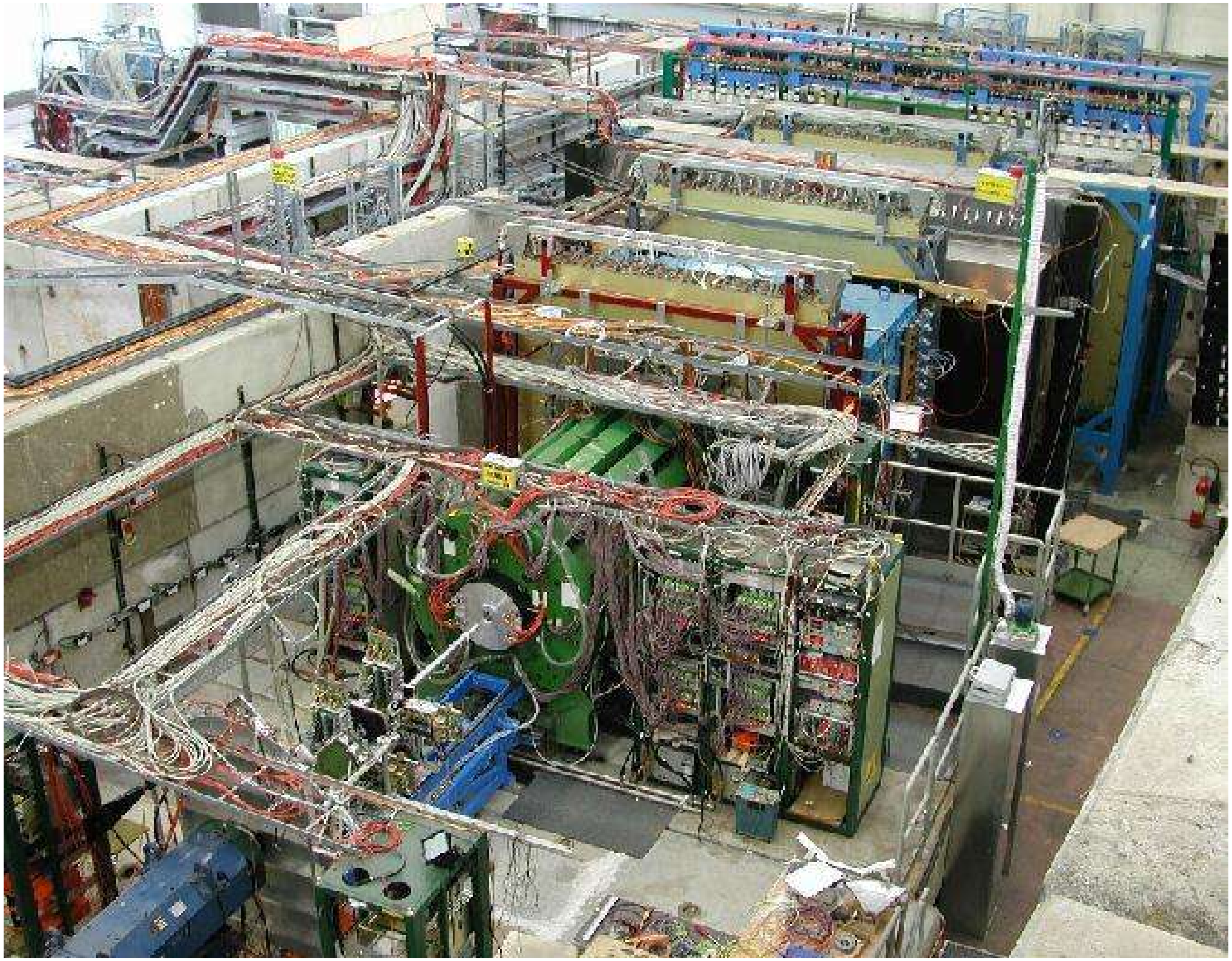
# HARP news

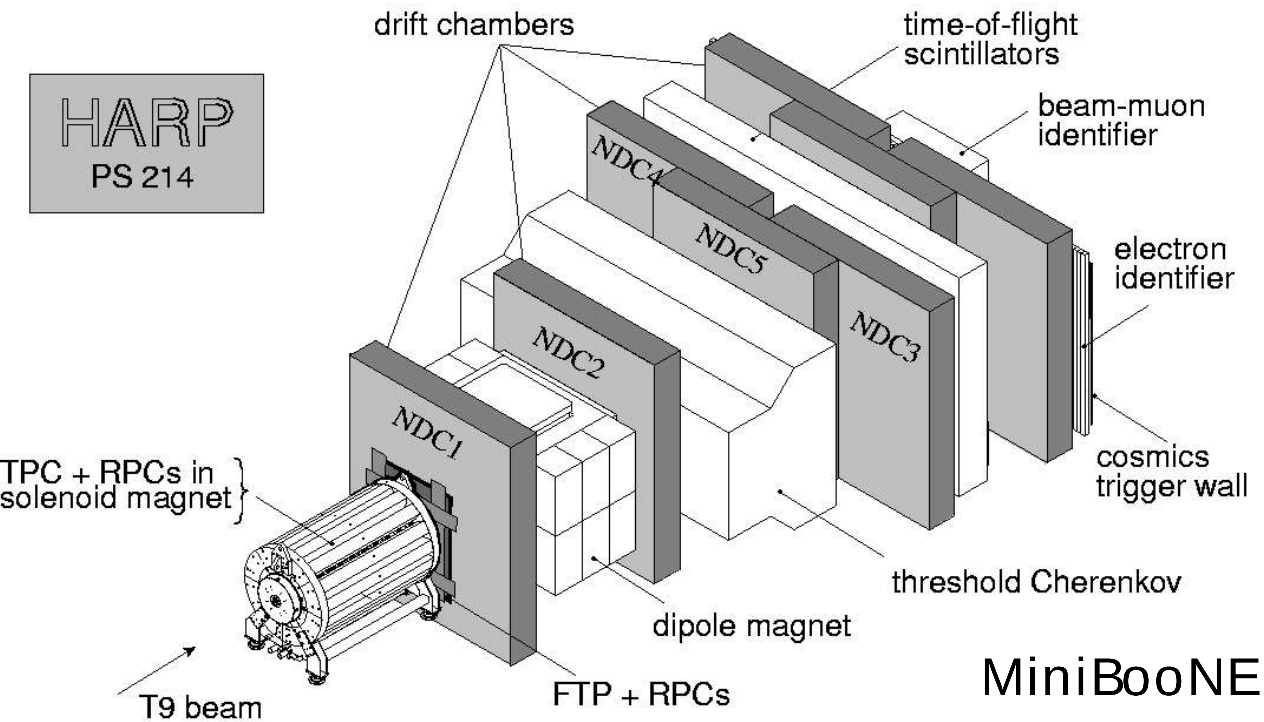


- harp
- latest results
  - forward region
  - large-angle
- plans

ISS meeting, MWG session
CERN, 22.9.05

Alex Grossheim (CERN)
on behalf of the HARP collaboration

# HARP detector

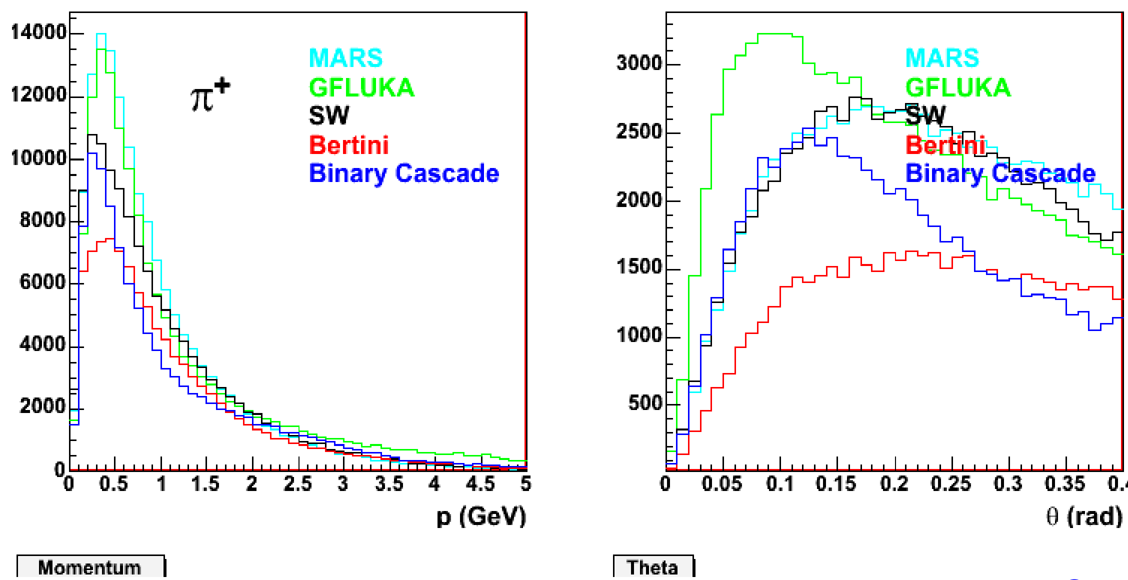



**Full solid-angle spectrometer to measure hadron production**

## HARP Physics Cases

- Neutrino factory design
- Atmopheric neutrino flux predictions
- hadronic generators
- Neutrino flux predictions for accelerator-based experiments: MiniBooNE and K2K

MiniBooNE pi+ flux predictions (D. Schmitz)



# HARP data sets

- harp
  - proposed in 1999
  - approved in 2000
  - built in 2000/01
  - data taking 2001/02

- 420 M events
- 30 TB of data
- > 100 settings

| | Target material | Target length (l%) | Beam Momentum (GeV) | #events (millions) |
|---|---|---|---|---|
| Solid targets | Be | 2 (2001) 5 100 | ±3 ± 5 ± 8 ± 12 ± 15 Negative only 2% and 5% | 233.16 |
| | C | | | |
| | Al | | | |
| | Cu | | | |
| | Sn | | | |
| | Ta | | | |
| | Pb | | | |
| 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 ± 5 ± 8 ± 12 ± 15 | 58.43 |
| | $0_8$ | | | |
| | $D_1$ | | | |
| | $H_1$ | | | |
| | $H_2$ | 18 cm | ±3, ±8, ±14.5 | 13.83 |
| Water | $H_20$ | 10, 100 | +1.5, +8(10%) | 9.6 |

# HARP analysis

- analysis has been split
  - common: beam and trigger related
  - forward (FW)
    - important for K2K and MiniBooNE
    - involves only FW spectrometer and beam/trigger
    - 1$^{st}$ physics paper submitted
  - large-angle (LA)
    - important for NF
    - involves only TPC and beam/trigger
- currently, FW and LA are being merged again

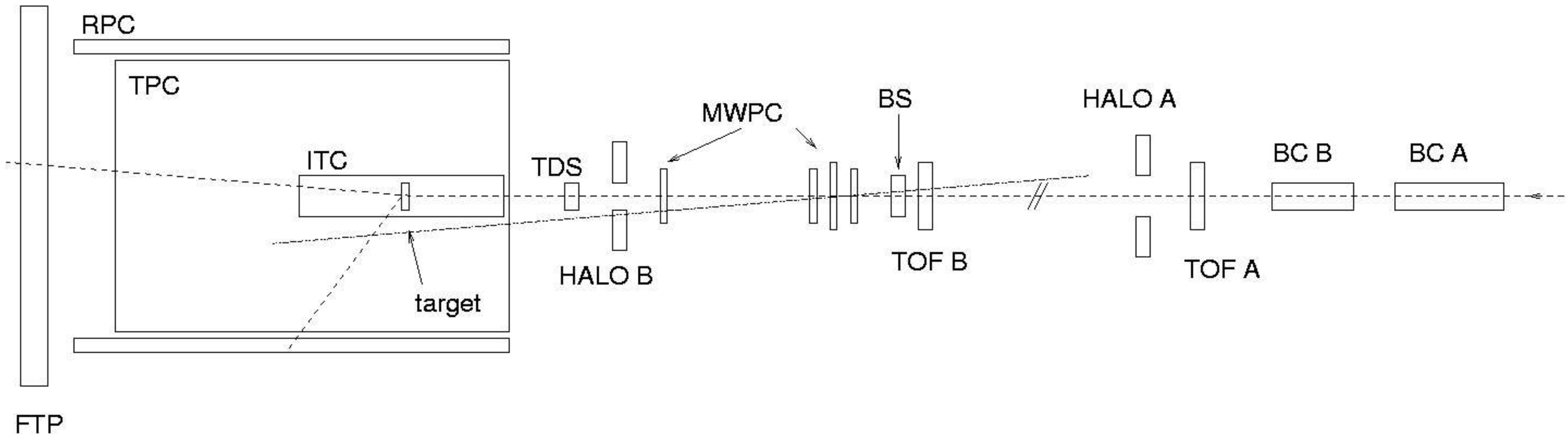
# Ingredients for Cross-Section Calculation

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

- Select events identified as primary protons interacting in the target
- For each event, reconstruct tracks and their 3-momentum
- Identify pions among secondary tracks
- Count protons on target corresponding to selected events
- Apply corrections, for reconstructed-to-true pion yield conversion:
  - Momentum resolution
  - Spectrometer angular acceptance
  - Track reconstruction efficiency
  - Efficiency and purity of pion identification
  - Other

OR multidimensional deconvolution: all-in-one

# Event Selection



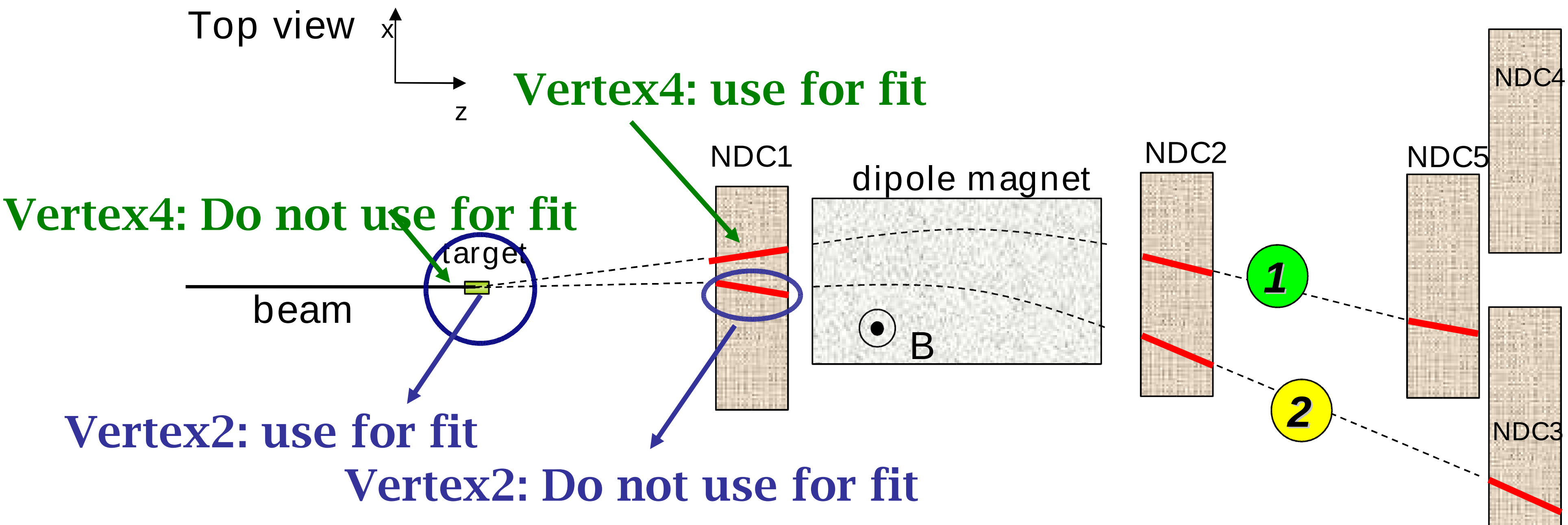

- **Event selection for protons on target***:*
  - Well-behaved transverse impact point and direction of primaries via 4 MWPCs and scintillators (BS, TDS, HALO A, HALO B)
  - Primaries identified as protons via beam TOF and Cherenkov systems (TOF A, TOF B, BC A, BC B). Beam TOFs also used for interaction time.

- **Event selection for proton inelastic interactions** ("physics trigger")**:**
  - Same as normalization trigger, plus signal in forward trigger scintillator plane (FTP)

- Beam particle identified as proton » ~100% purity
- exact normalization to protons on target

# FW Track Reconstruction

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




- **Momentum of tracks can be reconstructed in two ways:**
  - Vertex2 tracks: 3D track segment in NDC2 or 5, plus successful vertex match
    » sample used to measure pion yield.

**Number of reconstructed tracks in K2K analysis: 210,000**

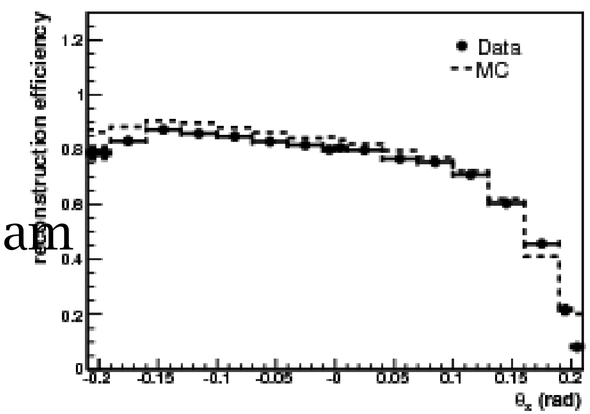
  - Vertex4 tracks: 3D track segment in NDC2 or 5, plus 3D segment in NDC1
  - » sample used to measure track reconstruction efficiency in data

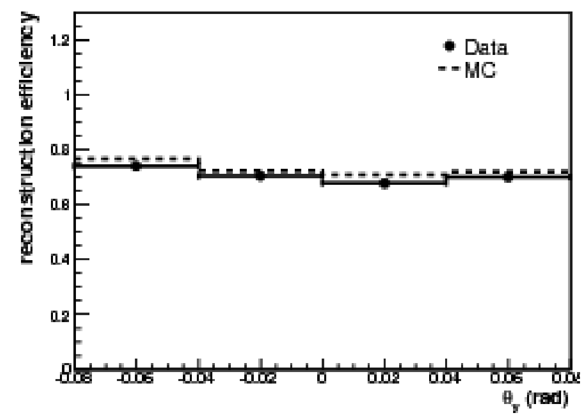
# FW Track Reconstruction Efficiency

- Due to rectangular geometry of the spectrometer and bending plane, the efficiency is computed (from the data) as a function of: $(p, \theta_x, \theta_y)$

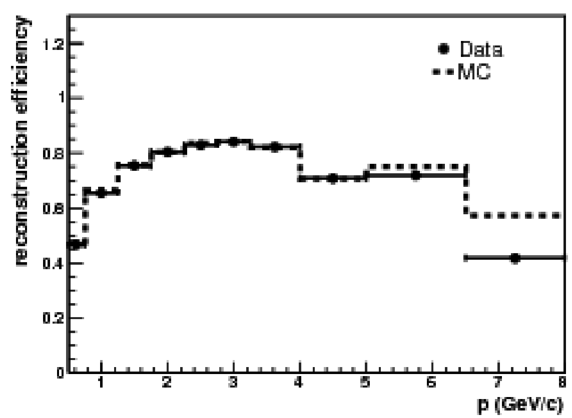
In spectrometer acceptance:

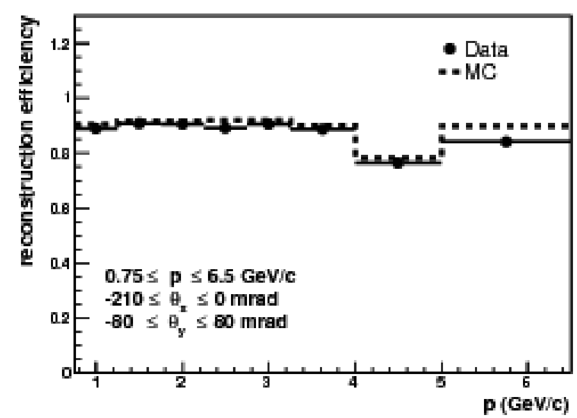
- Efficiency to reconstruct a track downstream of dipole: **99.5%**
- Efficiency to connect a downstream track to vertex (»momentum measurement): **98%**




- P-dependent drop for $\theta_x > 0$ due to positive tracks bent out of acceptance »only $\theta_x < 0$ used
- For $\theta_x < 0$, only (geometrical) acceptance correction needed can be computed analytically



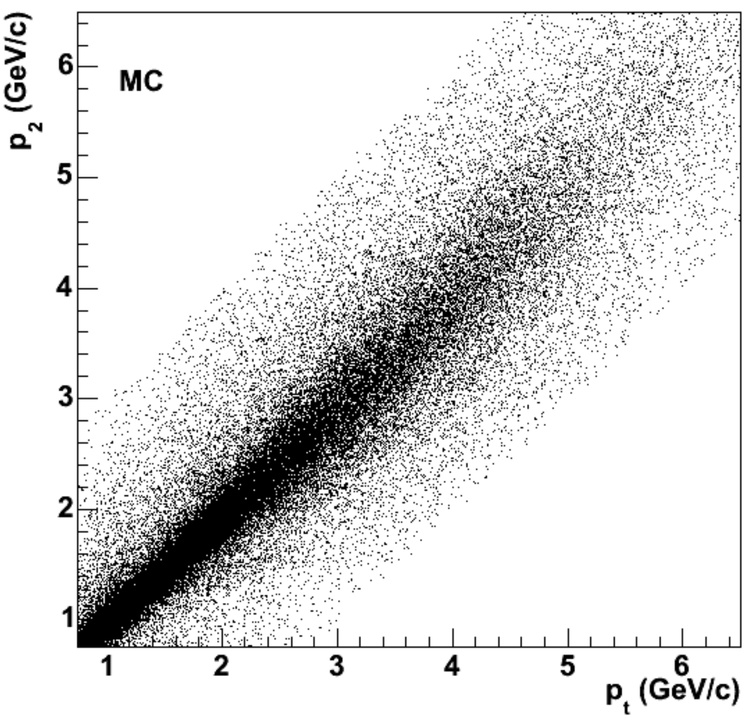



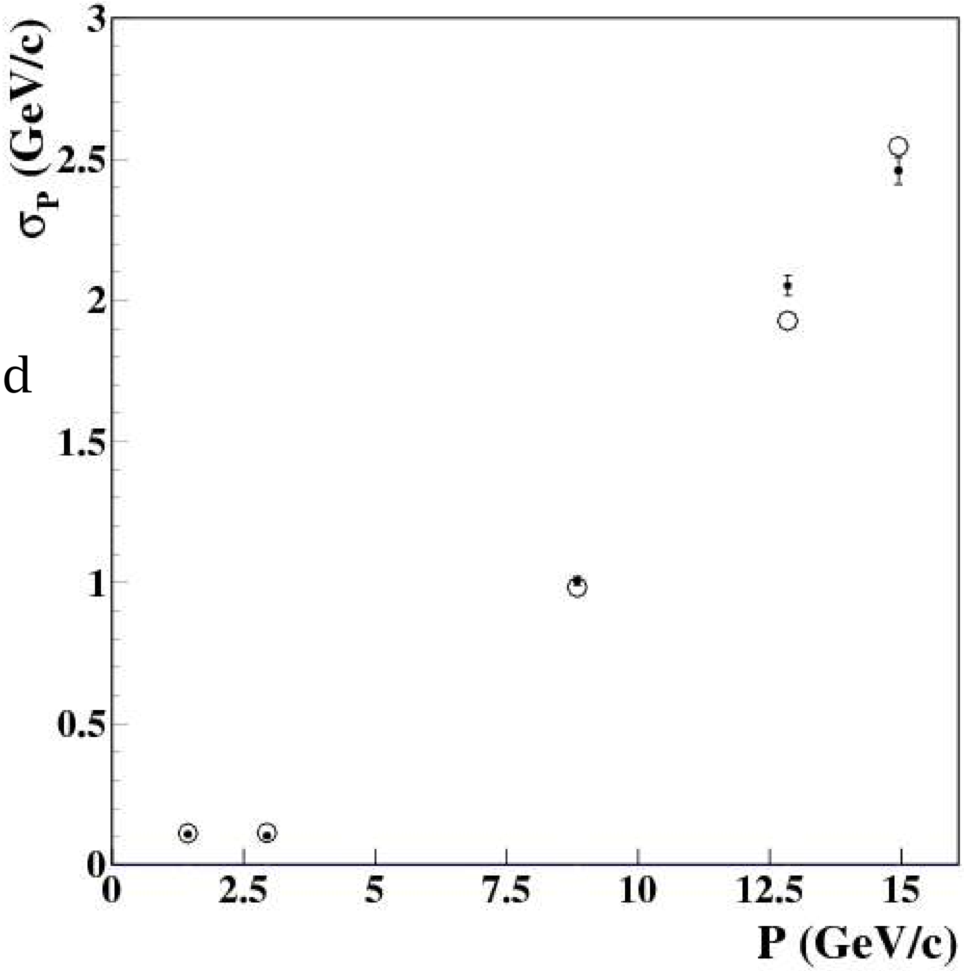
# FW Momentum Resolution

- p2: momentum reconstructed from downstream track and vertex constraint

Comparison of reconstructed .vs. true momentum shows:

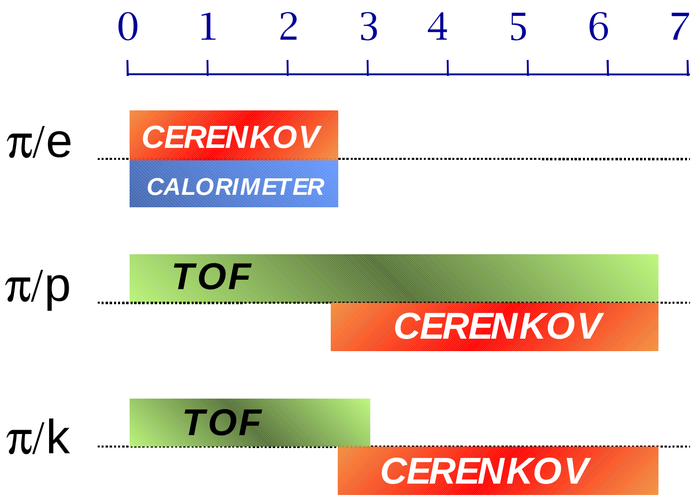
- **<u>No biases</u>** in reconstruction
- **<u>5–10% momentum resolution</u>**, unfolded in final result

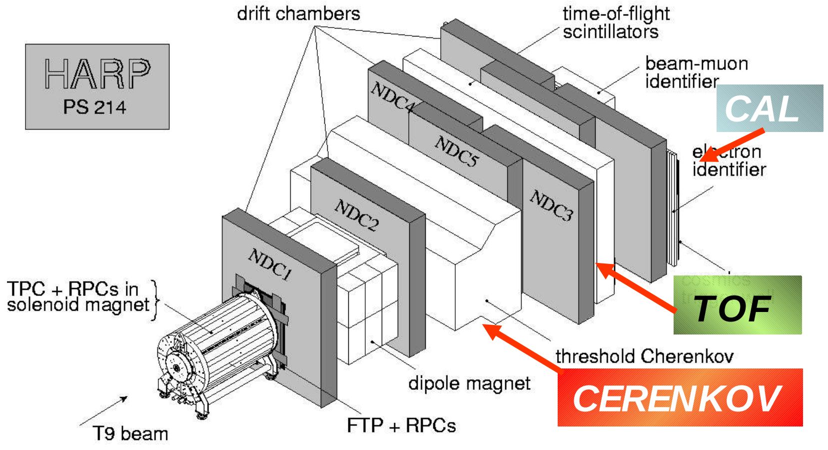


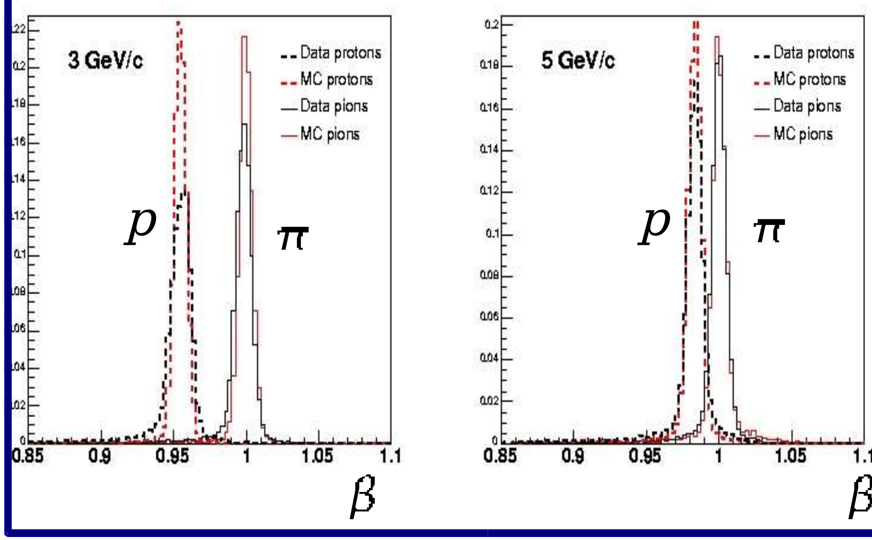

points: data
circles: MC

# FW Pion Identification



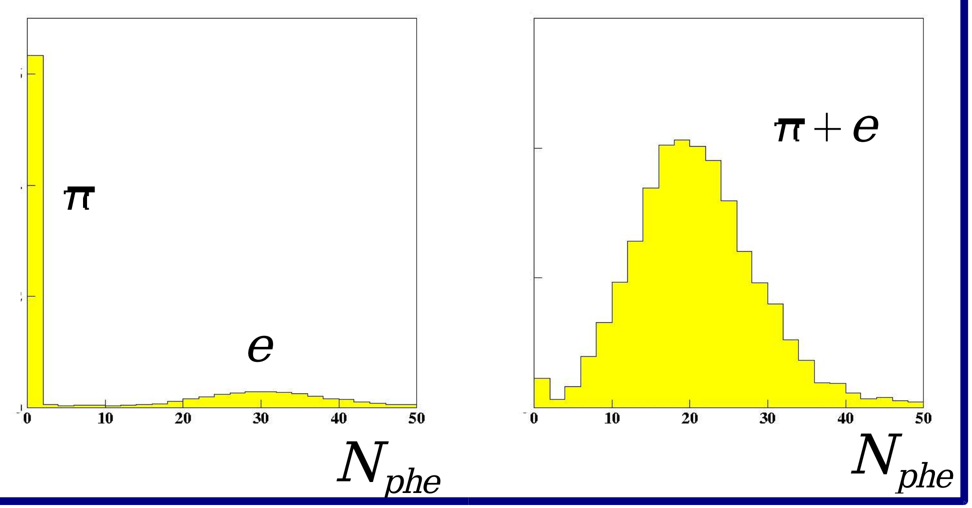

## TOF pi/p response for beam particles




## CHE pi/e response for negative particles

Below pion threshold

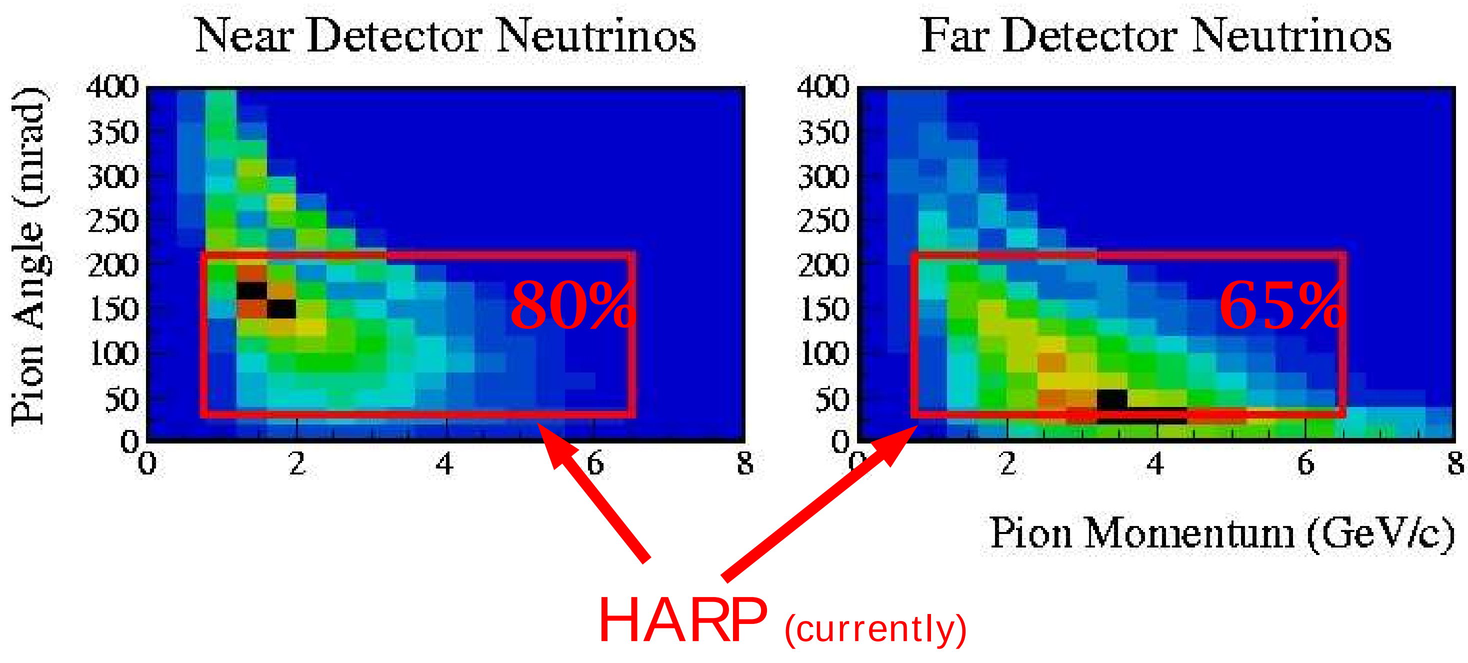
Above pion threshold



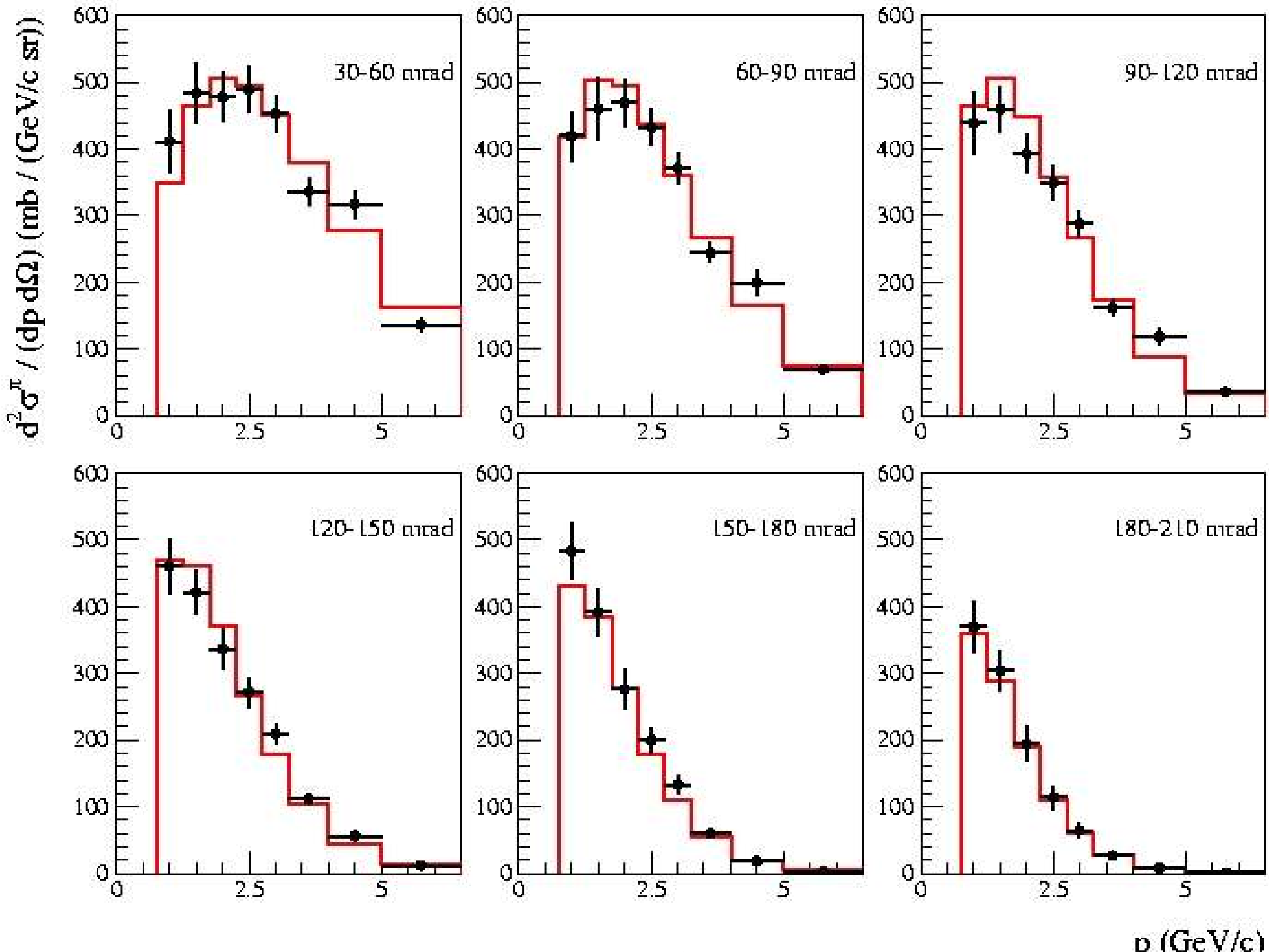
# Relevance of HARP for K2K

- Neutrino flux at far detector is obtained from near detector measurement, times far/near neutrino flux ratio obtained from the beam MC simulation
  - »F/N ratio is dominant systematic error in spectrum distortion analysis
- $\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$ decays are responsible for ~97% of all K2K neutrinos
- HARP pion production result covers: $0.75 < p_{\pi} < 6.5 \ GeV/c, \ 30 < \theta_{\pi} < 210 \ mrad$

**Good coverage of phase space of relevance to K2K**



# HARP Al 5% 12.9 GeV/c Results




HARP results in black, parametrization of HARP results in red

# FW Error Evaluation

- Thorough systematics error evaluation performed, to quantify errors on both:

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

Typical error: **8.2%**

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

Error on total integrated cross–section: **5.8%**

| Error Category | Error Source | $\delta_{\text{diff}}$ (%) | $\delta_{\text{int}}$ (%) |
|---|---|---|---|
| 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:**

- Momentum scale
- Tertiary subtraction
- empty target subtraction

# Parametrization of HARP Data

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

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

where:

$X$: *any other final state particle*

$p_{beam}=12.9$: *proton beam momentum* $(GeV/c)$

$p,\ \theta$: $\pi^+$ *momentum* $(GeV/c)$, *angle* $(rad)$

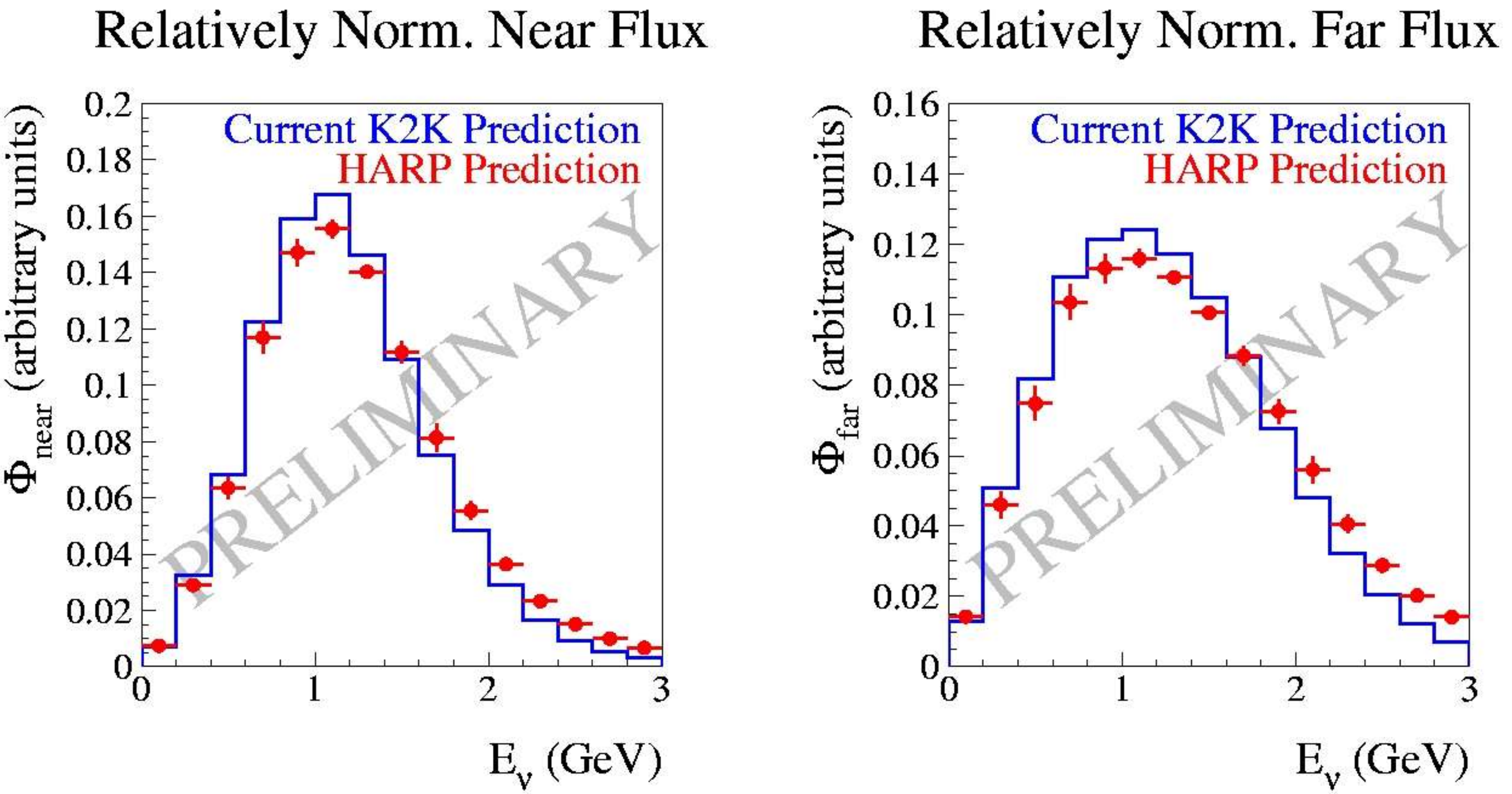
$d^2\sigma/(dp\,d\Omega)$ *units*: $mb/(GeV/c\,sr)$, *where* $d\Omega\equiv 2\pi\,d(\cos\theta)$

$c_{1,}\ldots,c_8$: *emprical fit parameters*

Sanford–Wang parametrization used to:

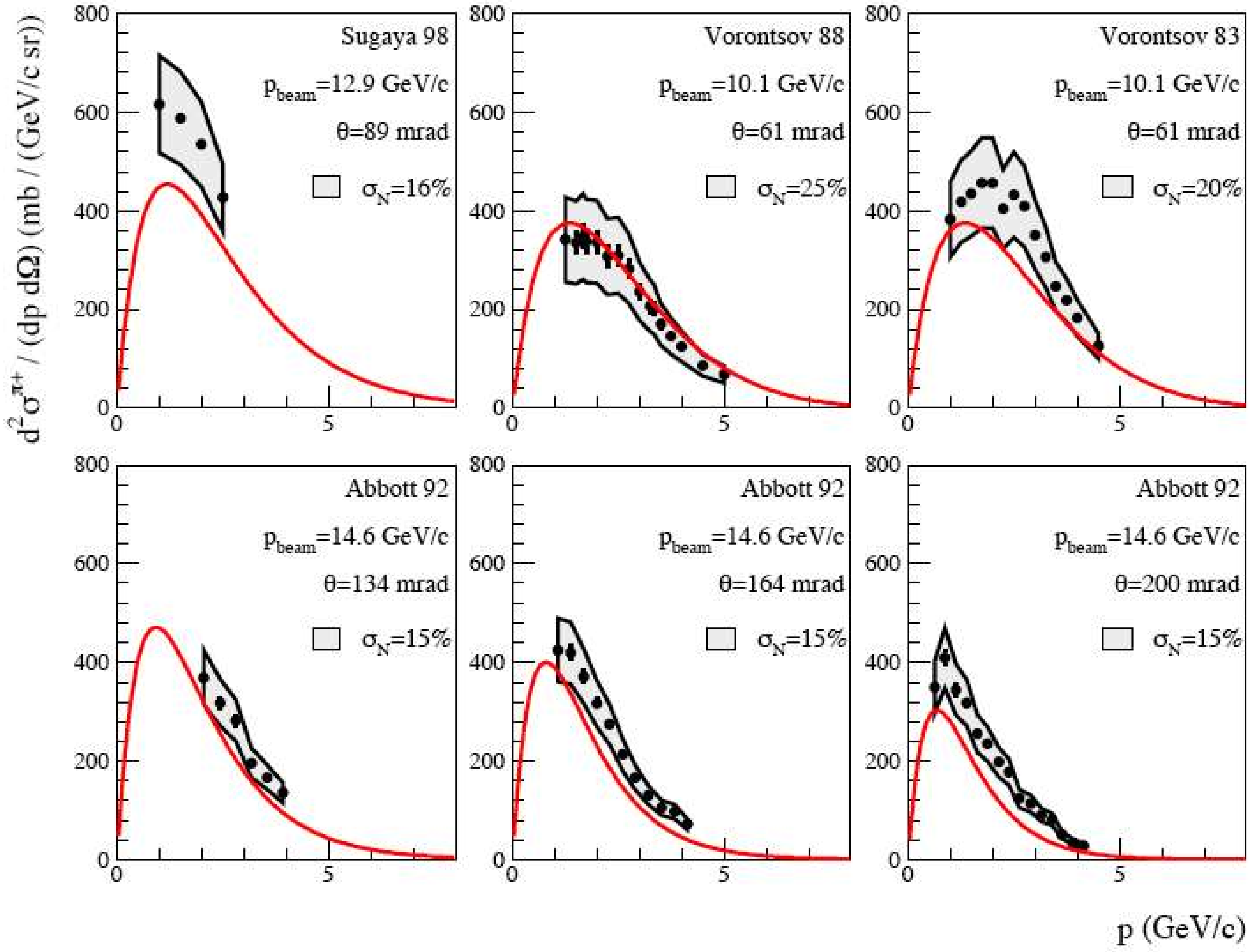
- Use HARP data in K2K and MiniBooNE beam MC
- Translate HARP pion production uncertainties into flux uncertainties
- Compare HARP results with previous results in similar beam momentum, pion phase space range

# Application to the K2K flux prediction

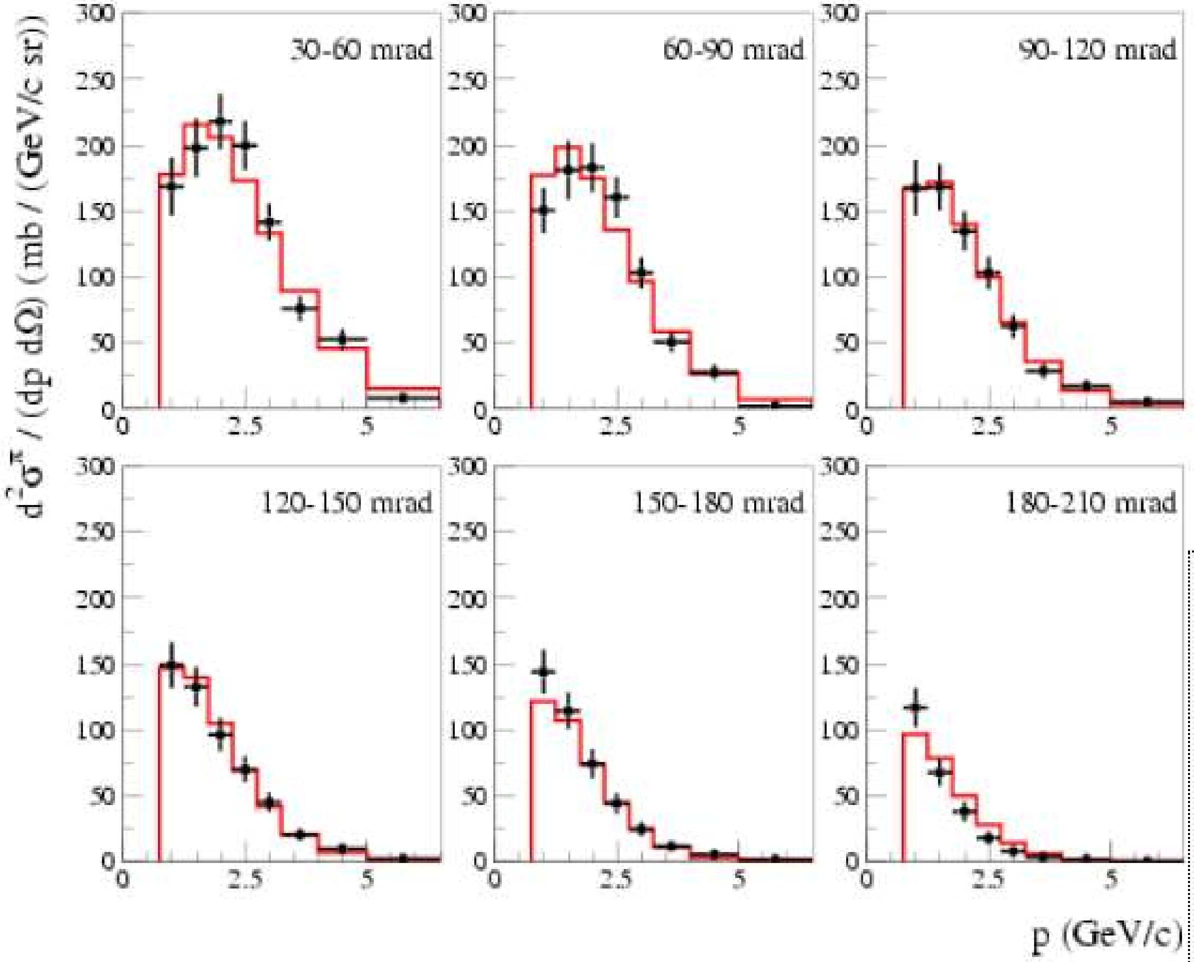



- Similar neutrino energy shapes arising from K2K default and HARP pion production assumptions in K2K beam MC
- Errors shown: HARP pion production and MC statistics

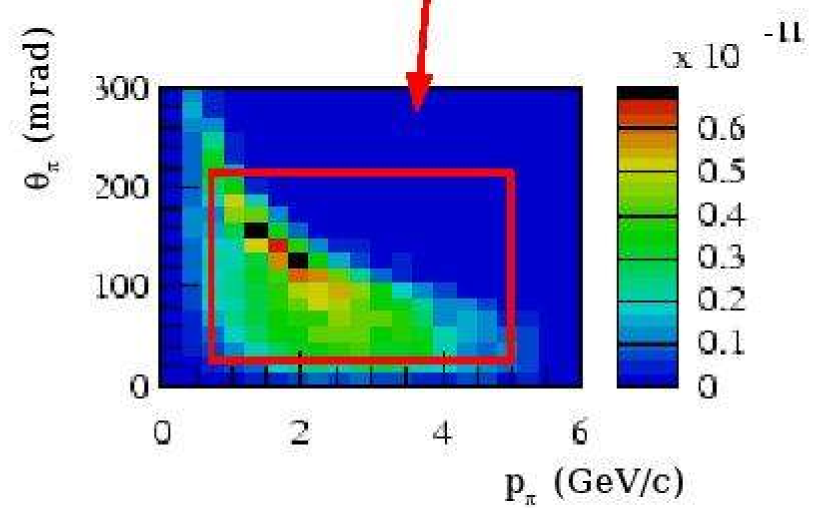
# Comparison with older data: Al



# Be results at 8.9 GeV/c for MiniBooNE

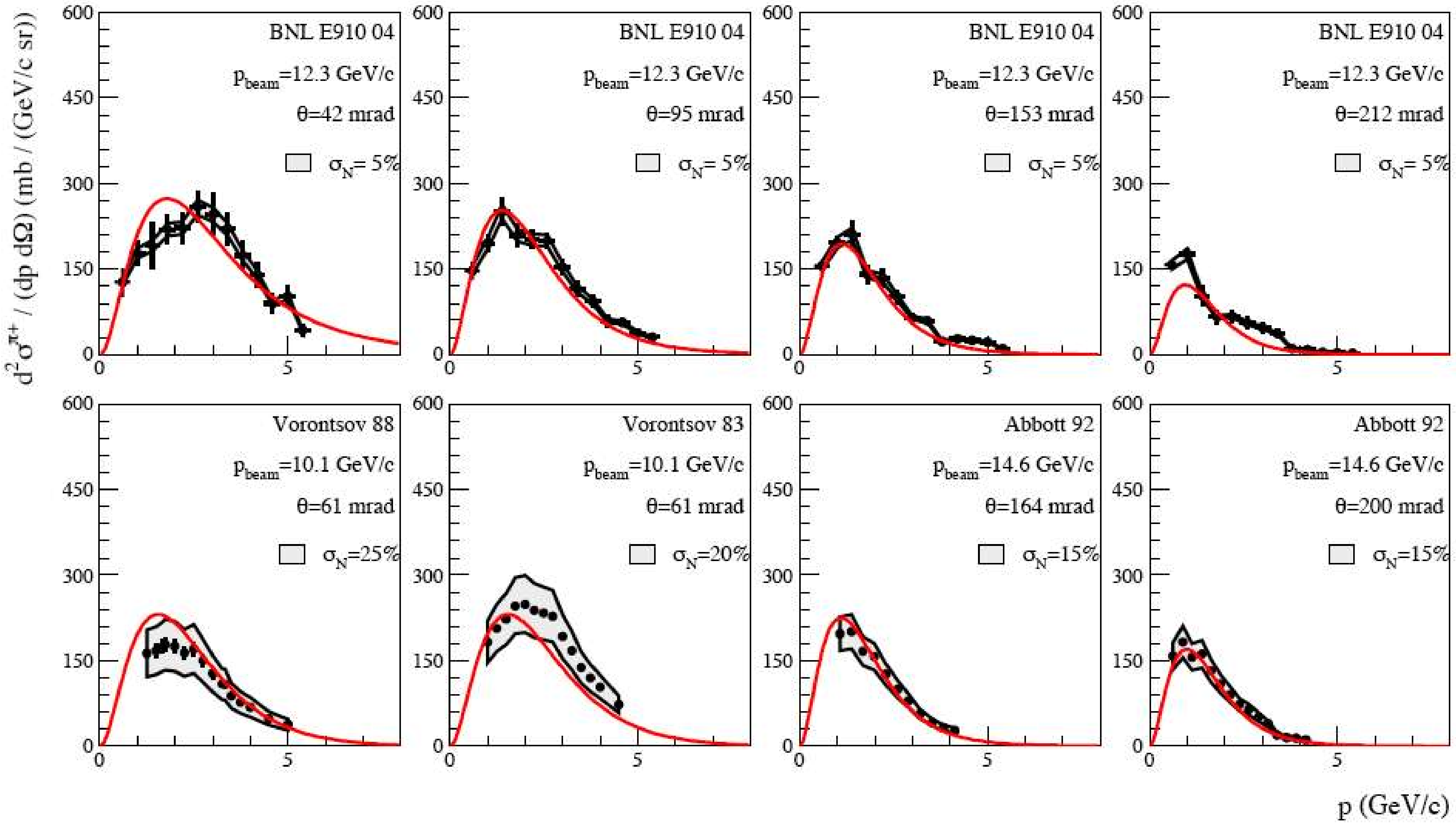



0.75<p<5
30<theta<210




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

# Comparison with older data: Be



# Forward Summary

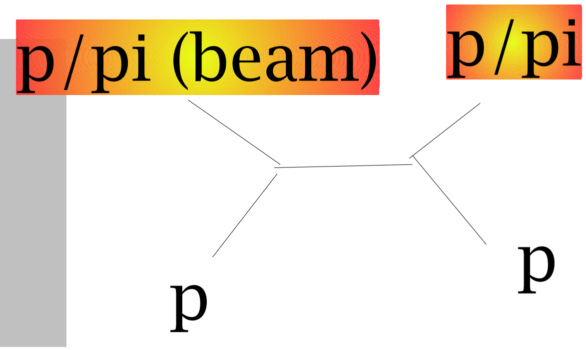
- basic elements: **tracking and PID stable**
- data provided in |p| theta bins according to resolution
- full unfolding of measurement available and validated
- **Sanford–Wang fit** to facilitate comparison and usage of results
- error of around 5% on total integrated cross–section
- results largely compatible with earlier measurements (but with smaller uncertainties)
- results for K2K and MiniBooNE have been presented and are **being published**
- **analysis scheme established** and being applied to large–angle

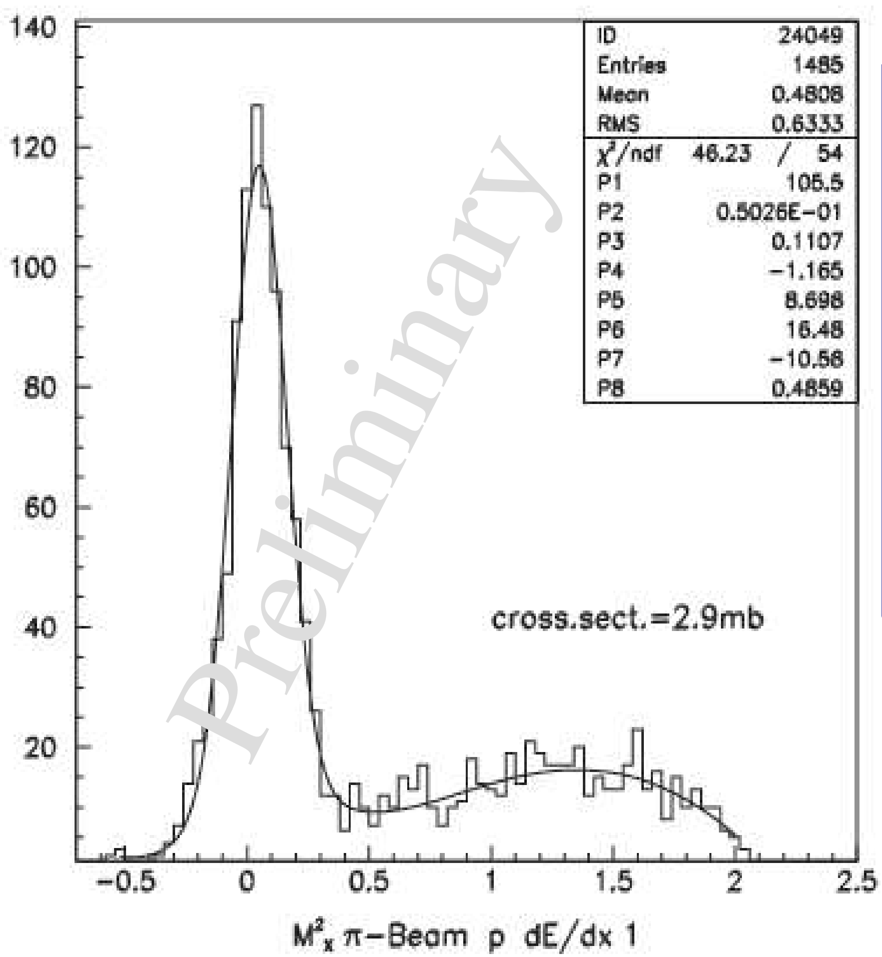
# Large–Angle Status

- The detectors at large–angle have now been calibrated
  - TPC: dE/dx measurement, momentum scale and resolution, efficiency
  - RPC: time drift, t0 calculation
- Performance checks and validation
  - pp and $\pi$p elastic scattering
  - preliminary pi+/pi– production spectra and ratios
- Plans
  - consolidation
  - close analysis loop (use FW analysis model)
  - process settings one by one starting with the ones most important for NF

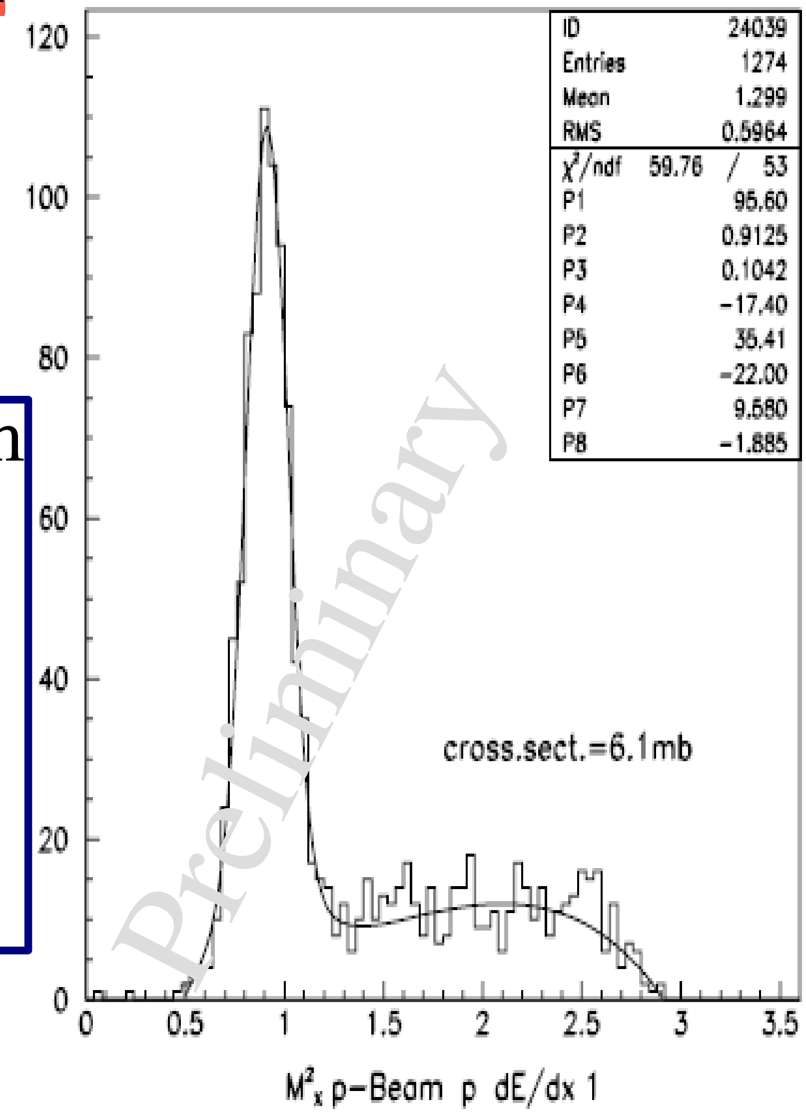
# Elastic scattering: calibration of TPC response

sensitive to
- *PID*
- *momentum*
- *normalization*




data taken with 3 GeV/c beam and liquid H2 target




**<u>compatible with PDG:</u>**

$\sigma_{pp\rightarrow pp} \simeq 6.6 \pm 0.27\ mb$

$\sigma_{\pi p\rightarrow \pi p} \simeq 3.2 \pm\ 0.14 mb$

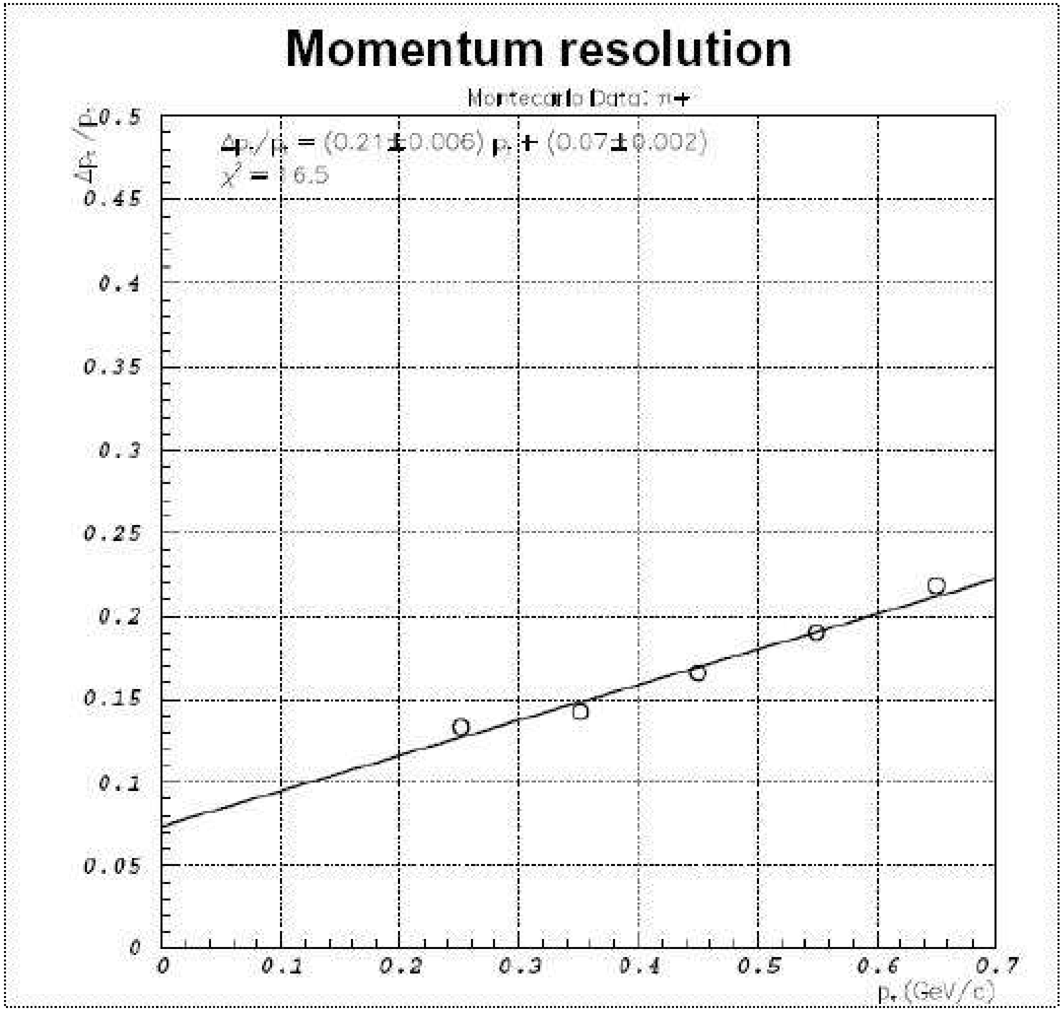
# 3 GeV/c Tantalum 5% analysis

- At least one track in TPC and only one beam particle
- Cuts on the beam particle:
  - TOF: to select protons as beam particle
  - MWPC: to select only beam particle that hits the target

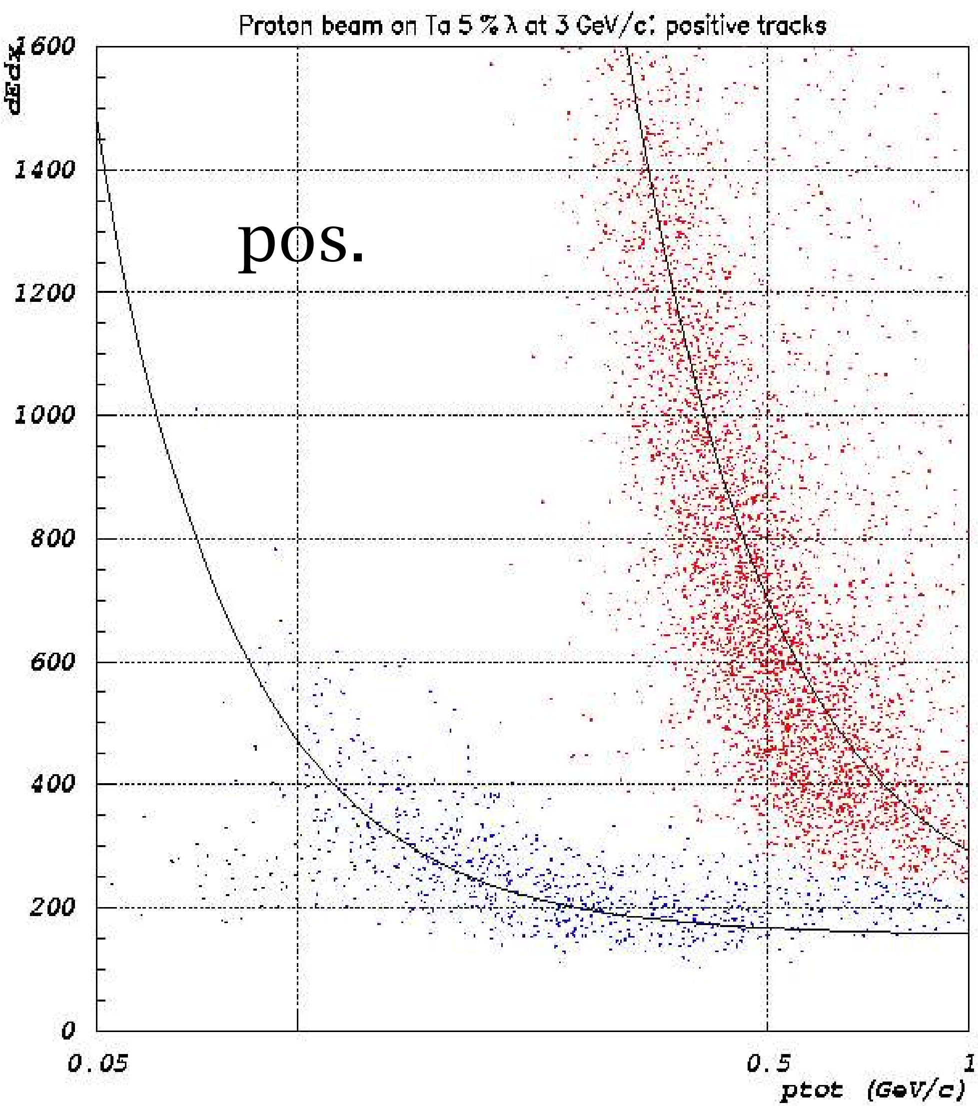
- ***Cuts on the trigger:***
  - ITC: to select event with an interaction at large angle (efficiency of ITC 99%)

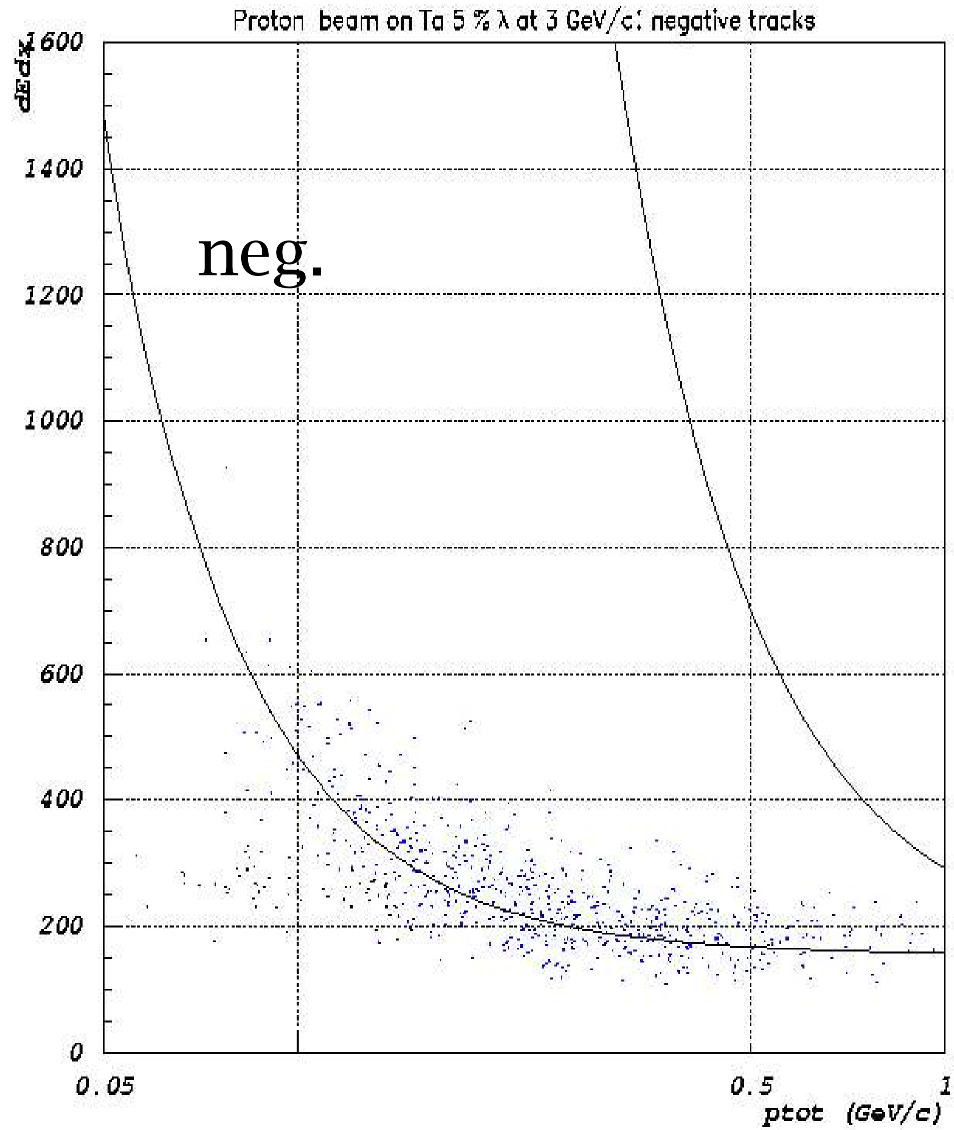
- ***Cuts on the event in spill***
  - To reject events strongly affected by the dynamic distortions

**Num$_{event}$=94 e3**



# PID via dE/dx in TPC

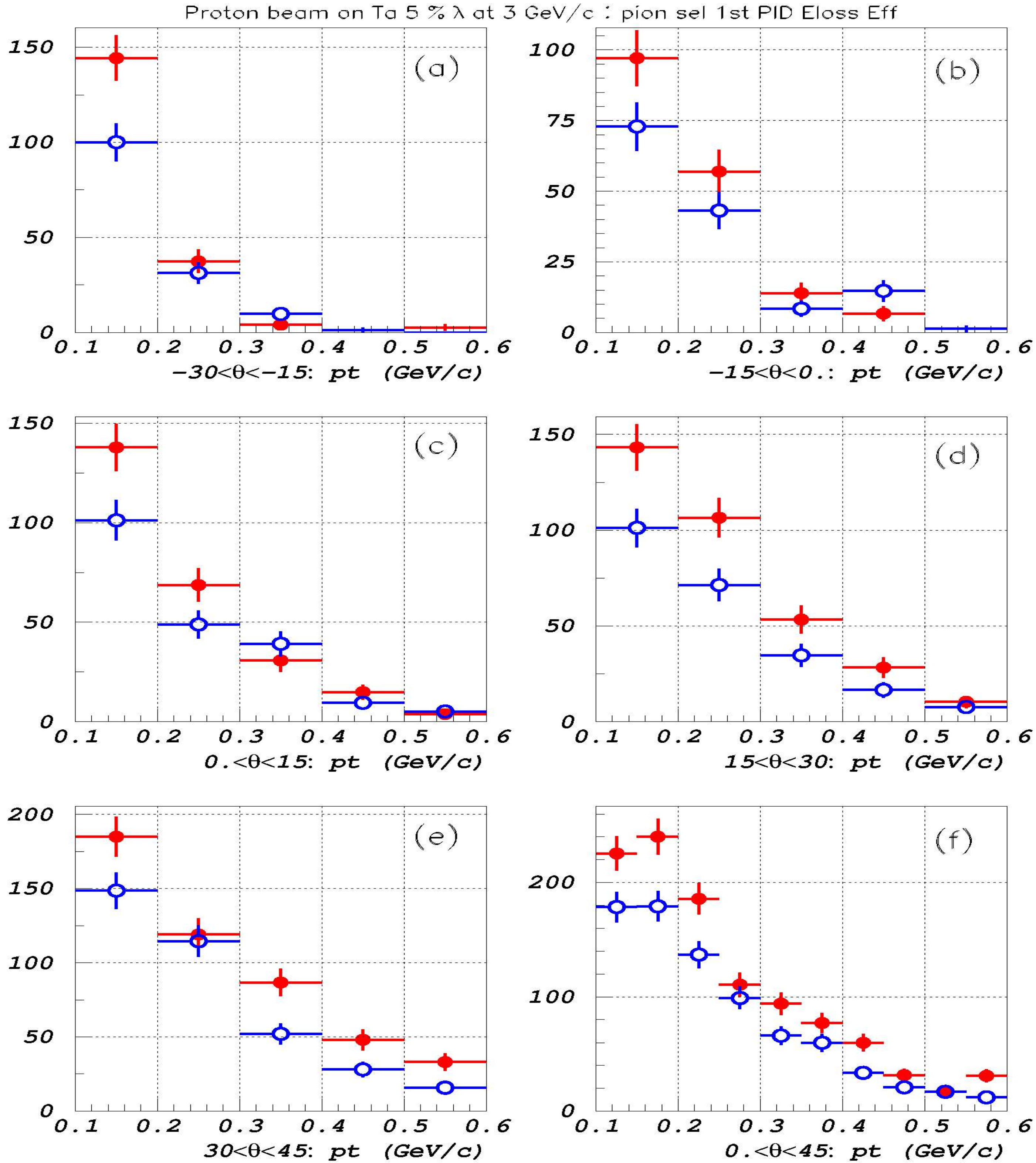


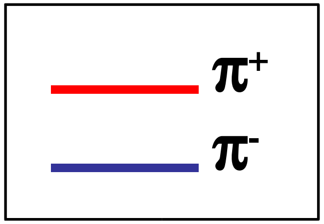




<u>concerns with the TPC which had to be overcome:</u>

*cross-talk* in the electronics and *distortions* of the field

# Pion yields



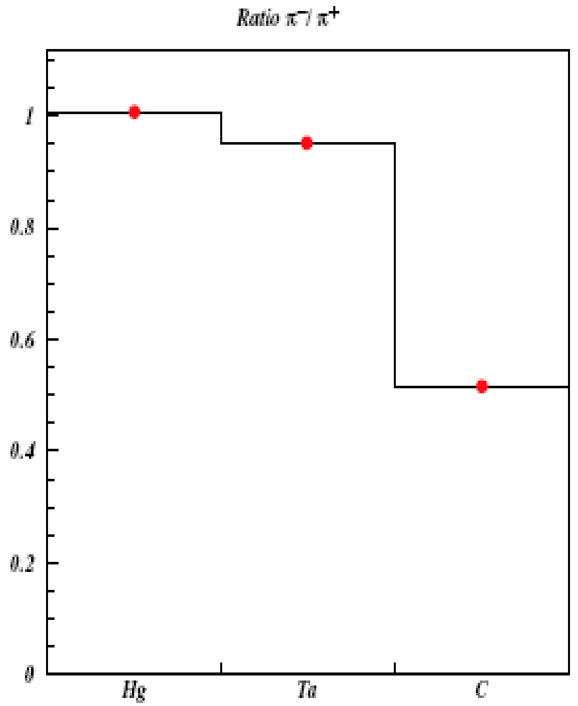

5% Ta target.
3 GeV/c beam.
preliminary.
not normalized.
efficiency-corrected.
only stat. errors.

pi+/pi- ratios already meaningful.

new, publication-ready (including systematics) results soon.

# Pion Ratios

| Material | $\pi^+$ per p.o.t. | $\pi^-$ per p.o.t. |
|---|---|---|
| C | 0.30 | 0.153 |
| Ta | 0.183 | 0.174 |
| Hg | 0.185 | 0.186 |




- First comparison possible: ratio N($\pi^-$) / N($\pi^+$) can be cross-checked with MonteCarlo simulations
- Presented data is generated by MARS in same conditions as data taking (3 GeV/c momentum, Ta target)
- so far compatible with preliminary HARP spectra..

## Conclusions FW

The thin target analysis for Al (K2K) and Be (MiniBooNE) are completed. Errors have been evaluated carefully and many cross checks, including agreement between UFO and Atlantic and Mock True/Rec give us confidence in our result.

Al cross section paper to be published shortly. Be cross section paper will follow.

Further results (Thick target, $\pi^+/\pi^-$ , $K/\pi$, 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.

During this past year the focus of the analysis was in Forward, given the urgency of K2K and MiniBoone results.

During the next year, the LA analysis will be a major priority.

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

Preliminary $\pi^+/\pi^-$ yields 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.

## Conclusions LA