The MINERνA Flux Prediction

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On behalf of the MINERvA Collaboration

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The 13th International Workshop on Neutrino-Nucleus Interactions in the Few GeV Regions

Seoul National University, Seoul, Korea

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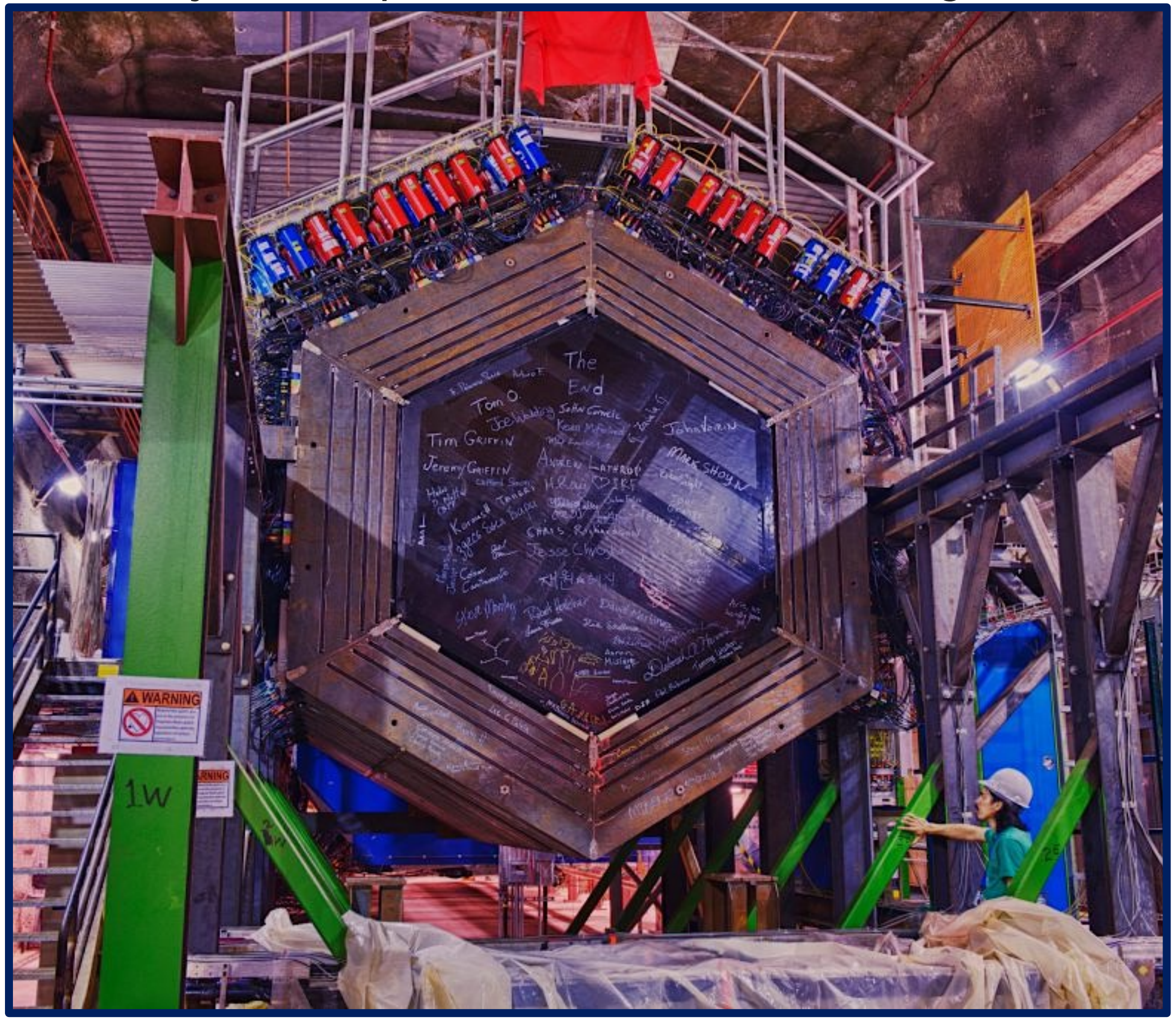
Flux @ MINERvA

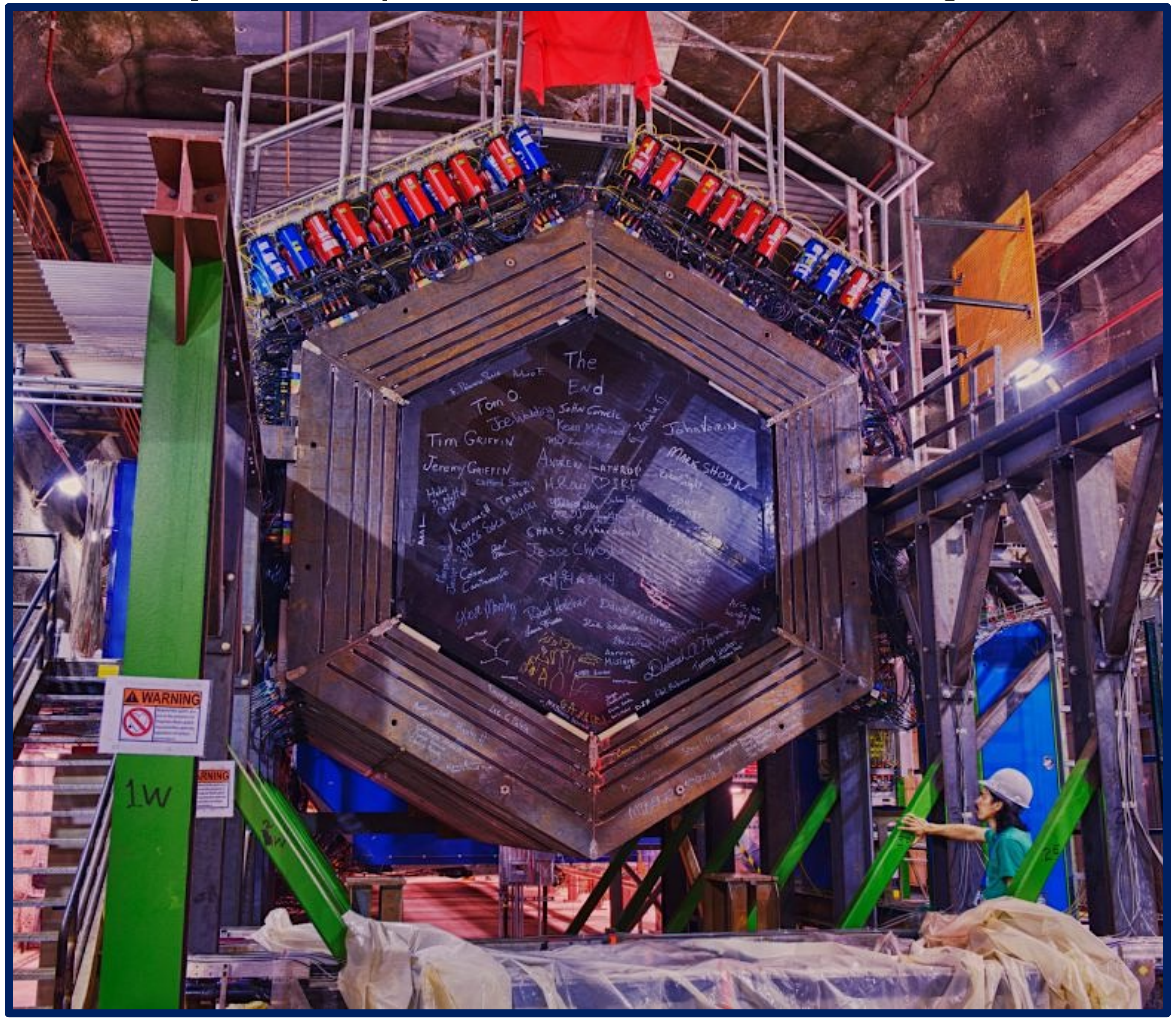
***M**ain **IN**jector **E**xpe**R**iment for ν-**A** scattering*



- The only currently active **neutrino cross-section experiment with high-statistics**, controlled systematics, different nuclear targets, and access to the DIS region
- 2009-2019 on axis in the **NuMI beamline** at Fermilab in 2 flux periods with 3.5 and 6 GeV flux peak, both in $\nu/\bar{\nu}$

Flux @ MINERvA

***M**ain **IN**jector **E**xpe**R**iment for **ν-A** scattering*



- **Dedicated flux campaign** with corrections to a-priori flux and in-situ measurements
  - Neutrino-nucleus scattering with low hadronic recoil
    - A. Bashyal et al. *JINST* **16** P08068 (2021)
  - Neutrino-electron elastic scattering
    - E. Valencia et al. Phys. Rev. D 100, 092001 (2019)
  - Inverse muon decay (IMD)
    - D. Ruterbories et al. Phys. Rev. D 104, 092010 (2021)
  - Combined constraint using $\nu/\bar{\nu}$-electron scattering and IMD
    - L. Zazueta et al. Submitted for publication, [hep-ex]:2209.05540 (2022)

MINERvA Detector

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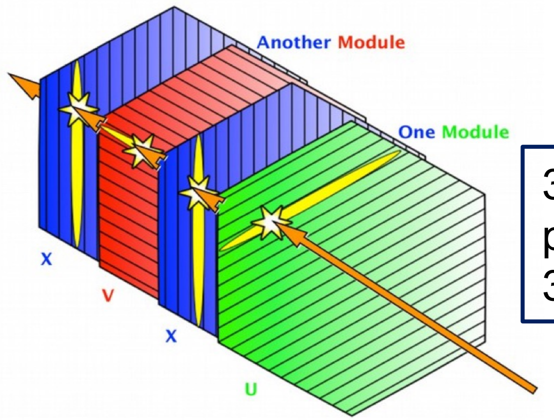
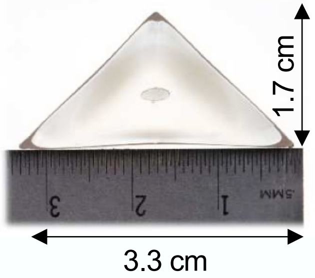
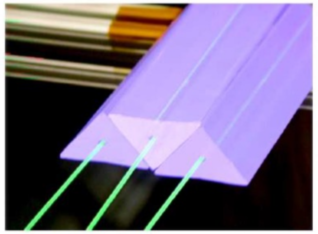


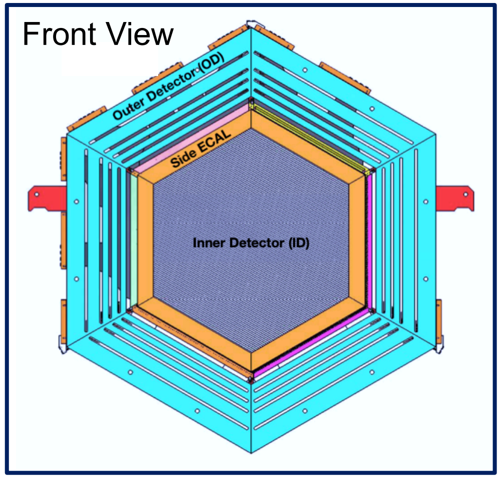
3 orientations of scintillator planes give unambiguous 3D track reconstruction.

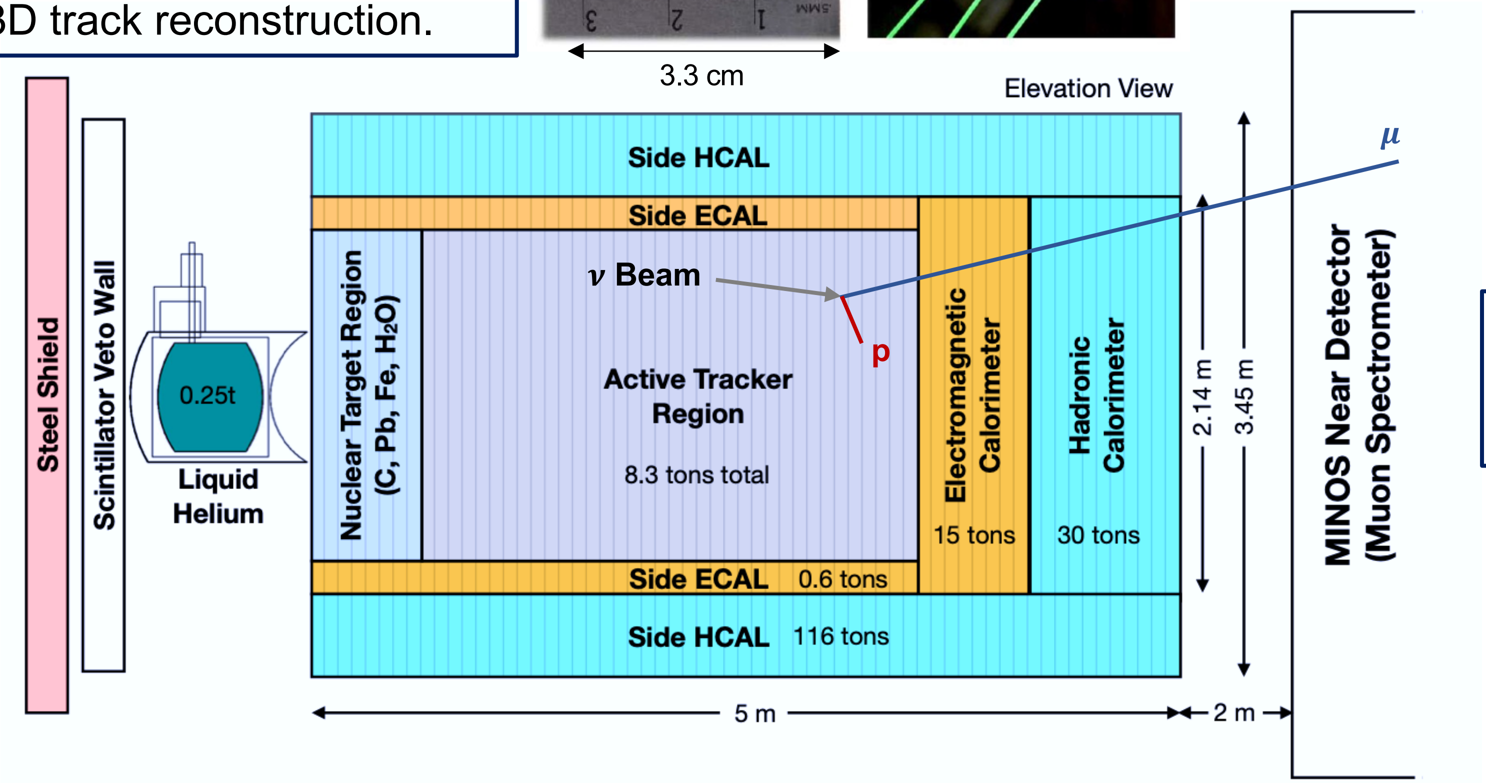
Triangular strips arranged to give a better position resolution.





Read out using wavelength-shifting (WLS) fibres and photomultiplier tubes (PMTs): timing resolution better than ~5 ns to distinguish overlapping events within a single spill (< 10 μs).





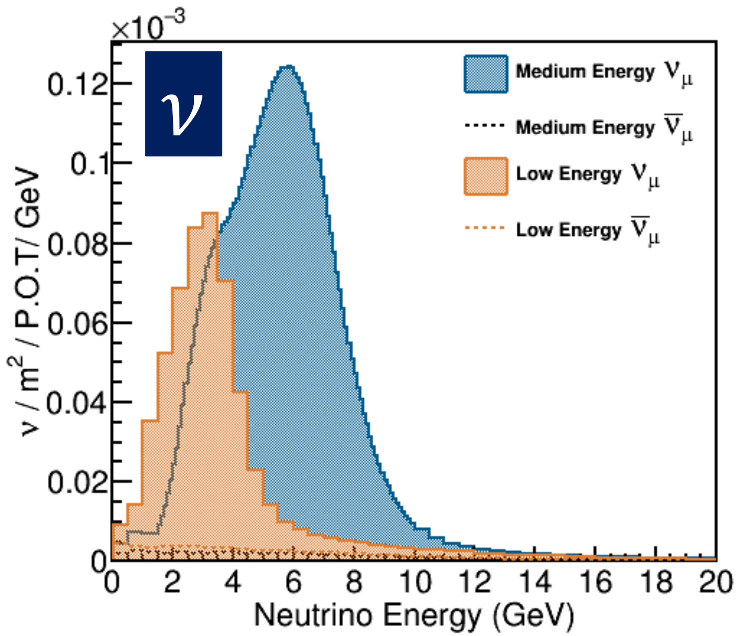
MINOS spectrometer: muon momentum and charge.

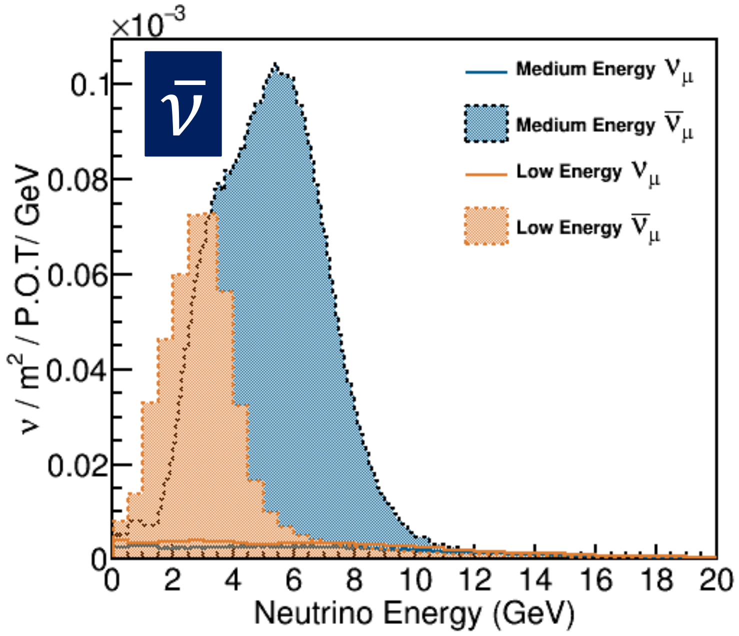
NuMI Flux

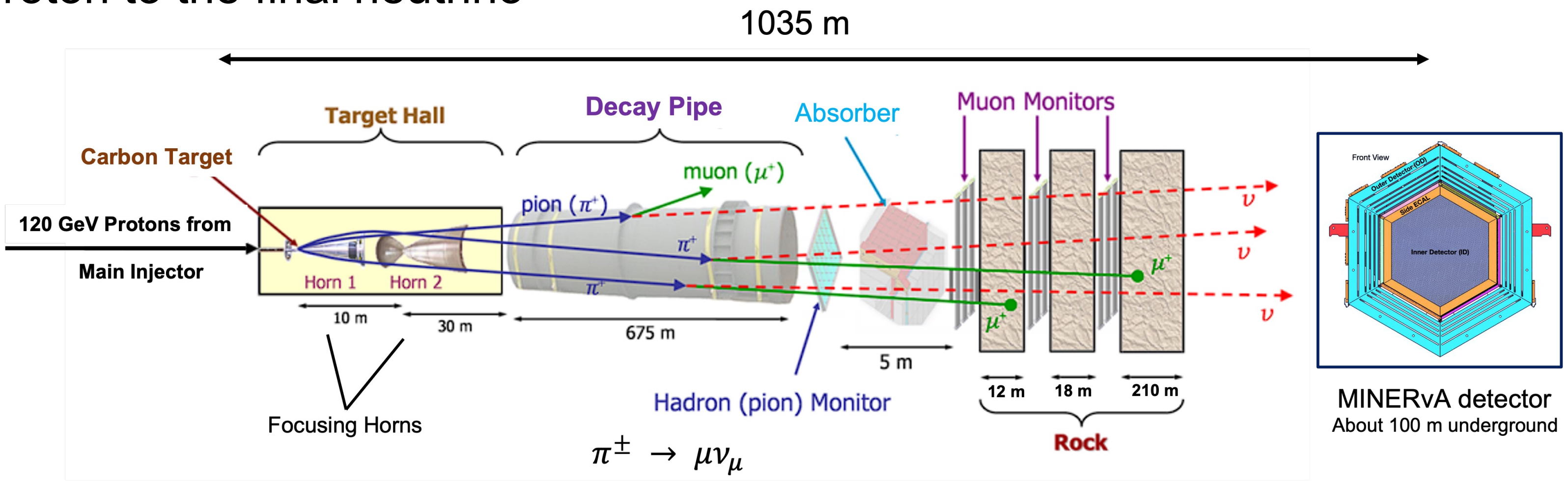
- 2 flux periods with 3.5 and 6 GeV flux peak, both in $\nu/\bar{\nu}$

Regime \ Mode	ν (POT)	$\bar{\nu}$ (POT)
Low (LE) ~ 3.5 GeV	4×10^{20}	1.7×10^{20}
Medium (ME) ~ 6 GeV	12.1×10^{20}	12.4×10^{20}

- Need to understand each step from the primary proton to the final neutrino







$$\pi^{\pm} \rightarrow \mu\nu_{\mu}$$

$$K^{\pm} \rightarrow \mu\nu_{\mu}$$

Simulation & Uncertainties

1. Calculate and correct the a-priori flux

G4NuMI beam simulation (from 120 GeV protons to focused mesons that decay to neutrinos) → Hadron production correction using external data - PPFX (NA49, MIPP) → Focusing and hadron production uncertainties (multi-universe method)

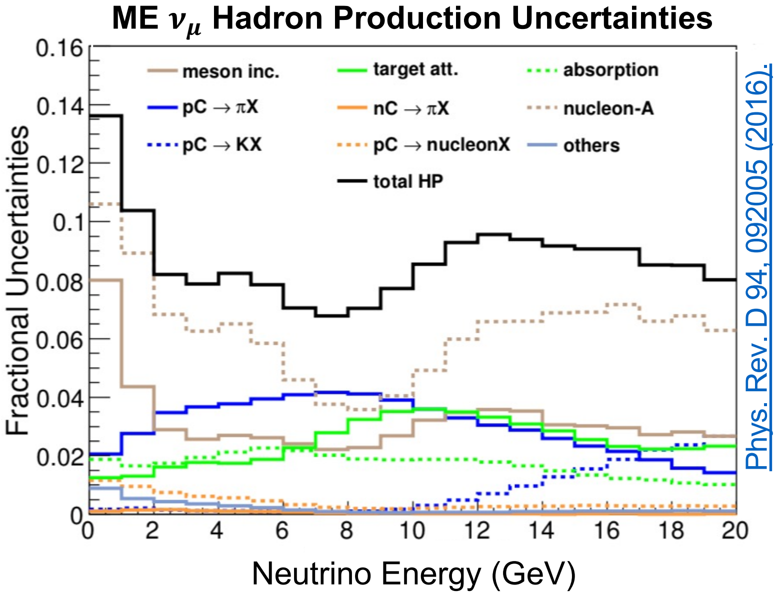
↓

2. Use in-situ measurements

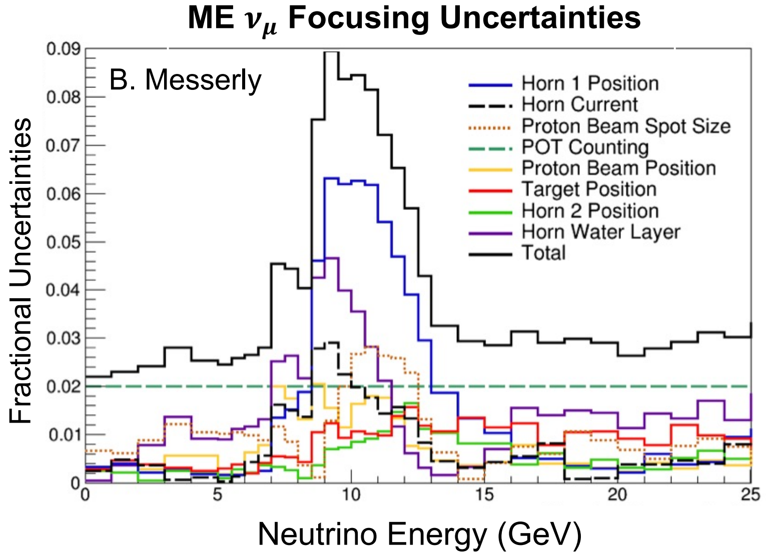
Flux shape correction (low recoil neutrino scattering)

↓

Flux normalization correction (scattering off atomic electrons)



Phys. Rev. D 94, 092005 (2016).



Small simulation inaccuracies have a big impact around the focusing peak!

In situ Measurements To Constrain Flux

Imperial College London

1. **Neutrino-nucleus scattering with low hadronic recoil**
2. (Anti)Neutrino-electron elastic scattering
3. Inverse muon decay (IMD)
4. Combined constraint using $\nu/\bar{\nu}$-electron and IMD

Neutrino-Nucleus Scattering w/ Low Hadronic Recoil

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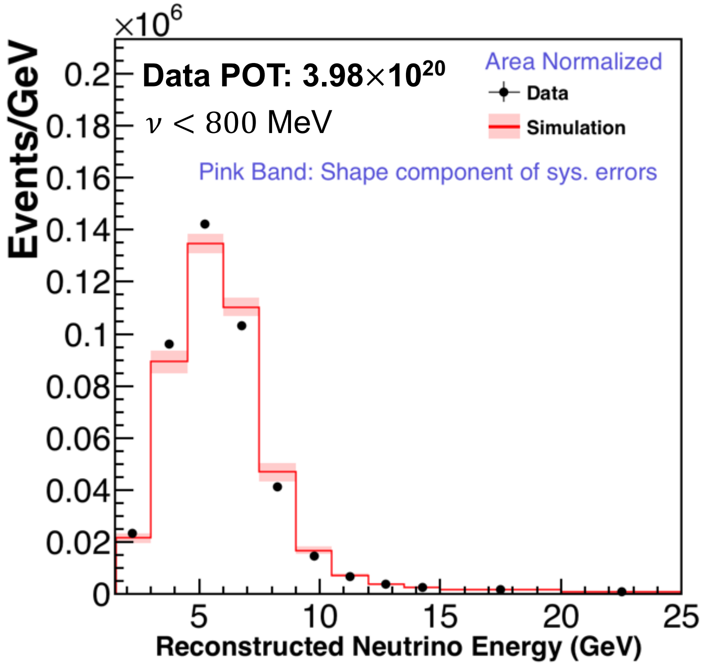
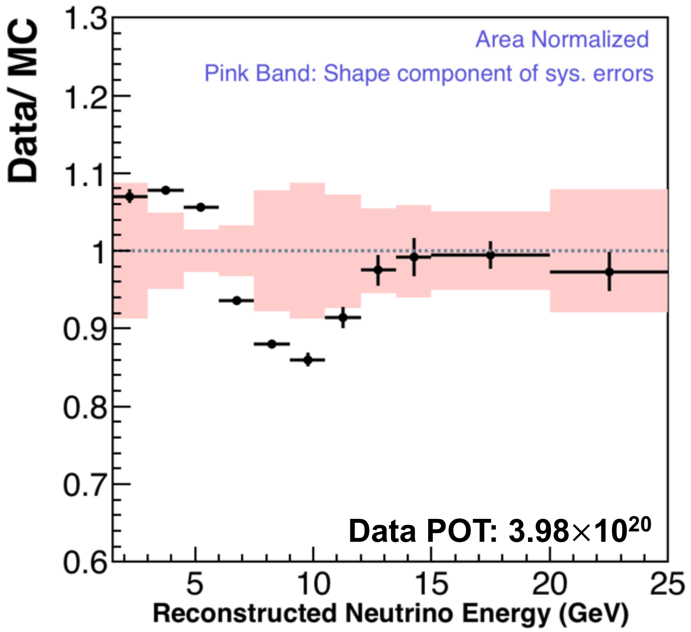
- CC ν_μ inclusive cross-section if ν/E_ν small ∝ const. and independent of energy

$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{\nu}{E_\nu}\left[F_2 + xF_3\right] + \frac{\nu}{2E_\nu^2}\left[\frac{Mx(1-R_L)}{1+R_L}F_2\right] + \frac{\nu^2}{2E_\nu^2}\left[\frac{F_2}{1+R_L} + xF_3\right]\right) dx$$

- Can measure **the shape of neutrino flux** by measuring the event rate(E_ν)





Discrepancies between data and MC predictions → due to mismodeling of our **focusing parameters** or **instrumental**.

JINST **16** P08068 (2021).

Flux Fit w/ Focusing Parameters

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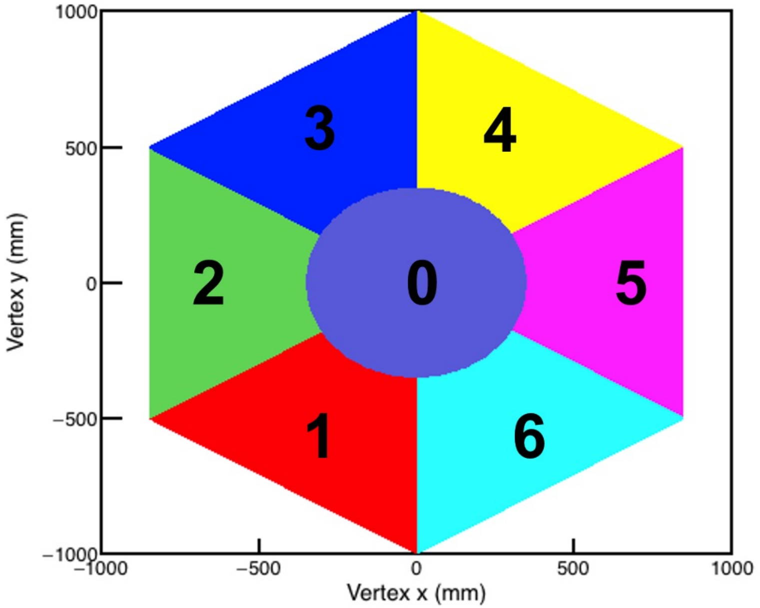
- Multi-parameter fit with focusing parameters to investigate the discrepancy
- Shifts in focusing parameters not uniform across the face of the detector → fit in 7 bins (and merge later)
- Fit suggests **large shifts** in **longitudinal target position** and **horn current**
- NuMI experts are confident the parameters were within the tolerance

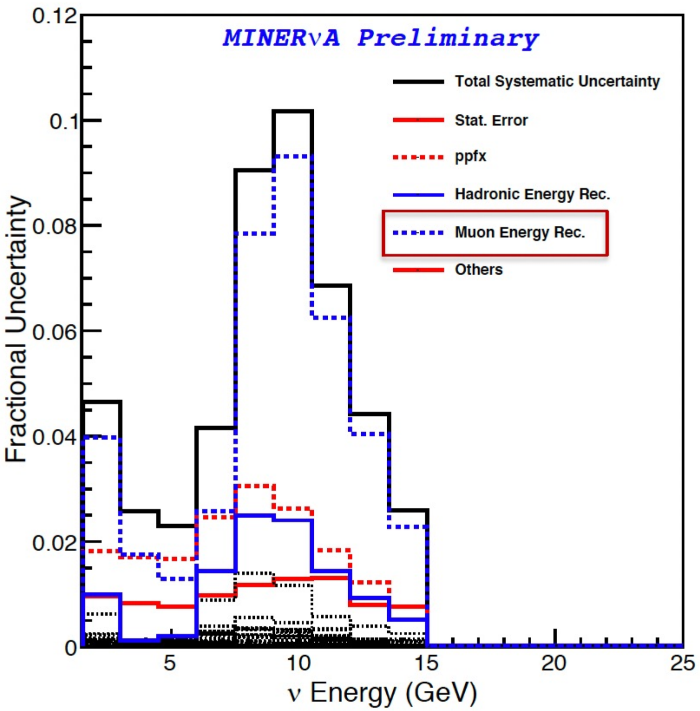
	Parameter	Nominal Value	New Value
	Beam Position (X)	0 mm	-0.2 ± 0.12 mm
	Beam Position (Y)	0 mm	-0.53 ± 0.14
	Beam Spot Size	1.5 mm	1.22 ± 0.14 mm
	Horn Water Layer	1 mm	0.895 ± 0.16 mm
2.6σ	Horn Current	200 kA	197.41 ± 0.76 kA
	Horn 1 Position (X)	0 mm	0. ± 0.17 mm
	Horn 1 Position (Y)	0 mm	-0.39 ± 0.17 mm
	Target Position (X)	0 mm	-0.32 ± 0.17 mm
	Target Position (Y)	0 mm	1.65 ± 0.5 mm
>10σ	Target Position (Z)	-1433 mm	-1419.44 ± 1.83 mm

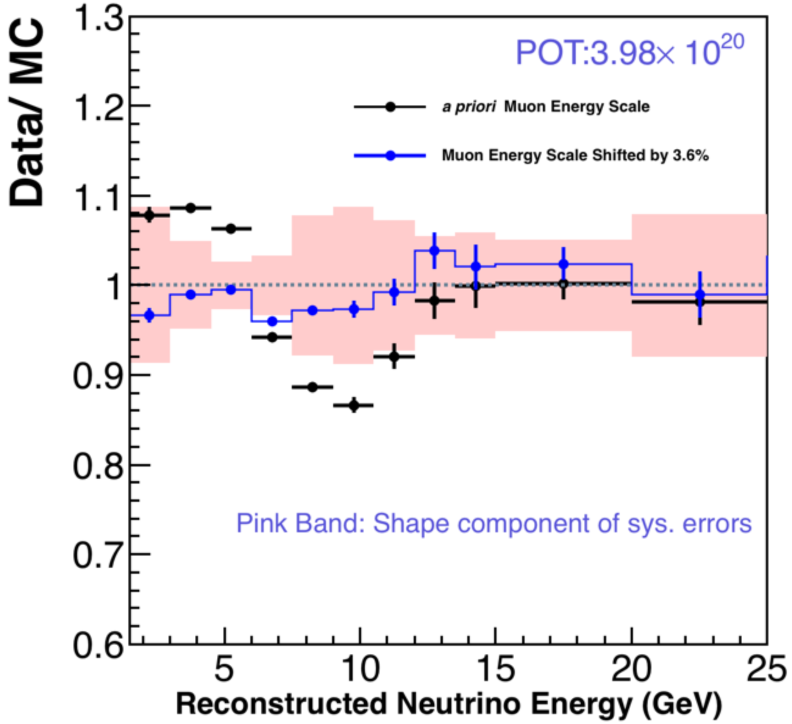
Note: X horizontal, Y vertical, Z longitudinal (along the beam)



An Instrumental Effect?

- Flux fit **sensitive to muon energy reconstruction**
- Added muon energy scale as a fitting parameter along with focusing parameters
- **Shift of 1.8σ in muon energy scale resolves the data/MC discrepancy**, other parameters within their standard deviations
- **MINERvA analyses shift muon energy scale in data by 1.8σ (3.6% of the nominal value)**
    - No shift to focusing parameters





Parameter	Nominal	Best Fit (No Prior)	Best Fit (Prior)
Beam Position (X)	0.0 mm	$-0.3 \pm 0.3 \pm 0.1$ mm	$-0.3 \pm 0.2 \pm 0.1$ mm
Beam Position (Y)	0.0 mm	$0.8 \pm 0.3 \pm 0.3$ mm	$0.7 \pm 0.2 \pm 0.2$ mm
Target Position (X)	0.0 mm	$-0.8 \pm 0.3 \pm 0.1$ mm	$-0.8 \pm 0.3 \pm 0.1$ mm
Target Position (Y)	0.0 mm	$2.3 \pm 0.7 \pm 1.2$ mm	$1.7 \pm 0.6 \pm 0.8$ mm
Target Position (Z)	-1433 mm	$-1432.4 \pm 2.4 \pm 0.3$ mm	$-1431 \pm 1.8 \pm 0.3$ mm
Horn 1 Position (X)	0.0 mm	$-0.3 \pm 0.4 \pm 0.5$ mm	$-0.1 \pm 0.3 \pm 0.1$ mm
Horn 1 Position (Y)	0.0 mm	$0.1 \pm 0.5 \pm 0.5$ mm	$0.0 \pm 0.3 \pm 0.3$ mm
Beam Spot Size	1.5 mm	$1.41 \pm 0.09 \pm 0.03$ mm	$1.32 \pm 0.09 \pm 0.03$ mm
Horn Water Layer	1.0 mm	$1.2 \pm 0.3 \pm 0.05$ mm	$1.3 \pm 0.25 \pm 0.1$ mm
Horn Current	200 kA	$198.0 \pm 1.4 \pm 1.4$ kA	$199.1 \pm 0.7 \pm 0.5$ kA
Muon Energy Scale	1.0	$1.032 \pm 0.004 \pm 0.008$	$1.036 \pm 0.004 \pm 0.006$

1.8σ

In situ Measurements To Constrain Flux

Imperial College London

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2. **(Anti)Neutrino-electron elastic scattering**
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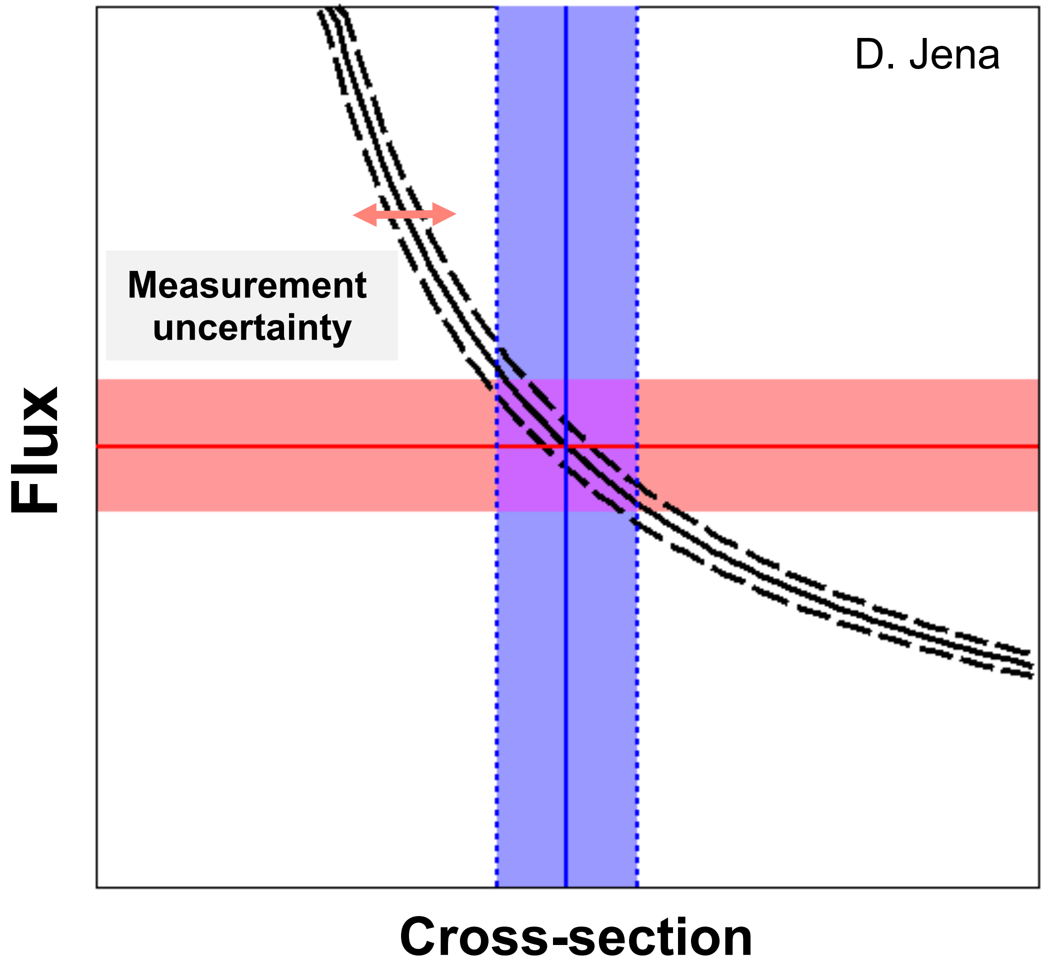
(Anti)Neutrino-Electron Elastic Scattering

- MINERvA uses the **standard candle for flux estimate** – (anti)neutrino-electron elastic scattering **BOTH in anti/neutrino beam in medium energy**

$$\nu_\mu + e \rightarrow \nu_\mu + e$$

$$\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$$

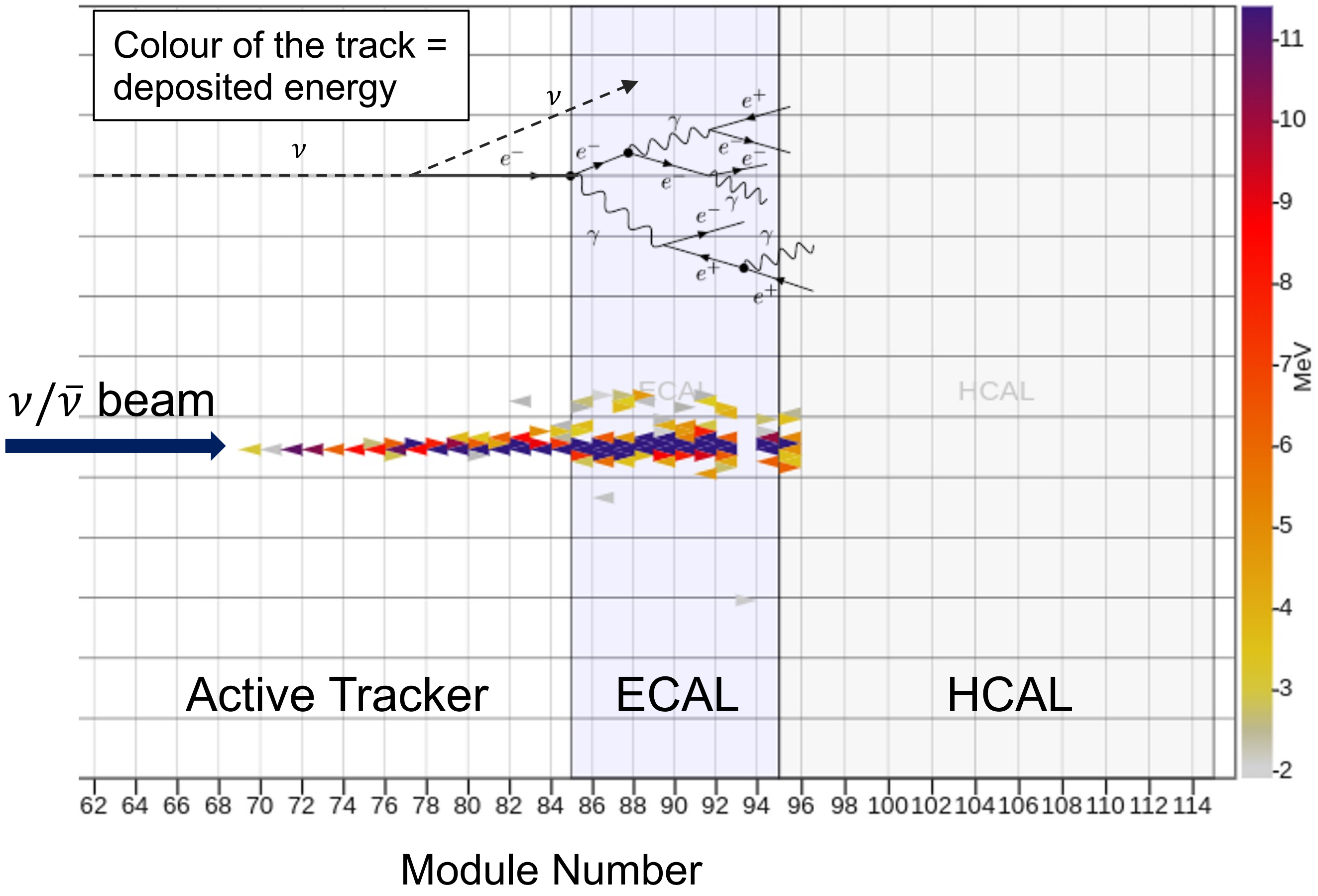
- Cross-section **precisely predicted** by the standard electroweak scattering theory
- **Limited statistics**: three orders of magnitude smaller than neutrino-nucleus cross-section
- Final state distribution of electron energies – **constraint on integrated flux** (improvement in normalization uncertainty)



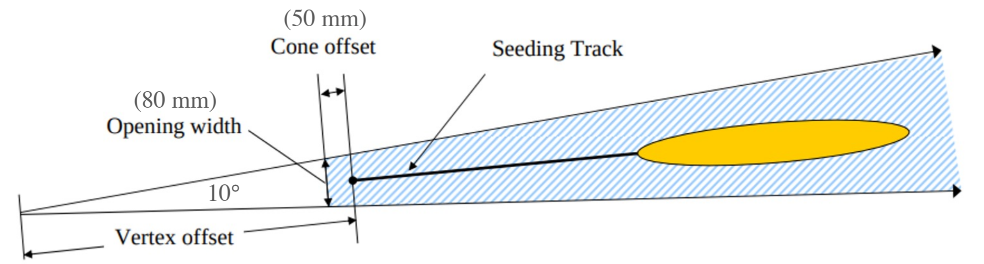
$$\text{Cross-section} = \frac{\text{\# of events}}{\text{Acceptance} \times \text{efficiency} \quad \text{Flux}}$$

Experimental Signature

- Very forward electromagnetic shower with vertex in the scintillator tracker and no other activity

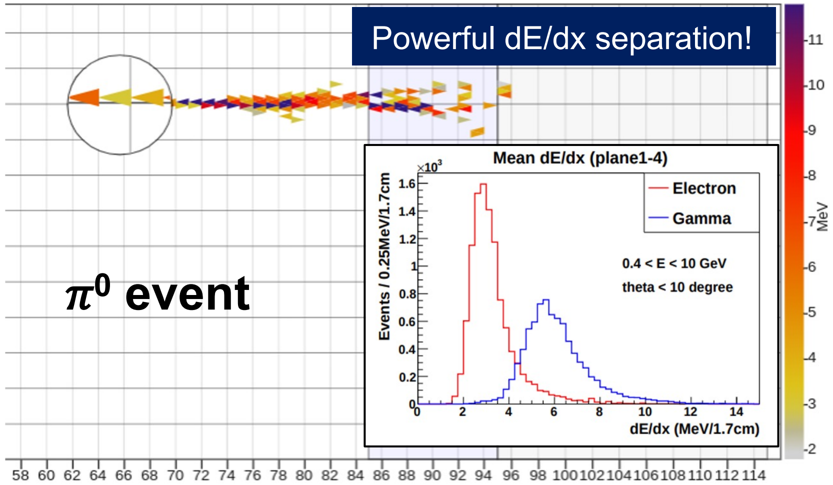


- Candidates reconstructed using cone algorithm



Main Background Rejection

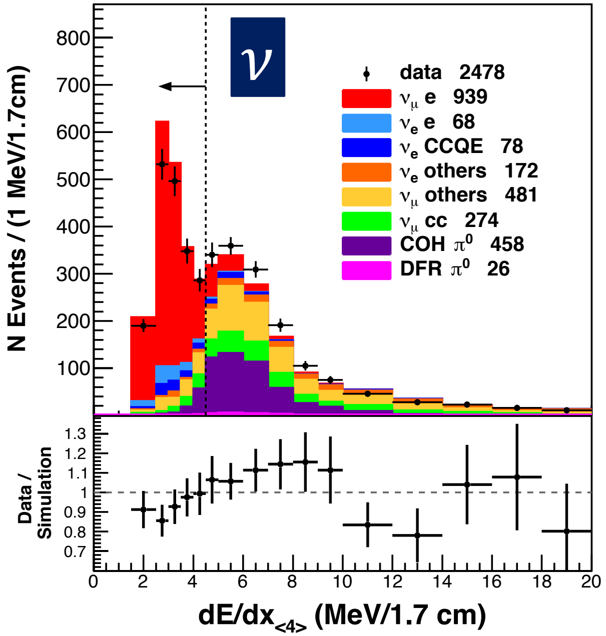
1. Photon background from π^0 vs EM shower pair production (signal)
   - Deposited energy per unit length dE/dx



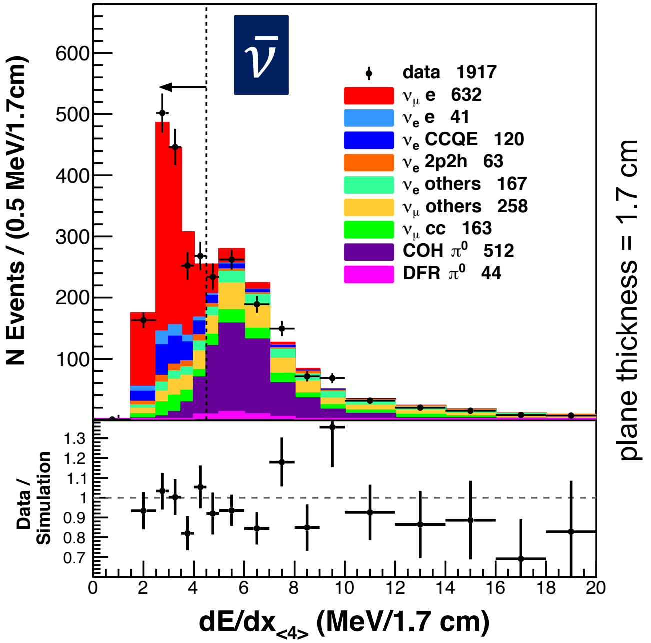
2. Kinematics of neutrino-electron elastic scattering

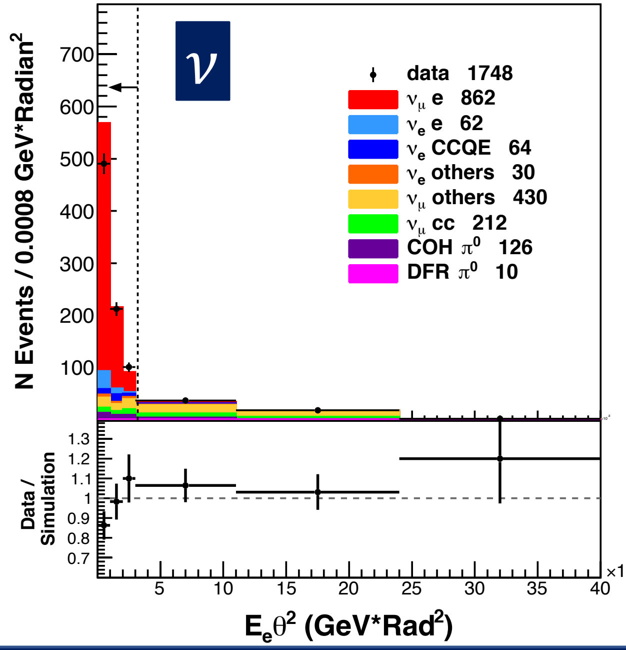
$$E_e\theta_e^2 < 2m_e$$

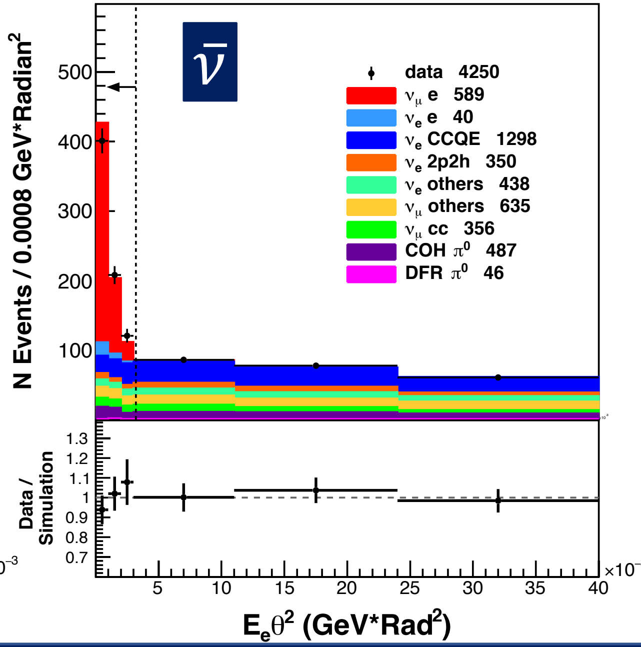
[Phys. Rev. D 100, 092001 (2019).]



[Submitted for publication, [hep-ex]:2209.05540.]



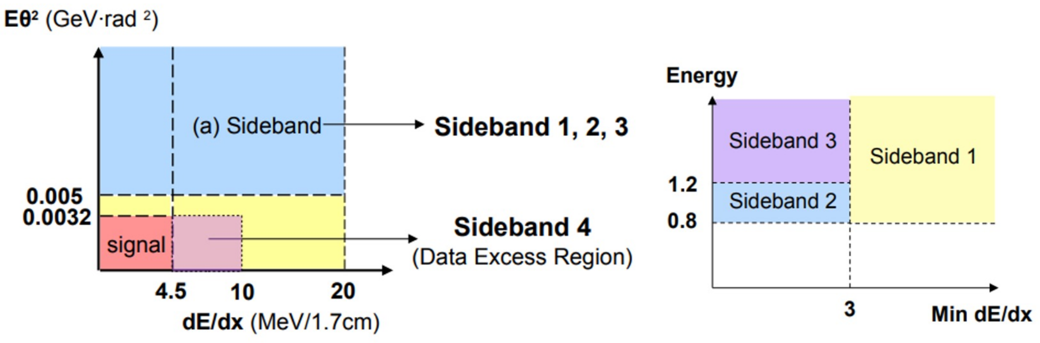




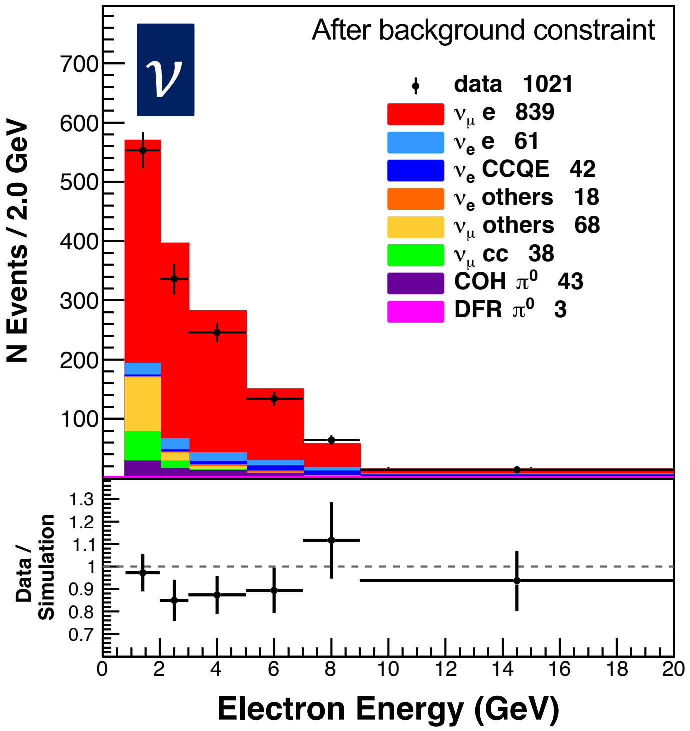
Background Prediction & Selected Sample

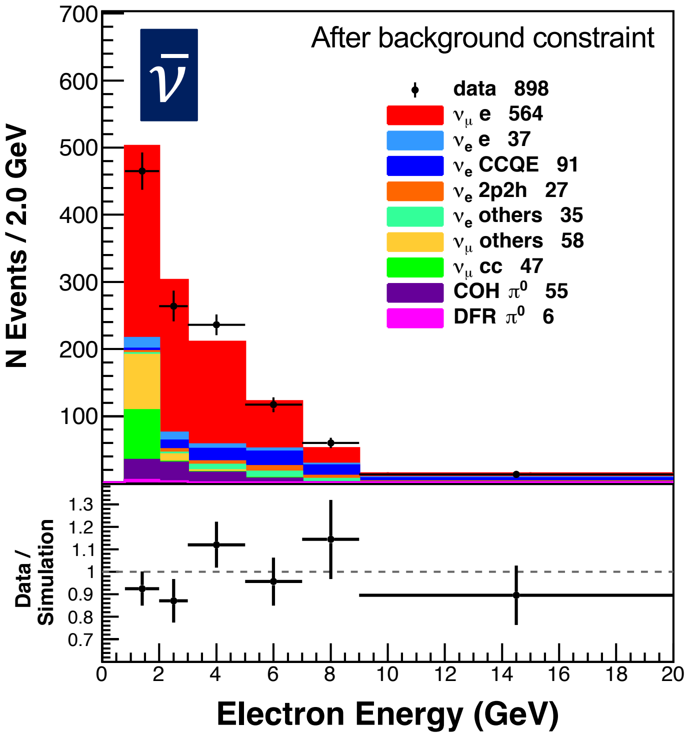
- Background predicted by the simulation – main source of uncertainty
- Constrained by simultaneous fit to 4 kinematic sidebands
  - Single normalization factor for ν_e, ν_μ CC, ν_μ NC
  - Normalization of coherent π^0 in 6 bins of electron energy

Background type		ν-mode		$\bar{\nu}$-mode
ν_μ neutral current coherent & diffractive π^0	}	~ 50%	/	~ 50%
ν_μ charged current	}	~ 20%	/	~ 35 %
ν_e interactions	}	~ 30 %	/	~ 15 %



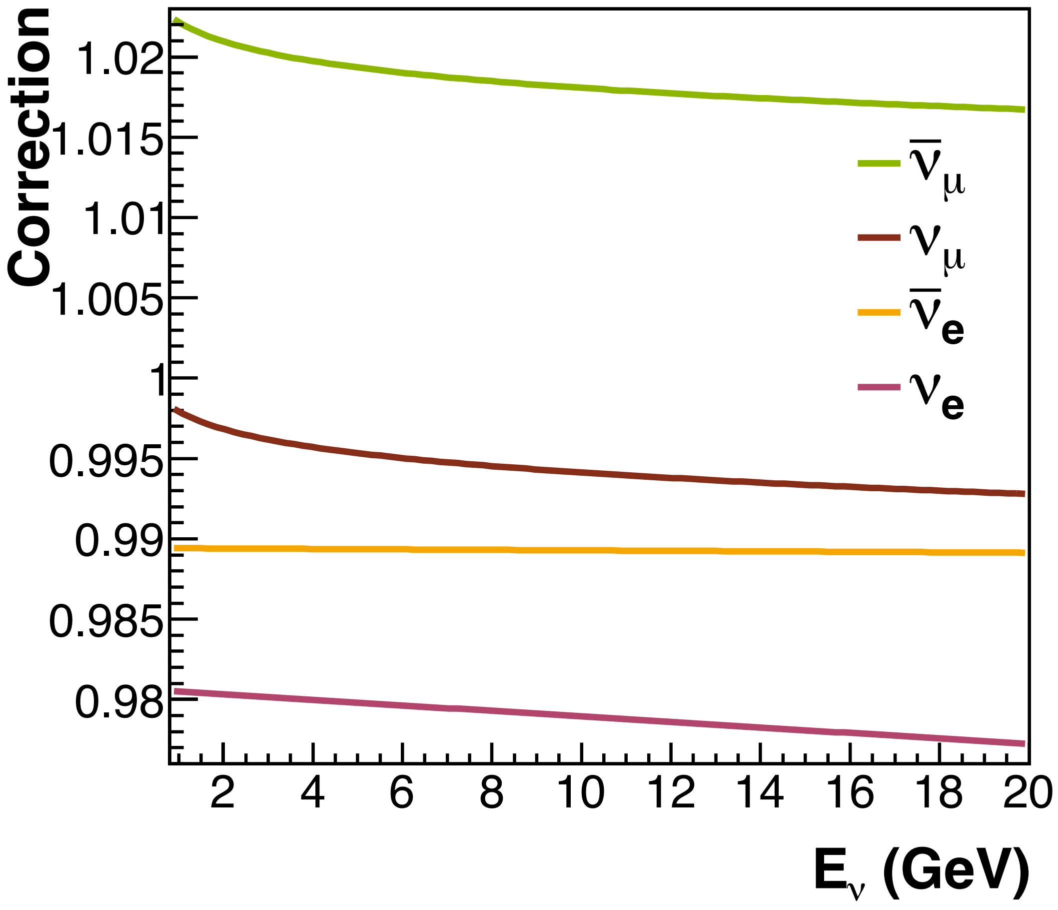
Sideband 1: shower + vertex activity; **Sideband 2:** ν_μ enriched
Sideband 3: ν_e enriched; **Sideband 4:** π^0 enriched





Radiative Corrections

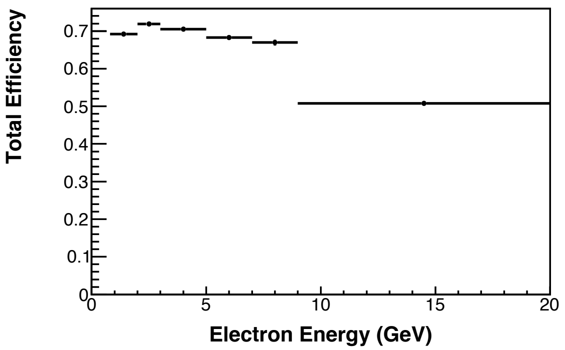
Ratio between Phys. Rev. D 101, 033006 (2020)
x-secs and GENIE 2.12.6.

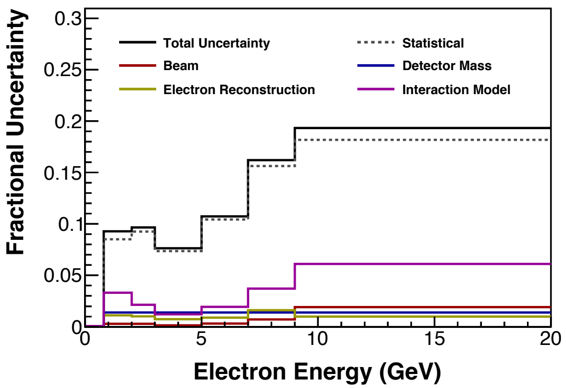


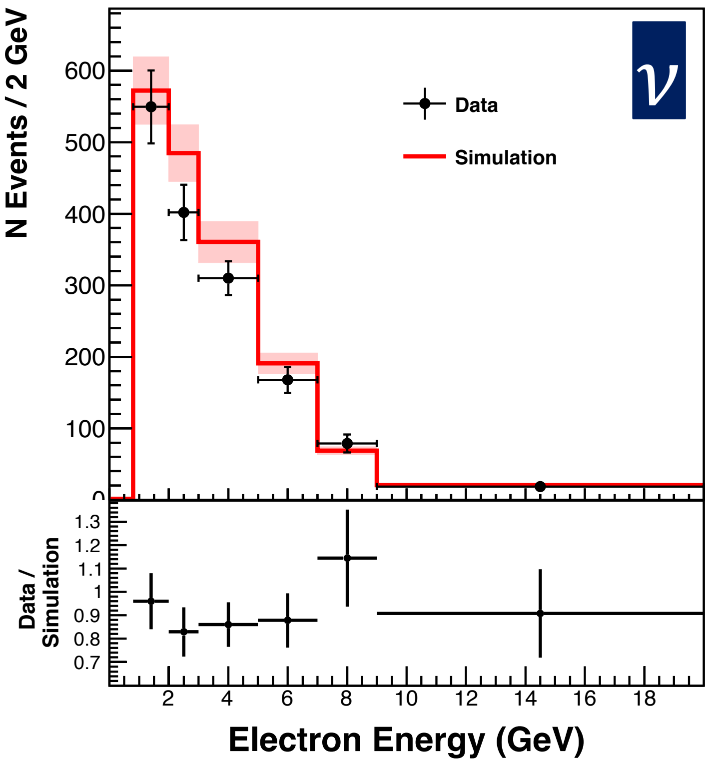
- GENIE tree-level cross-section reweighted to match the one calculated **including radiative corrections**
  - O. Tomalak, R. J. Hill. Phys. Rev. D 101, 033006 (2020)
  - Includes production of real photons in final state

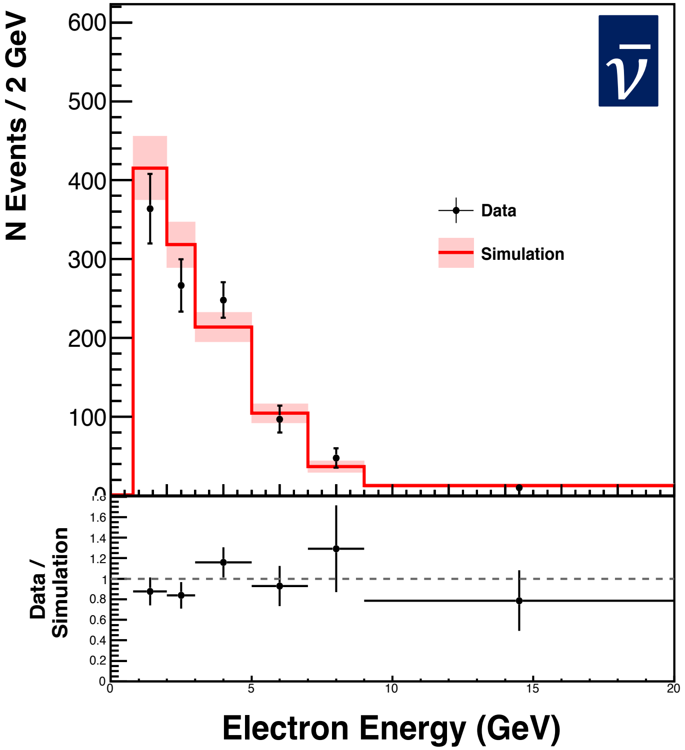
Final Electron Energy Spectra

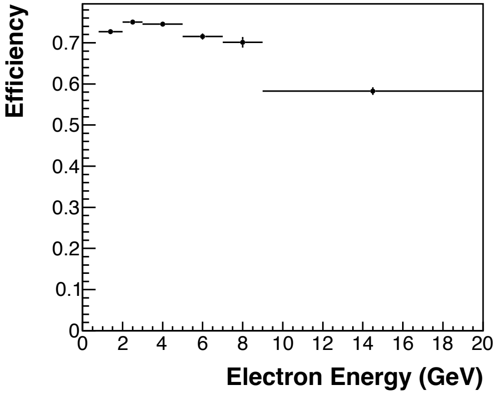
- Subtracted tuned background and corrected by the efficiency → dominated by statistical uncertainty

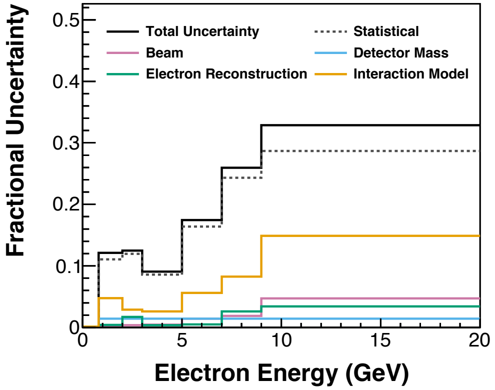












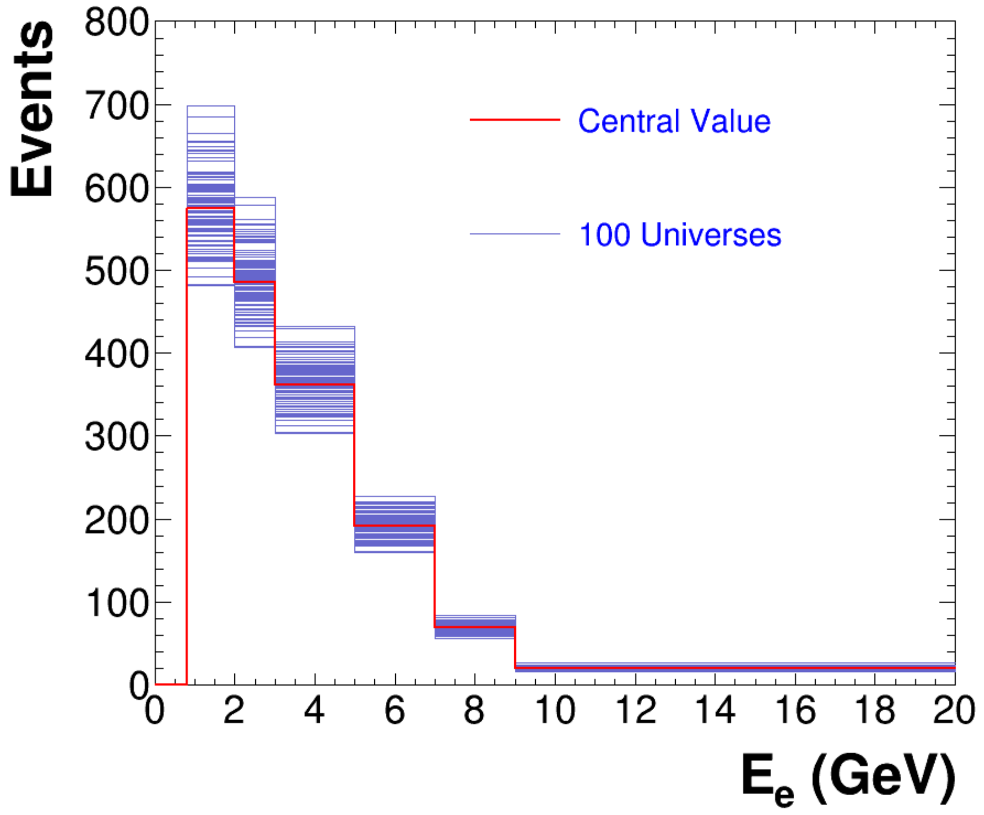
Flux Constraint Procedure

- Using Bayes' theorem

$$P(M|N_{\nu e\to\nu e}) \propto P(M)\,P(N_{\nu e\to\nu e}|M)$$

$P(M\|N_{\nu e\to\nu e})$	new prediction (posterior) probability of the flux prediction given the electron spectra measurement)
$P(M)$	flux prediction in each universe/model (prior)
$P(N_{\nu e\to\nu e}\|M)$	likelihood of the electron spectra measurement given the a-priori model

- A-priori flux uncertainty estimated using **multiverse method**
  - Ensemble of flux predictions by varying flux parameters within their uncertainties (hadron production, beam alignment)



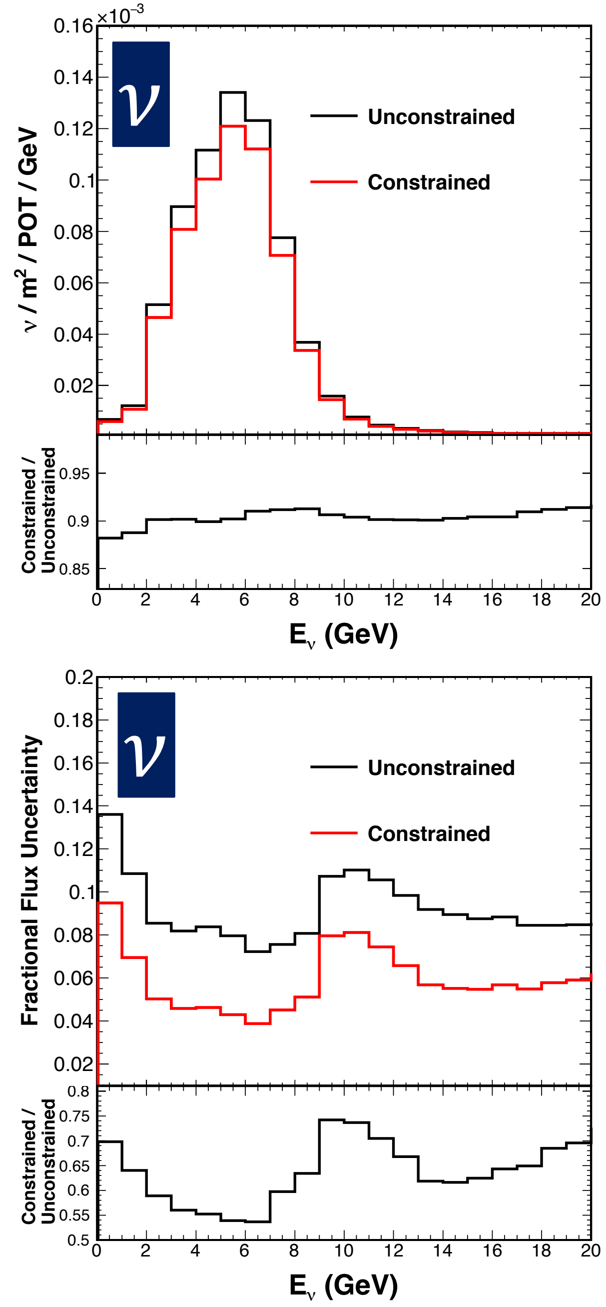
Neutrino Flux Constraint

- **Likelihood of the measurement** for each universe

$$P\left(N_{\nu e\rightarrow\nu e}|M\right) = \frac{1}{(2\pi)^{K/2}}\frac{1}{|\Sigma_{\mathbf{N}}|^{1/2}}e^{-\frac{1}{2}(\mathbf{N}-\mathbf{M})^T\Sigma_{\mathbf{N}}^{-1}(\mathbf{N}-\mathbf{M})}$$

N	vector containing the bin content of the measured energy spectrum of given process
M	same as N but for the MC prediction
Σ_N	covariance matrix of the uncertainties of N
K	number of the bins of the spectrum

- Predictions from universes with poor data agreement are weighted down → **reduces uncertainty** (spread of the universes)
- **In neutrino mode, the neutrino flux uncertainty is reduced from 7.6% to 3.9% (integrated flux over the energy range)**



Phys. Rev. D 100, 092001 (2019).

In situ Measurements To Constrain Flux

Imperial College London

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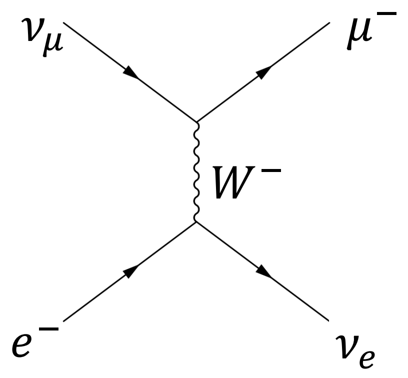
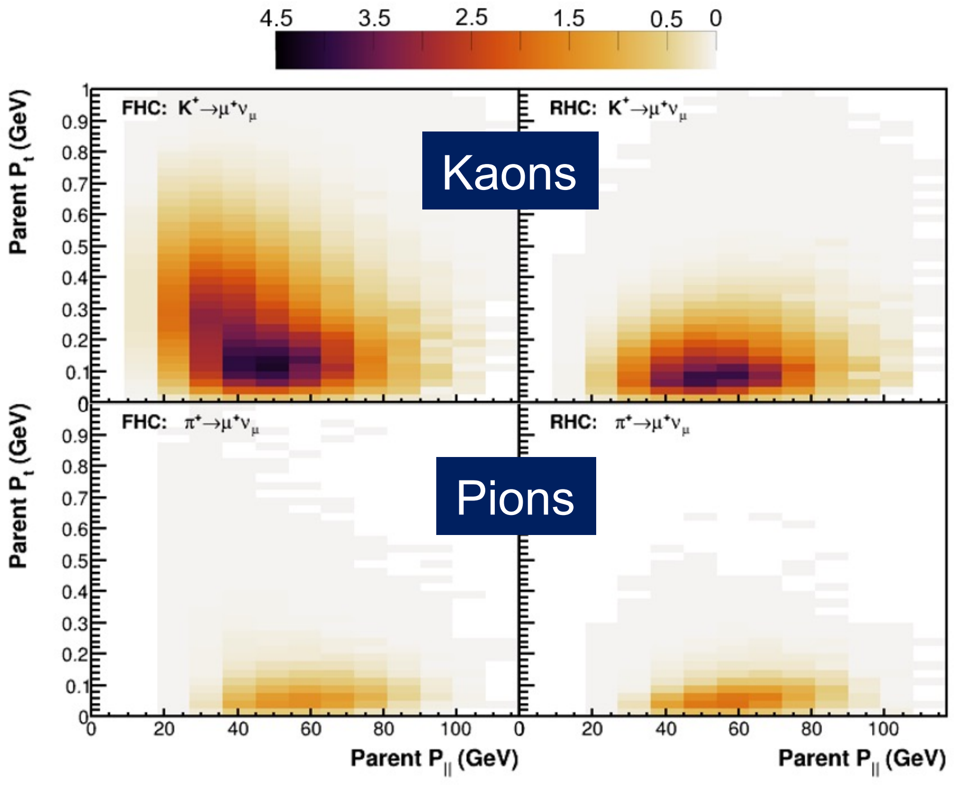
3. **Inverse muon decay (IMD)**
4. Combined constraint using $\nu/\bar{\nu}$-electron and IMD

Inverse Muon Decay (IMD)



- Cross-section can be predicted with very small uncertainties
- **Threshold of ≈ 11 GeV with very forward going muon**
  - Indistinguishable process $\bar{\nu}_e\, e^- \rightarrow\, \mu^- \bar{\nu}_\mu$ unimportant in MINERvA due to threshold
- Neutrinos from underfocused or unfocused K^+ and π^+
- Can **constrain the high-energy part of the flux** in the NuMI neutrino beam

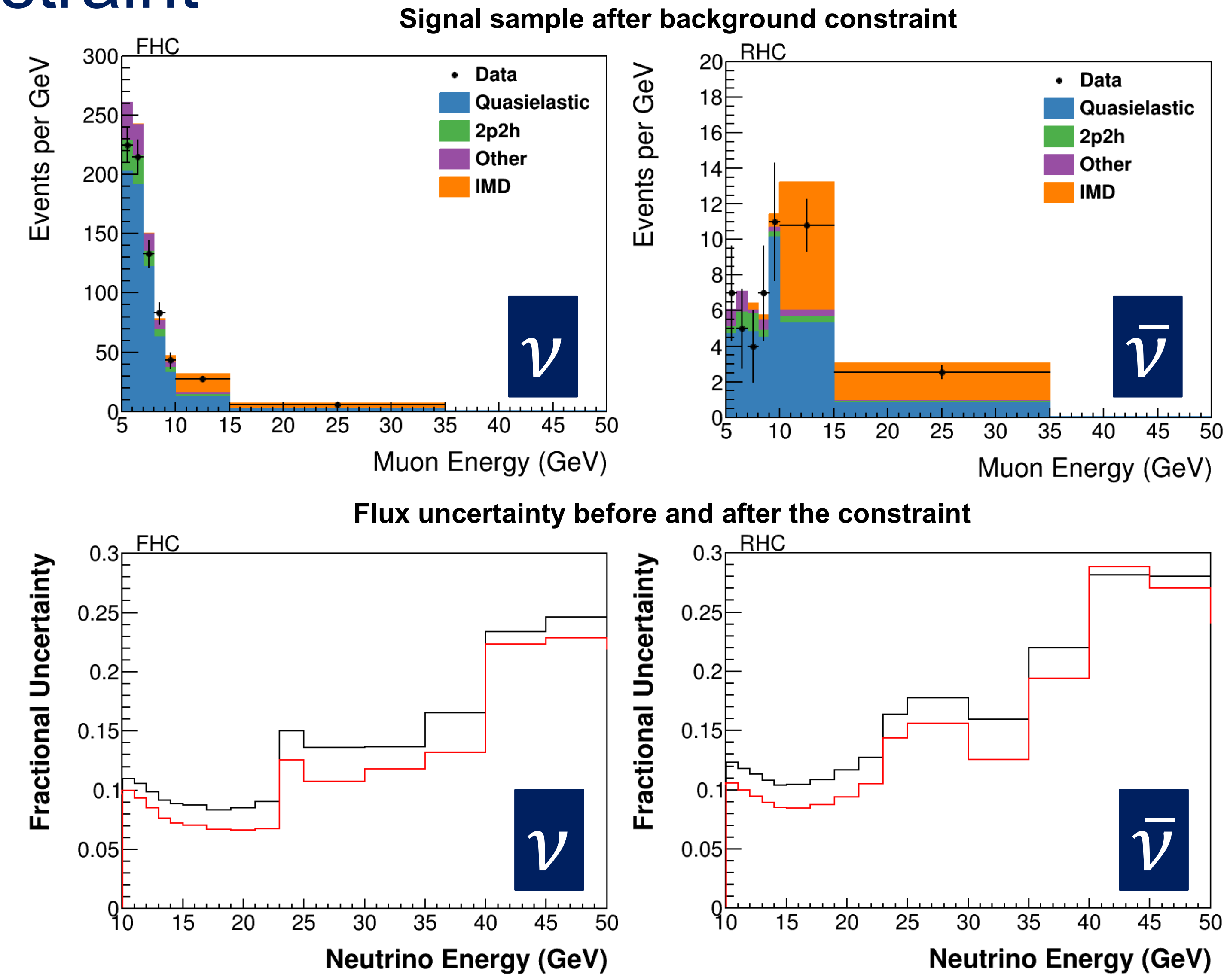


Phys. Rev. D 104, 092010 (2021).

IMD Sample & Flux Constraint

- Small sample ~ 0.006% of the inclusive CC sample in tracker
- Threshold, angle + no visible recoil (muon only)
- Main background from CCQE, constraint using E_μ, θ_μ sideband
- 127 (56) selected events in data for the neutrino (antineutrino) beam
- **Flux constraint extracted, reduced uncertainty in the high-energy tail of the flux**

Neutrino events in neutrino/antineutrino beam



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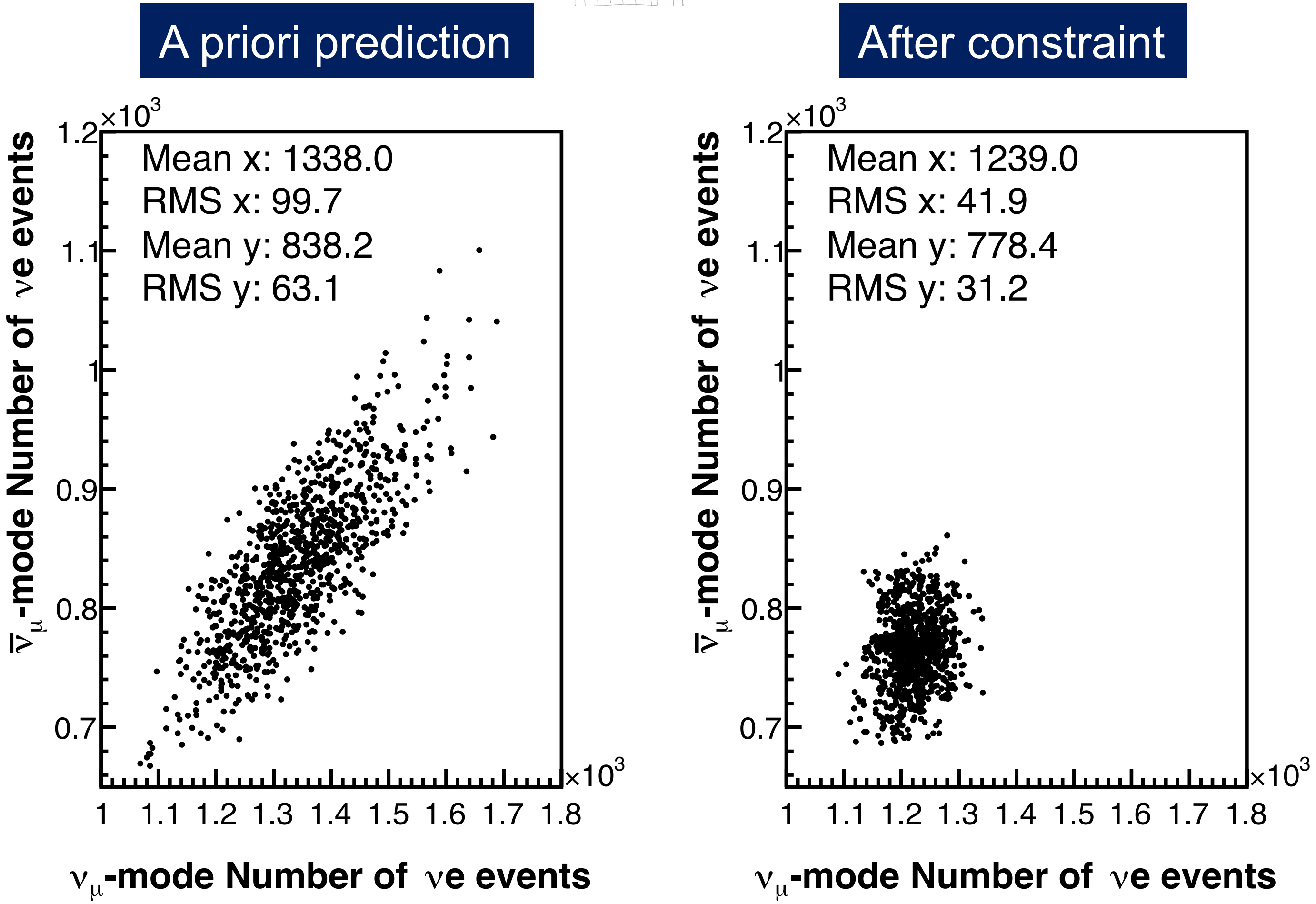
Combined Flux Constraint

- Extracted combined flux uncertainty using neutrino(antineutrino)-electron scattering result and IMD
- Uncertainties on $\nu/\bar{\nu}$-electron scattering correlated → predictions of # events correlated
  - Hadron production constraints from the same experiments and data



Predicted number of neutrino(antineutrino)-electron scattering events by each flux universe.

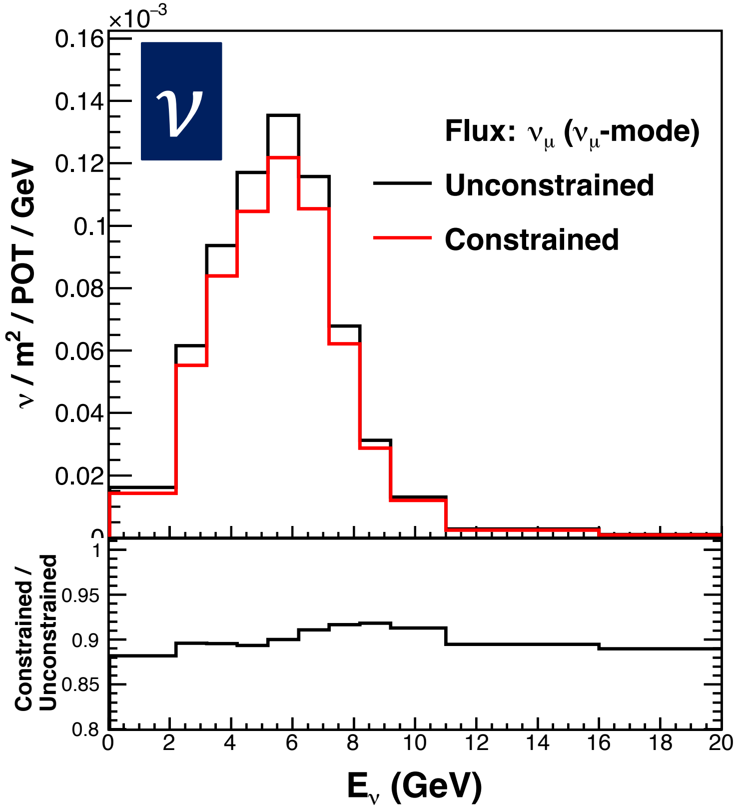
Submitted for publication, [hep-ex]:2209.05540.

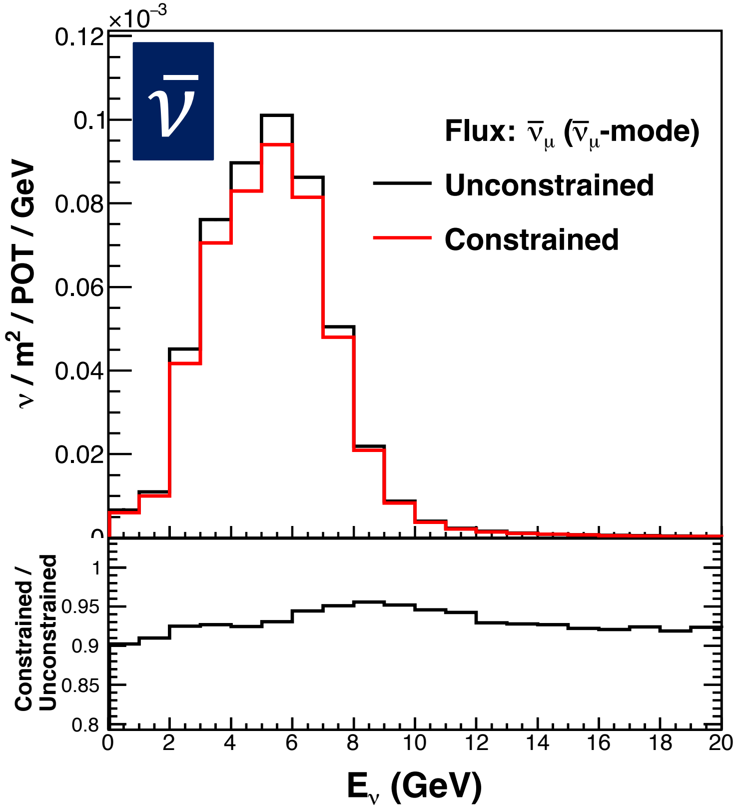
Predicted Flux

- $\nu(\bar{\nu})$-electron constraint the strongest in its respective mode
- IMD affects the high-energy tail

	$\bar{\nu}_\mu$-mode				ν_μ-mode			
	$\bar{\nu}_\mu$	$\bar{\nu}_e$	ν_μ	ν_e	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
a priori	7.76	7.81	11.1	11.9	7.62	7.52	12.2	11.7
ν_μ-mode νe^-	6.11	5.81	6.30	8.50	3.90	3.94	8.37	8.68
$\bar{\nu}_\mu$-mode νe^-	4.92	4.98	8.07	9.19	5.88	5.68	8.36	8.64
combined νe^-	4.68	4.62	5.56	7.80	3.56	3.58	7.15	7.84
combined νe^- + IMD	4.66	4.56	5.20	6.08	3.27	3.22	6.98	7.54

(Energy range integrated flux uncertainty)





Submitted for publication, [hep-ex]:2209.05540.

Fractional Uncertainties

- Flux uncertainty in $\boldsymbol{\nu}$ **mode** reduced **from 7.6% to 3.3%**
- In $\bar{\nu}$ **mode from 7.8% to 4.7%**
- Used in MINERvA analyses!

	$\bar{\nu}_\mu$-mode				ν_μ-mode			
	$\bar{\nu}_\mu$	$\bar{\nu}_e$	ν_μ	ν_e	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
a priori	7.76	7.81	11.1	11.9	7.62	7.52	12.2	11.7
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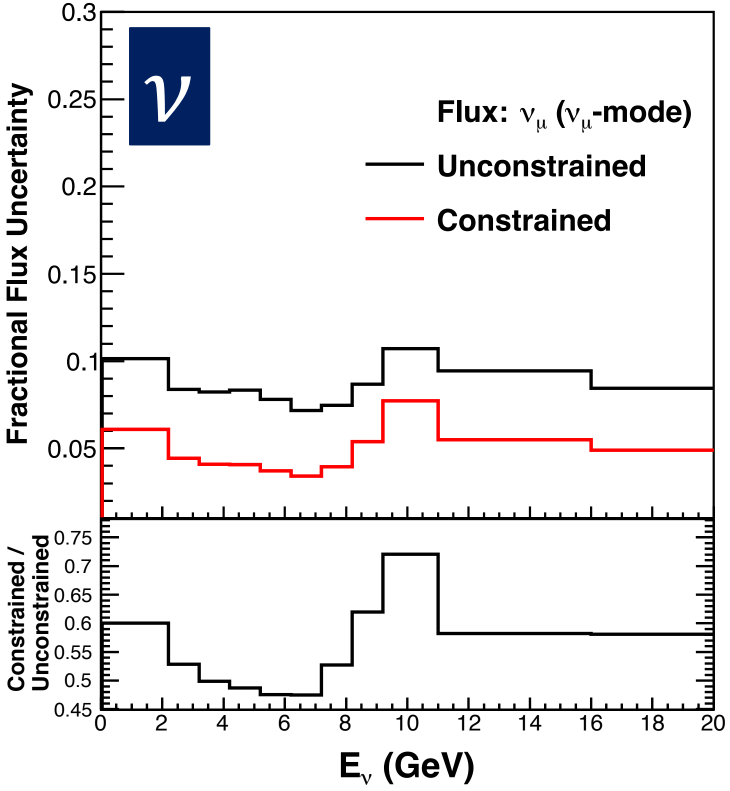
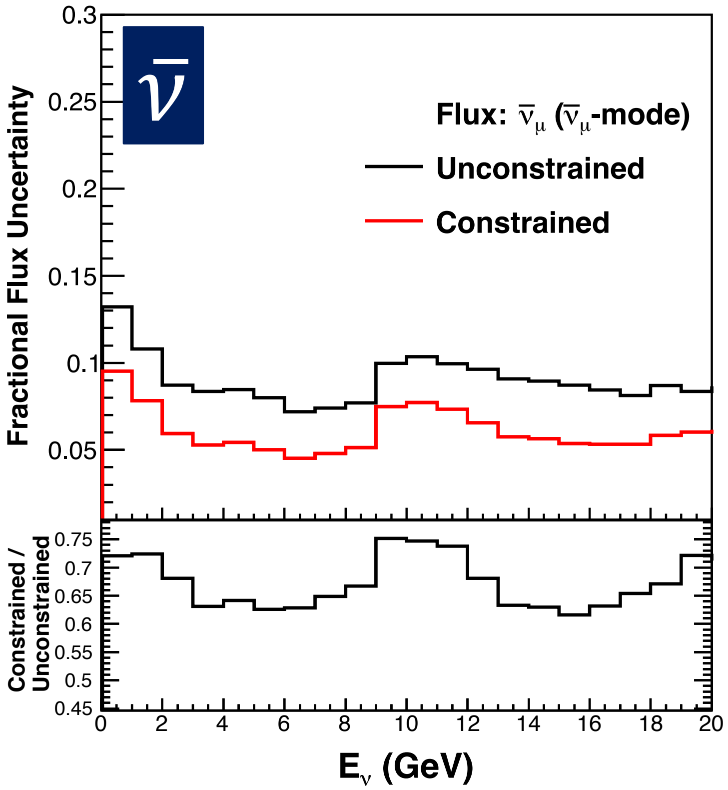
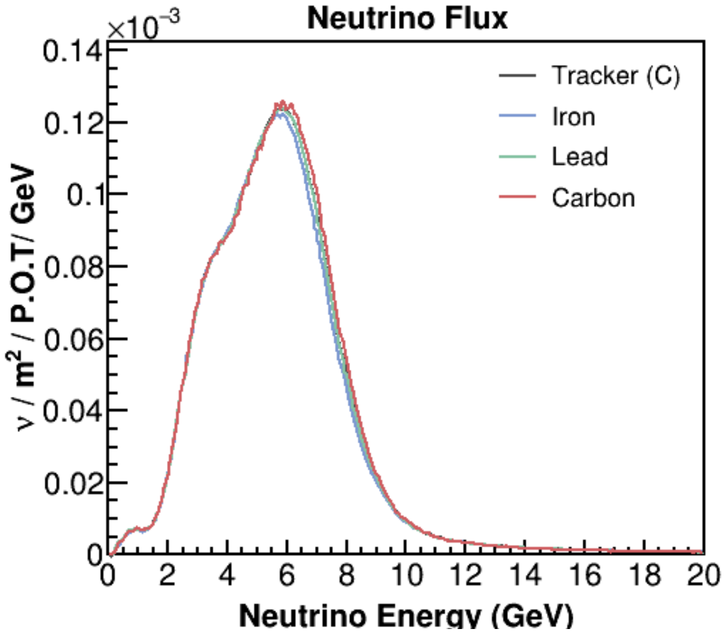


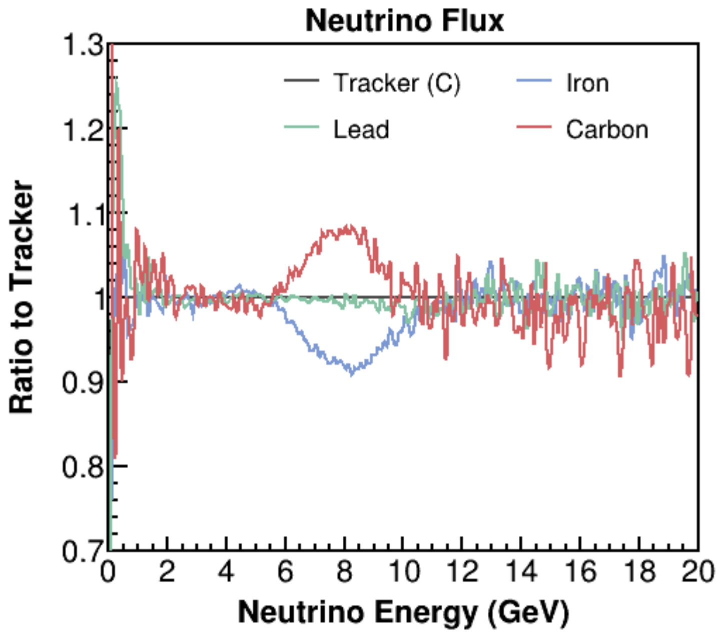


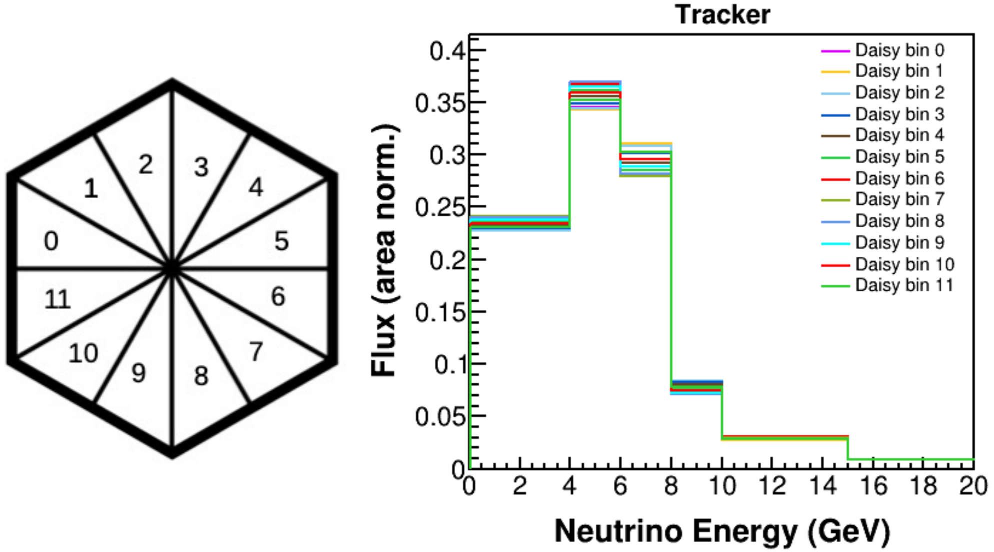
Submitted for publication, [hep-ex]:2209.05540.

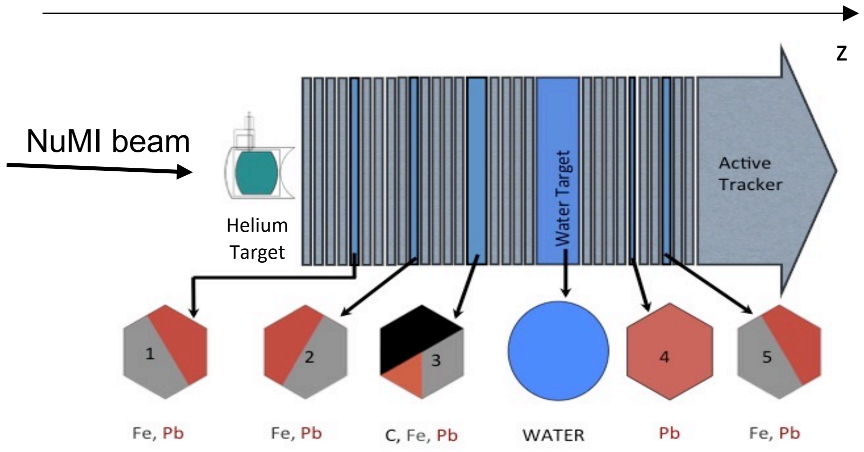
Flux for Cross-Section Ratios

- NuMI beam pointed downwards → transverse center of the beam changes as a function of the longitudinal position
- Difference in the flux shape + normalization in the nuclear targets compared to the tracker (problem for cross-section ratios)
- **"Daisy technique"** – take linear combination of tracker fluxes in 12 bins to match the target









Conclusions

- MINERvA is a neutrino-nucleus experiment with a dedicated flux campaign – **in-situ measurements to constrain flux**
- Measured neutrino-nucleus scattering with low hadronic recoil to constrain flux shape
  - Discrepancy in data/MC resolved by shifting muon energy scale by 1.8σ
- Measured (anti)neutrino-electron elastic scattering to constrain flux normalization, and inverse muon decay to constrain the high-energy tail
- Combined flux constraint of these 3 measurements **reduces the flux uncertainty from 7.6% to 3.3% in ν mode and 7.8% to 4.7% in $\bar{\nu}$ mode**
- Can use similar techniques to constrain flux at other accelerator-based neutrino experiments (e.g., DUNE)

Funding Acknowledgement: Funded by an Imperial College London President's PhD Scholarship.

Back-up

PPFX

= Package to Predict the Flux

- Experiment independent NuMI reweighting package, external of MINERvA framework
- Applies all relevant data, removes the model spread and handles correlated uncertainties
- Accounts for the attenuation of particles passing through NuMI materials
- Multiverse method for handling the uncertainty propagation
- Used by other NuMI experiments, e.g., MINOS+, NOvA, MicroBooNE

In situ Measurements To Constrain Flux

Imperial College London

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1σ Tolerances On Beam Parameters

Imperial College London

Parameter	Nominal Value	Final 1 σ shifts used in MINERvA analyses	Preliminary 1 σ shifts used in this work
Beam Position (X)	0 mm	0.4 mm	1 mm
Beam Position (Y)	0 mm	0.4 mm	1 mm
Beam Spot Size	1.5 mm	0.3 mm	0.3 mm
Horn Water Layer	1.0 mm	0.5 mm	0.5 mm
Horn Current	200 kA	1 kA	1 kA
Horn 1 Position (X)	0 mm	1 mm	1 mm
Horn 1 Position (Y)	0 mm	1 mm	1 mm
Horn 1 Position (Z)	30 mm	2 mm	-
Horn 2 Position (X)	0 mm	1 mm	1 mm
Horn 2 Position (Y)	0 mm	1 mm	1 mm
Target Position (X)	0 mm	1 mm	1 mm
Target Position (Y)	0 mm	1 mm	1 mm
Target Position (Z)	-1433 mm	1 mm	3 mm
POT Counting	0	2% of Total POT	-
Baffle Scraping	0	0.25% of POT	-

Systematic Uncertainties For The Simulated Neutrino Energy Distribution

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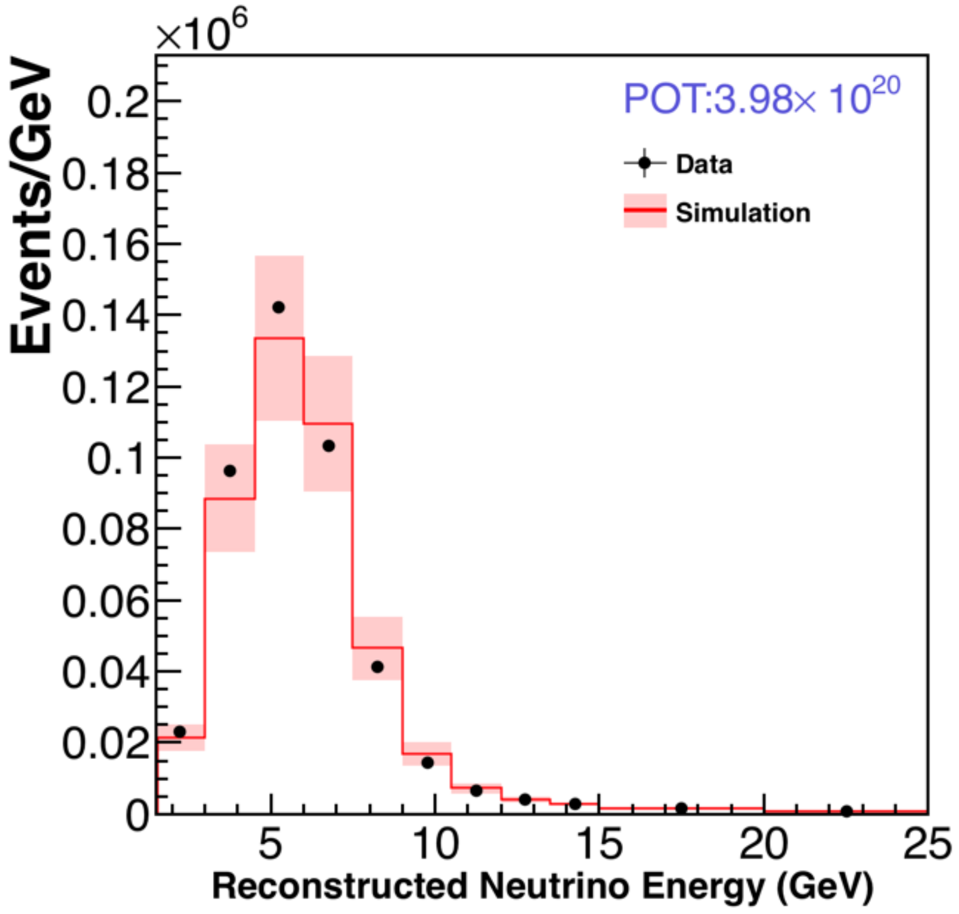

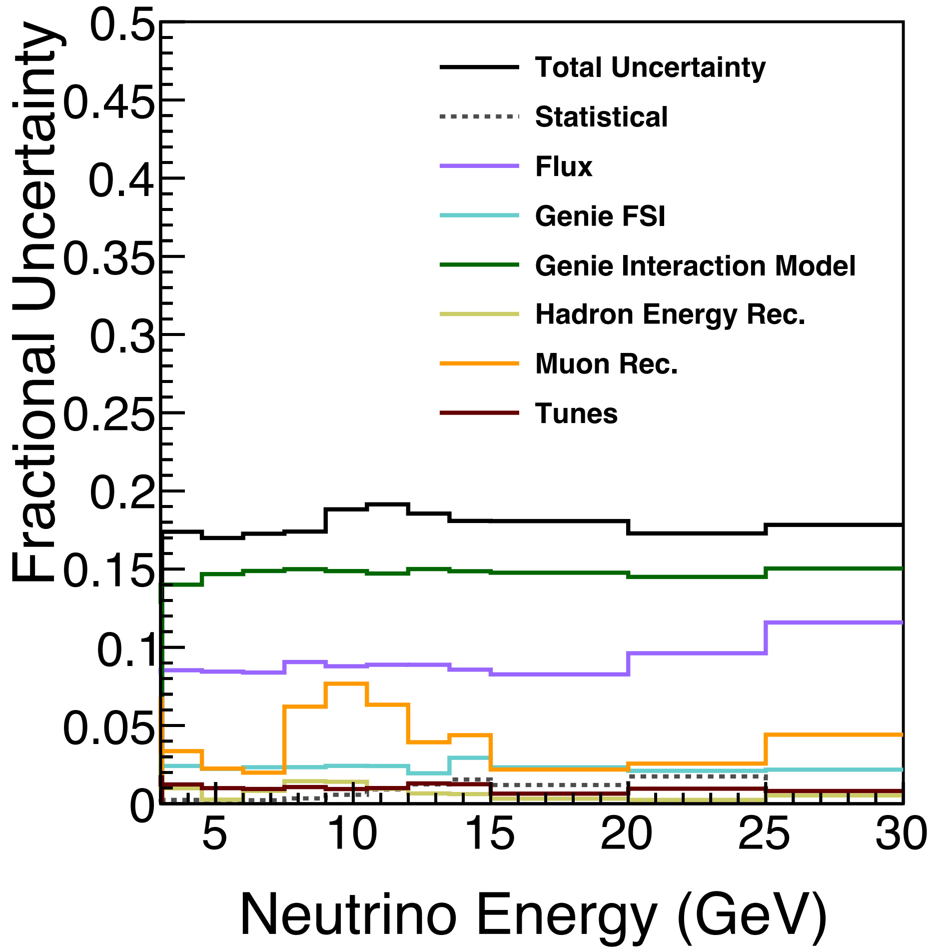

Systematic Uncertainties For The Simulated Neutrino Energy Distribution

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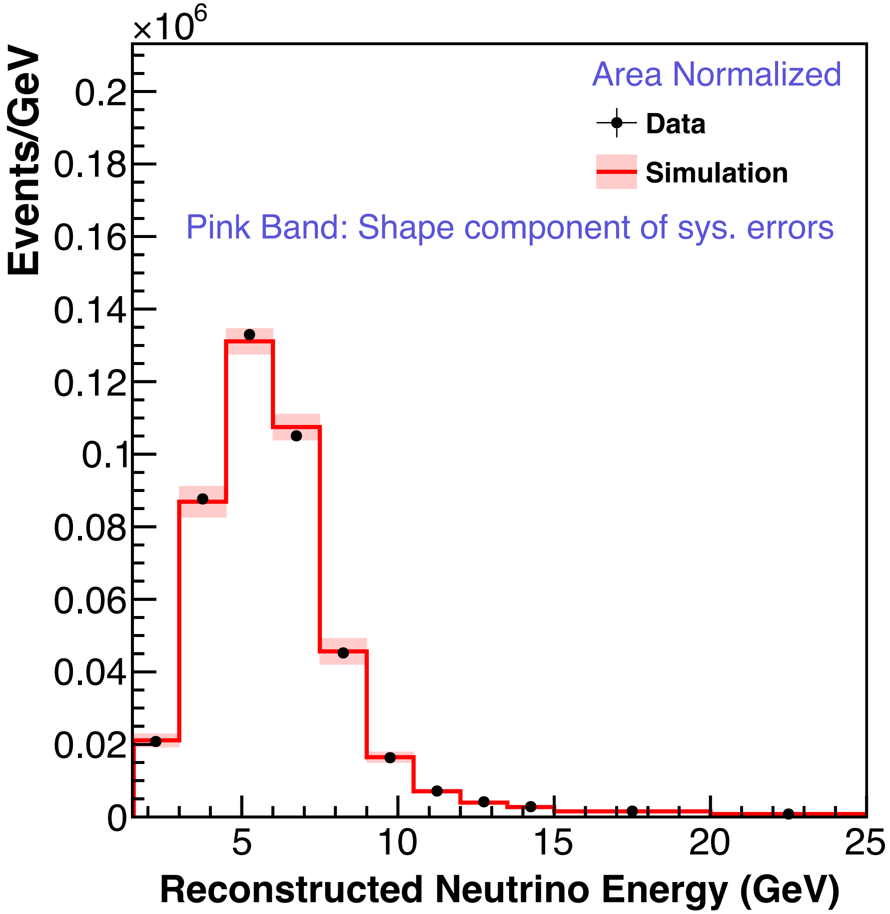

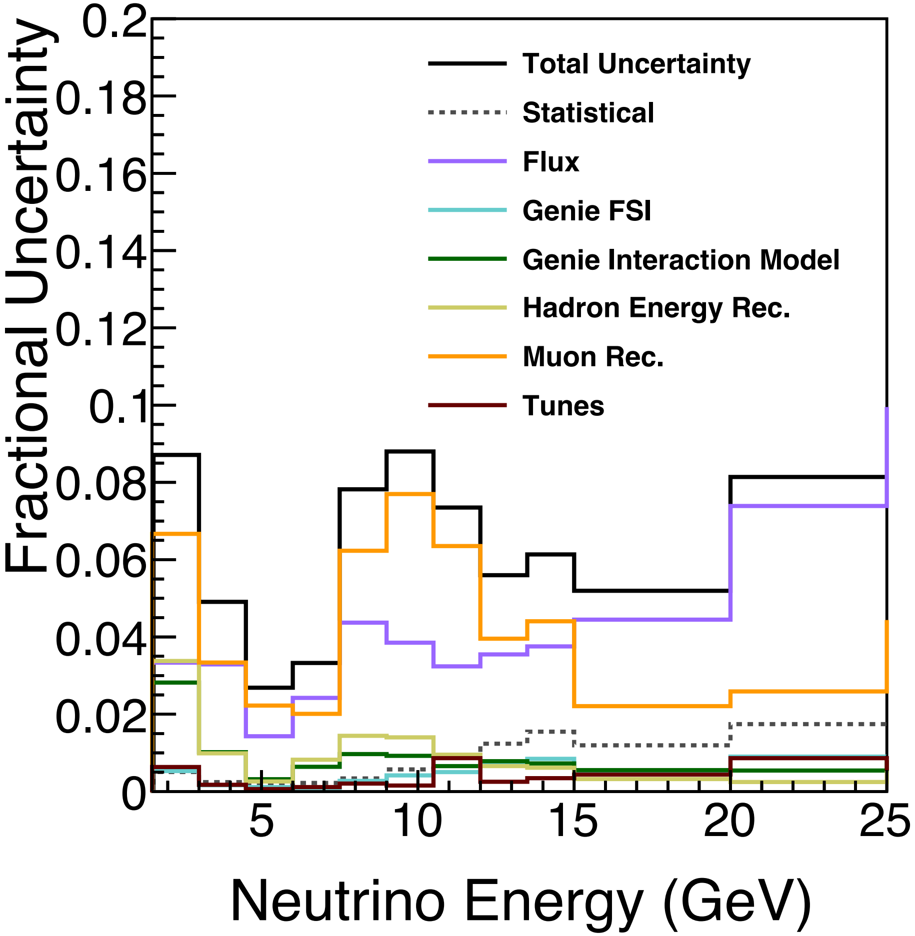

Fitting Procedure

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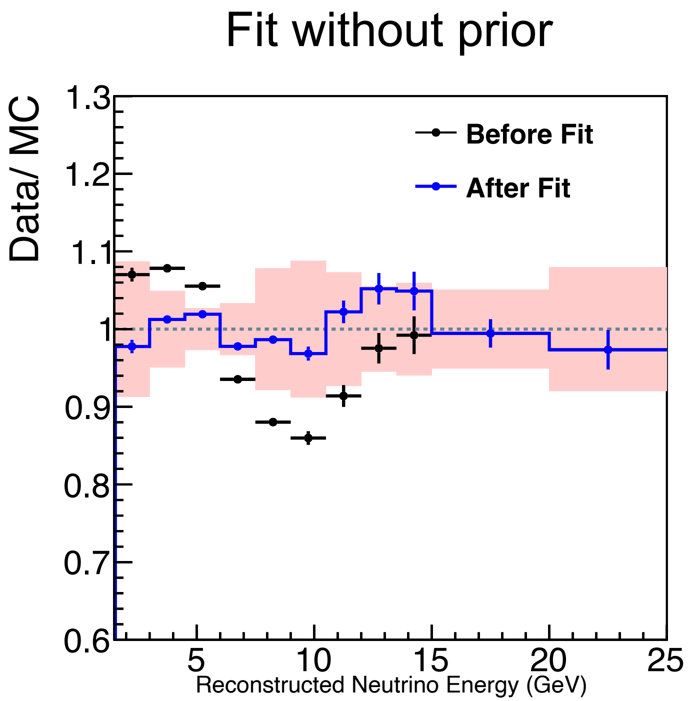
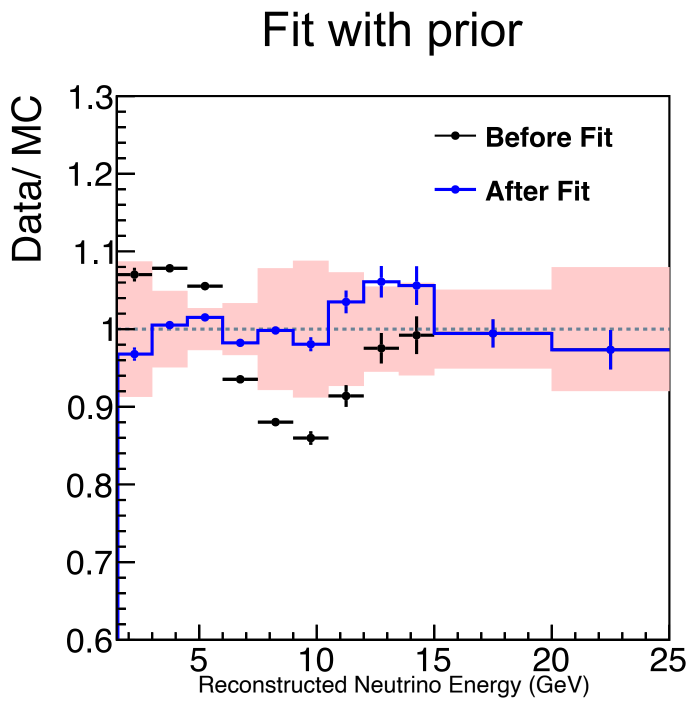
- Chi2 minimization: $$\chi^2_{prior} = \sum_{ij} \frac{(Data'_{ij} - MC'_{ij})^2}{\sigma^2_{ij}} + \sum_k (\alpha_k)^2$$

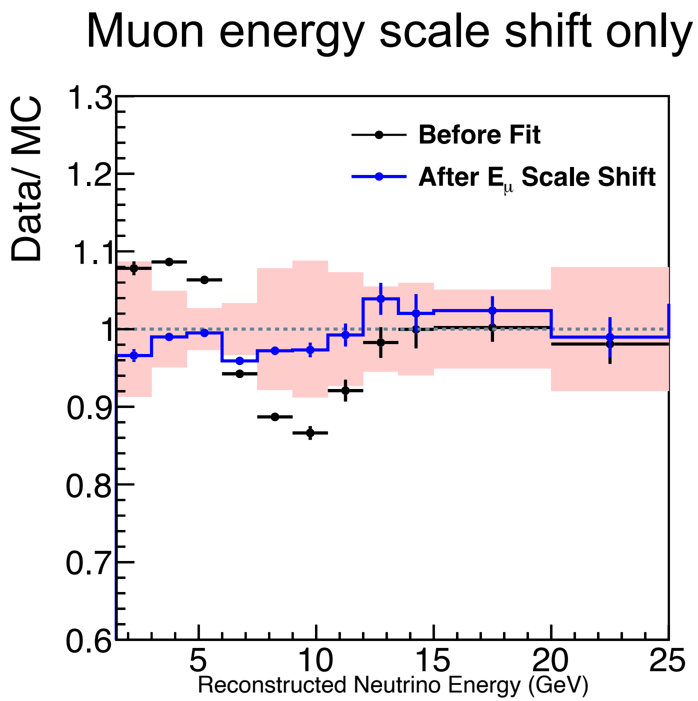
penalty term – number of standard deviations that the parameter *k* has been shifted from the nominal value

- Uncertainty: $$\sigma_{ij} = \sqrt{\sigma^2_{Data',ij} + \sigma^2_{MC'_{ij}}}$$

Fits w/ & w/o Priors For All Parameters vs Muon Energy Scale Fit Only







Best-Fit Parameters Correlation Matrix

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With priors

	beamXposition	beamsigmaXY	horncurrent	horn1Xoffset	targetXposition	targetZposition	beamYposition	horn1Yoffset	targetYposition	hornwaterlayer	muonEnergyRange	normalization
normalization	0.0216	0.2507	-0.0171	0.1504	-0.3879	0.0432	0.4016	-0.1160	0.1522	0.4841	-0.0424	1.0000
muonEnergyRange	0.0744	0.3772	0.3181	-0.0128	0.0373	-0.2434	0.3529	0.2460	-0.2708	-0.0719	1.0000	-0.0424
hornwaterlayer	-0.0473	-0.1005	0.2864	-0.0862	0.0618	-0.1341	0.0621	-0.0195	-0.1118	1.0000	-0.0719	0.4841
targetYposition	-0.0132	-0.3961	0.1631	0.0060	0.0010	-0.0926	0.0337	-0.2263	1.0000	-0.1118	-0.2708	0.1522
horn1Yoffset	0.0740	-0.0861	-0.0721	0.0134	0.0958	0.0275	0.6076	1.0000	-0.2263	-0.0195	0.2460	-0.1160
beamYposition	0.0507	0.1426	-0.1585	-0.0015	0.0480	0.0973	1.0000	0.6076	0.0337	0.0621	0.3529	0.4016
targetZposition	-0.0665	0.1724	0.2328	-0.0643	0.0082	1.0000	0.0973	0.0275	-0.0926	-0.1341	-0.2434	0.0432
targetXposition	0.4551	0.2871	-0.0329	-0.0117	1.0000	0.0082	0.0480	0.0958	0.0010	0.0618	0.0373	-0.3879
horn1Xoffset	0.6958	0.3808	0.1350	1.0000	-0.0117	-0.0643	-0.0015	0.0134	0.0060	-0.0862	-0.0128	0.1504
horncurrent	0.0711	-0.0150	1.0000	0.1350	-0.0329	0.2328	-0.1585	-0.0721	0.1631	0.2864	0.3181	-0.0171
beamsigmaXY	0.6020	1.0000	-0.0150	0.3808	0.2871	0.1724	0.1426	-0.0861	-0.3961	-0.1005	0.3772	0.2507
beamXposition	1.0000	0.6020	0.0711	0.6958	0.4551	-0.0665	0.0507	0.0740	-0.0132	-0.0473	0.0744	0.0216

In situ Measurements To Constrain Flux

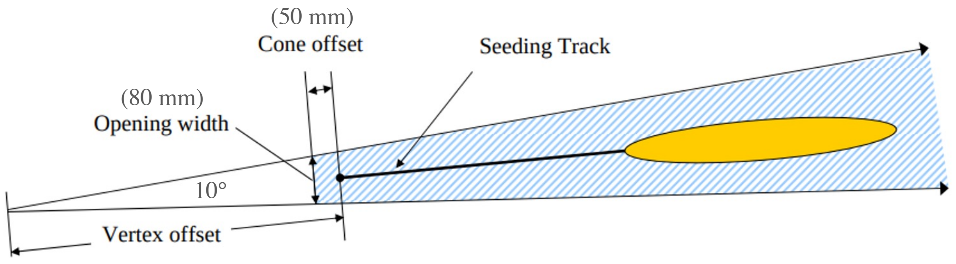
1. Neutrino-nucleus scattering with low hadronic recoil
2. **(Anti)Neutrino-electron elastic scattering**
3. Inverse muon decay (IMD)
4. Combined constraint using $\nu/\bar{\nu}$-electron and IMD

Selection Cuts

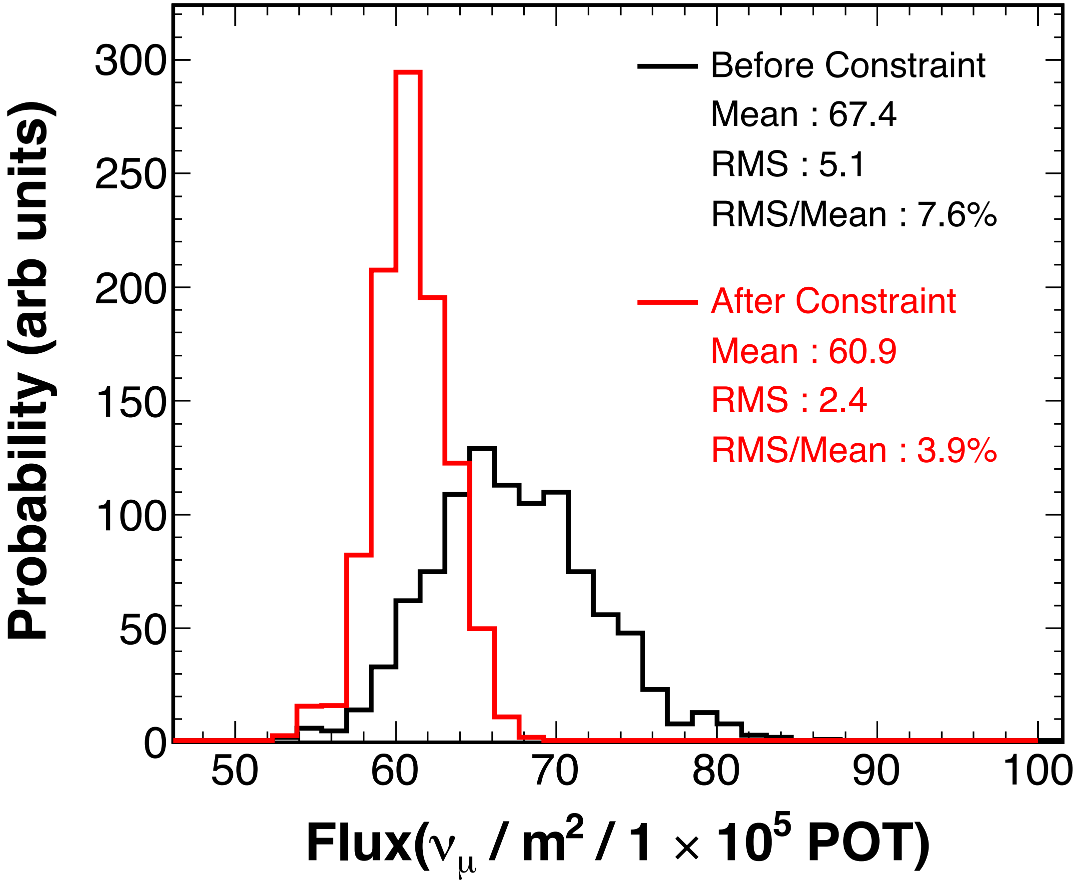
- Clean detector
  - Upstream energy < 300 MeV
  - Neighbouring energy < 120 MeV
- Other shower quality cuts
  - Energy balance between views
  - Not too wide transverse spread near the vertex
  - Straight tracks
- ν_μ rejection
  - $E_e > 800$ MeV
  - Reject tracks going out
- ν_μ rejection
  - Mean dE/dx in the first 4 planes < 4.5 MeV/1.7cm
  - Check for single photon consistency
- ν_e CC rejection
  - $E\theta^2$ < 0.0032 GeV Rad^2
  - QE $Q^2 < 0.02$ GeV

Cone Algorithm

- Seeded by either tracks or group of clusters
- Usually, clusters formed to tracks and fit using Kalman filter – start vertex and track direction
- Formed cone begins upstream of the vertex and extends downstream until no minimum-ionizing-level energy depositions are found within the cone volume
- Parameters chosen to maximize efficiency and containment for the signal in the simulation



Neutrino-Electron Scattering: Neutrino Flux Probability Distribution



Neutrino-Electron Scattering: Correlations Of Unconstrained And Constrained Flux Uncertainties

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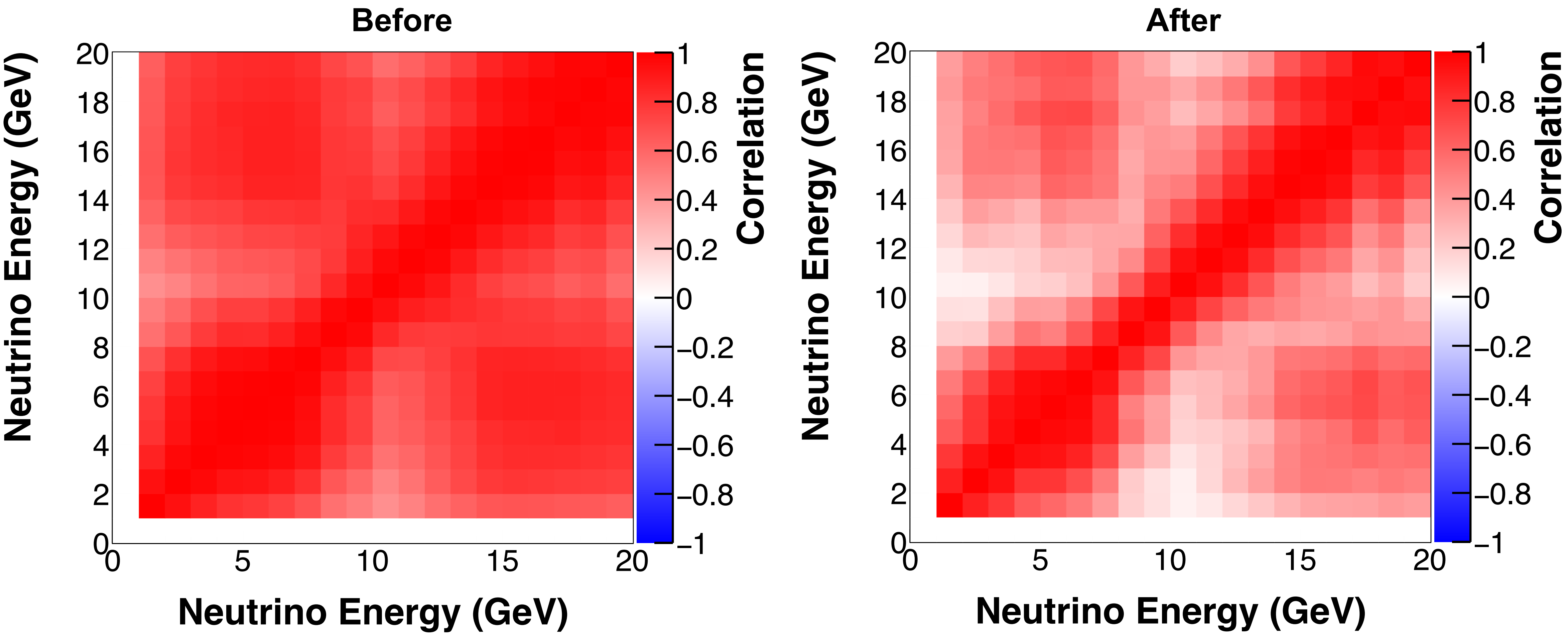
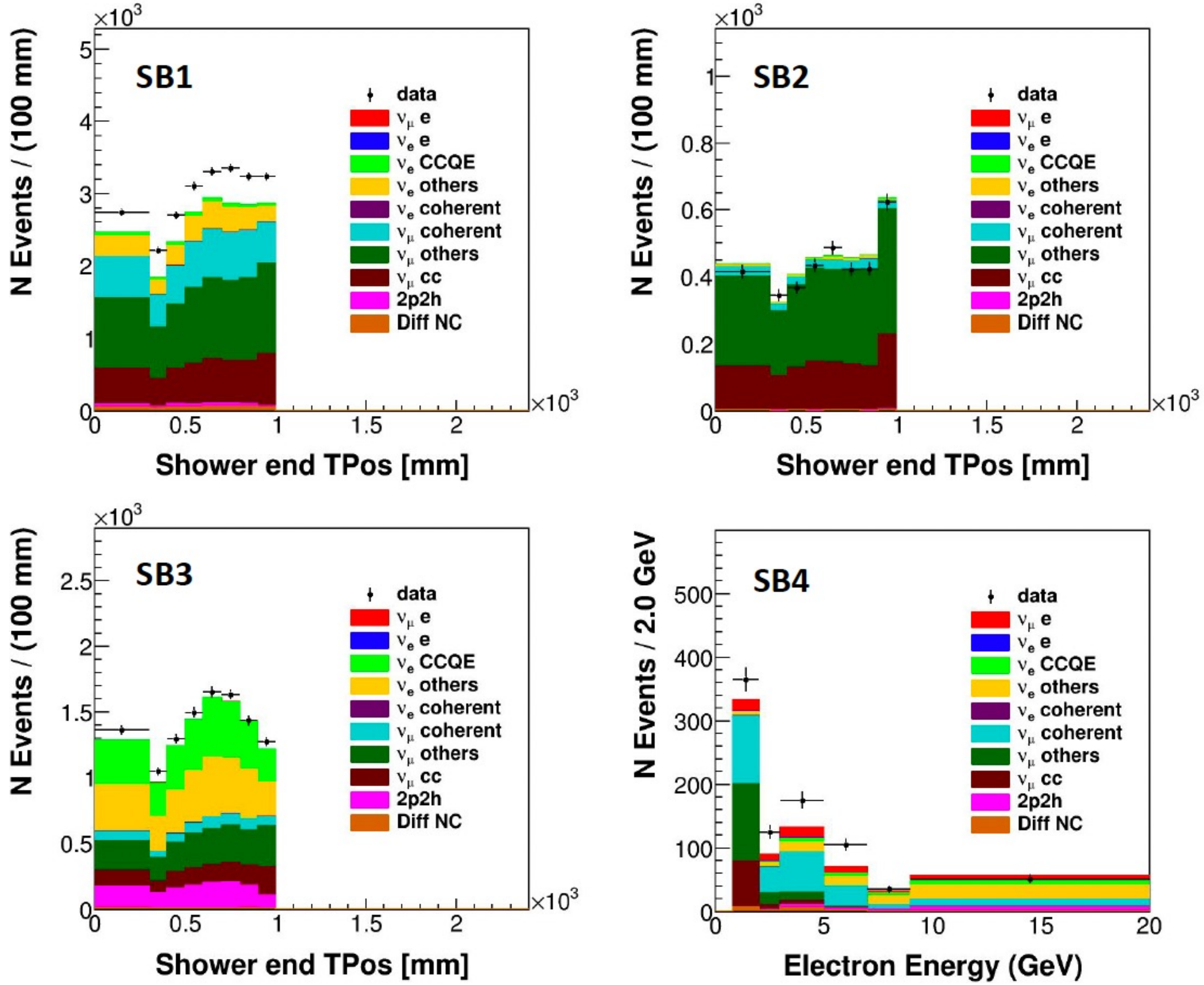
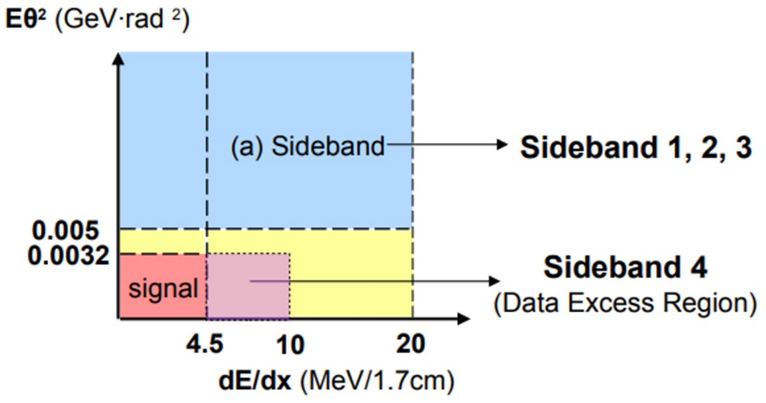
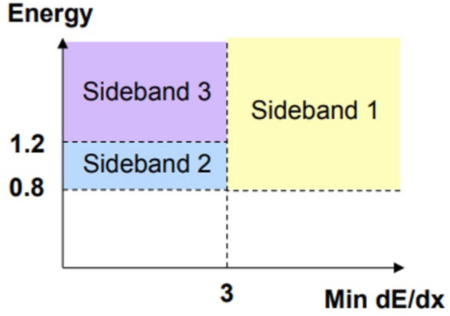


Antineutrino-Electron Scattering: Sideband Fit

Before



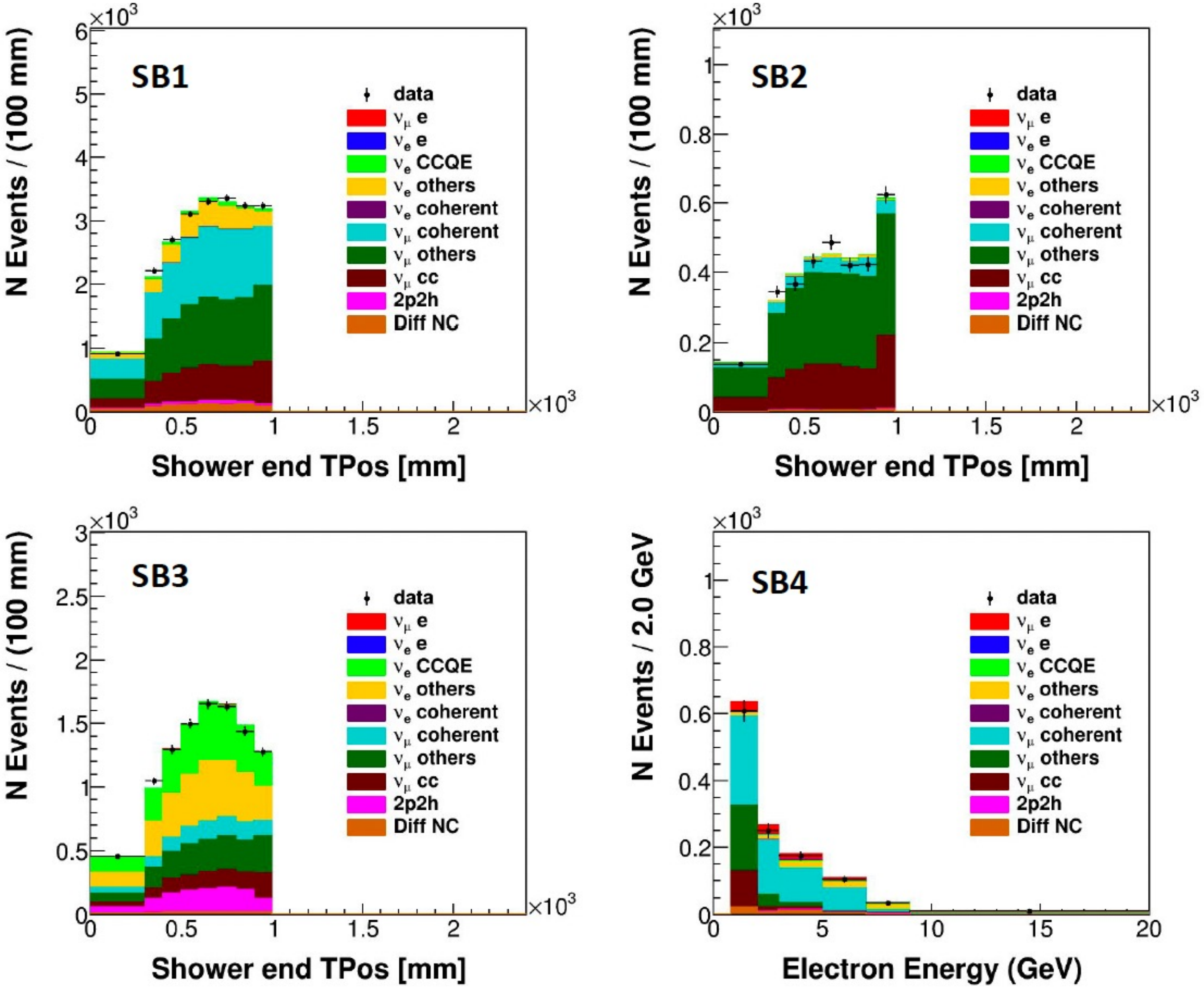




Sideband 1: shower + vertex activity; **Sideband 2:** ν_μ enriched
Sideband 3: ν_e enriched; **Sideband 4:** π^0 enriched

Antineutrino-Electron Scattering: Sideband Fit

After



Process	$\bar{\nu}_\mu$-mode	ν_μ-mode
ν_e	1.02 ± 0.02	0.87 ± 0.03
ν_μ CC	0.93 ± 0.03	1.08 ± 0.04
ν_μ NC	0.93 ± 0.03	0.86 ± 0.04
NC COH $0.8 < E_e < 2.0$ GeV	1.6 ± 0.2	0.9 ± 0.2
NC COH $2.0 < E_e < 3.0$ GeV	2.1 ± 0.3	1.0 ± 0.3
NC COH $3.0 < E_e < 5.0$ GeV	1.8 ± 0.2	1.3 ± 0.2
NC COH $5.0 < E_e < 7.0$ GeV	2.1 ± 0.4	1.5 ± 0.3
NC COH $7.0 < E_e < 9.0$ GeV	1.2 ± 0.7	1.7 ± 0.8
NC COH $9.0 < E_e$	0.8 ± 0.6	3.0 ± 0.9

In situ Measurements To Constrain Flux

Imperial College London

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3. **Inverse muon decay (IMD)**
4. Combined constraint using $\nu/\bar{\nu}$-electron and IMD

Sideband Fit

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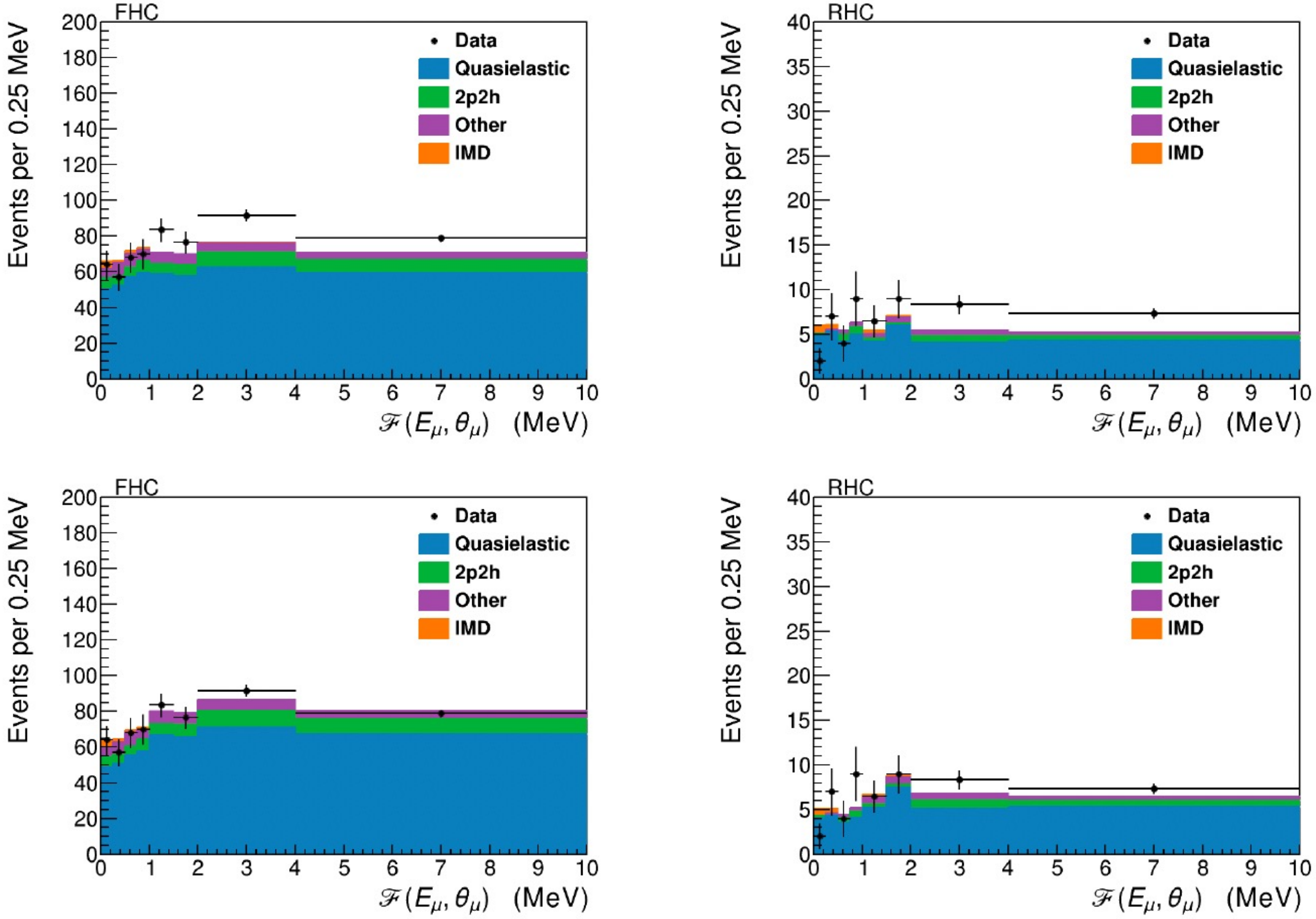
Before

After



Note:

$$\mathscr{F}\left(E_\mu, \theta_\mu\right) \equiv \frac{E_\mu \frac{\theta_\mu^2}{1 radian^2}}{1 - \frac{E_\mu}{E_\nu^{max}}}$$

Neutrino/antineutrino flux IMD events correlations

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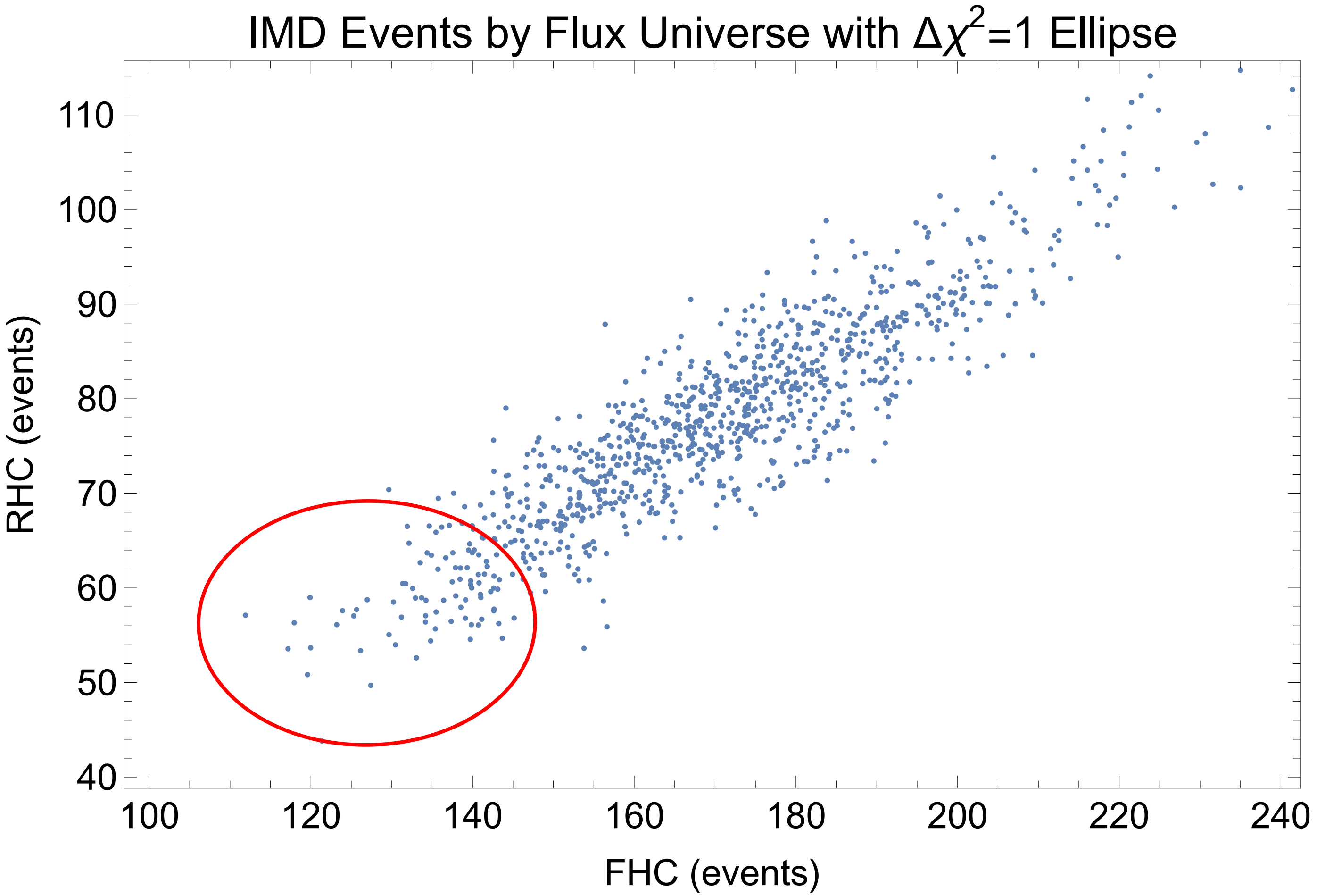

In situ Measurements To Constrain Flux

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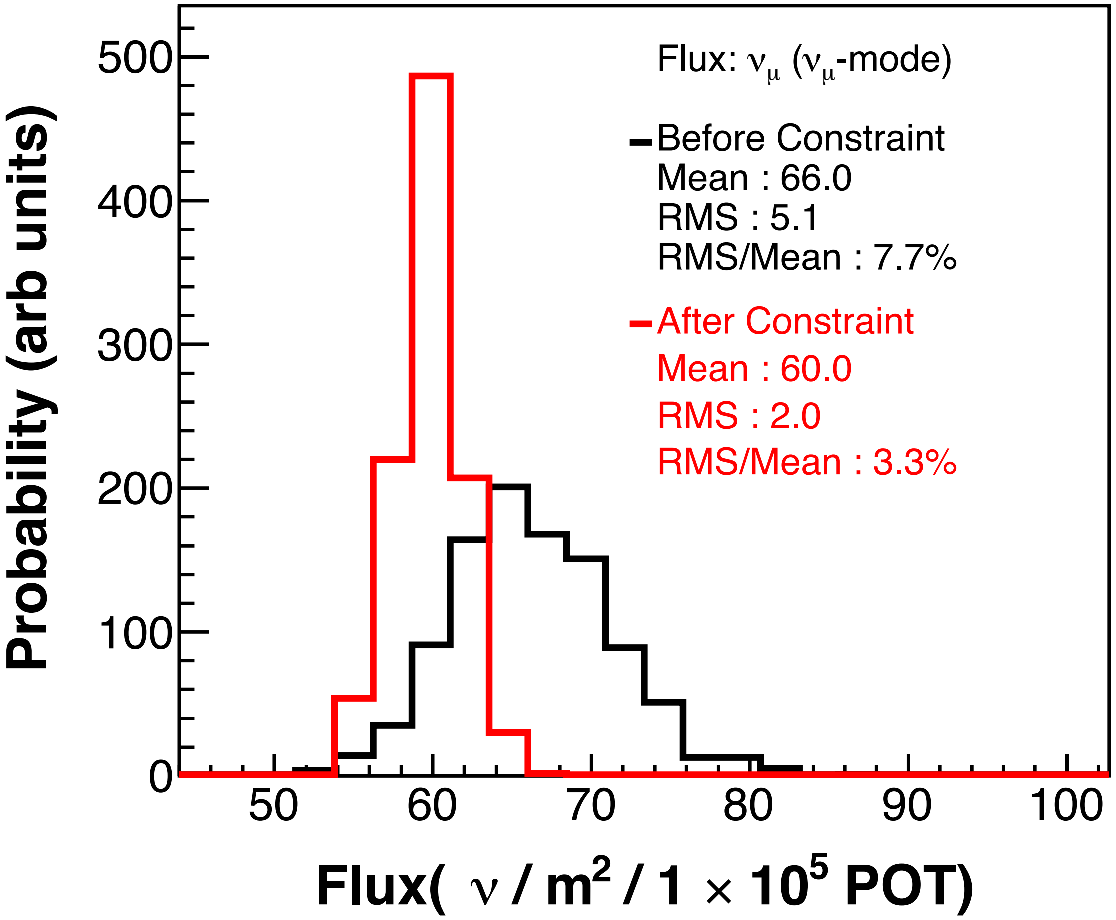
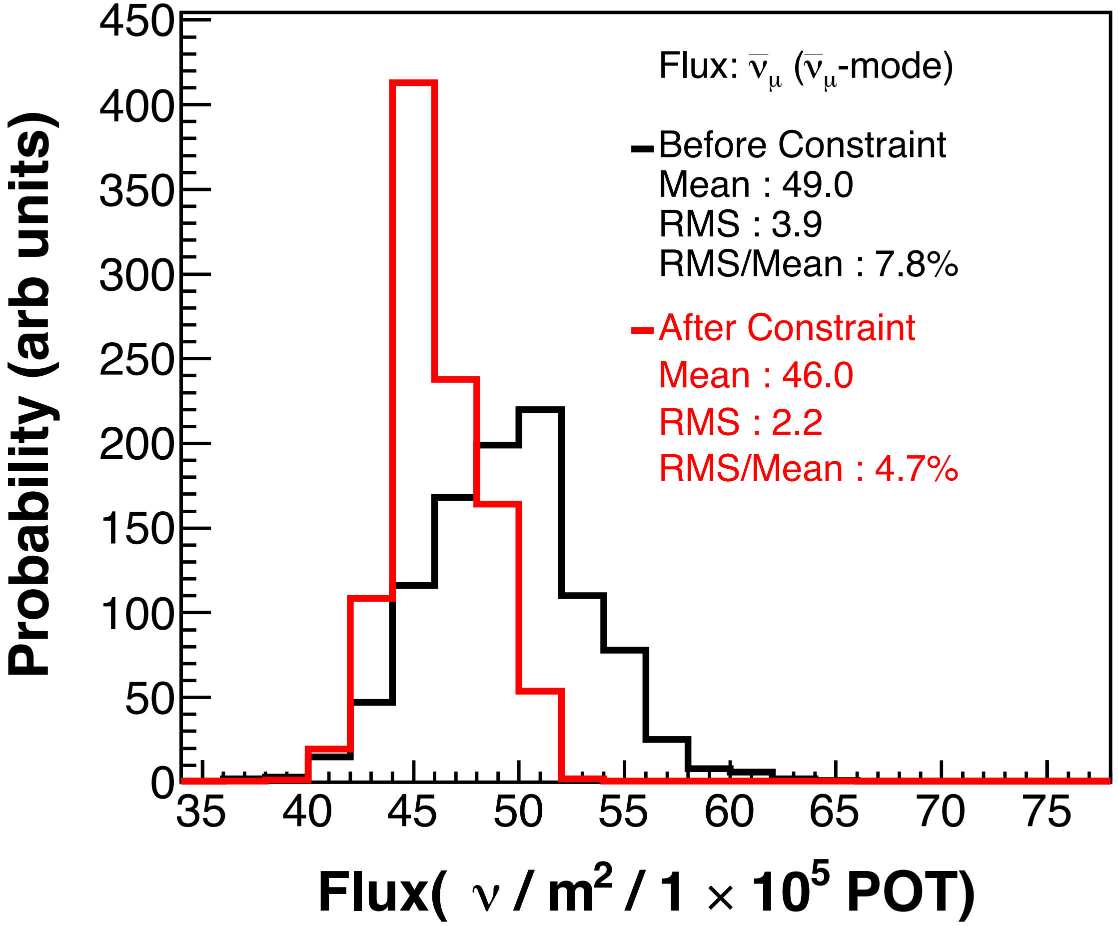
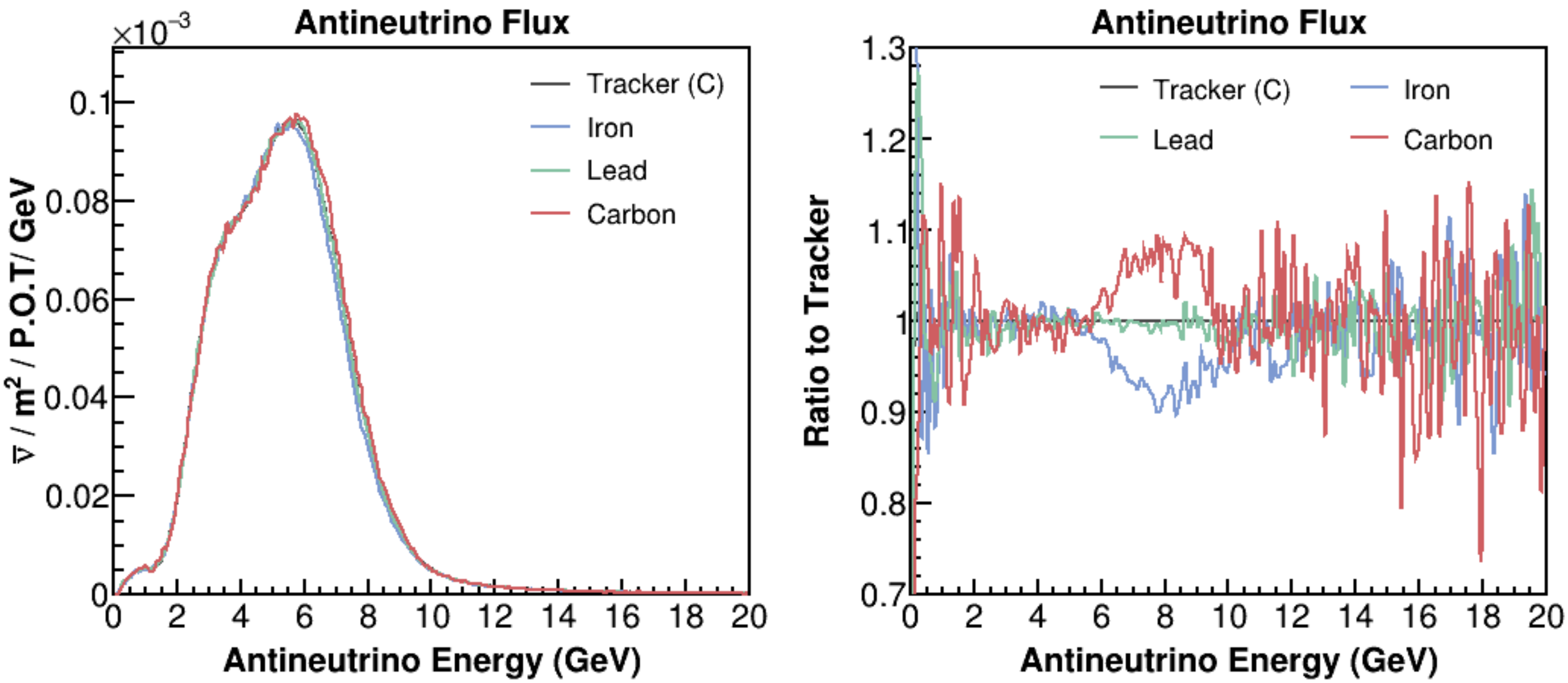
Combined Flux Constraint: Flux Probability Distributions





Antineutrino Flux in Targets



Simulation and Uncertainties

1. Calculate and correct the a-priori flux

G4NuMI beam simulation (from 120 GeV protons to focused mesons that decay to neutrinos) → Hadron production correction using external data - PPFX (NA49, MIPP) → Focusing and hadron production uncertainties (multi-universe method)

↓

2. Use in-situ measurements

Flux shape correction (low recoil neutrino scattering)

↓

Flux normalization correction (scattering off atomic electrons)