Neutrino-Electron Scattering Flux Constraint with MINERvA

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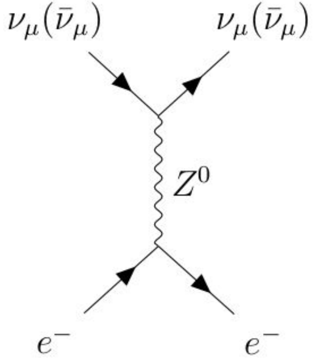
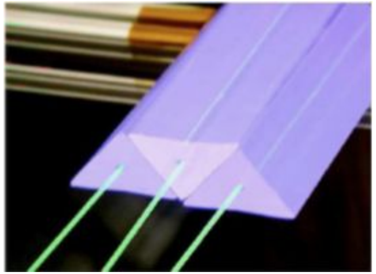
Neutrino-electron elastic scattering

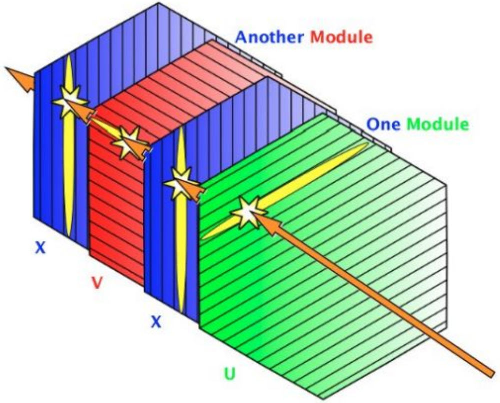
- Cross section known from the Standard Model
  - Small uncertainties on the Cross section
- Approximately four orders of magnitude smaller than the total neutrino CC cross section
- Actually four different cross sections, processes are indistinguishable.
- “Standard candle” for the flux

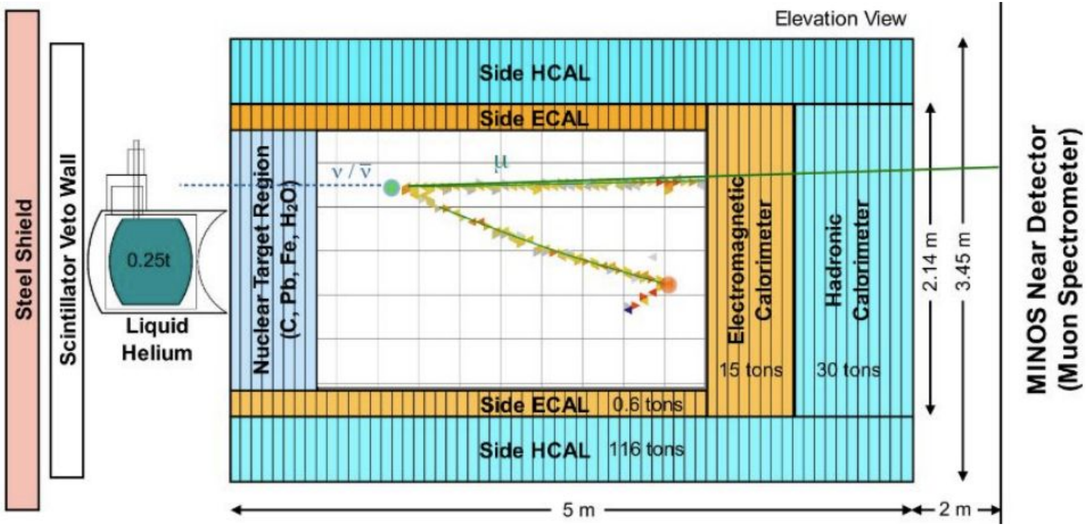


$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$
$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$
$$\nu_e + e^- \rightarrow \nu_e + e^-$$
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

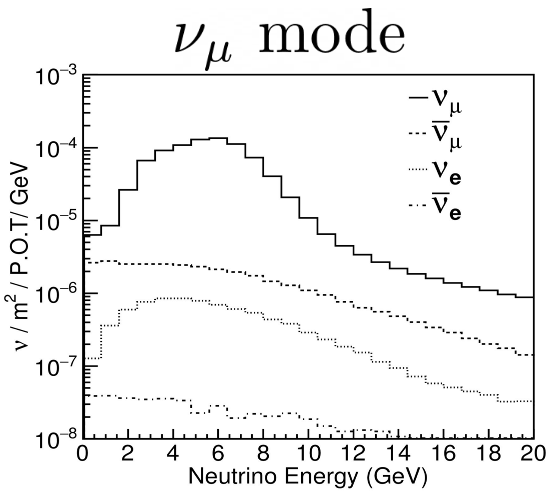
MINERvA

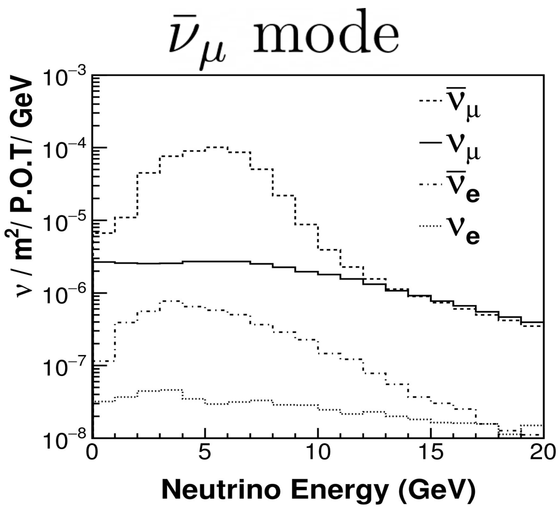



Another Module
One Module
X
V
X
U


Elevation View
Steel Shield
Scintillator Veto Wall
0.25t
Liquid
Helium
Nuclear Target Region
(C, Pb, Fe, H_2O)
$\nu / \bar{\nu}$
μ
Side HCAL
Side ECAL
Side ECAL 0.6 tons
Side HCAL 116 tons
Electromagnetic
Calorimeter
15 tons
Hadronic
Calorimeter
30 tons
2.14 m
3.45 m
5 m
2 m
MINOS Near Detector
(Muon Spectrometer)

MINERvA@NuMI



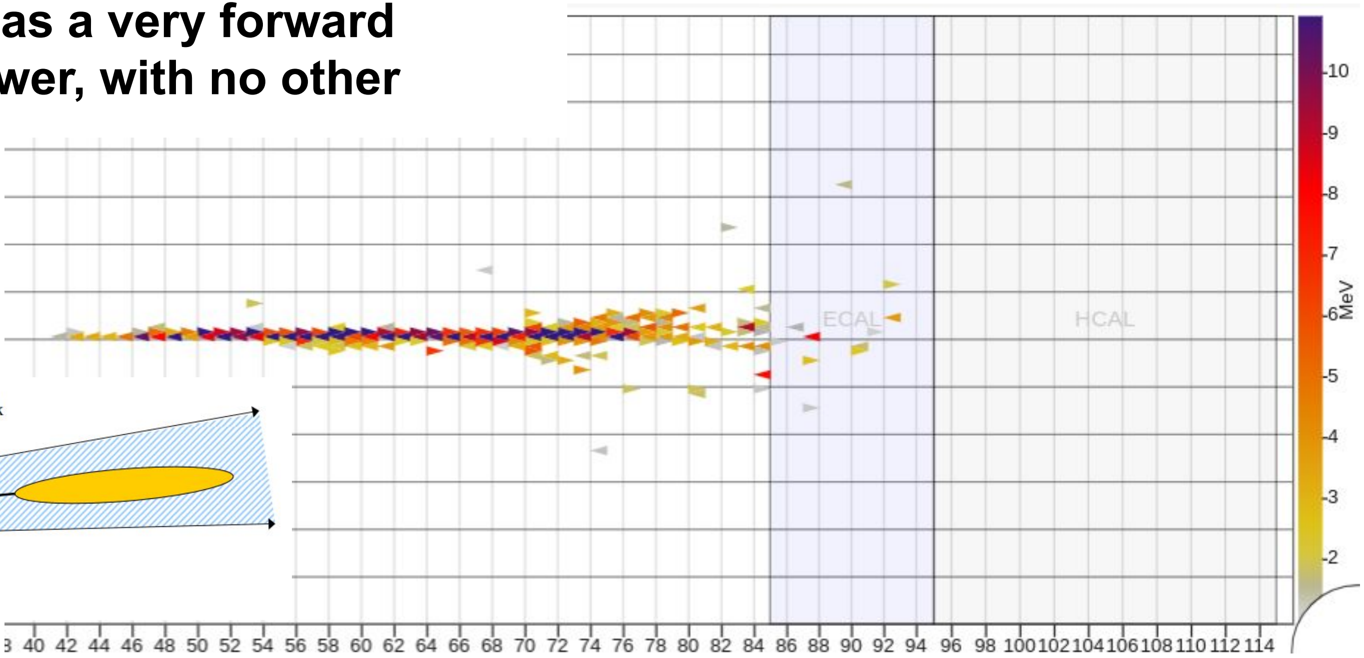


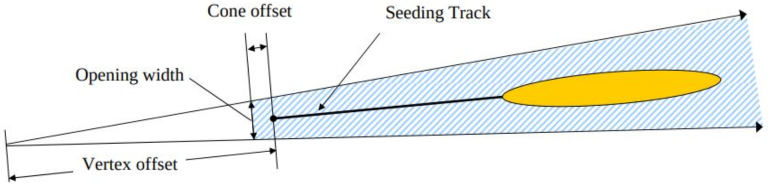
MINERvA has use this process successfully to constraint the neutrino flux

- Low energy beam, neutrino and anti-neutrino: Phys.Rev.D 93 (2016) 11, 112007
- Medium energy beam, predominantly neutrino: Phys.Rev.D 100 (2019) 9, 092001
- Medium energy beam, predominantly anti-neutrino, combination: Phys.Rev.D 107 (2023) 1, 012001

ν+e scattering at MINERvA

The electron is seen as a very forward electromagnetic shower, with no other activity

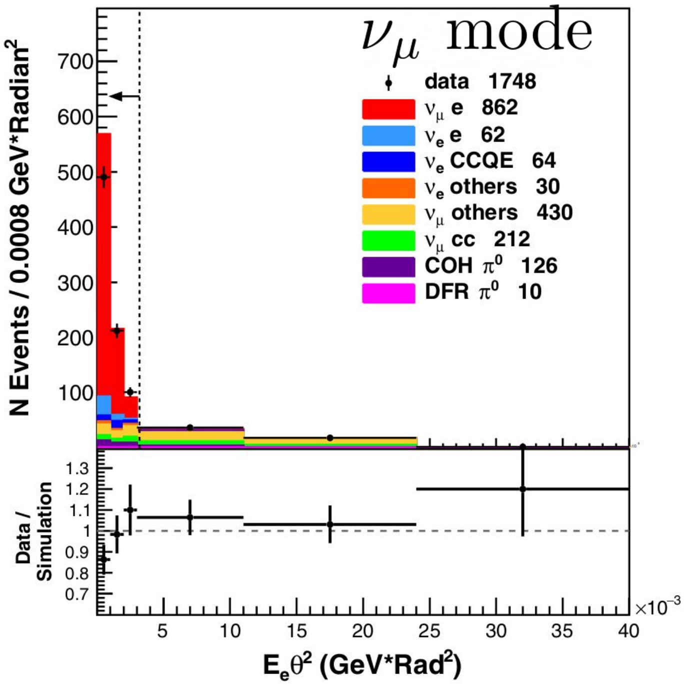


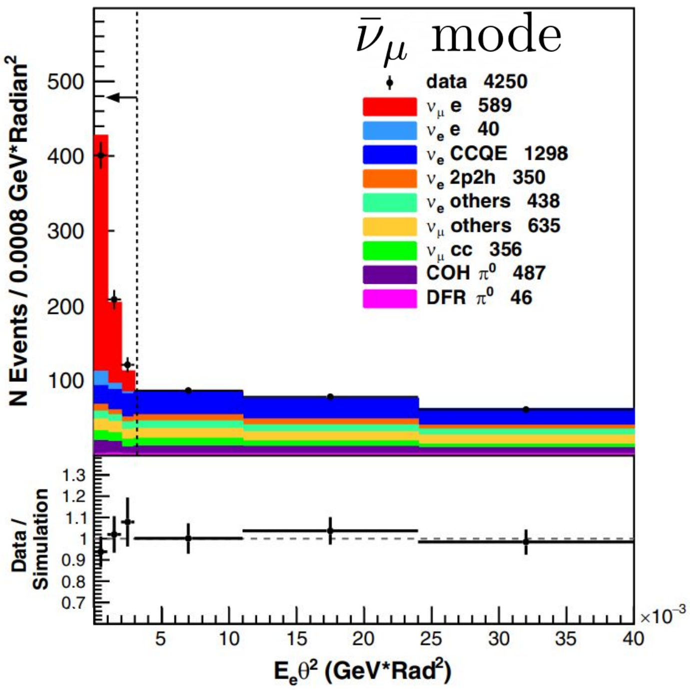


v+e elastic scattering obeys the kinematic constraint

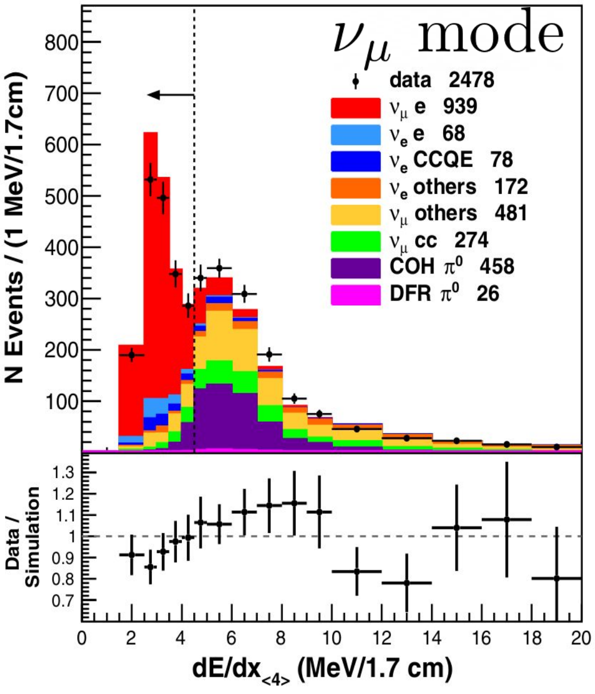
$$E_e\theta_e^2 < 2m_e$$

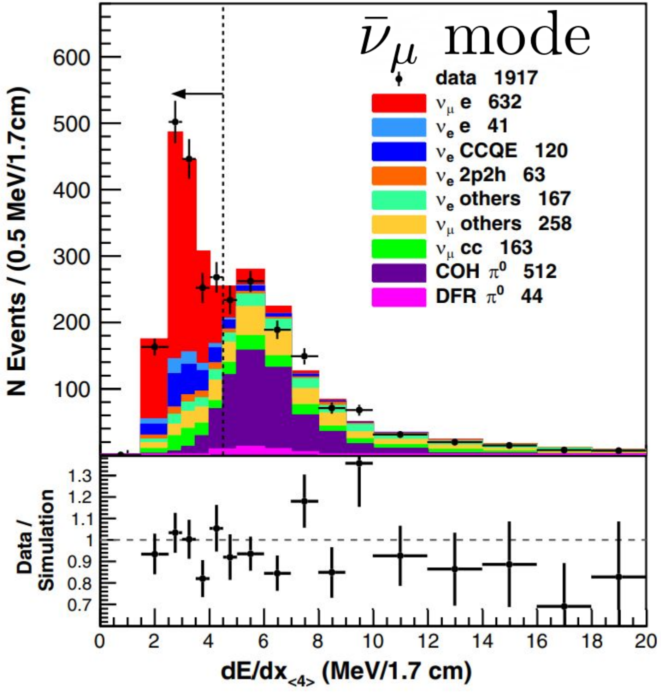
Due to smearing, the optimal cut is < 0.0032 GeV Rad^2
Essential to reject background

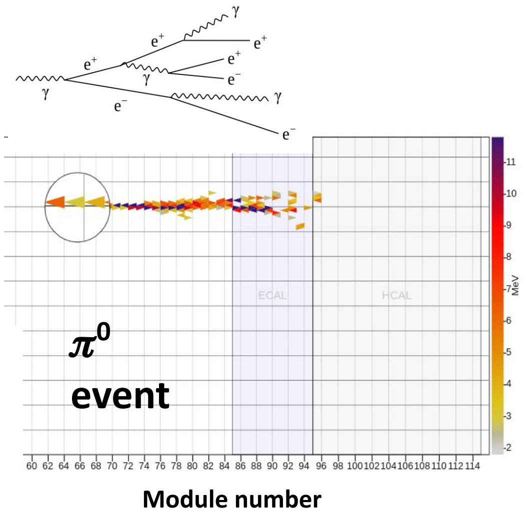




Photon Shower Rejection

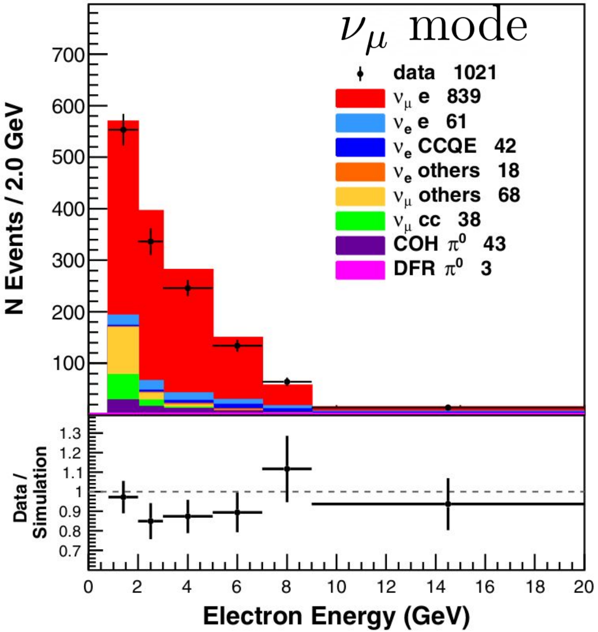


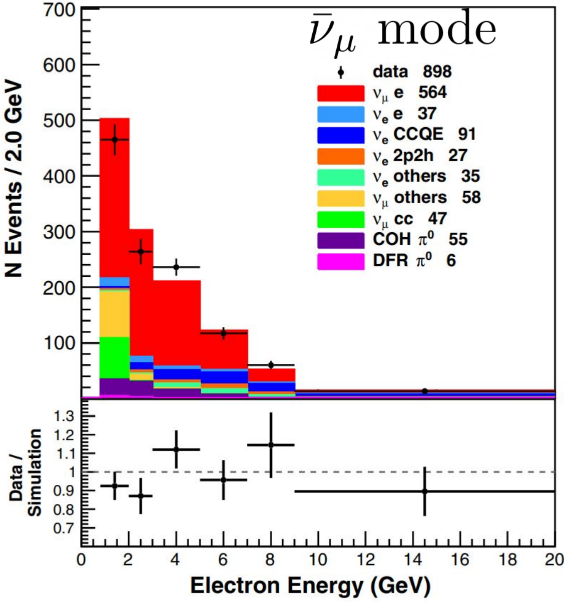




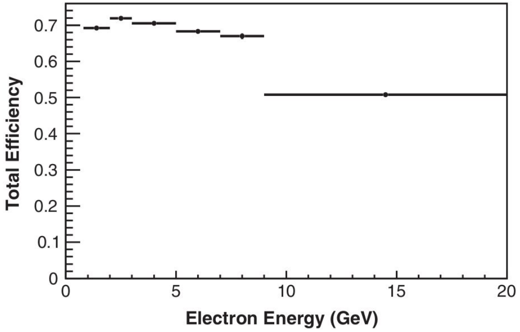
dE/dx to separate electron showers from photons

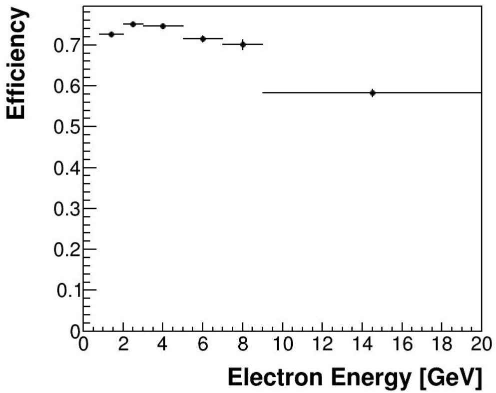
Background is constraint using a fit on four kinematic sidebands





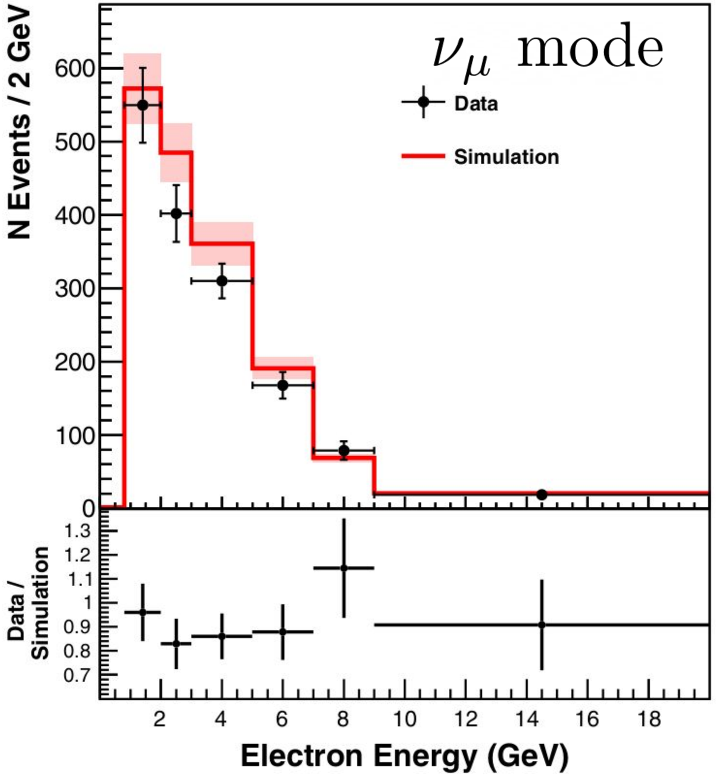
Efficiency correction

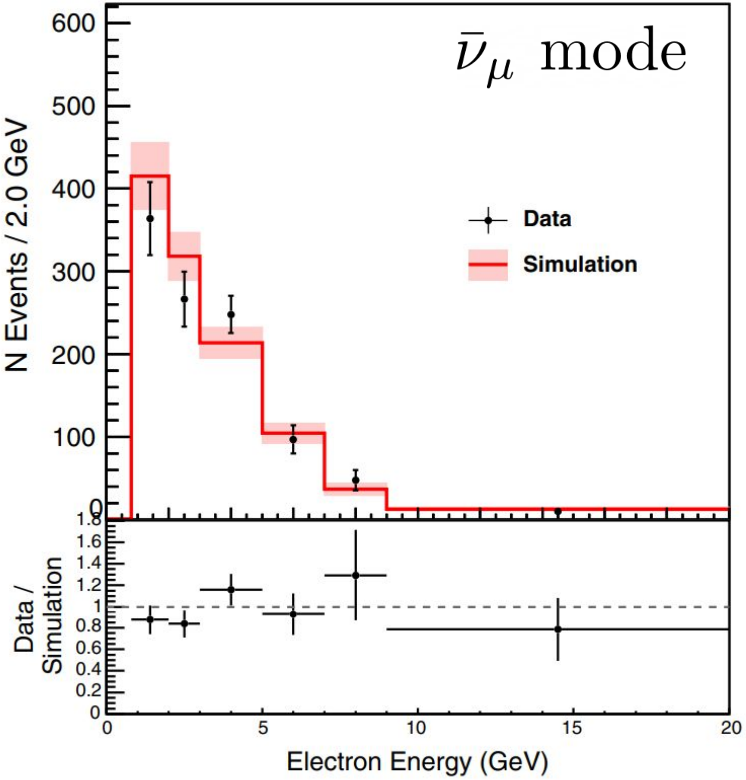




Measured spectrum

Background subtracted and efficiency corrected
Input for the constraint procedure

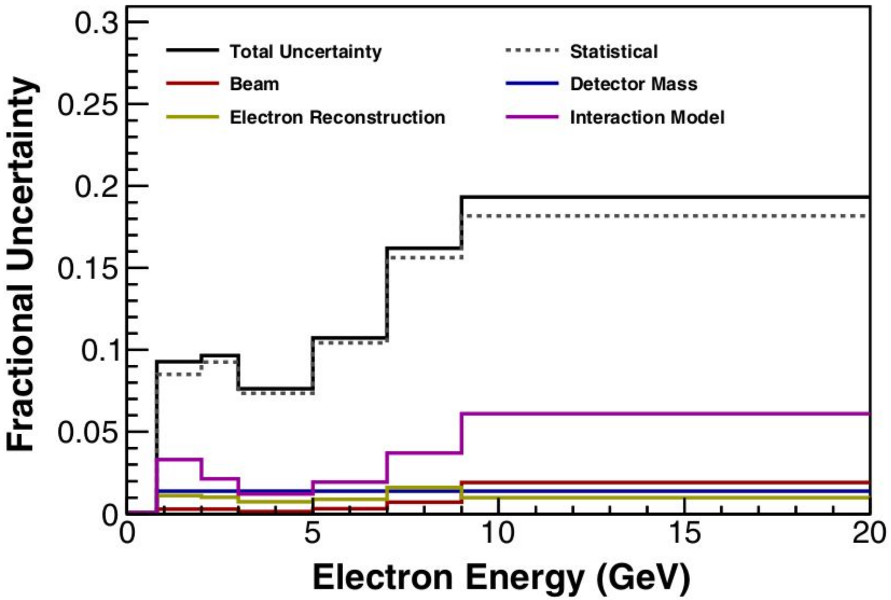




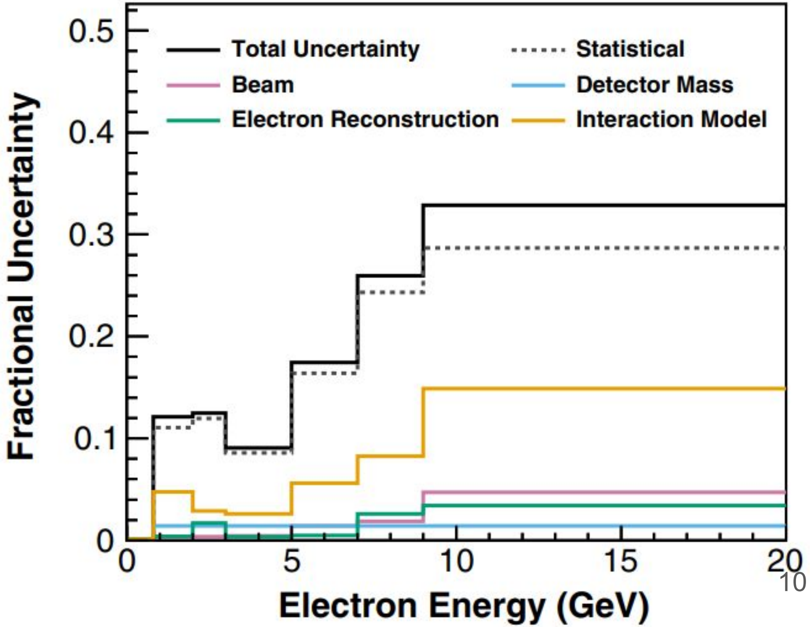
Uncertainty is dominated by statistics

	Uncertainty (%)	
Source	$\bar{\nu}_\mu$-mode	ν_μ-mode
Beam	0.22	0.21
Electron reconstruction	0.20	0.57
Interaction model	3.74	1.68
Detector mass	1.40	1.40
Total systematic	4.06	2.27
Statistical	5.49	4.17
Total	6.83	4.75

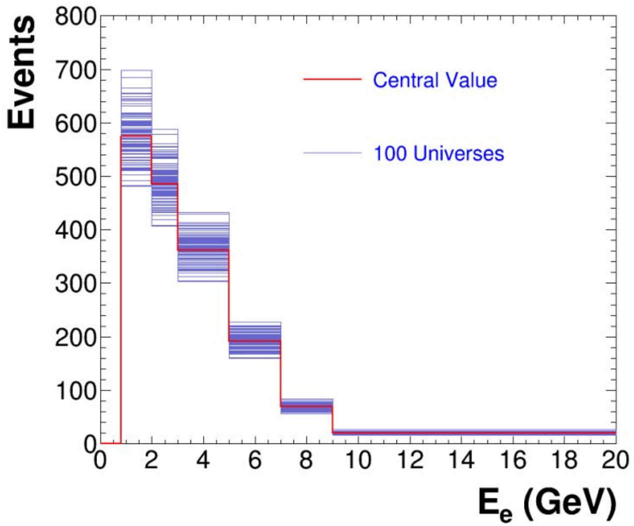
ν_μ mode



$\bar{\nu}_\mu$ mode



Flux reweight



Built a probability distribution for the flux

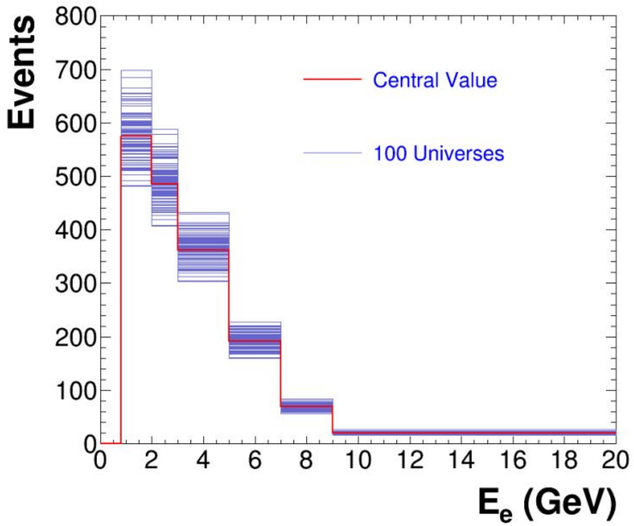
$$P(M|N_{\nu e \to \nu e}) \propto P(M)P(N_{\nu e \to \nu e}|M)$$

New prediction, given the observed measurement

a-priori model of the flux: flux simulation

Likelihood of the observed electron energy spectrum given the a-priori flux

Flux reweight

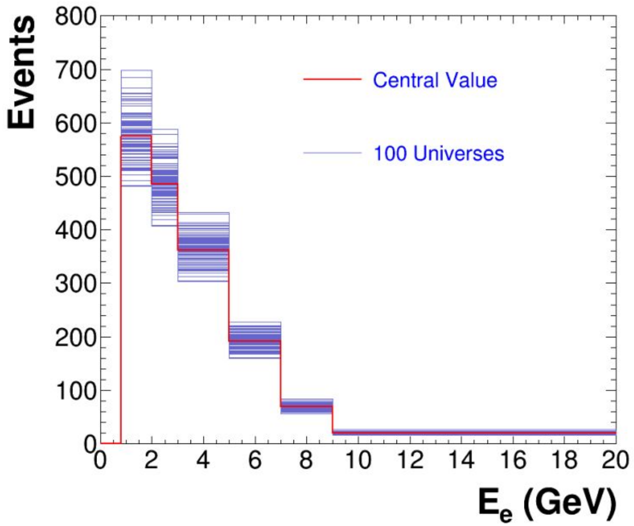


Built a probability distribution for the flux

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

- **1000 flux universes**
- **Up to this point all 1000 universes are equally valid**
- **This procedure enhances and suppress the contribution of individual universes according to P(N|M)**

Flux reweight



Built a probability distribution for the flux

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

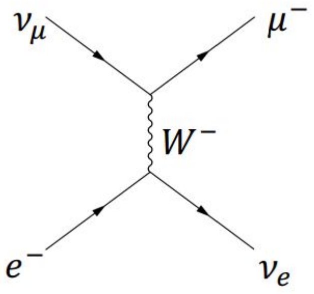
$$P(N_{\nu e \to \nu e}|M) = \frac{1}{(2\pi)^{K/2}} \frac{1}{|\Sigma_{\mathbf{N}}|^{1/2}} e^{-\frac{1}{2}(\mathbf{N}-\mathbf{M})^T \Sigma_{\mathbf{N}}^{-1} (\mathbf{N}-\mathbf{M})}$$

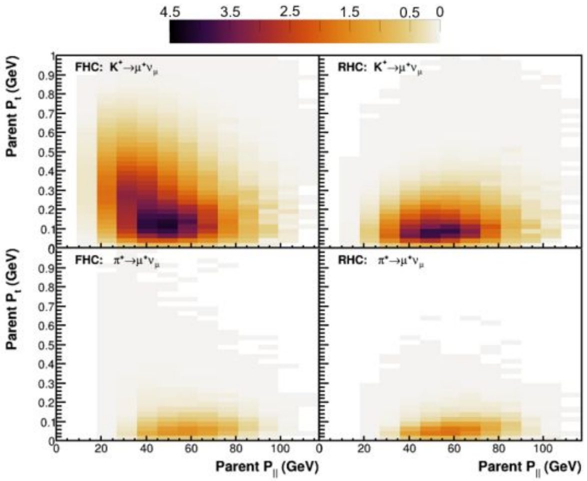
- **N is a vector containing the bin content of the measured energy spectrum of given process**
- **M is the same as N but for the MC prediction**
- **Σ_N is the covariance matrix of the uncertainties of N**
- **K is the number of bins of the spectrum**

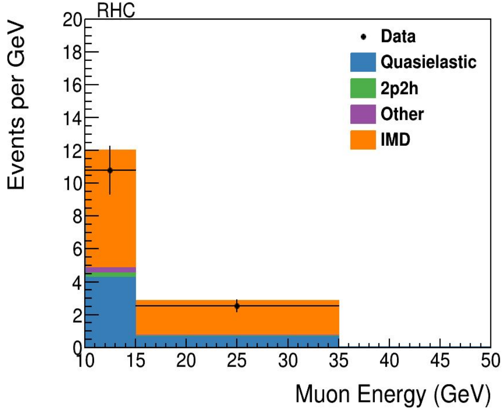
This is calculated for each flux universe.

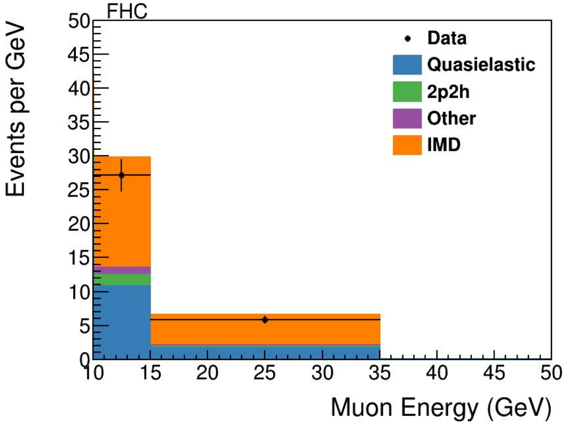
Inverse Muon Decay (IMD)

- Well-predicted cross section
- Small sample
  - Kinematic threshold about 11GeV
- Neutrino mainly from Kaon parent
- **Directly constrains the flux at high energies**





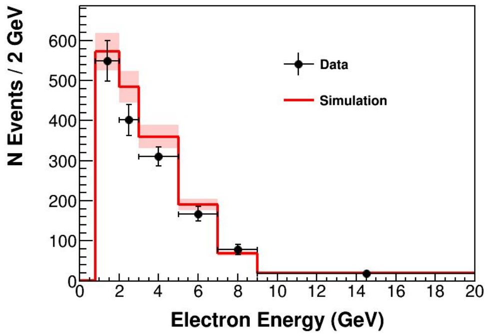




Phys.Rev.D 104 (2021) 9, 092010

Making a constraint with all the measurements

ν+e→ν+e on neutrino mode



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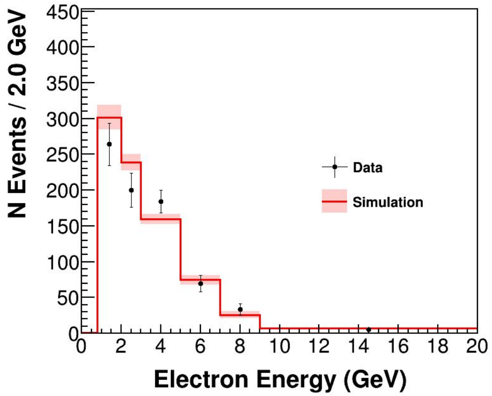
ν+e→ν+e on antineutrino mode



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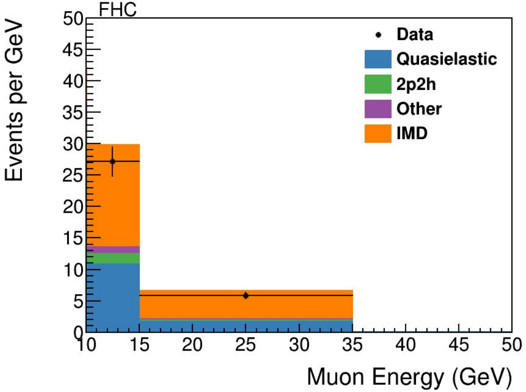
Inverse muon decay in both modes

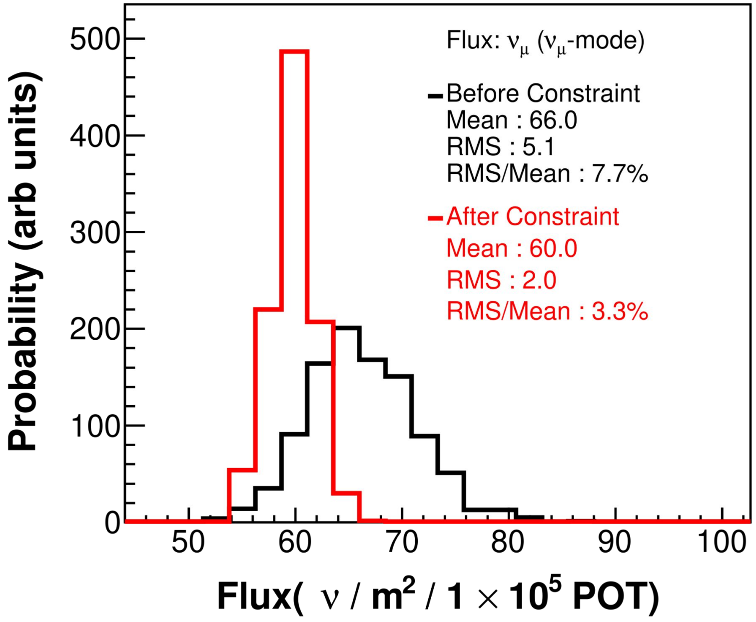


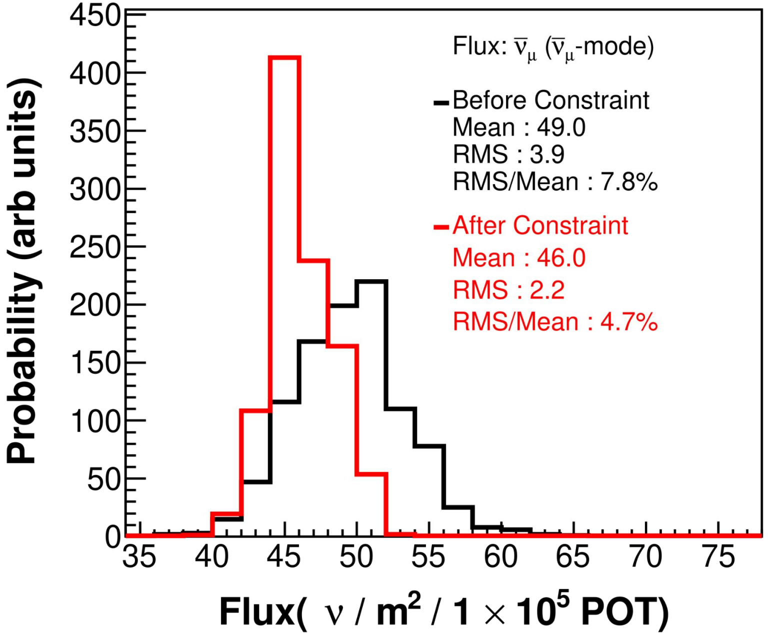
$$P(N_{\nu e\to\nu e}|M) = \frac{1}{(2\pi)^{K/2}}\frac{1}{|\Sigma_{\mathbf{N}}|^{1/2}}e^{-\frac{1}{2}(\mathbf{N}-\mathbf{M})^T\Sigma_{\mathbf{N}}^{-1}(\mathbf{N}-\mathbf{M})}$$

Need to construct a joint covariance matrix

Flux Probability distributions

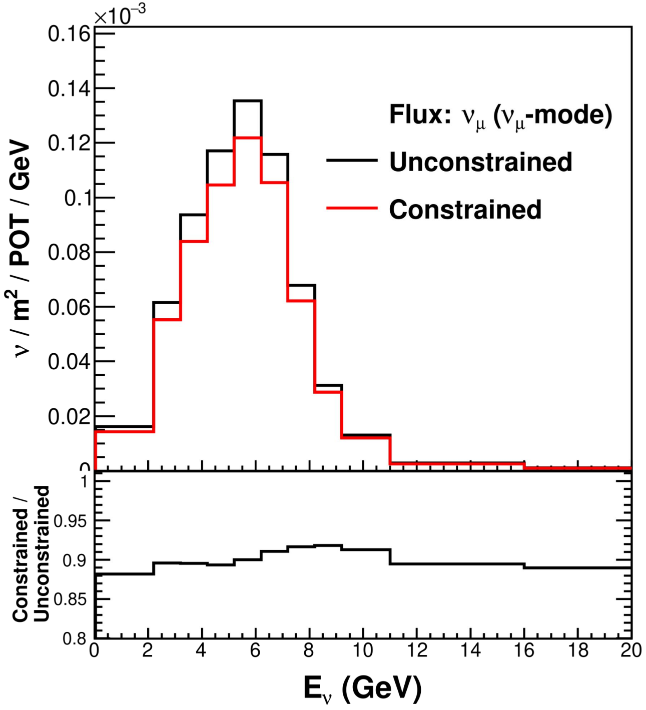
Spread of the distribution yields the integrated flux uncertainty

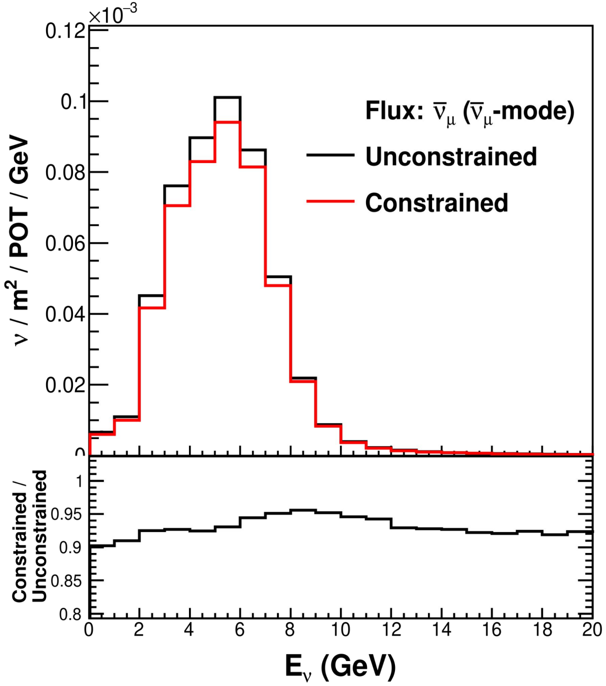




Constrained Flux

About 10% reduction on the normalization



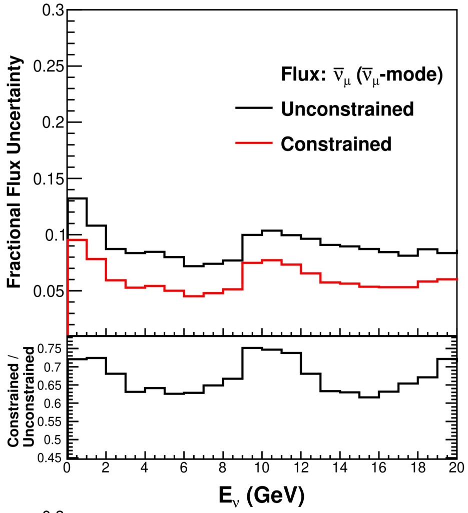


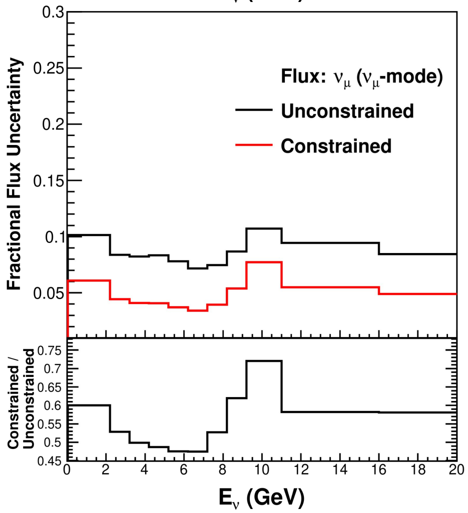
Constrained flux uncertainty

Fractional flux uncertainty of integrated flux between 2-20 GeV

	$\bar{\nu}_\mu$-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

- **Neutrino mode: 7.6% to 3.3%**
- **Antineutrino mode: 7.8% to 4.7%**





Summary

- **Neutrino-electron scattering successfully constrains the uncertainty of the flux at the MINERvA detector.**
  - **The constraint will reduce the flux uncertainty on future cross-section measurements from MINERvA.**
- **Statistics, electron identification and angular resolution are crucial**
- **Neutrino-electron scattering is a major design drivers for DUNE Near Detector**

DUNE ND Conceptual Design Report: arXiv:2103.13910

Table 1.5: ND-M3 capability requirements for ND-LAr.

Label	Description	Specification	Rationale	Ref. Req.
ND-C1.2	Sufficiently large sample of ν-e elastic events identified with high efficiency and low backgrounds	$\sim 2\%$	This is necessary to perform an adequate $\nu - e$ elastic measurement for the flux measurement.	ND-M3
ND-C1.2.1	Fiducial mass/statistics	> 2500 ev/yr	ND-LAr must collect sufficient statistics to allow $< 2\%$ statistical uncertainty in the measurement	ND-M3
ND-C1.2.2	$\nu - e$ identification		ND-LAr must be able to distinguish the outgoing electron from other particles (μ, γ, π^0)	ND-M3
ND-C1.2.3	Electron energy resolution	5%	Energy resolution is needed to identify the forward $\nu - e$ events.	ND-M3
ND-C1.2.4	Electron angular resolution	core< 5 mrad, tail< 12 mrad for $E_e >$2 GeV	A tight cut on forward electrons is needed to identify $\nu - e$ events	ND-M3
ND-C1.2.5	Vertex activity threshold	20 MeV	Identifying vertex activity is necessary to reject backgrounds	ND-M3

Modification to GENIE in this analysis

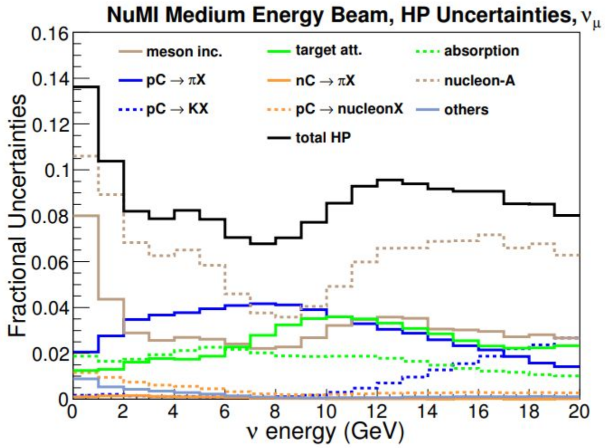
Modifications to GENIE simulation relevant to this analysis.

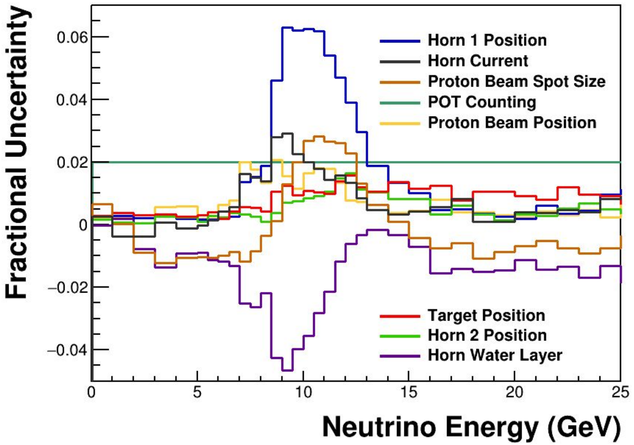
- Radiative correction to ν+e→ν+e cross section
  - Based on S. Tomalak et al, Phys.Rev.D 101 (2020) 3, 033006
- Weak charge screening - Random Phase Approximation (RPA)
  - Suppresses the Quasi-elastic cross section at low momentum transfer
- Interaction with correlated pairs - “two particle-two holes”(2p2h)
  - Based on the Valencia model PRC 70, 055503 (2004); PRC 83, 045501 (2011)
  - Added to GENIE. Data suggest an enhancement to model.

Flux uncertainties

- Uncertainty from hadron production at the target and focusing parameters
- Predicted by simulation of the beamline
- Hadron production is constrained using external data
  - Reduce the fractional uncertainty to ~8%

Phys.Rev.D 94 (2016) 9, 092005

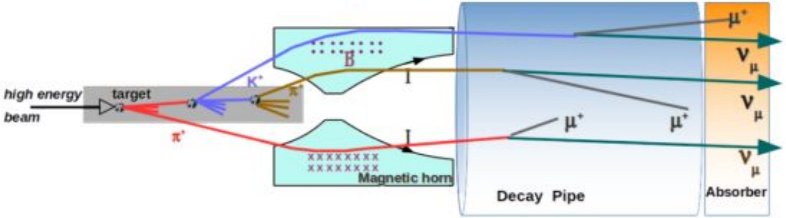




JINST 16 (2021) P08068

Hadron Production data

The simulations are tuned using external measurement from hadron production data



- Tabulate the hadronic cascade at generation with all kinematic information and store in the flux tuples
- MC interactions are weighted to the measured cross section.
- The beam attenuation in target (and other materials) is also corrected.
- Assign and propagate uncertainties.

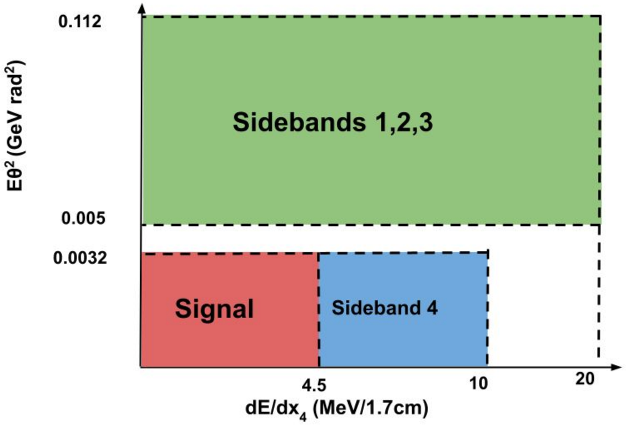
- Inelastic cross section:
  - Belletinni, Denisov, etc. cross sections of pC, πC, πAl etc.
  - **NA49: pC @ 158 GeV.**
  - NA61 pC @ 31 GeV.
- Hadron Production:
  - Barton: $pC \to \pi^{\pm}X$ @ 100 GeV $x_F > 0.3$.
  - **NA49: $pC \to \pi^{\pm}X$ @ 158 GeV $x_F < 0.5$.**
  - NA49: $pC \to n(p)X$ @ 158 GeV for $x_F < 0.95$.
  - NA49: $pC \to K^{\pm}X$ @ 158 GeV for $x_F < 0.2$.
  - NA61: $pC \to \pi^{\pm}X$ @ 31 GeV .
  - MIPP: π/K from pC at 120 GeV for $p_Z > 20GeV/c$.
- MIPP: proton on a spare NuMI target at 120 GeV:
  - $\pi^{\pm}$ up to 80 GeV/c.
  - K/π for $p_Z > 20GeV/c$.

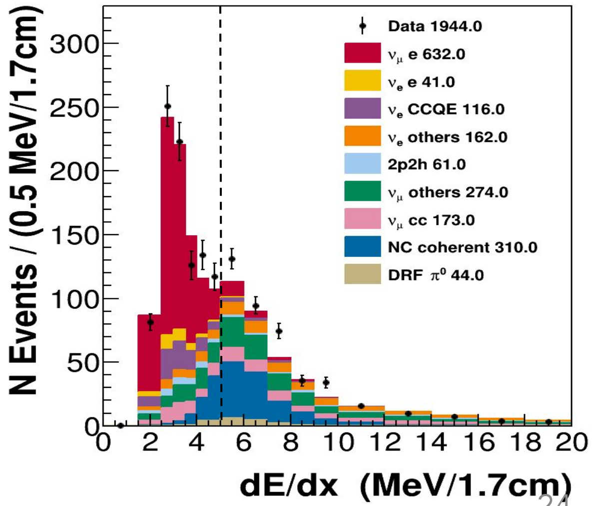
Data used by MINERvA

L.Aliaga

Constraining of the background using sidebands

- Make four background samples on the dE/dx - EΘ^2 plane
- Let the normalization of the background templates float in a chi-squared minimization
- Apply the normalization from the fit of the sideband regions to the background on the signal region





Constraining of the background using sidebands

Tuning parameters: Normalization of

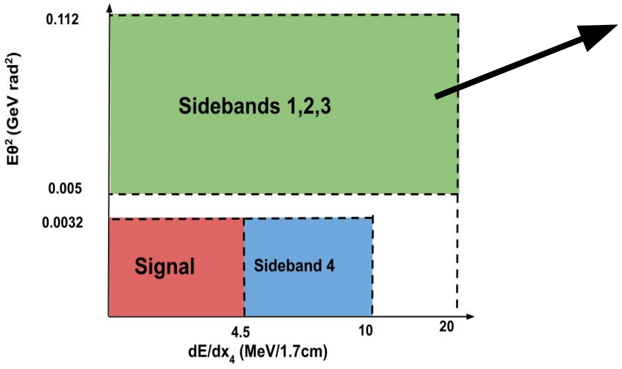
- ν_e background
- ν_μ except coherent NC
- Coherent NC in six bins of electron energy

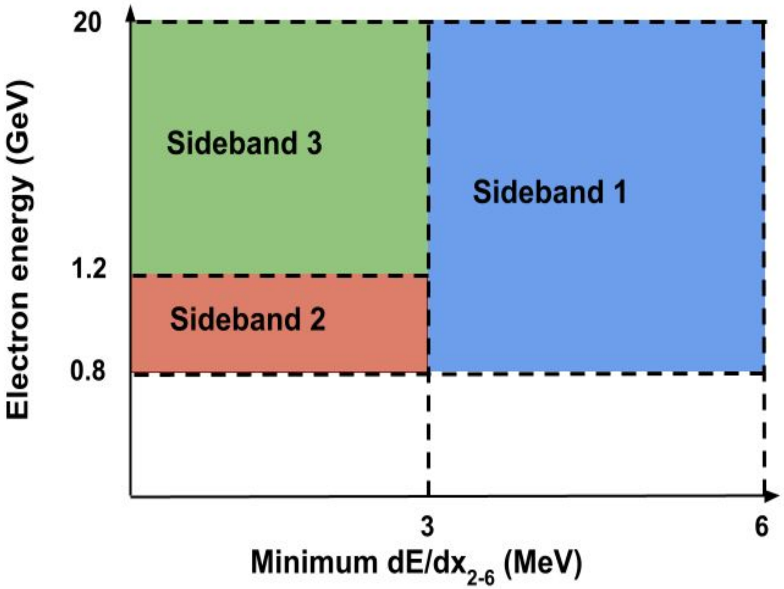
SB1 - Shower + Vertex activity

SB2 - ν_μ enriched

SB3 - ν_e enriched

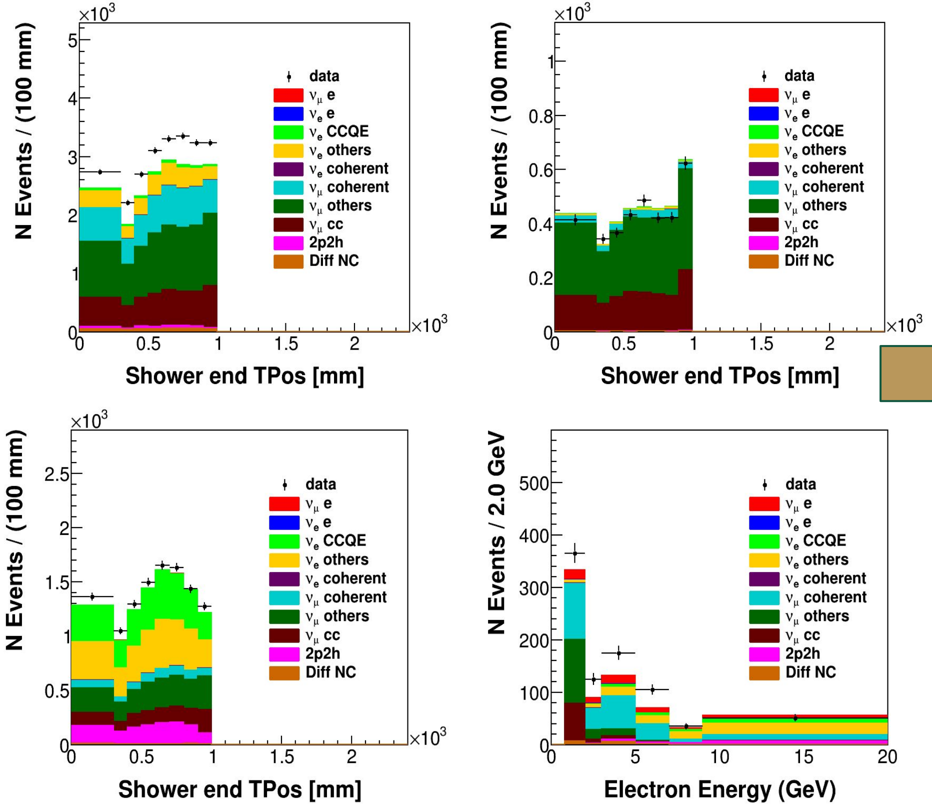
SB4 - π^0 enriched



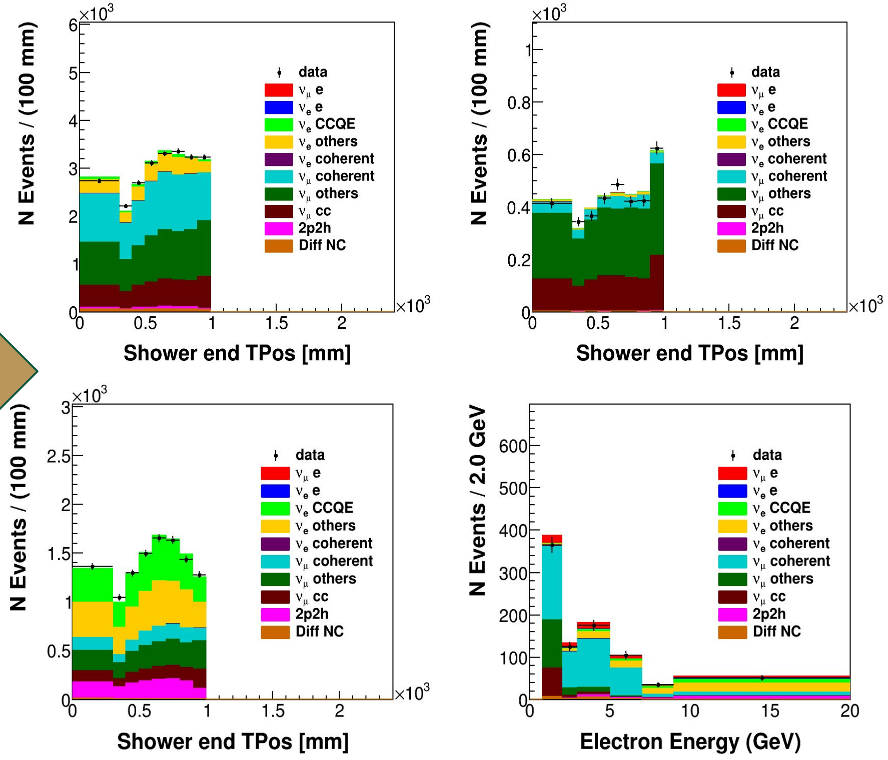


Change normalization following a Chi-square minimization

Before



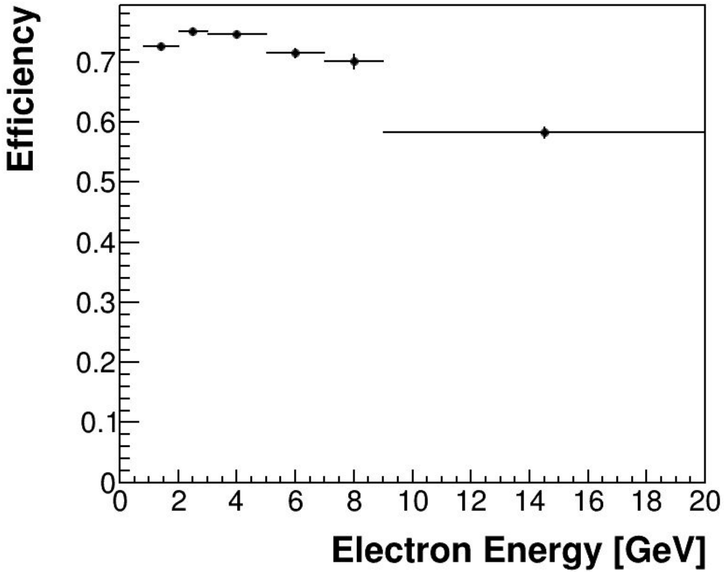
After

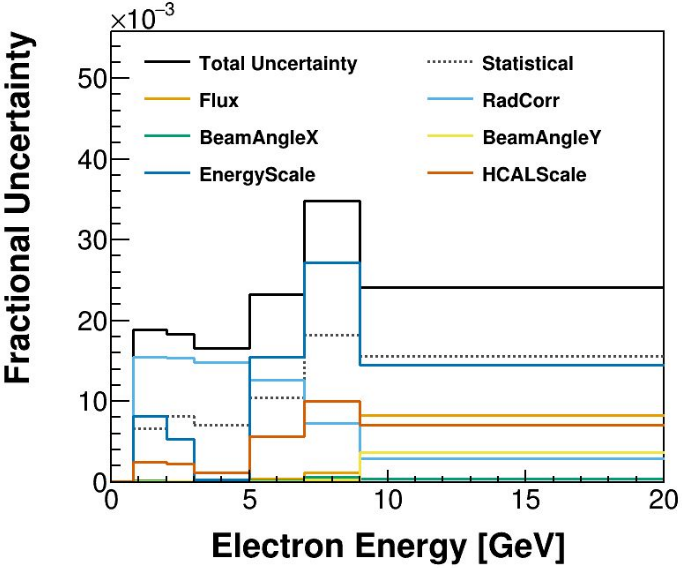


Efficiency correction

How many ν+e events do we miss?
Estimate using simulation

$$\text{efficiency} = \frac{\text{reco events that past all the cuts}}{\text{truth event that past the energy and fiducial cuts}}$$



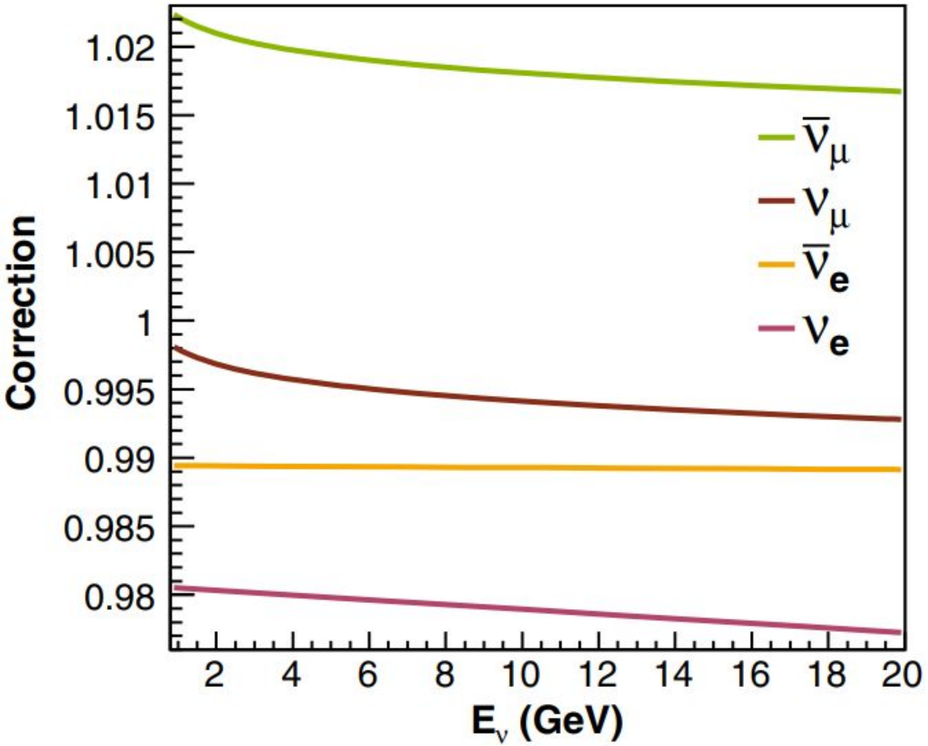


Radiative Corrections

GENIE tree-level cross-section reweighted to match the one calculated including radiative corrections from O. Tomalak, R. J. Hill. Phys. Rev. D 101, 033006 (2020)

- Includes production of real photons in final state

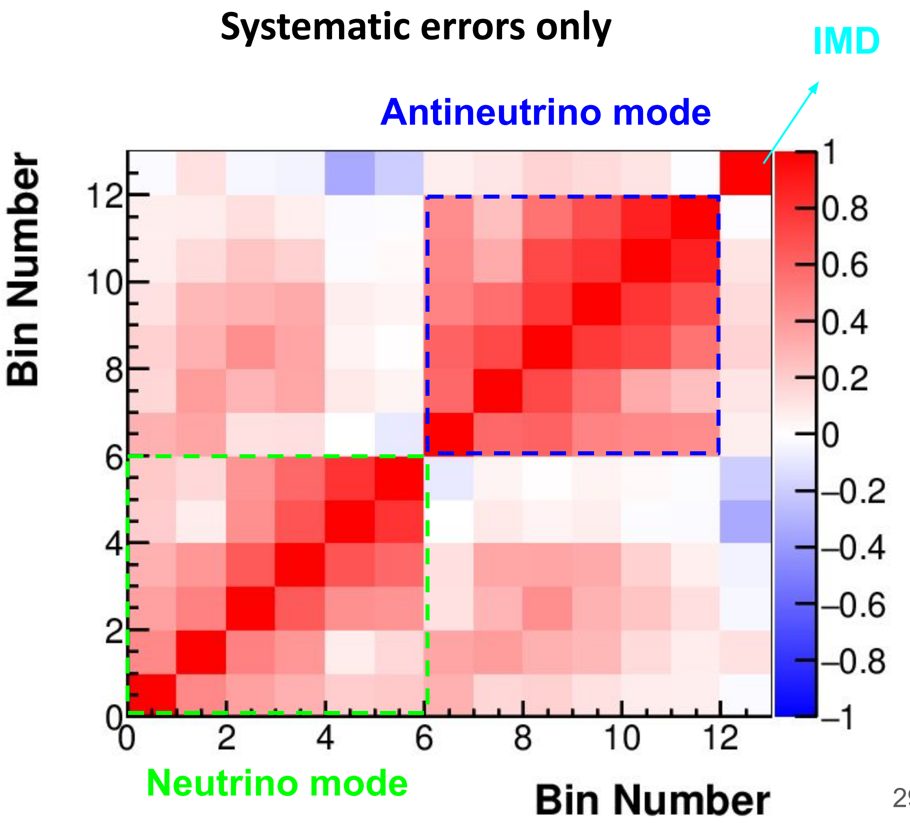
Ratio between Phys. Rev. D 101, 033006 (2020) x-secs and GENIE 2.12.6.



Make a covariance matrix

The pertinent systematics error are correlated between measurements

- **The GENIE uncertainties**
- **Specific uncertainties share by the two ν+e elastic measurements**

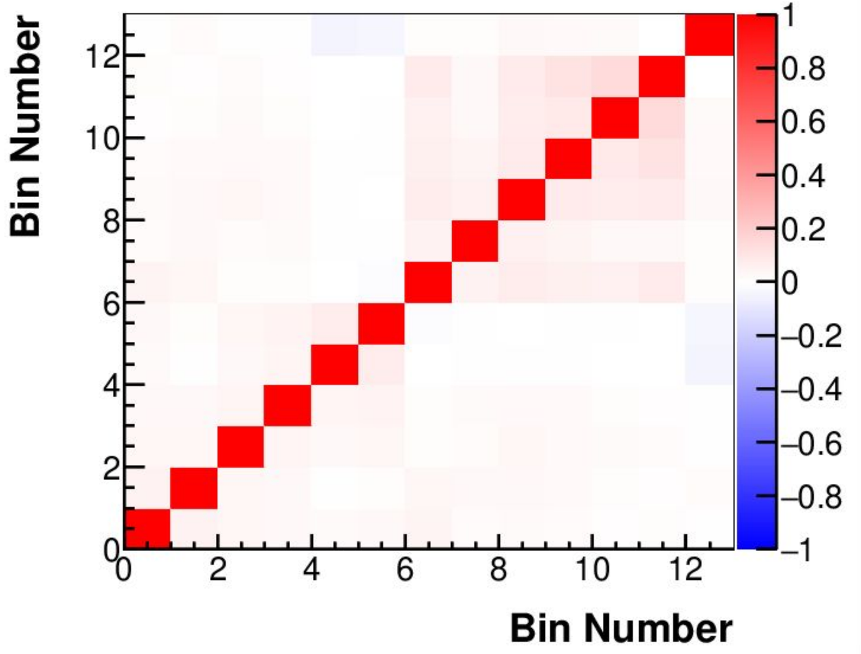


Make a covariance matrix

Dominant error is statistical

- **Effect of correlations end up being really small**

Statistical and systematic errors



Constrained flux uncertainty

Fractional flux uncertainty of integrated flux between 2-20 GeV

	$\bar{\nu}_\mu$-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

- **Constraints from one data set works better for that data**
- **Combination is better compared to individual, particularly on wrong-sign component**
- **IMD mostly improves muon neutrino flux and wrong-sign**