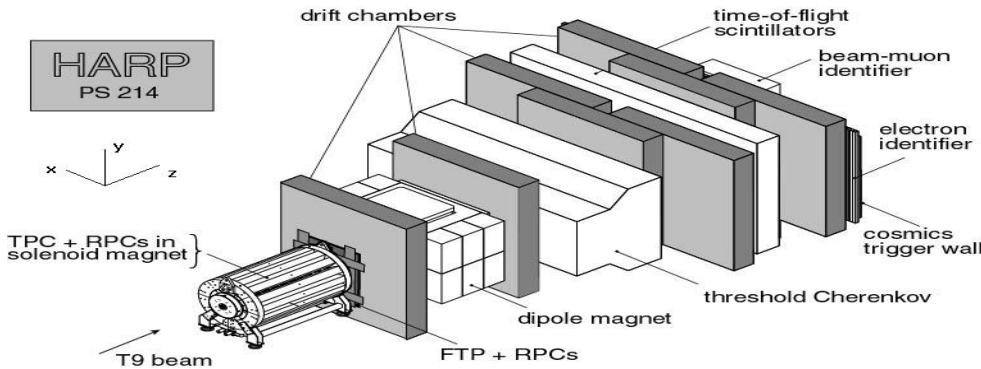
HARP and NA61 (SHINE) hadron production experiments

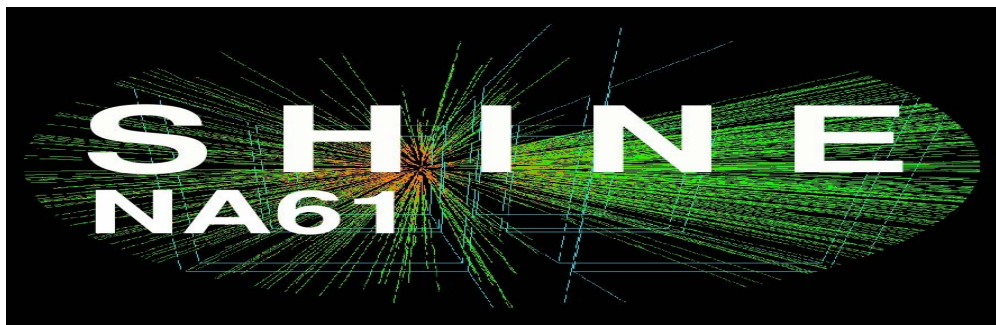
and their implications for neutrino physics

International Workshop on Next Nucleon decay and Neutrino detectors (NNN08)
11-13 September 2008, APC (Paris)

Boris A. Popov (LPNHE, Paris & JINR, Dubna) for the HARP and NA61 Collaborations

- HARP experiment
- Physics goals
- Results and Impacts
- NA61 experiment
- Status and plans
- Summary





HARP – PS214 at CERN

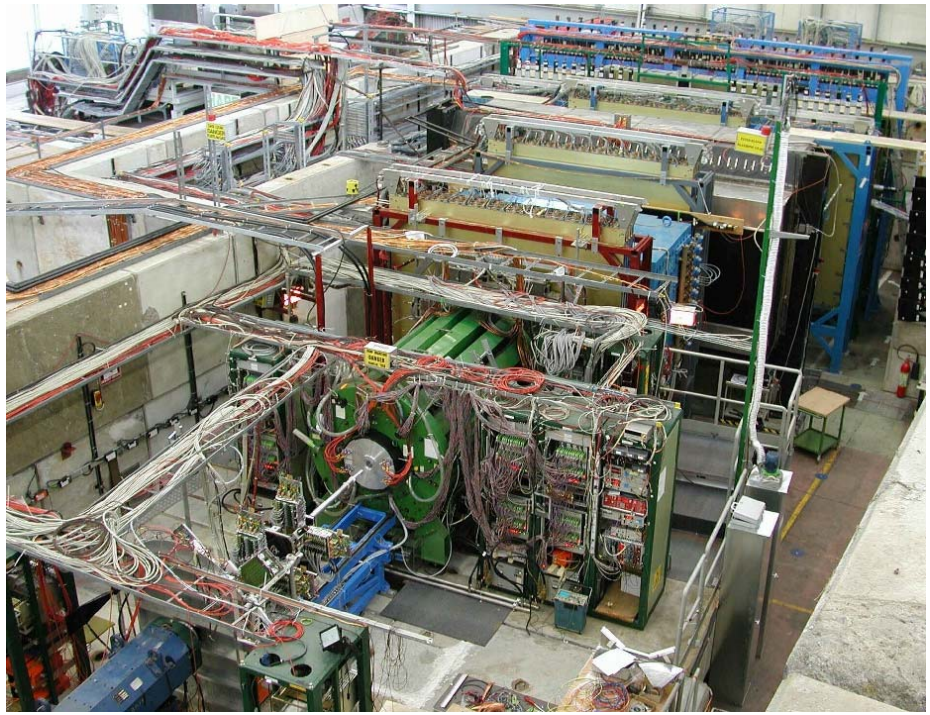
HARP is a large acceptance spectrometer to measure hadron production from various nuclear targets and a range of incident beam momenta

- 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

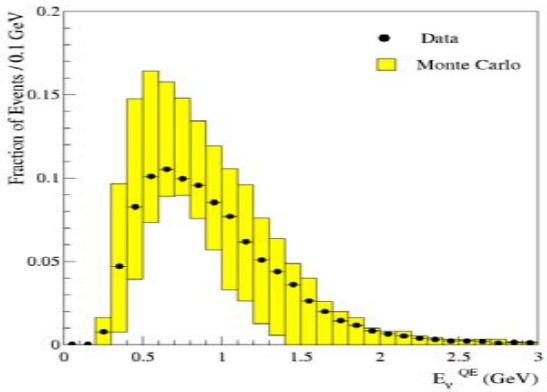
Data taking in 2001-2002

hadron production measurements in "*seven dimensions*"

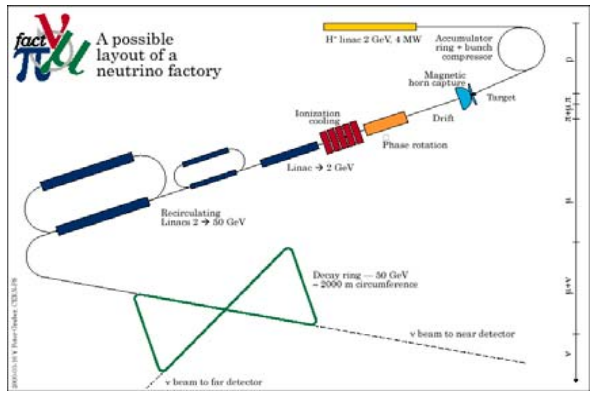
Detailed description of the experimental apparatus

NIM A571 (2007) 524

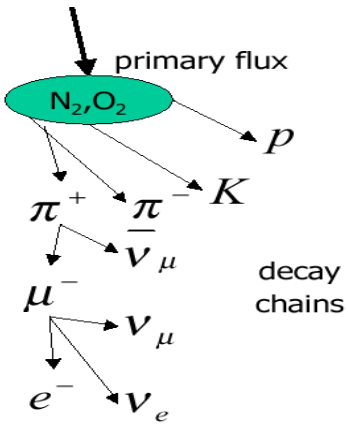
HARP physics goals



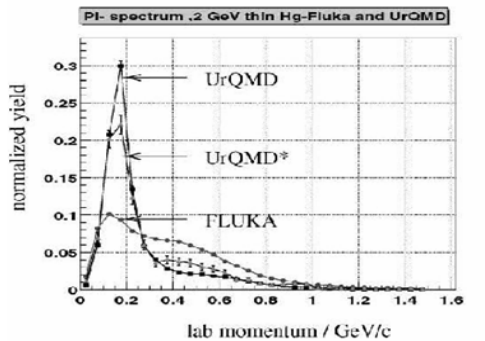
Input for prediction of neutrino fluxes for the **K2K** and **MiniBooNE / SciBooNE** accelerator experiments



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)



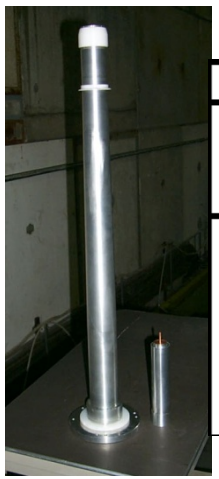
NIM-A 472 (2001) 557-560

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

HARP: Data taking summary

HARP took data at the CERN PS T9 beamline in 2001-2002

Total: 420 M events, ~300 settings



SOLID:

Be	C	Al	Cu	Sn	Ta	Pb	H_2O	Empty
2% 5% 100%	2% 5% 100%	2% 5% 100%	2% 5% 100%	2% 5% 100%	2% 5% 100%	2% 5% 100%	10% 100%	0%
+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+1.5, +3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+1.5, +3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+1.5,+8 GeV/c	+1.5, +3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c

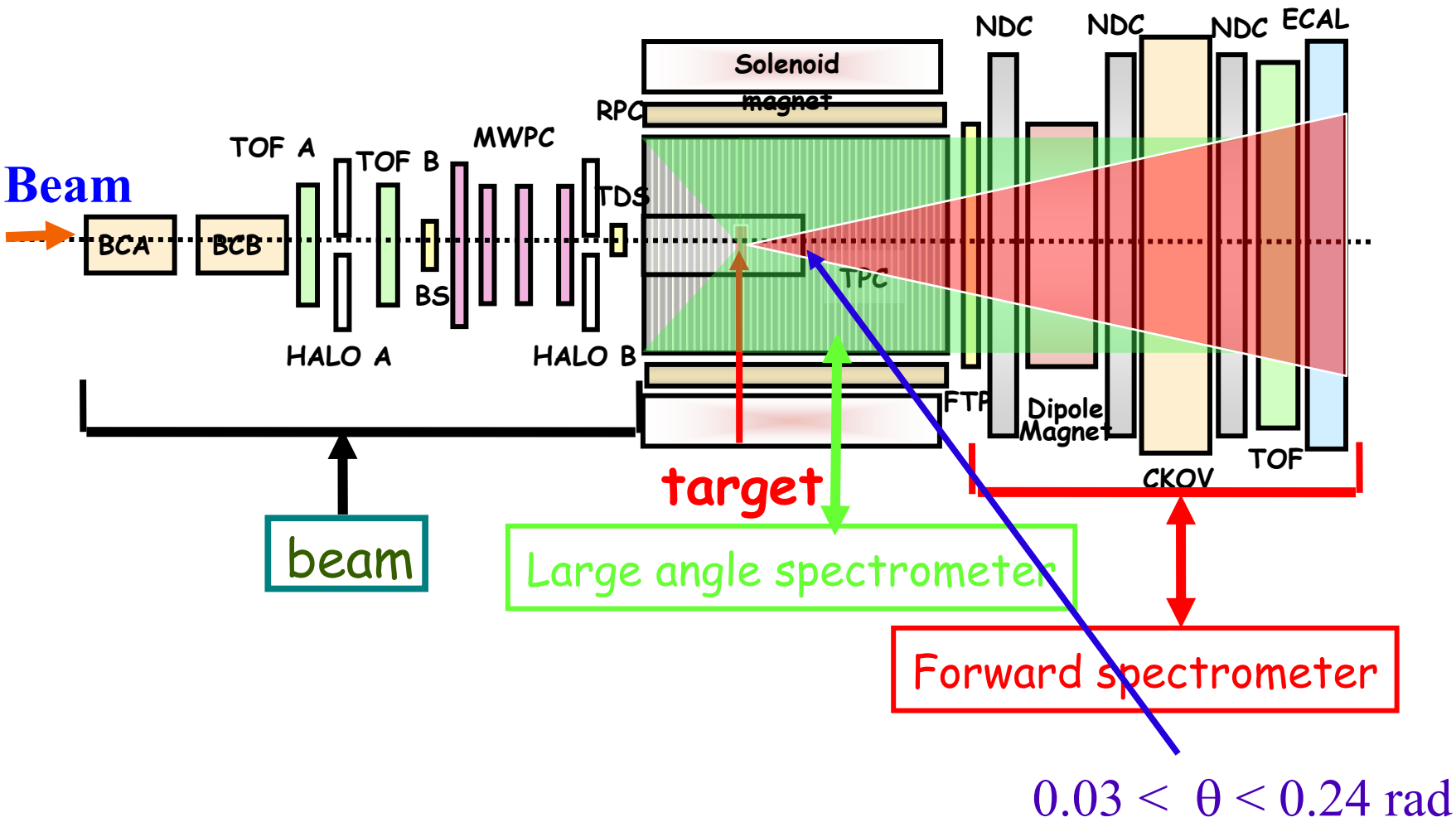
CRYOGENIC:

H	D	N	O	Empty
0.8% 2.4%	2.1%	5.5%	7.5%	0%
+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c	+3,+5,+8, +12,+15 -3,-5,-8, -12,-15 GeV/c

ν EXP

K2K: Al	MiniBooNE: Be	LSND: H_2O
5% 50% 100% Replica	5% 50% 100% Replica	10% 100%
+12.9 GeV/c	+8.9 GeV/c	+1.5 GeV/c

HARP: Analyses with the forward spectrometer



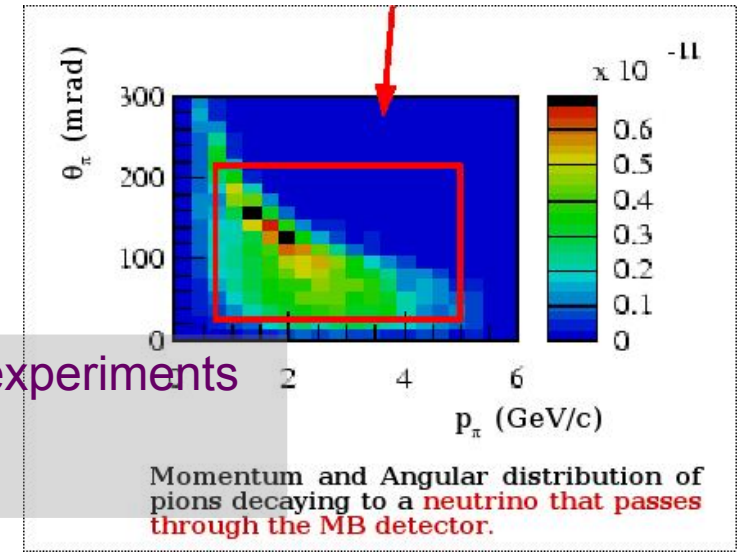
HARP: Analyses with the forward spectrometer

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
HARP p-Be data 8.9 GeV/c:
M. G. Catanesi et al., HARP Collaboration, Eur. Phys. J. **C52** (2007) 29
MiniBooNE results with HARP input:
A. A. Aguilar-Arevalo et al., MiniBooNE Collaboration, Phys. Rev. Lett. **98** (2007) 231801

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Nuclear Physics B 732 (2006) 1–45

NUCLEAR PHYSICS B

First HARP Physics Publication

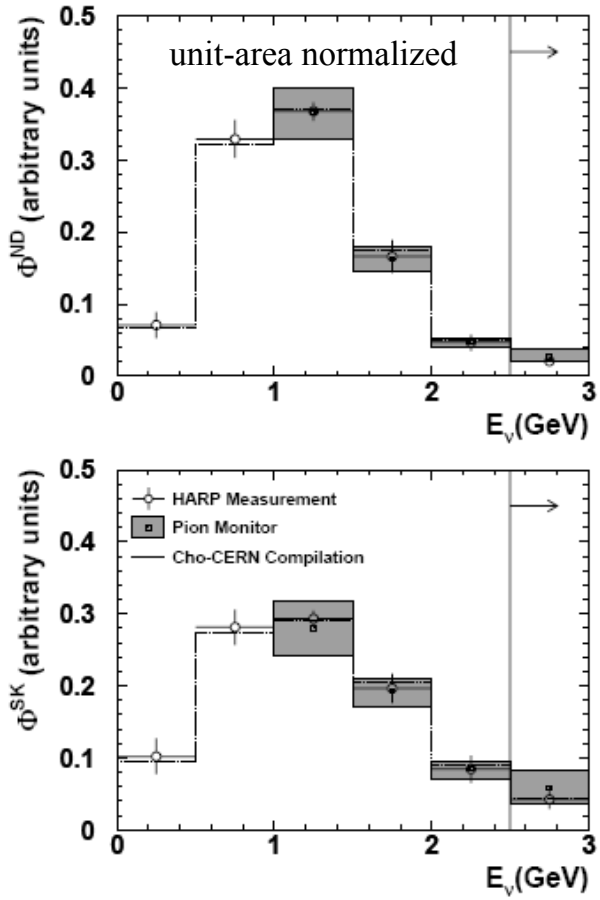
Measurement of the production cross-section of positive pions in p–Al collisions at 12.9 GeV/c

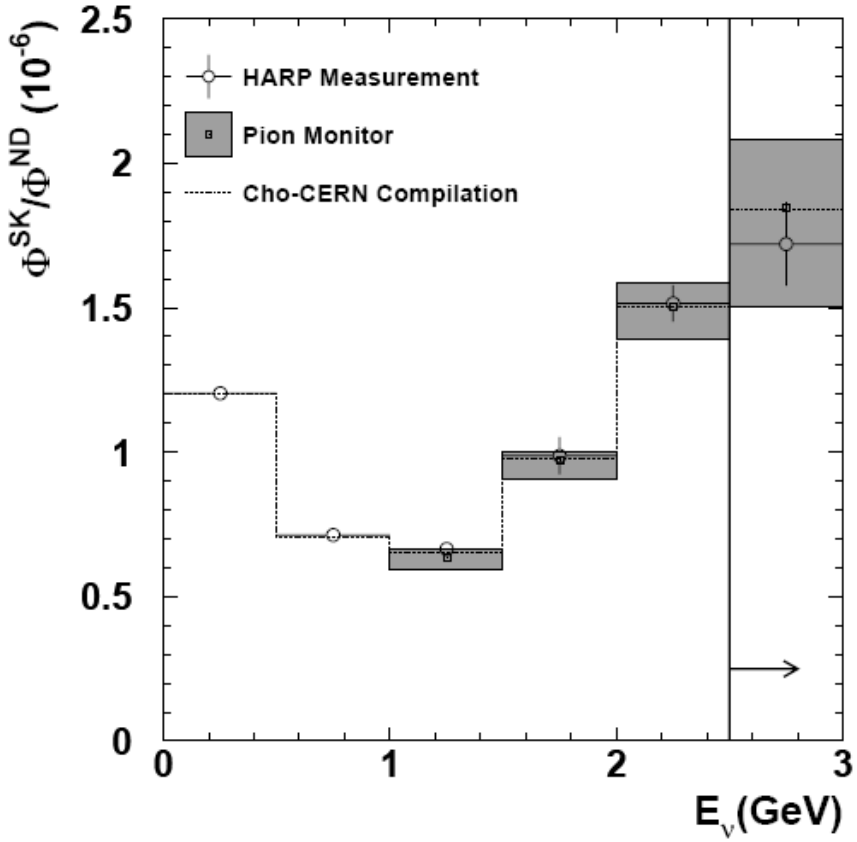
HARP Collaboration

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

Far-to-near (F/N) ratio

HARP measurements allowed to reduce the main systematic error by a factor of 2

- F/N ratio is no longer a dominant systematic error

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

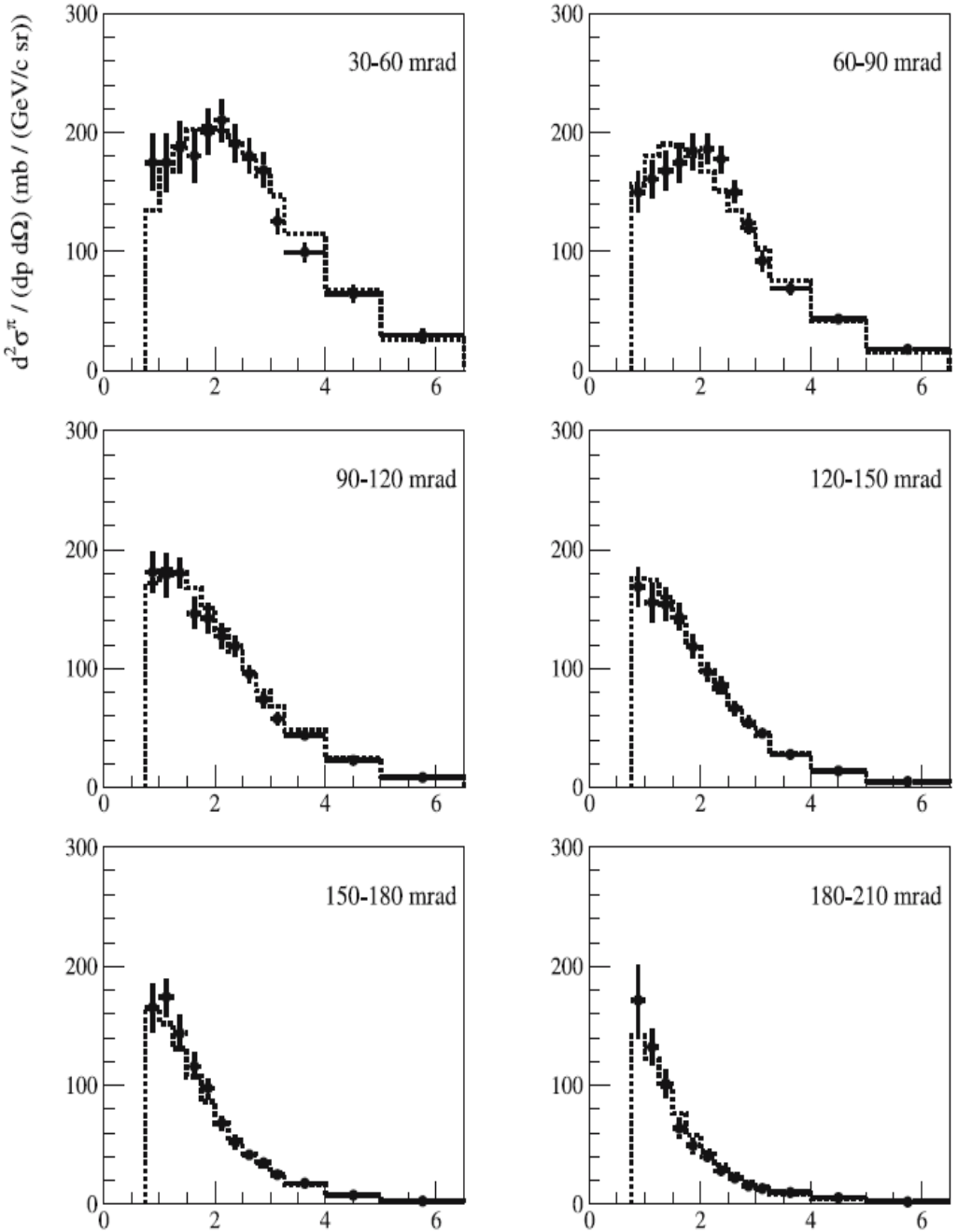
Regular Article – Experimental Physics

Measurement of the production cross-section of positive pions in the collision of 8.9 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 GeV/$c \leq p_\pi \leq$ 6.5 GeV/c and 30 mrad $\leq \theta_\pi \leq$ 210 mrad in the laboratory frame.

HARP : p+Be at 8.9 GeV/c



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%

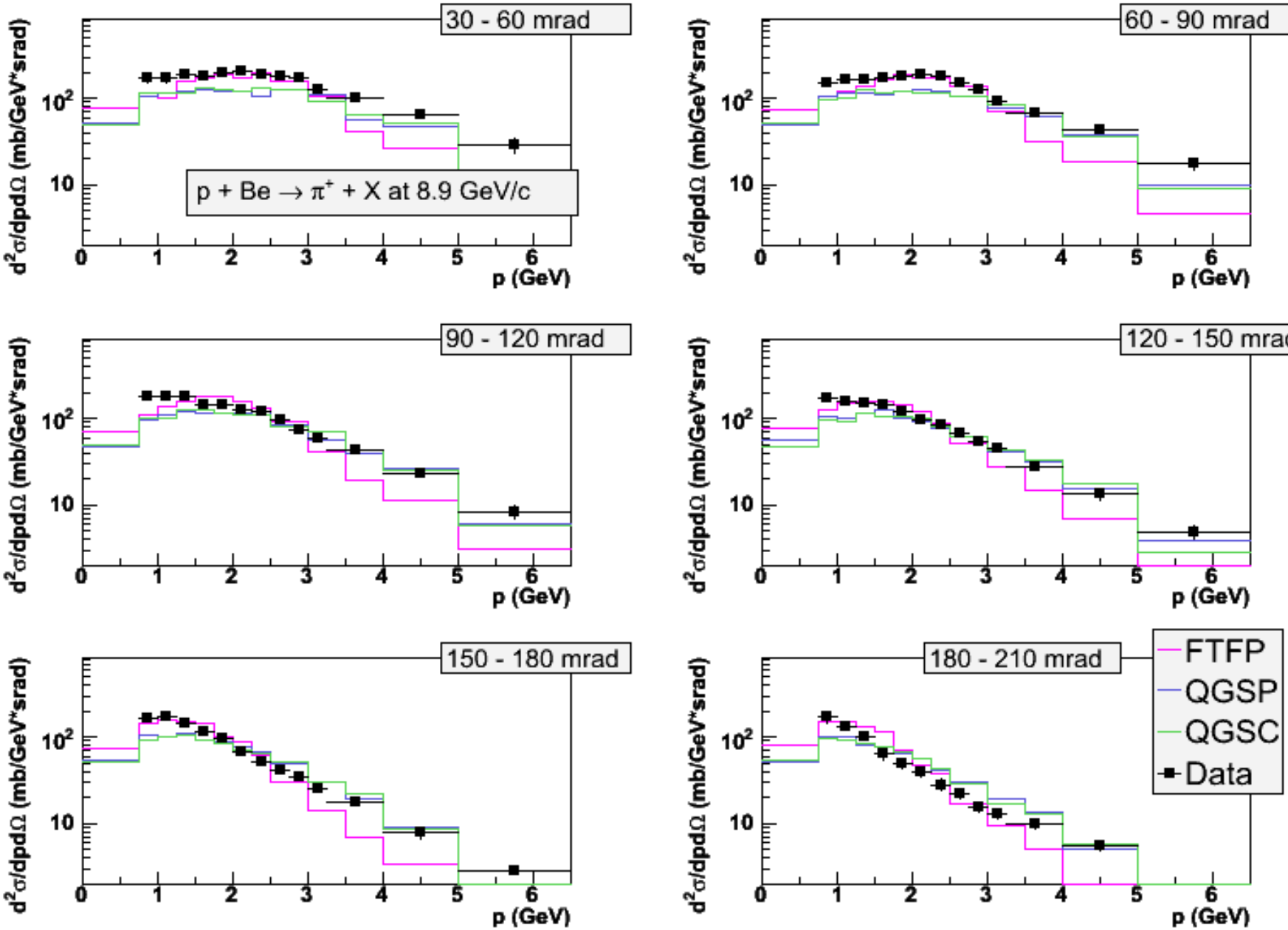
error on integral = 4.9%

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

p(8.9 GeV/c) + Be -> π^+ + X

HARP : p+Be at 8.9 GeV/c versus GEANT4 models

… as an example of many other comparisons made…



An aside on the SW parameterization

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

- 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

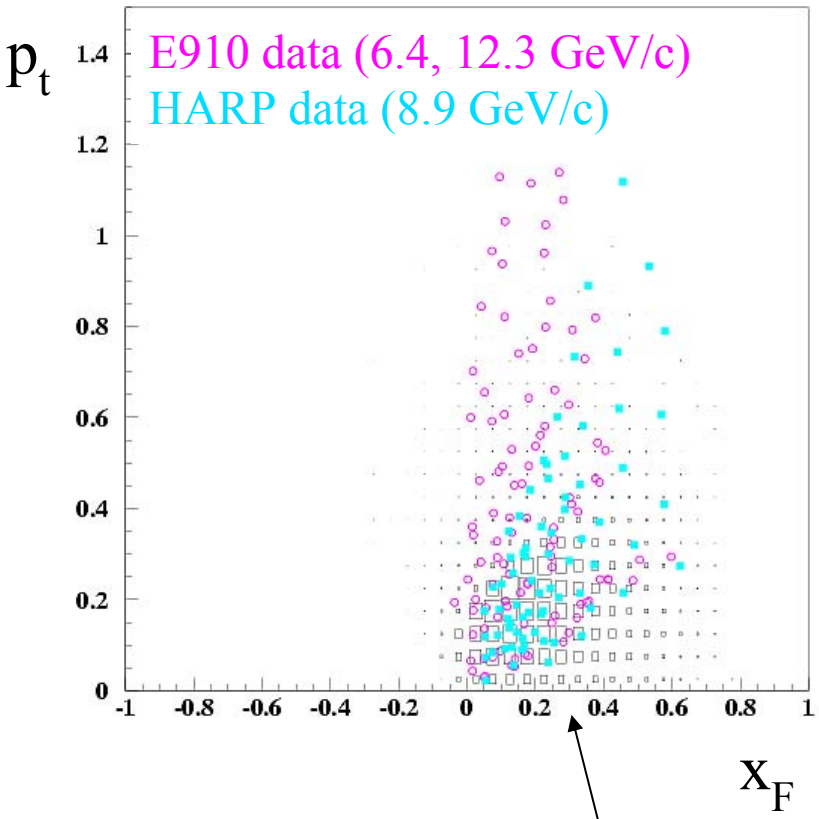
Parameter	Value
c_1	$(8.22 \pm 1.98)\cdot 10^1$
c_2	(6.47 ± 1.62)
c_3	$(9.06 \pm 2.03)\cdot 10^1$
$c_4 = c_5$	$(7.44 \pm 2.30)\cdot 10^{-2}$
c_6	(5.09 ± 0.49)
c_7	$(1.87 \pm 0.53)\cdot 10^{-1}$
c_8	$(4.28 \pm 1.36)\cdot 10^1$

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

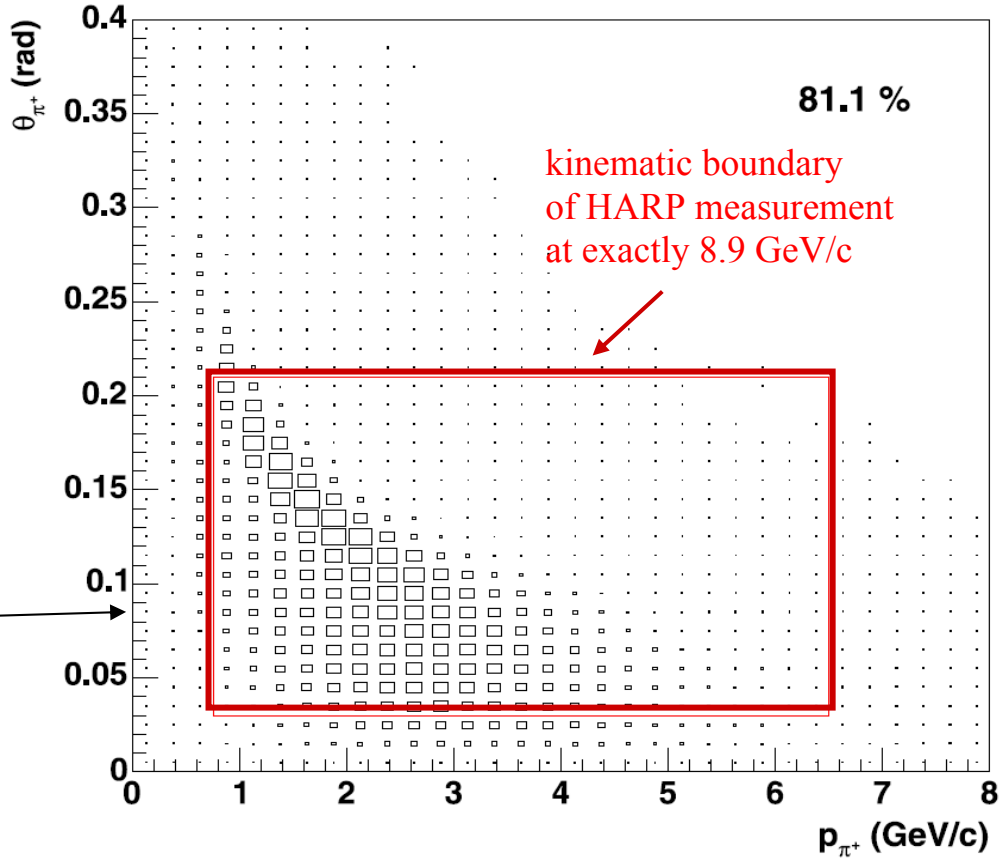


• black boxes are the distribution of π^+ which decay to a ν_μ that **passes through the MiniBooNE detector**

p(8.9 GeV/c) + Be -> π^+ -> ν_μ^{MB}

• 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



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

Phys. Rev. Lett. 98 (2007) 231801

0806.1449 [hep-ex]

More HARP data for accurate flux predictions

$K^{\pm}$ production data

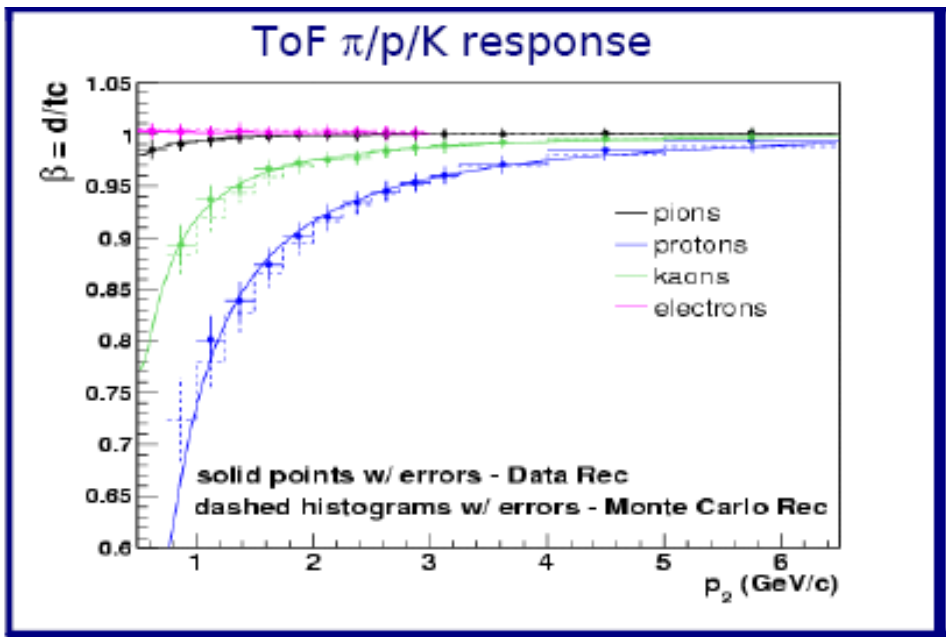
long targets

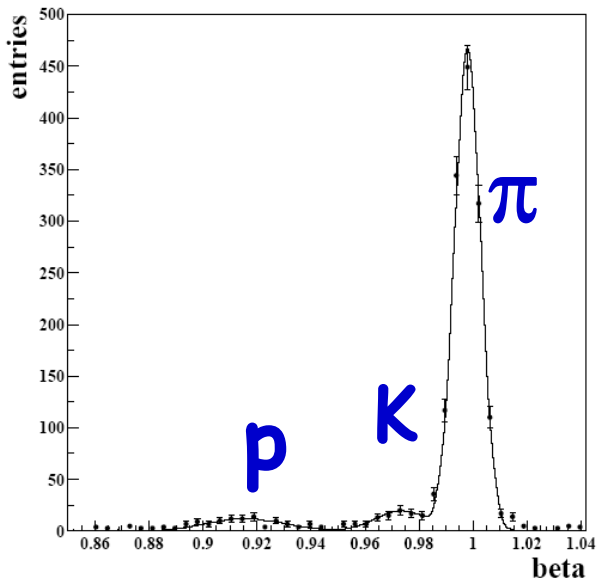
π^{-} production data

Main source of ν_e flux in MiniBooNE

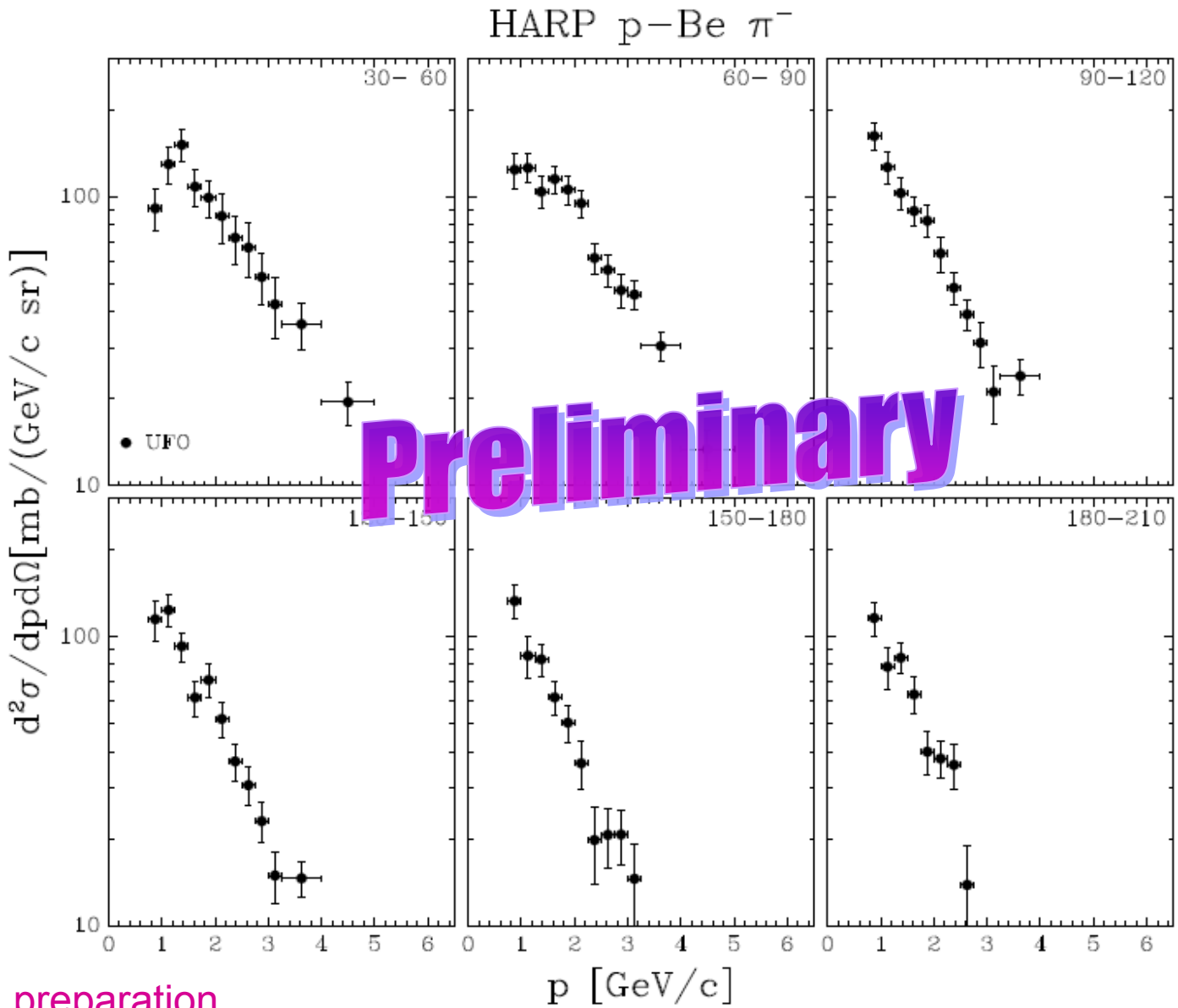
Direct measurement with rescattering and absorption

Antineutrino flux measurement





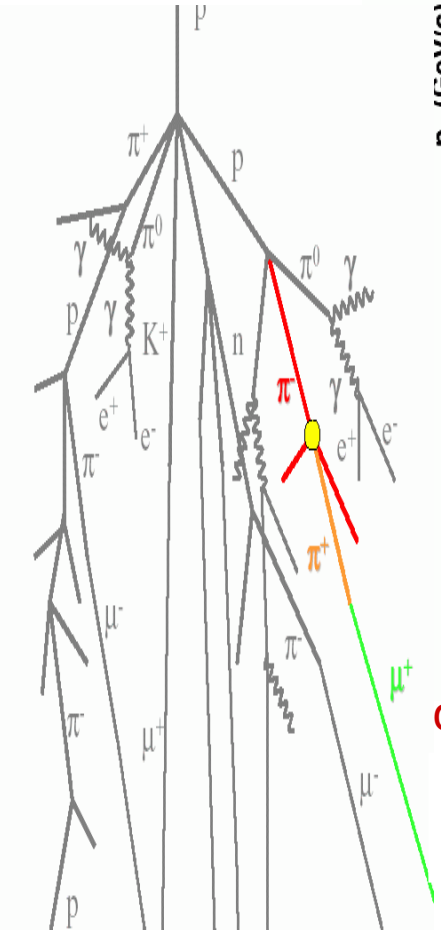
π^- data needed for MiniBooNE antineutrino flux

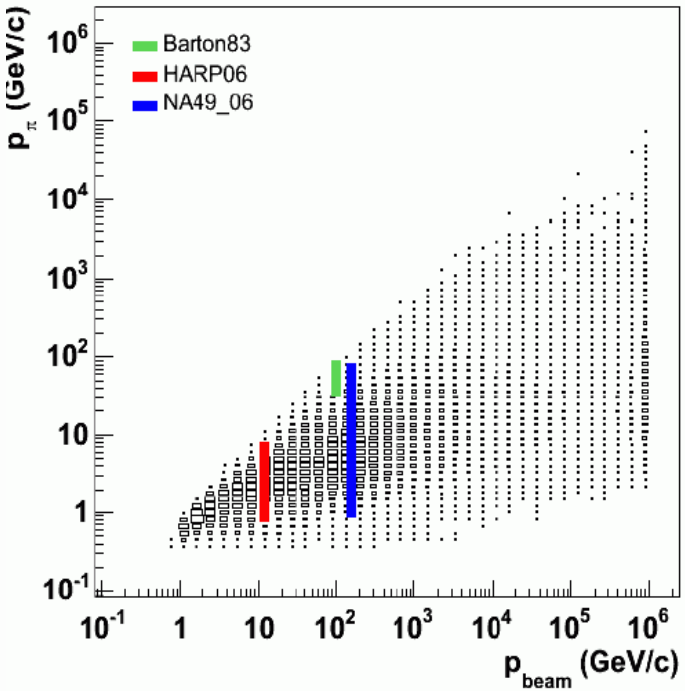


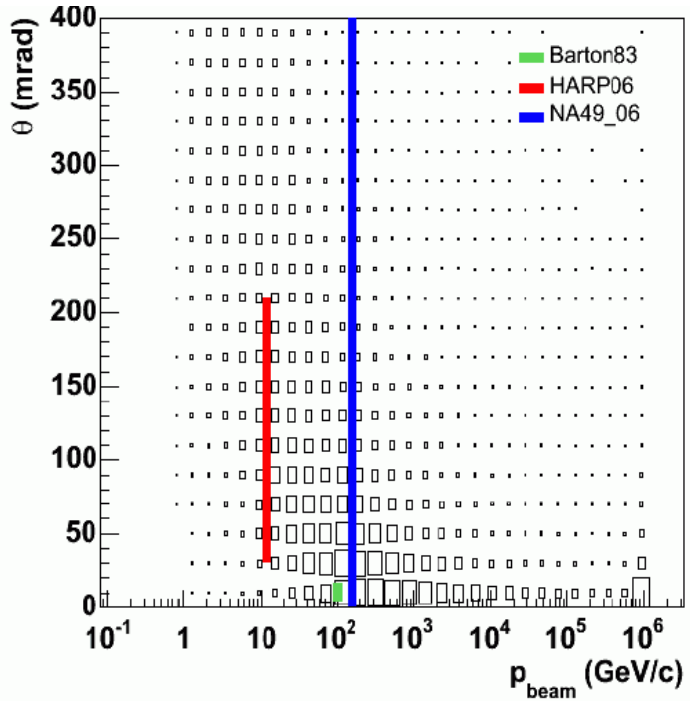
Paper in preparation

Atmospheric neutrino flux predictions

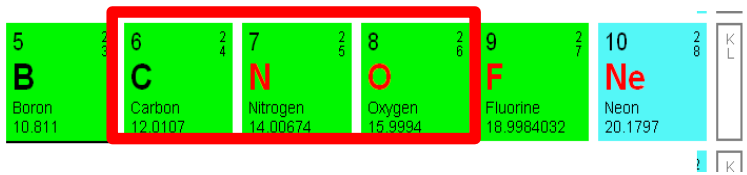
- **HARP p+C @ 12 GeV/c** data are relevant to the prediction of atmospheric neutrino fluxes and EAS simulations







carbon is isoscalar as nitrogen and oxygen



78% nitrogen

21% oxygen

Simulations predict that collisions of protons with a carbon target are very similar to proton interactions with air. This hypothesis can be tested with HARP data.

HARP Physics Publication

Available online at www.sciencedirect.com

ScienceDirect

Astroparticle Physics 29 (2008) 257–281

Astroparticle Physics

www.elsevier.com/locate/astropart

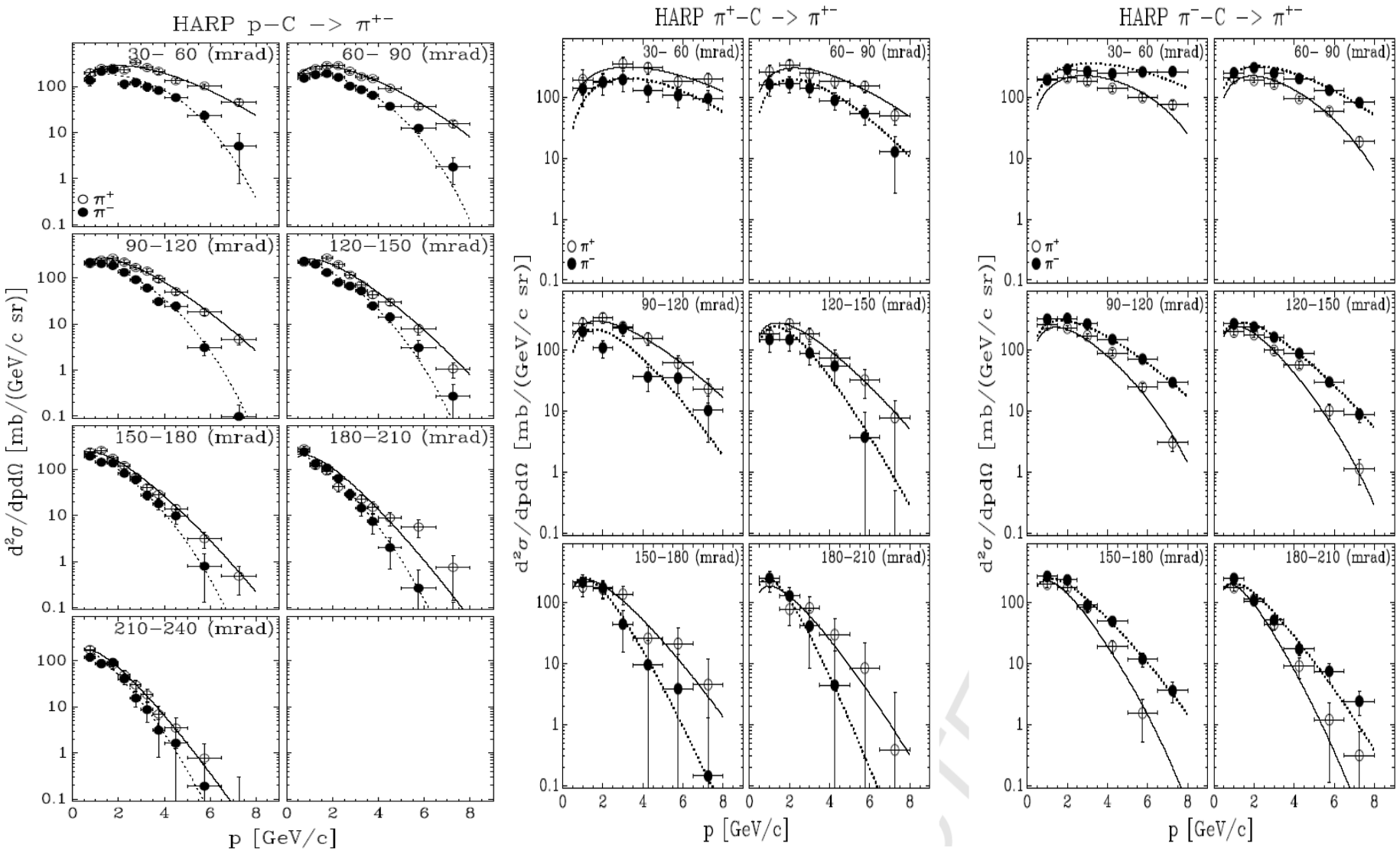
Measurement of the production cross-sections of $\pi^{\pm}$ in p–C and $\pi^{\pm}$–C interactions at 12 GeV/c

HARP Collaboration

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.

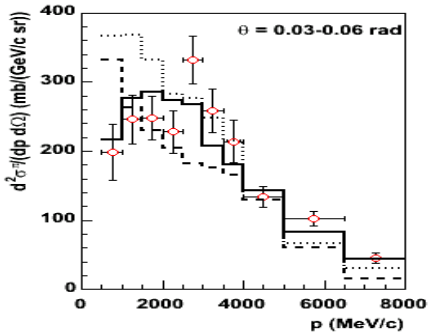
HARP : p, $\pi^{\pm}$ +C at 12 GeV/c and SW parameterizations

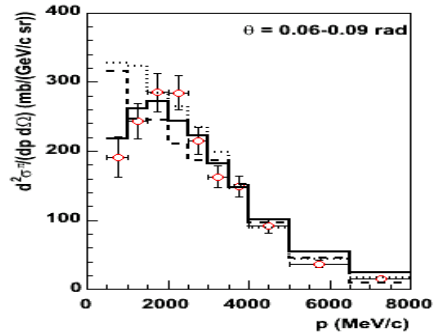


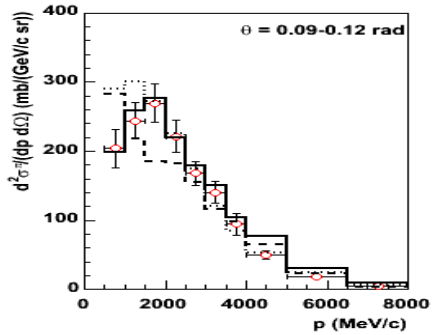
HARP p, $\pi^{\pm}$ +C @ 12 GeV/c data, SW parameterizations and comparison with models

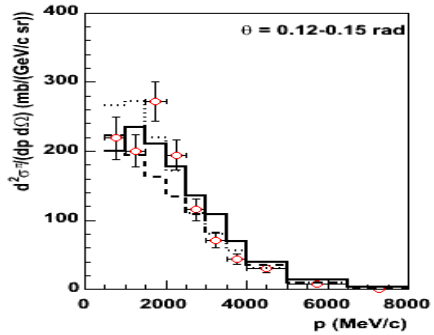
Incoming charged pion HARP data are the first precision measurements in this kinematic region

Astropart. Phys. 29 (2008) 257

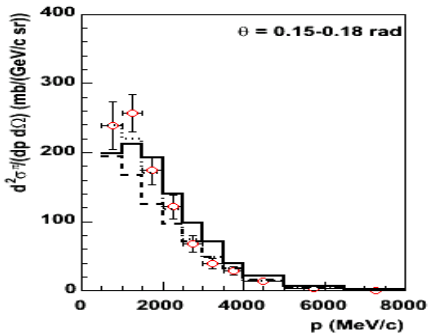


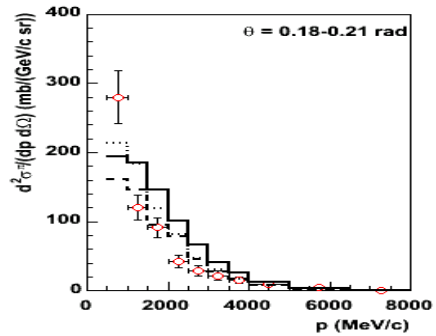


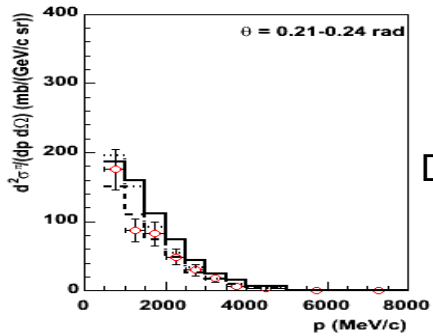


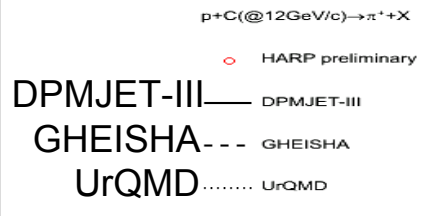


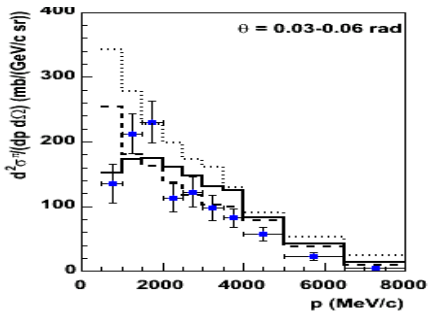
Model comparison: $p+C \rightarrow \pi^+ + X$

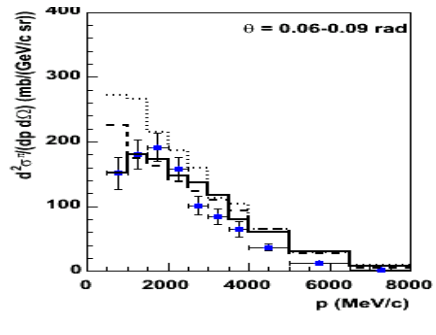


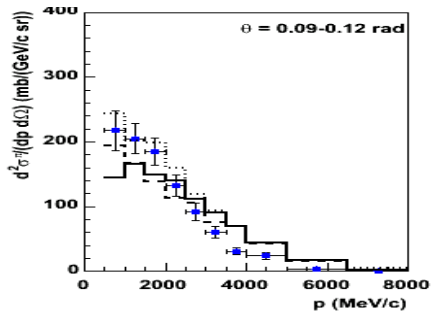


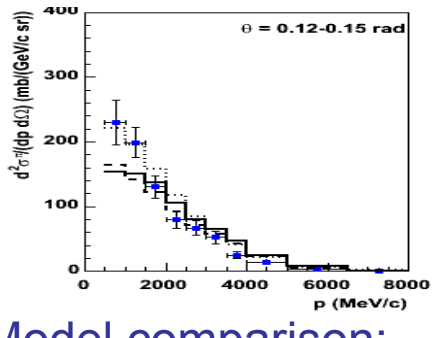




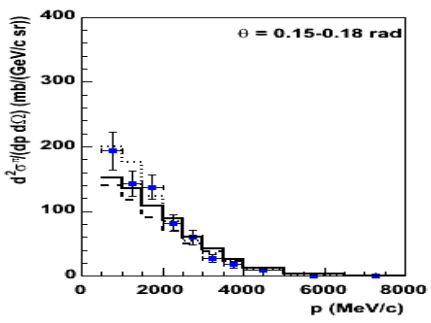


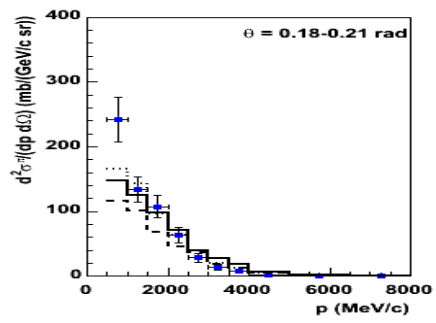


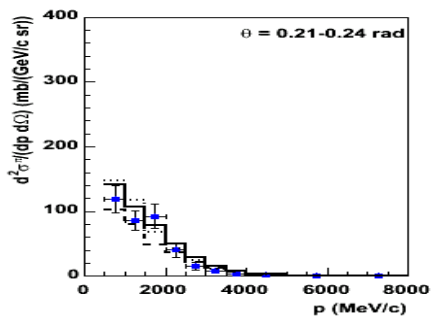


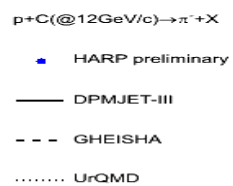


Model comparison: $p+C \rightarrow \pi^- + X$









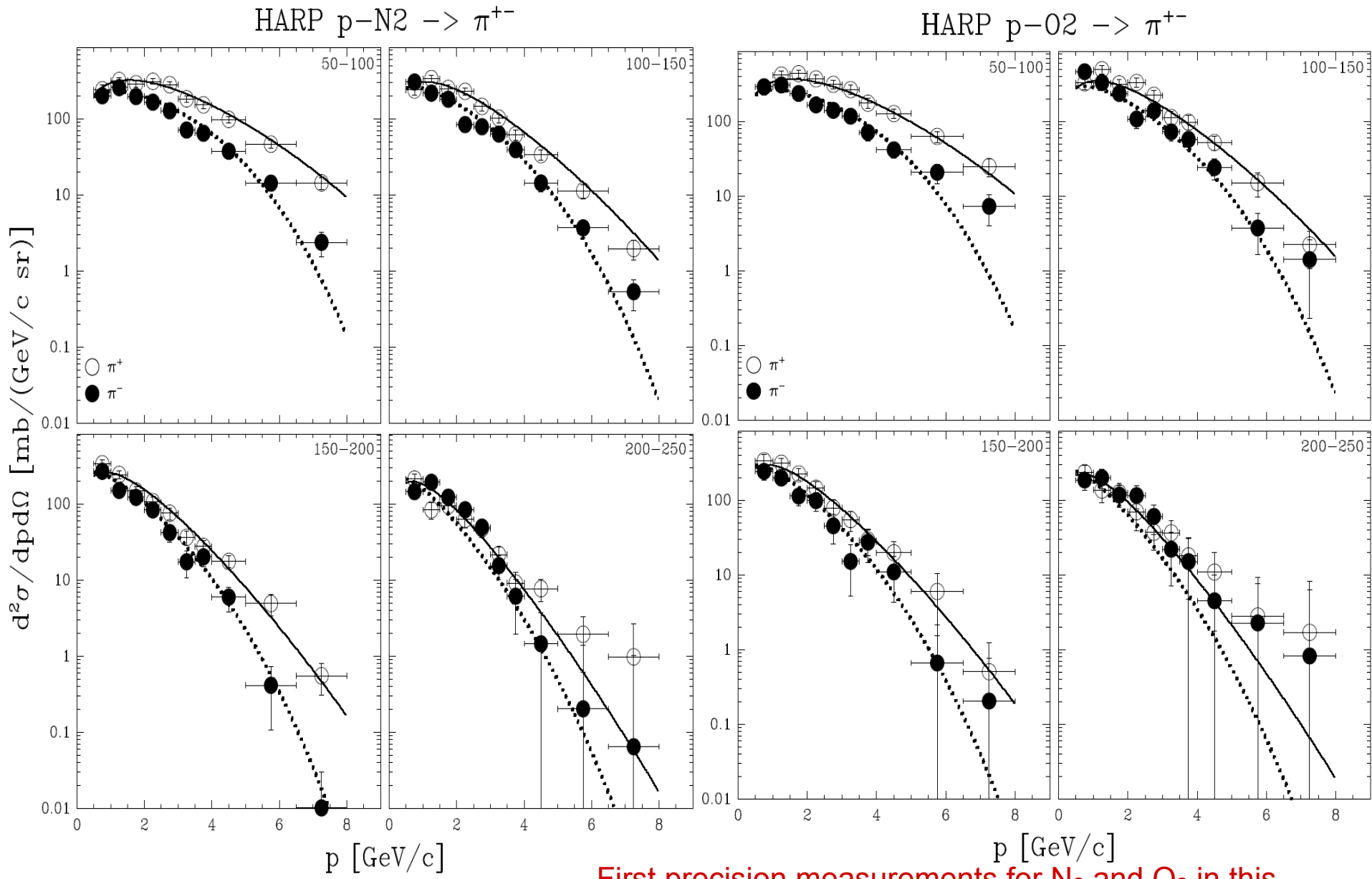
HARP : p / $\pi^{\pm}$ + C @ 12 GeV/c

We have compared the HARP measurements with 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.

Astropart. Phys. 29 (2008) 257

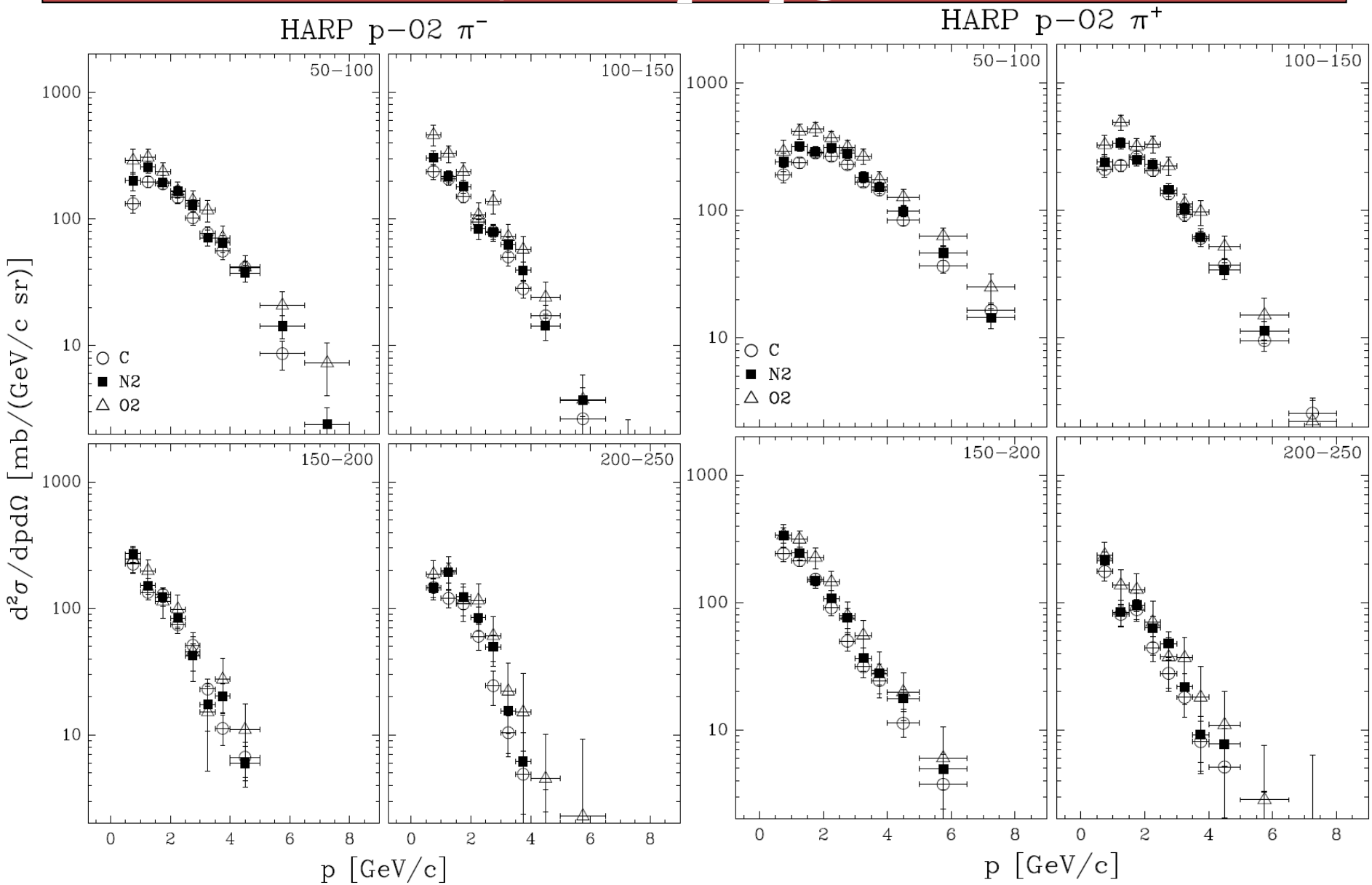
HARP : p + N_2 / O_2 @ 12 GeV/c



First precision measurements for N_2 and O_2 in this energy range, SW parameterizations from p-C data

CERN-PH-EP-2008-010

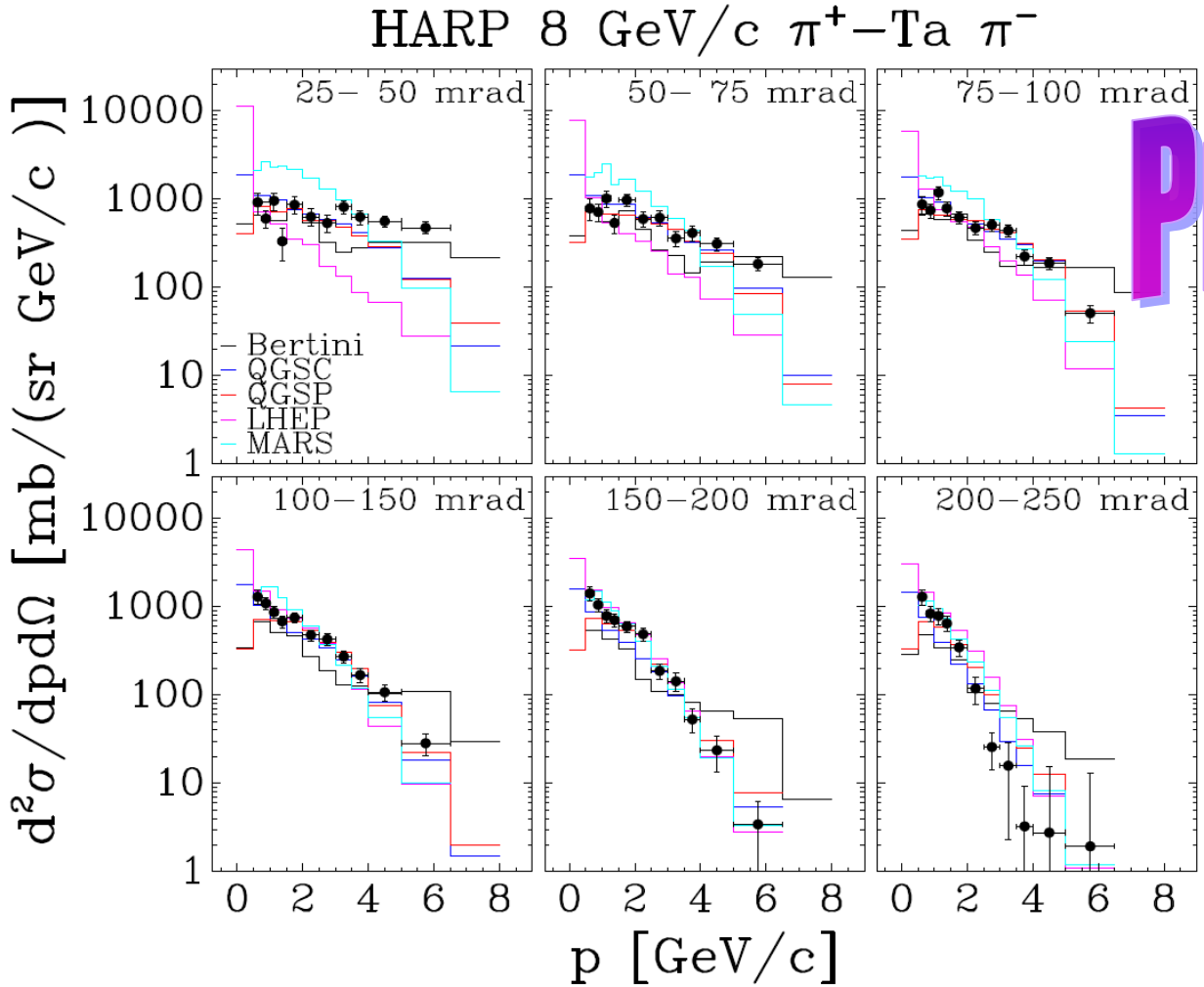
HARP : p + C / N_2 / O_2 @ 12 GeV/c



HARP results confirm that p-C data can be used to predict p-N_2 and p-O_2 pion production

CERN-PH-EP-2008-010

HARP : more data with incident $\pi^{\pm}$



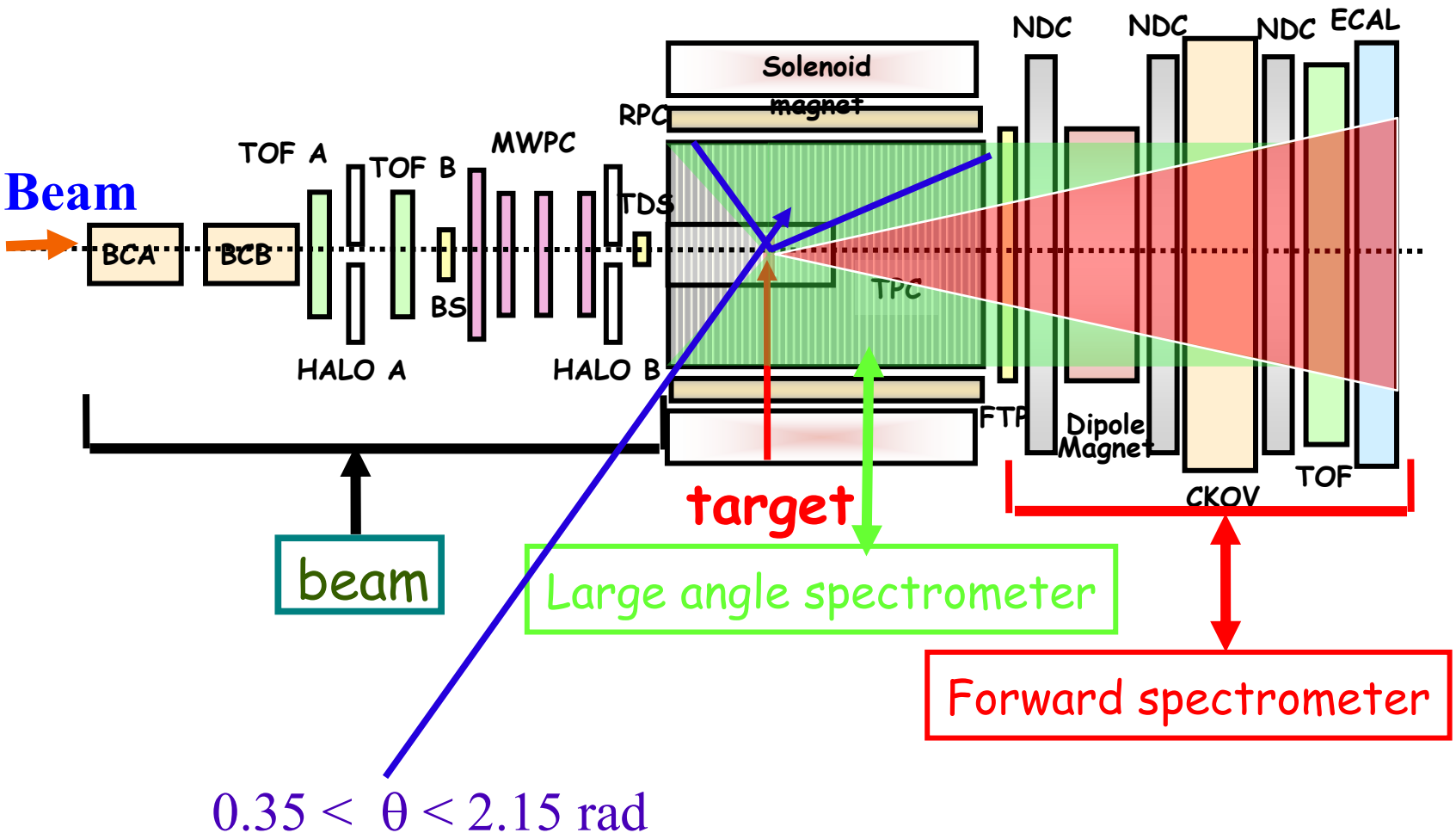
Preliminary

Just as an example of more HARP data on the FW production

- All thin target data taken in pion beams are also analysed
- Interesting to tune models for re-interactions (and shower calculations in calorimeters etc.)

HARP paper in preparation for incoming $\pi^{\pm}$

Large Angle spectrometer: TPC

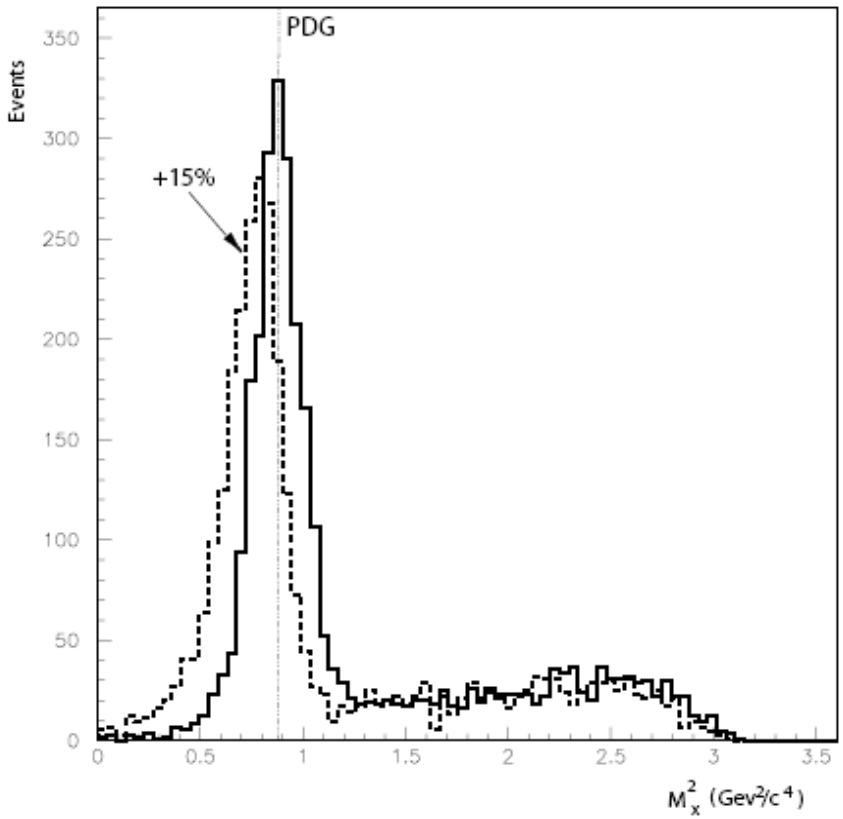


“Large Angle” analysis

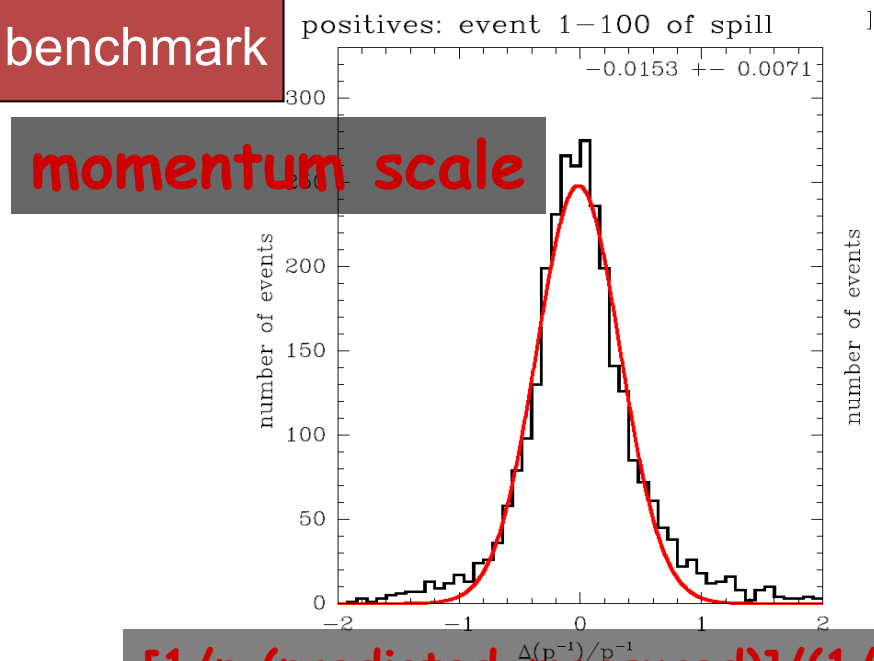
Beam momenta:
3, 5, 8, 12 GeV/c
beam particle selection and normalization same as previous analysis
Data:
5% λ targets Be, C, Al, Cu, Sn, Ta, Pb
Events:
require trigger in ITC (cylinder around target)
TPC tracks:
>11 points and momentum measured and track originating in target
PID selection
additional 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^{+-}.

Full statistics now analysed (“full spill data” with dynamic distortion corrections).
No significant difference is observed with respect to first analyses of the partial data (first 100-150 events in spill)

HARP TPC calibration: elastic scattering benchmark



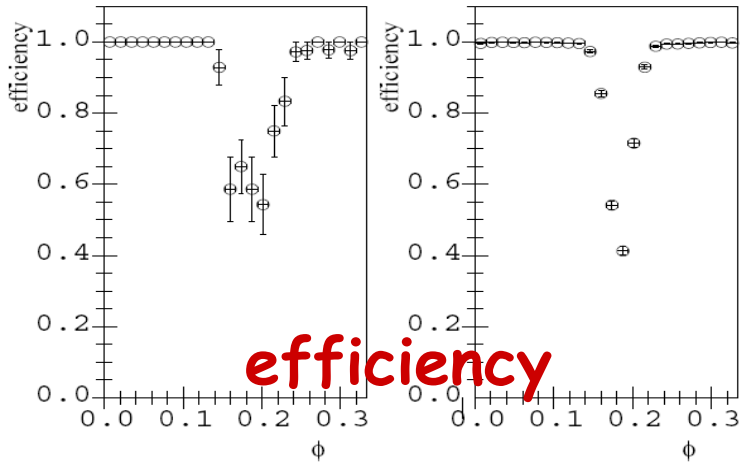
missing mass peak from large angle proton track (position of peak verifies momentum scale: +15% shift is completely excluded)



momentum scale

[1/p (predicted-measured)]/(1/p)

Comparison of predicted vs measured track allows LA tracking benchmark

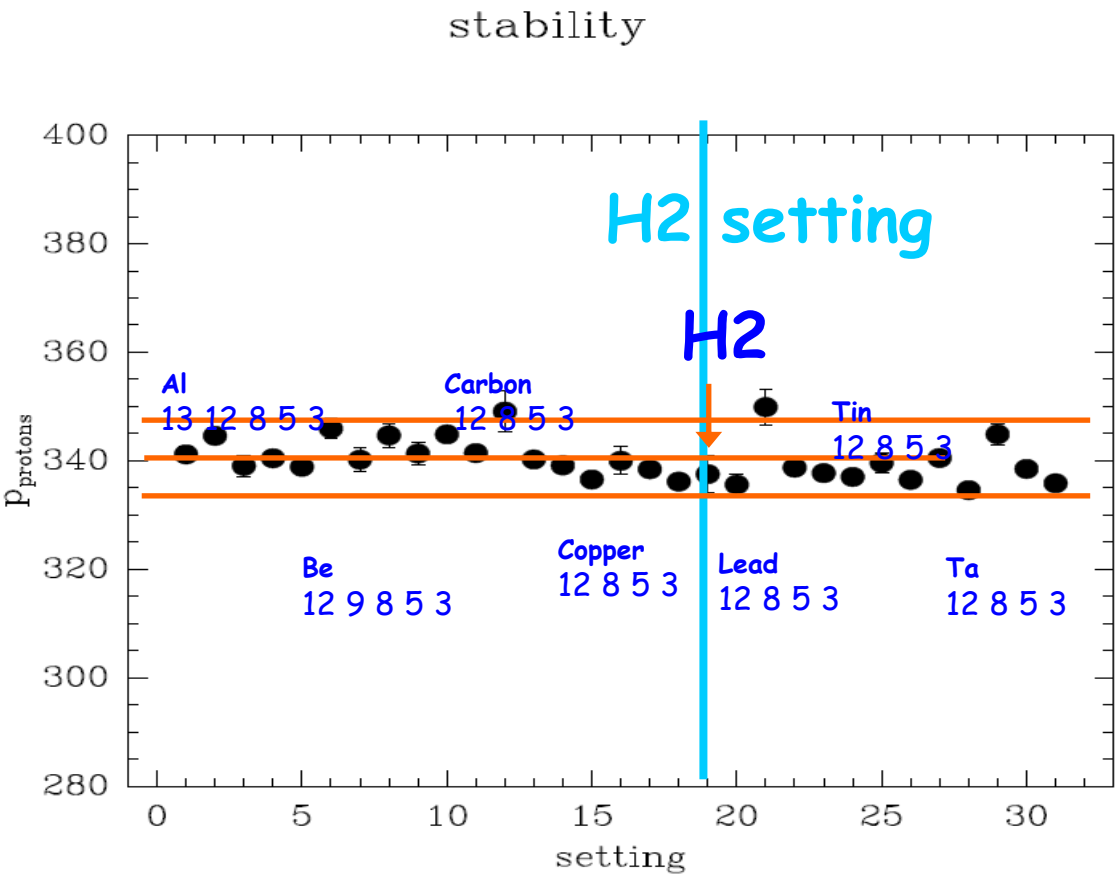


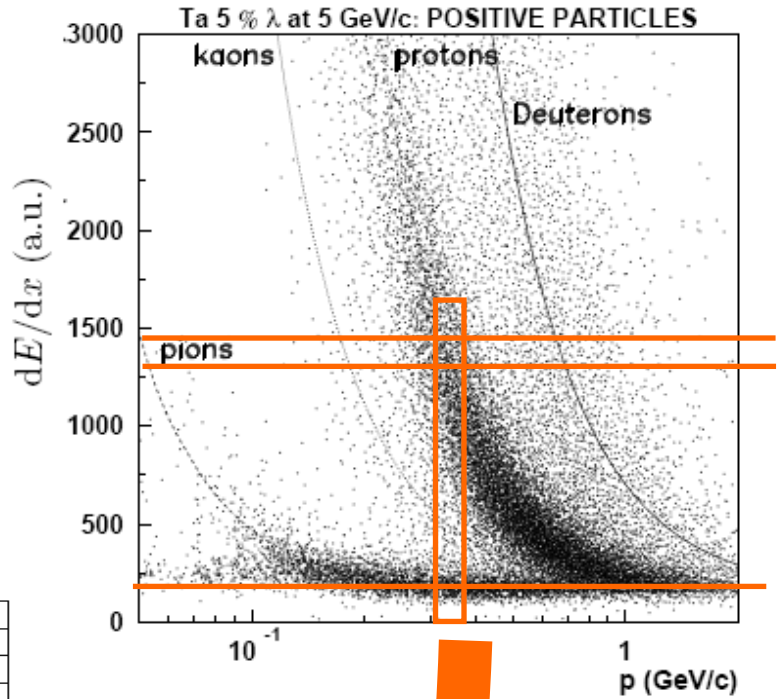
efficiency

JINST 3: P04007 (2008)

Stability from LH2 target to other targets

consider average momentum of protons with dE/dx ∈[7-8] MIPs





±2%

JINST 3: P04007 (2008)

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

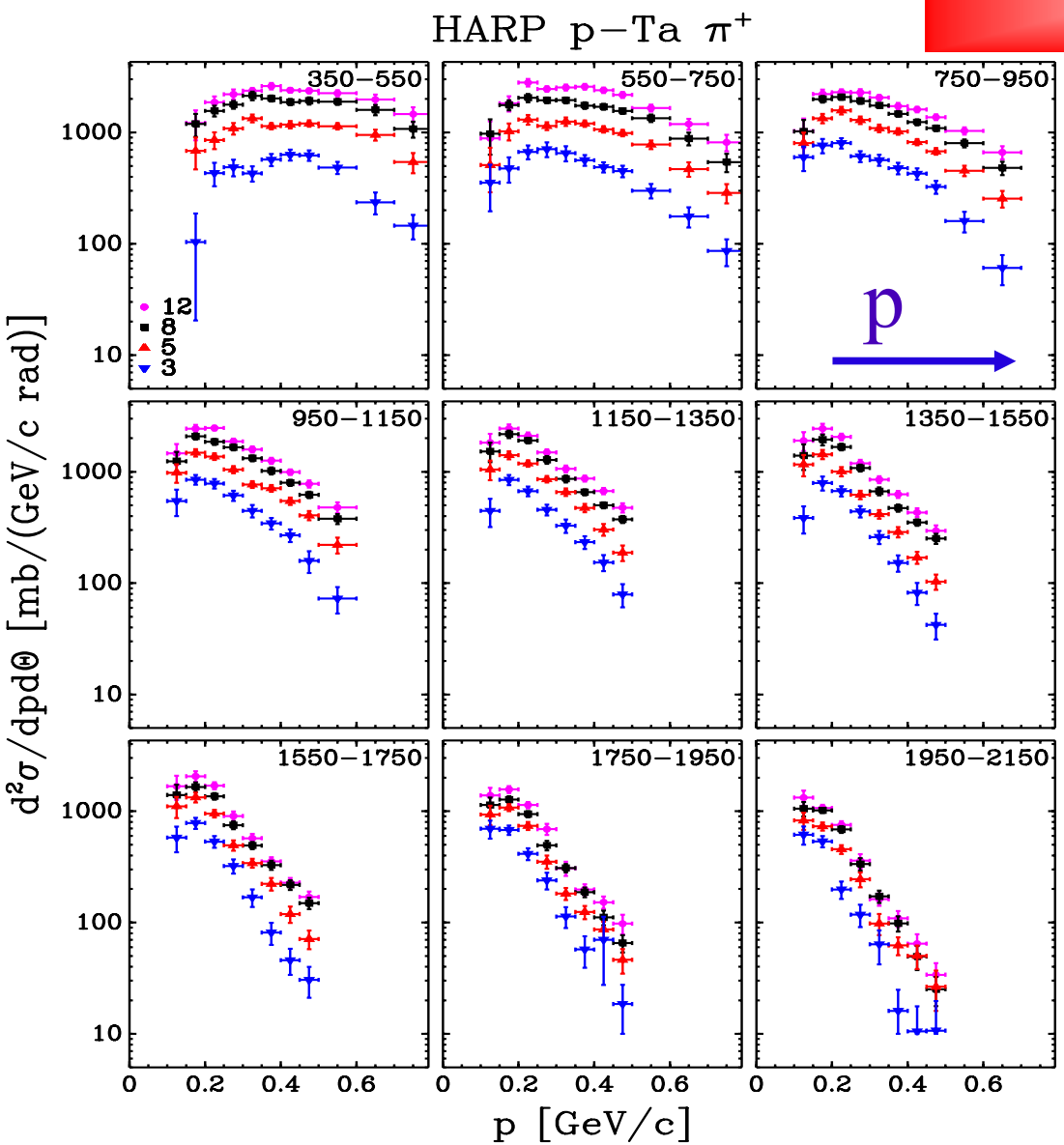
Measurement of the production of charged pions by protons on a tantalum target

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 $\mathrm{d}^2\sigma/\mathrm{d}p\mathrm{d}\theta$ 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.

Pion production yields

9 angular bins: p-Ta π^+



stat. and syst. errors combined

forward
$350 < \theta\ (\text{mrad}) < 1550$

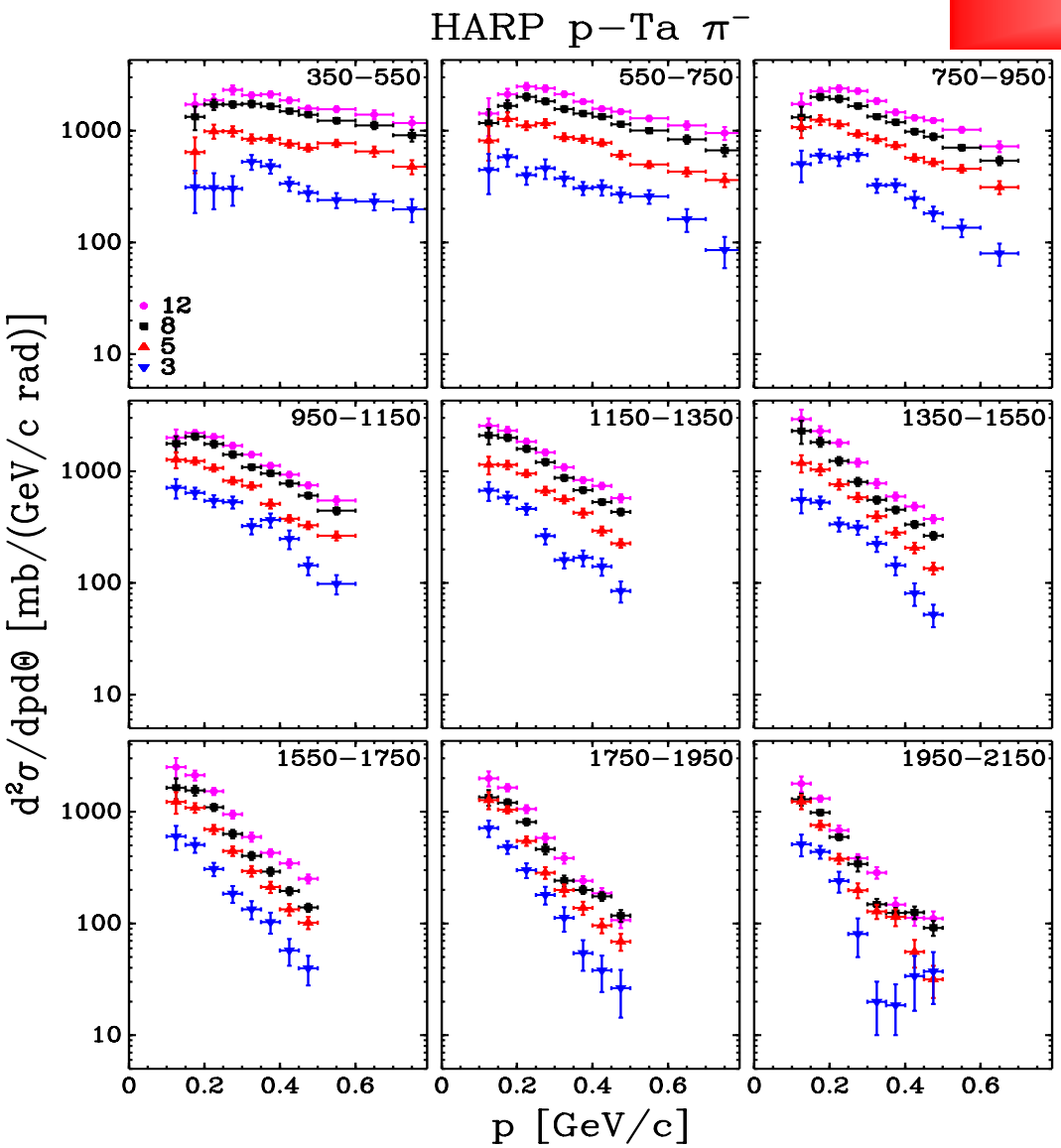
backward
$1550 < \theta\ (\text{mrad}) < 2150$

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

EPJ C 51 (2007) 787

Pion production yields

p-Ta π^-



stat. and syst. errors combined

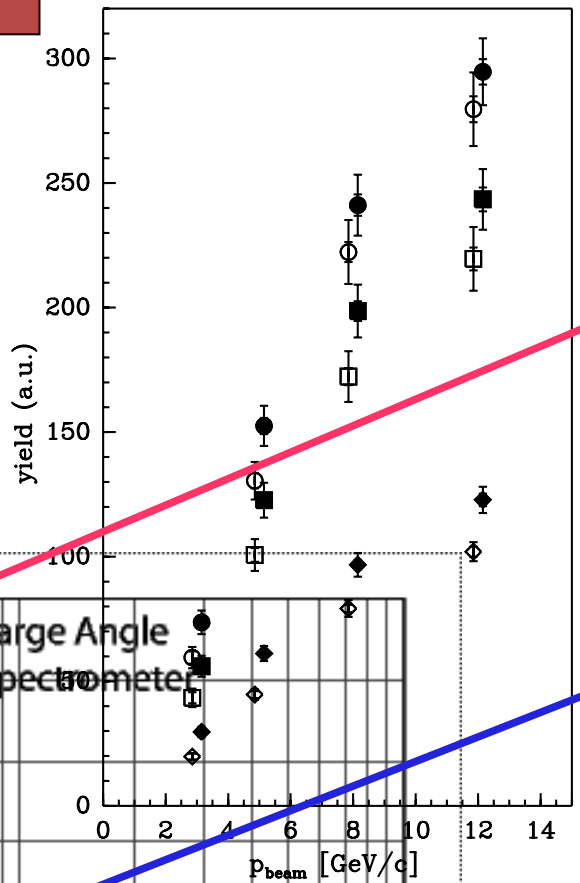
forward
$350 < \theta(\text{mrad}) < 1550$

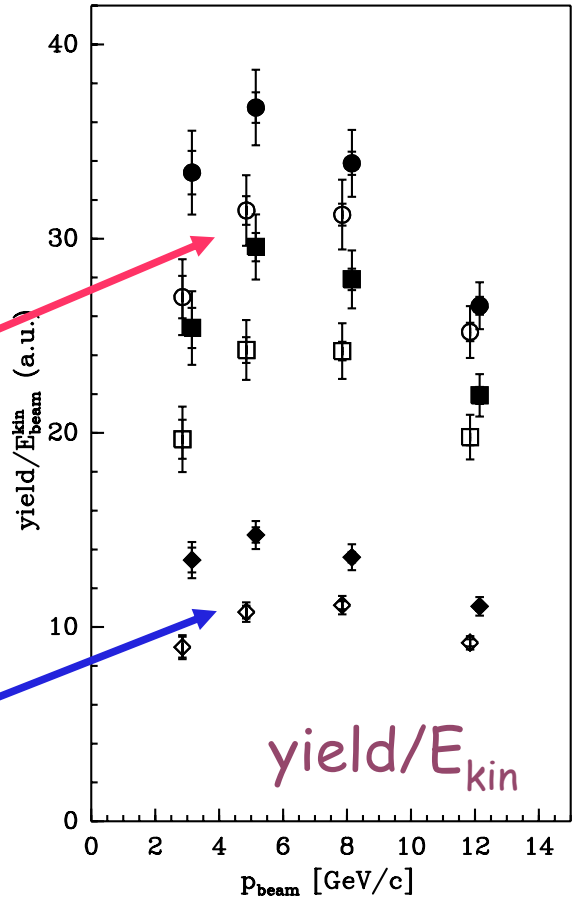
backward
$1550 < \theta(\text{mrad}) < 2150$

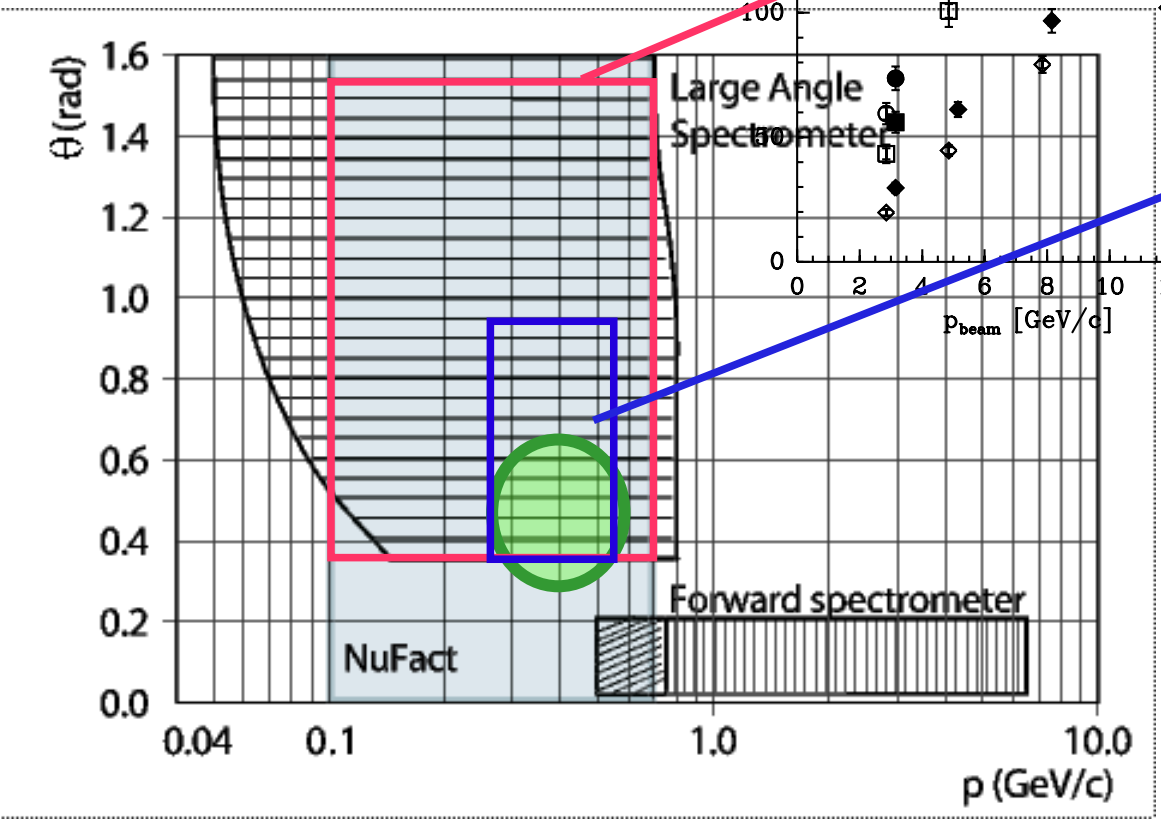
momentum range $0.1 < p < 0.8$ GeV/c

EPJ C 51 (2007) 787

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 54, 37–60 (2008)
DOI 10.1140/epjc/s10052-007-0517-y

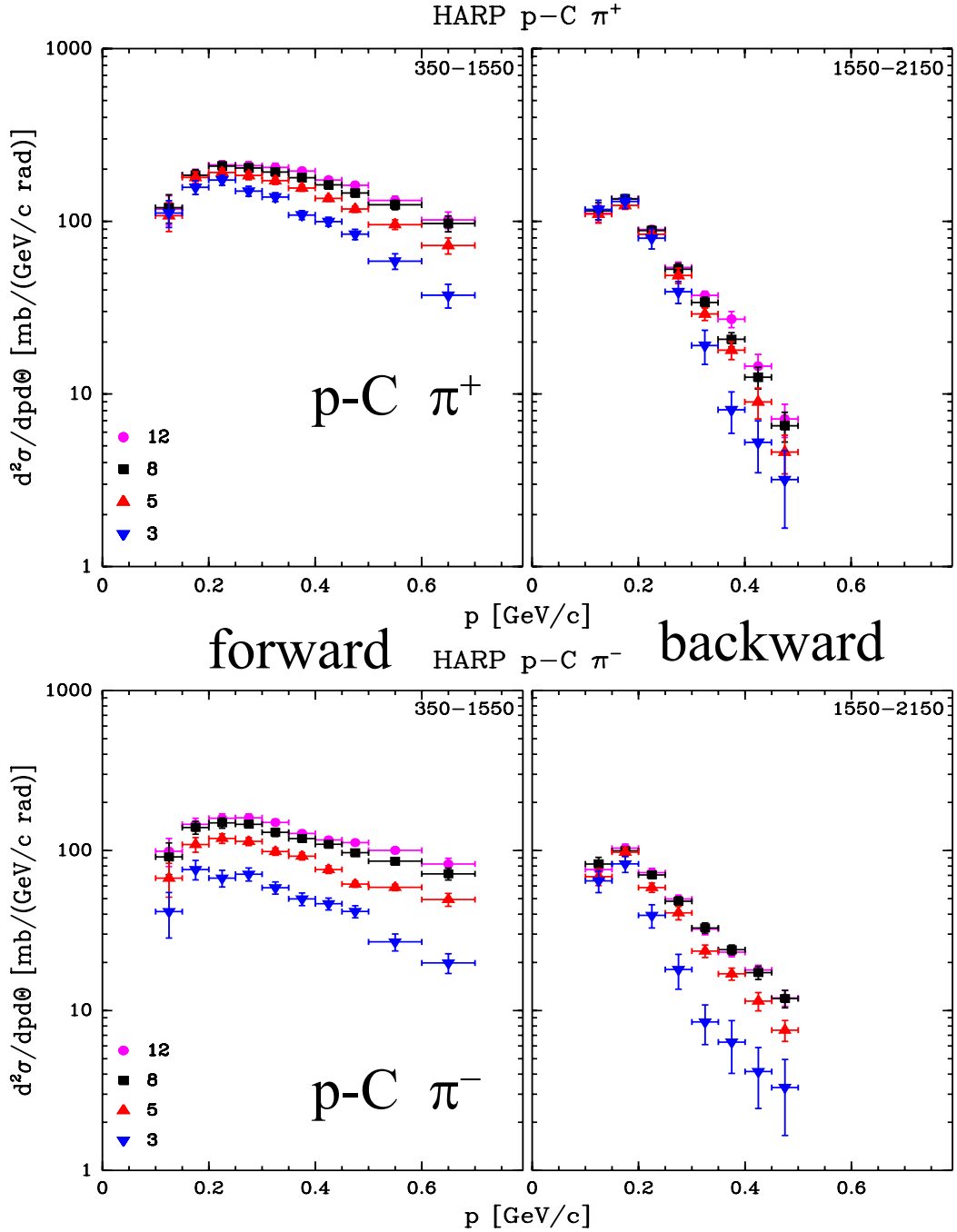
THE EUROPEAN PHYSICAL JOURNAL C

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

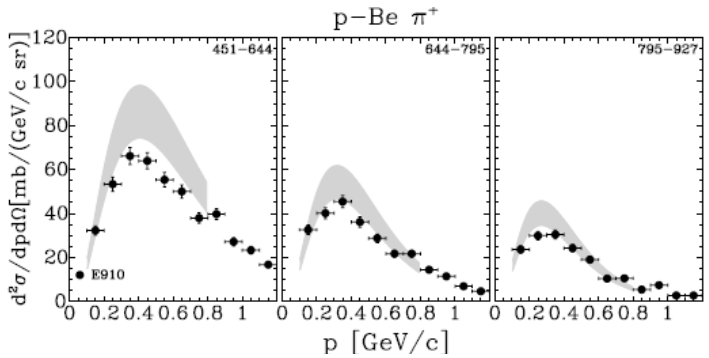
Pion yields

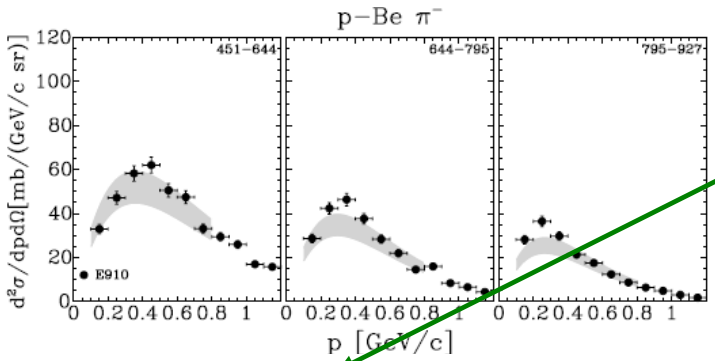


p-C data as an example of many other available spectra

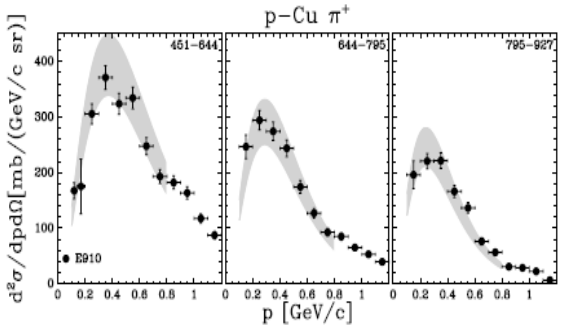
EPJ C 53 (2008) 177

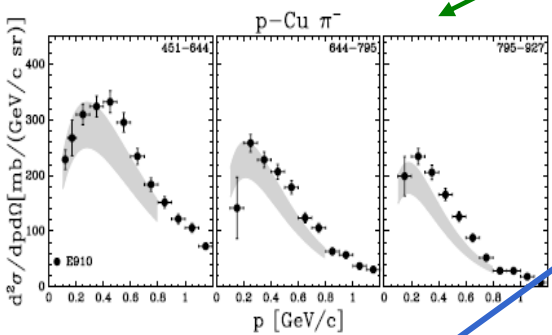
Comparison with…



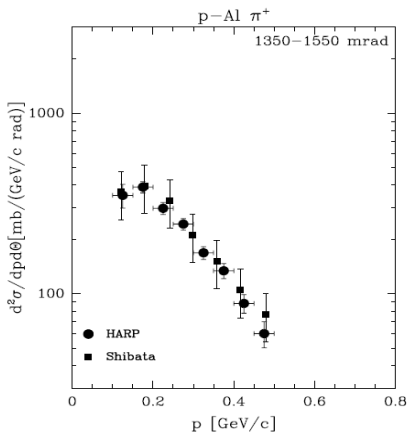


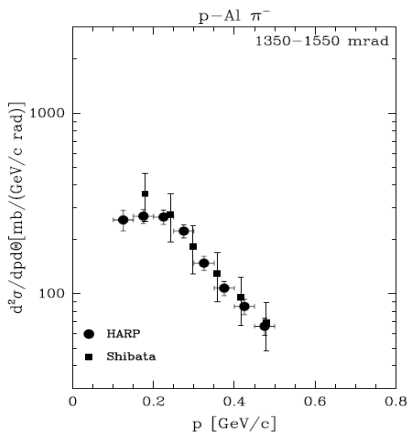
BNL E910 at 12.3 GeV/c: data points; HARP: shaded region

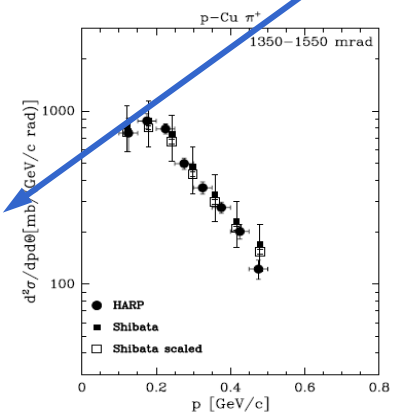


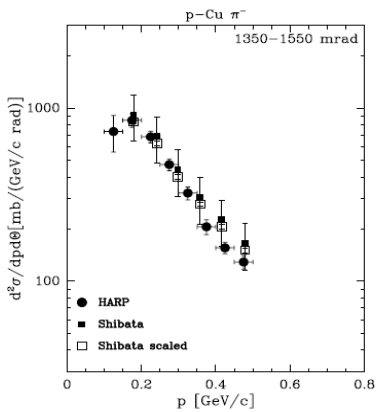


squares: Shibata et al. (KEK), 12 GeV/c at 90°; circles: HARP data









HARP Physics Publication

PHYSICAL REVIEW C 77, 055207 (2008)

Large-angle production of charged pions with 3–12.9 GeV/c incident protons on nuclear targets

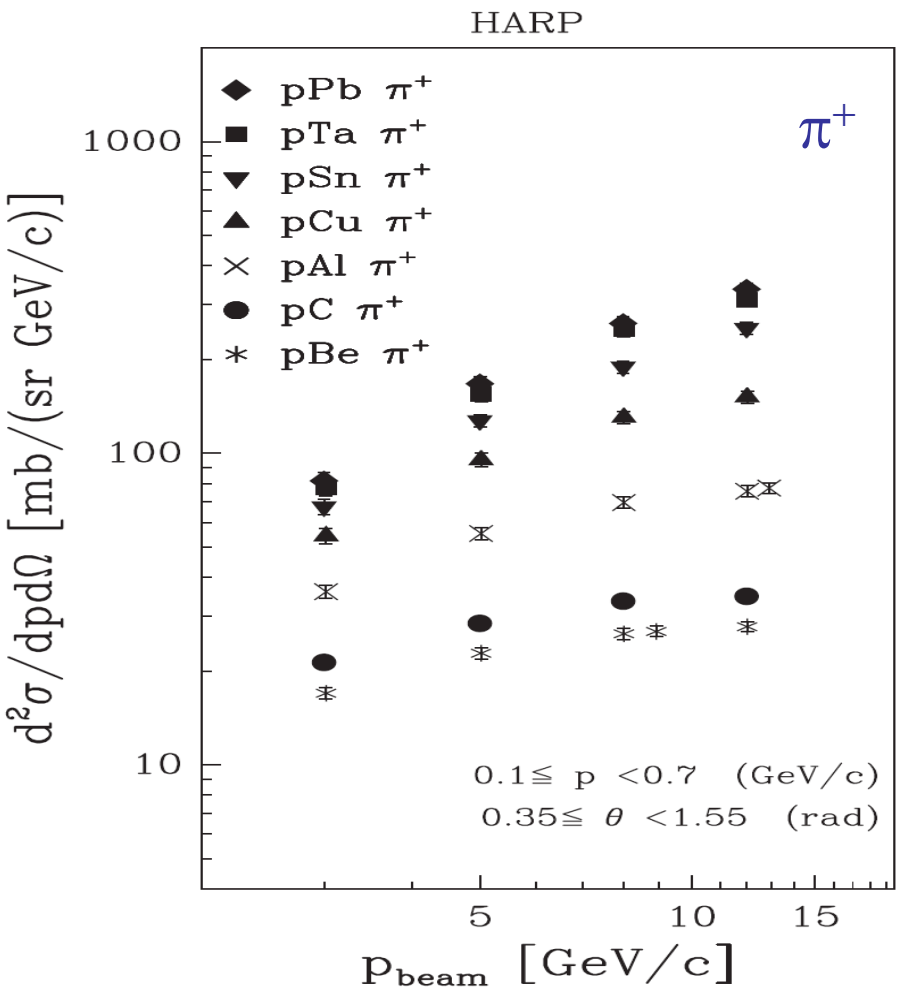
Abstract

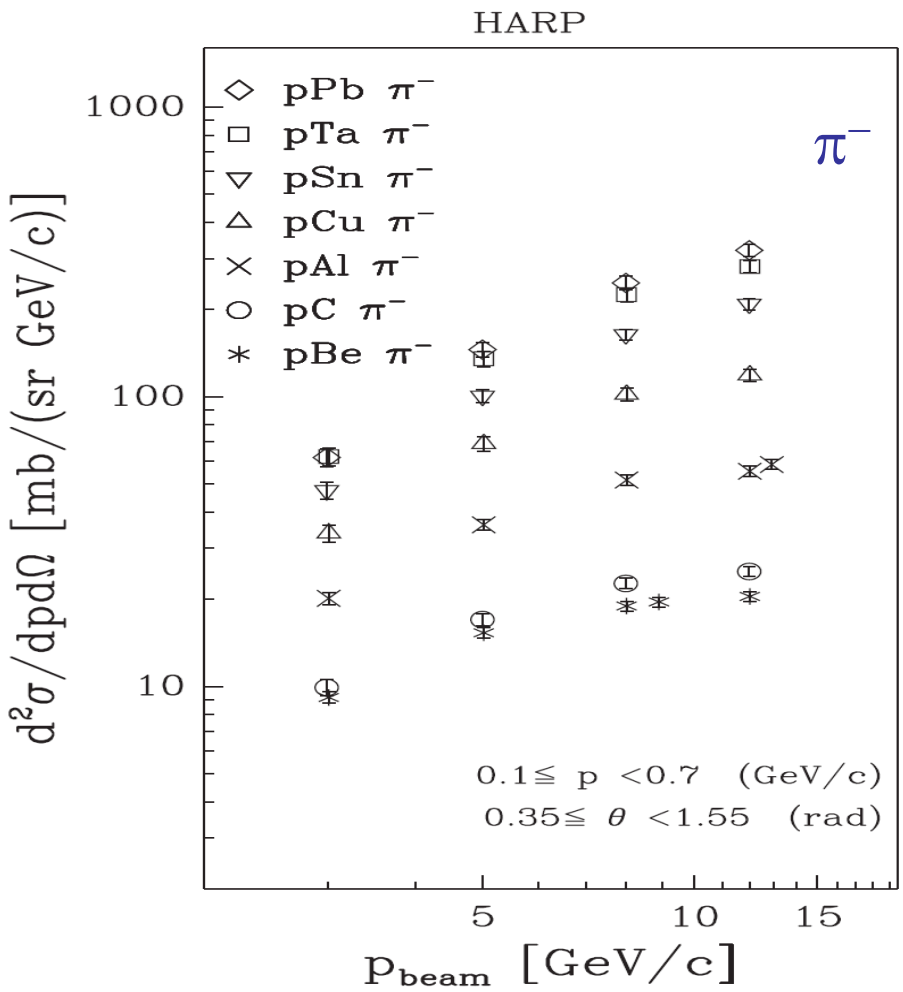
Measurements of the double-differential $\pi^{\pm}$ production cross-section in the range of momentum 100 MeV/c $\leq p \leq$ 800 MeV/c and angle 0.35 rad $\leq \theta \leq$ 2.15 rad in proton–beryllium, proton–aluminium, proton–carbon, proton–copper, proton–tin, proton–tantalum and proton–lead collisions 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 $d^2\sigma/dpd\theta$ 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 Monte Carlo simulation.

Pion yields

comparison of π^+ and π^- yields in p-A for Be, C, Al, Cu, Sn, Ta and Pb as a function of momentum (full spill data)

forward production only $0.35 < \theta < \mathbf{1.55}$ rad



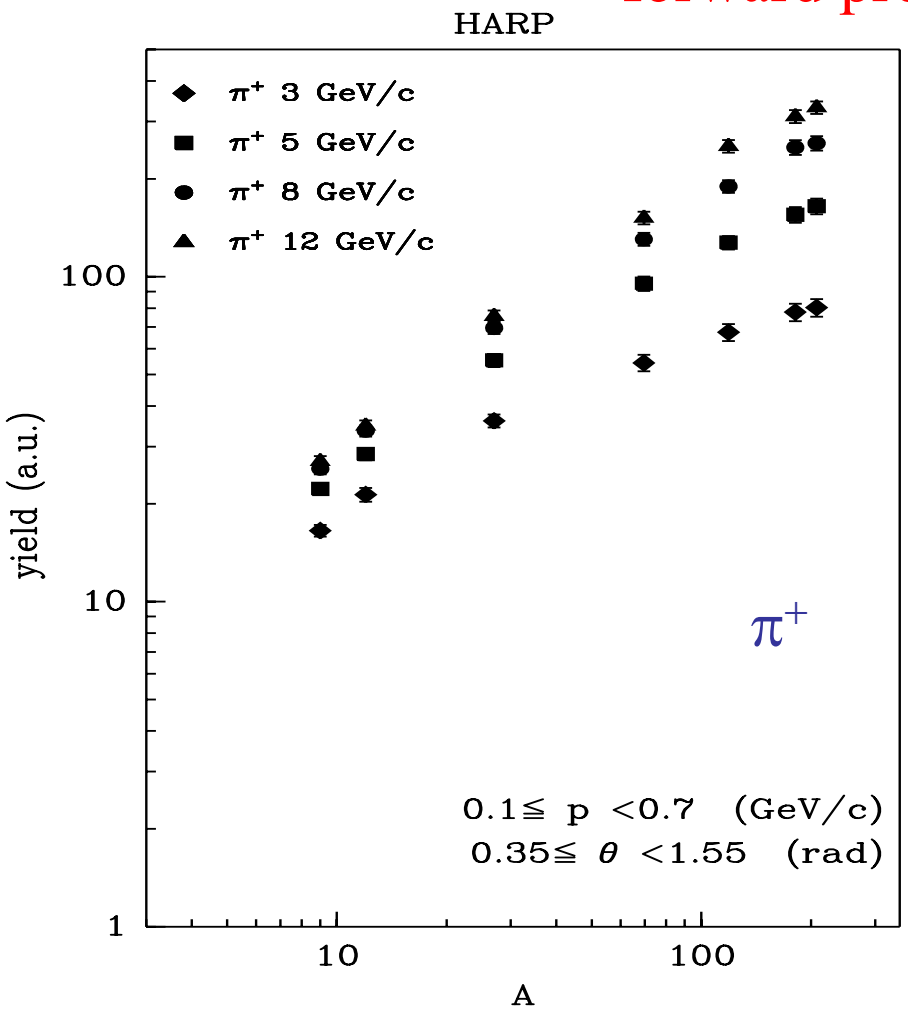


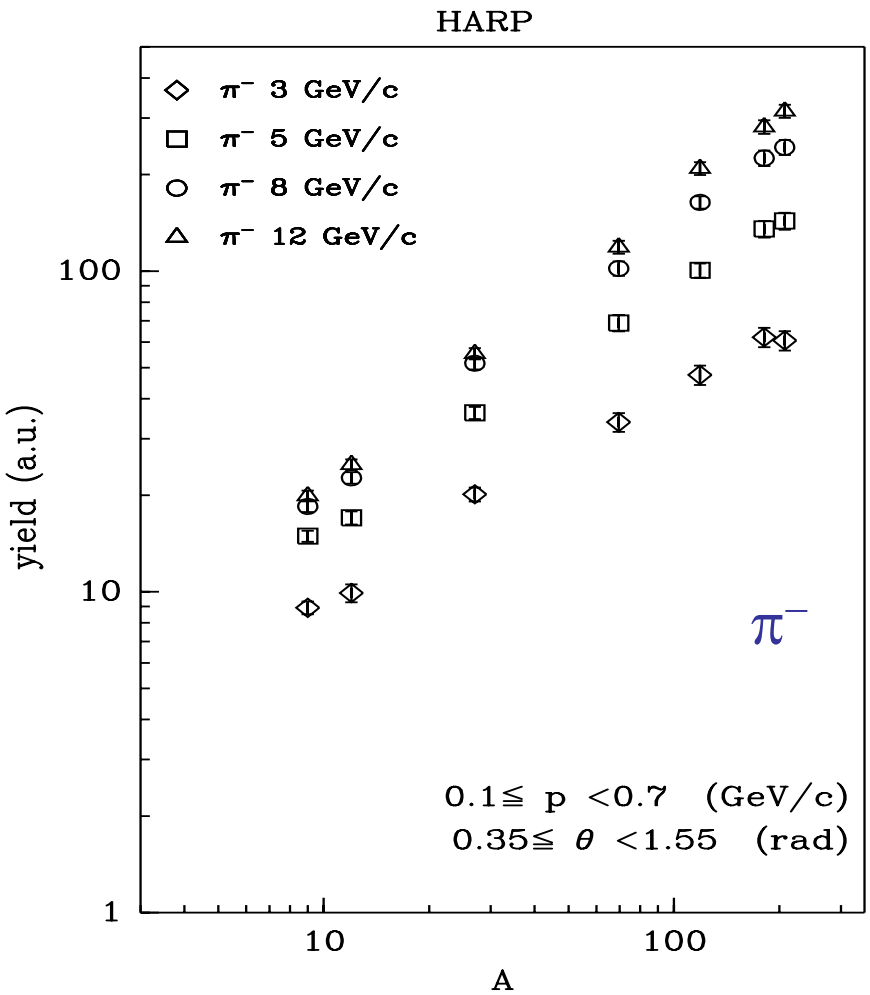
Phys. Rev. C 77 (2008) 055207

Pion yields

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

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





Phys. Rev. C 77 (2008) 055207

Measured with the same detector!

HARP: comparison with MC

Many comparisons with models from GEANT4 and MARS are being done

Some examples are shown for Ta

Binary cascade

Bertini cascade

Quark-Gluon string models (QGSP)

Fritiof (FTFP)

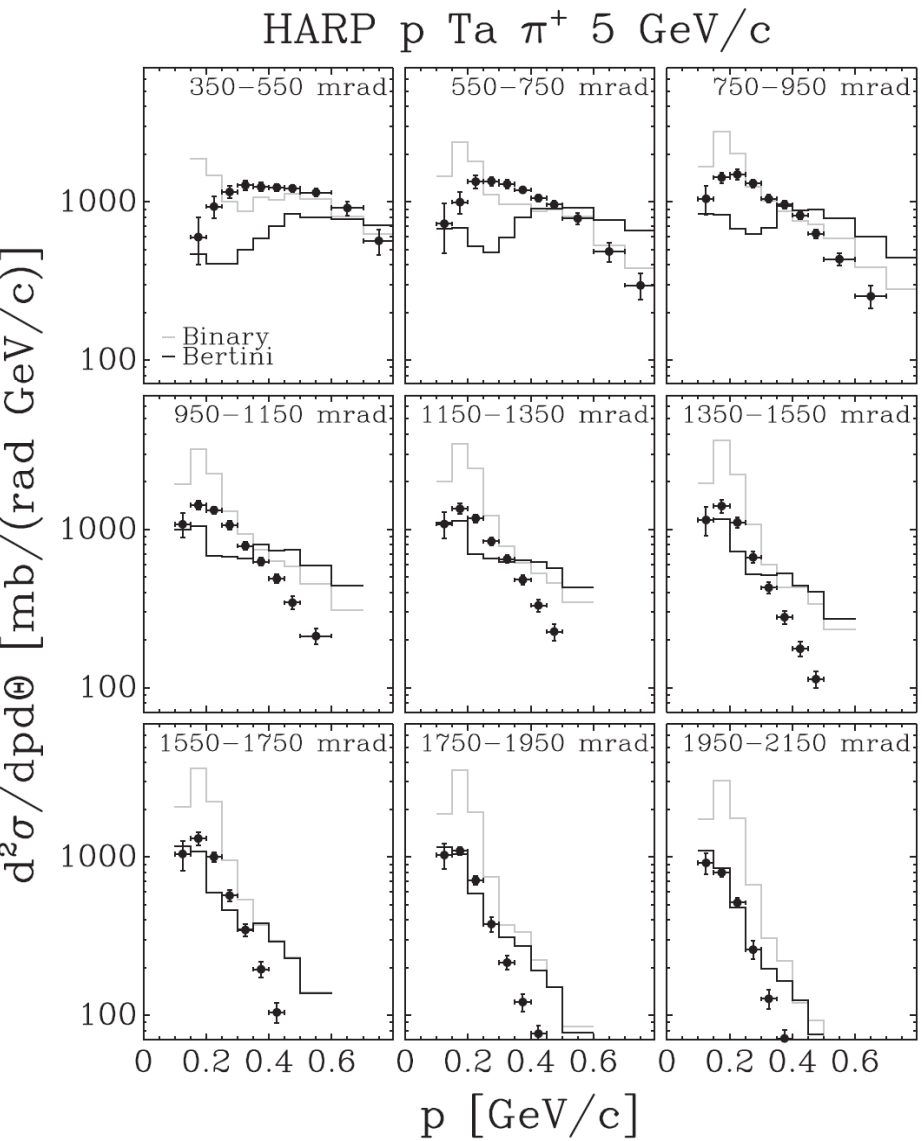
LHEP

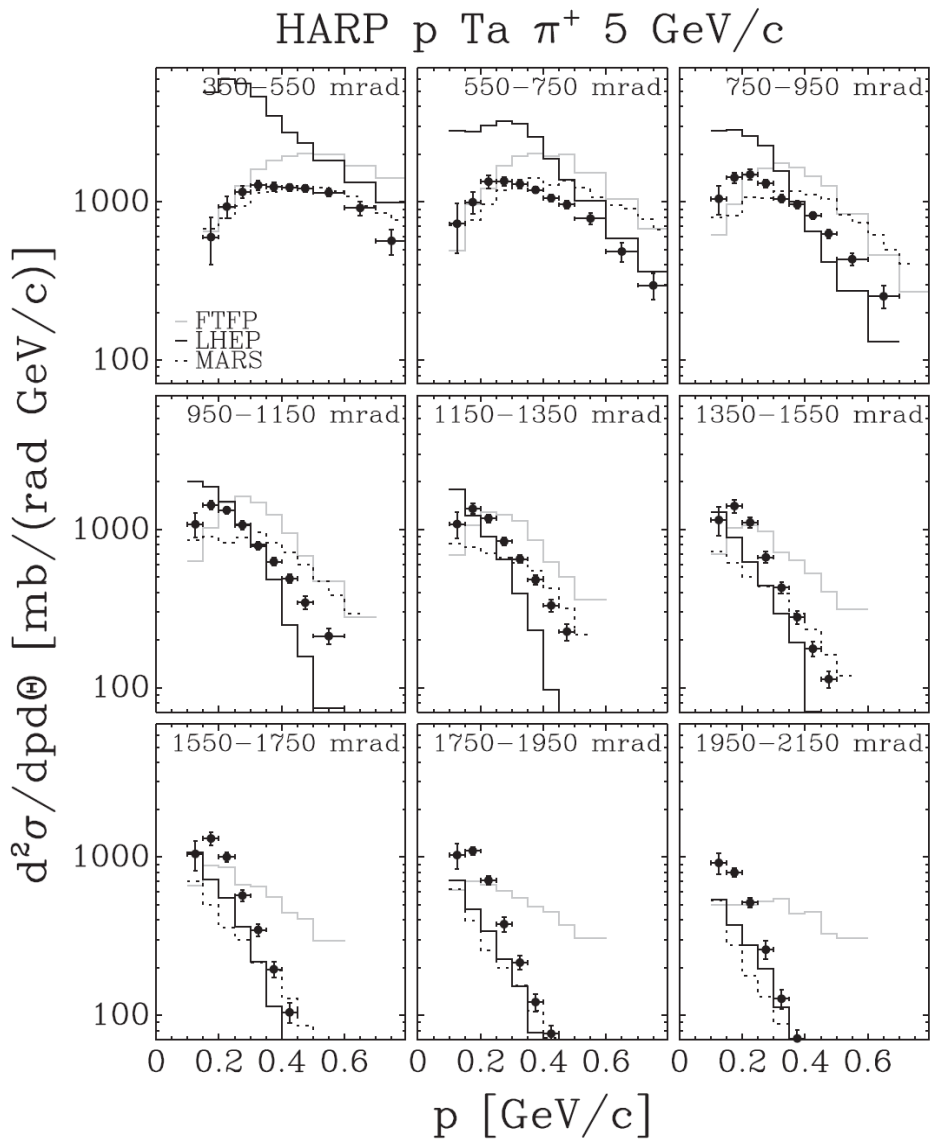
MARS

Some models do a good job in some regions, but there is no model that describes all aspects of the data

HARP: 5 GeV/c p-Ta π^+

… just as an example of many other comparisons made…





Phys. Rev. C 77 (2008) 055207

HARP: Summary

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

Results with Al target for **K2K** have been published and used for final K2K publication.

Results with Be target for **MiniBooNE/SciBooNE** have been published and used for the first MiniBooNE oscillation paper.

Tantalum results for the **Neutrino Factory** studies have been published as well as other targets (Carbon, Copper, Tin, Beryllium, Aluminium and Lead). Results for the full data set on these targets are also published now.

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

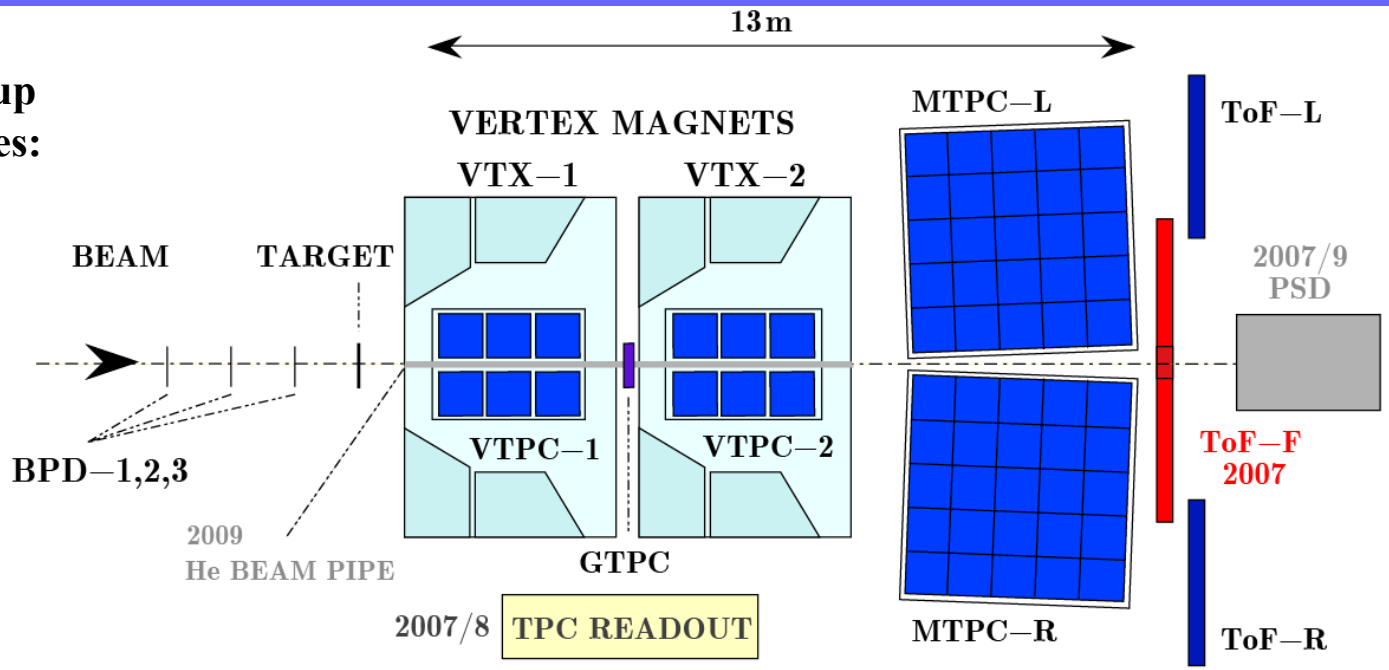
HARP measurements will be used to tune MC hadron production models.

More production cross-section measurements are now finalized (forward production with incident pions and protons on targets from Be to Pb, production with long targets, etc.).

The HARP detector is well understood and the analysis techniques established.

Only a small fraction of available results could be presented during this talk…

NA61/SHINE – Fixed Target Experiment at CERN SPS



- **Large Acceptance (up to 70%) Spectrometer for charged particles**
- **TPCs as main tracking devices**
- **2 dipole magnets with bending power of max 9 Tm over 7 m length** (2007-Run: 1.14 Tm)
- **New ToF-F to entirely cover T2K acceptance**
- **High momentum resolution:** $\sigma(p)/p^2 \approx 10^{-4}$ (GeV/c)$^{-1}$
- **Good particle identification:** σ(ToF-L/R) ≈ 60 ps, σ(ToF-F) ≤ 120 ps,

  $\sigma(dE/dx)/\langle dE/dx\rangle \approx 0.04$, $\sigma(m_{inv}) \approx 5$ MeV

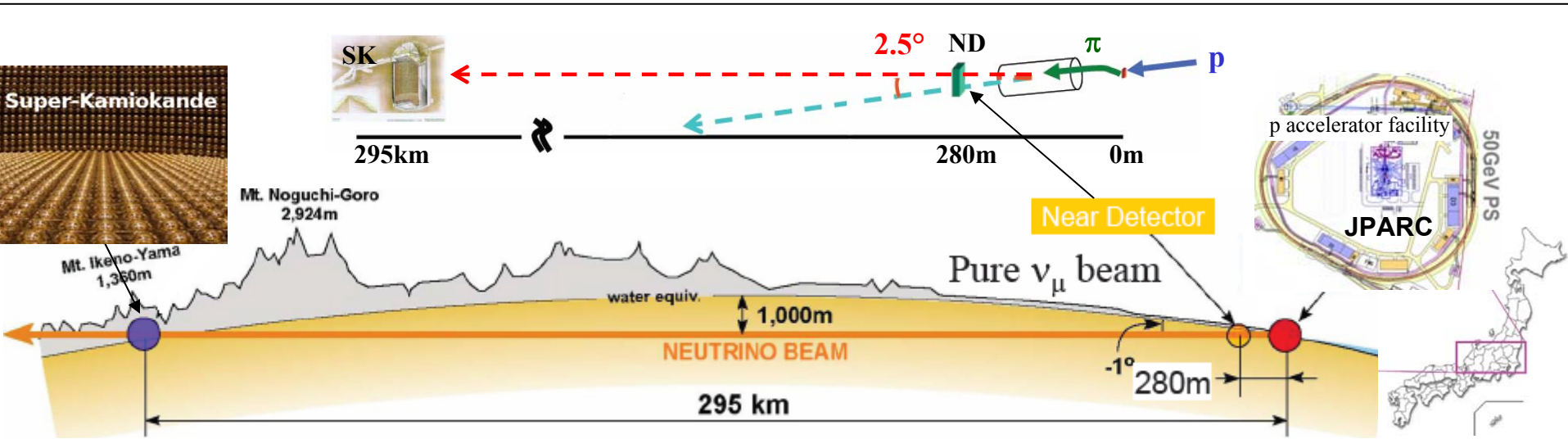
CERN-SPS-2006-034

NA61 : Physics Goals I

- **One of the main physics goals of NA61/SHINE:**

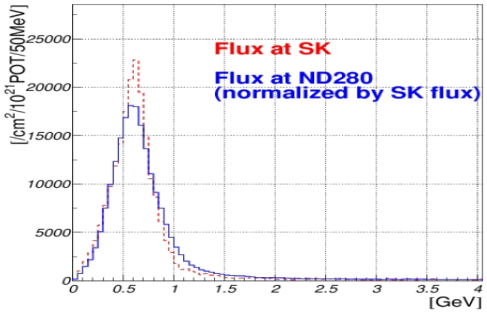
Precision measurements of hadron production for prediction of ν-fluxes in the T2K experiment

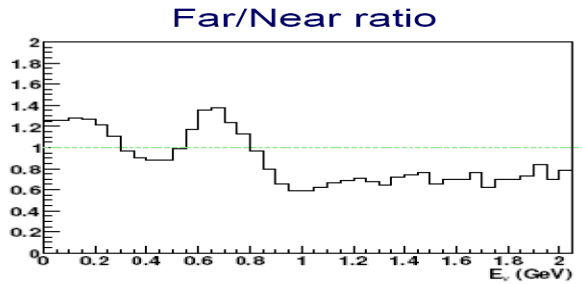
- **T2K @ JPARC (Japan):**
  - **Long baseline (295km) neutrino oscillation experiment**
  - **Protons (30-50GeV) + carbon target (90cm) → intense off-axis ν_μ–beam**
  - **Neutrino spectra measured at the near and far detectors: ND280 and SK**



NA61 : Physics Goals II

- **Main aims of T2K:**
  - o **Search for and measurement of the $\nu_\mu \rightarrow \nu_e$ appearance**
  - » **improved sensitivity to the so far unknown mixing angle θ_{13}**
  - o **Refinement of ν_μ disappearance measurements**
  - » **improved determination of θ_{23} and Δm^2_{23}**





- **Both analyses rely on the comparison of ν spectra measured at SK and the extrapolated spectra at SK from the ND measurement:**

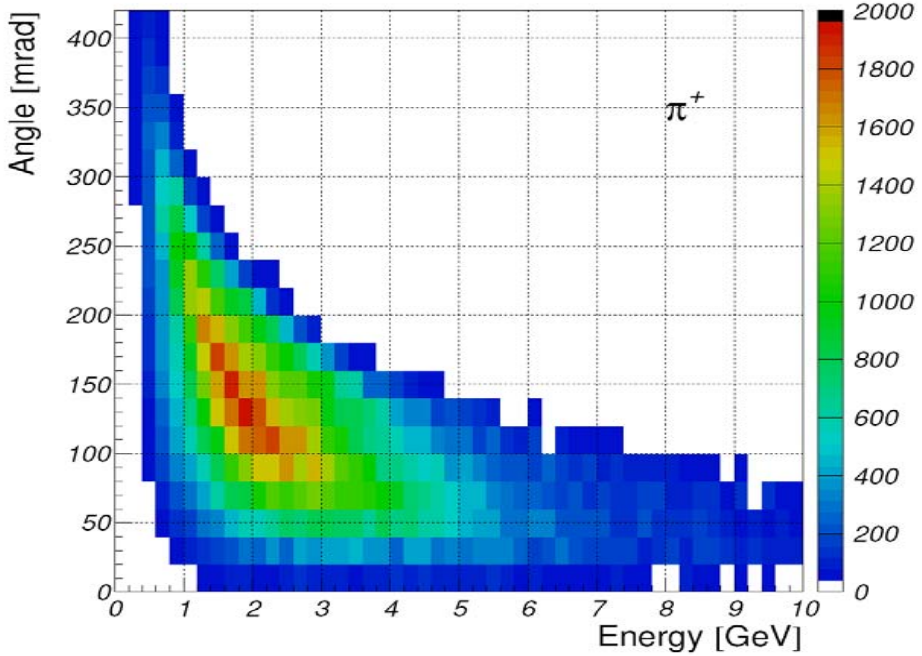
Extrapolated at SK ● $\Phi^{SK}_{\mu,e}(E_\upsilon) = R_{\mu,e}(E_\upsilon) \times \Phi^{ND}_{\mu,e}(E_\upsilon)$ ● Measured at ND

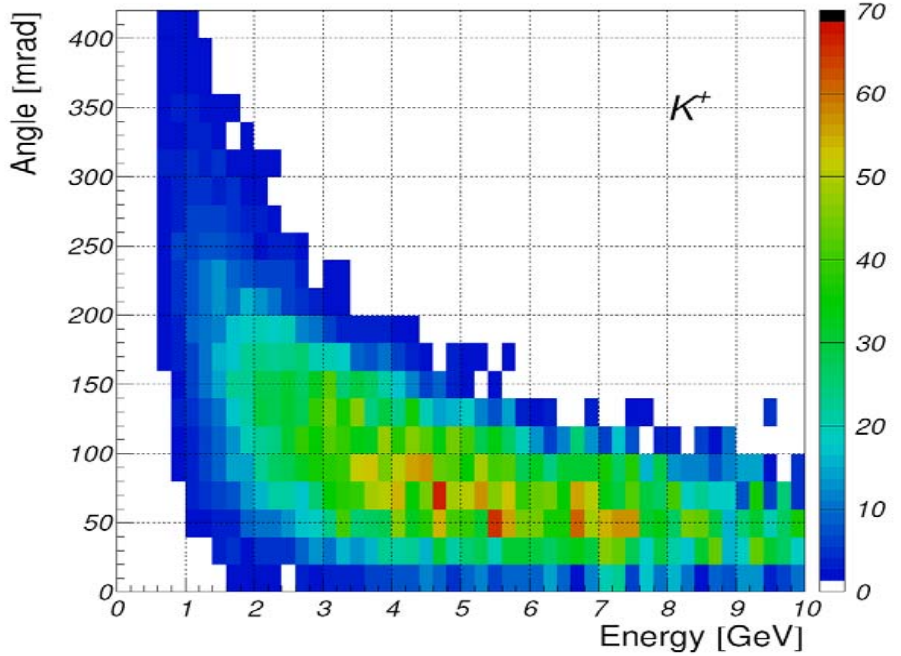
- **Far to Near (F/N) ratio R: is not constant with respect to the ν energy and therefore depends on the particle production properties**

→ To fulfill the T2K goals detailed information on the pion and kaon production off the T2K target is needed!

NA61 : Physics Goals III

Simulated distributions of pions and kaons whose daughter neutrinos pass through the SK





The goal is to reduce the error on the F/N ratio to a negligible level compared to other contributions to the systematics (ND280 spectrum measurements, cross-section, efficiencies, etc.), therefore we aim at: $\delta (R_{\mu,e}) < 3\%$

In order to reach this precision we need ~200k reconstructed π^+ tracks (at the same time we will collect a similar number of π^- since the NA61 acceptance is symmetric)

We also need to measure the K/π ratio with an uncertainty of: $\delta (K/\pi) < 10\%$

NA61 2007 DATA TAKING, CALIBRATION AND ANALYSIS

NA61 experiment was approved in June 2007

2007 run: September 27 – October 29:

- test of the PSD super-module with beams of muons and hadrons,

- optimization of the proton beam at 31 GeV/c, detector setup,

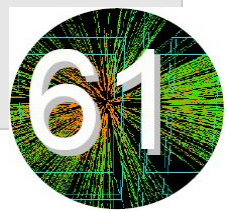
- pilot data taking with 31 GeV/c protons on the thin (2 cm) C target,

- pilot data taking with 31 GeV/c protons on the T2K replica (90cm) C target,

- TPC read-out test with the "FE Tester"

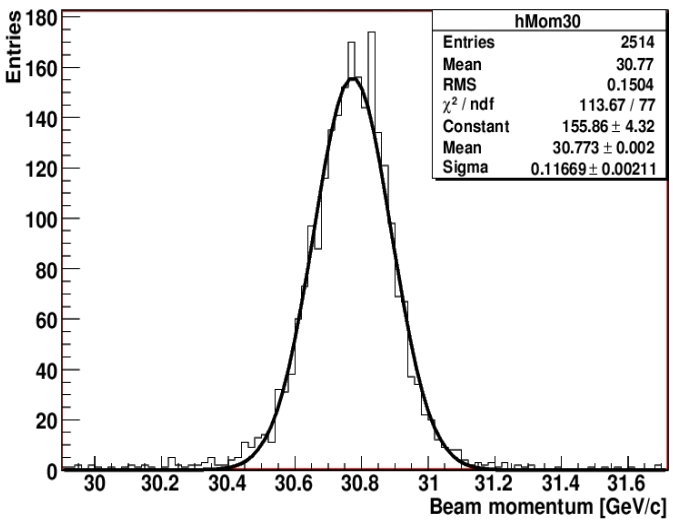
$1.5 \cdot 10^6$ events registered for the NA61 physics programme:

- 640 k events with the thin C target,
- 230 k events with the T2K replica target
- 80 k events without target

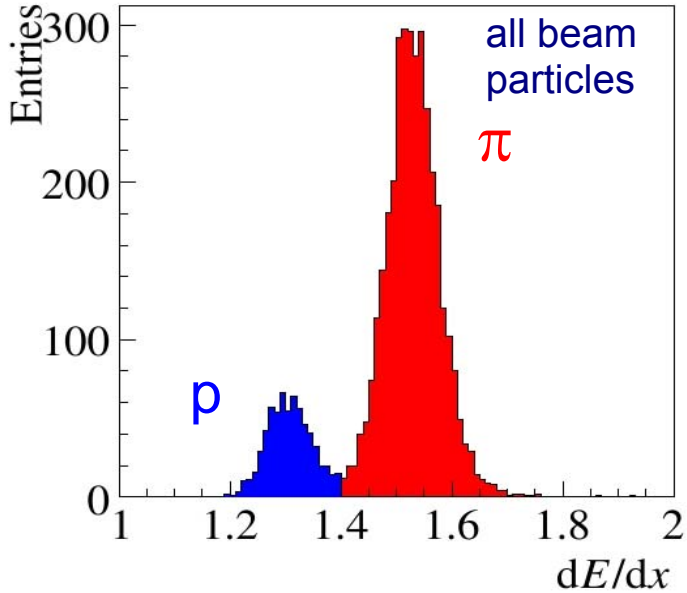


NA61 : BEAM PROPERTIES

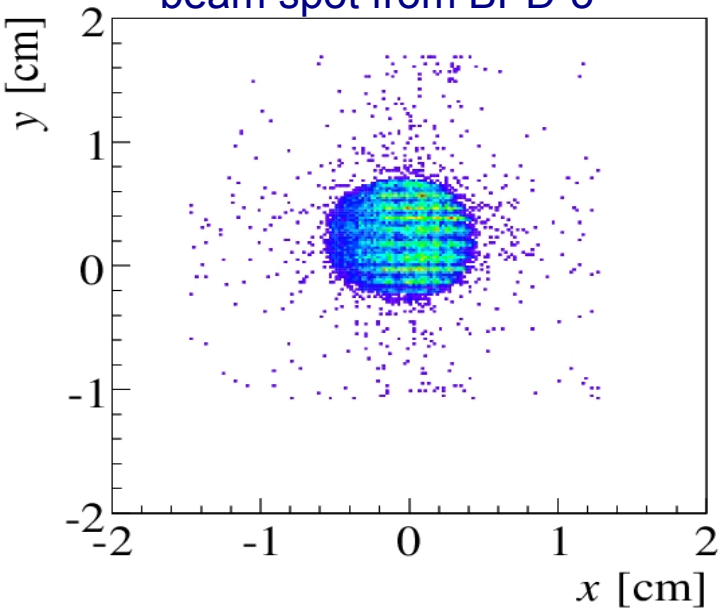
momentum from TPC

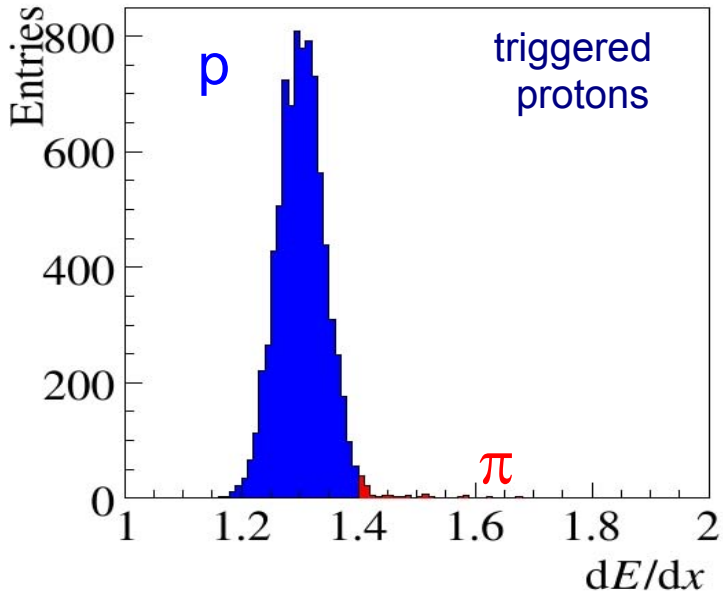


dE/dx from TPC



beam spot from BPD-3





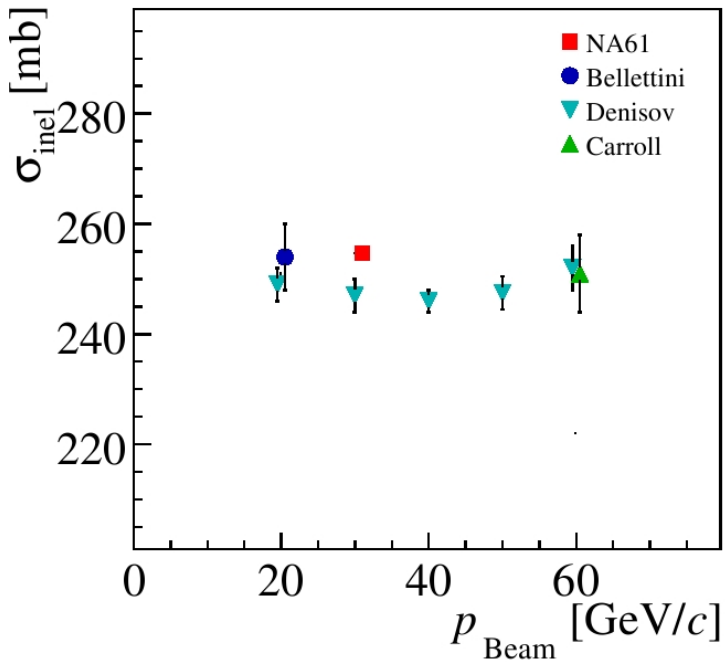
NA61 : INELASTIC p+C CROSS-SECTION AT 31 GeV/c

derived from the measured by NA61 trigger cross section
corrected using GEANT4 simulation for:

-a contribution of elastic interactions due to a large angle scattering,
-a loss of inelastic events when a secondary particle (proton, pion or kaon) hits the S4 counter

σ contribution	value (mb)
$\sigma_{trigger}$	297.5 $\pm$0.7
σ_{loss-p}	5.8 $\pm$0.2
$\sigma_{loss-\pi/K}$	0.6 $\pm$0.06
$\sigma_{elastic}$ contribution	-49.2 $\pm$0.6
σ_{inel}	254.7 $\pm$1.0

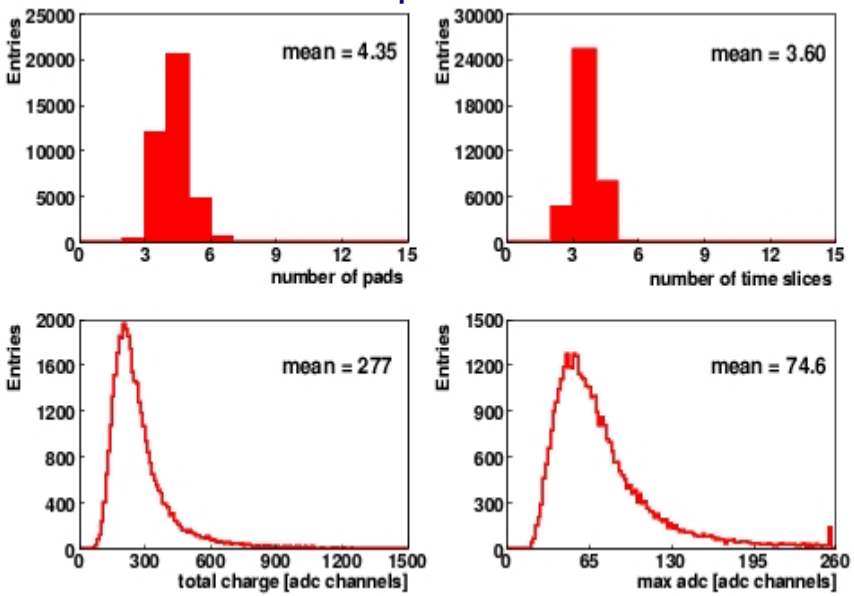
statistical errors only



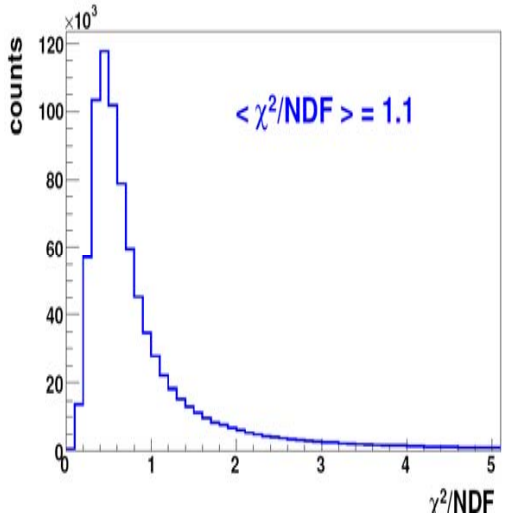
PRELIMINARY

NA61 : TRACKING PERFORMANCE

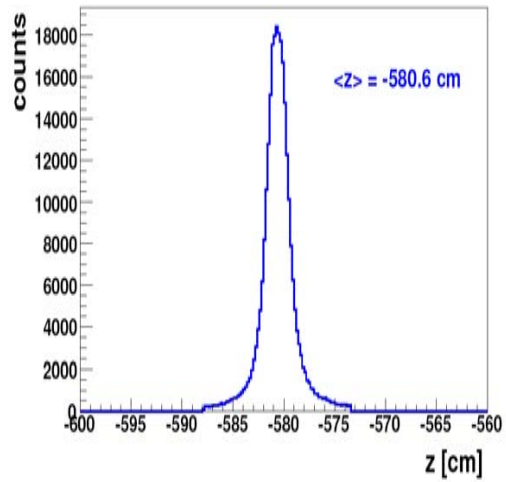
TPC cluster parameters



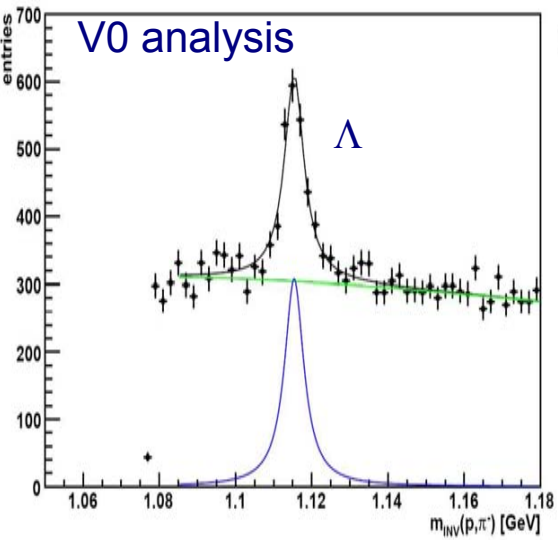
Momentum fit

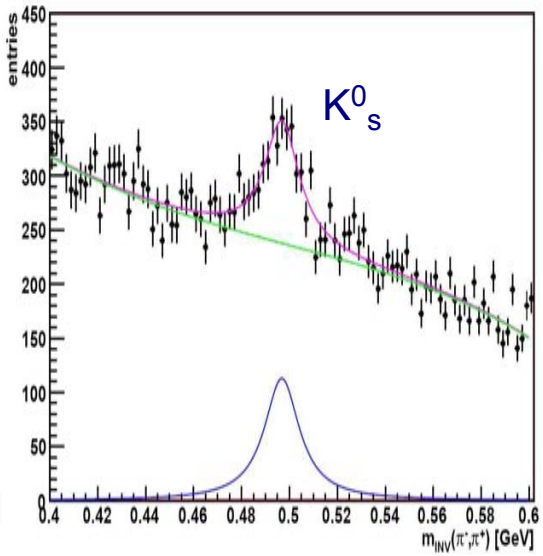


Vertex fit

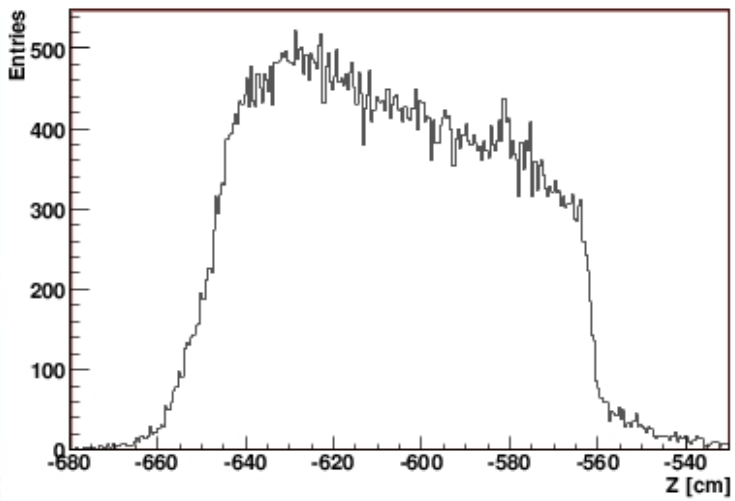


V0 analysis



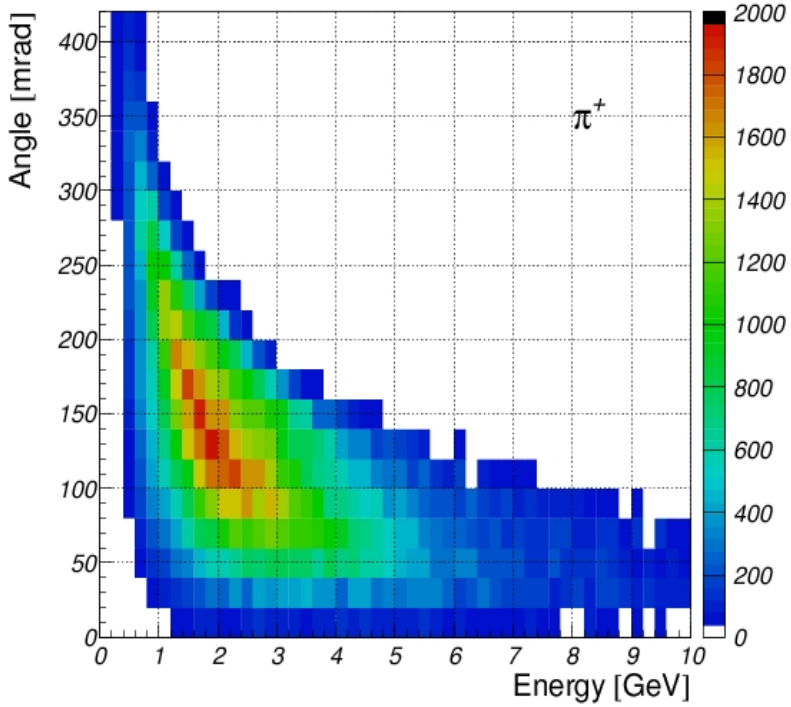


T2K replica vertex fit

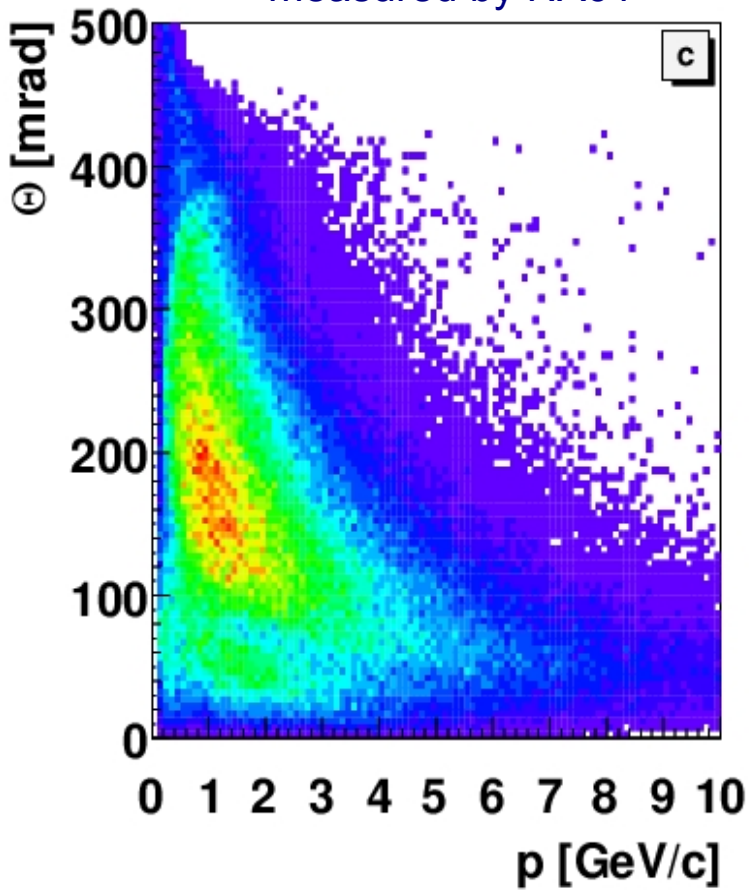


NA61 : NEGATIVELY CHARGED HADRONS

Pions which produce neutrinos measured by Super-Kamiokande

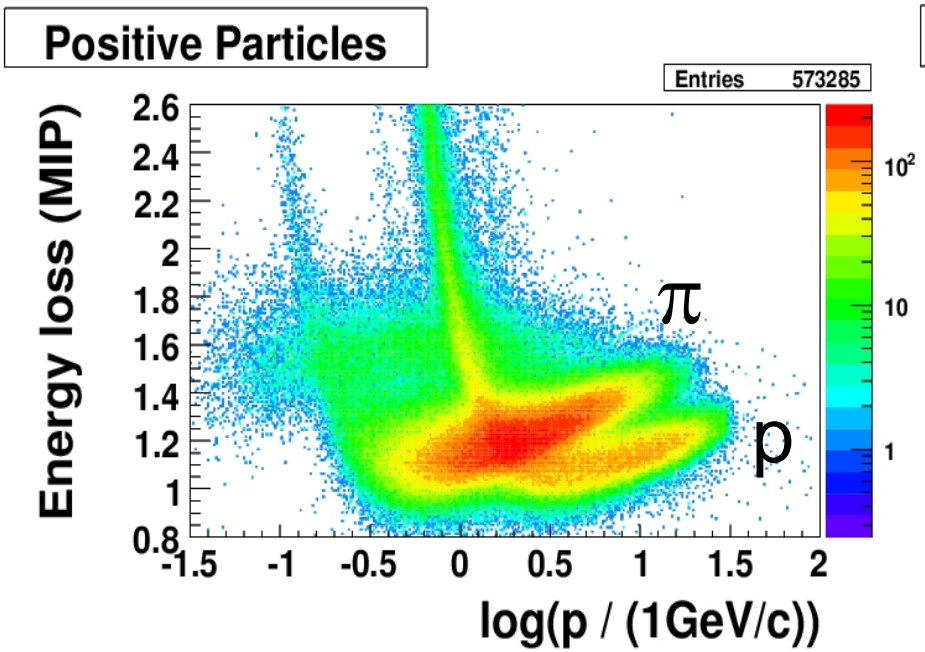


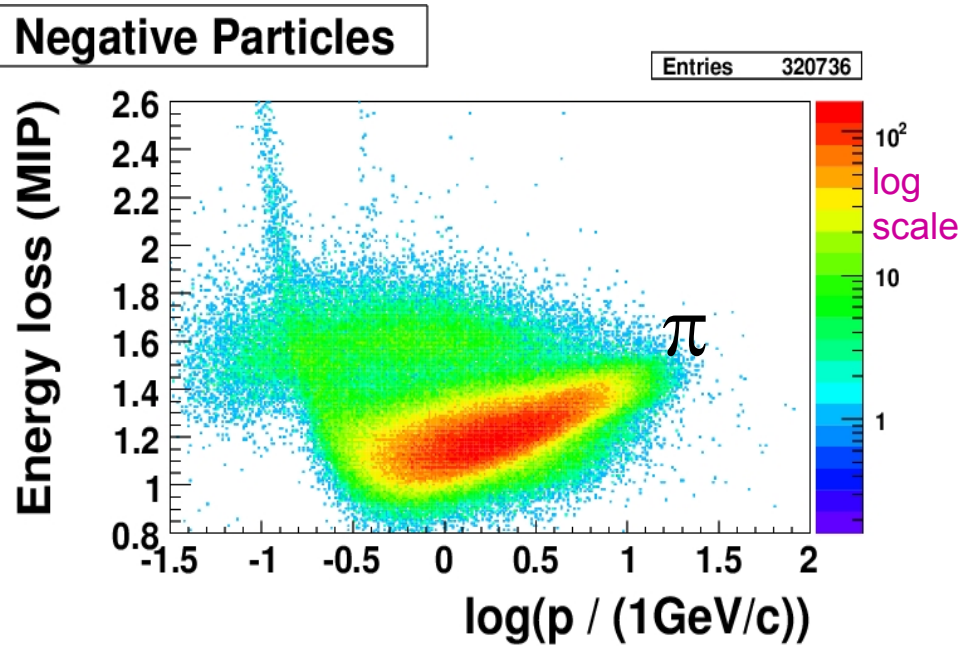
Raw distribution of negatively charged hadrons measured by NA61



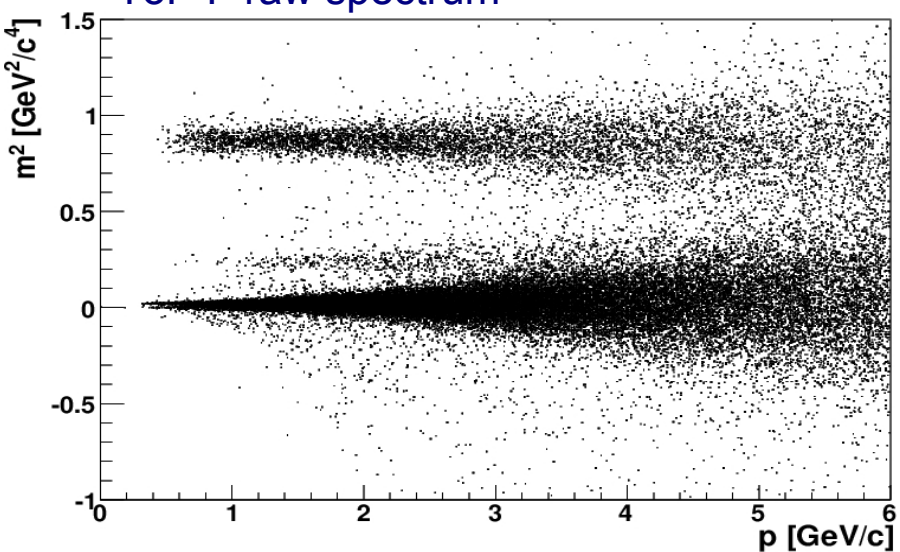
π^- = h^- - small (5%) corrections

NA61 : PID by dE/dx and TOF measurements

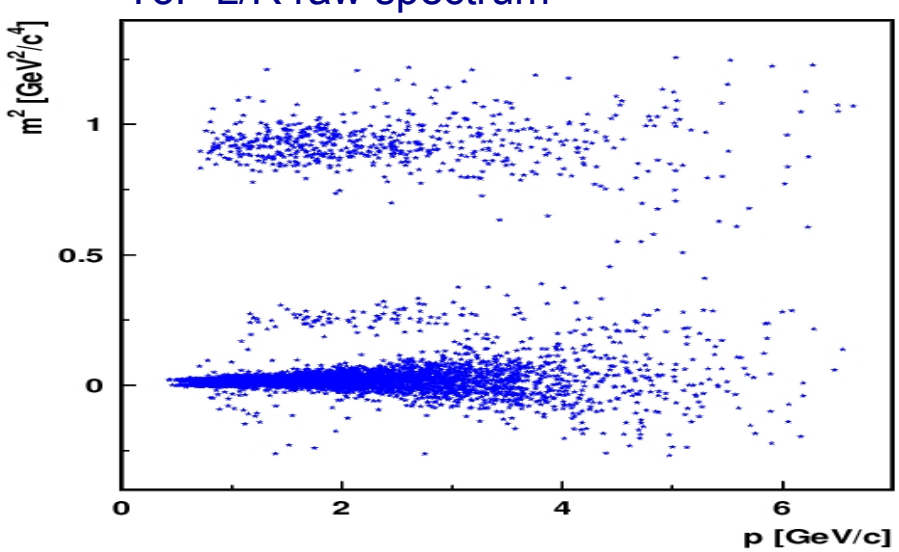




ToF-F raw spectrum

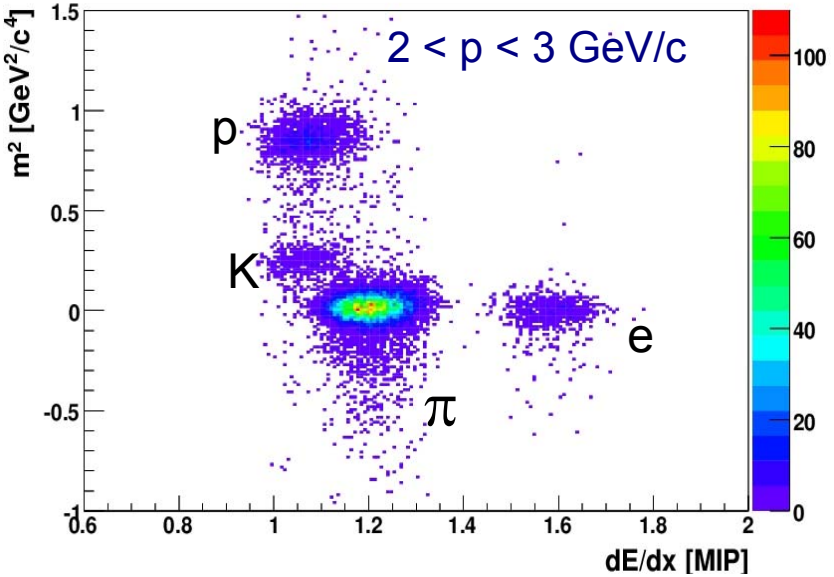


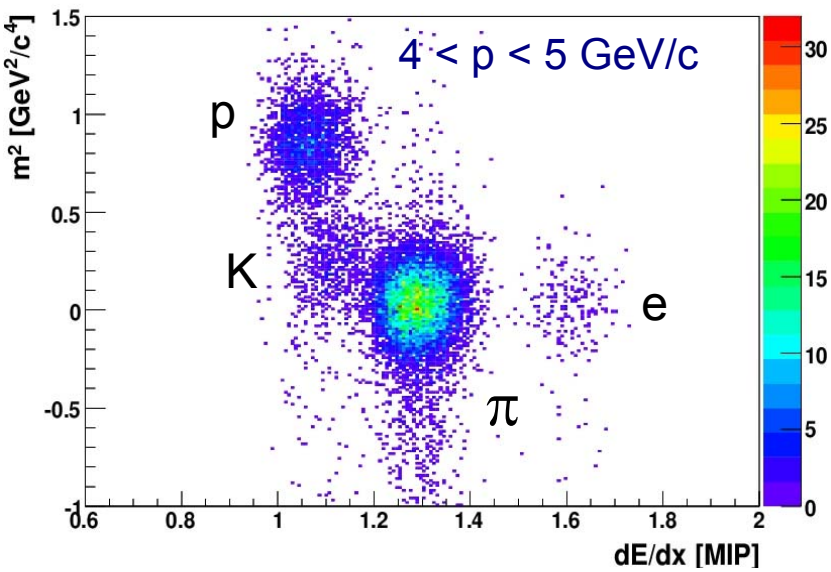
ToF-L/R raw spectrum

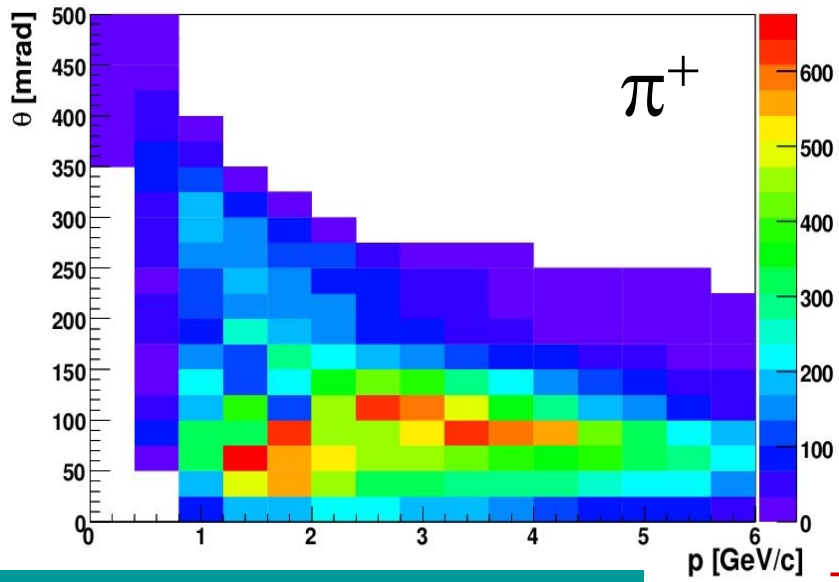


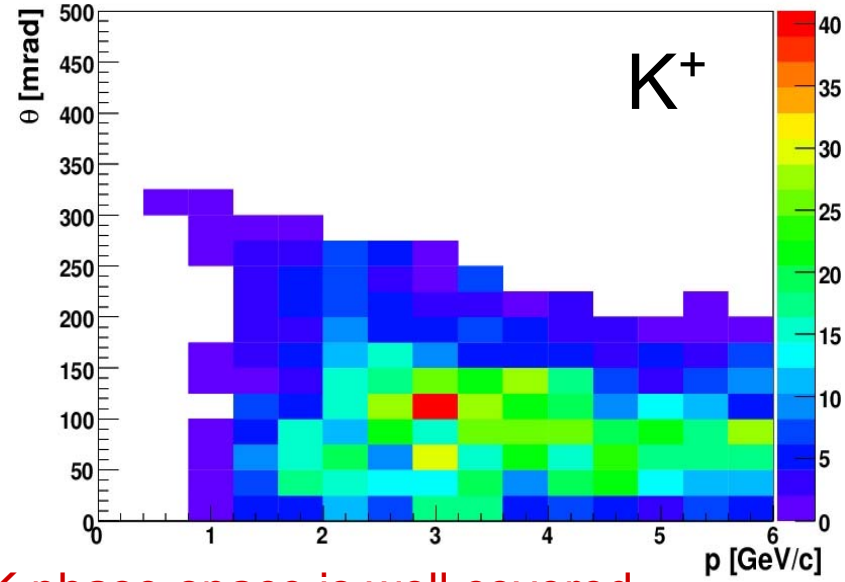
NA61 : PID by combined dE/dx and TOF measurements

ToF-F and TPCs









T2K phase-space is well covered

NA61 : MC SIMULATION AND CORRECTIONS

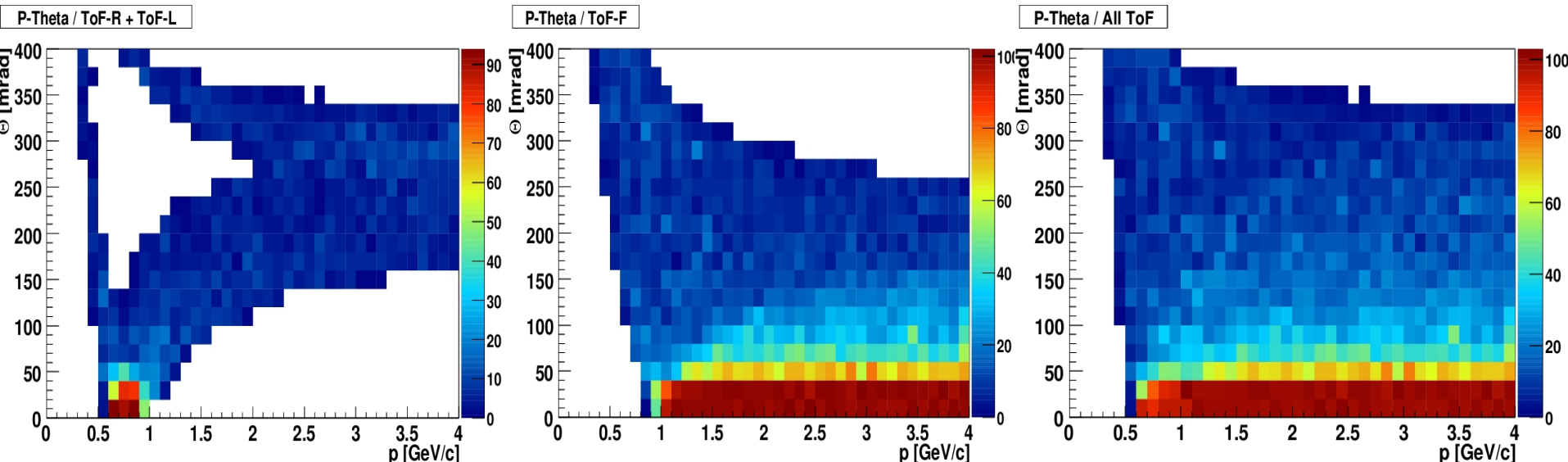
The corrections to the raw spectra are being calculated using the NA61 simulation chain which includes:

-event generation (VENUS, ...),
-particle propagation through the detector (GEANT 3.21),
-distortions and TPC digitization,
-embedding of the simulated raw data to real events,
-reconstruction of the simulated data

Example of acceptance studies: (TOF acceptance)

Old NA49 configuration

New NA61 configuration



NA61 : PLANS FOR THE 2008 RUN

August 28 – September 4: test of the PSD prototype, commissioning of the new beam position detectors,

September 5 – September 25: beam/trigger tunning, installation and commissioning of the TPC read-out and DAQ upgrade,

September 26 – October 30: data taking

TPC read-out and DAQ upgrade:

- crucial for the NA61 physics programme (x10 event rate),
- new TPC read-out electronics and DAQ designed and tested in 2008,
- total cost 400 k CHF,
- the production of the new electronics is almost completed,
- the installation and commissioning is scheduled for September 10-25

A new motherboard (one out of 250)

NA61 : SUMMARY

- NA61 experiment was approved at CERN in June 2007,

- the pilot run was performed during October 2007,

- calibration of all detector components have been performed successfully

- preliminary uncorrected spectra have been obtained,

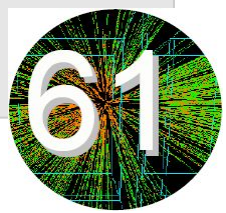
- high quality of track reconstruction and particle identification (similar to NA49) has been achieved,

- a preliminary result on the total inelastic p+C cross section at 31 GeV/c was obtained,

- the data and detailed simulations confirm that the phase-space needed for the T2K measurements is covered,

- first physics results from the 2007 run are expected soon

- the detector is under preparation for the 2008 run !



Thank you for your attention

Backup slides

HARP – PS214 at CERN

24 institutes
~120 collaborators

HARP collaboration

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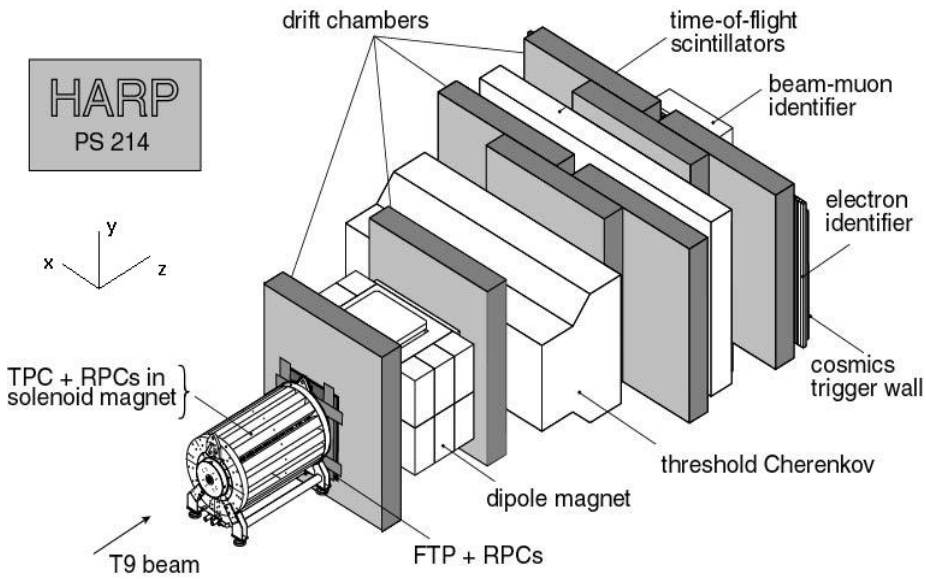
Instituto de Física Corpuscular, IFIC, CSIC and Universidad de Valencia, Spain

forward spectrometer



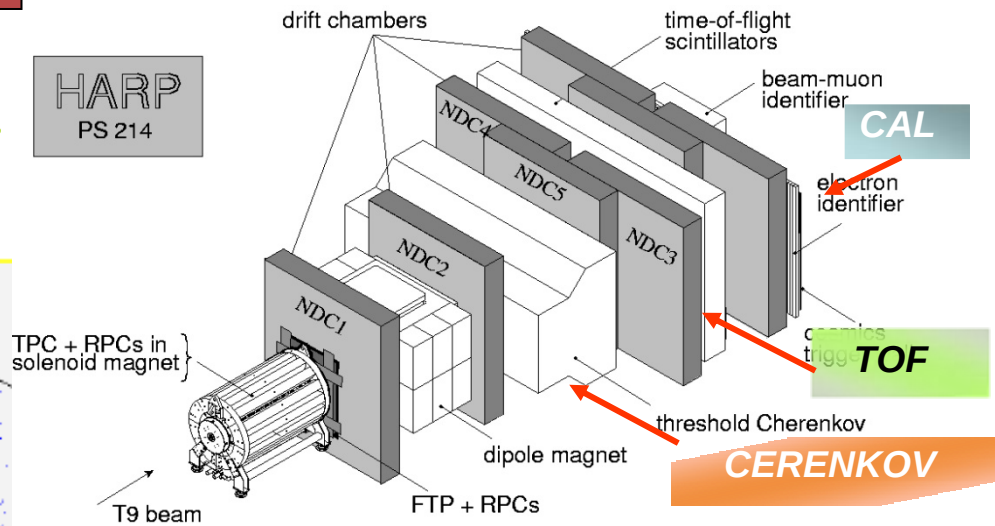
large-angle spectrometer

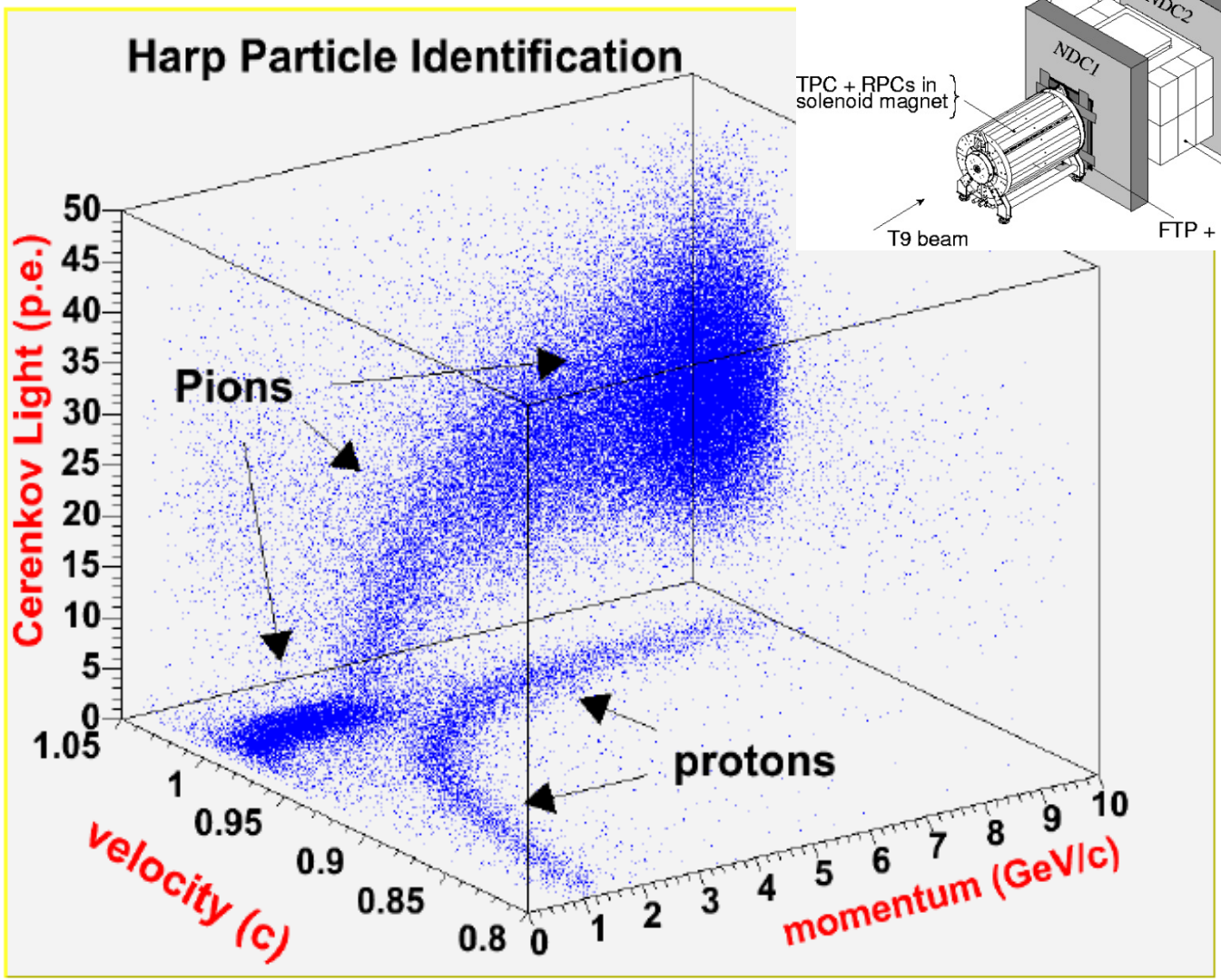
Detailed description of the experimental apparatus

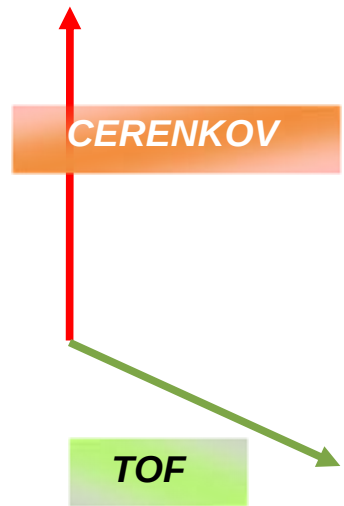
NIM A571 (2007) 524

FW: PID principle

HARP
PS 214

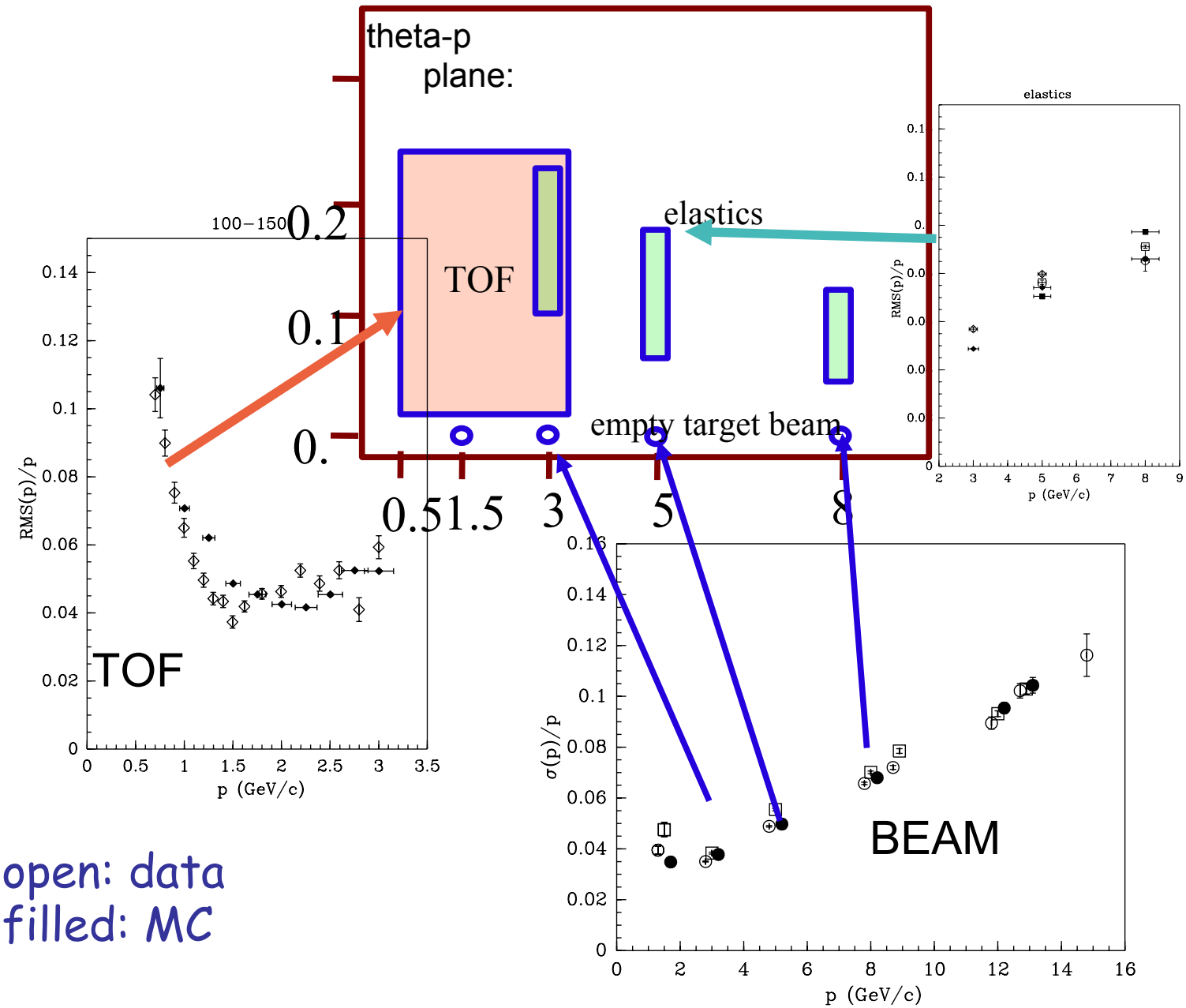






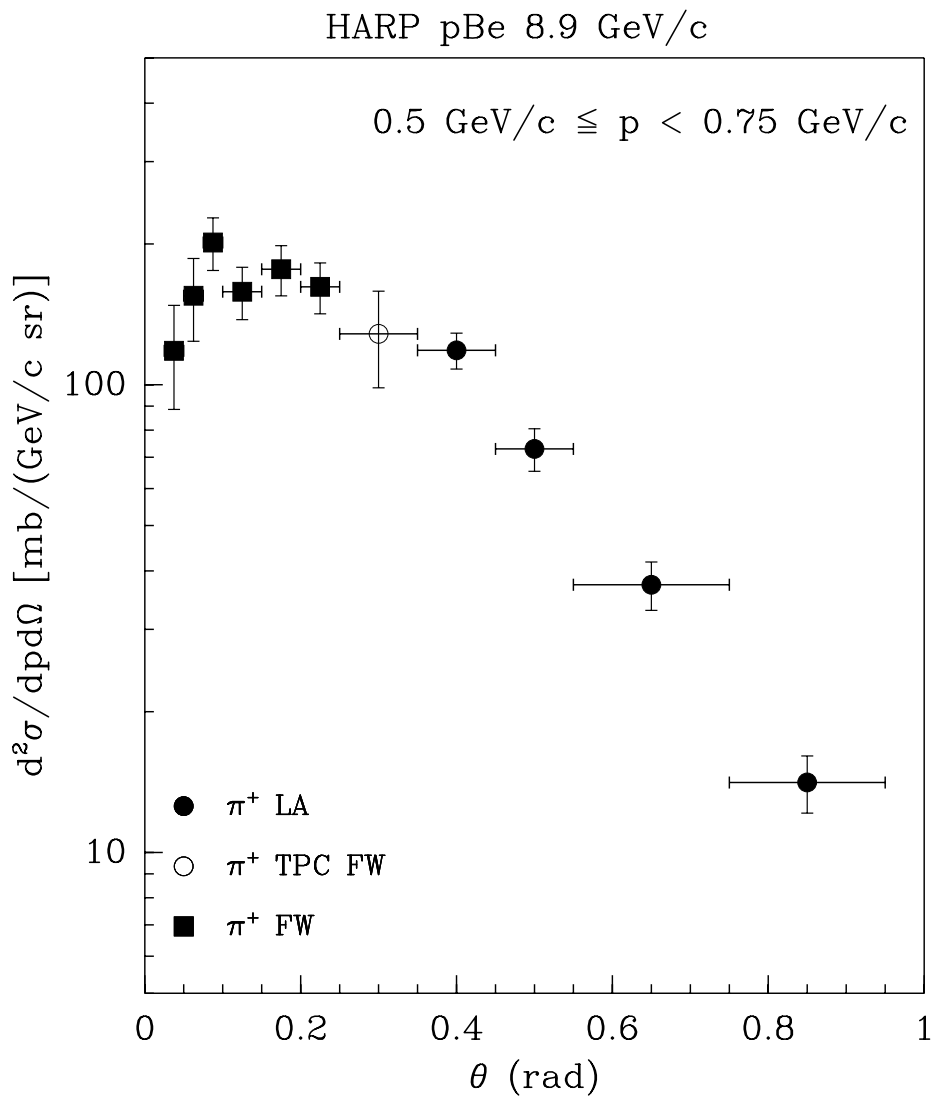
FW: Momentum Resolution

ELASTICS



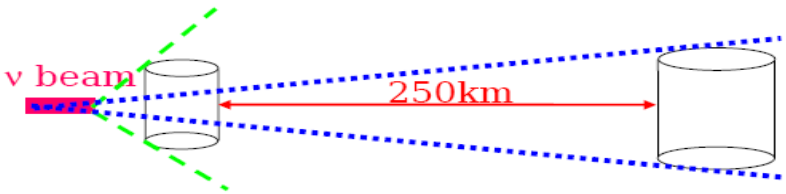
open: data
filled: MC

HARP: two spectrometers match each other

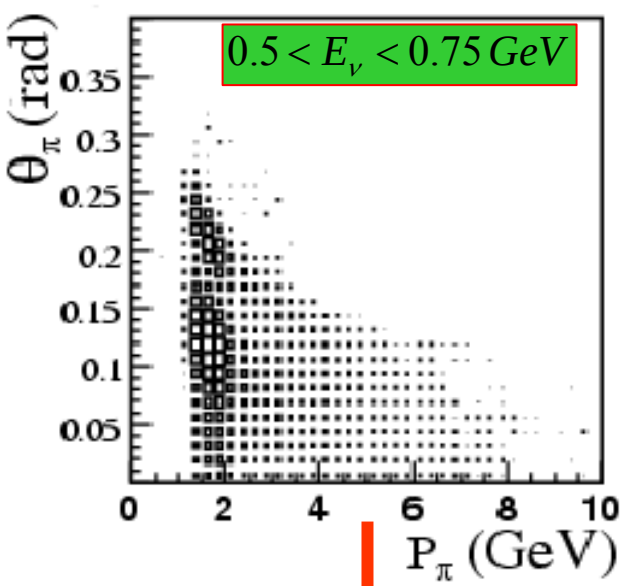


Relevance of HARP for K2K neutrino beam

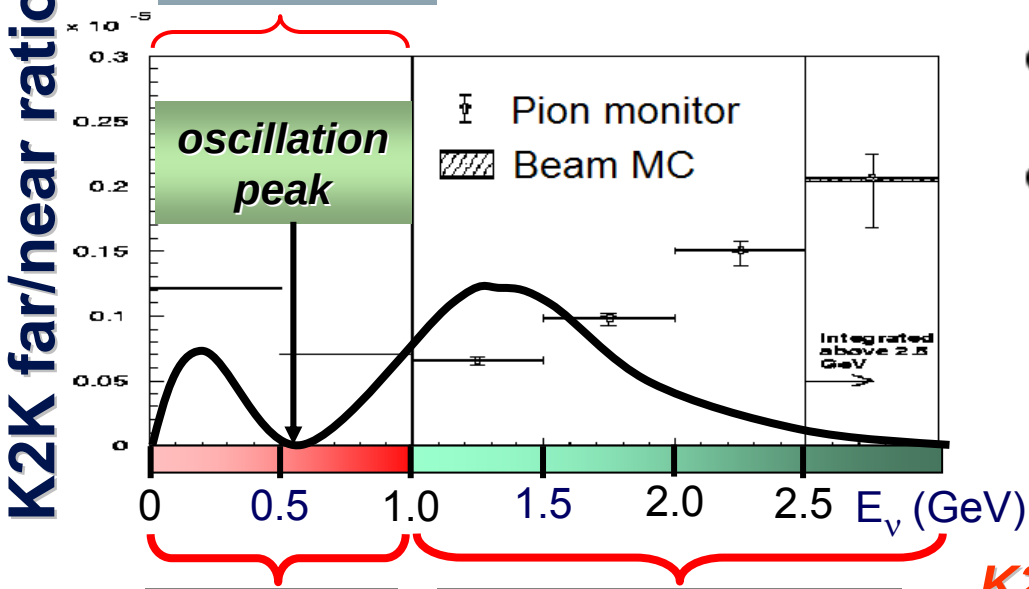
One of the largest K2K systematic errors comes from the uncertainty of the far/near ratio



pions producing neutrinos in the oscillation peak



measured by HARP



Beam MC

Beam MC confirmed by Pion Monitor

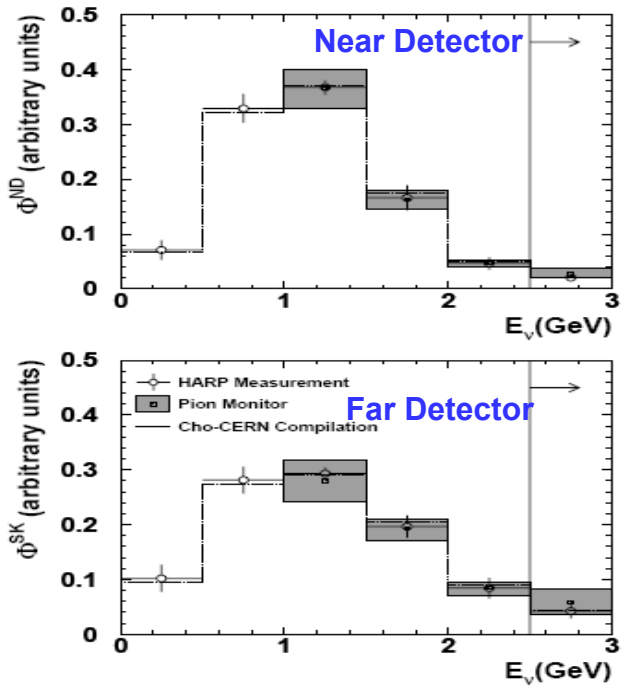
K2K interest

$$P_\pi > 1\,GeV$$

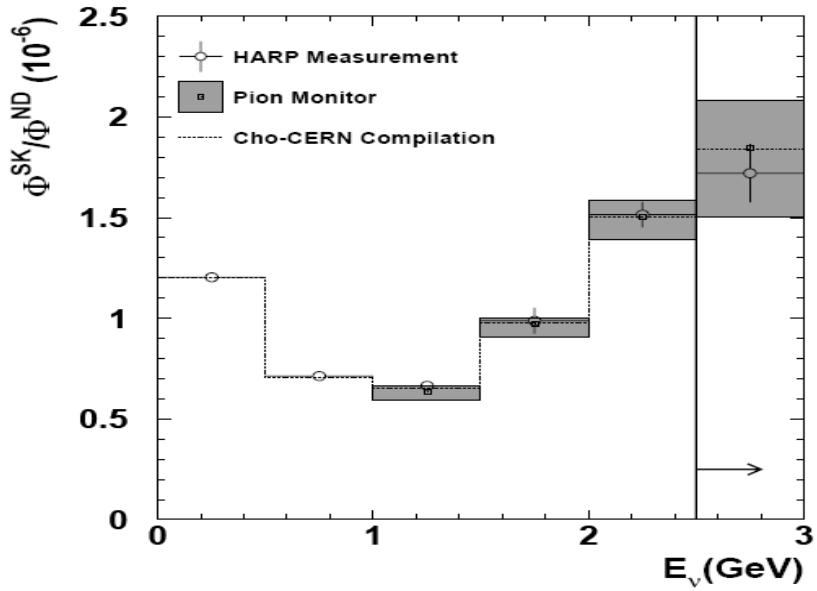
$$\theta_\pi < 250\,mrad$$

Far/Near Ratio in K2K

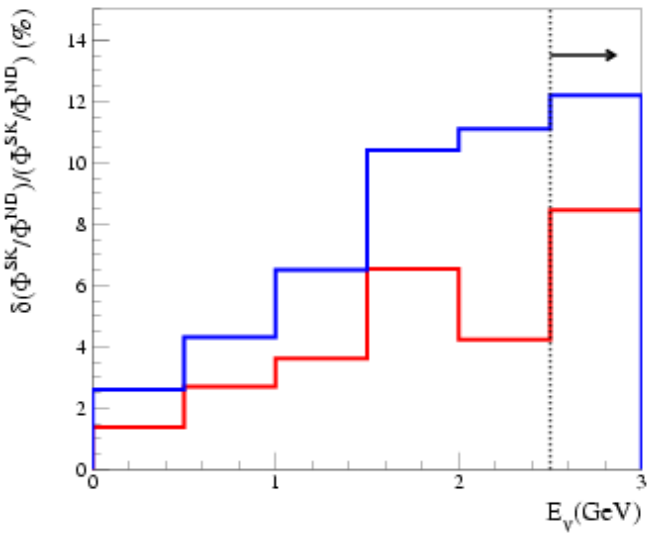
Predicted Flux Shape



Predicted Far/Near Ratio

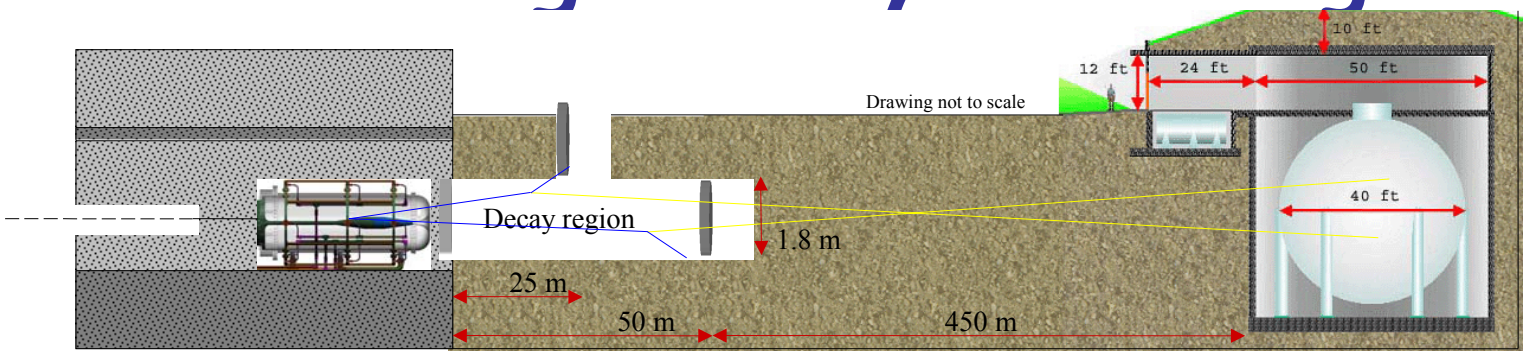


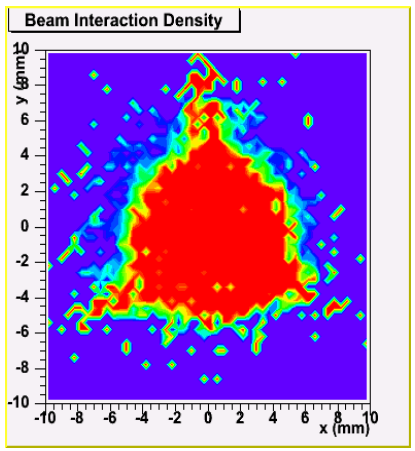
HARP gives ~ factor of 2 error reduction across all energies



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

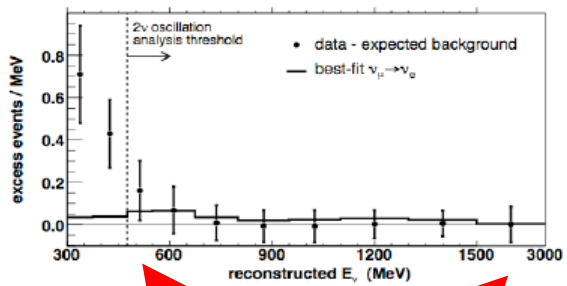
Miniboone: 8.9 GeV p beam hitting a beryllium target





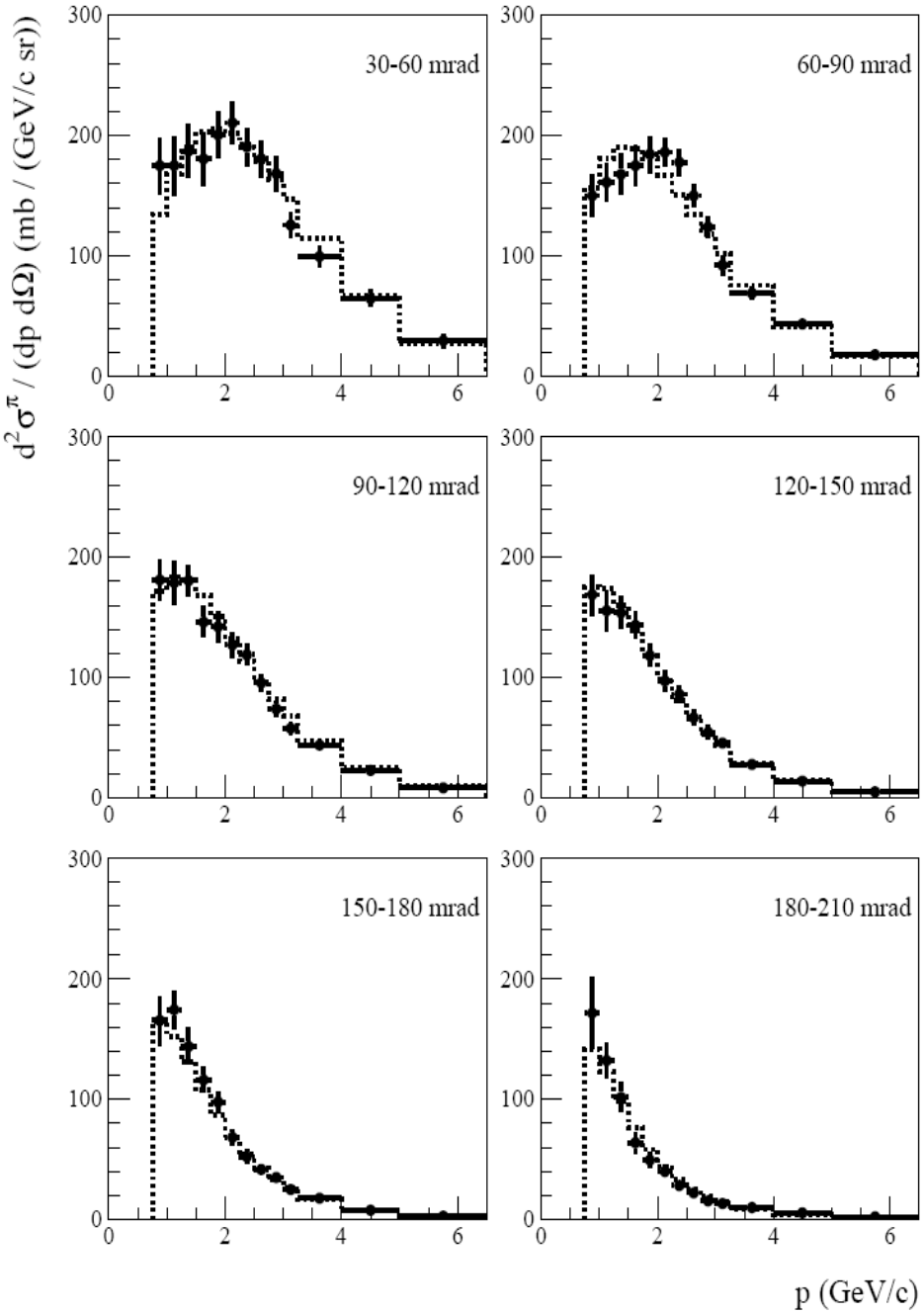
published on EPJc
hep-ex/0702024v2

Within the energy range defined by this oscillation analysis, the event rate is consistent with background.



The observed low energy deviation is under investigation.

The Harp data cover this region



HARP
Be 8.9 GeV/c data
Sanford-Wang parametrization

$$\frac{d^2\sigma(\mathrm{p+A}\rightarrow\pi^+ + X)}{dpd\Omega}(p,\theta) =$$

$$\exp[A]p^{c_2}(1-\frac{p}{p_{\mathrm{beam}}})(1+\frac{p}{p_{\mathrm{beam}}})^{c_9\theta(p-c_7p_{\mathrm{beam}}\cos^{c_8}\theta)}$$

$$A = c_1 - c_3\frac{p^{c_4}}{p_{\mathrm{beam}}^{c_5}} - c_6\theta(p-c_7p_{\mathrm{beam}}\cos^{c_8}\theta)\ ,$$

Parameter	Value
c_1	(5.13 ± 0.41)
c_2	(1.87 ± 0.52)
c_3	(6.67 ± 1.69)
$c_4 = c_5$	(1.56 ± 0.55)
c_6	$(1.19 \pm 0.18) \cdot 10^1$
c_7	$(1.73 \pm 0.31) \cdot 10^{-1}$
c_8	$(1.98 \pm 0.69) \cdot 10^1$
c_9	$(1.60 \pm 0.44) \cdot 10^1$

p-C π^-

LONG C TARGET

Preliminary

forward

$0.35 < \theta < 1.55$

---

backward

$1.55 < \theta < 2.15$

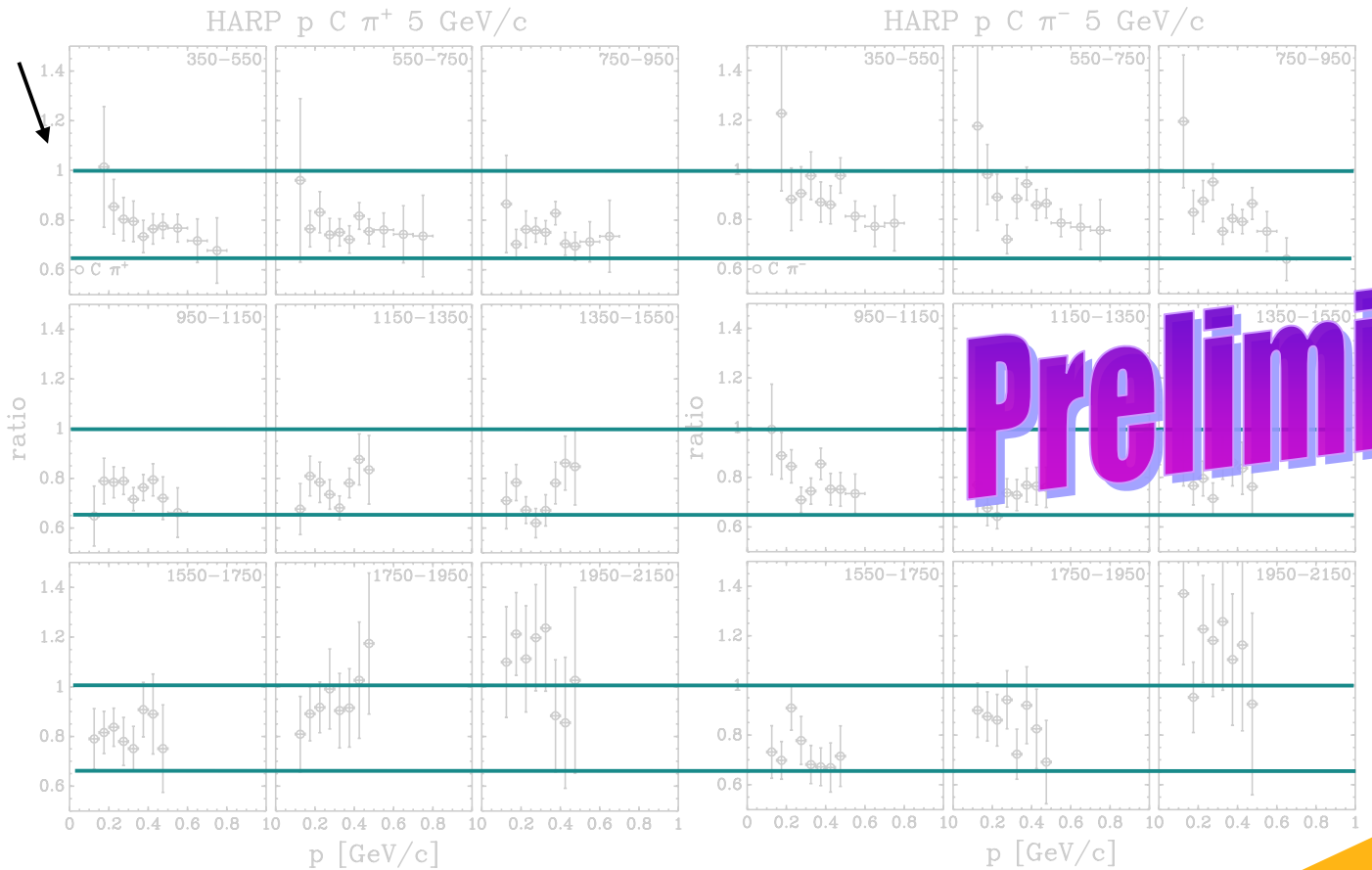
100% / 5% TARGET

bin-by-bin ratio
5 GeV/c beam: p-C $\pi^{+/-}$

Large corrections !

If no effect from absorption of p: expect ratio = 1

If all interacting p are lost: expect ratio = 0.65



Preliminary

π^+

π^-

PRELIMINARY

HARP: p-Be

Corrections for dynamic distortions

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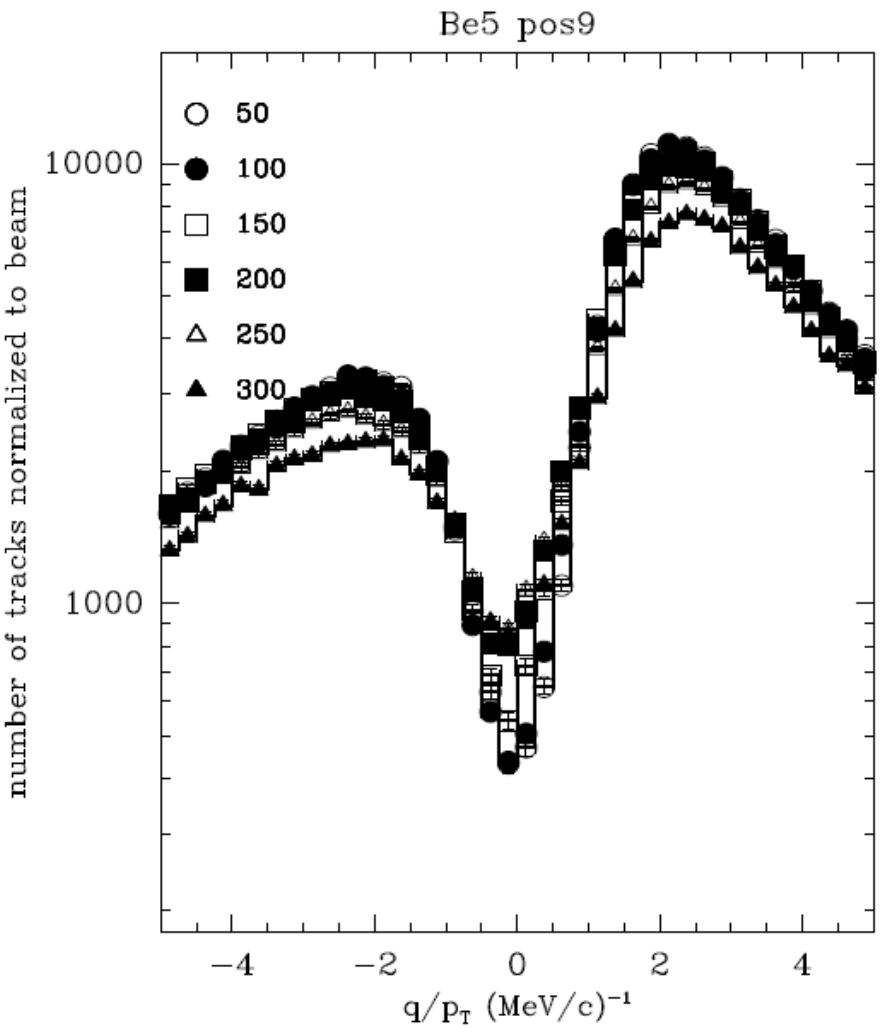
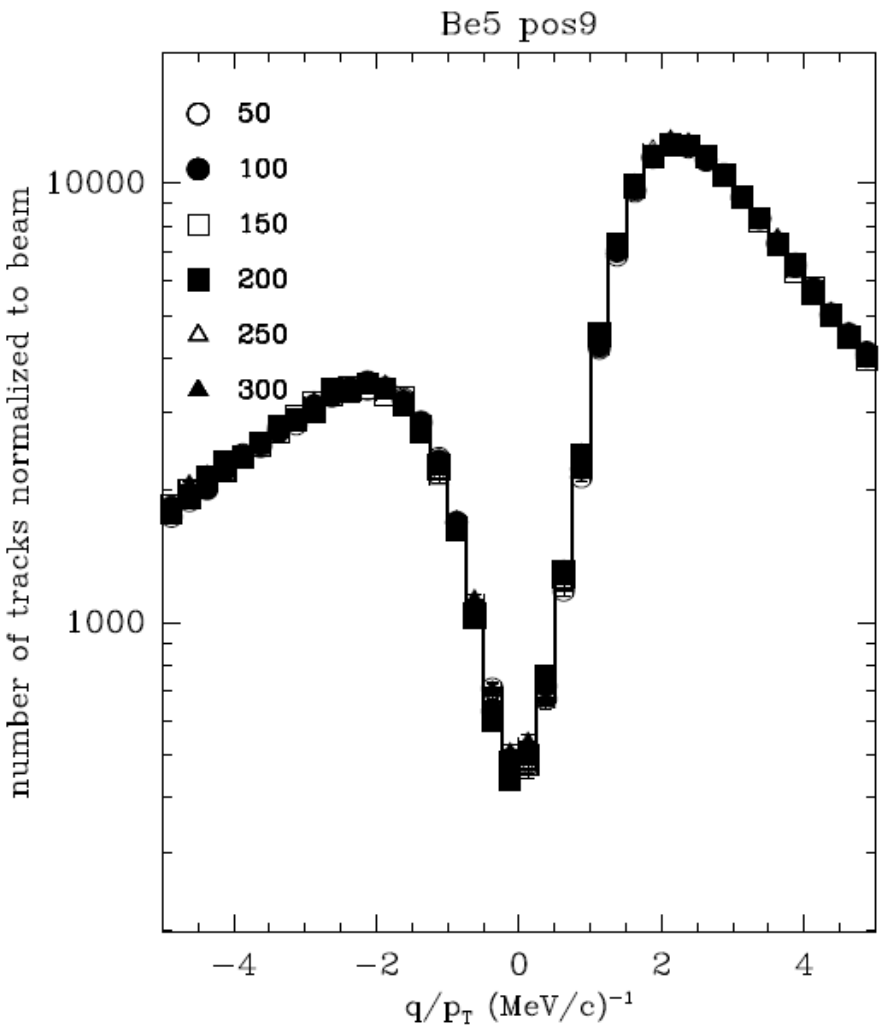
before



after



HARP: p-Be

Corrections for dynamic distortions: ratio of the cross-sections without and with corrections

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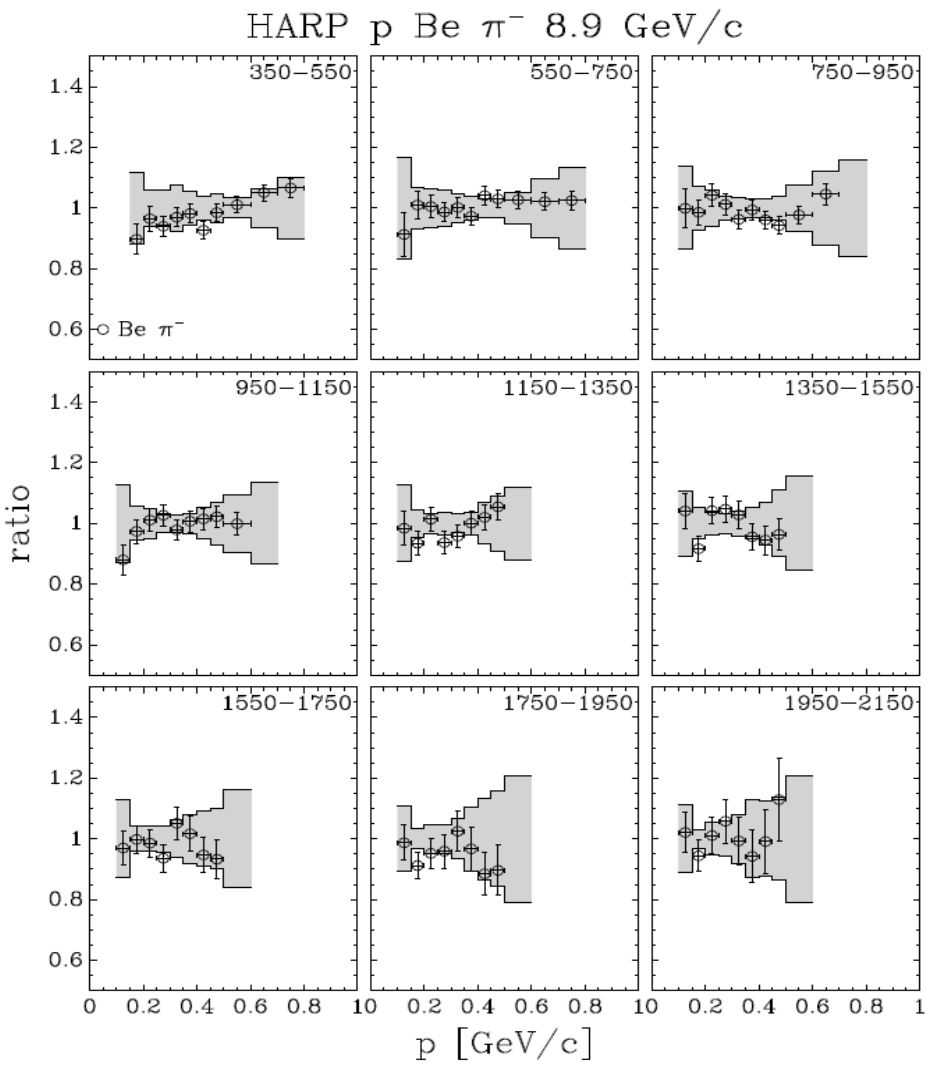
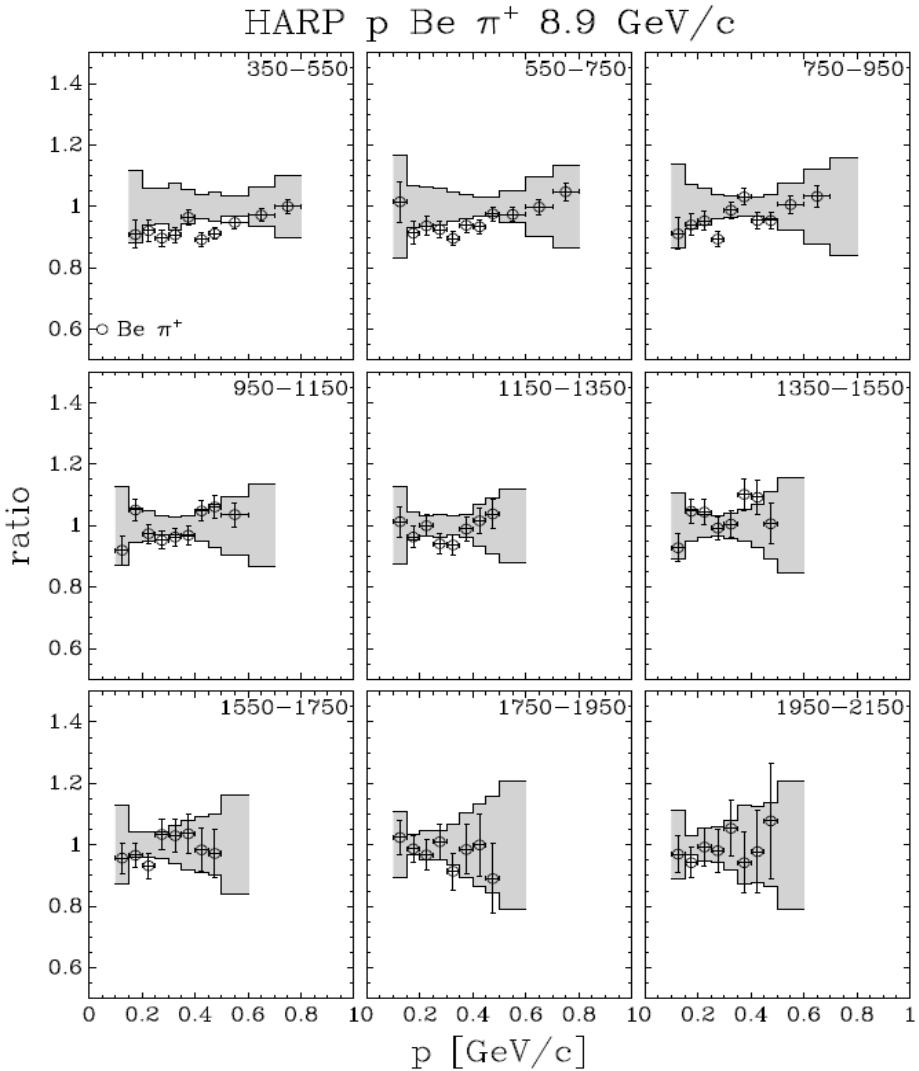
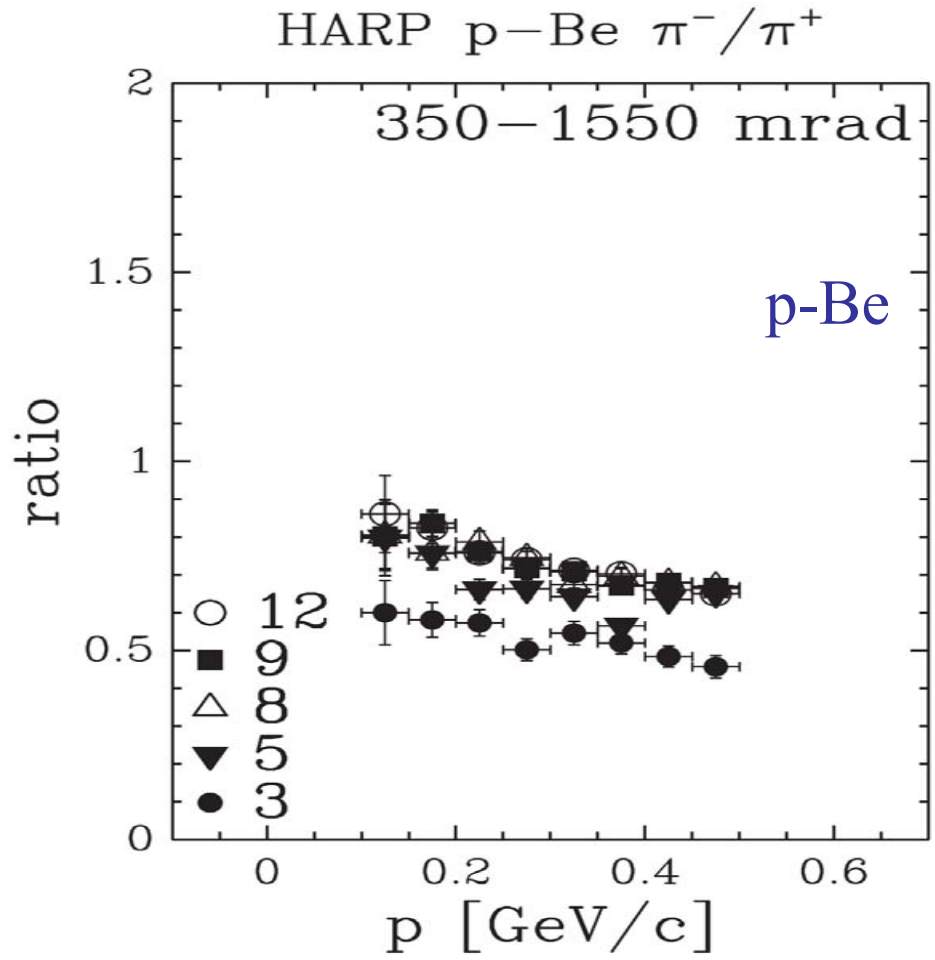


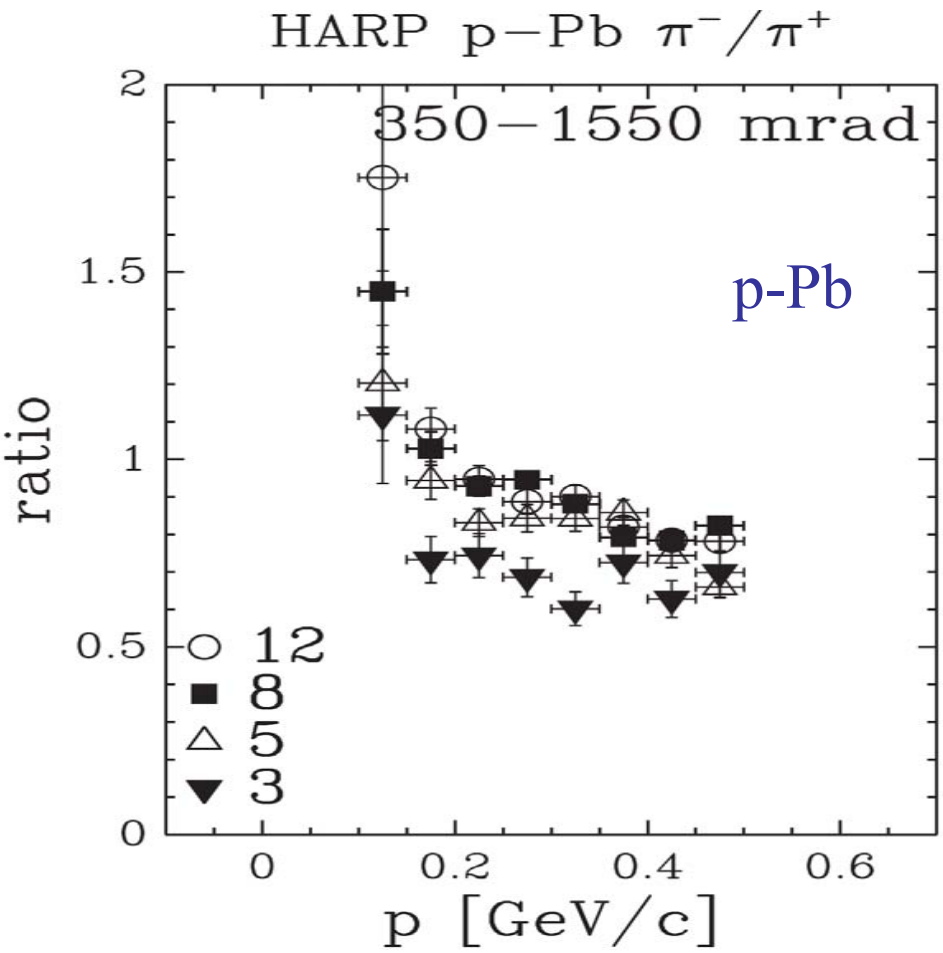


HARP: pion yields

comparison of π^-/π^+ ratio for light and heavy nuclei

forward production only $350 < \theta(\text{mrad}) < 1550$





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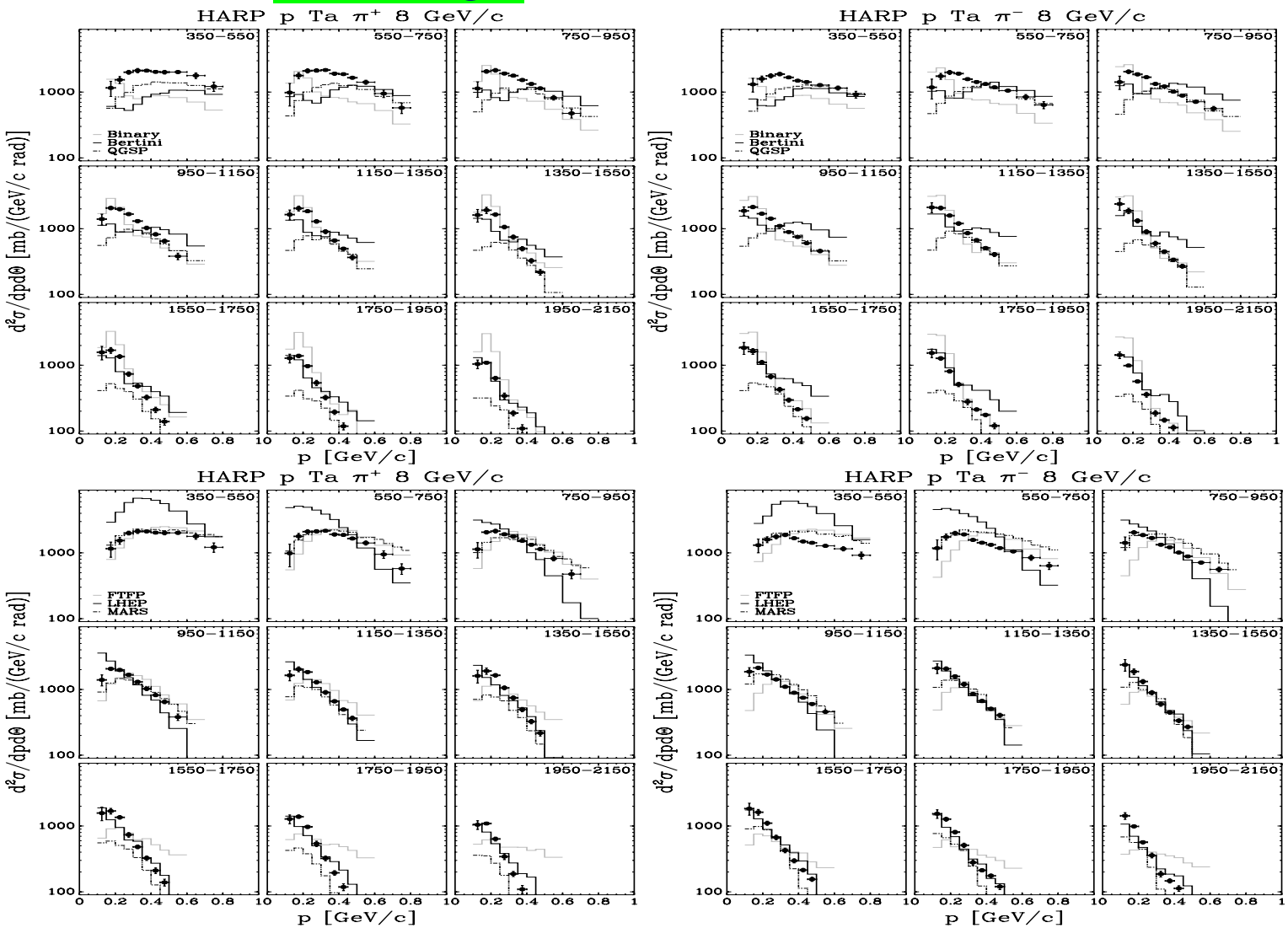
8 GeV/c p-Ta $\pi^{+/-}$

5% λ target

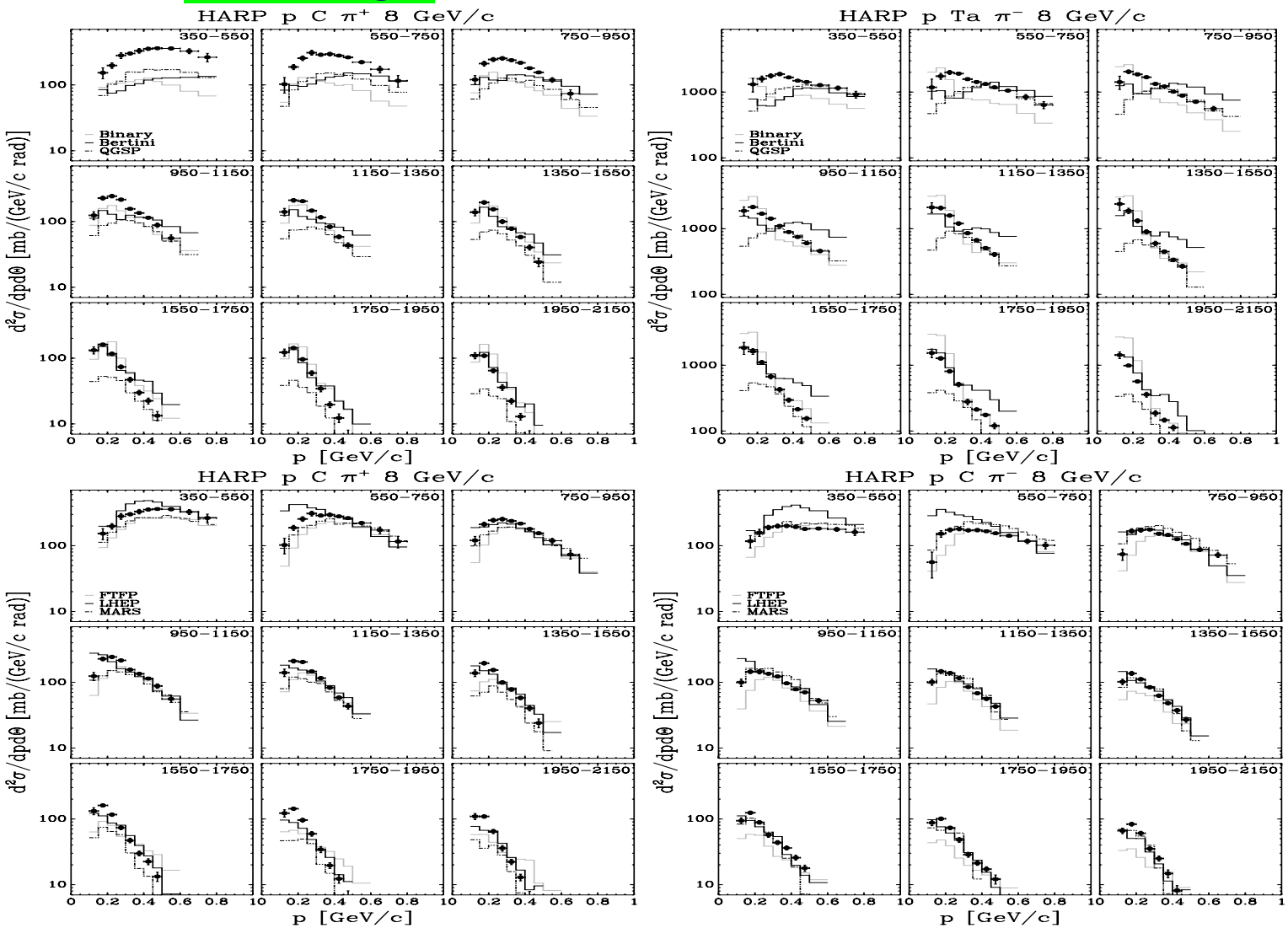
MODELS



8 GeV/c p-C $\pi^{+/-}$

5% λ target

MODELS



HARP: comparison with MC at LA

1. **Data available on many thin (5%) targets from light nuclei (Be) to heavy ones (Ta,Pb)**
2. **Comparisons with GEANT4 and MARS15 MonteCarlo show large discrepancies both in normalization and shape**
   - **Backward or central region production seems described better than more forward production**
   - **At higher energies FTP models (from GEANT4) and MARS look better, at lower energies this is true for Bertini and binary cascade models (from GEANT4)**
   - **In general π^+ production is better described than π^- production**
   - **Parametrized models (such as LHEP) have big discrepancies**

– **CONCLUSIONS: MCs need tuning with HARP data for $p_{inc} < 15$ GeV/c**

NA61 : PHYSICS GOALS

Physics of strongly interacting matter

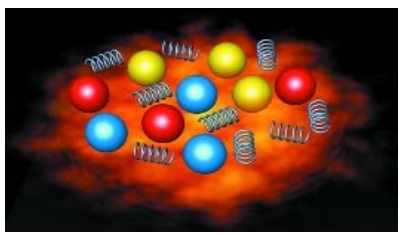
Discovery potential:

Search for the critical point of strongly interacting matter

Precision measurements:

Study the properties of the onset of deconfinement in nucleus-nucleus collisions

Measure hadron production at high transverse momenta in p+p and p+Pb collisions as reference for Pb+Pb results



Data for neutrino and cosmic ray experiments

Precision measurements:

Measure hadron production in the T2K target needed for the T2K (neutrino) physics

Measure hadron production in p+C interactions needed for T2K and cosmic-ray, Pierre Auger Observatory and KASCADE, experiments

NA61 : COLLABORATION

121 physicists from 24 institutes and 14 countries:

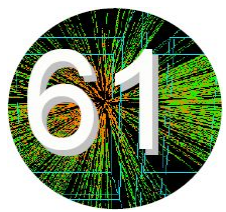
University of Athens, Athens, Greece
University of Bergen, Bergen, Norway
University of Bern, Bern, Switzerland
KFKI IPNP, Budapest, Hungary
Cape Town University, Cape Town, South Africa
Jagiellonian University, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
Fachhochschule Frankfurt, Frankfurt, Germany
University of Frankfurt, Frankfurt, Germany
University of Geneva, Geneva, Switzerland
Forschungszentrum Karlsruhe, Karlsruhe, Germany
Swietokrzyska Academy, Kielce, Poland
Institute for Nuclear Research, Moscow, Russia
LPNHE, Universites de Paris VI et VII, Paris, France
Pusan National University, Pusan, Republic of Korea
Faculty of Physics, University of Sofia, Sofia, Bulgaria
St. Petersburg State University, St. Petersburg, Russia
State University of New York, Stony Brook, USA
KEK, Tsukuba, Japan
Soltan Institute for Nuclear Studies, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
University of Warsaw, Warsaw, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
ETH Zurich, Zurich, Switzerland

NA61 : DOCUMENTS AND REFERENCES

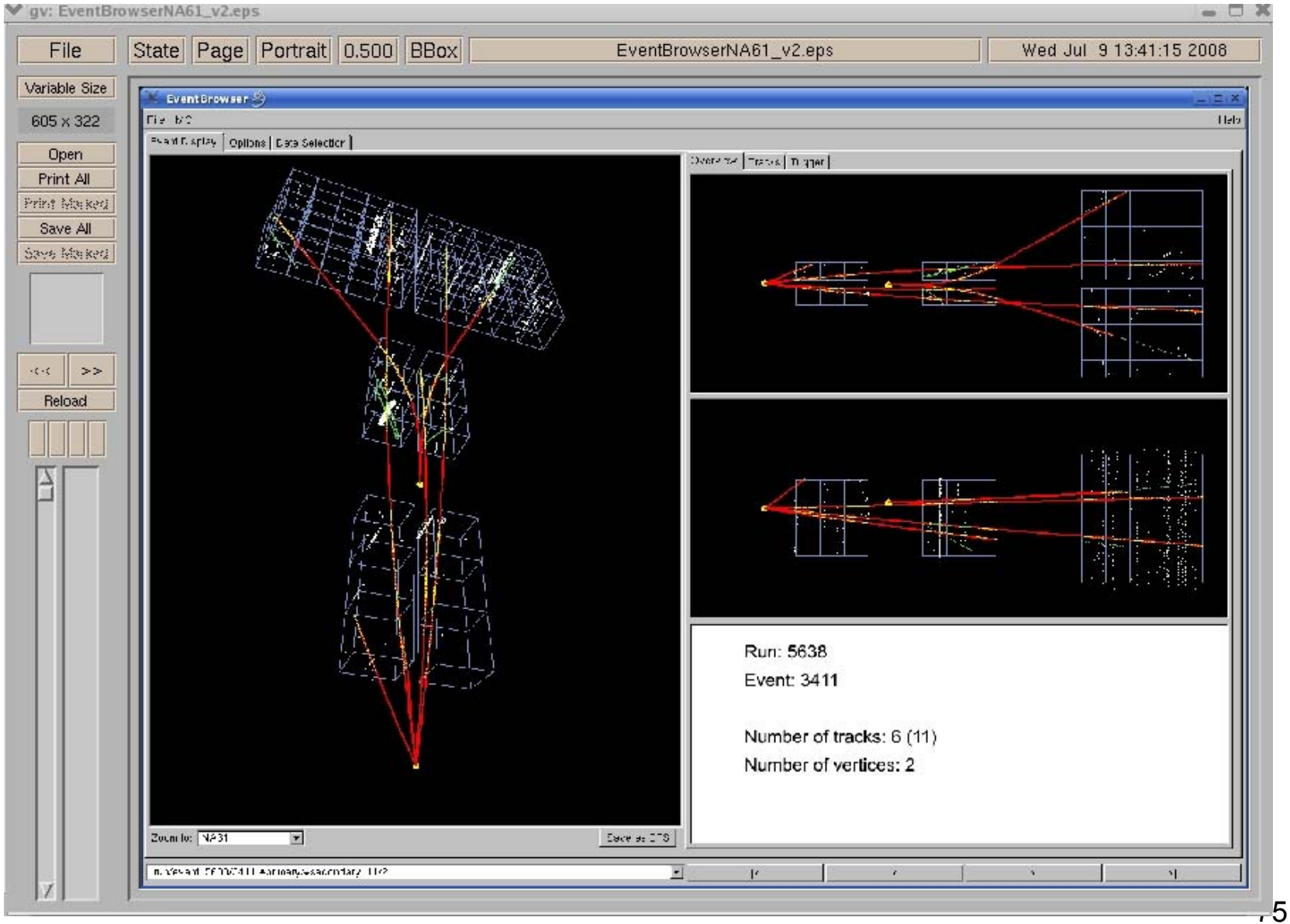
Status Report: *CERN-SPSC-2008-018, SPSC-SR-033 (July 2, 2008)*

Addendum-3	*CERN-SPSC-2007-033, SPSC-P-330 (November 16, 2007)*
Addendum-2:	*CERN-SPSC-2007-019, SPSC-P-330 (June 15, 2007)*
Addendum-1:	*CERN-SPSC-2007-004, SPSC-P-330 (January 25, 2007)*
Proposal:	*CERN-SPSC-2006-034, SPSC-P-330 (November 3, 2006)*
Status Report:	*CERN-SPSC-2006-023, SPSC-SR-010 (September 5, 2006)*
LoI:	*CERN-SPSC-2006-001, SPSC-I-235 (January 6, 2006)*
EoI:	*CERN-SPSC-2003-031, SPSC-EOI-001 (November 21, 2003)*

Report from the NA61/SHINE experiment at the CERN SPS, CERN-OPEN-2008-012
Na61/Shine at the CERN SPS, CPOD 2007, arXiv:0709.1867



-event visualization of data after different stages of reconstruction
and in different formats



NA61 : 2007 PILOT RUN