Prospects for better hadron production measurements with NA61/SHINE at CERN SPS

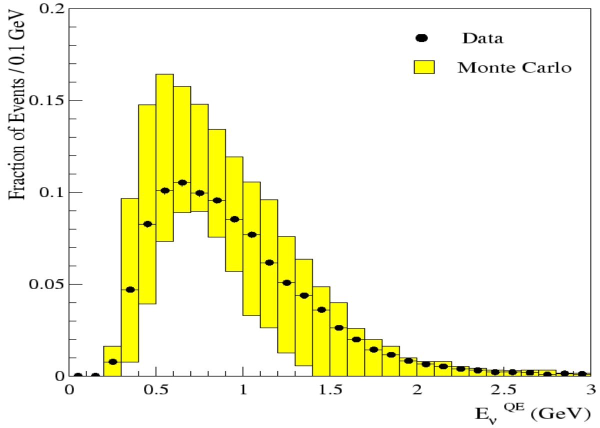
Nuclear physics for Galactic Cosmic Rays in the AMS-02 era,

LPSC, Grenoble, 3-4 December, 2012

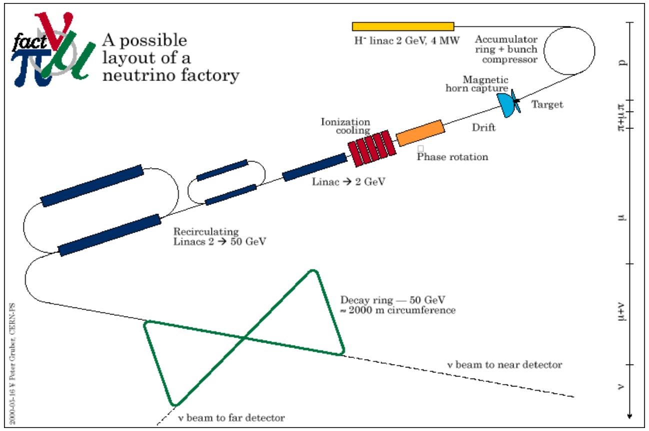
Boris A. Popov (LPNHE, Paris & JINR, Dubna)
for the NA61/SHINE collaboration

- Goals of hadroproduction experiments
- NA61/SHINE detector
- First physics results
- Status and plans

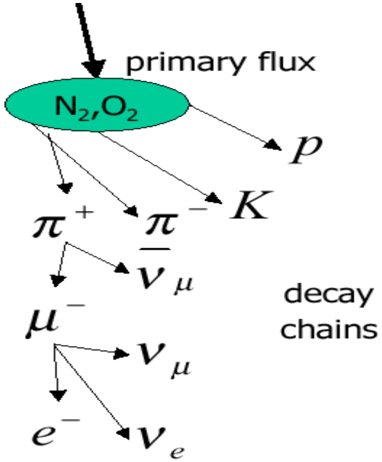
Goals of hadroproduction studies



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

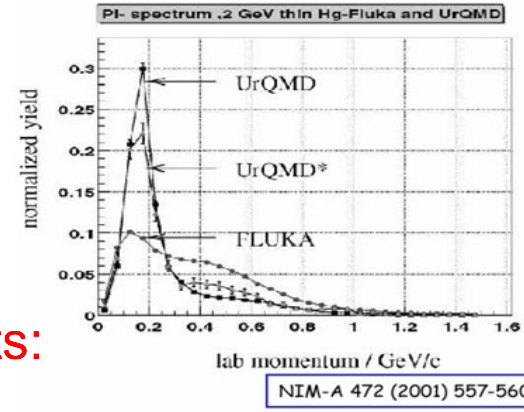


Pion/Kaon yield for the design of the proton driver and target system of **Neutrino Factories** and **Super-Beams**



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 (GEANT4 and others)



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

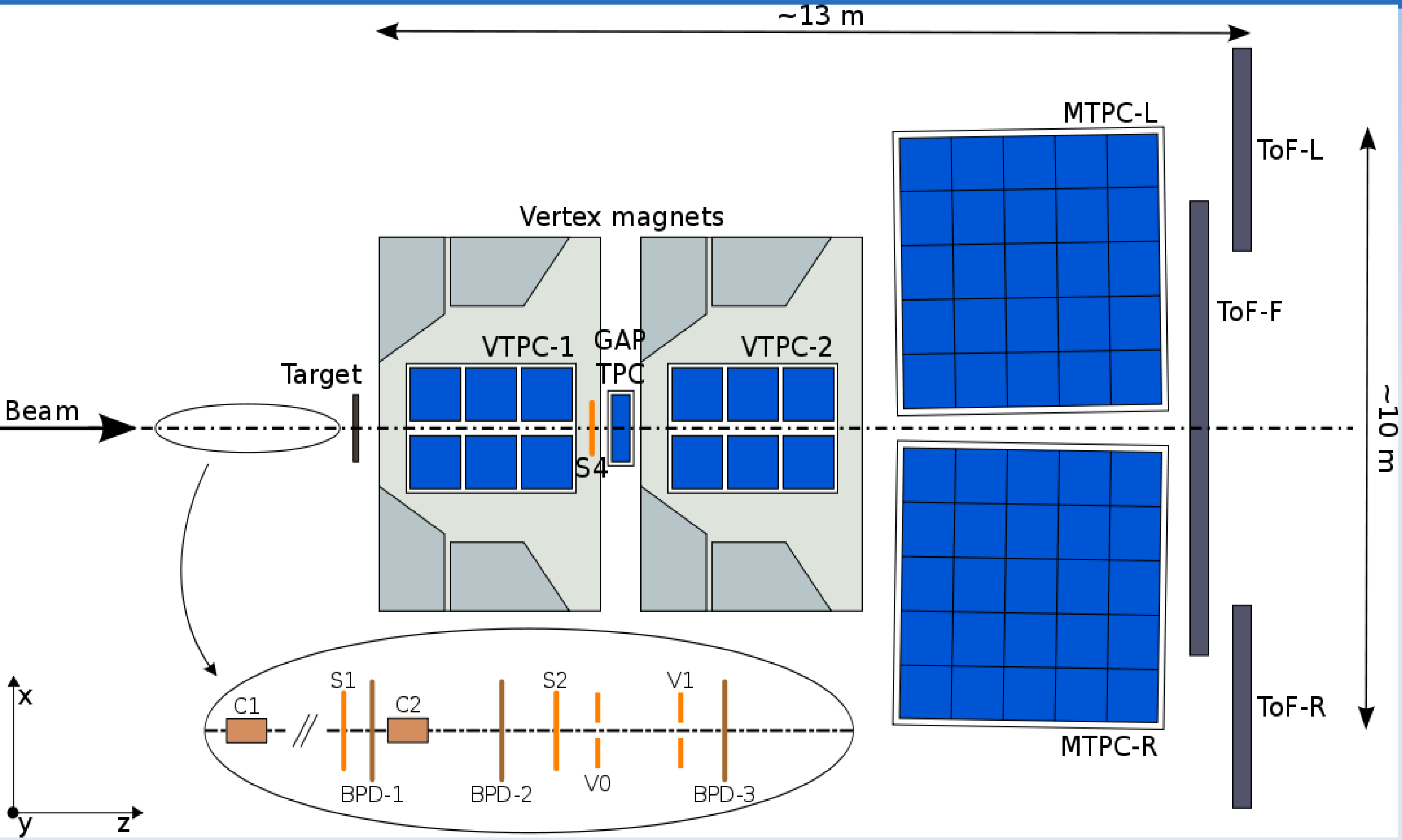
NA61/SHINE physics goals

SHINE = SPS Heavy Ion and Neutrino Experiment

- Hadron production reference measurements for accelerator neutrino (T2K,Fermilab,LBNO?) 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 measurments

NA61/SHINE: recorded (h + A) data

Reaction	p [GeV/c]	Year	$N_{triggers}$ [10^6]
p+C	31	2007	0.7
p+RT	31	2007	0.2
p+C	31	2009	5.4
p+RT	31	2009	2.
p+RT	31	2010	10.
π^-+C	158	2009	5.5
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
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: 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.

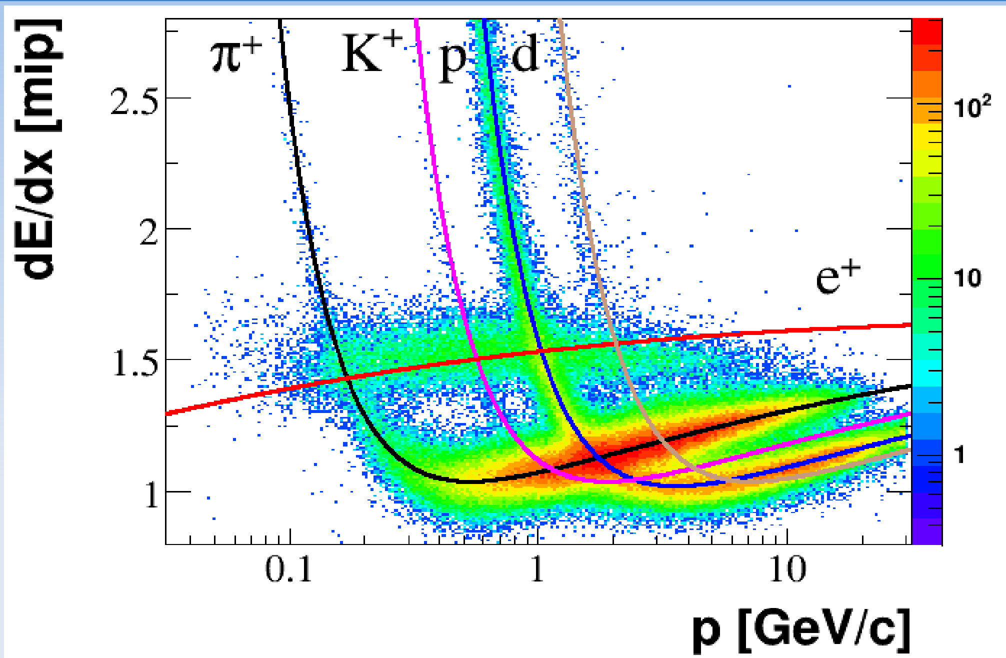
- Combined dE/dx + ToF analysis ($\pi^\pm$,$K^\pm$,p): yields fitted to 2-dimensional m^2 vs dE/dx distributions.

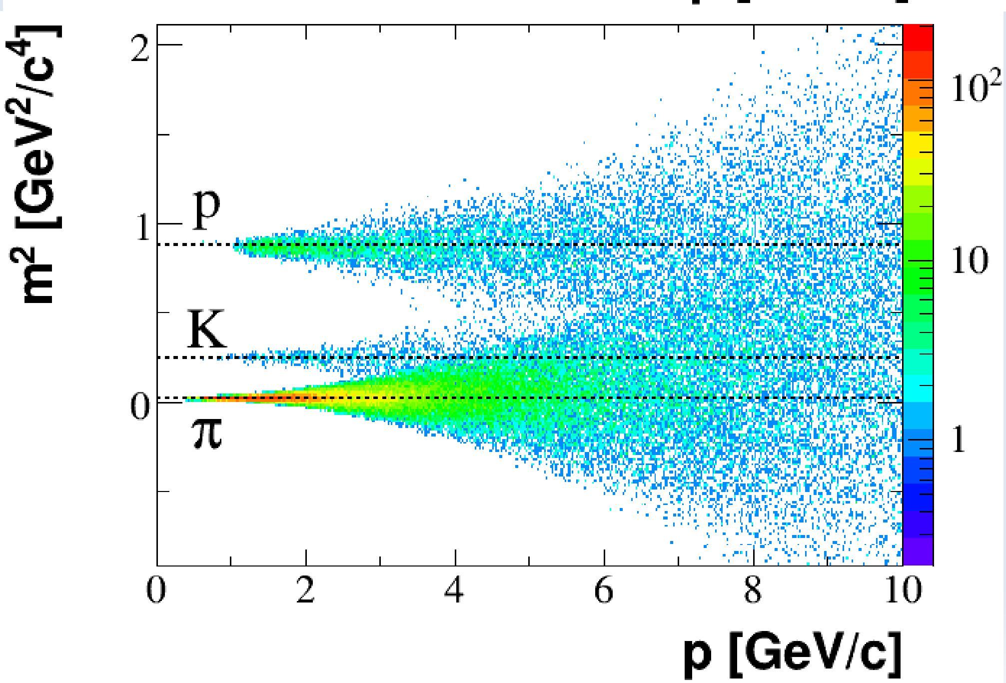
  Corrected spectra above 1 GeV/c in momentum.

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

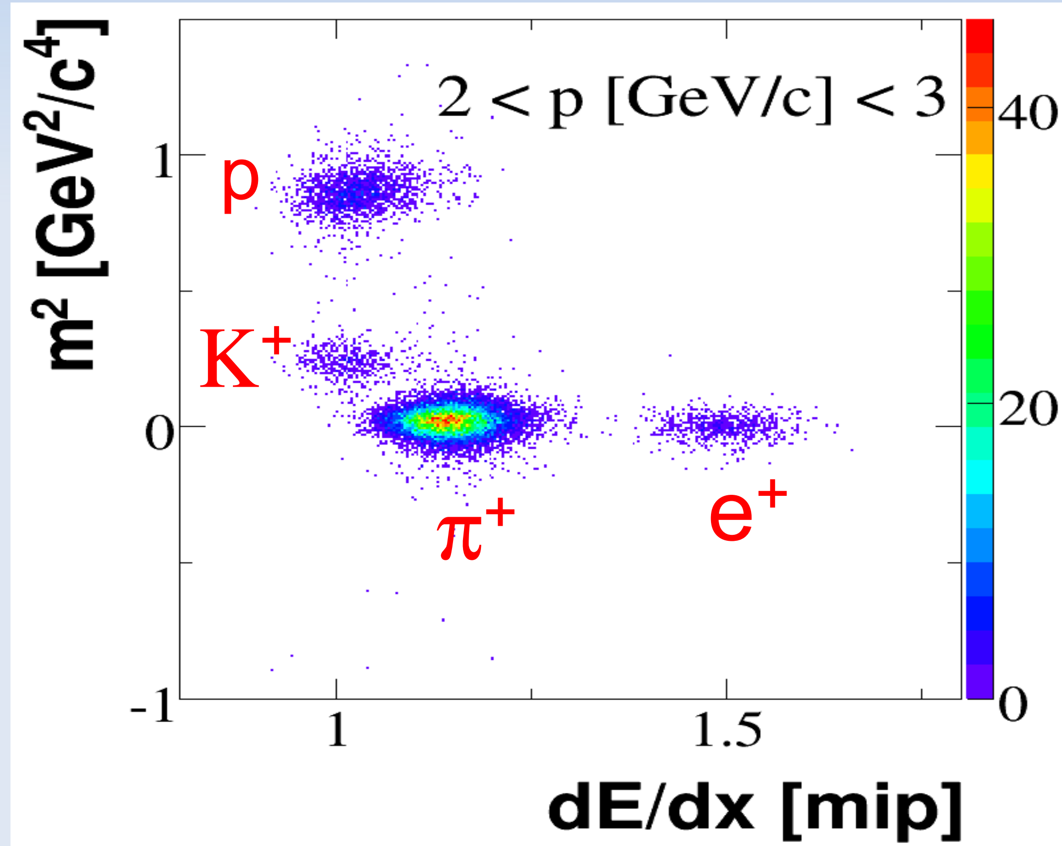
Phys. Rev. C84 (2011) 034604

NA61/SHINE PID capabilities

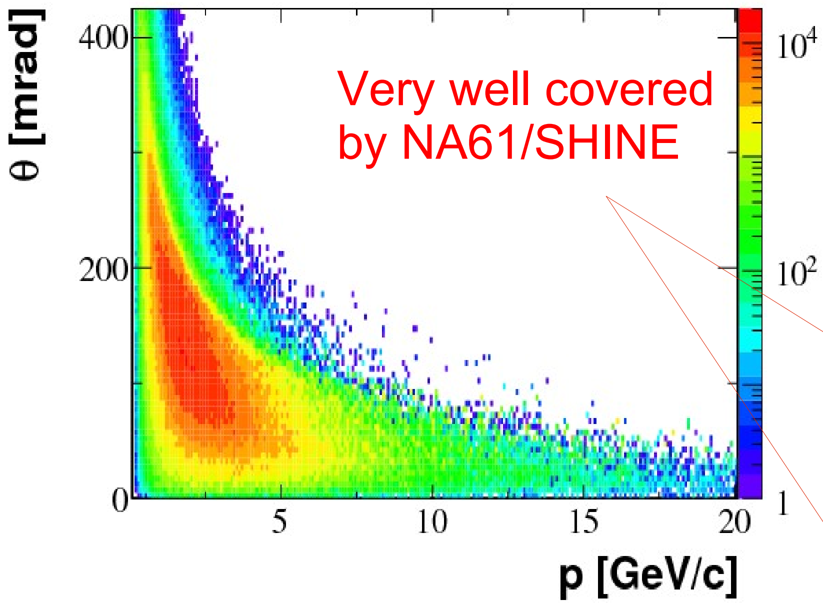




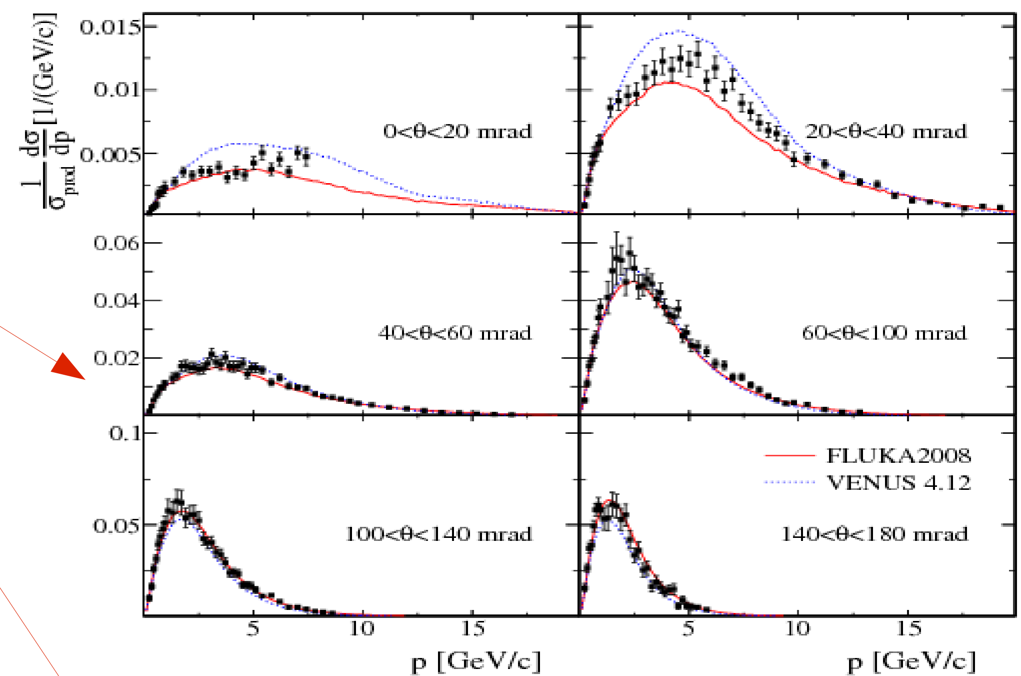
Combined dE/dx + ToF identification for positively charged particles

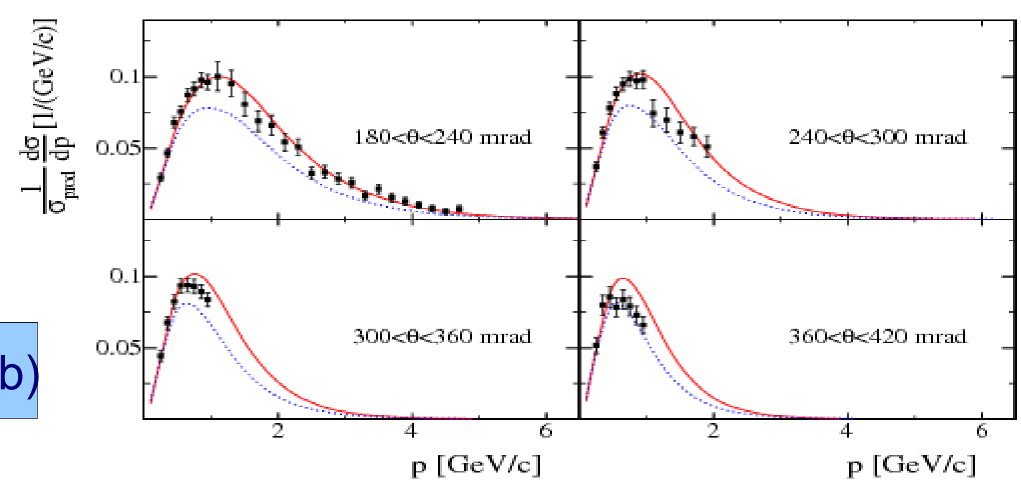


NA61/SHINE p+C@31GeV/c: π^+ (& π^-) results



π^+





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

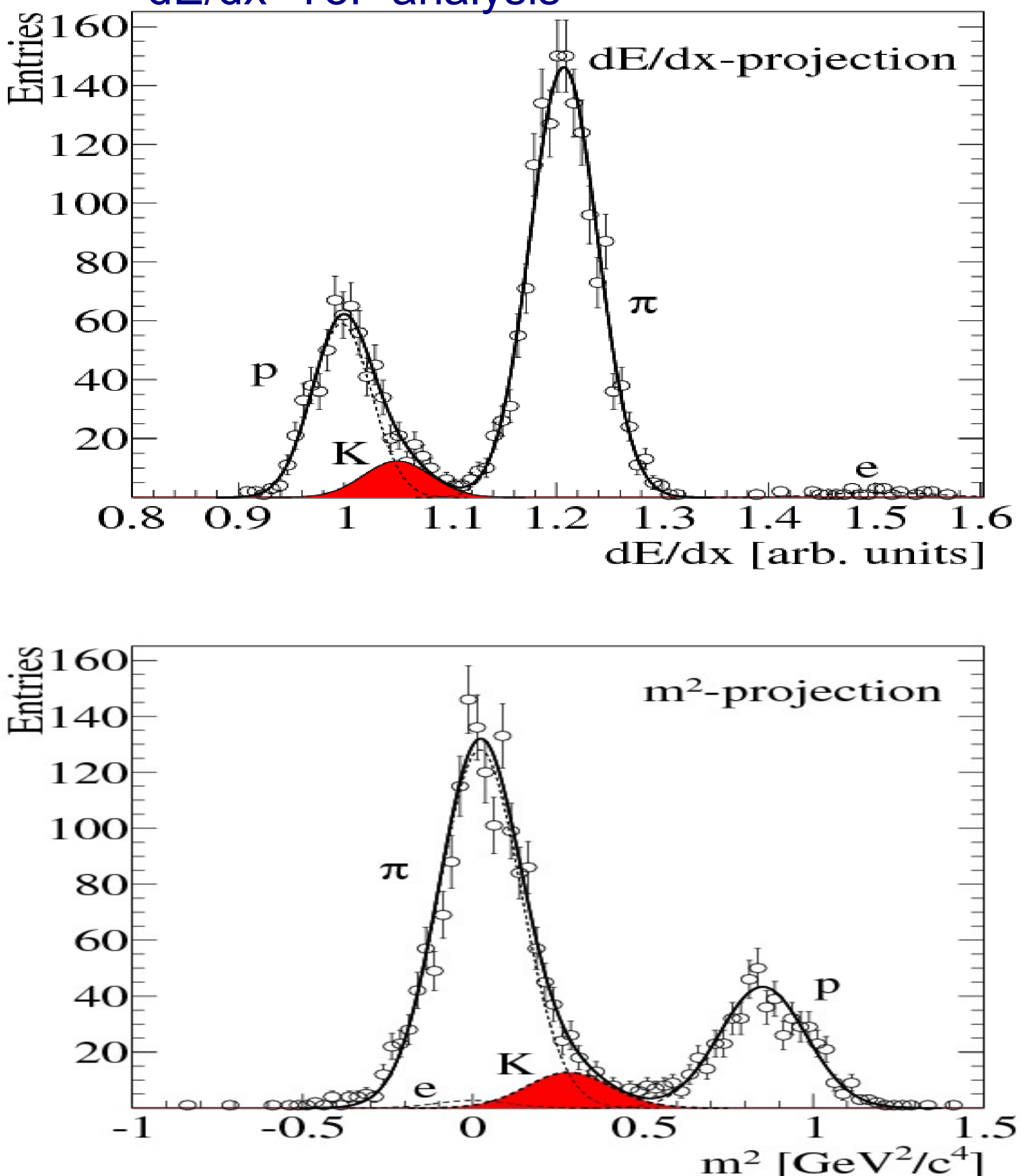
NA61/SHINE measurements

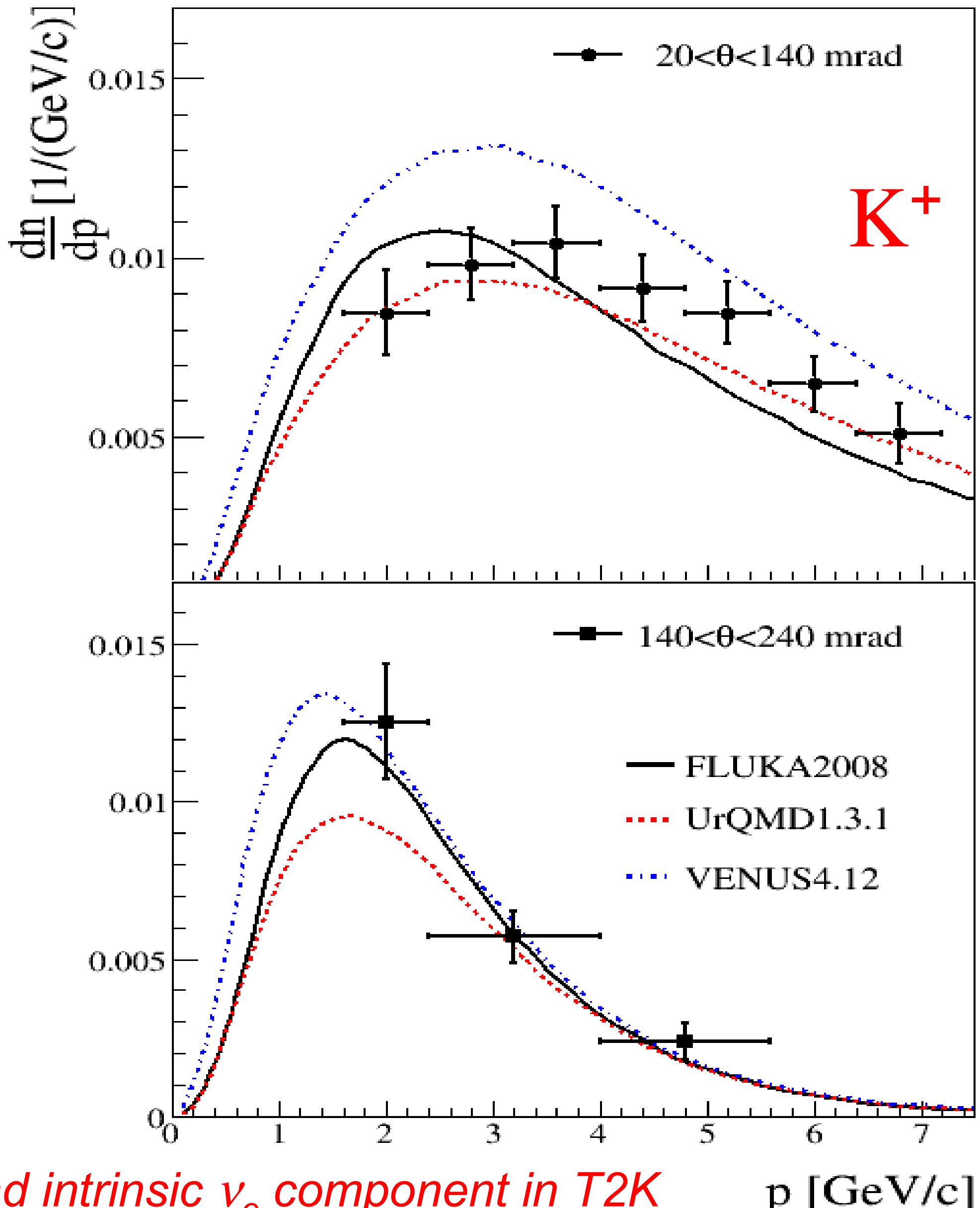
σ_{prod} (pC@31GeV/c)= 229.3 ± 1.9 ± 9.0 (mb)

Phys. Rev. C84 (2011) 034604

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

dE/dx+ToF analysis

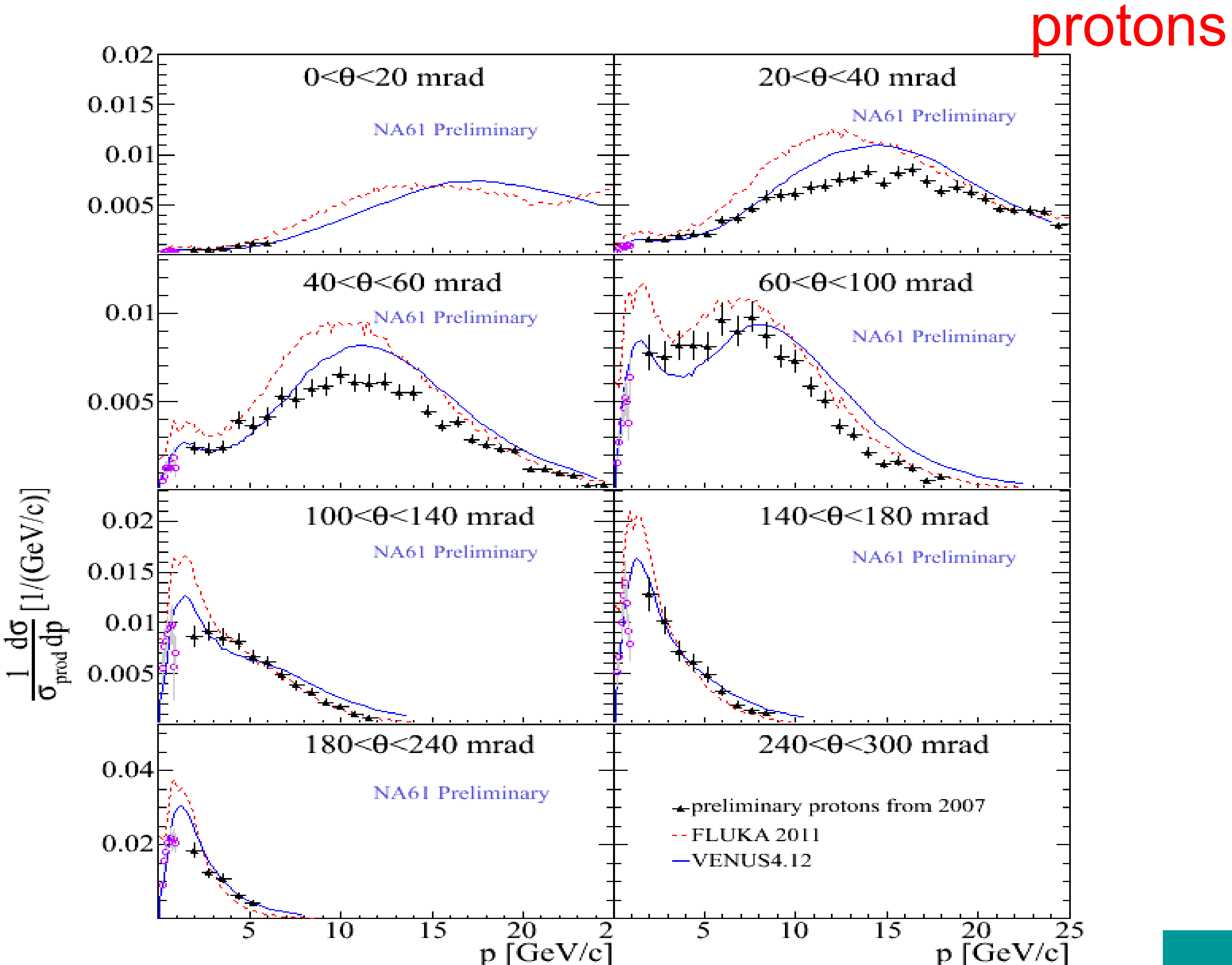




Relevant for high energy tail of ν_μ spectrum and intrinsic ν_e component in T2K

Phys. Rev. C85 (2012) 035210

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

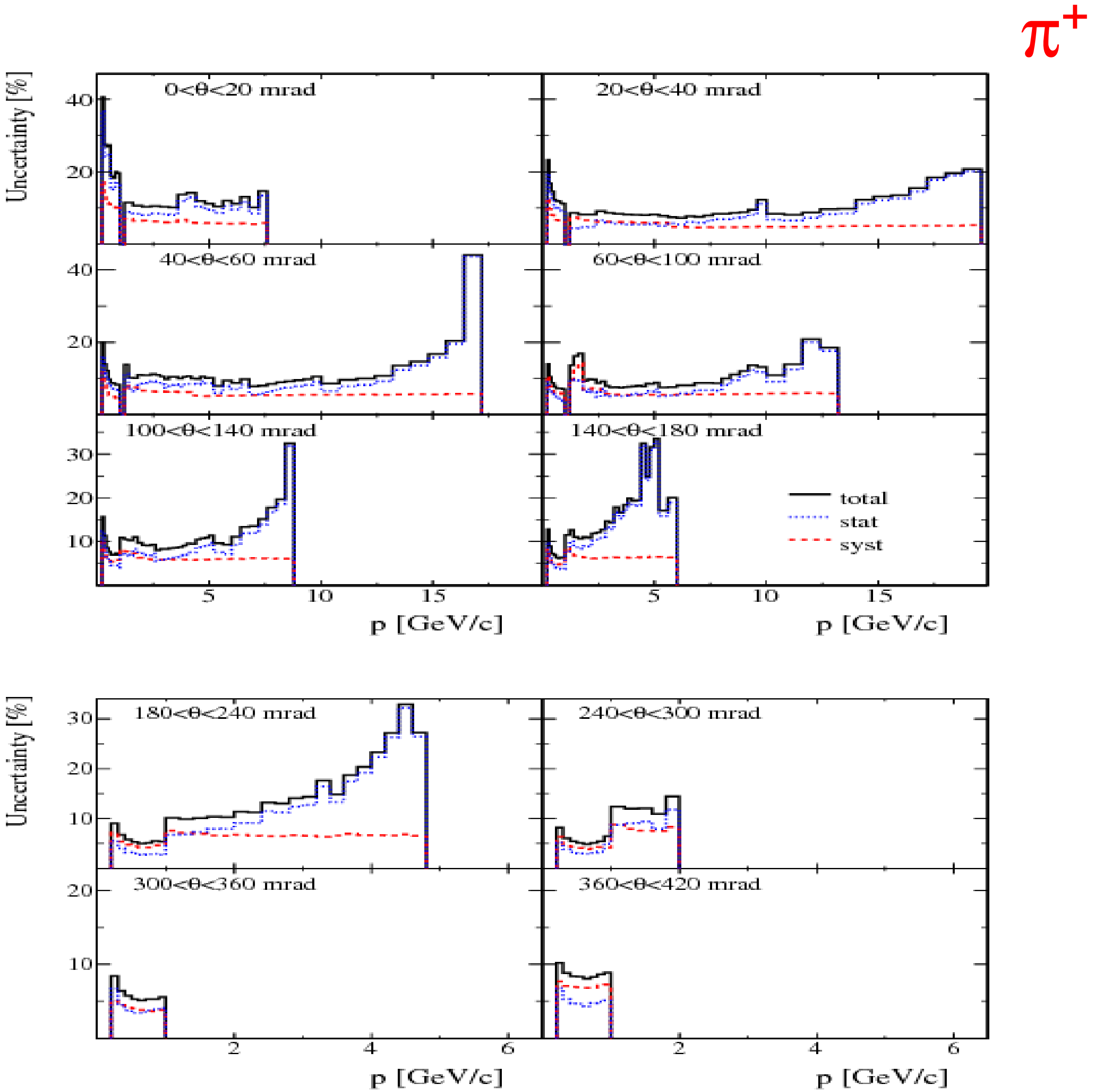


Preliminary results from 2007 data

CERN-SPSC-2012-029

M.Posiadala, PhD thesis, Univ. of Warsaw, 2012; S.Murphy, PhD thesis, Univ. of Geneva, 2012

NA61/SHINE p+C@31GeV/c: stat vs syst errors



In 2007 data analysis statistical errors dominate.

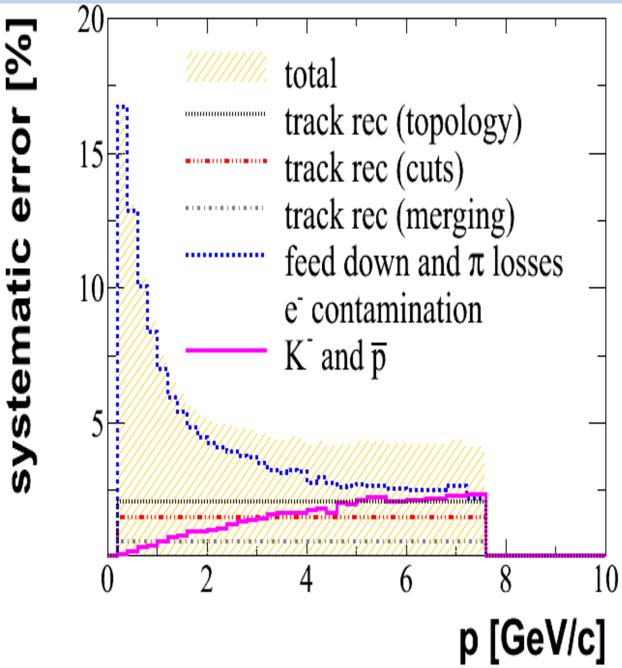
With 2009 data we hope to reduce statistical errors by a factor of 3.

Systematic errors will become more important

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

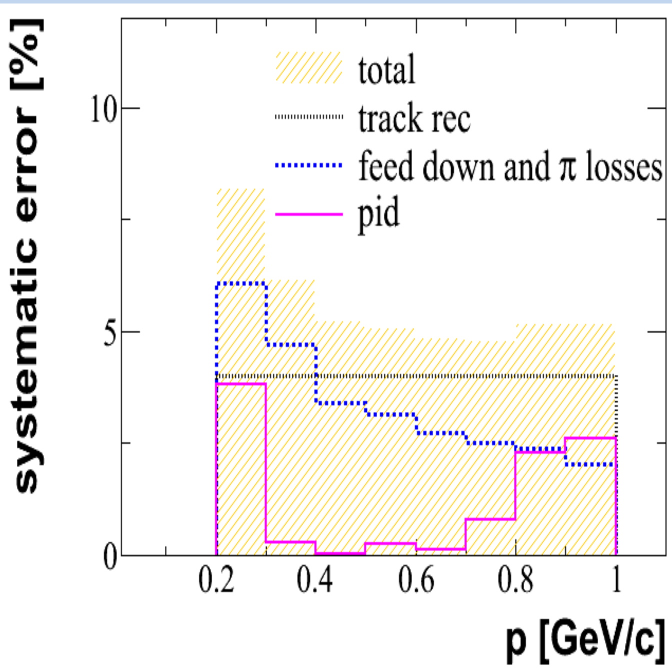
h- analysis

π^- θ=[140,180] mrad



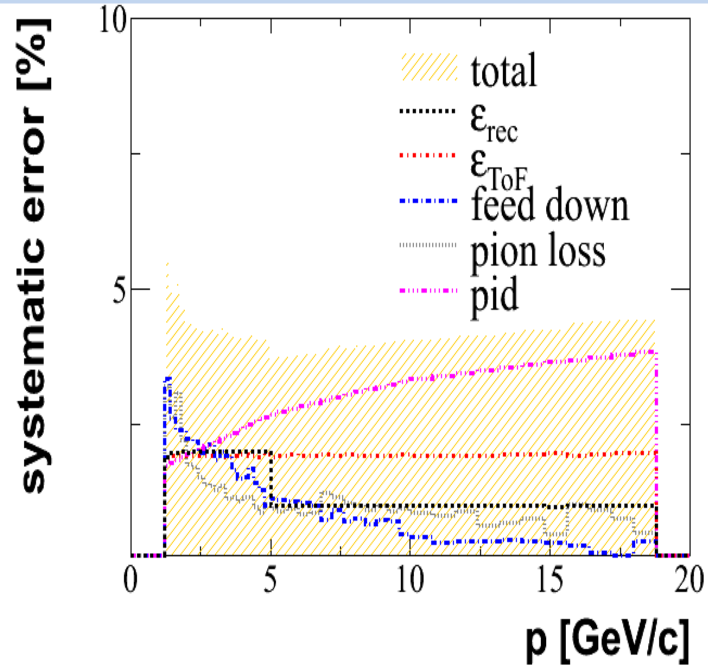
dE/dx analysis

π^+ θ=[140,180] mrad



dE/dx+ToF analysis

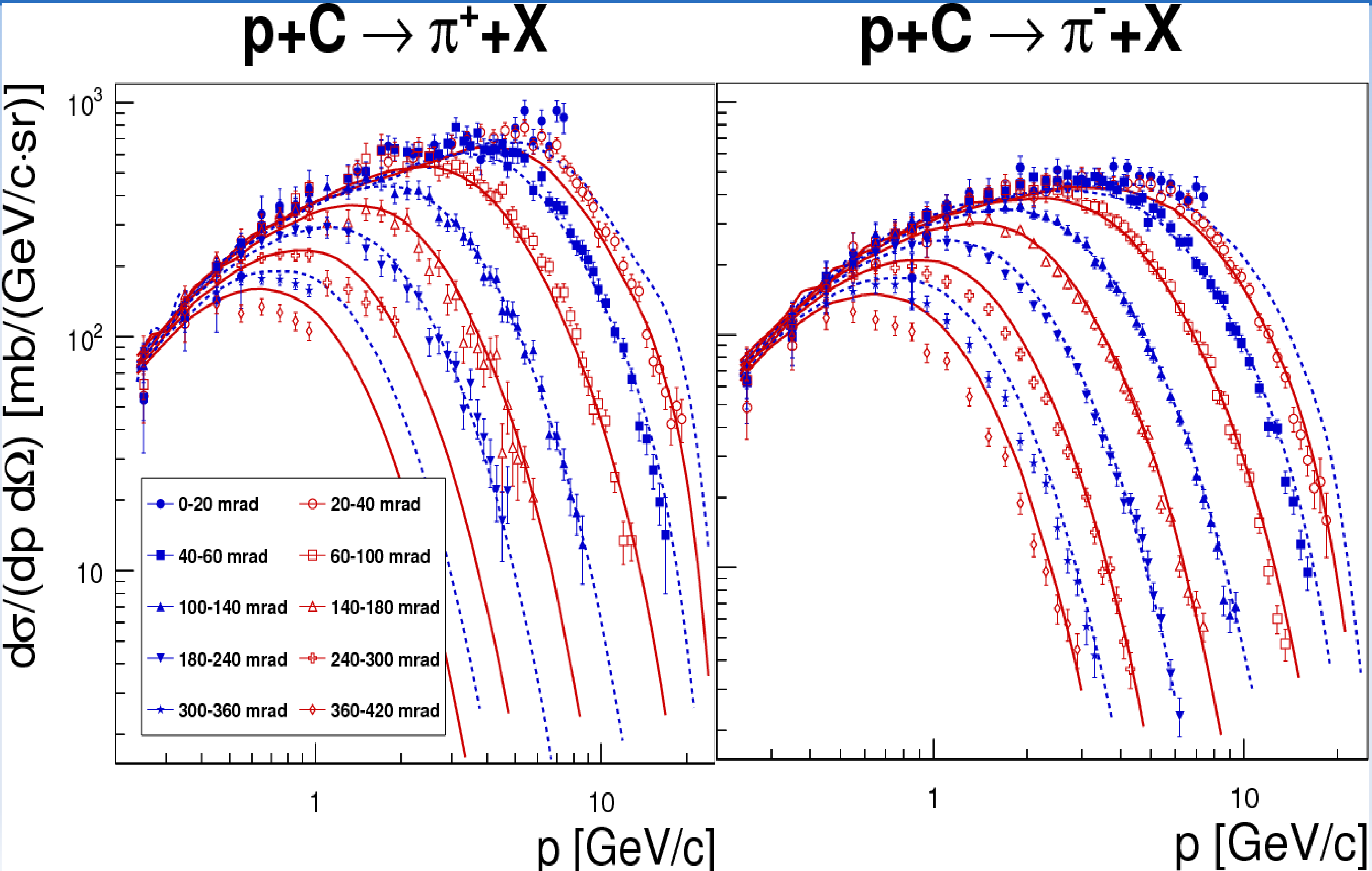
π^+ θ=[40,60] mrad



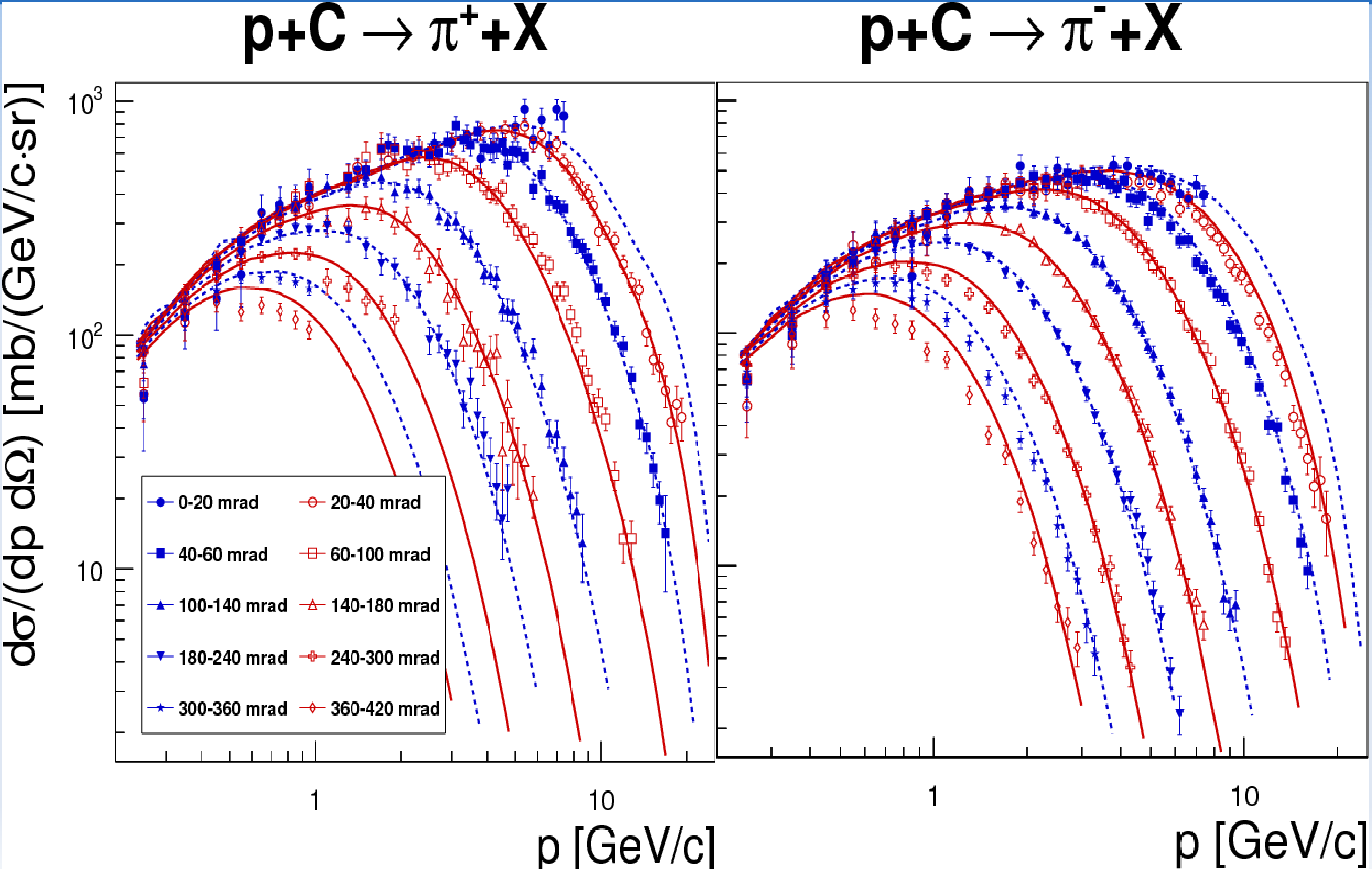
Typical value 6%
Hope to reduce down to 3-4%

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.

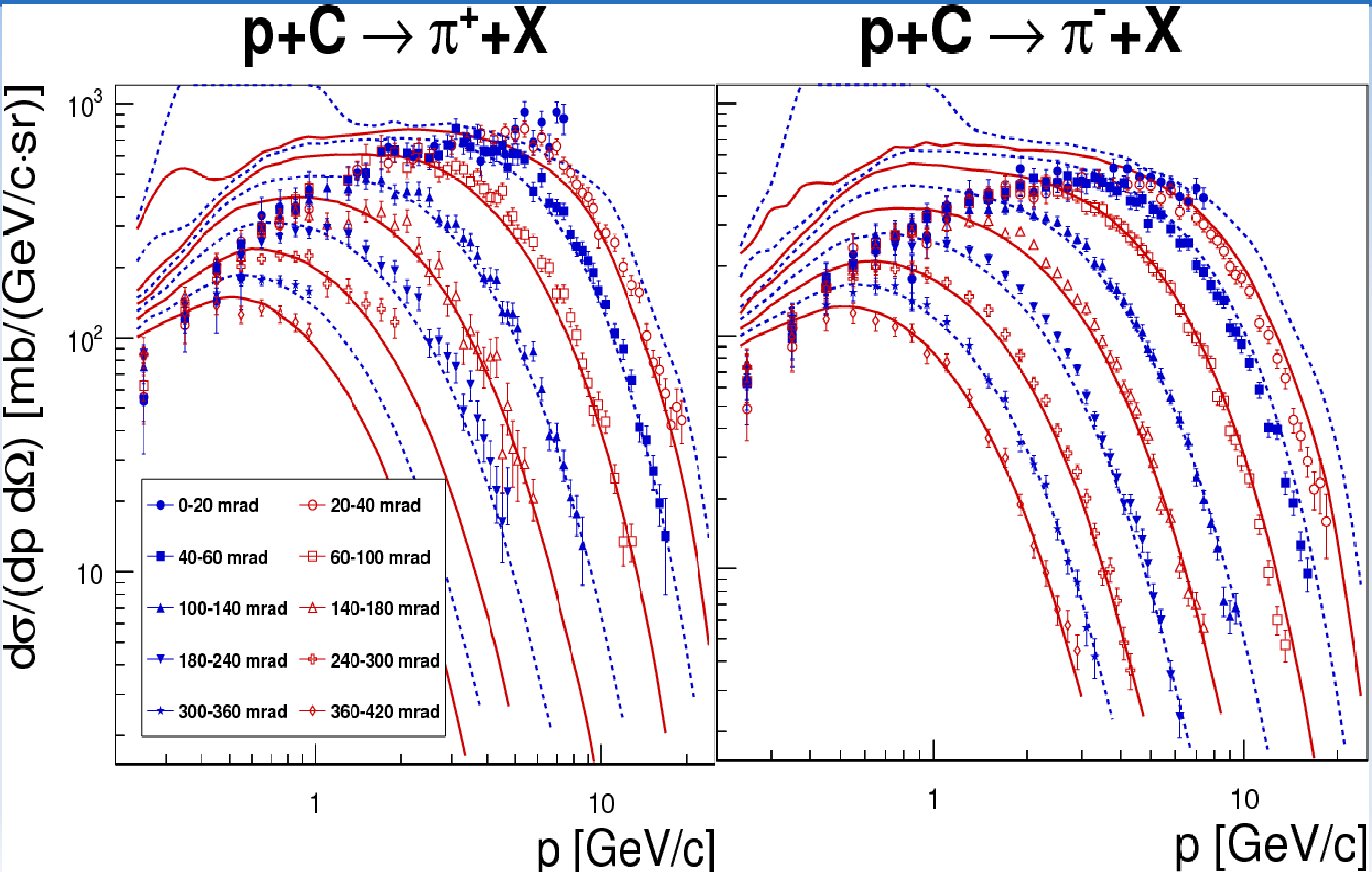
NA61/SHINE: p+C@31GeV/c vs FLUKA2008



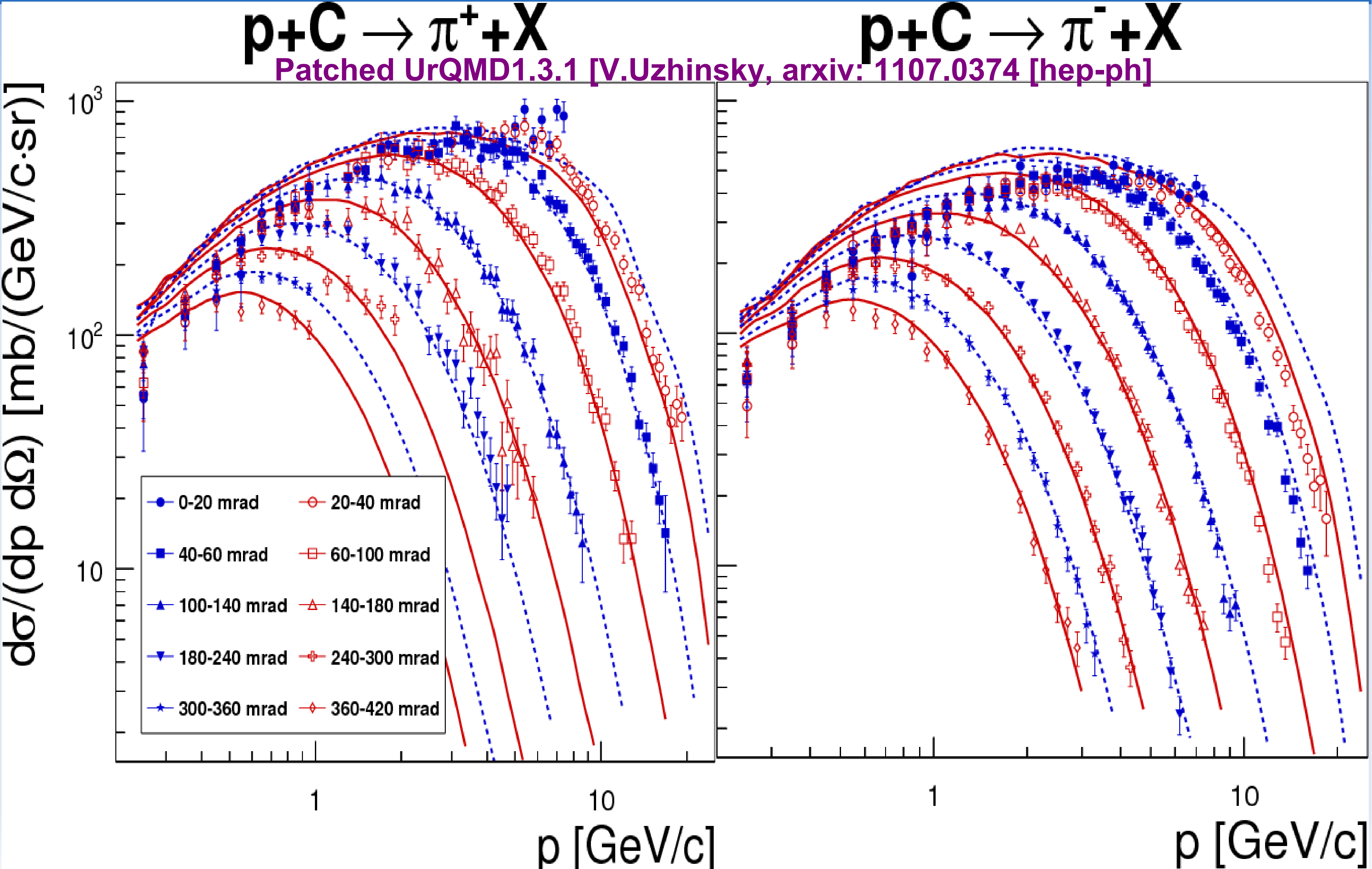
NA61/SHINE: p+C@31GeV/c vs FLUKA2011



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

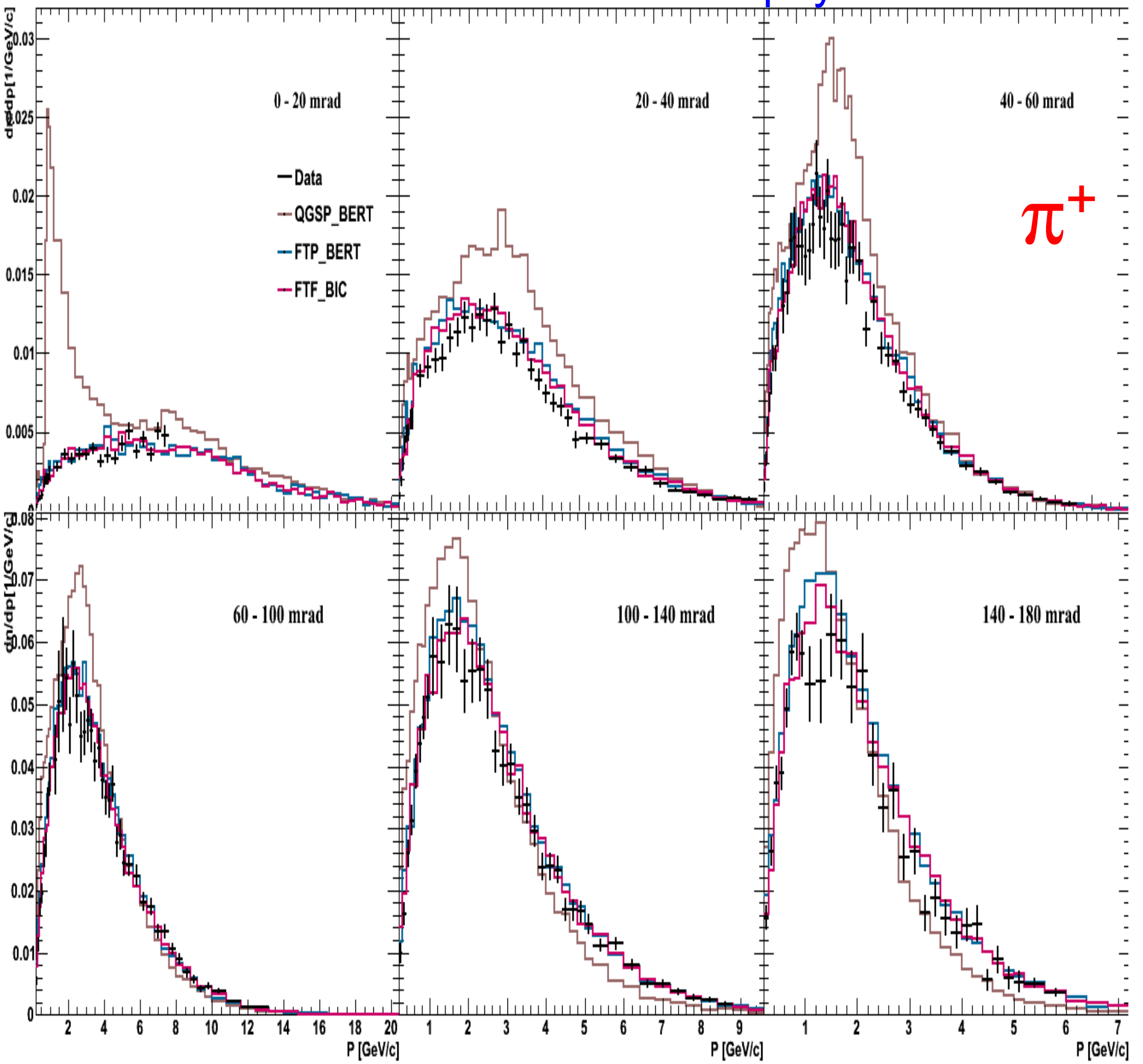


NA61/SHINE: p+C@31GeV/c vs UrQMD1.3.1*



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

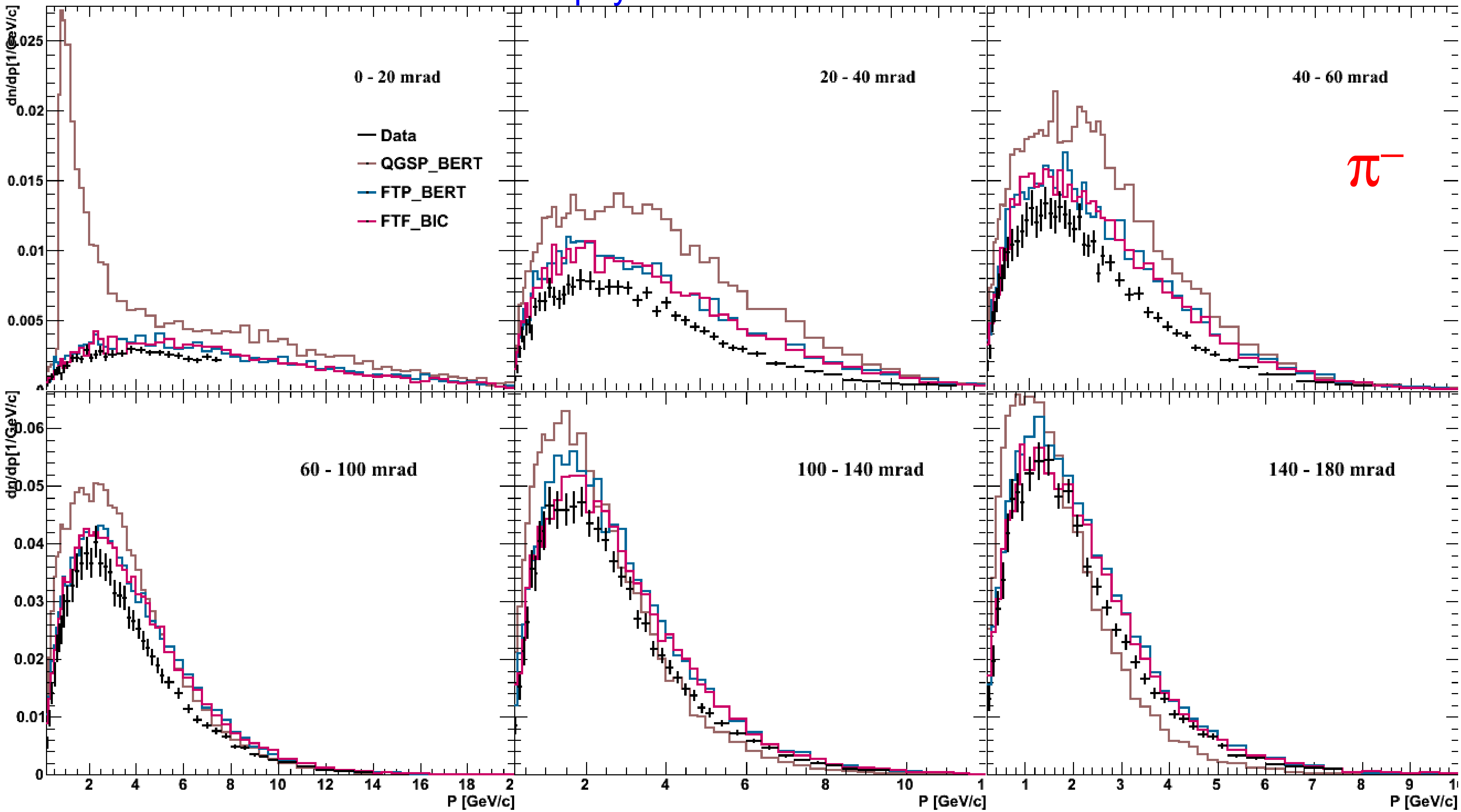
- easy to change geometry keeping the same physics models

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

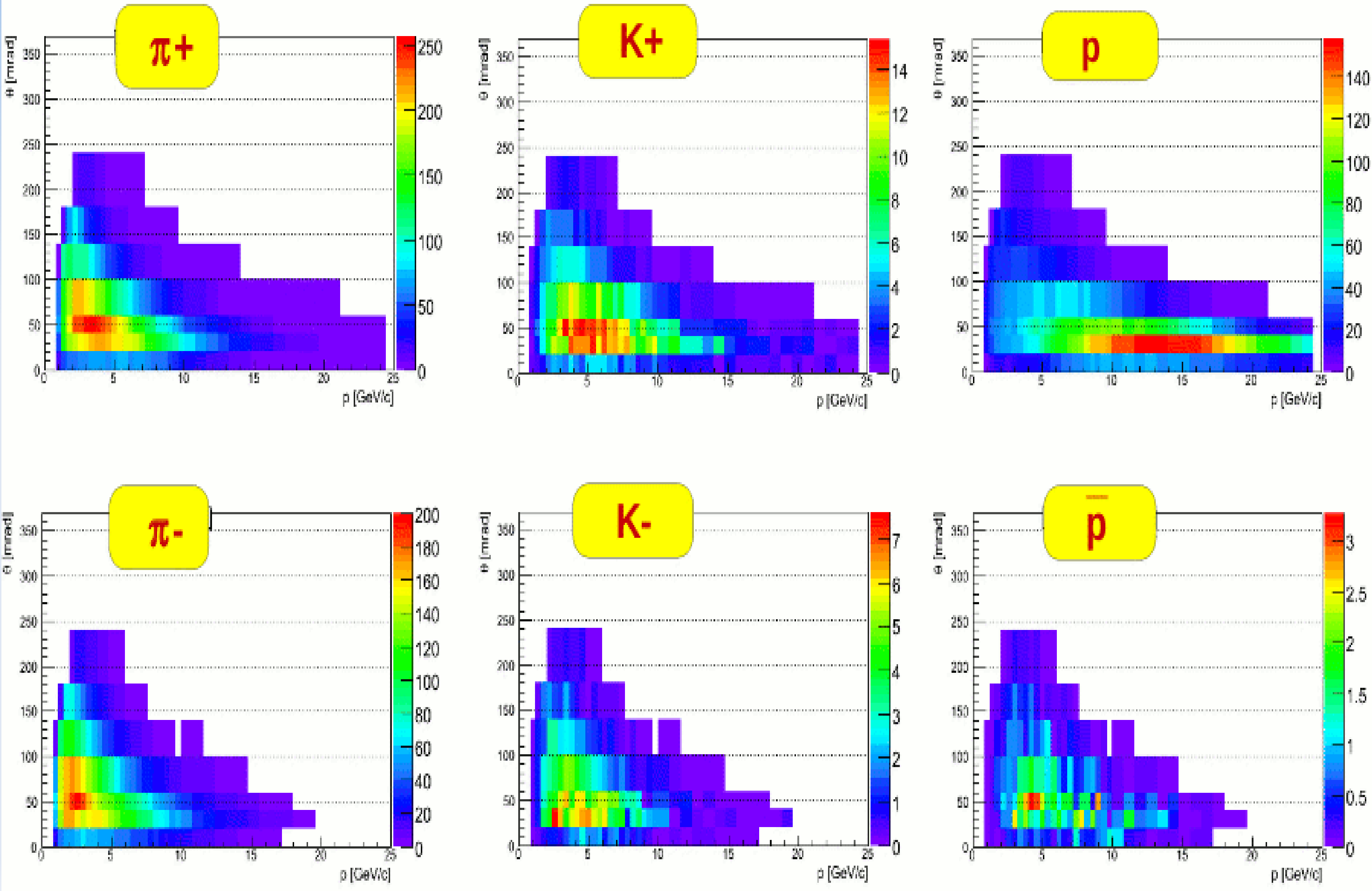
VMC-based development with GEANT4

NA61/SHINE data vs GEANT4 physics lists



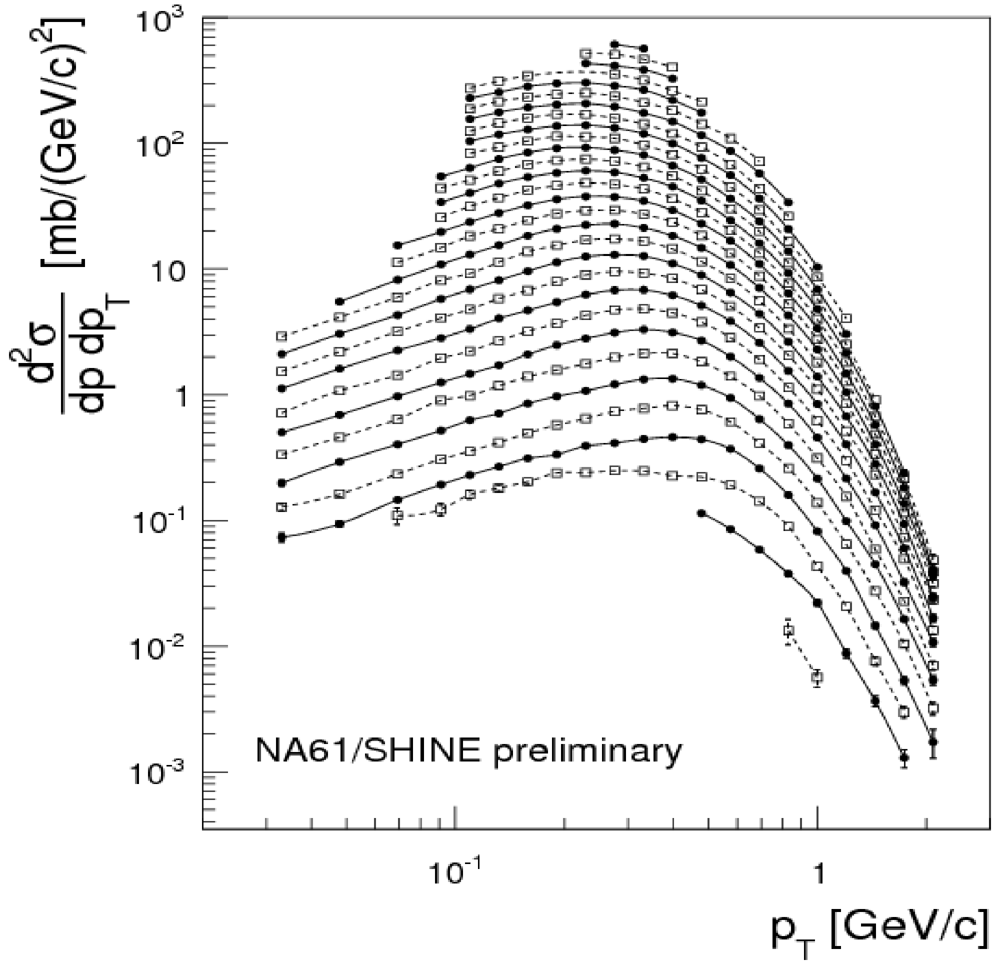
Detailed comparisons of NA61/SHINE data with some GEANT4 physics lists
https://edms.cern.ch/file/1250157/1/VMC_internal_note_laura.pdf

NA61/SHINE p+C@31GeV/c: 2009 data

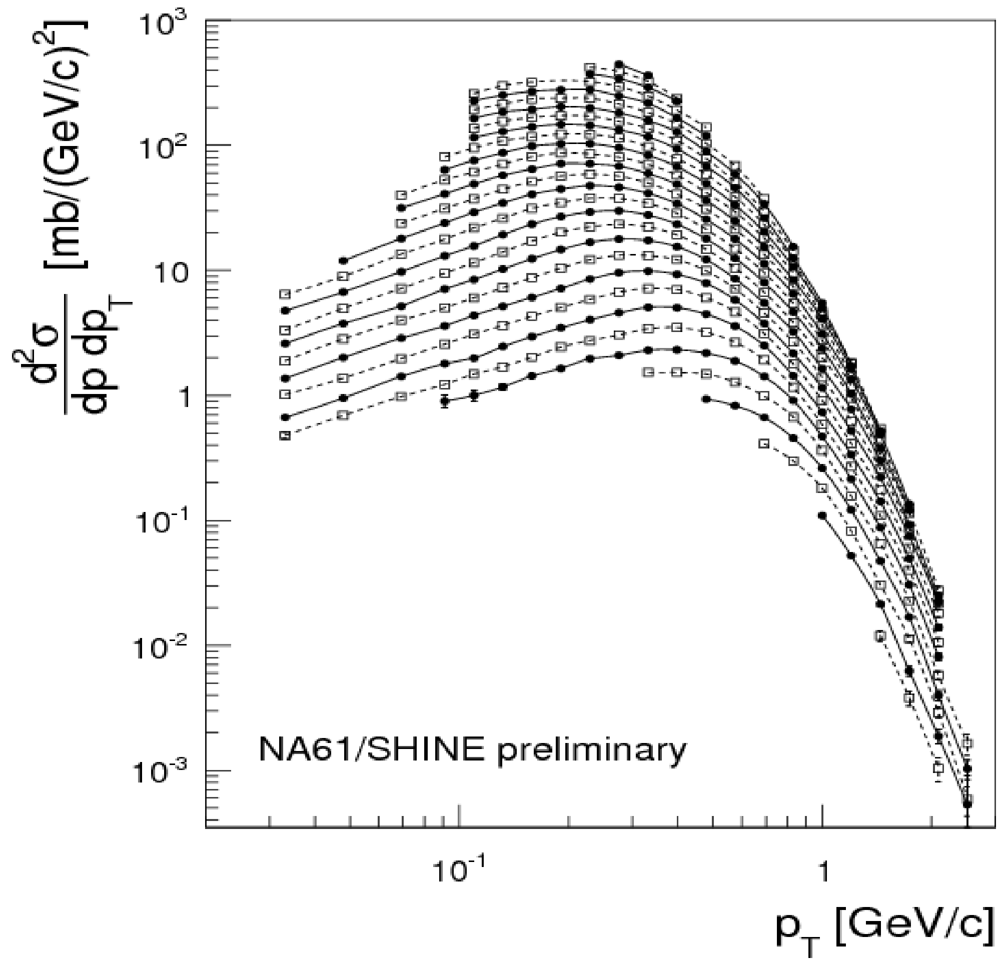


NA61/SHINE: π^-+C@158 GeV/c

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



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



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

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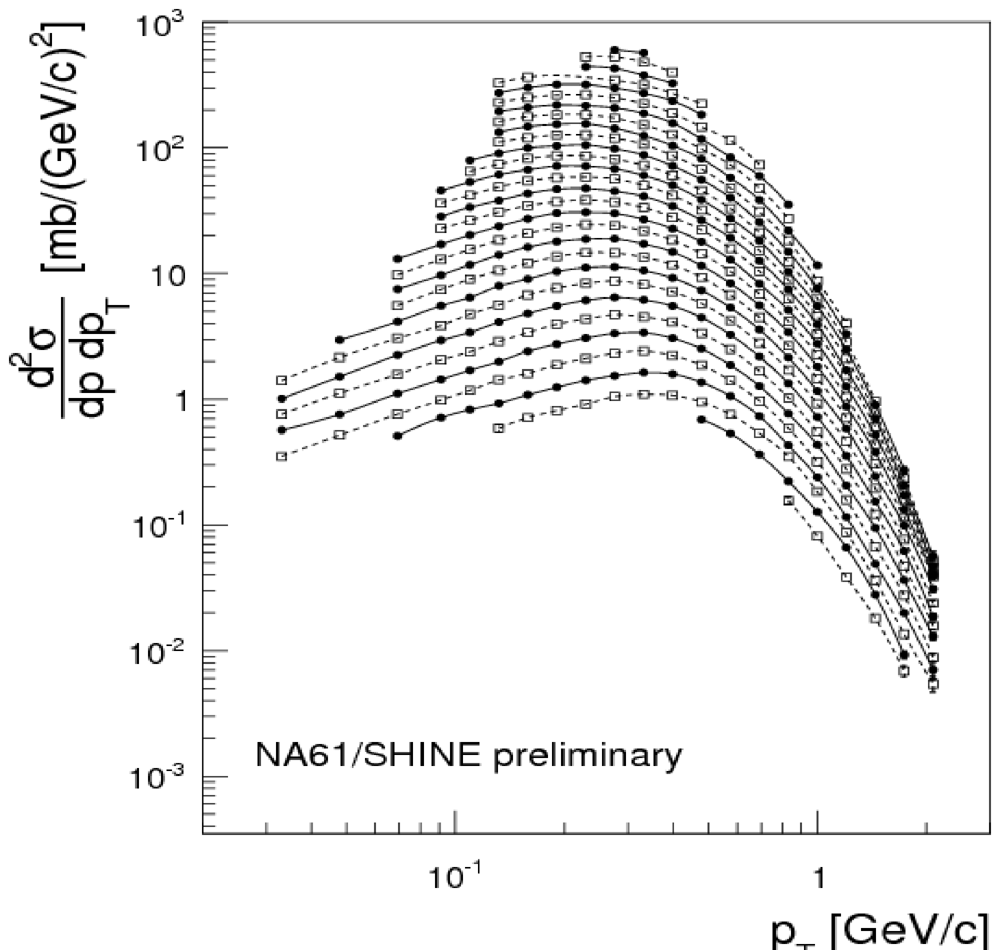
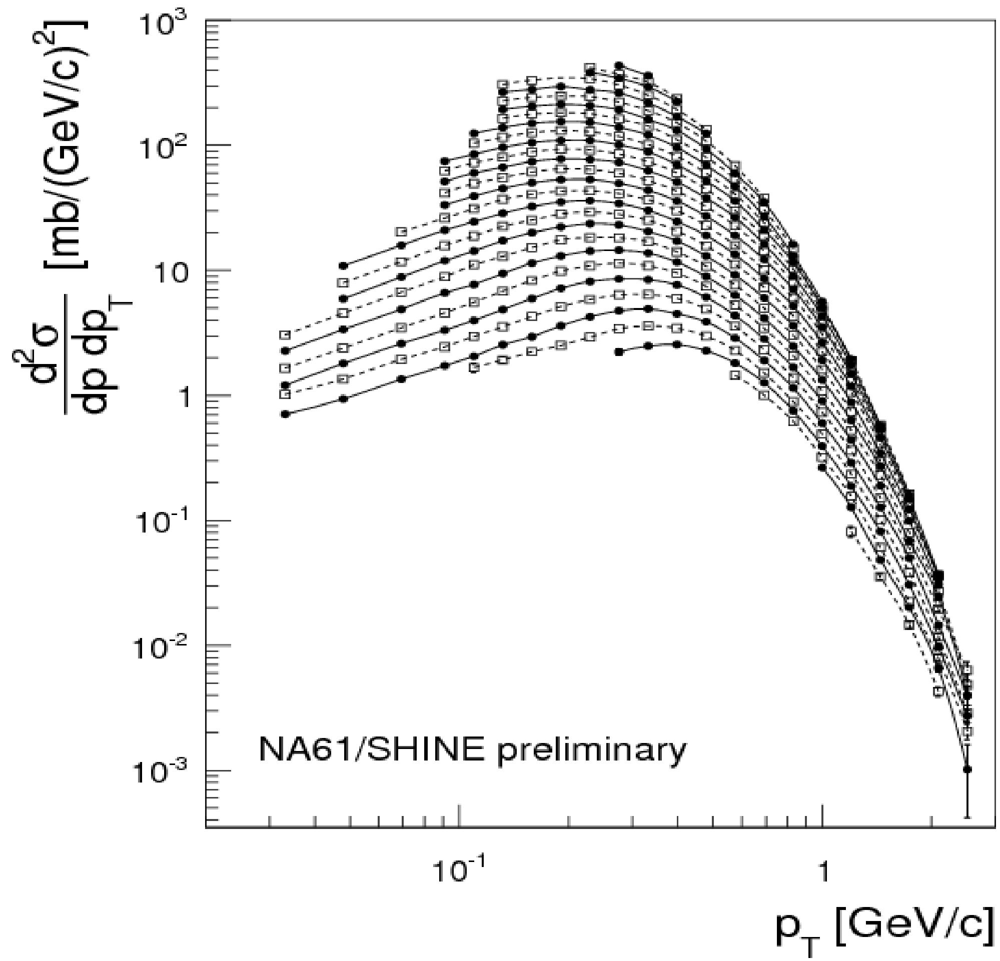
NA61/SHINE: π^-+C@350 GeV/c

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



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



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

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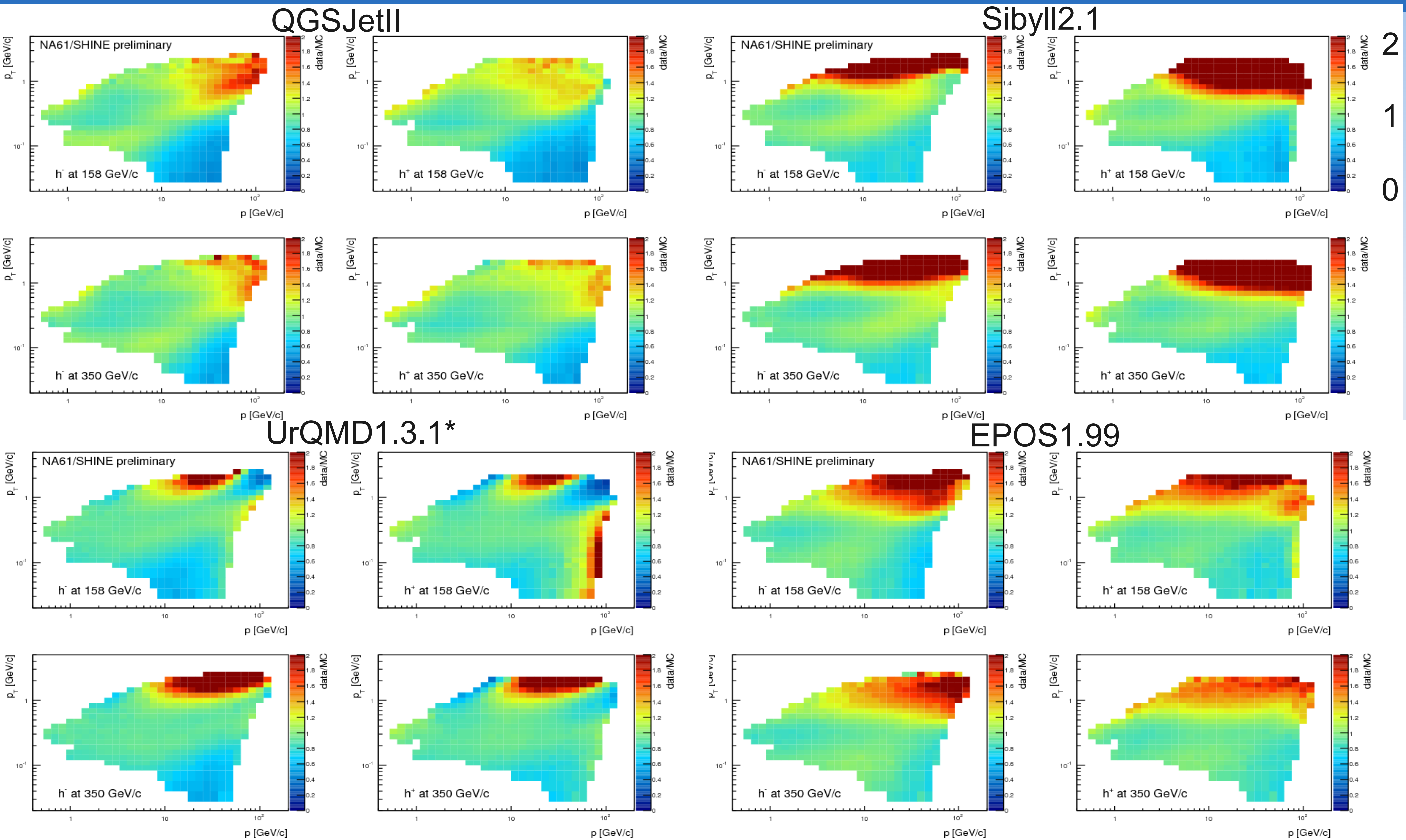
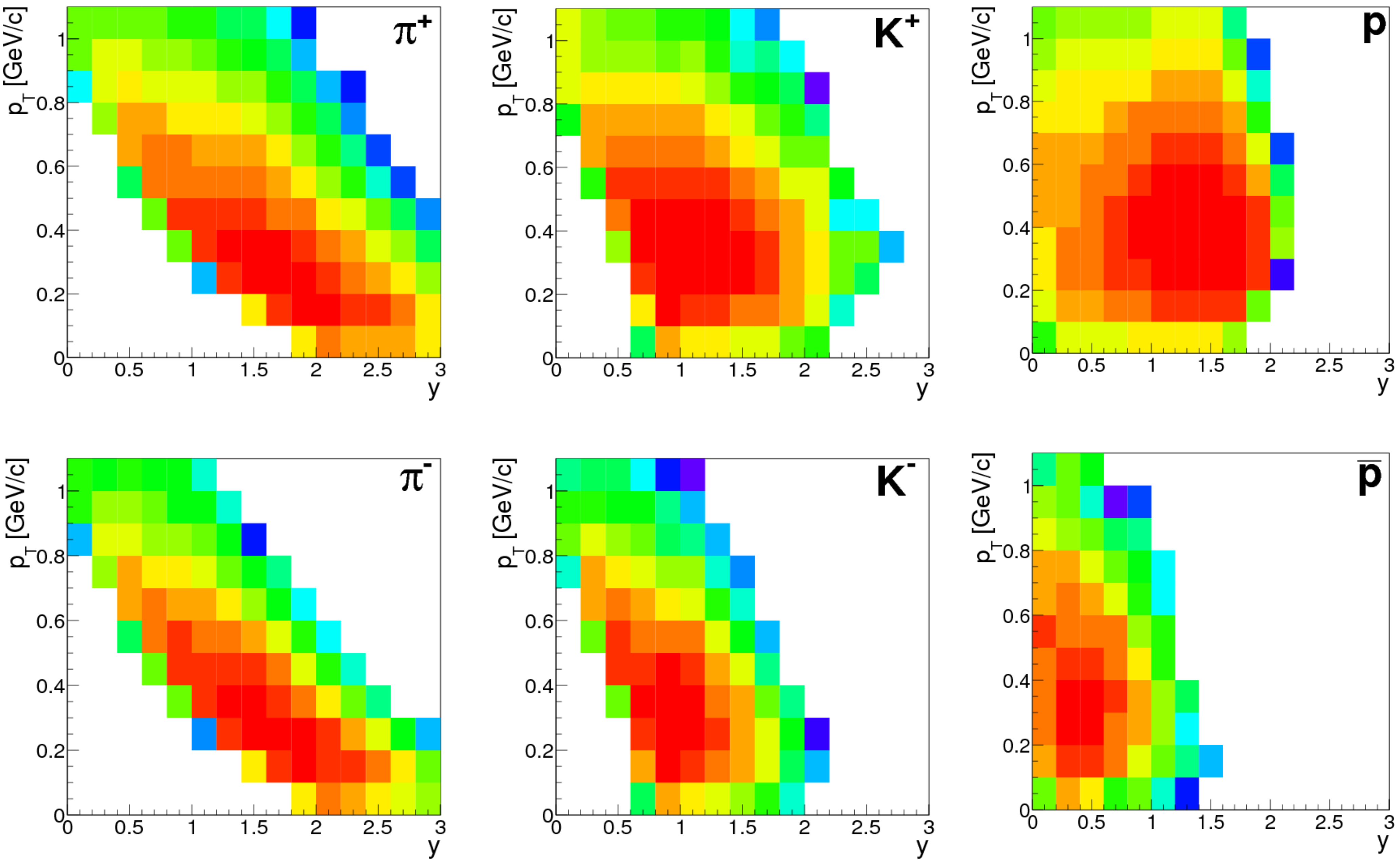
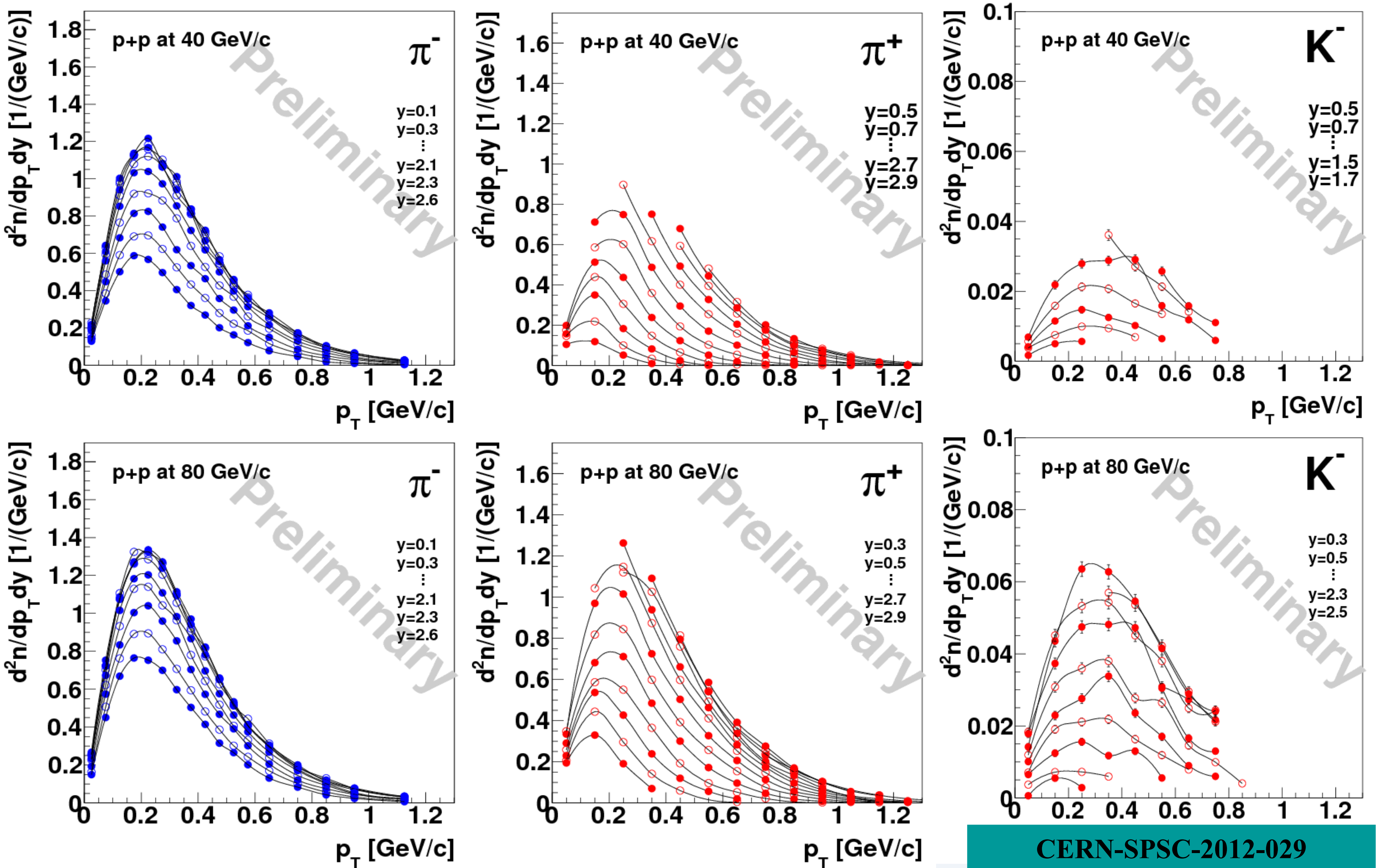
NA61/SHINE: π^-+C vs Models



NA61/SHINE: p+p@40GeV/c coverage



NA61/SHINE: p+p results



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NA61/SHINE: Conclusions

- First NA61/SHINE measurements of cross sections and charged pion and kaon spectra in proton-Carbon interactions at 31 GeV/c are now published [**Phys. Rev. C84 (2011) 034604 ; ibid. C85 (2012) 035210**] and used for improved neutrino flux predictions in the T2K experiment
- 2007 data have also been used to extract preliminary proton and K^0_S, Λ yields from the thin target and π^+ yields from the T2K replica target
- Analysis techniques established
- Further analysis of data collected for T2K in 2009 and 2010 with both thin and replica targets 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) is on-going
- Strong interest from our US colleagues to perform hadron production measurements for Fermilab neutrino experiments
- Existing NA61/SHINE spectrometer can be used for precision hadron production measurements relevant for future (neutrino) experiments

General conclusions

- Hadron production experiments have already contributed to recent advances in (neutrino) physics
- 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

- **Not discussed here... but still important to mention**
- **Precise NA49 measurements of π, K, proton, anti-proton, neutron, deuteron and triton 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; 1207.6520 [hep-ex]]**
- **E-802 data on anti-proton production in p-A interactions at 14.6 GeV/c [Phys. Rev. C47 (1993) 1351**

Thank you for your attention

Backup slides

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

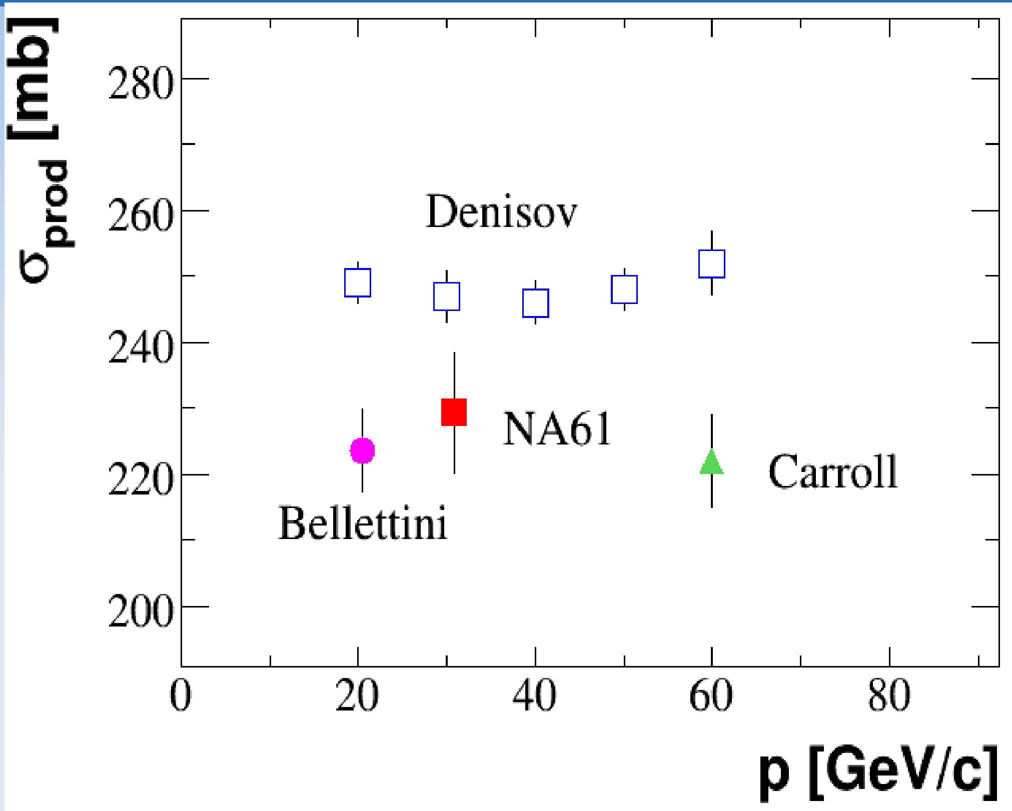
Phys. Rev. C84 (2011) 034604

NA61/SHINE p+C@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-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 the desintegration of the target nucleus (quasi-elastic interactions).

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

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

(229.3 ± 1.9 ± 9.0) mb = (257.2 ± 1.9 ± 8.9) mb - (27.9 ± 1.5) mb

from Glauber model calculations

C.Strabel, PhD thesis, ETHZ, 2011

NA61/SHINE: systematic errors

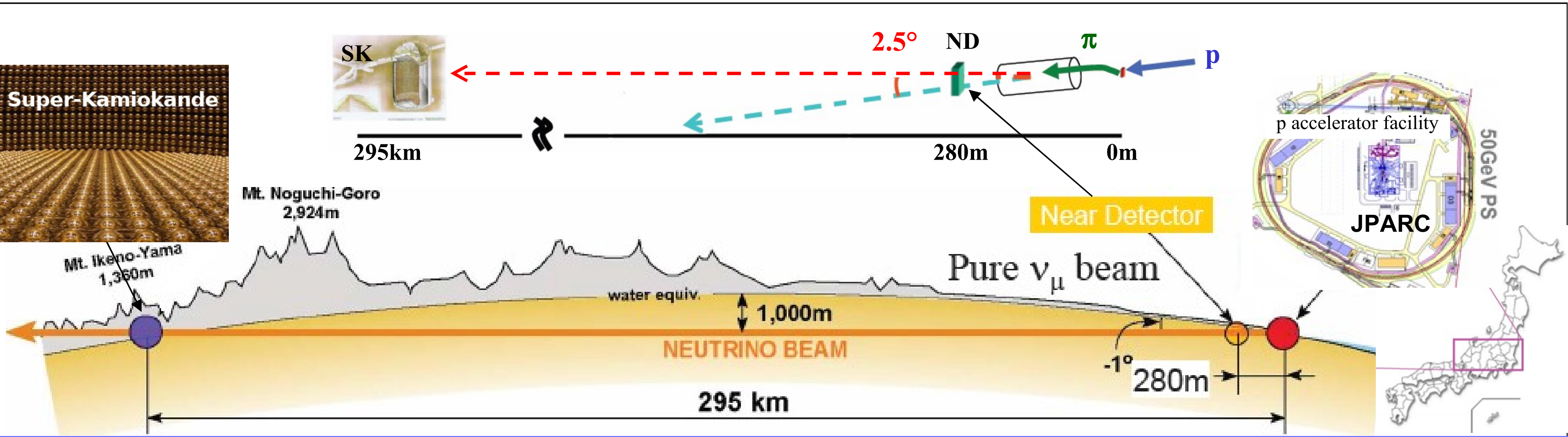
- Considered systematic errors
- Uncertainty of PID procedure for dE/dx and dE/dx+ToF analyses
- Feeddown: pions from weak decays and secondary interactions reconstructed at primary vertex
- Track topology
- Track cuts (number of points, azimuthal angle, impact parameter)
- Track merging algorithm
- Reconstructed efficiency
- ToF detection efficiency
- Electron, K- and antiproton contamination in the h- analysis
- Pion/kaon loss correction due to pion/kaon decay

NA61/SHINE for T2K

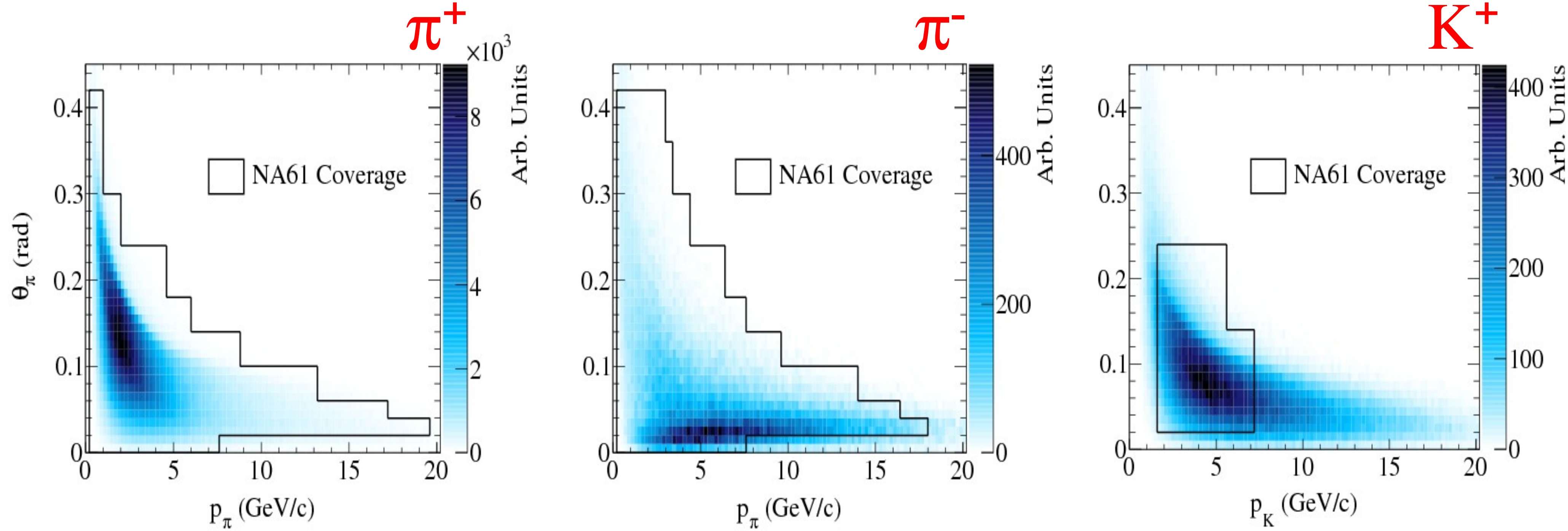
- **One of the main physics goals of NA61/SHINE:**

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**



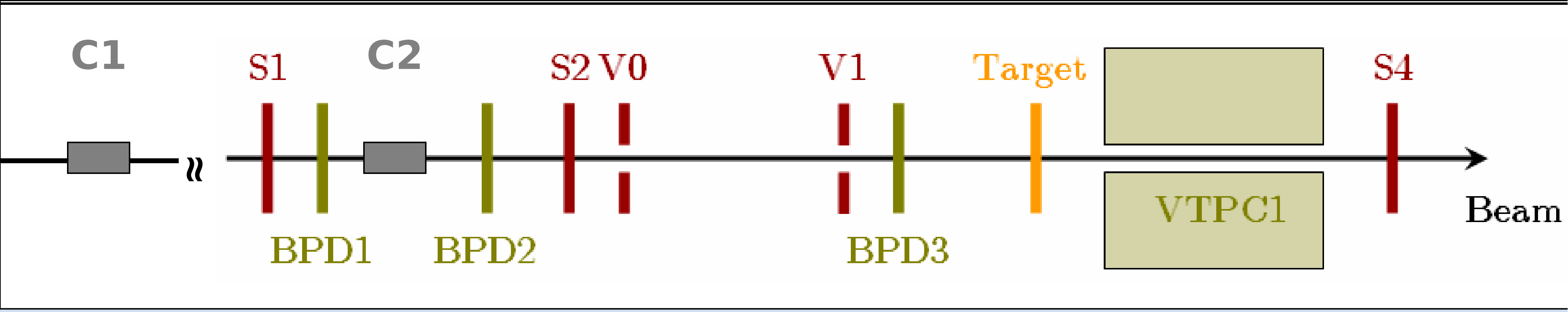
NA61/SHINE p+C@31GeV/c: T2K phase space



Phase space of changed pions and kaons contributing to predicted neutrino flux (positive focusing) at SK together with regions covered by NA61/SHINE 2007 data

"The T2K Neutrino Flux Prediction", 1211.0469 [hep-ex], to be published in PRD

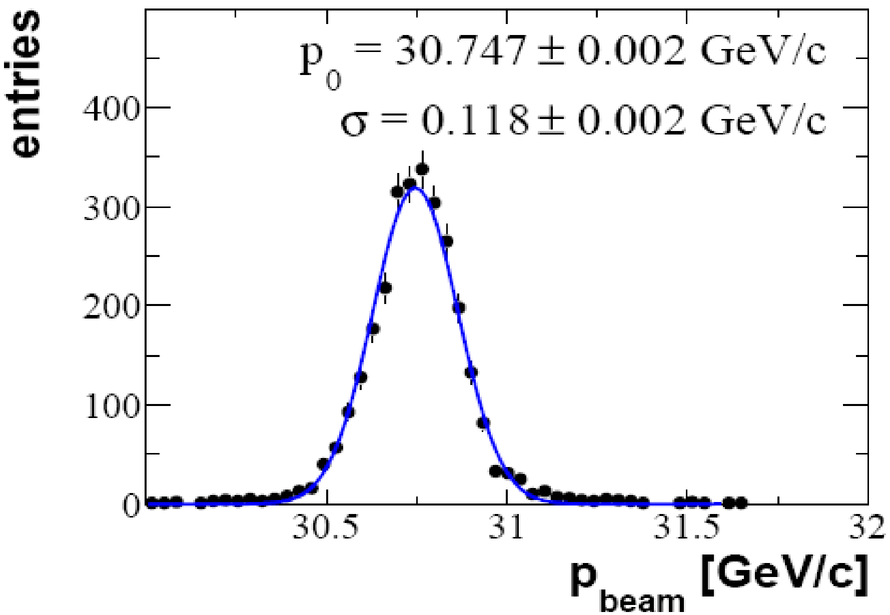
NA61/SHINE: beam-line setup



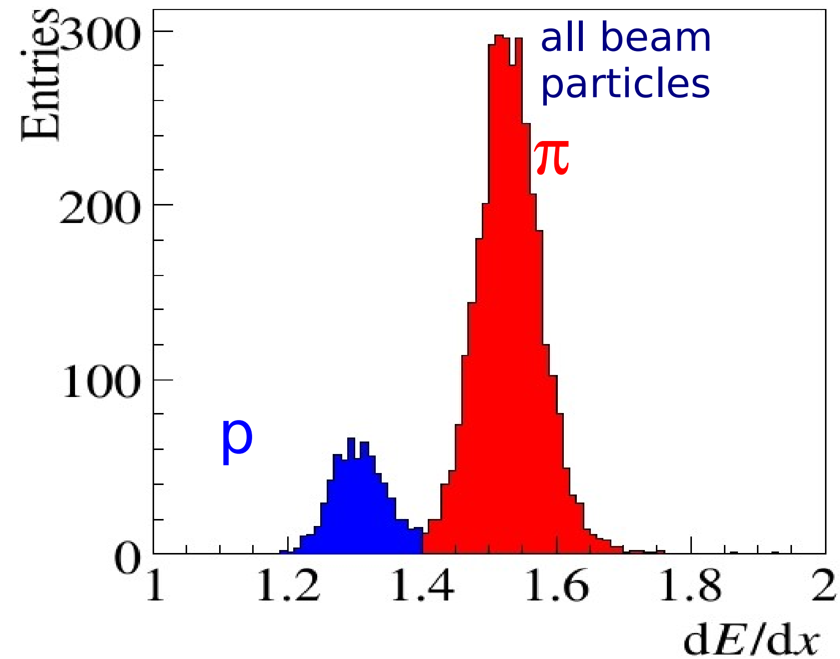
- 31 GeV/c secondary hadron beam composed of 83.7% π, 14.7% p and 1.6% K
- Proton beam particles identified by CEDAR (C1, 96% efficiency for 6th-fold coincidence) and threshold Cerenkov counters (C2)
- Incoming p then selected by several scintillator counters (S1, S2, $\overline{V0}$, $\overline{V1}$)
  → beam defined as Beam = $S1 \cdot S2 \cdot \overline{V} \cdot C1 \cdot \overline{C2}$
- 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 ($Beam \cdot \overline{S4}$)

NA61/SHINE: Beam properties

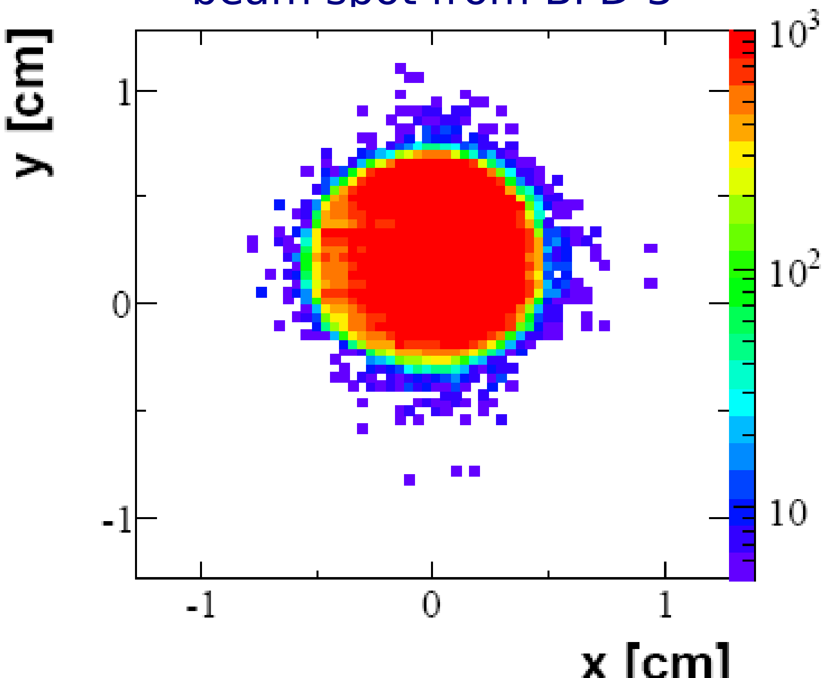
momentum measured in TPCs

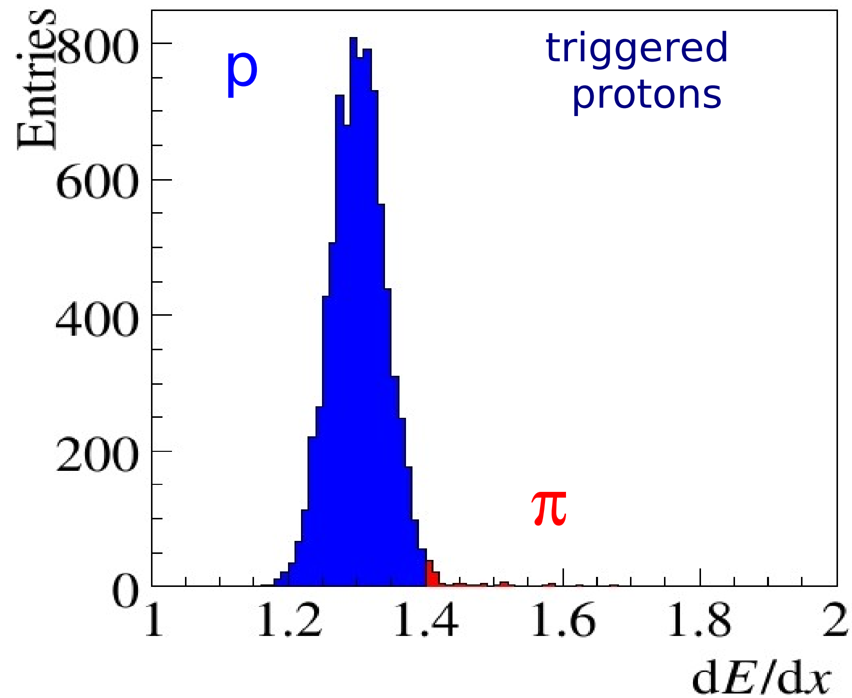


dE/dx from TPC



beam spot from BPD-3



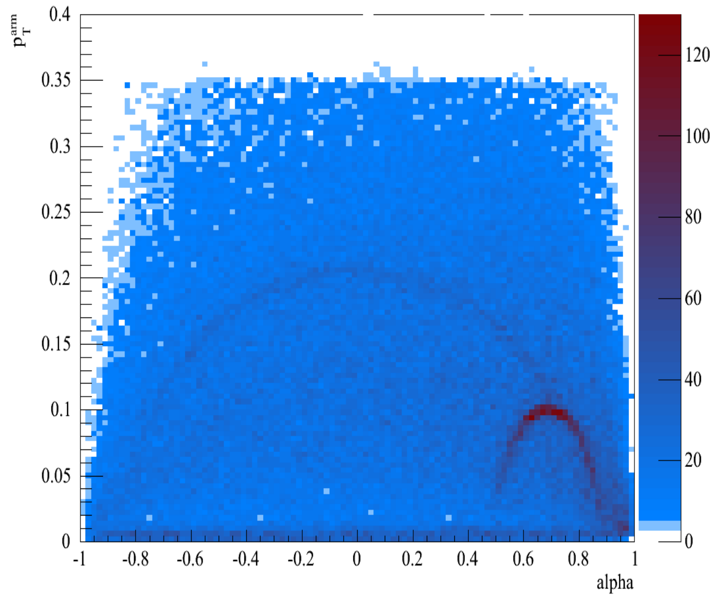


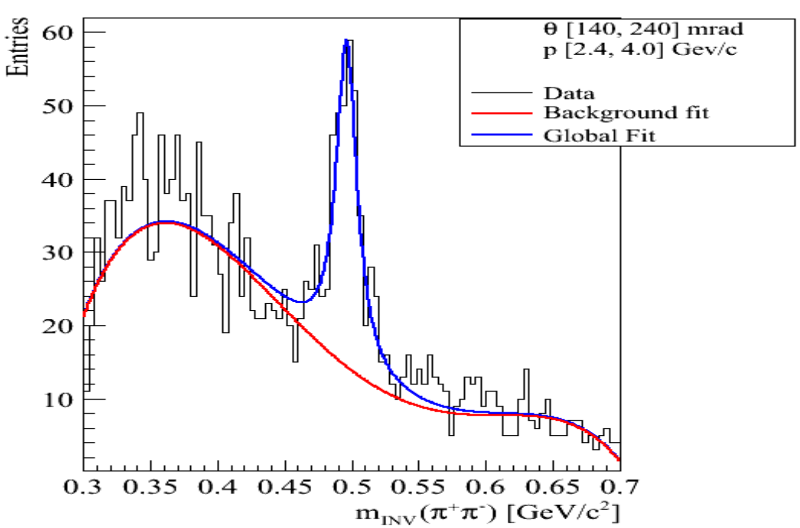
Identification of beam protons with a purity of about 99%

NA61/SHINE: recorded data for T2K

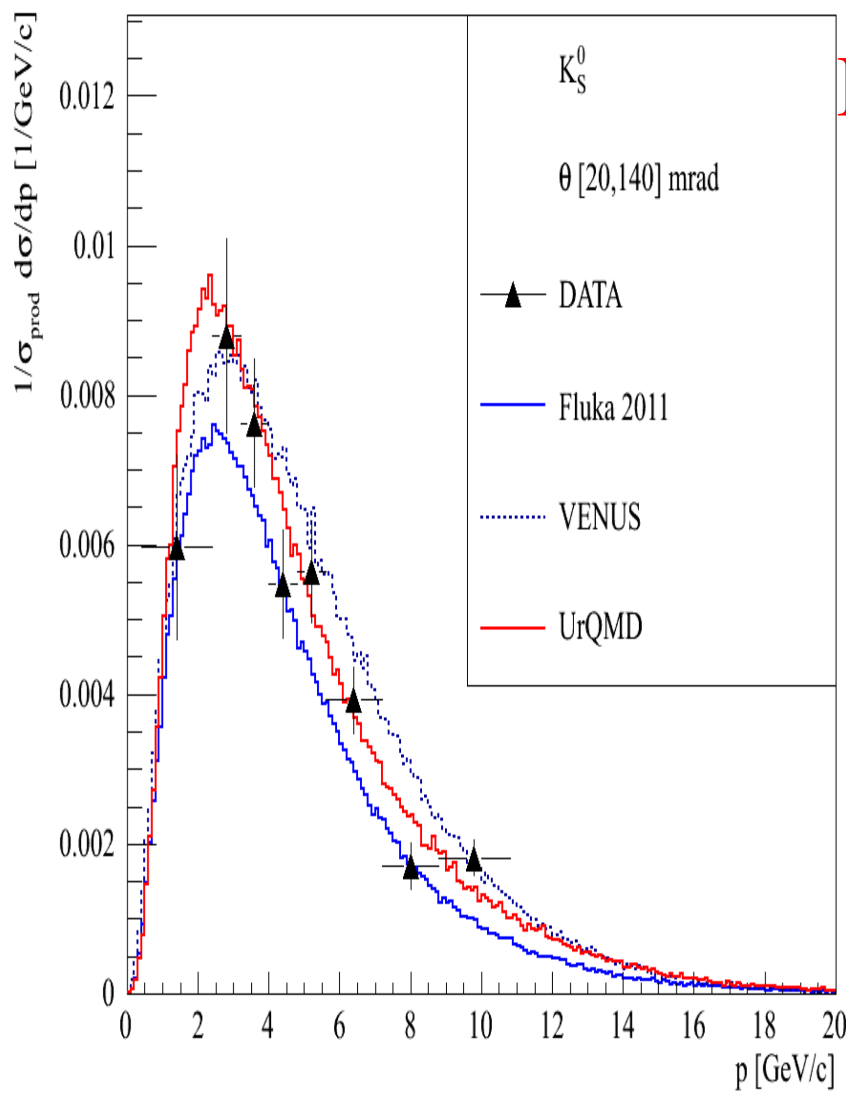
- Two different carbon (isotropic graphite) targets were used
- Thin target: 2 cm length, 2.5x2.5 cm cross section, ρ = 1.84 g/cm^3, ~0.04 λ_{int}
- T2K replica target: 90 cm length, 2.6 cm diameter, ρ = 1.83 g/cm^3, ~1.9 λ_{int}
- Data for T2K with incoming 31 GeV/c protons were collected:
- 2007 run (~670k triggers on thin target and ~230k triggers on replica target). Analysis finalized and corresponding results published.
- 2009 run (~6M triggers on thin target and ~2M triggers on replica target). These data are now fully calibrated and analysis is well advanced.
- 2010 run (~10M triggers on replica target). Data being calibrated now. Ultimate data set for most precise neutrino flux predictions.

NA61/SHINE p+C@31GeV/c: V0 analysis





Preliminary results from 2007 data

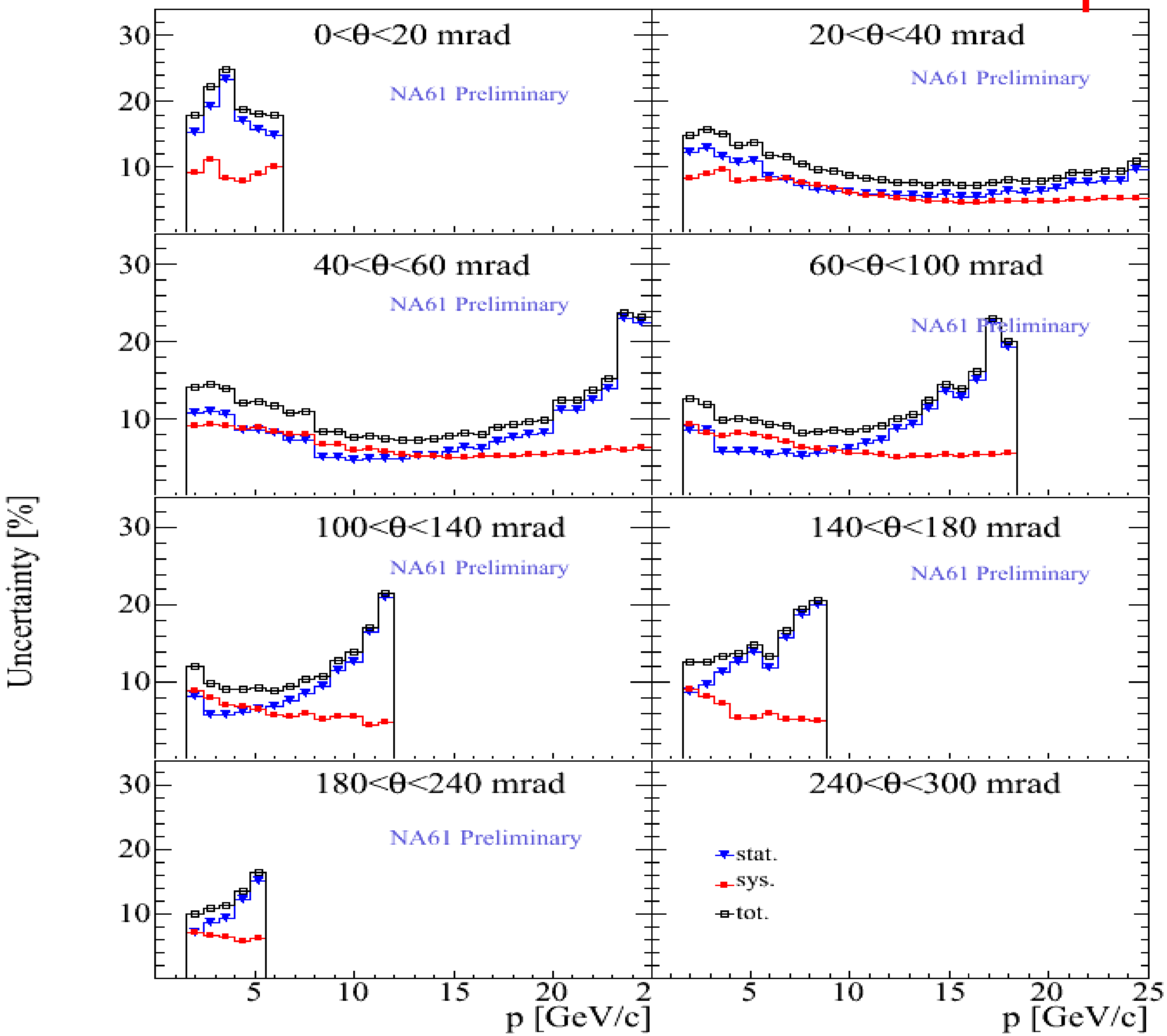


K_s^0

T.Palczewski, PhD thesis, National Centre for Nuclear Research, Warsaw, 2012

NA61/SHINE p+C@31GeV/c: stat vs syst errors

protons



Preliminary results from 2007 data

NA61/SHINE: prospects

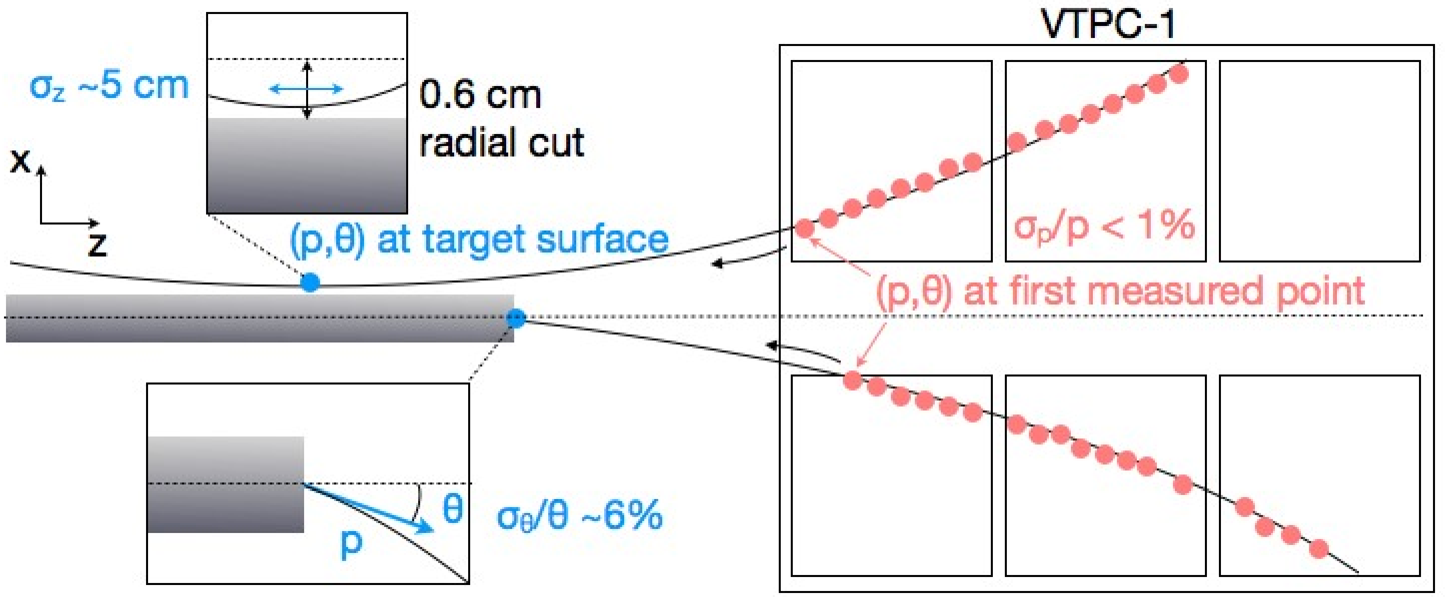
- Published NA61/SHINE pC@31GeV/c data have already been used for precise predictions of T2K neutrino fluxes and for tuning of hadron production models. Will be further improved with more data.
- All NA61/SHINE 2009 data sets are now fully calibrated. Some preliminary results already available. Will soon provide extensive dataset for model tuning.
- US groups involved in Fermilab neutrino experiments plan to join NA61 in order to perform required hadron production measurements
- Future accelerator neutrino experiments, etc. could definitely profit from the NA61/SHINE know-how (if proton momentum and target material are known)

NA61/SHINE: replica target analysis

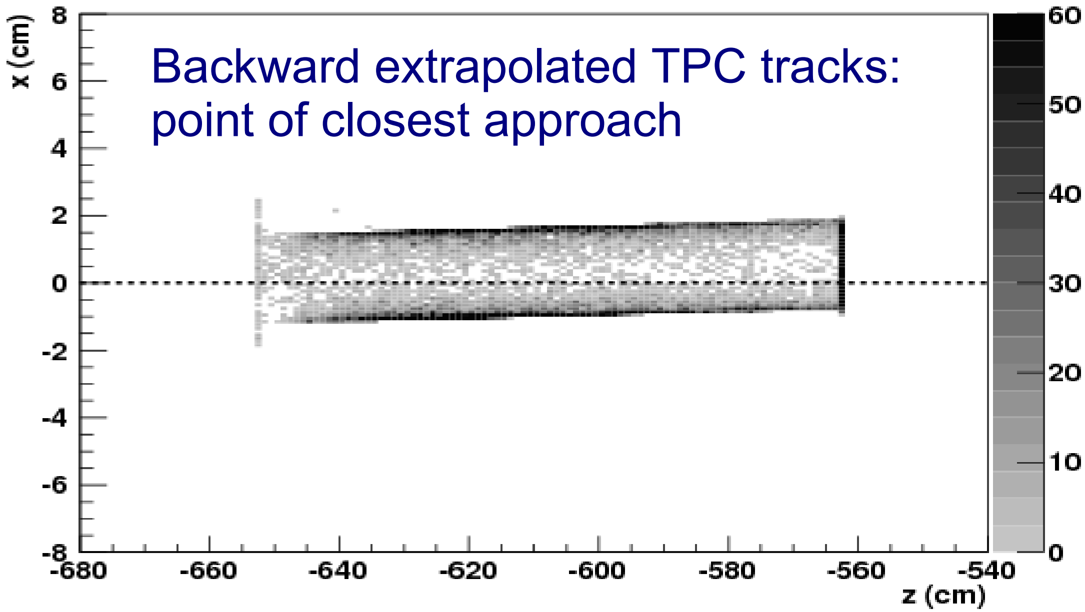
- Special reconstruction and analysis techniques developed for the replica target (RT)
- Pilot analysis on π^+ emission from the RT surface performed on 2007 data with 5 longitudinal bins along the target and target downstream face
- RT hadron production measurements allow to constrain up to 90% of neutrino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

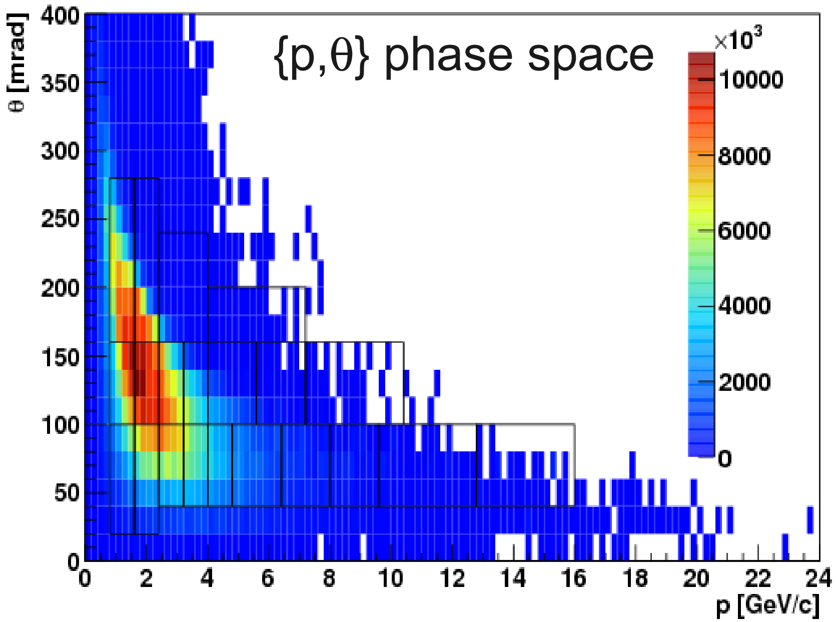
N.Abgrall, PhD thesis, Univ. of Geneva, 2011; "Pion emission from the T2K replica target: method, results and application", NIM A 701 (2013) 99; 1207.2114 [hep-ex]

NA61/SHINE: replica target analysis

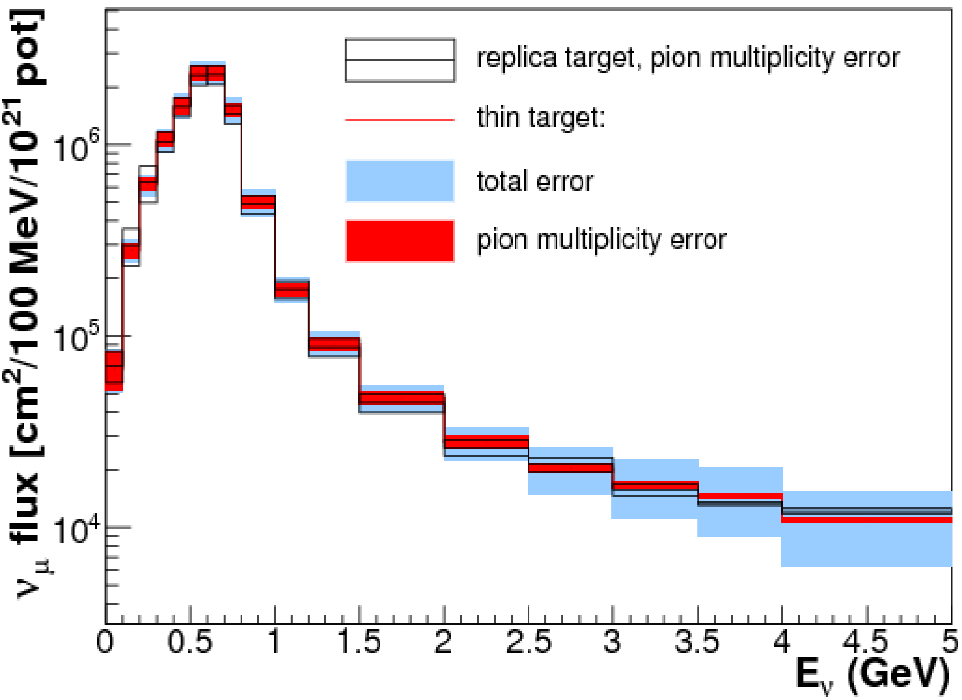


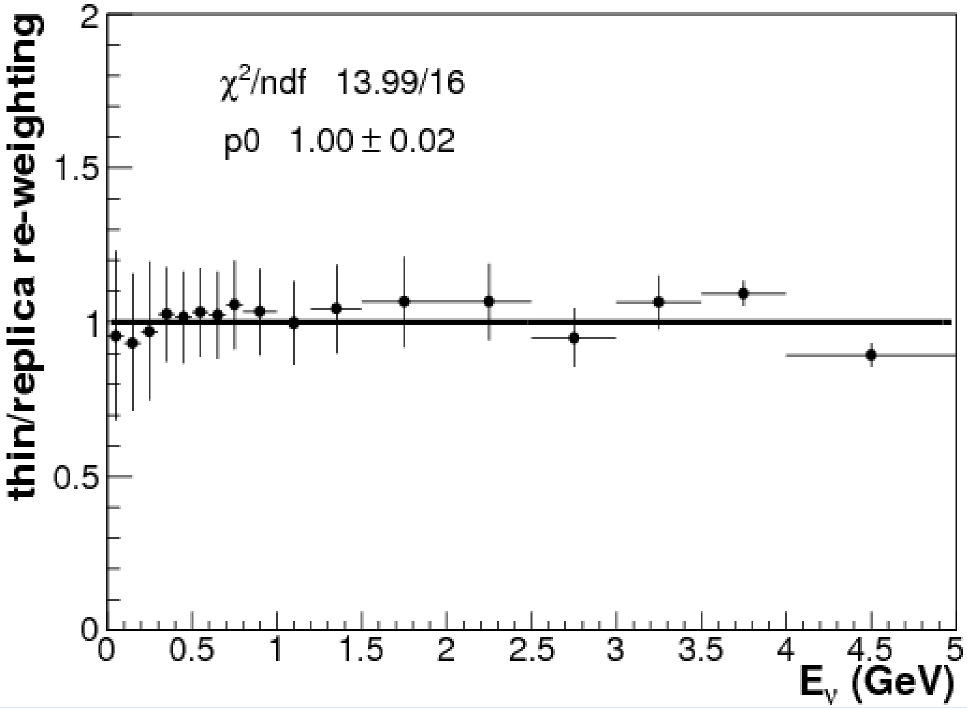
5 longitudinal bins of 18 cm each + target downstream face





NA61/SHINE: replica target analysis





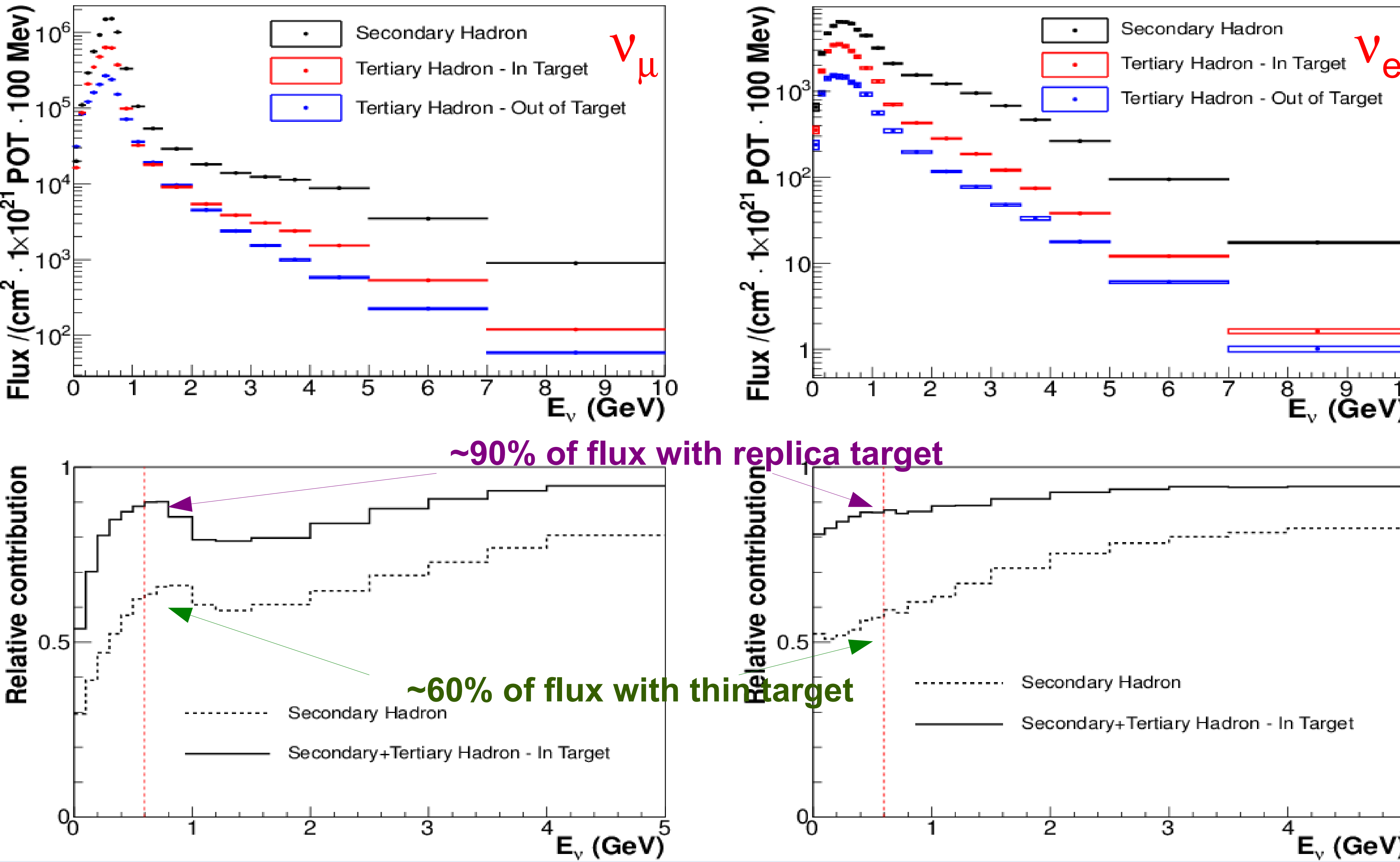
Replica target data are used for the first time for neutrino flux predictions.

Combination of thin and replica target measurements would allow to better understand effects of reinteractions in the long target.

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

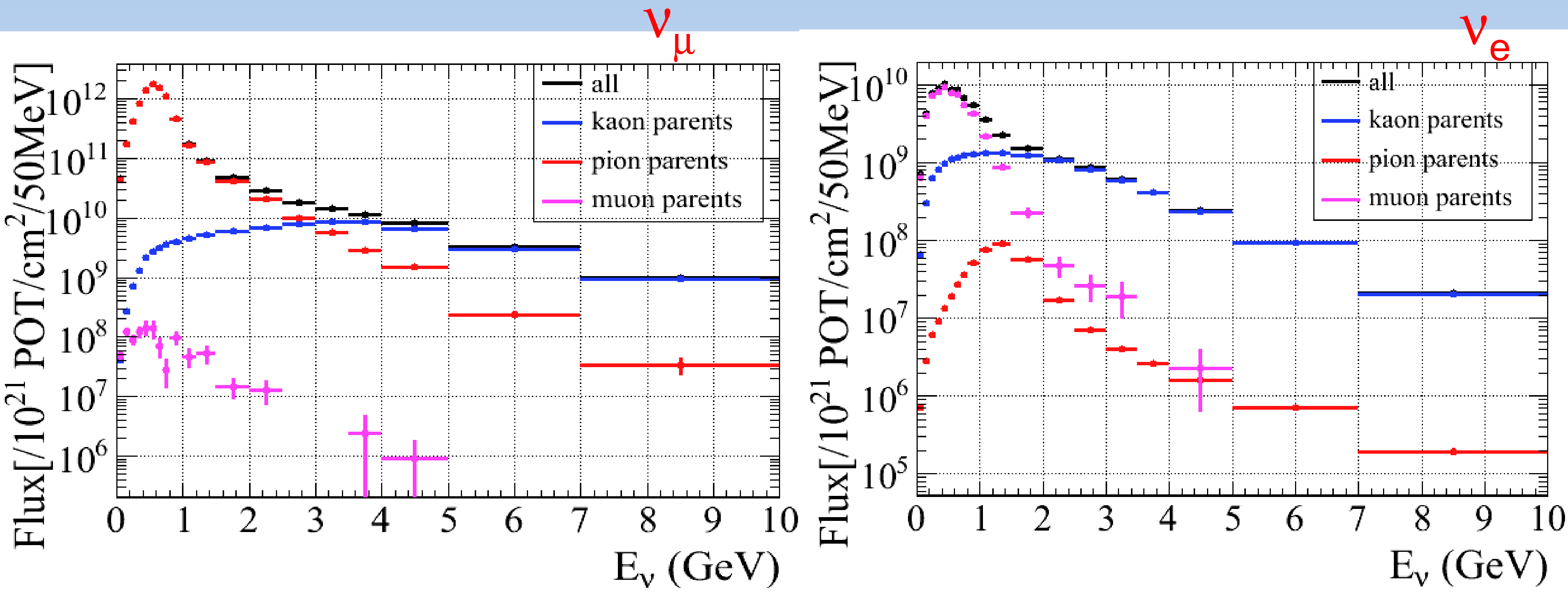
N.Abgrall, PhD thesis, Univ. of Geneva, 2011; "Pion emission from the T2K replica target: method, results and application", NIM A 701 (2013) 99; 1207.2114 [hep-ex]

NA61/SHINE for T2K



["Pion emission from the T2K replica target", NIM A 701 (2013) 99; 1207.2114 [hep-ex]]()

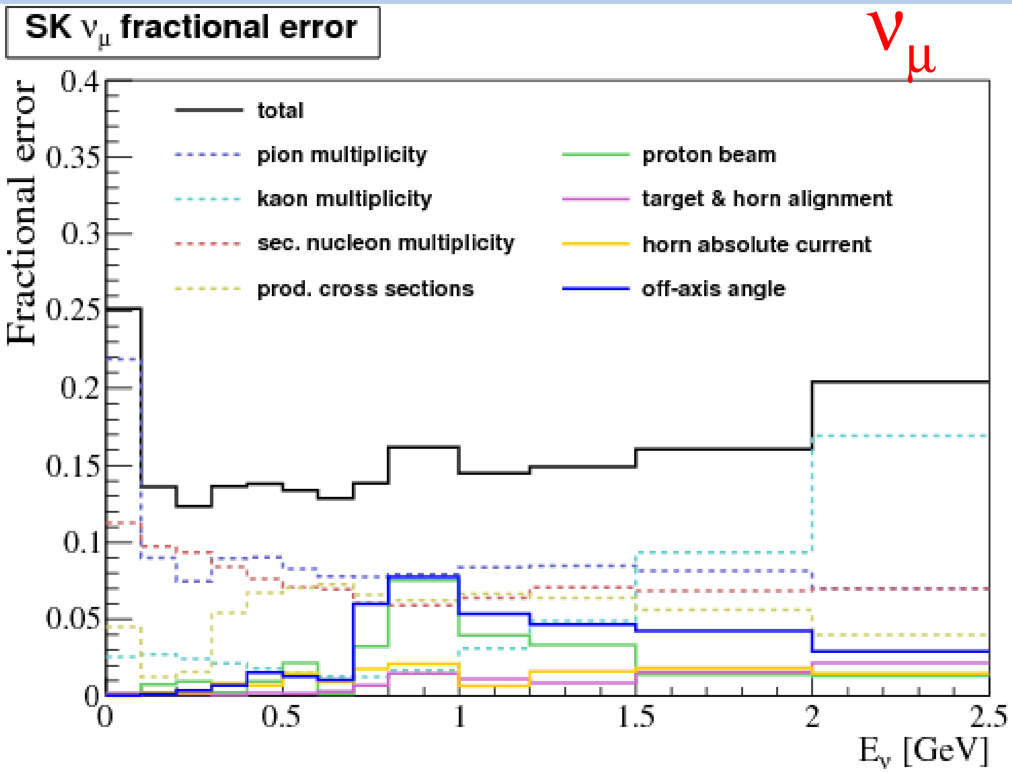
T2K neutrino fluxes

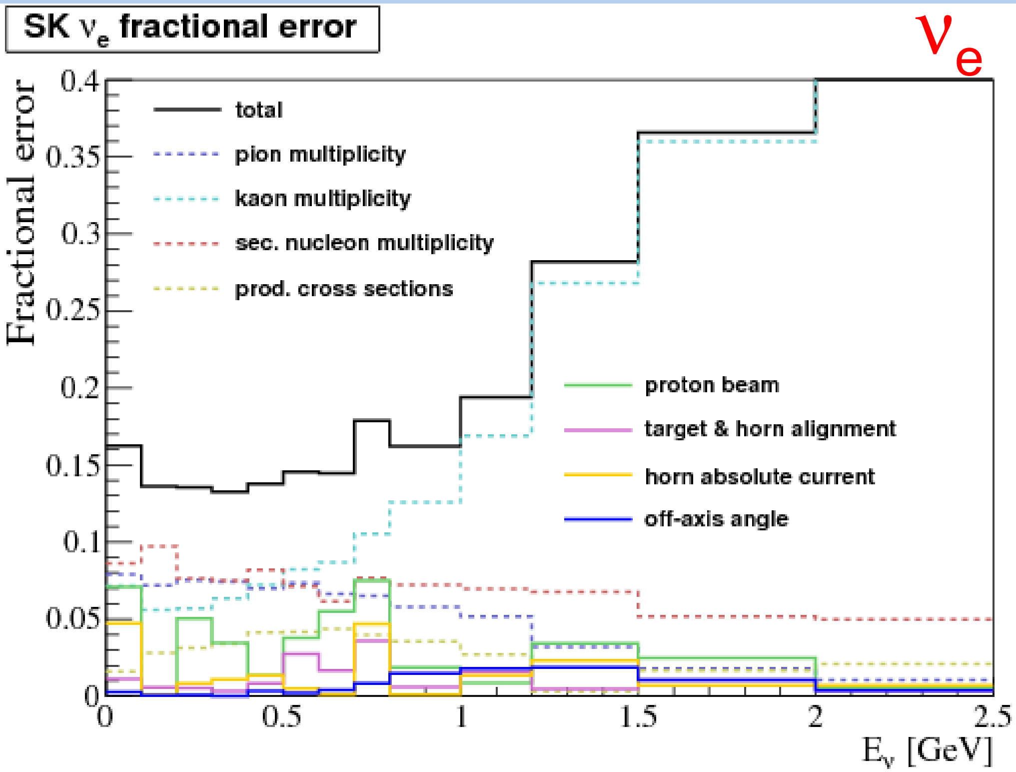


Predictions of the ν_μ and ν_e fluxes at the T2K near detector:
Based on FLUKA2008 and re-weighted by the NA61/SHINE thin target pion data

"The T2K Neutrino Flux Prediction", 1211.0469 [hep-ex], to be published in PRD

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

"The T2K Neutrino Flux Prediction", 1211.0469 [hep-ex], to be published in PRD

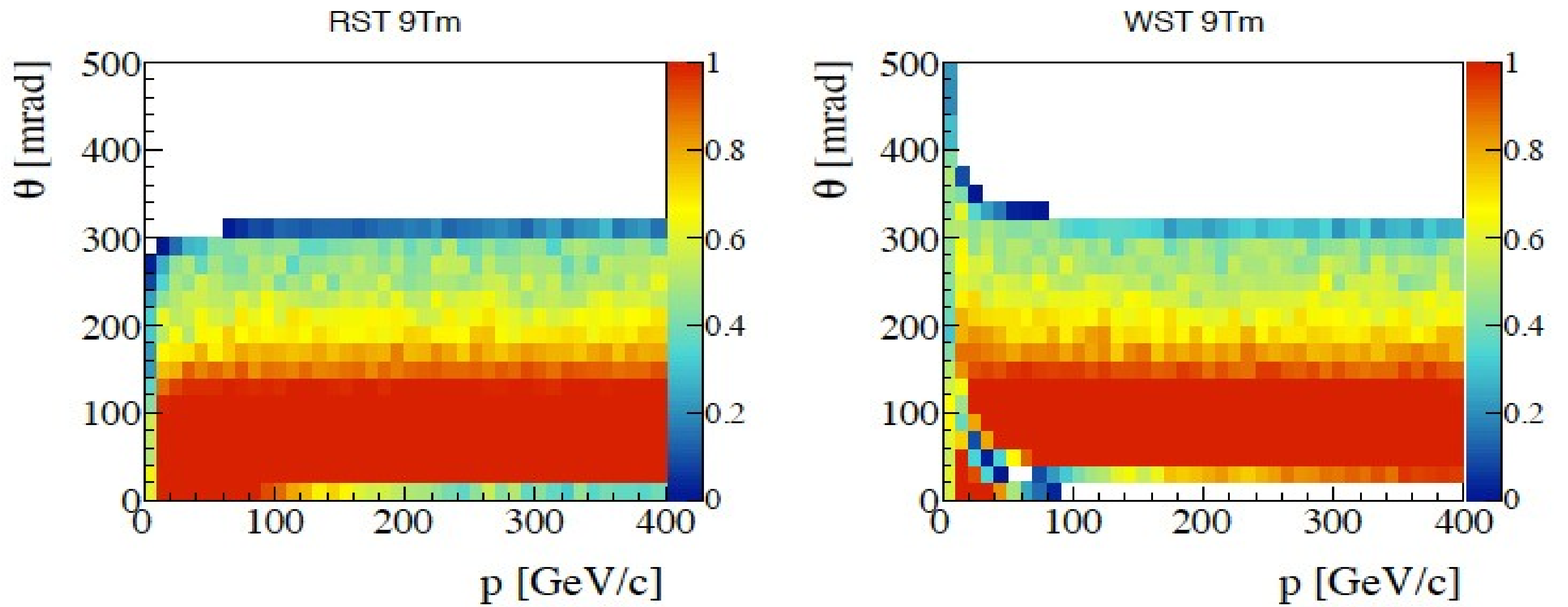
US Interest in NA61/SHINE

- **Institutions:** FNAL, LANL. University of Texas at Austin, TX, University of Colorado, Boulder, CO, Northwestern, IL, University of Pittsburgh, PA, University of Rochester, NY, 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.
- On May 2 US funding adgencies (DOE and NSF) have been informed of our plans: Submitted Letter of Intent (LOI) – Detailed full proposal to be submitted later this summer
- On May 3 the NA61 Collaboration Board and Spokesperson accepted the limited membership of the US groups in NA61.
- Thin target 120 GeV/c run planned for this summer using the T2K thin target and holder is important both to demostrate feasibitly of full plan and for US groups to gain experience with the NA61 detector → Hoping for several weeks of running during 2014

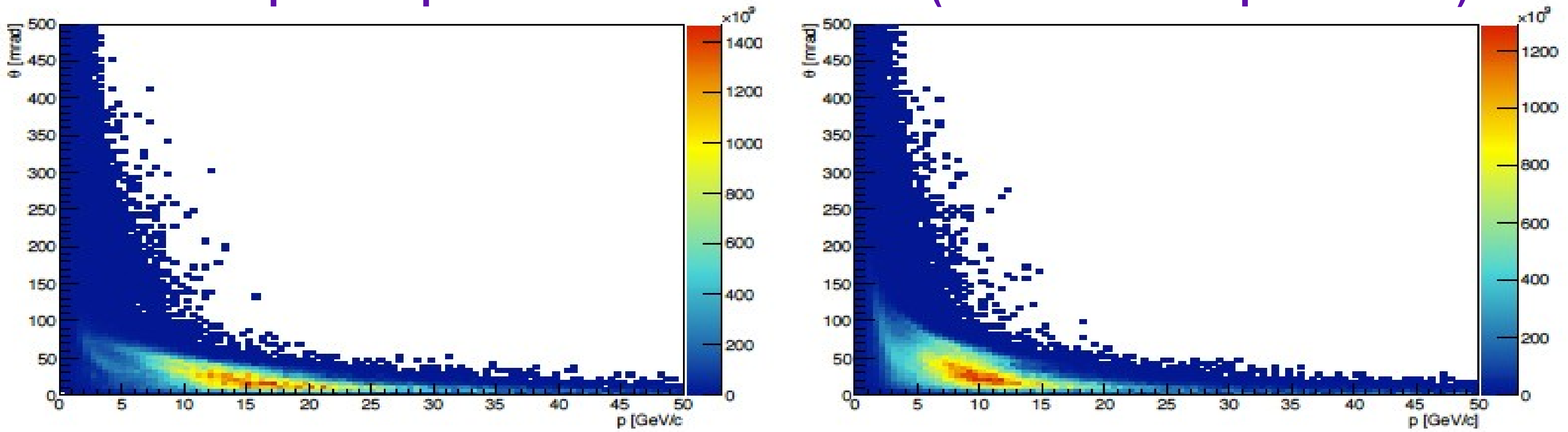
Valid for any future project

NA61/SHINE for LBNO

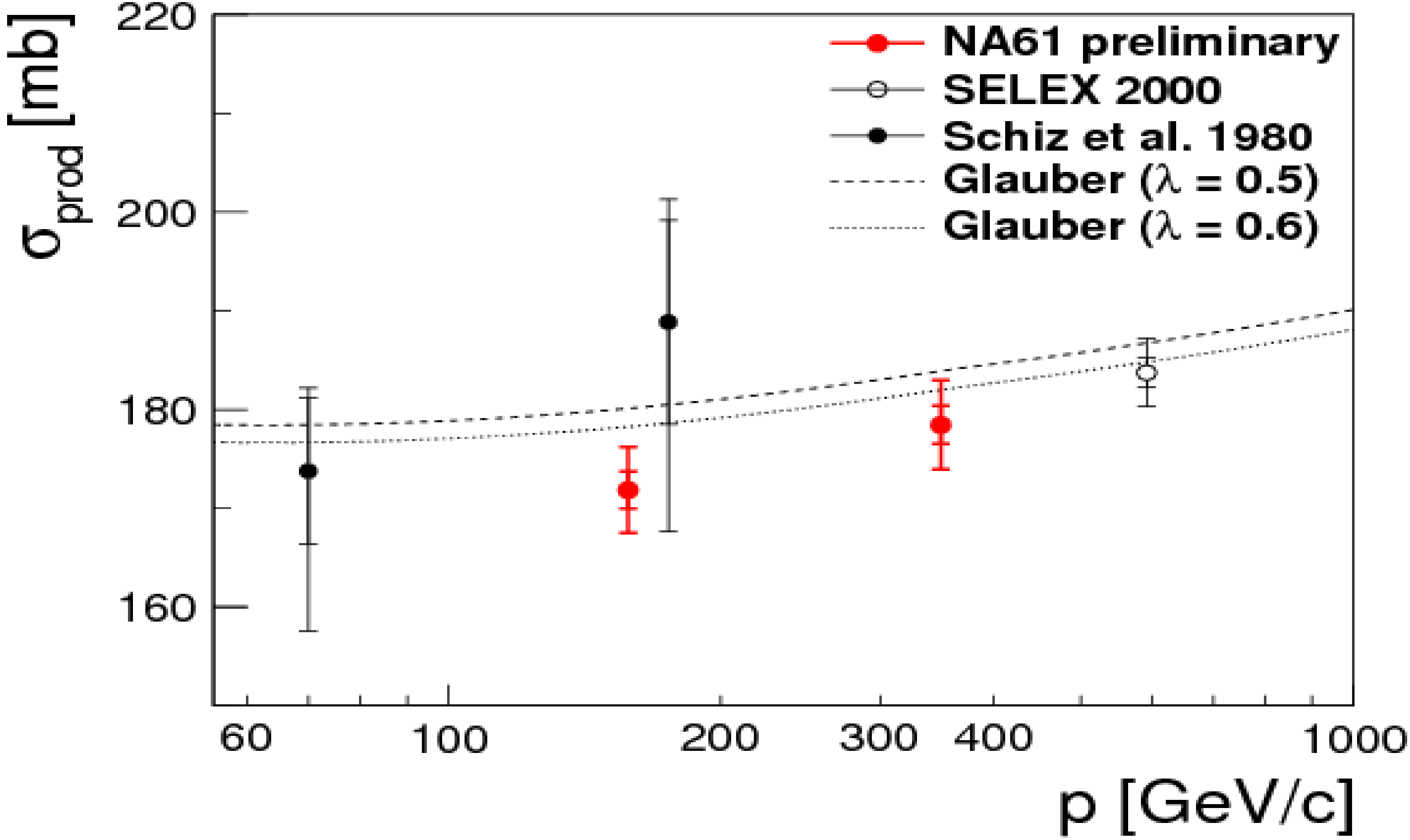
NA61/SHINE acceptance in the full-magnetic field configuration



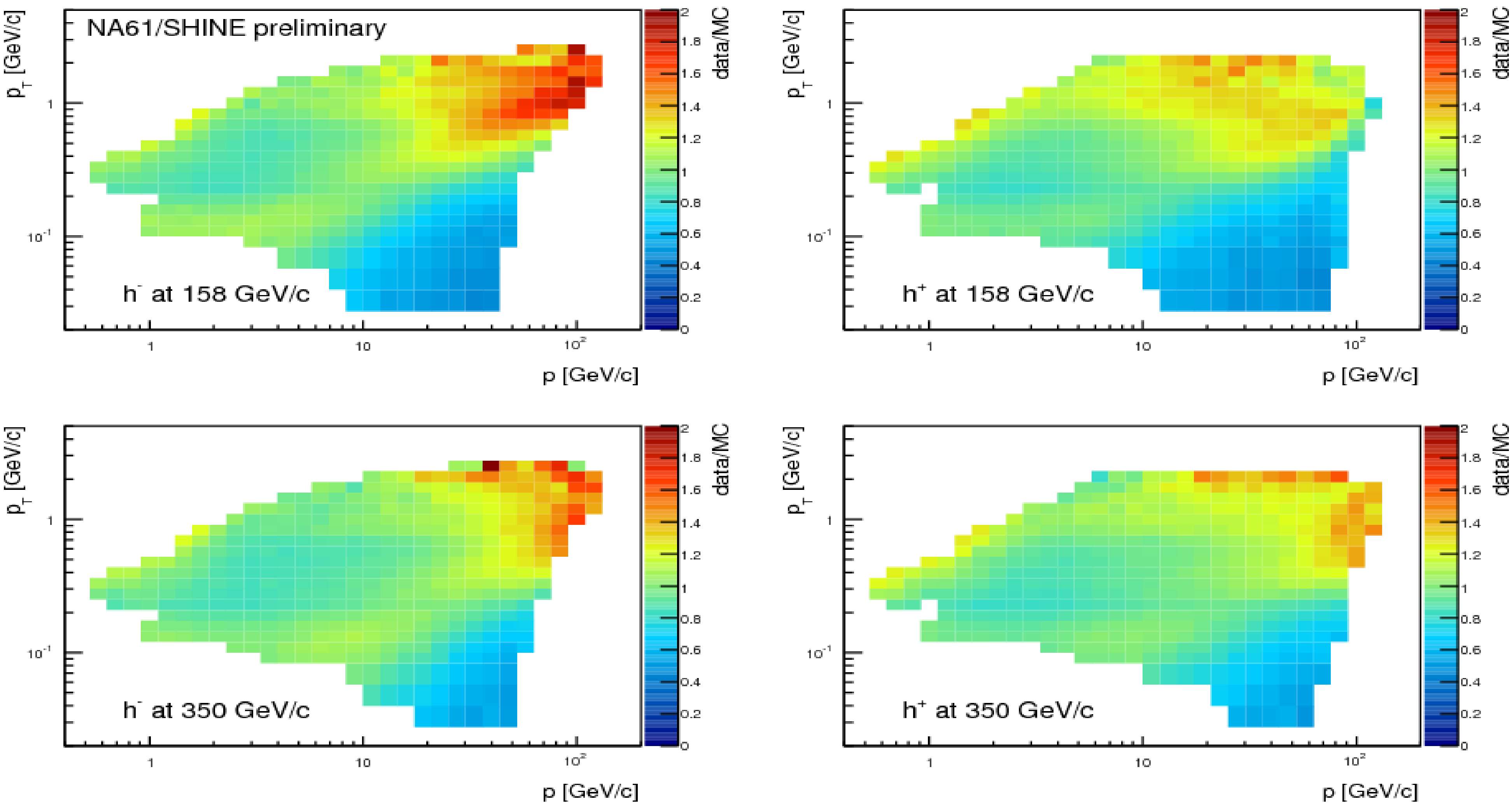
P-theta phase space of interest for LBNO (current beam optimization)



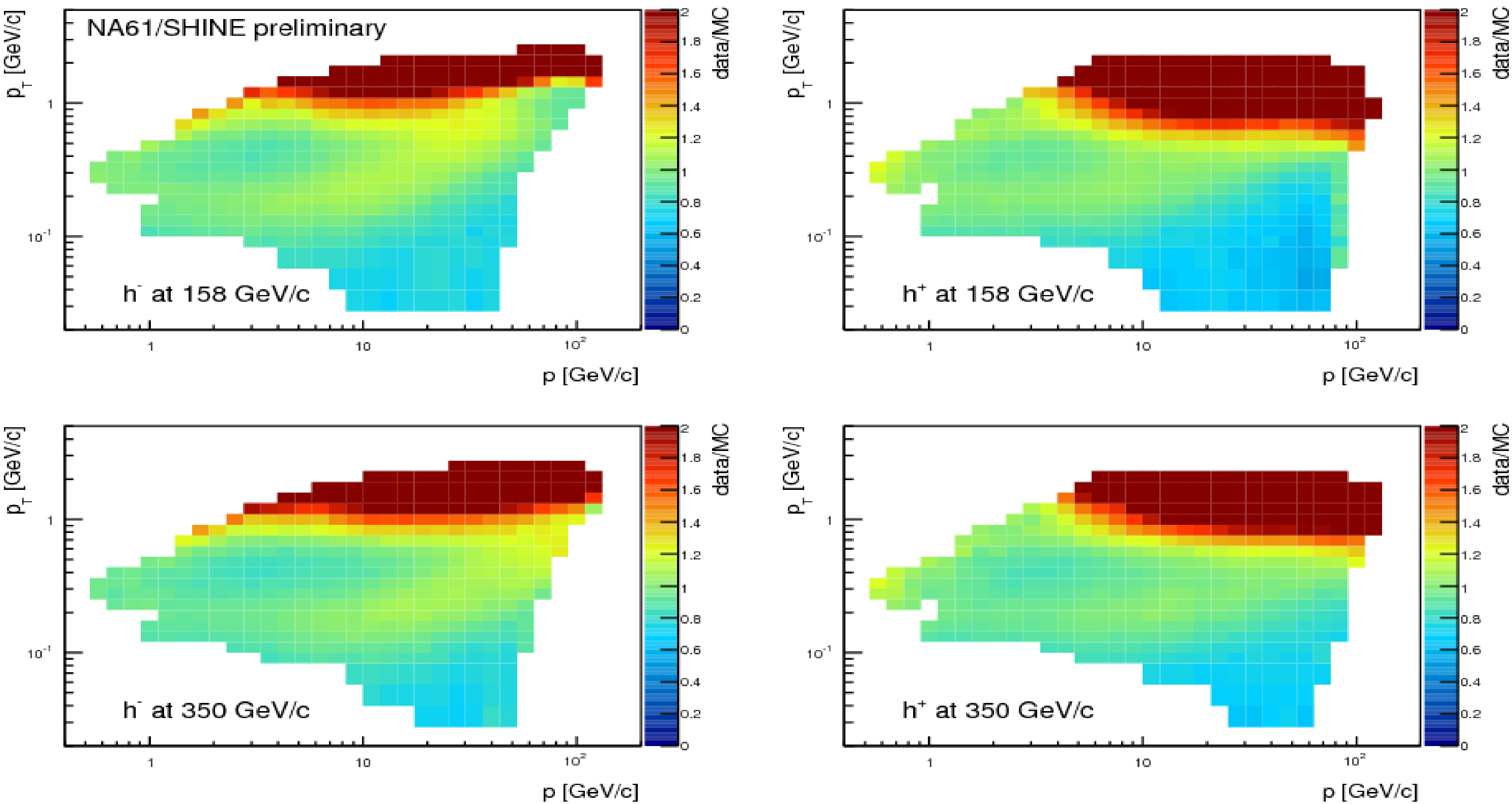
NA61/SHINE: π^-+C cross section



NA61/SHINE: π^-+C vs QGSJetII

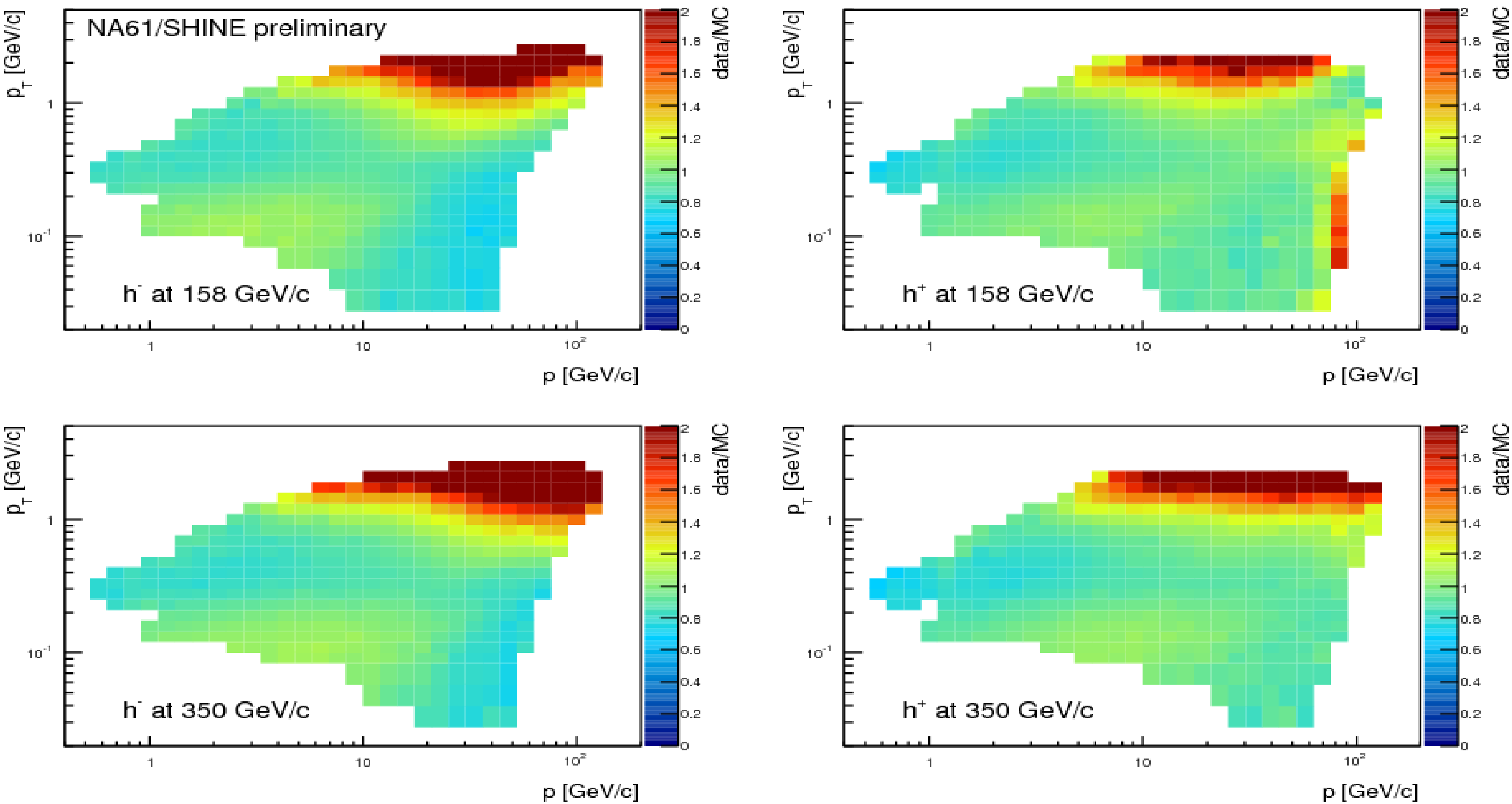


NA61/SHINE: π^-+C vs Sibyll2.1

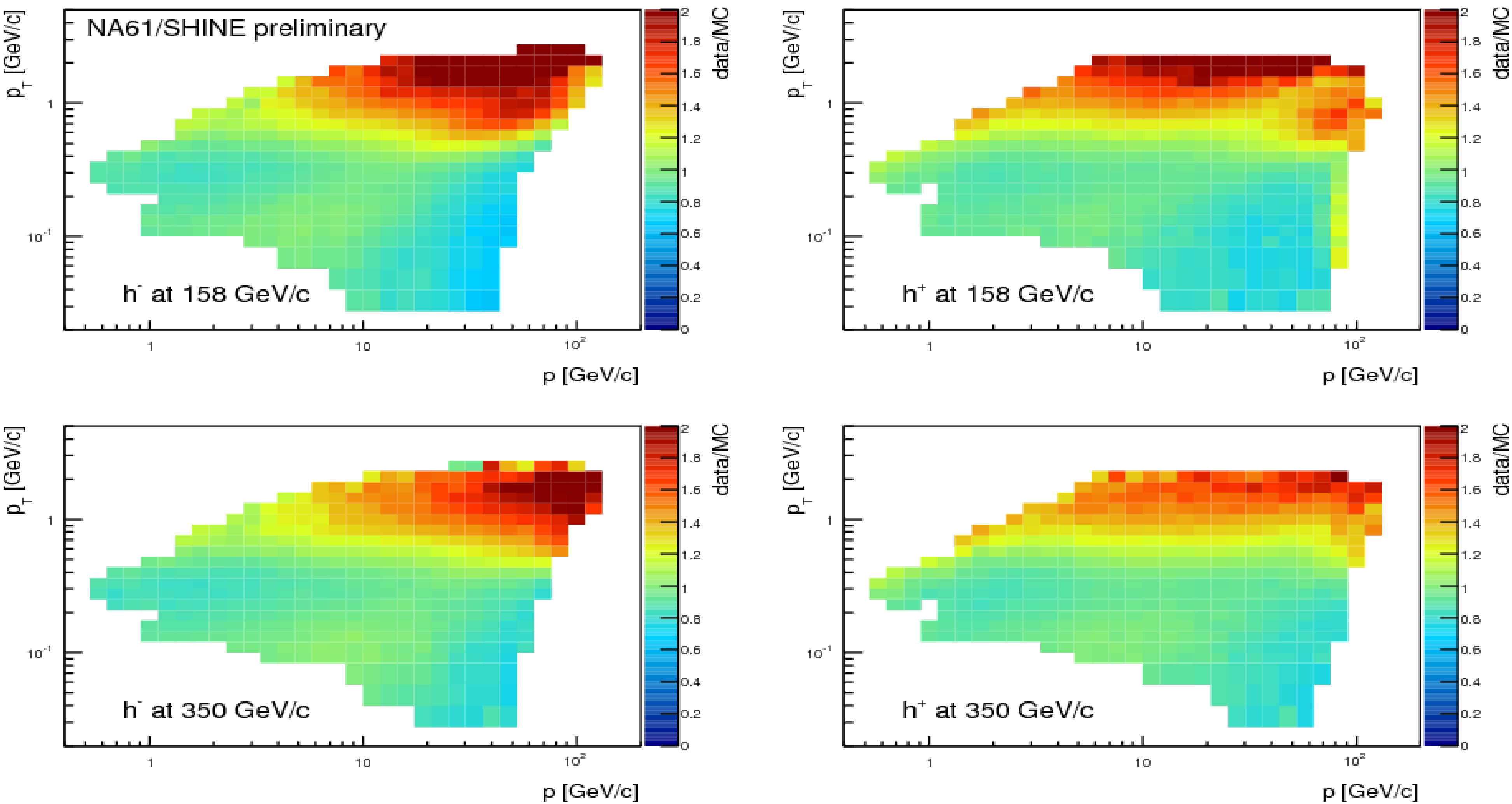


CERN-SPSC-2012-029

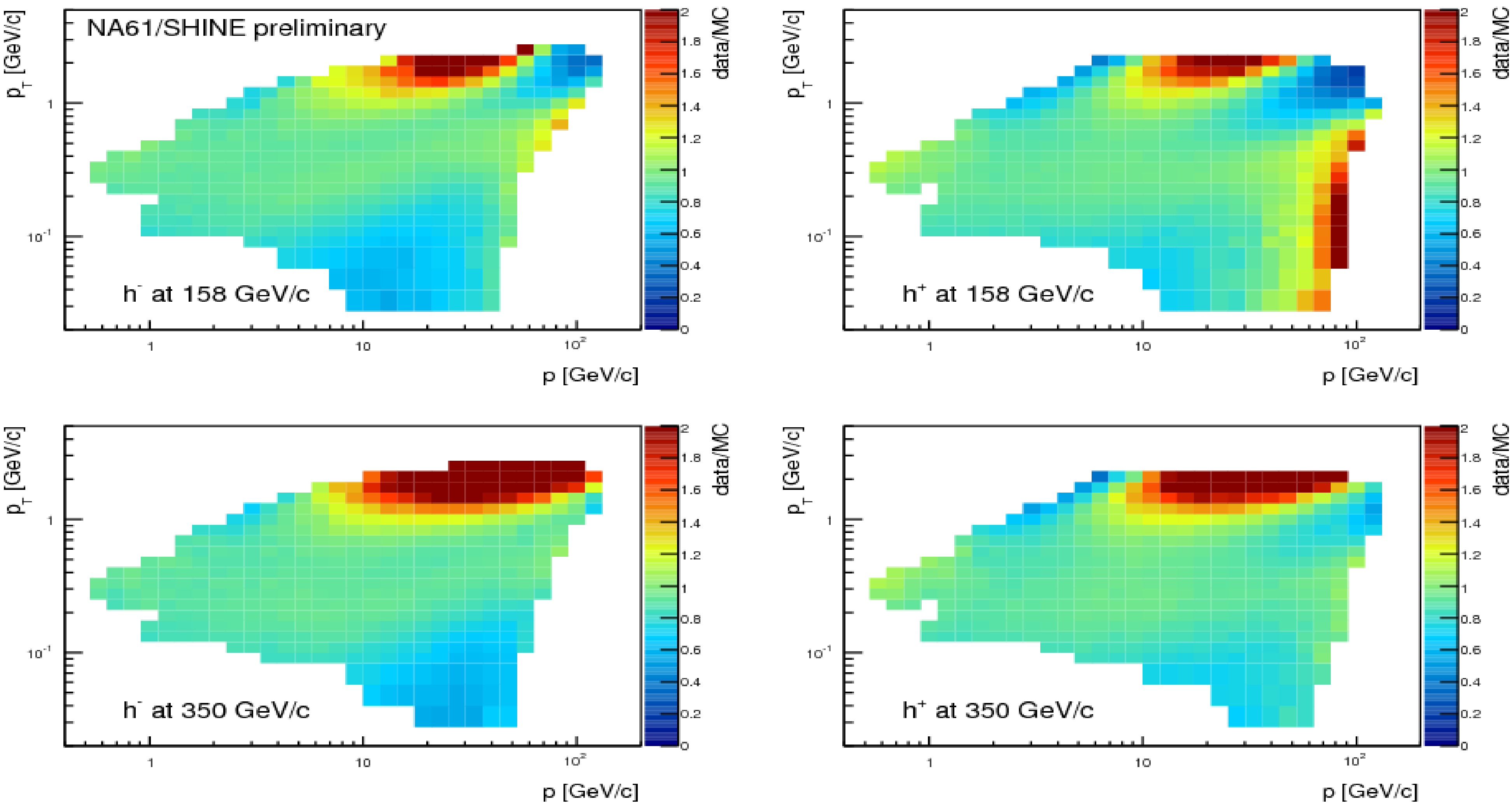
NA61/SHINE: π^-+C vs FLUKA2011



NA61/SHINE: π^-+C vs EPOS1.99



NA61/SHINE: π^-+C vs UrQMD1.3.1*



CERN-SPSC-2012-029

HARP: comparison with MC

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

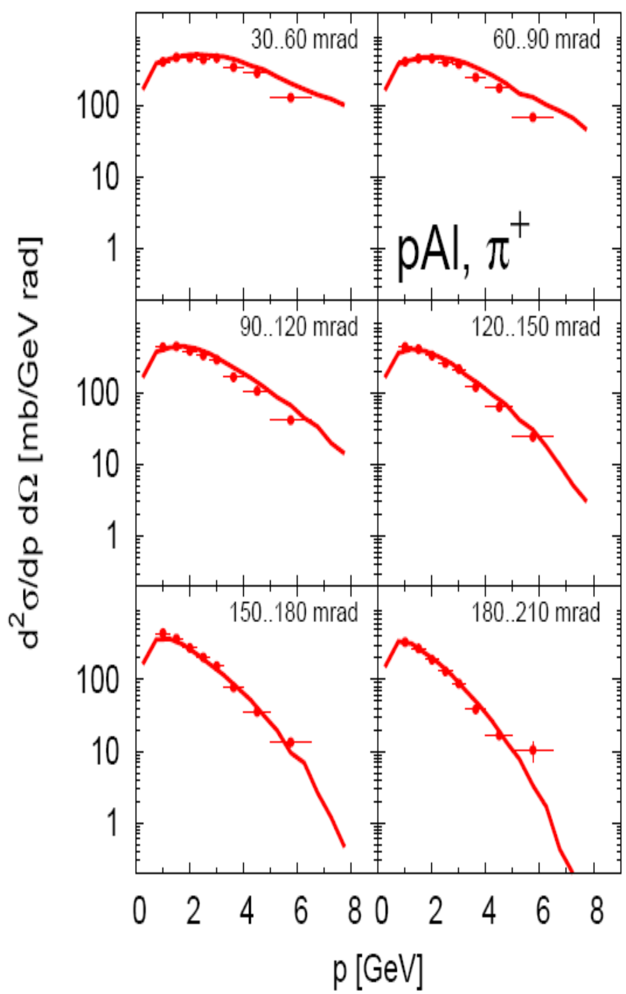
Only some examples are shown here

GEANT4:
- Binary cascade
- Bertini cascade
- Quark-Gluon string (QGS)
- Fritiof (FTFP)
- LHEP

FLUKA

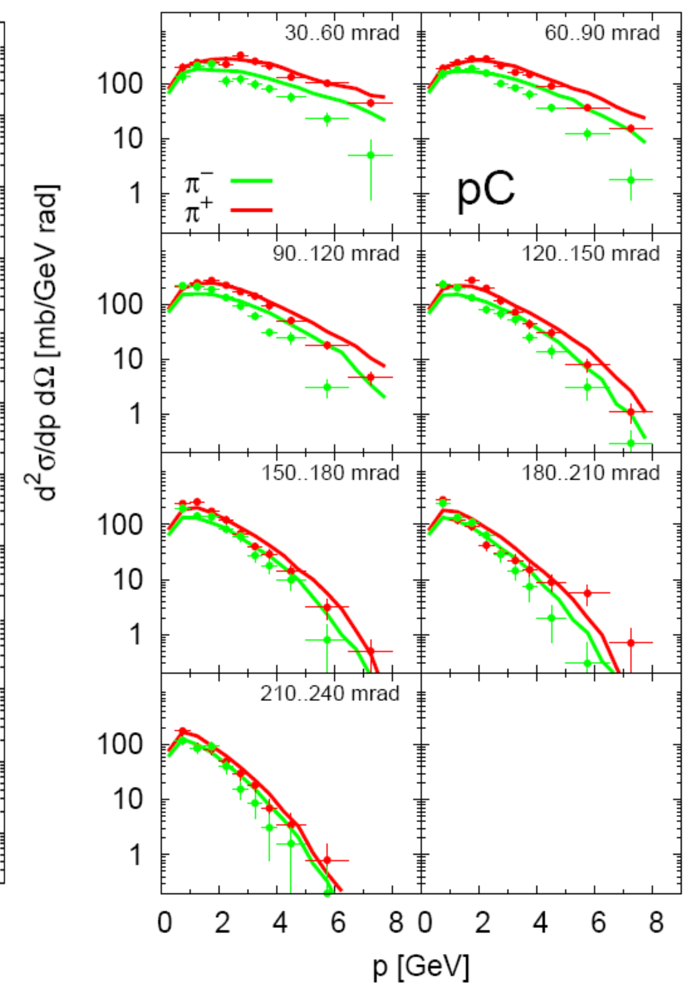
MARS

GiBUU



Nucl. Phys. A826 (2009) 151

HARP vs GiBUU



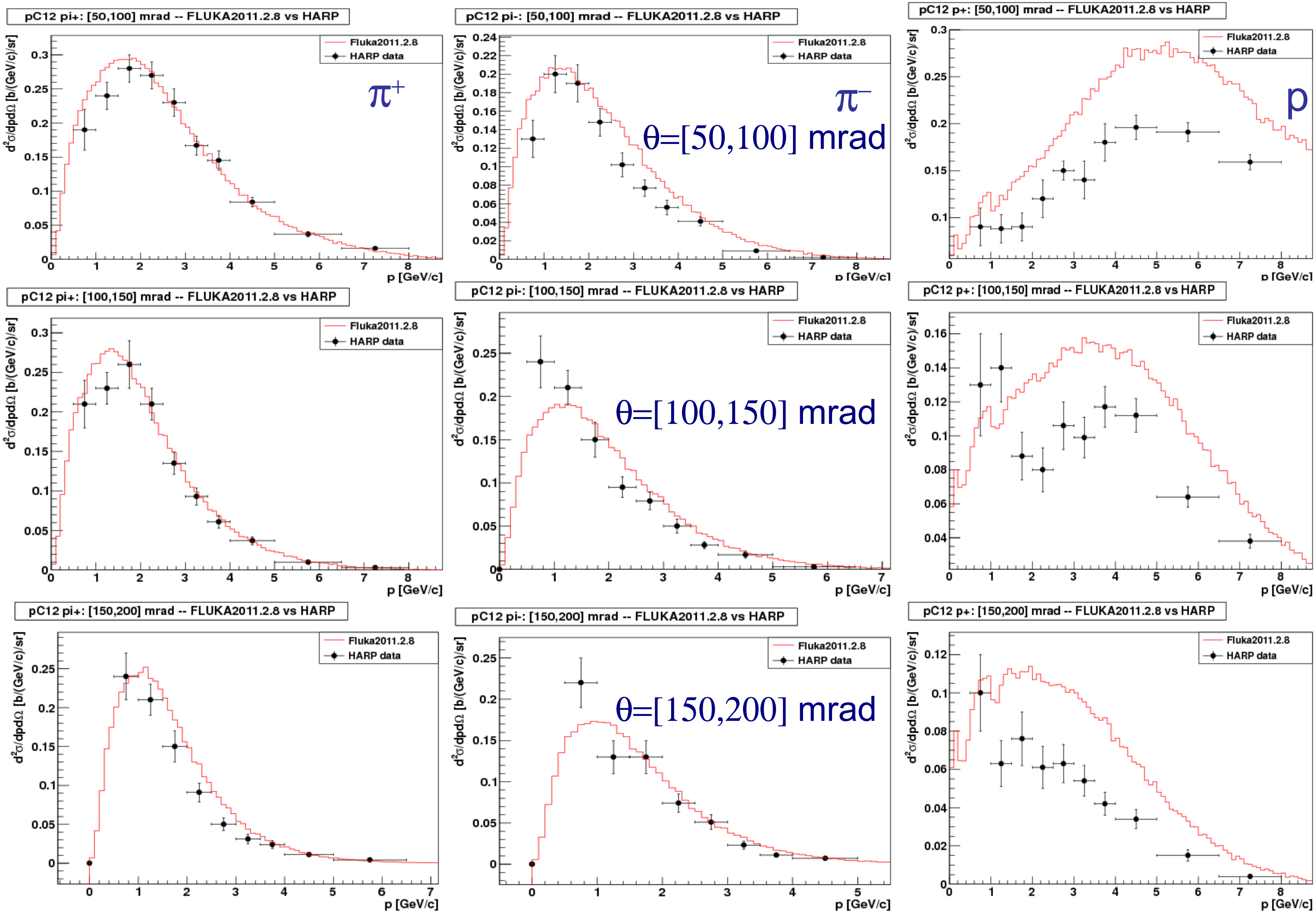
Phys. Rept. 512 (2012) 1

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 thechnical 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