NuMI @ ICARUS Flux

PPFX/G4.10.4 Studies Cont.

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ICARUS Collaboration Meeting
Fermilab
October 14-16, 2024

Changes to the NuMI Flux Simulation

- Updated geometry with DuRex (concrete coated steel) blocks included.
- Updated version of GEANT4: 4.9.2 $\longrightarrow$ 4.10.4
- Bug fix for missing uncertainties for hadron interactions with negative x_F.

- New nominal flux files with higher statistics ready for use in production.
  - Waiting on NOvA to merge in the 1MW geometry change. Will provide Reweights.
- Analysis package with PPFX weights and hadron prod. uncertainties are done.
- Focusing systematics are being vastly improved via high stat file generation.

New NuMI Flux Productions (Geant4-10.4)

2B POT – 700kW target geometry, missing g3Chase shielding blocks

```
/cvmfs/sbn.osgstorage.org/pnfs/fnal.gov/usr/sbn/persistent/stash/
                                physics/beam/GENIE/NuMI/standard/v03_00{,_RHC}/
```

Fatima and Karim produced another 1B (or 3B?) POT with shield blocks included

FHC: `/pnfs/icarus/persistent/users/faabdalr/numi_beamsim/run0/`

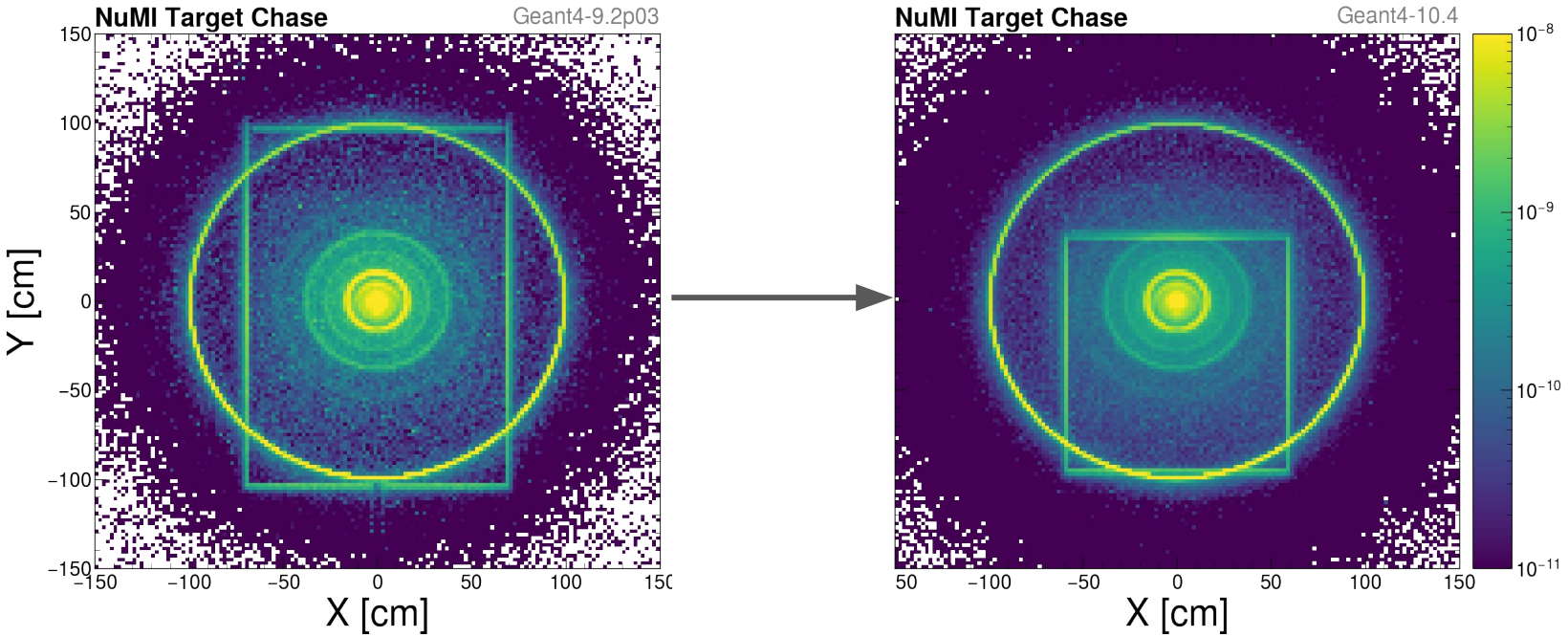
RHC: `/pnfs/icarus/persistent/users/hassinin/numi_beamsim/run0/`

250M POT production from Nitish Nayak which includes decay-at-rest particles

```
/pnfs/icarus/persistent/users/awood/g4numi_g4_10_4_p02d_nothresh/me000z{,-}200i/run0/files
```

Missing NuMI geometry components

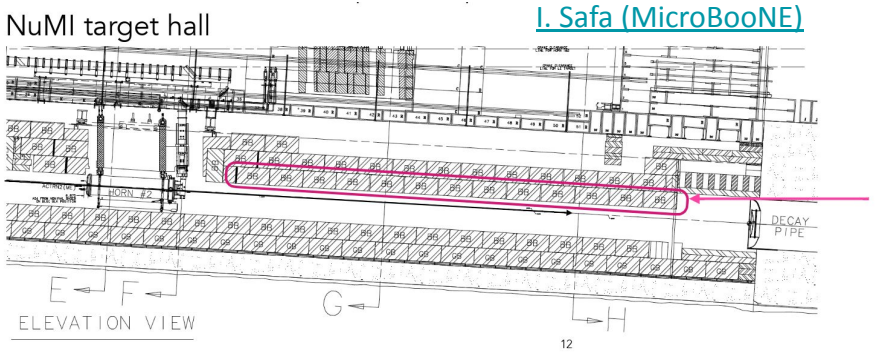
ν parent decay positions

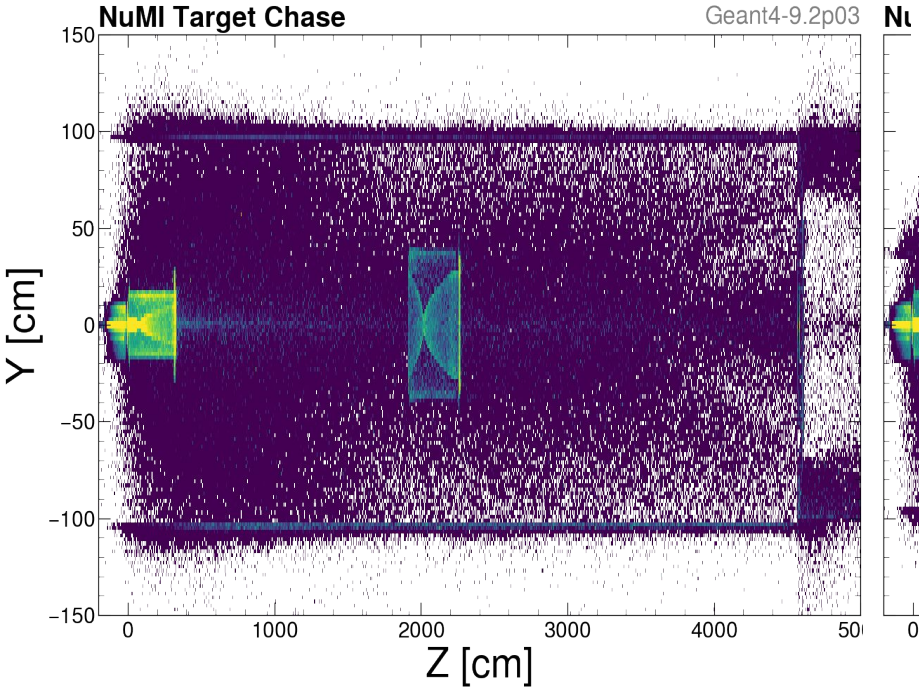


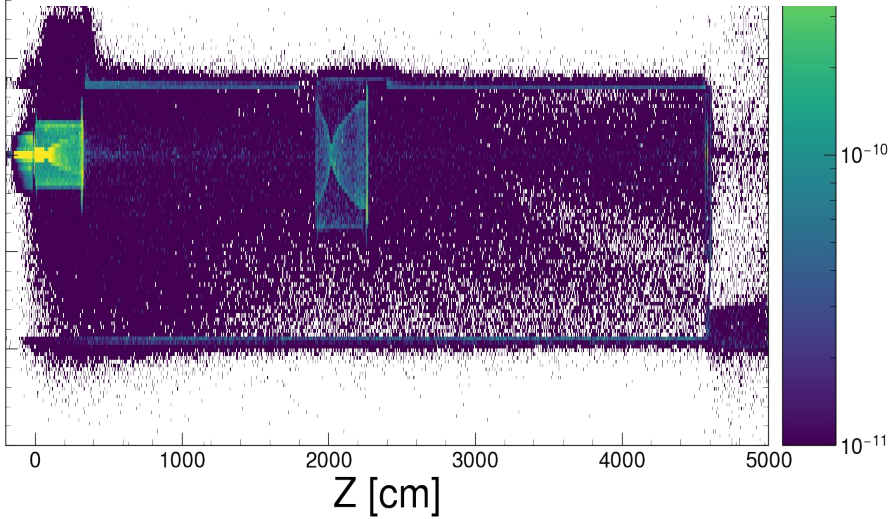
Concrete-encased steel shielding blocks omitted from NuMI simulation for O(10 yrs)

Reduces chase ceiling height by ~60 cm

Missing geometry components

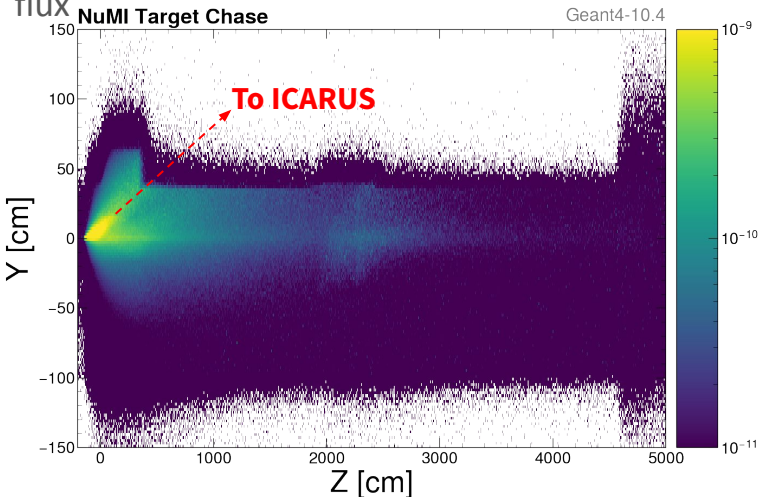


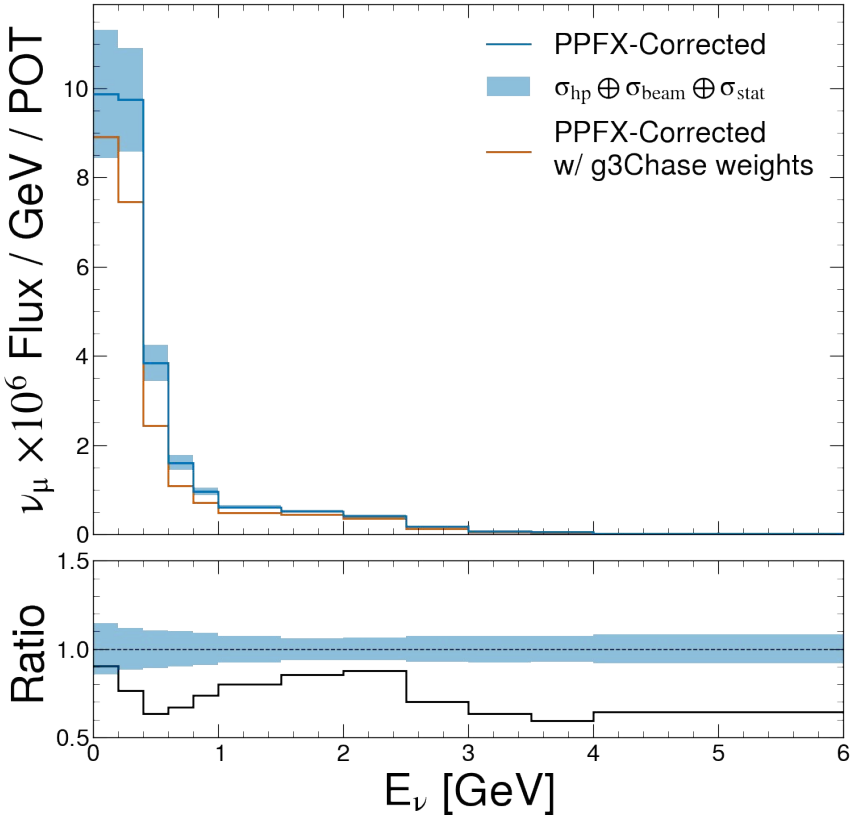




Flux attenuation from extra material

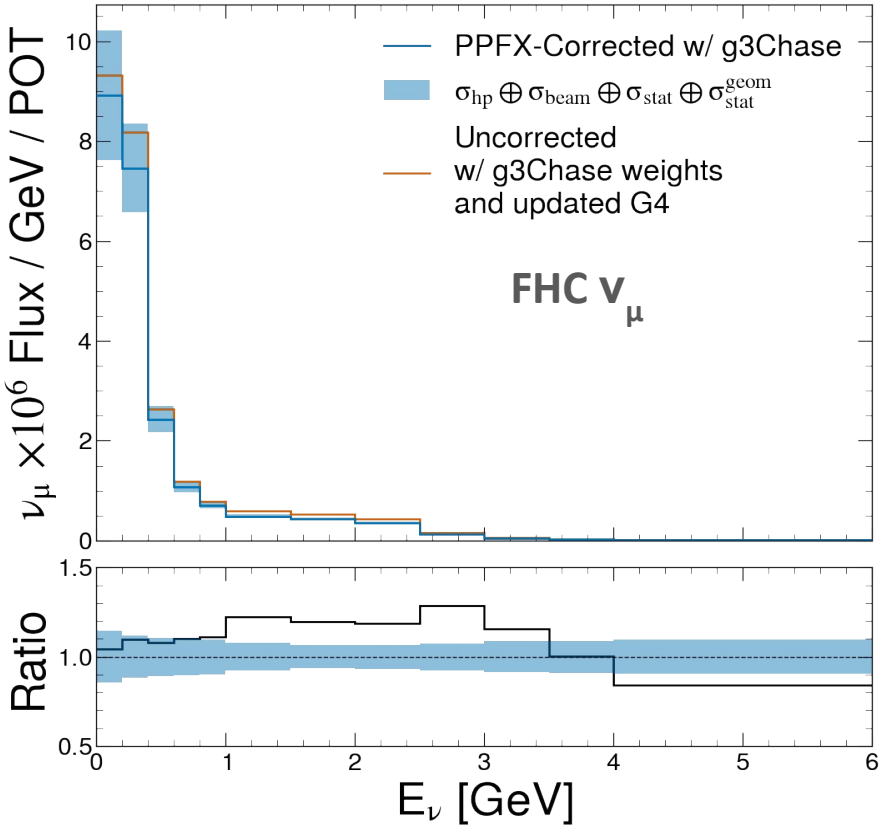
- Additional material added resulted in ~20-30% (avg) attenuation of the flux
  - Less space for π/K to decay in flight
- Calculated weights based on the new geometry and applied to the PPFX-corrected flux



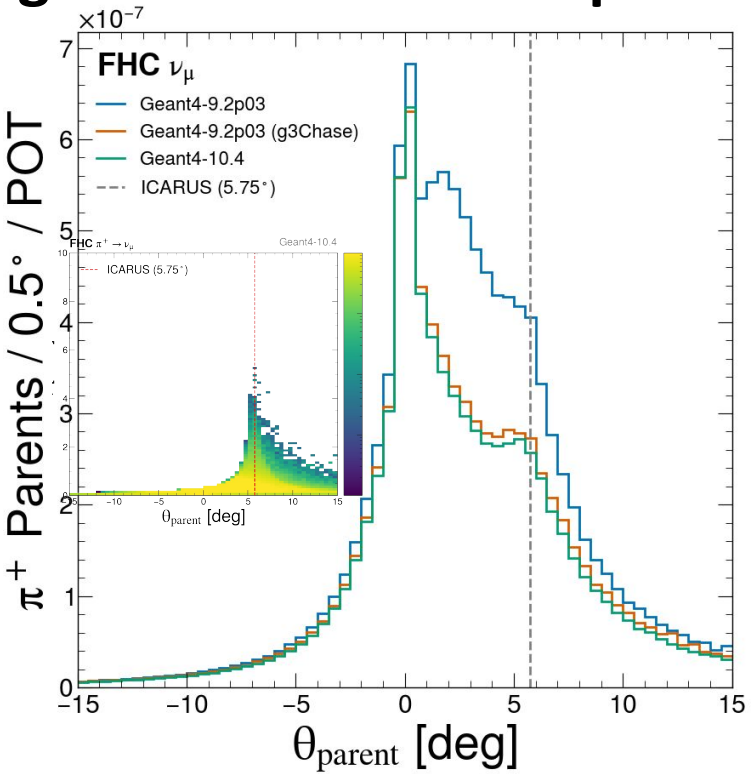


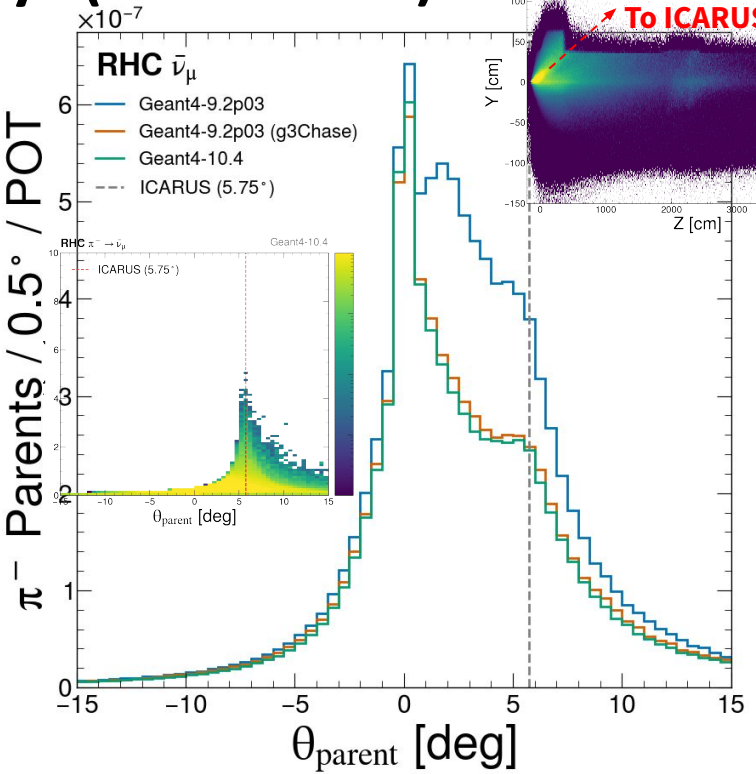
Comparison of flux with and without G4 update

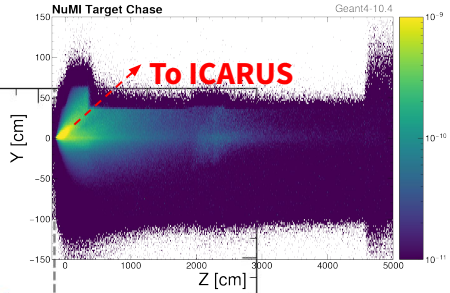
- LE consistent with uncertainties
- ~20% normalization inc. between 1 – 3.5 GeV region not covered by uncertainties
- K^+ production rates appear to be increased with changes to nuclear model



Angular distribution of pion decays (FHC vs RHC)

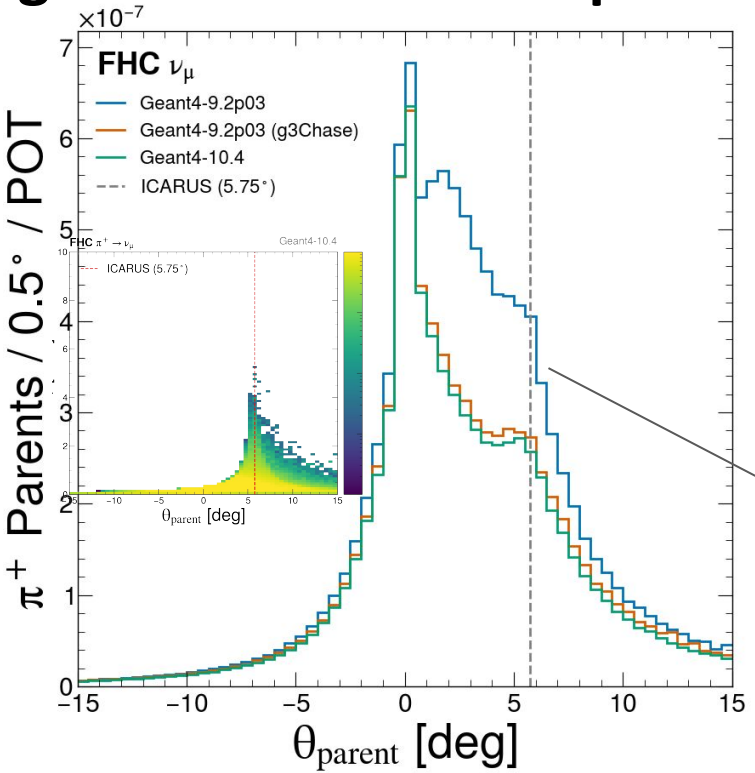


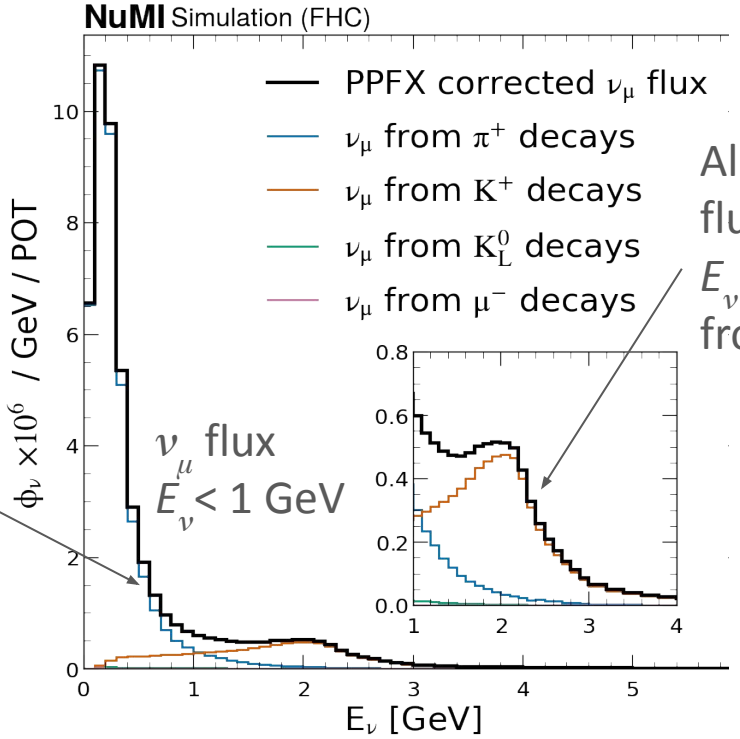




However, the pion distributions are much more similar between FHC nu vs. RHC nubar

Angular distribution of pion decays (FHC vs RHC)





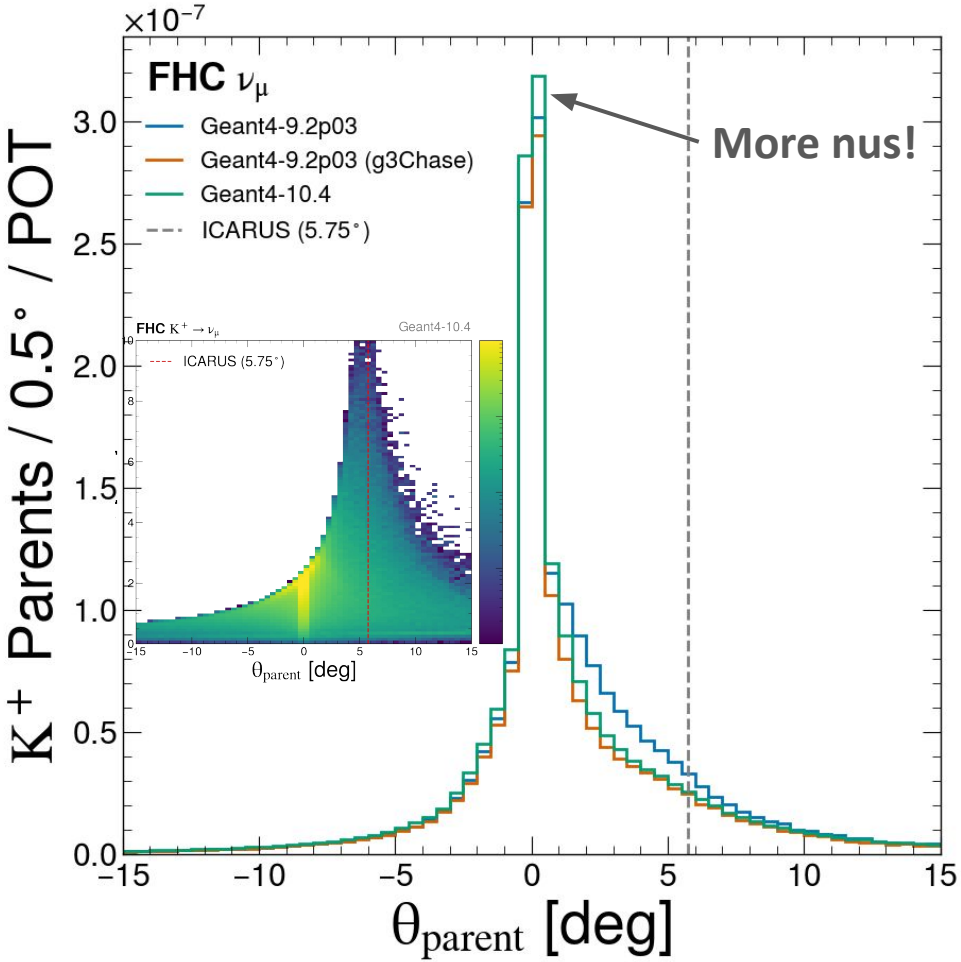
ν_μ flux
$E_\nu < 1$ GeV

All ν_e and ν_μ flux
$E_\nu > 1$ GeV
from Kaons

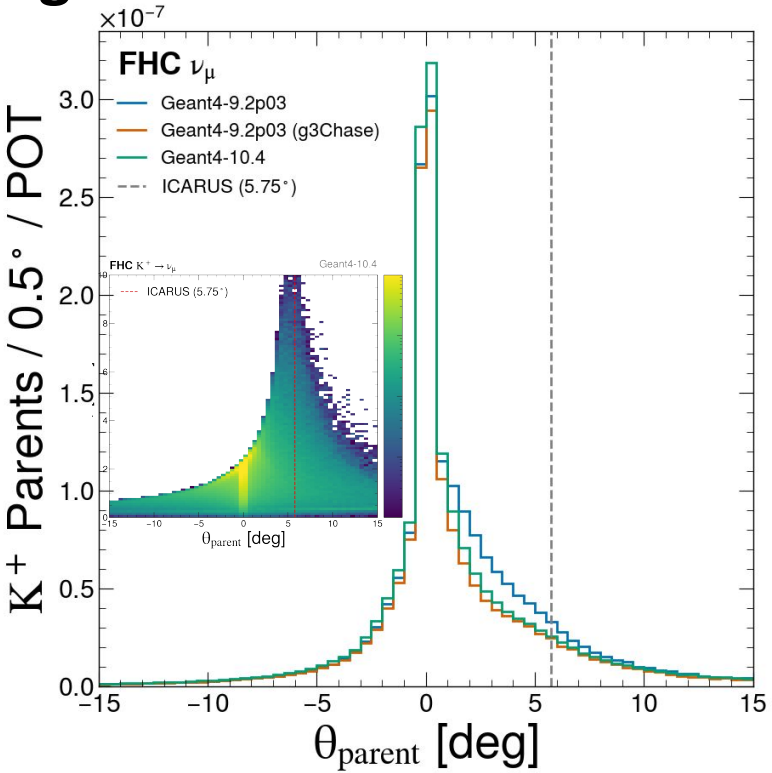
However, the pion distributions are much more similar between FHC nu vs. RHC nubar

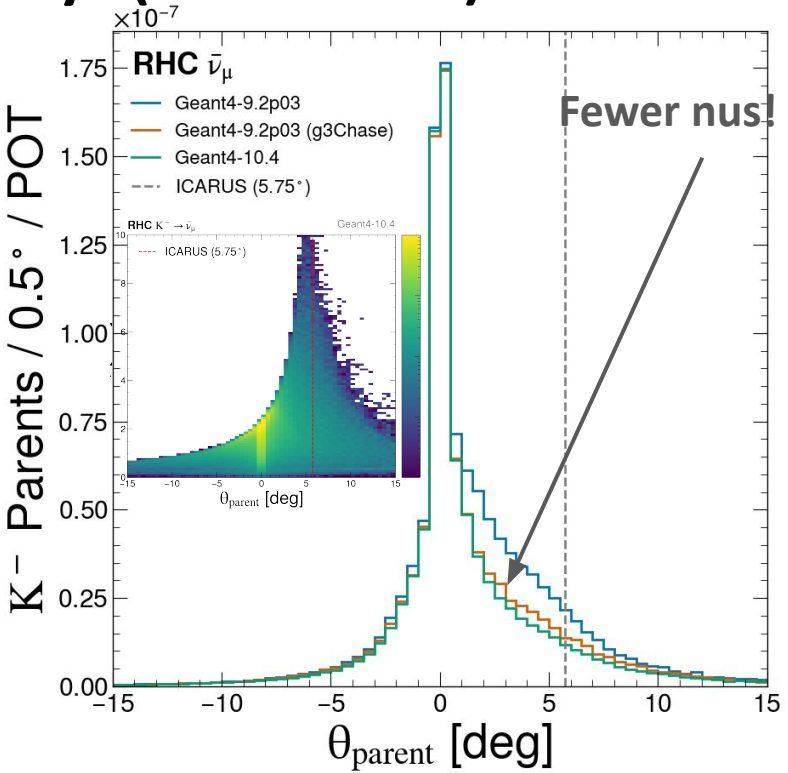
Angular distribution of kaon decays

- In all 3 cases, majority of nu come from kaons directed along beam axis with wide decay kinematics
- Extra material added by g3Chase eats the flux from parent K directed toward ICARUS
- G4 update gives us slightly more nus



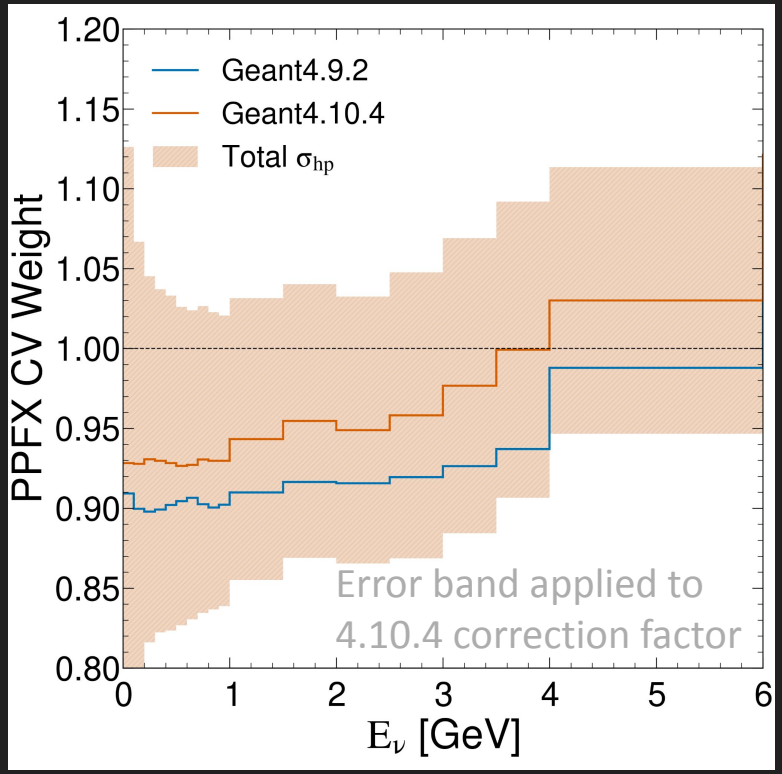
Angular distribution of kaon decays (FHC vs RHC)





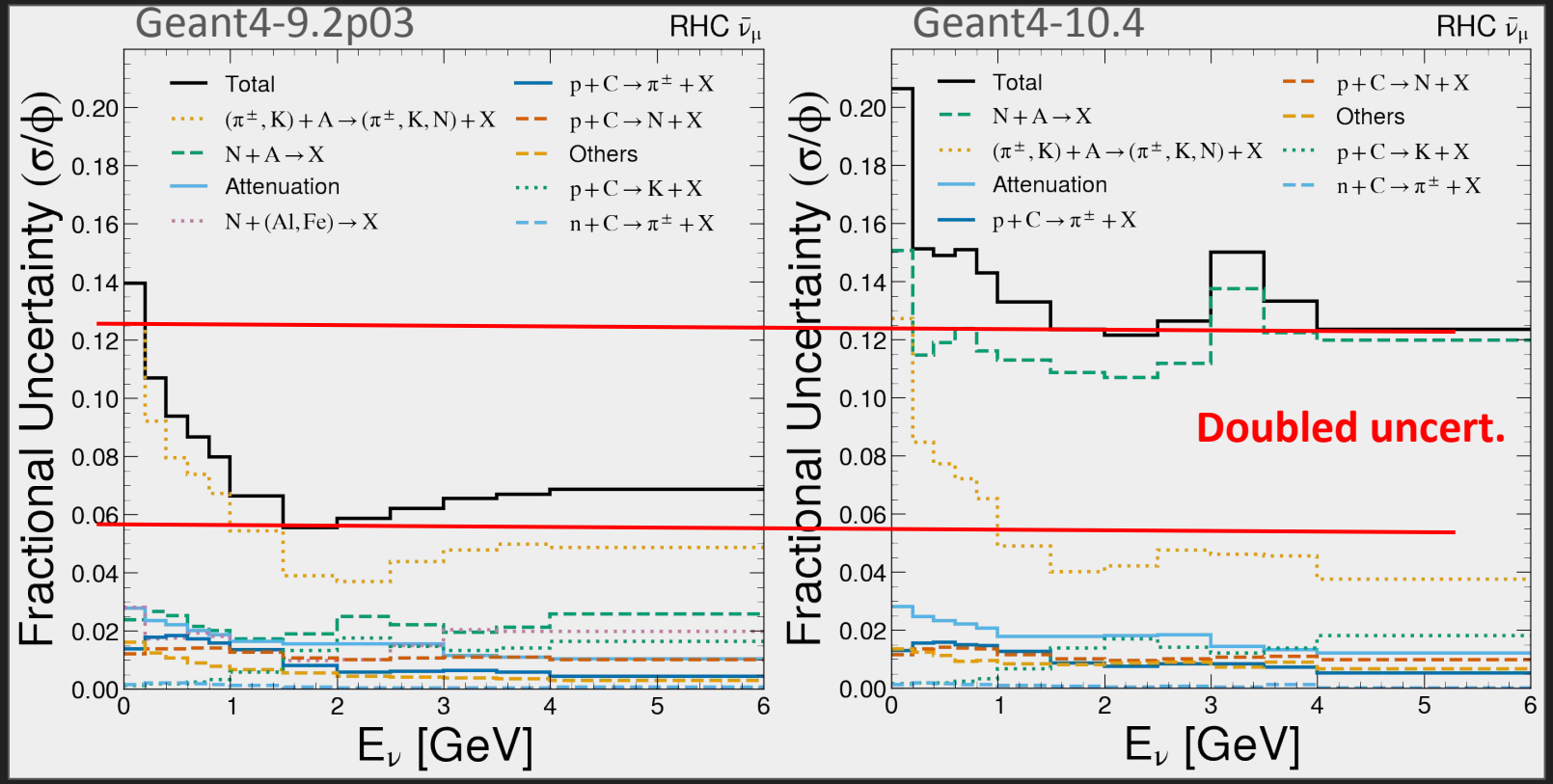
Nuclear model changes affect K^+/K^- production asymmetrically

PPFX Corrections Before and After GEANT4 Changes - FHC

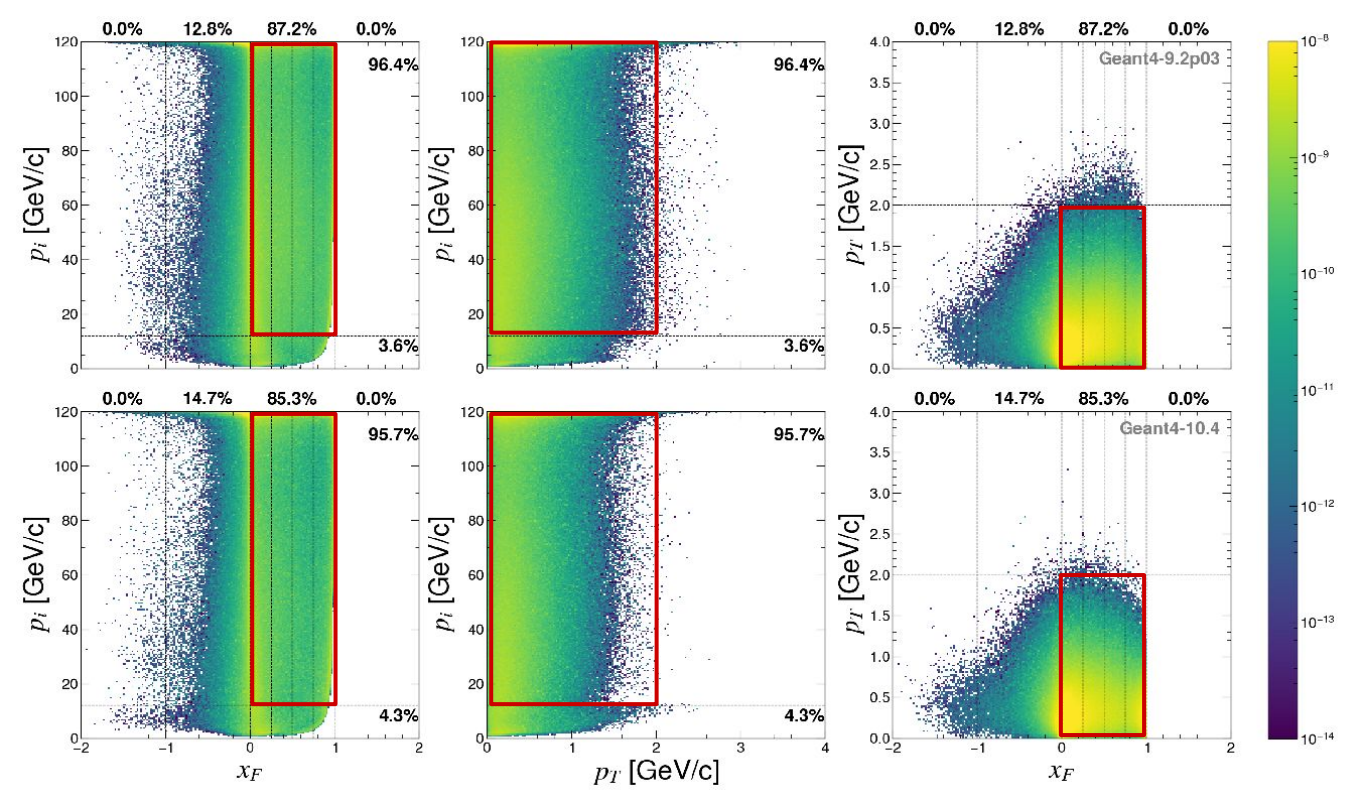


- PPFX Still prefers to weight the flux down form the nominal prediction
- Post correction fluxes should be very close in data regions
- Tune has impact on non-data regions
- New model tuned to similar/same data so new correction is reduced

First Pass HP Uncertainties After PPFX Bug Fix:

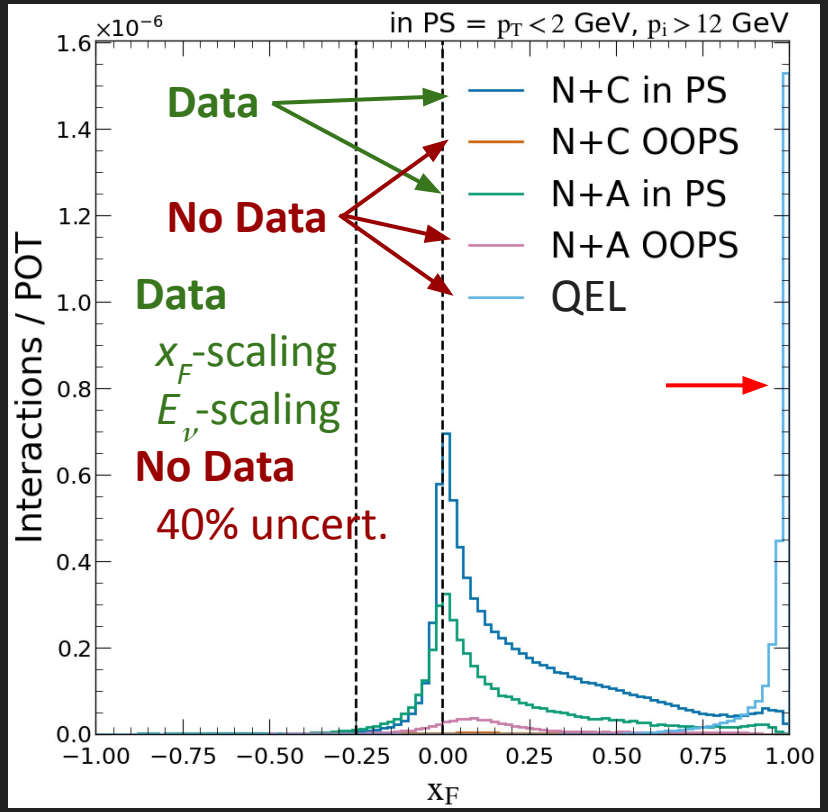


PPFX Phase Space Coverage



- Data from NA49
- p+C interactions
- x_F-scaling in energy
- *A*-scaling for p+A (A≠C)
- No data for $p_i < 12$ GeV, $p_T > 2$ GeV, $x_F < 0$ (any A)

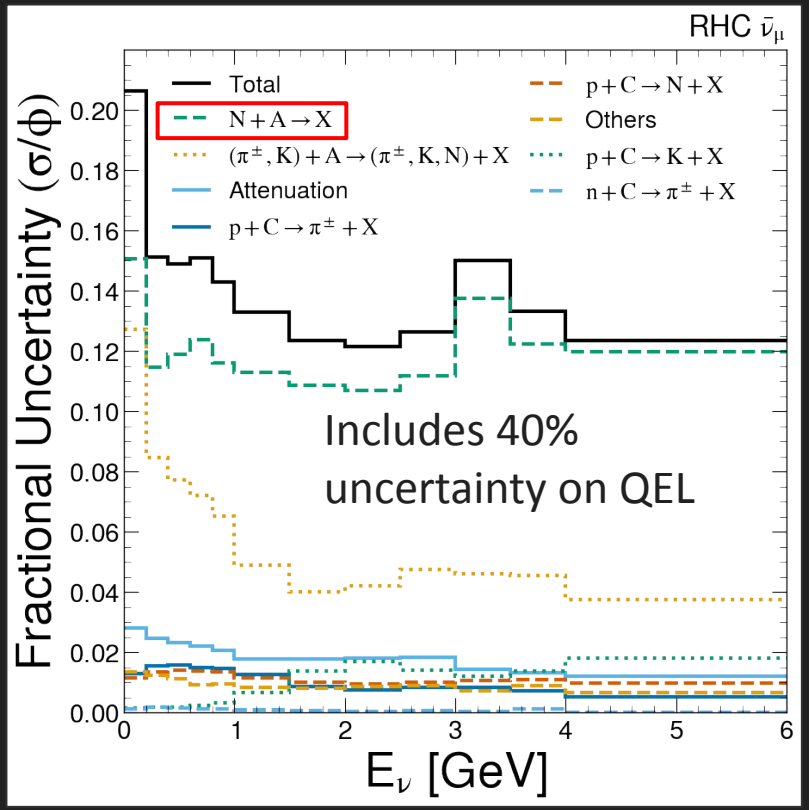
Merging the bugfix re-introduced nucleon (quasi-)elastic scatters

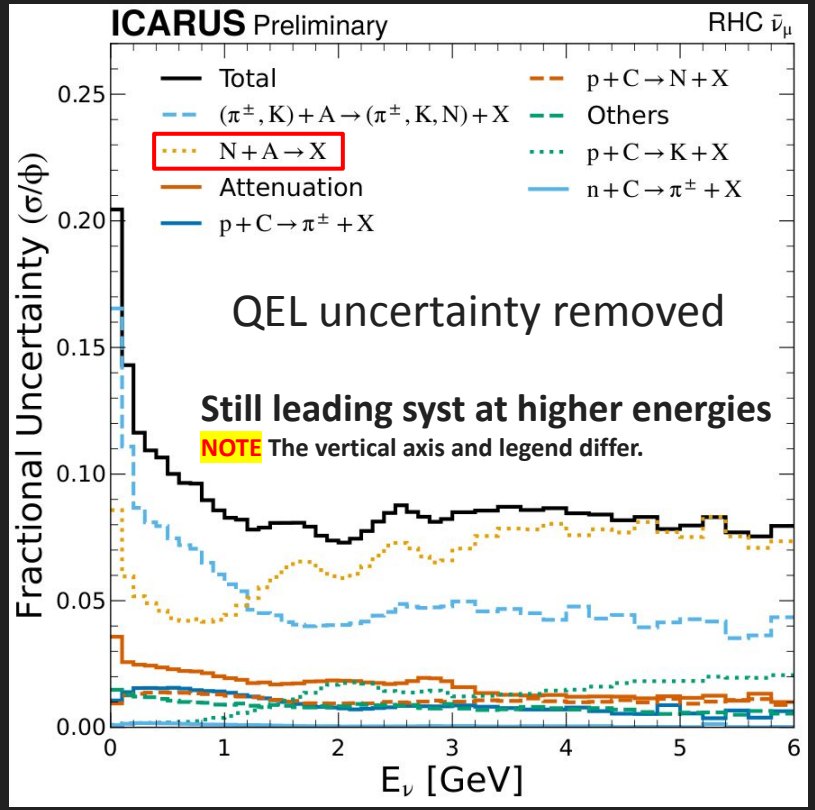


"In PS" → PPFX weights to data
"A" → Non-C / outside of target region

- Forward-going nucleons not covered by exp. HP data
- ~45% of all nucleon interactions
  - 36% in previous Geant version
- Each instance receives the 40% uncertainty on xsec
- Elected to exclude these
  - Negligible impact on primary hadron production
  - See Tech Note (Sec 2.4.2)

HP Uncertainties Neglecting Elastics

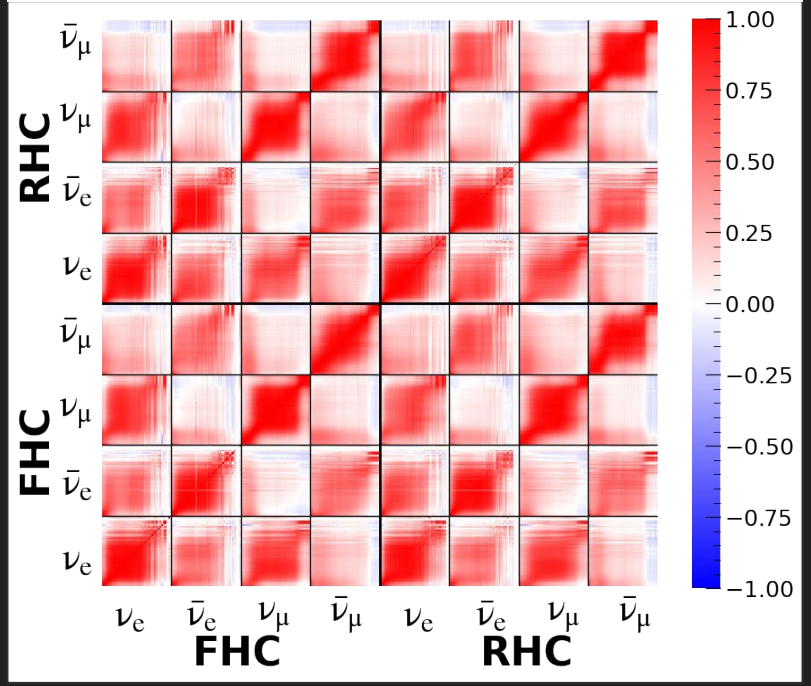




HP Correlation Matrix and Integrated Uncertainties

Updated

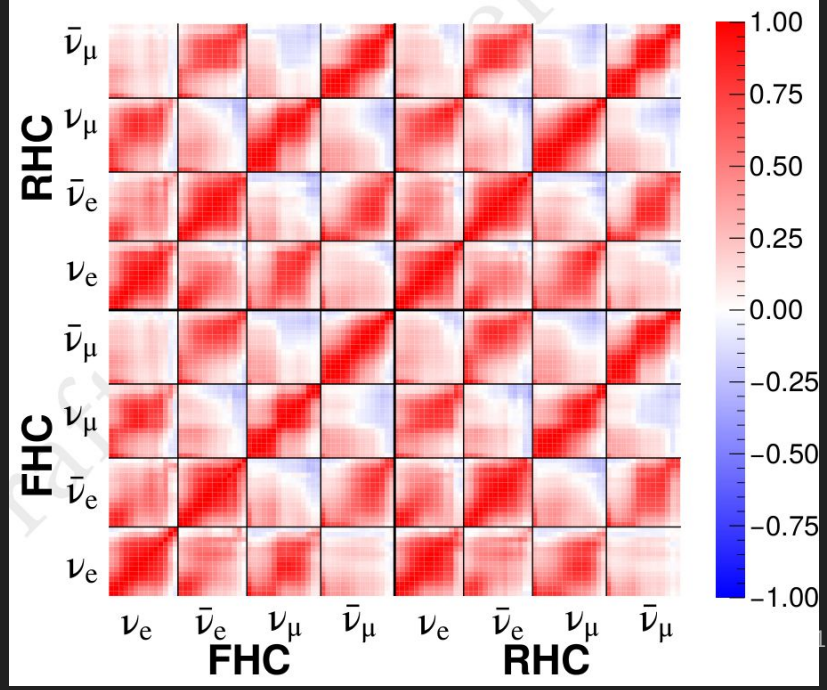
		ν_e	$\bar{\nu}_e$	$\nu_e + \bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	$\nu_\mu + \bar{\nu}_\mu$	$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$
Hadron	FHC	8.61	11.25	8.90	11.00	13.73	10.74	7.72
	RHC	10.46	9.26	9.36	12.71	11.86	11.06	7.94



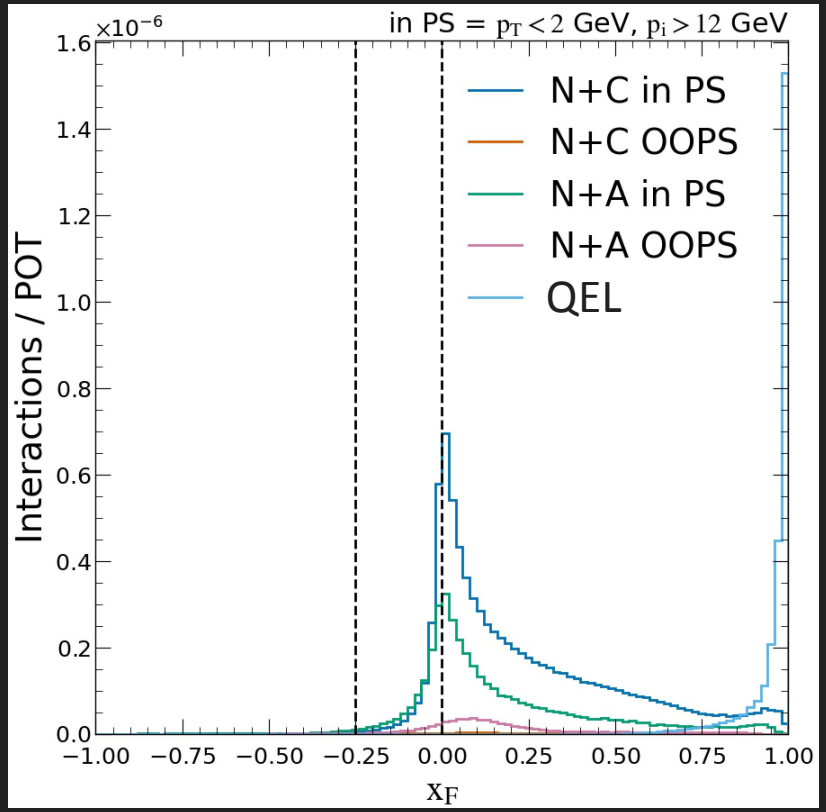
Tech Note

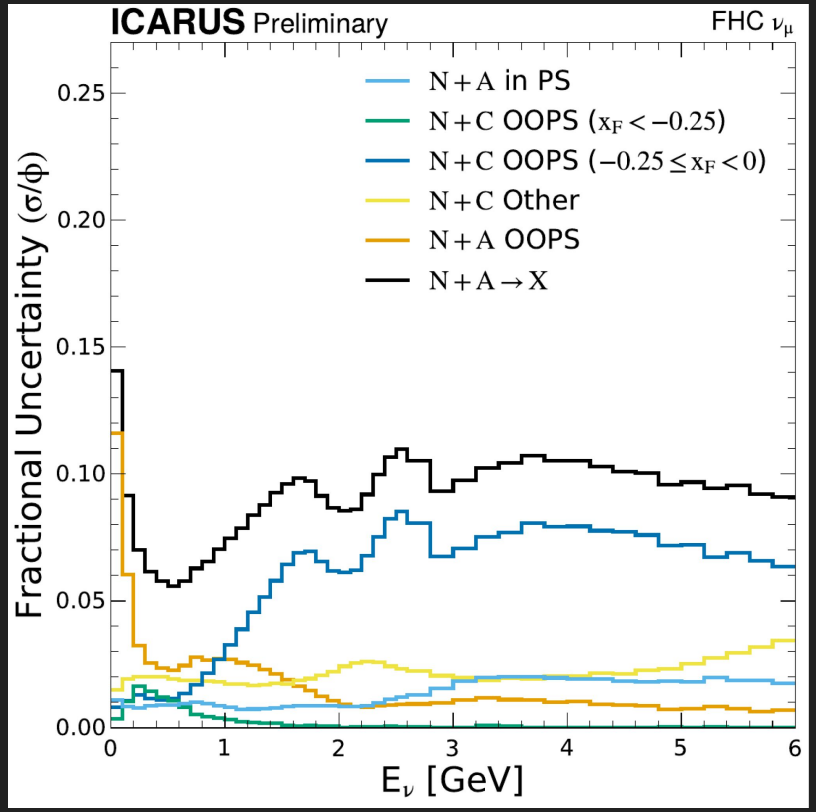
Hadron

FHC	6.63	5.84	5.76	11.32	10.19	9.08	6.83
RHC	5.86	6.76	5.77	10.74	11.27	9.45	6.92

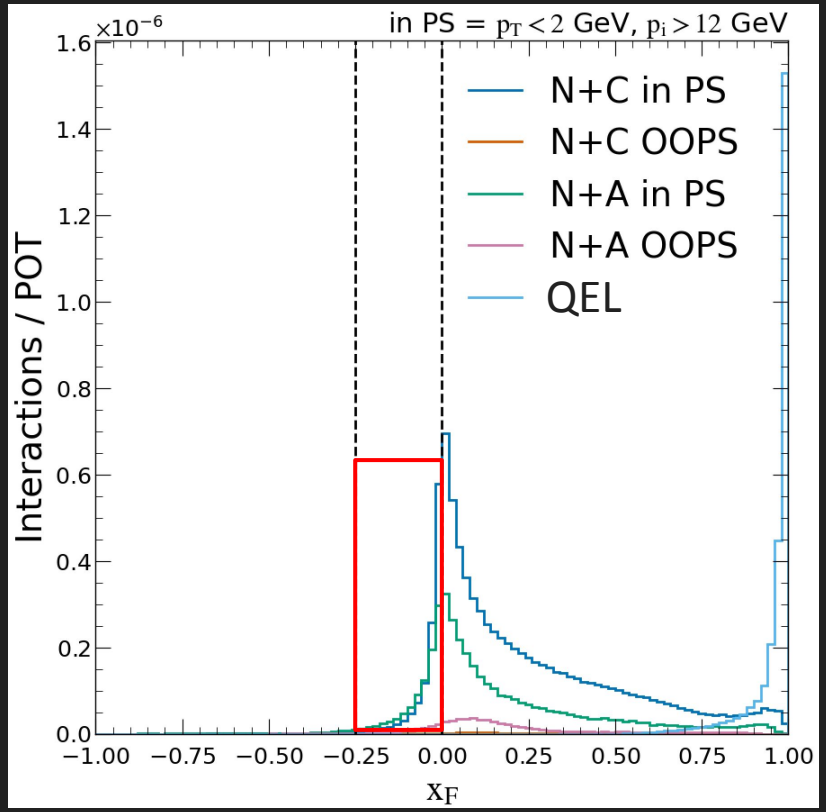


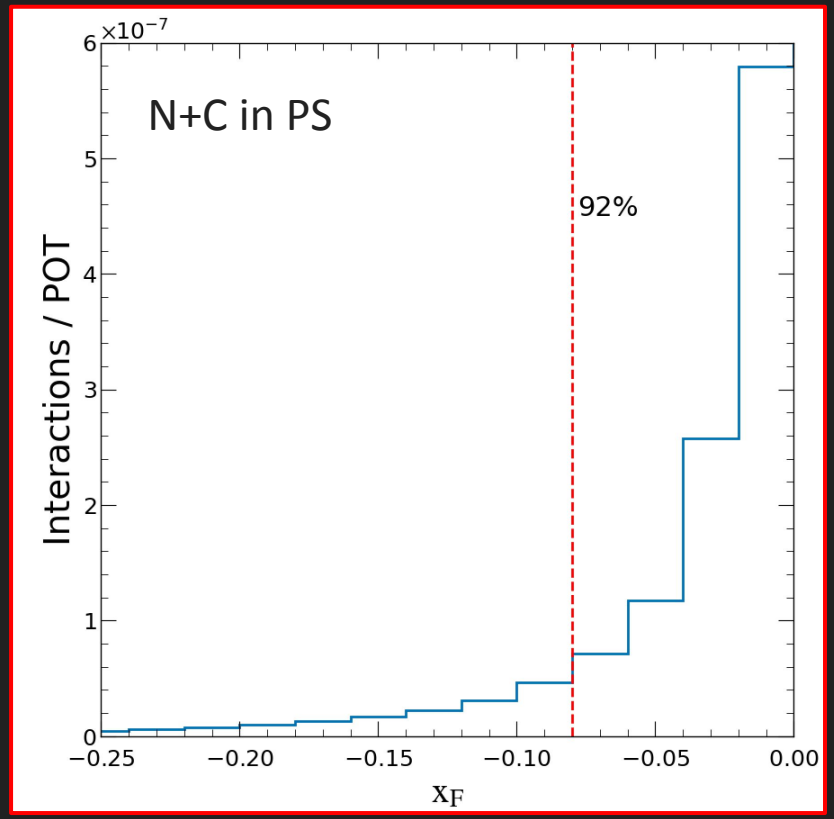
N+A systematic has large contribution from interactions with xF < 0



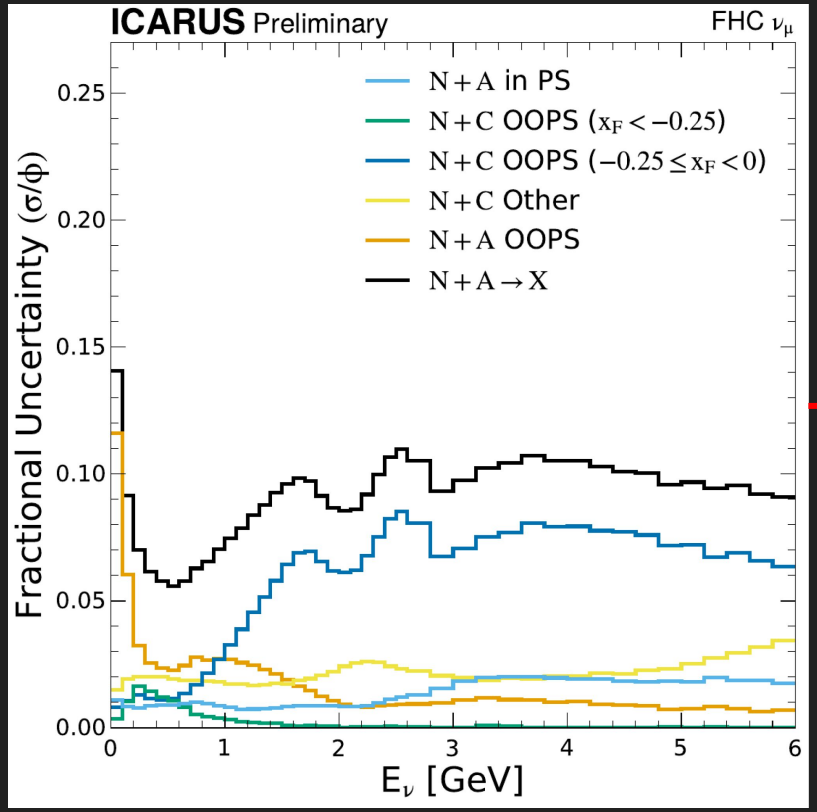


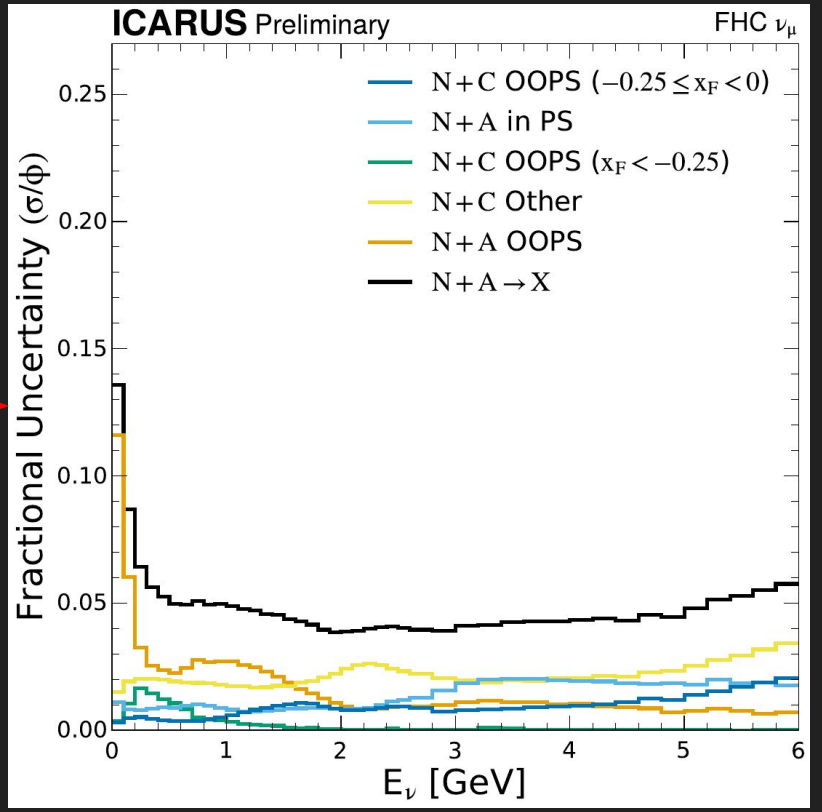
N+A systematic is driven by interactions with xF < 0



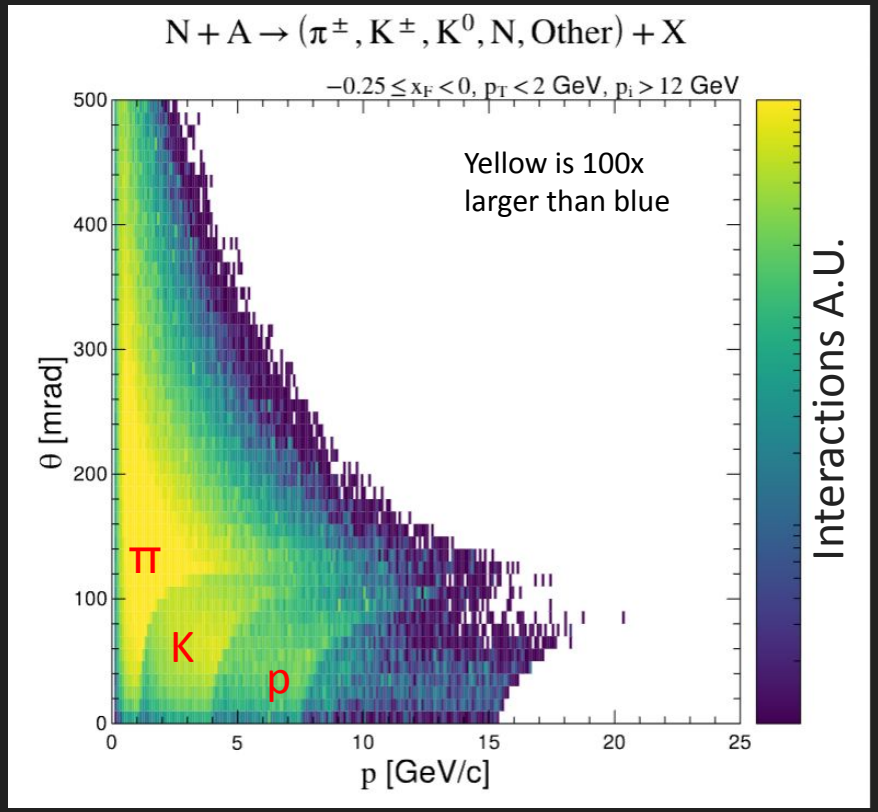


Effect of “mirroring” xF





Looking for More HP Data



After a quick chat with Leo and Vittorio

- Identified some overlap of this PS with the 2023 NA61 data release (120 GeV)
- Implementing it in PPFX would require:
  - Generate model predictions for xsecs in terms of p-theta
  - Only applicable to protons at/near 120 GeV
- Short-term approach → override the 40% conservative uncert estimate with a number based on the NA61 data/MC differences and data uncertainties

Conclusion

- We can re-sim the flux with high stats relatively quickly.
  - 2B POT FHC+RHC = 8k jobs at ~3.5 hours average per job.
  - Issues related to disk space persist, but we can work around this using tape storage.
- Slightly-out-of-phase nucleon interactions ($-X_F$) now have the largest contribution to the HP uncertainty at higher energies (e.g. above 1 GeV for FHC ν_μ).
- New NA61 data potentially covers these interactions.
  - Working on a plan to implement that data and improve N+A treatment in the interim.
- Authoring an addendum to the Flux TN, which describes the impacts of the geometry and model changes. First draft completed.
- Fatima and Karim are working on updated beam focusing systematics using new, high stats flux simulation. Timeline for completion is order weeks.

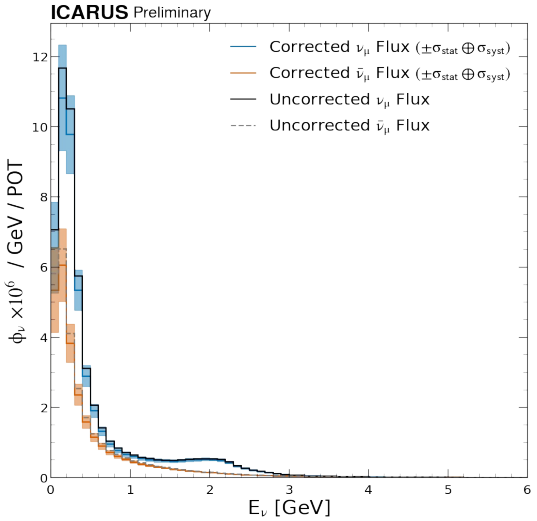
Backup

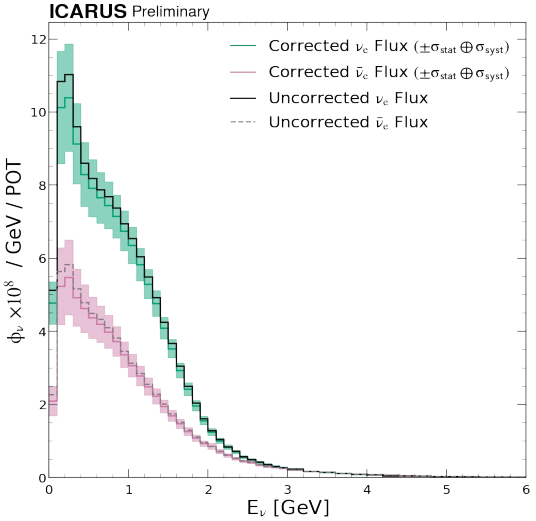
Changes to the hadron interaction model

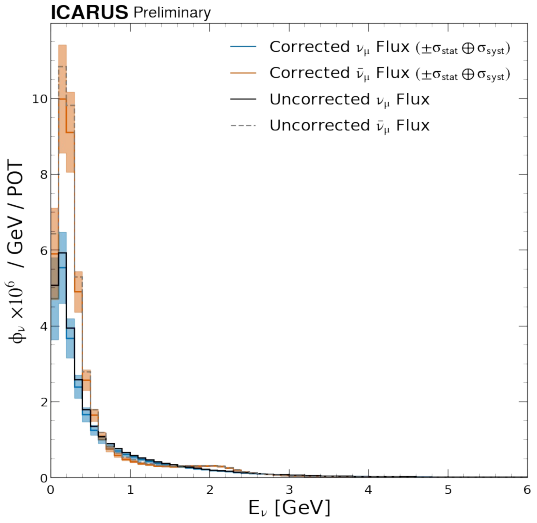
- G4NuMI updated to a more recent Geant4 version
  - Incorporates available HP data as constraints on the fit of the FTF nuclear model
  - Not the same as reweighting performed by PPFX→improved model-data agreement
  - **Allows for changes on the model outside of regions where there's data coverage**
  - See talk by I. Safa (MicroBooNE)
- NuMI MC produced with this version are incompatible with current PPFX version
- There is an ongoing effort, particularly by N. Nayak (MicroBooNE), to reconcile these changes with PPFX. (Meeting ***tomorrow***!)
- Once that integration is complete, can push toward a reevaluation of the HP systematics with the updated HP model.

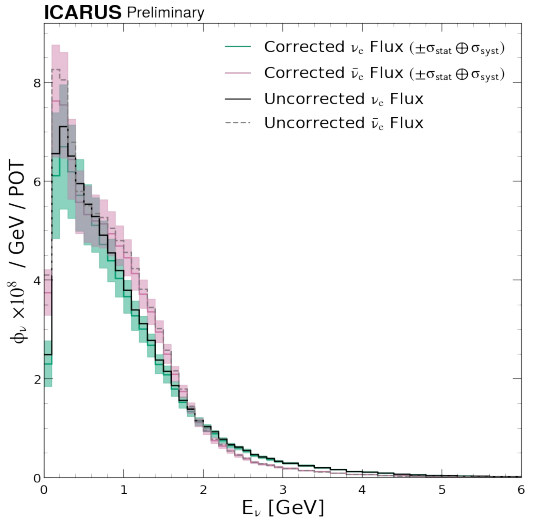
Flux Prediction

HP syst only





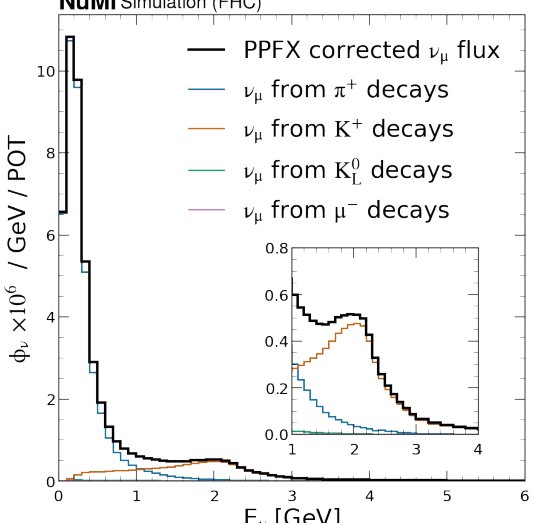


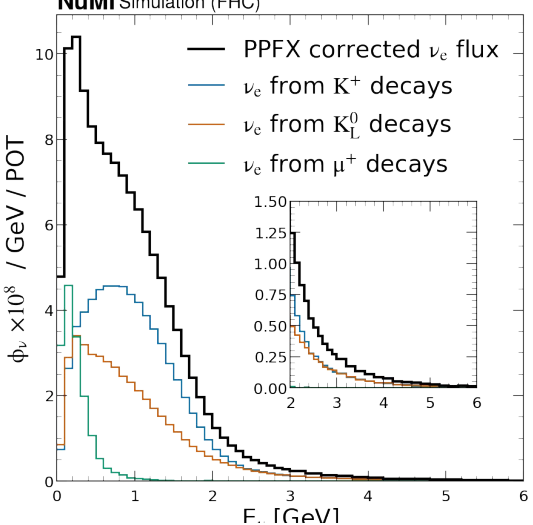


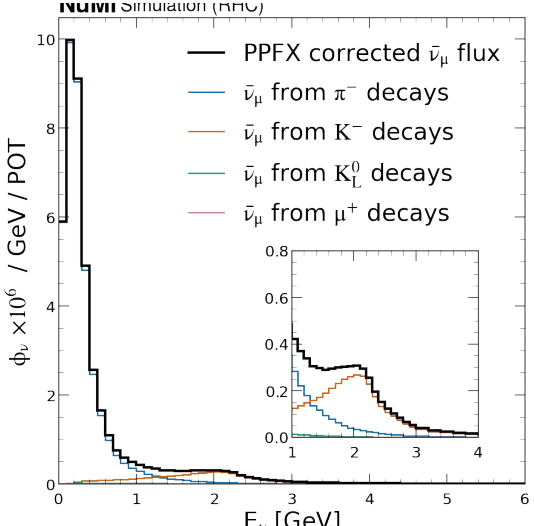
Flux Prediction

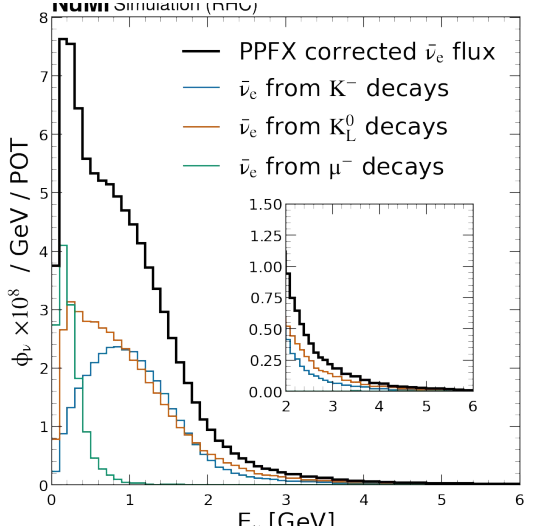
Parent Hadrons

Right-sign





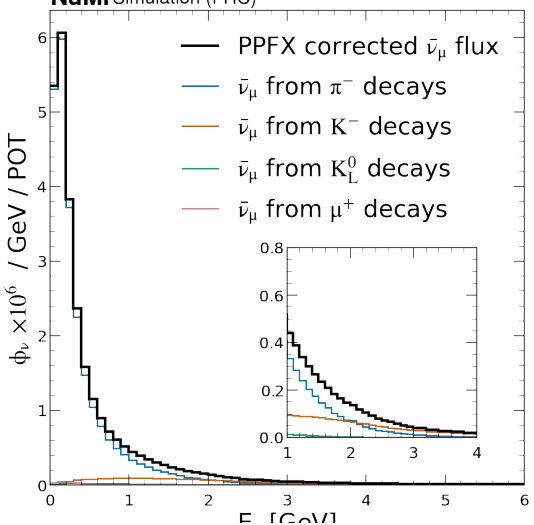


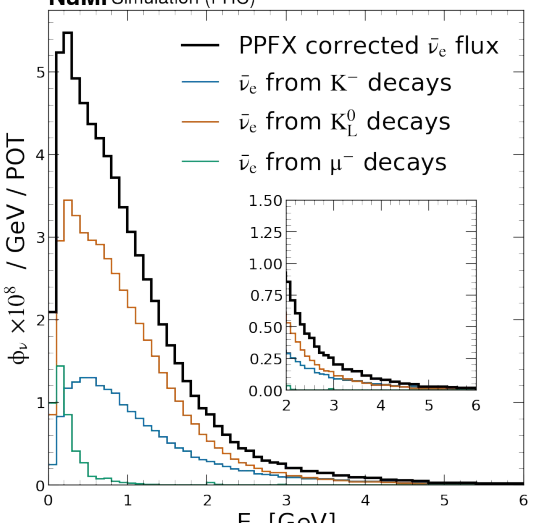


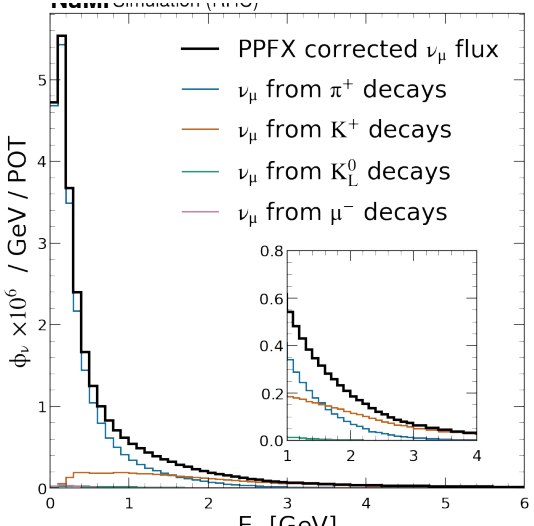
Flux Prediction

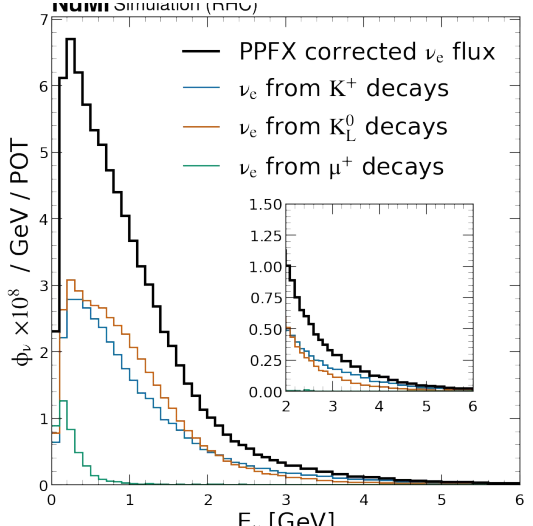
Parent Hadrons

Wrong-sign





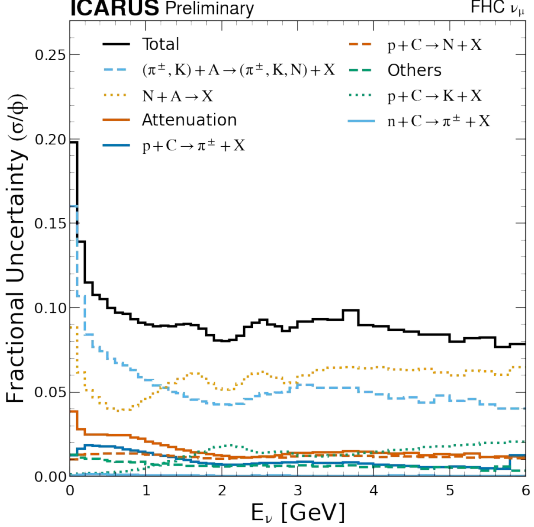


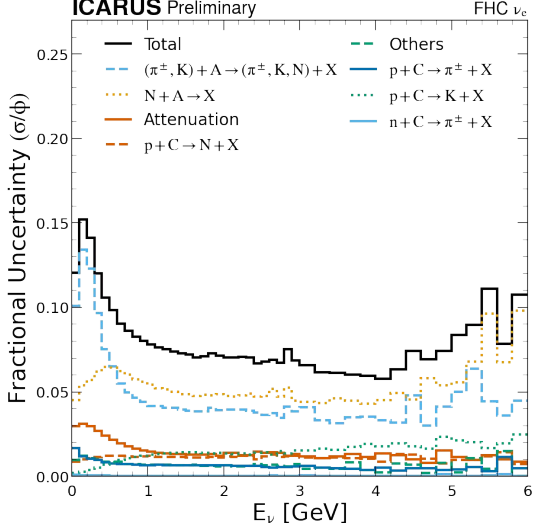


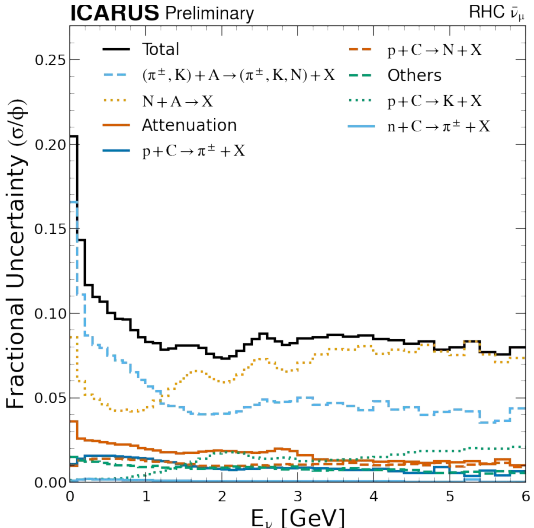
Flux Prediction

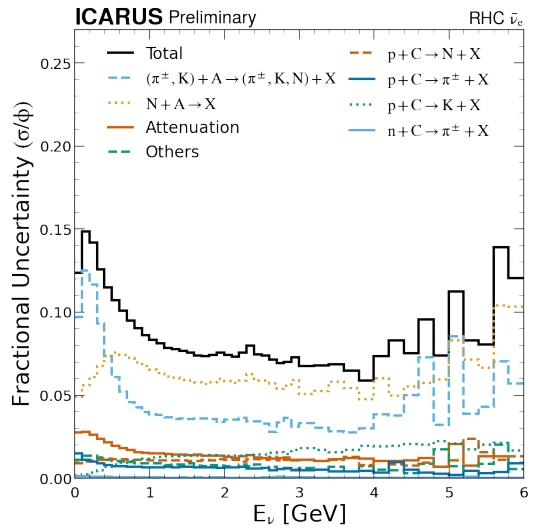
HP Uncertainties

Right-sign





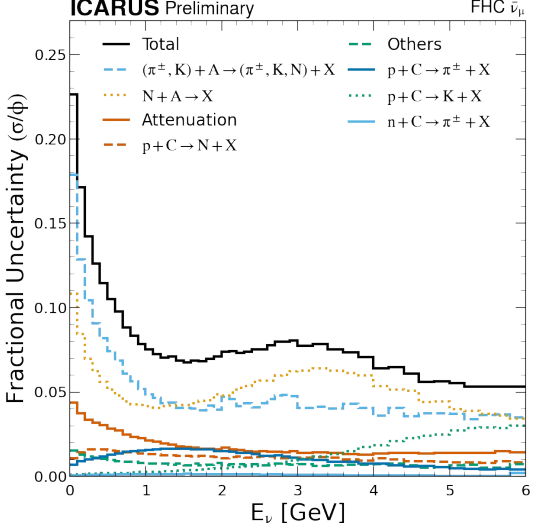


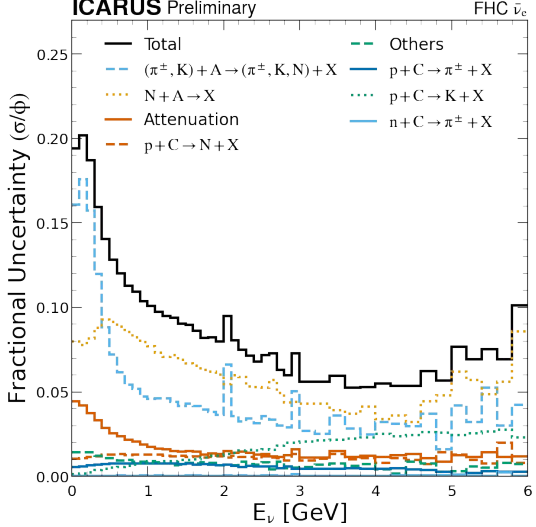


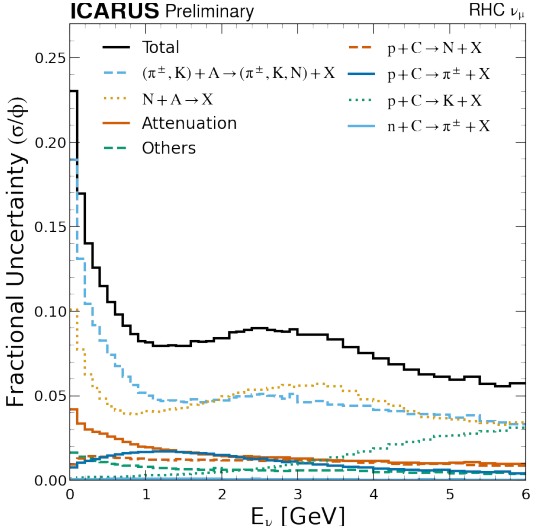
Flux Prediction

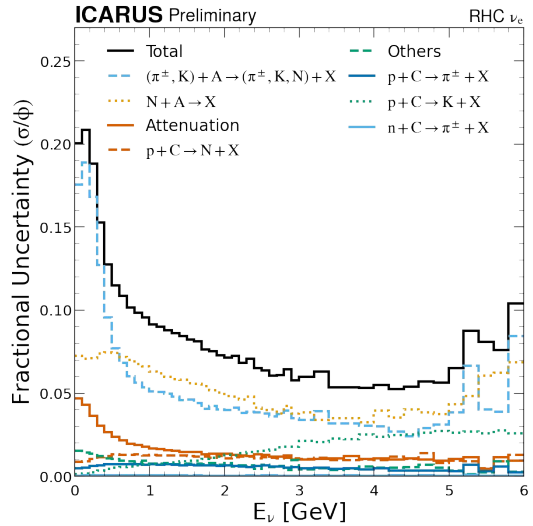
HP Uncertainties

Wrong-sign







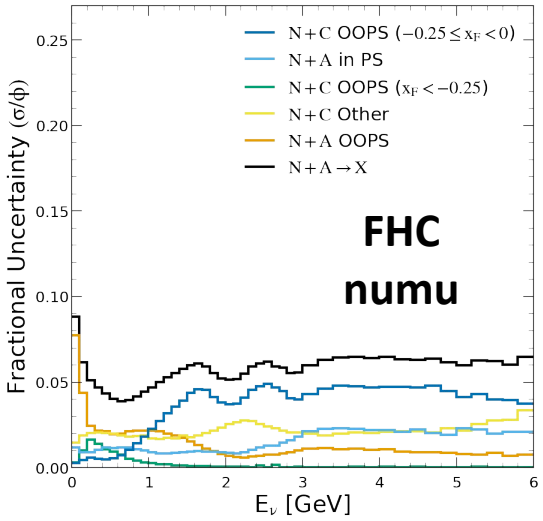


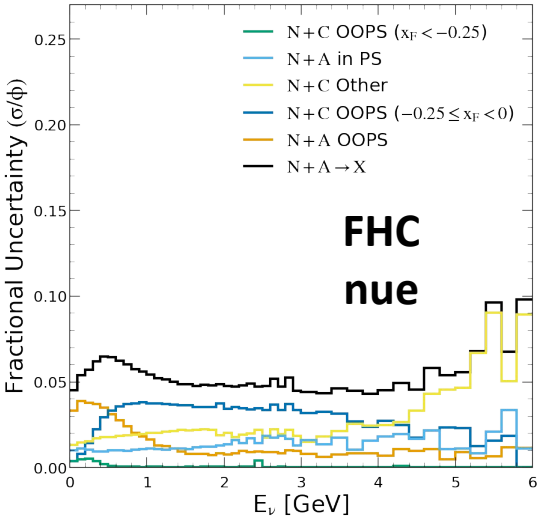
Flux Prediction

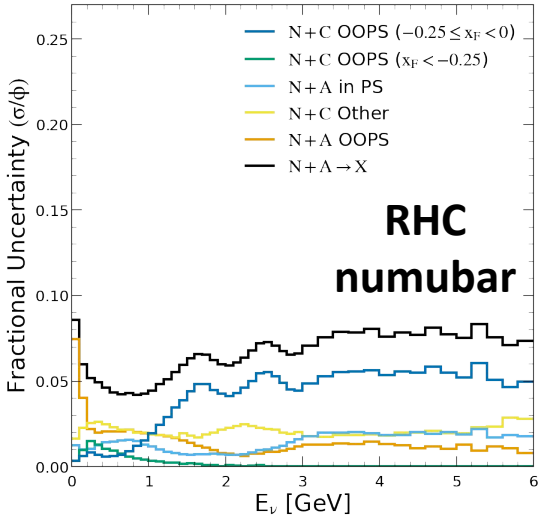
HP Uncertainties

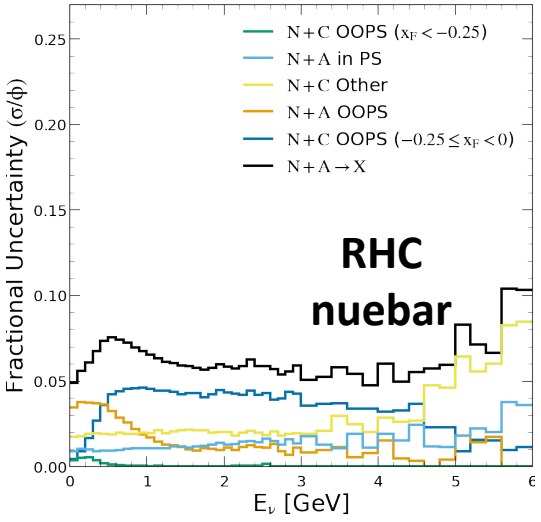
N+A Breakout

Right-sign







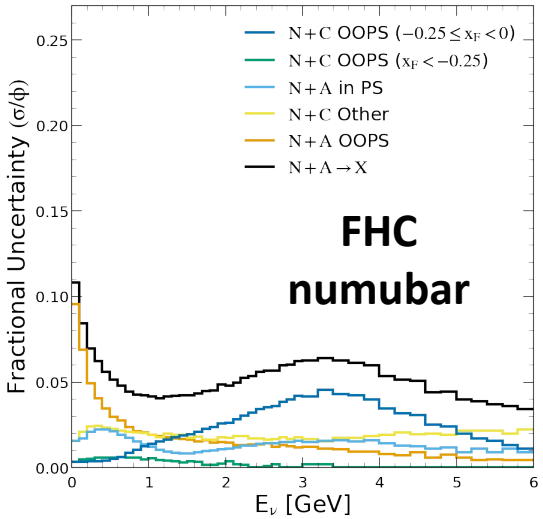


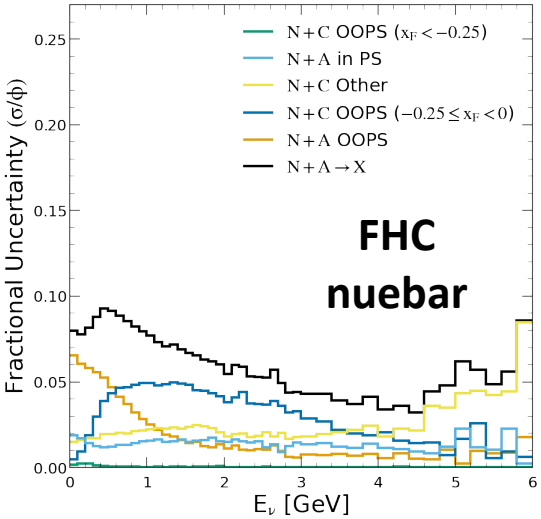
Flux Prediction

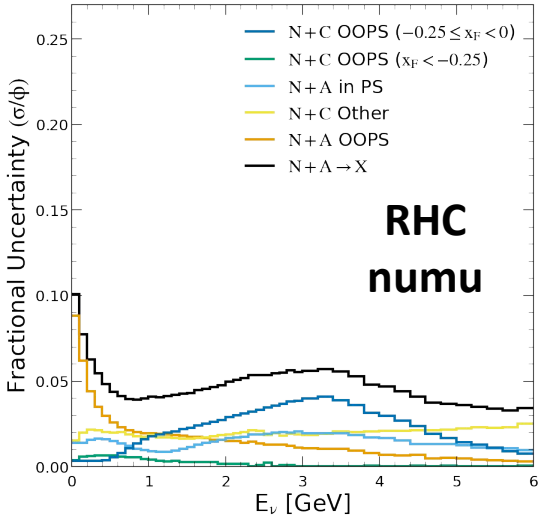
HP Uncertainties

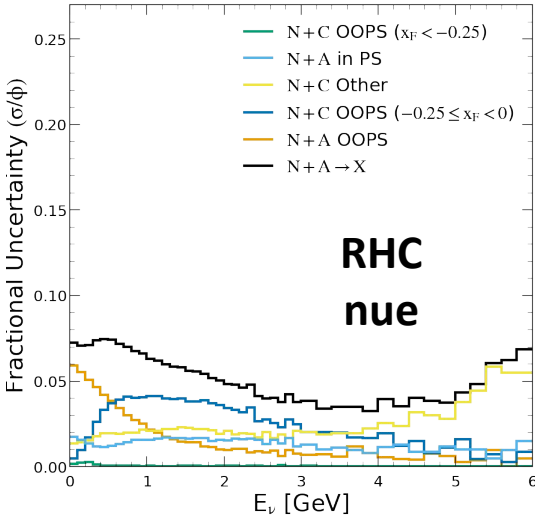
N+A Breakout

Wrong-sign



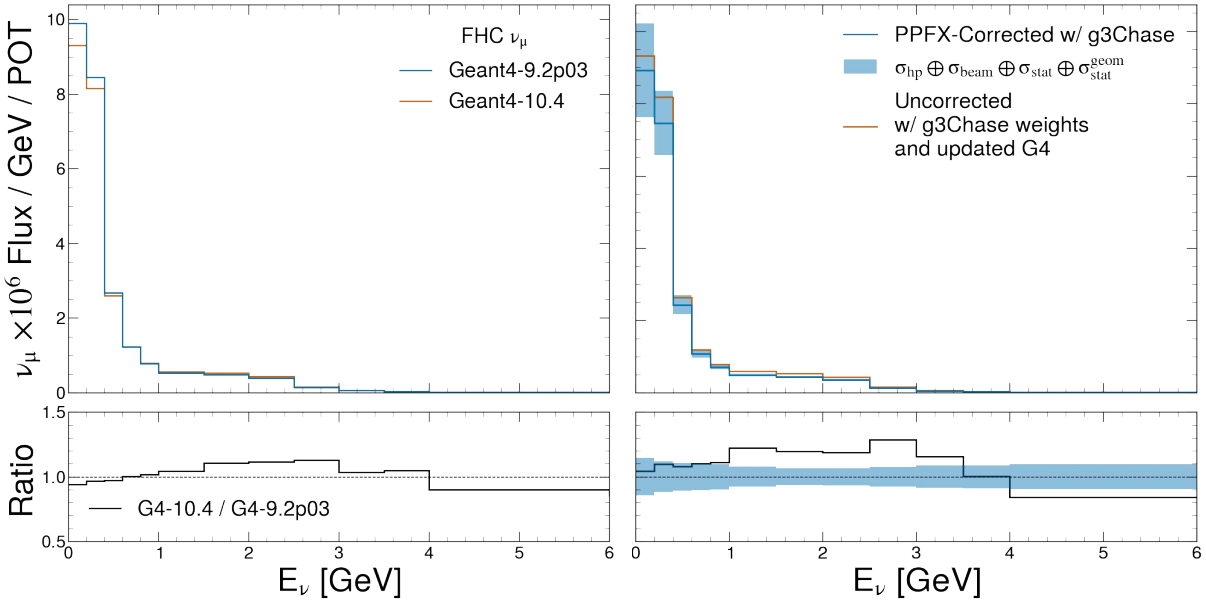






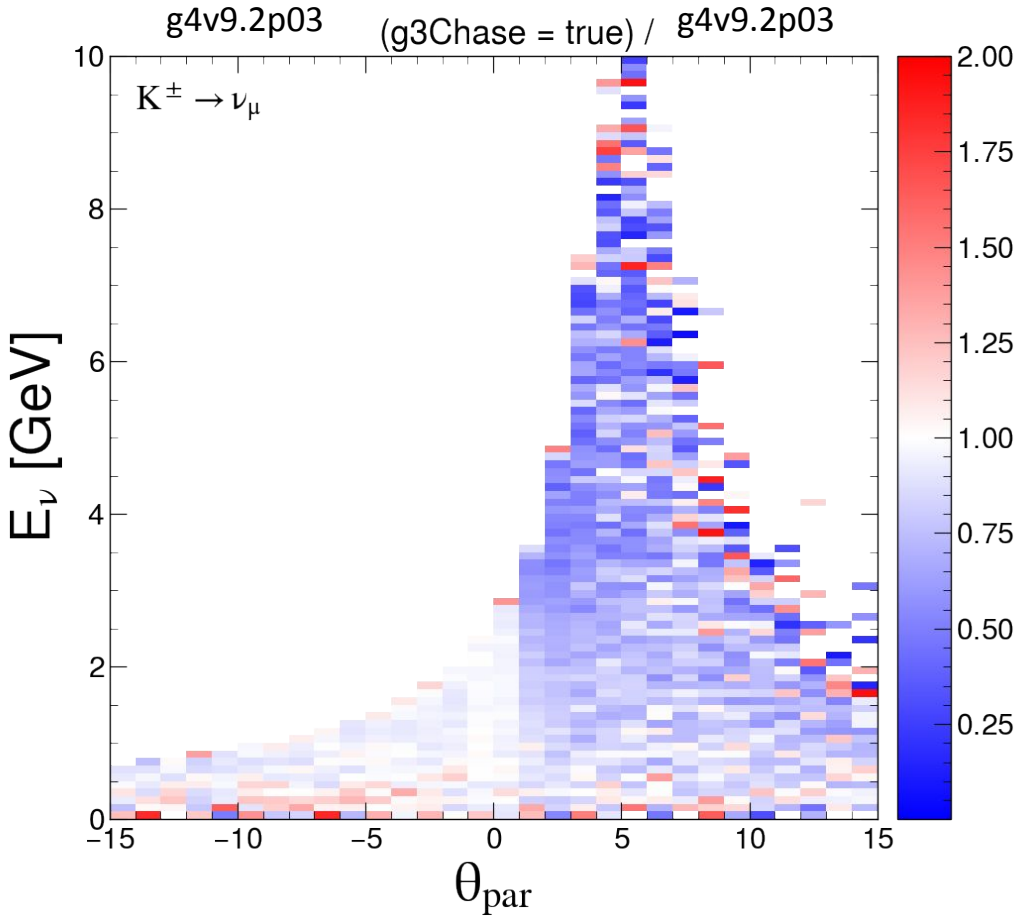
Comparison of flux with and without G4 update

- PPFX pulls kaon peak downward, but the G4 update increases the p+C⟶K+A rate
- Actively studying the source of discrepancy
- i.e., overlap between datasets included in PPFX vs. G4 update



Nu Energy vs. Parent Angle Ratios

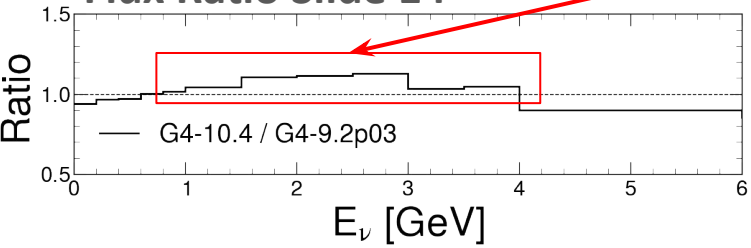
- Parents directed >1° off-axis is impacted by the extra material
- Large fraction of our flux, esp. HE, come from decays directed toward ICARUS

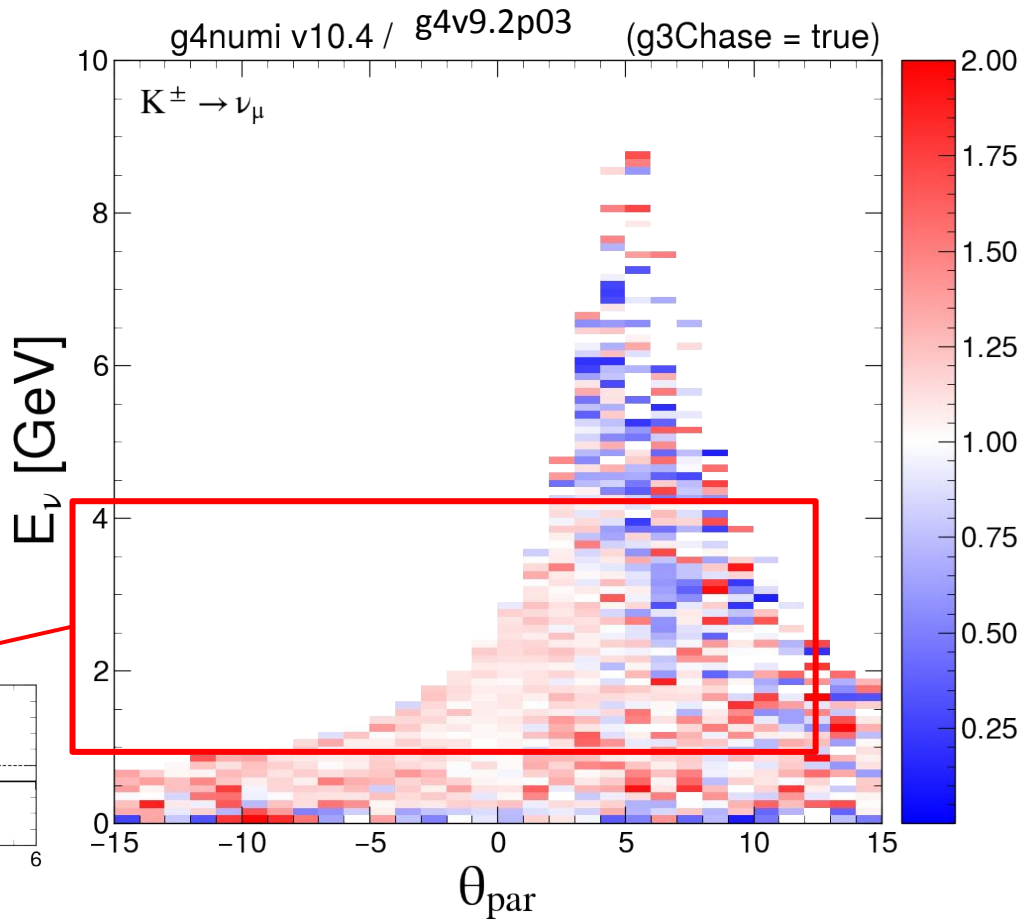


Nu Energy vs. Parent Angle Ratios

- Parents directed >1° off-axis is impacted by the extra material
- Large fraction of our flux, esp. HE, come from decays directed toward ICARUS
- G4 update gives us back more K⟶nu decays broadly across the angular range, esp. up to 3-4 GeV.

Flux Ratio Slide 14

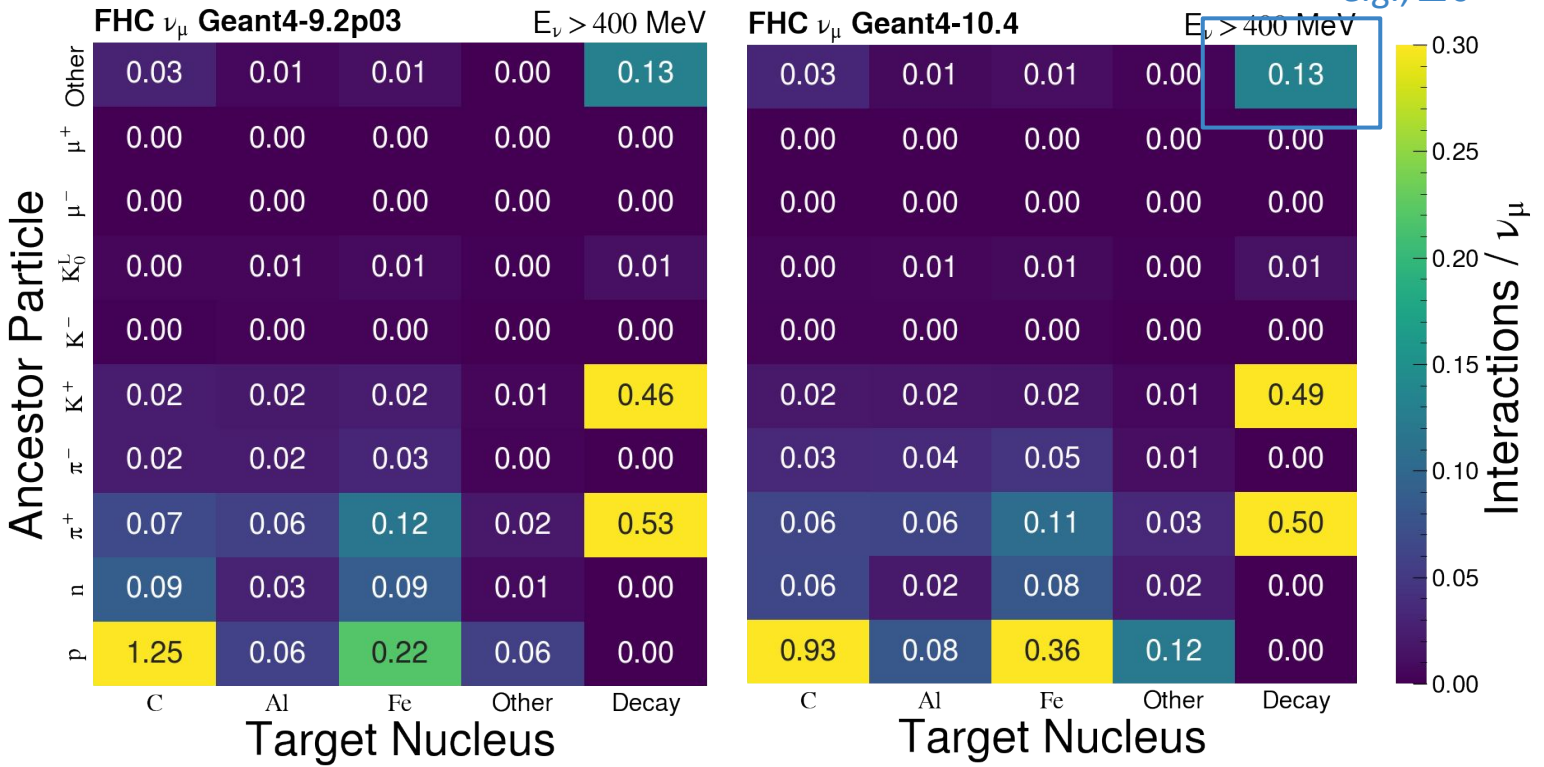




Number of interactions with new hadron interaction model

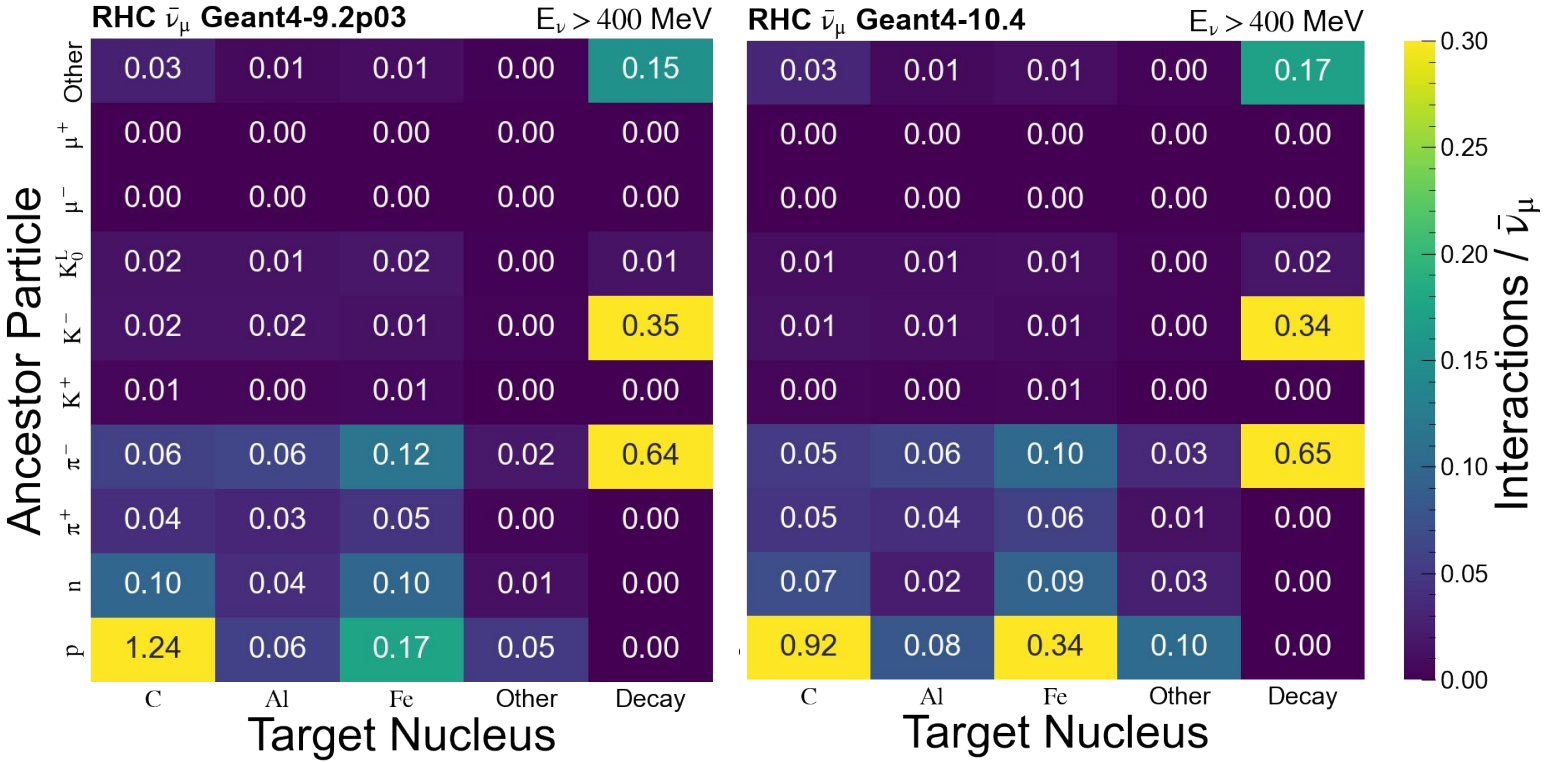
Intermediate decays, e.g., Δ's

Fewer p+C, more p+X



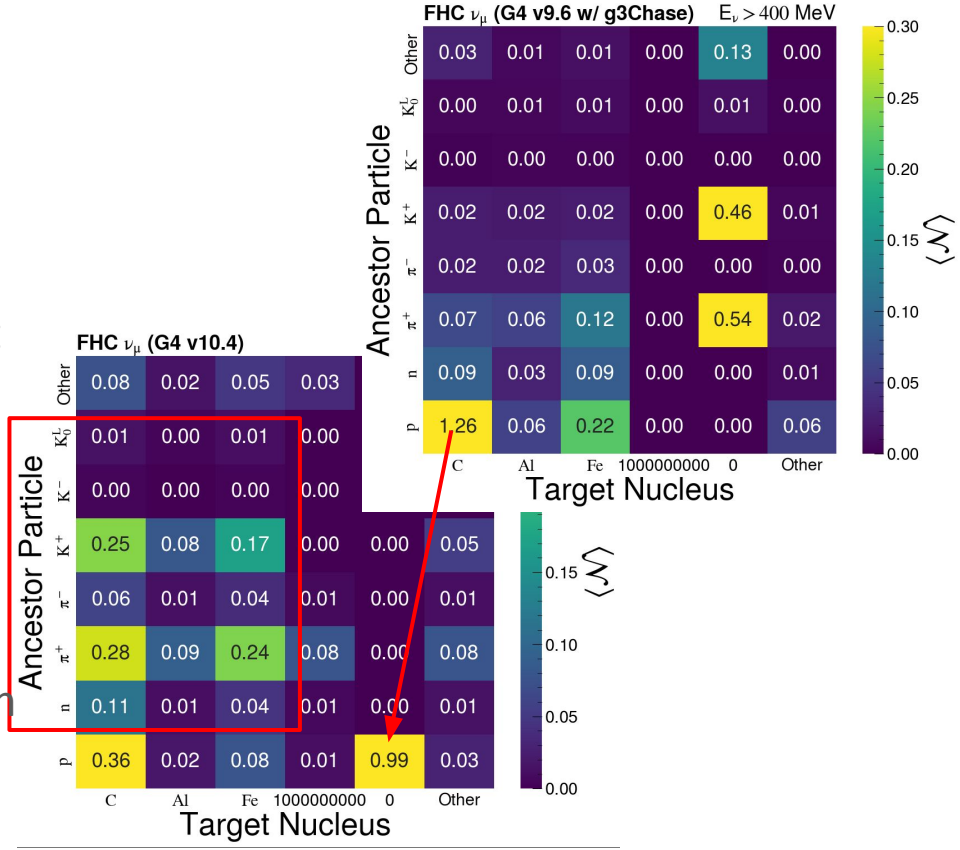
Number of interactions with new hadron interaction model (RHC)

Fewer p+C, more p+X



Apparent convention change (or bug?) in the new G4NuMI version…

- Updating G4 apparently shifted the particle associations
  - **Before**: incident + target
  - **Now**: incident + parent's target
  - And new code to distinguish decays from the initial proton
- Confirmed with R. Hatcher that this was unknown/unexpected
- Possible implications for PPFX, which reads the interaction chain

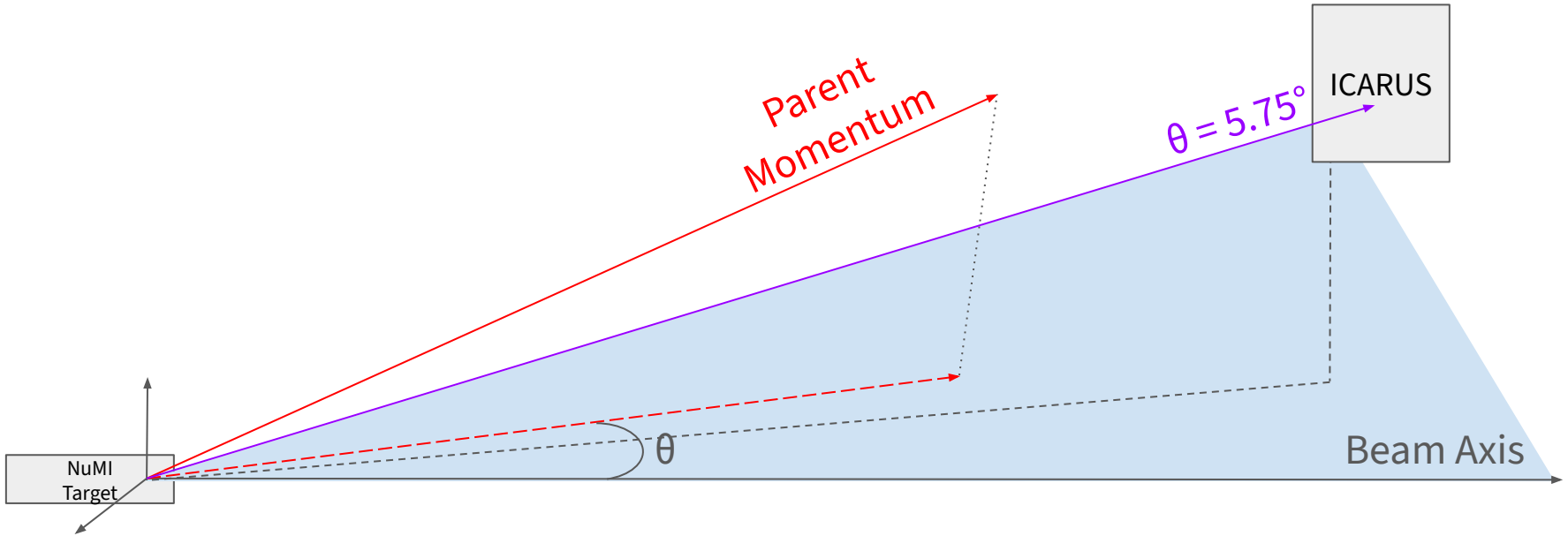


Next steps

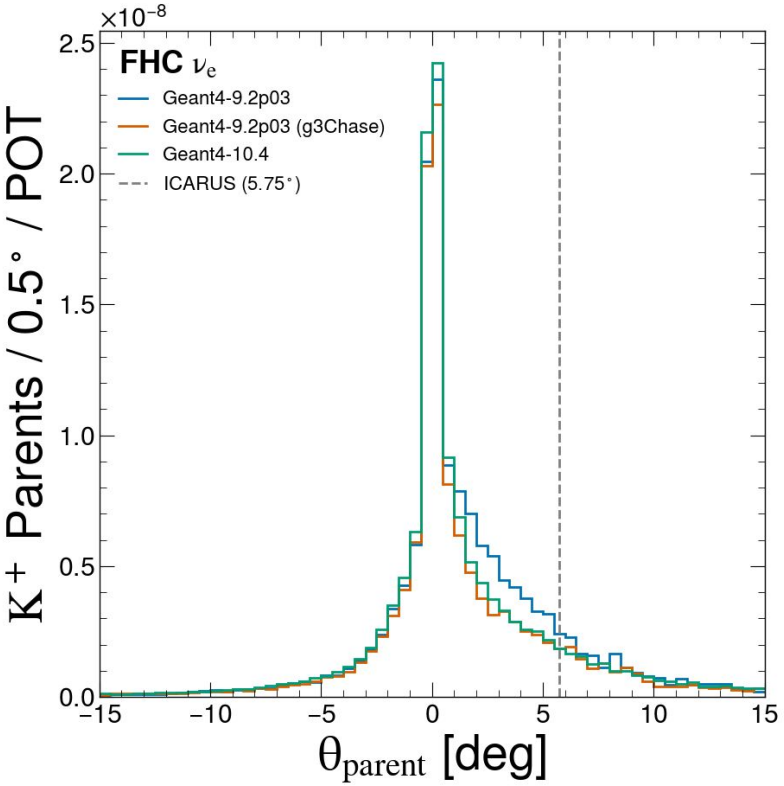
- Unearthed geometry and model changes has prompted an immediate reevaluation of the NuMI flux for ICARUS
- Galvanized interest from multiple experiments to work toward a modernization of the high-stats NuMI flux production
    - Validation of the NuMI geometry and other aspects of the simulation
    - **Reassess the suite of beam focusing systematics**
- Initial PPFX updates integrating new Geant4 version are available, so I will be testing in the very near term
- Addendum and 2nd note in the near future

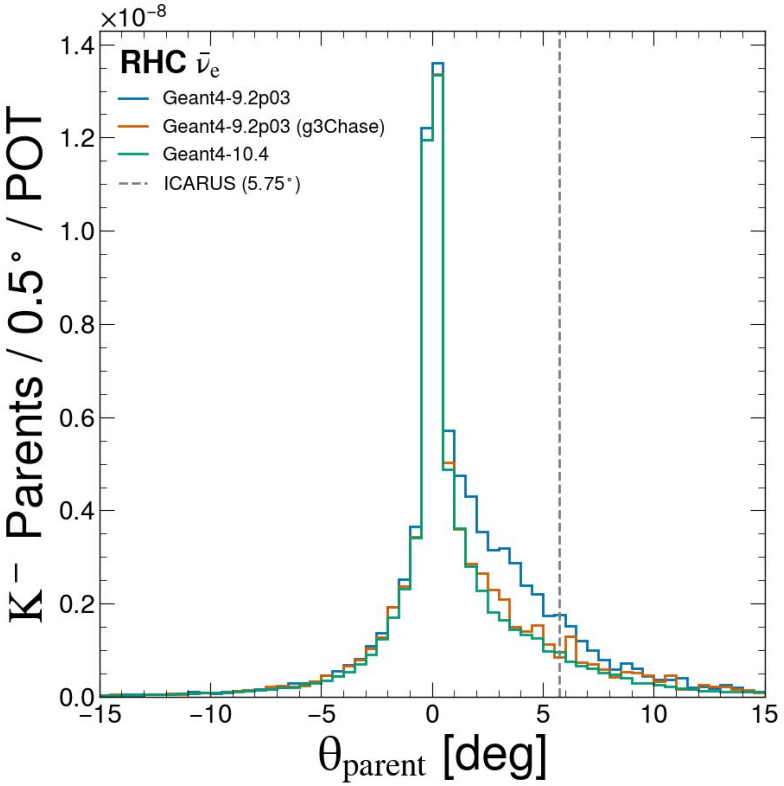
Backup

Angular distribution of parent particle momentum at decay pt

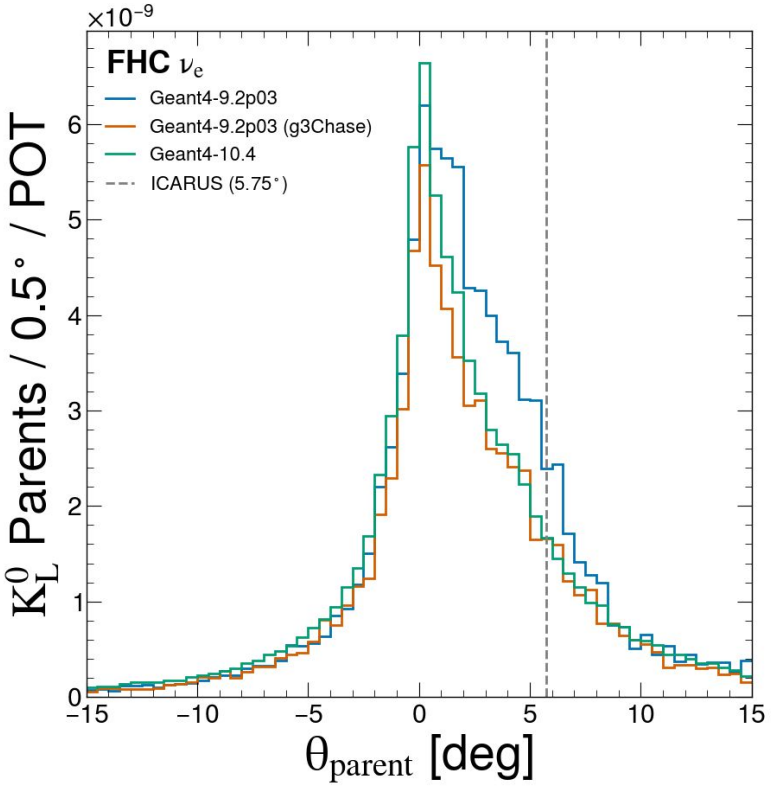


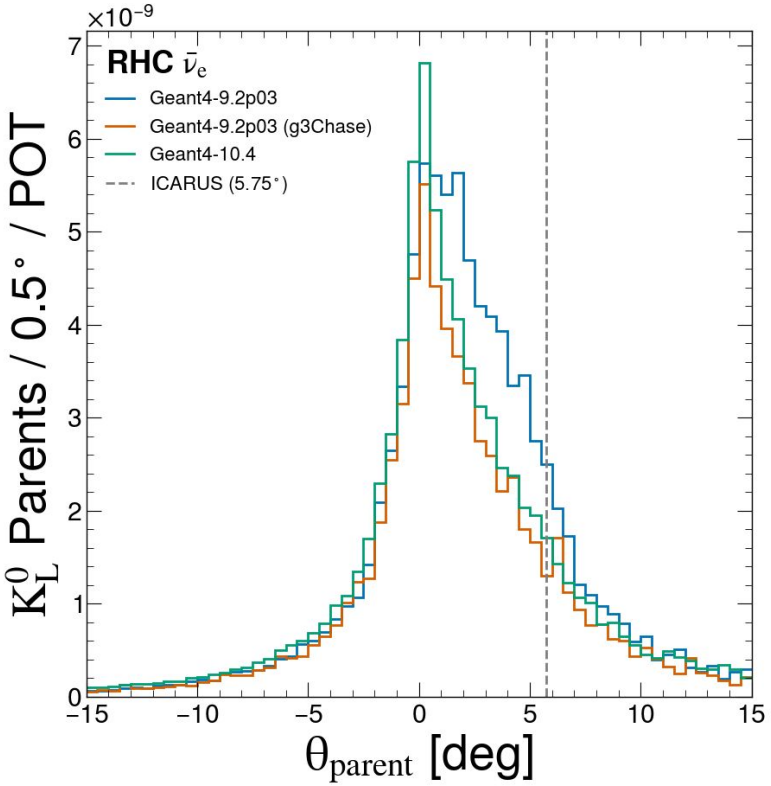
Parent Angle – $K^{\pm} \rightarrow$ electron (anti-)neutrino



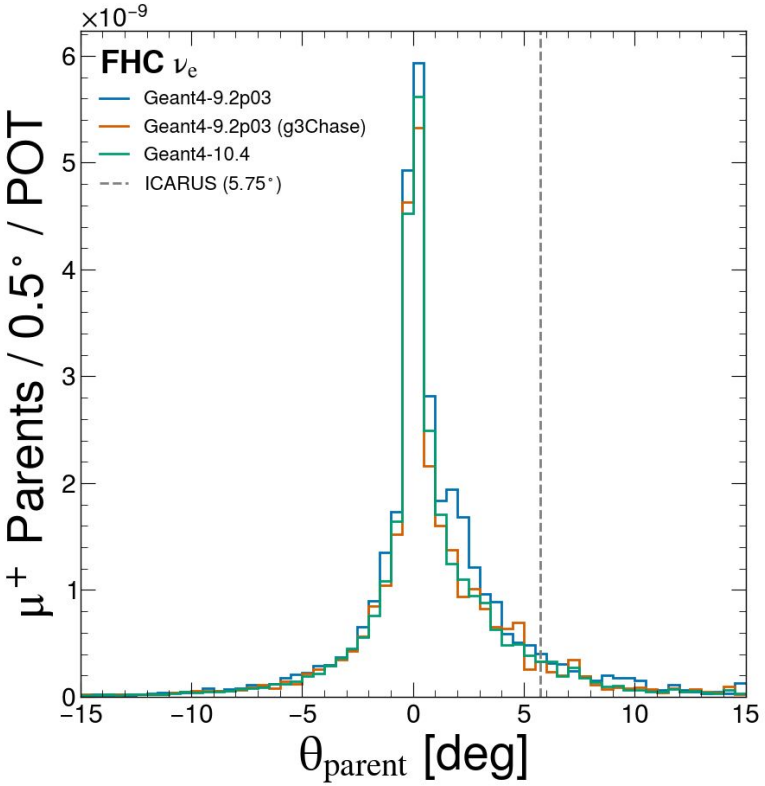


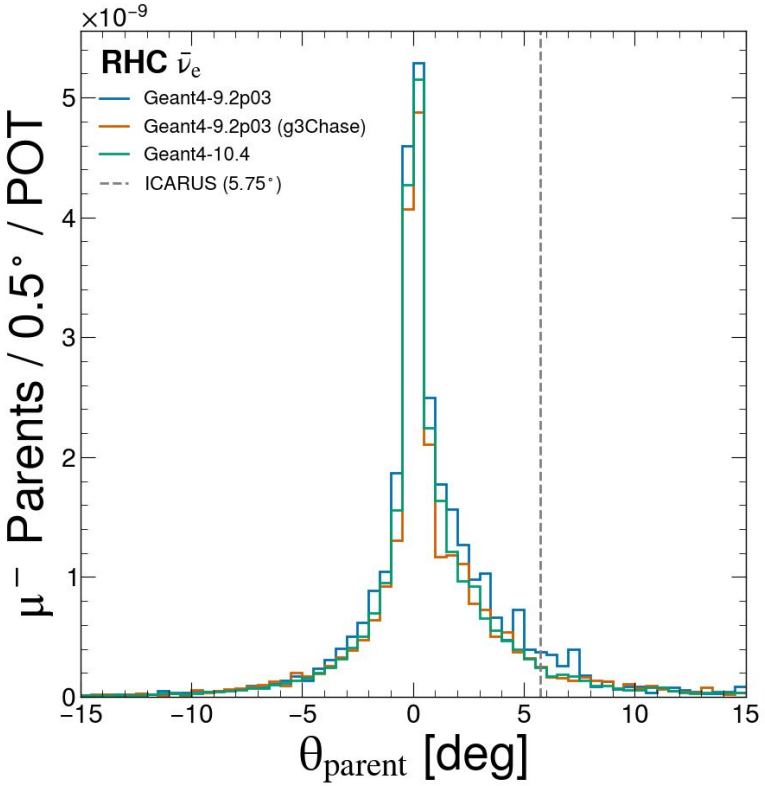
Parent Angle – $K_L^0 \rightarrow$ electron neutrino

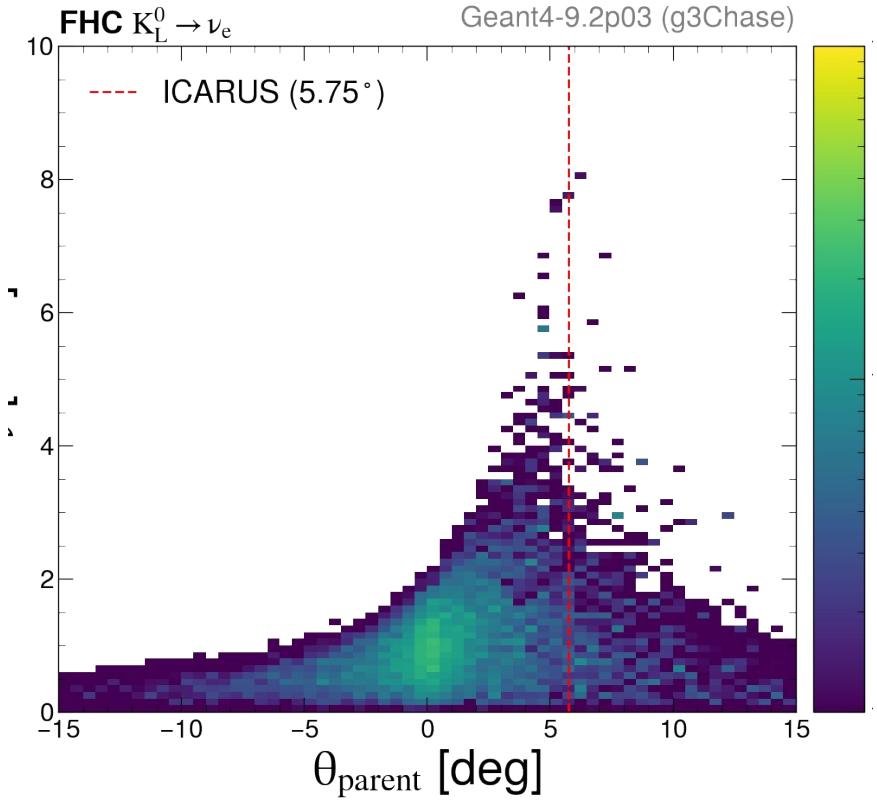


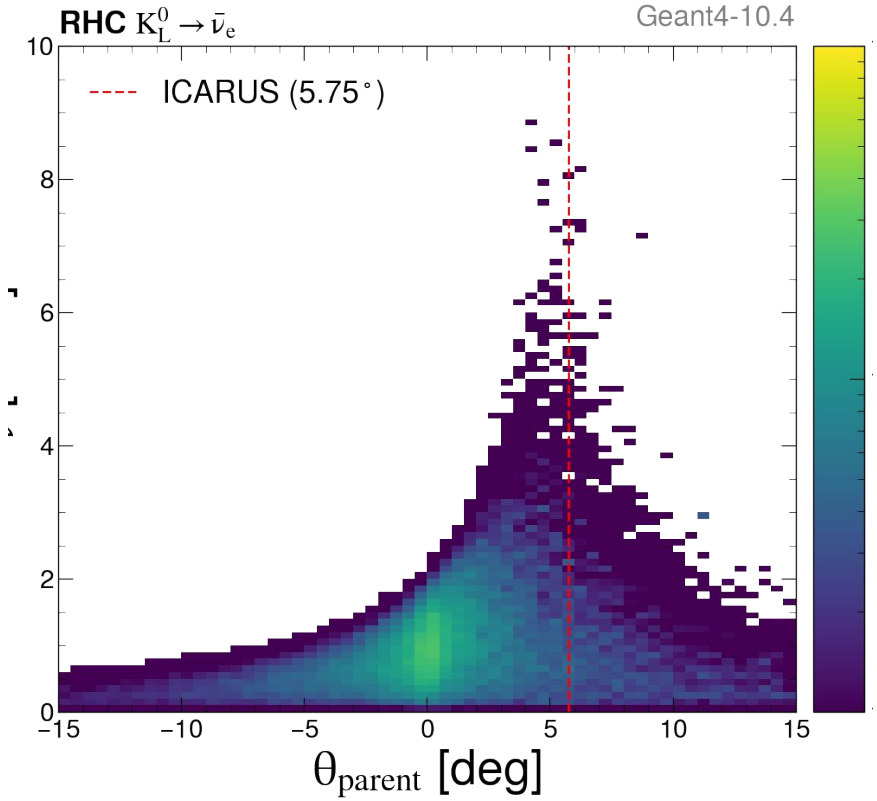


Parent Angle – $\mu^{\pm} \rightarrow$ electron (anti-)neutrino

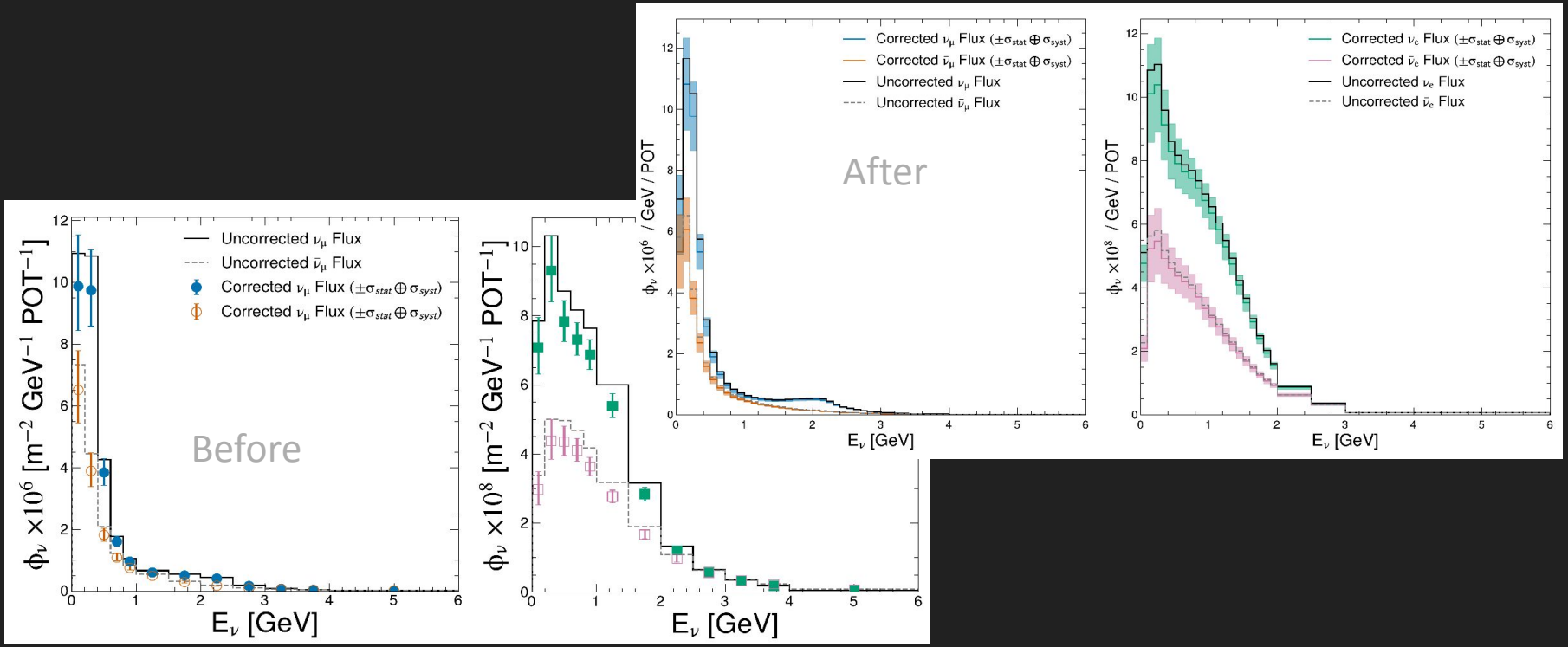




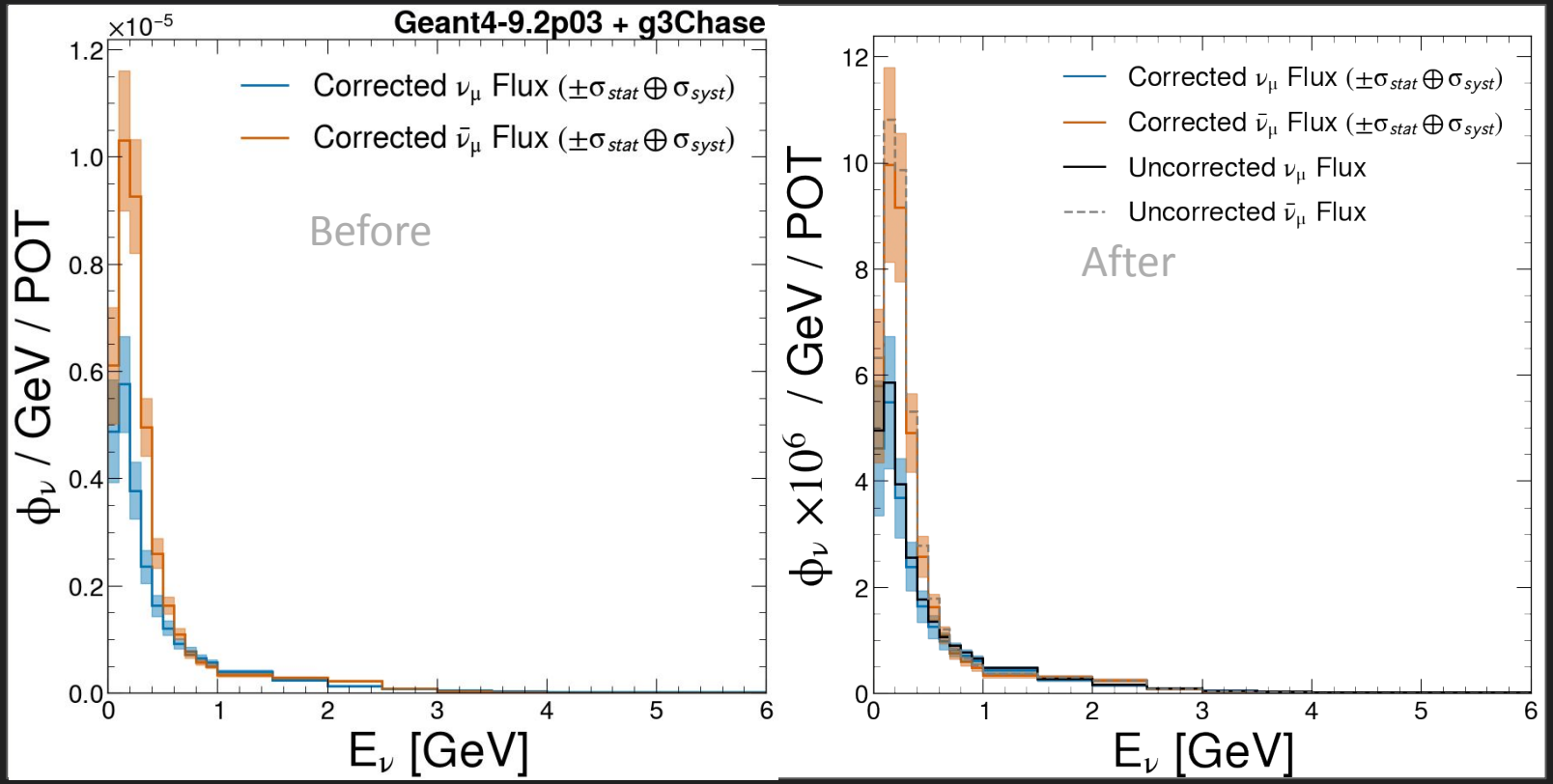

FHC $K^0_L \to \nu_e$
Geant4-9.2p03 (g3Chase)
ICARUS (5.75°)
θ_{parent} [deg]


RHC $K^0_L \to \bar{\nu}_e$
Geant4-10.4
ICARUS (5.75°)
θ_{parent} [deg]

PPFX Corrections Before and After GEANT4 Changes - FHC



PPFX Corrections Before and After GEANT4 Changes - RHC



Smaller effect on the pi→nu moving to updated G4