T2K neutrino beam flux prediction with improved MC tuning using latest NA61/SHINE hadron production data

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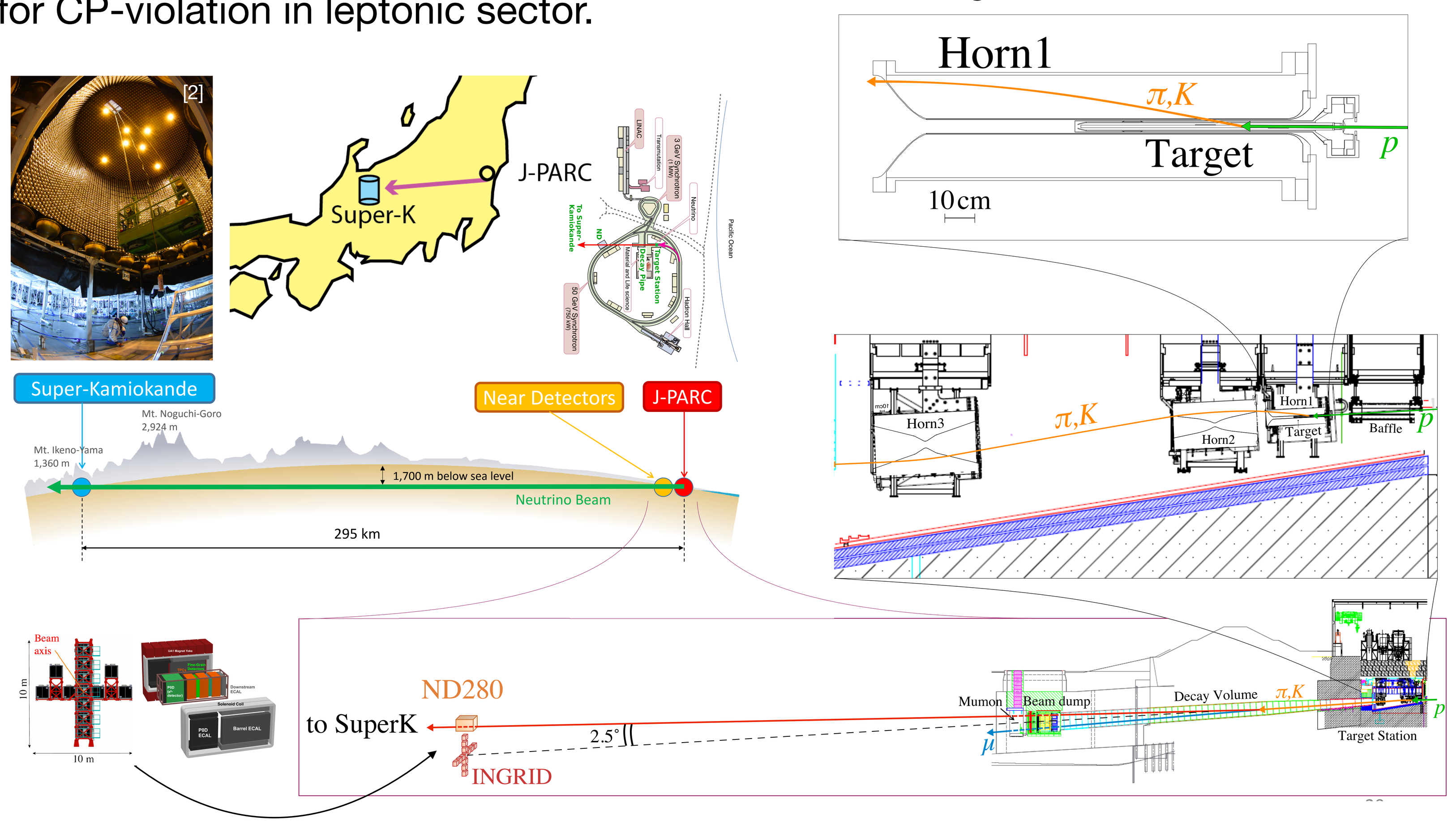
1. The T2K Experiment [1]

Study neutrino oscillation with accelerator neutrinos. Goal: 3σ evidence for CP-violation in leptonic sector.

How to generate a neutrino beam:



2. Neutrino flux prediction [3]

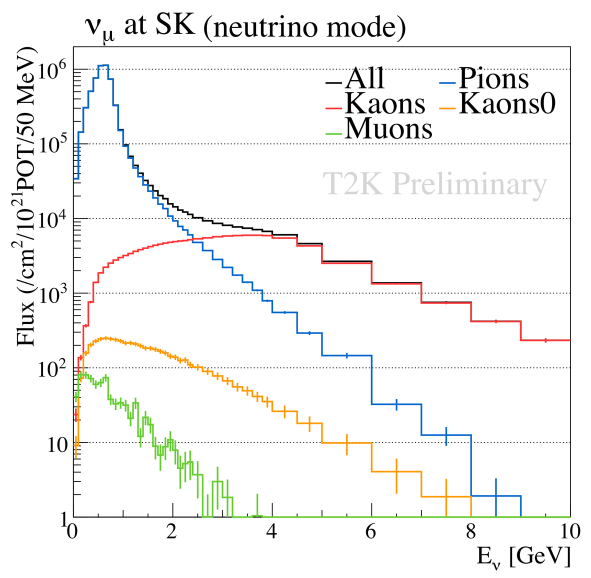
Protons produce π,K mesons from hadronic interactions in target → simulate with FLUKA.

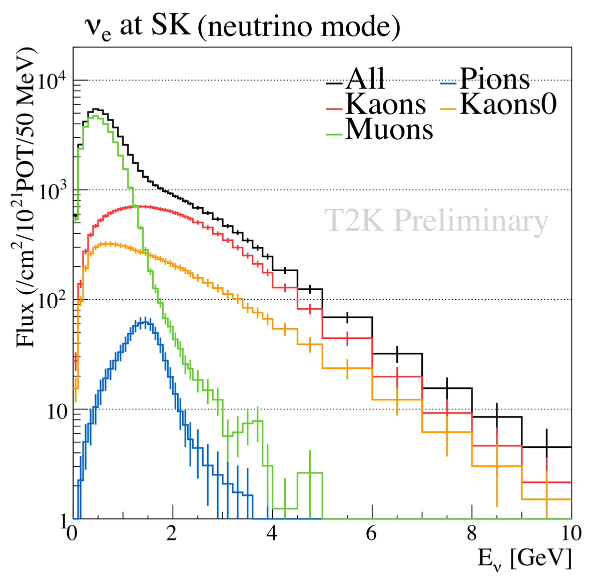
Outgoing mesons are focused with magnetic horns and produce neutrinos in decay tunnel → simulate with Geant3.

Afterwards apply weights to **tune** each simulated hadronic interaction to experimental data (mostly NA61).

Why improve flux?

- Flux is leading systematic for xsec measurements.
- SK/ND280 flux covariance matrix essential for oscillation analysis.



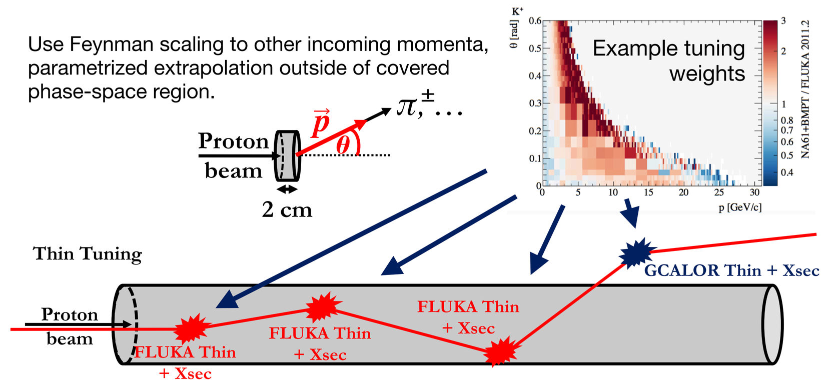


Thin tuning (conventional method)

Differential multiplicities binned by (p,θ) and outgoing PID, for protons hitting 2 cm thin target.

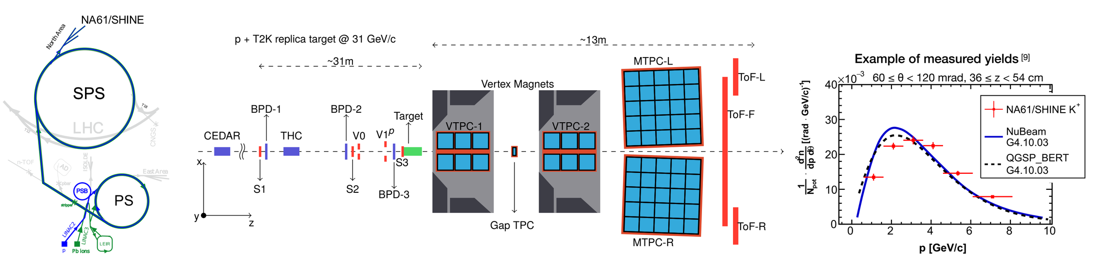
For each interaction apply DATA/MC weights of multiplicities. For interaction length (~cross section) also apply attenuation weights e^{-L/λ_I}.

Use Feynman scaling to other incoming momenta, parametrized extrapolation outside of covered phase-space region.



3. NA61 measurements for T2K

NA61/SHINE: hadron production experiment [4] at CERN. Momentum reconstruction with TPCs in superconducting magnets, PID with dE/dx and time of flight. Multiple datasets were collected specifically for T2K.



Beam	Target	Year	Stat (10^6)	Outgoing PID	Usage at T2K
protons at 31 GeV/c	Thin (2cm)	2007 [5]	0.7	$\pi^\pm, K^\pm, K^0_S, \Lambda$	past
		2009 [6]	5.4	$\pi^\pm, K^\pm, p, K^0_S, \Lambda$	in use for K, p
	T2K replica (90cm)	2007 [7]	0.2	$\pi^\pm$	–
		2009 [8]	2.8	$\pi^\pm$	in use for $\pi^\pm$ [10,11]
		2010 [9]	10	$\pi^\pm, K^\pm, p$	*this work*

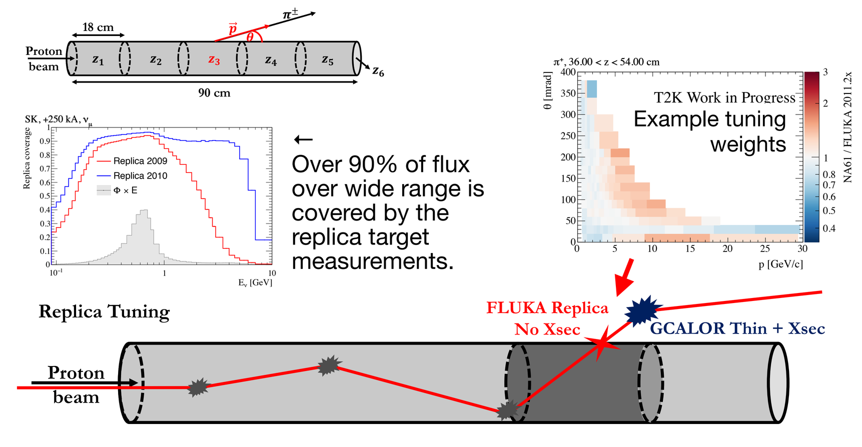
Most notably, the replica tuning method is extended to $K^\pm$ and p

Replica tuning (recently developed)

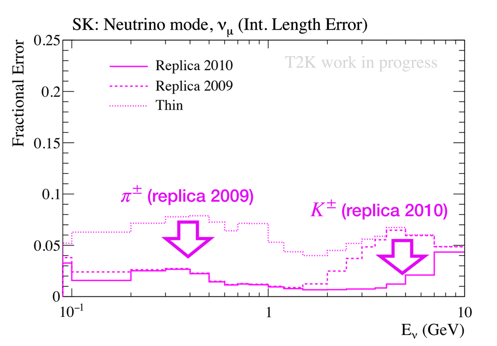
Outgoing particle yields binned by (z,p,θ) and PID for protons interacting with full size (90 cm) replica of T2K target.

Apply DATA/MC weights for exiting point only.

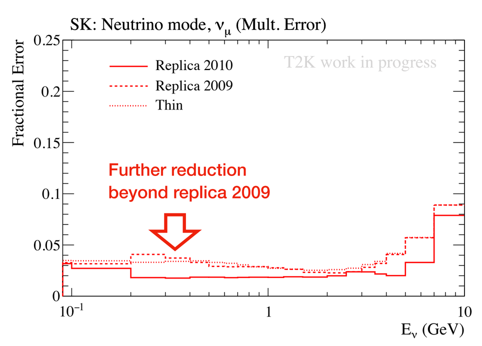
For uncovered particles and phase-space regions use thin tuning.



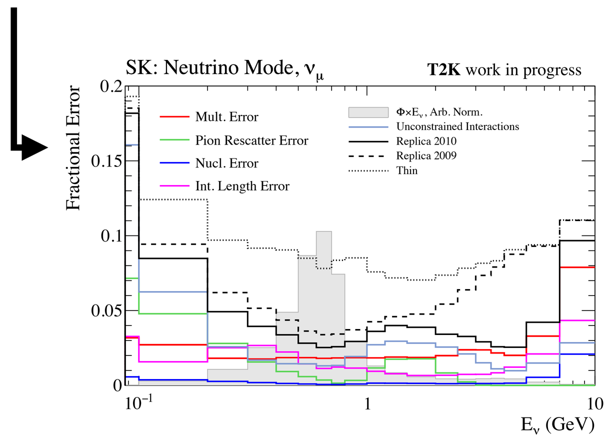
4. Uncertainties on hadronic interactions



Significant reduction of interaction length uncertainty with replica tuning. (because no tuning of interactions in target) 2010 dataset newly includes K±.



Increased statistics in 2010 dataset further reduce uncertainty on number of produced pions.



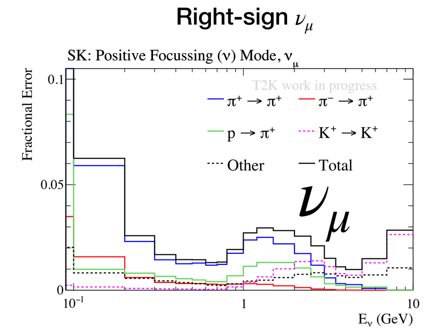
Total uncertainty on hadronic interactions down to 4% level for wide energy range.

5. Unconstrained interactions

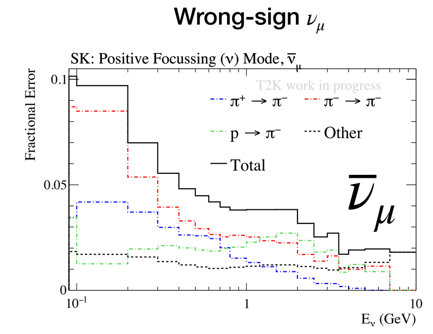
Even after replica tuning, and using available thin target measurements, some interactions cannot be assigned an uncertainty from data.
Conservative error to cover MC model differences is assigned in (x_F, p_T) space.

In particular few-GeV $\pi^\pm$, K scattering on Al (horns) and Fe (walls) outside the target are dominant contribution to wrong sign flux unc.
These can cause ν_e/ν_μ uncorrelated errors (problematic for precise measurement of leptonic CP violation) and need to be reduced in future with new hadron production measurements.

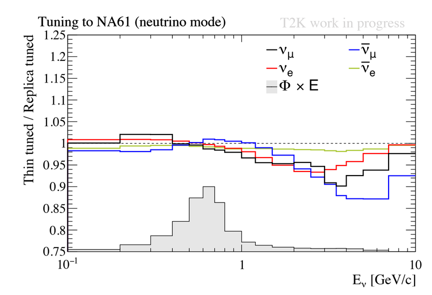
Right-sign ν_μ



Wrong-sign ν_μ



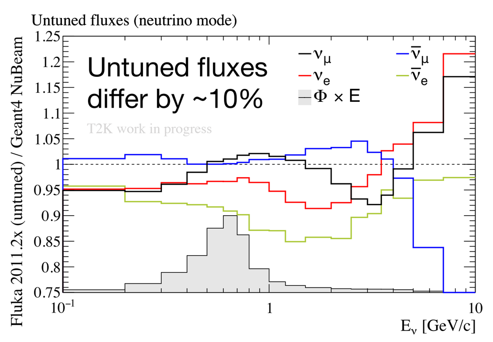
6. Compatibility with thin tuning



Good agreement near flux peak, for higher energies discrepancy is observed.

Parametrized fits suggest origin is re-scattering model of very forward π±, K± in *thin* tuning. We think replica tuning is more reliable.

7. Consistency checks using fake data



Treat different MC generator (GEANT4*) as fake "truth" and attempt to tune FLUKA to it using the two methods.

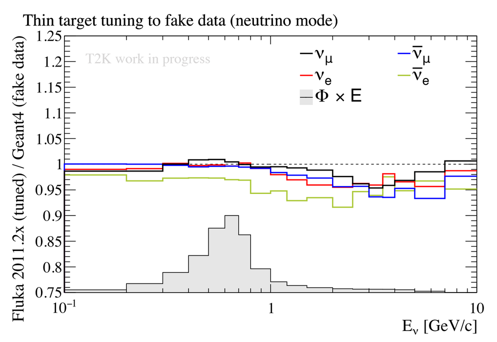
Finally compare to "true" neutrino flux.

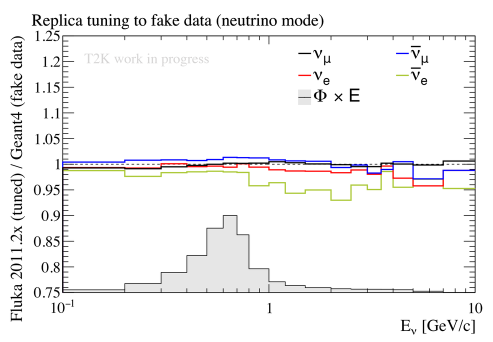
* NuBeam physics list, essentially FTFP_BERT

After thin tuning good match near flux peak. Discrepancy at high E_ν mostly due to missing meson scattering data.

Replica tuning shows much better agreement.

Note: ν_e-bar is mostly thin tuning because of neutral kaons.

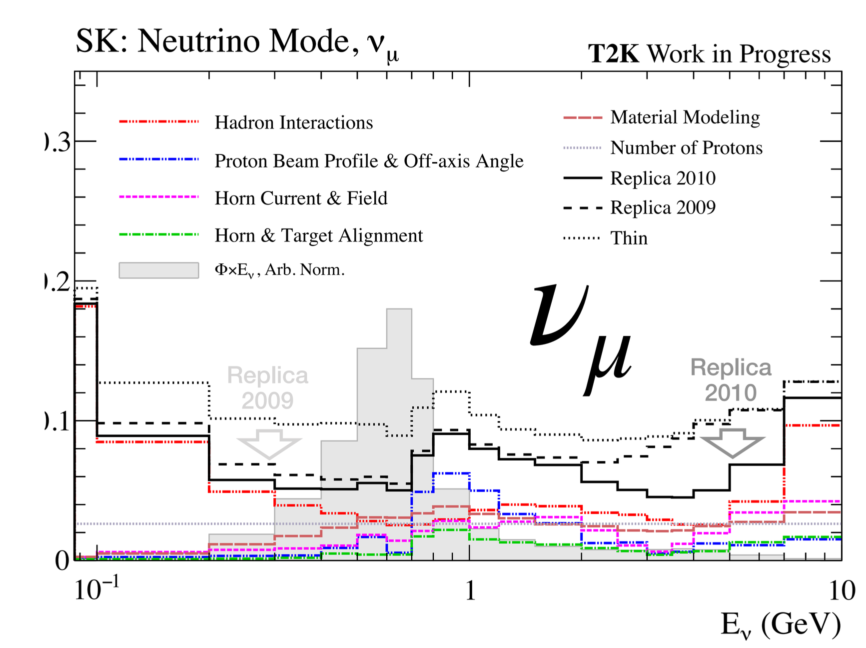


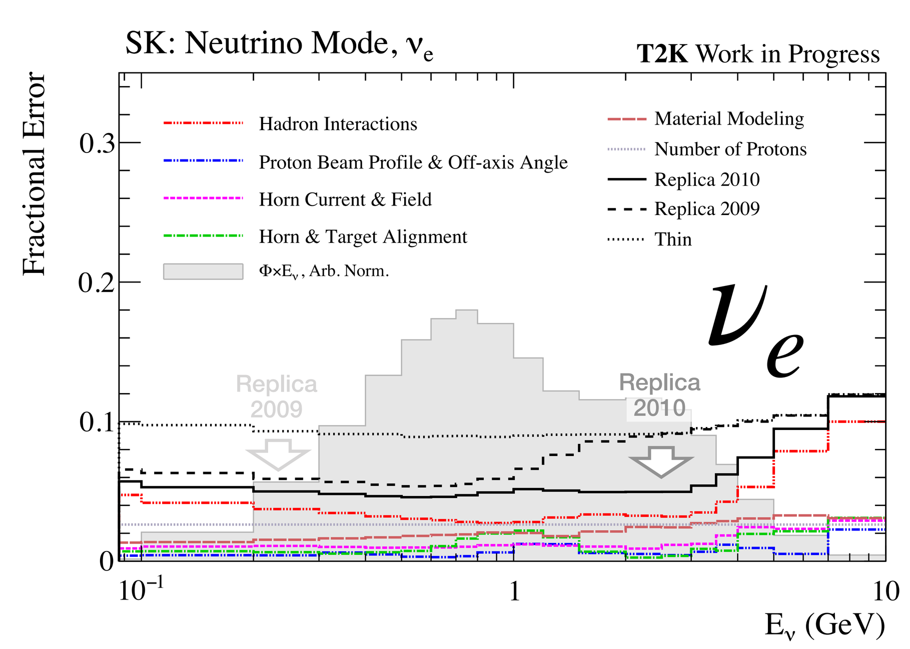


8. Total uncertainty on flux & summary

Final uncertainty on flux goes down from 9–12% with thin tuning to 5–7% with replica tuning, comparable to non-hadronic systematics. With most recent 2010 replica measurements, these low errors are achieved up to high energies, will be used in the upcoming oscillation analysis.

For further reduction need meson scattering data from future hadron production experiments. Studies ongoing for reduction of other systematics like proton beam profile and proton number uncertainty.





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