NuMI at ICARUS Flux Systematic Uncertainties

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ND Prototypes Analysis Workshop
Saturday, May 20, 2023

Flux Files

`/pnfs/numix/flux/g4numi_syst_3rd_ana/test_g4numi_v6/me000z200i/minervame/run0015`

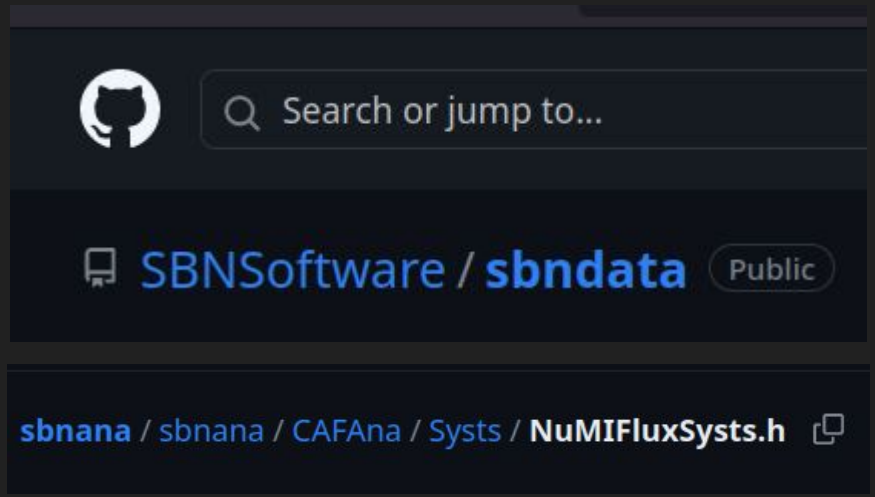
Beam focusing systematic uncertainties samples for NOvA 3rd analysis

- NOvA docDB 17608
- 700 kW configuration used in 2014–2018
- 1 MW configuration is used since 2019
  - Characterization in progress, but differences don’t exceed stats

Flux Products

Products file contains everything that will be presented today, especially:

1. Flux weights
2. Flux systematic uncertainties
    a. Covariance matrices
    b. PCA



Most recent version lives in my scratch area for now…

```
/pnfs/icarus/scratch/users/awood/numi_flux_systs_05162023/2023-05-16_out_450.37_7991.98_79512.66_QEL11.root
```

Hadron Production Systematics with PPFX

1. $\mathbf{p + C \rightarrow \pi^{\pm} + X}$
2. $\mathbf{p + C \rightarrow K + X}$
3. $\mathbf{n + C \rightarrow \pi^{\pm} + X}$
4. $\mathbf{p + C \rightarrow N + X}$
5. $\mathbf{(\pi^{\pm}, K) + A \rightarrow (\pi^{\pm}, K, N) + X}$
6. $\mathbf{N + (Al,Fe) \rightarrow X}$
7. $\mathbf{N + A \rightarrow X}$
8. **others**
9. **attenuation**

Flux universes generated from hadron interaction modelling uncertainties

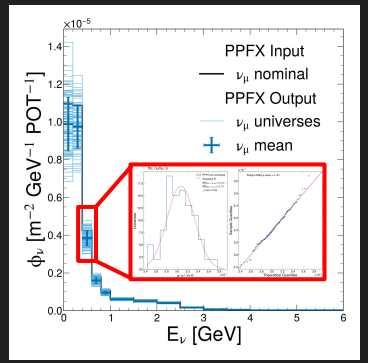
- For channels or kinematic regions with no supporting data, PPFX assigns conservative 40% uncertainty
- N + (Al, Fe) introduced specifically for ICARUS
  - Split from N + A

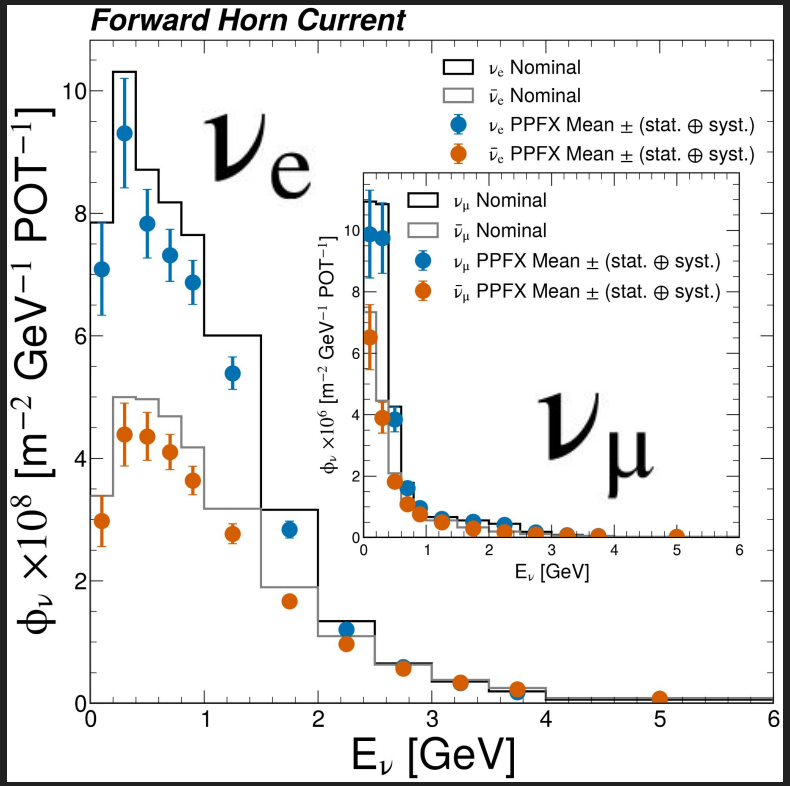
Hadron Production Systematics with PPFX

Flux prediction = PPFX mean

Hadron systematic uncertainty = sigma

PPFX weights stored in products file are calculated as the ratio of the mean to the nominal for each bin

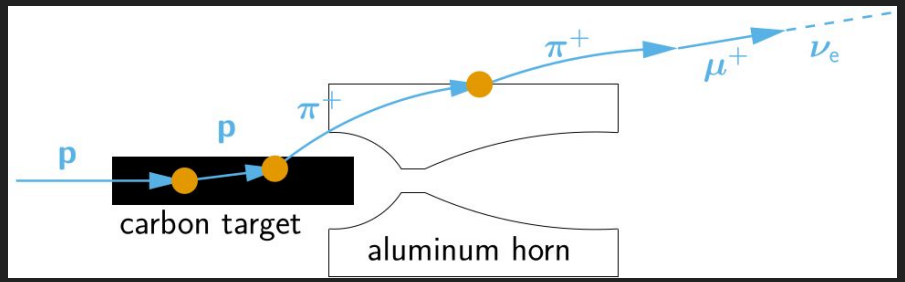


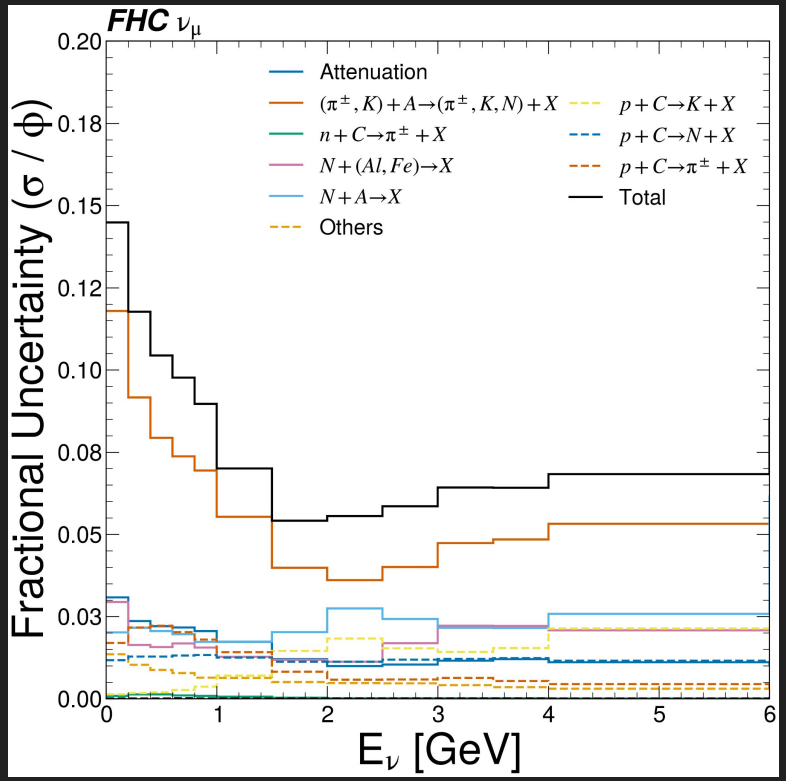


Hadron Production Systematics with PPFX

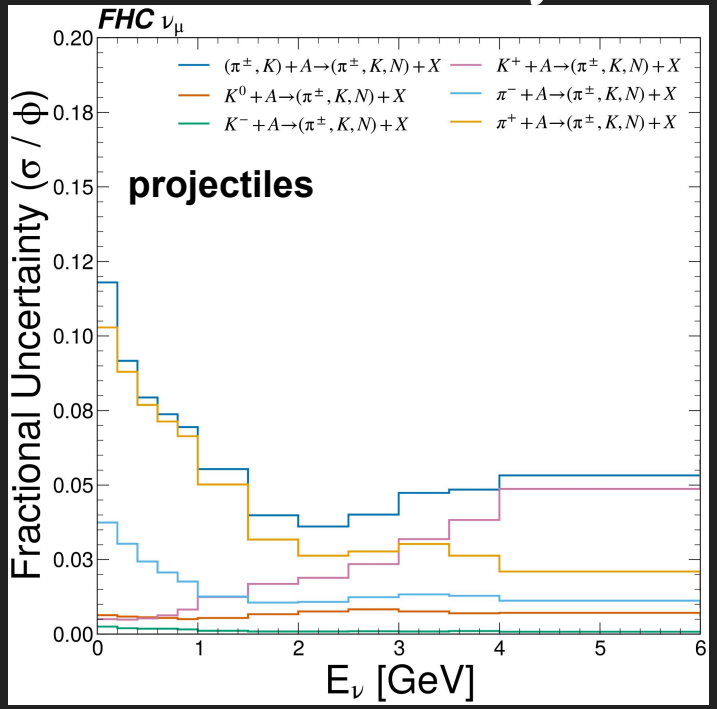
Leading uncertainty → meson interactions (solid orange)

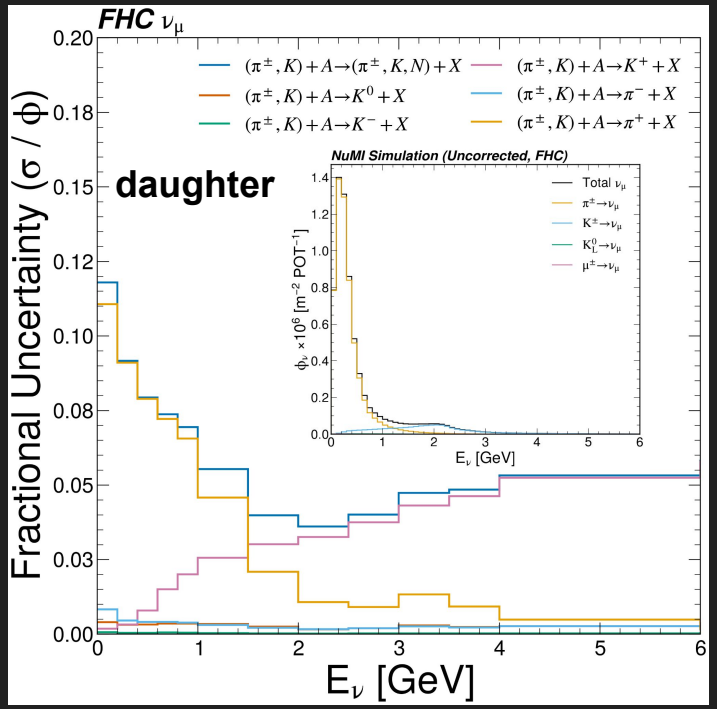
- **Parent light mesons can interact multiple times with beam structure before decaying to a neutrino**





Hadron Production Systematics with PPFX



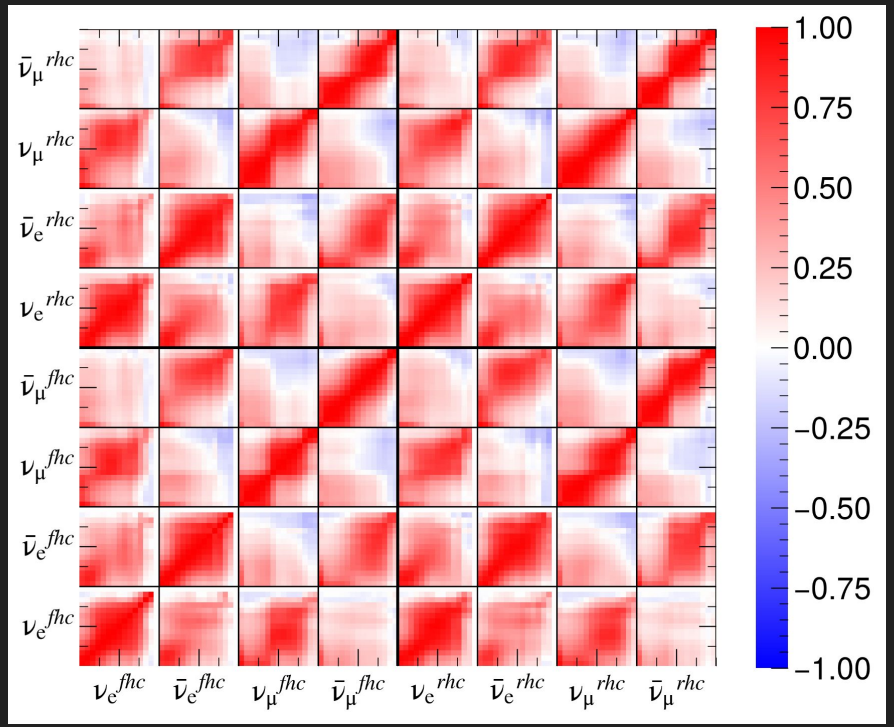


Pion/kaon uncertainties track with flux composition.

Hadron Production Systematics with PPFX

Covariance is calculated for each pair of neutrino energy-flavor bins

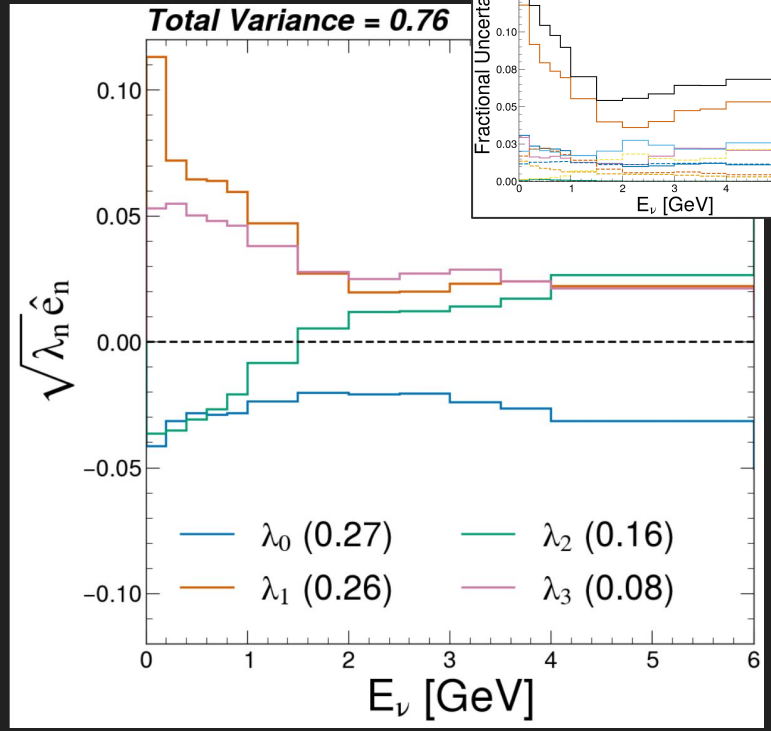
- Accounts for all effects
- Tells us how regions of the flux move together



Hadron Production Systematics with PPFX

PCA performed on the hadron covariance matrix

- Describe hadron systematics within a few PCs
- Use PCs to implement hadron systematics
  - Includes correlative effects between neutrino modes
  - Can specify the desired number of PCs at analysis level



Beam Systematics

Compute fractional shifts from nominal followed by covariance matrix

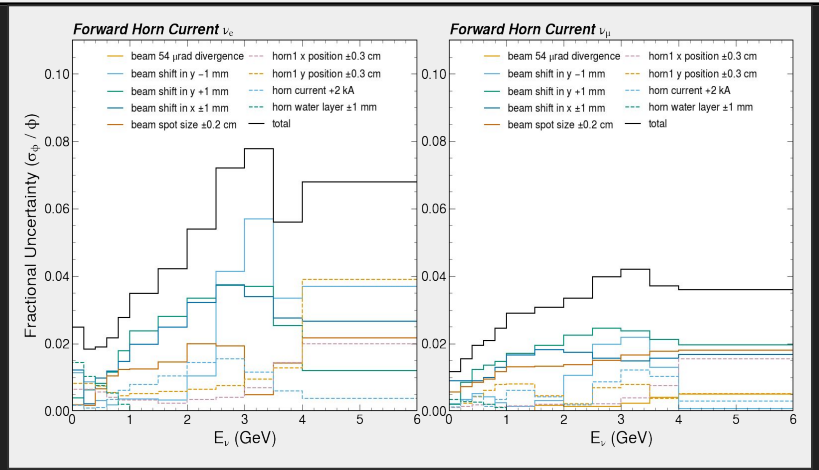
- Excluded systematics smaller than statistical uncertainties

This MC doesn't exist for the new beam geometry used for 2x2

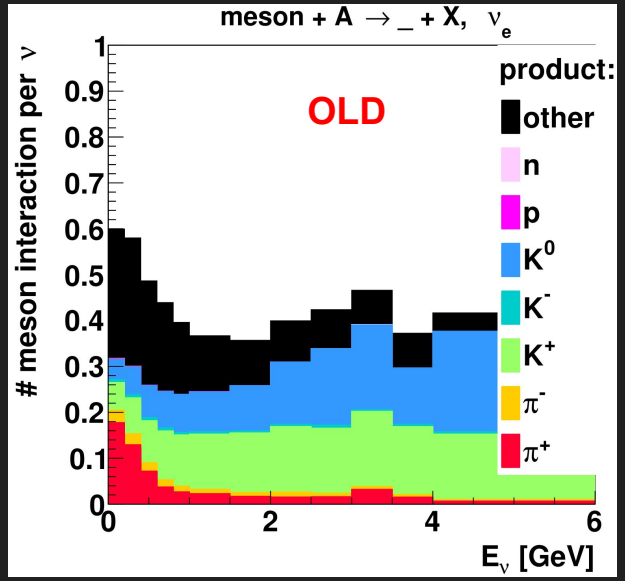
Either:

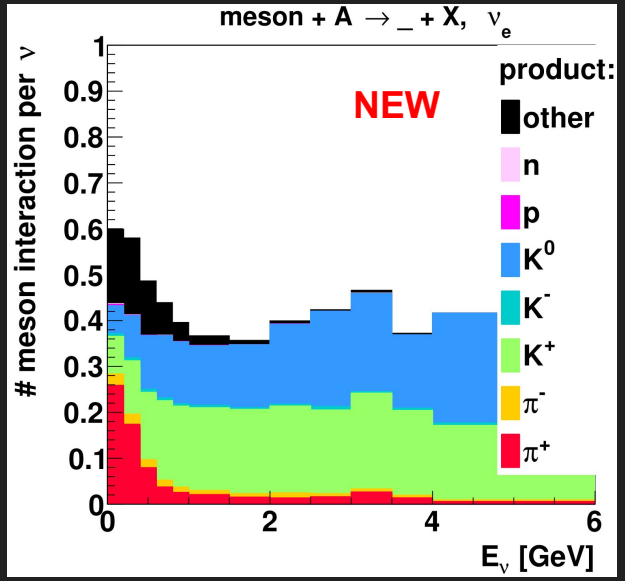
1. Generate beam systs
2. Revert to old geometry and reweight

Run ID	Description	Inclusion Status
8 – 9	horn current ±2 kA	−2 kA **excluded**
10 – 13	horn1 x/y ±0.3 cm	included
15	nominal configuration	N/A
14 – 16	beam spot size ±0.2 cm	included
17 – 20	horn2 x/y ±0.3 cm	**excluded**
22 – 23	horn water layer ±1 mm	**excluded** > 1 GeV
24 – 27	beam shift x/y ±1 mm	included
28 – 29	target z ±7 mm	**excluded**
30	B-field in decay pipe	**excluded**
32	54 μrad beam divergence	**excluded** < 1 GeV



Feynman-X Calculation Bug Fix





xF bug pushed many interactions into the “Other” category, creating strong correlations

For more details https://indico.fnal.gov/event/59606/#5-bug-fix

Integrated Flux Uncertainty

0 – 20 GeV		Uncertainty (%)						
		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	5.86	6.76	5.77	10.74	11.27	9.45	6.92
	RHC	6.63	5.84	5.76	11.32	10.19	9.08	6.83
Beam	FHC	2.80	1.78	2.35	1.62	1.56	1.15	1.47
	RHC	1.32	1.75	1.06	1.21	2.66	1.62	1.54
Statistical	FHC	0.19	0.27	0.16	0.05	0.08	0.05	0.16
	RHC	0.24	0.22	0.16	0.08	0.05	0.05	0.17
Total	FHC	6.50	6.99	6.23	10.86	11.38	9.52	7.08
	RHC	6.76	6.10	5.86	11.38	10.53	9.22	7.00

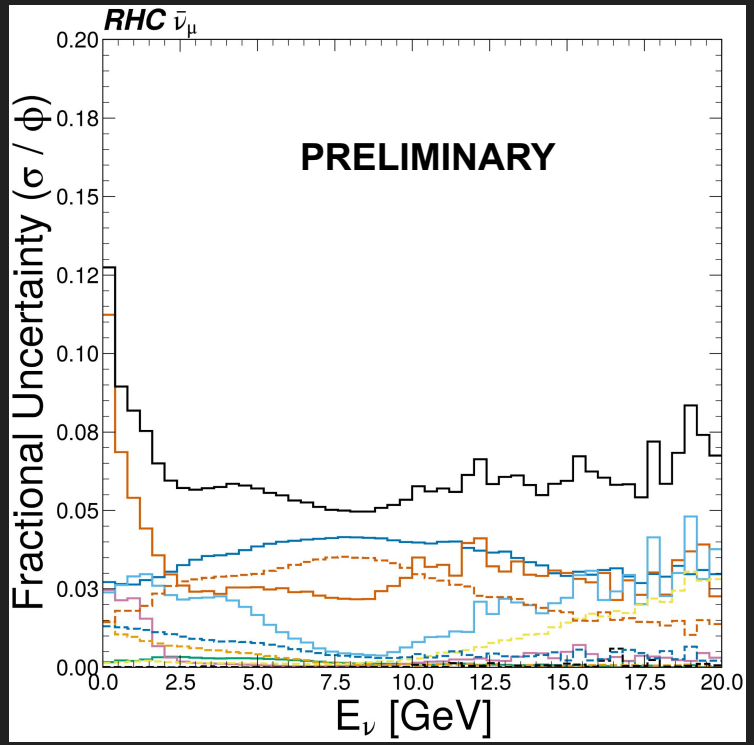
Calculated integrated uncertainties using stats + beam cov + hadron cov

Summary

The Houston group is starting a work-up on the NuMI flux for the DUNE 2x2, similar to what was done for ICARUS

What other studies would you like to see?

Thanks for listening!



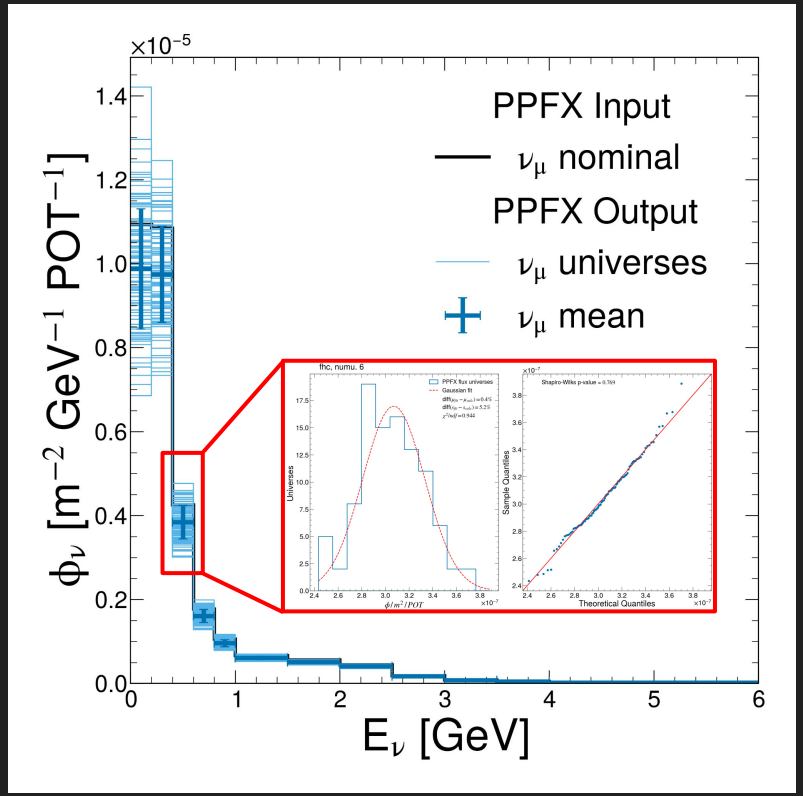
Backup

Hadron Production Systematics with PPFX

Flux prediction and systematics estimation are based on assumption that PPFX universe distribution is normal in each bin

3 methods to verify normality

- Compared calculated mean/sigmas vs. fit parameters
- Shapiro-Wilk statistic
- QQ-plot demonstrating the true distribution vs. the distribution sampled from a Gaussian of the same mean/sigma



Beam Systematics

Compute fractional shifts from nominal

- Some basic smoothing applied to tame stat fluctuations

Kept regions larger than statistical uncertainty (post-smoothing)

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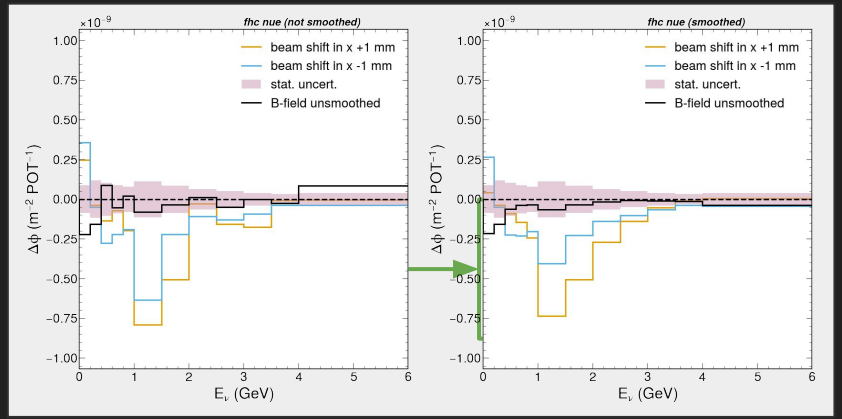
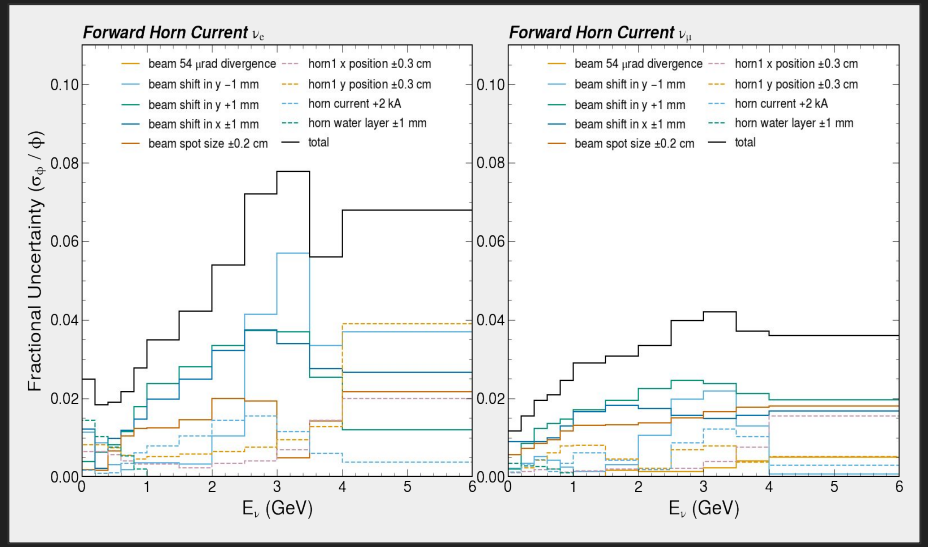


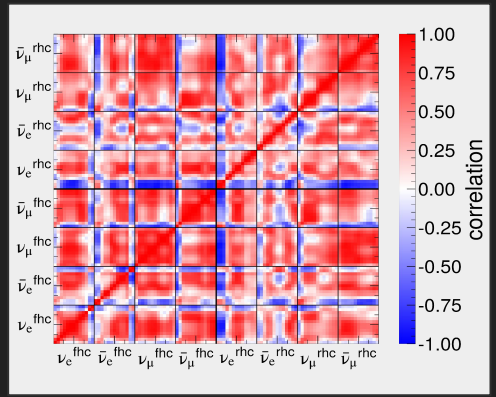
Beam Systematics

Covariances/uncertainties calculated from remaining spectra

Sub-dominant to hadron systs

- Inflated uncertainties driven by low statistics
- To characterize more robustly, we would need higher statistics beam MC





Feynman-X Calculation Bug Fix

- Formulae from PDG, Sec 49.2:

where θ is the angle between the particles. In the frame where one particle (of mass m_2) is at rest (lab frame),

$$E_{\rm cm} = (m_1^2 + m_2^2 + 2E_{1\,\rm lab}\, m_2)^{1/2} \ . \tag{49.3}$$

The velocity of the center-of-mass in the lab frame is

$$\boldsymbol{\beta}_{\rm cm} = \boldsymbol{p}_{\rm lab}/(E_{1\,\rm lab} + m_2) \ , \tag{49.4}$$

where $\boldsymbol{p}_{\rm lab} \equiv \boldsymbol{p}_{1\,\rm lab}$ and

$$\gamma_{\rm cm} = (E_{1\,\rm lab} + m_2)/E_{\rm cm} \ . \tag{49.5}$$

- When calculating x_F in interactions in the beam, PPFX assumes the mass of the target m_2 is the same as the mass of the projectile m_1
- As a result, for light mesons, x_F is underestimated, and often pushed towards negative, even non-physical values