

# Muon-neutrino charged-current cross sections from MicroBooNE:

first simultaneous measurements of final states with and without protons for muon-neutrino scattering on argon



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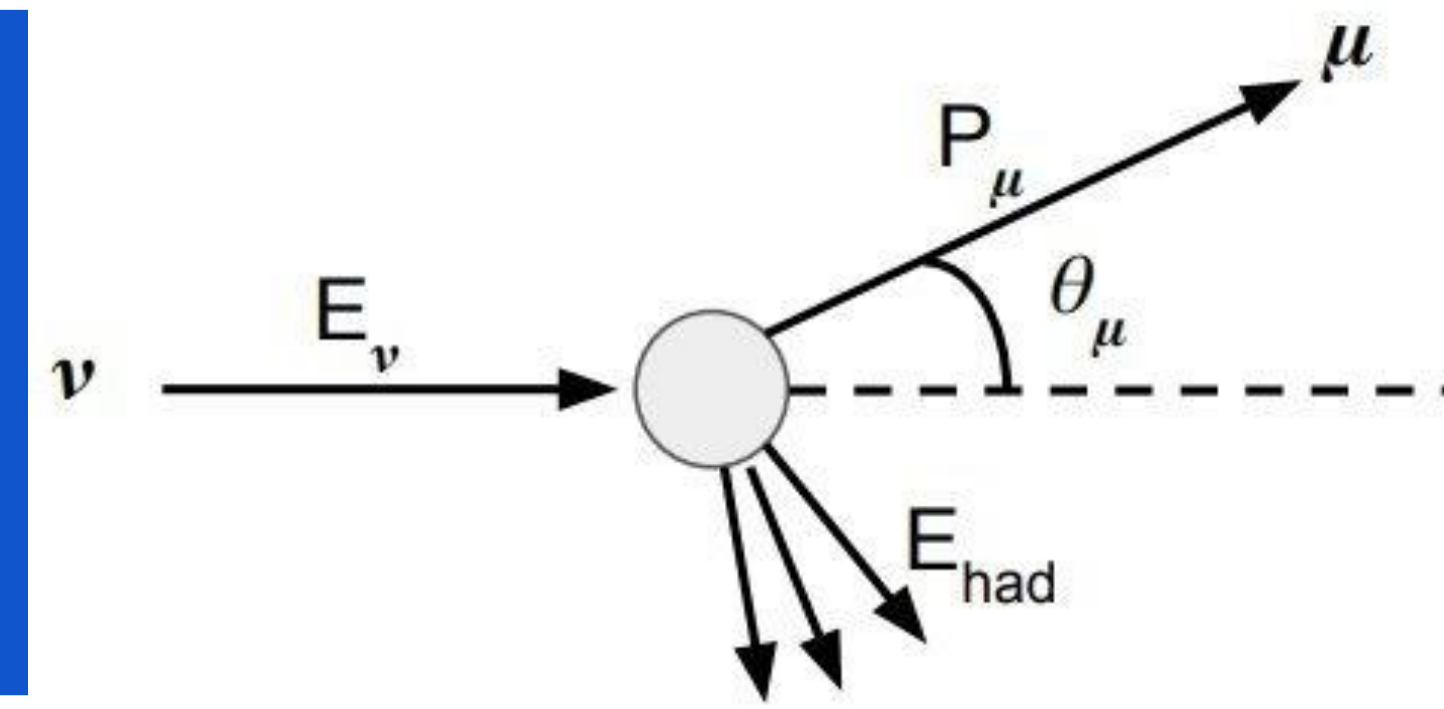
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References: [1] Phys. Rev. D 105, 112005 (2022)  
[2] JINST, 12, P10002 (2017) [3] Phys. Rev. Lett. 131, 101802 (2023) [4] arXiv:2402.19281 [5] arXiv:2402.19216

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## Measuring of 0p and Np final states in MicroBooNE

- New detailed set of cross section measurements for inclusive charged current muon-neutrino scattering with the channel divided into final states with (Np) and without (0p) protons.
- Exploration of the hadronic final state provides additional sensitivity to nuclear effects which complicate cross section modeling.



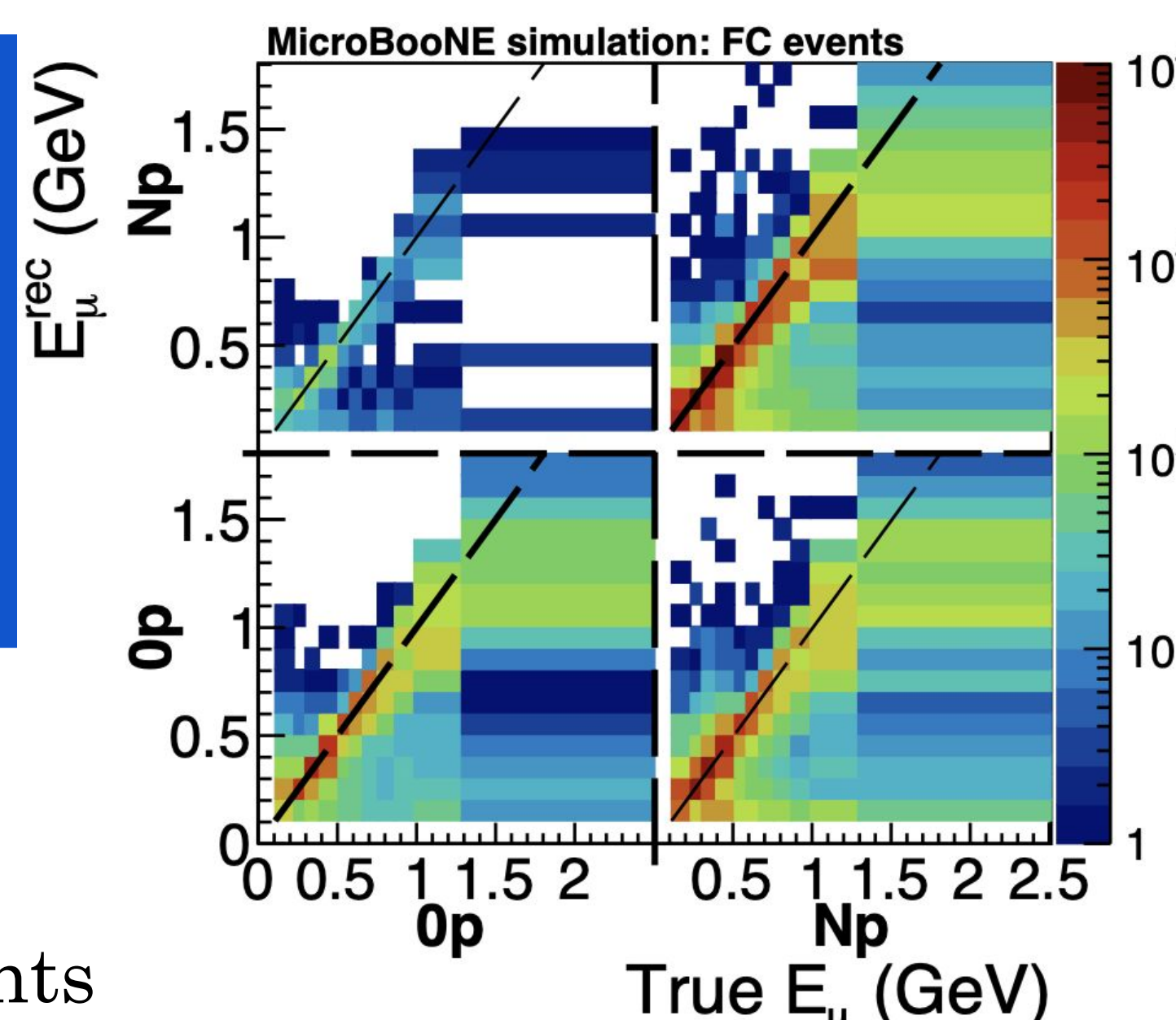
## Event Selection and Unfolding

- The inclusive  $\nu_\mu$  CC selection [1] and signal is divided into 0p and Np based on a proton kinetic energy ( $K_p$ ) threshold of 35 MeV.
- The 0p and Np cross sections are extracted simultaneously with Wiener-SVD [2].
- Simultaneous extraction is achieved by unfolding Eq. 1 using the response matrix,  $R$ , in Fig 1.

$$\begin{pmatrix} M_{0p} \\ M_{Np} \end{pmatrix} = \begin{pmatrix} R_{0p0p} & R_{0pNp} \\ R_{Np0p} & R_{NpNp} \end{pmatrix} \cdot \begin{pmatrix} S_{0p} \\ S_{Np} \end{pmatrix} + \begin{pmatrix} B_{0p} \\ B_{Np} \end{pmatrix}$$

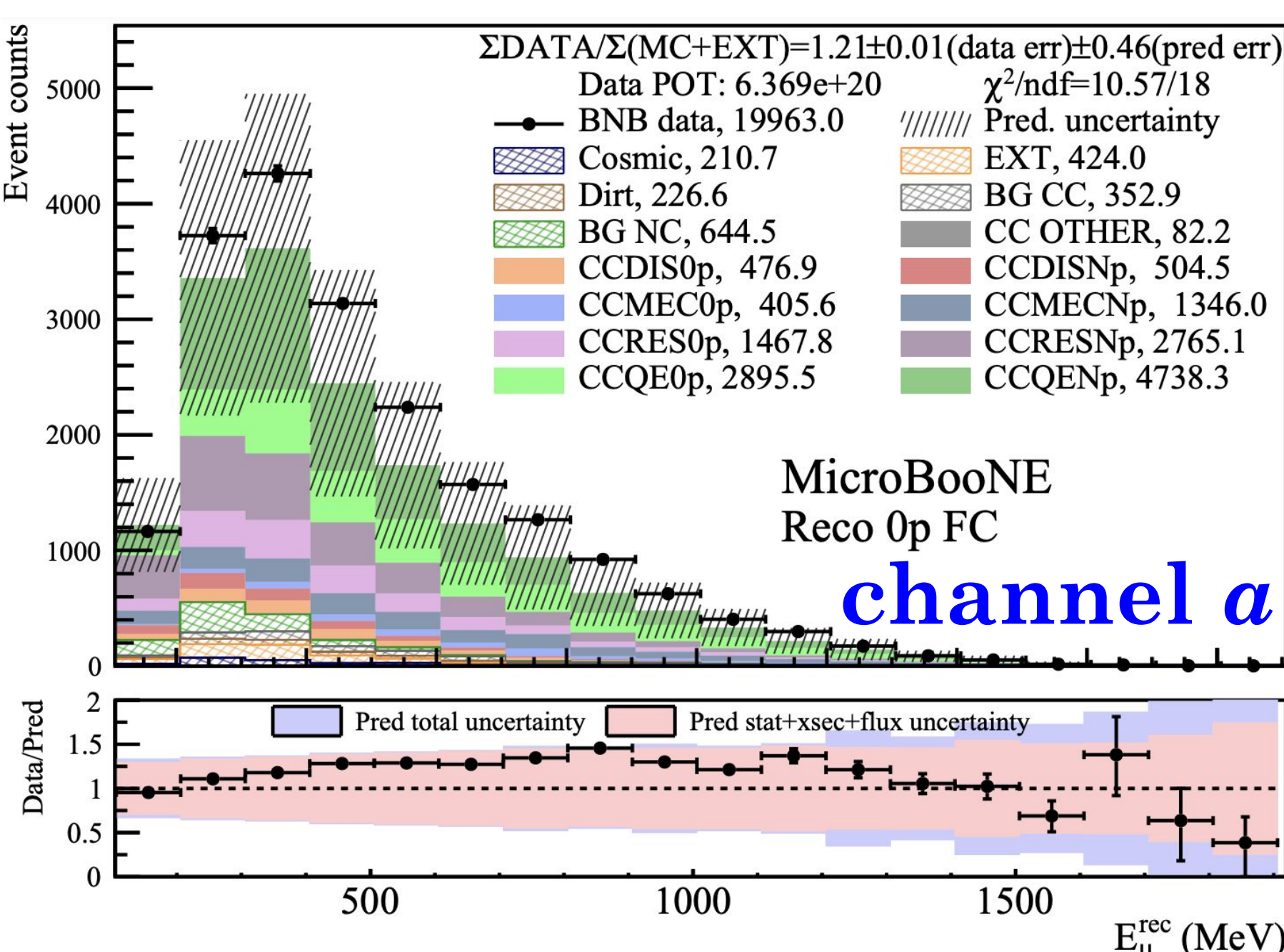
**Eq. 1** :  $M$  measurement,  $R$  response matrix,  $B$  non- $\nu_\mu$  CC background

**Fig. 1:** Reconstructed vs. true muon energy for selected signal events. Both Fig. 1 and Eq. 1 contain off diagonal blocks for true Np (0p) events reconstructed as 0p (Np).



## Data-Driven Model Validation

- Data-driven model validation is employed to detect mismodeling that may bias the results beyond uncertainties.
- Aims to validate all relevant aspect of the model, including the  $K_p$  distribution and the missing hadronic energy in the context of 0p and Np final states.
- The validation relies on goodness-of-fit tests between data and model and the conditional constraint formalism in Eq. 2.
- The constraints use correlations, which describe the model's predicted relationship between distributions, and data observations to reduce uncertainties and update the prediction.



**Fig 3.** The measured and predicted muon kinematics (channel  $a$ )

## channel $a$ constrains channel $b$

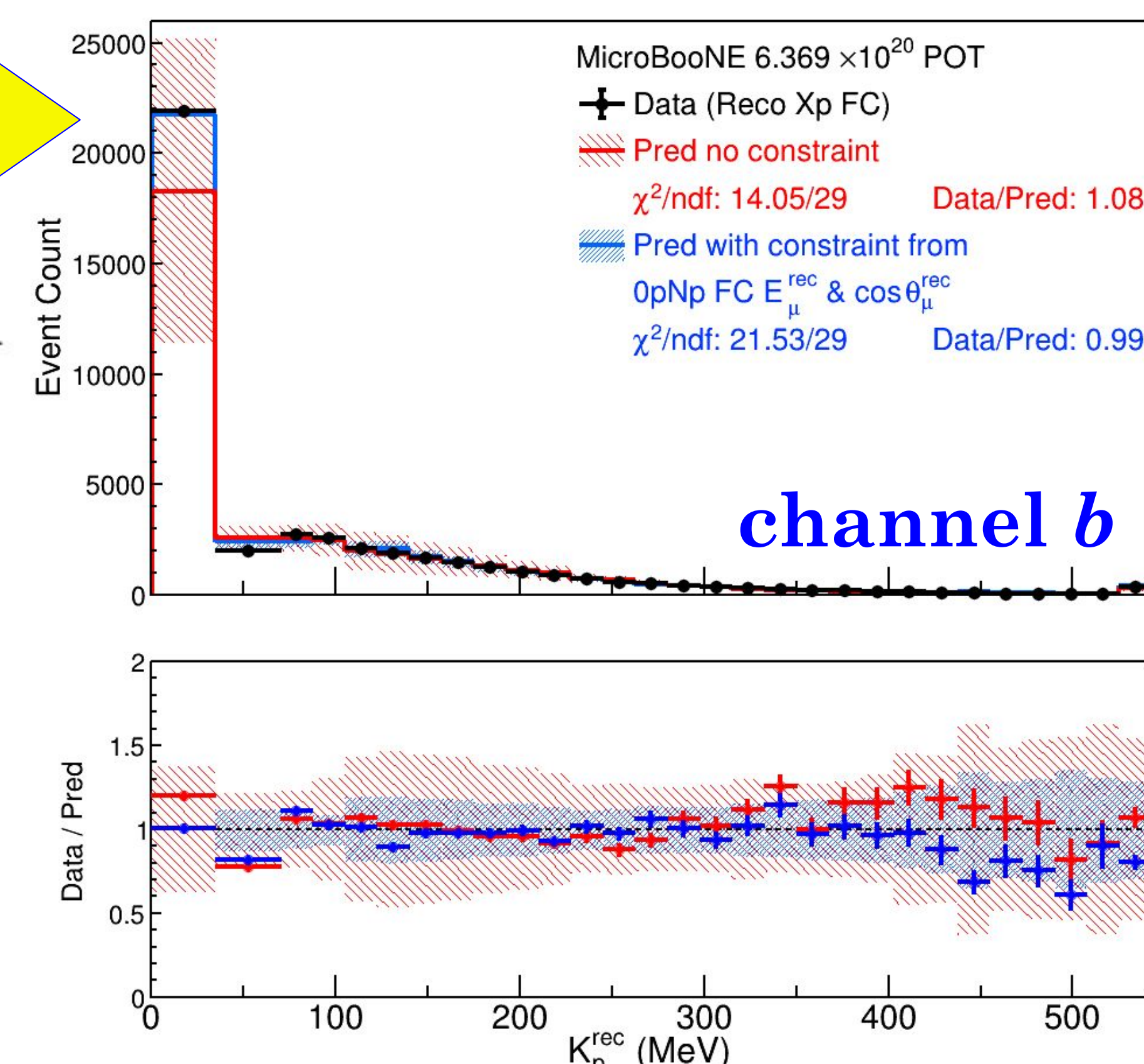
$$\Sigma = \begin{pmatrix} \Sigma_{aa} & \Sigma_{ab} \\ \Sigma_{ba} & \Sigma_{bb} \end{pmatrix} : \text{covariance, } y : \text{measurement, } \mu : \text{prediction}$$

$$\hat{\mu}_{a|y_b} = \mu_a + \Sigma_{ab} (\Sigma_{bb})^{-1} (y_b - \mu_b) : \text{updated prediction}$$

$$\hat{\Sigma}_{aa|y_b} = \Sigma_{aa} - \Sigma_{ab} (\Sigma_{bb})^{-1} \Sigma_{ba} : \text{reduced uncertainties}$$

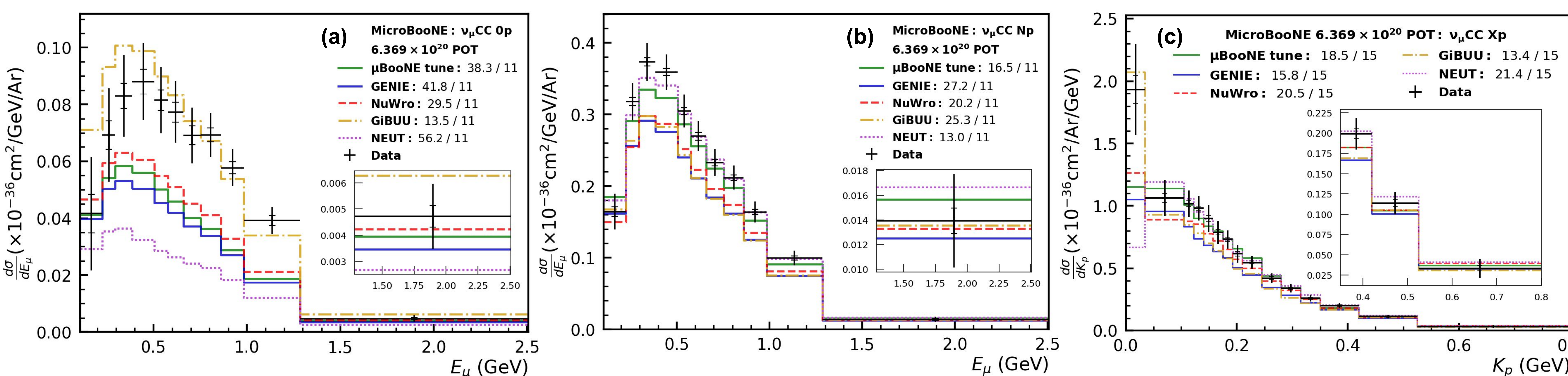
(Top) **Eq. 2:** Formalism for using data observation in channel  $b$  to constrain the prediction for channel  $a$ .

(Right) **Fig. 3:** Goodness of fit test on the  $K_p$  distribution (channel  $b$ ) before and after constraint from the muon kinematics (channel  $a$ ).



## Results: underprediction of 0p final states

- An underprediction of the 0p cross section is seen by all generators except for GiBUU.
- The  $K_p$  data distribution peaks sharply in the first bin. GiBUU mirrors this feature, but the other generators do not.
- This better description of the 0p and  $K_p$  distributions is possible attributable to GiBUU's more sophisticated FSI model. Other MicroBooNE measurements targeting quasielastic-like events [3] support this hypothesis.
- Generators describe the Np cross section at a more comparable level.
- Generators still tend to underpredict the Np cross section, especially around the peak of the muon energy distribution.
- See [4] and [5] for the full set of 14 cross sections measurements.



**Fig. 3:** Simultaneously extracted 0p (a) and Np (b)  $E_\mu$  differential cross sections. (c) Extracted  $K_p$  differential cross section. The first bin includes events without a final-state proton. Generator prediction are shown in colored lines with corresponding  $\chi^2/ndf$  in the legend.