TRIUMF

Hadron production overview

Current and future projects

Matej Pavin,
on behalf of NA61/SHINE and EMPHATIC collaborations

17. 10. 2018.

EMPHATIC

SHINE

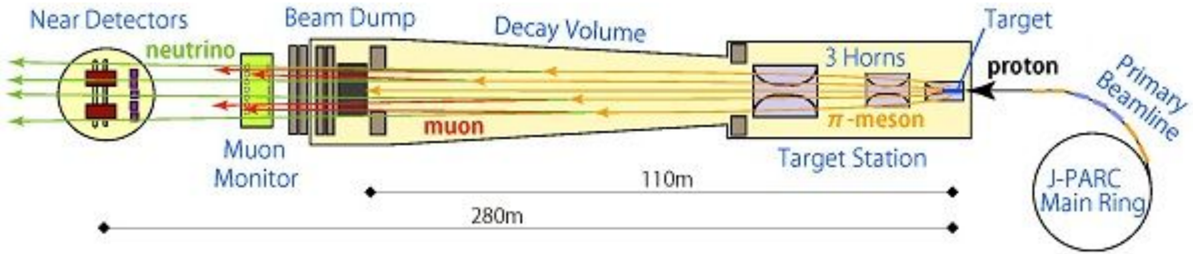
T2K

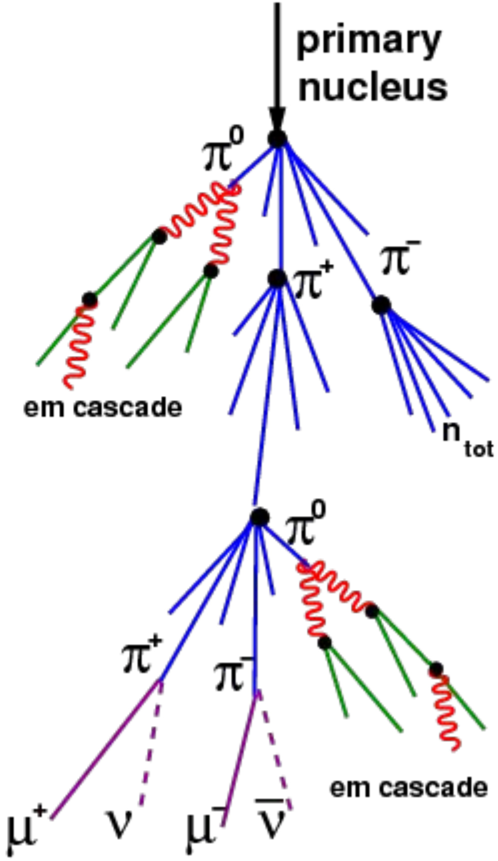
Outline

- Overview of the hadron production measurements used in neutrino flux simulations
- Why we need hadron production data?
- Hadron production experiments and results
- Future prospects

Motivation (I)

- Neutrinos in atmospheric and accelerator-based experiments are produced from pion, kaon and muon decays
- Pions, kaons, and muons are produced in hadronic interactions with the atmosphere or the target
- Beams used for neutrino flux production are at: J-PARC (30 GeV), NuMi (120 GeV) and Booster (8 GeV)
- Cosmic rays: up to 10^{20} GeV

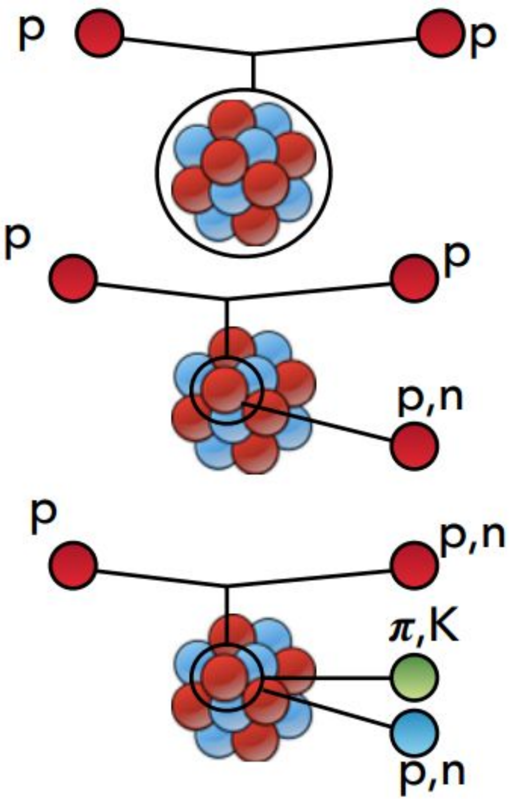




Motivation (II)

- Produced neutrino flux cannot be directly measured ➜ we rely on simulations of hadronic interactions
- Large differences between models ➜ large uncertainty of the neutrino flux
- Hadron production data is necessary to select or tune the models
- Neutrino flux uncertainty is the dominant uncertainty in many neutrino measurements
- Single detector measurements are mostly affected (neutrino-nucleus cross-section measurements, sterile neutrino searches, measurement of CP violation in atmospheric neutrinos)

Hadron interactions for neutrino physicists



Coherent elastic interactions (σ_{el})

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{qel}} + \sigma_{\text{prod}}$$

$$\sigma_{tot} = \sigma_{\text{el}} + \sigma_{\text{inel}}$$

Quasi-elastic interactions (σ_{qel})

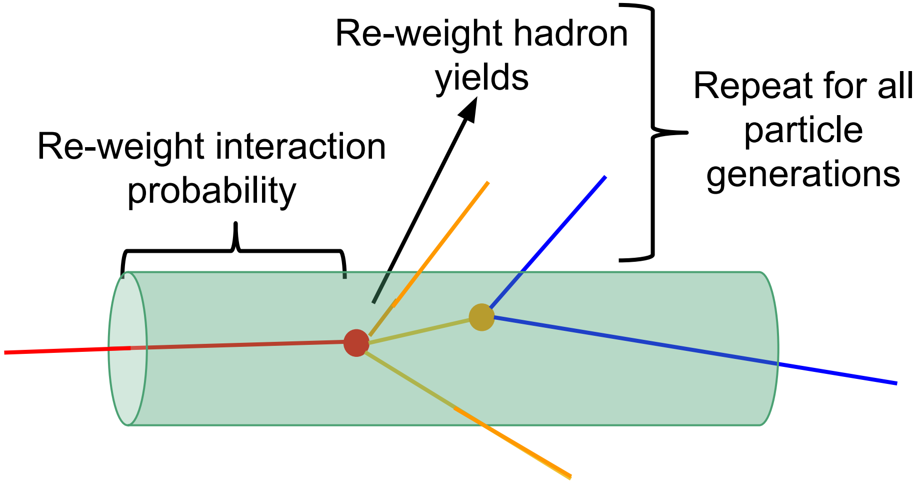
Particle production (σ_{prod})

Inelastic interactions (σ_{inel})

Hadron production measurements

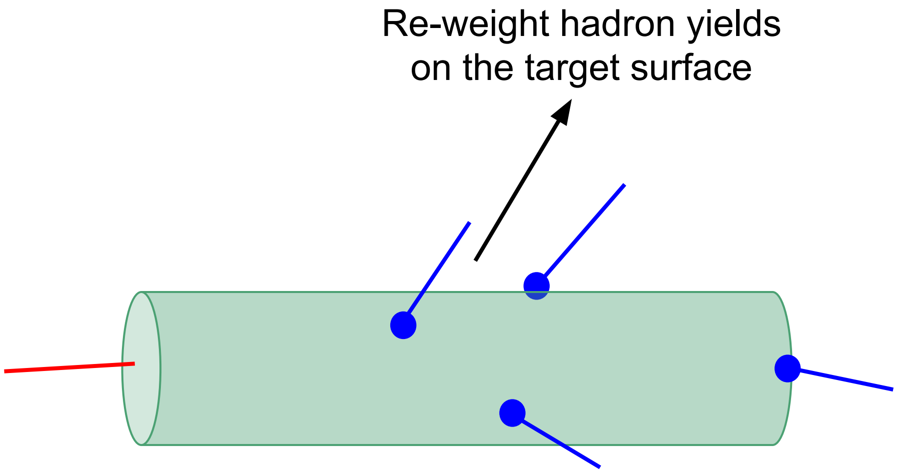
- **Hadron production measurements can be used to tune models**

① Thin target measurements



Useful for all experiments!

② Replica target measurements



Mostly useful for a single experiment

Both approaches are necessary!

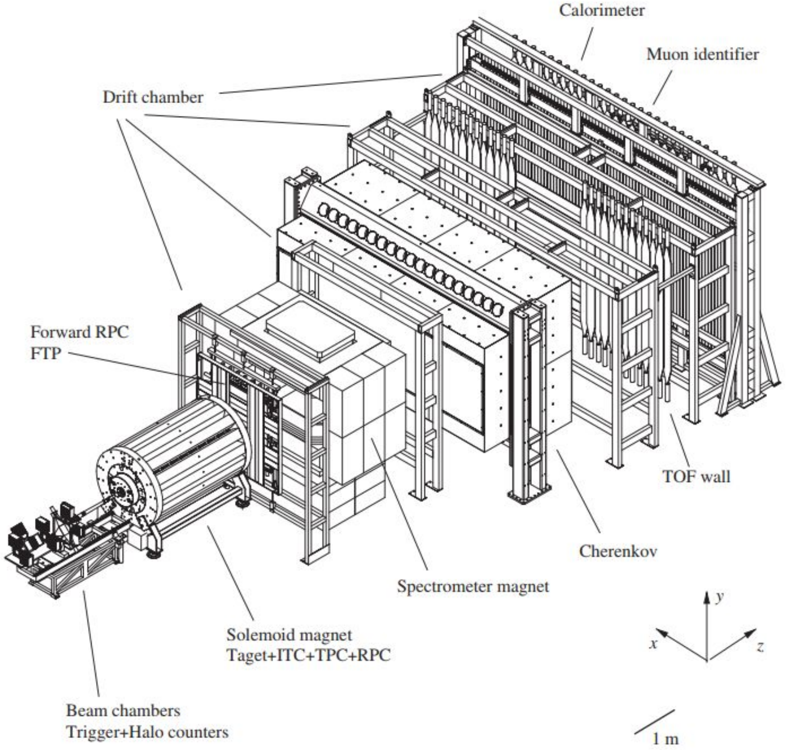
Hadron production experiments

- Two measurements are needed: **production cross section** (probability of interaction) and **particle multiplicities** (number of produced hadrons)
- Only some of the experiments measuring both quantities will be mentioned in this talk (otherwise, the talk would be too long)
- For an extensive list of hadron production measurements check Phys. Rev. D 87, 012001 (2013)
- Old cross-section measurements
    - Results are often confusing ➔ it is not clear which cross-section was measured (inelastic or production)

In this talk:
HARP
MIPP
NA49
NA61/SHINE
EMPHATIC

HARP (Hadron Production Experiment)

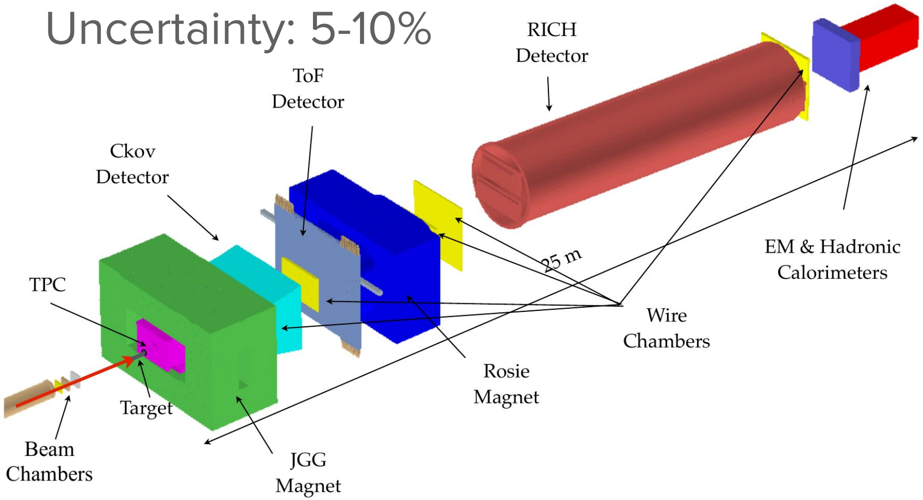
- CERN PS
- Beam momentum: 1.5-15 GeV/c
- Targets: A = 1-200
- **$p+A \to \pi^{\pm}$ (3-12 GeV/c):** Phys.Rev. C80 (2009) 035208
- **$\pi^{\pm}+A \to \pi^{\pm}$ (3-12 GeV/c):** Nucl.Phys. A821 (2009) 118-192)
- **$p+N2, O2 \to \pi^{\pm}$ (12 GeV/c):** Astropart.Phys. 30 (2008) 124-132)
- Low angle configuration 0-250 mrad
- High angle configuration 350 - 2150 mrad
- Systematics : 5% due to re-interactions

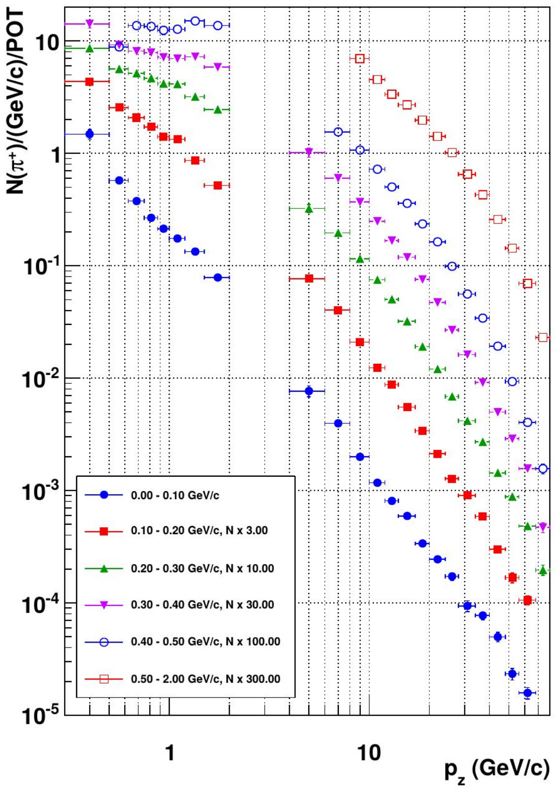


Nucl. Instr. Meth. A 571(2007) 527 13

MIPP (The Main Injector Particle Production Experiment)

- Secondary beam from the Main Injector
- Targets: H, D, Be, C, N, Cu, Bi, U, NuMI
- Beam: π, K, p, beam momentum: 5 - 120 GeV/c (primary and secondary beam)
- p_t: 0-2 GeV/c
- p_z: 0-80 GeV/c
- Uncertainty: 5-10%

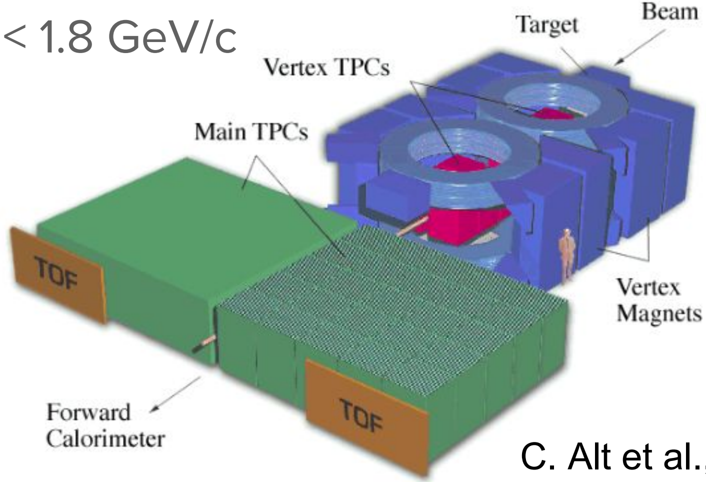


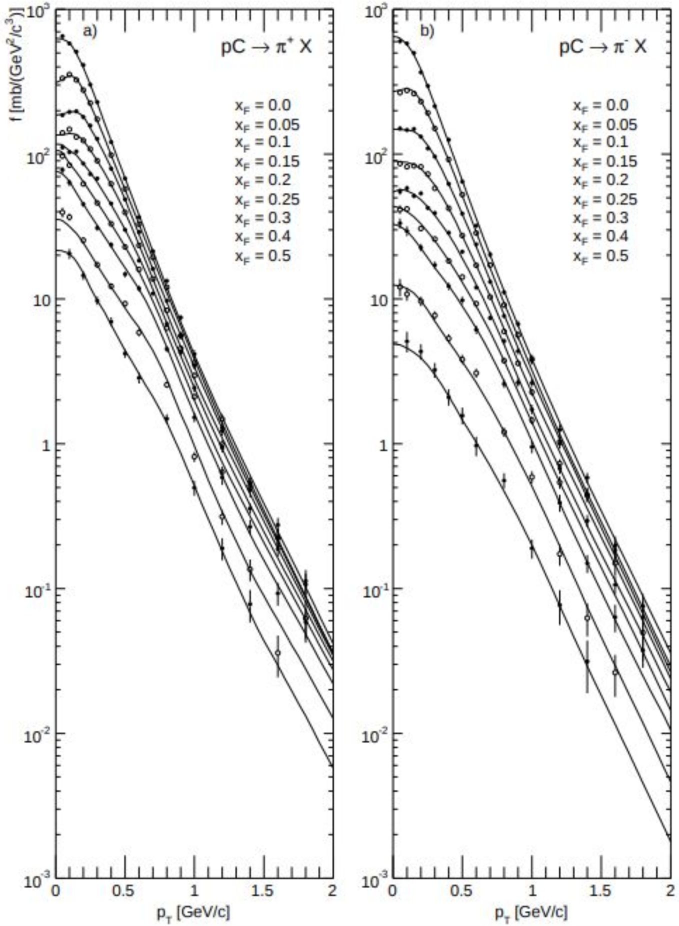


Phys.Rev. D90 (2014) 032001

NA49

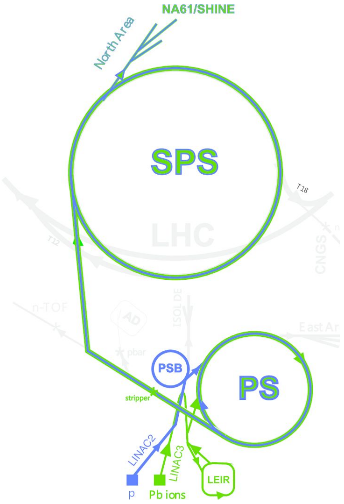
- CERN SPS
- Main physics goal is not related to neutrino physics
- Beam: 158 GeV/c
- p+p, p+A, A+A collisions
- p+C measurements are useful for NuMI flux predictions
- Systematics: 3-8%
- x_F: -0.1 - 0.5, $p_t < 1.8$ GeV/c

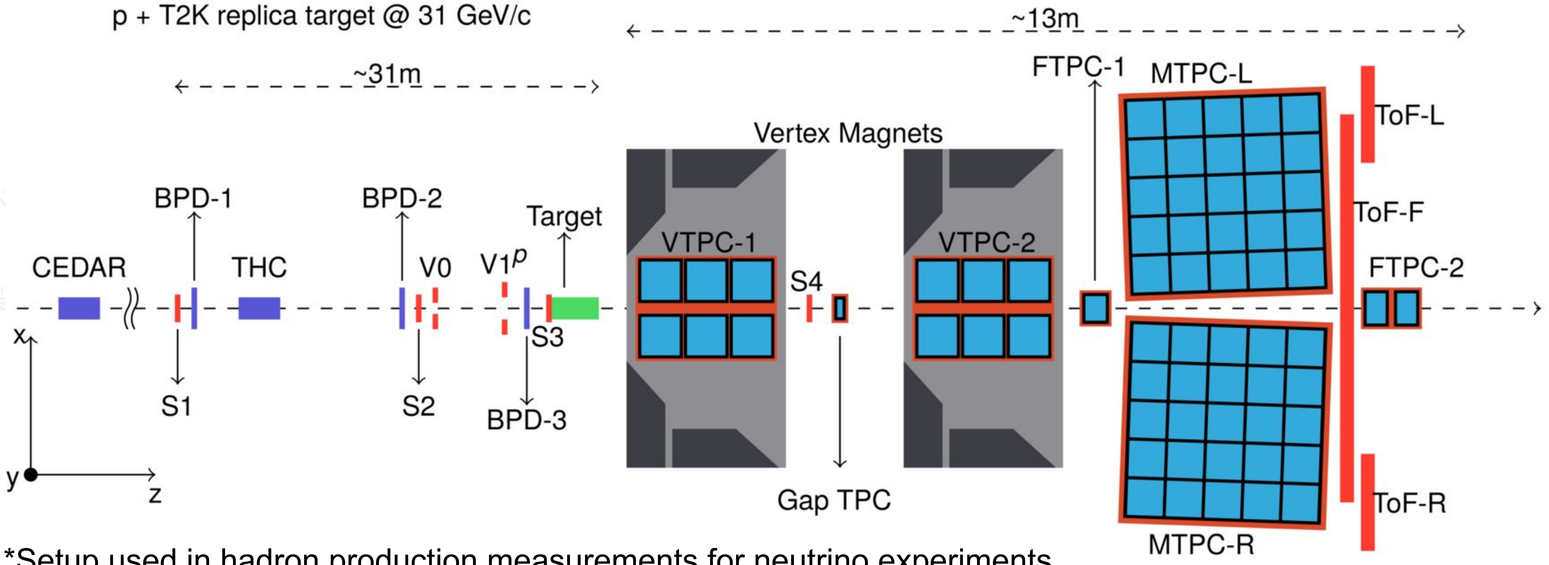




C. Alt et al., Eur.Phys.J. C49 (2007) 897-917

North Area 61 / SPS Heavy Ion and Neutrino Experiment
NA61 / SHINE





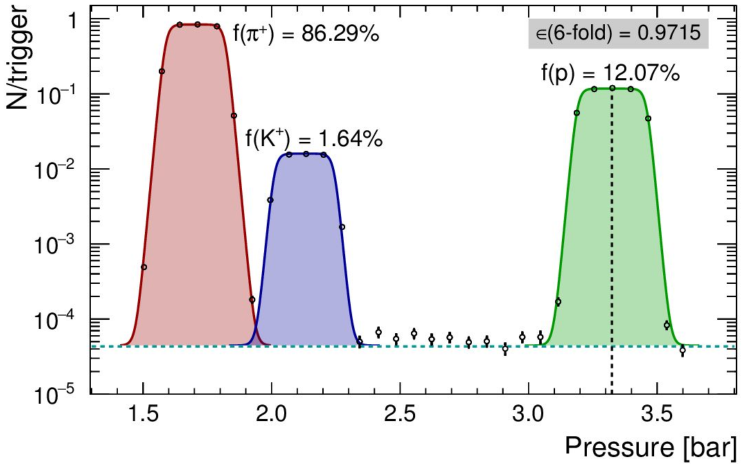
*Setup used in hadron production measurements for neutrino experiments

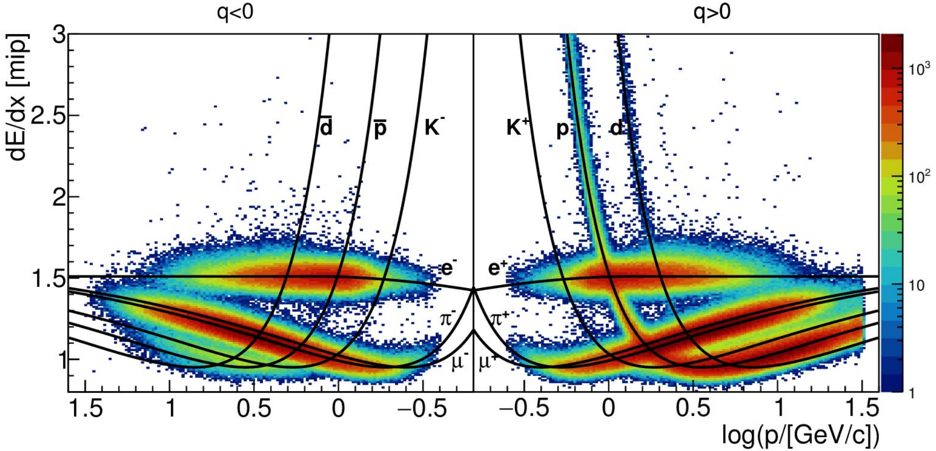
- Precise hadron production measurements for neutrino flux re-weighting in T2K and Fermilab neutrino experiments

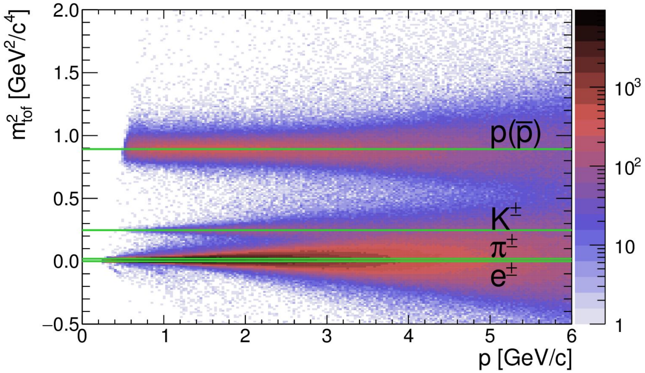
ONGOING **FINISHED**

Capabilities of the NA61/SHINE detector

- Beam momentum between 13 and 160 AGeV/c
- Beam purity for hadrons is very high (at 31 GeV/c > 99.9%)
- Large acceptance (for T2K measurements 400 mrad)
- PID: dE/dx + tof



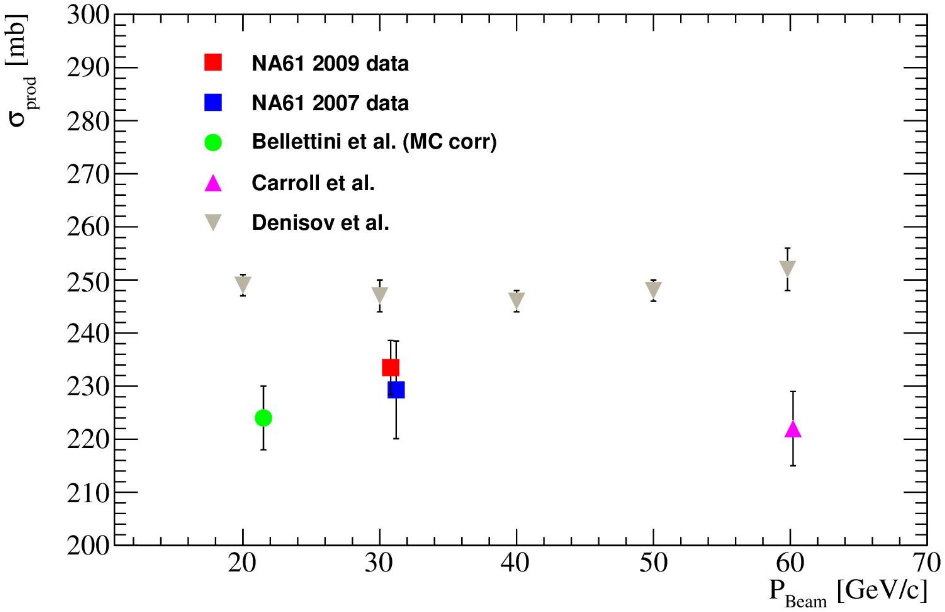




NA61/SHINE thin target measurements for T2K

- 2 cm thick graphite target and 30.92 GeV/c proton beam
- Inelastic and production cross section + double differential hadron (**$\pi^{\pm}$, $K^{\pm}$, K^0_s, p, Λ**) yields

Year	[10^6] events	Results
2007	0.7	$\pi^{\pm}$, K^{+}, K^0_s, Λ [1,2]
2009	5.4	$\pi^{\pm}$, $K^{\pm}$, K^0_s, p, Λ [3]

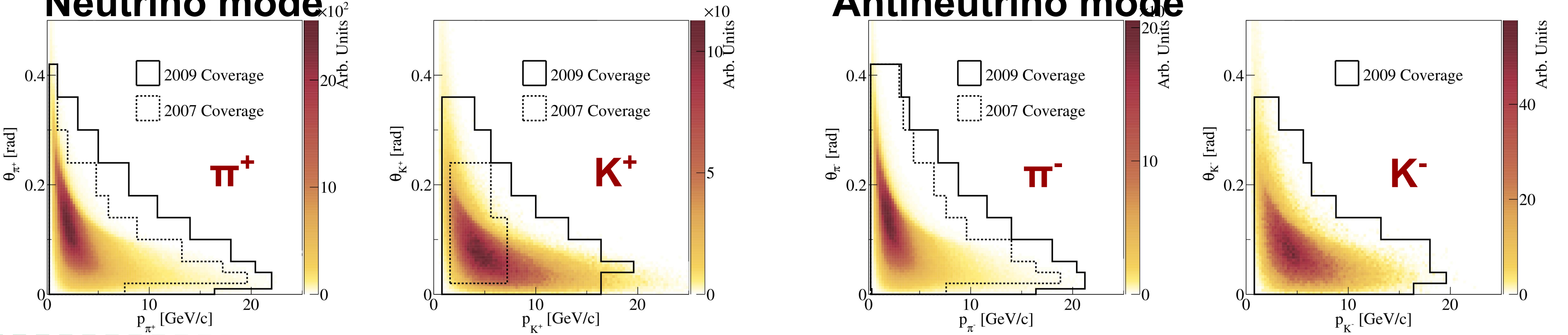


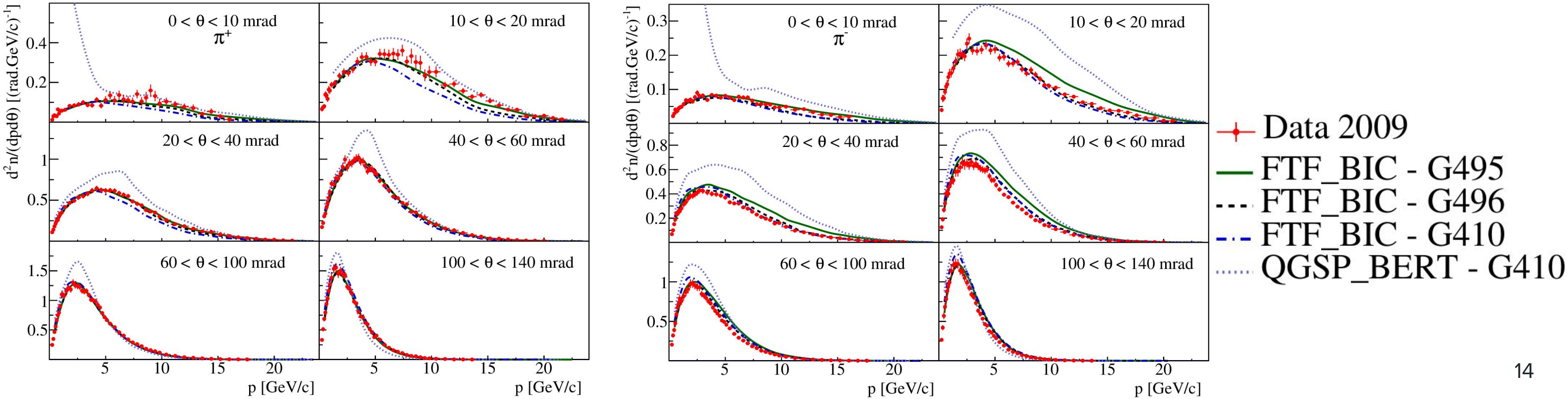
$$\sigma_{\rm prod} = \left(230.7 \pm 2.7({\rm stat}) \pm 1.2({\rm det})^{+6.3}_{-3.4}({\rm mod})\right) mb$$

[1] Phys. Rev. C84, 034604 (2011). [3] Eur. Phys. J. C (2016) 76: 84
[2] Phys. Rev. C85, 035210 (2012).

NA61/SHINE thin target measurements for T2K

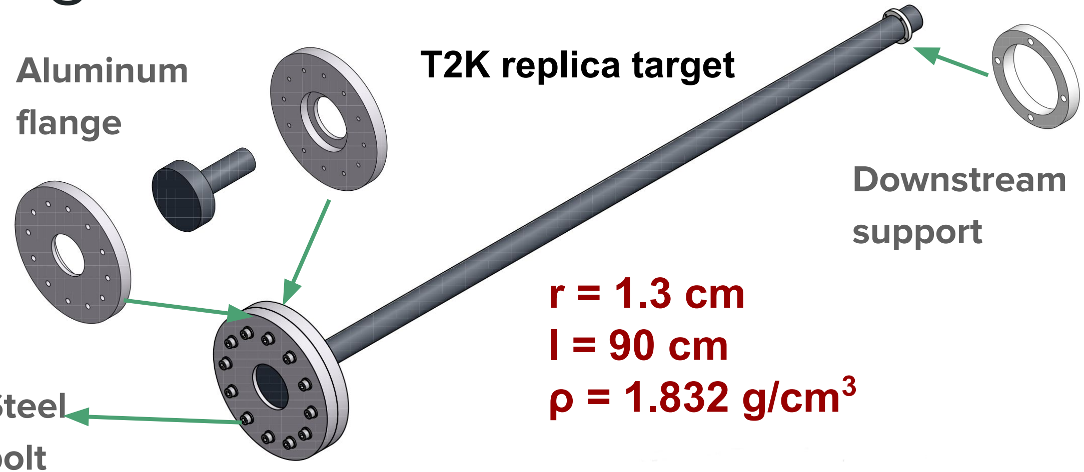
Neutrino mode **Antineutrino mode**





NA61/ SHINE replica target measurements for T2K

- Around 2 interaction lengths
- Interaction vertices are not reconstructed ➔ TPC tracks are extrapolated to the target surface
- Measurement of the production cross section is not necessary

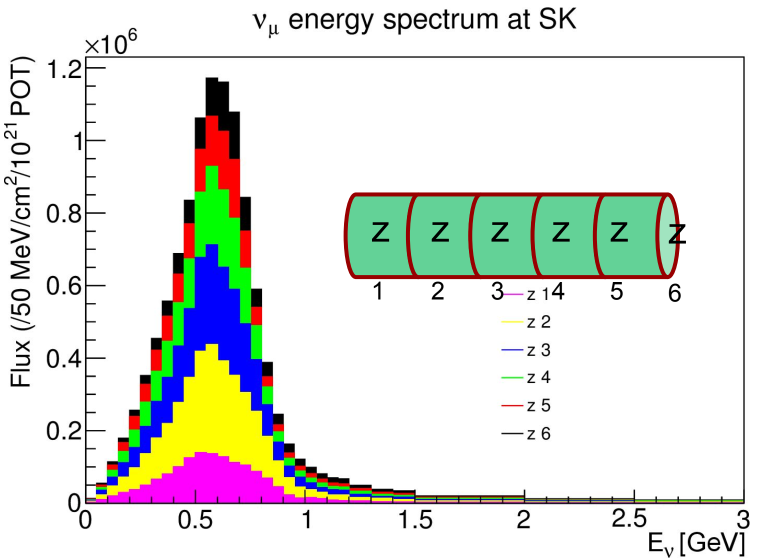


Year	POT [10^6]	Results
2007	0.2	proof of concept [1]
2009	4.0	$\pi^\pm$ yields [2]
2010	**10.2**	**$\pi^\pm$, $K^\pm$, p yields [3]**

[1] N. Abgrall et al., Nucl. Instrum. Meth., A701:99, 2013.
[2] N. Abgrall et al. Eur. Phys. J., C76(11):617, 2016.
[3] N. Abgrall et al., arXiv:1808.04927 [hep-ex], submitted to EPJC

Replica target measurements for T2K (2010)

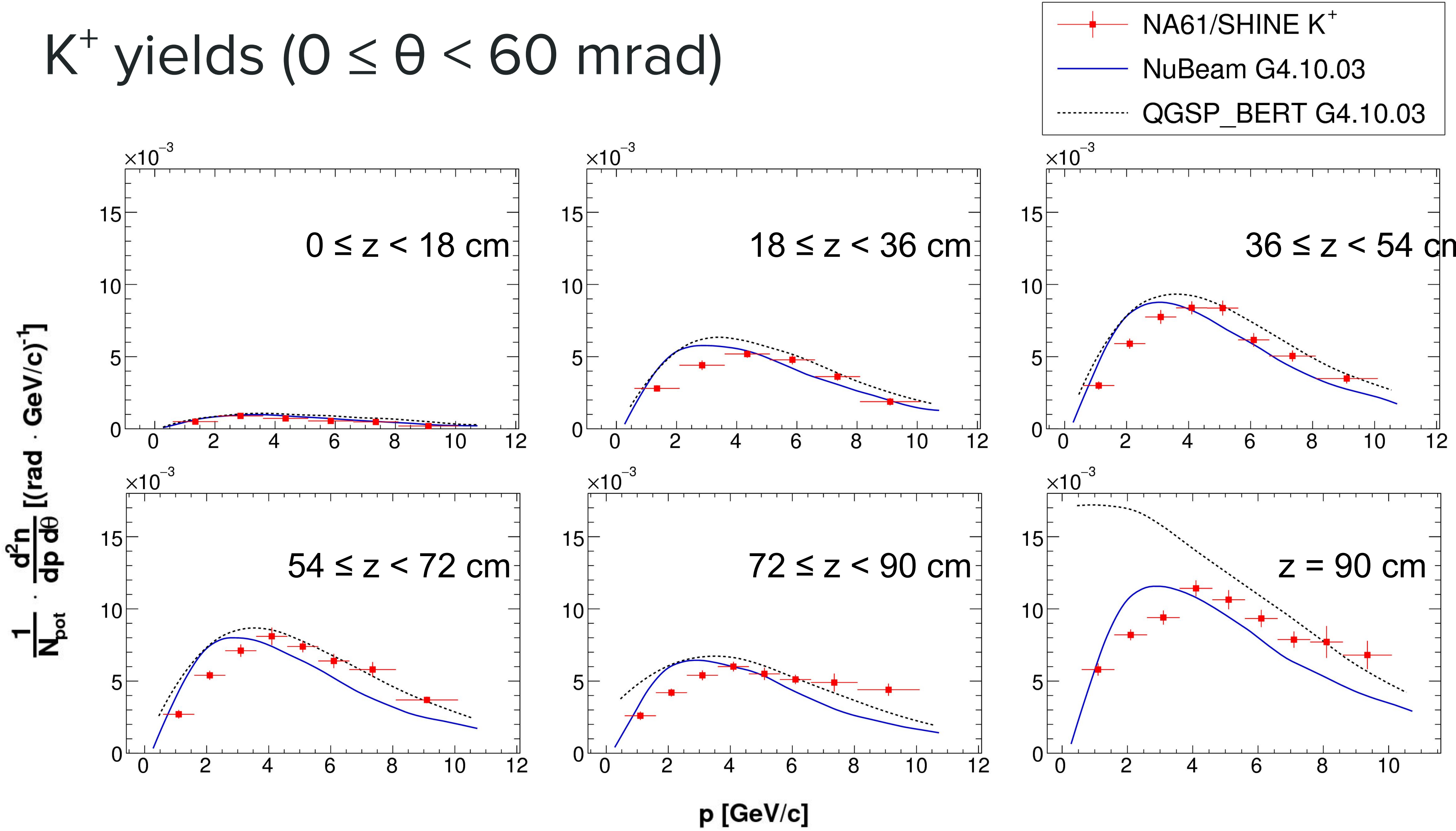
- Measurements are done as a function of momentum (p), polar angle (θ) and longitudinal position of the exit point on the target surface (z)
- 5 z bins (18 cm in size) + downstream target face
- p and θ bin size depend on the statistics



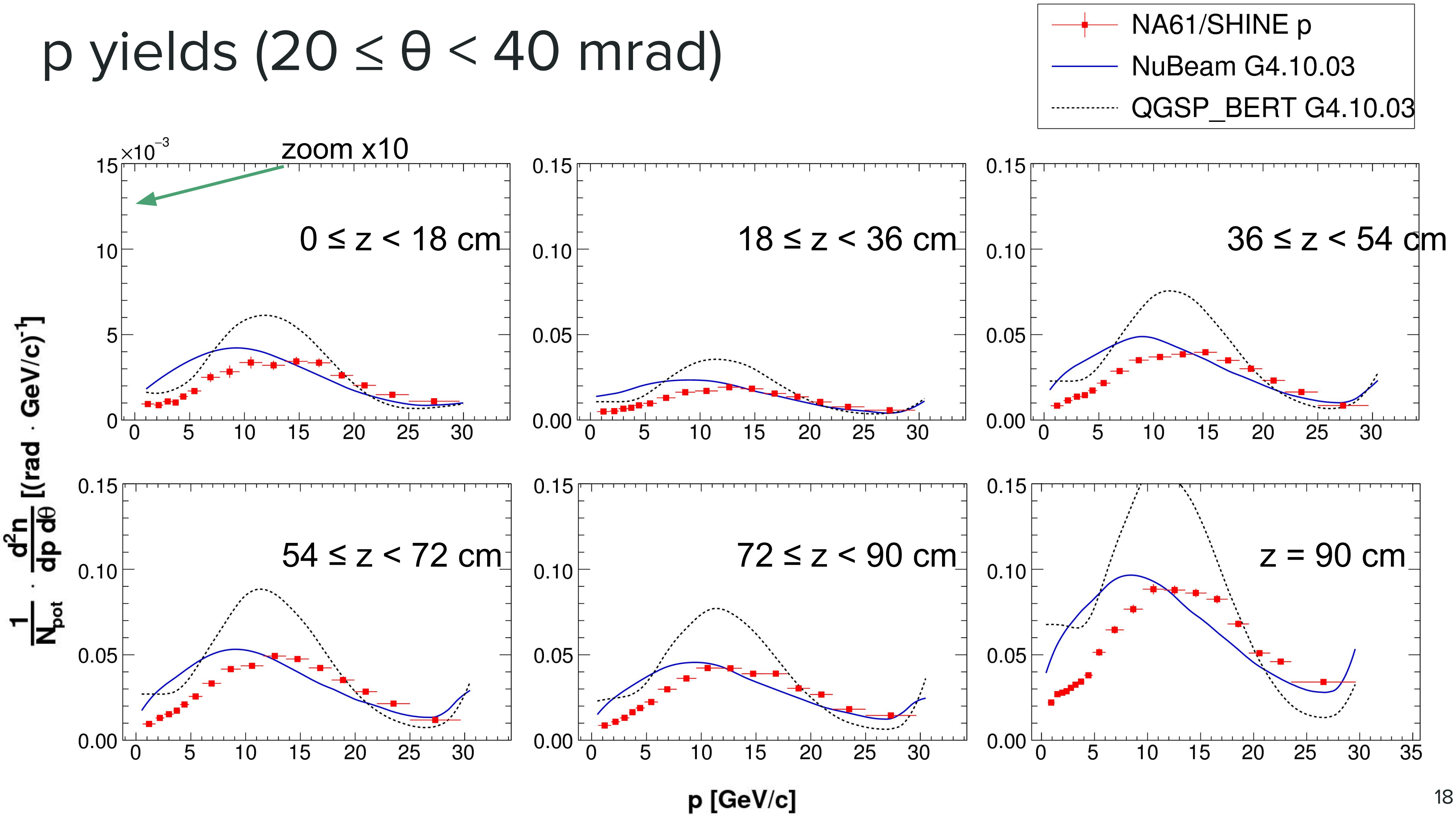
- percentage of neutrino flux produced from hadrons exiting the target covered by the replica target measurement

mode	π^+ [%]	π^- [%]	K^+ [%]	K^- [%]	p [%]	Tot [%]
ν	99.22	97.47	84.50	83.08	71.65	96.92
anti-ν	97.03	98.89	72.56	89.61	69.66	96.62

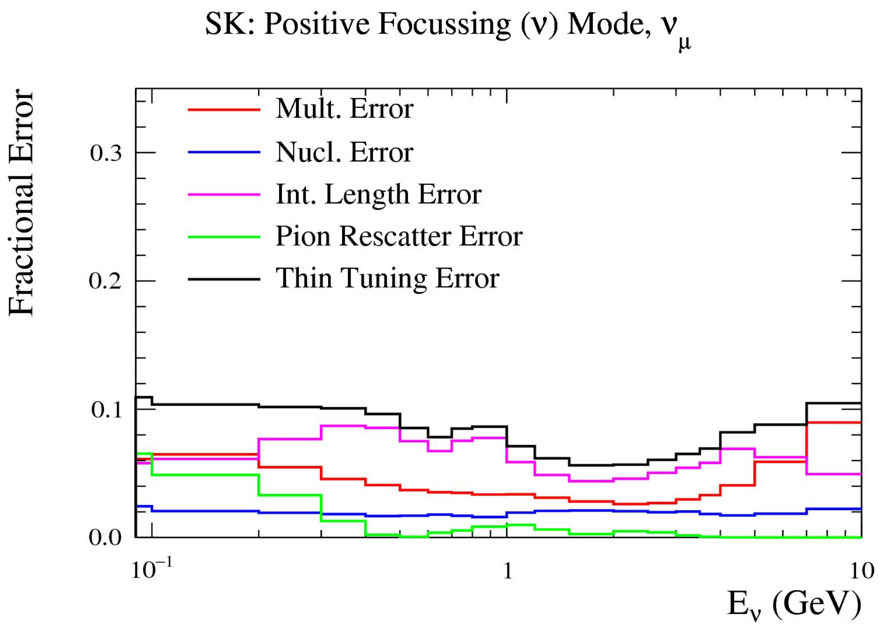
K^+ yields ($0 \leq \theta < 60$ mrad)

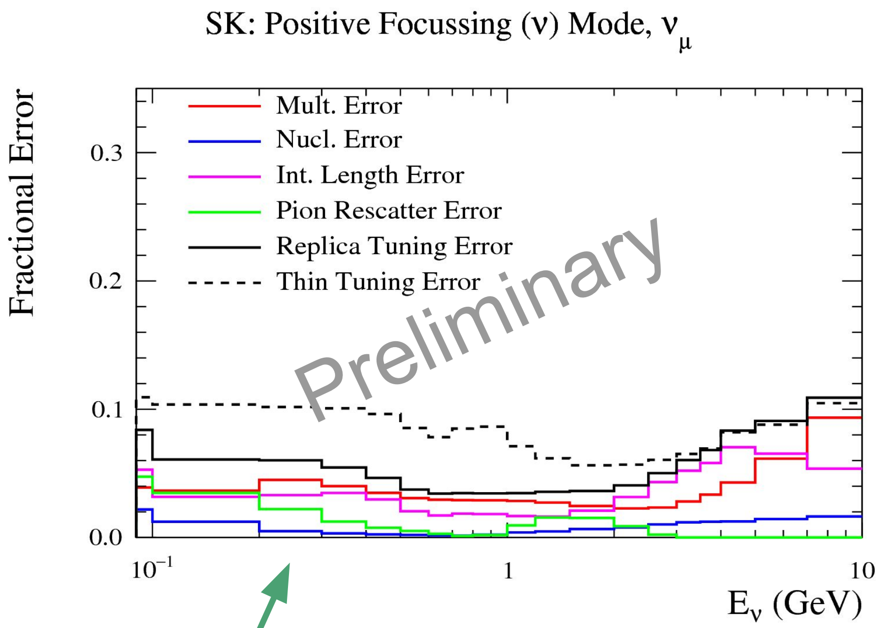


p yields (20 ≤ θ < 40 mrad)



T2K neutrino flux uncertainty





Please see Tomislav's talk!

Only $\pi^\pm$ replica-target measurements from 2009 data were used

Measurements for Fermilab neutrino programme

- Data-taking 2012 - 2018
- Data-taking will finish in October
- NOvA replica target data taken this summer
- Most of the data is still being analyzed

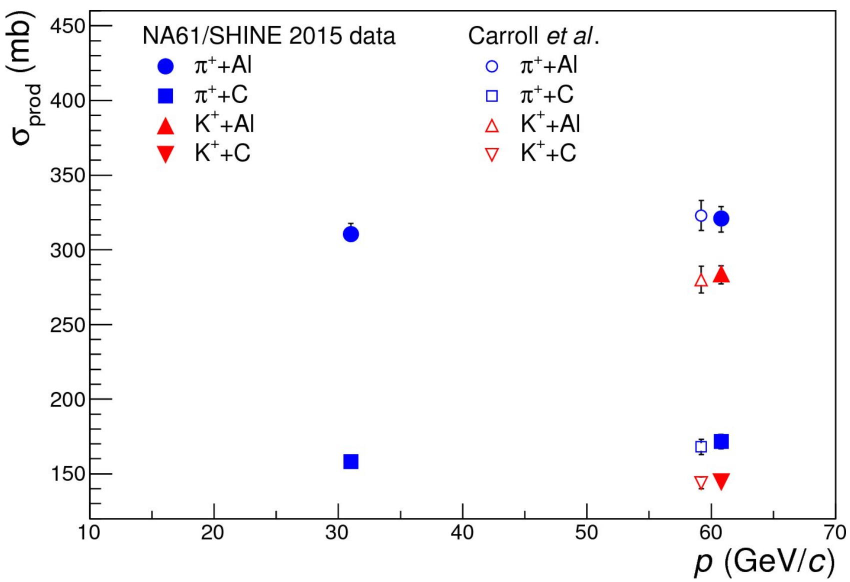
	31 GeV/c				60 GeV/c				90 GeV/c				120 GeV/c			
	Be	C	Al	NOvA	Be	C	Al	NOvA	Be	C	Al	NOvA	Be	C	Al	NOvA
p																
π^+																
π^-																
K^+																

Data taken with magnets off

Data taken with magnets on

Measurements of total production cross sections

- NuMI beam uses 120 GeV/c protons
- Measurements at lower momenta are used to re-weight re-interactions



Phys.Rev. D98 (2018) no.5, 052001

Interactions below 15 GeV/c

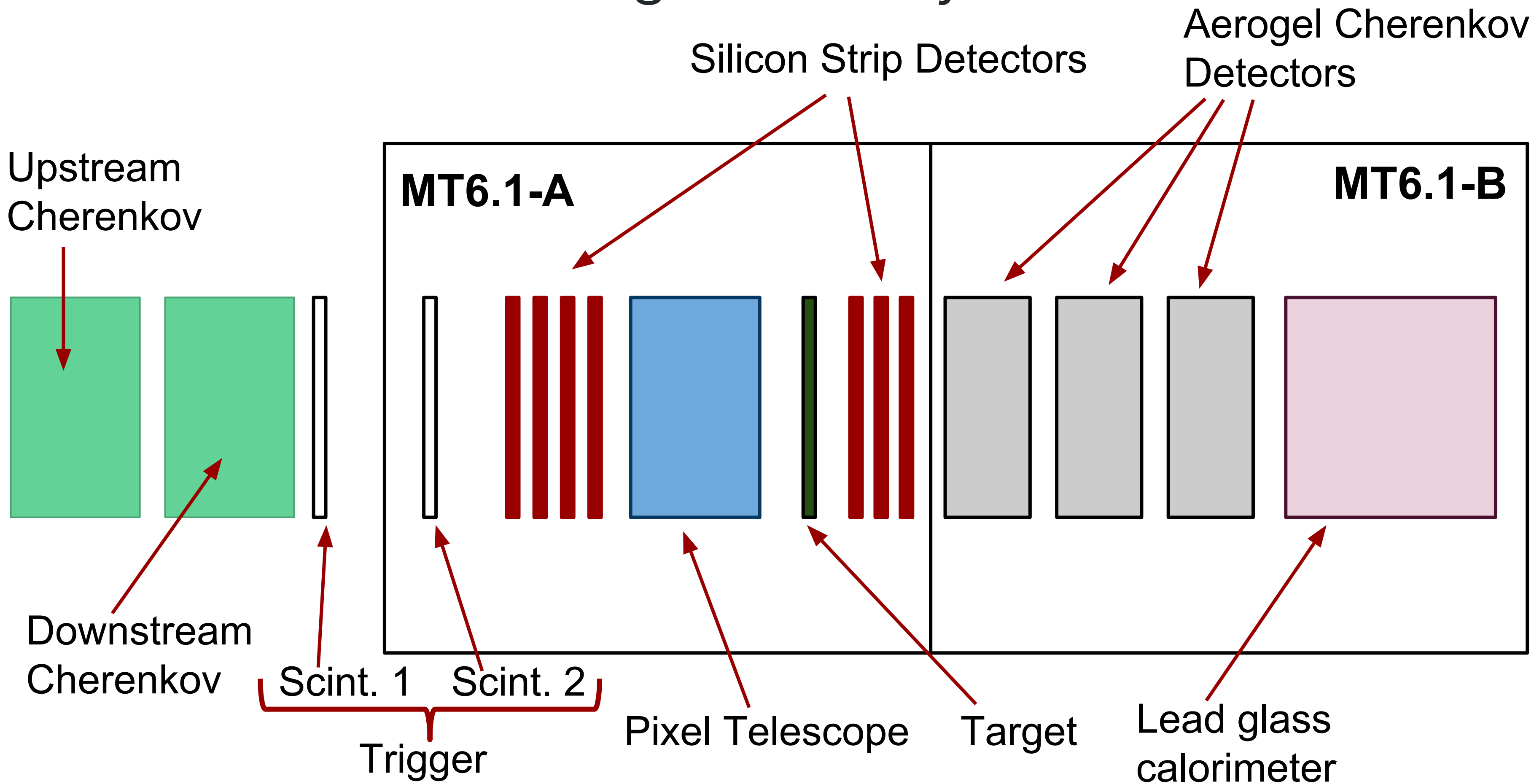
- NA61/SHINE beam cannot go below 13 AGeV/c
- Why we need lower beam momentum?
  - Low momentum re-interactions are starting to be dominant contribution in the T2K flux uncertainty (π+Al, K+Al, …) ➜ the same limitations will apply to T2HK
  - Low-momentum re-interactions are also the dominant uncertainty in the NuMI and LBNF flux predictions
  - Sub-GeV sample in atmospheric neutrino oscillations is sensitive to CP violation ➜ size of the effect is around 3-4% ➜ atmospheric flux uncertainty is larger and comes from low energy pion production
- **Low momentum beam is available at Fermilab Test Beam Facility**
- **Compact hadron production experiment (1m in size) can be designed to measure low momentum interactions ➜ EMPHATIC**

EMPHATIC

- **E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**estbeam **I**n **C**hicagoland
- Fermilab Test Beam Facility (FTBF) ➔ beam 2 - 120 GeV/c
- **Complementary to NA61/SHINE**
- Physics goals:
  - Measurement of untuned interactions in the T2K neutrino beam simulation
  - Measurements for NuMI beam simulation
  - Hadron production measurements for atmospheric neutrinos
  - Cross-check of the NA61/SHINE production cross-section measurement

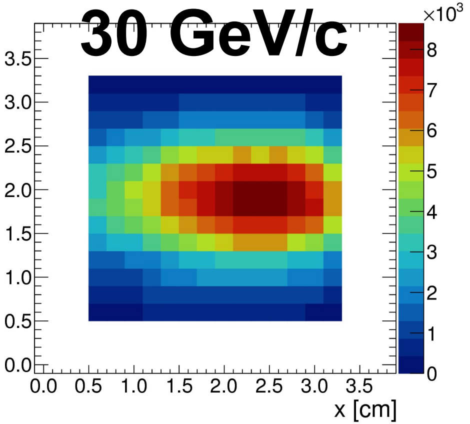
(first three physics goals:) **p_b < 15 GeV/c**

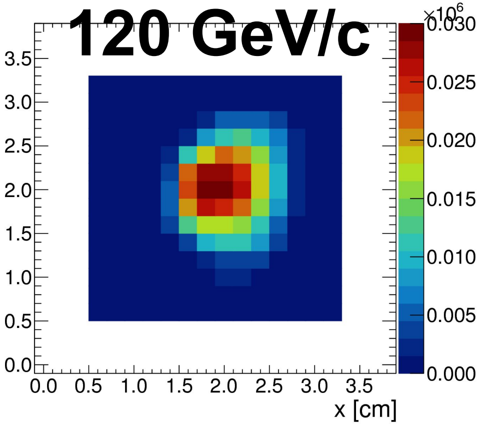
EMPHATIC data-taking in January 2018

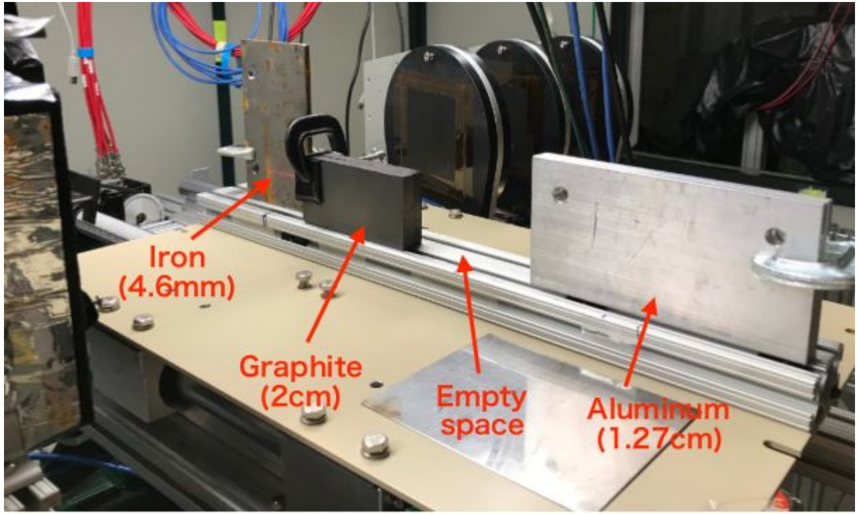


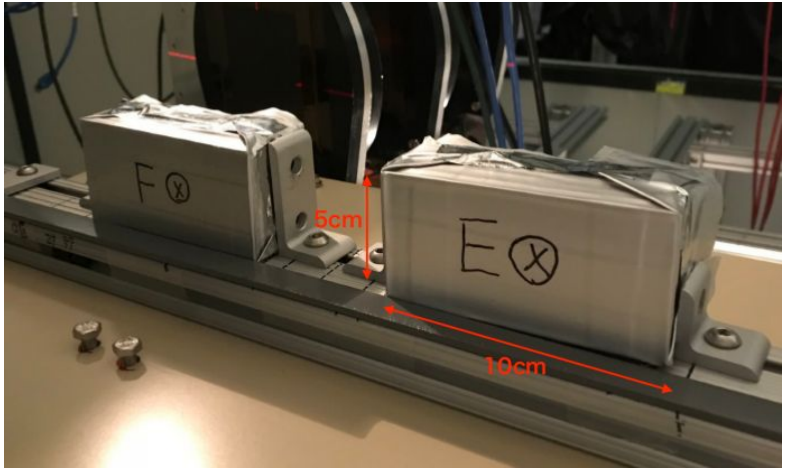
Targets and beam

- Graphite, aluminum, steel and empty targets
- Emulsion targets with graphite
- Beam momentum: 2, 10, 20, 30, 120 GeV/c
- Beam composition:
  - **p < 10 GeV/c → fraction of $e^{\pm}$ > 50%**
  - **p = 30 GeV/c → fraction of p ~ 45%, K ~ 3%, π ~ 50%, e^{+} ~ 2%**









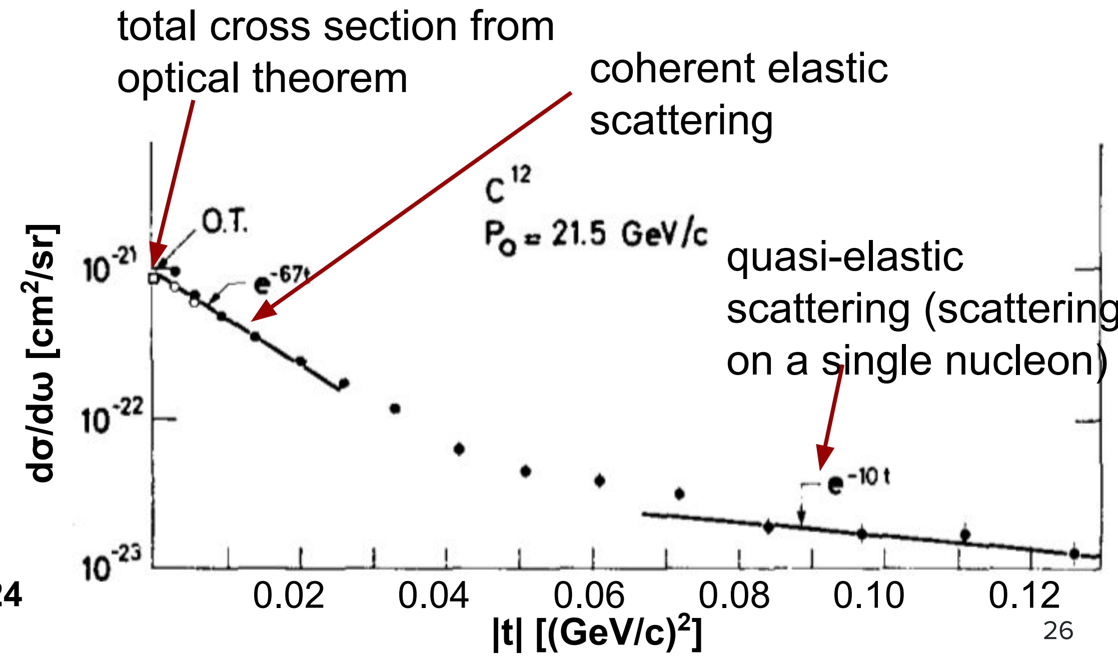
What can we do with the data?

- **p + C @ 20, 30, 120 GeV/c data**
- **Measurement of total, elastic and quasi-elastic cross section**
- Momentum measurement is not necessary
- PID is not necessary

$$|t| \approx p^2\theta^2$$

Beam momentum (p)

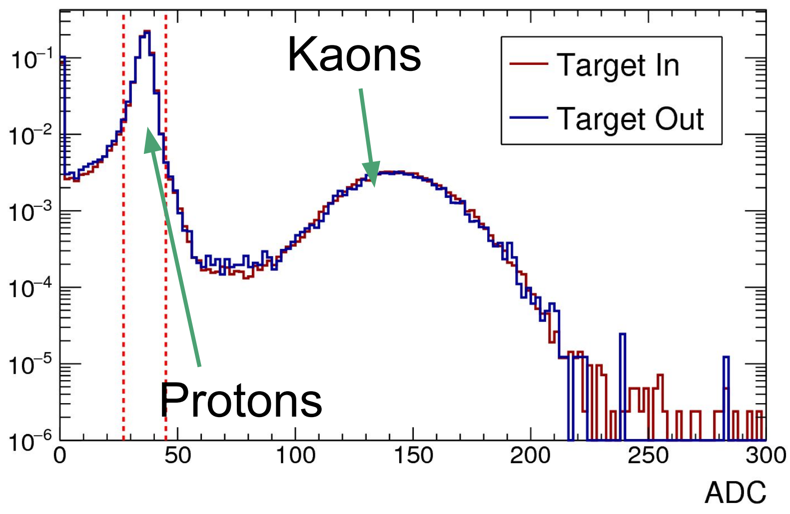
Scattering angle (θ)



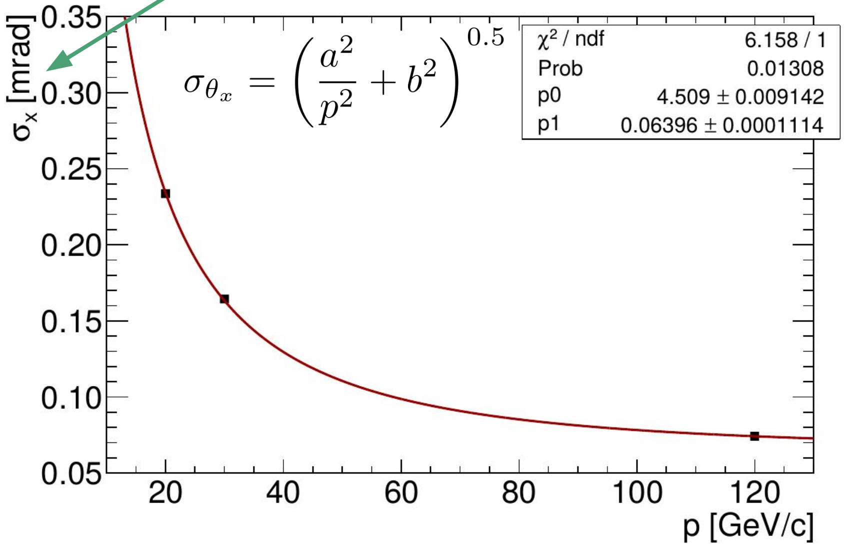
Bellettini et al., Nucl.Phys. 79 (1966) 609-624

Detector performance

1. Proton beam is contaminated by kaons ➔ Cherenkov selection
2. Alignment of the SiSDs ➔ 7 detectors (14 planes)
   - 3.846 x 3.846 cm, pitch: 60 µm
3. SiSDs efficiency > 99%

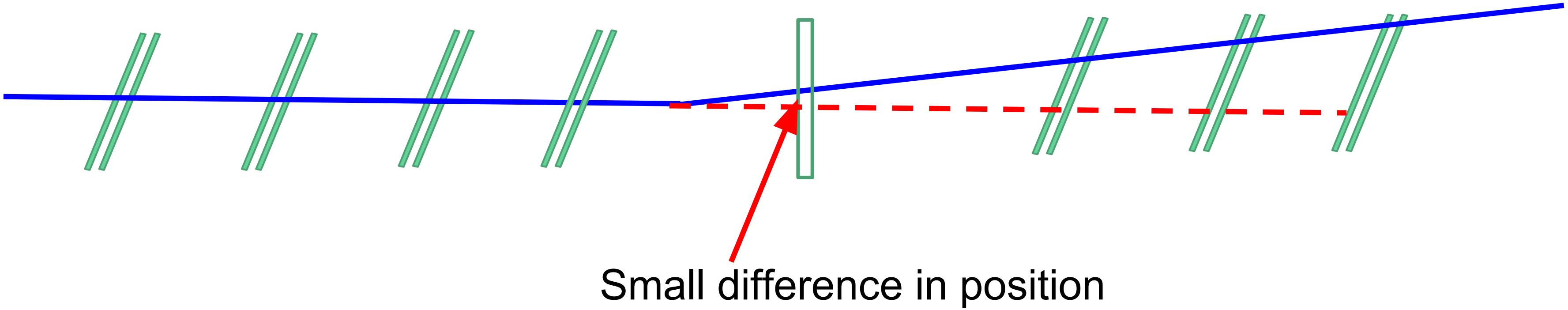


Angular resolution in x-z plane

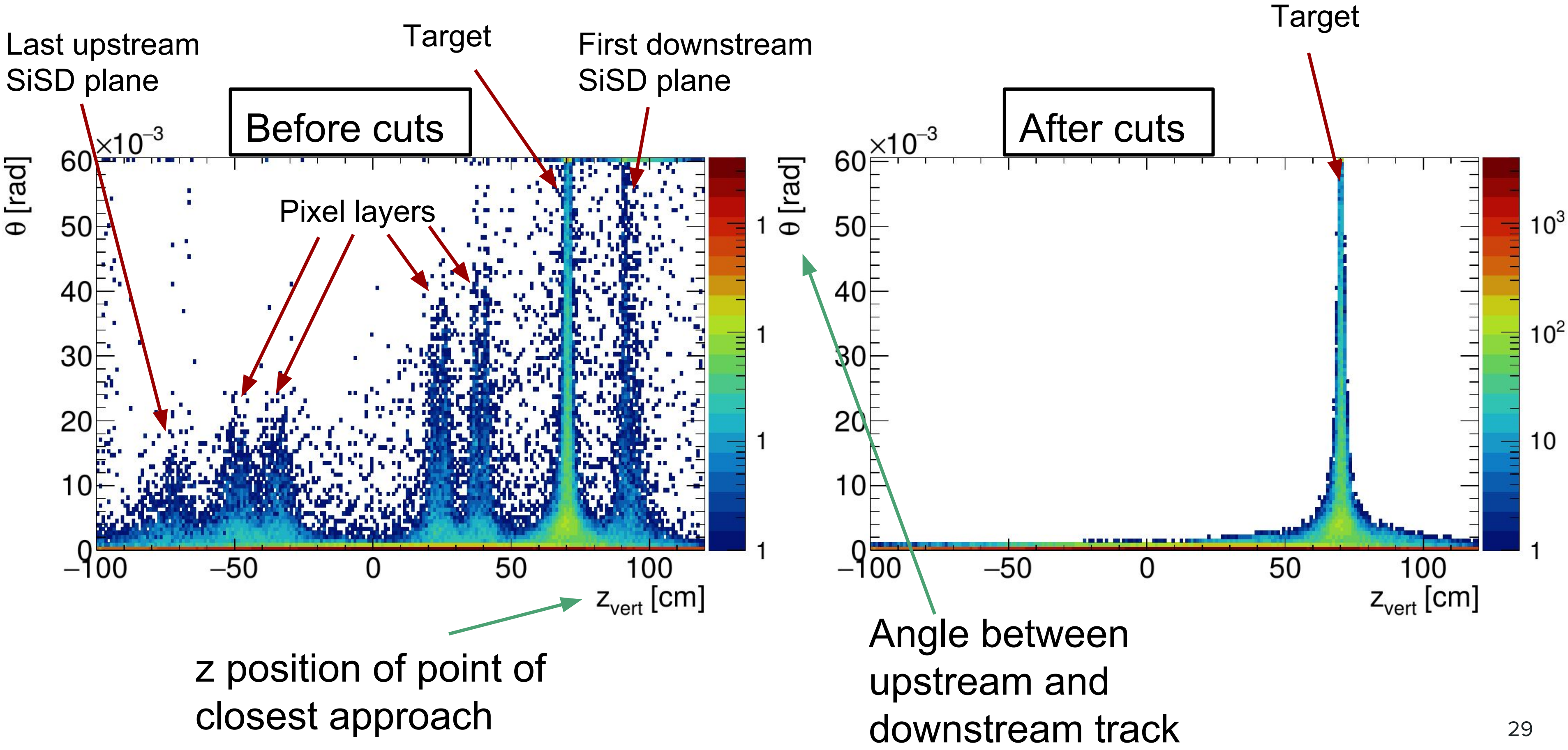


Interactions outside of the target

- Pixel telescope ➔ not used in the measurements (additional material in the beamline)
- Possible interactions in the last upstream and the first downstream SiSD
- Cut on x and y distances between upstream and downstream track at target z

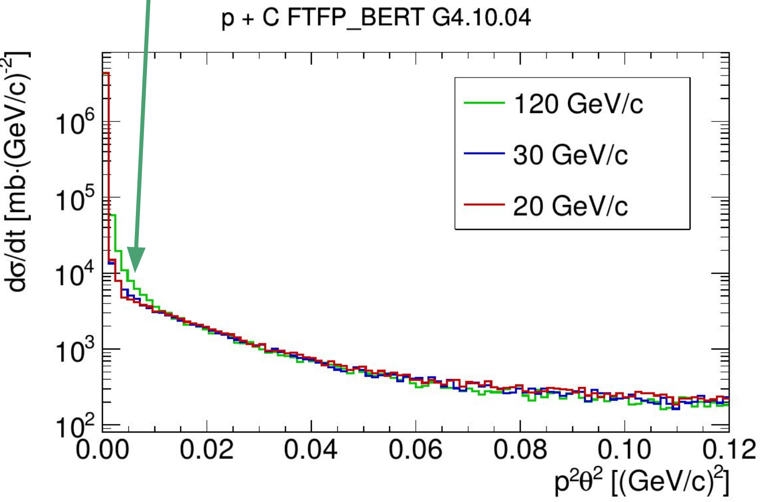


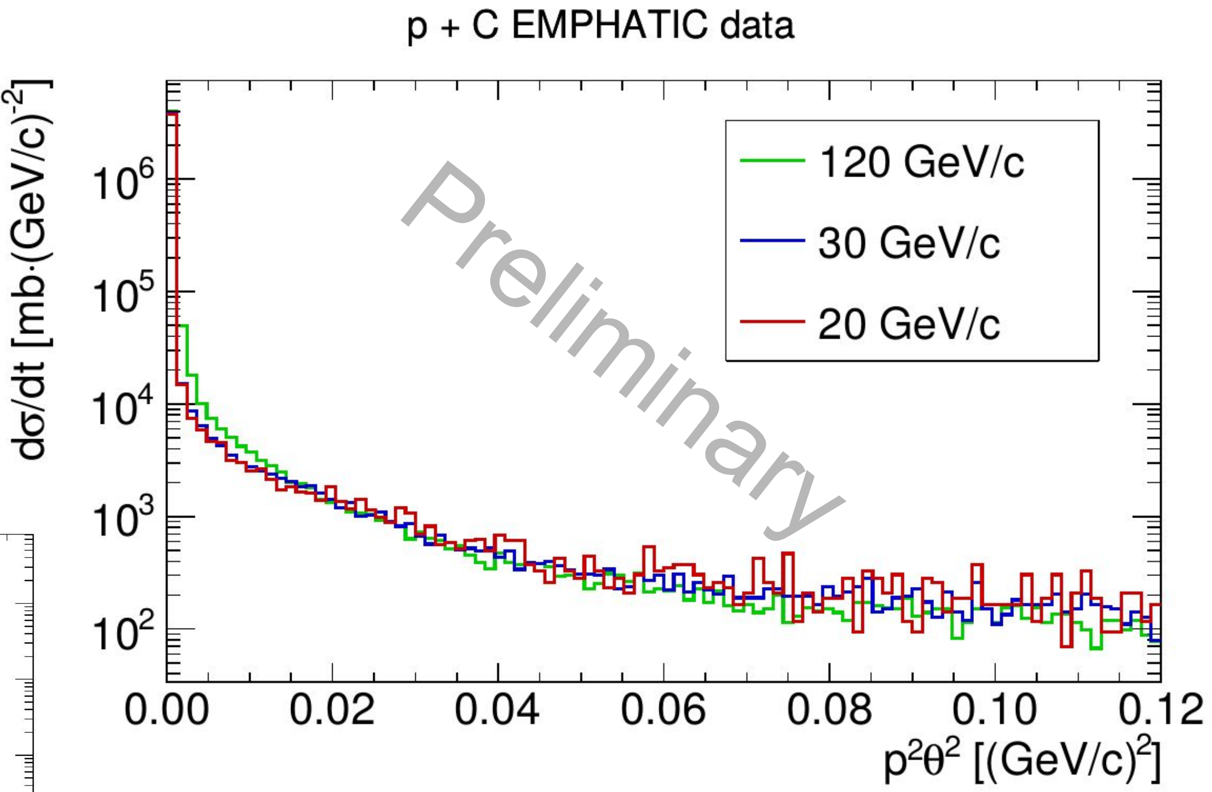
Interactions outside of the target



Raw t-distributions

Monte Carlo shows similar difference

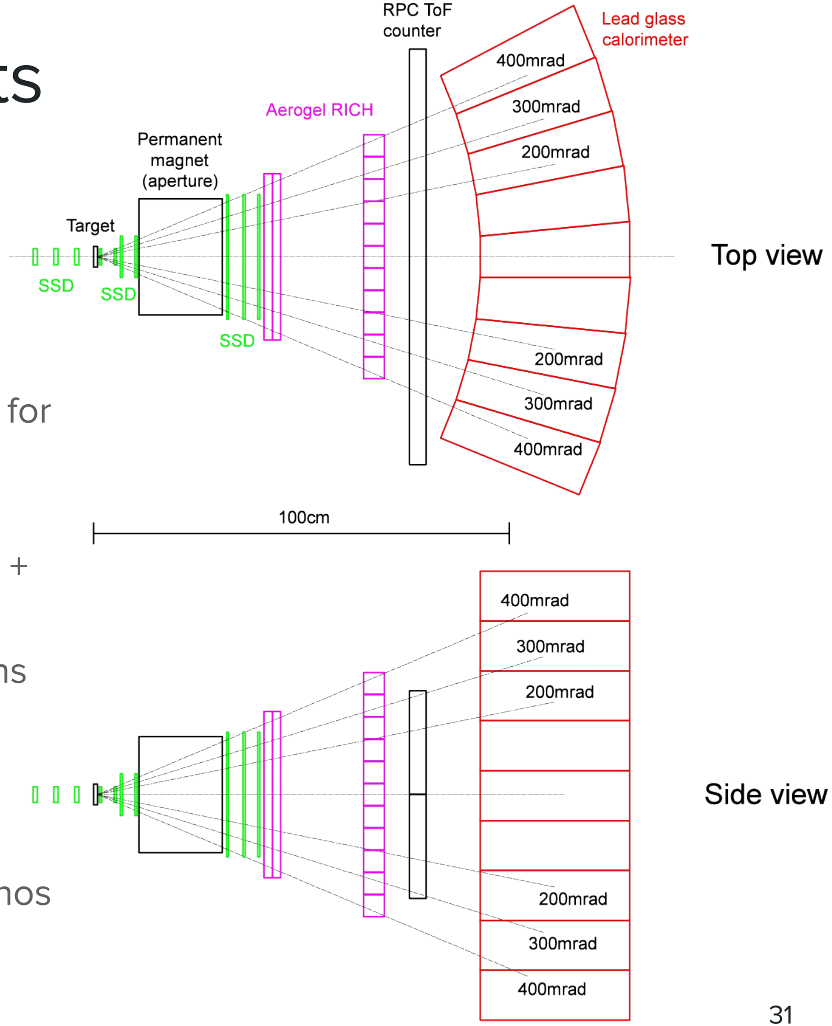




- Distributions overlap → cross-section is slowly changing or nearly constant with momentum
- Differences for 120 GeV/c data come from worse t resolution

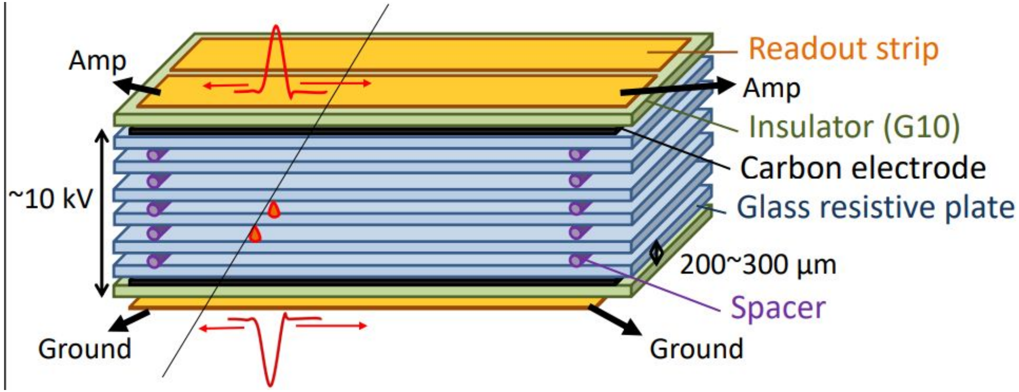
Future EMPHATIC measurements

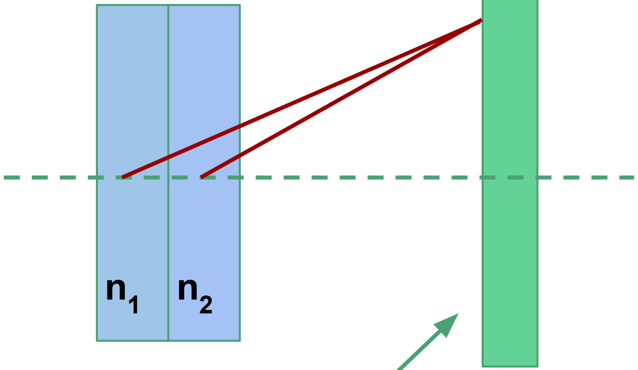
- 2 phases
- Phase 1 (late 2019):
  - p(π) + C, Al, Fe, @ 4, 8, 12, 20, 31 GeV/c
  - 5, 10 and 20% λ_I C targets
  - First measurement of hadron yields (100k interactions for 5% λ_I target ➔ data-taking 3 hours)
  - Beam aerogel Cherenkov
  - Magnet + TOF (resolution ~70 ps, PID up to 1.5 GeV/c) + Aerogel RICH (π id up to 8 GeV/c)
  - Calorimeter (lead glass) ➔ can identify electrons, muons and neutrons
- Phase 2 (2020/21):
  - p(π) + C, Al, Fe @ 4, 8, 12, 20, 31, 60, 120 GeV/c
  - Additional targets B, BN, B_2O_3 for atmospheric neutrinos
  - DAQ upgrades
  - RICH upgrade up to 15 GeV/c



Future EMPHATIC measurements

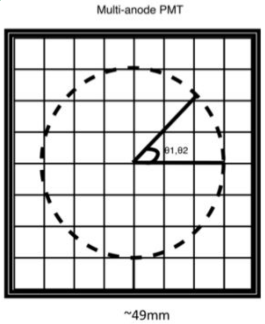
- Cooperation with E50 collaboration from Japan
  - Multigap Resistive Plate Chambers (MRPCs) and aerogel RICH





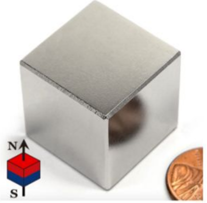
Aerogels

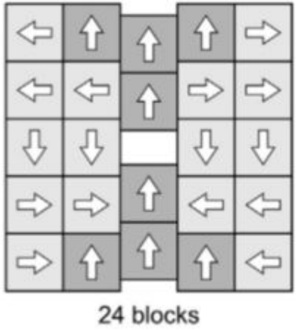
Multianode PMT



- Magnet: small or large aperture?
  - Halbach array → 20 cm long with ~10 cm gap → field strength > 1T

N52 magnet → internal field 1.44 T





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Conclusion

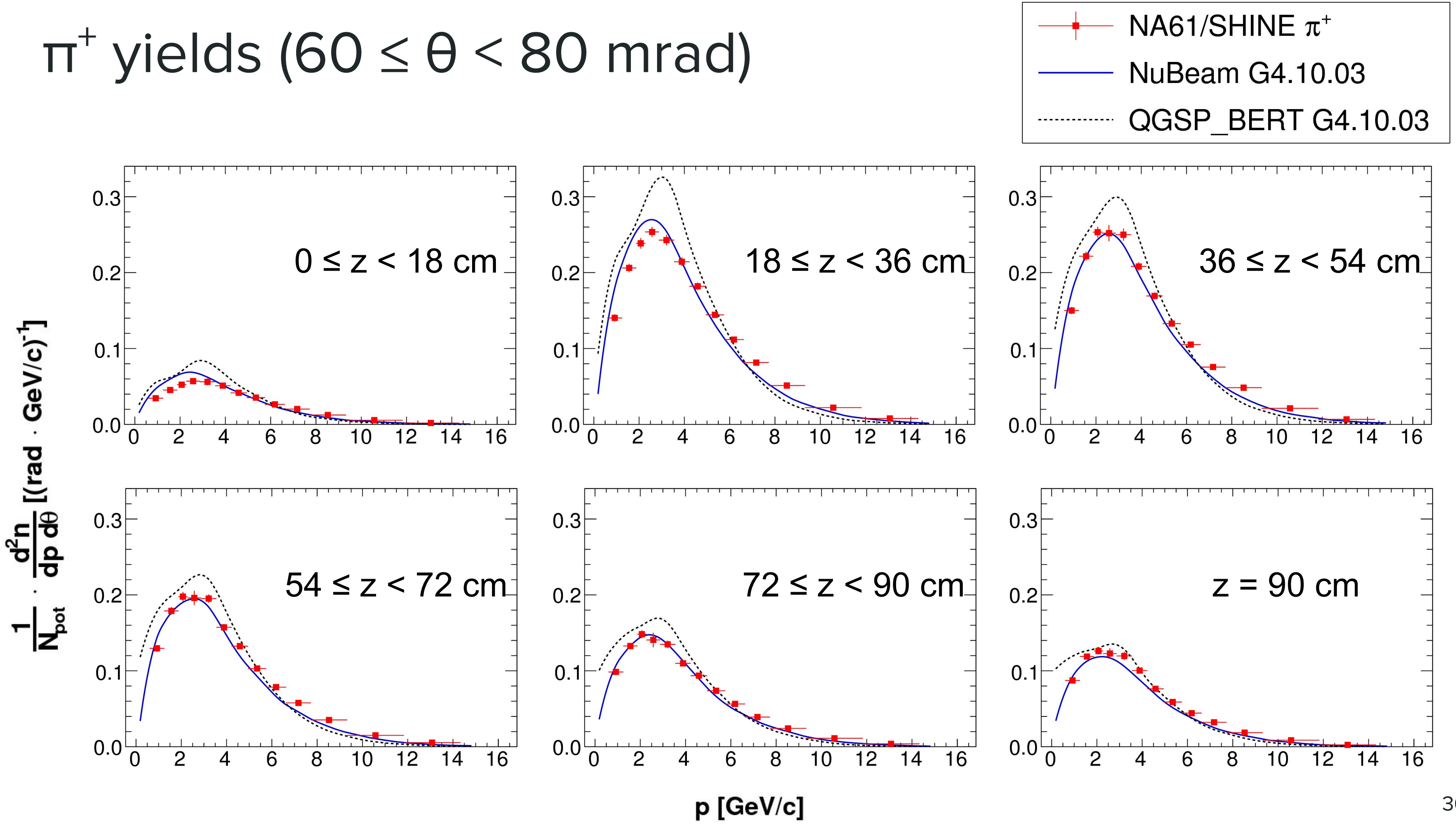
- The modeling of hadron interactions limits knowledge of the atmospheric and accelerator-based neutrino fluxes
- Measurements are needed to reduce this uncertainty
- Many past experiments, but we need more
  - hadrons which produce neutrinos have a wide range of energies
- NA61/SHINE experiment at CERN, only experiment on the market which recently delivered measurements
  - Successful measurement for T2K and Fermilab experiments
- EMPHATIC ➔ new experiment complementary to NA61/SHINE
  - Lower beam momentum
  - Measurements for atmospheric neutrinos
  - Measurements are planned for 2019 and 2020
- We are entering the era of precision neutrino physics ➔ hadron production measurements will be even more important

Future prospects for hadron production experiments

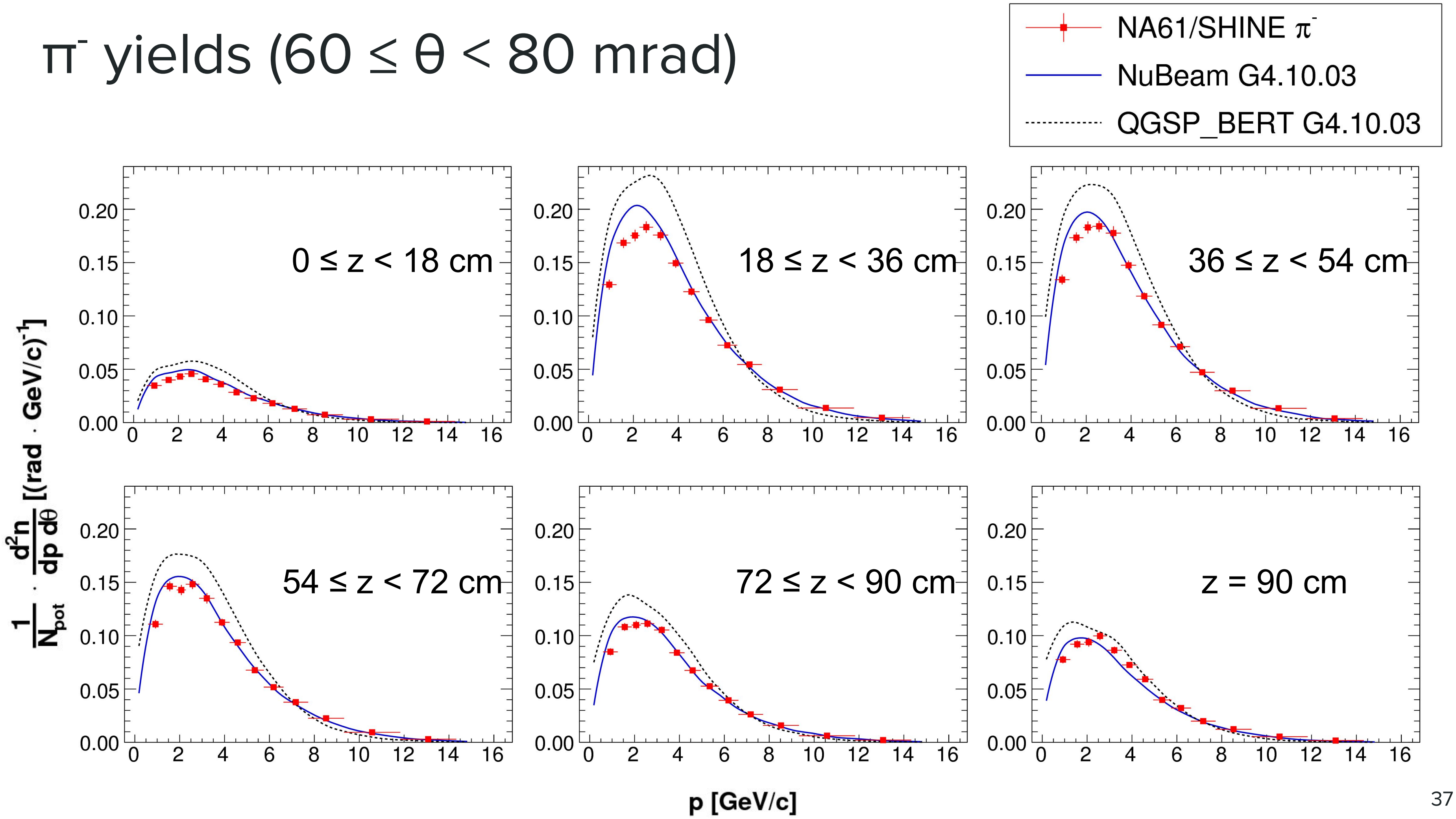
- We need to rely on NA61/SHINE and EMPHATIC
- NA61/SHINE
  - very useful for replica target measurements and higher momentum (>15 GeV/c)
  - Probably another run with HK replica target will be necessary
  - More data for DUNE?
- EMPHATIC
  - Lower momentum measurements (< 15 GeV/c)
  - Very useful for atmospheric neutrinos

BACKUP

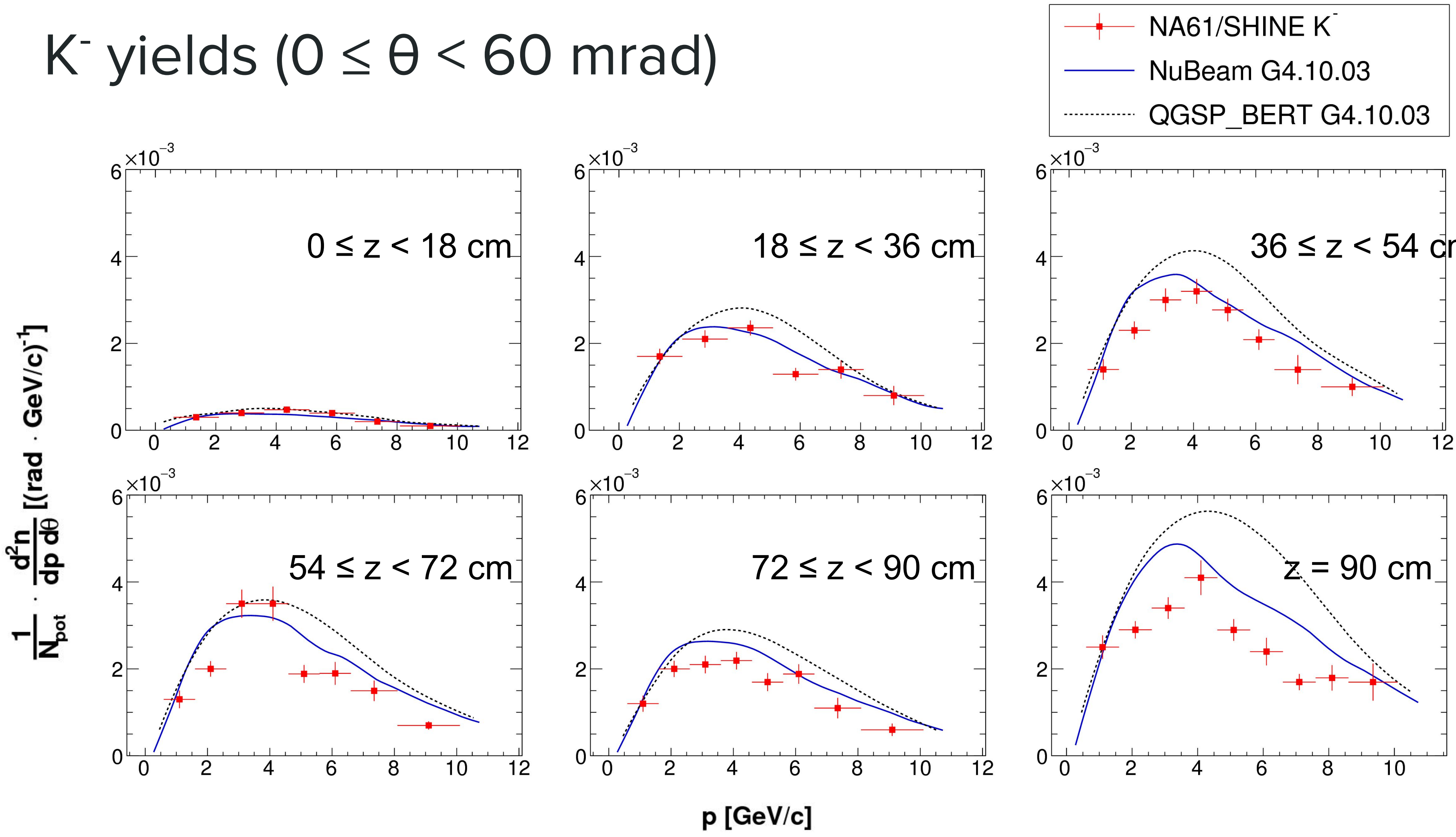
π^+ yields ($60 \leq \theta < 80$ mrad)



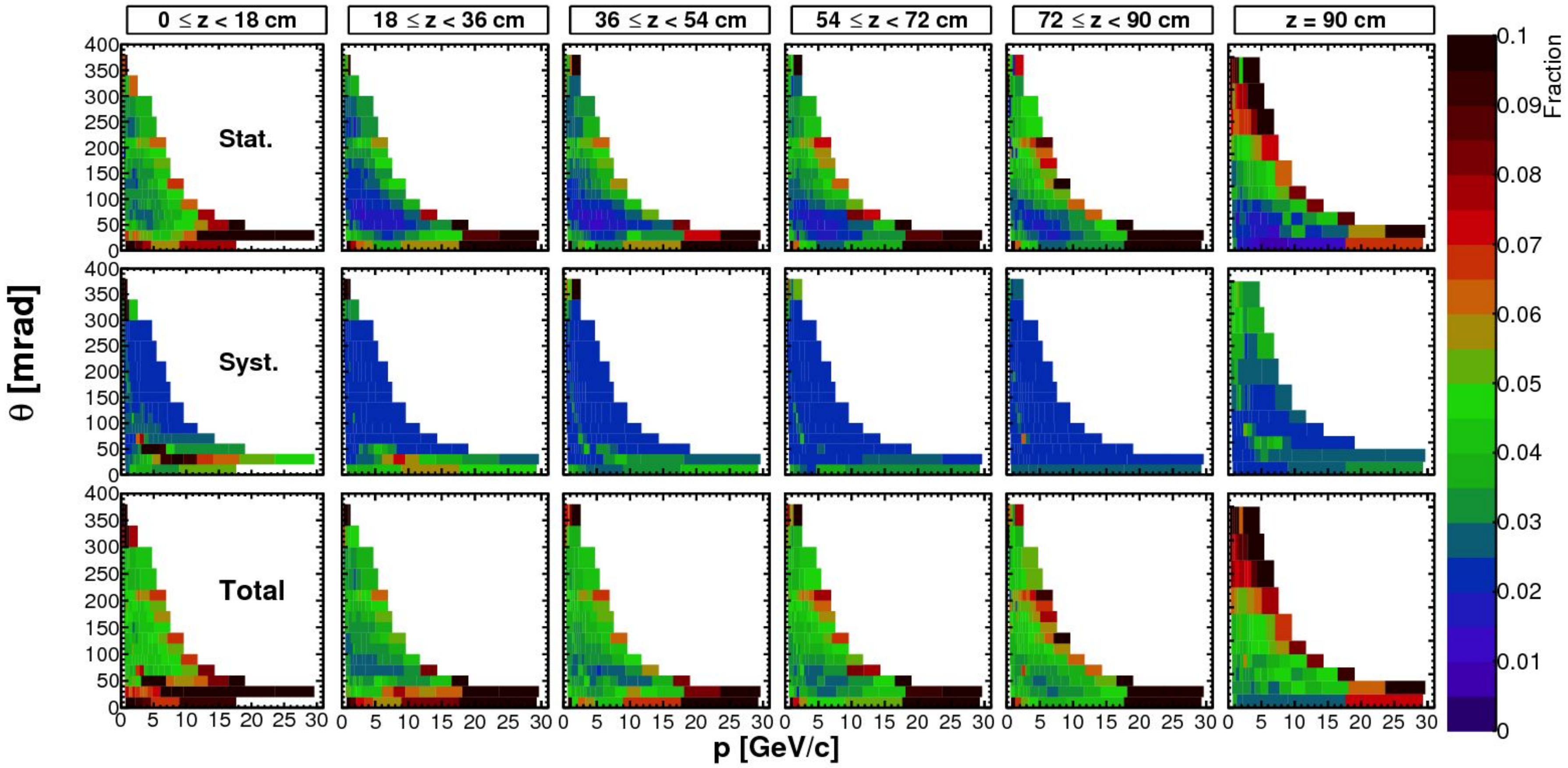
π^- yields ($60 \leq \theta < 80$ mrad)



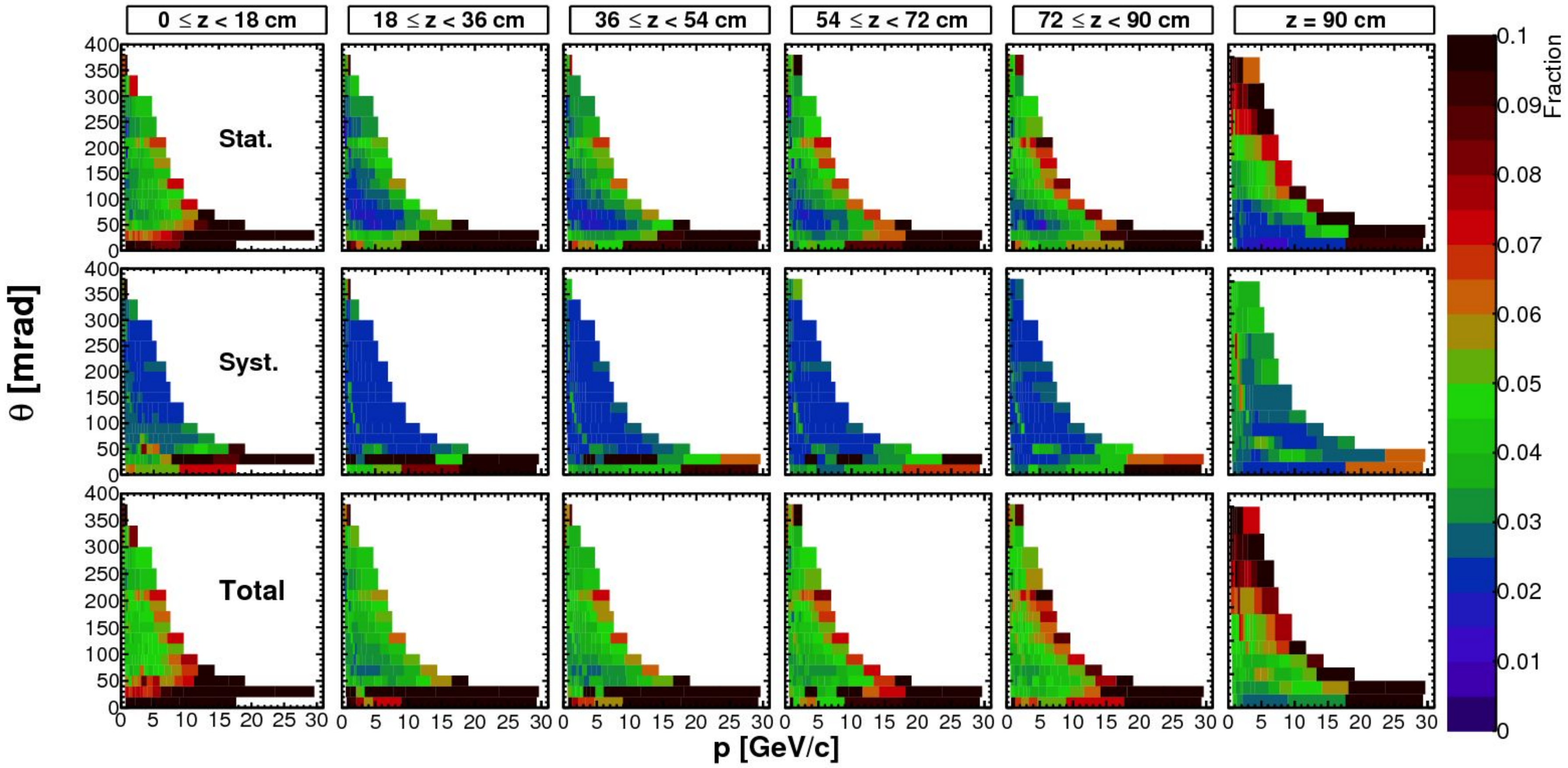
K^- yields ($0 \leq \theta < 60$ mrad)



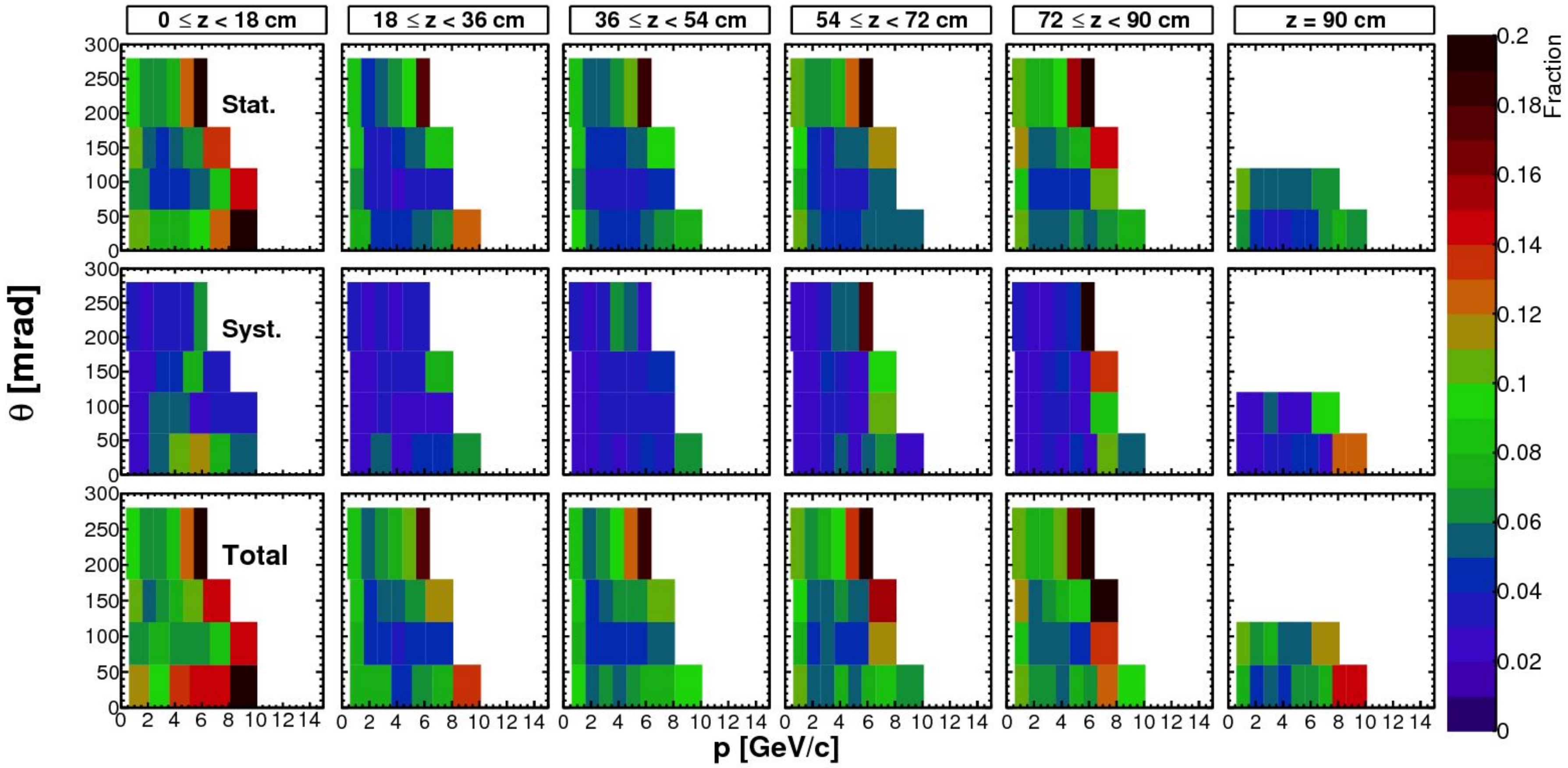
NA61/SHINE replica target π^+ uncertainties



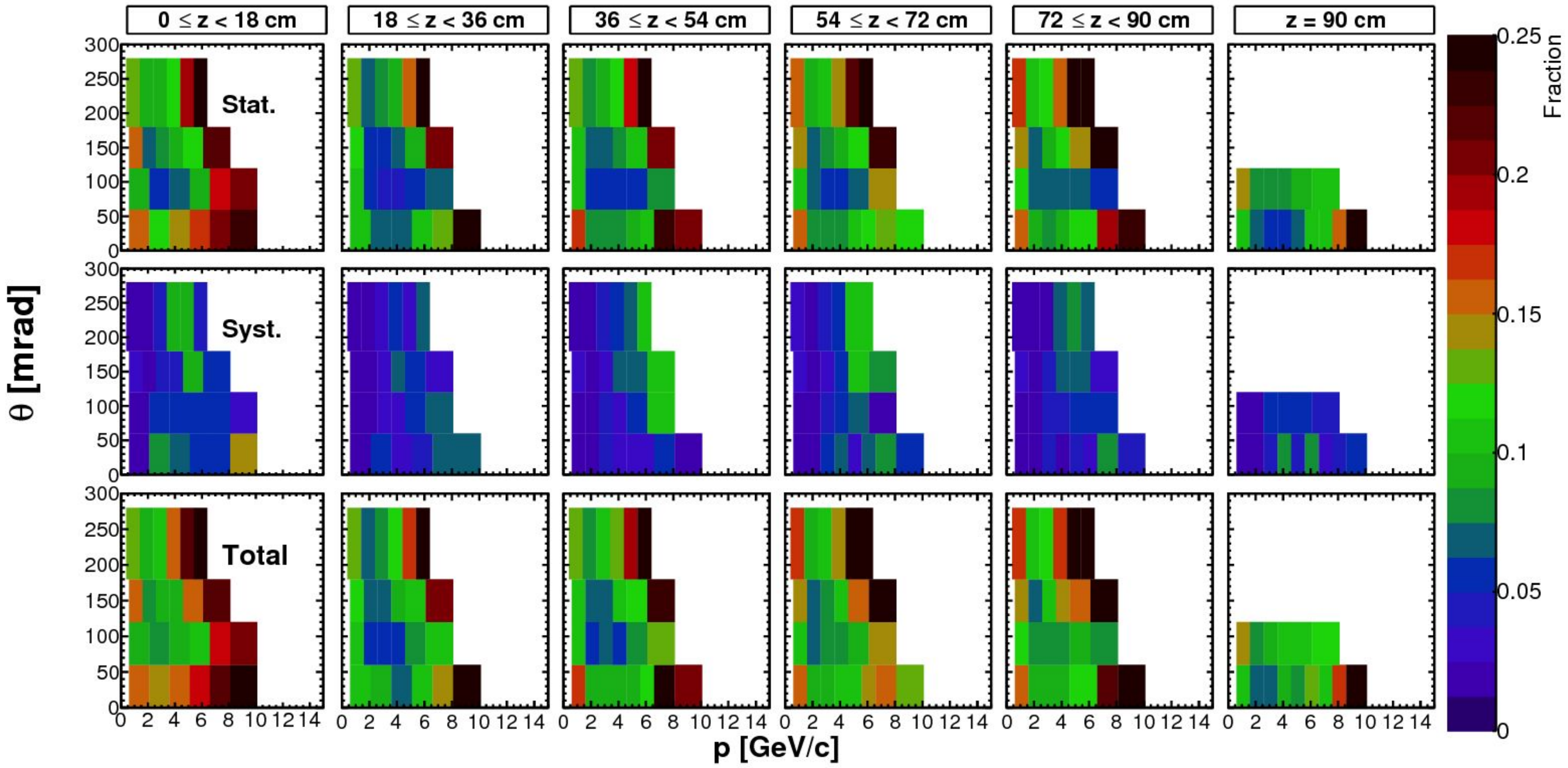
NA61/SHINE replica target π⁻ uncertainties



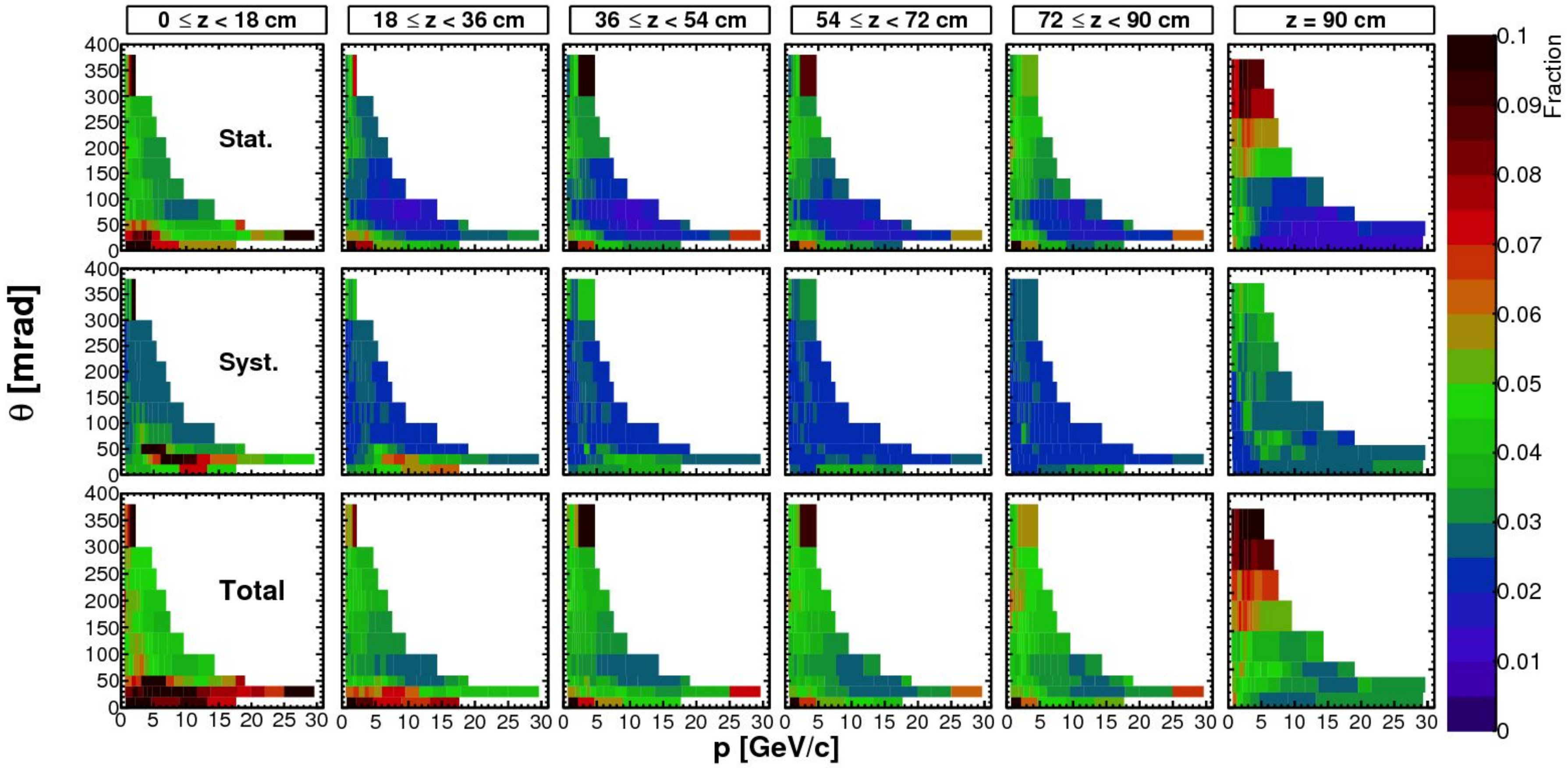
NA61/SHINE replica target K^+ uncertainties



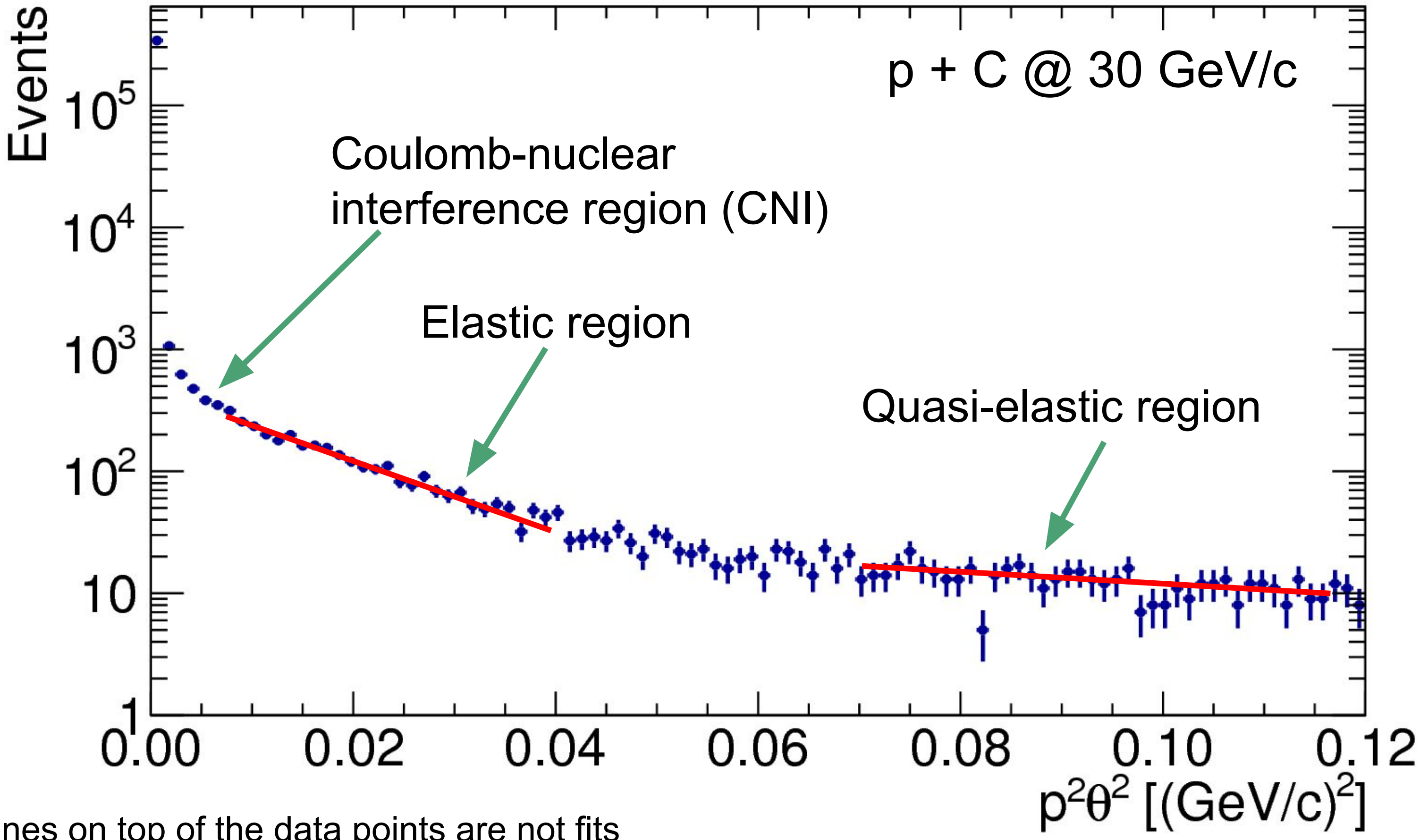
NA61/SHINE replica target K^- uncertainties



NA61/SHINE replica target p uncertainties



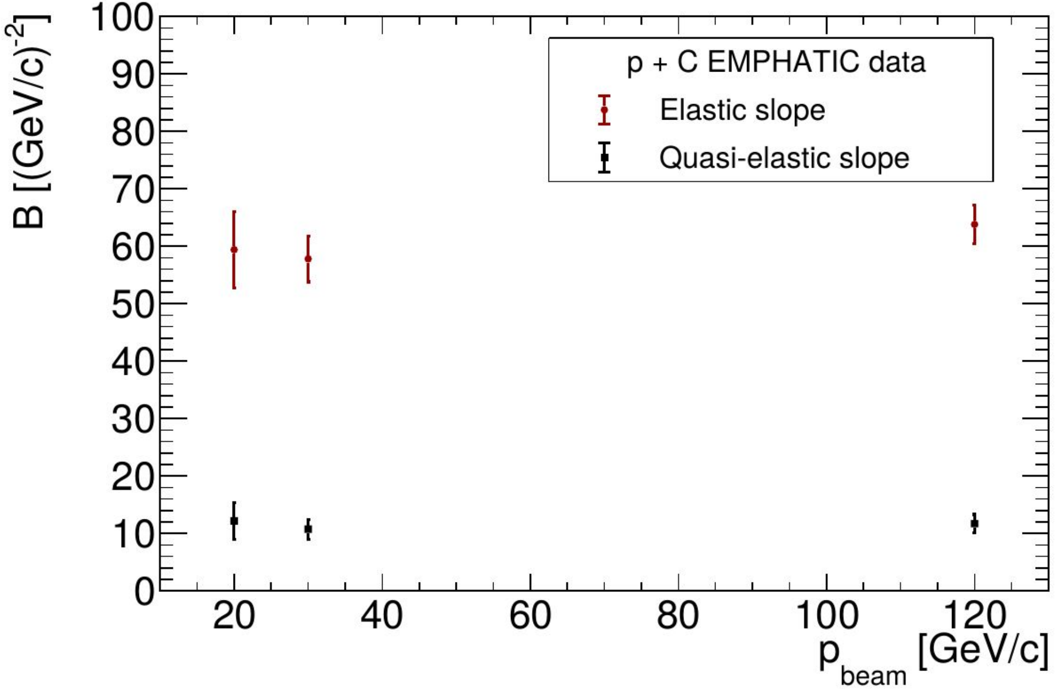
4-momentum transfer (30 GeV/c data)



*Lines on top of the data points are not fits

How to use this data

- σ_{prod} can be extracted from t distributions
- t distribution can be used to reduce the model dependence of the NA61/SHINE σ_{prod} measurement



NA61/SHINE production cross-section measurement

- NA61/SHINE trigger system has a veto scintillator which discards non-production events (2 cm in size, angular coverage ~2 mrad)
- Some of the elastic and quasi-elastic events are accepted, while some of the production events are removed ➔ inefficiency is corrected with MC

$$\sigma_{prod} = (\sigma_{\mathrm{trig}} - f_{\mathrm{el}}\sigma_{\mathrm{el}} - f_{\mathrm{qel}}\sigma_{\mathrm{qel}})\frac{1}{f_{\mathrm{prod}}}$$

Trigger cross-section

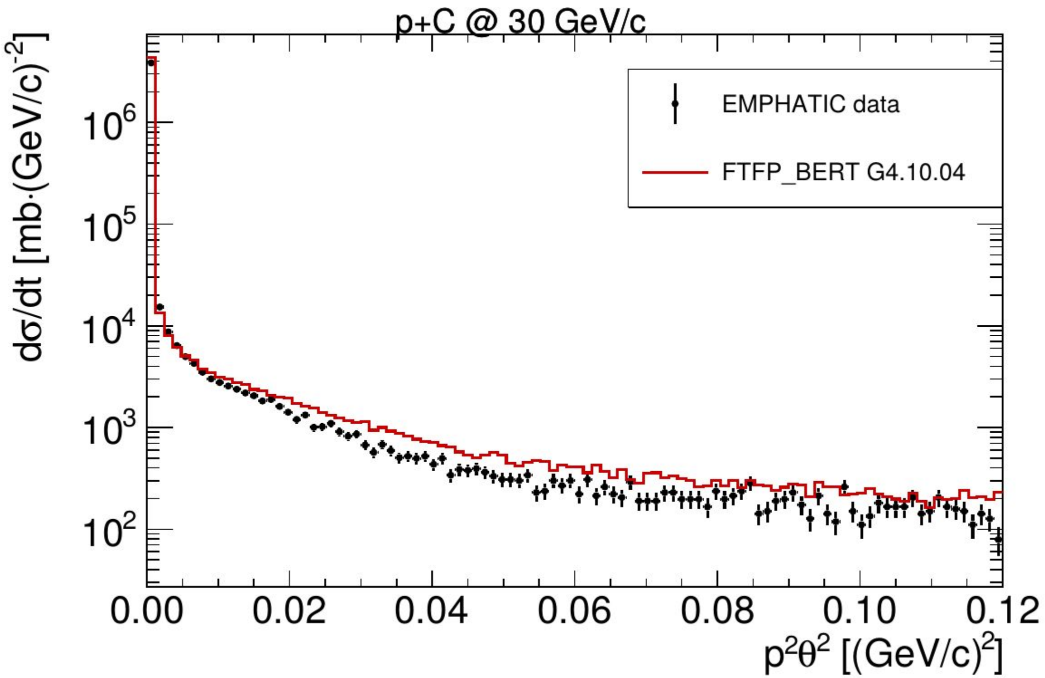
Fraction of accepted elastic events

Fraction of accepted quasi-elastic events

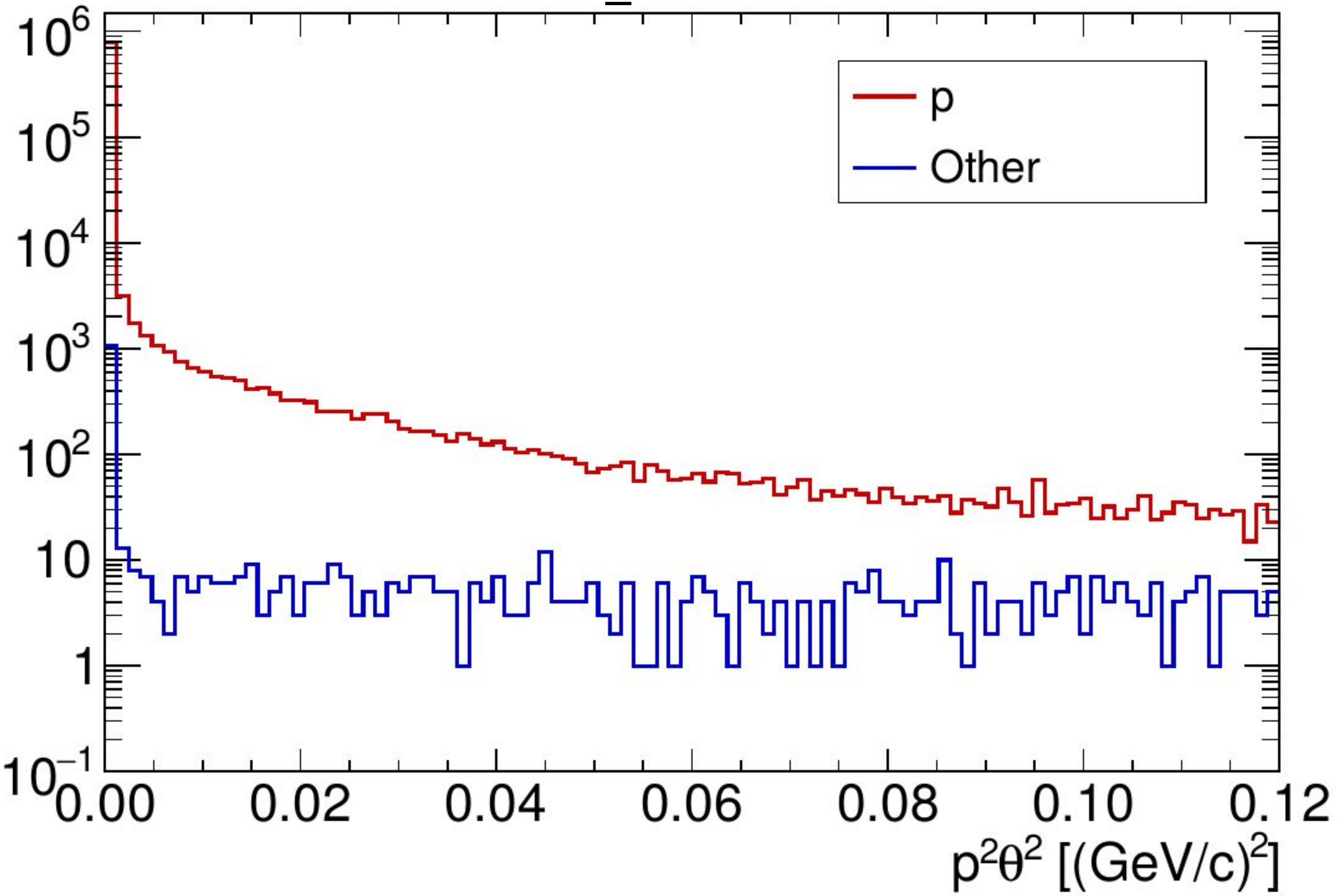
Fraction of removed production events

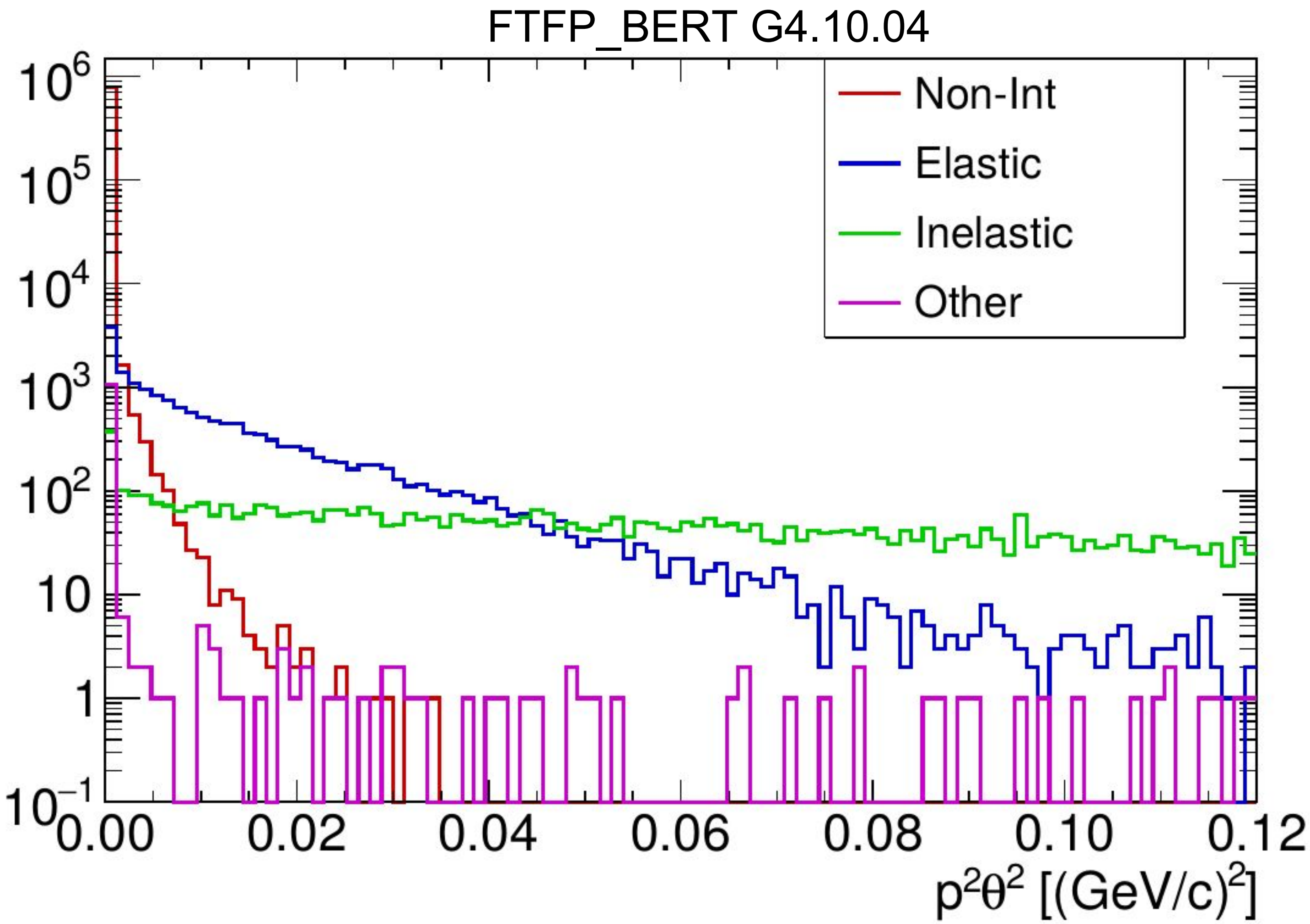
NA61/SHINE production cross-section measurement

- Systematic uncertainty is calculated by comparing corrections produced by different MC models
- EMPHATIC measures t distribution at low t ➡ p+C @ 30 GeV/c
  EMPHATIC data can be used to re-weight Monte Carlo prediction and estimate f_{el} and f_{qel} corrections in p+C at 31 GeV/c σ_{prod} measurements



FTFP_BERT G4.10.04




FTFP_BERT G4.10.04
Non-Int
Elastic
Inelastic
Other
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
0.00
0.02
0.04
0.06
0.08
0.10
0.12
p^2θ^2 [(GeV/c)^2]

EMPHATIC - test beam in January 2018

q·p [GeV/c]	Graphite	Aluminum	Steel	Empty
120	1.63M	0	0	1.21M
30	3.42M	0.98M	1.01M	2.56M
-30	0.31M	0.31M	0.13M	0.31M
20	1.76M	1.76M	1.71M	1.62M
10	1.18M	1.11M	0.97M	1.17M
2	0.11M	0.11M	0.18M	0.11M

RICH performance