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

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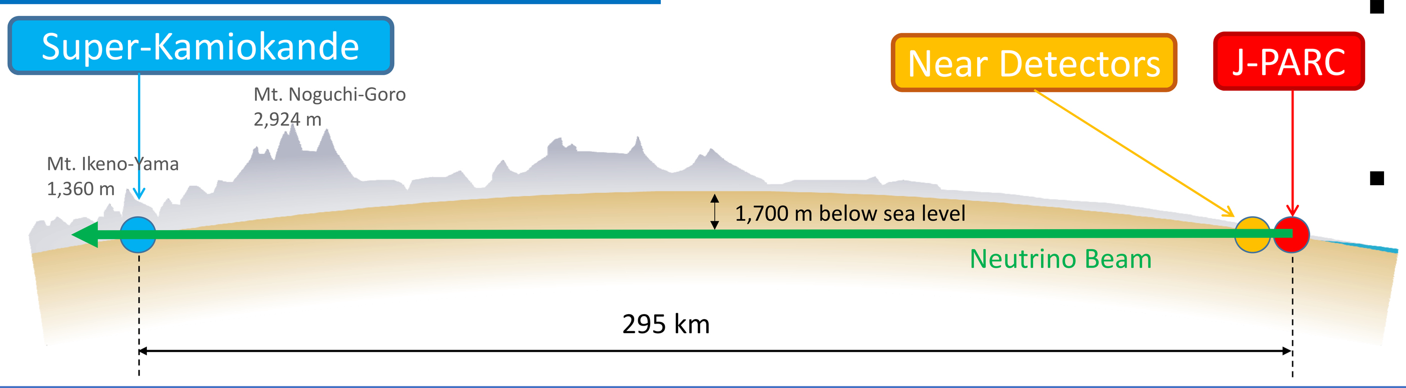
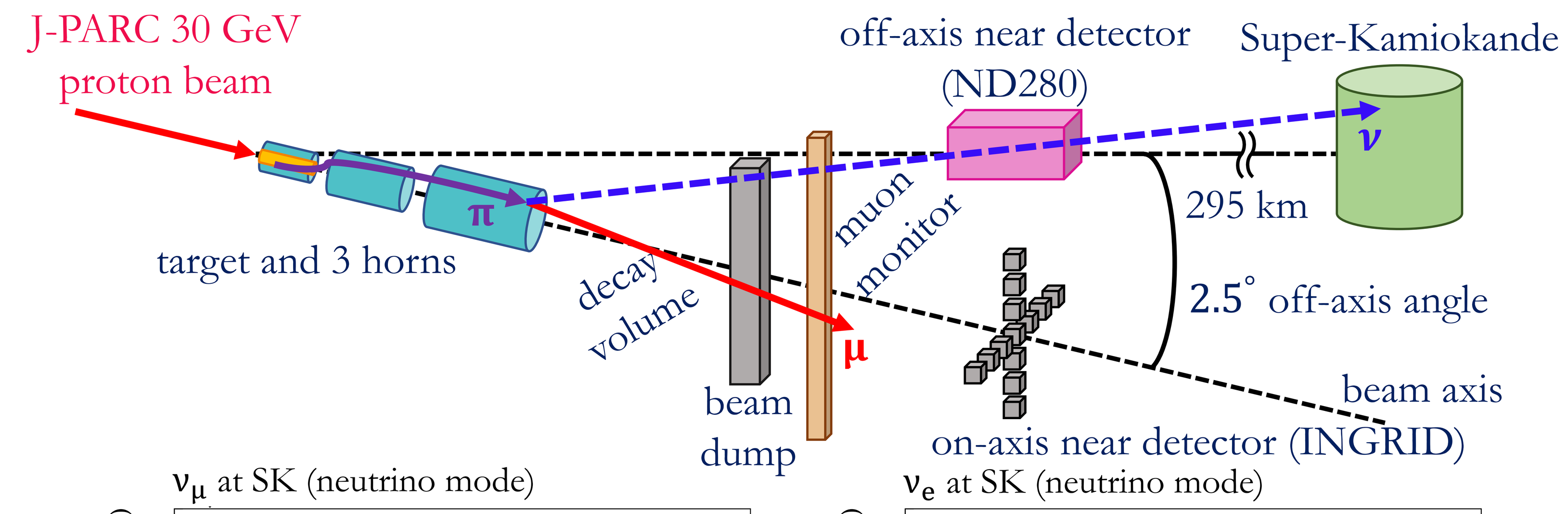
1. The T2K Experiment [1]

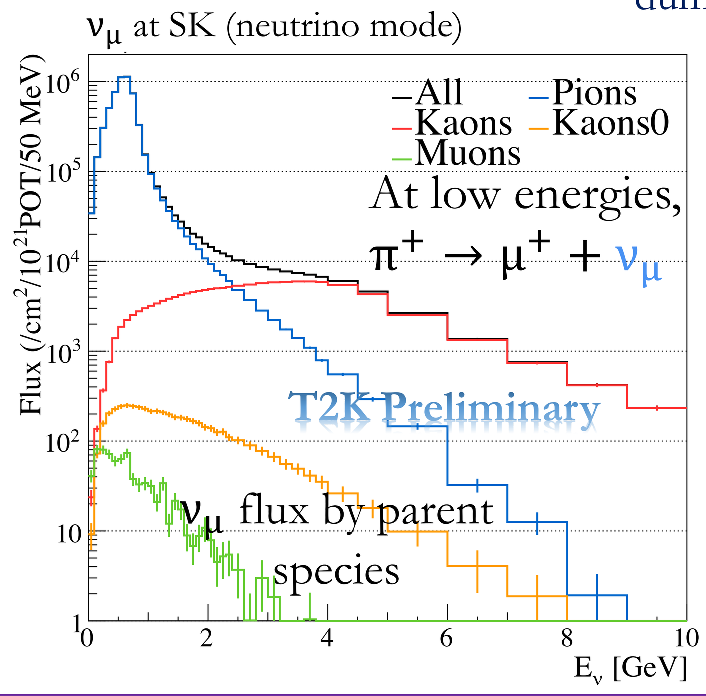


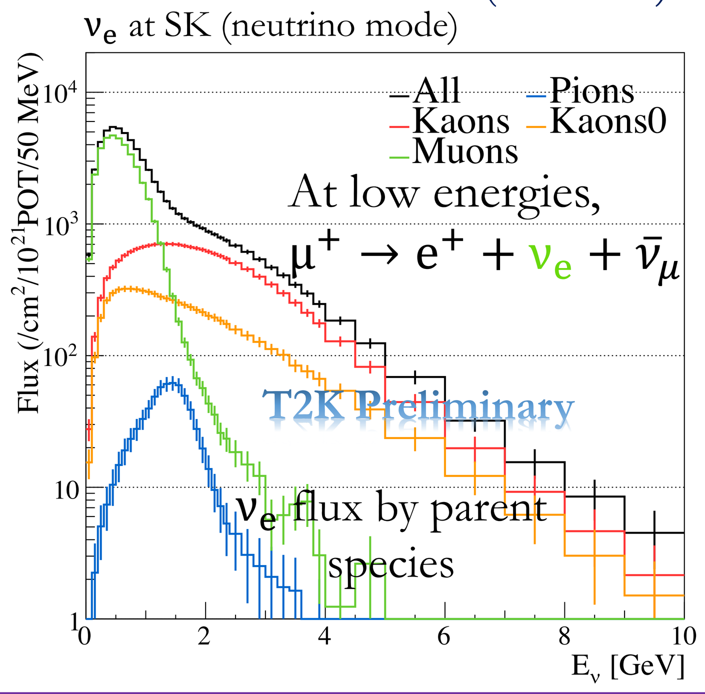
- Long-baseline neutrino oscillation experiment located in Japan
- Measures ν_μ ($\bar{\nu}_\mu$) disappearance and ν_e ($\bar{\nu}_e$) appearance in ν ($\bar{\nu}$) mode

2. The Neutrino Flux [2]

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

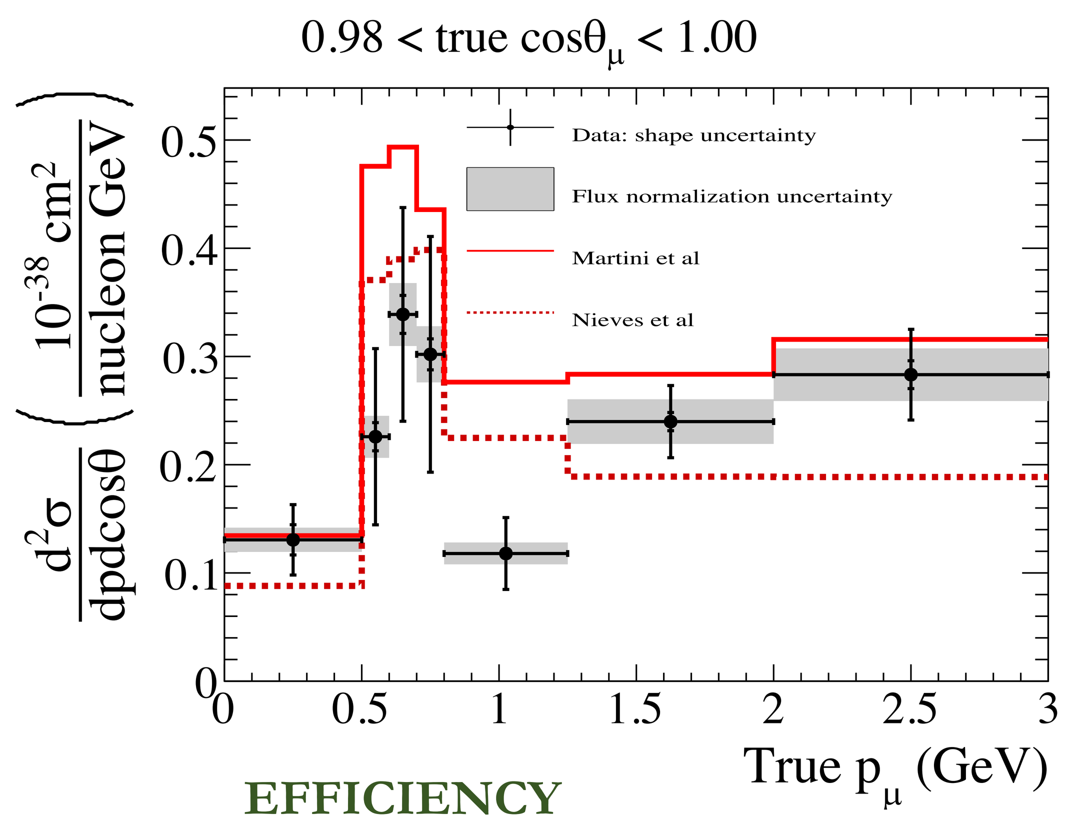






3. Importance of Constraining the Neutrino Flux [3]

- Flux uncertainty is the biggest systematic for neutrino cross section measurements
- Reducing neutrino flux systematics is important for maximising T2K's sensitivity to CP asymmetry (δ_{CP})
- Maximizing the likelihood for the observed number of events at the far detector under the neutrino oscillation hypothesis determines the oscillation parameters:



$$N^{FD,observed}_{\nu_k}(E_i, \theta_{23}, \Delta m^2_{32}, \delta_{CP}, \ldots) = \sum_j^{\text{flavours}} P_{\nu_j \to \nu_k} \times \sum^{\vec{p},\theta} \underbrace{\Phi^{FD}_{\nu_j}(E_i)}_{\text{FLUX}} \times \underbrace{\sigma^{FD}_{\nu_j}(\vec{p}, \theta, E_i)}_{\text{CROSS SECTION}} \times \underbrace{\epsilon^{FD}(\vec{p}, \theta)}_{\text{EFFICIENCY}} \times \underbrace{p^{FD}(\vec{p}, \theta)}_{\text{PURITY}}$$

Constrained flux systematics enter here!

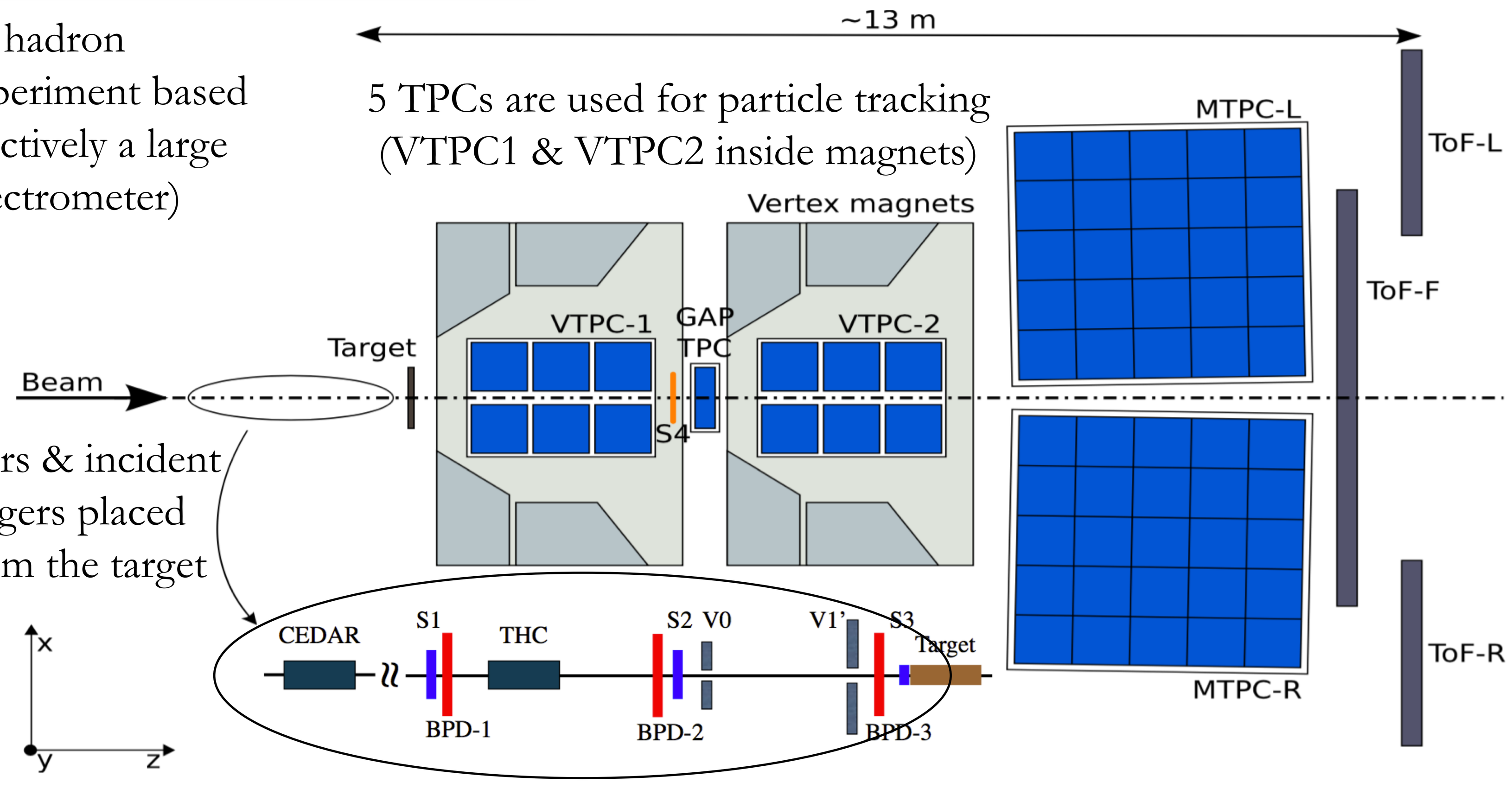
- **New flux reweighting procedure reduces the T2K peak flux uncertainty by ~50%**

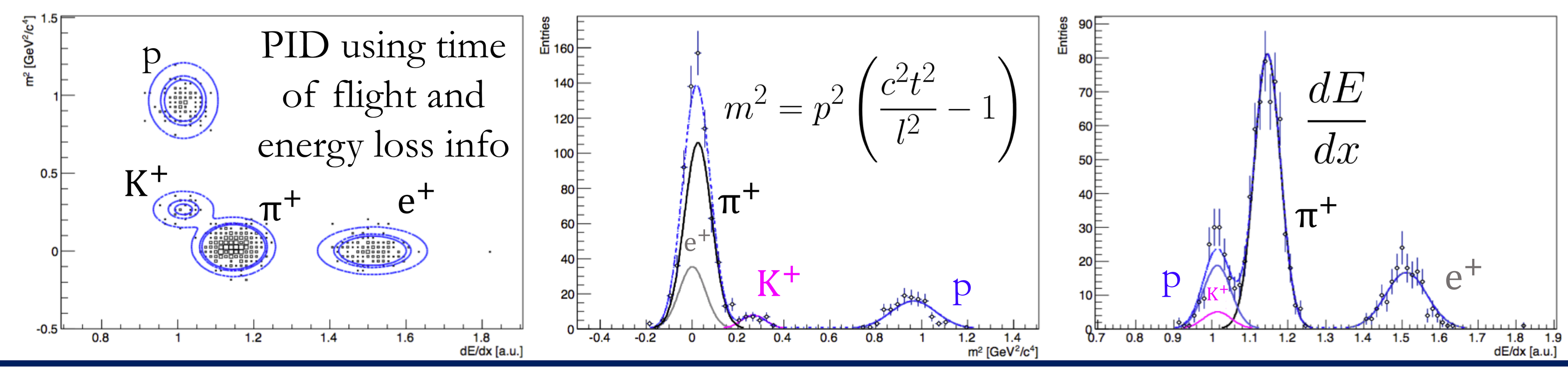
4. The NA61/SHINE Experiment [4,5,6,7]

- 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



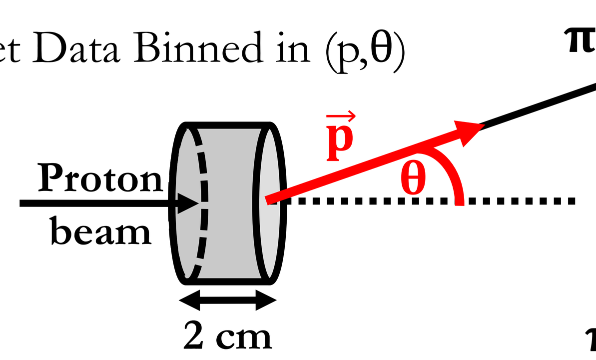


5. NA61 Datasets for T2K [6,7]

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

Thin-Target Data Binned in (p,θ)

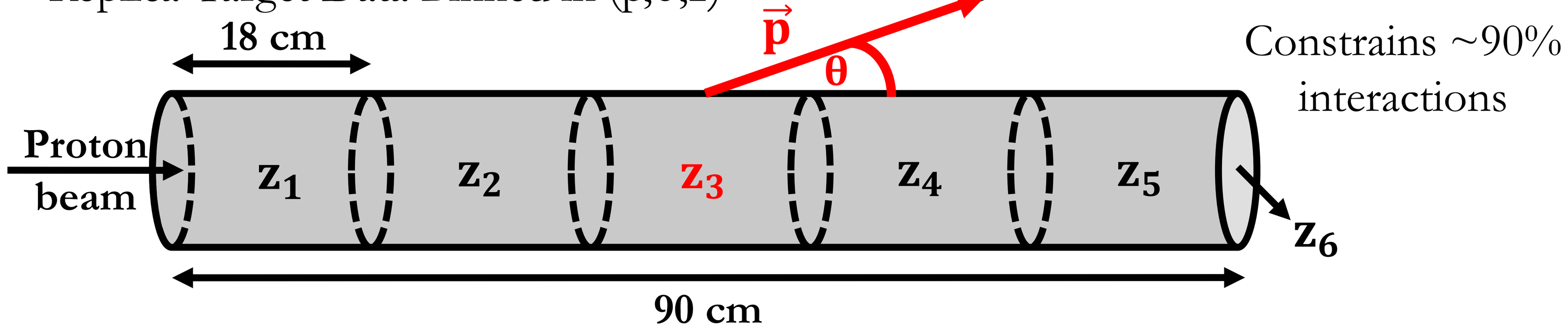
Constrains ~60% interactions



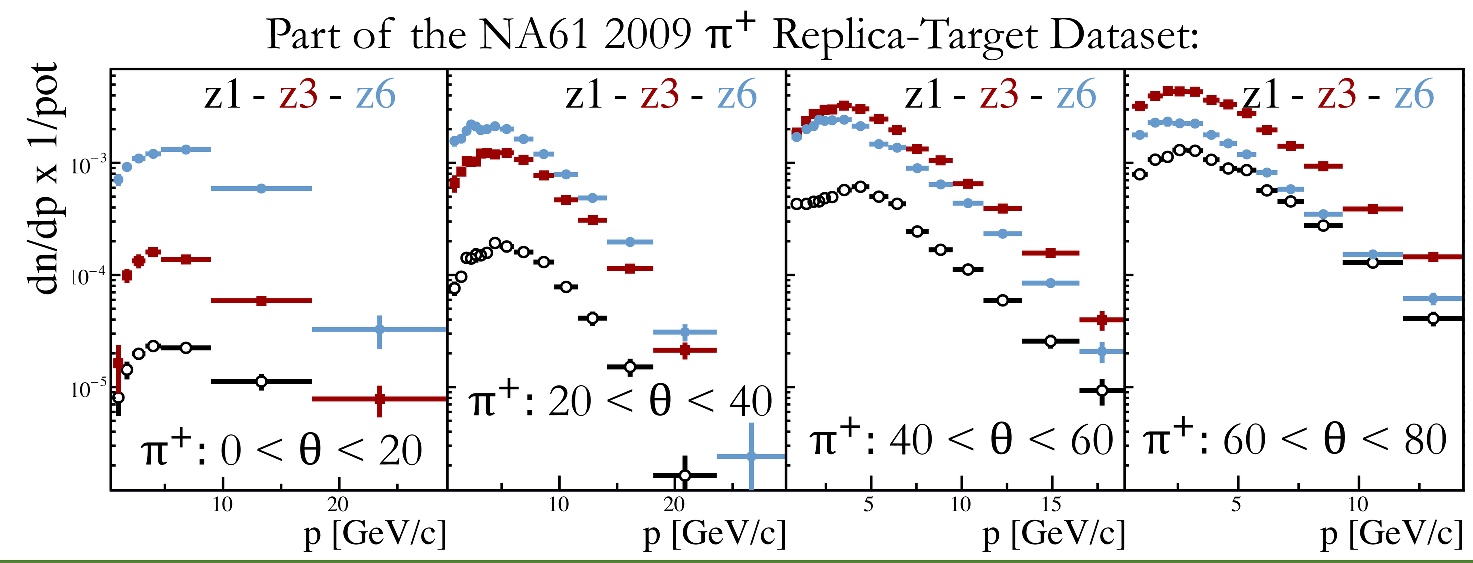
Replica-Target Data Binned in (p,θ,z)

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

Constrains ~90% interactions



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



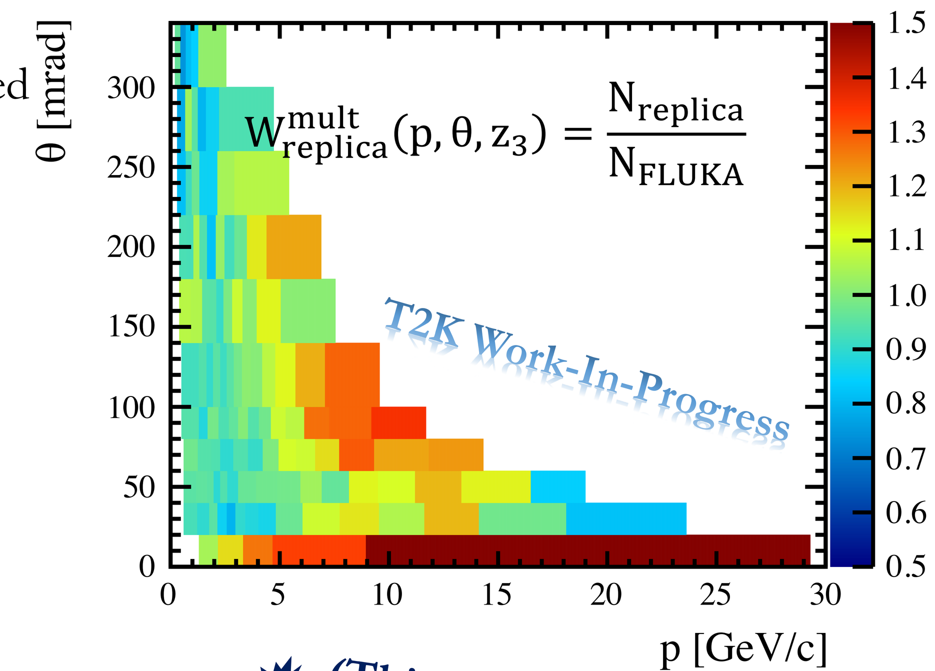
6. Tuning the T2K Neutrino Flux to NA61 Data (Thin vs. Replica) [2]

- A weight is applied to the neutrino yield based on its hadronic interaction history
- The multiplicity weight corrects the neutrino yield based on the momentum and direction of the emitted ancestor hadrons:

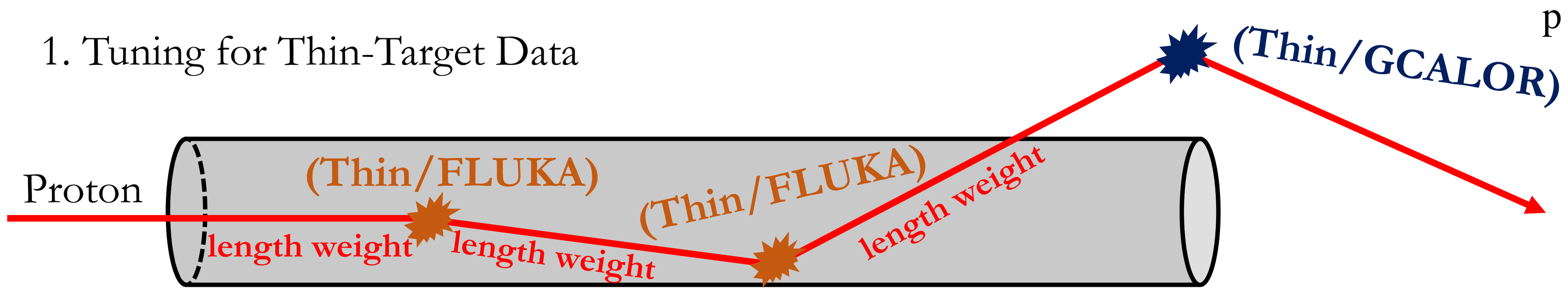
$$W^{mult}_{thin}(p,\theta) = \frac{N_{thin}}{N_{sim}} \quad \& \quad W^{mult}_{replica}(p,\theta,z) = \frac{N_{replica}}{N_{FLUKA}}$$

- The interaction length weight corrects the neutrino yield based on the distance travelled by ancestor hadrons through different materials before interacting:

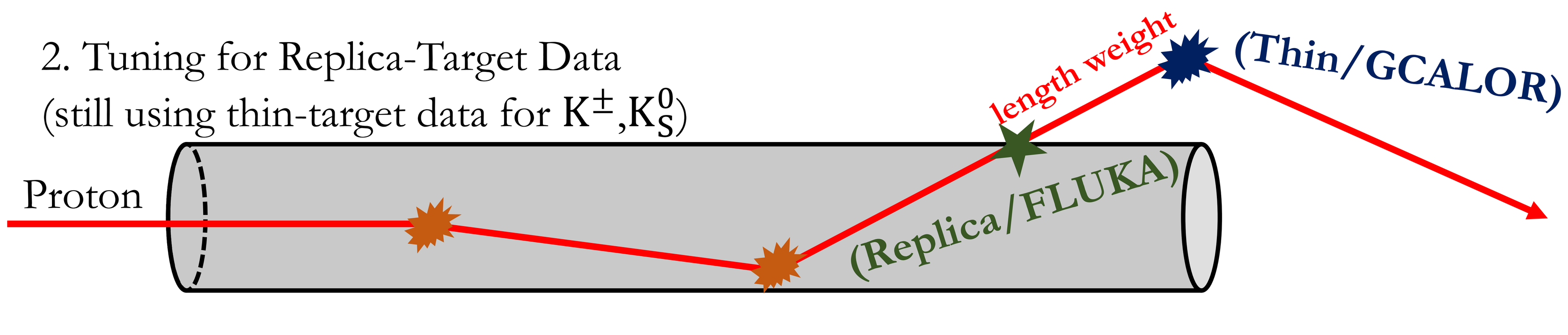
$$W^{length}_{thin}(p,x) = \frac{\sigma_{data}}{\sigma_{sim}} e^{-\rho x(\sigma_{data}-\sigma_{sim})}$$



1. Tuning for Thin-Target Data



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

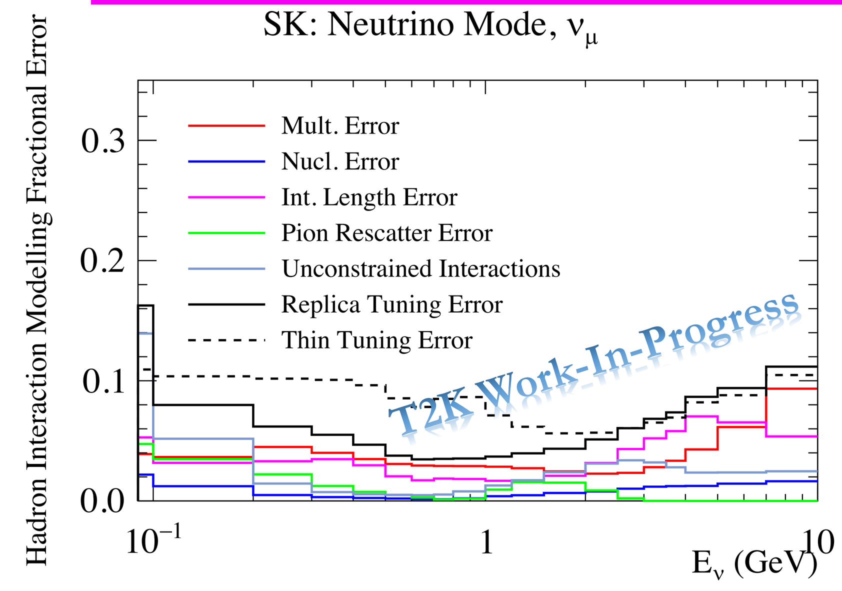


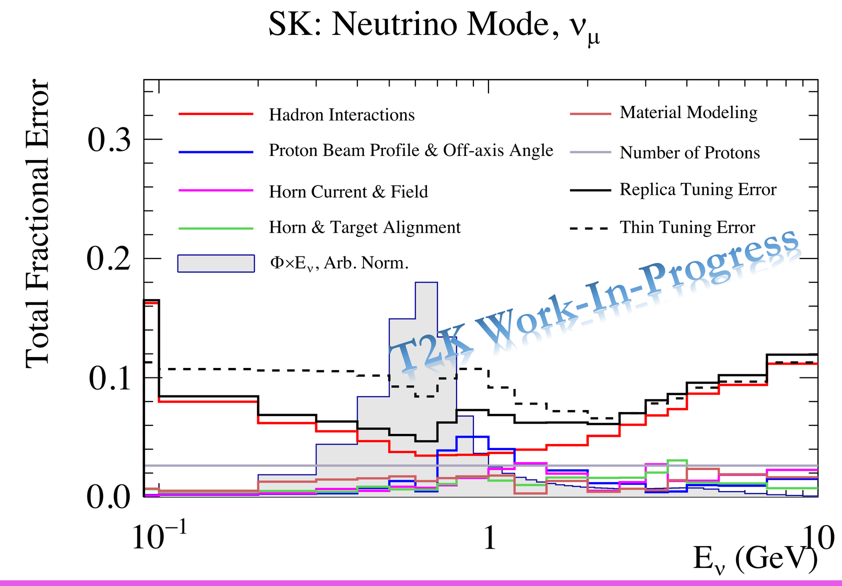
- Hadron production models used by T2K are: FLUKA2011.2c (in-target) and GCALOR (out-of-target)

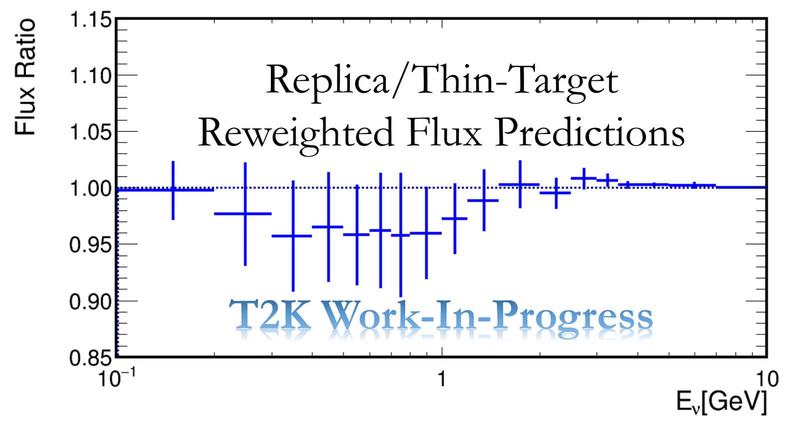
7. T2K Neutrino Flux Uncertainties [2,8,9]

- 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 [8])
  - Interaction Length Error (production cross section data)
  - Nucleon Error (secondary baryon interactions multiplicity weights)

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







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

Further improvements are expected with the inclusion of NA61 2010 replica-target measurements of $\pi^\pm, K^\pm, p$ yields [9]

8. References

[1] : K. Abe et al. (T2K Collab) NIM A659 (2011) 106
[2] : K. Abe et al. (T2K Collab) PRD 87 (2013) 012001
[3] : K. Abe et al. (T2K Collab) PRD 93 (2016) 112012
[4] : N. Abgrall et al. (NA61/SHINE Collab) NIM A 99-114 (2013)
[5] : A. Haesler, CERN-THESIS-2015-103 (2015)
[6] : N. Abgrall et al. (NA61/SHINE Collab) Eur.Phys.J. C76 (2016) no.2, 84
[7] : N. Abgrall et al. (NA61/SHINE Collab) Eur.Phys.J. C76 (2016), 617
[8] : M. Apollonio et al. (HARP Collab) Nucl.Phys. A821:118–192 (2009)
[9] : M.Pavin, CERN-THESIS-2017-233 (2017)