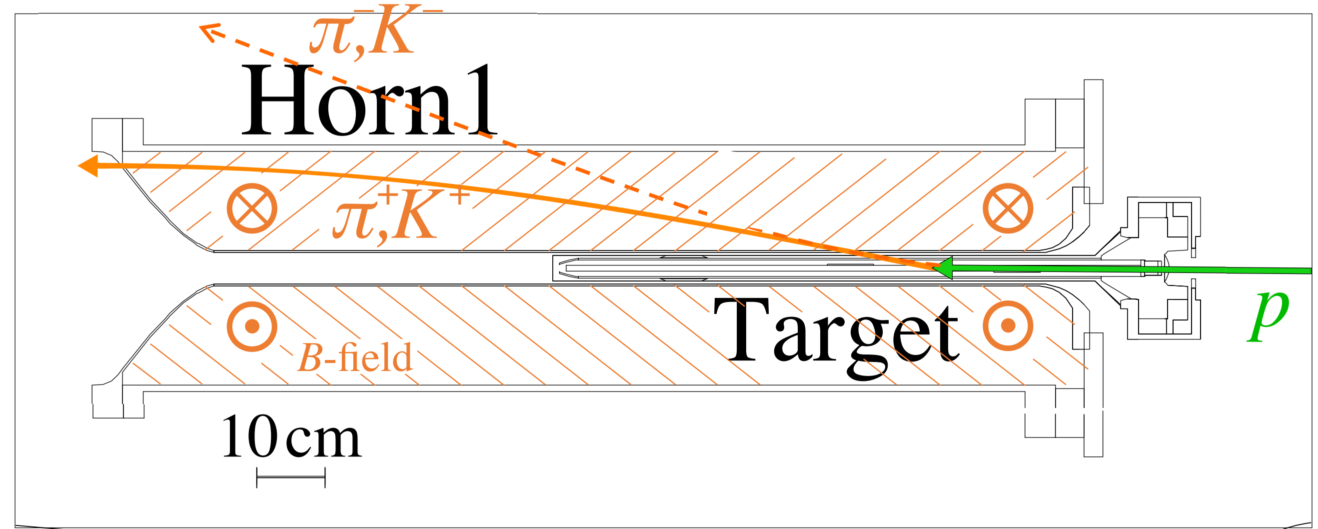
Low energy hadron production motivation for T2K/HK beam

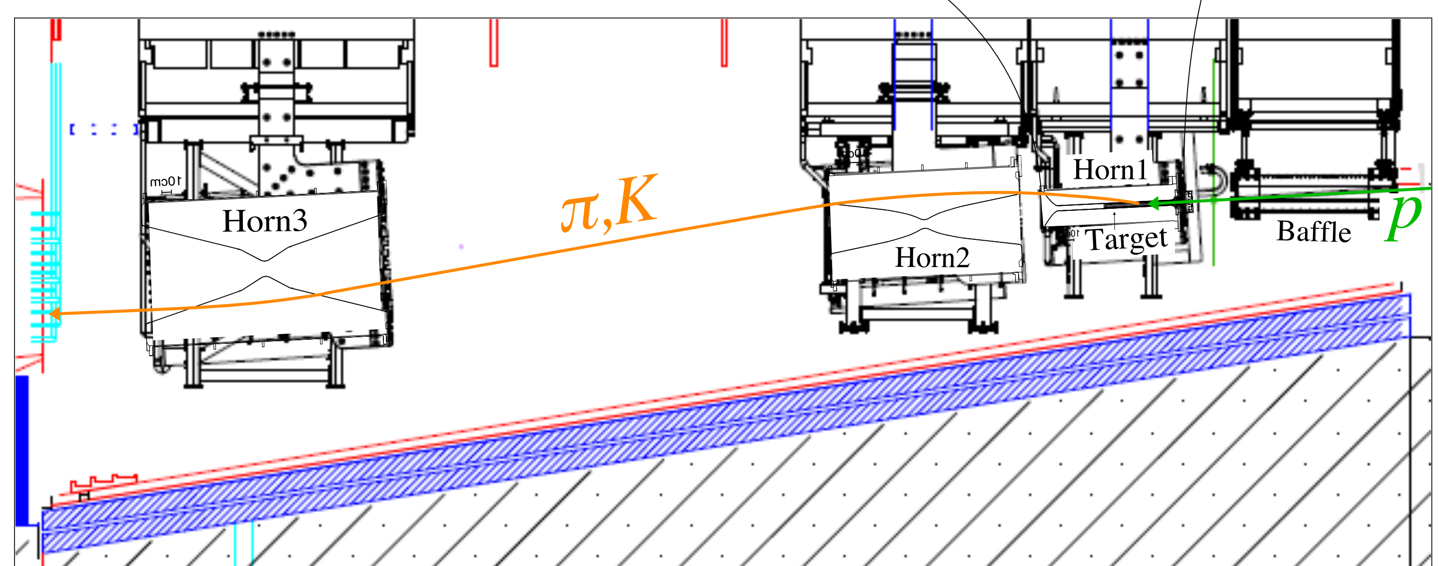
NA61 low-E workshop, 2020-12-10

Lukas Berns (T2K/HK)

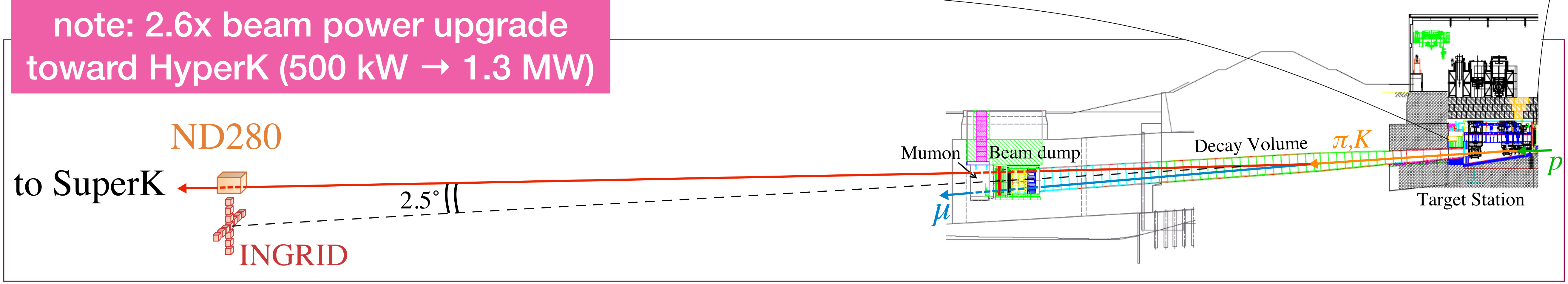
J-PARC ν-beamline

- 30 GeV protons produce π,K in 90 cm graphite target
- Three magnetic horns selectively focus π^+,K^+ or π^-,K^- to produce ν_μ or $\bar{\nu}_\mu$ beam (decay in-flight).
- Muon monitors and on-axis ν detector (INGRID) monitor beam stability and direction.



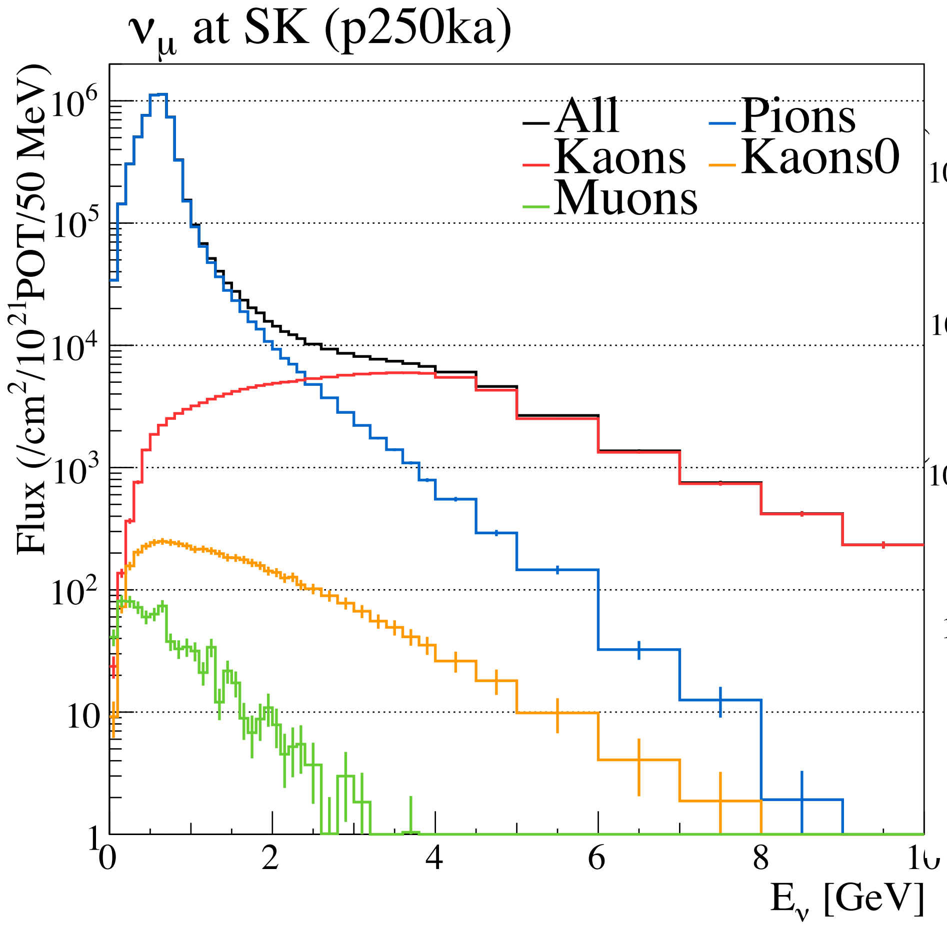


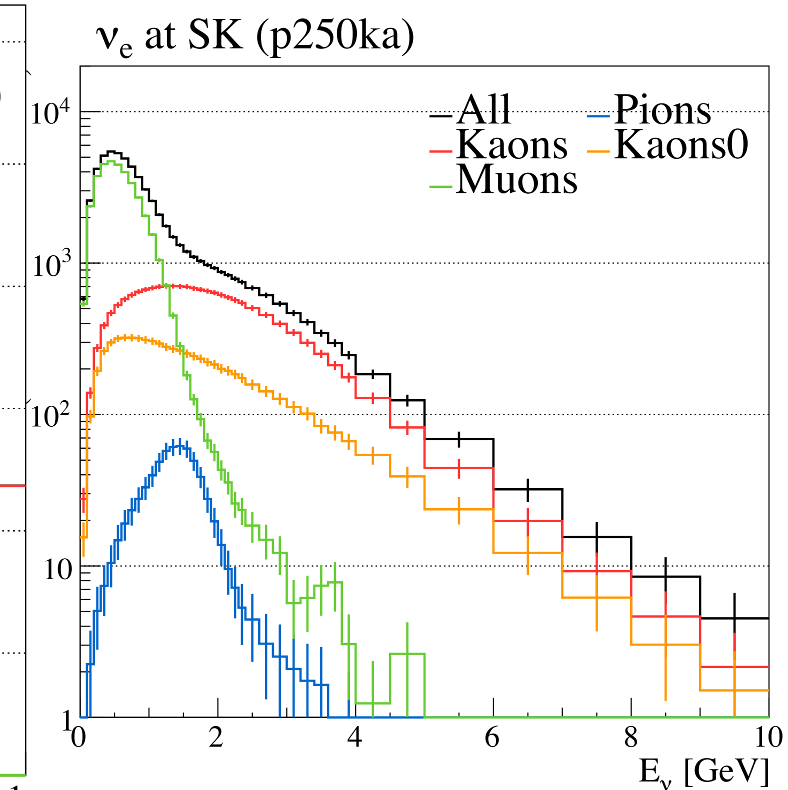
note: 2.6x beam power upgrade toward HyperK (500 kW → 1.3 MW)



Right-sign ν_μ flux with 650 MeV peak from $\pi^\pm$ decay. Above 3 GeV K± decay.

Above each peak contribution from mis-focused and forward particles.



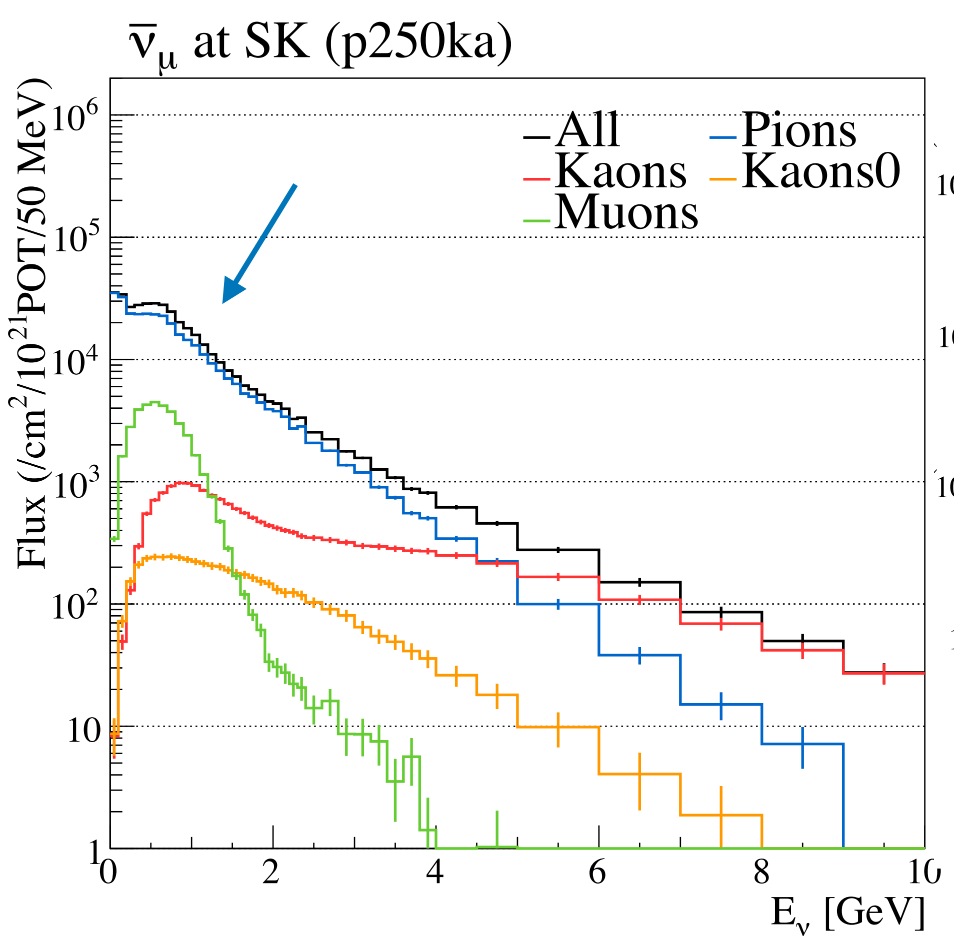


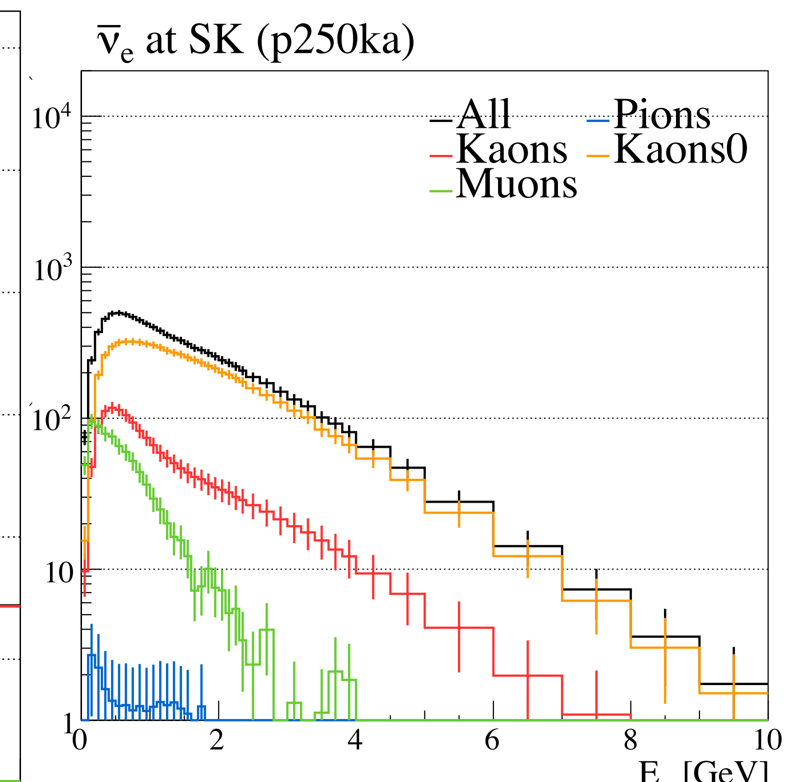
Small ν_e contamination from μ-decay in tunnel and K-decay.

For RHC the contribution from K_L^0 increases.

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

Wrong sign component from rescattered pions (low-E) and forward mesons from target downstream face of target that “miss” the horns (high-E).





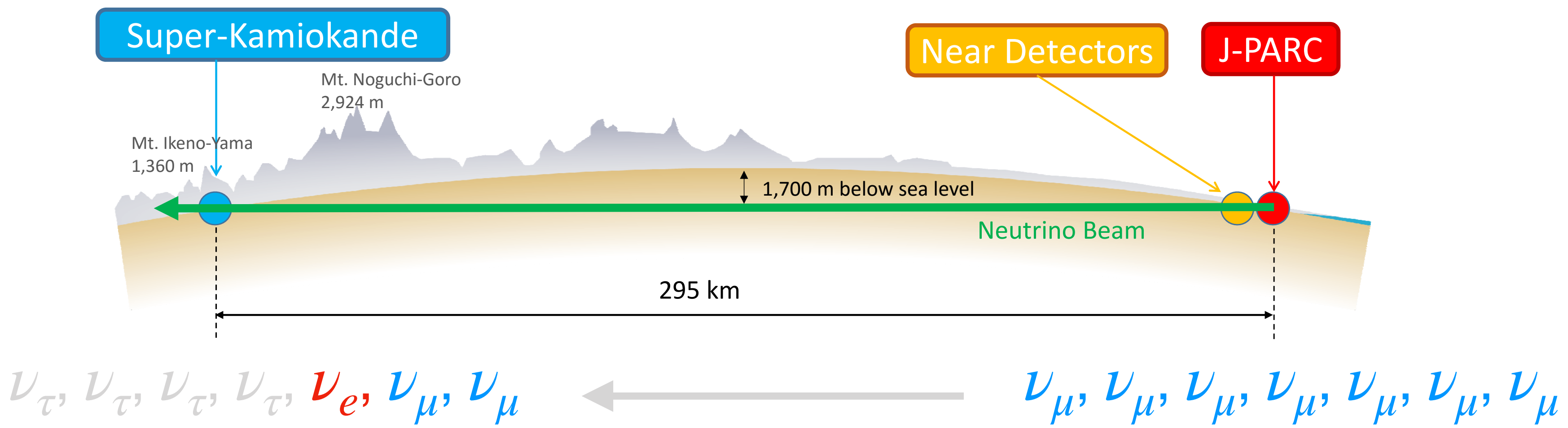
Wrong sign ν_e component entirely from 3-body decay of kaons, mostly K_L^0.

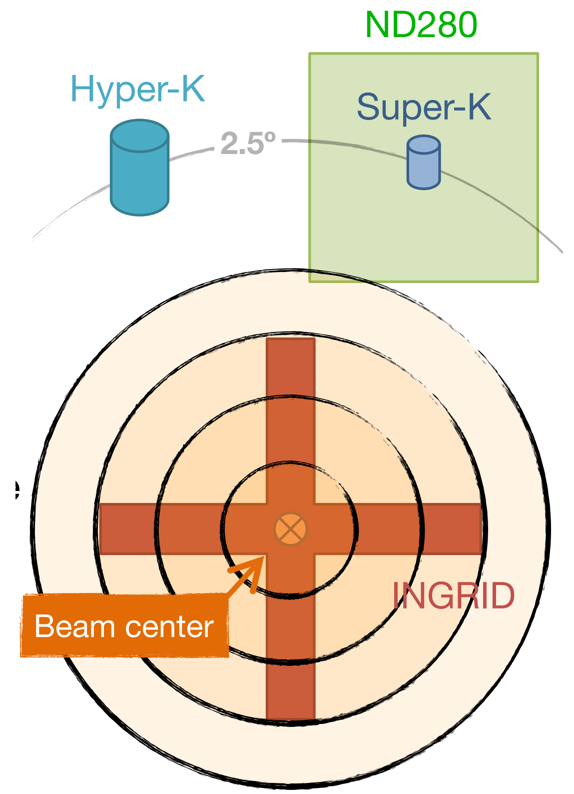
For RHC contribution from K^+ increases.

Oscillation analysis

- ND280 constrains flux*xsec:
  flux: 5% → 3% (uncertainty on #evts)
  flux*xsec: 11% → 2%
  If flux can be understood better than 3%, will be able to improve the xsec constraint through flux?
- Constraint is propagated to SK flux by constraining the SK/ND280 flux covariance matrix.

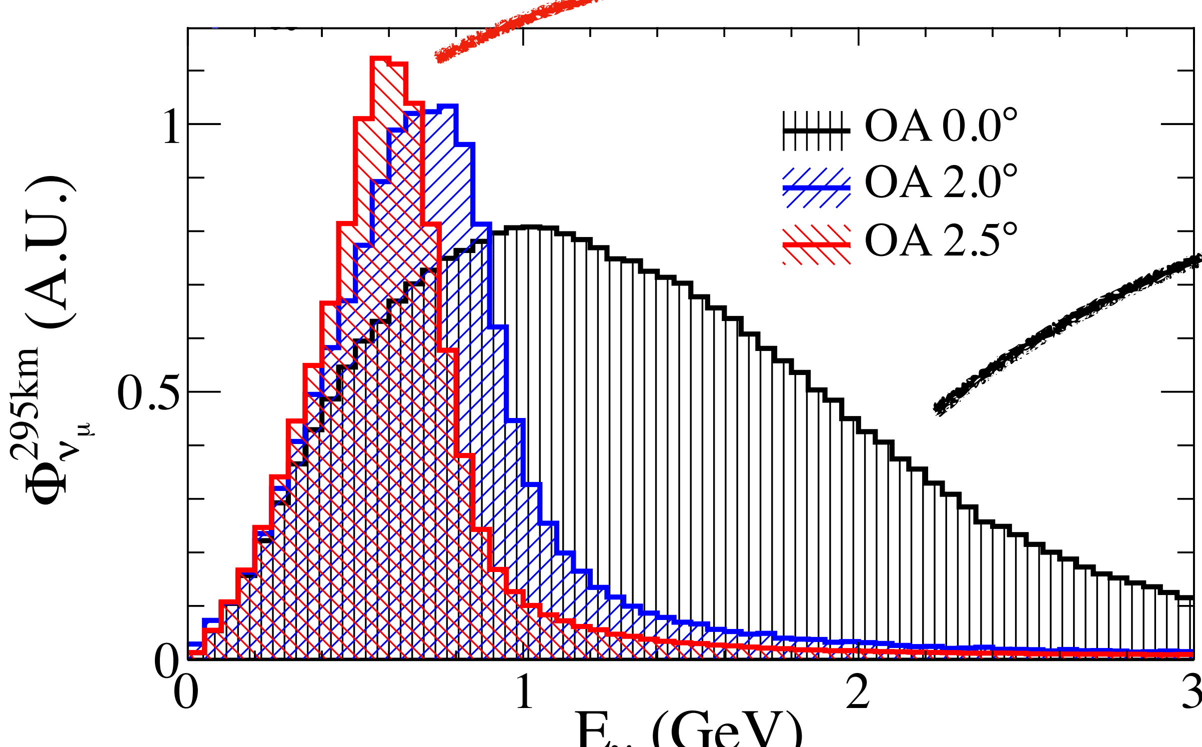
- Currently only μ-like samples fit at ND280, and e-like flux constraint relies on flux covariance matrix. Similarly when the near-detector has troubles running, the flux uncertainty relies on run-by-run correlations estimated with MC and INGRID monitoring data.
- Constraint on osc. params is stats-dominated, and the post-fit flux systematic plays a small role in the systematics.
- For HK expect to have larger contribution from non-hadronic systematics due to direction differences between HK and SK/ND280.





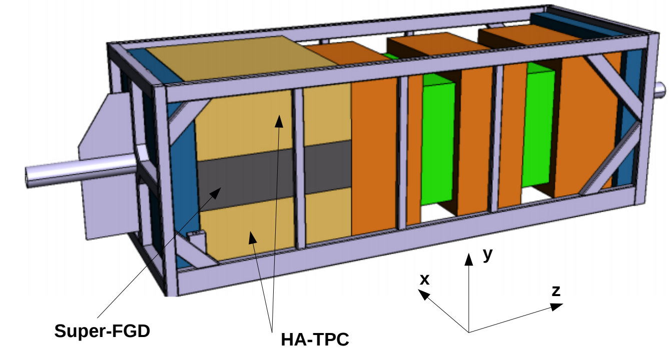
Near detectors

- Various near detectors perform wide variety of xsec measurements
- Flux uncertainty is dominant systematic on the xsec normalization
- Combined analyses at various off-axis angles allow studying energy dependence etc.



2.5º off-axis

ND280
magnetized near detector
to be upgraded soon



same off-axis angle as SK/HK

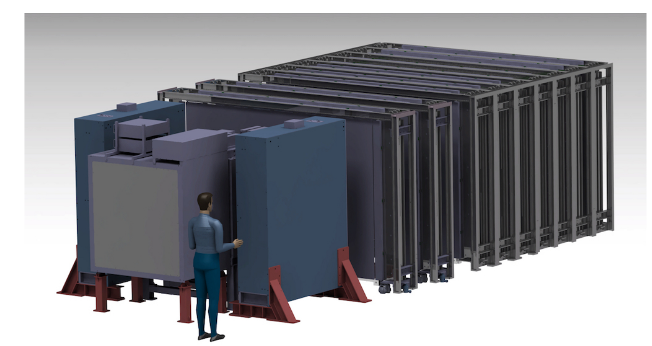
1.5º off-axis

WAGASCI + BabyMIND **+ NINJA**
(not part of T2K)

Water + scintillators

Compact magnetized iron μ range detector

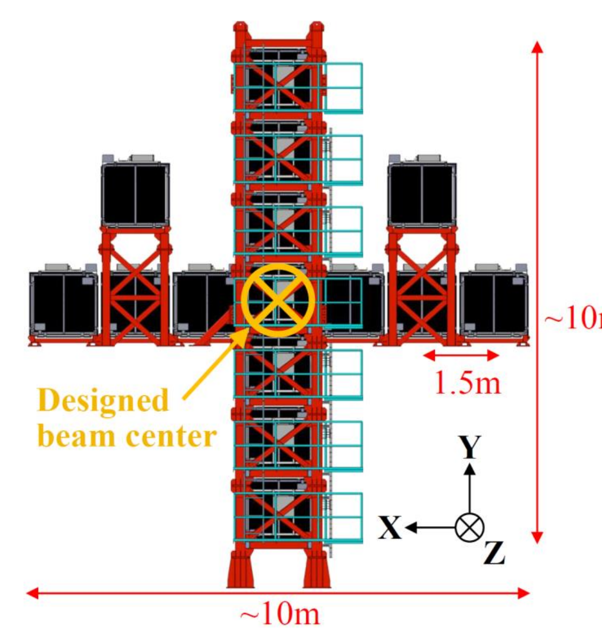
Emulsion detector



on-axis

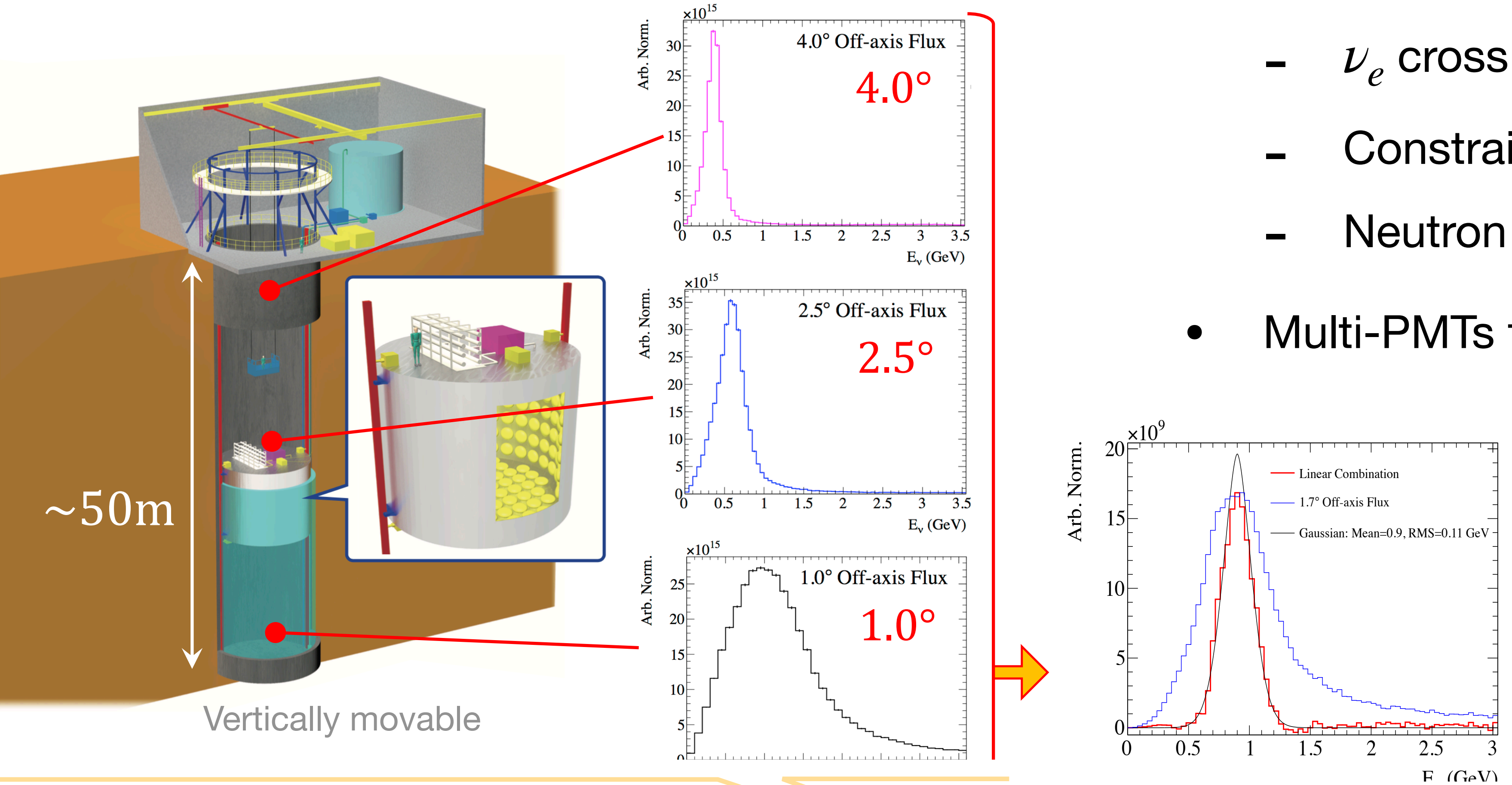
INGRID
monitor ν beam rate + direction

14 modules of unmagnetized iron-scintillator sandwich detectors

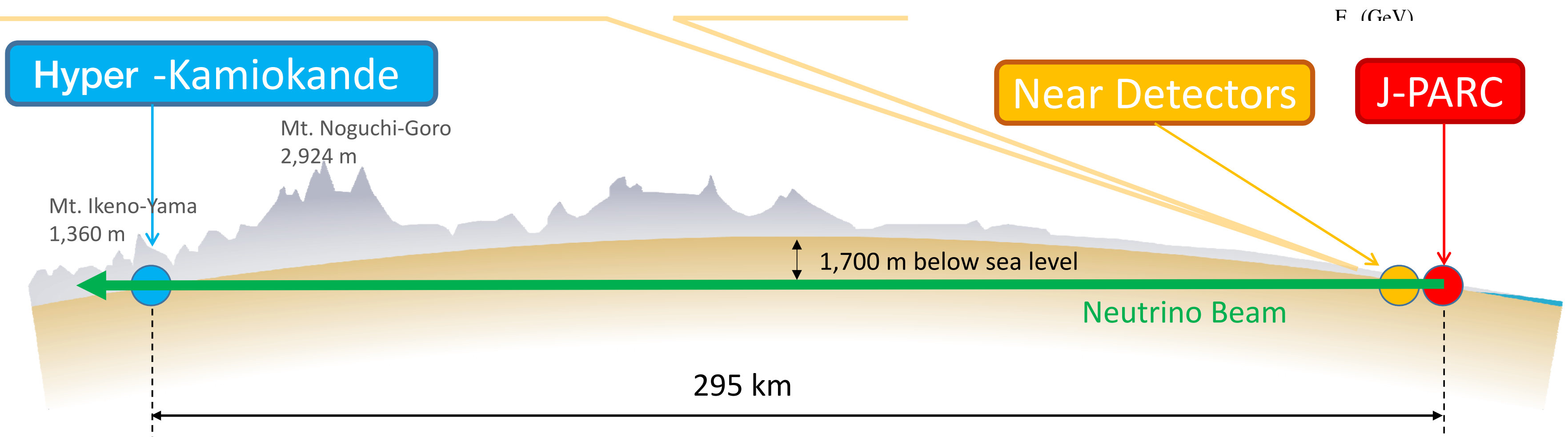


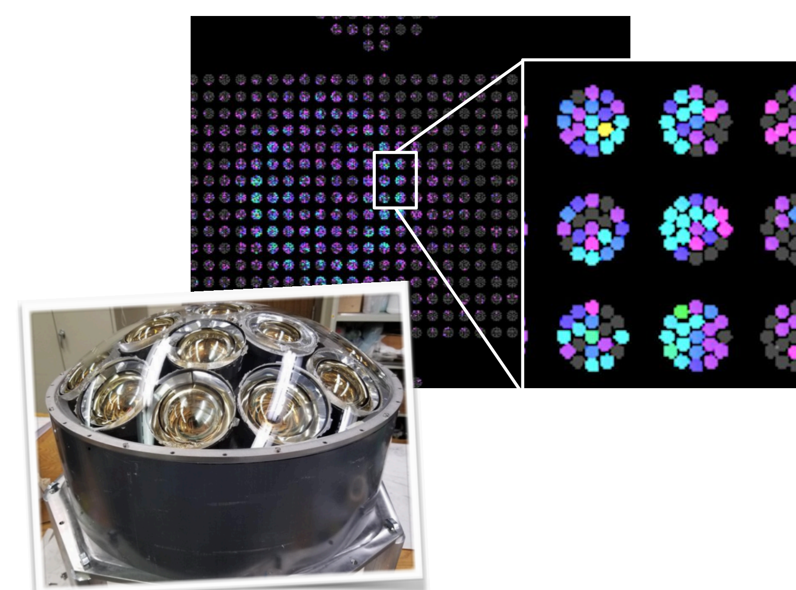
Intermediate Water Cherenkov Detector

- New 1 kton scale water-Cherenkov detector at ~1 km baseline planned with goals:
  - ν-interaction with combined measurement of fluxes at various off-axis angles
  - ν_e cross section
  - Constrain NC and ν_e background
  - Neutron multiplicity with Gd loading
- Multi-PMTs for higher granularity + directionality

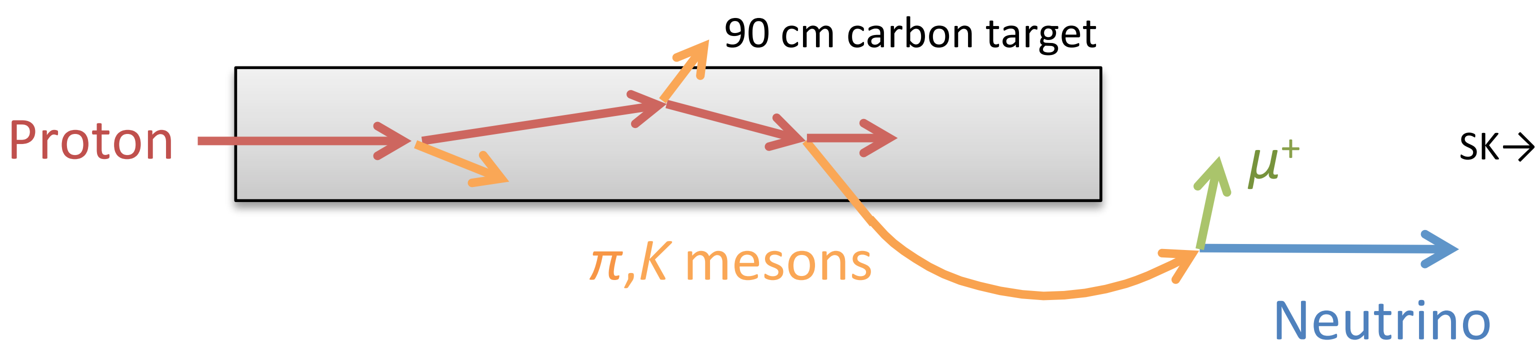


need precise understanding of flux





$\nu_\tau, \nu_\tau, \nu_\tau, \nu_\tau, \nu_e, \nu_\mu, \nu_\mu$ ← $\nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$

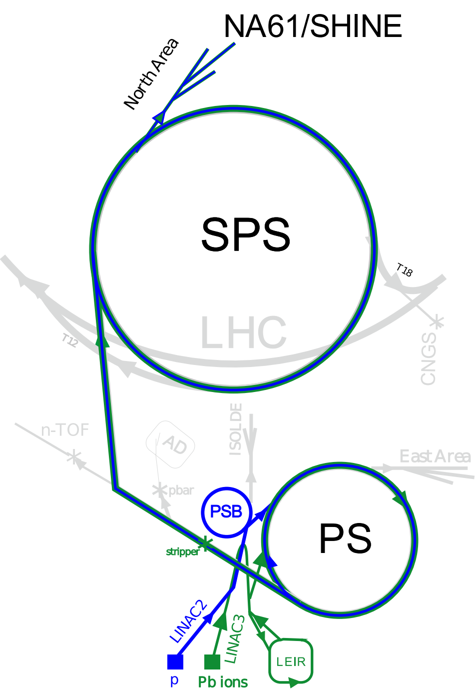


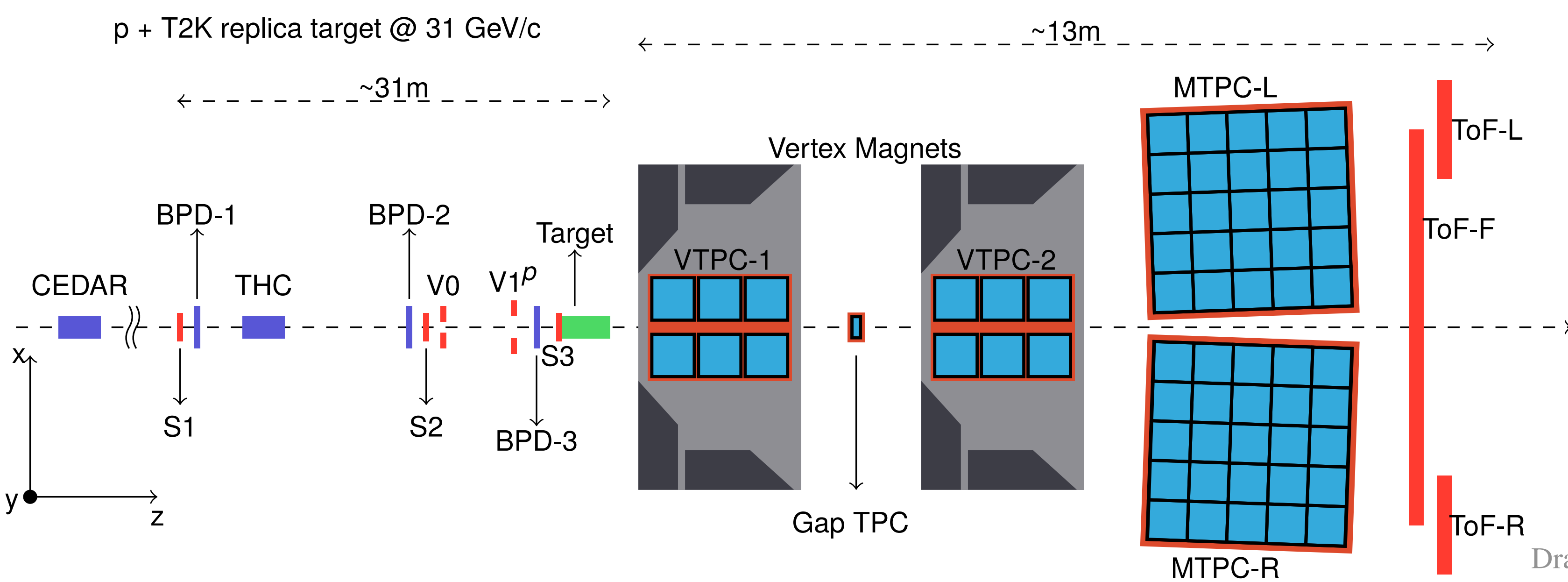
Flux Prediction

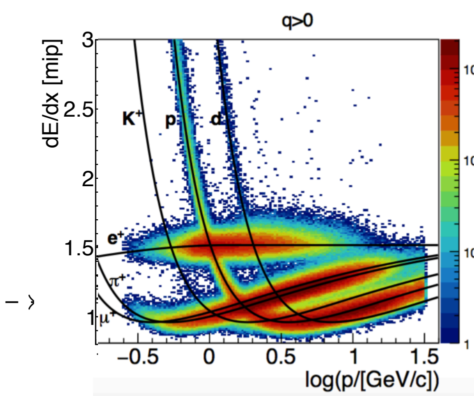
- Interactions of protons **inside target** simulated with **FLUKA** based on proton beam profile measured with upstream beam monitors.
- Horn **focusing** and **out-of-target** interactions (Al in horns and Fe in walls) of outgoing mesons using **Geant3 + GCalor**.
- Afterwards go through interaction 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.

NA61 measurements for T2K

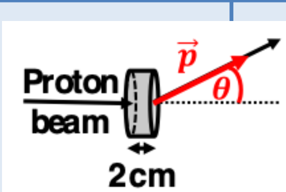
- Hadron production experiment, momentum measurement with TPCs in superconducting magnets, PID with dE/dx (Bethe-Bloch) and time of flight.



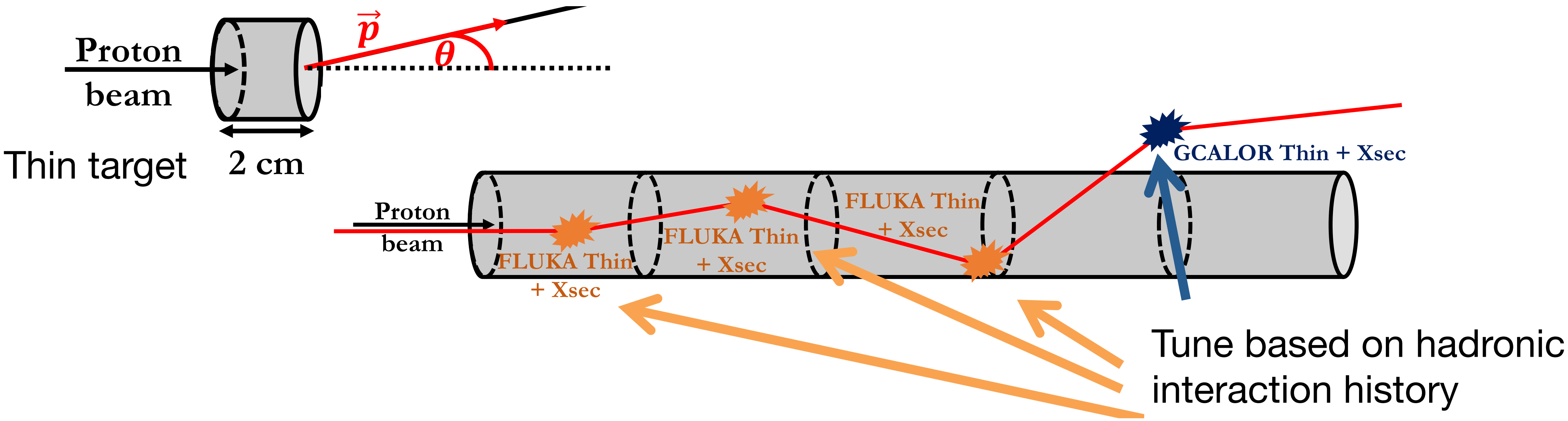




Drawings+plots from M.Pavin's Ph.D. thesis, slightly modified for clarity.

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

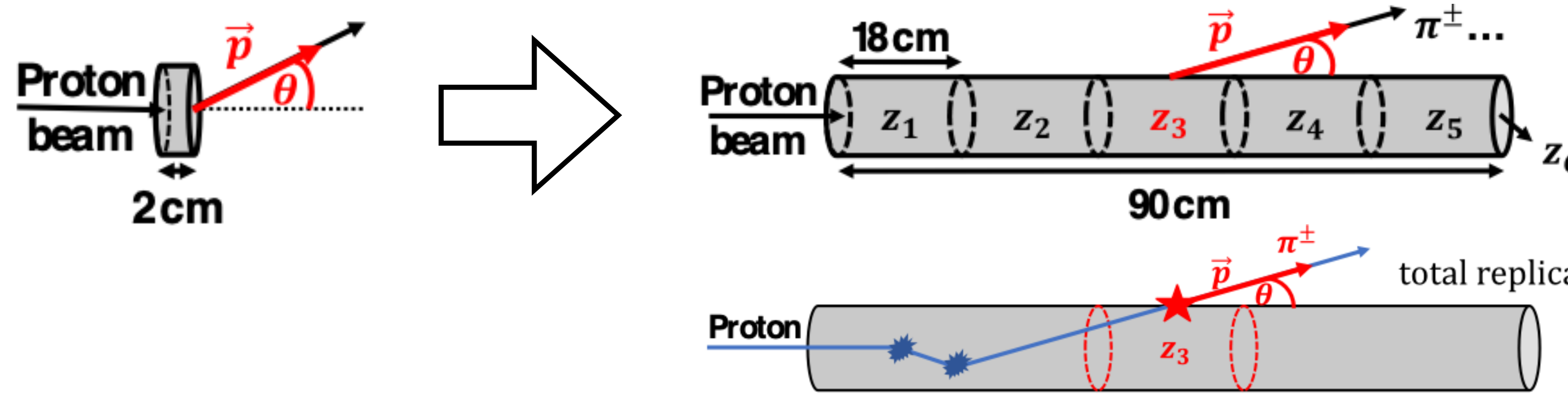
Thin target tuning



	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.

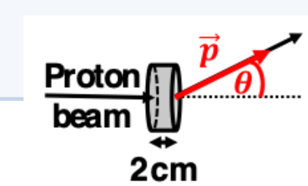
Replica tuning

- 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 
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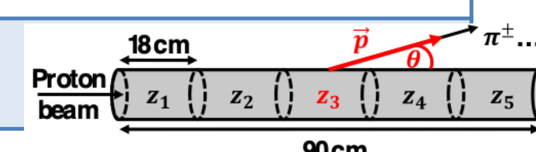
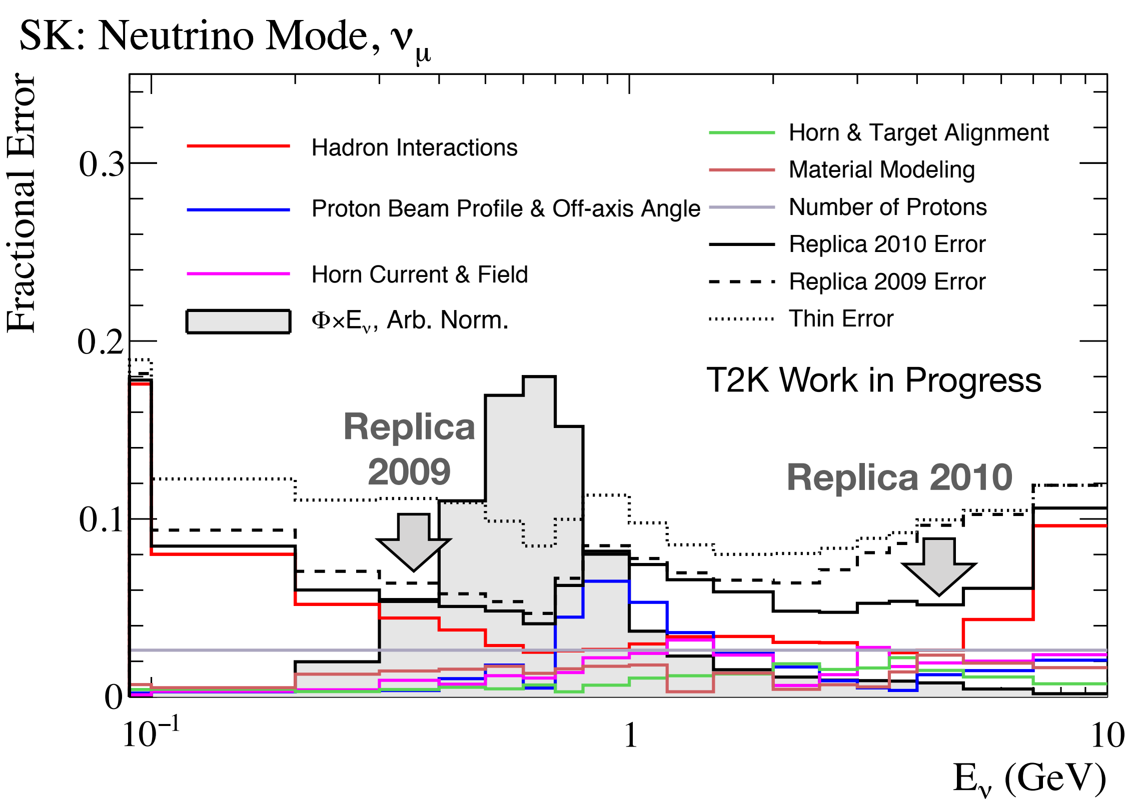
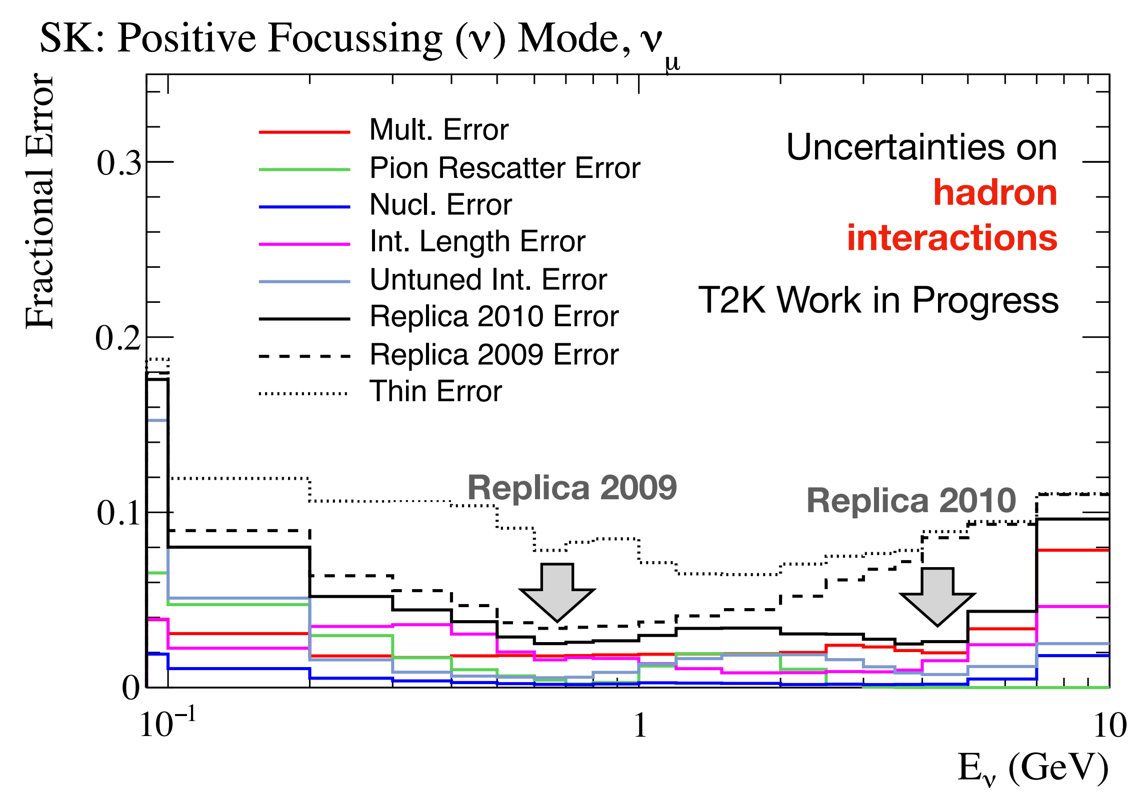
	T2K replica (90cm)	2007	0.2	$\pi^{\pm}$	 latest T2K results
		2009	2.8	$\pi^{\pm}$	
		2010	10.	$\pi^{\pm}, K^{\pm}, p$	in development

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





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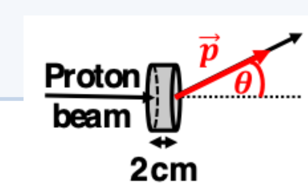
protons at 31 GeV/c	Thin (2cm)	2007	0.7	$\pi^{\pm}, K^{\pm}, K^0{}_S, \Lambda$	past 
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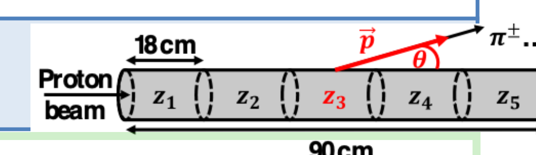
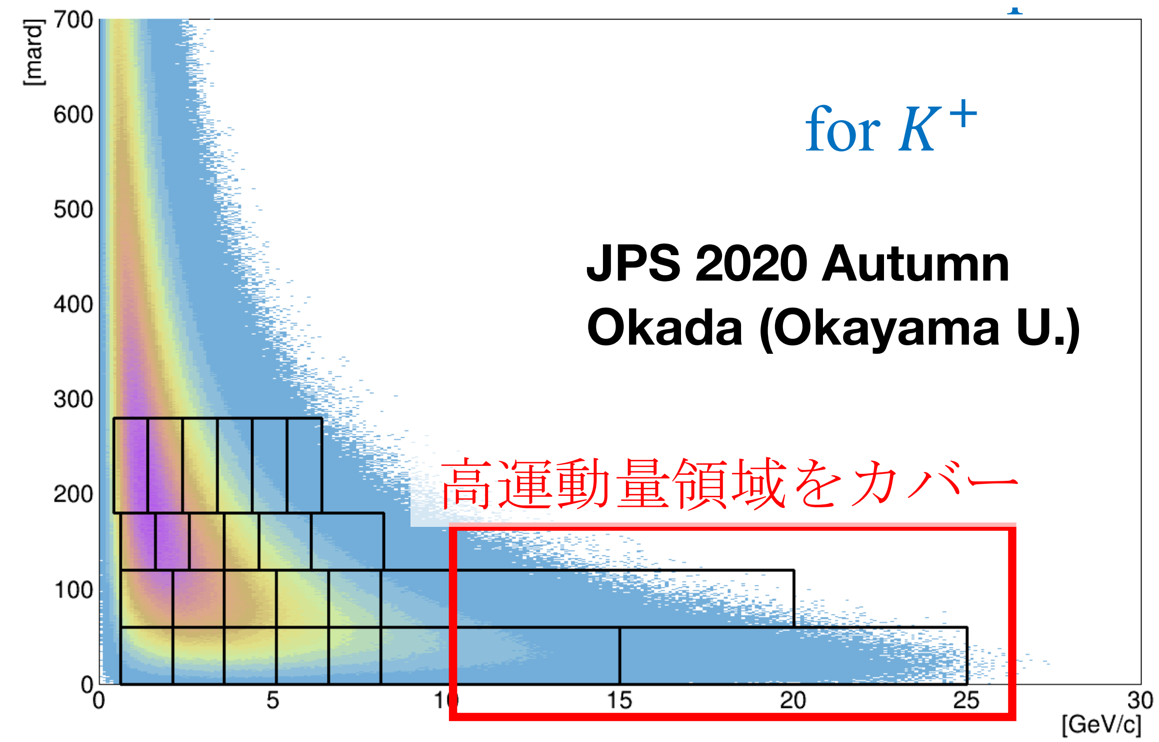
	T2K replica (90cm)	2007	0.2	$\pi^{\pm}$	
		2009	2.8	$\pi^{\pm}$	next T2K results
		2010	10.	$\pi^{\pm}, K^{\pm}, p$	in development

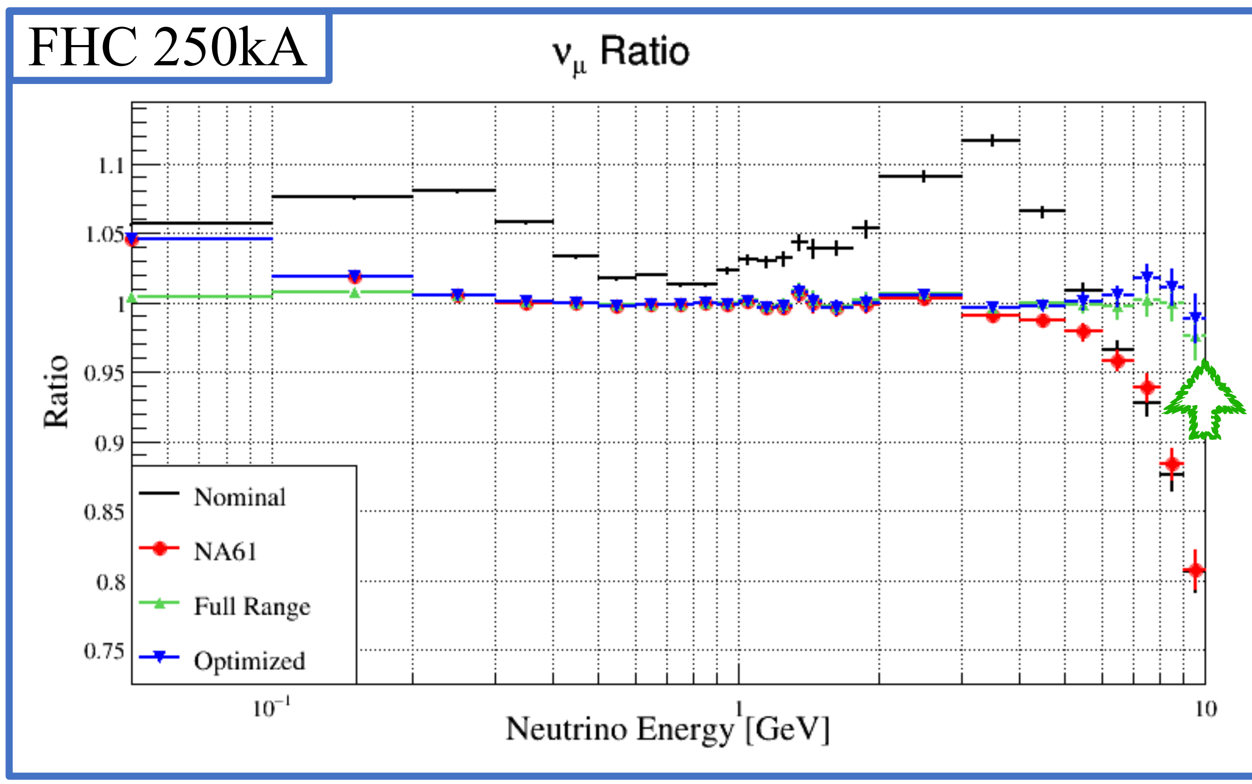
Future hadron production

- NA61
  - many upgrades e.g. 10x higher trigger rate
  - more replica target data (SPSC approved) with extended Kaon coverage?
  - p + N,O for constraining atmospheric flux production
  - if tertiary beamline can be built, π→π scattering at few GeV/c

today's topic

- EMPHATIC
  - focus on forward region (quasi-elastic)
  - subtraction of quasi-elastic (QE) xsec important for estimating the “production” cross section as prod = total — elastic – QE
  - plan to measure π,K,p scattering on various materials starting from few GeV





Future hadron production

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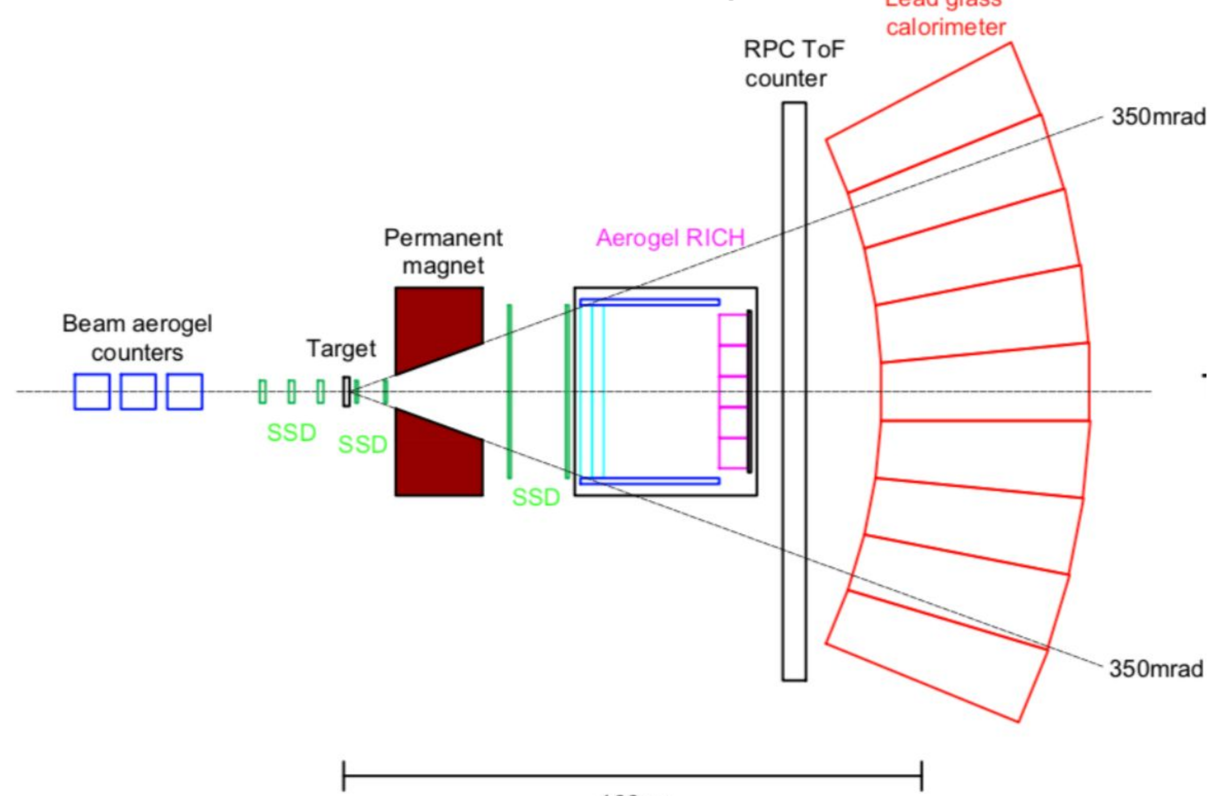
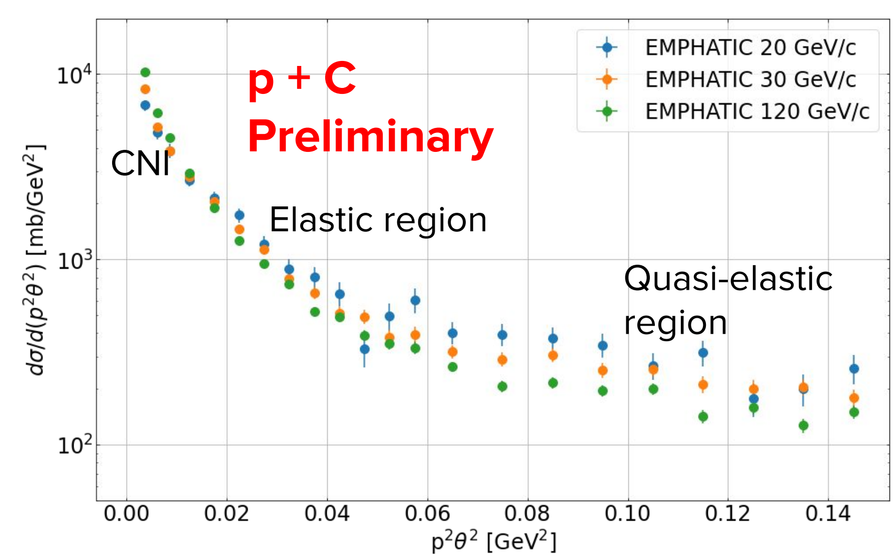
- EMPHATIC
  - focus on forward region (quasi-elastic)
  - subtraction of quasi-elastic (QE) xsec important for estimating the "production" cross section as prod = total — elastic – QE
  - plan to measure π,K,p scattering on various materials at 2–15 GeV

Experiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**estbeam **I**n **C**hicagoland





from M. Pavin, Neutrino 2020

Interactions not covered by replica data

Interaction in C	"Thin tuning"	Uncertainty
Proton prod xsec	NA61 2009 for p_{in}>20GeV/c	QE xsec (Belletini model)
Meson prod xsec	FLUKA is treated as nominal, and GCALOR outside target is tuned to FLUKA xsec	QE xsec (Belletini model)
p+C→meson multiplicity	NA61 2007+2009 with Feynman scaling for p_{in}<31GeV/c, BMPT extrapolation outside coverage	NA61 uncertainty Use other data with smaller p_{in} instead of Feynman scaling BMPT on/off
p+C→p multiplicity	NA61 2009 with outside region set by baryon number constraint on leading baryon. Only primary interaction is tuned.	NA61 uncertainty Secondary interaction tuning on/off (using Feynman scaling) NA49 p+C→n and NA61 p+C→Λ etc.
meson→meson multiplicity	—	HARP tuning (π→π) on/off. For others and outside coverage, a 50% correlated and 50% uncorrelated uncertainty in xF-pT space.
meson elastic+QE	—	multiplicity treated in cell above, xsec not treated
proton elastic+QE	—	—

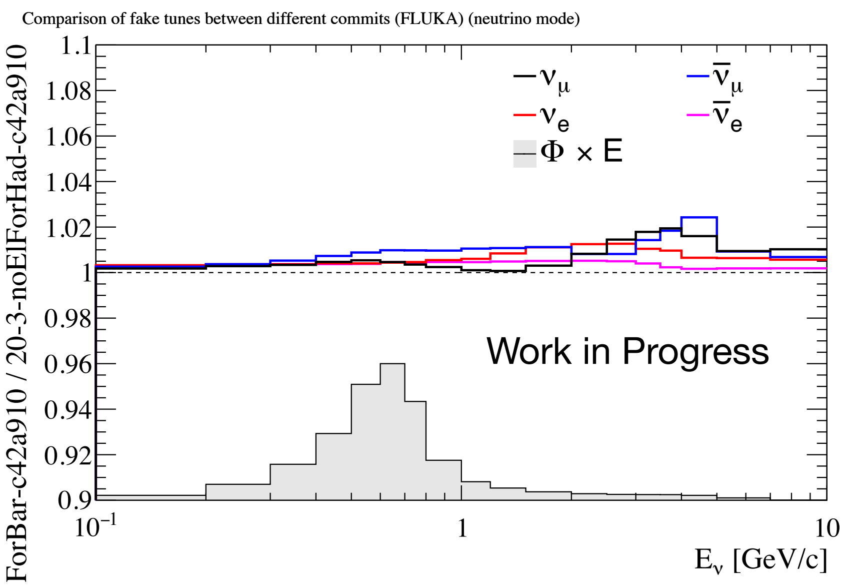
relevant for this talk

Effect of additional tuning

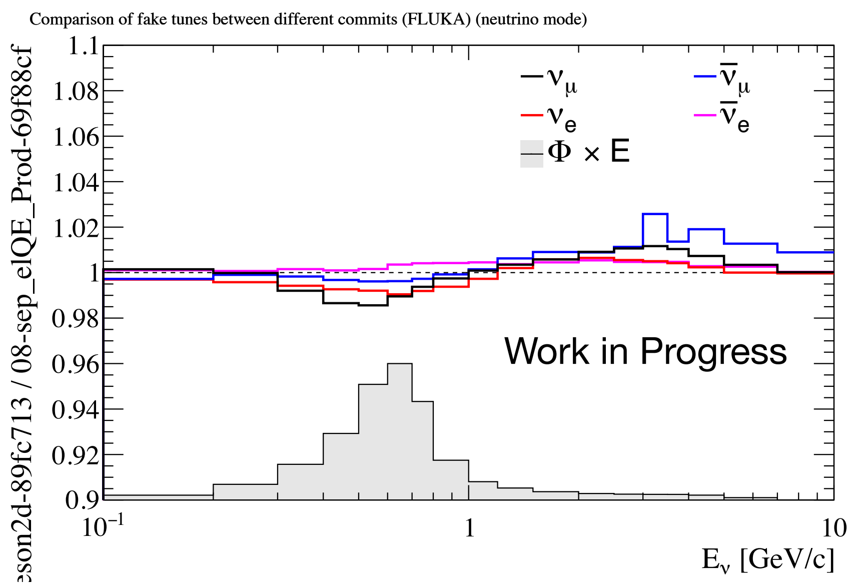
Here tuning from FLUKA to Geant4 FTFP_BERT
— keep in mind that the physics are somewhat similar —

FHC

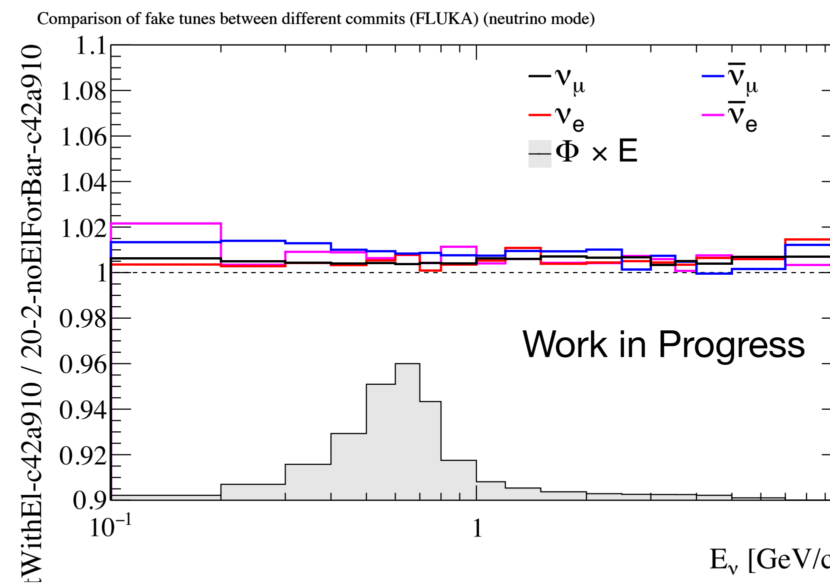
el+QE tuning of mesons



2d multiplicity tuning of mesons

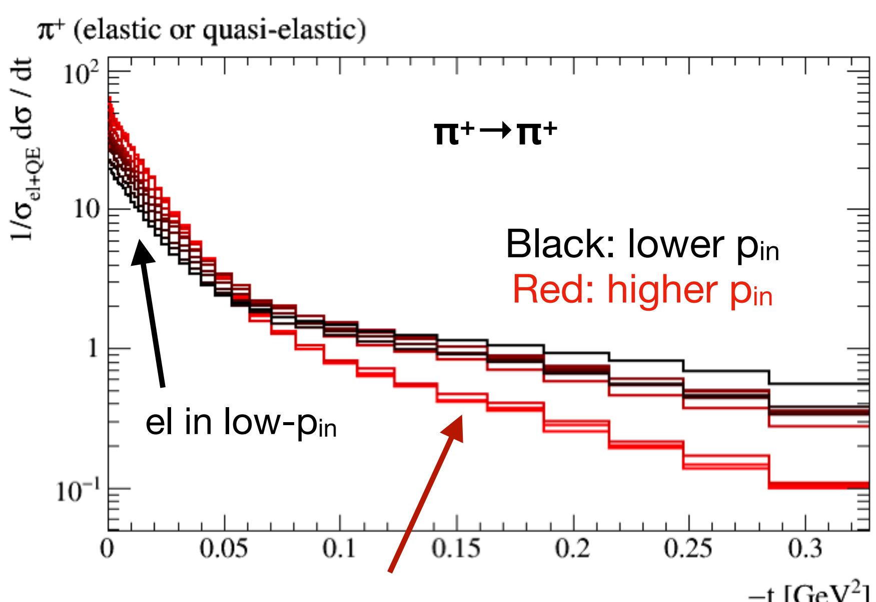


el+QE tuning of protons

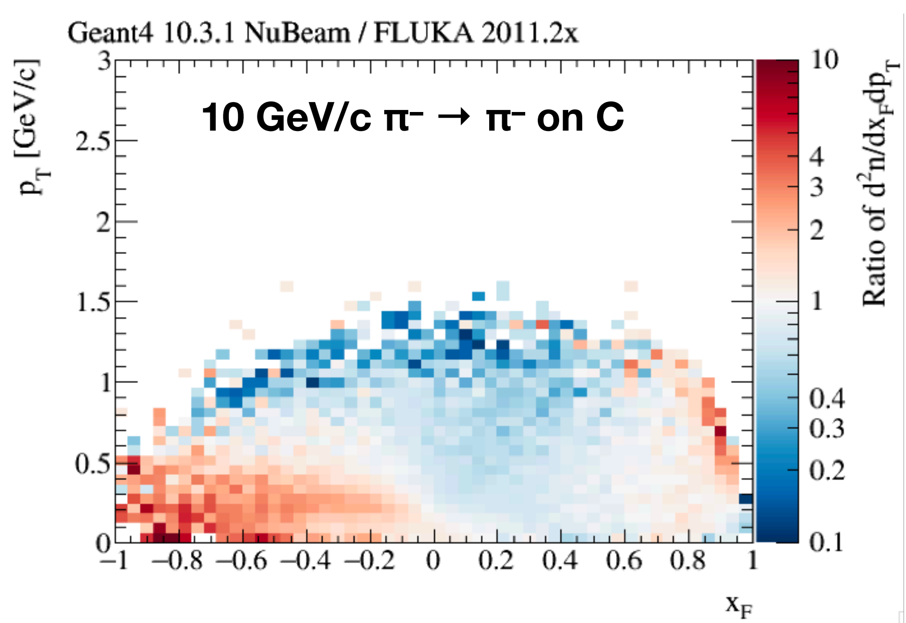


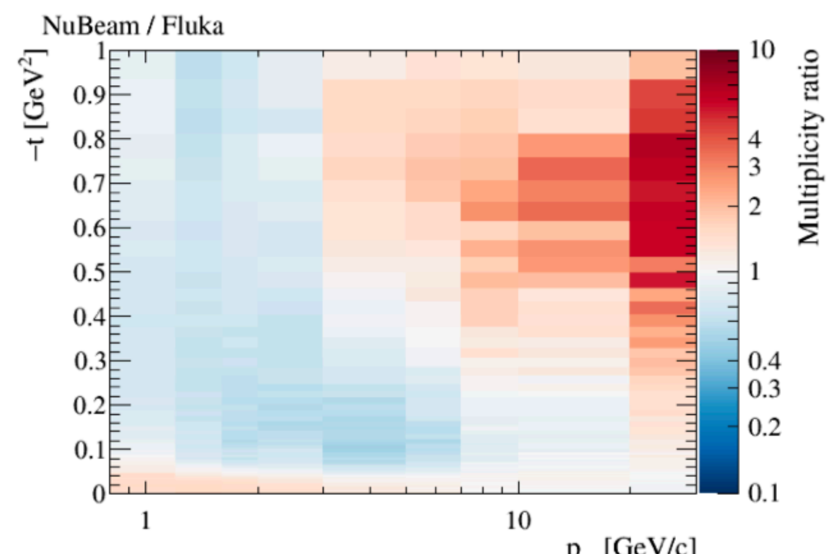
Need to check whether currently assigned uncertainty is large enough

This has no uncertainty assigned right now.
Might be possible to tune with EMPHATIC data.



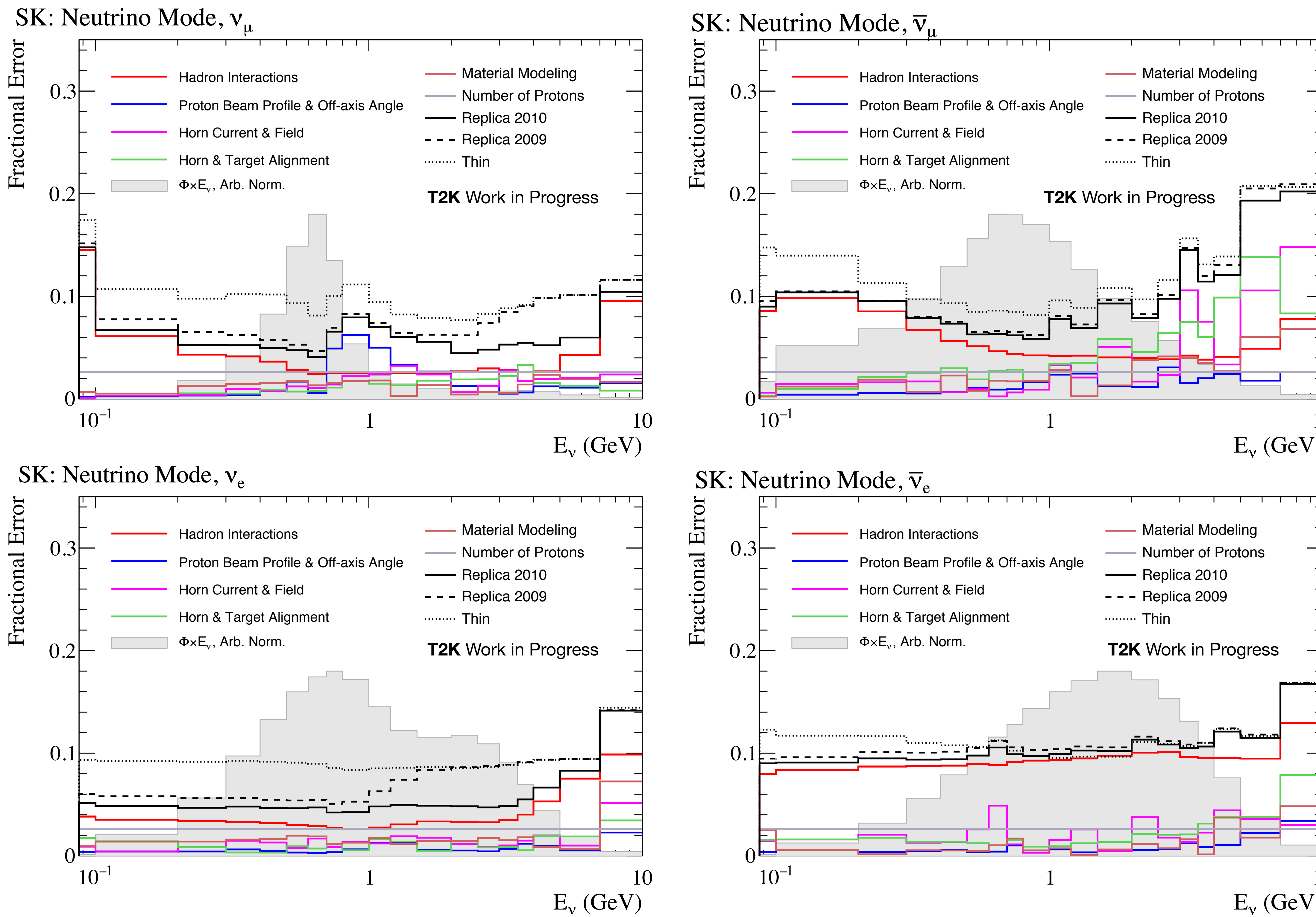
Above p_{in} ~ 6 GeV/c, slope at
$-t$ > 0.06 GeV^2 becomes steeper
due to strange(?) modeling of QE



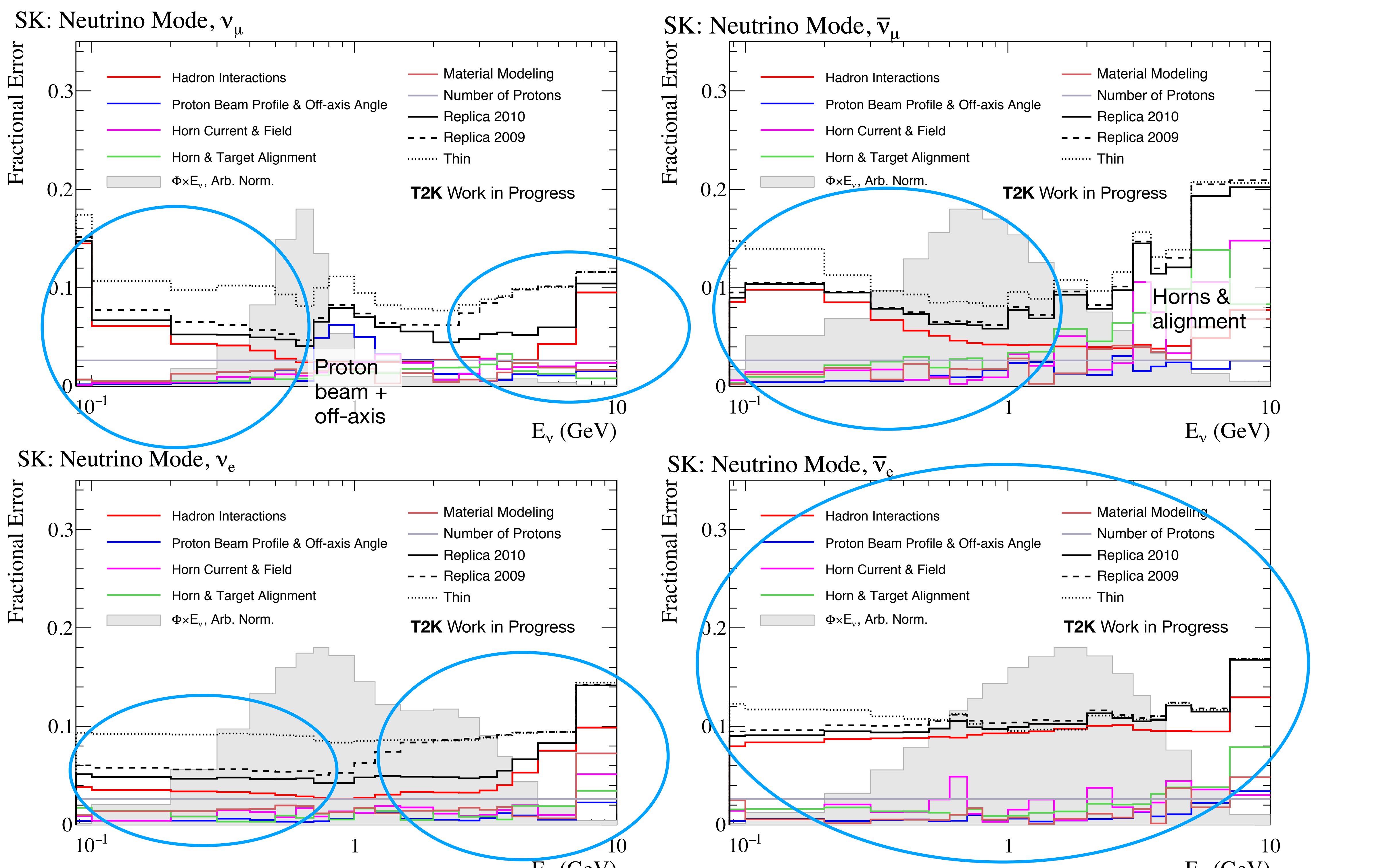


Multiplicity: $\dfrac{1}{\sigma_{\mathrm{elQE}}} \dfrac{d\sigma}{dt}$

Total flux uncertainty

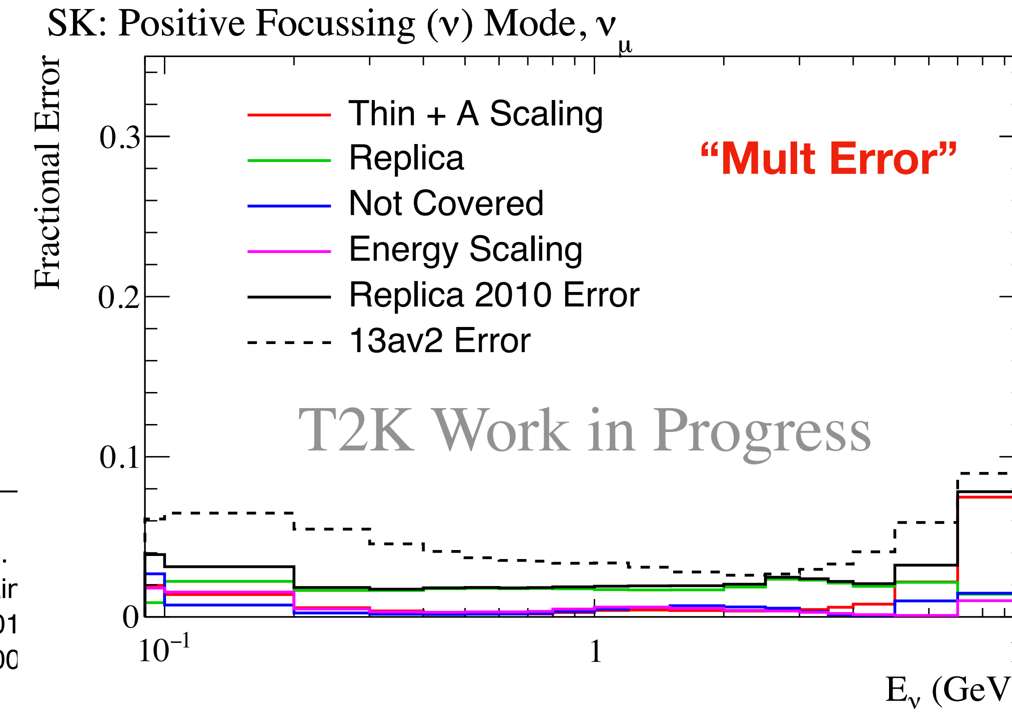


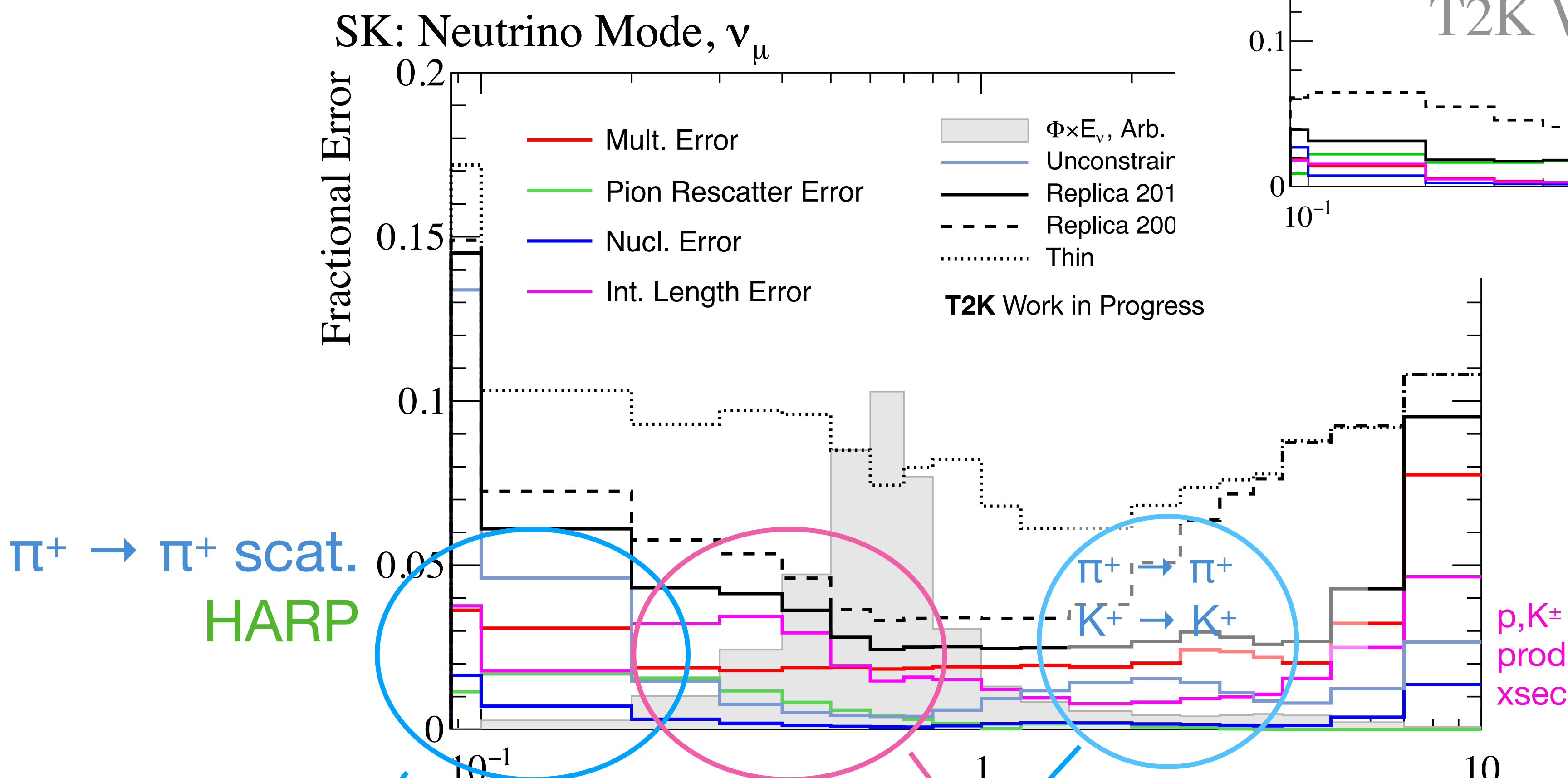
Total flux uncertainty

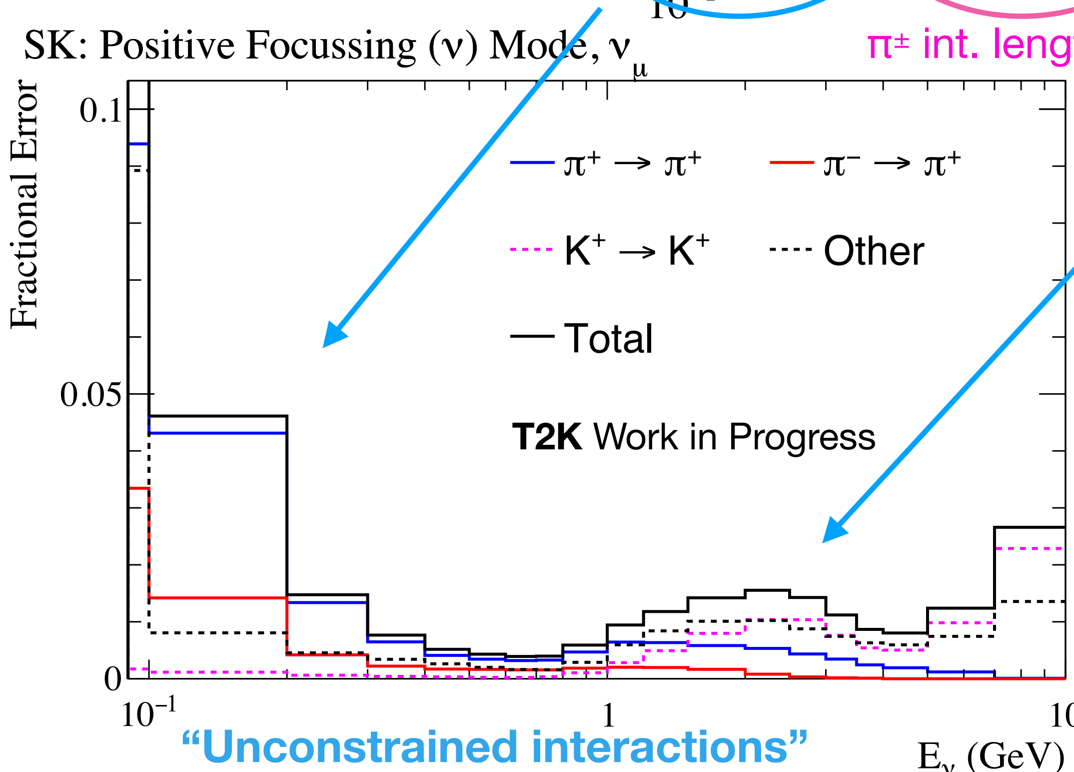


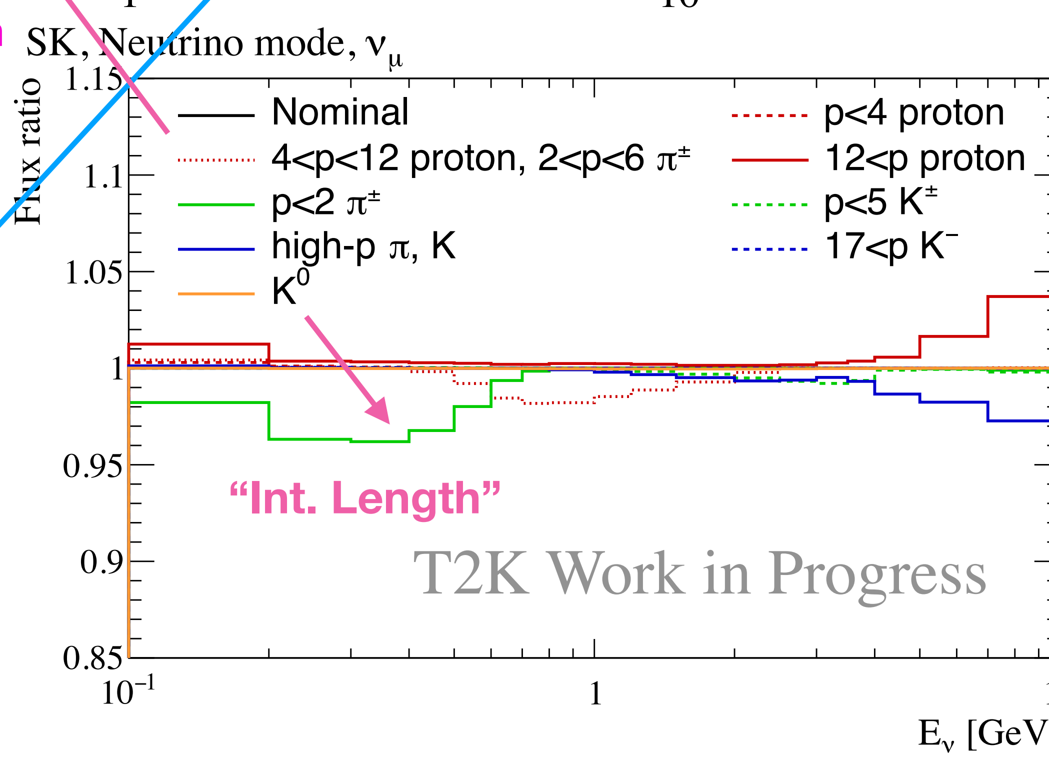
After replica 2010 tuning, hadron int. uncertainty still dominant in most regions

Right-sign ν_μ

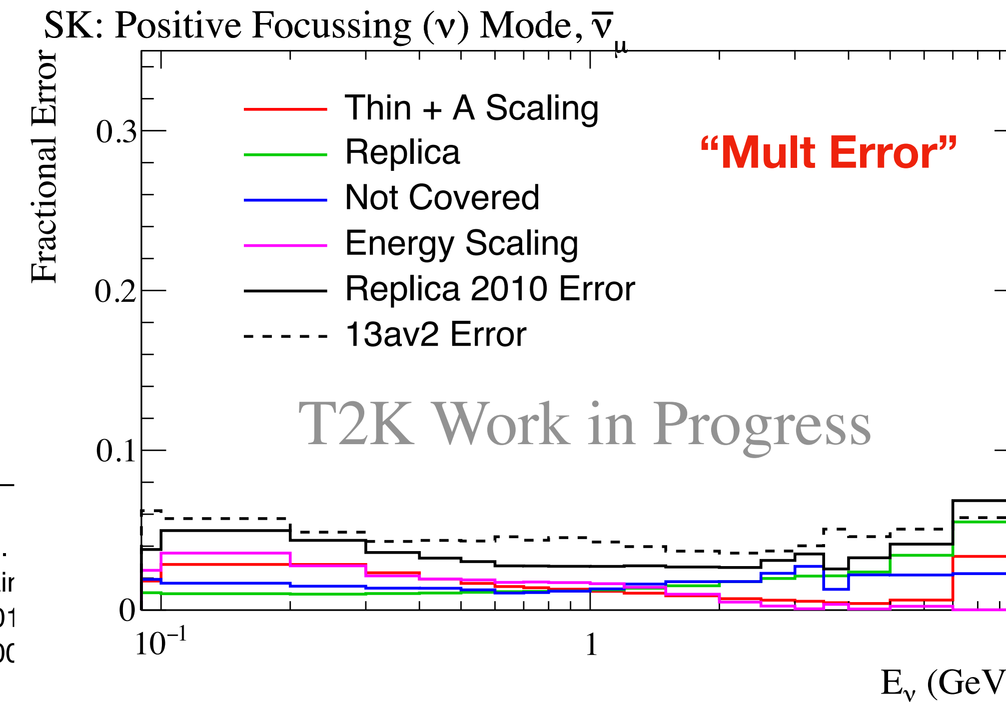


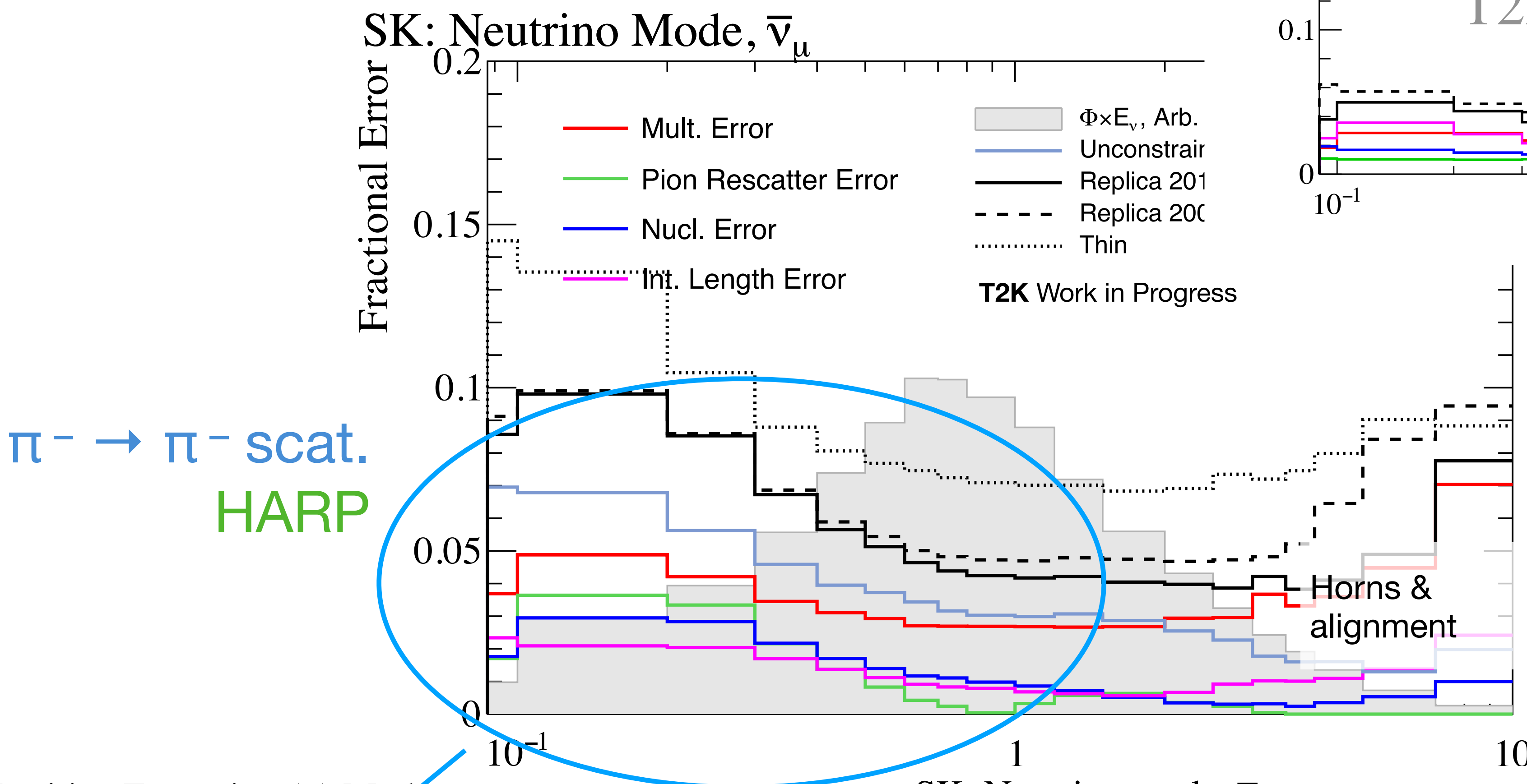


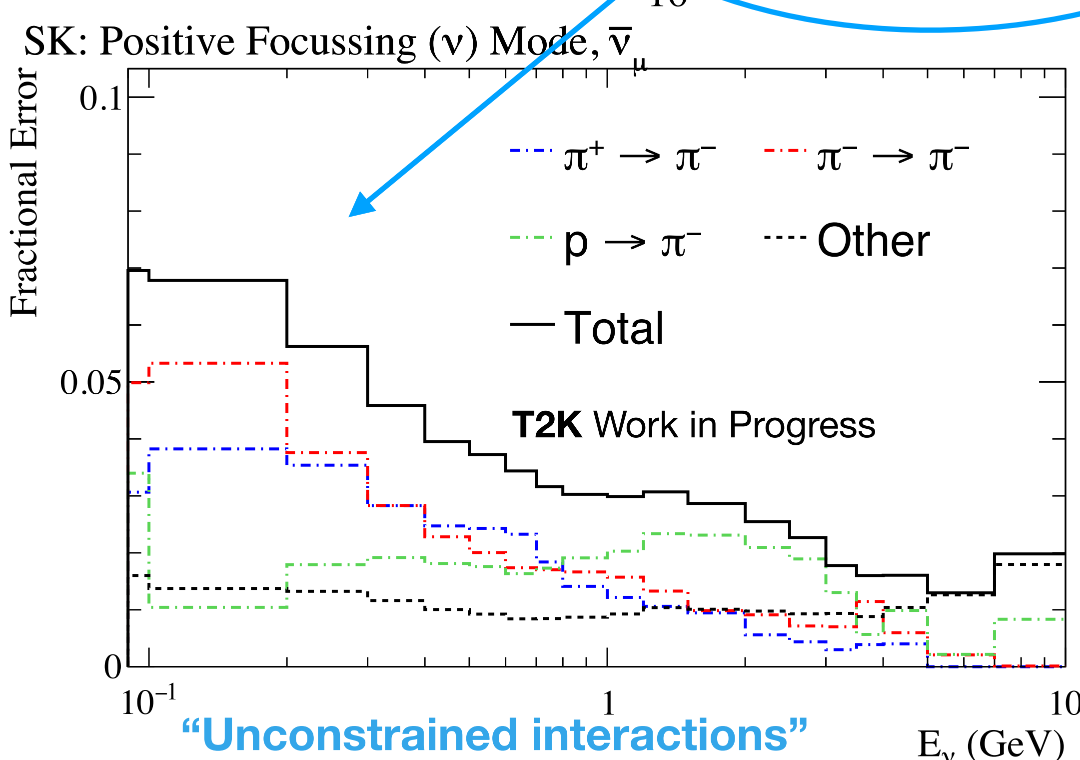


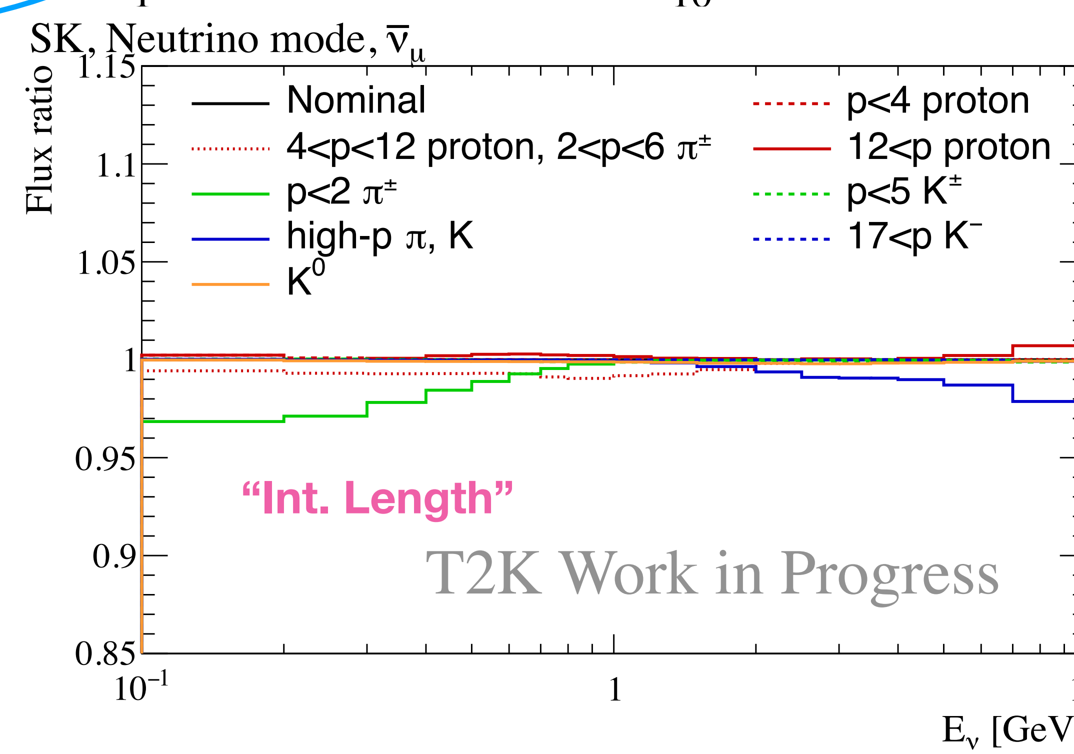


Wrong-sign ν_μ

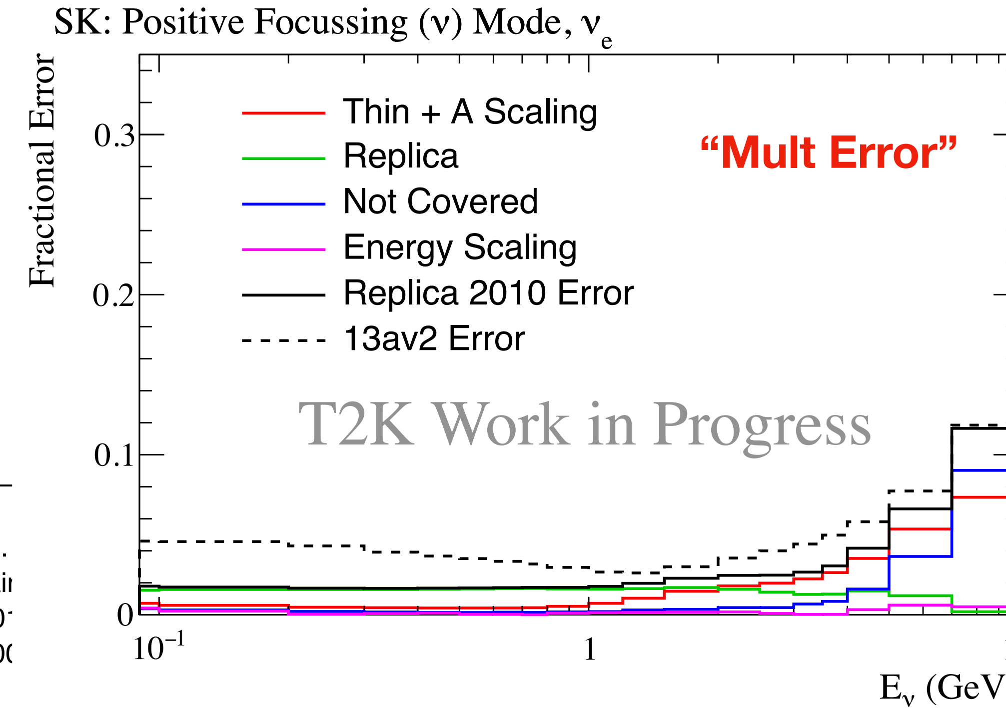




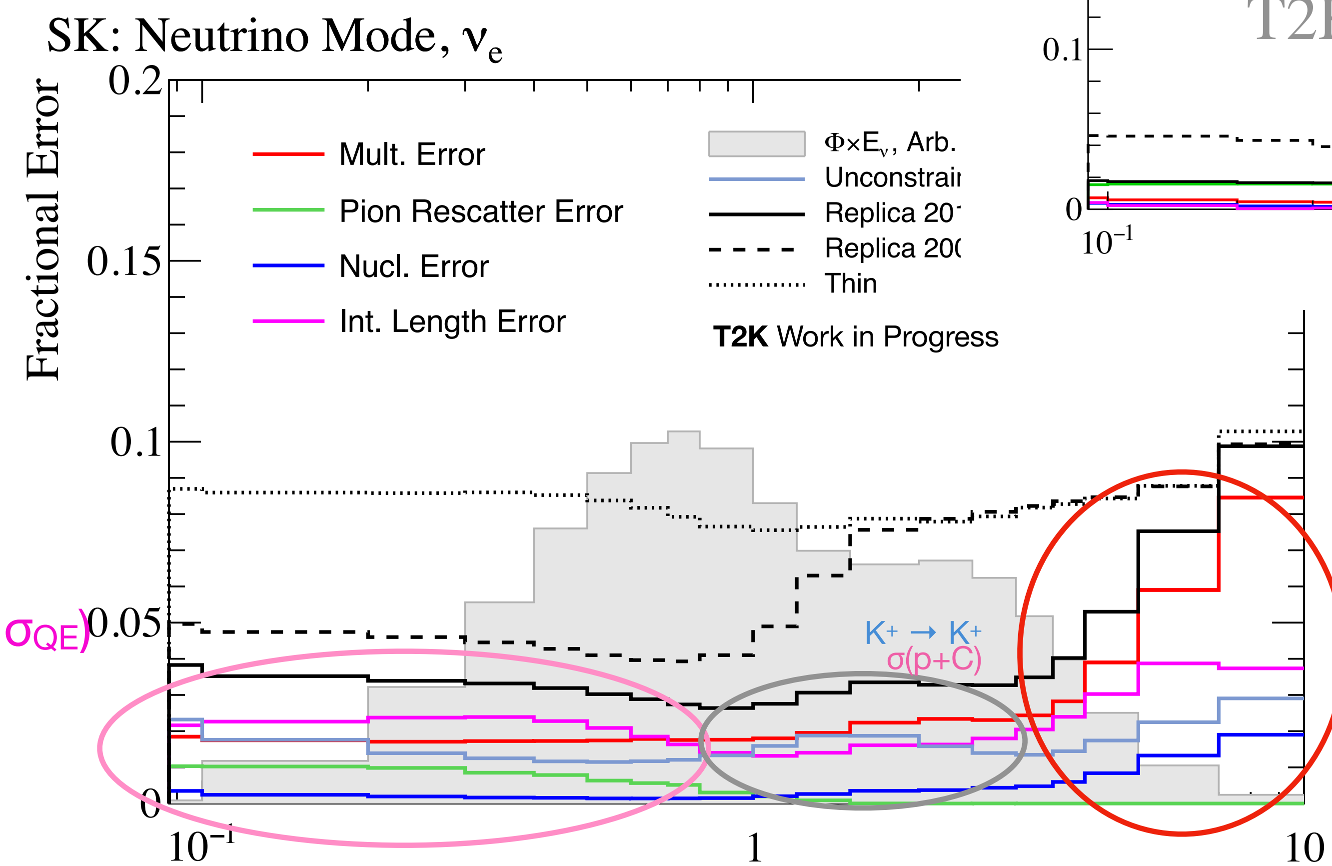




Right-sign ν_e

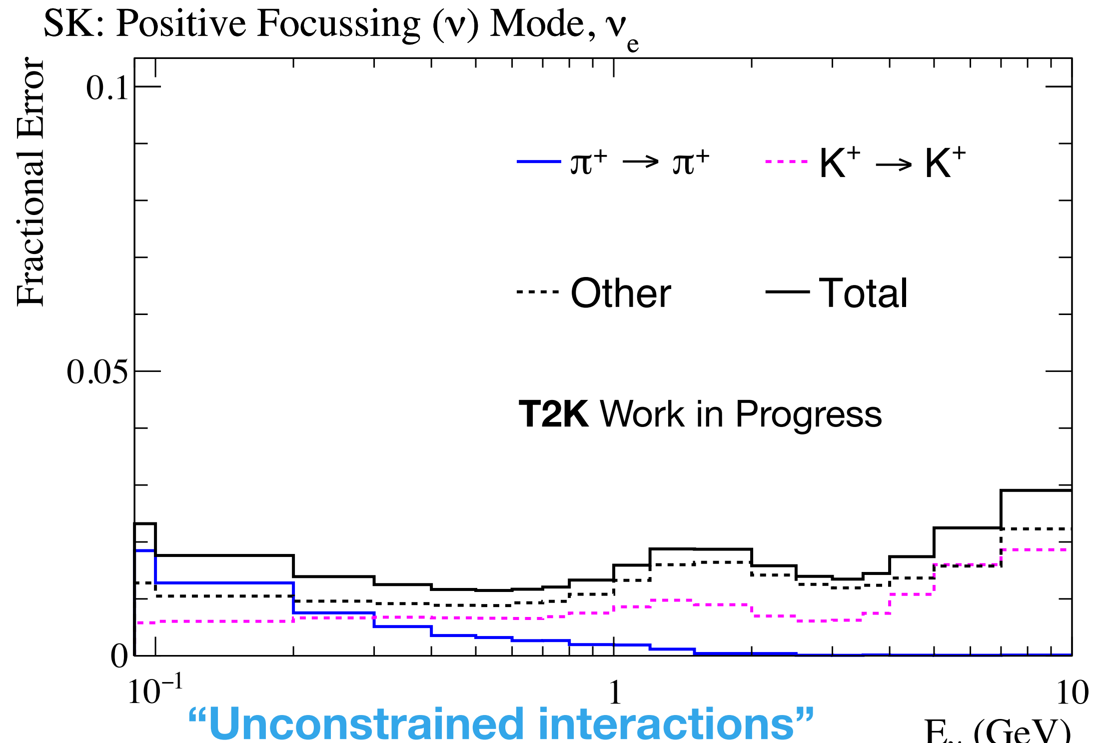


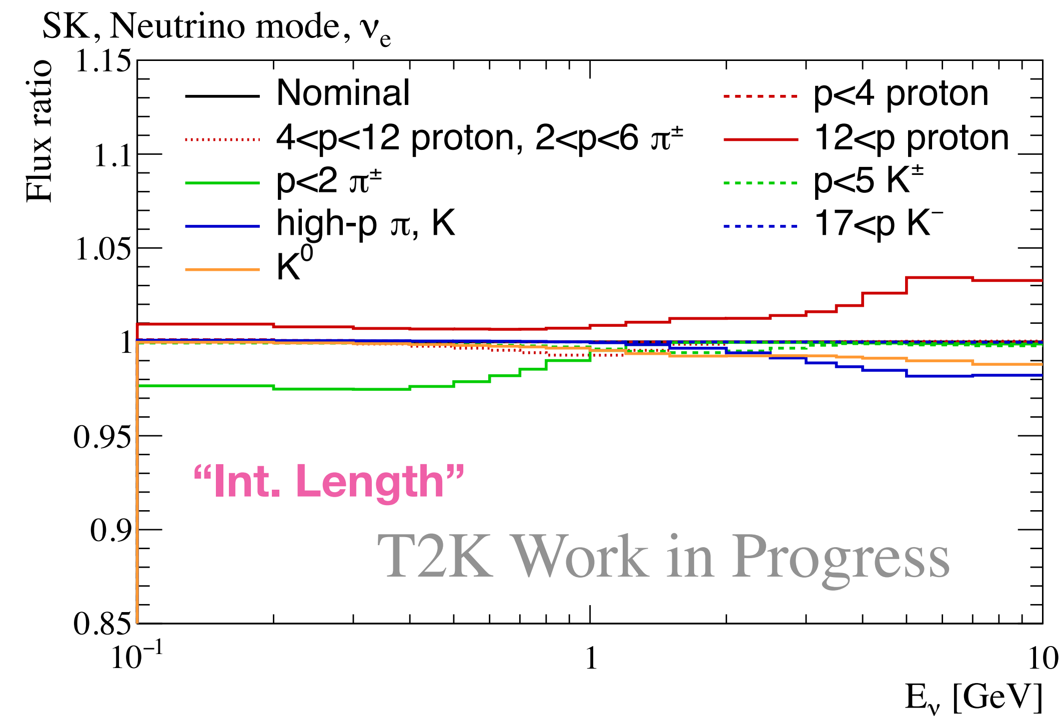
π± prod xsec
uncertainty (taken σ_QE)



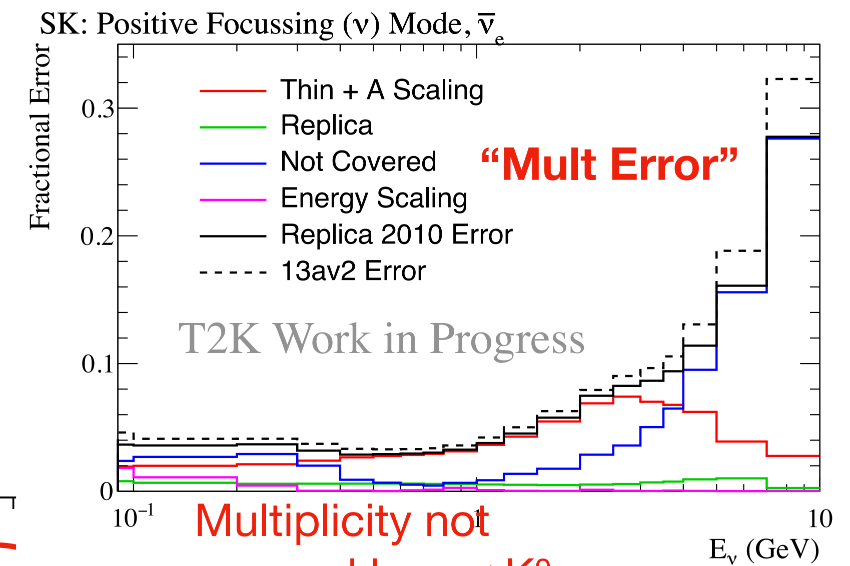
NA61 thin coverage
+ mult. error
(i.e. not covered by replica)

p, K+ prod.
xsec

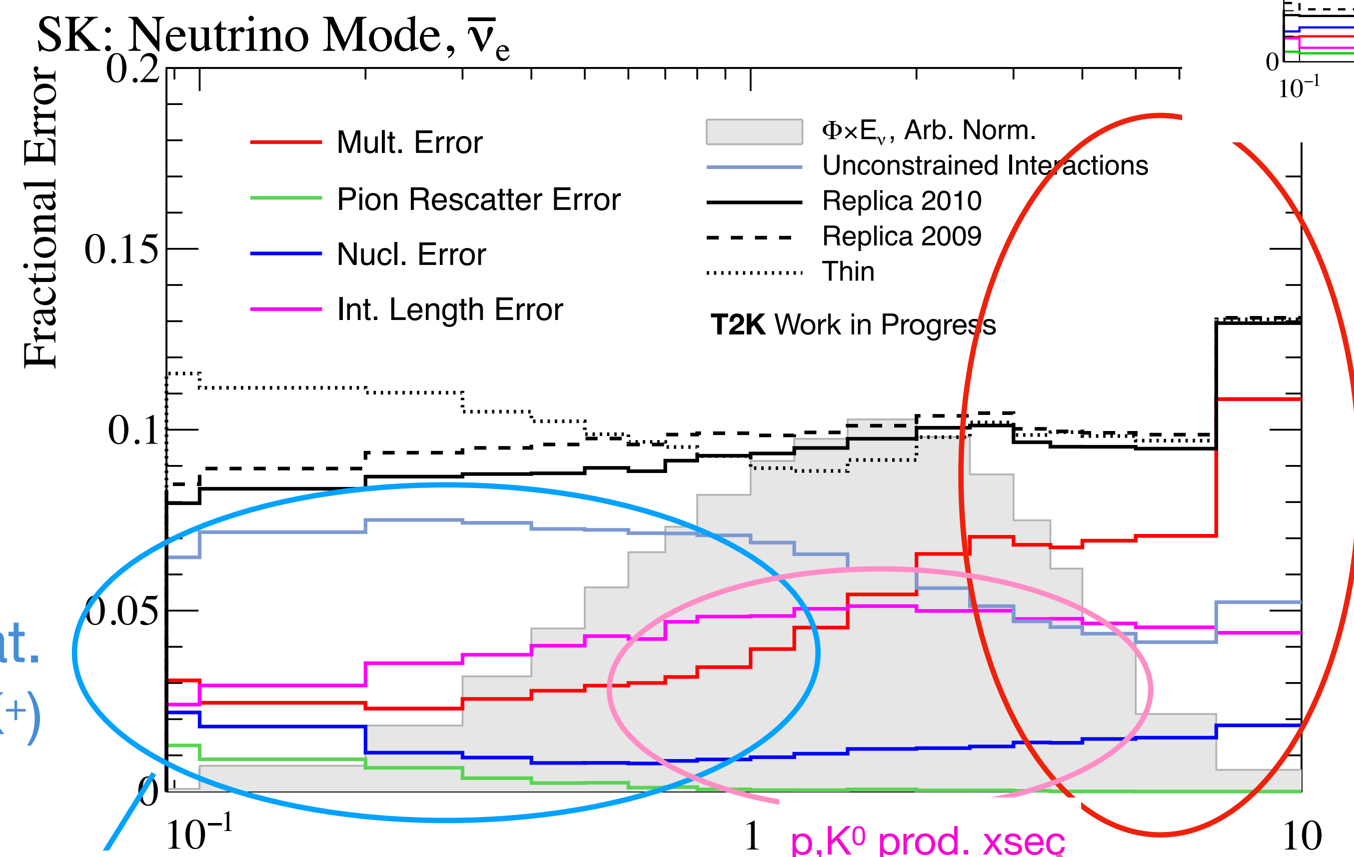




Wrong-sign ν_e

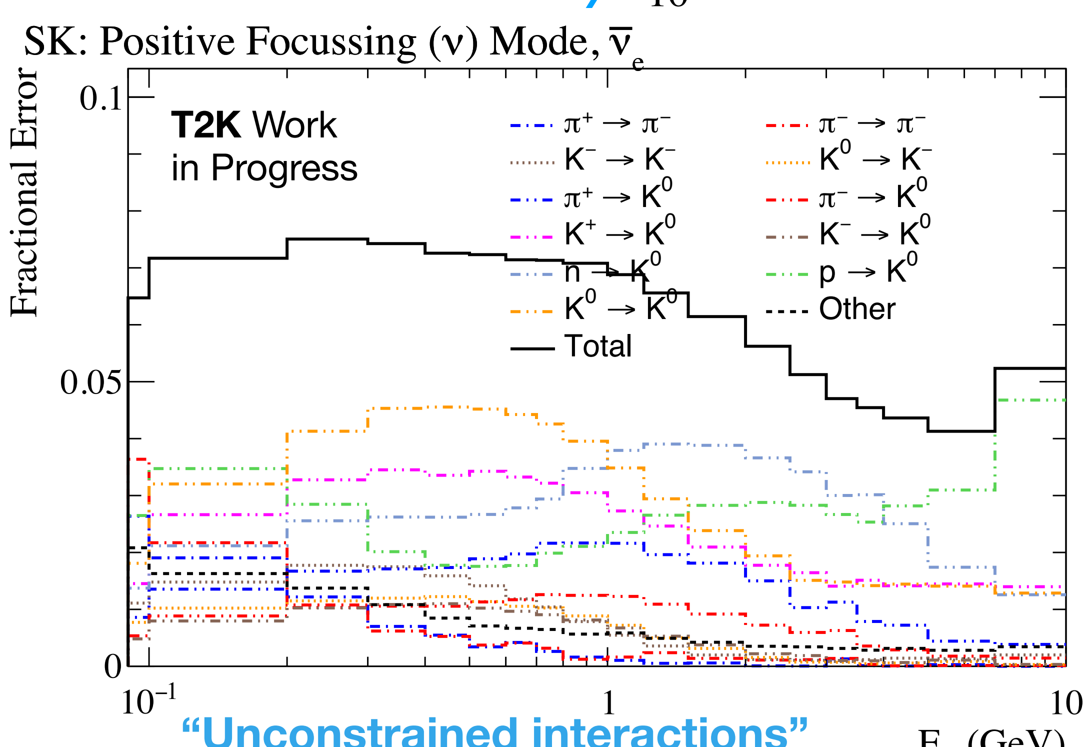


Multiplicity not covered by p→K^0 thin data

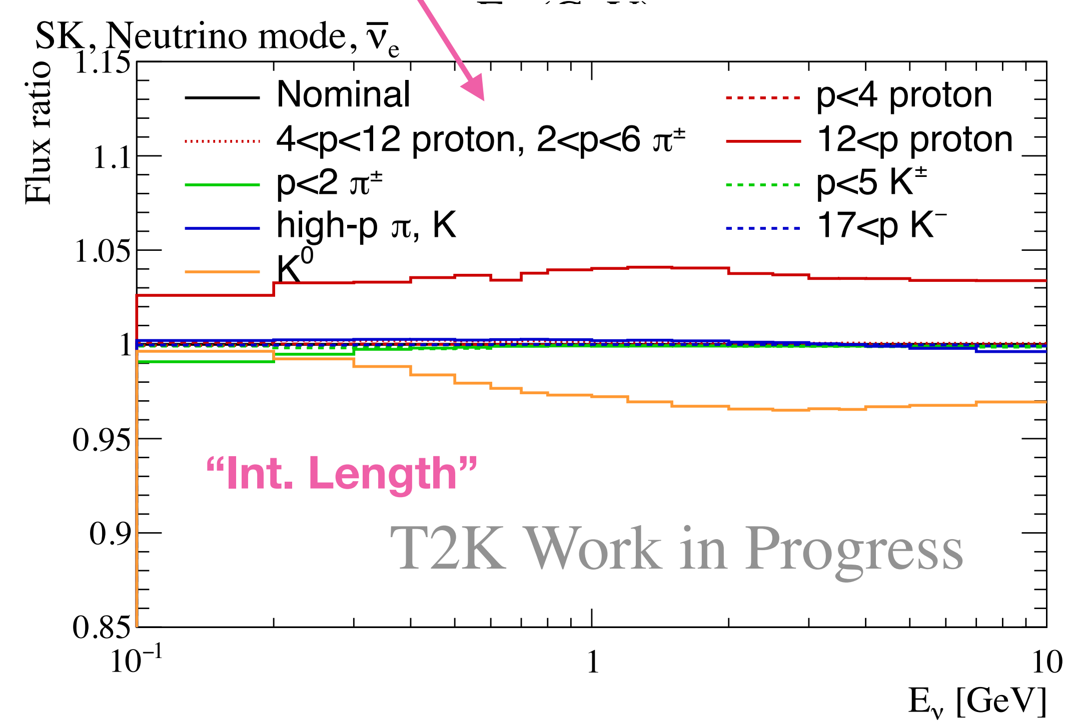


K^0 → K^0 scat.
(for RHC also K^+→K^+)

p,K^0 prod. xsec



“Unconstrained interactions”

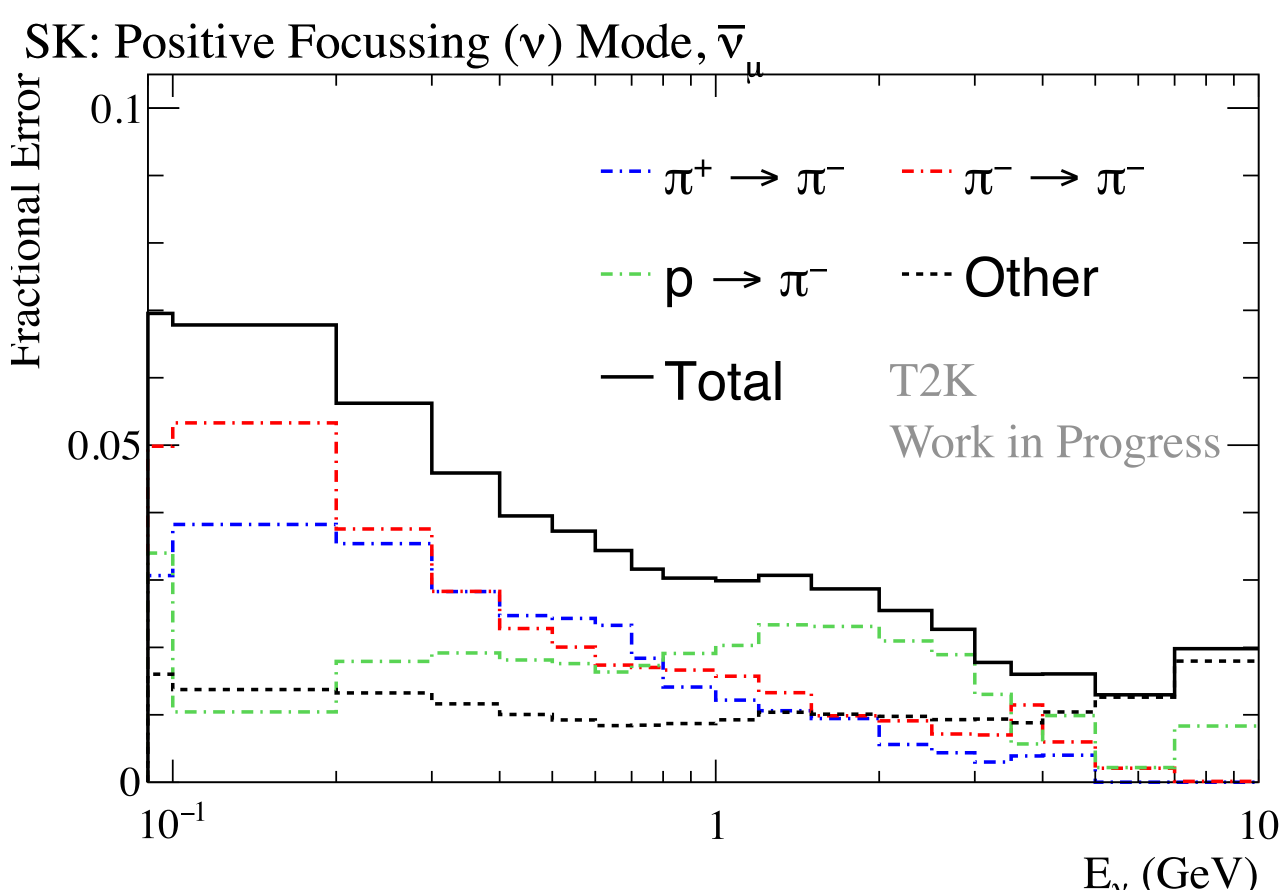


Pion scattering at low-E

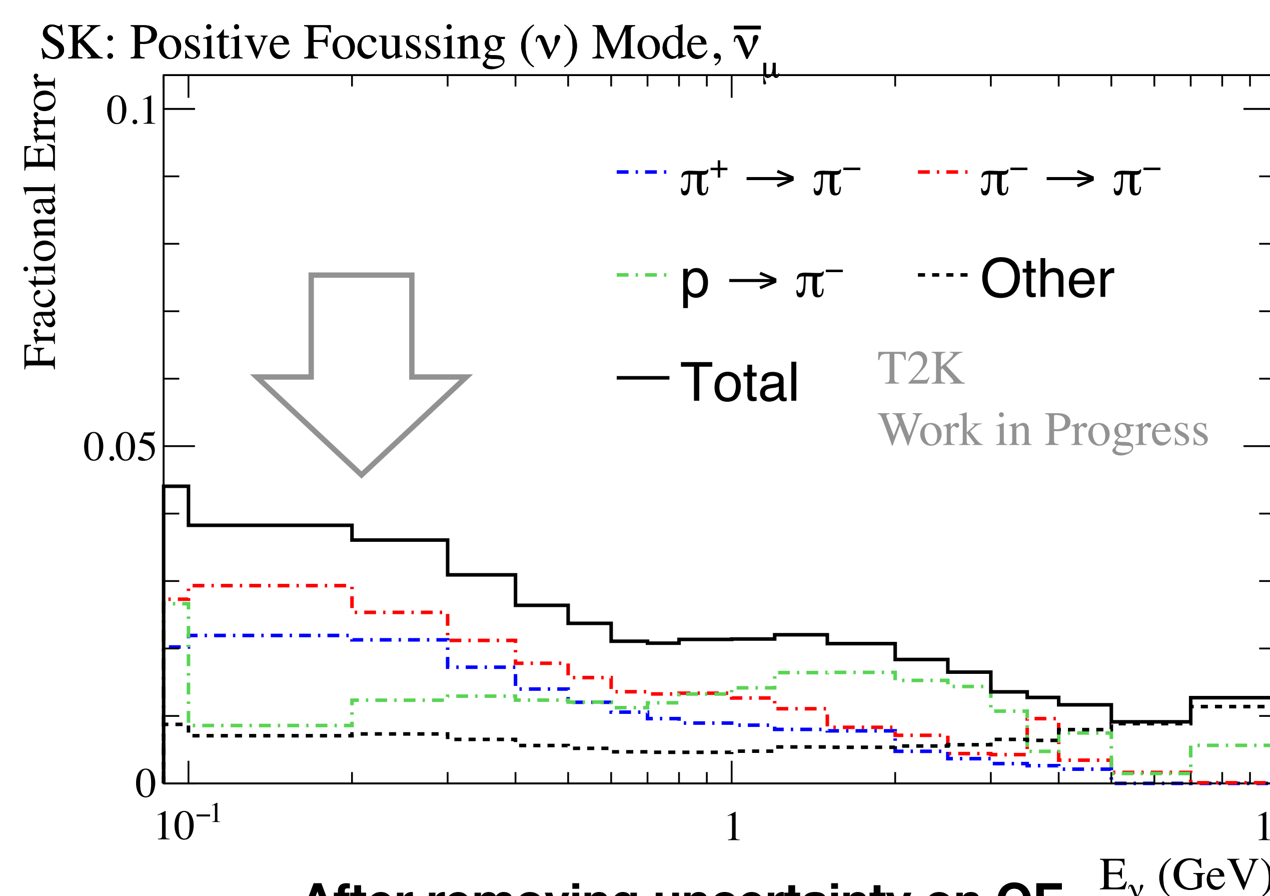
- Since exiting pions are mostly covered by replica data, most important materials are Al (horns), Fe (decay volume walls)

note: for QE number of neutrinos doesn't change, so xsec is not as important, but t-distribution can matter

- Same sign scattering is to a large part QE:



Uncertainty on all interactions



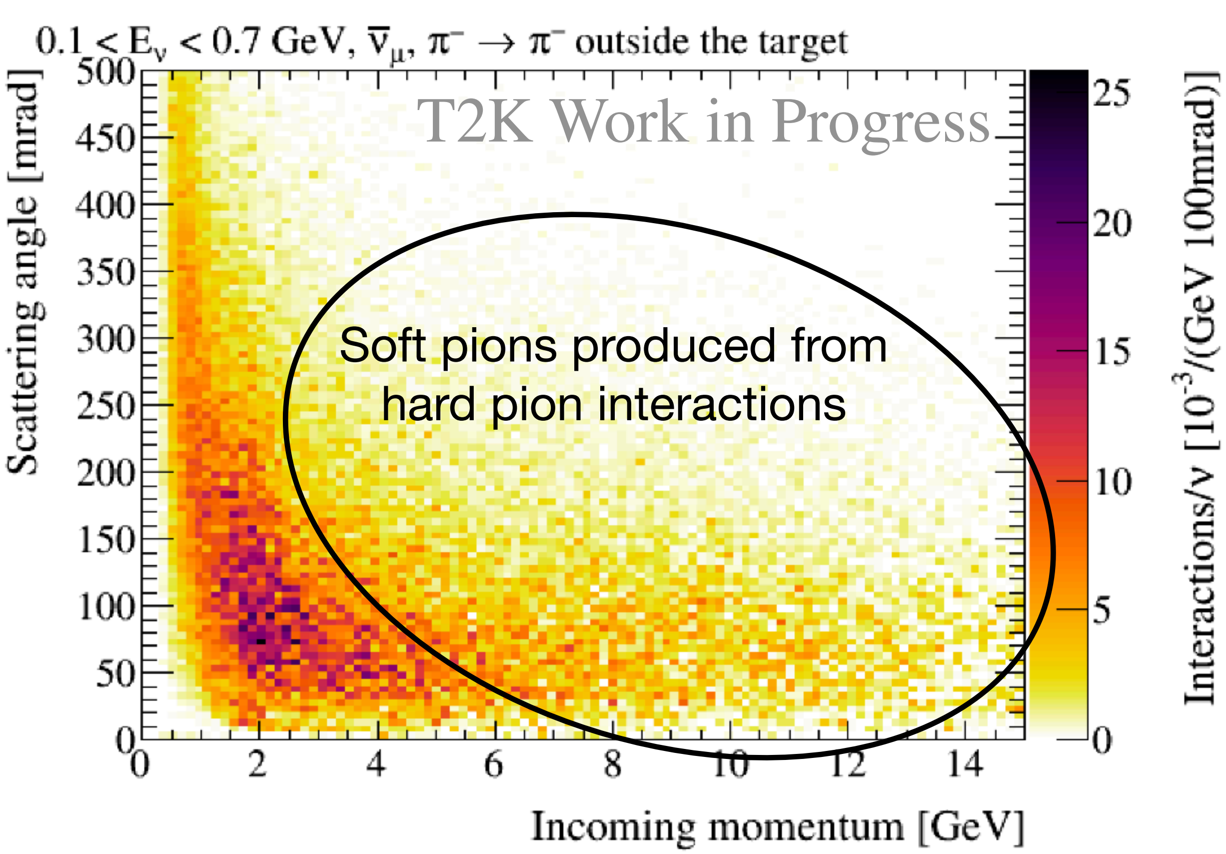
After removing uncertainty on QE

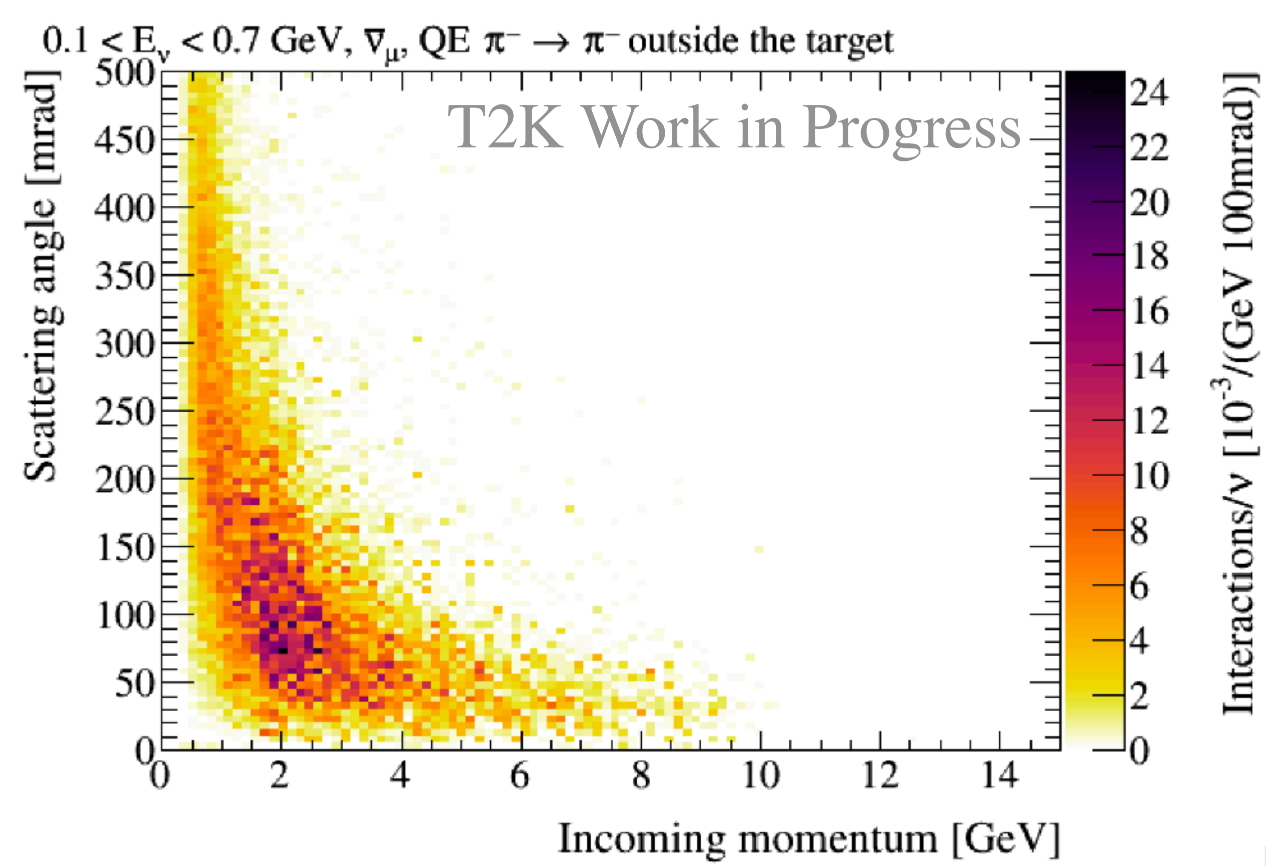
Pion scattering at low-E

- Since exiting pions are mostly covered by replica data, most important materials are Al (horns), Fe (decay volume walls)

note: for QE number of neutrinos doesn't change, so xsec is not as important, but t-distribution can matter

- Same sign scattering is to a large part QE:

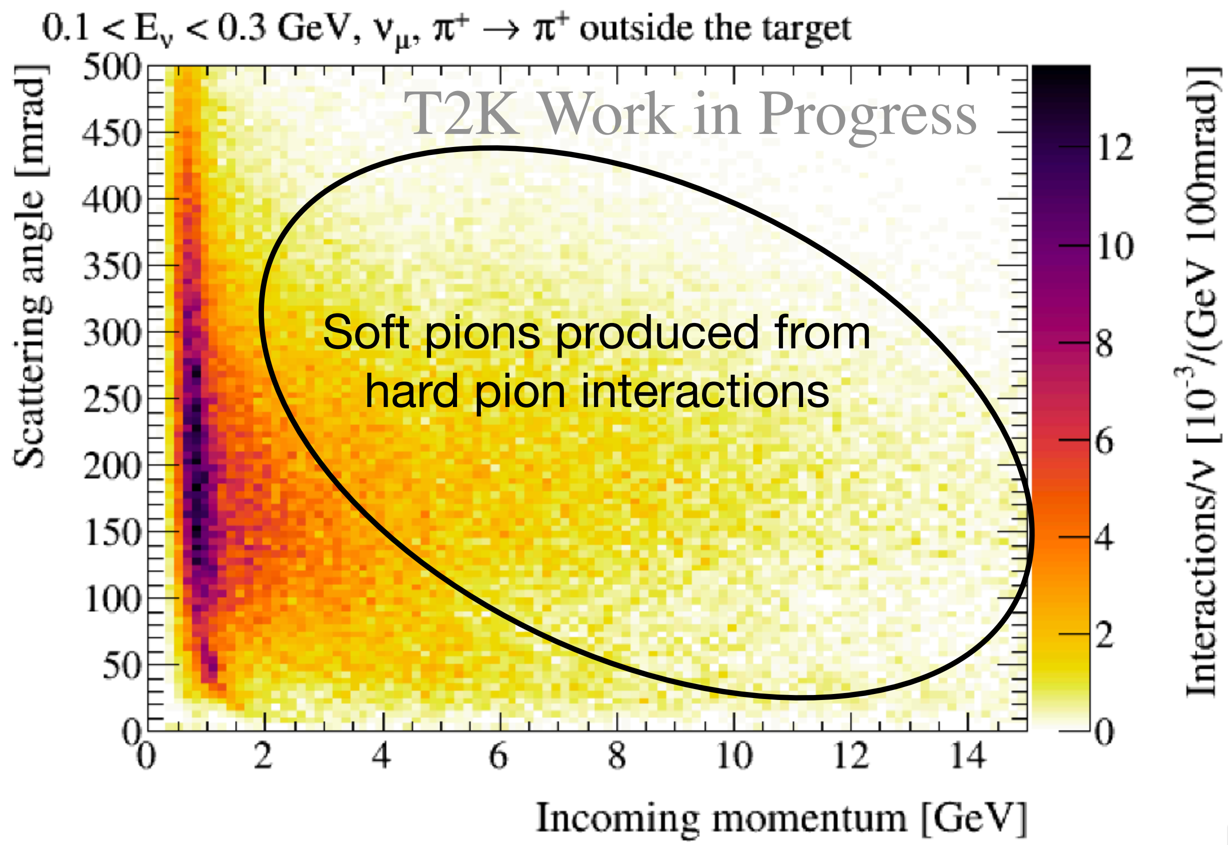




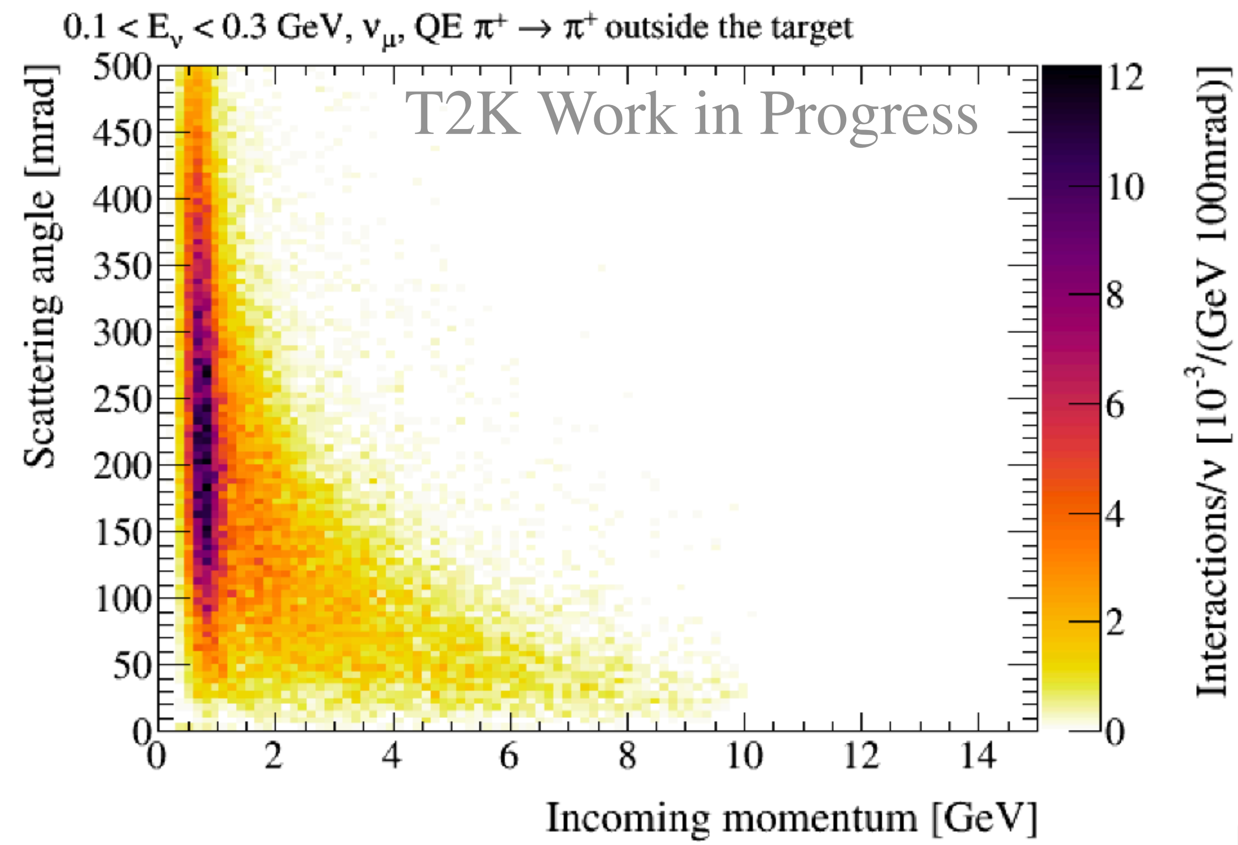
All interactions $\cos\theta := 1 - Q^2/(2|p_{in}|\,|p_{out}|)$ **QE interactions**

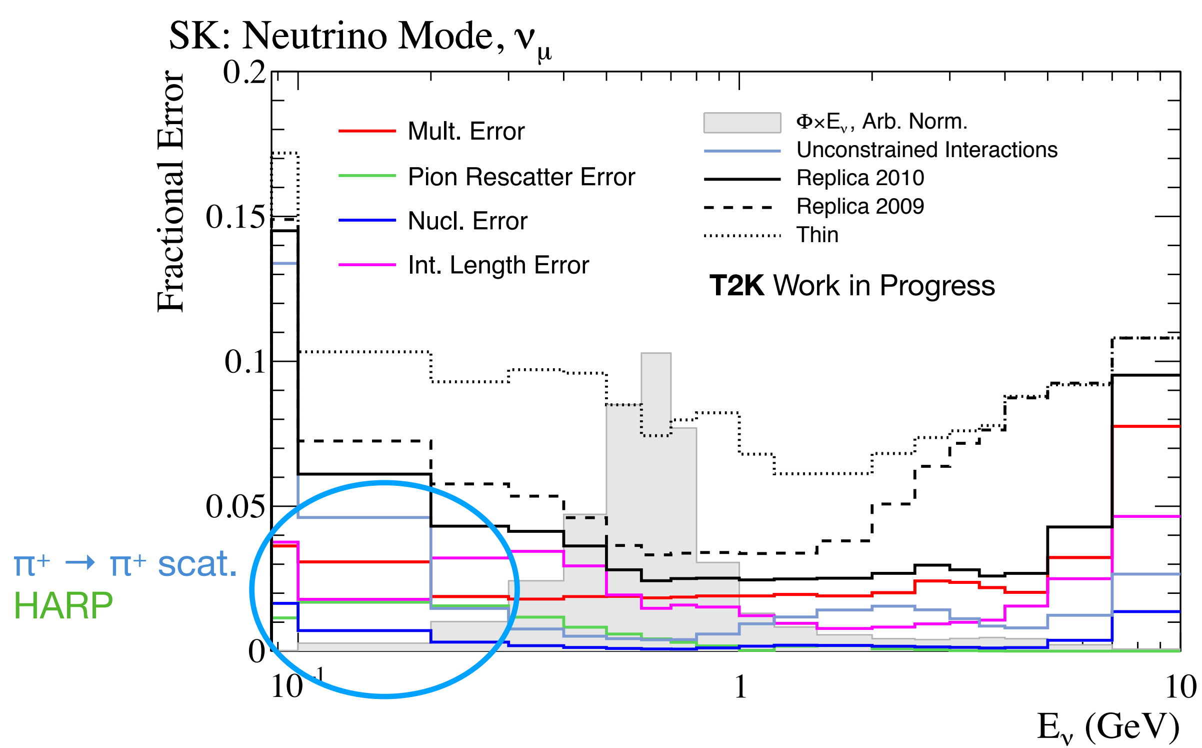
$\cos\theta := 1 - Q^2/(2|p_{in}|\,|p_{out}|)$

All interactions



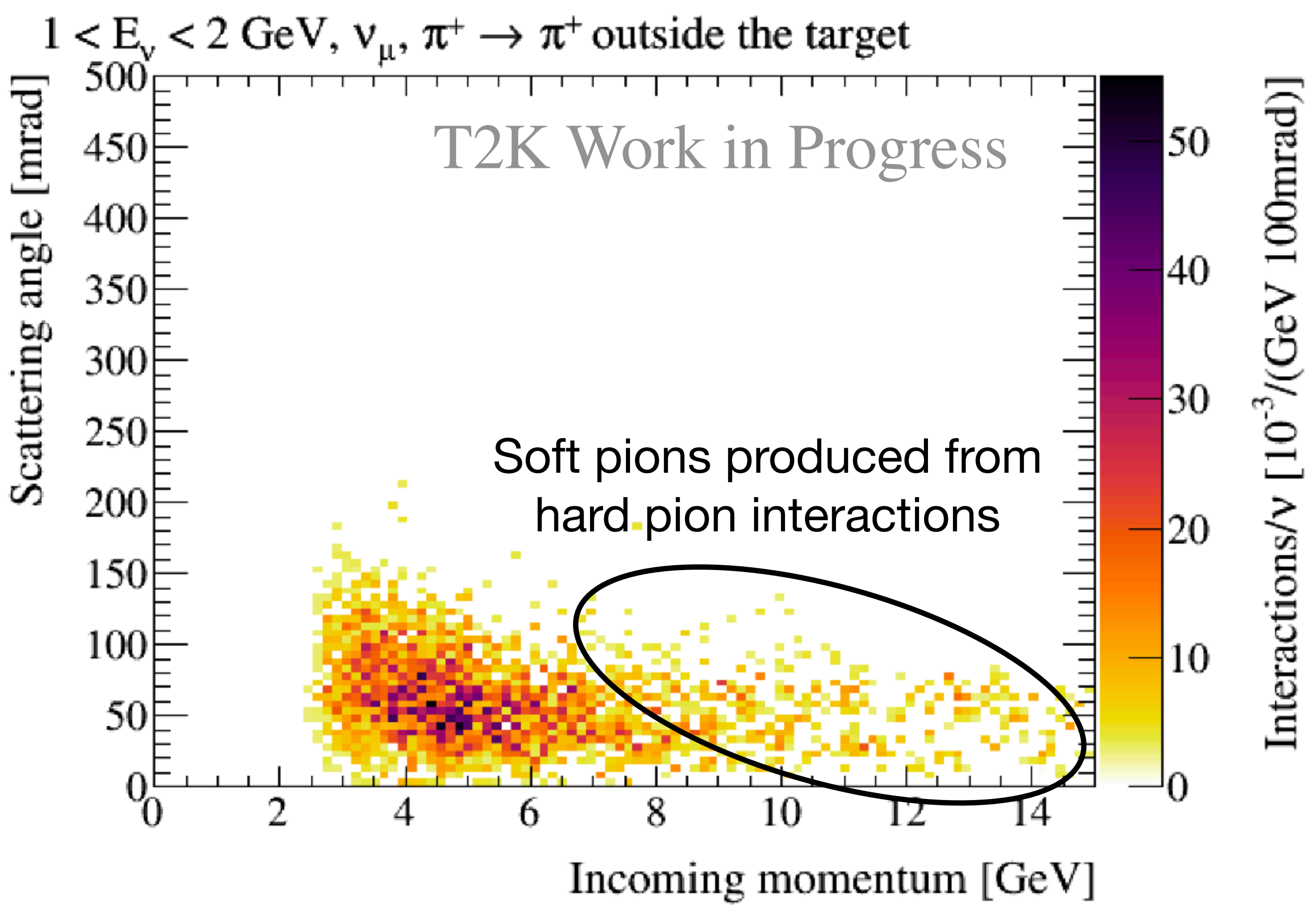
QE interactions



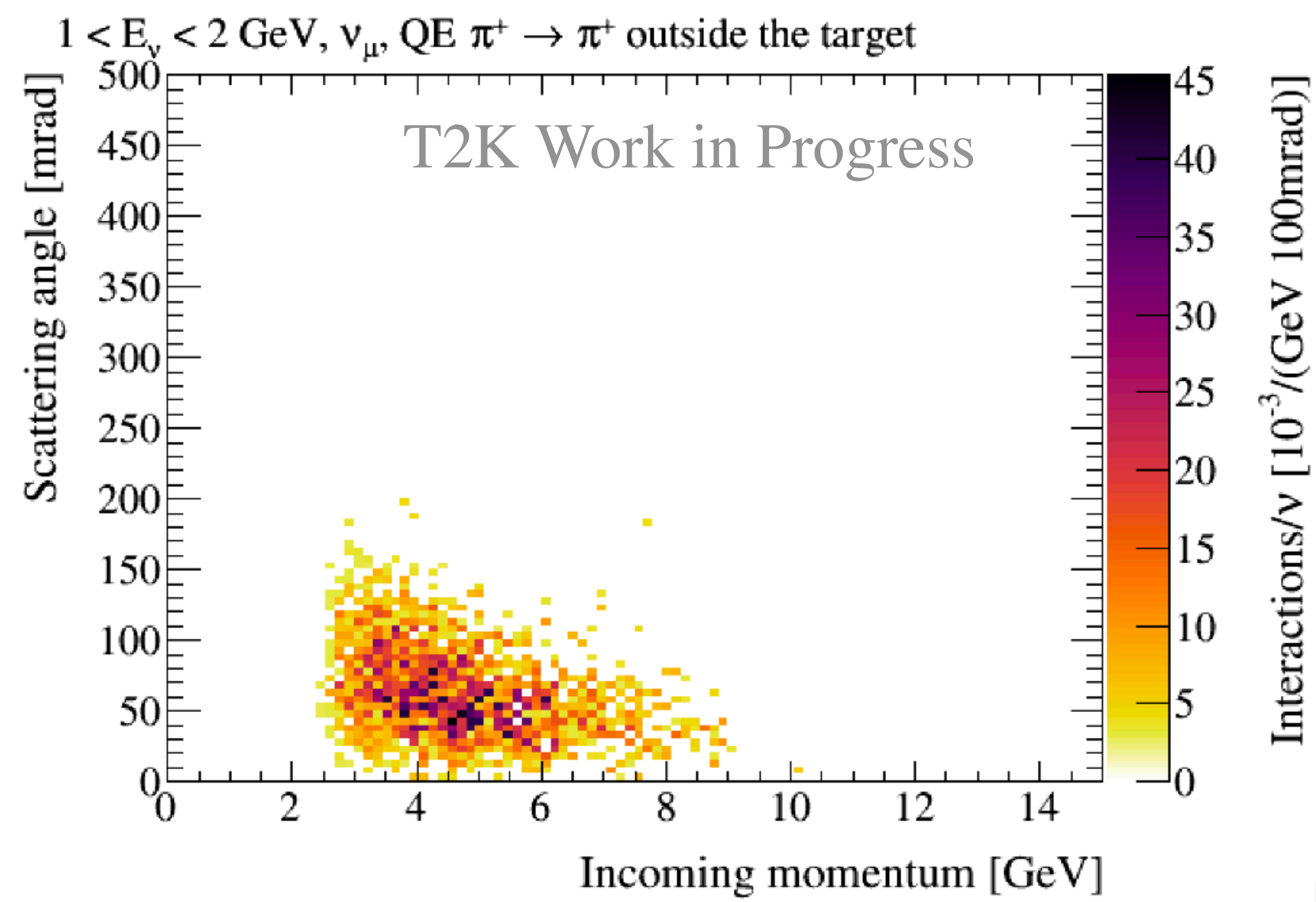


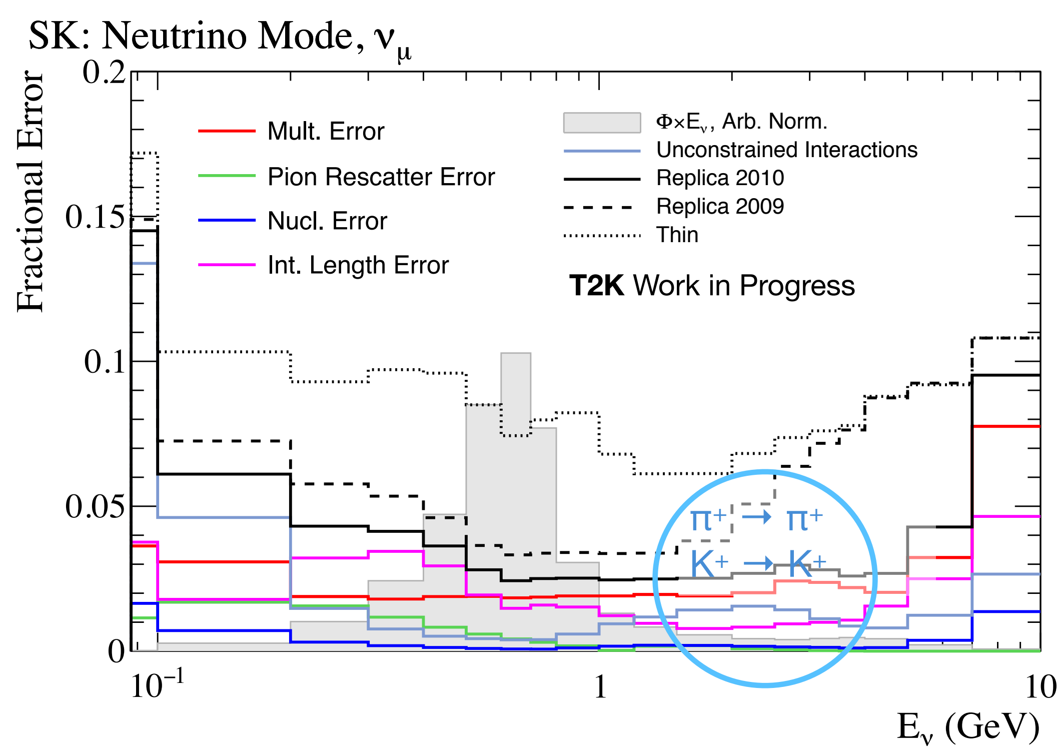
$\cos\theta := 1 - Q^2/(2|p_{in}|\,|p_{out}|)$

All interactions



QE interactions



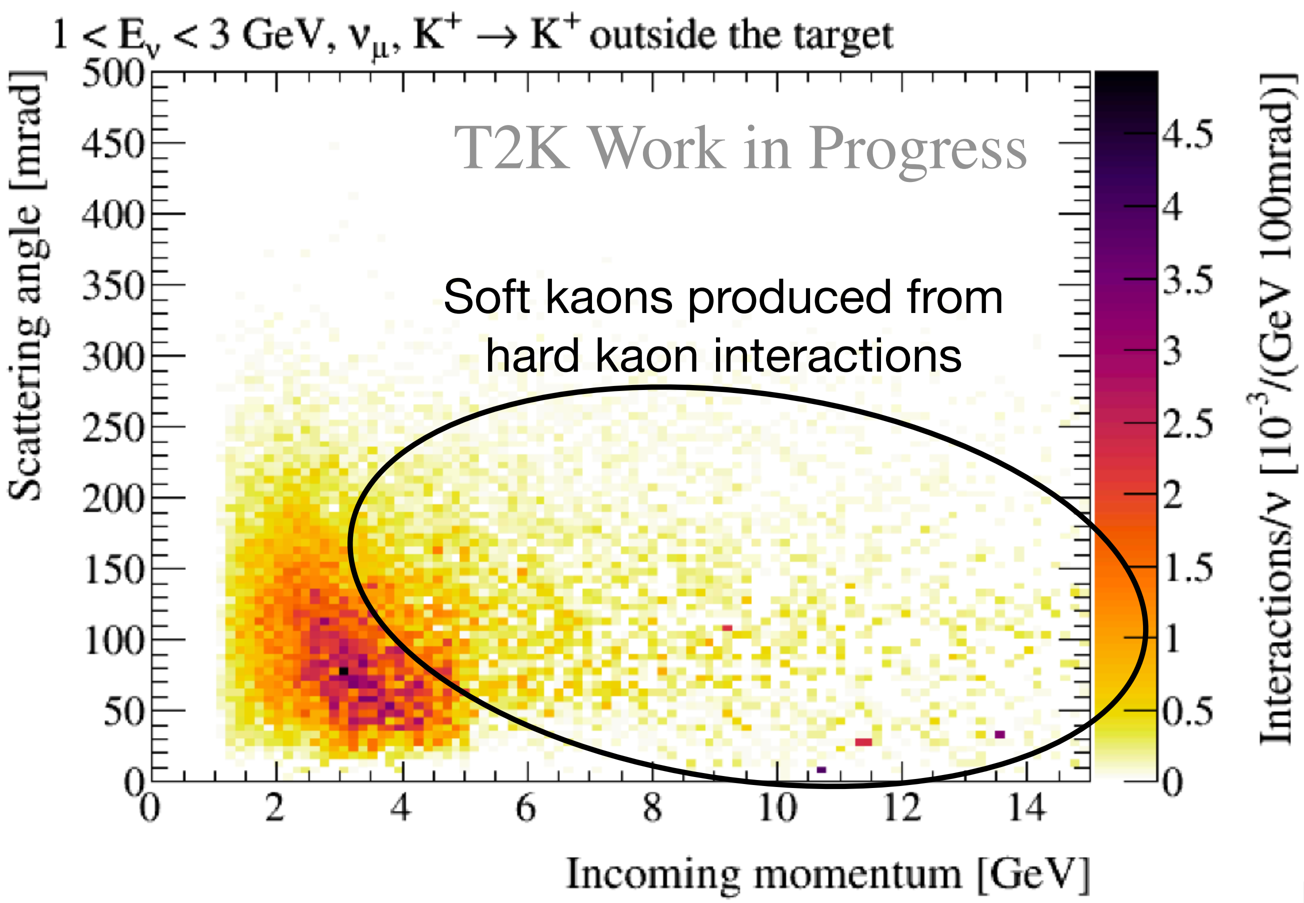


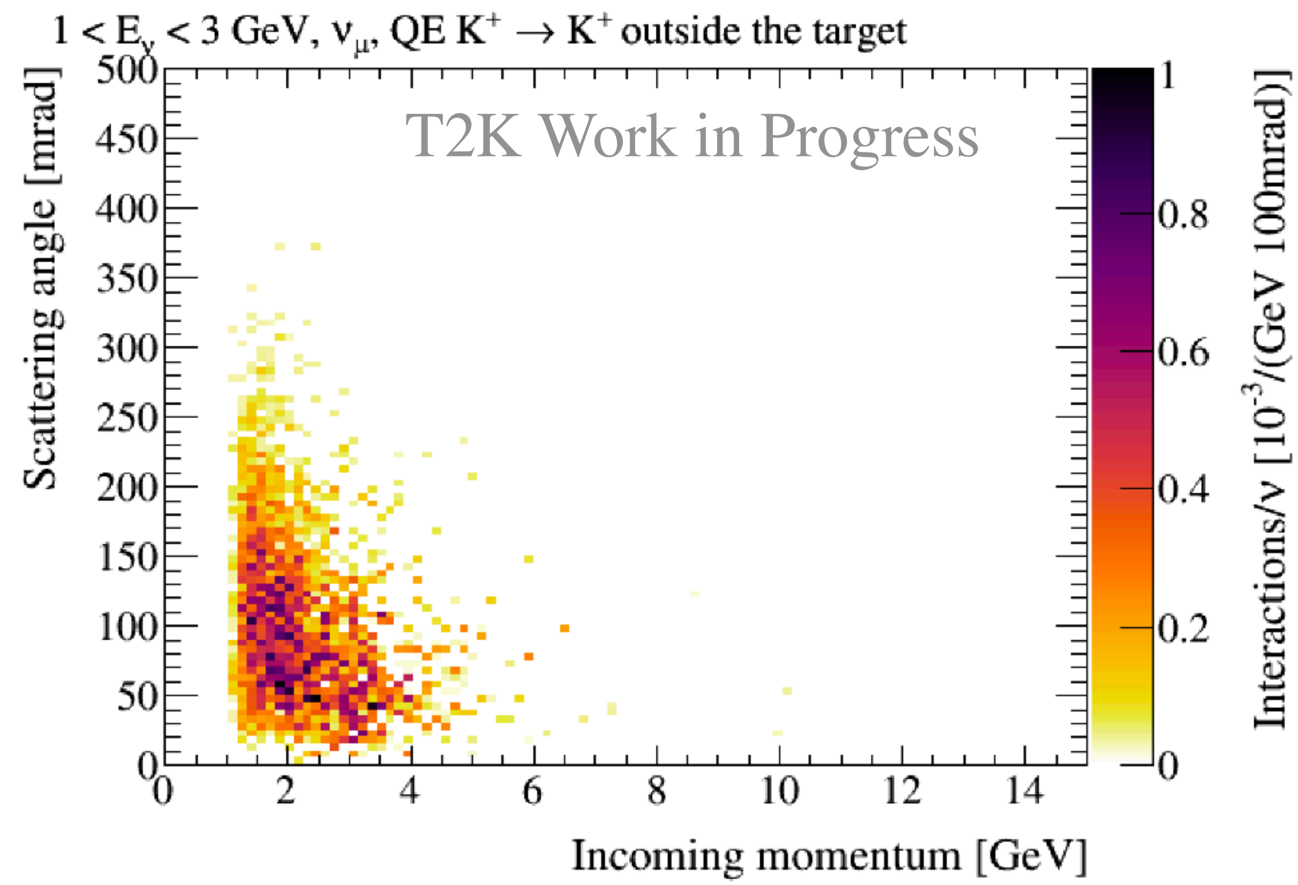
All interactions

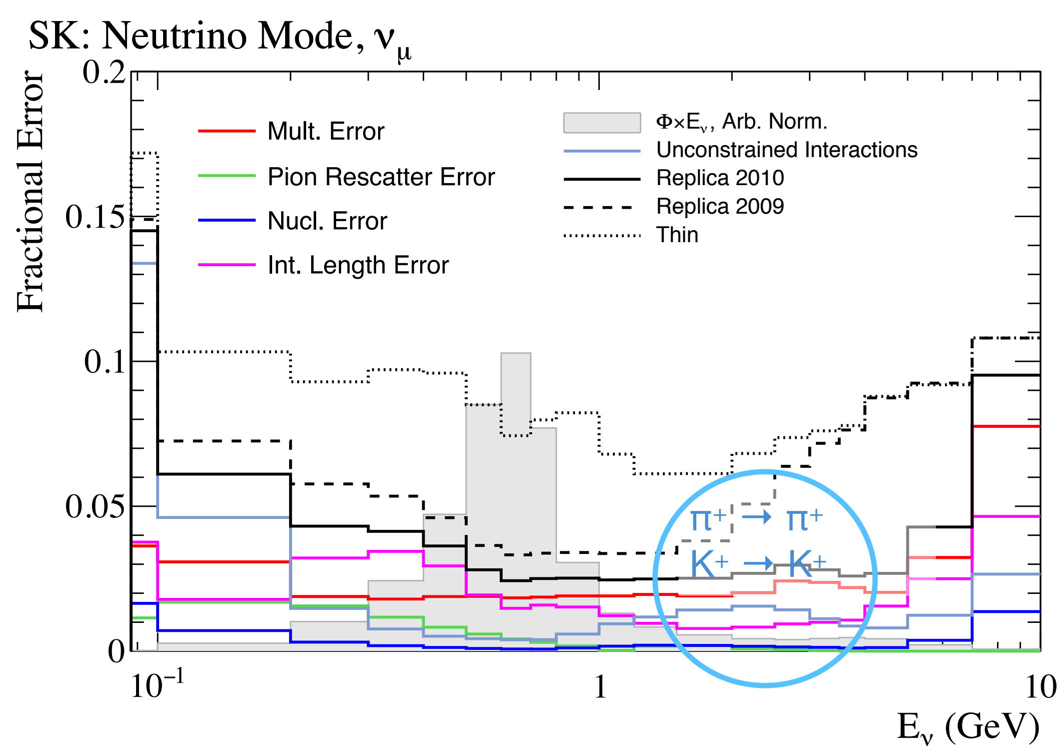
$\cos\theta := 1 - Q^2/(2|p_{in}|\,|p_{out}|)$

I think should take m_K into account for proper angle

QE interactions







Note:

This $K^{\pm}$ scattering may get covered by the proposed high-stats replica data taking with extended coverage, so need to check

Flux-weighted fractions of “unconstrained interactions”

SK, Neutrino mode

	$\to$ Carbon	$\to$ Aluminum	$\to$ Iron	$\to$ Titanium	$\to$ Helium	$\to$ Other
$\pi^+ \to$	8.87	9.08	7.76	2.06	2.19	0.36
$\pi^- \to$	5.35	5.23	5.69	0.88	0.26	0.35
$K^0 \to$	4.22	3.33	1.71	0.24	0.05	0.11
$K^+ \to$	4.08	4.85	1.20	0.31	0.11	0.11
$K^- \to$	0.94	1.14	0.36	0.07	0.01	0.03
$n \to$	2.52	1.77	1.73	0.09	1.36	0.57
$p \to$	3.02	0.91	0.56	0.06	8.96	0.44
$\bar{p} \to$	0.21	0.33	0.09	0.02	0.01	0.01
$\Lambda \to$	2.78	1.21	0.11	0.14	0.00	0.01
$\Sigma \to$	0.94	0.22	0.03	0.03	0.00	0.00
$\bar{n} \to$	0.29	0.46	0.14	0.03	0.01	0.01

largest contributions:

Channel	Flux-weighted fraction [%]
$\pi^+ \to$ Aluminum	9.08
$p \to$ Helium	8.96
$\pi^+ \to$ Carbon	8.87
$\pi^+ \to$ Iron	7.76
$\pi^- \to$ Iron	5.69
$\pi^- \to$ Carbon	5.35
$\pi^- \to$ Aluminum	5.23
$K^+ \to$ Aluminum	4.85
$K^0 \to$ Carbon	4.22
$K^+ \to$ Carbon	4.08
Other	35.90

SK, Anti-neutrino mode

	$\to$ Carbon	$\to$ Aluminum	$\to$ Iron	$\to$ Titanium	$\to$ Helium	$\to$ Other
$\pi^+ \to$	7.26	7.09	8.02	1.25	0.39	0.42
$\pi^- \to$	6.17	6.47	5.79	1.45	1.59	0.30
$K^0 \to$	3.77	3.06	1.69	0.22	0.05	0.11
$K^+ \to$	2.75	2.81	1.35	0.17	0.04	0.13
$K^- \to$	1.35	1.95	0.35	0.13	0.04	0.03
$n \to$	4.49	1.60	1.67	0.07	1.35	0.53
$p \to$	2.78	0.88	0.68	0.06	7.23	0.61
$\bar{p} \to$	0.27	0.43	0.12	0.03	0.02	0.01
$\Lambda \to$	6.17	1.57	0.12	0.18	0.01	0.01
$\Sigma \to$	1.81	0.27	0.03	0.04	0.00	0.00
$\bar{n} \to$	0.23	0.37	0.14	0.02	0.01	0.01

largest contributions:

Channel	Flux-weighted fraction [%]
$\pi^+ \to$ Iron	8.02
$\pi^+ \to$ Carbon	7.26
$p \to$ Helium	7.23
$\pi^+ \to$ Aluminum	7.09
$\pi^- \to$ Aluminum	6.47
$\pi^- \to$ Carbon	6.17
$\Lambda \to$ Carbon	6.17
$\pi^- \to$ Iron	5.79
$n \to$ Carbon	4.49
$K^0 \to$ Carbon	3.77
Other	37.54

T2K Work in Progress

Flux-weighted fractions of "unconstrained interactions"

SK, Neutrino mode

	π^+	π^-	K^0	K^+	K^-	n	p	$\bar{p}$	Λ	Σ
$\pi^+ \to$	20.74	5.15	1.98	1.28	0.26	0.29	0.35	0.00	0.11	0.16
$\pi^- \to$	8.99	6.00	1.38	0.58	0.21	0.30	0.15	0.00	0.07	0.08
$K^0 \to$	2.49	0.64	3.69	2.08	0.65	0.03	0.02	0.00	0.03	0.04
$K^+ \to$	2.70	0.42	2.73	4.73	0.02	0.02	0.02	0.00	0.01	0.01
$K^- \to$	0.76	0.26	0.79	0.02	0.67	0.01	0.00	0.00	0.02	0.02
$n \to$	0.90	1.12	0.06	1.76	0.27	0.11	2.73	0.00	0.52	0.56
$p \to$	6.35	3.57	2.65	0.64	0.18	0.13	0.21	0.00	0.15	0.07
$\bar{p} \to$	0.47	0.15	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
$\Lambda \to$	1.87	0.20	0.47	0.10	0.10	0.14	0.05	0.00	0.68	0.63
$\Sigma \to$	0.44	0.04	0.15	0.03	0.02	0.03	0.02	0.00	0.16	0.33
$\bar{n} \to$	0.73	0.15	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00

largest contributions:

Channel	Flux-weighted fraction [%]
$\pi^+ \to \pi^+$	20.74
$\pi^- \to \pi^+$	8.99
$p \to \pi^+$	6.35
$\pi^- \to \pi^-$	6.00
$\pi^+ \to \pi^-$	5.15
$K^+ \to K^+$	4.73
$K^0 \to K^0$	3.69
$p \to \pi^-$	3.57
$n \to p$	2.73
$K^+ \to K^0$	2.73
Other	35.31

SK, Anti-neutrino mode

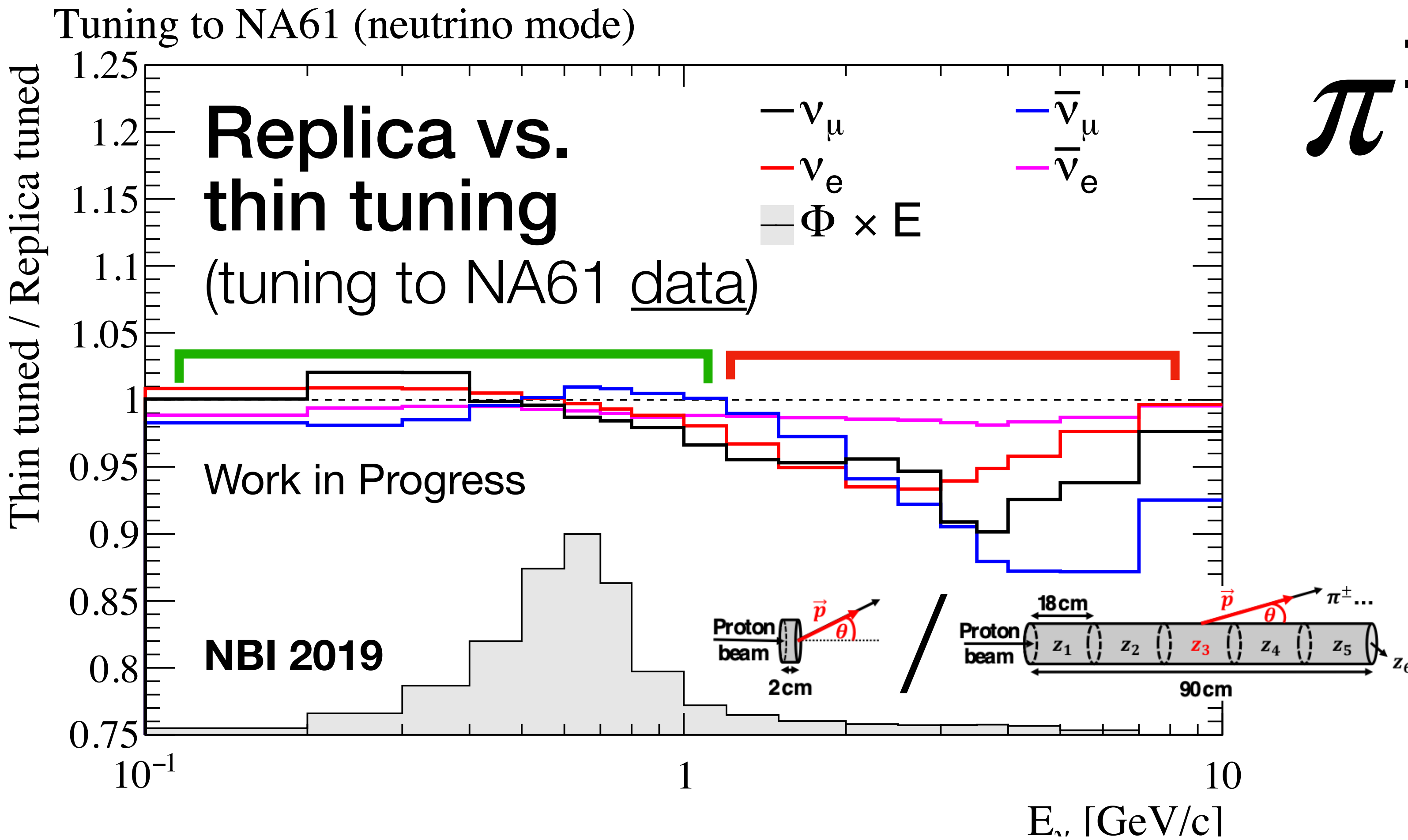
	π^+	π^-	K^0	K^+	K^-	n	p	$\bar{p}$	Λ	Σ
$\pi^+ \to$	8.15	12.06	1.87	0.68	0.43	0.33	0.26	0.00	0.39	0.27
$\pi^- \to$	3.70	15.07	1.32	0.33	0.39	0.37	0.12	0.00	0.25	0.24
$K^0 \to$	0.63	2.31	3.51	1.14	1.08	0.03	0.01	0.00	0.10	0.08
$K^+ \to$	0.61	1.70	2.49	2.31	0.03	0.03	0.02	0.00	0.03	0.02
$K^- \to$	0.17	1.30	0.81	0.01	1.41	0.01	0.00	0.00	0.07	0.06
$n \to$	0.72	1.26	0.06	1.07	0.40	0.10	2.25	0.00	1.97	1.86
$p \to$	4.29	4.04	2.65	0.53	0.17	0.12	0.20	0.00	0.15	0.08
$\bar{p} \to$	0.13	0.70	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00
$\Lambda \to$	0.19	1.80	0.45	0.03	0.28	0.18	0.03	0.00	3.48	1.61
$\Sigma \to$	0.05	0.41	0.14	0.01	0.07	0.04	0.01	0.00	0.83	0.61
$\bar{n} \to$	0.19	0.54	0.02	0.00	0.01	0.00	0.00	0.00	0.01	0.00

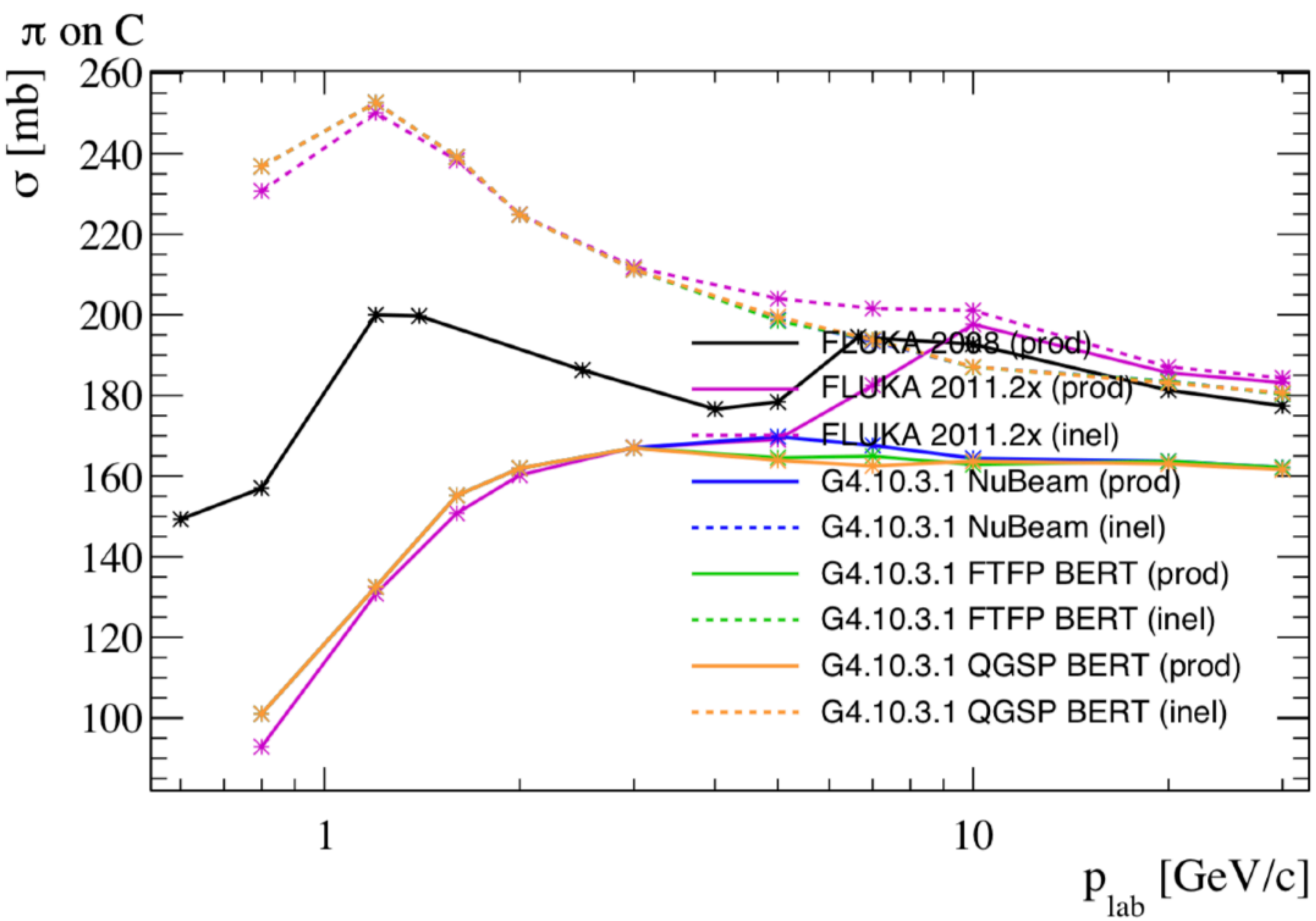
largest contributions:

Channel	Flux-weighted fraction [%]
$\pi^- \to \pi^-$	15.07
$\pi^+ \to \pi^-$	12.06
$\pi^+ \to \pi^+$	8.15
$p \to \pi^+$	4.29
$p \to \pi^-$	4.04
$\pi^- \to \pi^+$	3.70
$K^0 \to K^0$	3.51
$\Lambda \to \Lambda$	3.48
$p \to K^0$	2.65
$K^+ \to K^0$	2.49
Other	40.57

T2K Work in Progress

$\pi^{\pm}$ prod. xsec





- Tuning using replica data and thin data only gives ~10% difference in flux prediction at high-energies
- Possibly caused by $\pi^{\pm}$ prod. xsec on C, the FLUKA 2011 values seem to be tuned to Denisov et al., which comparing to the recent NA61 30 GeV/c measurement is prod+QE, not prod xsec.
- Fits to replica data actually suggest that one needs to move this more than just the Denisov/NA61 xsec difference at 30 GeV. Would be good to have measurements between 5~20 GeV

(below 5 GeV the MC generators are tuned to Vlasov et al?)

Summary

- Better understanding of flux important for success of J-PARC neutrino program (T2K, many near detectors, IWCD, HK, …)
- Dominant systematic at low energy wrong-sign ν_μ flux from few-GeV $\pi^\pm$ scattering inside horns (Al) and decay volume (Fe)
- Similarly for right-sign ν_μ + few-GeV $K^\pm$ scattering above flux peak
- For wrong-sign ν_e neutral Kaon scattering
- Having the option to run accurate thin target tuning will also be important toward HK era until HK-target replica tuning becomes available

backup

Alternative tunes

FHC, thin target tuning