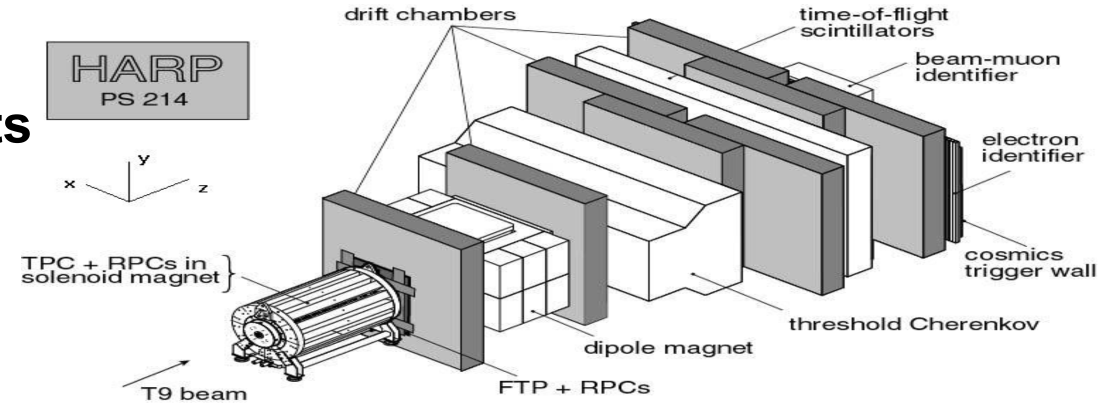
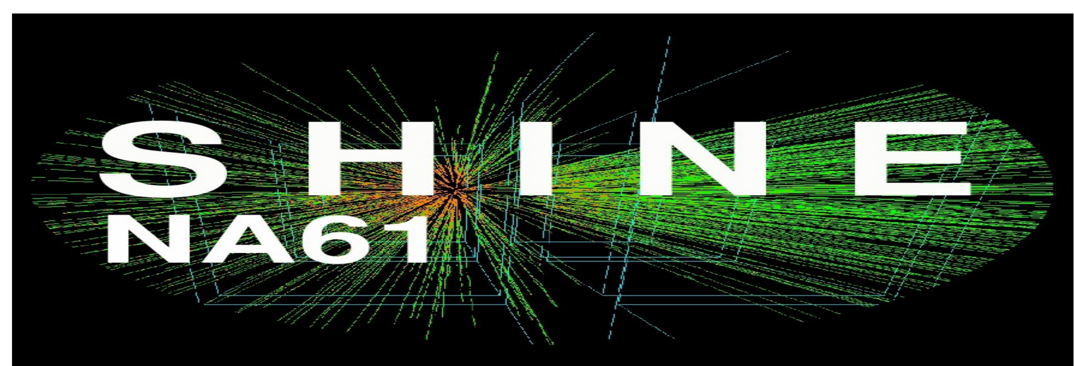
Fixed-target hadron production experiments

International Symposium on Very High Energy Cosmic Ray Interactions,
ISVHECRI 2014, August,18-22 2014, CERN

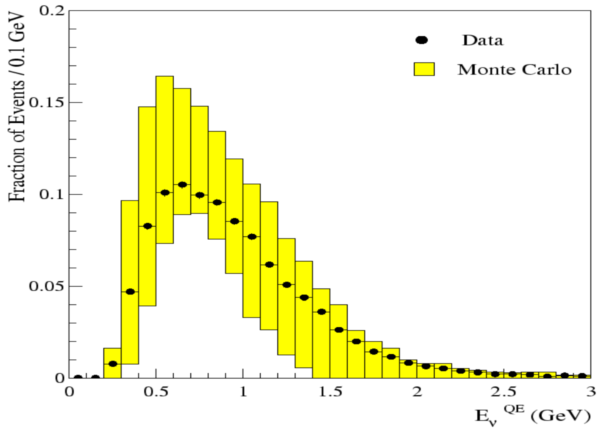
Boris A. Popov (LPNHE, Paris & JINR, Dubna)

- **Goals of hadroproduction experiments**
- **Briefly on previous measurements (HARP, MIPP, NA49)**
  - *Results and Impacts*
- **On-going NA61/SHINE experiment**
  - *Results, status and plans*
- **Summary**

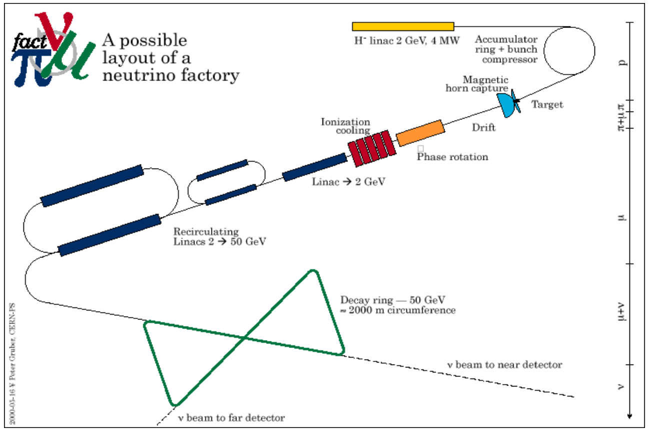




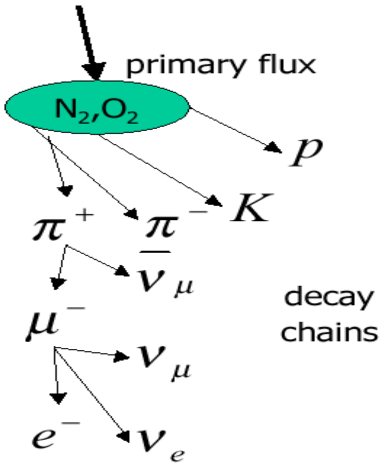
Goals of hadroproduction studies



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

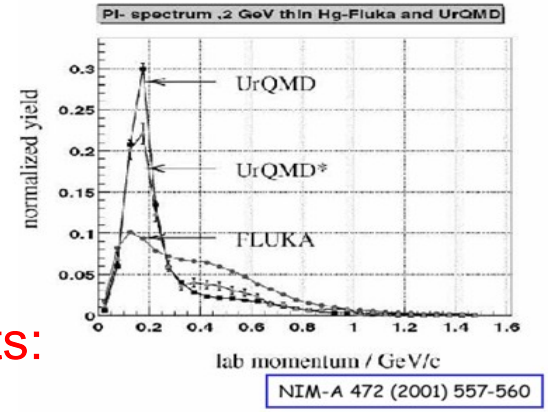


Pion/Kaon yield for the design of the proton driver and target system of new accelerator facilities, e.g. **Neutrino Factories** and **Super-Beams**



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 validation/tuning of **Monte Carlo** generators (e.g. GEANT4 and many others)



Significant progress during the last decade. Dedicated experiments: HARP, MIPP, NA49, NA61/SHINE…

HARP – PS214 at CERN

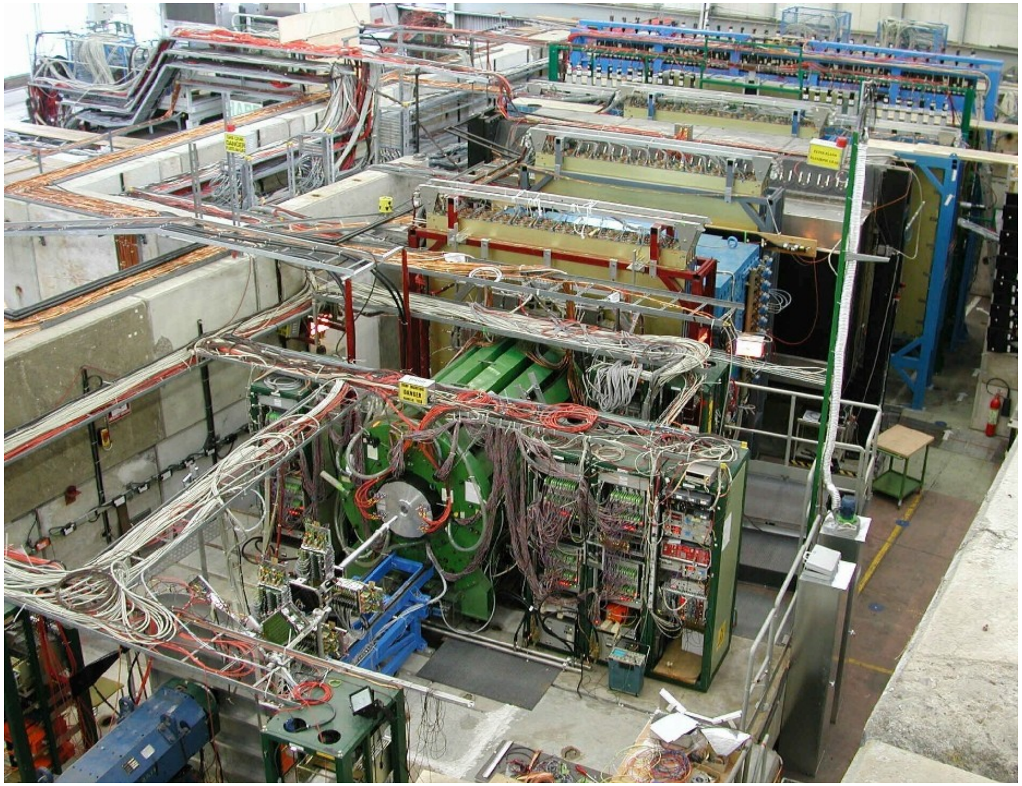
HARP is a large acceptance spectrometer to measure hadron production from various nuclear targets and a range of incident beam momenta

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

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)

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: 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

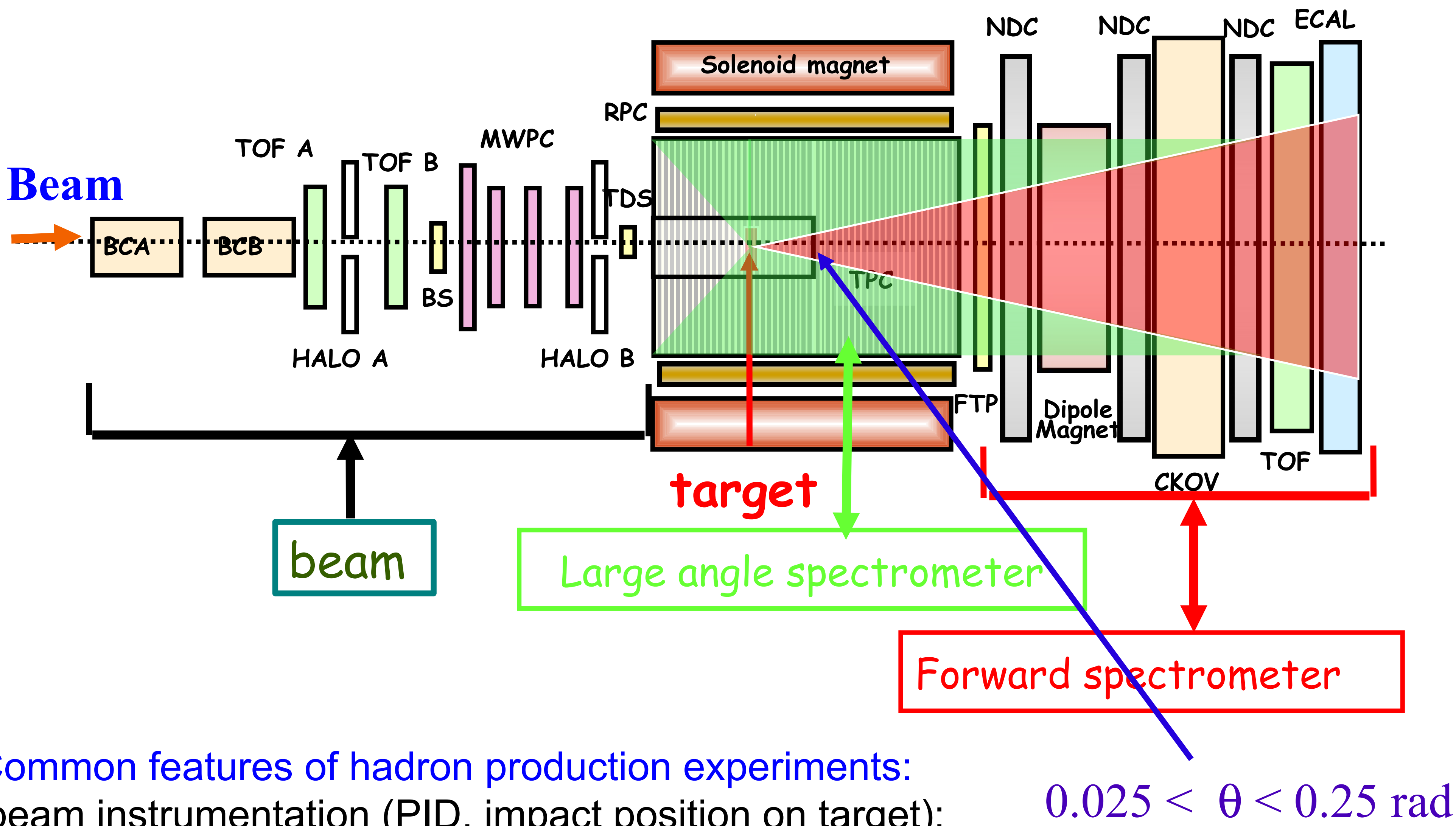
CRYOGENIC:

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;

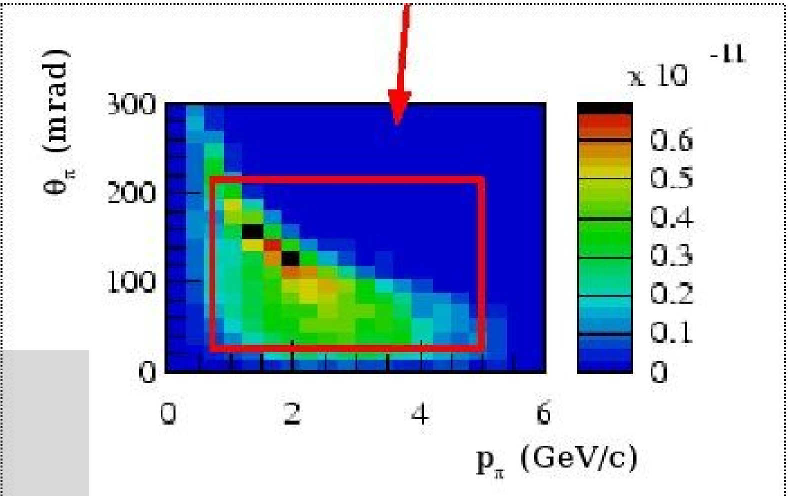
HARP: Analyses with the forward spectrometer

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:*



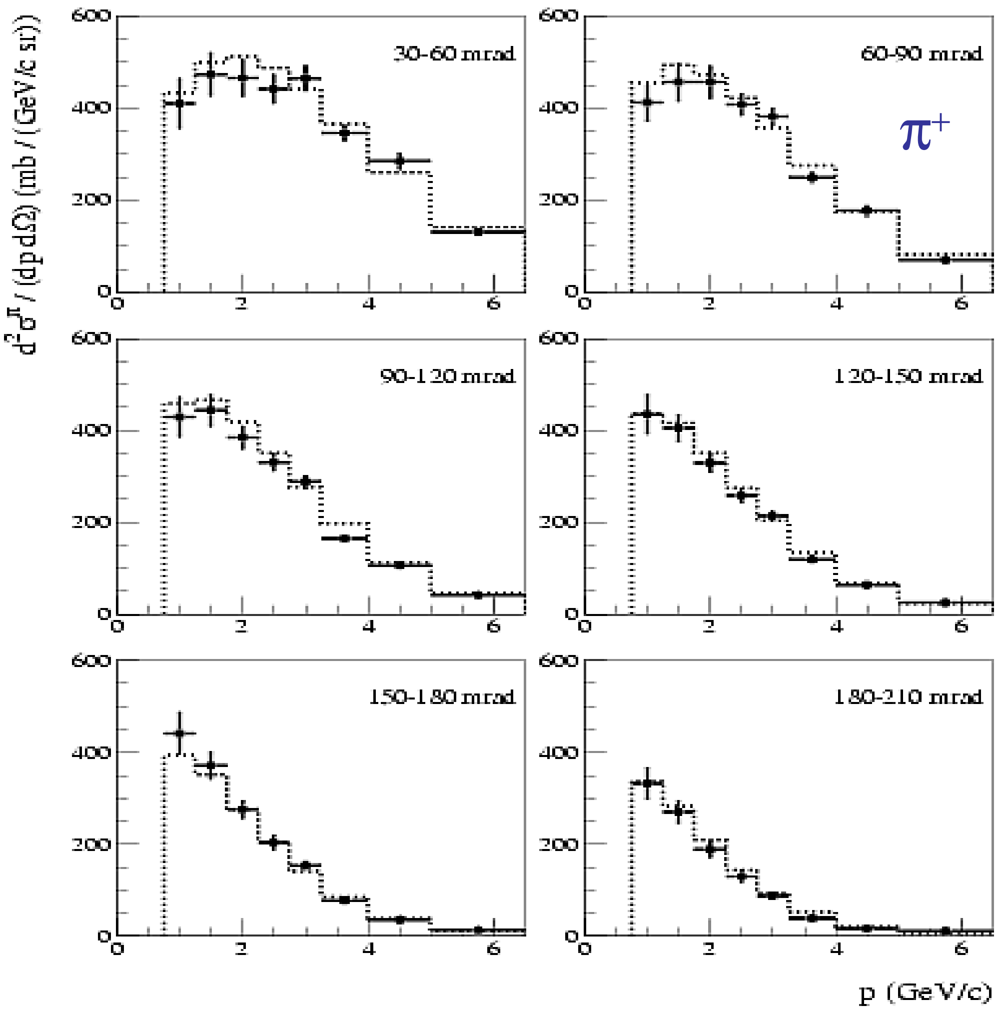
Momentum and Angular distribution of pions decaying to a neutrino that passes through the MB detector.

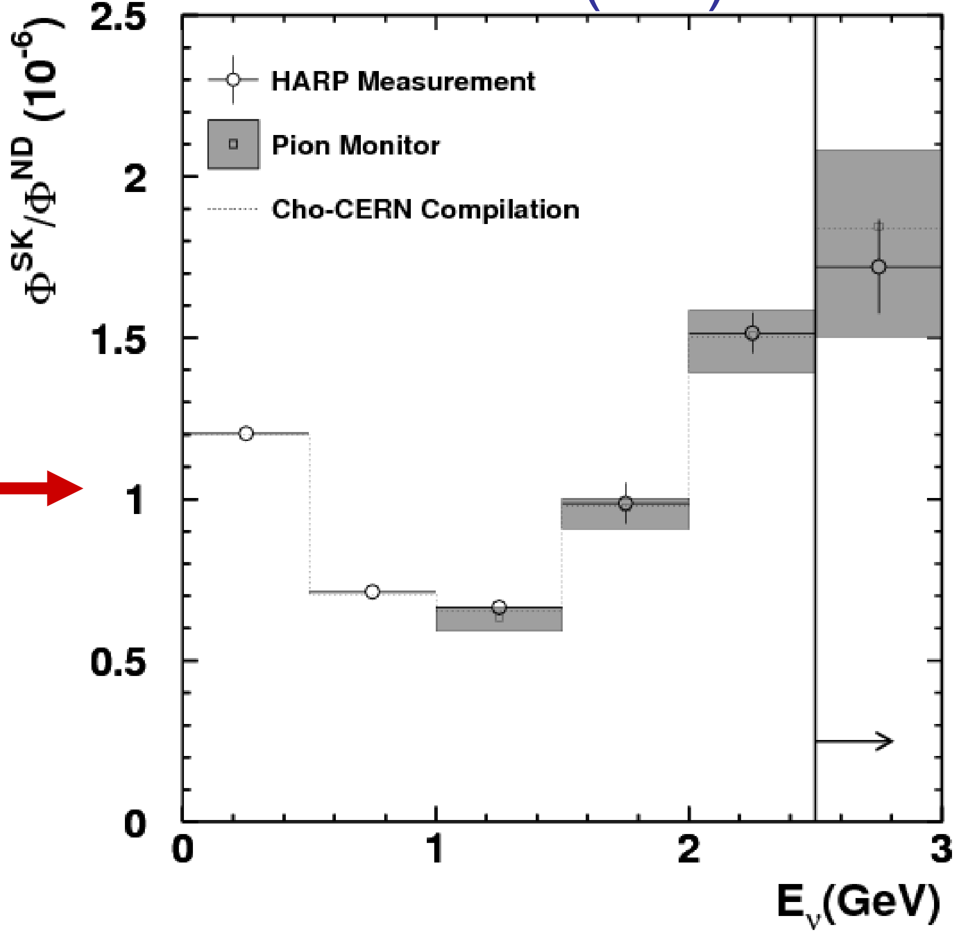
Removes *major* source of uncertainties for these experiments

(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

HARP: p+Al at 12.9 GeV/c for K2K Far/Near flux ratio





Nucl. Phys. B732 (2006) 1

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

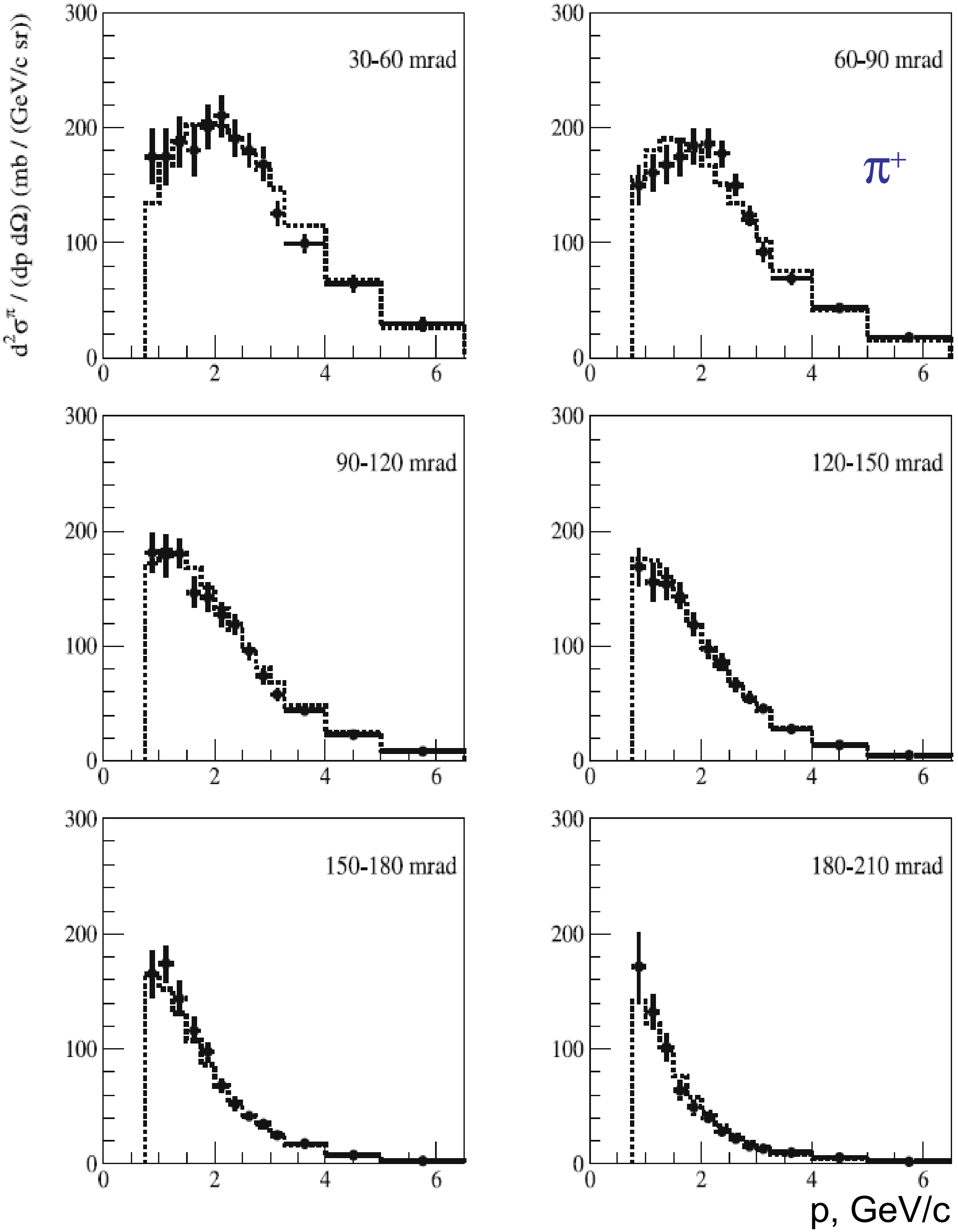
- HARP pAl@12.9GeV/c cross-section results have provided an important cross-check on previous K2K flux predictions. Results completely consistent in shape

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 for MiniBooNE



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 $\rightarrow \pi^+$ + X

An aside on the SW* parameterization

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

- 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

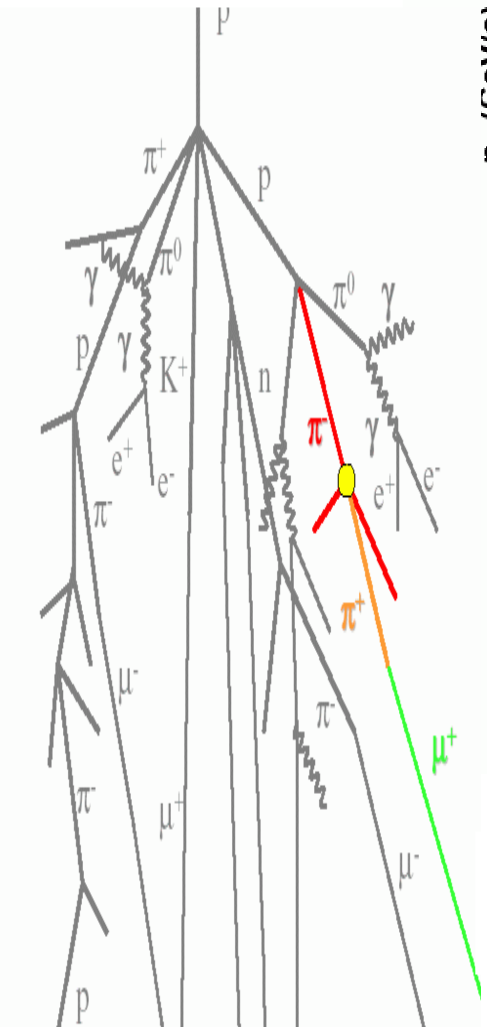
HARP measurements for p+Be at 8.9 GeV/c

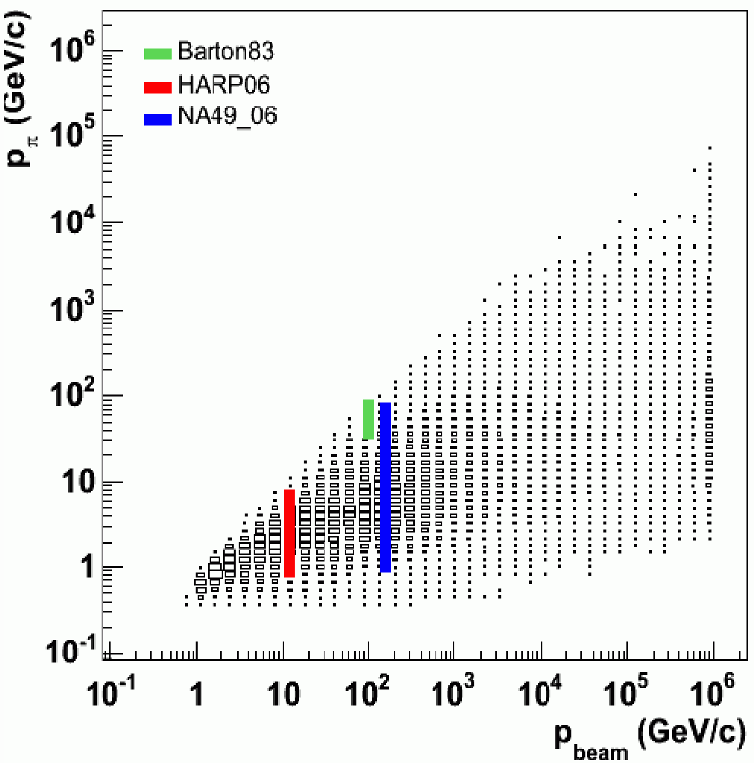
*) **J. R. Sanford and C. L. Wang "Empirical formulas for particle production in p-Be collisions between 10 and 35 BeV/c", Brookhaven National Laboratory, AGS internal report, (1967) (*unpublished*)**

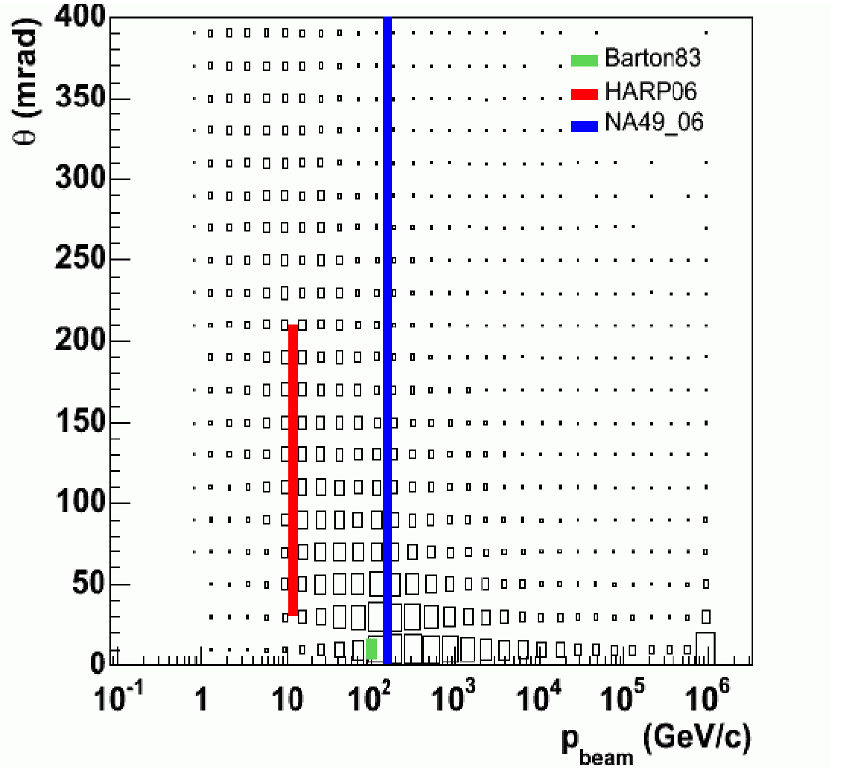
EPJ C 52 (2007) 29

Atmospheric neutrino flux and EAS predictions

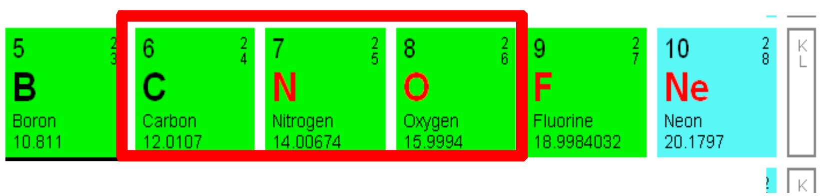
- **HARP p+C @ 12 GeV/c** data are relevant to the prediction of atmospheric neutrino fluxes (e.g. *M.Honda et al., Phys. Rev. D83 (2011) 123001*) and to the production of muons in EAS







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.

Muons in UHE Air Showers

energy of last interaction before decay to μ

air shower $\rightarrow$ hadron + air $\rightarrow \pi/K + X$

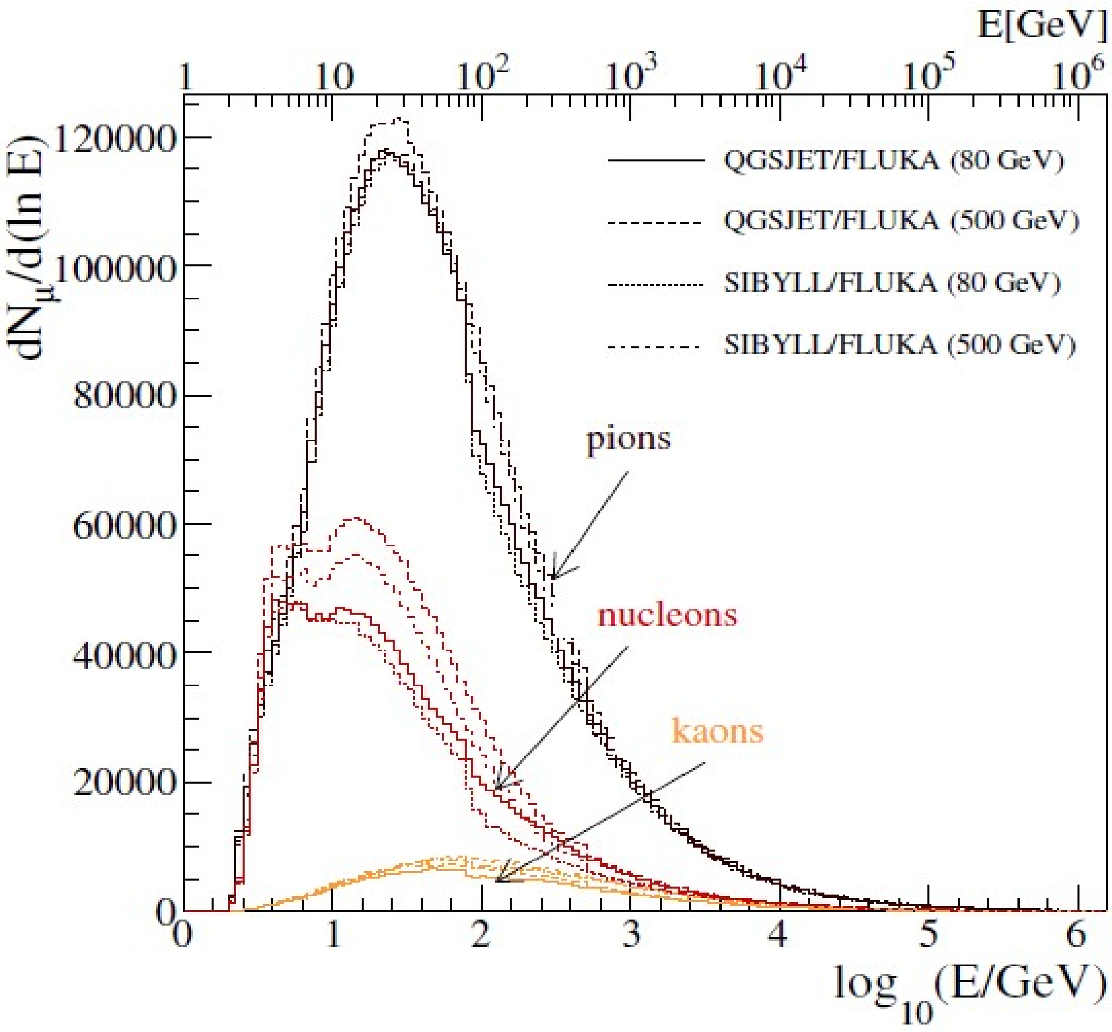
$\searrow$

$\mu + \nu_\mu$

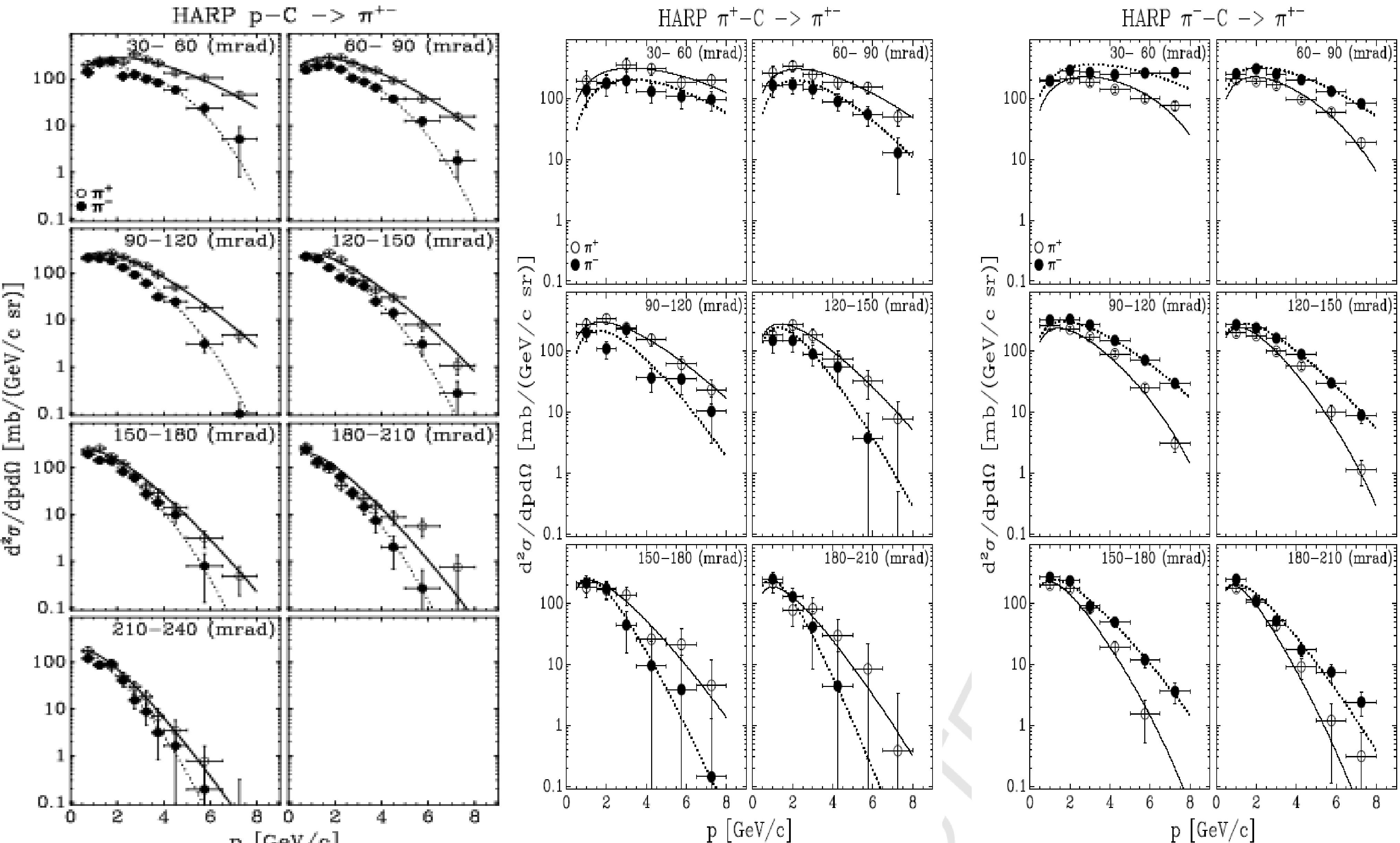
low energy air shower

e.g. KASCADE:

- $E_0 = 10^{19}$ eV
- $r = 1000$ m
- $E_\mu \geqslant 150$ MeV



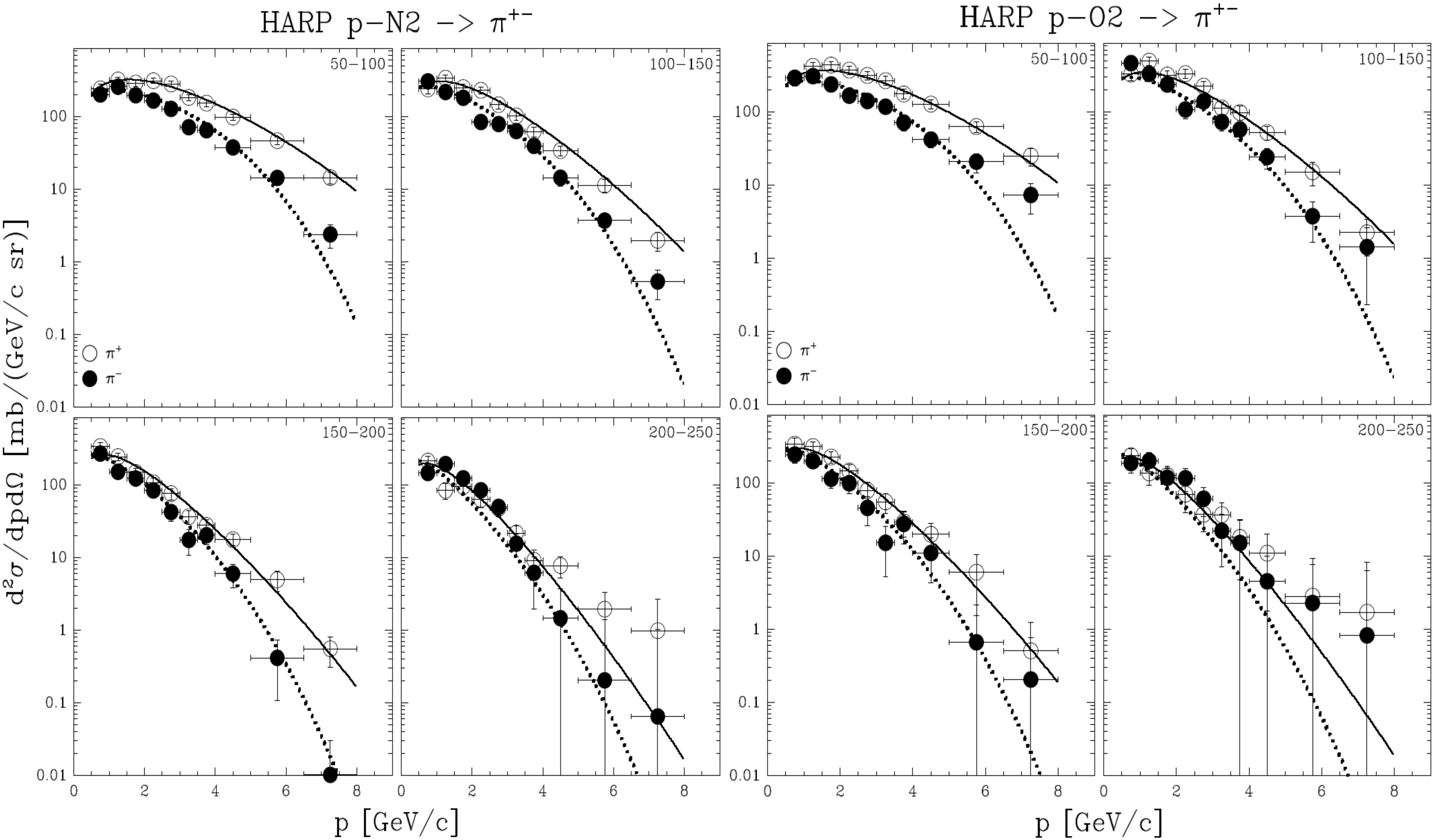
HARP : p, $\pi^{\pm}$ +C @ 12 GeV/c and SW parameterizations



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

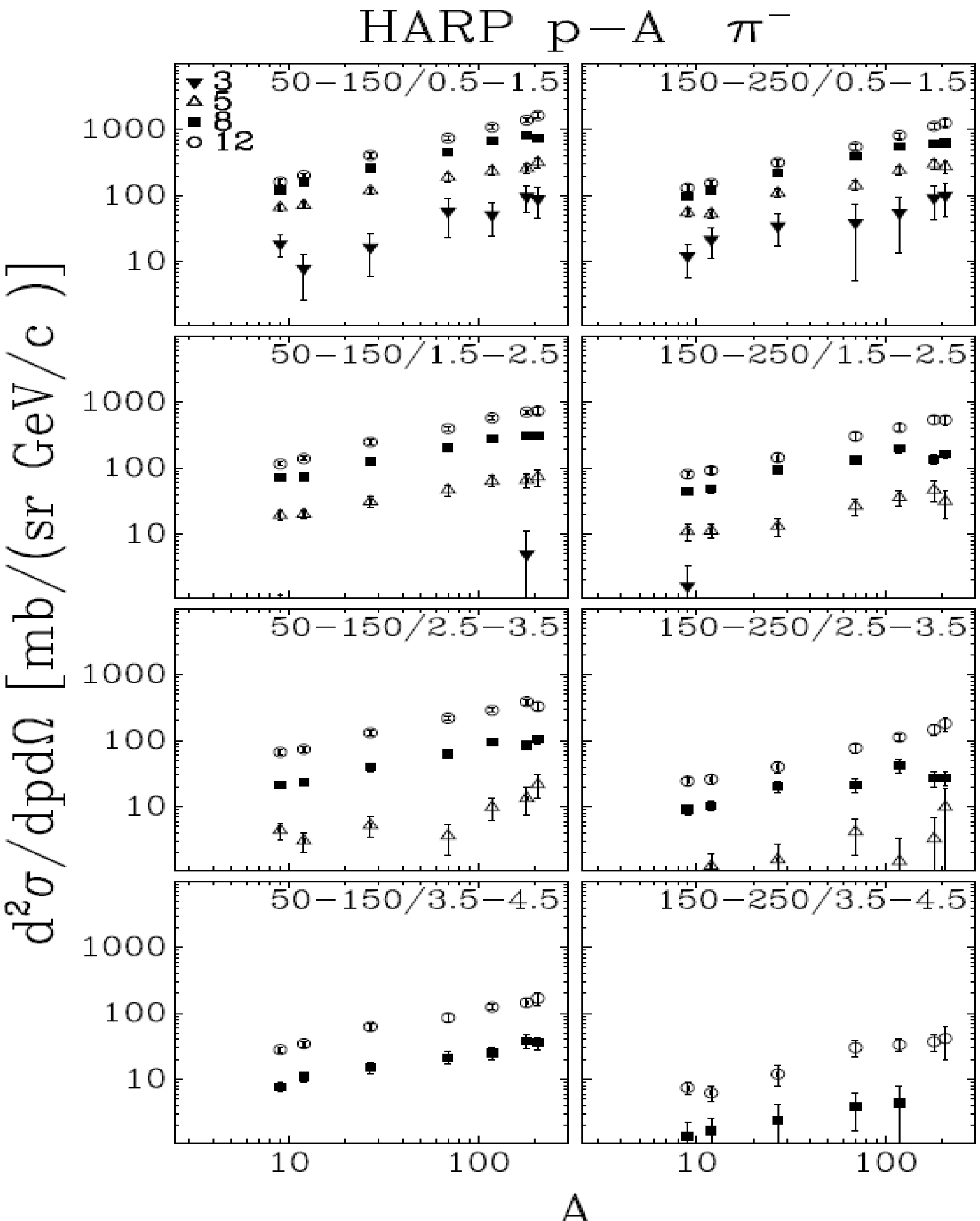


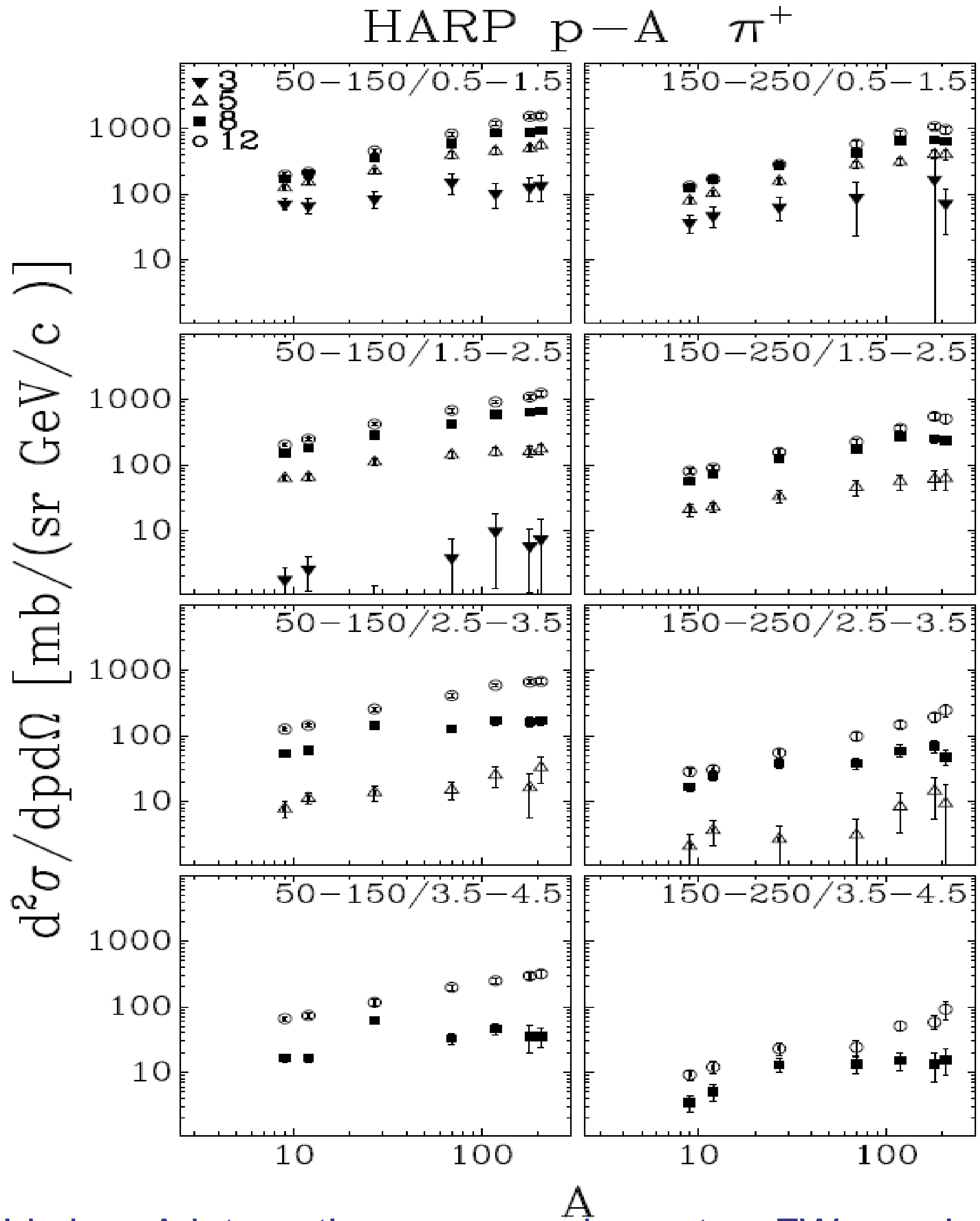
First precision measurements for N_2 and O_2 in this energy range, SW parameterizations for p-C data

Astropart. Phys. 30 (2008) 124

HARP results confirm that p-C data can be used to predict pion production in $p\text{-}N_2$ and $p\text{-}O_2$

HARP : more FW pion data with incident protons

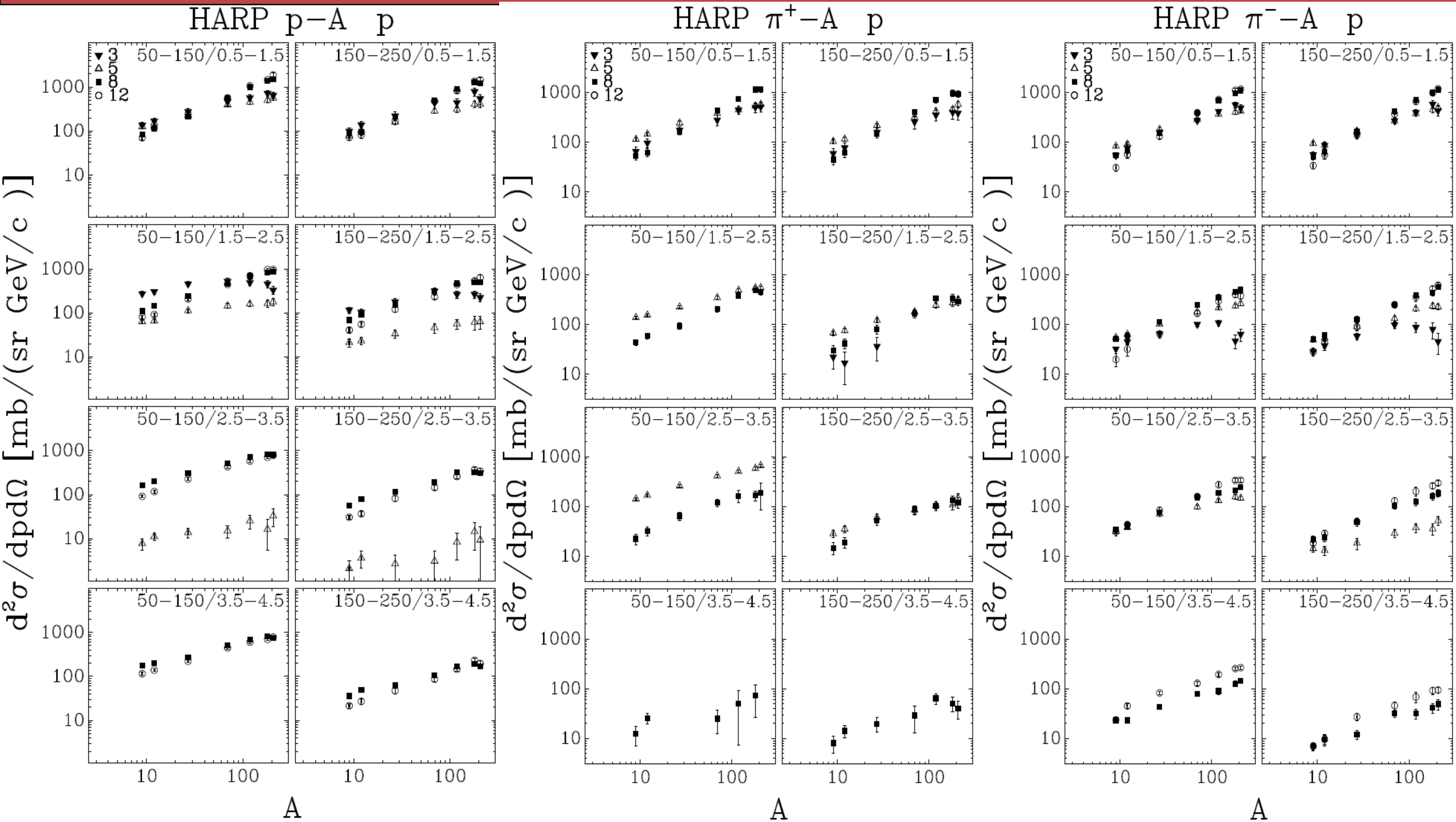




Dependence on the atomic number A of the pion yields in p-A interactions averaged over two FW angular regions ([50,150], [150,250] mrad) and four momentum regions ([0.5-1.5], [1.5,2.5], [2.5,3.5], [3.5,4.5] GeV/c) for incoming beam momenta 3,5,8,12 GeV/c

Phys. Rev. C80 (2009) 035208

HARP : more FW proton data with incident protons and pions



Dependence on the atomic number A of the proton yields in p-A and 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

Phys. Rev. C82 (2010) 045208

HARP: comparison with MC

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

Only some examples are shown here

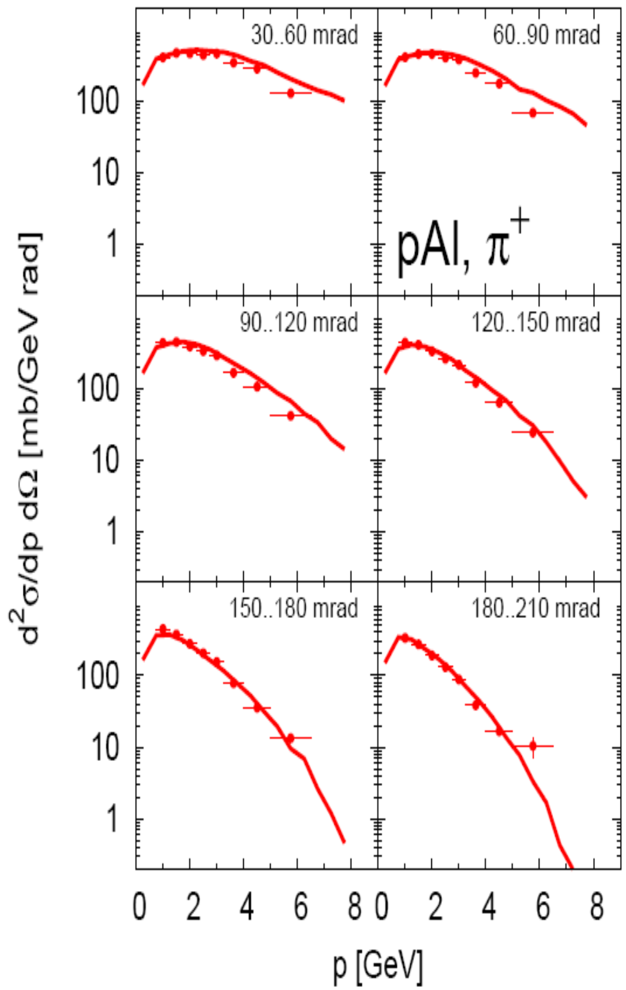
GEANT4:

- Binary cascade
- Bertini cascade
- Quark-Gluon string (QGS)
- Fritiof (FTFP)
- LHEP

FLUKA

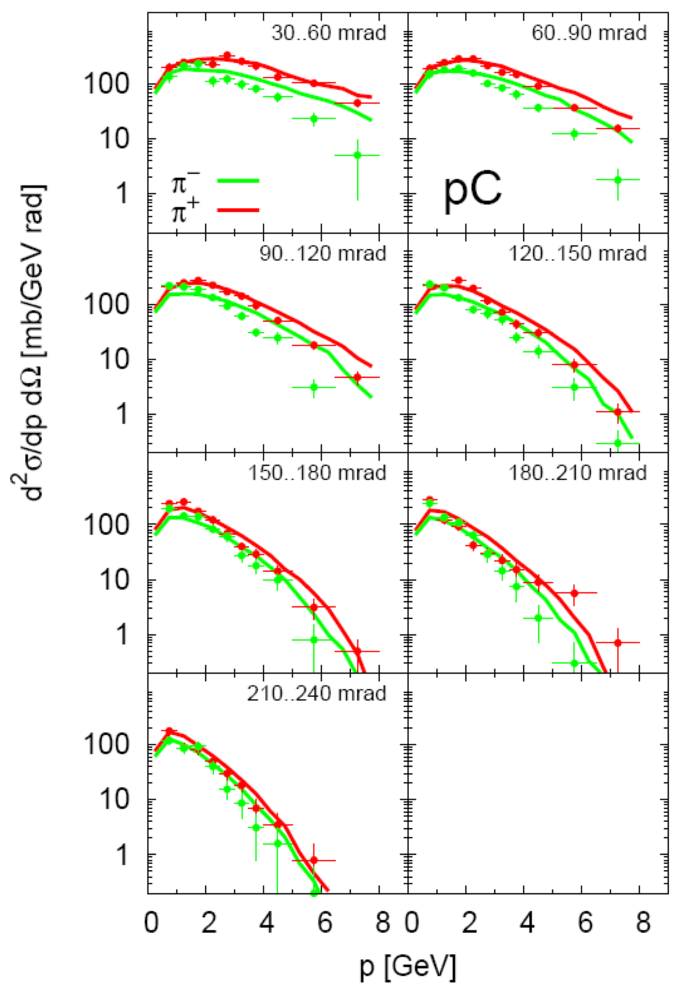
MARS

GiBUU



Nucl. Phys. A826 (2009) 151

HARP vs GiBUU



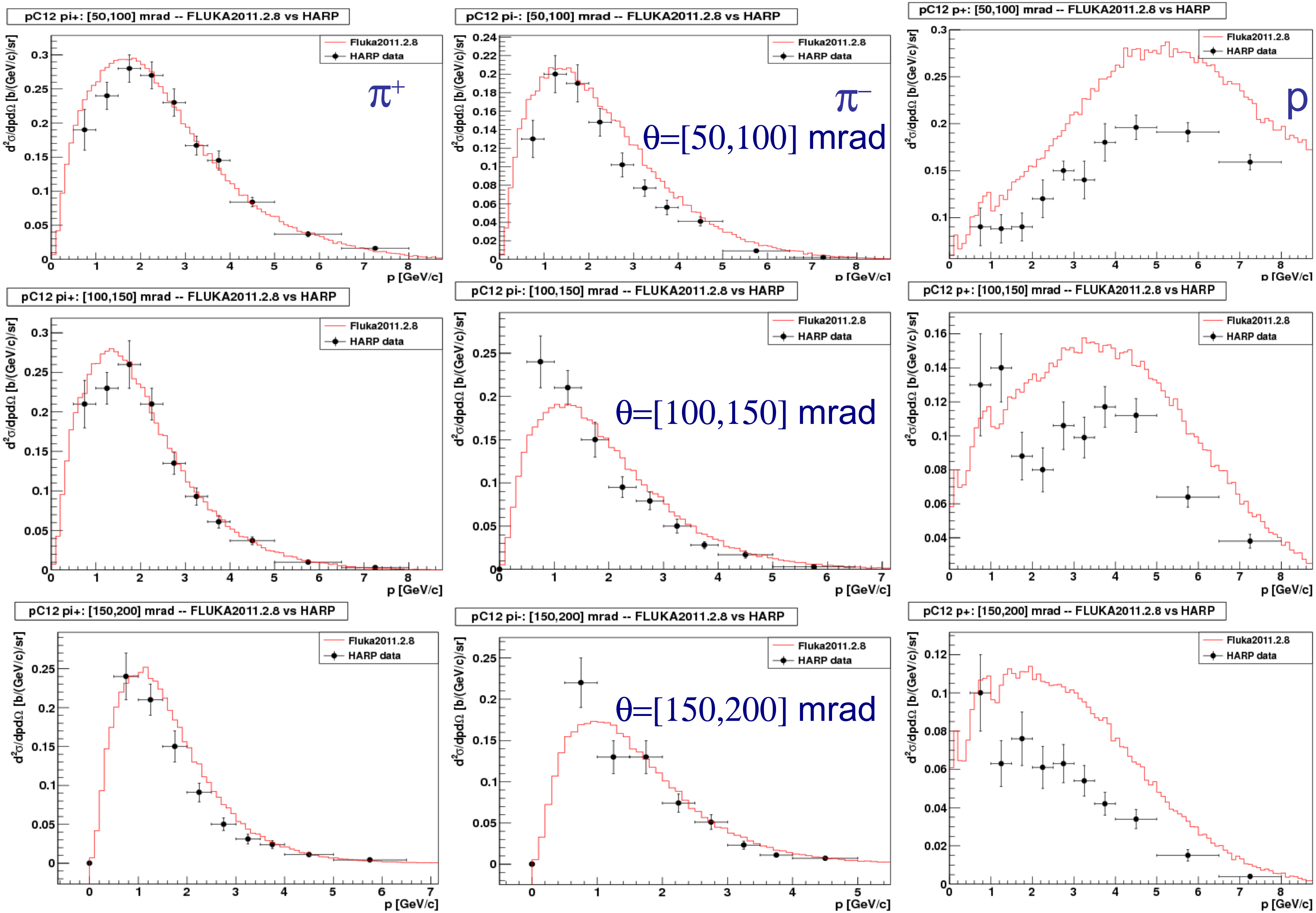
Phys. Rept. 512 (2012) 1

Some models do a good job in some regions,

but there is no model that describes all aspects of the data

HARP: comparison with MC

HARP vs FLUKA2011 e.g. for pC@12GeV/c



A lot more comparison plots can be found in the technical notes
https://edms.cern.ch/file/1184197/2/fluka2011_harp_updated.pdf
https://edms.cern.ch/file/1218221/1/fluka2011_harp_ta.pdf
for charged pion and proton production in proton- and charged pion-
Interactions at 3, 5, 8 and 12 GeV/c on C, Al and Ta targets

HARP: Summary

HARP hadron production experiment has made important contributions to hadronic cross-section measurements relevant to neutrino and cosmic ray 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** and predictions of **EAS development** 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!**

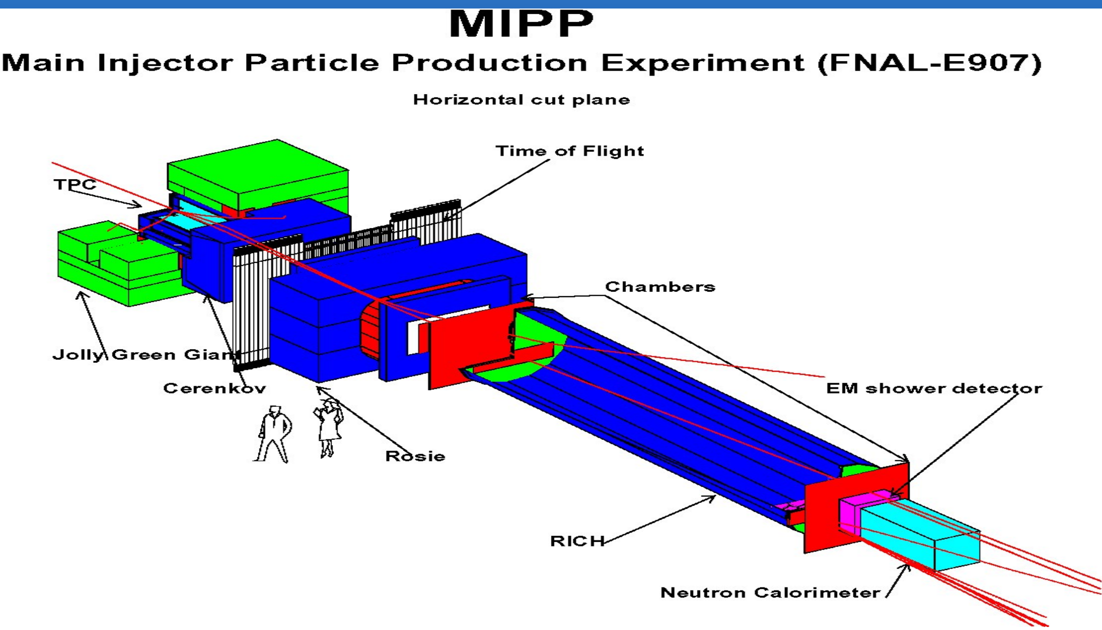
Comparisons of charged pion production with incident protons on cylindrical long and short targets (for C, Ta and Pb) have been performed.

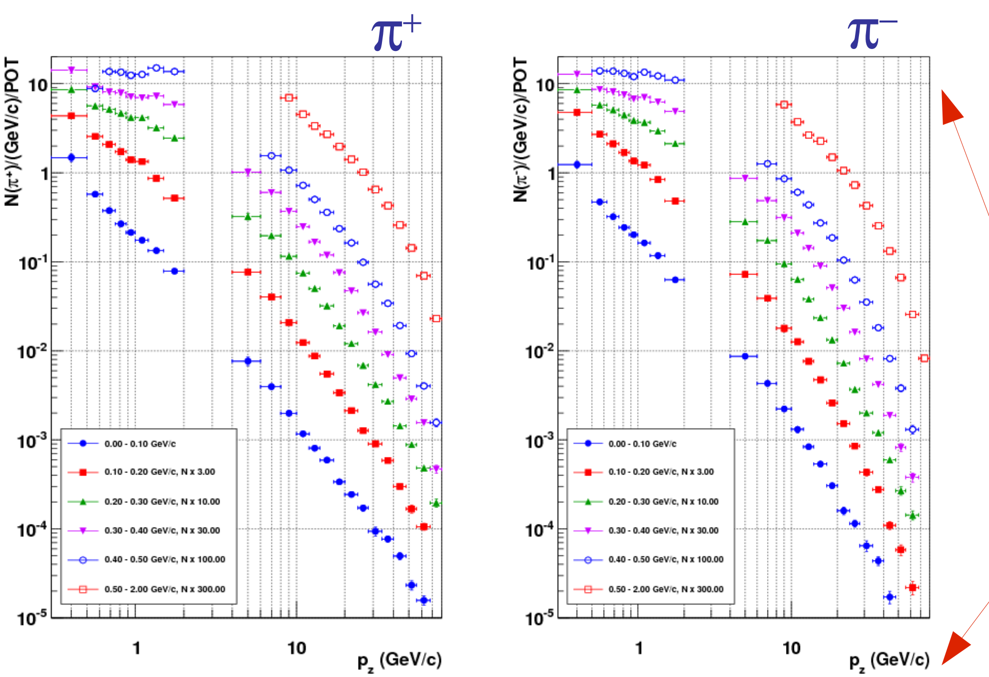
HARP measurements are being used to validate/tune MC hadron production models.

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 experiment at Fermilab





Approved in 2001
Data-taking in 2005-2006
Used 120 GeV/c Main Injector primary protons to produce secondary beams of $\pi^{\pm}$, $K^{\pm}$ and p in the momentum range from 5 to 85 GeV/c to measure particle production cross sections on various nuclei including hydrogen.
TPC is used to measure momenta of charged particles. Identification is performed using a combination of dE/dx, ToF, Cherenkov and RICH technologies.

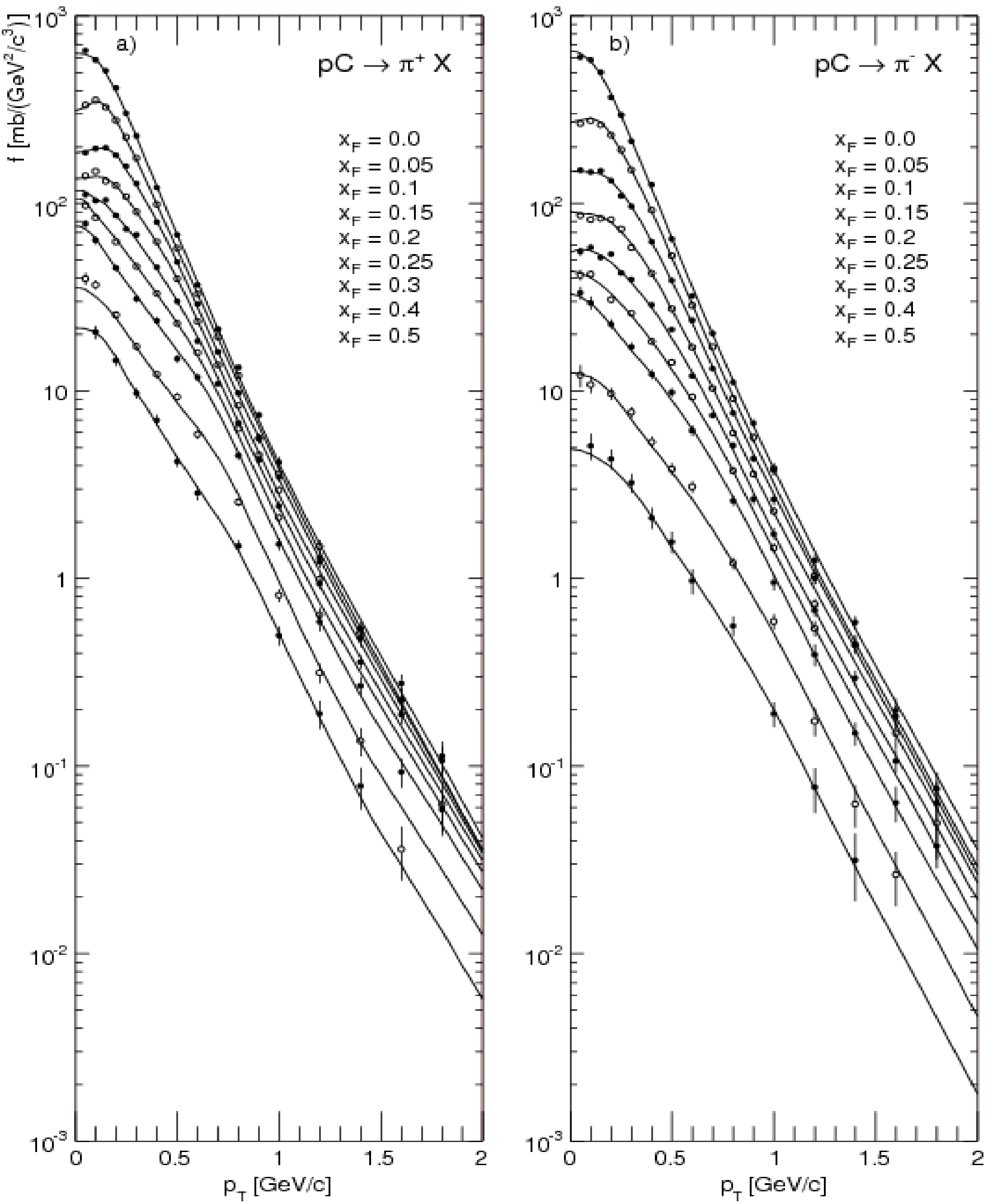
Publications:

- forward neutron production in p-A interactions at 58, 84 and 120 GeV/c
Phys. Rev. D83 (2011) 012002;

- measurement of charged pion production yields off the NuMI (long) target
arXiv:1404.5882 [hep-ex];

http://ppd.fnal.gov/experiments/e907

NA49 experiment at CERN SPS



Detailed analysis of hadronic interactions

in pp@158GeV/c:
- pions
- (anti-)protons
- neutrons
- kaons

in pC@158GeV/c:
- pions
- (anti-)protons
- neutrons

Typical total (stat.+syst.) error below 10%

Publications:

Eur. Phys. J. C45 (2006) 343;
Eur. Phys. J. C49 (2007) 897;
Eur. Phys. J. C65 (2010) 9;
Eur. Phys. J. C68 (2010) 1;
Eur. Phys. J. C73 (2013) 2329;
Eur. Phys. J. C73 (2013) 2364;

http://spshadrons.web.cern.ch/spshadrons

NA61/SHINE experiment at CERN SPS

Detailed comparisons of NA61/SHINE data with some available hadroproduction models in e.g.
https://edms.cern.ch/file/1186772/1/fluka_vs_na61.pdf
https://edms.cern.ch/file/1219646/1/gibuu.pdf

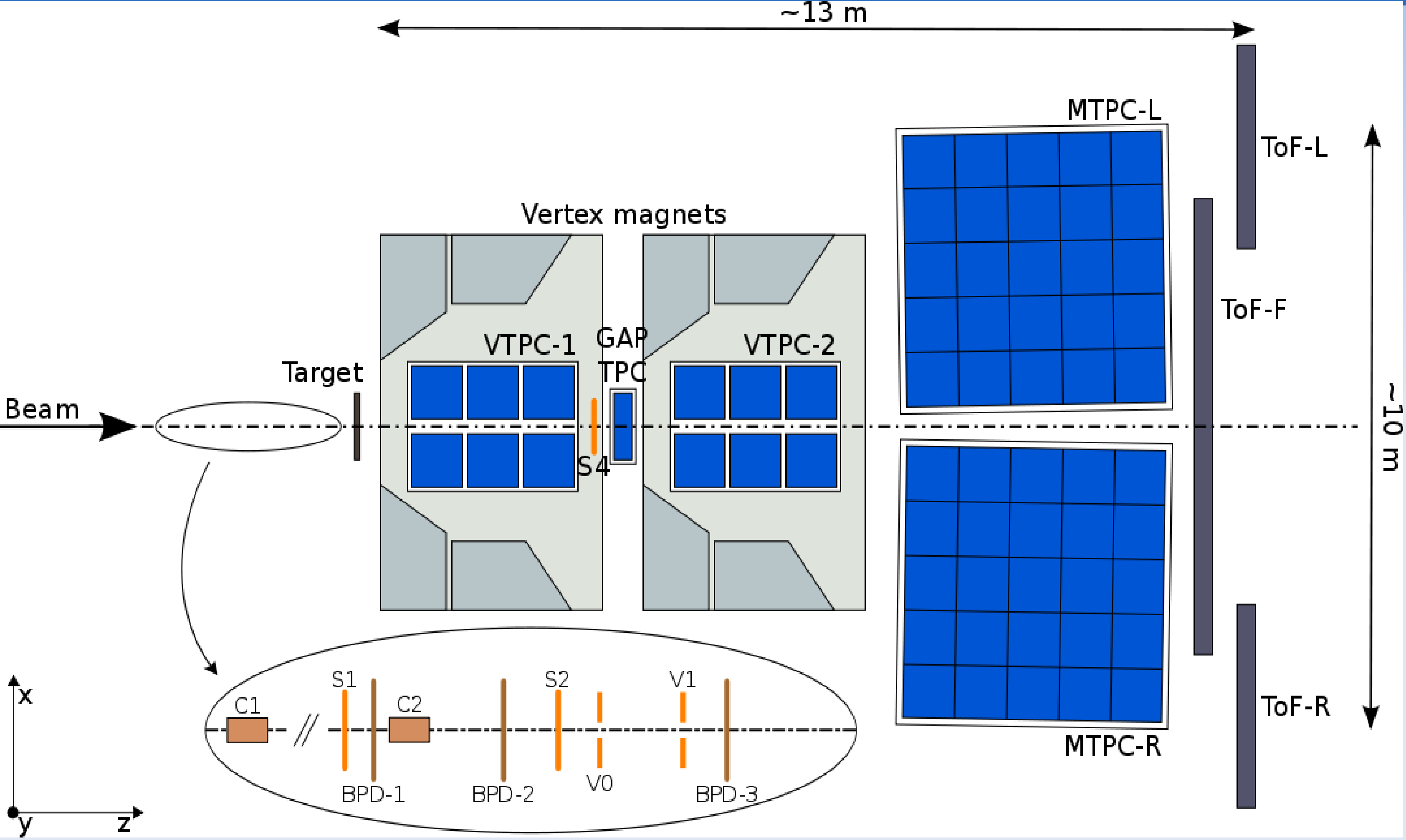
NA61/SHINE physics goals

SHINE = SPS Heavy Ion and Neutrino Experiment

- Hadron production reference measurements for accelerator neutrino (T2K, Fermilab) and cosmic ray (Pierre Auger Observatory, KASCADE) experiments
- Search for the critical point of strongly interacting matter
- Study the properties of the onset of deconfinement in nucleus-nucleus collisions

Not discussed here

NA61/SHINE setup at CERN SPS



TPCs as main tracking devices

2 dipole magnets with max bending power of 9 Tm

New ToF-F array to fully cover T2K acceptance

High momentum resolution

Good particle identification

Beam line instrumentation

Large acceptance spectrometer with excelent capabilities for momentum, charge and mass measurements

Detailed description of the experimental apparatus

JINST 9 (2014) P06005

NA61/SHINE: recorded (h + A) data

Reaction	p [GeV/c]	Year	$N_{triggers}$ [10^6]	
p+C	31	2007	0.7	Pilot run; Results published
p+RT	31	2007	0.2	
p+C	31	2009	5.4	New preliminary results
p+RT	31	2009	2.	
p+RT	31	2010	10.	
π^-+C	158	2009	5.5	Preliminary results
π^-+C	350	2009	4.6	
p+p	13	2010	0.7	
p+p	13	2011	1.4	
p+p	20	2009	2.2	
p+p	31	2009	3.1	New results published
p+p	40	2009	5.2	
p+p	80	2009	4.5	
p+p	158	2009	3.5	
p+p	158	2010	44.	
p+p	158	2011	15.	
p+Pb	158	2012	4.5	

RT= T2K replica target

NA61/SHINE: derivation of spectra

- The corrected number of particles α in p bins and θ intervals with the target inserted (Δn_α^I) and the target removed (Δn_α^R) are used to compute inclusive differential cross-sections:

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

- 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 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 in momentum

Phys. Rev. C84 (2011) 034604

NA61/SHINE: analysis techniques

- Three complementary analysis techniques which differ by PID method
- h^- analysis (π^-): No PID required; a small non-pion contamination from negatively charged hadrons is corrected for by model-based Monte Carlo

  Corrected π^- spectra in a broad kinematic range.

- dE/dx analysis at low momenta ($\pi^\pm$,p): yields fitted to dE/dx distributions in the low ($1/\beta^2$) momentum region

  Corrected spectra of π^+/p (π^-) up to 1 GeV/c (3 GeV/c) in momentum.

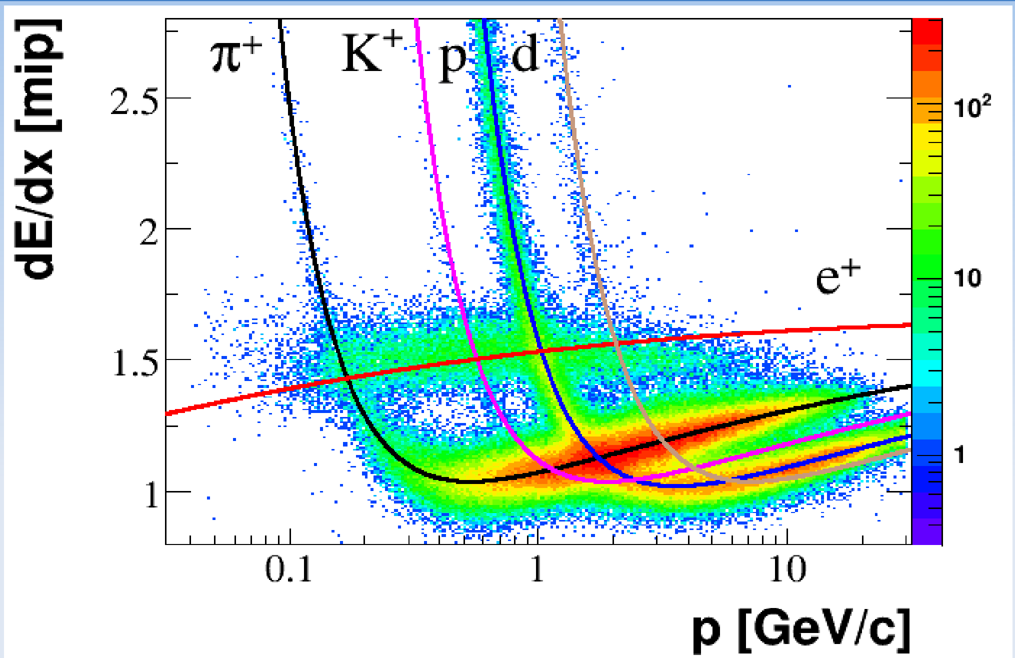
- Combined dE/dx + ToF analysis ($\pi^\pm$,$K^\pm$,p): yields fitted to 2-dimensional m^2 vs dE/dx distributions.

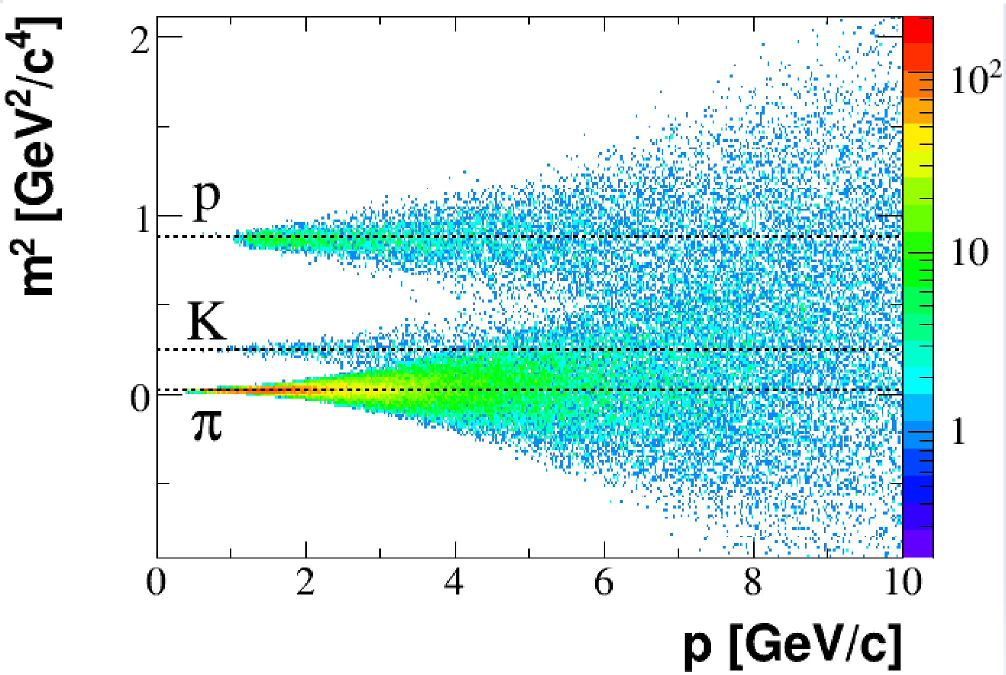
  Corrected spectra above 1 GeV/c in momentum.

- All results are corrected for geometrical acceptance, reconstruction efficiency, contamination of electrons and other particles, secondary interactions and weak decays ("feeddown").

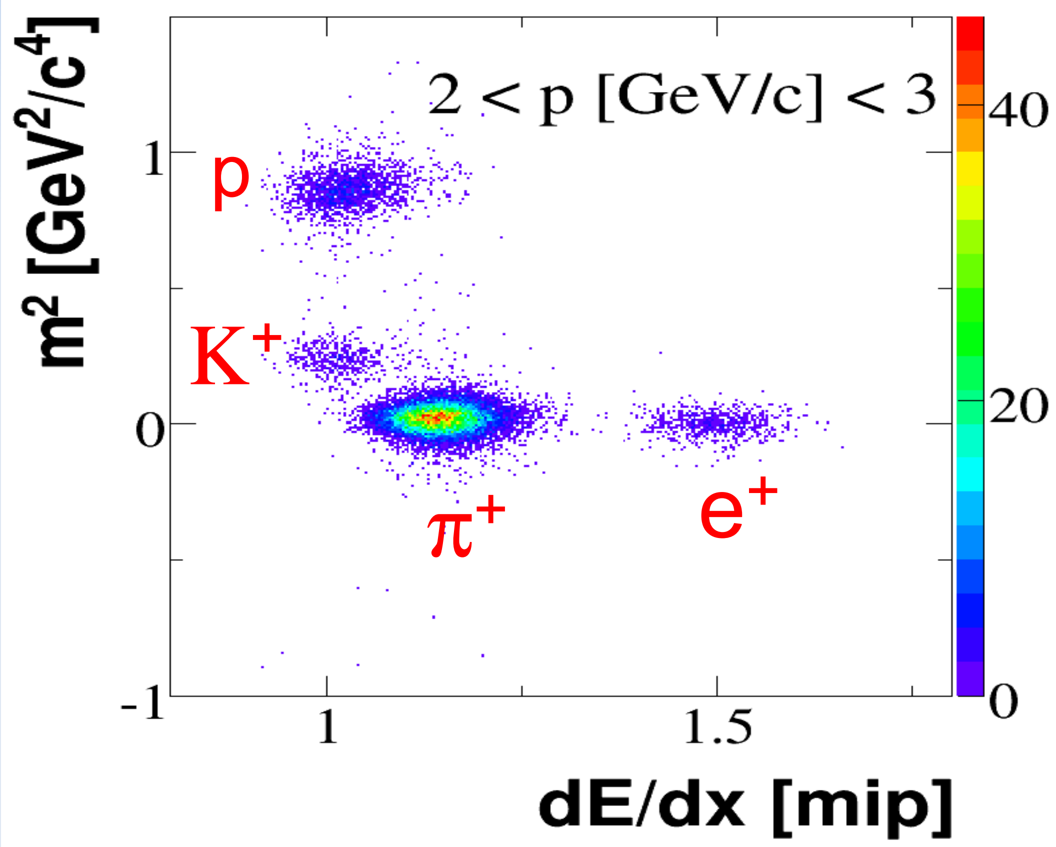
Phys. Rev. C84 (2011) 034604

NA61/SHINE PID capabilities

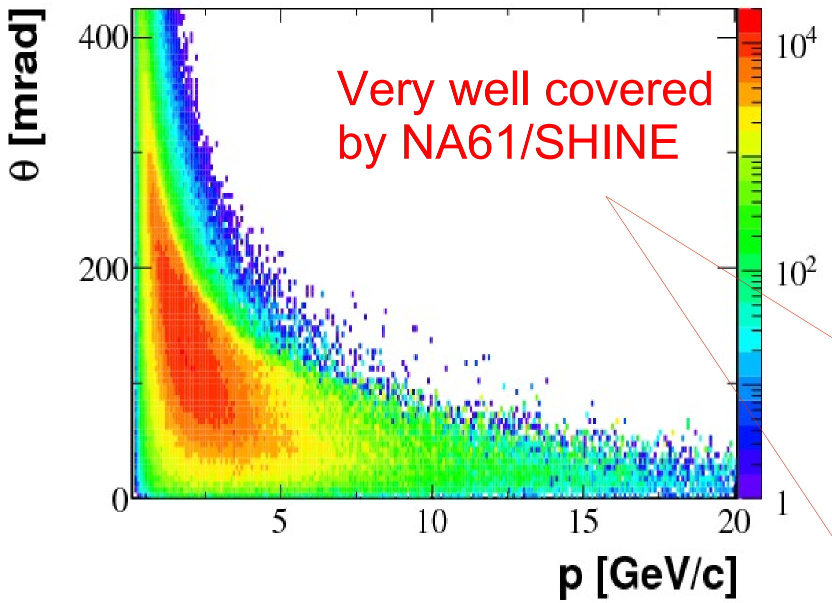




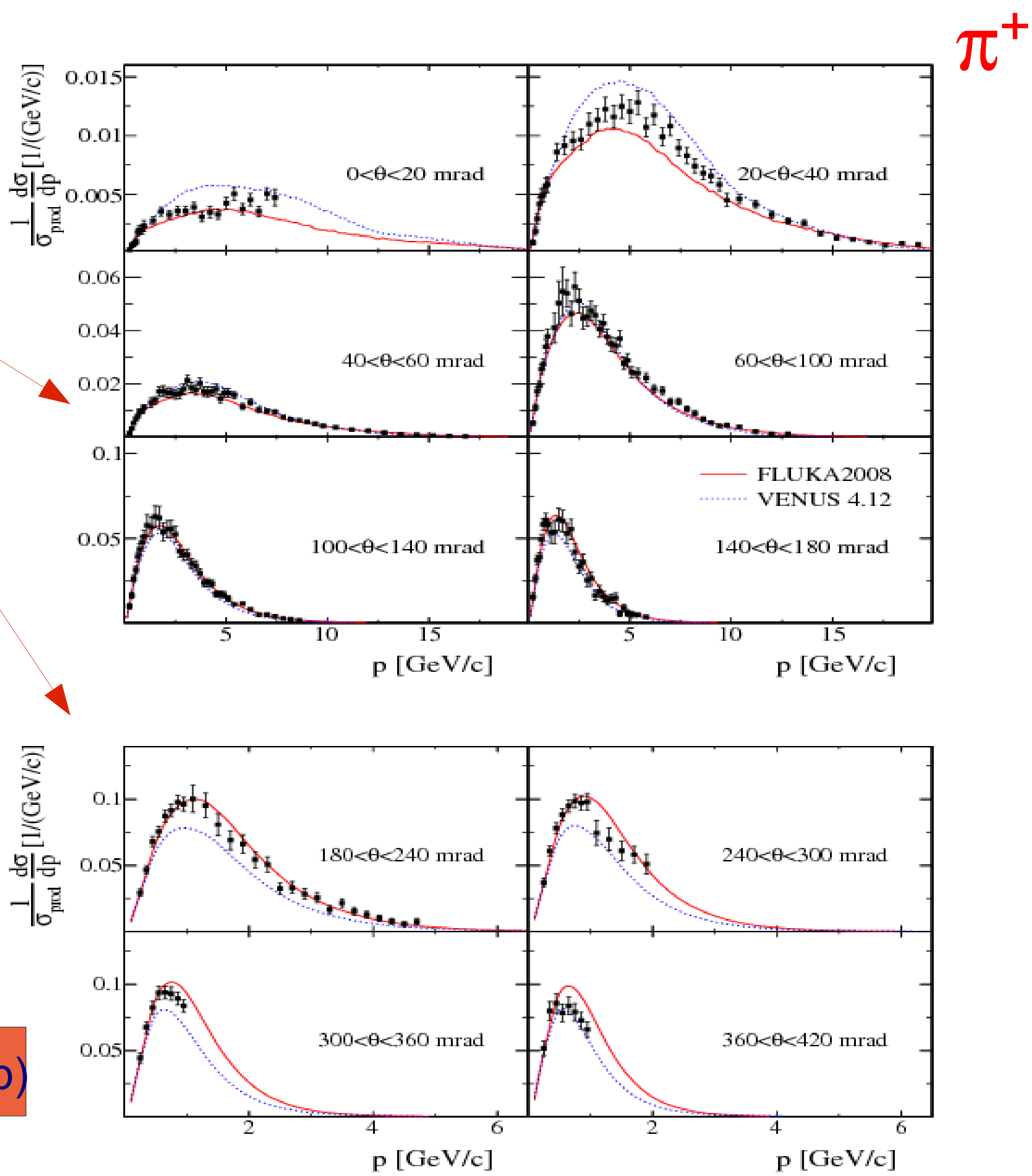
Combined dE/dx + ToF identification for positively charged particles



NA61/SHINE p+C@31GeV/c: π^+ (& π^-) results



T2K beam simulation: the {p,θ} distribution for π^+ weighted by the probability that their decay produces a ν_μ passing through SK



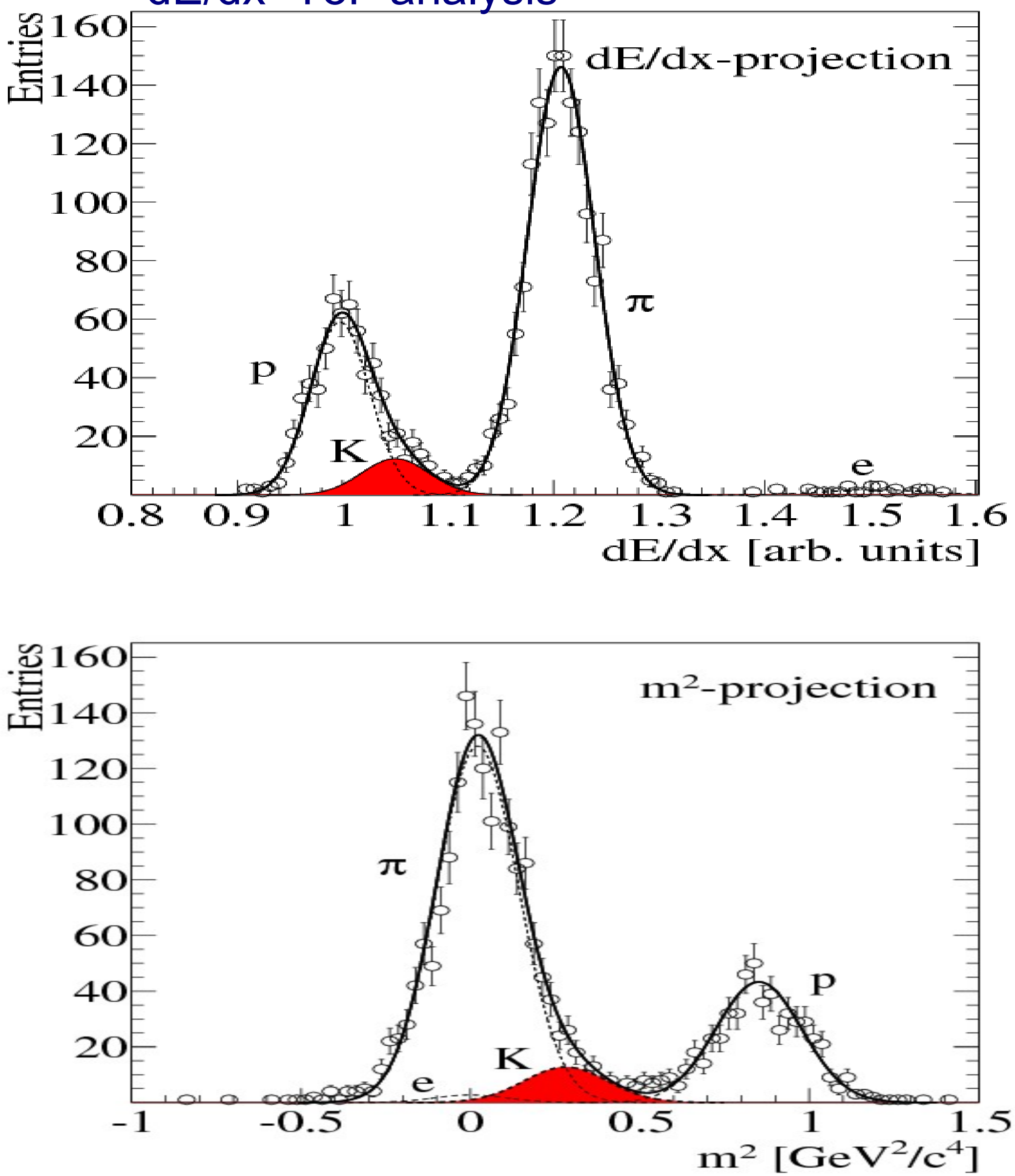
NA61/SHINE measurements

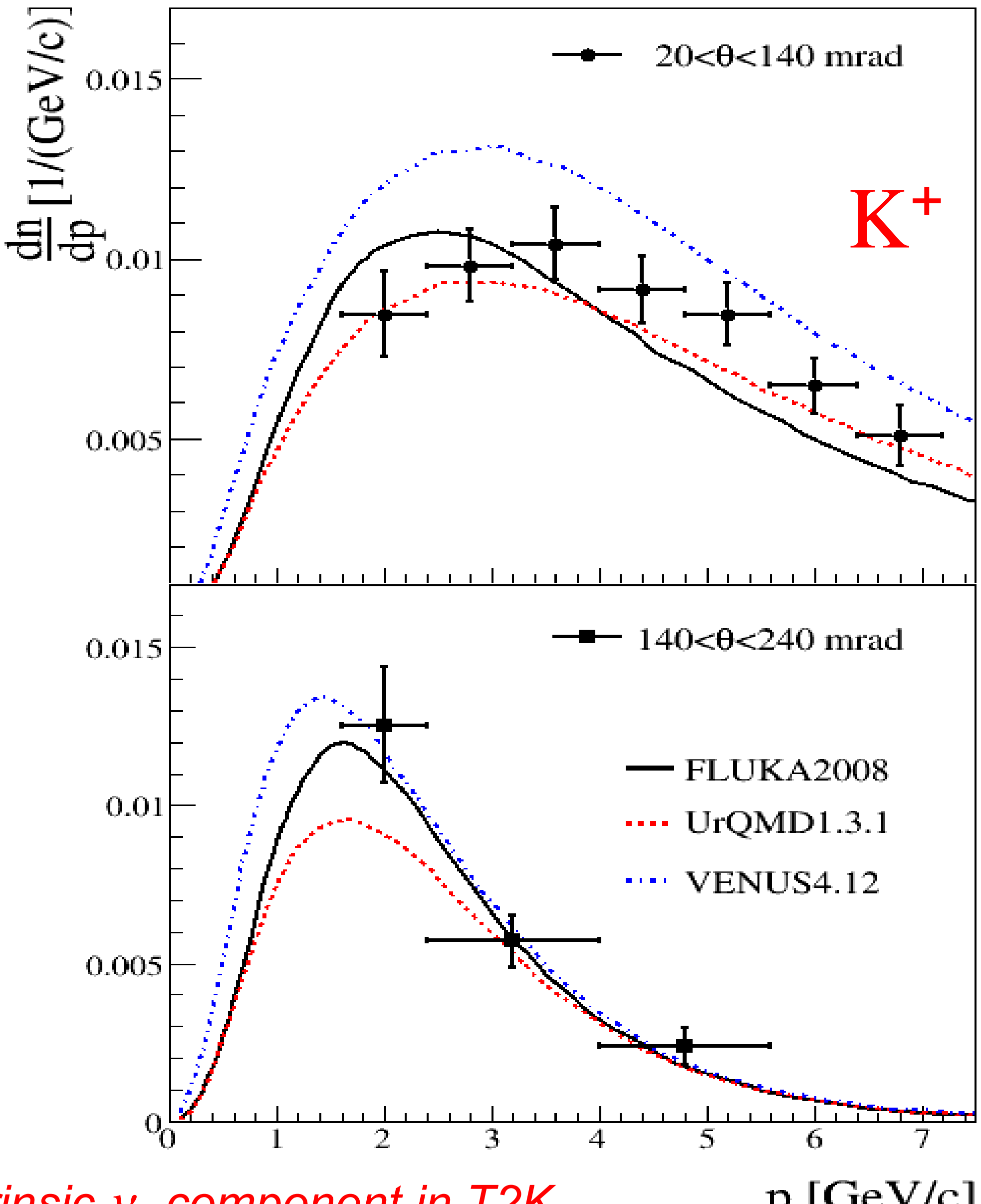
σ_{prod} (pC@31GeV/c)= 229.3 ± 1.9 ± 9.0 (mb)

Phys. Rev. C84 (2011) 034604

NA61/SHINE p+C@31GeV/c: K^+ results

dE/dx+ToF analysis

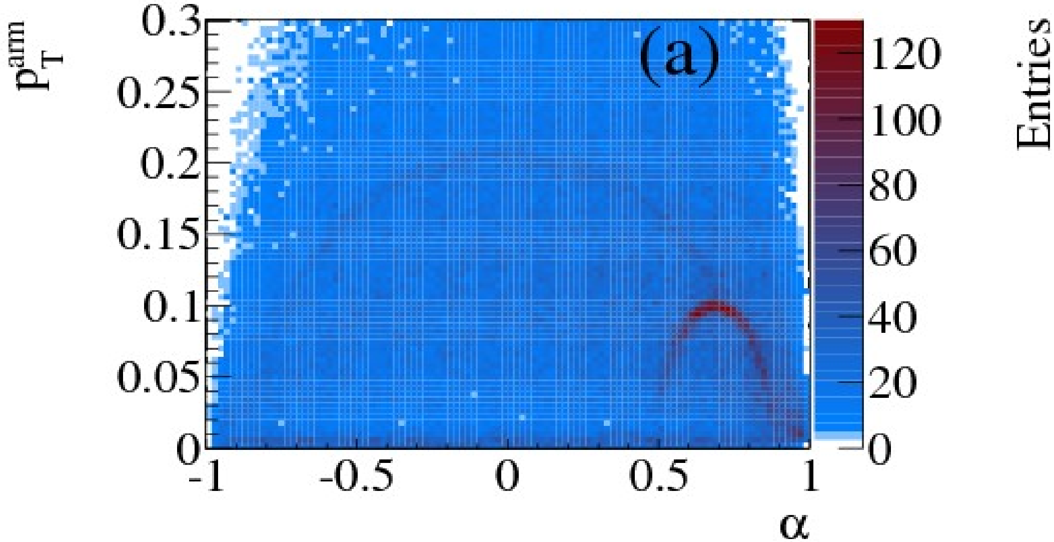


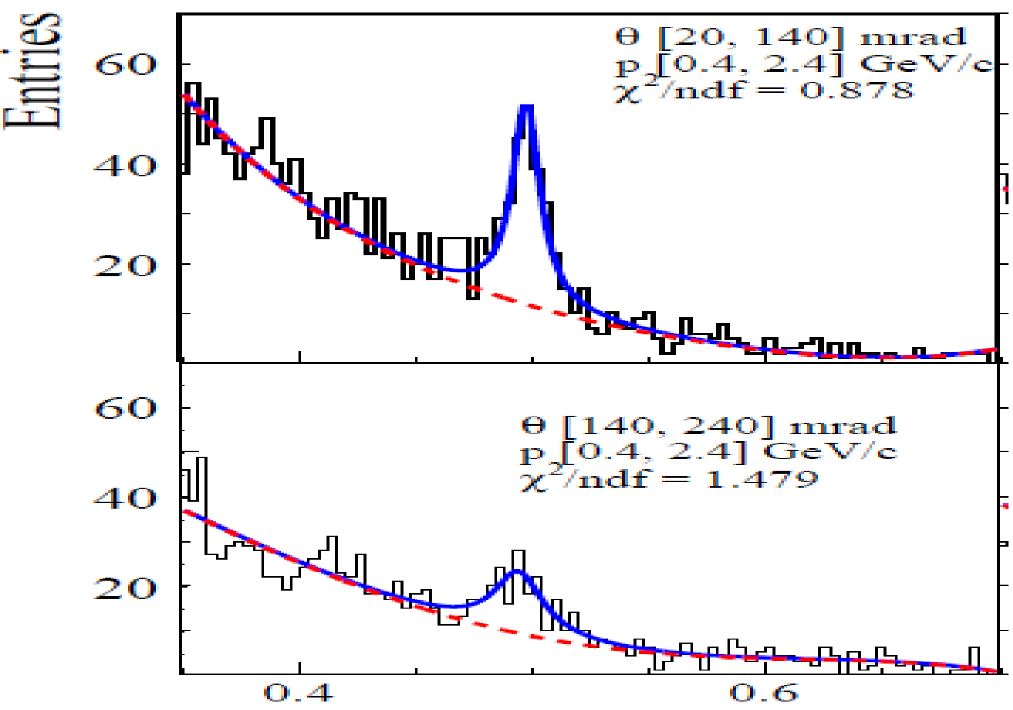


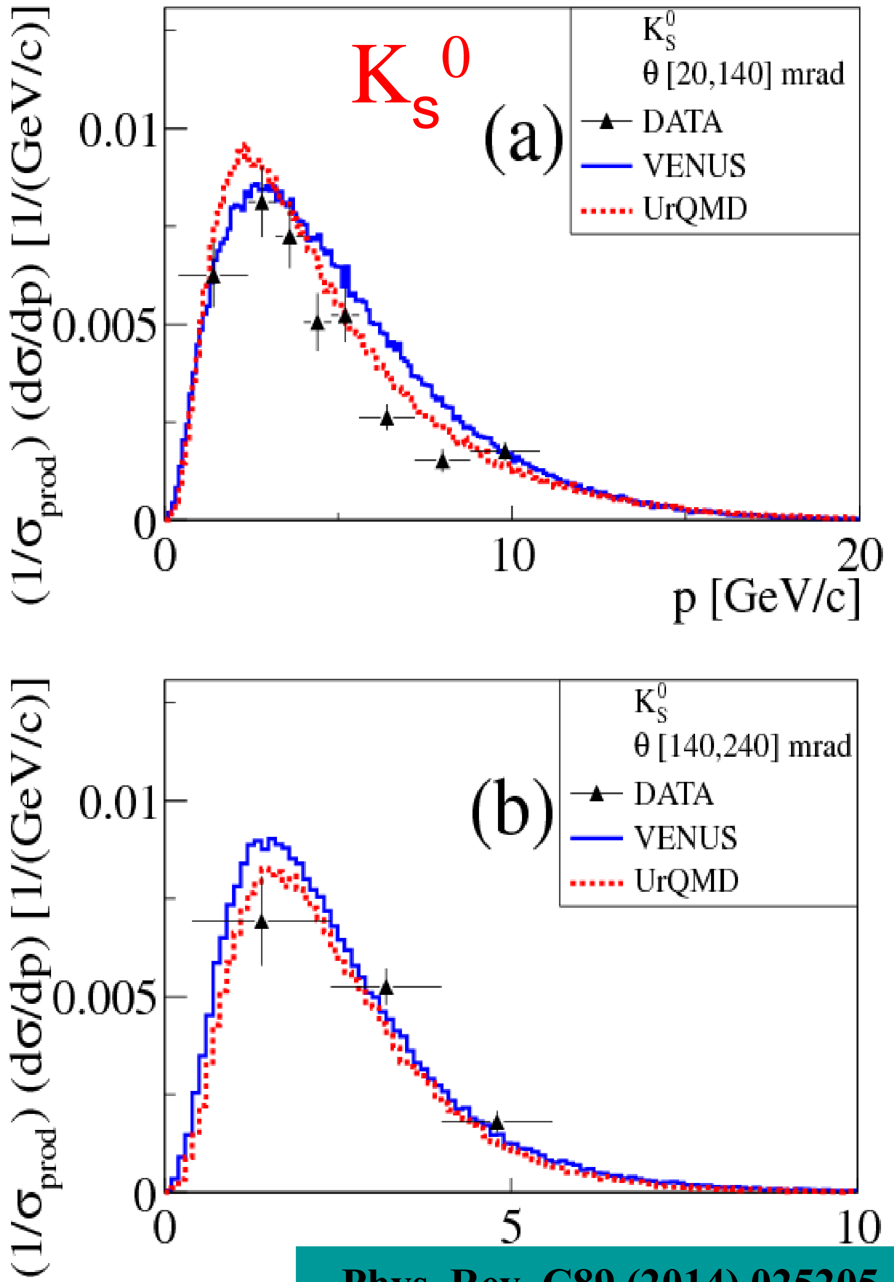
Relevant for high energy tail of ν_μ spectrum and intrinsic ν_e component in T2K

Phys. Rev. C85 (2012) 035210

NA61/SHINE pC@31GeV/c: V0 analysis

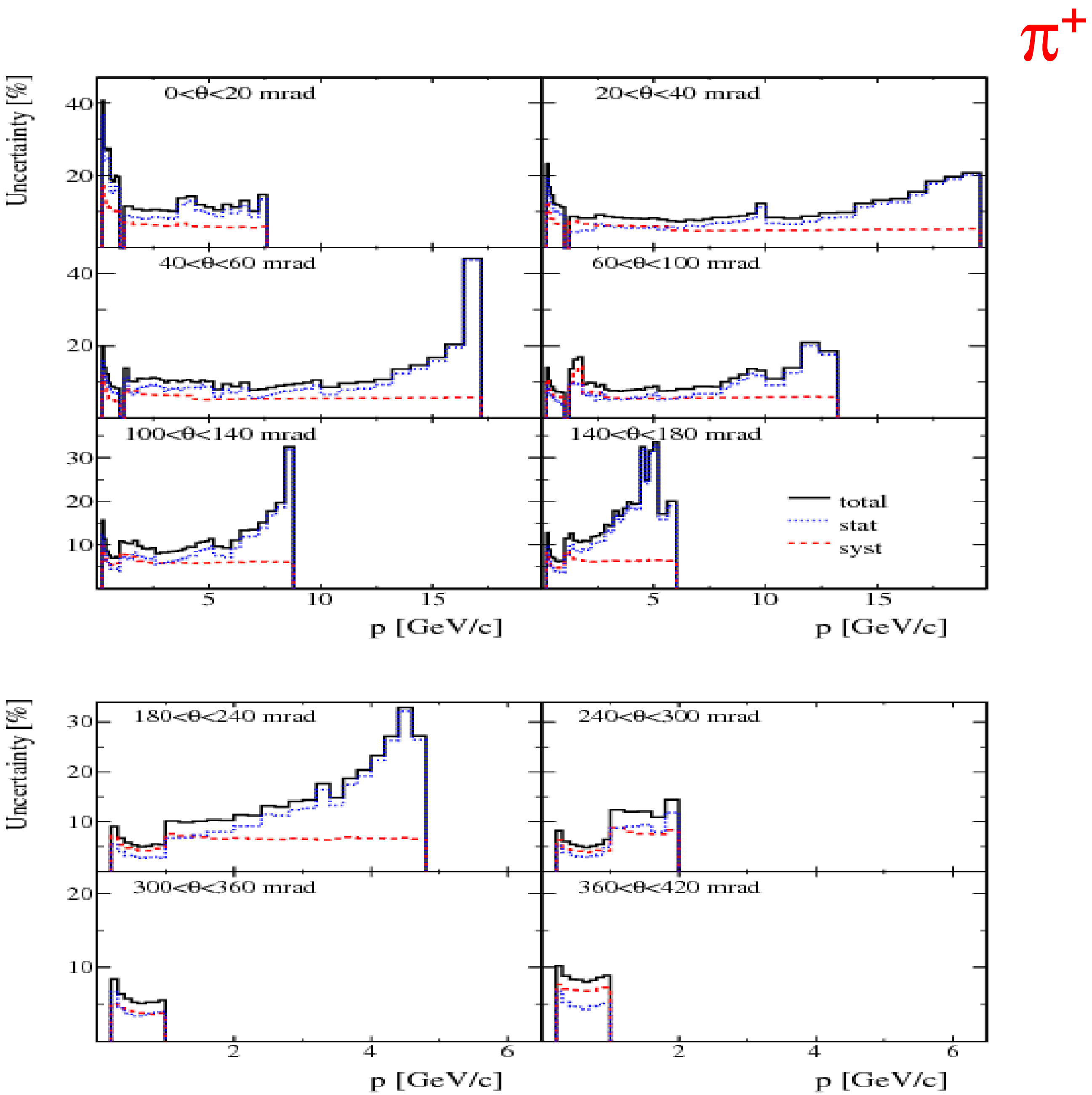






Phys. Rev. C89 (2014) 025205

NA61/SHINE pC@31GeV/c: stat vs syst errors



In the analysis of pilot (2007) data statistical errors dominate.

With full set of pC@31GeV/c (2009) data we hope to reduce statistical errors by a factor of 3.

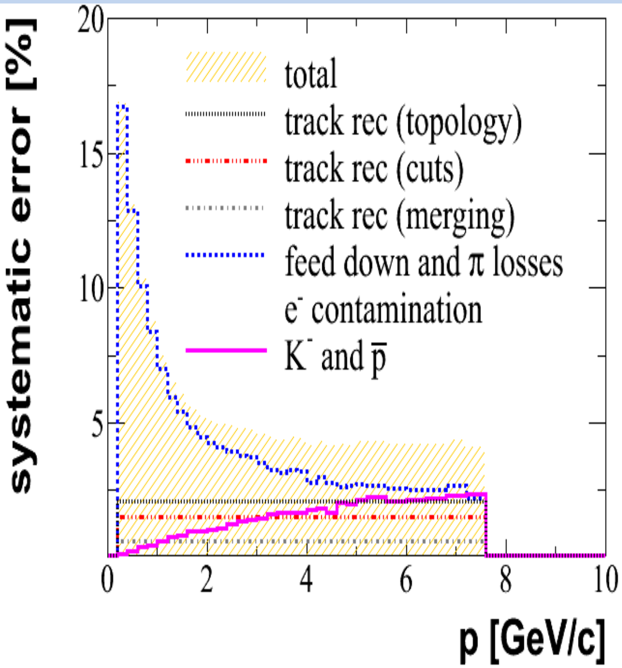
Systematic errors will become more important

Phys. Rev. C84 (2011) 034604

NA61/SHINE p+C@31GeV/c: systematic errors

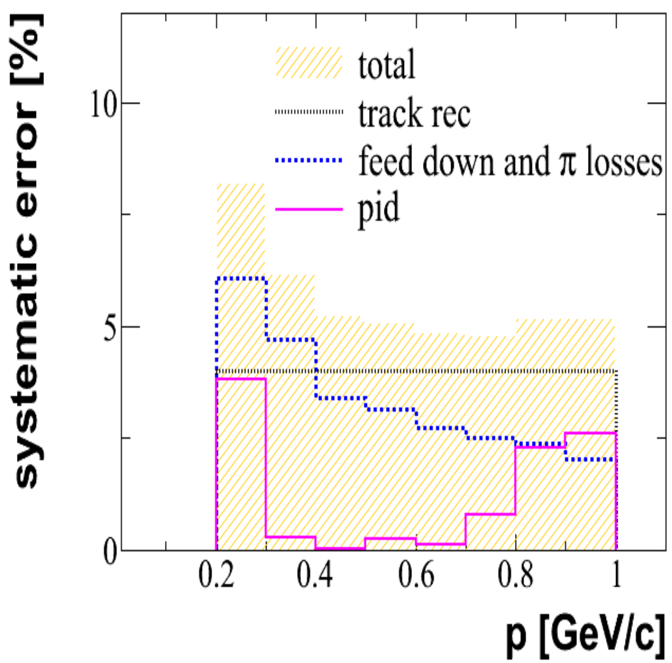
h- analysis

π^- θ=[140,180] mrad



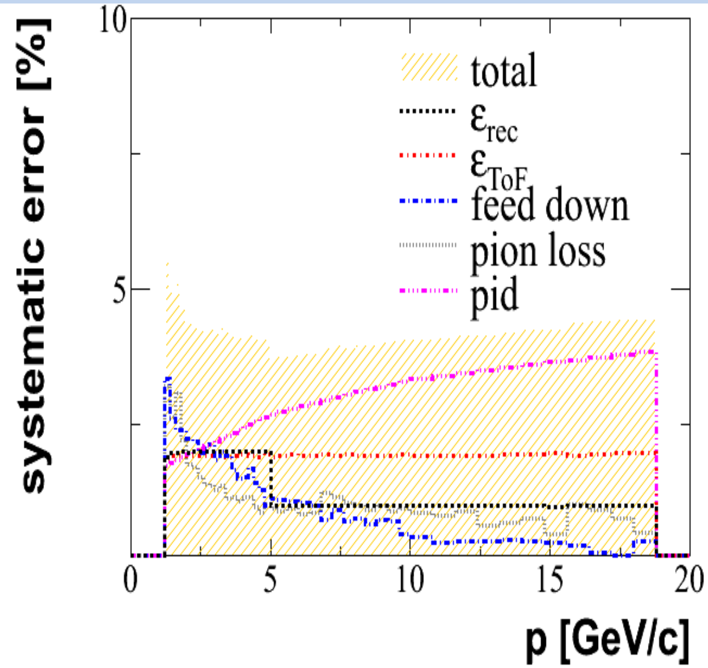
dE/dx analysis

π^+ θ=[140,180] mrad



dE/dx+ToF analysis

π^+ θ=[40,60] mrad



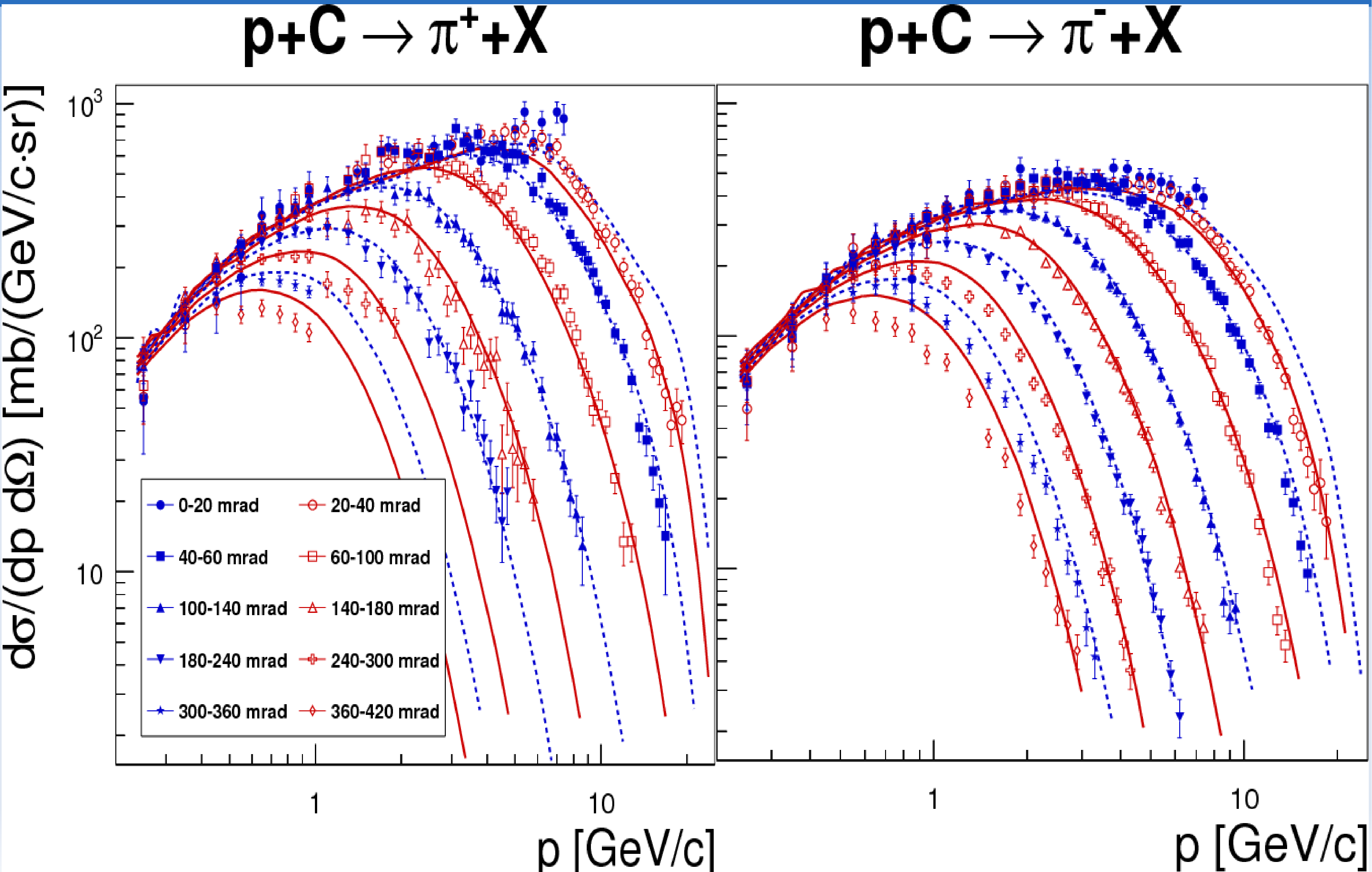
Typical value 6%

Hope to reduce down to about 4%

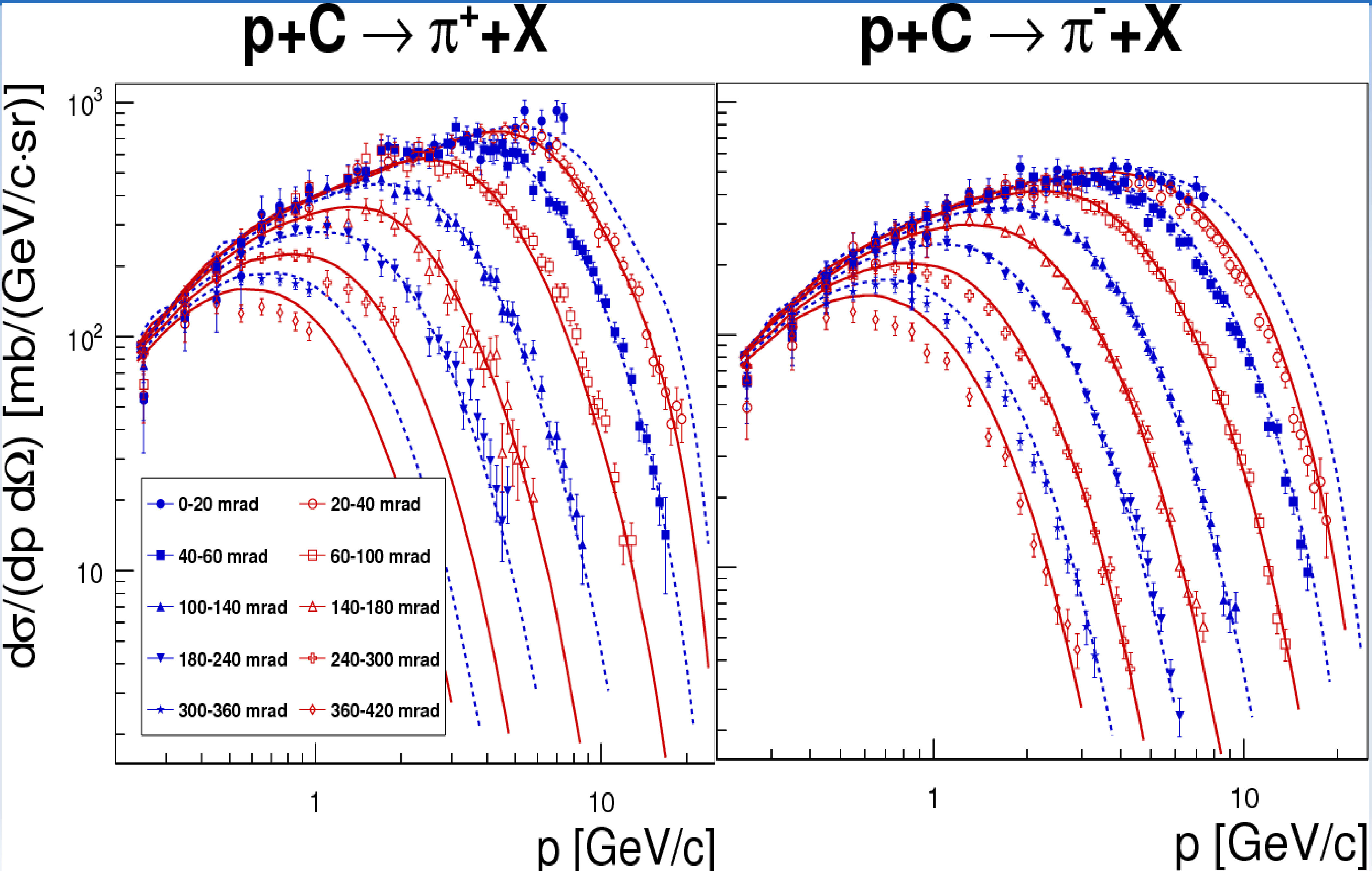
Systematic error due to uncertainty of the feeddown correction is larger for π^- than for π^+ due to contribution from Λ hyperon decays. NA61/SHINE measurements of neutral strange particle production will allow to reduce this systematic error.

Phys. Rev. C84 (2011) 034604

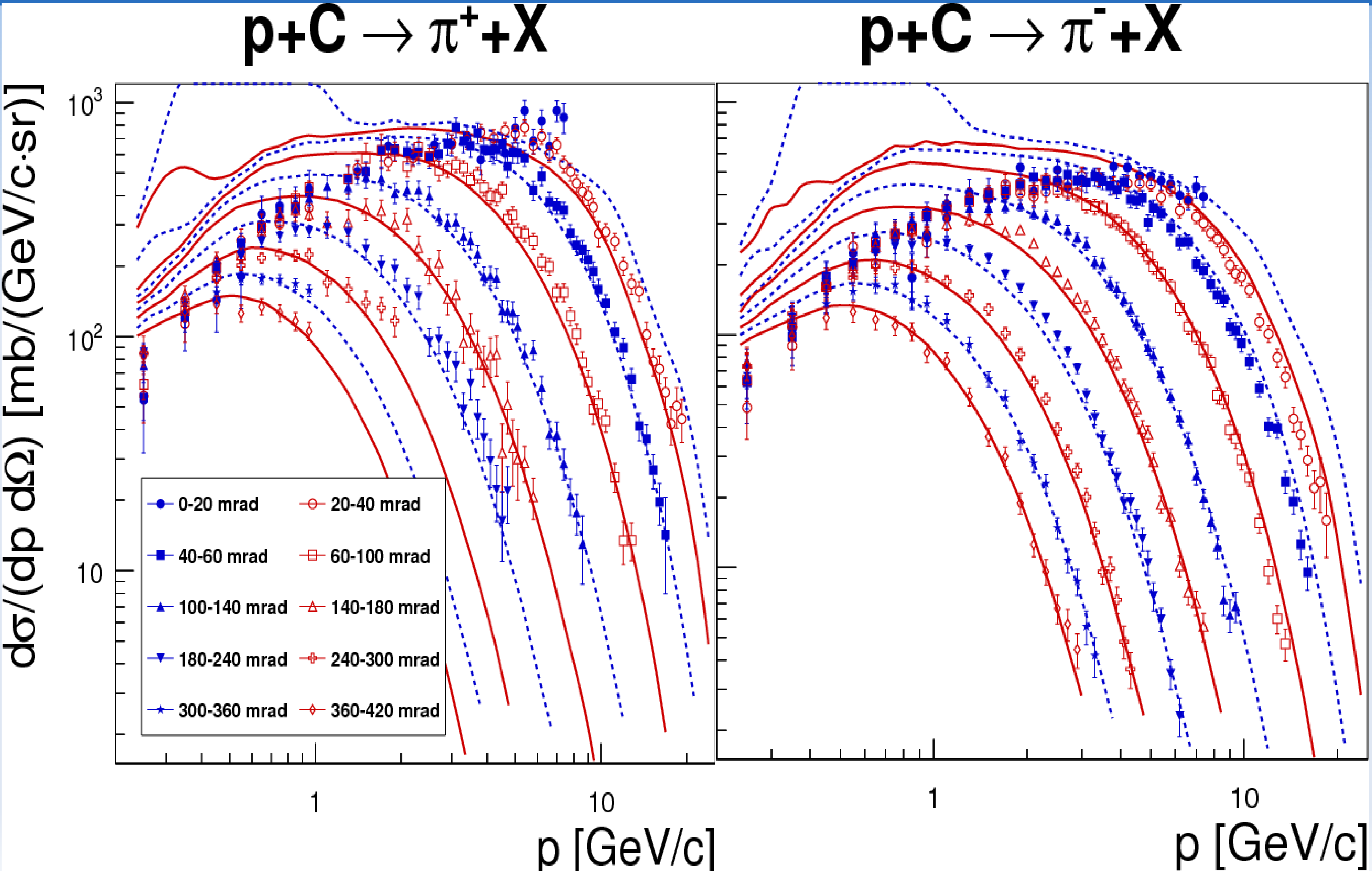
NA61/SHINE: p+C@31GeV/c vs FLUKA2008



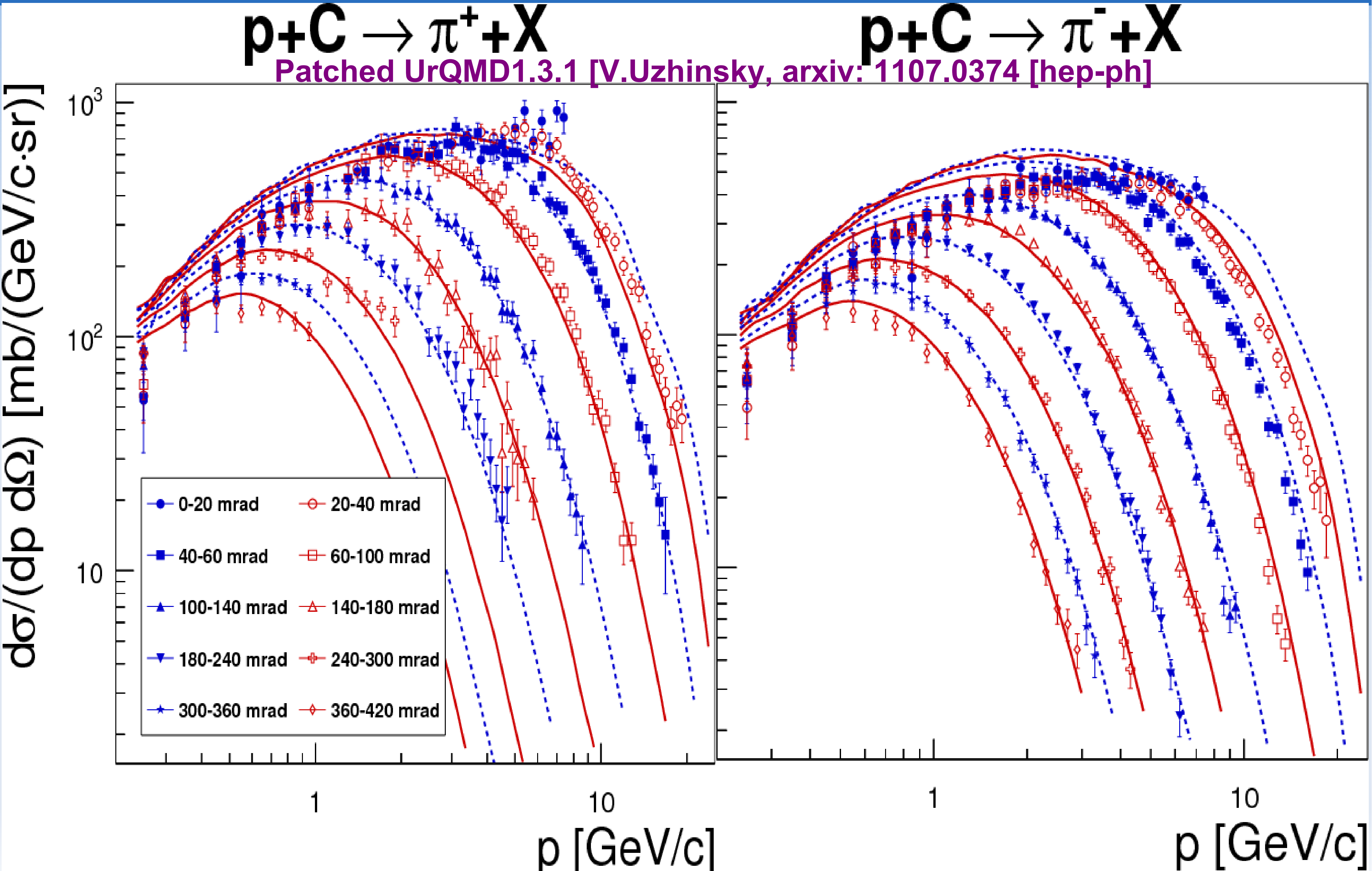
NA61/SHINE: p+C@31GeV/c vs FLUKA2011



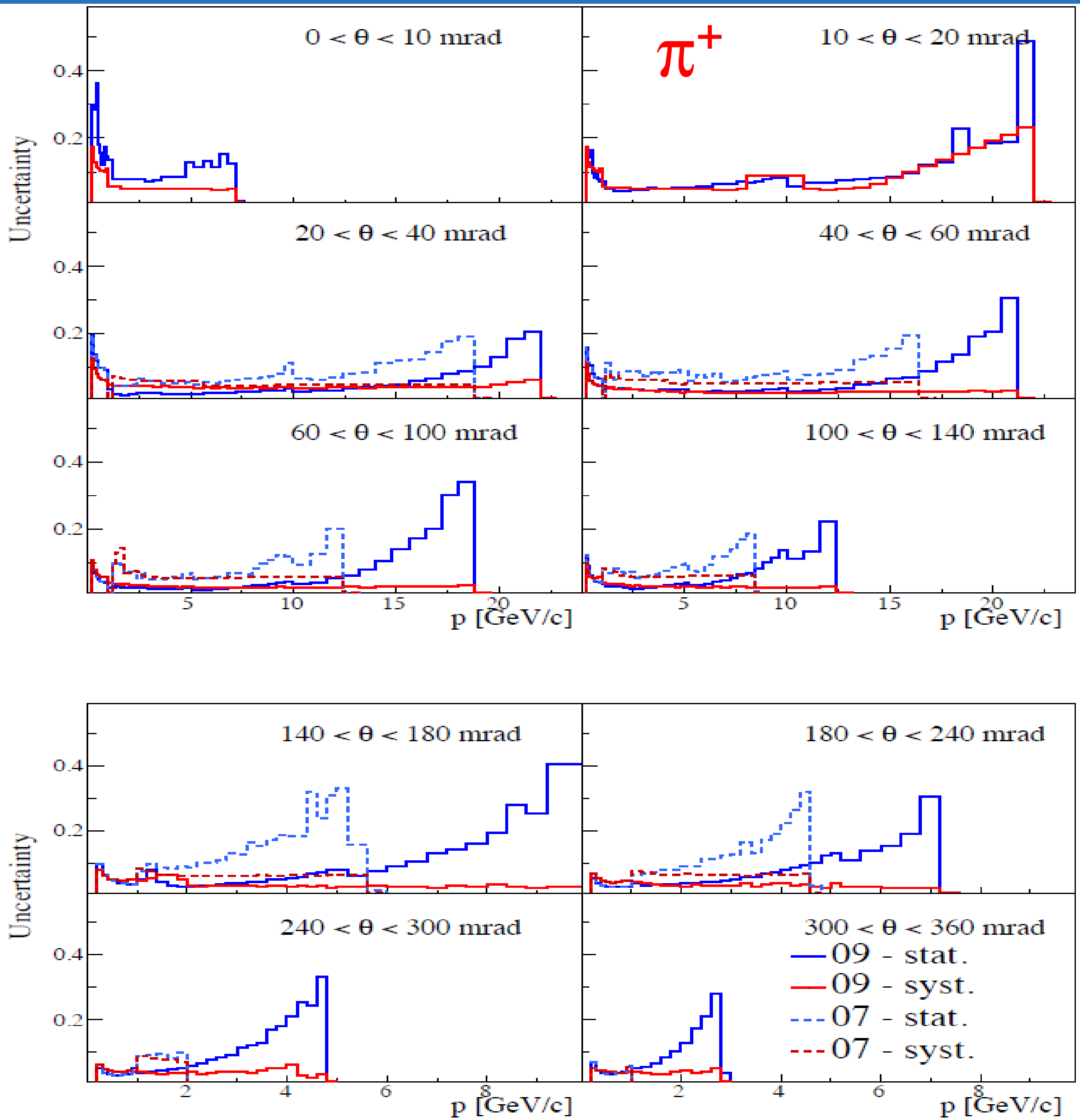
NA61/SHINE: p+C@31GeV/c vs UrQMD1.3.1



NA61/SHINE: p+C@31GeV/c vs UrQMD1.3.1*



pC@31GeV/c: new stat vs syst errors



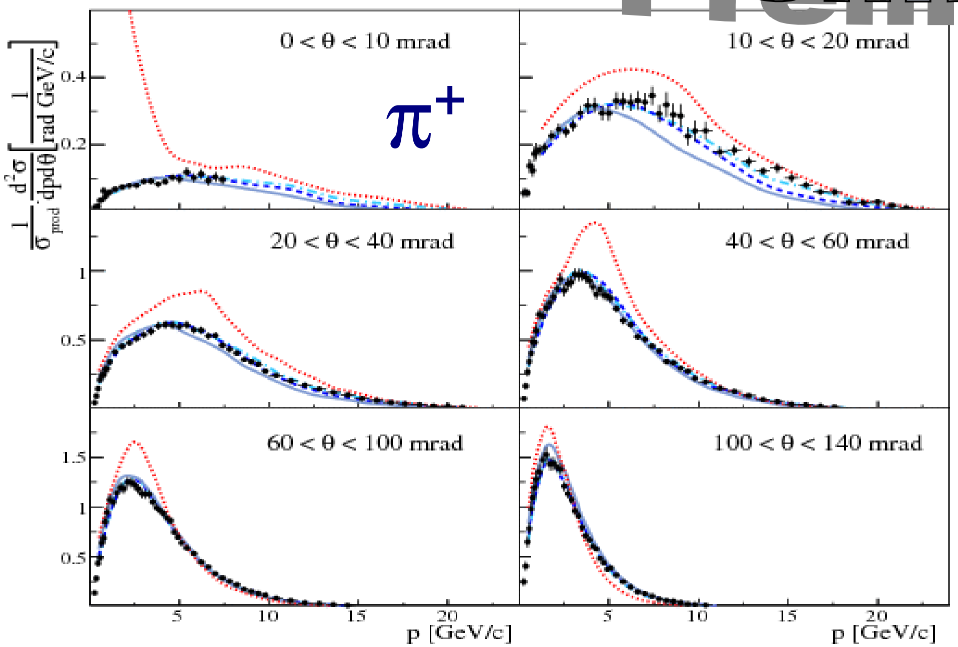
Indeed, with full set of pC@31GeV/c (2009) data we obtain a significant reduction of statistical errors w.r.t. our previous results (based on the pilot 2007 run).

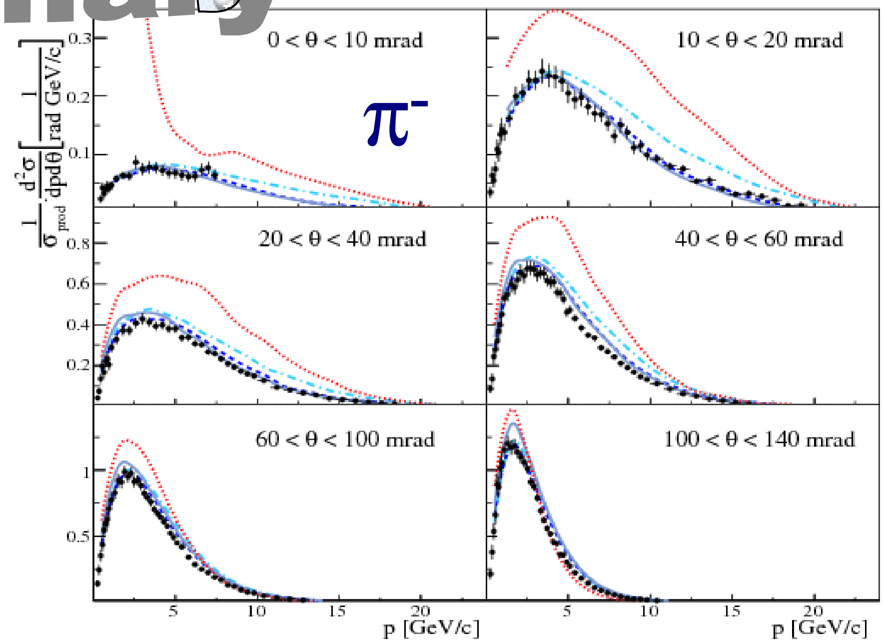
Some improvements in systematic errors.

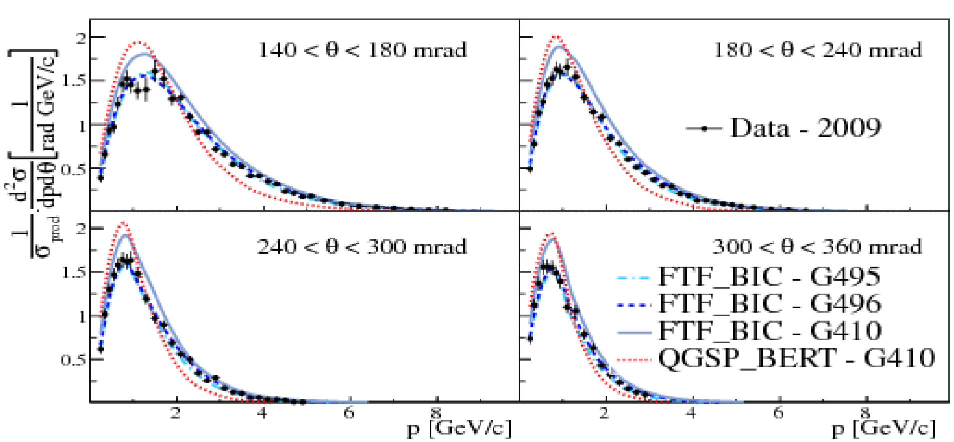
NA61/SHINE: new p+C@31GeV/c results

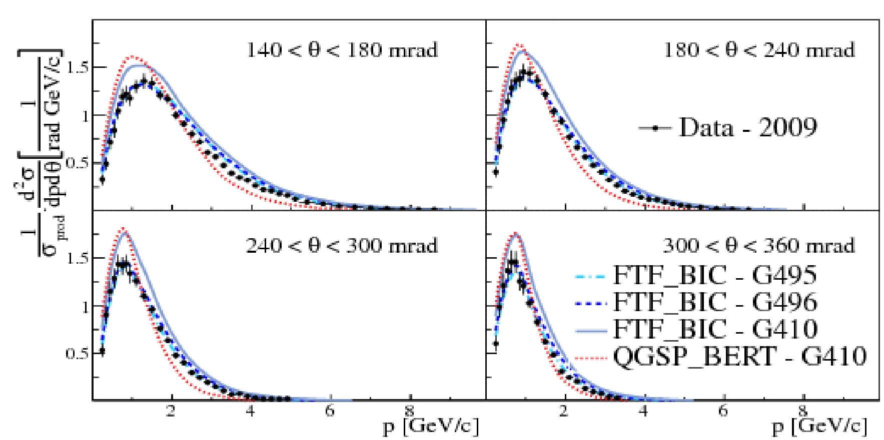
Comparisons with selected GEANT4 physics lists

Preliminary



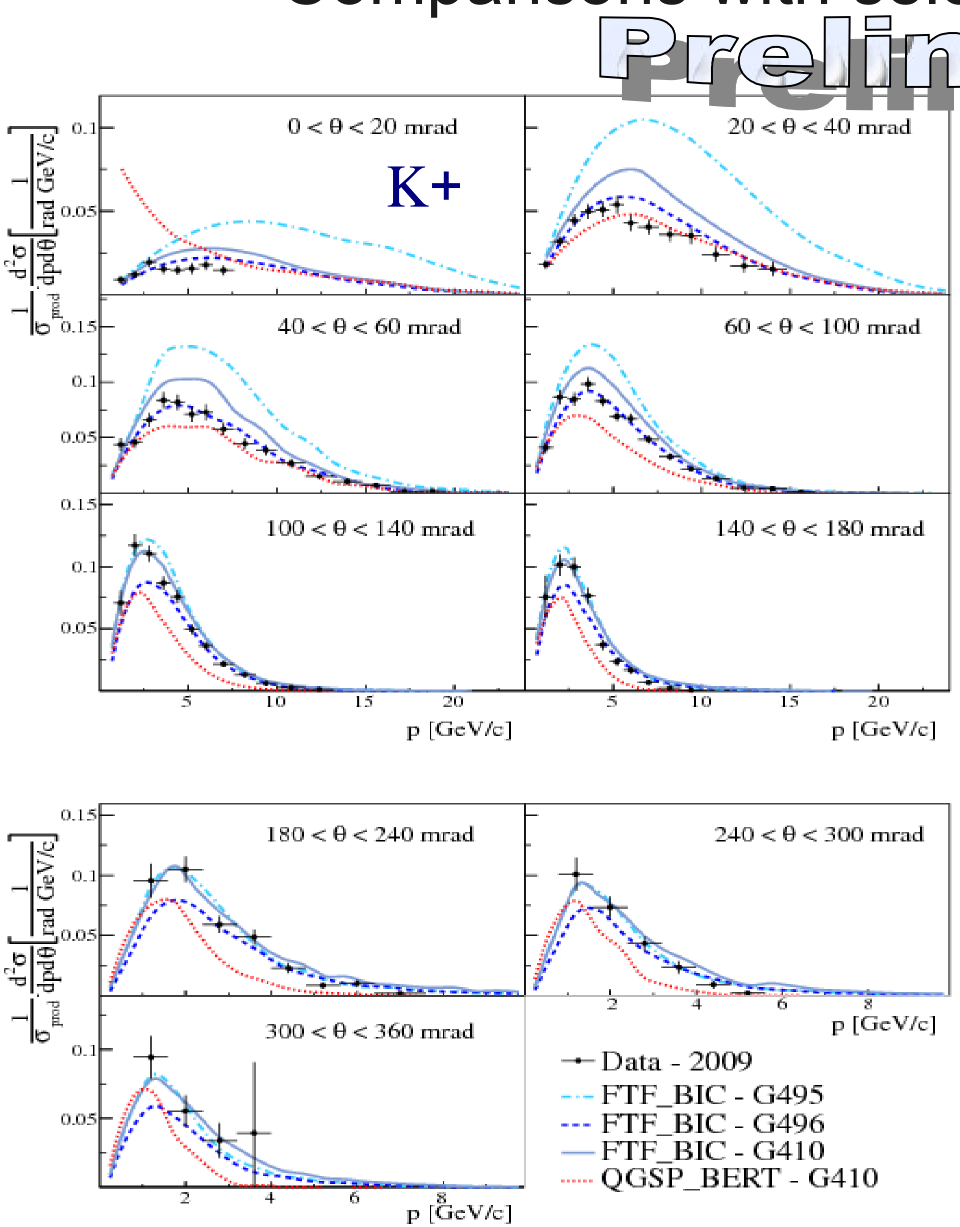


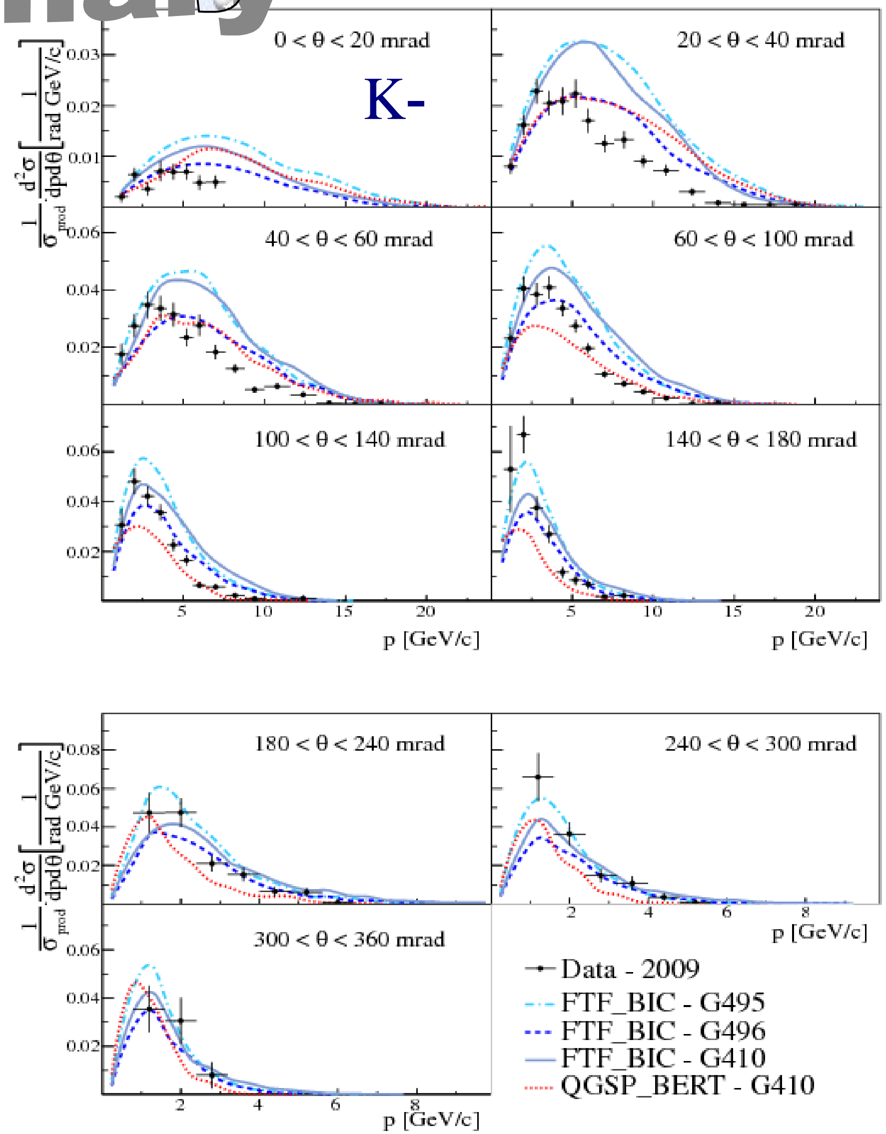




NA61/SHINE: new p+C@31GeV/c results

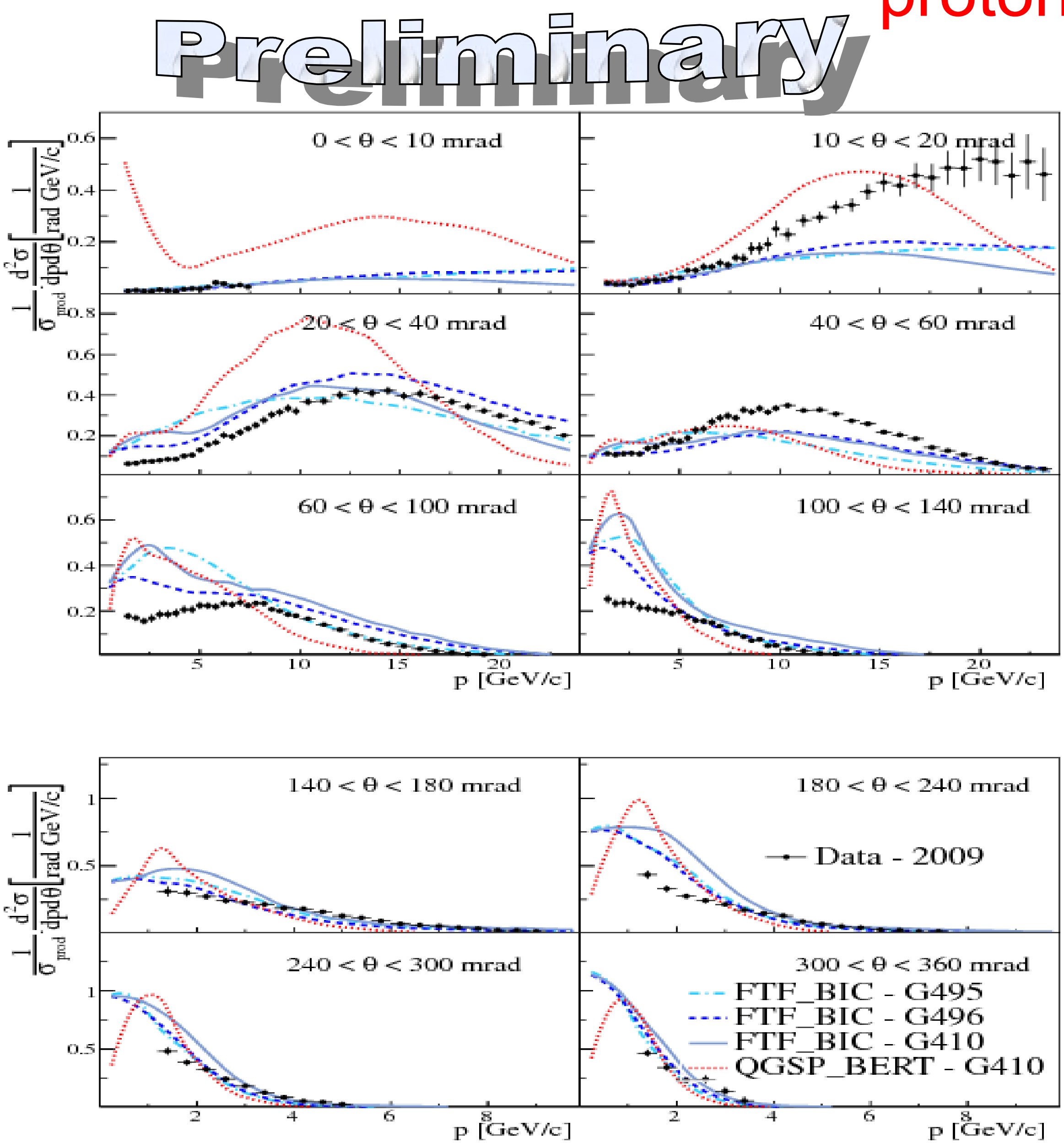
Comparisons with selected GEANT4 physics lists





NA61/SHINE: new pC@31GeV/c results

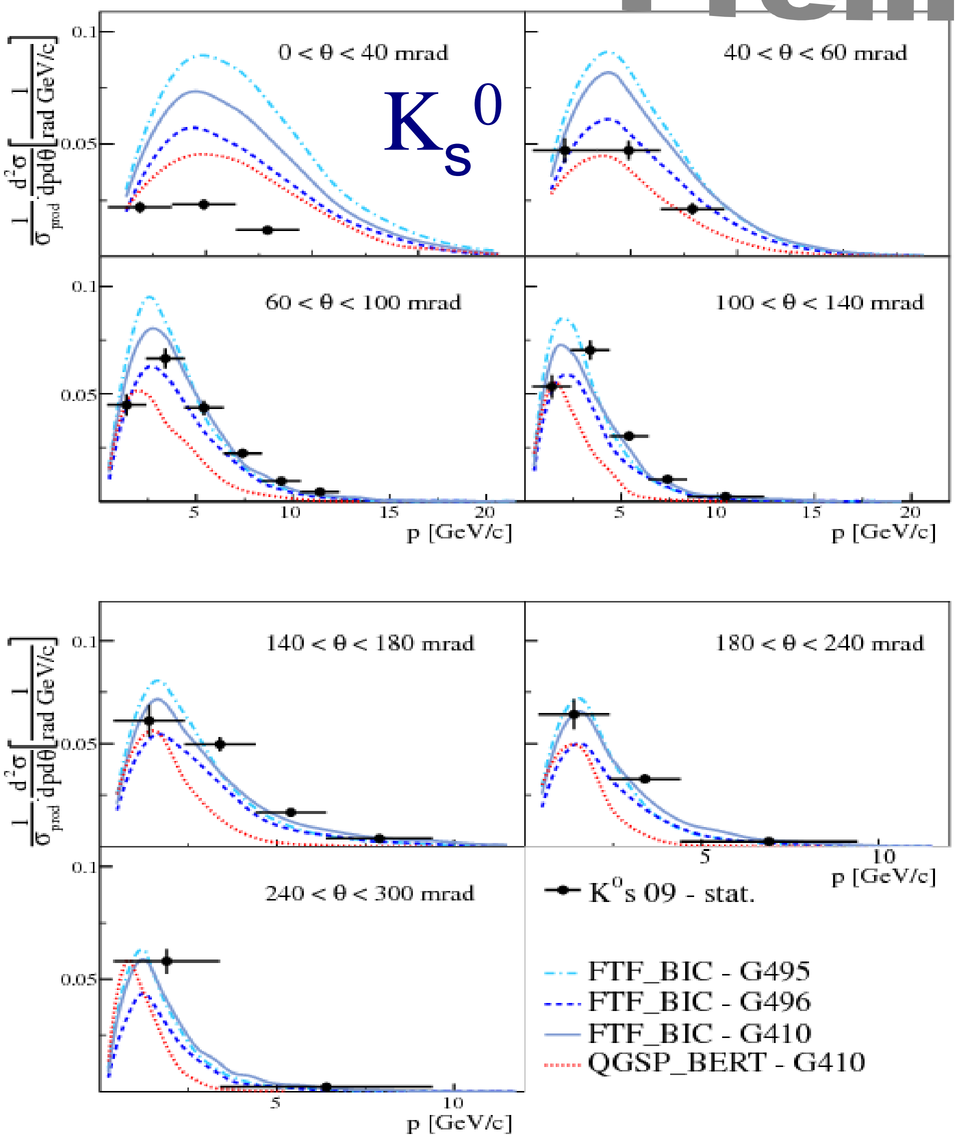
protons

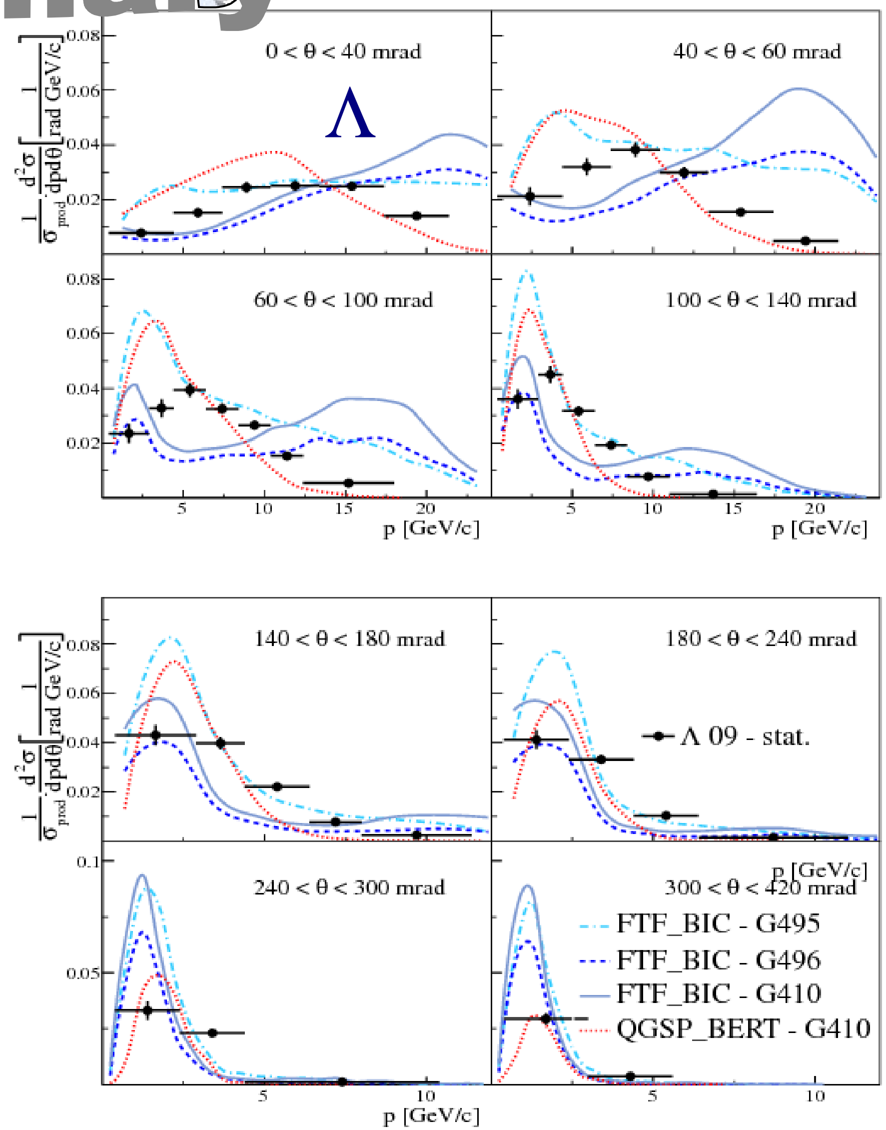


NA61/SHINE: new p+C@31GeV/c results

Comparisons with selected GEANT4 physics lists

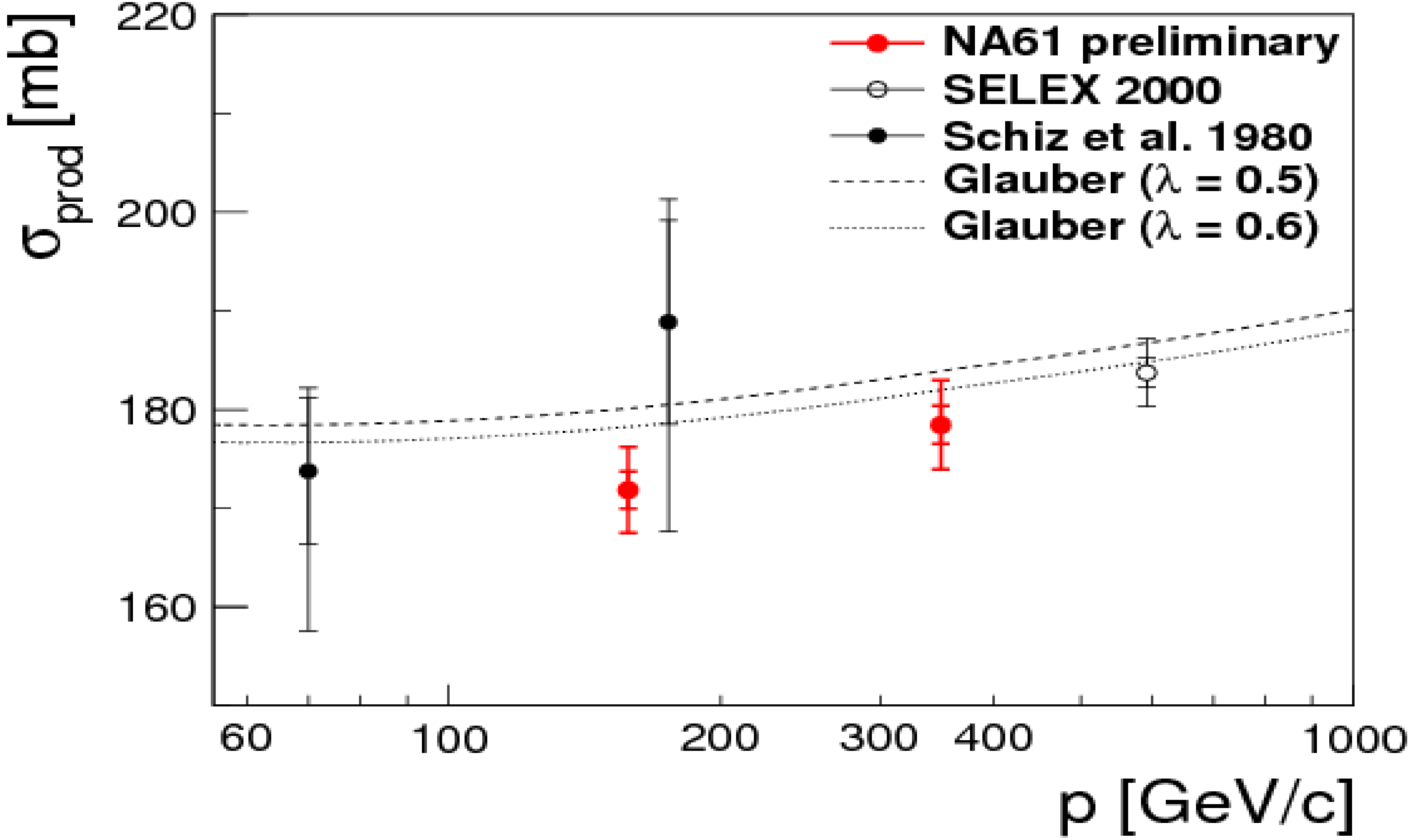
Preliminary





NA61/SHINE: π^-+C cross section

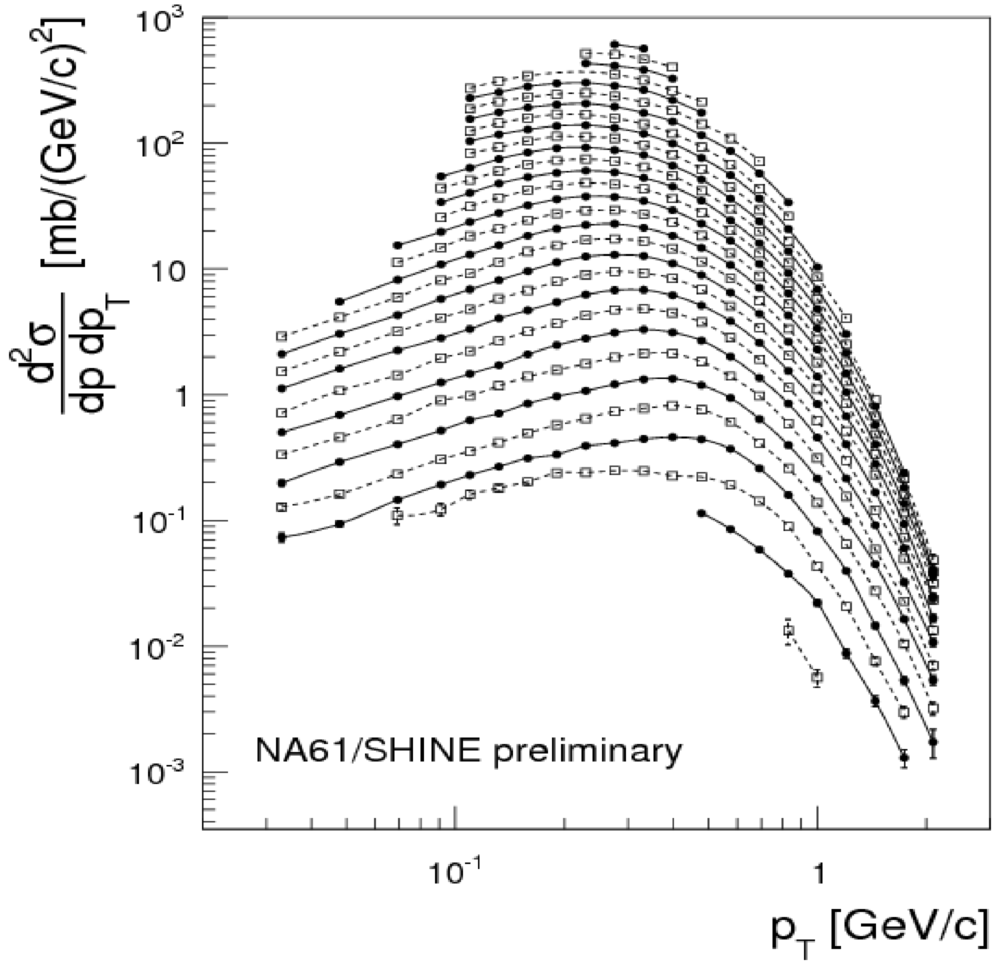
π-C production cross section measurements at 158 and 350 GeV/c



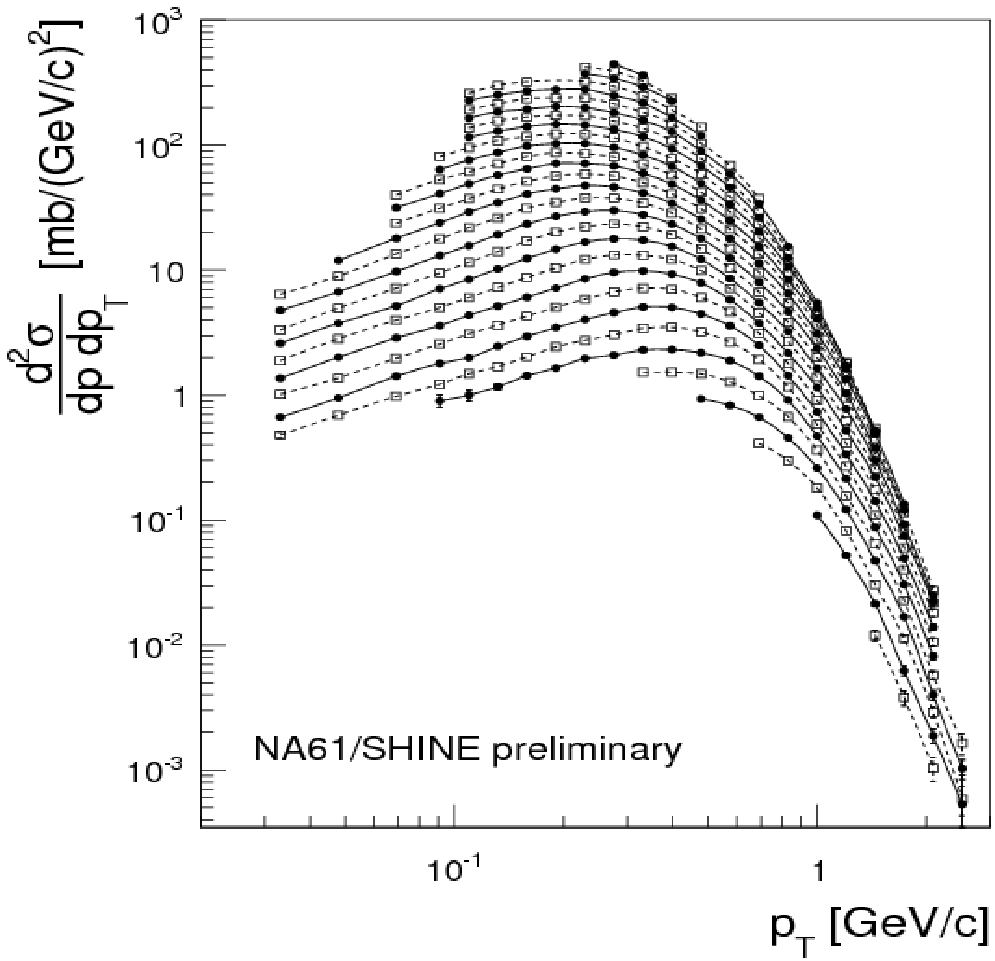
CERN-SPSC-2012-029

NA61/SHINE: π^-+C@158 GeV/c

$\pi^- + C \rightarrow h^+ + X$



$\pi^- + C \rightarrow h^- + X$

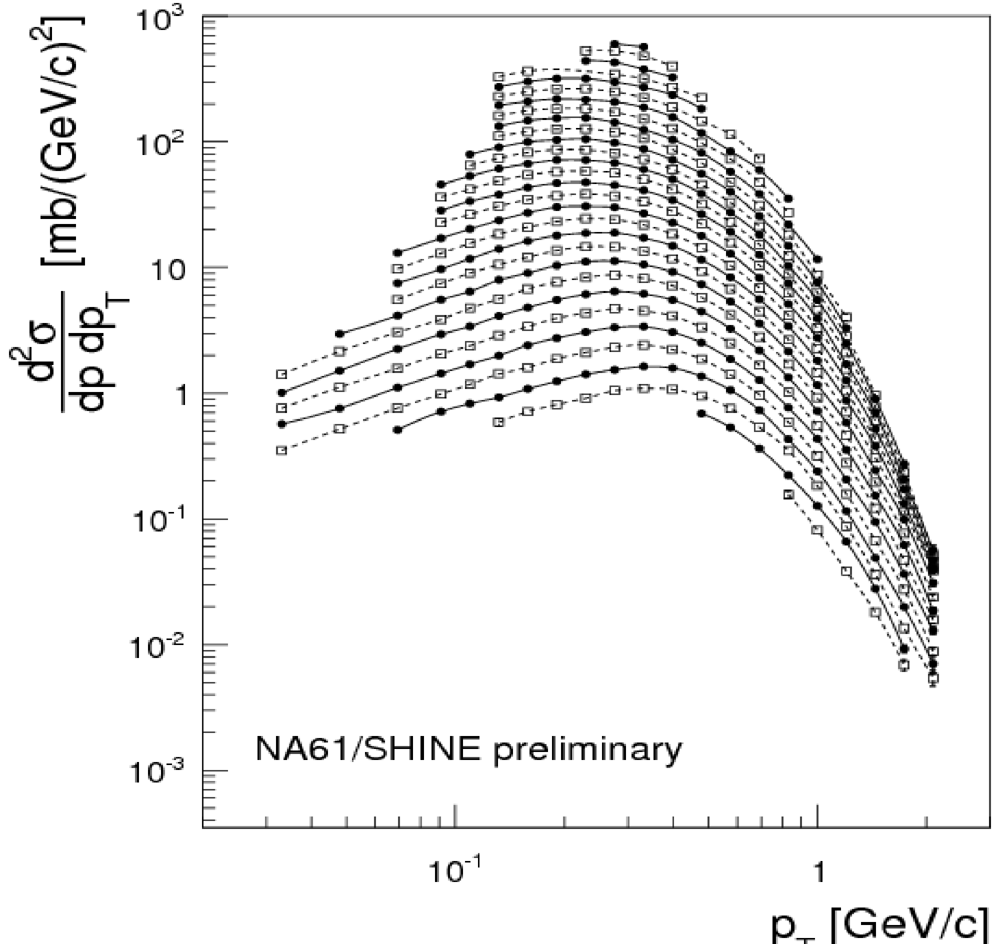


p = 0.6 … 121 GeV/c in steps of lg p/(GeV/c) = 0.08

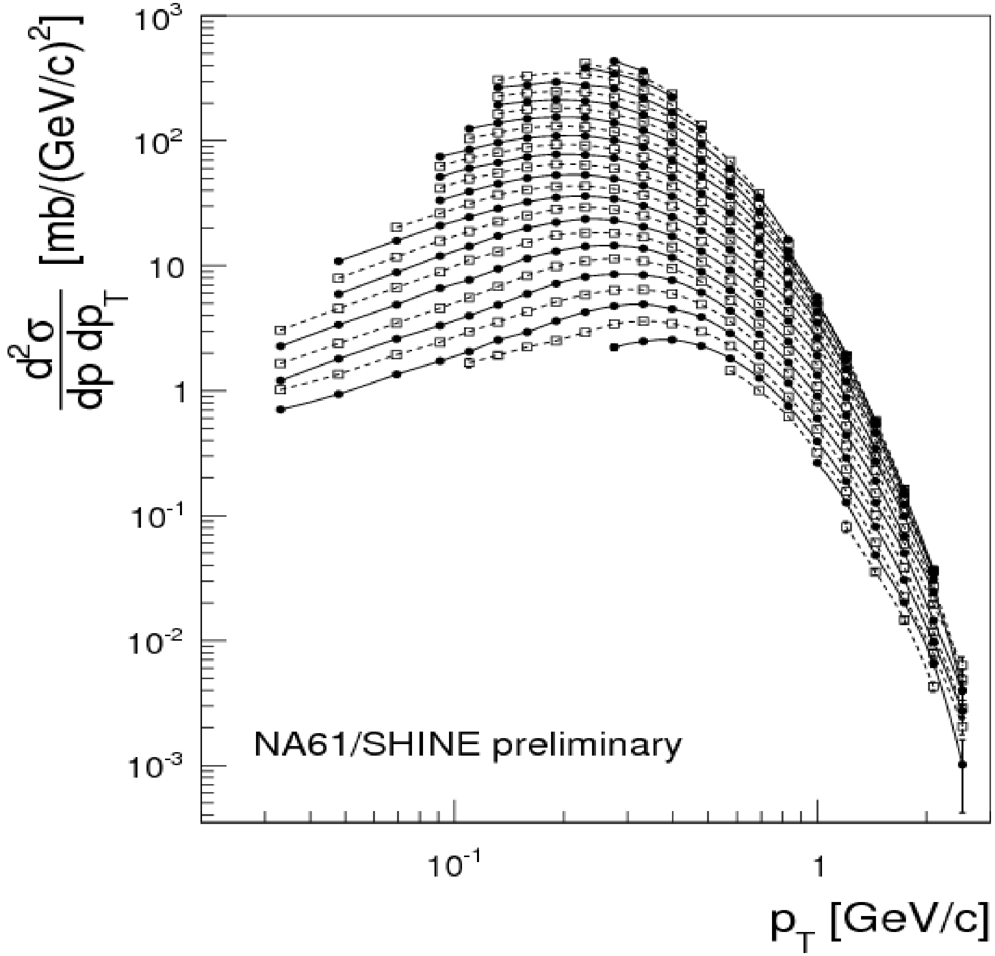
CERN-SPSC-2012-029

NA61/SHINE: π^-+C@350 GeV/c

$\pi^- + C \rightarrow h^+ + X$



$\pi^- + C \rightarrow h^- + X$

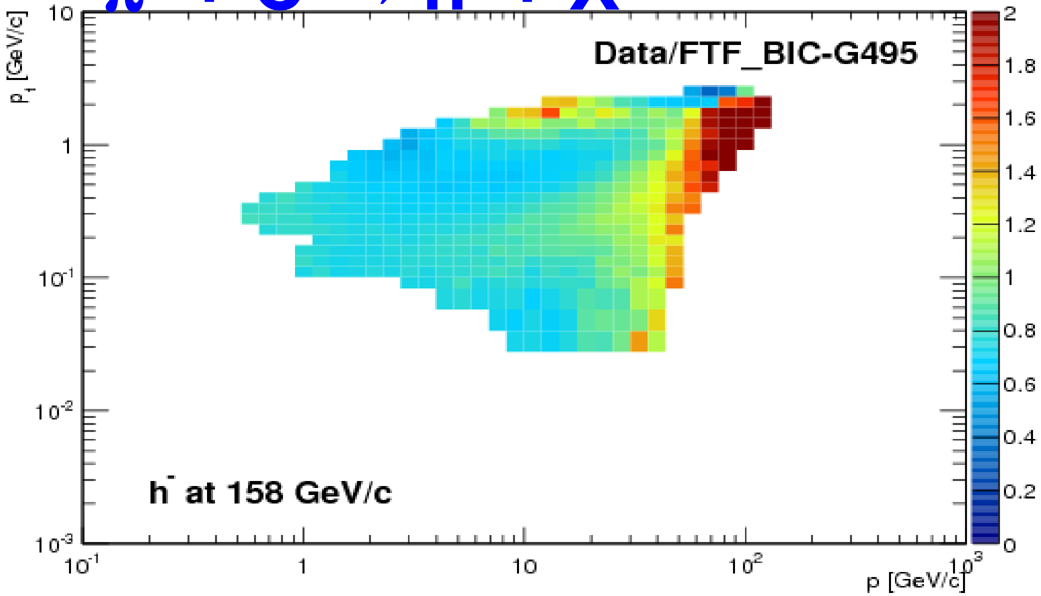


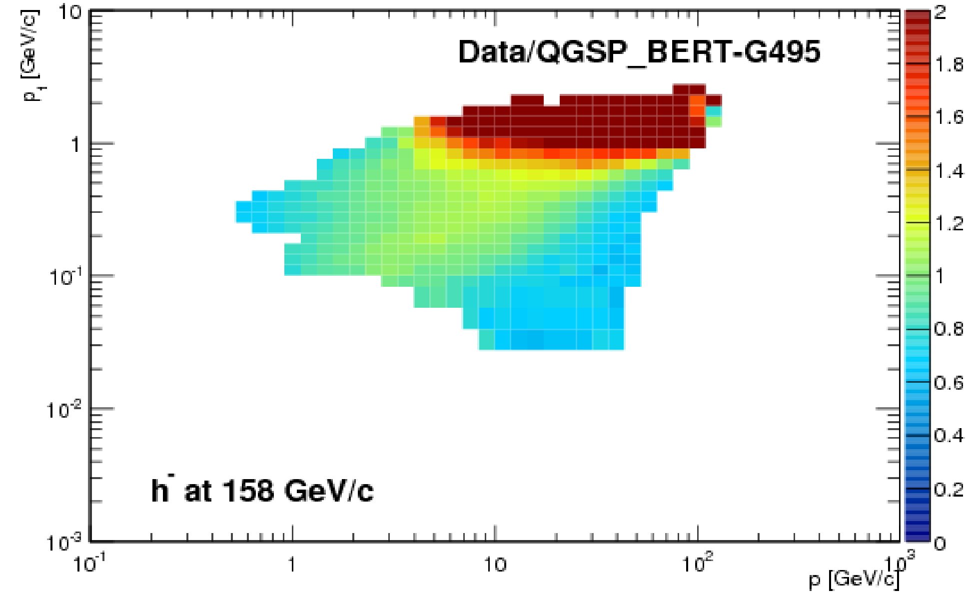
p = 0.6 … 121 GeV/c in steps of lg p/(GeV/c) = 0.08

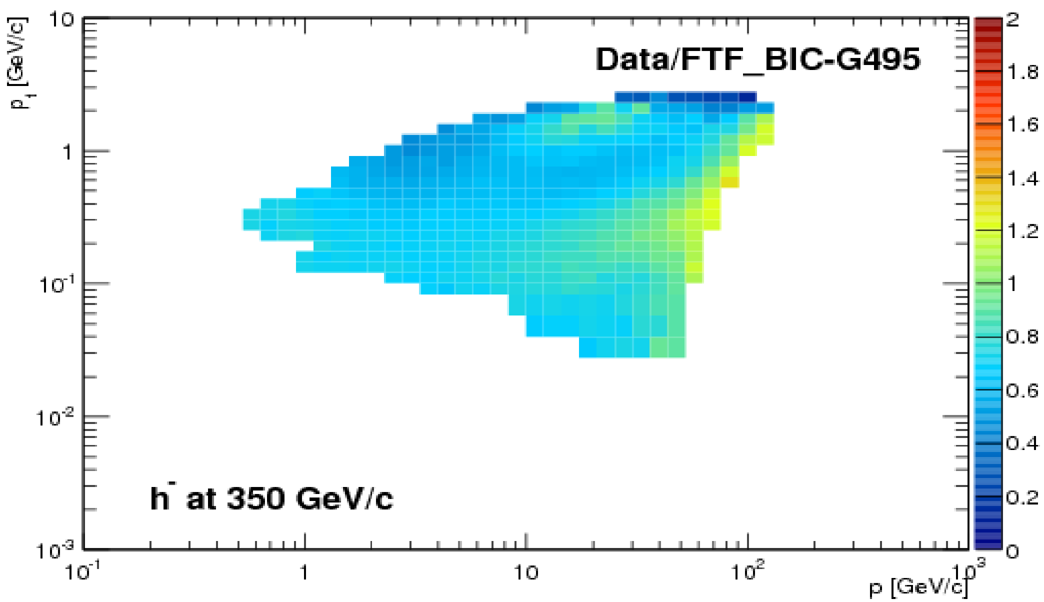
CERN-SPSC-2012-029

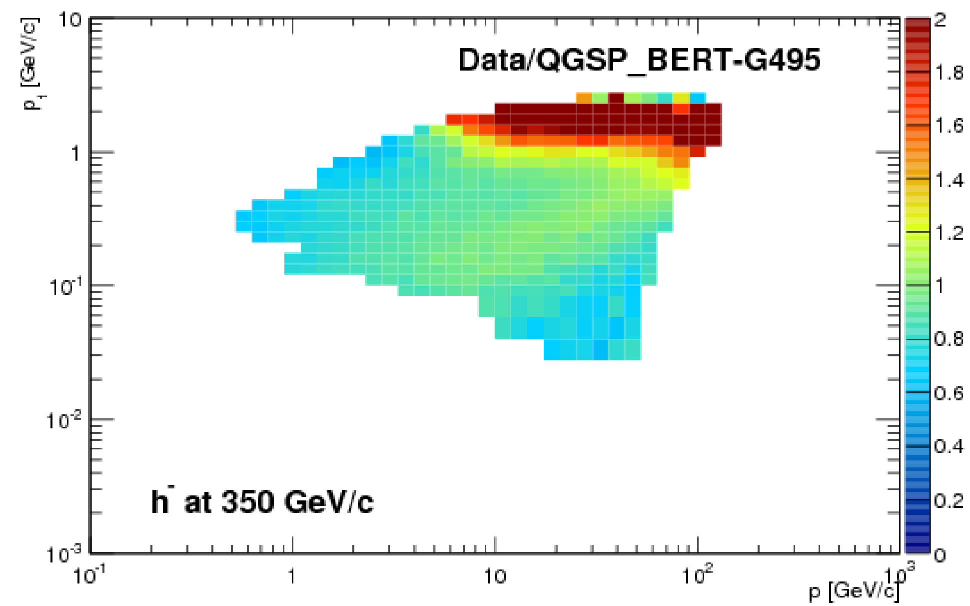
NA61/SHINE: π^-+C vs G4 physics lists

$\pi^- + C \rightarrow h^- + X$



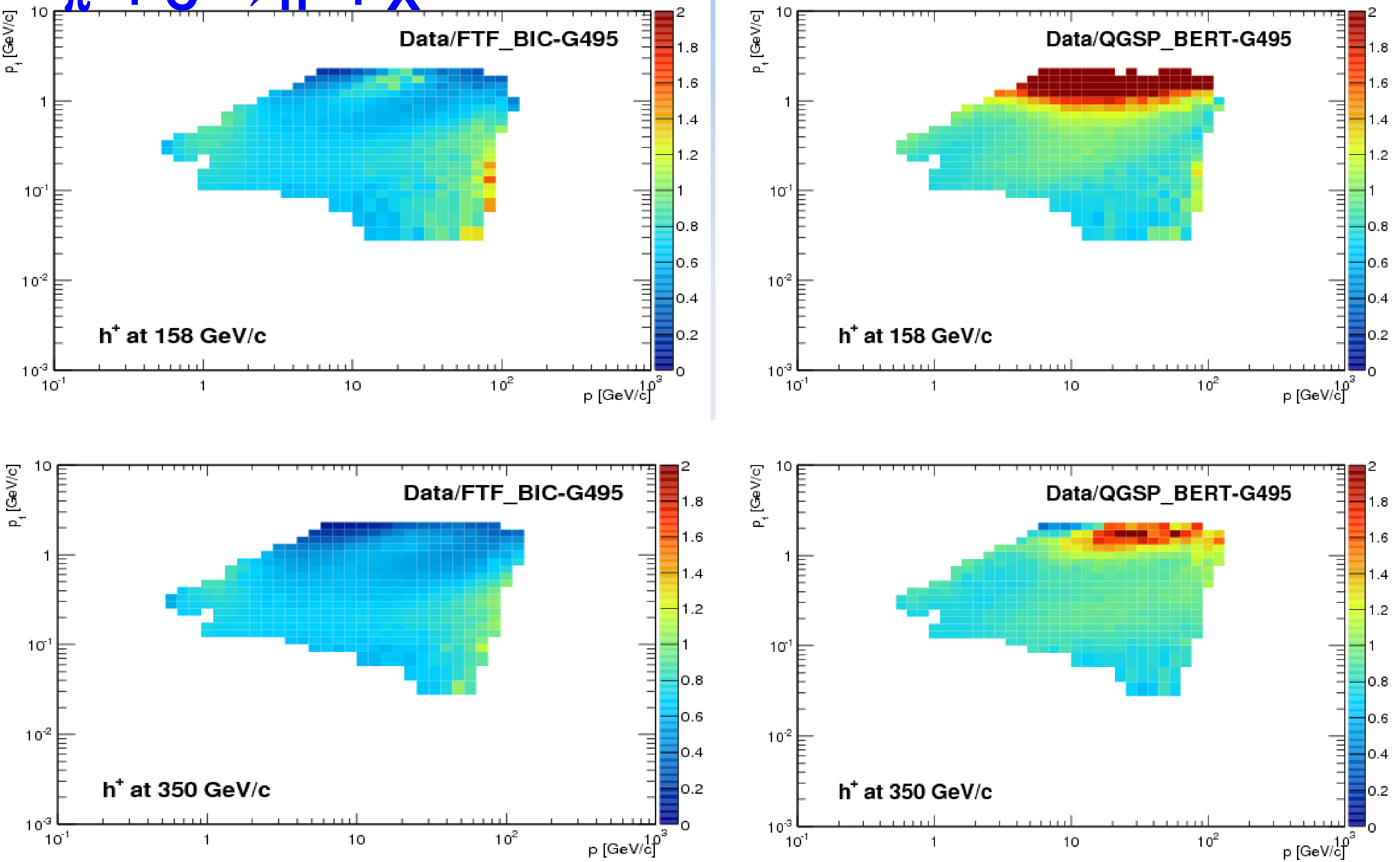




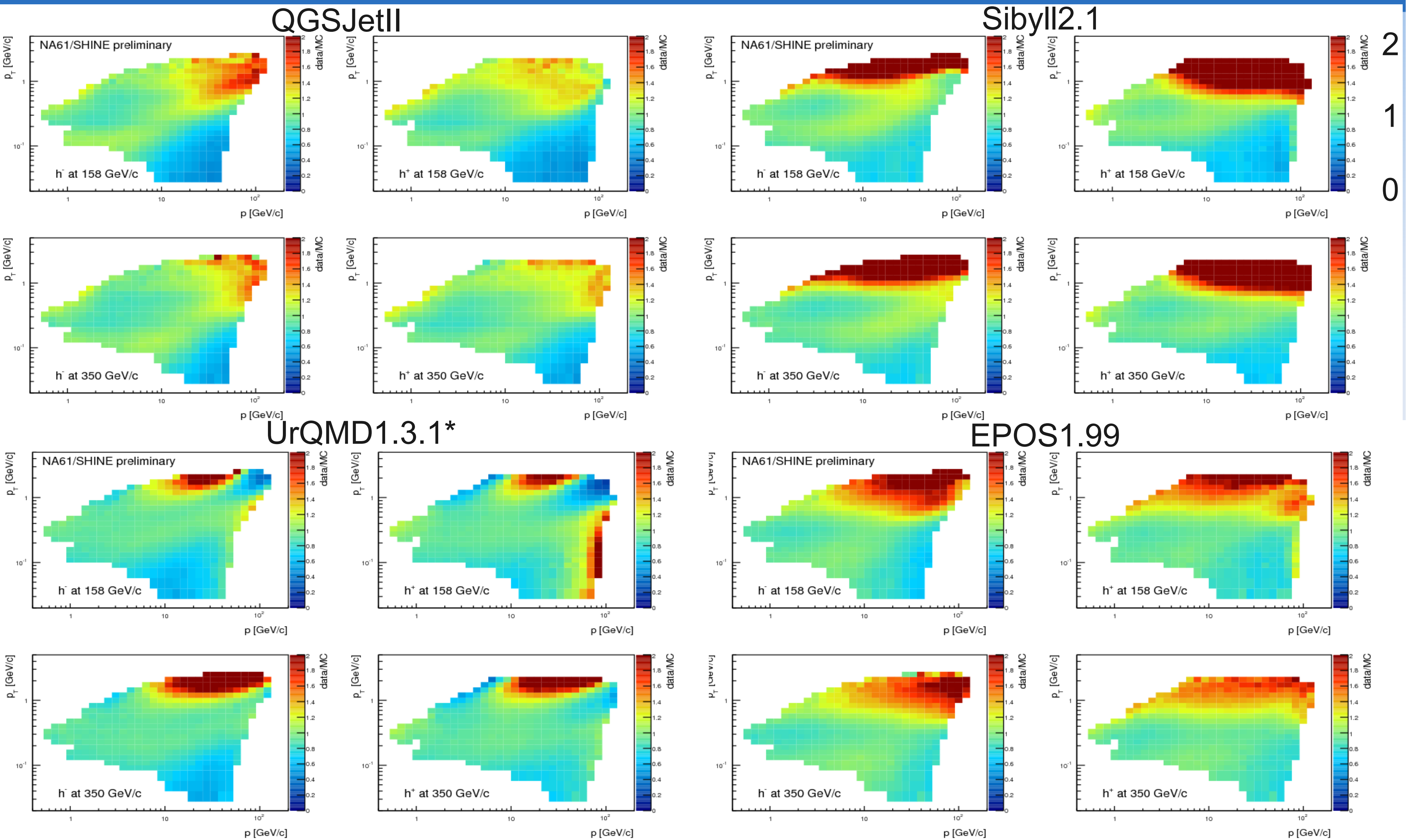


NA61/SHINE: π^-+C vs G4 physics lists

$\pi^- + C \rightarrow h^+ + X$

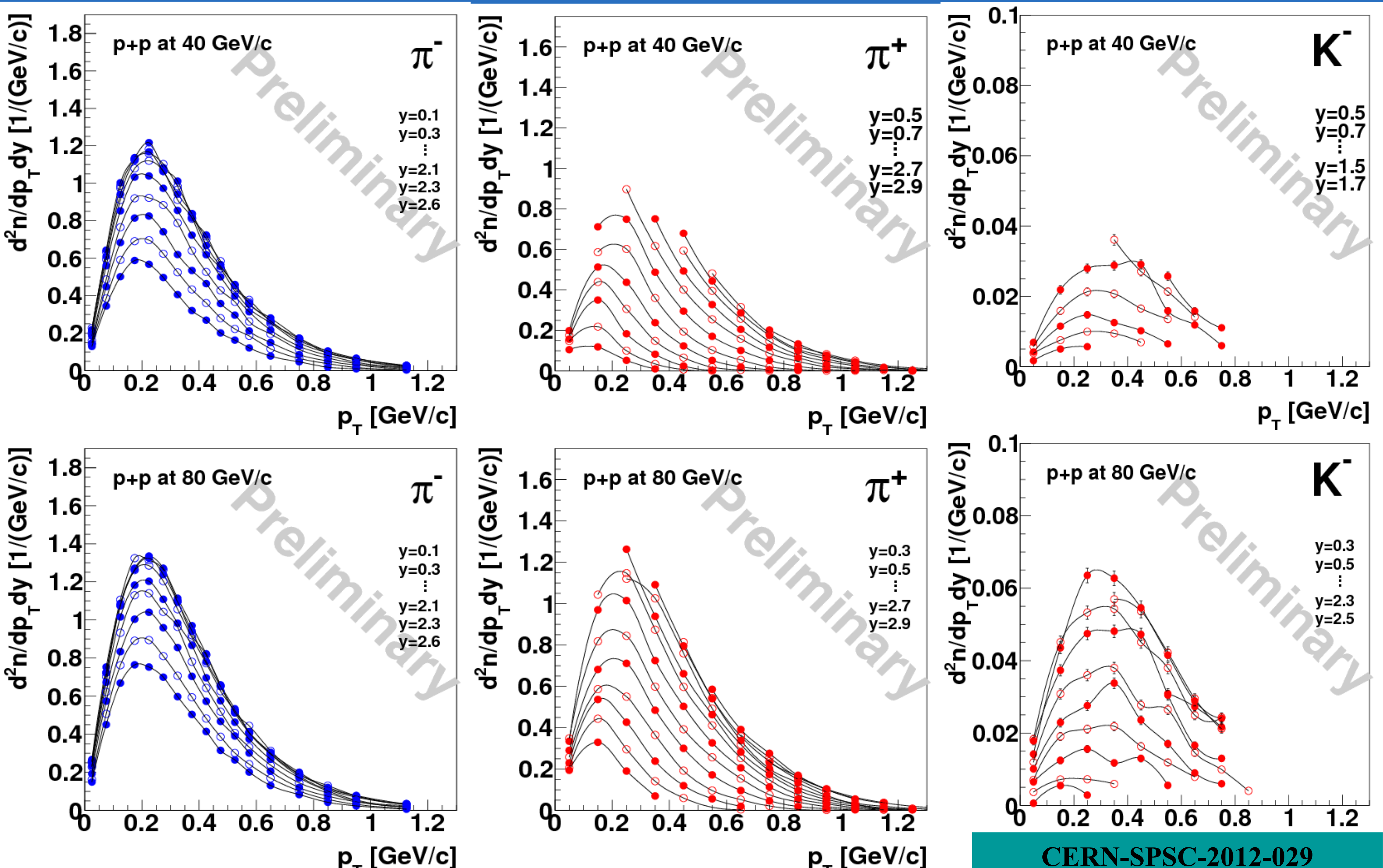


NA61/SHINE: π^-+C vs Models



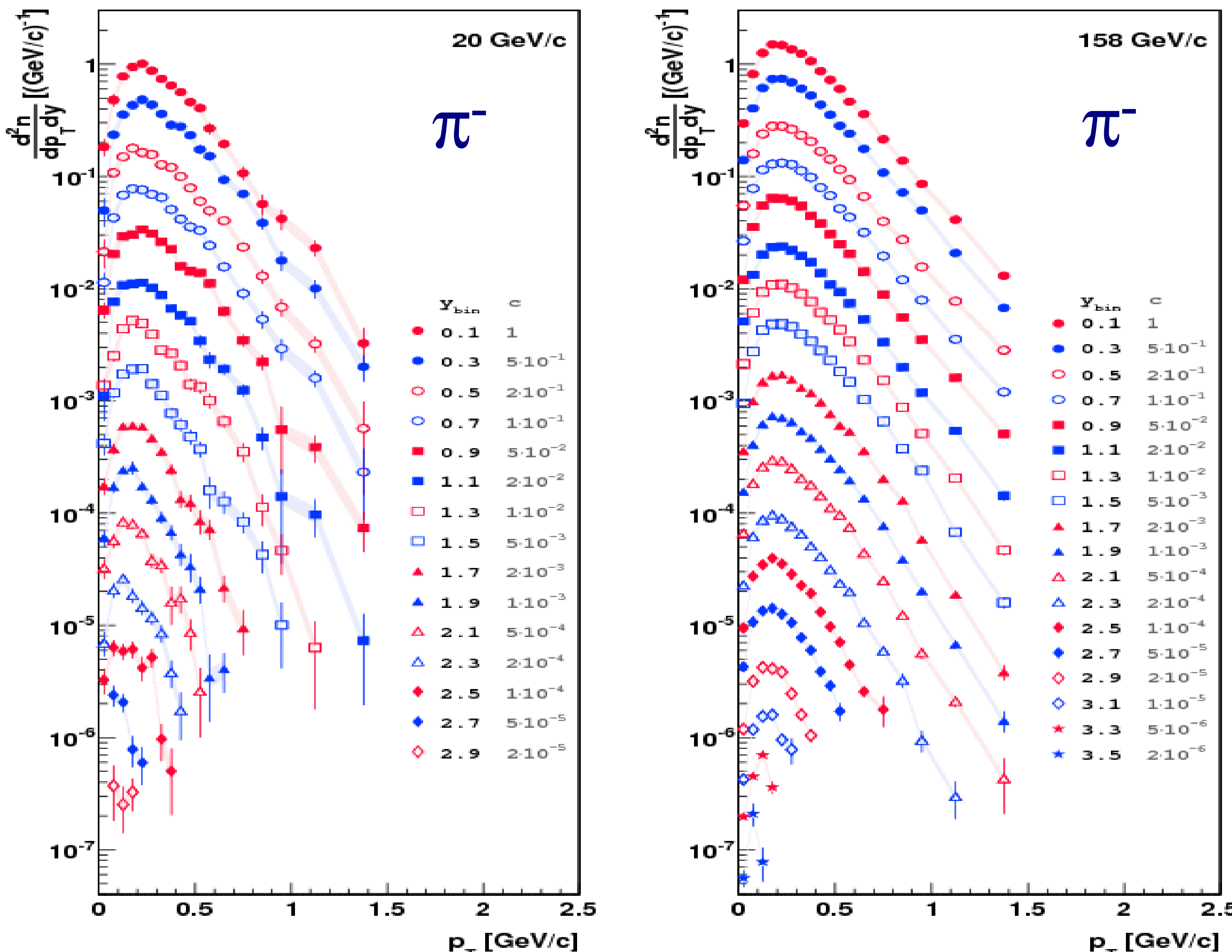
CERN-SPSC-2012-029

NA61/SHINE: p+p results



CERN-SPSC-2012-029

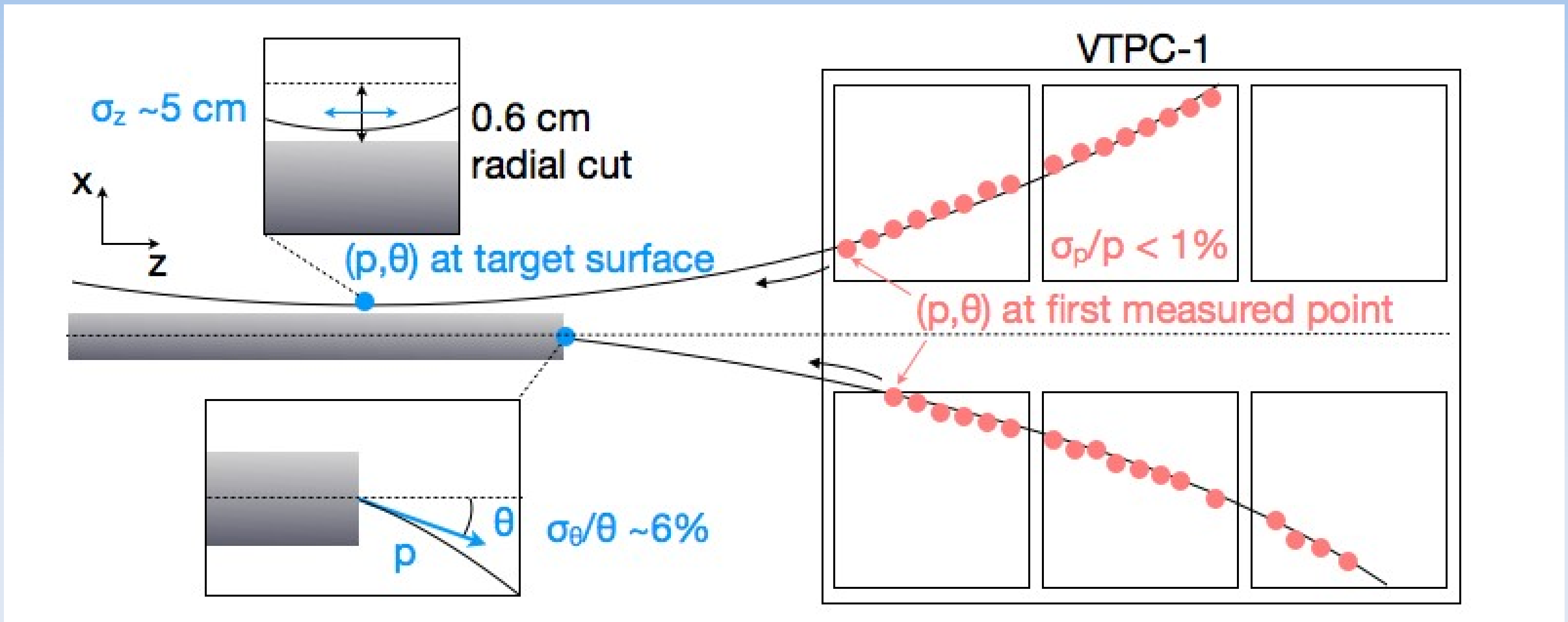
NA61/SHINE: p+p results



Measurement of π- spectra in inelastic pp interactions at 20, 31, 40, 80 and 158 GeV/c

Eur. Phys. J. C74 (2014) 2794

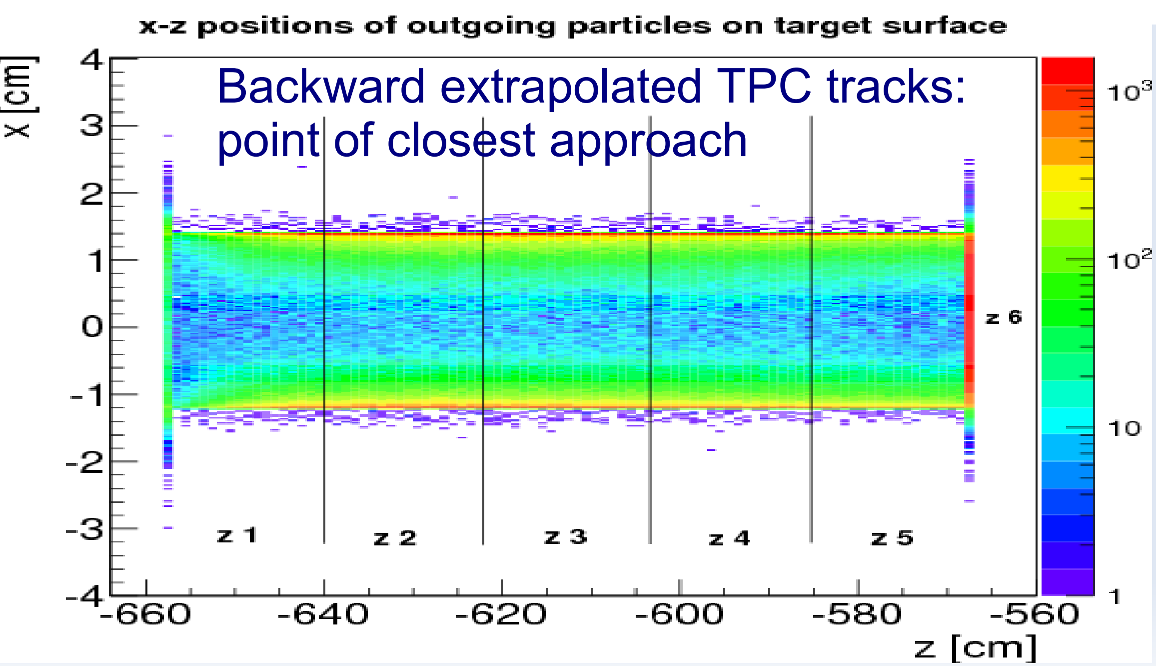
NA61/SHINE: replica target analysis

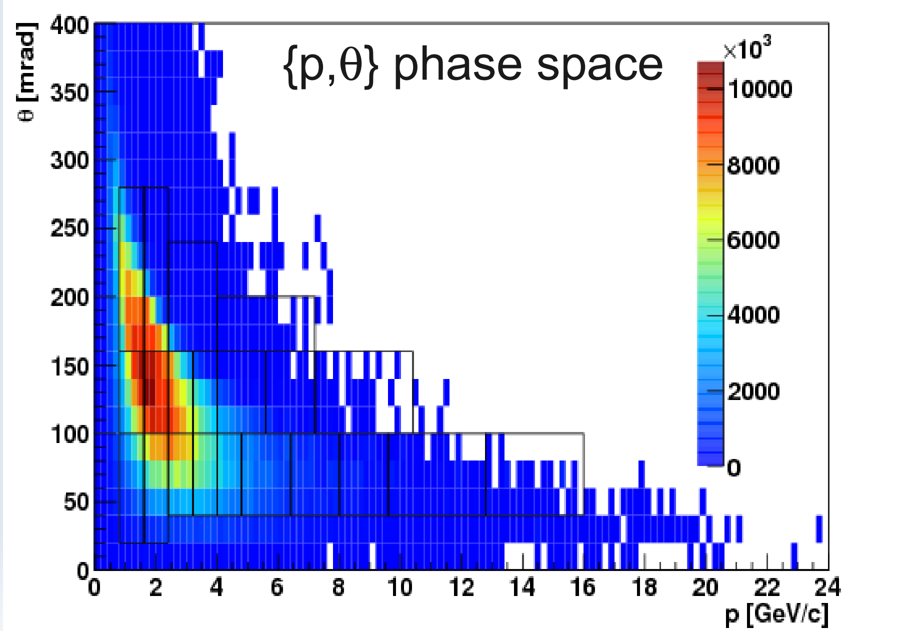


5 longitudinal bins of 18 cm each + target downstream face

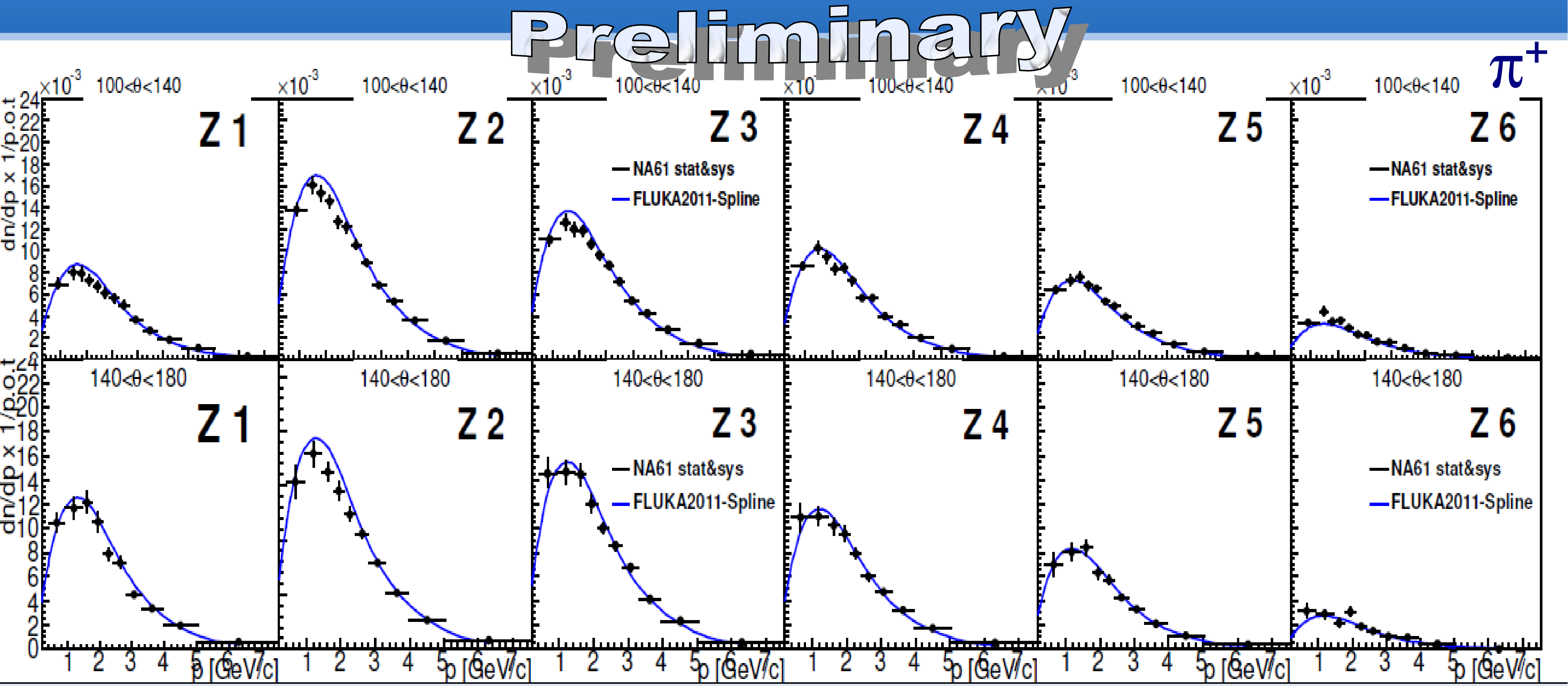
Analysis technique developed using pilot data, see

NIM A701 (2013) 99





NA61/SHINE: new replica target analysis



Combination of thin and replica target measurements would allow to better understand effects of reinteractions in the long target as well as the overall normalization to the number of incident protons.

Ultimate precision on T2K neutrino flux will be achieved with replica target re-weighting, once 2010 NA61/SHINE data are analyzed.

A.Hasler, PhD thesis, Univ. of Geneva; in preparation

US Interest in NA61/SHINE

- **Institutions:** FNAL, LANL, University of Texas at Austin, TX, University of Colorado, Boulder, CO, Northwestern, IL, University of Pittsburgh, PA, William and Mary, VA
- These institutions listed are interested in precise neutrino flux constraints for NuMI experiments (MINOS, NOvA, Minerva) and the future (LBNE).
  - Neutrino oscillation experiments require an understanding of the unoscillated neutrino spectrum. For cross-section experiments the hadron production uncertainties directly impact the final answer.
  - Both redundancy and over-constraining hadronic production modeling through measurements will be useful in reducing all sorts of backgrounds and systematics
  - Using NA61 is an opportunity to do it relatively fast and in a cost effective way and mutually beneficial.

Valid for any future project

Hadron Production Measurements

for Fermilab Neutrino Beams

US participation in the NA61/SHINE experiment at CERN

Proposal

July 23, 2014

Abstract

We propose to develop a collaboration with the NA61/SHINE experiment at CERN to exploit its powerful capabilities for particle production measurements. This effort would allow the US group to collect dedicated and optimized high-precision hadron production data needed to improve modeling of current and future Fermilab neutrino beams. We plan

Data-taking plans:

proton+pion event totals	Incident proton/pion beam momentum		
Target	120 GeV/c	60 GeV/c	30 GeV/c
NuMI (spare) replica	(*future*)		
LBNE replica	(*future*)		
thin graphite ($< 0.05\lambda_I$)	3M	3M	(T2K data)
thin aluminum ($< 0.05\lambda_I$)		3M	(*future*)
thin steel ($< 0.05\lambda_I$)	(*future*)	(*future*)	(*future*)
thin beryllium ($< 0.05\lambda_I$)	3M	3M	(*future*)
thin concrete ($< 0.05\lambda_I$)	(*future*)	(*future*)	(*future*)

Table 1: A table of proton+pion event totals for target and beam settings which are relevant to US long baseline neutrino experiments, that would be run after the CERN 2013-14 shutdown. Proton and pion data may be taken simultaneously with the proper trigger settings. The first set of runs, expected in 2015, are labeled with 3M (the number of incident pion and proton triggers), and the other relevant runs are labeled *future*.

NA61/SHINE: Conclusions

- First NA61/SHINE measurements of cross sections and charged pion and kaon spectra in proton-Carbon interactions at 31 GeV/c have been published [**Phys. Rev. C84 (2011) 034604 ; ibid. C85 (2012) 035210**] and used for improved neutrino flux predictions in the T2K experiment
- Pilot data have also been used to extract K^0_S and Λ yields from the thin target [**Phys. Rev. C89 (2014) 035205**] and π^+ yields from the T2K replica target [**NIM A701 (2013) 99**]
- Analysis techniques are well established
- Further analysis of data for T2K as well as for Cosmic Ray experiments (π^-C @158 and @350 GeV/c) and for Heavy Ion program (pp @ 20,30,40,80,158 GeV/c) [**Eur. Phys. J. C74 (2014) 2794**] is on-going
- Strong interest from our US colleagues to perform hadron production measurements for Fermilab neutrino experiments
- The NA61/SHINE spectrometer can be used for hadron production measurements relevant for future (neutrino and CR) experiments

General conclusions

- Hadron production experiments have already contributed to recent advances in many areas of modern physics (in particular, neutrino physics)
- A large amount of data collected over the last decade
- These data are important for validation and tuning of hadron production models in MC generators
- Hadron production studies is a MUST for precision (neutrino and cosmic ray) experiments

Detailed comparisons of NA61/SHINE data with some available hadroproduction models in e.g.
https://edms.cern.ch/file/1186772/1/fluka_vs_na61.pdf
https://edms.cern.ch/file/1219646/1/gibuu.pdf
https://edms.cern.ch/file/1250157/1/VMC_internal_note_laura.pdf

Thank you for your attention

Backup slides

NA61/SHINE : 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

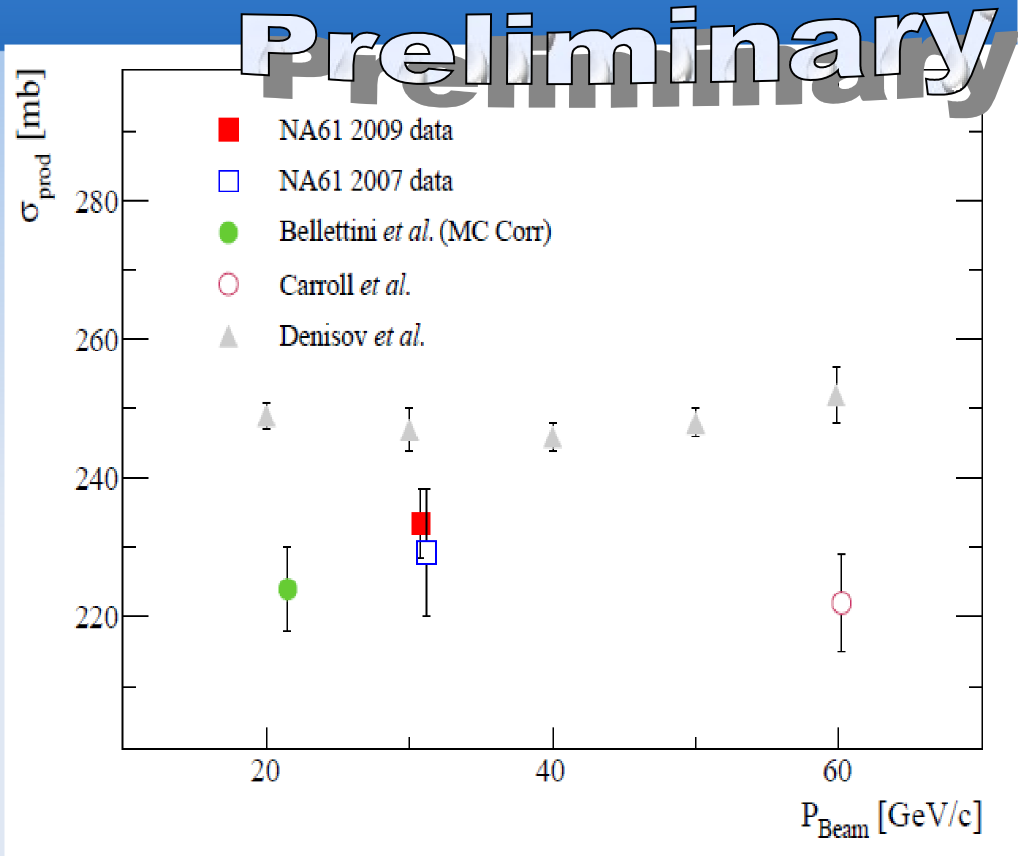
Empty target: ~80k triggers

NA61/SHINE pC@31GeV/c: cross-sections

- To obtain inelastic cross-section, the "trigger" cross-section was corrected for:

  1) the contribution of the coherent elastic pC scattering giving trigger signal in the experiment. Simulated by GEANT4.9.5-FTF_BIC [47.45±0.42(stat)±2.14(det) ±0.25(mod)] mb [subtraction]

  2) the loss of inelastic events due to the emitted charged particles hitting S4 trigger counter [2.7±0.07(stat)± 0.26(det) ±0.18(mod)] mb for protons and [0.39±0.03(stat)±0.04(det)±0.05(mod)] mb for pions and kaons [addition]



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

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

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

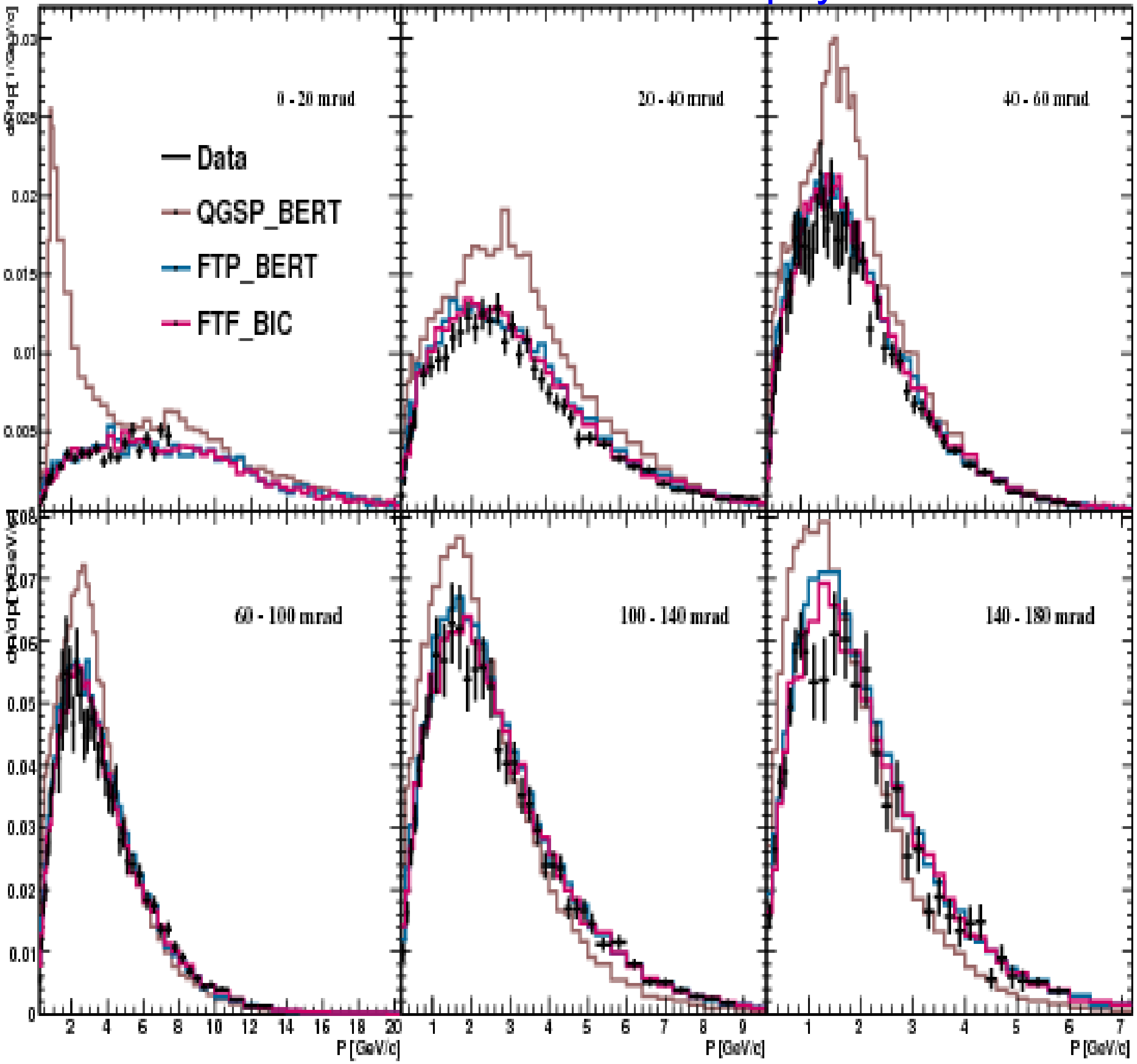
(233.5 ± 2.8 ± 2.4 ± 3.6) mb = (261.3 ± 2.8 ± 2.4± 0.3) mb - (27.8 ± 0.22 ± 3.6) mb

from Glauber model calculations

NA61 Collaboration, paper in preparation

VMC-based development with GEANT4

NA61/SHINE data vs GEANT4 physics lists



Generic tool for neutrino flux predictions and trigger bias corrections:

- allows to run MC simulations within the same framework using different hadron production models (GEANT3, GEANT4 and originally FLUKA)

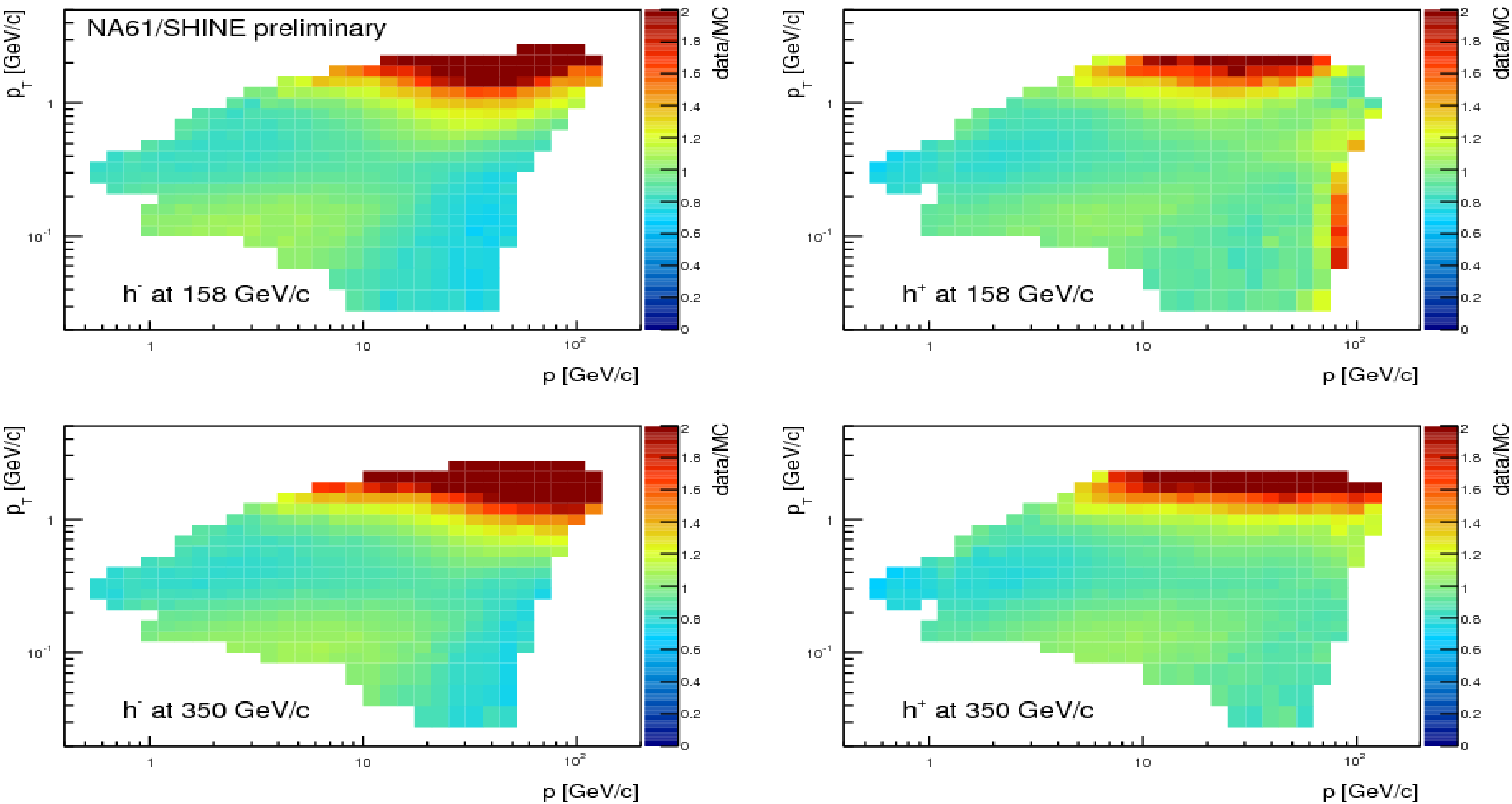
- easy switch between physics models keeping the same code/geometry,e.g. computation of the production cross section using different G4 physics lists

- easy to change geometry keeping the same physics models

Tuning of the GEANT4 FRITIOF (FTF) Model with NA61/SHINE data [V.Uzhinsky, arxiv: 1109.6768 [hep-ph]

Detailed comparisons of NA61/SHINE data with some GEANT4 physics lists
https://edms.cern.ch/file/1250157/1/VMC_internal_note_laura.pdf

NA61/SHINE: π^-+C vs FLUKA2011



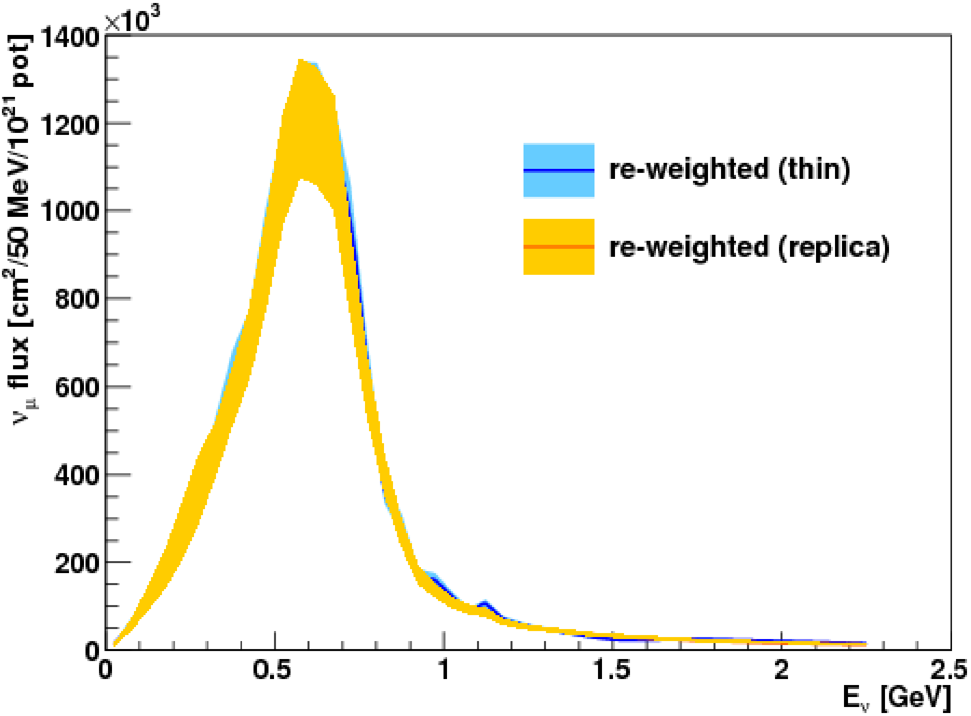
CERN-SPSC-2012-029

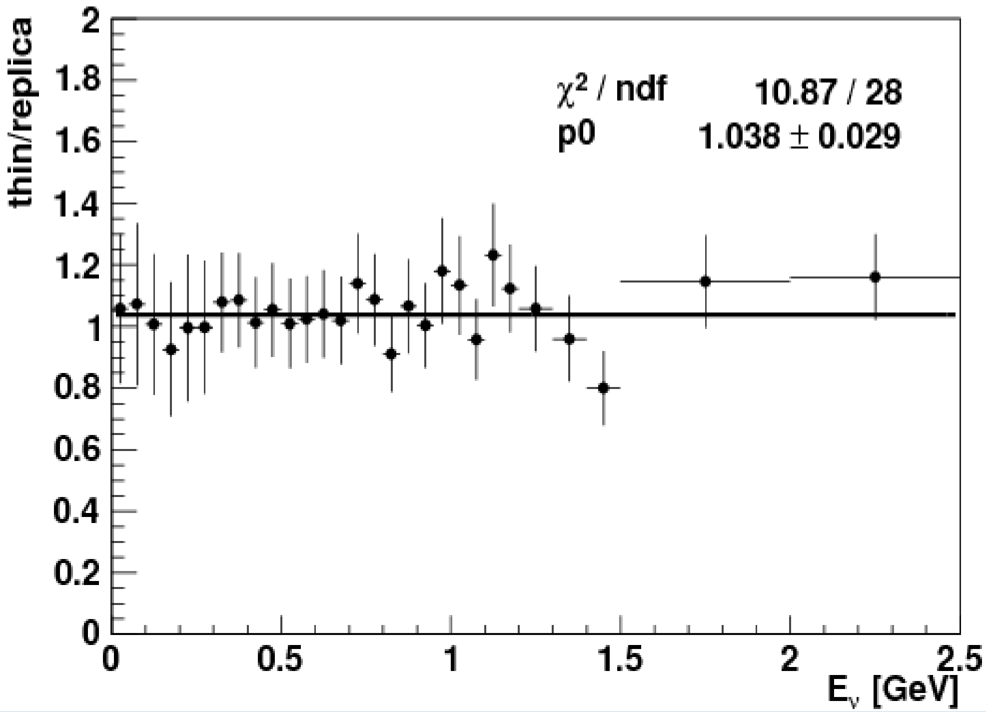
NA61/SHINE: replica target analysis

- Special reconstruction and analysis techniques developed for the replica target (RT)
- Pilot analysis on π^+ emission from the RT surface performed on 2007 data with 5 longitudinal bins along the target and target downstream face
- RT hadron production measurements allow to constrain up to 90% of neutrino flux in T2K
- Proof-of-principal neutrino flux re-weighting performed with NA61/SHINE RT data
- Results consistent with the thin target tuning

NIM A701 (2013) 99

NA61/SHINE: replica target analysis





Replica target data are used for the first time for neutrino flux predictions.

Combination of thin and replica target measurements would allow to better understand effects of reinteractions in the long target as well as the overall normalization to the number of incident protons.

Ultimate precision on T2K neutrino flux will be achieved with replica target re-weighting, once 2010 NA61/SHINE data are analyzed.

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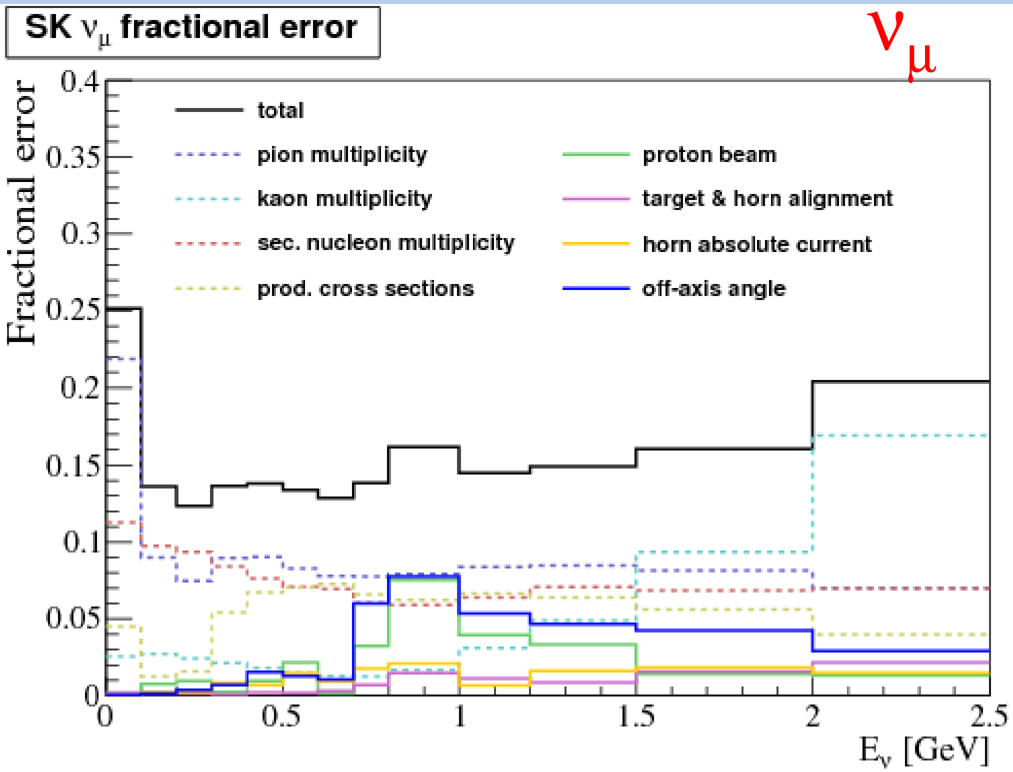
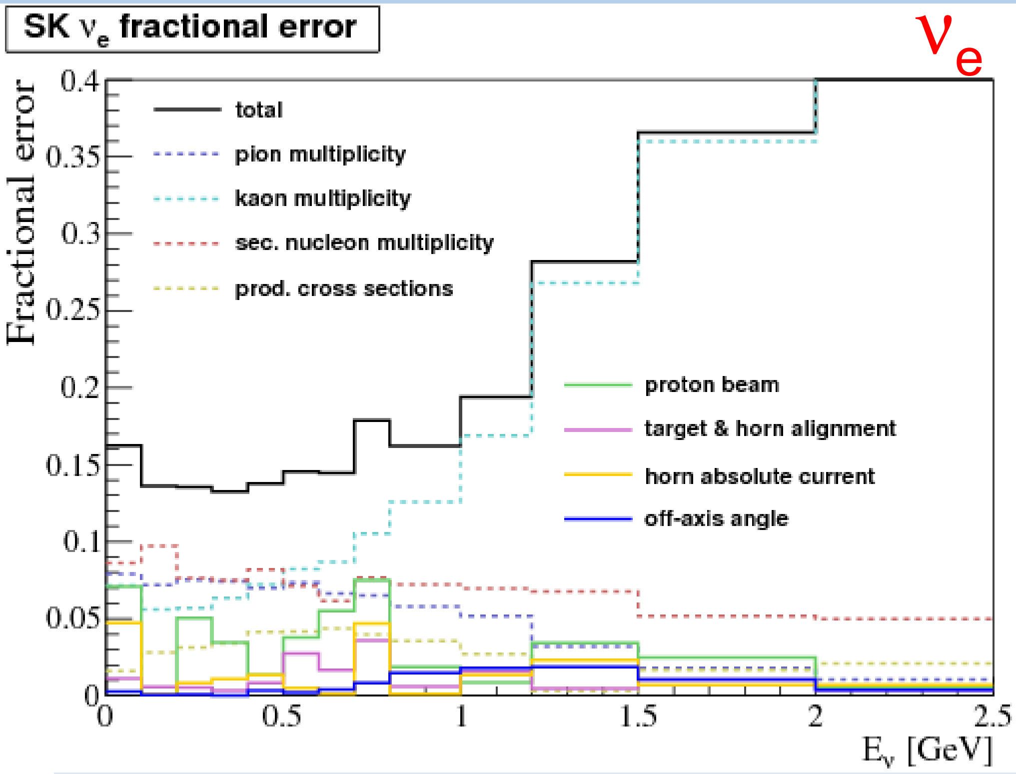
T2K neutrino flux uncertainties



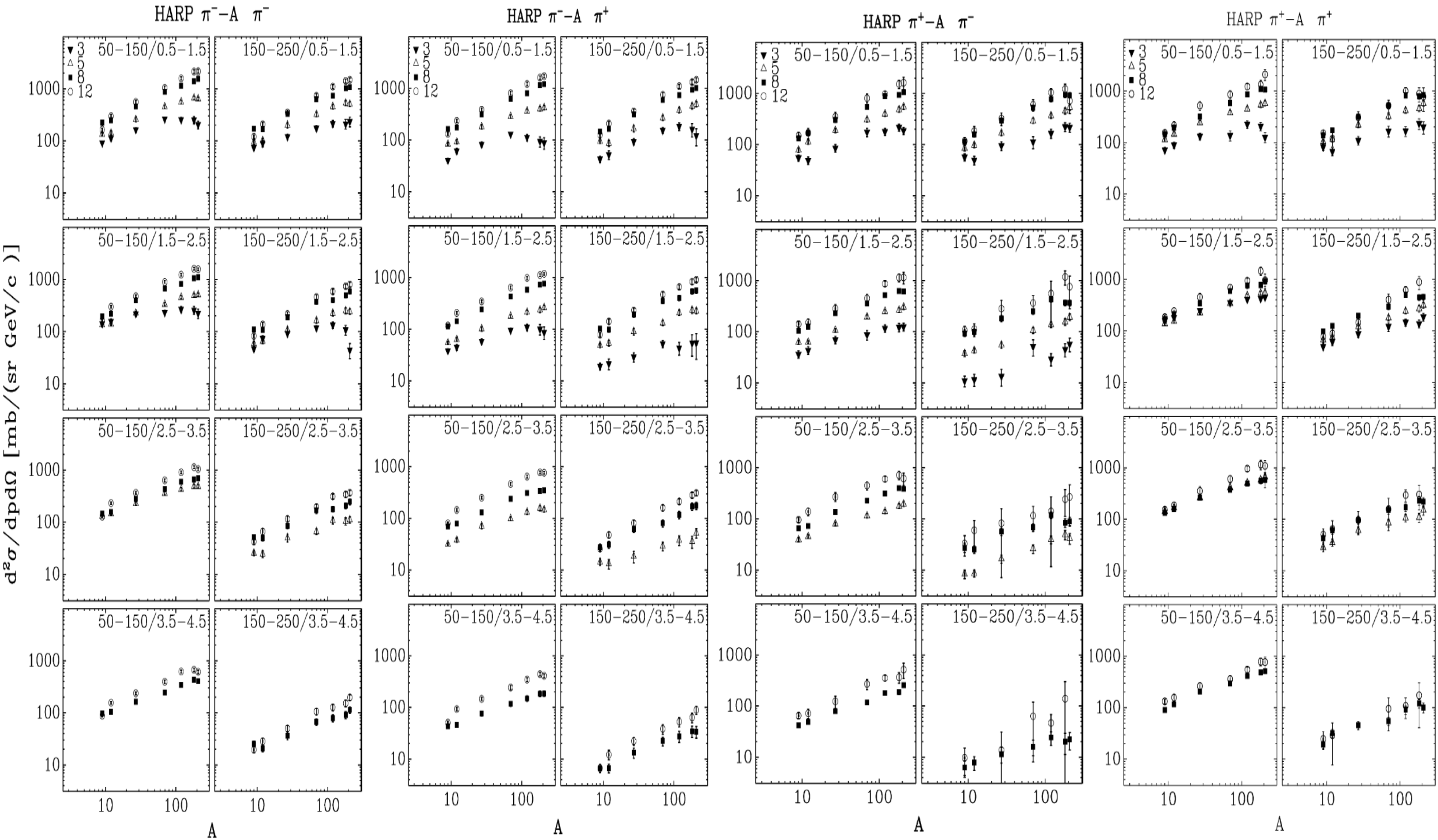


Fractional errors on the ν_μ and ν_e fluxes at the T2K far detector in the first published T2K analysis

PRL 107 (2011) 041801; PRD 85 (2012) 031103

Have recently been improved with the inclusion of the new NA61/SHINE K^+ measurements

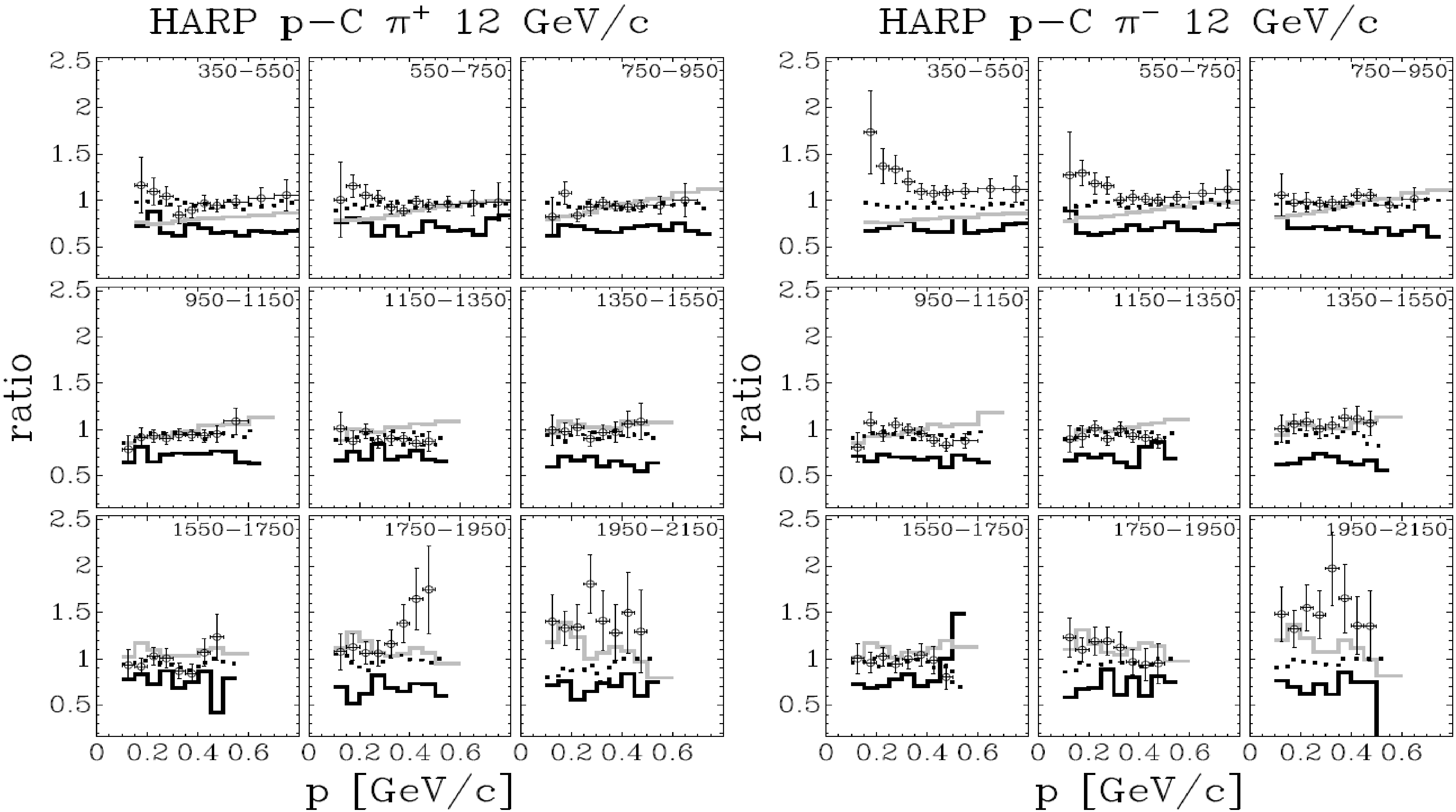
HARP : more FW pion data with incident pions



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: long target analyses



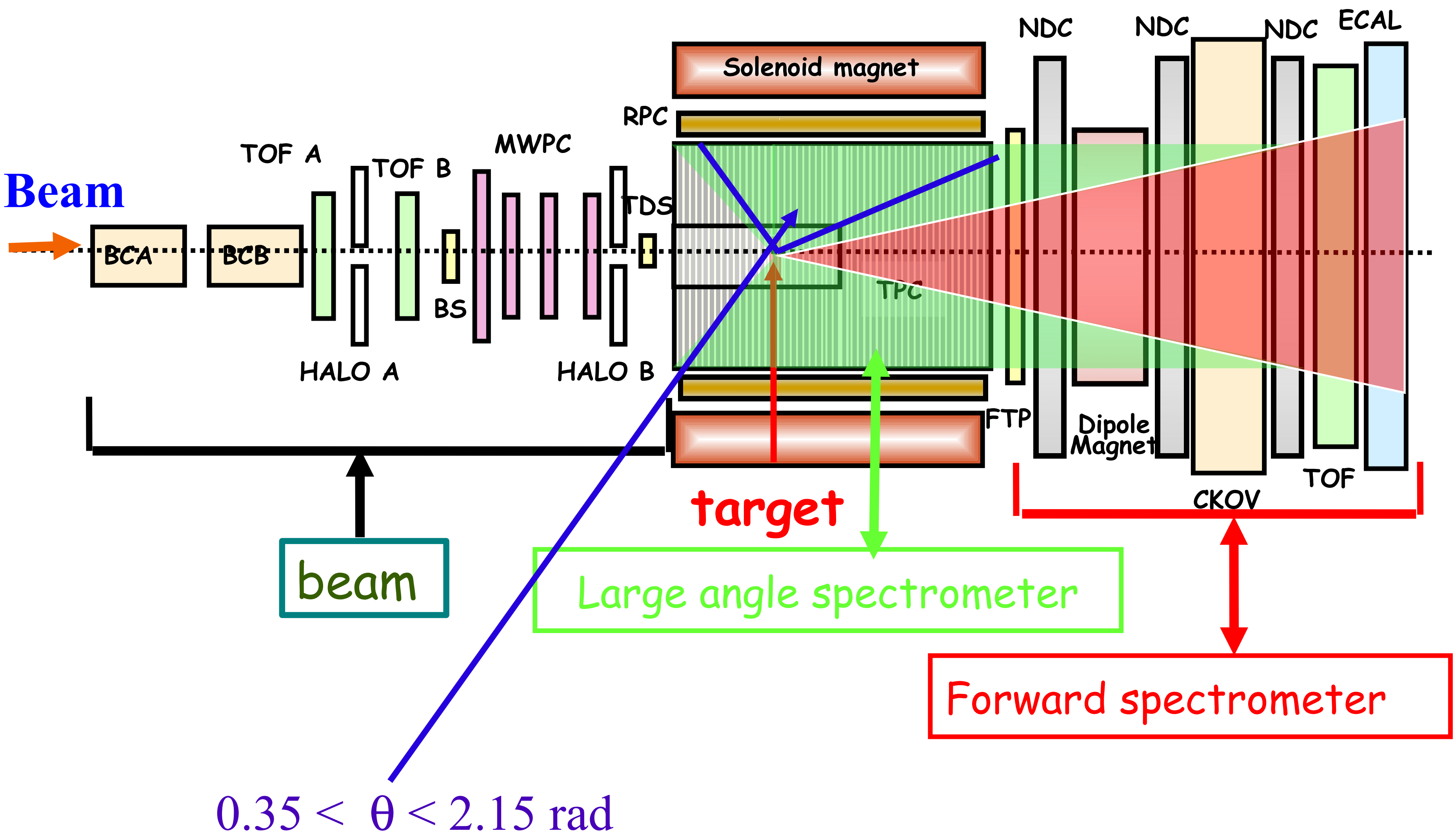
Ratio of charged pion yields in 100% λ over 5% λ Carbon target; solid line – MARS predictions; dotted line – ratio of pions produced by "first generation" beam proton to all pions in MARS grey line – GEANT4 (Bertini, QGSP) predictions.

Phys. Rev. C80 (2009) 065204

Analysis performed for C, Ta and Pb 100% λ targets for 5,8,12 GeV/c protons

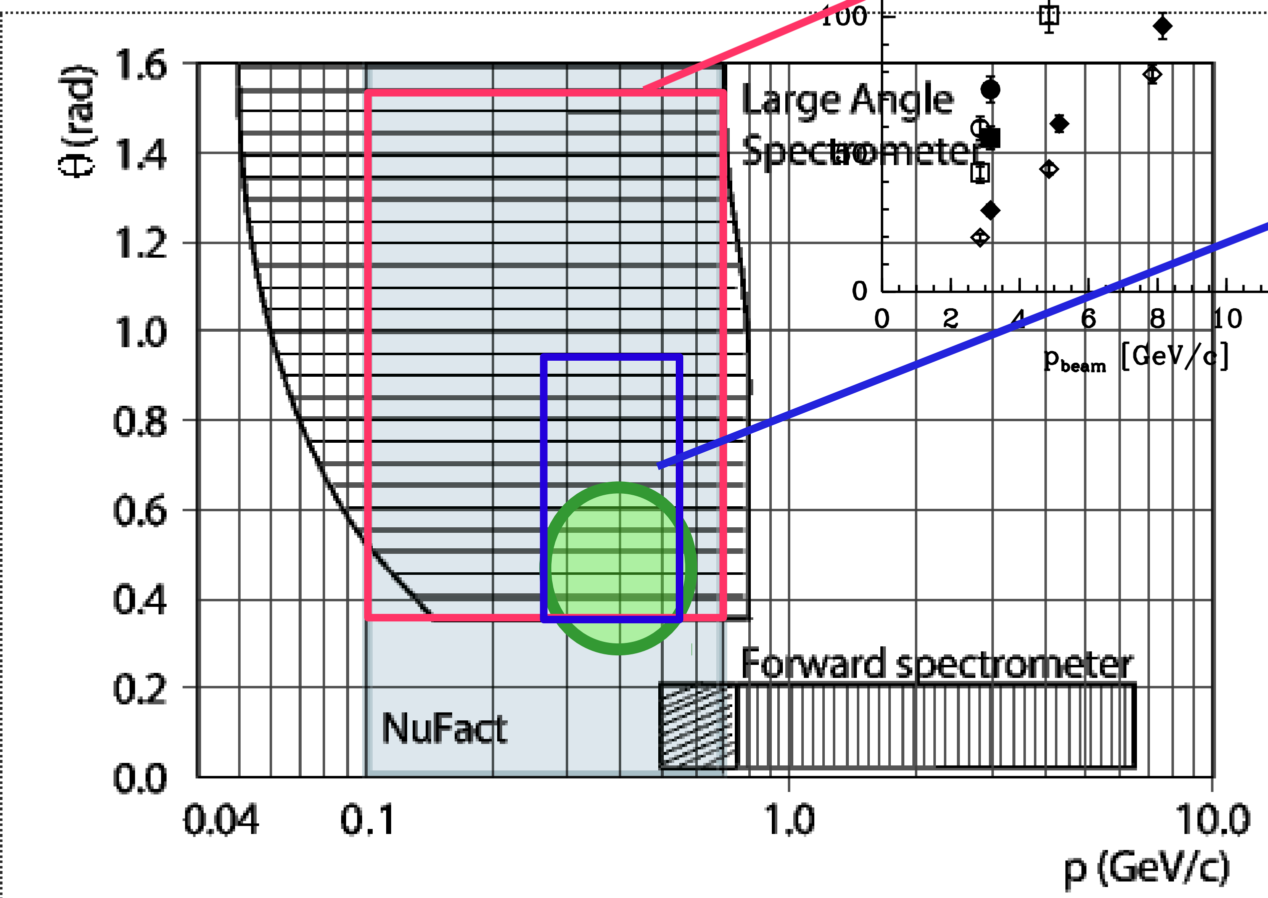
HARP: Analyses with the large angle spectrometer

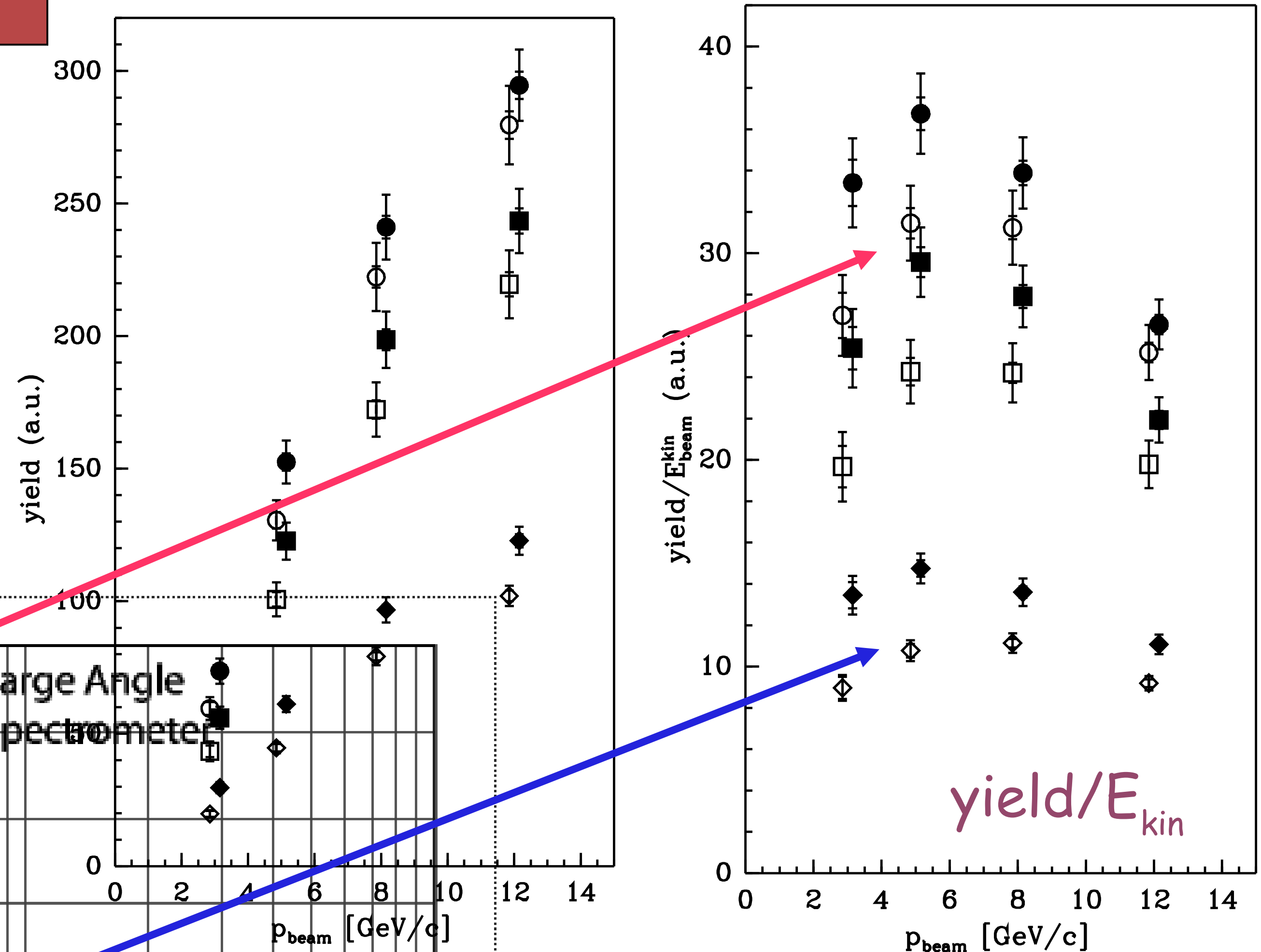
Large Angle (LA) spectrometer: TPC



Full statistics 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)

Neutrino factory study





π^- open symbols

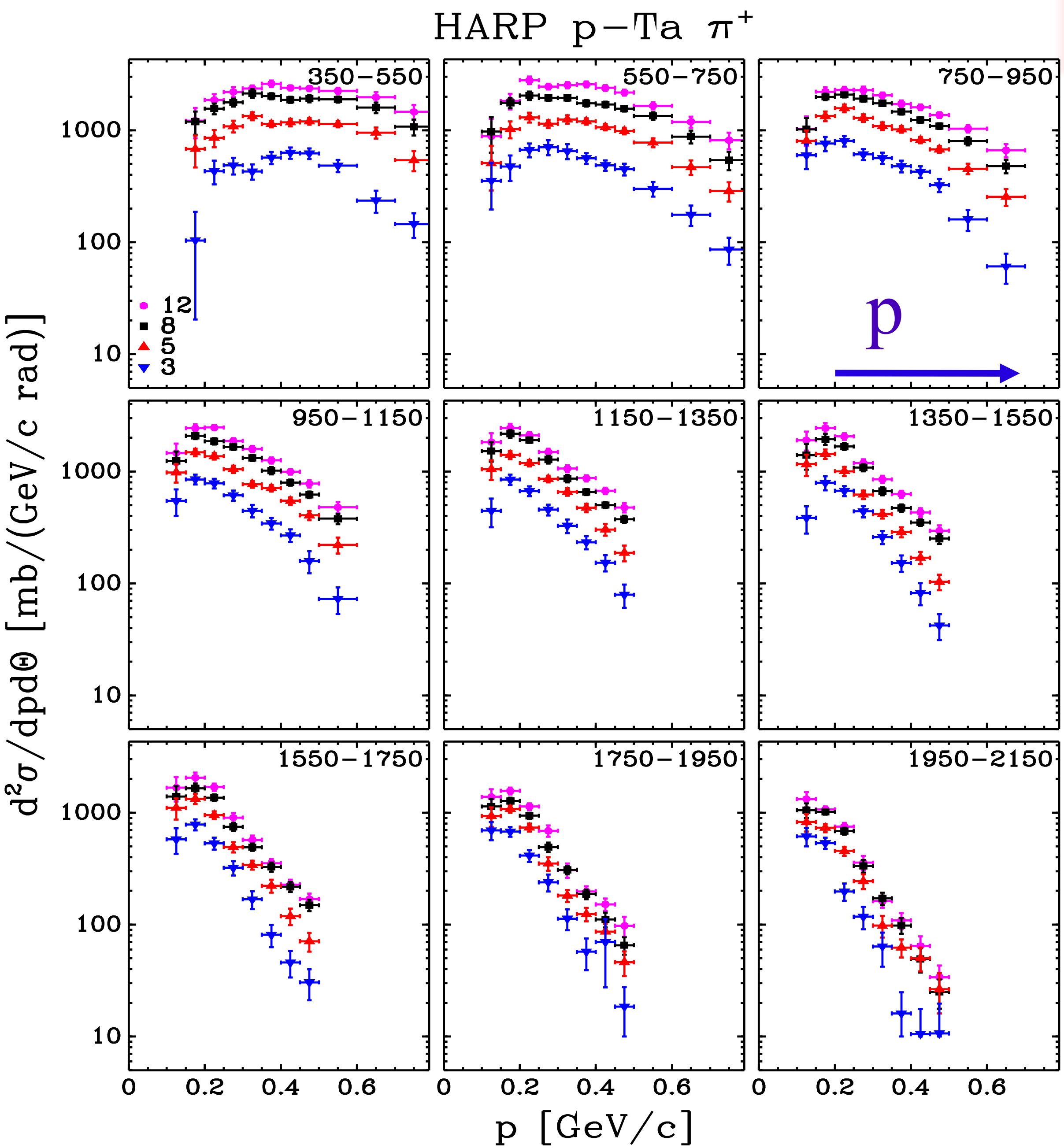
π^+ closed symbols

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

(*e.g. J.Strait et al., Phys. Rev. ST Accel. Beams 13 (2010) 111001; X.Ding et al., ibid 14 (2011) 111002*)

9 angular bins: p-Ta π^+

Pion production yields



stat. and syst. errors combined

forward
350 < θ (mrad) < 1550

backward
1550 < θ (mrad) < 2150

EPJ C 51 (2007) 787

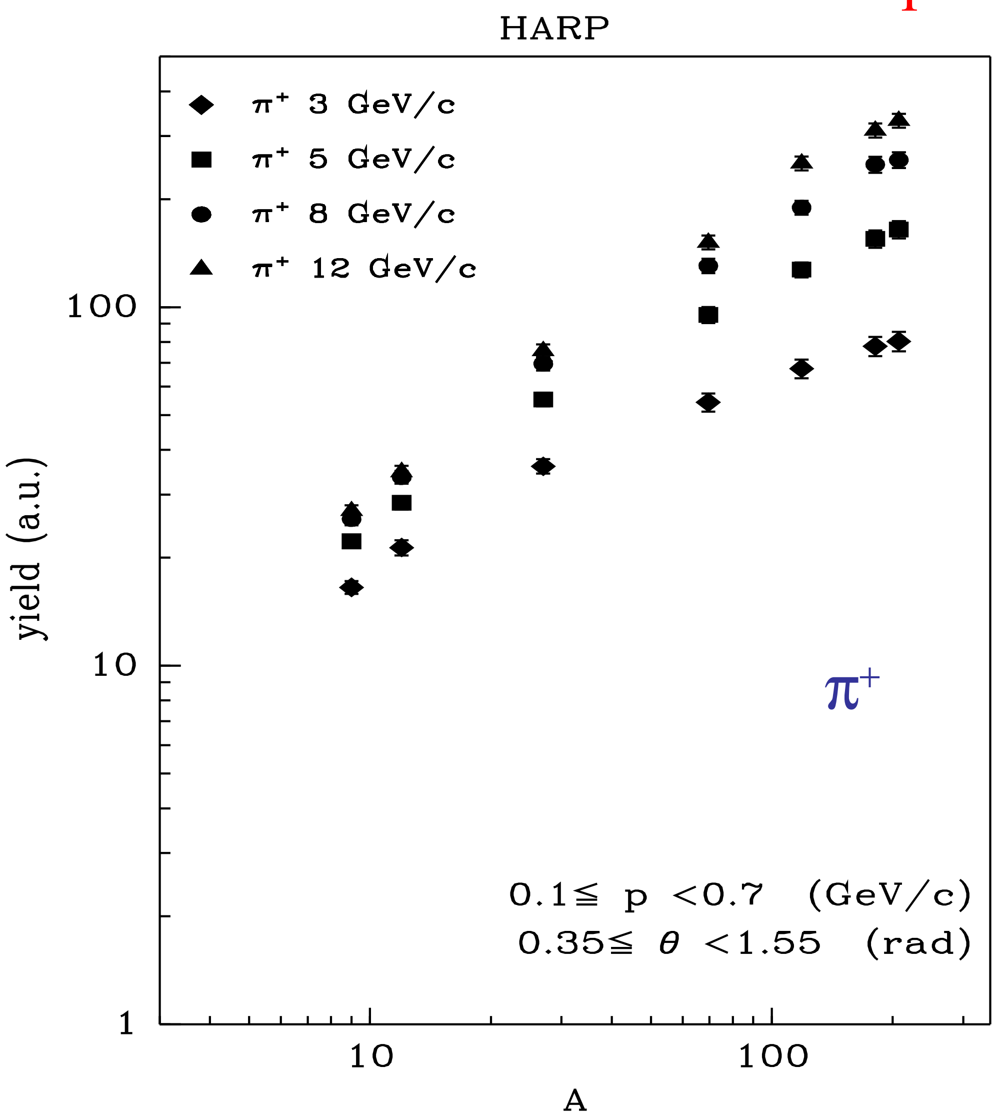
momentum range 0.1 < p < 0.8 GeV/c

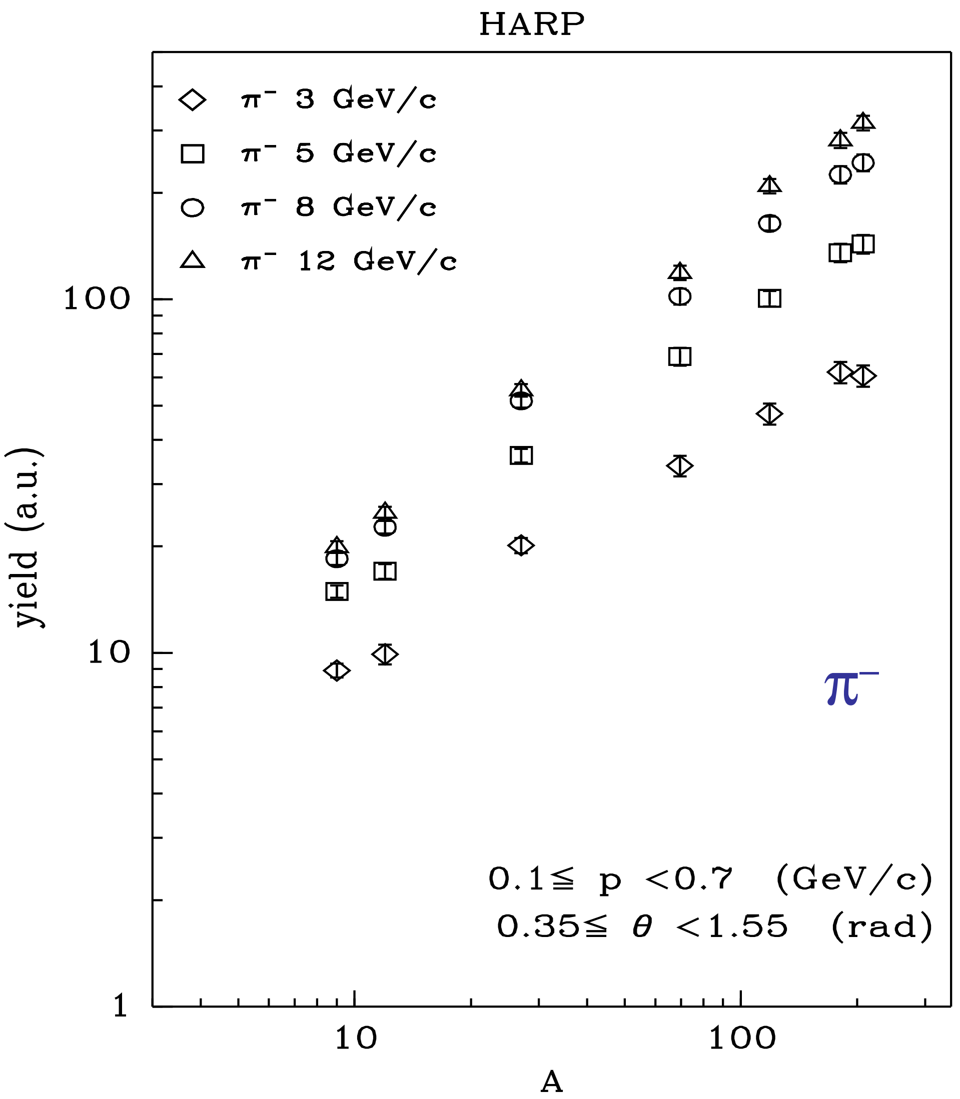
Pion yields

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

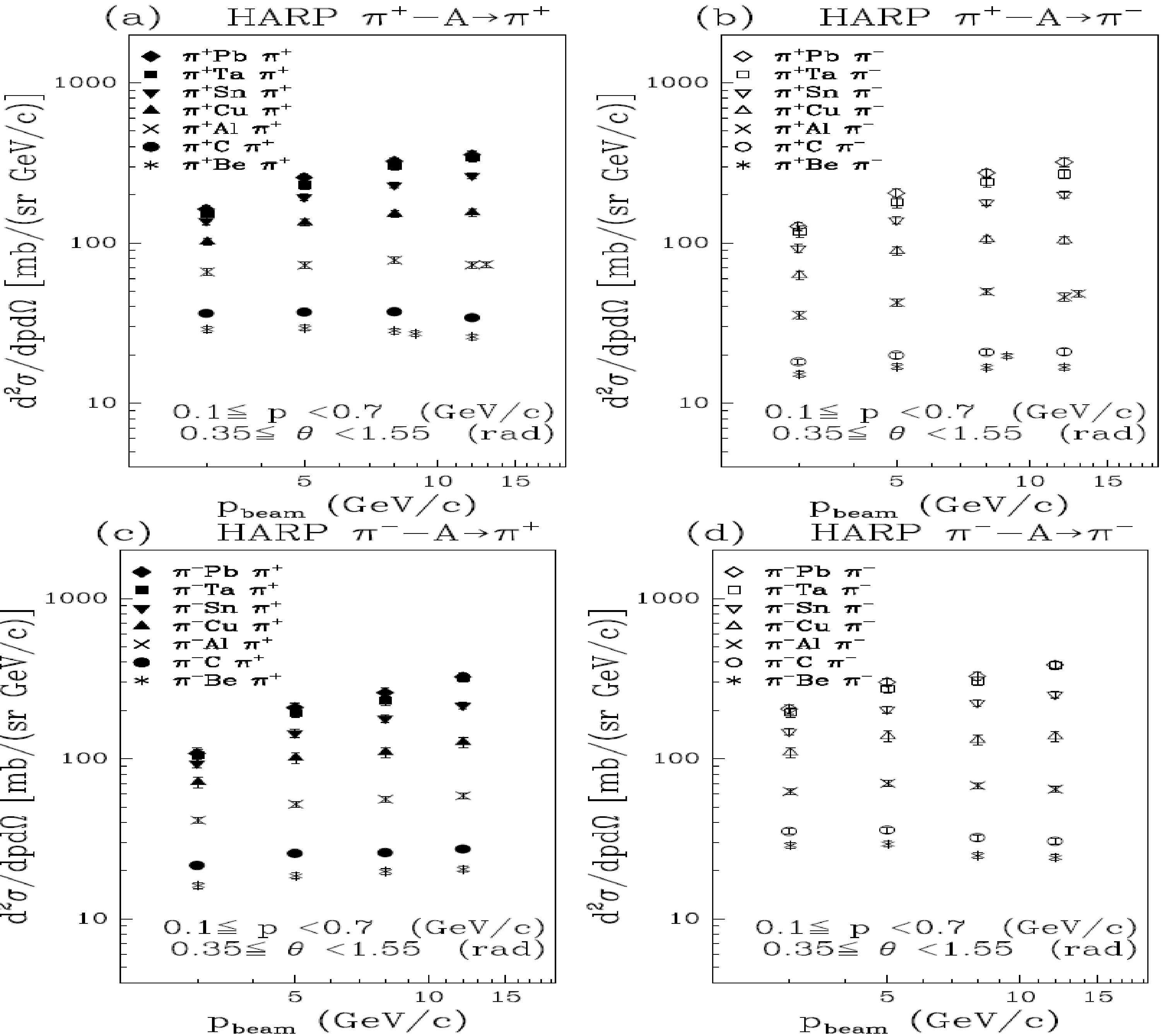




Phys. Rev. C 77 (2008) 055207

Measured with the same detector!

HARP: LA data with incoming pion beams



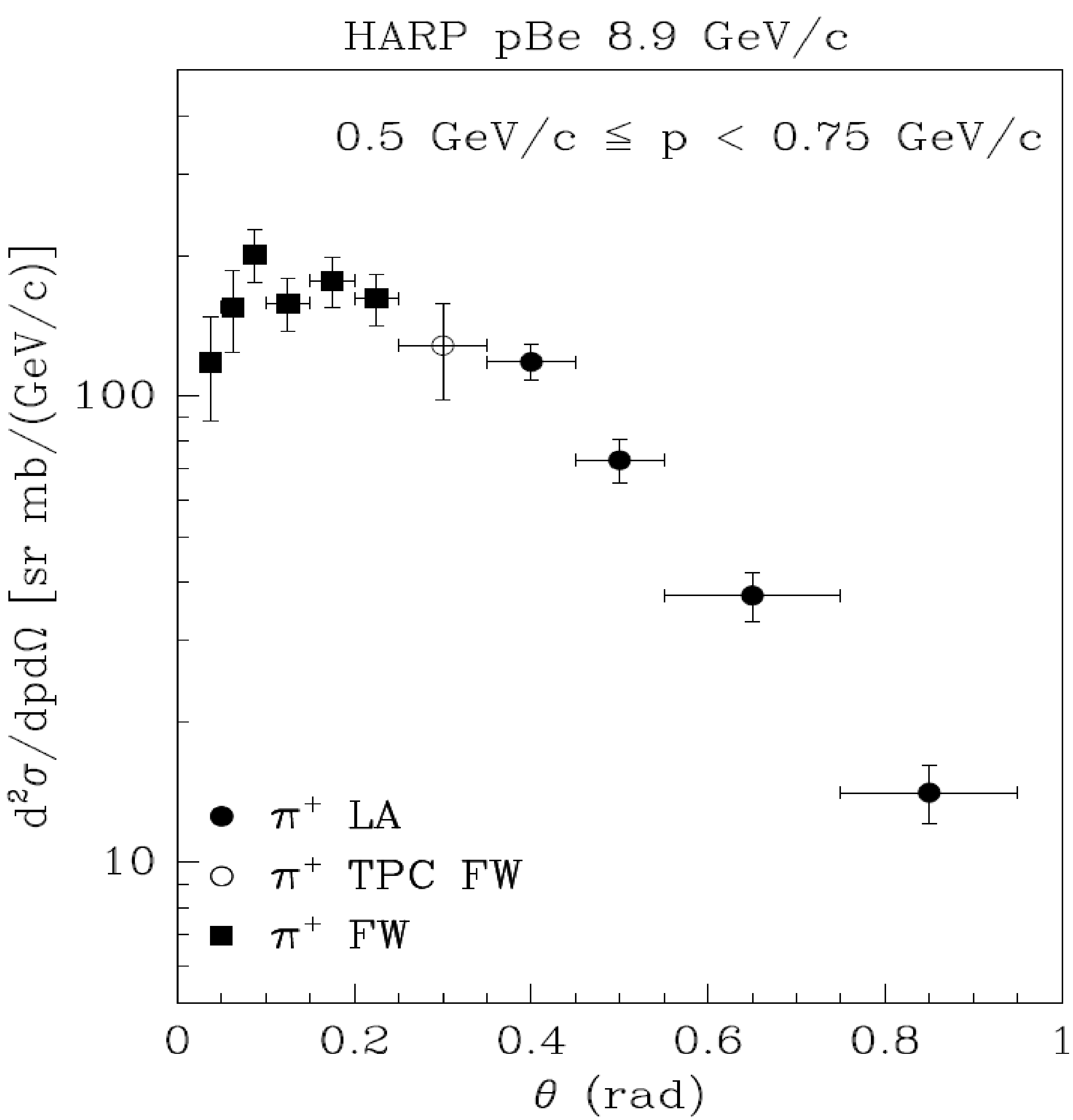
Similar measurements of the $\pi^{\pm}$ production for all available targets have been performed using beams of incident $\pi^{\pm}$

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)

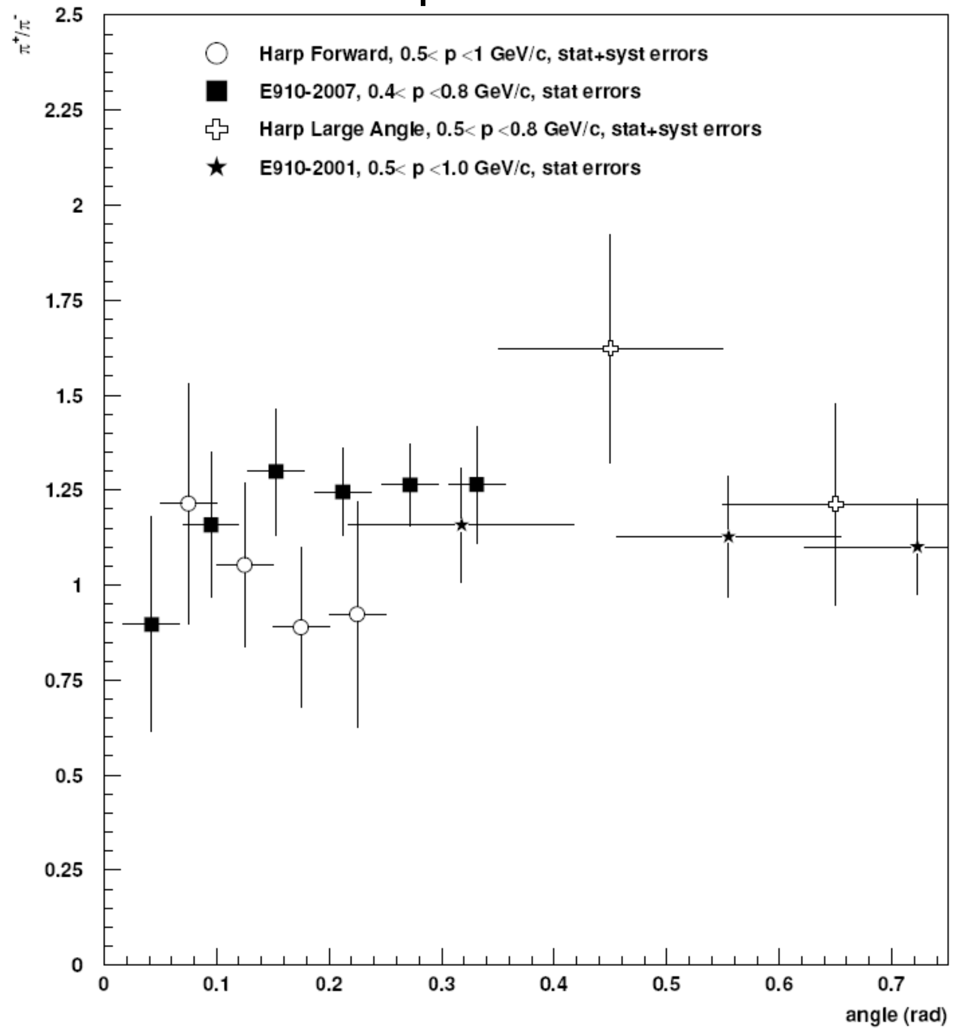
Phys. Rev. C80 (2009) 065207

forward production $0.35 < \theta < 1.55$ rad

HARP: two spectrometers match each other



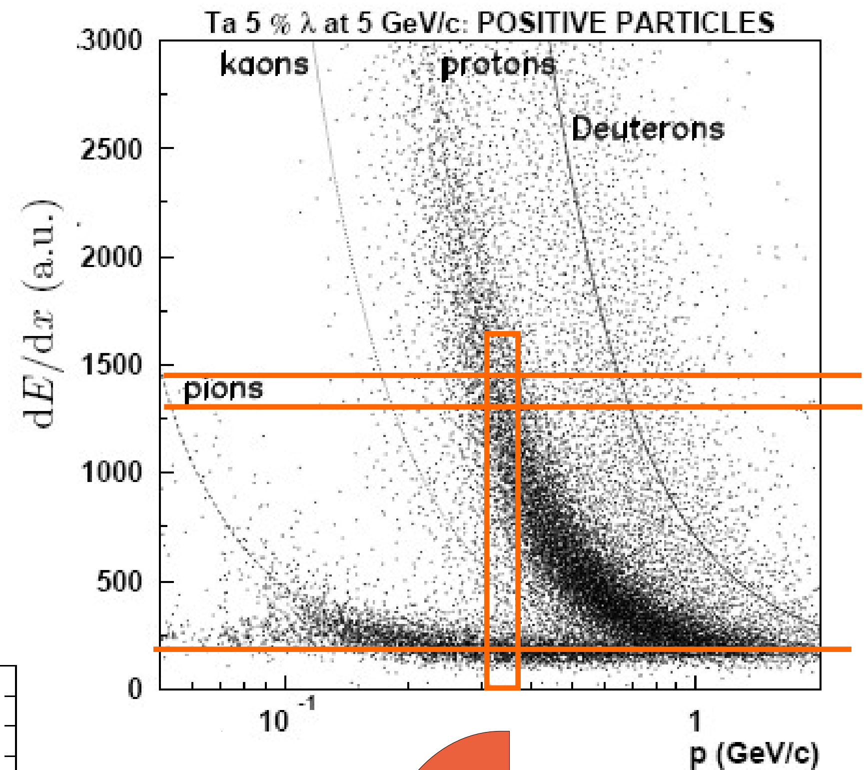
π⁺ / π⁻ ratio in pBe at 12 GeV/c

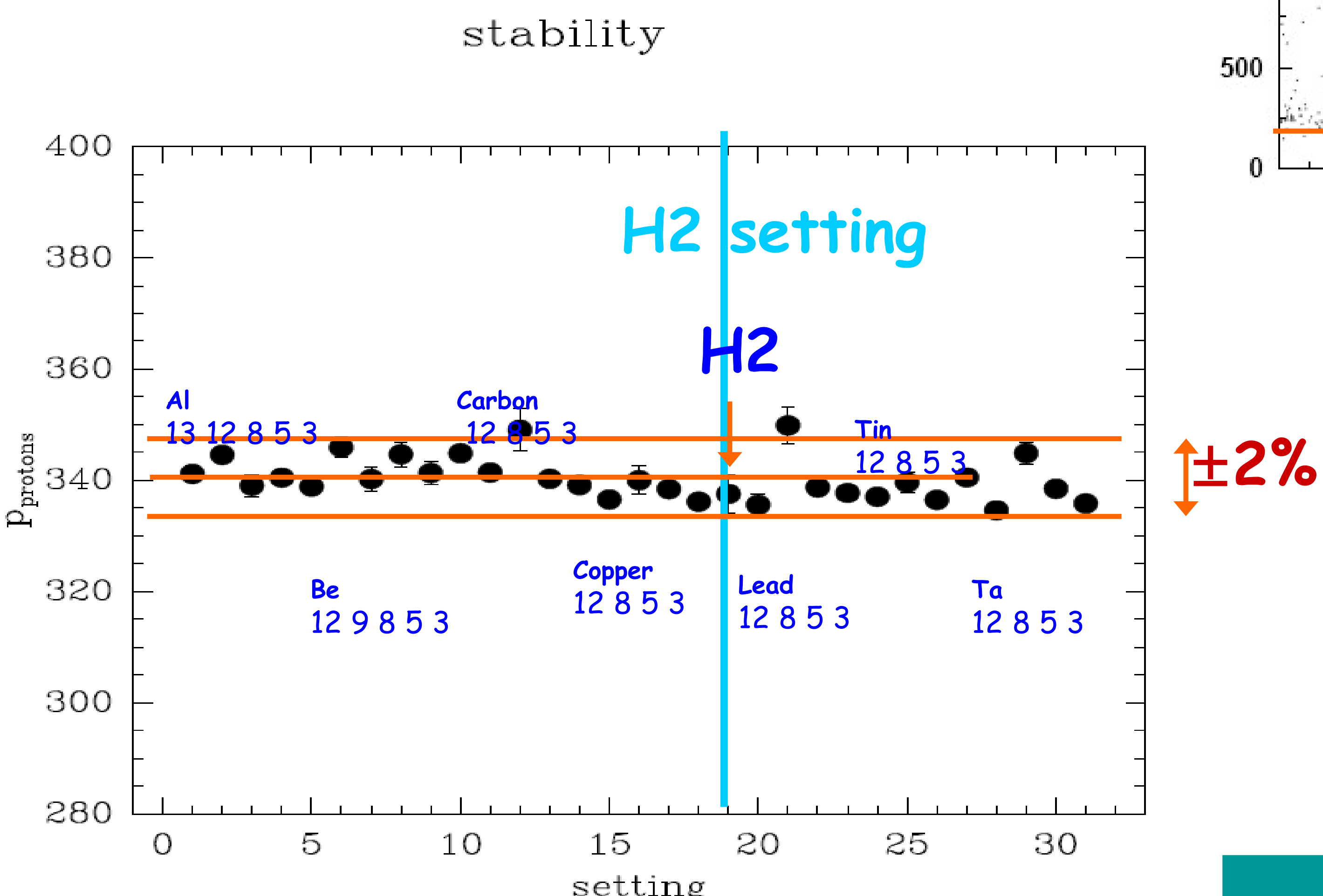


CERN-SPSC-2008-030 / SPSC-SR-038

Stability from LH2 target to other targets

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





JINST 3: P04007 (2008)