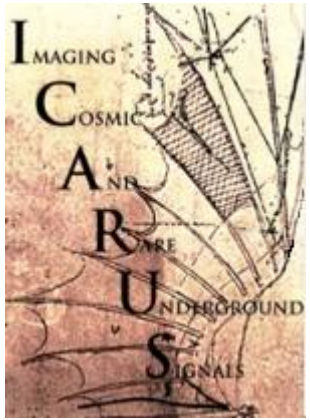
The NuMI Flux at ICARUS



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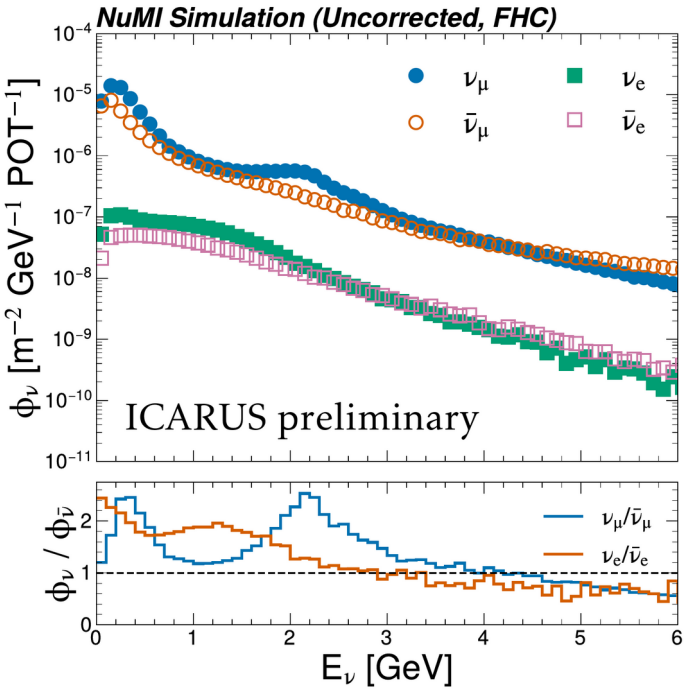
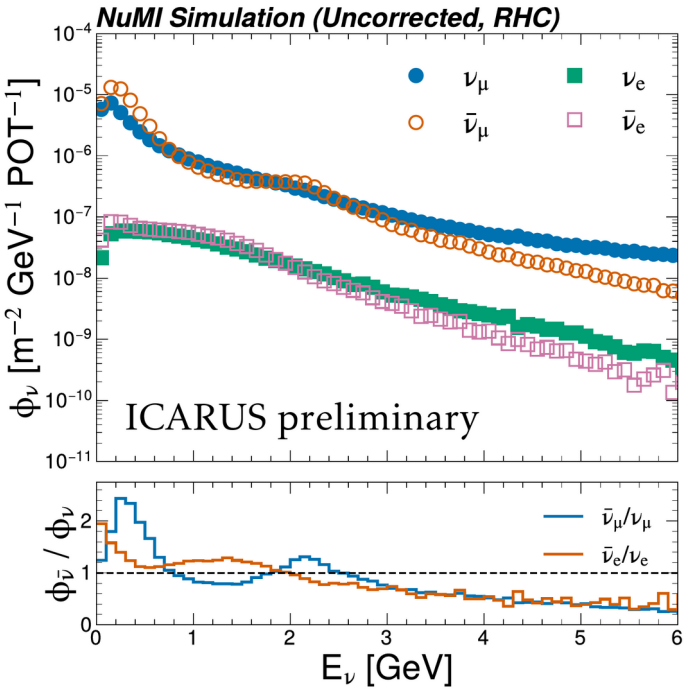
Why Do We Care?

- NuMI neutrinos at ICARUS provide unique opportunity to measure cross sections on Ar in the ~1-3 GeV range
  - Both FHC and RHC contain significant ν and $\bar{\nu}$
  - The ν_e to ν_μ cross section ratio between 1-3 GeV is ~5-9%
- Inputs for DUNE:
  - DUNE will have a peak energy in the 1-3 GeV region
  - The DUNE ND will measure these processes with high statistics
  - Models constrain $\bar{\nu}/\nu$ and ν_e/ν_μ ratios
  - Data based measurements and uncertainties will provide useful priors
- Understanding the flux reduces error on background subtraction and cross section extraction
- The NuMI flux and uncertainties have not been studied in detail at 5.75° off-axis

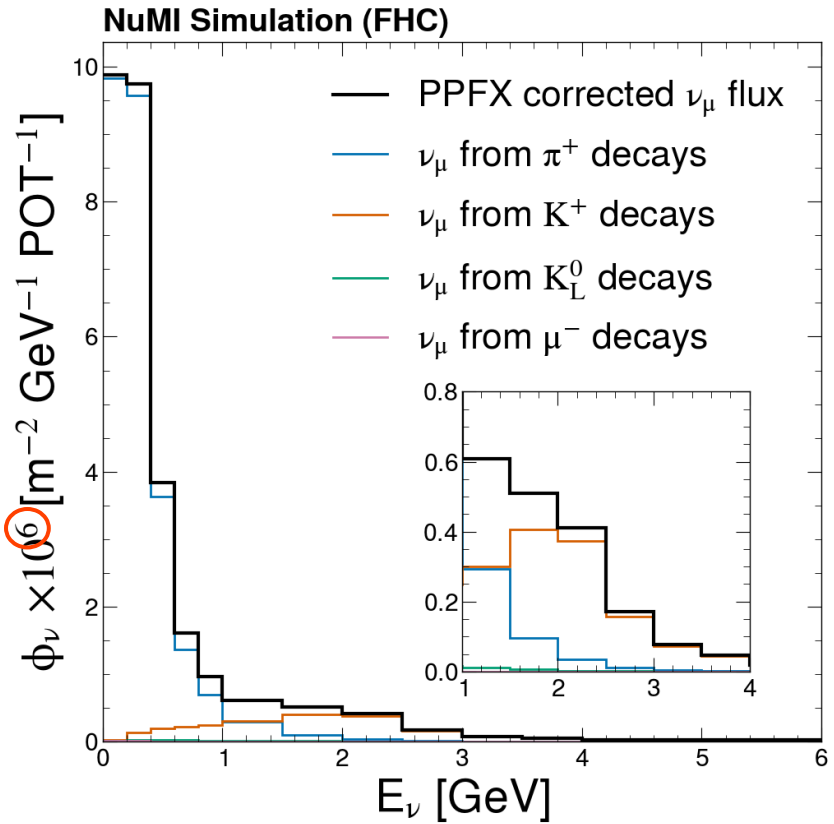
Neutrino Flux at ICARUS

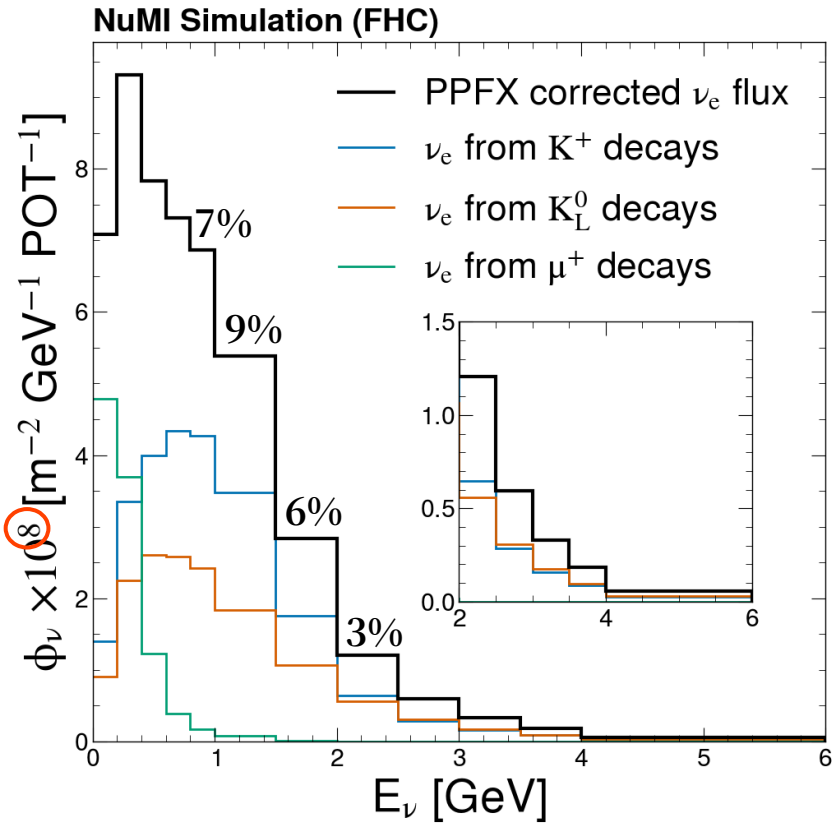




- Large low energy ν_μ peak
- Useful "shoulder" at to ~2.5 GeV
- Large wrong-sign contamination
- Relatively high ν_e to ν_μ ratio

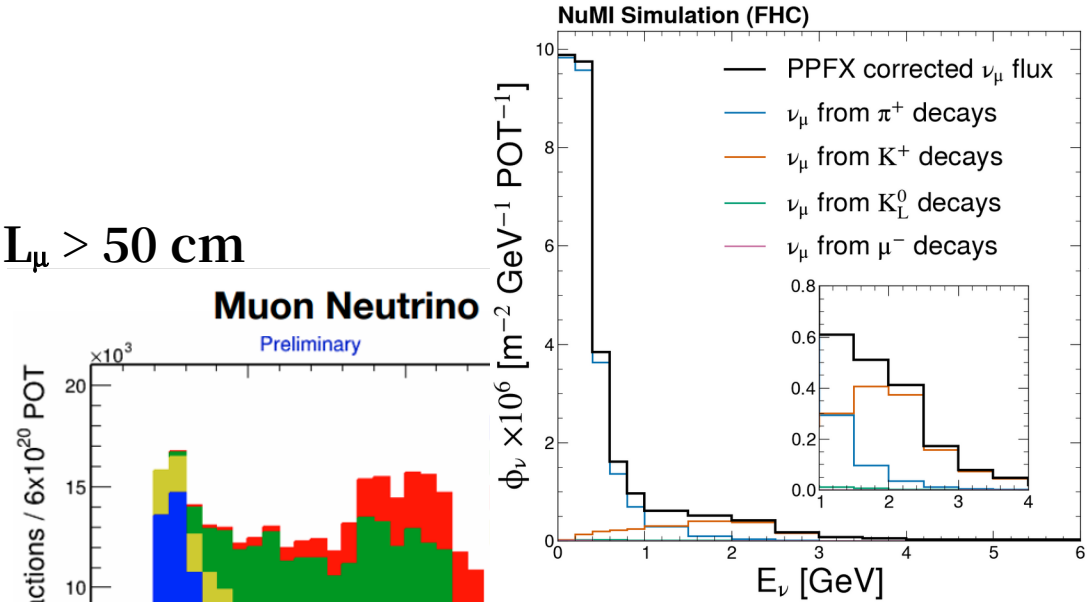
FHC Neutrino Flux at ICARUS

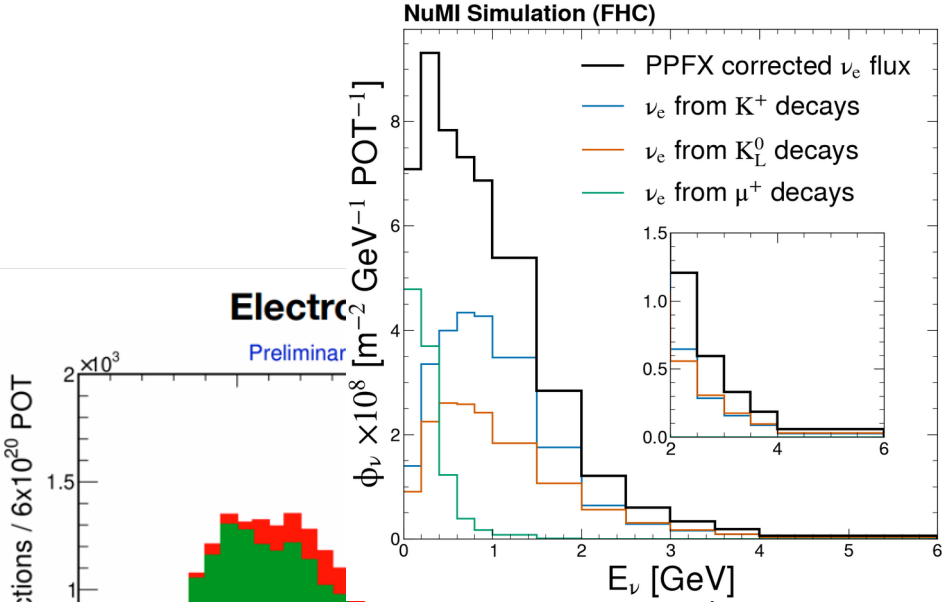




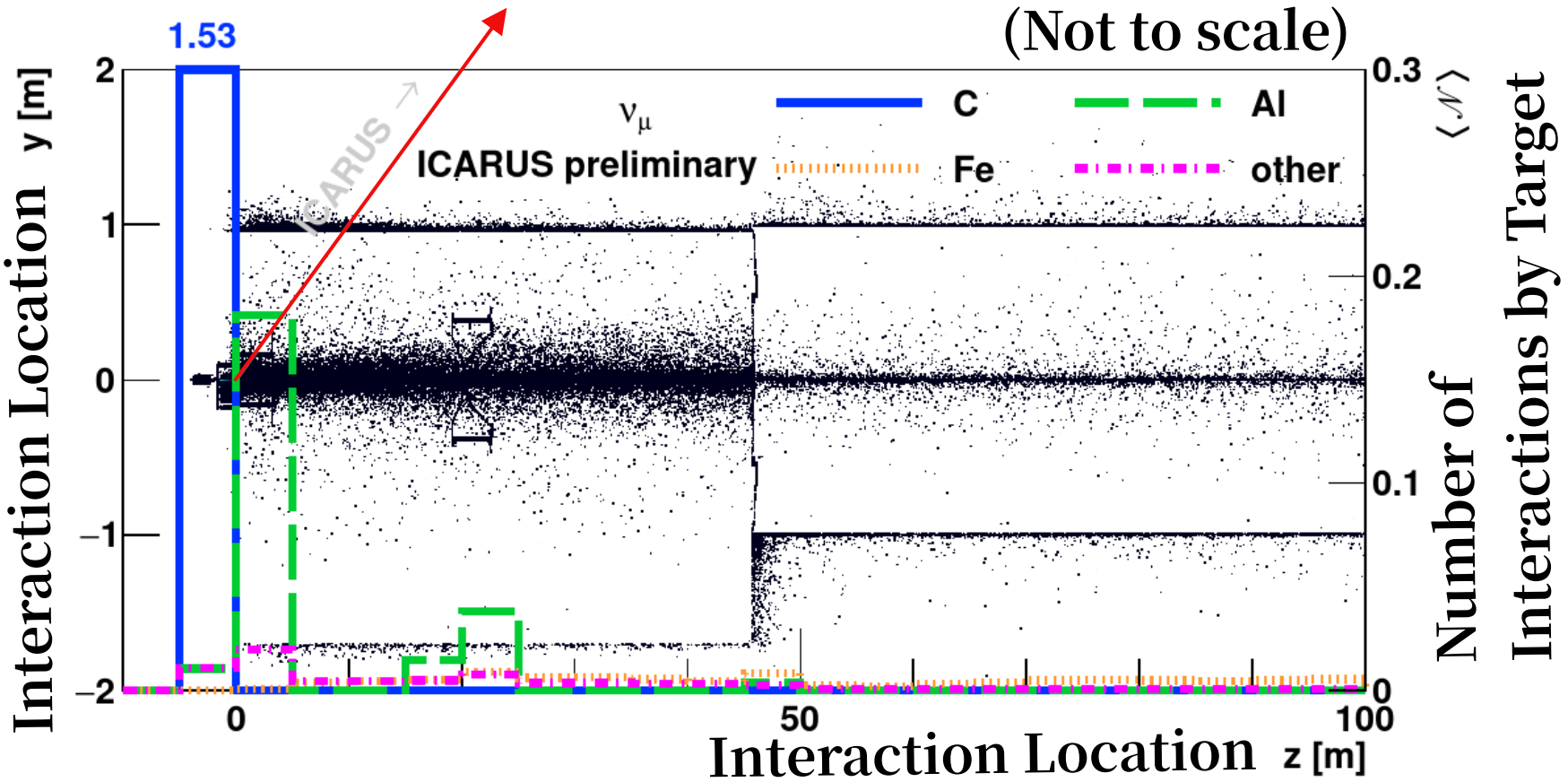
Cross Section Shifts Energy Peak

$L_\mu > 50$ cm

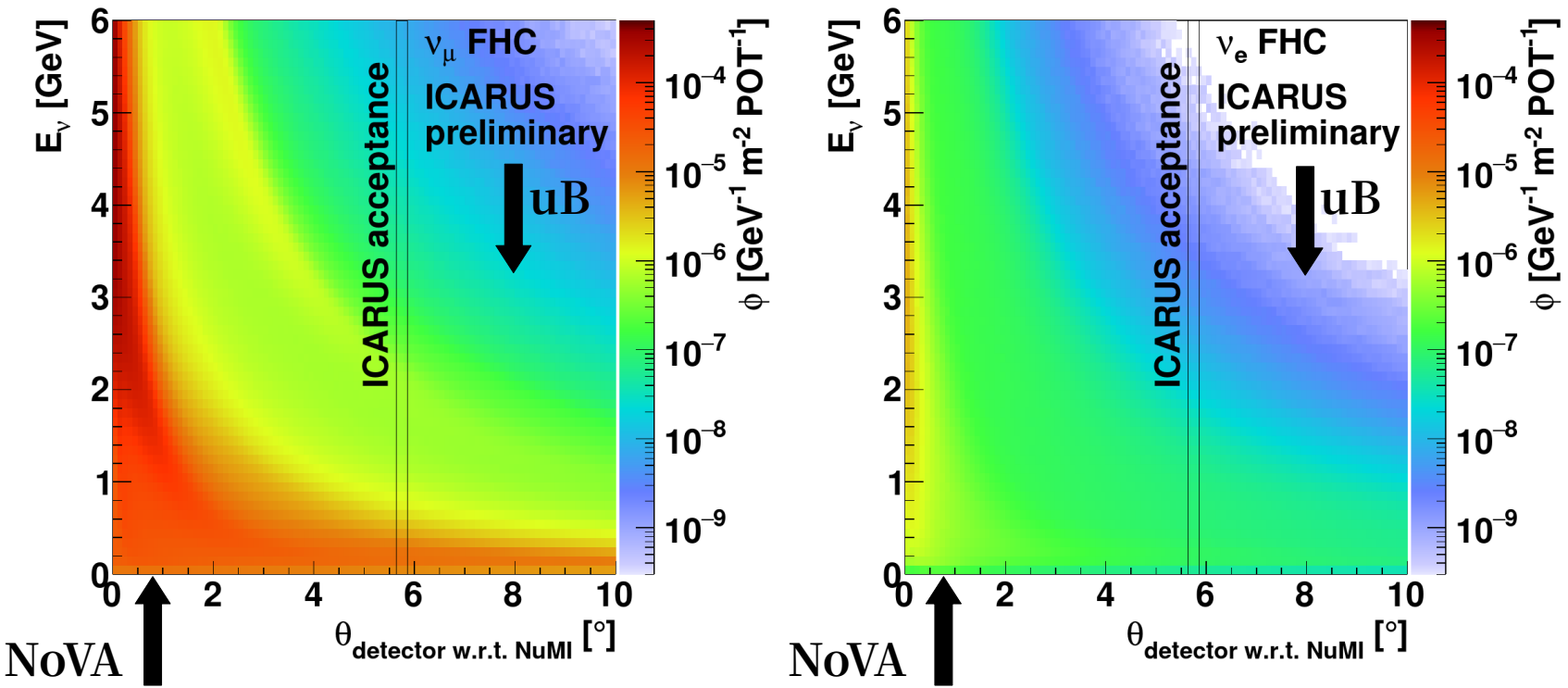




Location of Hadronic Interactions



Energy vs Off-axis Angle



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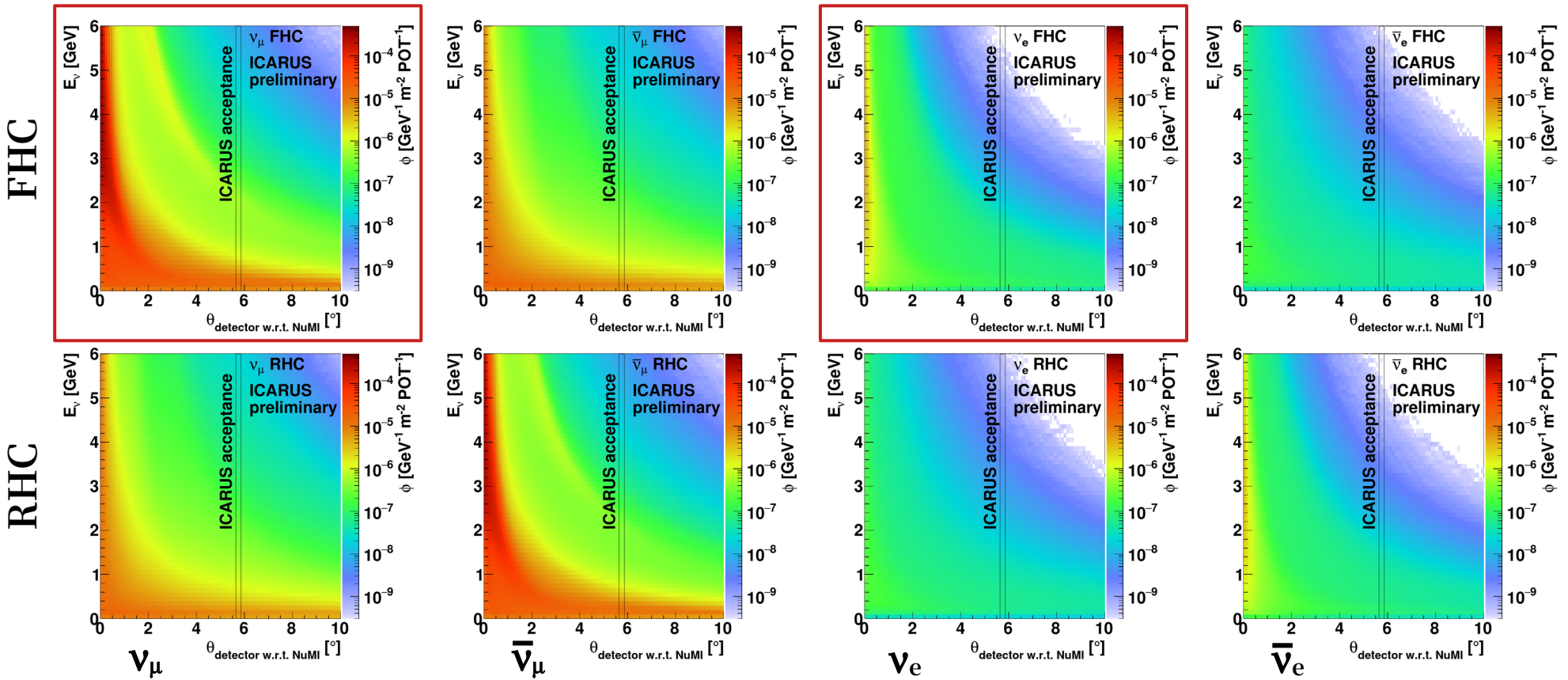
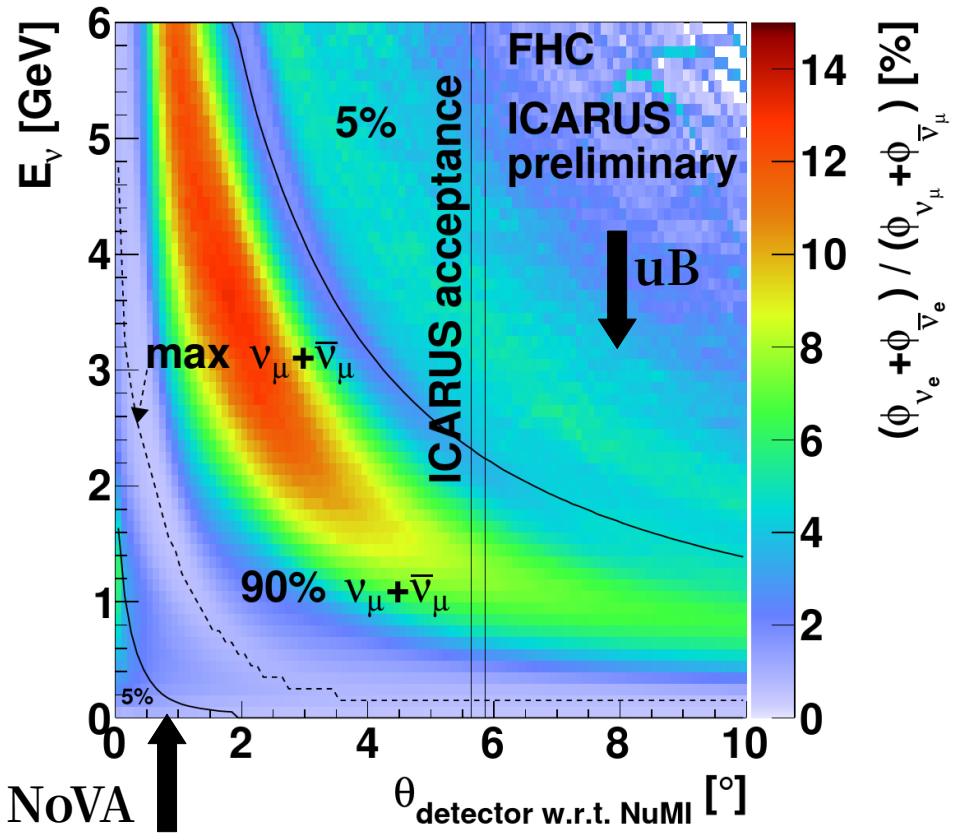
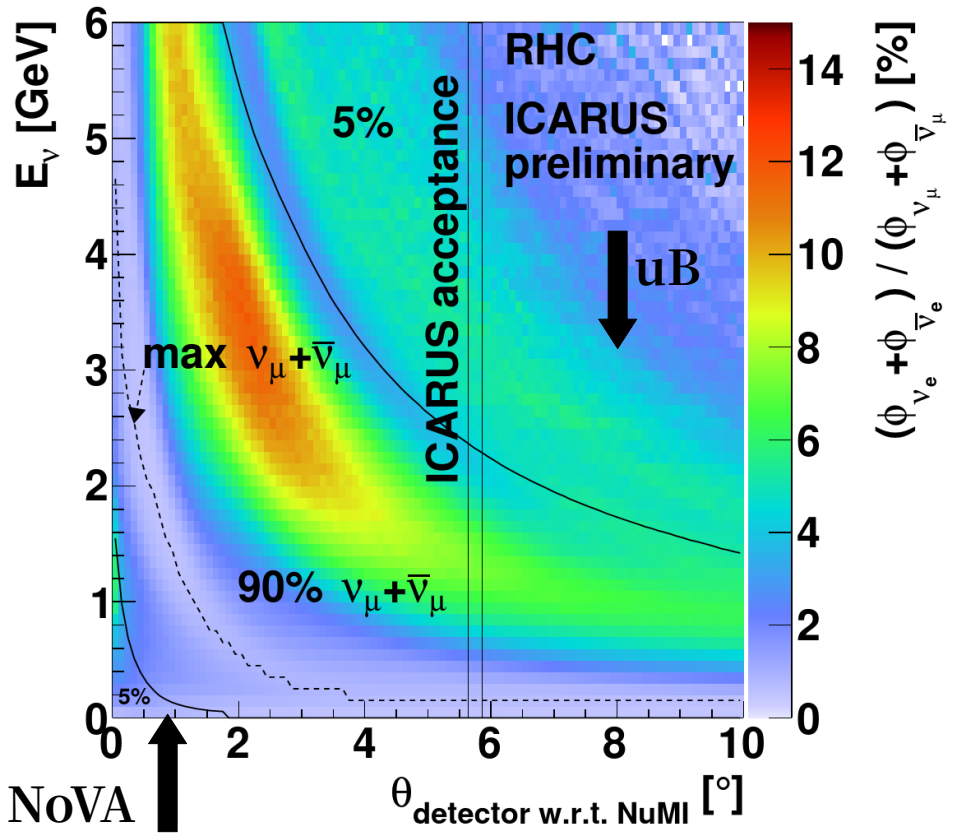
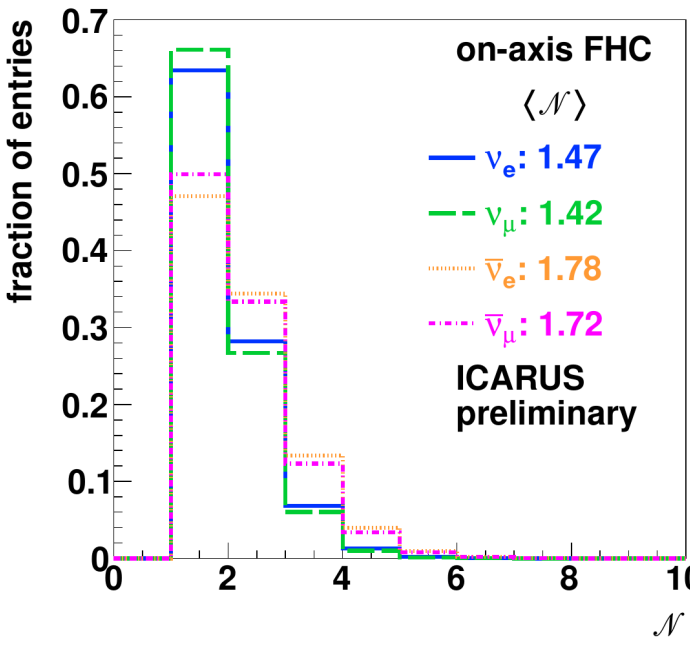


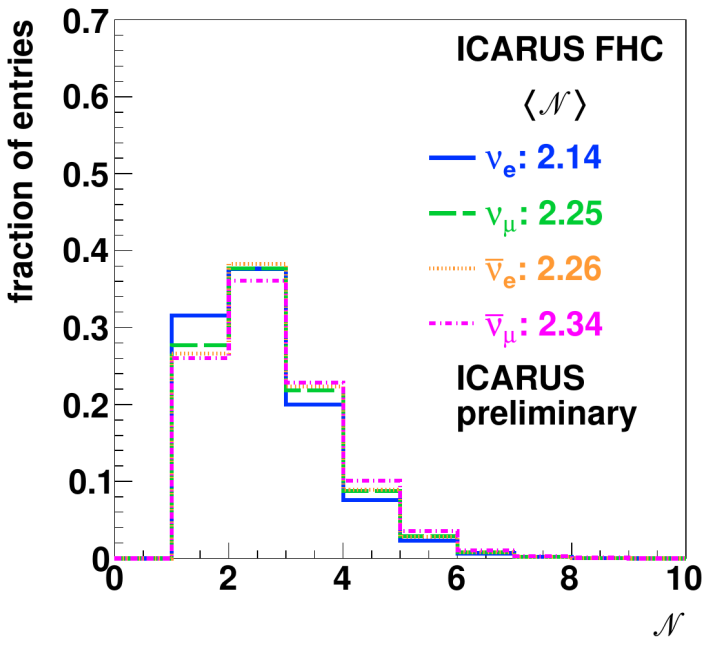
ν_e to ν_μ Ratio





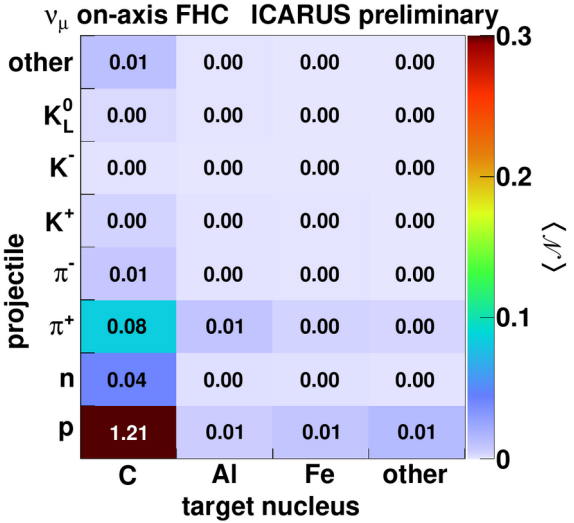
Interactions per Neutrino

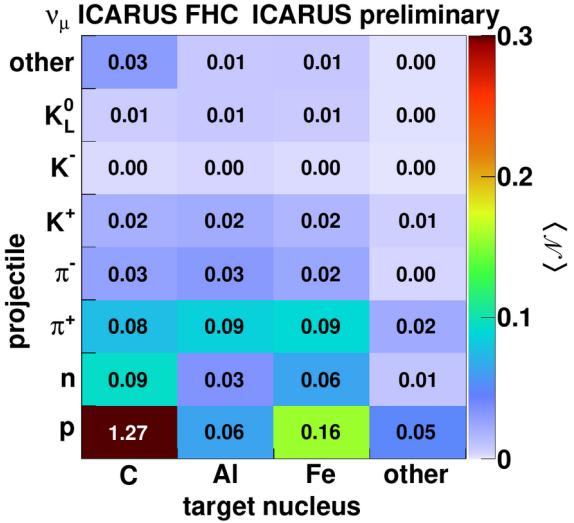


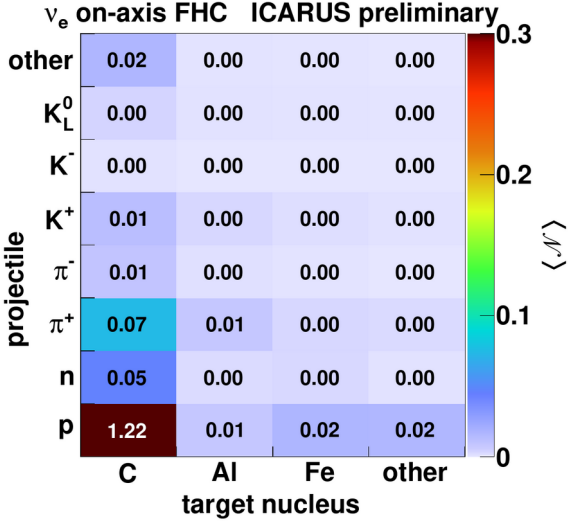


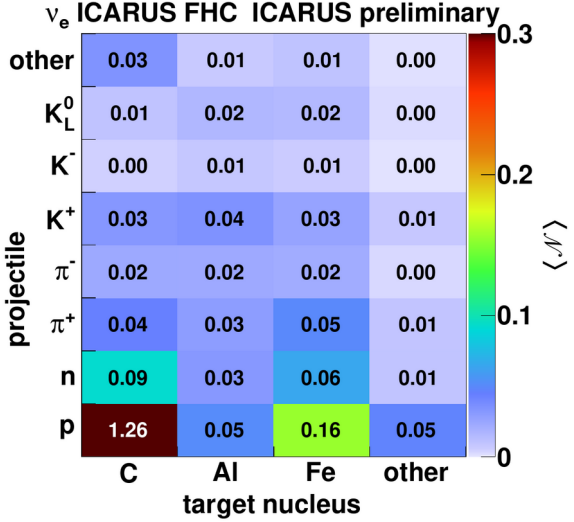
- Includes primary pC interaction
- More interactions per neutrino
- What are projectiles and targets?
- 7 hadrons projectiles
- Nuclei that compose
  - Target
  - Horns
  - Target chase
  - Decay pipe

Interactions per Neutrino





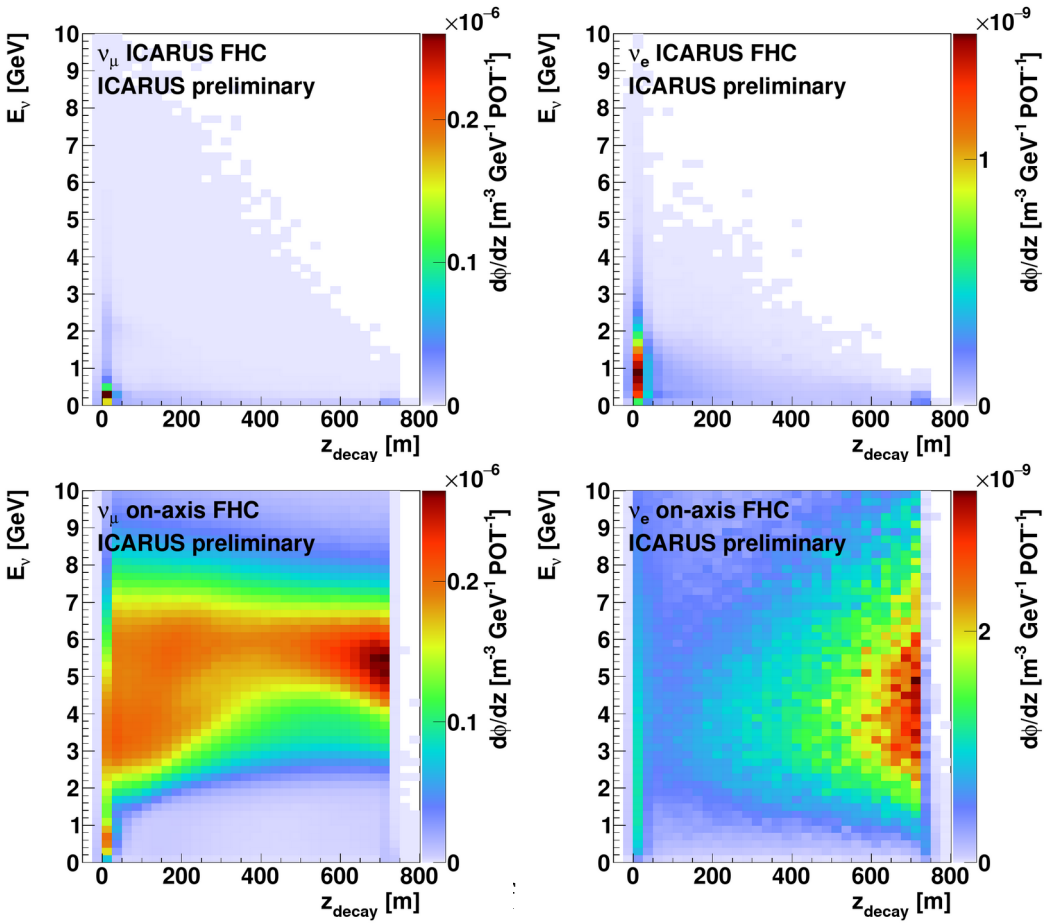




← On axis | Off axis →

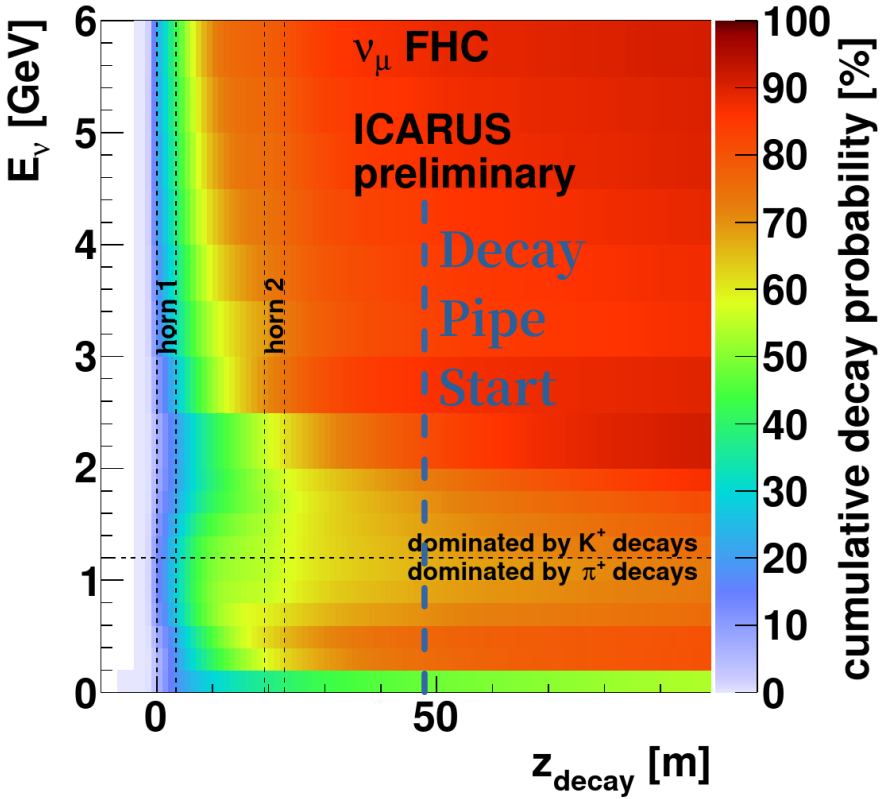
- Many more interactions on A ≠ C^{12}
- Many more meson projectiles
- Target/projectiles combinations as function of E_ν

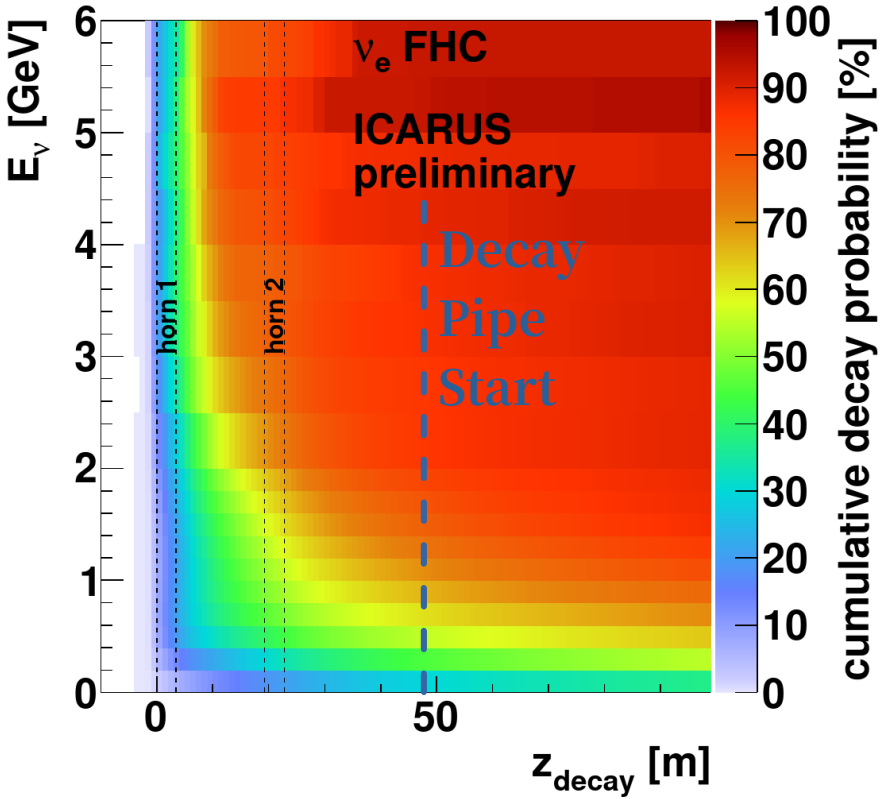
Decay z-Position



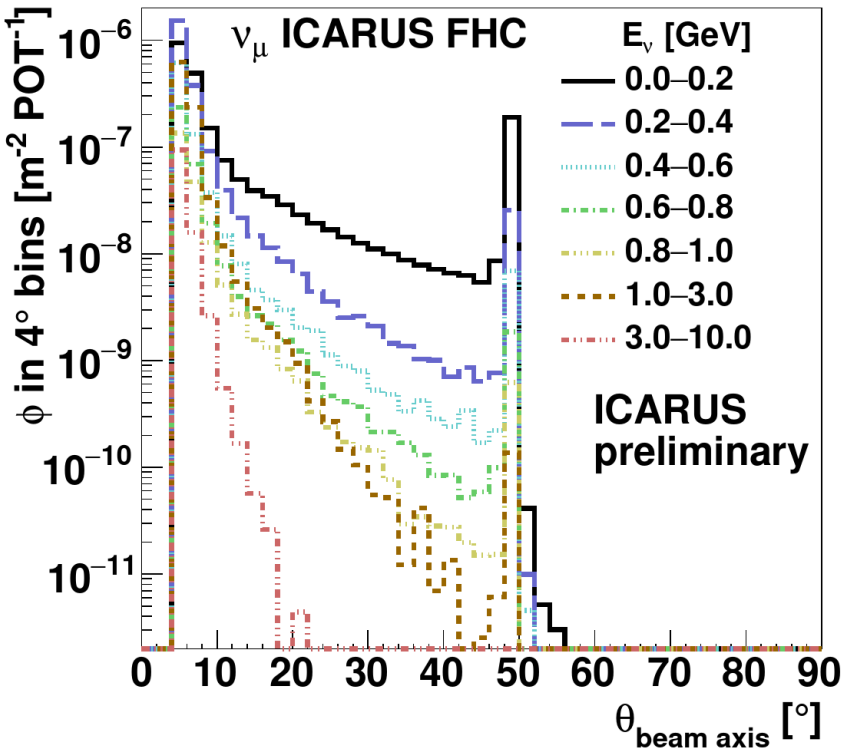
- Most ICARUS ν come from target region
  - High energy tail from target
  - Lowest energies from decay pipe
- On-axis ν come from decay pipe
  - Kaon decays near target
  - Decays of $\pi^{\pm}(\nu_\mu)$ and $\mu(\nu_e)$ along decay pipe.

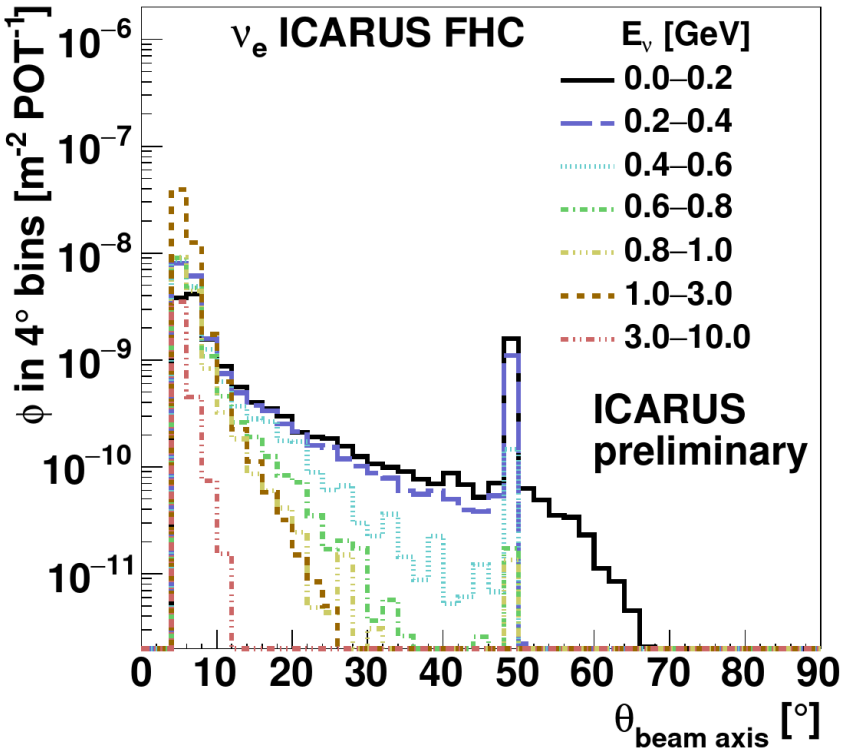
Decay z-Position (Cumulative)





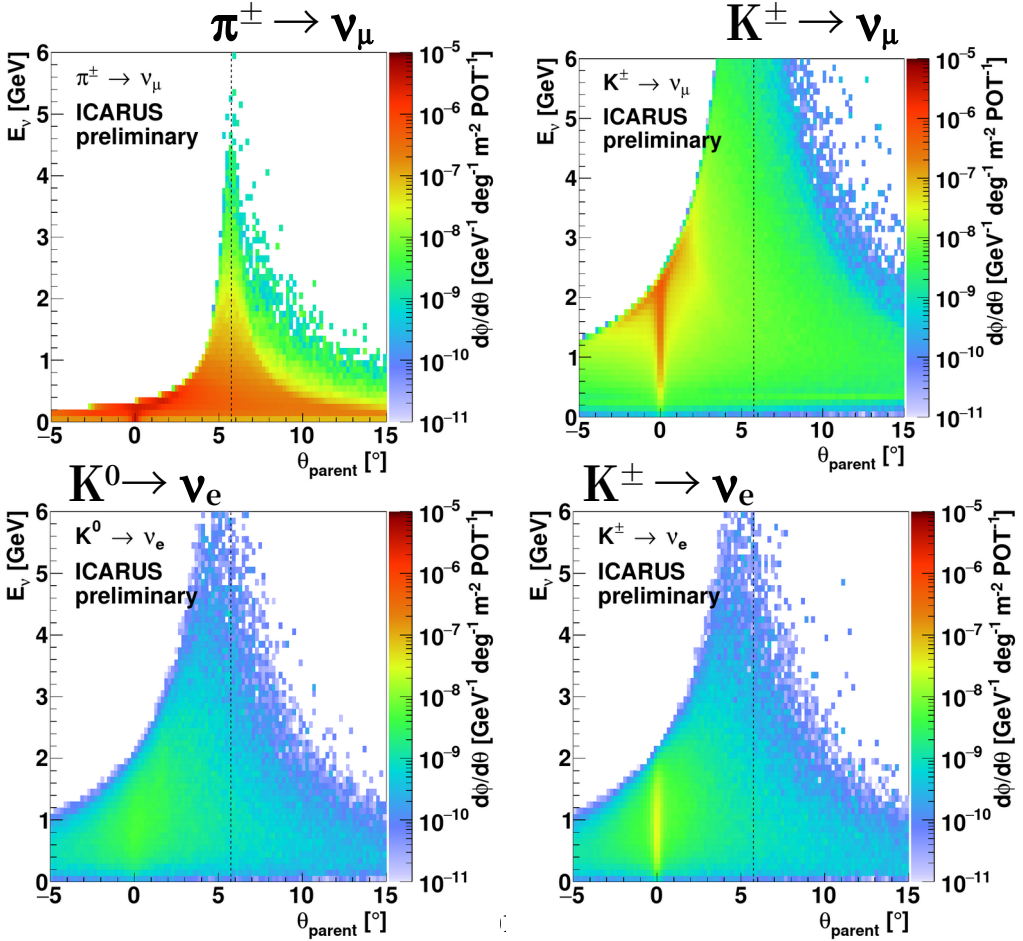
Hadron Contributions by Decay Angle





Lower energy = wider range of decay angles

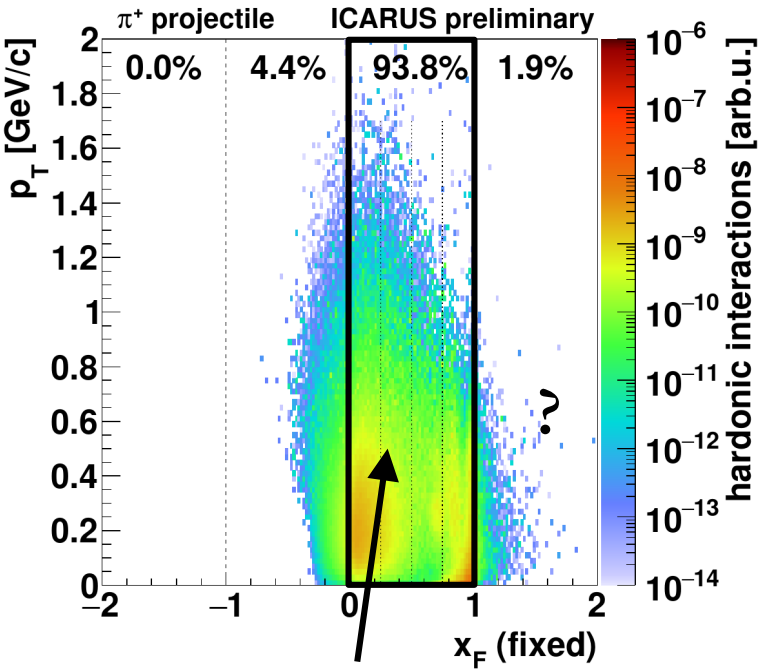
Hadron Contributions by Decay Angle



- Along dotted line:
  - $\theta = 5.75°$ → meson points to ICARUS
- $\theta < 5.75°$
  - more forward going meson
  - higher angle decay
- $\theta > 5.75°$
  - reinteraction in decay pipe
  - low energy meson pointing back to ICARUS
- Pions point to ICARUS
- Forward going Kaons with wide decay kinematics
- K's point to ICARUS → Higher energy ν

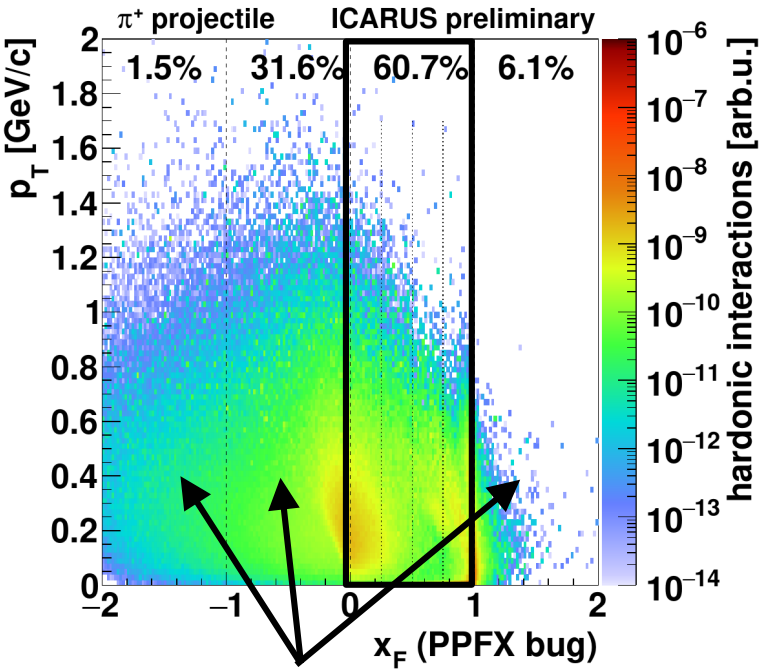
x_F Bug in PPFX

Bug Fixed



4 independent bins (×35 targ./proj. pairs)

With Bug

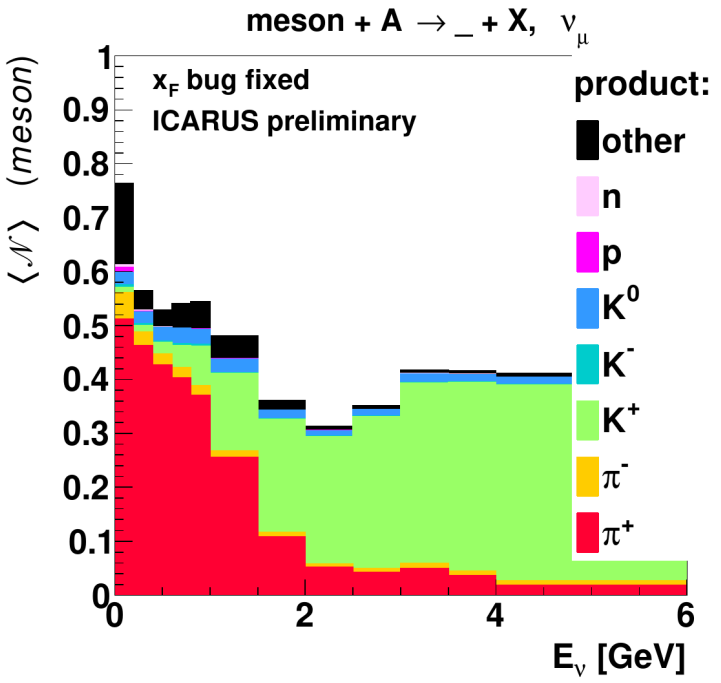


Single bin across all 35 targ./proj. pairs

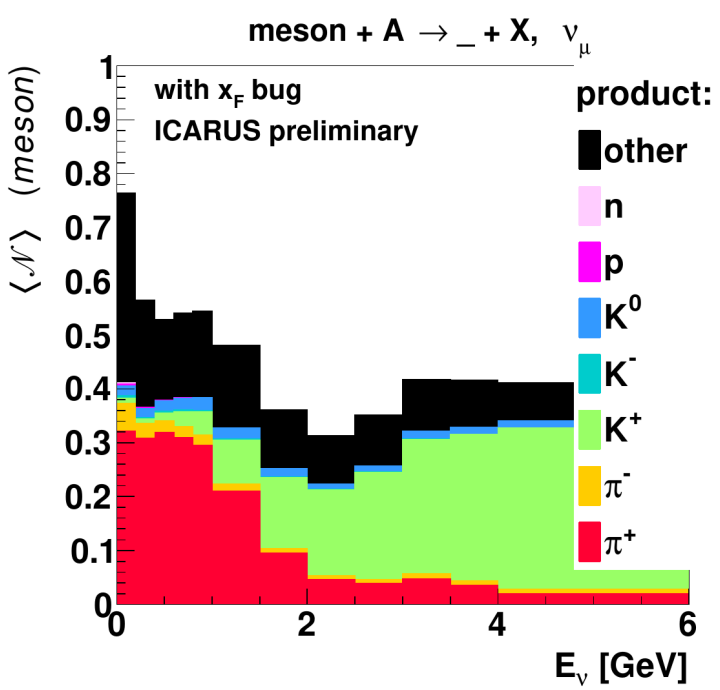
- Bug: hard code $m_{targ.} = m_{proj.}$ in x_F calculation
- Breaks for incoming mesons
- With bug: correlated errors inflate total uncertainty
- Fixed Bug: introduces more shape uncertainty
- <u>Small effect on axis!</u>

x_F Bug in PPFX

Bug Fixed



With Bug



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  in x_F calculation
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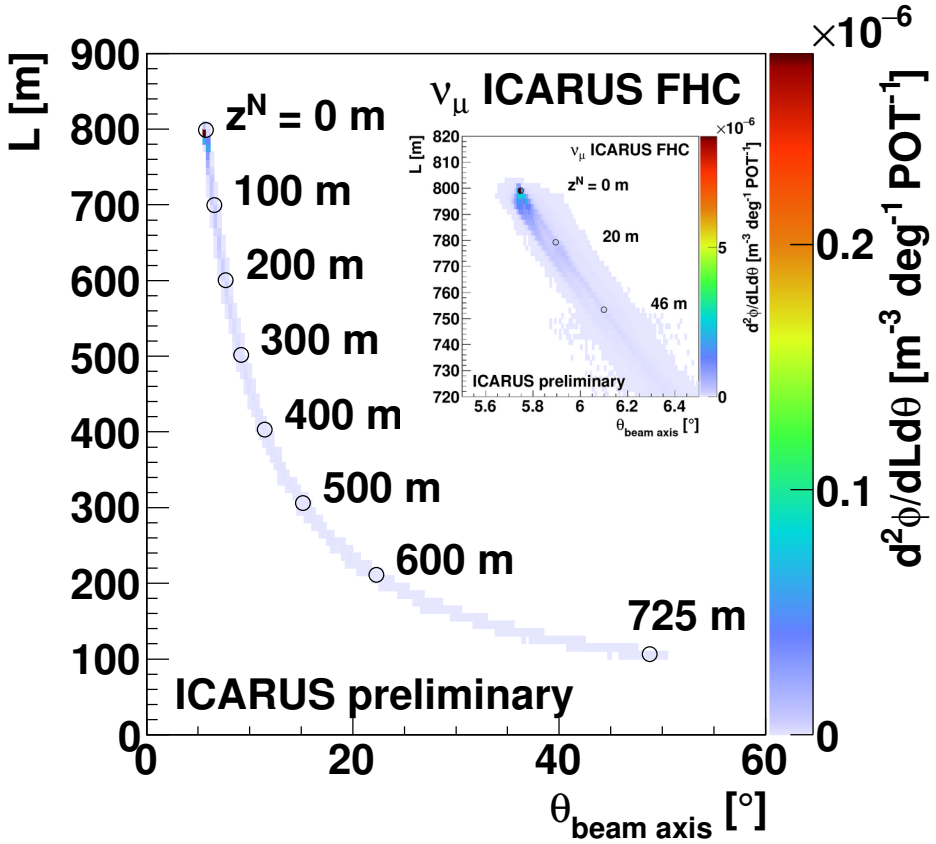
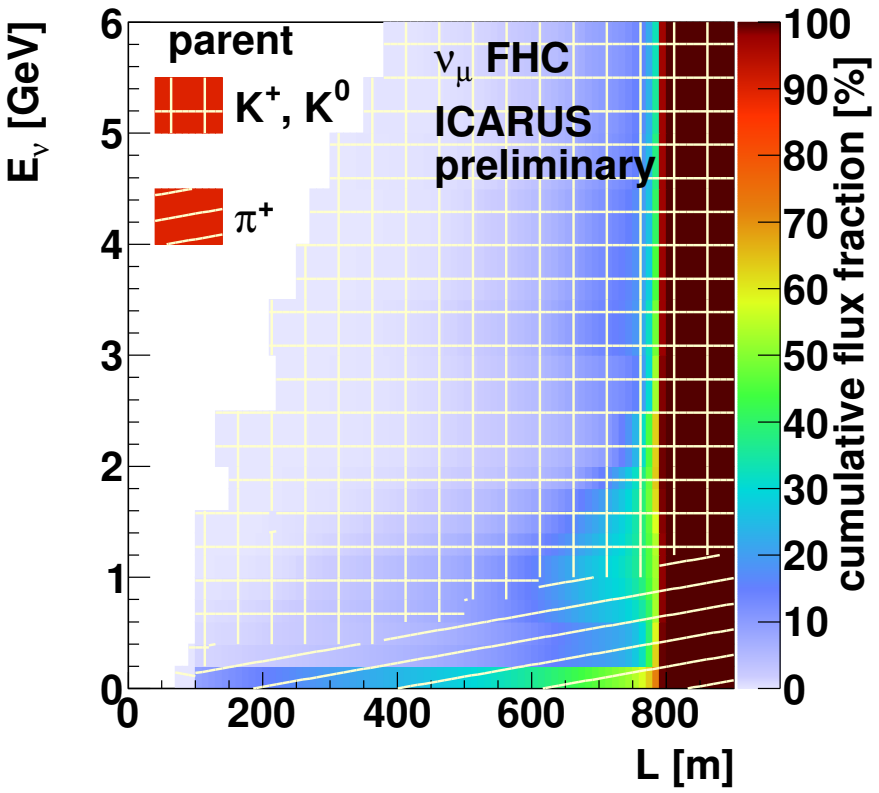
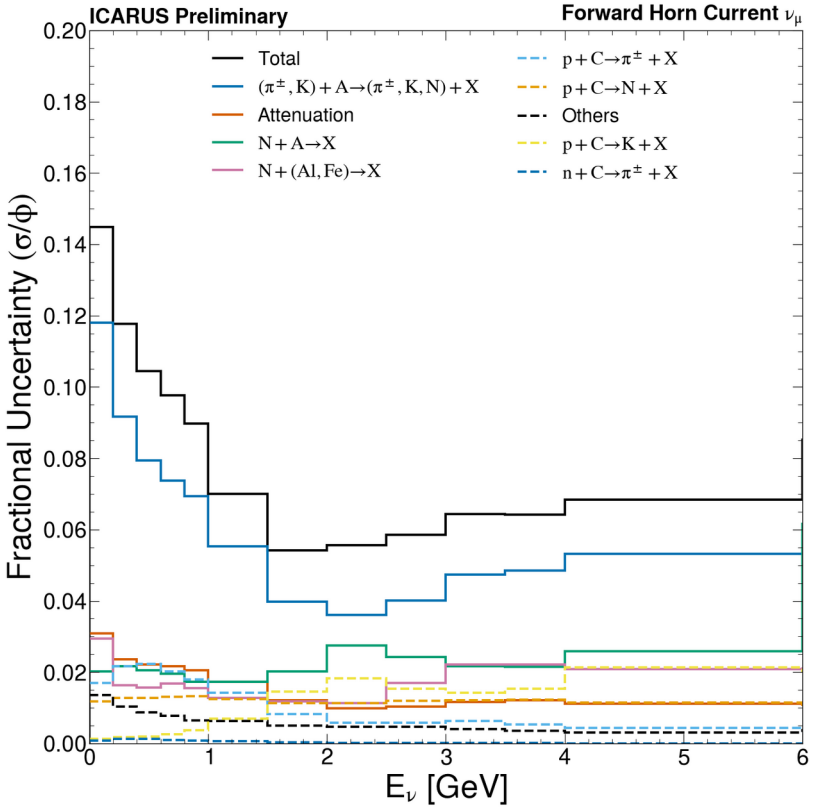
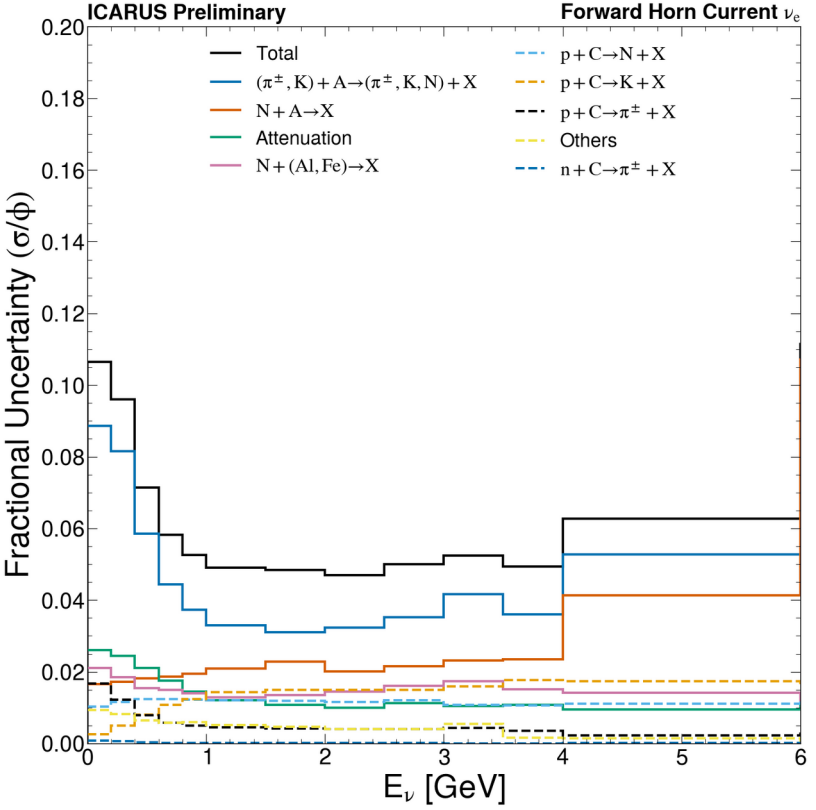
Baseline (L) vs Energy & Angle



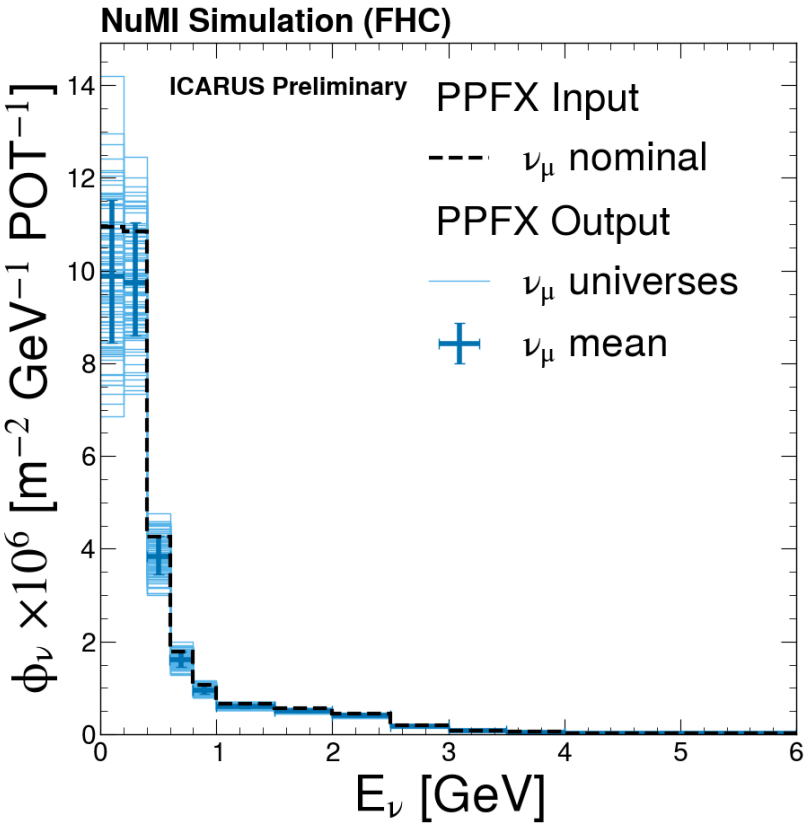


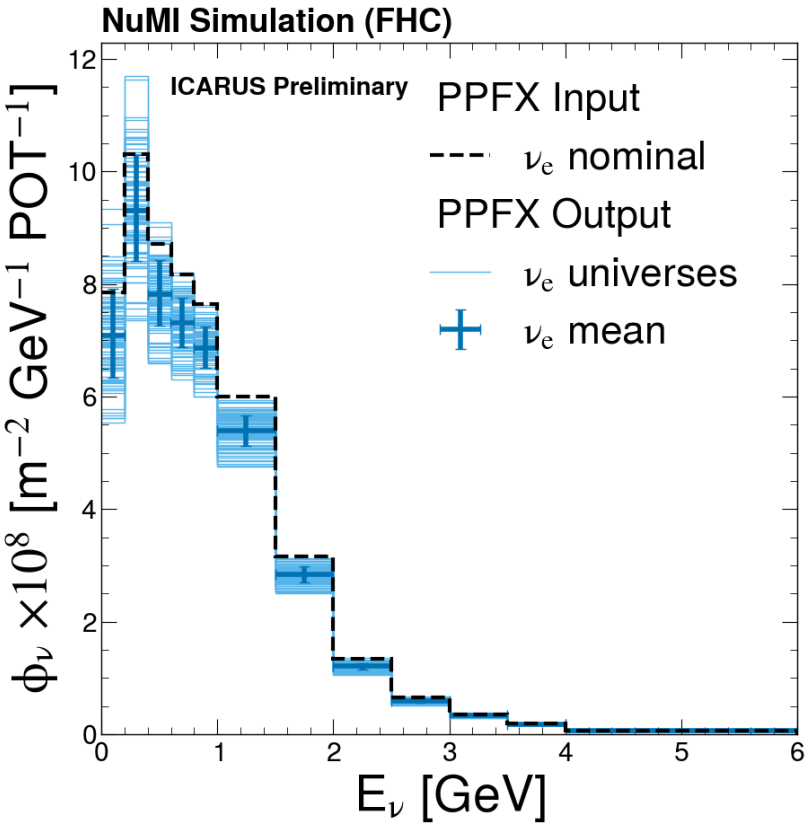
Hadron Production Uncertainties



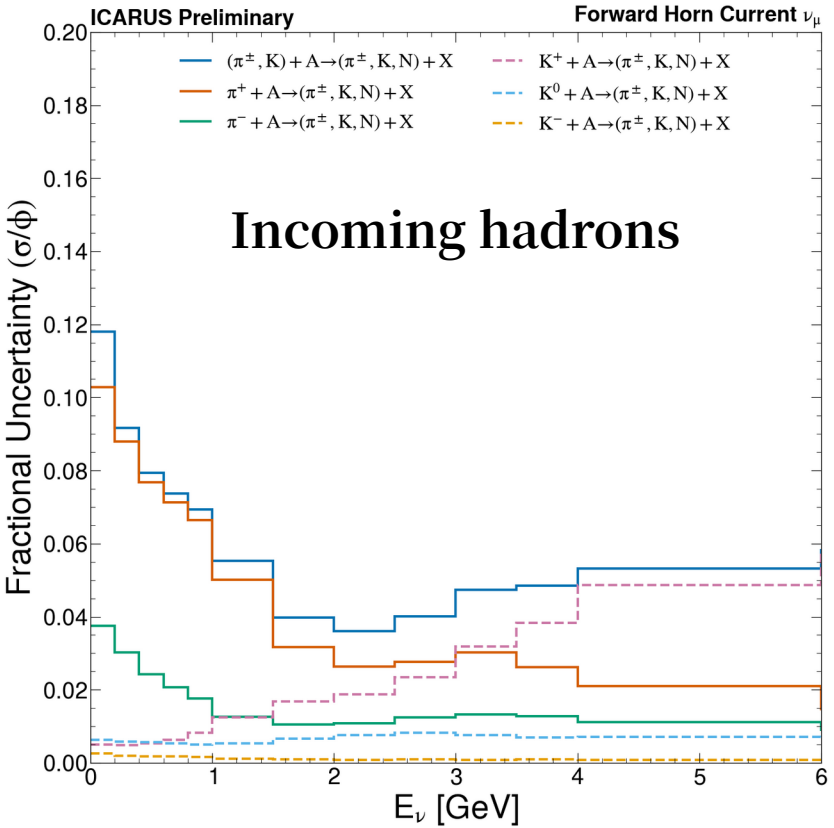


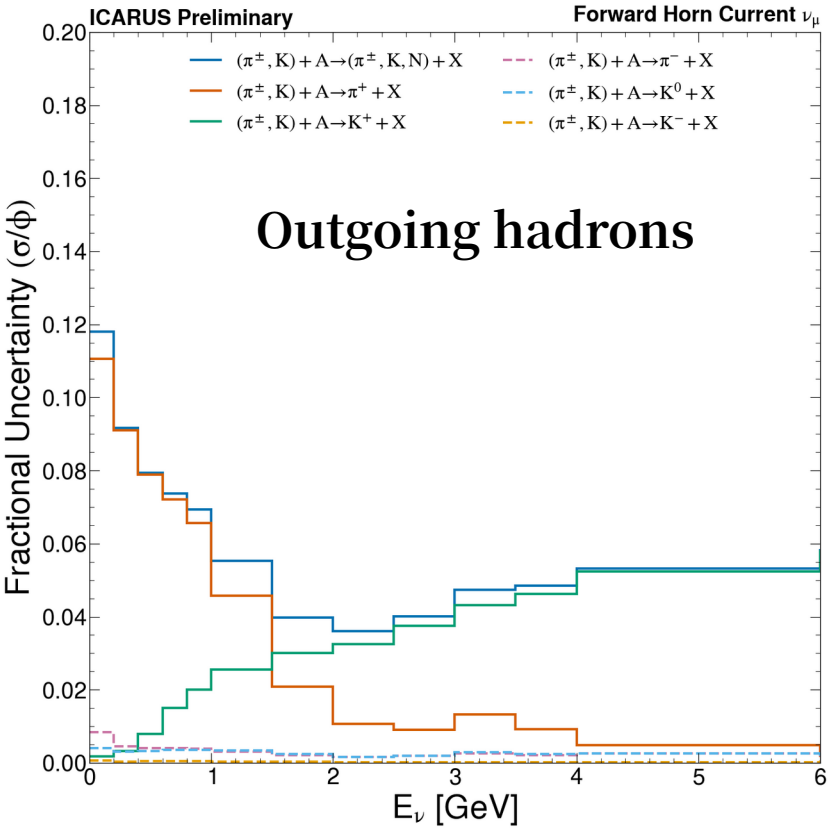
PPFX Corrections and Uncertainties



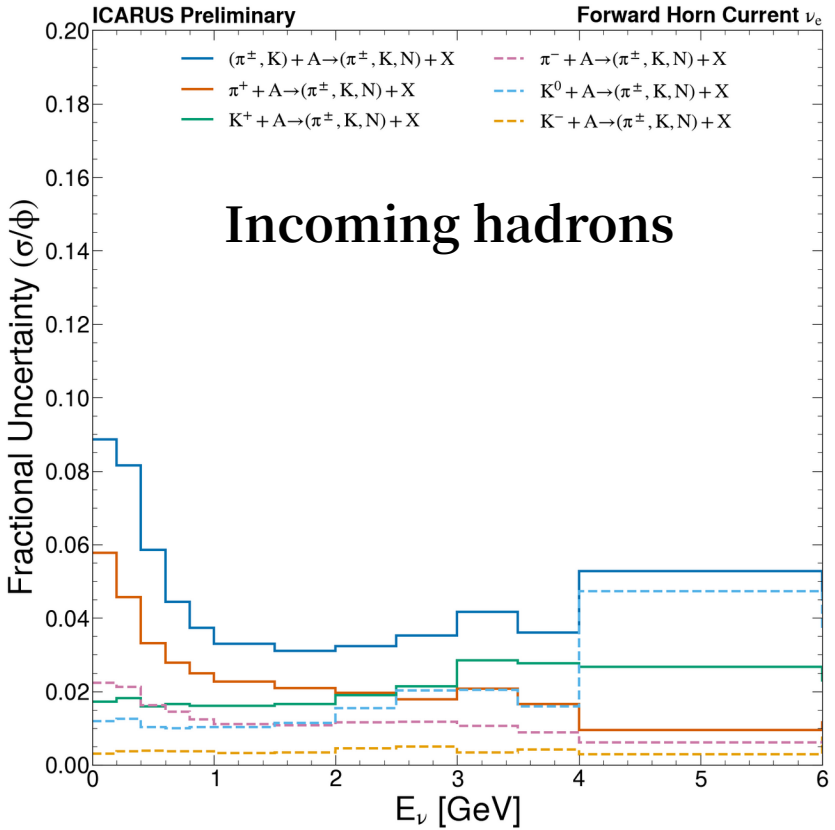


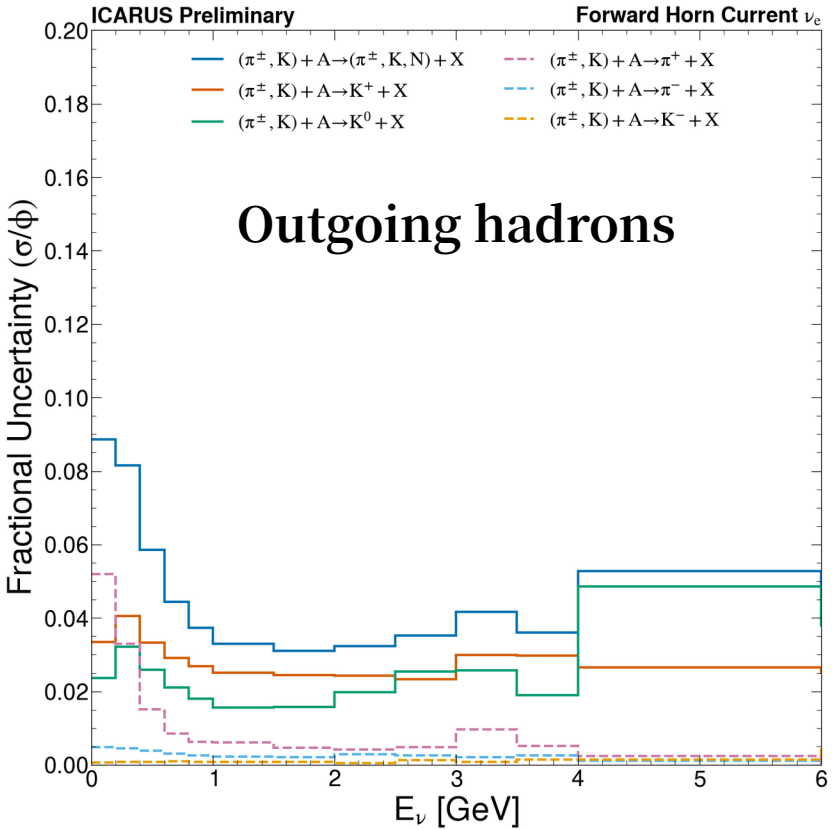
Meson Inclusive Breakdown - ν_μ



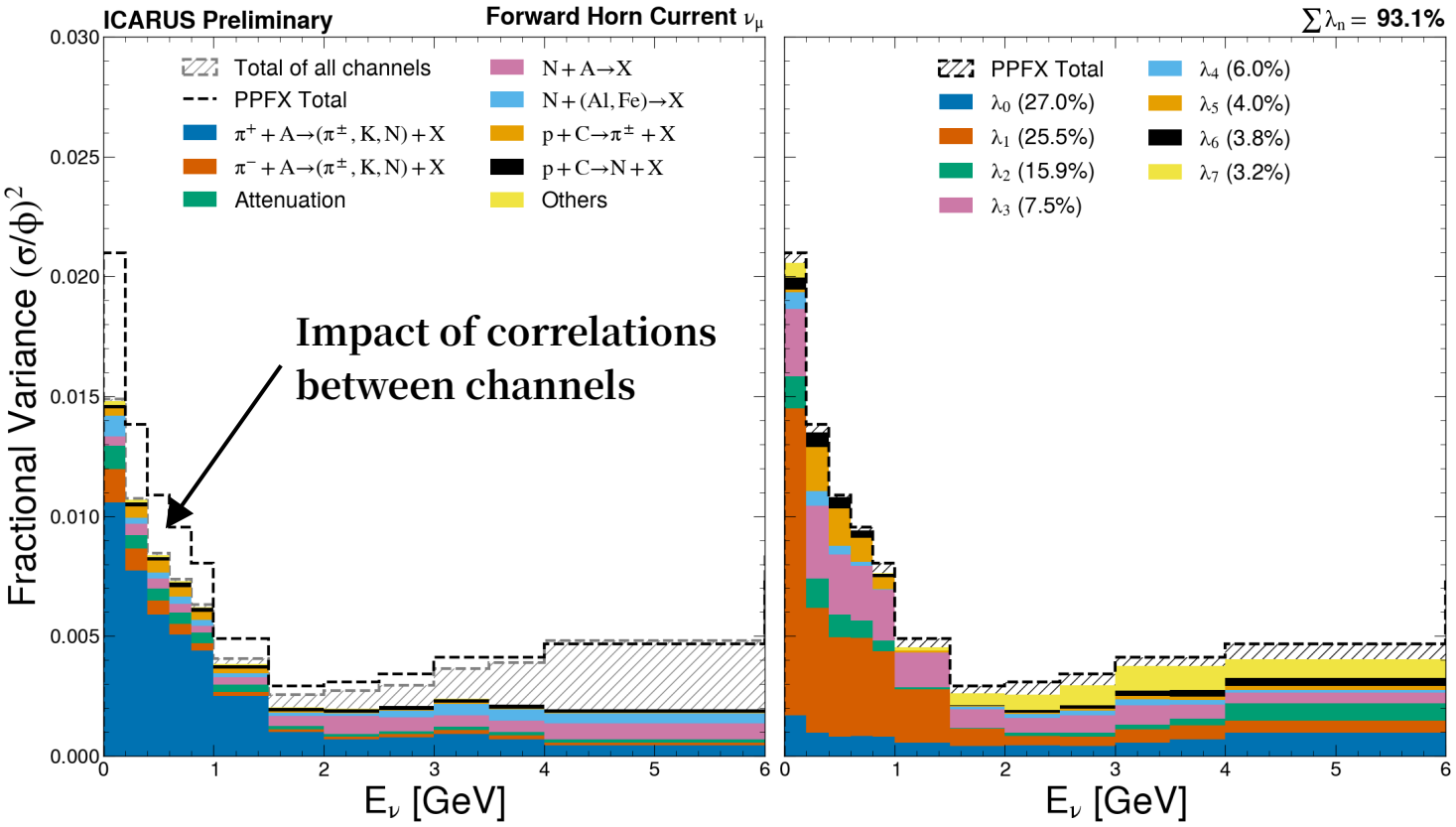


Meson Inclusive Breakdown - ν_e



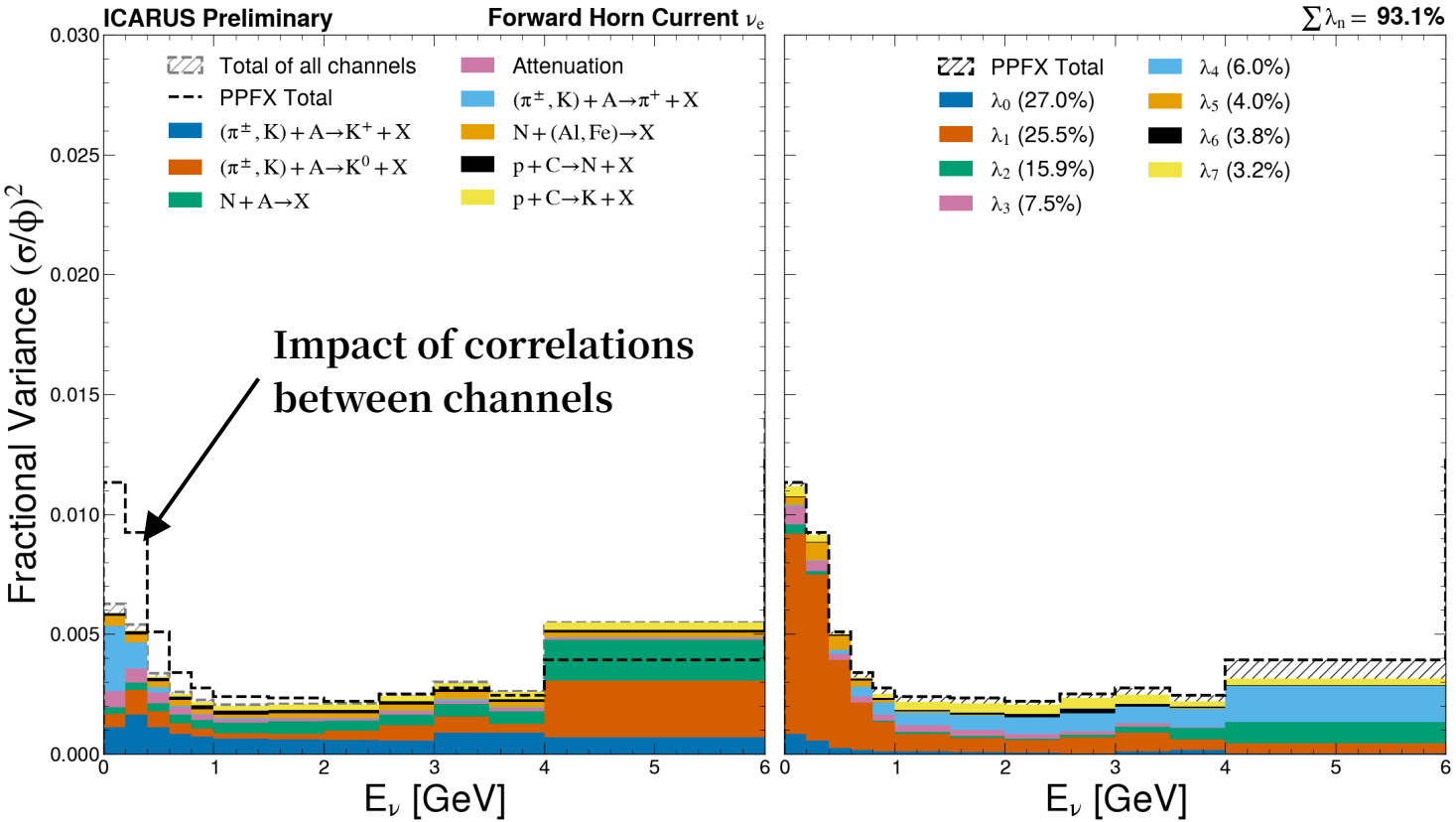


Physics vs. PCA Comparisons - ν_μ



- Variances, so components add
- Physics channels: correlated
- PCs: independent
- Hashed: total of unshown channels
- RHS white space:
  - Impact of correlations
  - Correlated components do not add quadratically

Physics vs. PCA Comparisons - ν_e



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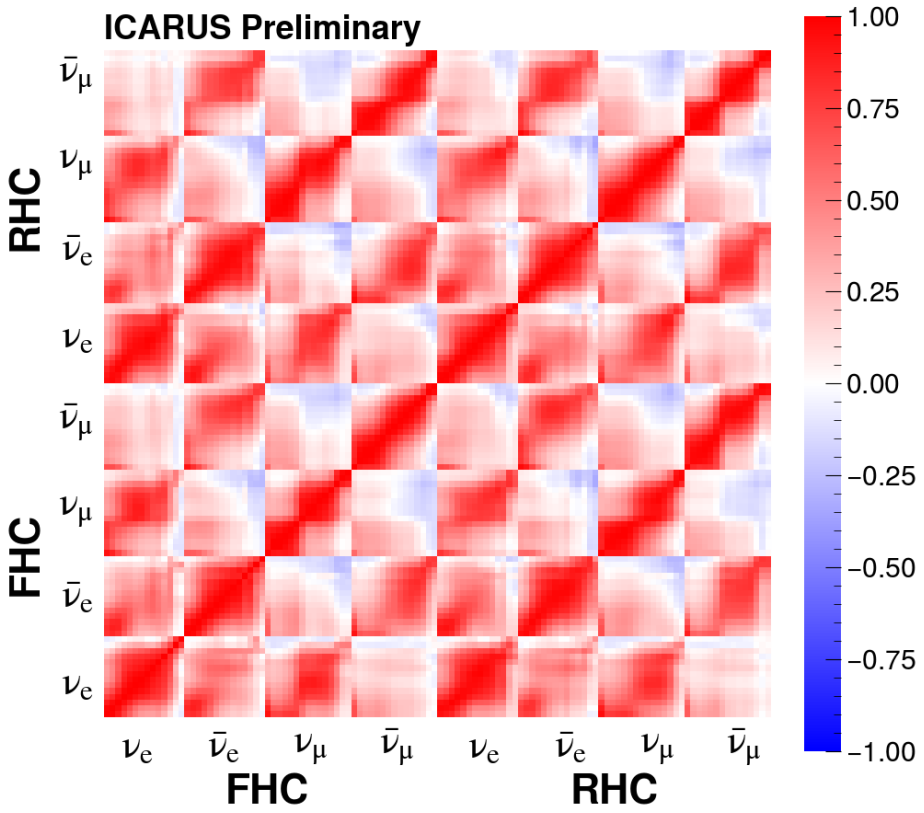
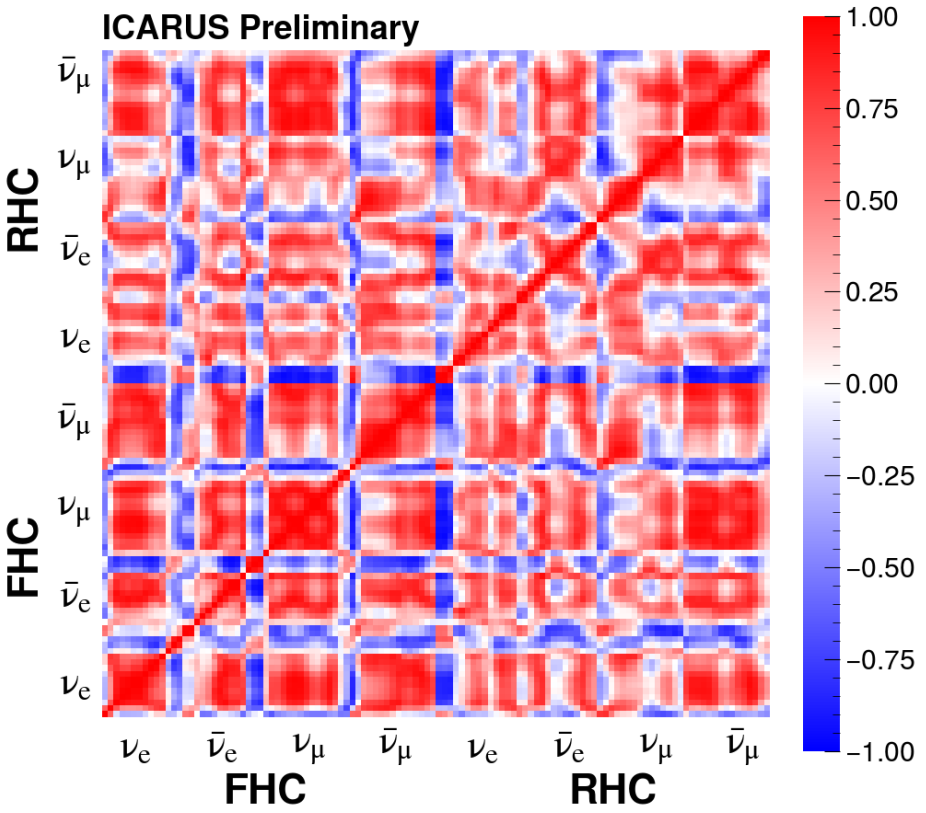
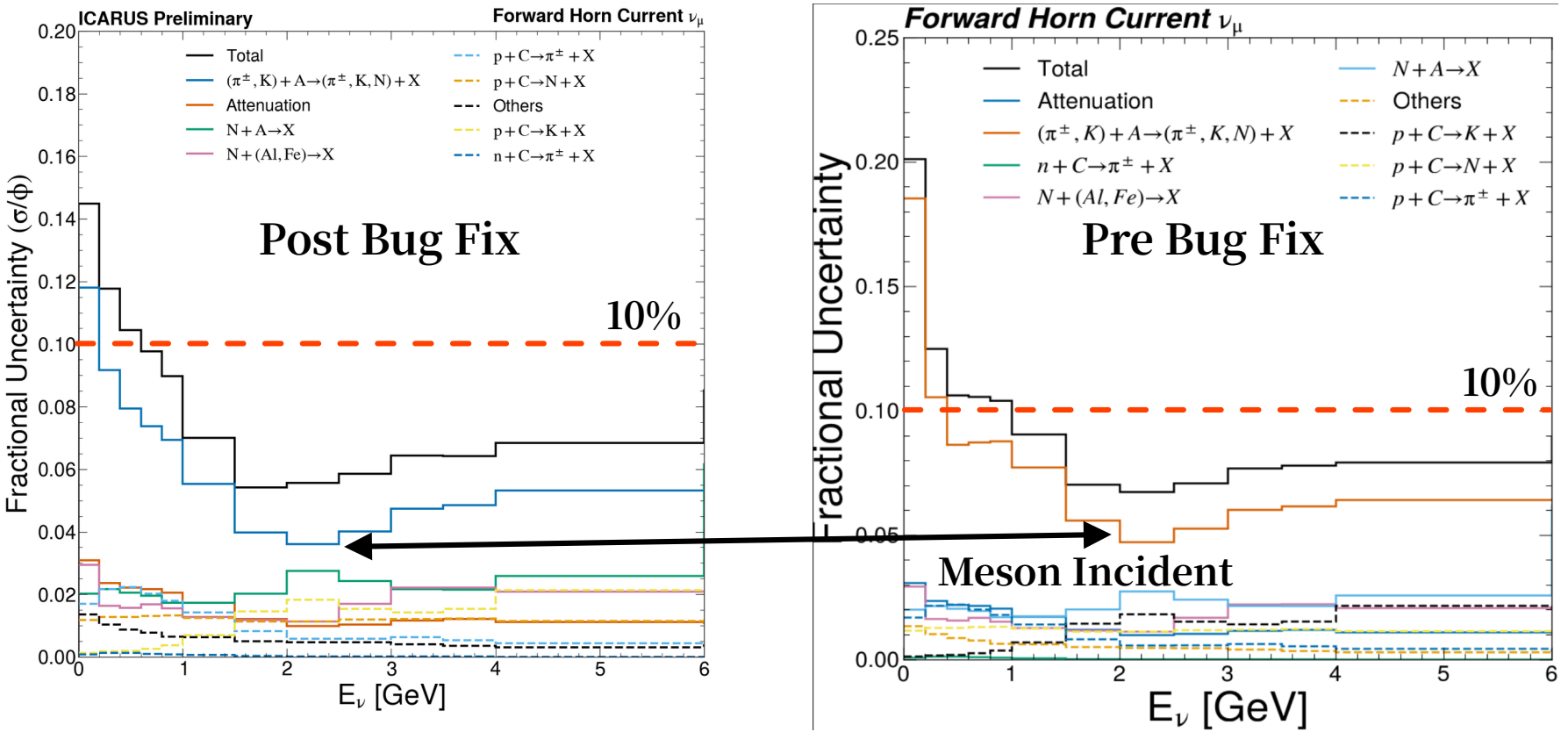
Covariance Matrices



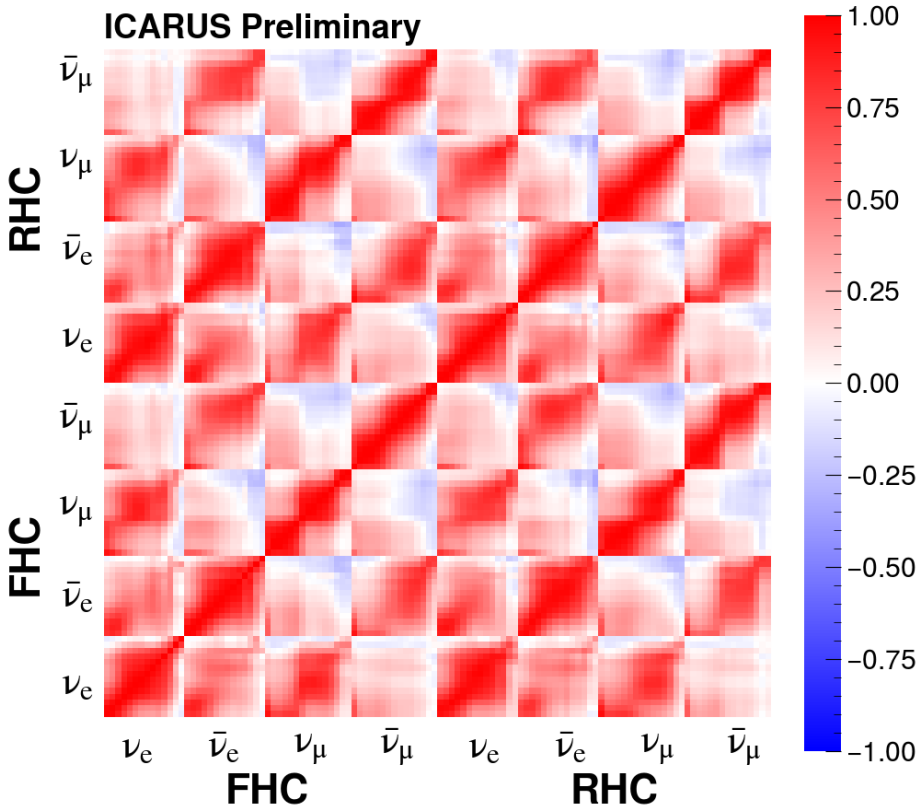


Bug Fix: Impact on Uncertainties

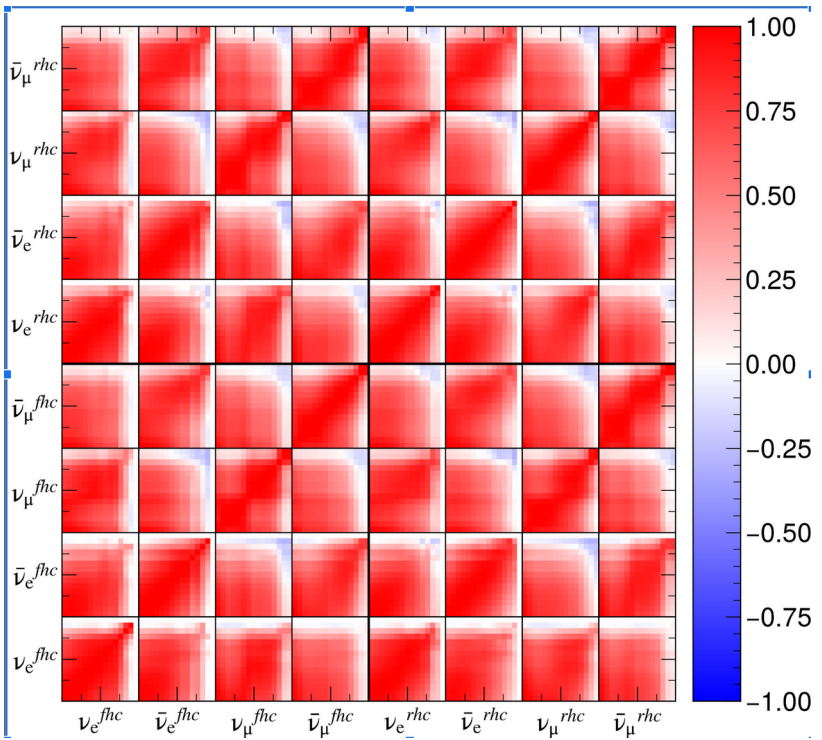


Bug Fix: Impact on Correlations

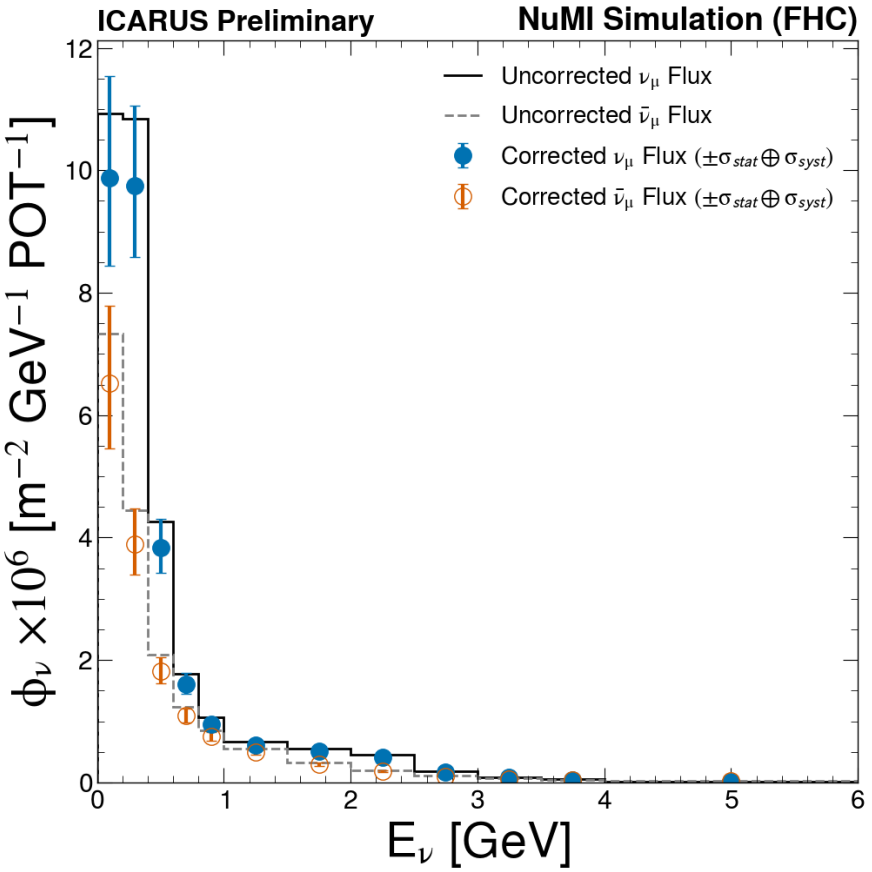
Post Bug Fix

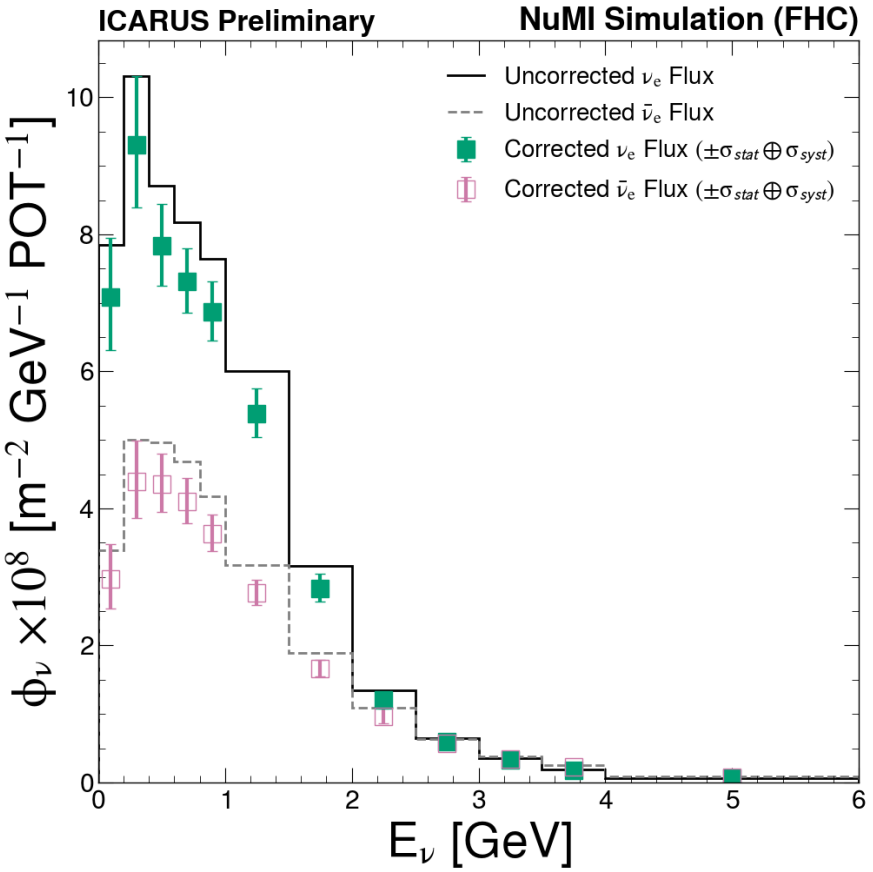


Pre Bug Fix



PPFX Corrections and Total Errors





Summary & Outlook

- Ongoing cross section and exotics program using NuMI @ ICARUS
  - Many exciting potential measurements on the horizon
  - Lots of ongoing work on reconstruction, event selection, and systematics
  - Accumulated: ~3×10^{20} POT FHC
  - Start RHC running this Fall
- NuMI flux fully characterized at ICARUS 5.75° off-axis position
  - Beamline and focusing uncertainties
  - PPFX hadron production uncertainty corrections and error bars
  - Leading uncertainties: meson interactions (2^{nd} is pA for non C nuclei)
  - Fully implemented into analysis software

} **New data samples in PPFX**

- NuMI upgraded to 1MW
  - Currently using flux ratio as correction (NOvA) / uncertainty (ICARUS)
  - Next step: regenerate all beamline systematic alterations at high statistics this Fall & rerun