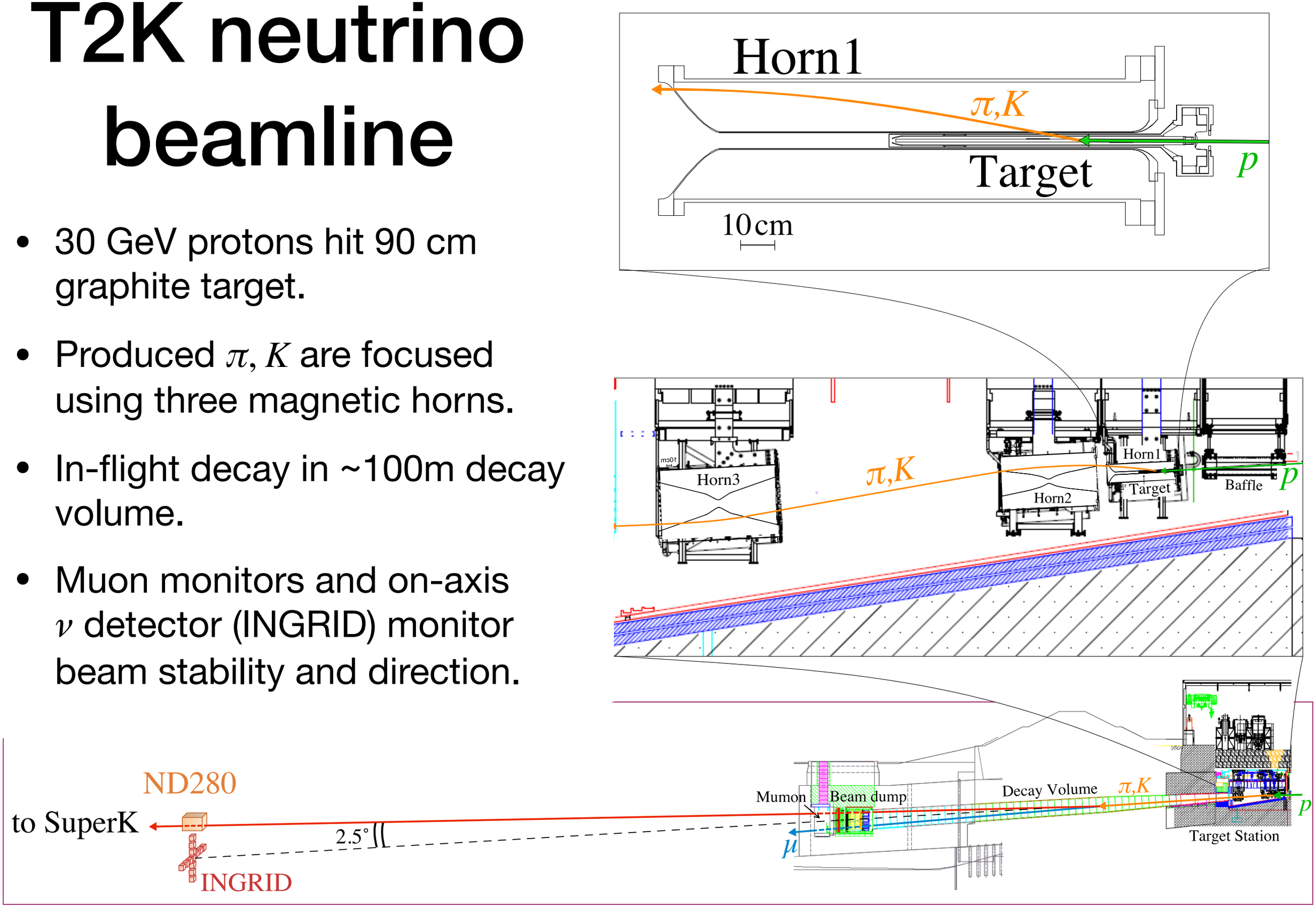
T2K flux prediction

Lukas Berns, Tokyo Institute of Technology
on behalf of the T2K collaboration

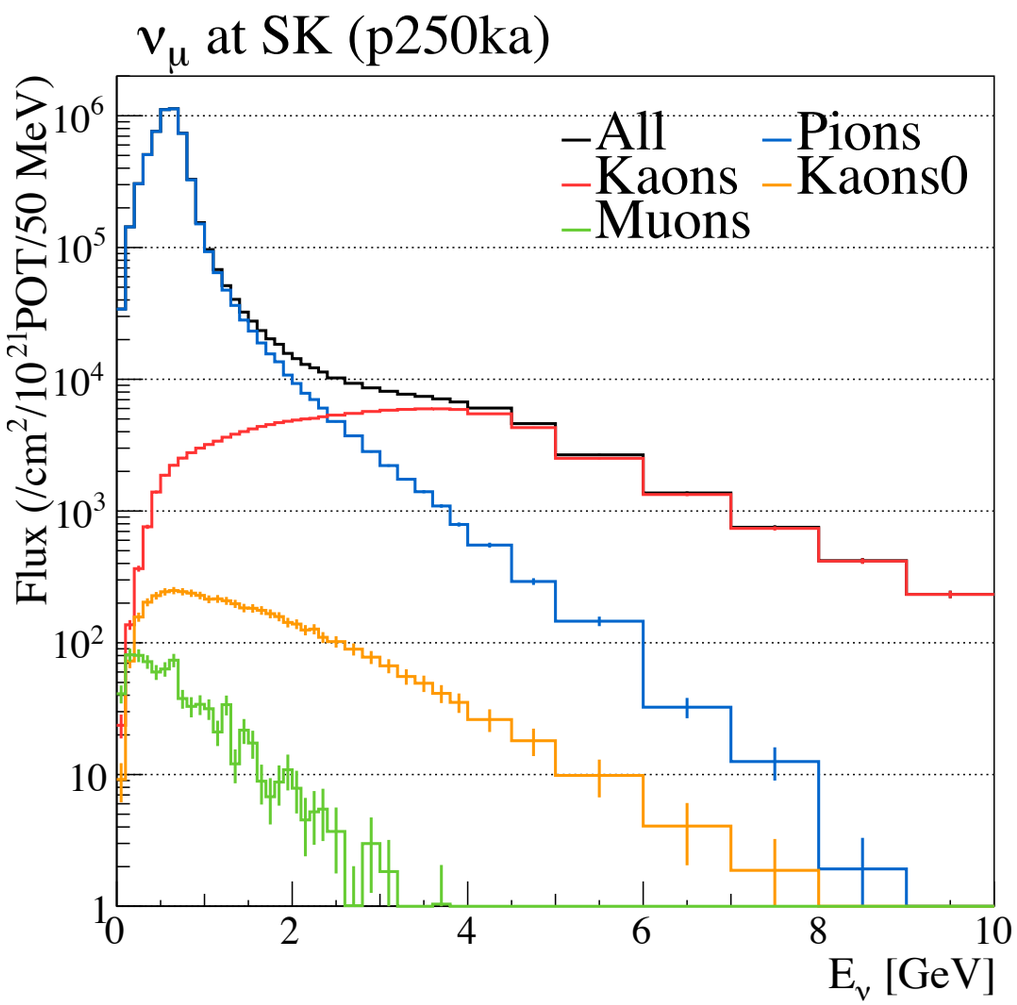
NBI 2019 @ Fermilab, 2019-10-22

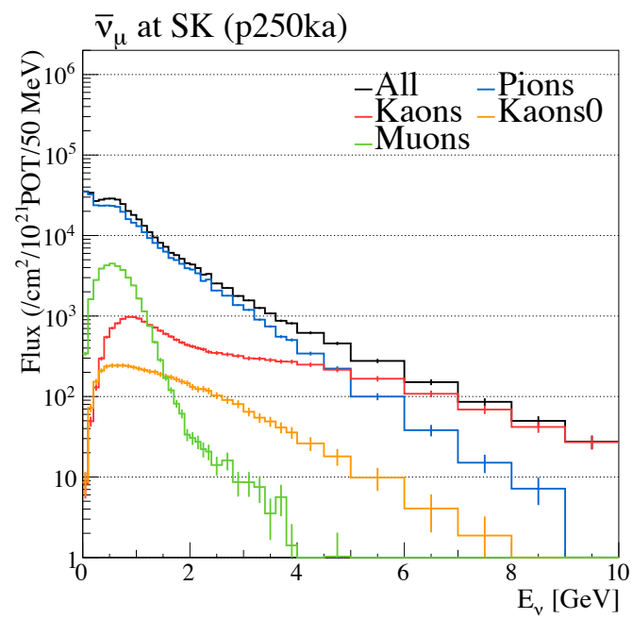
T2K neutrino beamline

- 30 GeV protons hit 90 cm graphite target.
- Produced π, K are focused using three magnetic horns.
- In-flight decay in ~100m decay volume.
- Muon monitors and on-axis ν detector (INGRID) monitor beam stability and direction.

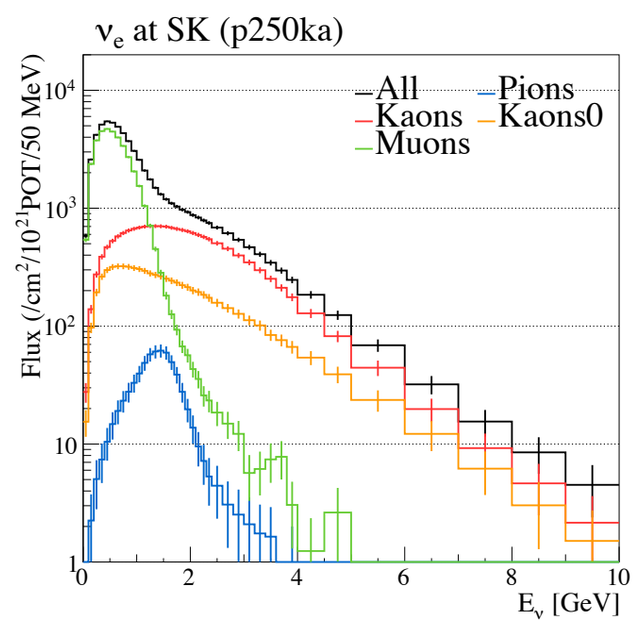


Understanding the flux





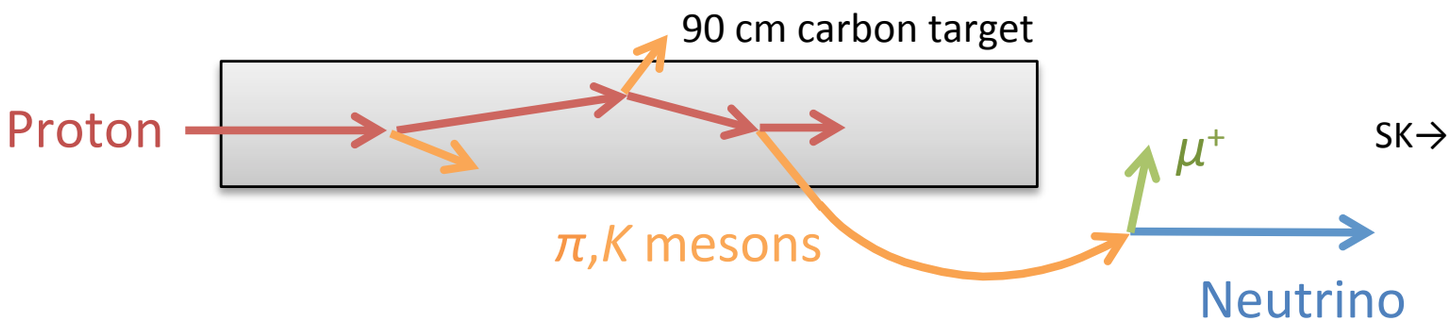
Wrong sign component from re-scattered pions (low-E) and forward mesons from target downstream face of target that "miss" the horns (high-E).



Small ν_e contamination from μ-decay in tunnel and K-decay.

Dominant ν_μ flux with 650 MeV peak from $\pi^\pm$ decay. Above 3 GeV $K^\pm$ decay.

Flux composition is $\nu_\mu > \bar{\nu}_\mu > \nu_e > \bar{\nu}_e$ (in neutrino-mode) roughly differing by factor 10 each.



Flux Prediction

- Interactions of protons **inside target** simulated with **FLUKA** based on proton beam profile measured with upstream beam monitors.

- Horn **focusing** and **out-of-target** interactions (Al in horns and Fe in walls) of outgoing mesons using **Geant3 + GCalor**.

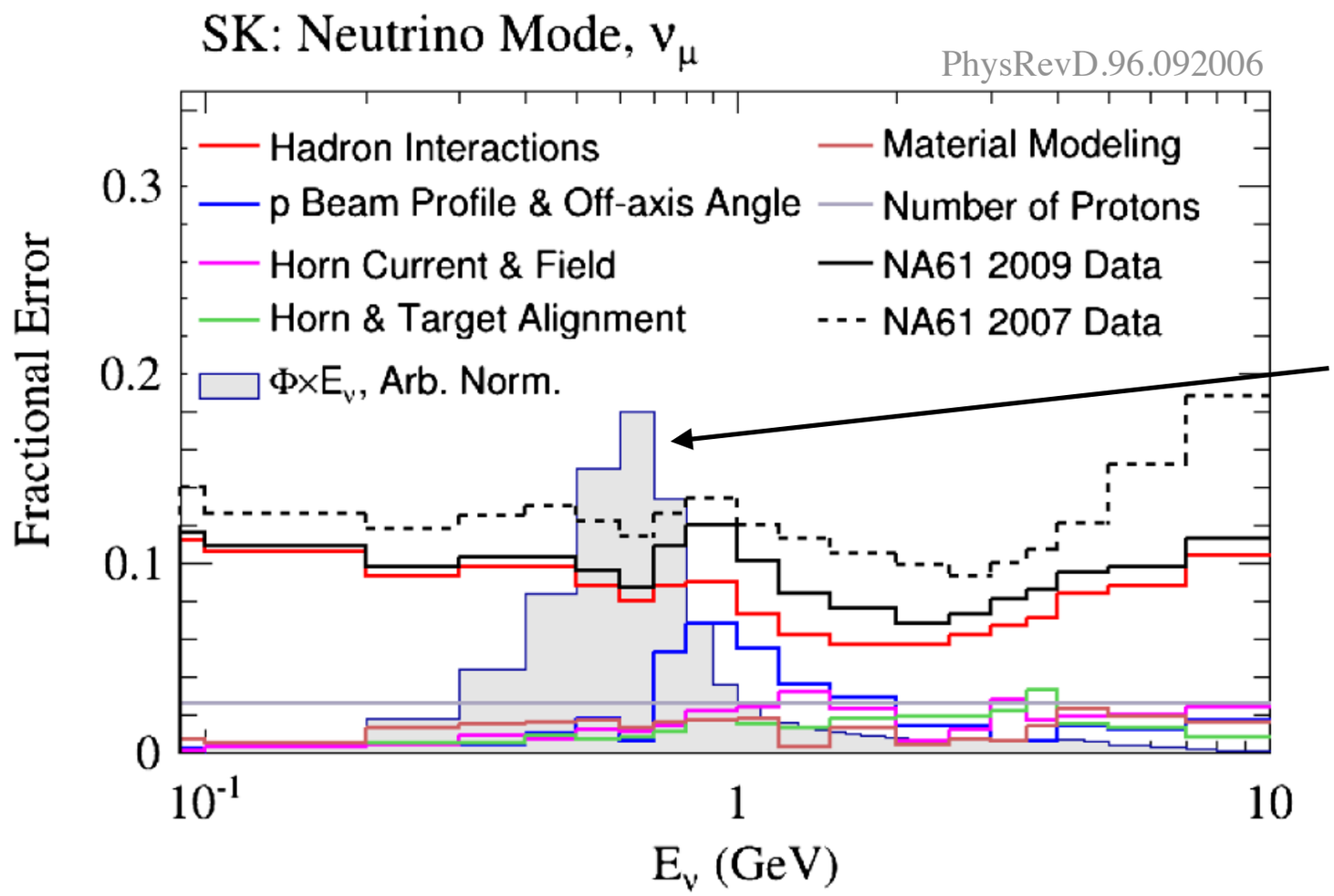
- Afterwards go through interaction chain and **apply weights** to **tune** output of MC generators to external hadron production data (mostly NA61/SHINE).

- **Covariance matrix** is used to constrain SuperK flux using near detector measurements.

Uncertainties on neutrino flux

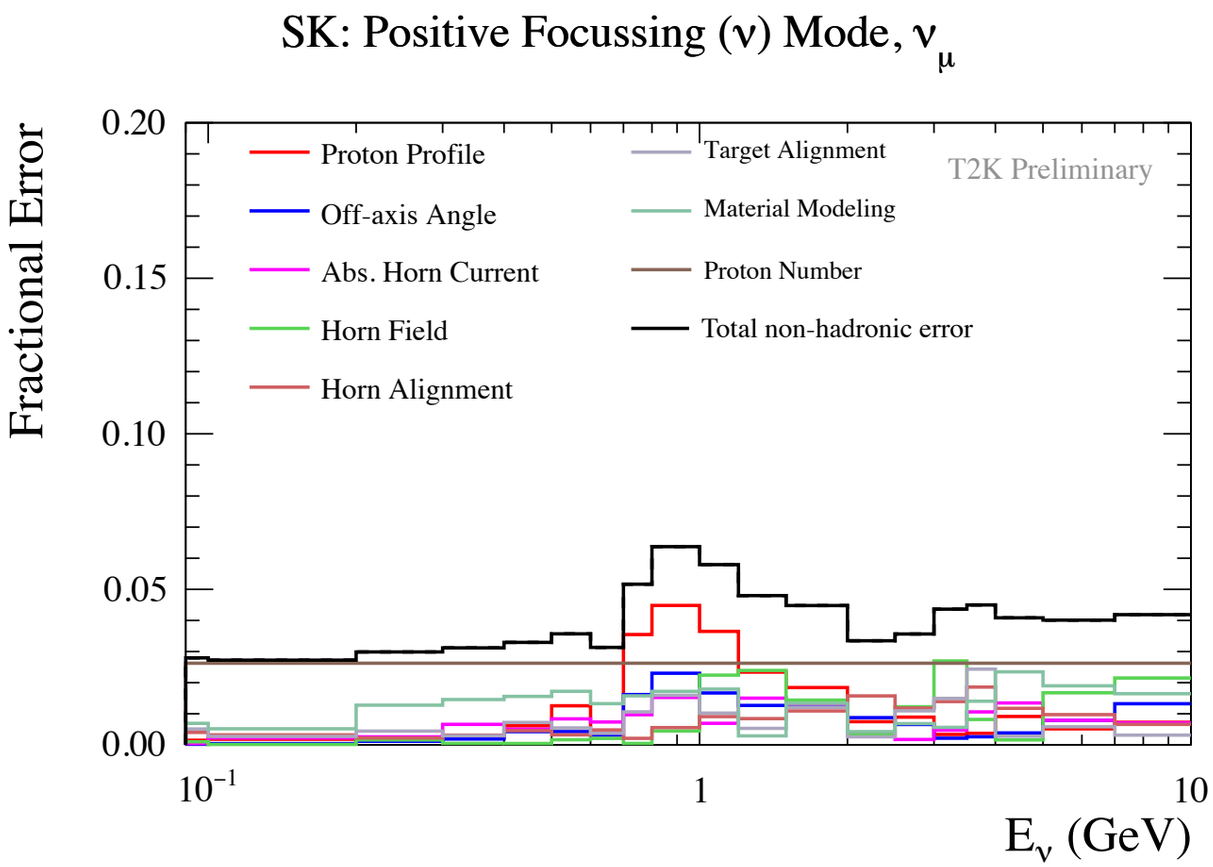
- Beam profile and off-axis angle
- Horn current, field, number of protons
- Beamline alignment, modeling
- Hadron interactions (largest uncertainty)

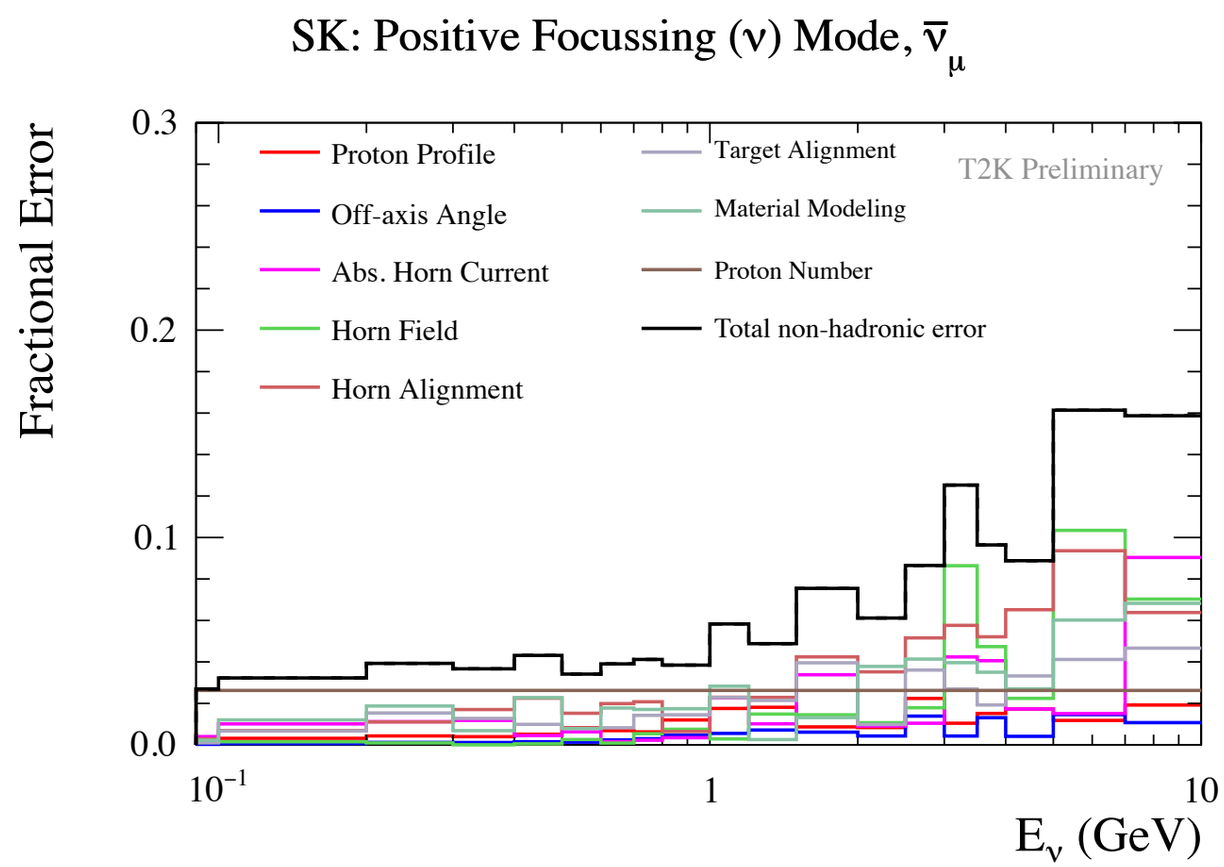
Non-hadronic uncertainties (next slide)



Shaded backdrop: (unoscillated) **flux** scaled by energy as approx. ***ν* xsec**

Non-hadronic uncertainties

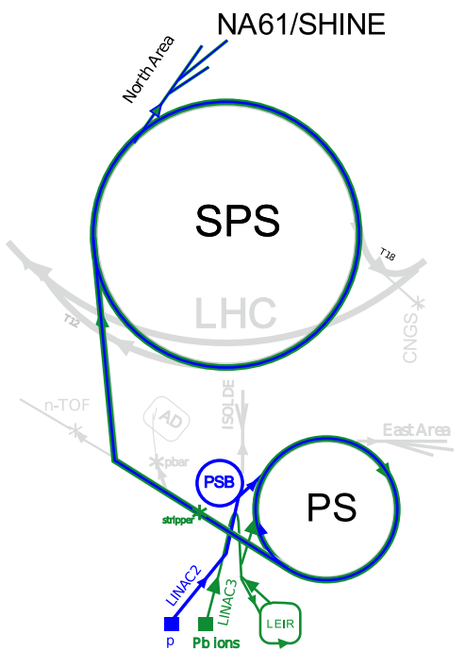


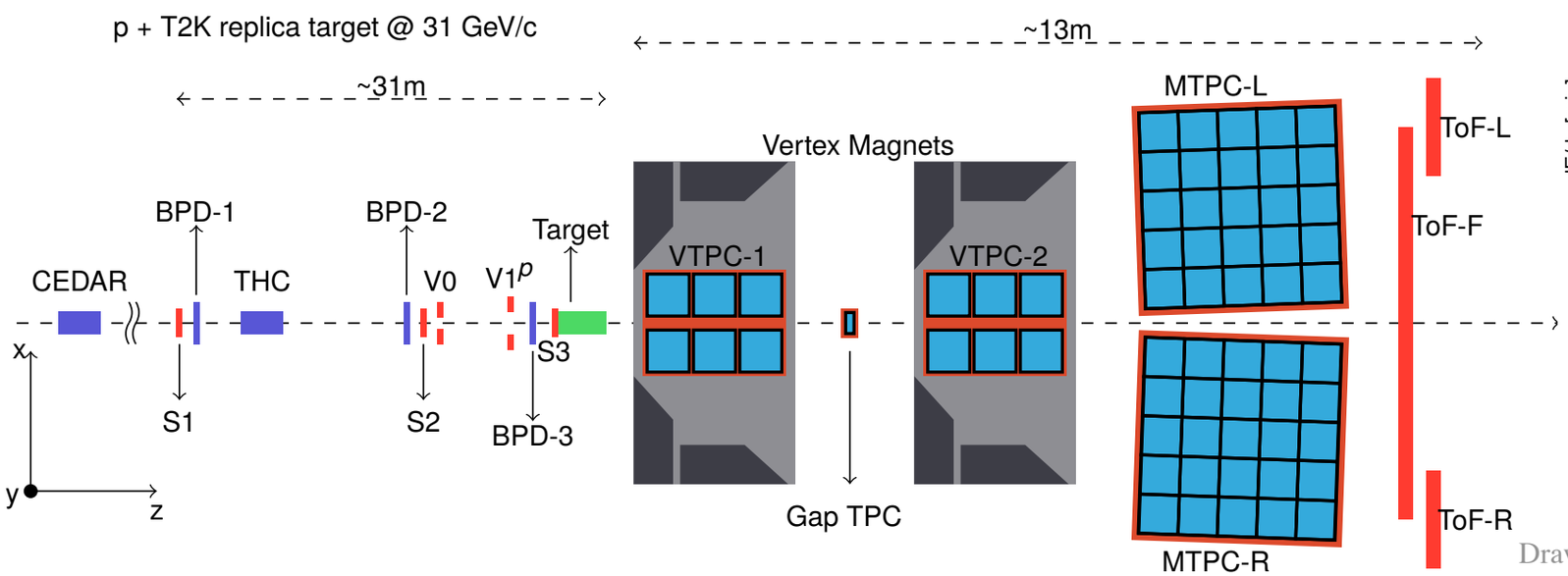


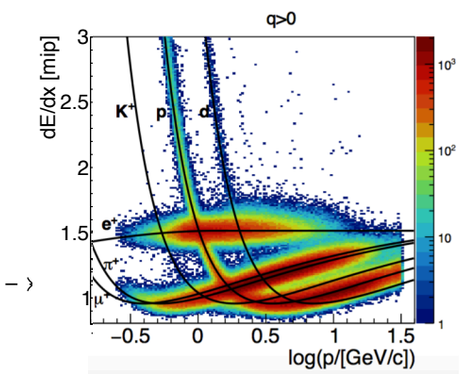
- For right-sign ν_μ **proton beam** profile is most important. → causes peak energy shift due to ν beam direction change
- For **cooling water**, 1 mm layer for horn1 inner conductor is considered (<2% near flux maximum). We are trying to check with spare horn1 whether this 1 mm assumption is sufficient.
- For wrong-sign ν_μ above 1 GeV, **horn** + **target** alignment and **horn field** asymmetries important

NA61 measurements for T2K

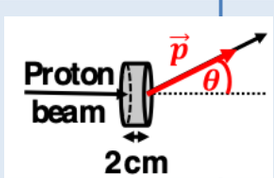
- Hadron production experiment, momentum measurement with TPCs in superconducting magnets, PID with dE/dx (Bethe-Bloch) and time of flight.



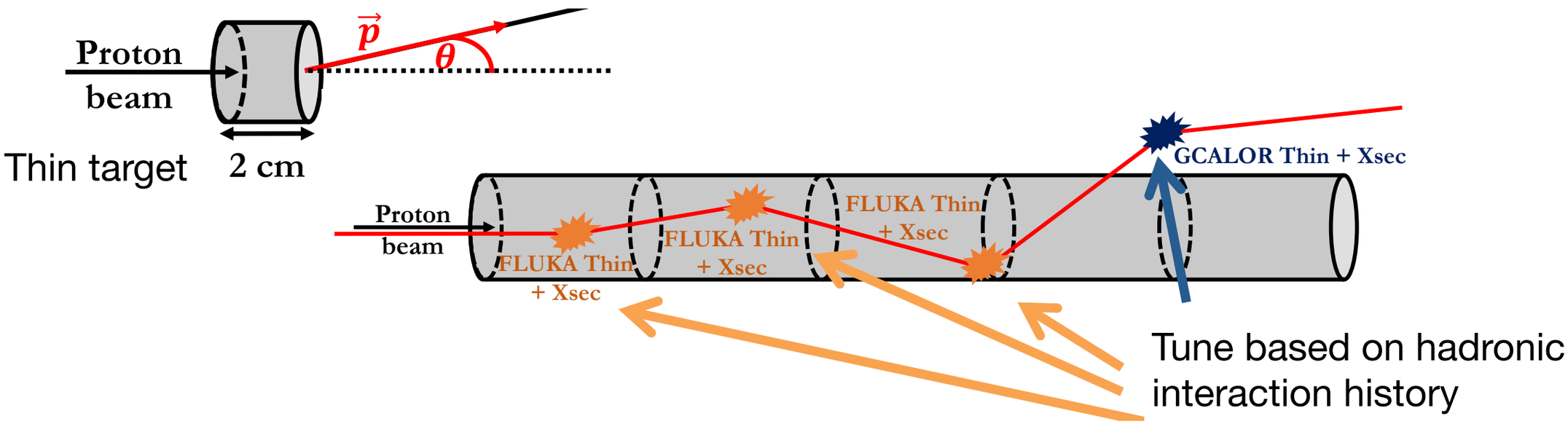




Drawings+plots from M.Pavin's Ph.D. thesis, slightly modified for clarity.

Beam	Target	Year	Stat (10^6)	Outgoing PID	Usage at T2K
protons at 31 GeV/c 	Thin (2cm)	2007	0.7	$\pi^{\pm}, K^{\pm}, K^0_S, \Lambda$	past
		2009	5.4	$\pi^{\pm}, K^{\pm}, p, K^0_S, \Lambda$	in use
	T2K replica (90cm)	2007	0.2	$\pi^{\pm}$	
		2009	2.8	$\pi^{\pm}$	next T2K results
		2010	10.	$\pi^{\pm}, K^{\pm}, p$	in development

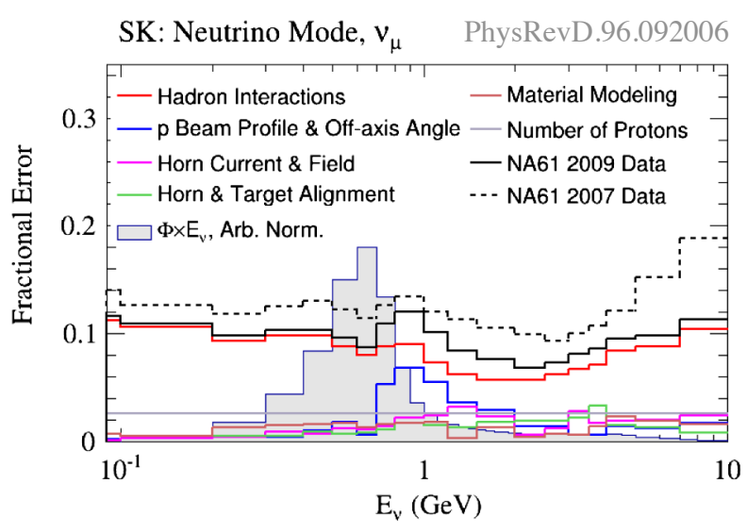
Thin target tuning



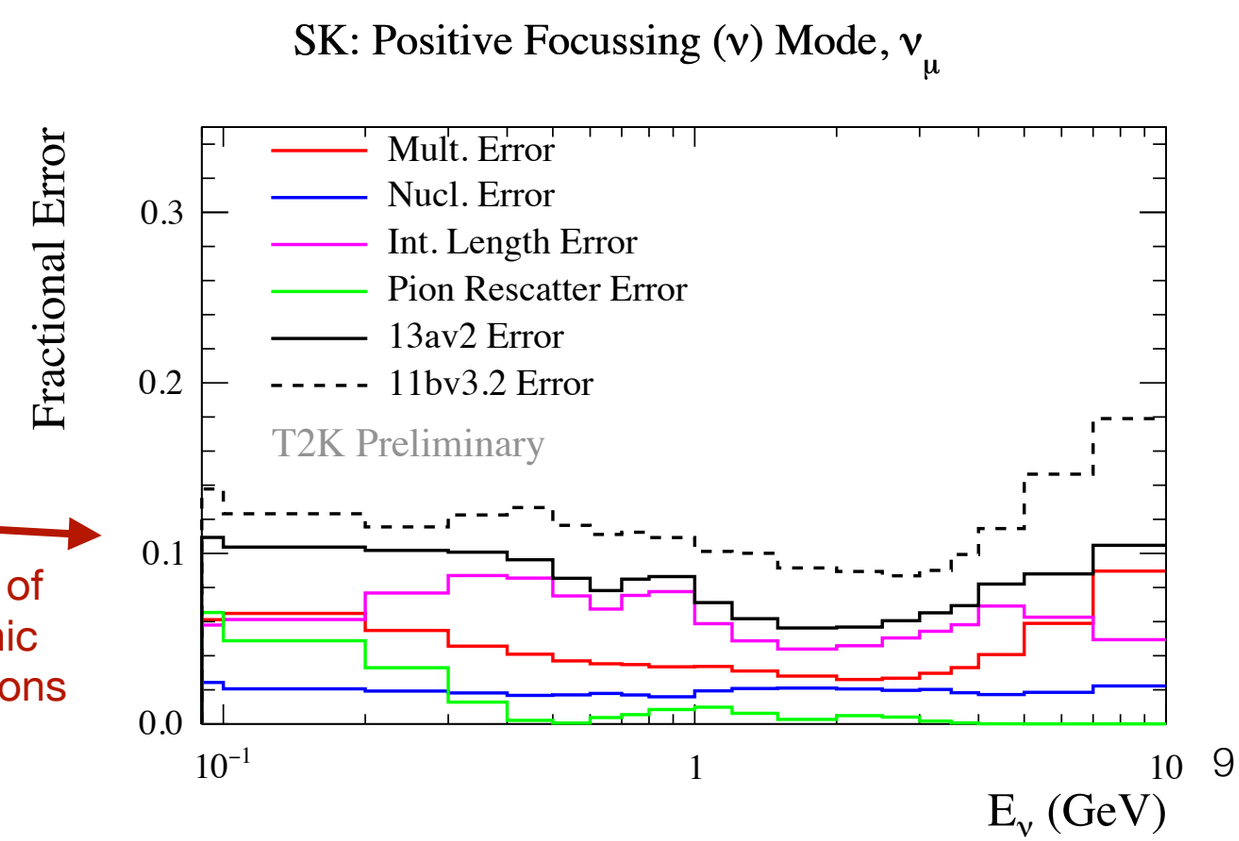
	Interaction length tune σ_{prod}(p+C) to NA61 measurement	**Multiplicity** Mostly 30 GeV p+C data by NA61
At interaction	"Vertex" weight $\sigma_{\mathrm{DATA}} / \sigma_{\mathrm{MC}}$	$\left(\frac{\mathrm{d}^2 n}{\mathrm{d}p\,\mathrm{d}\theta}\right)_{\mathrm{DATA}} \Big/ \left(\frac{\mathrm{d}^2 n}{\mathrm{d}p\,\mathrm{d}\theta}\right)_{\mathrm{MC}}$ p, θ: outgoing particle kinematics
For distance L traversed in matter	"Attenuation" weight $e^{-(\sigma_{\mathrm{DATA}}-\sigma_{\mathrm{MC}})\,\rho L}$	N.A.

Most important hadronic uncertainties with thin tuning

- Interaction length (mostly proton prod. xsec)
- Multiplicity uncertainties for mesons and protons
  - propagated from NA61
  - Feynman scaling to relevant momentum scale
  - Extrapolation beyond coverage
- Pion rescattering

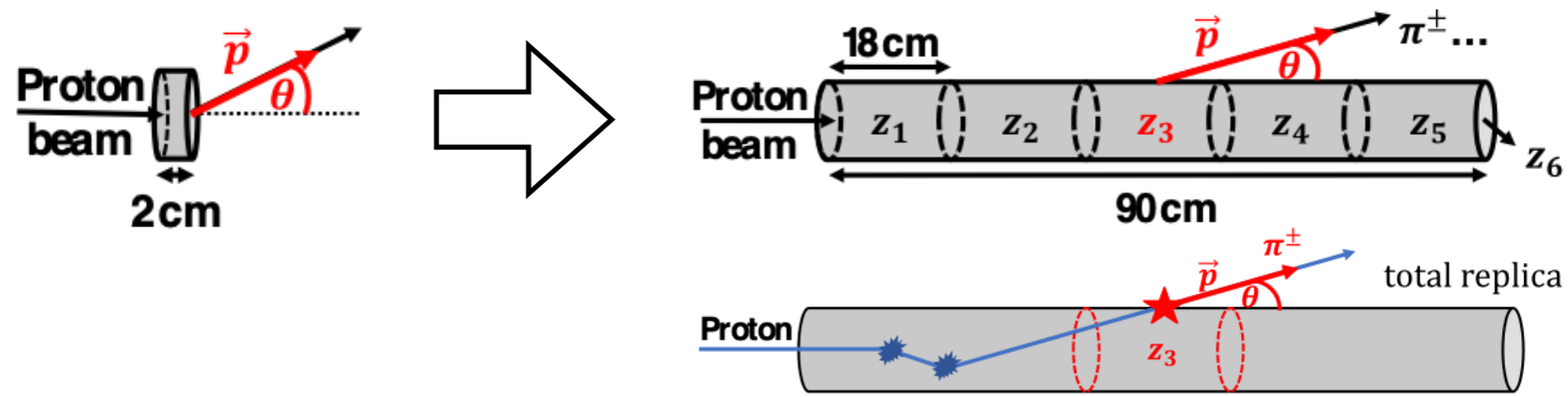


Details of hadronic interactions



Move to replica tuning

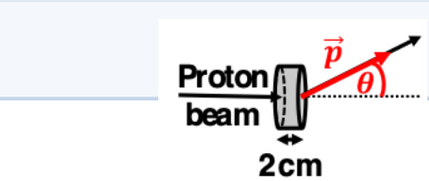
- NA61 took data with **full-sized replica** of T2K target, binned by (z, p, θ)
- Ignore interactions inside the target and apply **single DATA/ MC weight** based on exiting particle.
- **Out-of-target** interaction and outgoing particles **not covered** by replica data are tuned with thin target data.

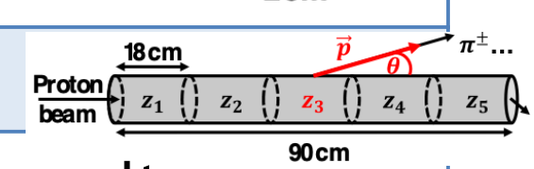


Reduced uncertainty from

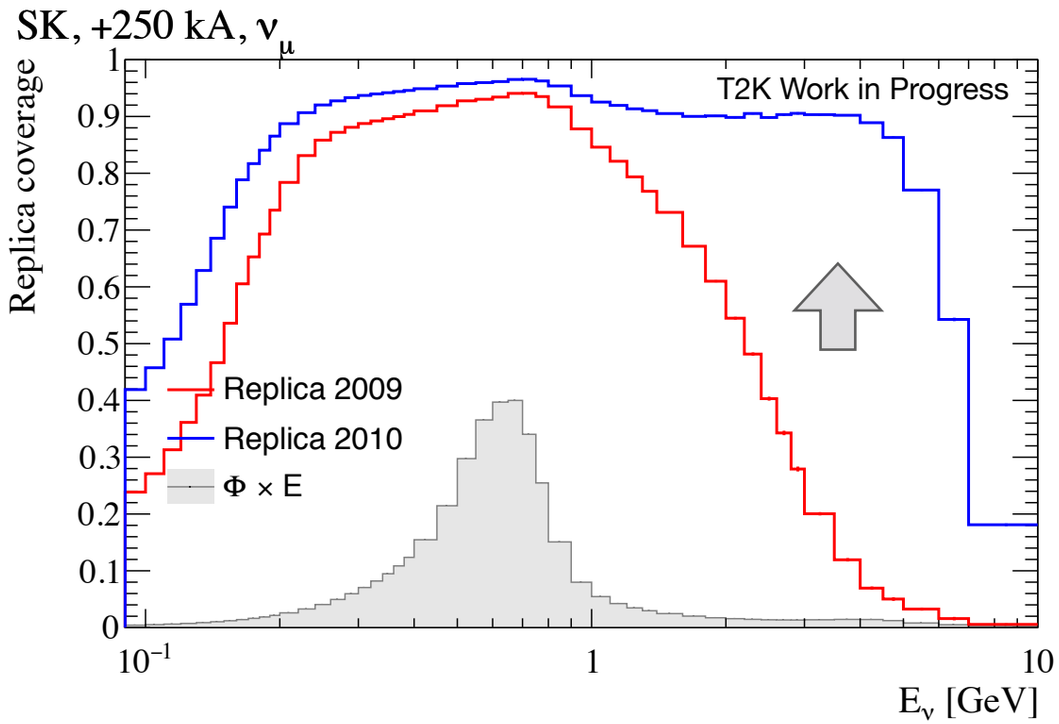
- no interaction length uncertainty
- single weight per exiting particle

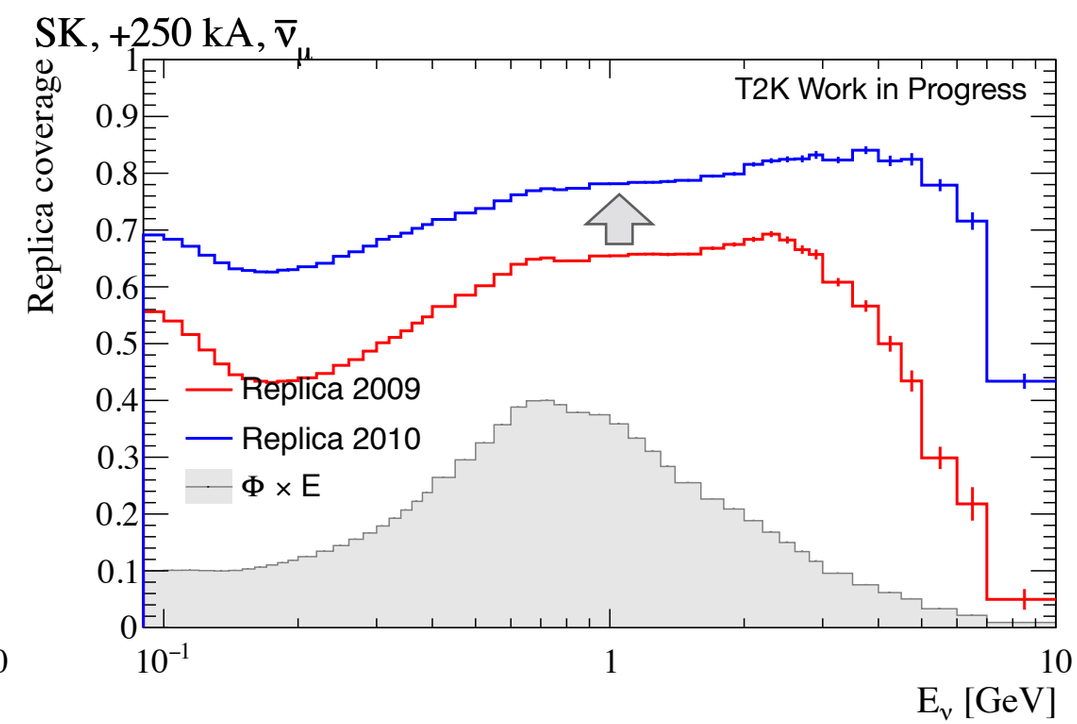
Beam	Target	Year	Stat (10^6)	Outgoing PID	Usage at T2K
protons at 31 GeV/c	Thin (2cm)	2007	0.7	$\pi^{\pm}, K^{\pm}, K^0_S, \Lambda$	past
		2009	5.4	$\pi^{\pm}, K^{\pm}, p, K^0_S, \Lambda$	in use
	T2K replica (90cm)	2007	0.2	$\pi^{\pm}$	
		2009	2.8	$\pi^{\pm}$	next T2K results
		2010	10.	$\pi^{\pm}, K^{\pm}, p$	in development





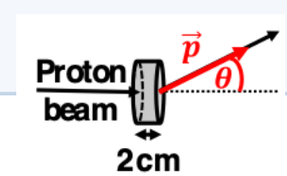
Move to replica tuning

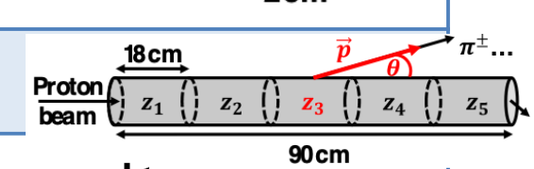




~90% of right-sign ν_μ, ~70% of wrong-sign ν_μ is covered by 2010 replica data

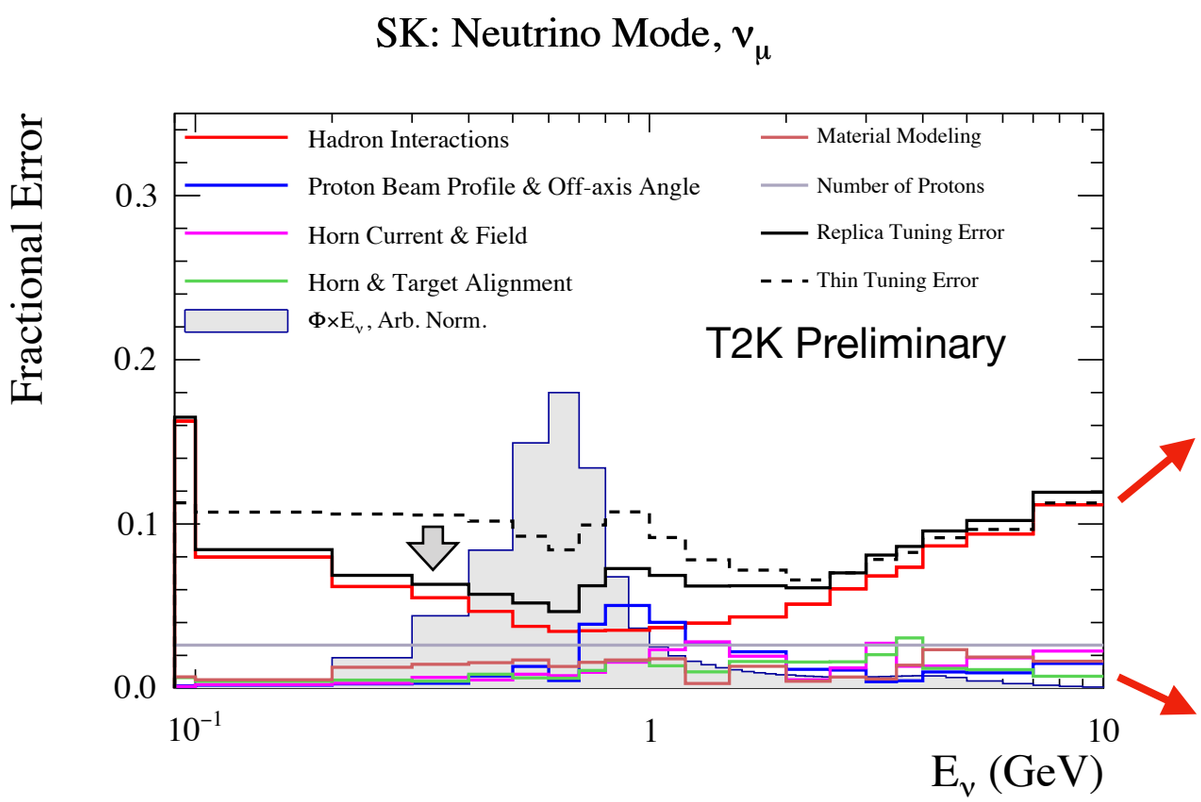
Beam	Target	Year	Stat (10^6)	Outgoing PID	Usage at T2K
protons at 31 GeV/c	Thin (2cm)	2007	0.7	$\pi^\pm, K^\pm, K^0_S, \Lambda$	past
		2009	5.4	$\pi^\pm, K^\pm, p, K^0_S, \Lambda$	in use
	T2K replica (90cm)	2007	0.2	$\pi^\pm$	
		2009	2.8	$\pi^\pm$	next T2K results
		2010	10.	$\pi^\pm, K^\pm, p$	in development



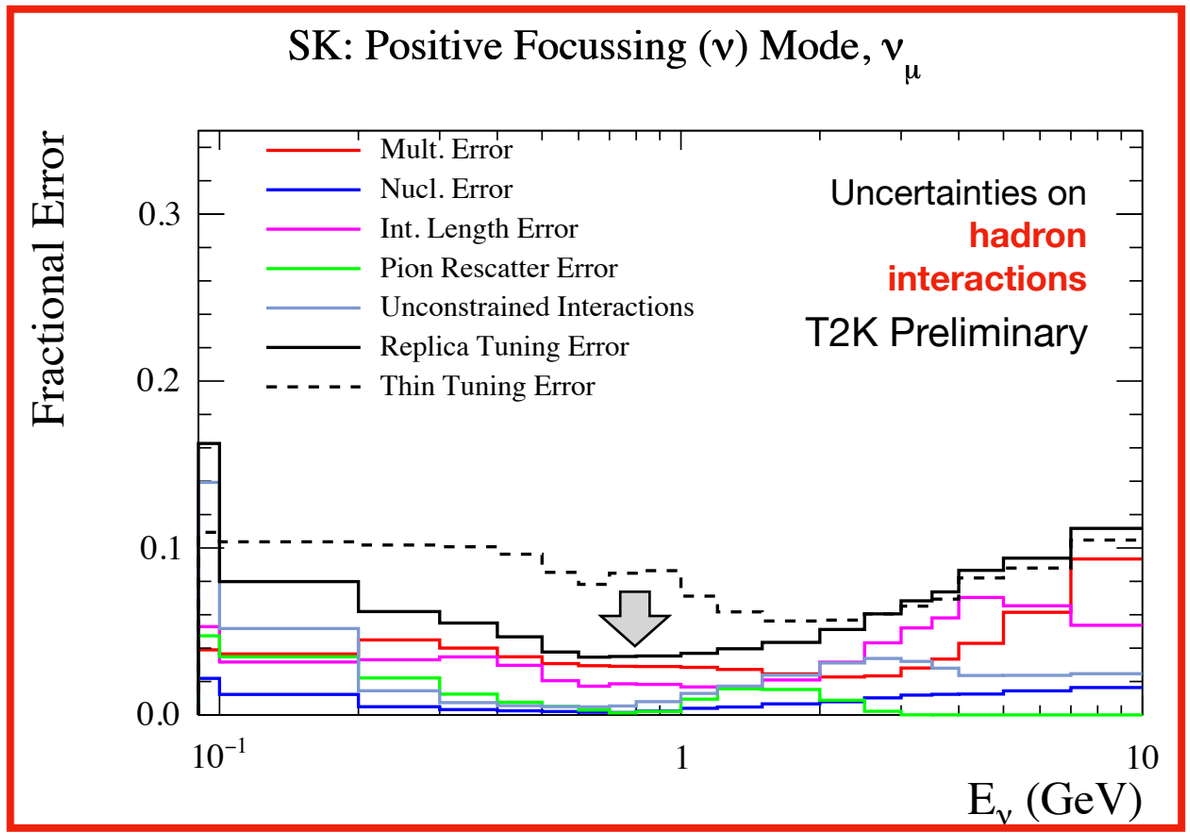


Replica tuning with 2009 data ($\pi^{\pm}$)

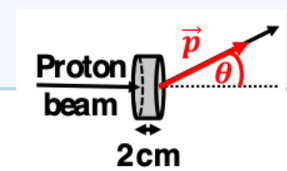
Achieve 5-8% uncertainty near the flux peak from reduced interaction length uncertainty.

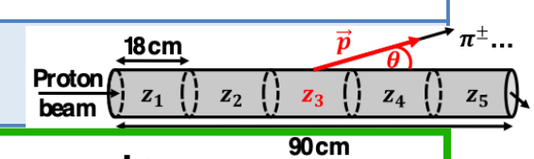


For interactions that do not receive tuning weights from replica or thin tuning ("unconstrained interactions"), assign multiplicity uncertainty in x_F,p_T space motivated by MC-MC comparisons.



Beam	Target	Year	Stat (10^6)	Outgoing PID	Usage at T2K
protons at 31 GeV/c	Thin (2cm)	2007	0.7	$\pi^{\pm}, K^{\pm}, K^0_S, \Lambda$	past
		2009	5.4	$\pi^{\pm}, K^{\pm}, p, K^0_S, \Lambda$	in use
	T2K replica (90cm)	2007	0.2	$\pi^{\pm}$	
		2009	2.8	$\pi^{\pm}$	next T2K results
		2010	10.	$\pi^{\pm}, K^{\pm}, p$	in development

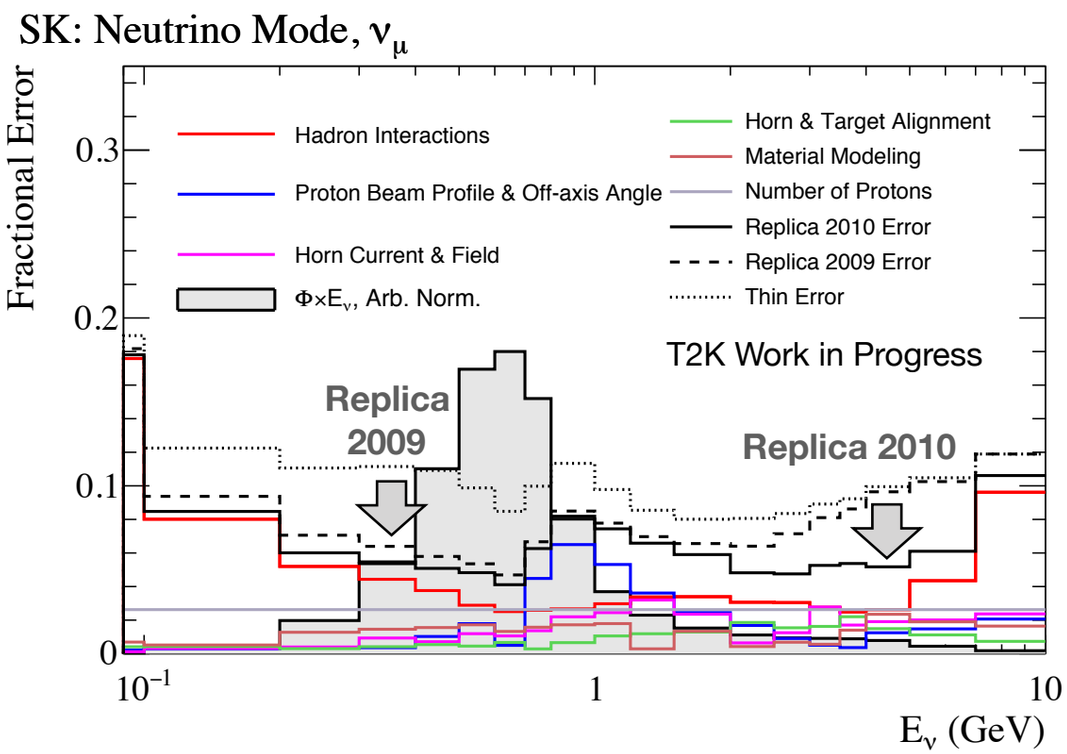


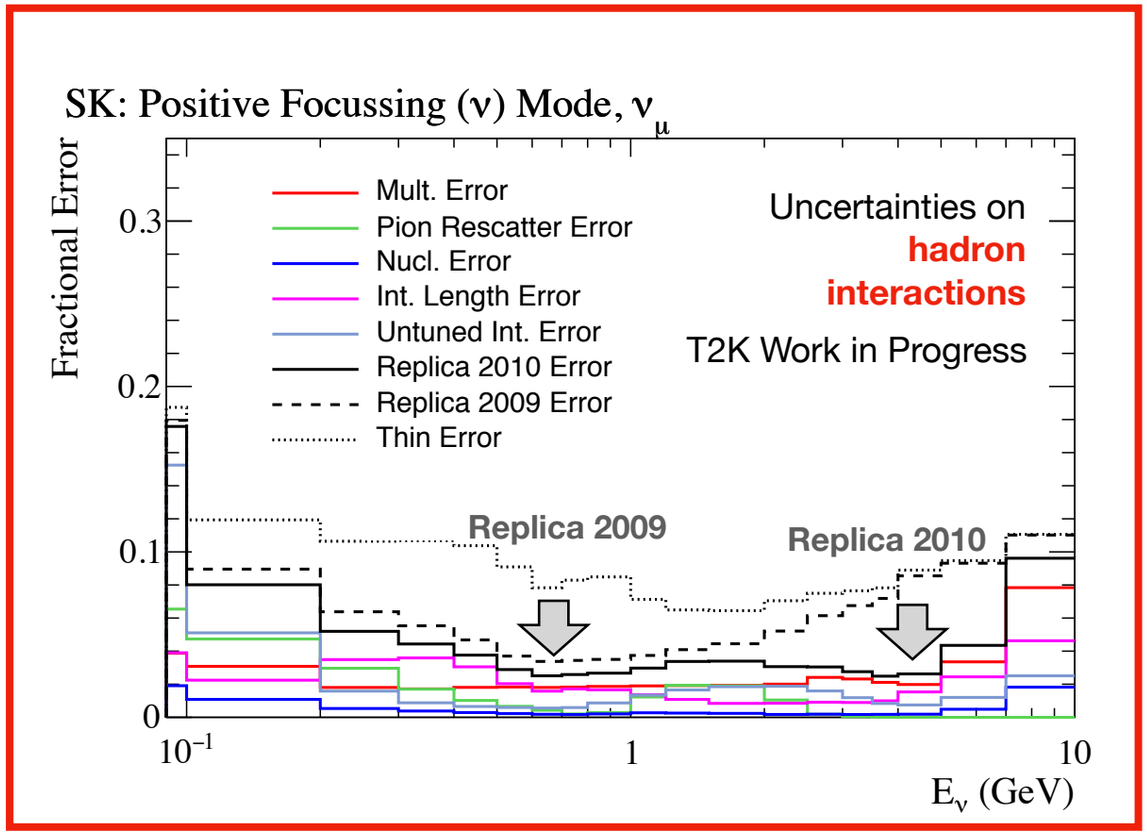


Replica tuning with 2010 data ($\pi^{\pm}, K^{\pm}, p$)

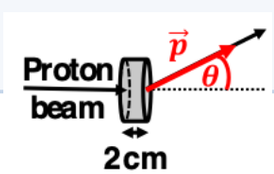
Adds K± and proton yields + increased stats.
Achieve ~4% hadron interaction uncertainty over wide energy range.

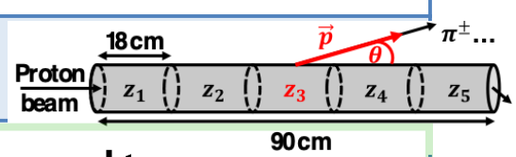
1. checked additional systematics → seems robust
2. checking consistency with thin tuning





Beam	Target	Year	Stat (10^6)	Outgoing PID	Usage at T2K
protons at 31 GeV/c	Thin (2cm)	2007	0.7	$\pi^{\pm}, K^{\pm}, K^0_S, \Lambda$	past
		2009	5.4	$\pi^{\pm}, K^{\pm}, p, K^0_S, \Lambda$	in use
	T2K replica (90cm)	2007	0.2	$\pi^{\pm}$	
		2009	2.8	$\pi^{\pm}$	next T2K results
		2010	10.	$\pi^{\pm}, K^{\pm}, p$	in development





Consistency checks of tuning methods

- Conventional tuning

$$\text{FLUKA MC} \times \frac{\text{NA61 DATA}}{\text{“NA61” w/FLUKA}} \rightarrow \text{tuned flux}$$

- Fake tuning using fake data

can check consistency by comparing with “fake truth”

$$\text{FLUKA MC} \times \frac{\text{“NA61” w/Geant4}}{\text{“NA61” w/FLUKA}} \rightarrow \text{“tuned” flux}$$

$$\Updownarrow$$

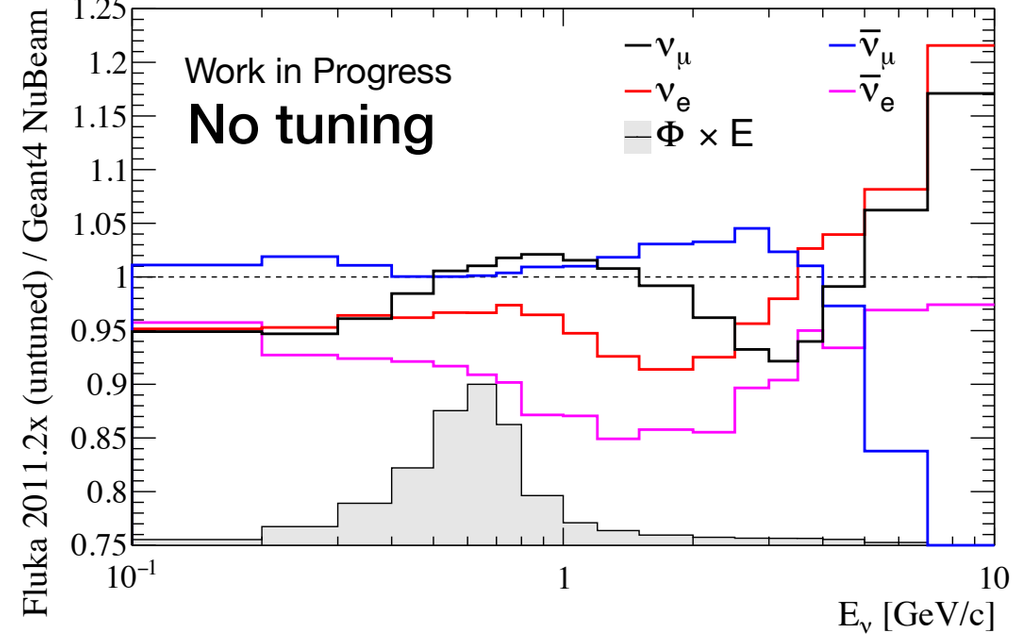
$$\text{Geant4 MC} \rightarrow \text{“true” flux}$$

Mainly comparing to Geant4's NuBeam physics list, which is mostly FTFP BERT in kinematic region of interest.

Consistency checks of tuning methods

Before tuning

- Fluka/NuBeam differ by about 0~7% below 5 GeV.



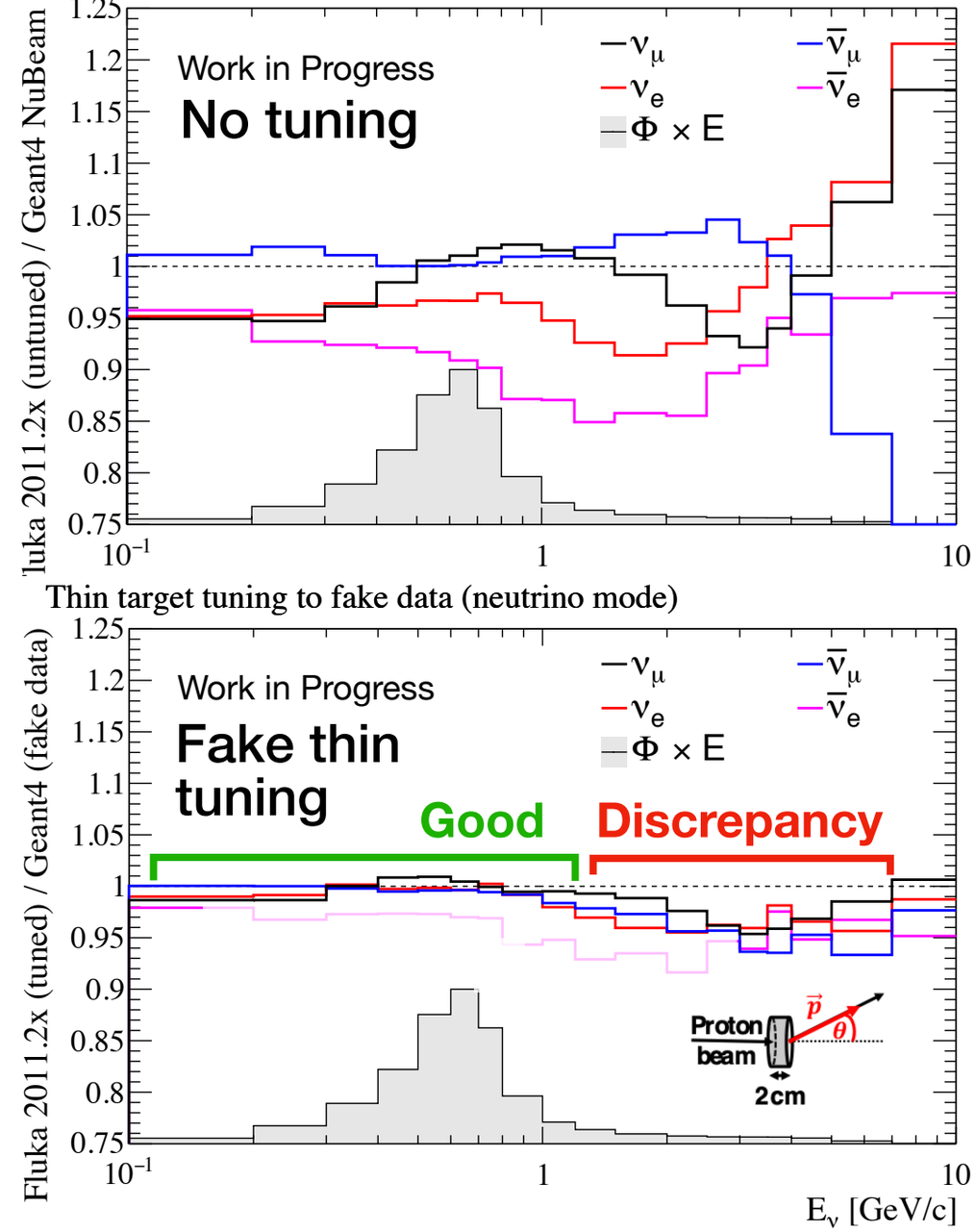
Consistency checks of tuning methods

Before tuning

- Fluka/NuBeam differ by about 0~7% below 5 GeV.

Fake <u>thin</u> tuning

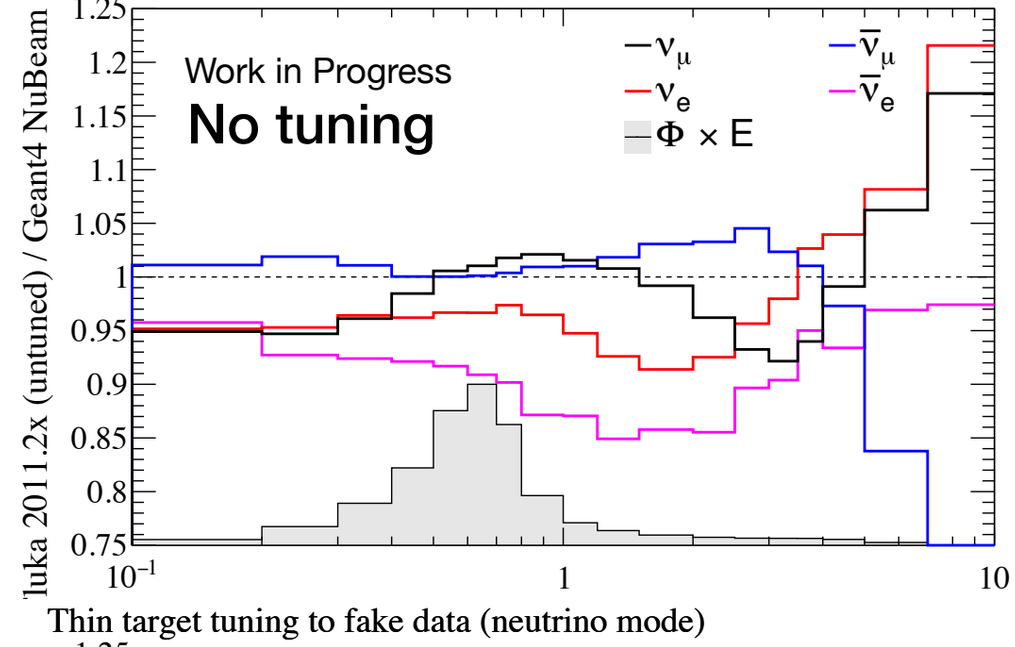
- **Agreement** at 2% level below 1 GeV. 👍
- **Discrepancy** of about 5% at 2~5 GeV range. ⚡



Consistency checks of tuning methods

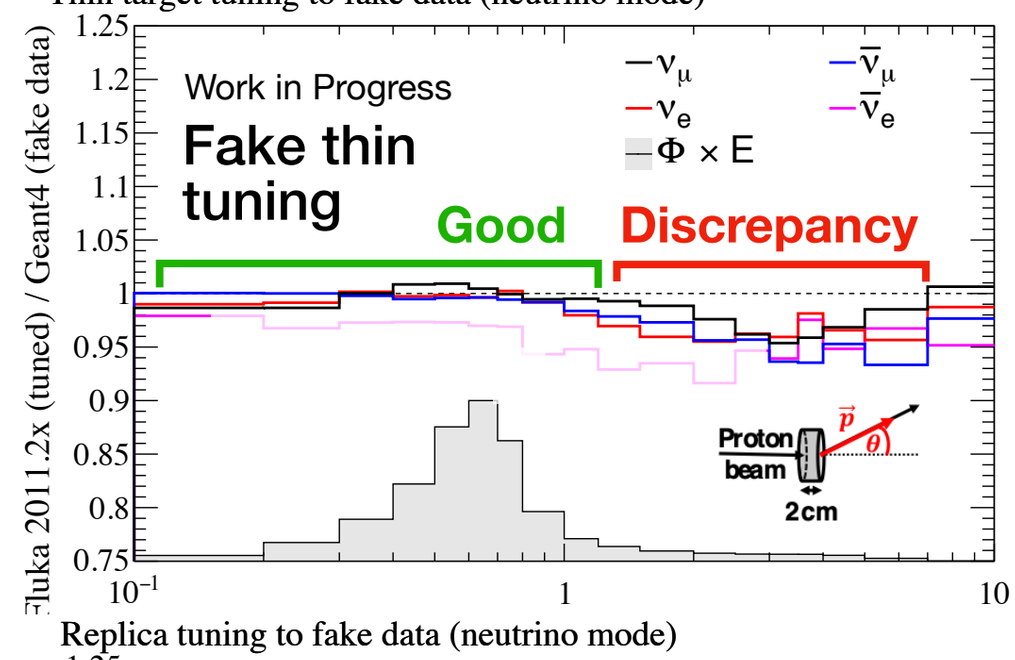
Before tuning

- Fluka/NuBeam differ by about 0~7% below 5 GeV.



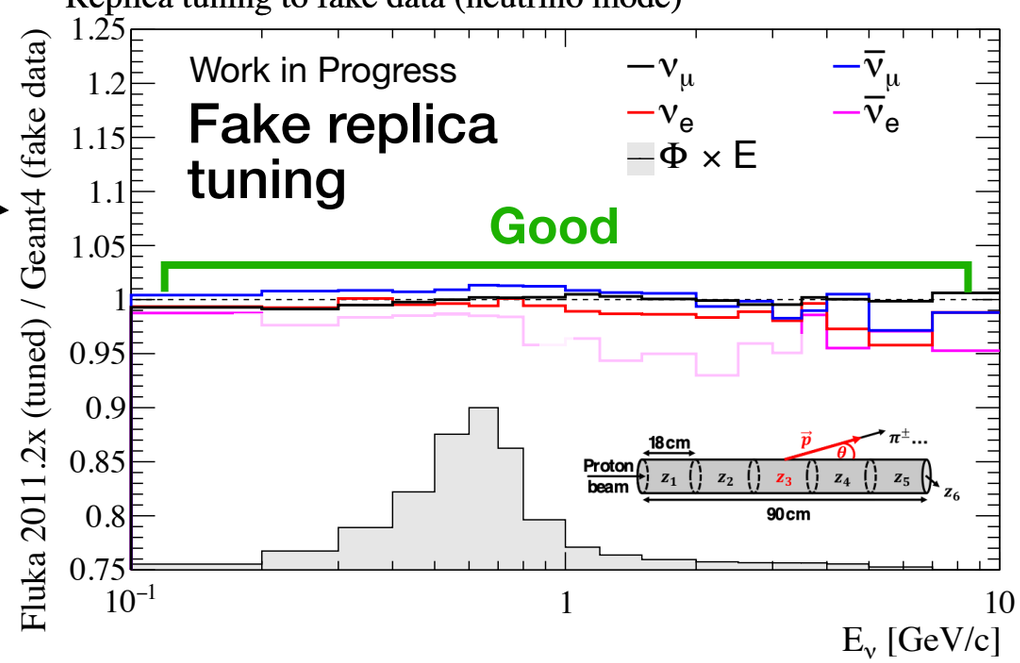
Fake thin tuning

- **Agreement** at 2% level below 1 GeV. 👍
- **Discrepancy** of about 5% at 2~5 GeV range. ⚡

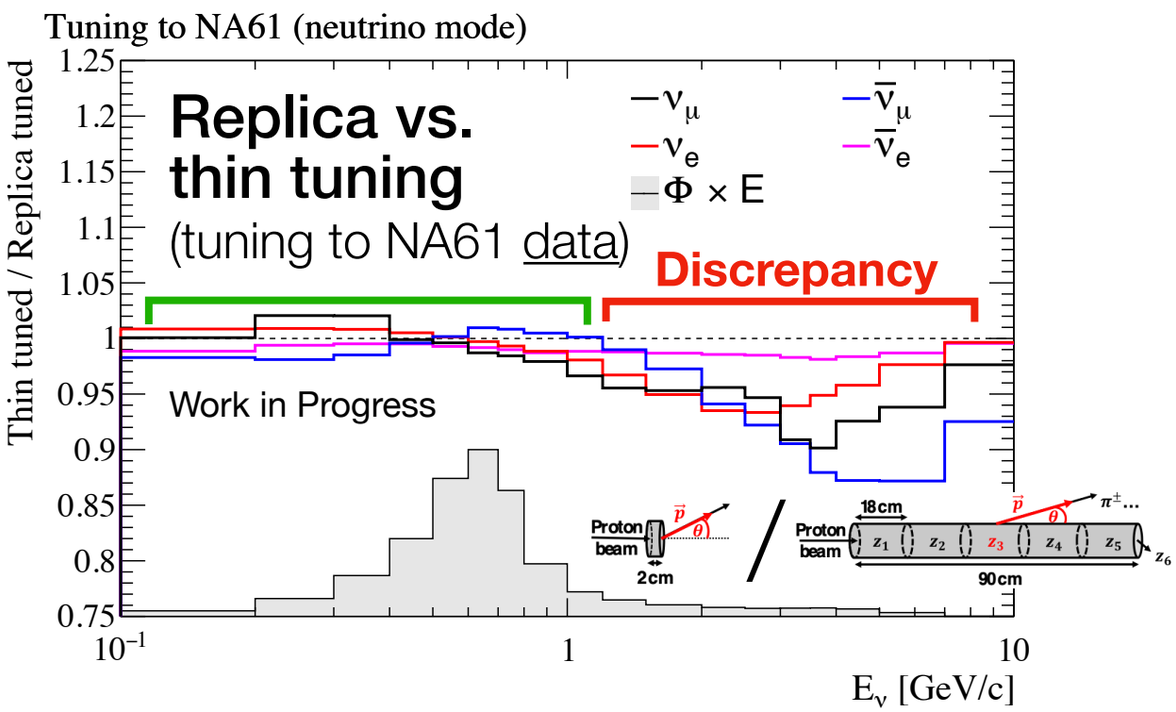


Fake replica tuning

- **Agreement** at 2% level for wide range up to 5 GeV. 👍

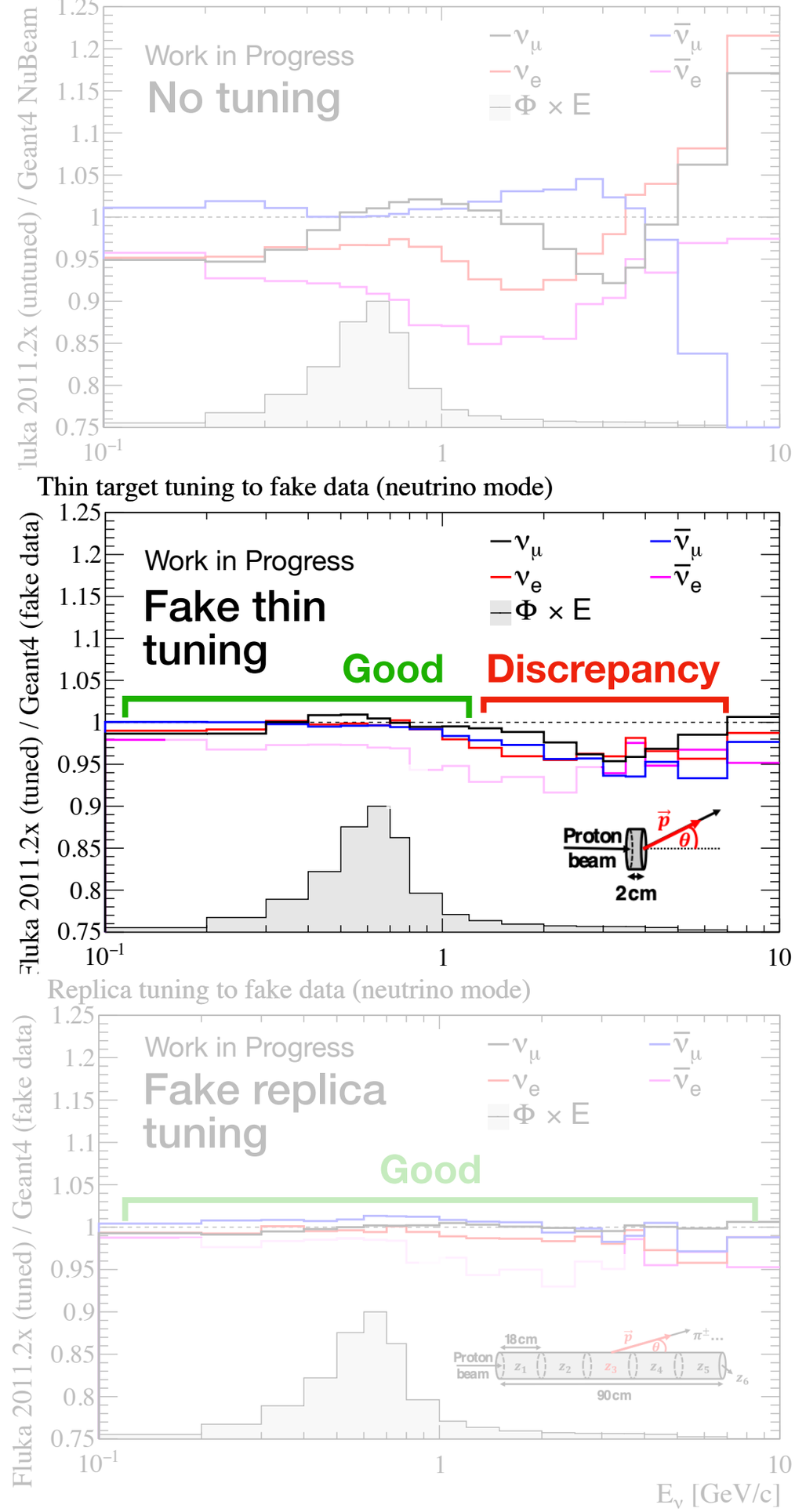


Consistency checks of tuning methods

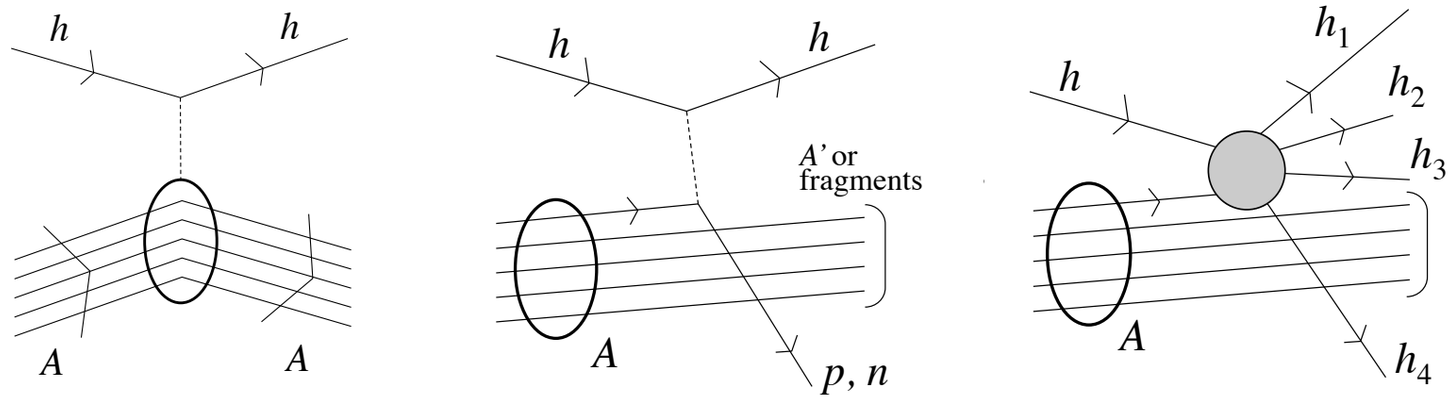


For tuning to NA61 data no "truth" is available, but can compare thin and replica tuned fluxes. Above 1 GeV a **discrepancy** similar to that seen in fake thin tuning is observed.

Seems to be related to interactions with insufficient data for **thin** tuning?
→ extend fake thin tuning to understand origin and assess systematic assignment



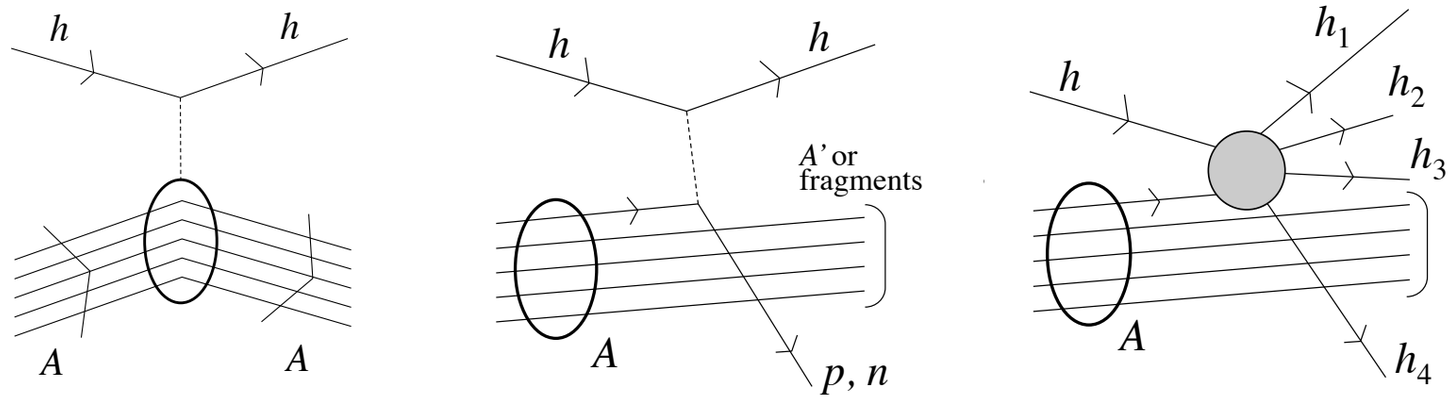
Treatment of interactions in thin target tuning



Incoming particle	Elastic	Quasi-elastic	Production
Proton	✖	✖	✔ tuning ✔ uncertainty
Meson	✖	✖ ✔ Limited error model	✖ tuning ✔ uncertainty

Most important for ν-beams

Treatment of interactions in thin target tuning

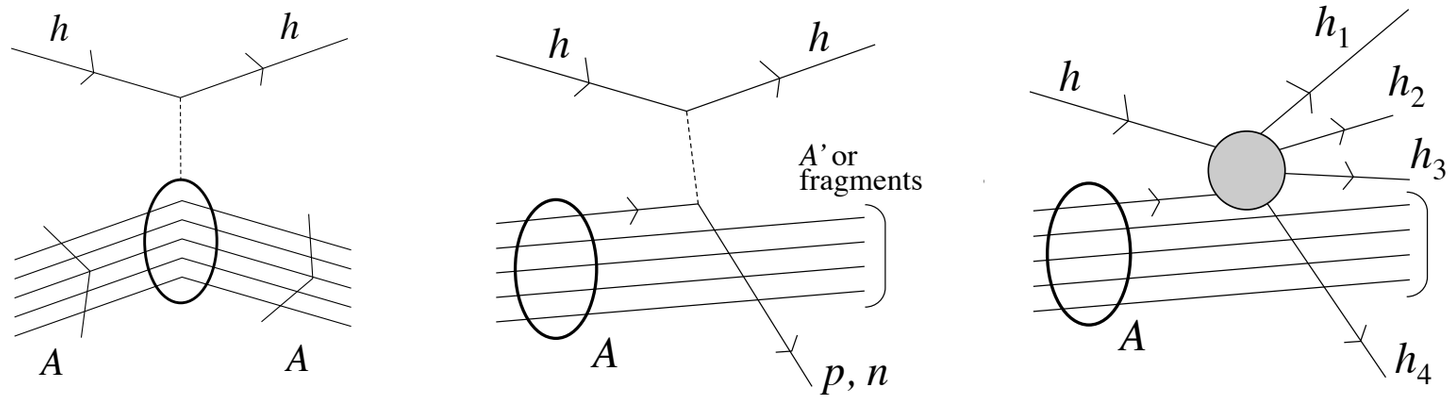


Incoming particle	Elastic	Quasi-elastic	Production
Proton	✖	✖	✔ tuning ✔ uncertainty
Meson	✖	✖ ✔ Limited error model	✖ tuning ✔ uncertainty

Most important for ν-beams

Relying on MC-MC comparisons for some systematics due to insufficient hadron production data.

Treatment of interactions in thin target tuning



Incoming particle	Elastic	Quasi-elastic	Production
Proton	✖	✖	✔ tuning ✔ uncertainty
Meson	✖	✖ ✔ Limited error model	✖ tuning ✔ uncertainty

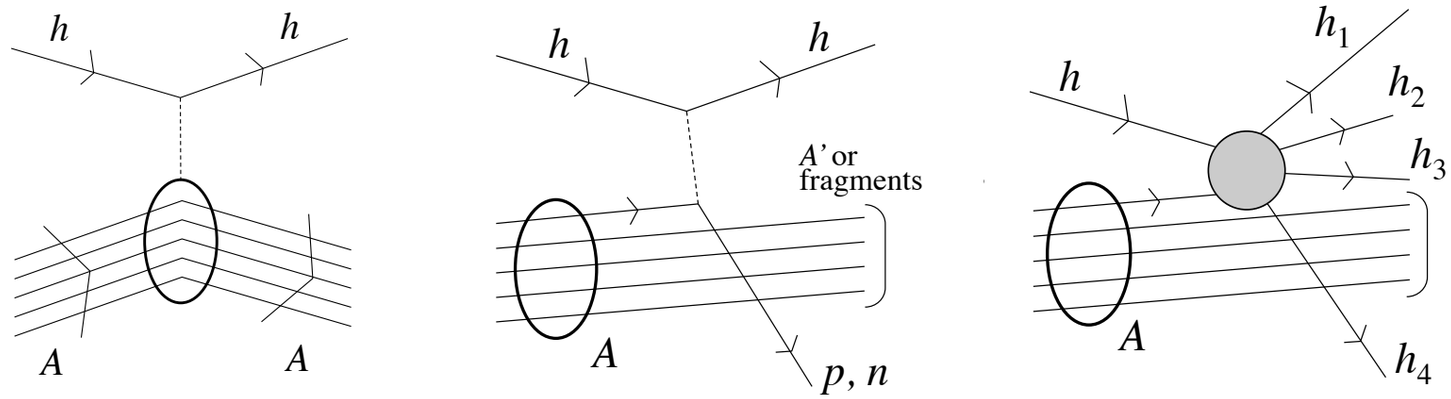
Most important for ν-beams

Mostly just a change in momentum **direction**, no change in number of mesons → indirect effect on neutrino flux.

However: for E>1GeV flux even O(10mrad) change can affect neutrino flux if particle is not focused by horns.

Relying on MC-MC comparisons for some systematics due to insufficient hadron production data.

Treatment of interactions in <u>thin</u> target tuning



Incoming particle	Elastic	Quasi-elastic	Production
Proton	✖	✖	✔ tuning ✔ uncertainty
Meson	✖	✖ ✔ Limited error model	✖ tuning ✔ uncertainty

Most important for ν-beams

Mostly just a change in momentum **direction**, no change in number of mesons → indirect effect on neutrino flux.

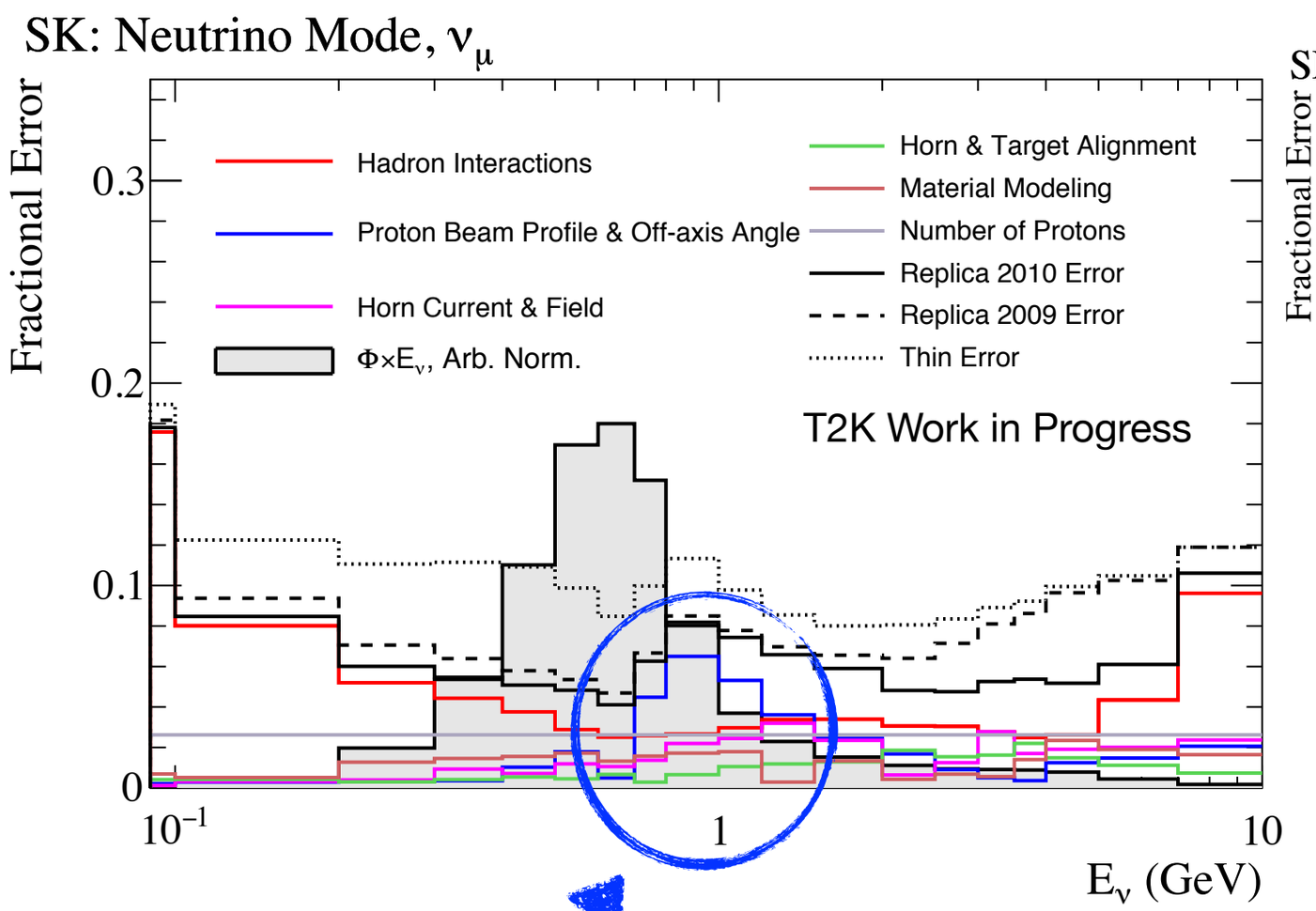
However: for E>1GeV flux even O(10mrad) change can affect neutrino flux if particle is not focused by horns.

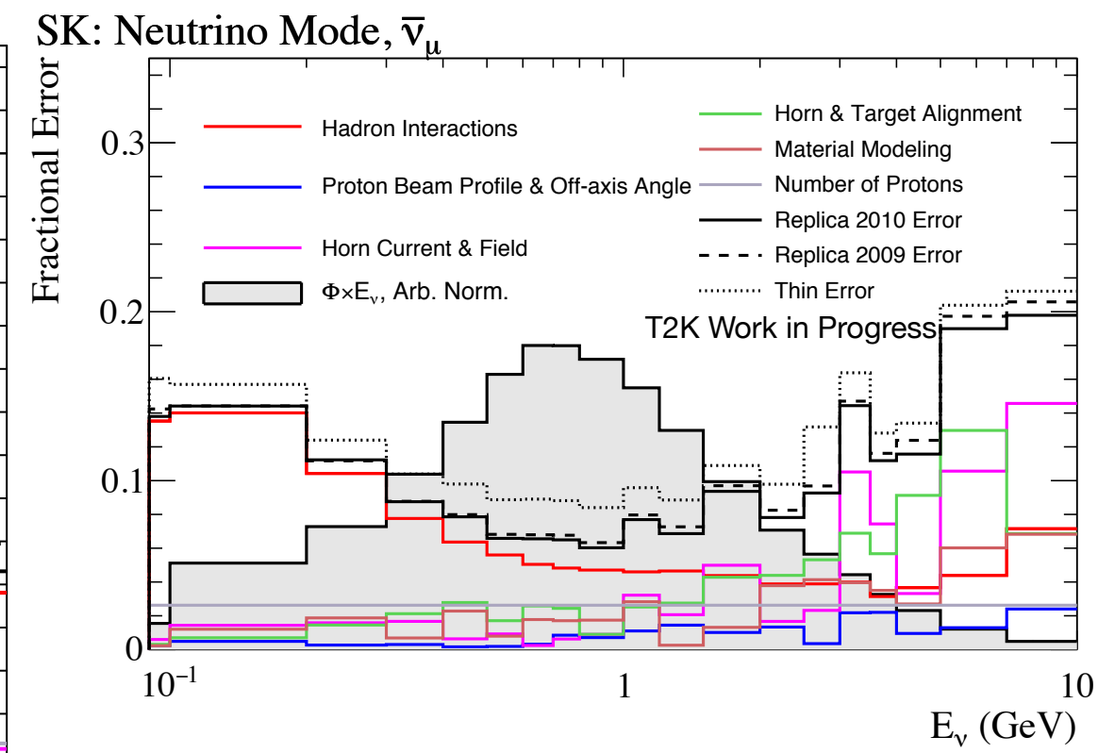
Relying on MC-MC comparisons for some systematics due to insufficient hadron production data.

At fake tuning level it seems that **both elastic and inelastic** scattering of mesons contribute to the observed discrepancy. Proper treatment and systematics assignment should be investigated in the future.

Note with replica 2010 tuning ~90% of flux is covered with **replica data**, so this matters mostly for remaining 10% and out-of-target interactions.

Towards further improvements



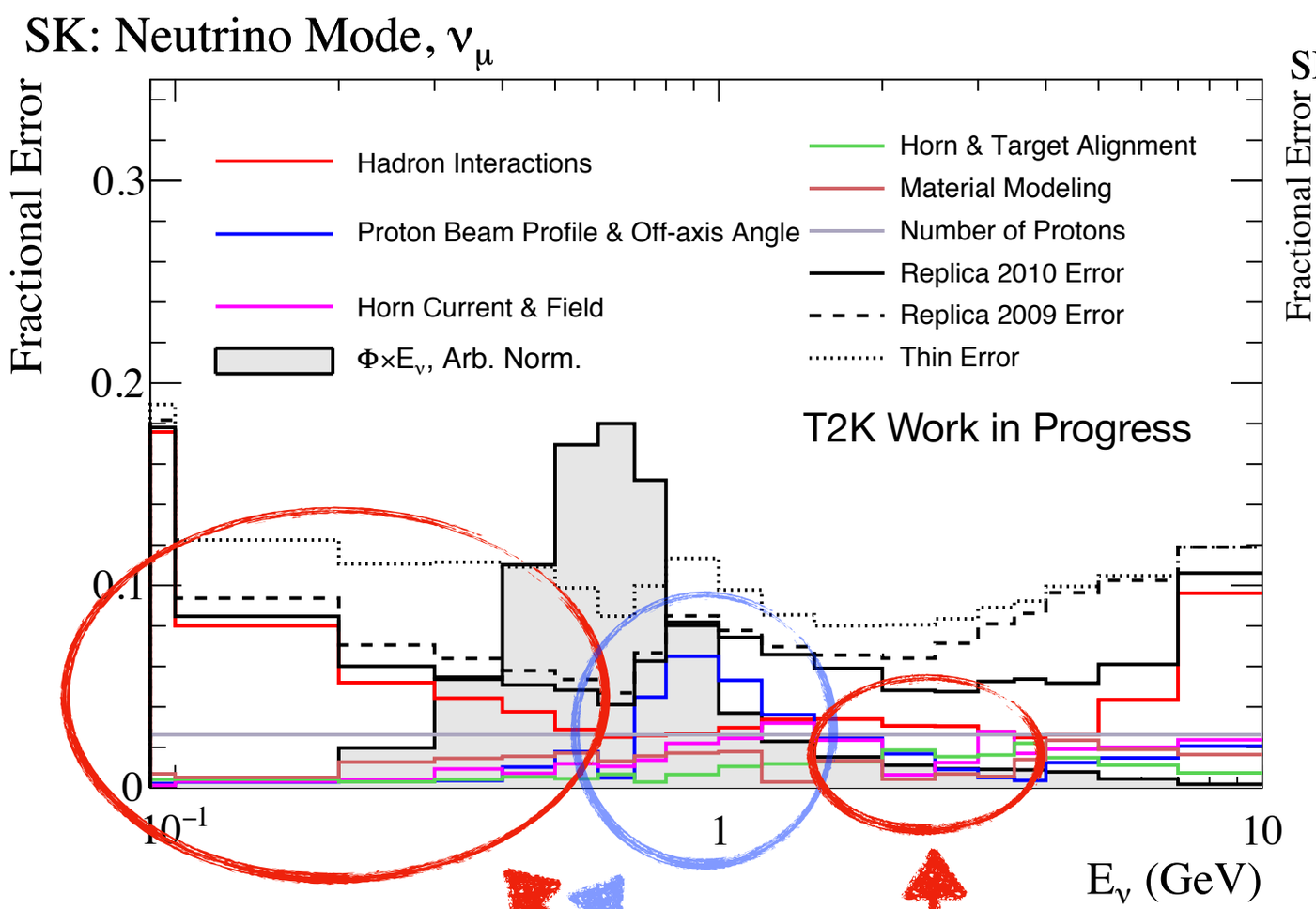


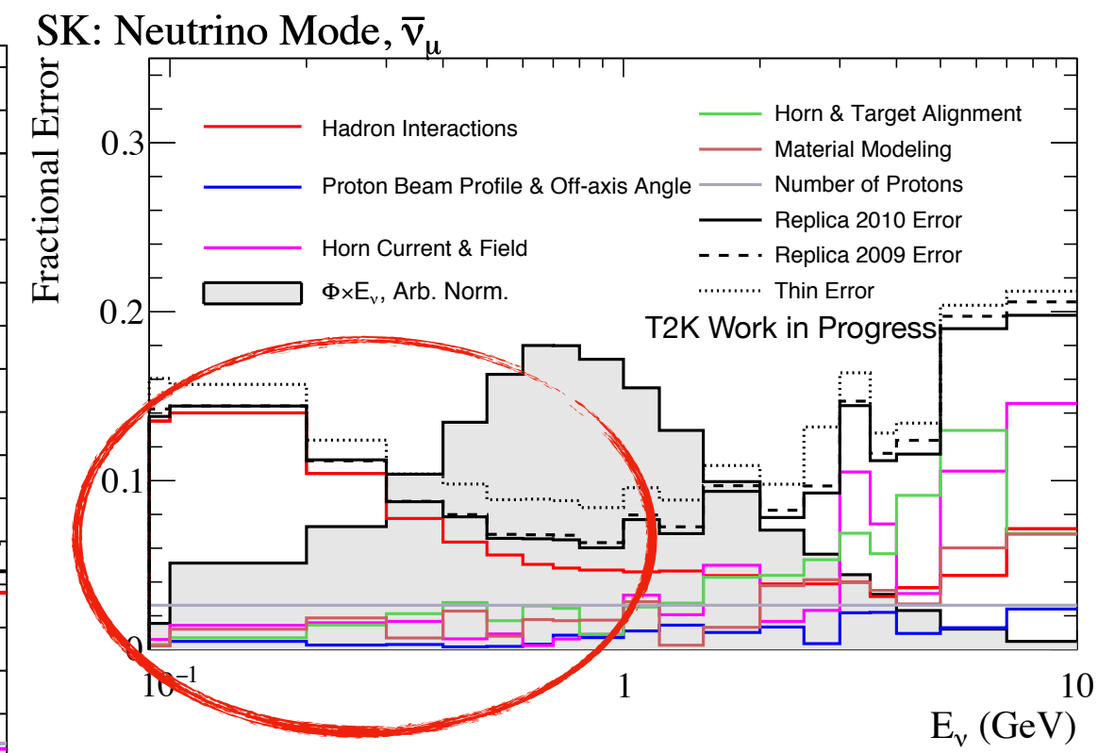
Near flux peak **proton beam profile**

→ can be constrained to ~1/3 using INGRID **beam direction** measurement?

see also Mark's talk toward HyperK

Towards further improvements



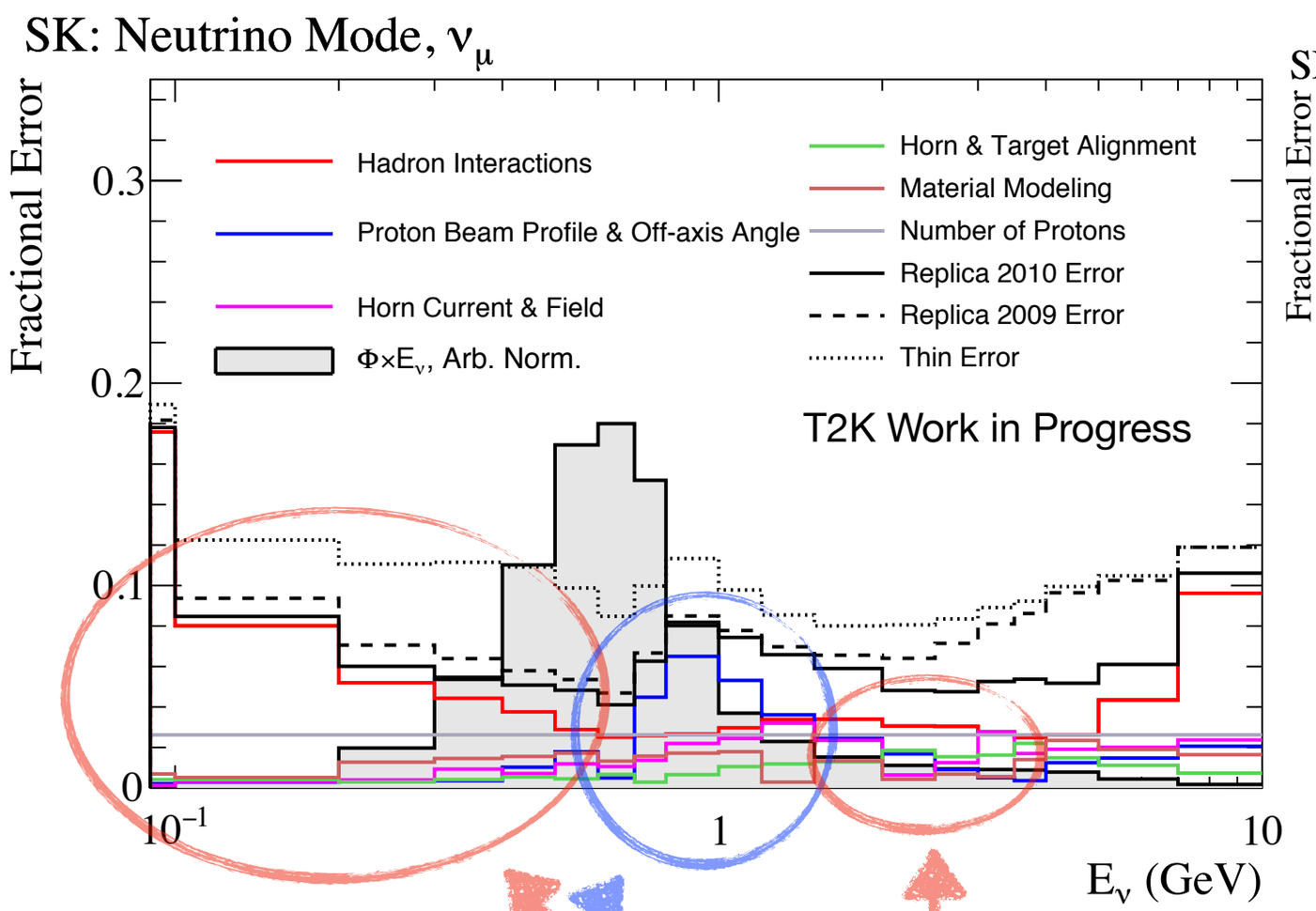


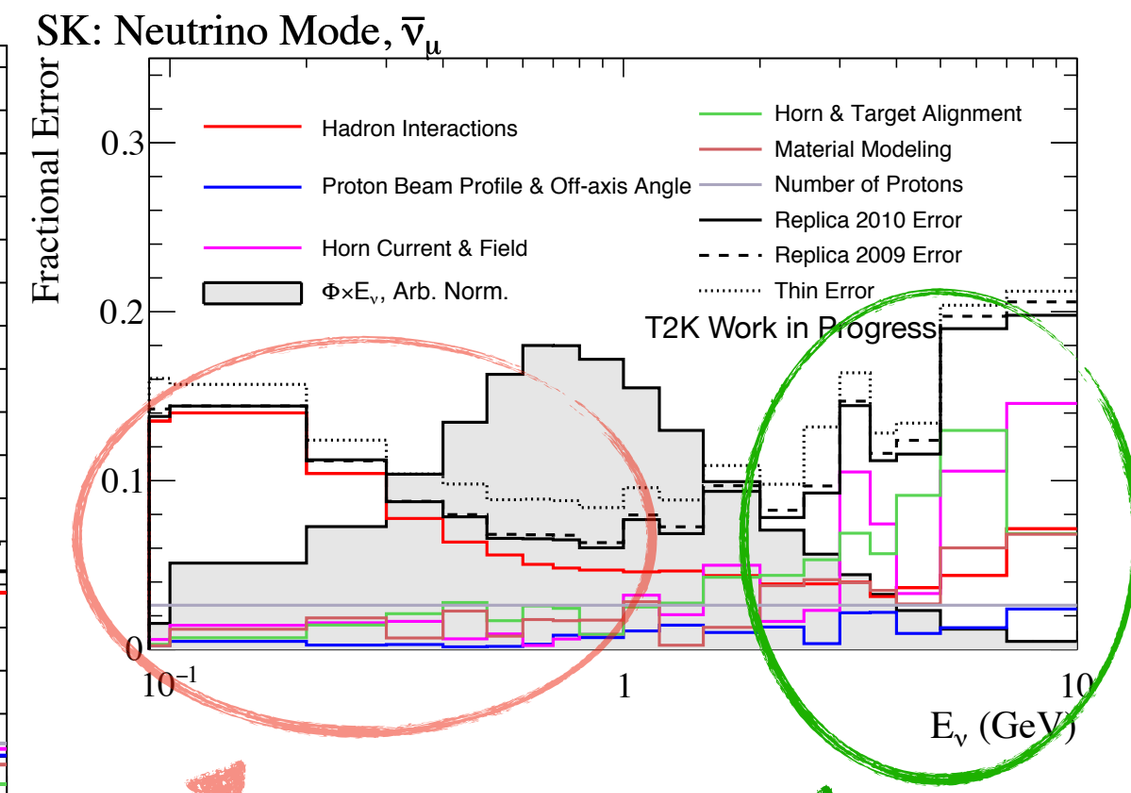
Near flux peak **proton beam profile**
→ can be constrained to ~1/3 using INGRID **beam direction** measurement?

Low-energy flux error dominated by **π-rescattering** (Al, Fe).
At higher energies also K-scattering.
→ future hadron production data from NA61, EMPHATIC, …?

see also Mark's talk toward HyperK

Towards further improvements





Near flux peak **proton beam profile**
→ can be constrained to ~1/3 using INGRID **beam direction** measurement?

Low-energy flux error dominated by **π-rescattering** (Al, Fe).
At higher energies also K-scattering.
→ future hadron production data from NA61, EMPHATIC, …?

At high-E for wrong-sign flux **beamline optics** dominant source of systematics.

see also Mark's talk toward HyperK

Summary

- By moving from thin to **replica target** tuning, T2K achieves significant reduction of hadron interaction uncertainties to 5% level near the flux peak. Will be used in upcoming physics analyses.

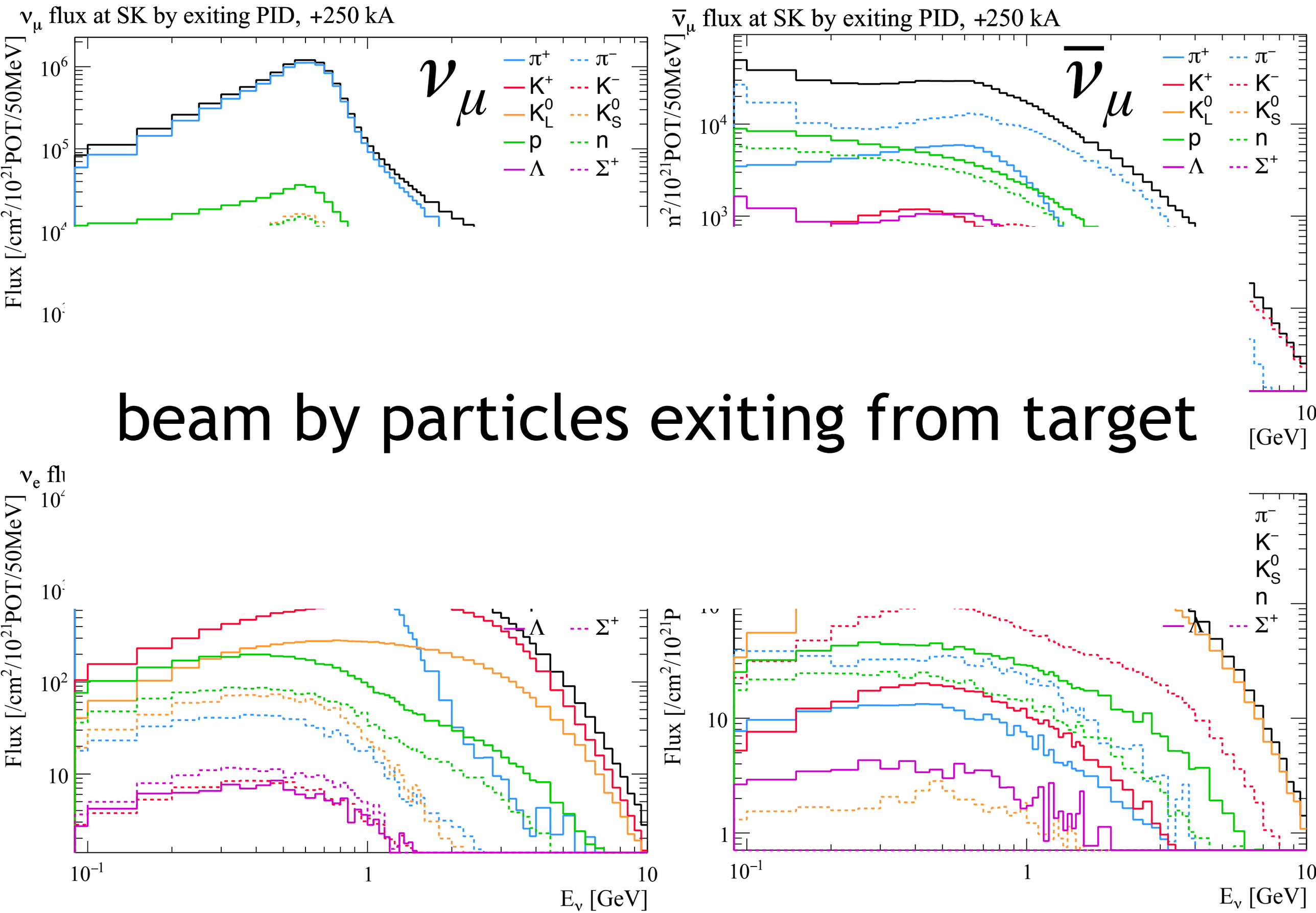
- Soon we expect **5% level error** for wide energy range (up to high-E) from additional K, p data in replica 2010 tuning.

- Using fake data, confirmed both thin and replica target tuning are **consistent** with “fake truth” to ~2% level near flux peak. With replica tuning we see better consistency up to higher energies.

- Further systematic reduction with **meson scattering** data, and also utilizing INGRID **beam direction** measurements.

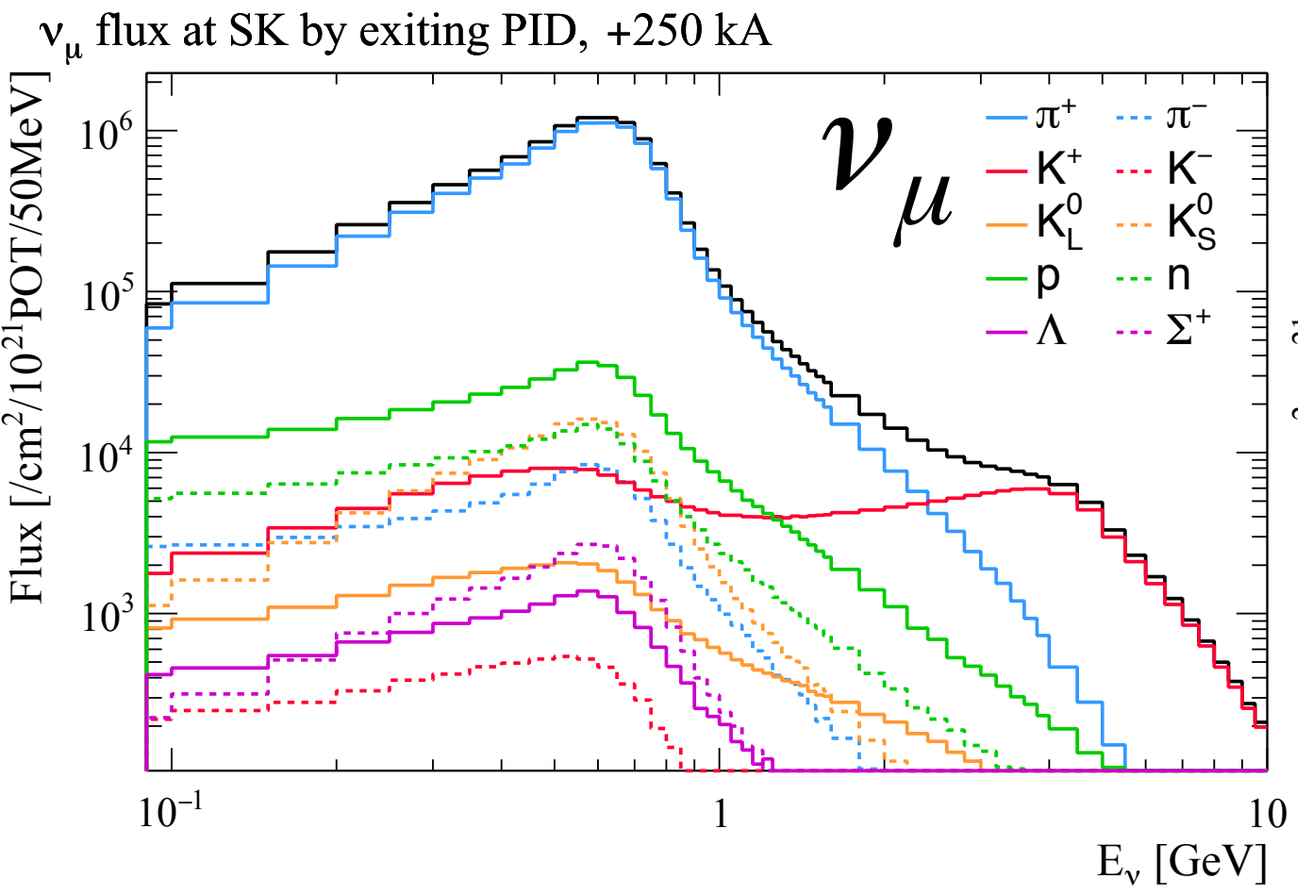
backup

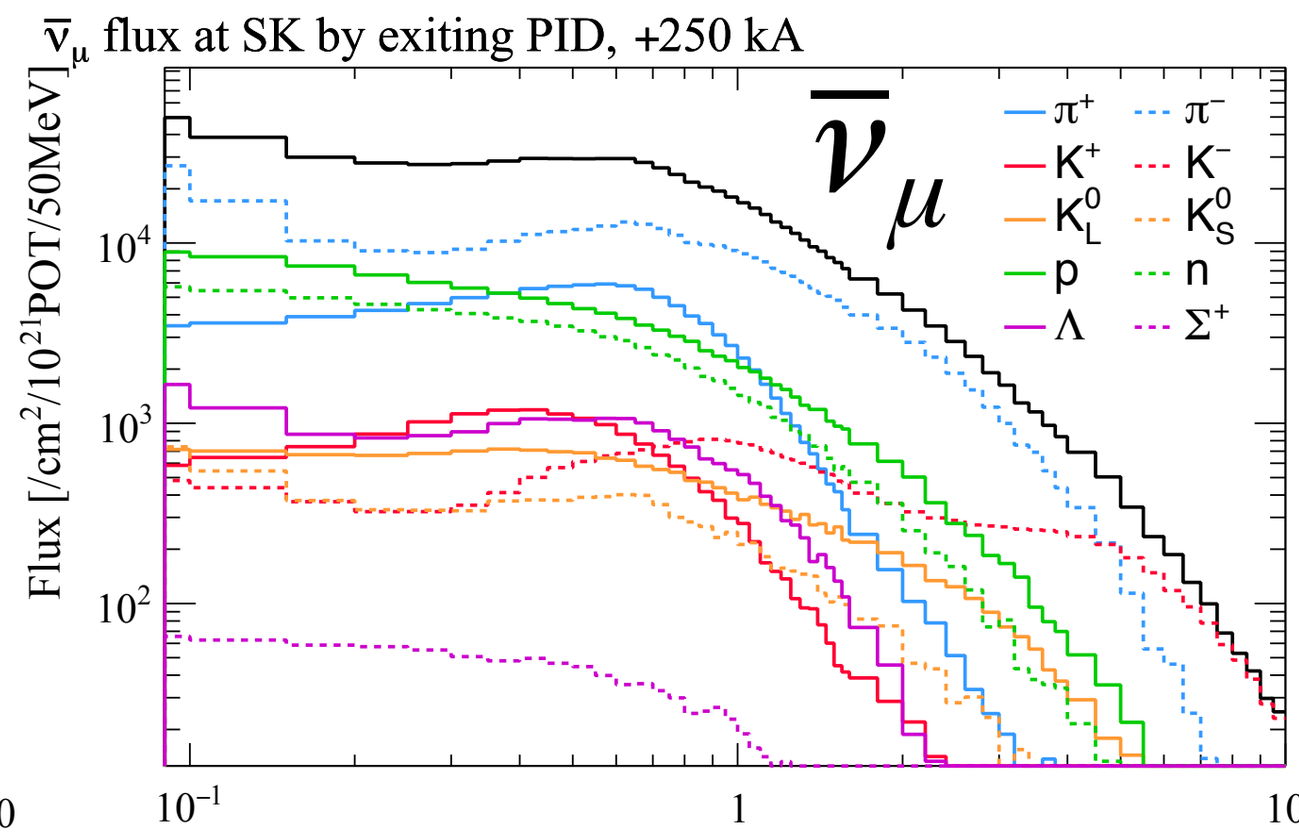
Neutrino mode (13a nominal FLUKA 2011.2x.2)

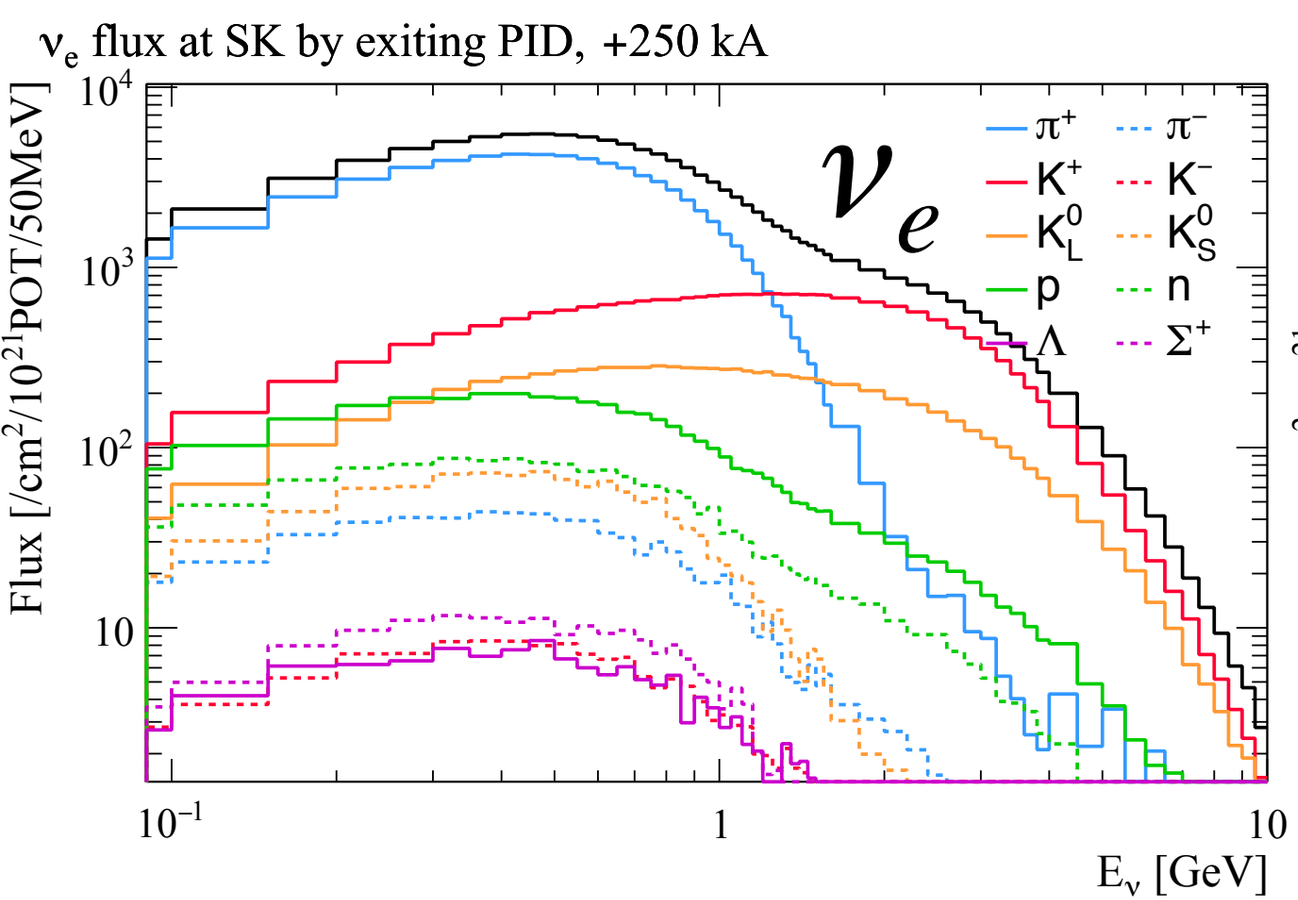


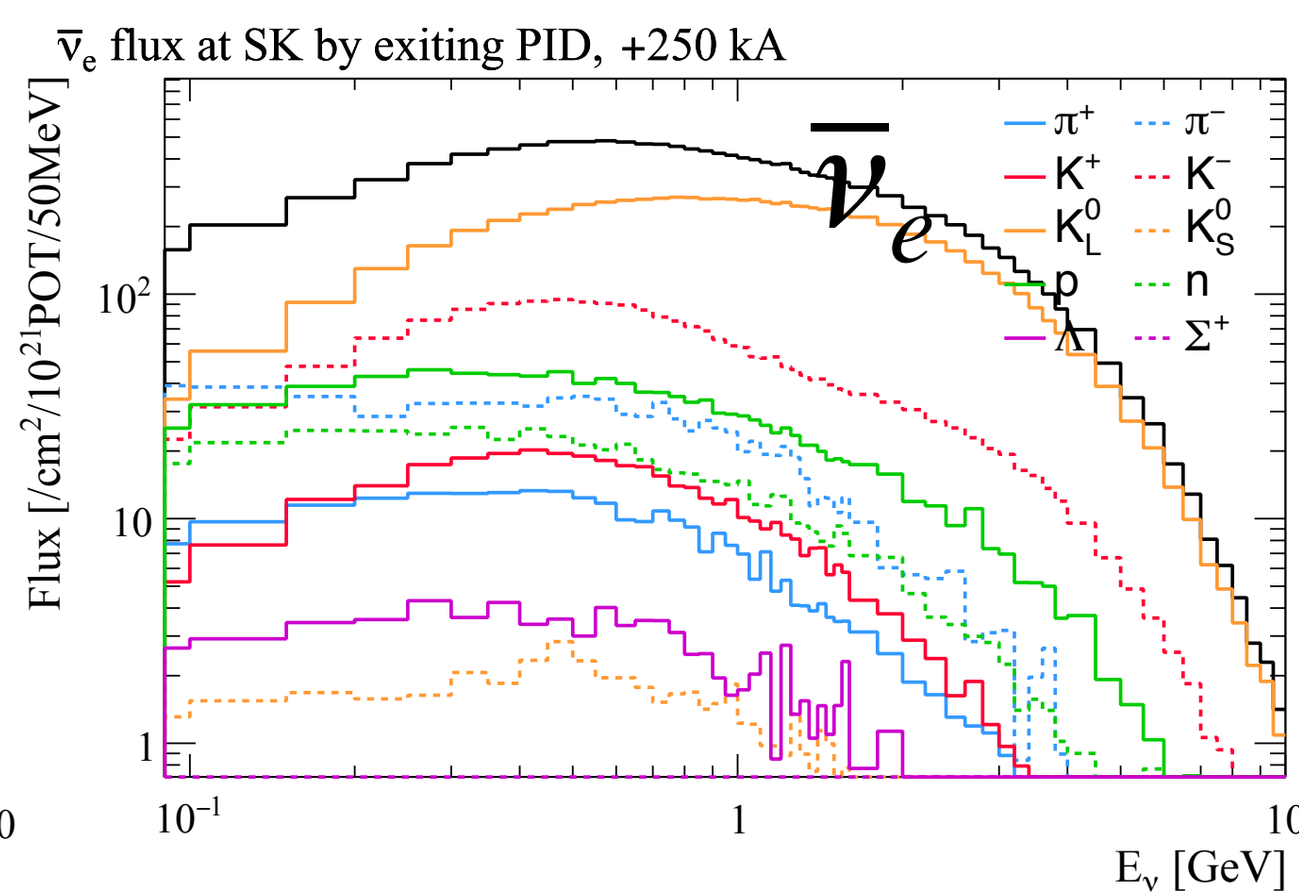
beam by particles exiting from target

Neutrino mode (13a nominal FLUKA 2011.2x.2)

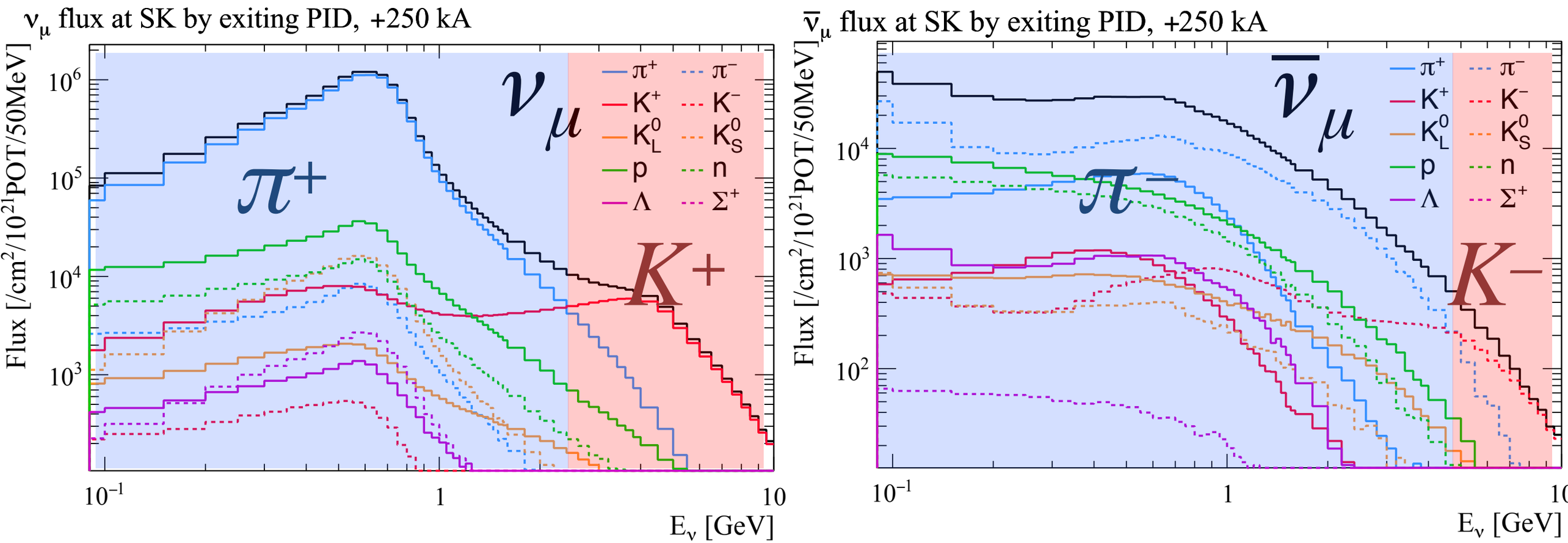


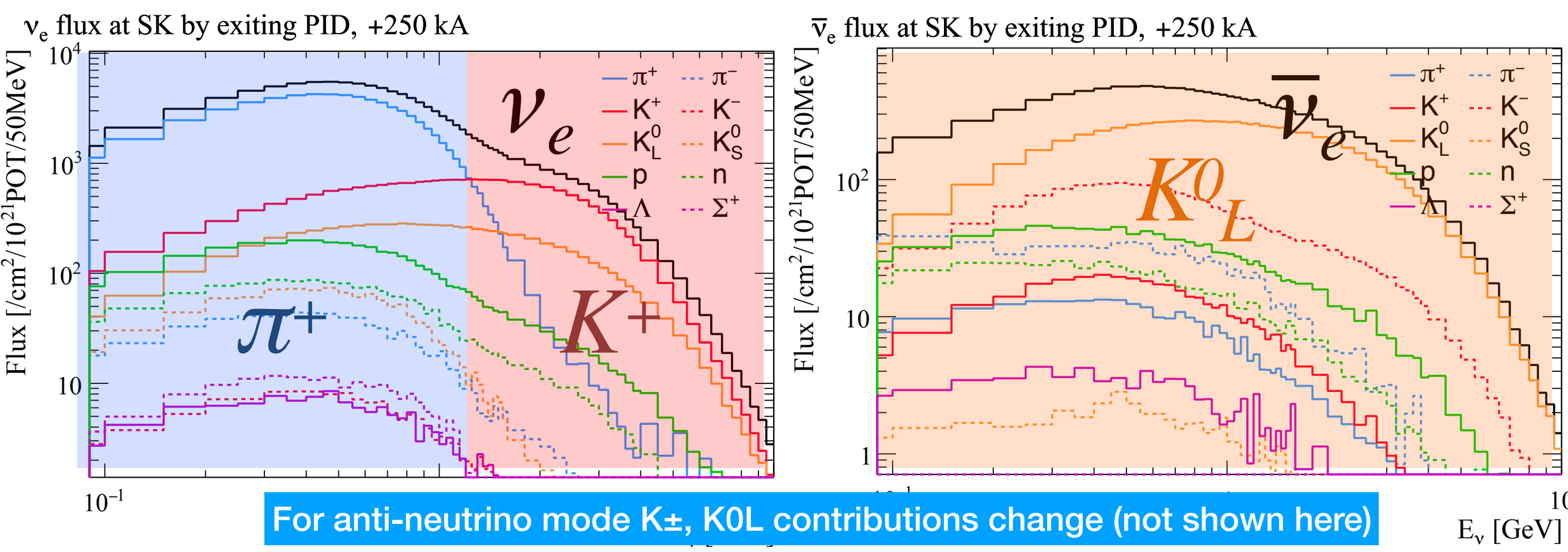






Neutrino mode (13a nominal FLUKA 2011.2x.2)





For anti-neutrino mode K±, K0L contributions change (not shown here)