

Measurement of charged-current quasi elastic-like and inclusive muon (anti-) neutrino interactions using NuMI beam with the ICARUS detector

Promita Roy, Bruce Howard, Jaesung Kim and Dihan Senadheera on behalf of ICARUS collaboration

Email: promita@vt.edu



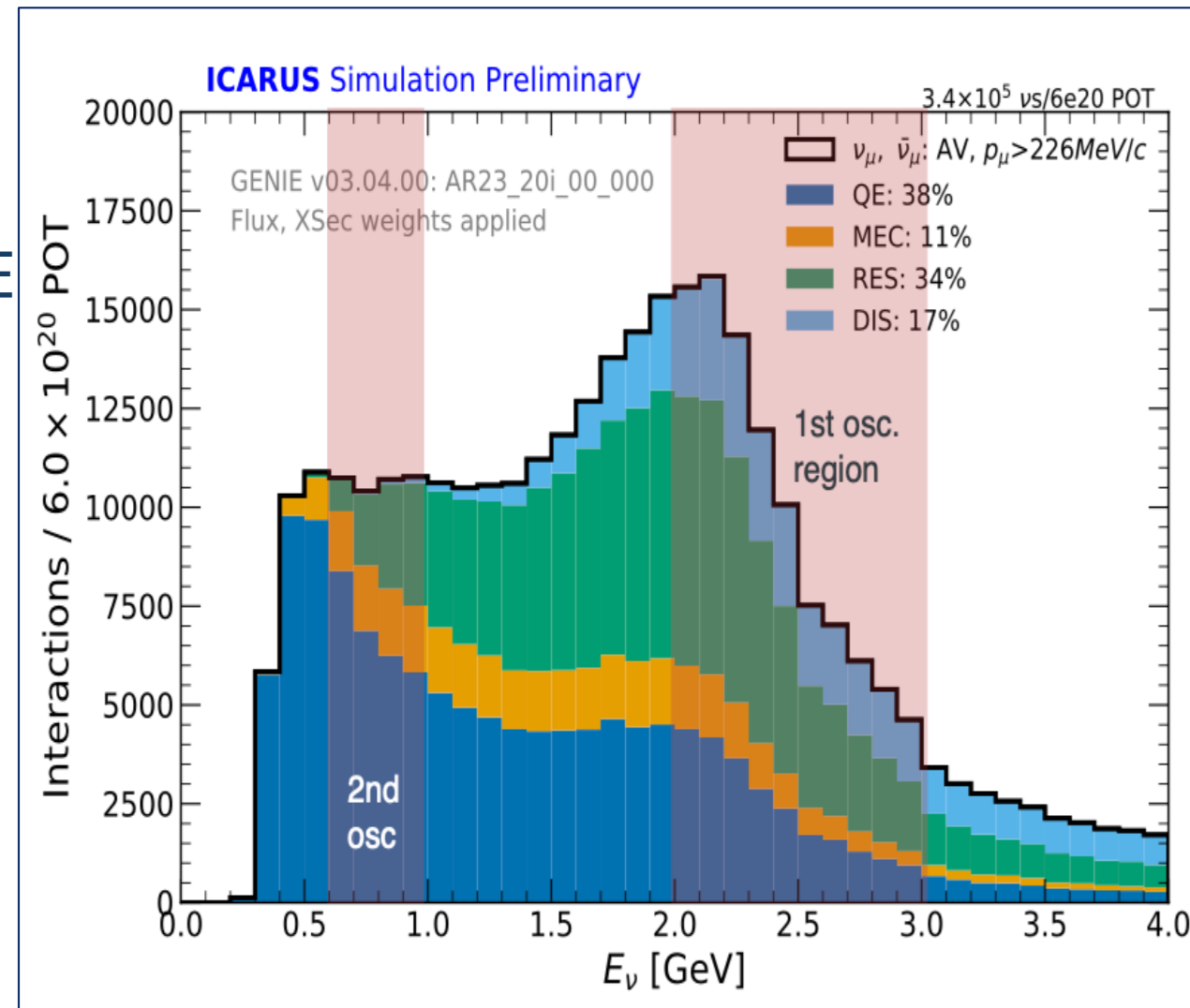
FERMILAB-POSTER-26-0100-PPD

ICARUS at NuMI

ICARUS serves as the far detector of Short Baseline Neutrino program and started its first run of physics data taking in **June 2022** with TPC, PMT and CRT fully operational.

Apart from BNB, ICARUS also receives neutrinos from off-axis NuMI beam.

The NuMI spectrum overlaps significantly with the expected DUNE neutrino energy spectrum, providing an excellent opportunity to perform neutrino-argon cross-section studies relevant to the future DUNE program.



ν_μ -Ar CCQE-like Cross Sections

Signal definition

PANDORA based workflow

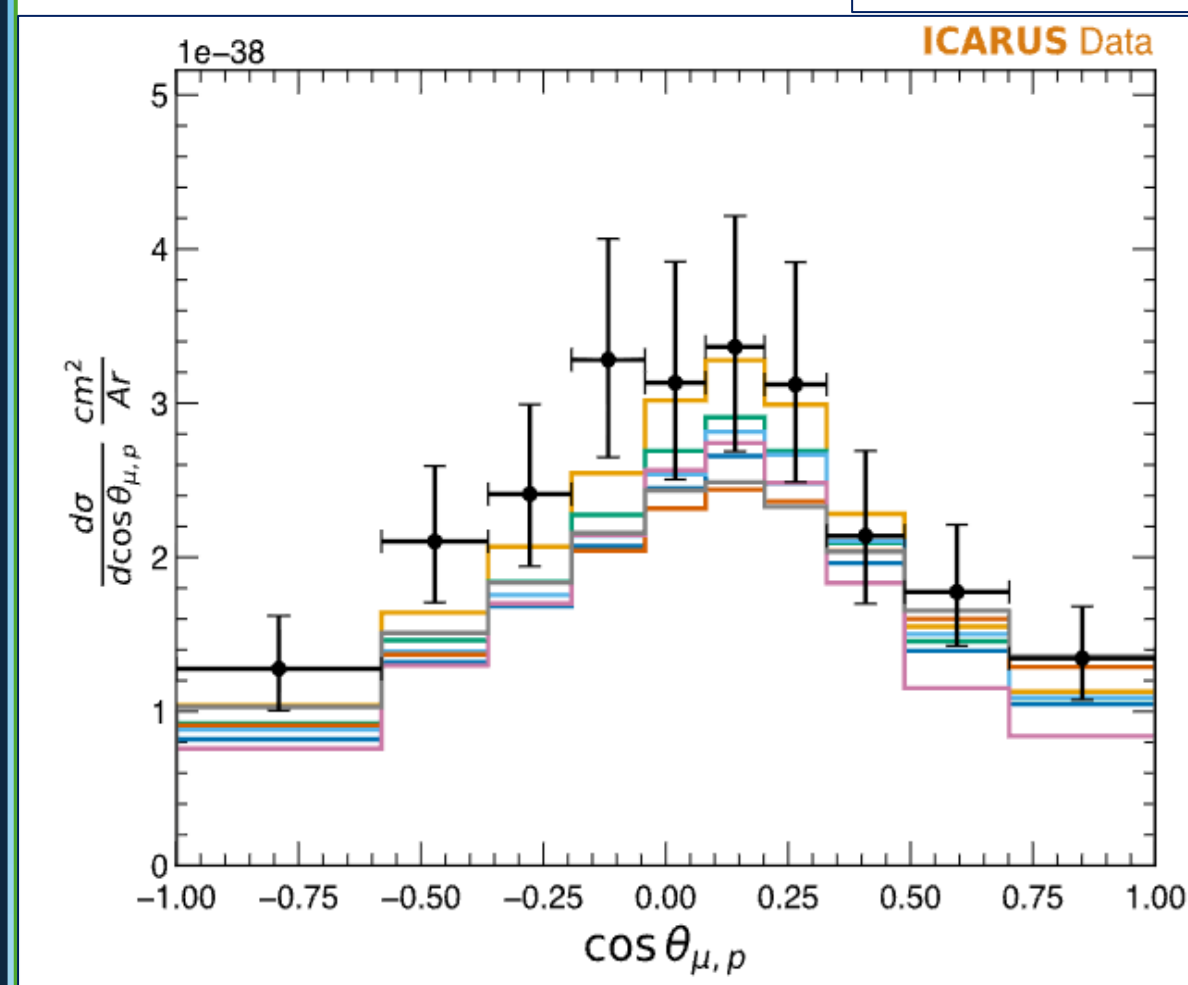
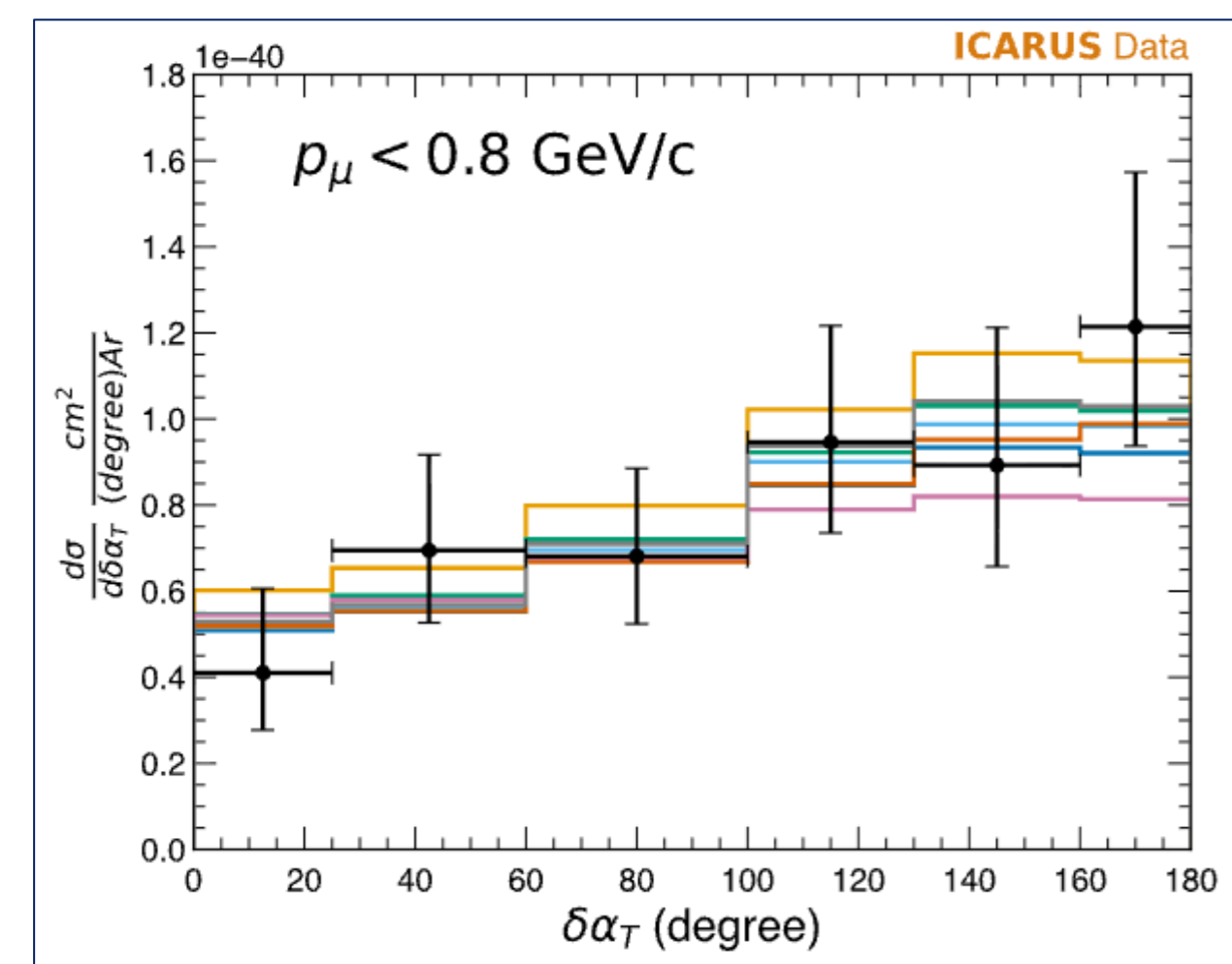
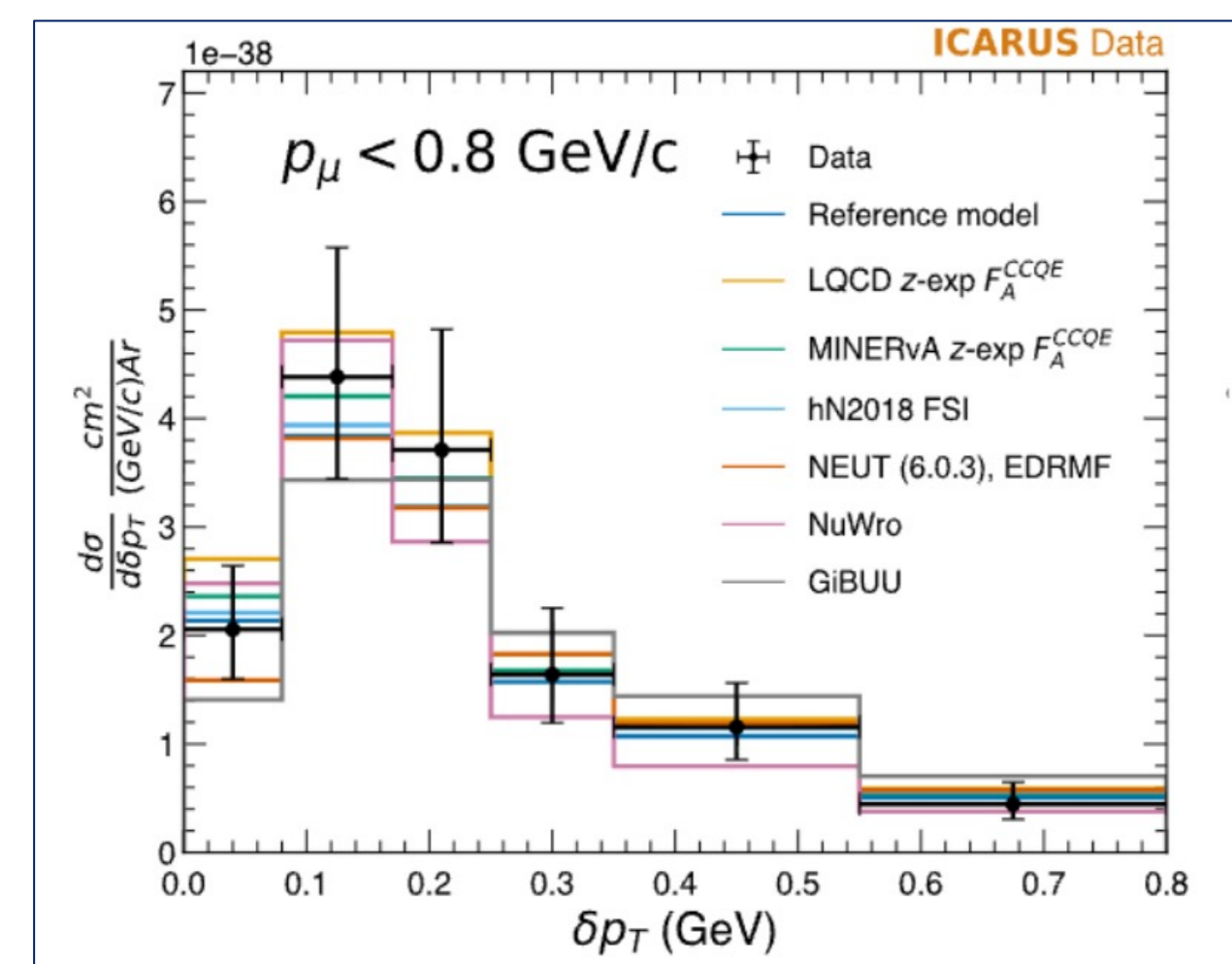
- 1 muon with $p_\mu > 226$ MeV/c
- $N > 0$ protons, with leading p_p between 400 MeV/c and 1 GeV/c
- no charged or neutral pions in the final state

Measurements

Sensitivity to form-factor, initial nuclear motion and final state interactions

Joint measurement of angle of the muon wrt neutrino direction ($\text{Cos}\theta_{\mu}$) and the opening angle between muon and the leading proton ($\text{Cos}\theta_{\mu,p}$)

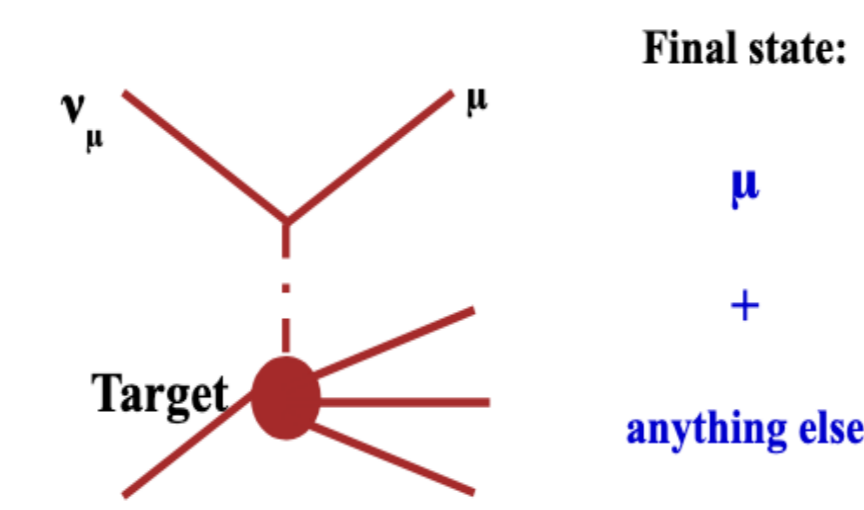
Transverse kinematic imbalance ($\delta p_T, \delta \alpha_T$)



This is the first cross-section measurement from ICARUS with the NuMI beam: <https://arxiv.org/abs/2604.24925>

ν_μ -Ar CC Inclusive Cross Sections

- Benchmarks ν_μ Argon interactions with ICARUS NuMI data
- Constrains cross-section systematics relevant to upcoming multi-kiloTon DUNE experiment



Signal definition

- ν_μ CC
- Within fiducial volume
- $p_\mu > 226$ MeV/c

Signal selection

PANDORA based workflow

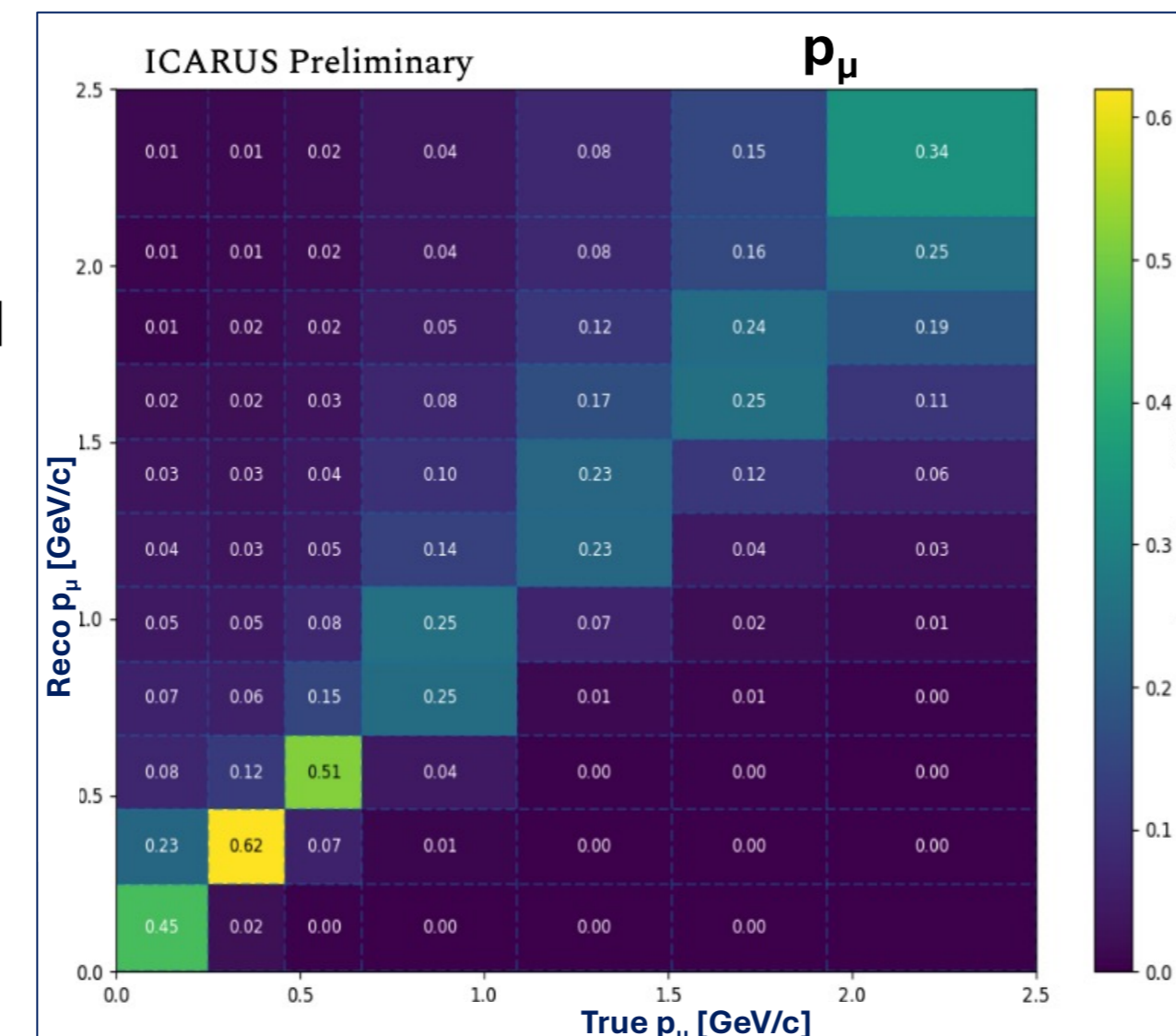
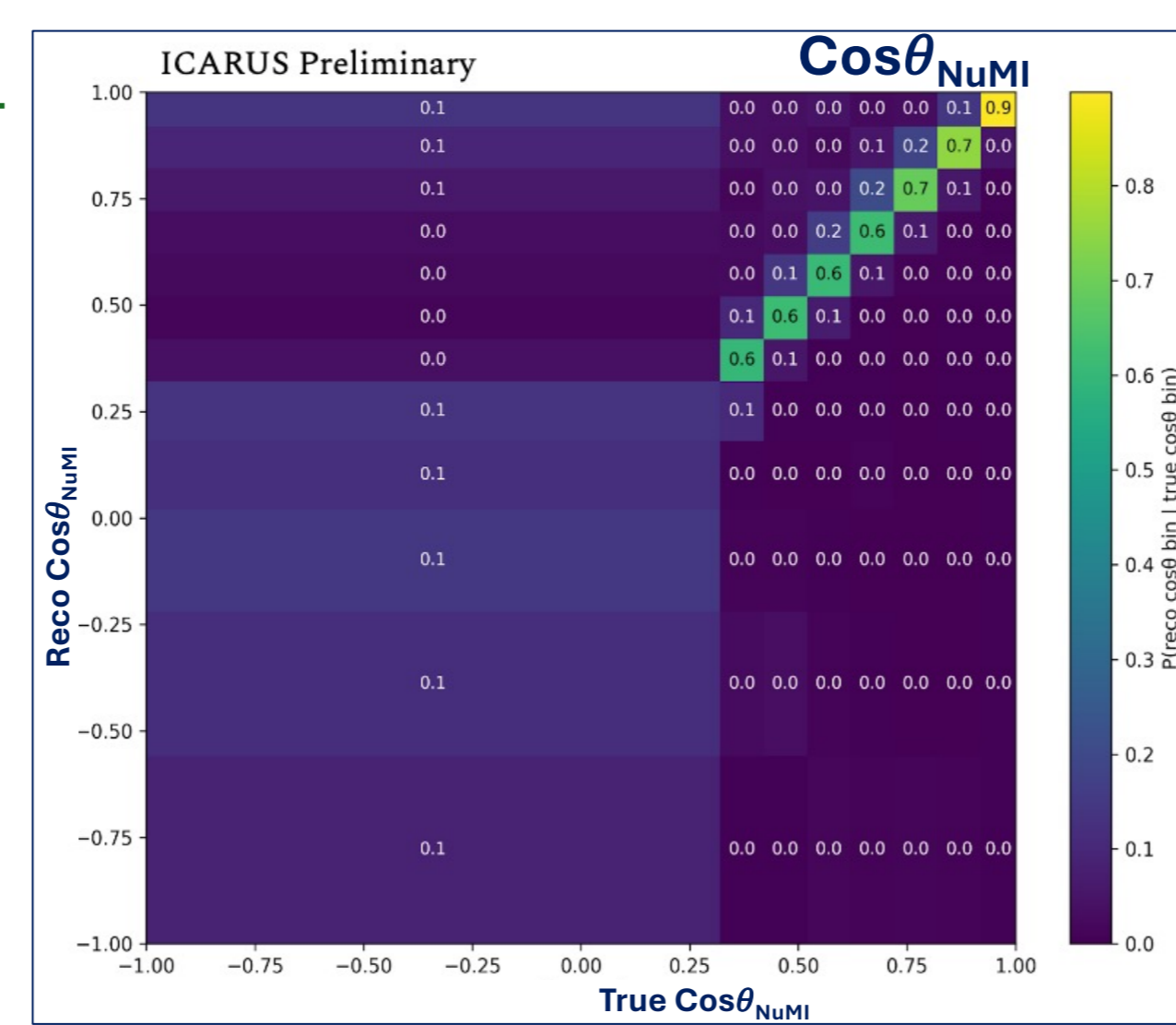
- Not a Pandora clear cosmic, vertex within FD volume
- Flash matching and CRT-PMT spill cut
- Distance from Vertex < 10 cm, Length > 50 cm
- Contained: $\chi^2_\mu < 30$ & $\chi^2_p > 60$

Smearing matrices

For this analysis contained as well as exiting tracks are used.

Muon momentum has been estimated using range method and Multiple Coulomb Scattering (MCS) for contained and exiting tracks respectively.

Bin has been optimized taking into account detector resolution and statistics in each bin

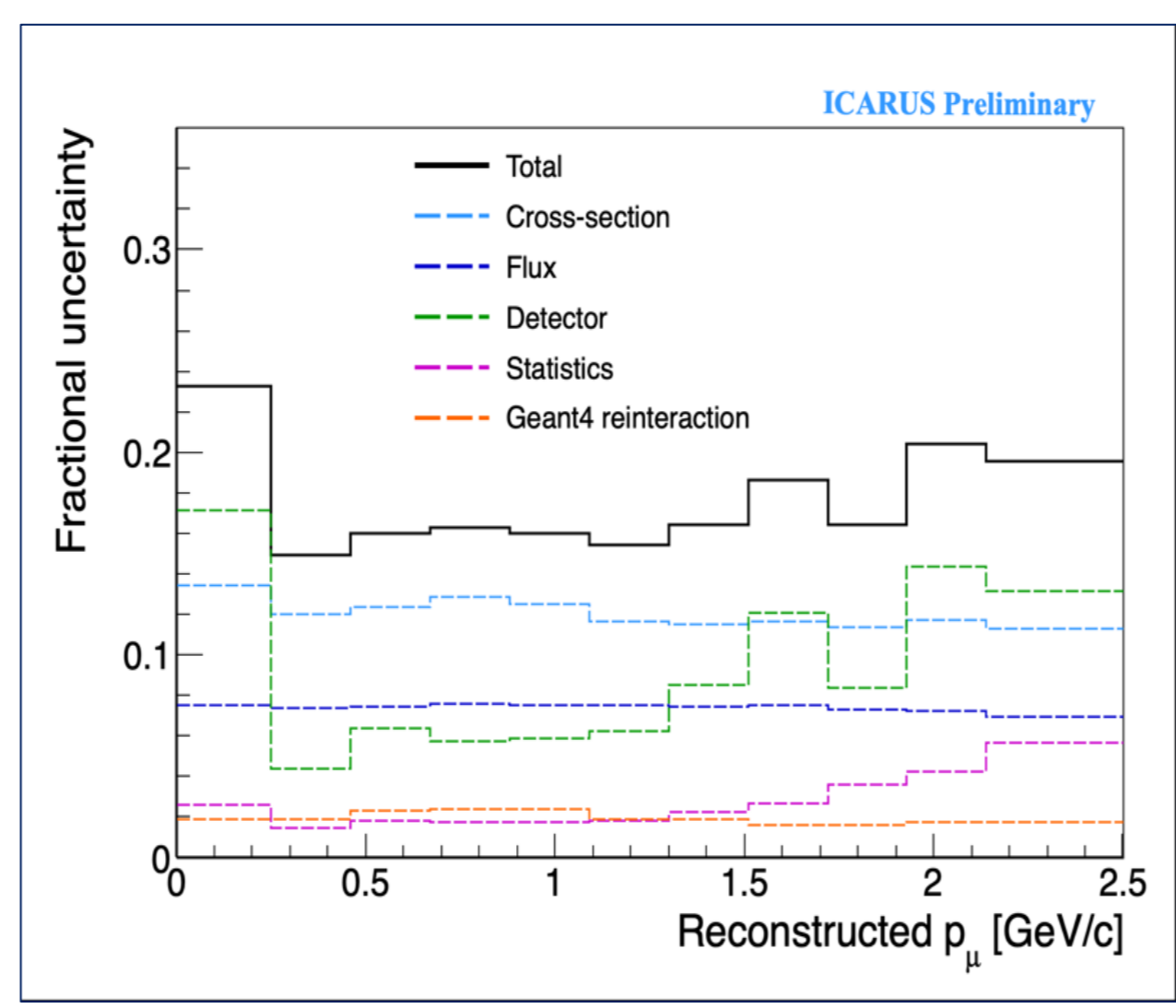


Systematic uncertainty

Sources of uncertainties include:

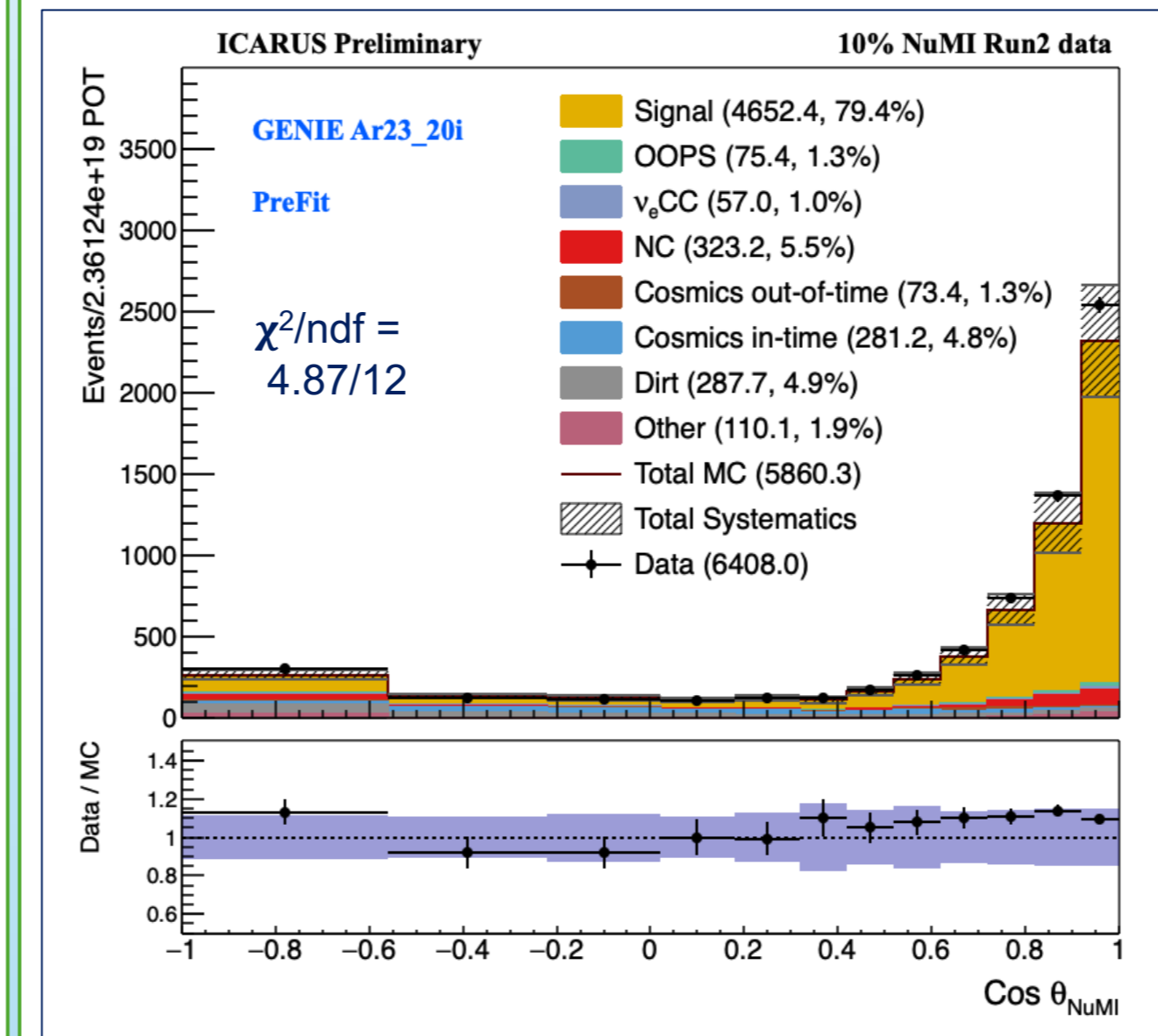
- Interaction model
- Detector
- Flux
- Geant4 Hadron reinteraction
- Statistics

The dominant source is interaction systematics



ν_μ -Ar CC Inclusive Cross Sections continue...

Cross-section observables



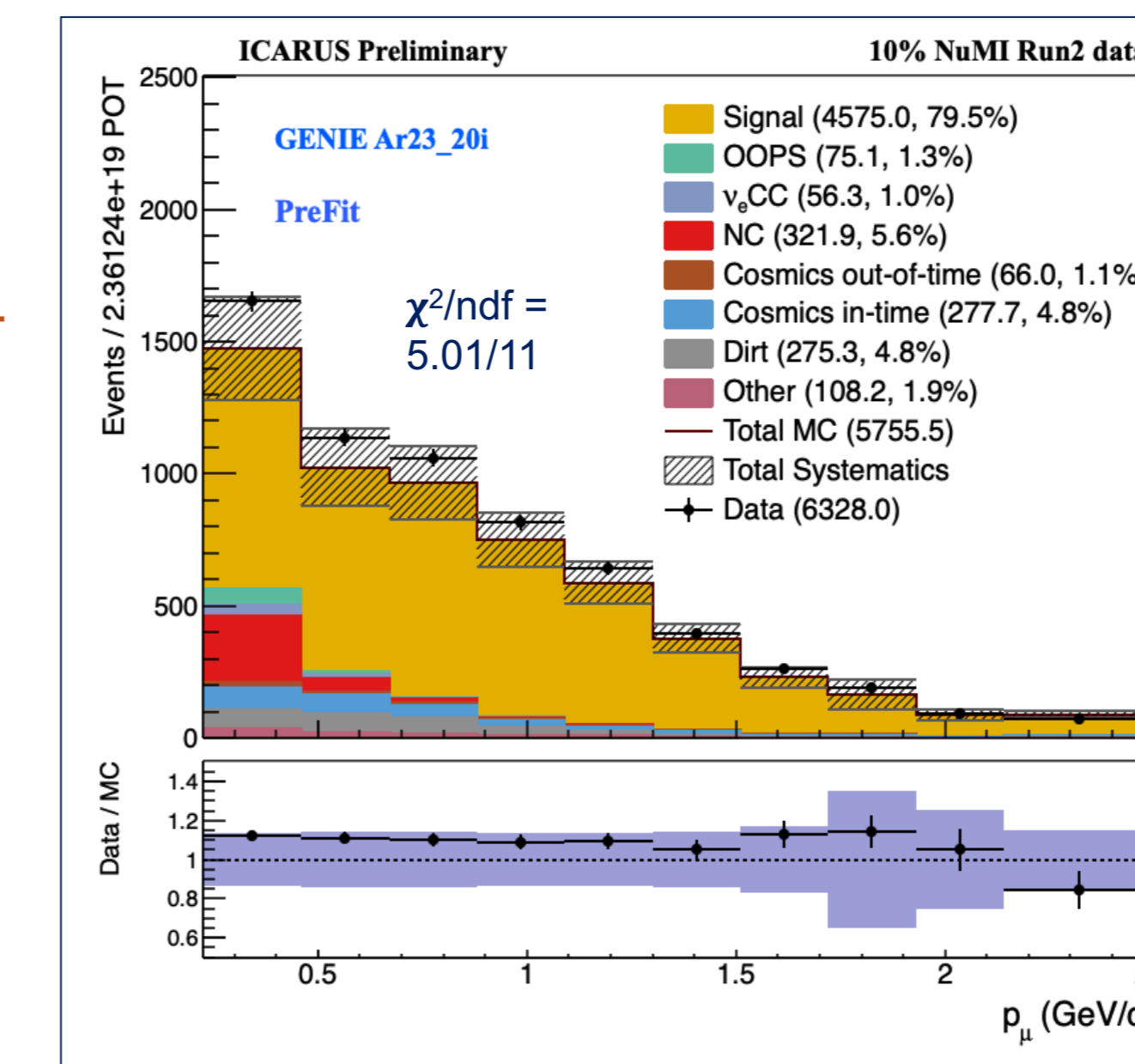
Observables are the following:

- Cosine of the angle of the outgoing muon wrt NuMI beam, $\text{Cos}\theta_{\text{NuMI}}$
- Muon momentum, p_μ

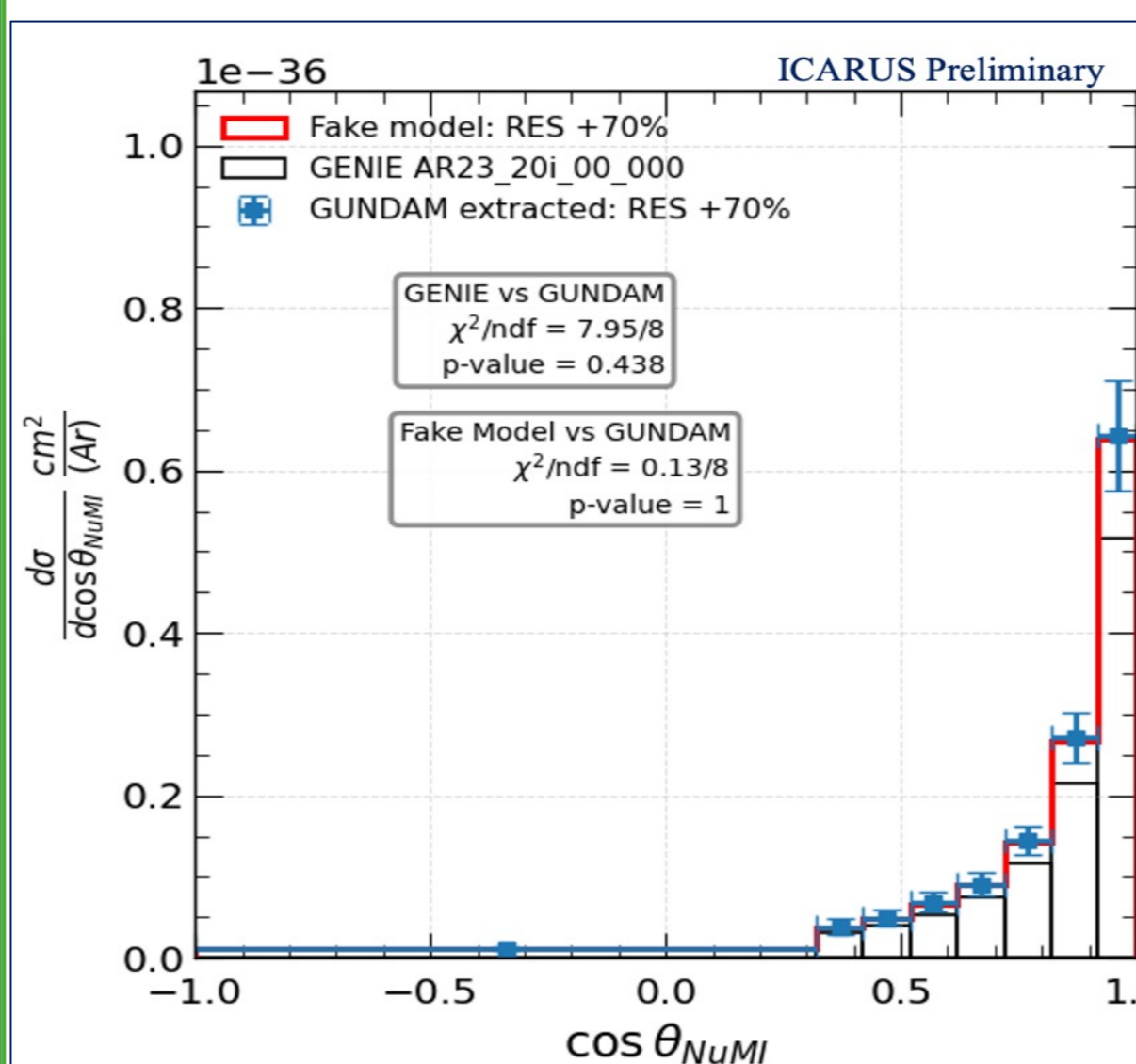
Efficiency: 56%
Purity: 82%

Data-MC comparison

- With full suite of systematics
- Good agreement between MC and 10% of unblinded NuMI data



Cross-section extraction with mock data



The cross section in true bin i of kinematic variable X is given by:

$$\frac{d\sigma}{dx}_i = \frac{N_i^{\text{sig}}}{\epsilon_i \Phi N_{\text{tgt}} (\Delta x)_i} \frac{1}{N_{\text{tgt}}}$$

Number of signal events, background subtracted + corrected for detector smearing

Incoming ν_μ flux

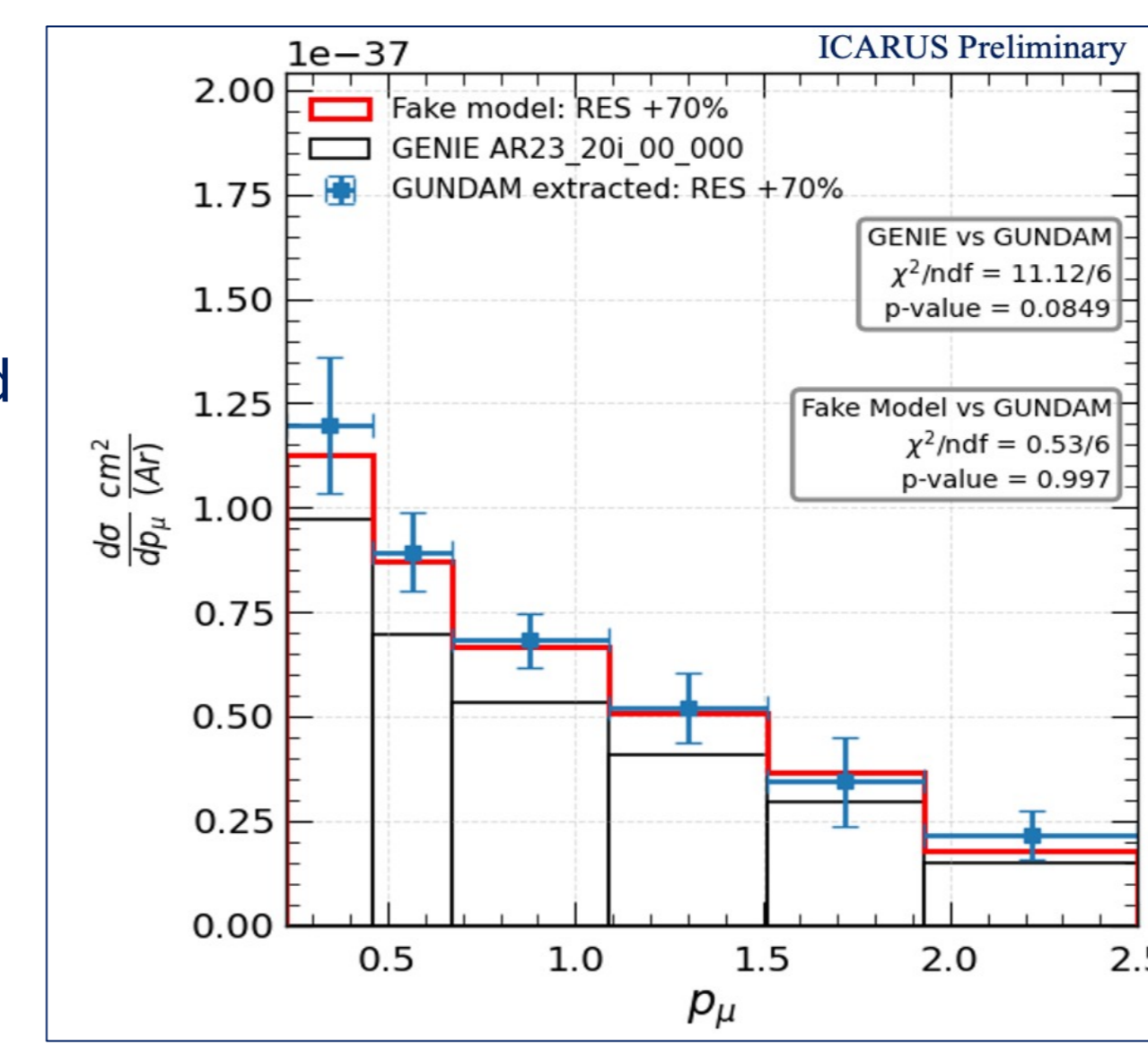
Number of targets (nucleons)

<https://github.com/gundam-organization/gundam>

For extracting cross-section, likelihood based fitting framework GUNDAM is used.

Here MC with 70% enhanced true resonance interactions is used as a mock data.

The p-value calculated against the fake model shows the performance of the fitter.

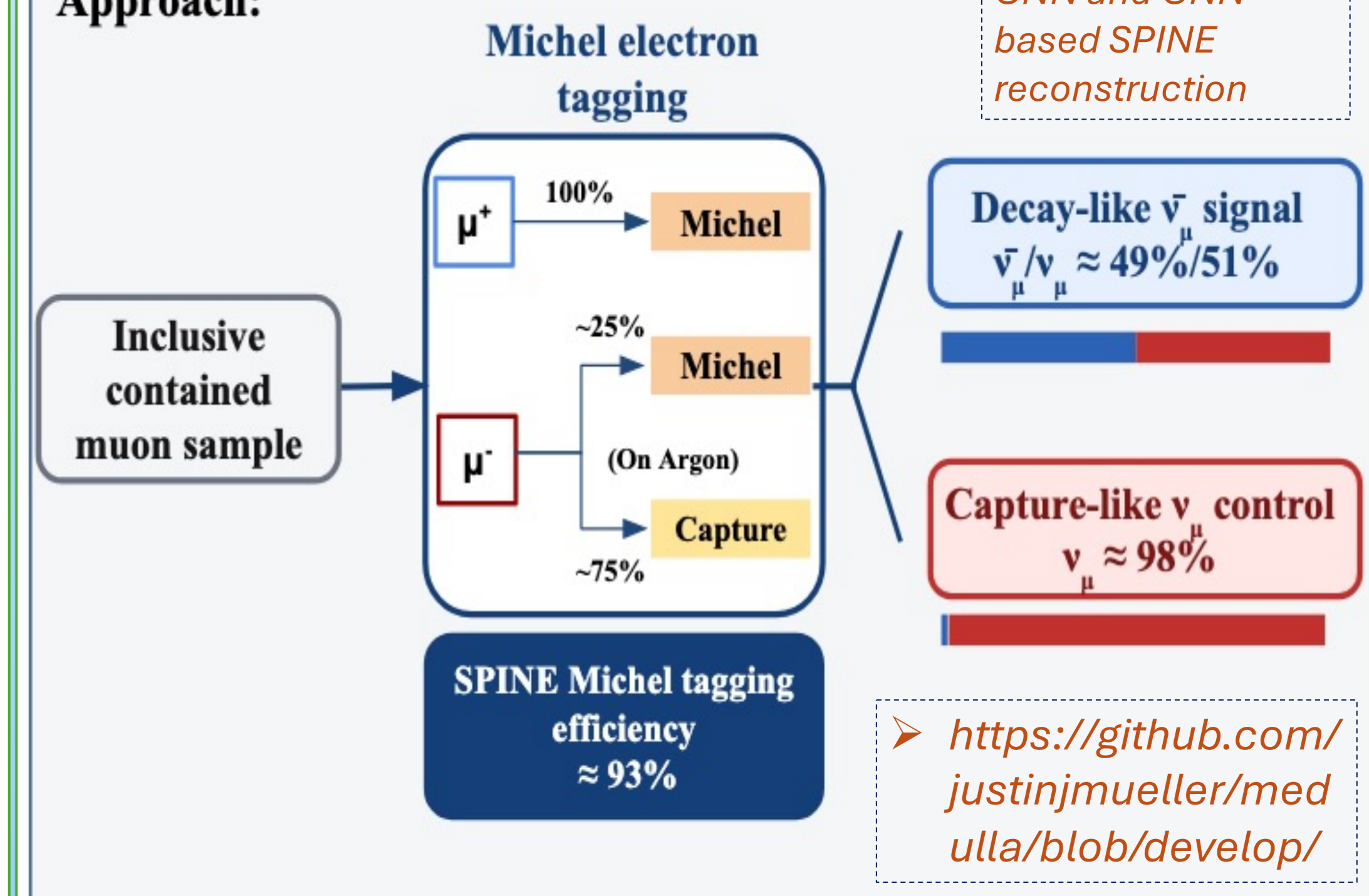


$\bar{\nu}_\mu$ -Ar CC Inclusive Cross Sections

Motivation and challenge:

- DUNE needs accurate $\bar{\nu}_\mu$ -Ar modeling, but sparse $\bar{\nu}_\mu$ -Ar data
- NuMI at ICARUS covers DUNE relevant few GeV energies
- Main challenge: wrong-sign (ν_μ) contamination
- In contained muon sample only 23% anti-neutrinos

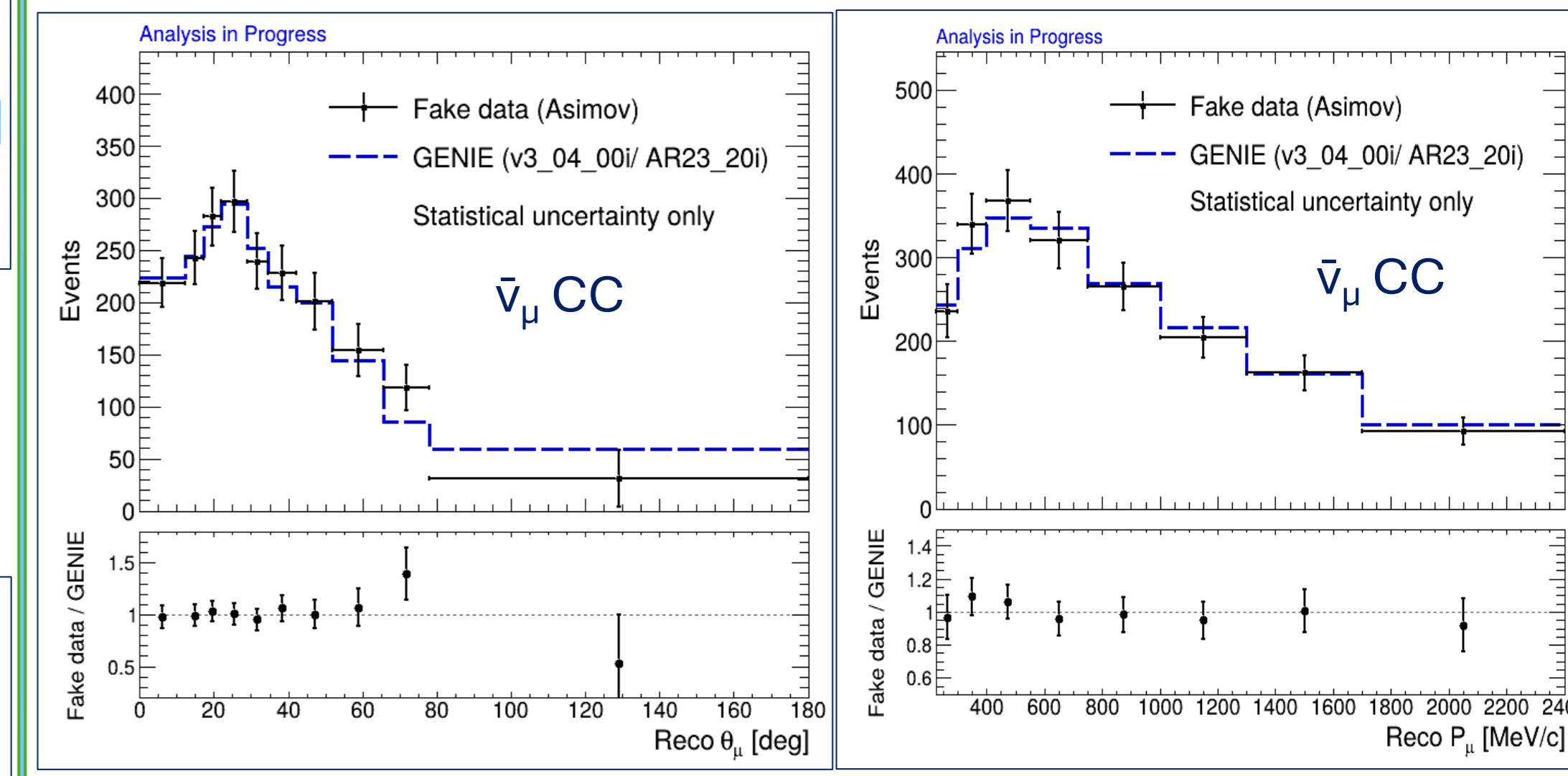
Approach:



Cross-section extraction with mock data

Goal is to extract background constrained $\bar{\nu}_\mu$ -Ar CC inclusive cross sections as a function of muon momentum and muon angle

Asimov studies: MC sample has been used as mock data



Apart from these, there are multiple measurements with ICARUS detector utilizing NuMI beam are going on.

Stay tuned for these exciting measurements !!!!

