The T2K Flux Predictions

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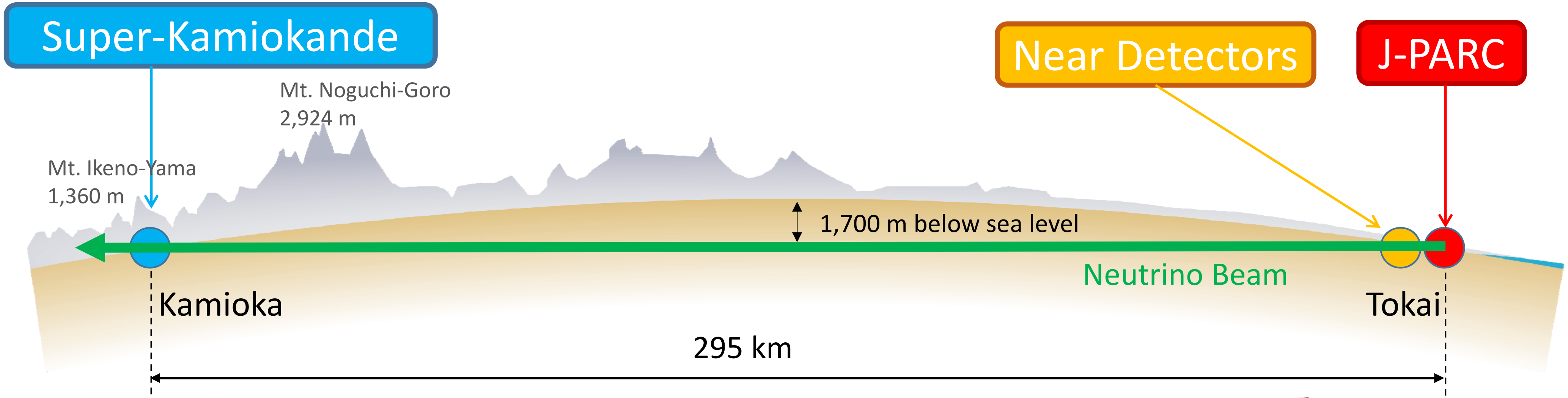
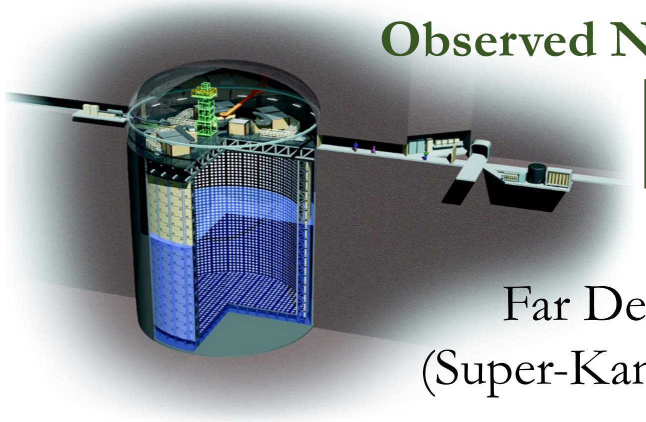
On behalf of the T2K Collaboration

The T2K Experiment

- T2K (Tokai-to-Kamioka): 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
- Precise knowledge of the neutrino flux is vital for T2K ν cross-section measurements
- Oscillation analysis also relies on the flux calculation to estimate the expected number of events at detectors





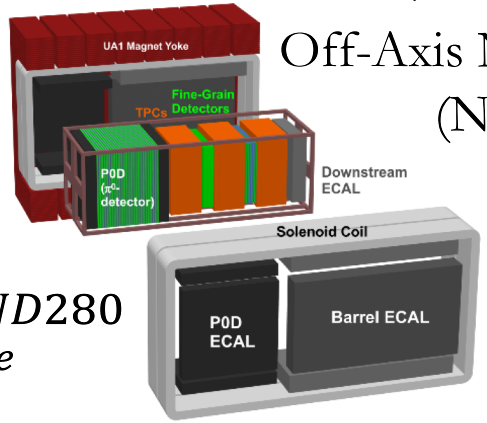
Far Detector
(Super-Kamiokande)

Observed Number of Events

$$N_{\nu_e}^{SK} = P_{\nu_\mu \to \nu_e} \times \Phi_{\nu_\mu}^{SK} \times \sigma_{\nu_e}^{SK}$$

Unoscillated Flux Prediction

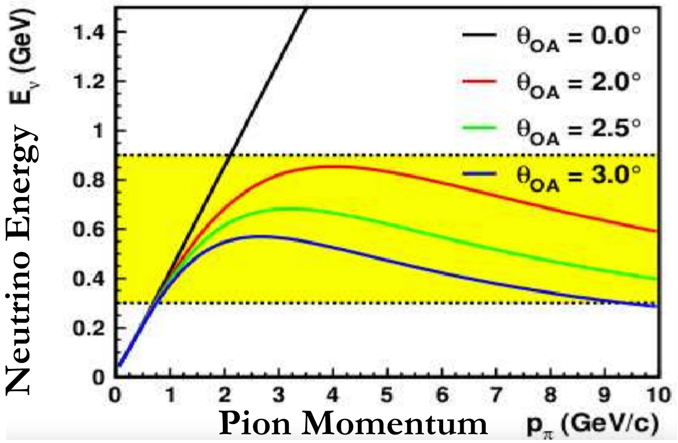
$$N_{\nu_e}^{ND280} = \Phi_{\nu_\mu}^{ND280} \times \sigma_{\nu_e}^{ND280}$$

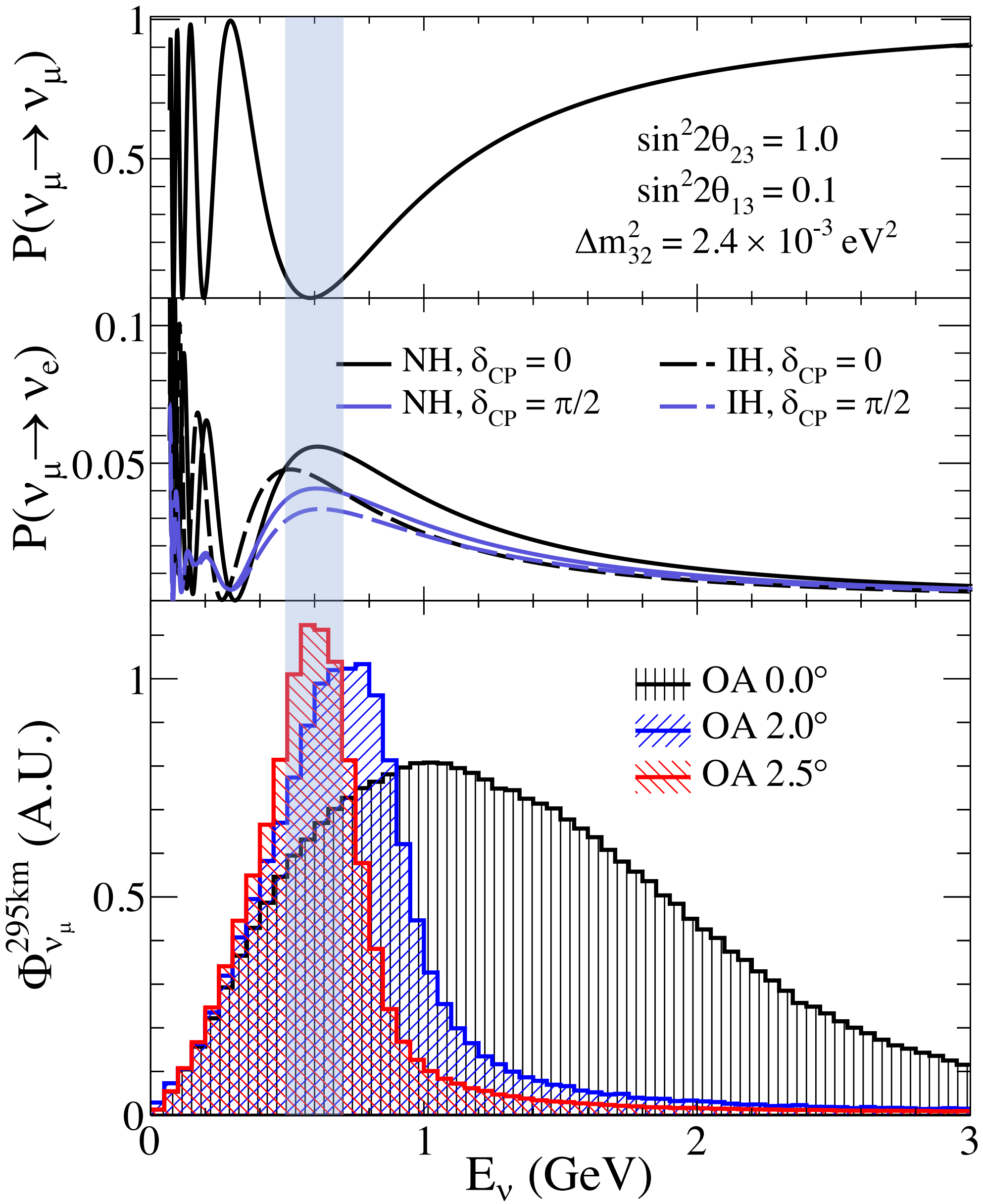


Off-Axis Near Detector
(ND280)

The T2K Off-Axis Neutrino Flux

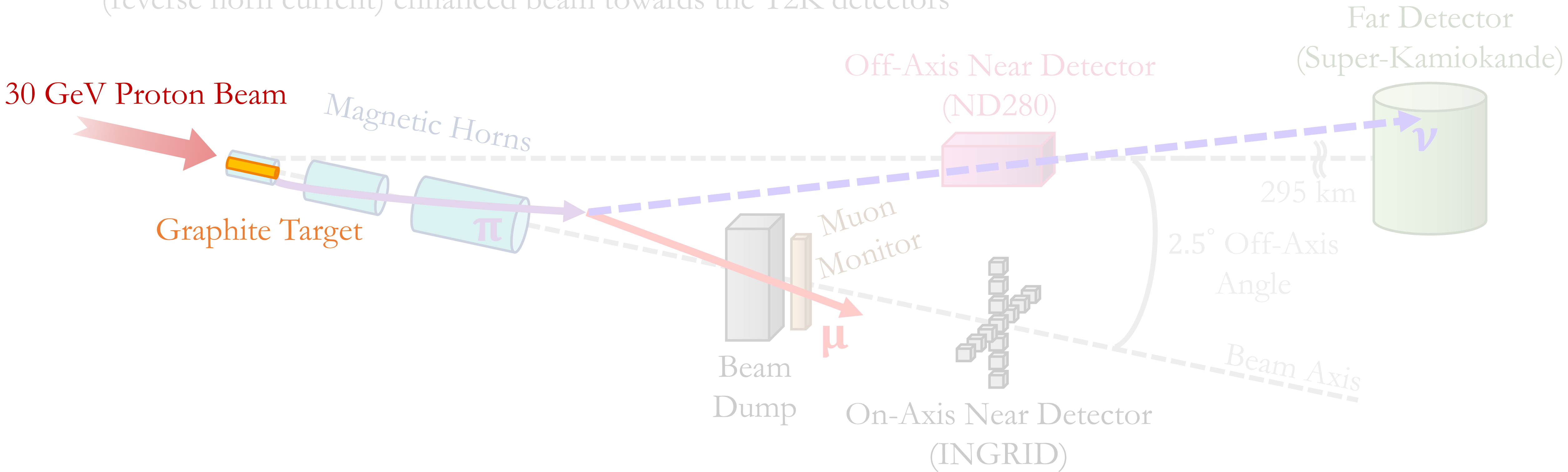
- SK and ND280 are placed at 2.5° off-axis angle with respect to the primary proton beam direction
- On-axis near detector (INGRID) used to monitor beam stability and direction
- Off-axis beam makes the ν_μ flux more narrow and peaked around the energies needed for observing the first oscillation maximum at SK (295 km baseline)
- High energy tail gets reduced





T2K Neutrino Flux Secondary Beamline

- 30 GeV (kinetic energy) protons striking the 90 cm long T2K graphite target
- Hadronic cascade is produced (chain of hadronic interactions)
- 3 magnetic horns used to focus pions and kaons exiting from the target
- Out-of-target interactions with secondary beamline components (horns, decay volume walls etc.)
- In-flight pion and kaon decays inside the decay volume (~96 m) produce neutrinos
- Changing the horn current direction focuses either a neutrino (forward horn current) or an anti-neutrino (reverse horn current) enhanced beam towards the T2K detectors



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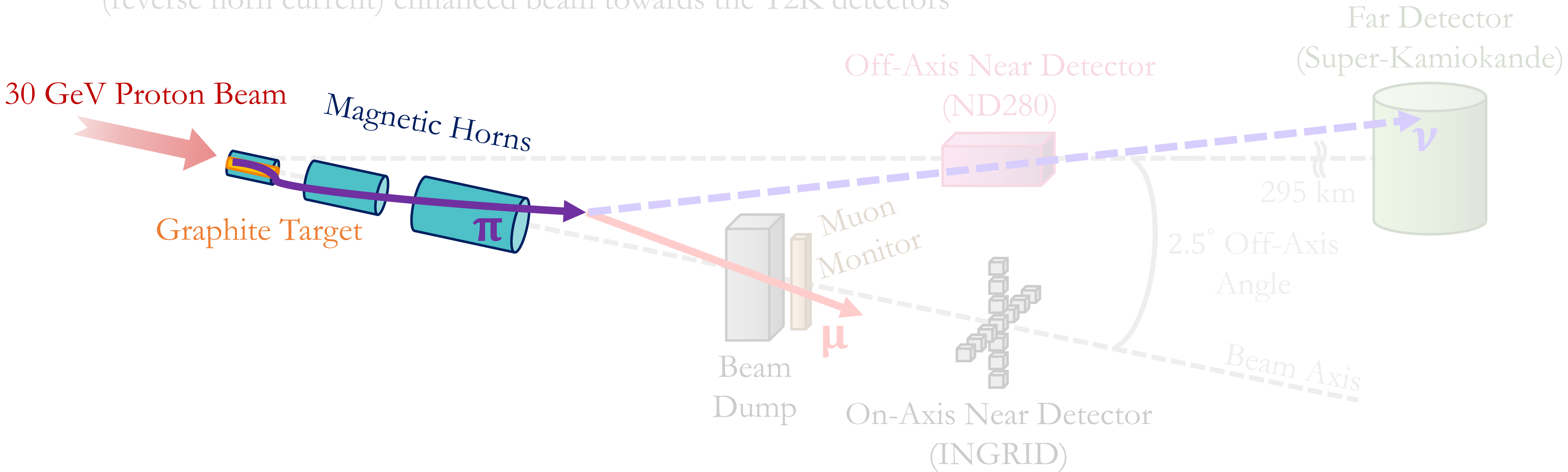

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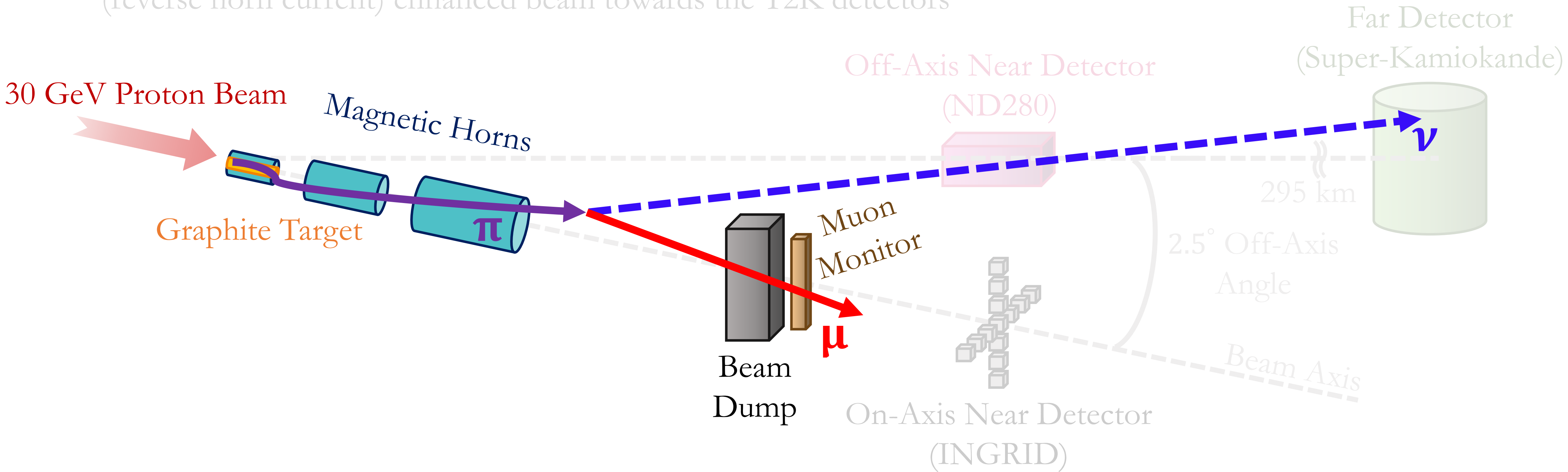

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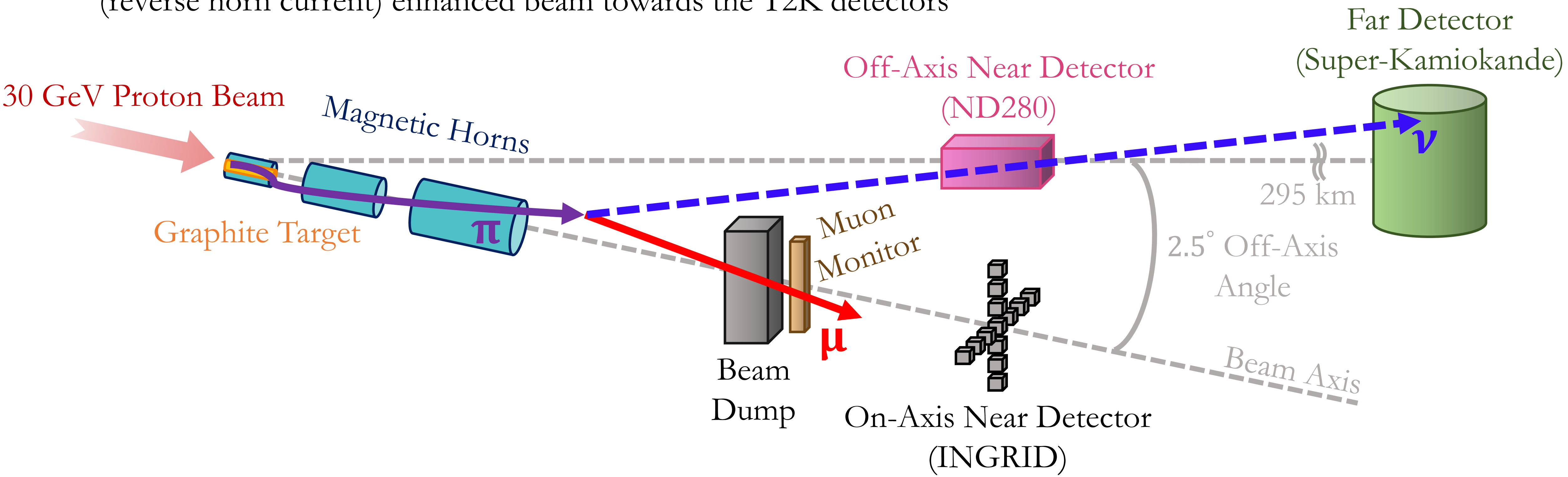
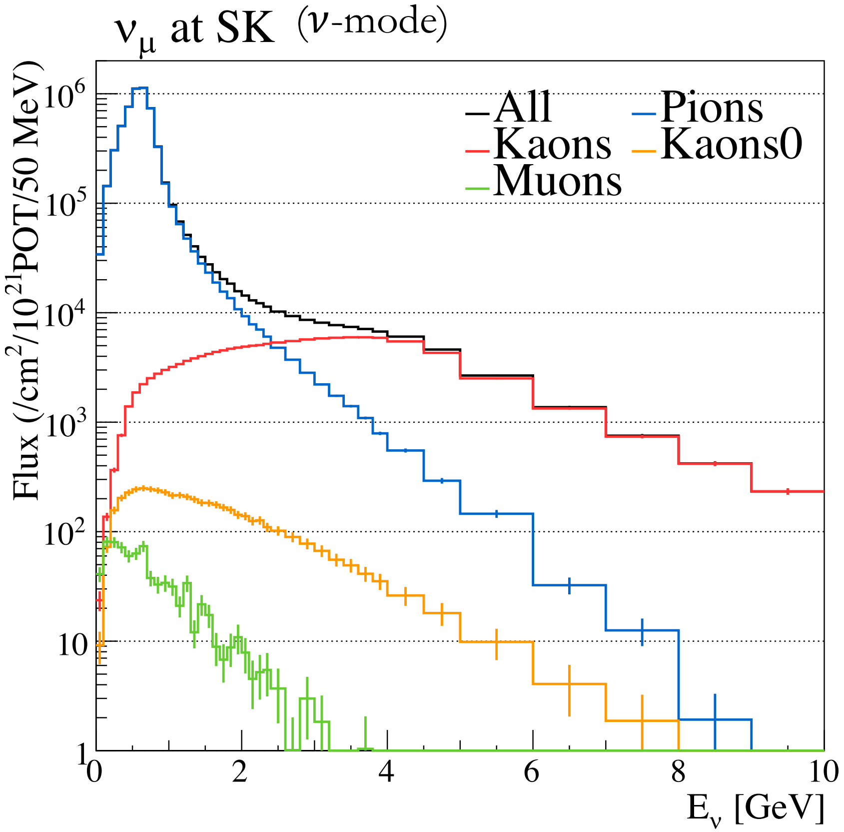
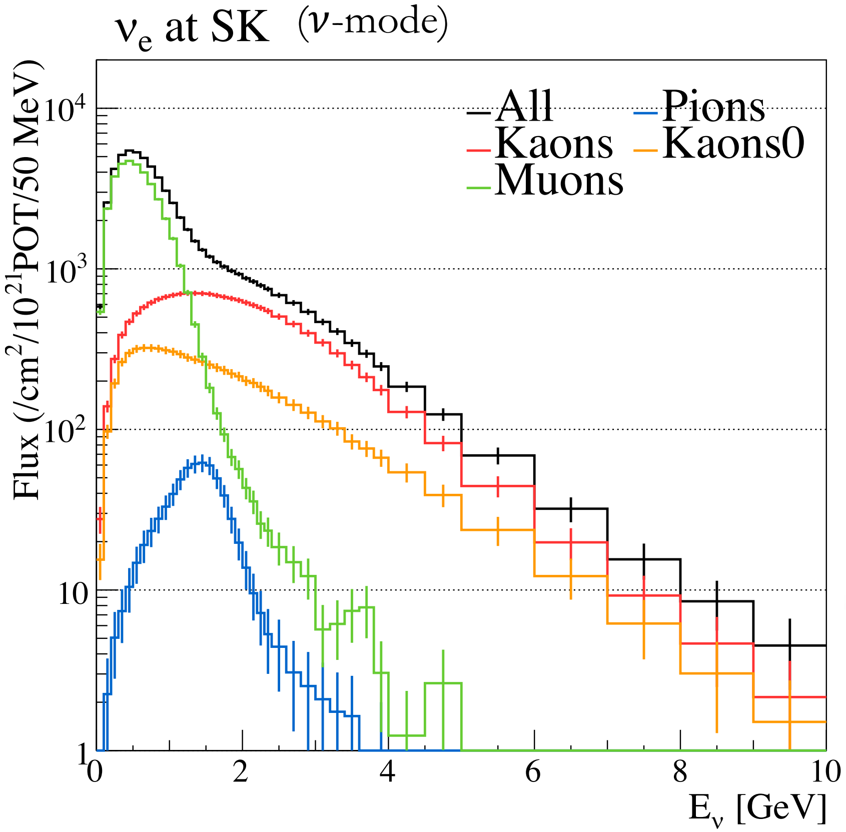


Understanding The T2K Neutrino Flux

- Neutrino production dominated by pion (and muon) decays at low energies, and kaon decays at high energies
- Uncertainty on the hadron production models limits the neutrino flux uncertainty
- Solution: Constrain model predictions with external hadron production data!

Neutrino Ancestry (Parents)





Main ν-producing channels

Decay Products	Decay Fraction (Γ_i/Γ)
$\pi^+ \rightarrow \mu^+\nu_\mu$	99.9877%
$\pi^+ \rightarrow e^+\nu_e$	1.23×10^{-4}
$K^+ \rightarrow \mu^+\nu_\mu$	63.55%
$K^+ \rightarrow \pi^0\mu^+\nu_\mu$	3.353%
$K^+ \rightarrow \pi^0 e^+\nu_e$	5.07%
$K_L^0 \rightarrow \pi^\pm\mu^\mp\overline{\nu}_\mu(\nu_\mu)$	27.04%
$K_L^0 \rightarrow \pi^\pm e^\mp\overline{\nu}_e(\nu_e)$	40.55%
$\mu^+ \rightarrow e^+\overline{\nu}_\mu\nu_e$	100%

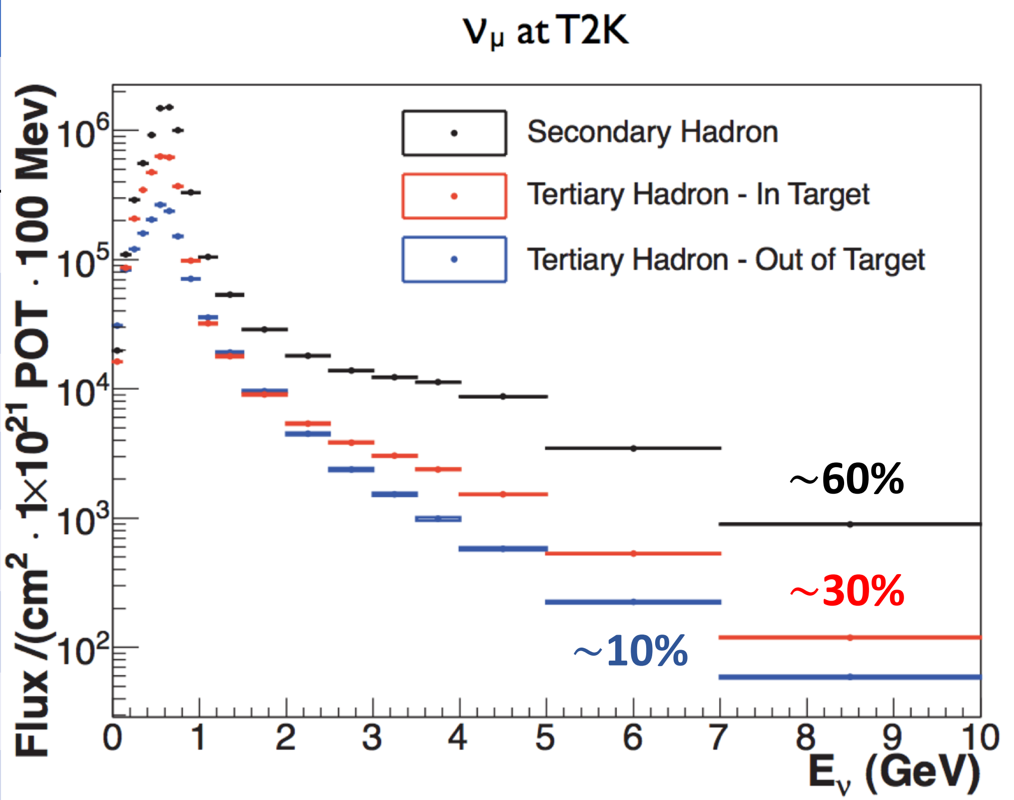
Particle Data Group

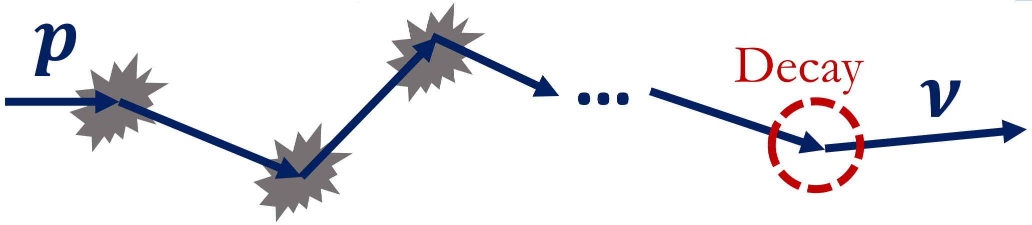
http://pdg.lbl.gov/index.html

Secondary and tertiary hadronic interactions

- Hadronic interactions not only with the graphite target, but also the horns (Al), decay volume walls (Fe), decay volume itself (He), target housing (Ti) etc.

	Number of Interactions in Hadronic Ancestry		
	1 Interaction	≥2 Interactions	≥ 1 Out-of-target Interaction
ND280 ν_μ flux	63.2%	36.8%	12.6%
ND280 $\bar{\nu}_\mu$ flux	39.5%	60.5%	49.8%
ND280 ν_e flux	60.1%	39.9%	13.6%
ND280 $\bar{\nu}_e$ flux	50.7%	49.3%	32.2%
SK ν_μ flux	63.2%	36.8%	12.4%
SK $\bar{\nu}_\mu$ flux	41.5%	58.5%	45.1%
SK ν_e flux	61.7%	38.3%	12.7%
SK $\bar{\nu}_e$ flux	54.0%	46.0%	27.2%

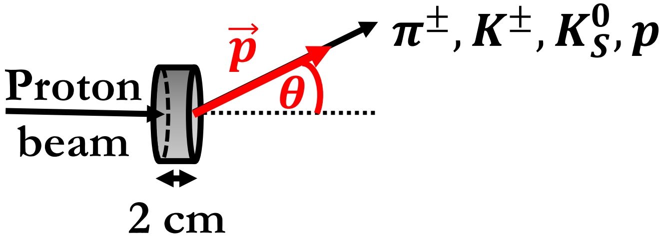


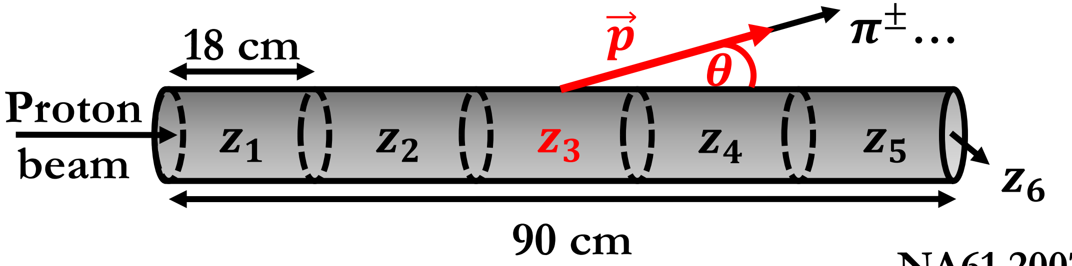


Almost half of wrong-sign ($\bar{\nu}_\mu$) flux in the ν_μ enhanced beam comes from out-of-target interactions!

NA61/SHINE Hadron Production Datasets for T2K

- Two different graphite target configurations are used:
  - Thin-target TT (2 cm, 0.04 λ_I): directly constrains ~60% of T2K flux
  - Replica-target RT (90 cm, 1.9 λ_I): potential to directly constrain up to ~90% of T2K flux



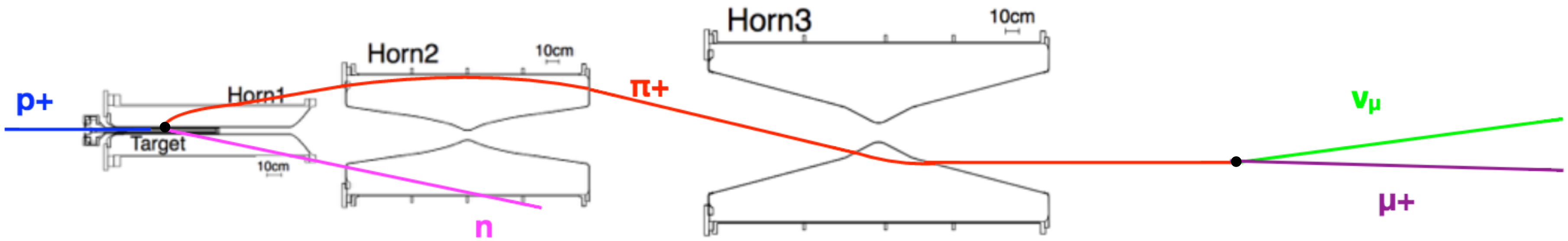


Beam + Graphite target	Mom (GeV/c)	year	Data	POT ($\times 10^6$)
p+TT	31	2007	$\pi^{\pm}, K^{+}$	0.7 (pilot run)
p+TT	31	2009	$\pi^{\pm}, K^{\pm}, K^0_S, p$	5.4
p+T2K RT	31	2007	$\pi^{\pm}$	0.2 (pilot run)
p+T2K RT	31	2009	$\pi^{\pm}$	2.8
p+T2K RT	31	2010	$\pi^{\pm}, K^{\pm}, p$	10

NA61 2007 thin-target dataset
10.1103/PhysRevC.84.034604
10.1103/PhysRevC.85.035210
NA61 2009 thin-target dataset
10.1140/epjc/s10052-016-3898-y
NA61 2009 replica-target dataset
10.1140/epjc/s10052-016-4440-y
NA61 2010 replica-target dataset
arXiv:1808.04927

- **Thin tuned flux**: official T2K flux prediction tuned with **NA61/SHINE 2009 thin-target data**
- **Replica tuned flux**: flux prediction using **NA61/SHINE 2009 replica-target data** to constrain pions exiting from the target. The yield of other hadrons from the target, the pion yield not covered by the replica-target dataset, as well as out-of-target interactions are still constrained with **NA61 2009 thin-target data**.

The T2K Neutrino Flux Simulation

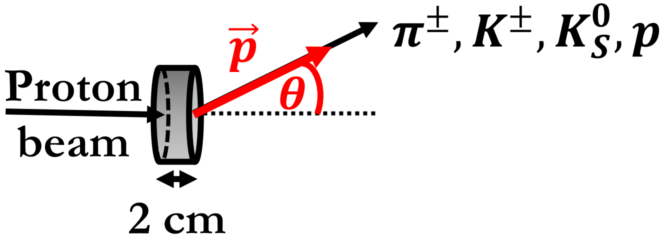


FLUKA2011.2c → GEANT3+GCALOR → FLUX TUNING

- Modelling hadronic interactions inside the graphite target
- T2K beam profile measurements used as inputs for running FLUKA

- Propagates particles exiting from the target through the horns and the decay volume
- Detailed knowledge of the secondary beamline is needed
- Out-of-target interactions are modelled using GCALOR

- Constraining the hadron production model with available external hadron production data (NA61/SHINE, HARP etc.)



NA61 2009 thin-target data used for the official T2K flux calculation so far

Flux Tuning Procedure: Phenomenology

- **A weight is applied to the neutrino yield based on its history (from the hadronic ancestry cascade)**
- There are two distinct aspects of hadron interaction/propagation that we care about:

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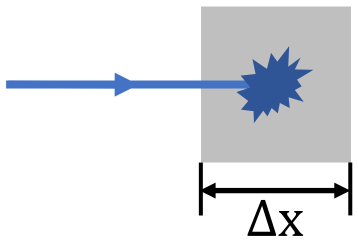

Cross Section Measurements

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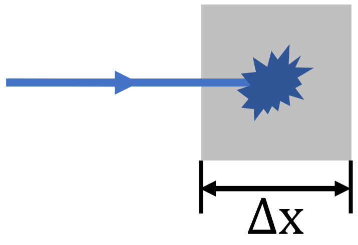
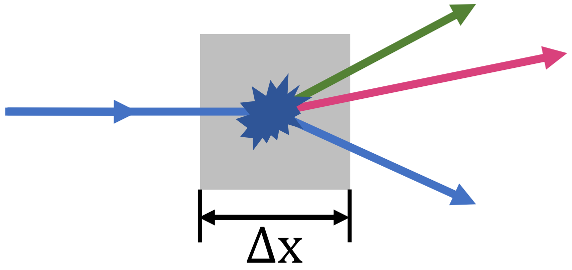


Cross Section Measurements

  - **How many particles of different species and kinematics get produced when the primary particle traverses a material?**



Differential Production Cross Section Measurements Collected on Targets of Various Thicknesses (thin, replica etc.)

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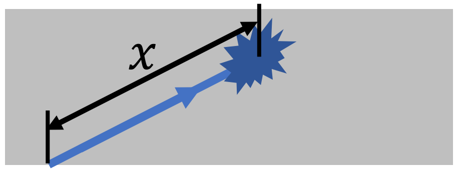
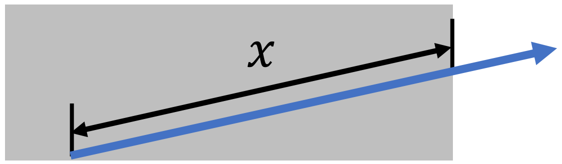
  - **Interaction Length Weight** (corrects the yield based on the length travelled by the hadron through different materials before interacting)



$$weight(x) = \frac{\sigma_{data}}{\sigma_{MC}} e^{-\rho(\sigma_{data}-\sigma_{MC})x}$$



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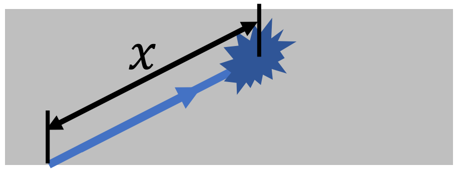

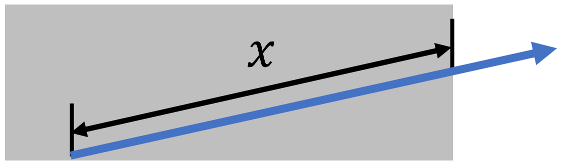

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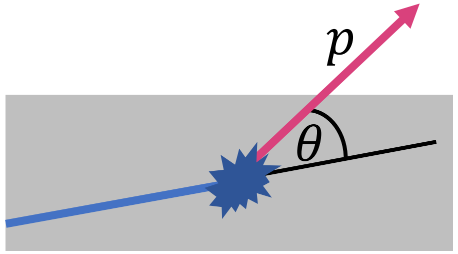
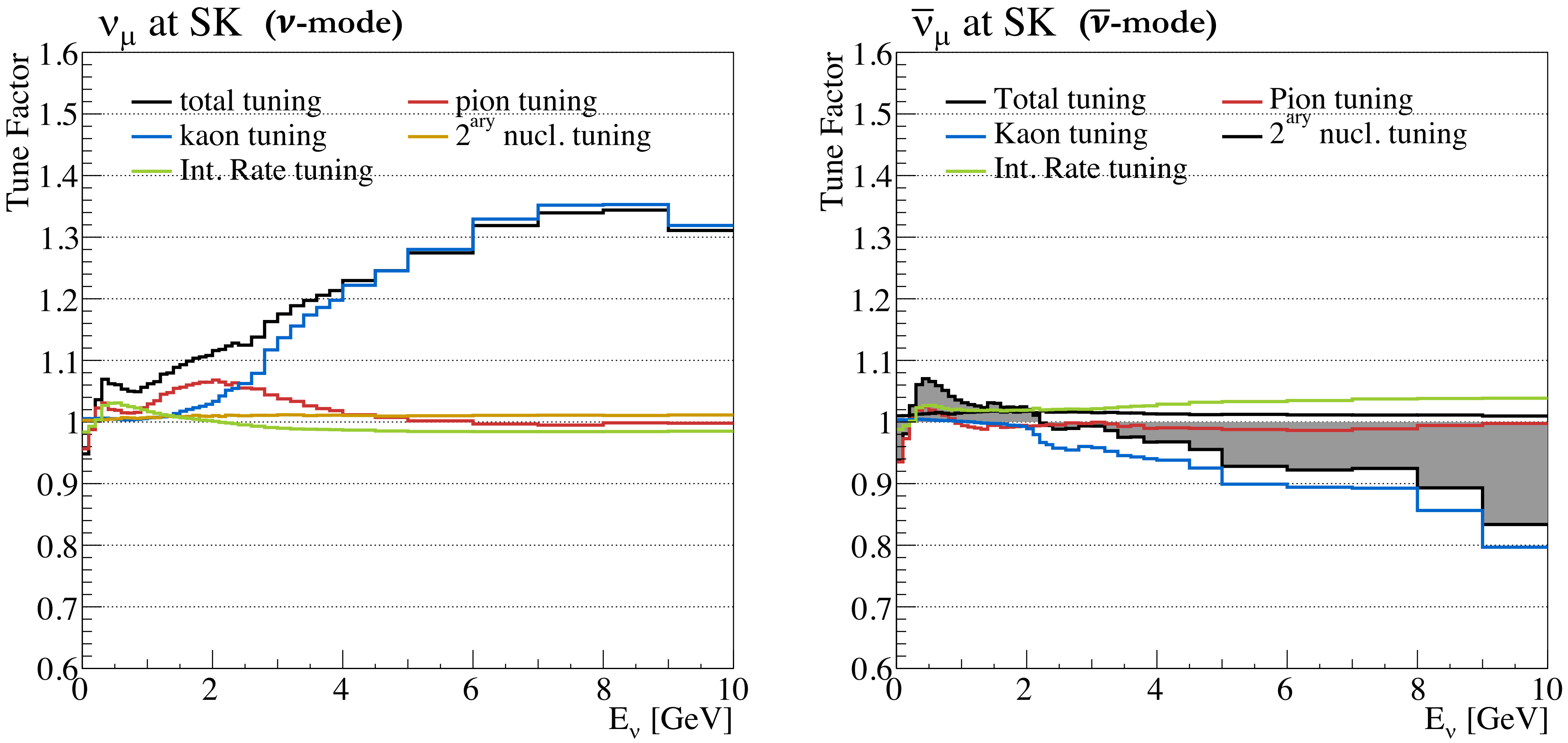
  - **Multiplicity Weight** (corrects the yield based on the momentum and direction of the outgoing hadron produced in the interaction)



$$weight(p,\theta) = \frac{\left[\frac{d^2n(p,\theta)}{dpd\theta}\right]_{data}}{\left[\frac{d^2n(p,\theta)}{dpd\theta}\right]_{MC}}$$

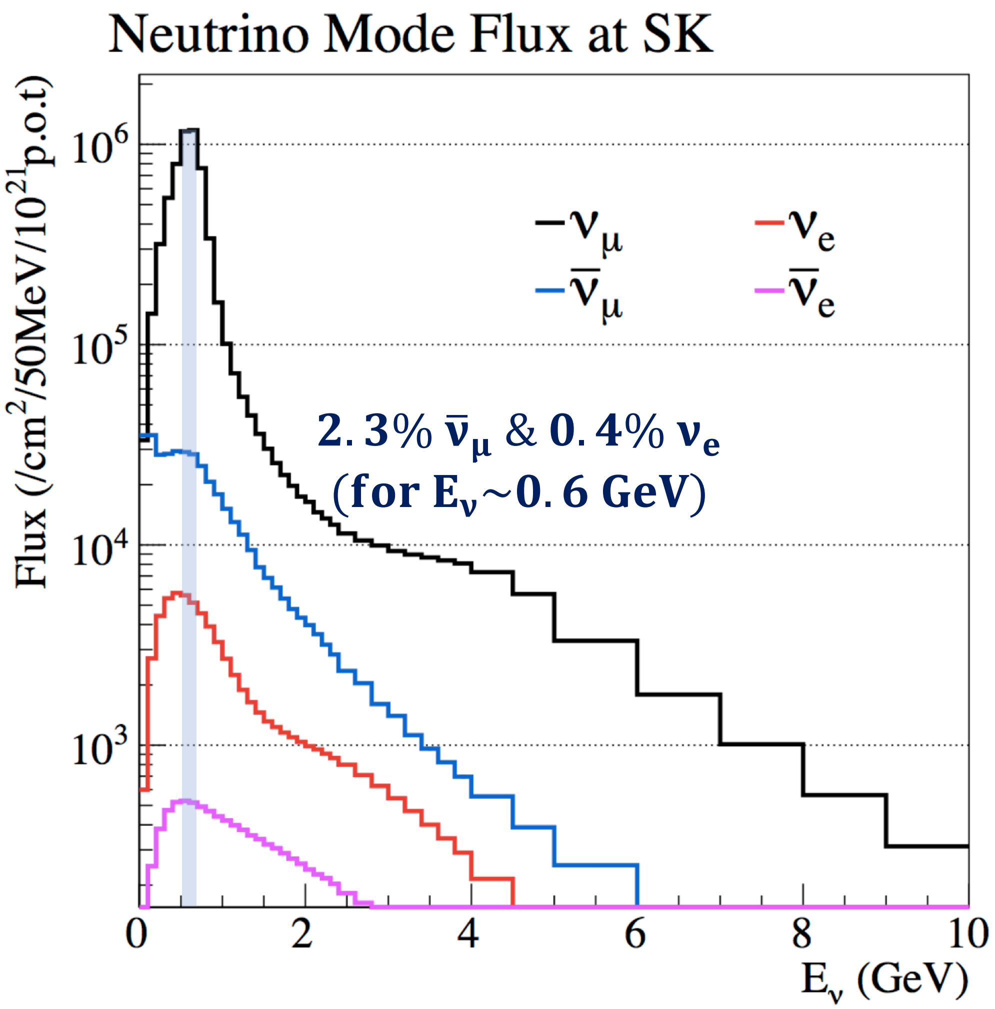
Flux Tuning: Weight Factors

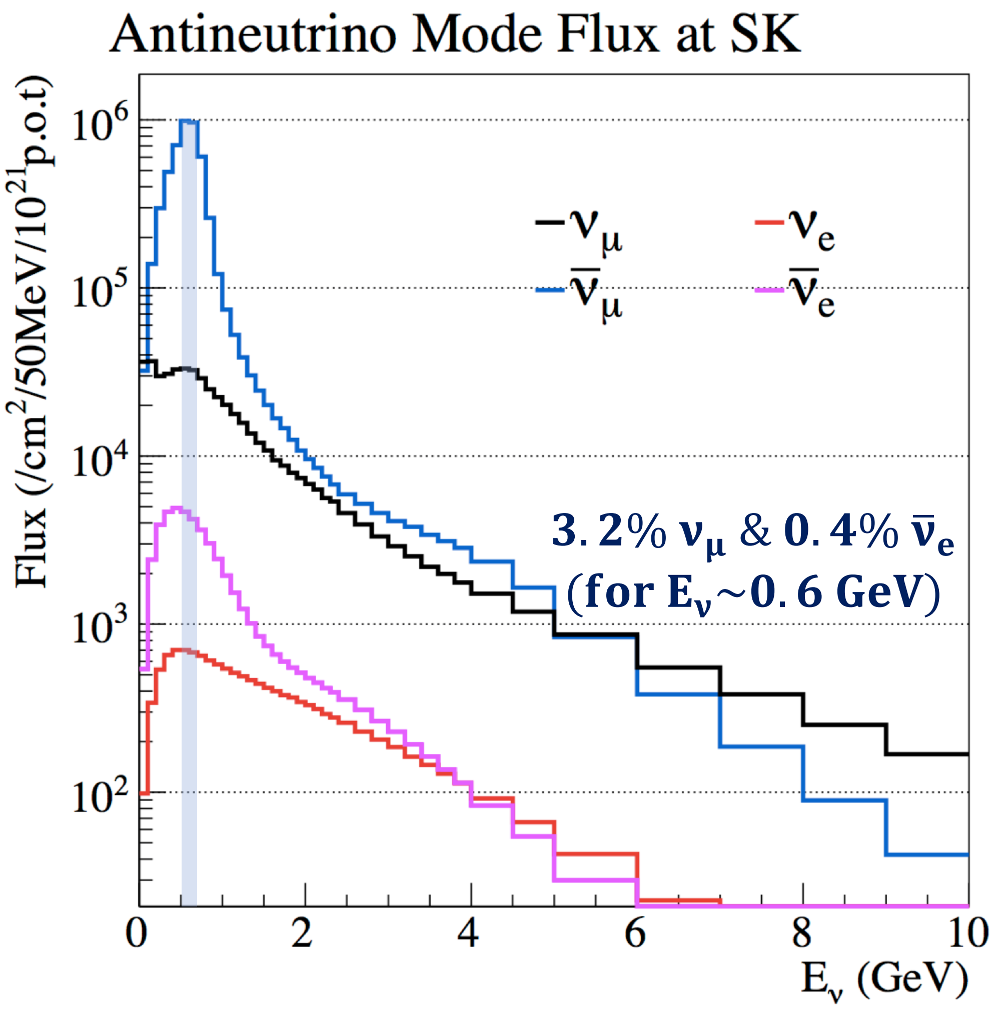
- The tuning procedure changes the nominal neutrino flux prediction
- The weight assigned to every neutrino event is given by the product of interaction length and multiplicity weights for every interaction in the hadronic cascade



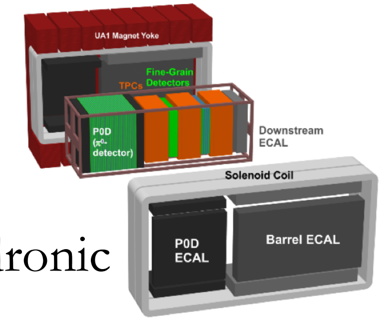
The T2K Neutrino Flux Calculation

- Understanding the intrinsic ν_e ($\bar{\nu}_e$) flux is important for the $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance analysis
- Wrong sign contamination is greater in $\bar{\nu}$ mode flux (isoscalar target and proton beam)

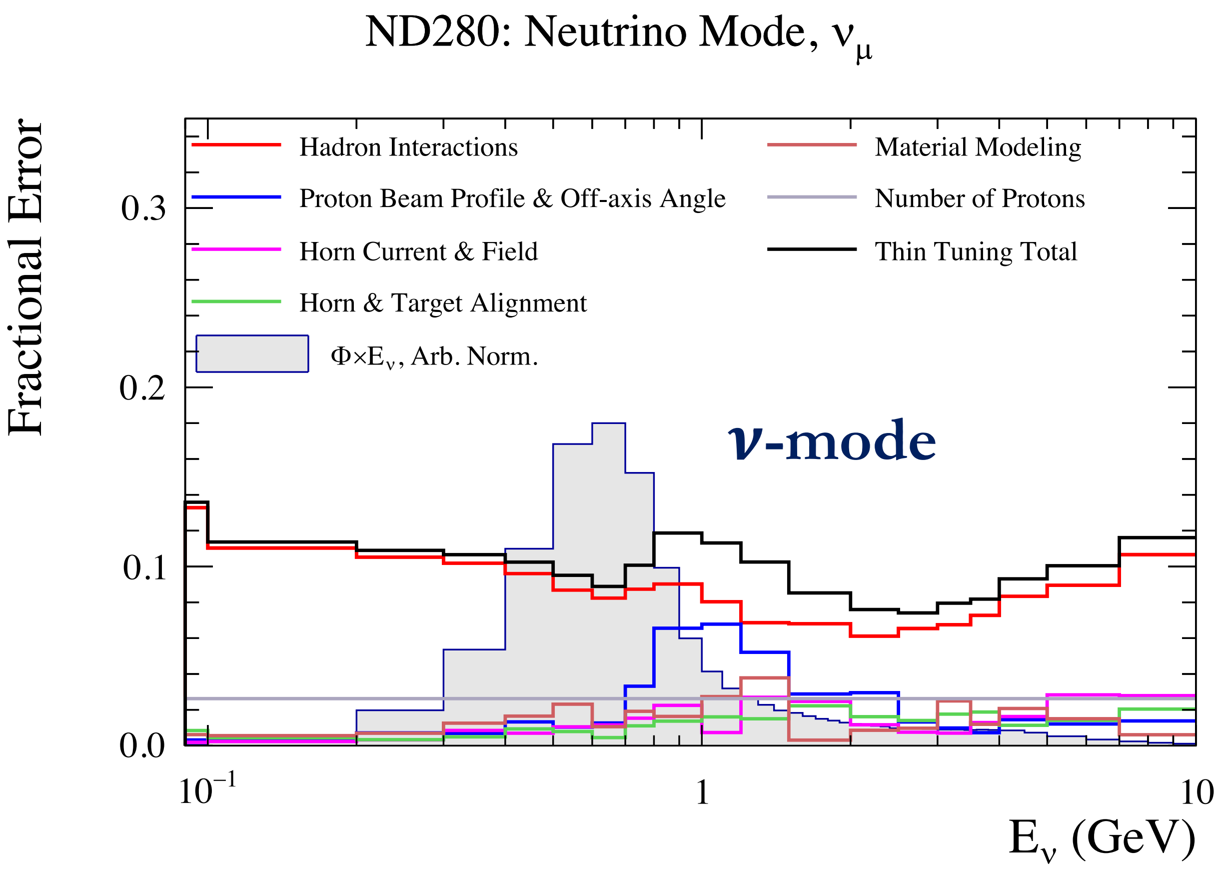


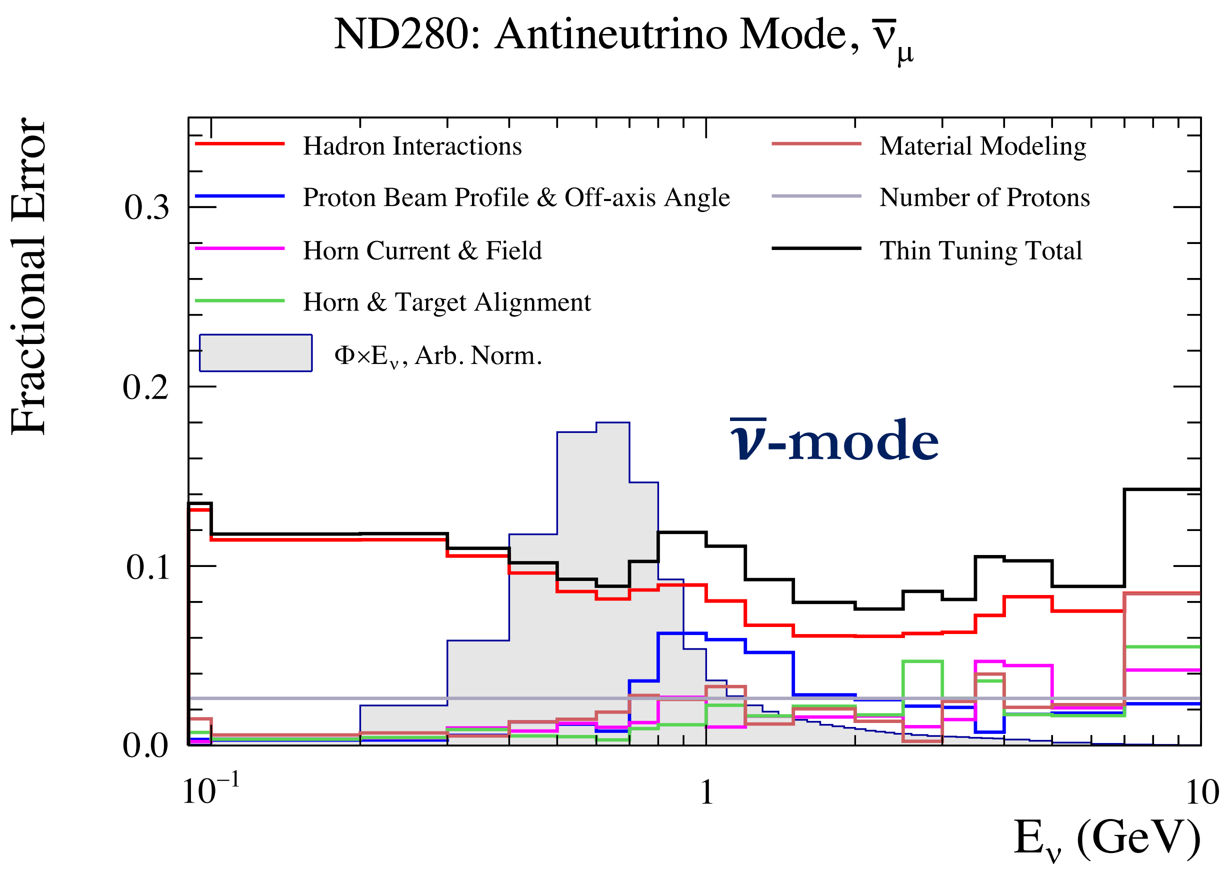


Total T2K Thin-Tuned Flux Prediction Uncertainties

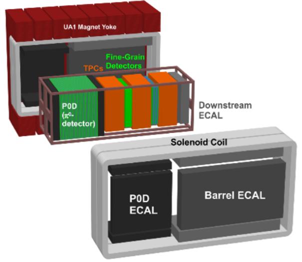


- NA61 thin-target data directly constrains primary p + C interactions inside the target (~60%)
- The total uncertainty on the neutrino flux is still dominated by our limited understanding of hadronic interactions inside the long graphite target and within the secondary beamline
- Flux uncertainty at T2K signal peak is ~9%





T2K Flux Uncertainties Separated Into Different Contributions



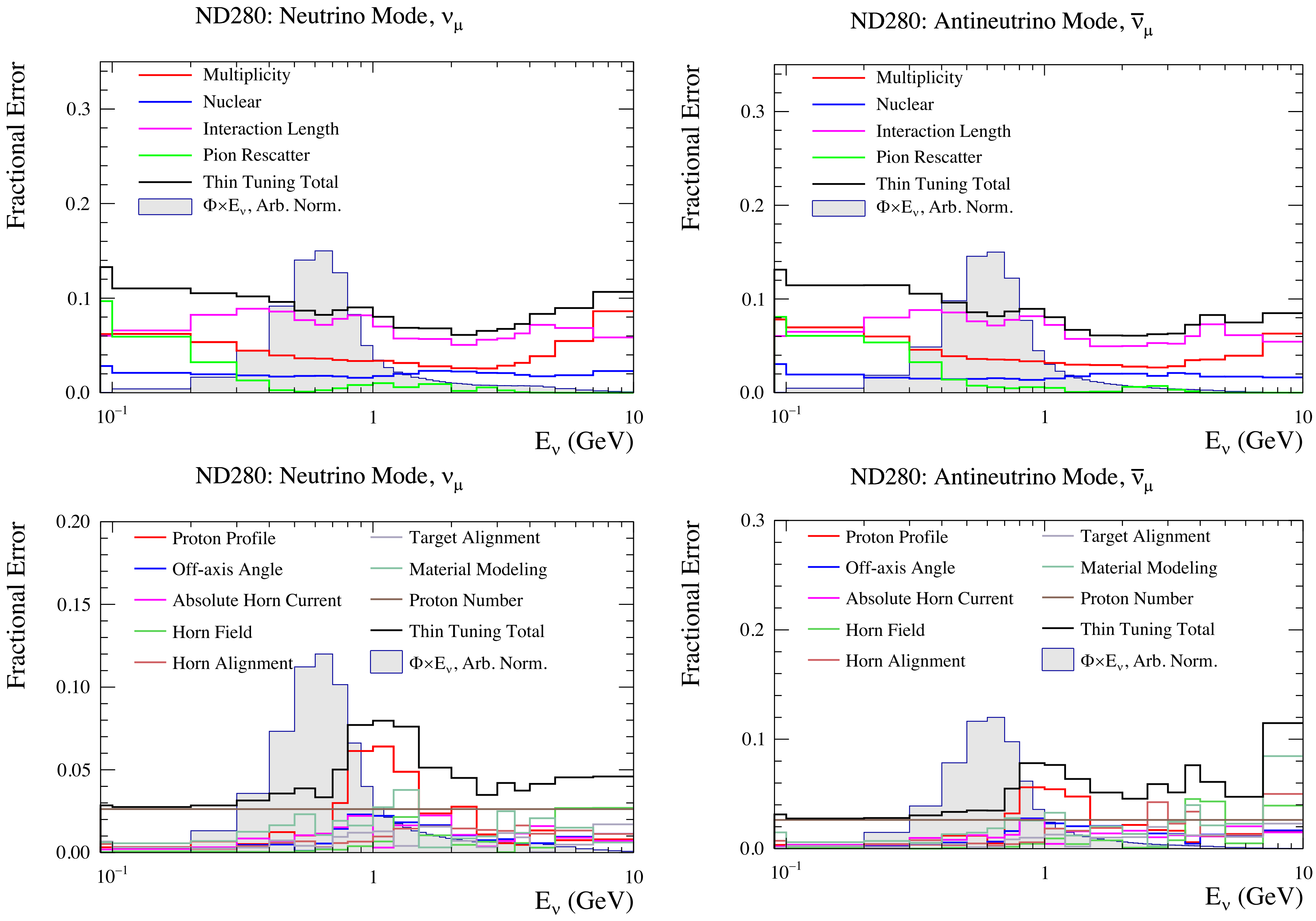
Using 2009 thin-target data

Hadronic Interaction Modelling Component

Interaction length uncertainty, multiplicity uncertainty (NA61 systematics) etc.

Non-Hadronic Component

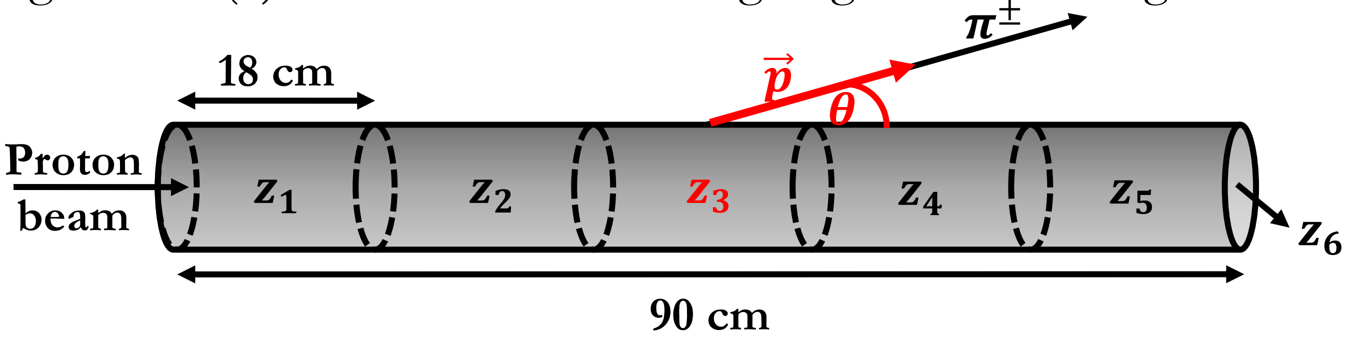
Proton beam profile, POT uncertainty etc.



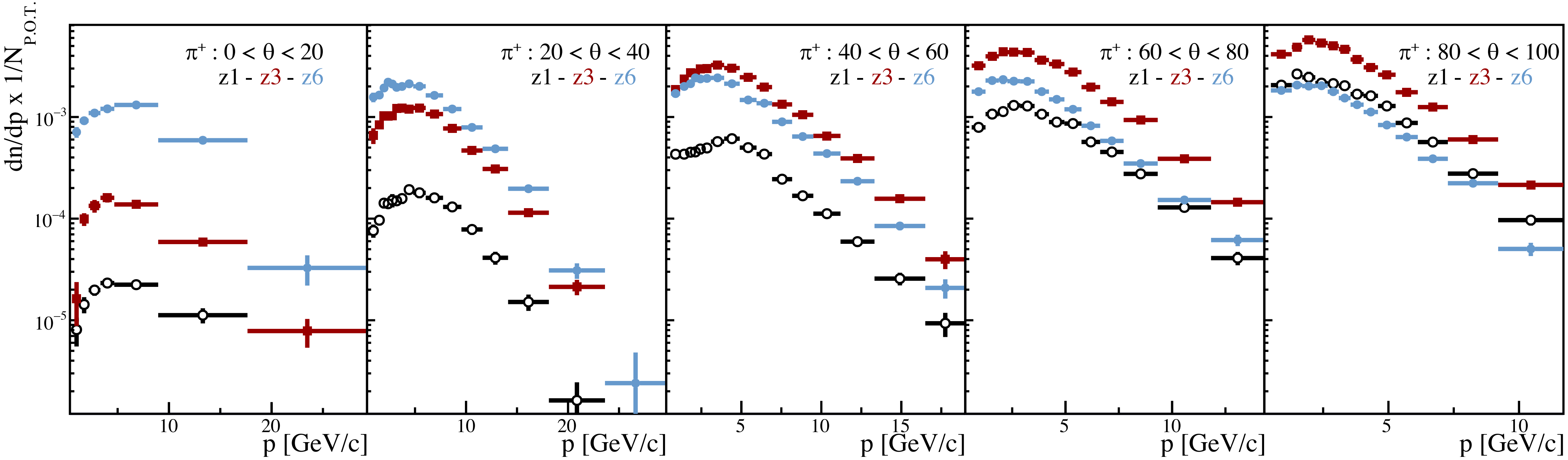
T2K Neutrino Flux Prediction: Where next?

NA61 2009 replica-target dataset
arXiv:1603.06774

- NA61 also collected multiple sets of data with an exact replica of the T2K target
- Incorporating the **NA61 2009 replica-target data** ($\pi^{\pm}$ multiplicities) into the flux reweighting procedure
- Replica-target data is additionally binned in the longitudinal (z) coordinate of the outgoing hadron exiting position, besides the standard (p, θ) bins
- This dataset is expected to constrain up to 90% of hadronic interactions

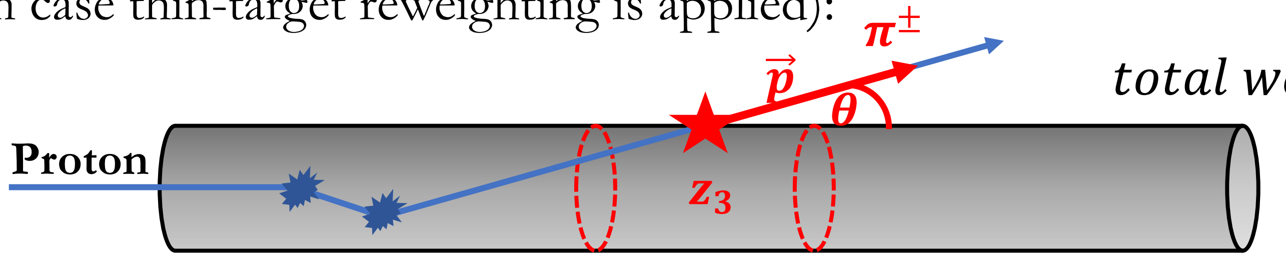


Part of NA61 2009 Replica Target Data for π^+:

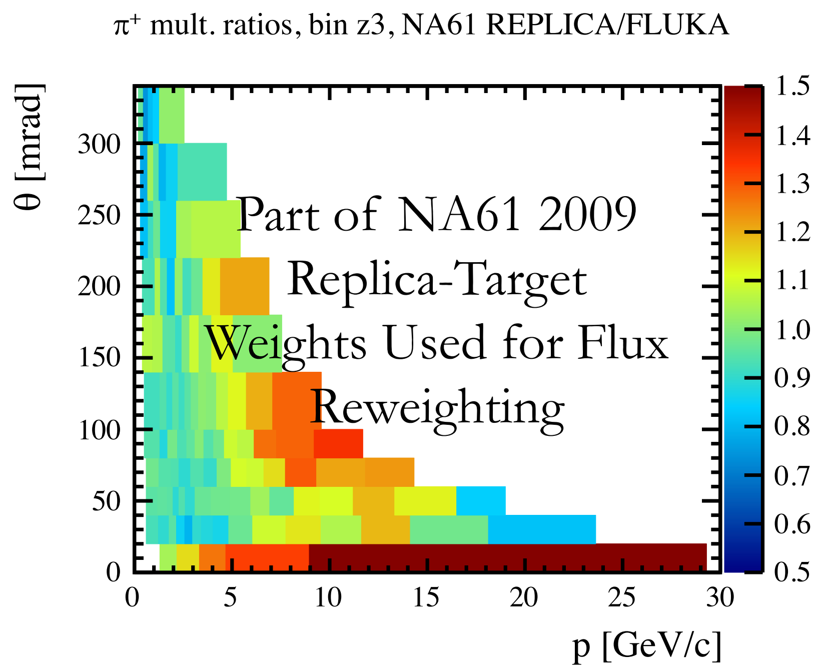


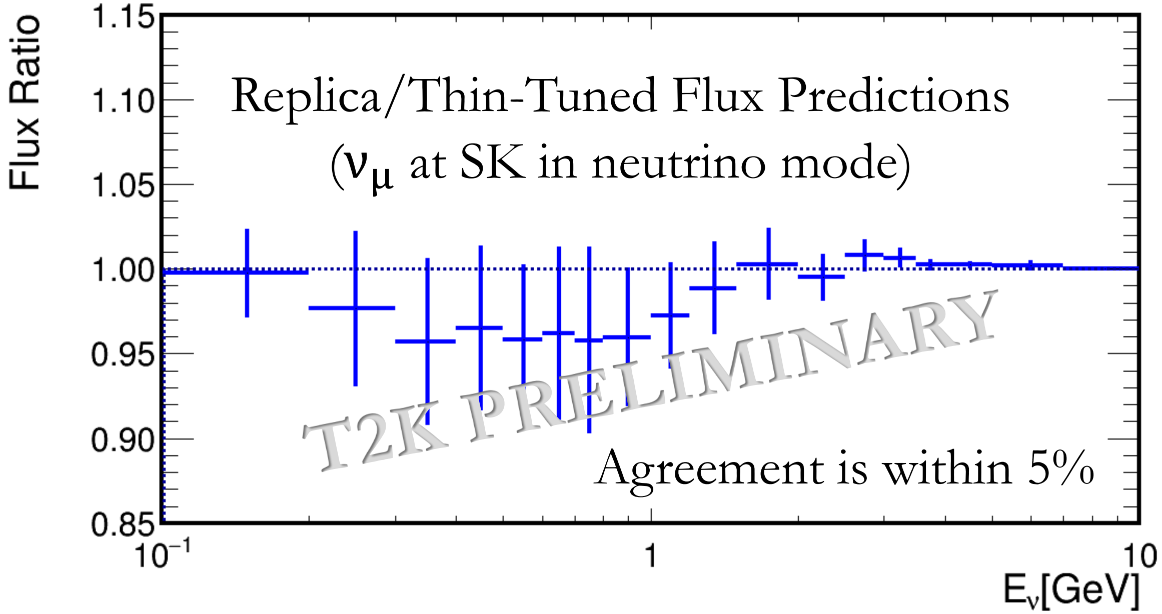
NA61/SHINE 2009 Replica-Target Flux Tuning Procedure

- Replica-target tuning corrects only the outgoing rate for charged pions exiting the T2K target (no reweighting is applied for interactions inside the target, unless the exiting particle is different from a pion, in which case thin-target reweighting is applied):

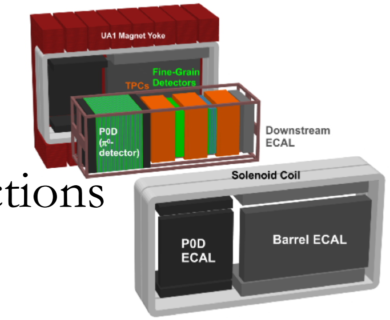


$$total\ weight = weight(p, \theta, z_3)$$



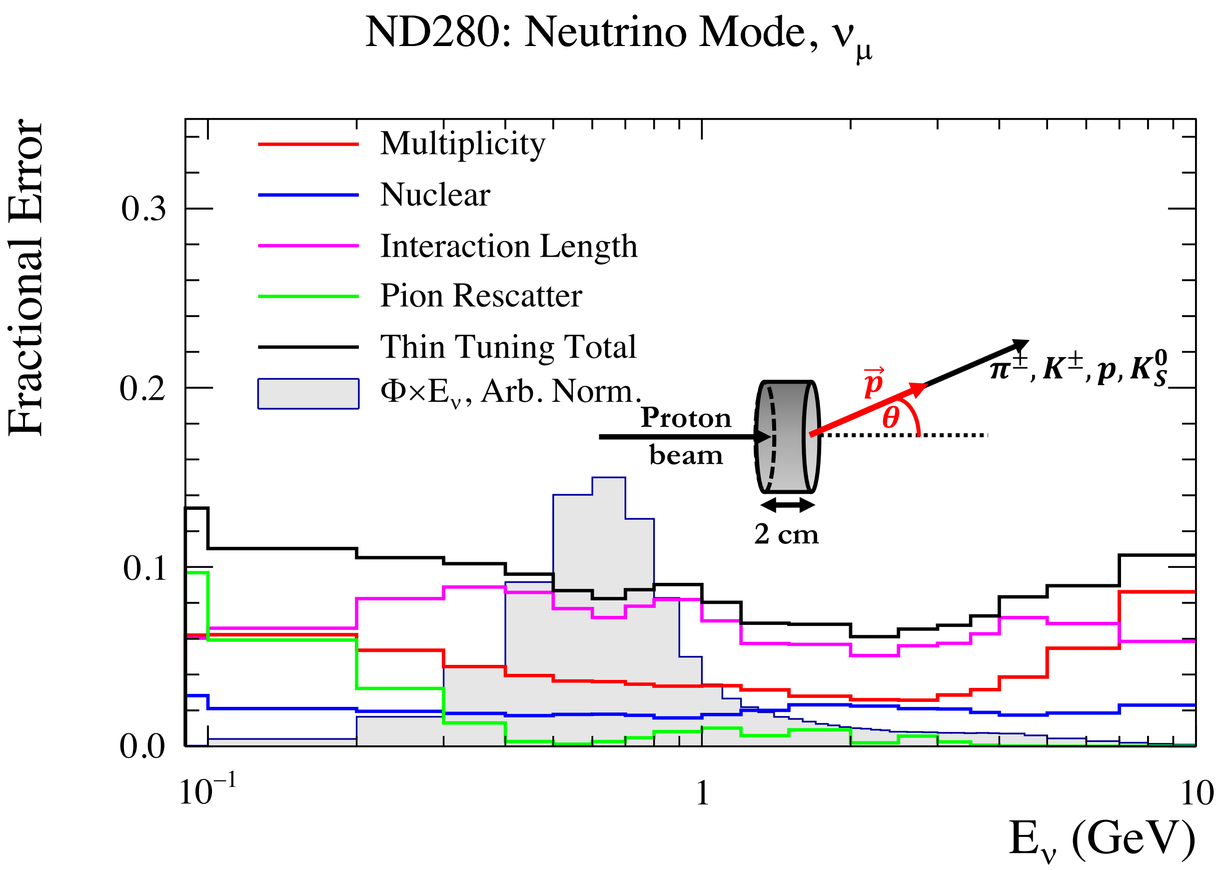


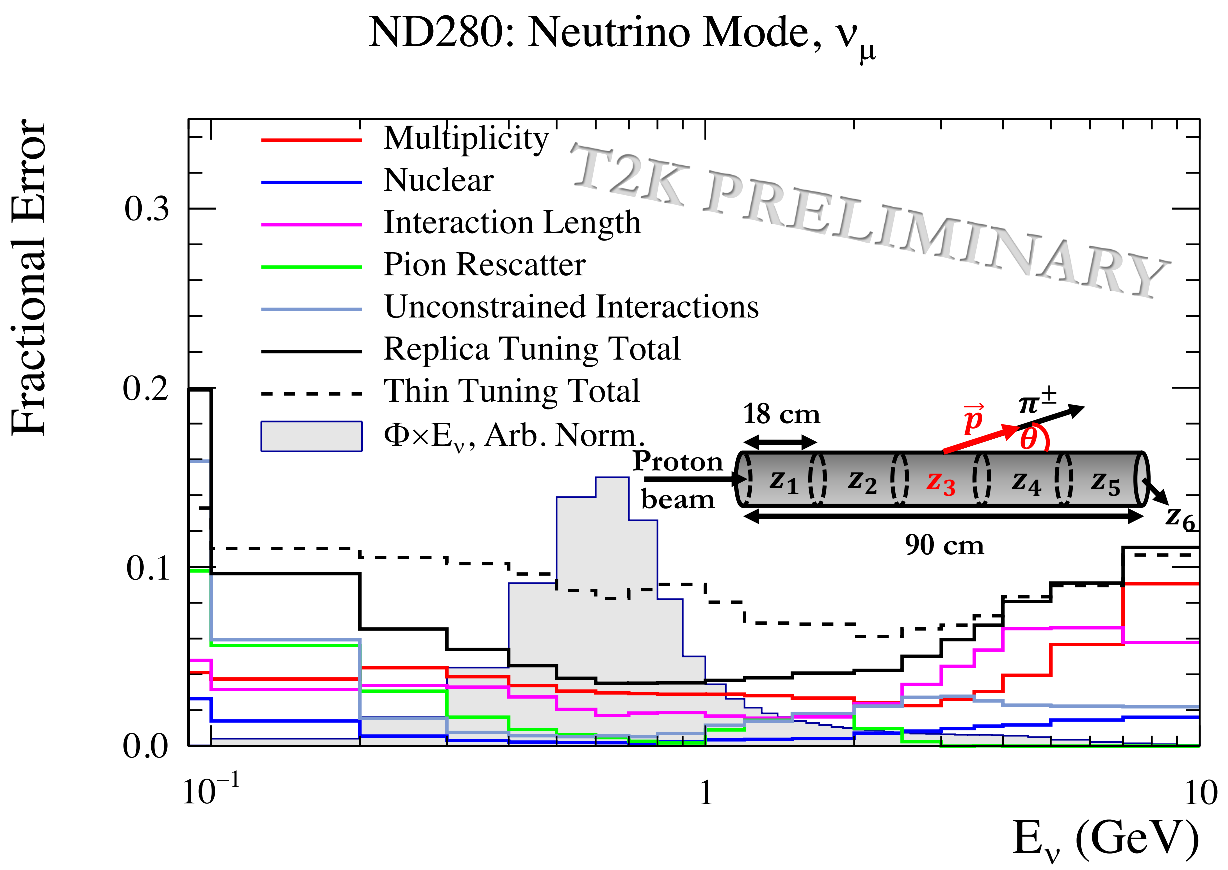
Comparing 2009 Thin-Tuned and 2009 Replica-Tuned Hadron Interaction Modelling Flux Uncertainties



- Replica-target data directly constrains both in-target primary interactions and in-target re-interactions

- A decrease from ~9% to ~5% is observed in the hadron interaction length part of the flux uncertainty with the inclusion of the 2009 replica-target dataset





Unconstrained hadronic interactions at ND280: We need more hadron production measurements!

- A significant number of hadronic interactions contributing to neutrino production (especially for wrong sign and wrong flavour fluxes) cannot be constrained with existing measurements

External Measurements	Fraction of Constrained Interactions in the Hadronic Ancestry							
	ND280 ν_μ ν-mode	ND280 $\bar{\nu}_\mu$ ν-mode	ND280 ν_e ν-mode	ND280 $\bar{\nu}_e$ ν-mode	ND280 ν_μ $\bar{\nu}$-mode	ND280 $\bar{\nu}_\mu$ $\bar{\nu}$-mode	ND280 ν_e $\bar{\nu}$-mode	ND280 $\bar{\nu}_e$ $\bar{\nu}$-mode
NA61 2009 Thin Data	86.0%	80.1%	84.0%	75.8%	80.4%	85.5%	76.6%	83.5%
+ NA61 2009 Replica Data	94.0%	83.4%	89.7%	76.2%	83.7%	93.7%	76.9%	90.2%
+ HARP data	96.5%	87.3%	91.2%	76.7%	87.2%	96.3%	77.3%	91.8%

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External Measurements	Fraction of Constrained Interactions in the Hadronic Ancestry							
	ND280 ν_μ ν-mode	ND280 $\bar{\nu}_\mu$ ν-mode	ND280 ν_e ν-mode	ND280 $\bar{\nu}_e$ ν-mode	ND280 ν_μ $\bar{\nu}$-mode	ND280 $\bar{\nu}_\mu$ $\bar{\nu}$-mode	ND280 ν_e $\bar{\nu}$-mode	ND280 $\bar{\nu}_e$ $\bar{\nu}$-mode
NA61 2009 Thin Data	86.0%	80.1%	84.0%	75.8%	80.4%	85.5%	76.6%	83.5%
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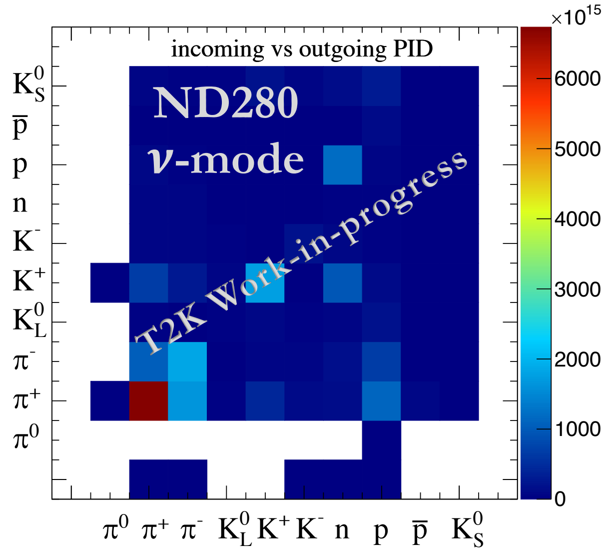
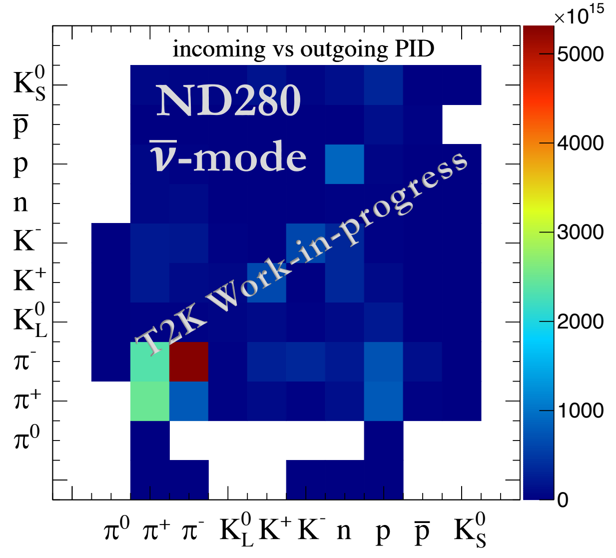
- Unconstrained FHC (RHC) interactions: dominated by low energy inclusive $\pi^{+(-)} \to \pi^{+(-)}$ interactions on Al, Fe, C, Ti etc.

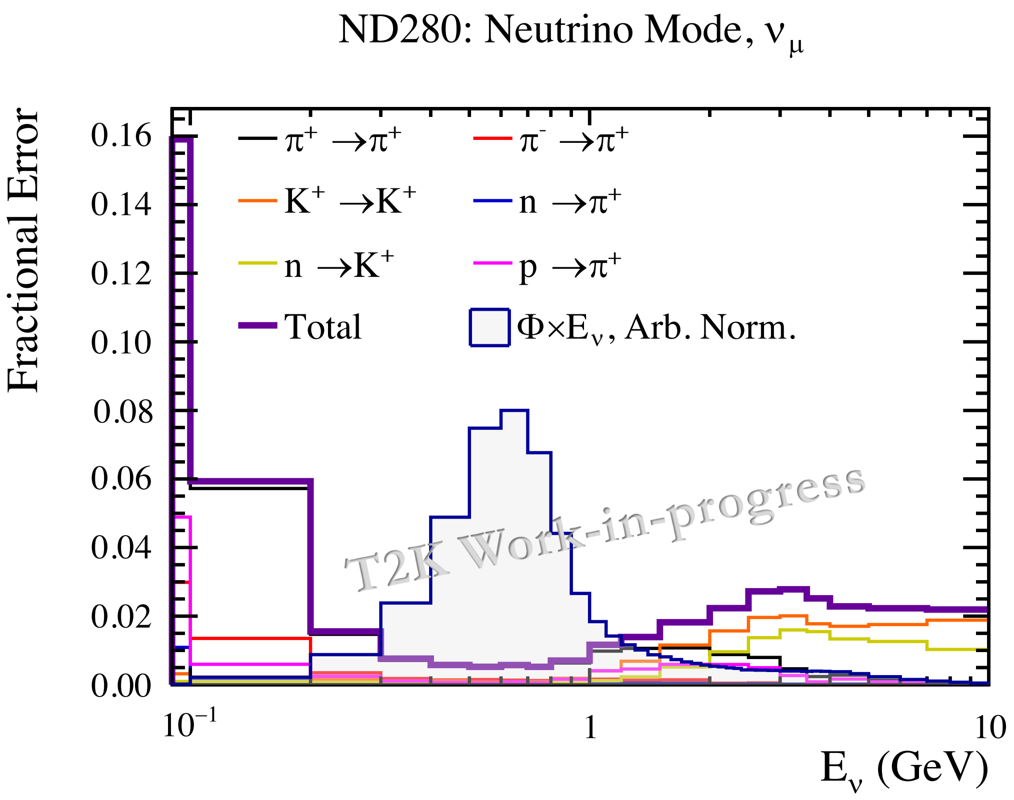
← Increasing Importance

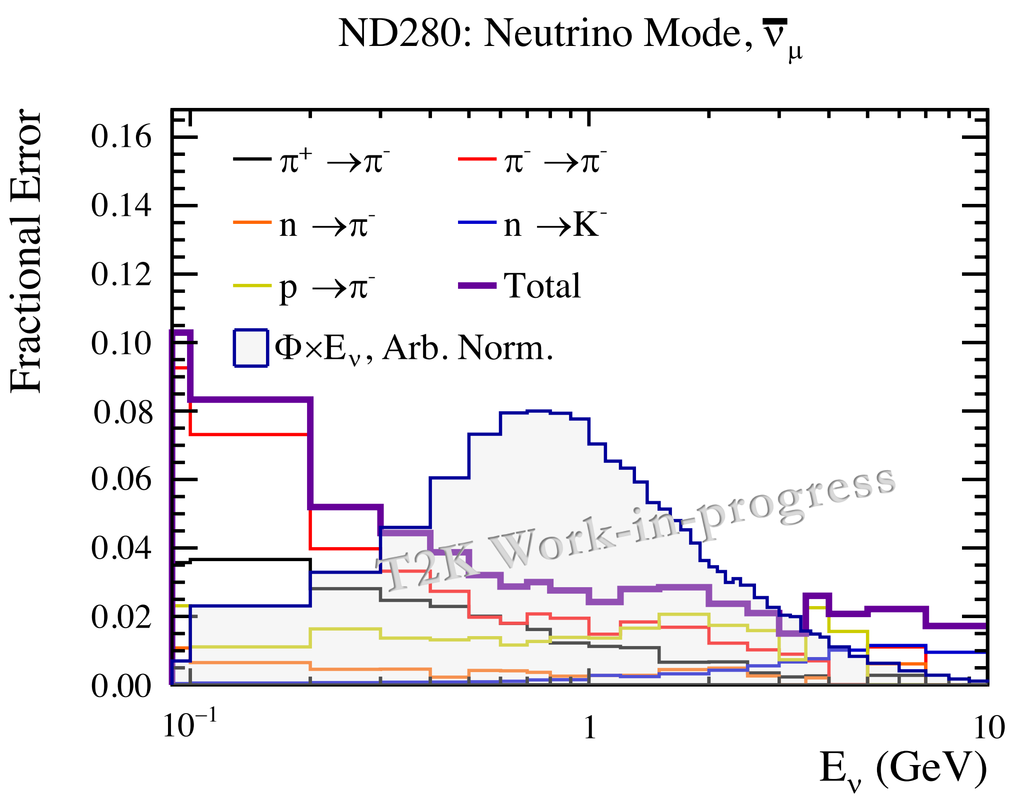




Assigning flux uncertainties

- The dominant flux uncertainty for some flavours and energies becomes the uncertainty on interactions not constrained by data
- Significant variation in predictions from different generators (FLUKA, GEANT4 physics lists etc.)
- A proper estimation of these uncertainties is challenging





Conclusions

- Current uncertainty on the T2K neutrino flux prediction is ~9% at peak T2K neutrino energy
  - Flux reweighting is based on the NA61 2009 thin-target data

- NA61 replica-target data directly constrains up to ~30% more hadronic interactions than thin-target data

- Inclusion of the 2009 replica-target data reduces the flux uncertainty from ~9% to ~5% at T2K flux peak

- Implementation of the 2010 replica-target data (with kaon yields from the replica target) into the T2K flux calculation is in progress: stay tuned for results in 2019

- **Our ability to probe interactions of neutrinos from conventional fluxes** (accelerator, atmospheric etc.) **will always be tied our understanding of the underlying hadron production**, but with clever choices of future hadron production measurements the future is bright!

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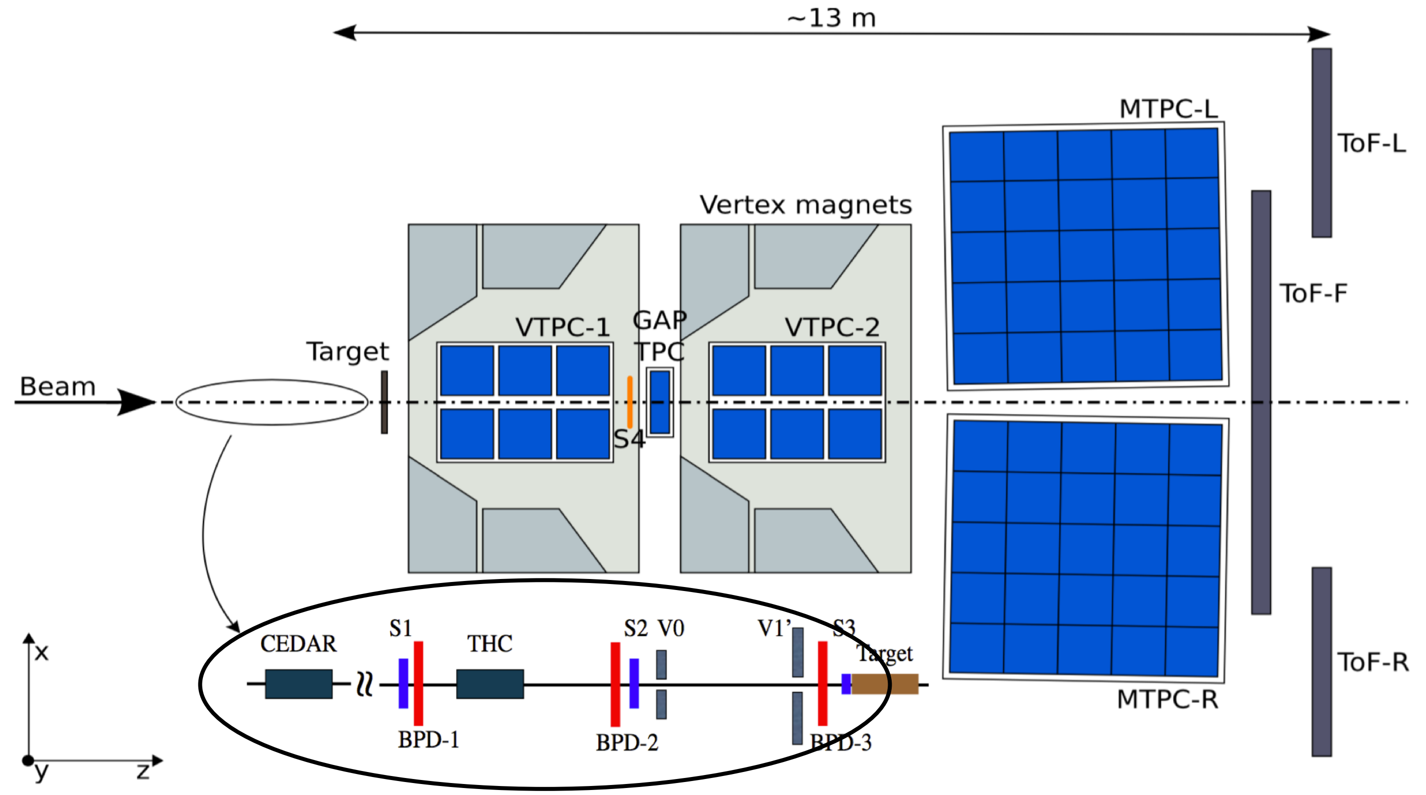
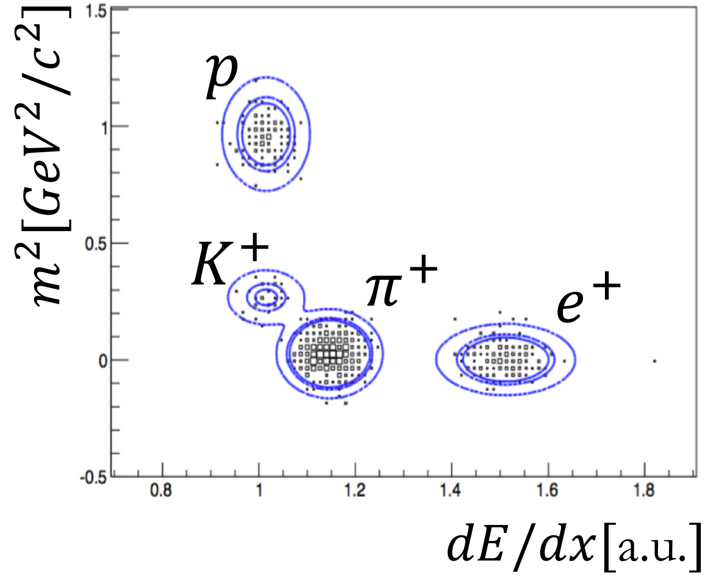
Backup

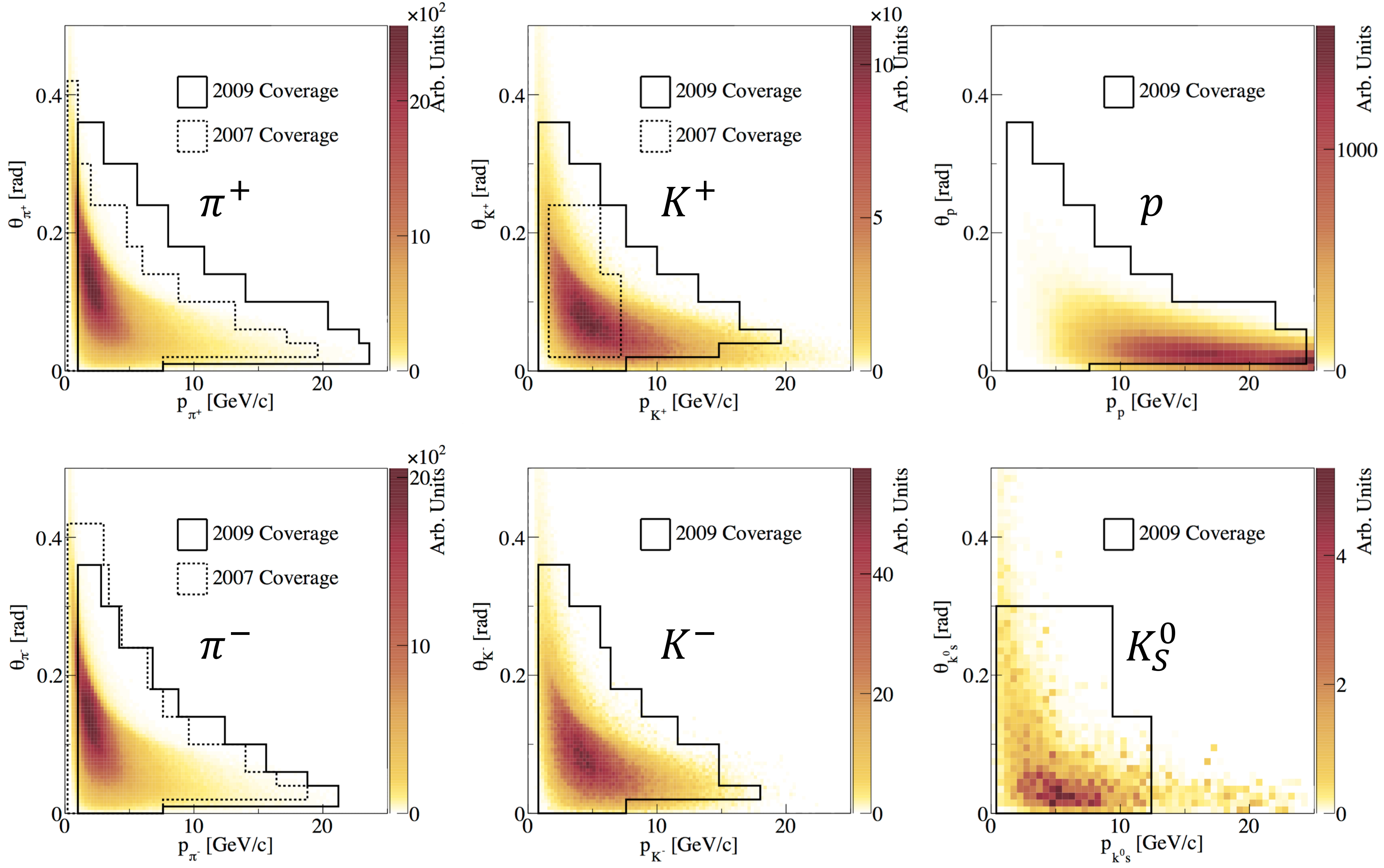
NA61/SHINE Experimental Setup

- Multi-purpose hadron production experiment based in CERN (effectively a large spectrometer)
- Different targets can be inserted (two target configurations used for T2K, thin-target and replica-target)
- Triggering on incoming particle type and energy
- 5 time projection chambers (TPCs) combined with magnets used for particle tracking
- Time-of-flight (ToF) and energy-loss analysis employed for outgoing PID

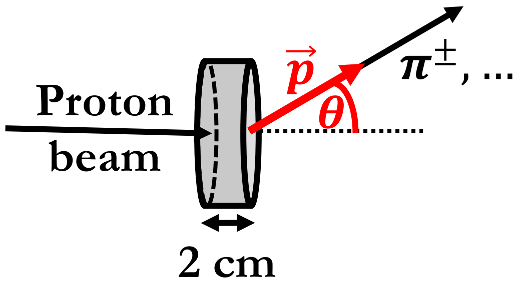




Phase Space Coverage Of NA61 Thin-Target Data (2007 & 2009)



- Thin-target: 2 cm thick graphite
- Good coverage of the phase space relevant for the T2K neutrino flux prediction



NA61 2007 thin-target dataset

arXiv:1102.0983

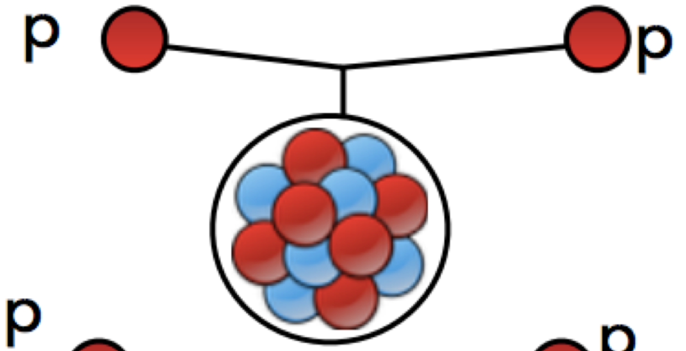
arXiv:1112.0150

NA61 2009 thin-target dataset

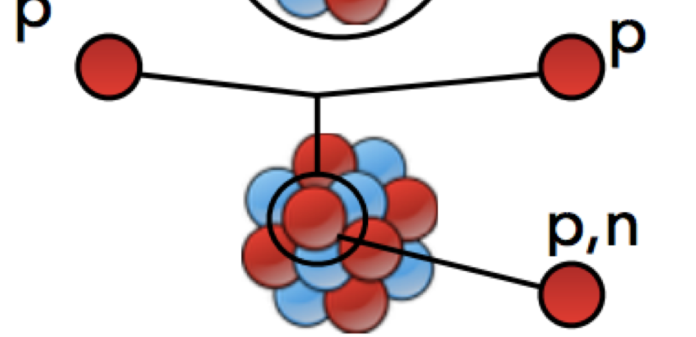
arXiv:1510.02703

Side Note on Interaction Lengths

- It is important to define the “hadronic interactions” that are measured in hadronic cross section measurements

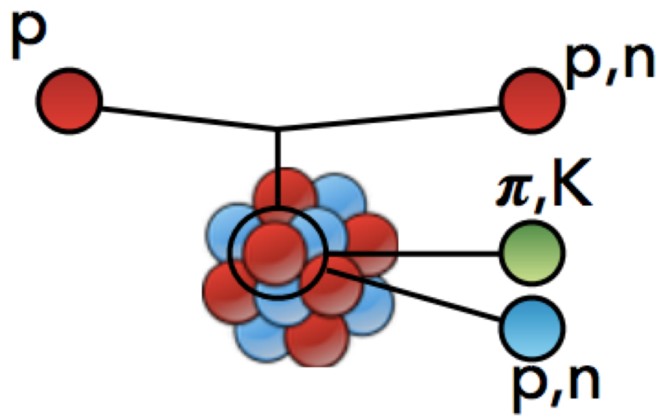


Coherent elastic scattering on the nucleus



Quasi-elastic scattering on bound nucleons

Kinematic properties similar to proton-nucleon

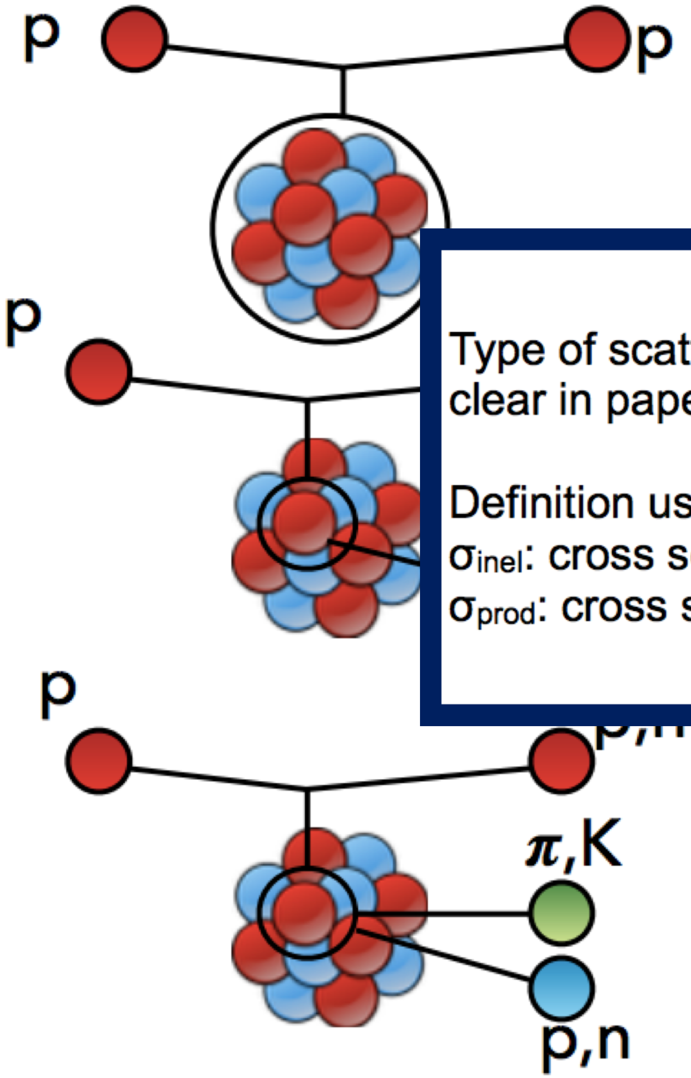


Scattering with particle production (small contribution from coherent scattering on nucleus)

~70% of the hadronic cross section

Side Note on Interaction Lengths: Ambiguous Definitions

- It is important to define the "hadronic interactions" that are measured in hadronic cross section measurements



Coherent elastic scattering on the nucleus

ns

cleon

Type of scattering included in inelastic cross section measurement is not always clear in papers. Can make interpretation of data difficult.

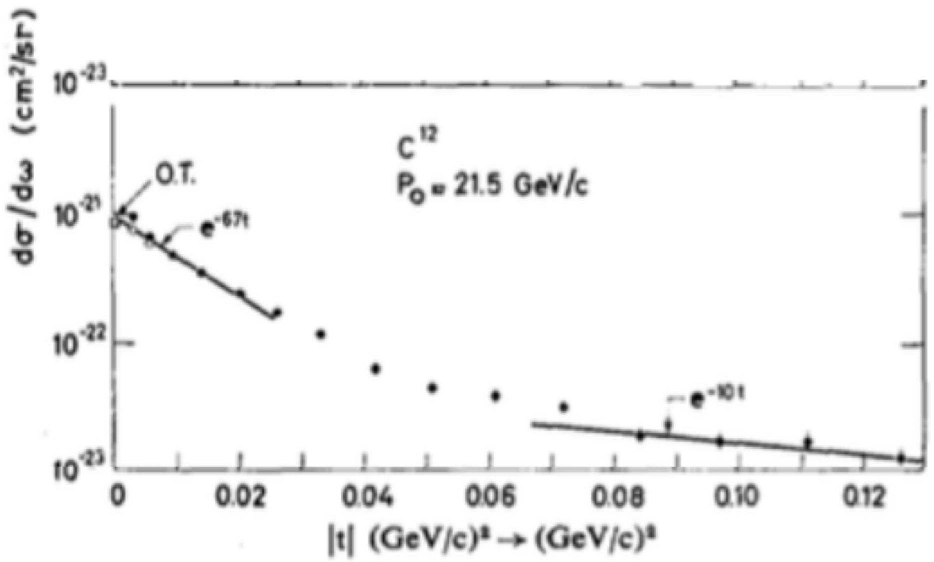
Definition used by T2K
σ_{inel}: cross section for quasi-elastic and particle production
σ_{prod}: cross section for particle production only

Scattering with particle production (small contribution from coherent scattering on nucleus)

~70% of the hadronic cross section

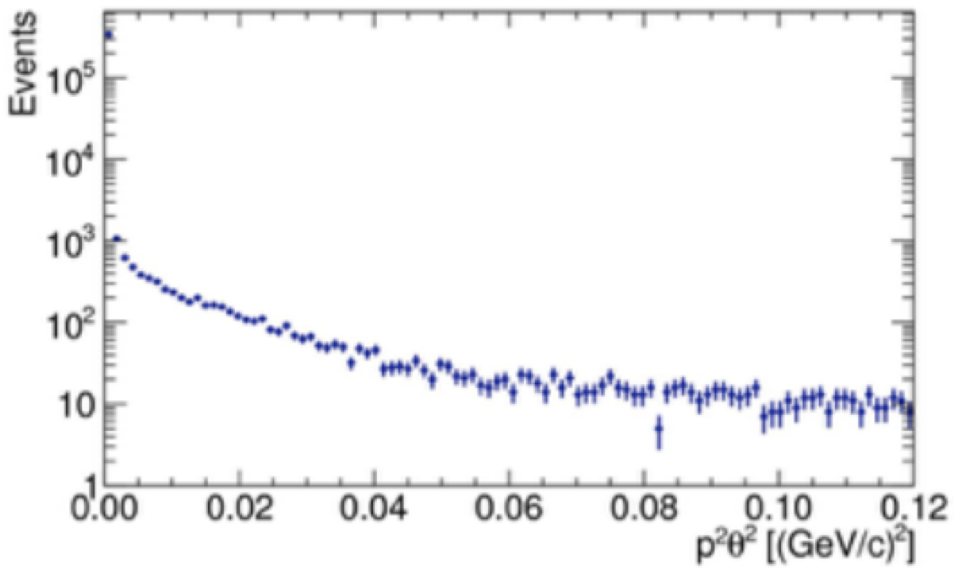
Limitations of Data

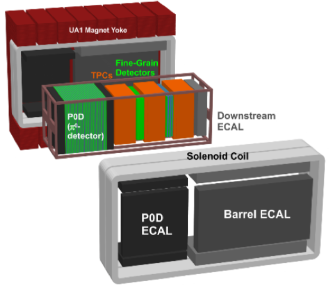
- We have trouble reconciling the NA61 thin target and replica target data
- Replica target data appears to prefer a smaller σ_{prod} than thin target data (200 mb vs. 230 mb)
  - Problem with definition of quasi-elastic vs. production cross sections?
- We should just measure the cross section as a function of the 4 momentum transfer (done in old Bellettini et. al. paper)



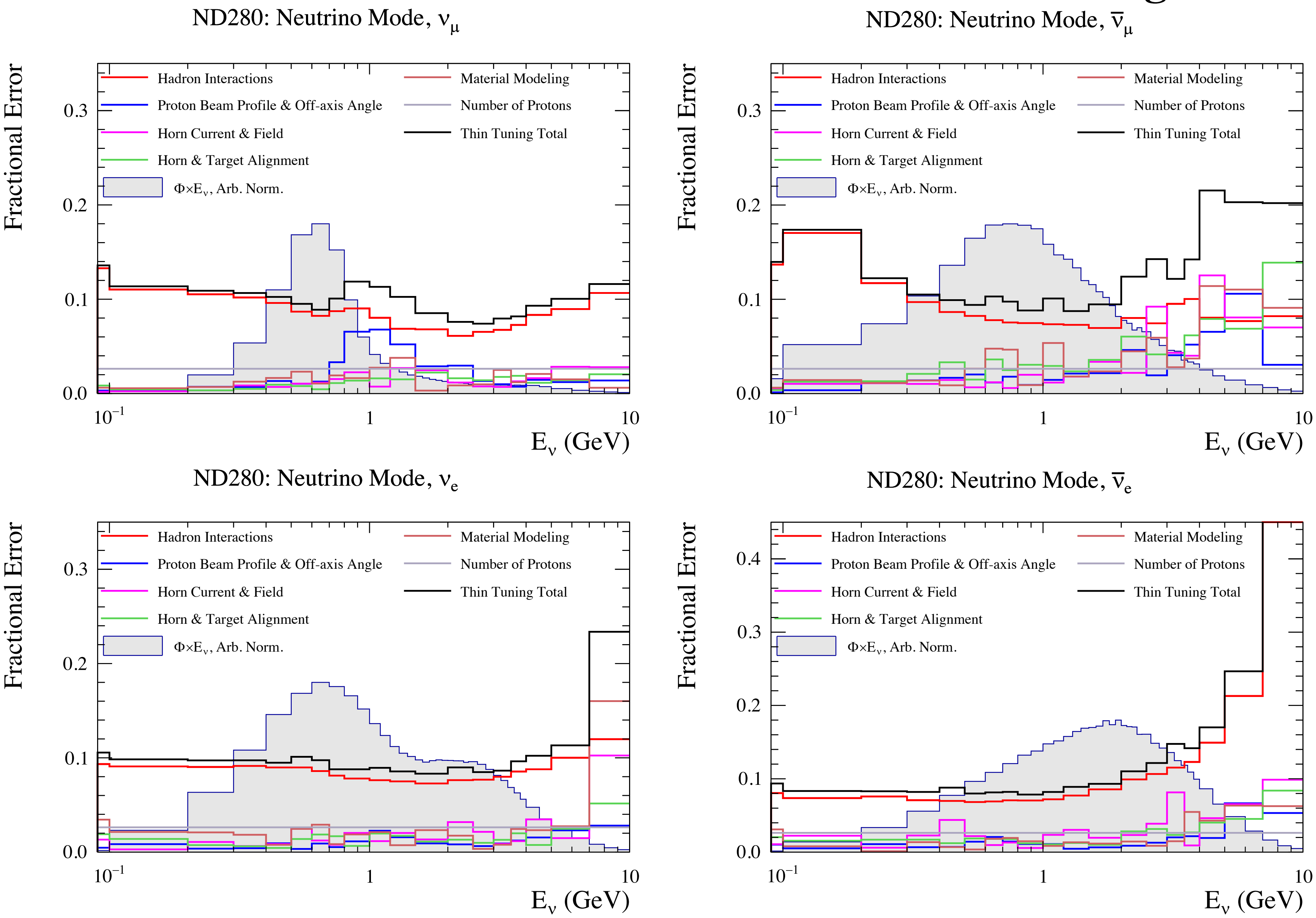
G. Bellettini et al., Nucl. Phys 79, 609 (1966).

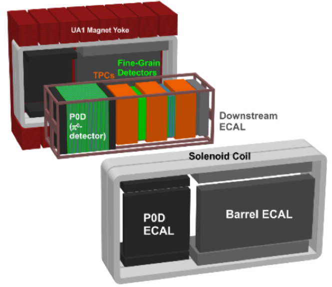
EMPHATIC Data (M. Pavin, this workshop)



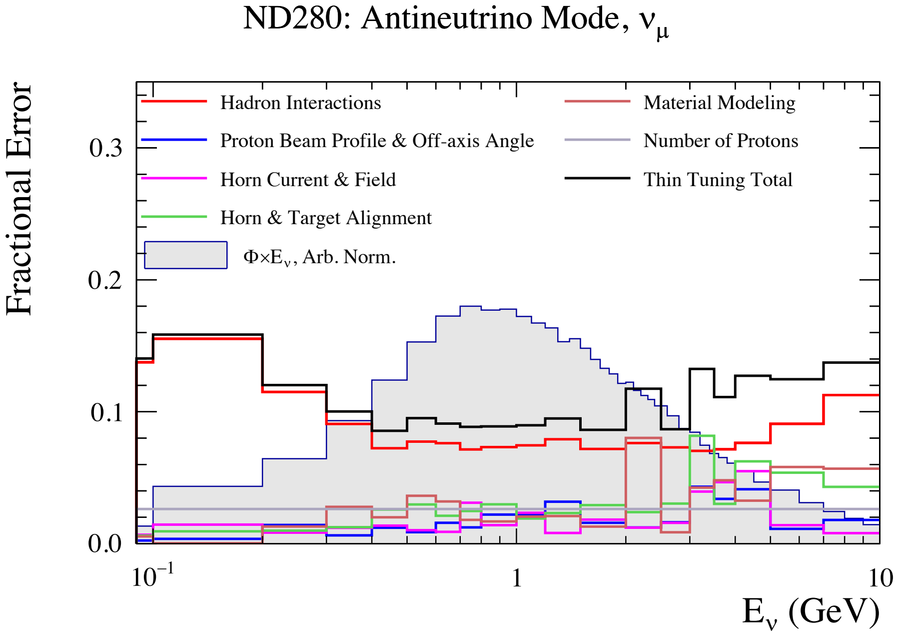


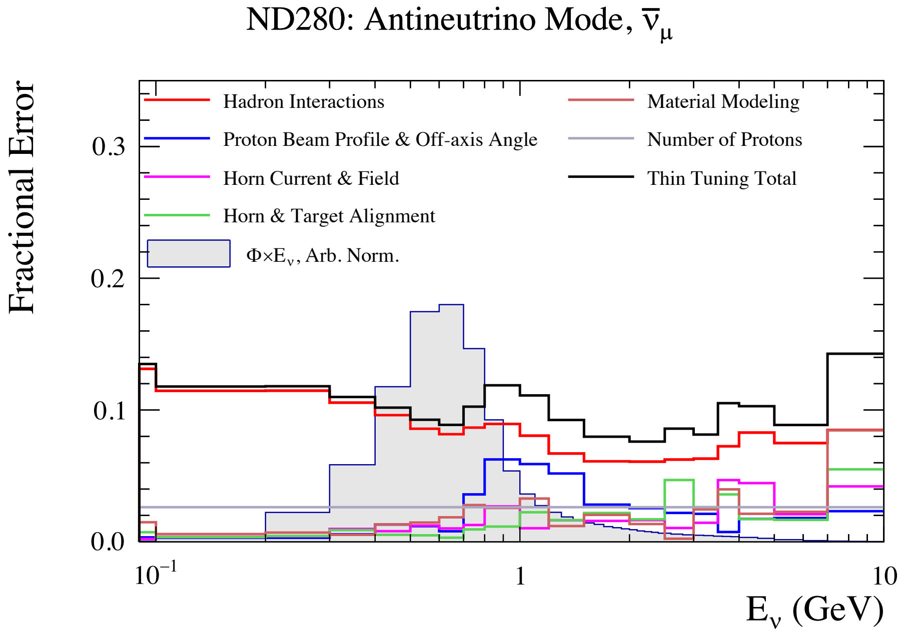
Flux Uncertainties at ND280 in ν-mode with 2009 thin-target data

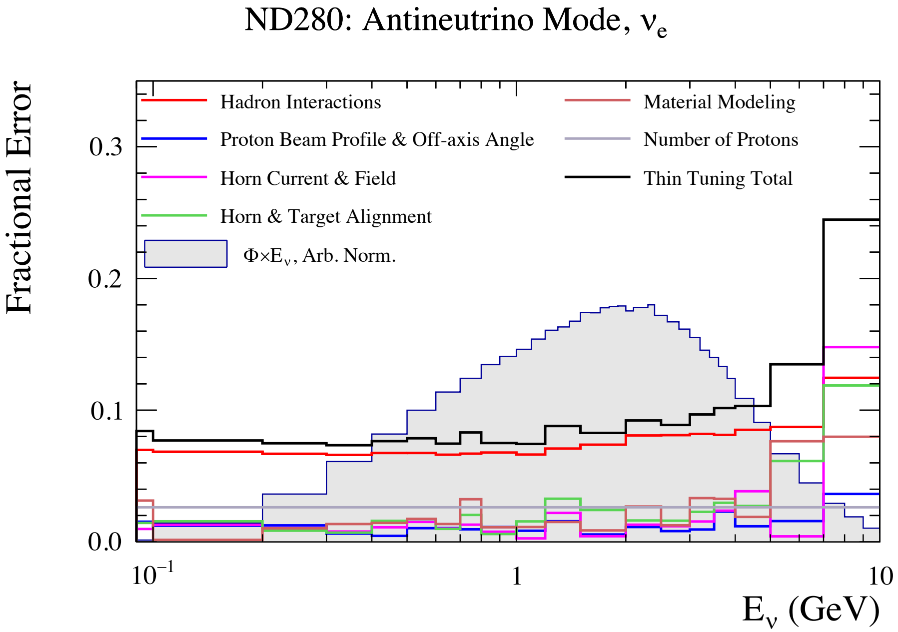


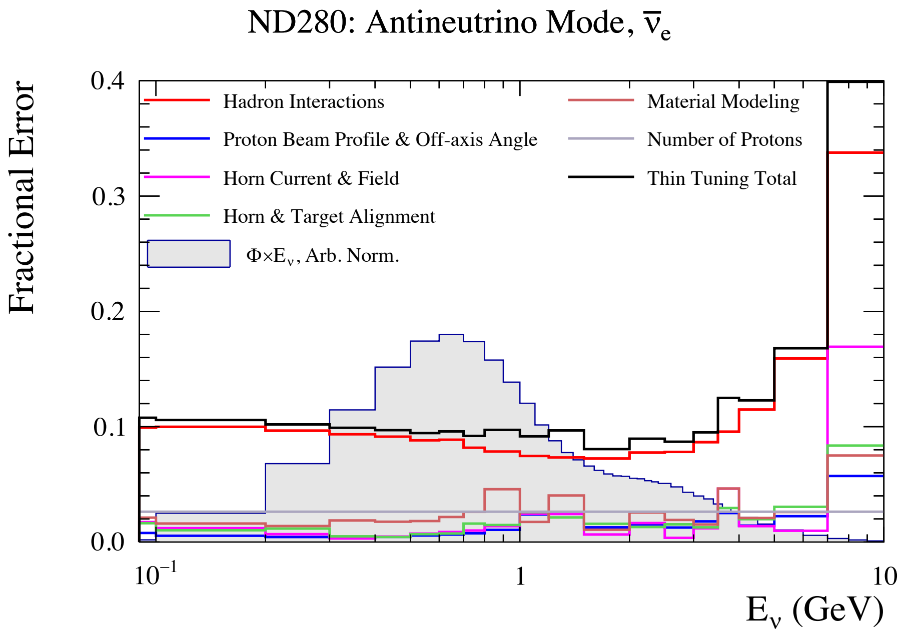


Flux Uncertainties at ND280 in $\bar{\nu}$-mode with 2009 thin-target data









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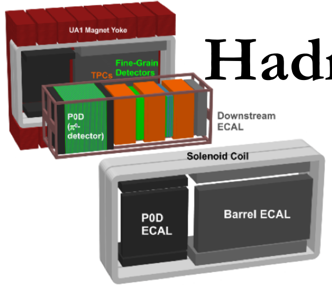
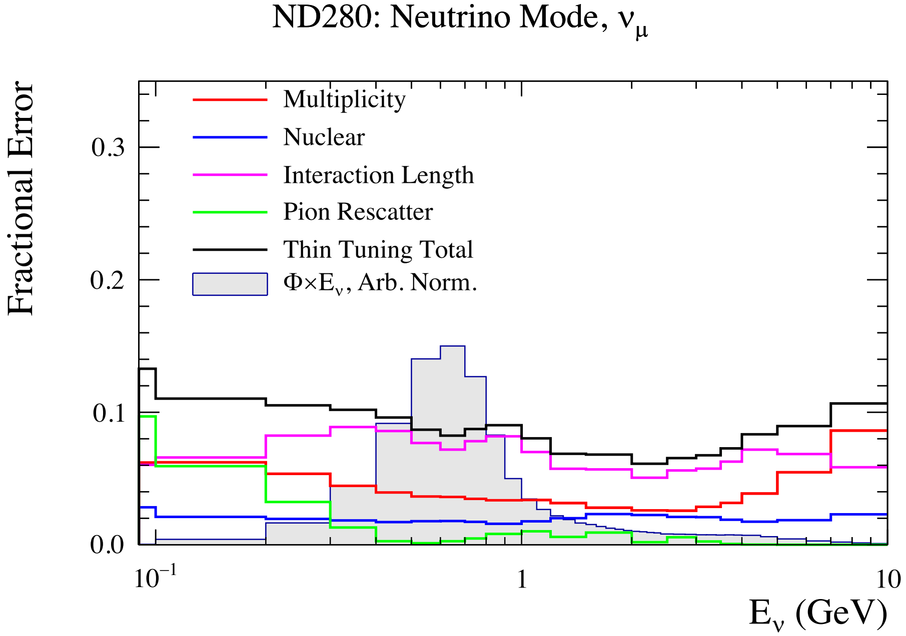
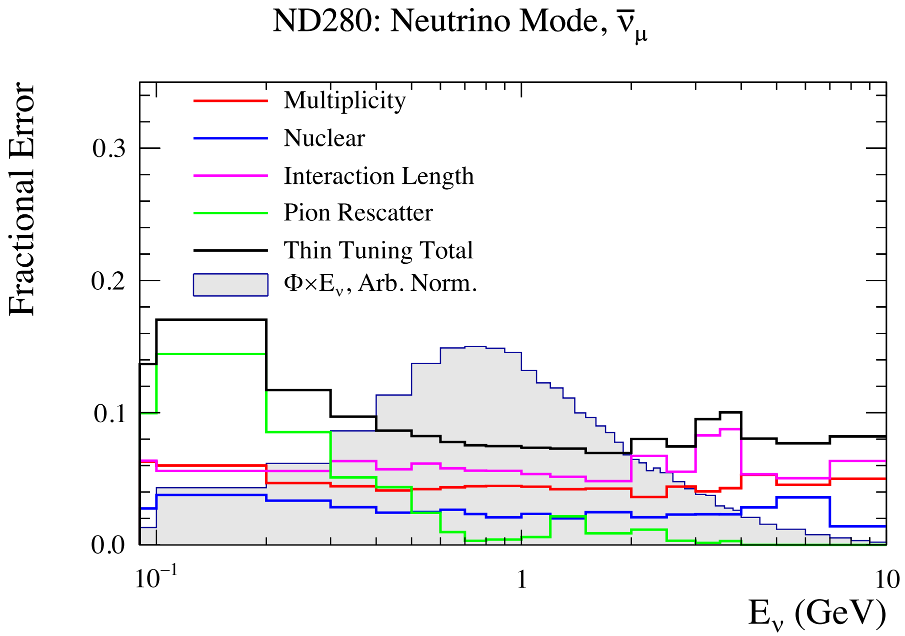
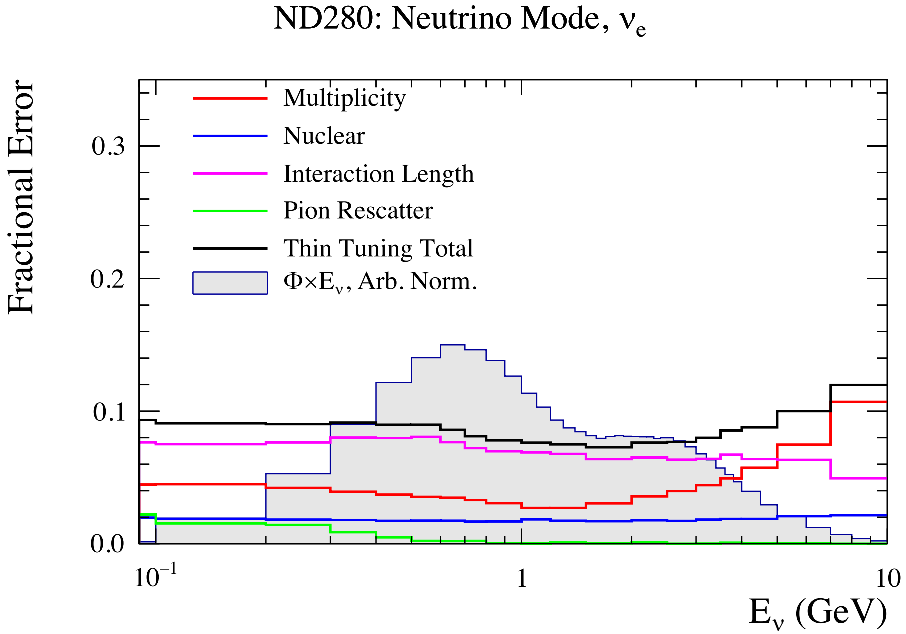
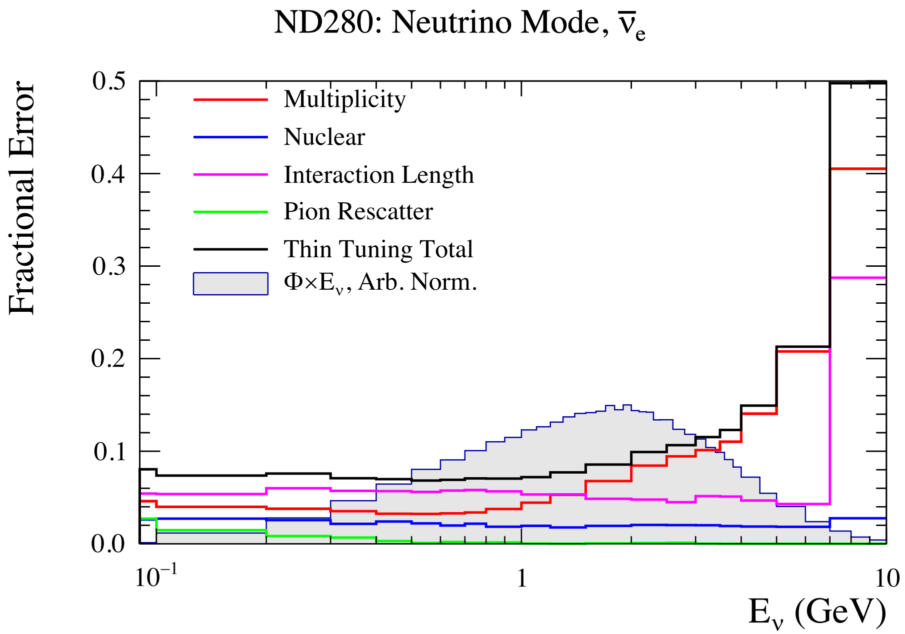


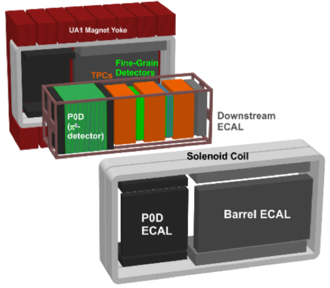


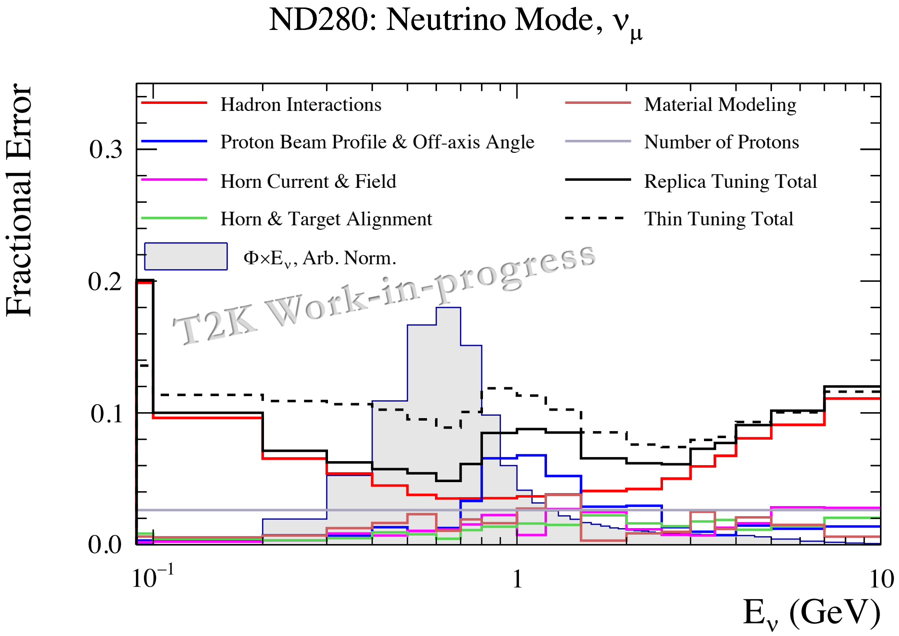


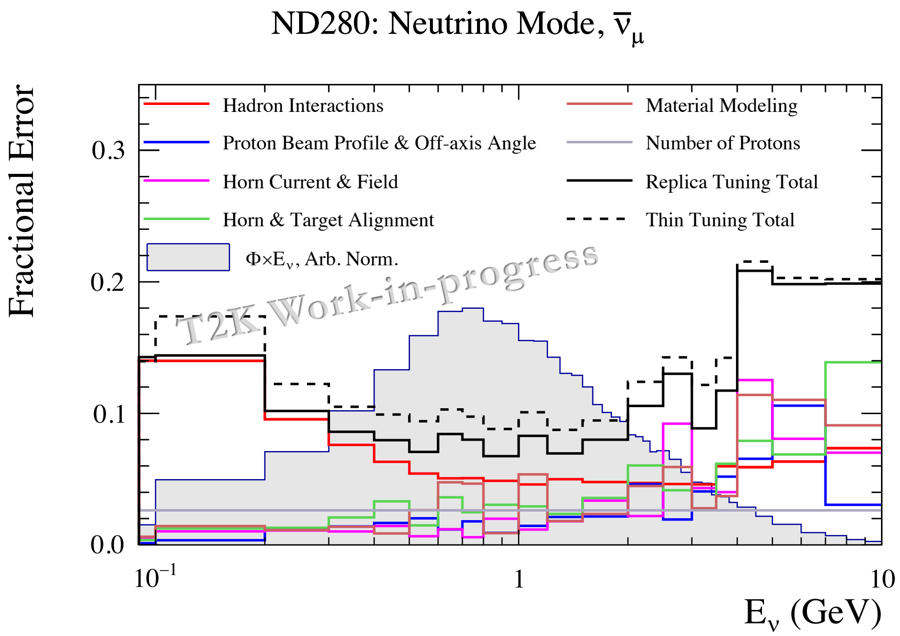


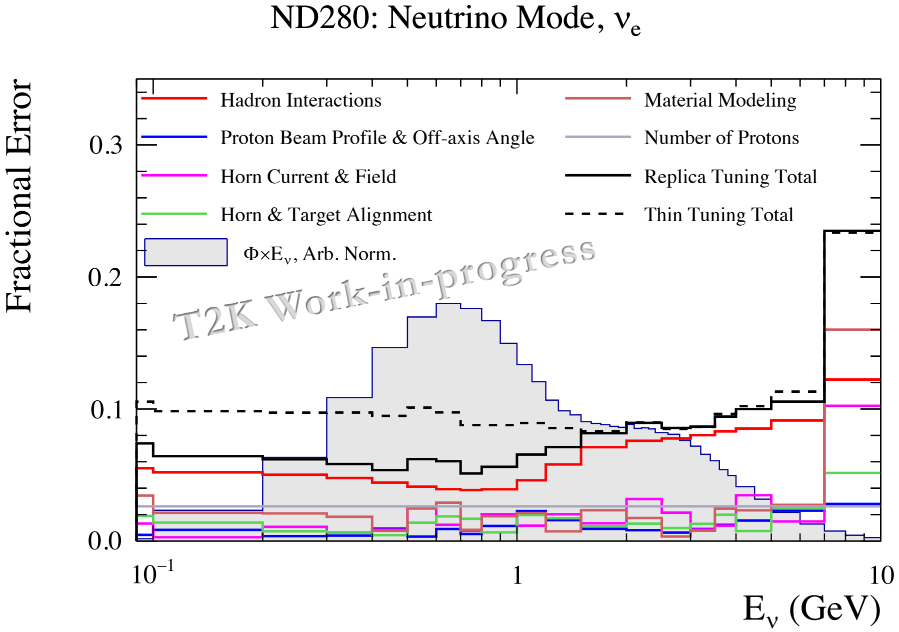


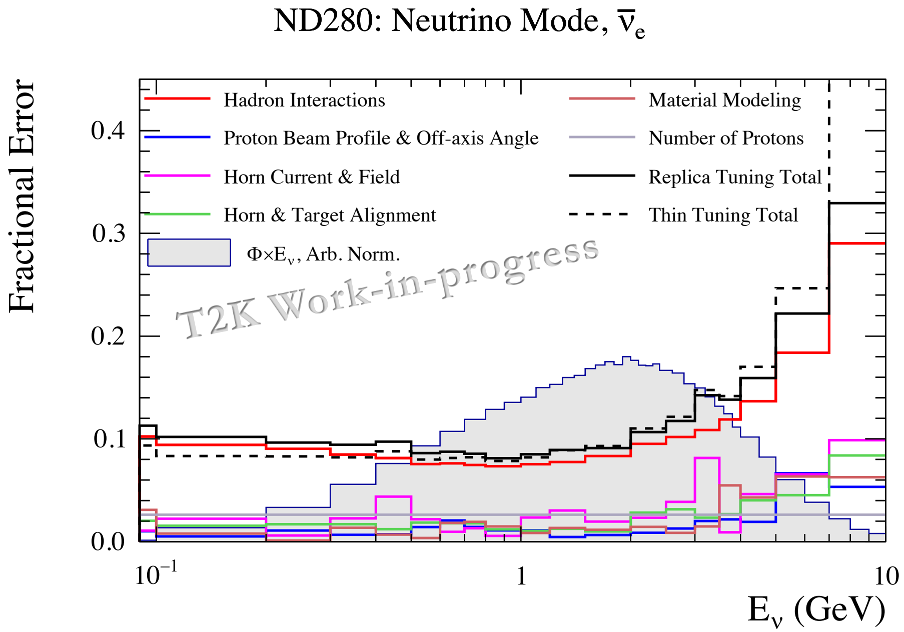
Flux Uncertainties at ND280 in ν-mode with 2009 replica-target data











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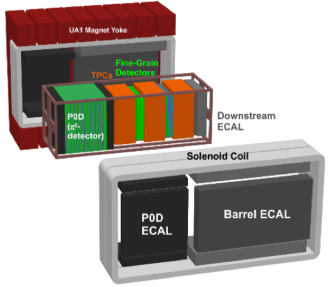

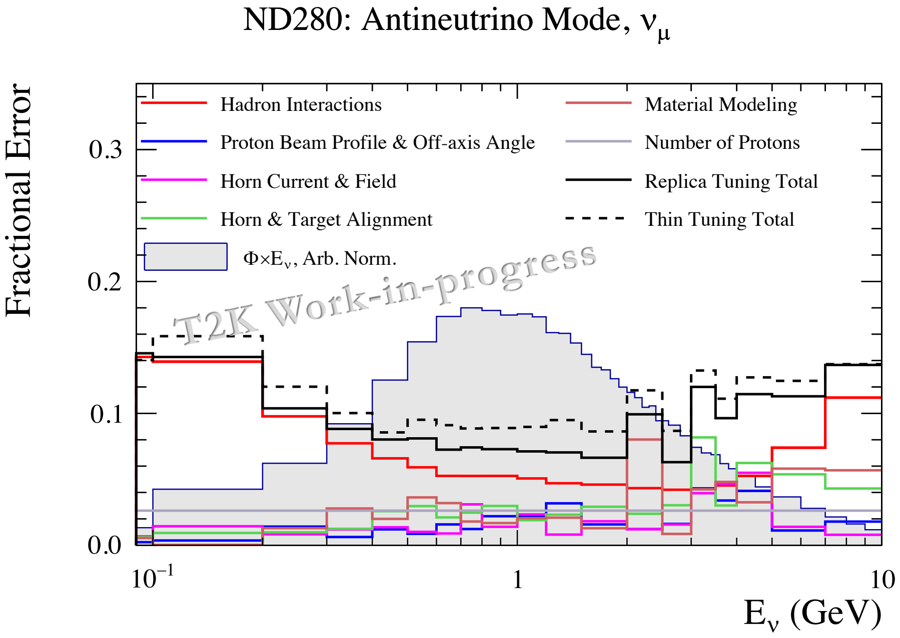

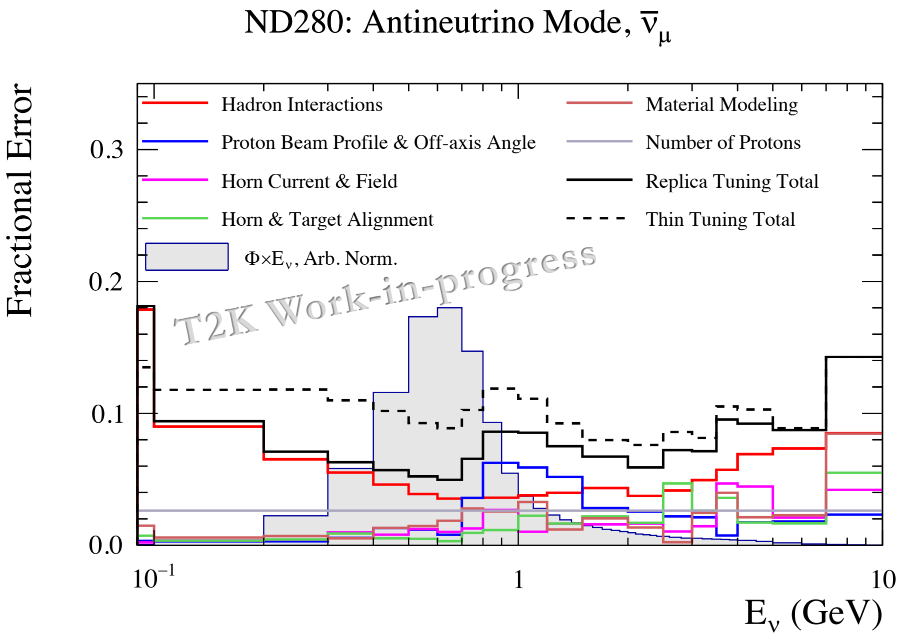

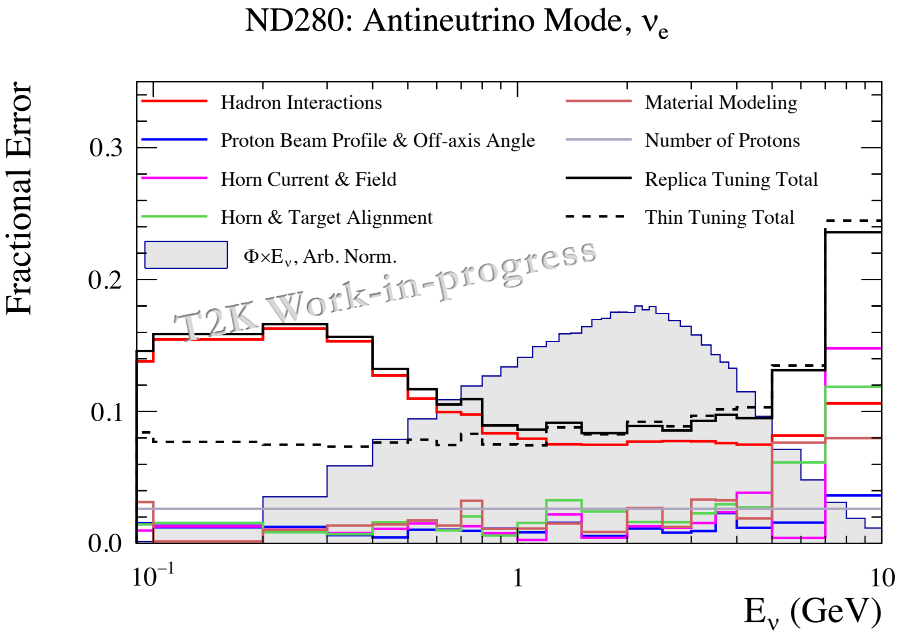

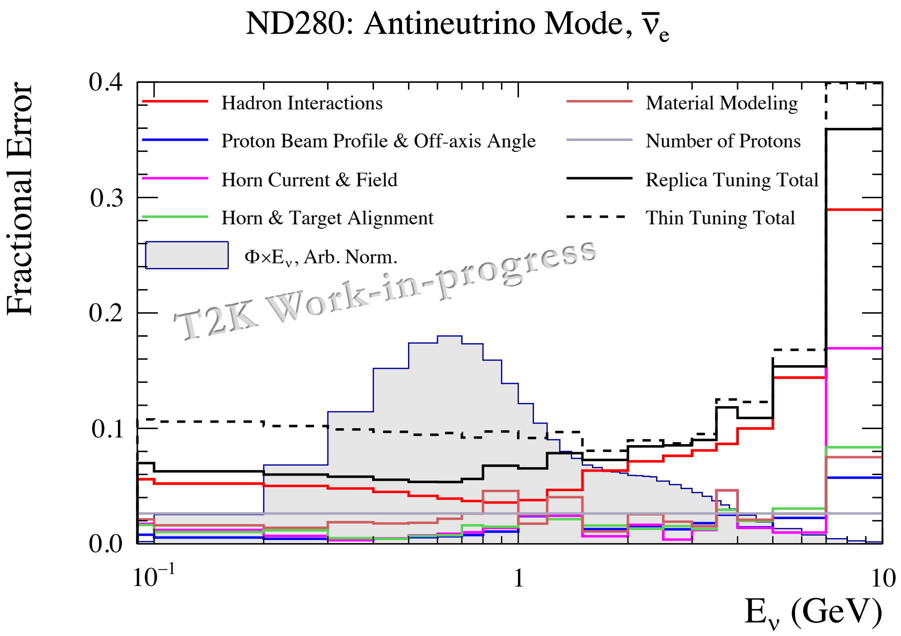

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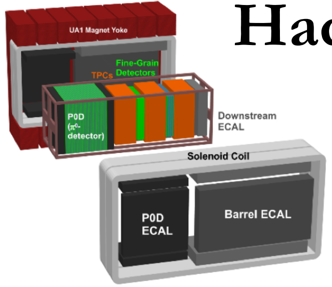

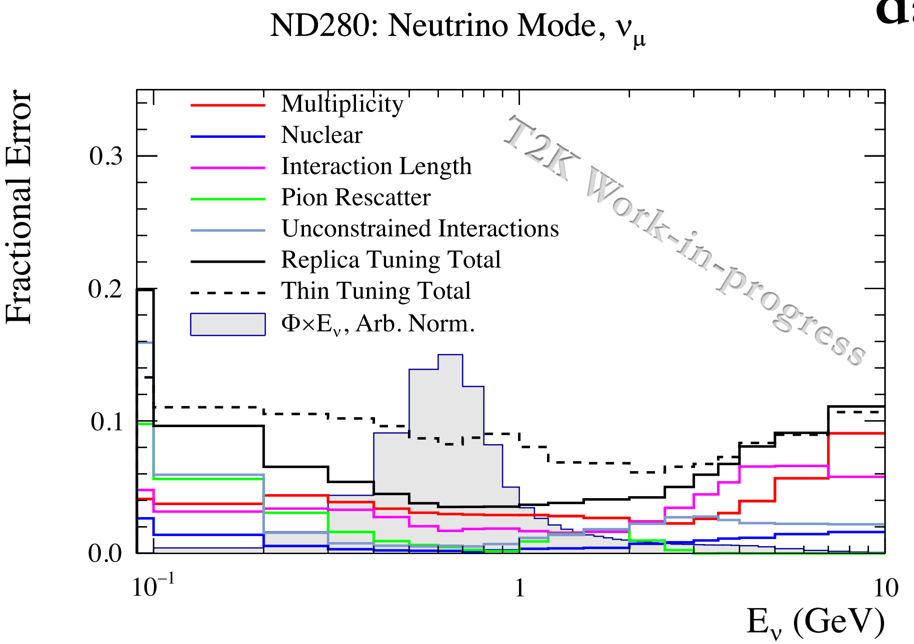

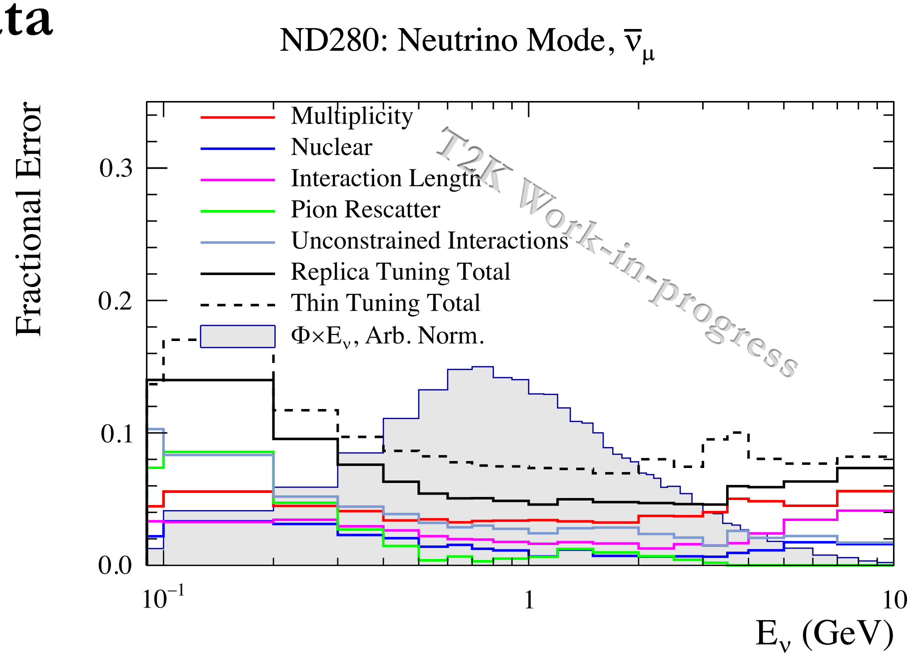

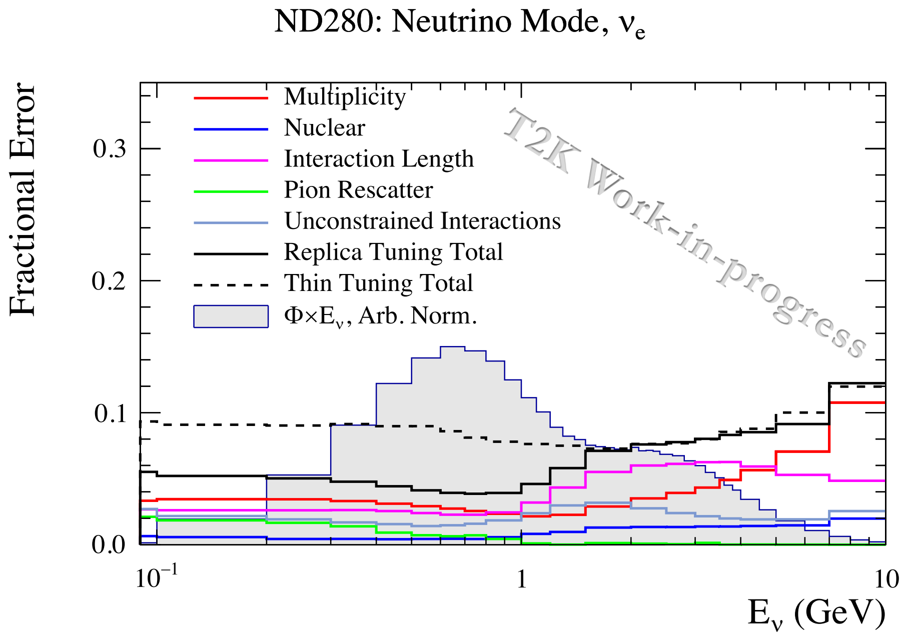

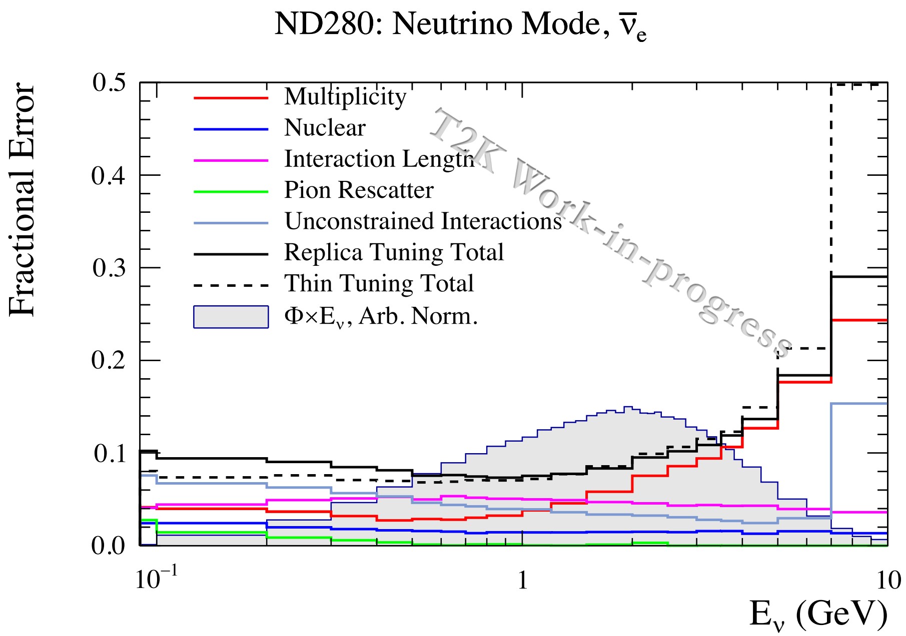

Unconstrained hadronic interactions at SK: We need more hadron production measurements!

- A significant number of hadronic interactions contributing to neutrino production (especially for wrong sign and wrong flavour fluxes) cannot be constrained with existing measurements

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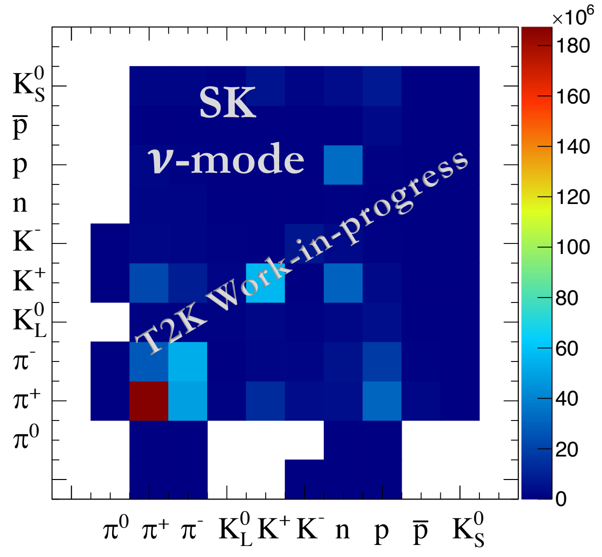
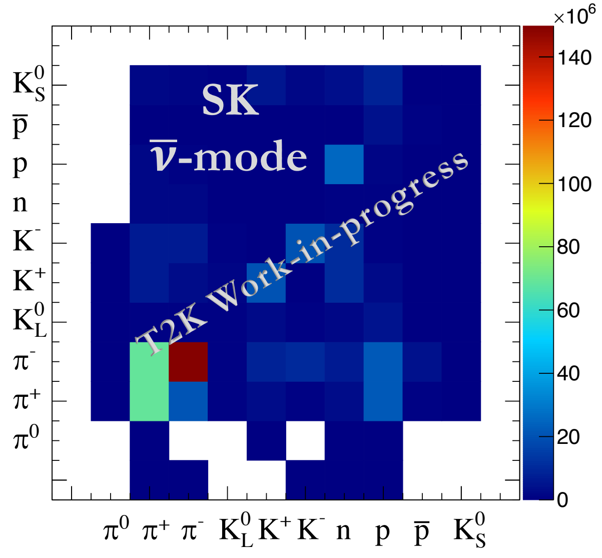
Increasing Importance

incoming vs outgoing PID

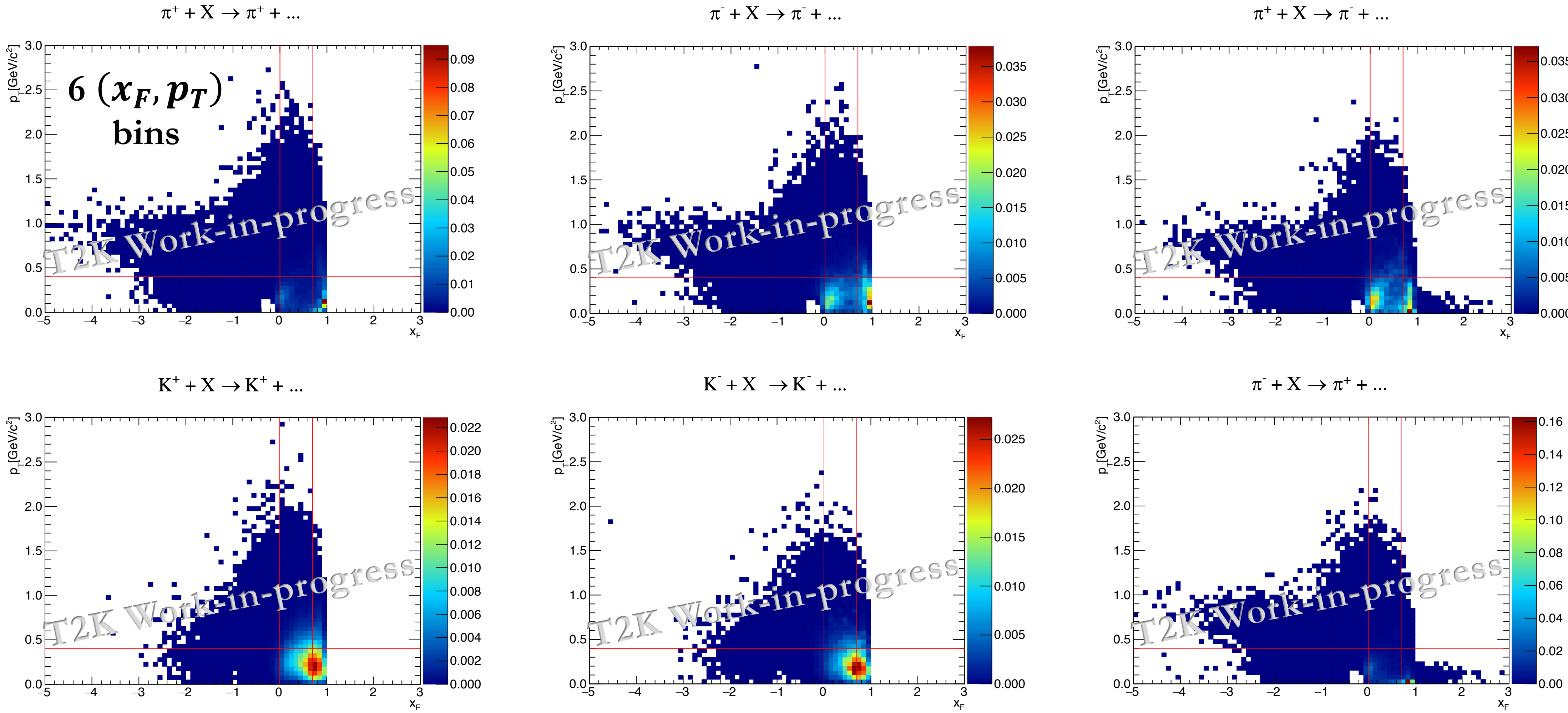


incoming vs outgoing PID



Phase Space of Unconstrained Interactions at SK in Neutrino Mode

- Baryon multiplicity tuning must be such to conserve the total baryon number → <u>focusing on unconstrained meson multiplicities which will dominate the unconstrained flux uncertainty</u>



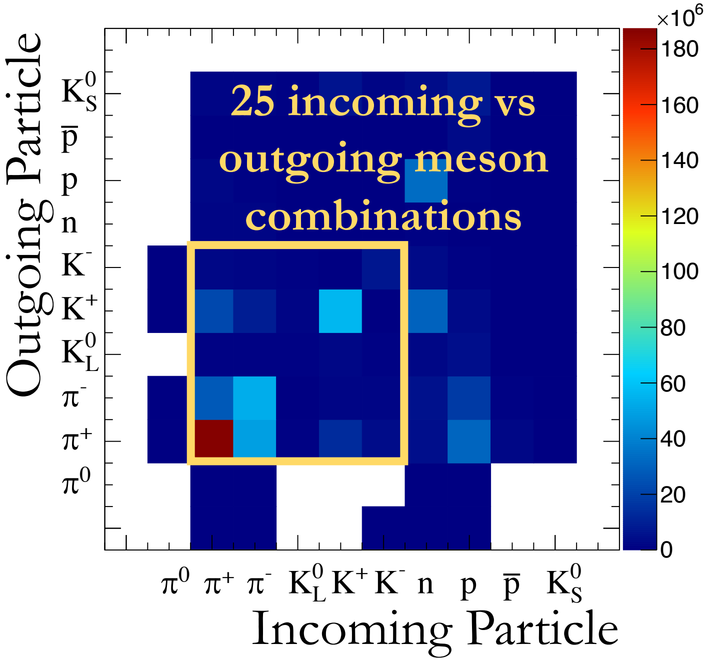
Assigning Preliminary Unconstrained Interaction Uncertainties

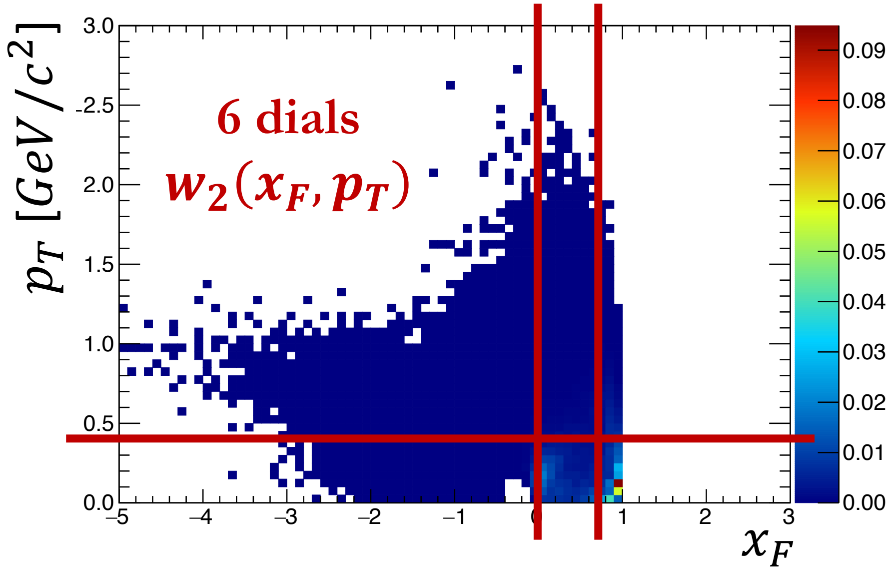
- Evaluate separate error for every unconstrained incoming vs outgoing meson combination (25 new flux systematics)

- For every interaction, generate 300 sets of Gaussian throws for 7 dials ($\mu = 1.0$ and $\sigma = 0.5$): **6 dials for w_2** plus **1 normalisation dial w_1**

- For every set of throws tune the outgoing meson yield via: $weight = w_1 \times w_2(x_F, p_T)$

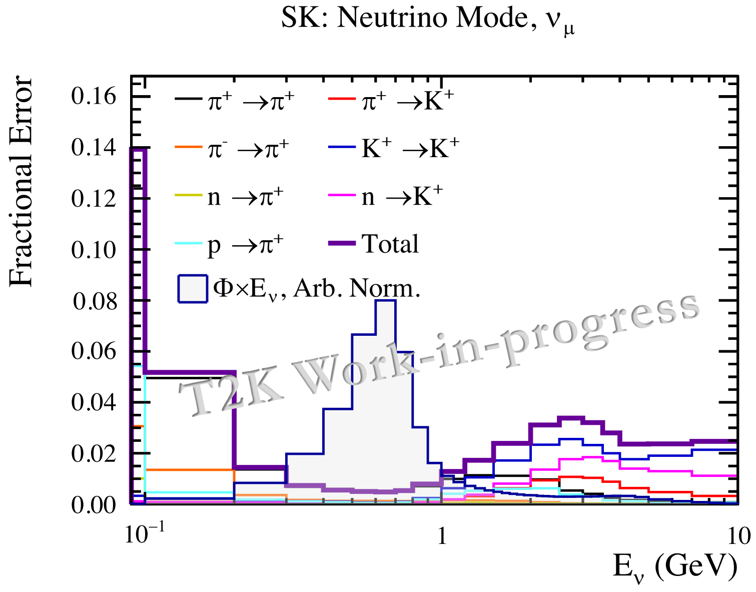
- Get 300 systematic variations on the nominal flux → extract the associated covariance matrix

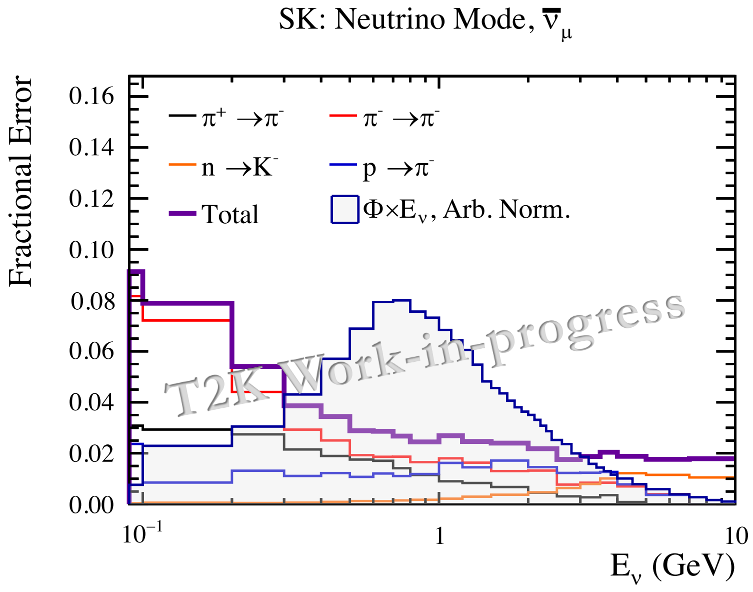


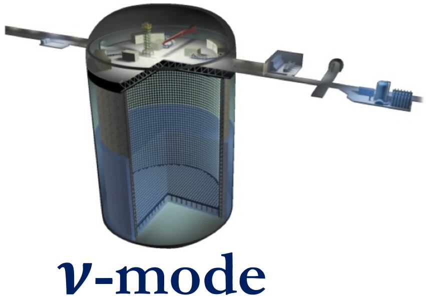


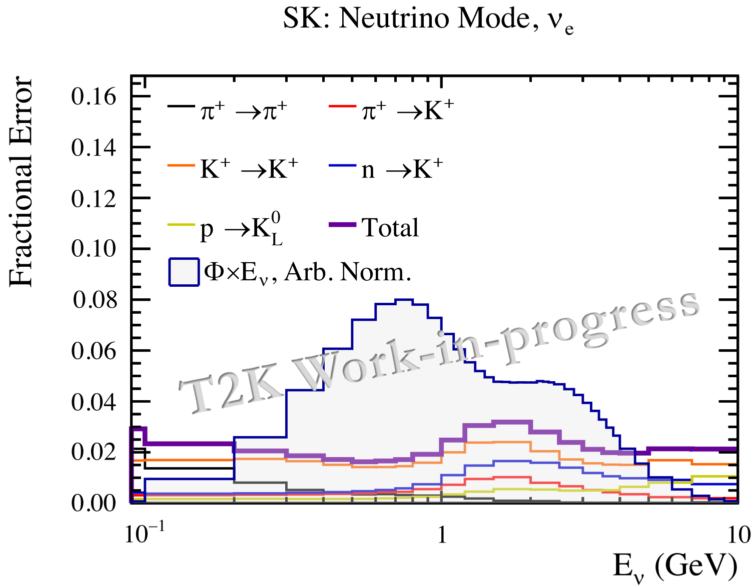
Flux Uncertainty at SK in Neutrino Mode due to Unconstrained Interactions

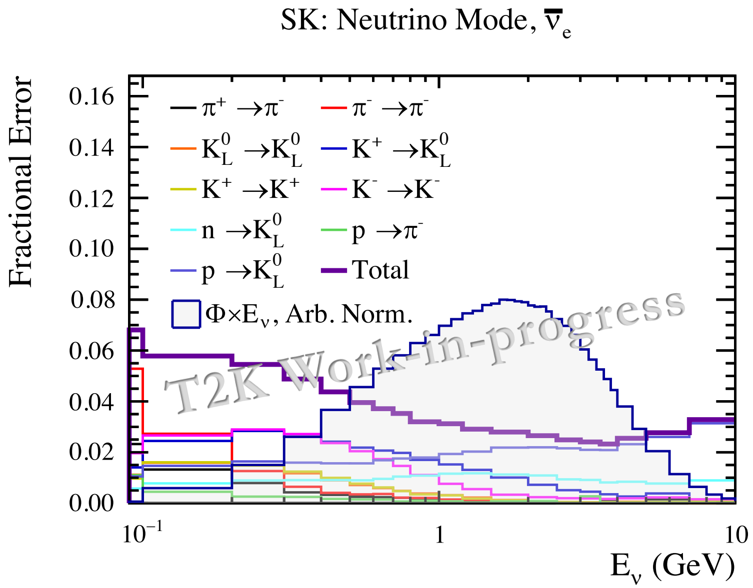
Assuming 50% multiplicity normalization error and 50% multiplicity uncorrelated error on 6 different (x_F, p_T) bins





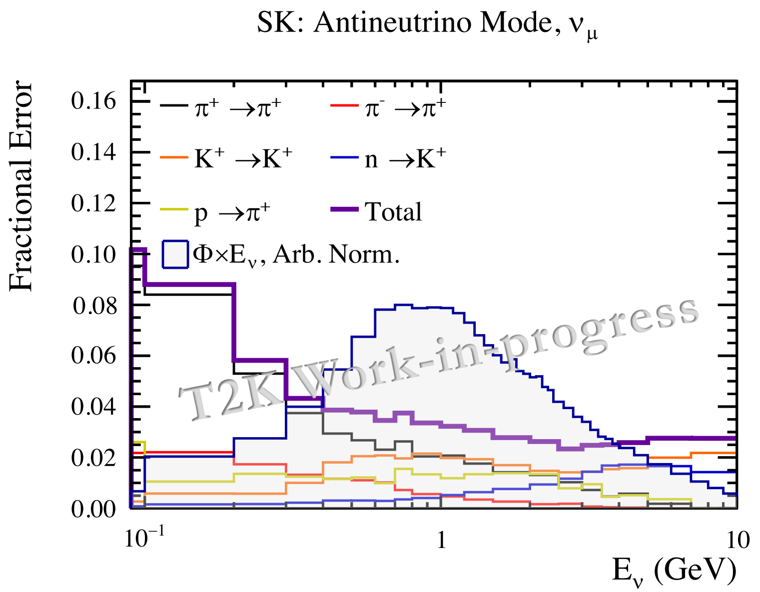


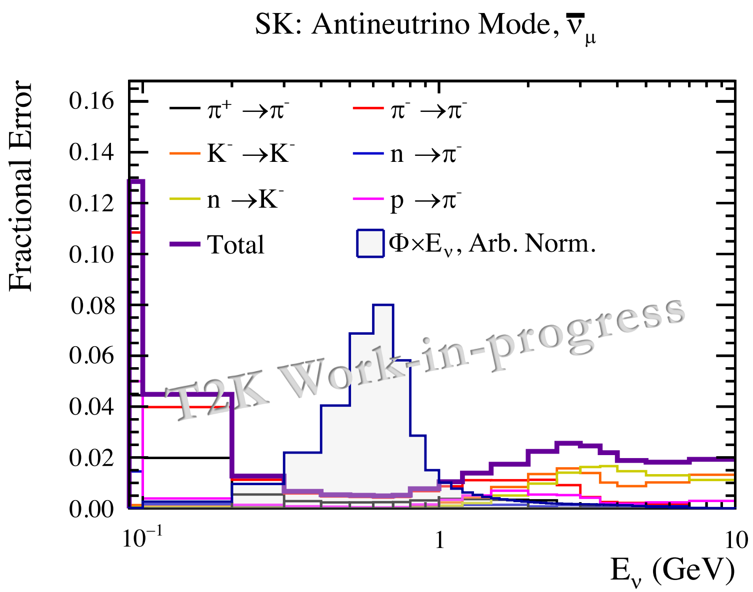


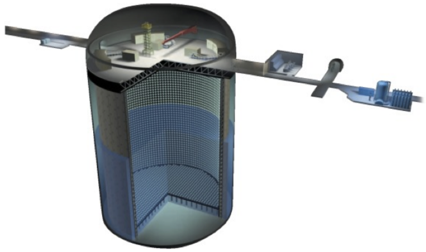


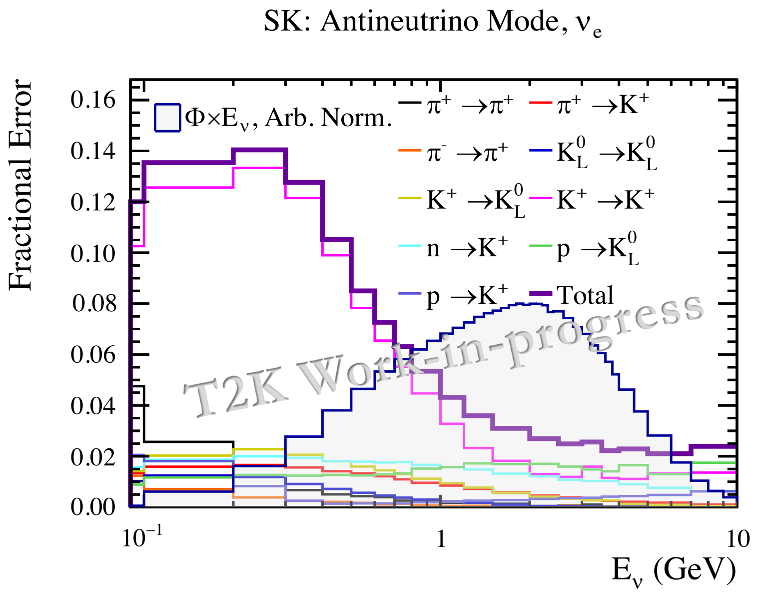
Flux Uncertainty at SK in Antineutrino Mode due to Unconstrained Interactions

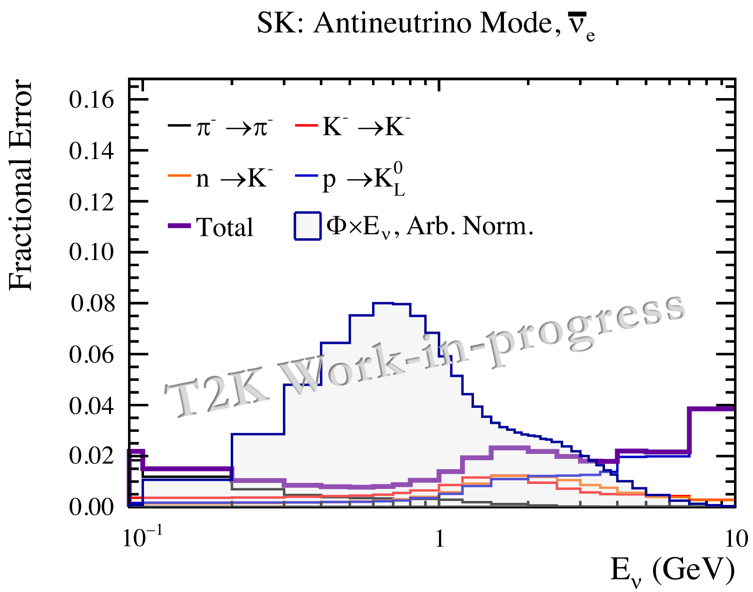
Assuming 50% multiplicity normalization error and 50% multiplicity uncorrelated error on 6 different (x_F, p_T) bins







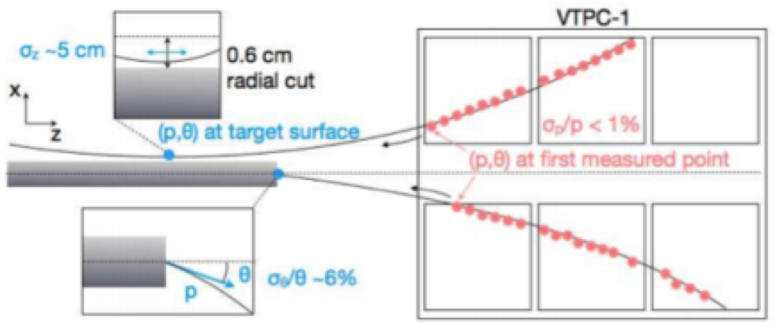


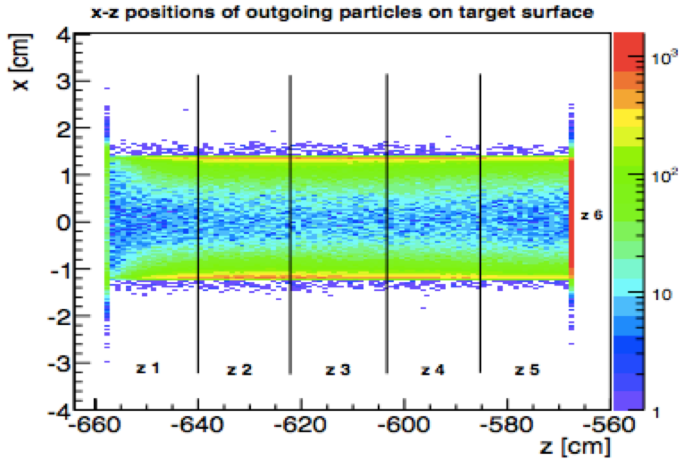


Long Target (T2K Replica) Analysis

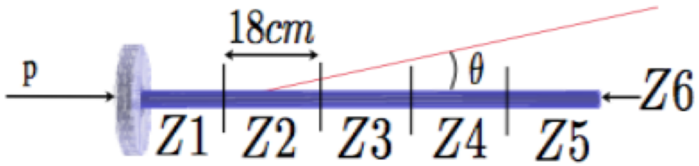
Neutrinos are coming from hadrons produced in **primary p+C interactions** (~60%) and in **interactions of secondary particles** either in the target (~30%) or outside the target (~10%)

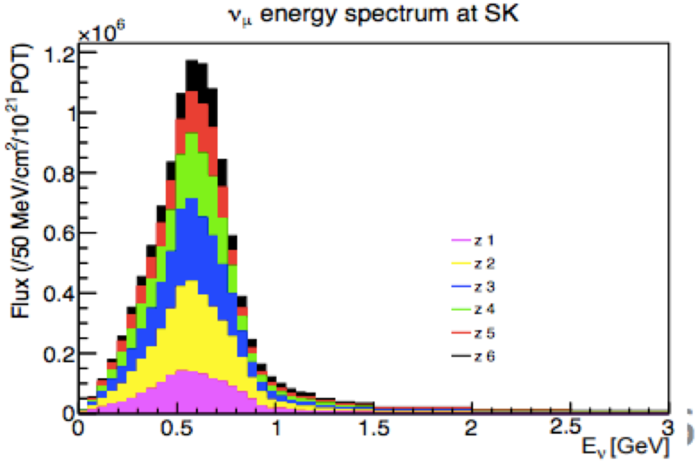
- Multiplicities measured at the surface of the T2K replica target (tracks extrapolated backwards)





- Measurements in bins of {p,θ,Z}
- 5 bins along beam Z-direction + 1 bin target downstream face
- Shape of E_ν depends on the additional Z-binning

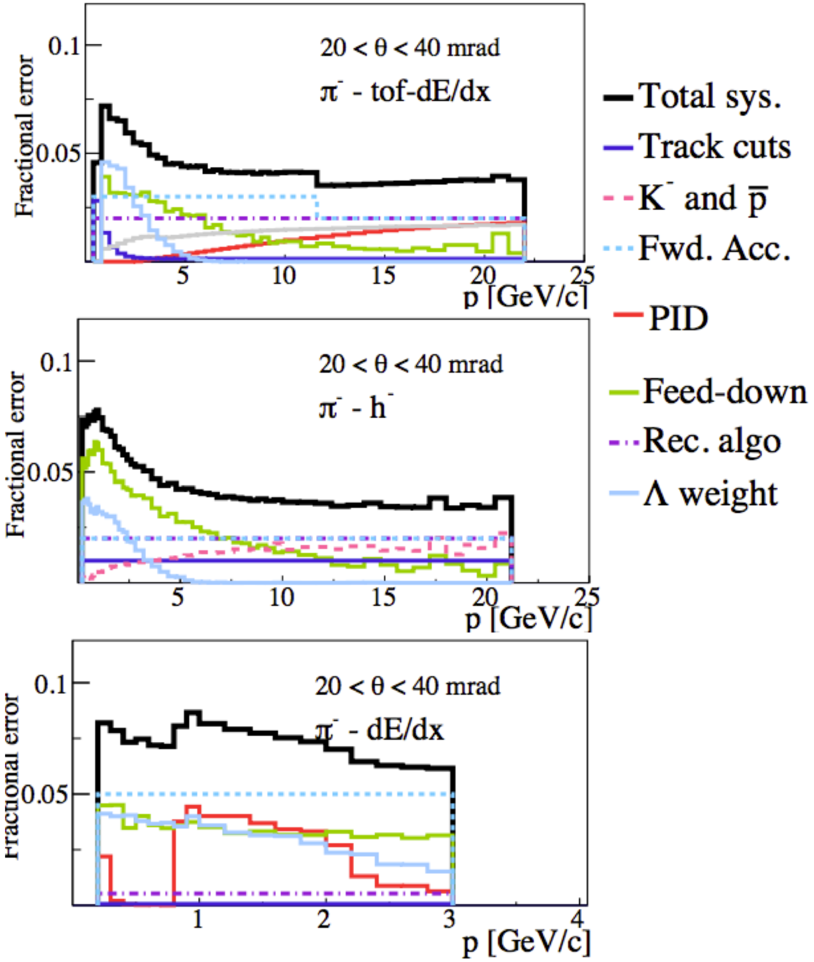




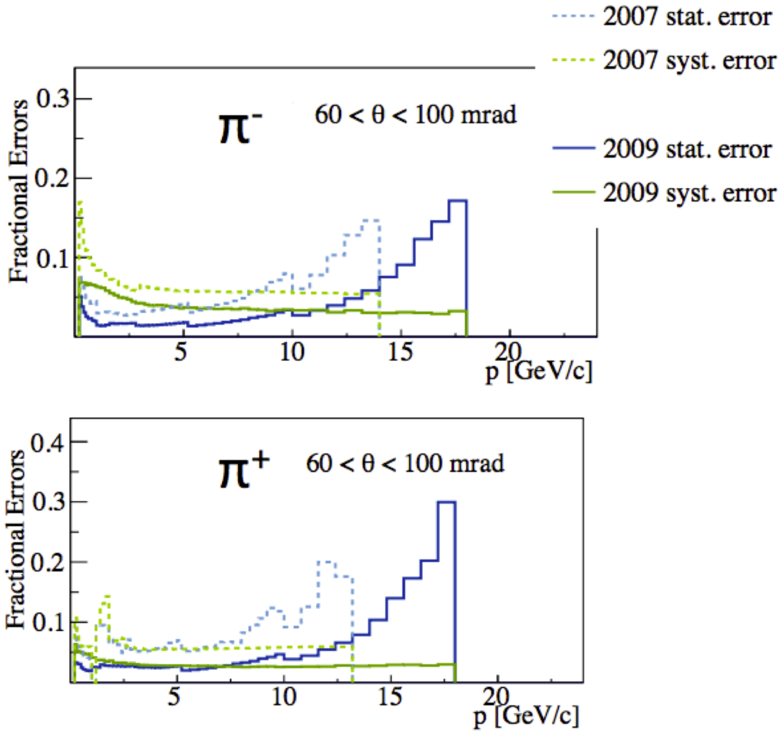
NA61 2009
Thin-Target
Data
Uncertainties

Pion Spectra Uncertainties

The largest contributions to sys. error:
feed-down improved with studies of decay of strange particles (K^0_s and Λ), particle identification (PID) and forward acceptance



Improvements in 2009 compared to pilot run:
- Statistical precision improved by factor 2-3
- Systematic error reduced by factor 2



Systematic errors are dominant at low p while at high p statistical errors still are the largest

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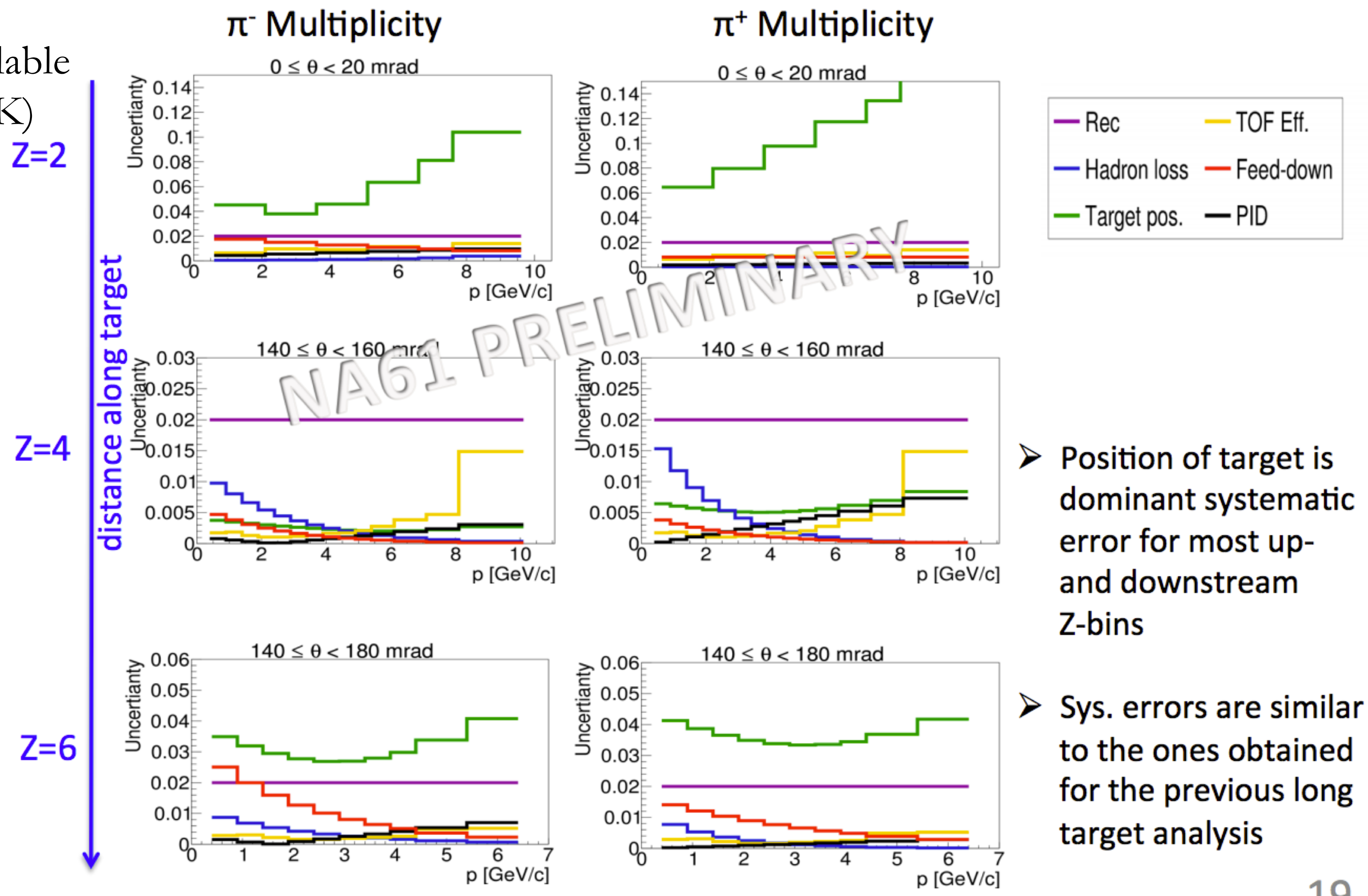
Taken from Katarzyna Kowalik's talk at NuInt2017

Preliminary NA61 2010 **Replica-Target** Data Uncertainties (Largest Available Dataset Collected for T2K)

$\pi^{\pm}$ Systematic Uncertainties



- Position of target is dominant systematic error for most up- and downstream Z-bins
- Sys. errors are similar to the ones obtained for the previous long target analysis

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