T2K Future Flux Improvements and Possible Further Hadron Production Measurements

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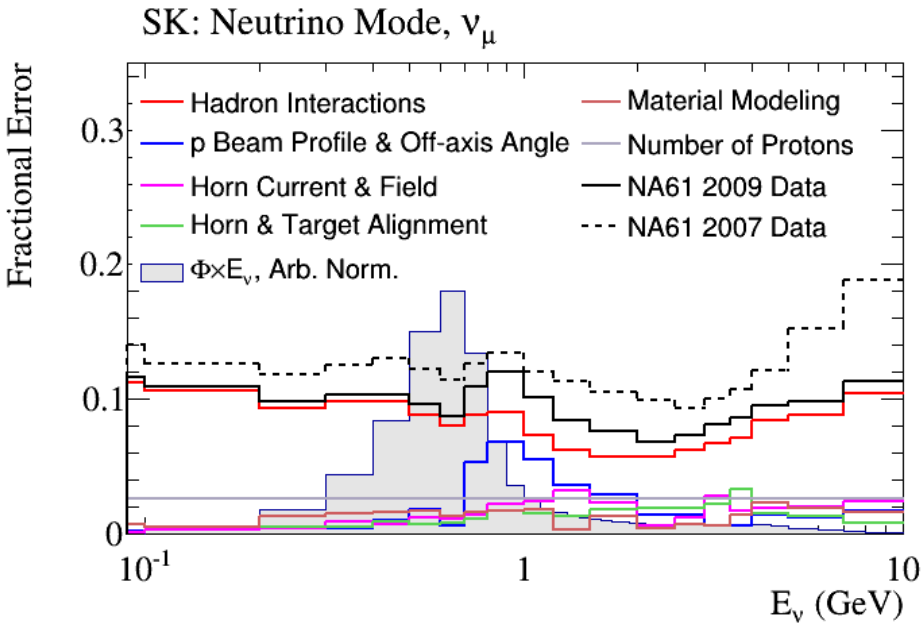
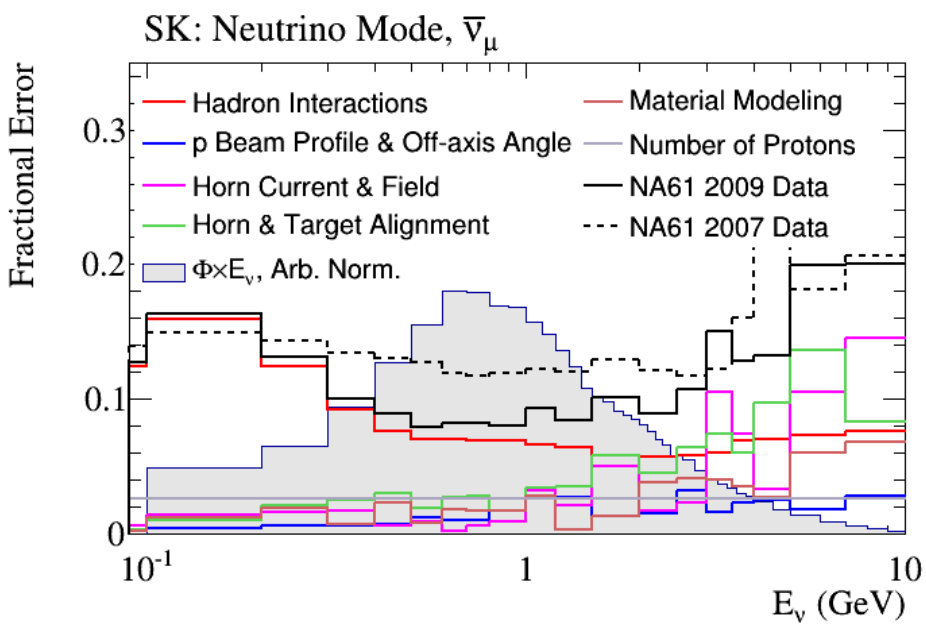
Outline

- Near-Term T2K Flux Error Improvements
  - NA61 Replica Target Analysis
  - T2K Beam Analysis Improvements
- Possible Future Flux Error Improvements
  - Ideas for future NA61 Measurements
- Other Possible Future Flux Considerations
  - Future T2K2 (T2HK?) Beam, Target Upgrades

Current T2K Flux Errors

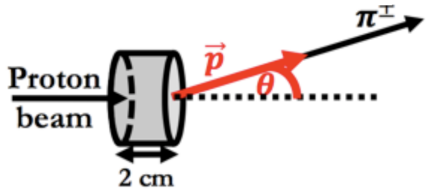




- Total current flux uncertainty is $\sim$10% at the peak neutrino energy
  - Now predominantly comes from hadron production uncertainties
  - Currently using : NA61 2009 thin target data set to constrain predicted hadron production

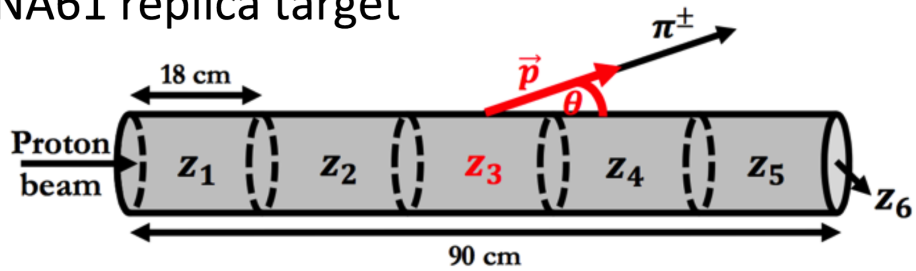
Near Future T2K Flux Errors – NA61 T2K Replica Target Data

NA61 thin target



Thin target : study primary p+C interaction

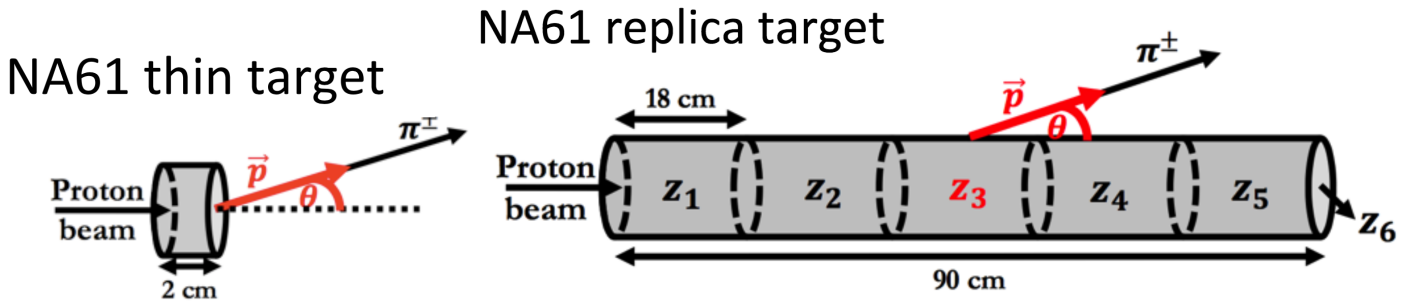
NA61 replica target



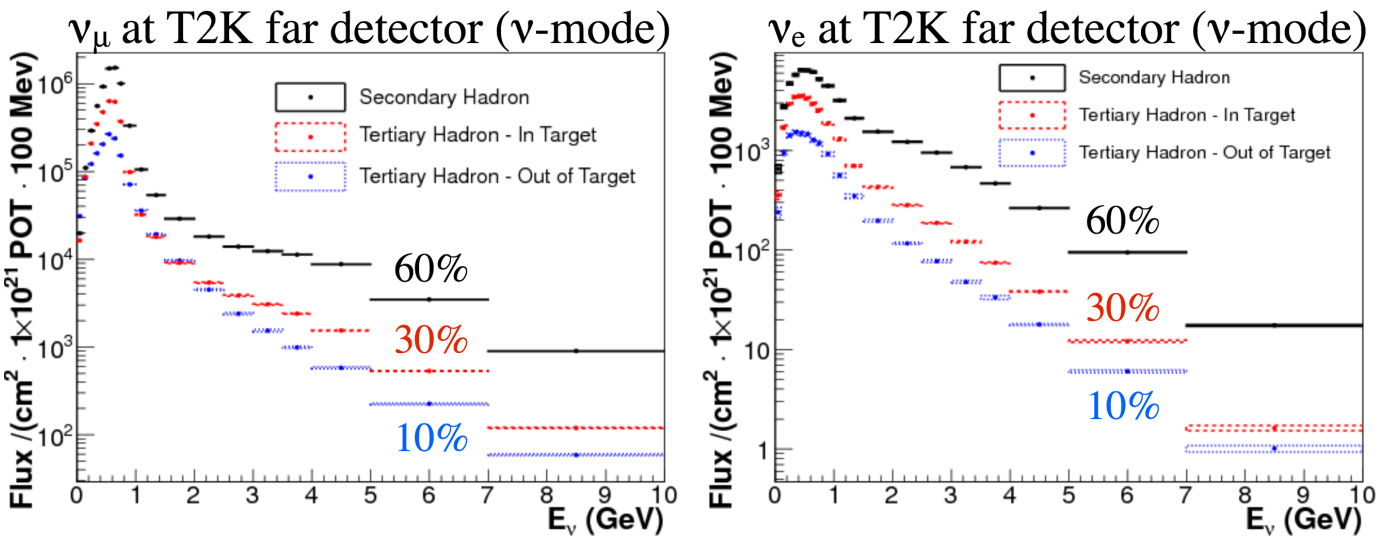
Replica target : accounts for re-interactions in the target

Target	Year	Stat ($\times 10^6$)	NA61 Status	T2K Status
Thin	2007	0.7	published : $\pi^{\pm}$, K^{+}, K^{0}_{S}, Λ	used
	2009	5.4	published : $\pi^{\pm}$, $K^{\pm}$, p, K^{0}_{S}, Λ	used
Replica	2007	0.2	published : $\pi^{\pm}$	method developed
	2009	2.8	published : $\pi^{\pm}$, $K^{\pm}$, p, K^{0}_{S}, Λ	work ongoing
	2010	$\sim$10	analysis ongoing	–

Near Future T2K Flux Errors – NA61 T2K Replica Target Analysis



- 60% of the flux (at the T2K peak energy) is directly tunable with the NA61 thin target data
- Up to 90% will be directly tunable once the replica target data is implemented



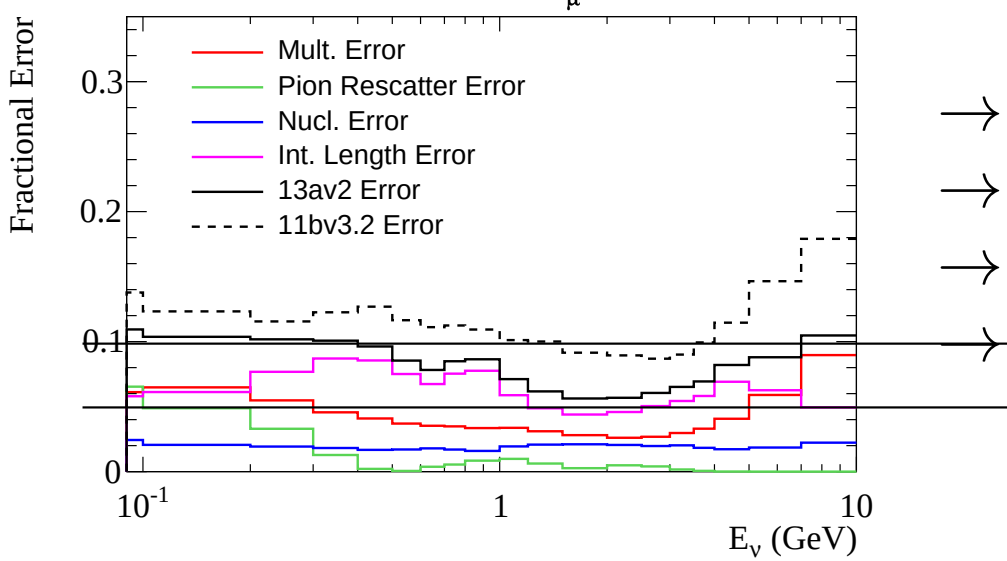
Near Future T2K Flux Errors – NA61 T2K Replica Target Analysis

- Now implementing NA61 2009 long target data into T2K flux MC
- Two analysis methods for implementing long target tuning are under development in parallel :
  1.
     - Fit hadron production model to NA61 replica target data
     - Use the tuned model (specified by fit parameters) for calculating T2K neutrino fluxes
  2.
     - Use nominal hadron production model (FLUKA 2011)
     - Reweight rates of $\pi^{\pm}$ outgoing from T2K target directly to NA61 replica target data
     - Effectively, NA61 data used as initial conditional for flux simulation
- Some effects still being studied :
  - Effect of difference in NA61 vs T2K beam profile on flux prediction
  - NA61 replica target data favors a lower value for the proton production cross section compared to the thin target data
    - Fit to long-target data lowers the proton σ_{prod} by 5.9σ compared to NA61 thin target result ($\sigma_{prod} = 230.7^{+7.0}_{-4.5}$mb $\rightarrow$ 204mb)

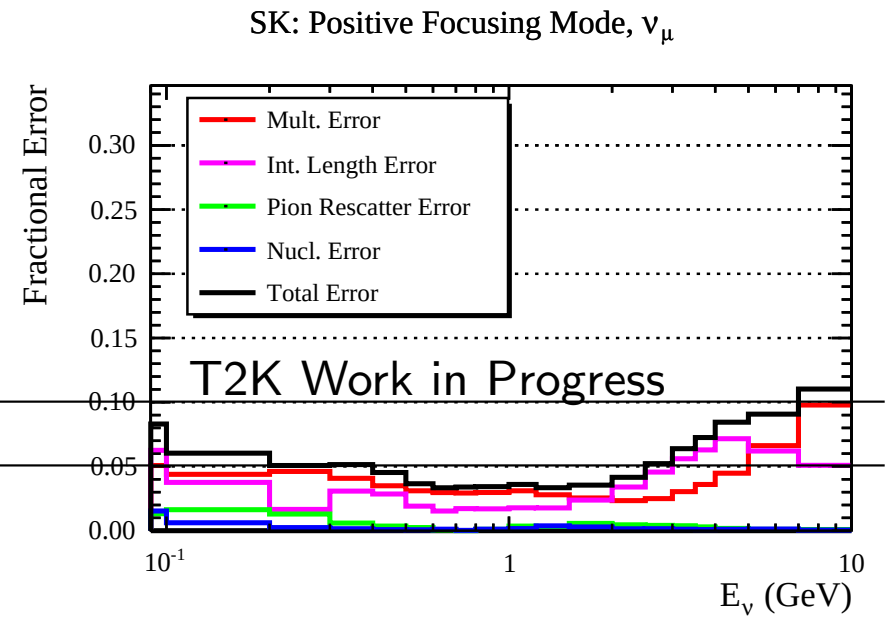
Near Future T2K Flux Errors – ν-Mode

- T2K flux errors will also be updated updated after including NA61 replica target data (work in progress)
  - Preliminary results suggest reduction of systematic error due to hadron production uncertainties from $\sim$10% to $\sim$5% at the peak neutrino energy

Errors with Thin Target Tuning



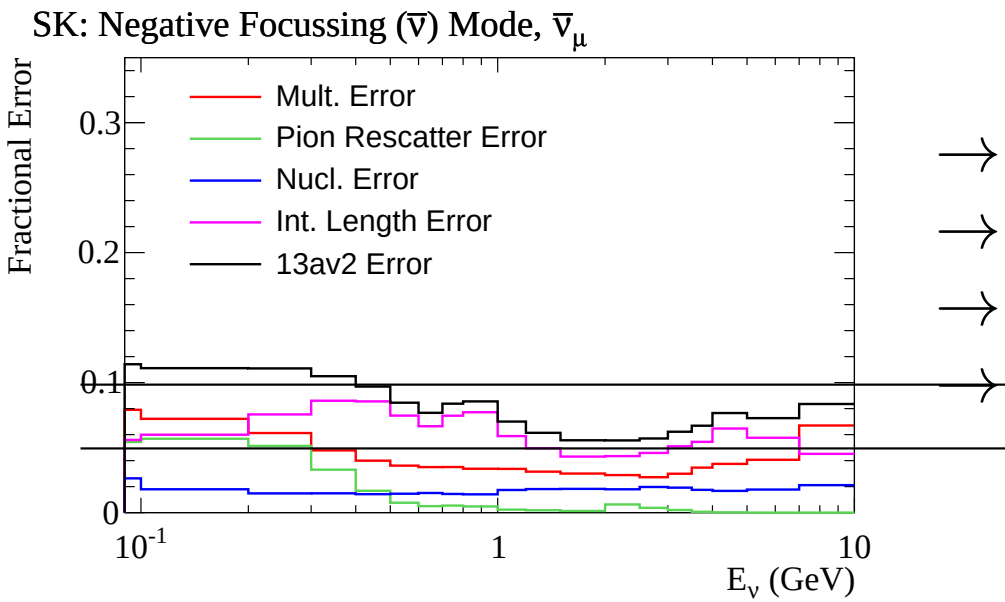
Errors with Replica Target Tuning



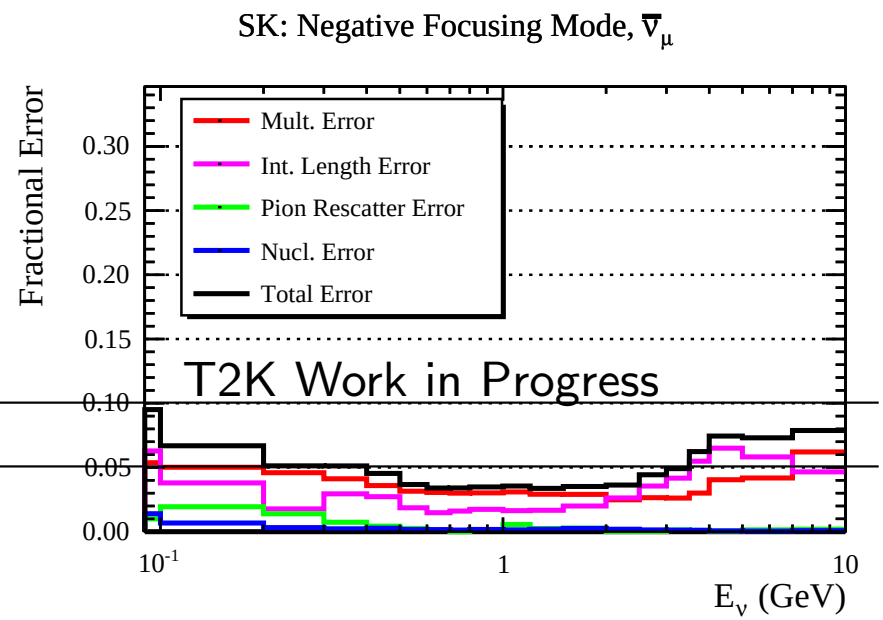
Near Future T2K Flux Errors – $\bar{\nu}$-Mode

- T2K flux errors will also be updated updated after including NA61 replica target data (work in progress)
  - Preliminary results suggest reduction of systematic error due to hadron production uncertainties from ∼10% to ∼5% at the peak neutrino energy

Errors with Thin Target Tuning



Errors with Replica Target Tuning

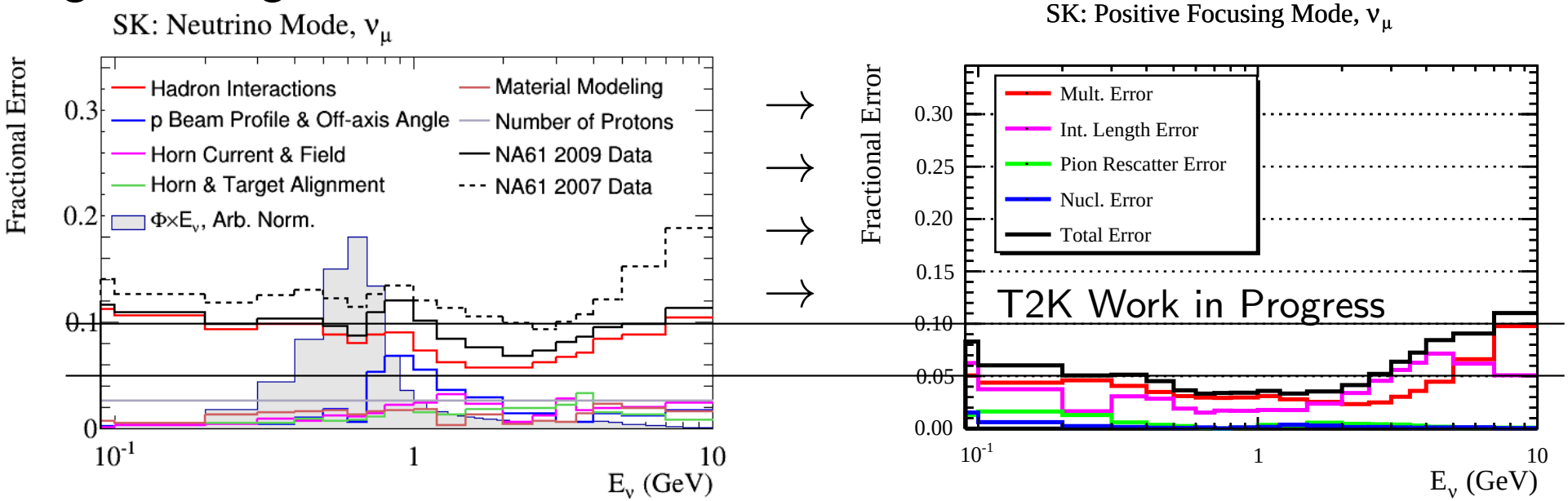


Near Future T2K Flux Errors

- Hadron production errors will no longer be dominant contributor to total error ..?
  - Need to ensure that other T2K flux related errors are also reduced as we improve the hadron production errors
    - Proton beam profile and off-axis angle
    - Proton number normalization

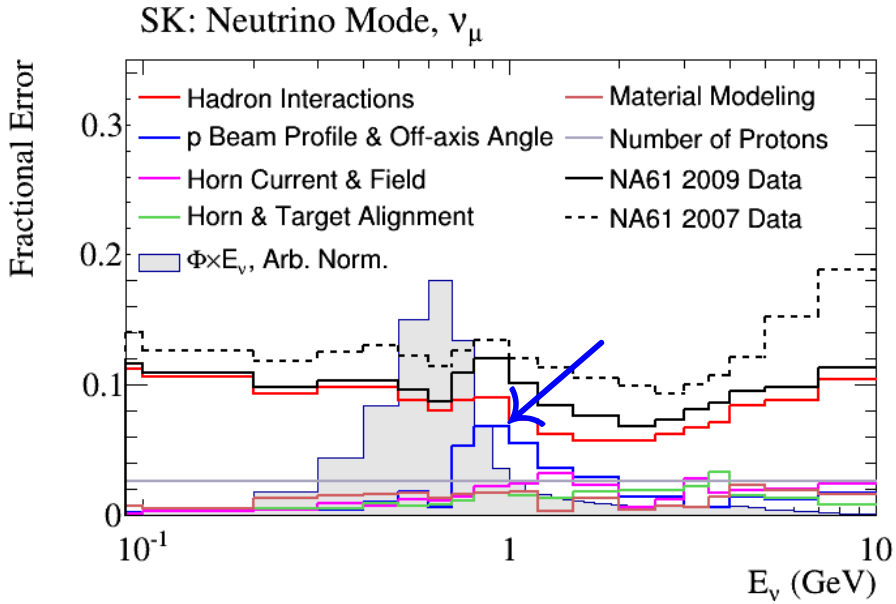
Total Current Errors with Thin Target Tuning

Hadron Production Errors with Replica Target Tuning



Reduction of Non-Hadron T2K Flux Errors – Beam Profile Uncertainties

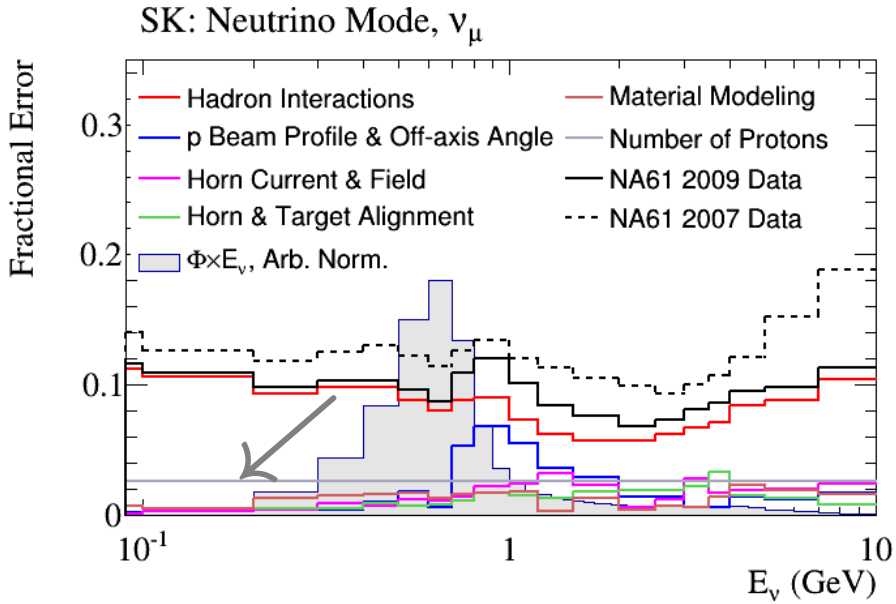
- Dominant source of proton beam profile error is uncertainty in the proton beam y, θ_y measurement
  - Comes partly from uncertainty in primary-secondary beamline alignment..



- Error is currently assigned by a fit to proton beam profile monitor measurement + INGRID (on-axis T2K near detector) neutrino beam profile measurement
- Uncertainties are Δy$\sim$0.6mm, $\Delta\theta_y\sim$0.3mrad
  $\rightarrow$ Cause 6% flux error at 1 GeV
- Currently, the error is being double counted
  - Proton beam profile + INGRID off-axis angle measurement are treated as separate, uncorrelated flux error sources
  $\rightarrow$ Now starting work on an improved analysis technique

Reduction of Non-Hadron T2K Flux Errors – Flux Normalization Error

- Flux normalization error comes from uncertainties on proton number measurement
  - Measured by Current Transformers (CTs) in the T2K proton beamline

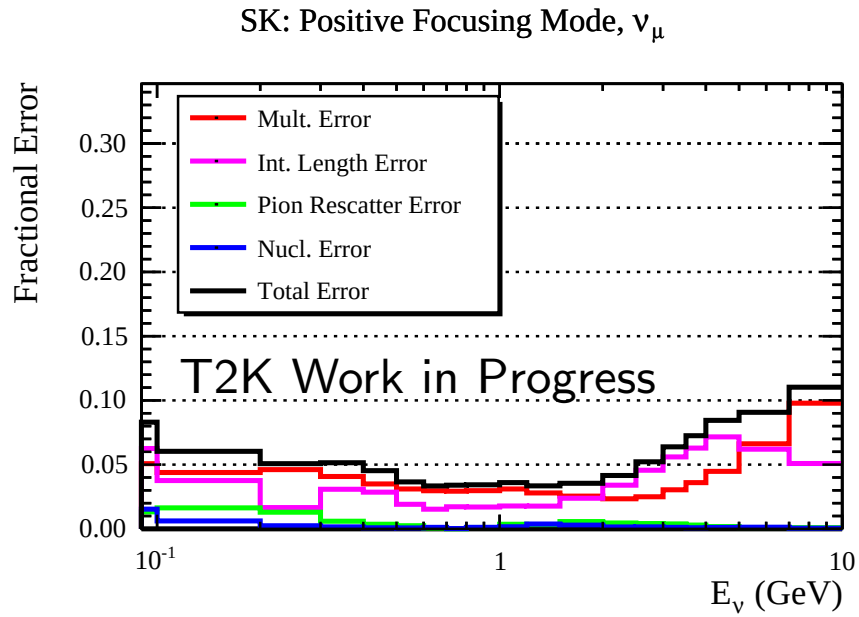


- Last year, updated CT analysis method and absolute calibration to reduce the POT normalization uncertainty from 2.7% to ∼2.0%
  → To be fully implemented in T2K analysis soon
- Normalization error has basically no effect on oscillation analysis, since a far/near neutrino flux ratio is used, but can have some effect on near detector cross section measurements

Reduction of Hadron-Production Flux Errors – Improved Cross Section Measurements

- Meson multiplicity and interaction length errors will be dominant contributions to hadron production flux error after NA61 replica target data is included
  → Some improvement can come from reduction of the total cross section uncertainties (rather than hadron production cross section uncertainties)

Hadron Production Errors with Replica Target Tuning



- These errors can be reduced by improved elastic/quasielastic cross section measurement at NA61 ?
  - Now there are a couple of early proposals for such measurements at NA61 + FNAL

Additional NA61 Data to Improve Errors ?

- Out-of-target interactions (on Al, Fe, Ti) contribute to a significant fraction of the wrong sign flux
  - Can be substantial contribution to $\bar{\nu}$-mode beam flux (compared to ν-mode) since :
    - In ν-mode, $\sim$0.12 interactions/ν take place outside of the target
    - In $\bar{\nu}$-mode $\rightarrow$ $\sim$0.43$\sim$0.5 interactions/ν
- NA61 data are used to tune the predicted production of mesons in secondary or tertiary interactions
  1. For incident neutrons, assume an isoscalar nuclear target and apply an isospin rotation to the NA61 data
  2. Since the incident secondary or tertiary proton or neutron has energy less than 30 GeV, scaling is applied so that the NA61 tuning can be applied to the interaction
  3. For out-of-target interactions, NA61 data are scaled to Al, Fe, Ti targets using parameterized fits to multiplicity data on multiple nuclear targets
     - Use parameterized fits to Allaby, BNL-E802, HARP data + cross check to Eichten
- May be useful to take dedicated NA61 data on different targets (Al, Fe, Ti, H_2O ?), at lower beam energies (down to $\sim$10GeV)

Other Additional NA61 Data to Improve Errors ?

- General ideas from some brainstorming within T2K beam group.. :
  - NA61 took some high magnetic field data, but more data could be useful ?
  - Improve measurement by taking data with new target position (insert into magnet) ?
  - Additional NA61 empty target data useful ?
  - NA61 vs T2K target density uncertainty may contribute to flux errors – possible measurements with different target densities ?

Other J-PARC Neutrino Beamline Future Upgrades

- Different beam energy ?
- New T2K target ?
  - See next slides

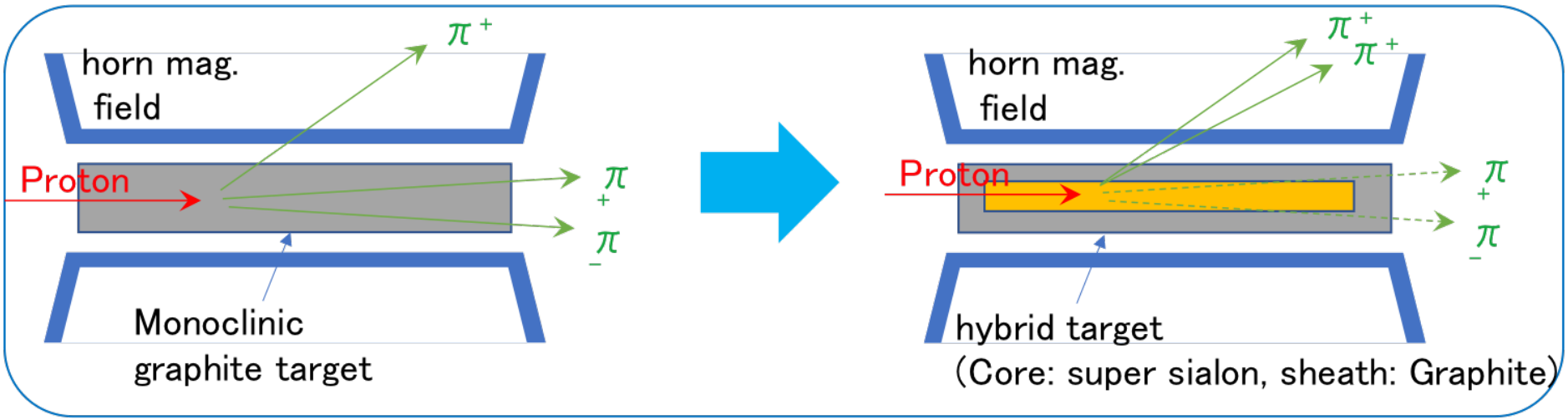
Possible Upgrade of T2K Target – Motivation

- Aim to enhance the CP-violation search sensitivity of T2K-II by upgrading the production target
  - Increase ν-beam yield / POT = Increase π yield / POT and/or π focusing efficiency
  - Decrease wrong-sign component (ν component in $\bar{\nu}$-beam) = Suppress very-forward π^+ production during π^- focusing

  $\rightarrow$ Use higher-density material for target
  - Cf. IG-430 (Graphite used for T2K target) = $\sim$1.8 g/cm^3
  - But, the heat generated by beam exposure is also increasing – any new material should have the enough thermal sock resistance
    $\rightarrow$ Candidate materials :
    - SiC/SiCcomposite : density=2.5$\sim$3.1g/cm^3
    - Super-Sialon (Si_3N_4+Al_2O_3) : density=$\sim$3.22 g/cm^3 $\leftarrow$ Good Candidate (http://www.hitachimetals.com/materials-products/ceramics/sialon.php)

New T2K Target Conceptual Design: Hybrid-target

- Just replacing graphite with some other dense material does not work well
  - Increase of π absorption cancels increase of π production
    $\rightarrow$ Replace only the core part of the target



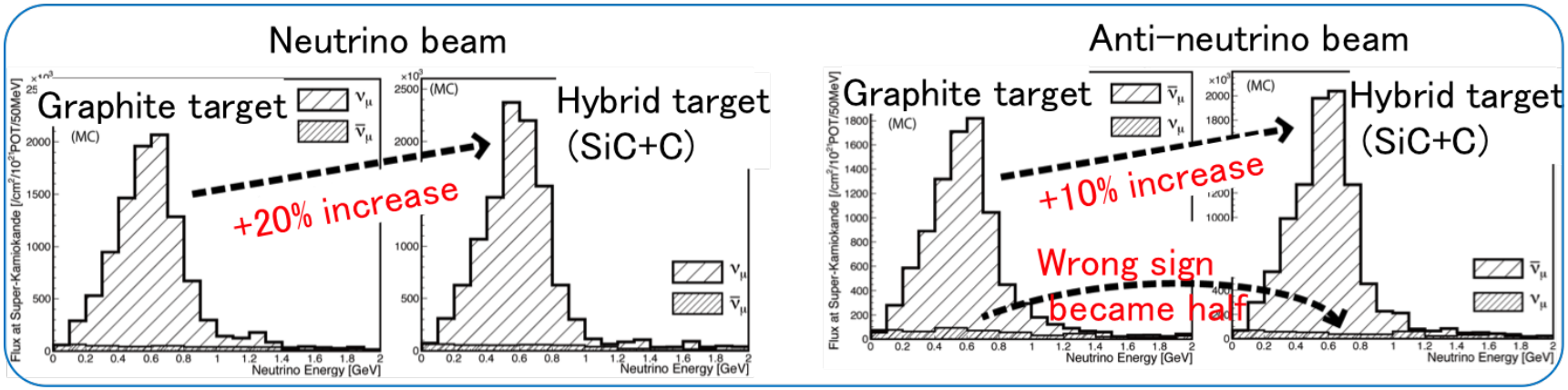
Pros:
+Increases pion production w/o increasing pion absorption for pions in horn acceptance
+ Production point becomes point-like → better focusing
+ Decreases forward pions outside horn acceptance
+ Even if the core is damaged, it is contained by a graphite sheath

Cons:
+ Cooling method
(How to keep thermal contact btw. the core and sheath?)

Prospects + To Do for T2K Target Upgrade

Neutrino flux simulation

(Hadron production model: GFLUKA, Hybrid target: SiC + C)



- To do:
  - Optimization of the core / sheath dimension based on the latest hadron production model & more realistic material properties
  - Mechanical design, Cooling design, etc.
  - After finalizing a realistic design and having a prospect for real target production in the future, it may be necessary to measure the hadron production with the actual material
    - Measurement with a thin target made of the core material (Super-Sialon?)
    - Measurement with a long target with the actual hybrid target structure

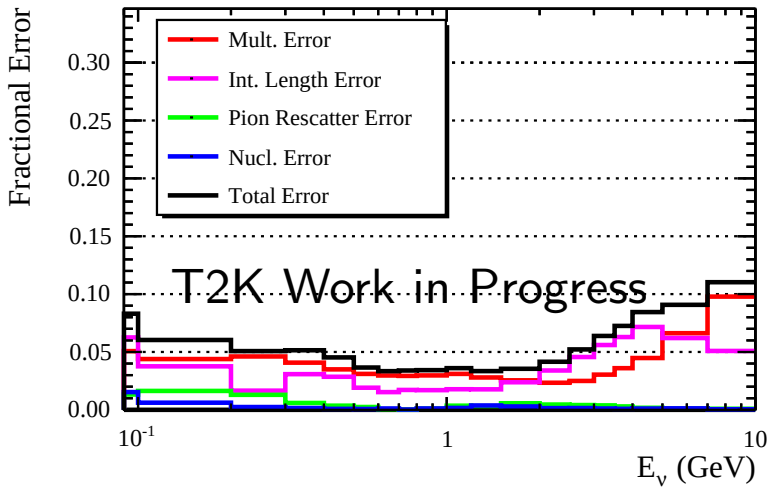
Conclusion

- Near-Term T2K flux error improvements, such as implementation of NA61 replica target analysis, some T2K beam analysis improvements, are underway
- Possible future flux error improvements can come from further NA61 measurements
  - Improved elastic/quasielastic cross section measurements ?
  - Measurements on different targets at lower beam energies ?
  - Others ?
- Other possible future flux considerations for T2K
  - Future T2K2 (T2HK?) beam energy, target upgrades should be kept in mind

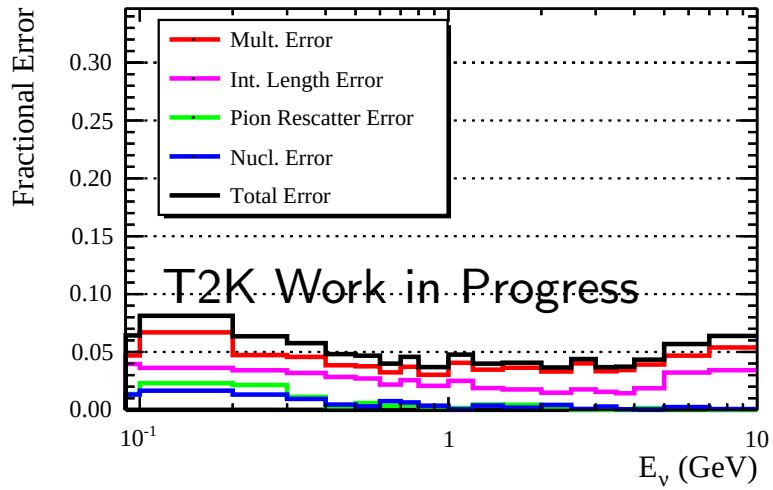
Backup Slides

Replica Target Errors – ν-Mode

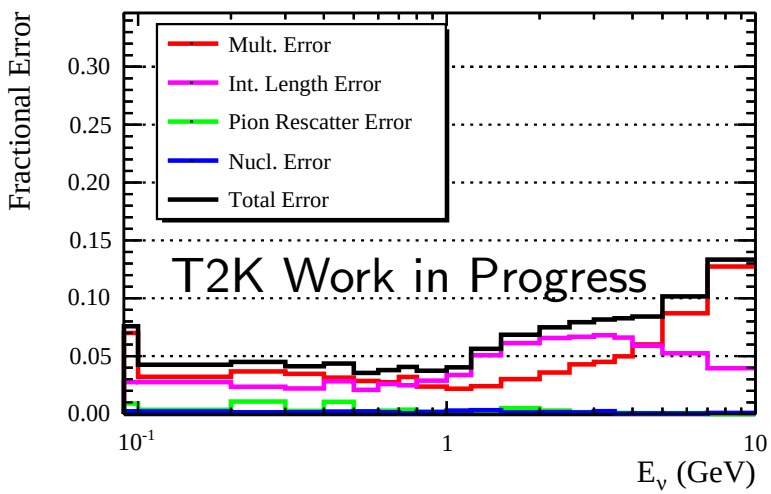
SK: Positive Focusing Mode, ν_μ



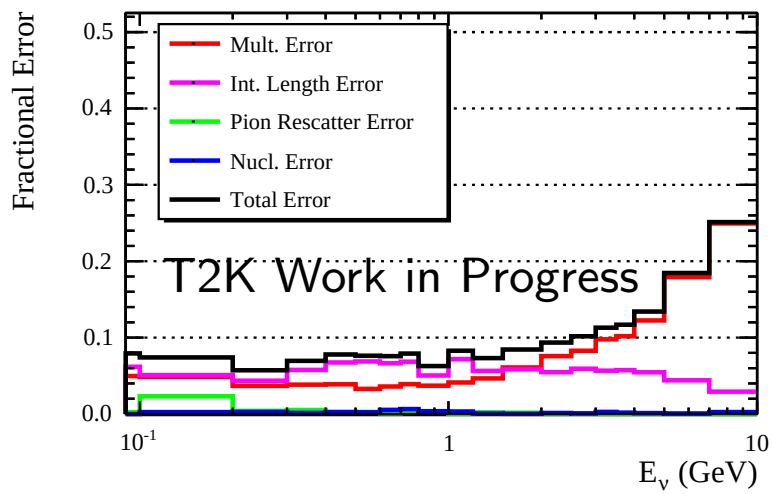
SK: Positive Focusing Mode, $\bar{\nu}_\mu$



SK: Positive Focusing Mode, ν_e



SK: Positive Focusing Mode, $\bar{\nu}_e$



Replica Target Errors – $\bar{\nu}$-Mode