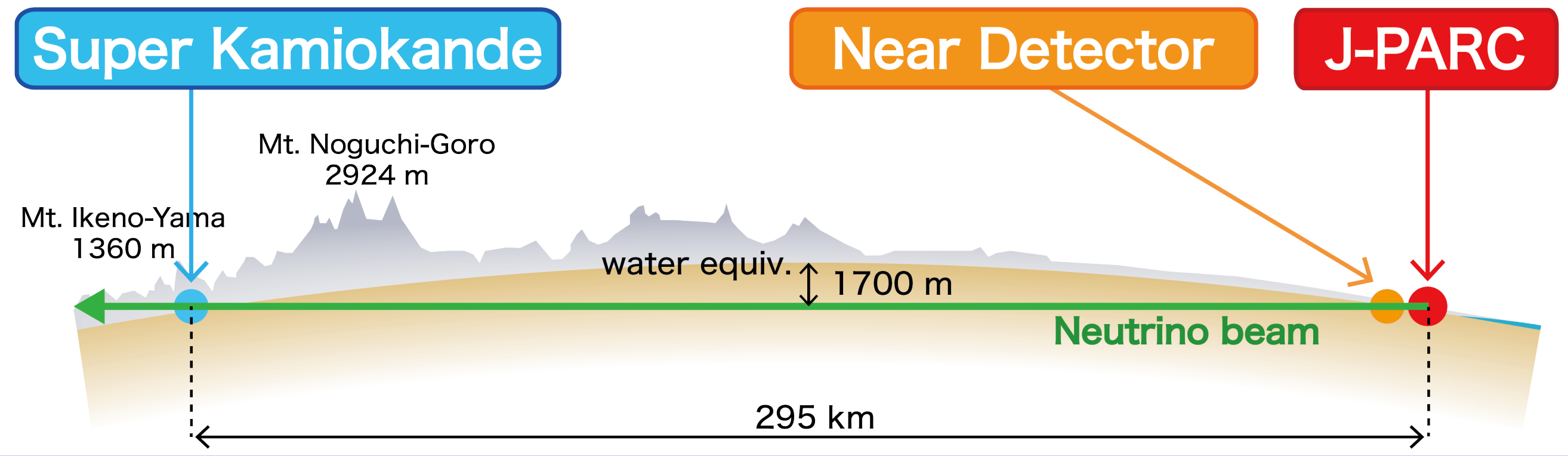
Constraining the T2K Neutrino Flux with NA61/SHINE 2009 Replica-Target Data

Tomislav Vladisavljevic
tomislav.vladisavljevic@physics.ox.ac.uk

UNIVERSITY OF OXFORD
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

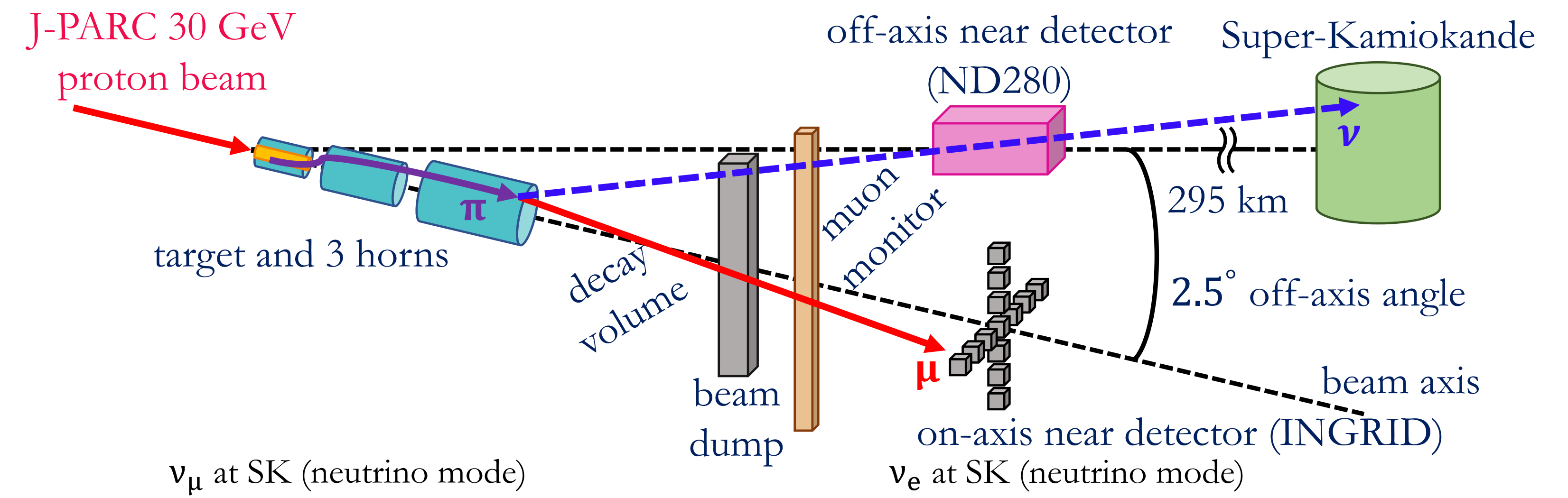
1. The T2K Experiment [1]



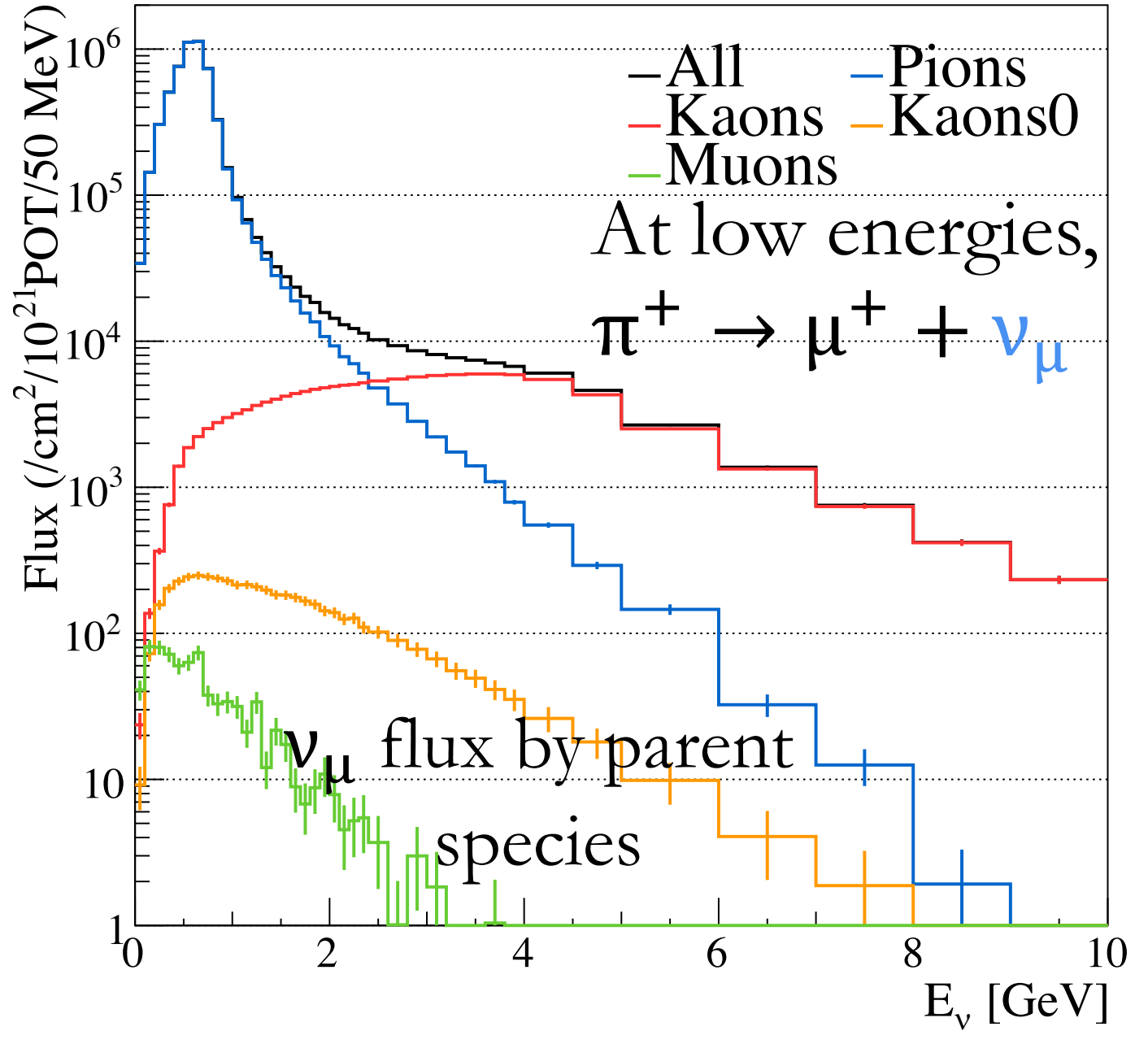
- Long-baseline neutrino oscillation experiment located in Japan
- Measures ν_μ ($\bar{\nu}_\mu$) disappearance and ν_e ($\bar{\nu}_e$) appearance in ν ($\bar{\nu}$) mode

2. The Neutrino Flux [2]

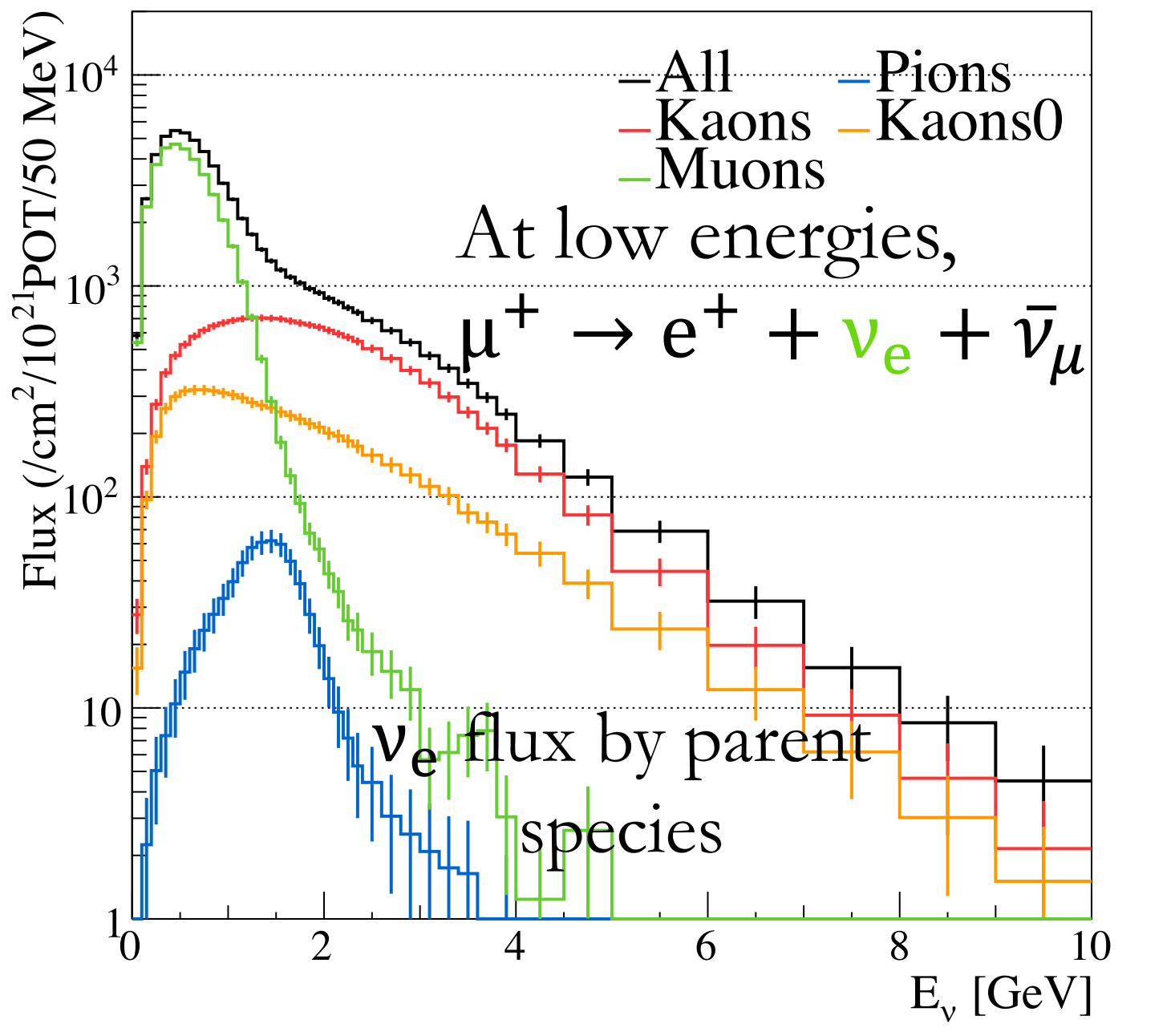
- 30 GeV proton beam colliding with the T2K graphite target (length of 90 cm)



ν_μ at SK (neutrino mode)



ν_e at SK (neutrino mode)



3. Importance of Constraining the Neutrino Flux [3,4]

- T2K is primarily sensitive to oscillation parameters θ_{23}, Δm^2_{23}, δ_{CP}
- Maximizing the likelihood for observed number of events at the far detector under the neutrino oscillation hypothesis determines the oscillation parameters:

$$N^{FD,obs}_{\nu_k}(E_i, \theta_{23}, \Delta m^2_{32}, \delta_{CP}, \ldots) = \sum_j^{flavours} P_{\nu_j \to \nu_k} \times N^{FD,unosc}_{\nu_j}(E_i)$$

$$N^{FD,unosc}_{\nu_j}(E_i) = \sum^{\vec{p},\theta} \underbrace{\boxed{\Phi^{FD}_{\nu_j}(E_i)}}_{\text{FLUX}} \times \underbrace{\boxed{\sigma^{FD}_{\nu_j}(\vec{p},\theta,E_i)}}_{\text{CROSS SECTION}} \times \underbrace{\boxed{\epsilon^{FD}(\vec{p},\theta)}}_{\text{EFFICIENCY}} \times \underbrace{\boxed{p^{FD}(\vec{p},\theta)}}_{\text{PURITY}}$$

Neutrino flux systematic errors enter here!

- Reducing the neutrino flux systematics is crucial as T2K prepares for entering the regime of high precision neutrino oscillation measurements: current goal is 3σ exclusion of $\delta_{CP} = 0$
- Limited understanding of hadron interactions inside the T2K target makes the neutrino flux modelling very challenging → use external data for constraining the model
- Can get away with high neutrino flux uncertainties by further constraining the flux parameter with the near detector data:

$$N^{ND,obs}_{\nu_j}(E_i) = \sum^{\vec{p},\theta} \Phi^{ND}_{\nu_j}(E_i) \times \sigma^{ND}_{\nu_j}(\vec{p},\theta,E_i) \times \epsilon^{ND}(\vec{p},\theta) \times p^{ND}(\vec{p},\theta)$$

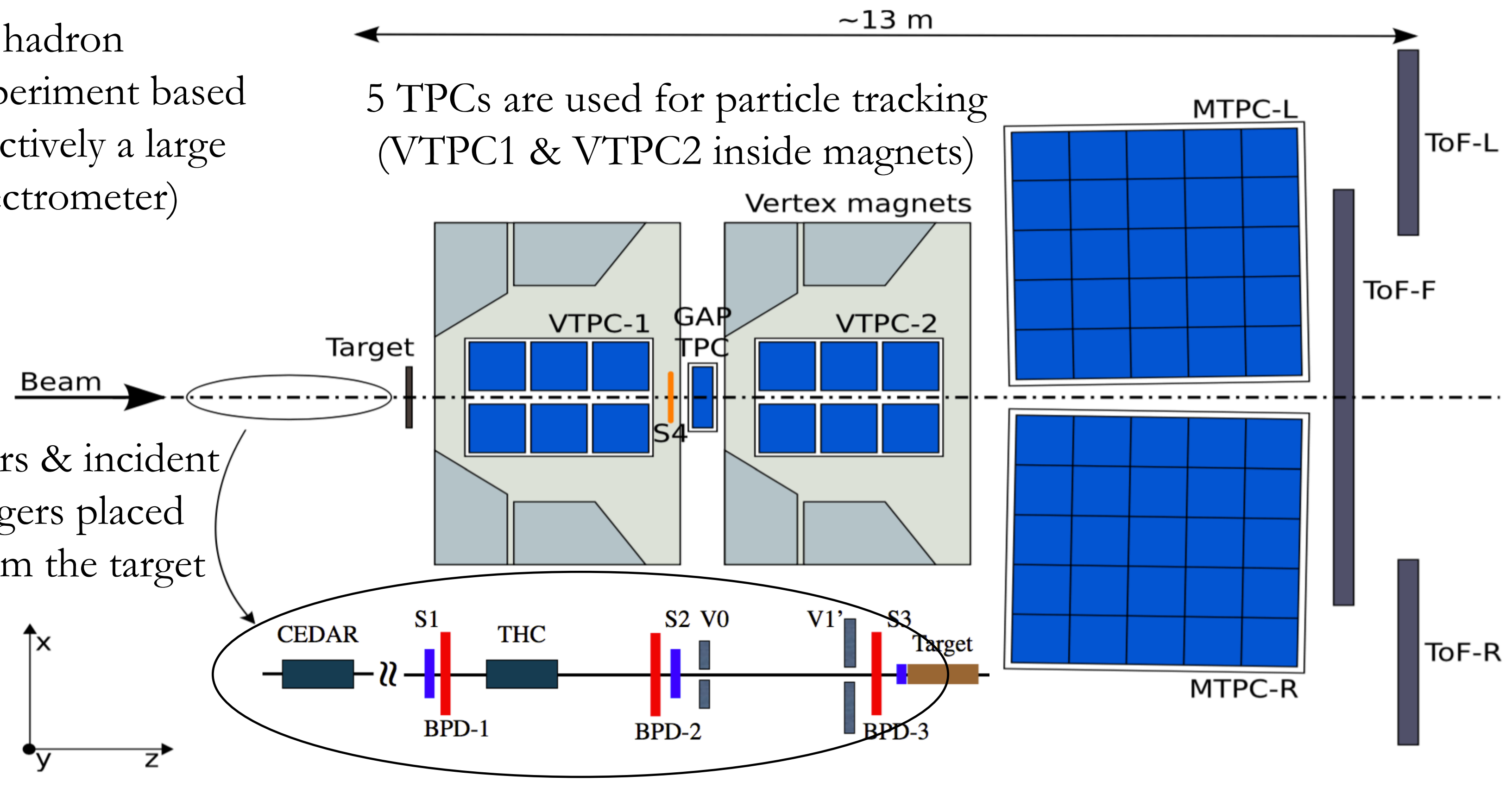
- Constrained neutrino flux is then extrapolated to the far detector
- Reducing neutrino flux uncertainties is also vital for T2K's neutrino cross section programme at ND280

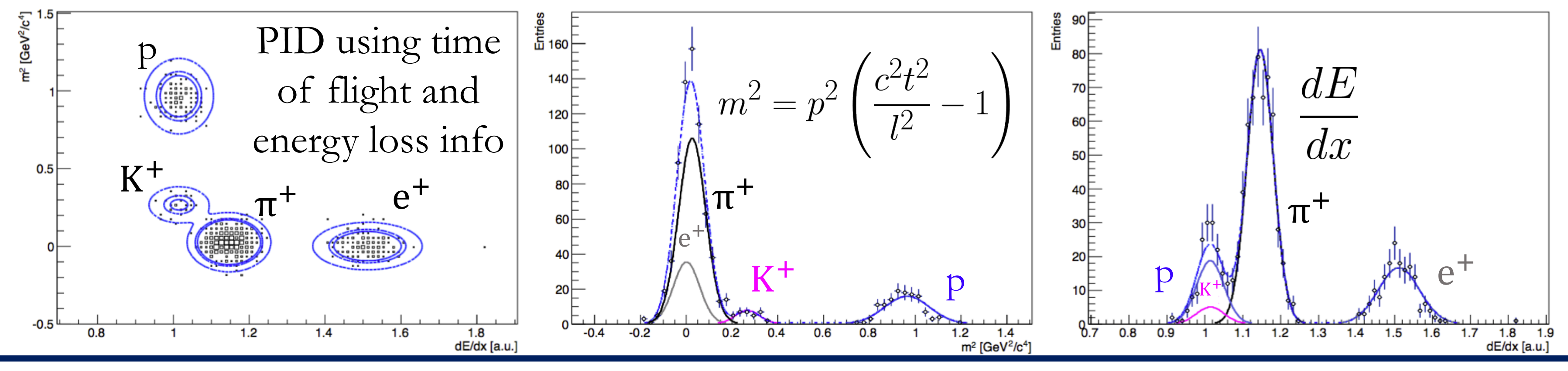
4. The NA61/SHINE Experiment [5,6]

- Multi-purpose hadron production experiment based in CERN (effectively a large acceptance spectrometer)

5 TPCs are used for particle tracking (VTPC1 & VTPC2 inside magnets)

- Beam detectors & incident particle triggers placed upstream from the target



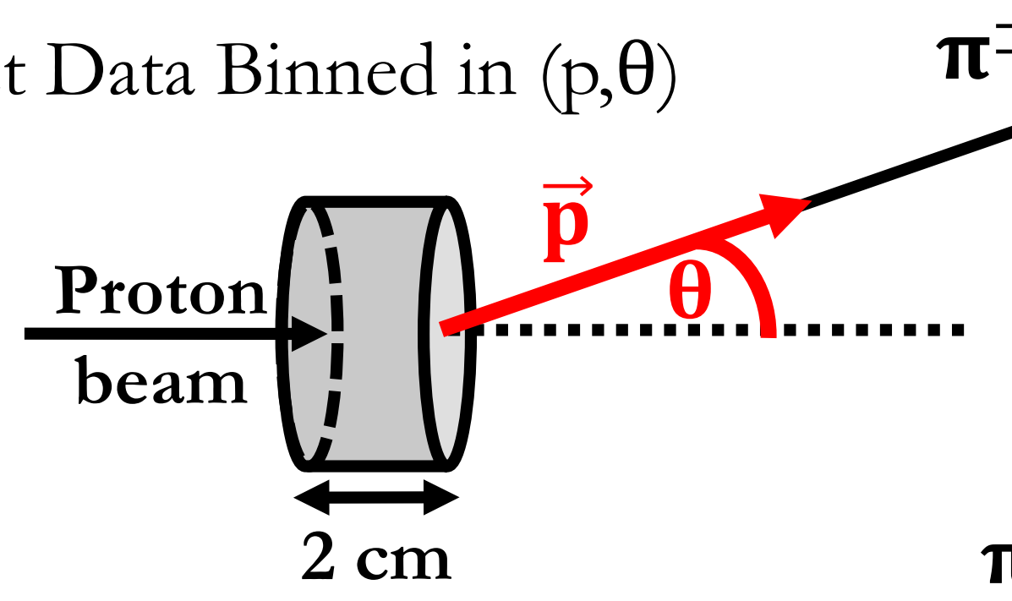


5. NA61 Datasets for T2K [7]

- Consists of exiting hadron multiplicities collected with thin-/replica-target setups:

Thin-Target Data Binned in (p,θ)

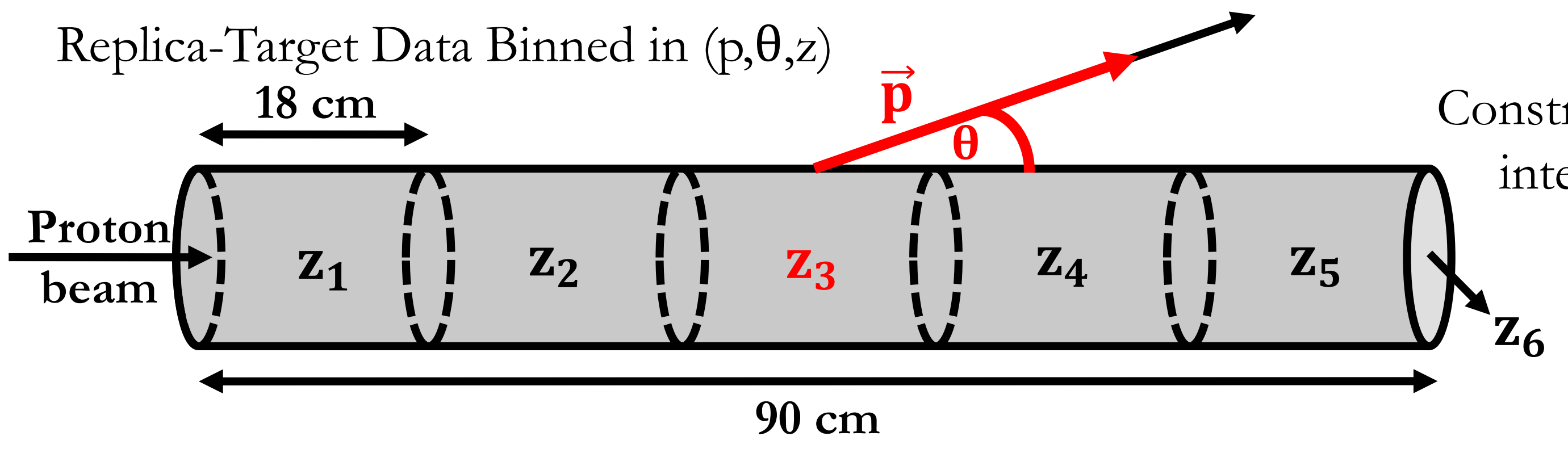
Constrains ~60% interactions



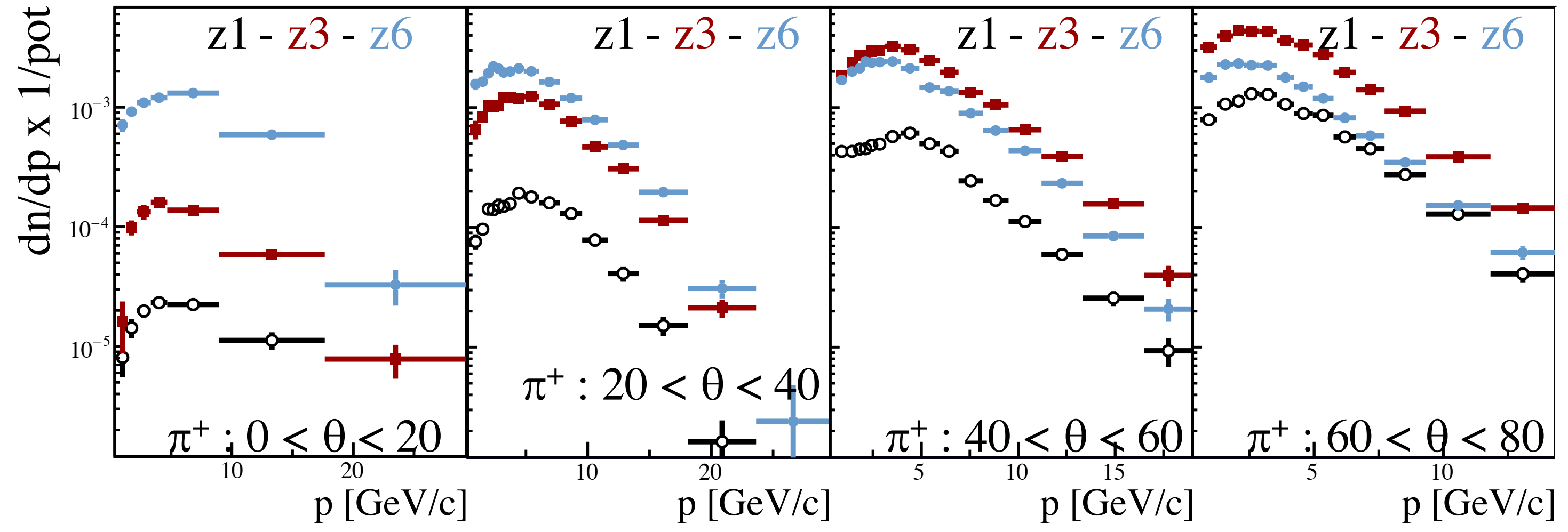
$\pi^\pm$ (2009 replica-target dataset)

Replica-Target Data Binned in (p,θ,z)

Constrains ~90% interactions



Part of the NA61 2009 π^+ Replica-Target Dataset:

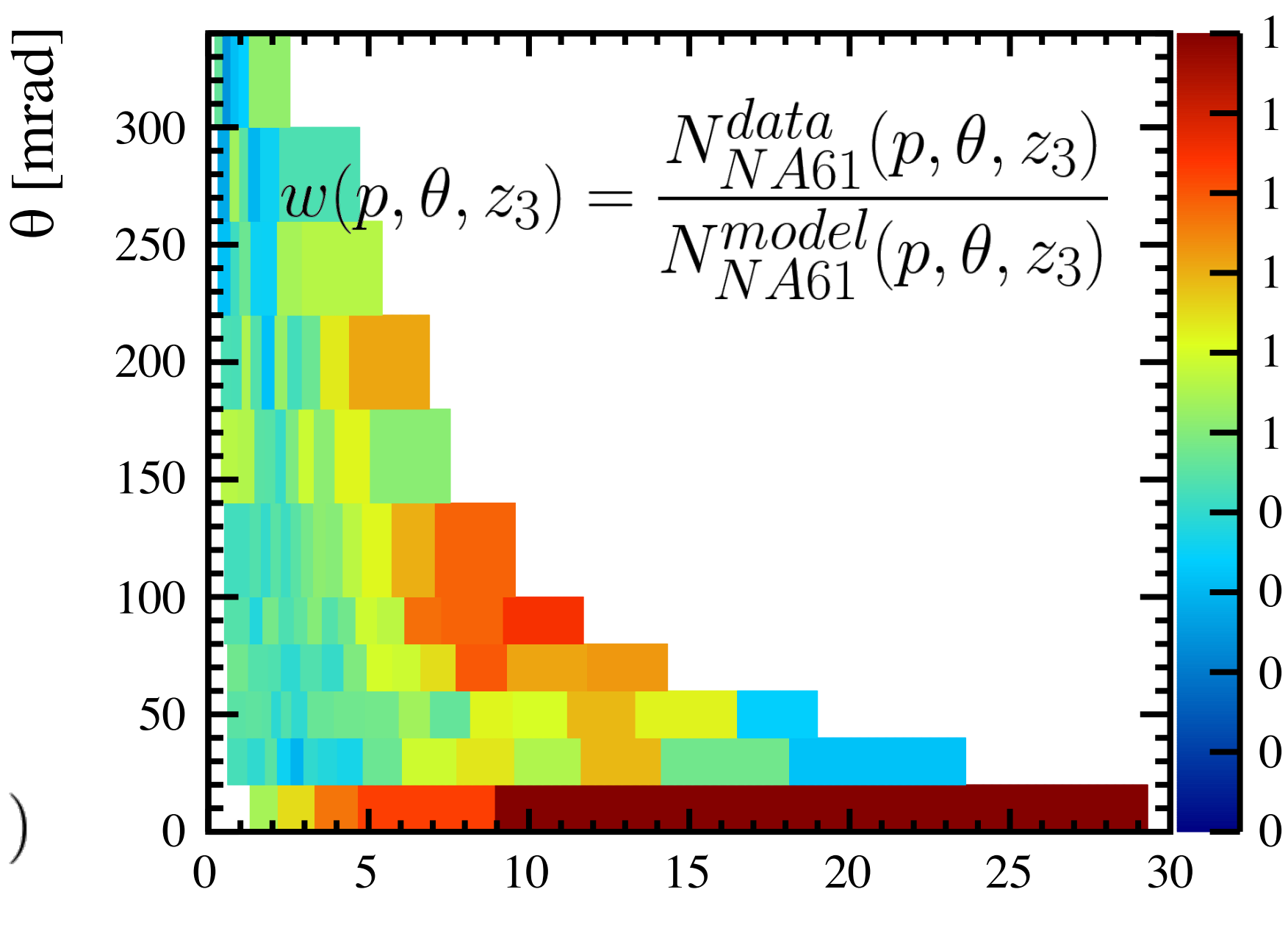


6. Reweighting the T2K Neutrino Flux to NA61 Data (Thin vs. Replica)

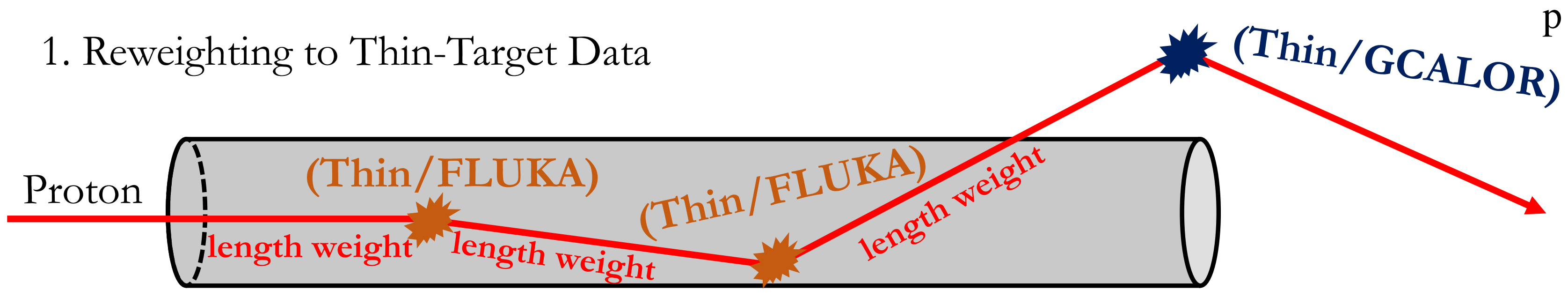
[8,9]

- A weight is applied to the neutrino yield based on its hadronic interaction history
- Two reweighting factors are applied
- The multiplicity weight corrects the neutrino yield based on the momentum and angle (with respect to the beam direction) of the produced ancestor hadrons: $w(p,\theta) = \frac{N^{data}_{NA61}(p,\theta)}{N^{model}_{NA61}(p,\theta)}$
- The interaction length weight corrects the neutrino yield based on the distance travelled by ancestor hadrons through different materials before interacting: $w(p,d) = \frac{\sigma^{data}}{\sigma^{sim}} exp(-\rho d(\sigma^{data} - \sigma^{sim}))$

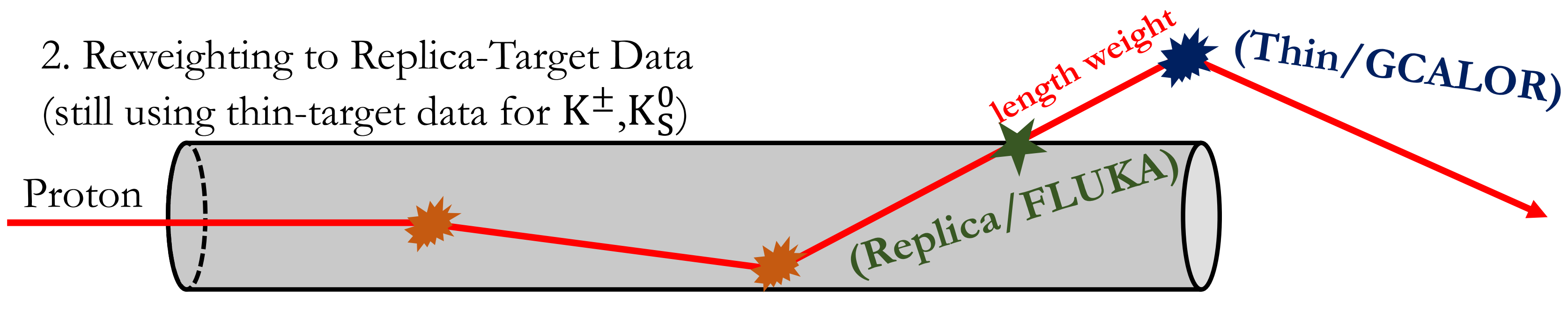
π^+ mult. ratios, bin z3, NA61 REPLICA/FLUKA



1. Reweighting to Thin-Target Data



2. Reweighting to Replica-Target Data
(still using thin-target data for $K^\pm$,K^0_S)



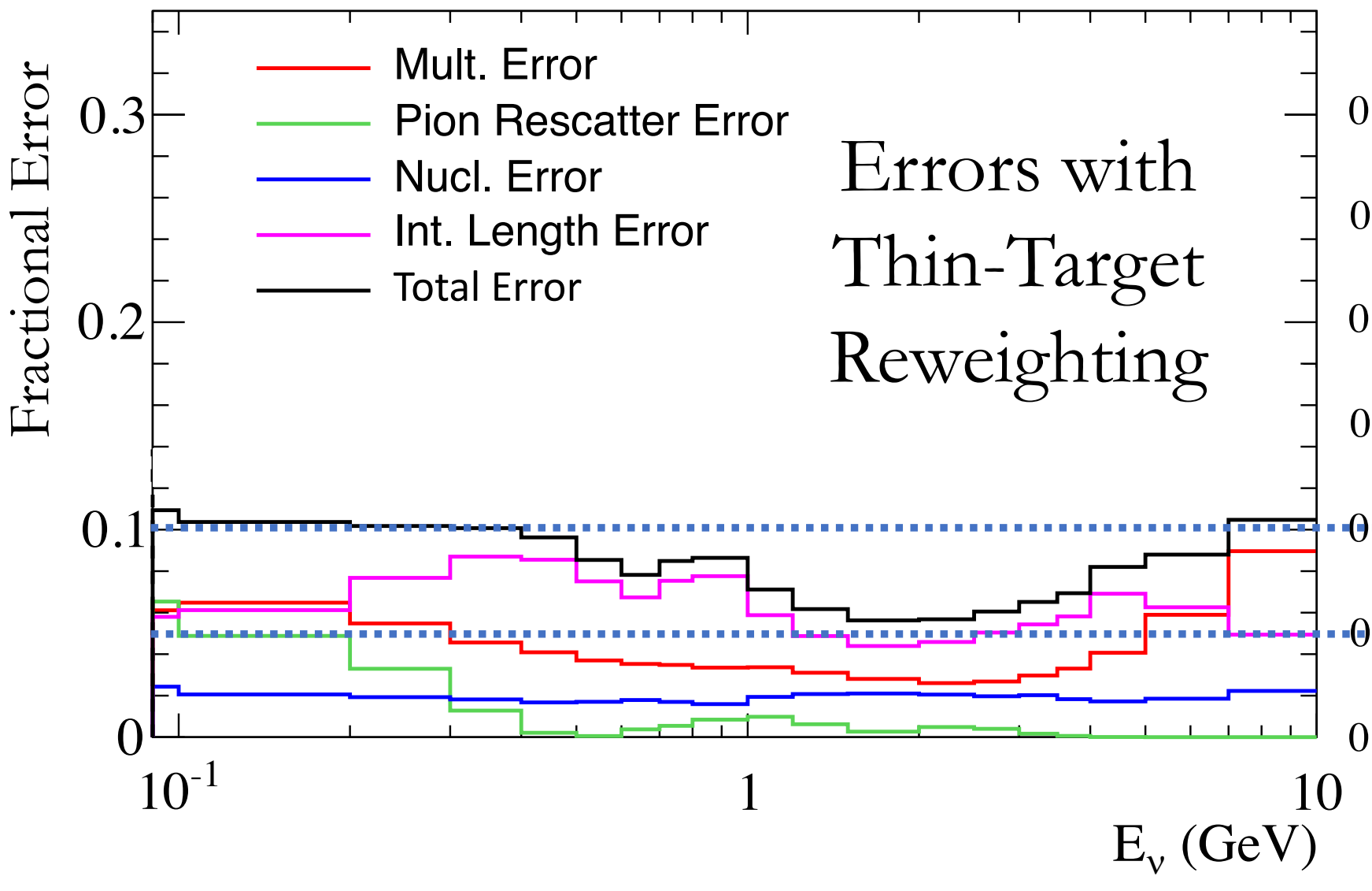
- Hadron production models used by T2K are: FLUKA2011.2c (in-target) and GCALOR (out-of-target)

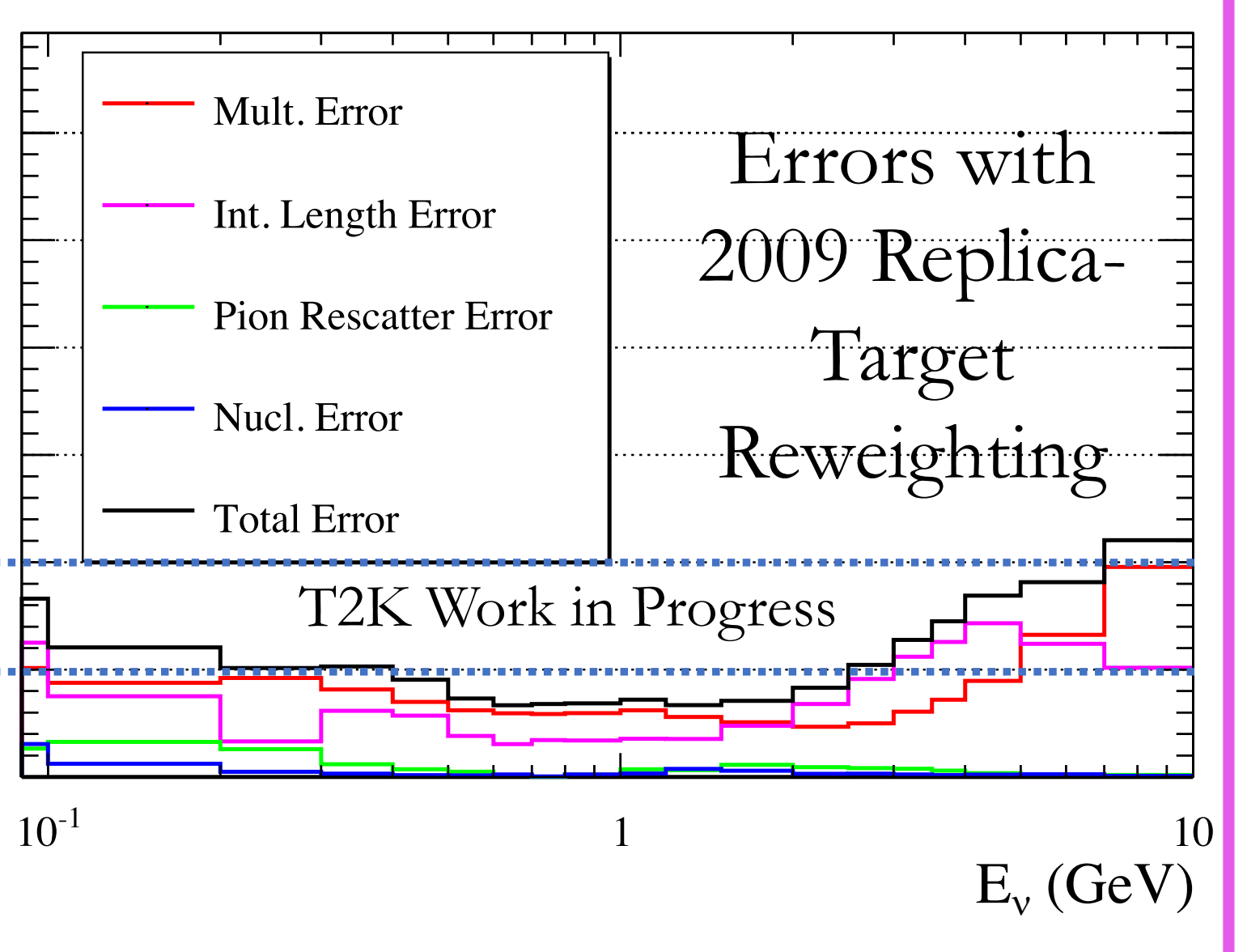
7. T2K Neutrino Flux Uncertainties [8,9]

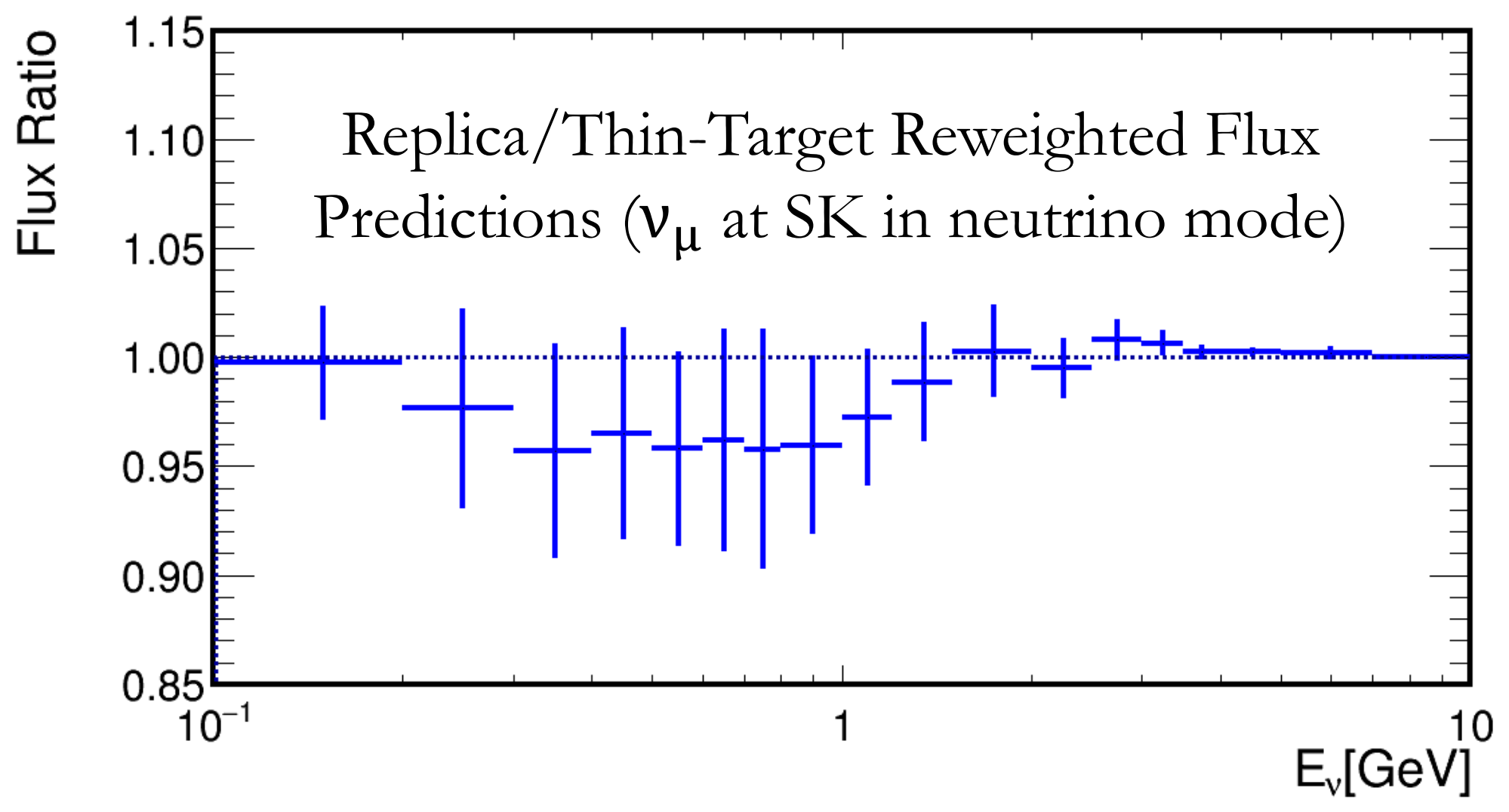
- T2K ν-flux errors mostly come from the hadron interaction model uncertainties:
  - Multiplicity Error (NA61 thin-target and replica-target data)
  - Pion Rescatter Error (HARP multiplicity data)
  - Interaction Length Error (production cross section data)
  - Nucleon Error (secondary baryon interactions multiplicity weights)

Preliminary results suggest error reduction from ~10% to ~5%

SK: Positive Focussing (ν) Mode, ν_μ







NA61 replica-target data favours a lower value for the proton production cross section compared to the thin-target data (refer to [6])

8. References

[1] : K. Abe et al., NIM A659 (2011) 106
[2] : K. Abe et al., PRD 87 (2013) 012001
[3] : K. Abe et al., PRD 87 (2013) 092003
[4] : N. Abgrall et al., NIM A 99-114 (2013)
[5] : A. Haesler, PhD Thesis, University of Geneva, CERN-THESIS-2015-103
[6] : N. Abgrall et al., Eur. Phys. J. C (2016) 76: 617
[7] : L. Zambelli, Neutrino2016 Poster, P1.043 (2016)
[8] : T2K internal documents
[9] : M. Apollonio et al., Nucl.Phys., A821:118–192 (2009)