Results from hadroproduction experiments and their implications for neutrino physics

XIV International Workshop on "Neutrino Telescopes", March,15-18 2011, Venice

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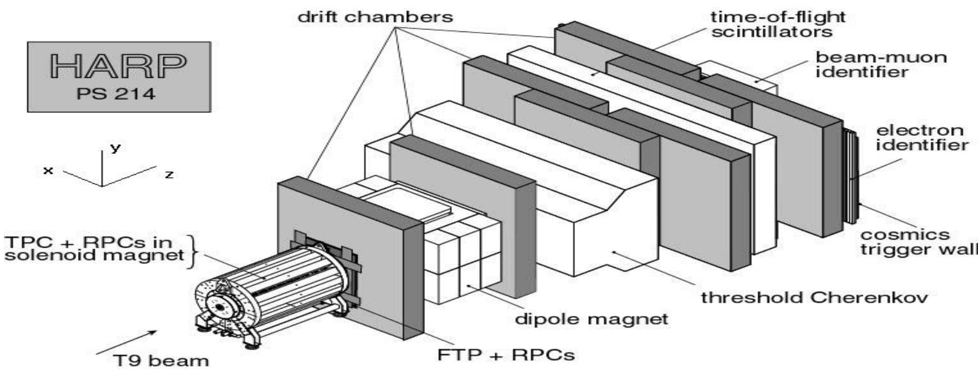
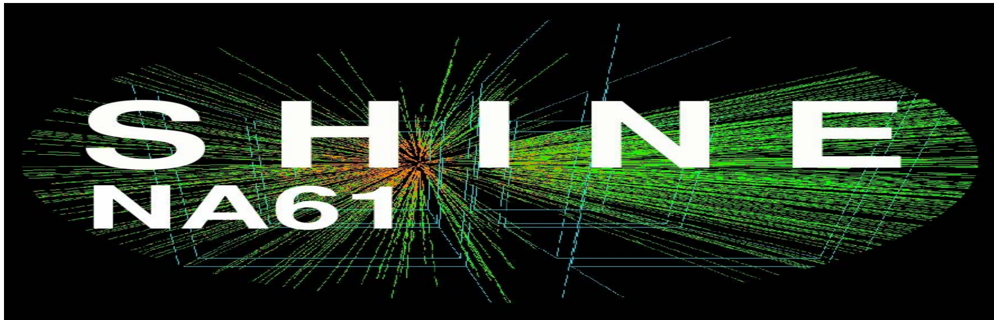
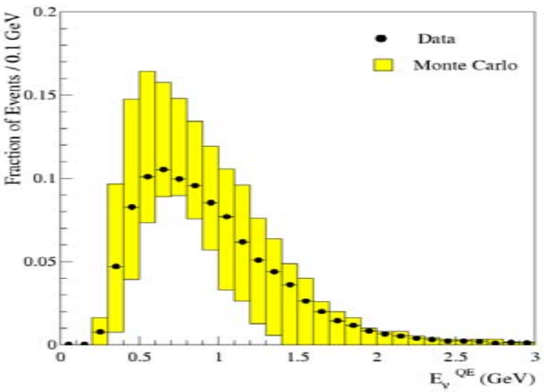
- **Goals of hadroproduction experiments**
- **HARP experiment**
  - *Results and Impacts*
- **MIPP experiment**
  - *Current status*
- **NA61 experiment**
  - *First results, status and plans*
- **Summary**



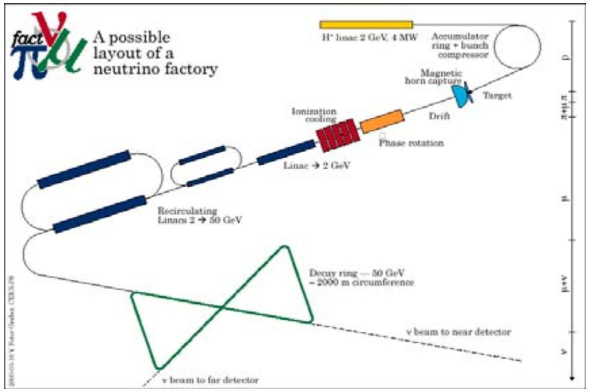


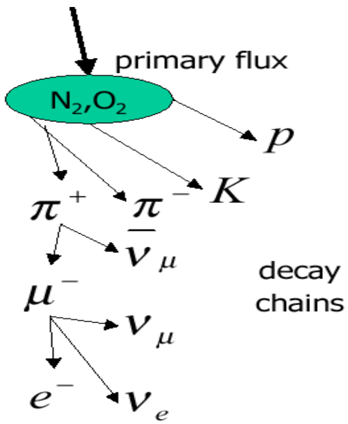
Goals of hadroproduction studies



Input for prediction of **neutrino fluxes** in modern accelerator neutrino experiments

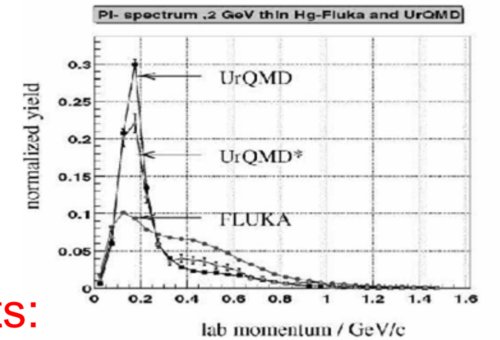
Pion/Kaon yield for the design of the proton driver and target system of **Neutrino Factories** and **Super-Beams**





Input for precise calculation of the **atmospheric neutrino** flux (from yields of secondary π,K) and for interpretation of air showers initiated by **UHE cosmic rays**

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



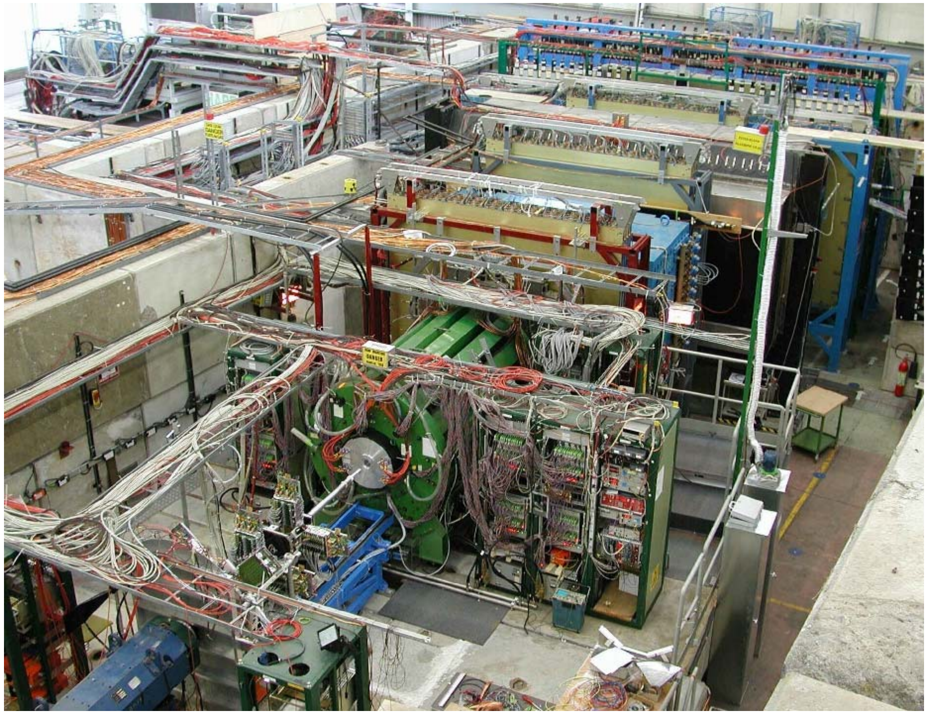
NIM-A 472 (2001) 557-560

Significant progress during the last decade. Dedicated experiments: HARP, MIPP, NA61/SHINE…

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

forward spectrometer



large angle spectrometer

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

Data taking in 2001-2002

p = 0.5 – 8.0 GeV/c θ = 25 – 250 mrad   (forward)

p = 0.1 – 0.8 GeV/c θ = 350 – 2150 mrad   (large angle)

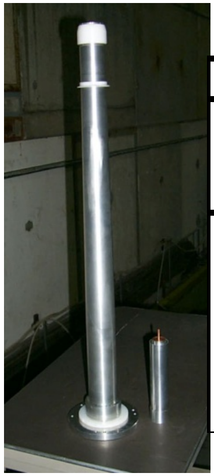
hadron production measurements in "*seven dimensions*"

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

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

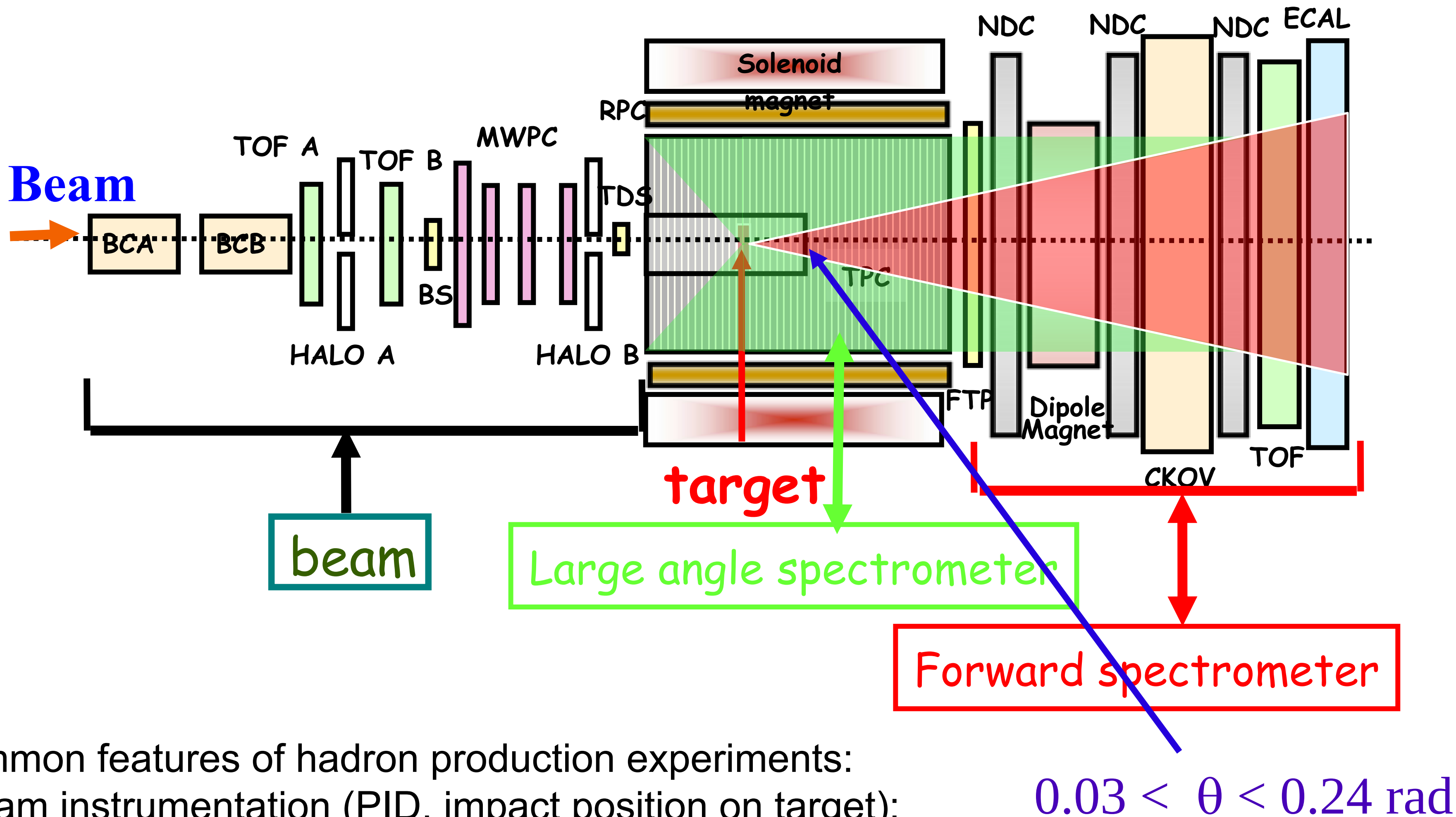
CRYOGENIC:

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



Common features of hadron production experiments:
- beam instrumentation (PID, impact position on target);
- target under study with an elaborate trigger system;
- magnetic spectrometer with PID capabilities;

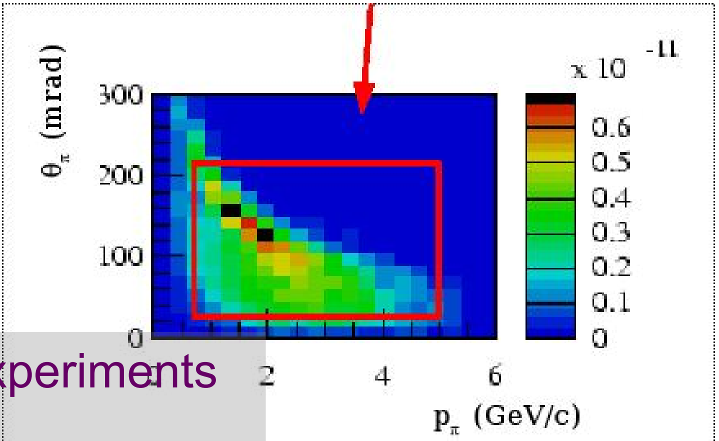
HARP: Analyses with the forward spectrometer

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*)

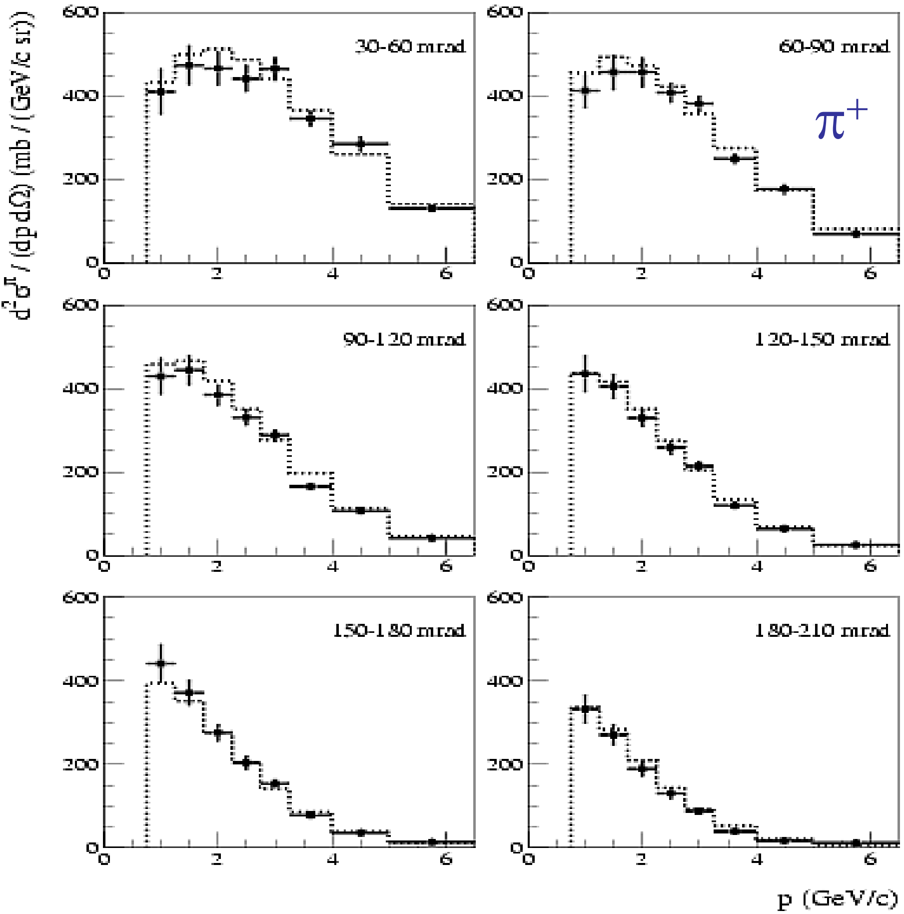
HARP p-Al data 12.9 GeV/c: M. G. Catanesi et al. [HARP Collaboration], Nucl. Phys. **B732** (2006) 1

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

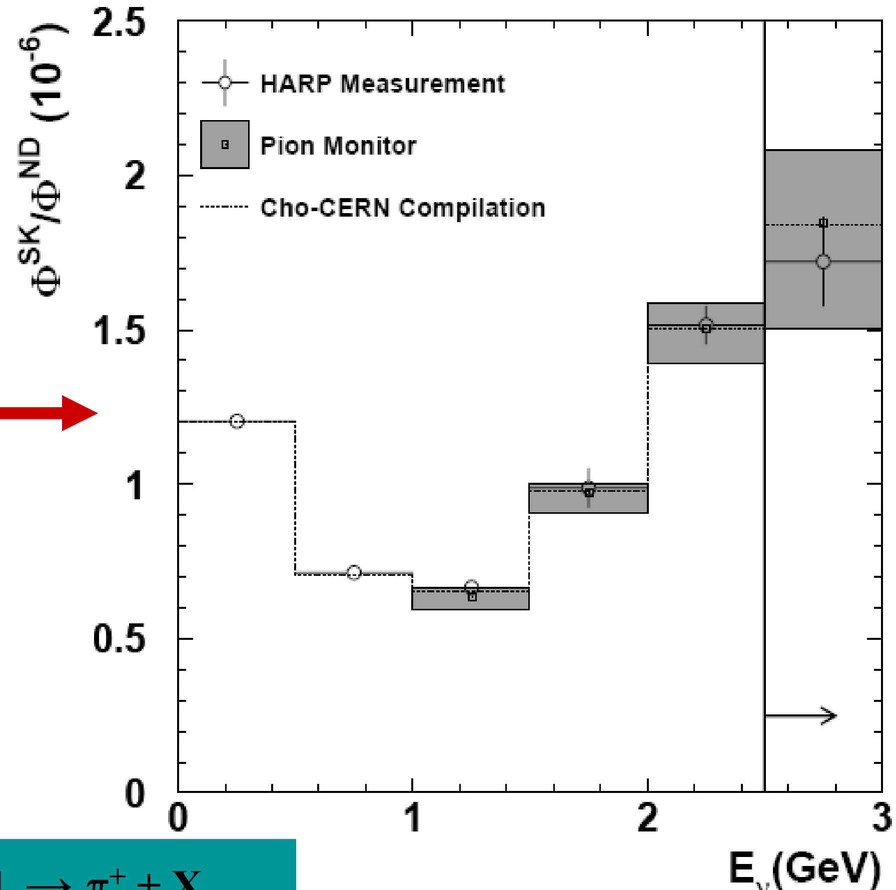
HARP p-Be data 8.9 GeV/c: M. G. Catanesi et al. [HARP Collaboration], Eur. Phys. J. **C52** (2007) 29

MiniBooNE results with HARP input:
A. A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], Phys. Rev. Lett. **98** (2007) 231801,
Phys. Rev. D79 (2009) 072002

K2K Far/Near flux ratio prediction



Far-to-near (F/N) ratio



Nucl. Phys. B732 (2006) 1

p(12.9 GeV/c) + Al $\rightarrow \pi^+ +$ X

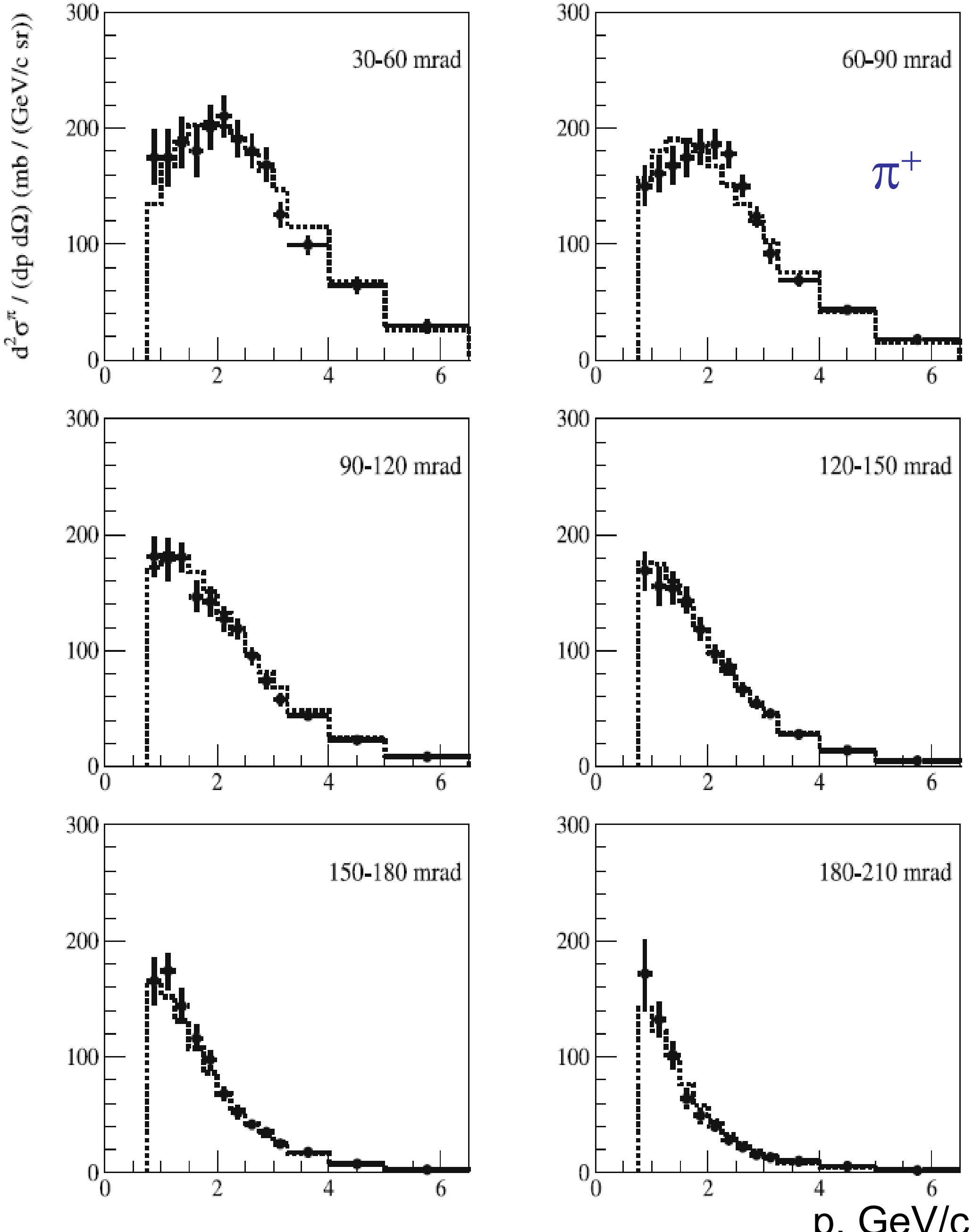
- HARP Al cross-section results have provided an important cross-check on previous K2K flux predictions. Results completely consistent in shape

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 : 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 $\longrightarrow \pi^+$ + X

An aside on the SW* parameterization

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

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

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

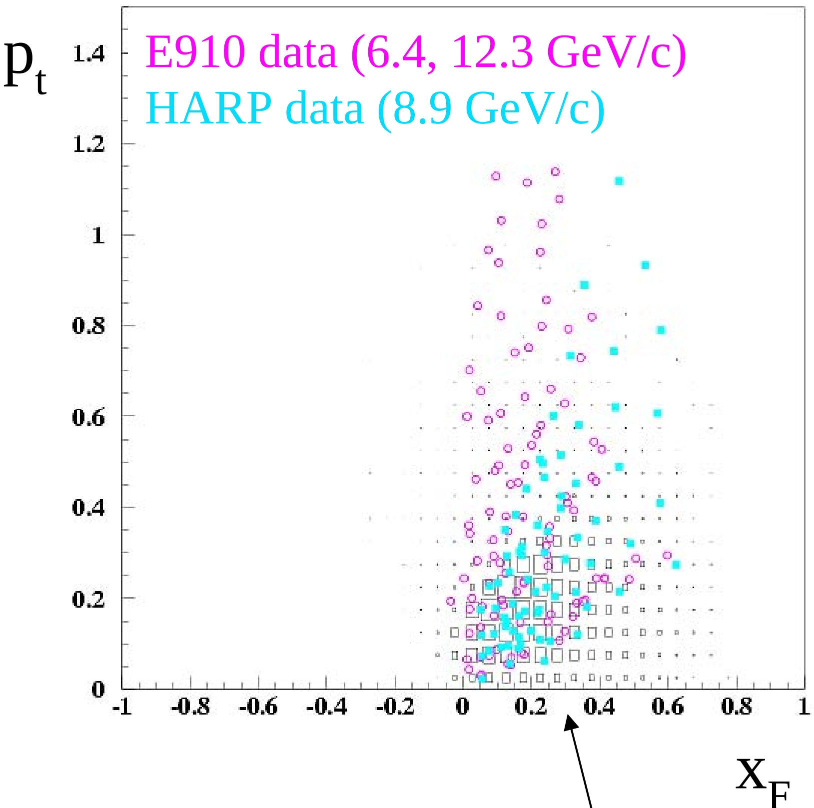
Parameter	c_1	c_2	c_3	$c_4 = c_5$	c_6	c_7	c_8
c_1	1.000						
c_2	0.327	1.000					
c_3	0.986	0.482	1.000				
$c_4 = c_5$	-0.559	0.596	-0.411	1.000			
c_6	0.091	-0.467	-0.006	-0.545	1.000		
c_7	0.011	-0.101	-0.004	-0.129	0.234	1.000	
c_8	-0.080	0.411	0.006	0.471	-0.776	0.215	1.000

HARP measurements for p+Be at 8.9 GeV/c

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

EPJ C 52 (2007) 29

MiniBooNE ν_μ flux prediction

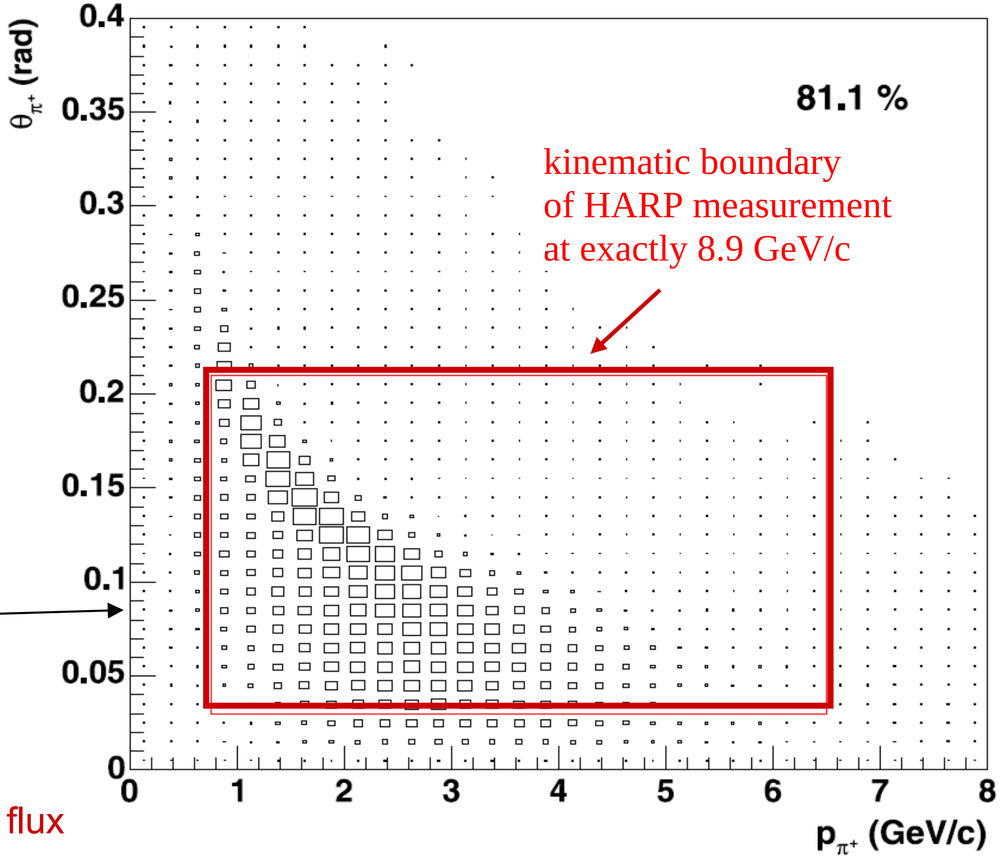


- black boxes are the distribution of π^+ which decay to a ν_μ that **passes through the MiniBooNE detector**

p(8.9 GeV/c) + Be $\rightarrow \pi^+ \rightarrow \nu_\mu^{MB}$

- 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



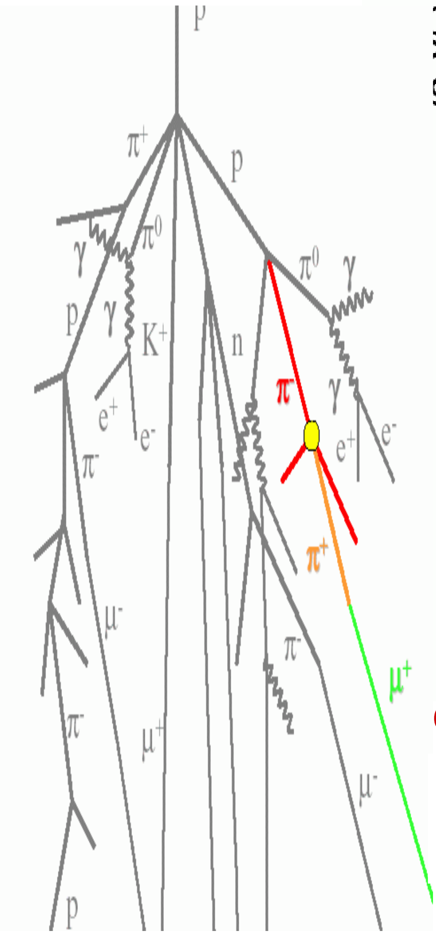
HARP Be measurements were used for the neutrino flux prediction in MiniBooNE

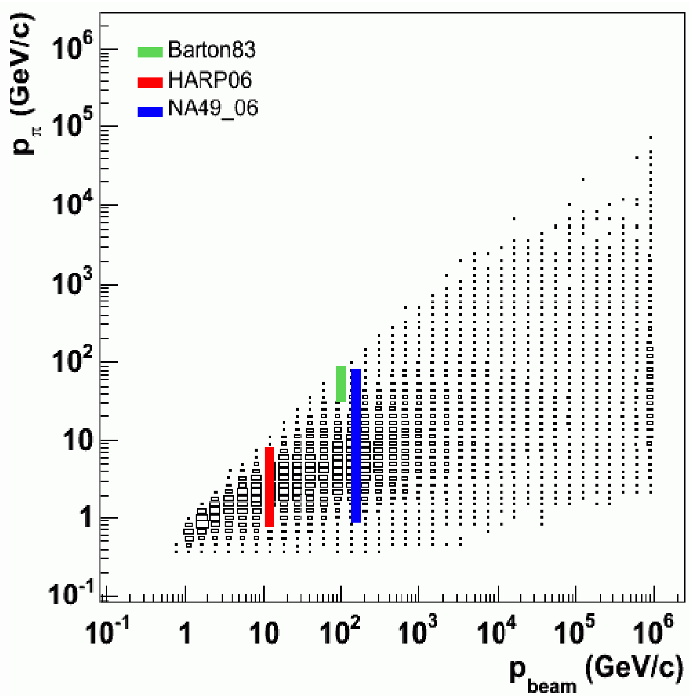
Phys. Rev. Lett. 98 (2007) 231801

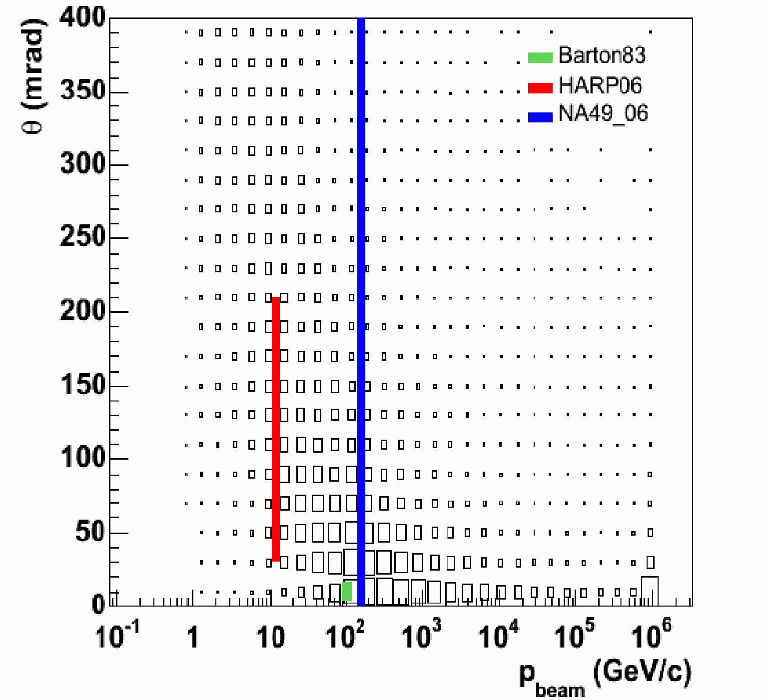
Phys. Rev. D79 (2009) 072002

Atmospheric neutrino flux predictions

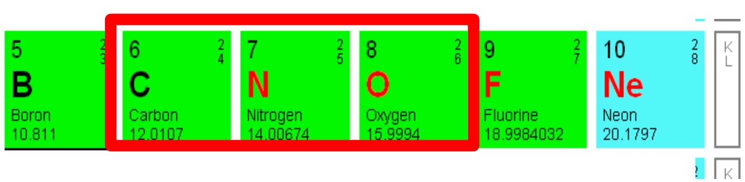
- **HARP p+C @ 12 GeV/c** data are relevant to the prediction of atmospheric neutrino fluxes and EAS simulations







carbon is isoscalar as nitrogen and oxygen

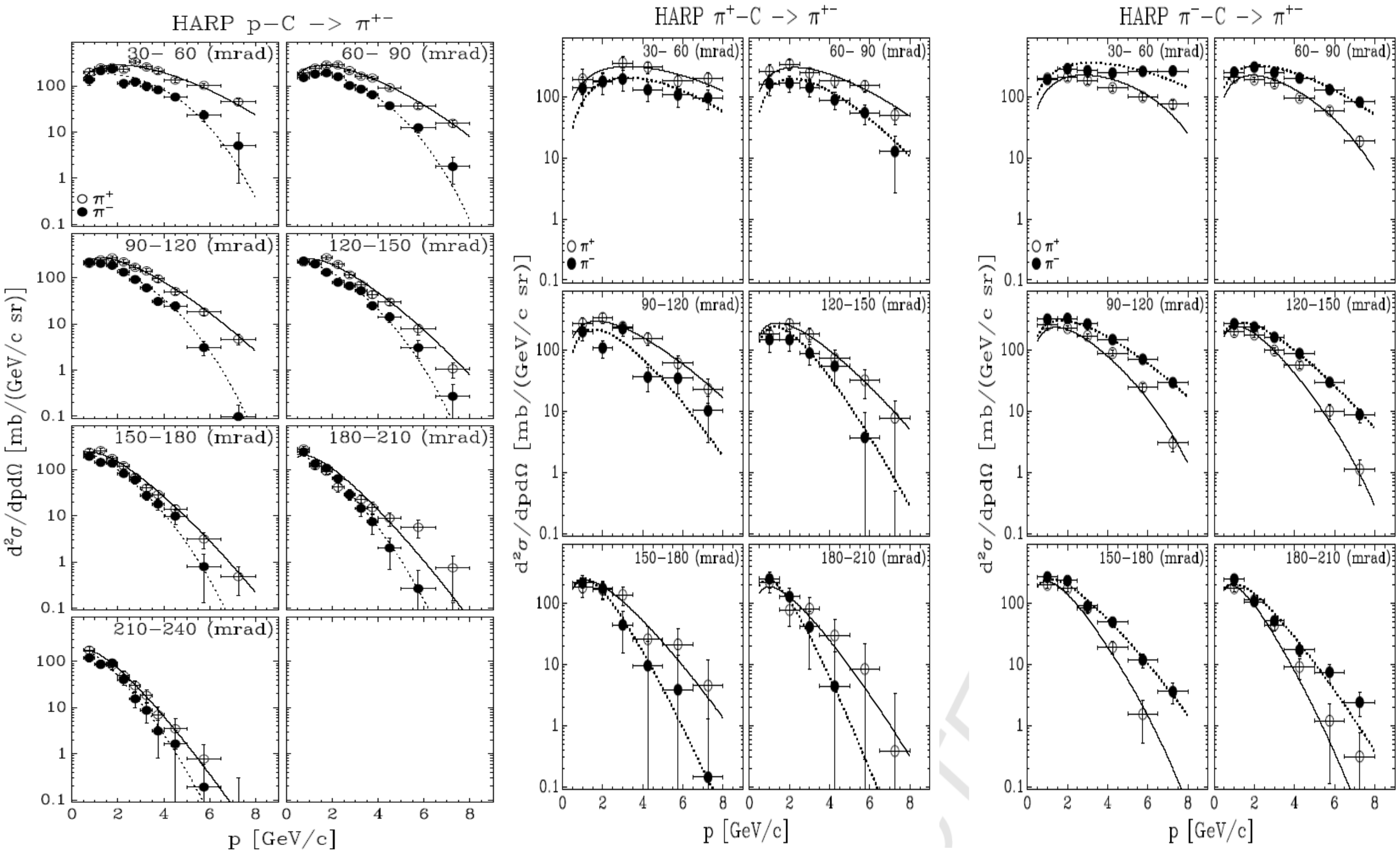


78% nitrogen

21% oxygen

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

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

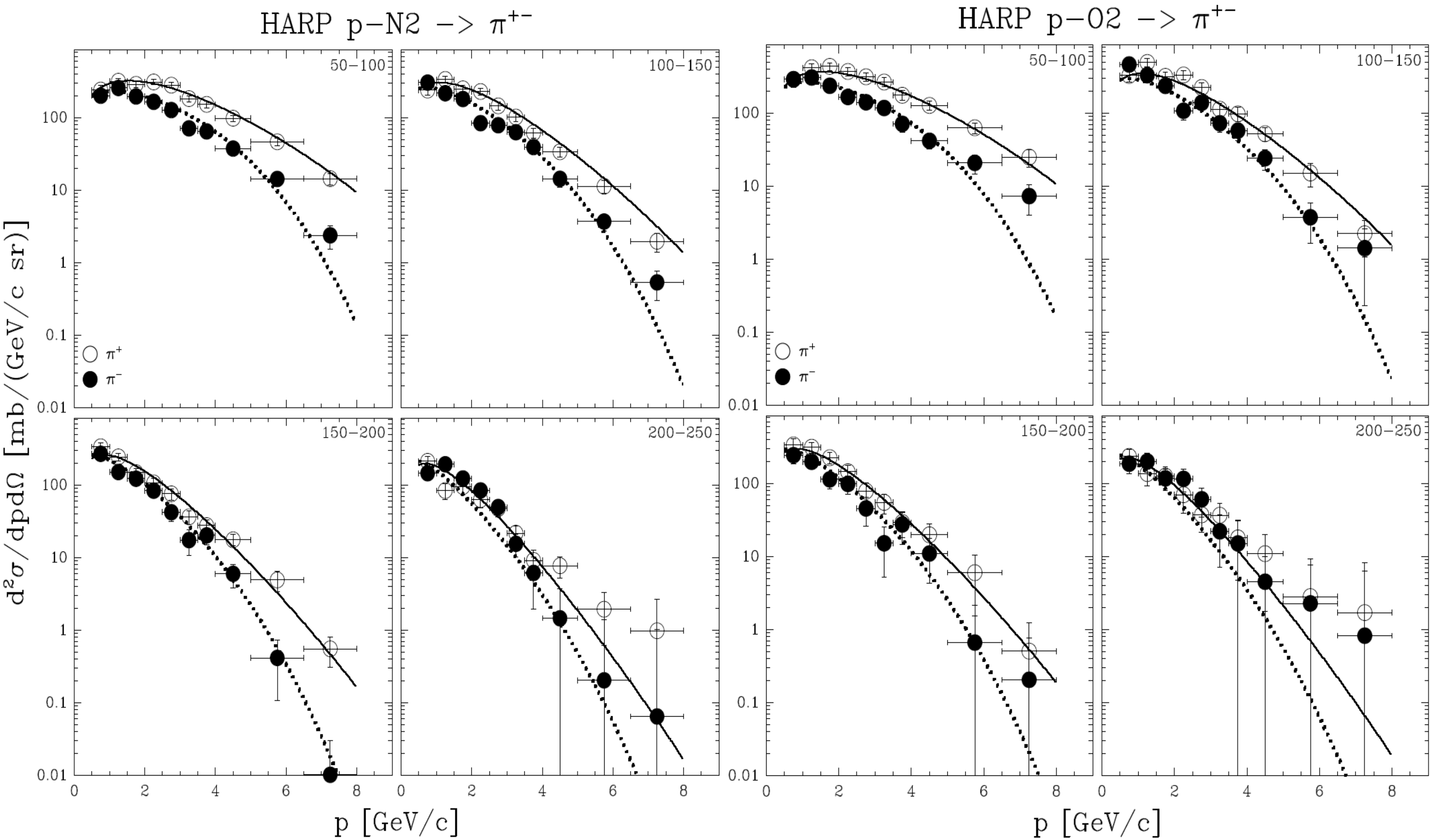


HARP p, $\pi^{\pm}$ +C @ 12 GeV/c data, SW parameterizations and comparison with models

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

Astropart. Phys. 29 (2008) 257

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

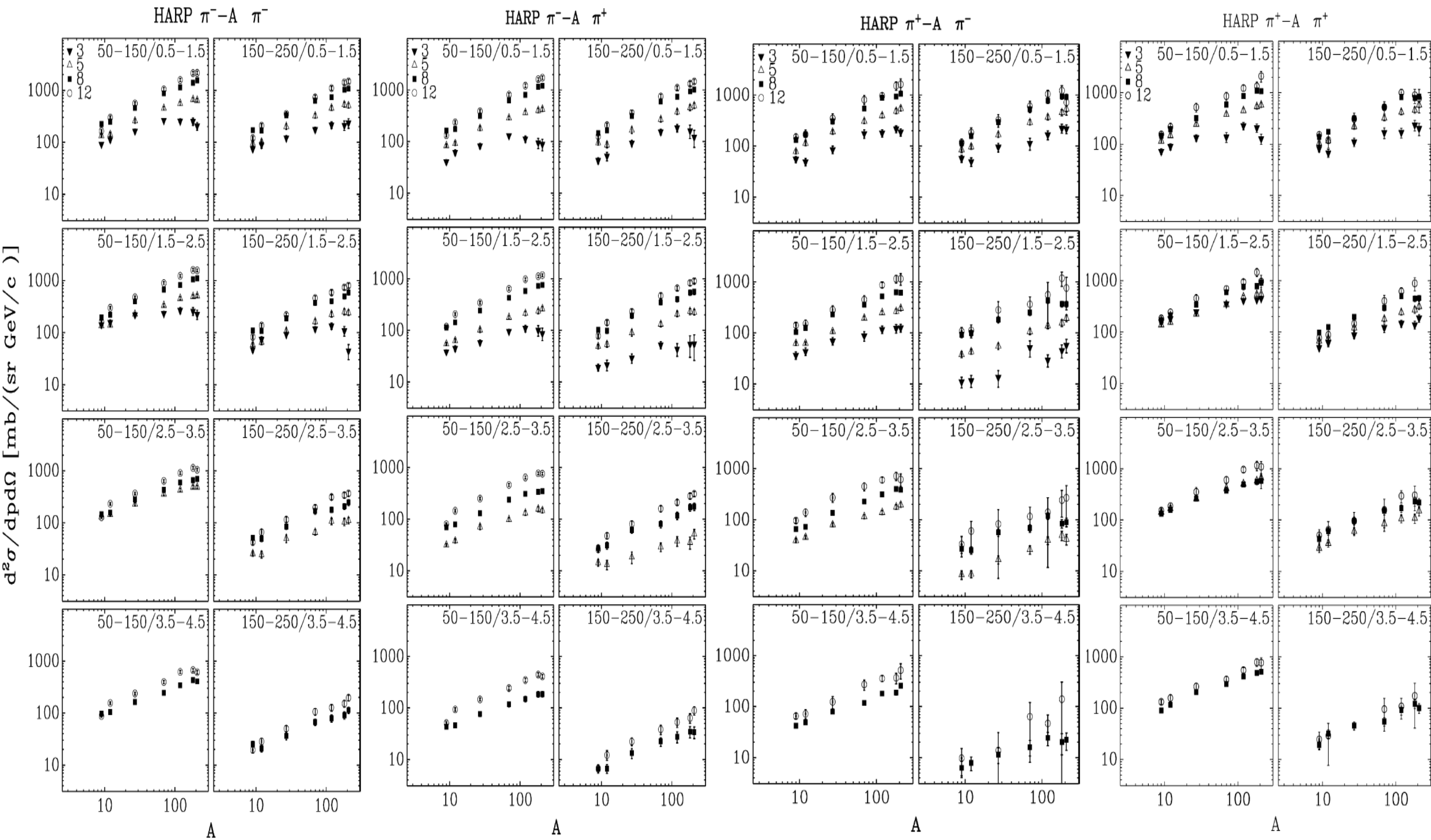


First precision measurements for N_2 and O_2 in this energy range, SW parameterizations for p-C data

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

Astropart. Phys. 30 (2008) 124

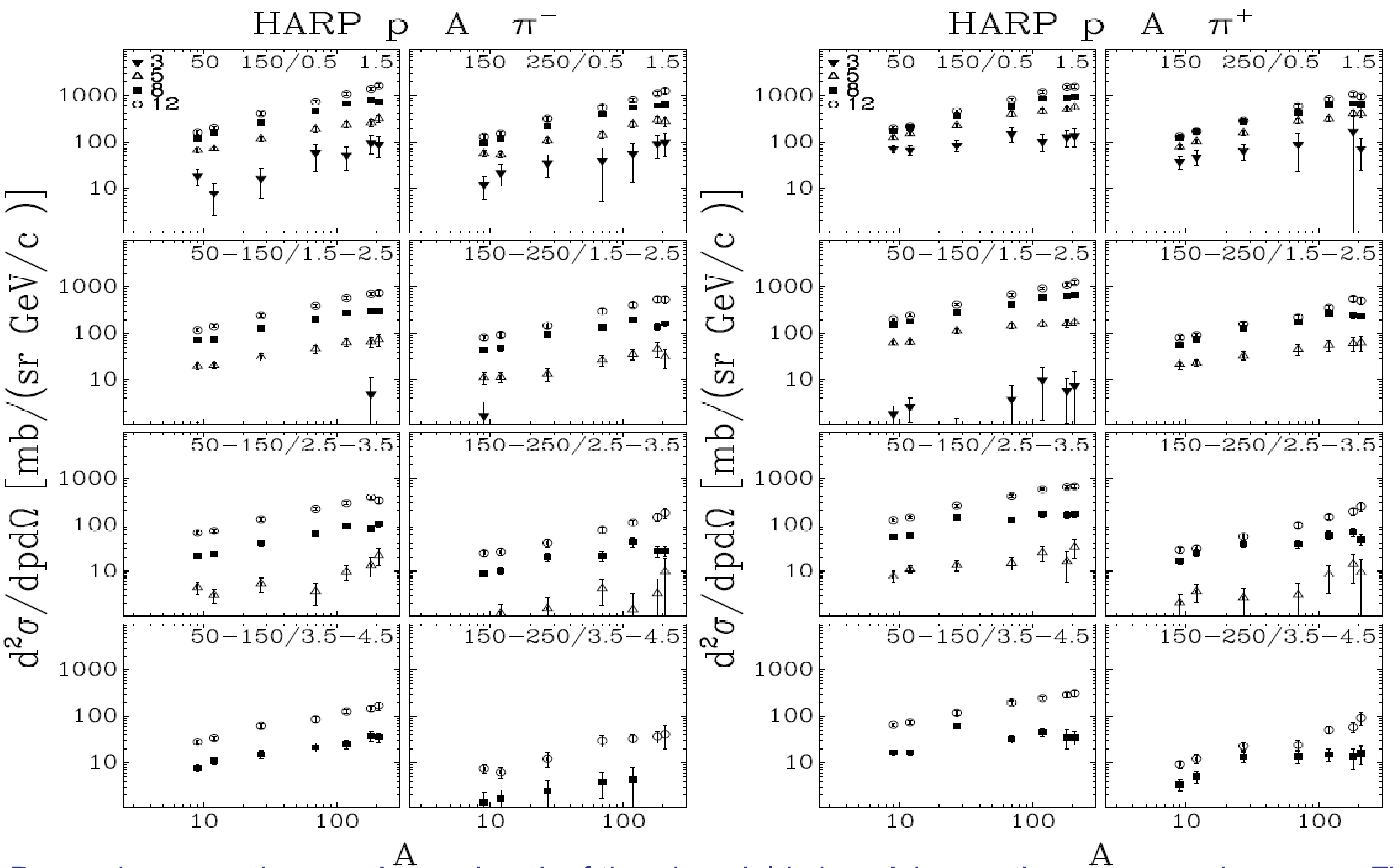
HARP : more FW pion data with incident pions



Dependence on the atomic number A of the pion yields in π-A interactions averaged over two FW angular regions ([50,150], [150,250] mrad) and four momentum regions ([0.5-1.5], [1.5,2.5], [2.5,3.5], [3.5,4.5] GeV/c) for incoming beam momenta 3,5,8,12 GeV/c

Nucl. Phys. A 821 (2009) 118

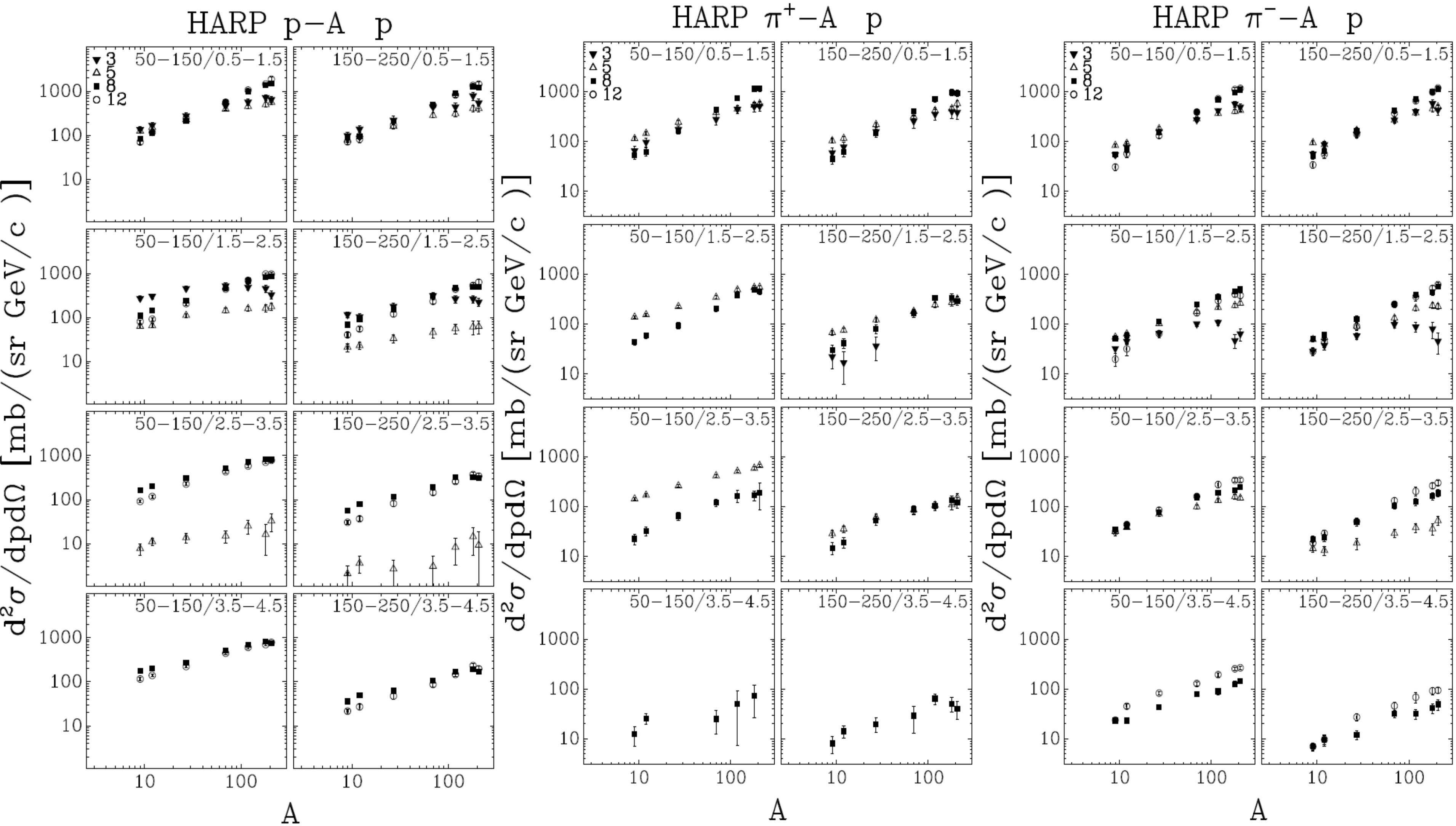
HARP : more FW pion data with incident protons



Dependence on the atomic number A of the pion yields in p-A interactions averaged over two FW angular regions ([50,150], [150,250] mrad) and four momentum regions ([0.5-1.5], [1.5,2.5], [2.5,3.5], [3.5,4.5] GeV/c) for incoming beam momenta 3,5,8,12 GeV/c

Phys. Rev. C80 (2009) 035208

HARP : more FW proton data with incident protons and pions

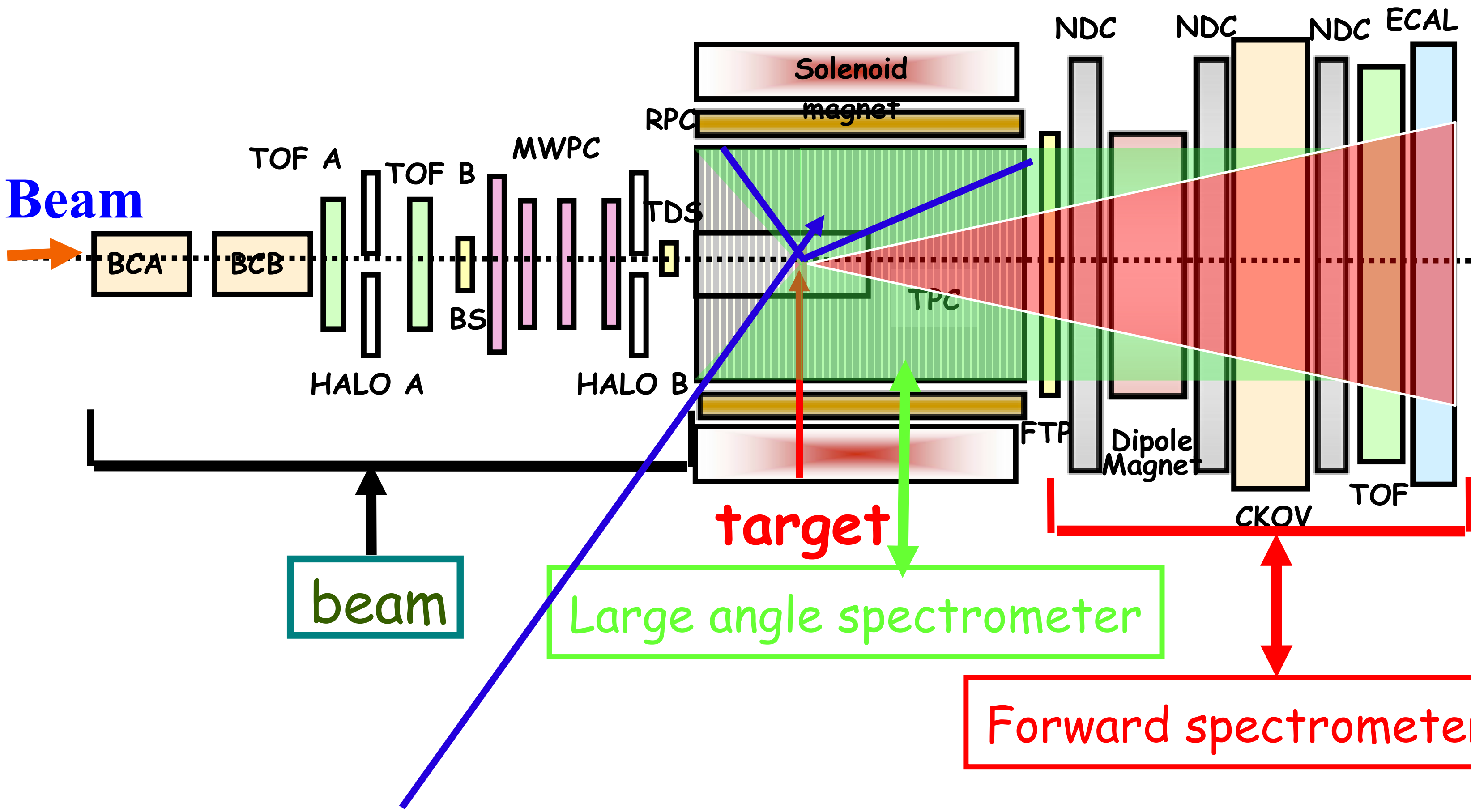


Dependence on the atomic number A of the pion yields in p-A interactions averaged over two FW angular regions ([50,150], [150,250] mrad) and four momentum regions ([0.5-1.5], [1.5,2.5], [2.5,3.5], [3.5,4.5] GeV/c) for incoming beam momenta 3,5,8,12 GeV/c

Phys. Rev. C82 (2010) 045208

HARP: Analyses with the large angle spectrometer

Large Angle (LA) spectrometer: TPC

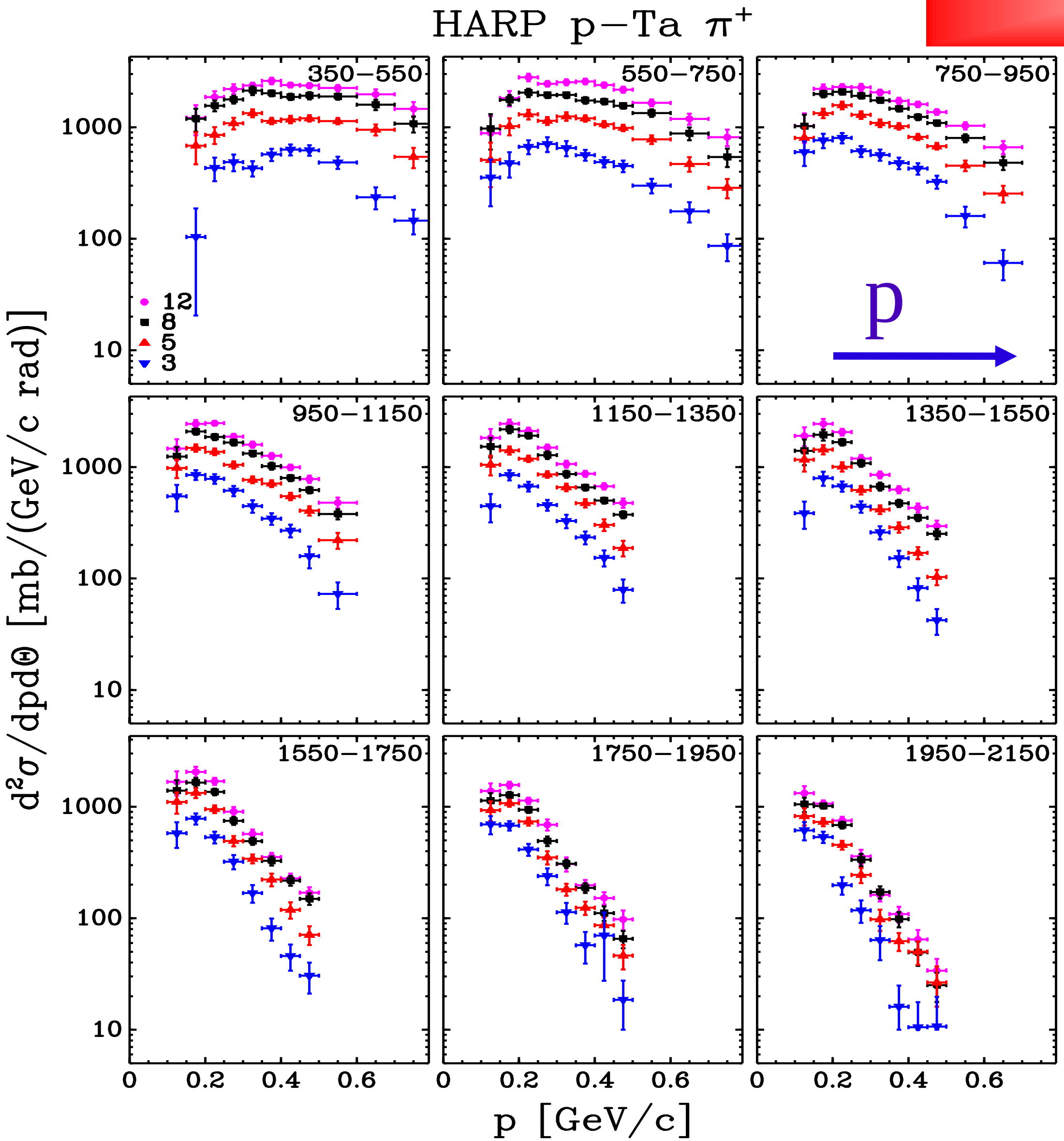


$0.35 < \theta < 2.15$ rad

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)

Pion production yields

9 angular bins: p-Ta π^+



stat. and syst. errors combined

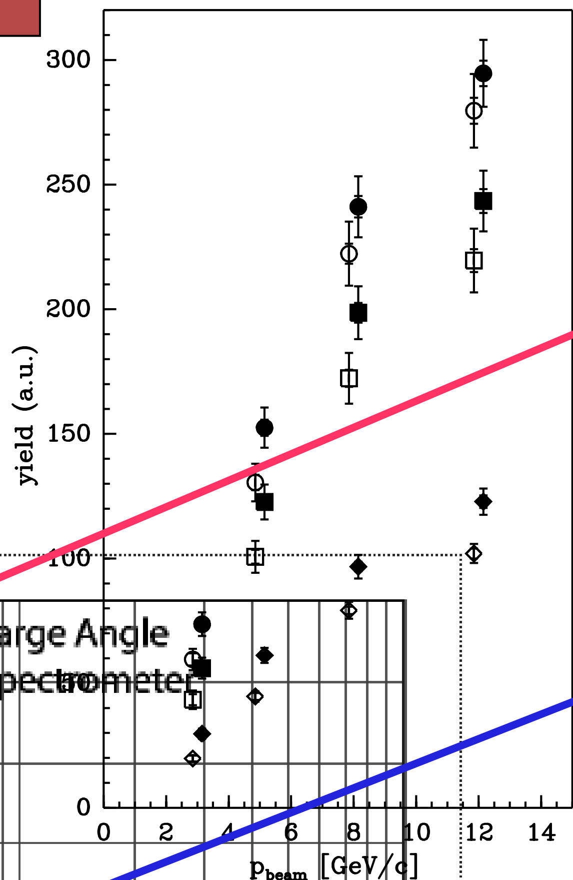
forward
350 < θ (mrad) < 1550

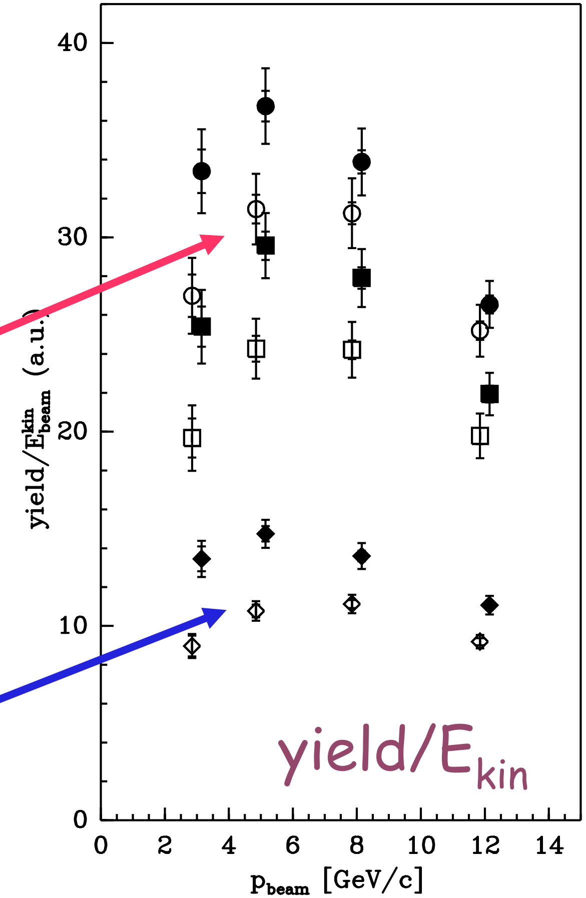
backward
1550 < θ (mrad) < 2150

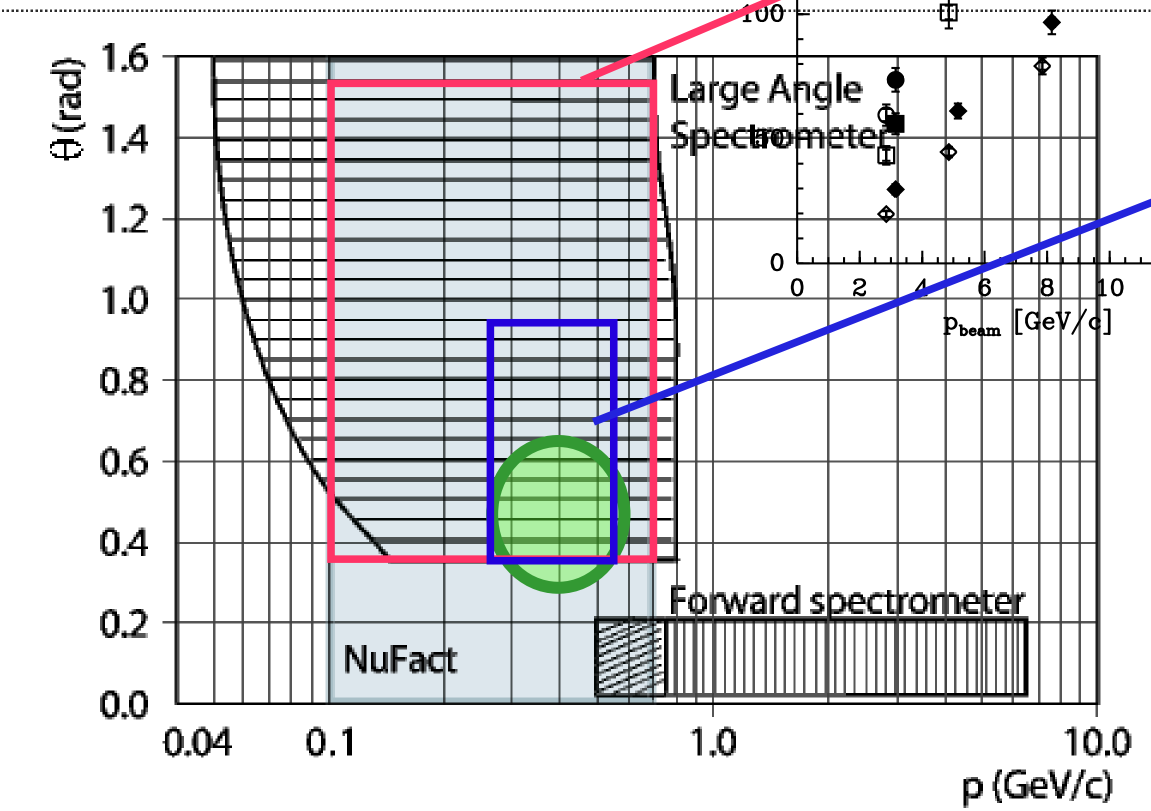
momentum range 0.1 < p < 0.8 GeV/c

EPJ C 51 (2007) 787

Neutrino factory study







π^- open symbols
π^+ closed symbols

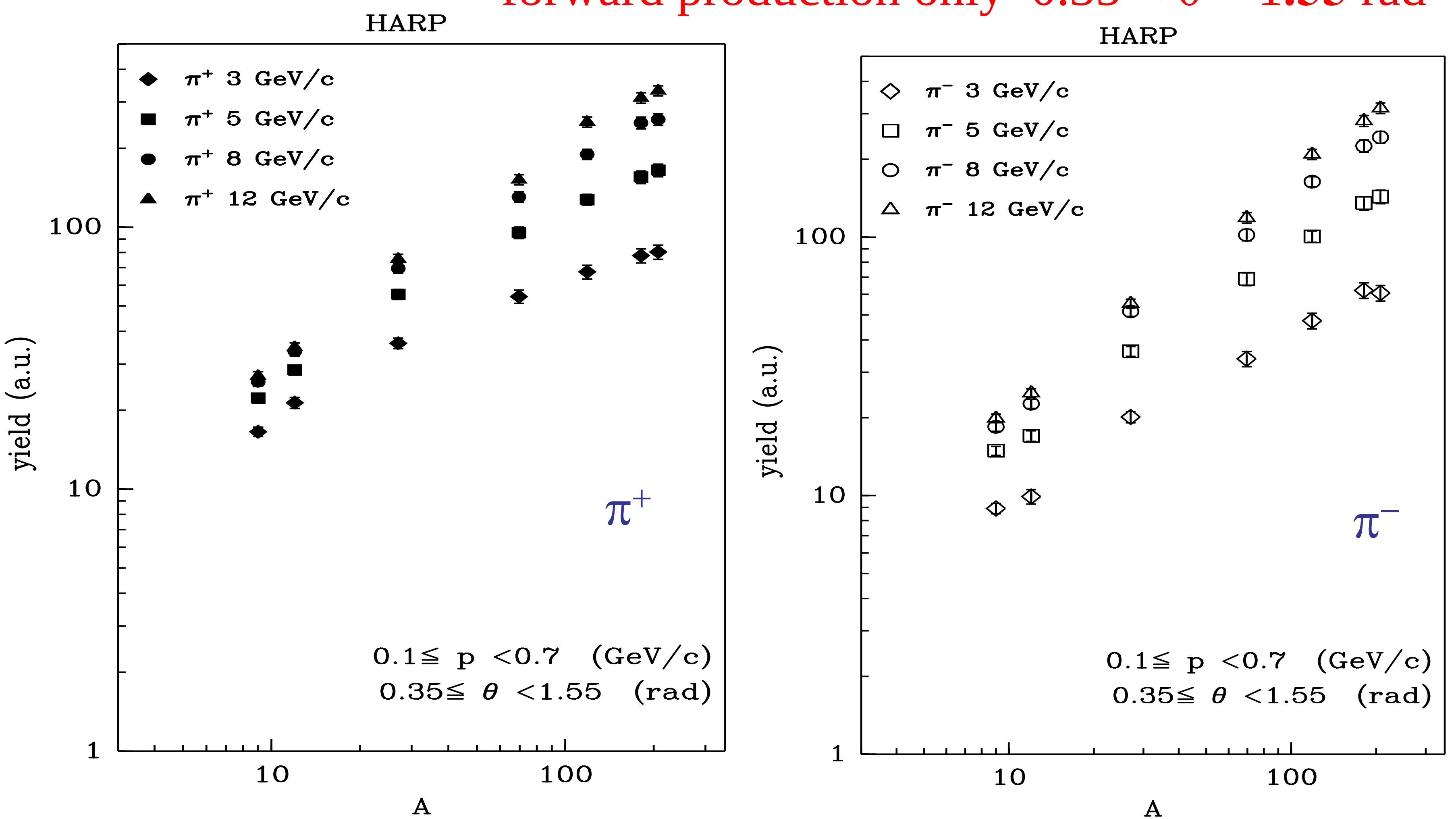
Cross-sections are fed into neutrino factory studies to find optimum design

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

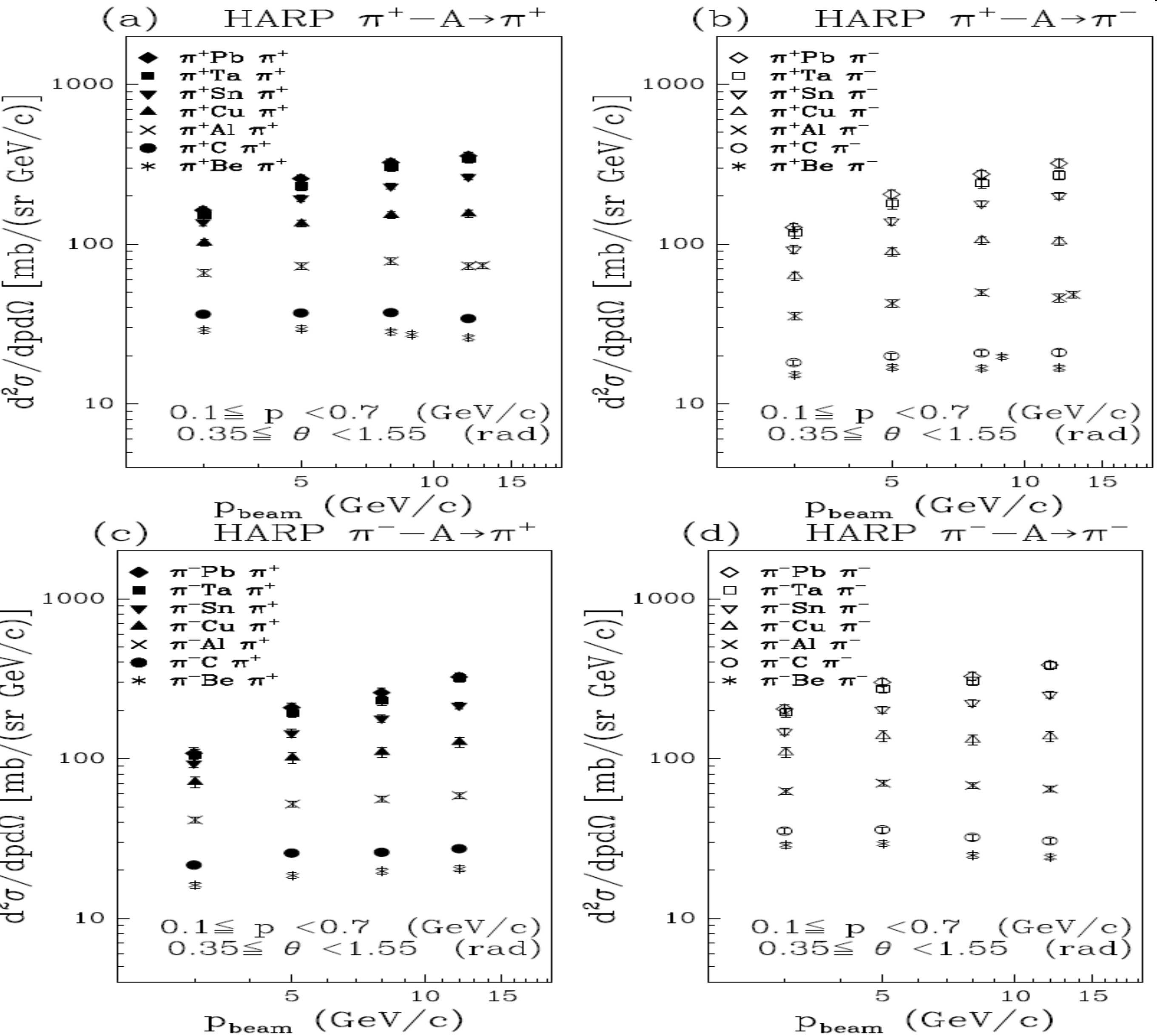
forward production only $0.35 < \theta < 1.55$ rad



Phys. Rev. C 77 (2008) 055207

Measured with the same detector!

HARP: LA data with incoming pion beams



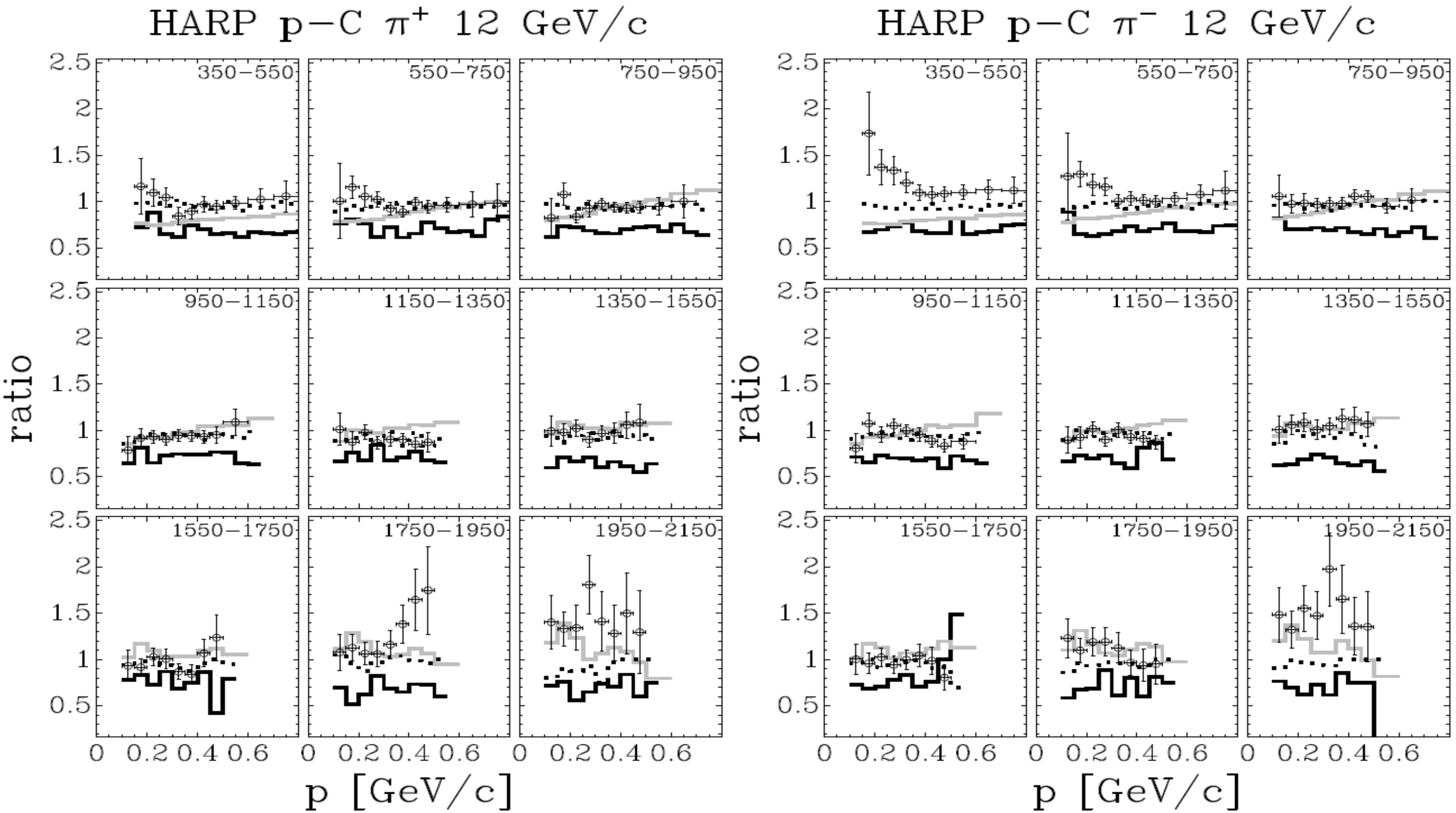
Similar measurements of the $\pi^\pm$ production for all available targets have been performed using beams of incident $\pi^\pm$

Dependence of the π^+ and π^- yields in $\pi^\pm$-A interactions for Be, C, Al, Cu, Sn, Ta, Pb as a function of beam momentum (full spill data)

Phys. Rev. C80 (2009) 065207

forward production $0.35 < \theta < 1.55$ rad

HARP: long target analyses



Ratio of pion yields in 100% λ over 5% λ Carbon target; solid line – MARS predictions; dotted line – ratio of pions produced by "first generation" beam proton to all pions in MARS grey line – GEANT4 (Bertini, QGSP) predictions.

Phys. Rev. C80 (2009) 065204

HARP: comparison with MC

Many comparisons with models GEANT4, MARS, GiBUU are being done

Only some examples are shown here

Binary cascade

Bertini cascade

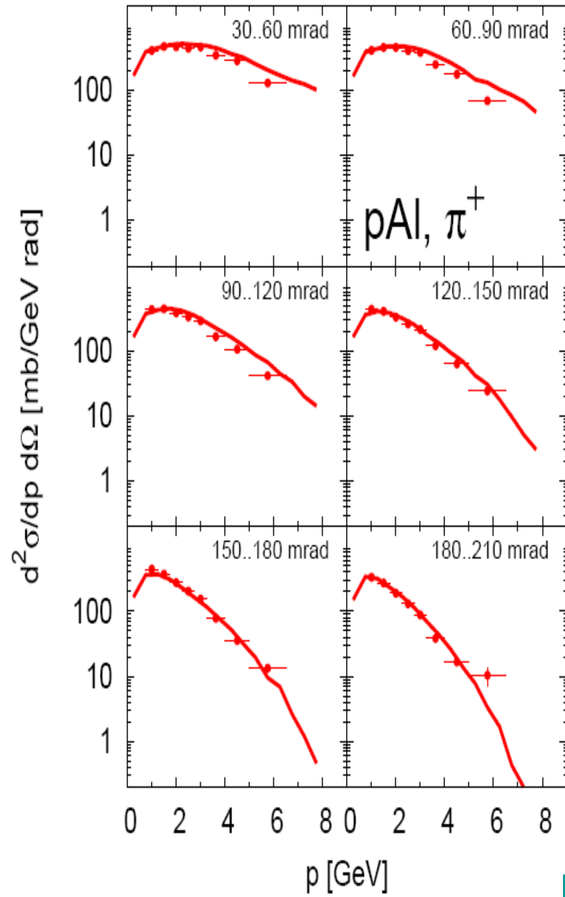
Quark-Gluon string (QGS)

Fritiof (FTFP)

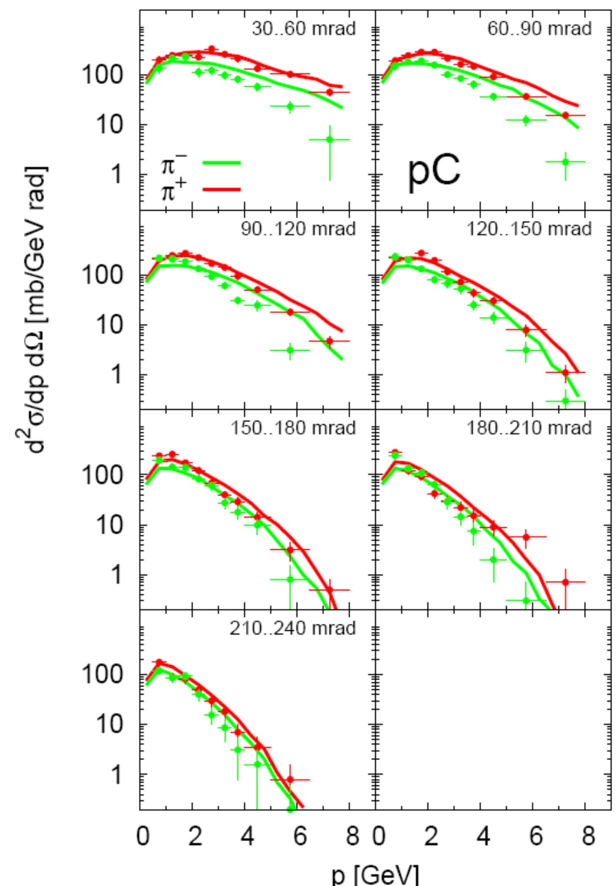
LHEP

MARS

GiBUU



HARP vs GiBUU



Nucl. Phys. A826 (2009) 151

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

HARP: Summary

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

HARP results with Al target for **K2K** have been used for the final K2K publication.

HARP results with Be target for **MiniBooNE/SciBooNE** have been used for neutrino flux predictions and for MiniBooNE oscillation and neutrino cross-section papers.

HARP results for the **Neutrino Factory** studies for the full data set with all targets (Carbon, Copper, Tin, Beryllium, Aluminium, Tantalum and Lead) have been published.

HARP results for Carbon, N_2 and O_2 targets for **atmospheric neutrino fluxes** are published.

Production cross-section measurements for production of charged pions and protons with incident protons and pions on targets from Be to Pb have been published **using the same detector!**

Comparisons of charged pion production with incident protons on cylindrical long and short targets (for C, Ta and Pb) have been performed.

HARP measurements are being used to validate/tune MC hadron production models.

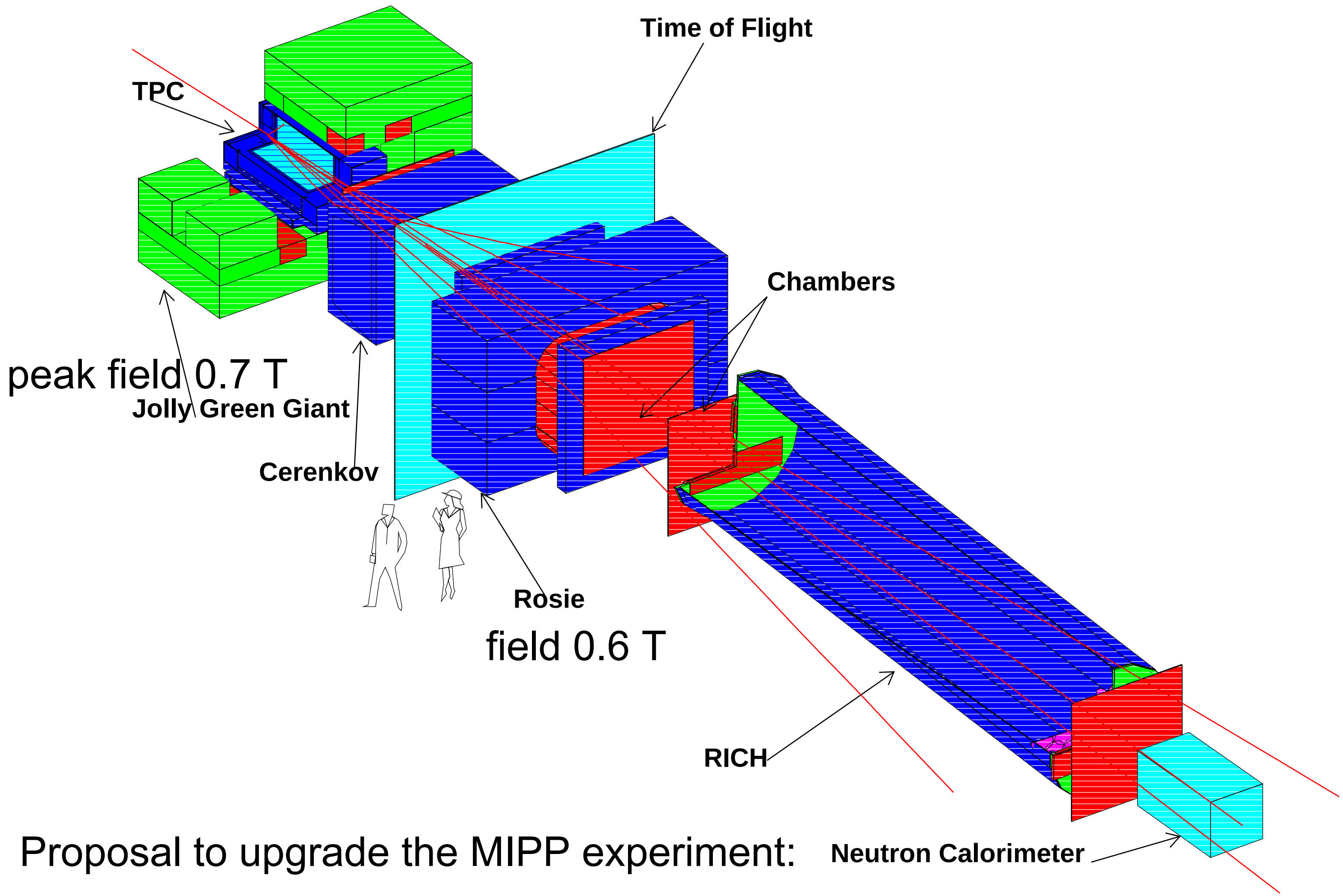
Only a small fraction of available **HARP** results could be presented during this talk…

Tables with HARP results are available e.g. from the DURHAM data-base .

MIPP

Main Injector Particle Production Experiment (FNAL-E907)

MIPP slides provided by Rajendran Raja



Proposal to upgrade the MIPP experiment:

https://mipp-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=1046

MIPP: Brief Description of Experiment

- Approved November 2001
- Situated in Meson Center 7
- Uses 120 GeV Main Injector Primary protons to produce secondary beams of $\pi^{\pm}$ $K^{\pm}$ $p^{\pm}$ from 5 GeV/c to 85 GeV/c to measure particle production cross sections of various nuclei including hydrogen.
- Using a TPC we measure momenta of ~all charged particles produced in the interaction and identify the charged particles in the final state using a combination of dE/dx, ToF, MultiCell Cherenkov and RICH technologies.
- Open Geometry- Lower systematics. TPC gives high statistics 3D track reconstruction. Existing data poor quality.
- First Physics run- 18 million events 2005. Ended Feb 2006. We will present briefly the results.
  - » Forward neutron paper sent for publication Phys. Rev. D83 (2011) 012002, arXiv:1010.6291v2 [hep-ex]
  - » NuMI Target analysis 95% complete.

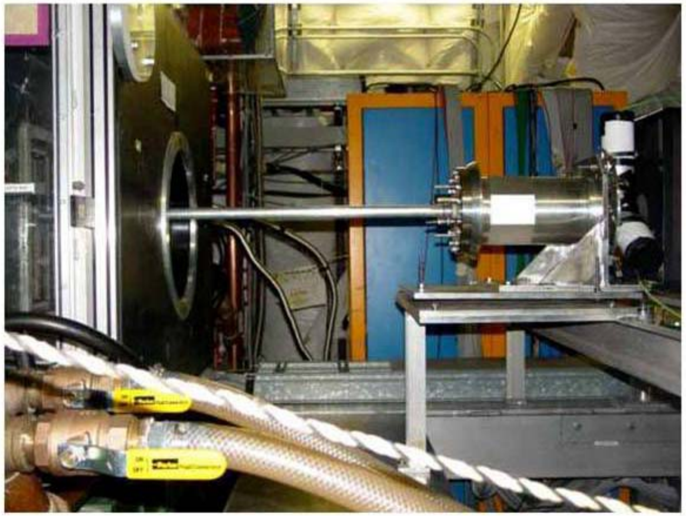
MIPP: Data taken so far (20Hz)

Data Summary 27 February 2006			Acquired Data by Target and Beam Energy Number of events, x 10^6									
Target			E									Total
Z	Element	Trigger Mix	5	20	35	40	55	60	65	85	120	
0	Empty	Normal		*0.10*	*0.14*			*0.52*			*0.25*	*1.01*
	K Mass	No Int.				*5.48*	*0.50*	*7.39*	*0.96*			*14.33*
	Empty LH	Normal		*0.30*				*0.61*		*0.31*		**7.08**
1	LH	Normal	0.21	**1.94**				**1.98**		**1.73**		
4	Be	*p* only									1.08	**1.75**
		Normal			0.10			0.56				
6	C	Mixed						**0.21**				**1.33**
	C 2%	Mixed		**0.39**				**0.26**			**0.47**	
	NuMI	*p* only									**1.78**	**1.78**
13	Al	Normal			*0.10*							*0.10*
83	Bi	*p* only									1.05	**2.83**
		Normal			0.52			1.26				
92	U	Normal						1.18				**1.18**
Total			**0.21**	**2.73**	**0.86**	**5.48**	**0.50**	**13.97**	**0.96**	**2.04**	**4.63**	**31.38**

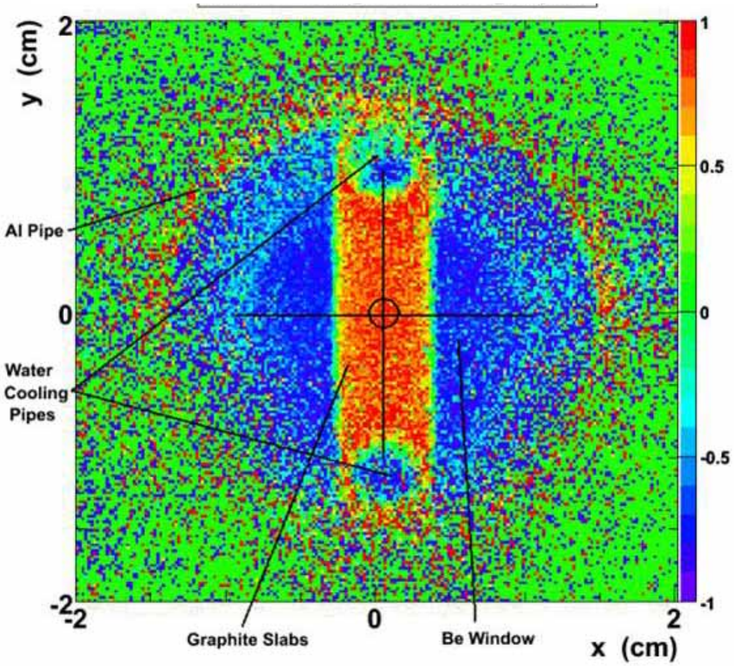
MIPP upgrade goal: DAQ rate up to 3000 Hz (~5 M events/day)

MIPP: NuMI Target analysis

Actual NuMI target in MIPP upstream of the TPC. This target was then installed in NuMI.

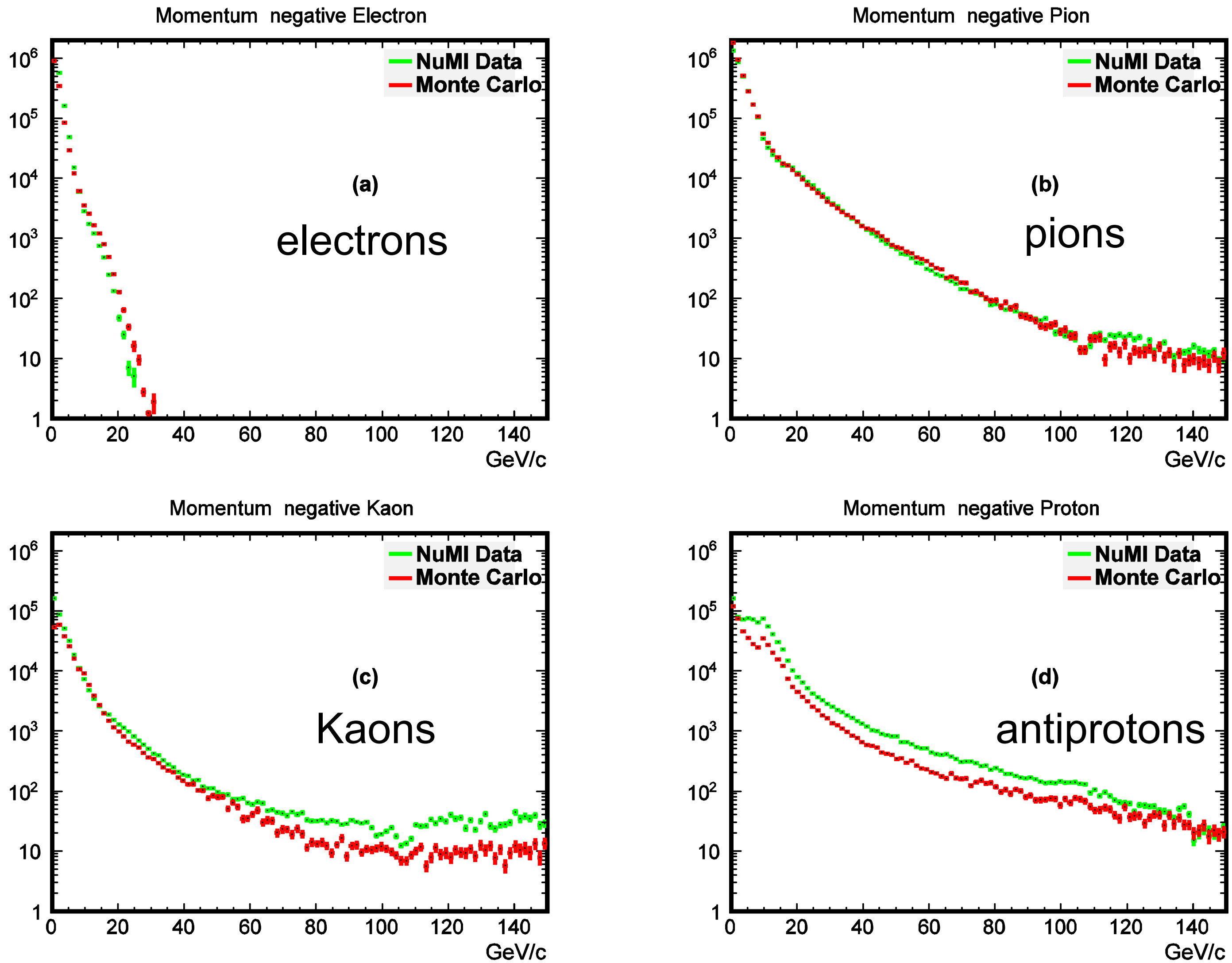


These data are needed In order to minimize the systematics in the far-to-near ratio in the MINOS experiment



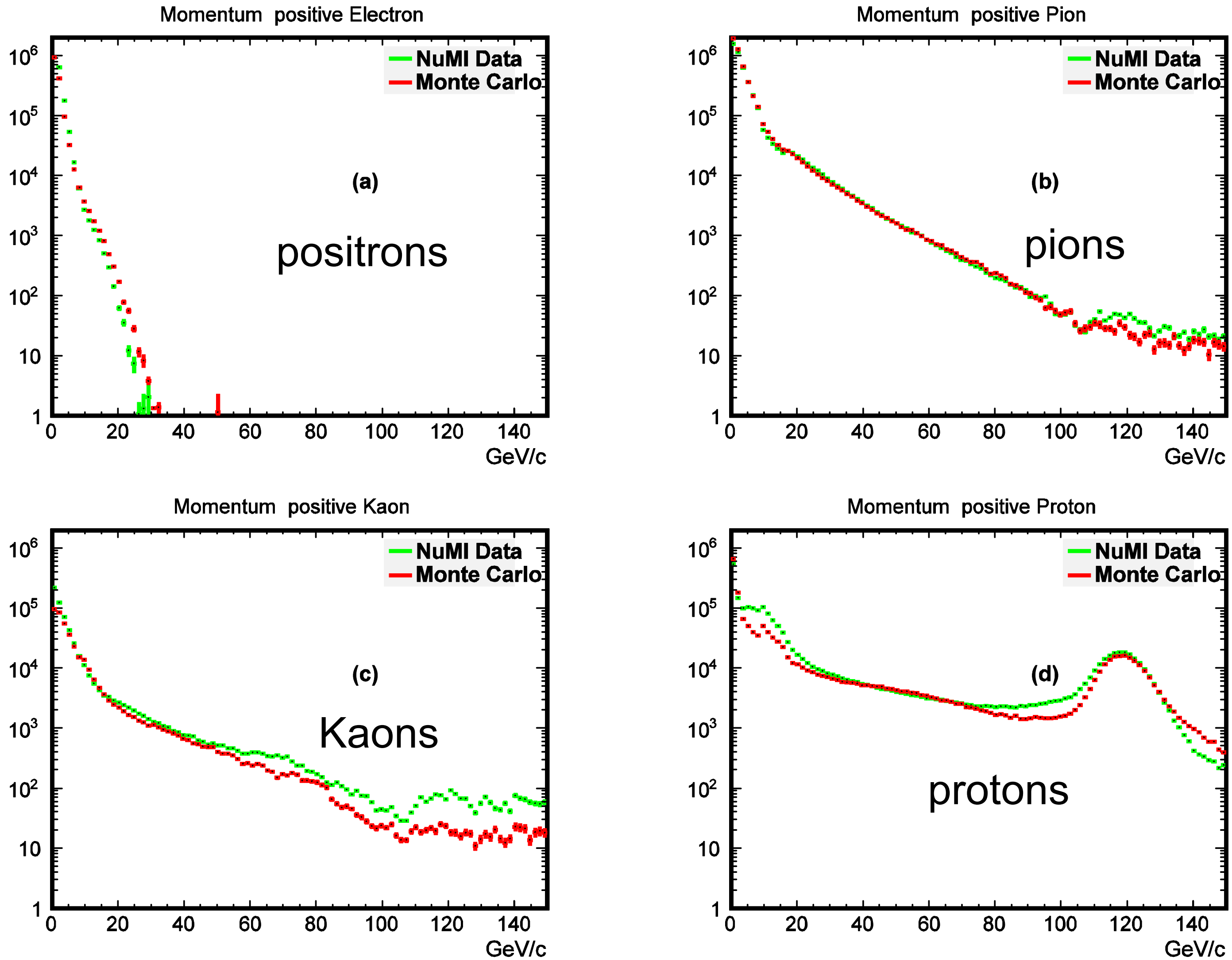
Radiograph of NuMI target in MIPP taken with a defocused 120 GeV/c proton beam

MIPP: Comparison of Data and MC for negatives--Preliminary



Monte Carlo = FLUKA 2006

MIPP: Comparison of Data and MC for Positives-- Preliminary



Monte Carlo = FLUKA 2006

MIPP: Results from Data acquired so far

- Five PhD's awarded
  - Ratio of Pion Kaon Production in Proton Carbon Interactions (A. Lebedev, Harvard)
  - Measurement of Pi-K Ratios from the NuMI Target (S. Seun, Harvard)
  - Measurement of the Charged Kaon Mass with the MIPP RICH (N. Graf, Indiana) (published)
  - Charged pion production cross section using 120 GeV/c proton beam on carbon target (G. Aydin, Iowa)
  - Cross section measurements in the Main Injector Particle Production (FNAL-E907) experiment at 58 GeV/c (Y. Gunaydin, Iowa)
- Publications
  - Kaon mass: NIM A631 (Mar. 2010)- NEW TECHNIQUE TO MEASURE CHARGED KAON MASS OF BOTH CHARGES
  - Calorimeter performance: NIM A598 (Jan. 2009)
- Analysis status
  - NuMI target particle yields-95% complete
  - Forward neutron production cross sections- Published PhysRevD.83.012002(2011)
- Soon
  - More analyses in progress on cross sections with particle id on nuclei

NA61 (SHINE) EXPERIMENT AT CERN SPS: PHYSICS GOALS

SHINE = SPS Heavy Ion and Neutrino Experiment

Physics of strongly interacting matter

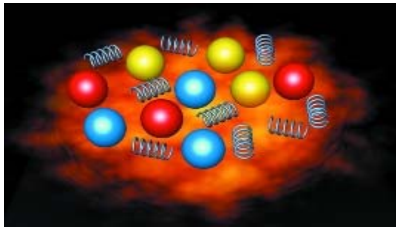
Discovery potential:

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 : Physics Goals (I)

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

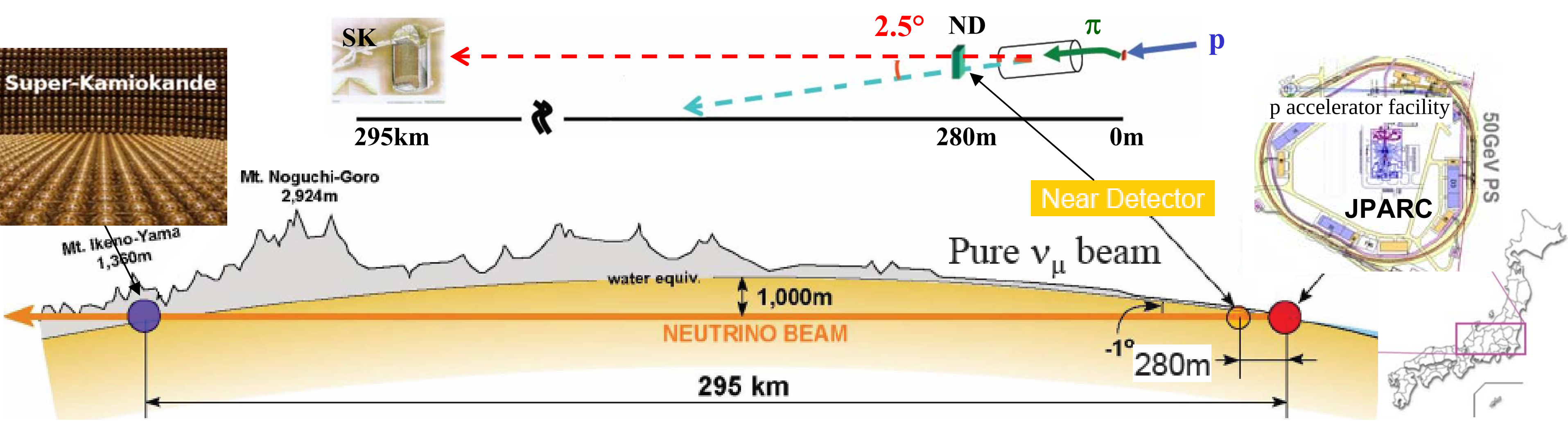
Precision measurements of hadron production for prediction of ν-fluxes in the T2K experiment

- **T2K @ J-PARC (Japan):**

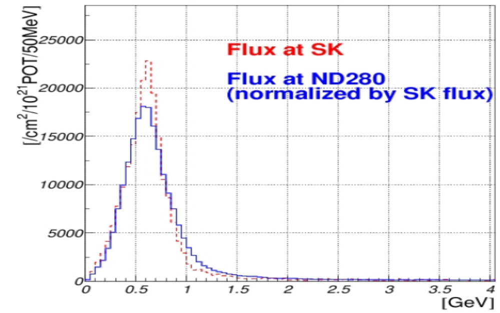
  - Long baseline (295 km) neutrino oscillation experiment

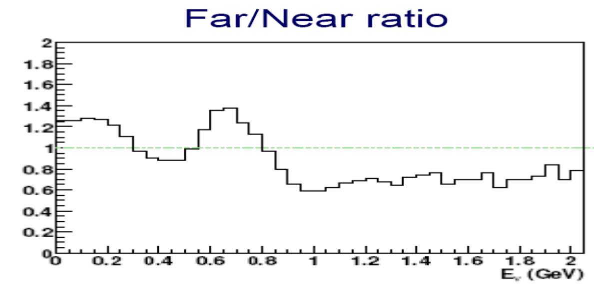
  - Protons (30 GeV) + carbon target (90 cm) → intense off-axis ν_μ–beam

  - 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

$$\boxed{\Phi^{SK}_{\mu,e}(E_\upsilon)} = \boxed{R_{\mu,e}(E_\upsilon)} \times \boxed{\Phi^{ND}_{\mu,e}(E_\upsilon)}$$

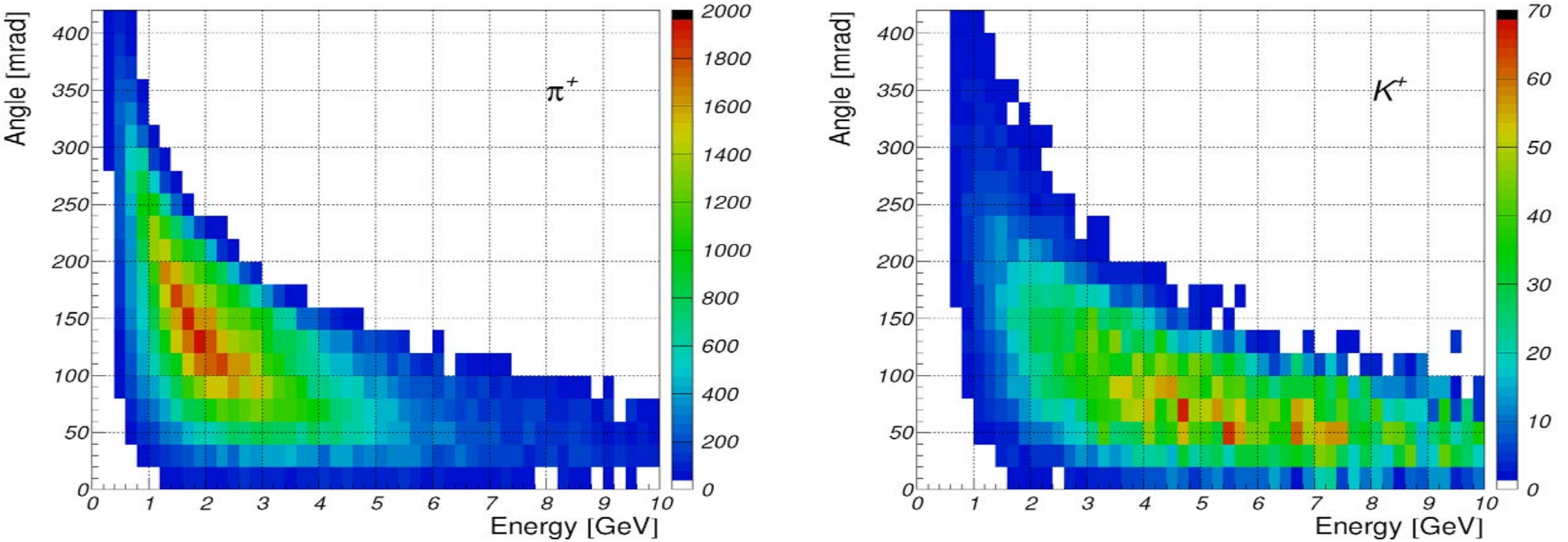
Measured at ND

• **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

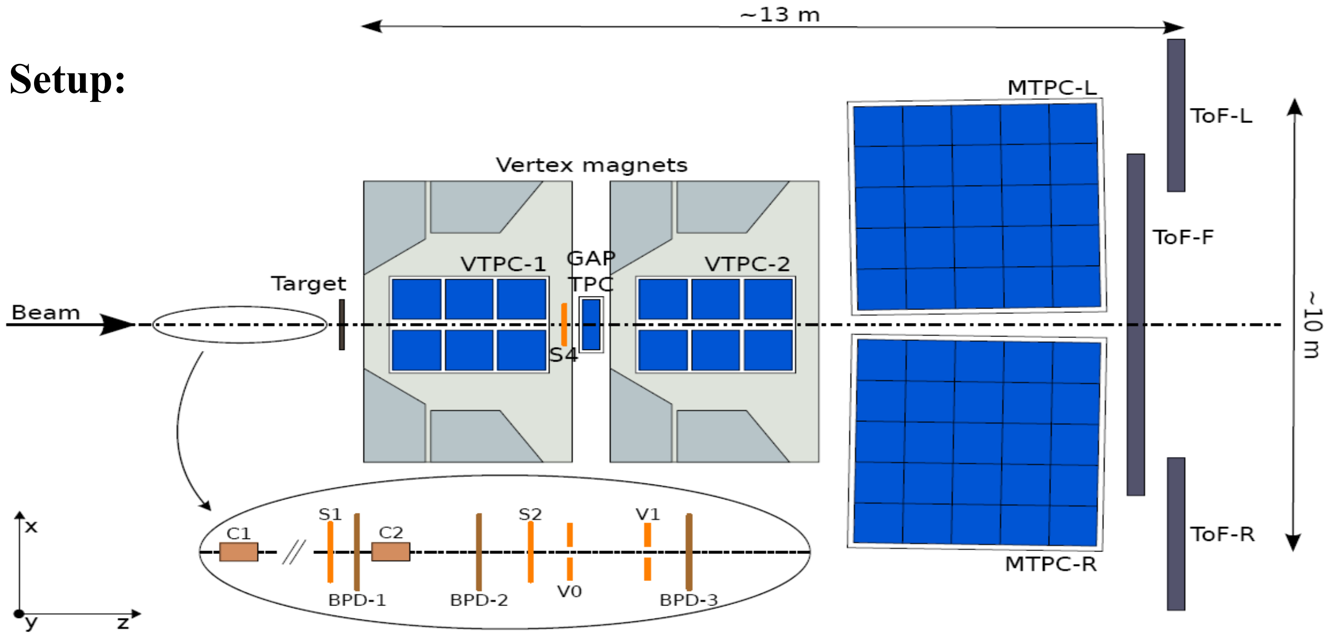


The goal is to reduce the error on the F/N ratio to a negligible level compared to other contributions to the systematics (ND280 spectrum measurements, cross-section, efficiencies, etc.), therefore we aim at: $\delta\ (R_{\mu,e}) < 3\%$

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

NA61/SHINE – Fixed Target Experiment at CERN SPS

NA61/SHINE Setup:



- **Large Acceptance 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**
- **Good particle identification:** σ(ToF-L/R) < 90 ps, σ(ToF-F) ≤ 120 ps,

  σ(dE/dx)/<dE/dx> ≈ 0.04, $\sigma(m_{inv}) \approx 5$ MeV

CERN-SPS-2006-034

NA61 : Carbon Targets

- 2 different carbon targets (isotropic graphite)

Thin Carbon Target
- length=2 cm, cross section 2.5x 2.5 cm^2
- ρ = 1.84 g/cm^3
- ~0.04 λ_{int}

T2K replica Target
- length = 90 cm, Ø=2.6 cm
- ρ = 1.83 g/cm^3
- ~1.9 λ_{int}

- Data-taking since 2007; long physics runs in 2009 and 2010
- First run in October 2007 (~30 days):

- taken pilot physics data for T2K with 30.9 GeV/c protons (~2 weeks)

Thin target: ~670k triggers

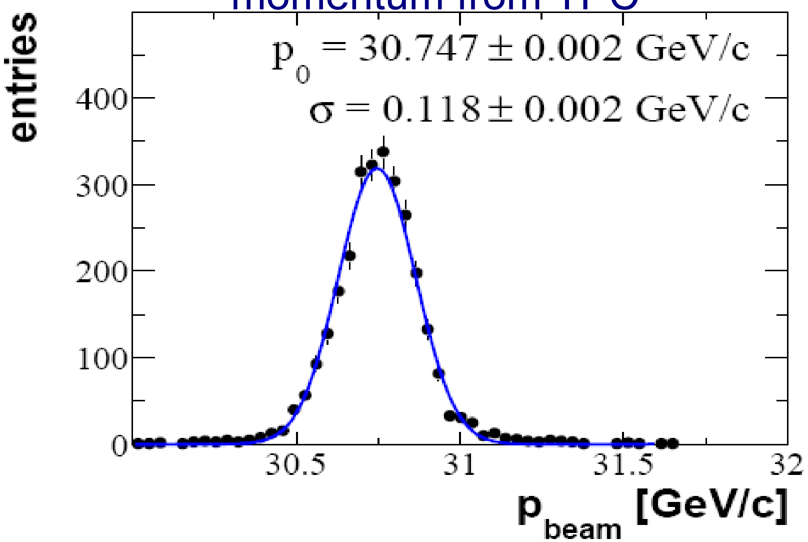
Replica target: ~230k triggers

Empty target: ~80k triggers

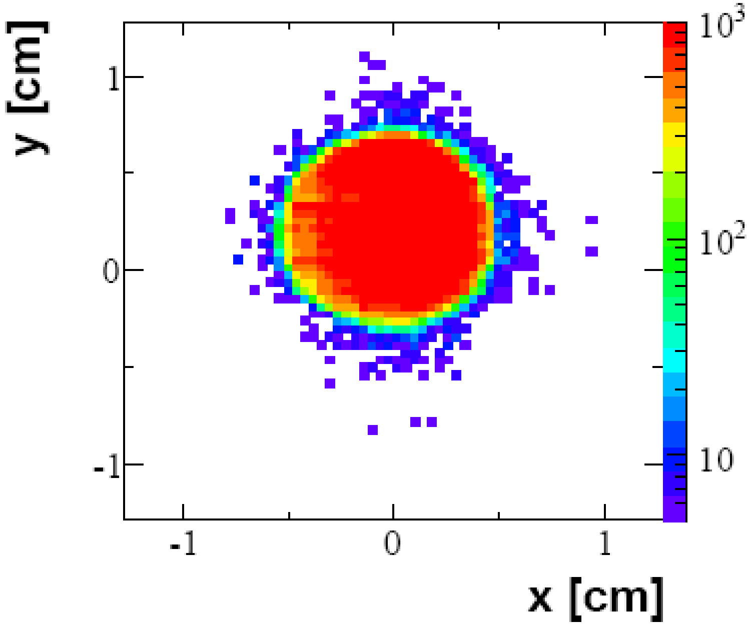
First results available

NA61 : BEAM PROPERTIES

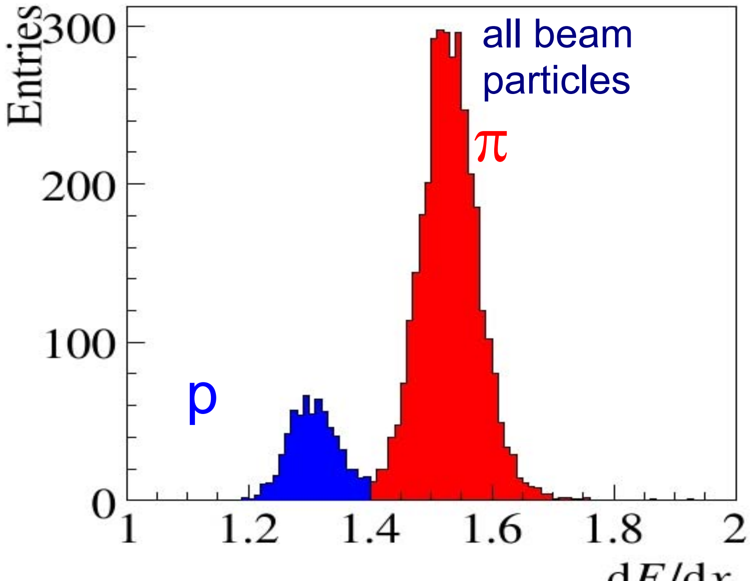
momentum from TPC

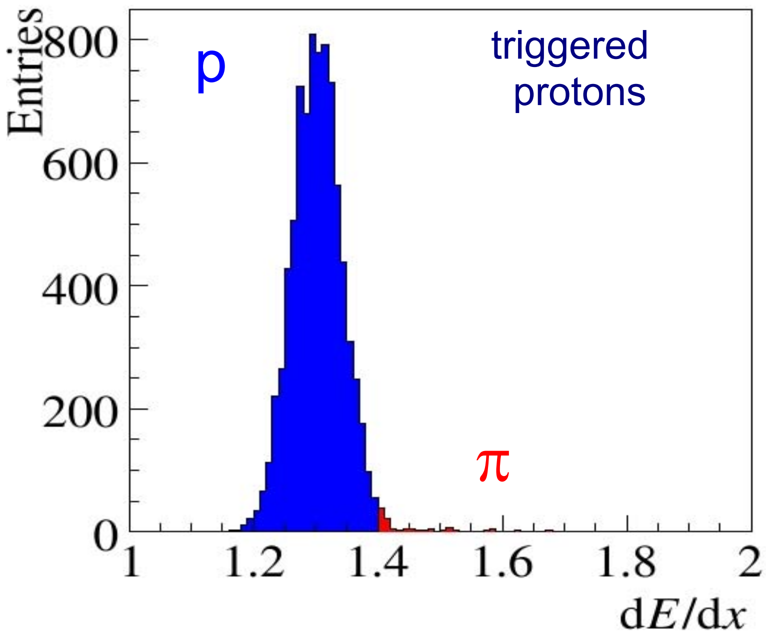


beam spot from BPD-3



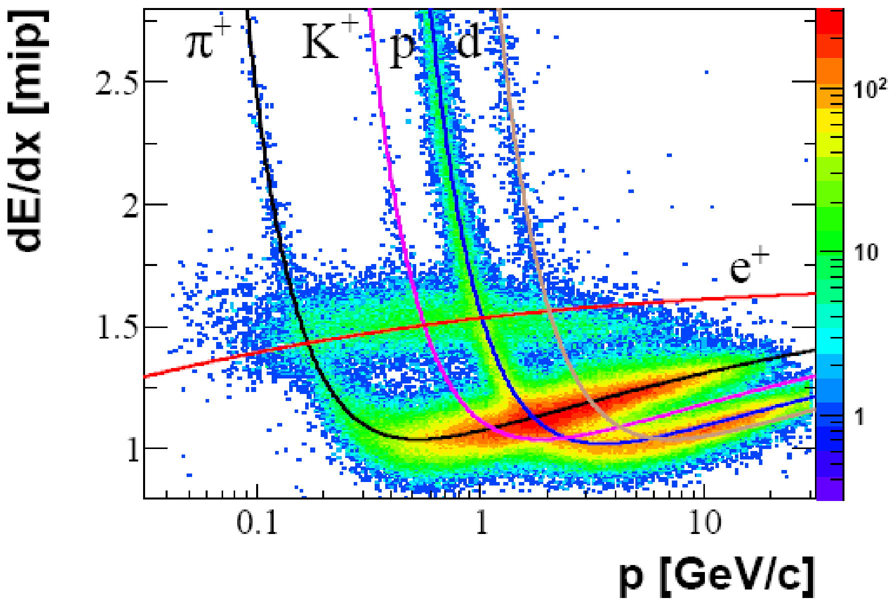
dE/dx from TPC

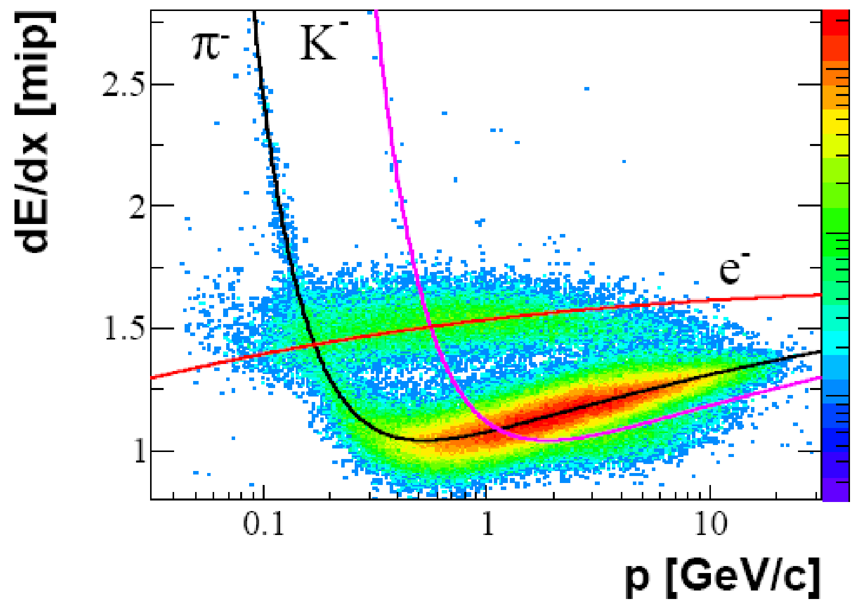




Identification of beam protons with a purity of about 99%

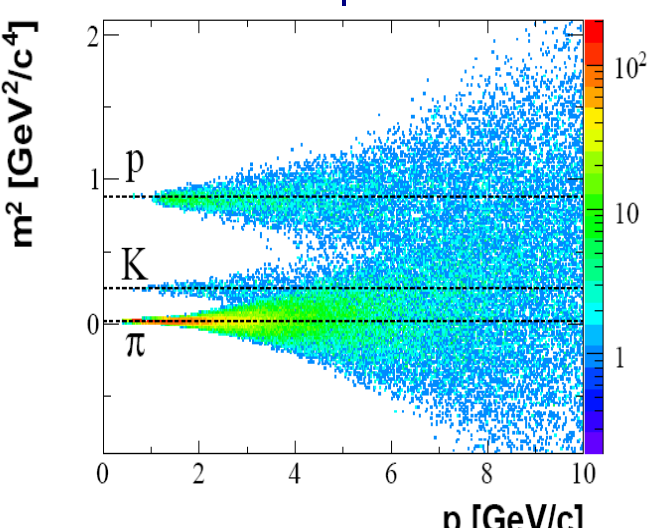
NA61 : PID by dE/dx and TOF measurements



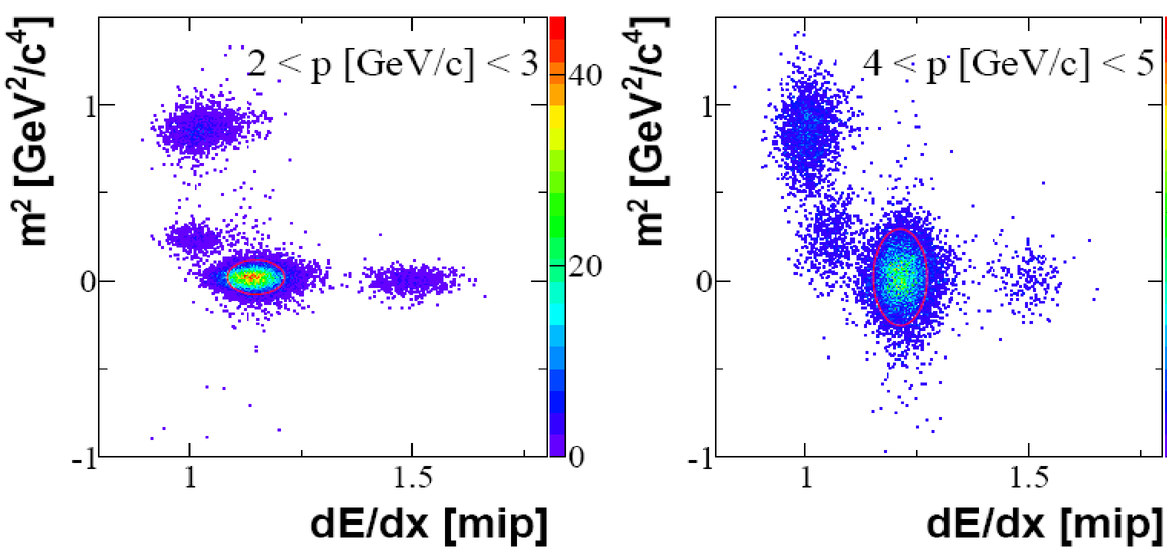


log scale

ToF-F raw spectrum

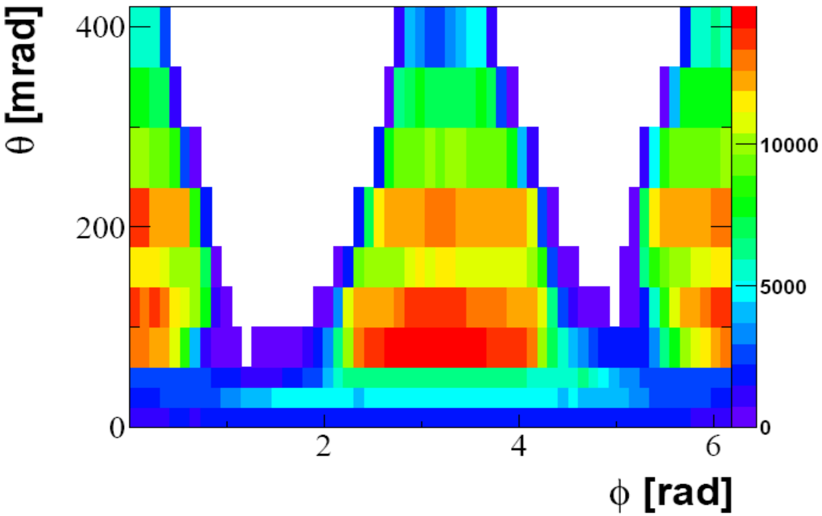


Combined ToF vs dE/dx PID

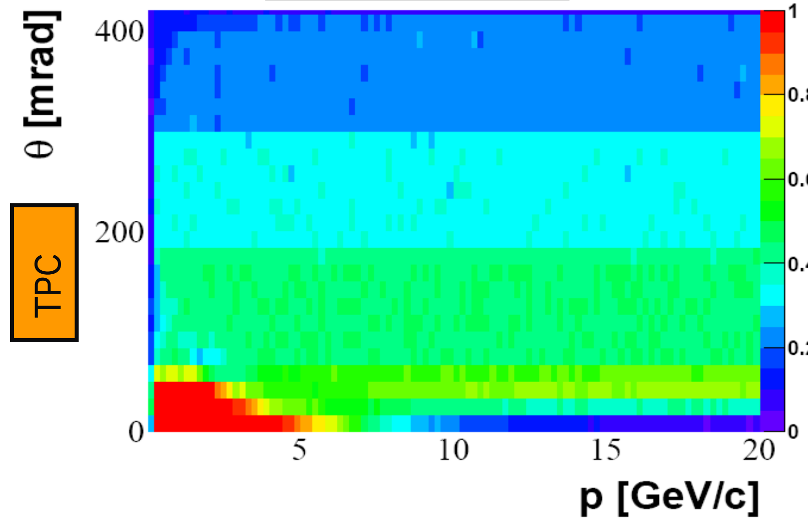


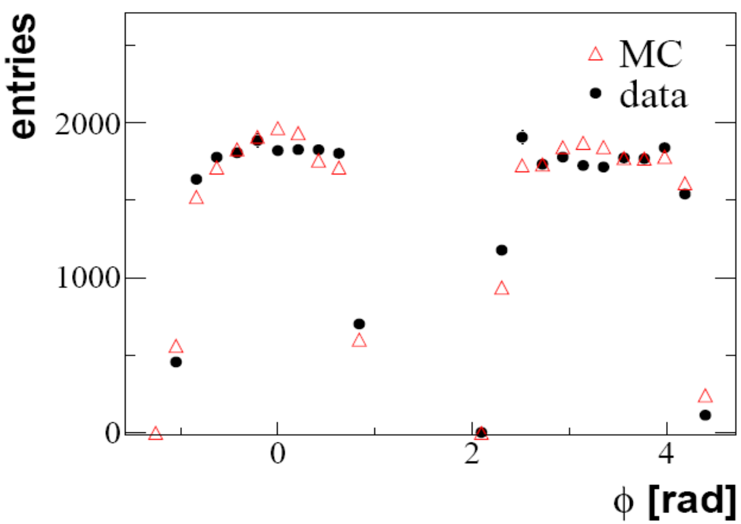
NA61 : DETECTOR ACCEPTANCE

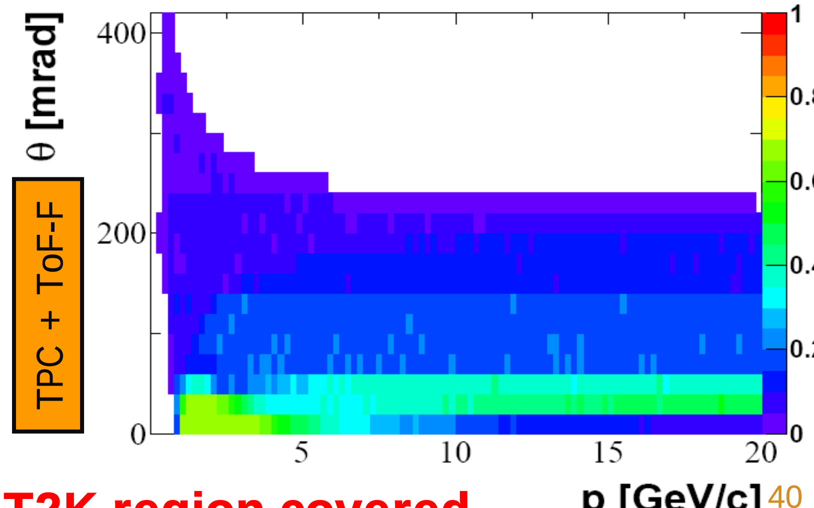
polar angle θ vs azimuthal angle ϕ



Acceptance







T2K region covered

NA61 : Analysis techniques

Three complementary analysis techniques have been developed:

h- analysis (π^-): no PID required; global MC corrections are applied to correct for: contribution of electrons and other particles (K-), geometrical acceptance, reconstruction efficiency, secondary interactions and weak decays (“feed down”) .

Corrected spectra of π^- are obtained in a broad kinematic range

dE/dx analysis at low momenta (π^+ & π^-):

for each (p,θ) bin a maximum likelihood fit is applied to the dE/dx distributions (PDFs are assumed to be Gaussian distributions with the momentum dependent mean given by the Bethe-Bloch parametrization fitted to the data).

Corrected spectra of π^+ till 1 GeV/c and π^- till 3 GeV/c in momentum

combined dE/dx + ToF analysis (π^+ & π^-): for each (p,θ) bin a maximum likelihood fit is applied to the m^2 vs dE/dx distributions; pion yields are calculated summing all entries within 2σ around the fitted pion peak. Factorized MC corrections for: geometrical acceptance, track reconstruction efficiency, ToF detection efficiency, losses due to pion decays, “feed down”.

Corrected spectra of π^+ and π^- above 1 GeV/c in momentum

arXiv:1102.0983 [hep-ex]

NA61 : DERIVATION OF SPECTRA

1) The corrected numbers of π^- and π^+ mesons in p bins and θ intervals with the target inserted (Δn_α^I) and the target removed (Δn_α^R), where α stands for π^- and π^+, were used to compute inclusive differential cross section:

$$\frac{d\sigma_\alpha}{dp} = \frac{\sigma_{trig}}{1-\epsilon} \cdot \left(\frac{1}{N^I} \frac{\Delta n_\alpha^I}{\Delta p} - \frac{\epsilon}{N^R} \cdot \frac{\Delta n_\alpha^R}{\Delta p} \right)$$

The normalization factors are defined as:

- σ_{trig}=(298.1±1.9±7.3) mb is the „trigger" cross section – calculated from the number of interacting protons.
- N^I and N^R are the numbers of selected events with the target inserted and removed.
- ε=0.118±0.001 is the ratio of the interaction probabilities for removed and inserted target operation.
- Δp is the bin size of the momentum

2) Empty target subtraction implemented

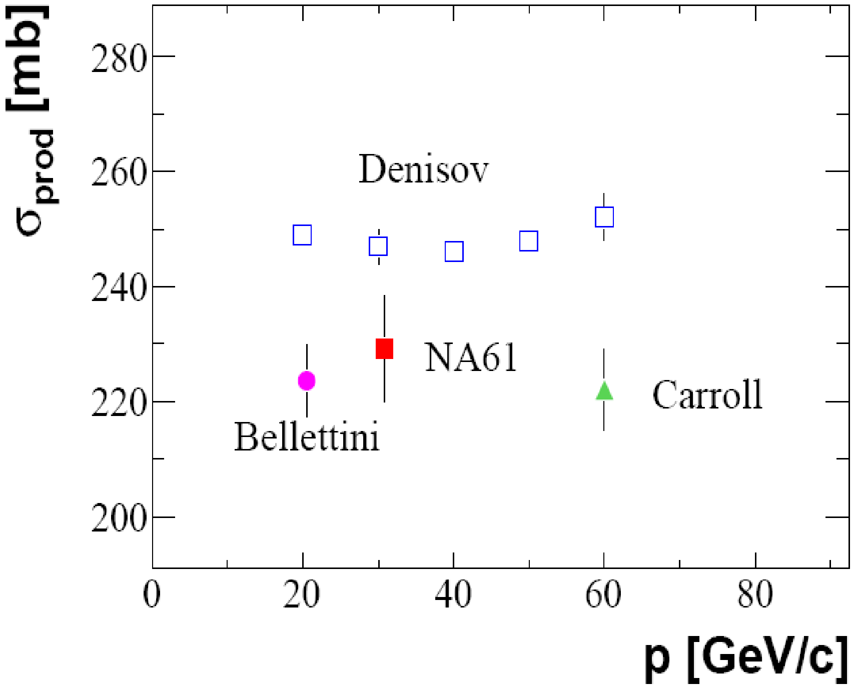
arXiv:1102.0983 [hep-ex]

NA61 : INELASTIC AND PRODUCTION CROSS-SECTIONS

To obtain inelastic cross section σ_{inel} the trigger cross section σ_{trig} was corrected for:

1) the contribution of the **coherent elastic scattering** (pC) giving trigger signal in the experiment. Simulated by GEANT4–QGSP_BERT (47.2±0.2±0.5) mb (**subtraction**).

2) the **loss of inelastic events** due to the emitted charged particles hitting S4 trigger counter (5.7±0.2±0.5) mb for protons and (0.57±0.02±0.35) mb for pions and kaons (**addition**)



The inelastic processes include the production processes and in addition interactions which result only in disintegration of the target nucleus (quasi-elastic interactions).

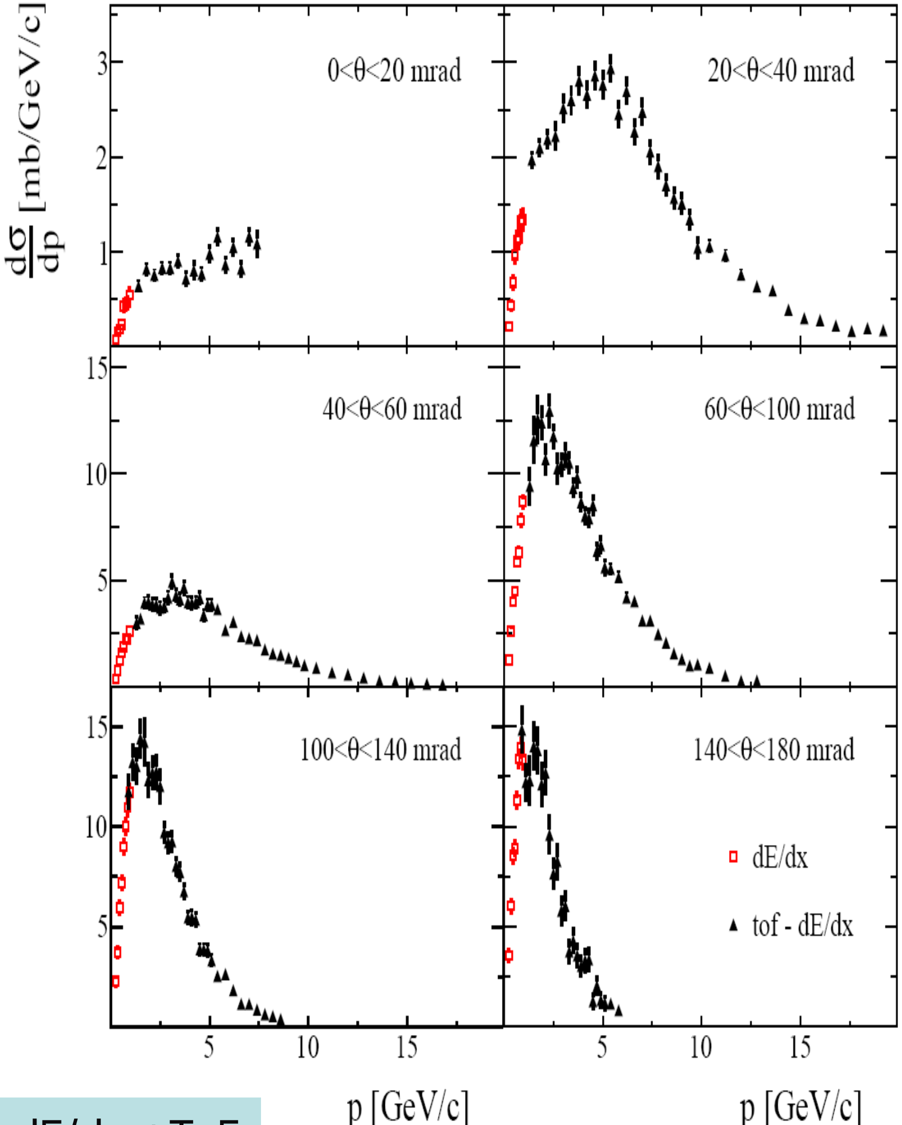
The production processes are defined as those in which new hadrons are produced.

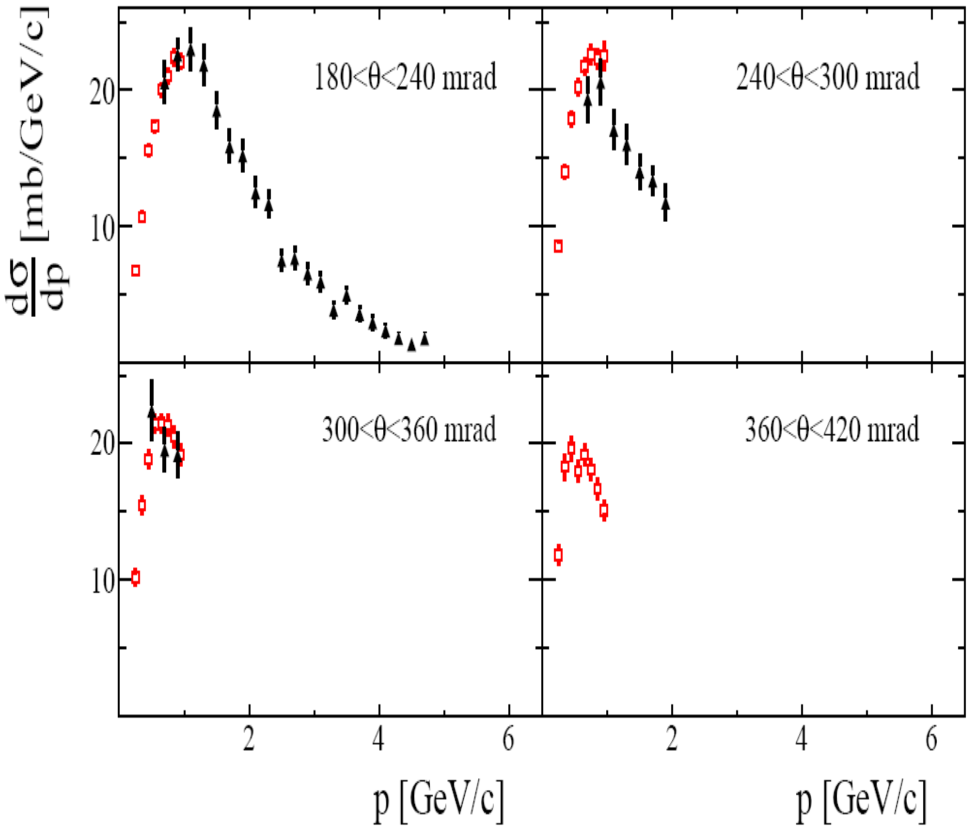
$$\sigma_{prod} = \sigma_{inel} - \sigma_{qel}$$

$$(229.3 \pm 1.9 \pm 9.0)\ \text{mb} = (257.2 \pm 1.9 \pm 8.9)\ \text{mb} - \underbrace{(27.9 \pm 1.5)\ \text{mb}}_{\text{value taken from Glauber model calculations}}$$

arXiv:1102.0983 [hep-ex]

NA61 : RESULTS π^+





Statistical errors only

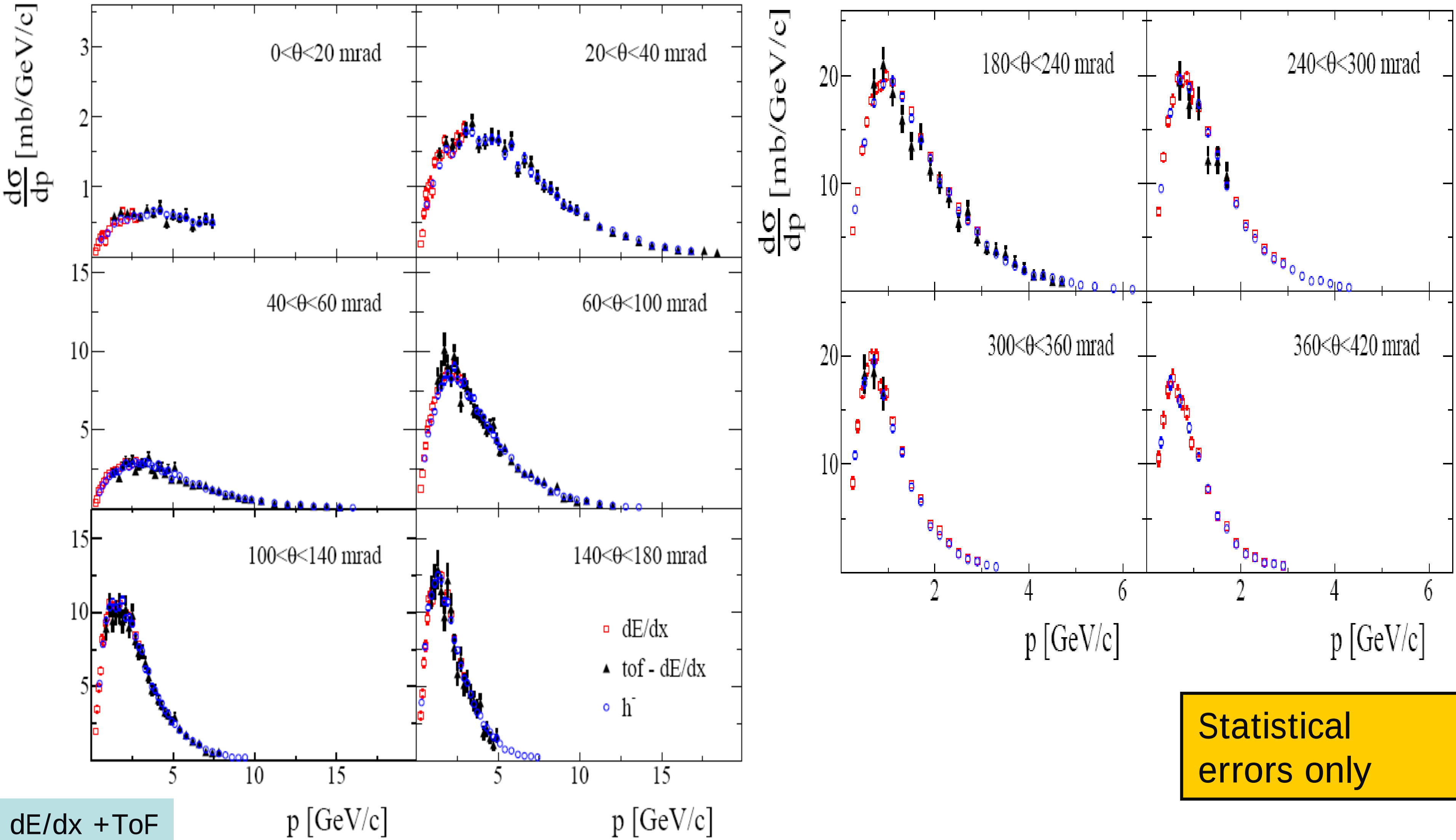
Agreement between spectra obtained by different methods is better than 10%.

dE/dx +ToF

dE/dx

arXiv:1102.0983 [hep-ex]

NA61 : RESULTS π^-



Statistical errors only

dE/dx +ToF

dE/dx

h^- analysis

arXiv:1102.0983 [hep-ex]

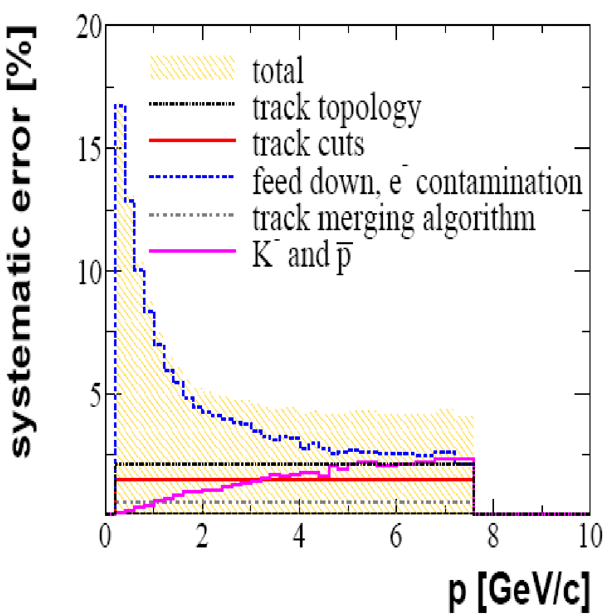
Considered systematic uncertainties:

1) Uncertainty of **PID** procedures for dE/dx and dE/dx+ToF analyses.
2) Feed down : pions from **weak decays and secondary interactions** reconstructed at primary vertex (model dependent; assumed 30% uncertainty) and electron contamination in the h- analysis (assumed 20% uncertainty).
3) Track topology.
4) Track cuts (number of points, azimuthal angle, impact parameter).
5) Track merging algorithm.
6) Reconstruction efficiency.
7) ToF detection efficiency.
8) K^- and antiproton contamination in the h- analysis
9) Pion loss correction due to pion decay in the (dE/dx +ToF) analysis

NA61 : SYSTEMATIC ERROR - EXAMPLES

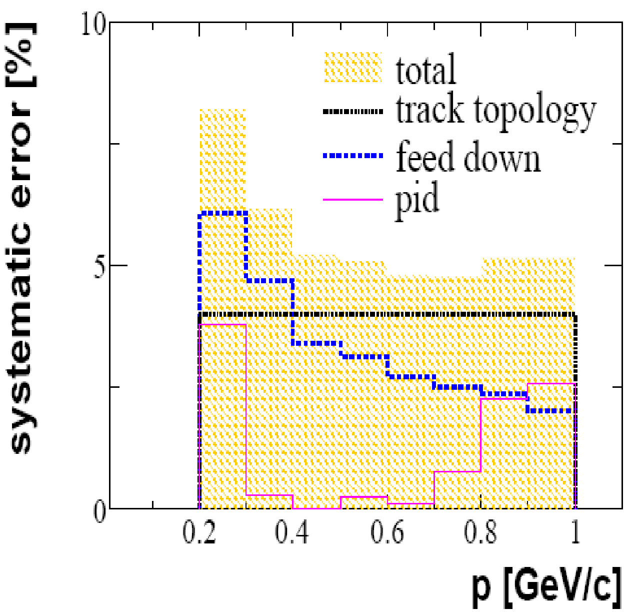
h$^-$ analysis

π^- θ=[140,180]mrad



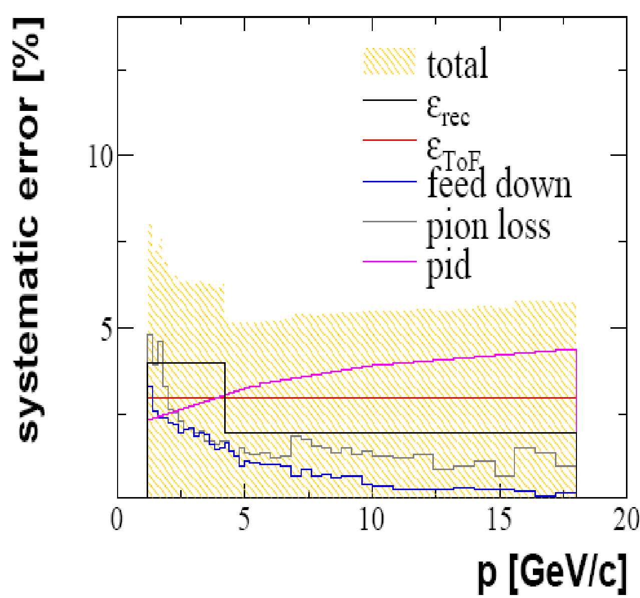
dE/dx

π^+ θ=[140,180]mrad



dE/dx +ToF

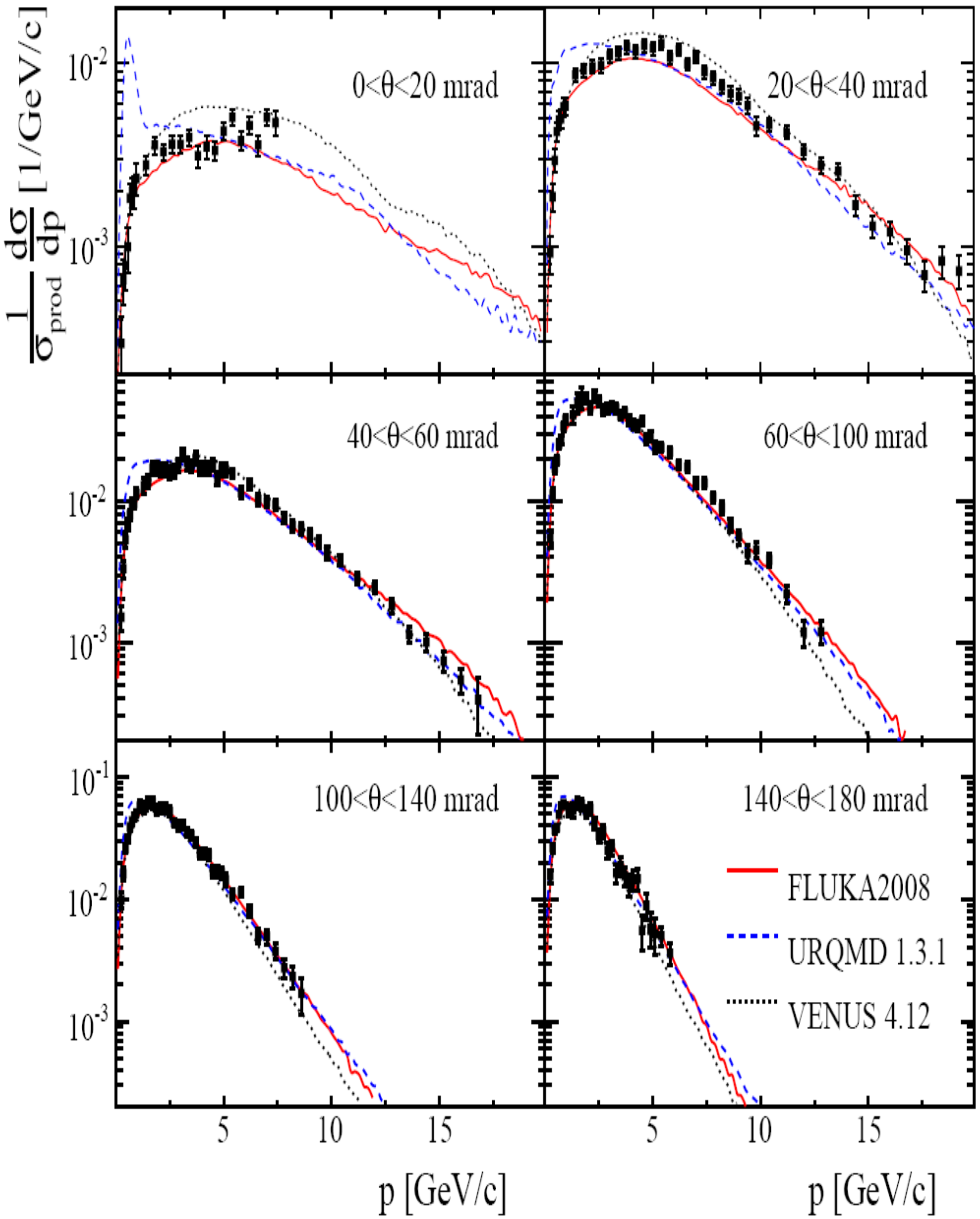
π^+ θ=[40,60]mrad

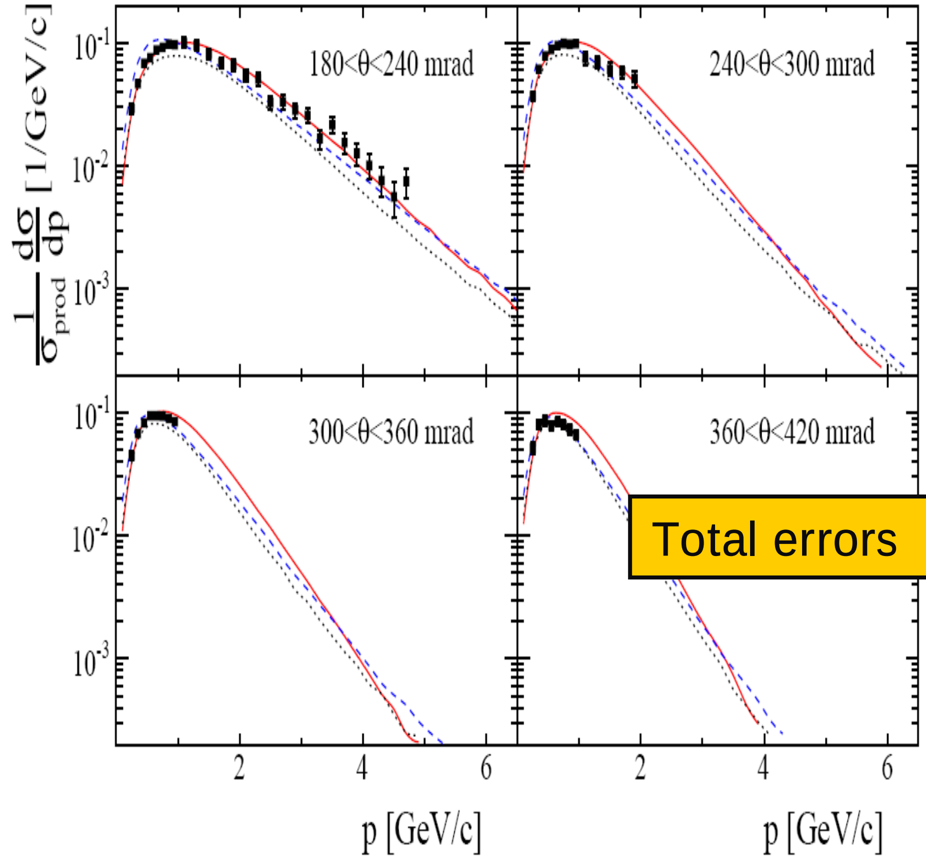


Typical value 6%

Feed down systematic error larger for π^- than for π^+ due to contribution from Λ hyperon decays (as expected).

NA61 : COMPARISON WITH MODELS π^+

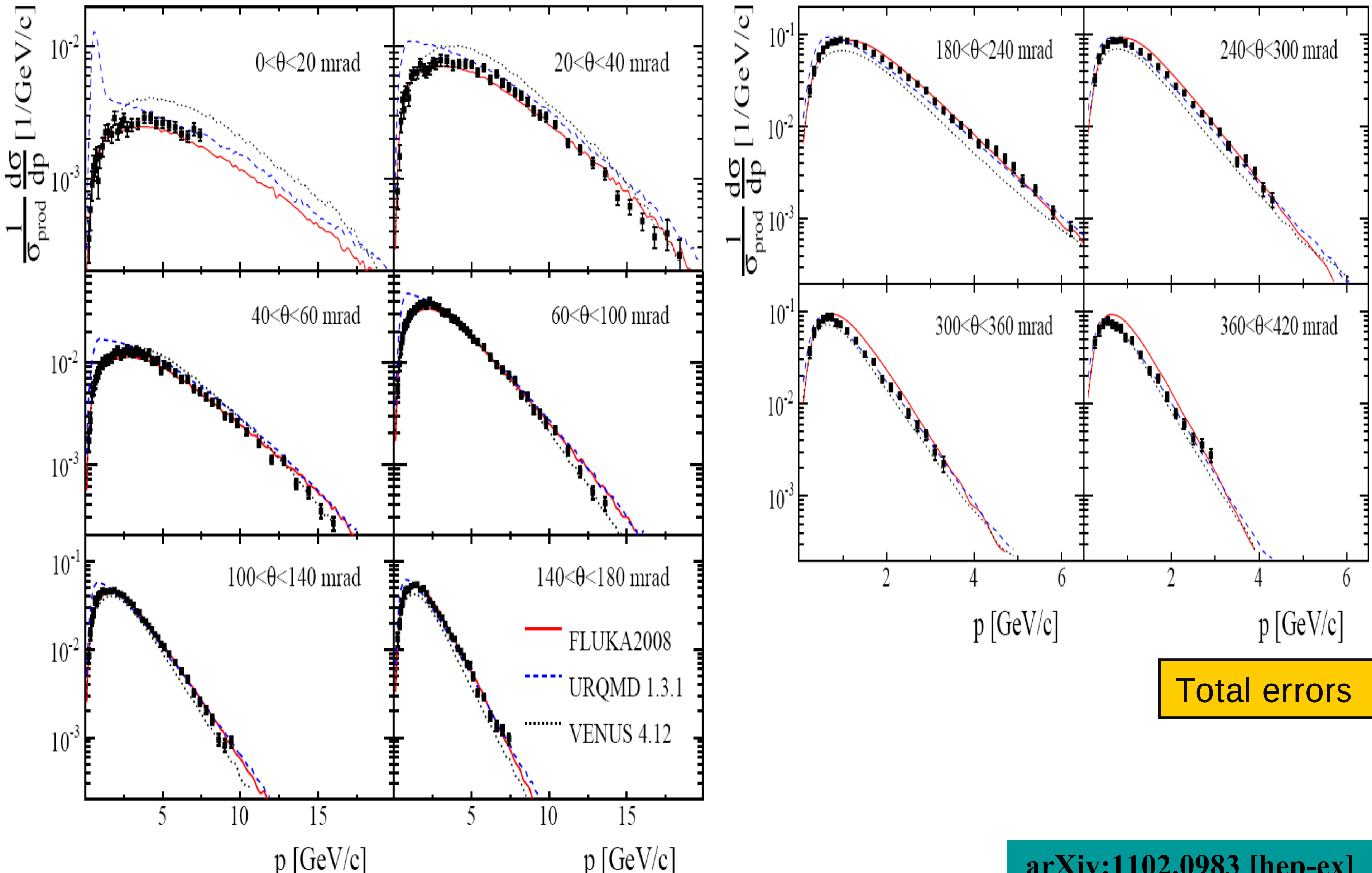




In the region of overlap we choose the measurement with the smallest total error.
Spectra normalized to the mean pion multiplicity in production events.
In addition the total normalization uncertainty is 2.3%

arXiv:1102.0983 [hep-ex]

NA61 : COMPARISON WITH MODELS π^-

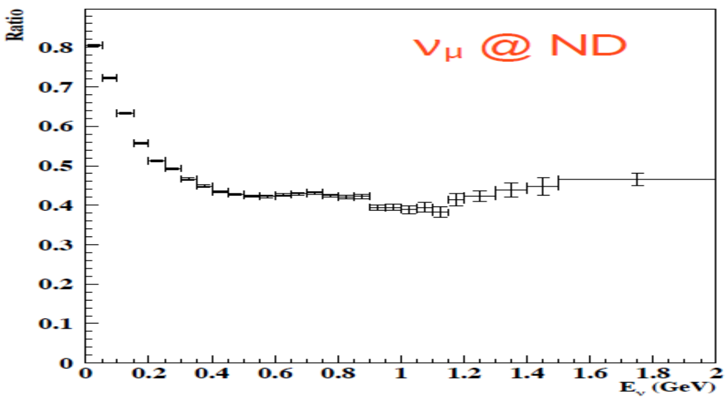


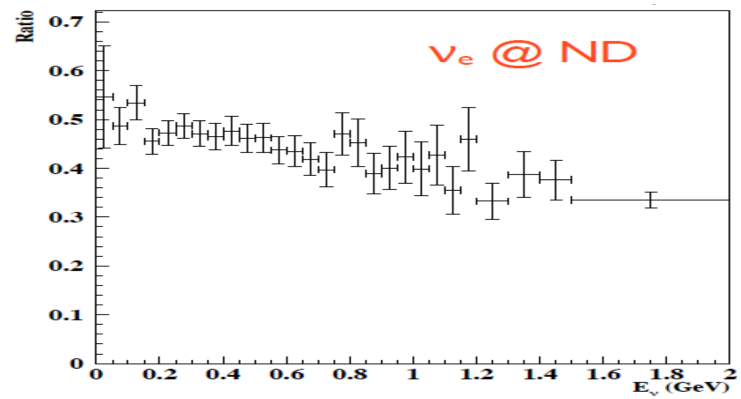
Total errors

arXiv:1102.0983 [hep-ex]

Motivations for T2K replica target data

Ratio of indirect / total contribution for ν_μ and ν_e ~ 40% at peak energy

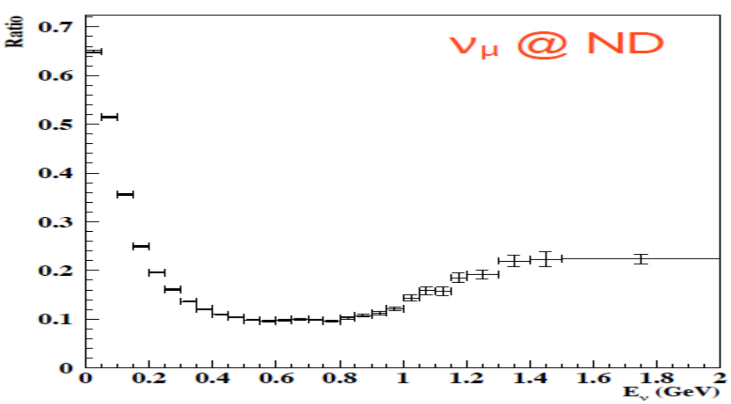


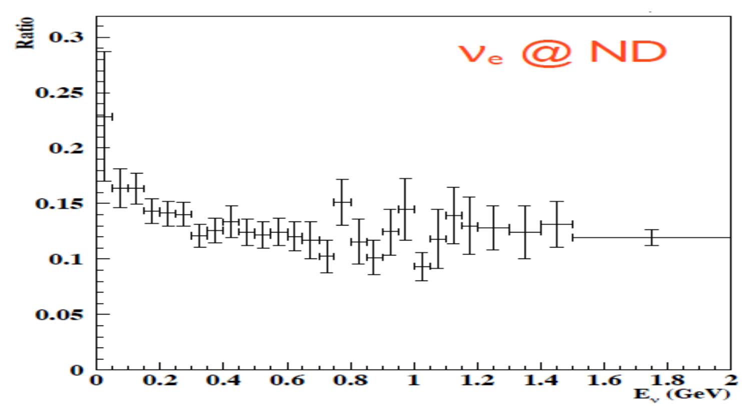


Thin target ~60% of ν flux

indirect contribution: neutrinos from particles coming from re-interactions

Ratio of out-of-target / total contribution for ν_μ and ν_e ~ 10% at peak energy

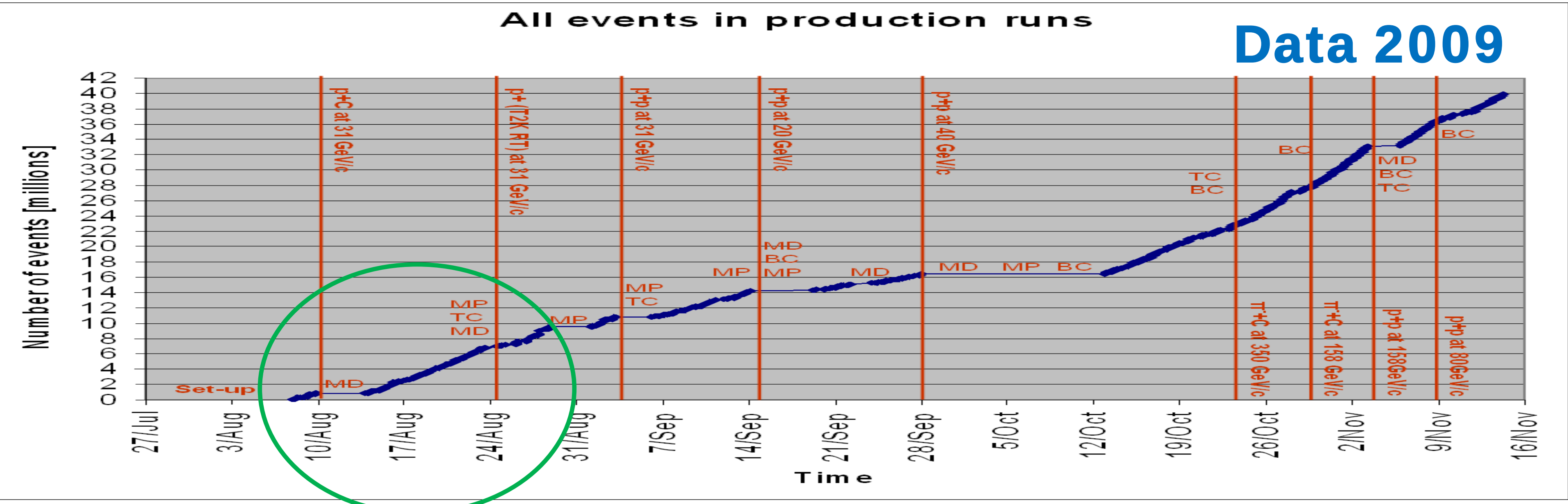




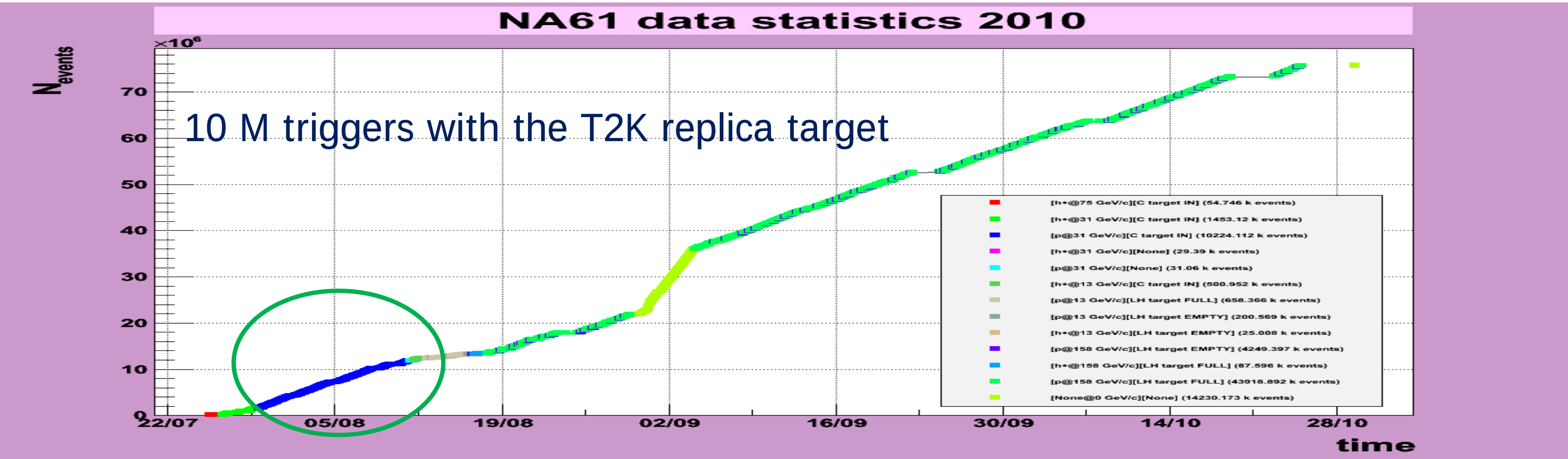
Replica target ~90% of ν flux

JNUBEAM 10a / GCALOR

NA61 : DATA COLLECTED IN 2009 AND 2010



Statistics for T2K is an order of magnitude larger compared to the 2007 run



NA61 : SUMMARY

- **First NA61/SHINE measurements of cross sections and charged pion spectra in proton-Carbon interactions at 31 GeV/c are released**
  - **arXiv:1102.0983 [hep-ex], submitted to Phys. Rev. C**
  - **already used to improve neutrino flux predictions in T2K**
- **2007 data are still being analysed to extract**
  - **Kaon yields (thin target)**
  - **pion yields from the T2K replica target**
- **High statistics 2009 and 2010 data samples are available (currently under calibration)**
- **Analysis techniques established**

- **Not presented here... But still important to mention very precise NA49 measurements of π, K and p production in p-p (p-C) interactions at 158 GeV/c:**

Eur. Phys. J. C45 (2006) 343; Eur. Phys. J. C49 (2007) 897; Eur. Phys. J. C65 (2010) 9; Eur. Phys. J. C68 (2010) 1

GENERAL CONCLUSION

- **Hadron production studies is a MUST for precision neutrino experiments!**

Thank you for your attention

Backup slides

HARP – PS214 at CERN

HARP collaboration

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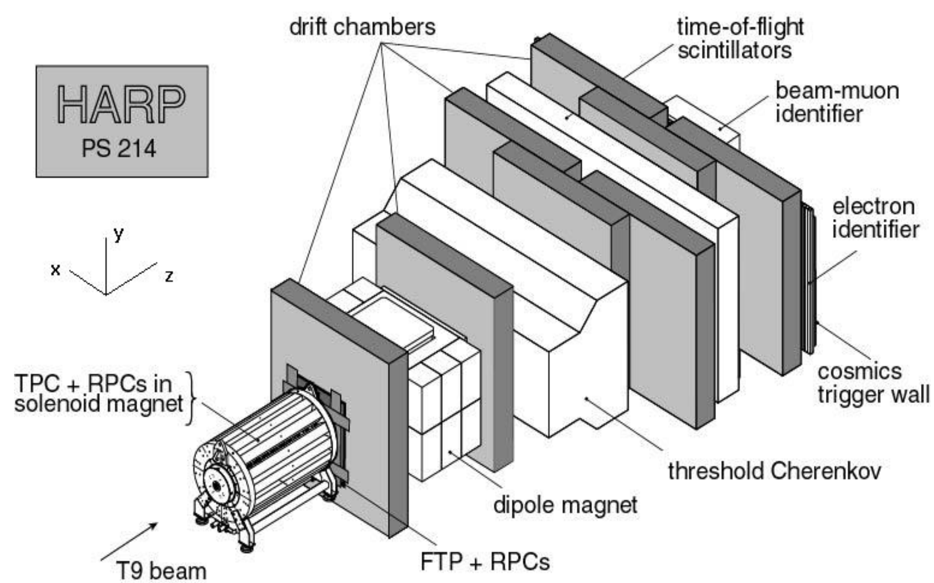
24 institutes
~120 collaborators

forward spectrometer



large-angle spectrometer

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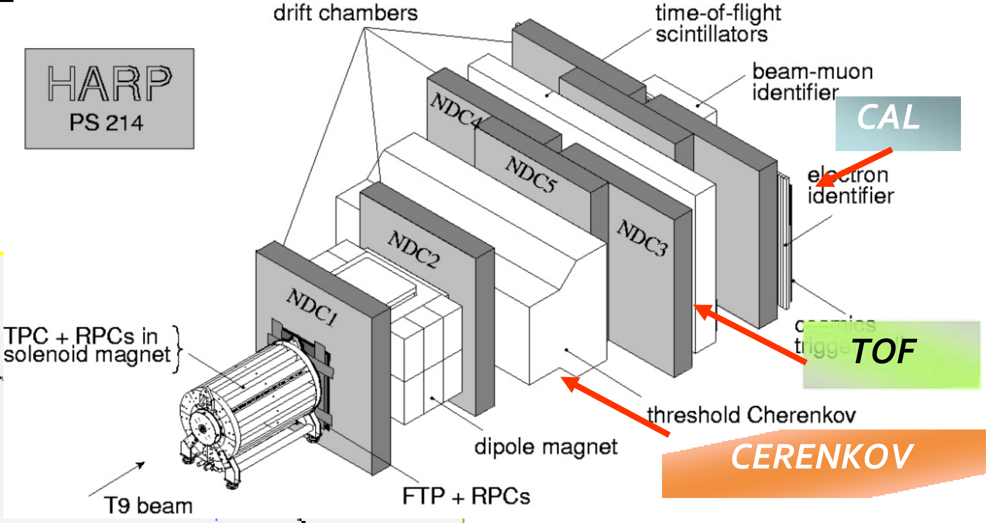
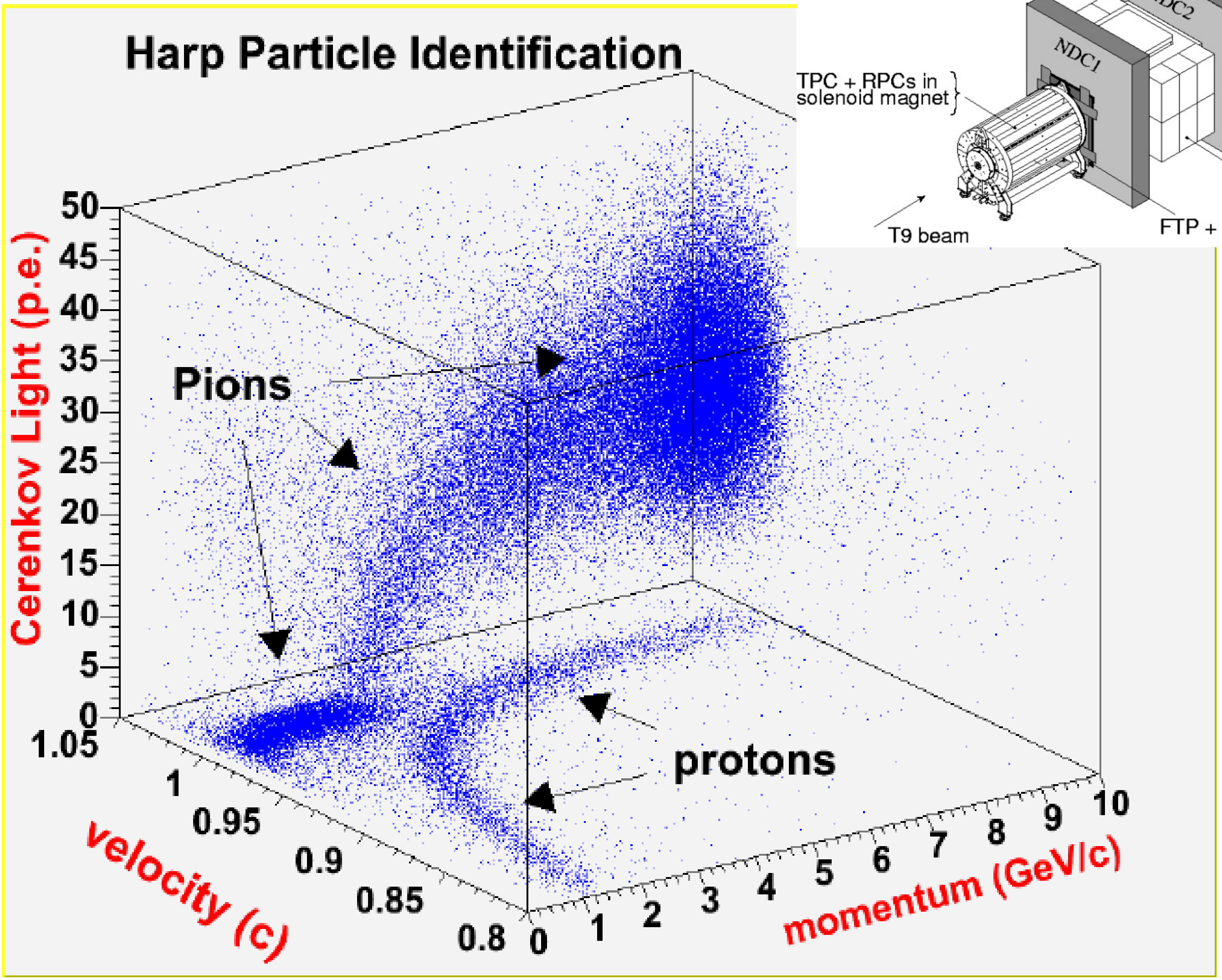
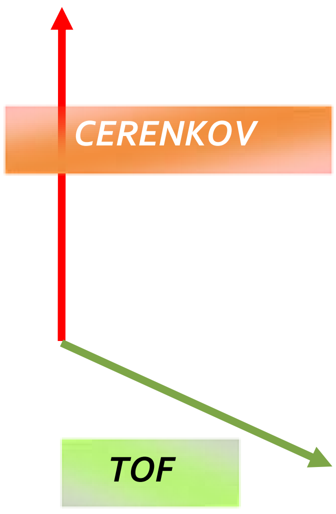
Detailed description of the experimental apparatus

NIM A571 (2007) 524

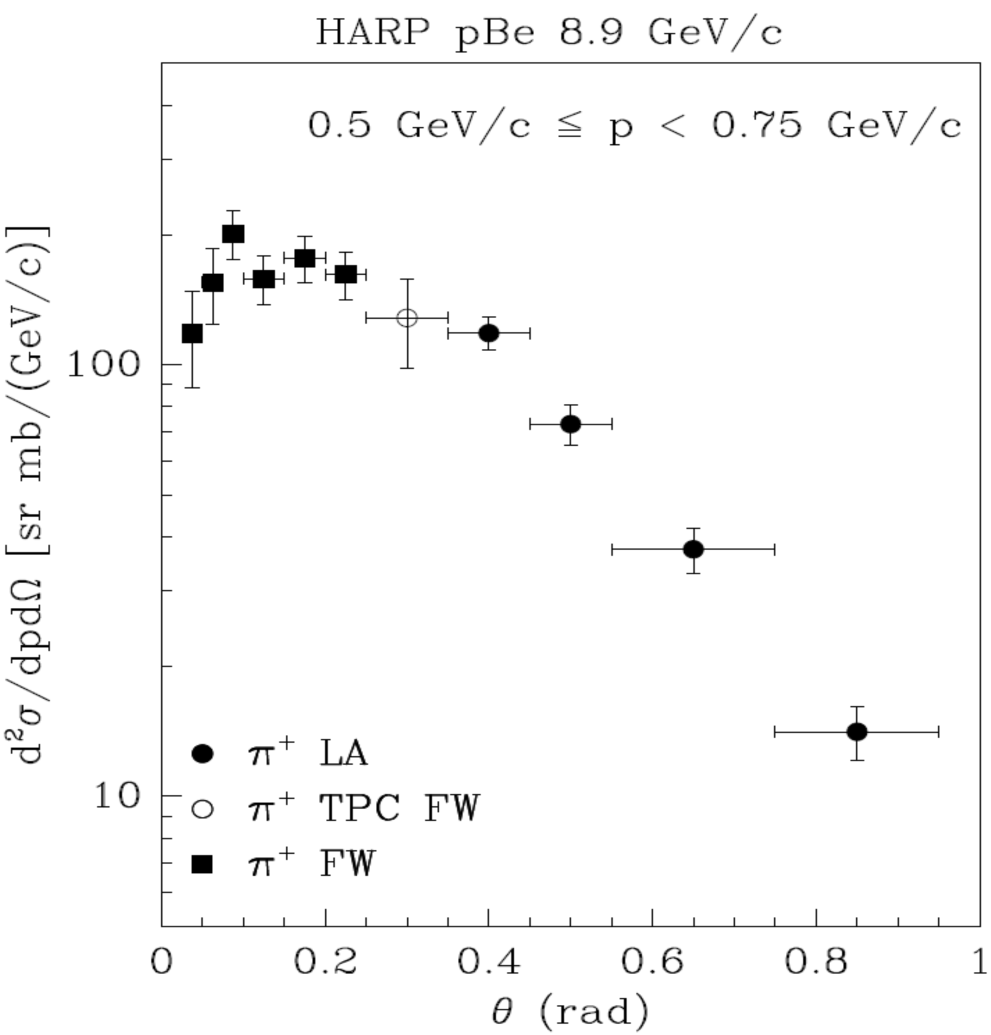
FW: PID principle

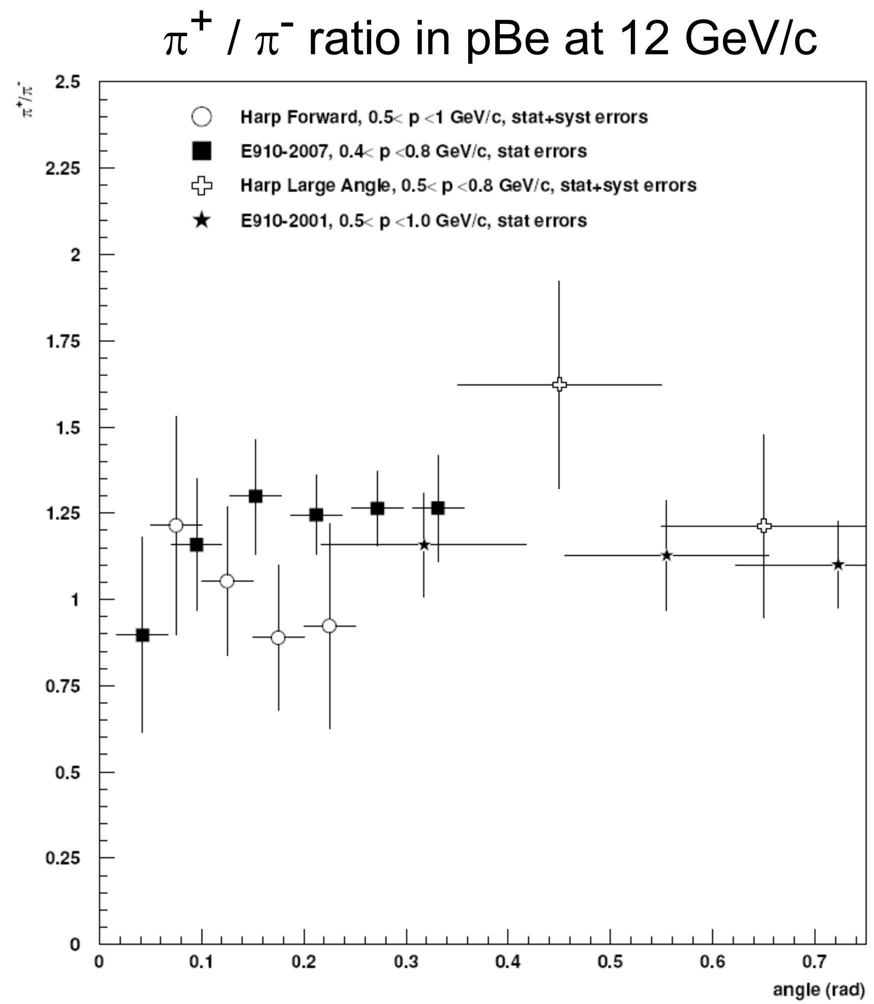






HARP: two spectrometers match each other



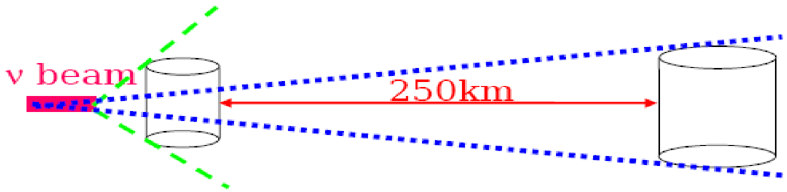


CERN-SPSC-2008-030 / SPSC-SR-038

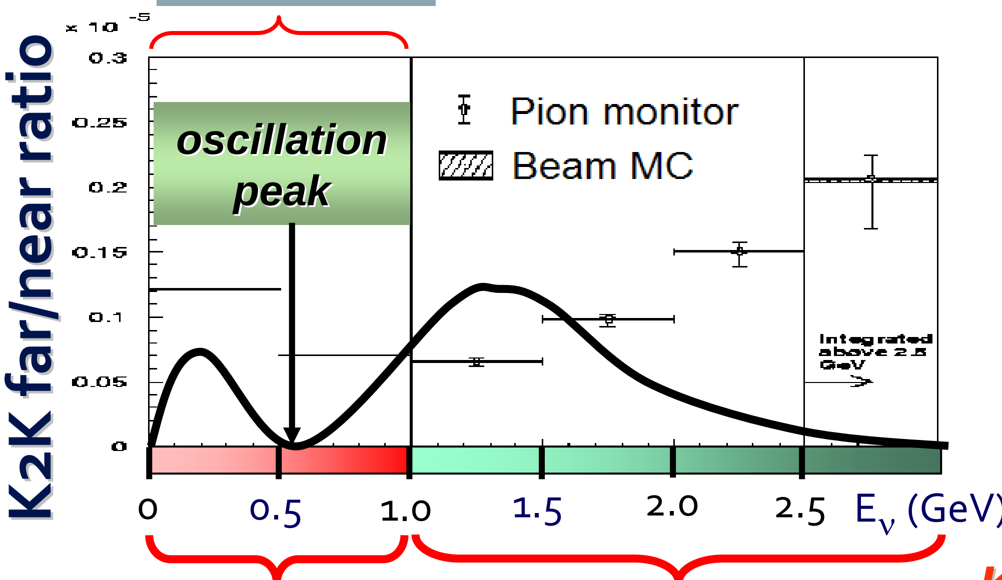
Relevance of HARP for K2K neutrino beam

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

pions producing neutrinos in the oscillation peak

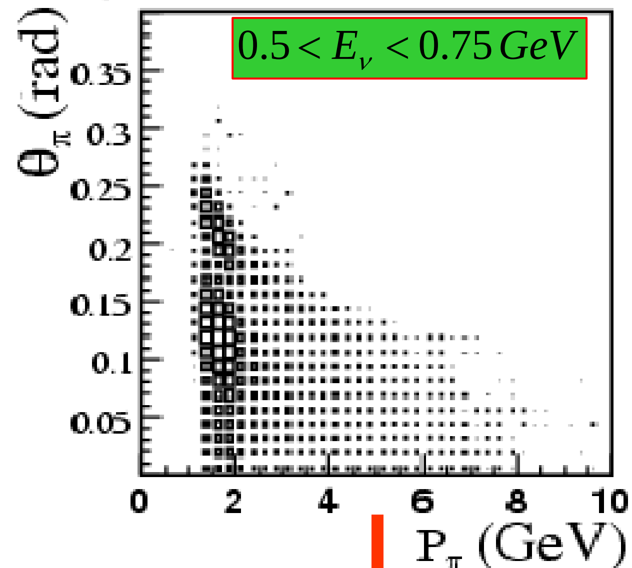


measured by HARP



Beam MC

Beam MC confirmed by Pion Monitor

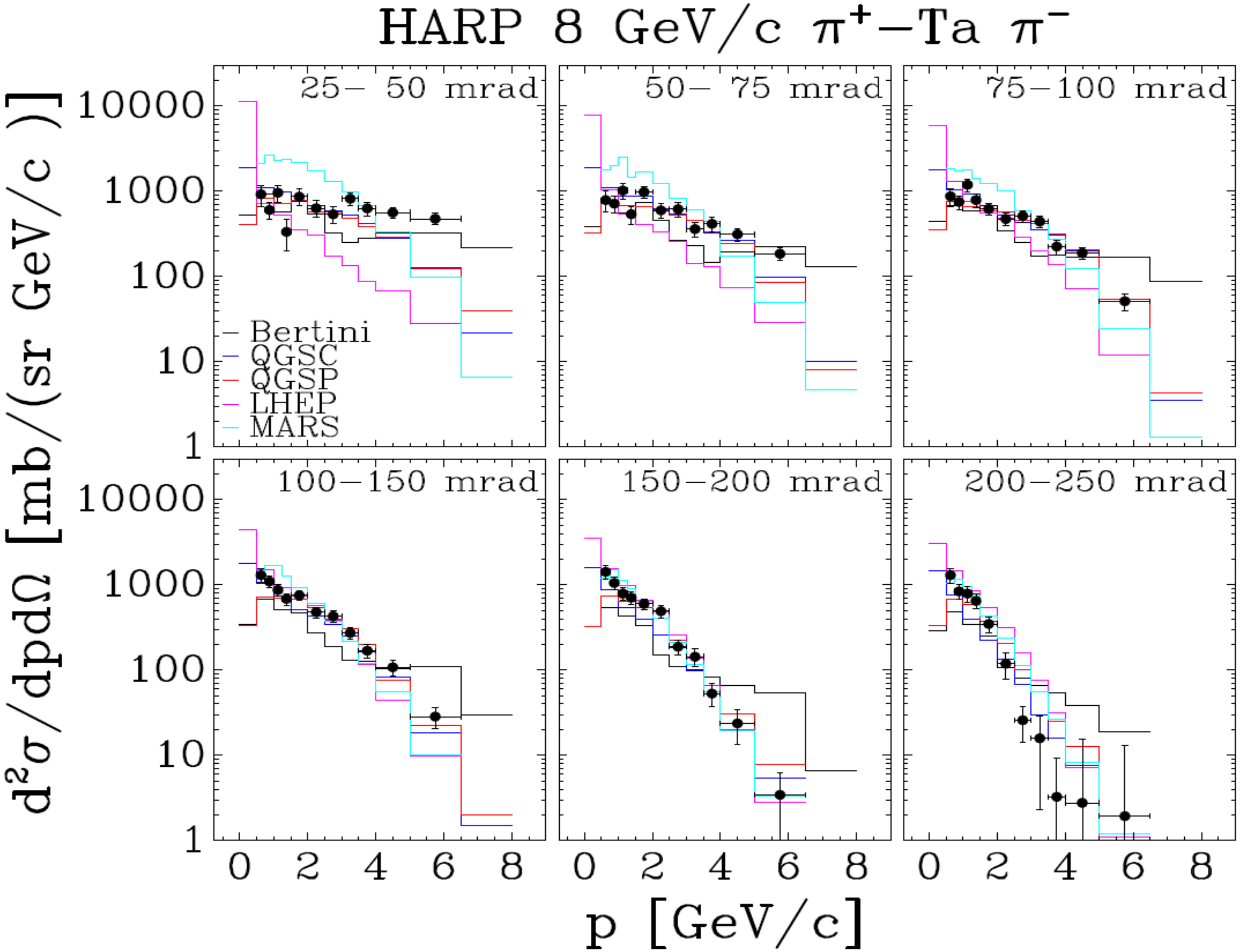


K2K interest

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

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

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



An example of more HARP data on the FW production with incident pions

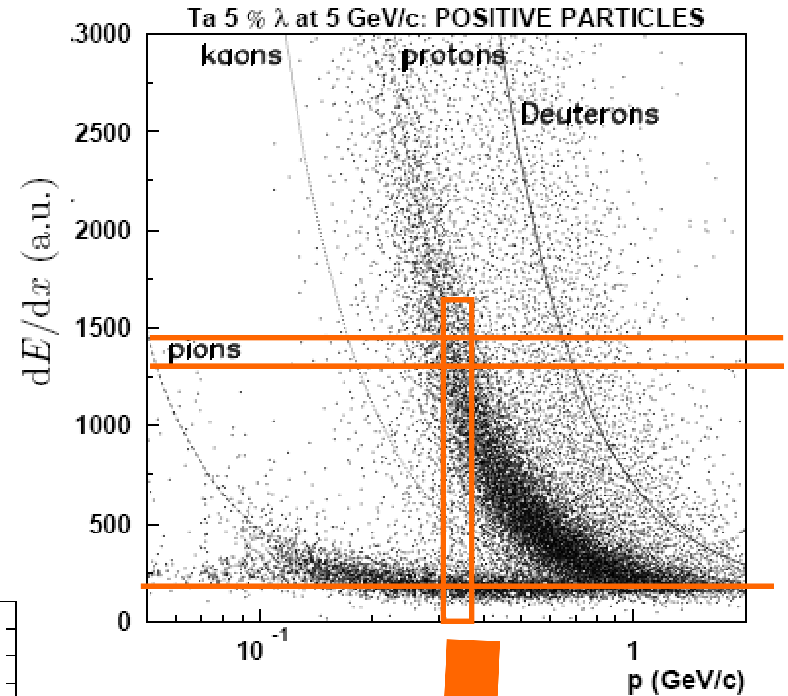
Model comparisons

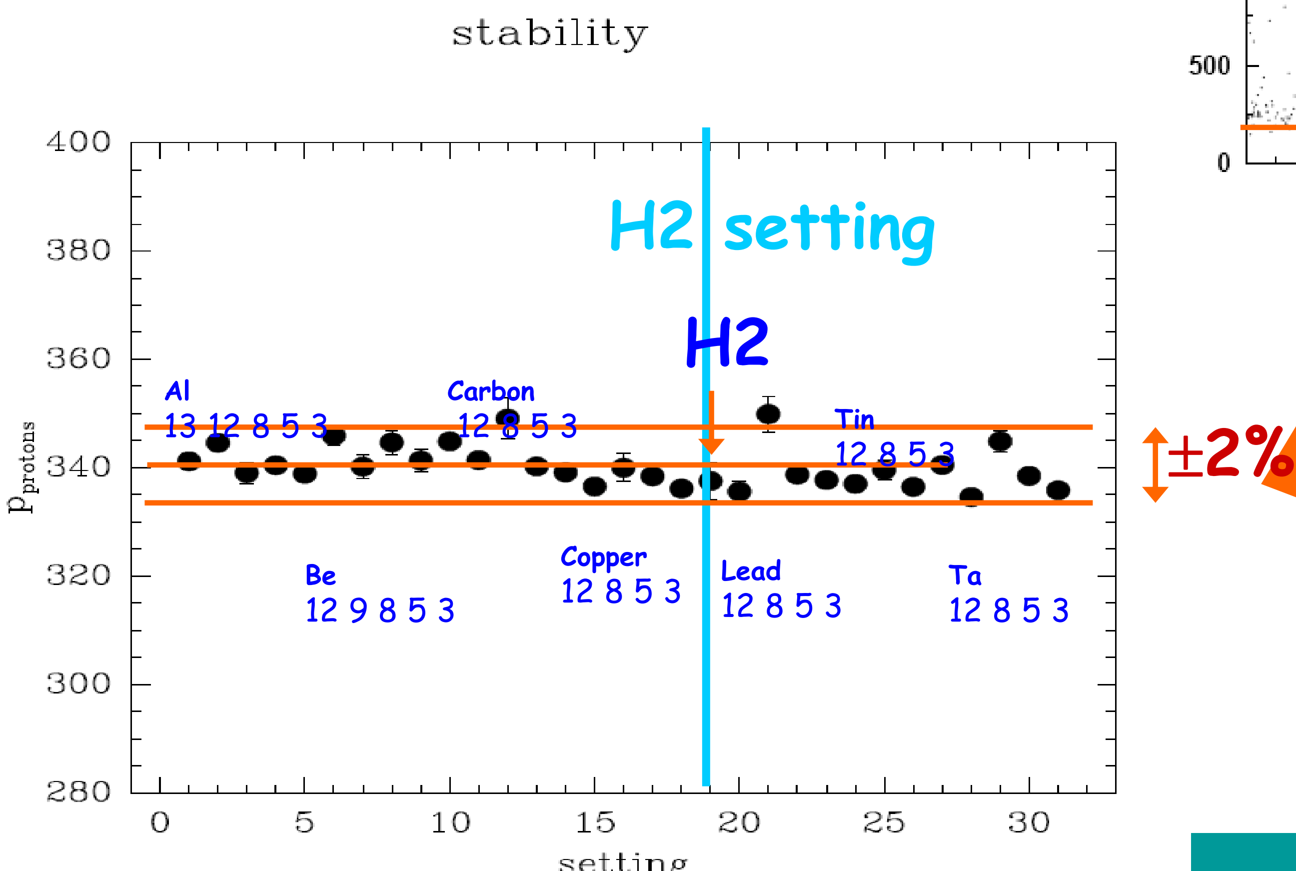
- All thin target FW data taken in pion beams are now published
- Interesting to tune models for re-interactions, etc.

Nucl. Phys. A 821 (2009) 118

Stability from LH2 target to other targets

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

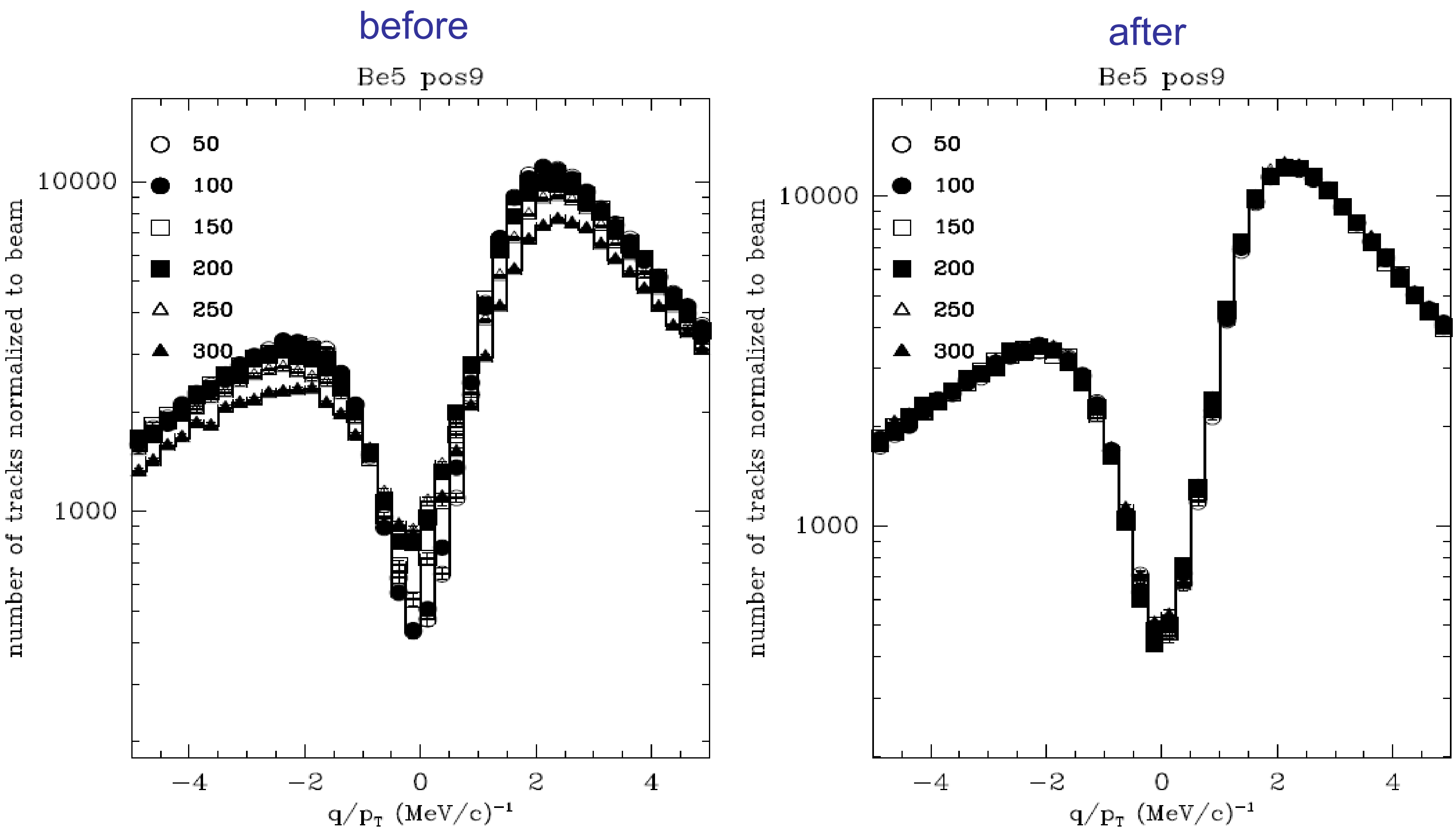




JINST 3: P04007 (2008)

HARP TPC: corrections for dynamic distortions

JINST 4: P11014 (2009)



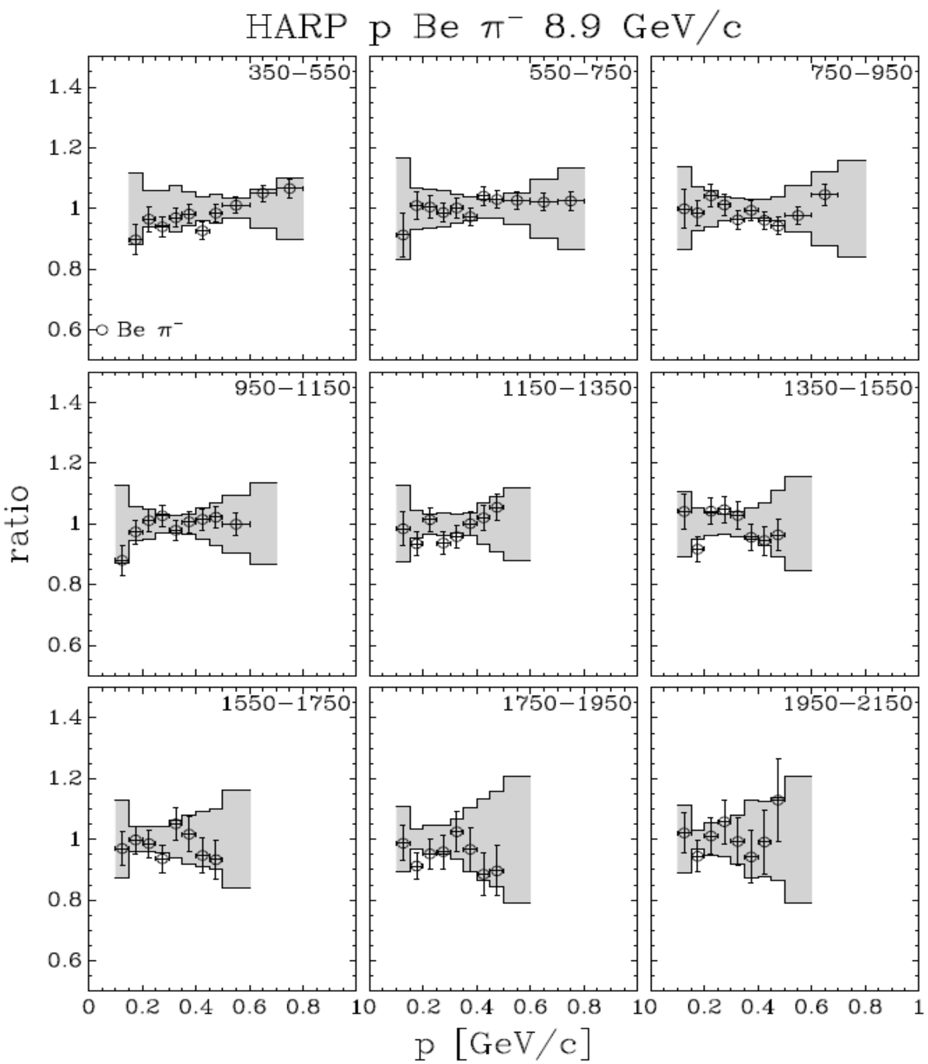
Analyses of full data sample

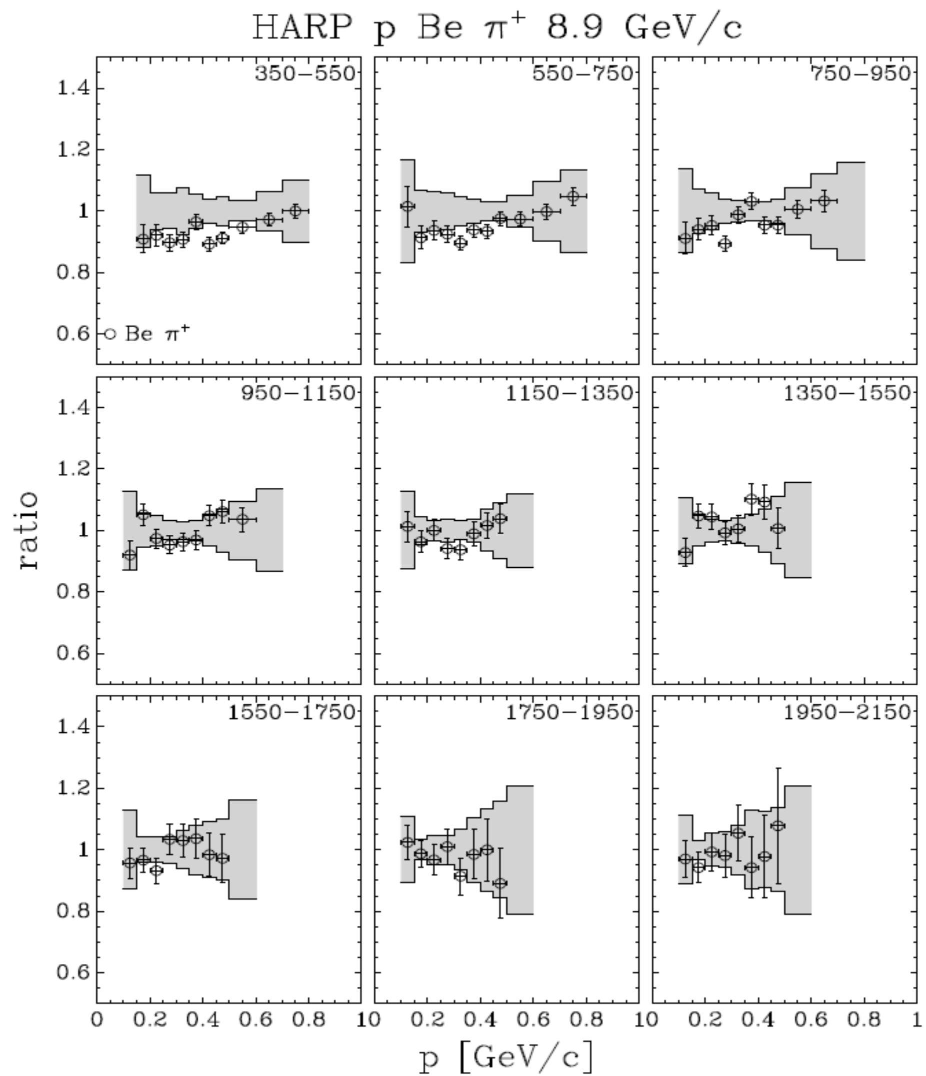
Phys. Rev. C 77 (2008) 055207

HARP: p-Be

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

Phys. Rev. C 77 (2008) 055207

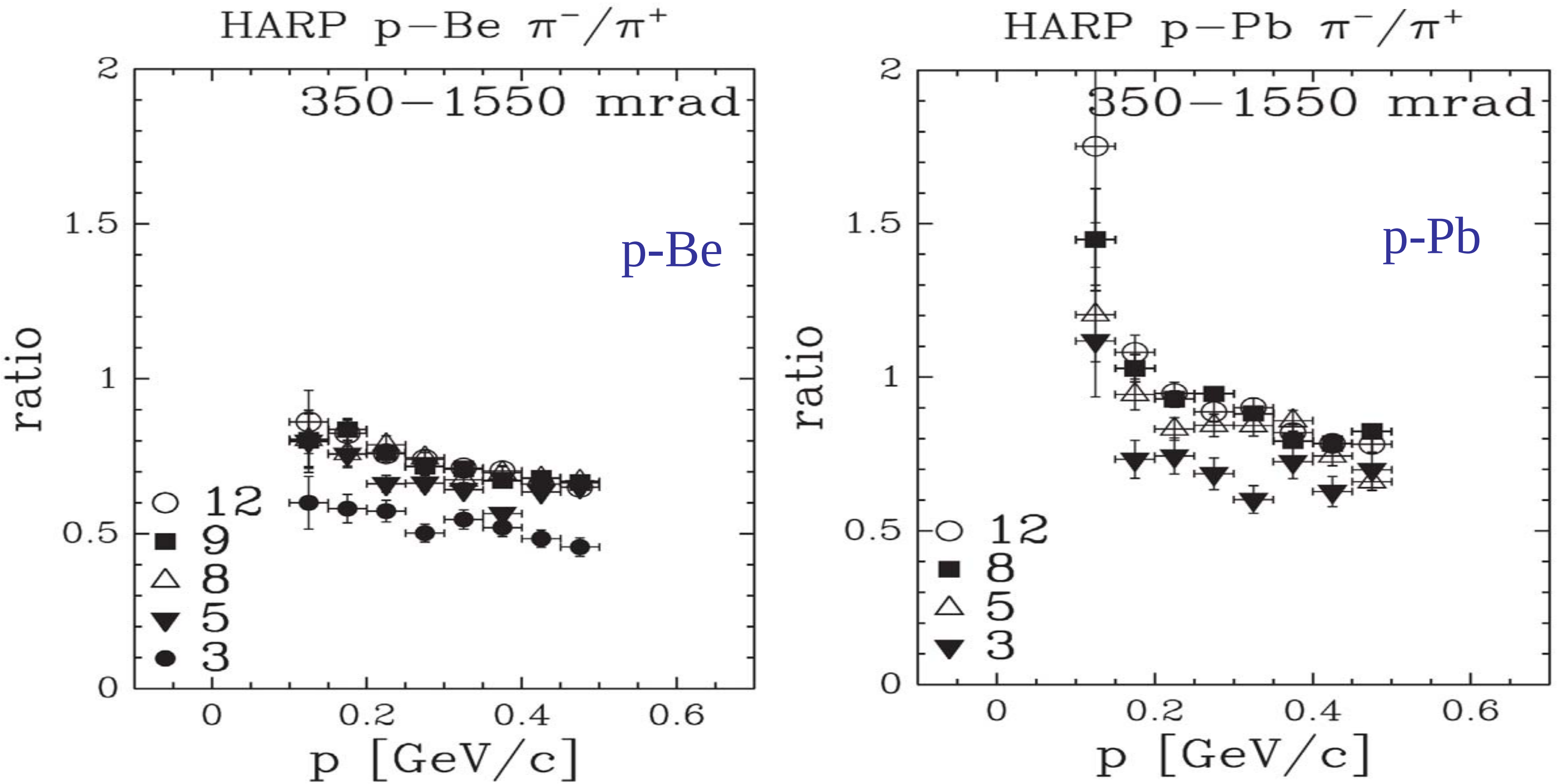




HARP: pion yields

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

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

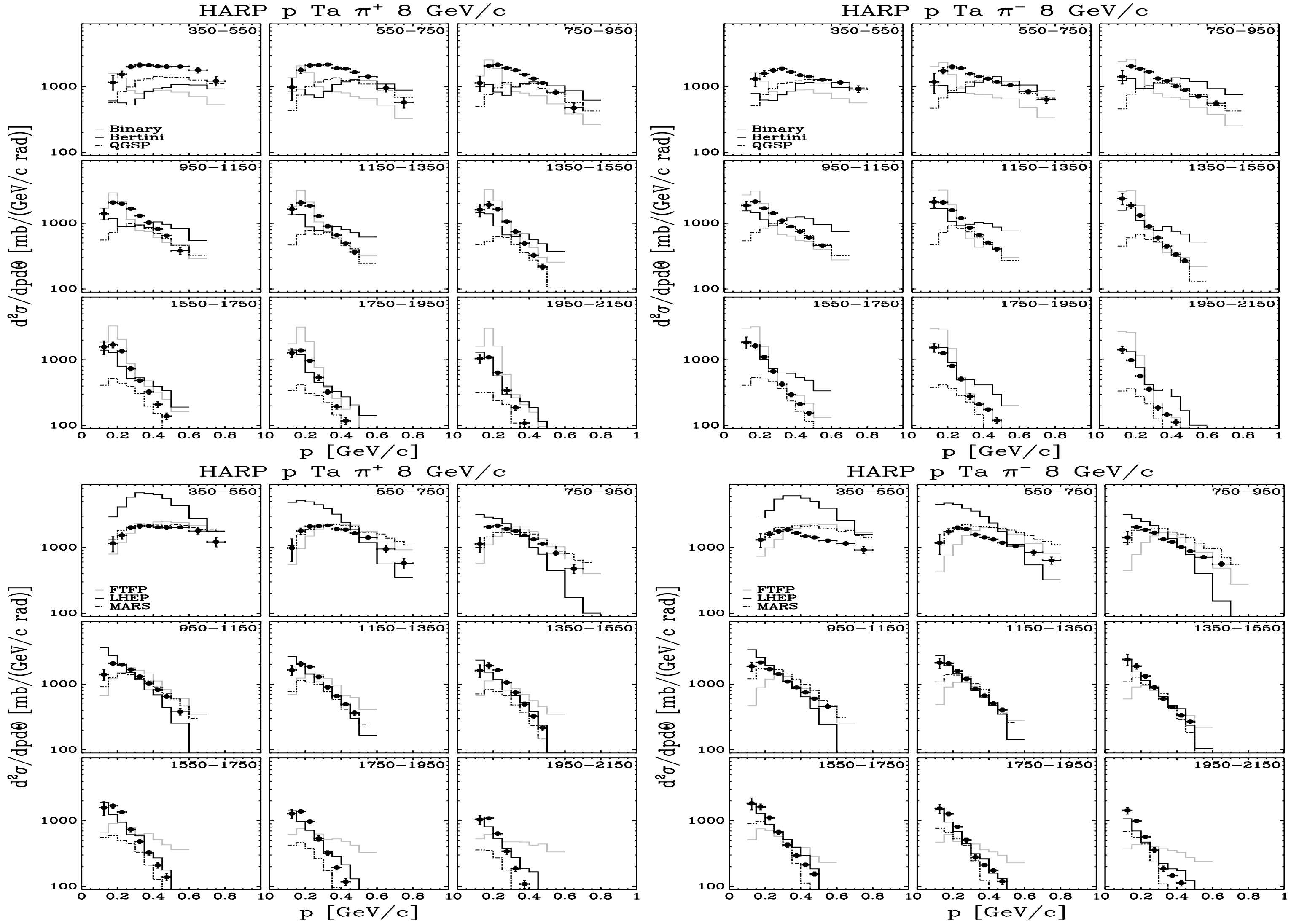


Phys. Rev. C 77 (2008) 055207

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

MODELS

5% λ target

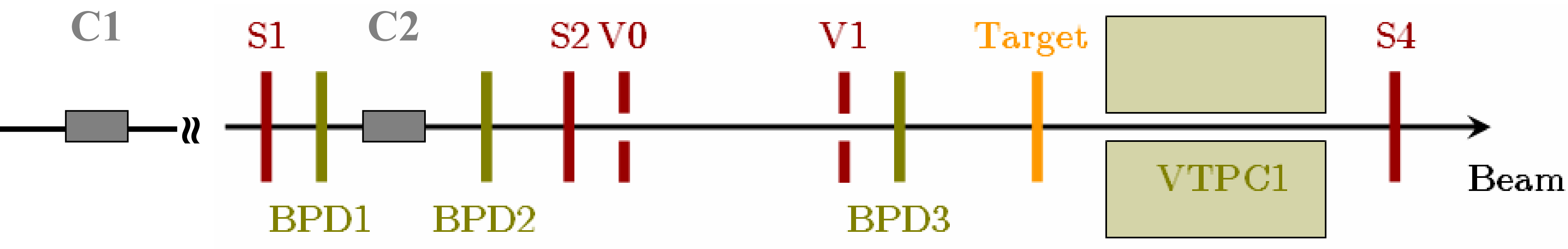


HARP: comparison with MC at LA

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: Setup of Beam-Line



- 31 GeV/c secondary hadron beam composed of 83.7% π, 14.7% p and 1.6% K
- Proton beam particles identified by CEDAR (C1, 96% efficiency for 6th-fold coincidence) and threshold Cerenkov counters (C2)
- Incoming p then selected by several scintillator counters (S1, S2, $\overline{\text{V0}}$, $\overline{\text{V1}}$)
  $\rightarrow$ beam defined as Beam = $S1 \bullet S2 \bullet \overline{V} \bullet C1 \bullet \overline{C2}$
- Trajectory of beam particles measured by the beam position detectors (BPD-1/-2/-3)
- Interactions in the target were selected by an anti-coincidence of the beam particle with a small scintillator S4 ($\text{Beam} \bullet \overline{S4}$)

NA61 : MC SIMULATION AND CORRECTIONS

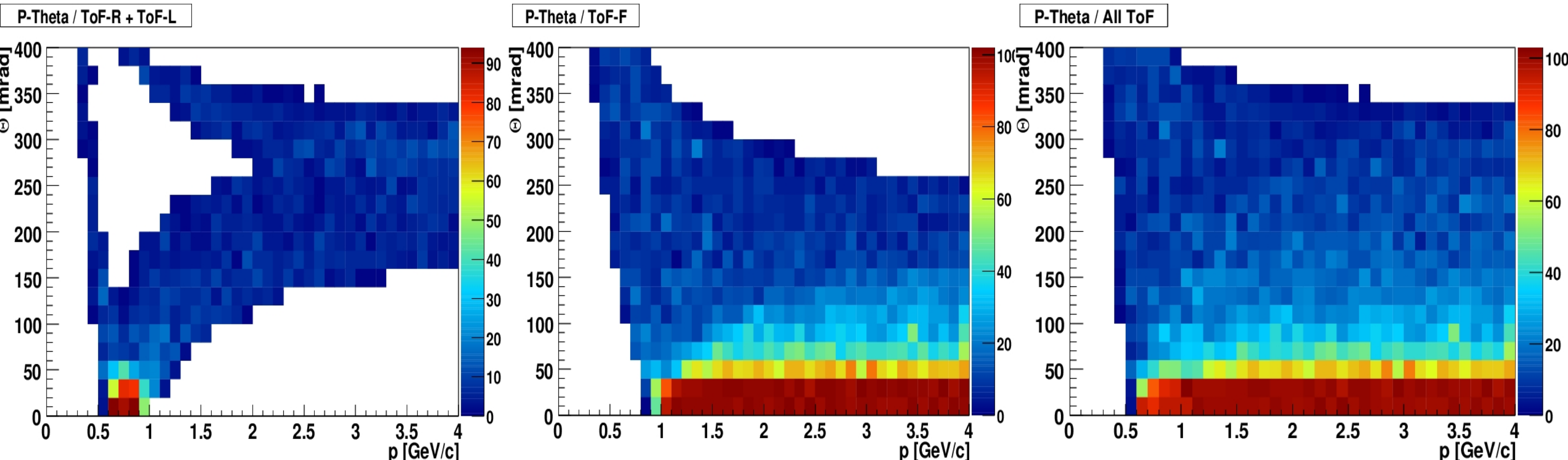
The corrections to the raw spectra are being calculated using the NA61 simulation chain which includes:

-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

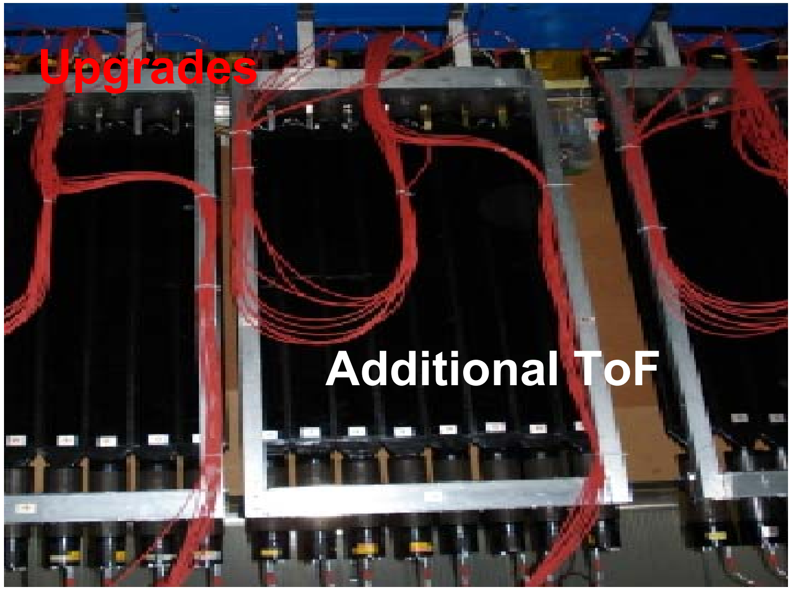
<u>Example of acceptance studies: (TOF acceptance)</u>

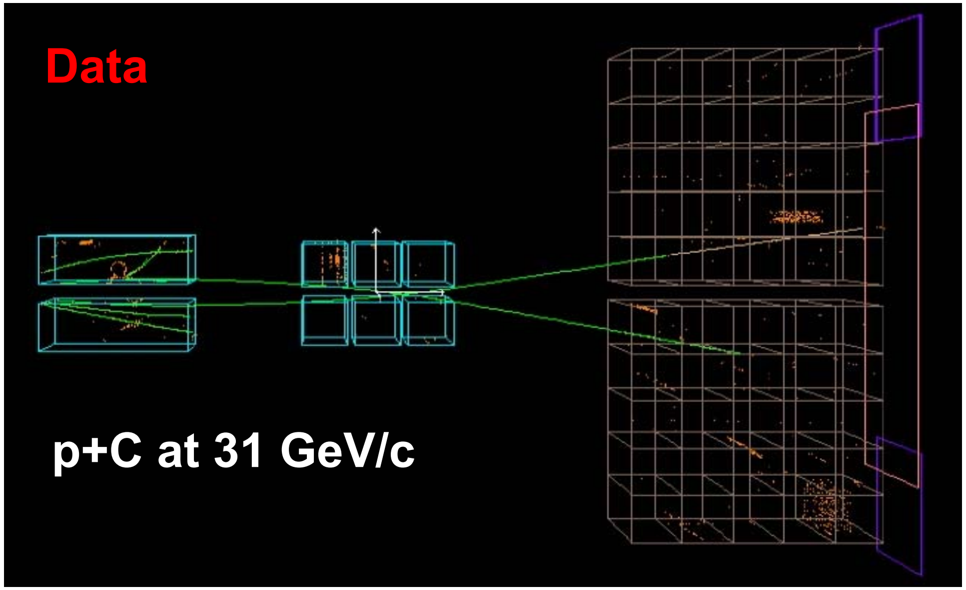
Old NA49 configuration

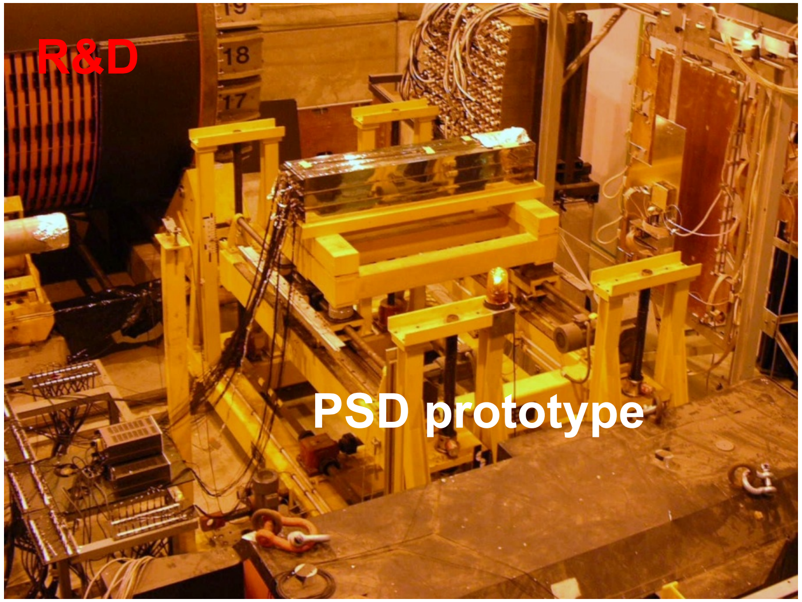
New NA61 configuration



NA61 : 2007 PILOT RUN







NA61 : RECONSTRUCTED EVENT