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

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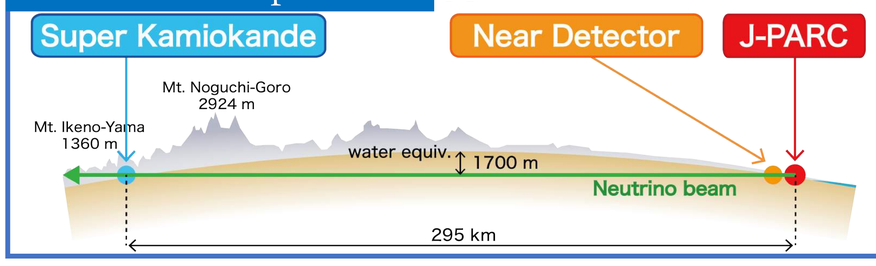
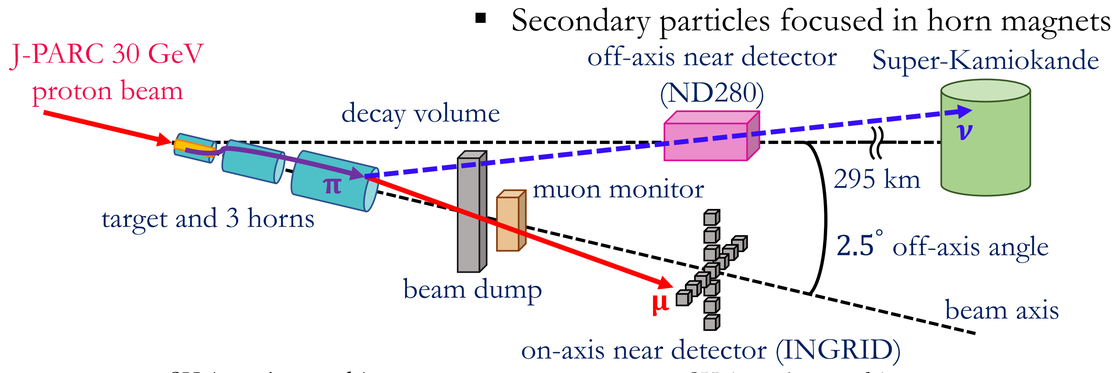
1. The T2K Experiment [1]

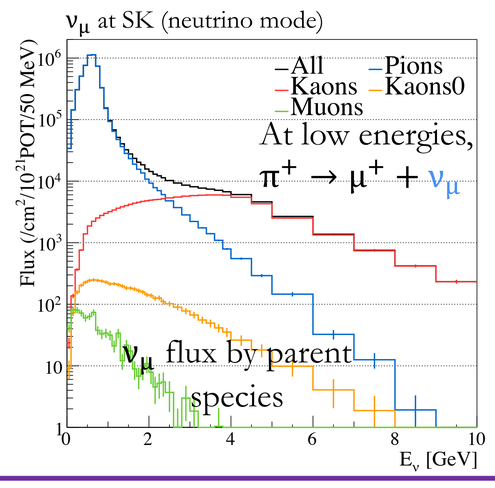


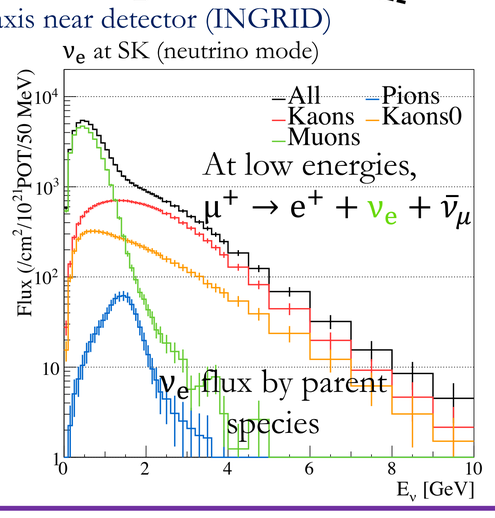
- Long-baseline neutrino oscillation experiment located in Japan
- Measures ν_μ ($\bar{\nu}_\mu$) disappearance and ν_e ($\bar{\nu}_e$) appearance in ν ($\bar{\nu}$) mode

2. The Neutrino Flux [2]

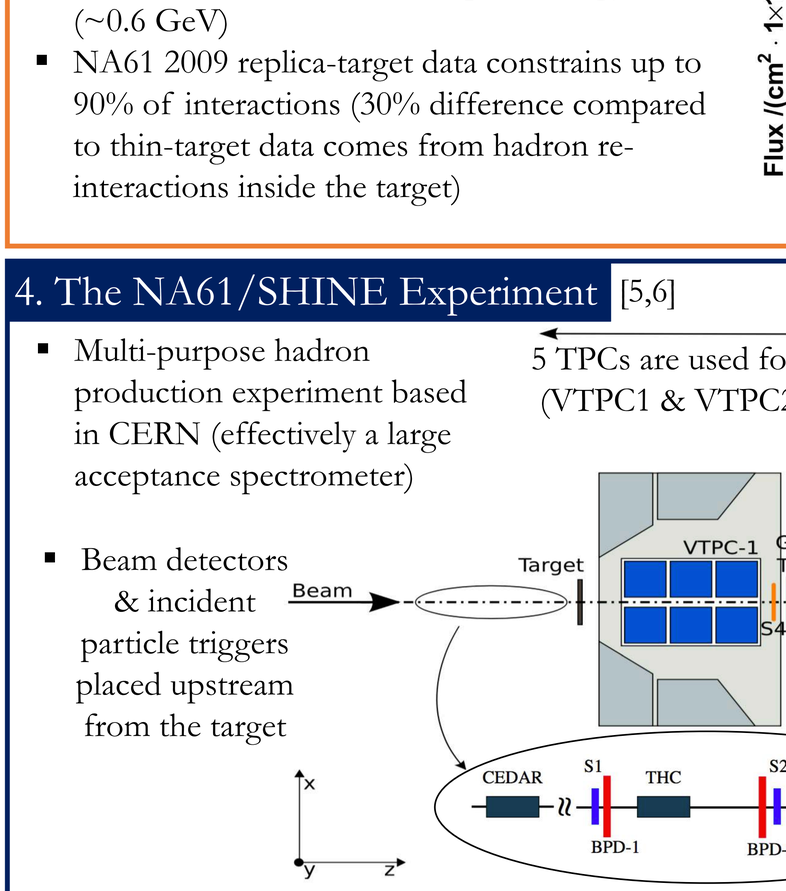
- 30 GeV proton beam colliding with the T2K graphite target (length of 90 cm)
- Secondary particles focused in horn magnets



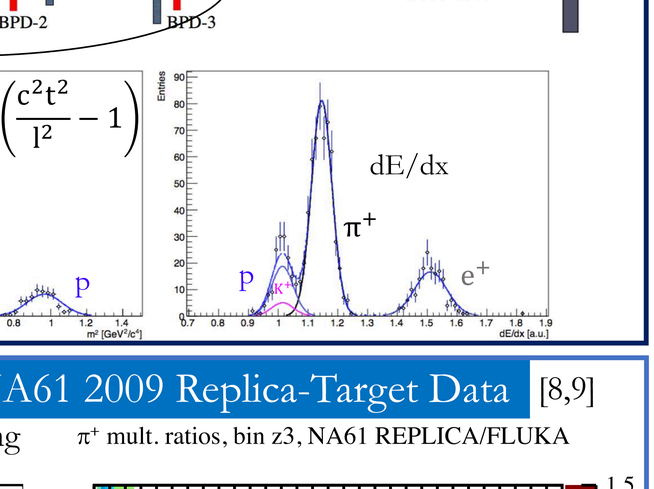




3. Impact on Neutrino Cross-Section Measurements [3,4]



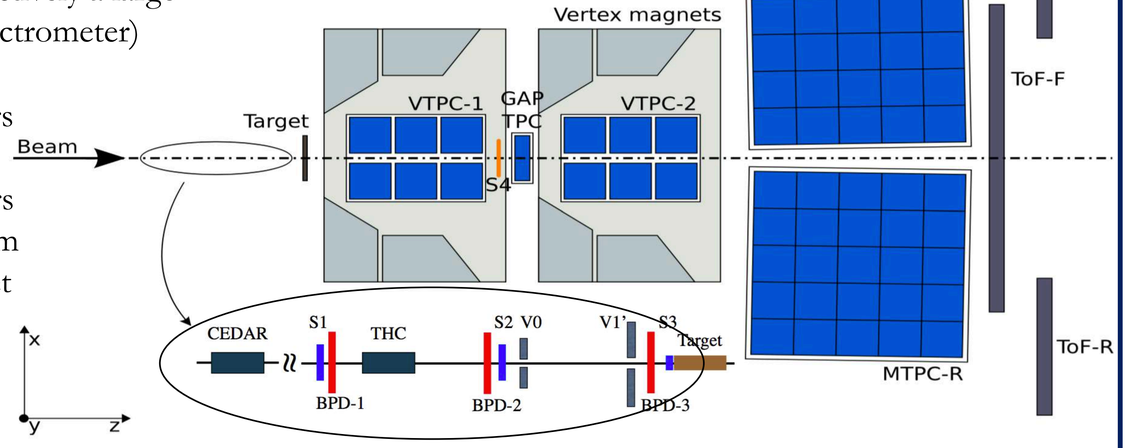
- Reduced flux errors are required for consistency checks between ν interaction models and data
- e.g. CC-inclusive differential ν cross-section on carbon has systematic errors ranging between 10% and 20% depending on muon angle
- For forward-going muons, the systematic errors are dominated by the ν flux errors
- Current errors smear out differences between interaction models, NEUT & GENIE



- The neutrino flux uncertainty is mostly caused by our limited understanding of parent hadron interactions inside the T2K target
- NA61 thin-target data constrains 60% of interactions at T2K neutrino peak energy (~0.6 GeV)
- NA61 2009 replica-target data constrains up to 90% of interactions (30% difference compared to thin-target data comes from hadron re-interactions inside the target)

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

- Multi-purpose hadron production experiment based in CERN (effectively a large acceptance spectrometer)
- Beam detectors & incident particle triggers placed upstream from the target

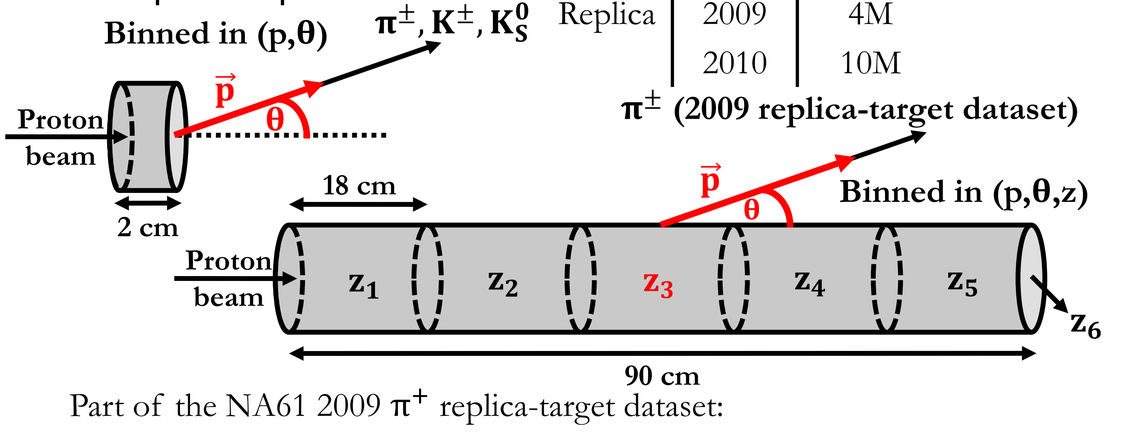


5. NA61 Datasets for T2K [7]

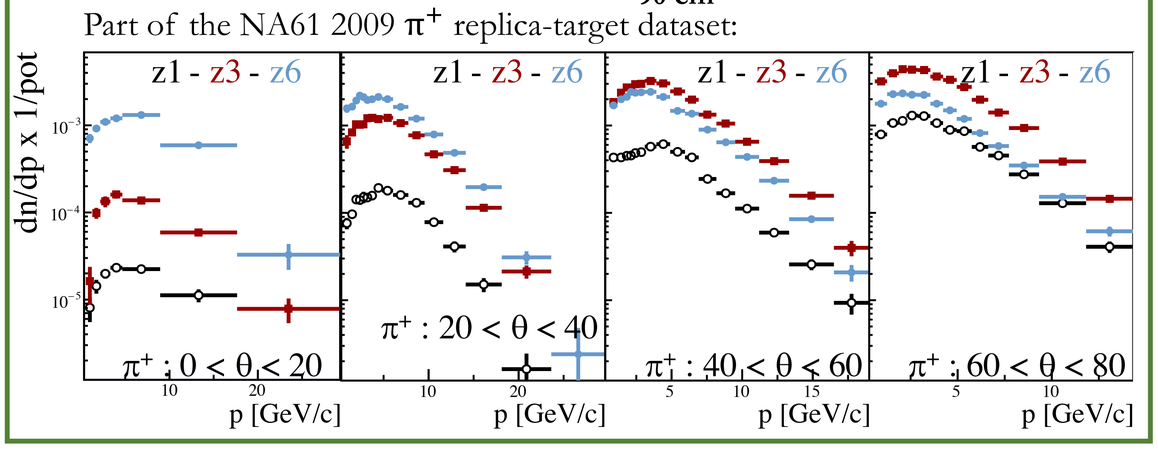
- Consists of exiting hadron multiplicities collected with thin-/replica-target setups

Target	Year	POT
Thin	2007	0.7M
	2009	5.4M

Target	Year	POT
Replica	2007	0.2M
	2009	4M
	2010	10M



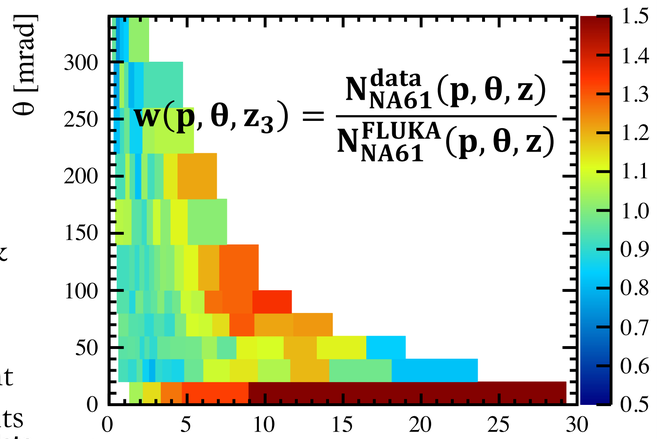
Part of the NA61 2009 π^+ replica-target dataset:



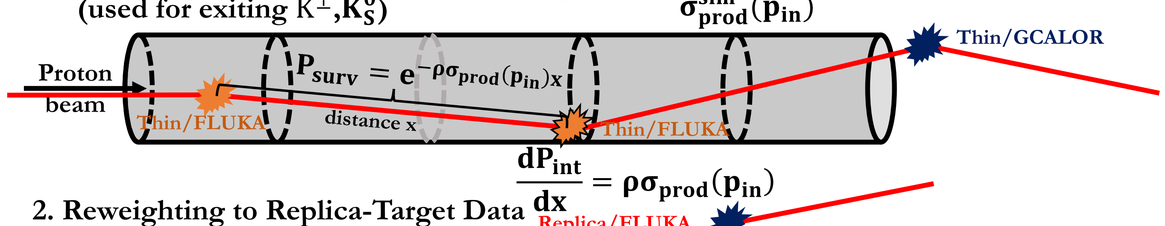
6. Reweighting the T2K Neutrino Flux to NA61 2009 Replica-Target Data [8,9]

- Flux is tuned to NA61 replica-target data by applying weights $\mathbf{w(p,\theta,z)} = \frac{\mathbf{N^{data}_{NA61}(p,\theta,z)}}{\mathbf{N^{sim}_{NA61}(p,\theta,z)}}$ to pions exiting the T2K target
- Thin-target data is still used for out-of-target interactions or the region of pion phase space not covered by replica-target data
- Corrections applied for non-carbon target nuclei & proton momenta less than 30 GeV
- HARP data used for reweighting pion scattering
- The distance travelled by hadrons through different materials is corrected by applying $\mathbf{w(p_{in},d)}$ weights

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

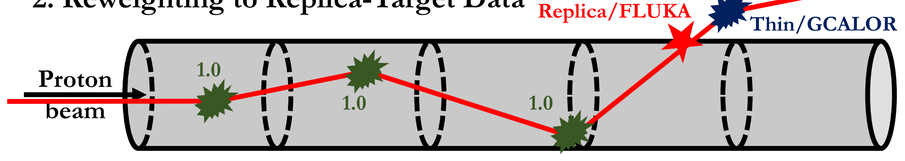


1. **Reweighting to Thin-Target Data (used for exiting $K^\pm$,K^0_S)** $\mathbf{w(p_{in},d)} = \frac{\sigma^{data}_{prod}(p_{in})}{\sigma^{sim}_{prod}(p_{in})} e^{-\rho\left(\sigma^{data}_{prod}(p_{in})-\sigma^{sim}_{prod}(p_{in})\right)x}$



$$\frac{dP_{int}}{dx} = \rho\sigma_{prod}(p_{in})$$

2. **Reweighting to Replica-Target Data**

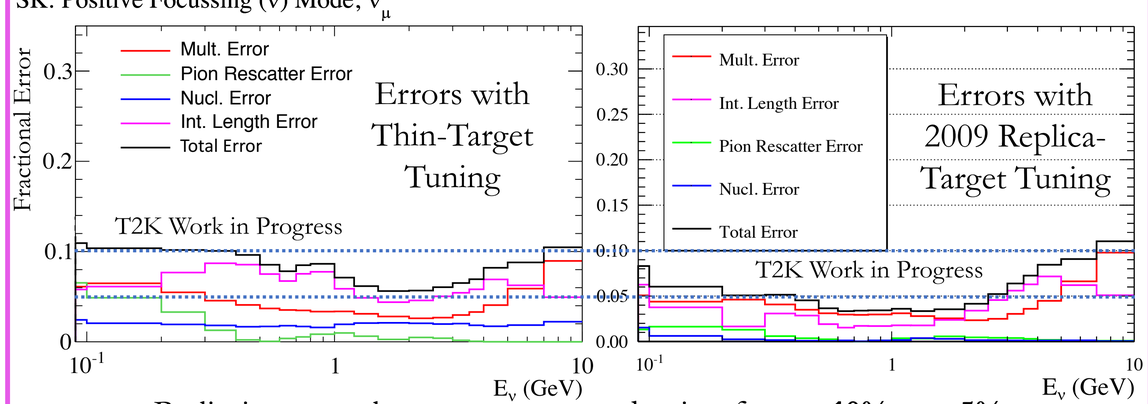


Hadron Production Models: FLUKA2011.2c (in-target) & GCALOR (out-of-target)

7. T2K Neutrino Flux Uncertainties [8,9]

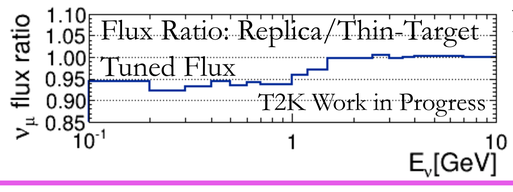
- Most of the T2K ν-flux error comes from hadron interaction model uncertainties
- Multiplicity Error: mostly comes from the NA61 covariance matrices (both 2009 replica-target and thin-target covariance matrices are used for generating multiplicity throws)
- Pion Rescatter Error (estimated with HARP data)
- Interaction Length Error (propagated from production cross-section errors)
- Nucleon Error (secondary baryon production and tuning)

SK: Positive Focussing (ν) Mode, ν_μ



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

NA61 & T2K use different beam profiles and slightly different target densities → the effect of this difference on flux errors is still being studied!



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)