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Neutrino Electron Scattering for Flux Constraint on SBND

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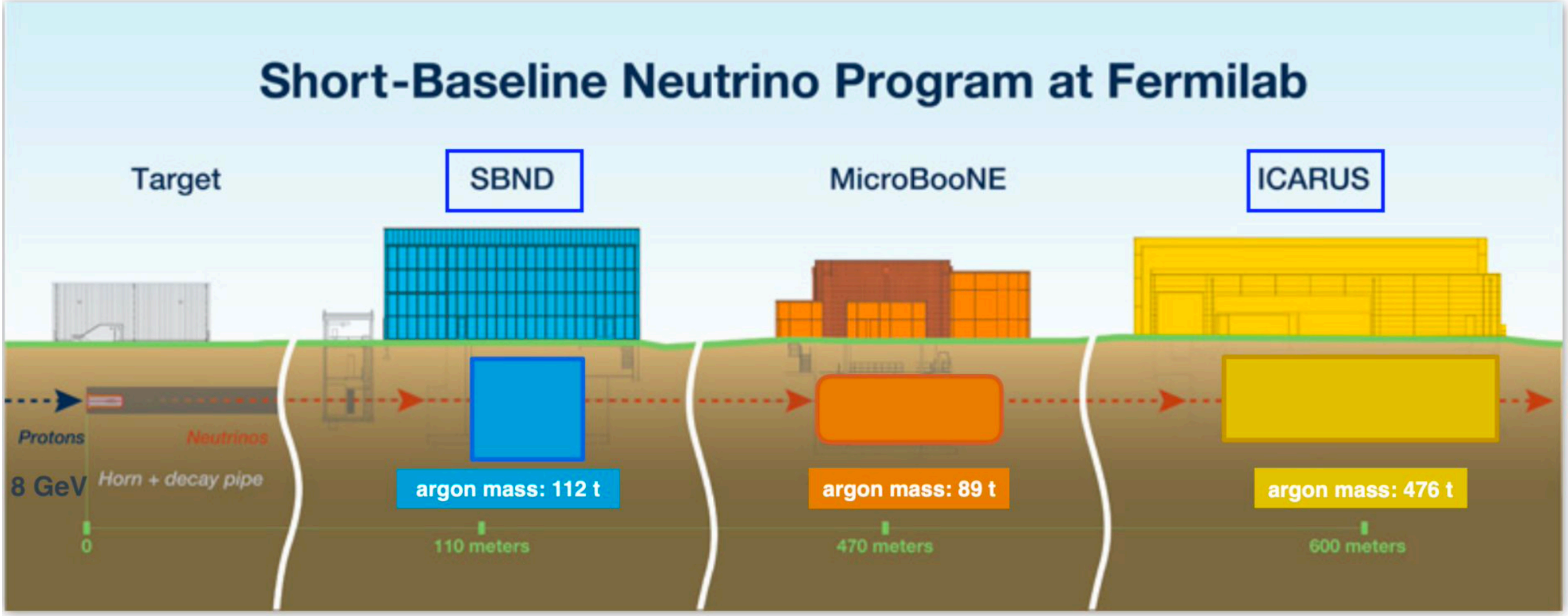
Booster Neutrino Beam (BNB)

- BNB is SBND's neutrino source located 110 m upstream



Booster Neutrino Beam (BNB)

2015-2021
Large production of scientific results

Beam composition:
ν_μ (93.6%)
$\bar{\nu}_\mu$ (5.9%)
$\nu_e + \bar{\nu}_e$ (0.5%)

Mean ν_μ energy: ~0.8 GeV

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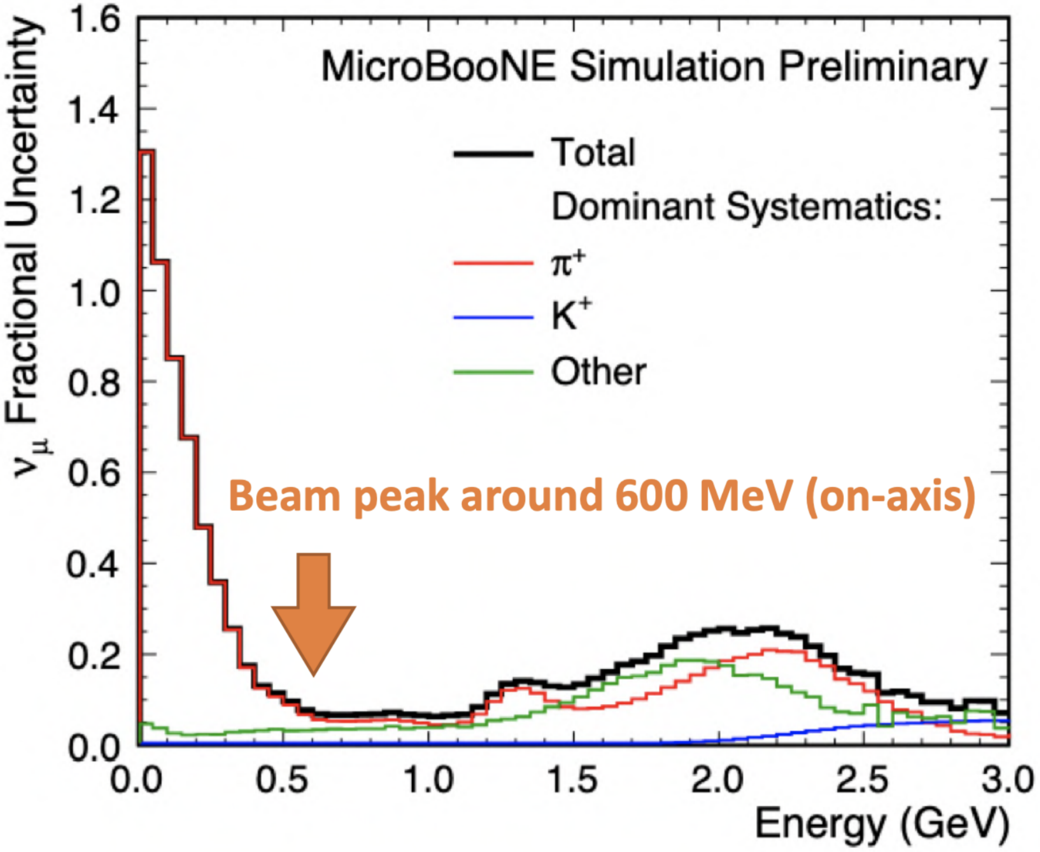
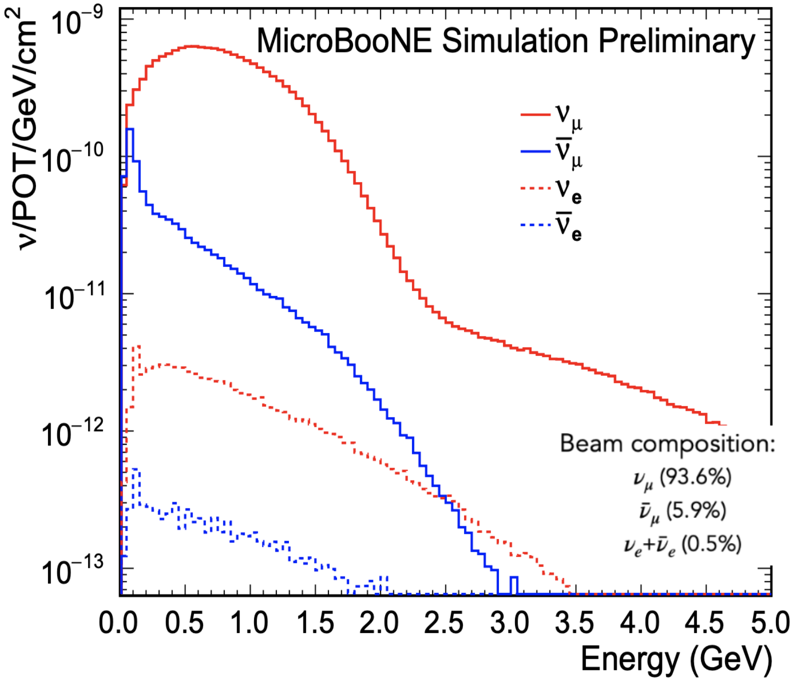


Beam peak around 600 MeV (on-axis)

ν_μ fractional uncertainty for BNB



BNB flux by flavor

https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1031-PUB.pdf

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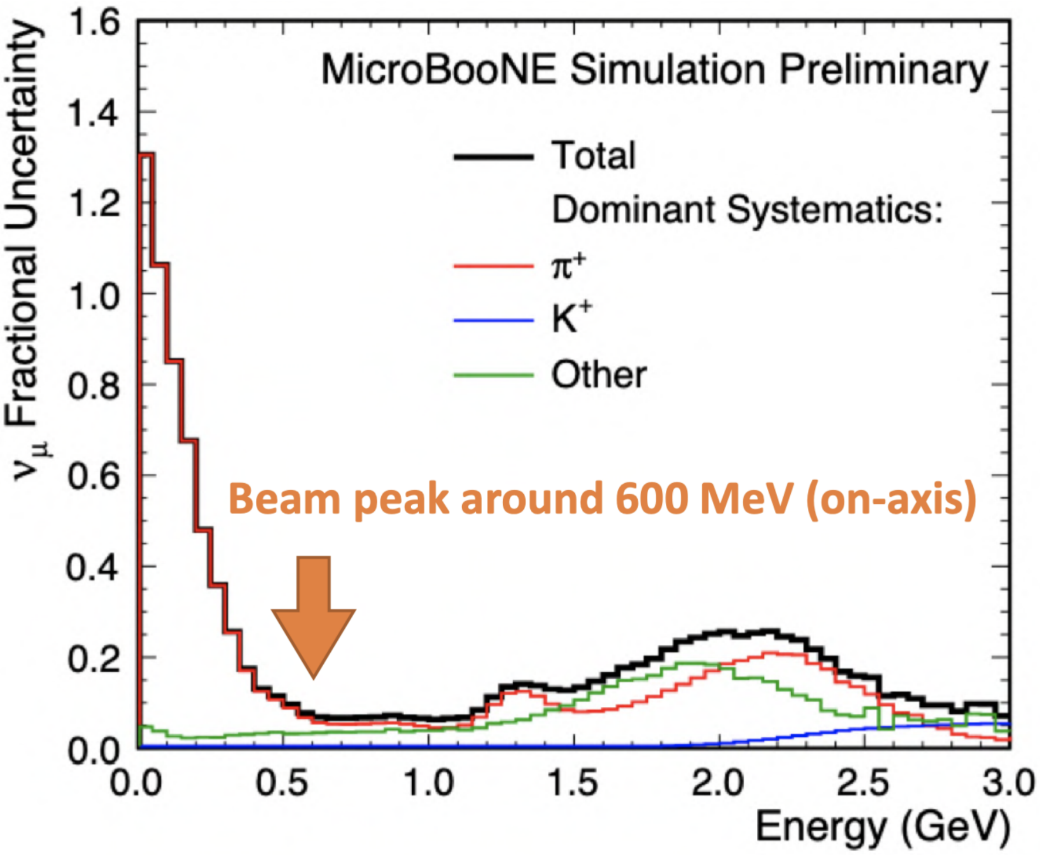

https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1031-PUB.pdf

- **Flux uncertainties** are currently one of the **largest** systematic uncertainties for SBND
- Flux uncertainties arise from underlying uncertainties in hadronic production
- BNB flux constrained to external data from HARP [1] and BNL E910 [2]
- Constrain flux by measuring a process with a well known cross section

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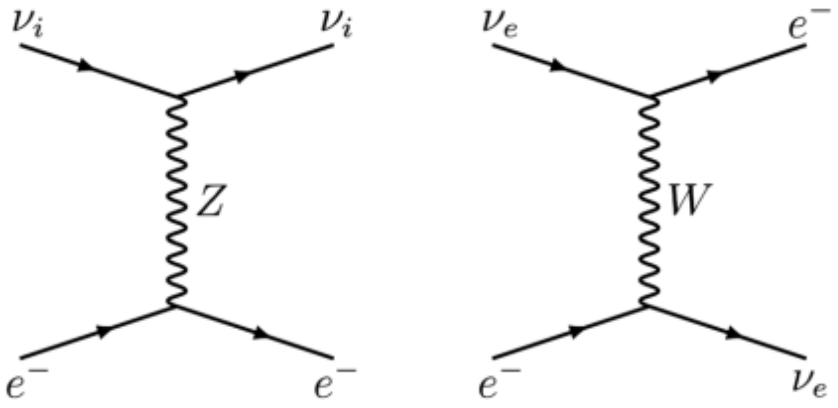
1. Pion production by protons on a thin beryllium target at 6.4-Ge, 12.3-GeV/c, and 17.5-GeV/c incident proton momenta (https://inspirehep.net/literature/755923)
2. Large-angle production of charged pions with 3–12.9 GeV/c incident protons on nuclear targets (https://journals.aps.org/prc/abstract/10.1103/PhysRevC.77.055207)

Neutrino Electron Elastic Scattering

- ν-e scattering is precisely described by the standard model
- Its cross section is up to 10^{-4} times smaller than ν-Ar $\mathcal{O}(10^{-42}\ \mathrm{cm}^2)$



$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{2G_F^2 m_e}{\pi}\left[g_1^2 + g_2^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_1 g_2 \frac{m_e T}{E_\nu^2}\right] \simeq 1.72 \times 10^{-41}\left\{g_1^2 + g_2^2\left(1 - \frac{E_R}{E_\nu}\right)^2\right\}\frac{\mathrm{cm}^2}{\mathrm{GeV}}$$

Neutrino Electron Elastic Scattering

- ν-e scattering is precisely described by the standard model
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$$\sigma(\nu_e e \to \nu_e e) = \frac{G_F^2 m_e E_\nu}{2\pi}[1 + 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$$

$$\sigma(\bar{\nu}_e e \to \bar{\nu}_e e) = \frac{G_F^2 m_e E_\nu}{2\pi}[\frac{1}{3} + \frac{4}{3}\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$$

$$\sigma(\nu_\ell e \to \nu_\ell e) = \frac{G_F^2 m_e E_\nu}{2\pi}[1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$$

$$\sigma(\bar{\nu}_\ell e \to \bar{\nu}_\ell e) = \frac{G_F^2 m_e E_\nu}{2\pi}[\frac{1}{3} - \frac{4}{3}\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$$

Flux Constraint

- Constraint used by MINERvA [3],[4],[5] which reweights flux universes using Bayes' theorem

$$P(\mathrm{M}\,|\,\mathrm{N}_{\nu+e}) \propto \pi(\mathrm{M})P(\mathrm{N}_{\nu+e}\,|\,\mathrm{M})$$

- **Universe** - prediction with underlying parameters varied from nominal values
- **M** is the set of flux models where the free parameters of the model are varied within their uncertainties
- $\pi(\mathrm{M})$ is the prior - *a priori* predictions of different flux universes
- $P(\mathrm{N}_{\nu+e}\,|\,\mathrm{M})$ is the likelihood - weights calculated from comparing ν-e events seen in data $\mathrm{N}_{\nu+e}$ and predicted $\mathrm{M}_{\nu+e}$ by a model M

3. Measurement of Neutrino Flux from Neutrino-Electron Elastic Scattering (https://arxiv.org/abs/1512.07699)
4. Constraint of the MINERvA Medium Energy Neutrino Flux using Neutrino-Electron Elastic Scattering (https://arxiv.org/abs/1906.00111)
5. Improved constraint on the MINERvA medium energy neutrino flux using v¯e−→v¯e− data (https://arxiv.org/abs/2209.05540)

Flux Constraint

- The likelihood of the data, given the MC prediction is shown below using a gaussian likelihood estimator

$$P(\mathrm{N}_{\nu+e}\,|\,M_n) = w_n = \frac{1}{(2\pi)^{K/2}}\frac{1}{\sqrt{|\Sigma|}}\mathrm{exp}\left(-\frac{1}{2}(\mathrm{N}_{\nu+e} - \mathrm{M}^n_{\nu+e})^T\Sigma^{-1}(\mathrm{N}_{\nu+e} - \mathrm{M}^n_{\nu+e})\right)$$

- $P(\mathbf{N}_{\nu+e}\,|\,M_n)$ can be though of as a weight w_n on universe n with flux parameters described by the flux model M_n
- Σ is the covariance matrix describing the uncertainties on $\mathrm{N}_{\nu+e}$
- K is the degrees of freedom = number of bins of cov. matrix

$$\Sigma^{syst}_{i,j} = \frac{1}{N}\sum_{n}^{N}(N_i^{CV} - N_i^n)(N_j^{CV} - N_j^n)$$

$$\Sigma^{stat}_{i,j} = \sqrt{N_i^{CV}N_j^{CV}}\delta_{ij}$$

Flux Constraint

- We have a vector set of weights w_n the same size of the number of universes given by $P(\mathrm{N}_{\nu+e} \,|\, \mathrm{M})$

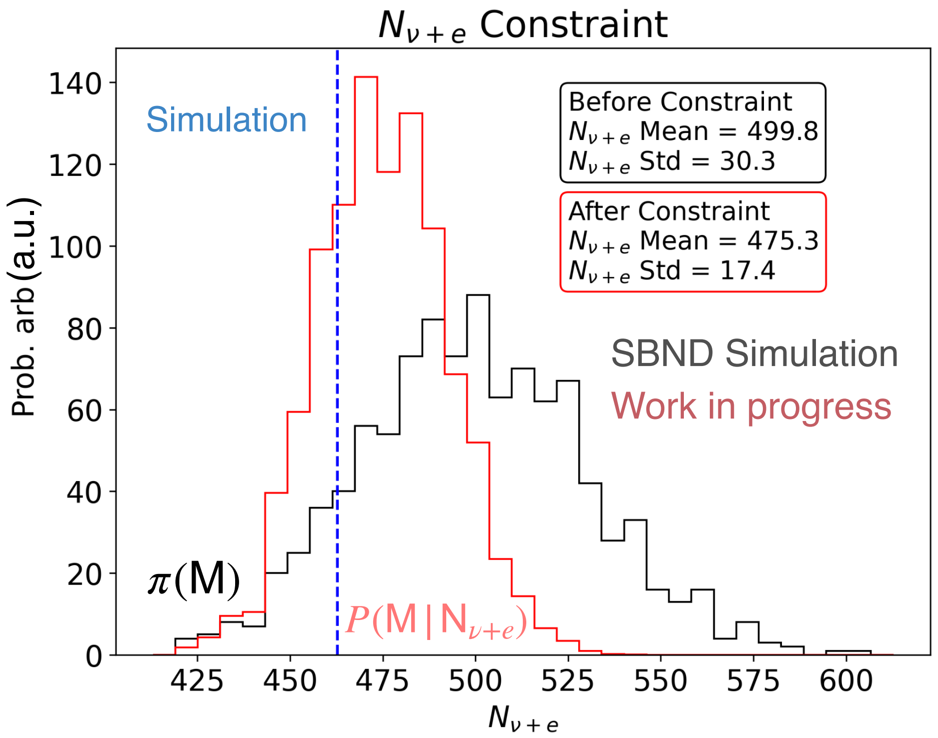
$$P(\mathrm{N}_{\nu+e} \,|\, M_n) = w_n = \frac{1}{(2\pi)^{K/2}} \frac{1}{\sqrt{|\Sigma|}} \mathrm{exp}\left(-\frac{1}{2}(\mathrm{N}_{\nu+e} - \mathrm{M}^n_{\nu+e})^T \Sigma^{-1} (\mathrm{N}_{\nu+e} - \mathrm{M}^n_{\nu+e}) \right)$$

- Reweight the *a priori* probability distribution $\pi(\mathrm{M})$ using the weights w_n
- The posterior $P(\mathrm{M} \,|\, \mathrm{N}_{\nu+e})$ is the reweighted probability distribution

Flux Constraint

- **Universes** - $M_{\nu+e}$ predicted by each flux model M_n
- **Simulated data -** $N_{\nu+e}$ used for data in likelihood calculation

- Mean is **shifted towards** simulated data
- Standard deviation **reduced** by reweighting
- The overall constraint reduces the uncertainty of the integrated ν-e scattering distribution

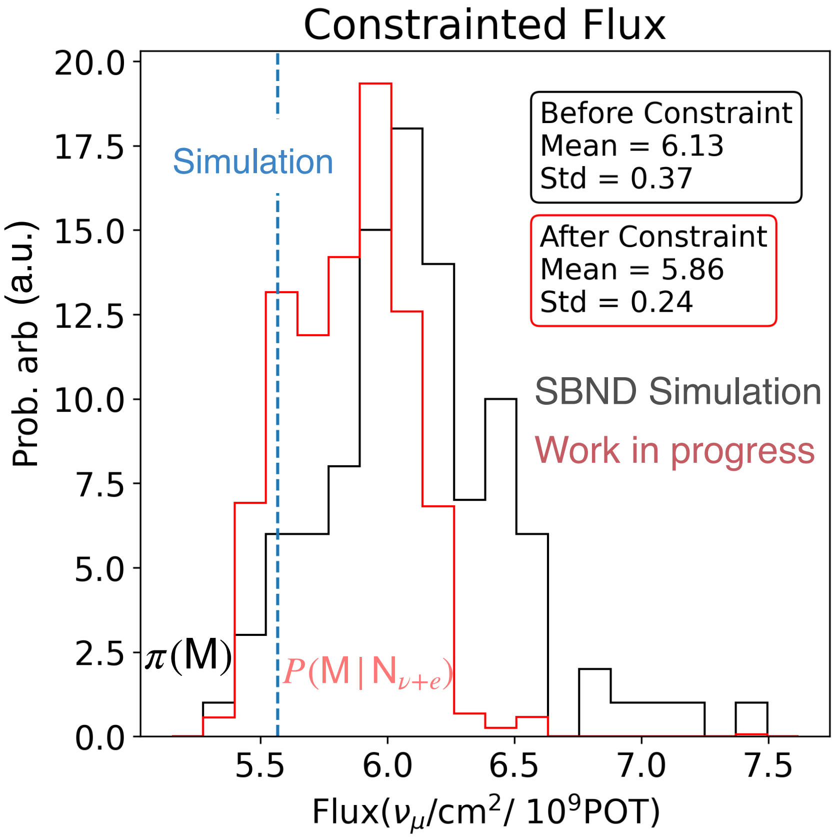


Total ν-e scattering events for each universe prediction before and after applying Bayesian constraint

Flux Constraint

- **Universes** - $M_{\nu+e}$ predicted by each flux model M_n
- **Simulated data -** $N_{\nu+e}$ used for data in likelihood calculation

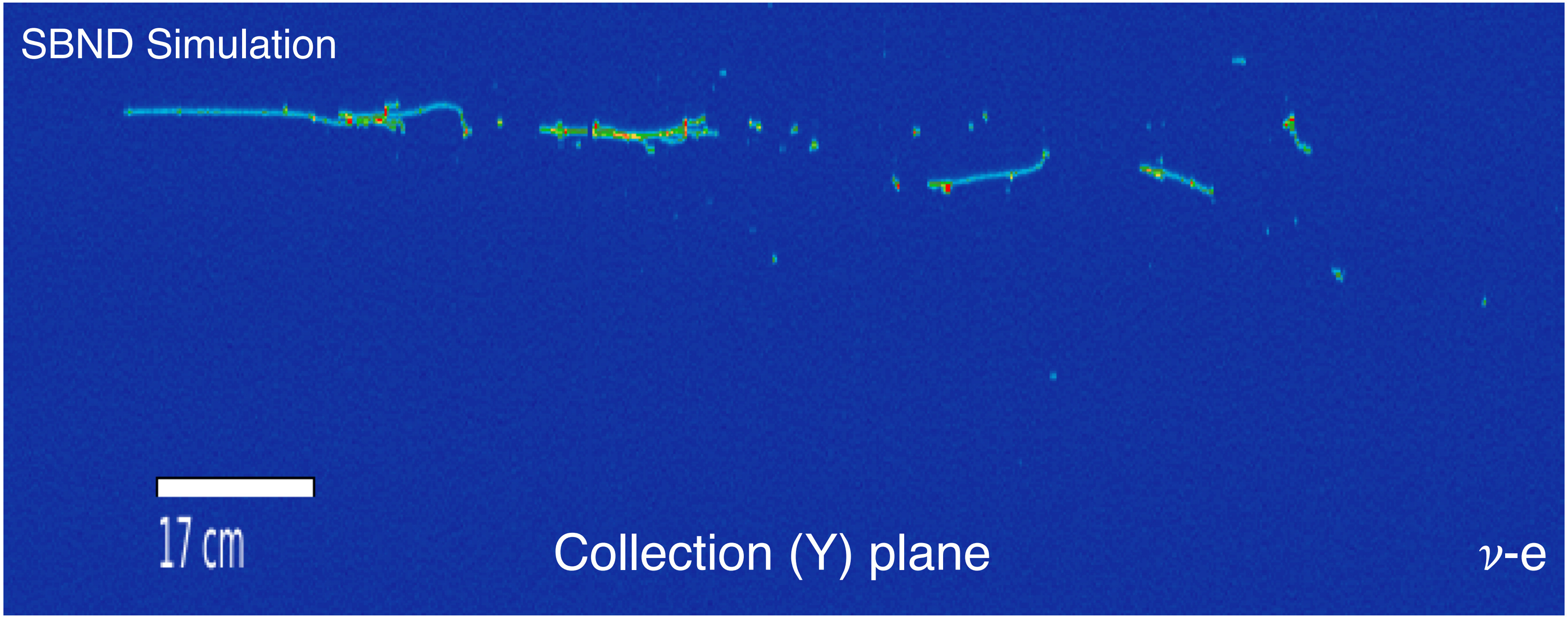
- Integrated ν_μ flux from the same flux universes used for ν-e constraint
- Blue line corresponds to flux measured in the **simulated data** universe
- Mean is **shifted towards** simulated data
- Standard deviation **reduced** by reweighting
- The constraint reduces the uncertainty of the integrated ν_μ flux



Integrated ν_μ flux constraint

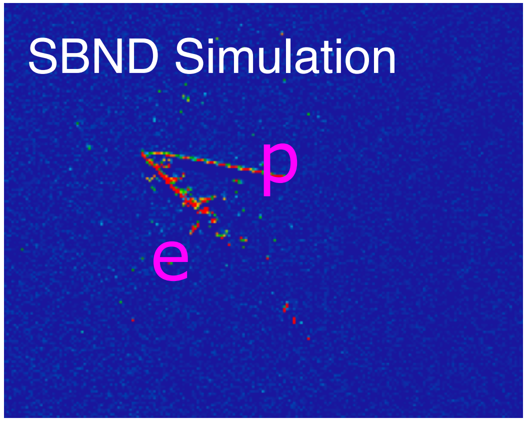
Event Selection

- SBND expects to see ~500 ν-e events over its ~3 year lifetime or 10^{21} protons on target (POT)
- ν-e scattering signal topology is a single beam-aligned electron reconstructed as a shower

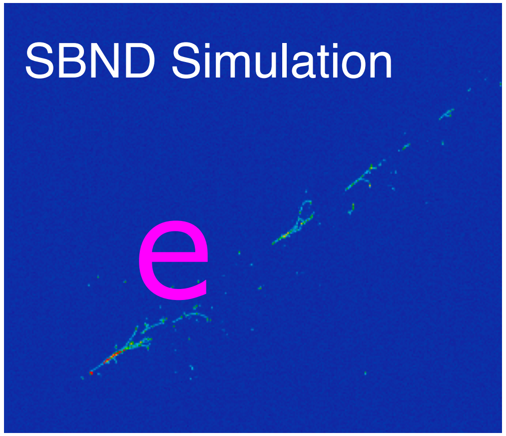


Event Selection

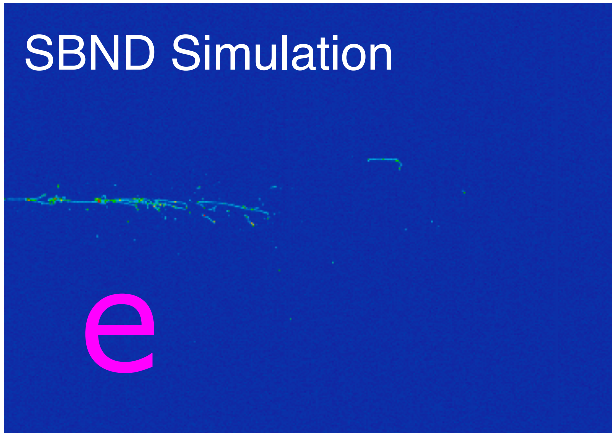
- CCQE ν_e with proton energy below threshold primary background



CC ν_e 1p0π



CC ν_e 0p0π



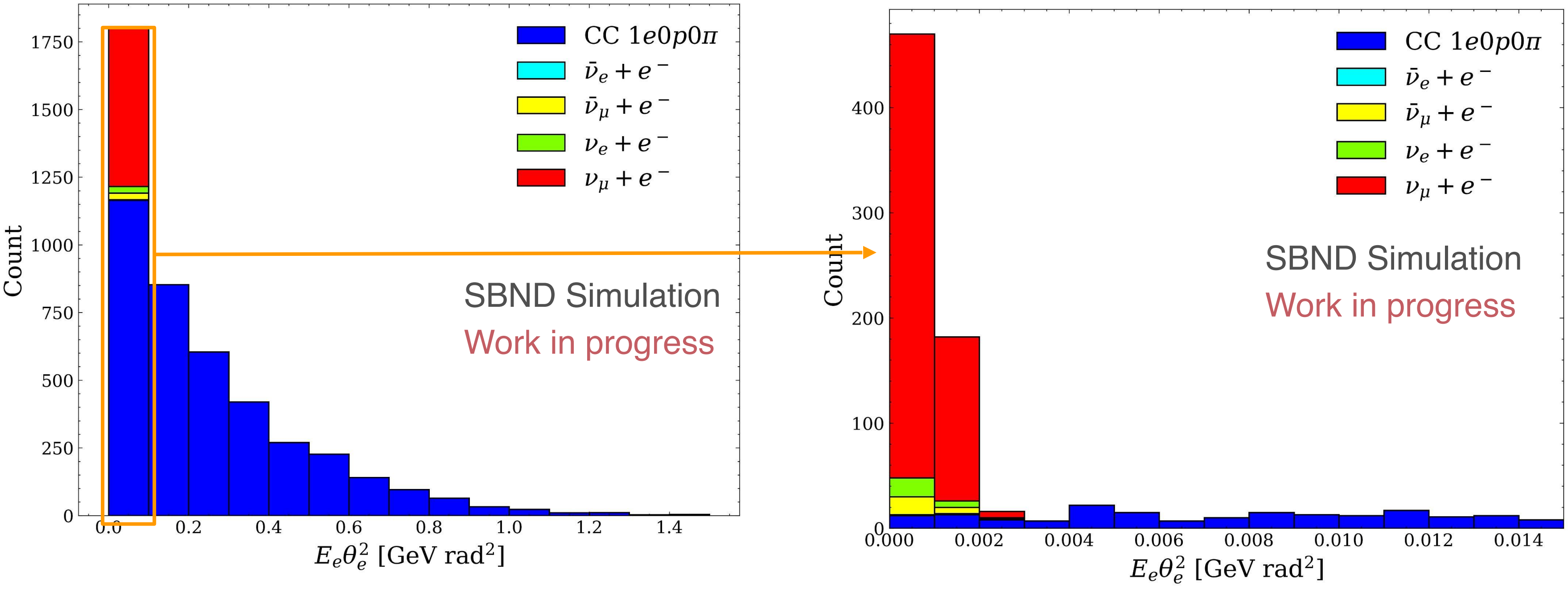
ν-e

Event Selection

- CCQE ν_e with proton energy below threshold primary background
- ν-e scattering has useful 2-body kinematic constraint

$$E_e\theta_e^2 \leq 2m_e$$

- Most of background can be excluded using $E_e\theta_e^2$

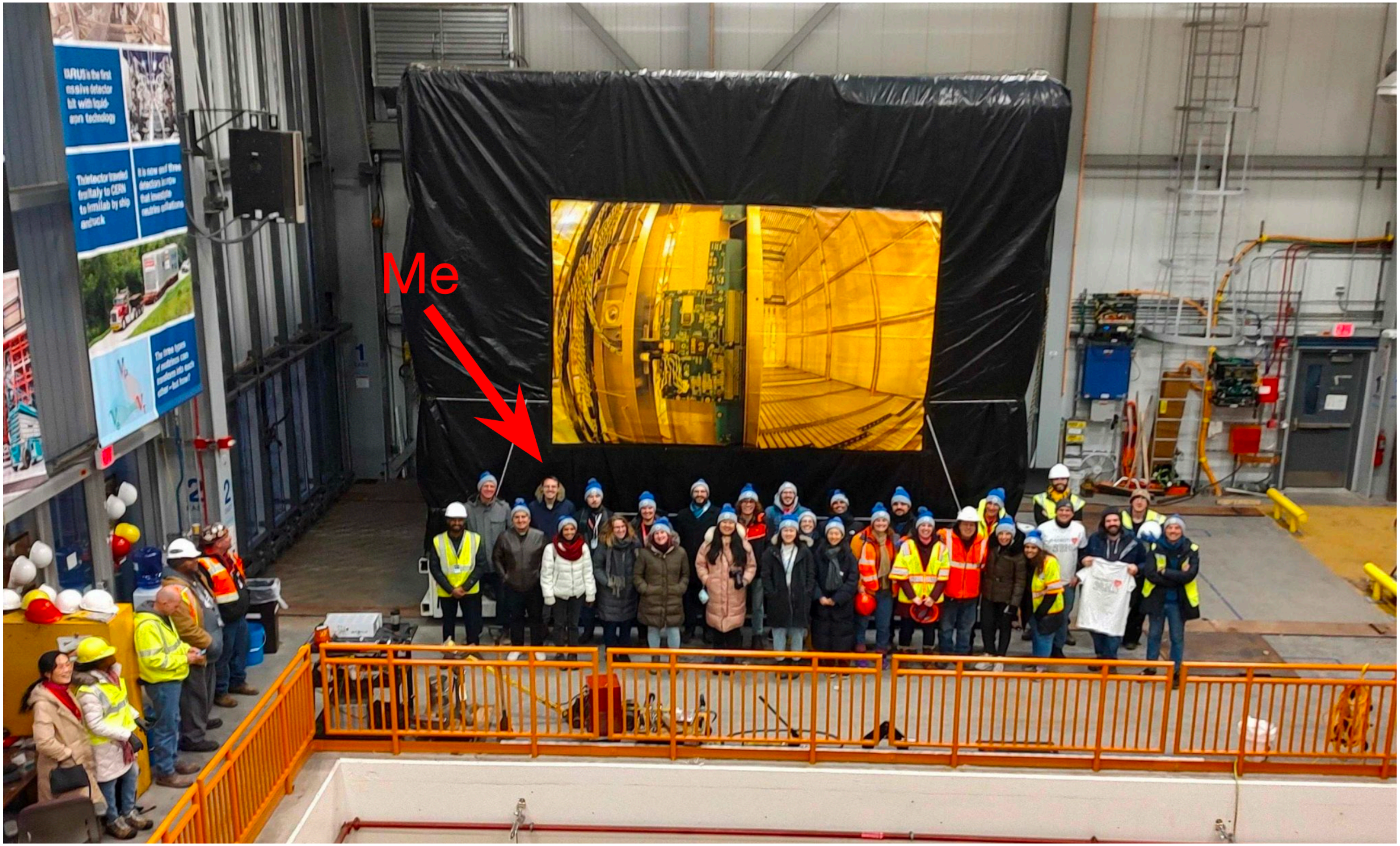


GENIE V3 $E_e\theta_e^2$ distribution for CC ν_e (blue) and ν-e for 10e20 POT

Conclusions

- Flux uncertainties are one of the largest uncertainties for SBND
- ν-e scattering can be used to constrain the flux models
- Demonstrated the procedure to constrain any distribution dependent on a flux model π(M) using simulated data
- ν_μ flux and ν-e scattering distribution uncertainties were both constrained using this method
- Constraint can be applied to all detectors on BNB
- We will see many ν-e events in SBND with high resolution

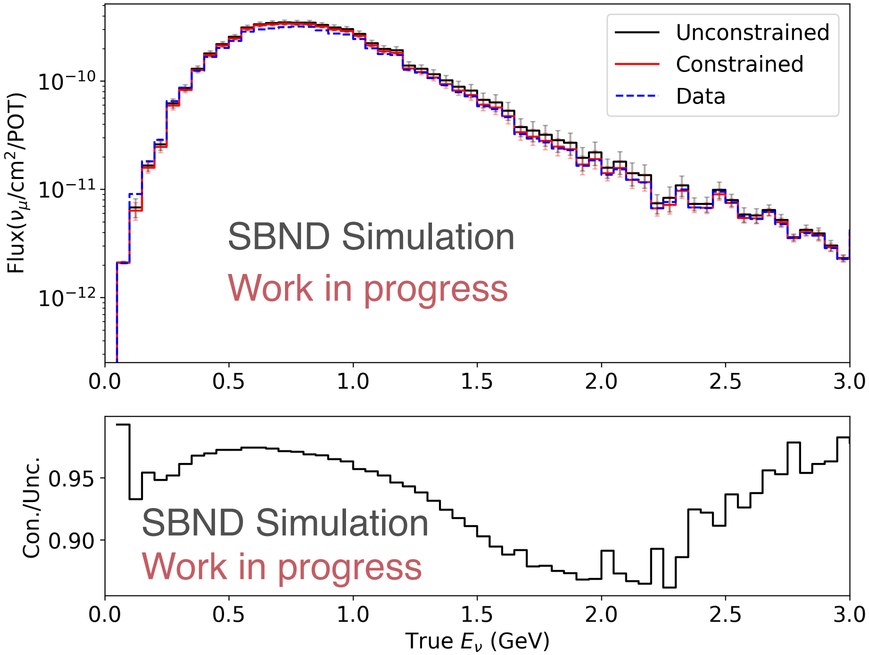
Thanks!



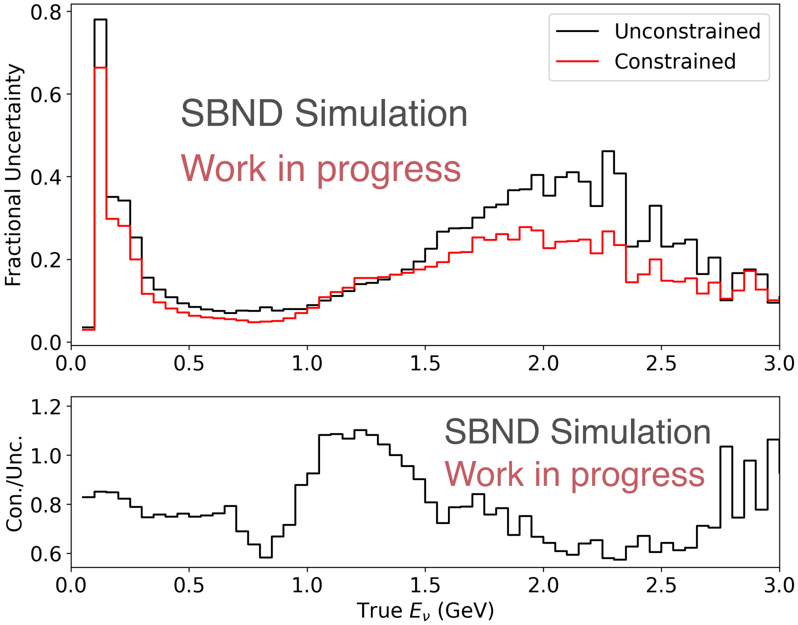
Backup

Flux Constraint

- ν_μ flux CV prediction of constrained and unconstrained flux models on left
- Fractional uncertainty before and after constraint on right



ν_μ flux before and after constraint



ν_μ fractional uncertainties

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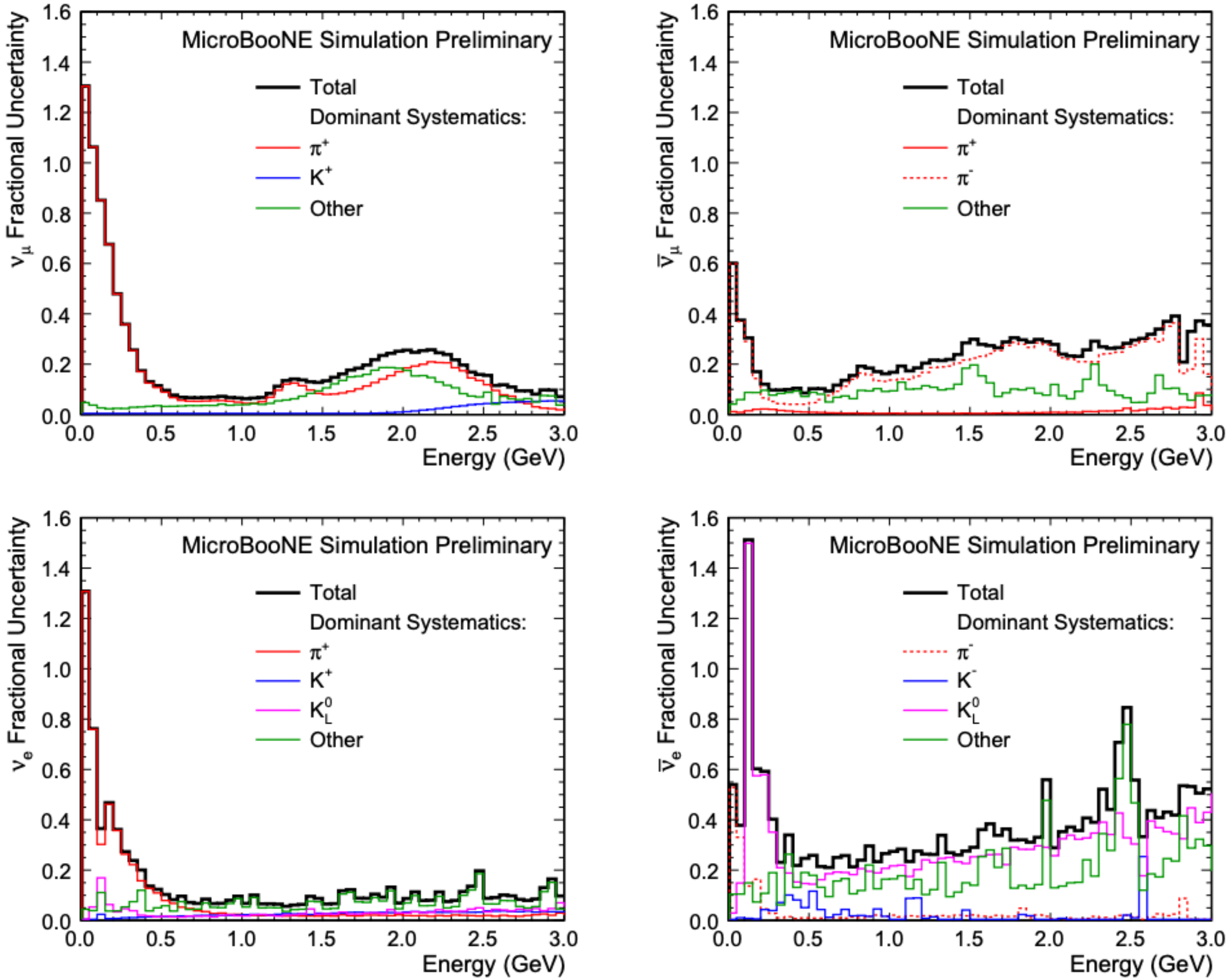

Neutrino Electron Constraint

- Statistical covariance matrix