NA61/SHINE and EMPHATIC measurements for neutrino physics

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on behalf of NA61/SHINE and EMPHATIC collaboration

12. 09. 2018.

EMPHATIC

Outline

- Hadron production measurements for neutrino experiments
- NA61/SHINE experiment
  - Data taken for T2K
  - Data taken for Fermilab neutrino programme
  - How did NA61/SHINE data improved T2K flux uncertainty?
- EMPHATIC experiment
  - Physics programme
  - Test beam measurements in January 2018
  - Future measurements

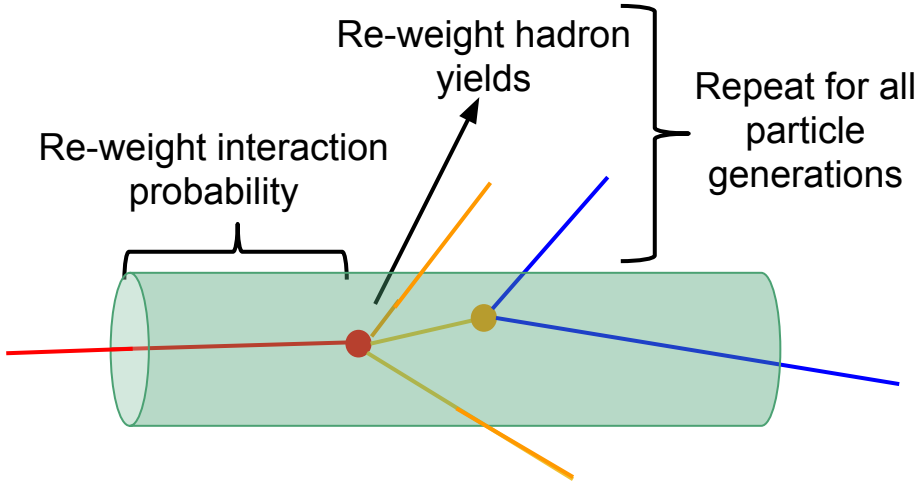
Motivation

- Neutrino flux in accelerator-based and atmospheric neutrino experiments is produced from decays of hadrons and muons
- 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)
- Accelerator-based neutrino oscillation experiments with near and far detector are less affected (far to near ratio)
- **Monte Carlo simulations are used to estimate neutrino flux (different models give different predictions)**

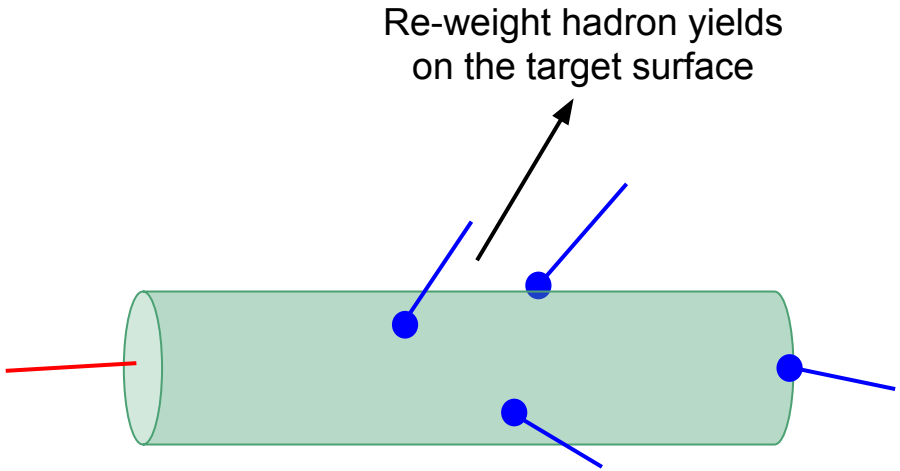
Hadron production measurements

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

1 Thin target measurements

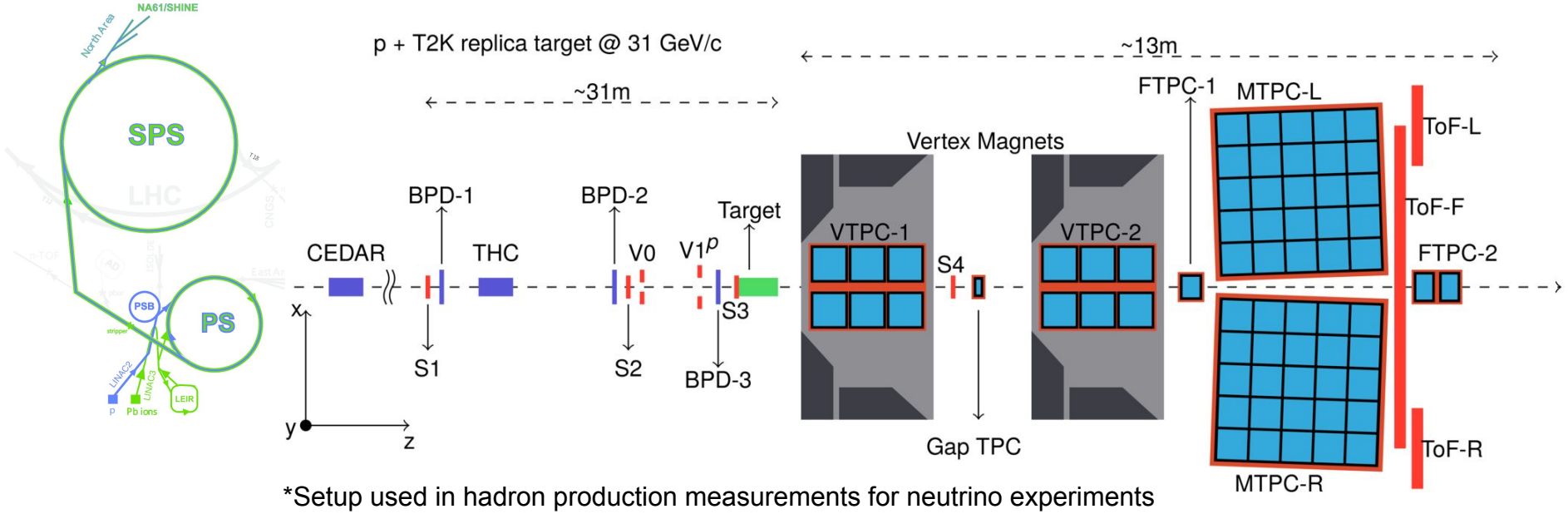


2 Replica target measurements



- **NA61/SHINE collaboration took data for neutrino experiments for a decade**

North **A**rea **61** / **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
NA61 / SHINE



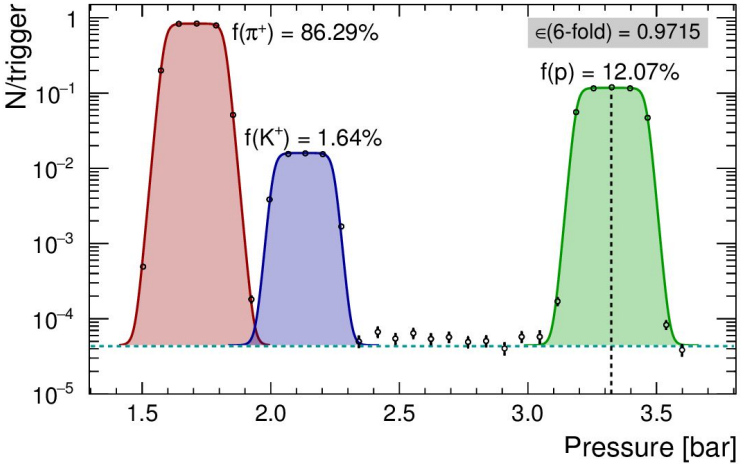
*Setup used in hadron production measurements for neutrino experiments

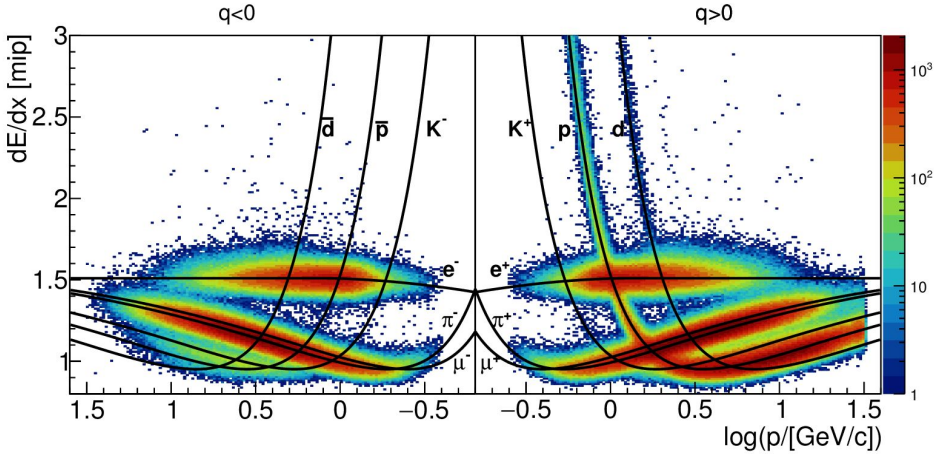
- Precise hadron production measurements for neutrino flux re-weighting in T2K and Fermilab neutrino experiments

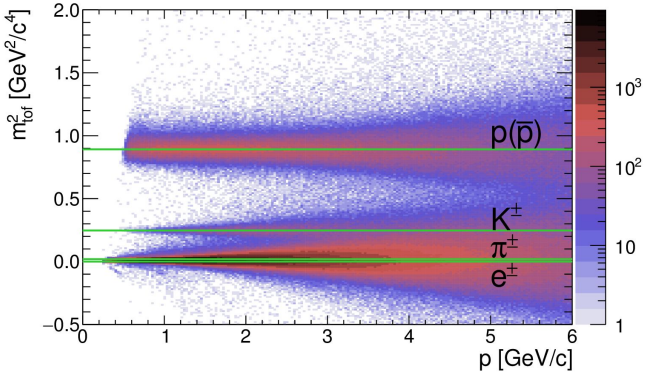
ONGOING **FINISHED**

Capabilities of the NA61/SHINE detector

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







Thin target measurements for T2K

- 2 cm thick carbon target (around 5% interaction length)
- Measurements of hadron yields and production cross section

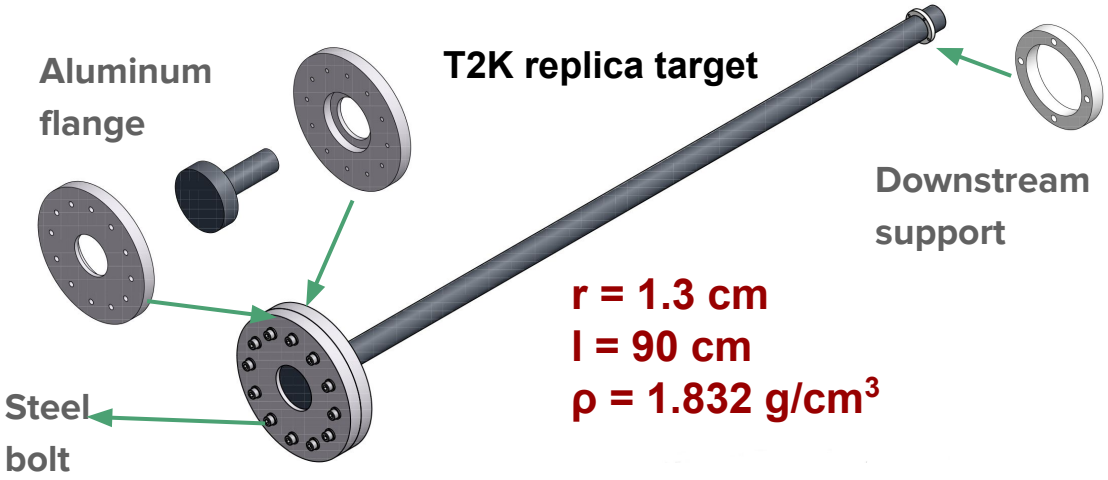
$$\sigma_{\mathrm{prod}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{qel}}$$

Year	# of Int. triggers [10^6]	Results
2007	0.7	$\pi^{\pm}$, K^{+}, K^{0}_{s}, Λ yields and σ_{prod} [1,2]
2009	5.4	$\pi^{\pm}$, $K^{\pm}$, K^{0}_{s}, p, Λ yields and σ_{prod} [3]

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

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

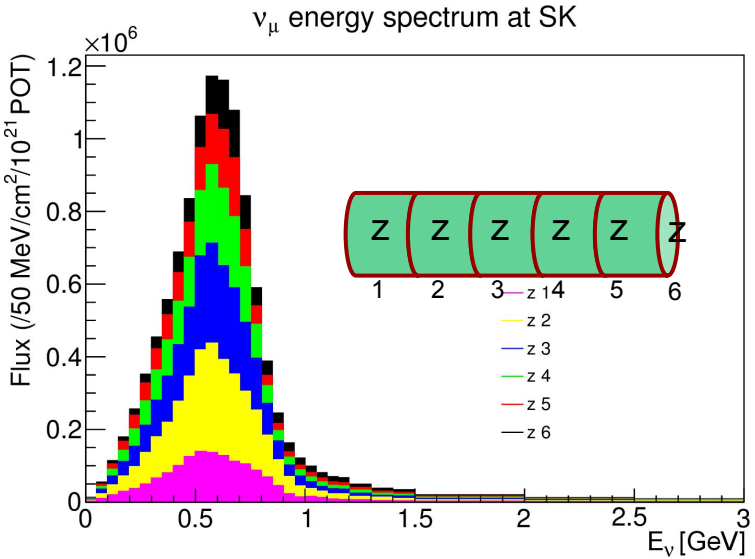


Year	POT [10^6]	Results
2007	0.2	proof of concept [1]
2009	4.0	$\pi^{\pm}$ yields [2]
2010	**10.2**	**$\pi^{\pm}$, $K^{\pm}$, p yields [3]**

[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)

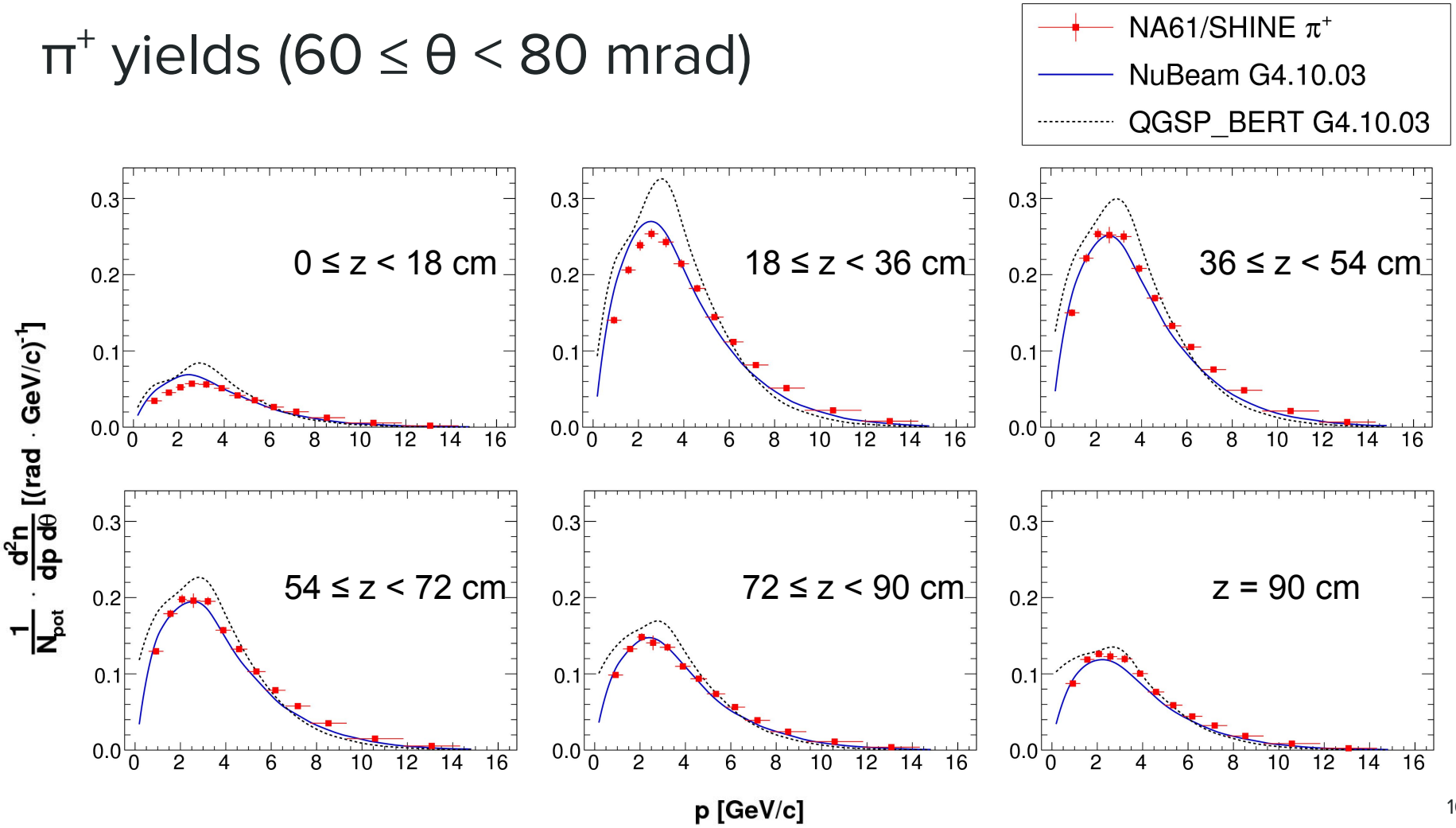
- Measurements are done as a function of momentum (p), polar angle (θ) and longitudinal position of the exit point on the target surface (z)
- 5 z bins (18 cm in size) + downstream target face
- p and θ bin size depend on the statistics



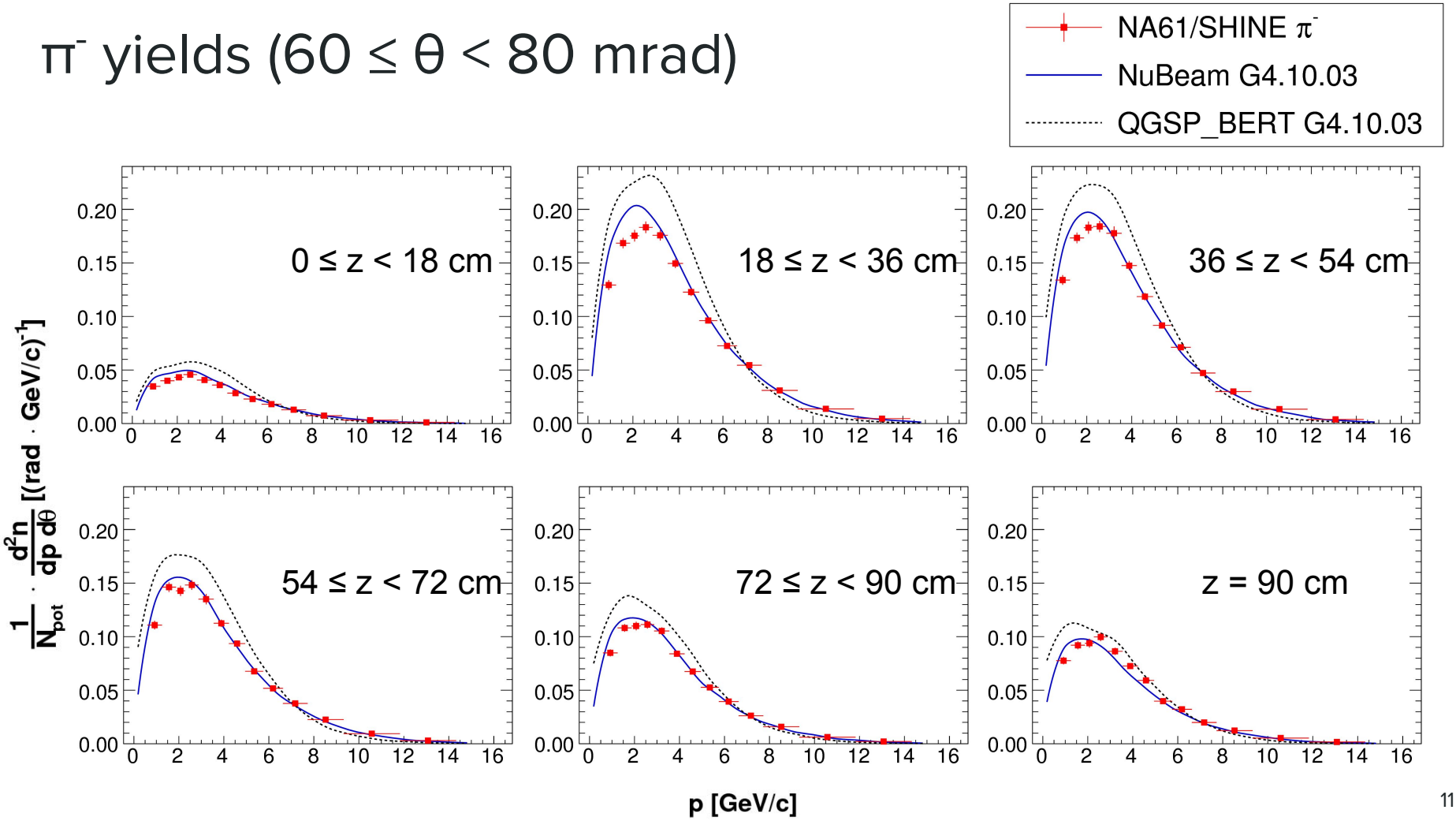
- percentage of neutrino flux produced from hadrons exiting the target covered by the replica target measurement

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

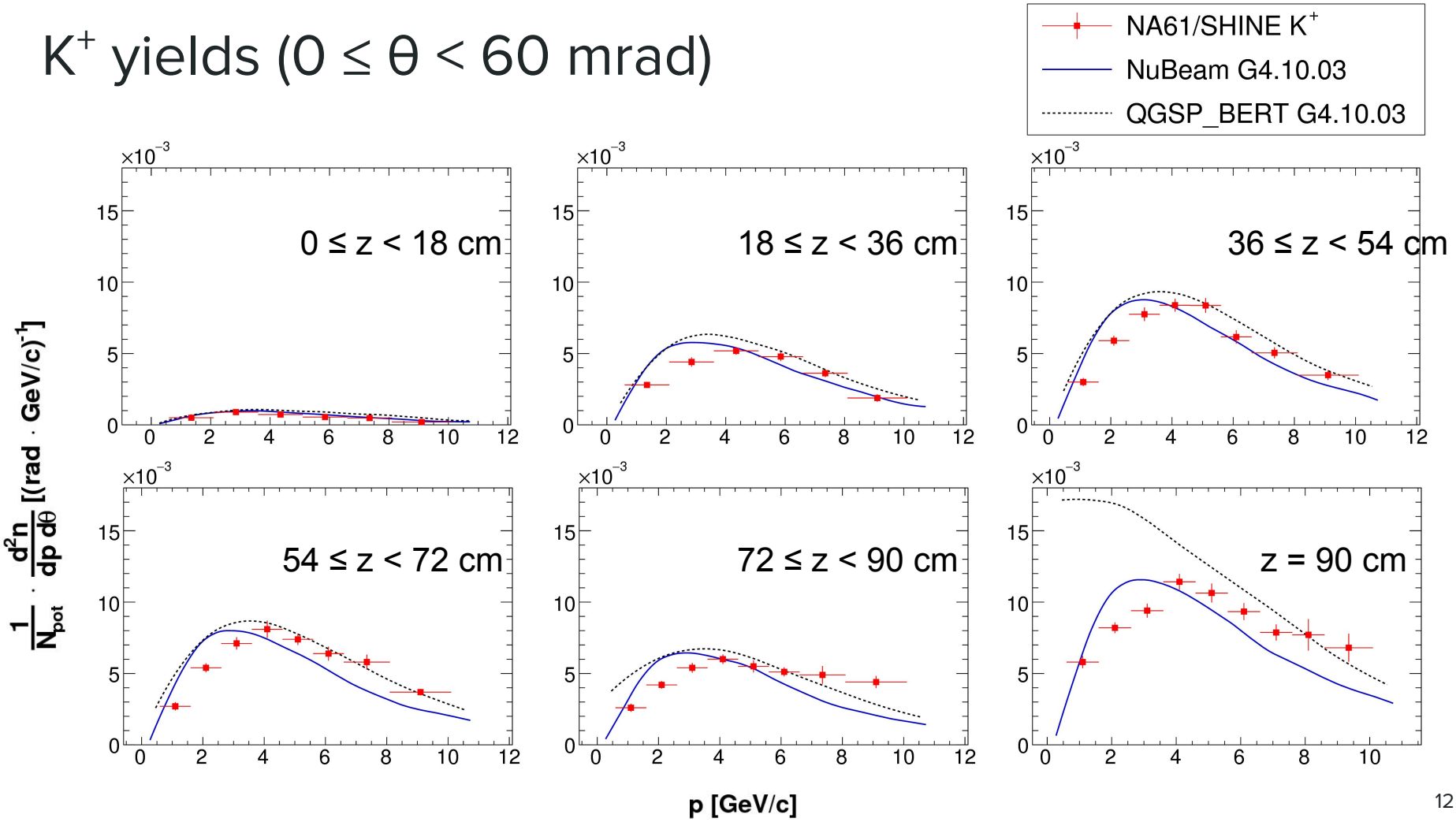
π^+ yields (60 ≤ θ < 80 mrad)



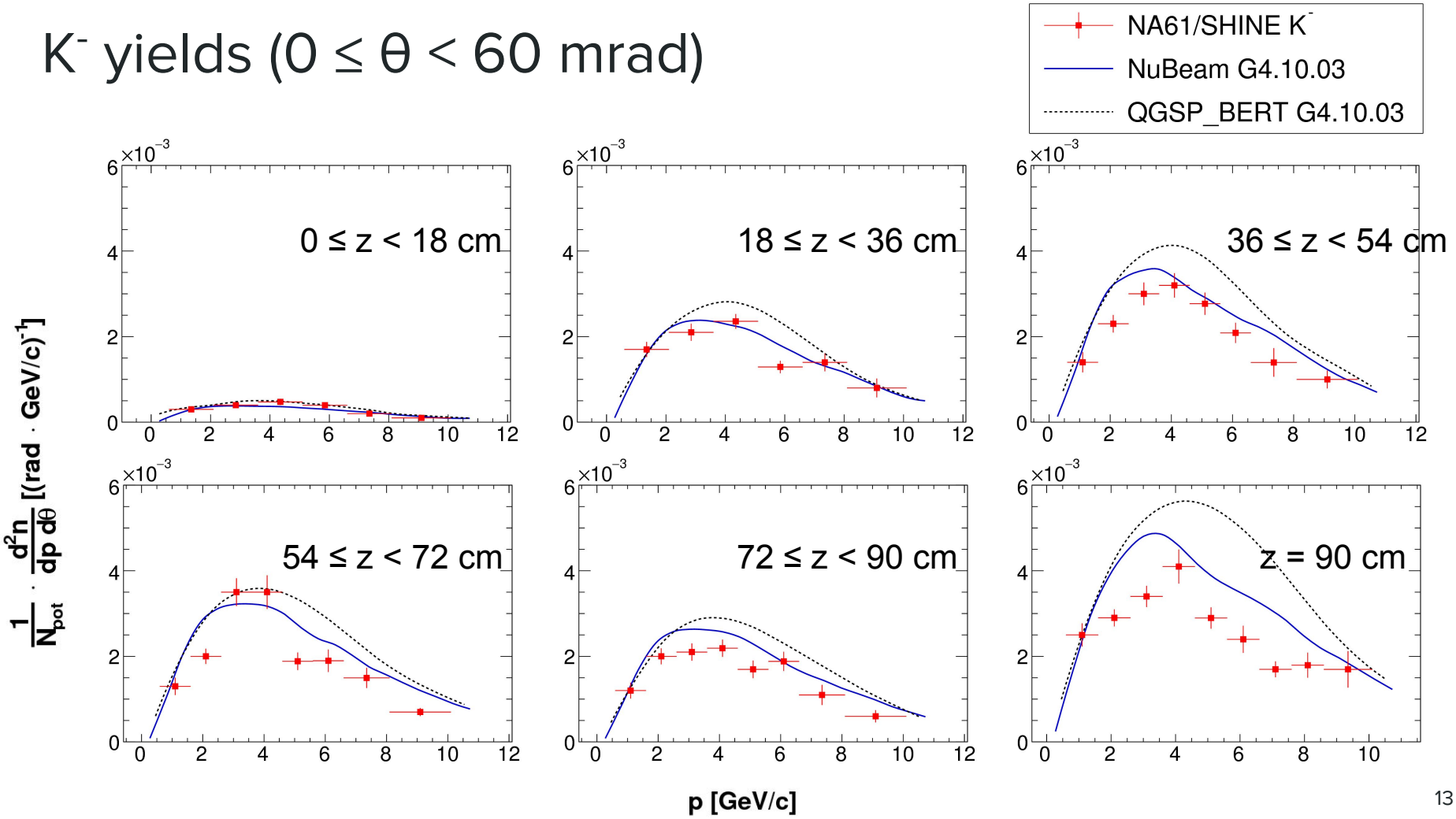
π^- yields ($60 \leq \theta < 80$ mrad)



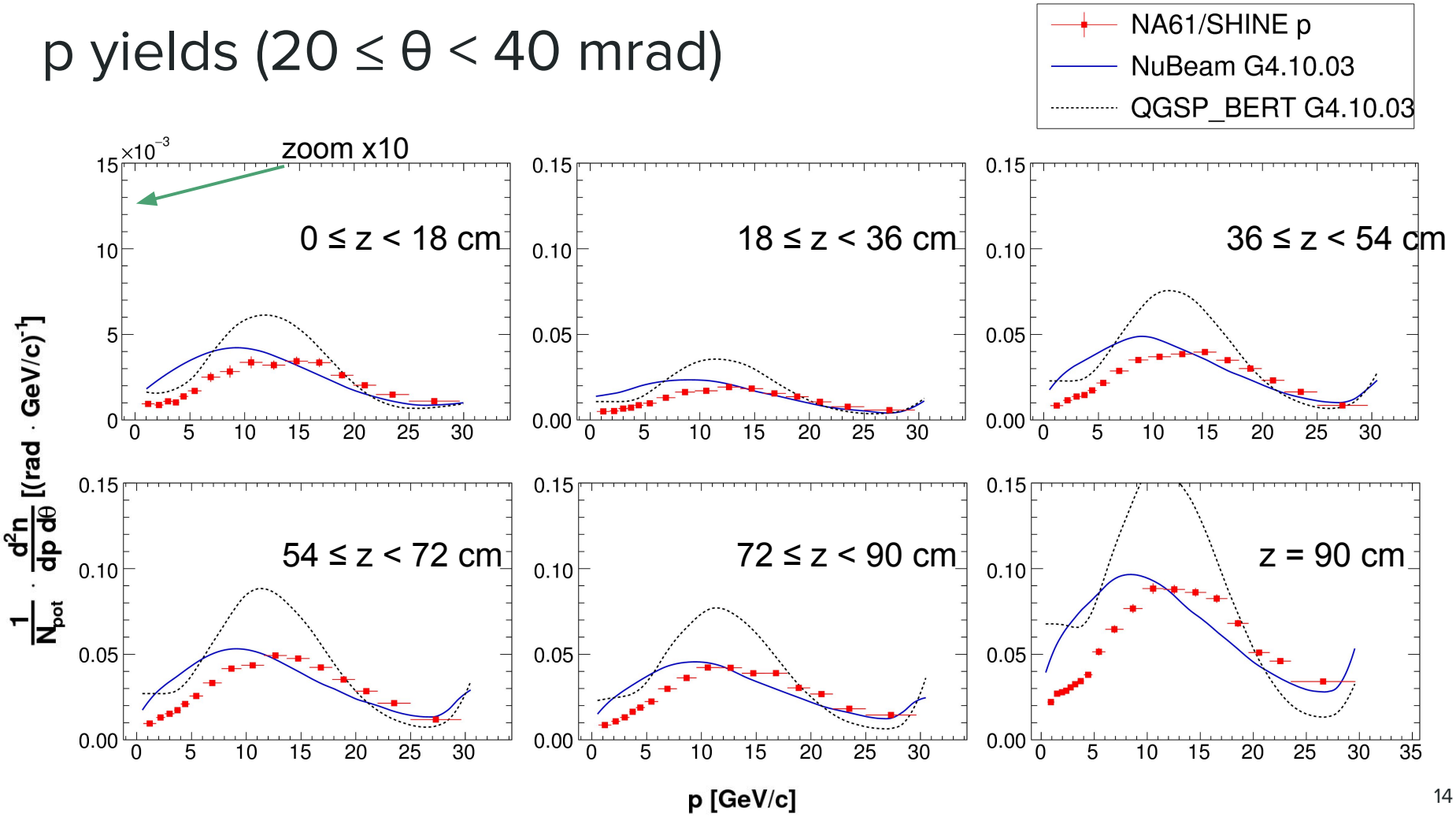
K^+ yields ($0 \leq \theta < 60$ mrad)



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

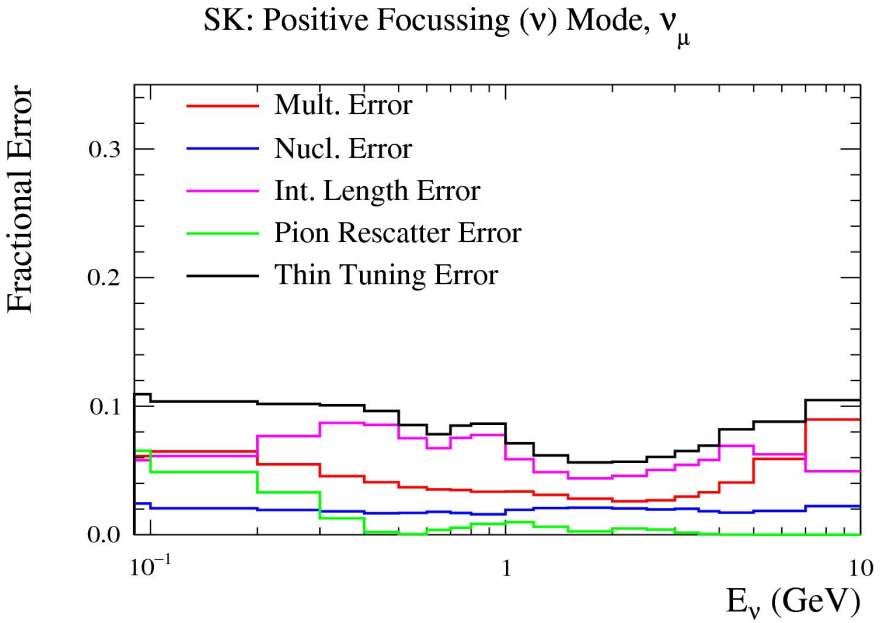


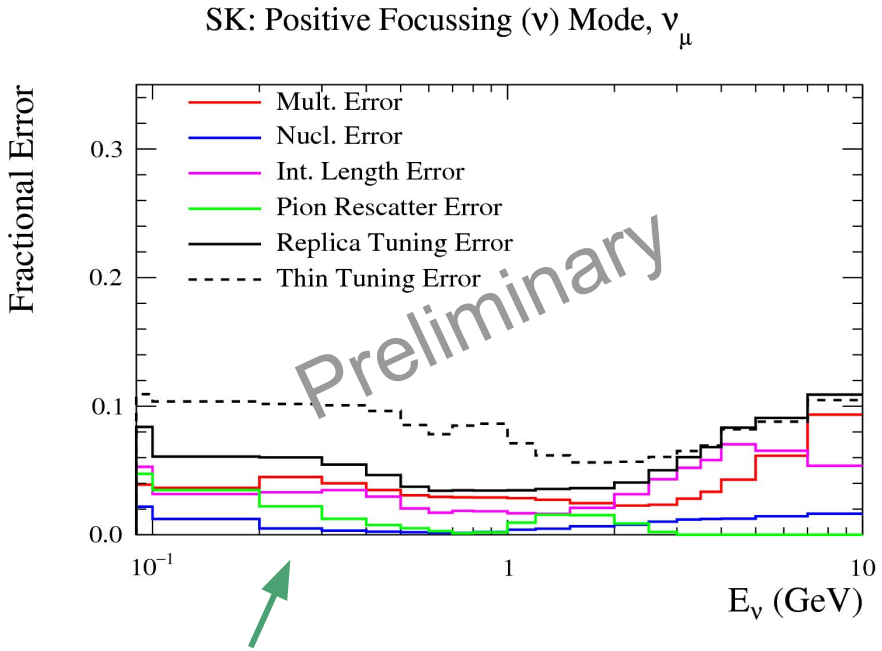
p yields (20 ≤ θ < 40 mrad)



T. Vladisavljevic, arXiv:1804.00272 [physics.ins-det]

T2K neutrino flux uncertainty

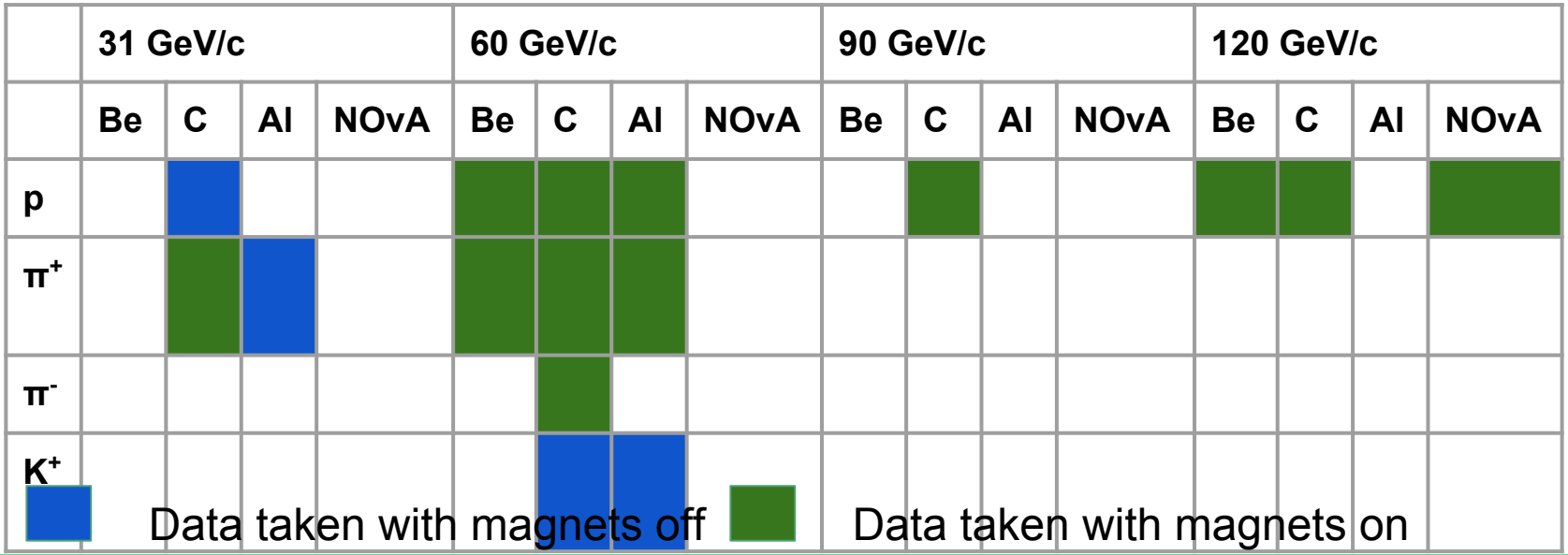




Only $\pi^{\pm}$ replica-target measurements from 2009 data were used

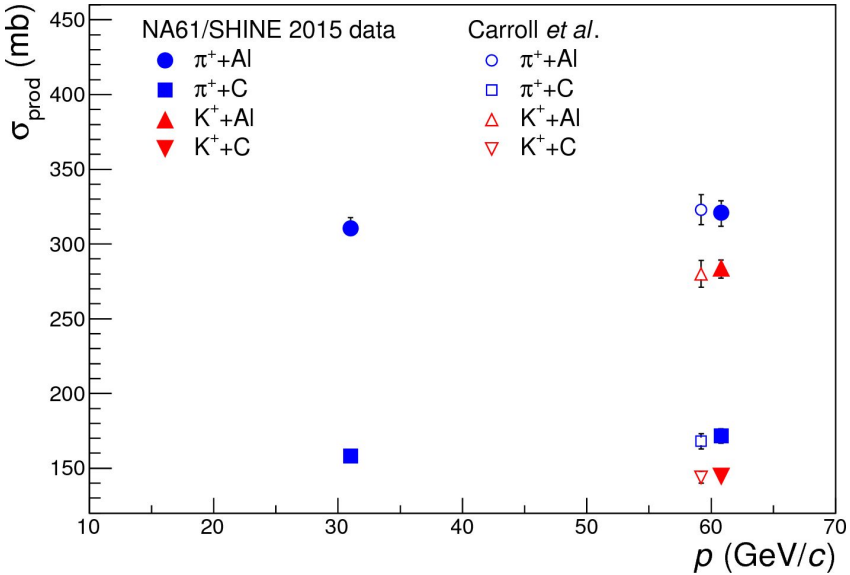
Measurements for Fermilab neutrino programme

- 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



Measurements of total production cross sections

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



A. Aduszkiewicz et al., arXiv:1805.04546 [hep-ex]
To appear in PRD

Interactions below 15 GeV/c

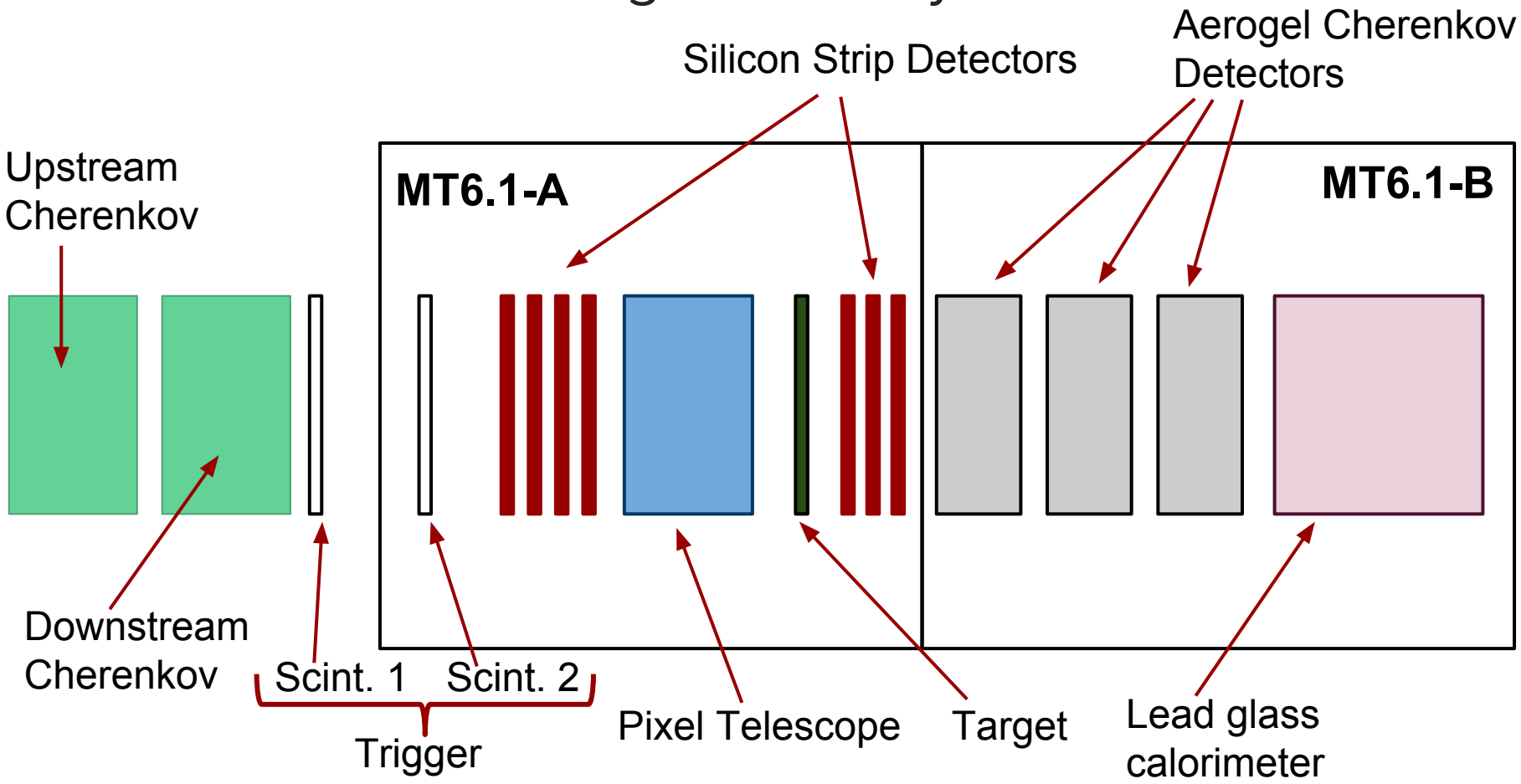
- NA61/SHINE beam cannot go below 13 AGeV/c
- Why we need lower beam momentum?
  - Low momentum re-interactions are starting to be limiting factor for T2K (π+Al, K+Al, ...)
  - The same limitations will apply to T2HK
  - Sub-GeV sample in atmospheric neutrino oscillations is sensitive to CP violation ➔ 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
- **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

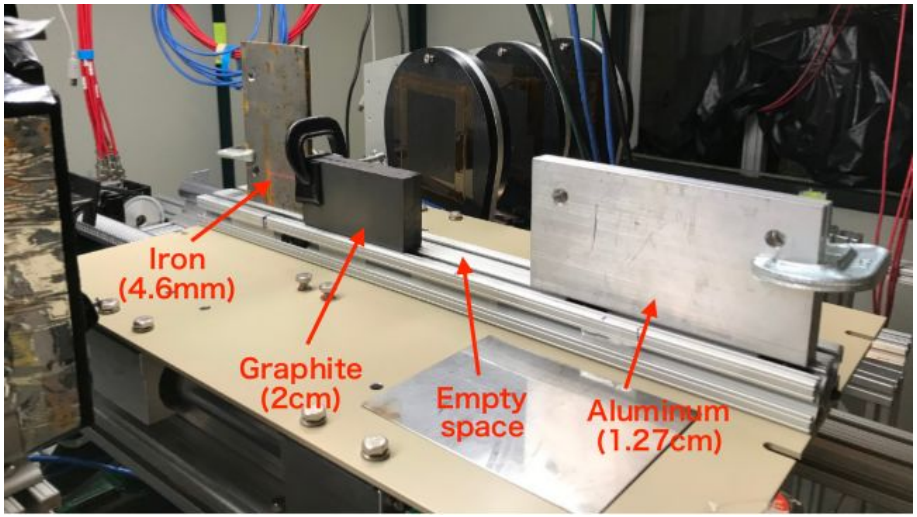
$p_b < 15$ GeV/c

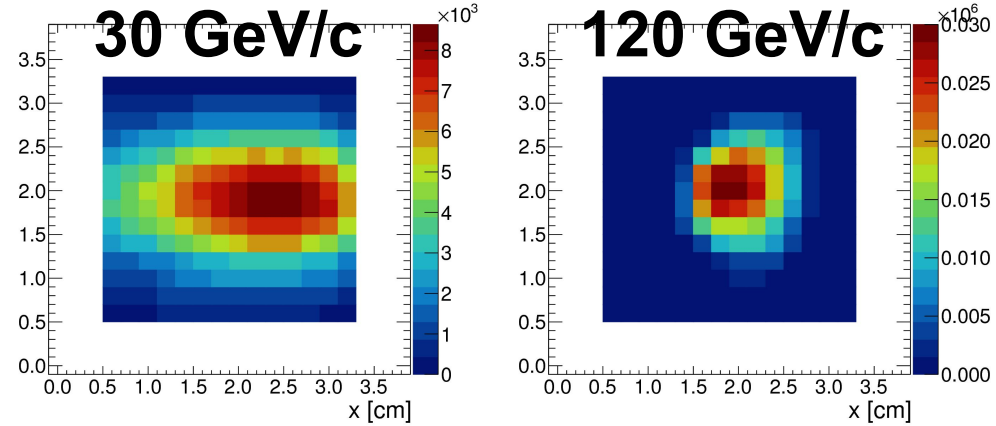
EMPHATIC data-taking in January 2018

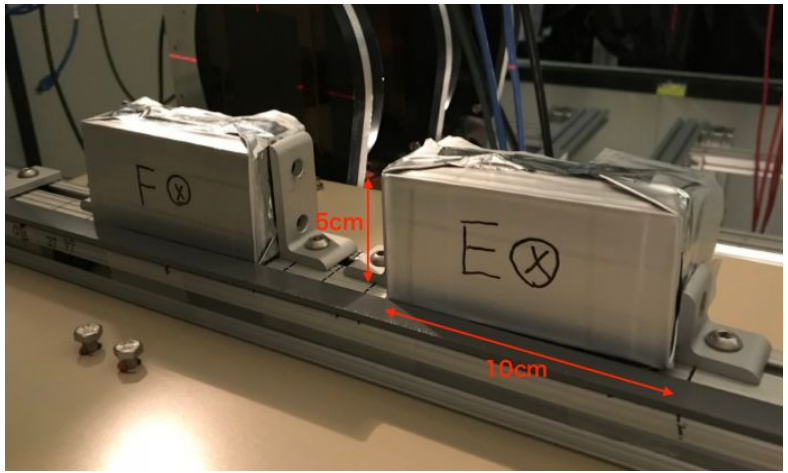


Targets and beam

- Graphite, aluminum and steel targets
- Emulsion targets with graphite
- Beam momentum: 2 - 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%**







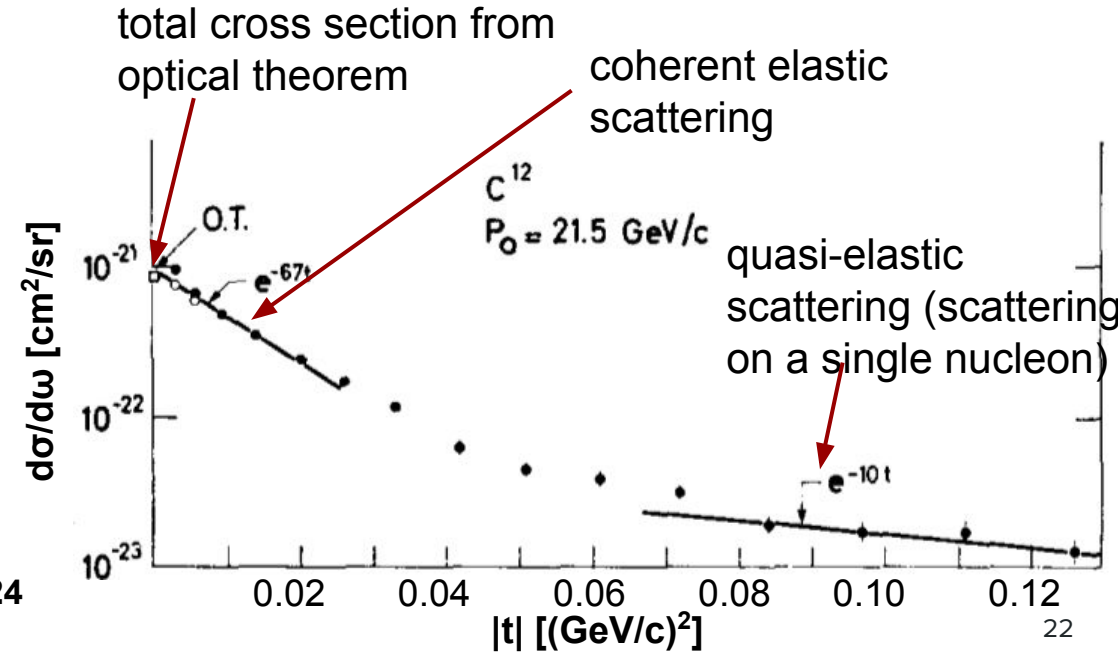
What can we do with the data?

- **Measurement of total, elastic and quasi-elastic cross section**
- Momentum measurement is not necessary
- PID is not necessary

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

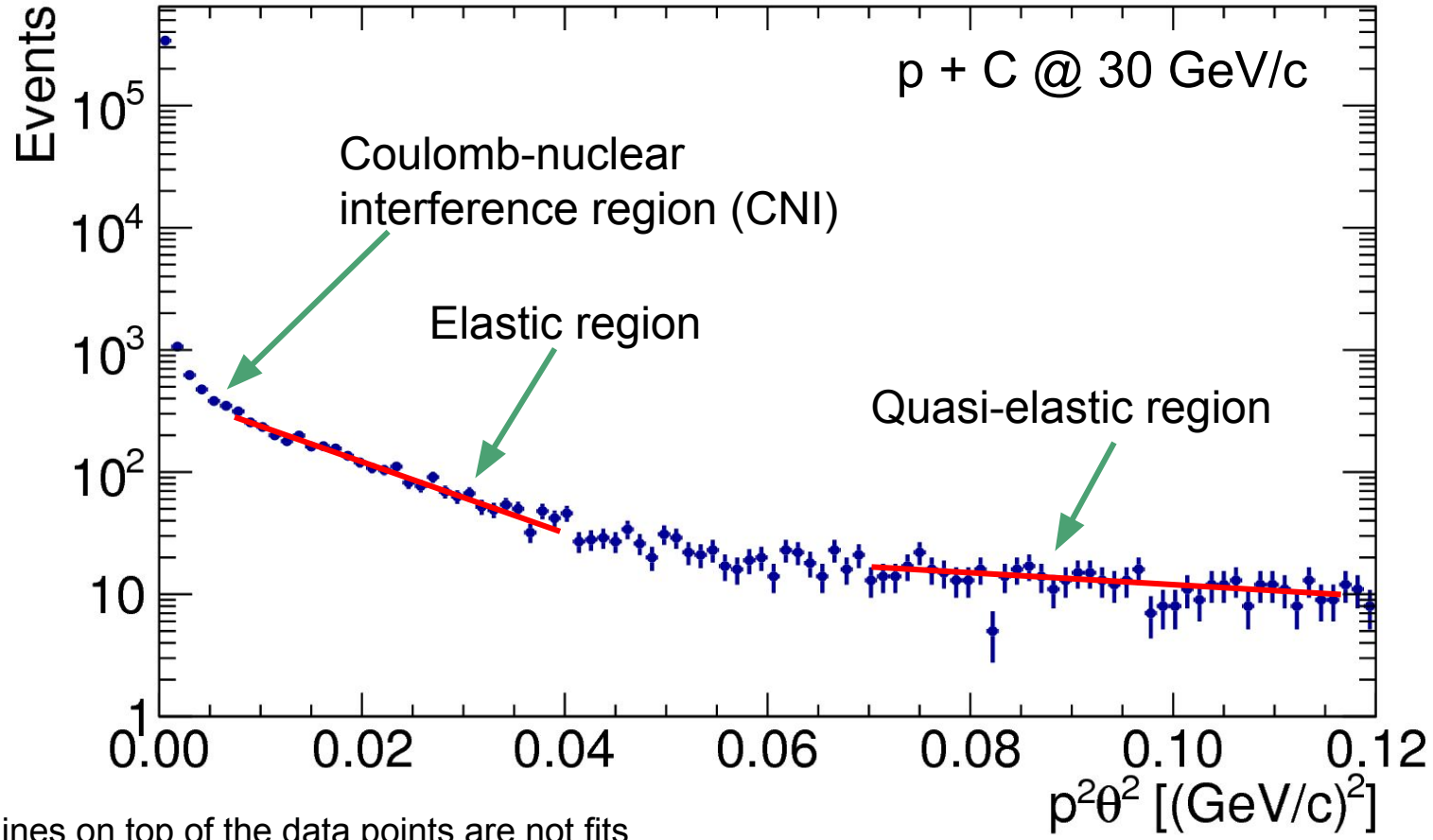
Beam momentum

Scattering angle



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

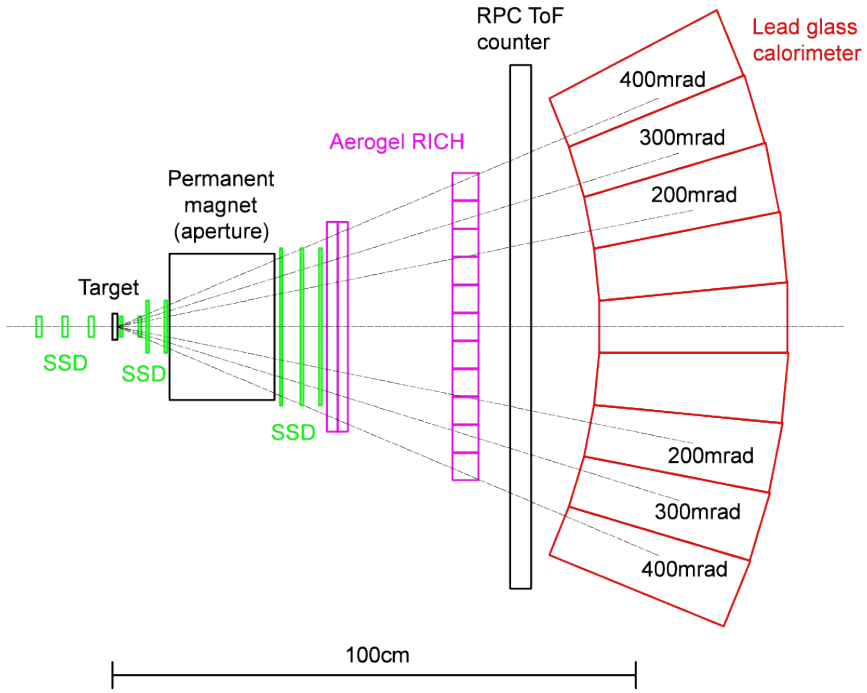
4-momentum transfer (raw data)



*Lines on top of the data points are not fits

Future EMPHATIC measurements

- Permanent magnet (Halbach array) ➔ fields > 1T are possible
- Magnet + Si strip detectors ➔ momentum resolution for 2 GeV/c particles is around 2%
- PID: TOF + aerogel RICH
- B, BN and B_2O_3 for atmospheric neutrinos
- C, Al and Fe targets for accelerator based experiments

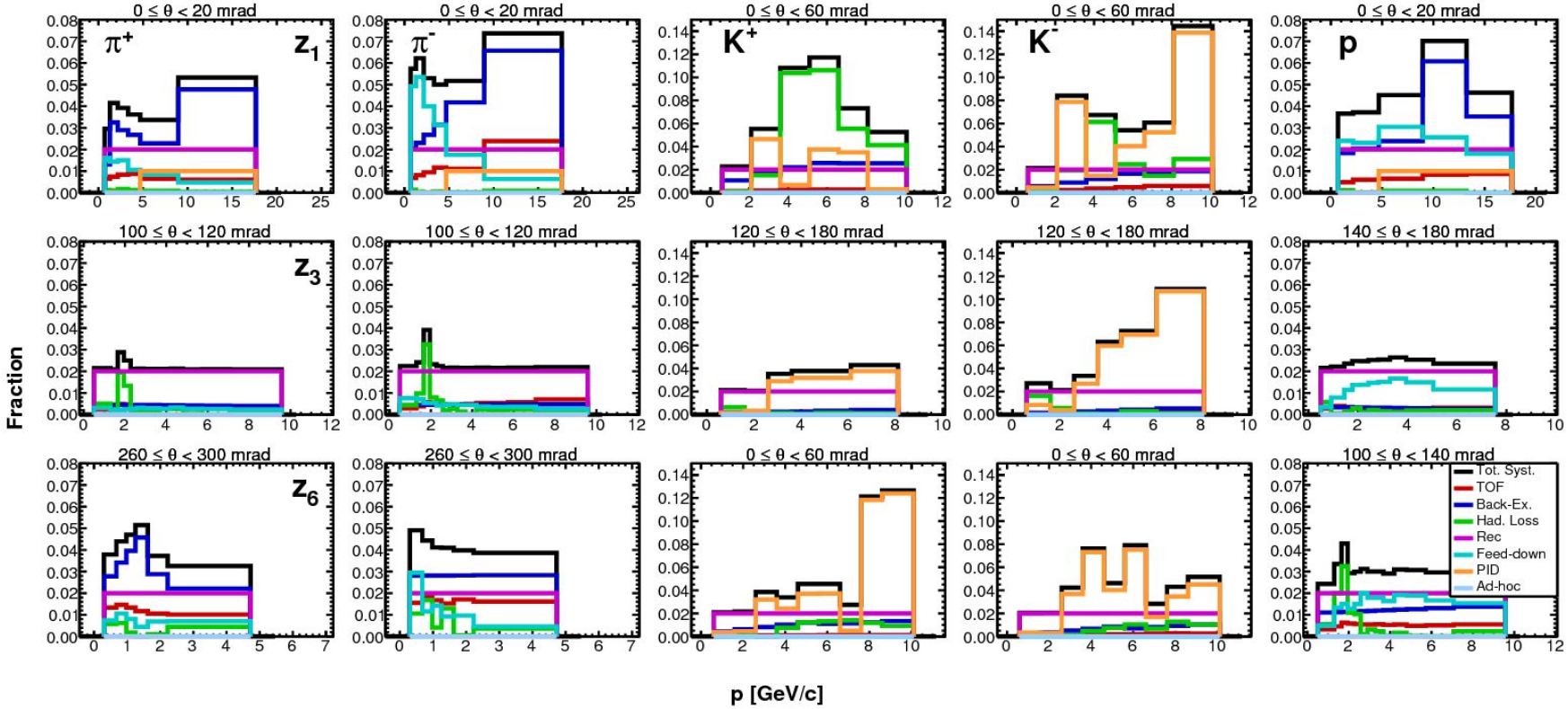


Conclusions

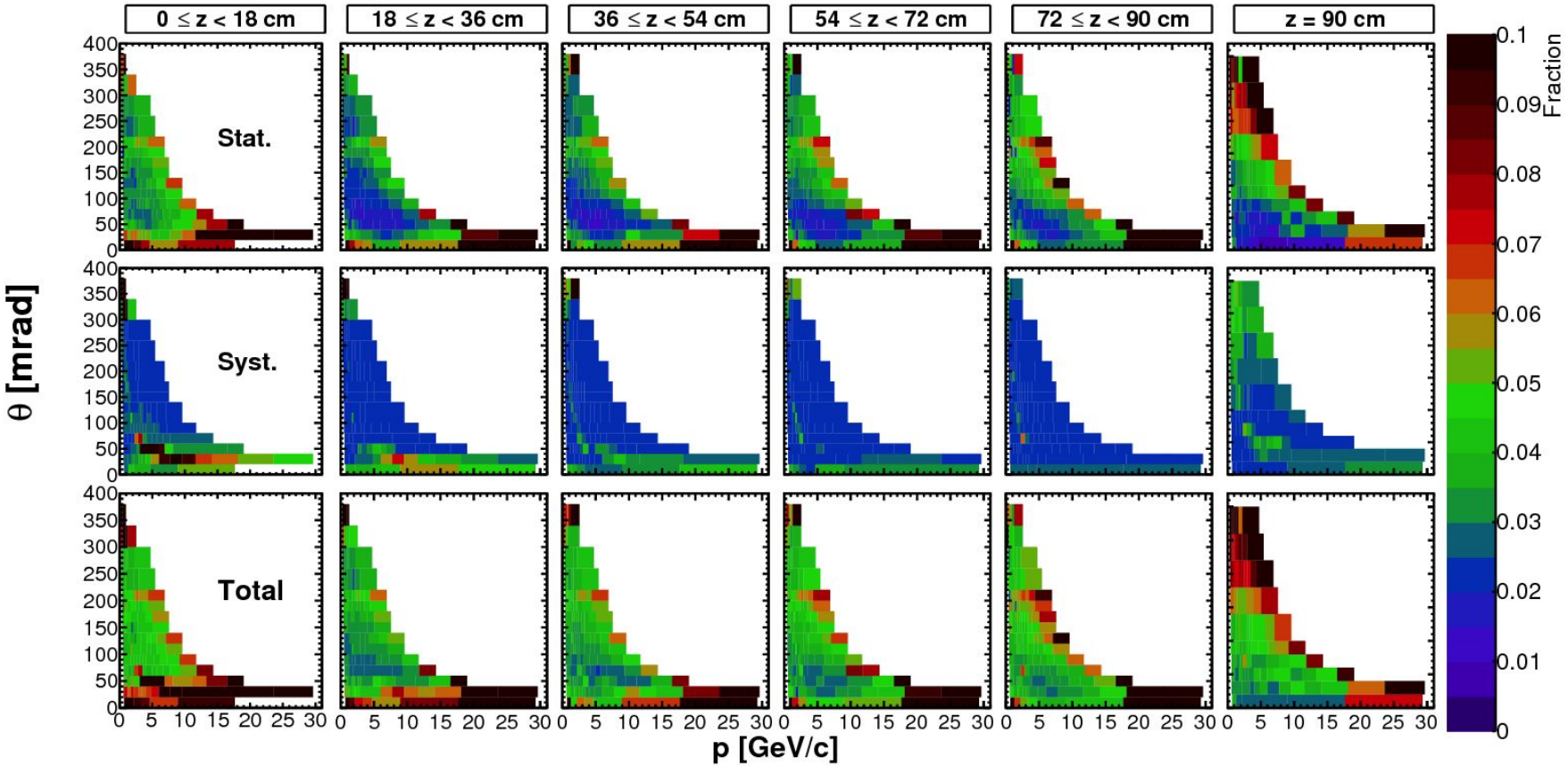
- Hadron production measurements are necessary for precise measurements of neutrinos
- NA61/SHINE took hadron production data for a decade
- Very successful T2K programme ➜ flux uncertainty reduced from > 20% to around 5%
- A lot of data was taken for the Fermilab neutrino programme
- Measurements with low momentum beams are needed
- EMPHATIC ➜ a table top experiment which can take low momentum data
- First EMPHATIC data is being analysed

BACKUP

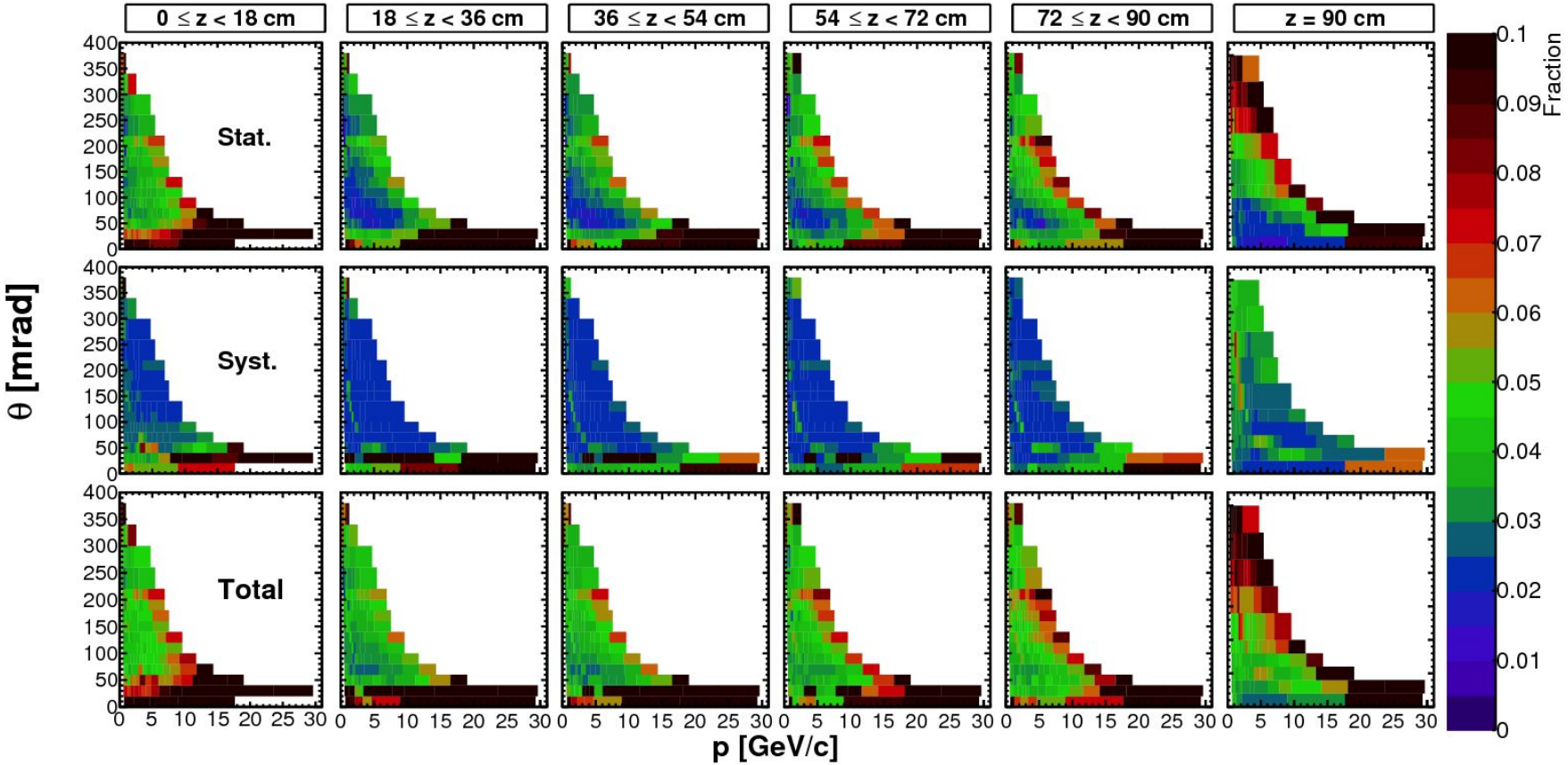
Uncertainties



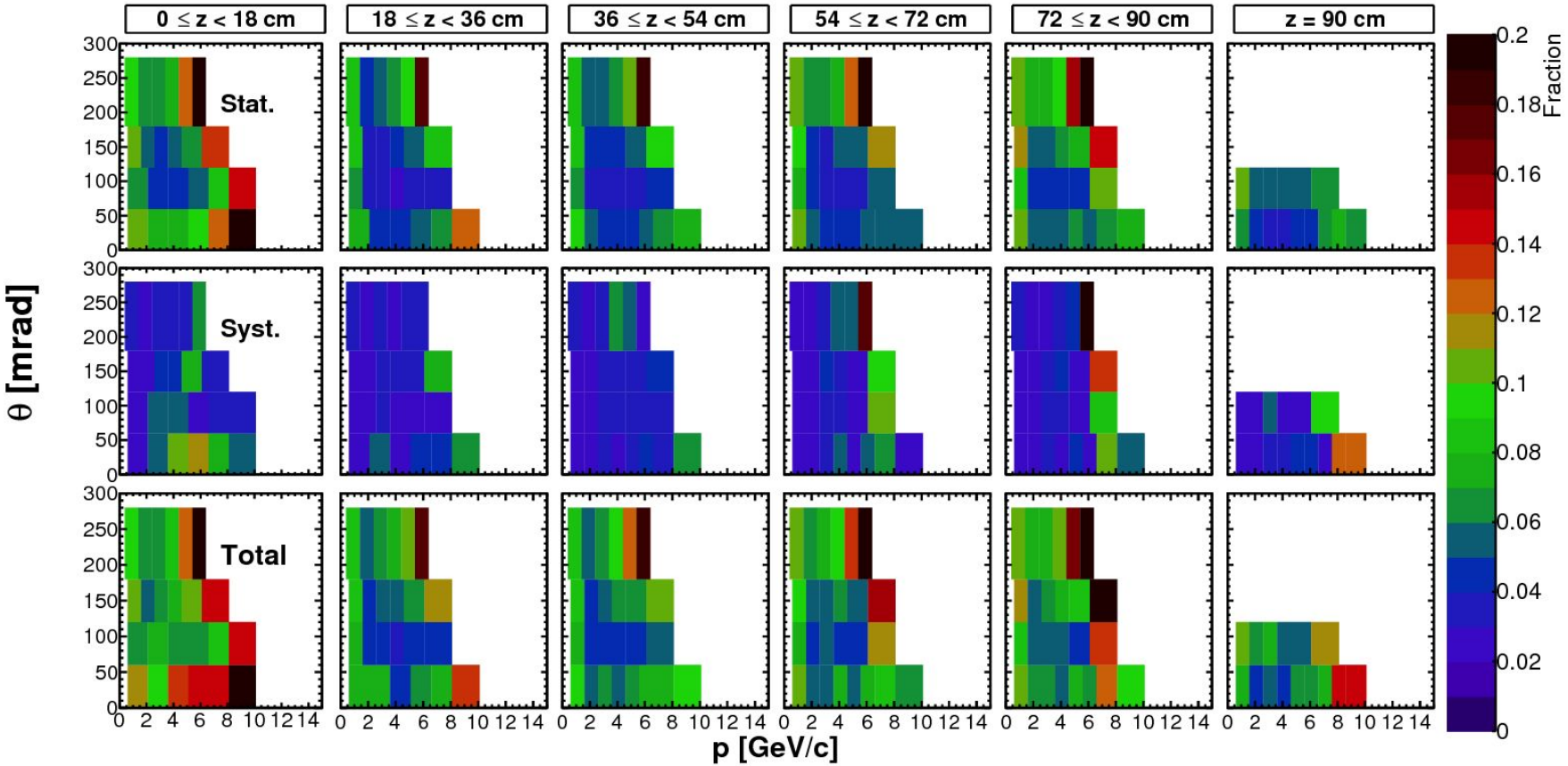
π^+ uncertainties



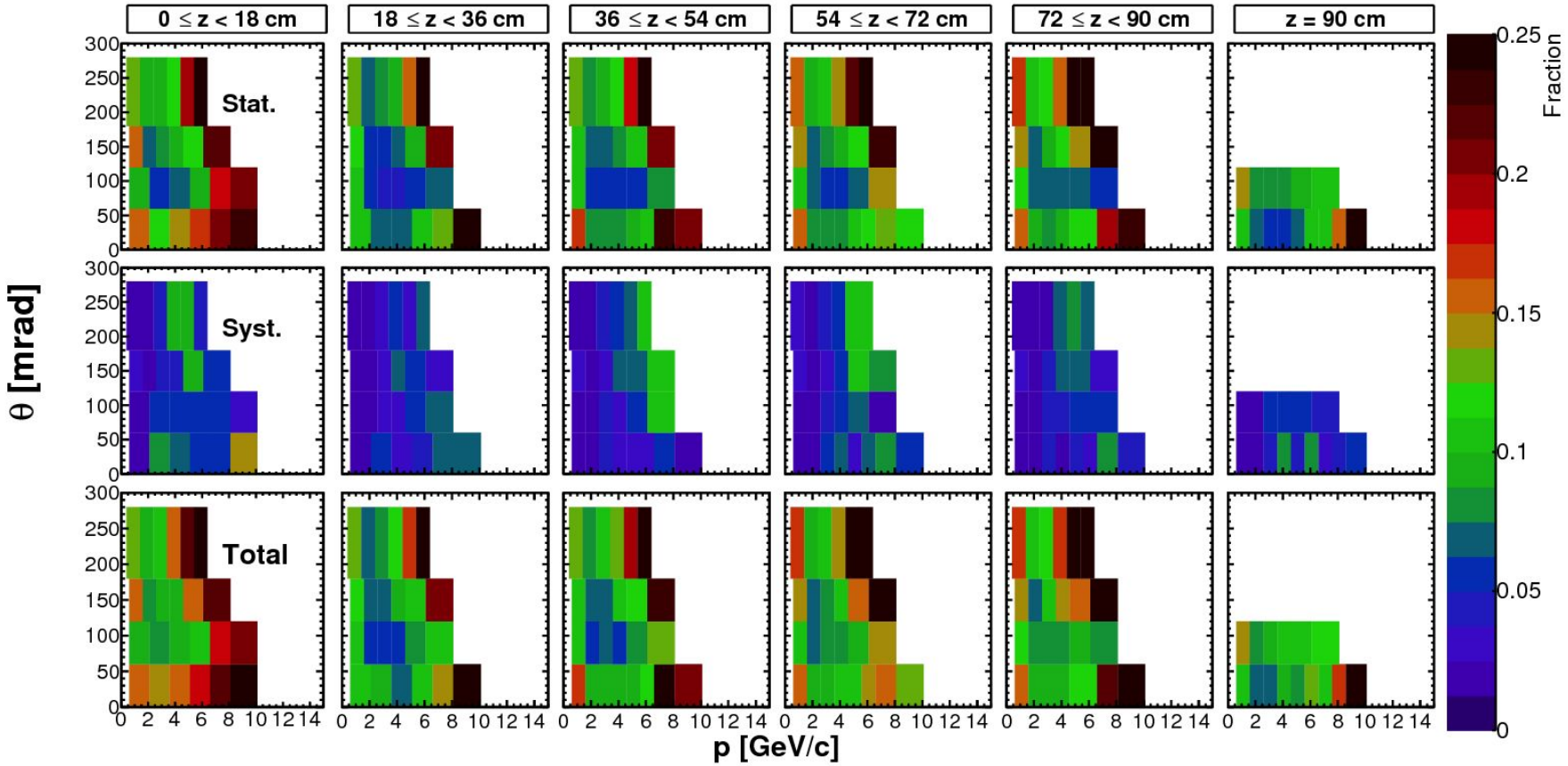
π^- uncertainties



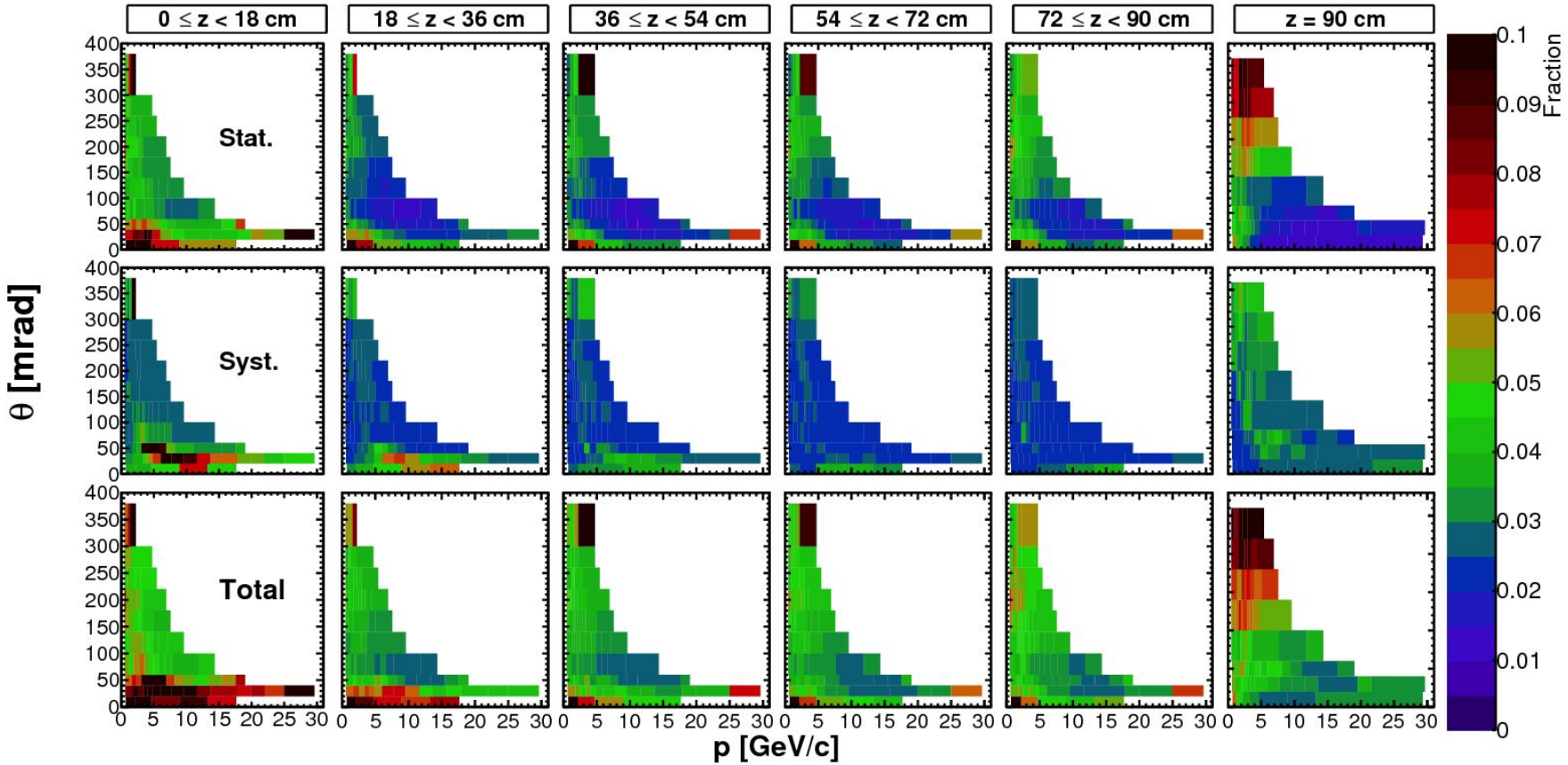
K^+ uncertainties



K^- uncertainties

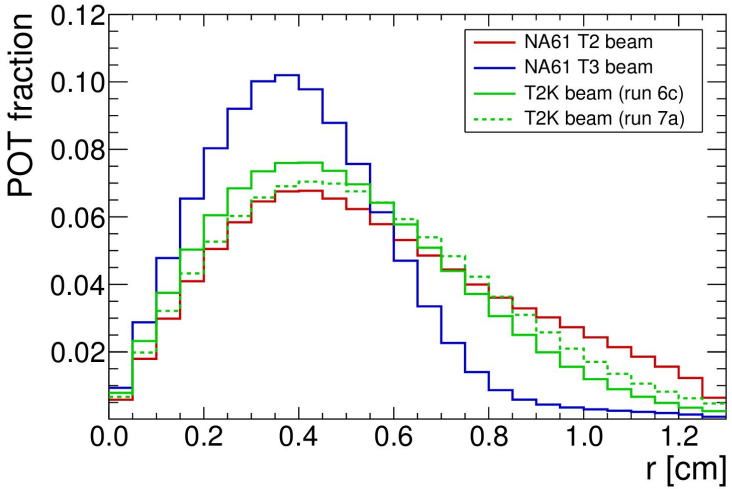


p uncertainties



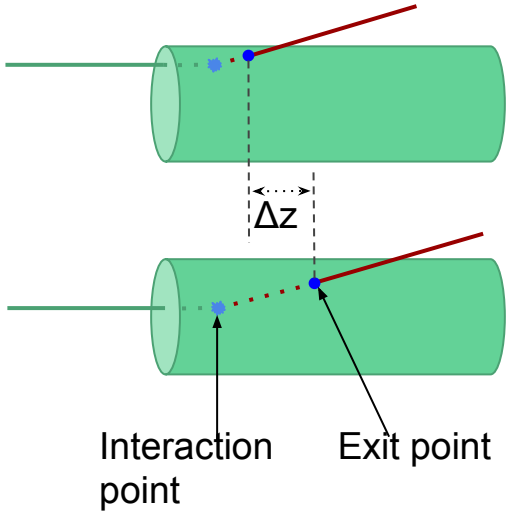
Beam profile re-weighting

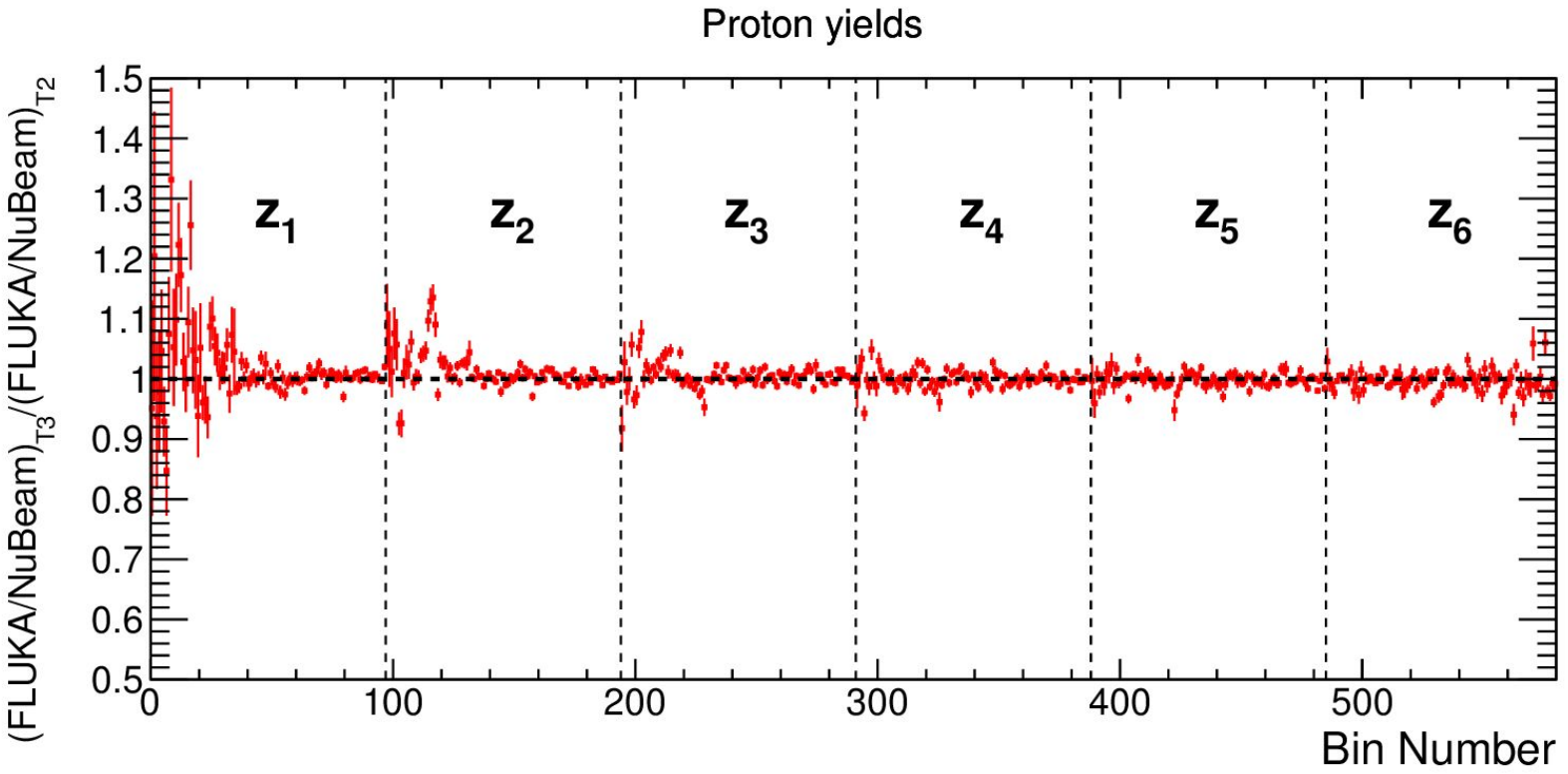
- hadron yields on the target surface depend on the beam profile
- narrower beam profile ➔ suppression of hadron yields for low θ and upstream z bins
- Only important parameter is radial position on the upstream target face
- T2K beam profile ≠ NA61 beam profile



r_b = 0.65 cm, θ = 20 mrad → Δz = 32.5 cm
θ = 250 mrad → Δz = 2.5 cm

r_b = 1.00 cm, θ = 20 mrad → Δz = 15.0 cm
θ = 250 mrad → Δz = 1.2 cm





- T2 beam width > T2K beam width > T3 beam width ➡ when using this data in T2K any bias would be smaller