New T2K/HK target materials and flux simulations

December 17th, 2022

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HYPER K T2K

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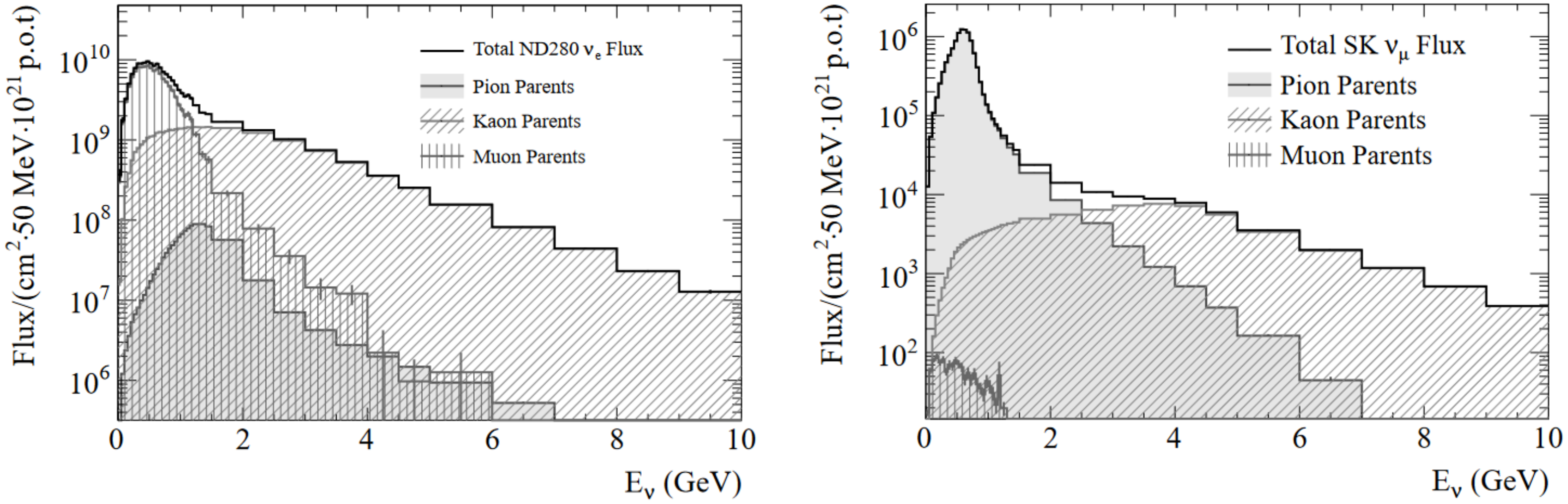
Motivation

The neutrino flux predictions is an essential issue of the T2K experiment for the successful prediction of neutrino interaction rates at both near and far detectors, having impacts in the neutrino oscillation and cross section measurements.

The Monte Carlo simulation, JNUBEAM, describing the physical processes producing neutrinos, is based on the no longer maintained simulation software GEANT3, and relies also on another software package, FLUKA, for the description of hadronic interactions that are fed to GEANT3. Meson yields are re-weighted using **NA61/SHINE data**.



Sample of flux predictions for the far and near detectors, from Phys. Rev. D 87, 012001 (2013).

A new simulation framework using GEANT4 is under development.

GEANT4 Framework

In development: a Monte Carlo simulation model based on GEANT4 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.

Main steps:

1) Pion yield validations with NA61/SHINE data (target, beam);

   Compare simulation results with NA61/SHINE data from 2010 run:

   - Consider geometry differences between T2K target and T2K replica target;
   - NA61 beam profile;

2) Full T2K beam simulation (magnetic horns, full T2K geometry);

3) Integration with T2K flux tuning and flux predictions.

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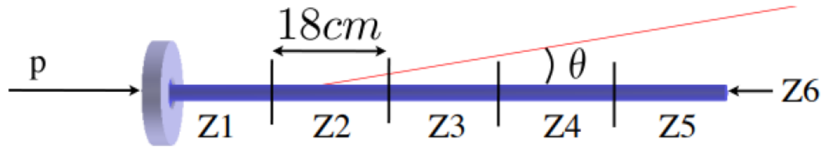

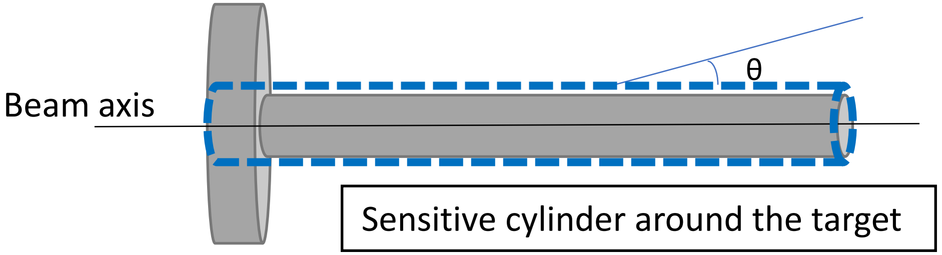

T2K replica target

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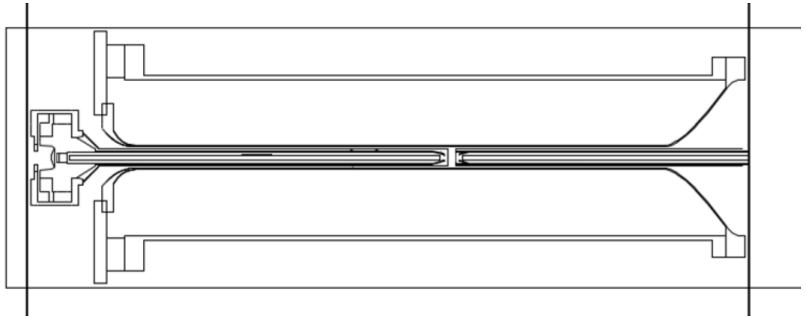
Explore different target options for Hyper-Kamiokande era.



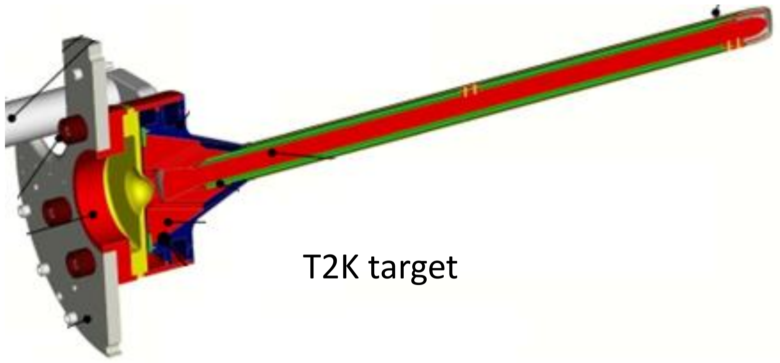
3) Integration with T2K flux tuning and flux predictions.

Target Differences

The T2K target geometry diverges from the T2K replica target geometry used in the NA61/SHINE experiment:

- Replica target 1.5% denser;
- 2 cm thick disk upstream, radius 3.5 cm;
- 88 cm long rod, radius 1.3 cm.

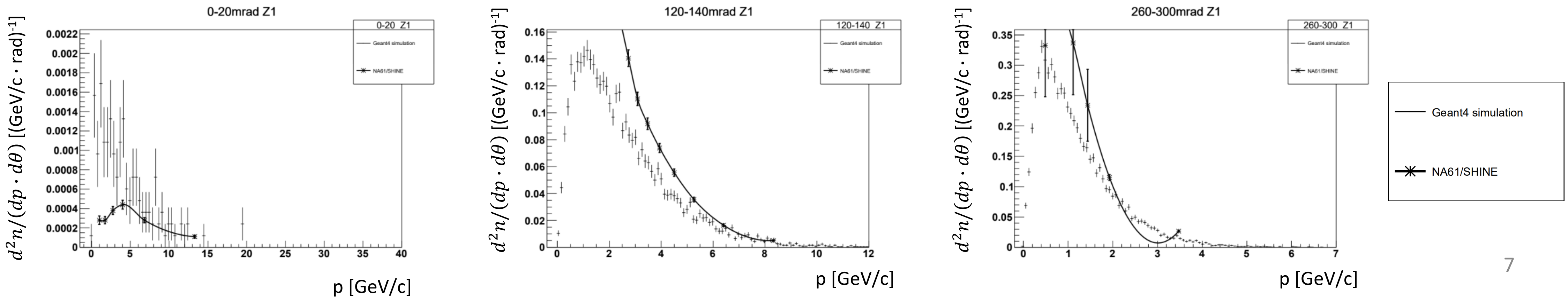
T2K replica target



T2K target

The T2K target has a 91.4 cm long rod with 1.3 cm radius and a complex structure upstream.

First attempts of comparing NA61/SHINE data with simulations using the T2K target showed a large discrepancy in the first 18 cm segment of the target:



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).

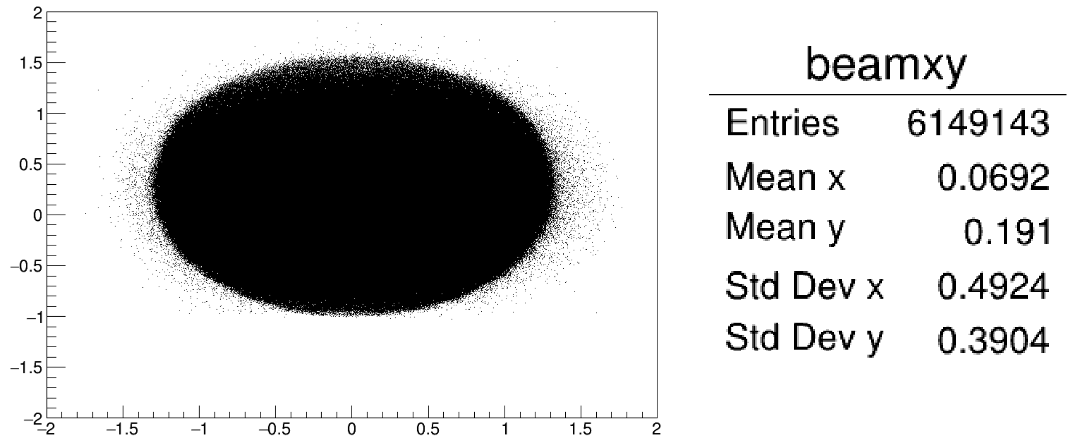
The target is made of Toyo Tanso IG-43 graphite. The density in the new target is 1.83 g cm^{-3} (T2K target: 1.804 g cm^{-3}).

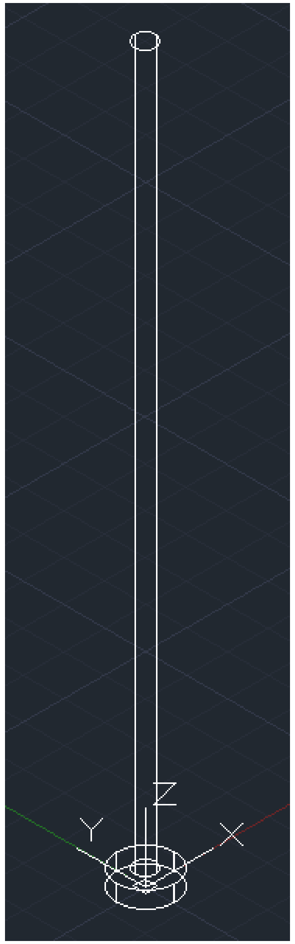
The beam profile used in the simulations follows the description in the paper:

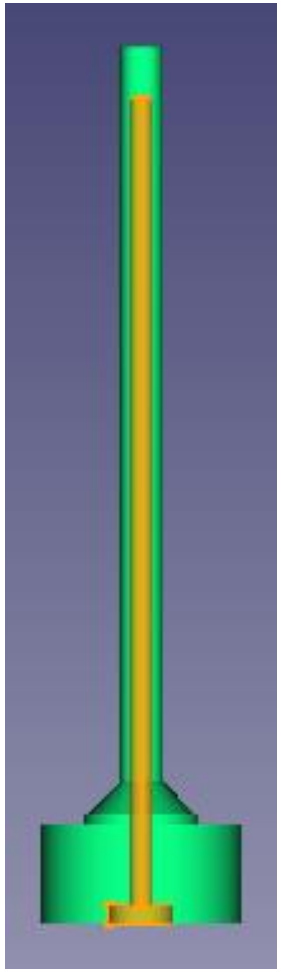
2D Gaussian beam

$(\sigma_x,\sigma_y) = (0.4924,0.3904)$ cm

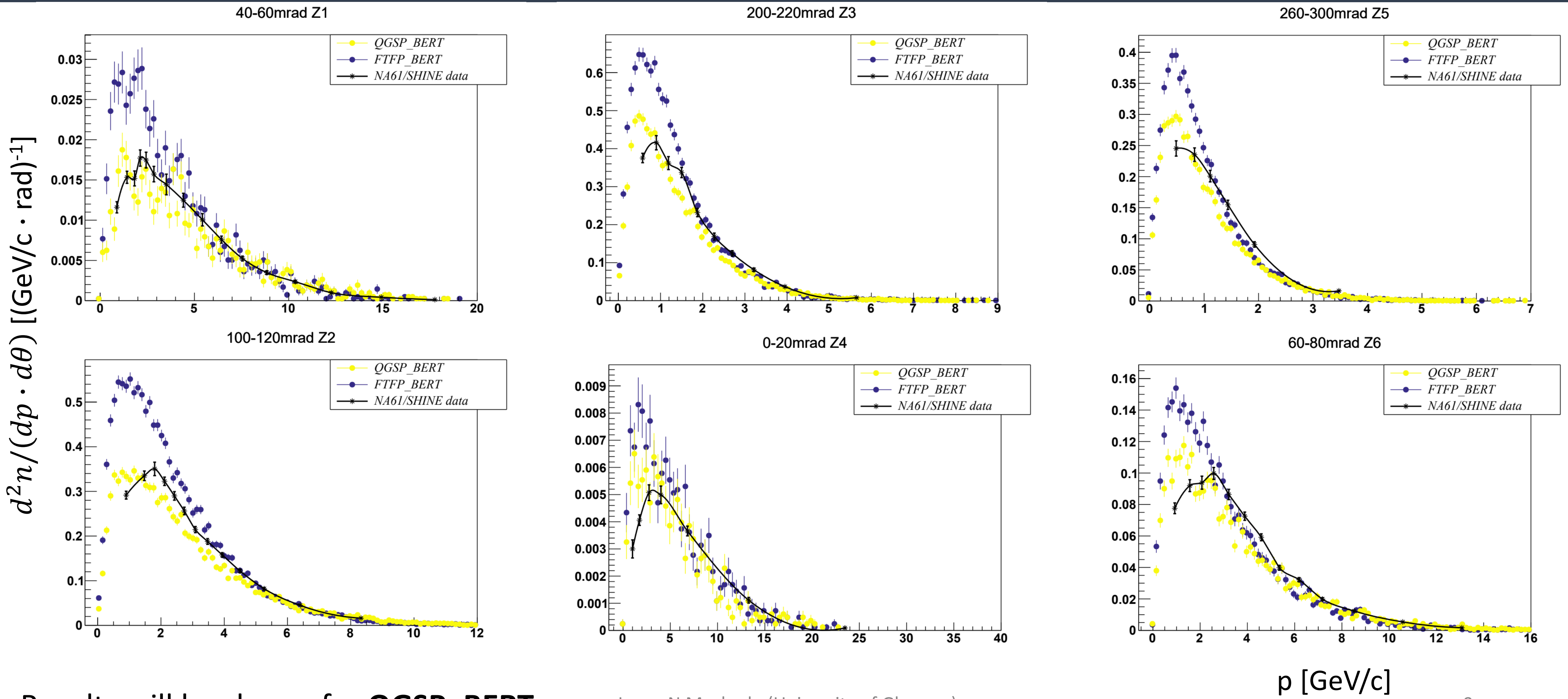
E = 30.92 GeV.





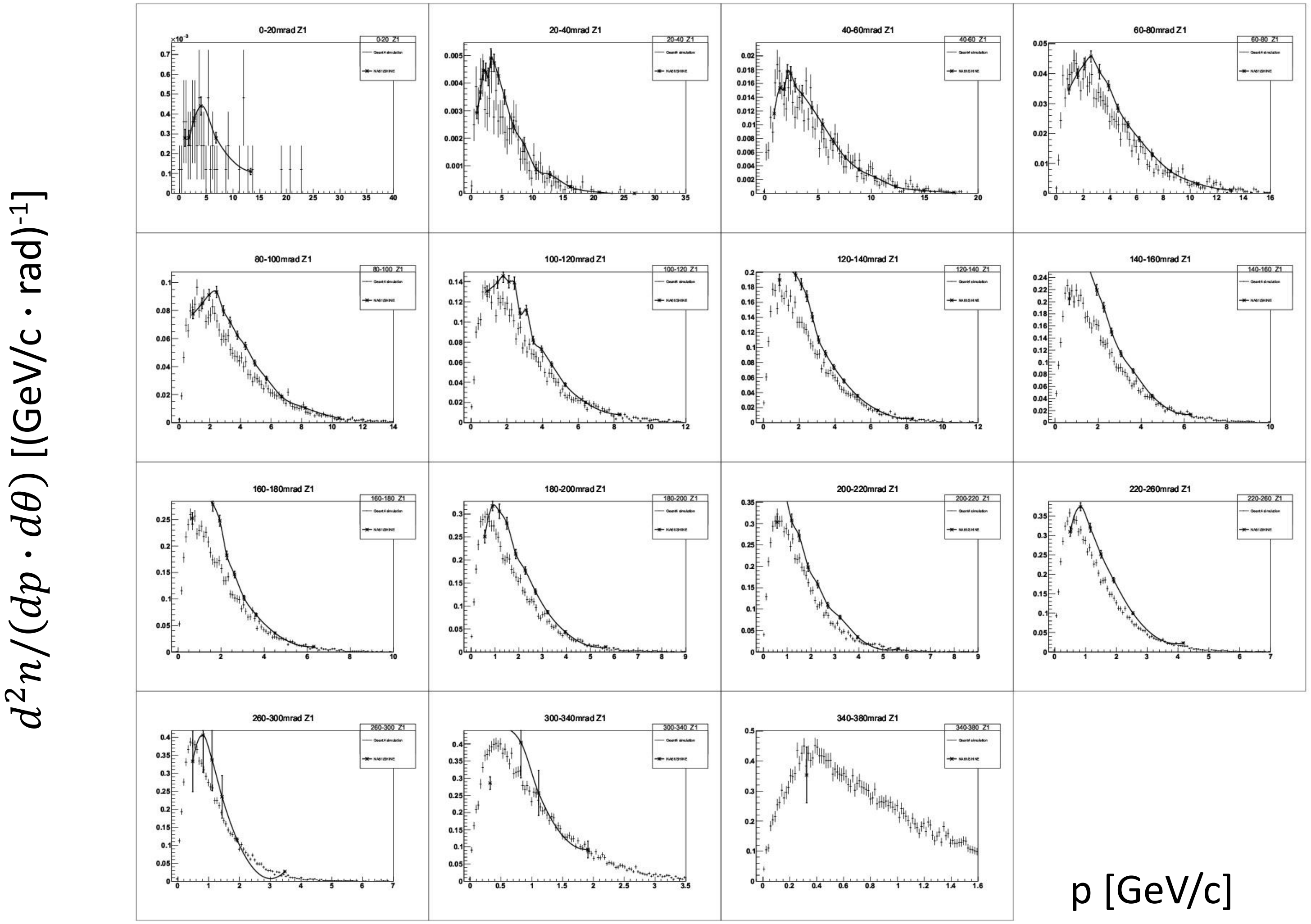


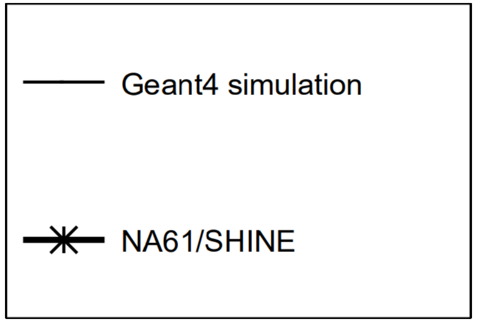
Physics Lists Comparisons (QGSP_BERT/FTFP_BERT)



Results will be shown for **QGSP_BERT**.

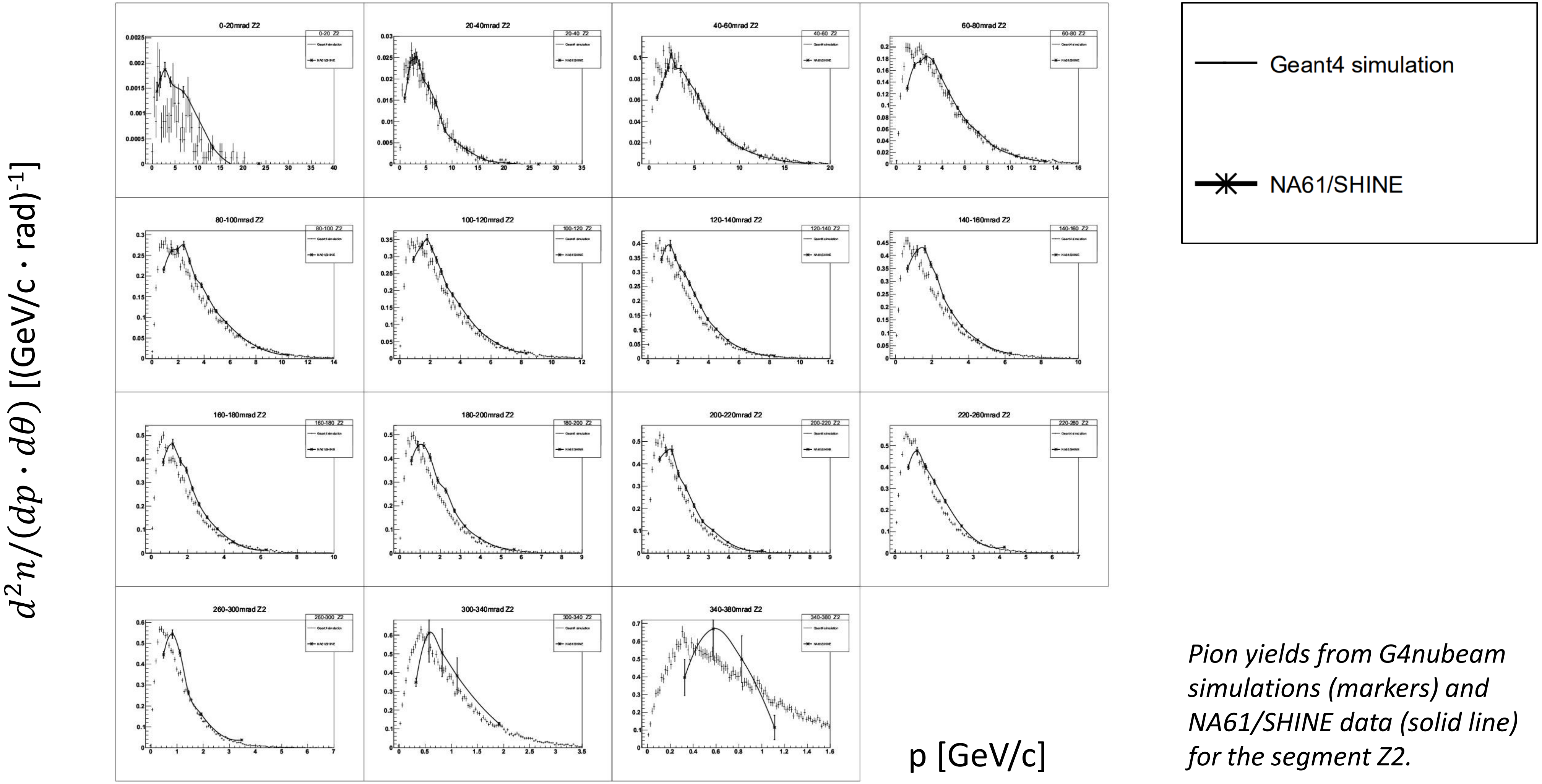
Results: Z1 (0-18 cm)





Pion yields from G4nubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z1.

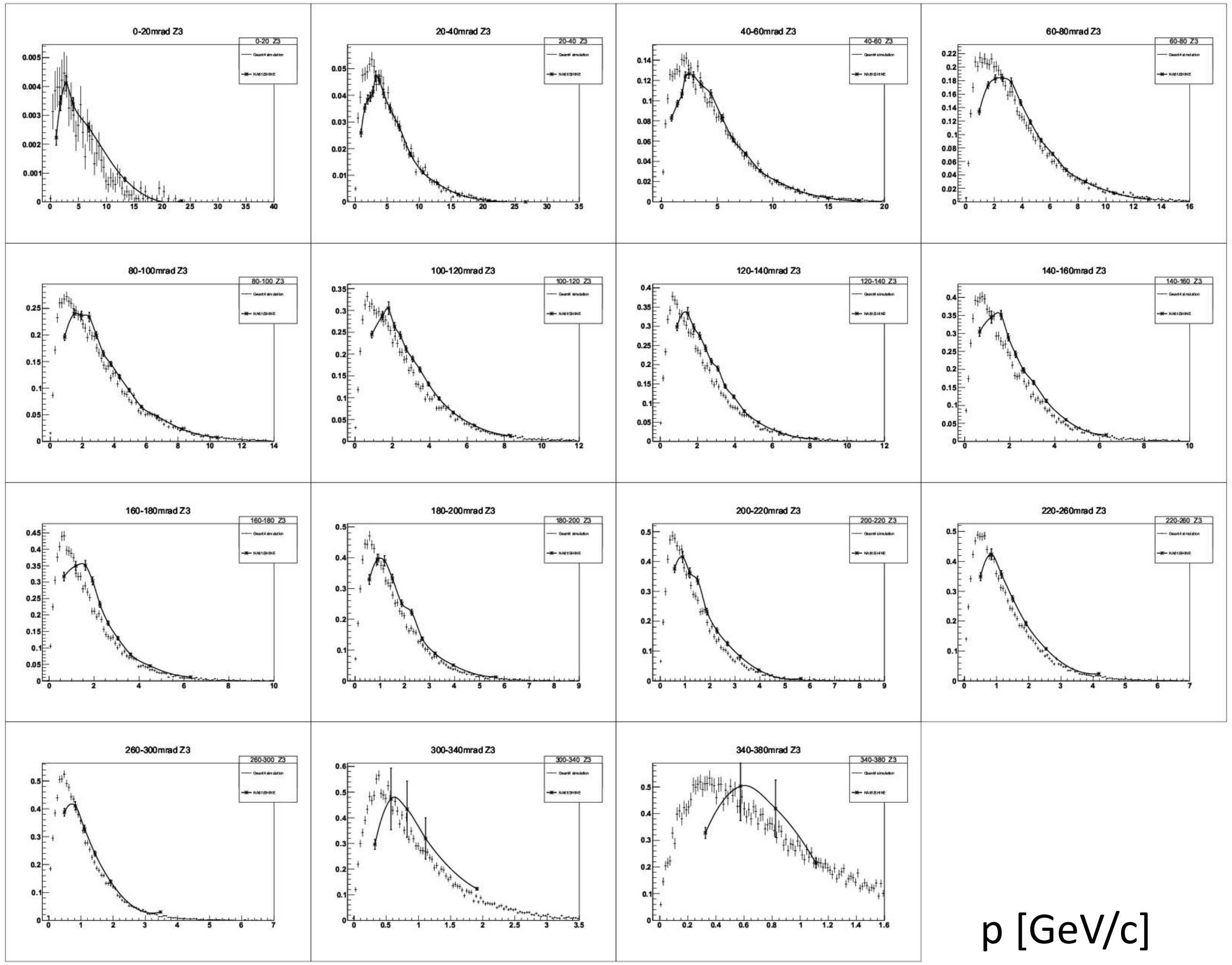
Results: Z2 (18-36 cm)



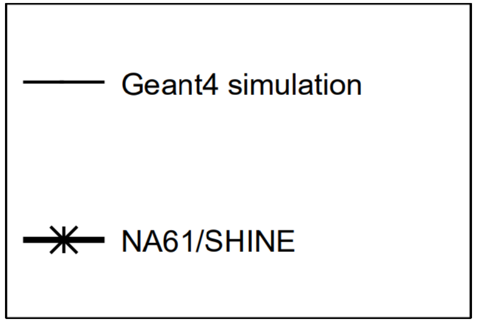
Pion yields from G4nubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z2.

Results: Z3 (36-54 cm)

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

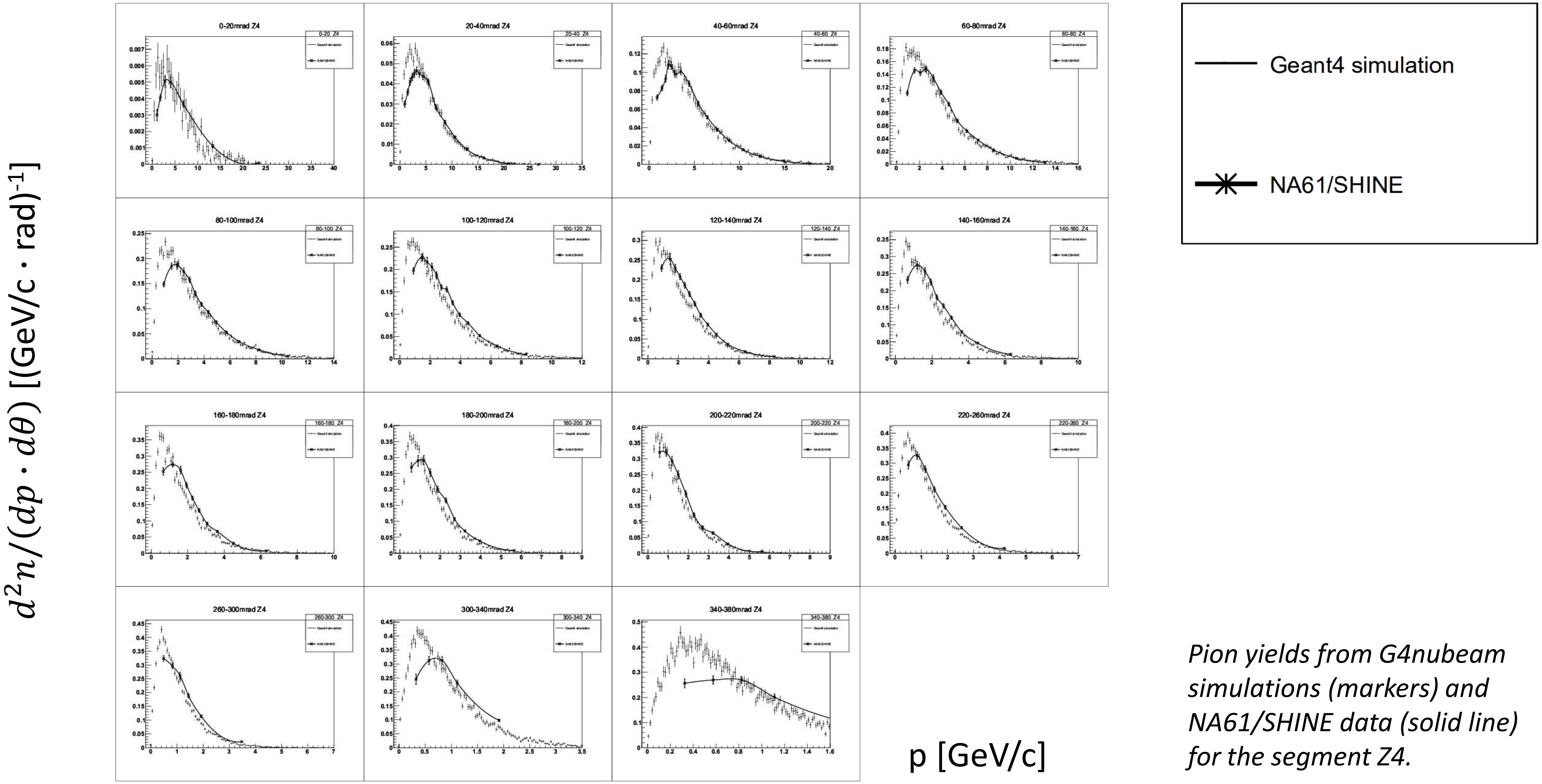


p [GeV/c]



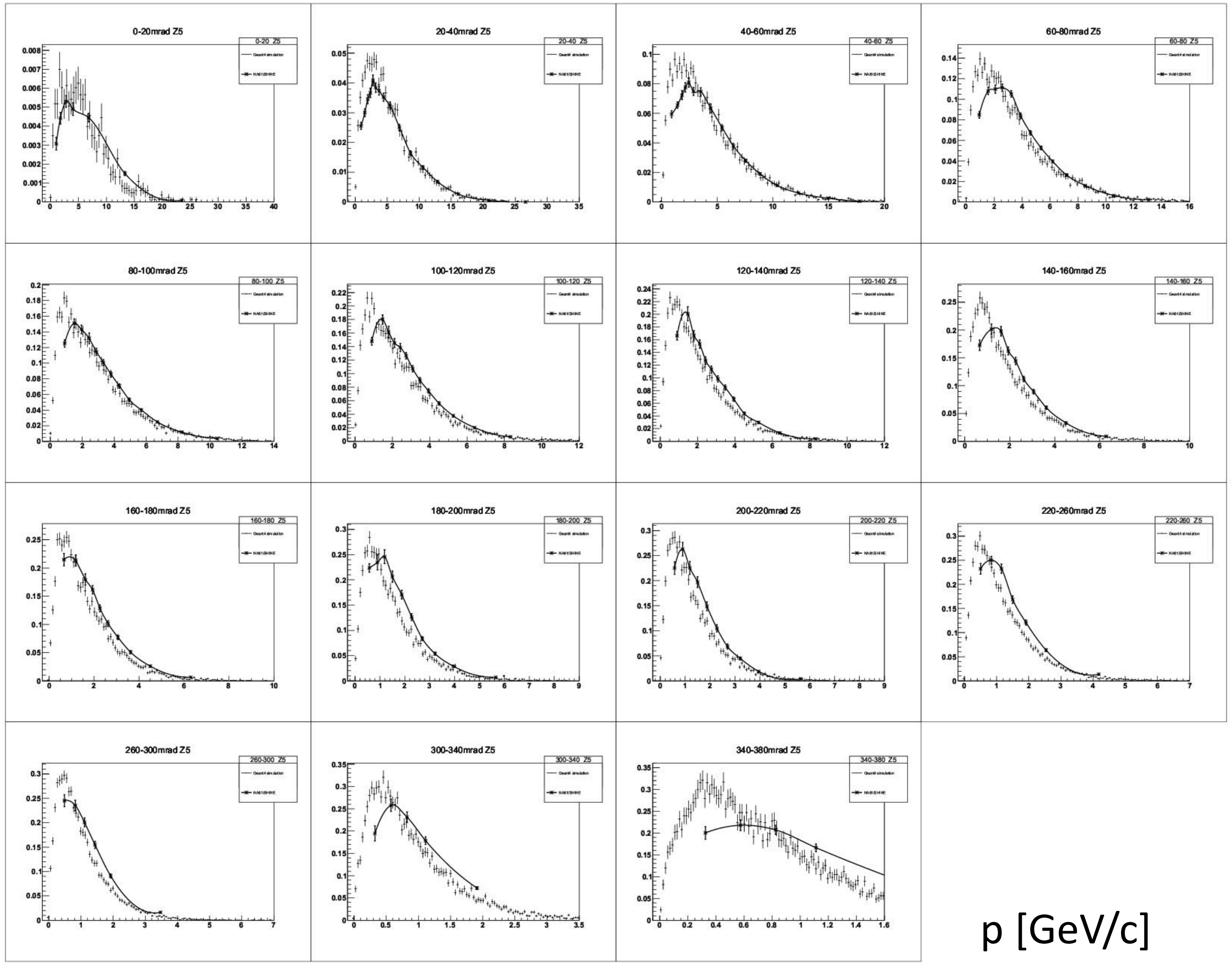
Pion yields from G4nubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z3.

Results: Z4 (54-72 cm)



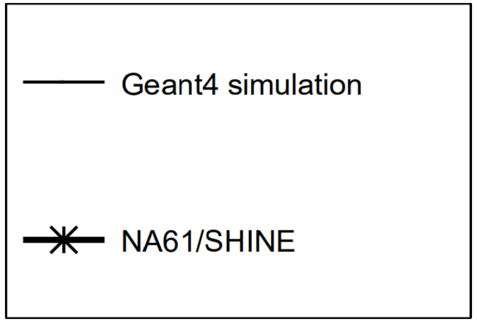
Pion yields from G4nubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z4.

Results: Z5 (72-90 cm)



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

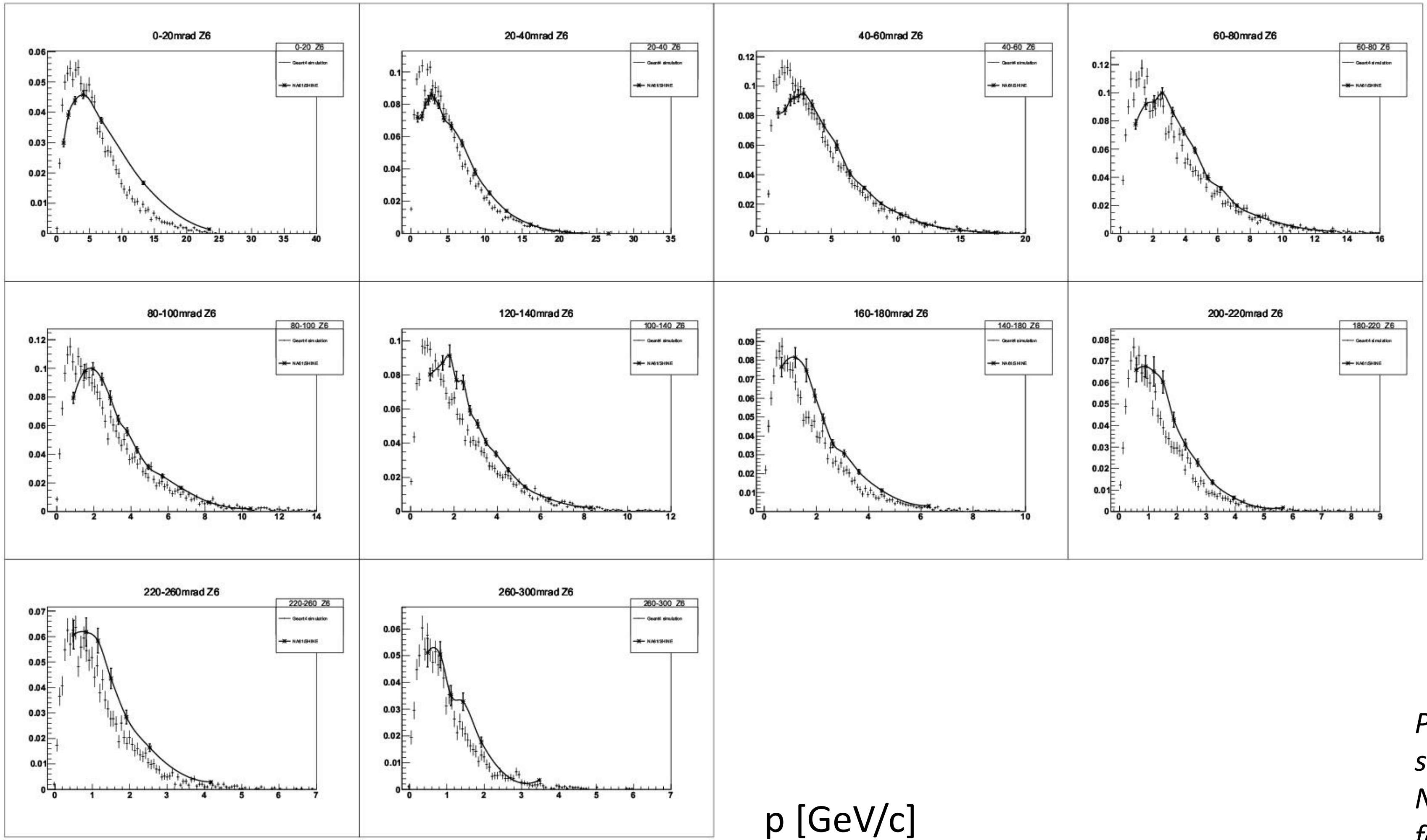
p [GeV/c]



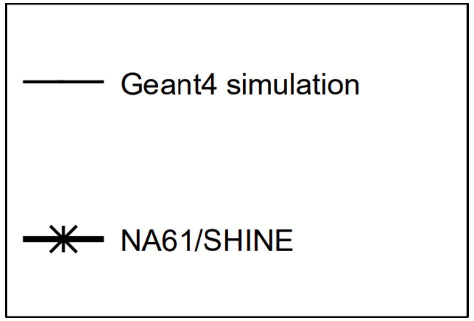
Pion yields from G4nubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z5.

Results: Z6 (90 cm)

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



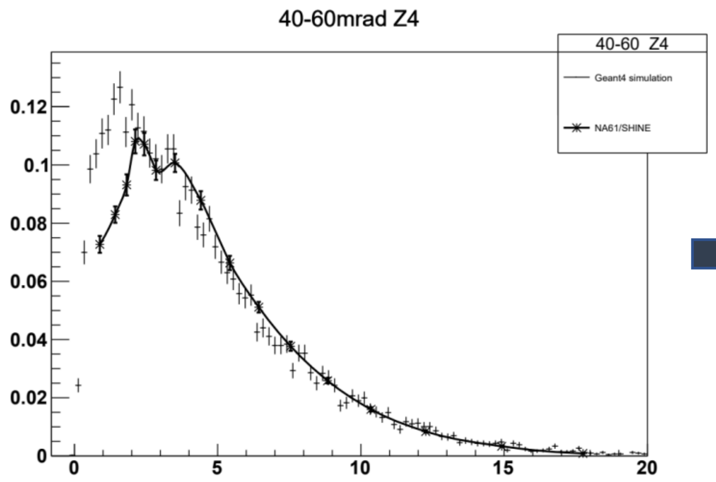
p [GeV/c]



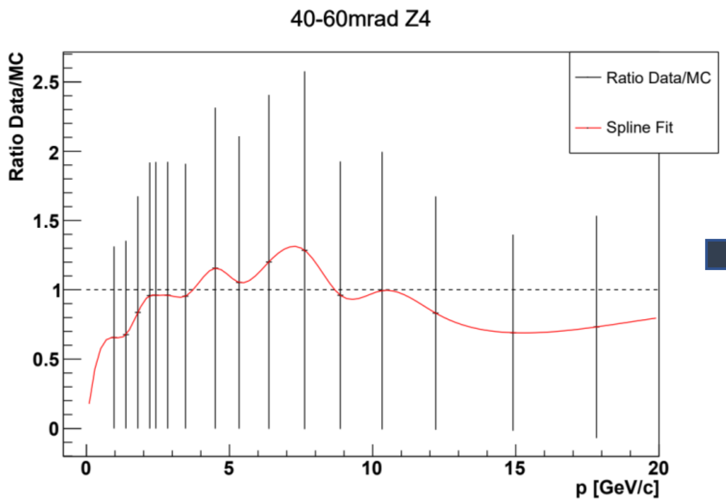
Pion yields from G4nubeam simulations (markers) and NA61/SHINE data (solid line) for the segment Z6.

Fitting

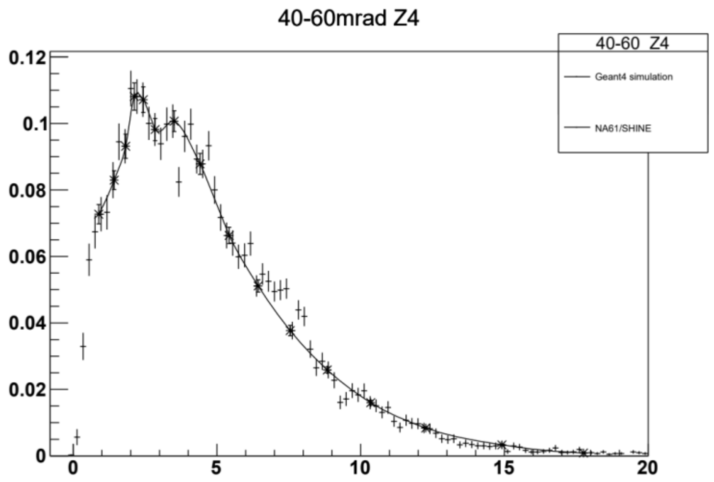
A cubic spline fit was applied to re-weight the Monte Carlo results, minimizing their differences with the NA61/SHINE data.



Comparison between pion yield simulation with G4nubeam (markers) and NA61/SHINE data (solid line) for segment Z4 with angles 40-60 mrad.



Cubic spline curve (red) fitting the ratio between data and Monte Carlo.

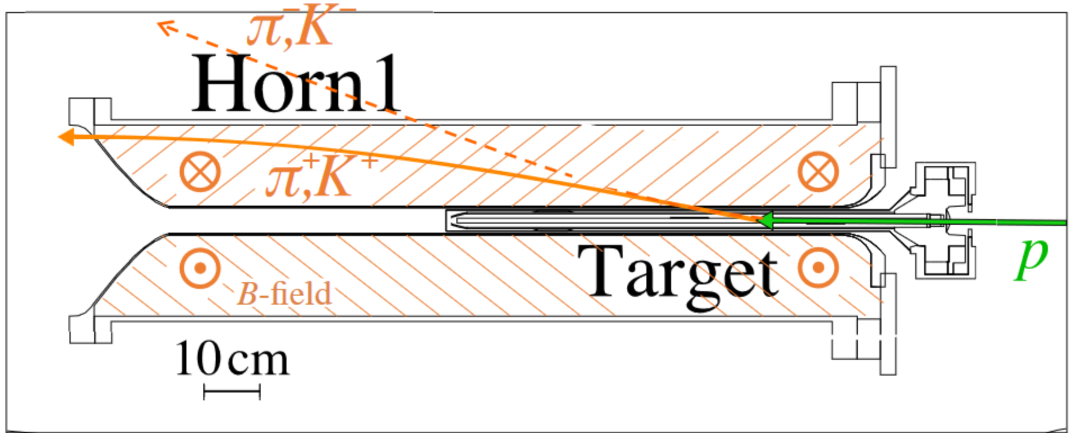


Re-weighted Monte Carlo results using the applied spline fit.

For more details, please check backup slides.

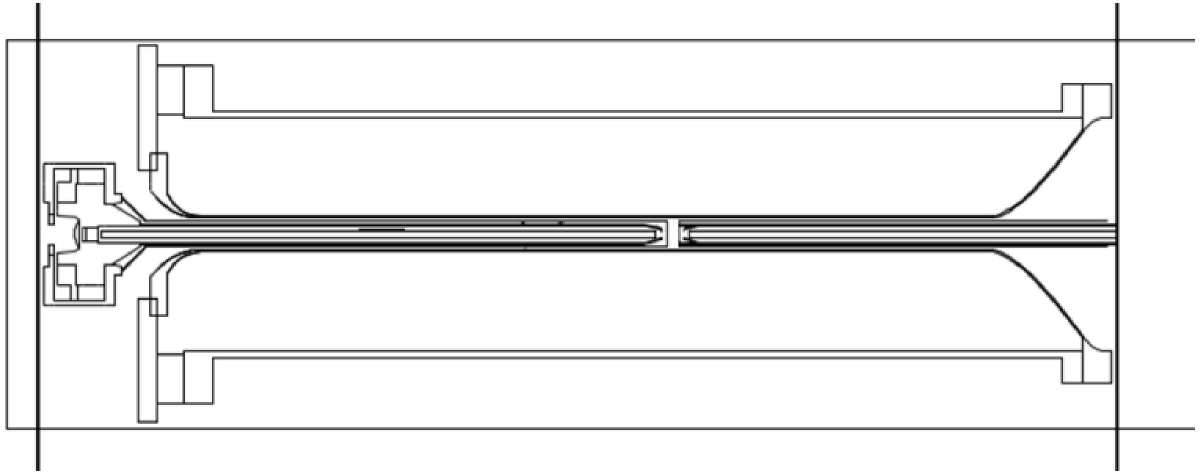
T2K Target Alternatives

The rate of particles that won't enter the magnetic field, and consequentially increasing the wrong sign contamination in the neutrino flux, is decreased as the length of the target increases.



Very forward-going particles creates wrong-sign neutrinos that reduce our sensitivity to CP violation.

- Can be improved by using a longer target, trading fewer direct pions for more horn-focussed pions;
- Current length is constrained to prevent deformation due to gravity - add second target inserted into downstream end of Horn 1;

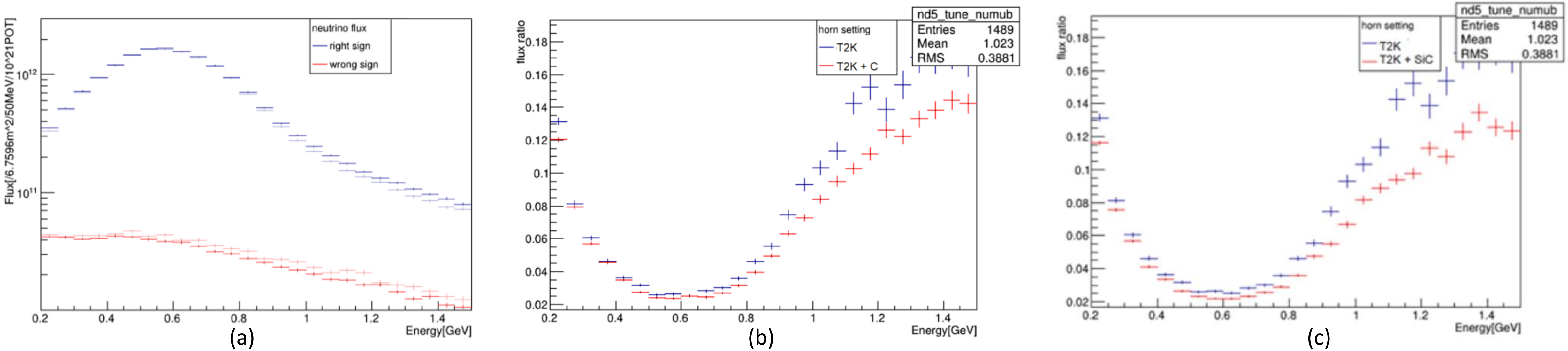


Our goal is to evaluate the impact of extended target in the simulation and explore different material choices for the second target such as:

- Graphite;
- Silicon Carbide (SiC): high heat resistance, same neutron/proton ratio as graphite.

T2K Target Alternatives

Studies using the current simulation framework in T2K, Jnubeam, were performed for different target options - Lai Hin Lam (MSc student Glasgow).



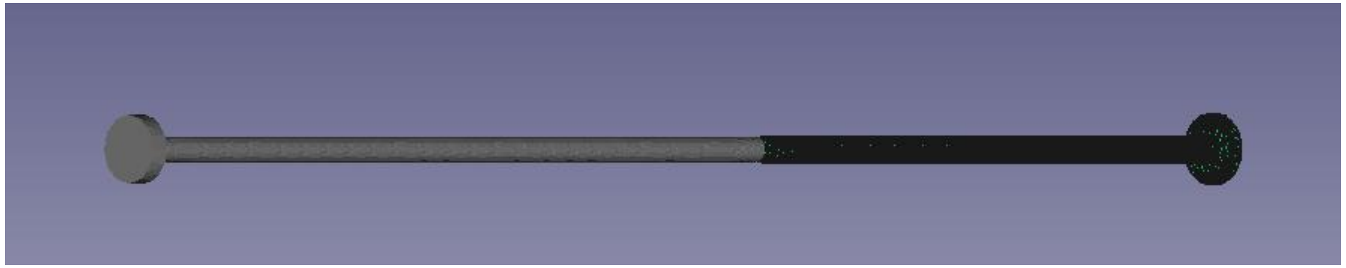
Comparison between the neutrino fluxes using the current T2K target and alternative extra targets downstream with the FHC neutrino beam configuration. (a) The lighter points are the fluxes from the current T2K target, and the darker points are the fluxes from the configuration that includes an extended graphite target; wrong sign ratio for extended (b) graphite target and (c) SiC target.

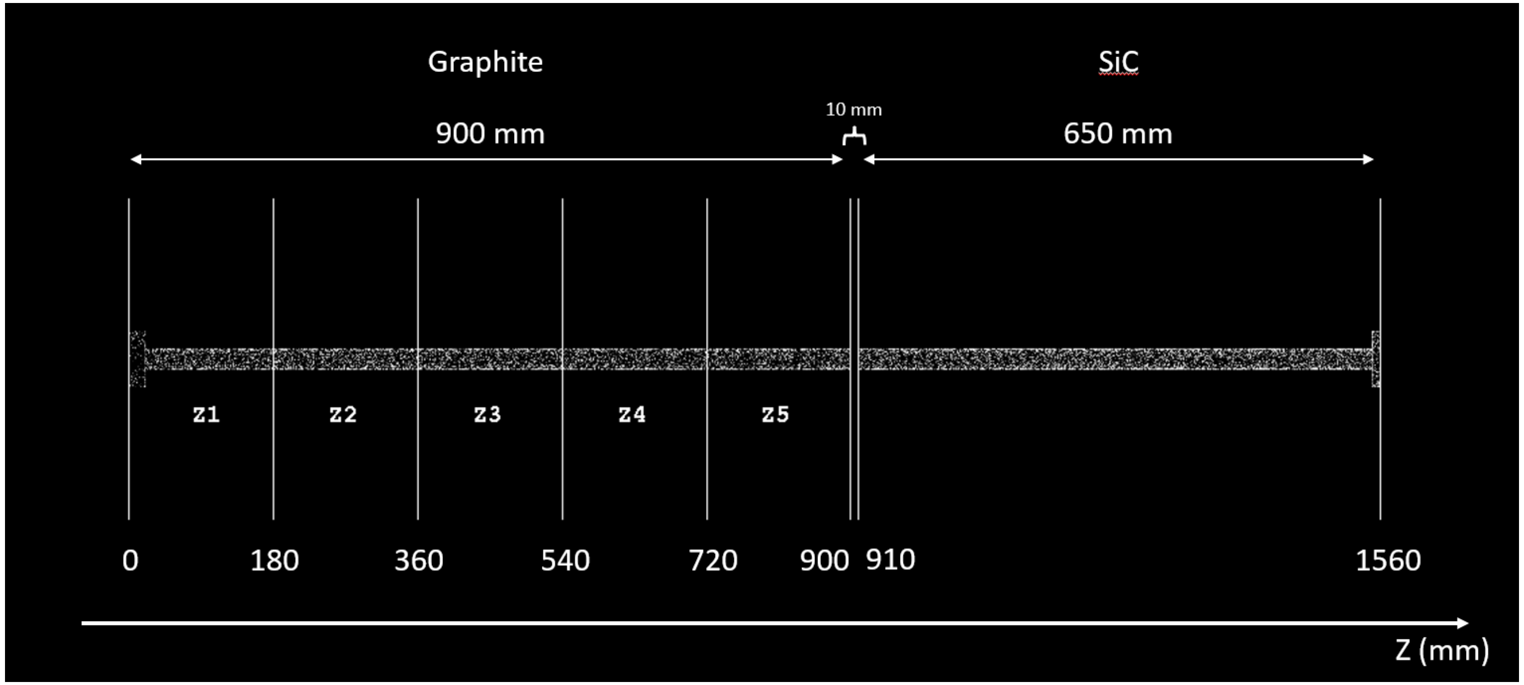
Overall, extra targets with denser materials than graphite, increase the right-sign neutrino flux yield and decrease the wrong-sign contamination.

Extended target with G4 framework

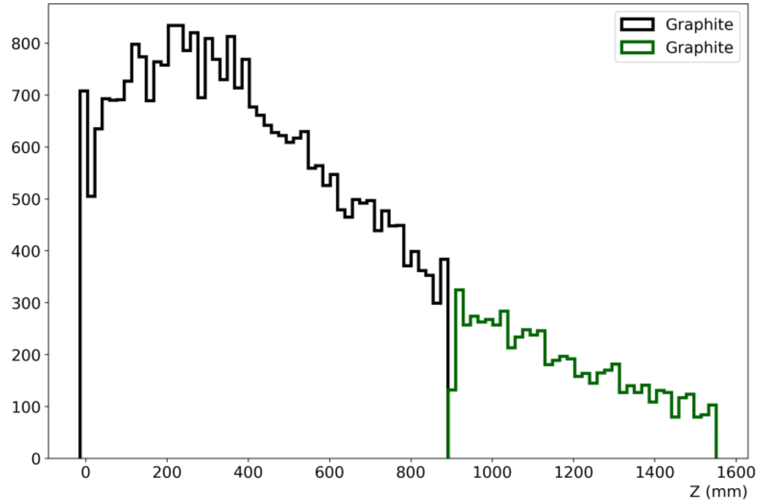
Similarly to what has been done for Jnubeam, extended target options are being studied using the GEANT4 framework.

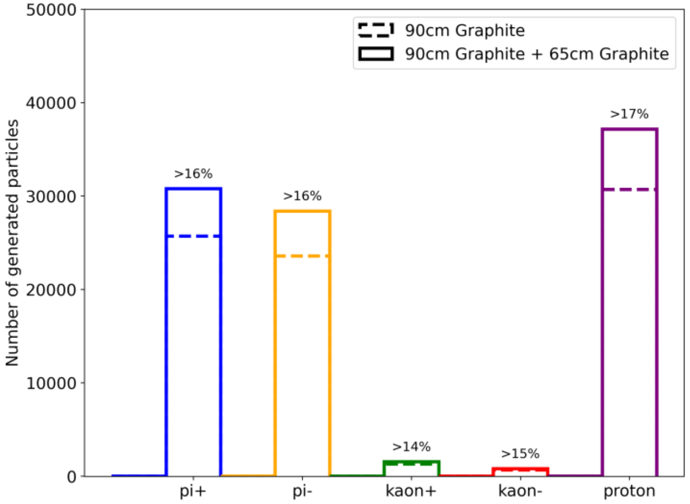
A 650 mm rod was inserted downstream of the original T2K replica target as shown in the figure:



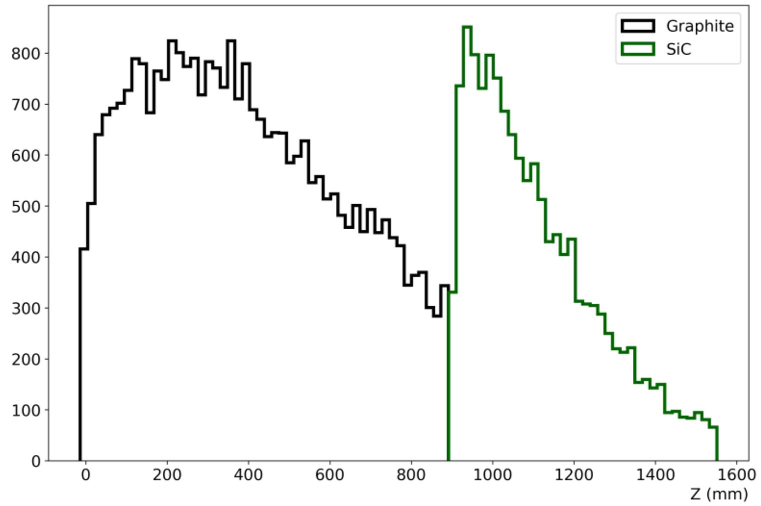


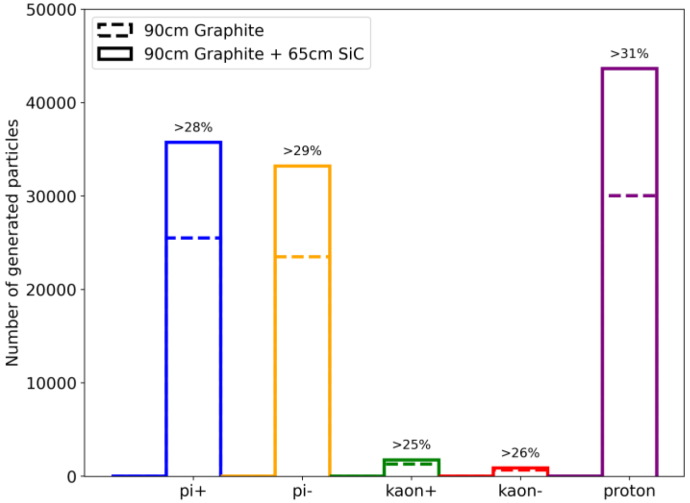
Extended target with G4 framework





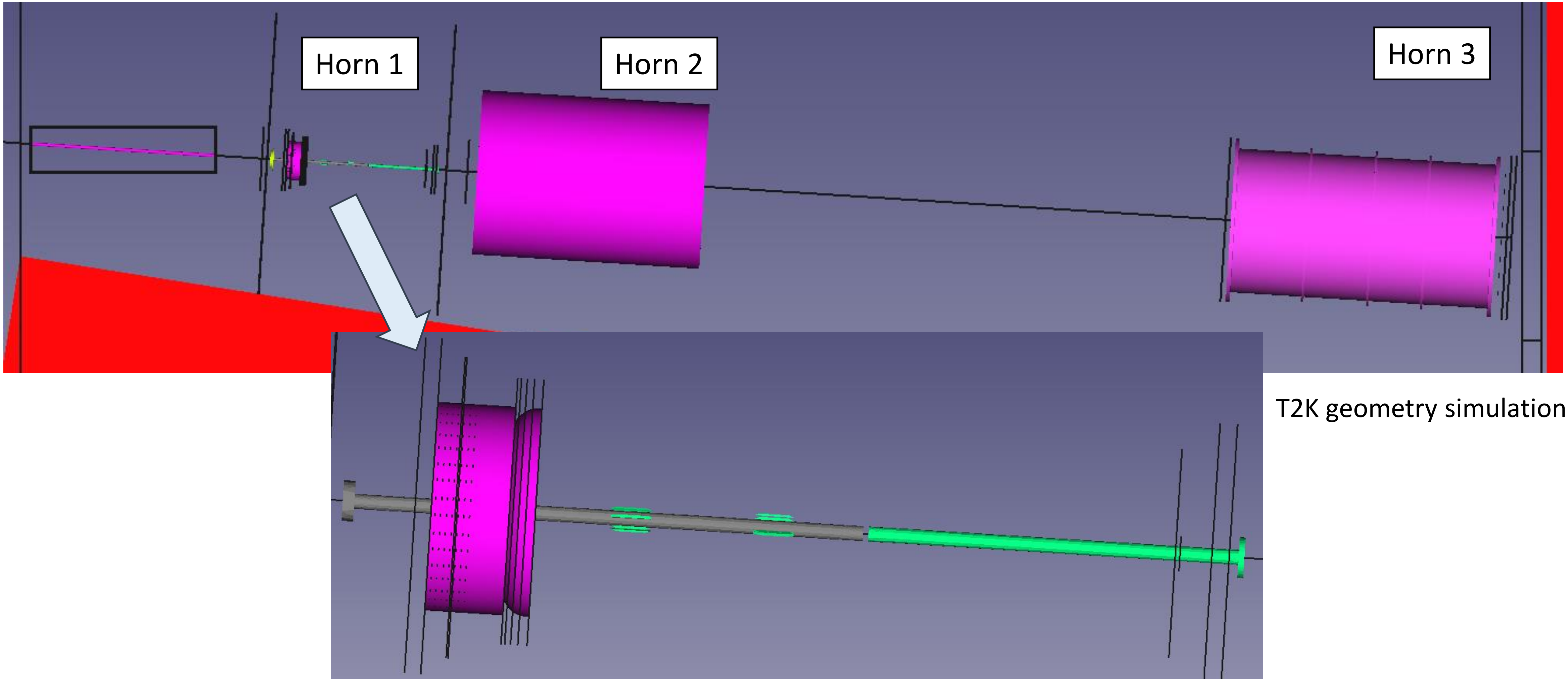
Increased pion yields in approximately 16% for an extended Graphite + Graphite target.





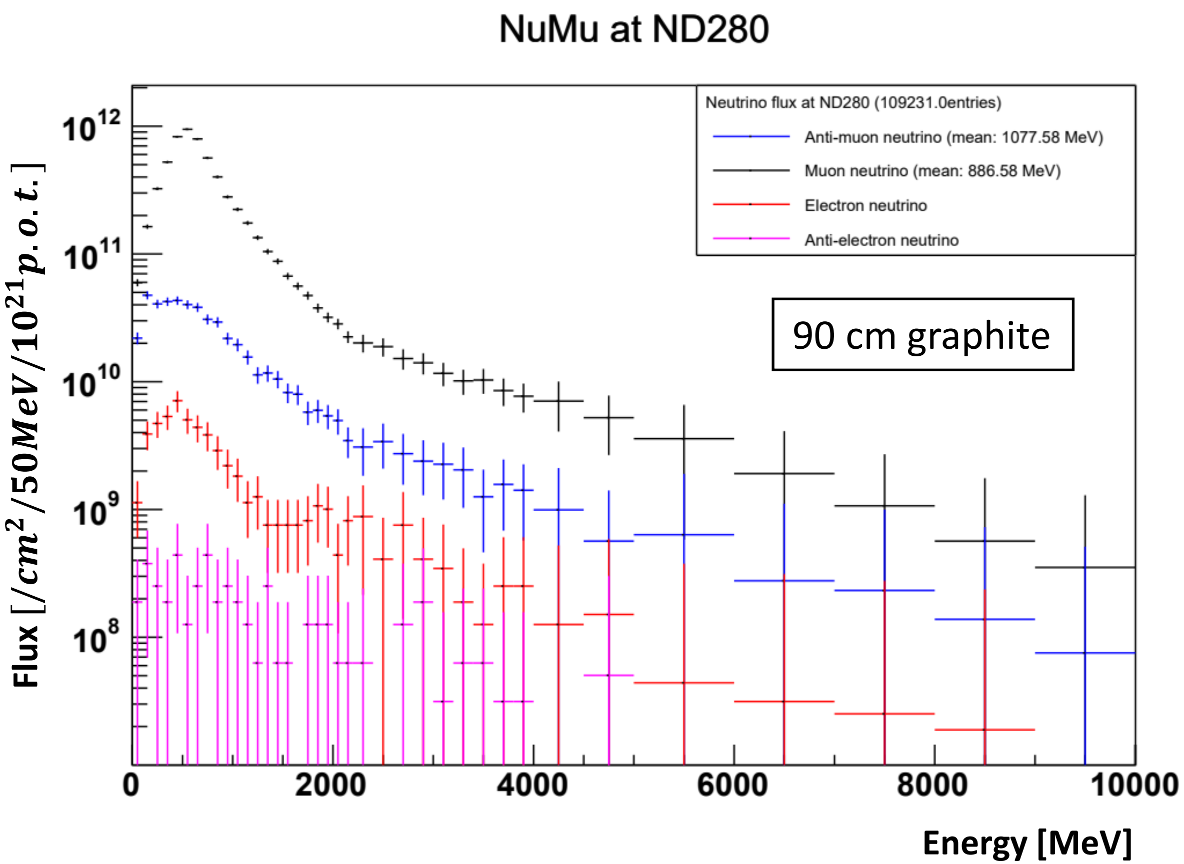
Increased pion yields in approximately 30% for an extended Graphite + SiC target.

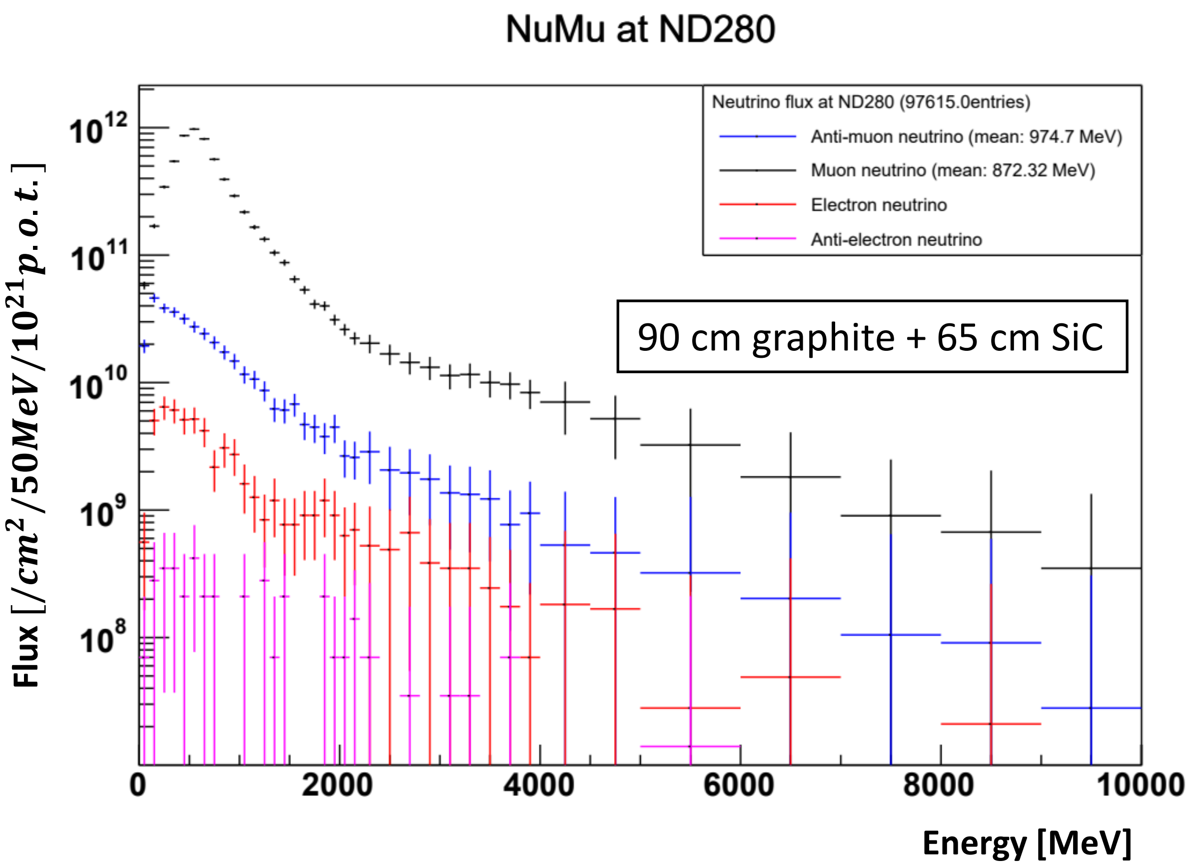
Full T2K simulation



T2K geometry simulation

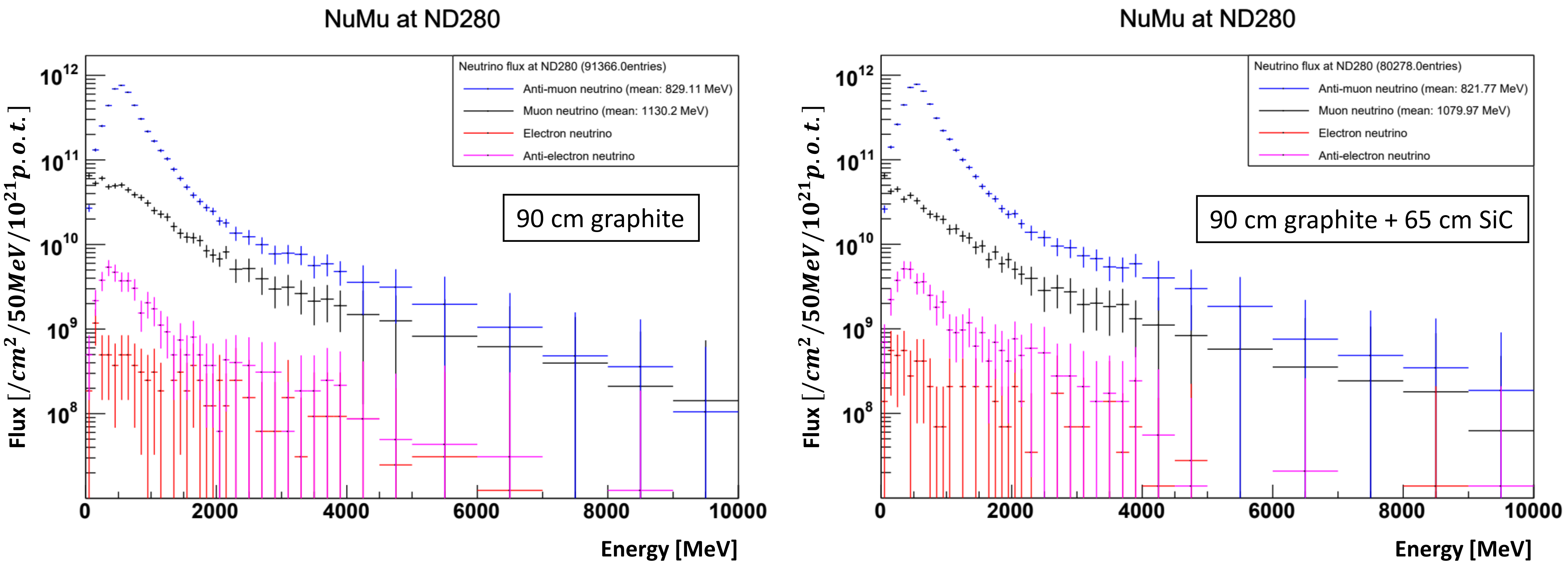
Flux predictions (FHC)





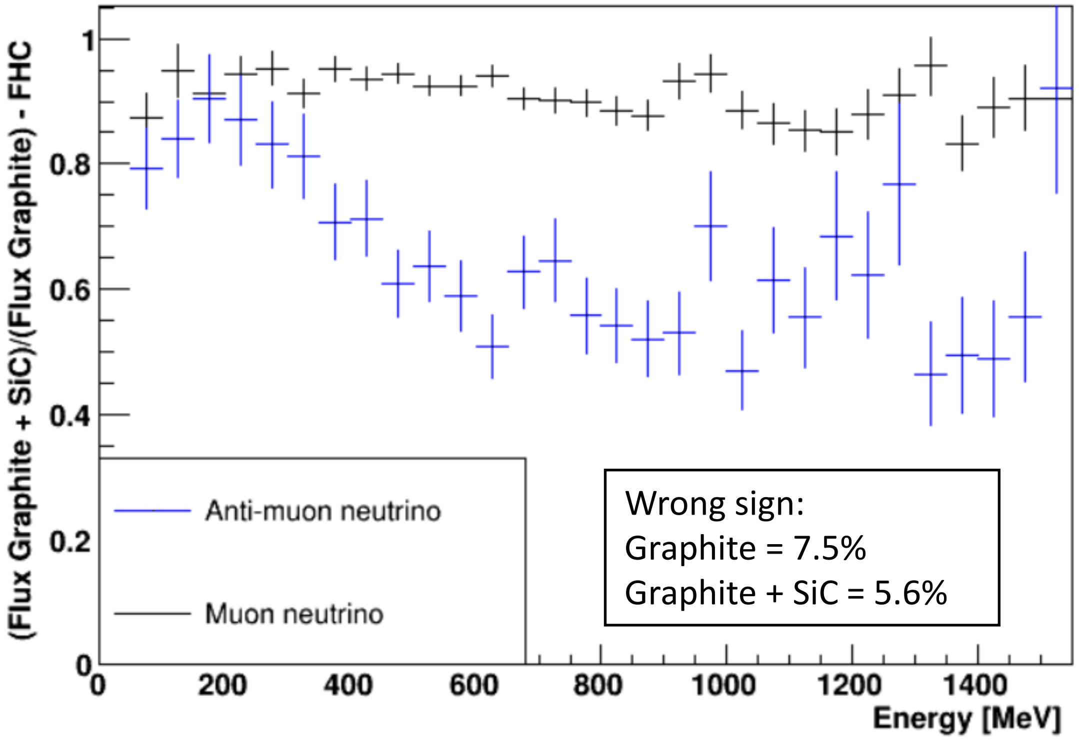
Neutrino fluxes in FHC configuration at ND280. Results are shown for 90 cm graphite only target (left) and with the addition of a 65 cm silicon carbide target (right).

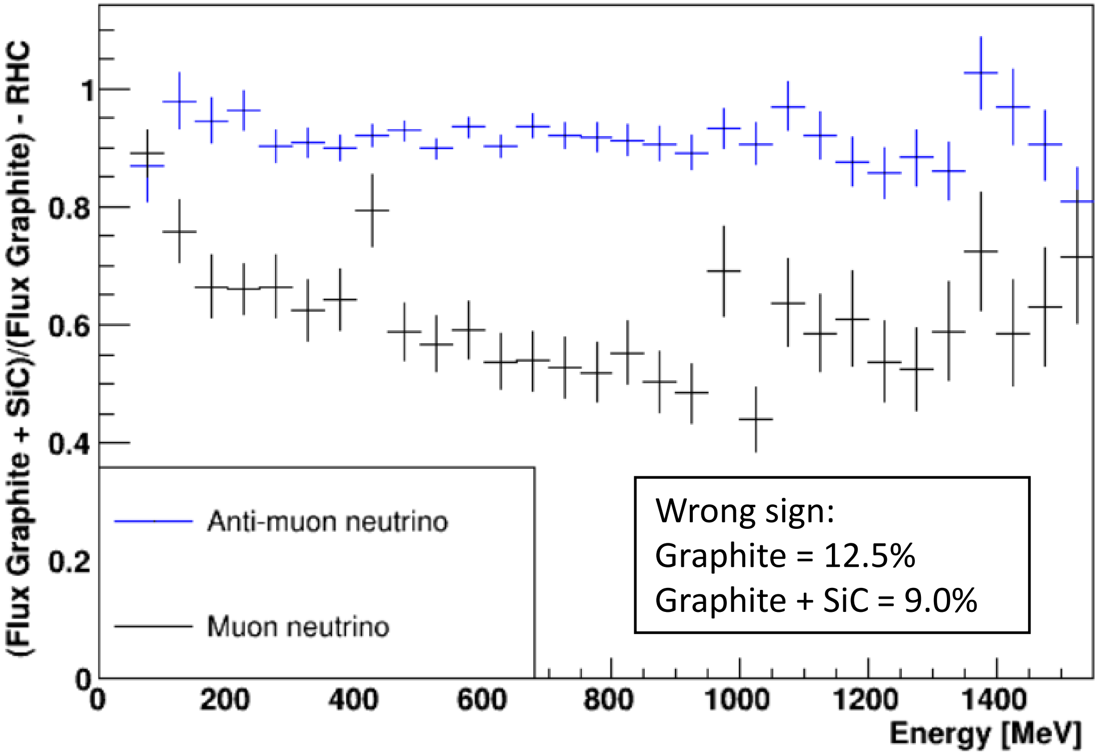
Flux predictions (RHC)



Neutrino fluxes in RHC configuration at ND280. Results are shown for 90 cm graphite only target (left) and with the addition of a 65 cm silicon carbide target (right).

Flux predictions





Ratio of neutrino fluxes (Extended Target/Original Target) at ND280 in FHC configuration (left) and RHC configuration (right).

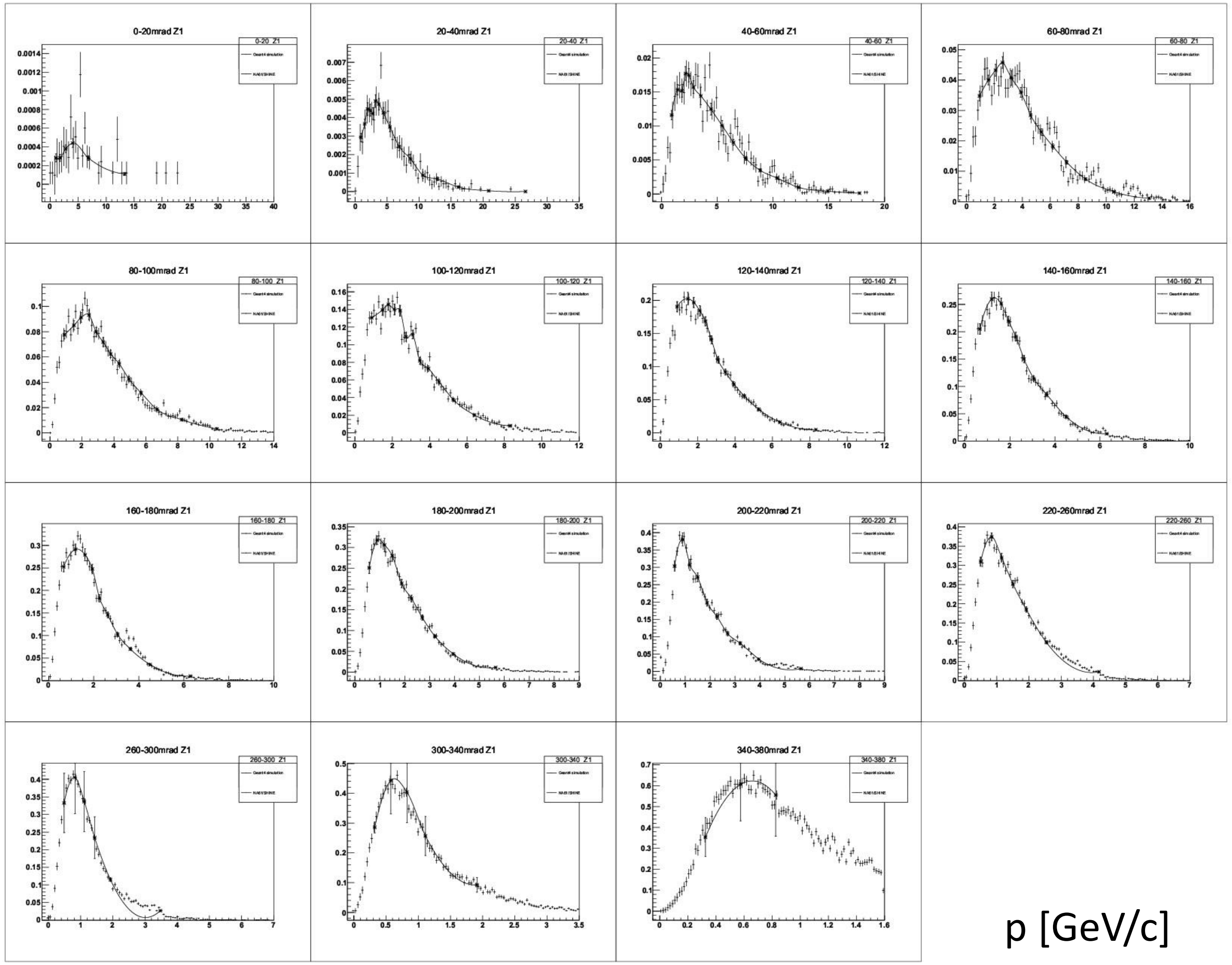
Target alternatives for Hyper-Kamiokande era would need pion yield measurements in future NA61++ with a new realistic replica target plus extension, to be able to perform the most accurate reweighing of the fluxes possible.

Summary

- Development of a GEANT4-based simulation to be used for the T2K neutrino flux predictions.
- Pion yield simulations are validated using NA61/SHINE data.
- Geometry differences between the T2K target and the NA61/SHINE T2K replica target seem to be affecting results;
- The pion yield simulations results improve by using a similar geometry to the replica target, in agreement with the NA61/SHINE data;
- Extended target options are considered for the Hyper-Kamiokande era;
- The production of pions increase in about 30% by adding an extra 65 cm silicon carbide target inside the first horn;
- Denser extra targets also increase the right-sign neutrino flux yield and decrease the wrong-sign contamination.

BACKUP

Spline Fitting: Z1 (0-18 cm)

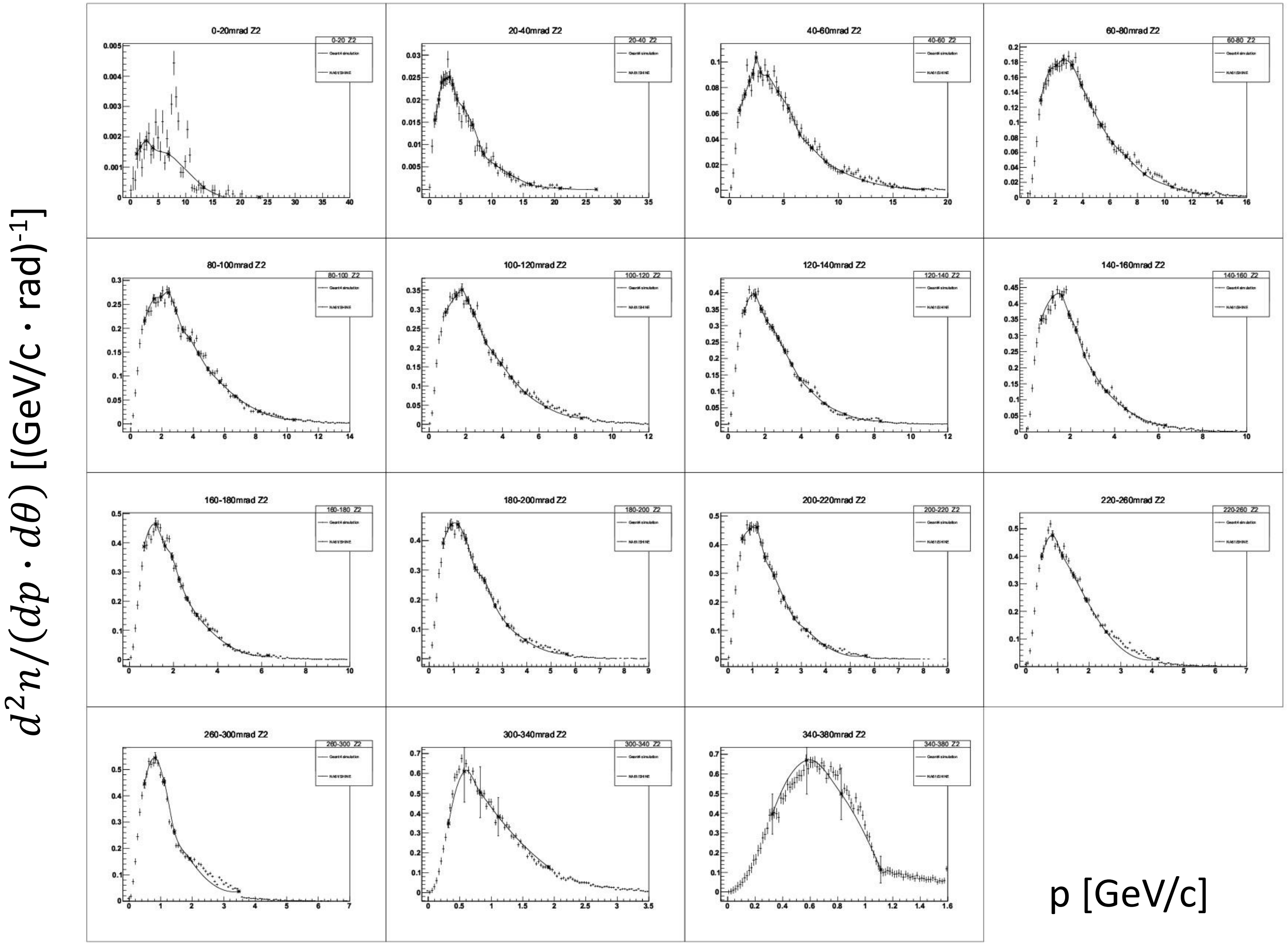


$d^2n/(dp \cdot d\theta)$ [(GeV/c · rad)$^{-1}$]

p [GeV/c]

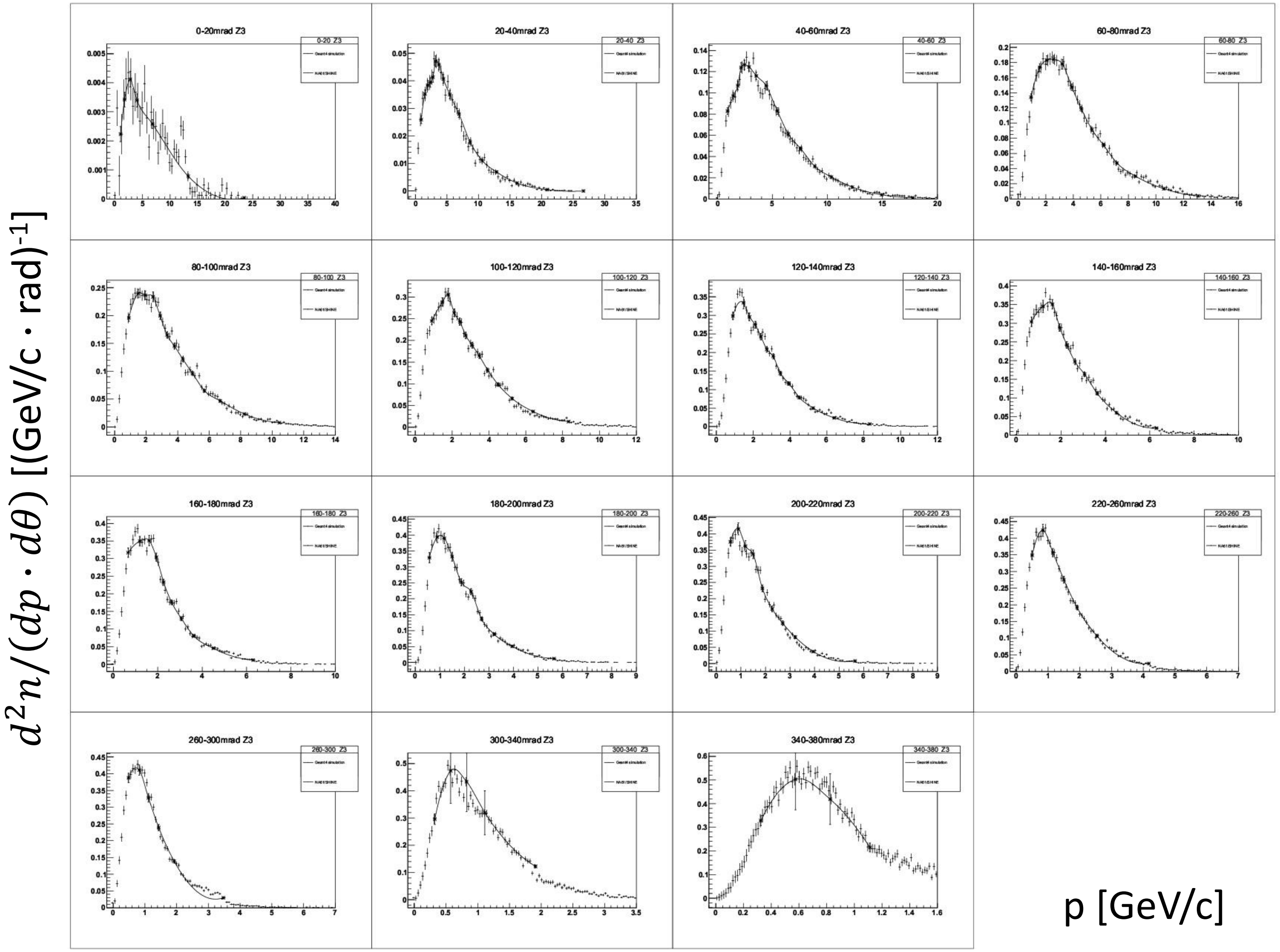
Fitting results of pion yields from G4nubeam simulations (markers) compared to NA61/SHINE data (solid line) for the segment Z1.

Spline Fitting: Z2 (18-36 cm)



Fitting results of pion yields from G4nubeam simulations (markers) compared to NA61/SHINE data (solid line) for the segment Z2.

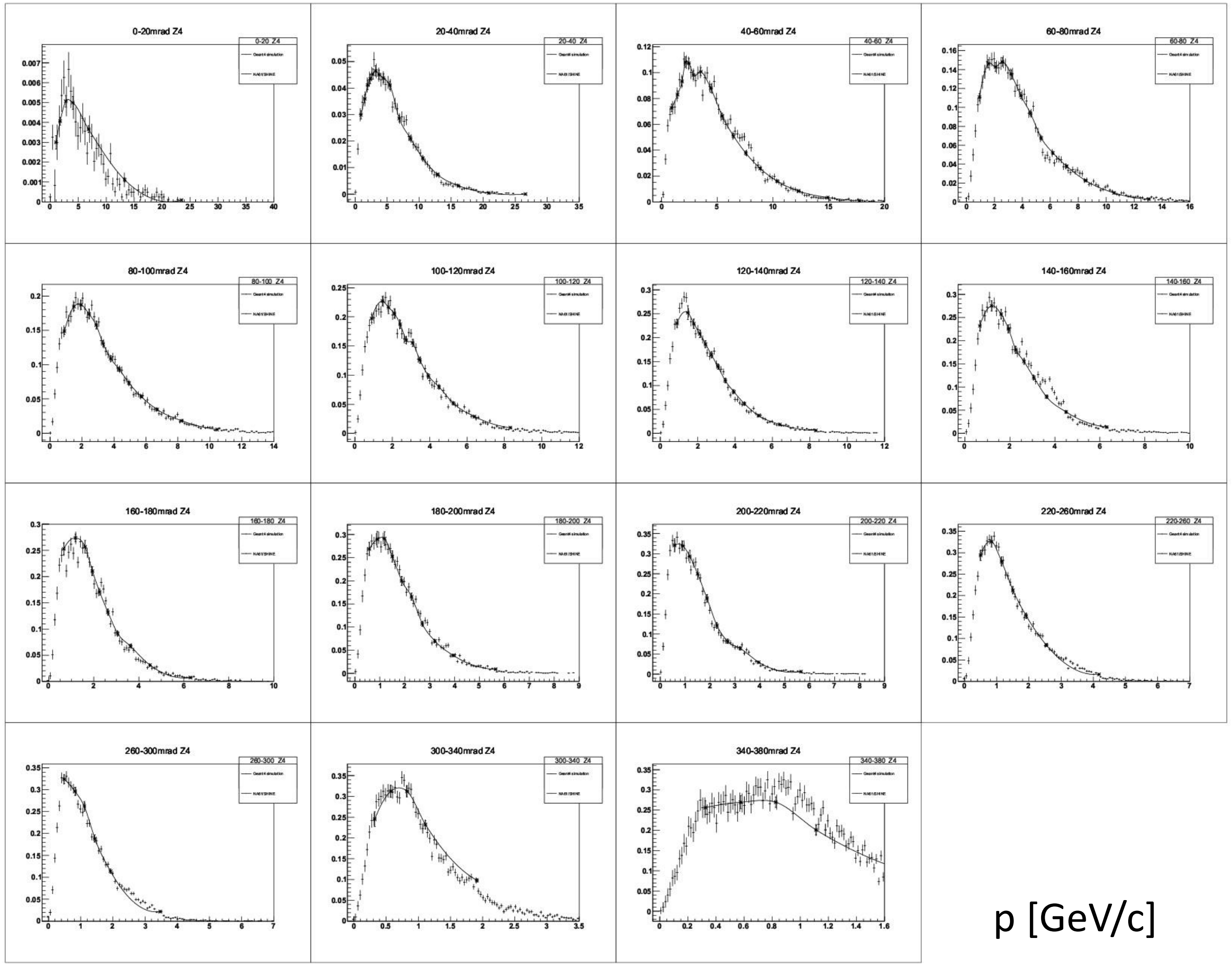
Spline Fitting: Z3 (36-54 cm)



Fitting results of pion yields from G4nubeam simulations (markers) compared to NA61/SHINE data (solid line) for the segment Z3.

Spline Fitting: Z4 (54-72 cm)

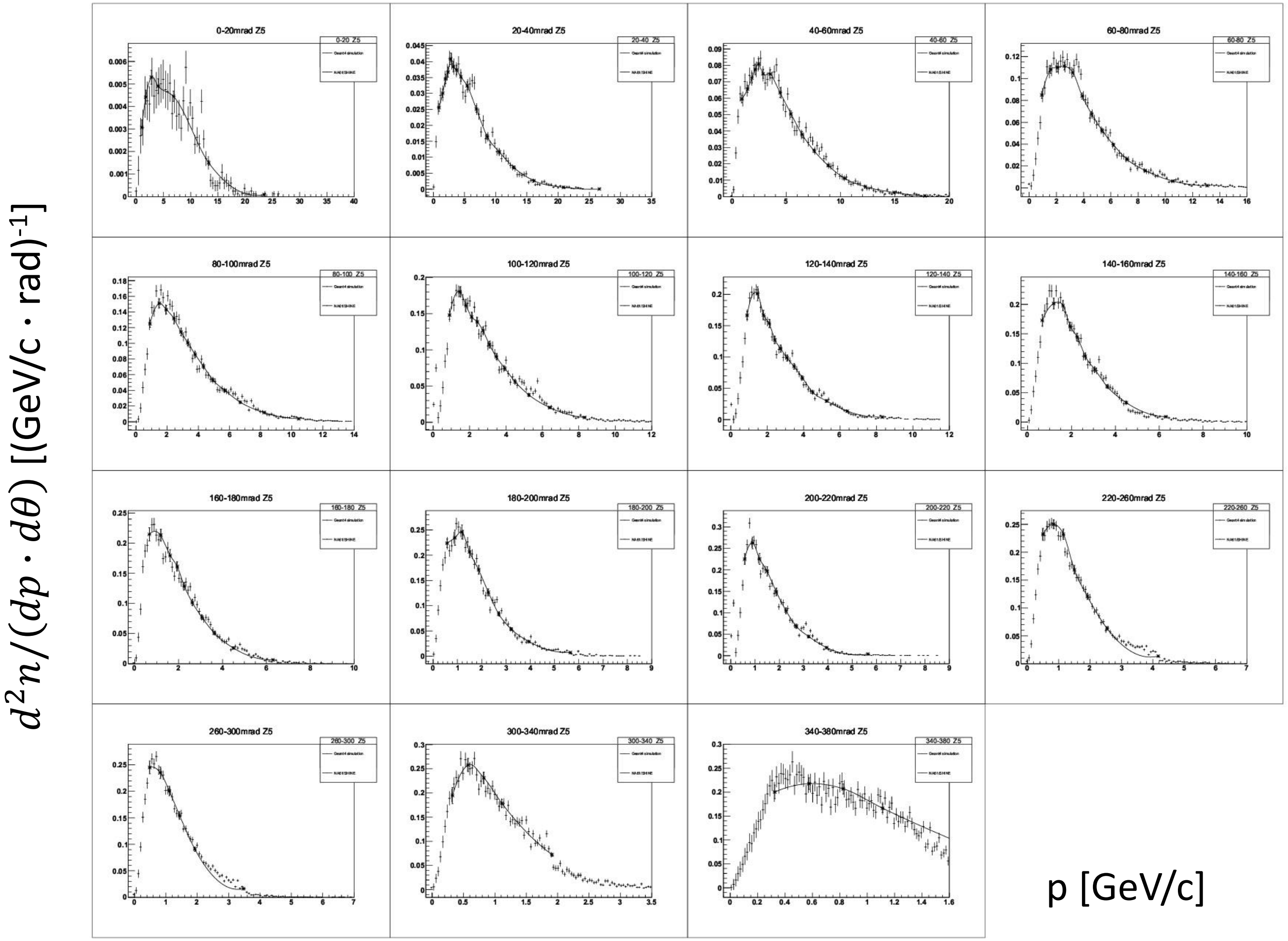
$d^2n/(dp \cdot d\theta)$ [(GeV/c · rad)$^{-1}$]



p [GeV/c]

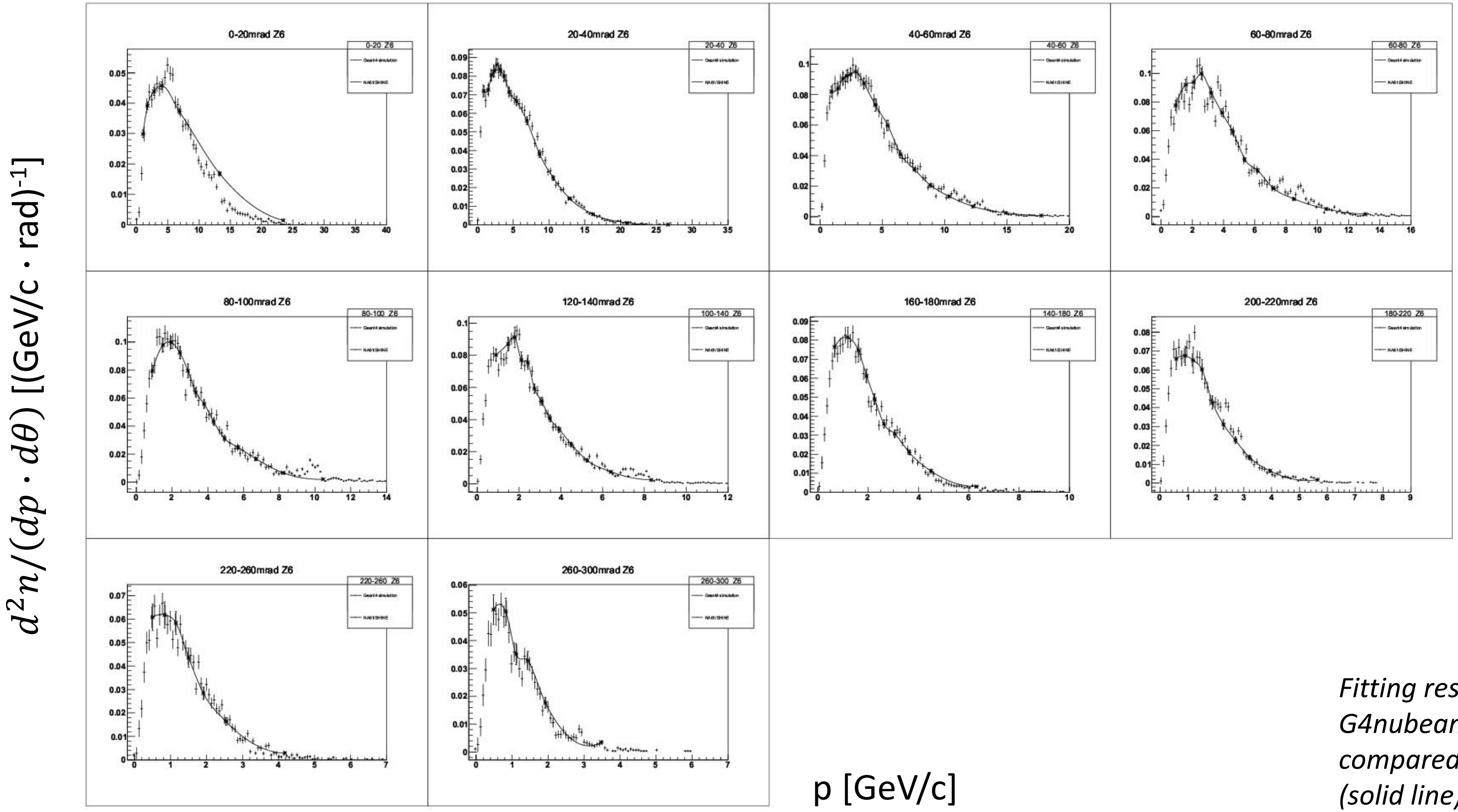
Fitting results of pion yields from G4nubeam simulations (markers) compared to NA61/SHINE data (solid line) for the segment Z4.

Spline Fitting: Z5 (72-90 cm)



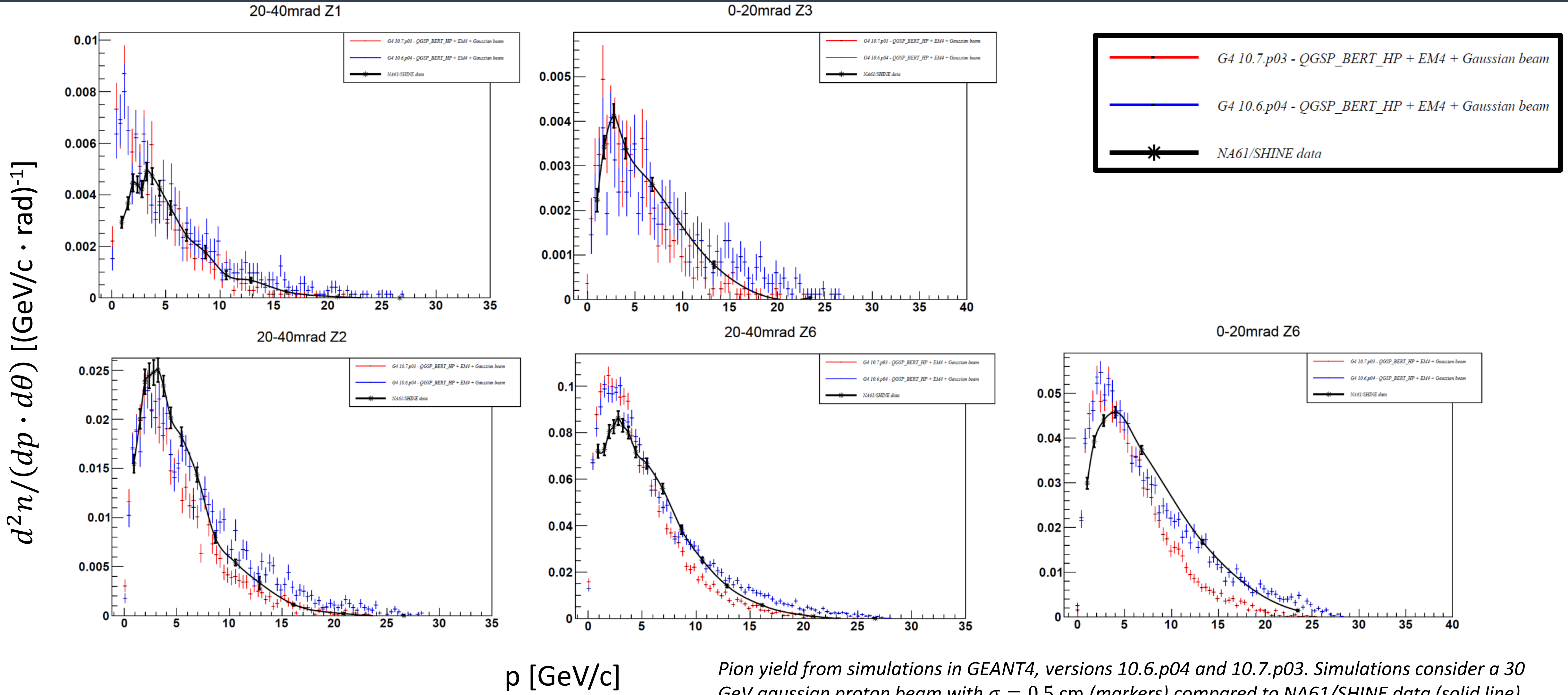
Fitting results of pion yields from G4nubeam simulations (markers) compared to NA61/SHINE data (solid line) for the segment Z5.

Spline Fitting: Z6 (90 cm)



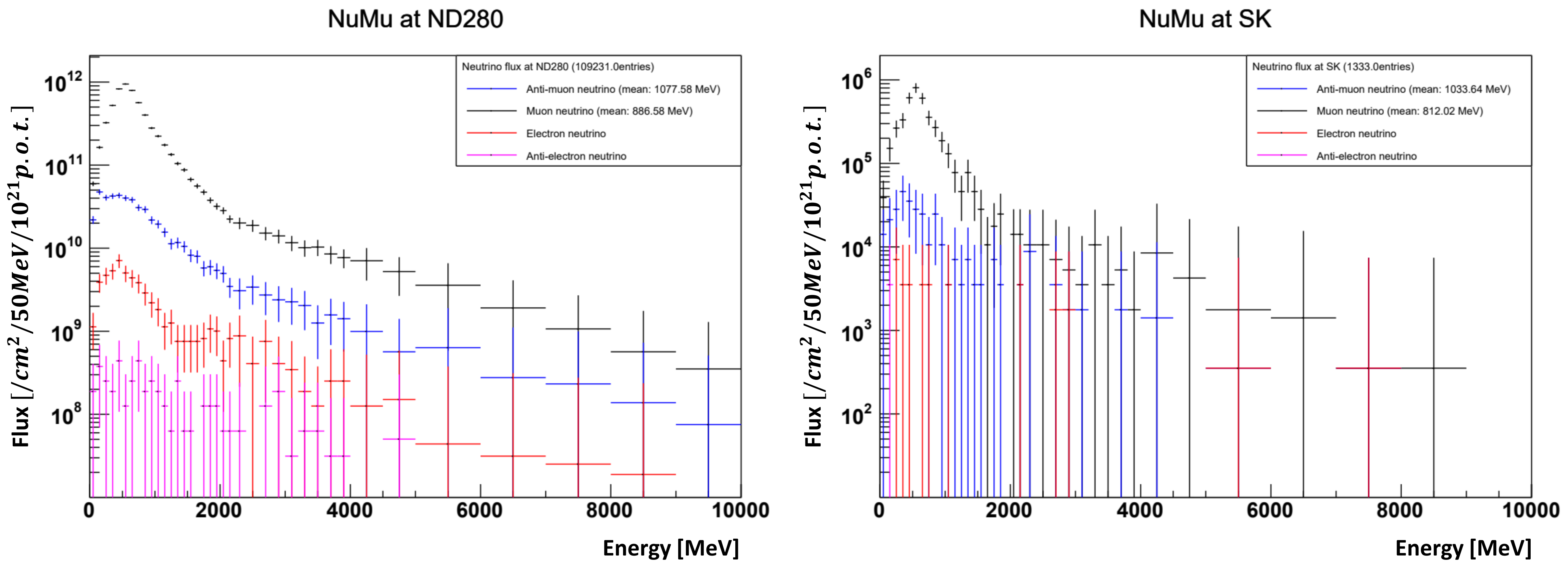
Fitting results of pion yields from G4nubeam simulations (markers) compared to NA61/SHINE data (solid line) for the segment Z6.

Comparing GEANT4 versions



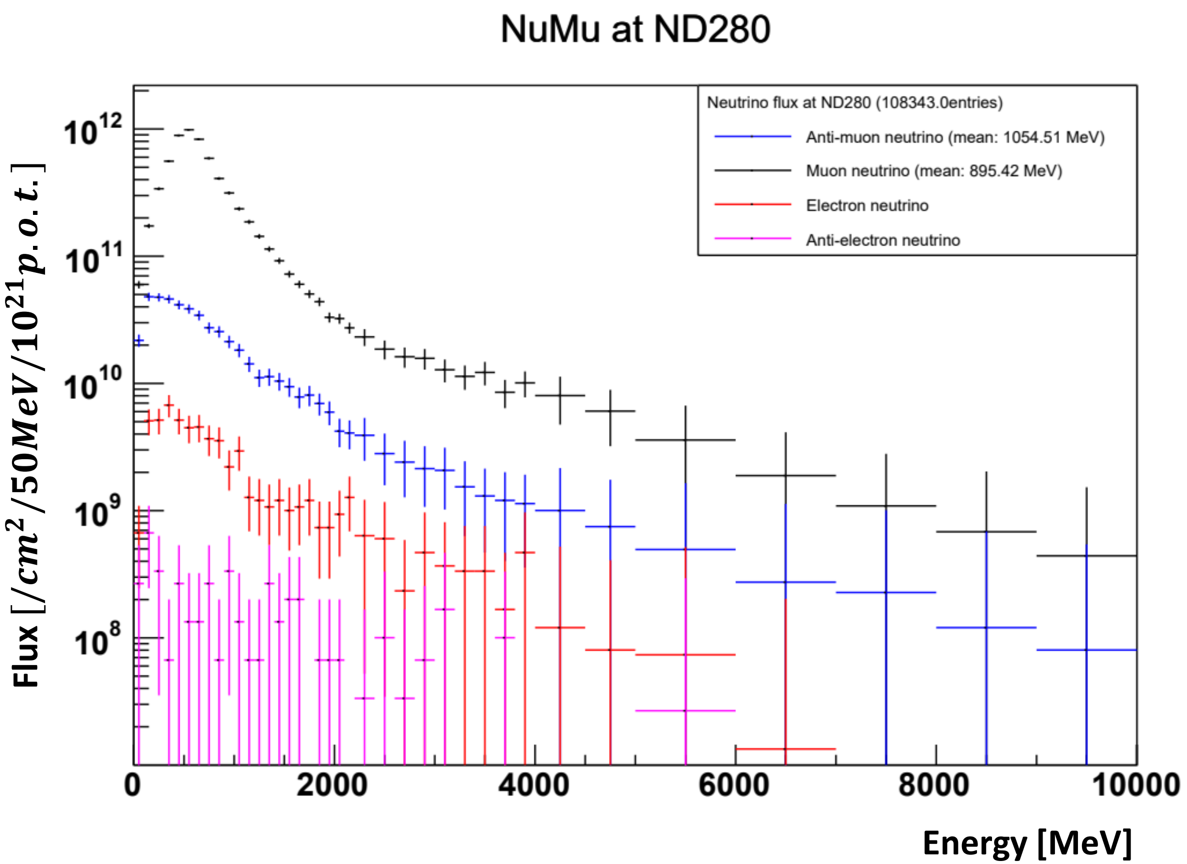
Pion yield from simulations in GEANT4, versions 10.6.p04 and 10.7.p03. Simulations consider a 30 GeV gaussian proton beam with $\sigma = 0.5$ cm (markers) compared to NA61/SHINE data (solid line).

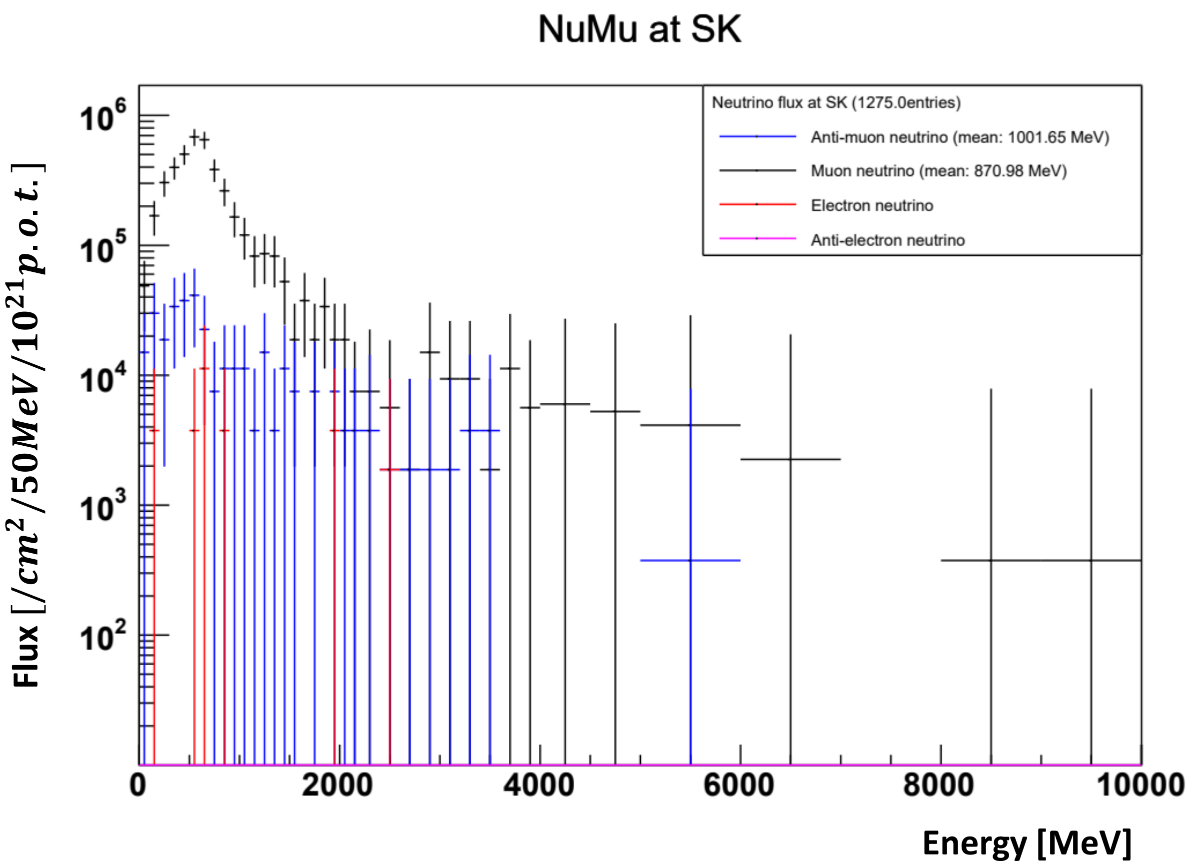
Flux predictions (Graphite only - FHC)



Neutrino fluxes in FHC configuration at ND280 (left) and Super-Kamiokande (right).

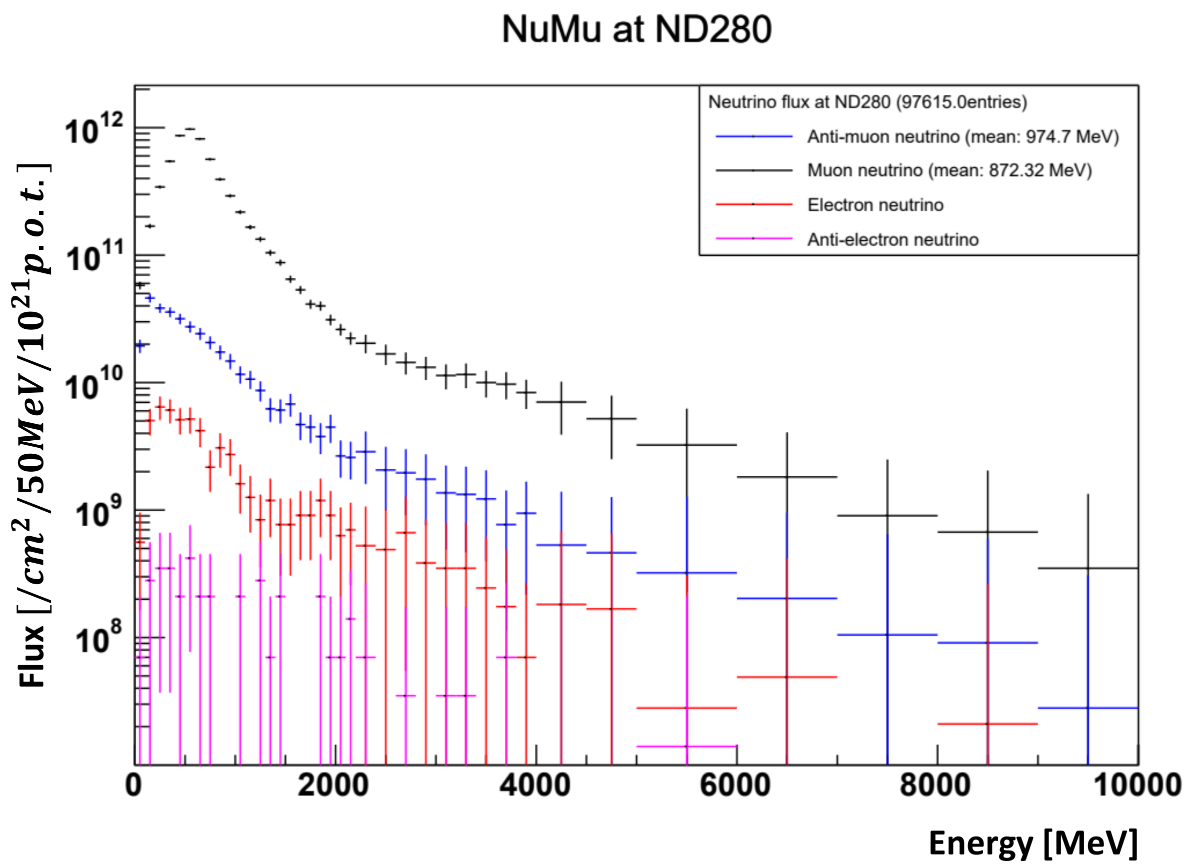
Flux predictions (Graphite + Graphite - FHC)

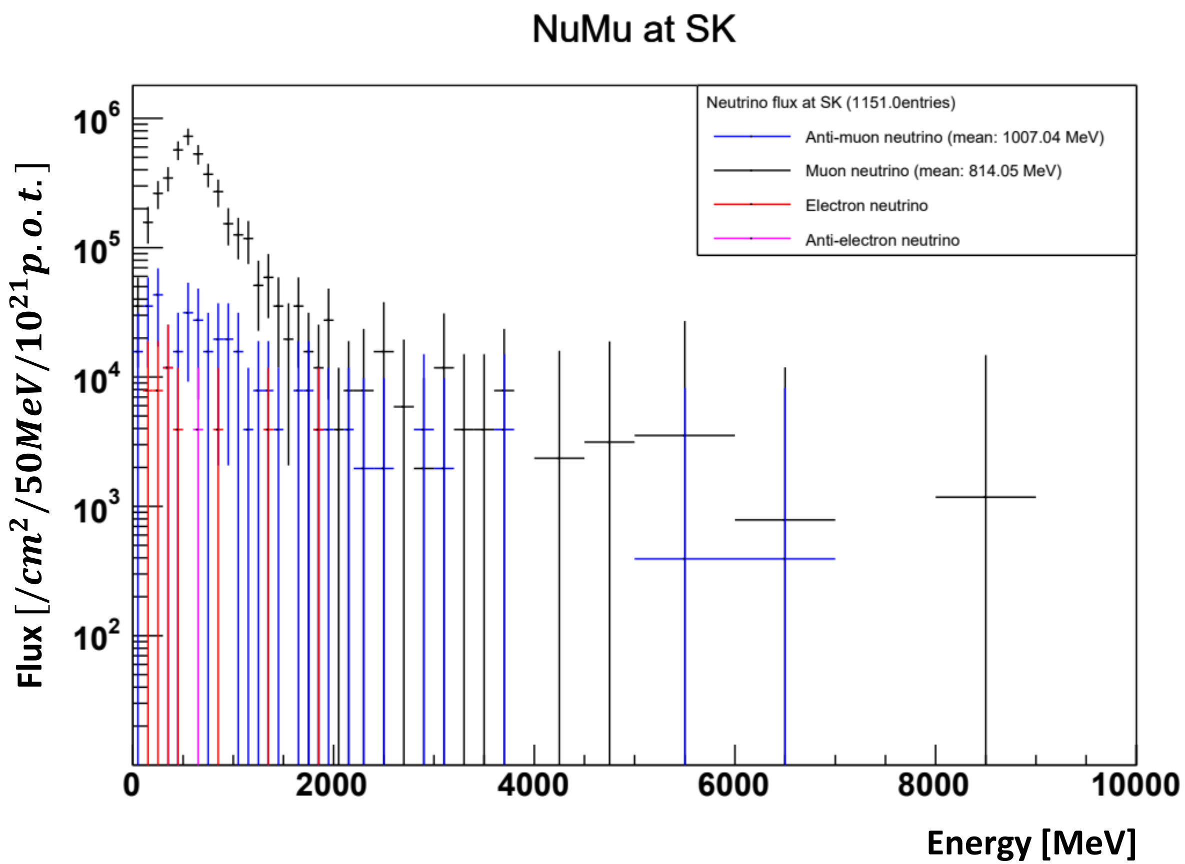




Neutrino fluxes in FHC configuration at ND280 (left) and Super-Kamiokande (right).

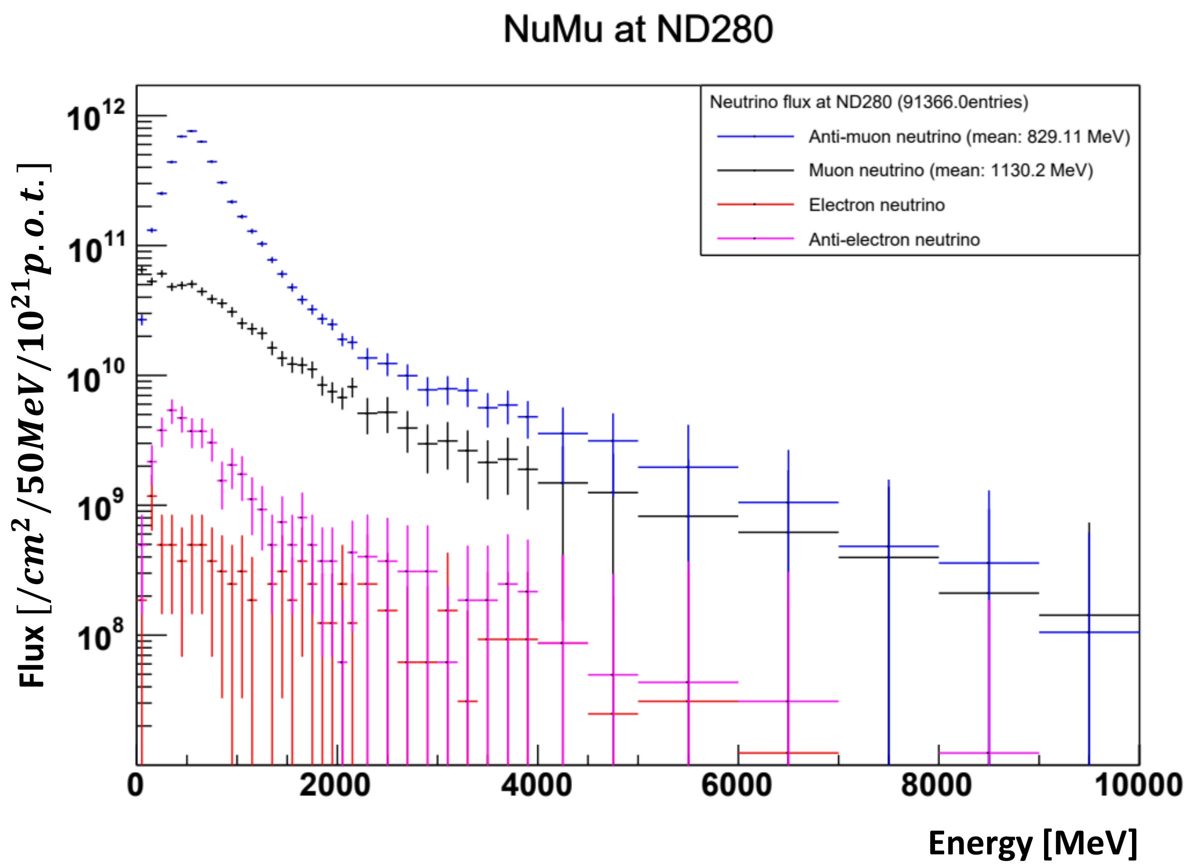
Flux predictions (Graphite + SiC - FHC)

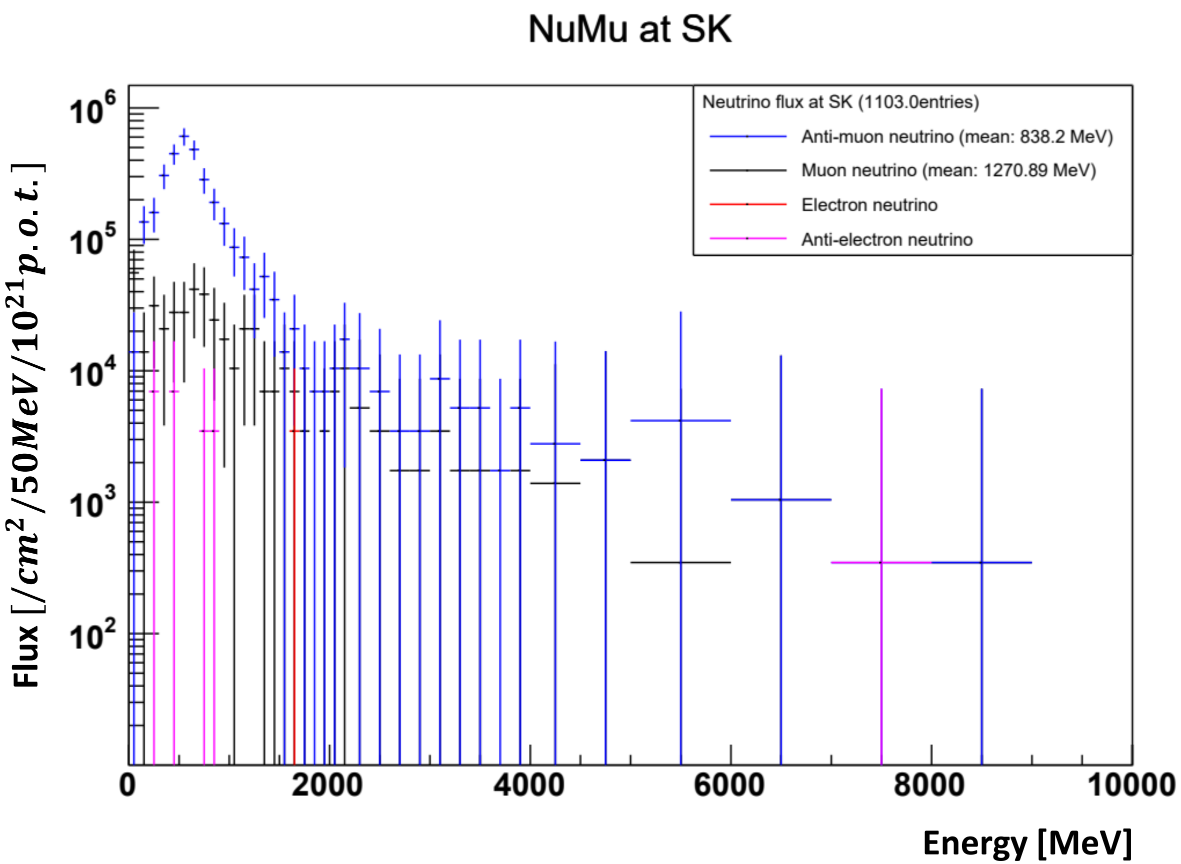




Neutrino fluxes in FHC configuration at ND280 (left) and Super-Kamiokande (right).

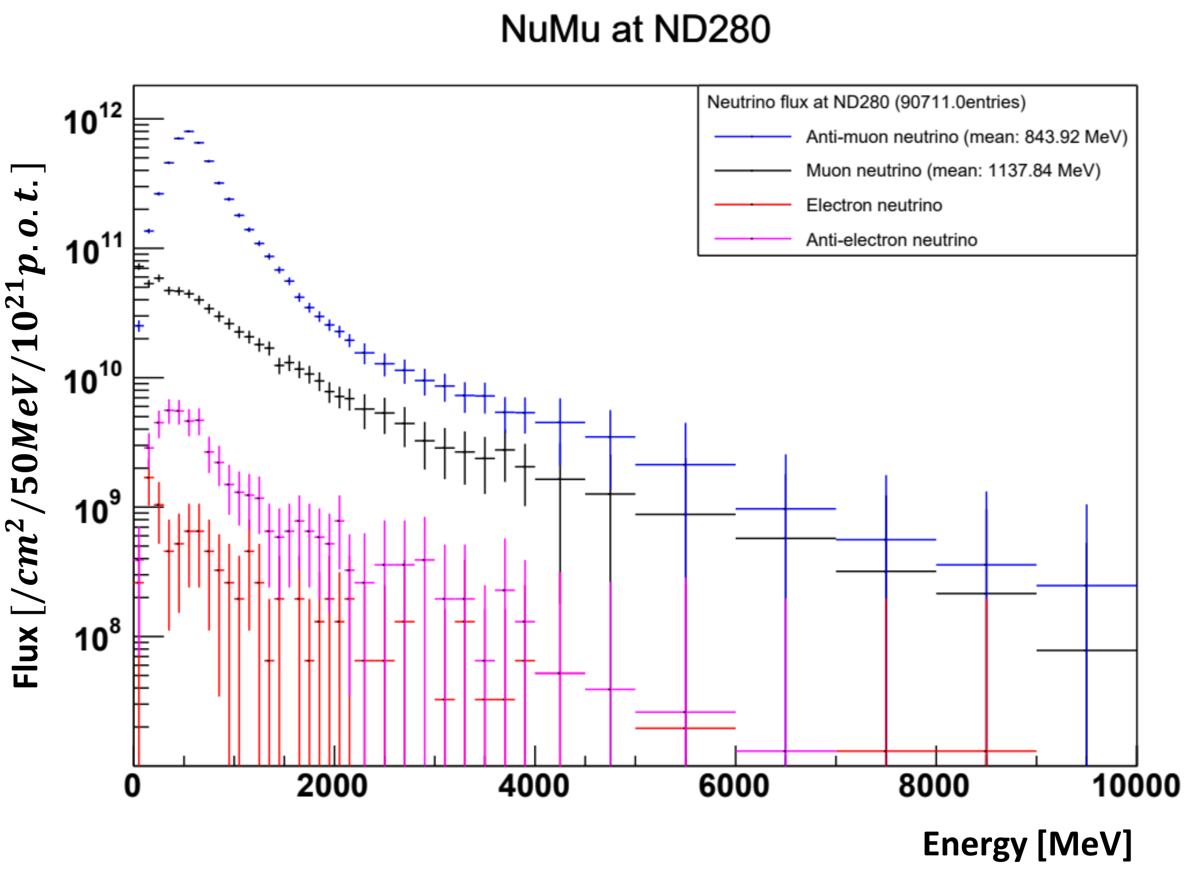
Flux predictions (Graphite only - RHC)

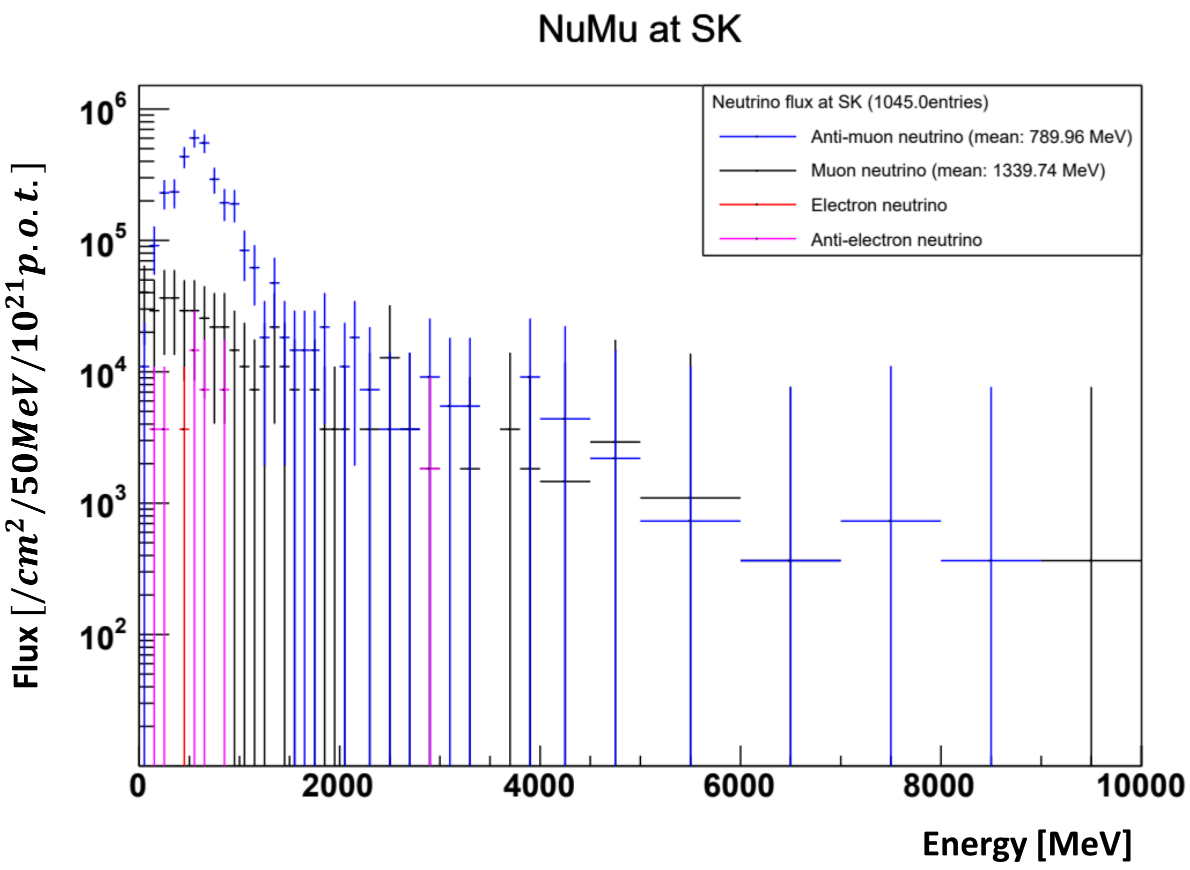




Neutrino fluxes in FHC configuration at ND280 (left) and Super-Kamiokande (right).

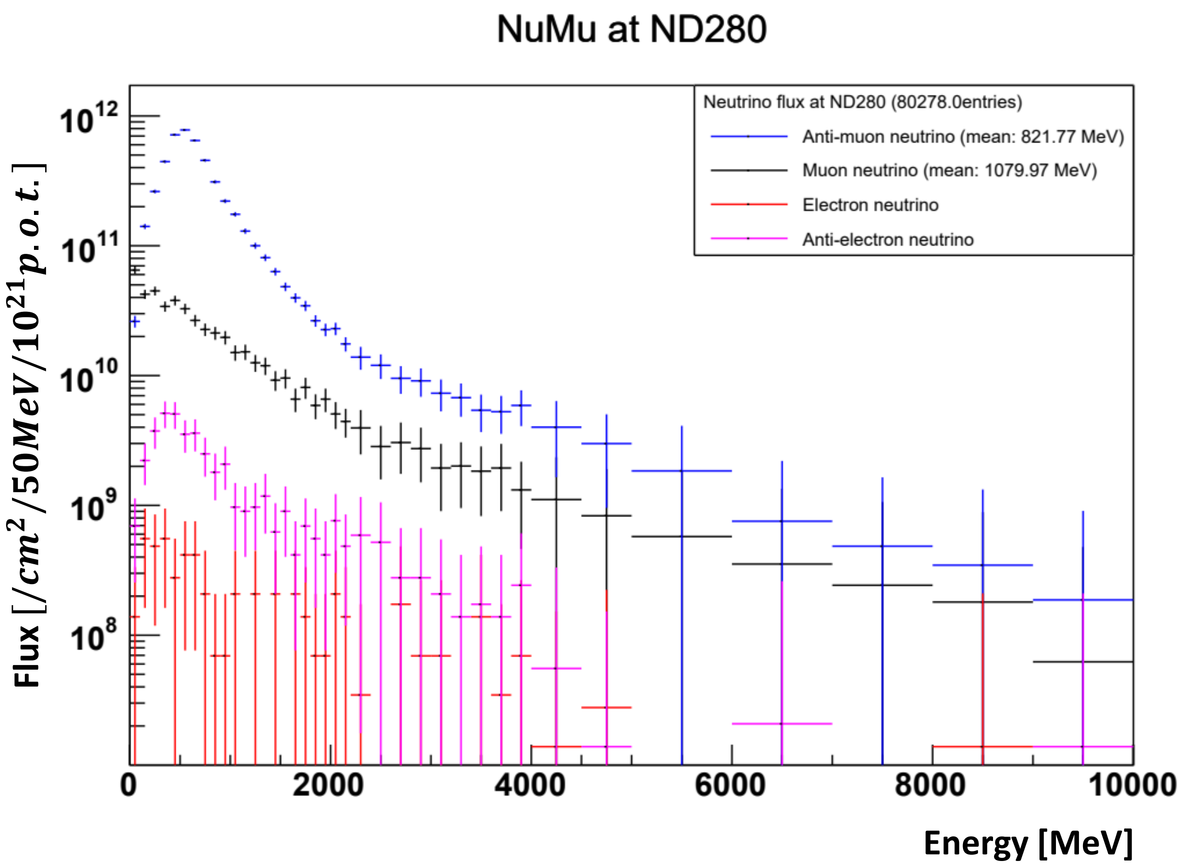
Flux predictions (Graphite + Graphite - RHC)

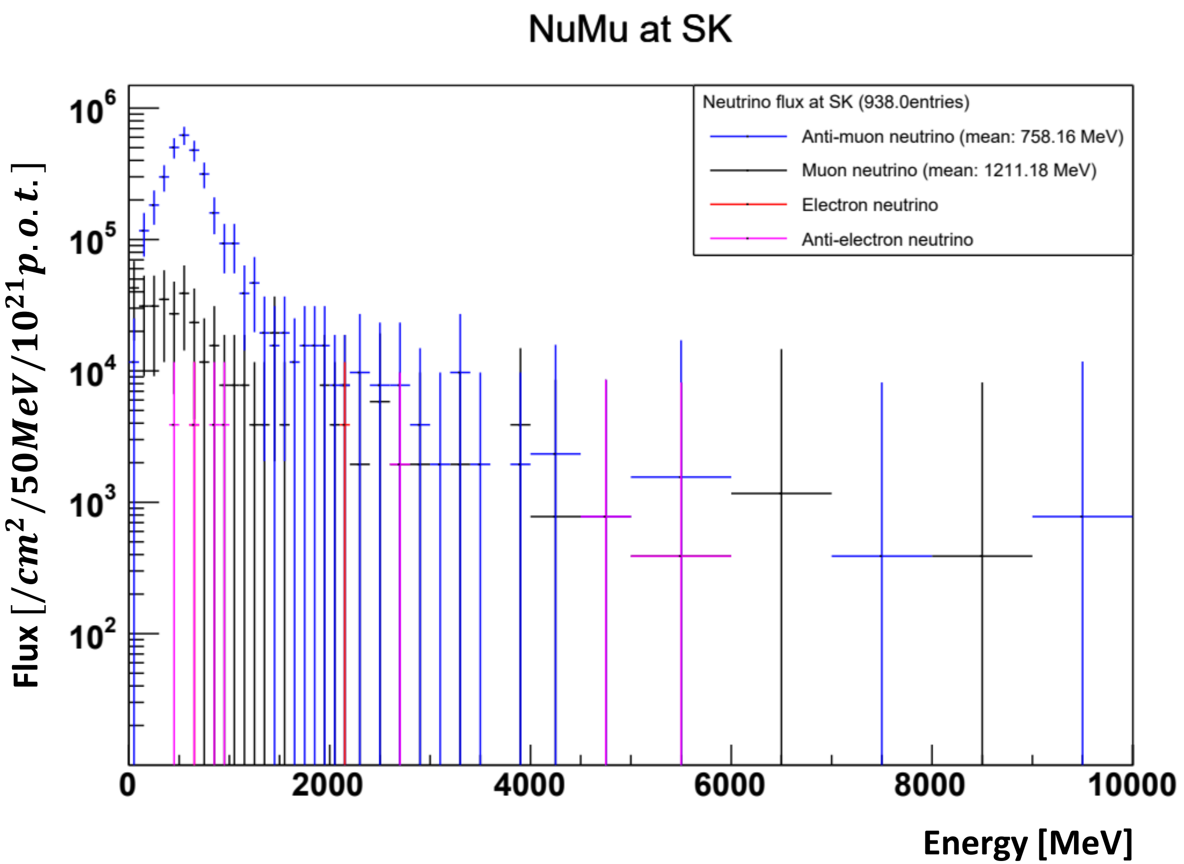




Neutrino fluxes in FHC configuration at ND280 (left) and Super-Kamiokande (right).

Flux predictions (Graphite + SiC - RHC)





Neutrino fluxes in FHC configuration at ND280 (left) and Super-Kamiokande (right).