GEANT4 neutrino beam simulations for the T2K experiment

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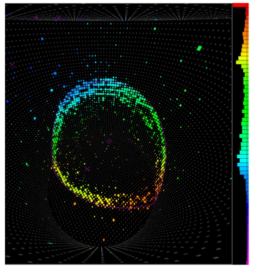
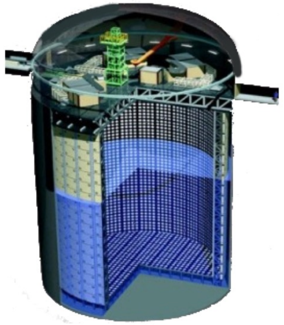
on behalf of the T2K Collaboration

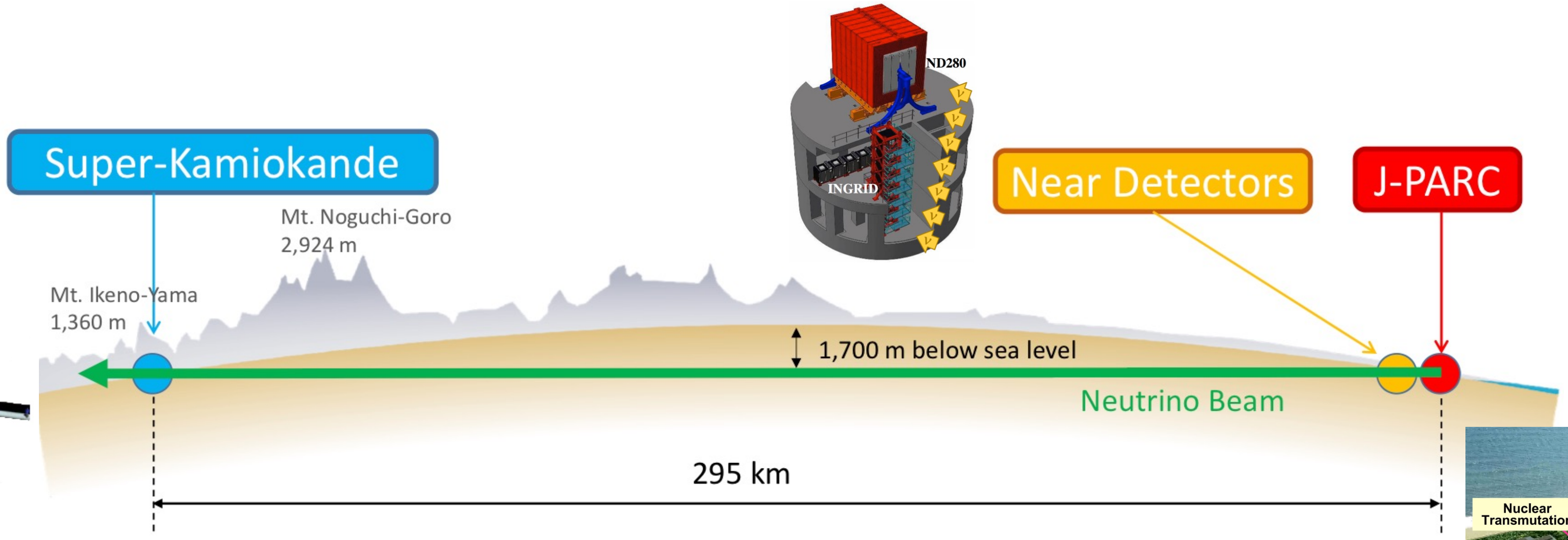
Particle Accelerators and Beams Conference 2023

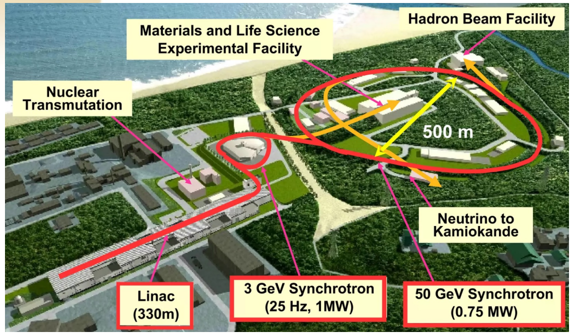
The T2K Experiment

T2K (Tokai-to-Kamioka) is a long baseline neutrino experiment in Japan. A neutrino beam is produced at the accelerator facility at the Japan Proton Accelerator Research Center (J-PARC) and travels from the east to west coasts of Japan to the Super-Kamiokande detector.









T2K studies the oscillation of neutrinos, observing the disappearance of ν_μ and appearance of ν_e by measuring the beam 280 m after production at the near detector ND280 and further away (295 km) at the far detector Super-Kamiokande.

The T2K Collaboration

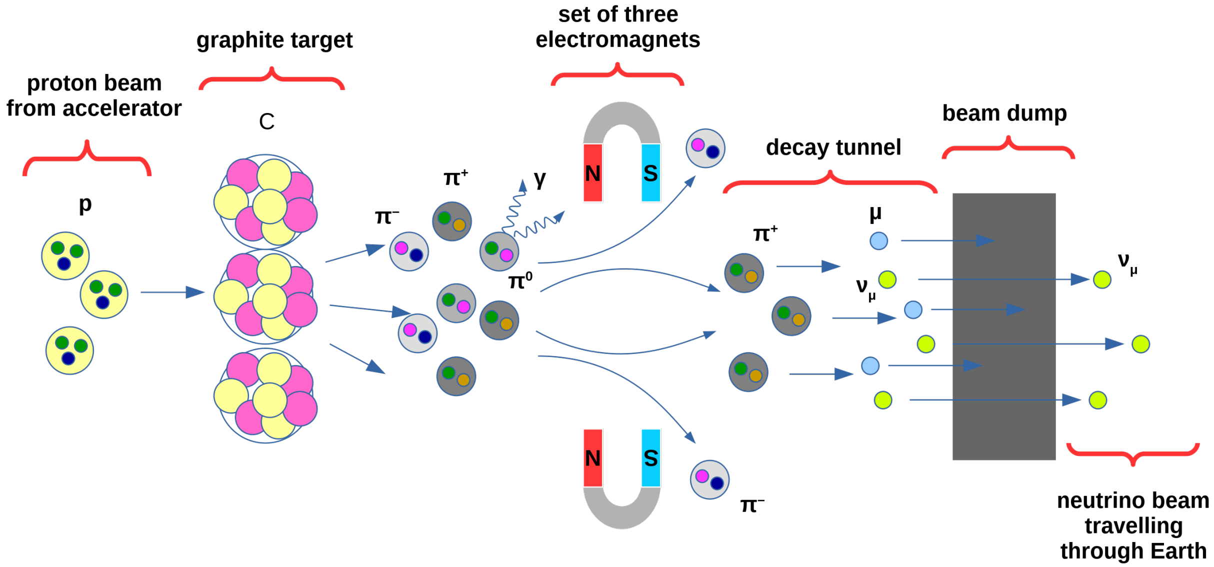
The T2K Collaboration consists of 572 members from 76 institutions in 14 countries.

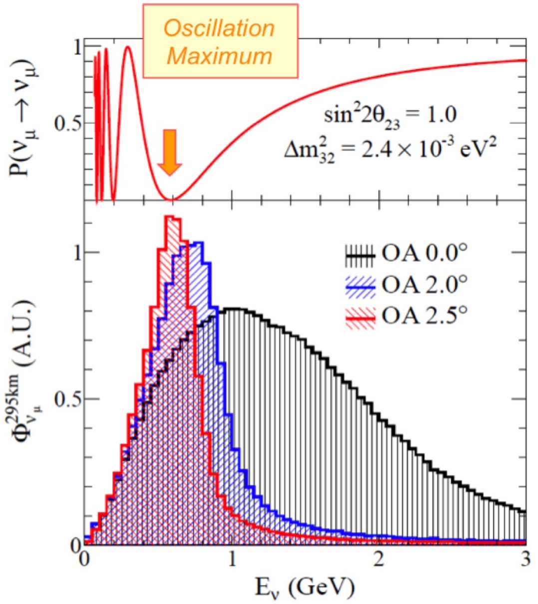
Photo taken in the last collaboration meeting – February 2023

T2K Neutrino Beam (1)

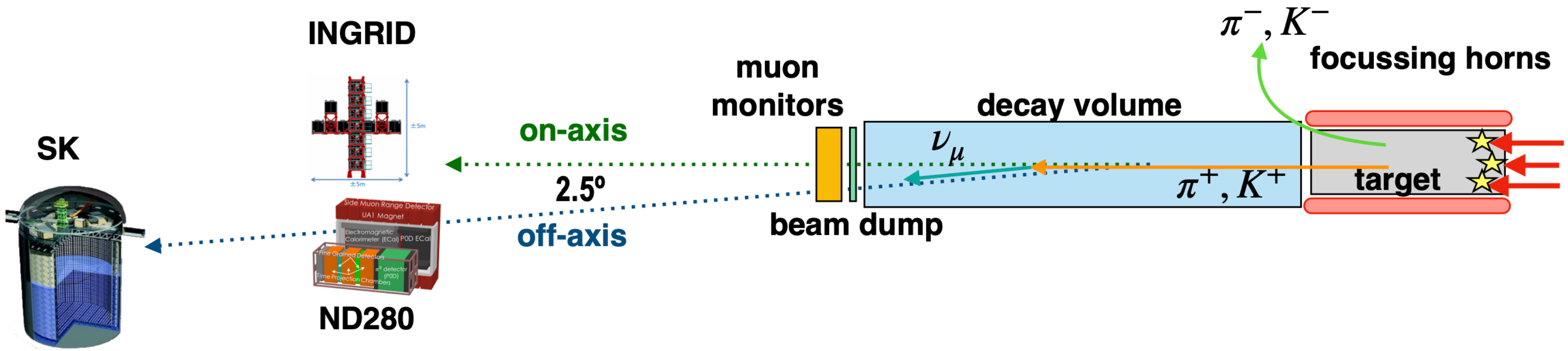
The production of the neutrino beam starts from protons directing a 30 GeV proton beam produced by the accelerator in J-PARC to a carbon target, which produces a secondary hadronic beam.

Hadrons are then focused by three magnetic horns and eventually decay into neutrinos in a decay volume.



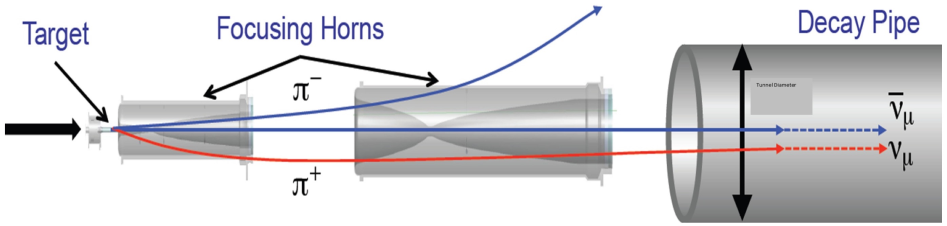


Neutrino fluxes for off-axis angles 0.0°, 2.0° and 2.5° [1]



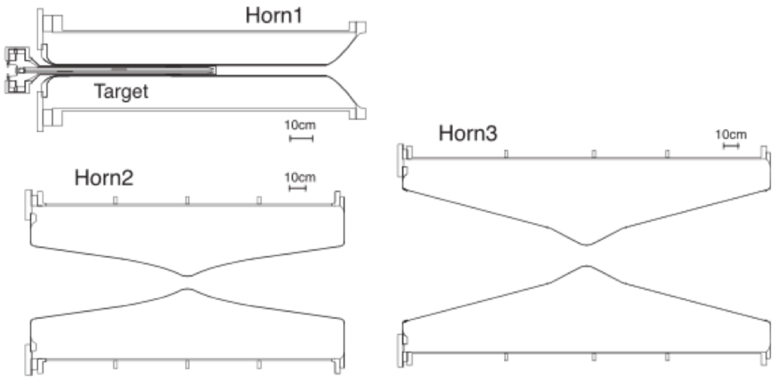
T2K Neutrino Beam (2)

The T2K target is 900 mm long graphite rod (around two interaction lengths) placed inside of the first magnetic horn. Graphite is surrounded by a titanium case and temperature is controlled by allowing helium to flow around the target.



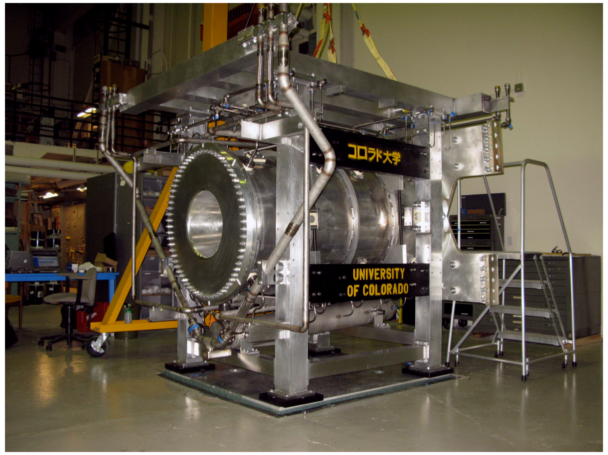
Picture of the T2K target before integration with horn [2].

Three magnetic horns are used to focus charged particles produce by the interactions of the protons in the target. They generate the magnetic field with a pulsed current of 320 kA.



Cross section of three magnetic horns.

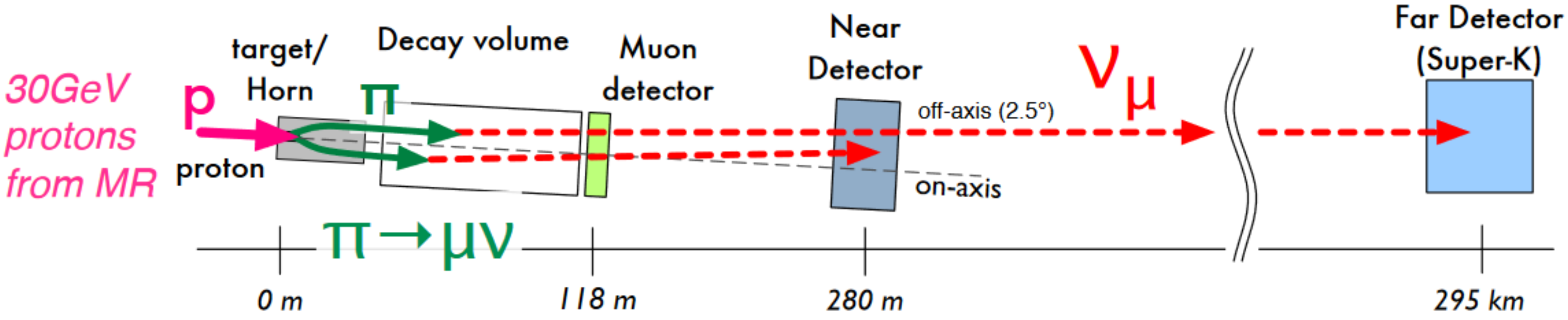
Region between the inner and outer conductors.



Horn 2

Current T2K Beam Simulations: JNUBEAM

The Monte Carlo simulation, JNUBEAM, describing the physical processes producing neutrinos, is based on the no longer maintained simulation software GEANT3, and relies also on FLUKA for the description of hadronic interactions that are fed to GEANT3.



FLUKA:
Hadronic interactions in the target

→

JNUBEAM:
Tracking of particles exiting the target; neutrino production

→

Re-weighting

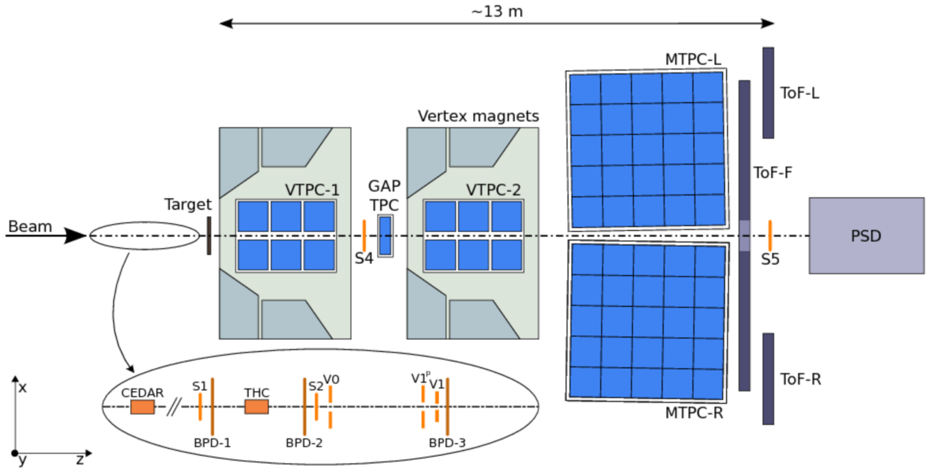
↓

Neutrino fluxes

Using **GEANT4** would be a modern approach to generate simulations, replacing both GEANT3 and FLUKA.

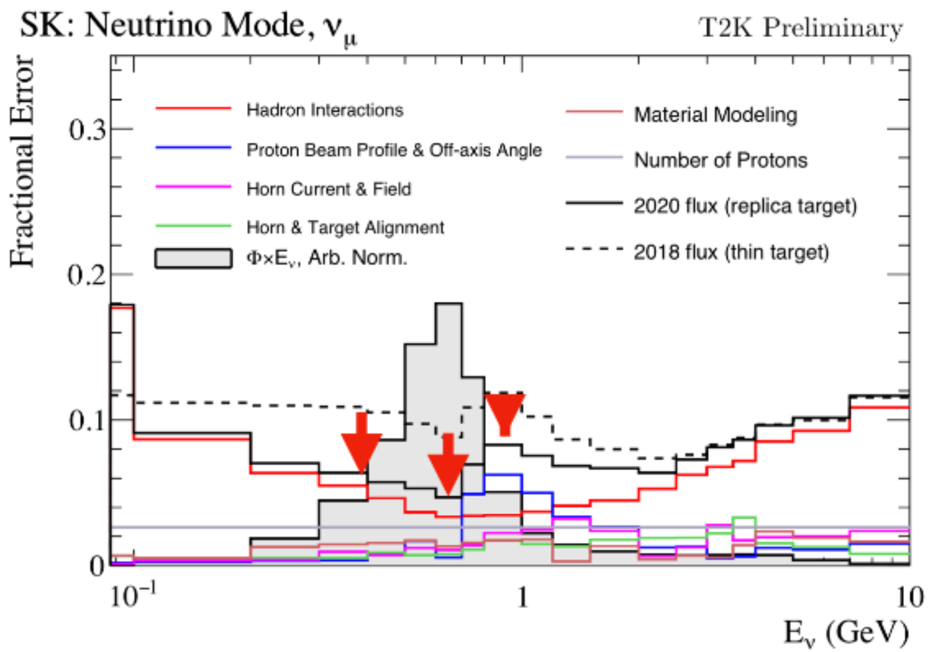
Current T2K Beam Simulations: Flux Tuning

One of the main systematic uncertainty sources of the neutrino flux predictions comes from the secondary hadrons produced from the interactions of the proton beam with the target. The NA61/SHINE experiment measures the produced hadrons around a T2K replica target [3], and the data is used to reweight the T2K neutrino fluxes.



Schematic view of the NA61/SHINE experiment [3]

T2K replica target



Flux prediction uncertainties vs neutrino energy in the neutrino mode for T2K, at the far detector site. The arrows highlight the reduction in the uncertainties from the earlier thin target case (dotted line) to the replica target case (bold line) [5].

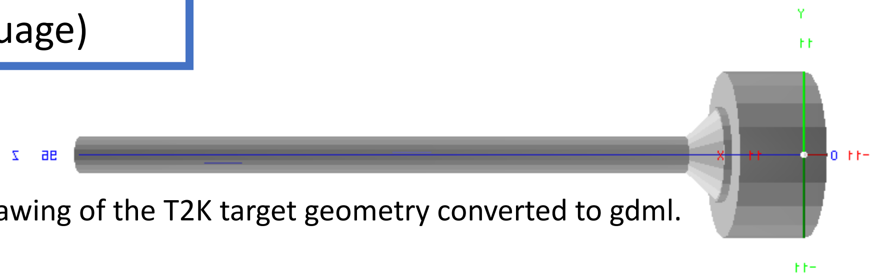
Flux errors are reduced from ~12% to ~5% by using the measurements from NA61/SHINE.

GEANT4 Framework - G4Jnubeam

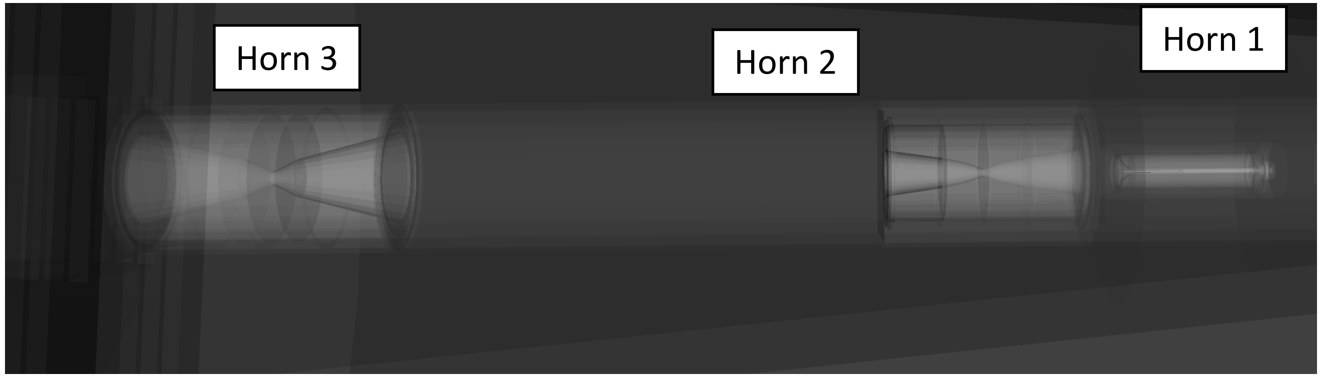
A new Monte Carlo simulation model based on GEANT4 is in development, aiming to describe the physical processes from the primary proton interactions in the T2K target to the decay of hadrons and muons producing neutrinos for the flux predictions at both near and far detectors.

- Converted the JNUBEAM geometry from GEANT3 to GEANT4;
- Framework is almost complete, already available to T2K collaborators;
- Pion yield simulations comparisons from G4Jnubeam are compared to NA61/SHINE data;
- Preliminary flux release diagrams in GEANT4.
- Next step: test in the T2K flux tuning code.

GDML
(Geometry Description
Markup Language)

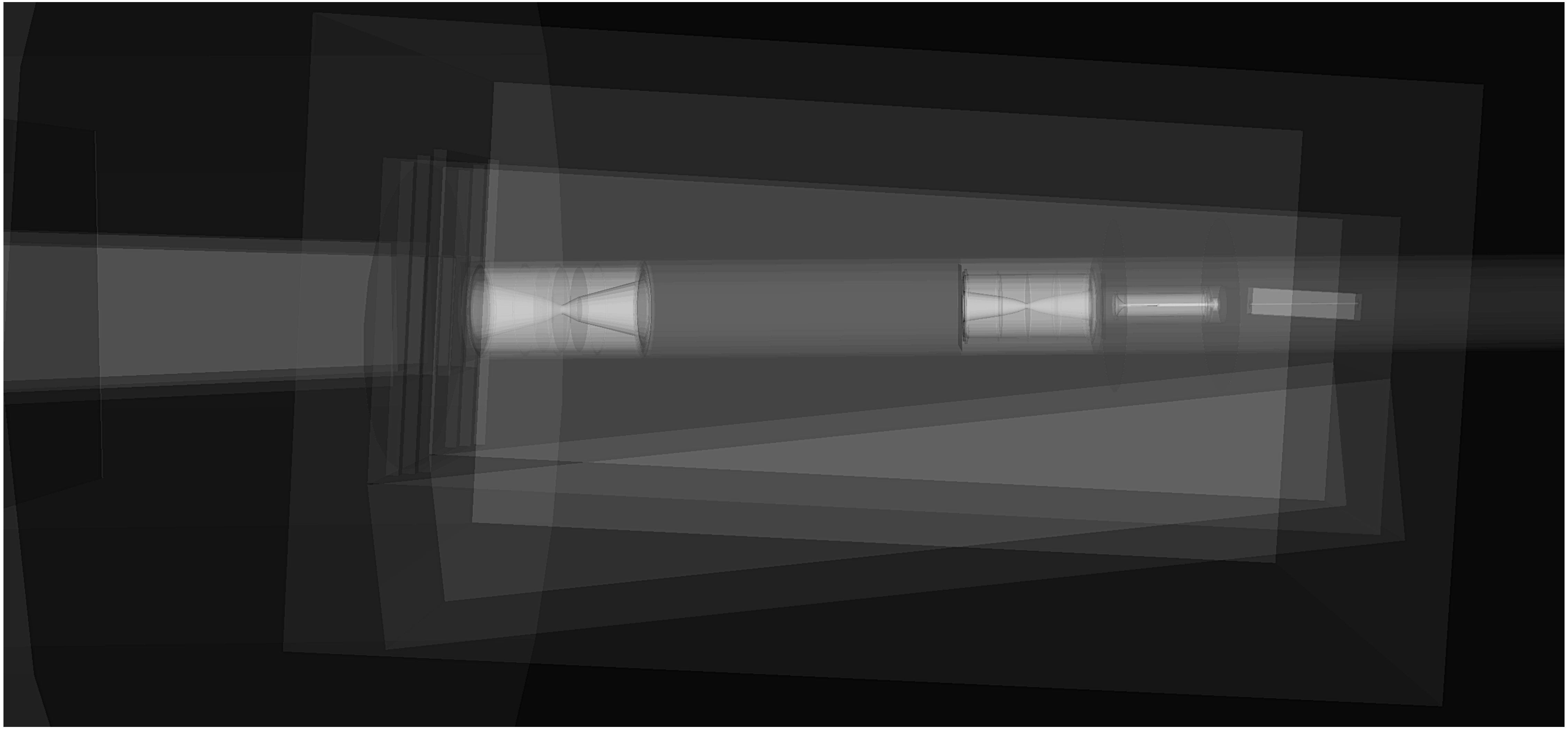


Drawing of the T2K target geometry converted to gdml.



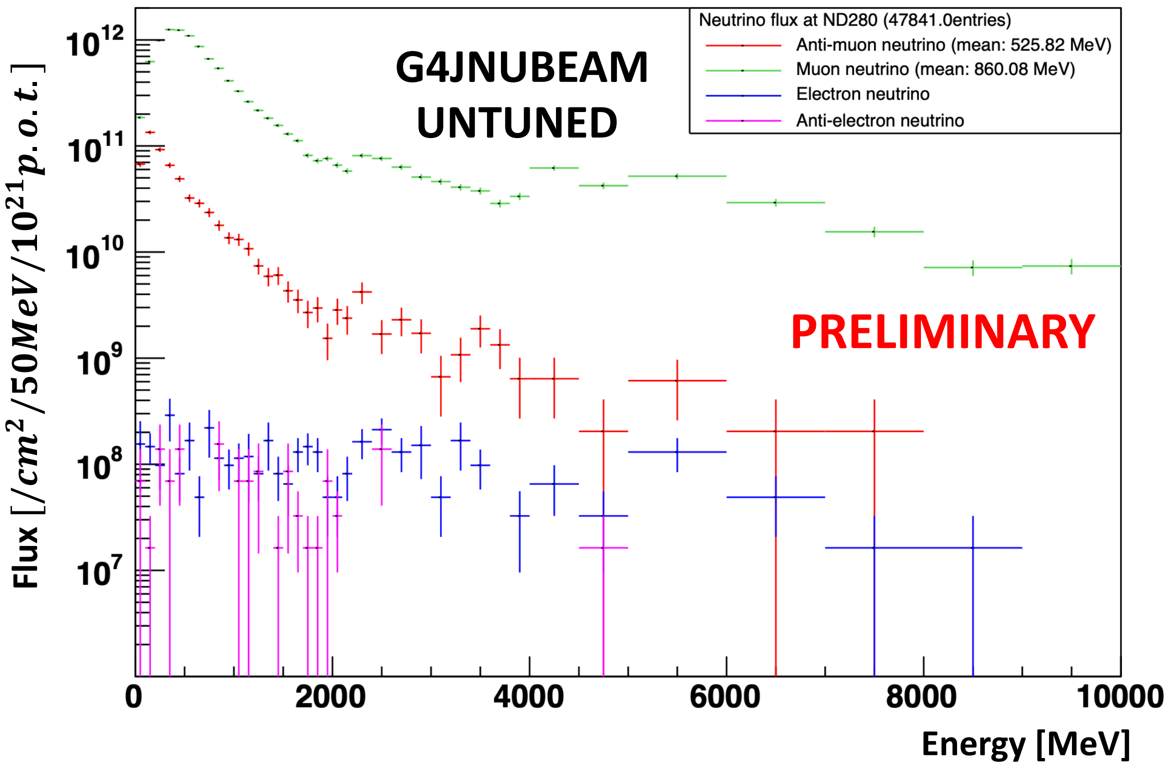
Visualization of magnetic horns from GEANT4 simulation

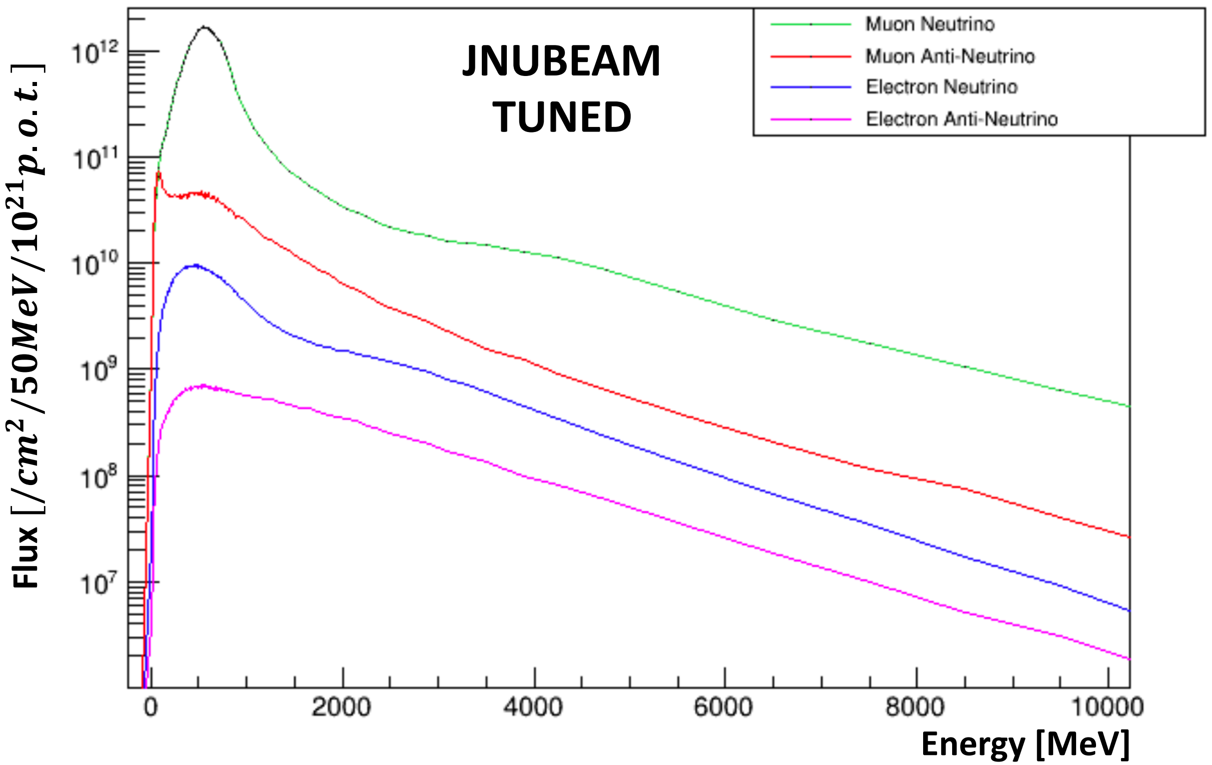
GEANT4 Simulation of T2K Geometry



Visualization from GEANT4 simulation

Neutrino Flux Predictions





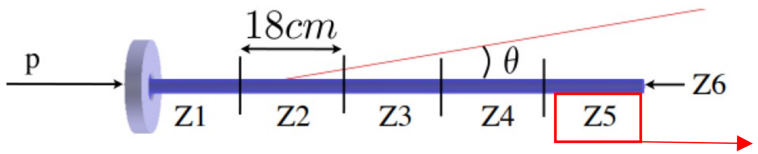
Neutrino fluxes in forward horn current configuration at ND280. Results are shown for G4Jnubeam (left) and JNUBEAM [5] (right).

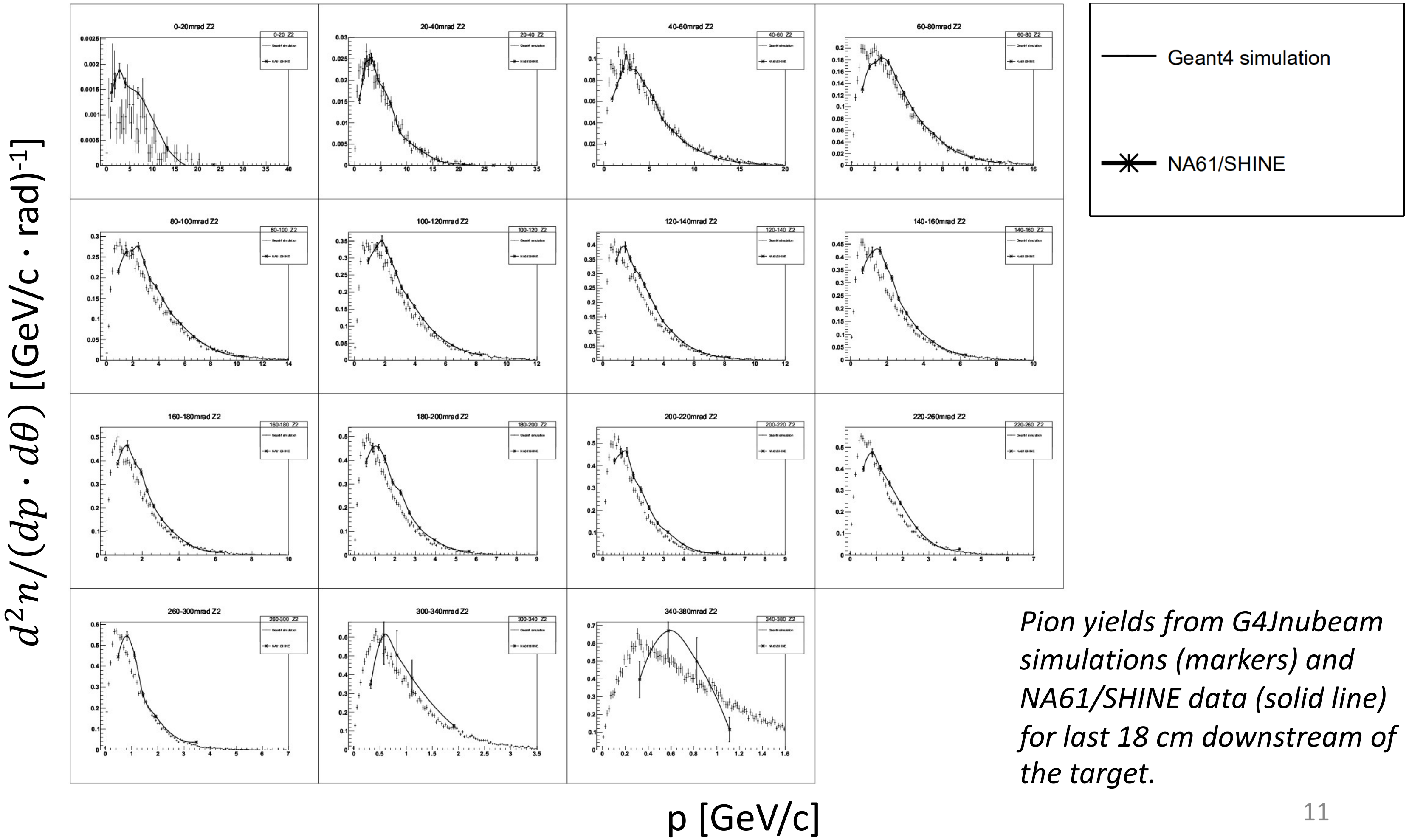
Validation with NA61/SHINE data

Pion yield data from NA61/SHINE data is used for validation of G4Jnubeam by comparing simulation results with data from 2010 run.

NA61/SHINE data is provided for six different segments: five 18 cm segments and downstream face of the target [3].

Data is also binned by the angle in each particles leave the target.

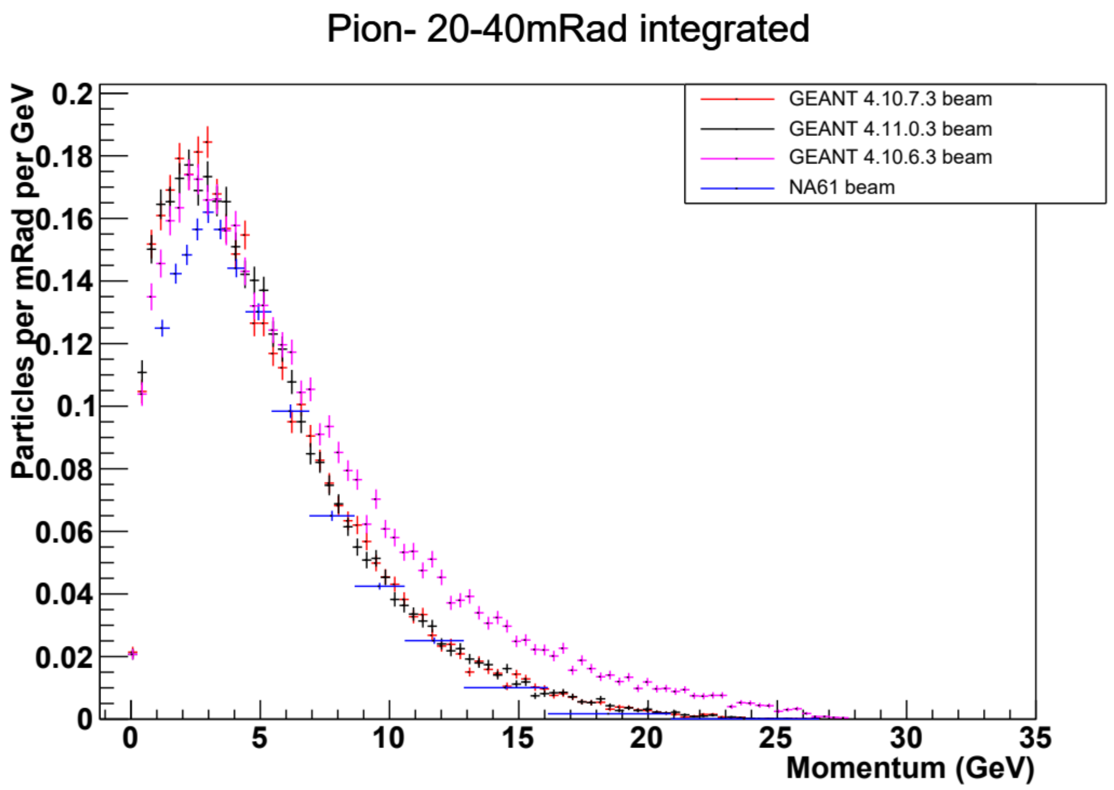


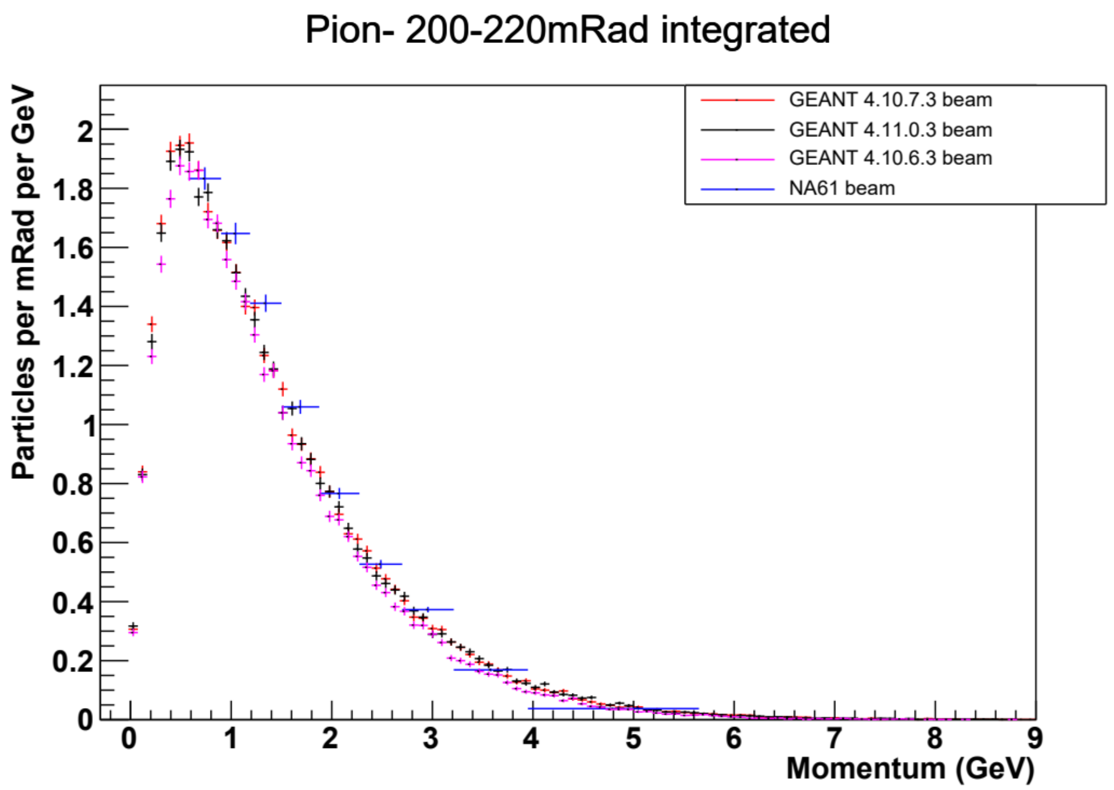


Pion yields from G4Jnubeam simulations (markers) and NA61/SHINE data (solid line) for last 18 cm downstream of the target.

Comparison between GEANT4 versions

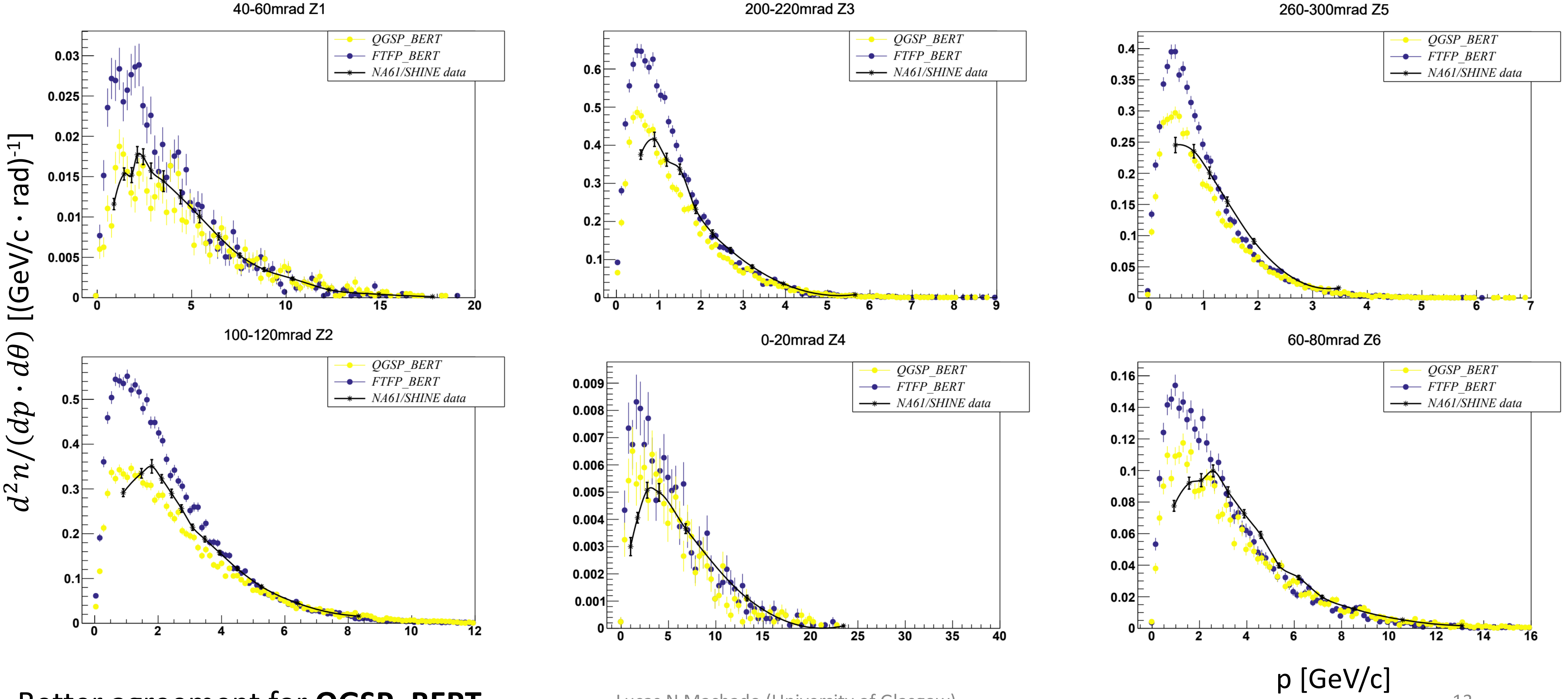
Comparison of three different GEANT4 versions were performed (4.10.6, 4.10.7 and 4.11.03):





Currently default version for G4Jnubeam: GEANT 4.11.0.3

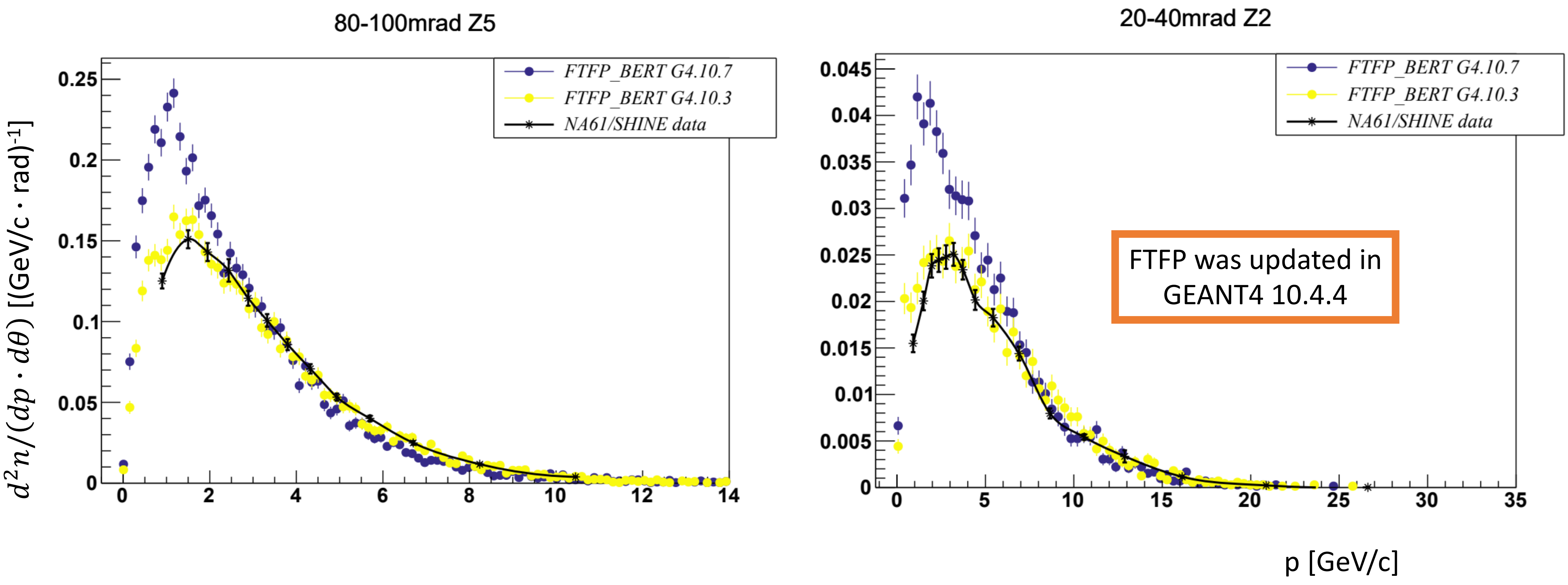
Physics Lists Comparisons (QGSP_BERT/FTFP_BERT)



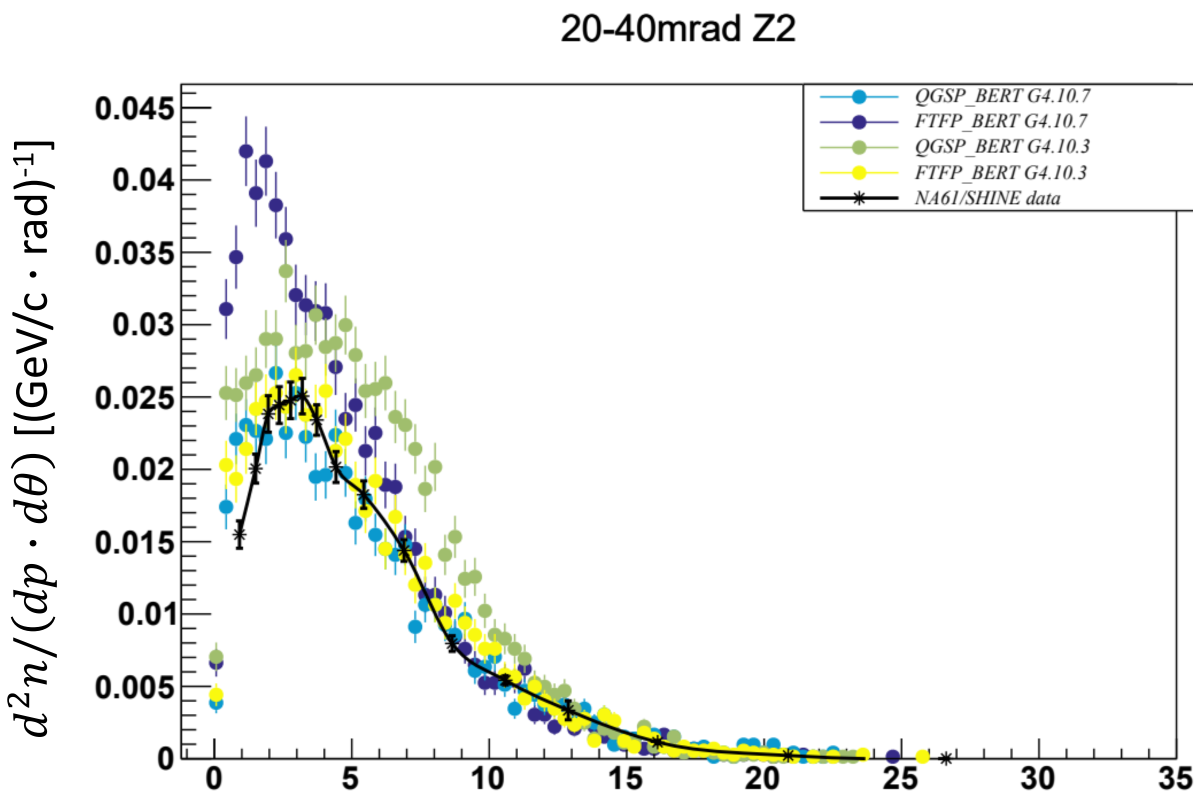
Better agreement for **QGSP_BERT**.

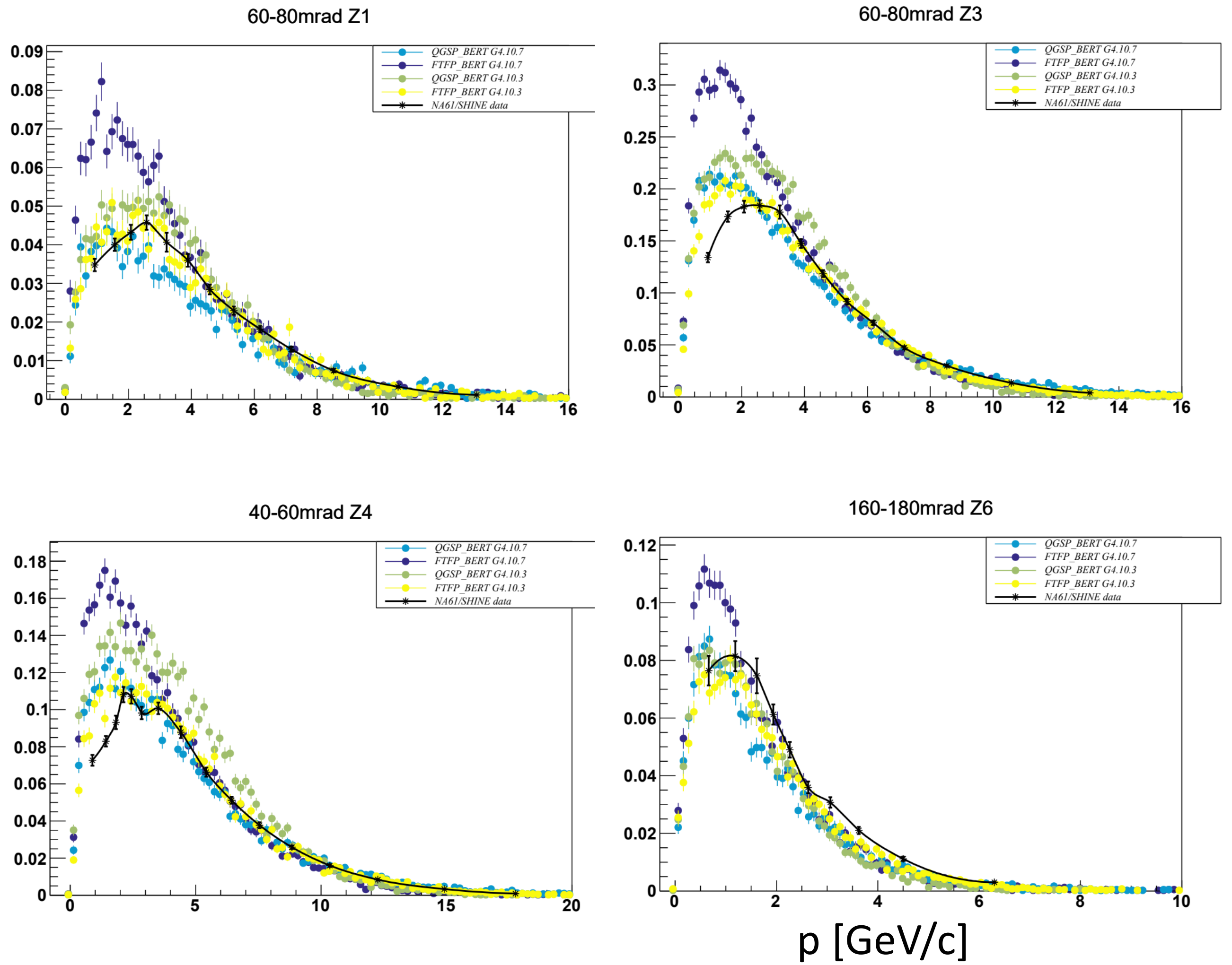
Comparison between QGSP and FTFP

Differences between physics lists are related be related to different GEANT4 versions.



Comparison between QGSP and FTFP





User will be allowed to chose between **QGSP_BERT and FTFP_BERT** in the input.

Outlook

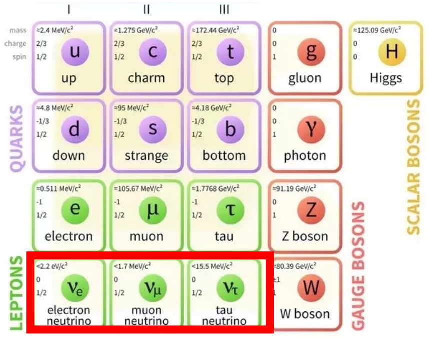
- Development of a G4Jnubeam is on-going. Validation of the simulation using NA61/SHINE data showed a very good agreement;
- The framework is available within T2K collaboration;
- Differences between the GEANT4 versions and physics lists are addressed and currently defined GEANT4.11.0.3 as default for G4Jnubeam;
- Better agreement setting QGSP_BERT than FTFP_BERT;
- Code is currently being optimized to be compatible with the T2K flux tuning (to apply reweights using NA61/SHINE data);
- Extended target options are considered for the Hyper-Kamiokande era. Denser extra targets will decrease the wrong-sign contamination to neutrino fluxes;

References

- [1] K. Abe et al., “T2K neutrino flux prediction,” Physical Review D, vol. 87, jan 2013
- [2] Densham, et al (2010). Design of the T2K target for a 0.75-MW proton beam. 560-562. Paper presented at 46th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams, HB 2010, Morschach, Switzerland.
- [3] NA61/SHINE Collaboration, “Measurements of π±, K± and proton yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS.” HEPData (collection), 2019.
- [4] Ali, Ajmi. (2022). Precision Measurements of the PMNS Parameters with T2K Data. 10.48550/arXiv.2207.06496.
- [5] https://t2k-experiment.org/result category/flux

BACKUP

Neutrino Oscillations



The three neutrino flavors, ν_e, ν_μ and ν_τ, existing in nature in mixing of three neutrino mass eigenstates. The relation between flavor (α) and mass (i) eigenstates:

$$|\nu_\alpha\rangle = \sum_i U_{i\alpha} |\nu_i\rangle \,,$$

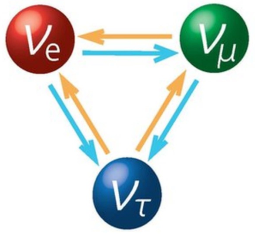
where the unitary matrix $U_{i\alpha}$ is referred as the PMNS (Pontecorvo–Maki–Nakagawa–Sakata) matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric Accelerator	Accelerator Reactors	Reactors Solar

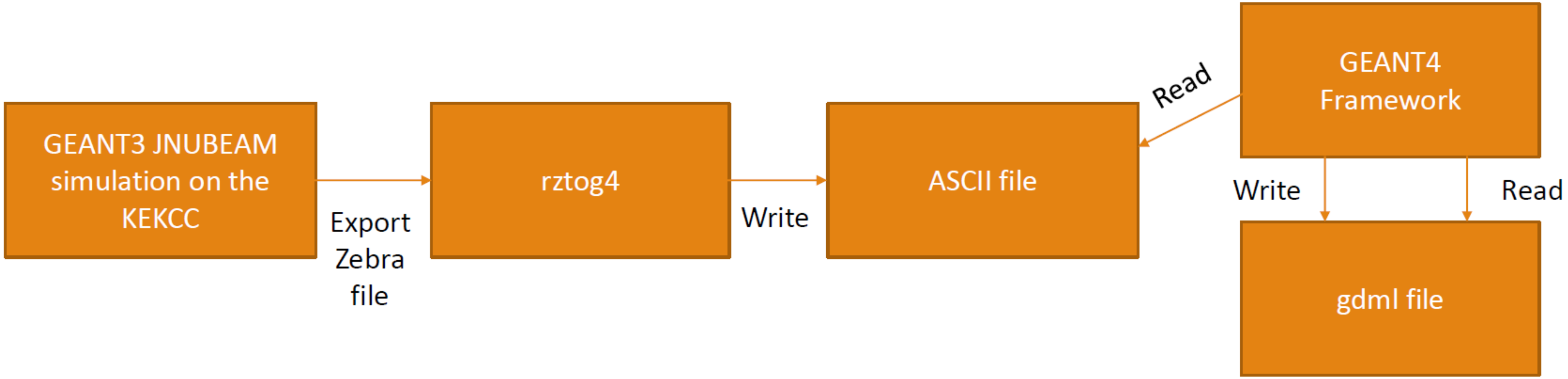
Current neutrino experiments are trying to answer questions regarding the neutrino mass ordering, θ_{23} octant precision and CP violation in the leptonic sector.

$$P(\nu_\mu \to \nu_\mu) \sim 1 - sin^2(2\theta_{23}) sin^2\left(1.27\Delta m^2_{23}\frac{L}{E_\nu}\right)$$



CP violation can explain the matter/anti-matter asymmetry in nature:
If $\delta_{CP} \neq 0$ and π, the oscillation probabilities: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

Steps to convert geometry from GEANT3 to GEANT4



Steps to convert JnuBeam geometry to GEANT4

T2K replica target + Beam Profile

A new target was implemented to the simulations following the specifications in ***Eur.Phys.J. C79 (2019) no.2, 100*** using AutoCAD Mechanical and freeCAD (with GDML Workbench).

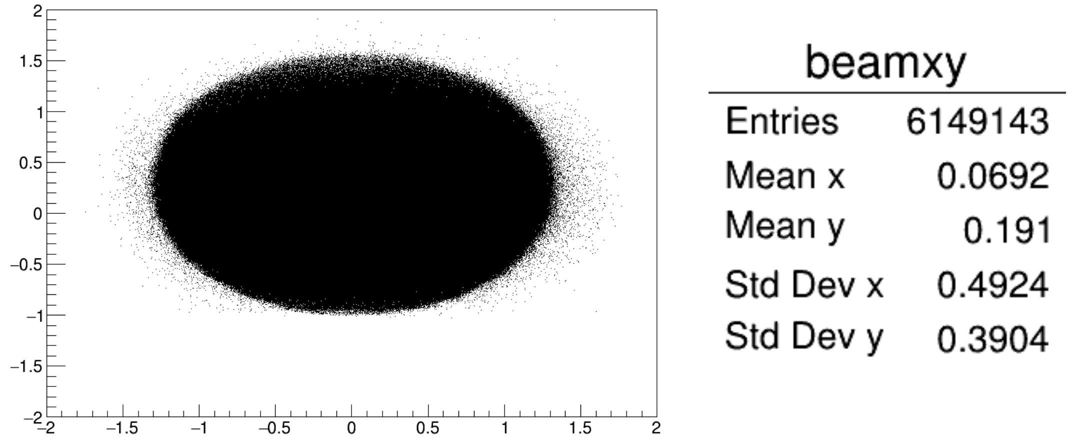
The target is made of Toyo Tanso IG-43 graphite. The density in the new target is 1.83 g cm^{-3} (T2K target: 1.804 g cm^{-3}).

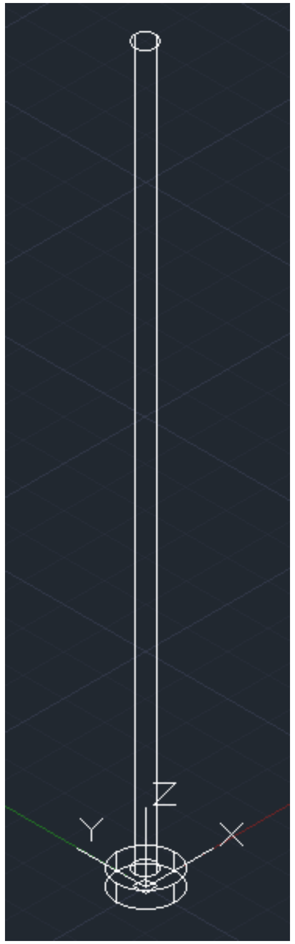
The beam profile used in the simulations follows the description in the paper:

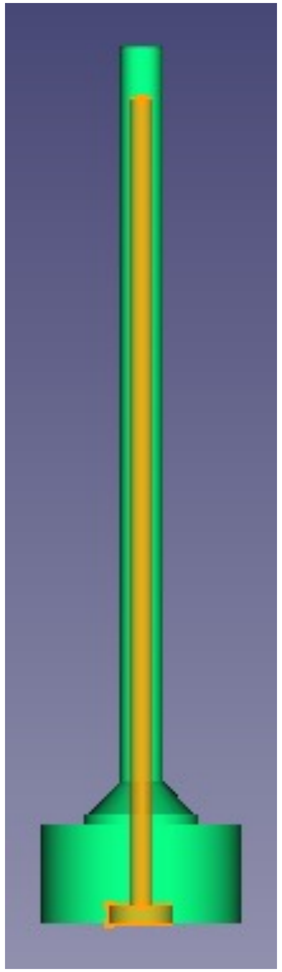
2D Gaussian beam

(σ_x,σ_y) = (0.4924,0.3904) cm

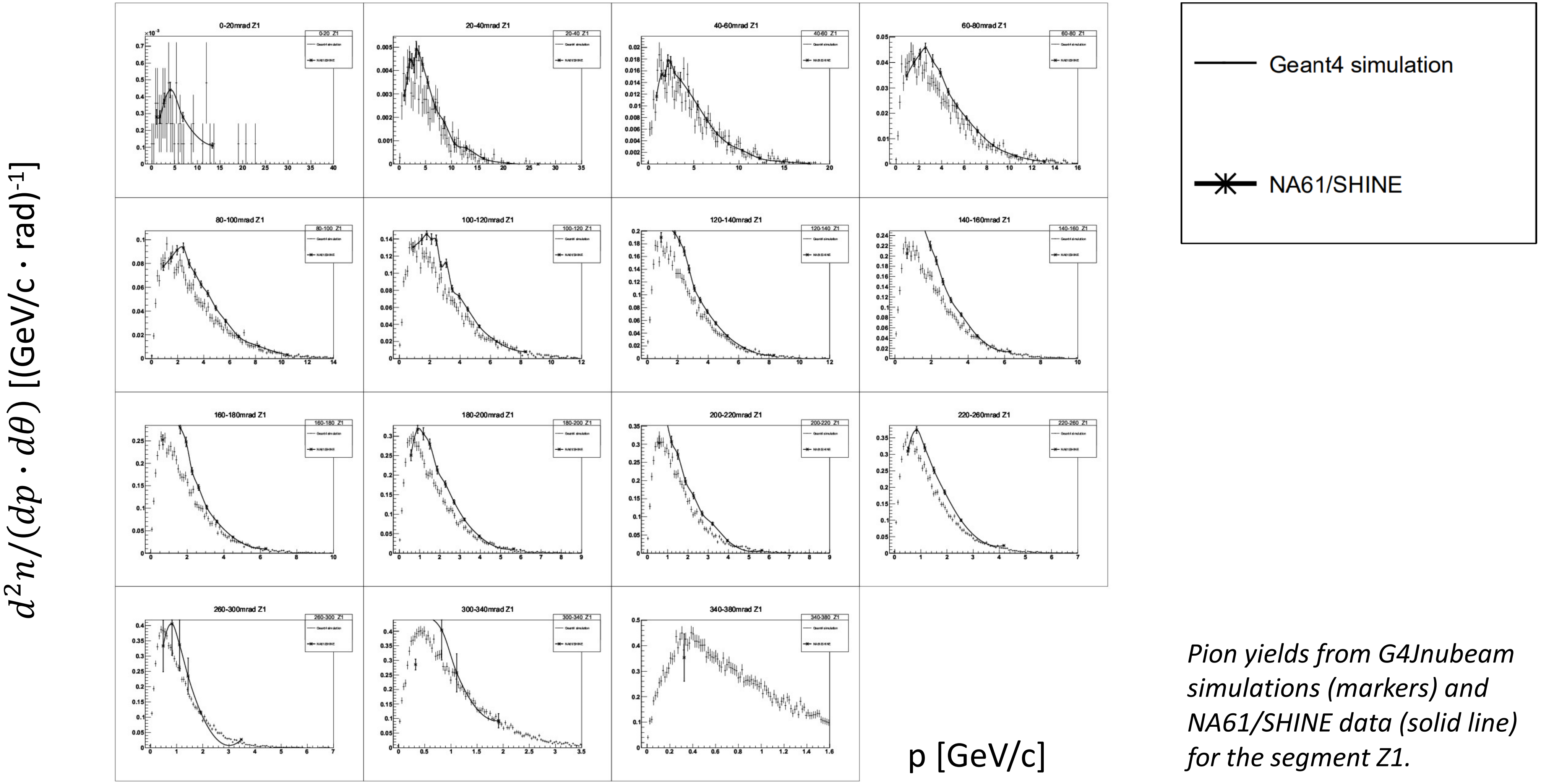
E = 30.92 GeV.







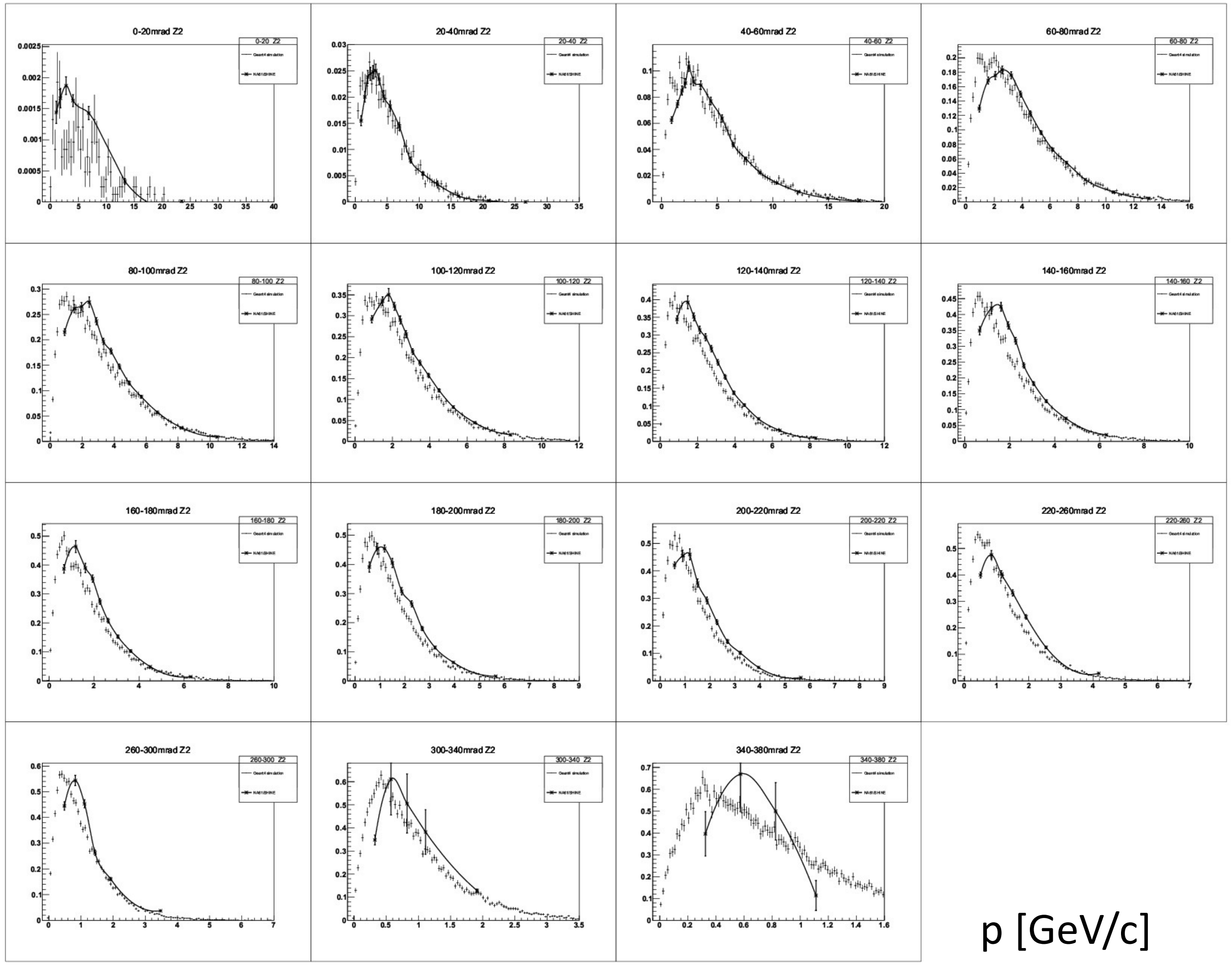
Results: Z1 (0-18 cm)



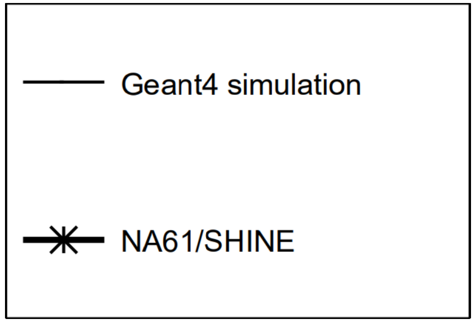
Pion yields from G4Jnubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z1.

Results: Z2 (18-36 cm)

$d^2n/(dp \cdot d\theta)$ [(GeV/c · rad)$^{-1}$]

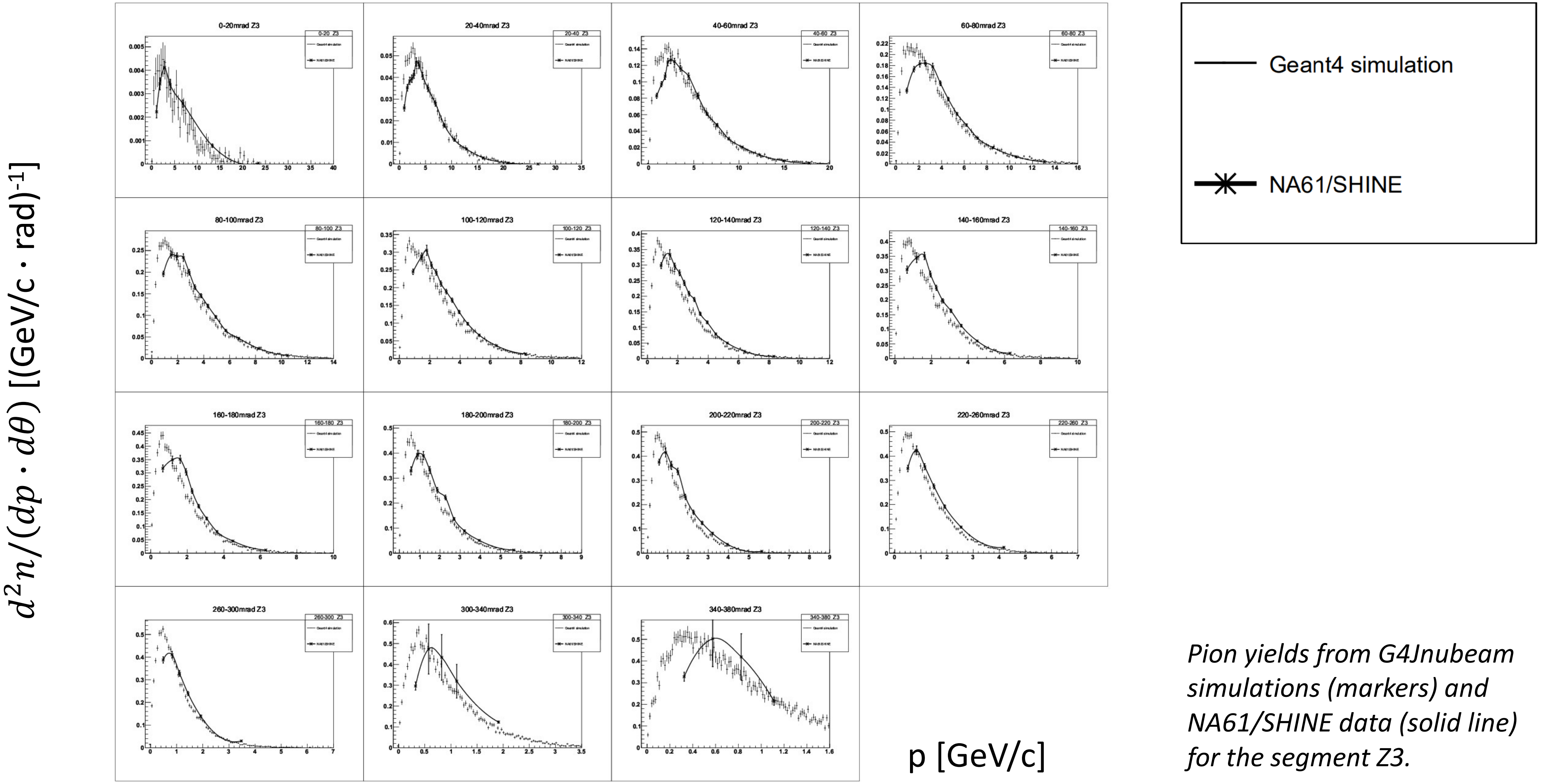


p [GeV/c]



Pion yields from G4Jnubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z2.

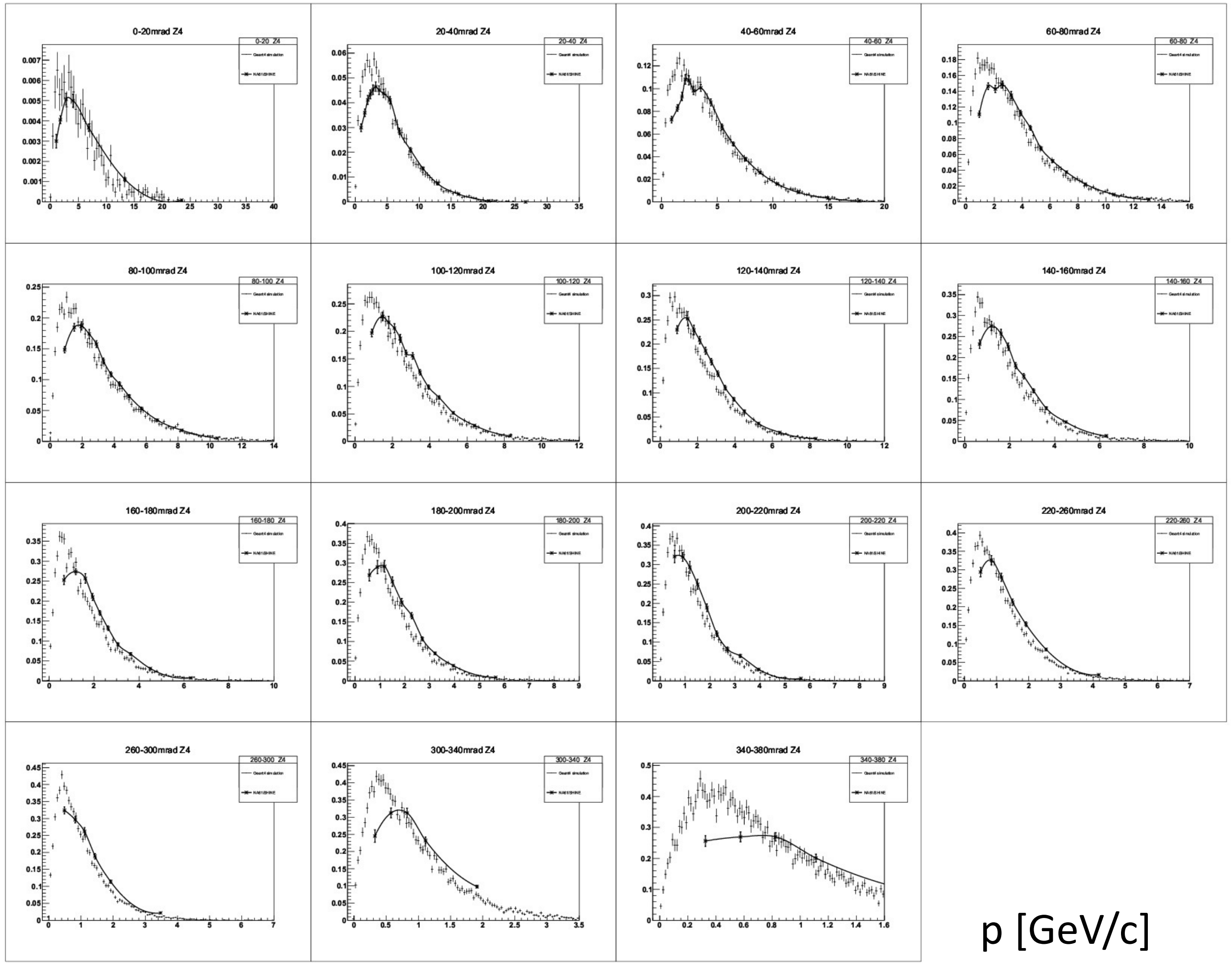
Results: Z3 (36-54 cm)



Pion yields from G4Jnubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z3.

Results: Z4 (54-72 cm)

$d^2n/(dp \cdot d\theta)$ [(GeV/c · rad)$^{-1}$]



p [GeV/c]

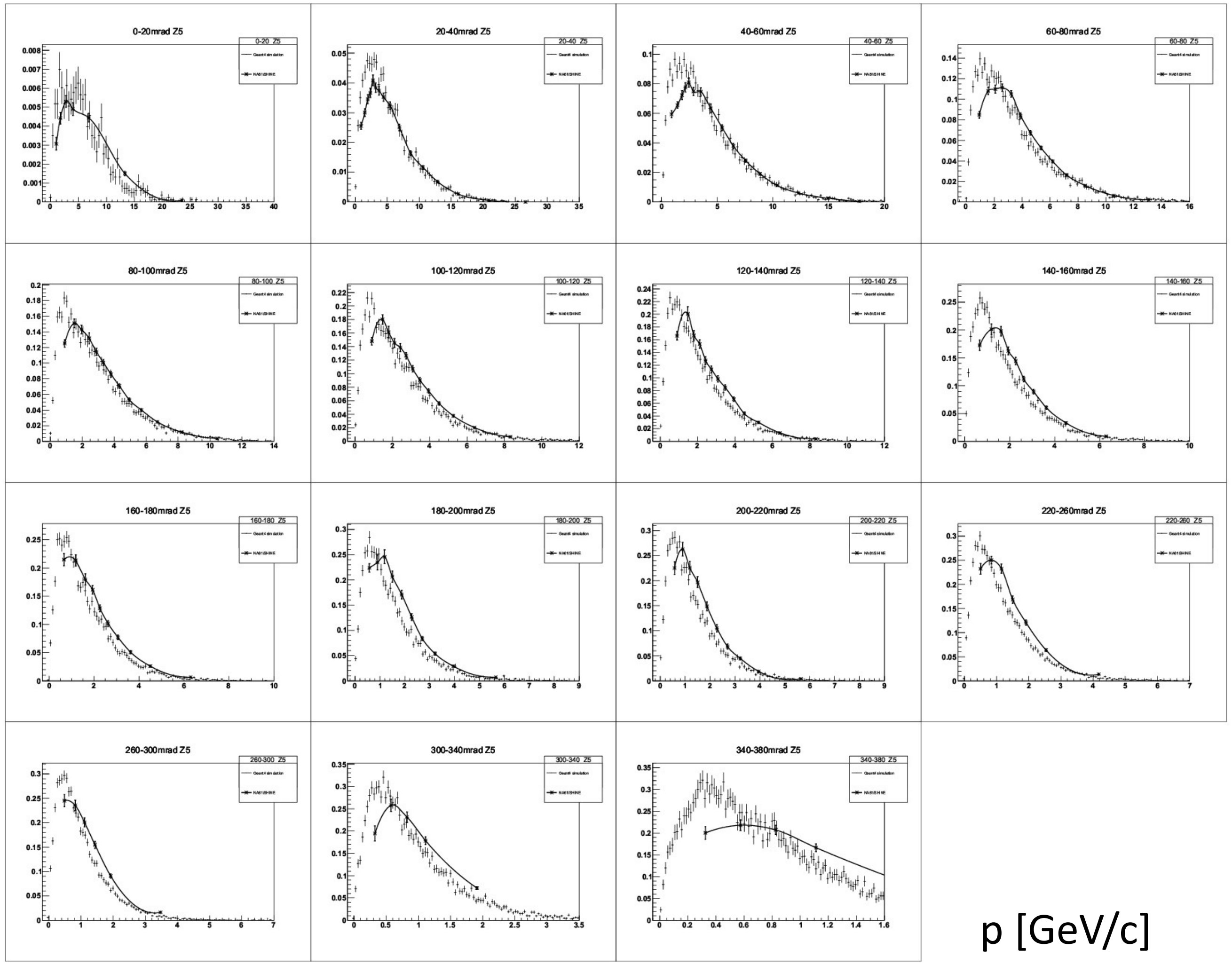
Geant4 simulation

NA61/SHINE

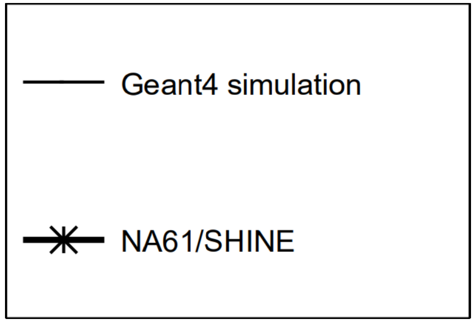
Pion yields from G4Jnubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z4.

Results: Z5 (72-90 cm)

$d^2n/(dp \cdot d\theta)$ [(GeV/c · rad)$^{-1}$]

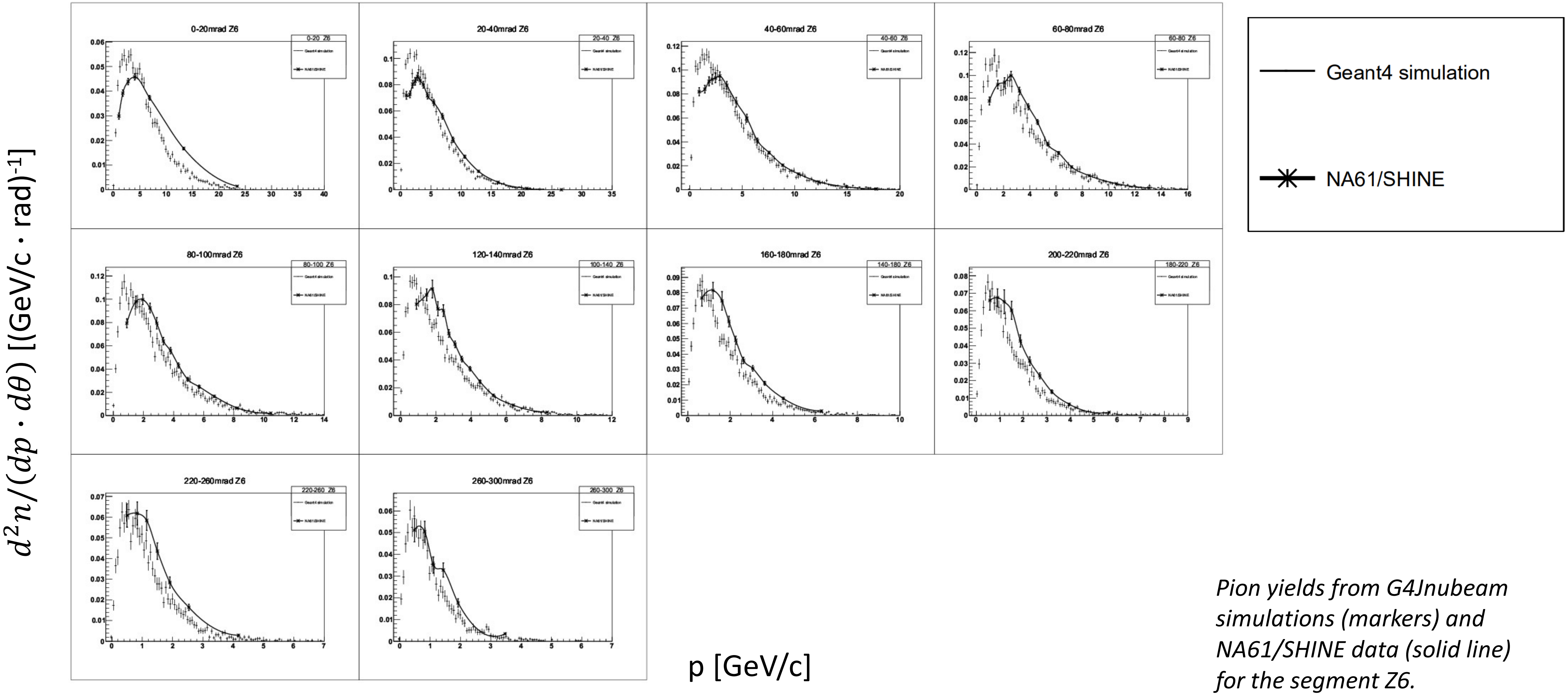


p [GeV/c]



Pion yields from G4Jnubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z5.

Results: Z6 (90 cm)



Pion yields from G4Jnubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z6.