Model Validation and Cross-Section Extraction of Inclusive ν_μCC

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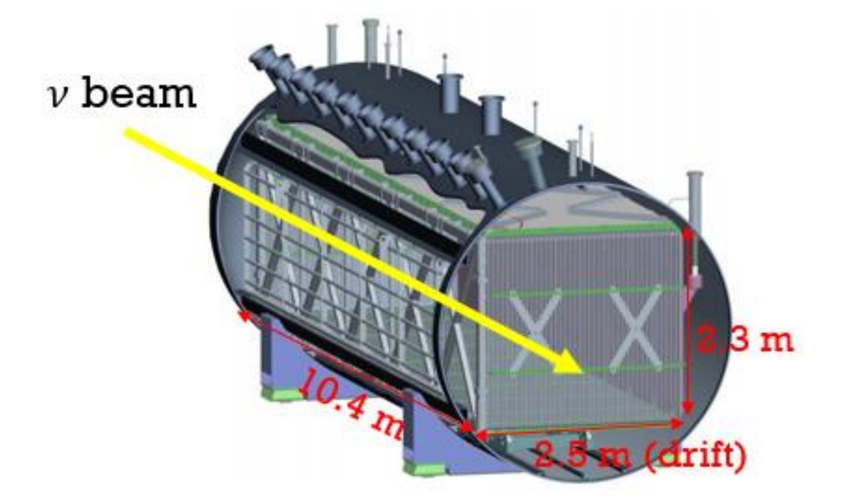
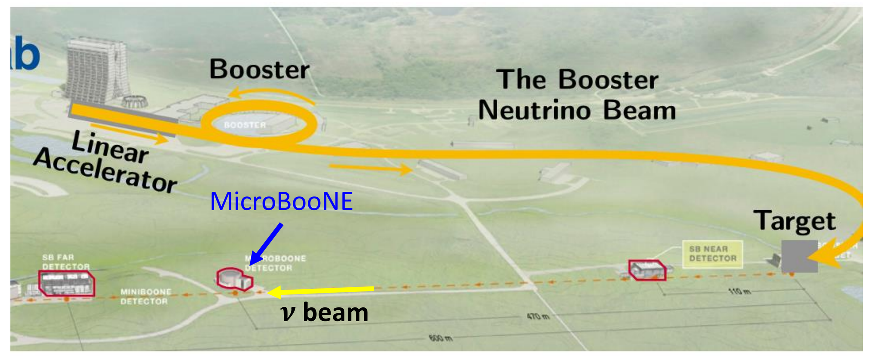
1. MicroBooNE

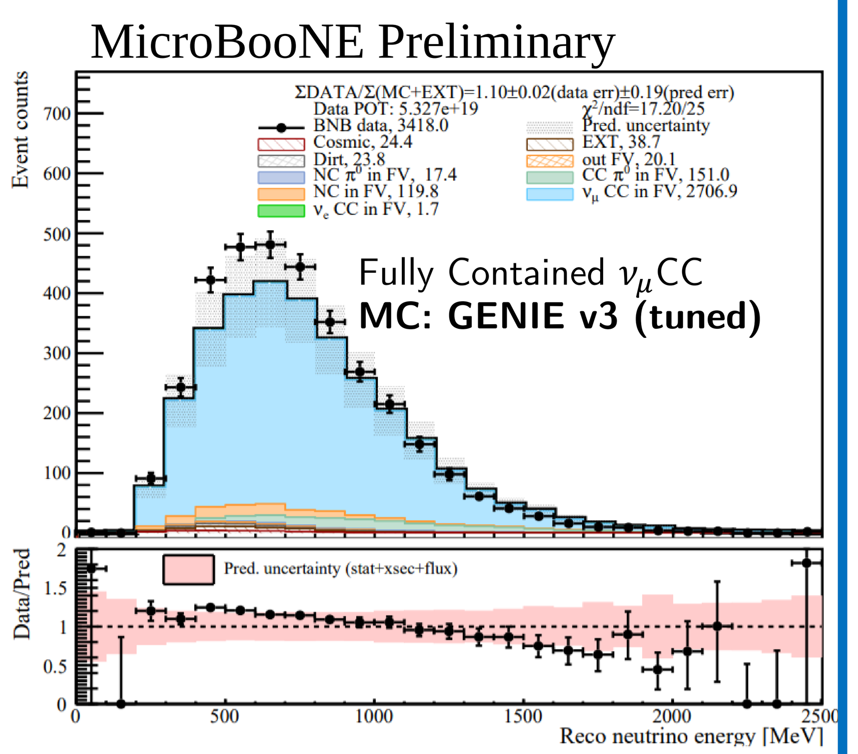




- Accelerator ν experiment at Fermilab
  - LArTPC with 85-ton active mass
  - Near-surface operation
- Main physics goals
  - Investigate MiniBooNE low-energy excess
  - Measure ν-Ar interaction cross sections

2. ν_μ CC inclusive selection

	Efficiency	Purity	Cosmic-μ rejection
Trigger	1	5e-5	1
Generic-ν detection	80%	65%	7e-6
ν_μCC (Fully & Partially Contained)	**64%**	**93%**	7e-7



- Achieved excellent cosmic-μ rejection
  - Wire-Cell reconstruction: arXiv:2101.05076
  - Generic-ν detection: arXiv:2012.07928, arXiv:2011.01375
- The **high-statistics** event selection allows for high-precision cross-section measurements
  - MICROBOONE-NOTE-1095-PUB

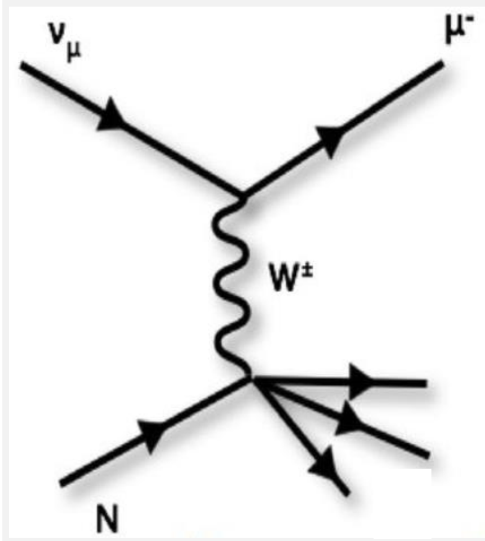
Calorimetric energy: $E_\nu^{rec} = E_\mu^{rec} + E_{had}^{rec}$

Reco lepton (muon) energy

Reco hadron energy

3. Model validation: E_ν to E_ν^{rec}

- **Neutrino energy modeling is crucial for neutrino oscillation measurements**
  - Key challenge: understanding ν-Ar cross section as a function of energy
- **A new procedure for validating E_ν^{rec} from model prediction:**
  - Reco muon energy and kinematics (E_μ^{rec}, $\cos\theta_\mu^{rec}$) are verified with data measurement first
  - Reco hadron energy (E_{had}^{rec}) is further validated given a **conditional constraint** of the muon kinematics



$E_\mu^{rec} \Rightarrow X$

$E_{had}^{rec} \Rightarrow Y$

Formalism of conditional Constraint

$$\mu_{X,Y} = \begin{pmatrix}\mu_X \\ \mu_Y\end{pmatrix}, \qquad \Sigma_{X,Y} = \begin{pmatrix}\Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY}\end{pmatrix}$$

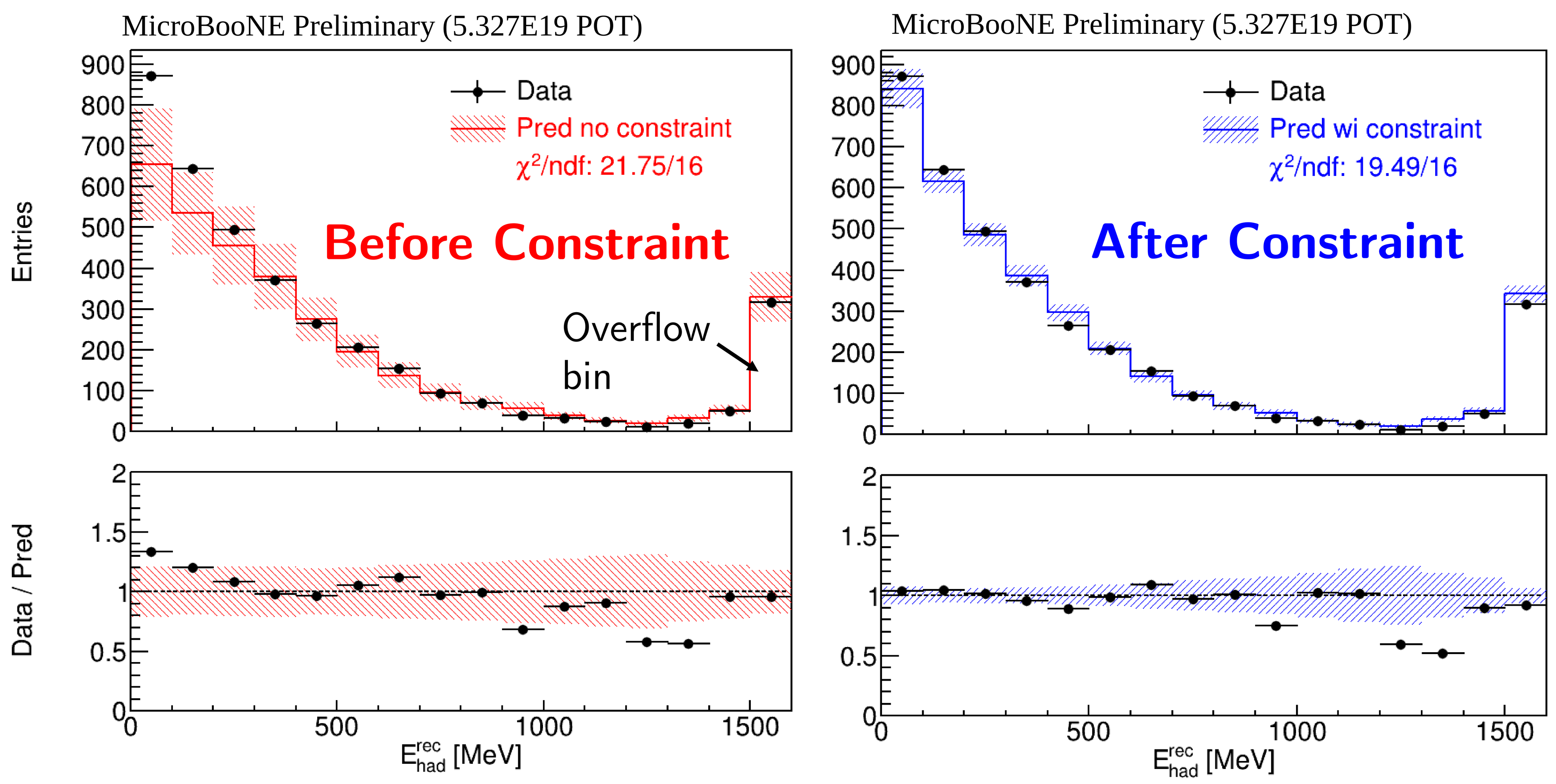
Joint mean   Joint covariance

$$\mu_{Y|X}^{\text{constrained}} = \mu_Y + \Sigma_{YX}\Sigma_{XX}^{-1}(X - \mu_X)$$

$$\Sigma_{Y|X}^{\text{constrained}} = \Sigma_{YY} - \Sigma_{YX}\Sigma_{XX}^{-1}\Sigma_{XY}$$

- A data-driven correction for the model prediction of Y given a measurement of X
- **Common systematic uncertainties (e.g., flux) are reduced ⇒ more stringent model validation**

4. Validation of hadron energy reconstruction



- **After constraint with E_μ^{rec} and $\cos\theta_\mu^{rec}$: no more excess at low hadronic energy**
  - Significant reduction in overall uncertainties (20% → 5%)
  - No sign of mis-modeling of the **hadron missing energy**

5. Towards a cross-section extraction

$$M(E_{rec}) = POT \cdot T \cdot \int F(E_\nu) \cdot \sigma(E_\nu) \cdot D(E_\nu, E_{rec}) \cdot \epsilon(E_\nu, E_{rec}) \cdot dE_\nu + B(E_{rec})$$

Measured # of events; Target nucleons; Cross section; Selection efficiency; Background; Proton-on-target; Neutrino flux; Detector response

- Extract the cross section $\sigma_{CC}(E_\nu)$ with data unfolding technique
- More dimensions are allowed: $d\sigma_{CC}/dE_\mu$, $d\sigma_{CC}/d\nu$, $d\sigma_{CC}/dE_\mu d\theta_\mu$

MC folding vs. data unfolding (a re-smearing process to extract truth model)

$$M_i = \sum_j R_{ij} S_j \quad \Longleftrightarrow \quad \hat{S} = A_C \cdot R^{-1} \cdot M$$

M: measured event distribution
S: binned true distribution
R_{ij}: response matrix (reco bin i and true bin j)
A_C: regularization, also applied to models when comparing result to theoretic predictions