Flux measurements in MINERvA

September 7, 2021

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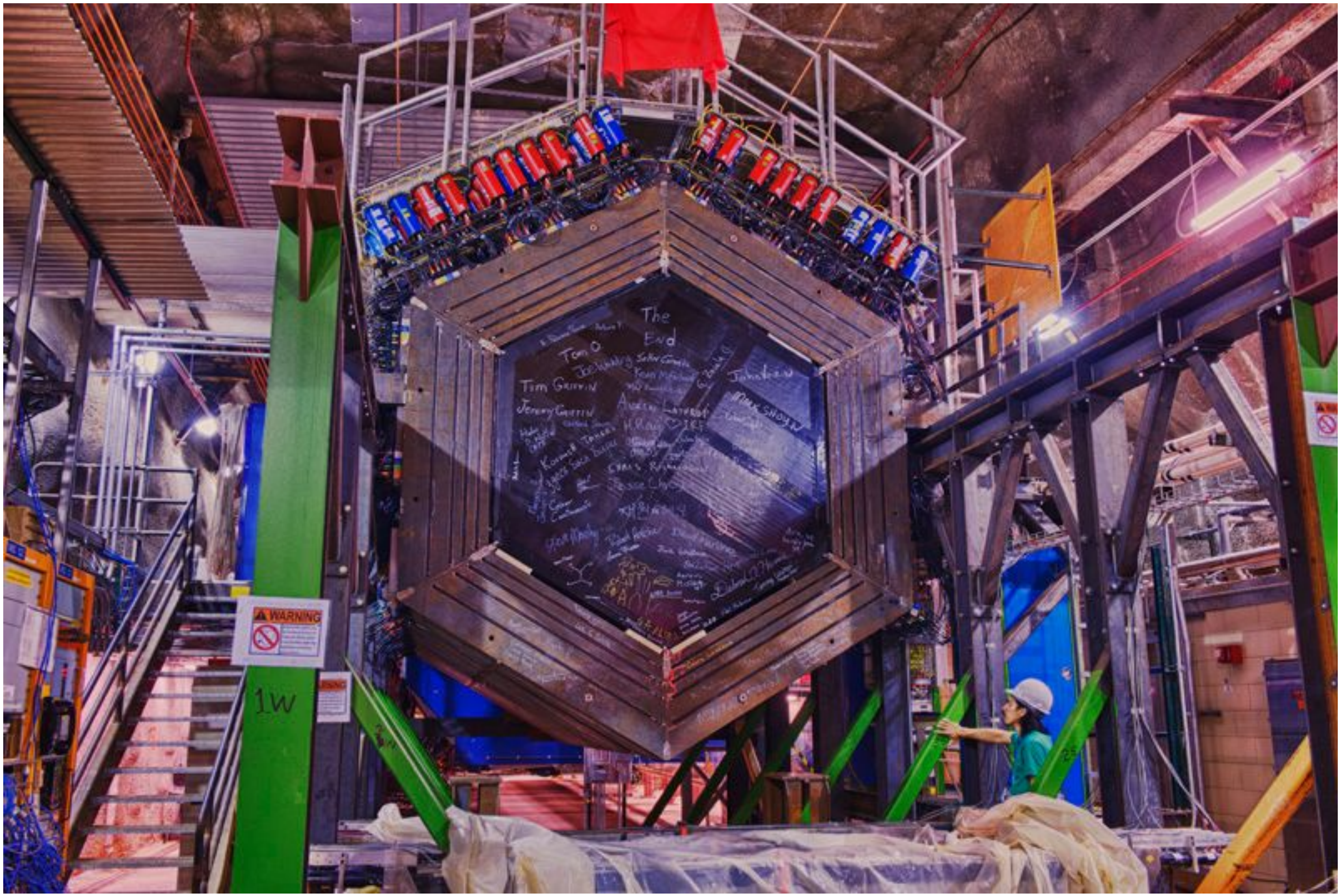
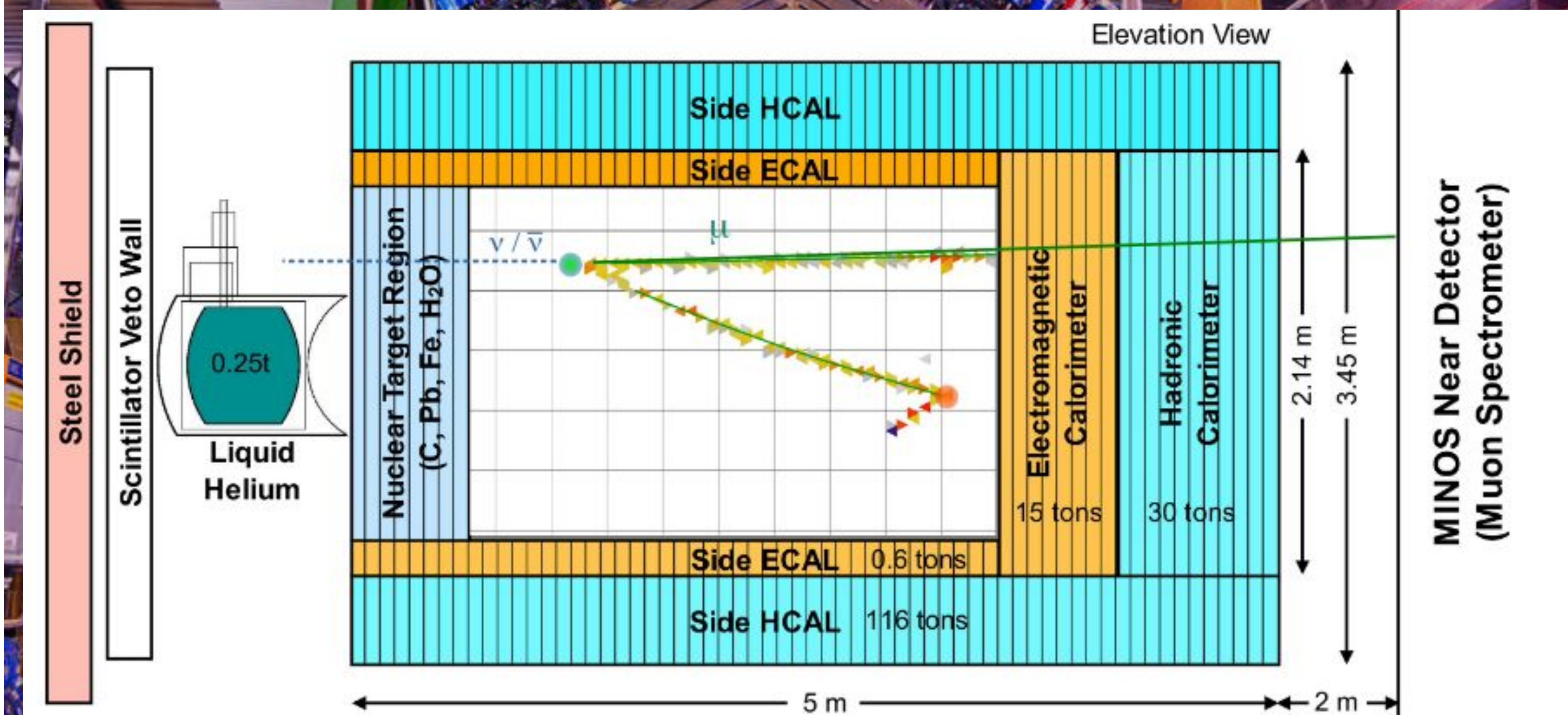
WILLIAM & MARY
CHARTERED 1693

The MINERvA Experiment



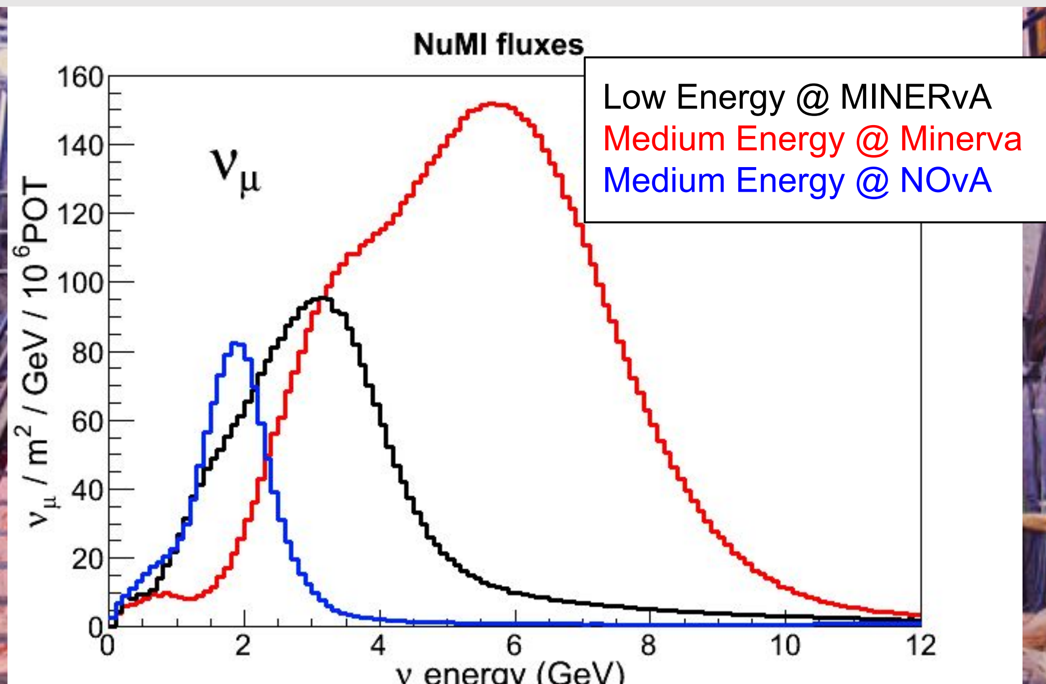
The MINERvA Experiment

- NuMI hall at Fermilab, upstream of MINOS ND
- Fully active scintillator tracker
- Embedded C,Fe,Pb, He, and H_20 targets



The MINERvA Experiment

- Ran between 2009-12 in the NuMI low energy (LE) configuration: E≈3.5 GeV
- 2013-19 in the medium energy (ME) configuration: E≈6 GeV
- Huge dataset, especially in the ME configuration
  - Neutrino mode:4.3e6 ν_μ-CC interactions with MINOS acceptance.
  - Anti-neutrino mode 2.5e6 anti-ν_μ-CC interactions



Motivation for measuring flux and cross-sections: Oscillation Experiments

The event rate at a near detector is a convolution of three terms

$$\Gamma_{\mathrm{ND}}(E_{\mathrm{reco}}) = \int \Phi_{\mathrm{ND}}(E_{\mathrm{true}})\ \sigma_{\mathrm{ND}}(E_{\mathrm{true}})\ R_{\mathrm{ND}}(E_{\mathrm{true}}, E_{\mathrm{reco}})\ dE_{\mathrm{true}}$$

Neutrino Flux

- Predicted, *a priori*, from a beam simulation (g4NuMI, g4LBNE)
- Hadron production data (NA49, NA61, MIPP, etc) used to improve the simulation. Incorporated via event by event reweighting.
- Uncertainties from the HP data, physics model, & beam optics propagated via many universes (a.k.a. multi-sim) approach.
- Some systematic control by changing horn currents, target position, or off axis position

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Cross-section

- Nucleus, and hence detector, dependent
- Usually the FD and ND have the same nuclei, so the cross-sections are the same at the two detectors
- Or the ND has a variety
- Various final states, some easier to measure than others.

* Mis-identified events / backgrounds complicate this but in a non-essential way. Let's ignore them.

Motivation for measuring flux and cross-sections: Oscillation Experiments

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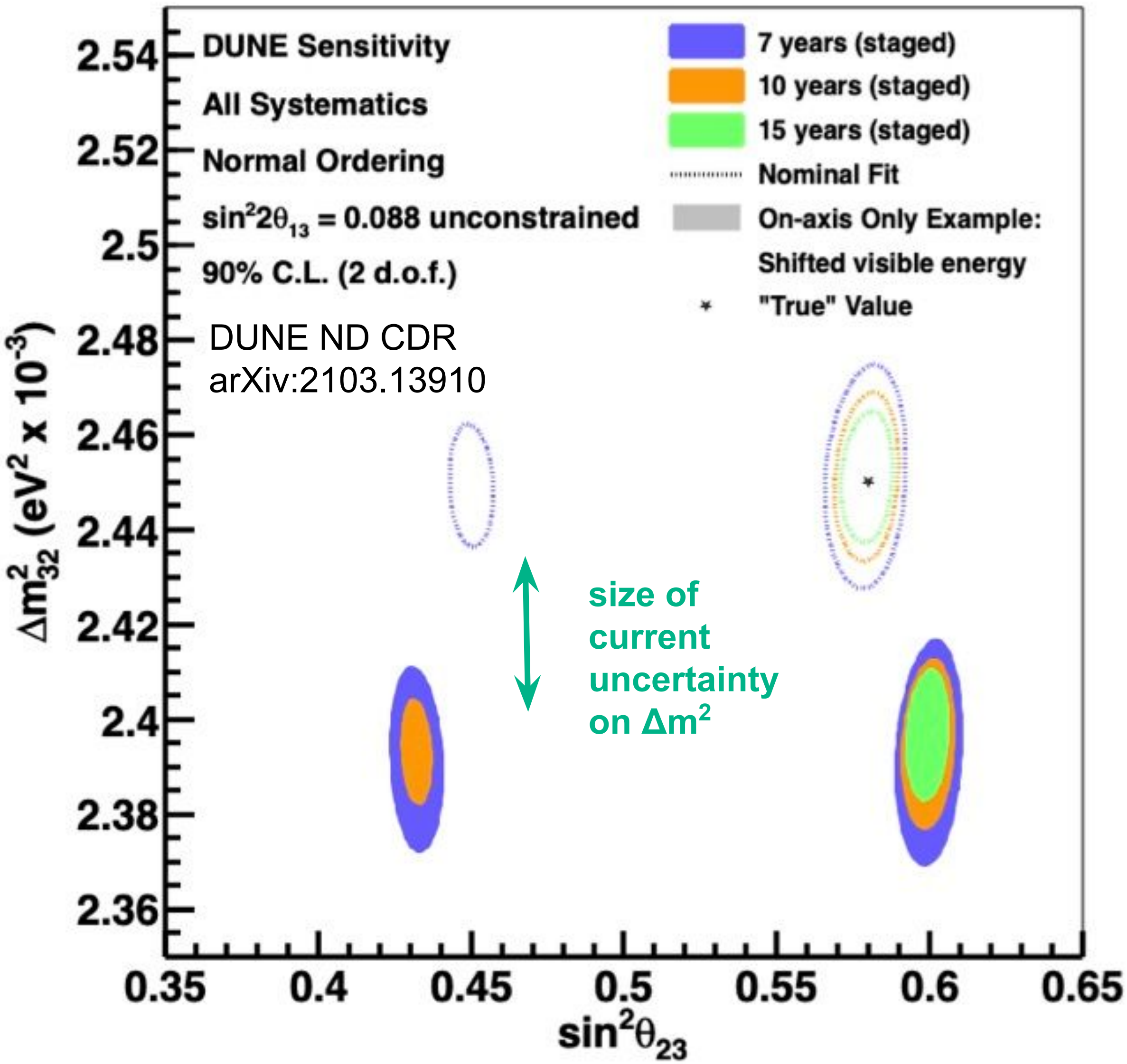
Detector Response

- Encodes the relationship between true and reconstructed energy
- Includes kinematic acceptance & smearing
- Predicted by a MC simulation: event generator + GEANT
- **Depends on the scattering channel / final state**

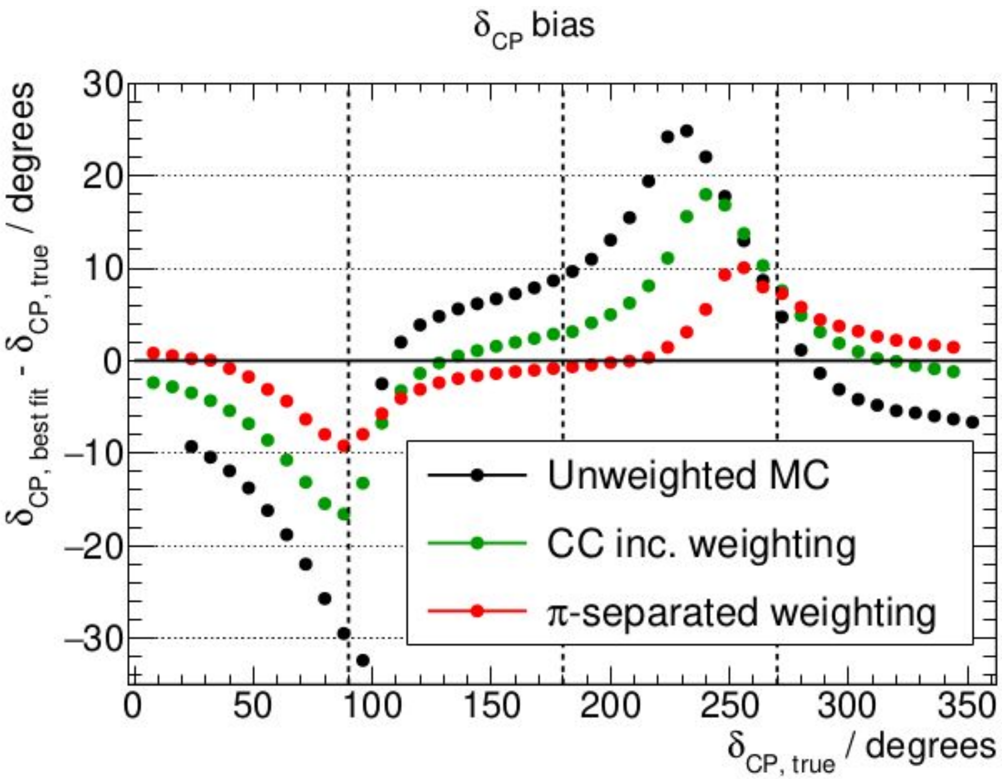
What if you get σ x R wrong?



- DUNE study where missing energy due to neutrons was not understood
- Model was tuned but using the wrong mechanism

What if you get σ x R wrong?

DUNE ND CDR
arXiv:2103.13910



- DUNE study where pion multiplicity (and a few other things) are not modeled correctly.
  - Mock data is NuWro, model is GENIE
- Affects R since one needs to correct for pion mass to get E_{reco}
- Large bias in δ_{cp} can be mitigated by cross-section measurements in the ND

Motivation for measuring flux and cross-sections: Oscillation Experiments

Oscillation Probabillity

The far detector has an additional term:

$$\Gamma_{\mathrm{FD}}(E_{\mathrm{reco}}) = \int \Phi_{\mathrm{FD}}(E_{\mathrm{true}})\, \sigma_{\mathrm{FD}}(E_{\mathrm{true}})\, R_{\mathrm{FD}}(E_{\mathrm{true}}, E_{\mathrm{reco}}) P_{\mathrm{osc}}(E_{\mathrm{true}}; \theta, \Delta m^2)\, dE_{\mathrm{true}}$$

- The goal is to extract the oscillation parameters
- Beam simulations predict $\boldsymbol{\Phi}_{FD}/\boldsymbol{\Phi}_{ND}$ fairly well (% level uncertainties) without oscillations.
- Constructing the two detectors out of the same nuclei gives the same σ at the FD and ND
- Functionally similar ND and FD can reduce the difference between R_{FD} and R_{ND}
- But the integral and unknown P_{osc} spoils direct cancellation
- Oscillation analyses end up being model dependent at some level
- Need to understand the models and/or reduce/remove dependency

$$\Gamma_{\mathrm{ND}}(E_{\mathrm{reco}}) = \int \Phi_{\mathrm{ND}}(E_{\mathrm{true}})\, \sigma_{\mathrm{ND}}(E_{\mathrm{true}})\, R_{\mathrm{ND}}(E_{\mathrm{true}}, E_{\mathrm{reco}})\, dE_{\mathrm{true}}$$

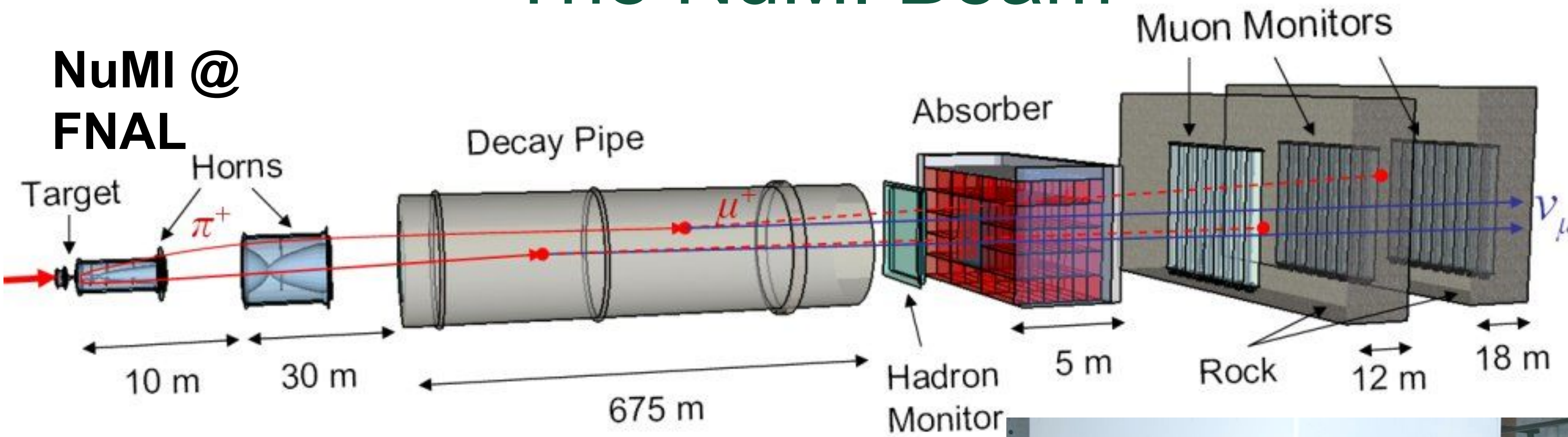
MINERvA: a ND without a pesky FD

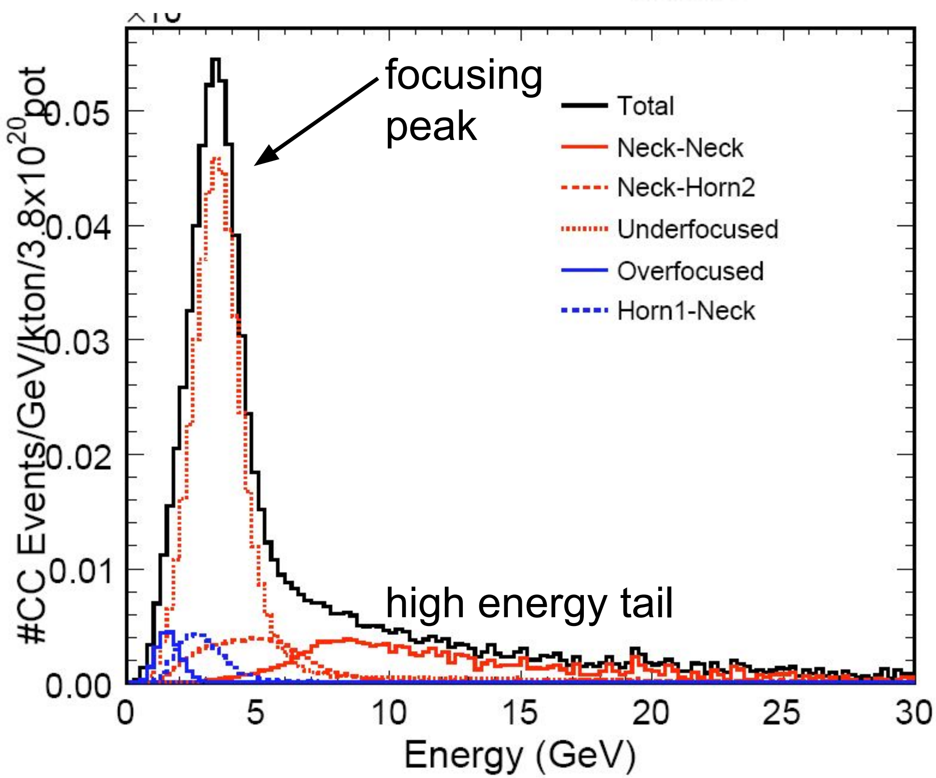
$$\Gamma_{\rm ND}(E_{\rm reco}) = \int \Phi_{\rm ND}(E_{\rm true})\ \sigma_{\rm ND}(E_{\rm true})\ R_{\rm ND}(E_{\rm true}, E_{\rm reco})\ dE_{\rm true}$$

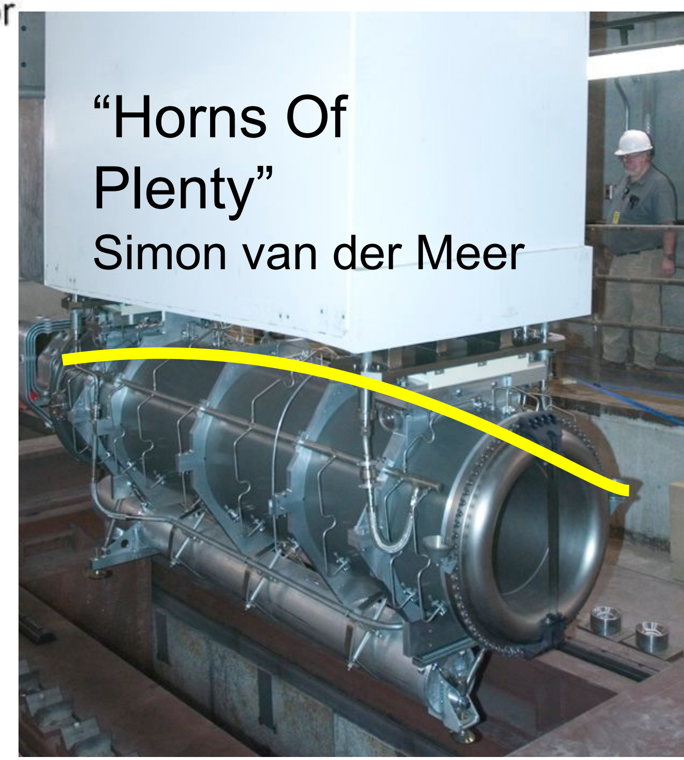
- MINERvA's goal is to tease apart this integral
- Factorize it into three parts:
  - Flux
  - Cross-section
  - Response
- I'll spend a good bit of time talking about the flux.
  - It's the first thing you'd like to get right.
  - MINERvA's flux campaign has unique elements enabled by the fined grained scintillator tracker and the large dataset.
  - Lessons and techniques apply directly onto future experiments (e.g., DUNE),
- The starting point is the NuMI beam simulation corrected with hadron production data.
- Then a series of in situ measurements are used to reduce uncertainties.

The NuMI Beam

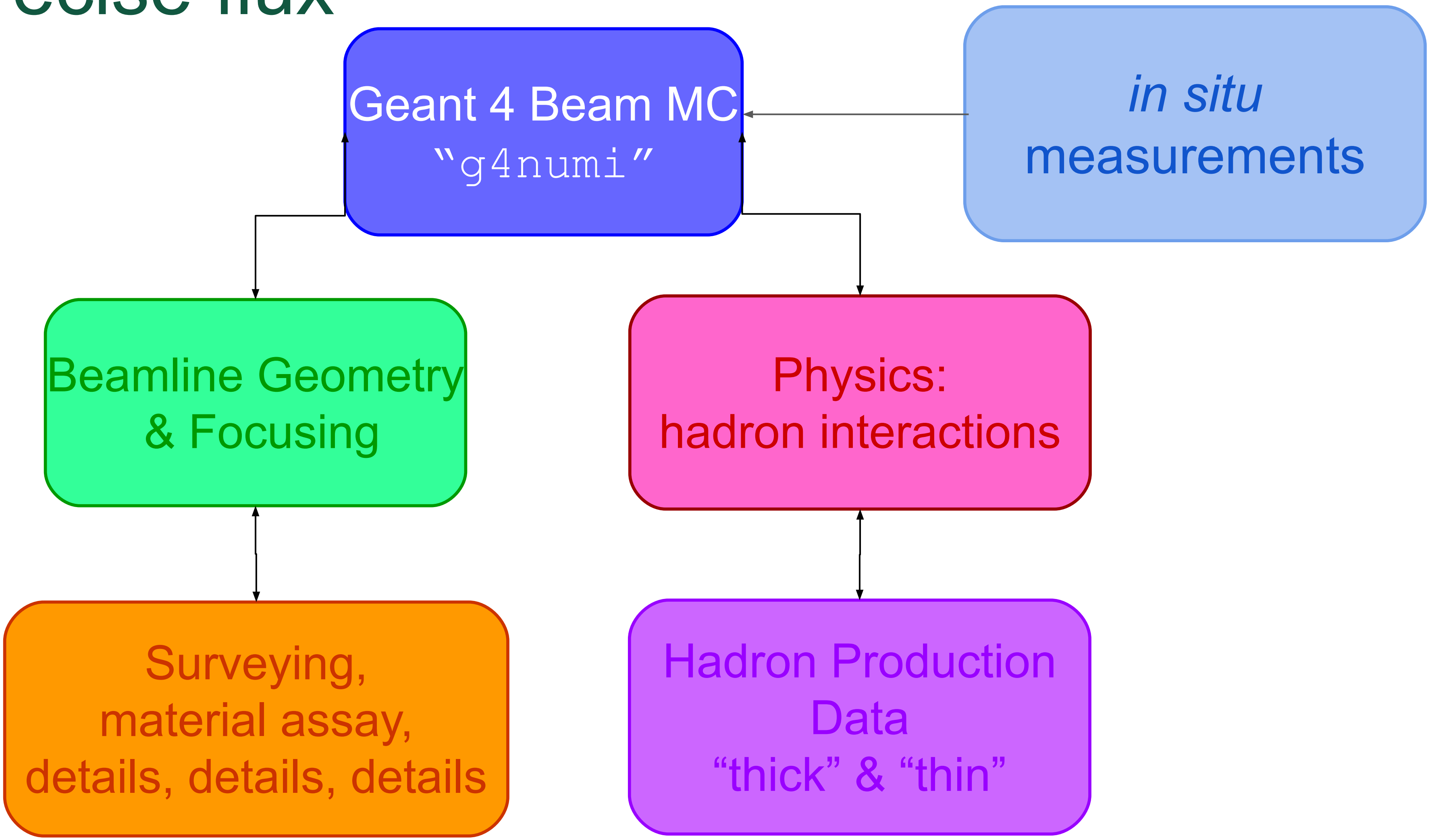
NuMI @ FNAL



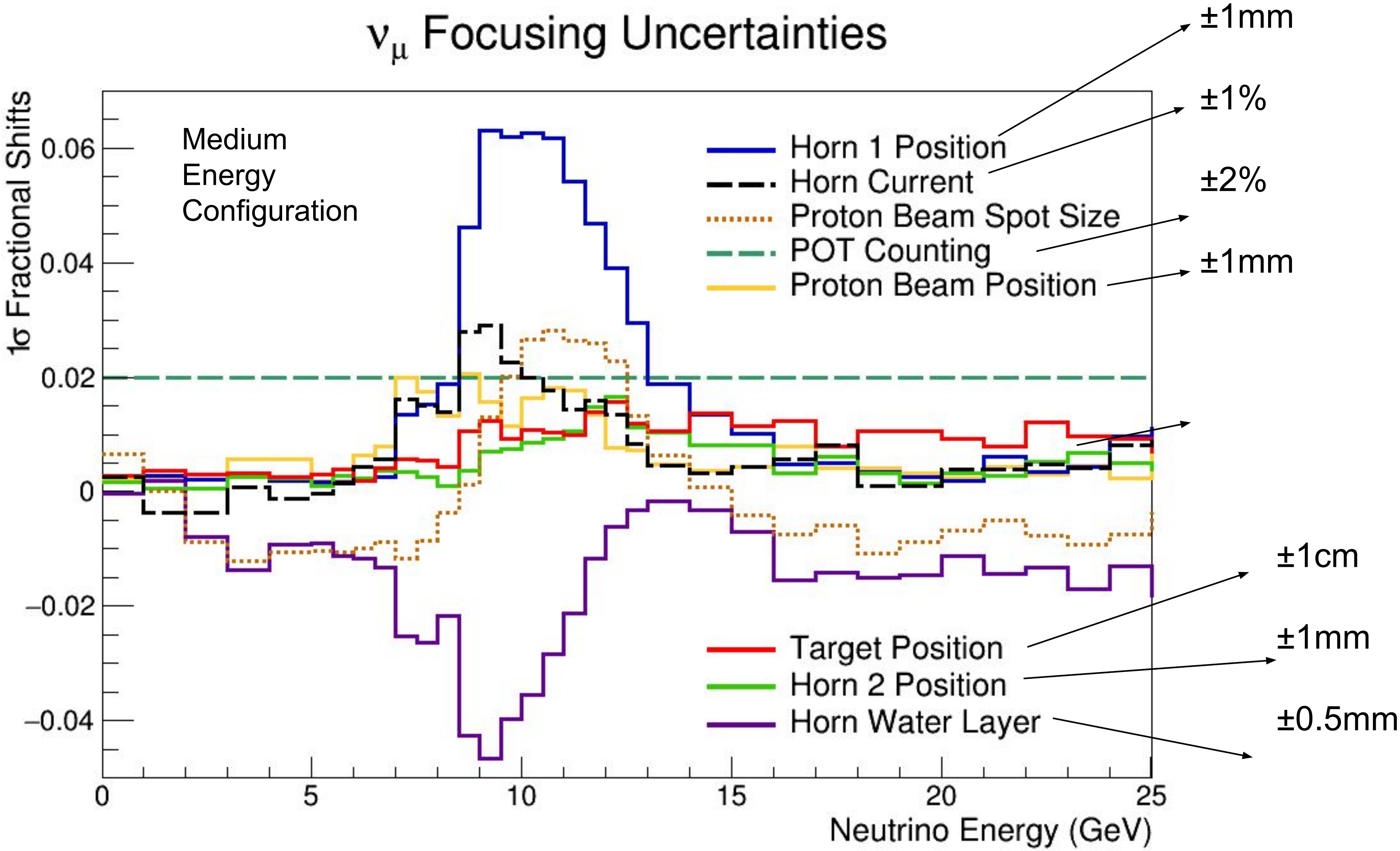




Getting to a precise flux



Focusing uncertainties

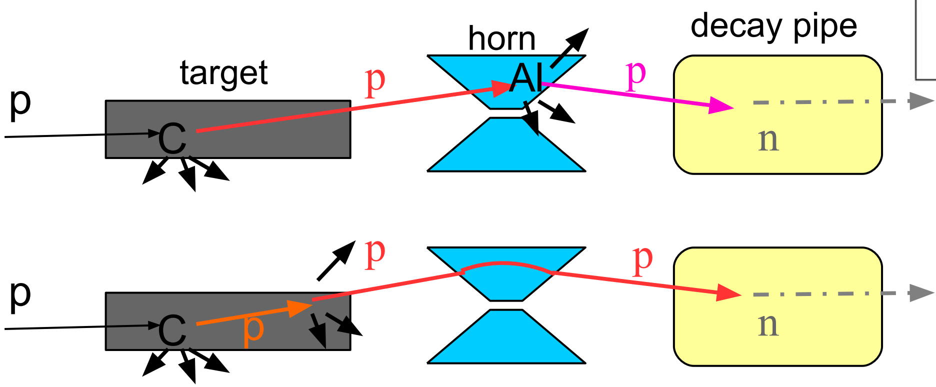


Small details matter!

Hadronic interactions

What a mess!

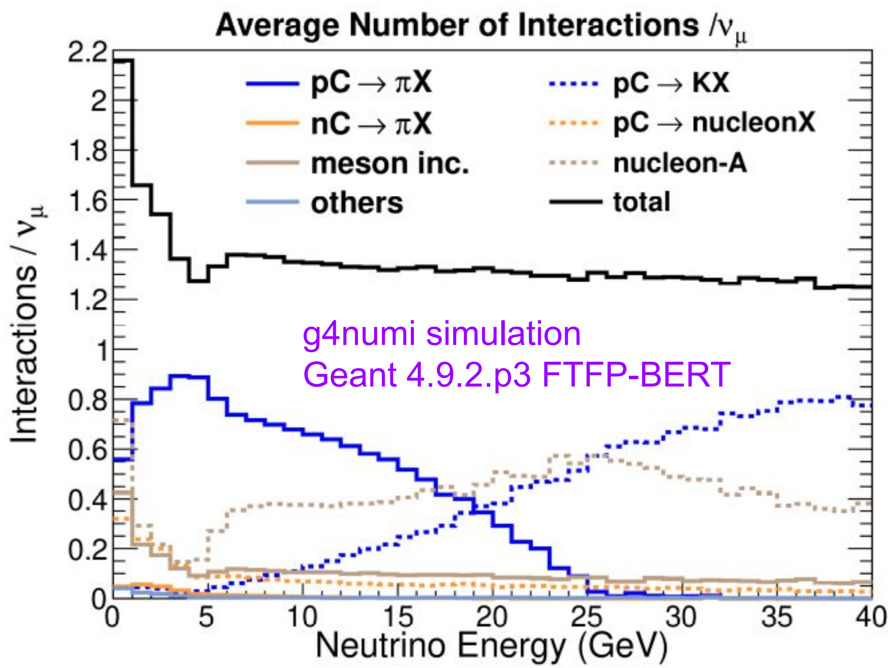
- Many neutrinos have multiple interactions in their “ancestry”



- Strong interactions & hadronization at low Q^2 in nuclei. Don't expect the MC to get it right!

# of interactions per ν_μ (x100)

Material							
Projectile	C	Fe	Al	Air	He	H_2O	Be
p	117.5	2.9	1.0	1.1	1.5	0.1	0.1
π^+	8.1	1.3	1.8	0.2	–	0.4	–
π^-	1.3	0.2	0.2	–	–	–	–
$K^\pm$	0.6	0.1	0.1	–	–	–	–
K^0	0.6	–	–	–	–	–	–
Λ/Σ	1.0	–	–	–	–	–	–



Constraining the simulation

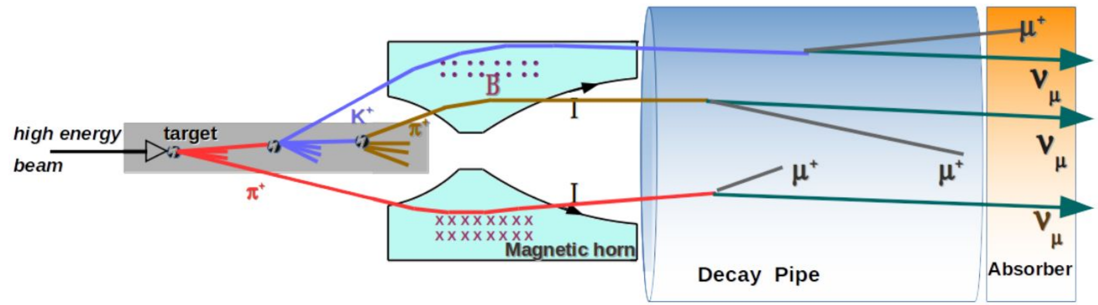
Our Strategy

1) Carefully tabulate interactions and material in each ν's ancestry

2) Find some relevant hadron production data

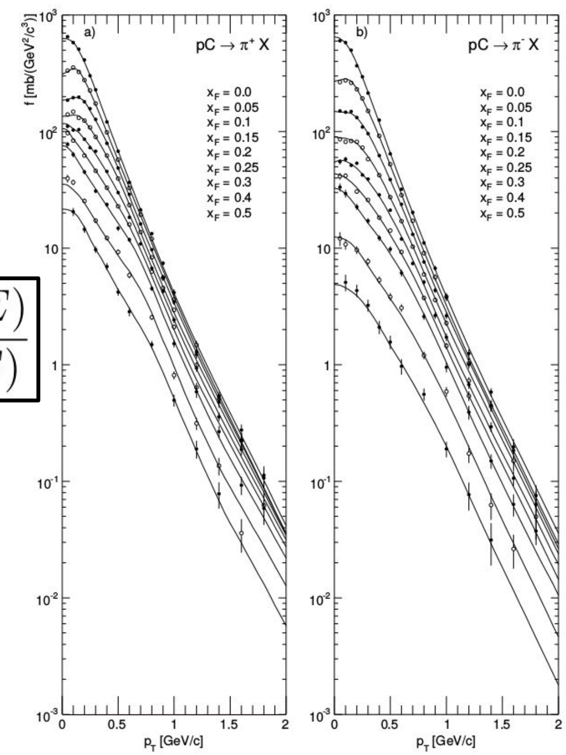
3) Weight interactions

4) Assign and propagate uncertainties



$$f_{Data} = \frac{1}{\sigma_{\mathrm{inel}}} E \frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}$$

$$w(x_F, p_T, E) = \frac{f_{Data}(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}$$



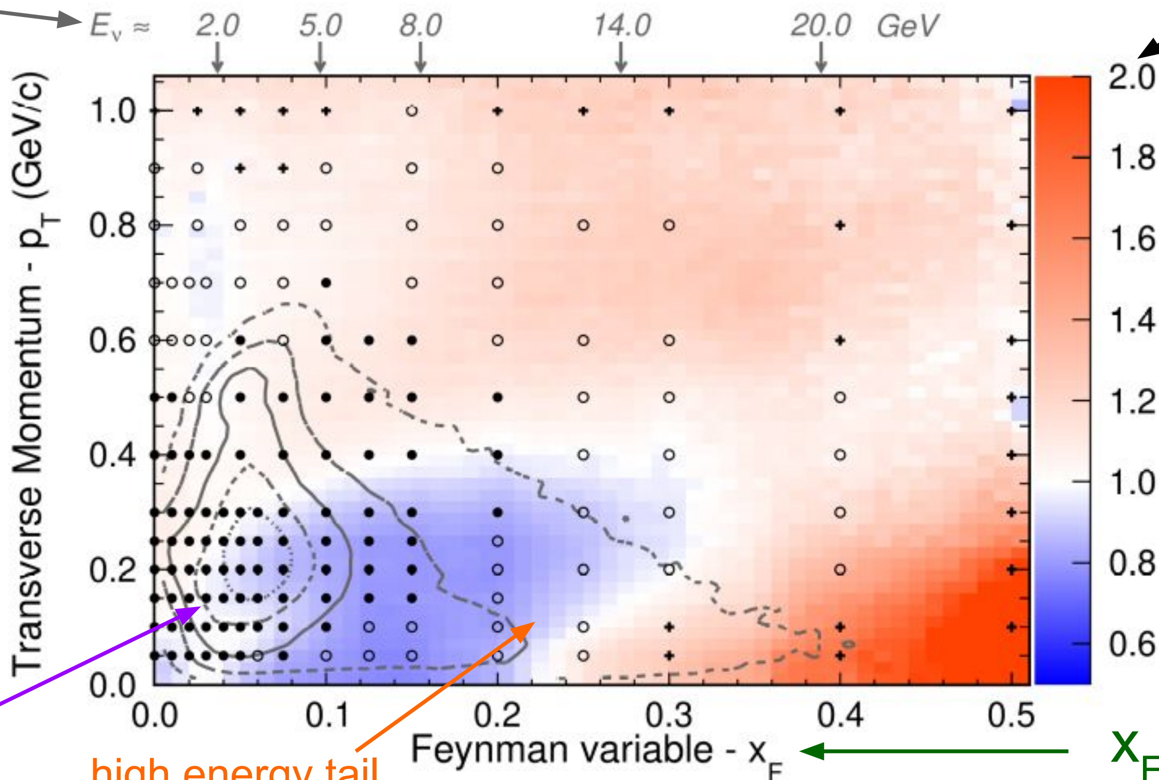
data from NA49 @ CERN

Thin target π production data

NA49 data: pC $\rightarrow$ pX @ 158 GeV/c
C. Alt *et al*, Eur. Phys. J. **C49**, 897 (2007)

neutrino energy

$\frac{\text{data}}{\text{MC}}$



Stat. Uncertainty

- ● <2.5%
- ○ 2.5 – 5.0%
- ✚ >5.0%

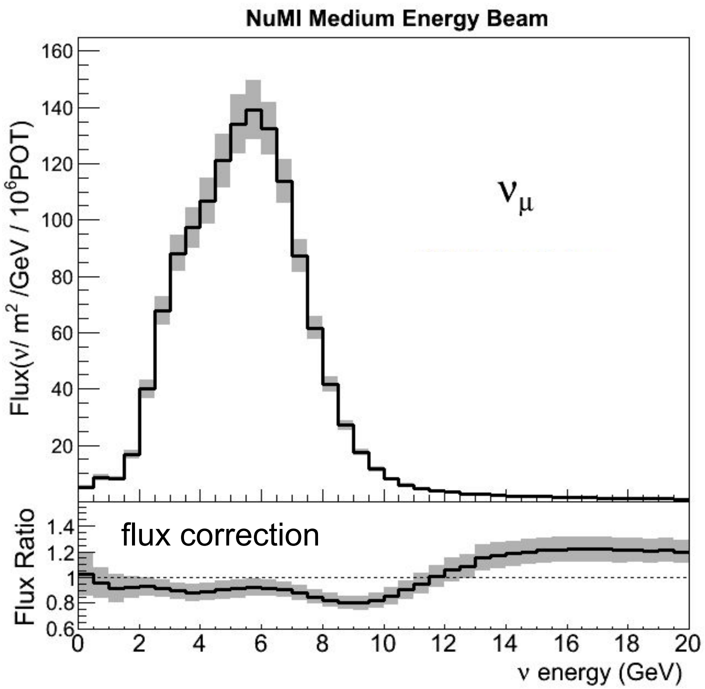
focusing peak

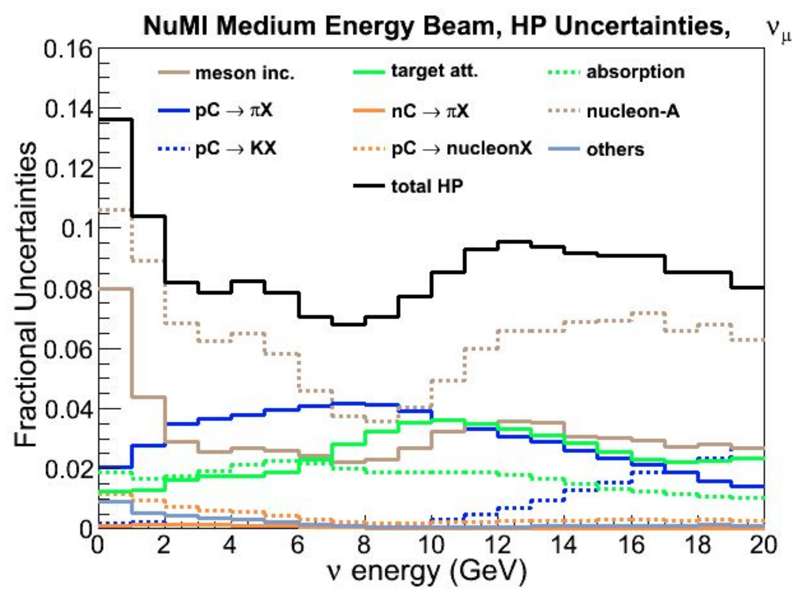
high energy tail

$x_F \approx p_\pi / p_p$

This is the major data-set used to make our flux prediction

The *a priori* flux prediction





- L. Aliaga PhD thesis. *Phys.Rev.D* 94 (2016) 9, 092005
- Uncertainty < 10% over most of the range.

in situ data: the low-nu technique

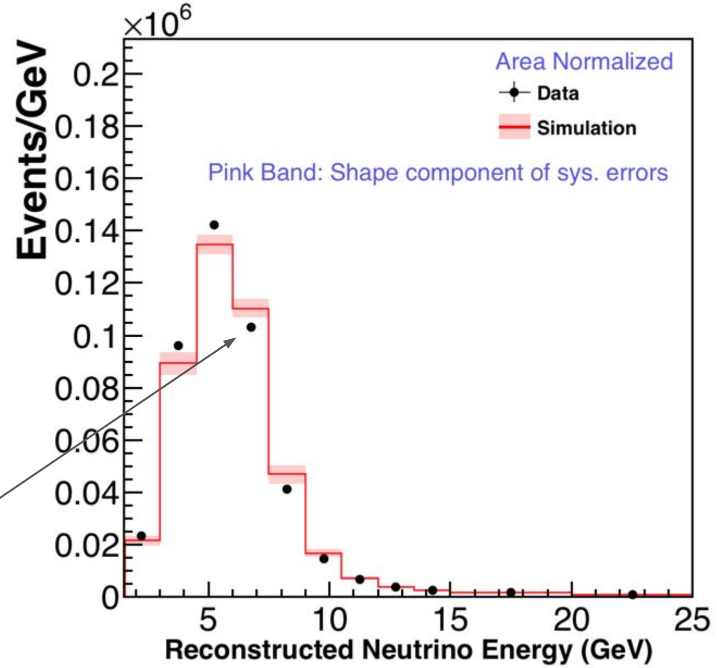
Cross-section as a function of the energy transfer ν

$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E_\nu} - \frac{C}{A}\frac{\nu^2}{E_\nu^2}\right)$$

Becomes constant for small ν/E, resulting in a measurement of the flux shape.

Normalized to well measured high energy neutrino CC cross-section

Data indicates a warping of the flux shape around the focusing peak. Best hypothesis is a 3.6% (1.8σ) shift in the muon energy scale .



- *"Use of Neutrino Scattering Events with Low Hadronic Recoil to Inform Neutrino Flux and Detector Energy Scale"* A. Bashyal et al (MINERvA), 2021 *JINST* **16** P08068

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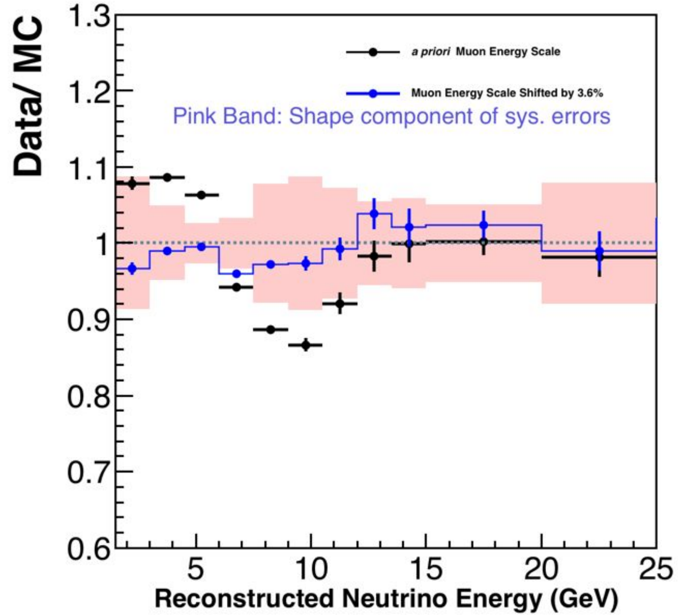

Weakness of this method is the potential circularity with cross-section measurements and model dependence.

As ever, the problem is the nucleus.

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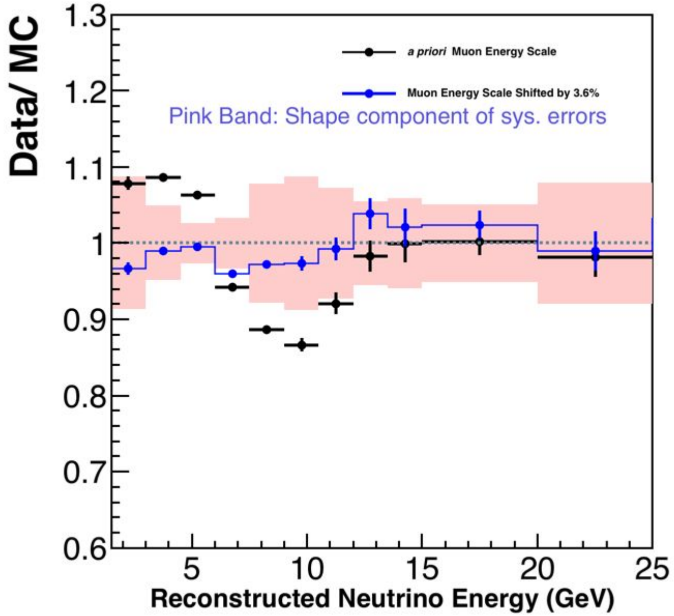
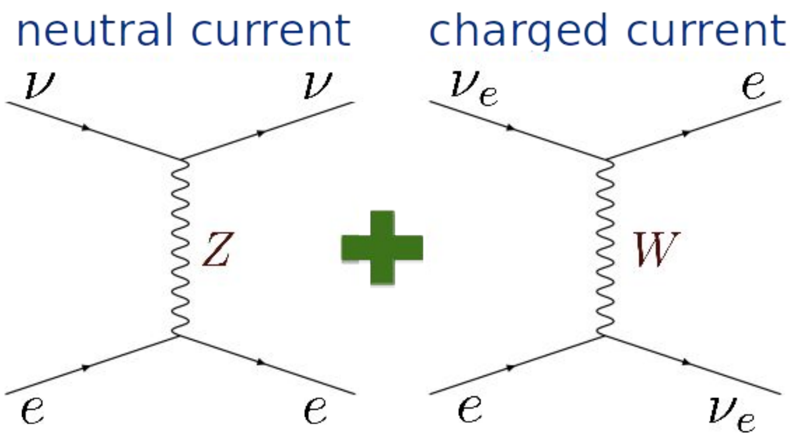
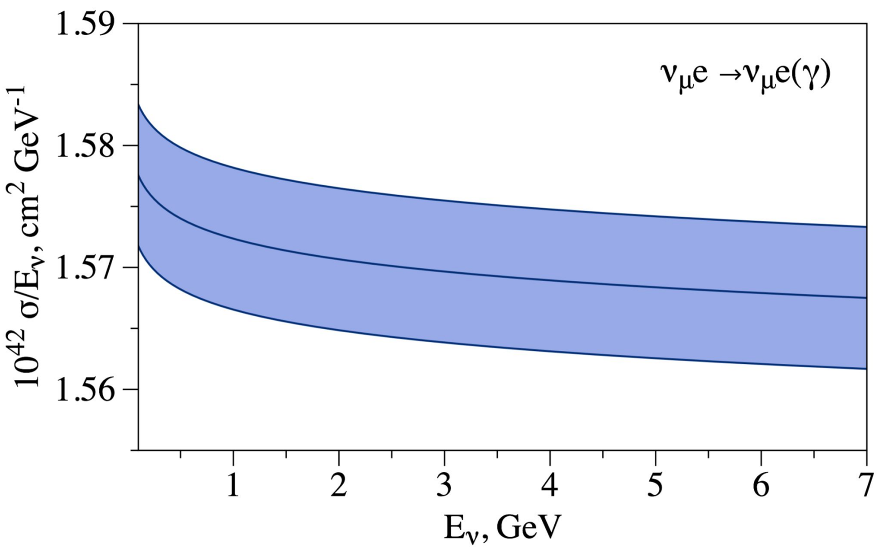


Weakness of this method is the potential circularity with cross-section measurements and model dependence.

As ever, the problem is the nucleus. → So, let's get rid of it.

Neutrino electron scattering





- *Cross-section is extremely well predicted by the SM*
- *~4000 times smaller than inclusive CC cross-section*
- *Radiative corrections important at the few % level*
- *J Park et al, Phys.Rev.D* 93 (2016) 11, 112007
- E. Valencia et al, *Phys.Rev.D* 100 (2019) 9, 092001
- *S. Tomalak et al, Phys.Rev.D* 101 (2020) 3, 033006
- *Fermilab Joint Experiment Theory Seminar, Nov 2019, S. Tomalak, L. Zazueta, D. Jena*

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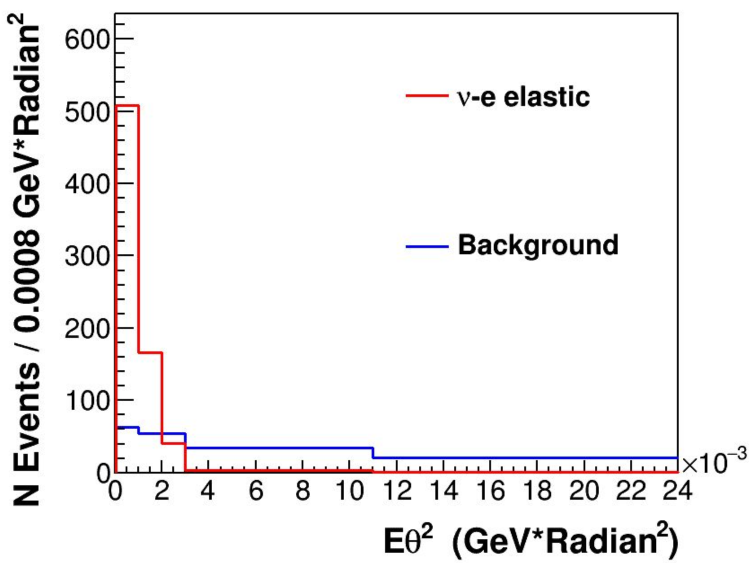
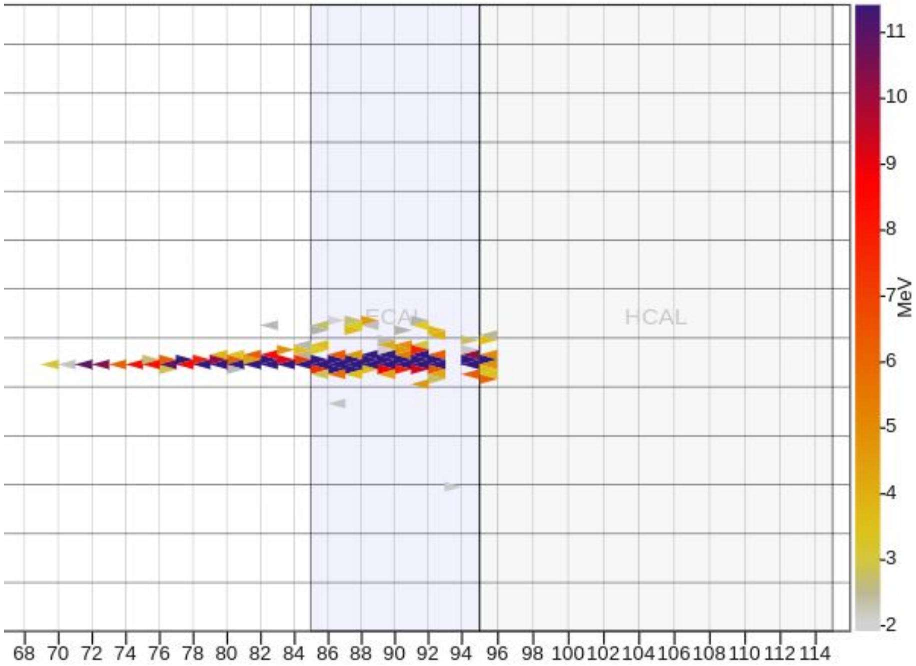
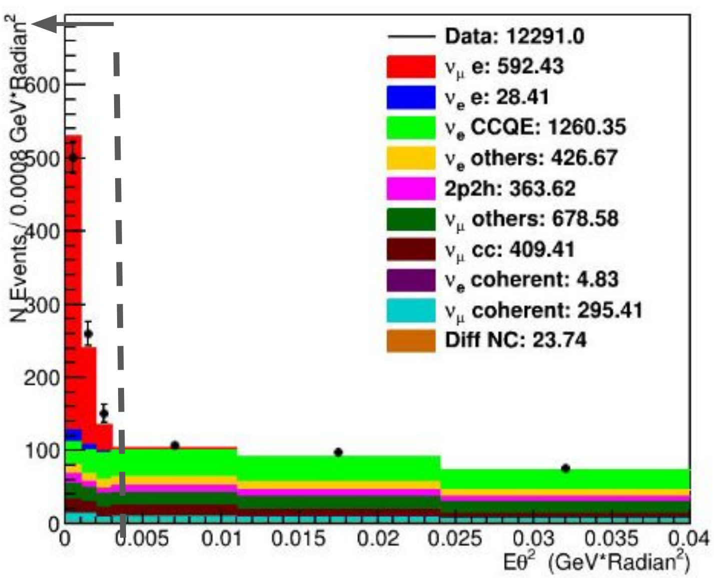


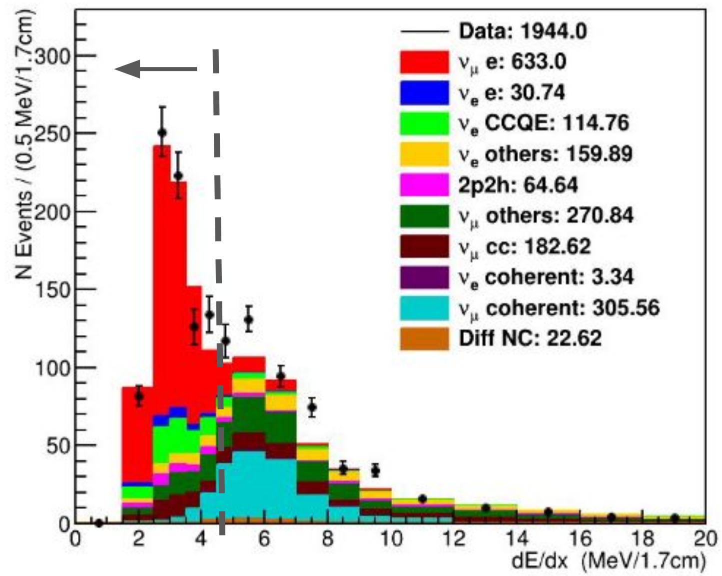


- *Kinematics requires that* $E_e\theta_e^2 < 2m_e$
- *The signature is a very forward energetic electron with no hadronic recoil.*
- *Electron can radiate real photons. Important to include them in the cross-section.*

Neutrino electron scattering

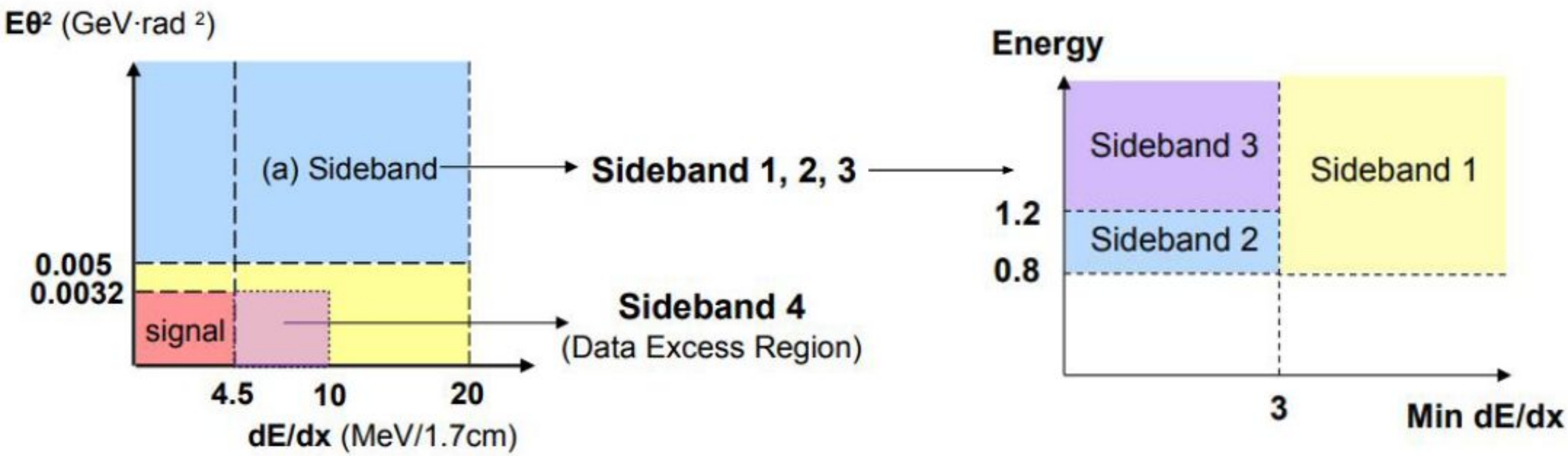
data from ME anti-neutrino beam





- *Two most important variables:*
    - $E_e \theta_e^2 < 0.0032$ *GeV * radian*^{2}
    - *dE/dx < 4.5 MeV/1.7cm*
- *Backgrounds constrained with a sideband fit in* $E_e \theta_e^2$ *and dE/dx space*

Neutrino electron scattering



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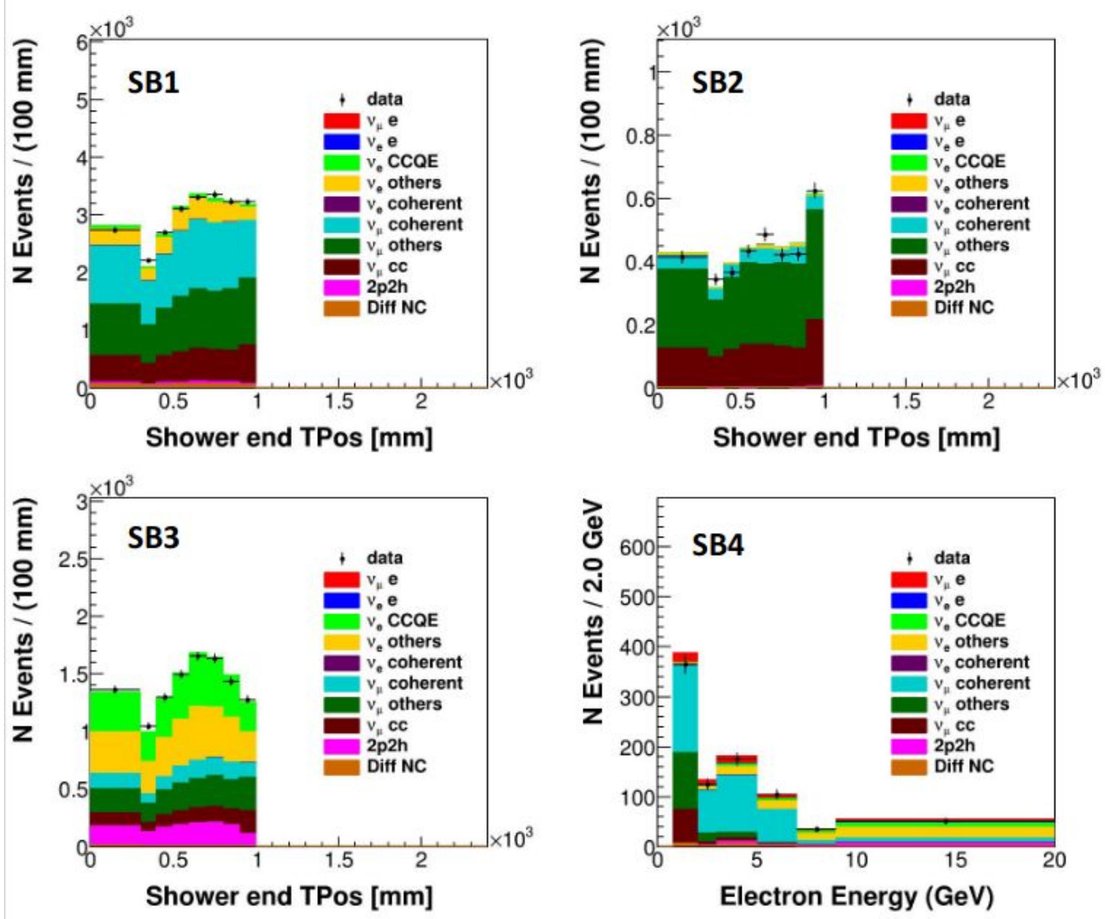

Nu_e	1.02 ± 0.02
Nu_mu	0.93 ± 0.03
Numu coherent 1	1.63 ± 0.20
Numu coherent 2	2.12 ± 0.29
Numu coh 3	1.81 ± 0.22
Numu coh 4	2.11 ± 0.36
Numu coh 5	1.24 ± 0.71
Numu coh 6	0.80 ± 0.60

Coherent π^0 production in 6 energy bins

- *Two most important variables:*
  - $E_e\,\theta_e^2$ *<0.0032 GeV/radian*^{2}
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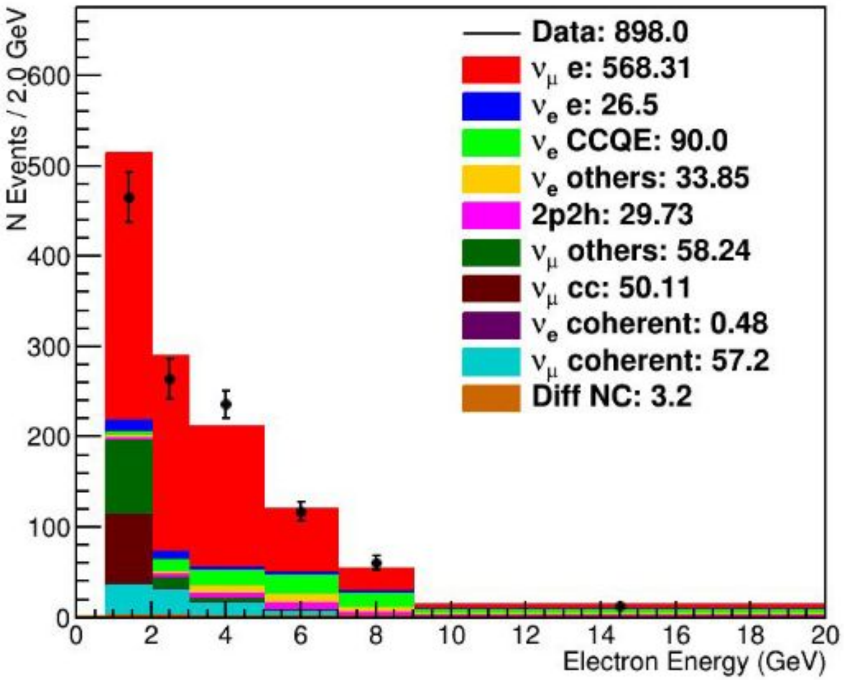
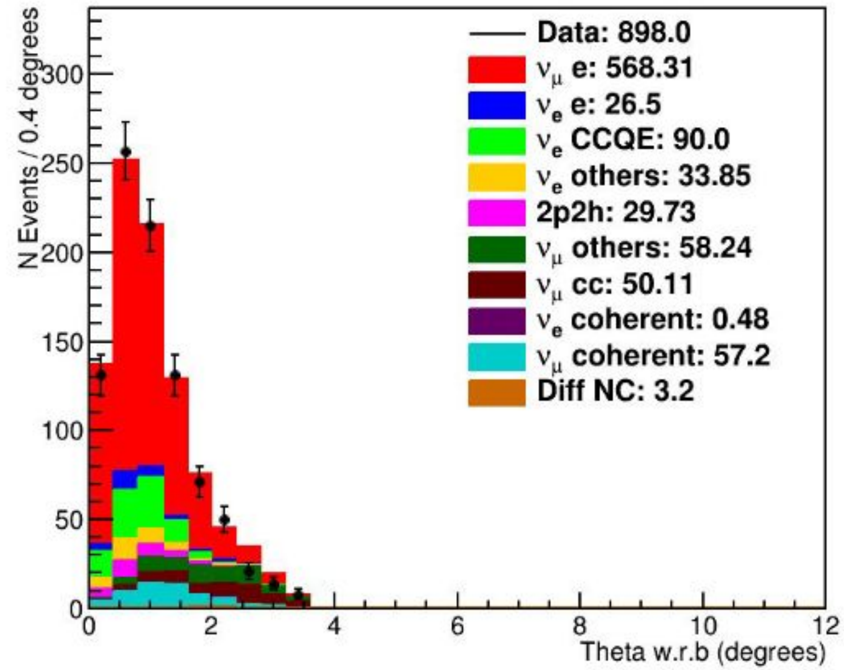
Neutrino electron scattering

distributions after sideband fit and
signal selection





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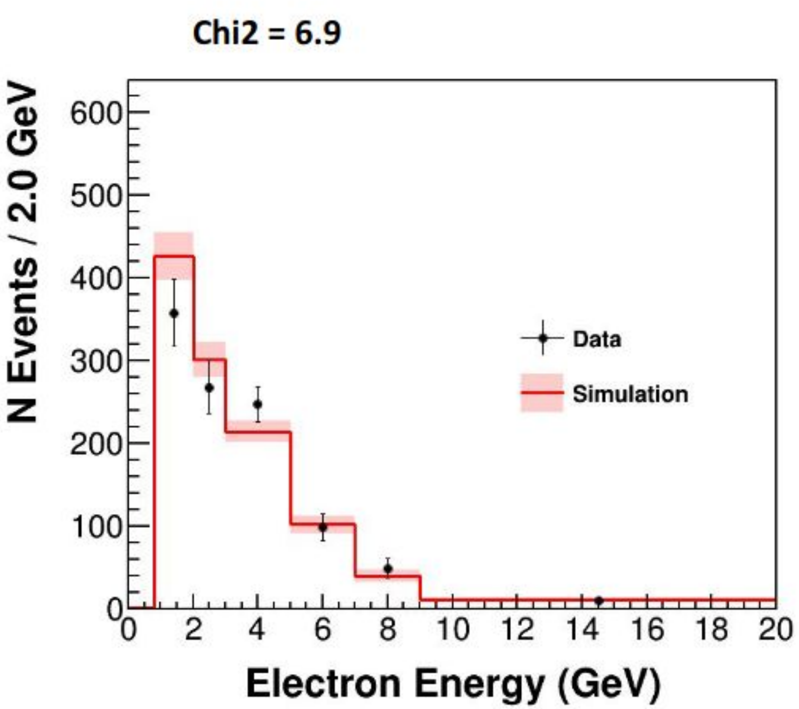
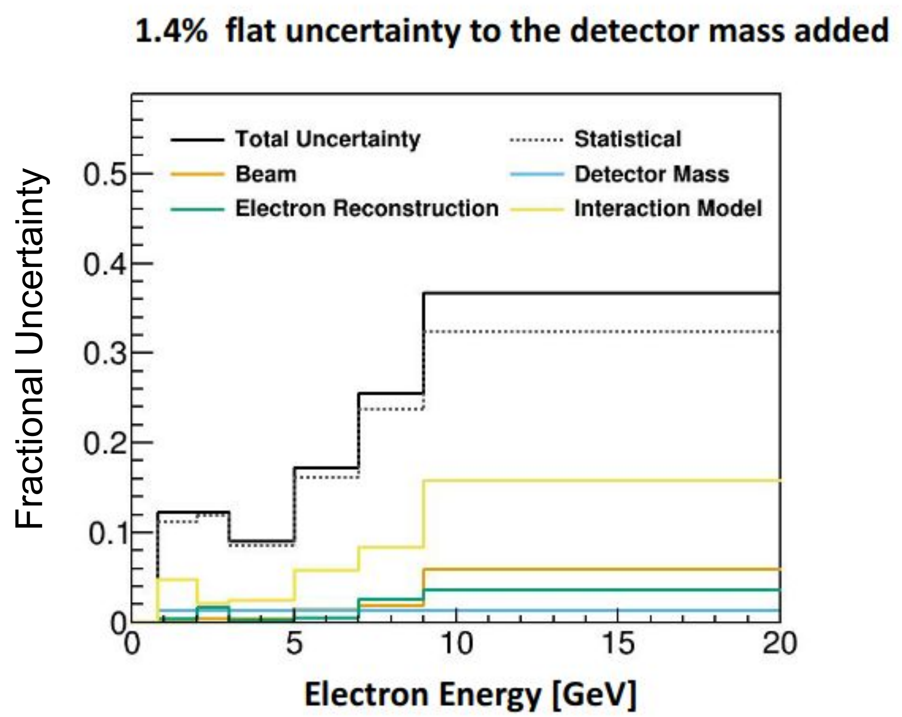
Neutrino electron scattering

After background subtraction and efficiency correction.





- *Uncertainty dominated by statistics. But, systematics < 10 %, especially at low electron energy where most events are.*

Constraining the flux

Bayes' theorem allow us to infer a new prediction of the flux given a measurement that uses our current prediction

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

New prediction, given the observed measurement

a-priori model of the flux

Likelihood of our data given the a-priori model

Constraining the flux

Likelihood of our data

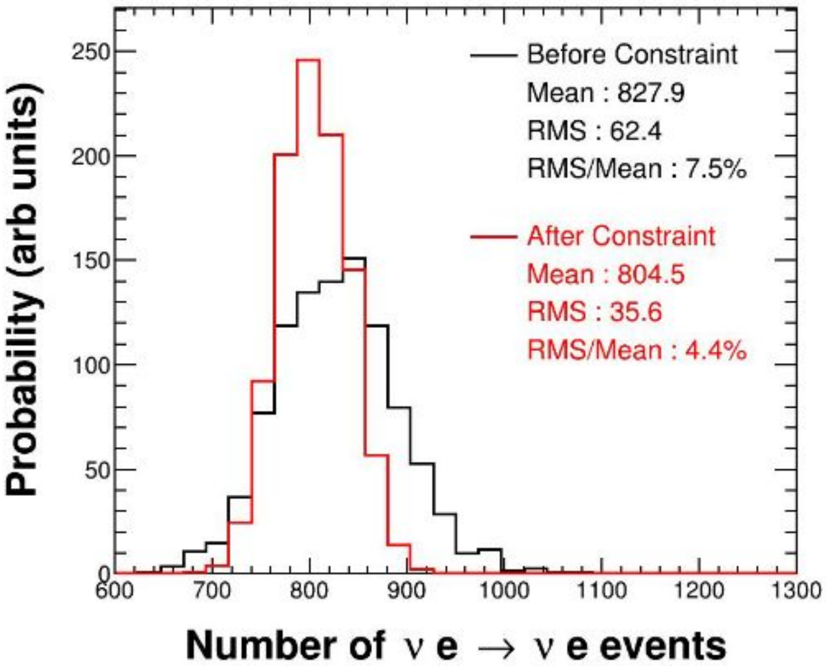
$$P(N_{\nu e\rightarrow\nu e}|M) = \frac{1}{(2\pi)^{K/2}}\frac{1}{|\Sigma_{\mathbf{N}}|^{1/2}}e^{-\frac{1}{2}(\mathbf{N}-\mathbf{M})^T\Sigma_{\mathbf{N}}^{-1}(\mathbf{N}-\mathbf{M})}$$

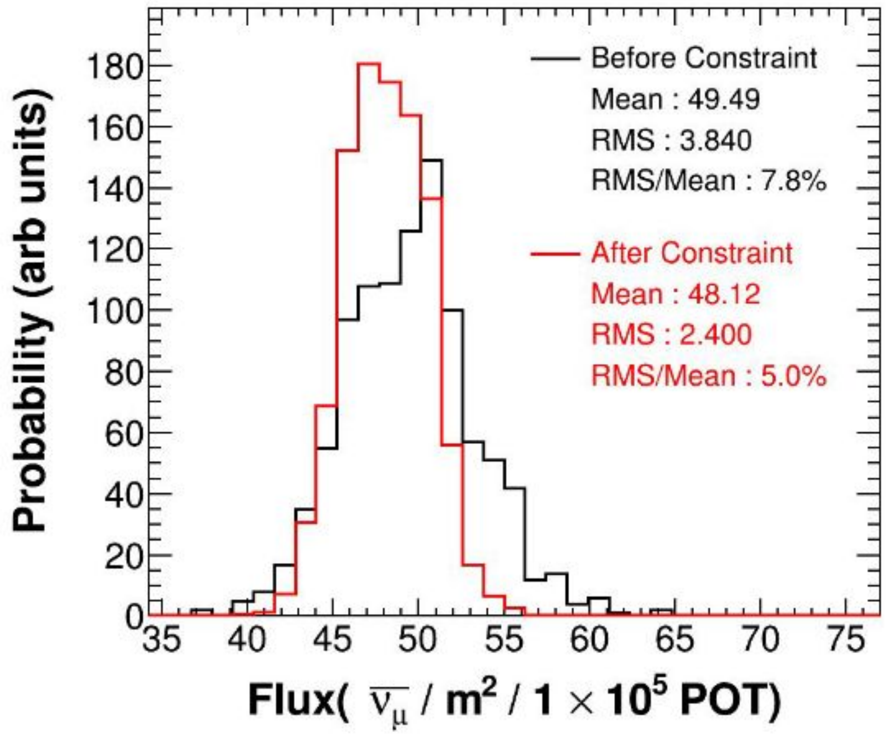
- N is a vector containing the bin content of the measured energy spectrum of given process
- M is the same as N but for the MC prediction
- Σ_N is the covariance matrix of the uncertainties of N
- K is the number of bins of the spectrum

This is calculated for each universe of the flux error band

Constraining the flux

data from ME anti-neutrino beam





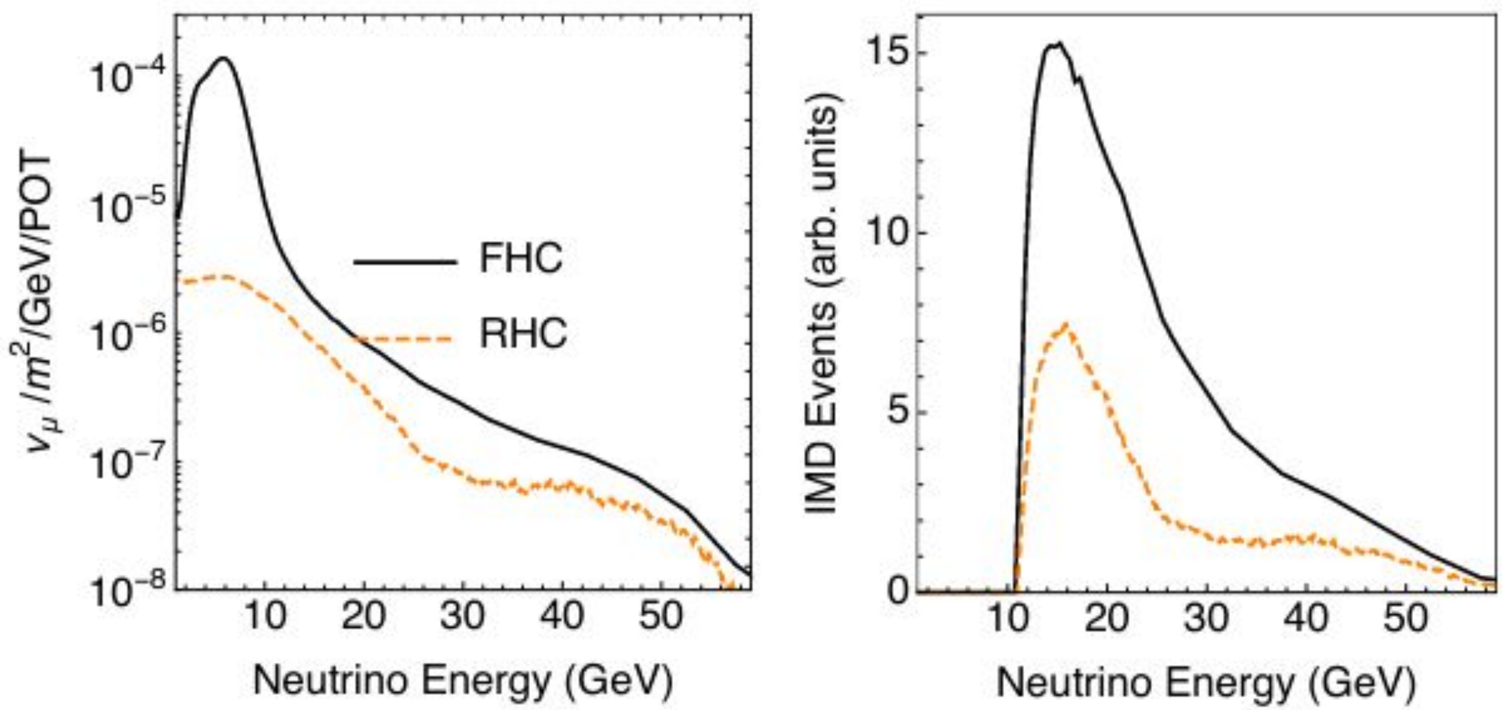
- These plots have a single constraint from neutrino electron scattering in the ME anti-neutrino beam configuration
- We also have a similar measurement in the ME neutrino beam configuration
- And, there is one more thing too...

One last thing: inverse muon decay

https://arxiv.org/abs/2107.01059

$$\nu_\mu e^- \rightarrow \mu^- \nu_e$$

- Similar to the neutrino electron elastic scattering, but with a very forward muon in the final state
- Threshold is ~11 GeV, so this process constrains the high energy component of the flux. Only sensitive to muon neutrinos.



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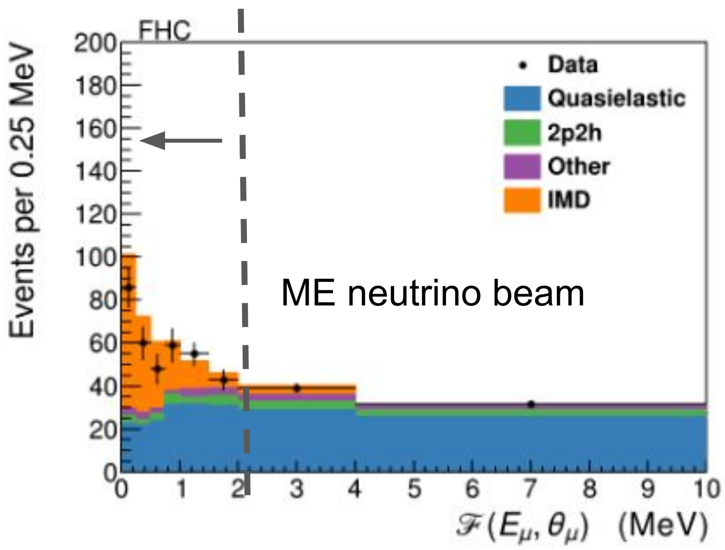
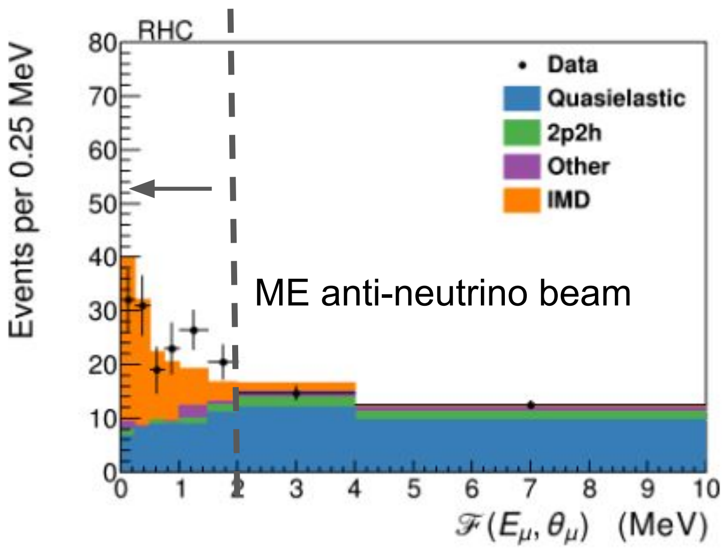


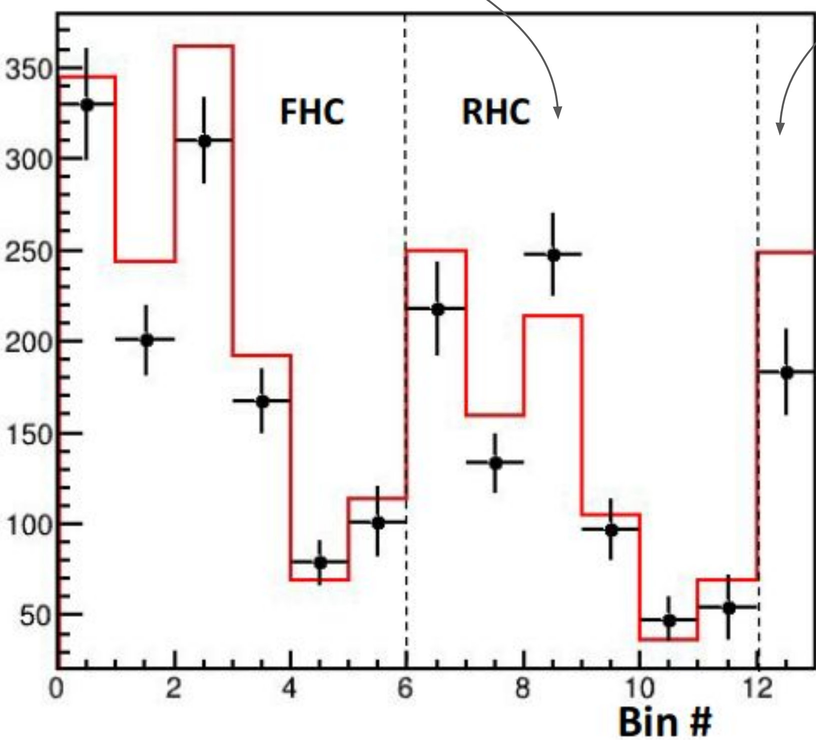


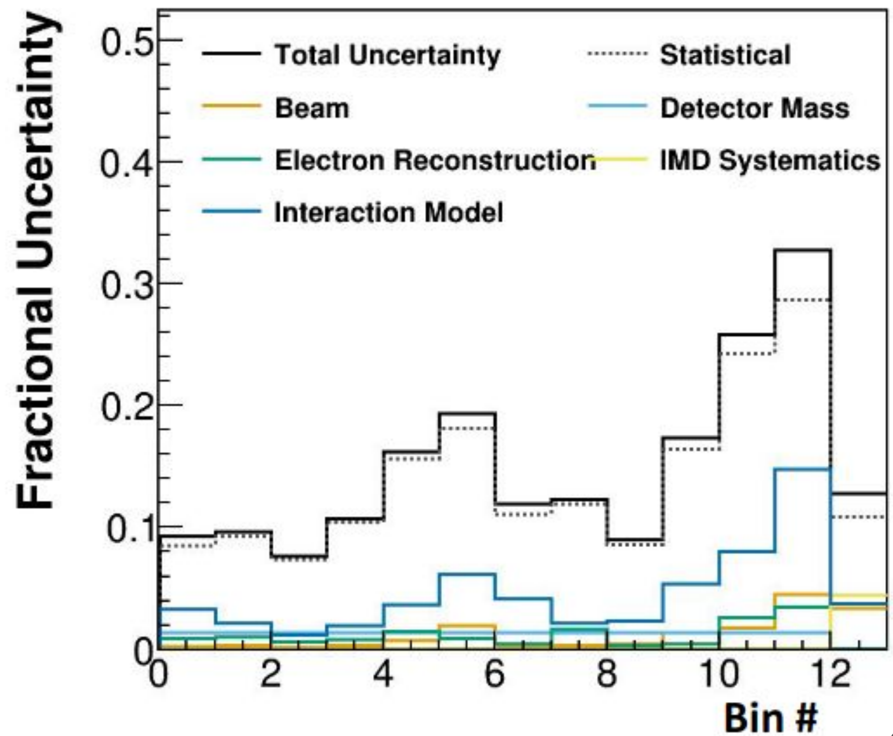
$$\mathscr{F}(E_\mu, \theta_\mu) \equiv \frac{E_\mu \frac{\theta_\mu^2}{1\mathrm{radian}^2}}{1 - \frac{E_\mu}{E_\nu^{max}}},$$

127 (56) IMD events in the FHC (RHC) beams.

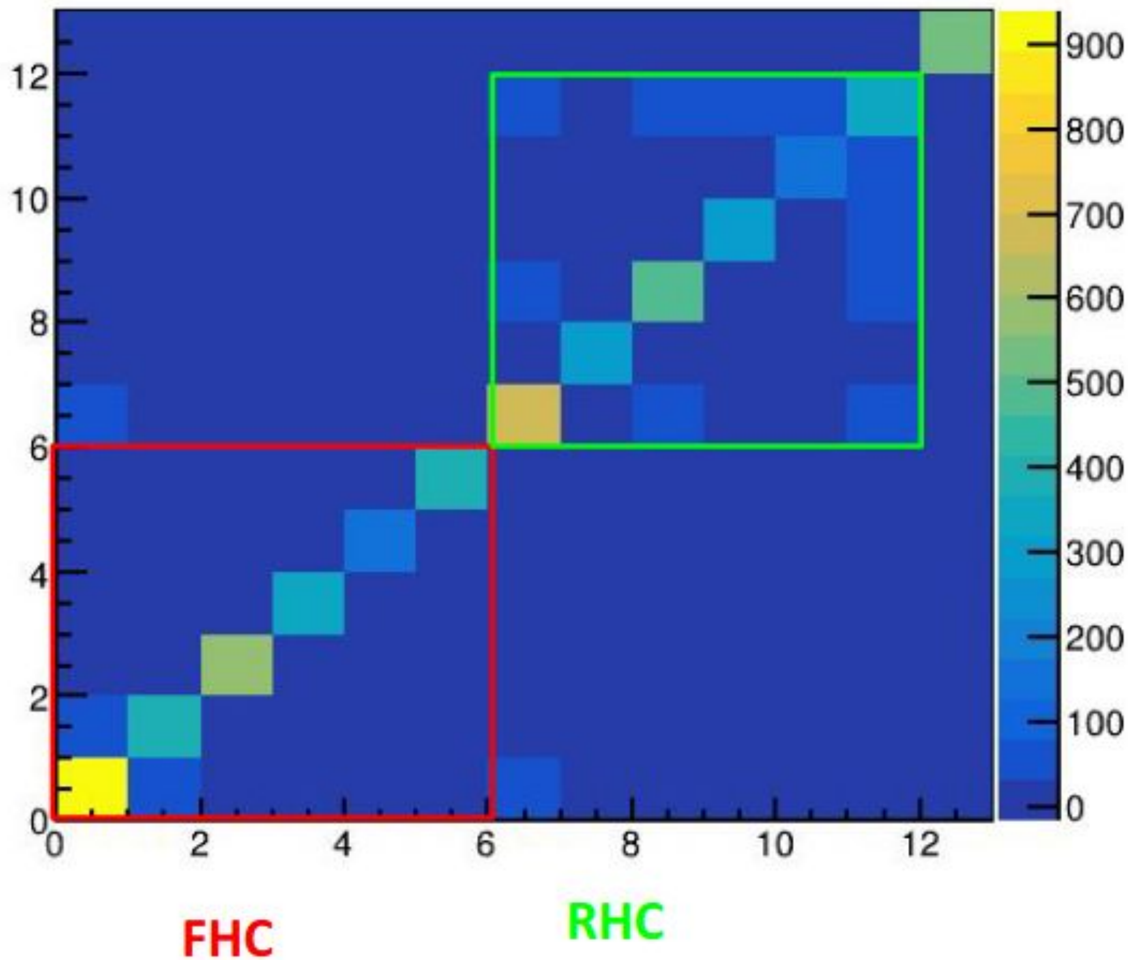
A combined constraint

- We combine the following to form a joint constraint
  - Neutrino electron scattering in the ME neutrino focused beam (a.k.a. Forward horn current = “FHC”)
  - Neutrino electron scattering in the ME anti-neutrino focused beam (reversed horn current = “RHC”)
  - Inverse muon decay in the ME beam



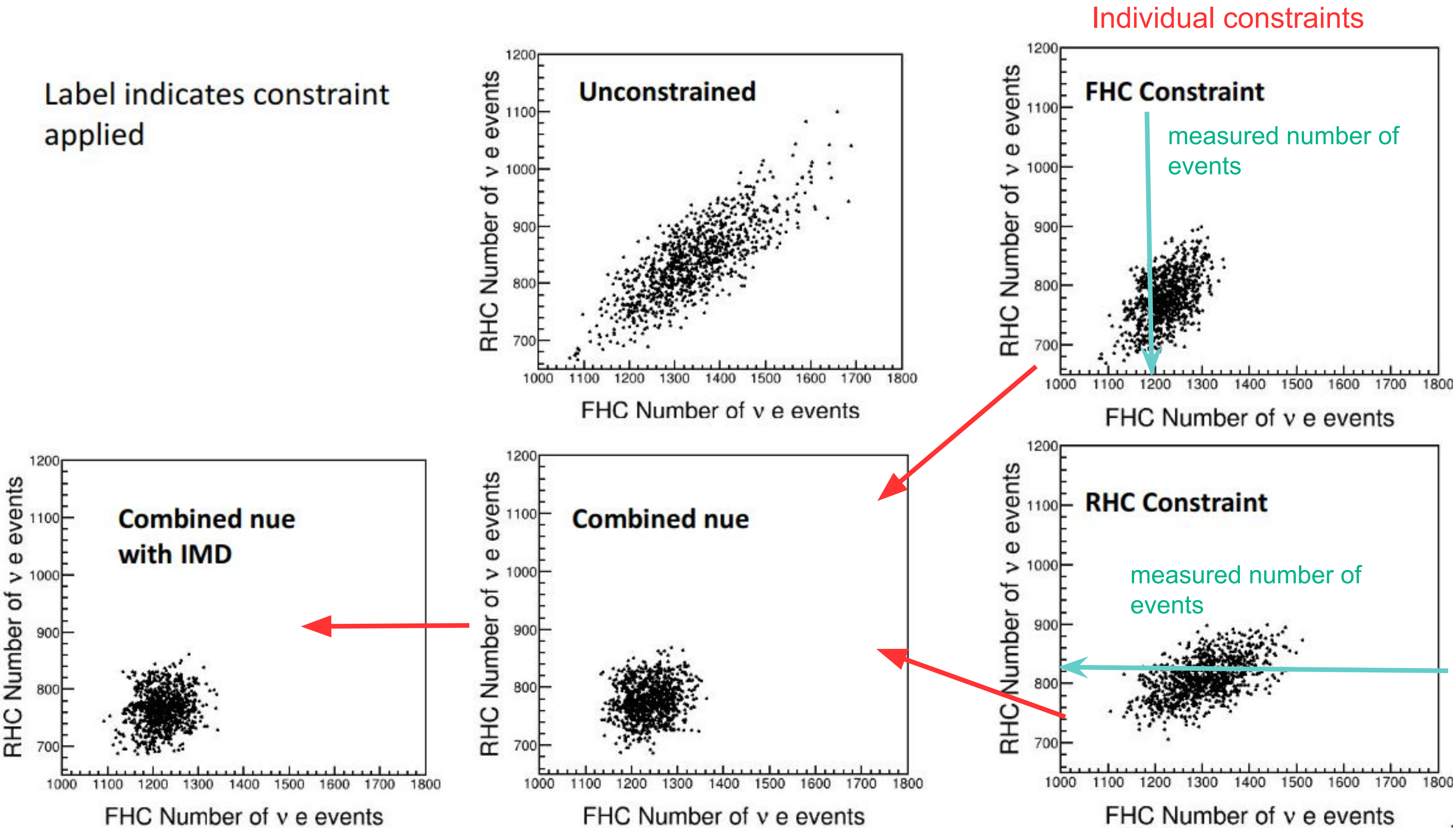


Covariance matrix

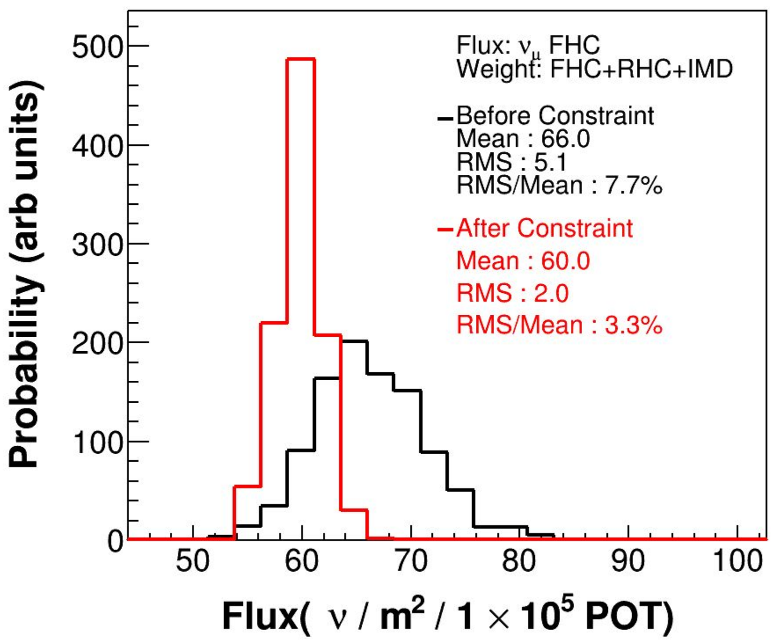


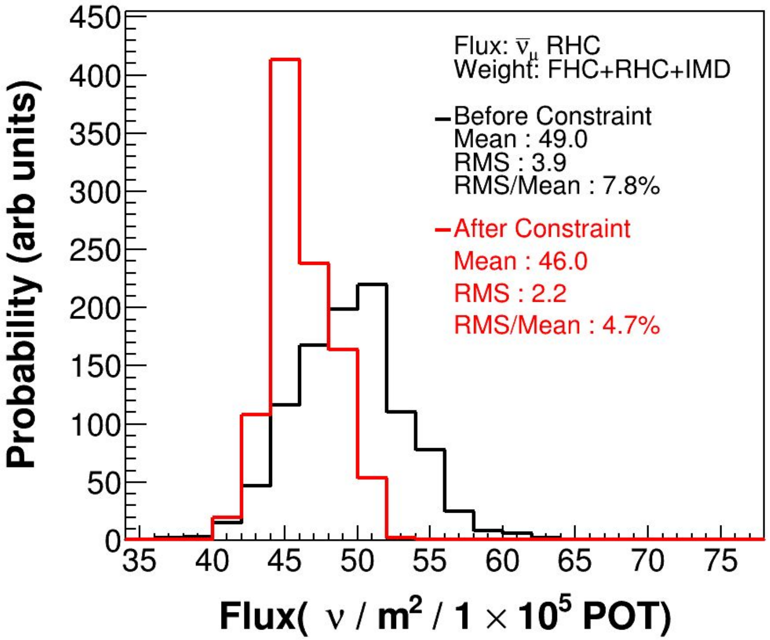
The effect of different constraints

Label indicates constraint applied

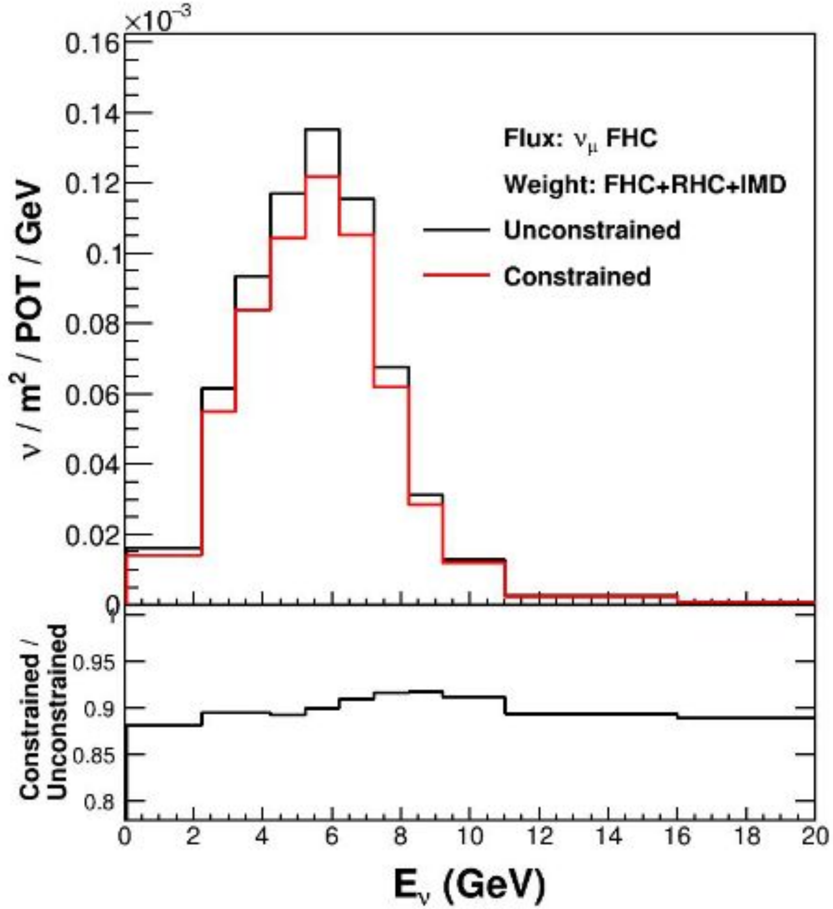


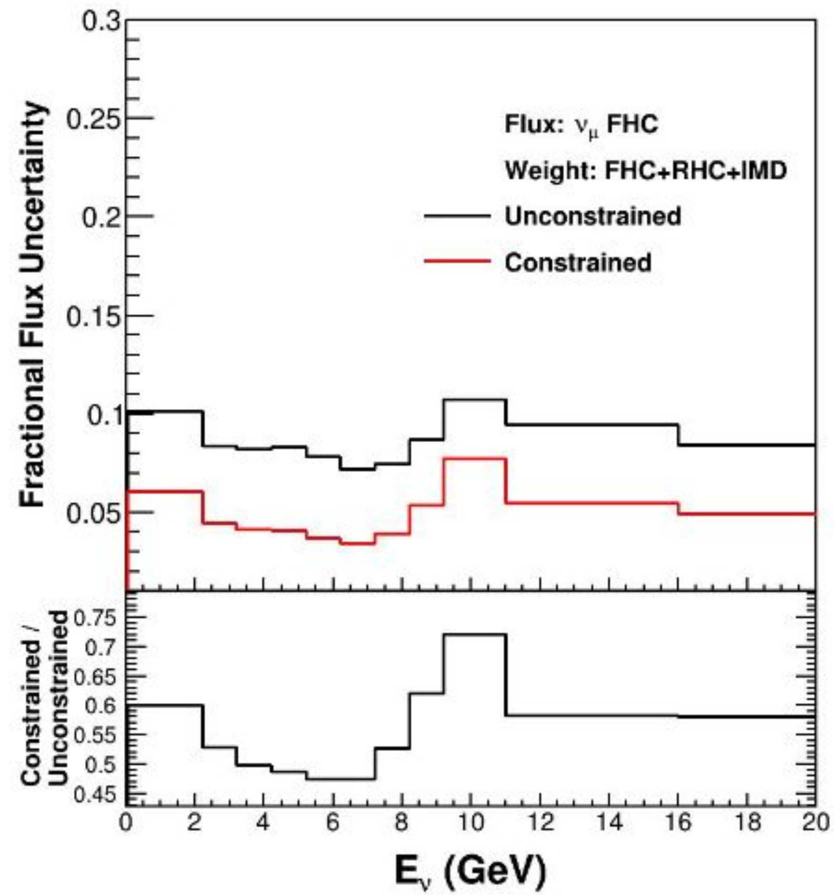
Combined results



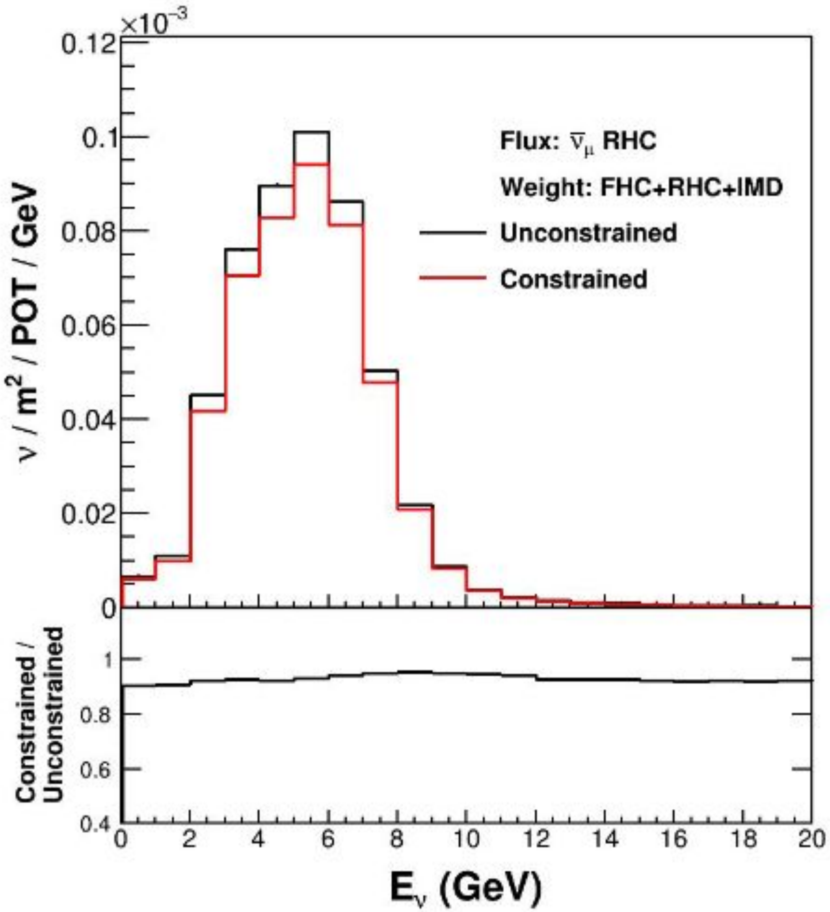


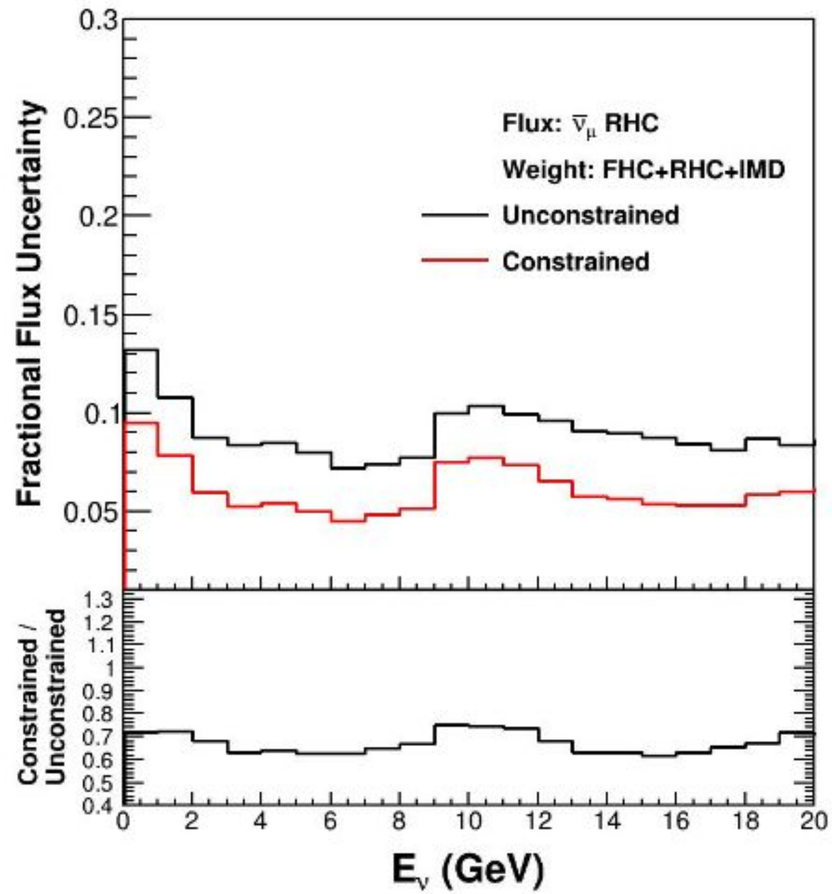
Constrained flux





Constrained flux





Post-constraint uncertainties (%)

Constraint applied

	anti-ν focused beam ("RHC")				ν focused beam ("FHC")			
	anti-ν_μ	ν_μ	anti-ν_e	ν_e	anti-ν_μ	anti-ν_μ	ν_e	anti-ν_e
A priori Uncertainty	**7.76**	**11.12**	**7.81**	**11.91**	**7.62**	**12.17**	**7.52**	**11.73**
FHC	**6.11**	**6.30**	**5.811**	**8.50**	**3.90**	**8.37**	**3.94**	**8.68**
RHC	**4.92**	**8.07**	**4.98**	**9.19**	**5.88**	**8.36**	**5.68**	**8.64**
FHC+RHC	**4.68**	**5.56**	**4.62**	**7.80**	**3.56**	**7.15**	**3.58**	**7.84**
FHC+RHC+IMD	**4.66**	**5.20**	**4.56**	**6.08**	**3.27**	**6.98**	**3.22**	**7.54**

Conclusions

- MINERvA's flux constraint uniquely combines a sophisticated and well tuned beam-line MC with in-situ data
- First ever joint constraint of a neutrino and anti-neutrino beam using neutrino electron scattering and inverse muon decay.
- Uncertainties beaten down to 3.3% and 4.7% for numu and anti-numu in the FHC and RHC beams, respectively.
- Statistics limited.
- Little shape information.
- A detector with very good angle and energy resolution will be able to do even better by constraining the shape of the flux.
  - For example, DUNE's LAr near detector : C. Marshall, et al *Phys.Rev.D* 101 (2020) 3, 032002
  - Huge sample. 22000 events events in 30t of LAr in 5 years of running.
- This is effectively the end of MINERvA's long flux campaign. Plan is to release results for NuMI on-axis (shown today) as well as off-axis locations.
- In principle, these results could also be rephrased to constrain the flux for LBNF/DUNE. That may be something we will try.