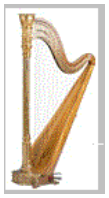


HARP collaboration results on the proton-nuclei interactions at a few GeV energies

HARP : ***A fixed-target experiment at the CERN Proton Synchrotron*** *(2000-2002)* **aimed at measurement of hadron production cross-sections for**:

Neutrino Factory
Atmospheric Neutrino Flux
Accelerator Neutrino Beams
Hadron Production Models

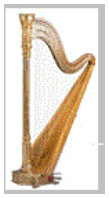
Overview of the results

Roumen Tsenov (University of Sofia)

on behalf of the HARP collaboration,

XLIII Rencontres de Moriond EW 2008,

La Thuile, 1-8 March 2008



Motivation

Neutrino oscillation experiments move from discovery to precision measurements.

Knowledge of neutrino cross-section and neutrino production is essential.

Hadron production measurements should be seen as integral part of the Neutrino Experiments.

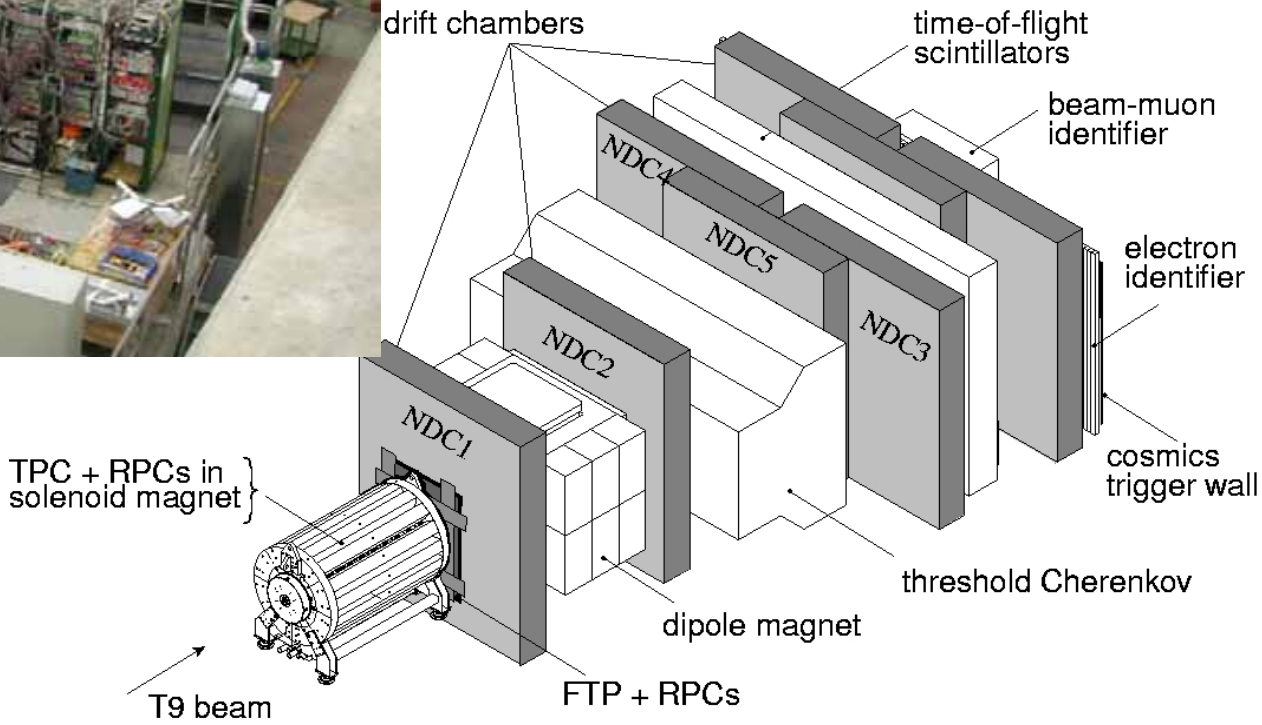
Present trends are:

- Full-acceptance detectors (vs. single arm spectrometers in the past);
- Measurement of meson production from the actual neutrino beam targets to reduce MC extrapolation to the possible minimum;
- Atmospheric neutrino flux predictions can be improved with similar measurements;
- Reduction of systematics in Extended Air Shower calculations;

HARP Detector

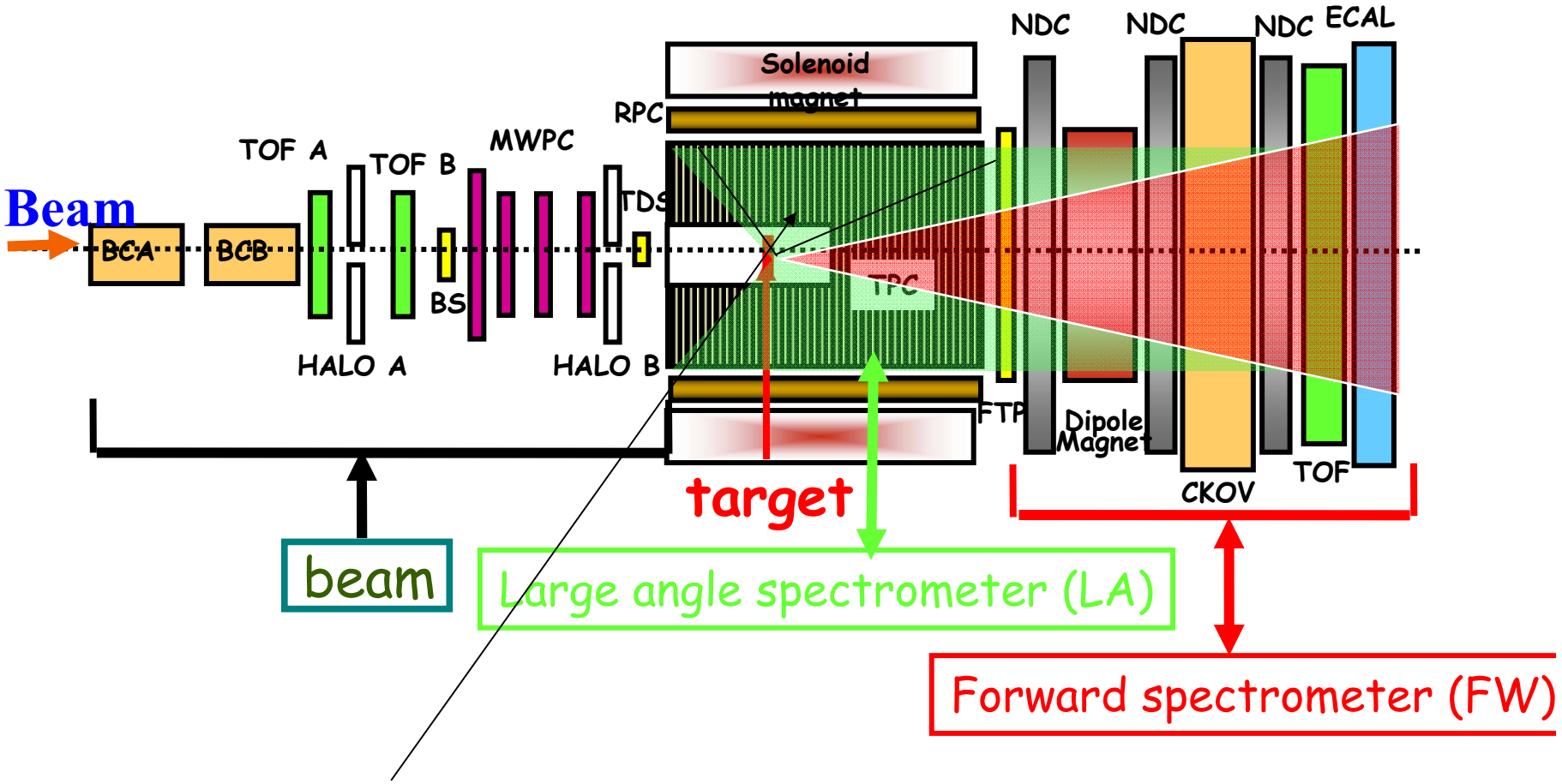
Large range of
beam momenta (3 - 15 GeV/c)
target materials (H – Pb)

the detector on
T9 beam line at
CERN PS



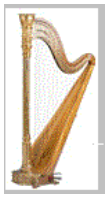
HARP: barrel spectrometer (ALEPH prototype TPC) + forward spectrometer (NOMAD DCs) to cover the full solid angle, complemented by PID detectors

HARP FW and LA spectrometers



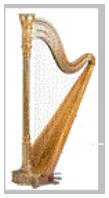
$0.35 < \theta < 2.15$ rad

The HARP detector at the CERN PS
NIM A 571 (2007) 527–561



Targets and momenta

Target material		Target length (λ%)	Beam Momentum (GeV)	#events (millions)
Solid targets	Be	2% (2001) 5% 100%	±3 ± 5 ± 8 ± 12 ± 15 For negative polarity, only 2% and 5%	233.16
	C			
	Al			
	Cu			
	Sn			
	Ta			
	Pb			
K2K	Al	5, 50, 100, replica	+12.9	15.27
MiniBooNE	Be		+8.9	22.56
Cu "button"	Cu		+12.9, +15	1.71
Cu "skew"	Cu	2	+12	1.69
Cryogenic targets	N_7	6 cm	±3 ± 5 ± 8 ± 12 ± 15	58.43
	O_8			
	D_1			
	H_1			
	H_2	18 cm	±3, ±8, ±14.5	13.83
Water	H_20	10, 100	+1.5, +8(10%)	9.6



Forwar spectrometer results:

$\pi^{\pm}$ – production in 3 -12 GeV/c

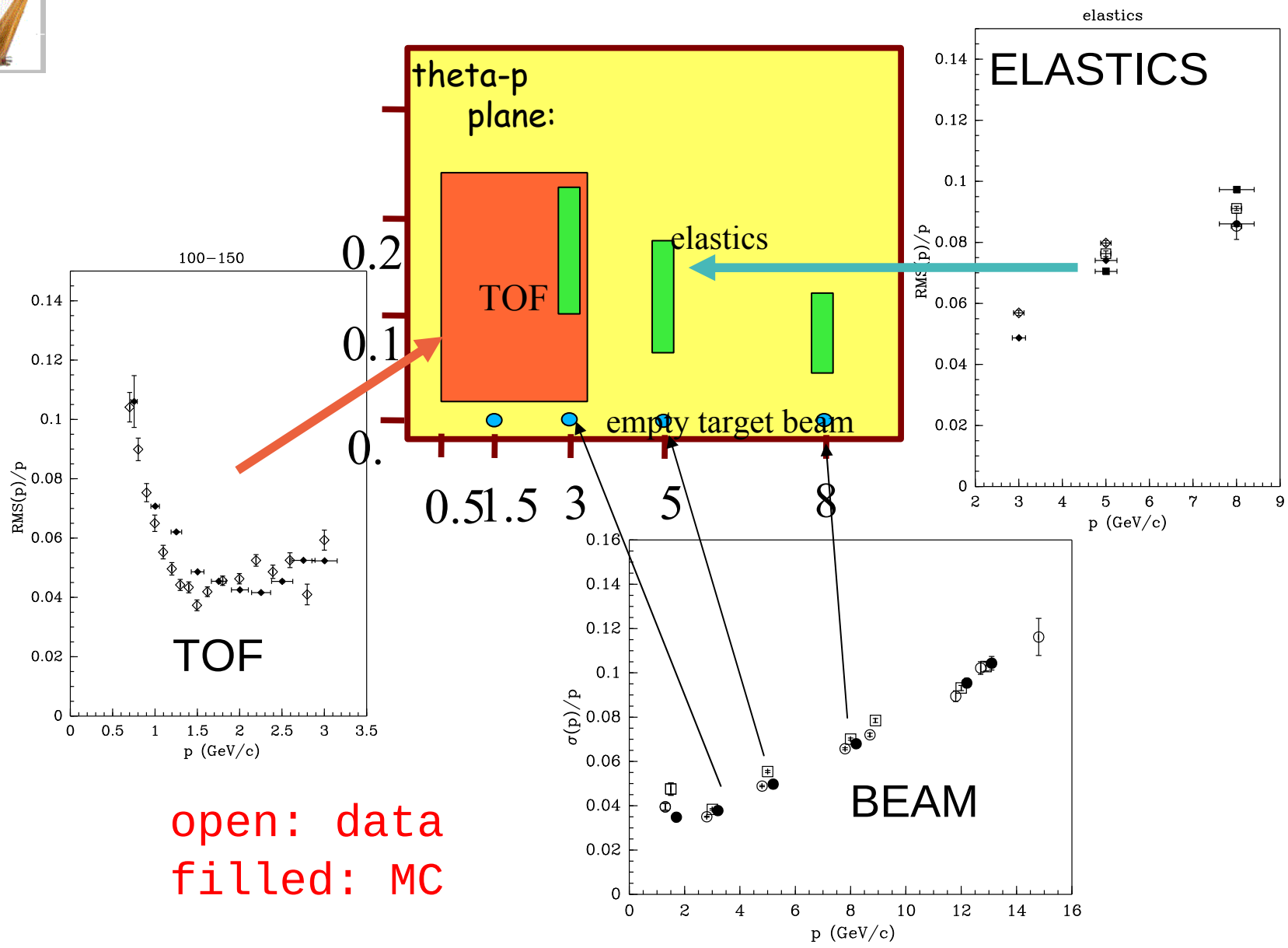
$\pi^{\pm}$ – and p–A collisions

in $p_{secondary}$ – θ range

0.5 – 8 *GeV/c*, 30 – 240 *mrad*

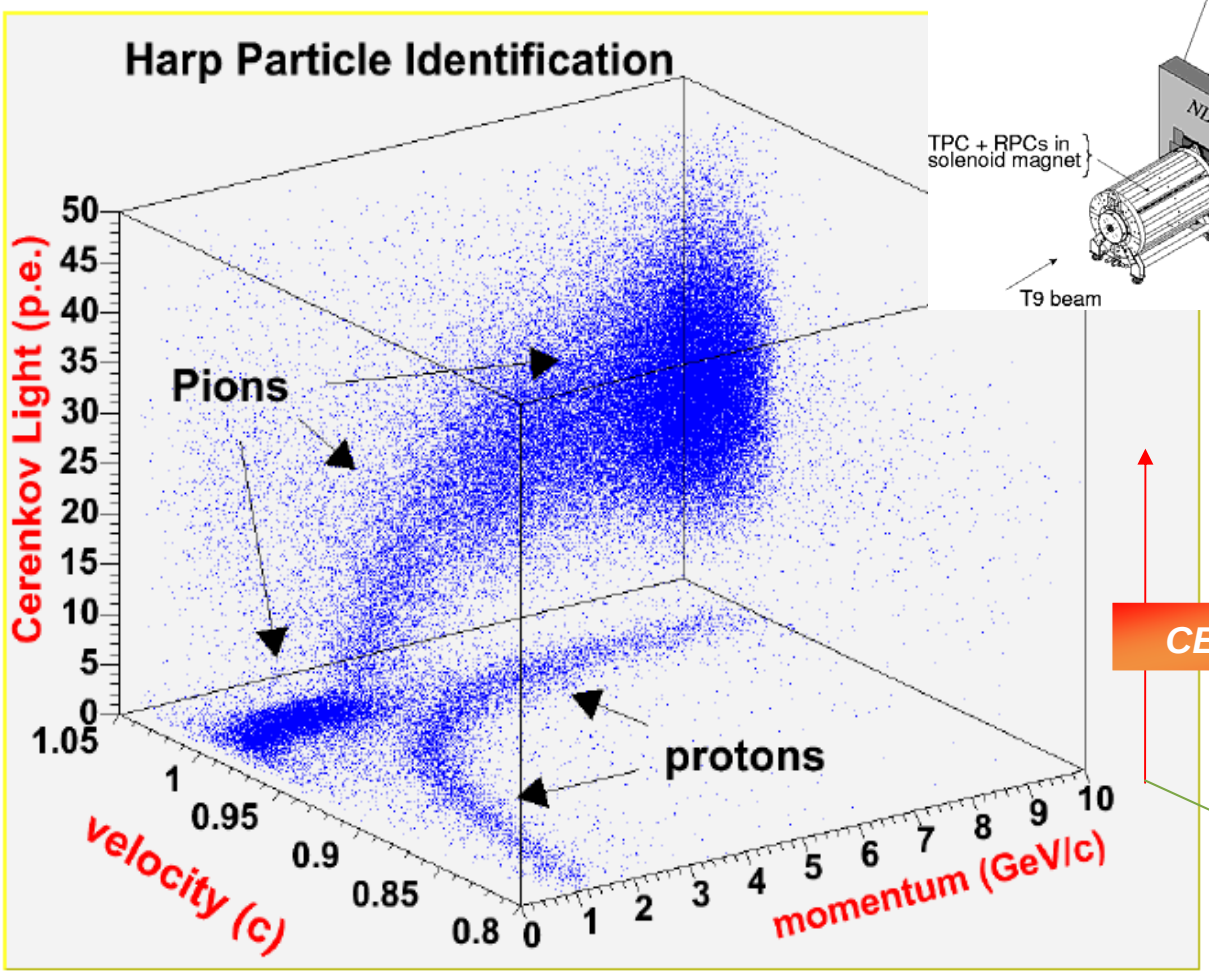
from Be, C, O_2, N_2, Al targets

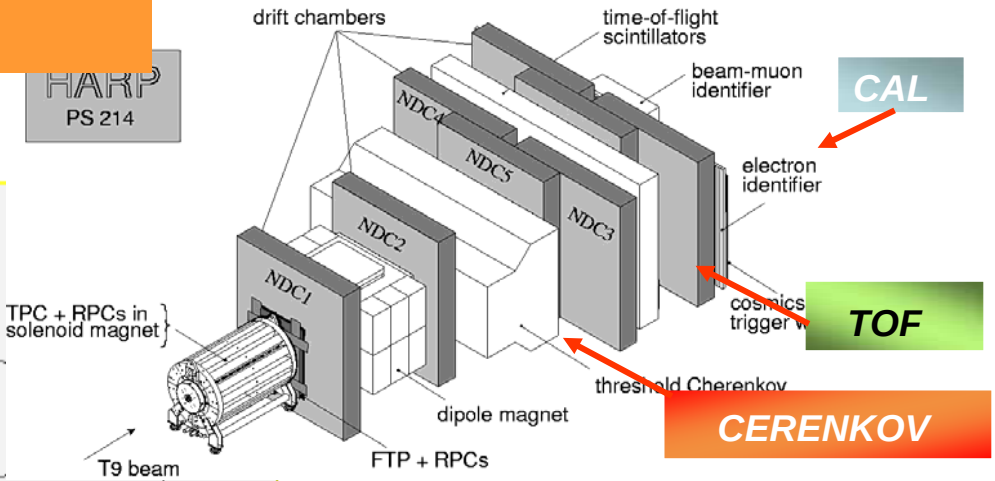
Momentum Resolution

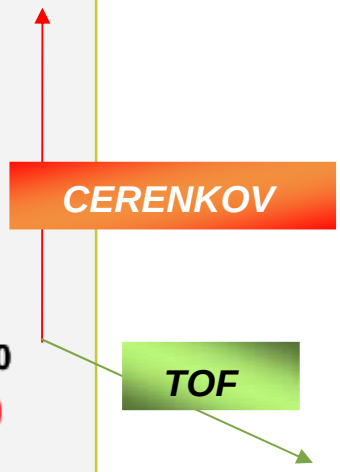


open: data
filled: MC

PID principle



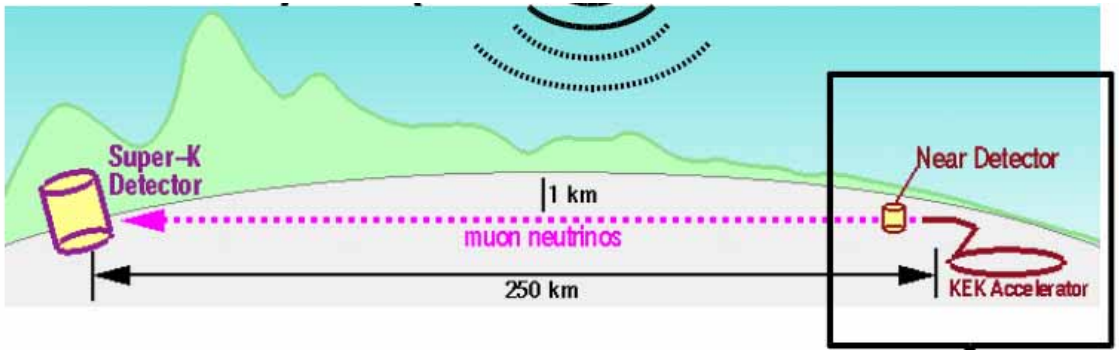




Particle identification algorithms for the HARP forward Spectrometer, NIM A **572** (2007) 899

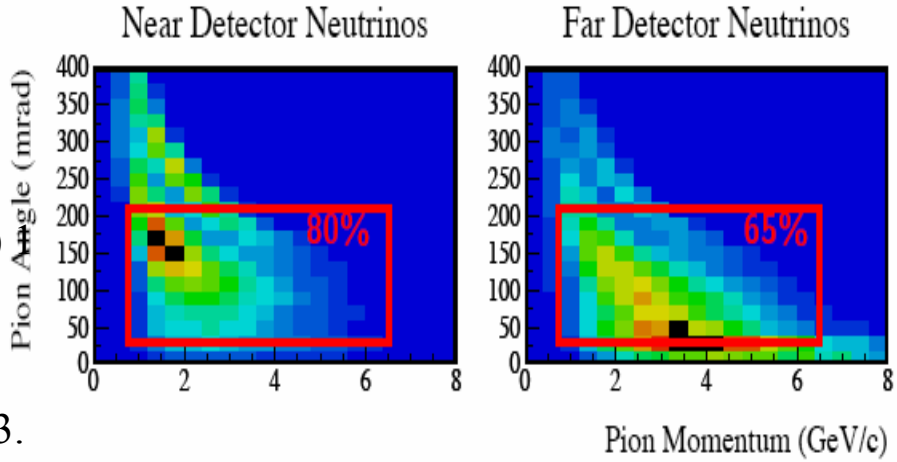
HARP measurement for K2K

K2K: Disappearance experiment to confirm atmospheric oscillation



Oscillation probability at 250 km from the source for atmospheric parameters: maximum effect at ~1GeV

- Good coverage of phase space of relevance to K2K flux predictions:



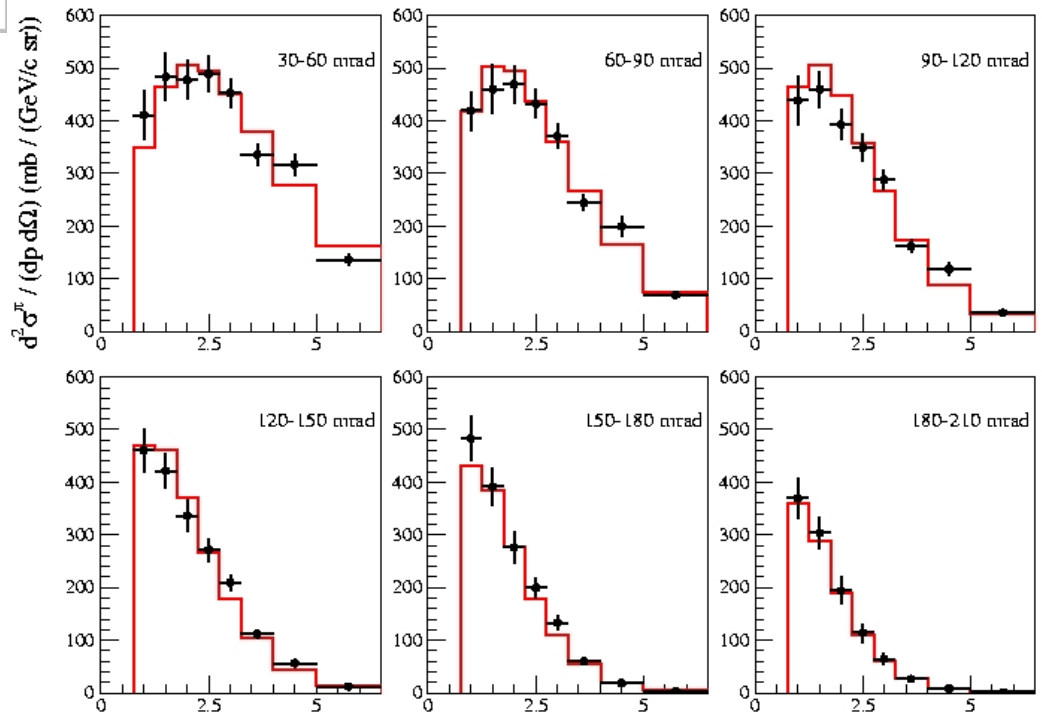
HARP p-AL data 12.9 GeV/c:

M. G. Catanesi et al., HARP, Nucl. Phys. **B732** (2006)

K2K results, with detailed discussion of relevance of production measurement:

M. H. Ahn et al., K2K, Phys. Rev. **D74** (2006) 072003. [arXiv:hep-ex/0606032]

HARP 12.9 GeV/c p+Al Results



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

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

where:

X: any other final state particle

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

p, θ: π^+ momentum(GeV/c), angle(rad)

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

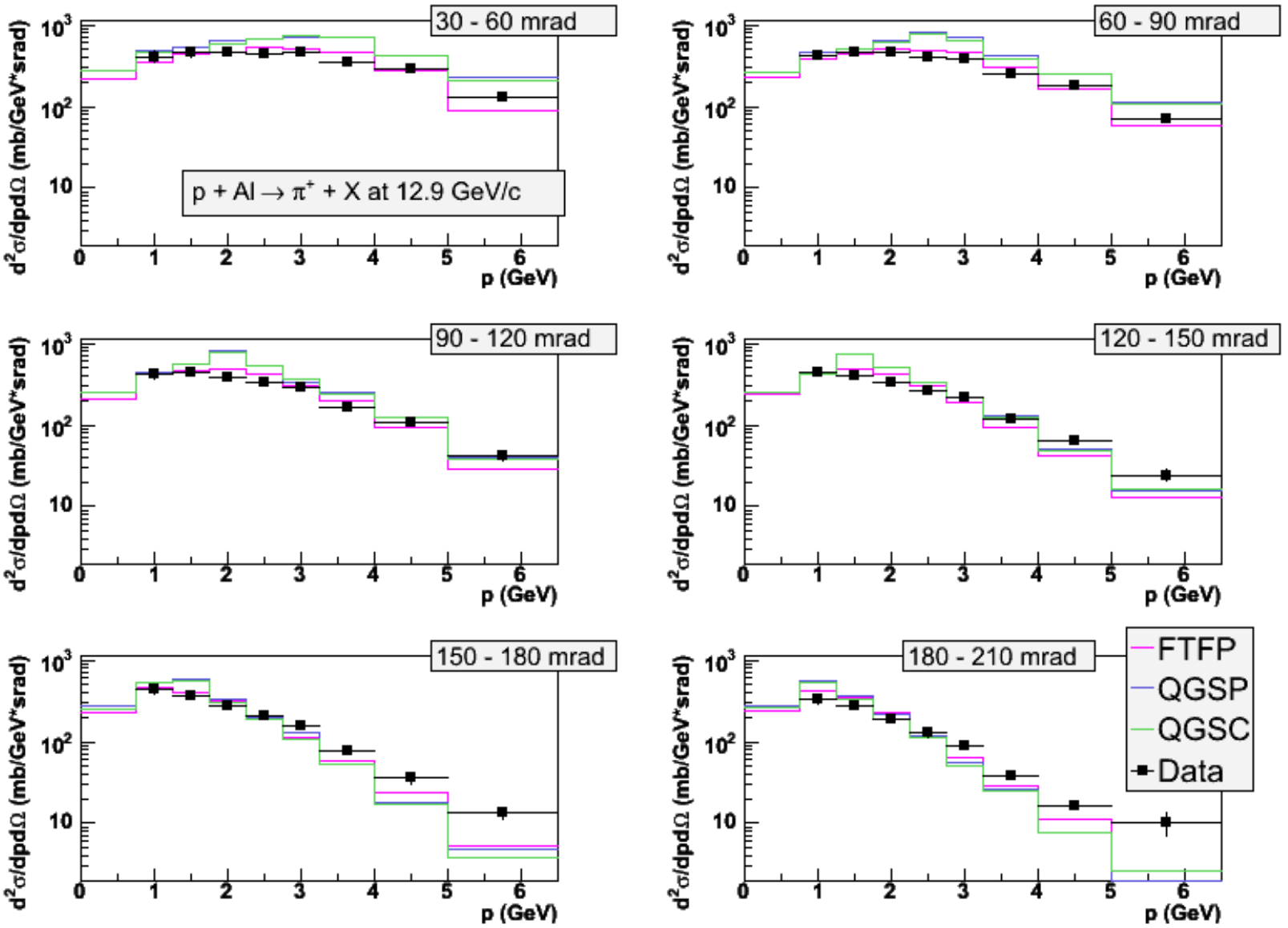
$c_1,\ldots,c_8$: emprical fit parameters

HARP results in black, **Sanford-Wang parametrization of HARP results in red** used to:

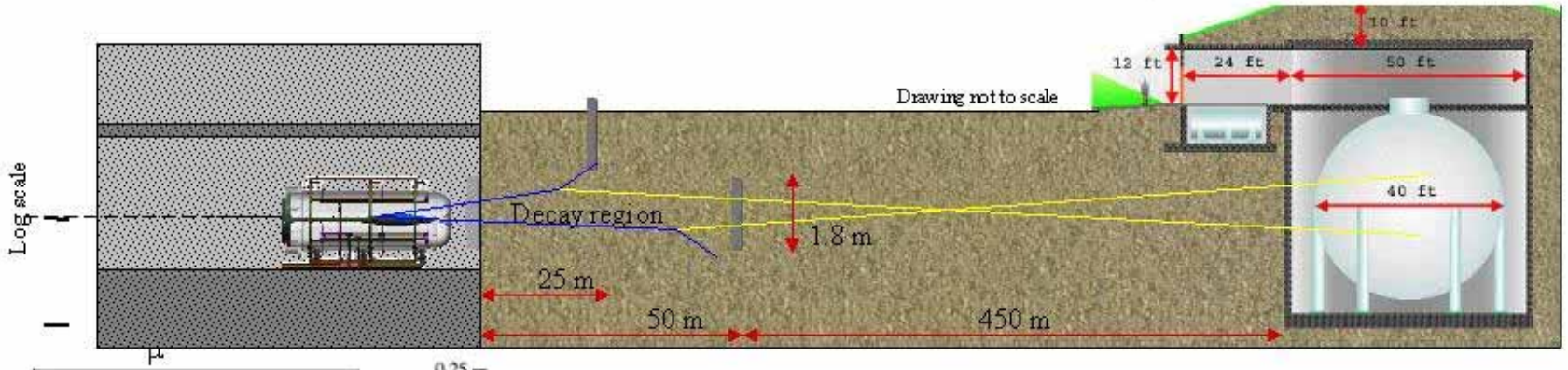
- Use HARP data in K2K and MiniBooNE beam MC
- Translate HARP pion production uncertainties into flux uncertainties
- Compare HARP results with previous results in similar beam momentum, pion phase space range

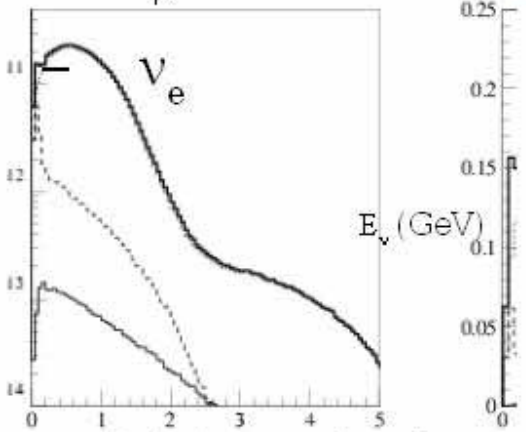
p+Al @ 3, 5, 8, 12 GeV/c available.

p+Al versus GEANT4

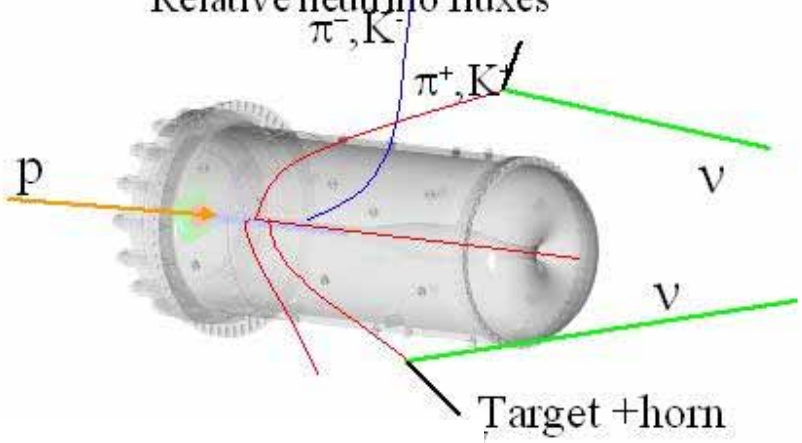


MiniBooNE Neutrino Beam





Relative neutrino fluxes



$\pi^+ \rightarrow \mu^+ + \nu_\mu$ ← ~90% of all ν flux

$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$K^+ \rightarrow \pi^0 + e^+ + \nu_e$

$K^0 \rightarrow \pi^- + e^+ + \bar{\nu}_e$

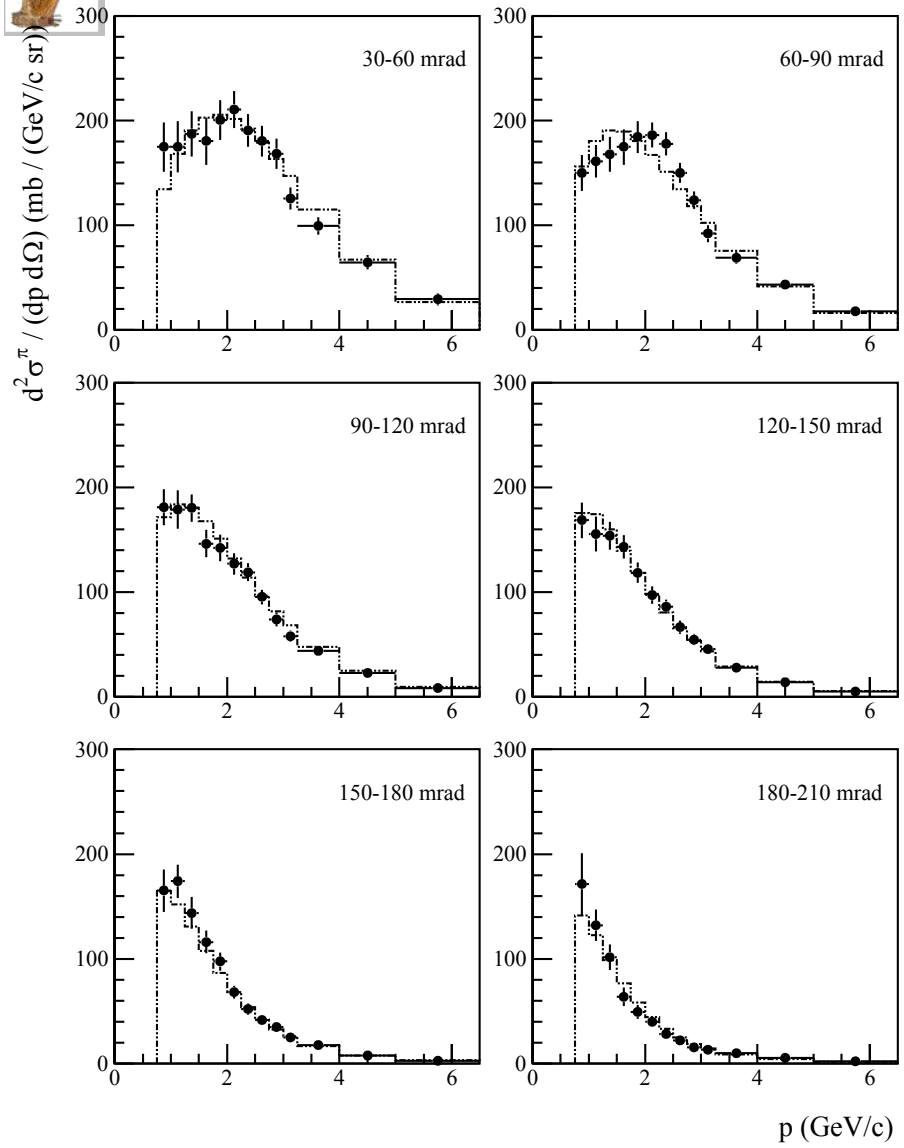
} ν_e ~0.6% of all ν's

$K^+ \rightarrow \mu^+ + \nu_\mu$

$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$

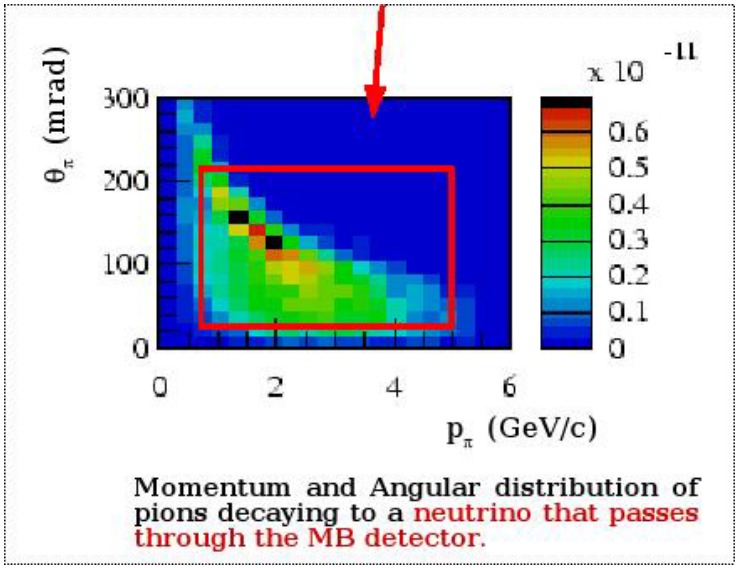
} ~3% of all ν's

HARP 8.9 GeV/c p+Be Results



HARP results (data points),
extended Sanford-Wang parametrization of HARP results (histogram)

Relevance for MiniBooNE

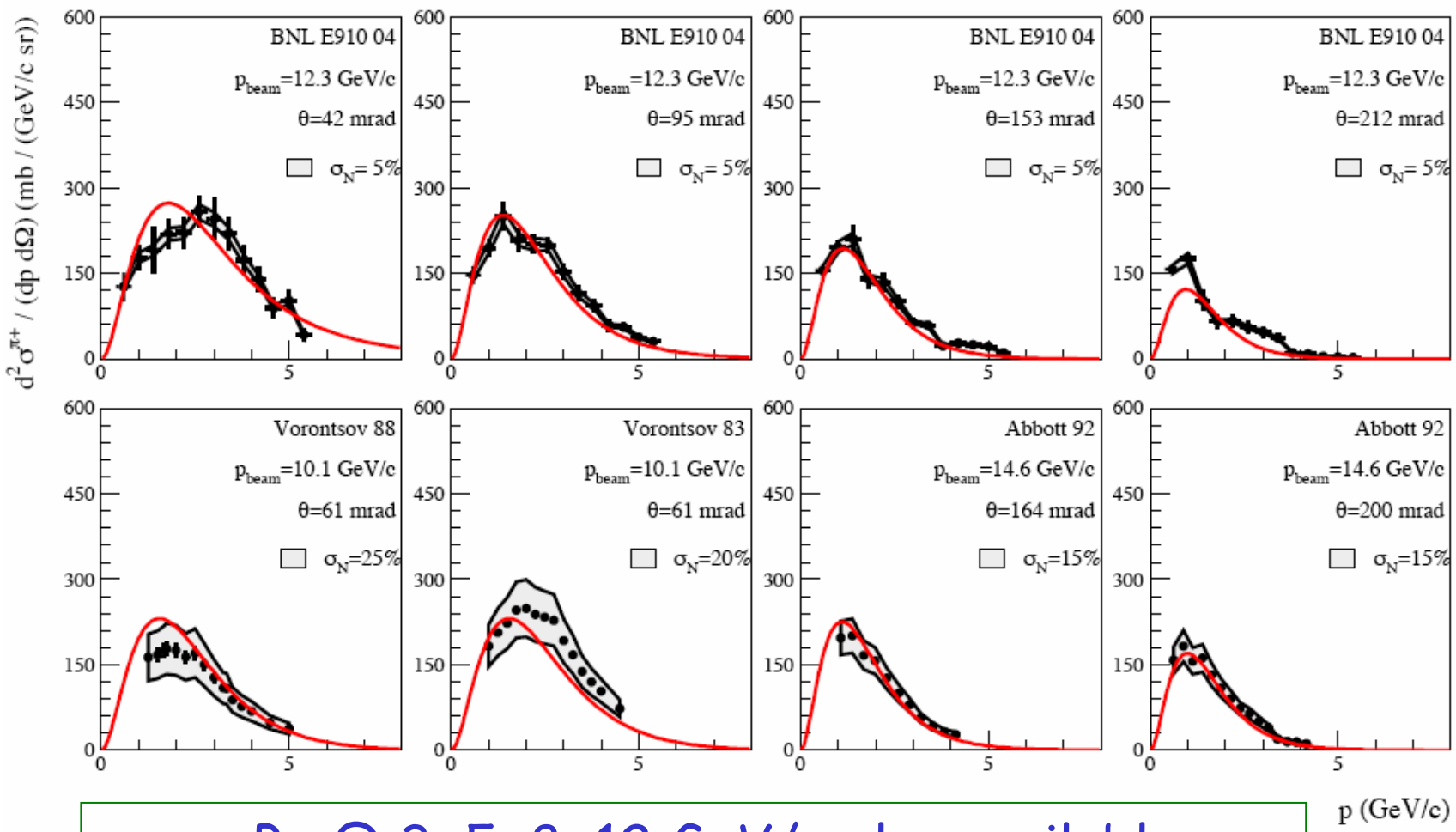


HARP p-Be data 8.9 GeV/c:
M. G. Catanesi et al., EPJC 52, 29–53 (2007) [arXiv:hep-ex/0702024]

MiniBooNE,
A.A.Aguilar-Arevalo et al., PRL **98**, 231801 (2007) [arXiv:0704.1500]

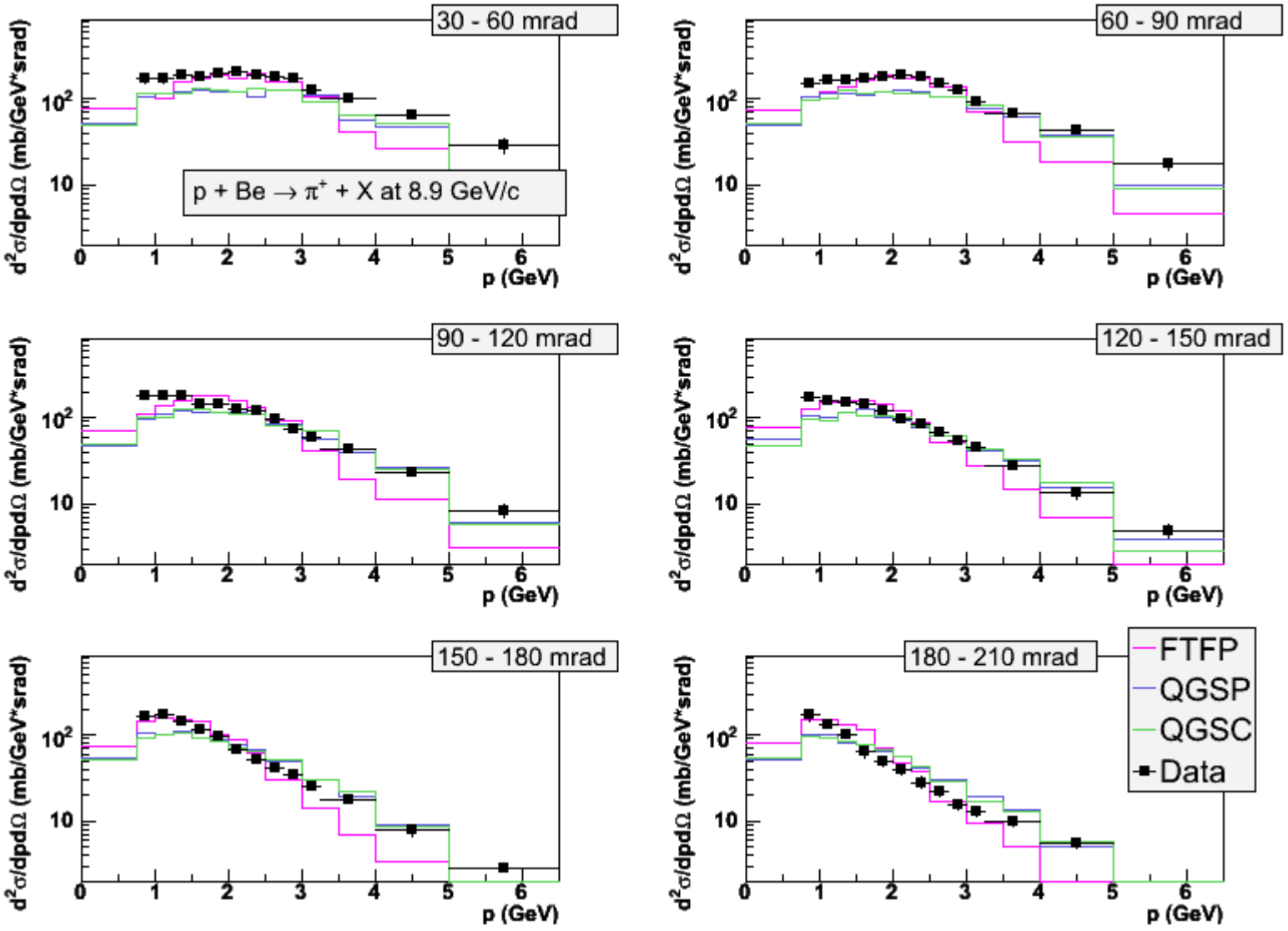
Comparison with older p+Be data

Our parametrization compared to BNL E910 data

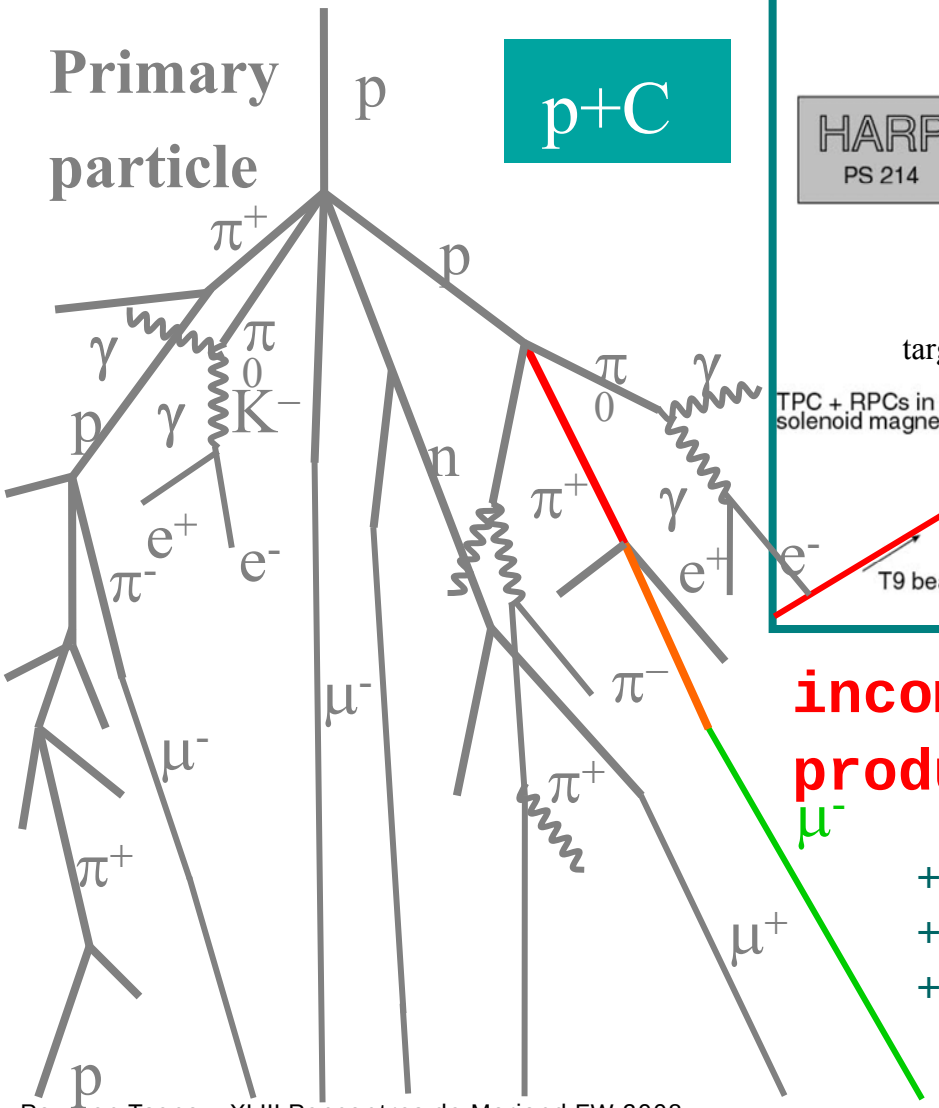


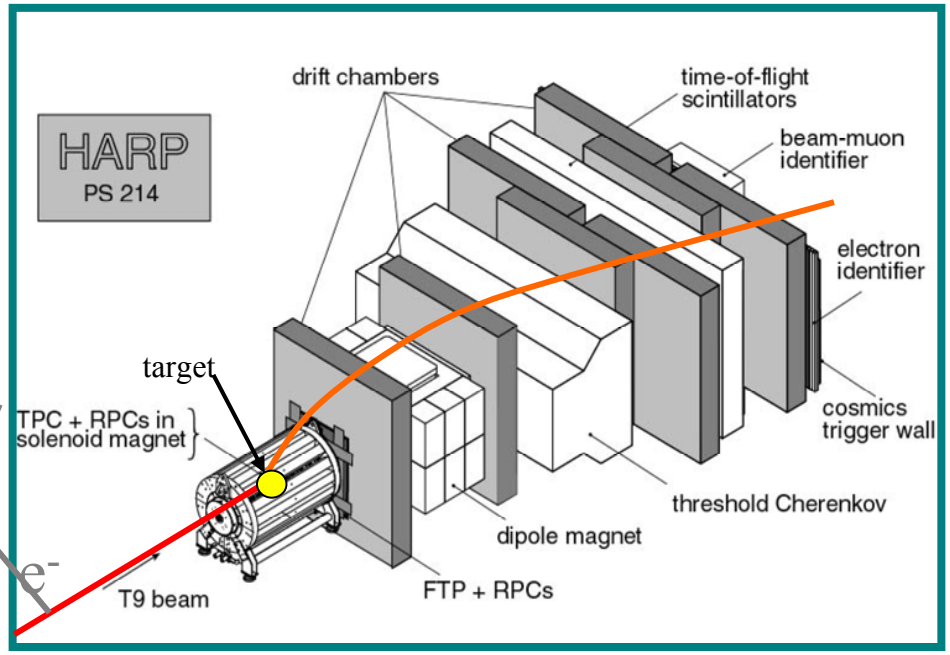
p+Be @ 3, 5, 8, 12 GeV/c also available.

p+Be versus GEANT4



HARP measurements for Extended Air Showers

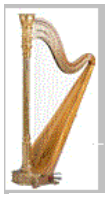




incoming protons and pions production: π^+ and π^-

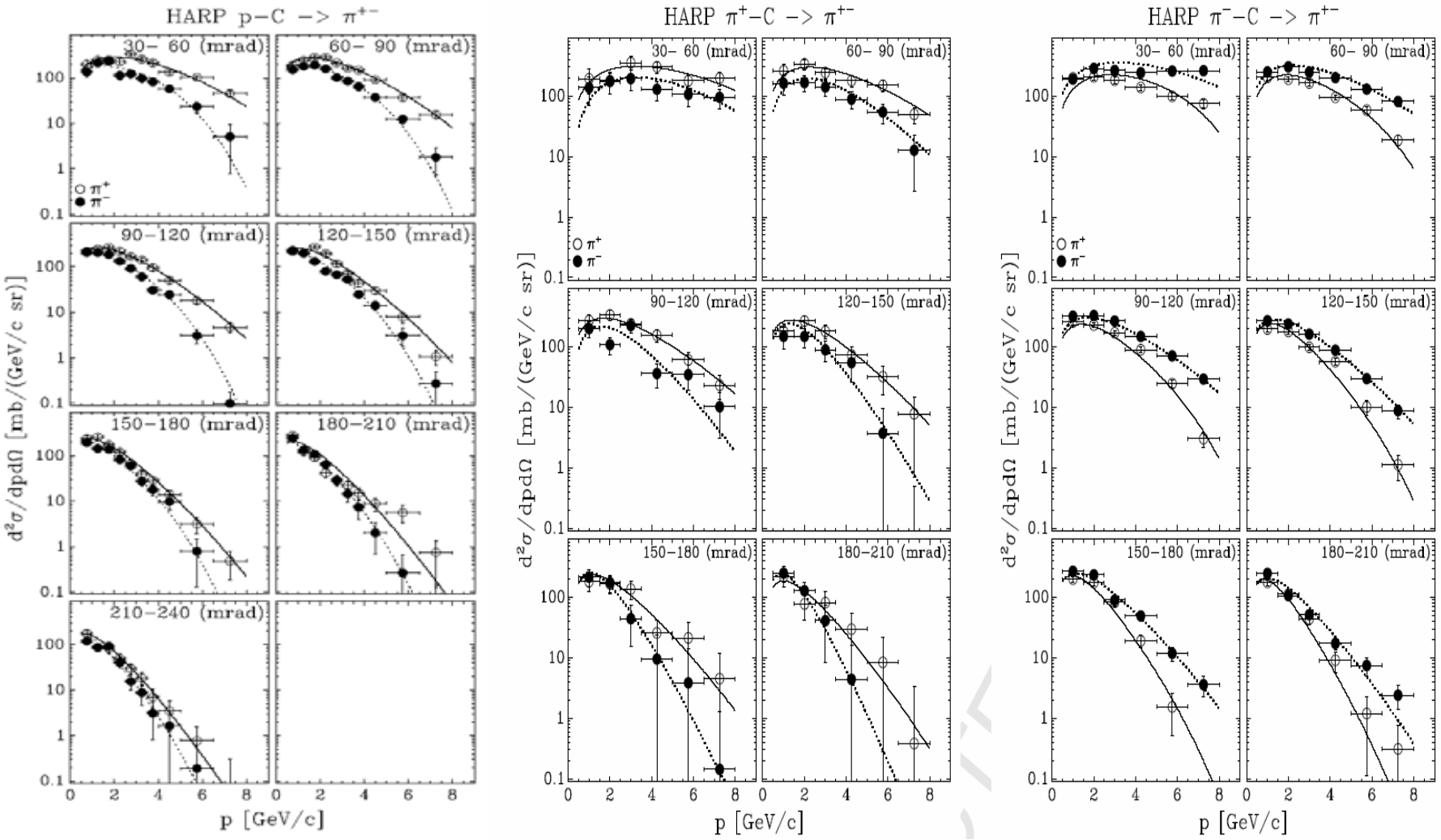
μ^-

+ Several targets
+ Forward direction
+ Relevant energy range: 10-400 GeV



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

and respective Sanfor-Wang parametrization

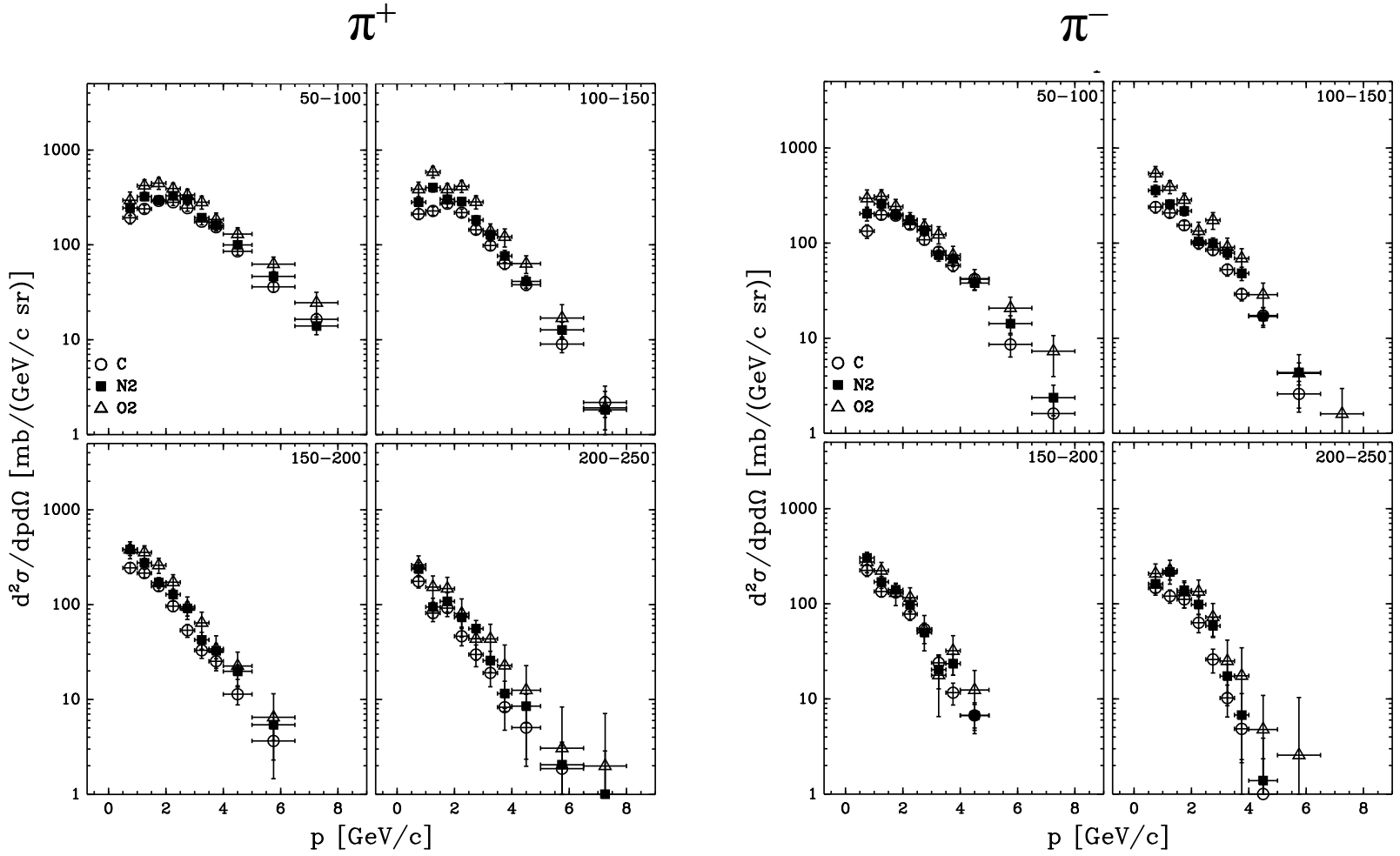


HARP p, $\pi^{\pm}$ +C @ 12 GeV/c data and comparison with models

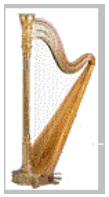
Astropart. Phys. (2008), doi:10.1016/j.astropartphys.2008.02.002 [arXiv:0802.0657]

p+C, N2, O2 @ 12 GeV/c

Spectra very similar



Submitted for publication



Realistic production targets

In practice production targets are not **thin**: Cascade calculations or dedicated measurements with "replica targets" are needed.

Low energy (HARP like) data are useful for cascade calculations.

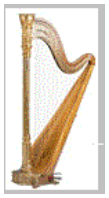
HARP has taken, albeit with somewhat lower statistics, and analysed. **p+A, π^++A and π^--A** data at different beam momenta with **100% λ_{int}** targets.

They can be used for parametrizations or tuning of models.

Preliminary spectra available:

p + Be, C, Al, Cu, Sn, Ta, Pb at 3, 5, 8, 12 GeV/c.

$\pi^{\pm}$ + A measurements are on the tapes and can be analysed on demand.



Large angle spectrometer results:

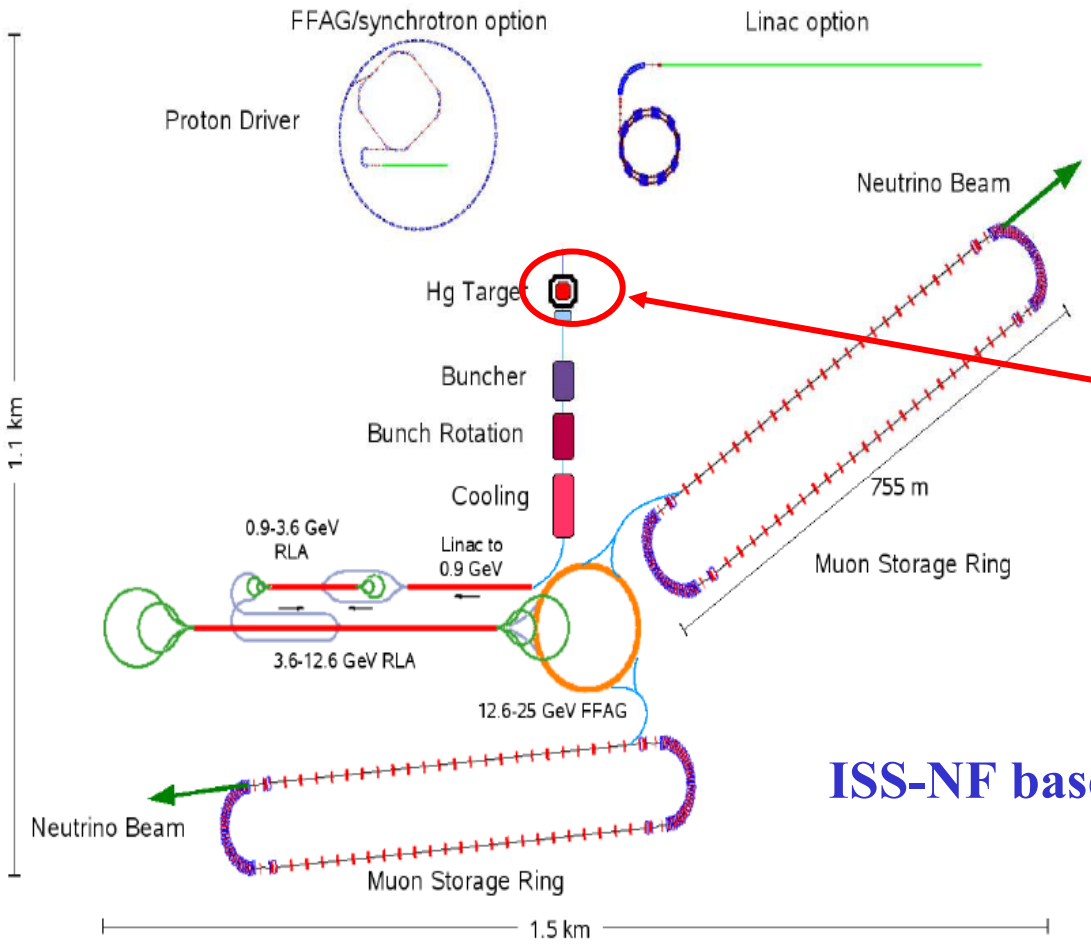
$\pi^{\pm}$ – production in $\pi^{\pm}$ – and p–A

3 – 12 GeV/c collisions in $p_{secondary}$ – θ range

0.1 – 0.8 *GeV/c*, 0.35 – 2.15 *rad*

from Be, C, Al, Cu, Sn, Ta, Pb targets

Neutrino Factory R&D



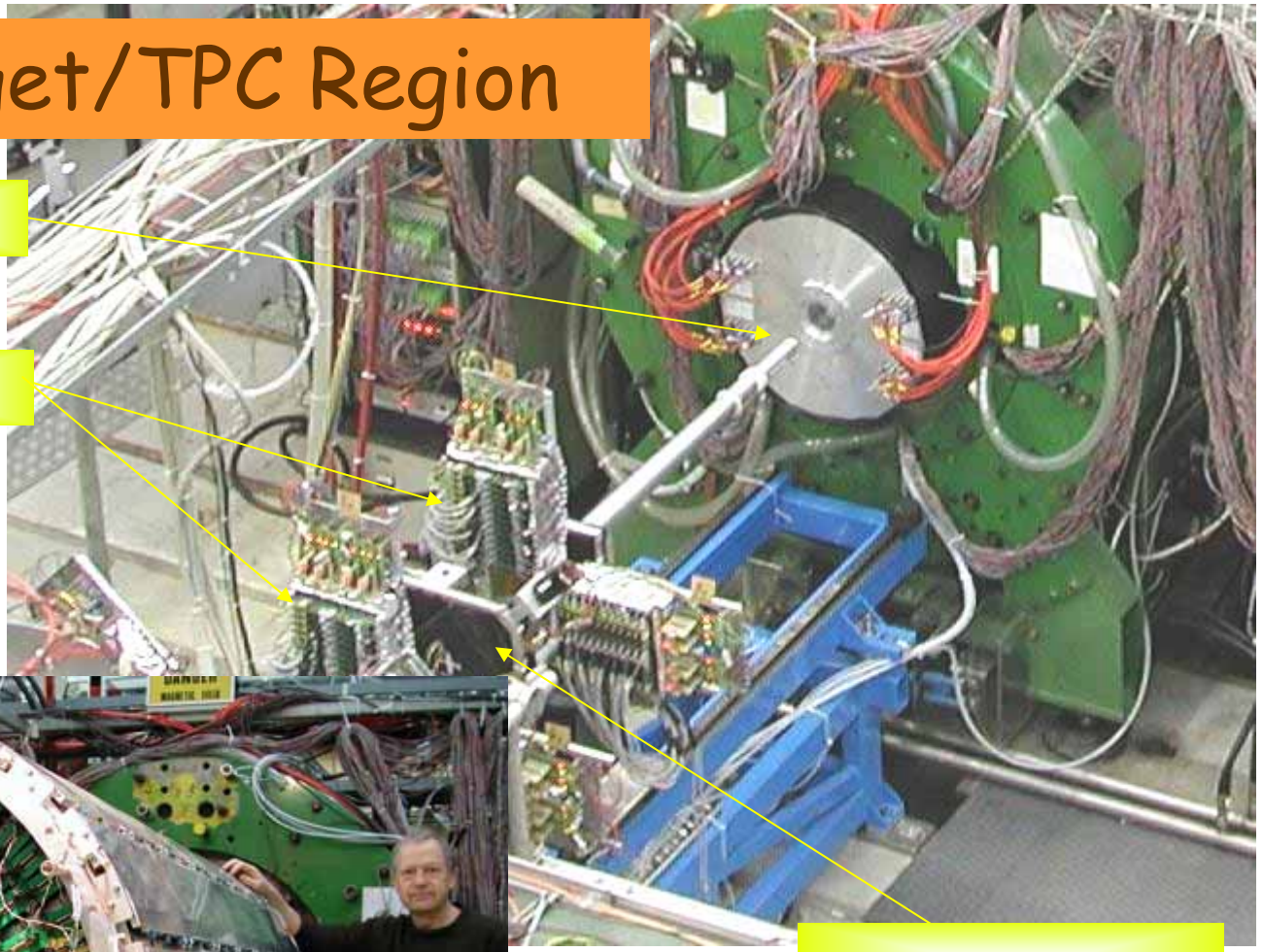
Maximize: π^+, π^- production rate (/proton /GeV)

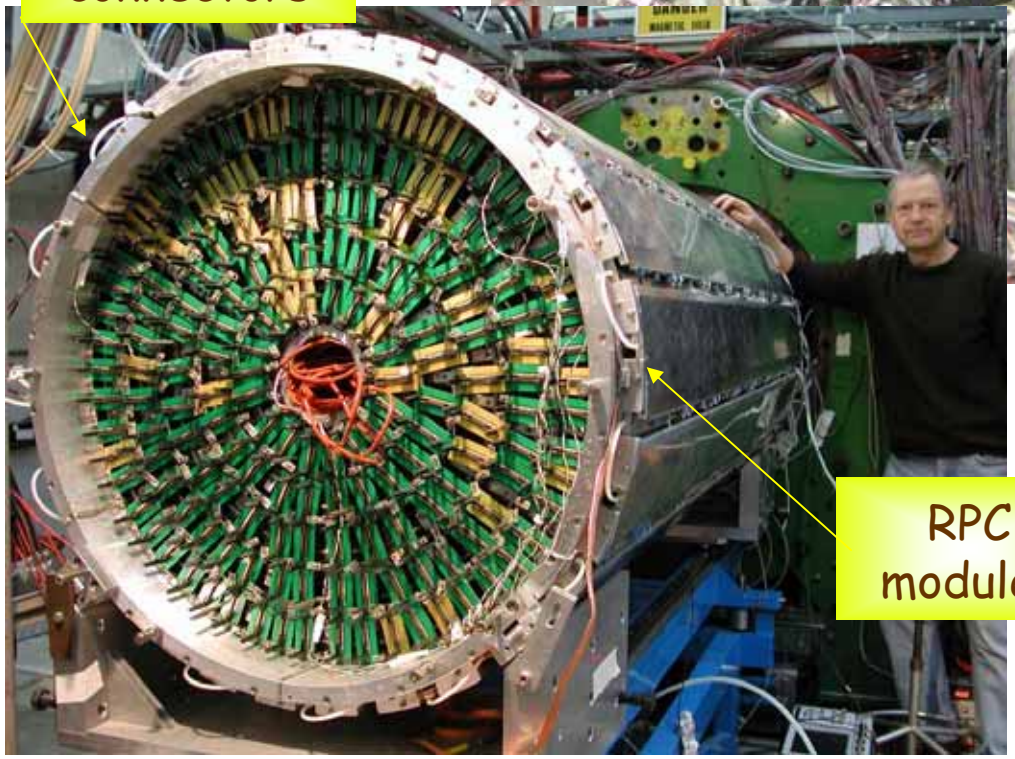
- Primary energy
- Target material
- Geometry
- Collection scheme

ISS-NF baseline

- Measure the p distribution with high precision
- Solid targets, preferably high Z

The Target/TPC Region



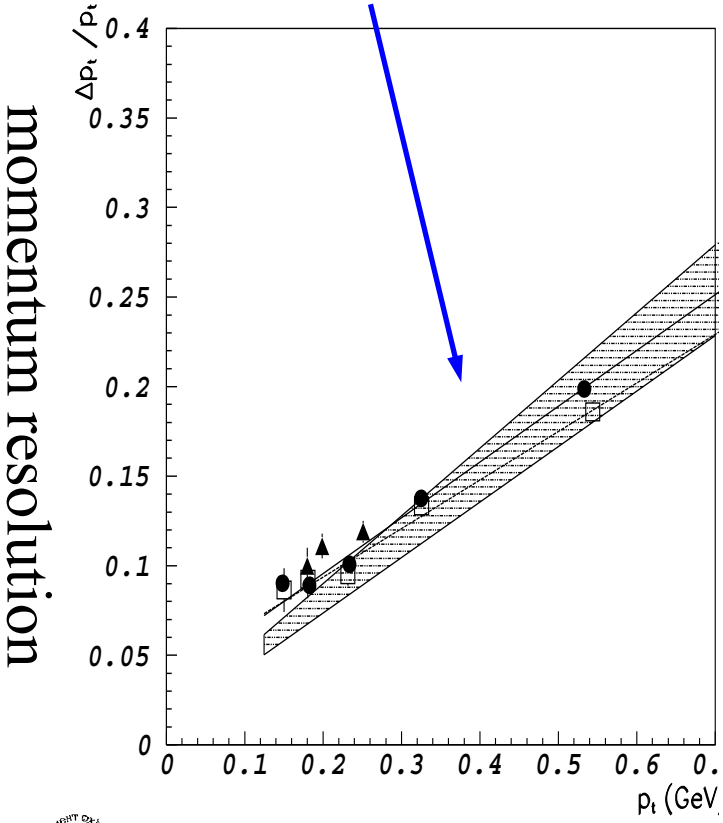


Spectrometer performance

momentum calibration:

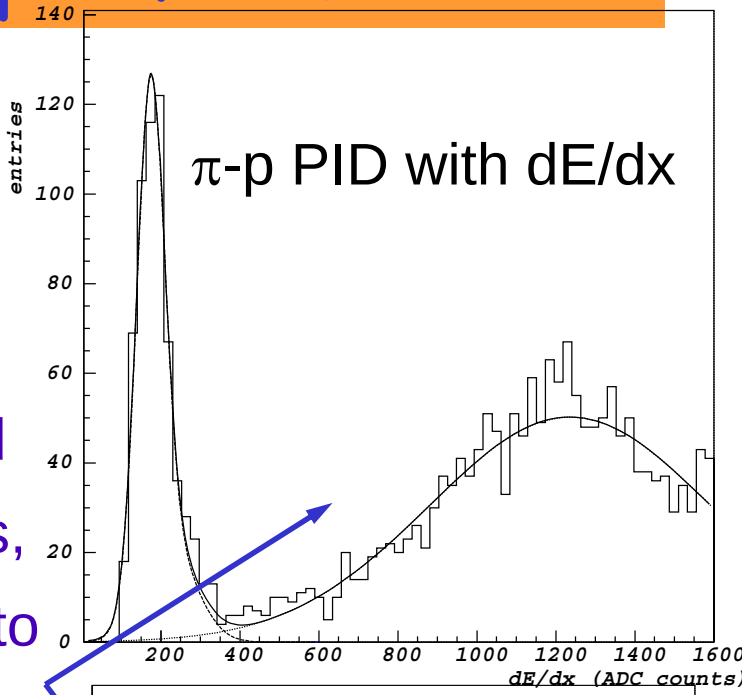
cosmic rays

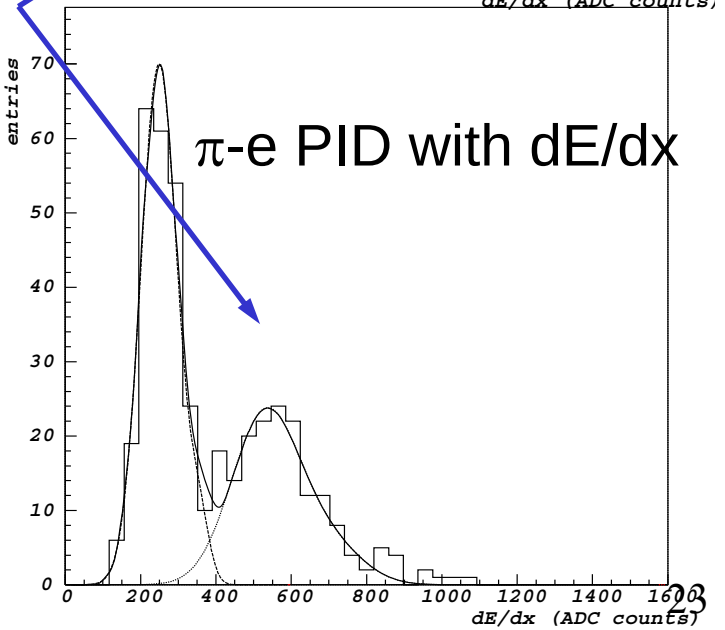
elastic scattering



PID:

dE/dx used for analysis, TOF used to determine efficiency

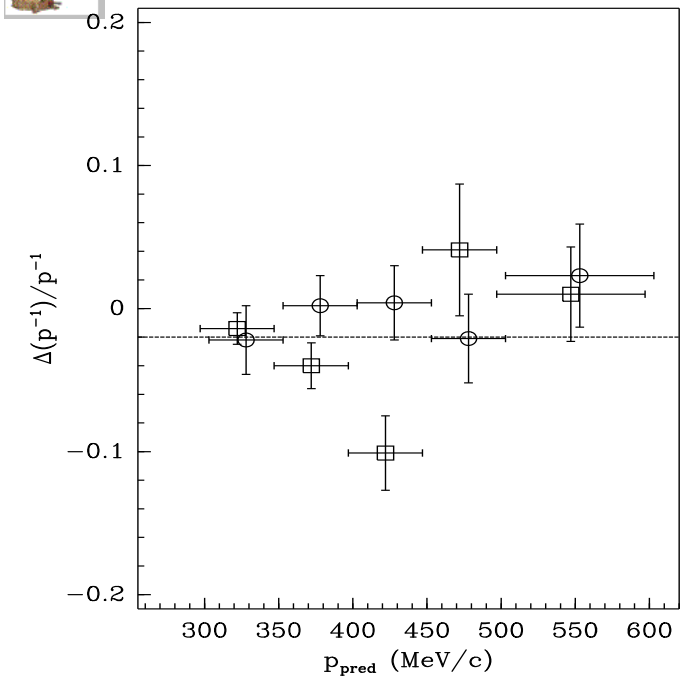


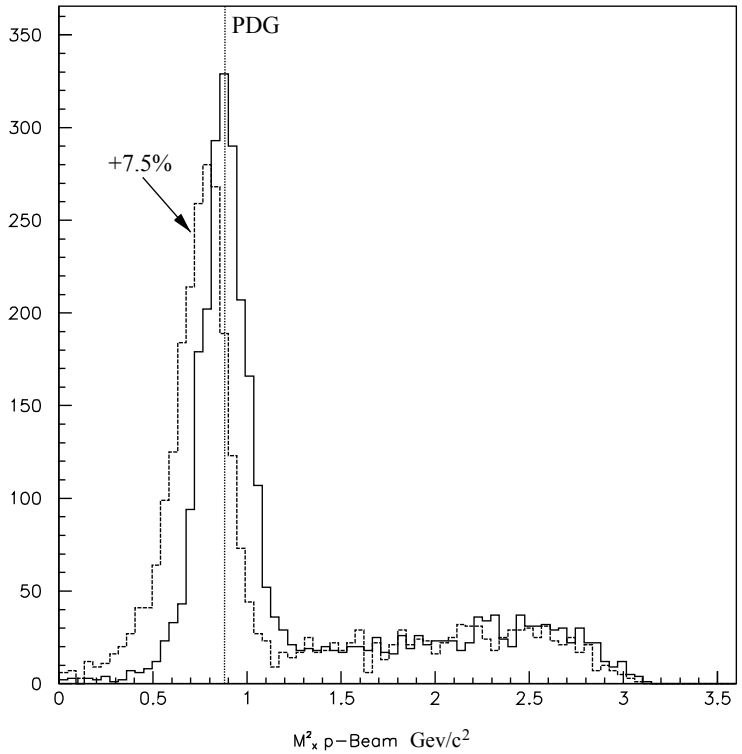


Elastic scattering

p-p elastic scattering: absolute calibration of efficiency, momentum, angle (two spectrometers!)

Momentum scale: ± 3.5%





Direct comparison of recoil proton angle with recoil momentum

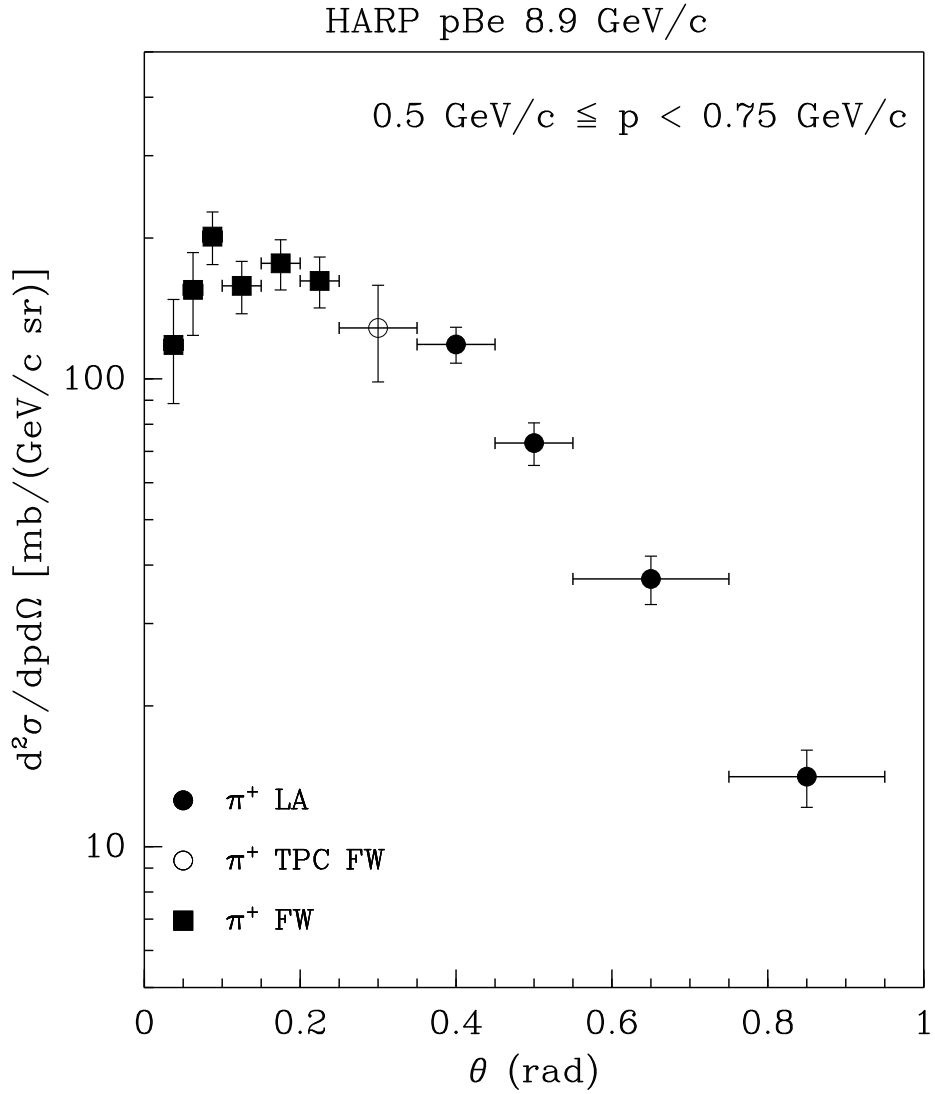
Peak at PDG value of proton mass

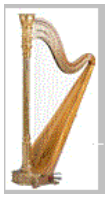
Measurement of the Production of Charged Pions by Protons on a Tantalum Target, **Eur. Phys. J. C51 (2007) 787-824, [arXiv:0706.1600];**

Momentum scale in the HARP TPC **arXiv:0709.2806 [physics.ins-det]**

Elastic scattering events selected by the forward spectrometer and RPC "proton" signal have been used to **MEASURE** the TPC global detection efficiency

The two spectrometers match each other



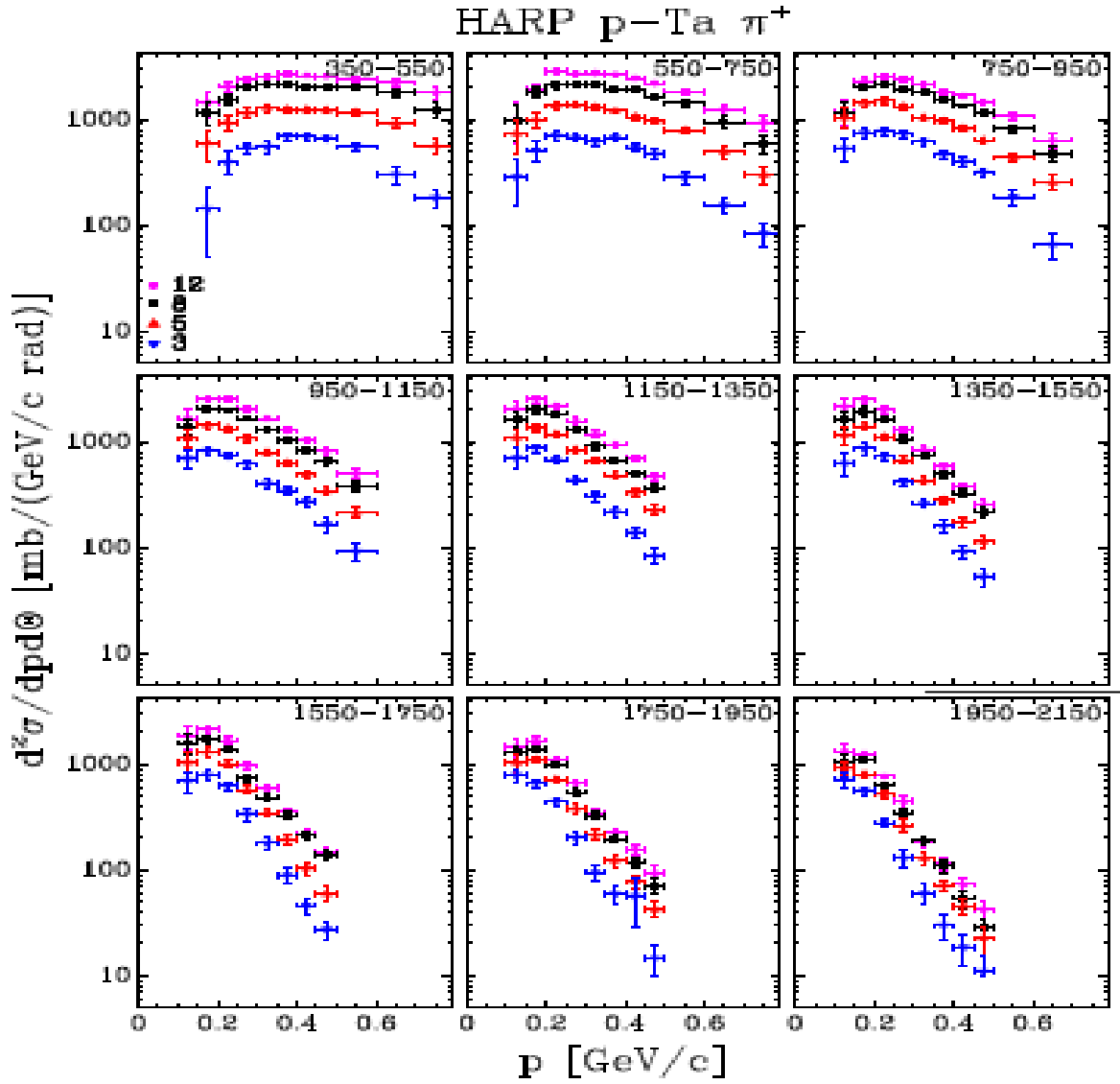


3 – 12 GeV/c proton beams on 5% λ_{int} targets

All thin target data taken in proton beams are available.

Full statistics analysed ("full spill data" with dynamic distortion corrections) - although no significant difference is observed with the first analysis of the partial data (first 100-150 events in the spill).

Full spill data: p+Ta → π^+

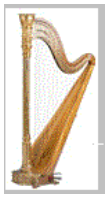


forward

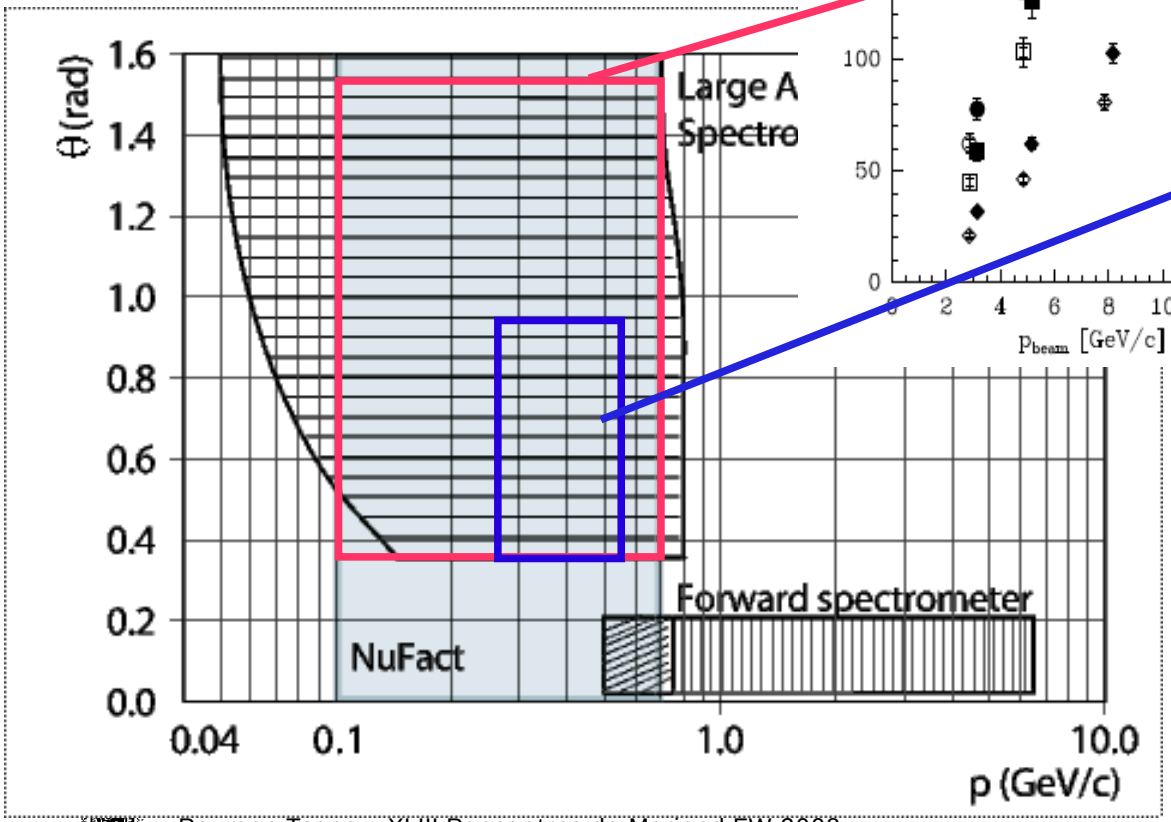
$0.35 < \theta < 1.55$

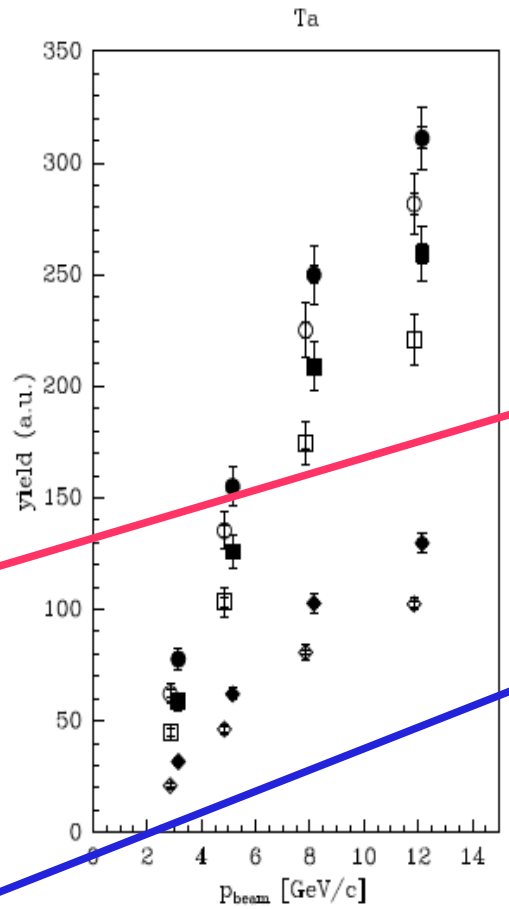
backward

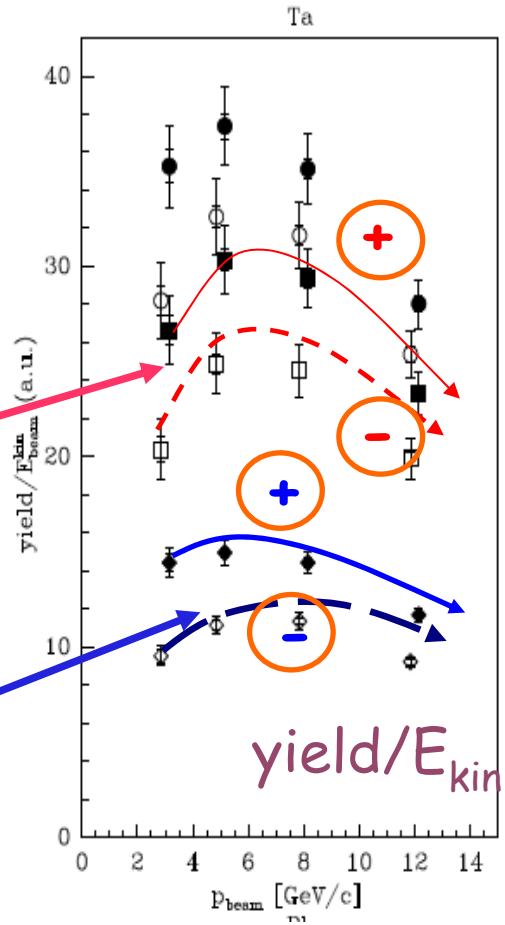
$1.55 < \theta < 2.15$



Neutrino Factory study







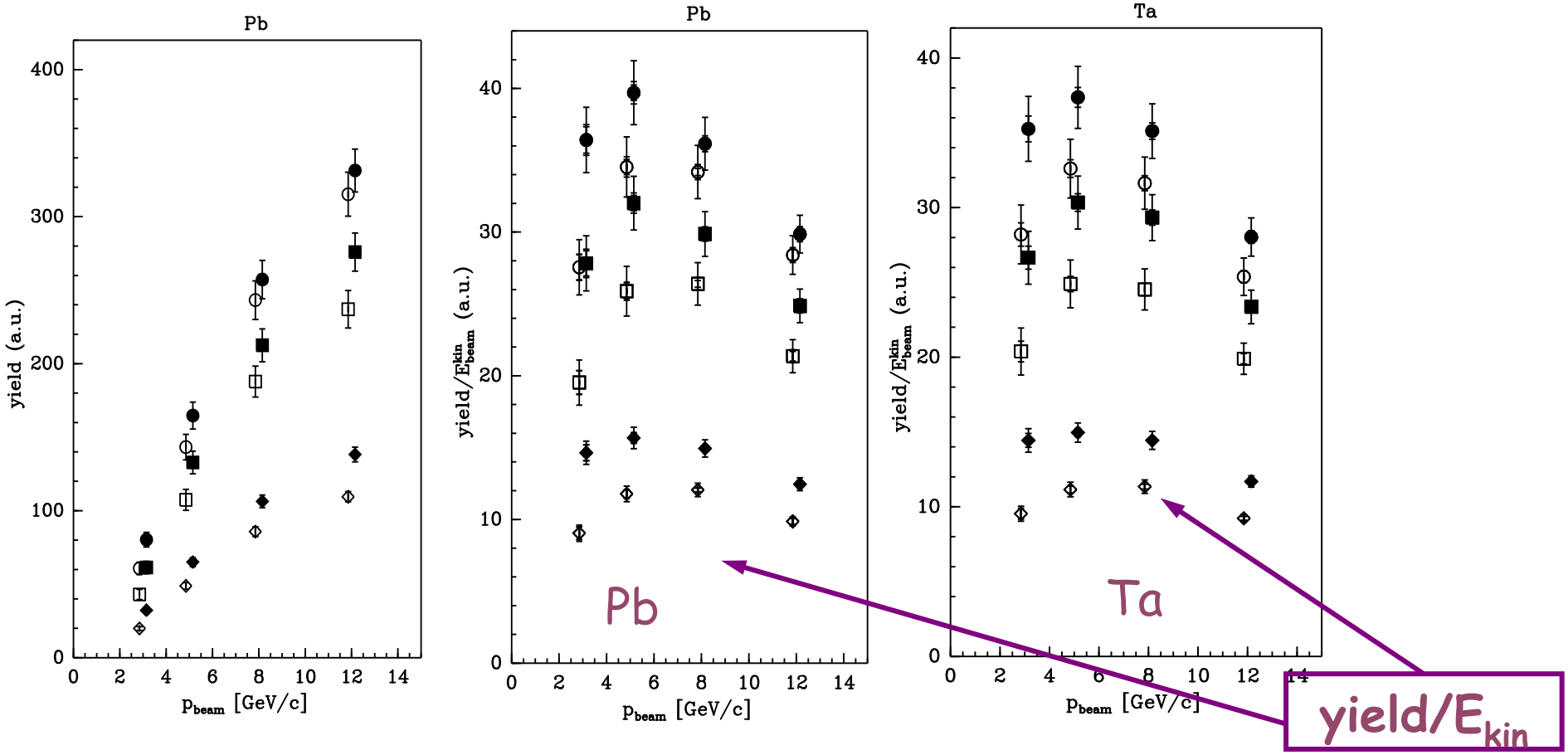
dσ/dpdΩ cross-sections can be fed into neutrino factory studies to find optimum design

<u>Warning</u> the above has fixed integration range, but optimization may be momentum dependent

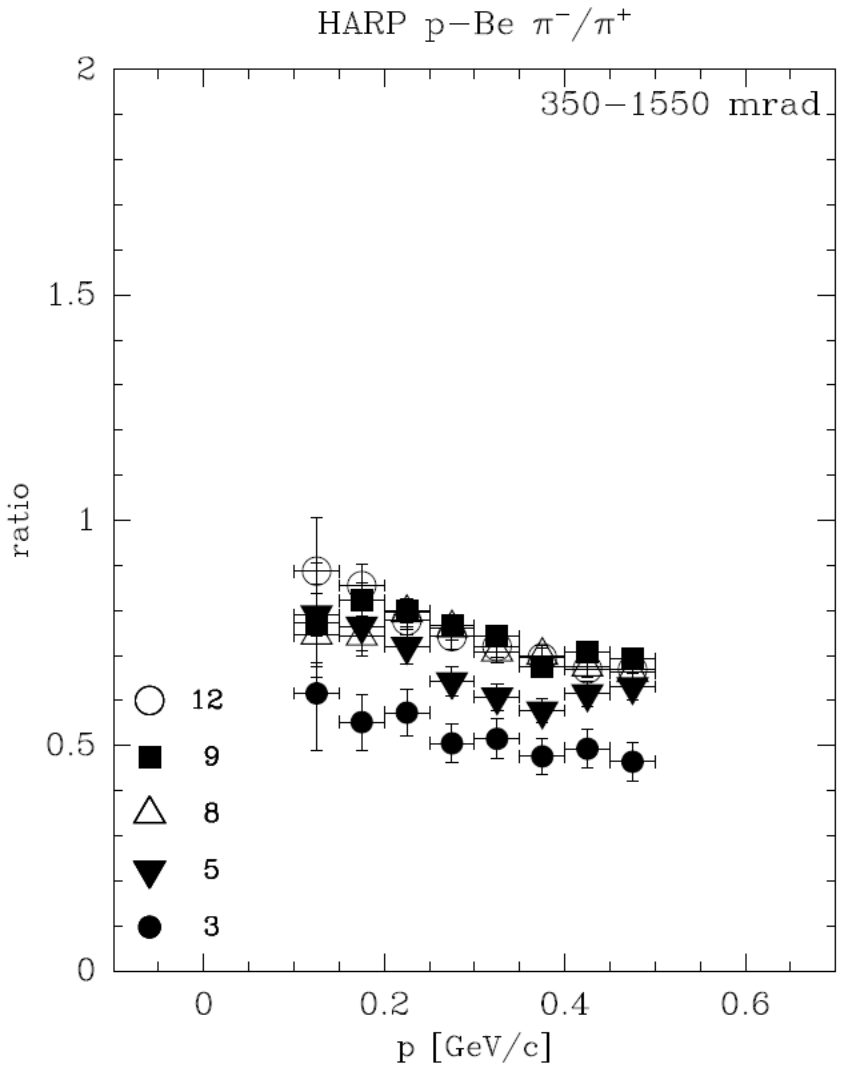
Ta and Pb

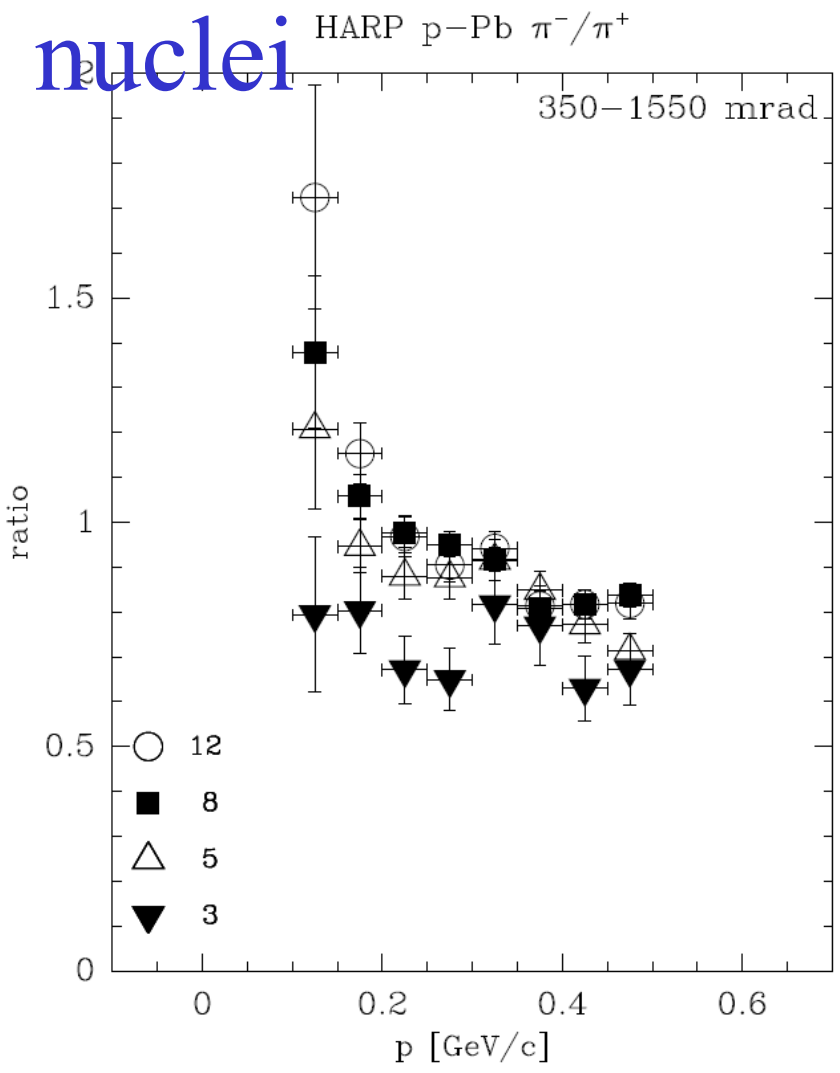
Same conclusions for $^{181}Ta_{73}$ and for $^{207}Pb_{82}$.

$^{201}Hg_{80}$ is between.



π^-/π^+ ratios for light and heavy nuclei

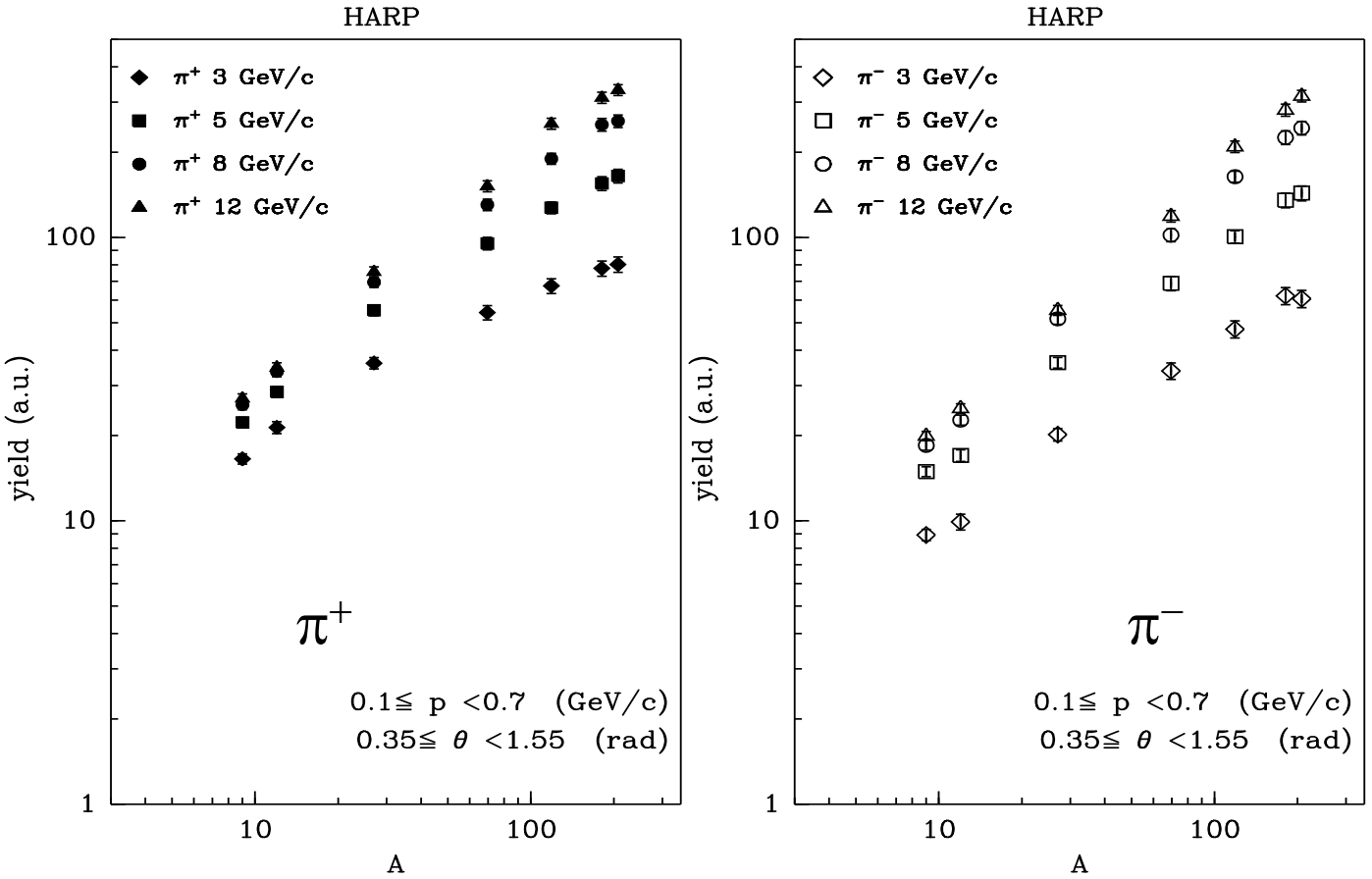




A-dependence of π^+ and π^- and yields for p-A

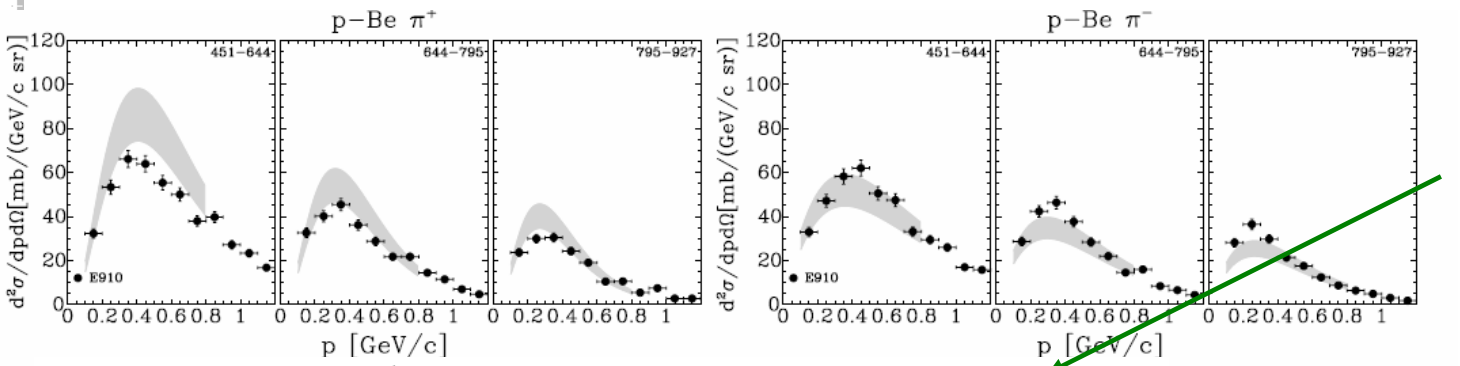
Be, C, Al, Cu, Sn, Ta and Pb

(3, 5, 8, 12 GeV/c) full spill data

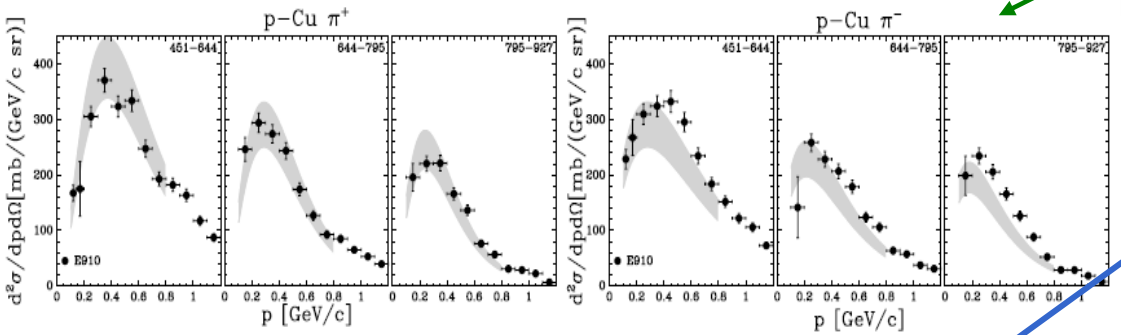


Submitted for publication

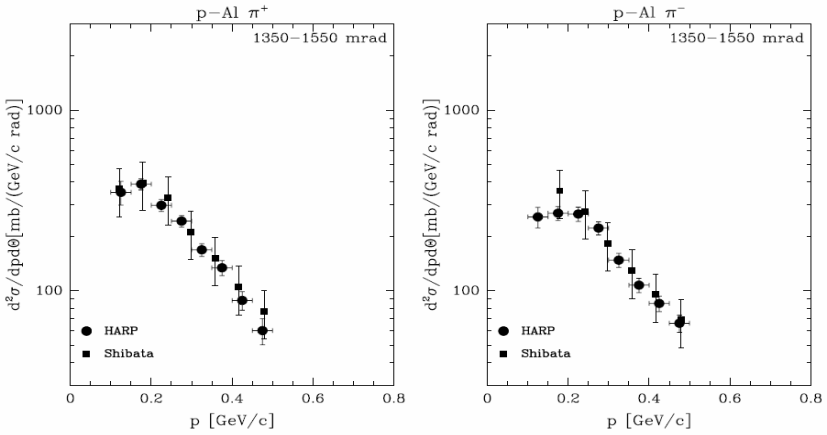
Comparison with…

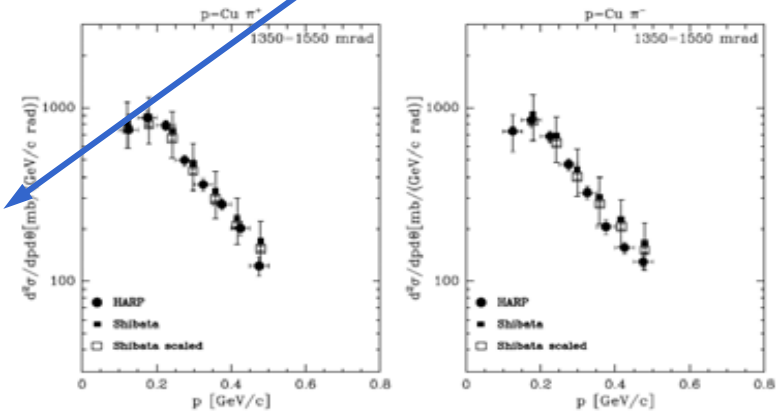


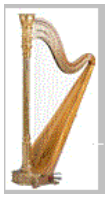
BNL E910 at 12.3 GeV/c: data points; HARP: shaded region



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







Proton beams on 100% λ_{int} targets

Data analysed on tantalum and carbon targets: 5, 8 ,12 GeV/c;

Especially useful for the neutrino factory target;

Interesting to tune models for re-interactions (and shower calculations in calorimeters etc.);

As for the thin targets, corrections for the absorption and re-interaction of the produced particles are made;

NO correction is made for the absorption and re-interaction of the beam proton (this is what we want to measure);

If no effect from absorption of the beam: **ratio** = 1;

If all interacting protons are lost:

ratio = [1-exp(-1)]*0.05/[1-exp(-0.05)]=0.648;

Warning: our targets are 30mm in diameter: re-interactions of the scattered proton.

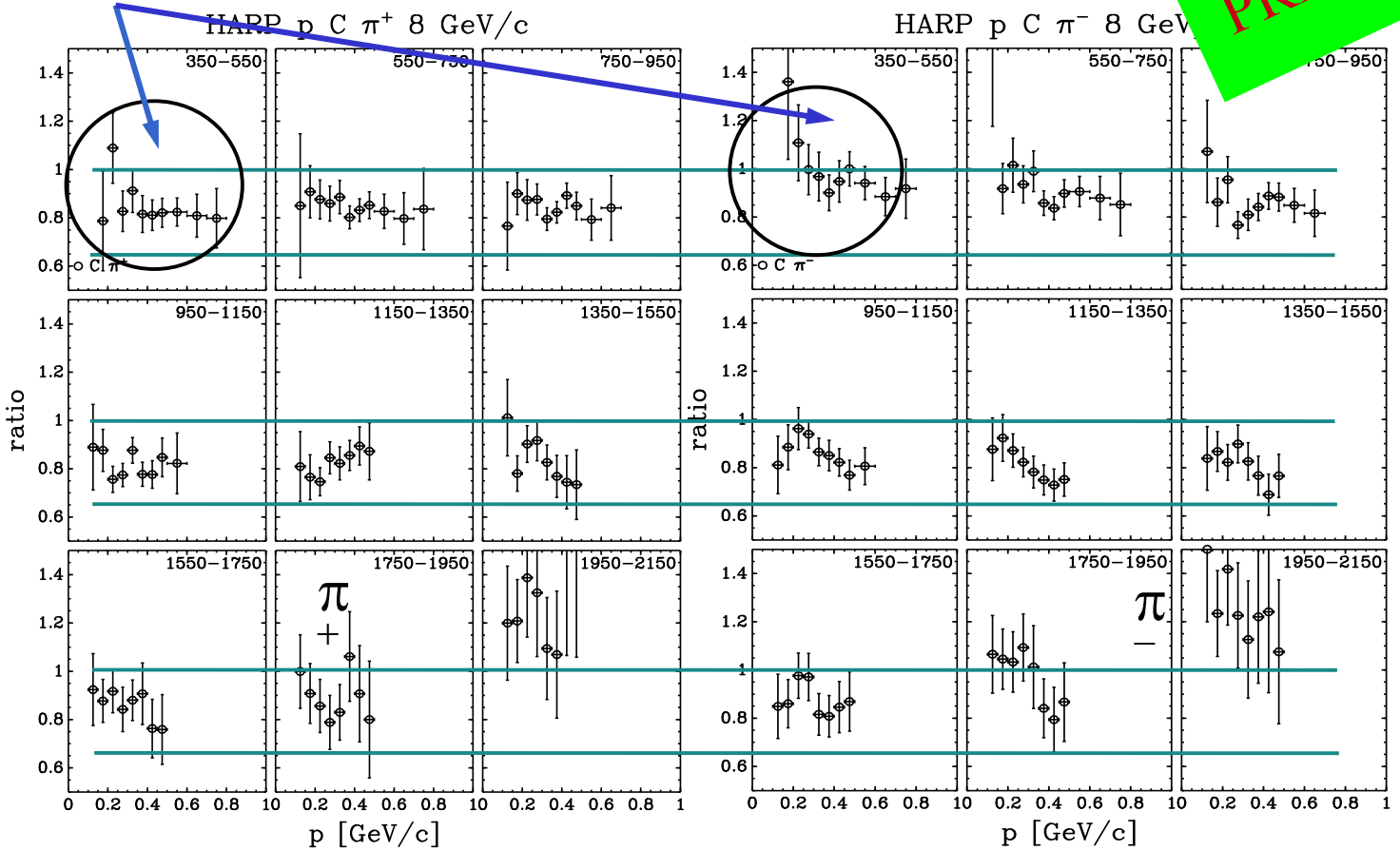
bin-by-bin ratio

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

100% / 5% TARGET

PRELIMINARY

large corrections



$\pi^{\pm}$ – beams

PRELIMINARY

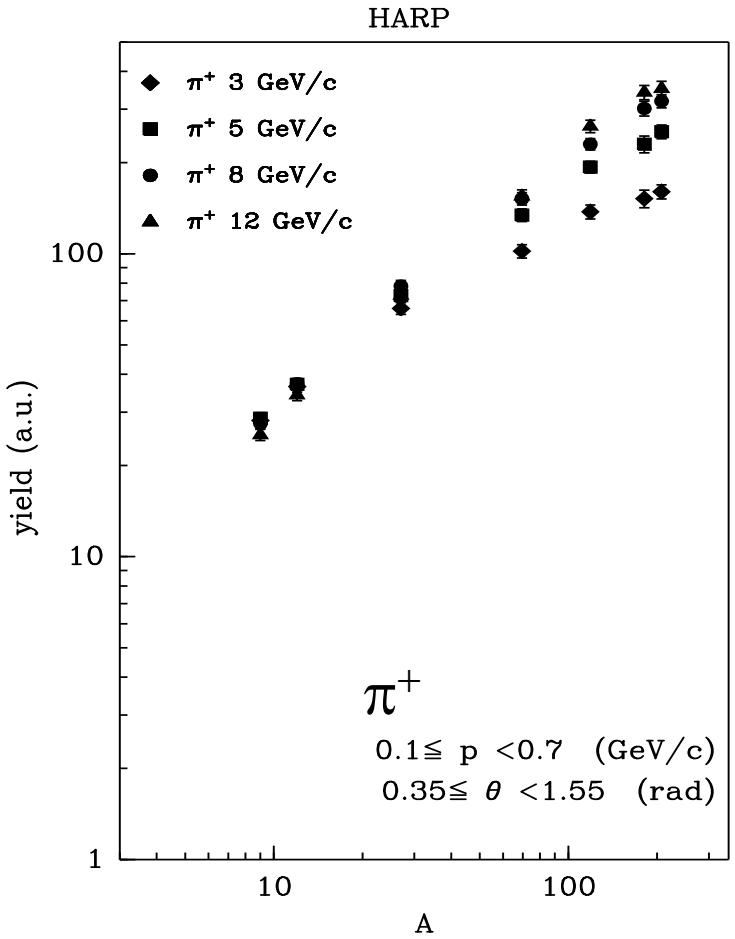
All thin target data taken in **pion** beams also available.

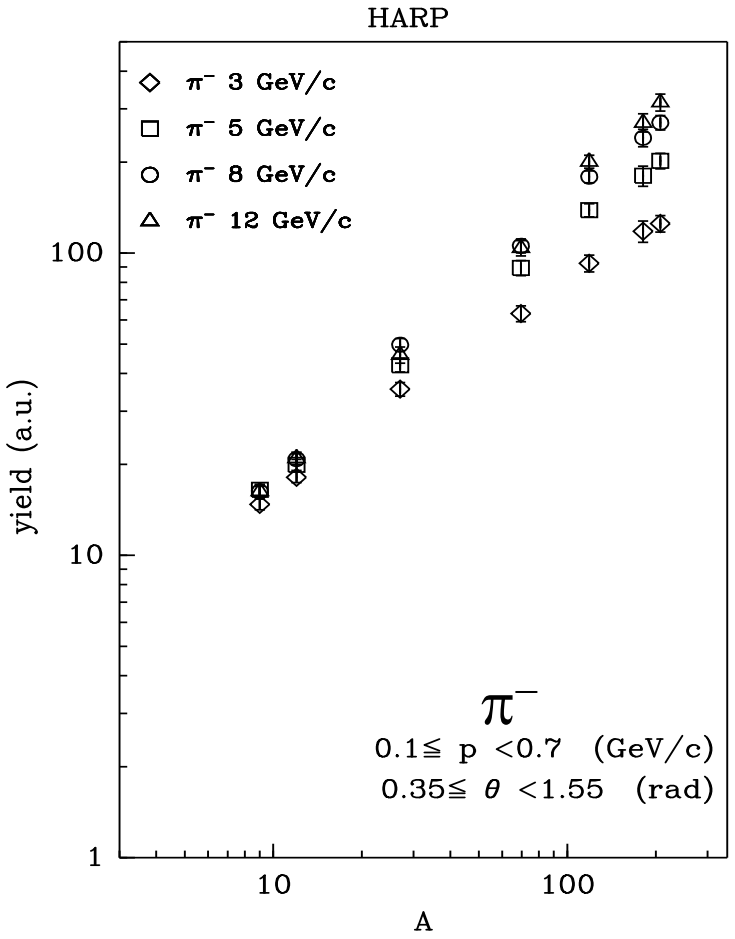
Interesting to tune models for re-interactions (and shower calculations in calorimeters etc.)

A-dependence of π^+ and π^- yields for π^+-A

Be, C, Cu, Sn, Ta and Pb

(3, 5, 8, 12 GeV/c) full spill data

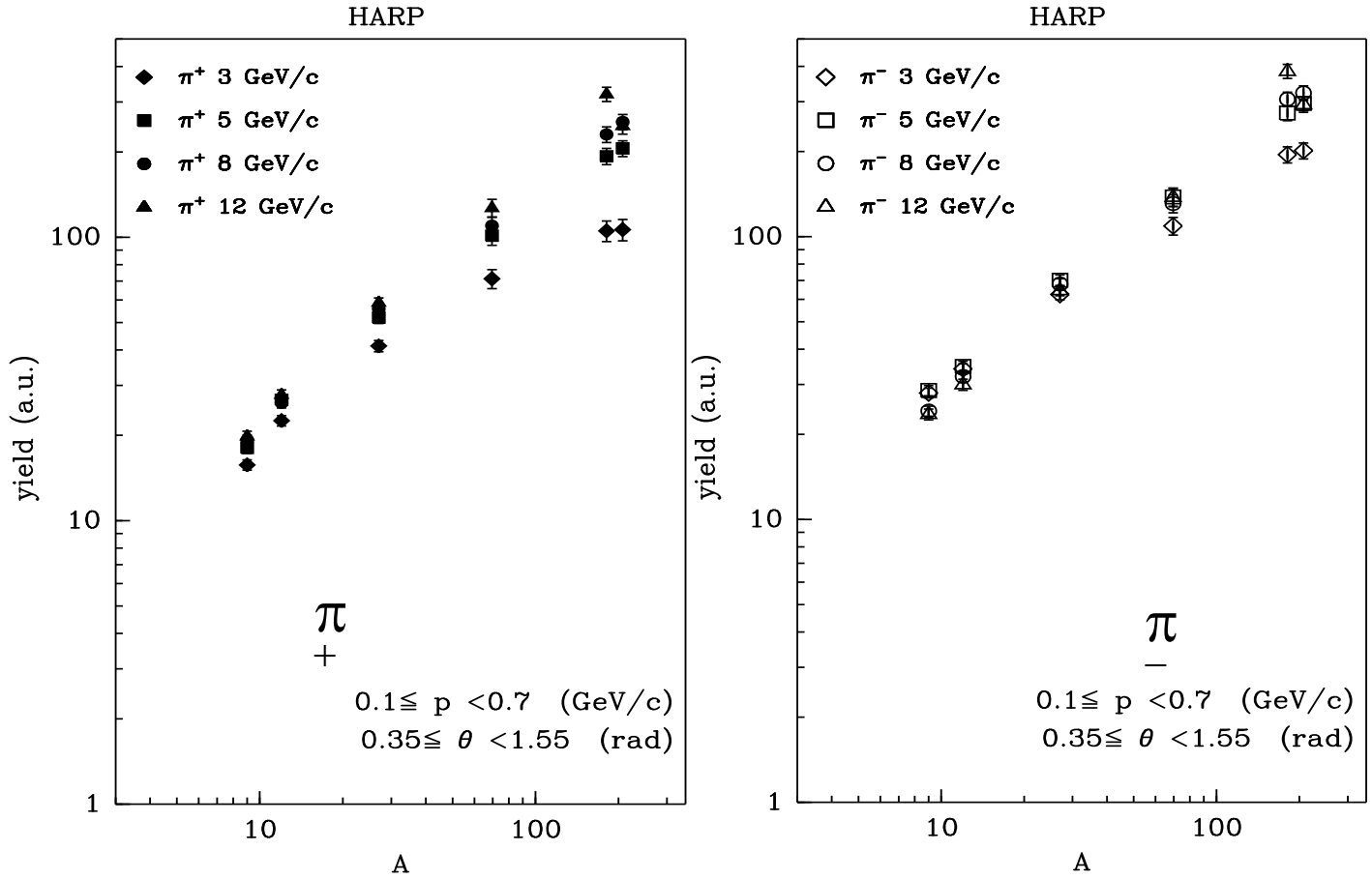


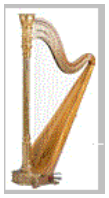


A-dependence of π^+ and π^- yields for π^- – A

Be, C, Cu, Sn, Ta and Pb

(3, 5, 8, 12 GeV/c) full spill data





MODELS

Many comparisons with models from GEANT4 and MARS are being done, starting with C and Ta

Some examples will be shown for 8 GeV/c

Binary cascade

Bertini cascade

Quark-Gluon string models (QGSP)

Frittiof (FTFP)

LHEP (successor of GEISHA)

MARS

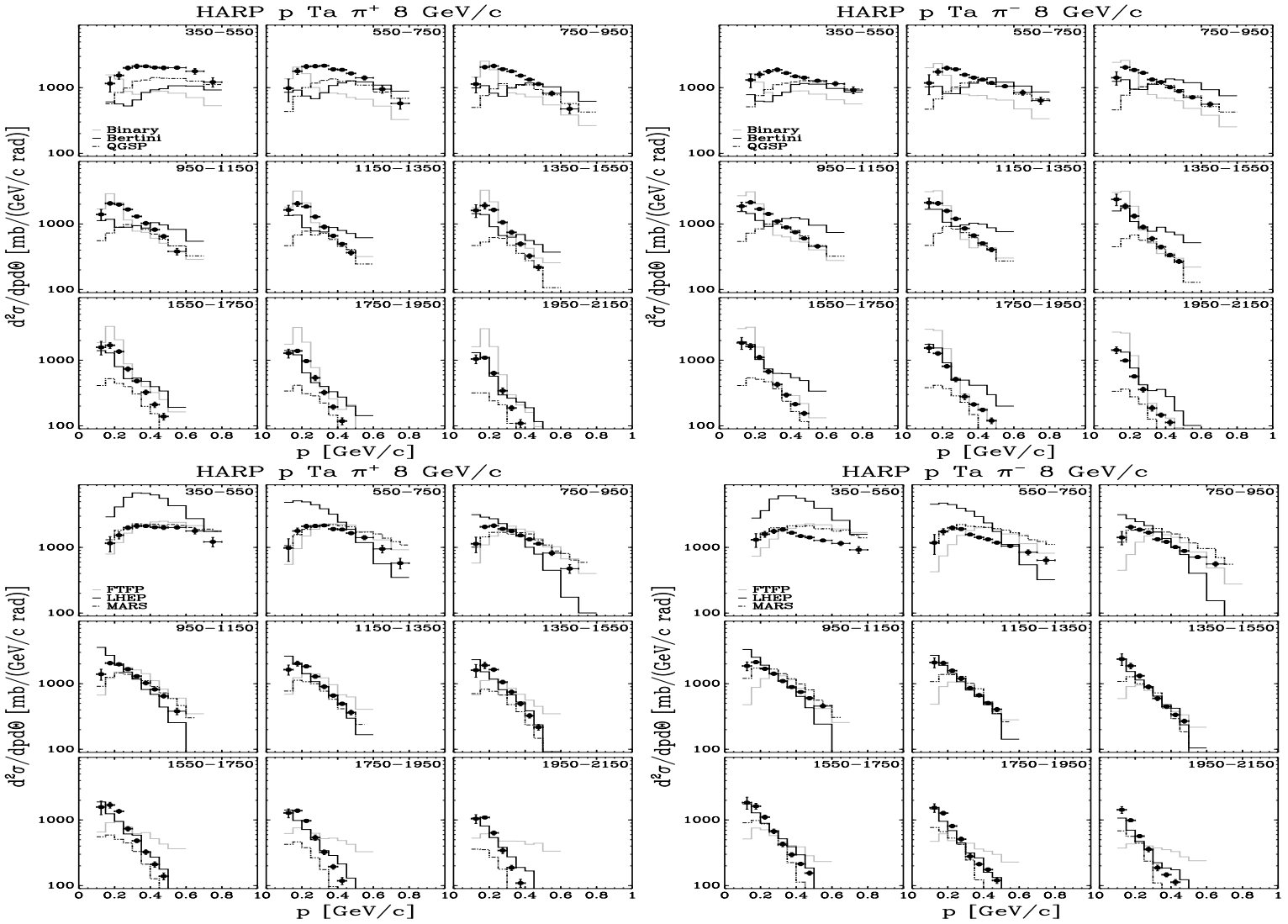
Some models do a good job in some regions, **but there is no model that describes all aspects of the data.**

Submitted for publication

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

5% λ target

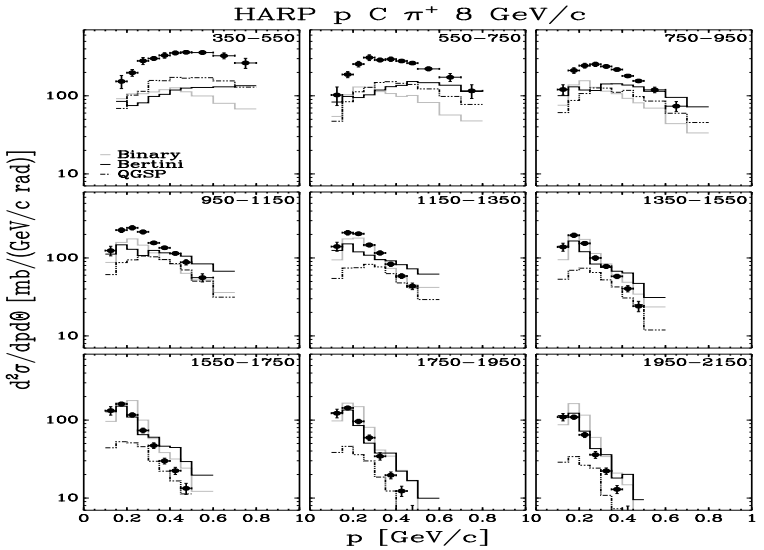
MODELS

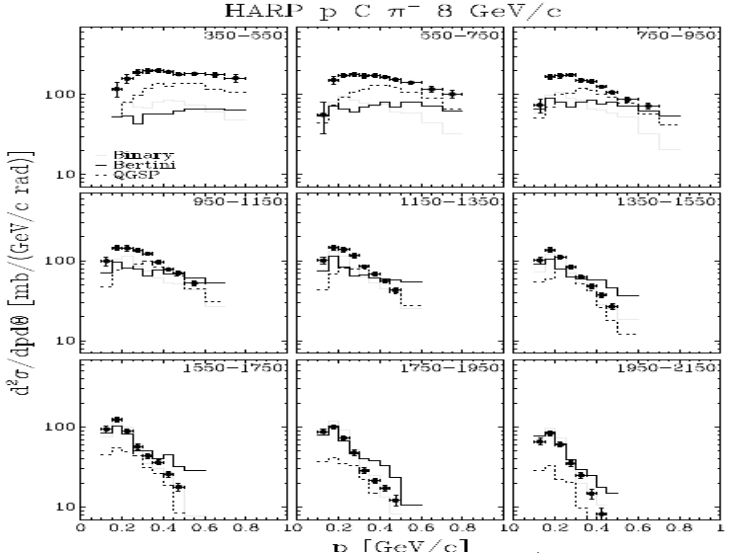


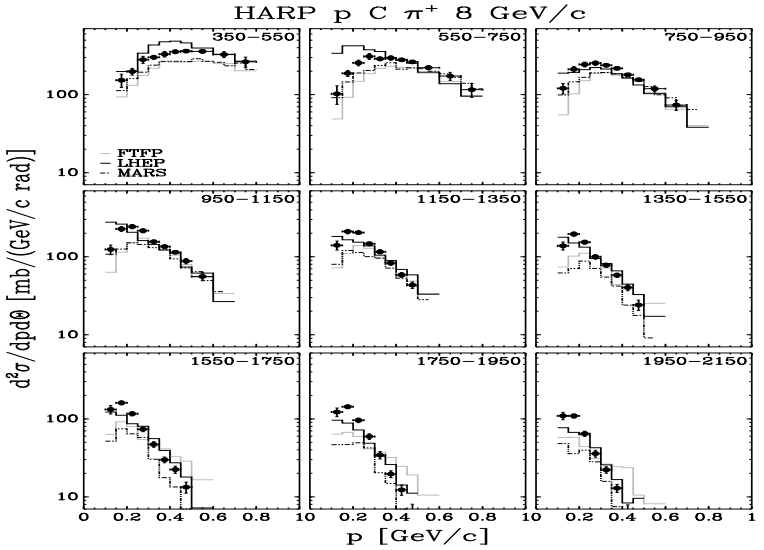
8 GeV/c p-C $\pi^{+/-}$

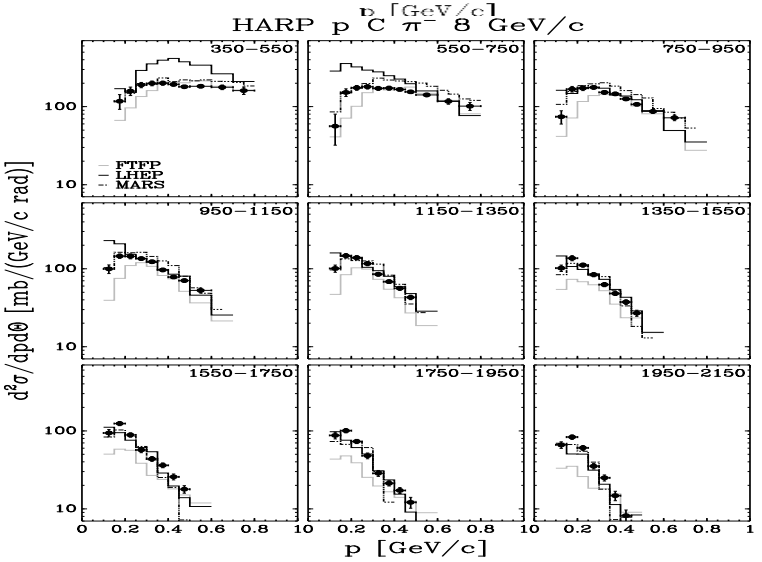
5% λ target

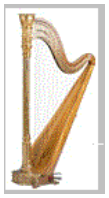
MODELS











Conclusions

HARP has measured pion production by 3 – 12 GeV/c protons and pions from nuclear targets (from Hydrogen to Lead) in the momentum – angular region 0.1 – 8 GeV/c and 0.03 – 2.15 rad.

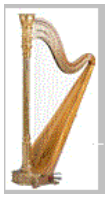
Large amount of data published, more in the pipe-line ☺.

(I managed to show just a fraction of the data already available ☹.)

NA61 (CERN SPS) starting up.

MIPP (FNAL Main Injector, E907 Exp.) coming soon with final results.

Models are now being challenged by the data, no single model describes all our data.



Published physics results

Measurement of the production cross-section of positive pions in p-Al collisions at 12.9 GeV/c, Nucl.Phys. **B732** (2006) 1-45

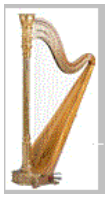
Measurement of the Production of Charged Pions by Protons on a Tantalum Target, Eur. Phys. J. **C51** (2007) 787-824 [arXiv:0706.1600].

Measurement of the production cross-section of positive pions in the collision of 8.9GeV/c protons on beryllium, Eur. Phys. J. **C52** (2007) 29-53 [hep-ex/0702024].

Large-angle production of charged pions by 3 GeV/c-12 GeV/c protons on carbon, copper and tin targets , Eur. Phys. J. C (2007) DOI 10.1140/epjc/s10052-007-0475-4 [arXiv:0709.3464]

Large-angle production of charged pions by 3 GeV/c-12.9 GeV/c protons on beryllium, aluminium and lead targets, Eur. Phys. J. C(2008) DOI 10.1140/epjc/s10052-007-0517-y, [arXiv: 0709.3458]

Measurement of the production cross-sections of $\pi^{\pm}$ in p-C and $\pi^{\pm}$ -C interactions at 12 GeV/c, Astropart. Phys. (2008), DOI 10.1016/j.astropartphys.2008.02.002 [arXiv:0802.0657]



Backup slides

Recipe for a cross-section

$$\frac{d^2\sigma^{\pi}}{dp\,d\Omega} = \frac{A}{N_A \rho\, t}\frac{1}{N_{\text{pot}}}\left[\text{correction factors}(p,\theta)\right]\frac{\Delta^2 N^{\pi}}{\Delta p\,\Delta\Omega}$$

yield

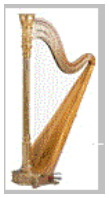
- Select events identified as primary protons interacting in the target
- For each event reconstruct tracks and their 3-momentum
- Identify pions among secondary tracks

eff. & mig.

- Apply corrections for reconstructed-to-true pion yield conversion:
  - Momentum resolution
  - Spectrometer angular acceptance
  - Track reconstruction efficiency
  - Efficiency and purity of pion identification
  - Other

norm.

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



Models

In the following we will show only some comparisons with publicly available Monte Carlo simulations: **GEANT4 [27] and MARS [39],** using different models. We stress that no tuning to our data has been done by the GEANT4 or MARS teams. The comparison will be shown for a limited set of plots and only for the C and Ta targets, as examples of a light and a heavy target.

At intermediate energies (up to 5-10 GeV), GEANT4 uses two types of intra-nuclear cascade models: the **Bertini model** [35, 36] (valid up to 10 GeV) and the **binary model** [34] (valid up to 3 GeV). Both models treat the target nucleus in detail, taking into account density variations and tracking in the nuclear field. The binary model is based on hadron collisions with nucleons, giving resonances that decay according to their quantum numbers. The Bertini model is based on the cascade code reported in [37] and hadron collisions are assumed to proceed according to free-space partial cross sections and final state distributions measured for the incident particle types.

At higher energies, instead, **two parton string models, the quark-gluon string (QGS) model [35, 38] and the Fritiof (FTP) model [38] are used, in addition to a High Energy Parametrized model (HEP) derived from the high energy part of the Gheisha code used inside GEANT3 [41].**

The **parametrized models of GEANT4 (HEP and LEP**) are intended to be fast, but conserve energy and momentum on average and not event by event.

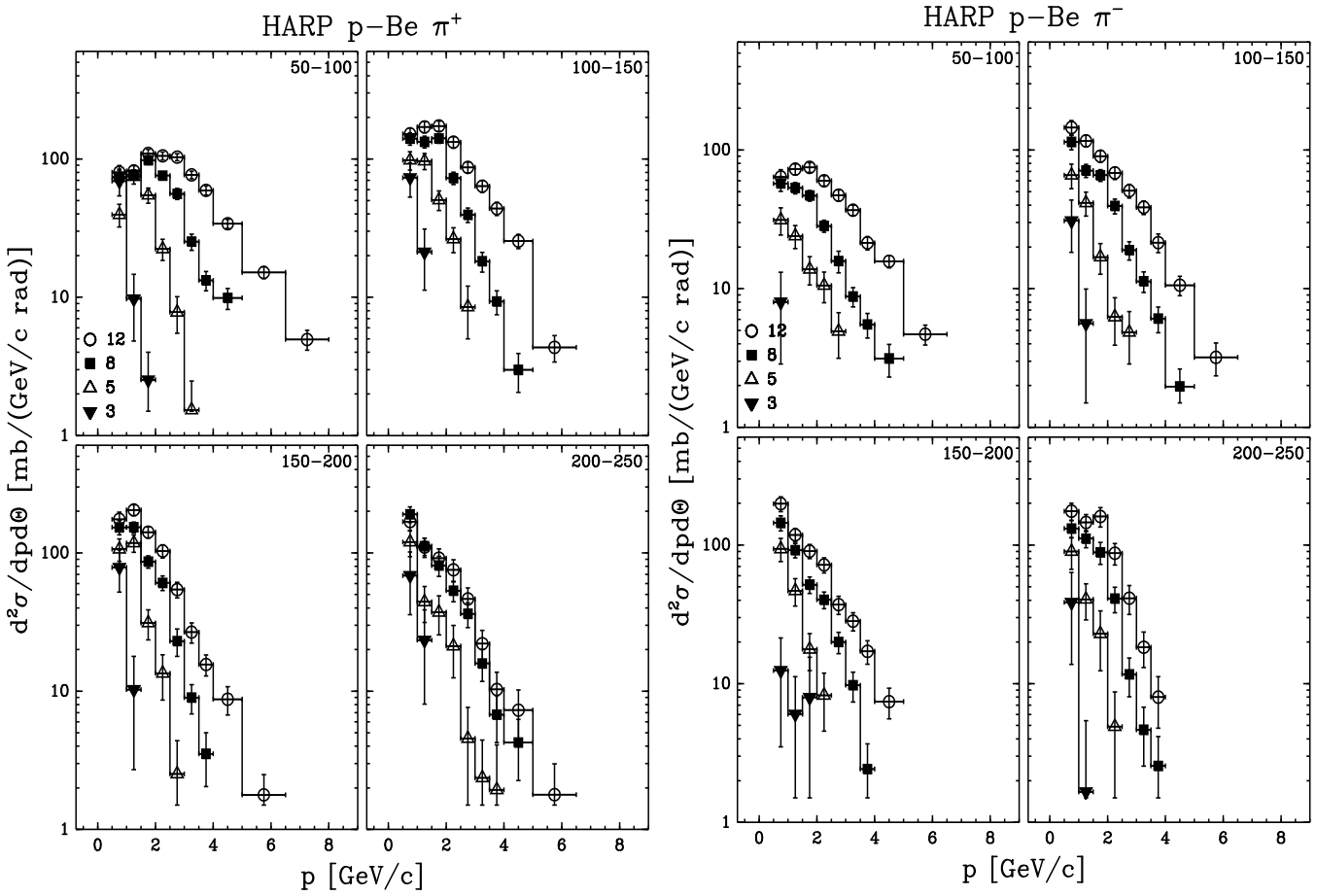
A realistic GEANT4 simulation is built by combining models and physics processes into what is called a "physics list". In high energy calorimetry the two most commonly used are the QGSP physics list, based on the QGS model, the pre-compound nucleus model and some of the Low Energy Parametrized (LEP) model and the LHEP physics list [33] based on the parametrized LEP model and HEP models.

The **MARS code system** [39] uses as basic model an inclusive approach multiparticle production originated by R. Feynmann. Above 3 GeV phenomenological particle production models are used, while below 5 GeV a cascade-exciton model [40] combined with the Fermi break-up model, the coalescence model, an evaporation model and a multifragmentation extension are used instead.

The comparison, just outlined in our paper, between data and models is reasonable, but some discrepancies are evident for some models especially at lower energies and small angles. Discrepancies up to a factor of three are seen.

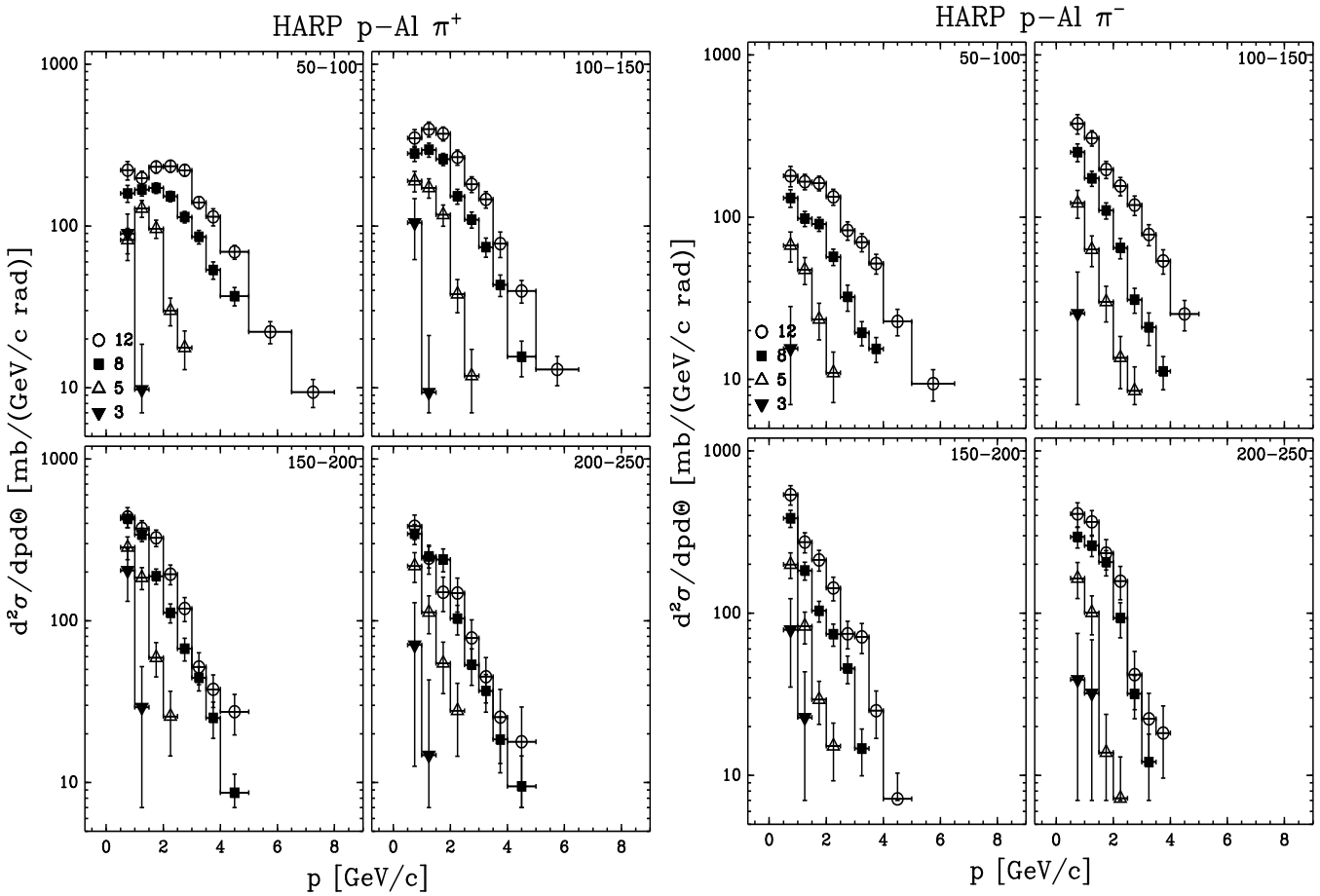
HARP p+Be @ 3, 5, 8, 12 GeV/c

Preliminary



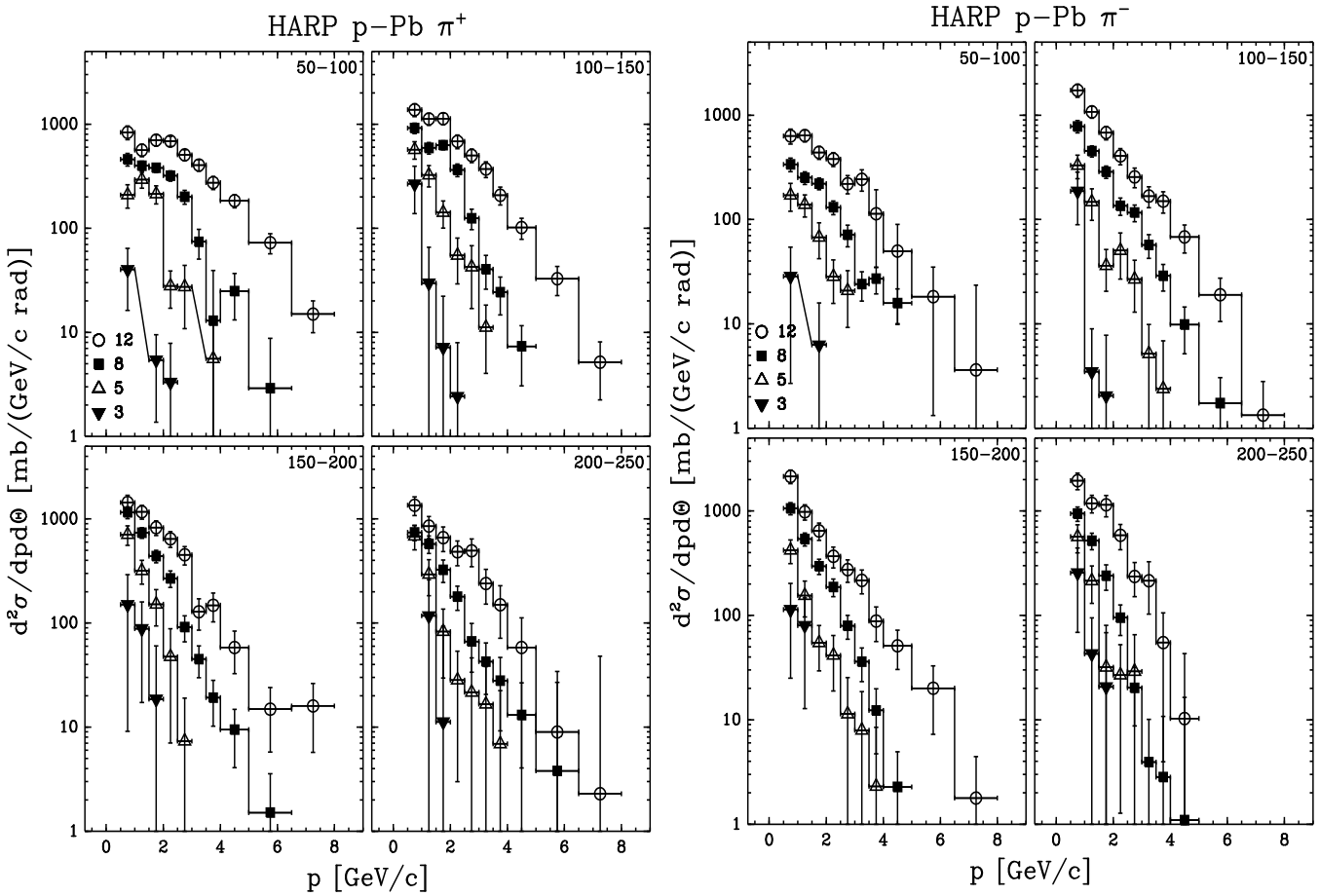
HARP p+Al @ 3, 5, 8, 12 GeV/c

Preliminary



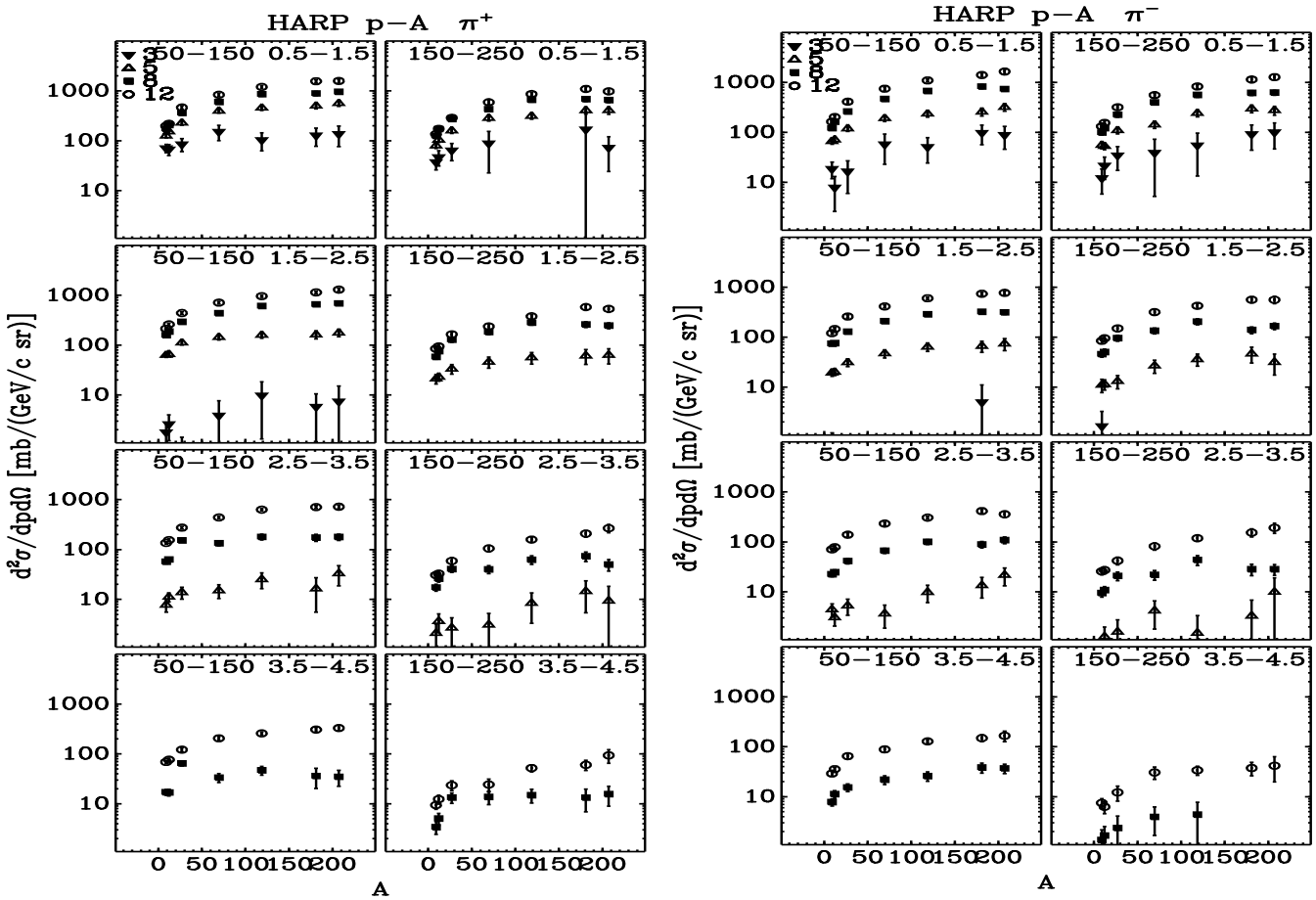
HARP p+Pb @ 3,5, 8, 12 GeV/c

Preliminary



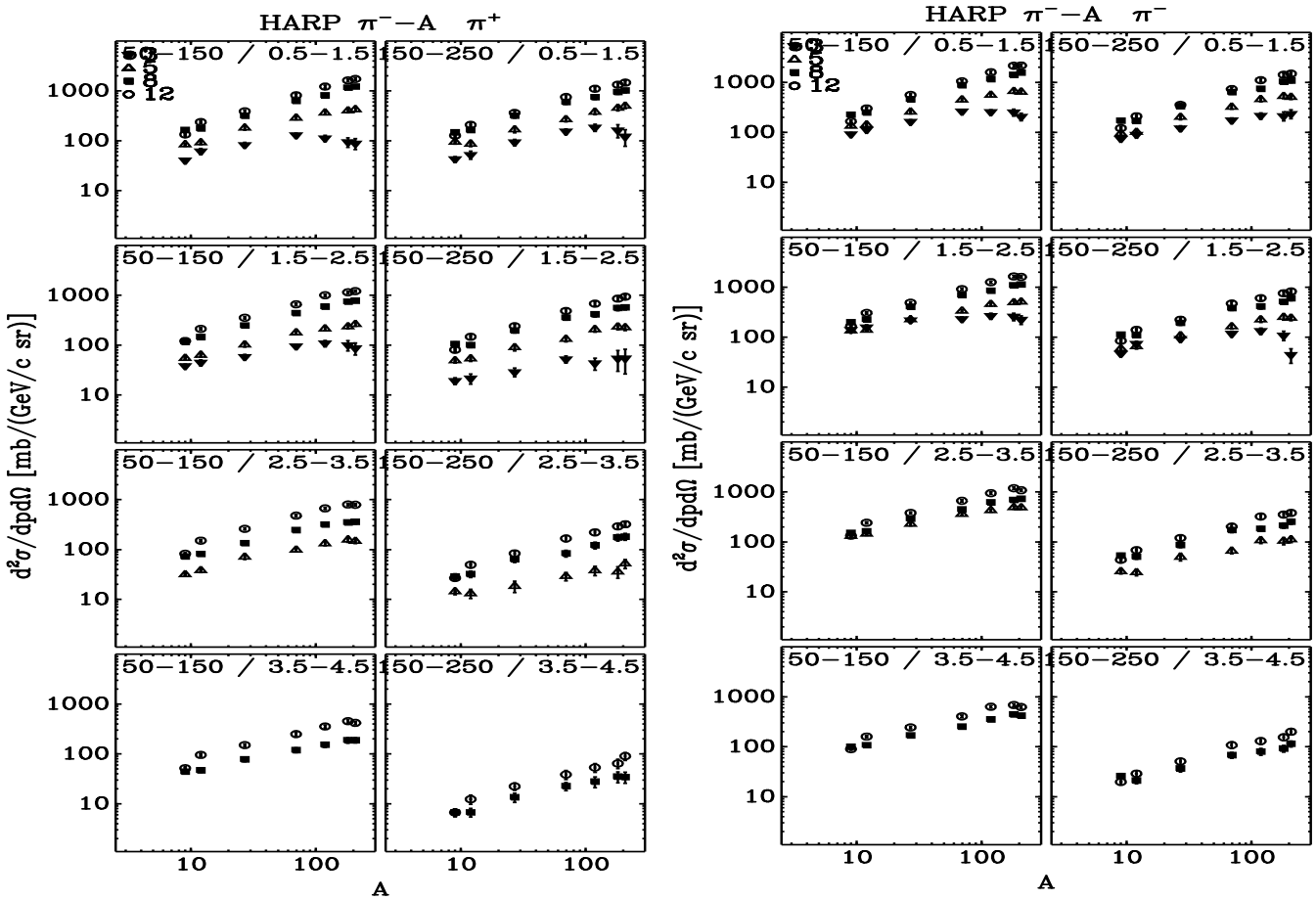
HARP pA trends with A

Preliminary



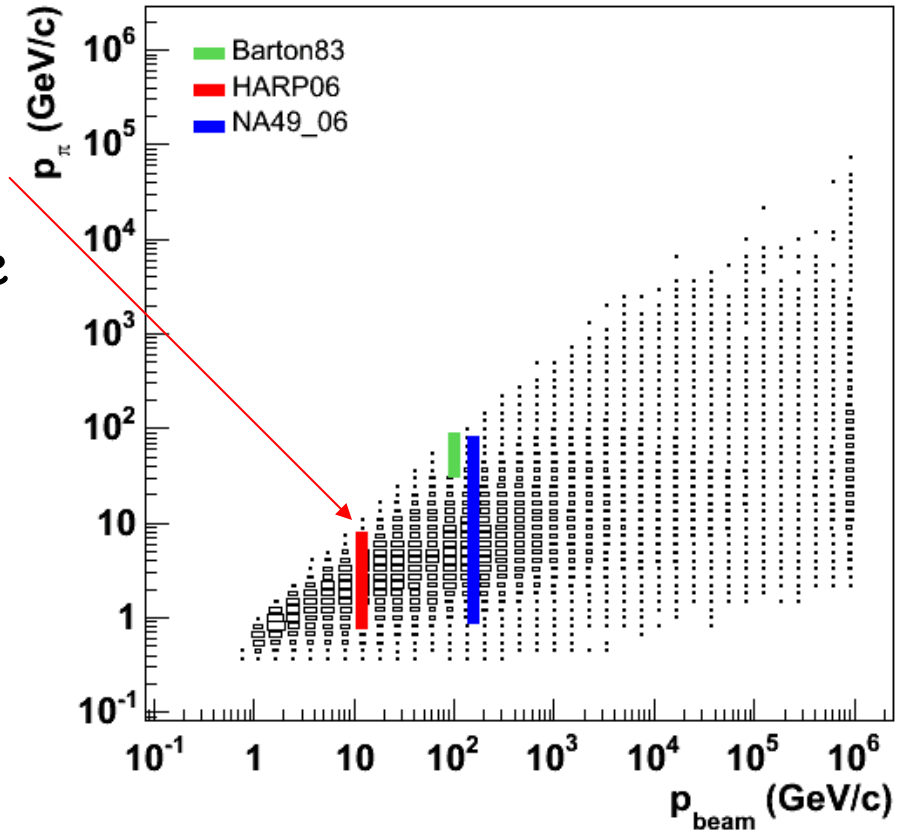
HARP π^-A trends with A

Preliminary



Phase space region

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

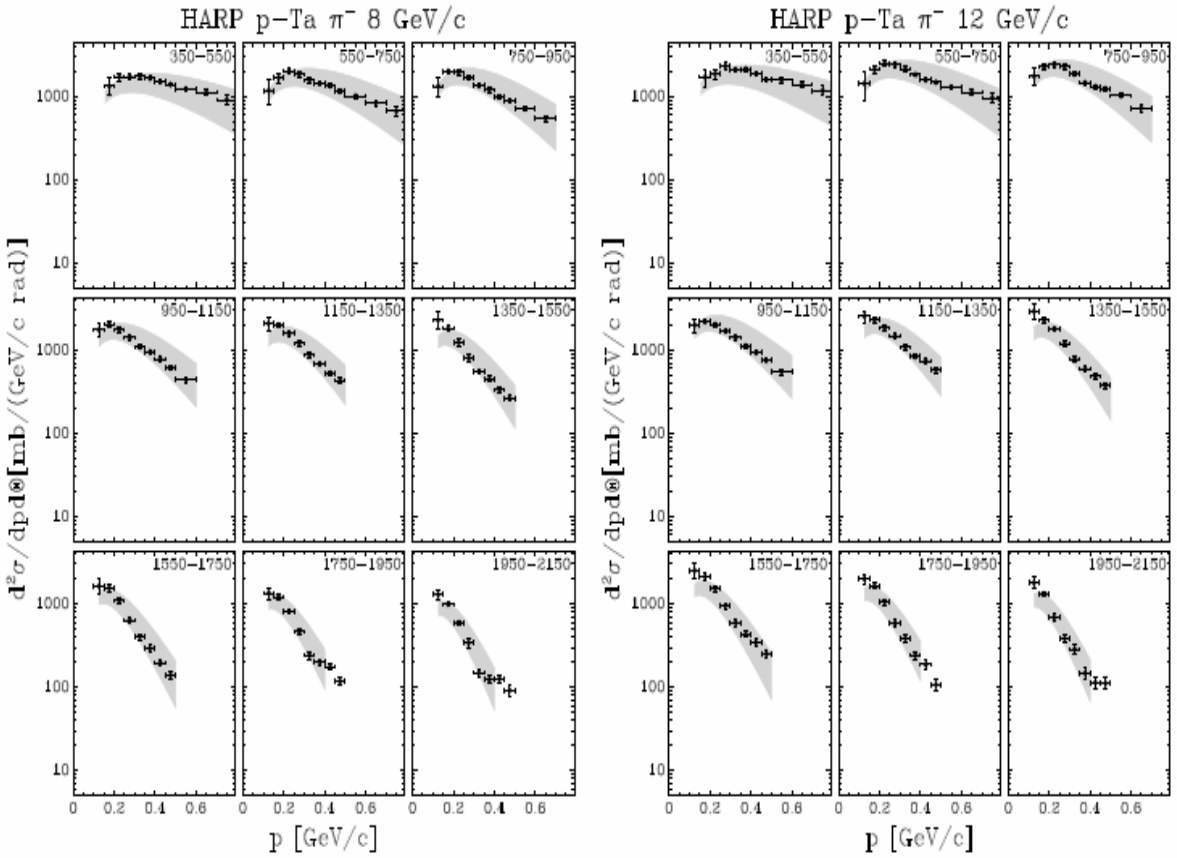


[Barton83] Phys. Rev. D 27 (1983) 2580 (Fermilab)

[NA49_06] Eur.Phys.J. C49 (2007) 897 (SPS)

[HARP] Astropart. Phys. (2008), doi:10.1016/j.astropartphys.2008.02.002 [arXiv:0802.0657] (PS)

Comparison with buble chamber data (1)
π^--production at 10 GeV/c p-Ta interactions (JINR-P1-91-191)



data points: HARP

shaded region: buble chamber data

Figure 28: Comparison of the HARP data with data from Ref. [33]. The left panel shows the comparison of the parametrization of the 10 GeV/c data of Ref. [33] with the 8 GeV/c data reported here; the right panel shows the comparison with the 12 GeV/c data. The absolute normalization of the parametrization was fixed to the data in both cases. The band shows the range allowed by varying the slope parameters given by [33] with two standard deviation and a 10% variation on the absolute scale.

Comparison with bubble chamber data
π^--production (2)

4.2 GeV/c data

G.H. Agakishiev et al., Sov. J. Nucl. Phys. 51, 1009 (1990)
JINR-P1-89-793, 1989

10 GeV/c data

D. Armutliiski et al., JINR-P1-91-191

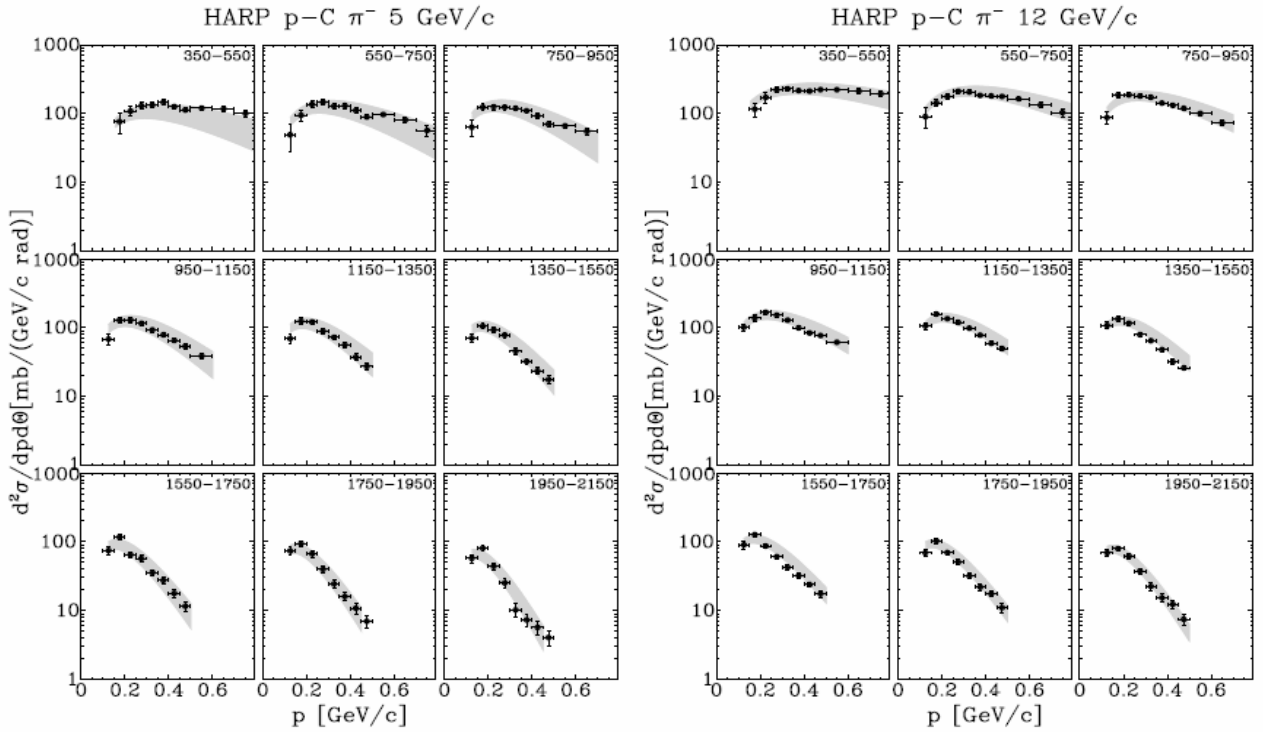


Fig. 8. Comparison of the HARP p–C results with data from [32, 33] and [34]. The *left panel* shows the comparison of the parametrization of the 4.2 GeV/c data of [32, 33] with the 5 GeV/c data reported here; the *right panel* shows the comparison of the 10 GeV/c parametrization of [34] with the 12 GeV/c data. The absolute normalization of the parametrization was fixed to the data in both cases. The *band* shows the range allowed by varying the slope parameters given by [32, 33] and [34] with two standard deviation and a 10% variation on the absolute scale. The angular ranges are shown in mrad in the panels

data points: HARP

shaded region: buble chamber data