Hadron Production results from the HARP Experiment

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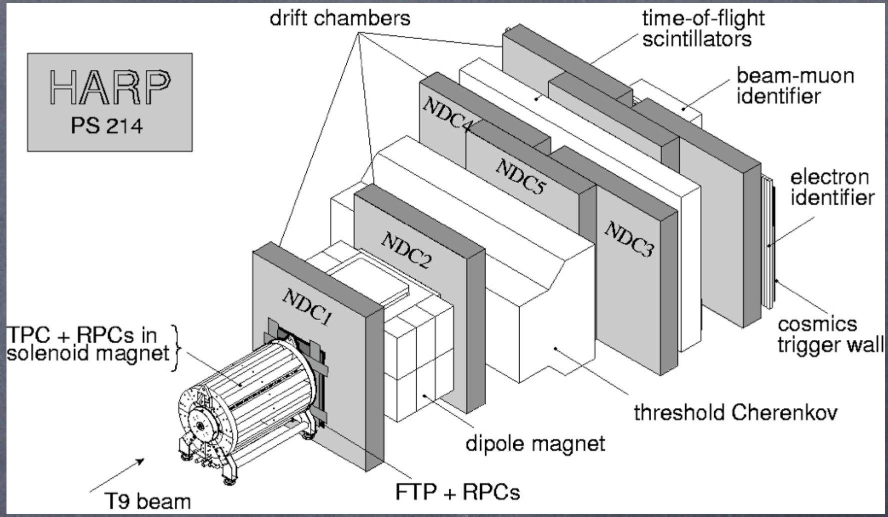
on behalf of the HARP Collaboration
Sendai - TAUP 2007

Outline

- HARP detector description
- Few highlights of calibration and performances
- Relevance for present ν-oscillation experiments
- Measurements dedicated to CR shower development
- Calibration data for NuFact and new beamlines studies
- Data available for general hardron production studies and MC calibration
- Conclusions

HARP

HARP is a full solid-angle spectrometer to measure hadron production from various nuclear targets and a range of incident beam momenta

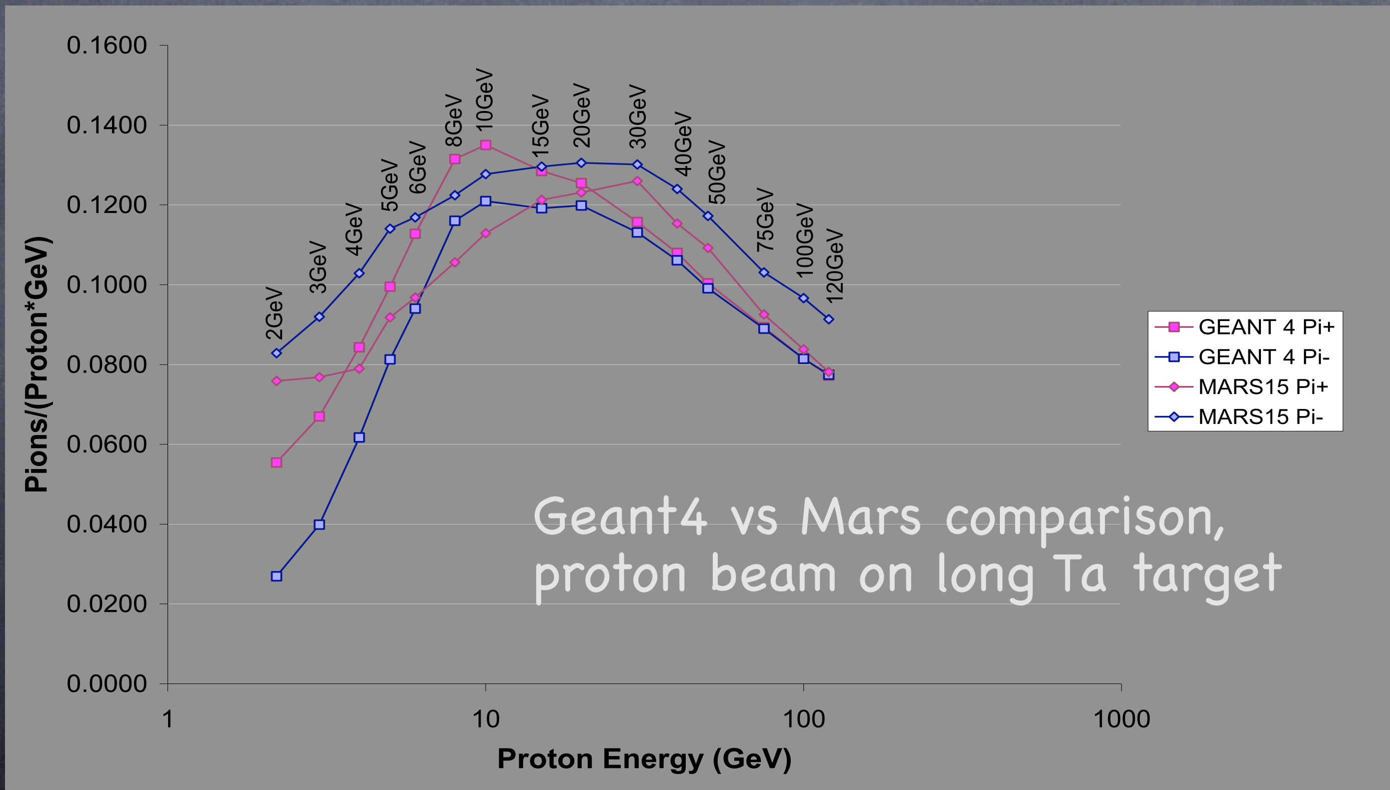


- Nuclear target materials: $A = 1 - 200$
- Nuclear target thickness: $\lambda = 2\% - 100\%$
- Beam particles: p, π^{+-}, e^{+-}
- Beam momenta: $1.5GeV/c - 15GeV/c$
- Measured secondaries: p, π^{+-}, K^{+-}
- Kinematical acceptance:
  - forward:
  $p = 0.5 - 8.0\ GeV/c,\ \theta = 20 - 250\ mrad$
  - large angle:
  $p = 0.1 - 0.7\ geV/c,\ \theta = 350 - 2150\ mrad$

Motivation(s)

- Oscillation experiments (K2K): near, far detectors. Far flux different from near flux (solid angle) in a way that is sensitive to primary hadron (p,θ) distribution.
- Even more so for experiments without near detector (MiniBooNE)
- Also: neutrino cross-sections are poorly known at low energies
- Near detector is/will be also a cross-section measurement device, but PROVIDED FLUX IS KNOWN ... ! (SciBooNE)
- **Hadron production measurements are beneficial for Cosmic Ray studies and detector sumulations**
- Production of secondaries on nuclear targets is complicated to model
- difficult to measure well
- data are sparse
- Monte-Carlos are very uncertain
- absolutely mandatory for neutrino beam experiments

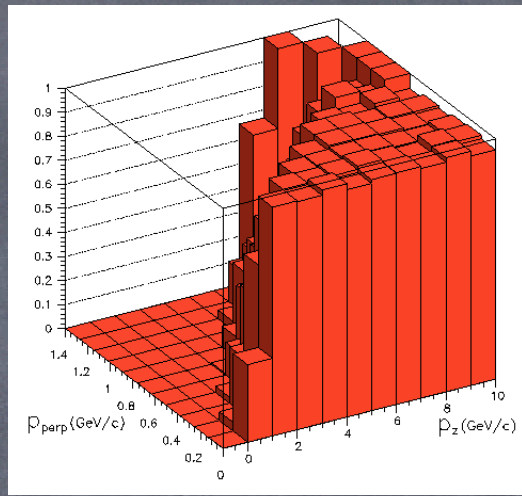
- Neutrino Factory and new ν Beam Design: maximize π^+, π^- production rate (/ proton /GeV)
- Larger discrepancy at lower energy (indicentally, the most interesting one for NuFact)
- Need to choose
  - Primary energy
  - Target material
  - collection geometry and scheme

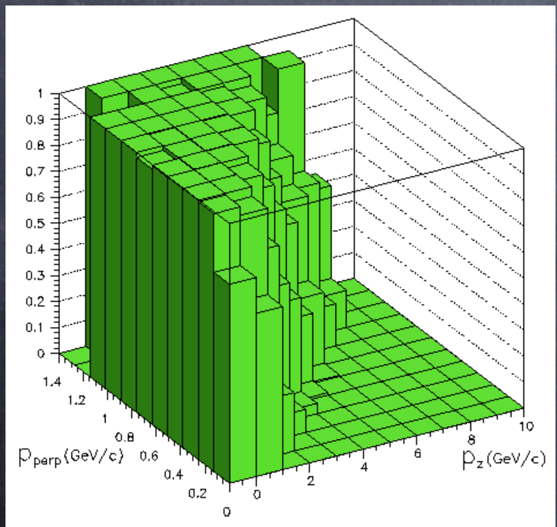


2 matching spectrometers

Large Angle Spectrometer:
Pion production and capture,
Neutrino Factories

- $0.45\ rad < \theta < 2.15\ rad$
- $100\ MeV/c < p < 700 MeV/c$

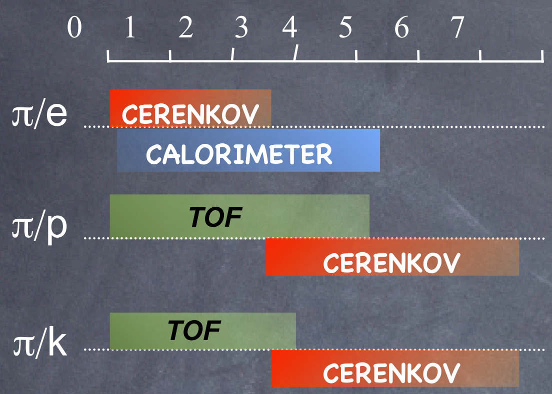


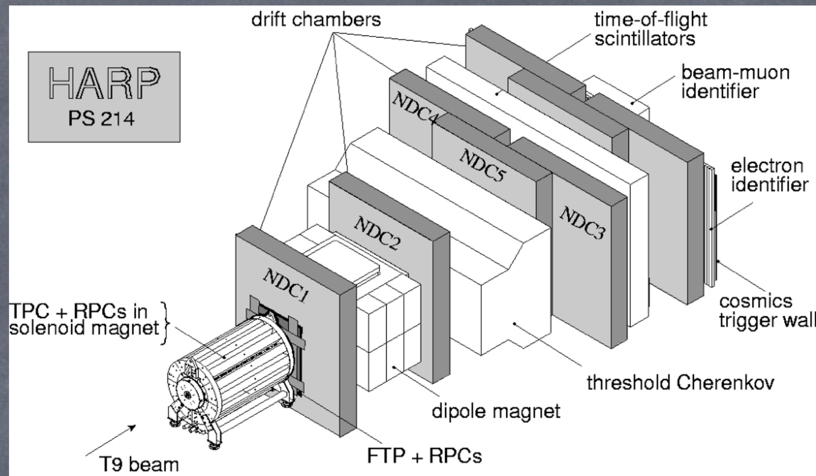


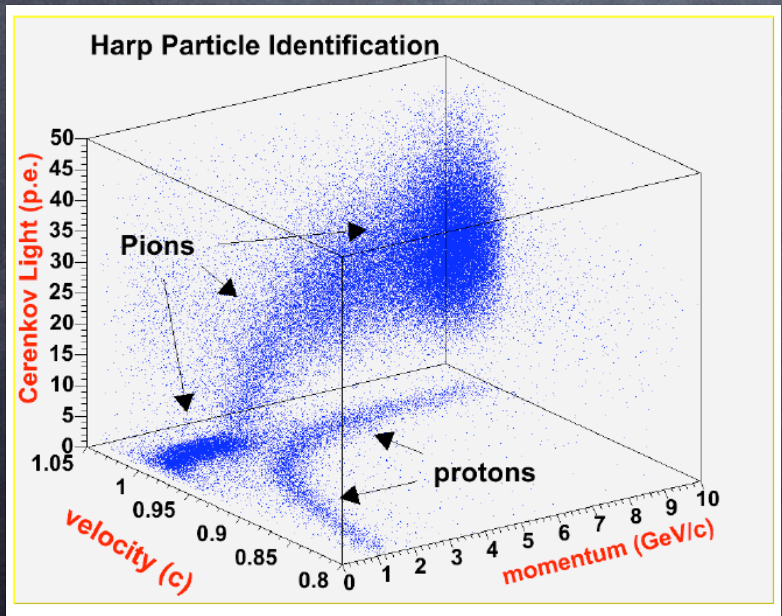
Forward Spectrometer
K2K, MiniBooNe, Cosmic rays

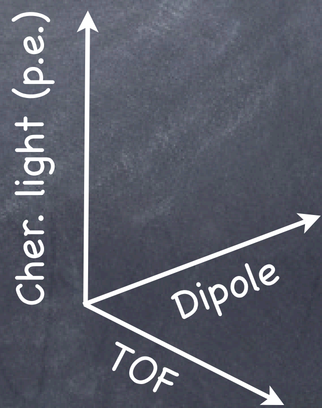
- $30\ mrad < \theta < 210\ mrad$
- $750 MeV/c < p < 6.5 geV/c$

PID + Momentum

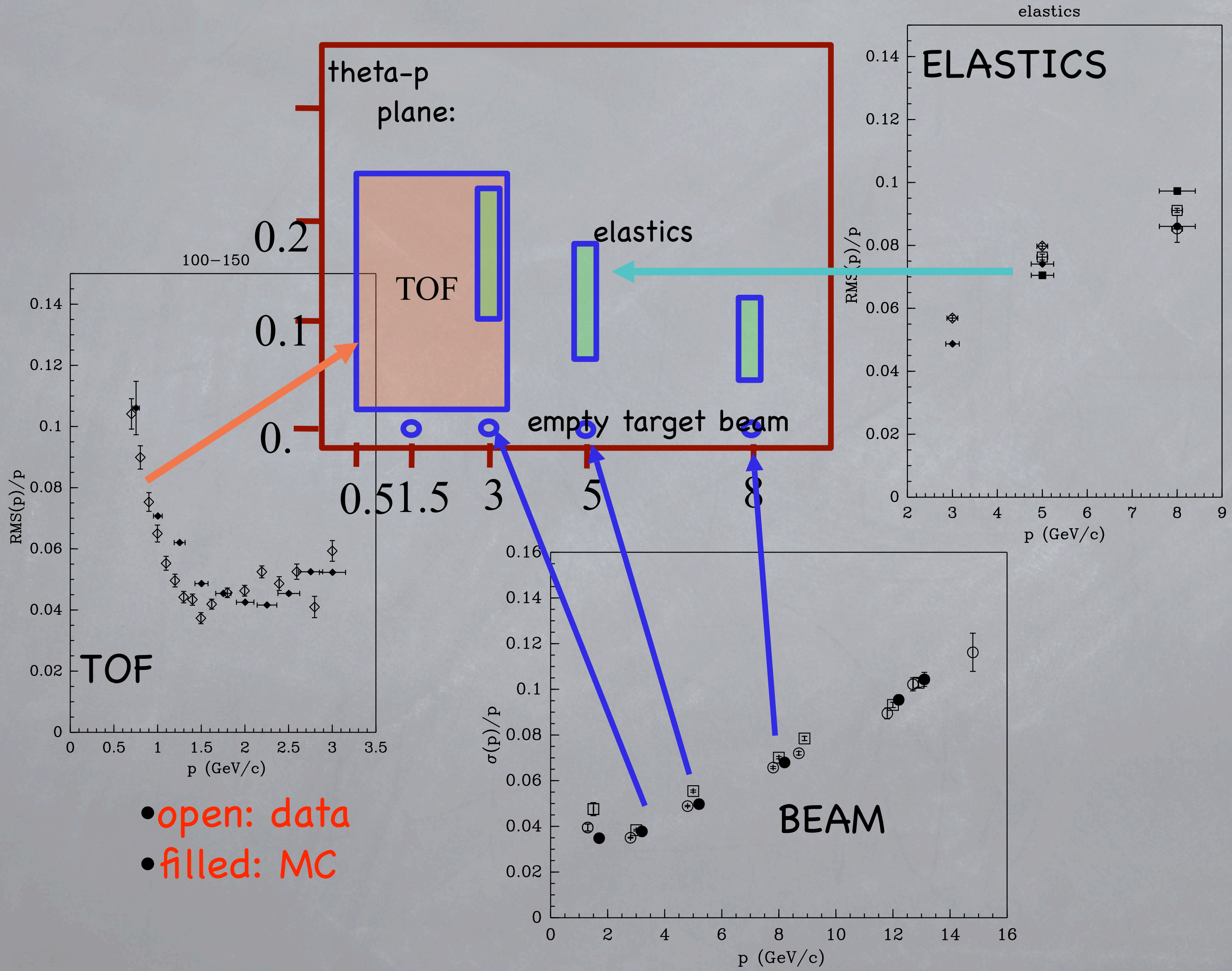








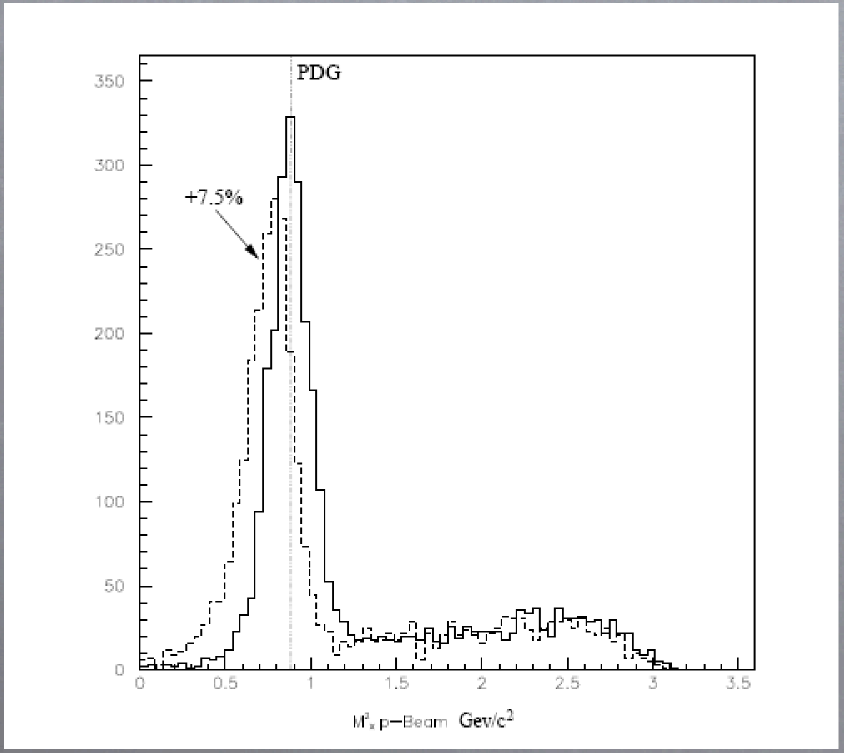
Example of redundancy: checks of momentum resolution

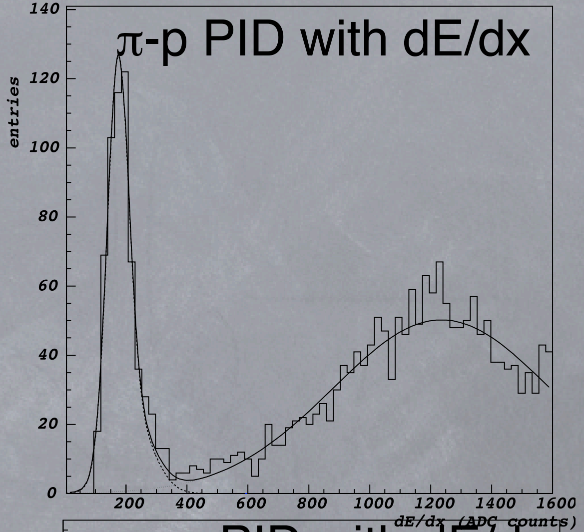


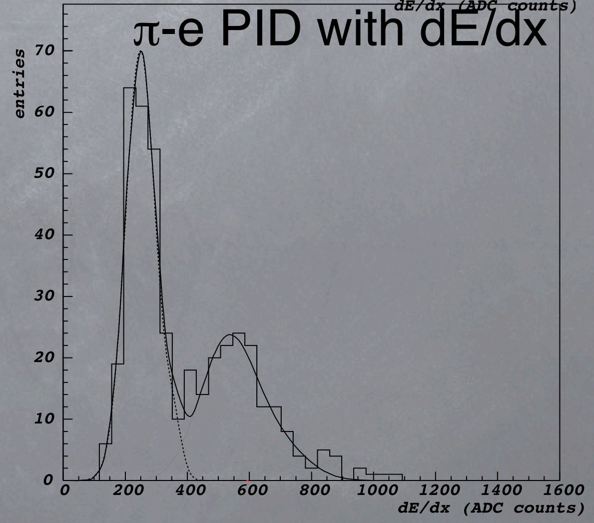
- open: data
- filled: MC

Momentum scale & PID in the TPC

- Elastic scattering of p, π allows to check the resolution and momentum scale
- Particle ID with dE/dx is cross-checked by means of the barrel RPC TOF system to evaluate efficiency





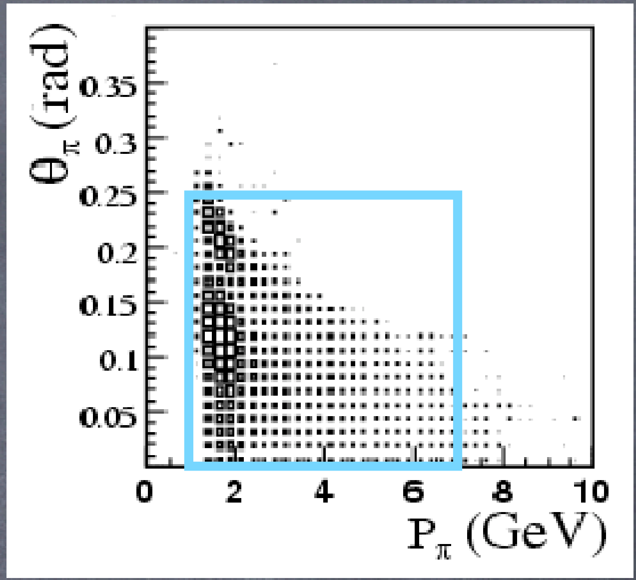


Papers on Detectors and Performance description

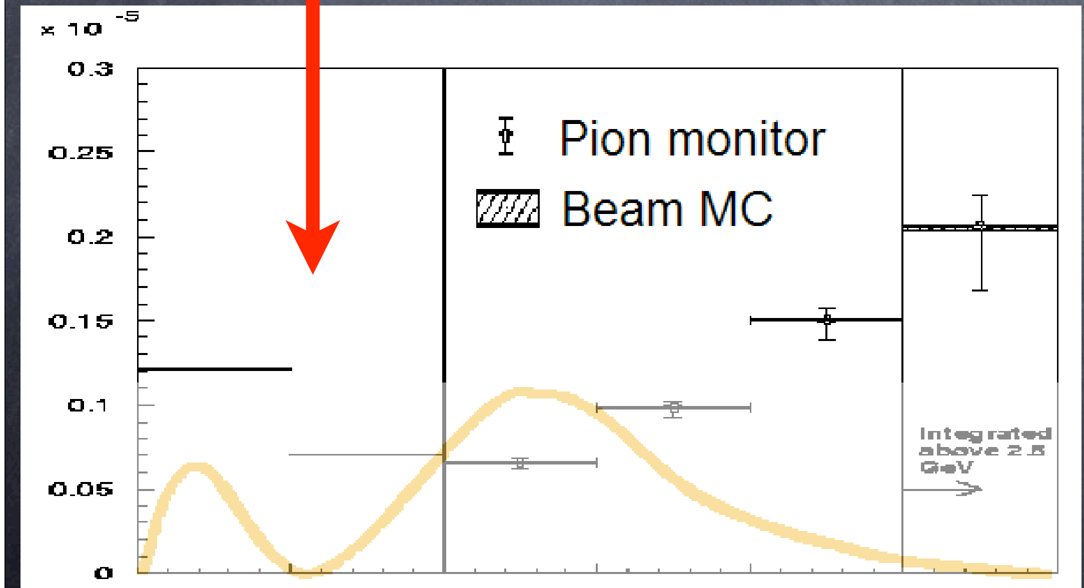
- Laser-Based Calibration for the HARP Time of Flight System - M. Bonesini et al, IEEE TRANS. NUCL. SCIENCE, VOL. 50, NO. 4, AUGUST 2003 1053
- The time-of-flight TOFW detector of the HARP experiment: construction and performance - M. Baldo-Ceolin et al, Nucl. Instr. Meth. A 532 (2004) 548-561
- Physics Performance of the Barrel RPC System of the HARP Experiment -Bogomilov et al. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 54, NO. 2 (2007)
- Particle identification algorithms for the HARP forward spectrometer - M. G. Catanesi et al, Nucl.Instrum.Meth. A521: 899-921 (2007)
- The HARP Detector at the CERN PS - G. Catanesi et al Nucl. Instrum. Meth. A571: 527-561 (2007), 564-573(2007) - V. Ammosov et al, Nucl. Instrum. Meth. A571: 561-564 (2007)

Relevance for K2K

One of the most relevant K2K systematic errors comes from the uncertainty in the near/far extrapolation



Region of $\nu_\mu \to \nu_\tau$ Oscillation maximum: only Beam MC

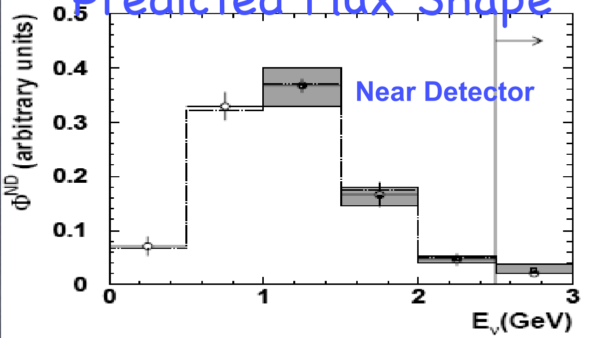


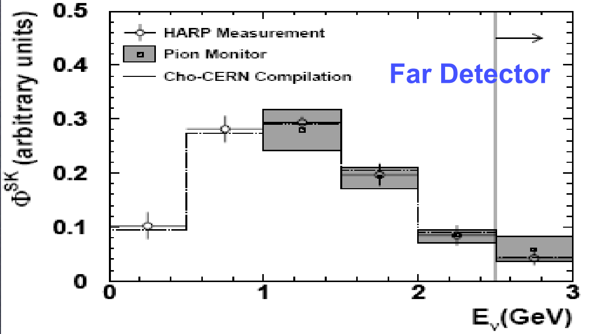
Pions producing ν at the oscillation peak $0.5 < E_\nu < 0.75\ [GeV/c]$:

- $P_\pi > 1\ GeV/c$
- $\theta_\pi < 250\ mrad$

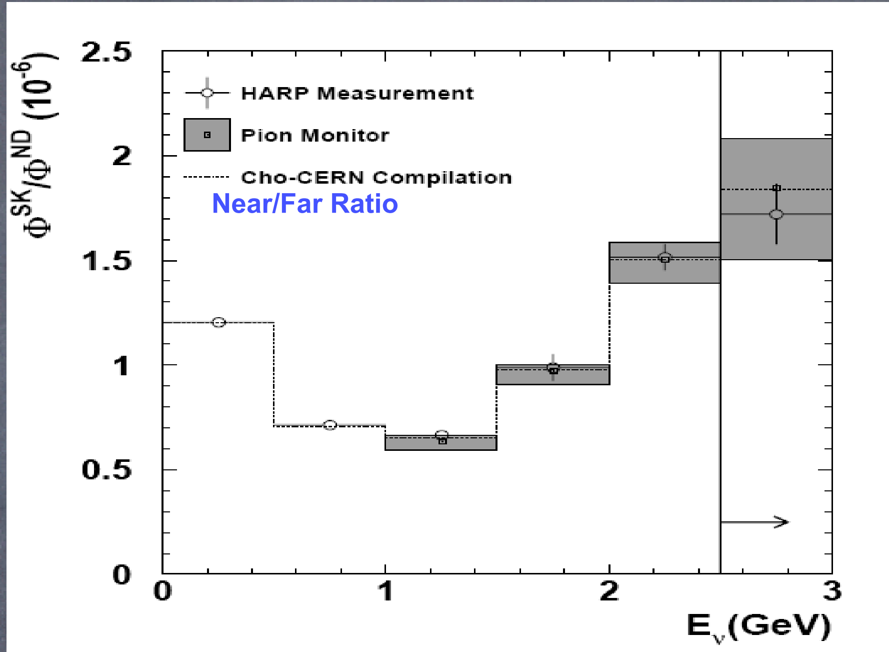
Far/Near Ratio in K2K

Predicted Flux Shape





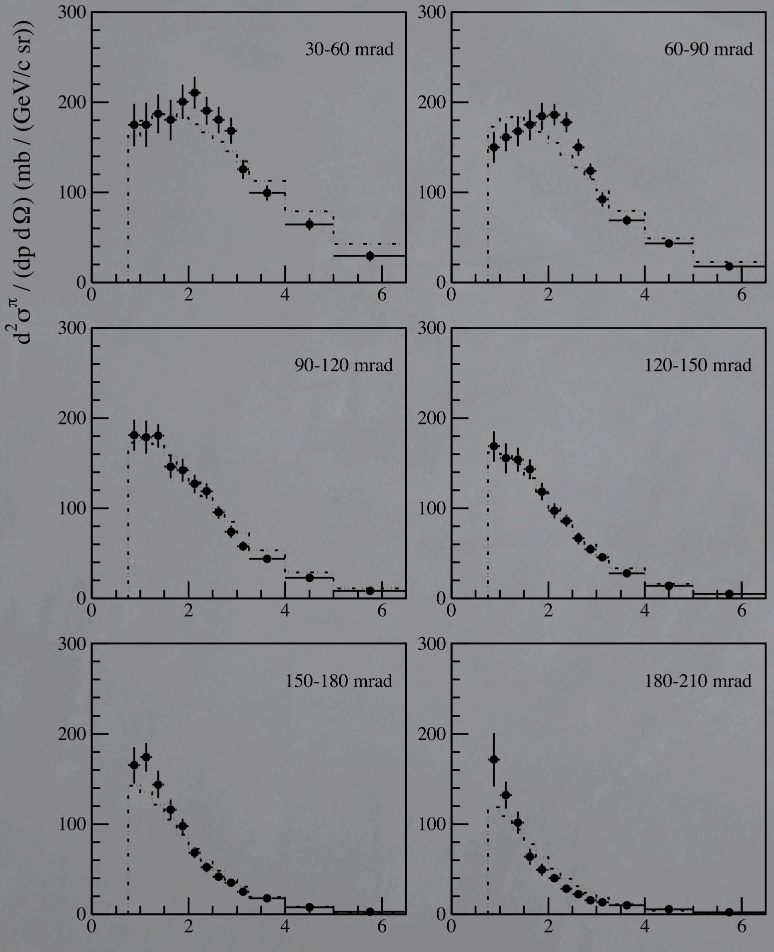
Predicted Far/Near Ratio



HARP gives ~ factor 2 error reduction across all energies

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

HARP Be 5% 8.9 GeV/c Results

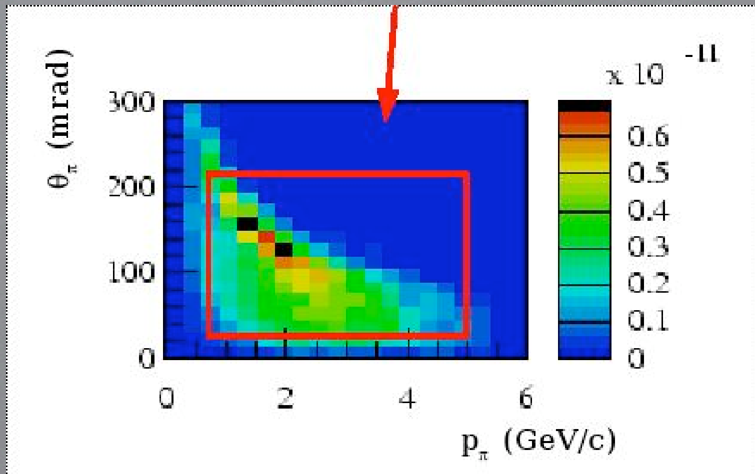


HARP results (data points), parametrization of HARP results (histogram)

Relevance for MiniBooNE:

- $0.75 < p < 5[GeV/c]$
- $30 < \theta < 210[mrad]$

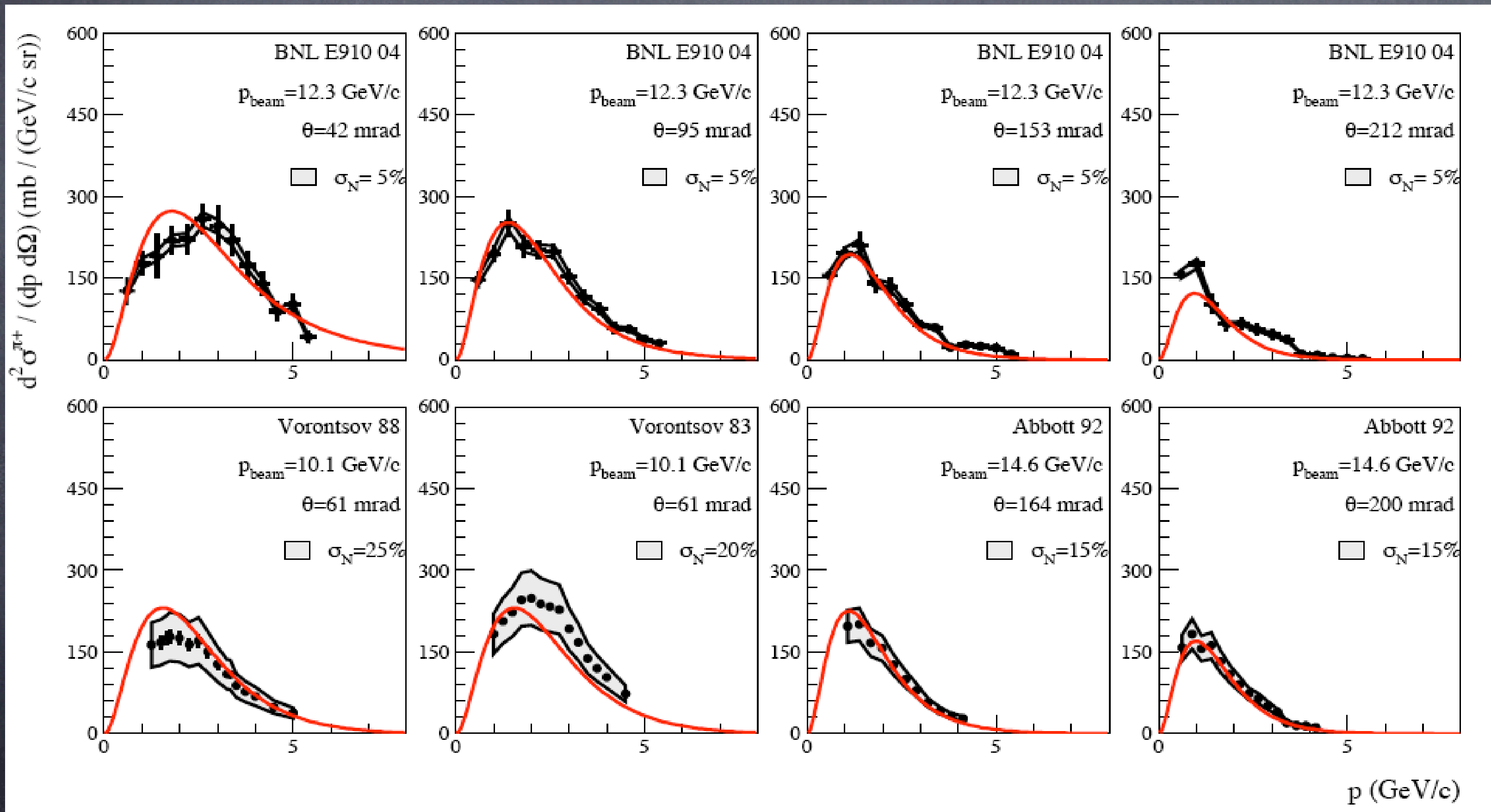
- MiniBooNE ν cross-section measurement by SciBooNE
- HARP data will provide useful normalization to SciBooNE too.



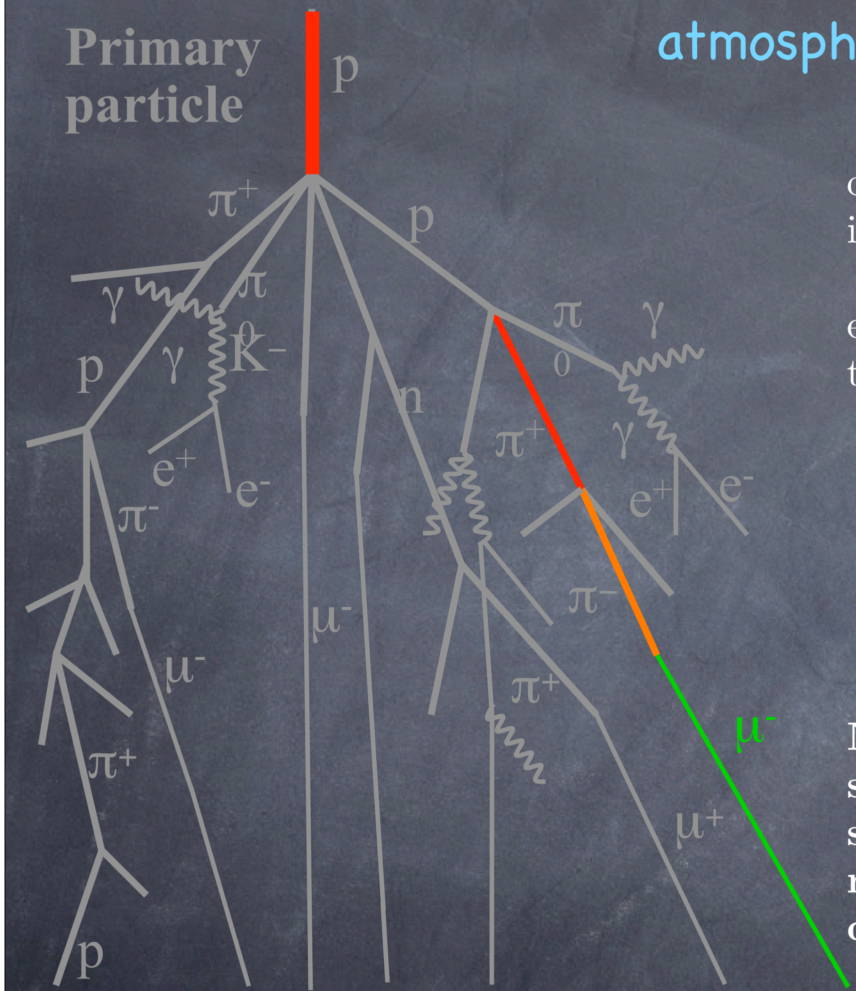
Momentum and Angular distribution of pions decaying to a neutrino that passes through the MB detector.

D. Schmitz

Comparison with older data data
(at different beam momenta)



Measurements relevant for air showers and atmospheric neutrino flux



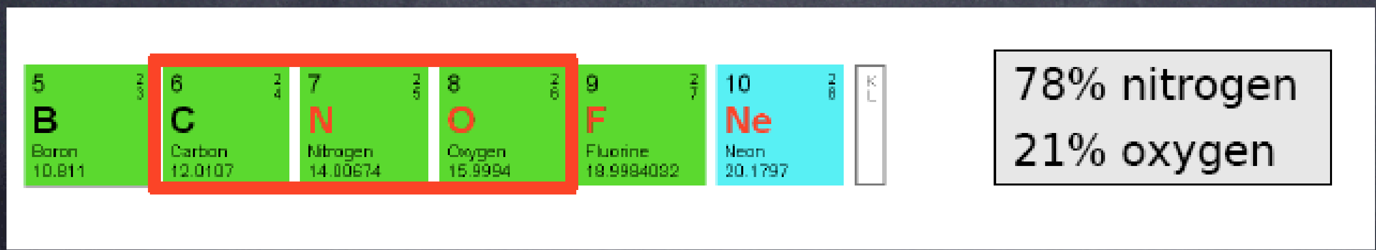
Most of the uncertainty comes from lack of data to construct a reliable hadron interaction model at *low* energy

One is now obliged to *model-dependent* extrapolations, leading to $\approx 30\%$ uncertainty in the computed fluxes.

Several measurements:

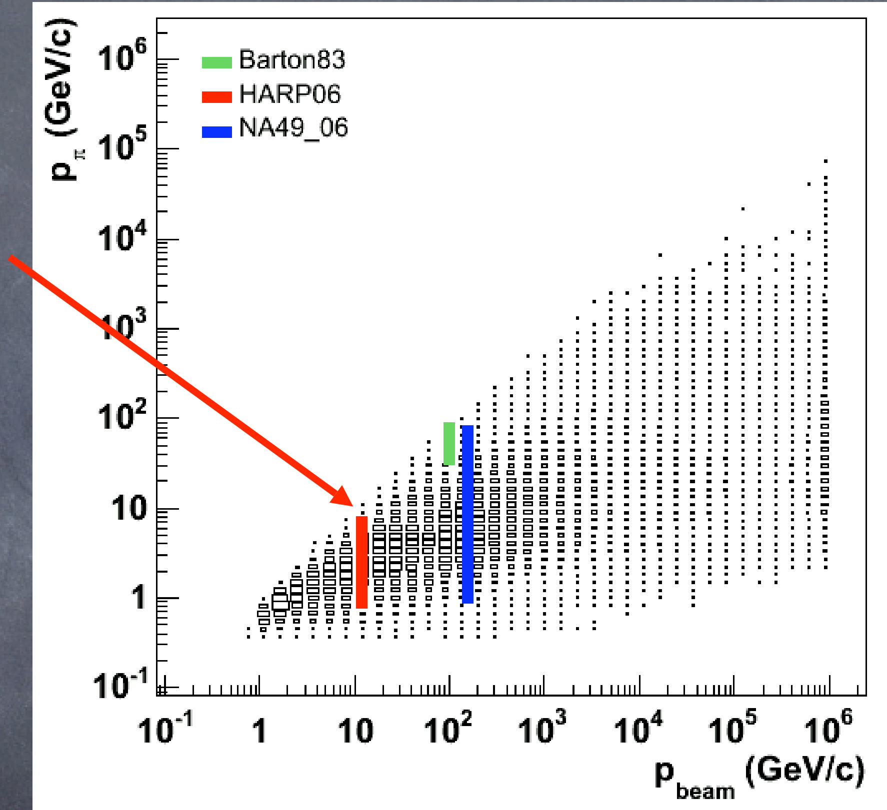
- Carbon, Liquid N_2 and O_2
- Positive and Negative beams: (p, π^+, π^-)
- Several beam energies

Notice, incidentally, that the same problems stand for precise (*predictive*) detector simulation for LHC experiments: lack of data to reliably simulate hadron showers (however in different materials)



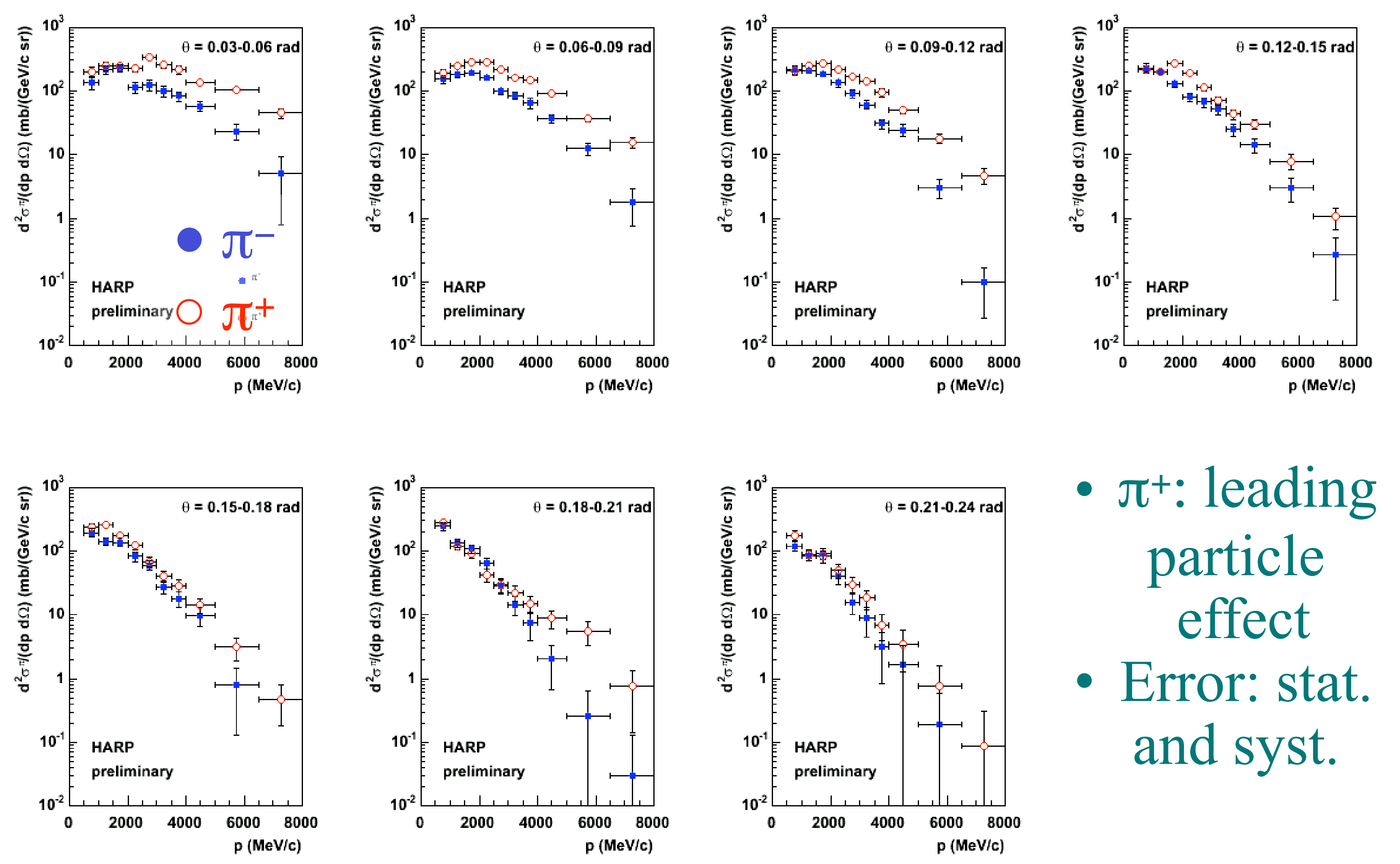
Phase space region

- New data sets
  (p+C, π^++C and π^-+C at 12 GeV/c)
- Important phase space region covered
- Data available for model tuning and simulations
- N2 and O2 data being processed now



[Barton83] Phys. Rev. D 27 (1983) 2580 (Fermilab)
[NA49_06] Eur. J. Phys., hep-ex/0606028 (SPS)
HARP (PS)

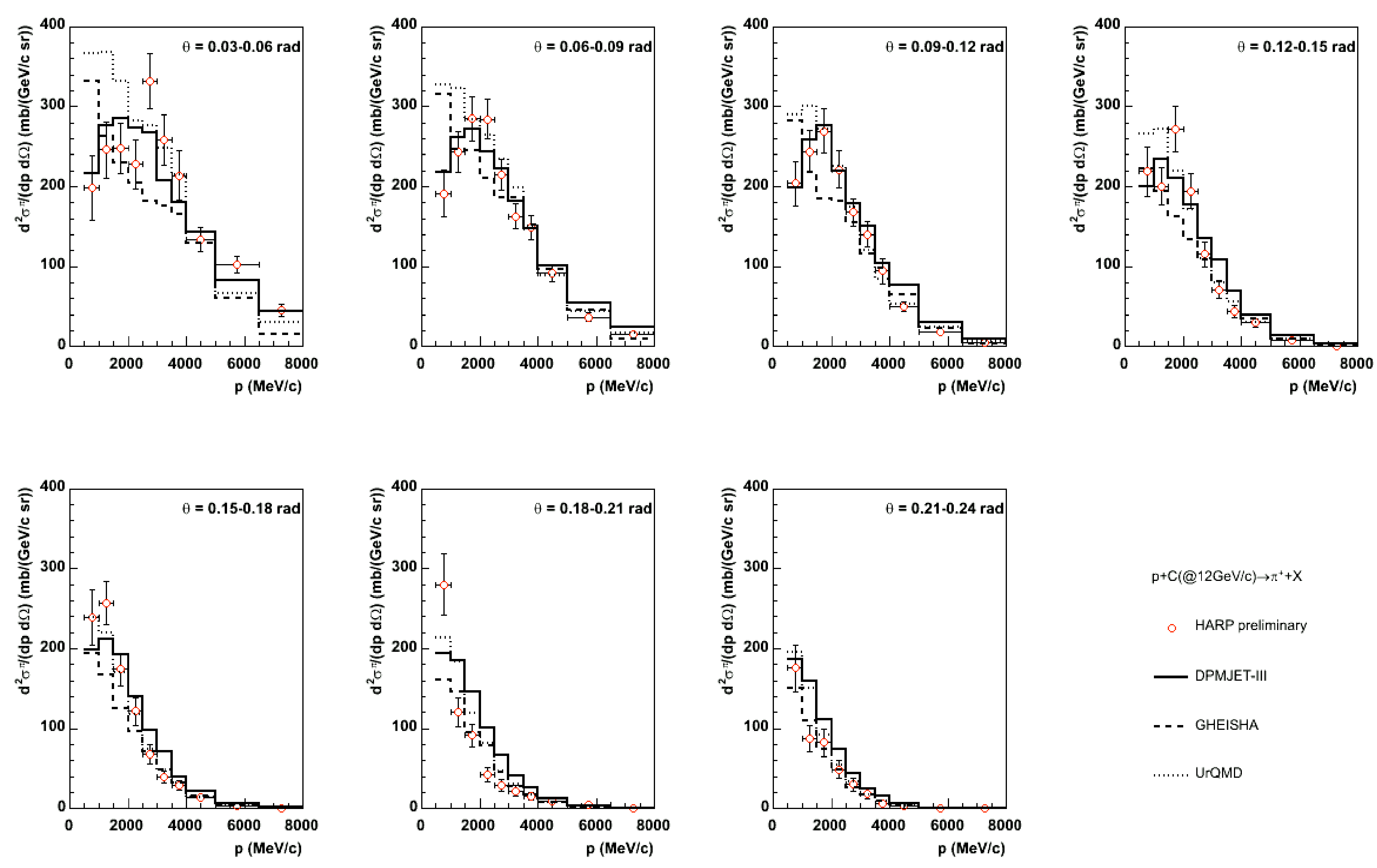
p+C @ 12 GeV/c



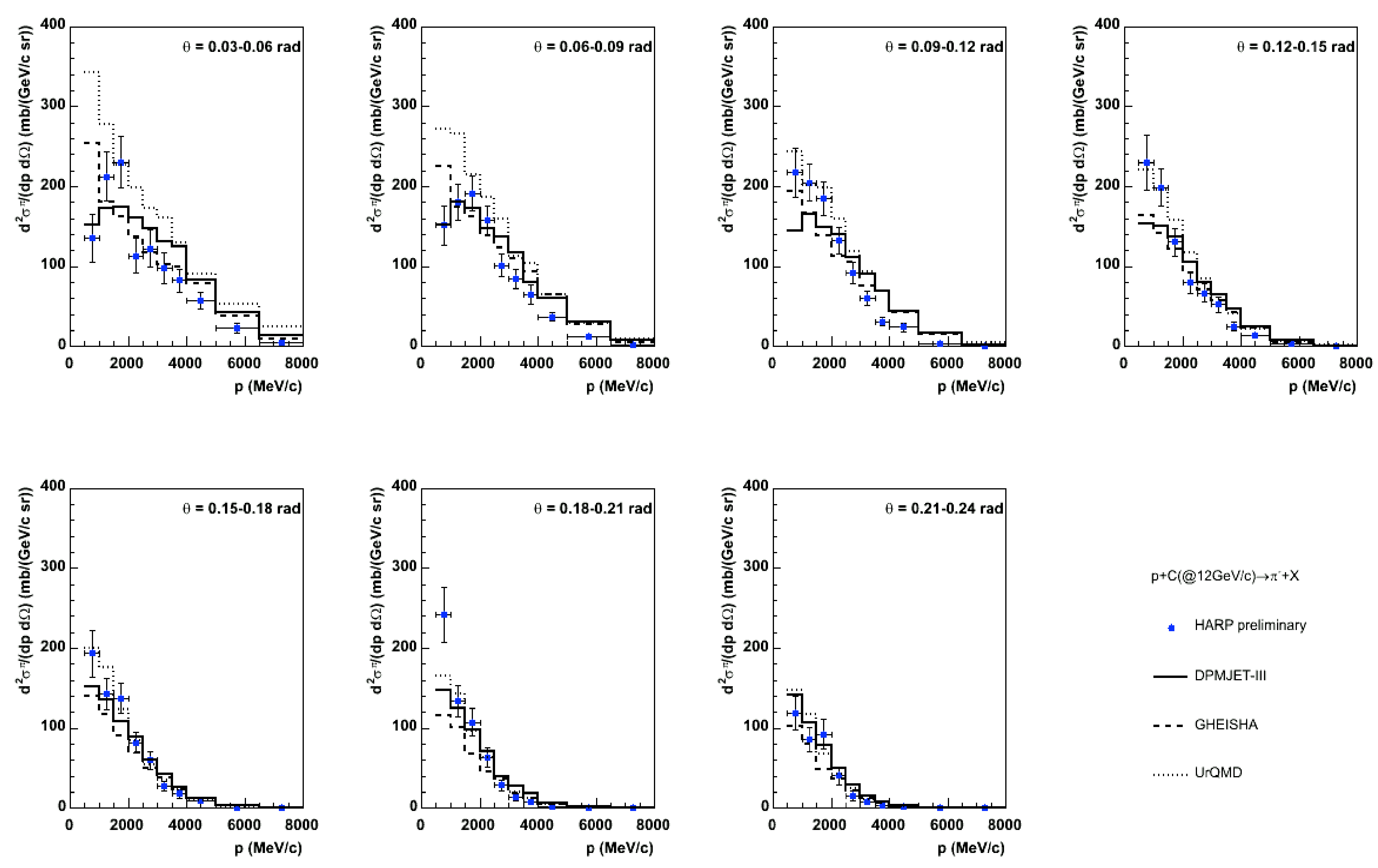
- π^+: leading particle effect
- Error: stat. and syst.

Draft in preparations

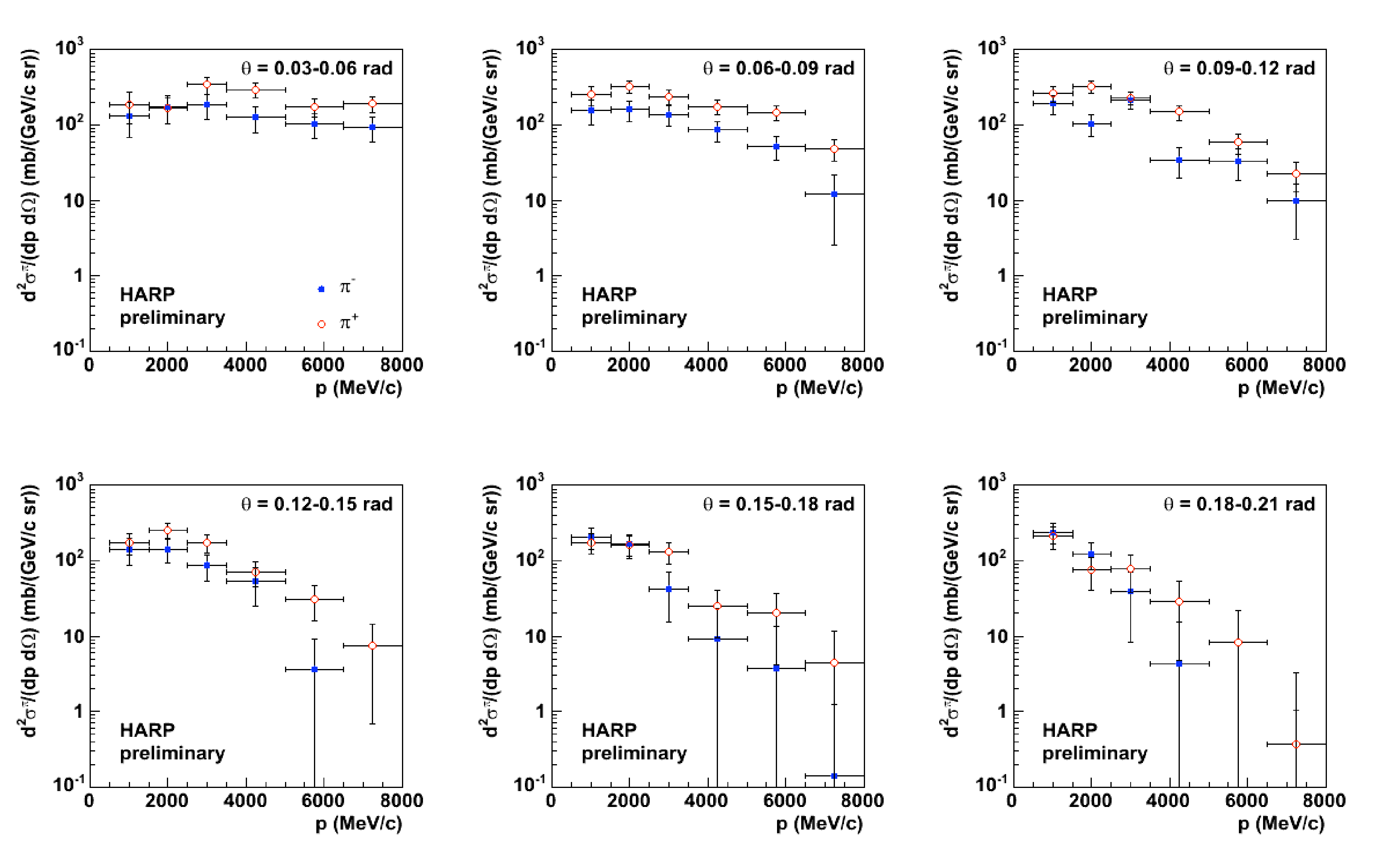
Model comparison: p+C→π⁺+X



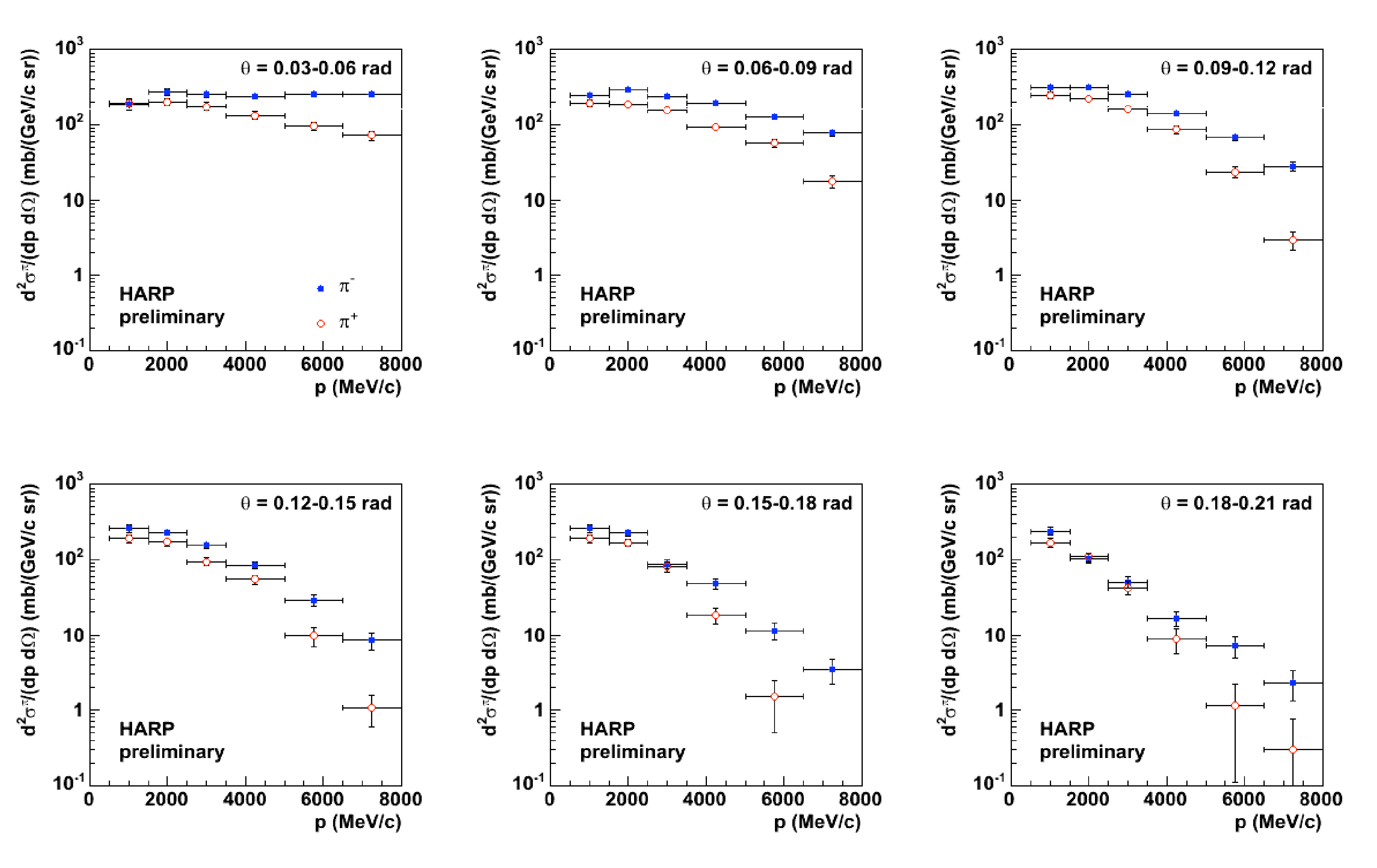
Model comparison: $p+C \to \pi^- + X$



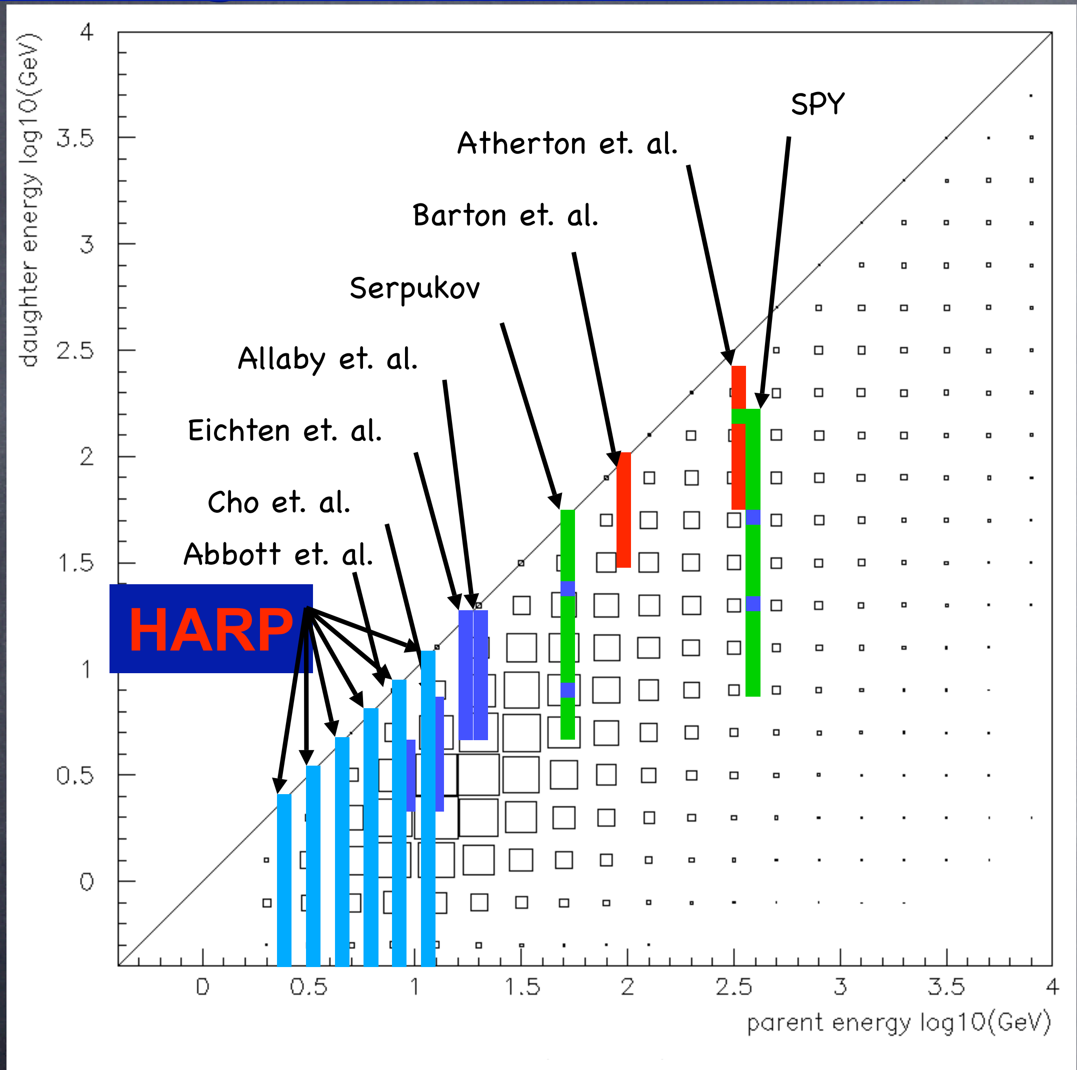
π^++C @ 12 GeV/c (lower statistics)



π^-+C @ 12 GeV/c (high statistics)



New Harp measurements



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

Measurements:

1-2 p_T points

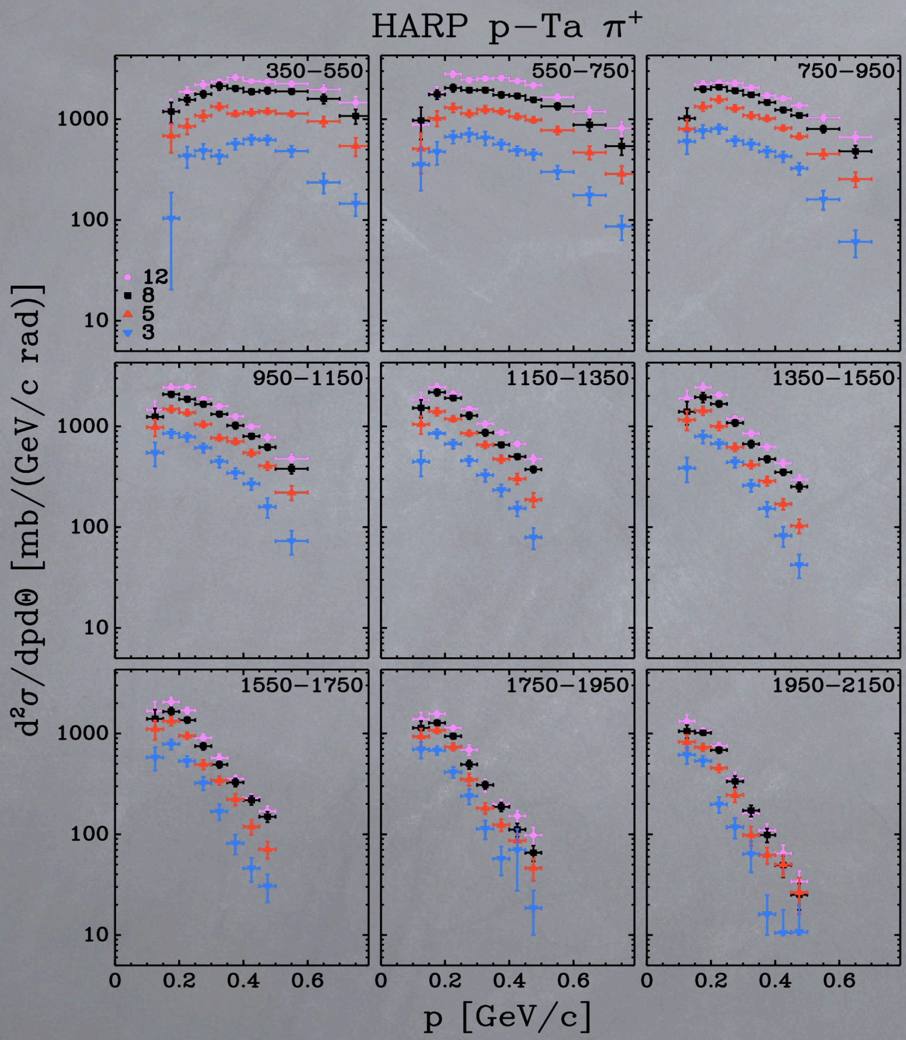
3-5 p_T points

>5 p_T points

Forward-region papers

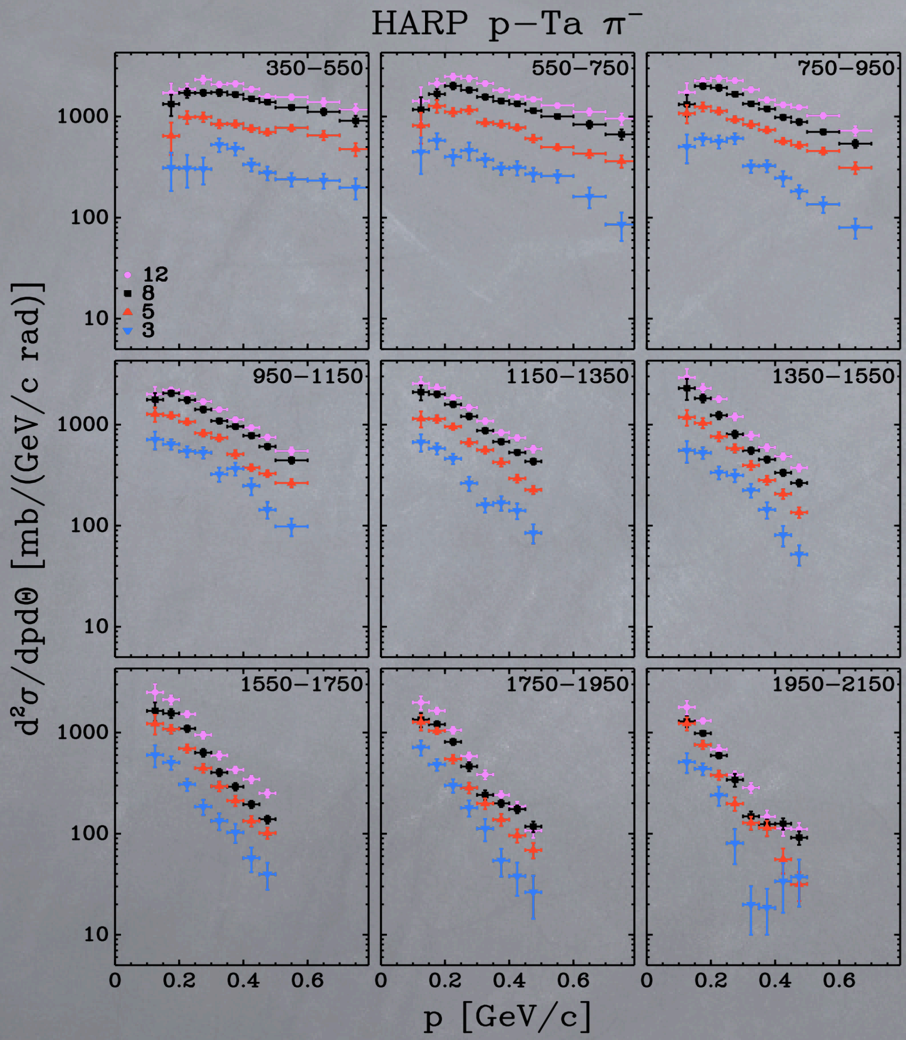
- **Measurement of the production cross-section of positive pions in p-Al collisions at 12.9 GeV/c (K2K target measurement)** - M.G. Catanesi et al, hep-ex/0510039, Nucl. Phys. B732: 1-45 (2006)
- **Measurement of the production cross-section of positive pions in the collision of 8.9 GeV/c protons on beryllium** (MiniBooNE target measurement) - M.G. Catanesi et al, hep-ex/0702024v2 to appear in Eur. Phys. J. C
- Thick + replica targets are on the way
- **In preparation: Charged pion production by 3 GeV/c-12 GeV/c protons on a carbon target** (Atmospheric Flux)

Large-Angle analysis, p+Ta 3,5,8,12 GeV/c



forward
$0.35 < \theta < 1.55$

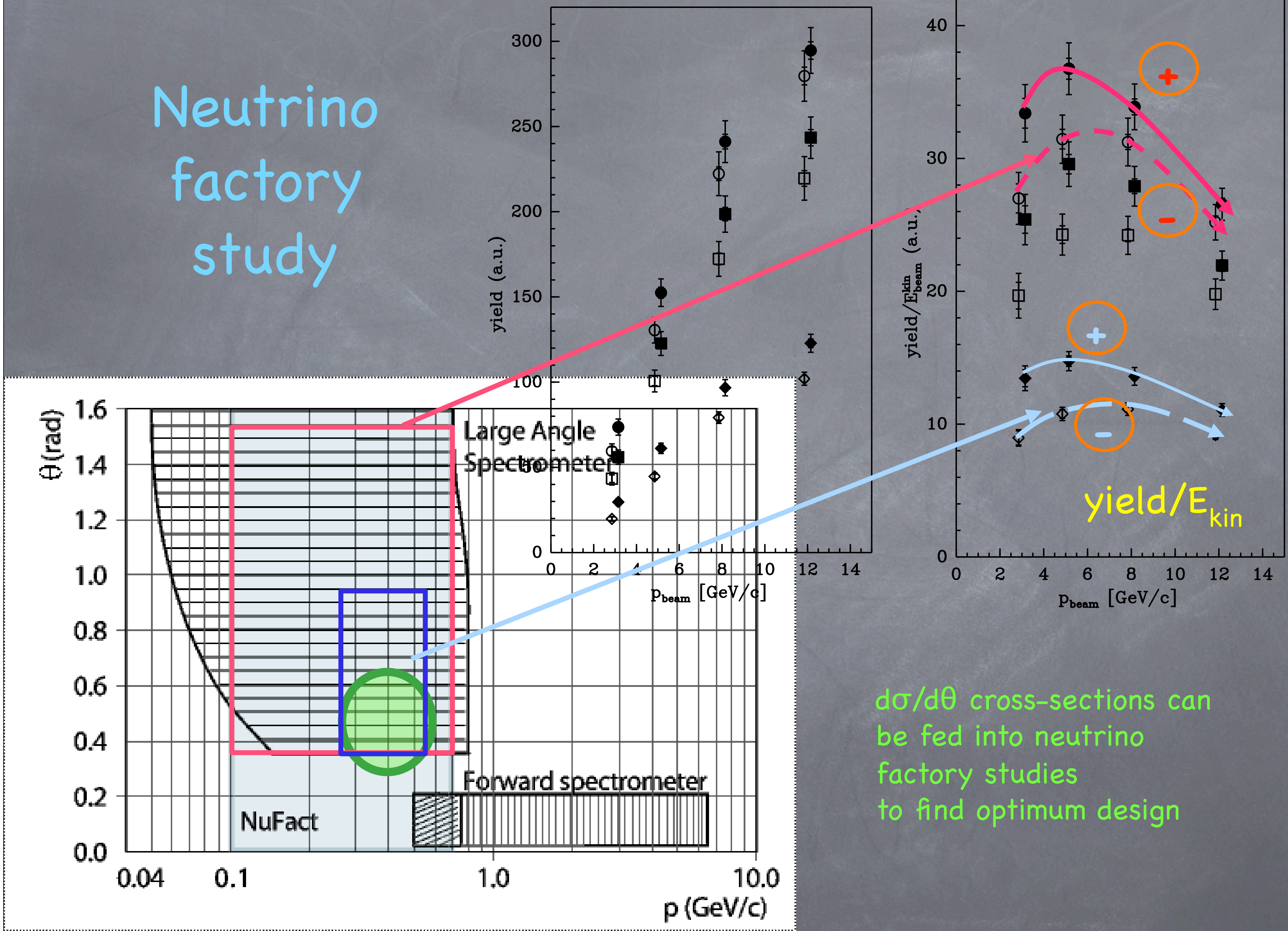
backward
$1.55 < \theta < 2.15$



forward
$0.35 < \theta < 1.55$

backward
$1.55 < \theta < 2.15$

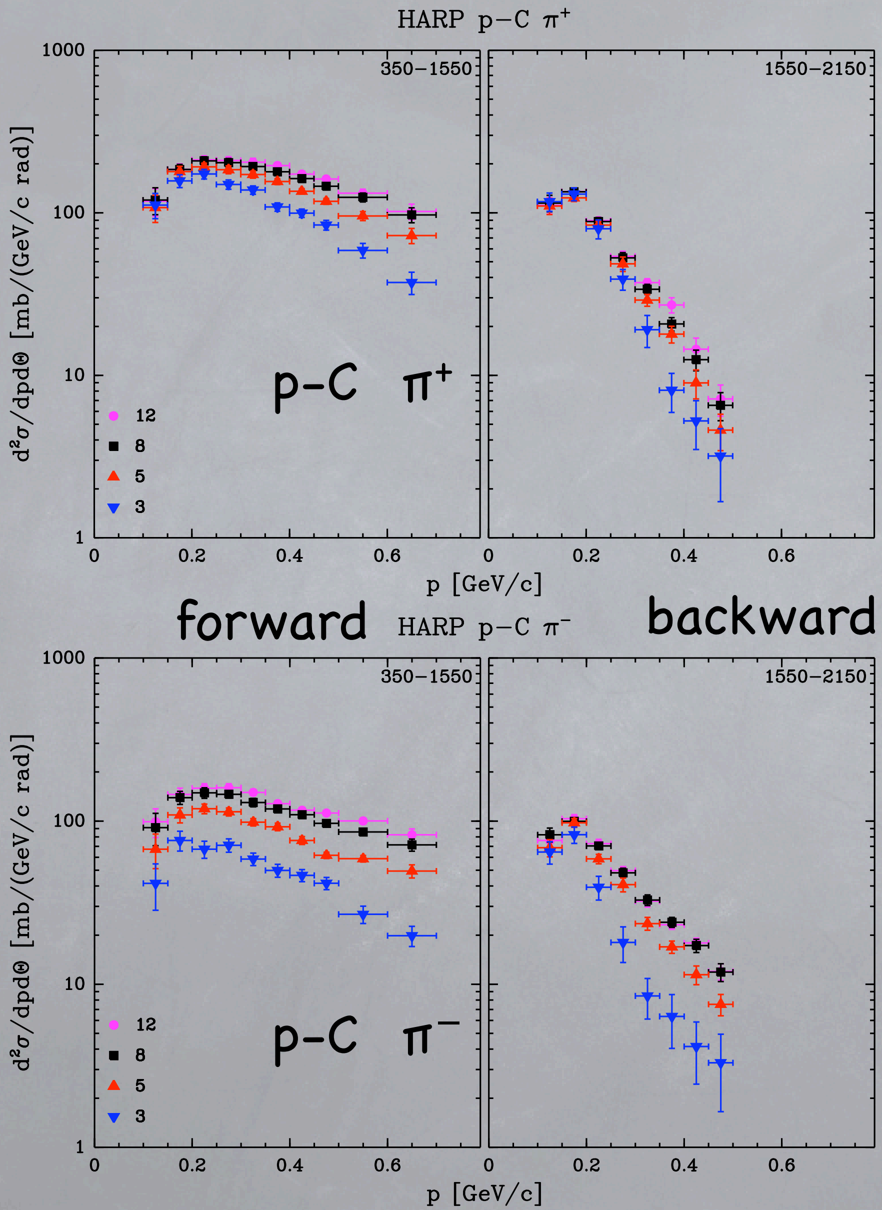
Neutrino factory study



dσ/dθ cross-sections can be fed into neutrino factory studies to find optimum design

Hadronic generators

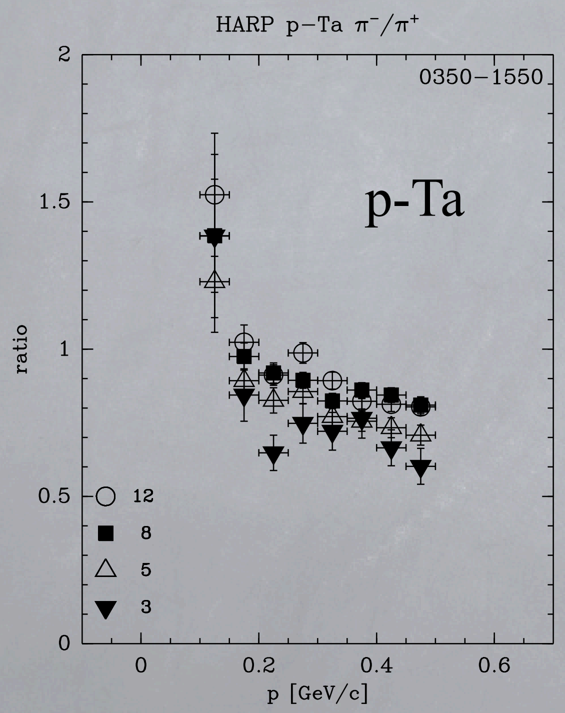
- Little experimental data to develop/calibrate the models --> large uncertainties
- Many targets at different beam energies and full solid-angle -->
- Input calibration data for hadronic generators (collaboration with GEANT-4)
- What follows is a collection of examples of secondary particle distributions

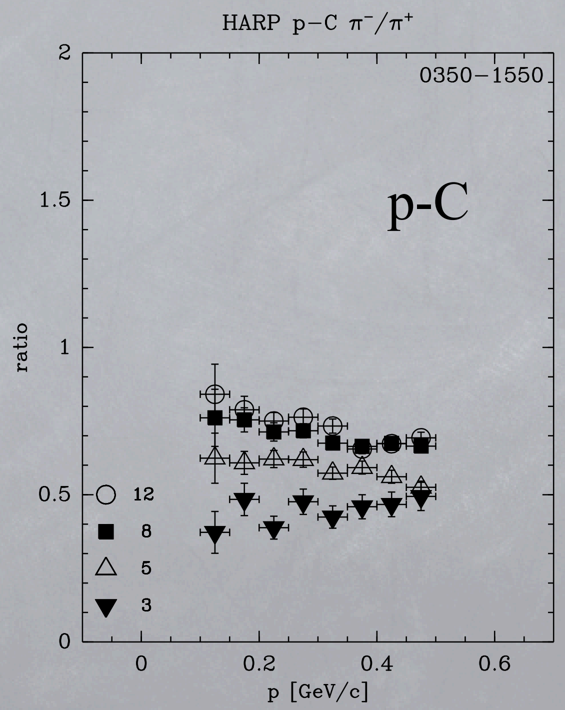


p-C data as an example of many other available spectra

comparison of p-C π^-/π^+ and p-Ta π^-/π^+ ratios

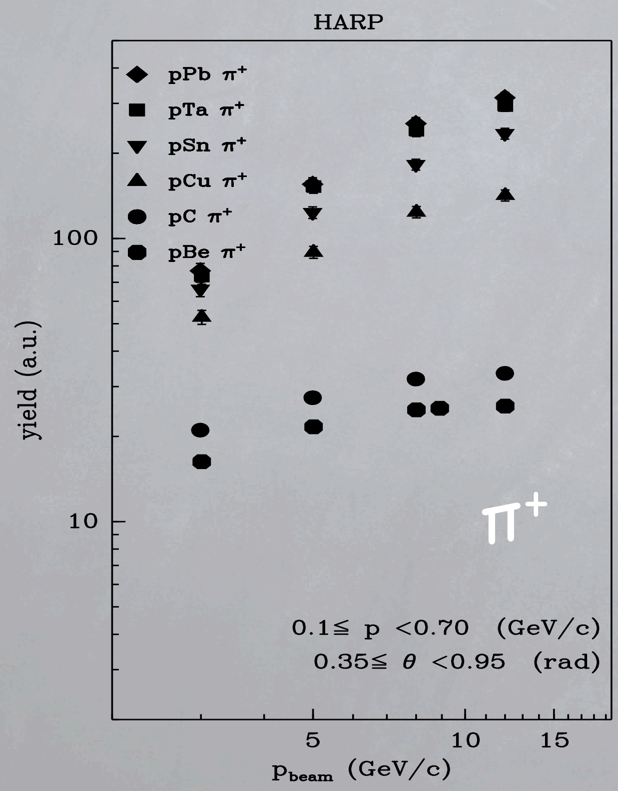
forward production only $0.35 < \theta < 1.55$ rad

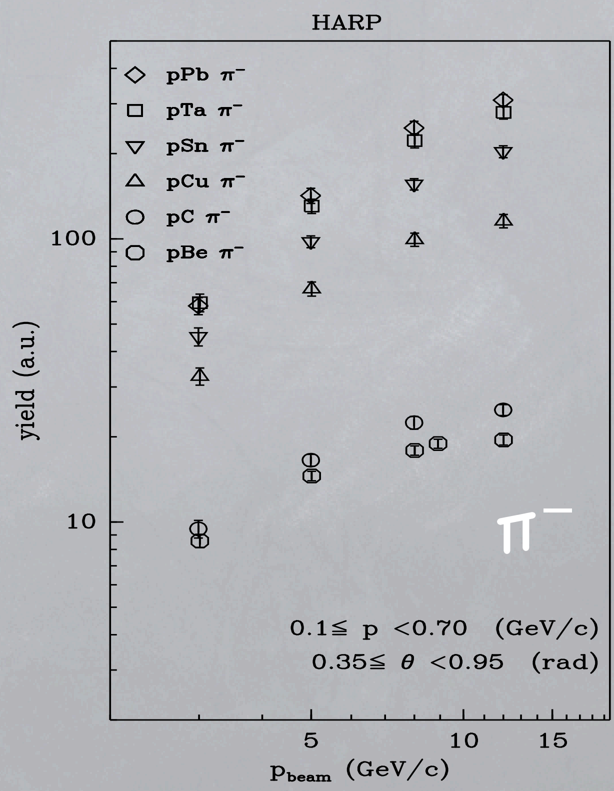




comparison of π^+ and π^- and yields for p-A for Be, C, Cu, Sn, Ta and Pb

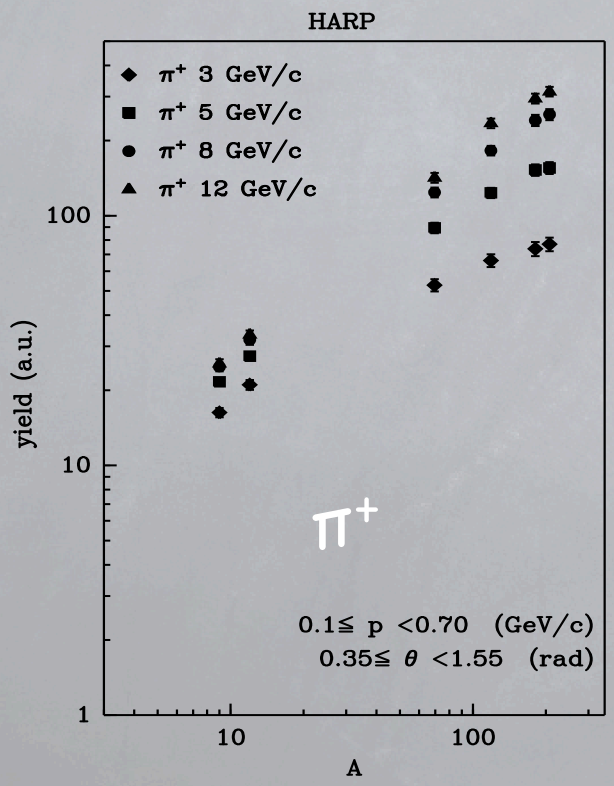
forward production only 0.35 < θ < **0.95** rad

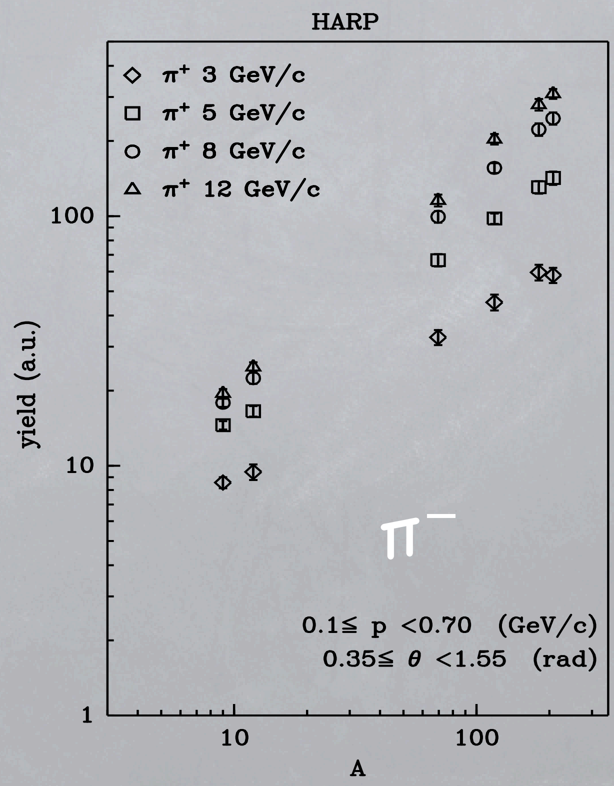




A-dependence of π⁺ and π⁻ and yields for p-A for Be, C, Cu, Sn, Ta and Pb (3, 5, 8, 12 GeV/c)

forward production only 0.35 < θ < **1.55** rad





papers on Large Angle analysis

- **Measurement of the production of charged pions by protons on a tantalum target** - M.G. Catanesi et al, arXiv: 0706.1600v1 to appear in Eur. Phys. J. C
- **Charged pion production by 3 GeV/c-12 GeV/c protons on a carbon target** - M.G. Catanesi et al, submitted to Eur. Phys. J. C
- **Large-angle production of charged pions by 3 GeV/c-12 GeV/c protons on copper and tin targets** - M.G. Catanesi et al, submitted to Eur. Phys. J. C
- **In preparation: Large-angle production of charged pions by 3 GeV/c -12.9 GeV/c**

Conclusions

- HARP has taken a comprehensive set of data and begin to produce hadron production cross-sections with errors in the 4-8% range over a large fraction of phase-space
- Started with forward analysis for K2K and MiniBooNE and large-angle analysis for Tantalum (NuFact) - only pions
- Will continue with analysis of other targets (automated procedure)
- Analysis improvements to come:
  - Forward Kaon production
  - Large angle analysis full spill analysis (better statistics - and maybe also systematics)
  - Thick targets (for tertiary production and real neutrino targets)