Results from HARP

and their implications for **neutrino physics**

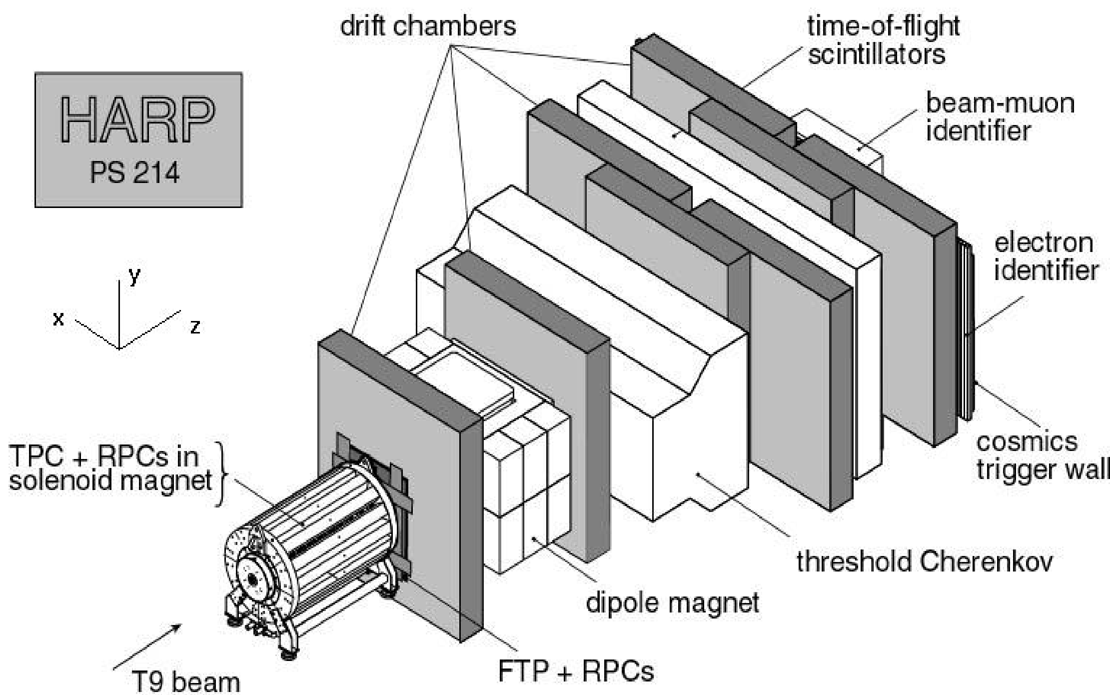
Workshop “Neutrino Physics at Accelerators”, January 2008, JINR, Dubna

Boris A. Popov

for the HARP Collaboration

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

HARP
PS 214



HARP – PS214 at CERN

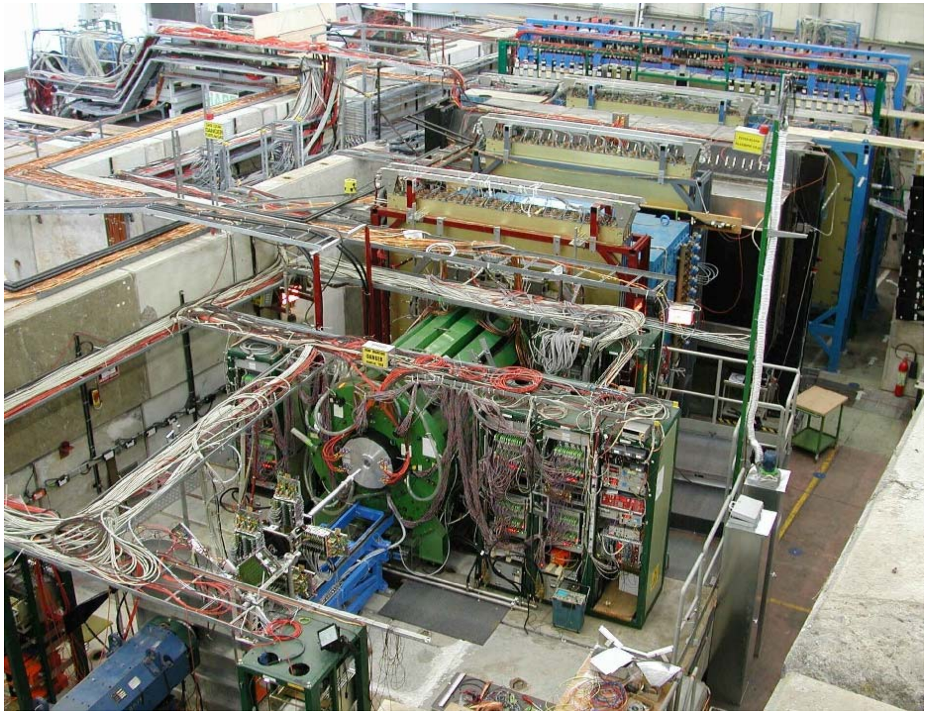
HARP is a large angle spectrometer to measure hadron production from various nuclear targets and a range of incident beam momenta

- 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



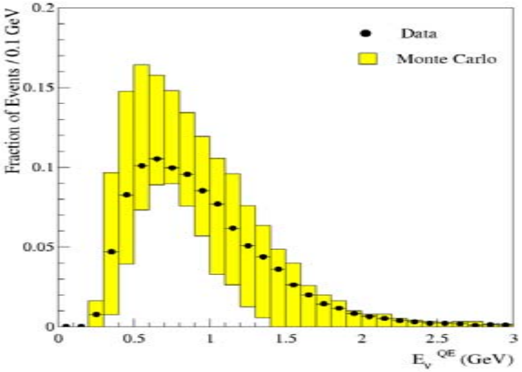
large angle spectrometer

Data taking in 2001-2002

hadron production measurements in "*seven dimensions*"

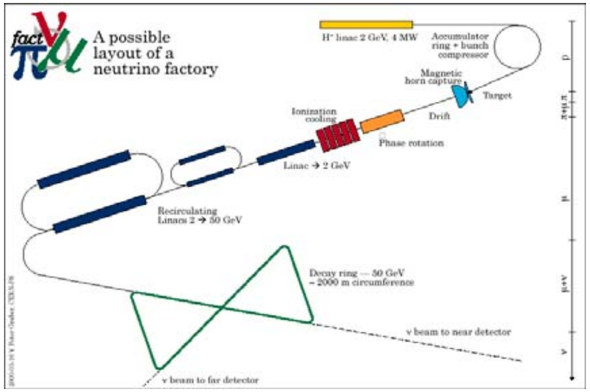
Detailed description of the experimental apparatus **NIM A571 (2007) 524**

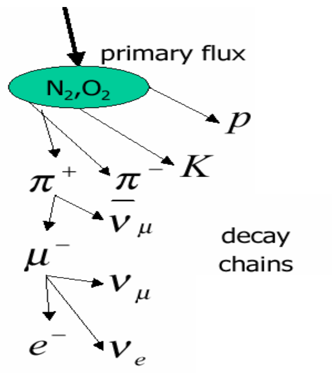
HARP physics goals



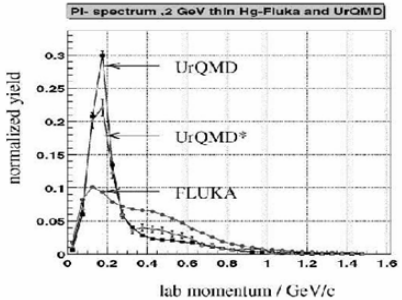
Input for prediction of neutrino fluxes for the **K2K** and **MiniBooNE / SciBooNE** accelerator experiments

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





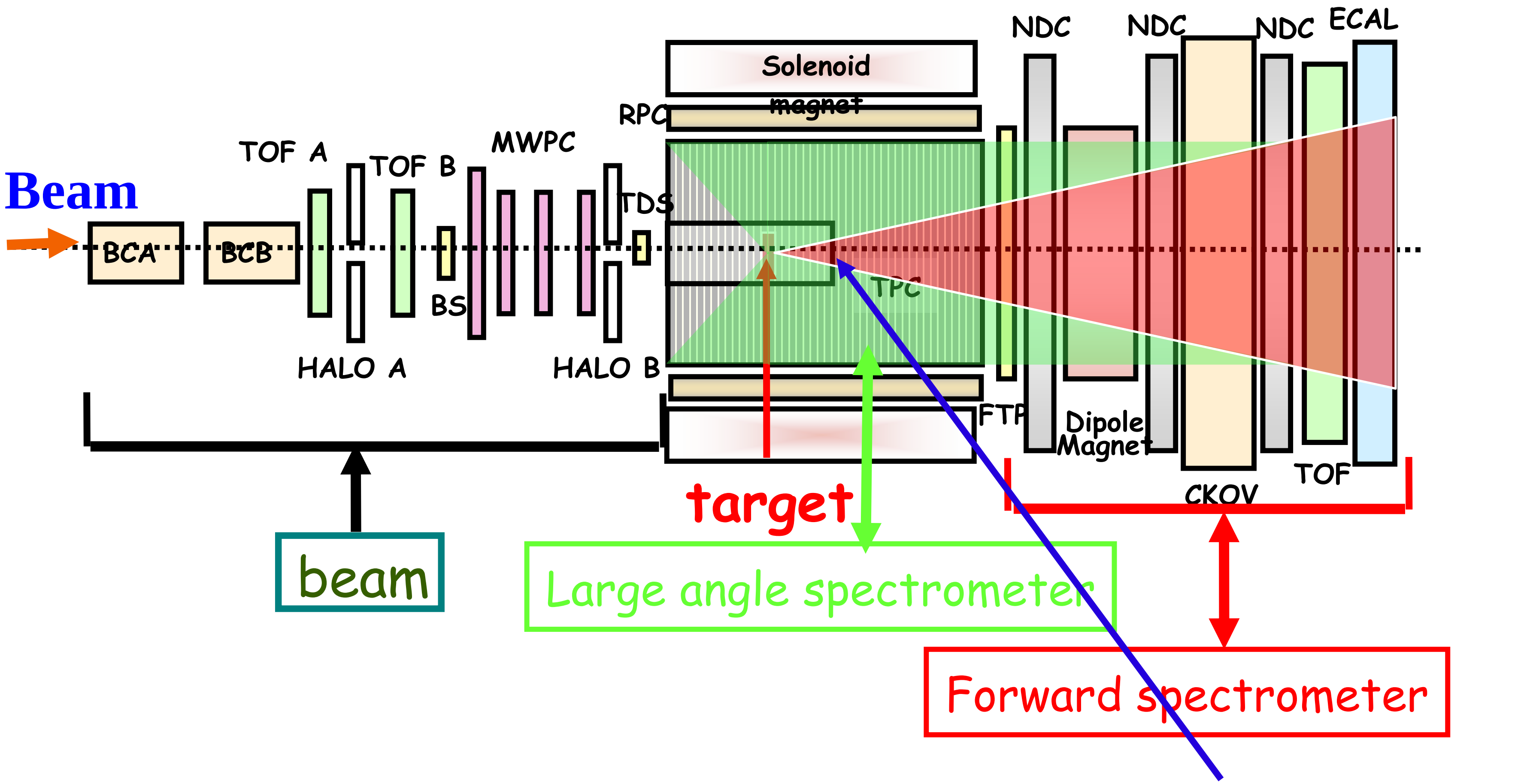
Input for precise calculation of the **atmospheric neutrino** flux (from yields of secondary π,K)



NIM-A 472 (2001) 557-560

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

Analyses with the HARP forward spectrometer



0.03 < θ < 0.24 rad

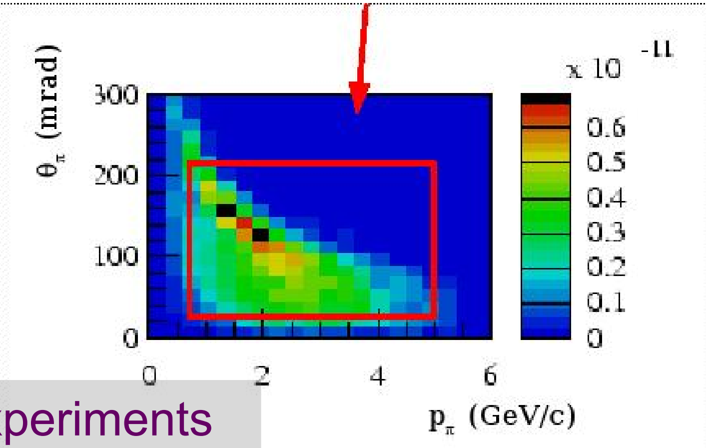
Analyses with the HARP forward spectrometer

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

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

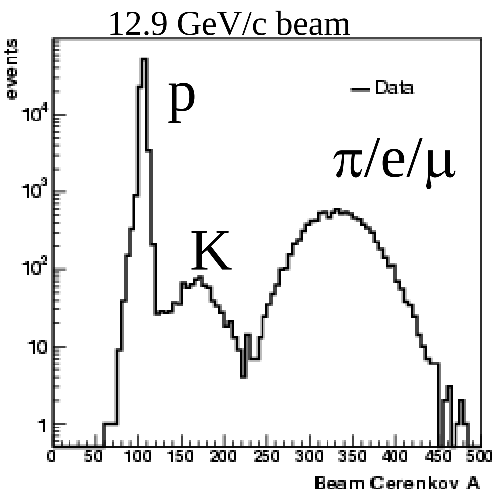
- Select events identified as primary protons interacting in the target
- For each event, reconstruct tracks and their 3-momentum
- Identify pions among secondary tracks
- Apply corrections, for reconstructed-to-true pion yield conversion:
  - Momentum resolution
  - Spectrometer angular acceptance
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

  from data (when possible)

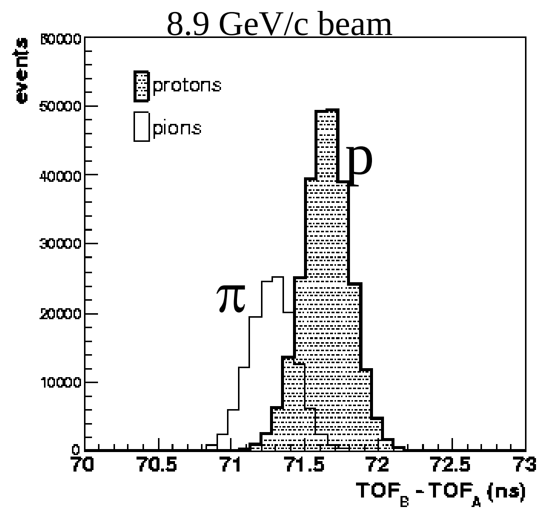
- Count protons on target corresponding to selected events
- Multiply by physics constants and accurately measured target properties

HARP – PS214 at CERN

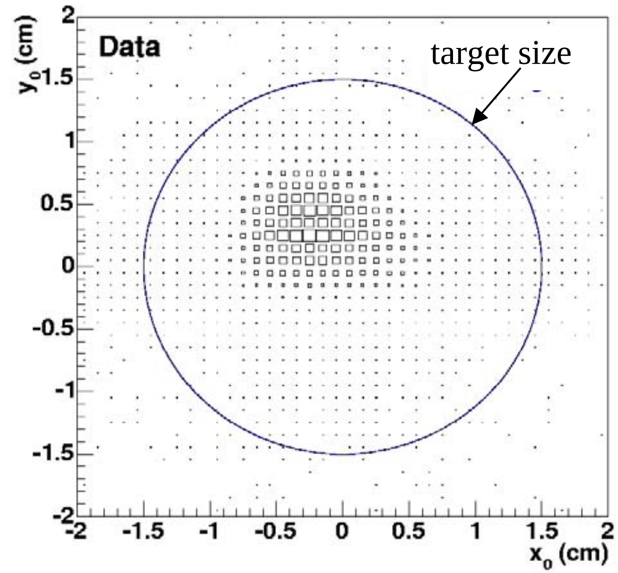
Event selection



2 Beam Cherenkov Detectors



3 Beam ToF Detectors

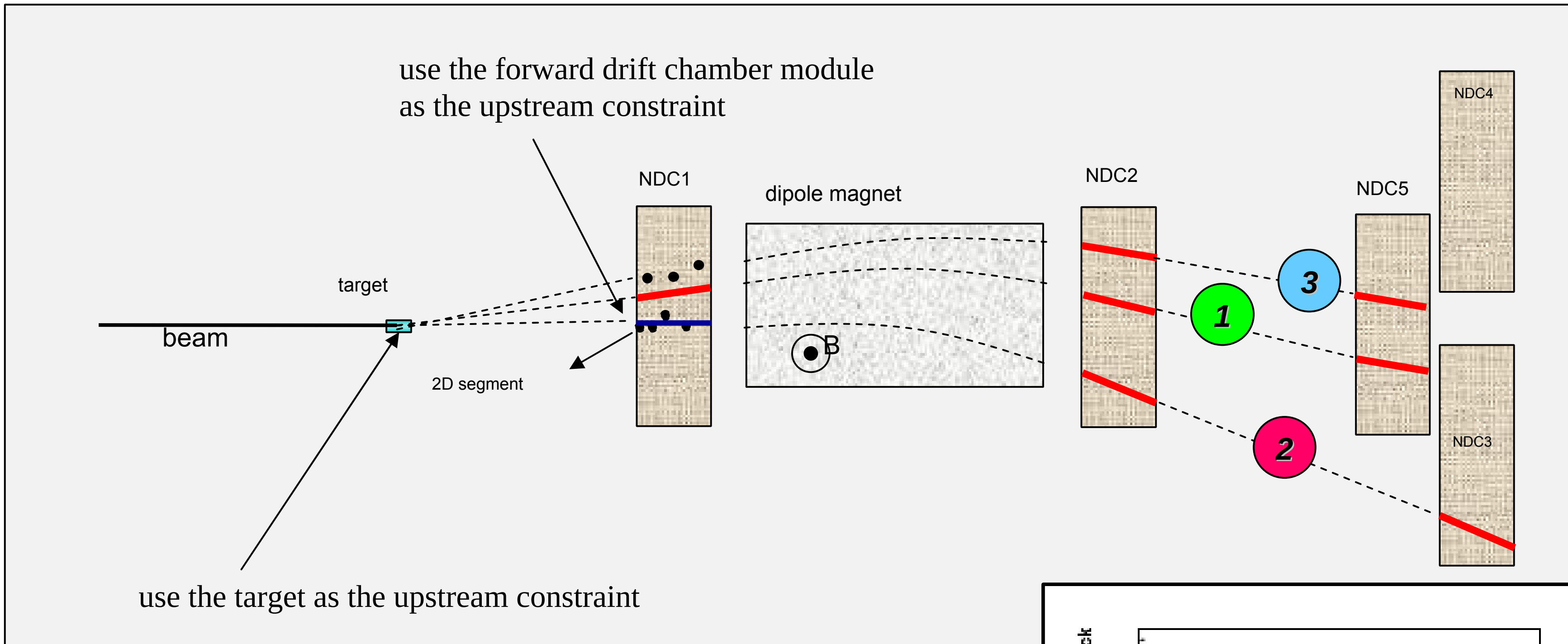


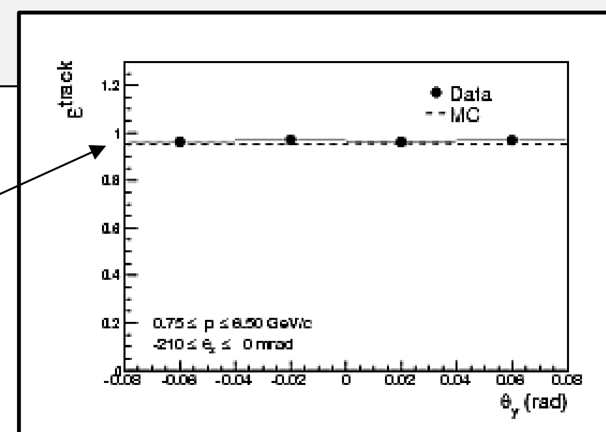
4 Multi-Wire Proportional Chambers

- **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

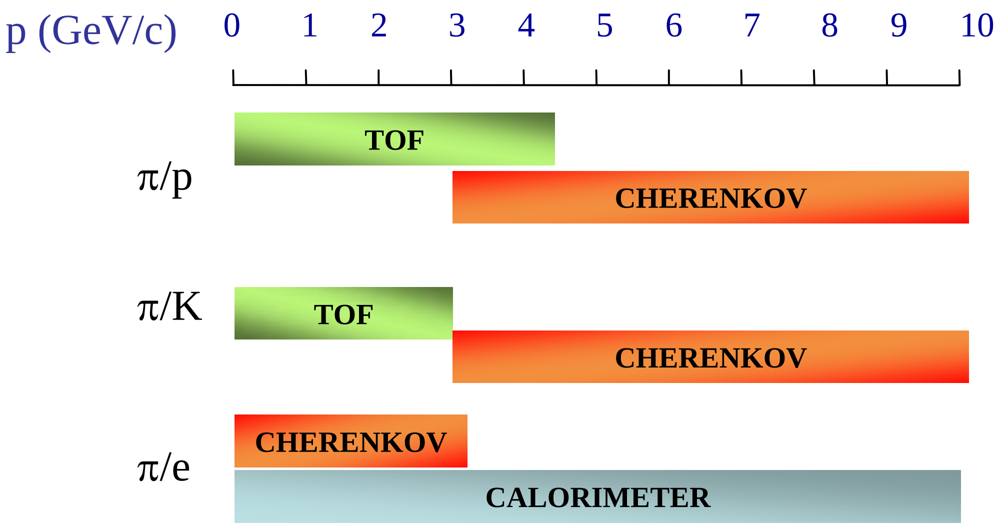


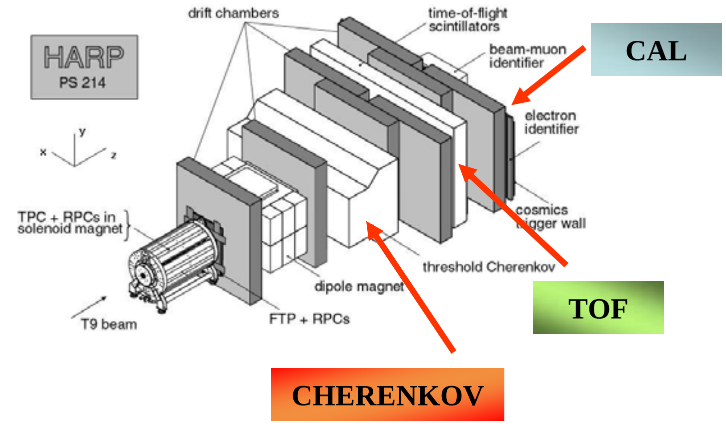


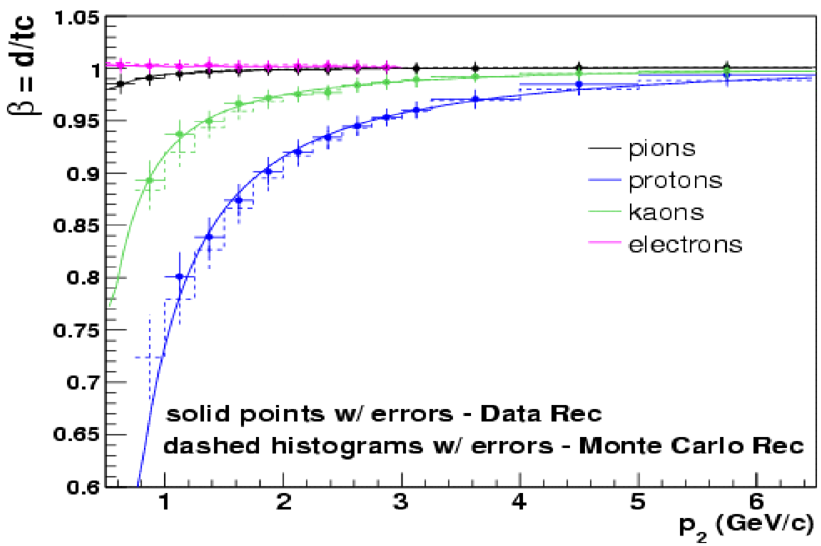
- redundancy in chambers and redundancy in vertex constraints allows determination of tracking efficiencies from the data themselves

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

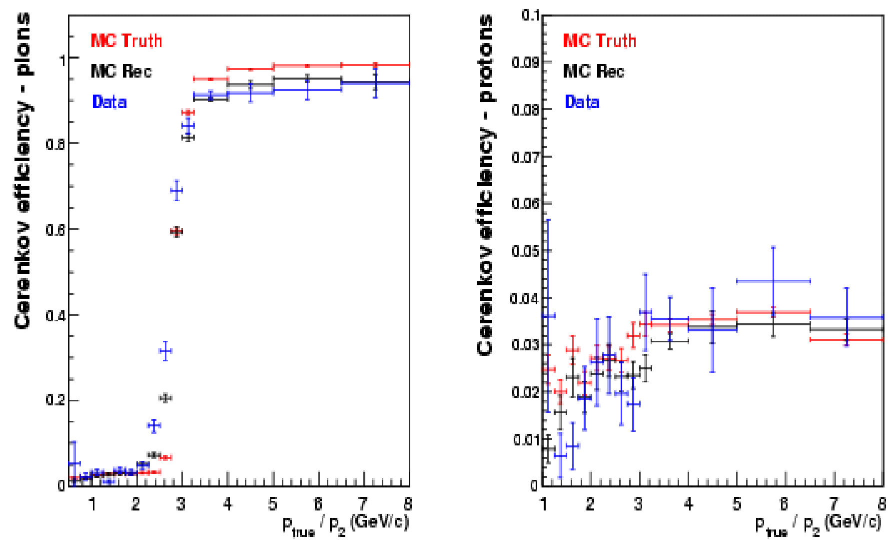
Particle identification in the forward spectrometer







TOF π/p/K response



CHERENKOV π/p response

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

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Nuclear Physics B 732 (2006) 1–45

NUCLEAR PHYSICS B

First HARP Physics Publication

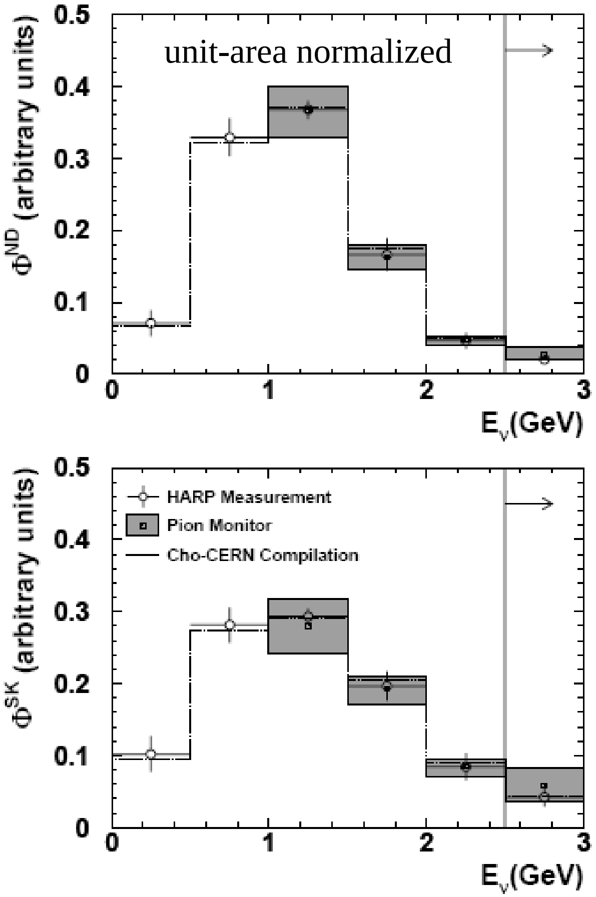
Measurement of the production cross-section of positive pions in p–Al collisions at 12.9 GeV/c

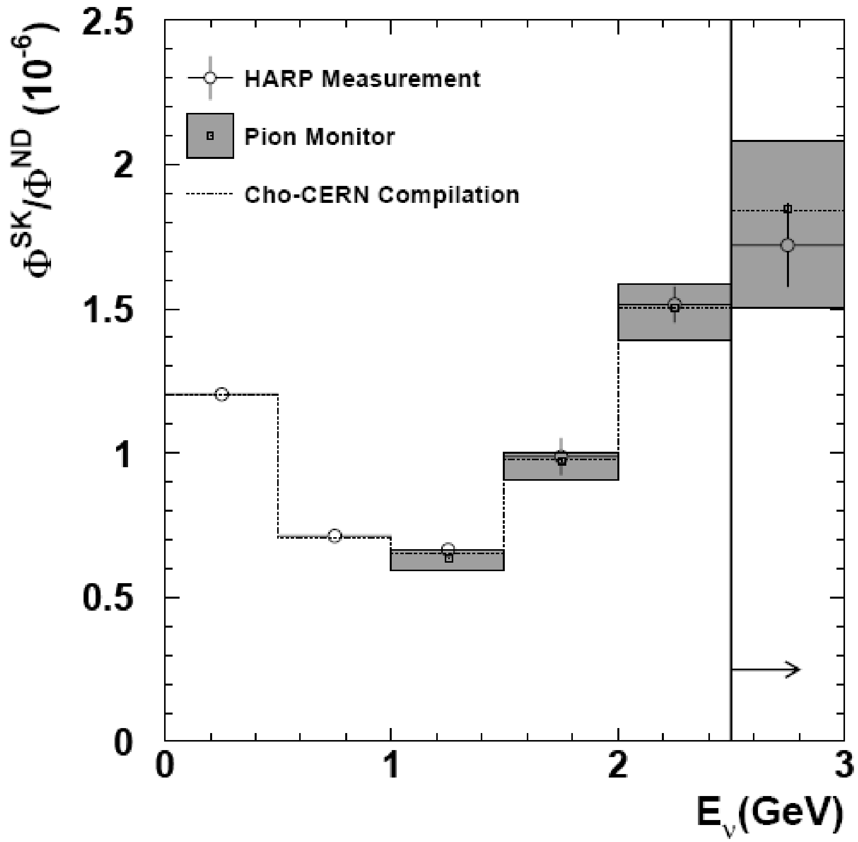
HARP Collaboration

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



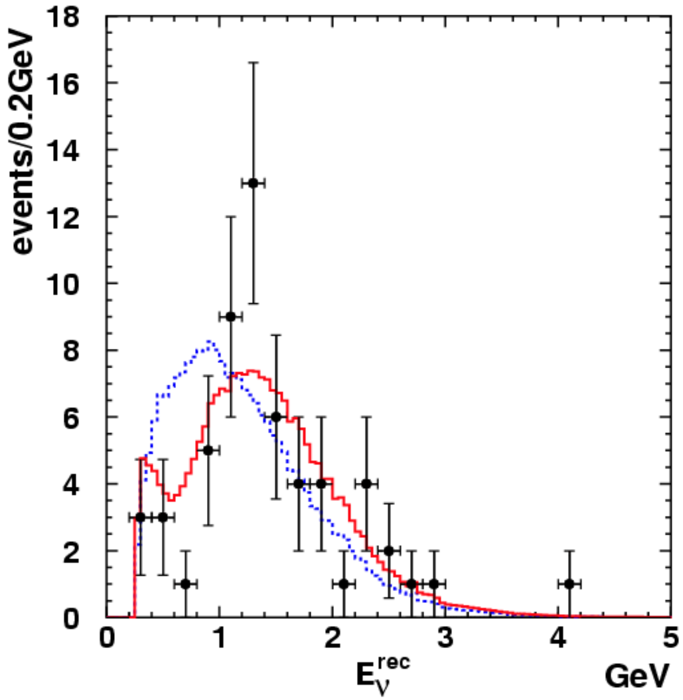


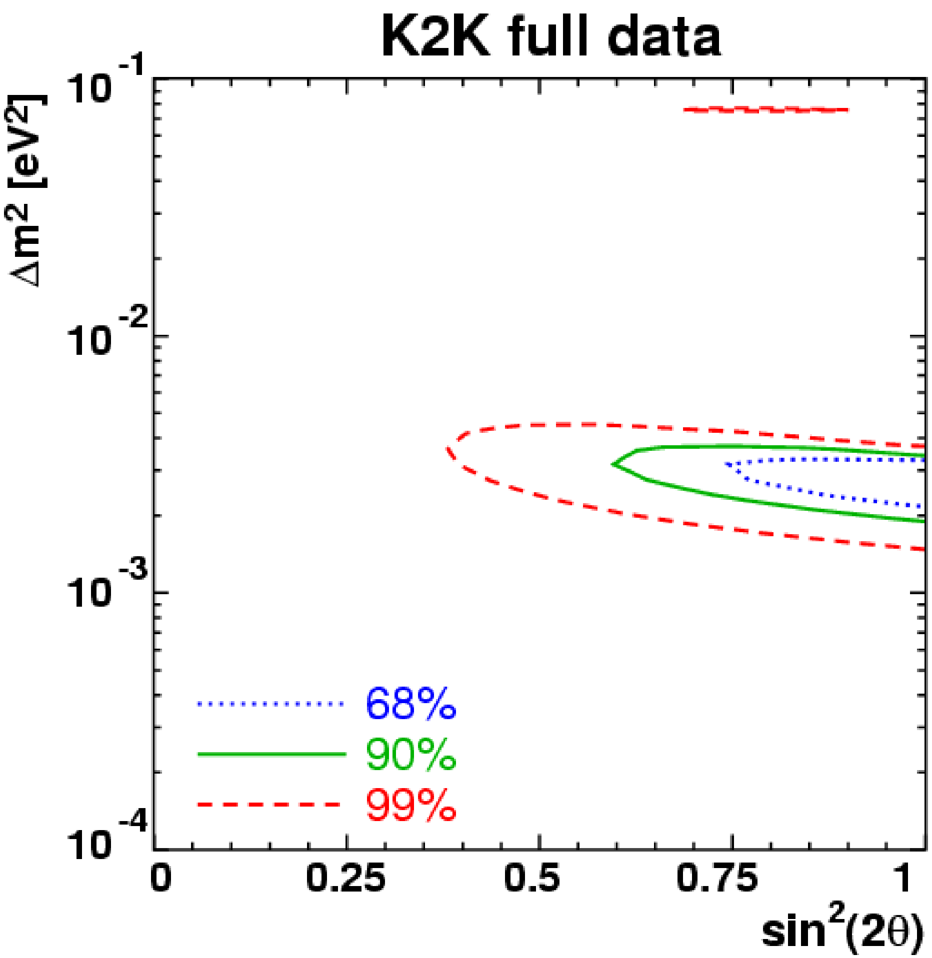
- HARP Al cross-section results have provided an important cross-check on previous K2K flux predictions. completely consistent in shape

- 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

HARP Physics Publication

Eur. Phys. J. C 52, 29–53 (2007)
DOI 10.1140/epjc/s10052-007-0382-8

THE EUROPEAN PHYSICAL JOURNAL C

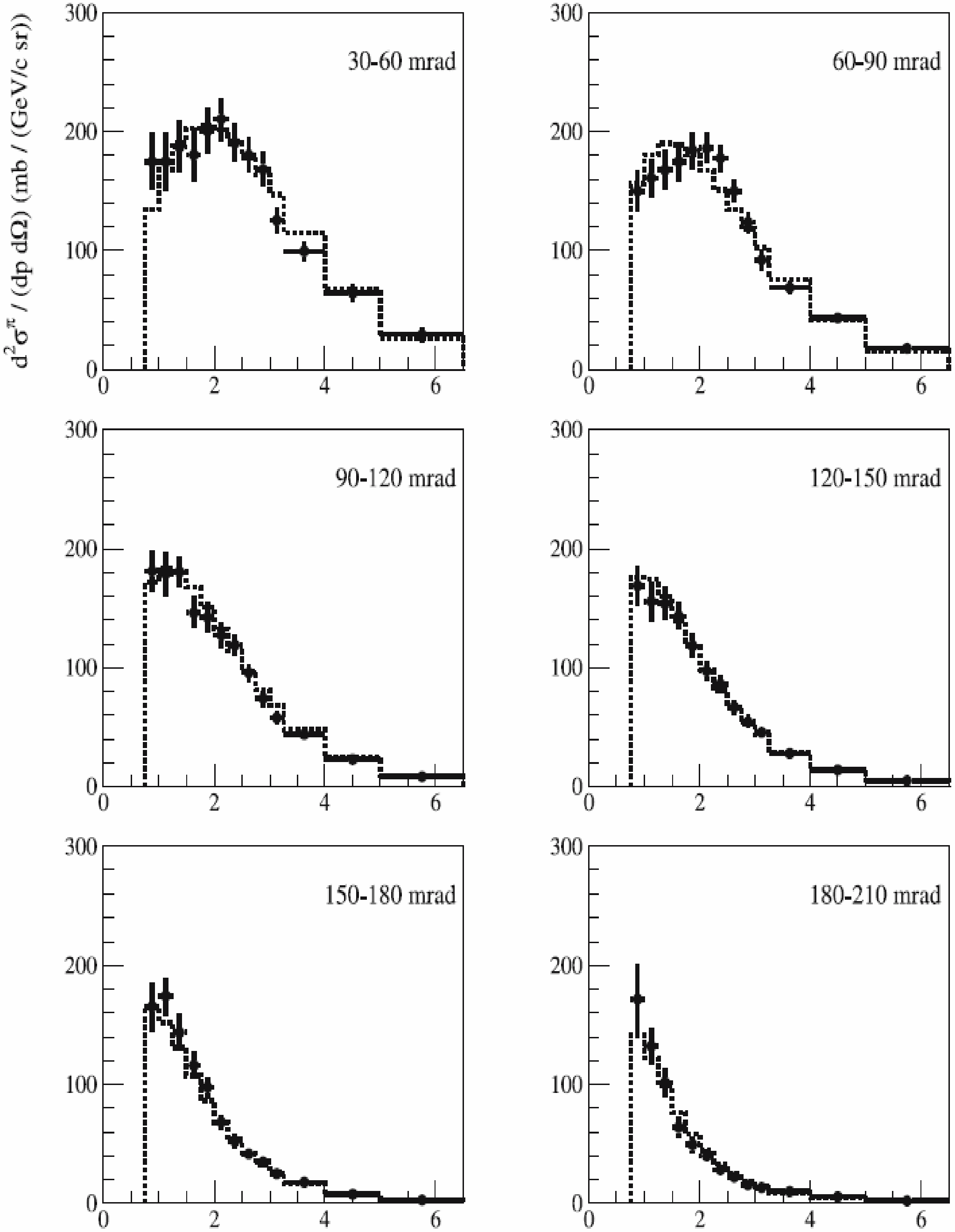
Regular Article – Experimental Physics

Measurement of the production cross-section of positive pions in the collision of $8.9\,\mathrm{GeV}/c$ protons on beryllium

The HARP Collaboration

Abstract. The double-differential production cross-section of positive pions, $\mathrm{d}^2\sigma^{\pi^+}/\mathrm{d}p\,\mathrm{d}\Omega$, measured in the HARP experiment is presented. The incident particles are 8.9 GeV/c protons directed onto a beryllium target with a 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 reconstructed secondary tracks which were used in this analysis. Cross-section results are presented in the kinematic range $0.75\ \mathrm{GeV}/c \leq p_\pi \leq 6.5\ \mathrm{GeV}/c$ and $30\ \mathrm{mrad} \leq \theta_\pi \leq 210\ \mathrm{mrad}$ in the laboratory frame.

HARP – PS214 at CERN



5% λ Be target

EPJ C 52 (2007) 29

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

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

- 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

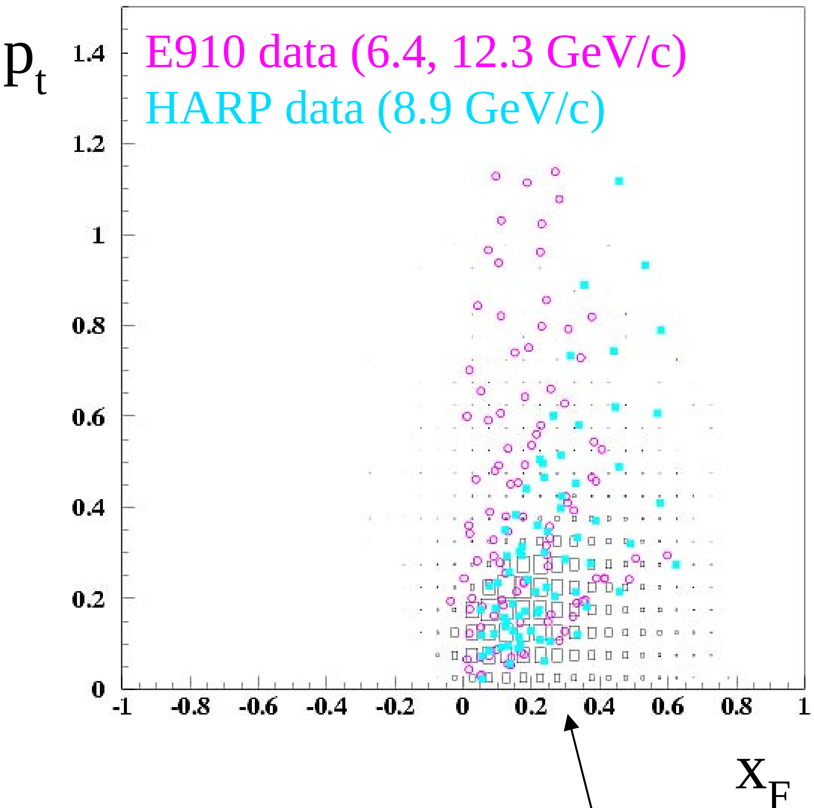
Parameter	Value
c_1	$(8.22 \pm 1.98) \cdot 10^1$
c_2	(6.47 ± 1.62)
c_3	$(9.06 \pm 2.03) \cdot 10^1$
$c_4 = c_5$	$(7.44 \pm 2.30) \cdot 10^{-2}$
c_6	(5.09 ± 0.49)
c_7	$(1.87 \pm 0.53) \cdot 10^{-1}$
c_8	$(4.28 \pm 1.36) \cdot 10^1$

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

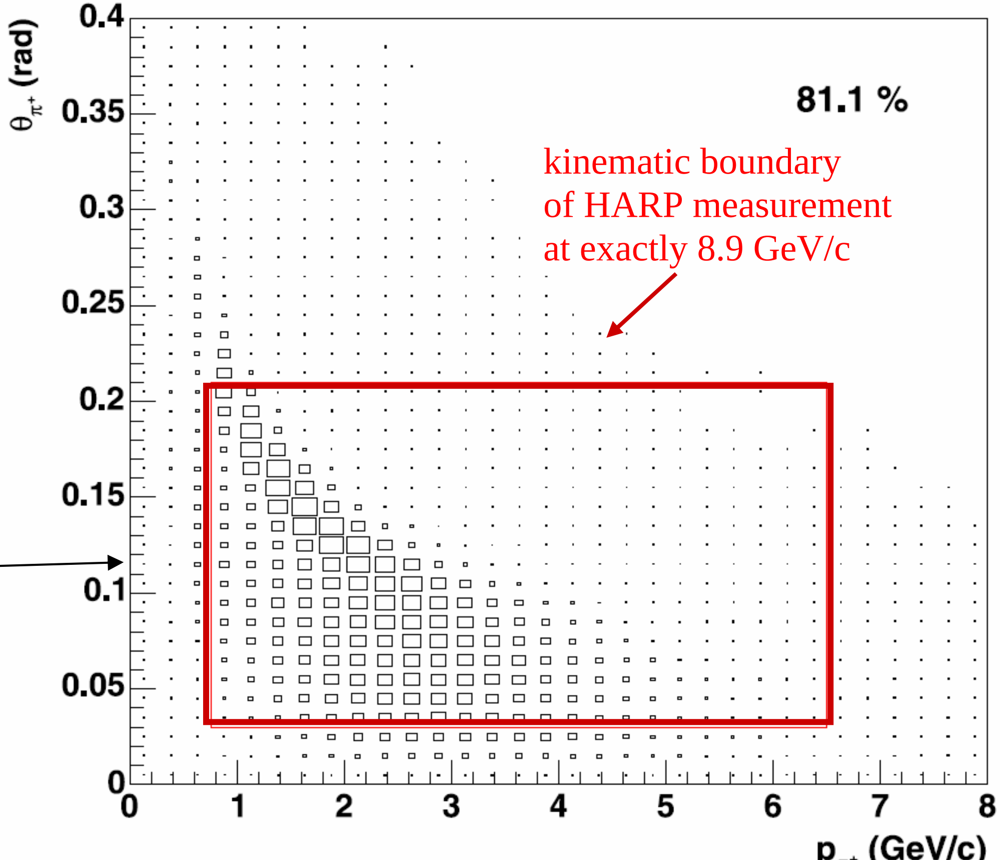
J. R. Sanford and C. L. Wang "Empirical formulas for particle production in p-Be collisions between 10 and 35 BeV/c", Brookhaven National Laboratory, AGS internal report, (1967) (*unpublished)*

MiniBooNE ν_μ flux prediction



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

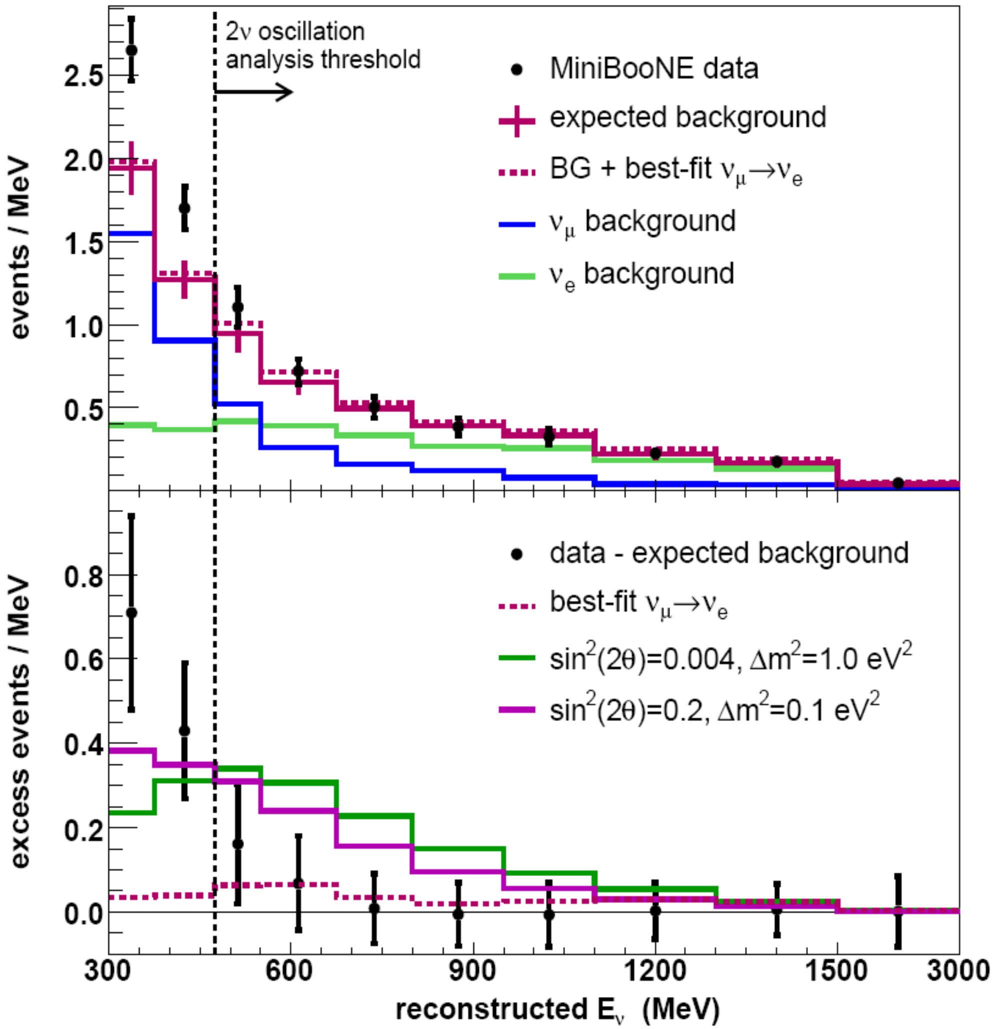
- Use the parameterization of Sanford and Wang and fit to both data sets combined

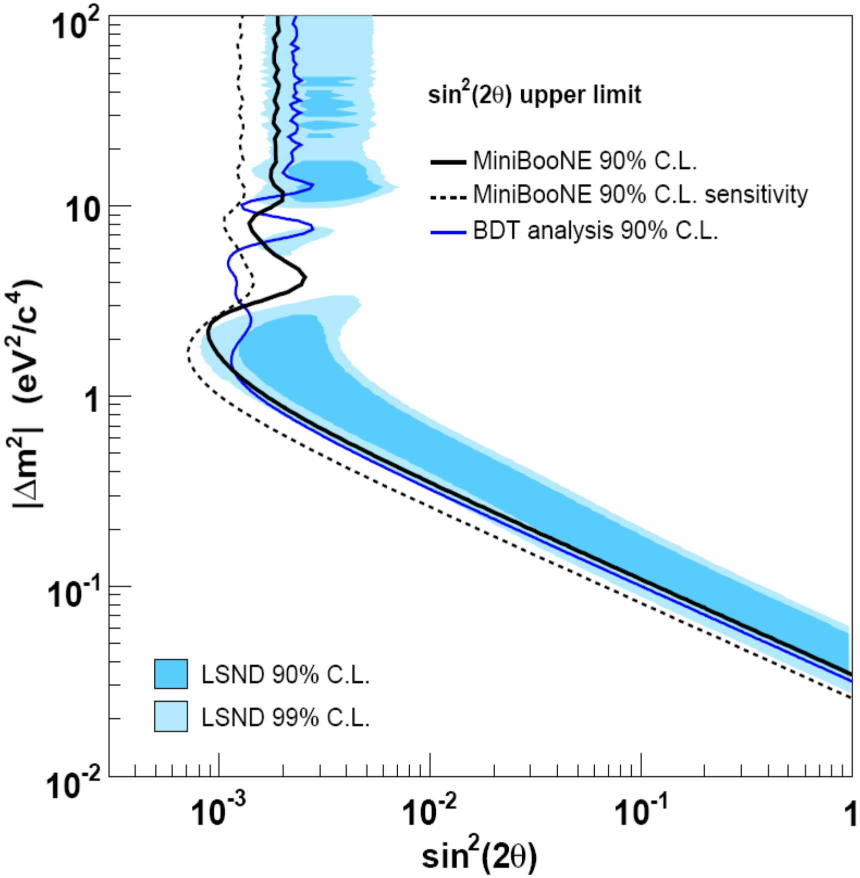


- black boxes are the distribution of π^+ which decay to a ν_μ that **passes through the MiniBooNE detector**

p(8.9 GeV/c) + Be -> π^+ -> ν_μ^{MB}

MiniBooNE oscillation results





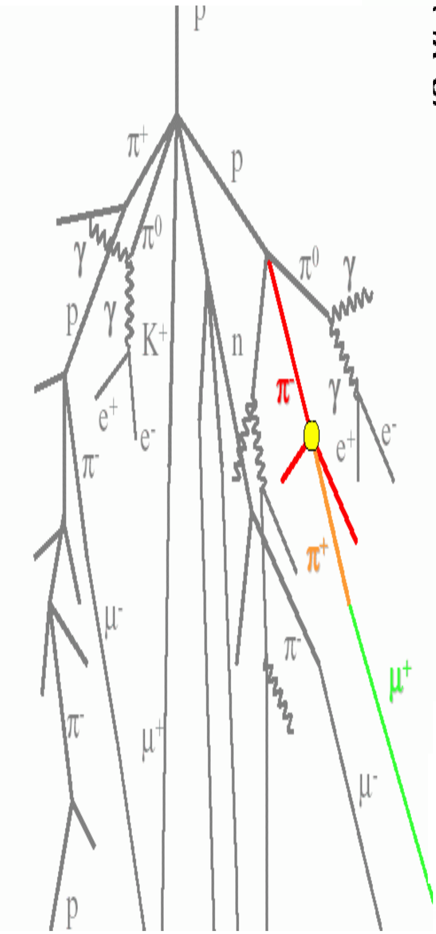
$475 < E_\nu < 3000$ MeV

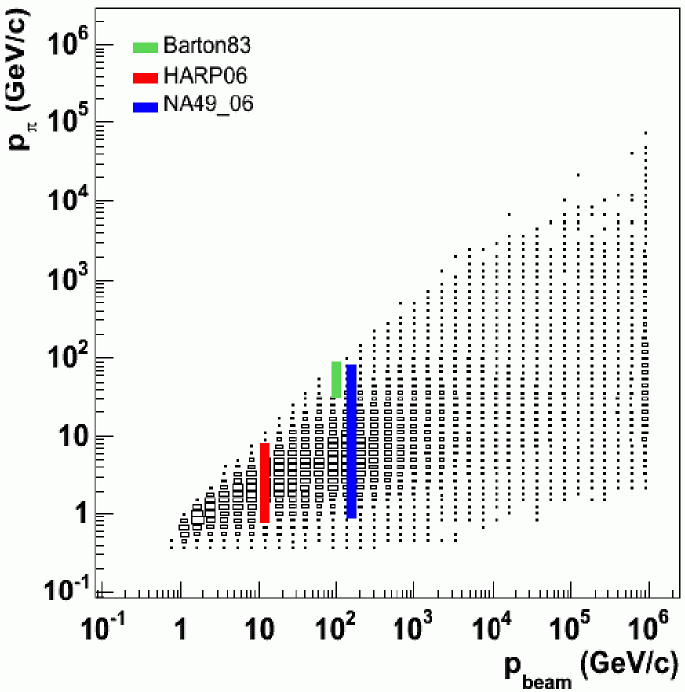
HARP Be measurements were used for the neutrino flux prediction in MiniBooNE

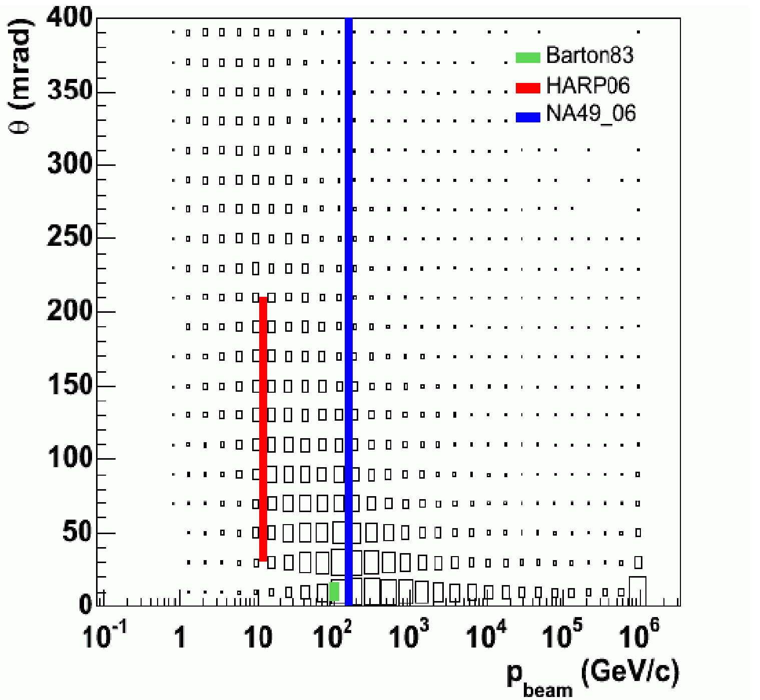
Phys. Rev. Lett. 98 (2007) 231801

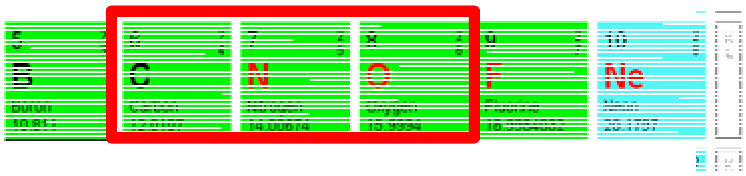
Atmospheric neutrino flux predictions

- 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

carbon is isoscalar as well as nitrogen and oxygen

Upcoming HARP Physics Publication

Measurement of the production cross-sections of $\pi^{\pm}$ in p-C and $\pi^{\pm}$-C interactions at 12 GeV/c

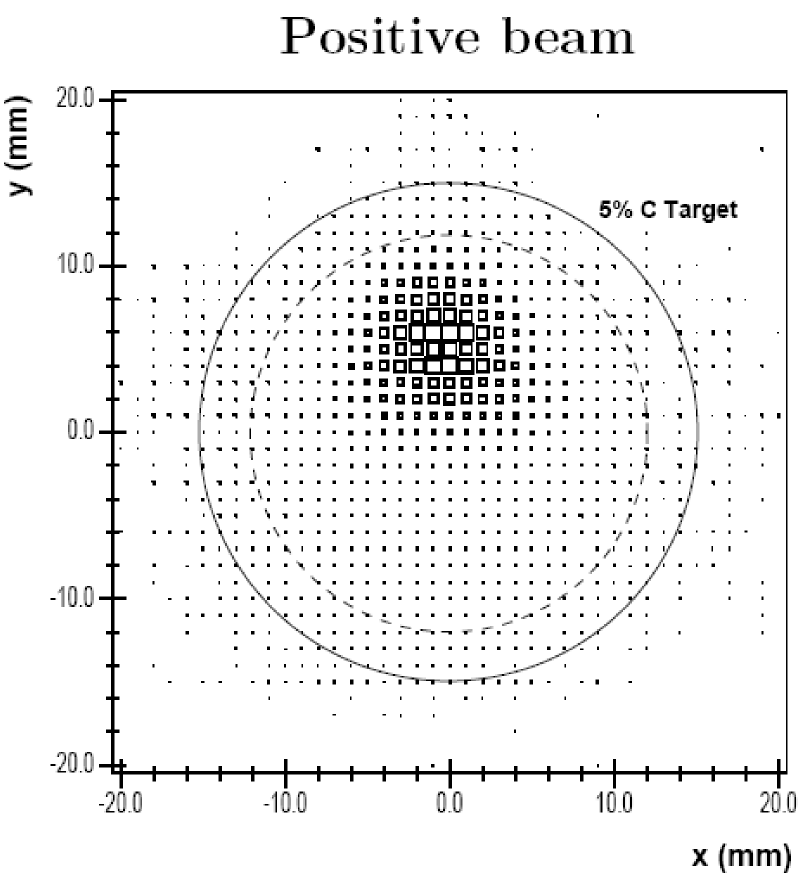
HARP Collaboration

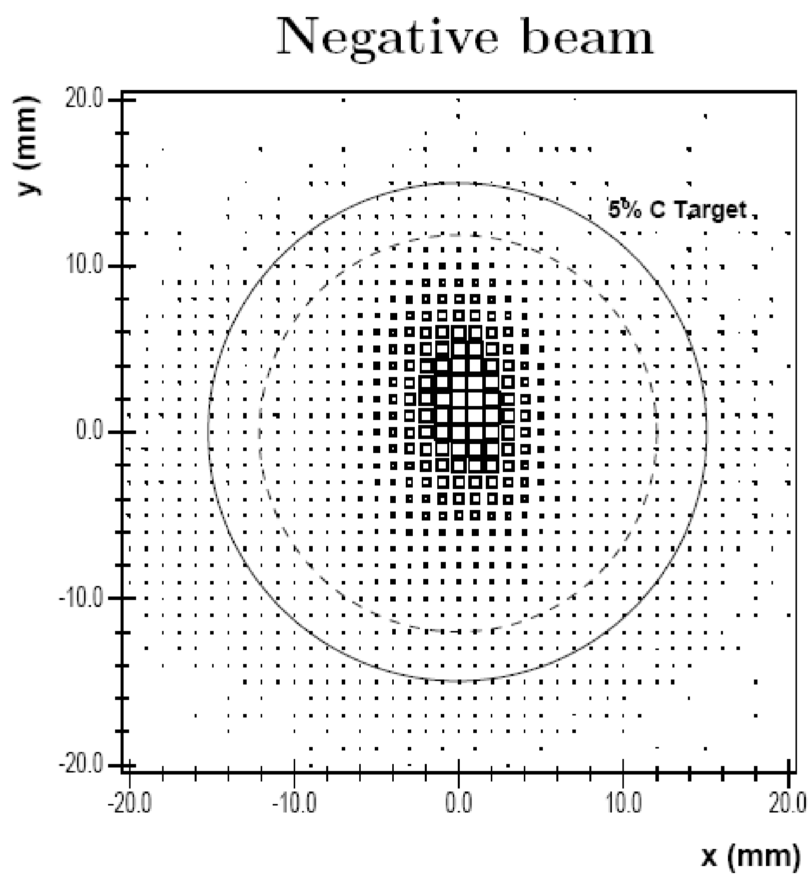
January 14, 2008

Abstract

The results of the measurements of the double-differential production cross-sections of pions, $d^2\sigma^{\pi}/dpd\Omega$, in p-C and $\pi^{\pm}$-C interactions using the forward spectrometer of the HARP experiment are presented. The incident particles are 12 GeV/c protons and charged pions directed onto a carbon target with a thickness of 5% of a nuclear interaction length. For p-C interactions the analysis is performed using 100 035 reconstructed secondary tracks, while the corresponding numbers of tracks for π^{-}-C and π^{+}-C analyses are 106 534 and 10 122 respectively. Cross-section results are presented in the kinematic range 0.5 GeV/$c \leq p_{\pi} < 8$ GeV/c and 30 mrad $\leq \theta_{\pi} < 240$ mrad in the laboratory frame. The measured cross-sections have a direct impact on the precise calculation of atmospheric neutrino fluxes and on the improved reliability of extensive air shower simulations by reducing the uncertainties of hadronic interaction models in the low energy range.

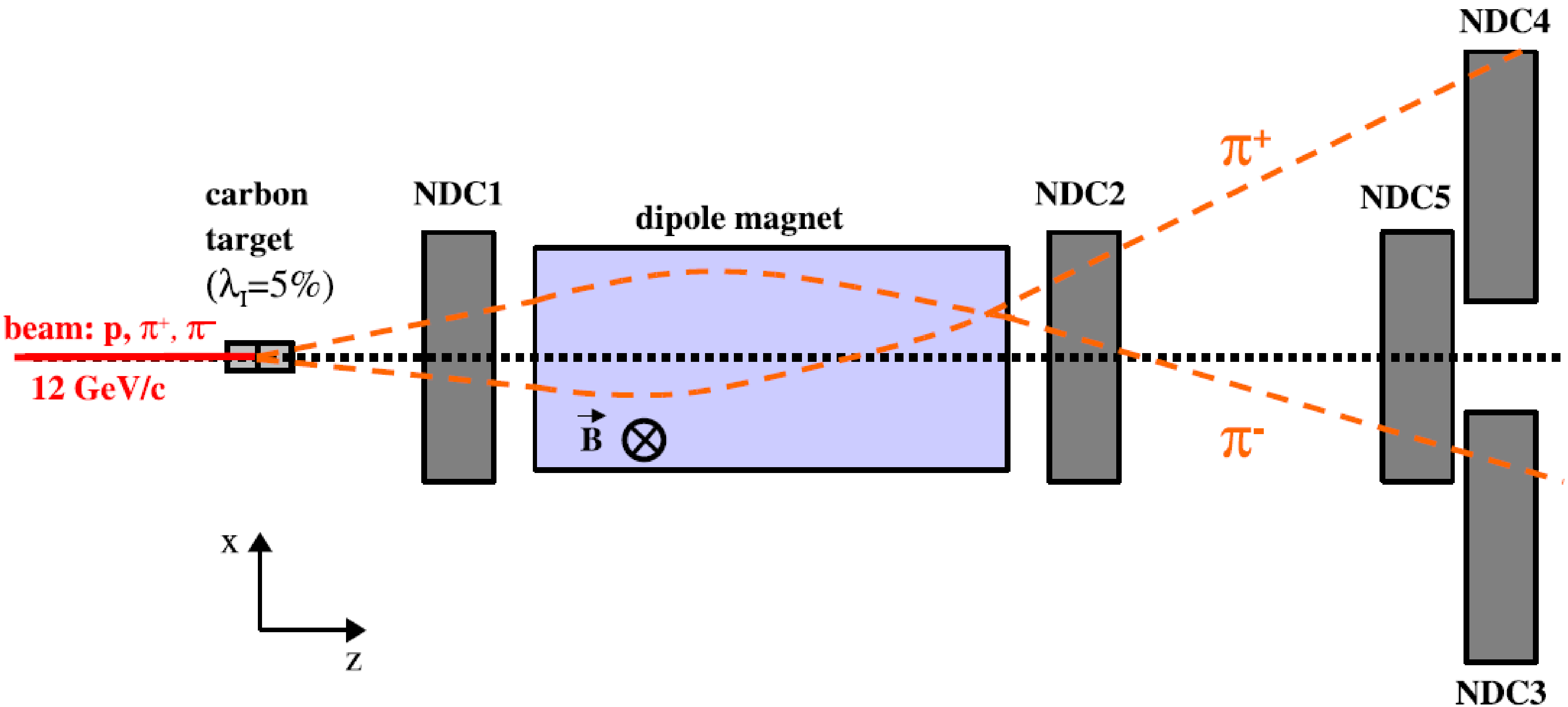
p/π + C @ 12 GeV/c





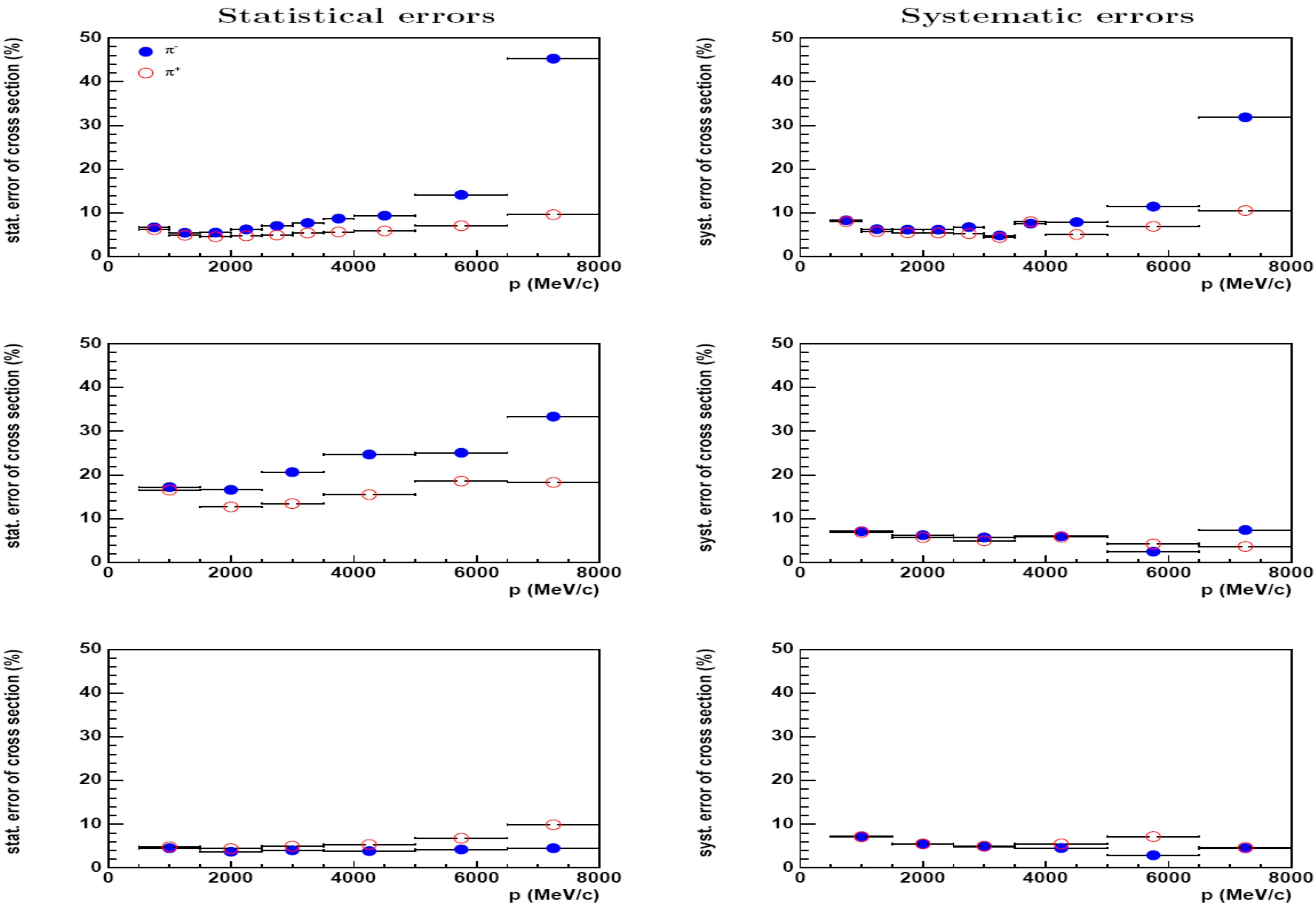
Selection	Number of reconstructed tracks	Number of selected tracks
p-C	2 057 420	100 035
π^+-C	192 976	10 122
π^--C	1 701 041	106 534

p/π + C @ 12 GeV/c



NDC4
carbon
target
(λ_I=5%)
NDC1
dipole magnet
NDC2
NDC5
π^+
beam: p, π^+, π^-
12 GeV/c
$\vec{B}$
π^-
x
z
NDC3

p/π + C @ 12 GeV/c


Statistical errors
Systematic errors
π-
π+
stat. error of cross section (%)
syst. error of cross section (%)
p (MeV/c)
0
10
20
30
40
50
2000
4000
6000
8000

p + C @ 12 GeV/c

Error category	**Error source**	$\delta^{\pi^-}_{\text{diff}}(\%)$	$\delta^{\pi^-}_{\text{int}}(\%)$	$\delta^{\pi^+}_{\text{diff}}(\%)$	$\delta^{\pi^+}_{\text{int}}(\%)$
Statistical	Data statistics	12.8	3.2	10.8	2.5
Track yield corrections	Reconstruction efficiency	1.6	1.3	1.1	0.5
	Pion, proton absorption	4.2	3.7	3.7	3.2
	Tertiary subtraction	9.8	4.2	8.6	3.7
	Empty target subtraction	1.2	1.2	1.2	1.2
	Subtotal	10.8	5.9	9.5	5.1
Particle identification	Electron veto	< 0.1	< 0.1	< 0.1	< 0.1
	Pion, proton ID correction	< 0.1	0.1	0.1	0.1
	Kaon subtraction	< 0.1	< 0.1	< 0.1	< 0.1
	Subtotal	0.1	0.1	0.1	0.1
Momentum reconstruction	Momentum scale	2.6	0.4	2.8	0.3
	Momentum resolution	0.7	0.2	0.8	0.3
	Subtotal	2.7	0.5	2.9	0.4
Angle reconstruction	Angular scale	0.5	0.1	1.3	0.5
Systematic error	Subtotal	11.2	5.9	10.0	5.1
Overall normalization	Subtotal	2.0	2.0	2.0	2.0
All	Total	17.1	7.0	14.9	6.1

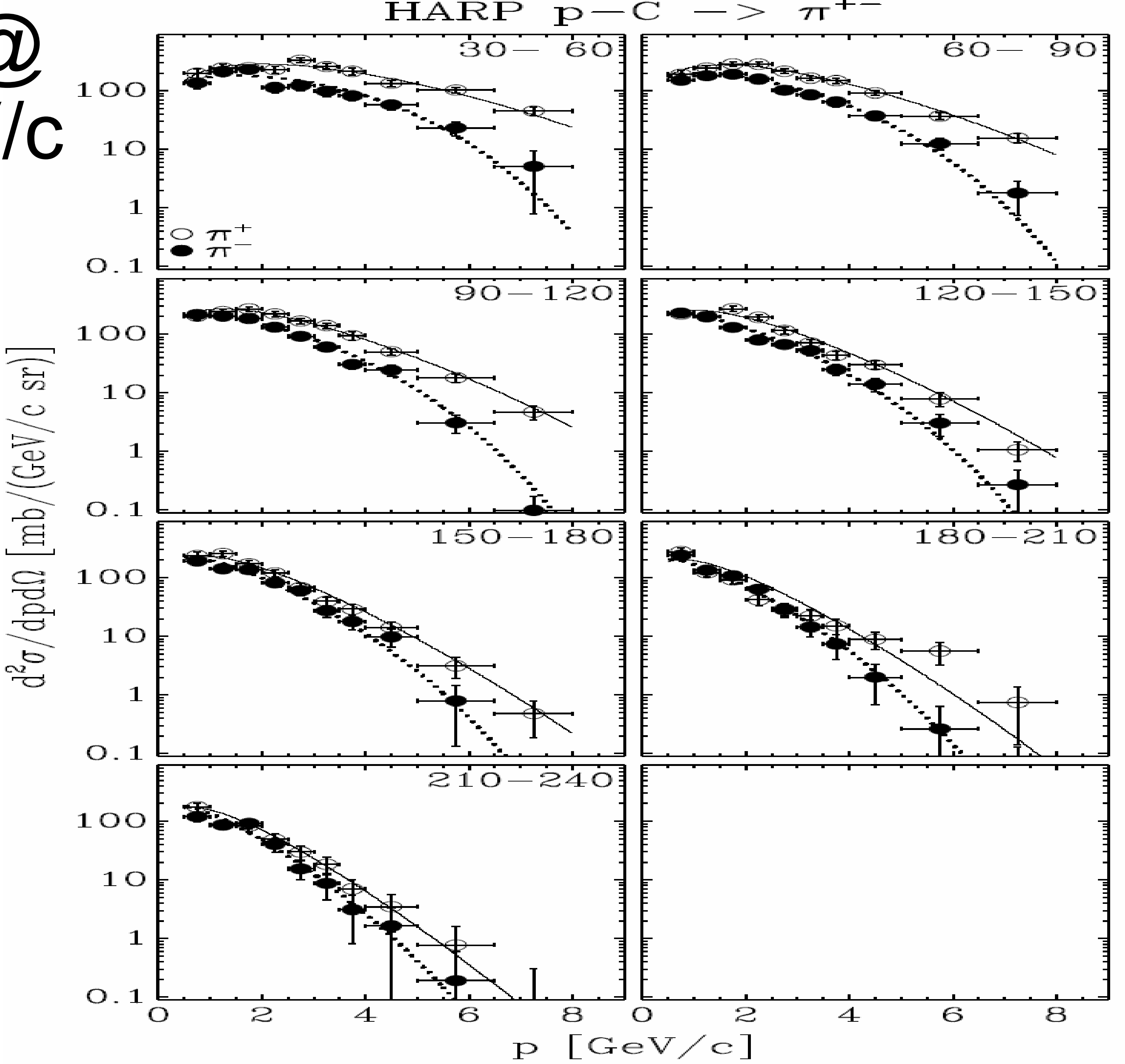
π^+ + C @ 12 GeV/c

Error category	**Error source**	$\delta^{\pi^-}_{\text{diff}}(\%)$	$\delta^{\pi^-}_{\text{int}}(\%)$	$\delta^{\pi^+}_{\text{diff}}(\%)$	$\delta^{\pi^+}_{\text{int}}(\%)$
Statistical	Data statistics	41.8	6.4	34.5	7.2
Track yield corrections	Reconstruction efficiency	1.4	0.7	0.9	0.5
	Pion, proton absorption	4.0	2.1	3.3	2.7
	Tertiary subtraction	9.3	4.7	7.6	6.3
	Empty target subtraction	1.0	0.7	1.0	1.0
	Subtotal	10.3	5.2	8.4	6.9
Particle identification	Electron veto	< 0.1	< 0.1	< 0.1	< 0.1
	Pion, proton ID correction	0.1	< 0.1	0.2	0.2
	Kaon subtraction	< 0.1	< 0.1	< 0.1	< 0.1
	Subtotal	0.1	0.1	0.2	0.2
Momentum reconstruction	Momentum scale	3.2	0.2	3.6	0.5
	Momentum resolution	0.9	0.2	1.1	0.3
	Subtotal	3.3	0.3	3.8	0.6
Angle reconstruction	Angular scale	1.7	0.1	1.3	0.5
Systematic error	Subtotal	10.9	5.3	9.2	7.0
Overall normalization	Subtotal	3.0	3.0	3.0	3.0
All	Total	43.7	8.5	35.8	10.2

$\pi^- + C$ @ 12 GeV/c

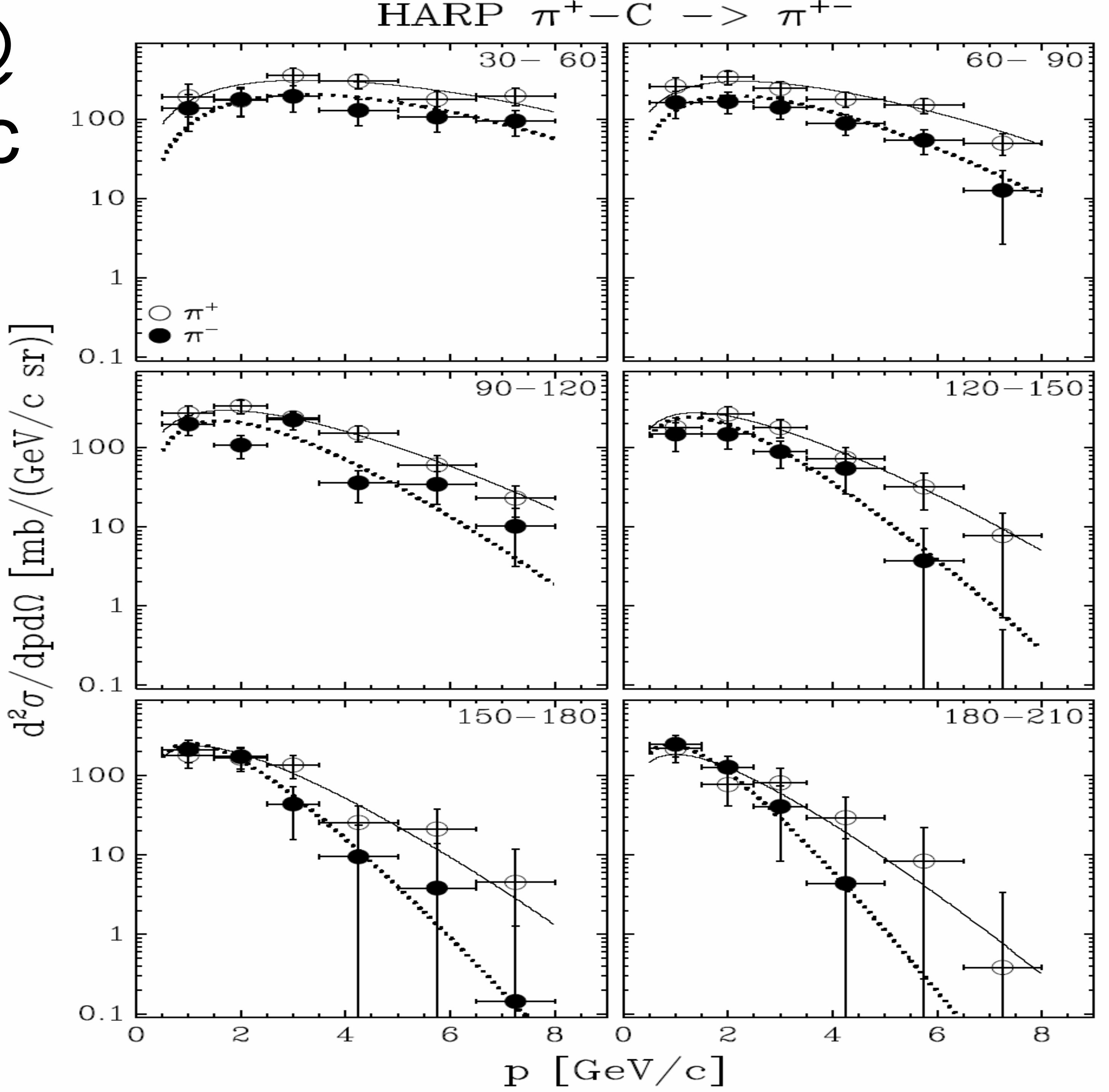
Error category	**Error source**	$\delta^{\pi^-}_{\text{diff}}(\%)$	$\delta^{\pi^-}_{\text{int}}(\%)$	$\delta^{\pi^+}_{\text{diff}}(\%)$	$\delta^{\pi^+}_{\text{int}}(\%)$
Statistical	Data statistics	8.5	2.2	10.0	1.9
Track yield corrections	Reconstruction efficiency	1.3	1.1	0.7	0.4
	Pion, proton absorption	3.5	3.1	3.8	2.3
	Tertiary subtraction	7.9	6.8	9.0	5.3
	Empty target subtraction	0.9	0.8	0.9	0.6
	Subtotal	8.8	7.6	9.8	5.8
Particle identification	Electron veto	< 0.1	< 0.1	< 0.1	< 0.1
	Pion, proton ID correction	0.1	0.1	0.1	0.1
	Kaon subtraction	< 0.1	< 0.1	< 0.1	< 0.1
	Subtotal	0.1	0.1	0.1	0.1
Momentum reconstruction	Momentum scale	2.3	0.7	2.7	0.3
	Momentum resolution	0.6	0.2	0.5	0.2
	Subtotal	2.4	0.7	2.7	0.4
Angle reconstruction	Angular scale	0.6	0.3	0.7	< 0.1
Systematic error	Subtotal	9.1	7.6	10.2	5.8
Overall normalization	Subtotal	3.0	3.0	3.0	3.0
All	Total	12.6	8.2	14.4	6.5

p + C @ 12 GeV/c



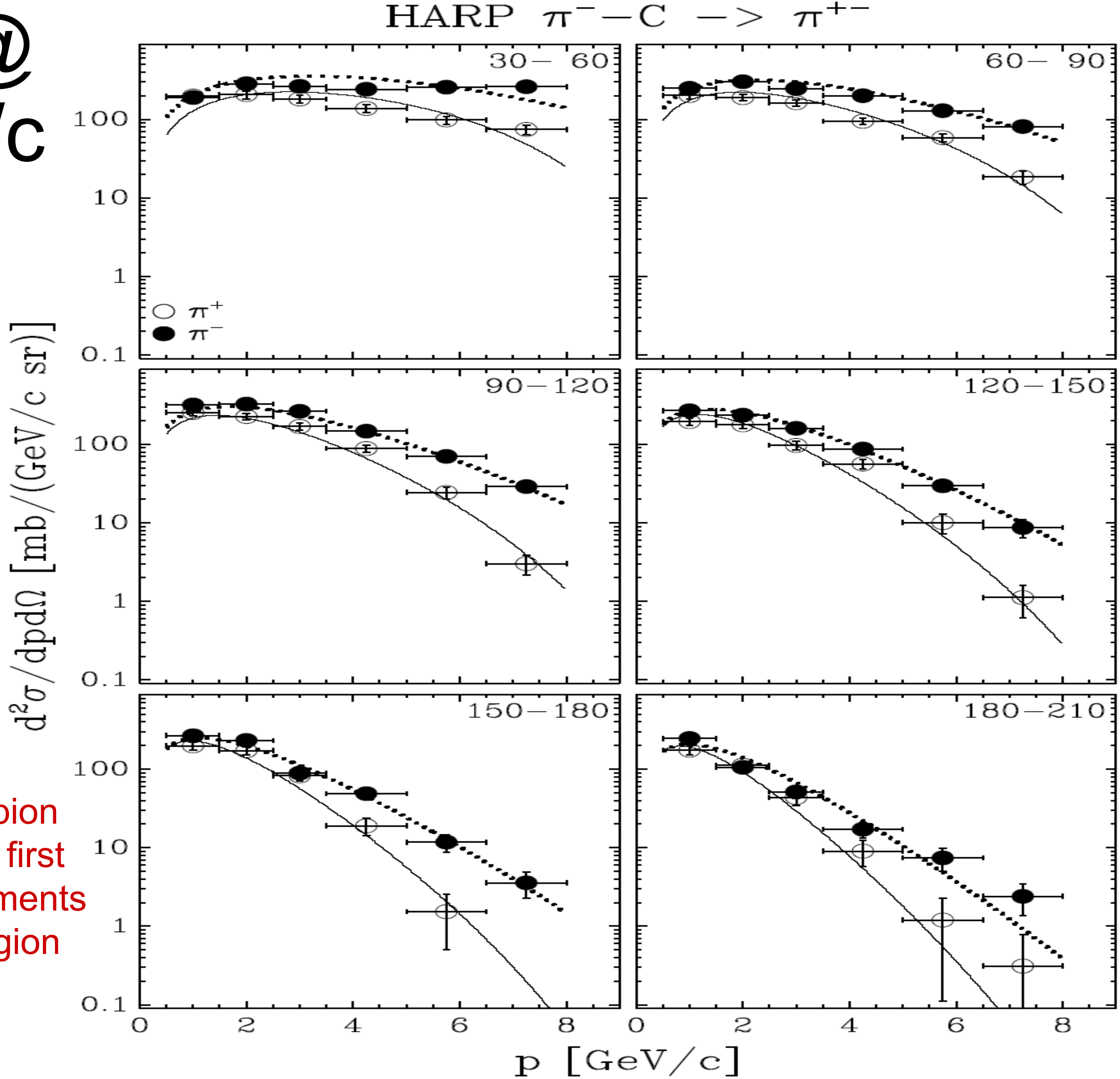
HARP p−C −> π+−
30− 60
60− 90
90−120
120−150
150−180
180−210
210−240
π+
π−
d²σ/dpdΩ [mb/(GeV/c sr)]
p [GeV/c]
0.1
1
10
100
0
2
4
6
8

π^+ + C @ 12 GeV/c



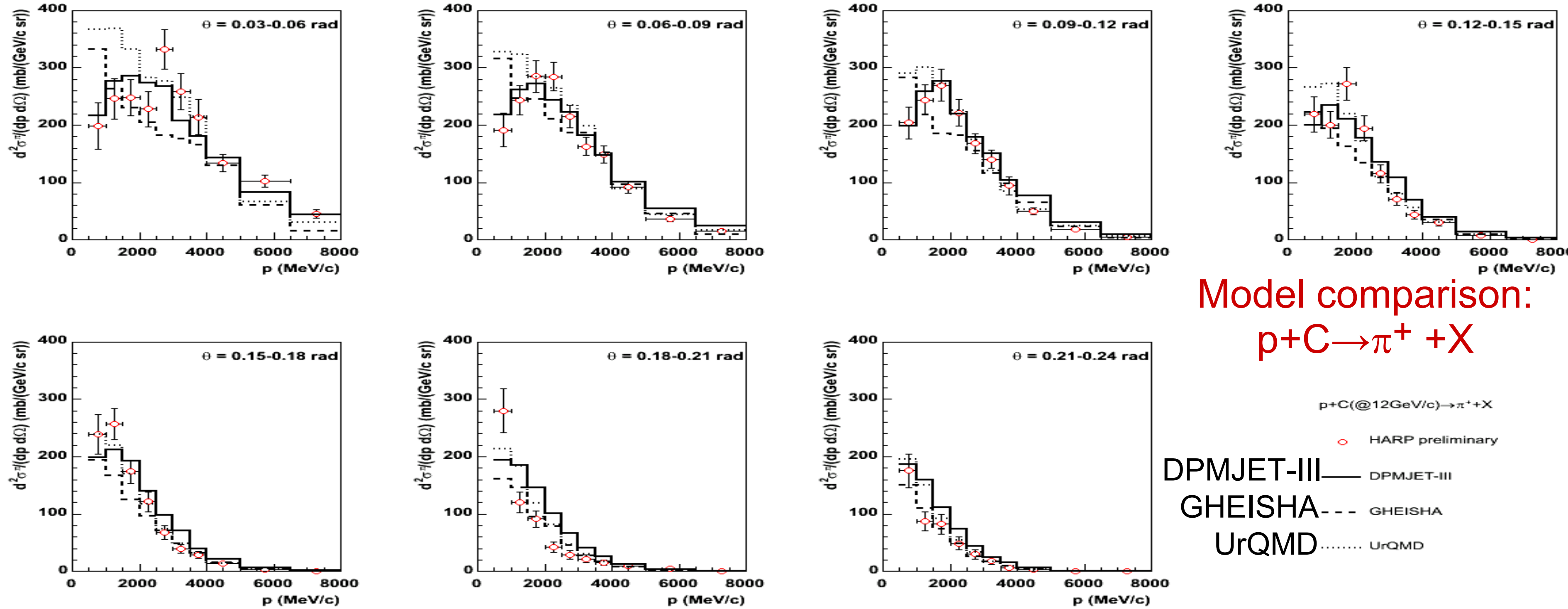
HARP π⁺−C −> π⁺⁻
30− 60
60− 90
90−120
120−150
150−180
180−210
π⁺
π⁻
d²σ/dpdΩ [mb/(GeV/c sr)]
p [GeV/c]

$\pi^- + C$ @ 12 GeV/c

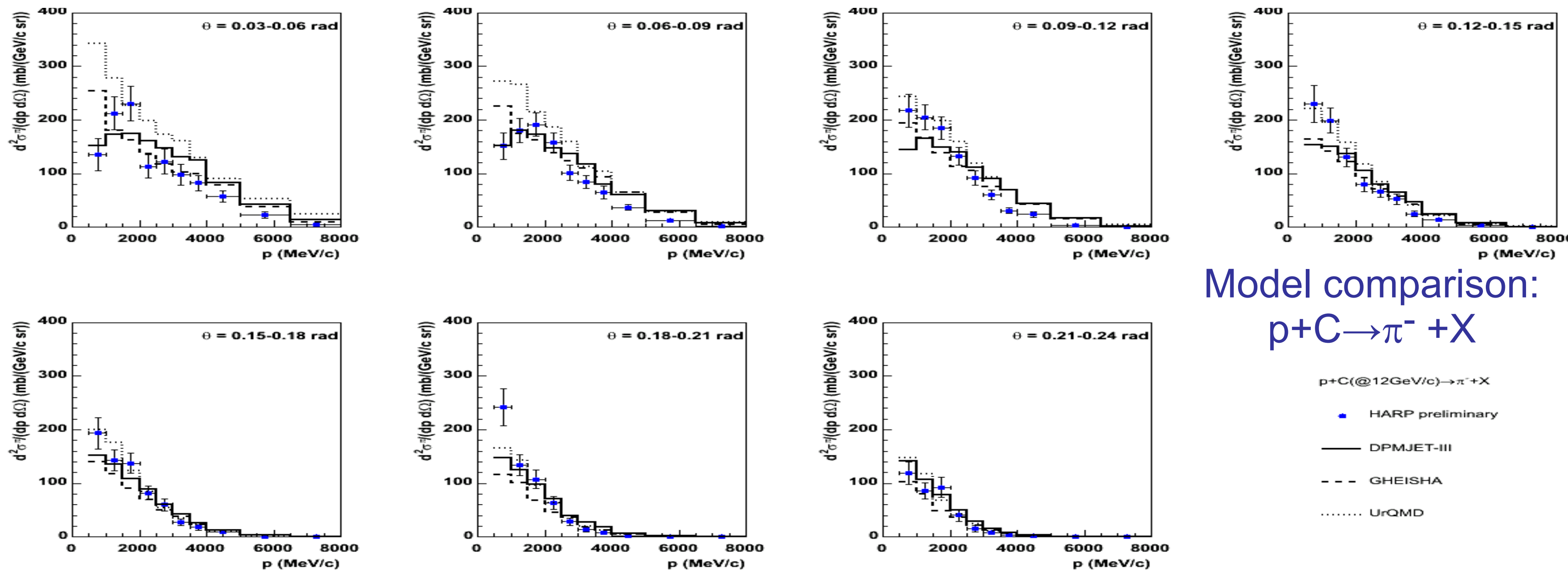


Incoming charged pion HARP data are the first precision measurements in this kinematic region

Model comparison: p+C→π^+ +X



Model comparison: p+C→π^- +X

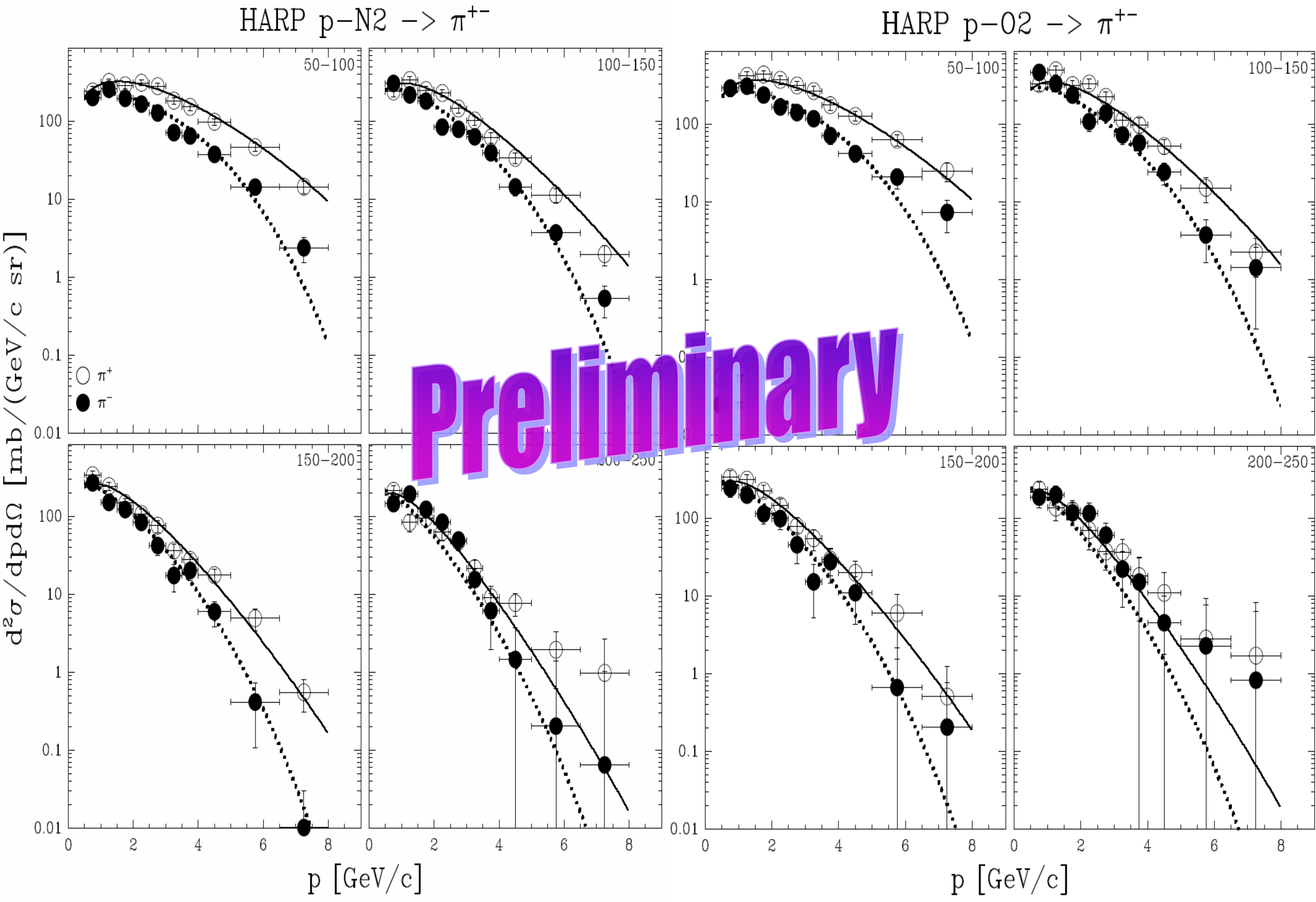


p/π + C @ 12 GeV/c

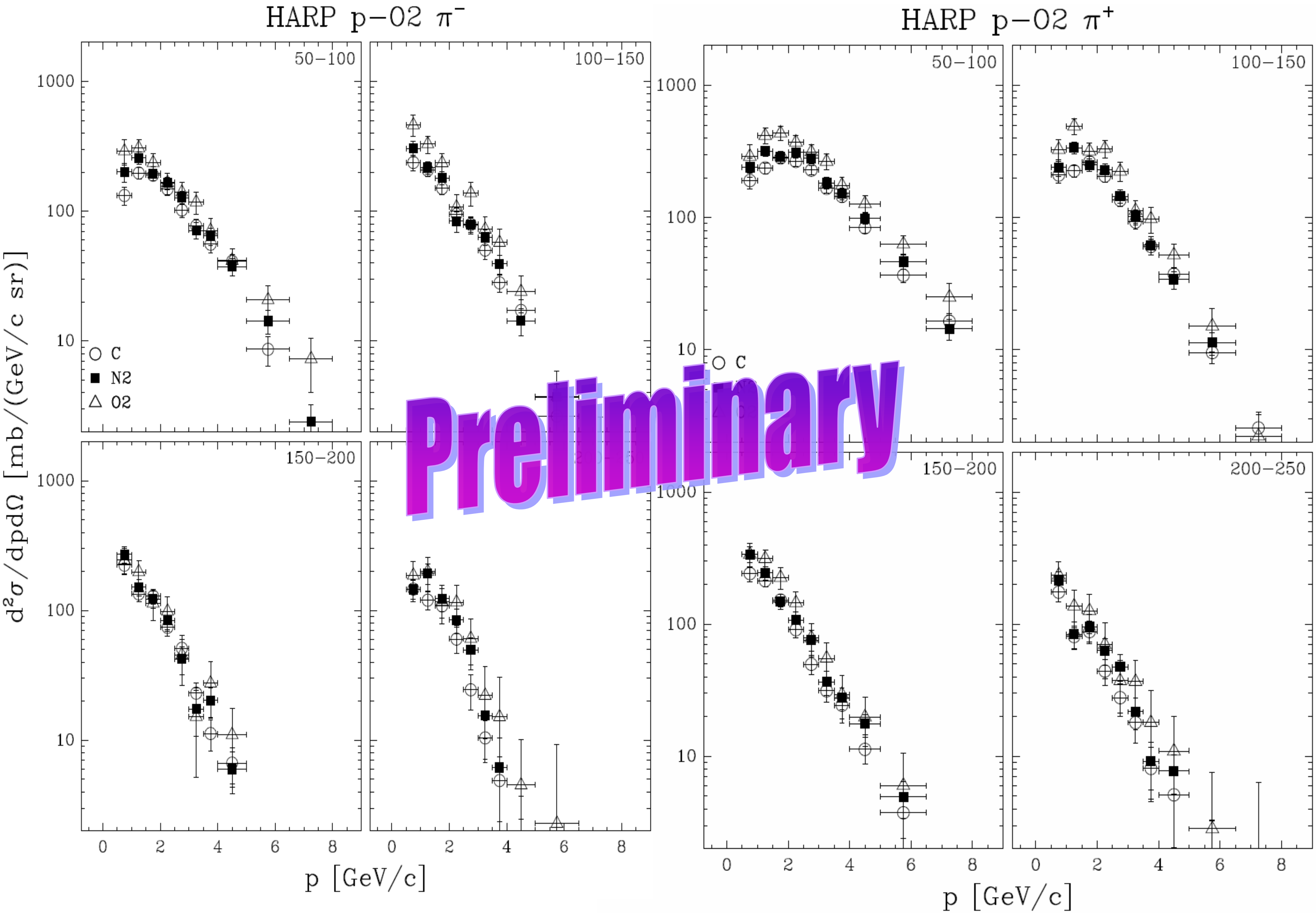
We have compared the HARP measurements with models used in the models typically used in the air showers simulations (GHEISHA, UrQMD, DPMJET-III) as well as with the GEANT4 models relevant in the energy domain studied (FTFP, QGSP, LHEP). From the χ^2 comparison of the HARP data with the model predictions one could draw the following conclusions:

- None of the models describe our data accurately;
- These models tend to describe the π^+ production more correctly than π^- productions for all three incoming particle types;
- Different models are preferable depending on the projectile type and the charge of the pion produced, e.g.
  - for proton projectiles and π^+ production, UrQMD, FTFP and GHEISHA are the best;
  - for proton projectiles and π^- production, FTFP is preferable;
  - for π^+ projectiles and π^+ production and for π^- projectiles and π^- production, DPMJET-III is best;
  - for π^+ projectiles and π^- production and for π^- projectiles and π^+ production, QGSP describes the data best.

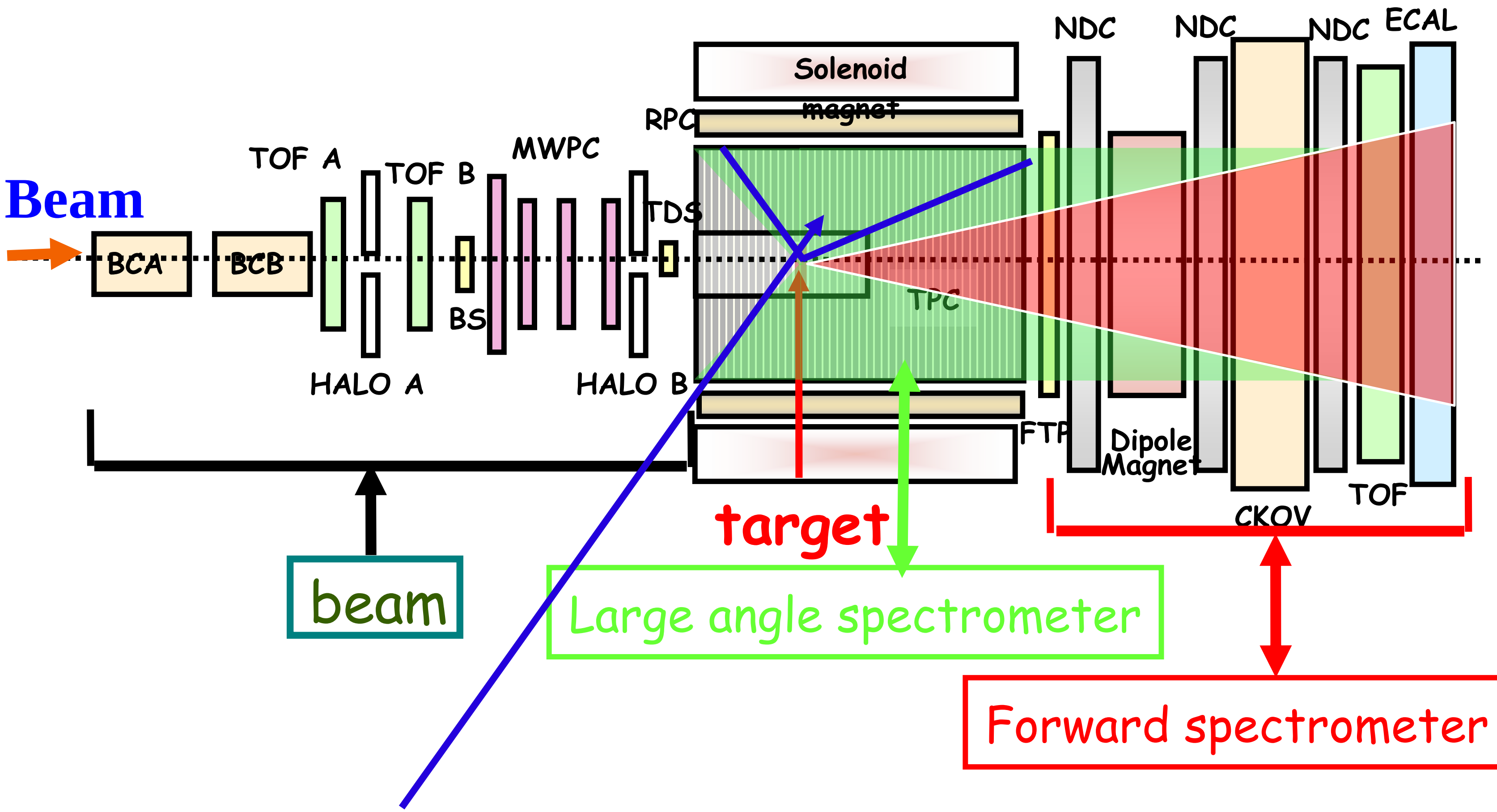
p + N_2/O_2 @ 12 GeV/c



p + C/N_2/O_2 @ 12 GeV/c



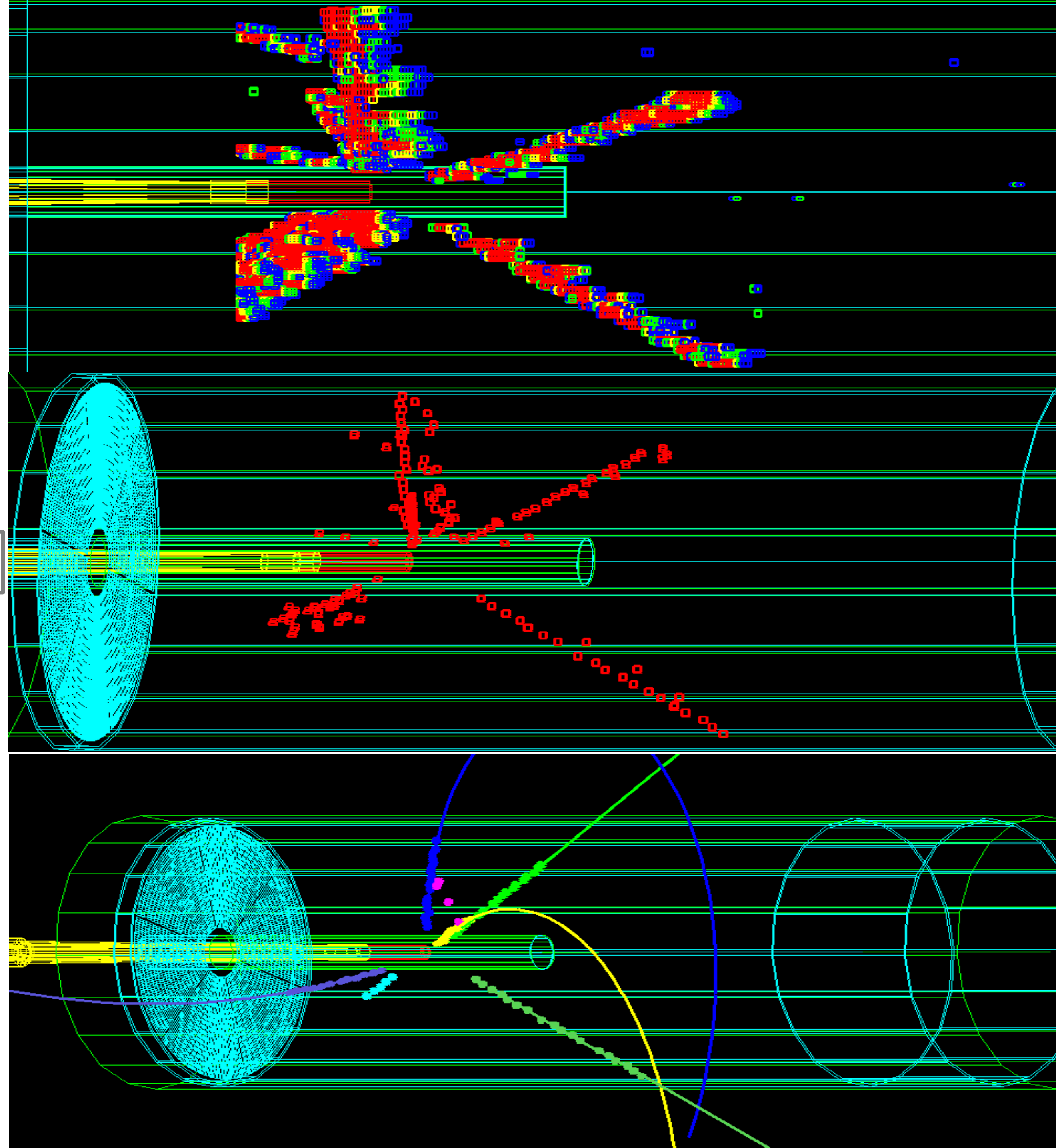
Large Angle spectrometer: TPC



$0.35 < \theta < 2.15$ 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)
all data in spill are analysed now (the results are compatible within errors)
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^{+-}.

HARP Physics Publication

Eur. Phys. J. C 51, 787–824 (2007)
DOI 10.1140/epjc/s10052-007-0361-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article – Experimental Physics

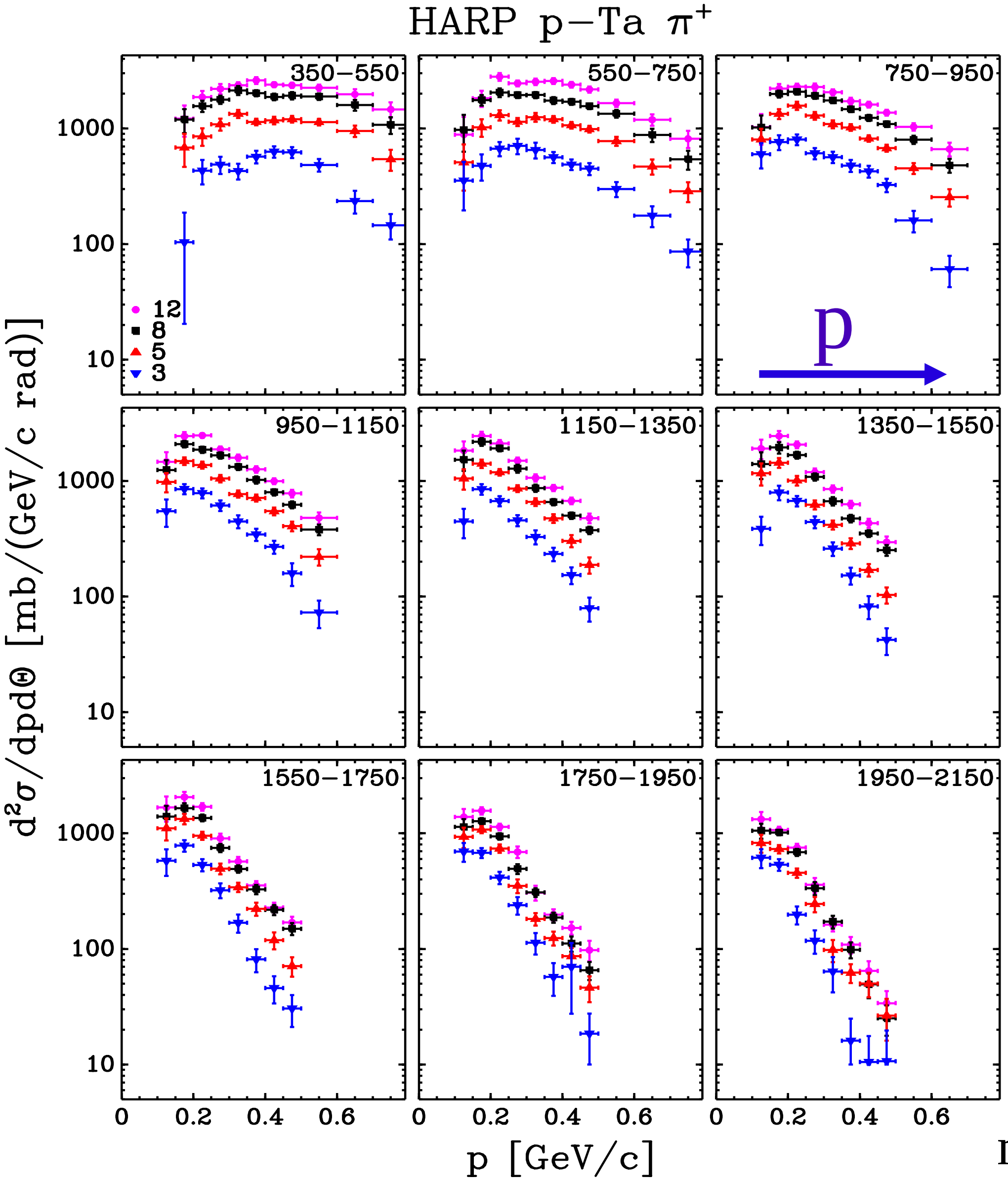
Measurement of the production of charged pions by protons on a tantalum target

The HARP Collaboration

Abstract. A measurement of the double-differential cross-section for the production of charged pions in proton–tantalum collisions emitted at large angles from the incoming beam direction is presented. The data were taken in 2002 with the HARP detector in the T9 beam line of the CERN PS. The pions were produced by proton beams in a momentum range from 3 GeV/c to 12 GeV/c hitting a tantalum target with a thickness of 5% of a nuclear interaction length. The angular and momentum range covered by the experiment (100 MeV/$c \leq p <$ 800 MeV/c and 0.35 rad $\leq \theta <$ 2.15 rad) is of particular importance for the design of a neutrino factory. The produced particles were detected using a small-radius cylindrical time projection chamber (TPC) placed in a solenoidal magnet. Track recognition, momentum determination and particle identification were all performed based on the measurements made with the TPC. An elaborate system of detectors in the beam line ensured the identification of the incident particles. Results are shown for the double-differential cross-sections $d^2\sigma/dp\,d\theta$ at four incident proton beam momenta (3 GeV/c, 5 GeV/c, 8 GeV/c and 12 GeV/c). In addition, the pion yields within the acceptance of typical neutrino factory designs are shown as a function of beam momentum. The measurement of these yields within a single experiment eliminates most systematic errors in the comparison between rates at different beam momenta and between positive and negative pion production.

9 angular bins: p-Ta π^+

Pion production yields



stat. and syst. errors combined

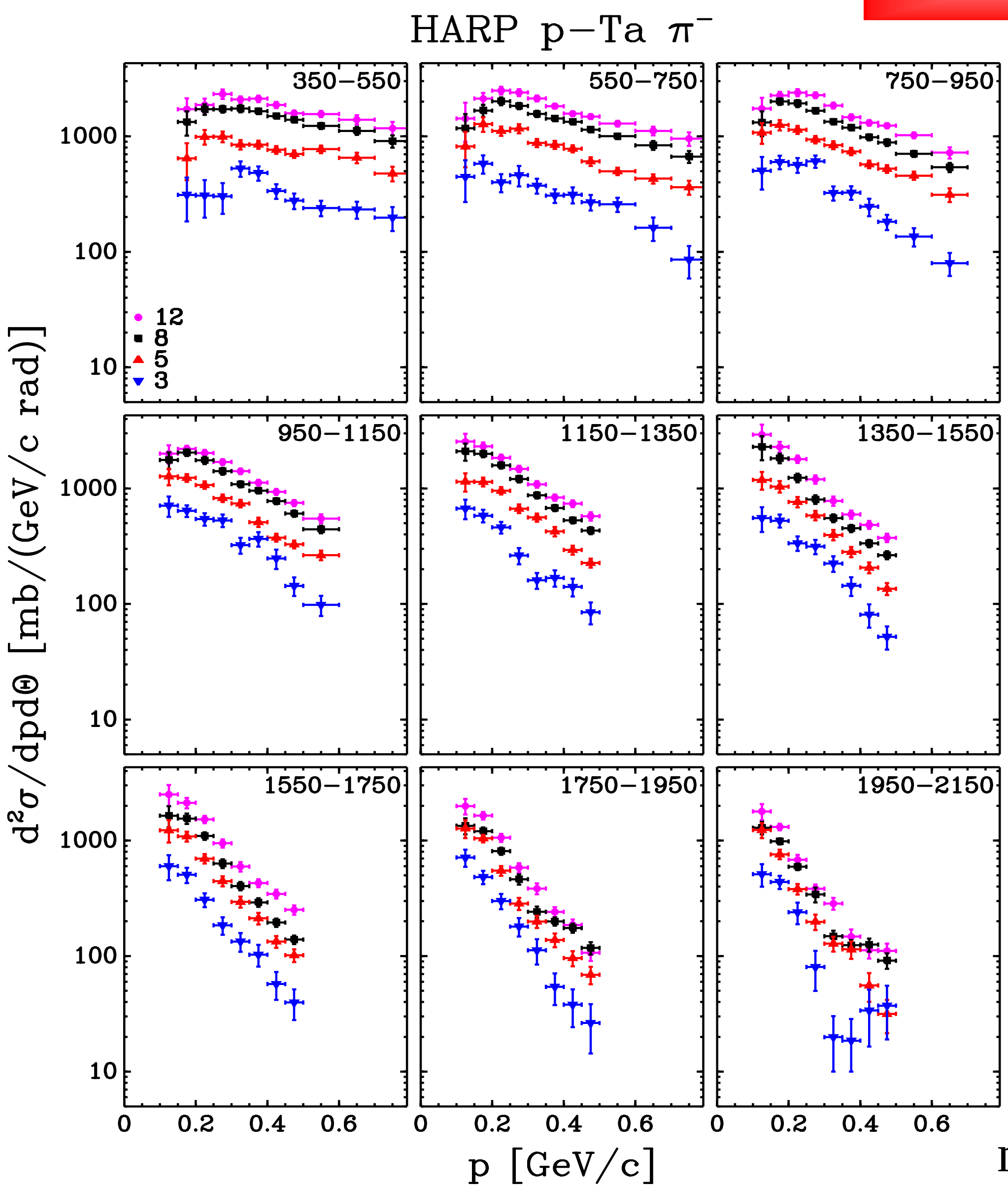
forward
$0.35 < \theta < 1.55$

backward
$1.55 < \theta < 2.15$

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

Pion production yields

p-Ta π^-



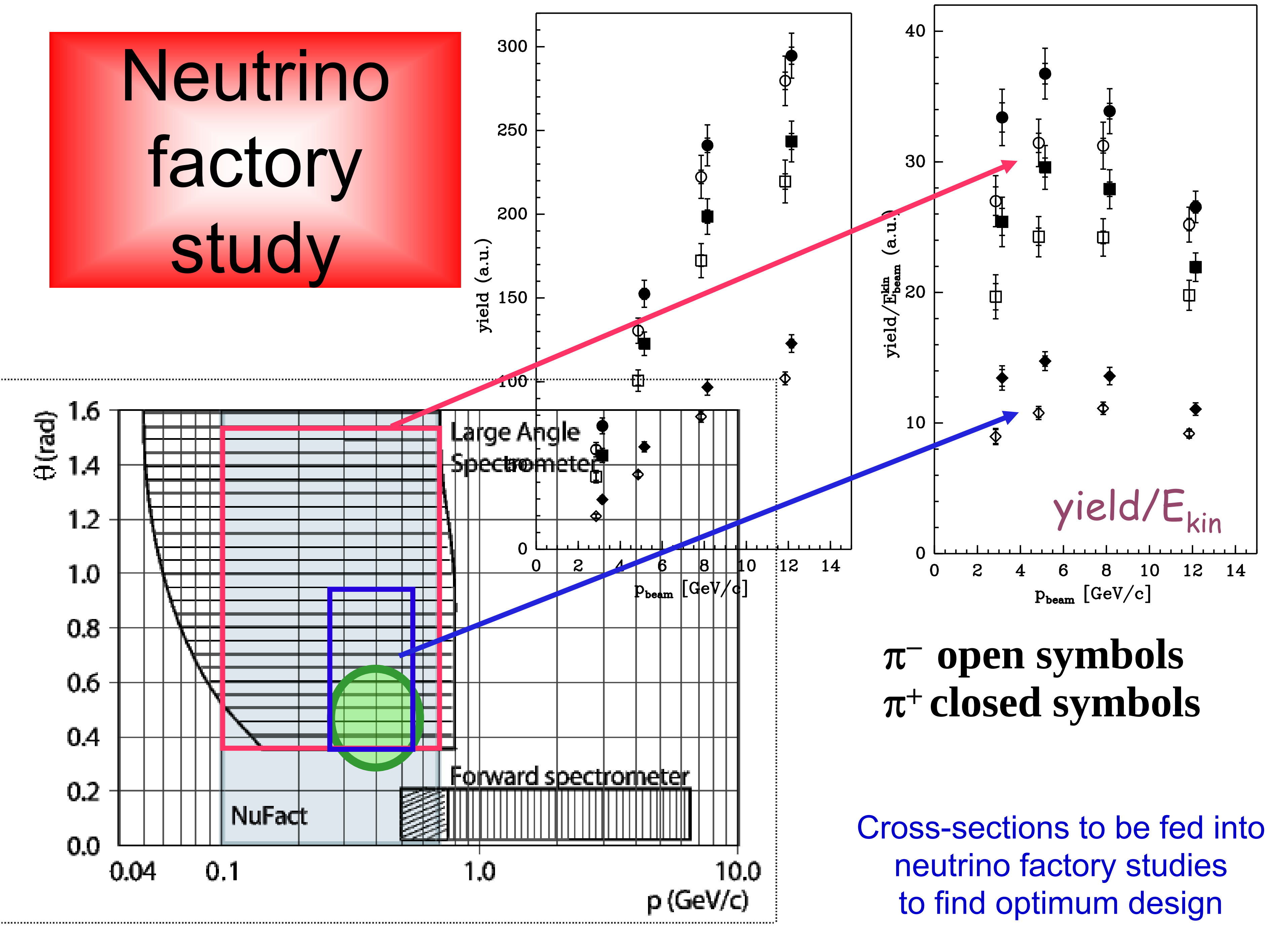
stat. and syst. errors combined

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

HARP Physics Publications

Eur. Phys. J. C 53, 177–204 (2008)
DOI 10.1140/epjc/s10052-007-0475-4

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article – Experimental Physics

Large-angle production of charged pions by 3 GeV/c–12 GeV/c protons on carbon, copper and tin targets

The HARP Collaboration

Eur. Phys. J. C 00, 1–24 (2007)
DOI 10.1140/epjc/s10052-007-0517-y

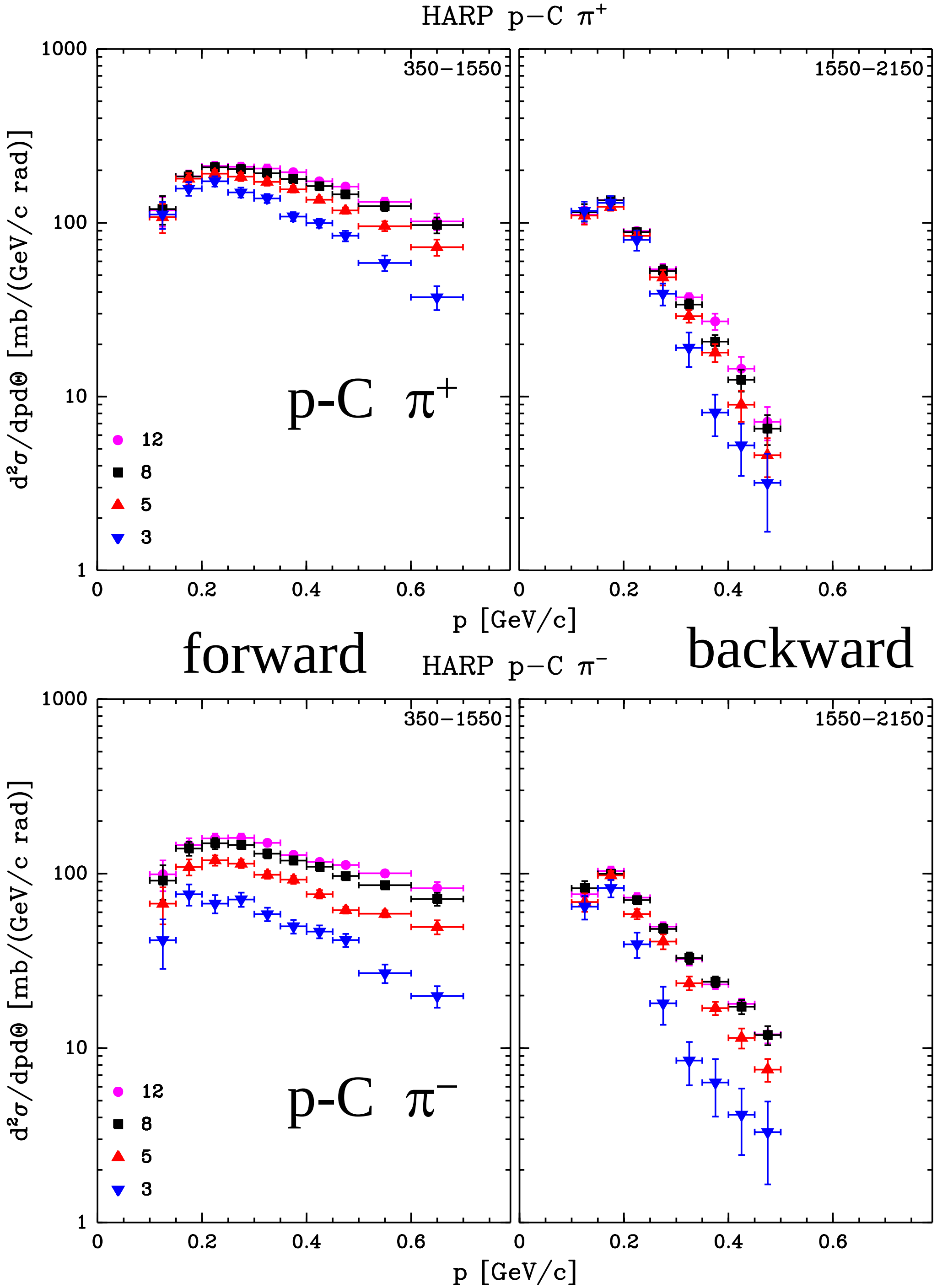
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article – Experimental Physics

Large-angle production of charged pions by $3 - 12.9$ GeV/c protons on beryllium, aluminium and lead targets

The HARP Collaboration

Pion yields

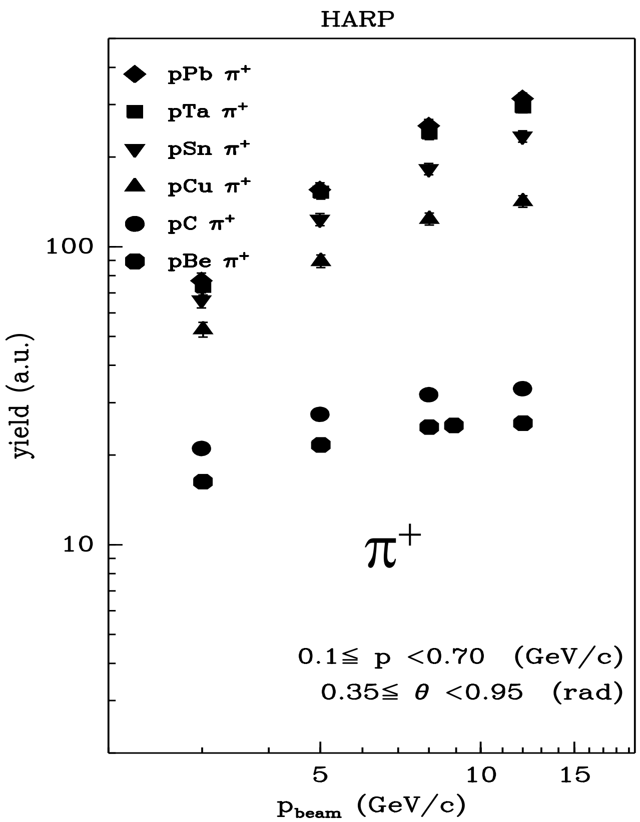


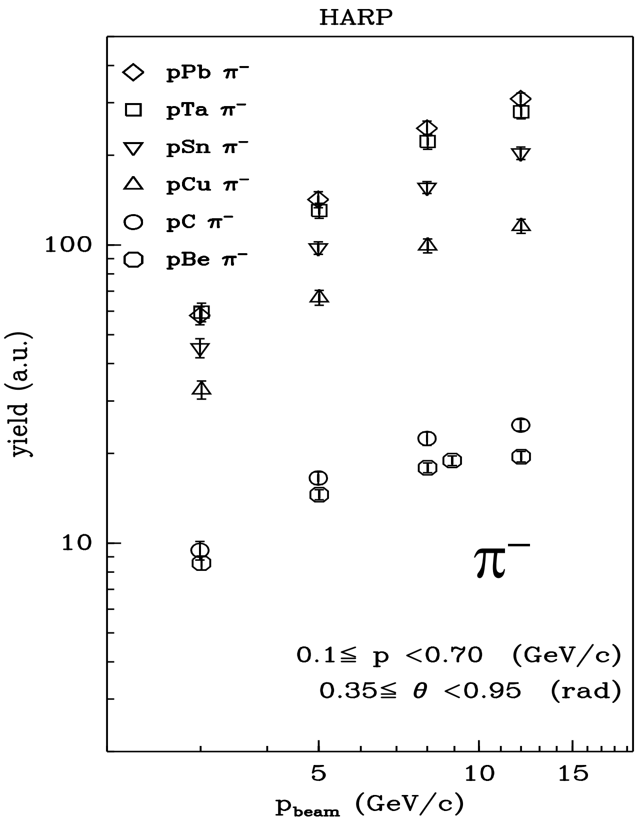
p-C data as an example of many other available spectra

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 $0.35 < \theta <$ **0.95** rad

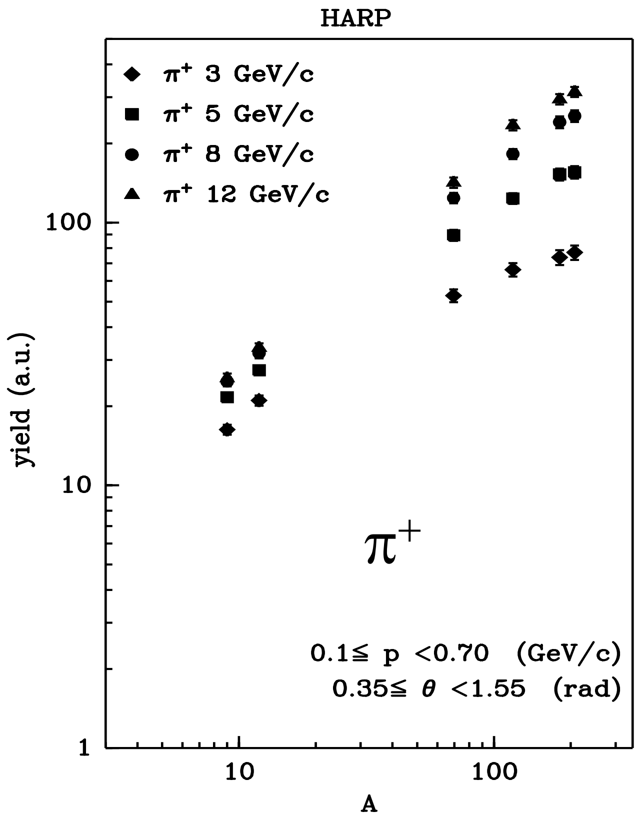


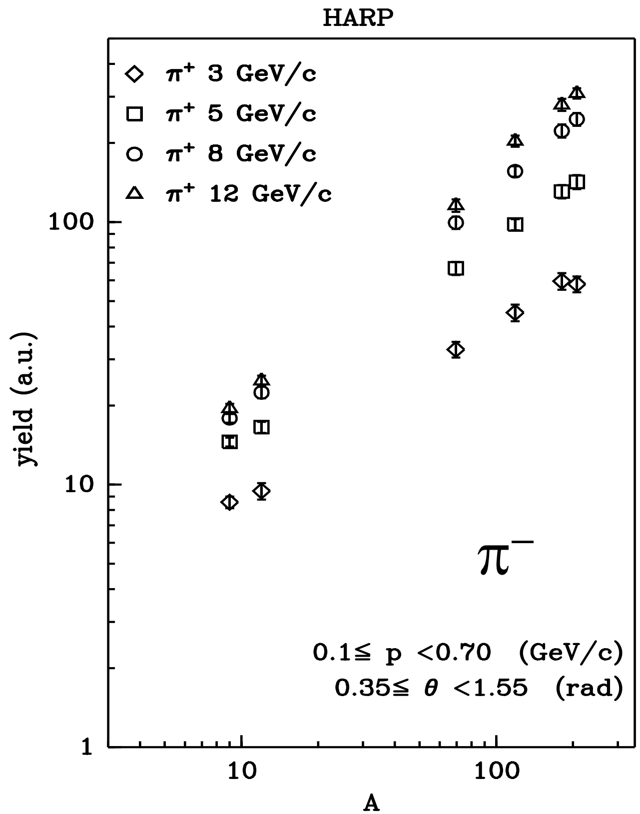


Pion yields

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!

Upcoming HARP Physics Publication

Large-angle production of charged pions in the HARP experiment with incident protons on nuclear targets

HARP Collaboration

December 26, 2007

Abstract

Measurements of the double-differential $\pi^{\pm}$ production cross-section in the range of momentum $100\ \mathrm{MeV}/c \leq p \leq 800\ \mathrm{MeV}/c$ and angle $0.35\ \mathrm{rad} \leq \theta \leq 2.15\ \mathrm{rad}$ in proton–beryllium, proton–aluminium, proton–carbon, proton–copper, proton–tin, proton–tantalum and proton–lead collisions are presented. The data were taken with the large acceptance HARP detector in the T9 beam line of the CERN PS. The pions were produced by proton beams in a momentum range from 3 GeV/c to 12.9 GeV/c hitting a target with a thickness of 5% of a nuclear interaction length. The tracking and identification of the produced particles was performed using a small-radius cylindrical time projection chamber (TPC) placed inside a solenoidal magnet. Incident particles were identified by an elaborate system of beam detectors. Results are obtained for the double-differential cross-sections $\mathrm{d}^2\sigma/\mathrm{d}p\mathrm{d}\theta$ at six incident proton beam momenta (3 GeV/c, 5 GeV/c, 8 GeV/c, 8.9 GeV/c (Be only), 12 GeV/c and 12.9 GeV/c (Al only)). They are based on a complete correction of static and dynamic distortions of tracks in the HARP TPC which allows the complete statistics of collected data set to be used, thereby reducing the overall error. The results include and supersede our previously published results and are compatible with these. HARP measurements are compared with the GEANT4 and MARS

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/SciBooNE** have been published and used for the first MiniBooNE oscillation paper.

Tantalum results for the **Neutrino Factory** studies have been published (results for Carbon, Copper, Tin, Beryllium, Aluminium and Lead are available and are accepted for publication).

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

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

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

Thank you for your attention