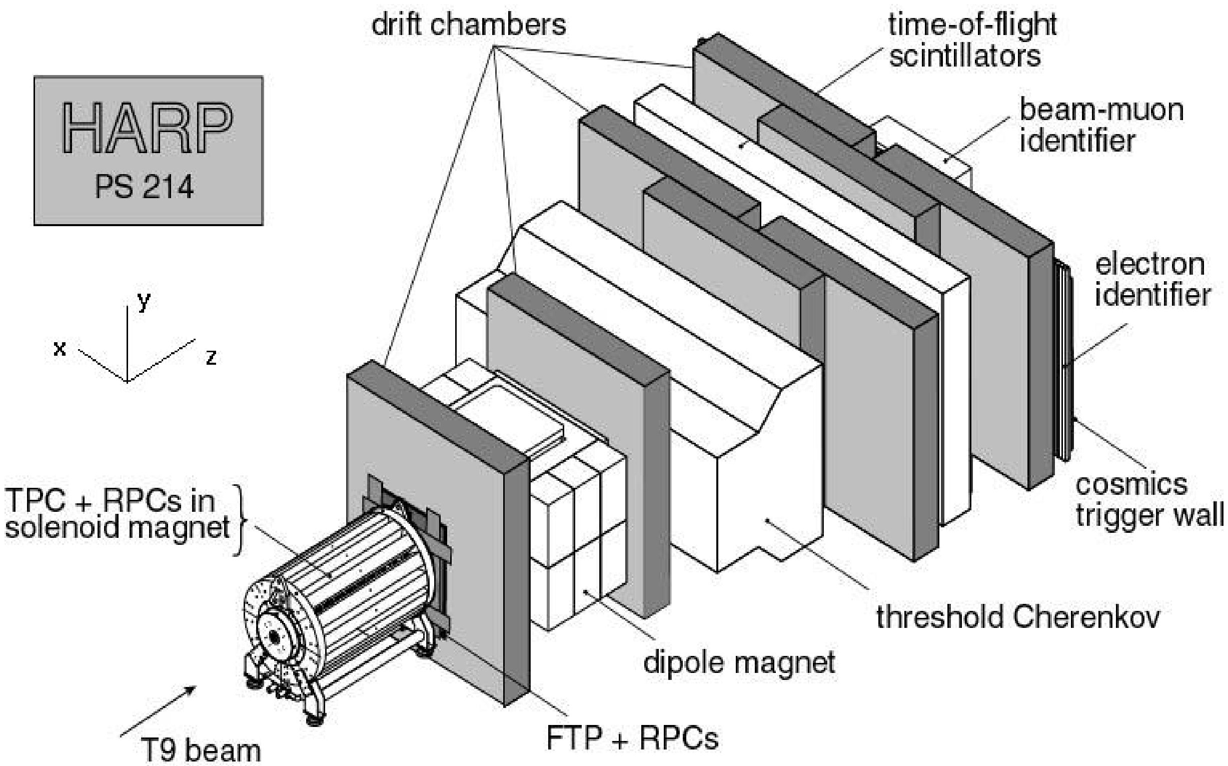
Results from HARP

and their implications for neutrino physics

Rencontres des Moriond 2007, Electroweak Interactions and Unified Theories

Boris A. Popov (JINR, Dubna)
for the HARP Collaboration

- HARP experiment
- Physics goals
- Results and Impacts
- Possibilities
- Conclusions



HARP – PS214 at CERN

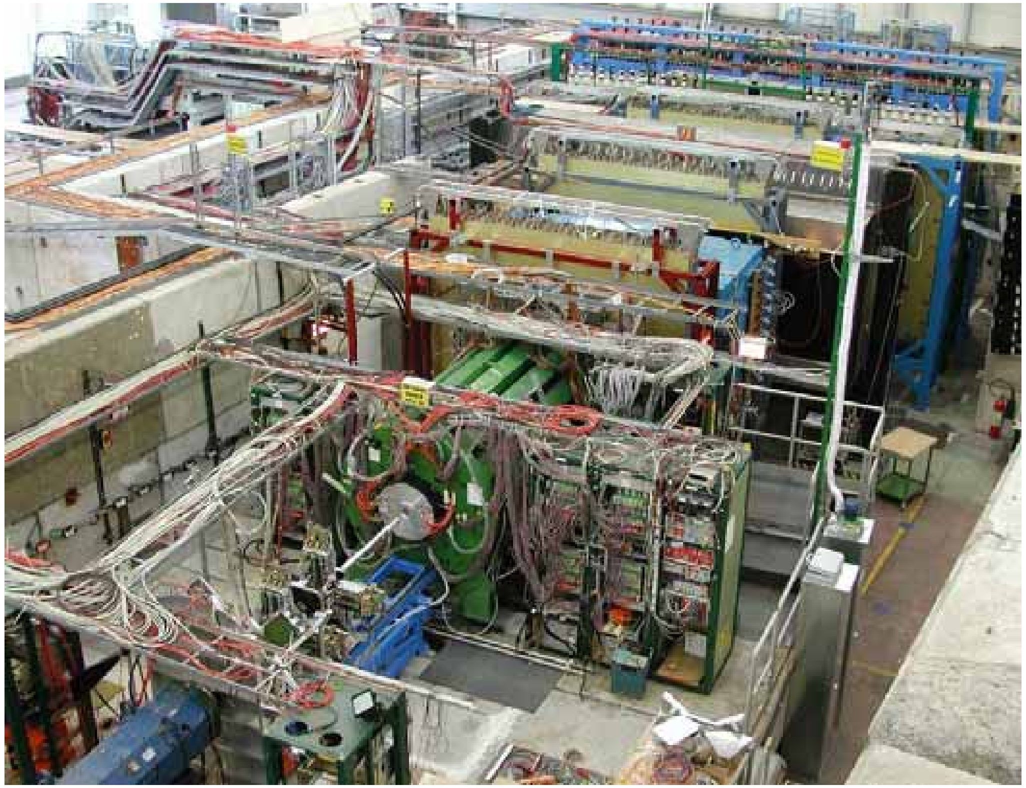
HARP is a large angle spectrometer to measure hadron production from various nuclear targets and a range of incident beam momenta

- Nuclear target materials : A = 1 – 200
- Nuclear target thickness : λ = 2 – 100 %
- Beam particles : h = p, π^{+-}, e^{+-}
- Beam momenta : p_{beam} = 1.5 – 15 GeV/c
- Secondaries measured : h = p, π^{+-}, K^{+-}
- Kinematic acceptance

p = 0.5 – 8.0 GeV/c θ = 20 – 250 mrad (forward)

p = 0.1 – 0.7 GeV/c θ = 350 – 2150 mrad (large angle)

forward spectrometer



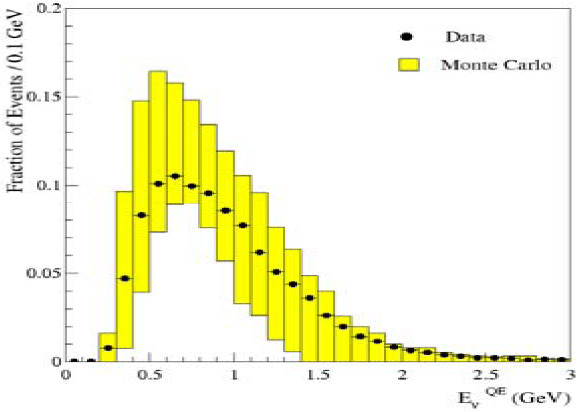
large angle spectrometer

Data taking in 2001-2002

hadron production measurements in "*seven dimensions*"

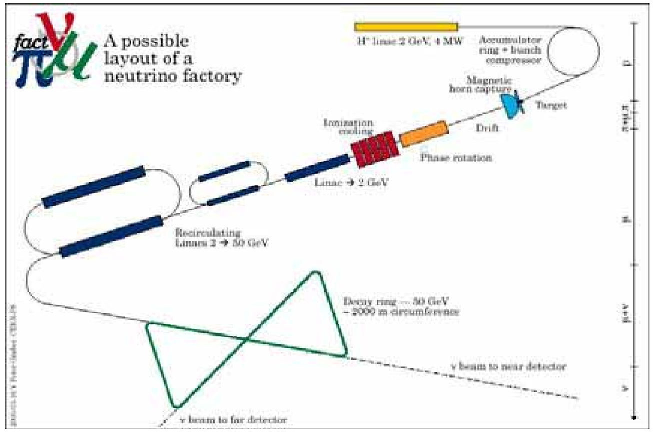
Detailed description of the experimental apparatus **NIM A571 (2007) 524**

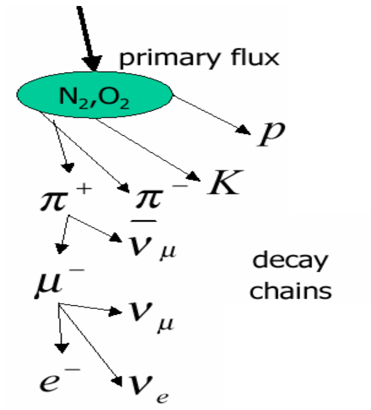
HARP physics goals



Input for prediction of neutrino fluxes for the **K2K** and **MiniBooNE / SciBooNE** accelerator experiments

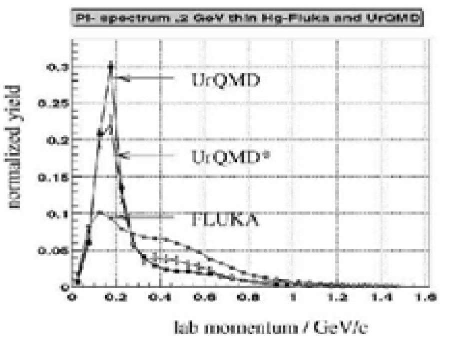
Pion/Kaon yield for the design of the proton driver and target system of **Neutrino Factories** and **Super-Beams**





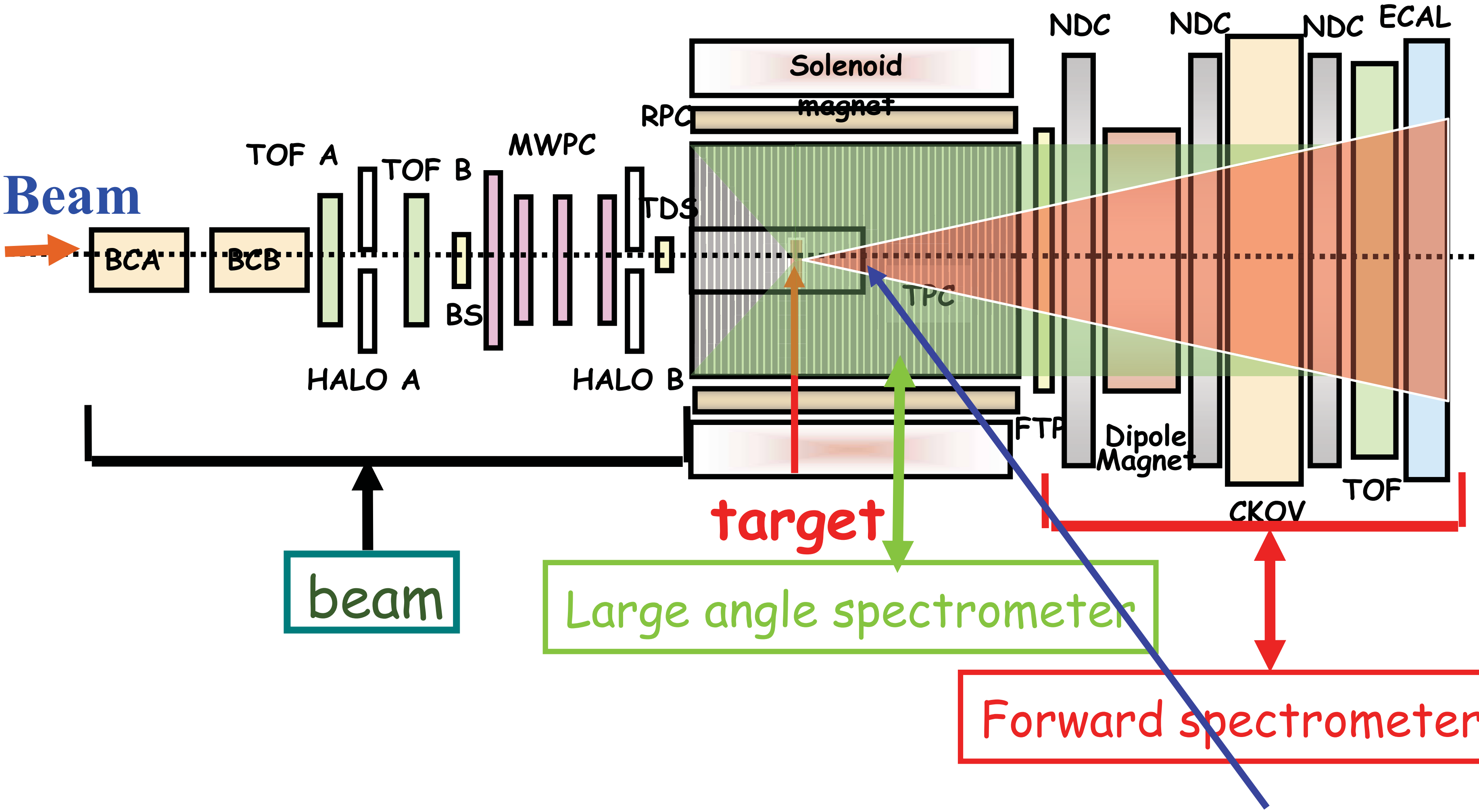
Input for precise calculation of the **atmospheric neutrino** flux (from yields of secondary π,K)

Input for **Monte Carlo** generators (GEANT4 and others)



NIM-A 472 (2001) 557-560

Analyses with the HARP forward spectrometer



$0.03 < \theta < 0.24$ rad

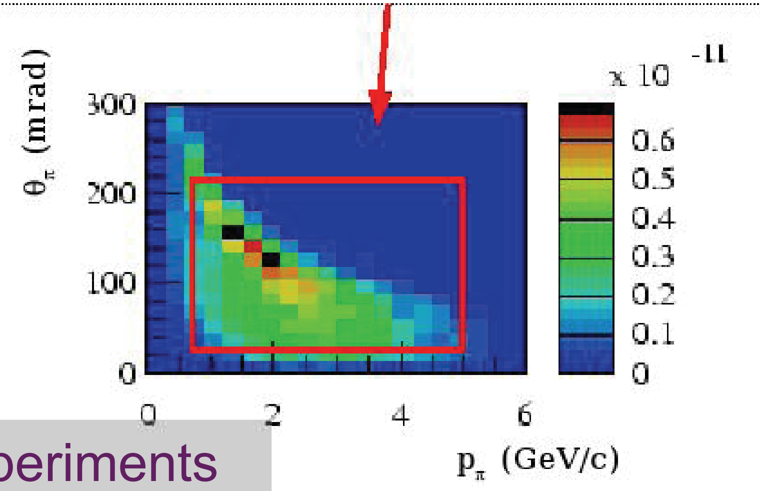
Analyses with the HARP forward spectrometer

Neutrino Oscillation Experiments at Accelerators

Neutrino fluxes of conventional accelerator neutrino beams *are not known accurately.*

measure pion and kaon production and use relevant targets and momenta:

- *K2K:* Al target, 12.9 GeV/c
- *MiniBooNE:* Be target, 8.9 GeV/c
- *SciBooNE:*



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

Removes *major* source of uncertainties for these experiments

(in collaboration with *K2K* and *MiniBooNE*)

HARP p-Al data 12.9 GeV/c:
M. G. Catanesi et al., HARP Collaboration, Nucl. Phys. **B732** (2006) 1

K2K results, with detailed discussion of relevance of production measurement:
M. H. Ahn et al., K2K Collaboration, Phys. Rev. **D74** (2006) 072003

Ingredients for Cross-section Calculation

$$\frac{d^2\sigma^\pi}{dpd\Omega} \sim \frac{\Delta N^\pi}{\Delta p \Delta \theta} \cdot \frac{\text{correction factors}(p,\theta)}{N_{pot}}$$

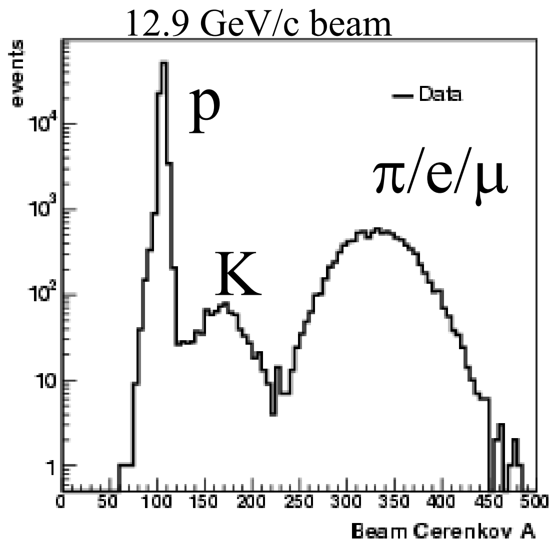
- Select events identified as primary protons interacting in the target
- For each event, reconstruct tracks and their 3-momentum
- Identify pions among secondary tracks
- Apply corrections, for reconstructed-to-true pion yield conversion:
  - Momentum resolution
  - Spectrometer angular acceptance
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

from data (when possible)

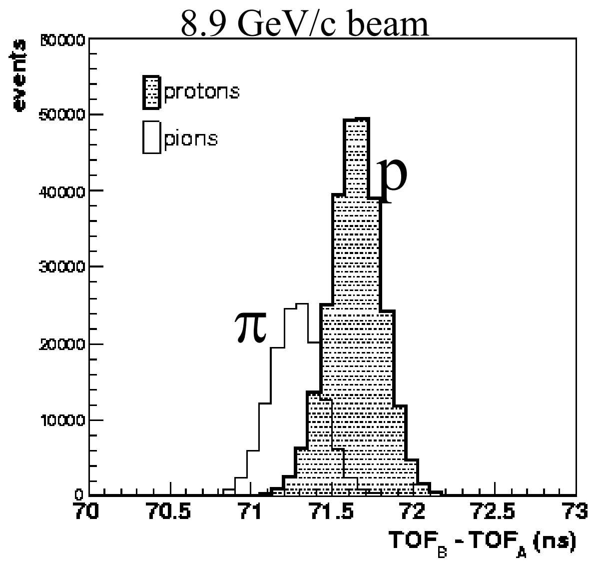
- Count protons on target corresponding to selected events
- Multiply by physics constants and accurately measured target properties

HARP – PS214 at CERN

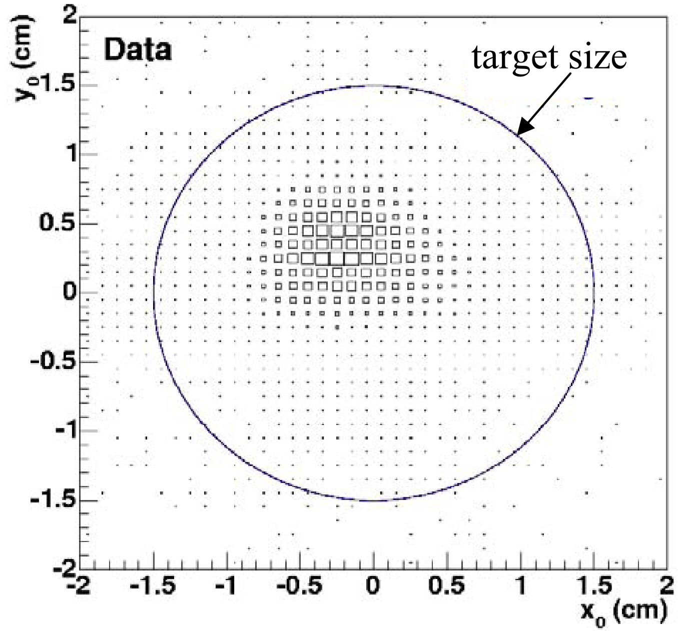
Event selection



2 Beam Cherenkov Detectors



3 Beam ToF Detectors

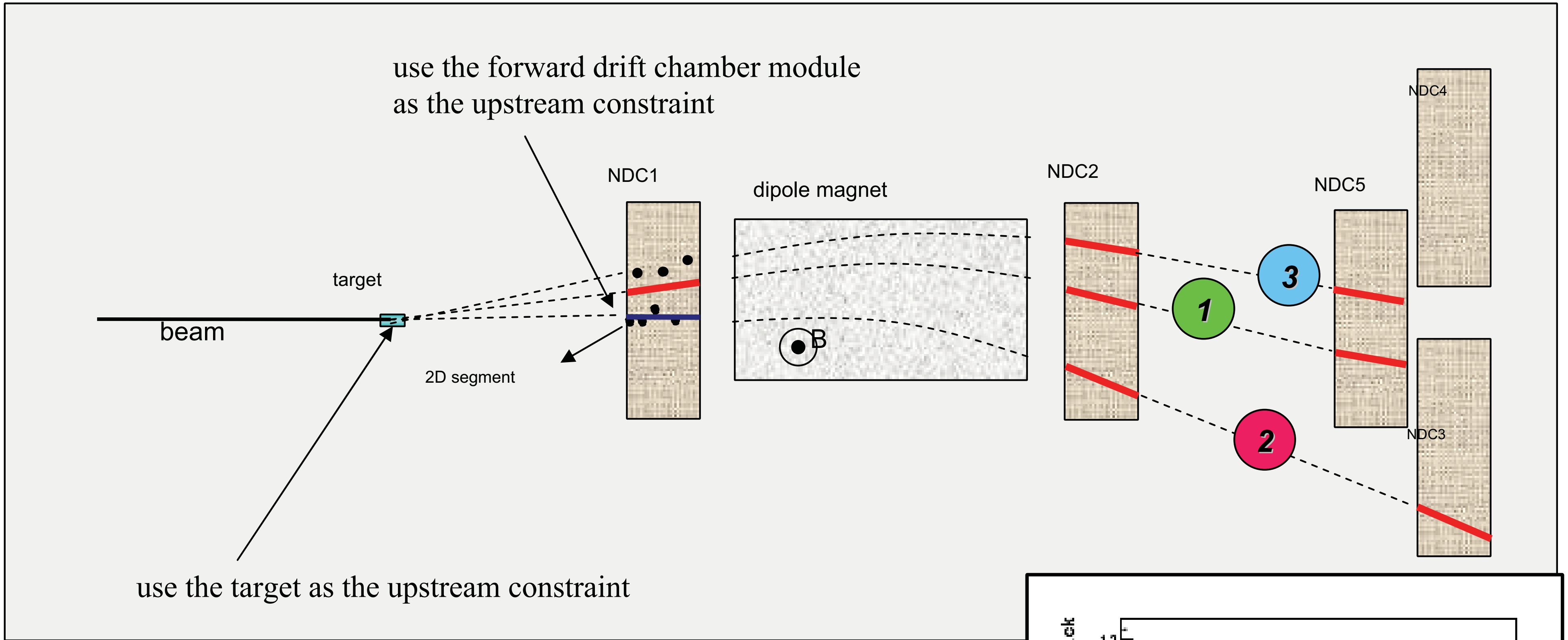


4 Multi-Wire Proportional Chambers

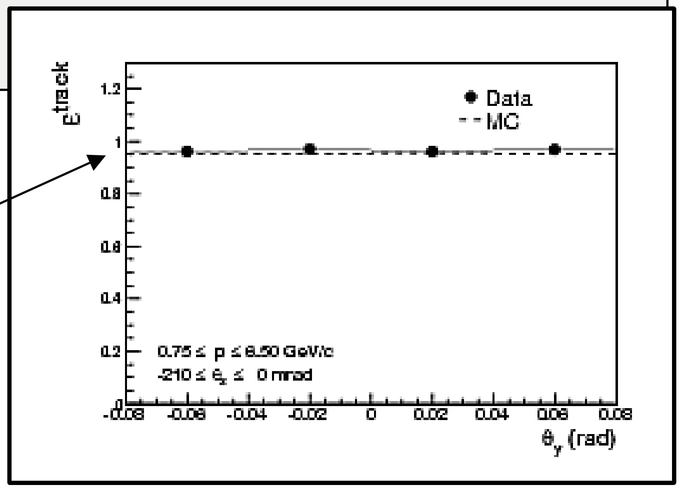
- **Event selection for protons on target** (“*normalization trigger”*)**:**
  - Well-behaved transverse impact point and direction of primaries via 4 MWPCs and scintillators (BS, TDS, HALO A, HALO B)
  - Primaries identified as protons via beam ToF and Cherenkov systems (TOFA, TOFB, BCA, BCB). Beam 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)

Track reconstruction in the forward spectrometer

- four overlapping downstream drift chamber modules and two independent methods of momentum reconstruction given a downstream segment



- redundancy in chambers and redundancy in vertex constraints allows determination of tracking efficiencies from the data themselves



- target constraint method **efficiency > 95%**.

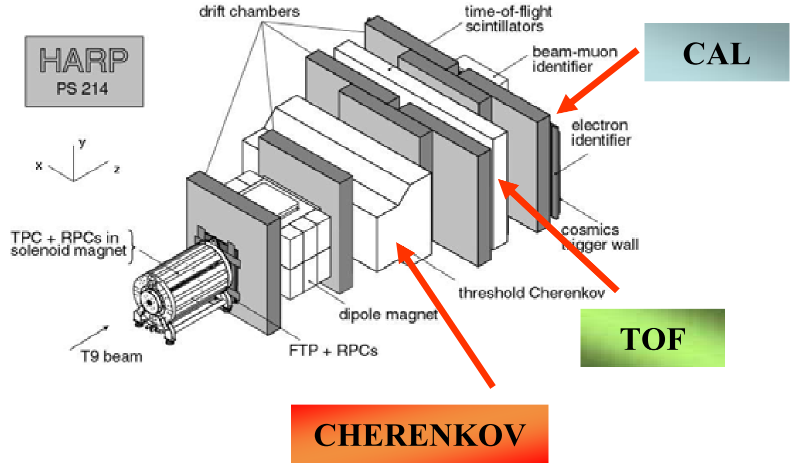
Particle identification in the forward spectrometer

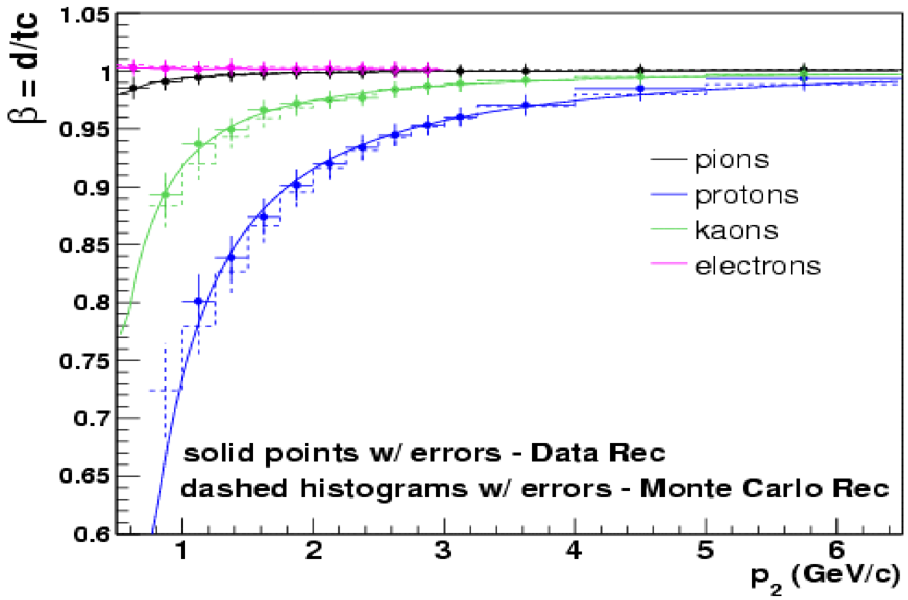
p (GeV/c) 0 1 2 3 4 5 6 7 8 9 10

π/p: TOF (0–4.5); CHERENKOV (3–10)

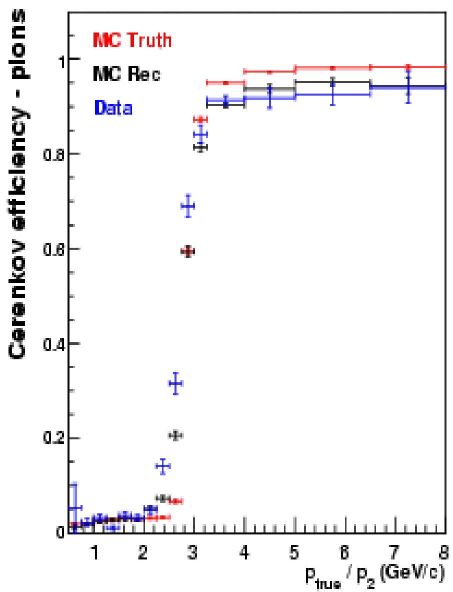
π/K: TOF (0–3); CHERENKOV (3–10)

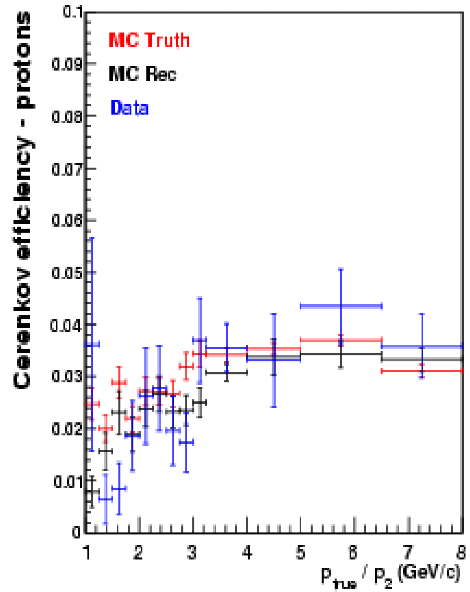
π/e: CHERENKOV (0–3.2); CALORIMETER (0–10)





TOF π/p/K response





CHERENKOV π/p response

PID algorithms for the forward spectrometer are described in **NIM A572 (2007) 899**

Upcoming HARP Physics Publication

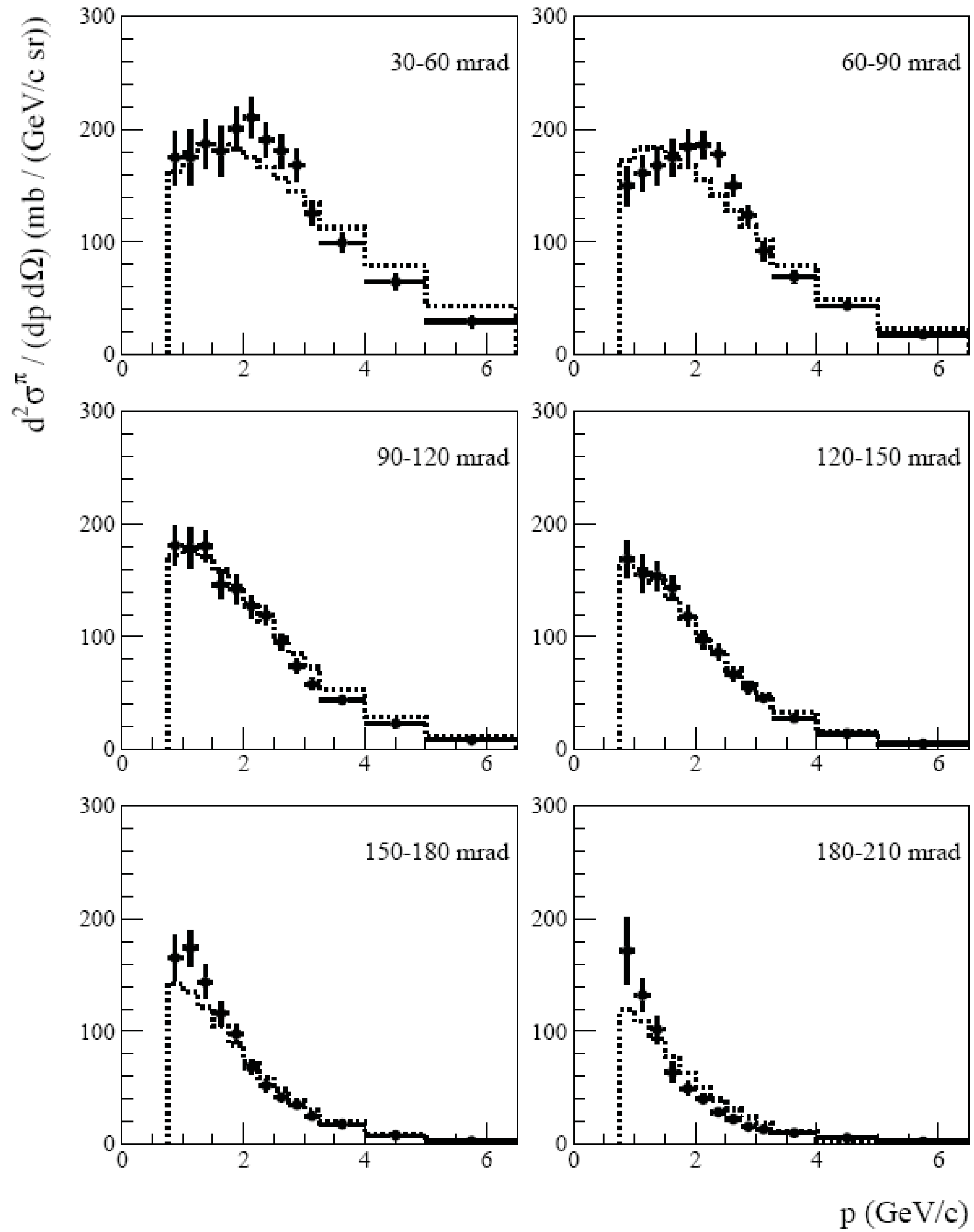
Measurement of the production cross-section of positive pions in the collision of 8.9 GeV/c protons on beryllium

HARP Collaboration

February 14, 2007

Abstract

The double-differential production cross-section of positive pions, $d^2\sigma^{\pi^+}/dpd\Omega$, measured in the HARP experiment is presented. The incident particles are 8.9 GeV/c protons directed onto a beryllium target with a nominal thickness of 5% of a nuclear interaction length. The measured cross-section has a direct impact on the prediction of neutrino fluxes for the MiniBooNE and SciBooNE experiments at Fermilab. After cuts, 13 million protons on target produced about 96,000 reconstructable secondary tracks which were used in this analysis. Cross-section results are presented in the kinematic range 0.75 GeV/$c \leq p_\pi \leq$ 6.5 GeV/c and 30 mrad $\leq \theta_\pi \leq$ 210 mrad in the laboratory frame.



5% λ Be target

hep/ex-0702034

θ_π = [30, 60, 90, 120, 150, 180, 210] mrad

p_π = [0.75 – 6.5] GeV/c

typical error on point = 9.8%

error on integral = 4.9%

analysis includes significant improvements relative to Al measurement in PID and momentum resolution description

p(8.9 GeV/c) + Be -> π^+ + X

Error Analysis: Overall error ~ 5%

5% λ Be target

$$\delta_{\text{diff}} \equiv \frac{\sum_i (\delta[\Delta^2\sigma^\pi/(\Delta p \Delta\Omega)])_i}{\sum_i (\Delta^2\sigma^\pi/(\Delta p \Delta\Omega))_i}$$

$$\delta_{\text{int}} \equiv \frac{\sqrt{\sum_{i,j} (\Delta p \Delta\Omega)_i C_{ij} (\Delta p \Delta\Omega)_j}}{\sum_i (\Delta^2\sigma^\pi)_i}$$

Error Category	**Error Source**	δ^π_{diff} (%)	δ^π_{int} (%)
Statistical	Be target statistics	4.2	0.6
	Empty target subtraction (stat.)	4.6	0.6
	Sub-total	**6.3**	**0.8**
Track yield corrections	Reconstruction efficiency	1.3	0.8
	Pion, proton absorption	3.6	3.7
	Tertiary subtraction	1.8	1.8
	Empty target subtraction (syst.)	1.3	1.2
	Sub-total	**4.6**	**4.3**
Particle Identification	Electron veto	0.2	<0.1
	Pion, proton ID correction	0.4	0.1
	Sub-total	**0.5**	**0.1**
Momentum reconstruction	Momentum scale	3.6	0.1
	Momentum resolution	3.4	1.0
	Sub-total	**5.2**	**1.0**
Overall normalization	**Sub-total**	**2.0**	**2.0**
All	**Total**	**9.8**	**4.9**

An aside on the SW parameterization

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

- X : any other final state particle
- p_{beam} : proton beam momentum (GeV/c)
- p, θ : pion lab-frame momentum (GeV/c) and angle (rad)
- c_1,..., c_8 : empirical fit parameters

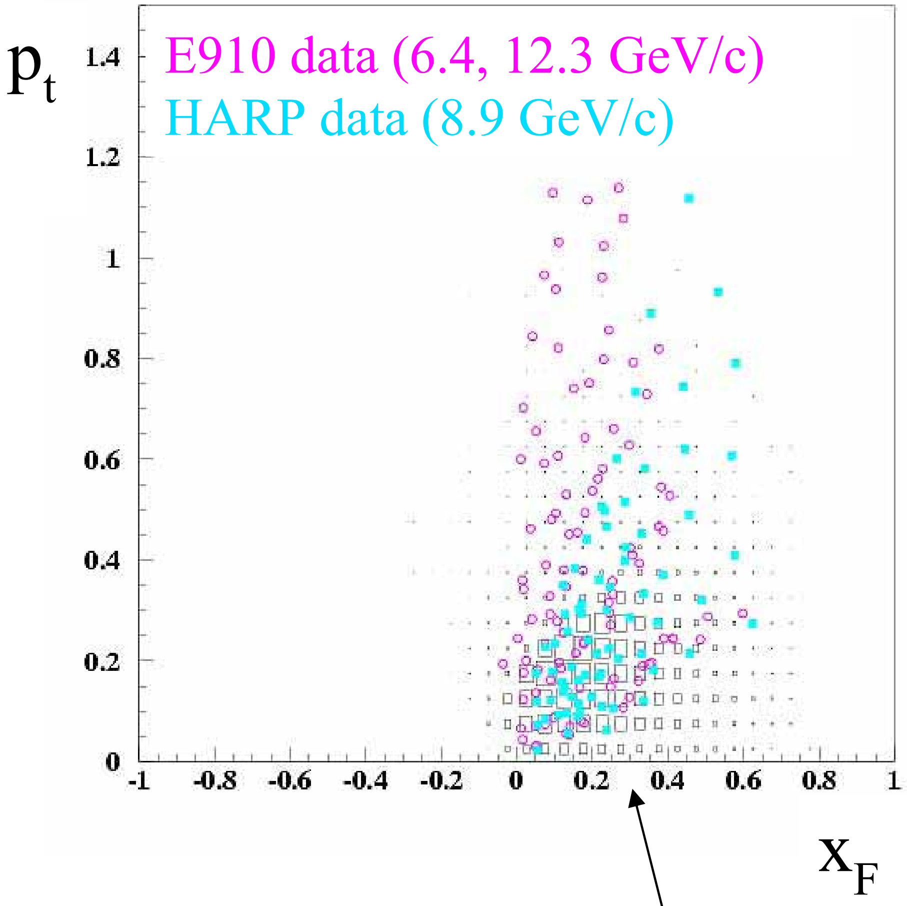
Parameter	Value
c_1	$(8.22 \pm 1.98) \cdot 10^1$
c_2	(6.47 ± 1.62)
c_3	$(9.06 \pm 2.03) \cdot 10^1$
$c_4 = c_5$	$(7.44 \pm 2.30) \cdot 10^{-2}$
c_6	(5.09 ± 0.49)
c_7	$(1.87 \pm 0.53) \cdot 10^{-1}$
c_8	$(4.28 \pm 1.36) \cdot 10^1$

Parameter	c_1	c_2	c_3	$c_4 = c_5$	c_6	c_7	c_8
c_1	1.000						
c_2	0.327	1.000					
c_3	0.986	0.482	1.000				
$c_4 = c_5$	-0.559	0.596	-0.411	1.000			
c_6	0.091	-0.467	-0.006	-0.545	1.000		
c_7	0.011	-0.101	-0.004	-0.129	0.234	1.000	
c_8	-0.080	0.411	0.006	0.471	-0.776	0.215	1.000

HARP measurements for p+Be at 8.9 GeV/c

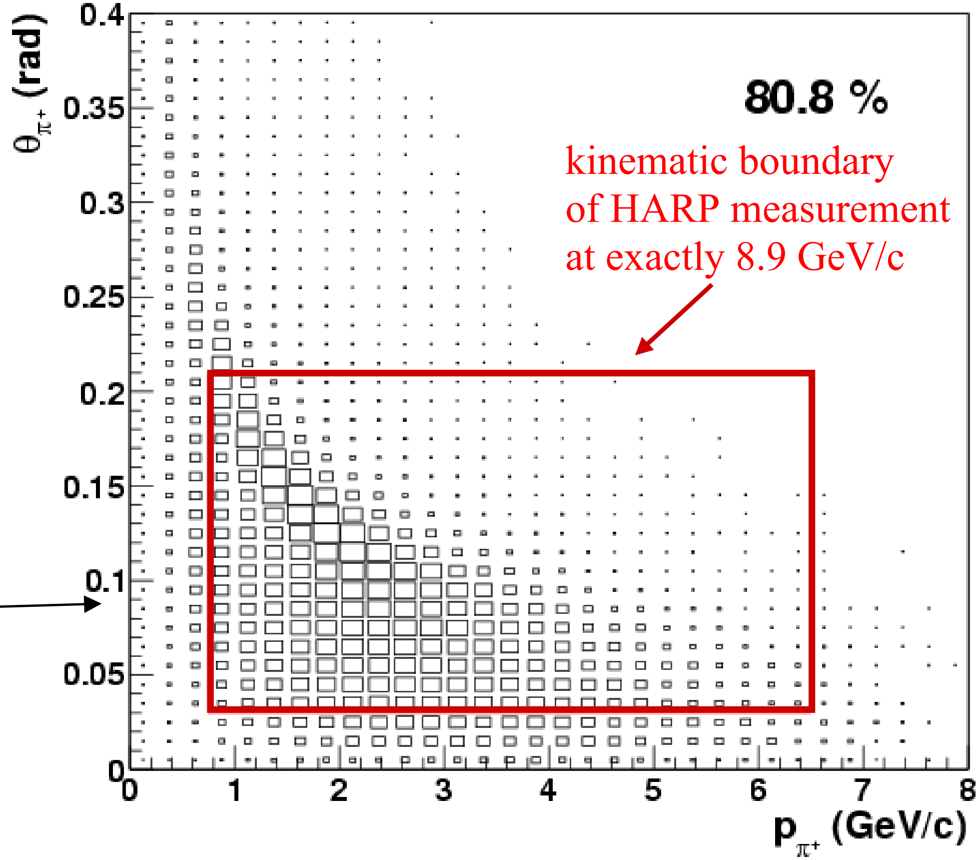
J. R. Sanford and C. L. Wang "Empirical formulas for particle production in p-Be collisions between 10 and 35 BeV/c", Brookhaven National Laboratory, AGS internal report, (1967) (*unpublished*)

MiniBooNE ν_μ flux prediction



• combining **HARP** and **E910** data gives maximal coverage of the relevant pion phase space for **MiniBooNE**

• Use the parameterization of Sanford and Wang and fit to both data sets combined

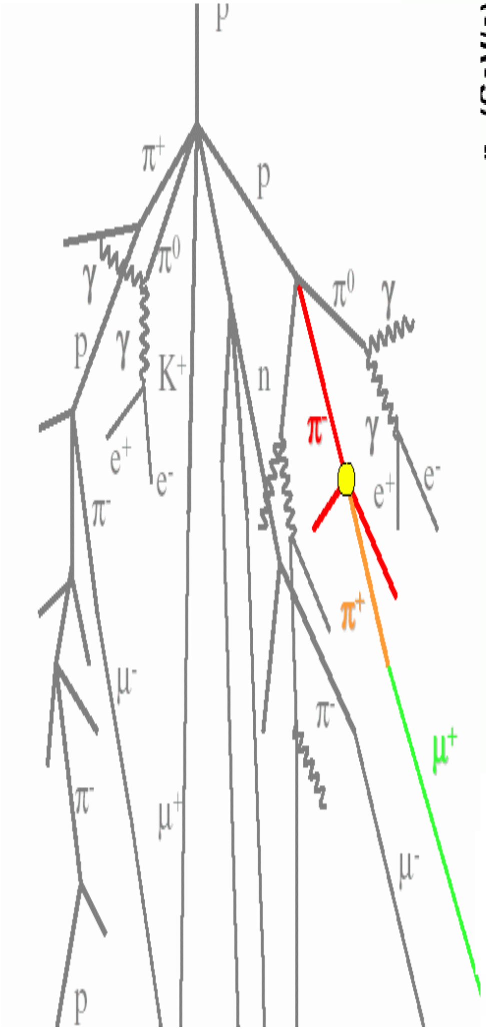


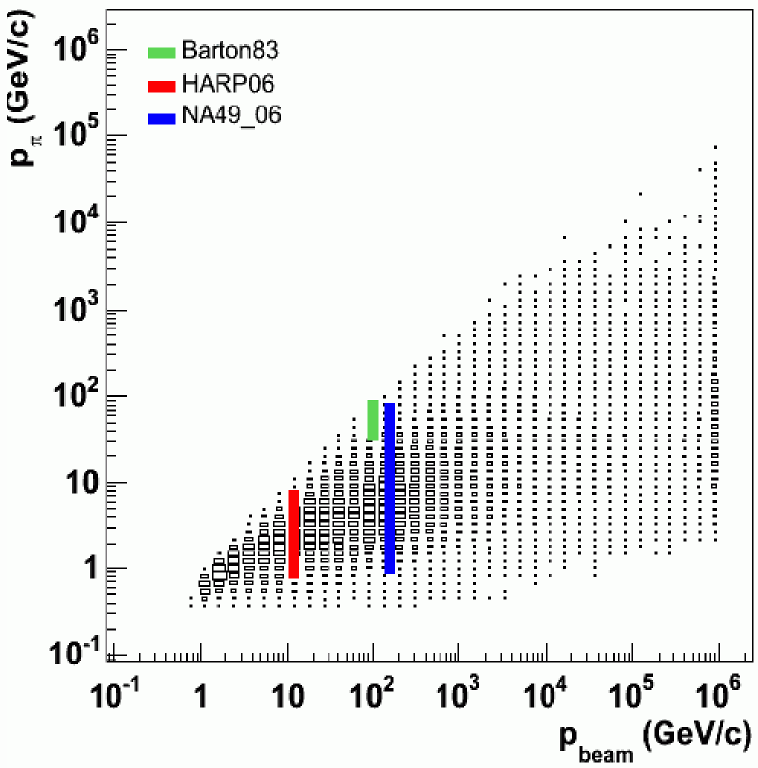
• black boxes are the distribution of π^+ which decay to a ν_μ that **passes through the MiniBooNE detector**

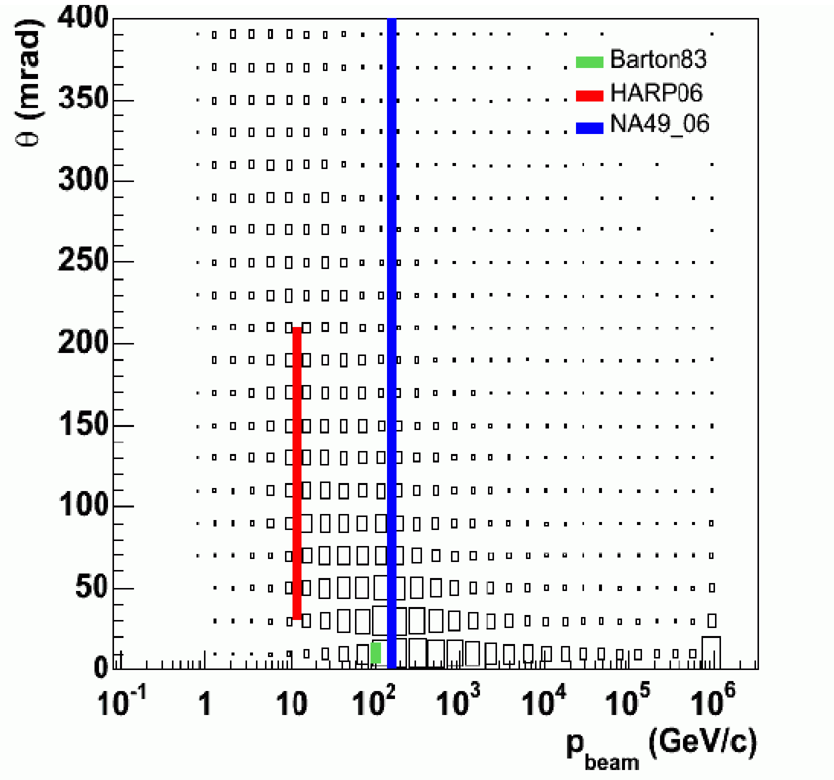
p(8.9 GeV/c) + Be -> π^+ -> ν_μ^{MB}

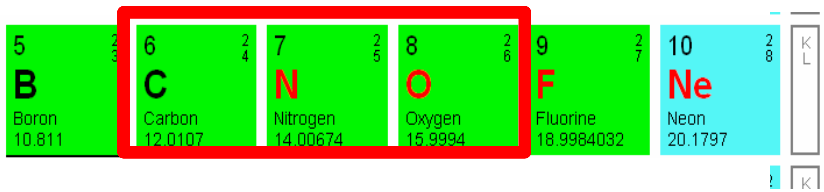
Atmospheric neutrino flux predictions

- the **HARP p+C @ 12 GeV/c** and the **NA49 p+C @ 158 GeV/c** are both relevant to the prediction of atmospheric neutrino fluxes







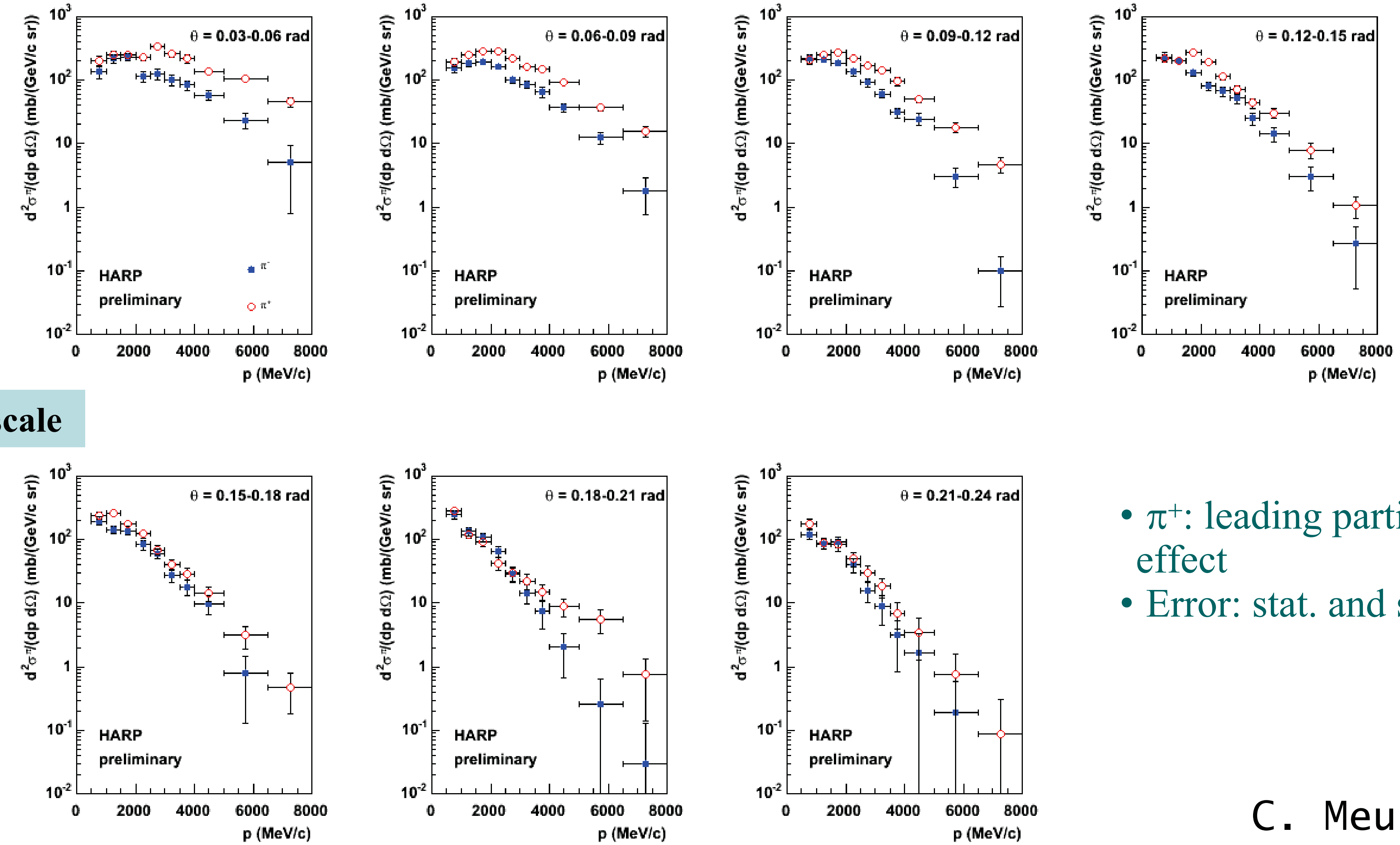


78% nitrogen

21% oxygen

p+C @ 12 GeV/c

● π^-
○ π^+

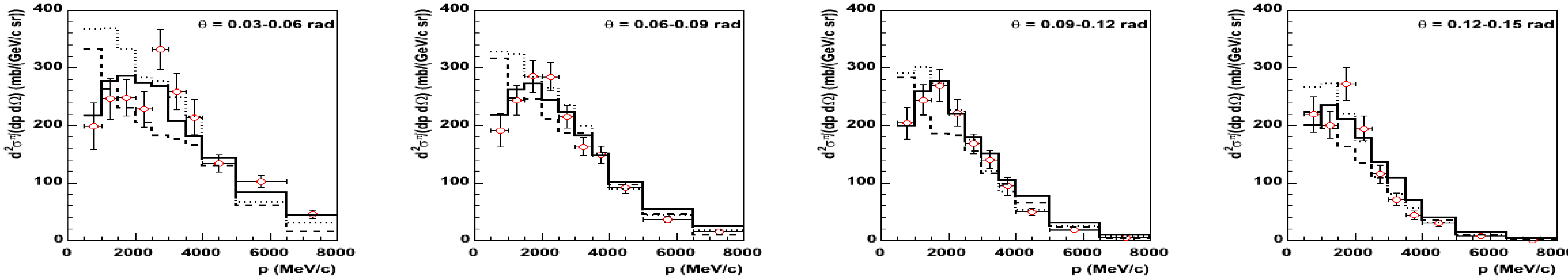


log scale

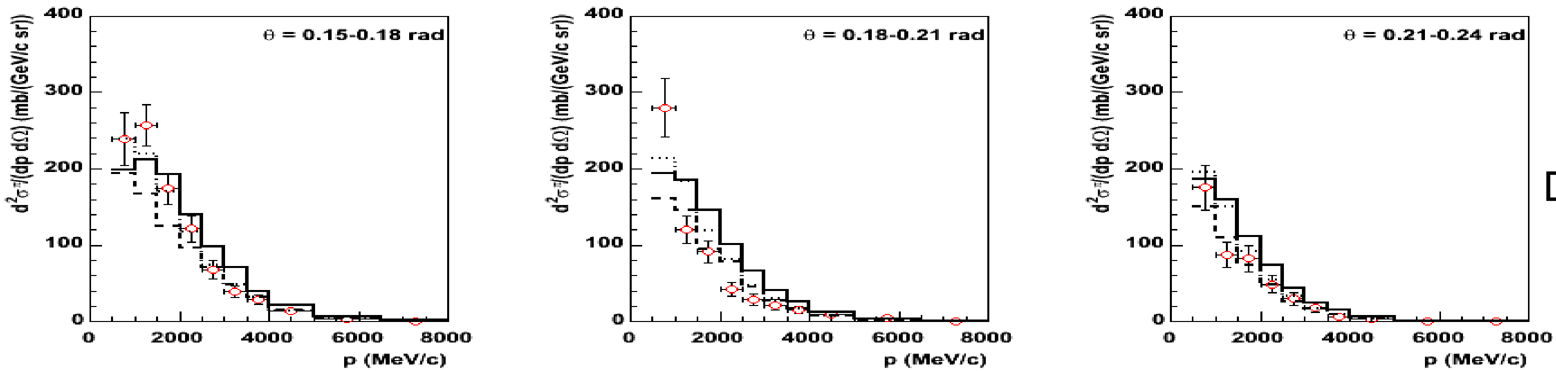
- π^+: leading particle effect
- Error: stat. and syst.

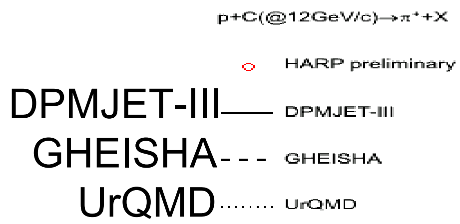
C. Meurer

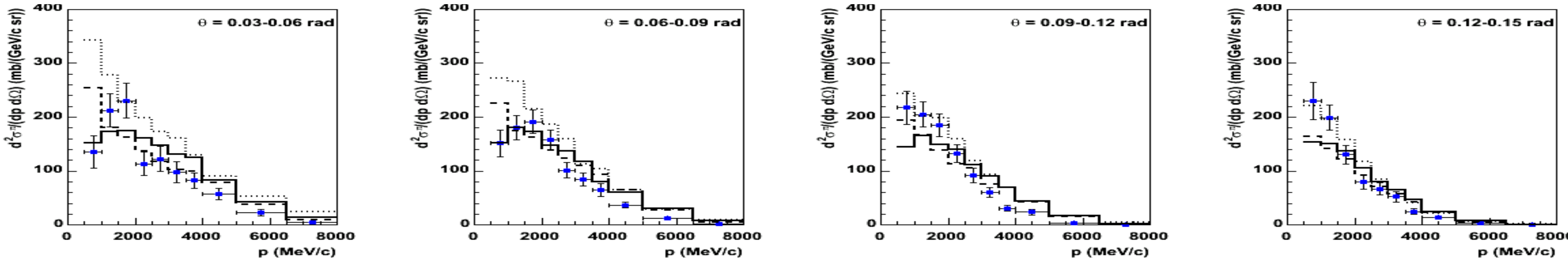
astro-ph/0612157



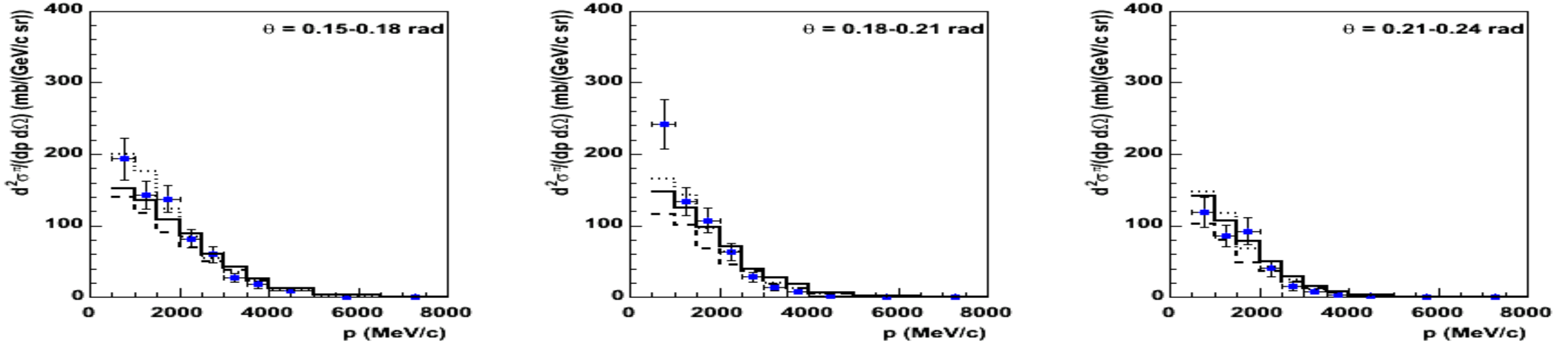
Model comparison: $p+C \rightarrow \pi^{+} + X$

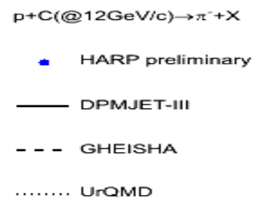






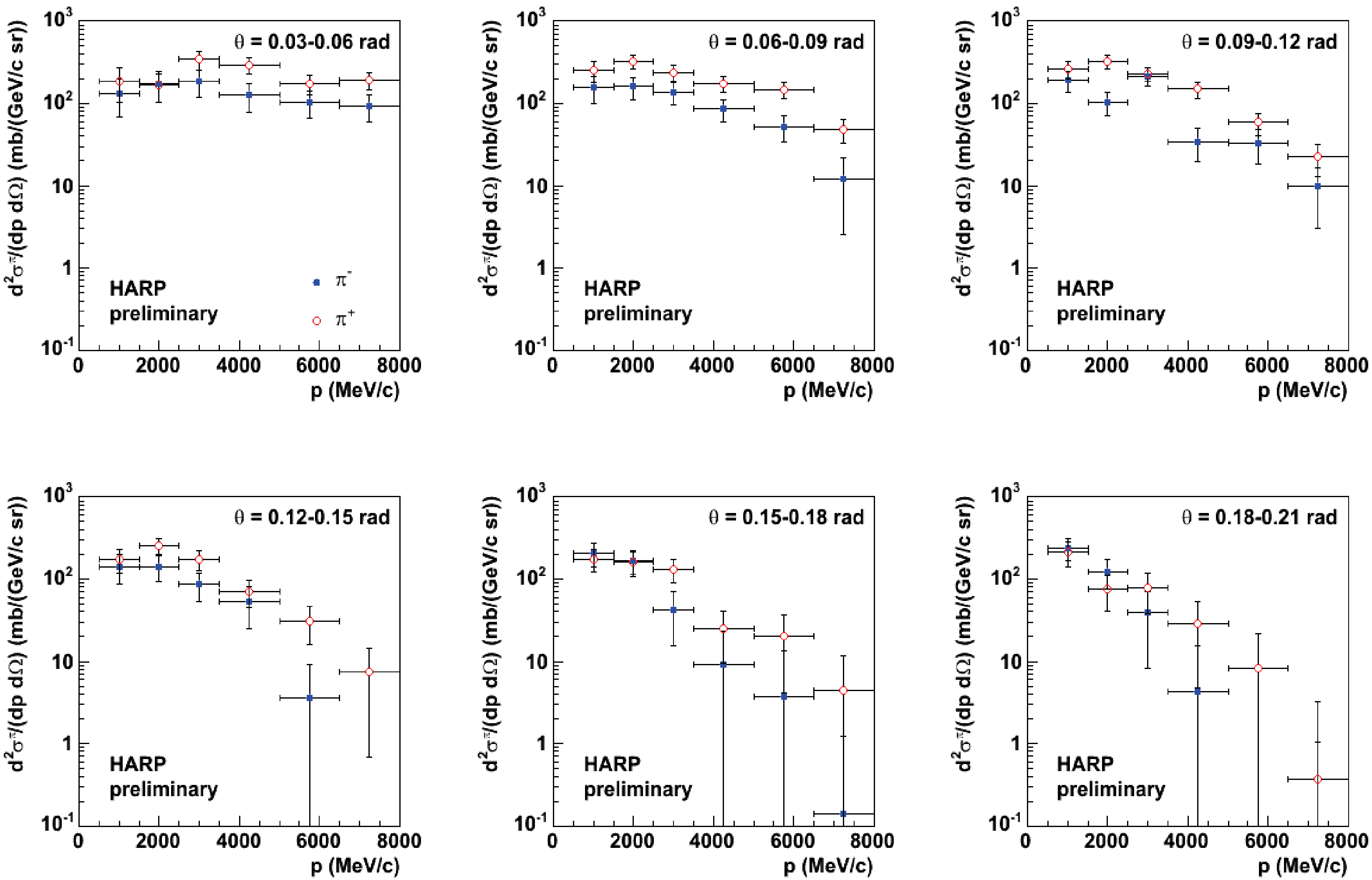
Model comparison: $p+C \rightarrow \pi^{-} + X$



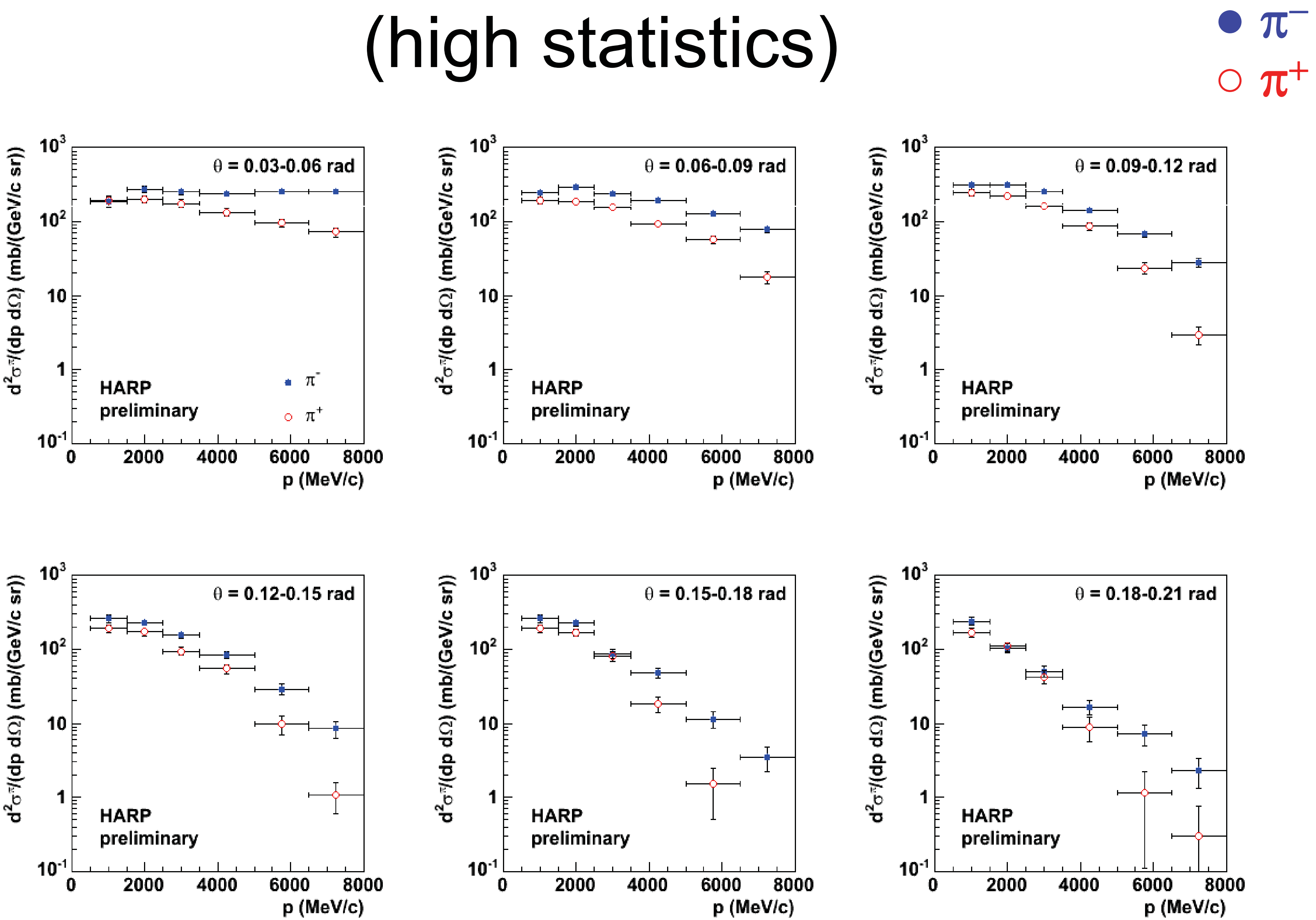


π^++C @ 12 GeV/c
(lower statistics)

● π^-
○ π^+

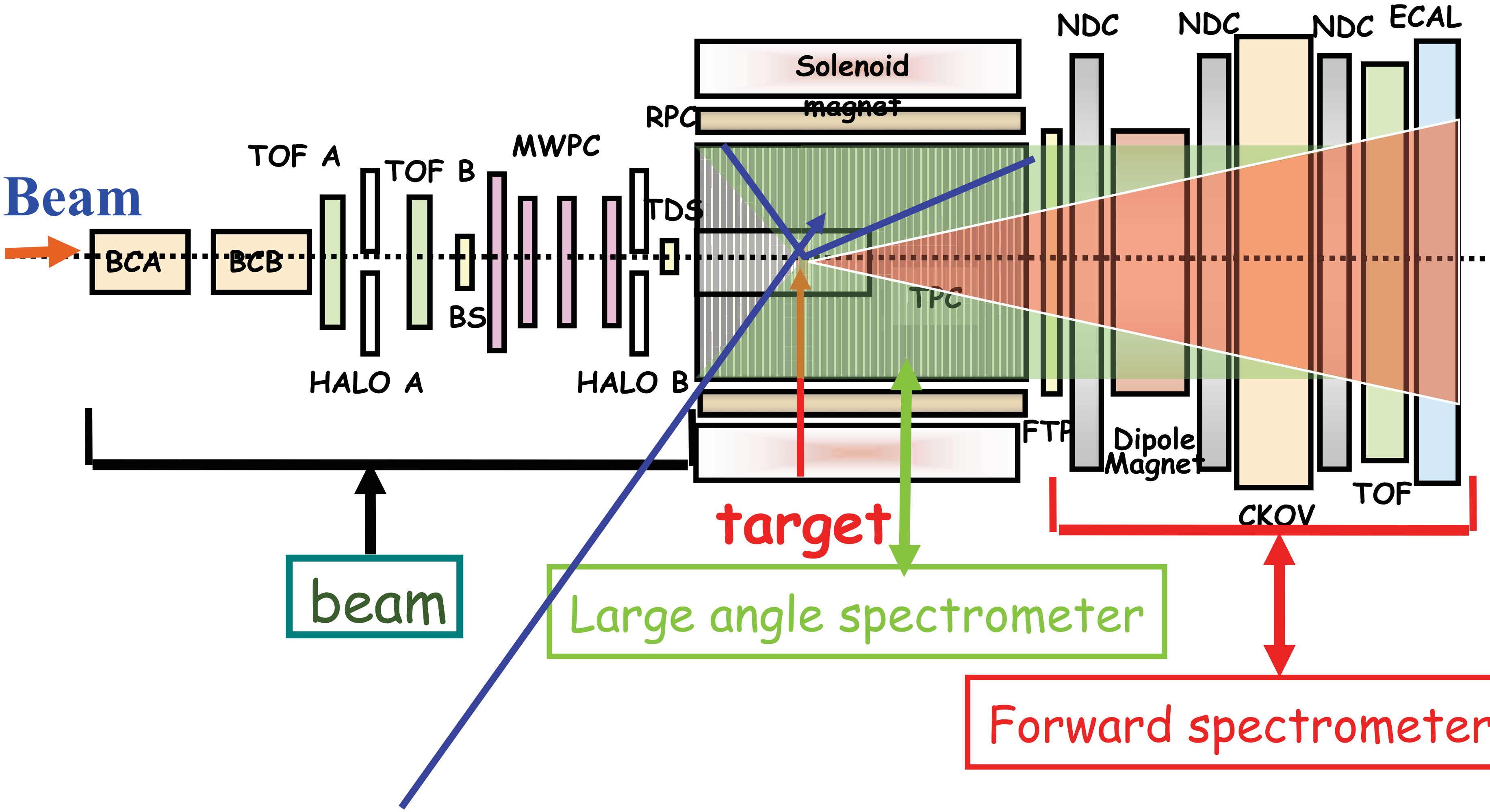


π^{-}+C @ 12 GeV/c
(high statistics)



Analyses with the HARP large angle spectrometer

Large Angle spectrometer: TPC



$0.35 < \theta < 2.15$ rad

TPC Track Reconstruction

Equalisation

↓

Clustering

↓

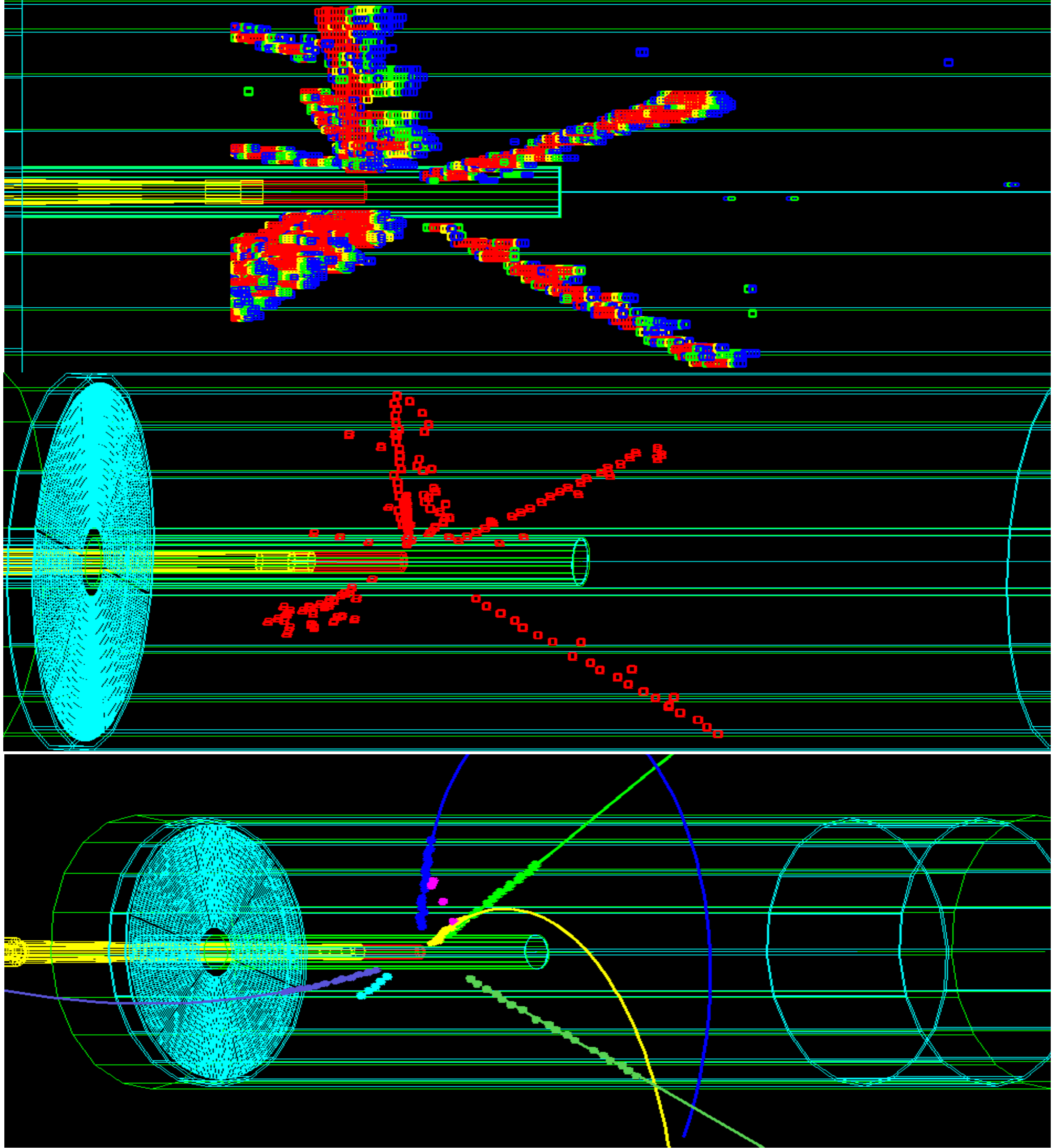
Pattern recognition

↓

Track fit (helix)

↓

Momentum fit



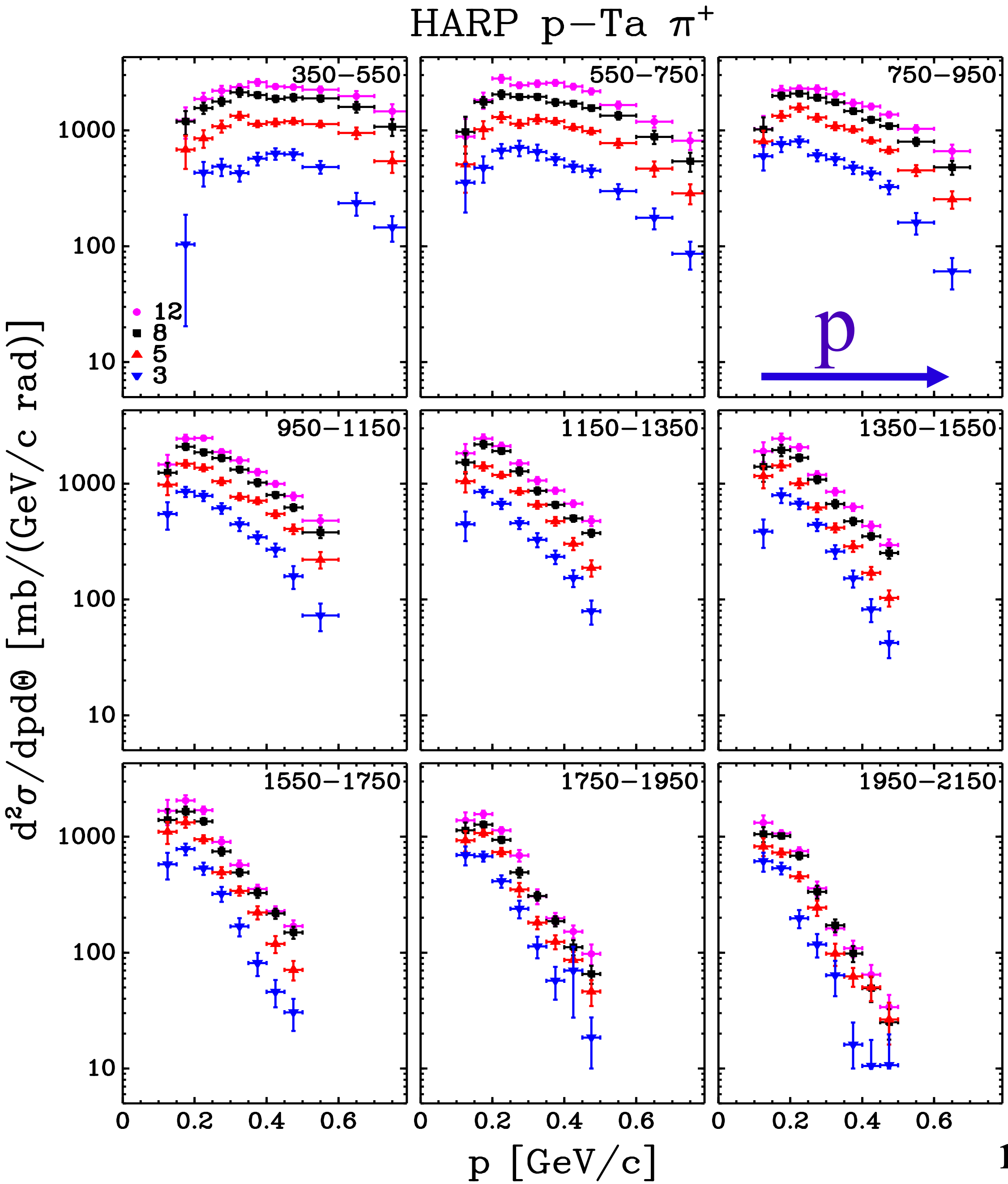
“Large Angle” analysis

beam momenta:
3, 5, 8, 12 GeV/c
beam particle selection and normalization same as previous analysis
events:
require trigger in ITC (cylinder around target)
TPC tracks:
>11 points and momentum measured and track originating in target
PID selection

additional selection to avoid track distortions due to ion charges in TPC:
first part of spill (30-40% typically of data kept, correction available for future)
Corrections:
Efficiency, absorption, PID, momentum and angle smearing by unfolding method
(same as p-C data analysis in forward spectrometer)
Backgrounds:
secondary interactions (simulated)
low energy electrons and positrons (all from π^0)
predicted from π^+ and π^- spectra (iterative) and normalized to identified e^{+-}.

9 angular bins: p-Ta π^+

Pion production yields



stat. and syst. errors combined

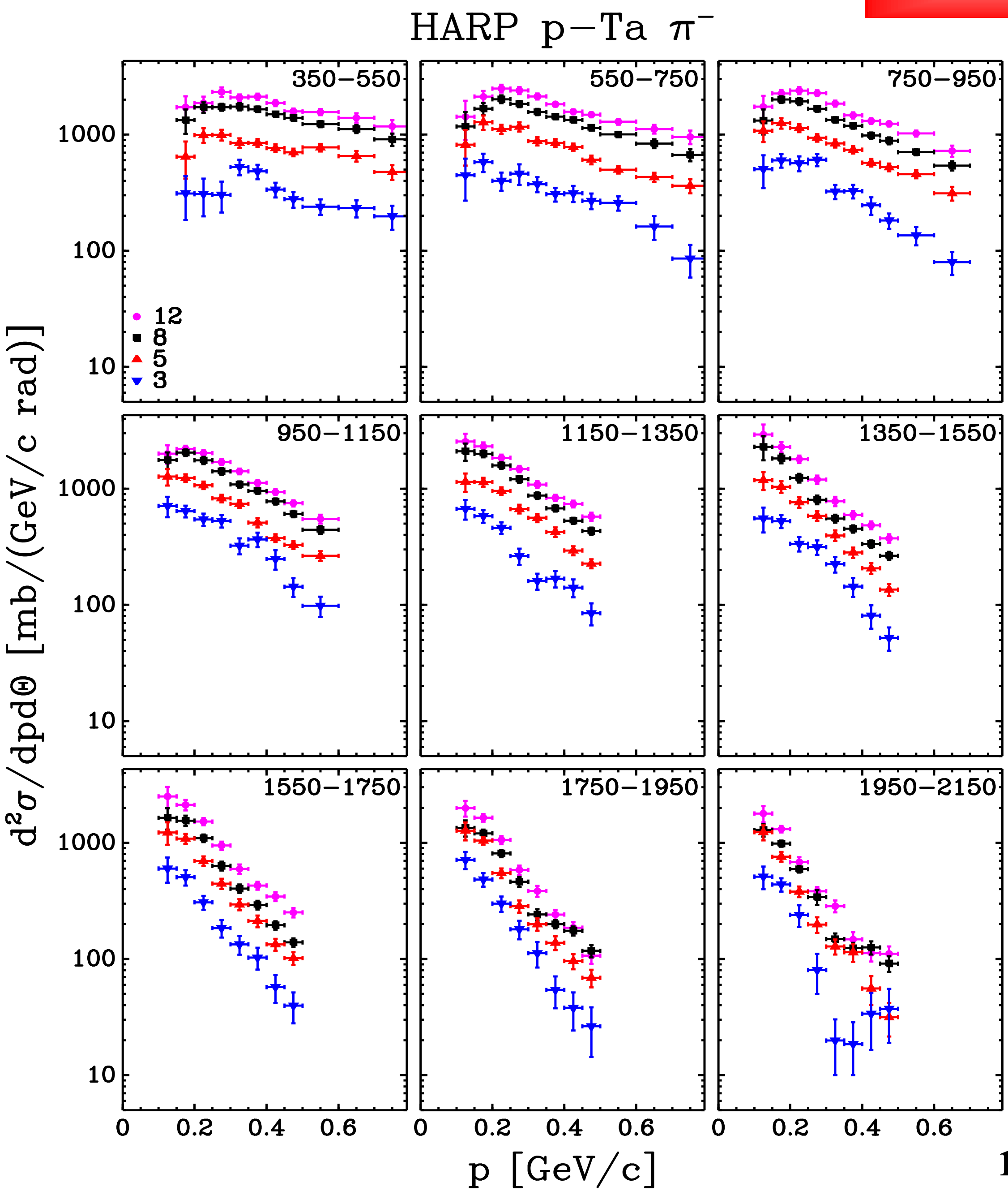
forward
$0.35 < \theta < 1.55$

backward
$1.55 < \theta < 2.15$

momentum range $0.1 < p < 0.8$ GeV/c

p-Ta π^-

Pion production yields



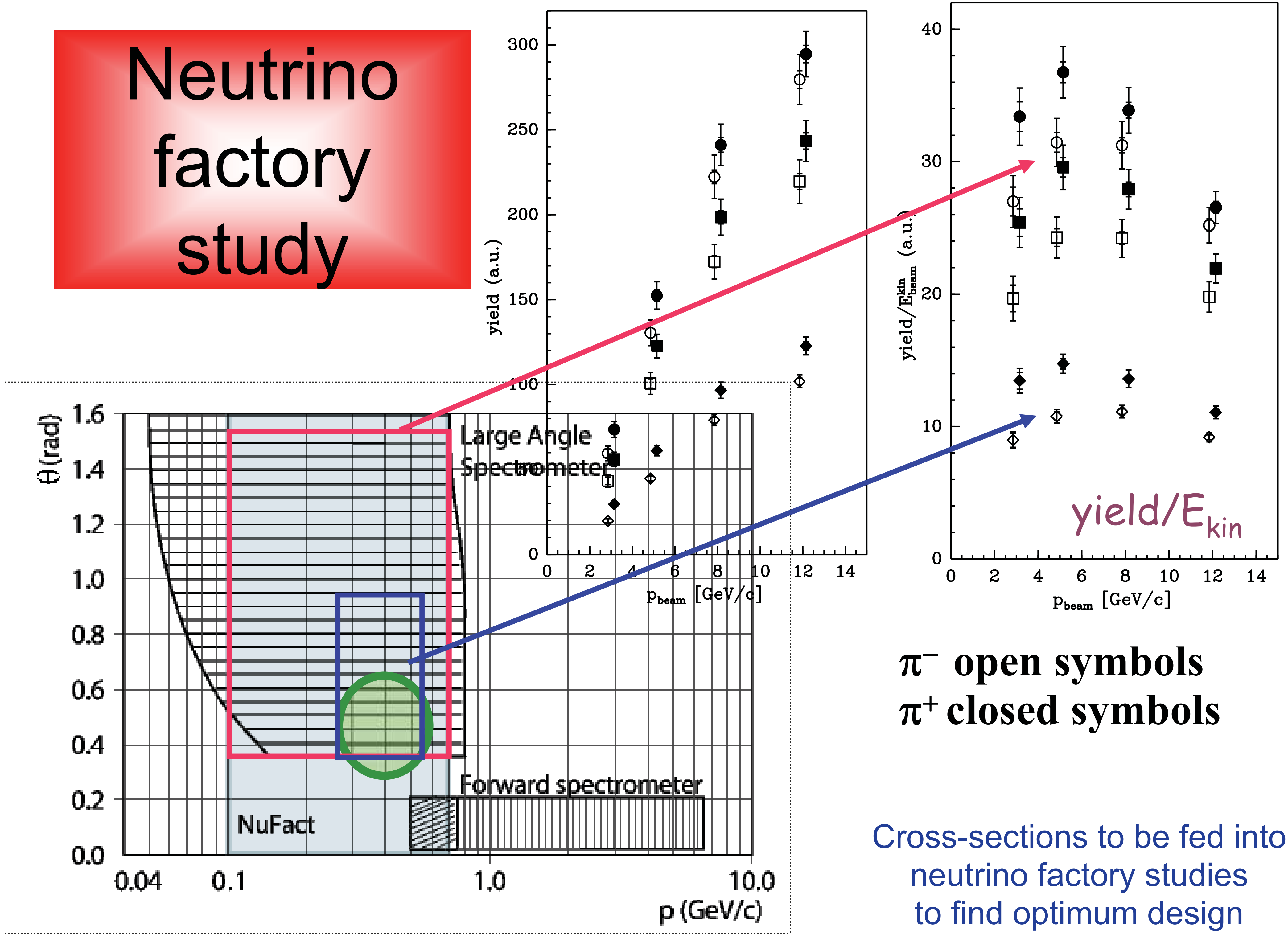
stat. and syst. errors combined

forward
$0.35 < \theta < 1.55$

backward
$1.55 < \theta < 2.15$

momentum range $0.1 < p < 0.8$ GeV/c

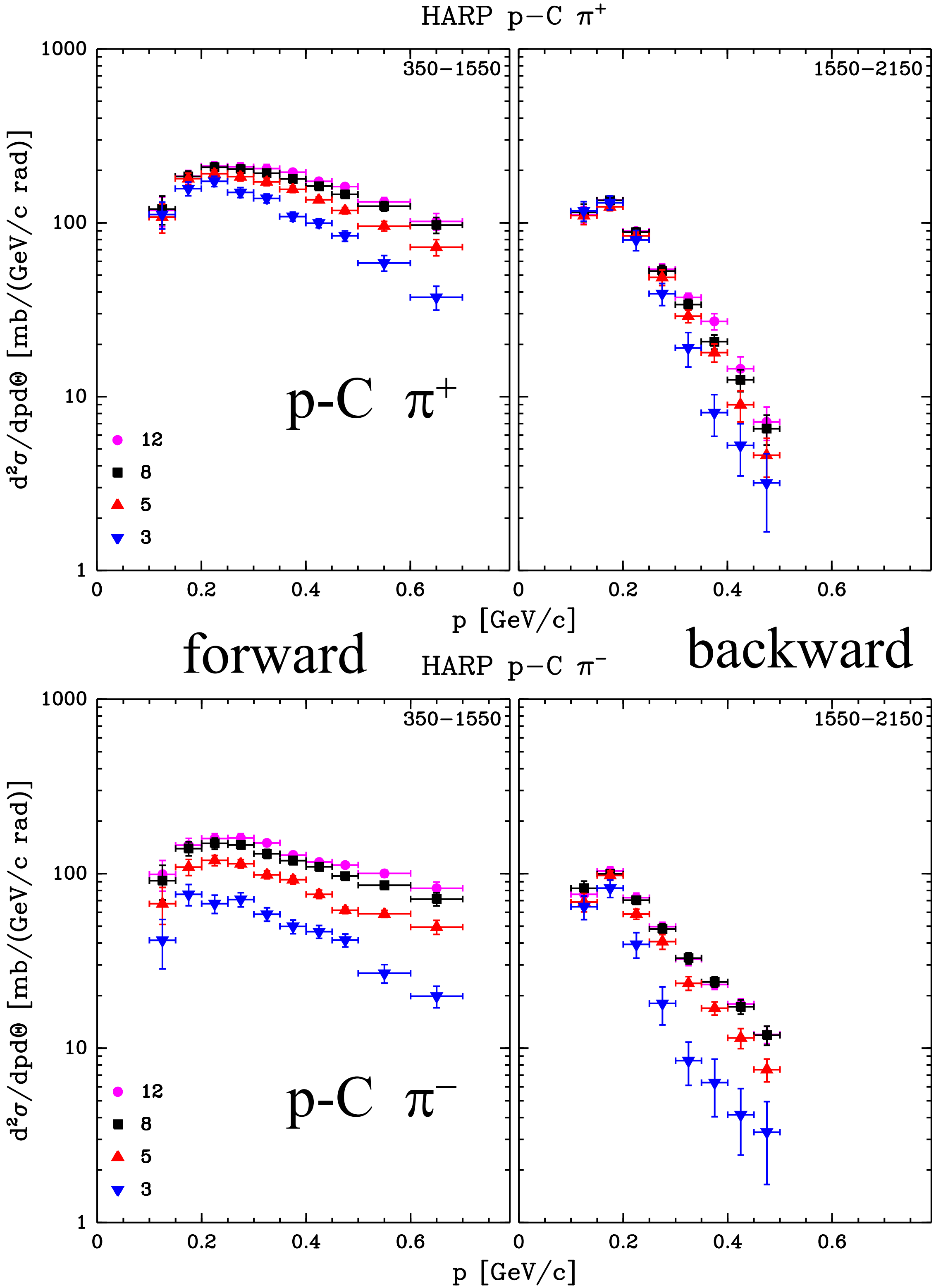
Neutrino factory study



π^- **open symbols**
π^+ **closed symbols**

Cross-sections to be fed into neutrino factory studies to find optimum design

Pion yields

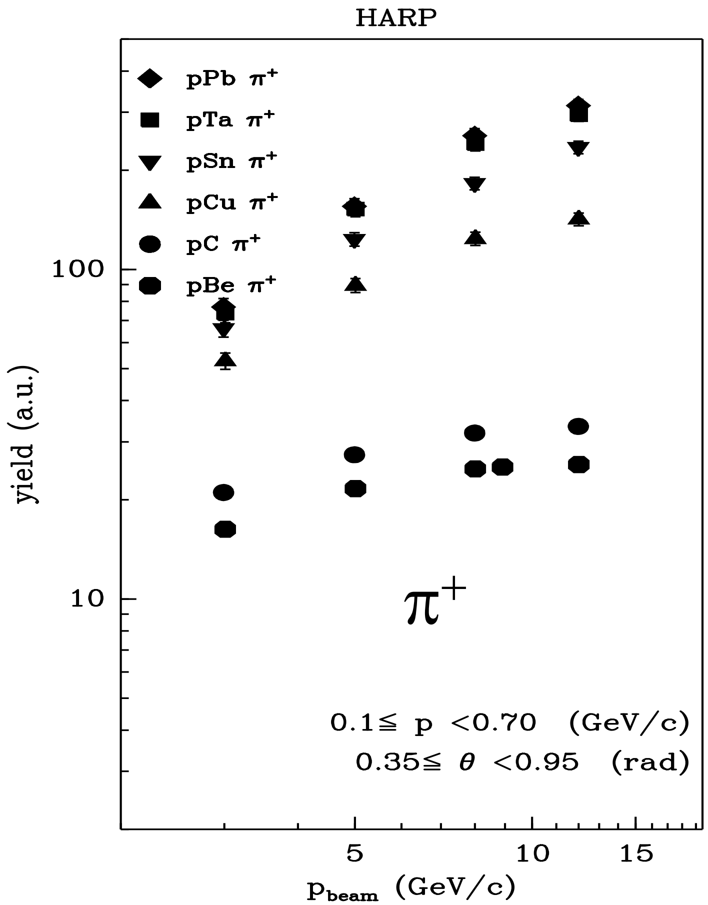


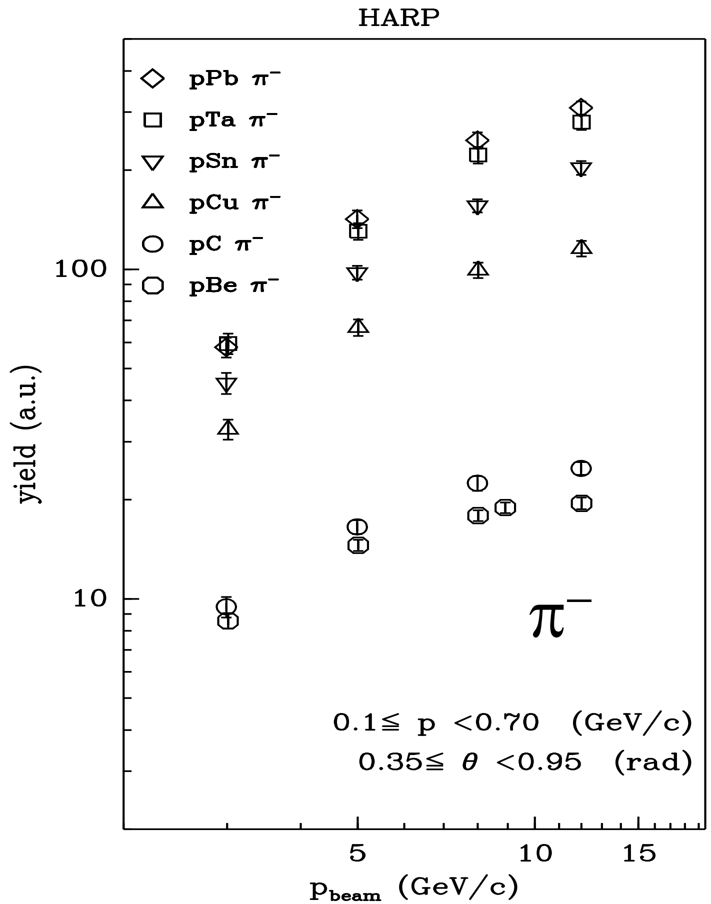
p-C data as an example of many other available spectra

Pion yields

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

forward production only $0.35 < \theta < \mathbf{0.95}$ rad

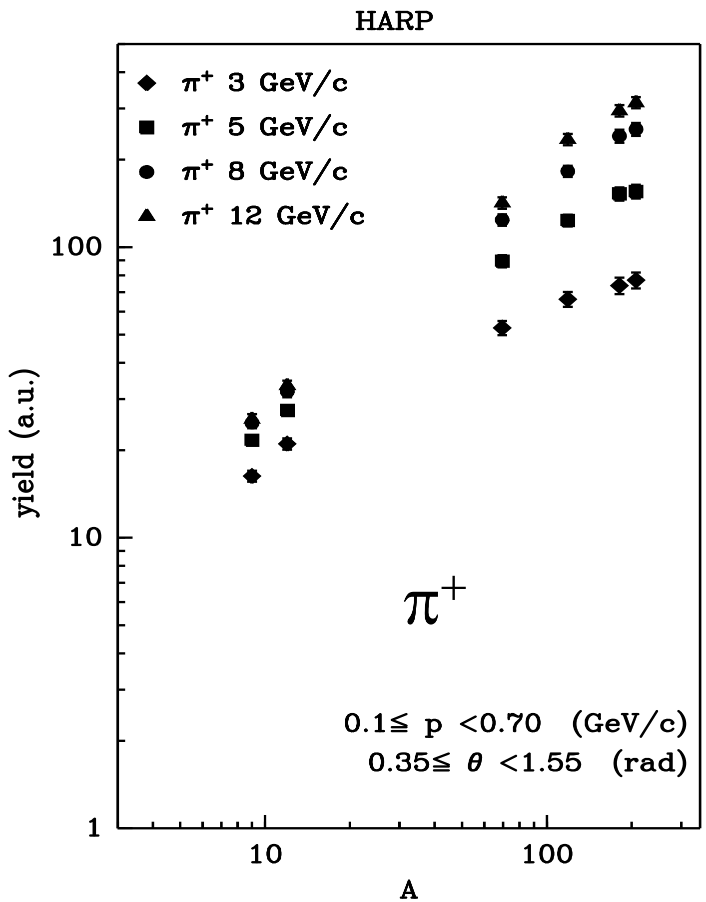


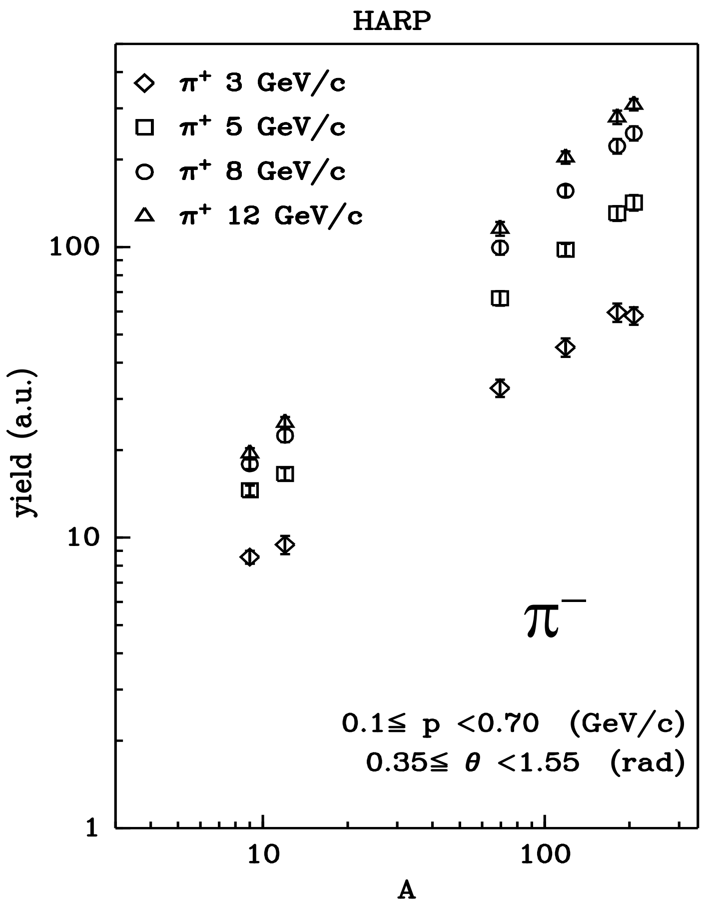


Pion yields

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

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





Measured with the same detector!

Conclusions

HARP hadron production experiment has already made important contributions to hadronic cross-section measurements relevant to neutrino experiments

Aluminium results for **K2K** have been published and used for final K2K publication.

Beryllium results for **MiniBooNE** are ready. These measurements are already being used by MiniBooNE collaboration.

Tantalum results for the **Neutrino Factory** studies are ready (Pb and others coming).

Carbon data for **atmospheric neutrino fluxes** are available (N_2, O_2 coming).

More production cross-section measurements are basically finished and can be used to tune hadron production models.

To get all data out, still a large number of data sets need day-to-day calibrations.
The detector is well understood and the analysis techniques established.

Thanks to the organisers for their support

Backup slides

HARP – PS214 at CERN

24 institutes
~120 collaborators

HARP collaboration

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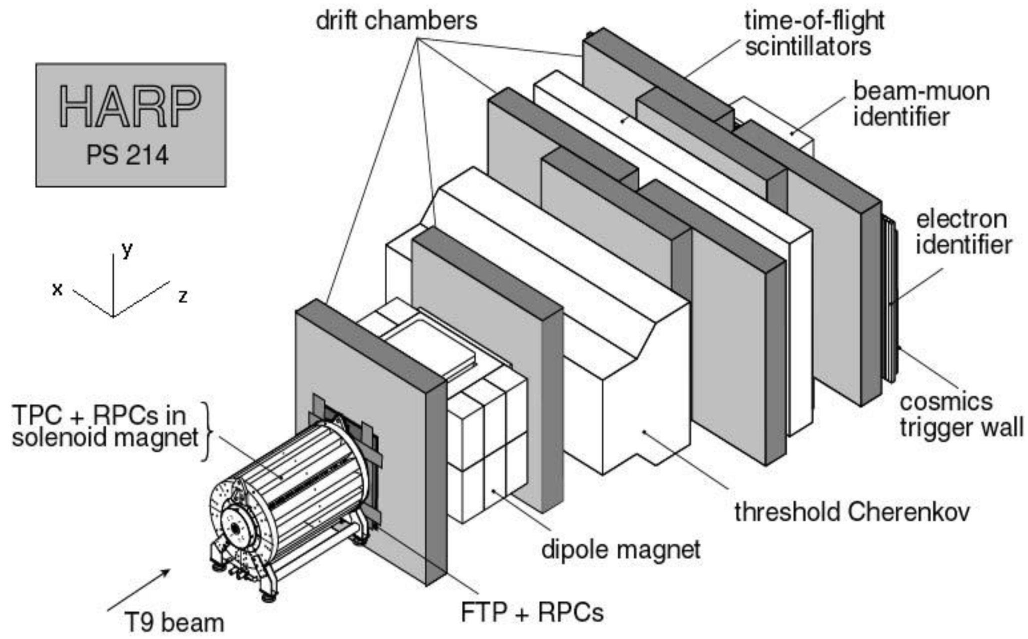
forward spectrometer



large-angle spectrometer

Detailed description of the experimental apparatus

NIM A571 (2007) 524

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Nuclear Physics B 732 (2006) 1–45

NUCLEAR PHYSICS B

First HARP Physics Publication

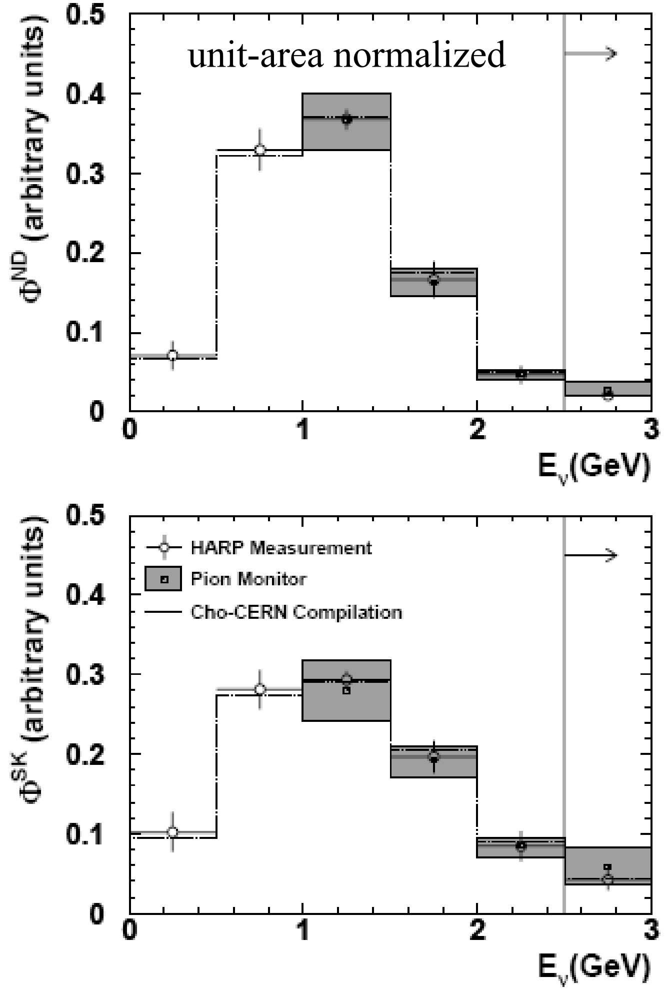
Measurement of the production cross-section of positive pions in p–Al collisions at 12.9 GeV/c

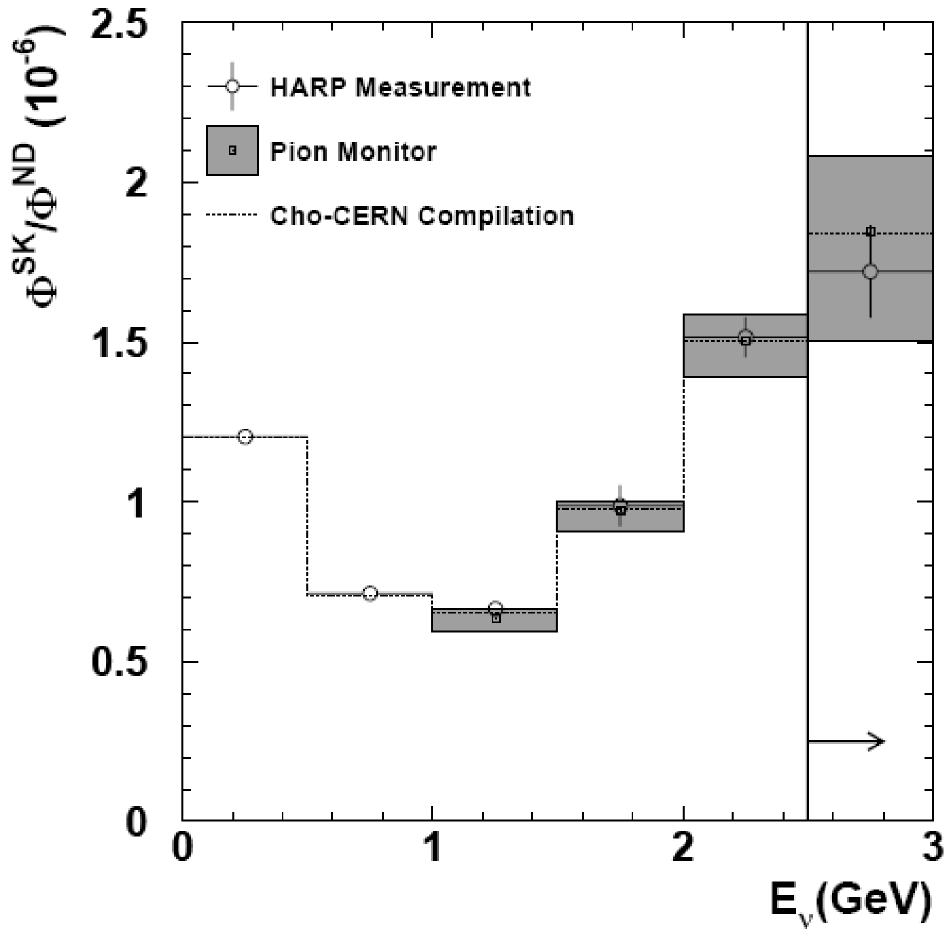
HARP Collaboration

Abstract

A precision measurement of the double-differential production cross-section, $d^2\sigma^{\pi^+}/dp\,d\Omega$, for pions of positive charge, performed in the HARP experiment is presented. The incident particles are protons of 12.9 GeV/c momentum impinging on an aluminium target of 5% nuclear interaction length. The measurement of this cross-section has a direct application to the calculation of the neutrino flux of the K2K experiment. After cuts, 210 000 secondary tracks reconstructed in the forward spectrometer were used in this analysis. The results are given for secondaries within a momentum range from 0.75 to 6.5 GeV/c, and within an angular range from 30 mrad to 210 mrad. The absolute normalization was performed using prescaled beam triggers counting protons on target. The overall scale of the cross-section is known to better than 6%, while the average point-to-point error is 8.2%.

K2K Far/Near flux ratio prediction



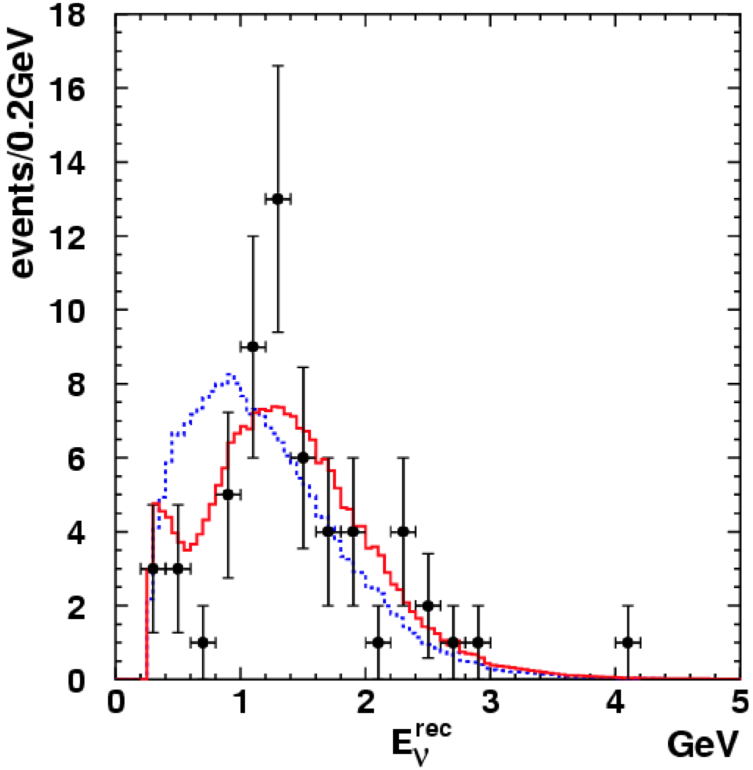


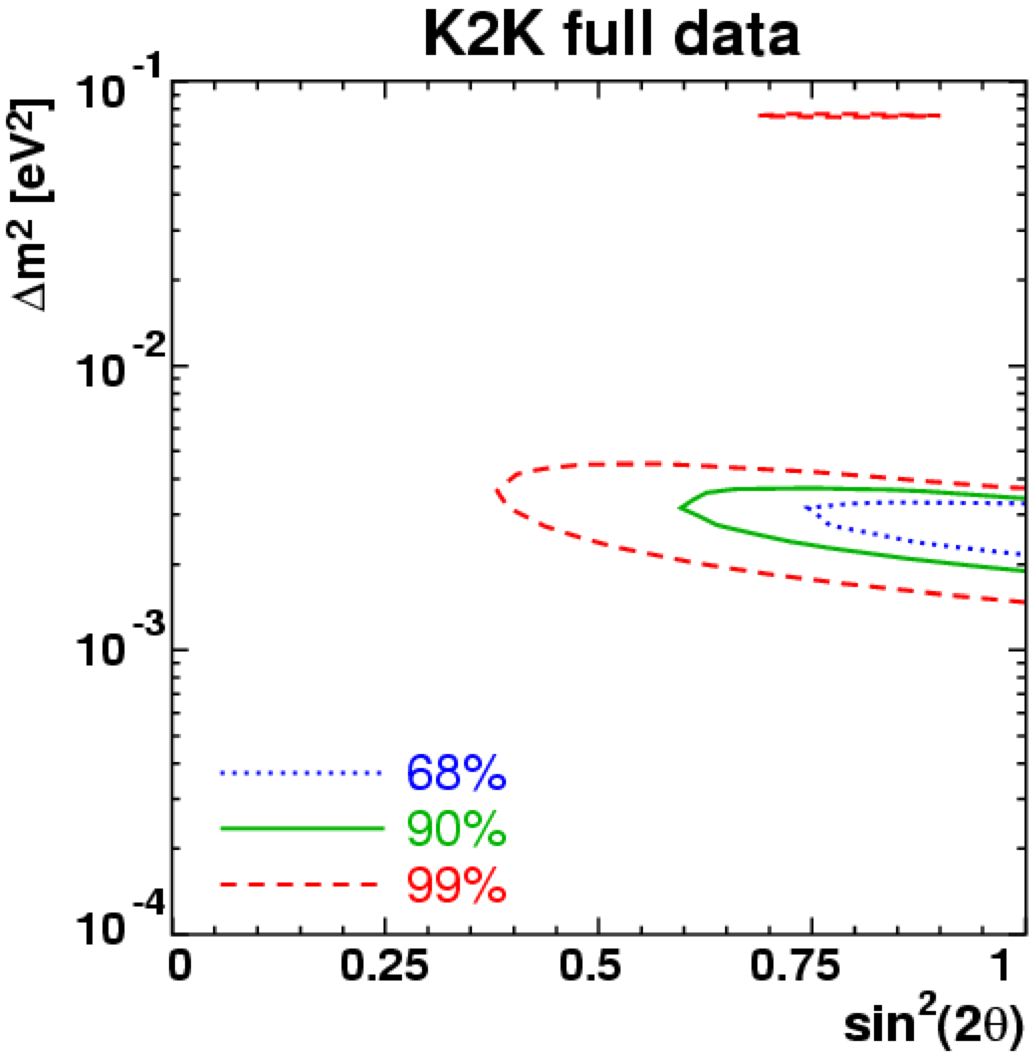
- HARP Al cross-section results have provided an important cross-check on previous K2K flux predictions. completely consistent in shape

- F/N ratio no longer dominant systematic error

Phys. Rev. D74 (2006) 072003

K2K Far/Near flux ratio prediction





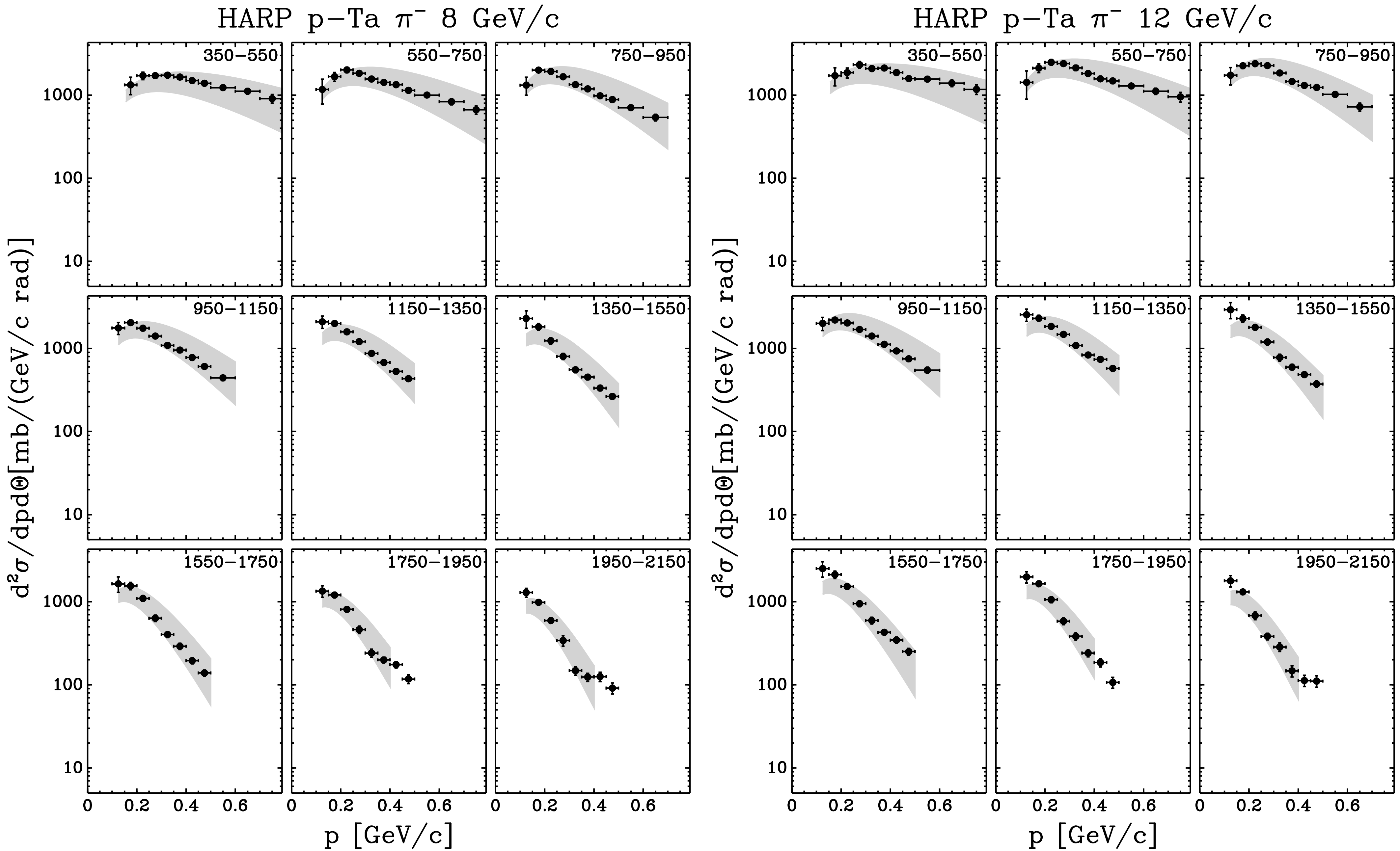
- The final K2K oscillation measurement has incorporated flux predictions based on the HARP Al measurement

  - 4.3 σ result
  - statistics limited

Phys. Rev. D74 (2006) 072003

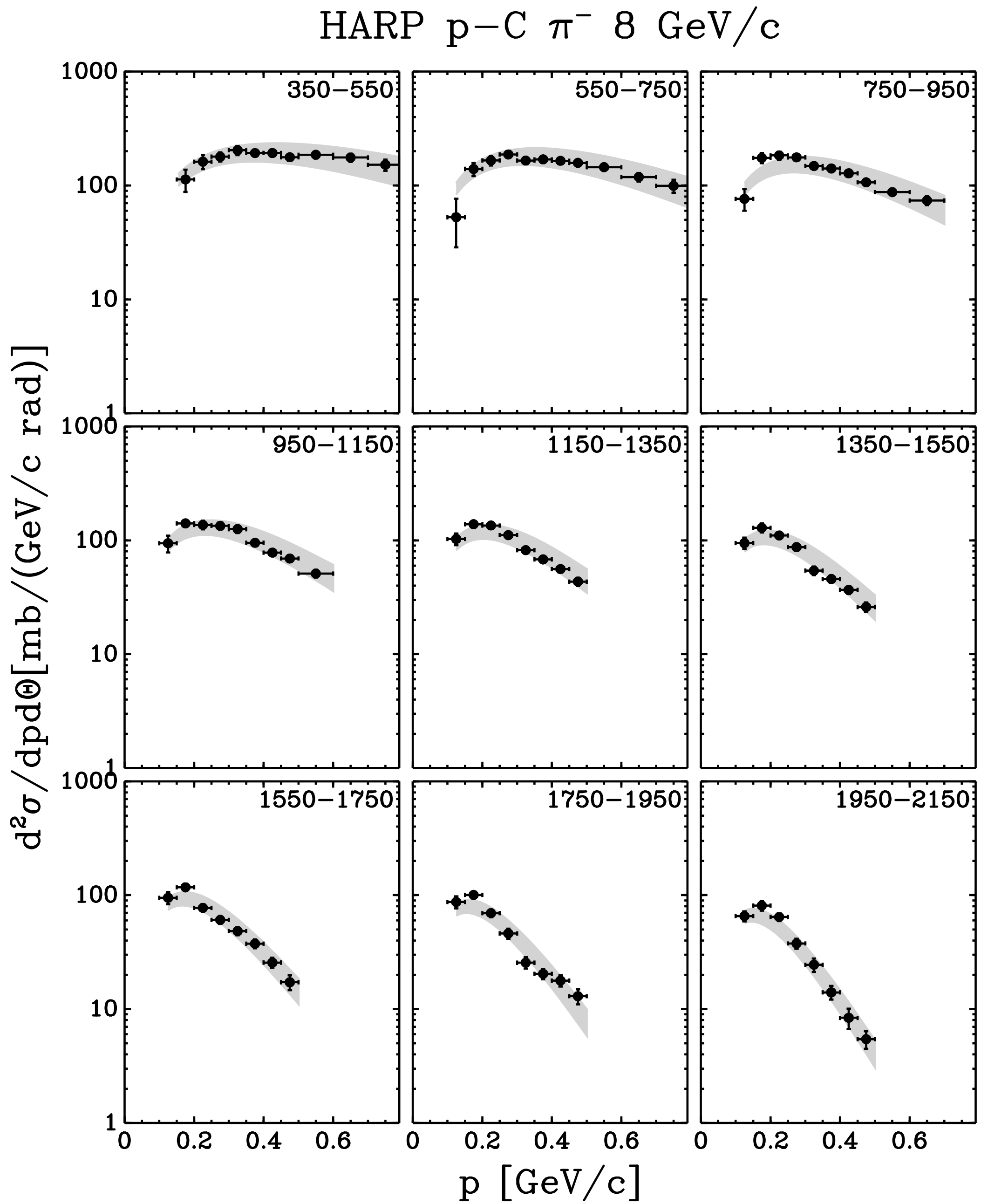
p-Ta

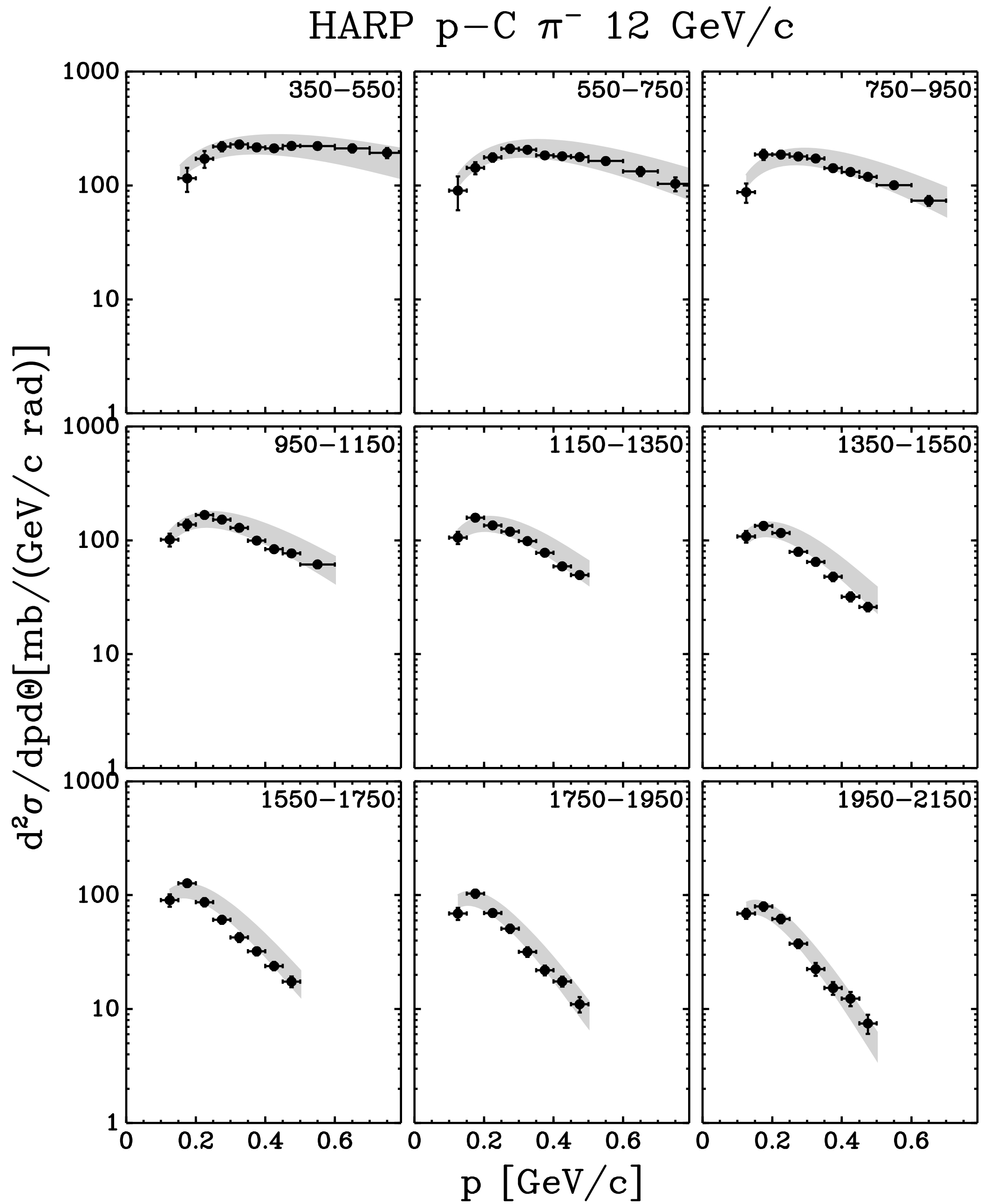
comparison with JINR 10 GeV/c data (bubble chamber), arbitrary normalization



p-C

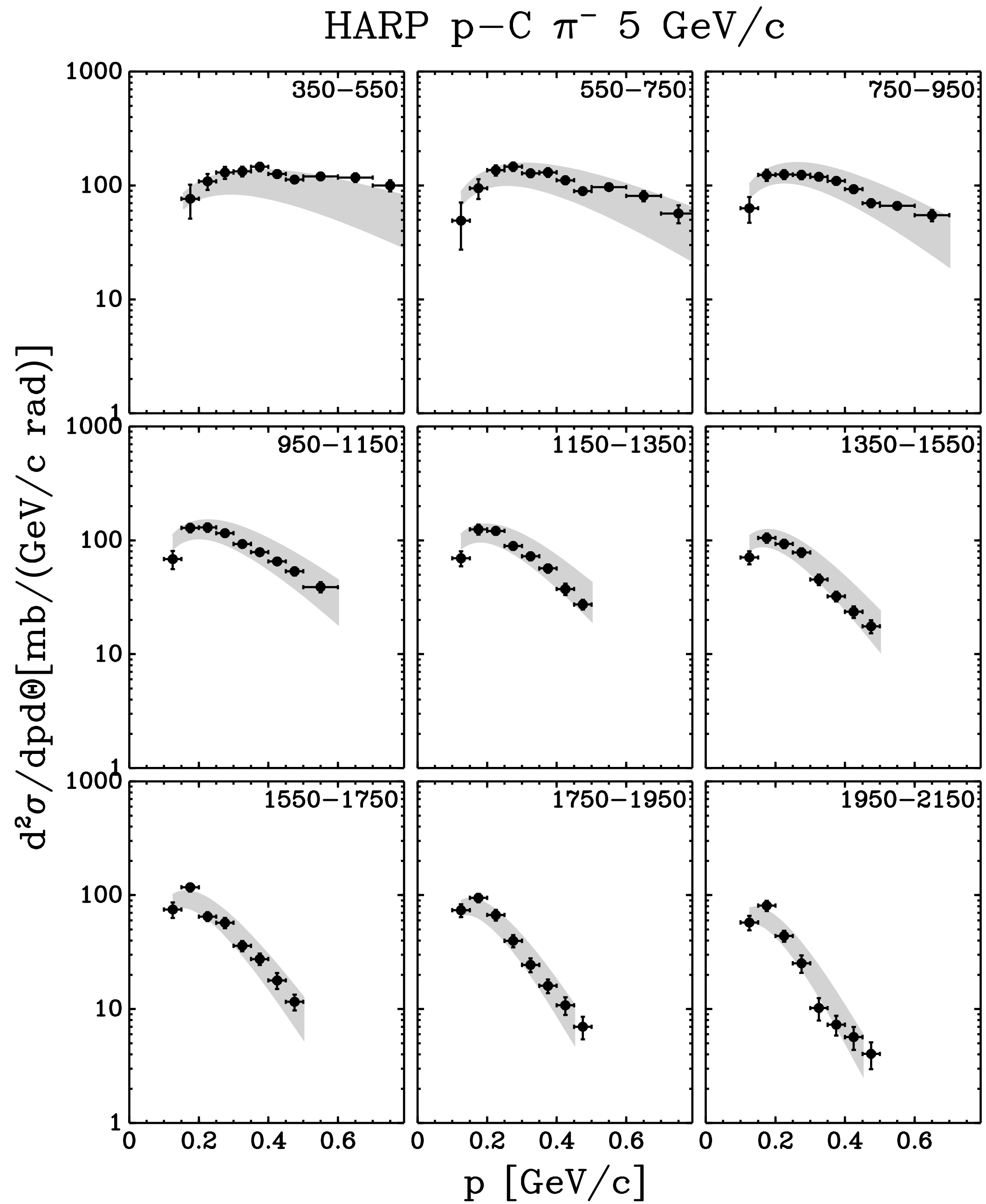
comparison with JINR 10 GeV/c data (bubble chamber), arbitrary normalization





p-C

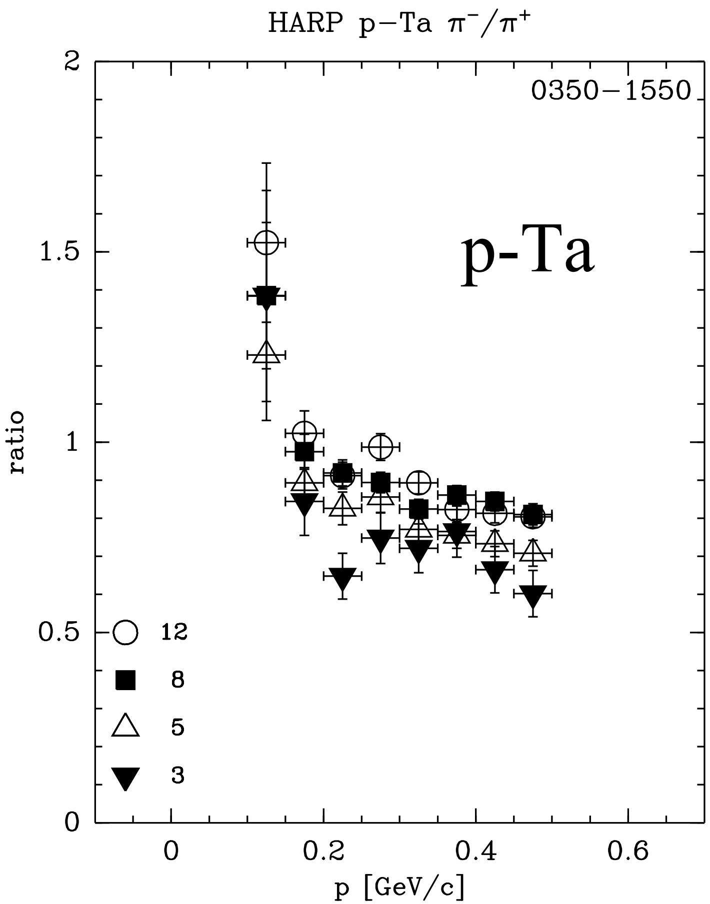
with JINR 4.2 GeV/c data (bubble chamber), arbitrary normalization

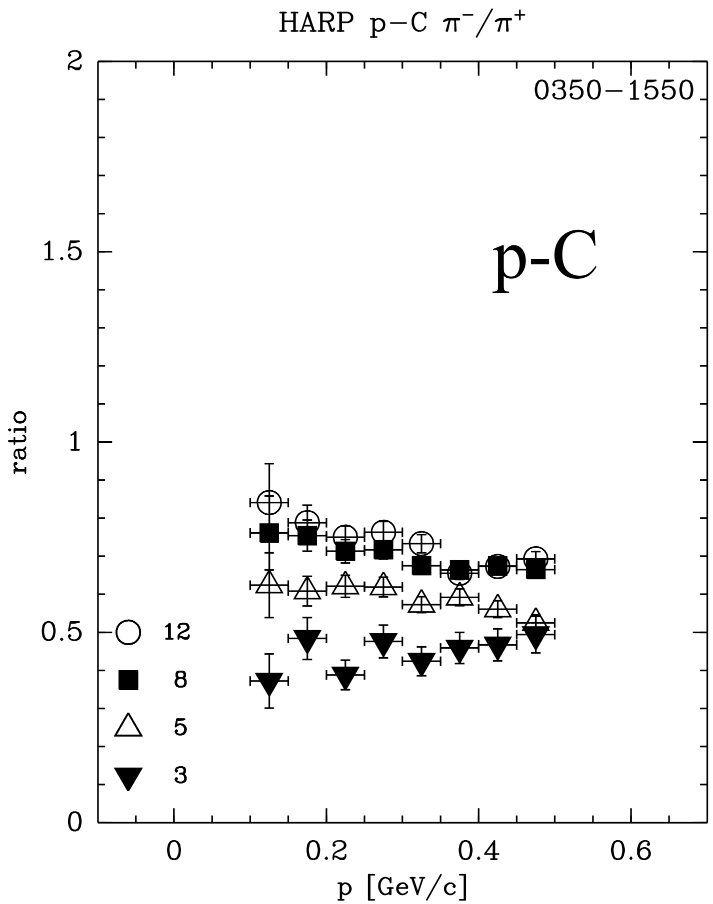


Pion yields

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

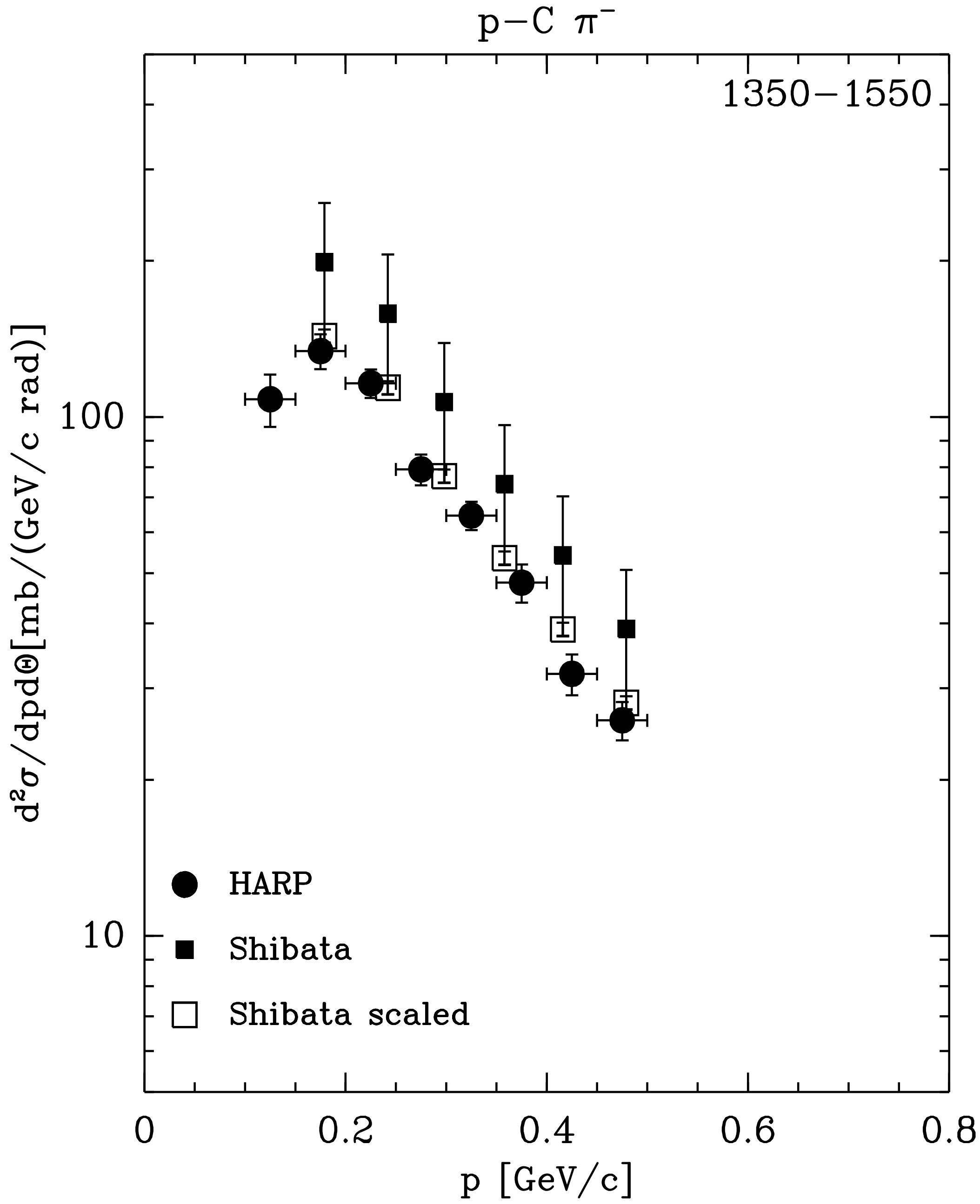
forward production only $0.35 < \theta < 1.55$ rad

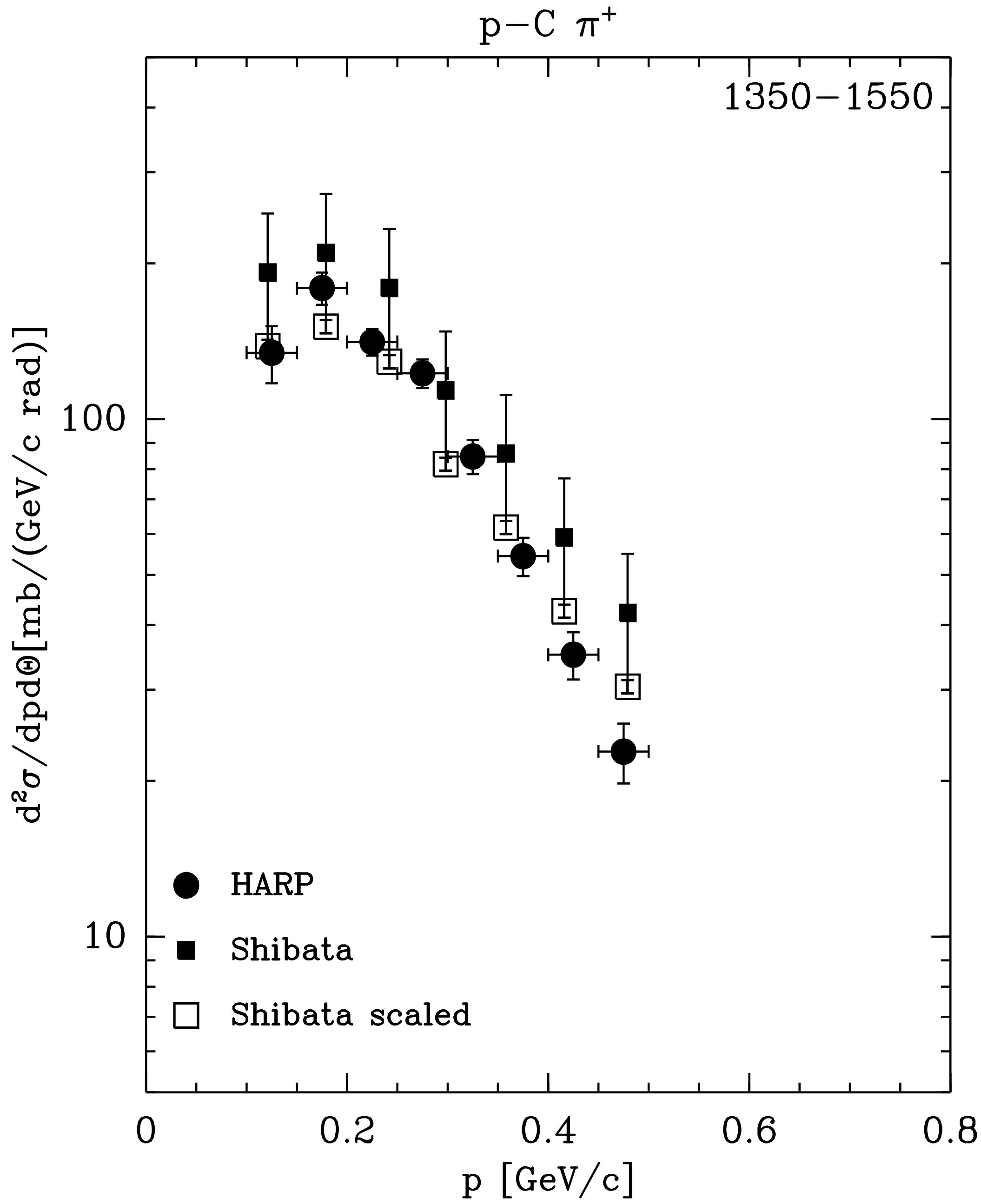




p-C

Shibata 12 GeV/c (magnetic spectrometer), 30% acceptance uncertainty, 3% p-t-p





p-Cu

Shibata 12 GeV/c (magnetic spectrometer), 30% acceptance uncertainty, 3% p-t-p