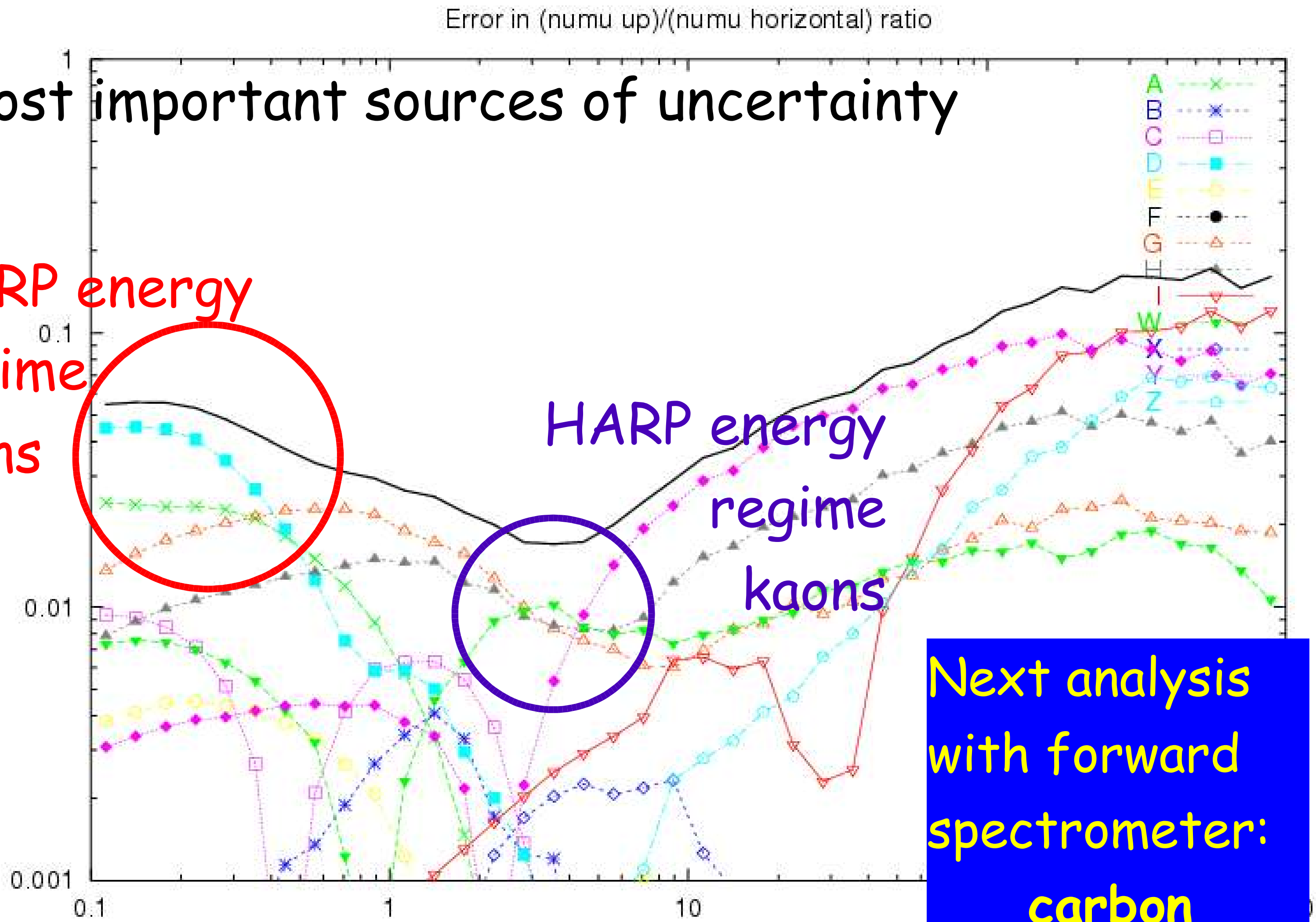


Boxes show importance of phase space region for contained atmospheric neutrino events.

New measurements.

G. Barr

Error in neutrino flux ratio: Up/Horiz.



Most important sources of uncertainty

HARP energy regime pions

HARP energy regime kaons

Next analysis with forward spectrometer: **carbon**

G. Barr

Outlook

HARP

after analysis for K2K and MiniBooNE beams:

tantalum at large angles for the neutrino factory

carbon (forward spectrometer) for atmospheric neutrinos

thick targets to understand better reinteractions

many more targets, momenta (e.g. Cryogenic targets)

MIPP at FNAL

large energy range: will go to higher energies

possibility to use **NA49** at CERN SPS

T2K beam

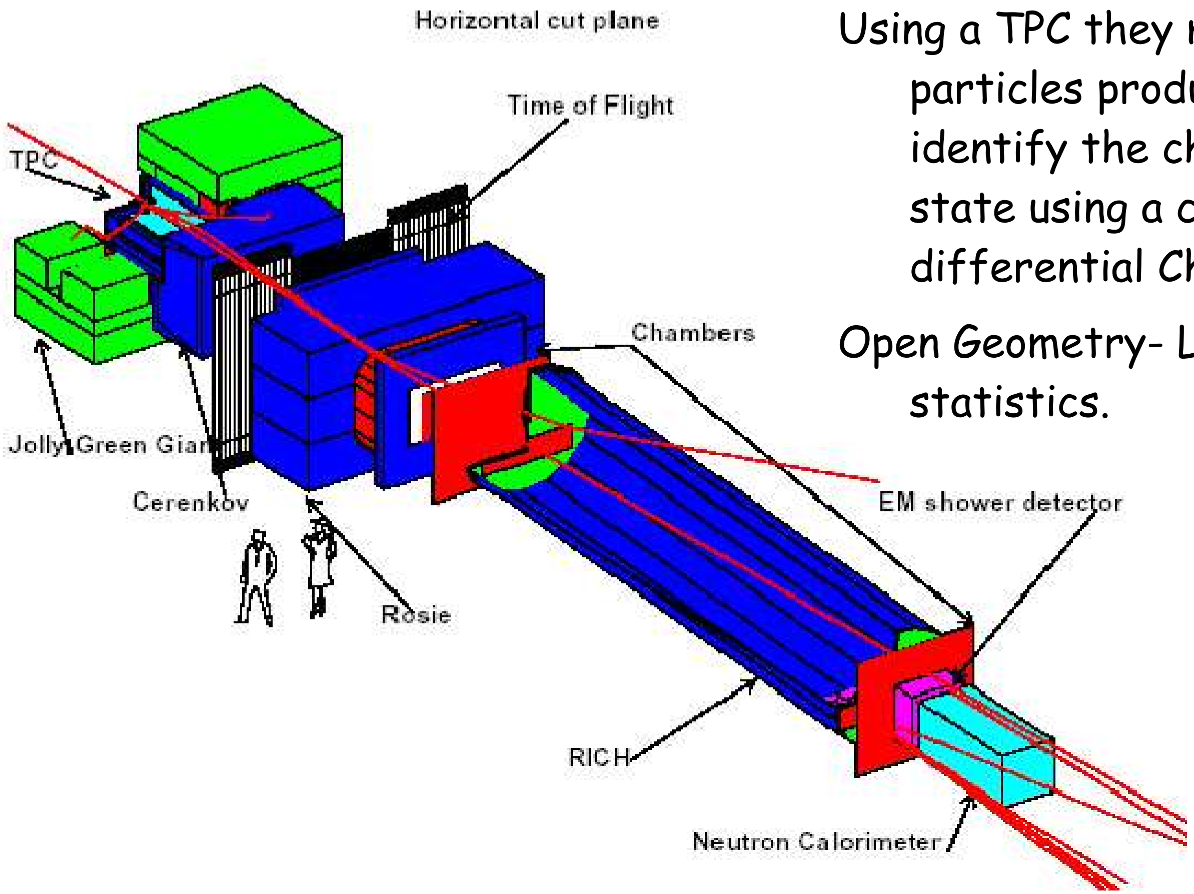
atmospheric neutrinos and muons

MIPP: FNAL-E907

Approved November 2001

Technical run 2004

Physics data taking 2005



Uses 120GeV Main Injector Primary protons to produce secondary beams of $\pi^{\pm}$ $K^{\pm}$ $p^{\pm}$ from 5 GeV/c to 100 GeV/c to measure particle production cross sections of various nuclei including hydrogen.

Using a TPC they measure momenta of ~all charged particles produced in the interaction and identify the charged particles in the final state using a combination of dE/dx, ToF, differential Cherenkov and RICH technologies.

Open Geometry- Lower systematics. TPC gives high statistics.

MIPP Physics Interest

- 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 production
  - Investigate light meson spectroscopy, pentaquarks?, glueballs
- Nuclear Physics
  - Investigate strangeness production in nuclei- RHIC connection
  - Nuclear scaling
  - Propagation of flavor through nuclei
- Service Measurements
  - Atmospheric neutrinos – Cross sections of protons and pions on Nitrogen from 5 GeV- 120 GeV
  - Improve shower models in MARS, Geant4
  - Make measurements of production of pions for neutrino factory/muon collider targets
  - Proton Radiography– Stockpile Stewardship- National Security
  - MINOS target measurements – pion production measurements to control the near/far systematics

Upgrade programme:

Speed up TPC DAQ by using ALICE ALTRO/PASA chips.

green light to acquire these chips from CERN ($80K).

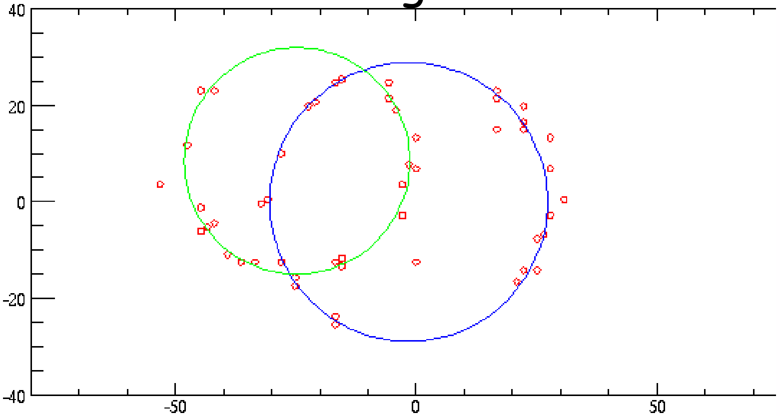
Speed up rest of DAQ.

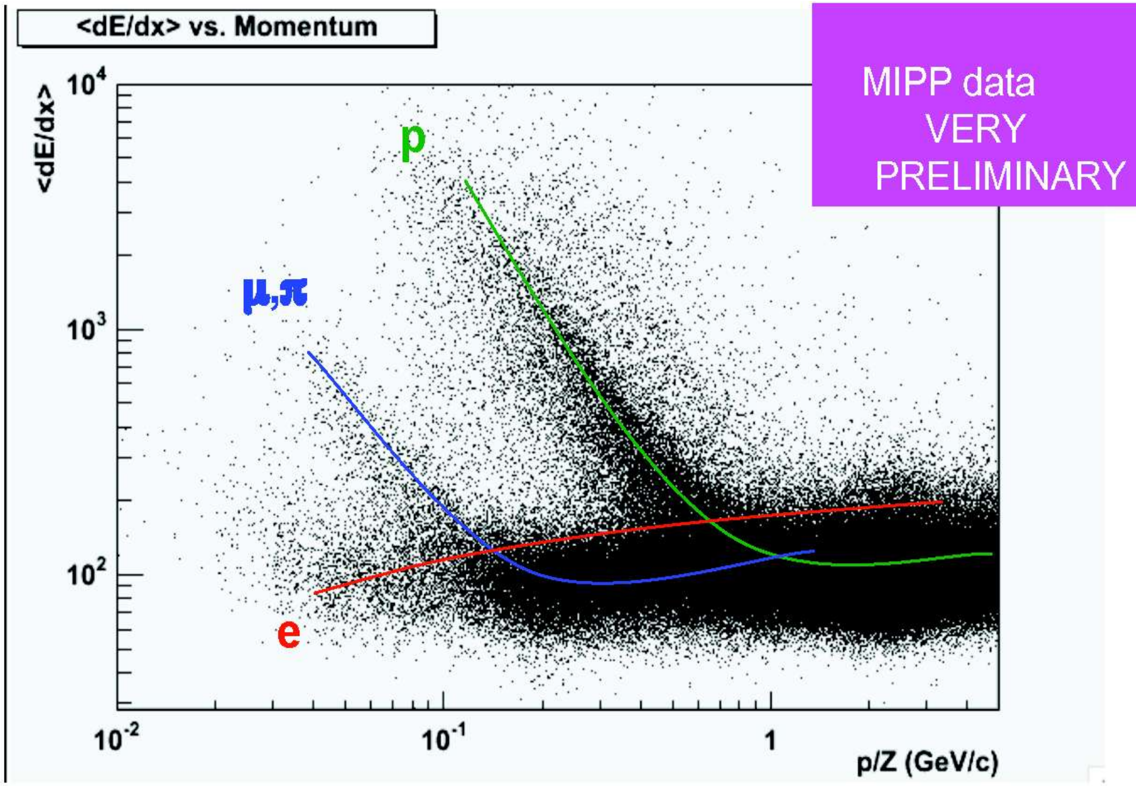
MIPP TPC and Cherenkov DATA

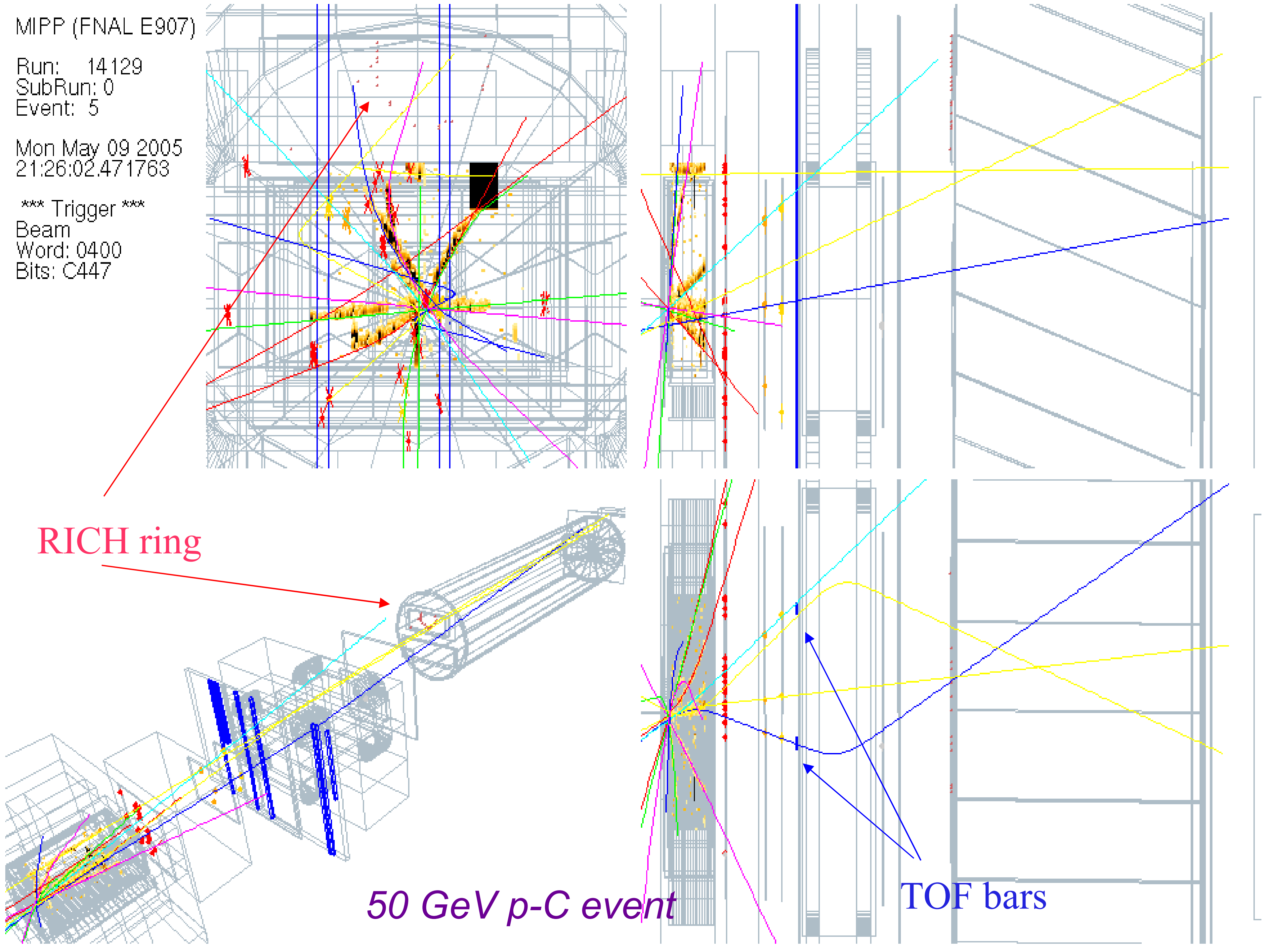
EOS TPC

dE/dx spectrum in MIPP run

RICH rings



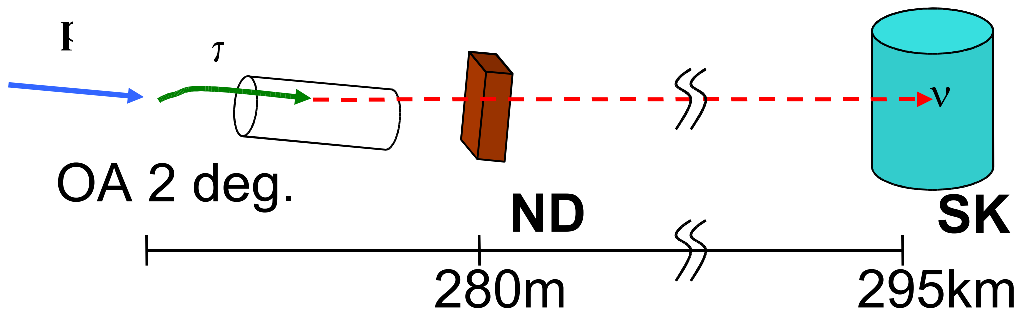


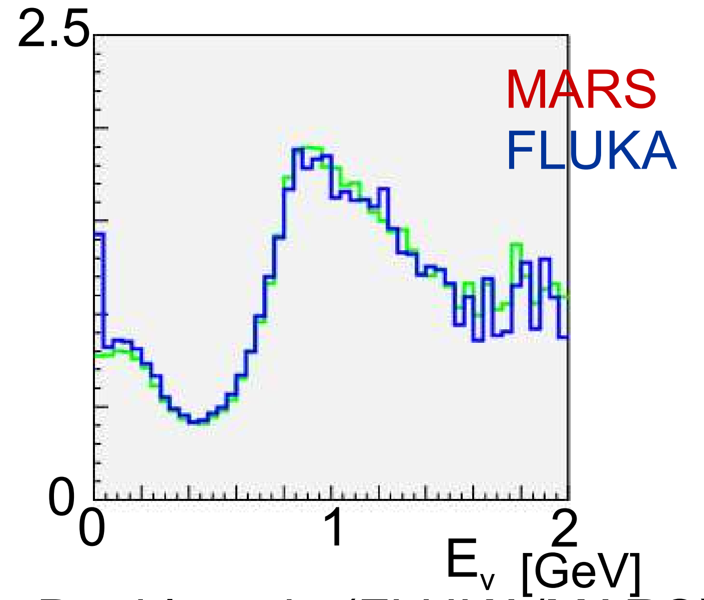

MIPP (FNAL E907)
Run: 14129
SubRun: 0
Event: 5
Mon May 09 2005
21:26:02.471763
*** Trigger ***
Beam
Word: 0400
Bits: C447
RICH ring
TOF bars
50 GeV p-C event

MIPP Timeline

- Run till next shutdown in current mode
- Acquire Altro/PASA chips
- Design New TPC Sticks
- Get approval for proposal: Run will be aproved when results from existing data shown
- Get new collaborators
- Run in 2006 (end of 2006) in upgraded mode with current beam.
- Design lower momentum beam. Beam Cherenkovs may need redesign (too much multiple scattering)
- Lots of graduate student theses
- Possible to affect shower simulators on 2007 time frame.

T2K far-near ratio





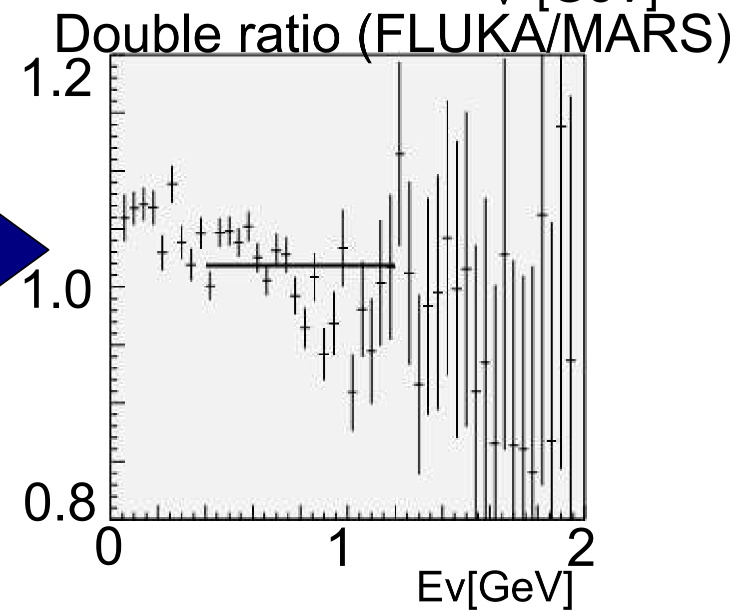
Flux @SK = Flux @ND ×[Far/near ratio]

From MC simulation

The Difference of Far/near ratio is ~1.9±0.4%

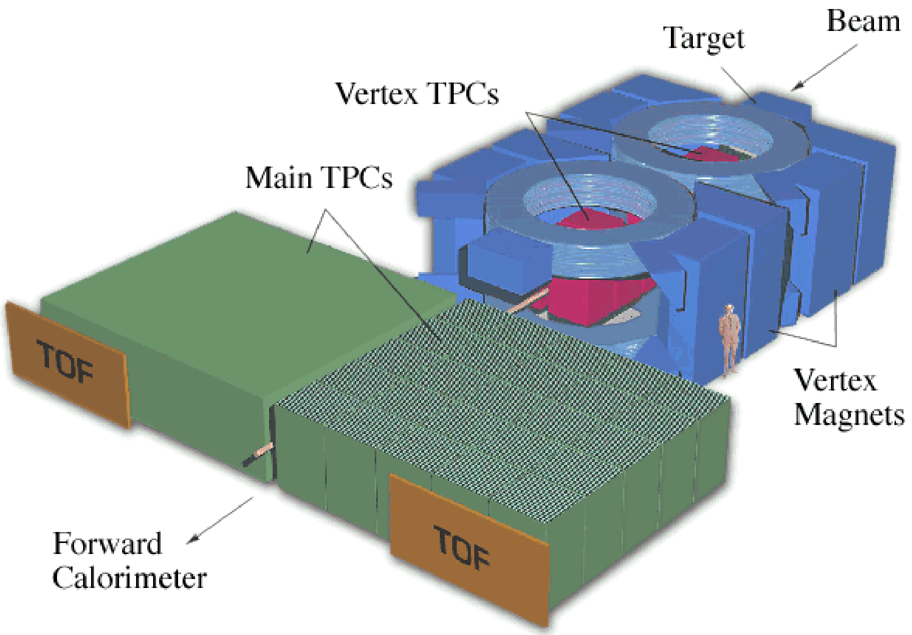
(Energy range:0.4>1.2[GeV])

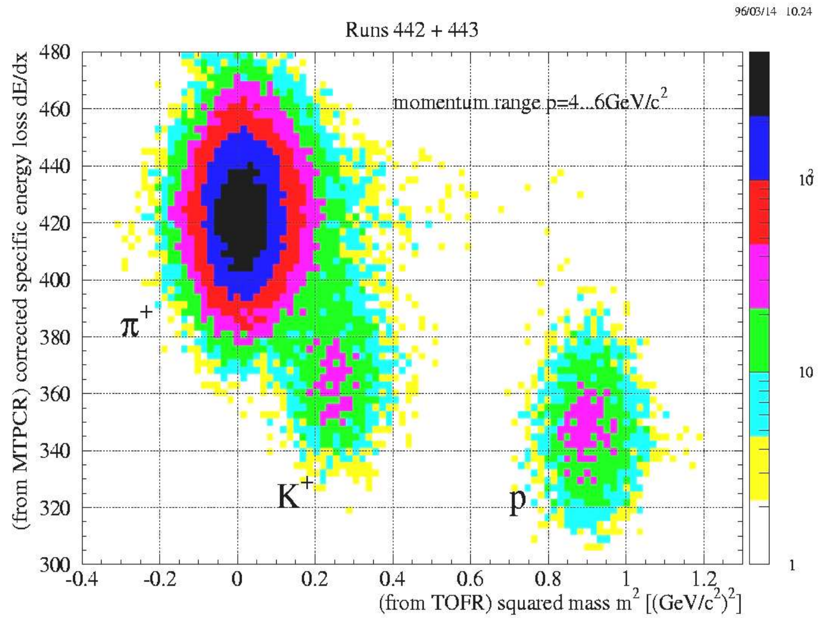
needed p-C data at 40 GeV/c



An existing facility: NA49

- particle ID in the TPC is augmented by TOFs
- rate somehow limited (optimized for VERY high multiplicity events).
  - order 10^6 event per week is achievable (electronic upgrade needed !)
- NA49 is located on the H2 fixed-target station on the CERN SPS.
  - secondary beams of identified π, K, p; 40 to 350 GeV/c momentum
- Measurements relevant for atmospheric neutrinos and NuMI have been performed in 2002 with two beam settings (100 and 158 GeV/c) with a 1% Carbon target
- New collaboration forming around hadron/heavy ion physics, and yields for atmospheric muons/neutrinos and neutrino beams





Summary (HARP)

The HARP thin target analysis for Al (K2K) and preliminary data for Be (MiniBooNE) have been shown. These will significantly improve the knowledge of these beams

The result is in general compatible with and more precise than, older data available in Be and Al.

Further results (Thick target, π^+/π^- , K/π, A and E dependence, Carbon) will appear over the next 6-12 months. Our goal is to make a major contribution to the understanding of neutrino fluxes for accelerator neutrinos as well as atmospheric fluxes.

Preliminary π^+/π^- yields in the large angle region have been obtained for Ta.

The Ta analysis will be completed over the next few months. Other targets and energies will be analyzed at large angle. Our goal is to make a major contribution to the design of the Neutrino Factory.

The elastic analysis provides a clean way to calibrate the momentum scale of the detector and to assess the impact of distortions.

Conclusions

Neutrino oscillation experiments move from discovery to precision measurements

Knowledge of neutrino cross-section and neutrino production is essential

Hadron production measurements should be seen as integral part of the Neutrino Experiments

Present trends (see HARP & MIPP) are

- Full-acceptance detectors (single arm spectrometers in the past)
- High statistics
- Characterization of the actual neutrino beam targets to reduce MC extrapolation to the minimum
- Direct interest of neutrino experiments in hadron production
- atmospheric neutrino predictions need similar measurements