

CC1 π Np CROSS-SECTION MEASUREMENT

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Transfer of Status Presentation – 18/06/2026



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THE MICROBOONE EXPERIMENT

Located in the Booster Neutrino Beam (BNB), MicroBooNE's Liquid Argon Time Projection Chamber (LArTPC) technology provides millimetre-scale spatial resolution for detailed reconstruction of complex neutrino final states.

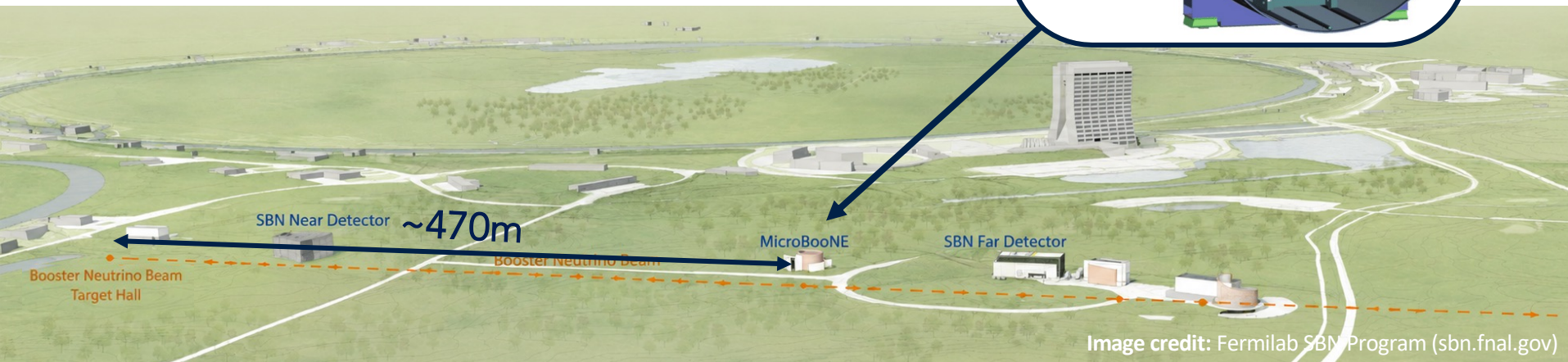
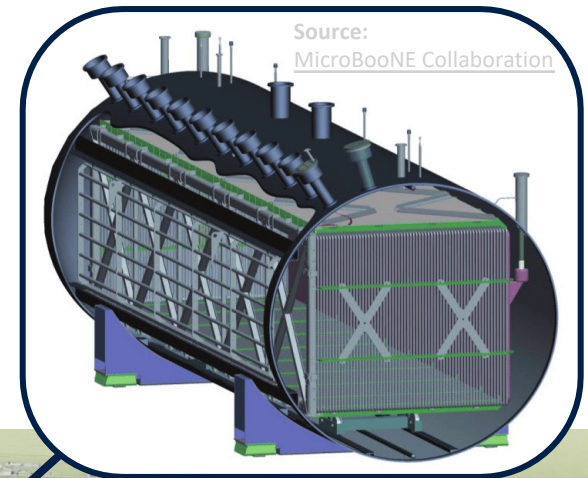
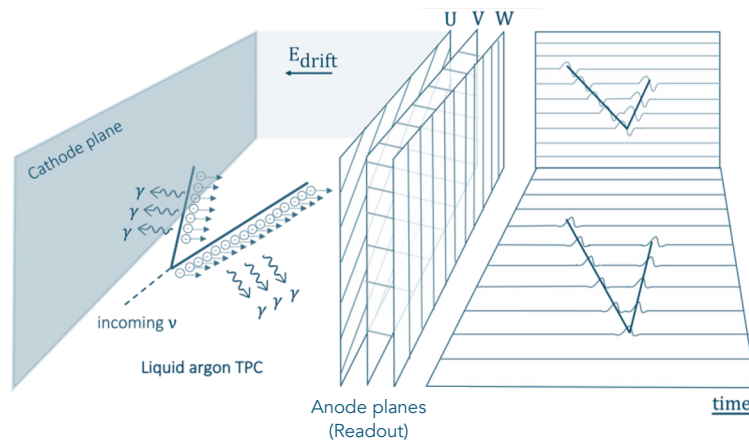


Image credit: Fermilab SBN Program (sbn.fnal.gov)

ANALYSIS MOTIVATION

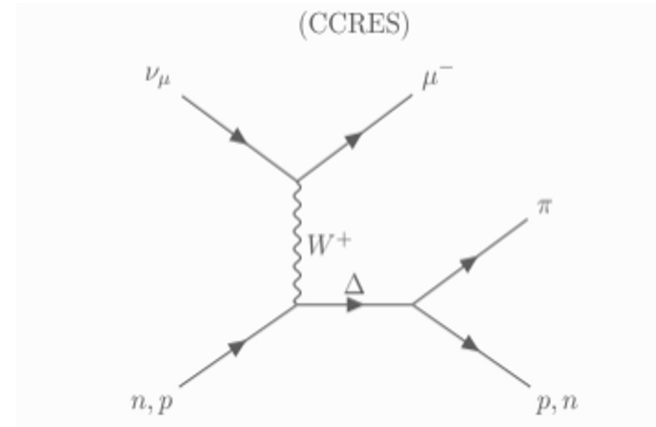
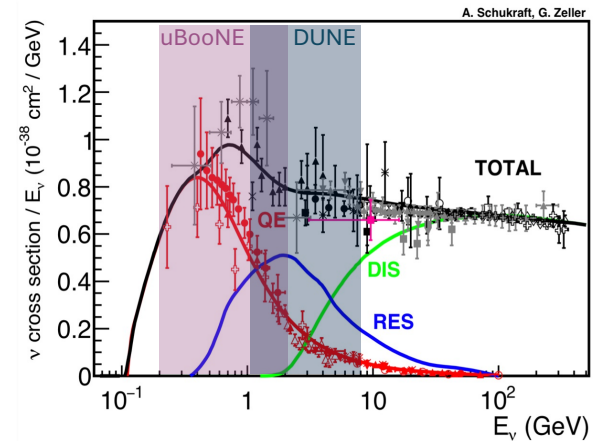
Neutrino oscillation experiments are crucial for determining the neutrino mass ordering, measuring CP violation in the lepton sector, and improving our understanding of physics beyond the Standard Model.

$$N_{\text{obs}} \sim \Phi(E) \times \sigma(E) \times \epsilon(E) \times P(\nu_\alpha \rightarrow \nu_\beta)$$

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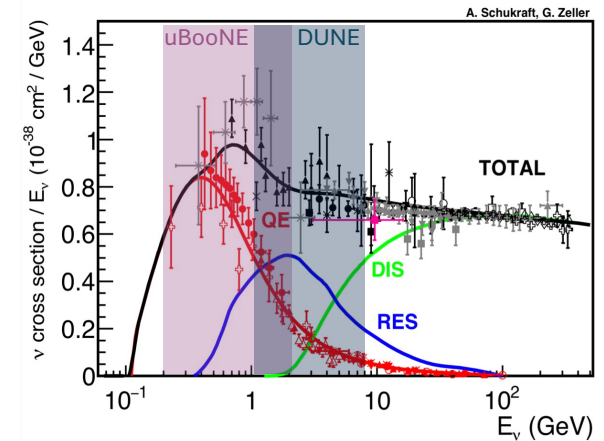
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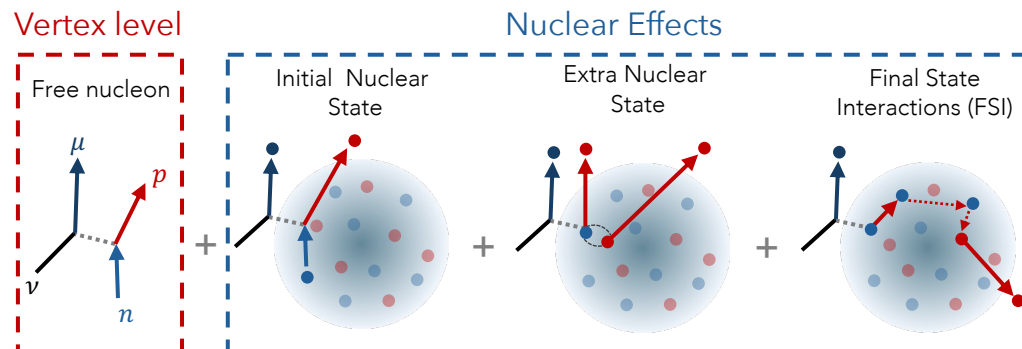
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However, extracting precise neutrino cross sections is challenging because neutrinos interact with nucleons bound inside complex nuclear environments.



CROSS-SECTION EXTRACTION

The diagram illustrates the formula for cross-section extraction, with color-coded labels and arrows pointing to the corresponding terms in the equation:

- Unfolding matrix** (blue text and arrow) points to $U_{a\mu}$.
- Observed Data** (red text and arrow) points to D_a .
- Predicted Background** (yellow text and arrow) points to B_a .
- Flux** (grey text and arrow) points to Φ .
- Number of target nuclei** (grey text and arrow) points to N_{target} .
- Bin width** (grey text and arrow) points to Δx_μ .

$$\left\langle \frac{d^n \sigma}{dx} \right\rangle_\mu = \frac{\sum_a U_{a\mu} (D_a - B_a)}{\Phi N_{\text{target}} \Delta x_\mu}$$

VARIABLES

Kinematic Variables:

- Momentum of muon, pion and leading proton
- $\cos\theta$ of muon, pion and leading proton

Global Kinematic Imbalance (GKI) observables:

- Missing momentum; estimate of the initial struck nucleon momentum.

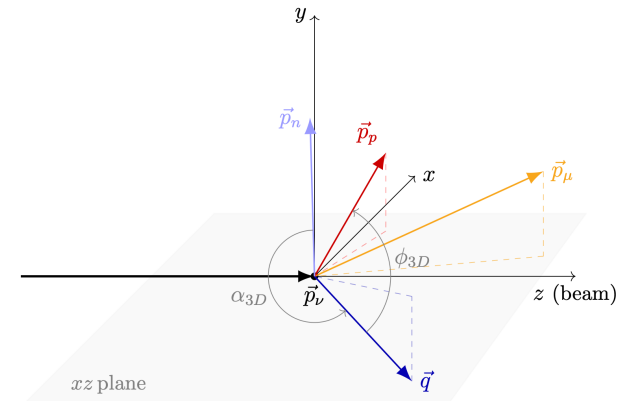
$$p_n = \sqrt{p_L^2 + \delta p_T^2}$$

- Opening angle between the momentum transfer vector $\vec{q}$ and the outgoing proton momentum vector.

$$\phi_{3D} = \cos^{-1} \left(\frac{\vec{q} \cdot \vec{p}_p}{|\vec{q}| |\vec{p}_p|} \right)$$

- Opening angle between the momentum transfer vector $\vec{q}$ and the missing momentum vector $\vec{p}_n$.

$$\alpha_{3D} = \cos^{-1} \left(\frac{\vec{q} \cdot \vec{p}_n}{|\vec{q}| |\vec{p}_n|} \right)$$



SIGNAL DEFINITION

ν_μ CC1 π Np

$$\nu_\mu + A \rightarrow 1\mu^\pm + Np + 1\pi^\pm + X$$

with

- $0.15 \leq p_\mu \leq 1.2 \text{ GeV/c.}$
- $0.3 \leq p_p \leq 0.9 \text{ GeV/c.}$
- $0.1 \leq p_\pi \leq 0.6 \text{ GeV/c.}$
- No π^0 or other mesons.
- Any neutrons can be present in the event.
- Vertex in FV

CC1 π N ρ EVENT SELECTION

1

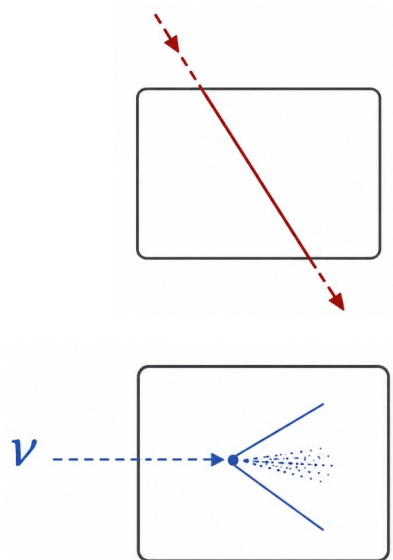
PRESELECTION

2

MUON
CANDIDATE

3

HADRON
CANDIDATES



SIGNAL

SELECTION

BINNING

SYSTEMATICS

DATA-MC

UNFOLDING

RESULTS

CC1 π N ρ EVENT SELECTION

1

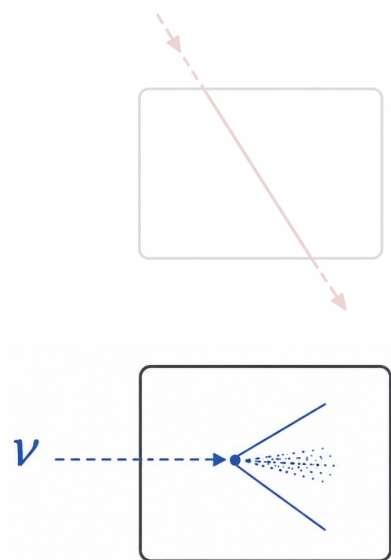
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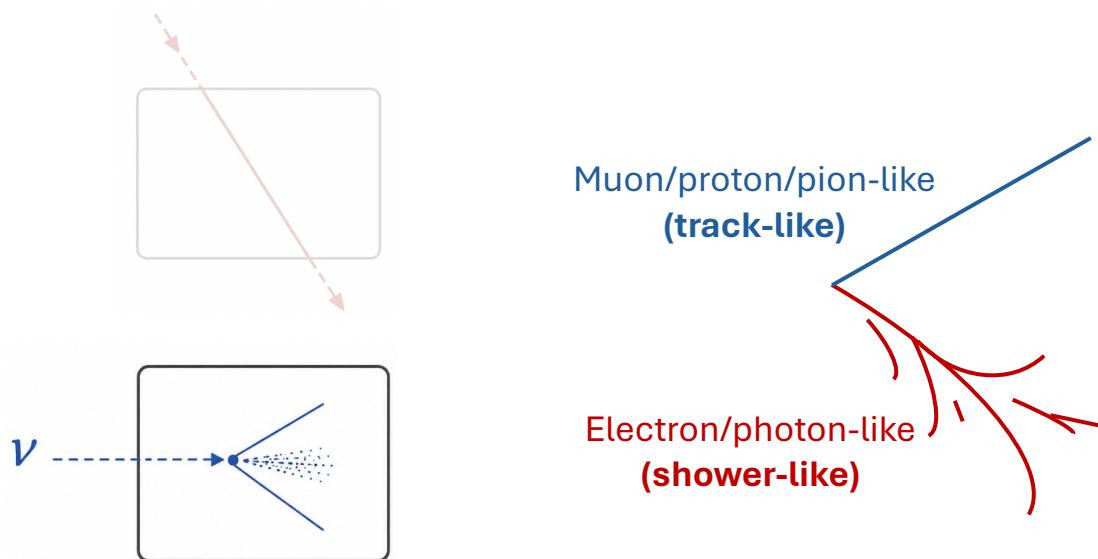
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CC1 π N ρ EVENT SELECTION

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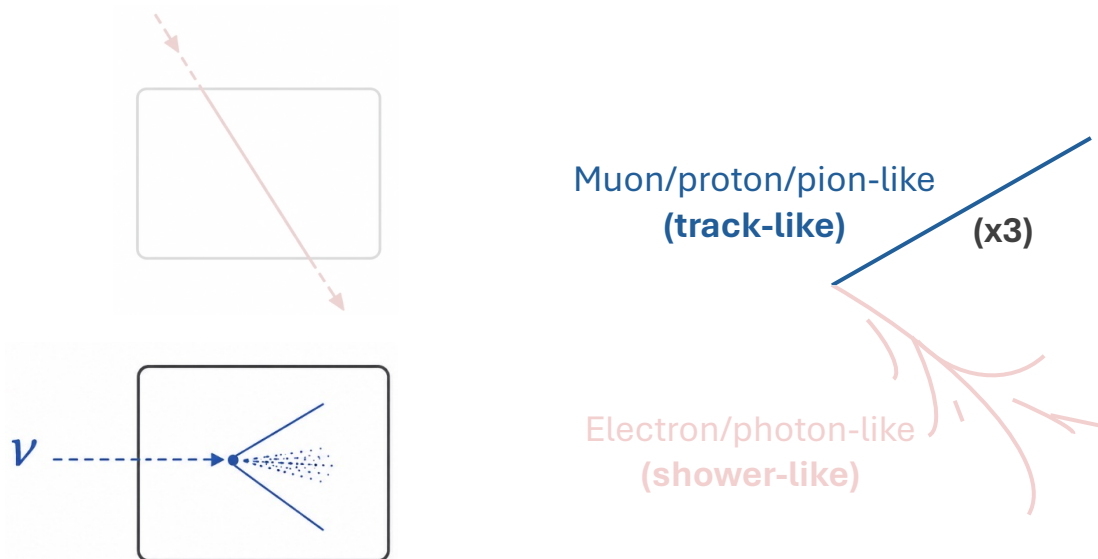
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CC1 π N ρ EVENT SELECTION

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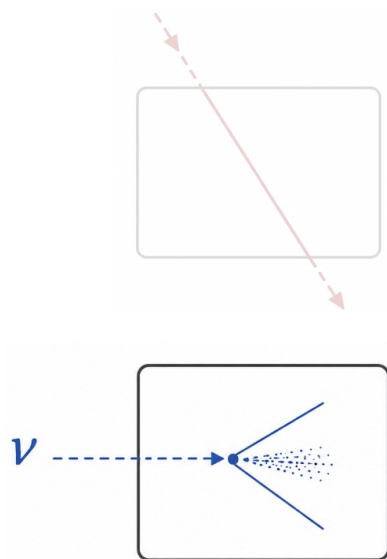
PRESELECTION

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Muon/proton/pion-like
(track-like)

(x3)

Electron/photon-like
(shower-like)

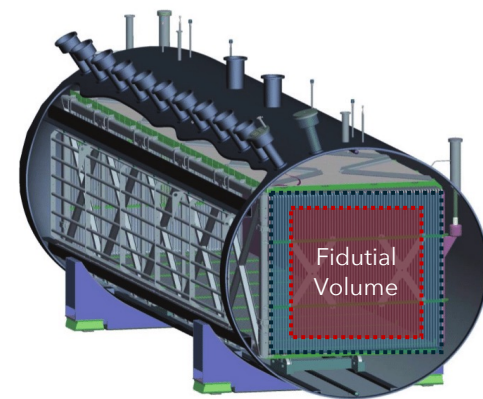


Image edited from: [MicroBooNE Collaboration](#)

SIGNAL

SELECTION

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UNFOLDING

RESULTS

CC1 π Np EVENT SELECTION



- Track length > 10cm
- Particle Identification score > 0.2
- μ momentum quality (25% MCS (Multiple Coulumb Scattering) vs range agreement)
- If multiple → track with highest PID score

CC1 π Np EVENT SELECTION

1

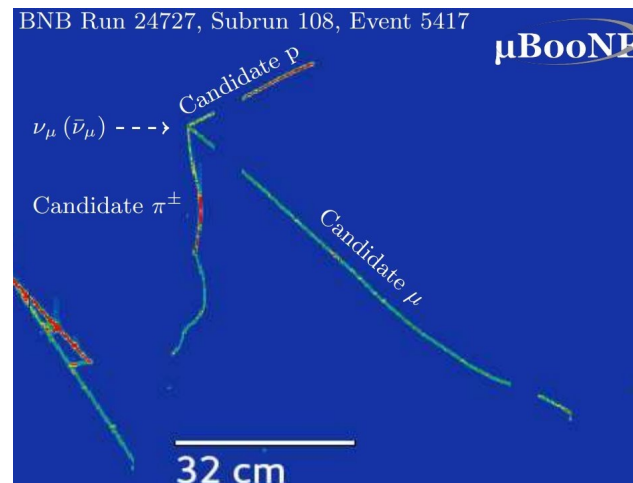
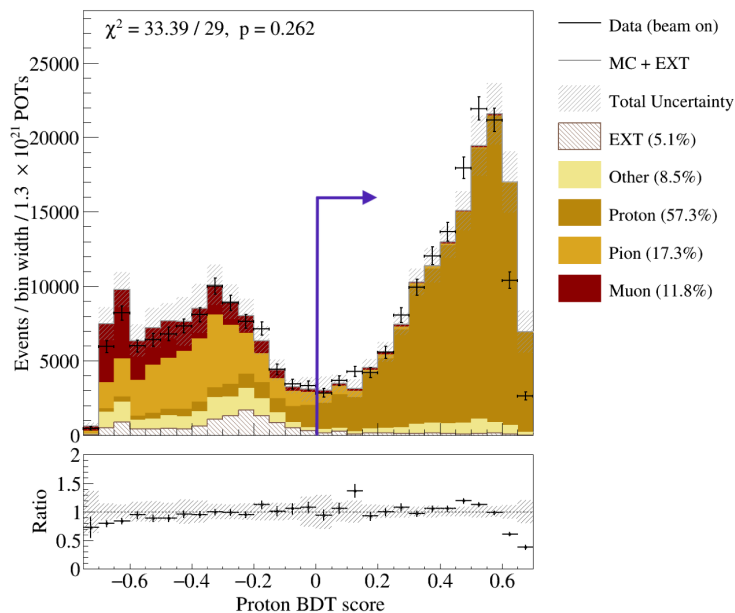
PRESELECTION

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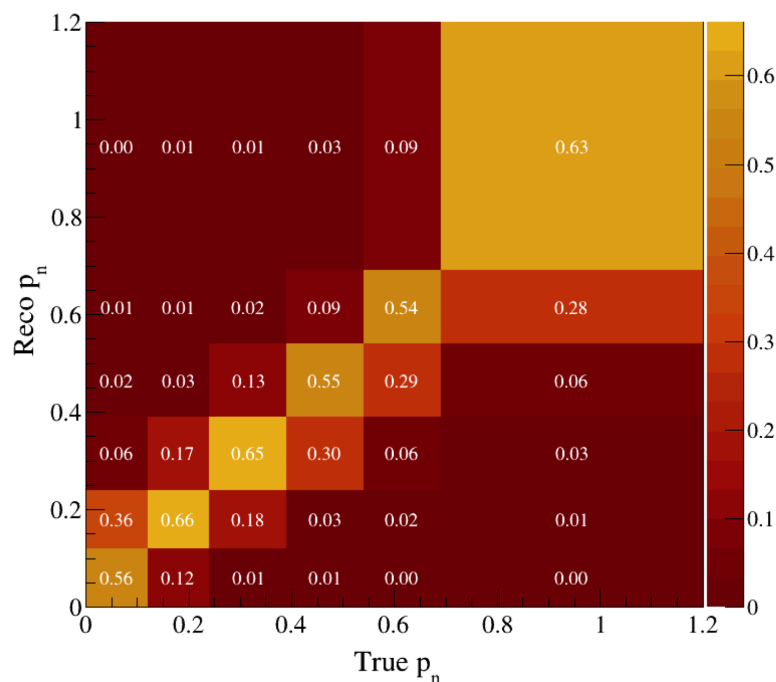
RESULTS

DETECTOR RESPONSE & BINNING

Response matrix R_{ij} : Probability that an event in true bin j is reconstructed in bin i .

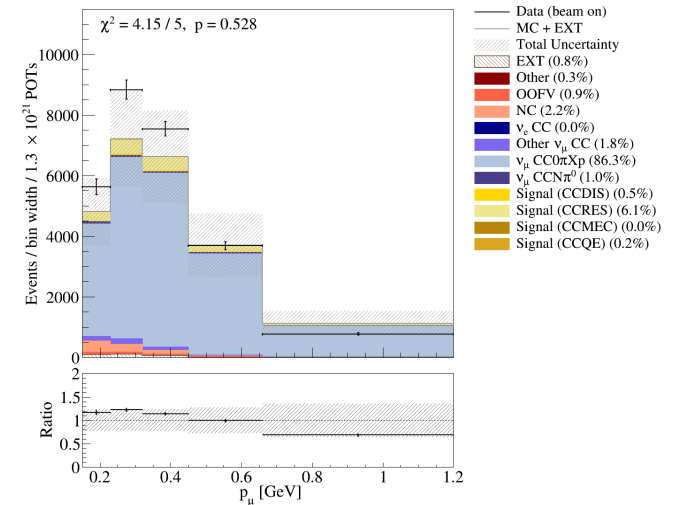
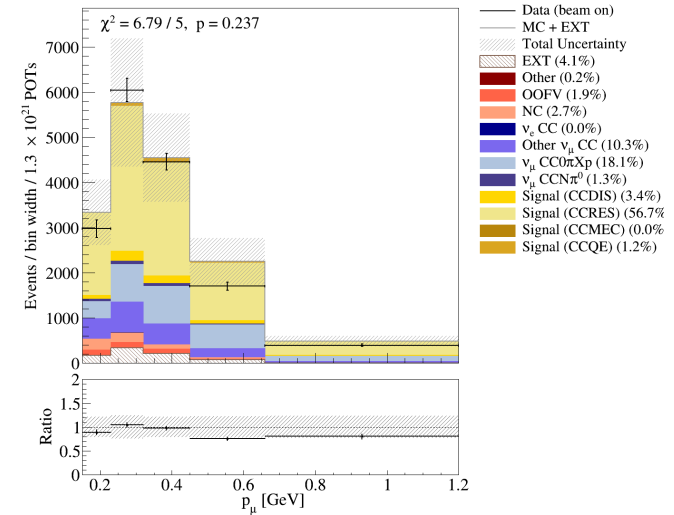
Binning:

- Diagonal entries above 50%.
- >40 events in reco bin.



DATA-MC COMPARISON

	MC CV [χ^2 /NDF]	
	CC1piNp	Sideband
p_μ	6.79/5	4.15/5
$\cos\theta_\mu$	5.57/6	11.54/6
p_π	1.06/4	0.85/4
$\cos\theta_\pi$	2.25/7	8.21/7
$p_{\text{lead } p}$	2.16/6	5.71/6
$\cos\theta_{\text{lead } p}$	2.00/6	3.60/6
p_n	10.35/6	4.32/6
α_{3D}	6.04/6	8.95/6
ϕ_{3D}	4.97/5	1.39/5
Total	0.17/1	0.03/1



Included in the backup

SIGNAL

SELECTION

BINNING

SYSTEMATICS

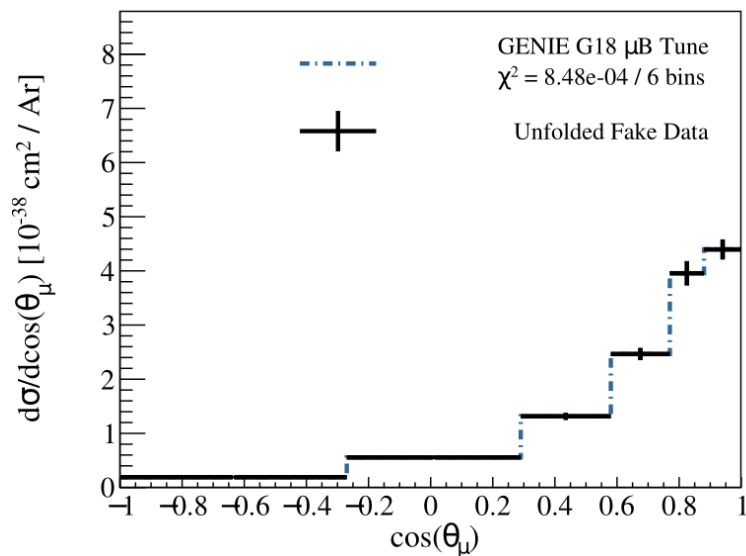
DATA-MC

UNFOLDING

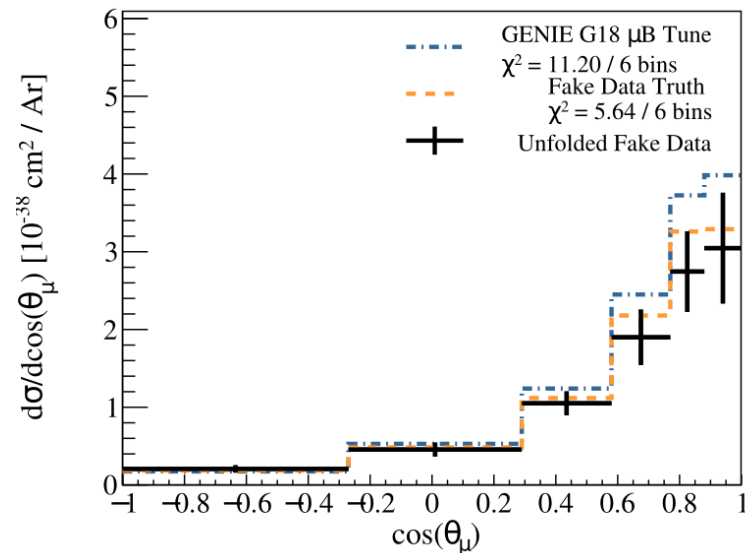
RESULTS

UNFOLDING TESTS

CLOSURE TEST

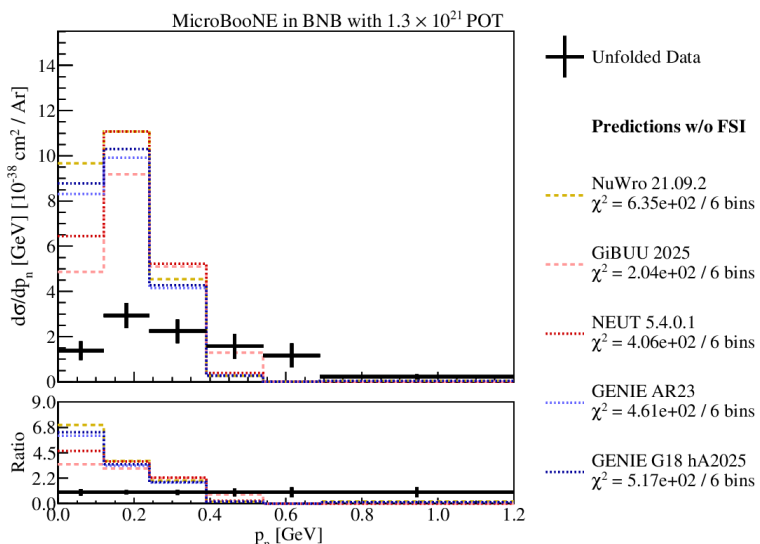


FAKE-DATA TEST

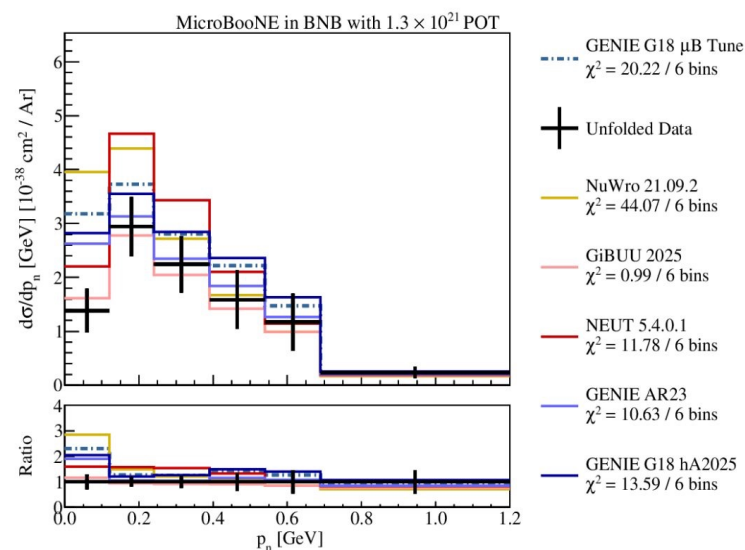


UNBLINDED RESULTS

PREDICTION W/O FSI



PREDICTION W/ FSI



Final results are under collaboration review. **Stay tuned for the upcoming publication!**

CONCLUSION

Completed the full MicroBooNE dataset **CC1 π Np analysis**, reporting the flux-average cross-section as a function of the kinematic and GKI variables.

OTHER ONGOING PROJECTS



DUNE:

- Reconstruction algorithms implementations for reconstruction in the ND-GAr ECAL.
- Implementation of ML techniques to make PID based on cluster information.
- Evaluation of different segmentation geometries and materials of the ECAL layers.

SBND:

- First look into the parameter space covered by GENIE in SBND in order to start a forward-folding framework as an alternative to current unfolding methods.

Thank you!

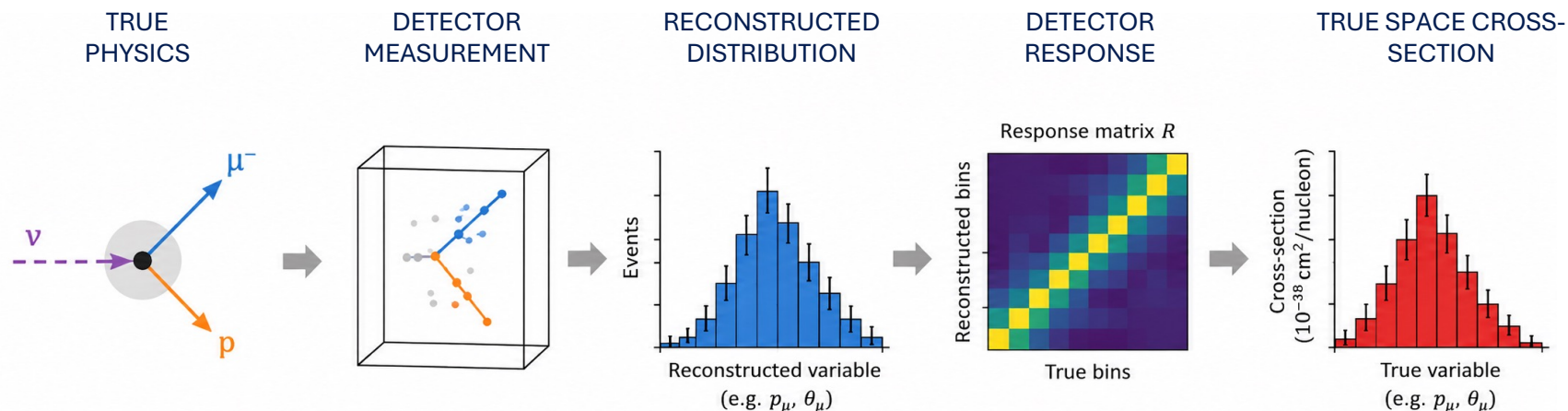
BACKUP SLIDES



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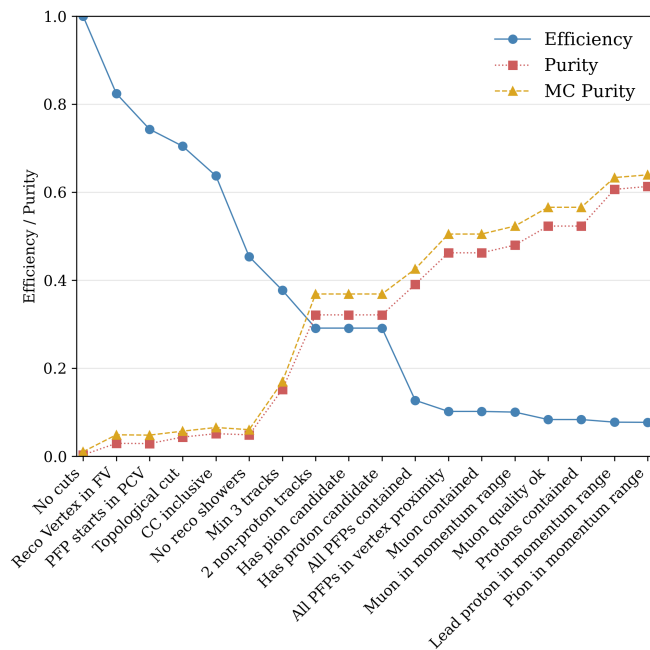
BACKGROUND

HOW TO MEASURE A CROSS-SECTION



SIGNAL & SELECTION SUMMARY

Selection Stage	N_{sig}	N_{all}	N_{MC}	Efficiency (%)	Purity (%)
No cuts	16756	5254662	1595582	100.02	0.32
Reco Vertex in FV	13810	467787	282114	82.43	2.95
PFP starts in PCV	12452	428867	258169	74.33	2.90
Topological cut	11803	269247	206167	70.45	4.38
CC inclusive	10674	207193	162864	63.71	5.15
No reco showers	7601	155446	125380	45.37	4.89
Min 3 tracks	6321	41553	37296	37.73	15.21
2 non-proton tracks	4881	15187	13233	29.14	32.14
Has pion candidate	4881	15187	13233	29.14	32.14
Has proton candidate	4881	15187	13233	29.14	32.14
All PFPs contained	2133	5460	5011	12.73	39.07
All PFPs in vertex proximity	1710	3698	3386	10.21	46.24
Muon contained	1710	3698	3386	10.21	46.24
Muon in momentum range	1684	3509	3219	10.05	47.99
Muon quality ok	1401	2678	2476	8.36	52.32
Protons contained	1401	2678	2476	8.36	52.32
Lead proton in momentum range	1301	2145	2054	7.77	60.65
Pion in momentum range	1295	2112	2025	7.73	61.32



CC1 π Np EVENT SELECTION

1

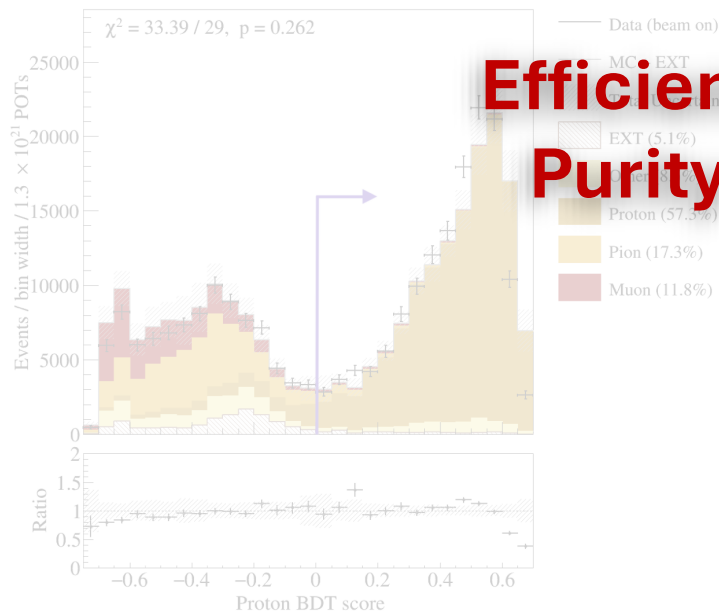
PRESELECTION

2

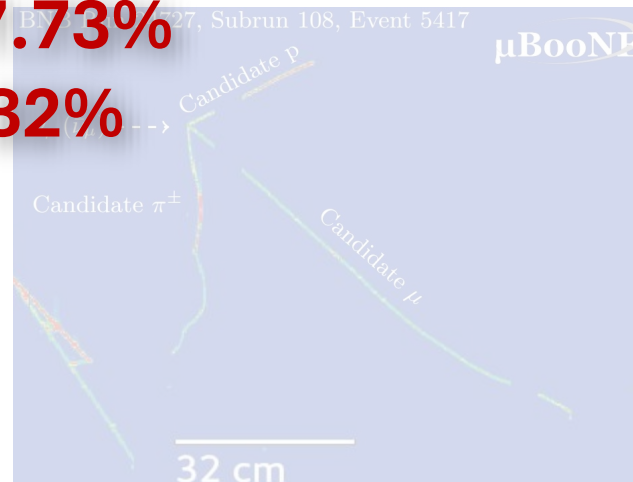
MUON
CANDIDATE

3

HADRON
CANDIDATES



Efficiency: 7.73%
Purity: 61.32%



SIGNAL

SELECTION

BINNING

SYSTEMATICS

DATA-MC

UNFOLDING

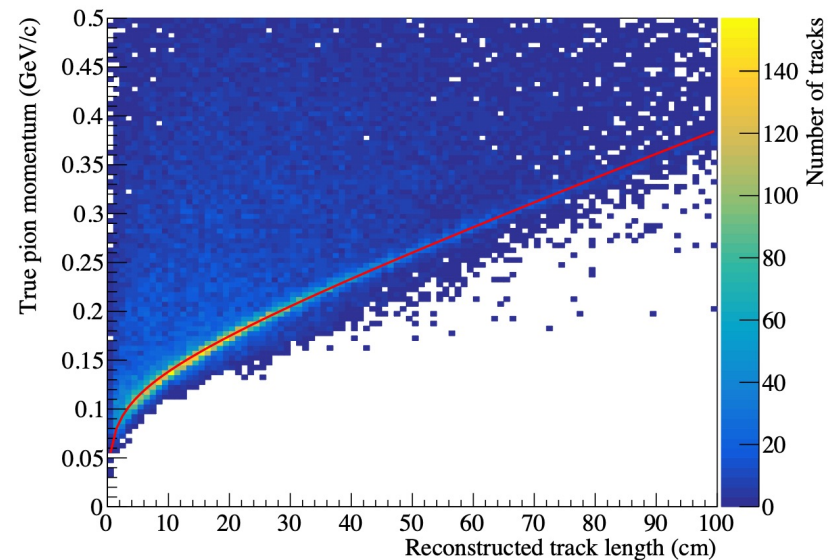
RESULTS

PION MOMENTUM RECO

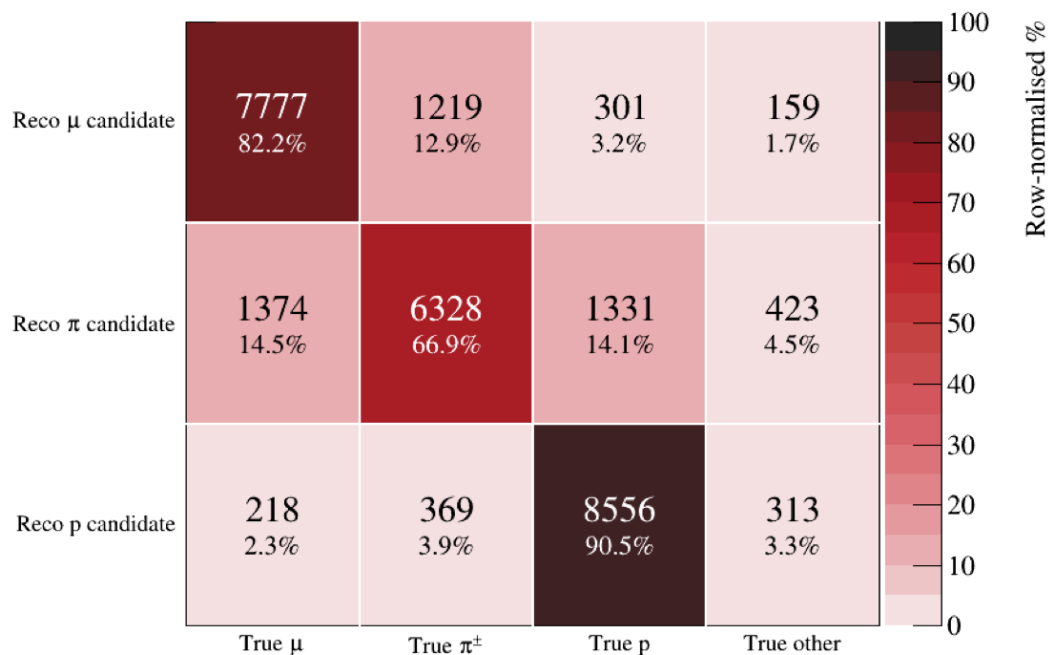
Fit to the true momentum of simulated charged pions as a function of the reconstructed track length of their best-matched reconstructed track.

$$p_{\pi} = A + BL - CL^{-D}$$

$A = 1.6353$, $B = 0.0022385$, $C = 1.5668$, $D = 0.013327$.



PARTICLE CONFUSION MATRIX



BINNING DEFINITION

The binning definition have been defined by ensuring that the diagonal entries of the detector response matrix were above 50% and ensuring enough statistic (>40 events in reco bins).

Kinematic Variables:

$p_\mu : \{0.15, 0.23, 0.32, 0.45, 0.66, 1.20\} \text{ GeV/c}$

$p_\pi : \{0.10, 0.16, 0.19, 0.22, 0.60\} \text{ GeV/c}$

$p_{\text{lead } p} : \{0.30, 0.38, 0.49, 0.57, 0.63, 0.70, 0.90\} \text{ GeV/c}$

$\cos \theta_\mu : \{-1.00, -0.27, 0.29, 0.58, 0.77, 0.88, 1.00\}$

$\cos \theta_\pi : \{-1.00, -0.70, -0.47, -0.25, 0, 0.39, 0.65, 1.00\}$

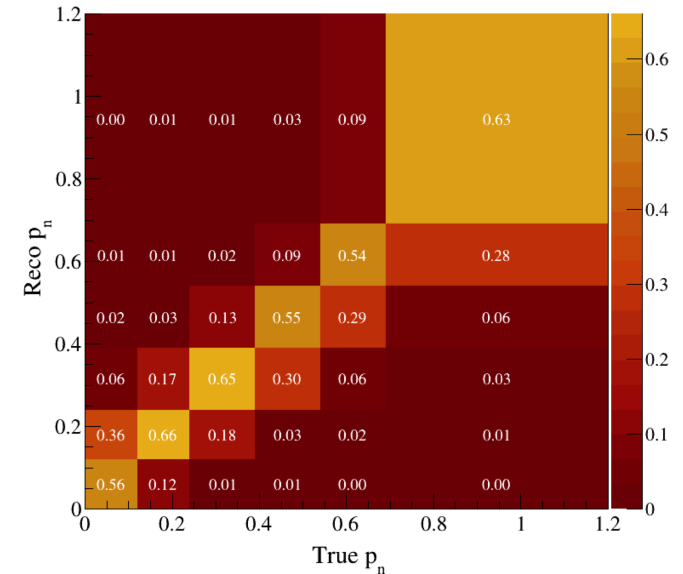
$\cos \theta_{\text{lead } p} : \{-1.00, -0.34, 0.07, 0.39, 0.65, 0.84, 1.00\}$

GKI observables:

$p_n : \{0.00, 0.12, 0.24, 0.39, 0.54, 0.69, \infty\} \text{ GeV/c}$

$\alpha_{3D} : \{0, 62, 98, 122, 140, 160, 180\}^\circ$

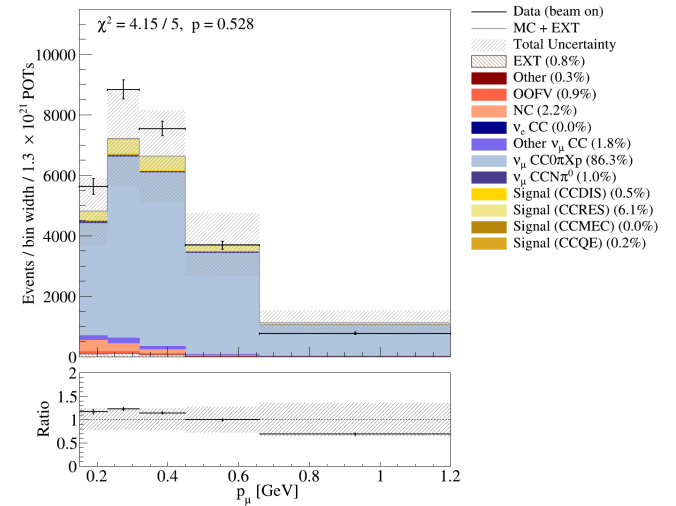
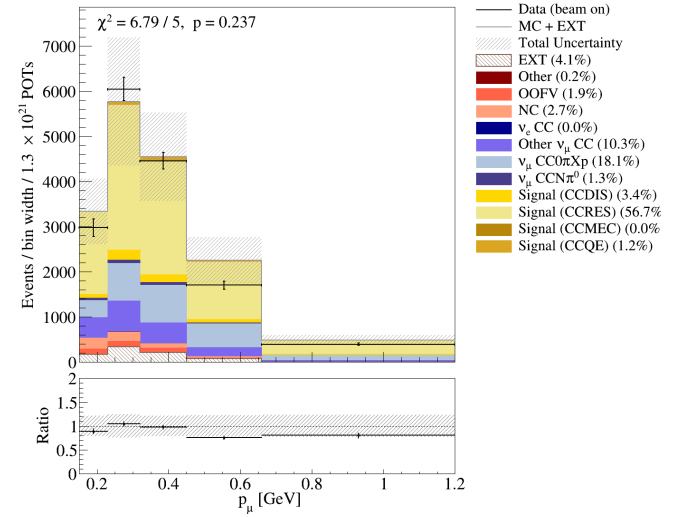
$\phi_{3D} : \{0, 15, 35, 55, 90, 180\}^\circ$



DATA-MC COMPARISON

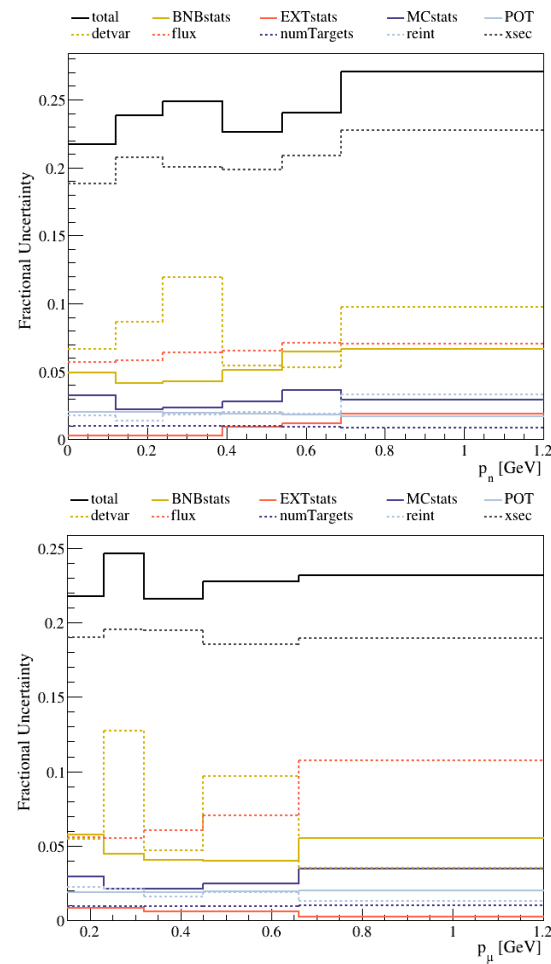
Distributions for the remaining variables are included in the backup

	MC CV [χ^2/NDF]	
	CC1piNp	Sideband
p_μ	6.79/5	4.15/5
$\cos\theta_\mu$	5.57/6	11.54/6
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SYSTEMATICS

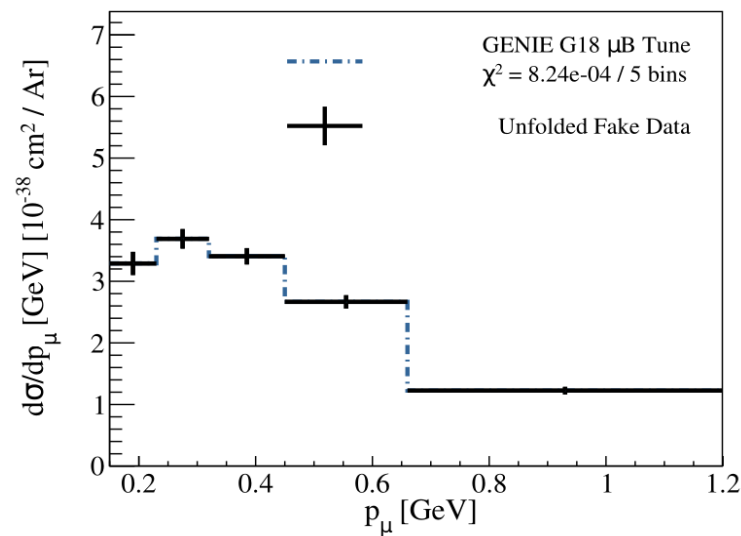
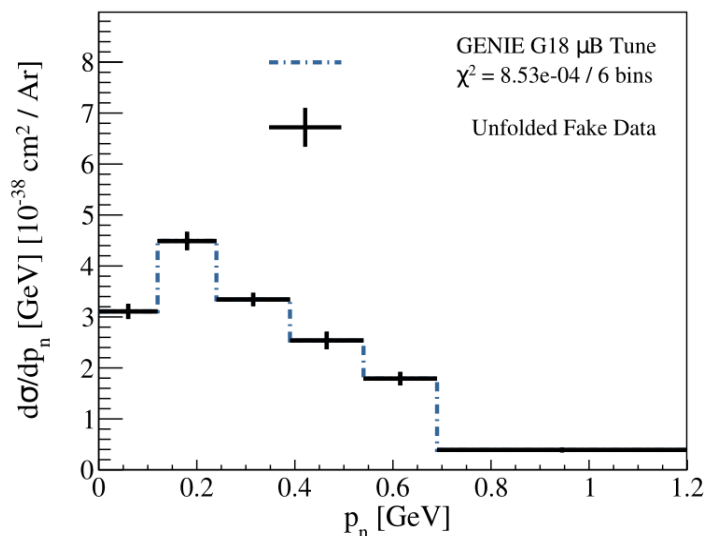
Source	Fractional Uncertainty [%]
Xsec modelling	18.8
Detector variations	6.34
Flux	6.21
BNB stats	2.07
POT normalisation	1.91
Hadron reinteraction	1.83
MC stats	1.12
Number of targets	0.96
EXT stats	0.32
Total	21.15



UNFOLDING TESTS

CLOSURE TEST

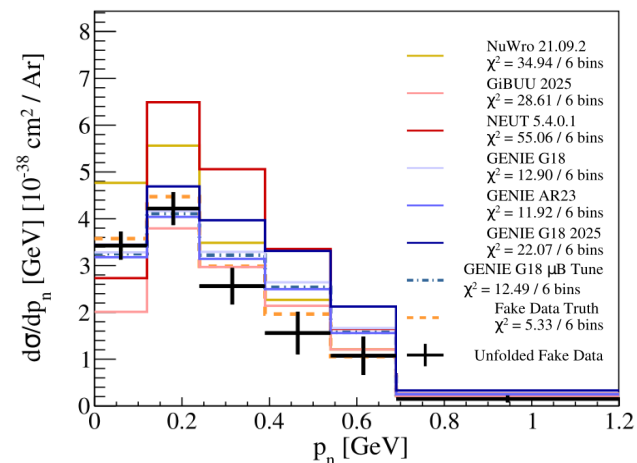
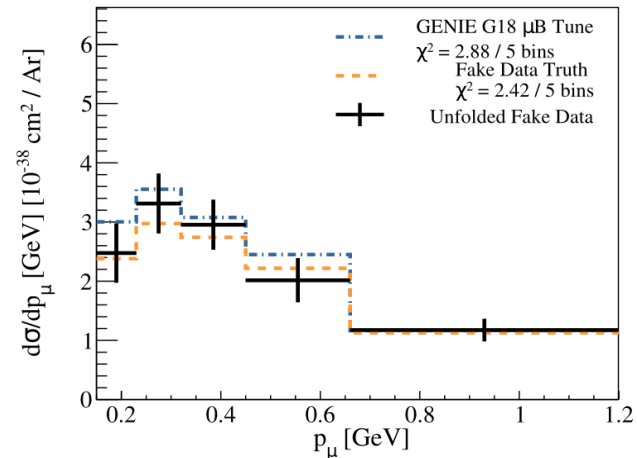
All the variables used for the flux-average differential cross-sections were shown to close (χ^2/NDF of order 10^{-4}). The unfolding is performed using Wiener-SVD with first-derivative regularisation.



UNFOLDING TESTS

FAKE DATA

	χ^2/NDF	
	GENIE CV	FAKE DATA
p_μ	2.88/5	2.4/5
$\cos\theta_\mu$	11.20/6	5.64/6
p_π	2.01/4	0.97/4
$\cos\theta_\pi$	6.87/7	4.62/7
$p_{\text{lead } p}$	2.69/6	2.51/6
$\cos\theta_{\text{lead } p}$	5.37/6	3.25/5
p_n	12.48/6	5.39/6
α_{3D}	17.41/6	4.82/6
ϕ_{3D}	9.91/5	3.23/5
Total	0.67	7.36e-5



BACKUP SLIDES

BACKGROUND THEORY



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ν -NUCLEUS CROSS-SECTION

DOMINANT INTERACTION CHANNELS

ENERGY

QUASIELASTIC (QE)

MECHANISM

Neutrino elastically scatters off an entire nucleon. The target nucleon changes flavor (e.g., n to p).

OUTCOME

The nucleon is ejected intact alongside a charged lepton. No new particles (such as pions) are produced.

RESONANCE (RES)

MECHANISM

Neutrino excites the target nucleon into a higher-mass resonant state, such as the $\Delta(1232)$ resonance.

OUTCOME

The unstable resonance rapidly decays, emitting a nucleon and one or more mesons (mostly pions).

SHALLOW/DEEP INELASTIC SCATTERING

MECHANISM

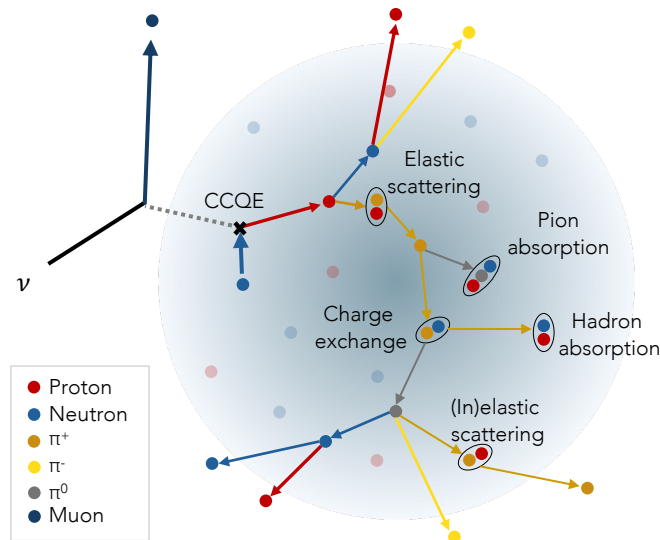
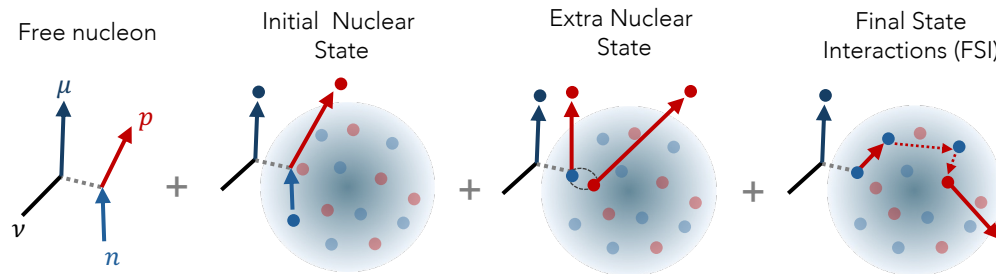
Neutrino resolves and scatters directly off the individual quarks (partons) deep inside the nucleon.

OUTCOME

The nucleon shatters into a hadronic shower. SIS is the messy transition region mixing multiple states.

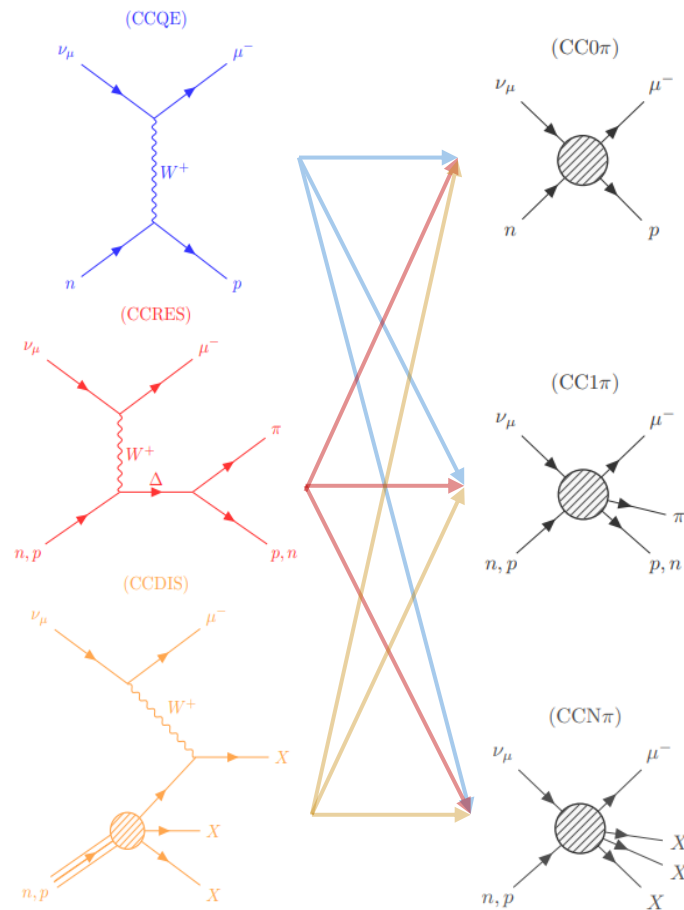
ν -NUCLEUS CROSS-SECTION

WHY DO WE TALK ABOUT TOPOLOGIES?



ν -NUCLEUS CROSS-SECTION

WHY DO WE TALK ABOUT TOPOLOGIES?



ν -NUCLEUS XSEC FORMALISM

THEORY LANDSCAPE: FOUNDATIONAL AND USED APPROACHES

FERMI GAS RELATED APPROACHES

Fermi Gas Models built on the Local Density Approximation (LDA).

Nucleus treated locally uniform nuclear matter characterised by position-dependent proton and neutron densities $\rho_{p,n}(r)$.

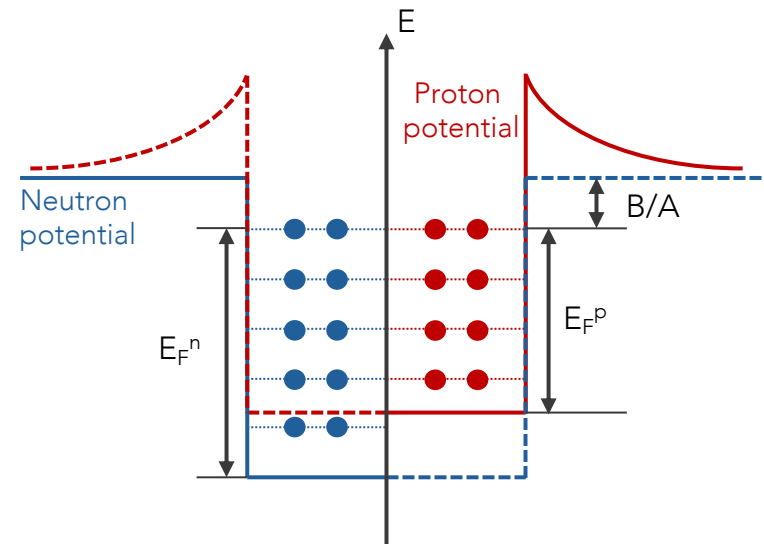
The ground state momentum distribution is described by a step function $\Theta(p_F - p)$. The Fermi momentum is directly related to the local nuclear density though:

$$p_F(r) = \hbar[3\pi^2\rho(r)]^{1/3}$$

The nuclear momentum distribution in the ground state is then approximated by,

$$n(\vec{p}, r) = \Theta(p_F(r) - |\vec{p}|)$$

Lacks fine grained shell structure required on exclusive reaction, extensions are included: incorporation of Random Phase Approximation (RPA)



ν -NUCLEUS XSEC FORMALISM

THEORY LANDSCAPE: FOUNDATIONAL AND USED APPROACHES

MEAN-FIELD APPROACHES

Hartree-Fock (HF) Approximation

Start from the many-body nuclear Hamiltonian:

$$H = \sum_i H^{[1]}(i) + \sum_{i < j} v(i, j)$$

Introduce an average **mean-field potential** $U(i)$:

$$H^{[1]}(i) = T(i) + U(i)$$

- Nucleons move independently in the average field generated by all other nucleons.
- Ground state represented by a **Slater determinant** of occupied single-particle states.
- Excitations are built from **particle-hole (1p-1h)** configurations, with higher-order states (2p-2h, 3p-3h, ...) constructed similarly.

Random Phase Approximation (RPA)

- Extends HF by including correlations between particle-hole excitations.
- Equivalent to an infinite summation of **ring diagrams**.
- Describes collective nuclear modes such as **giant resonances**.
- **CRPA** (Continuum RPA) further includes coupling to unbound continuum states.

ν -NUCLEUS XSEC FORMALISM

THEORY LANDSCAPE: FOUNDATIONAL AND USED APPROACHES

MEAN-FIELD APPROACHES

A **Slater determinant** is a mathematical way of constructing the wavefunction of a system of identical fermions (such as nucleons or electrons) while automatically satisfying the Pauli exclusion principle.

Definition

For A nucleons occupying single-particle states $\phi_1, \phi_2, \dots, \phi_A$, the many-body wavefunction is

$$\Psi(x_1, \dots, x_A) = \frac{1}{\sqrt{A!}} \begin{vmatrix} \phi_1(x_1) & \phi_2(x_1) & \cdots & \phi_A(x_1) \\ \phi_1(x_2) & \phi_2(x_2) & \cdots & \phi_A(x_2) \\ \vdots & \vdots & \ddots & \vdots \\ \phi_1(x_A) & \phi_2(x_A) & \cdots & \phi_A(x_A) \end{vmatrix}$$

where x includes position, spin, and other quantum numbers.

Fermions must obey:

$$\Psi(\dots, i, \dots, j, \dots) = -\Psi(\dots, j, \dots, i, \dots)$$

That is, exchanging two identical fermions changes the sign of the wavefunction.

A determinant automatically has this property because swapping two rows changes the sign of the determinant.

GKI CALCULATIONS

The calculation lives in the GKITools.cxx class within the xsec analyzer

Longitudinal momentum imbalance

$$p_L = p_{\mu,z} + p_{p,z}^{\text{lead}} + p_{\pi,z} - E_{\text{cal}}$$

Measures the momentum imbalance along the neutrino beam direction.

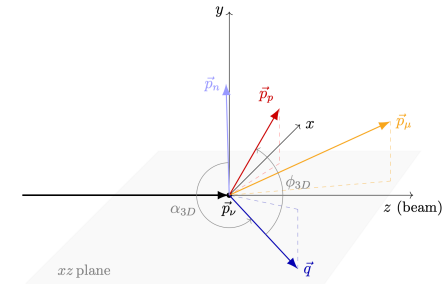
Transverse momentum imbalance

$$\delta \vec{p}_T = \vec{p}_{\mu,T} + \vec{p}_{p,T}^{\text{lead}} + \vec{p}_{\pi,T}$$

Represents the imbalance of reconstructed transverse momentum in the final state.

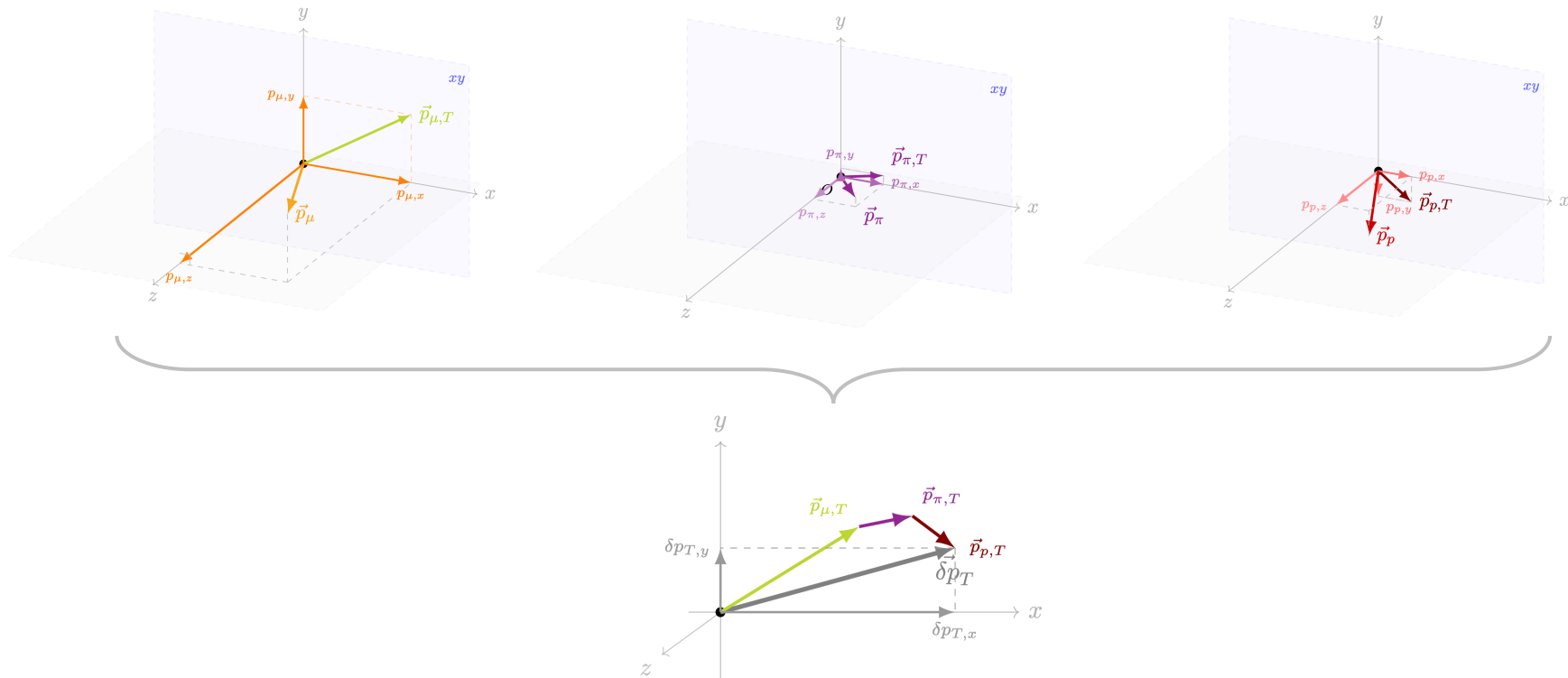
GKI CALCULATIONS

$$p_n = \delta \vec{p}_T + p_L$$



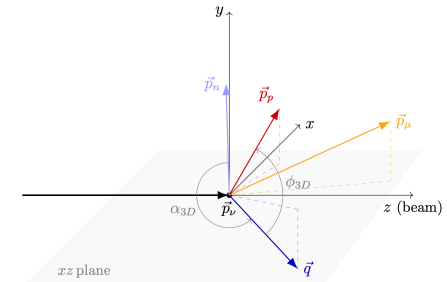
Transverse momentum imbalance: Represents the imbalance of reconstructed transverse momentum in the final state.

$$\delta \vec{p}_T = \vec{p}_{\mu,T} + \vec{p}_{p,T}^{\text{lead}} + \vec{p}_{\pi,T}$$



GKI CALCULATIONS

$$p_n = \delta \vec{p}_T + p_L$$



Longitudinal momentum imbalance: Measures the momentum imbalance along the neutrino beam direction.

$$p_L = p_{\mu,z} + p_{p,z}^{\text{lead}} + p_{\pi,z} - E_{\text{cal}}$$

Calorimetric neutrino energy

$$E_{\text{cal}} = E_{\mu} + T_p^{\text{lead}} + E_{\pi} + E_{\text{exc}}$$

Diagram illustrating the components of the calorimetric neutrino energy equation:

- Total muon energy (points to E_{μ})
- kinetic energy of the leading proton (points to T_p^{lead})
- Total pion energy (points to E_{π})
- Argon excitation energy (30.9 MeV) (points to E_{exc})

The neutrino momentum is assumed to be aligned with the beam direction:

$$\vec{p}_\nu = (0, 0, E_{\text{cal}}, E_{\text{cal}})$$

The momentum transfer vector is defined as: $\vec{q} = \vec{p}_\nu - \vec{p}_\mu$

BACKUP SLIDES

ADDITIONS TO THE ANALYSIS



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REWEIGHTED GENIE

Mohamed's studies
([MicroBooNE-doc-45583-v1](#))

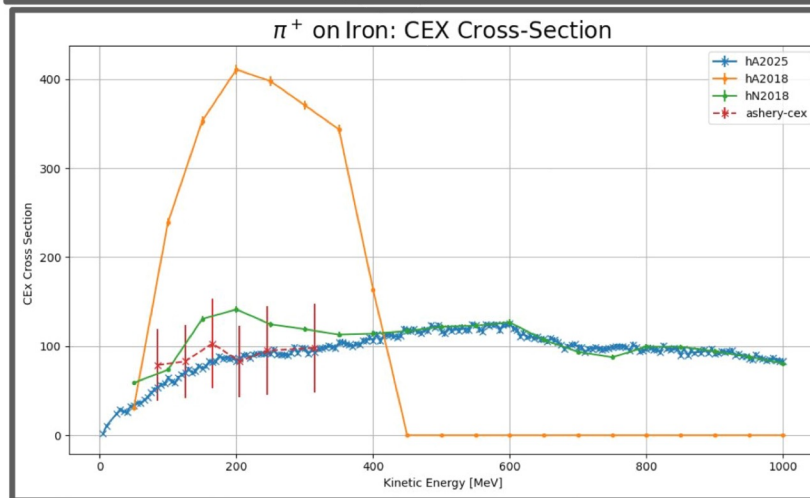
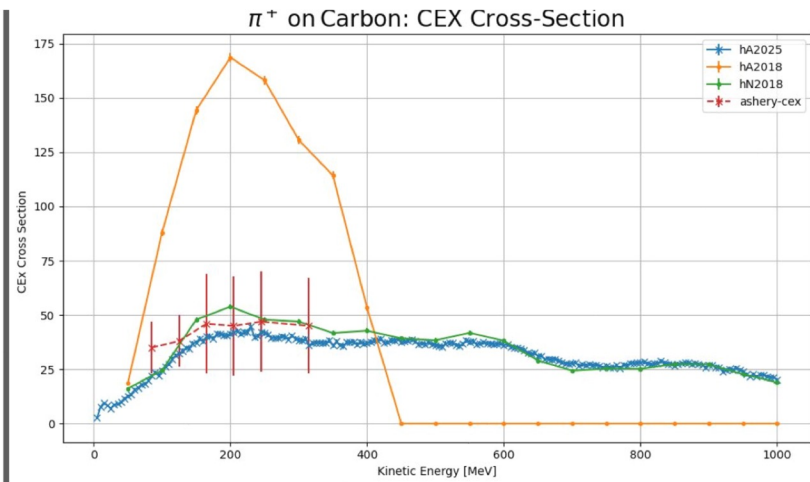
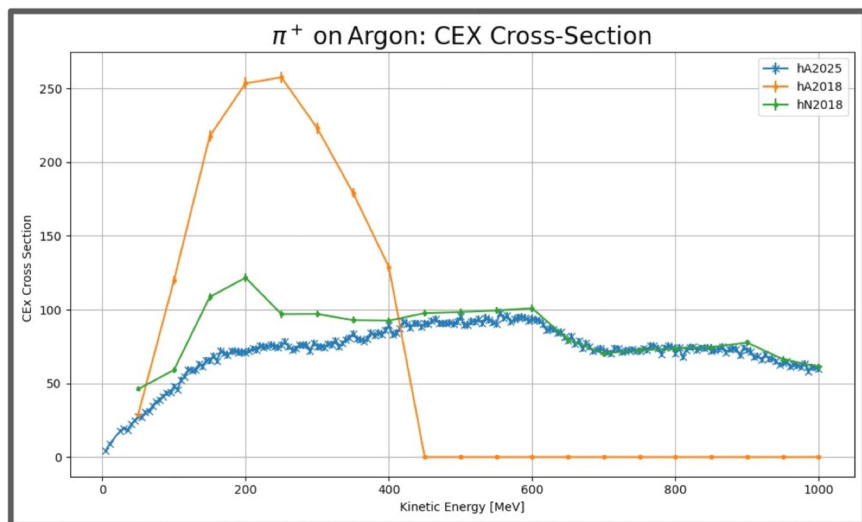
Validation: CEX (π^+ A)

Red: data (also uboone fix)

Orange: hA2018 (bug)

Blue: final fix (hA2025)

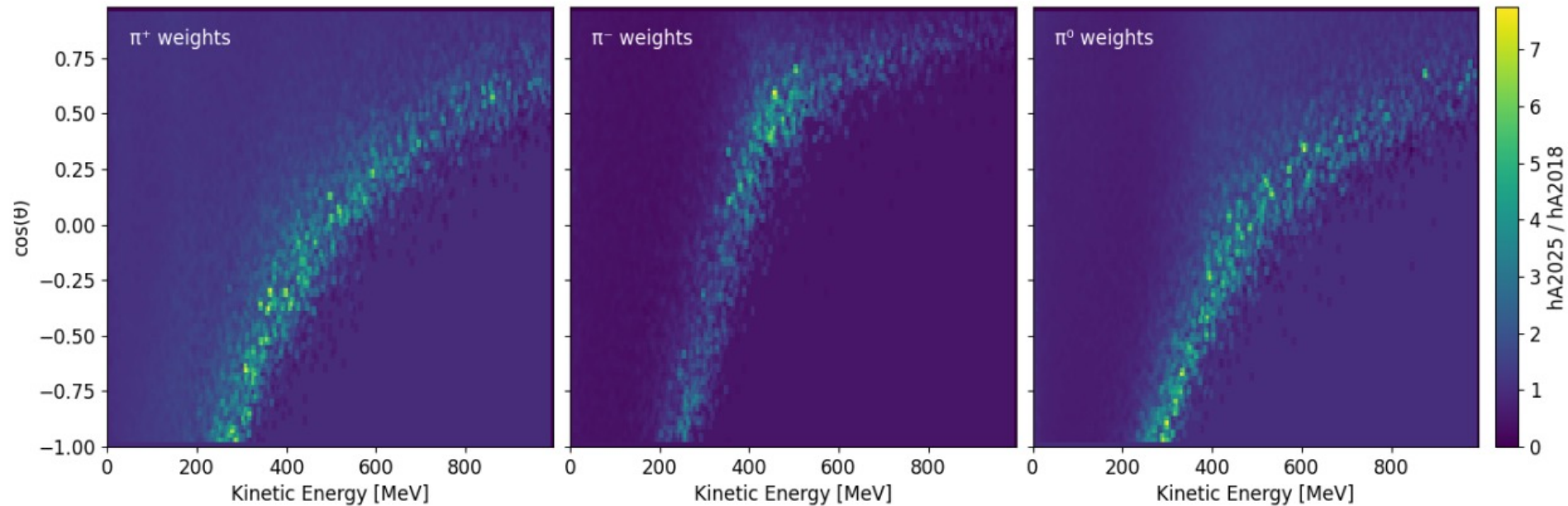
green: hN



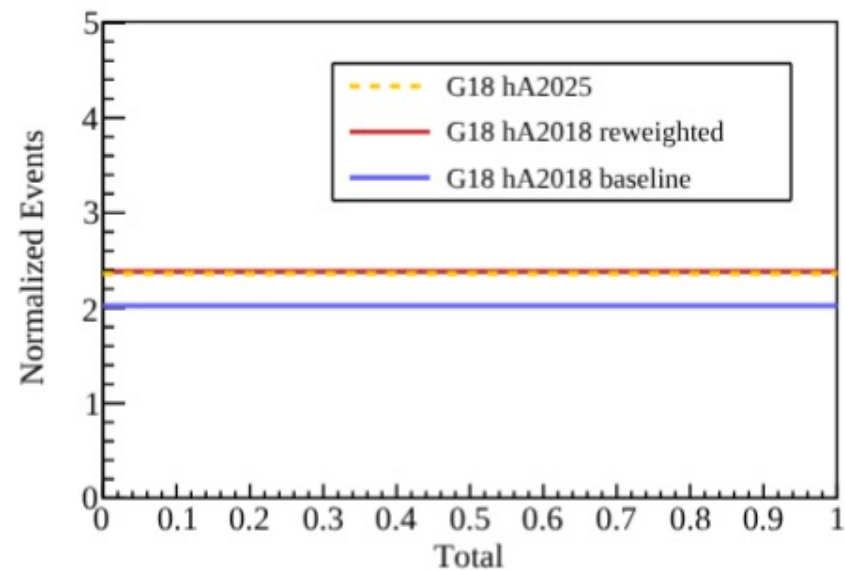
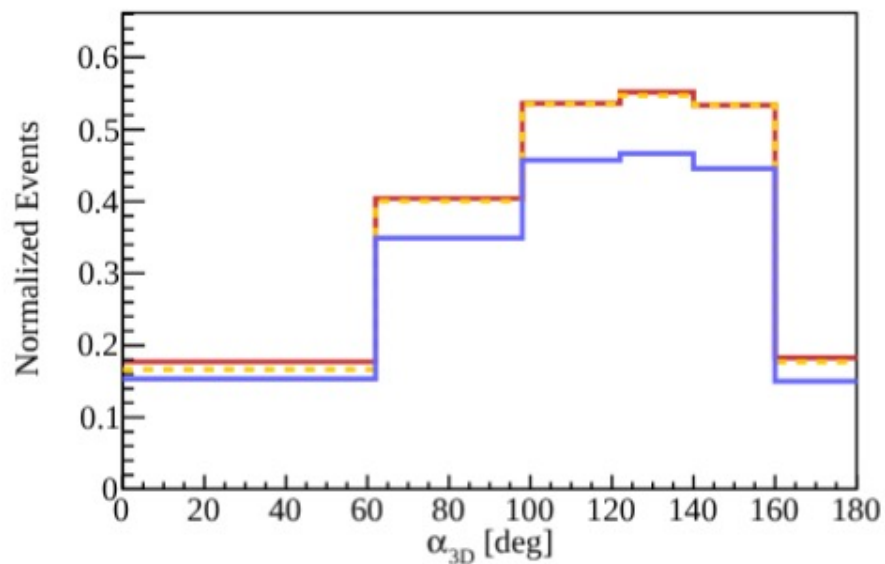
15

REWEIGHTED GENIE

$$w(T_\pi, \cos \theta_\pi) = \frac{d\sigma^{\text{hA2025}}}{d\sigma^{\text{hA2018}}}$$



REWEIGHTED GENIE



ADDITION OF MISSING DATA

COMPARISON OF SELECTION

To have the full dataset in the analysis, the following files have been included:

- Open trigger era:

```
/pnfs/uboone/persistent/users/cthorne/PELEE_2023/run1_openttrigger/run1_beamon_openttrigger_bnb_pando  
ra_3v_a_reprocessing_v08_00_00_83_ntuple_ntuple_ana.root 5.89E+19 15639842
```

```
/pnfs/uboone/persistent/users/cthorne/PELEE_2023/run1_openttrigger/run1_beamon_openttrigger_bnb_pando  
ra_3v_b_reprocessing_v08_00_00_83_beam_good_ntuple_ntuple_ana.root 8.93E+19 19789737
```

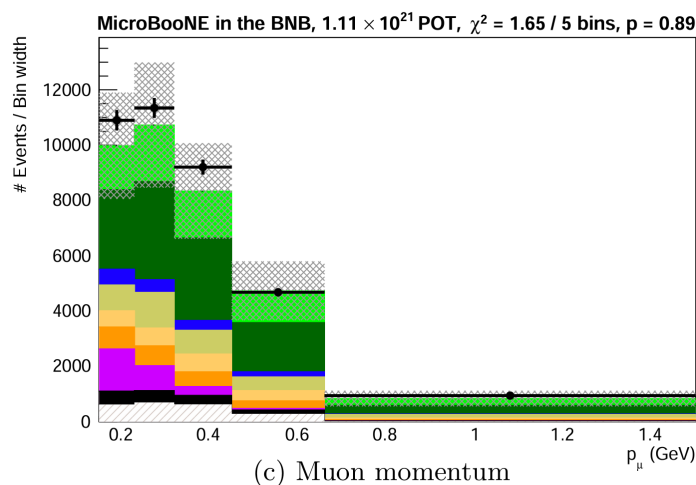
- Detector variations for Runs 4 and 5 (their location can be found [here](#)).

To include the BDT scores into them, Karolina's existing code was used
(/exp/uboone/app/users/kwresilo/ubcc1pi/ubcc1pi_standalone)

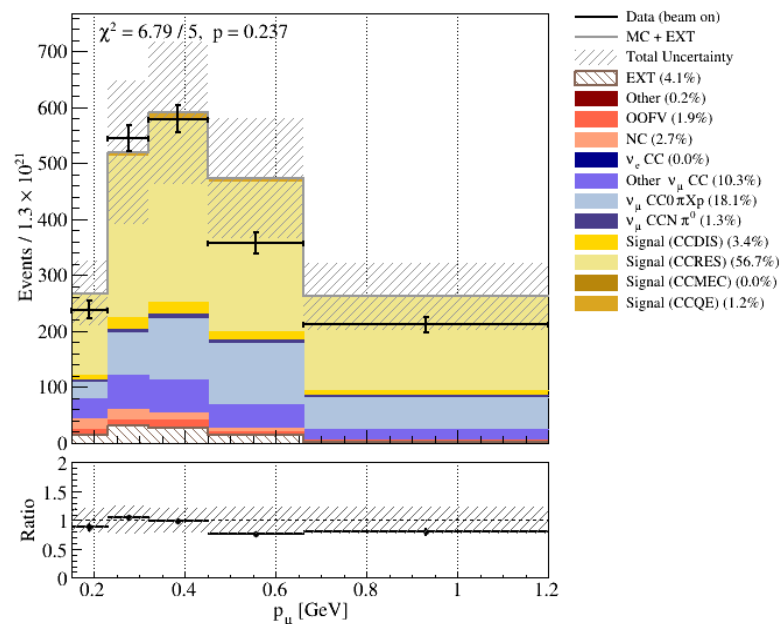
KINEMATIC VARIABLES

MOTIVATION

Following EB feedback, we have included kinematic variables in these studies. Their addition is important because the phase space differs after applying the proton requirement and refined selection, motivating a new measurement rather than an extension of the original.



[J. P. Detje Paper](#)



KINEMATIC VARIABLES

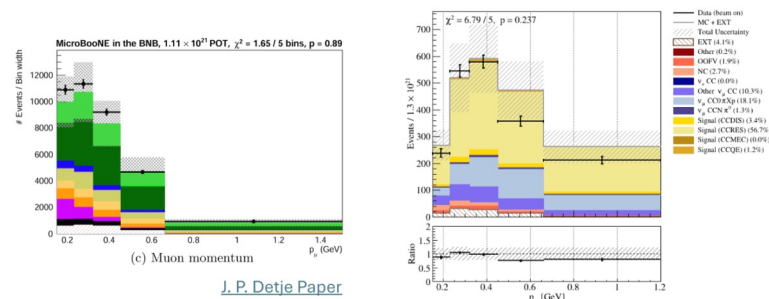
DIFFERENCES IN BETWEEN THE MUON MOMENTUM PLOT

The factor-of-two difference observed in the plots (philip's and mine normalised by bin-width) arises from the proton selection requirement in the signal definition.

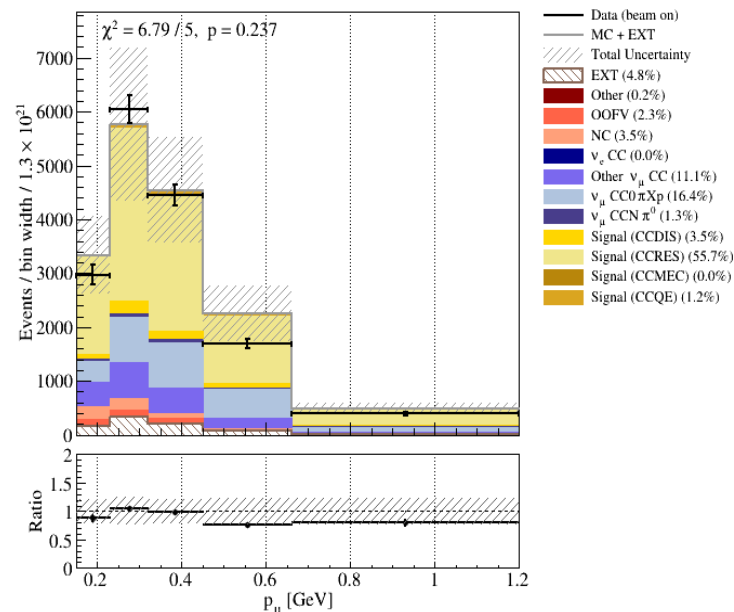
KINEMATIC VARIABLES

MOTIVATION

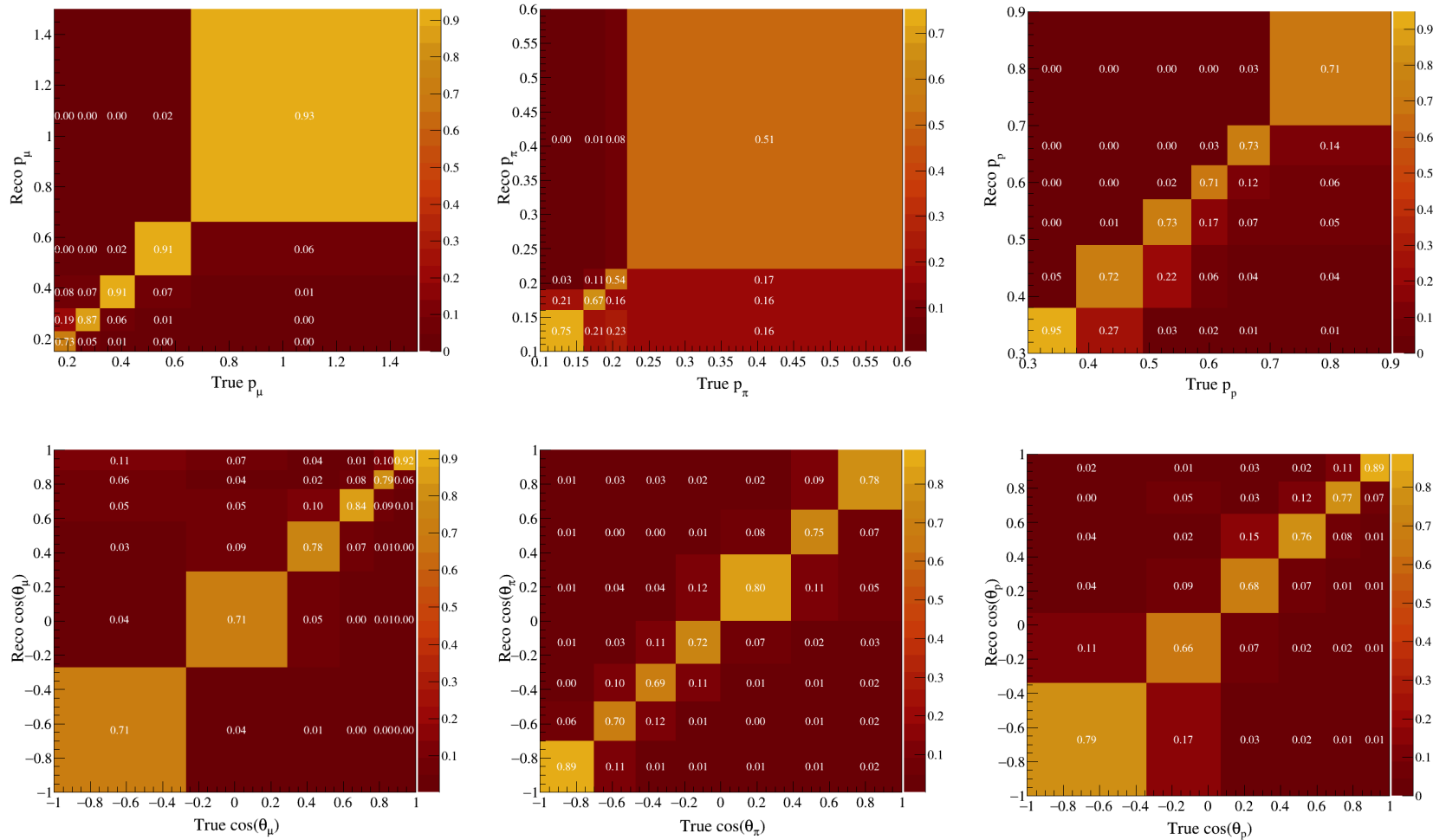
Following EB feedback, we have included kinematic variables in these studies. Their addition is important because the phase space differs after applying the proton requirement and refined selection, motivating a new measurement rather than an extension of the original.



CORRECTED PLOT NORMALISED BY BIN-WIDTH



KINEMATIC VARIABLES BINNING



BACKUP SLIDES

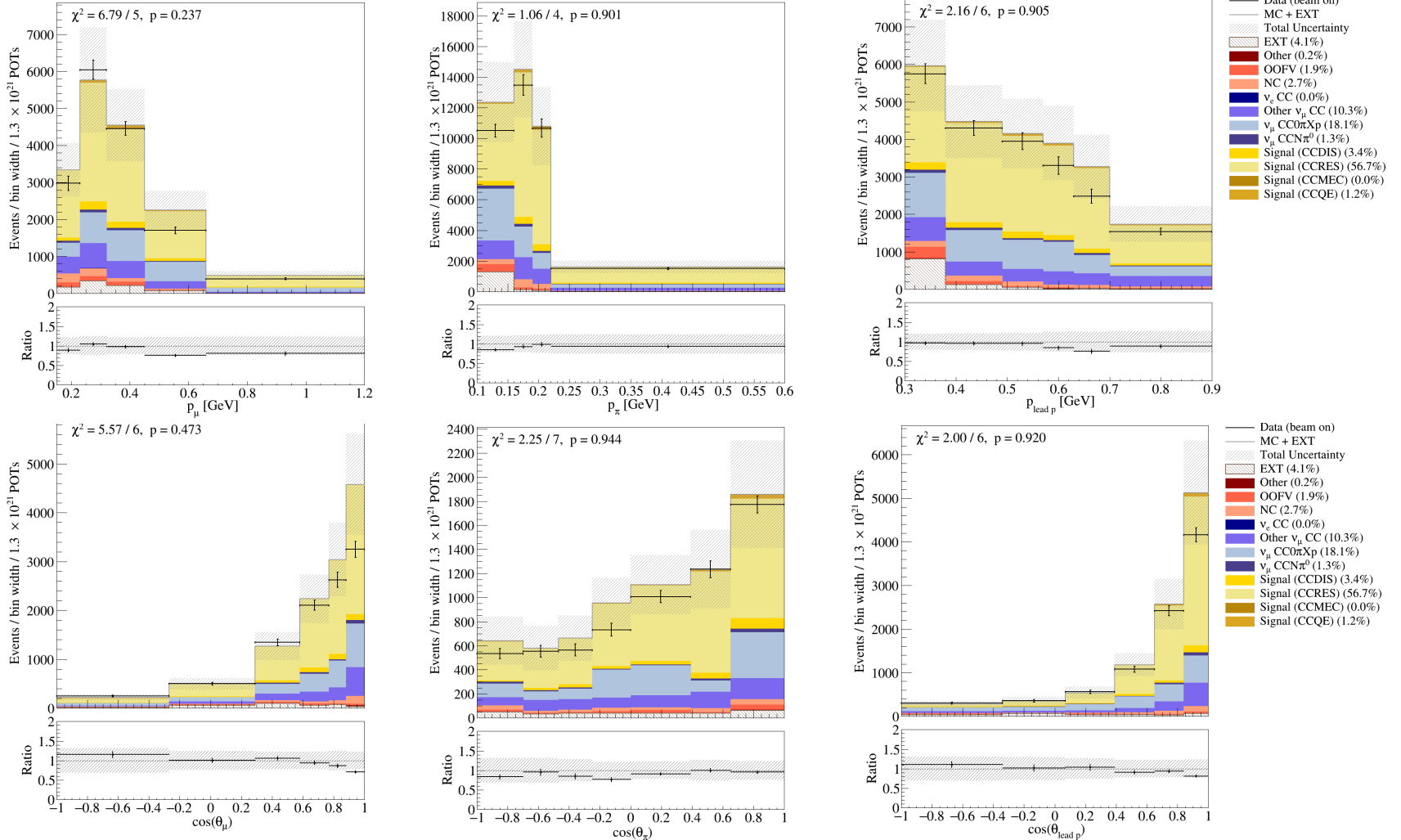
DATA-MC COMPARISON



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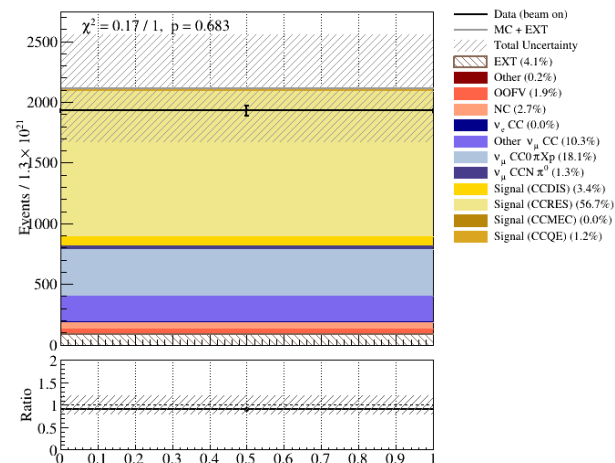
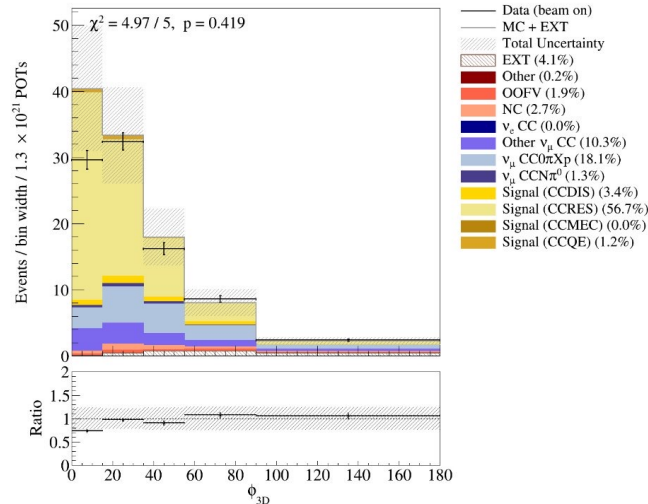
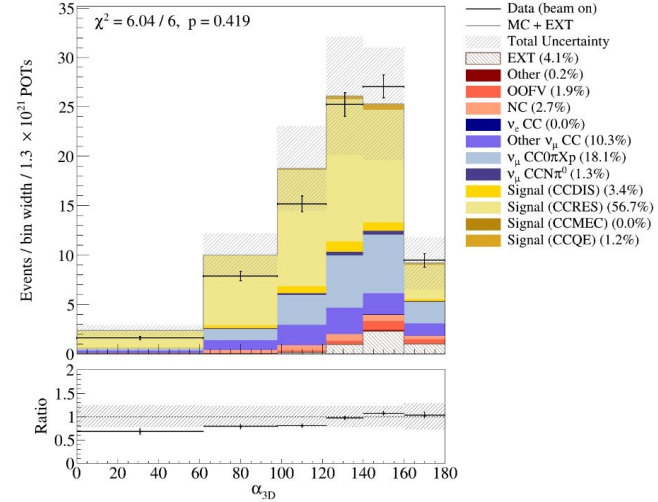
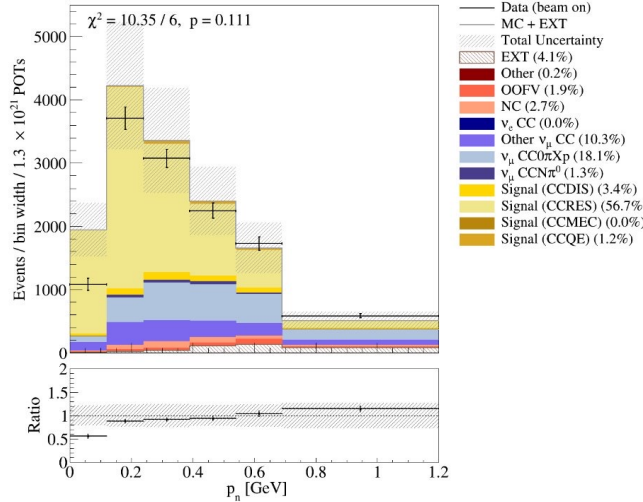
DATA-MC COMPARISON

KINEMATIC VARIABLES

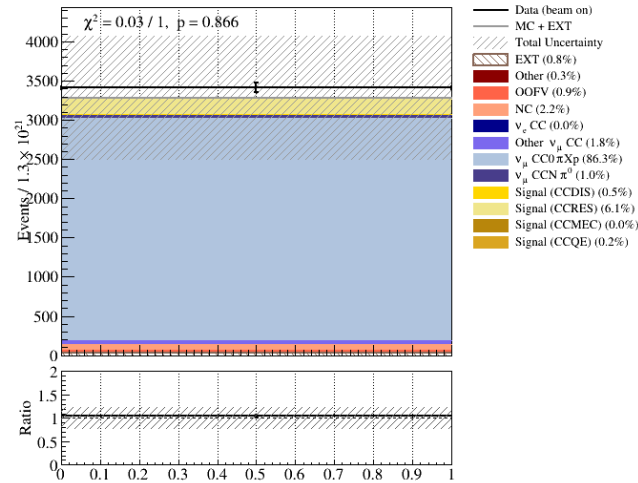
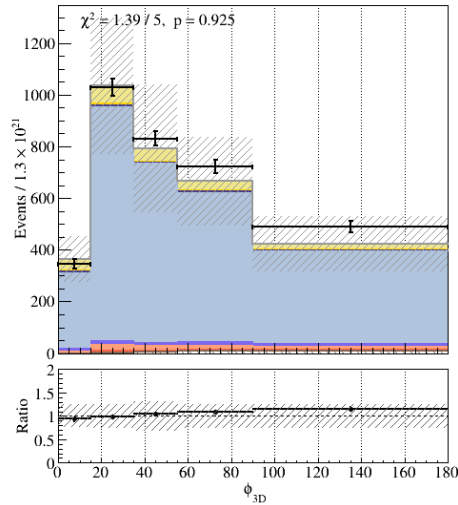
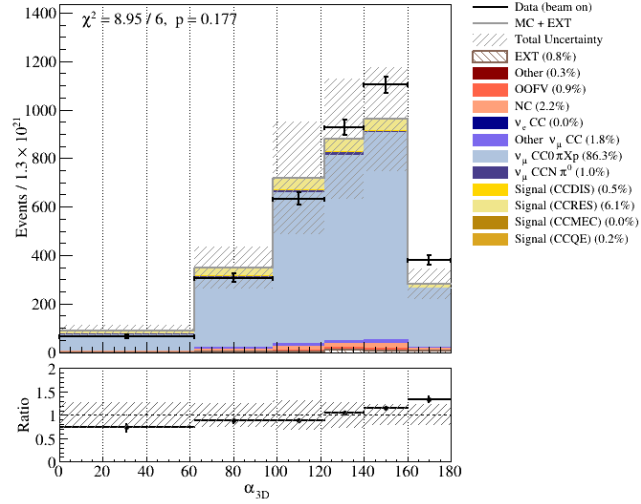
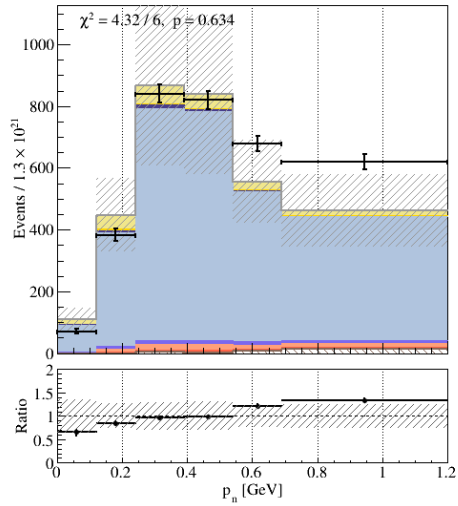


DATA-MC COMPARISON

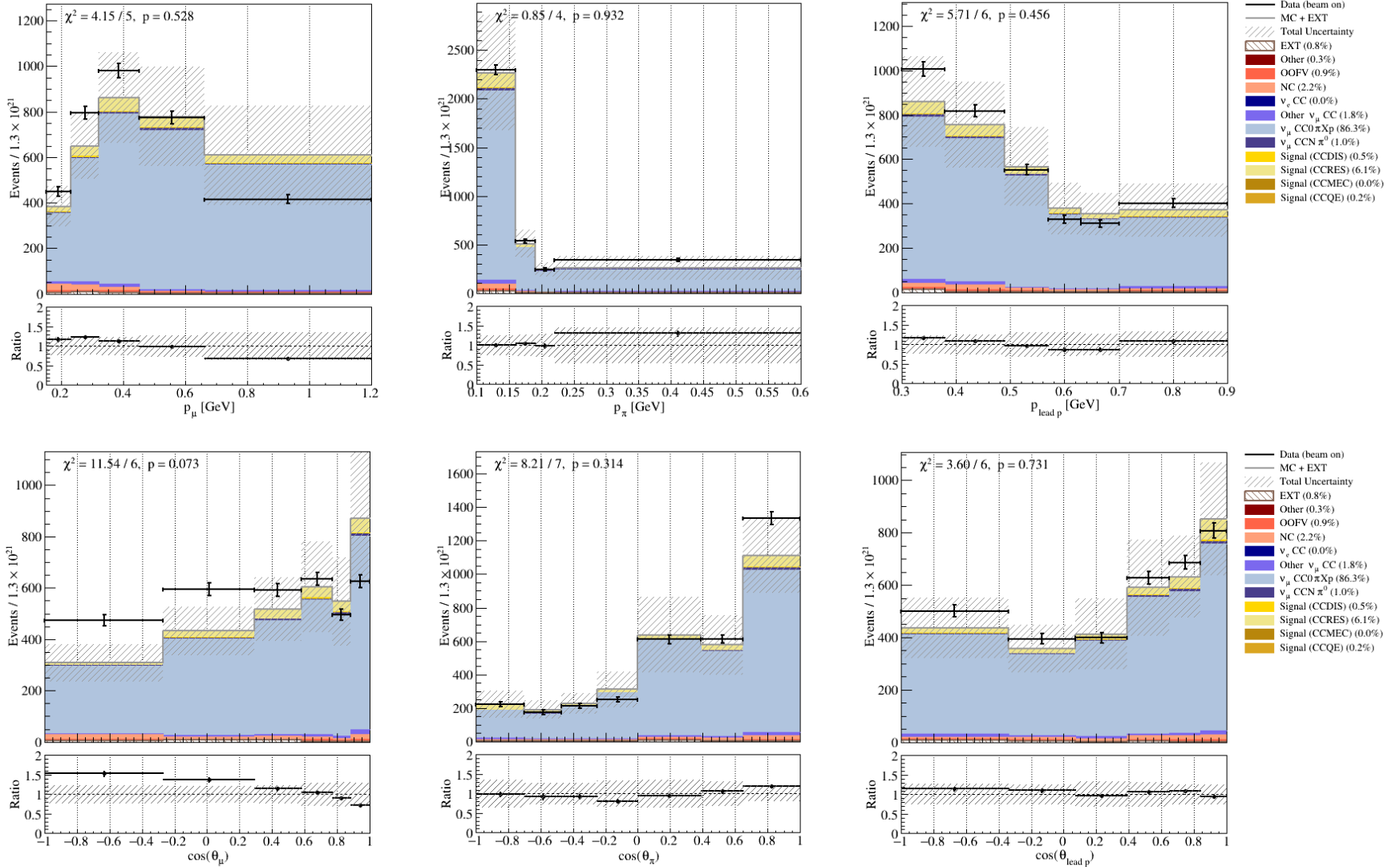
GKI VARIABLES



SIDEBAND DATA-MC COMPARISON



SIDEBAND DATA-MC COMPARISON



BACKUP SLIDES

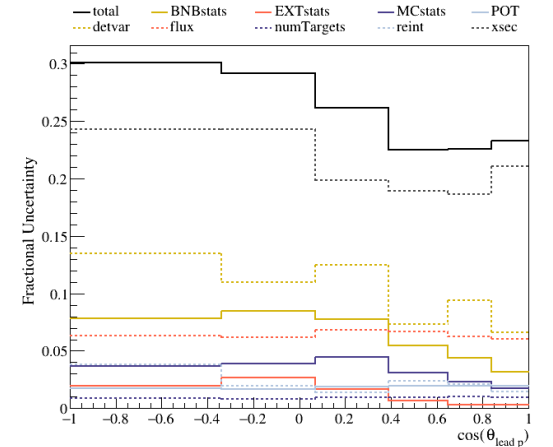
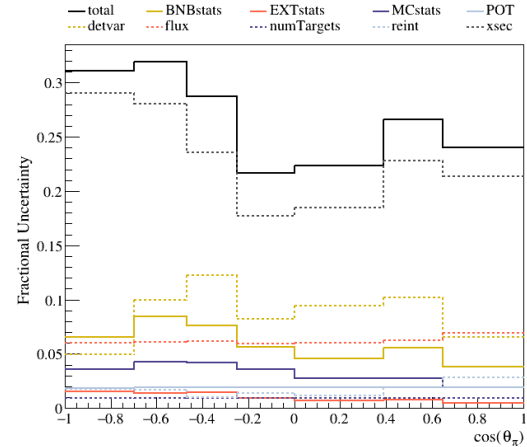
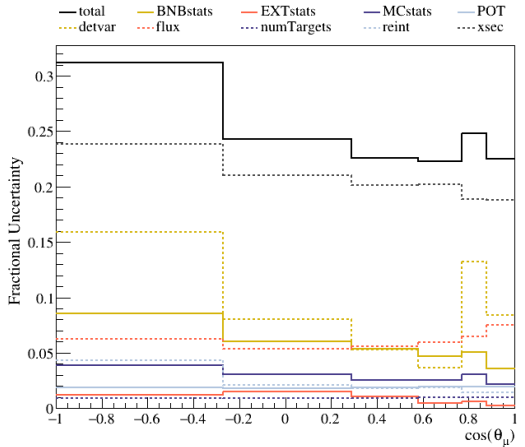
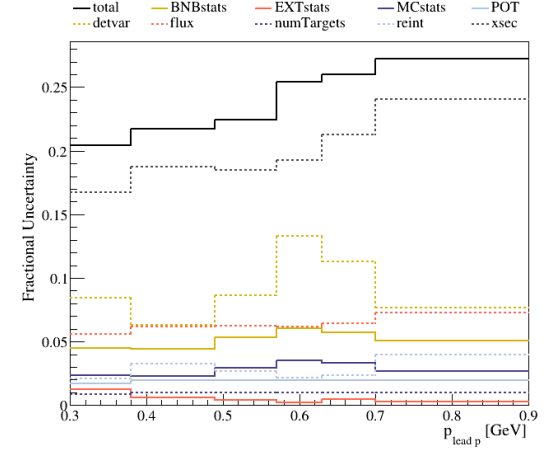
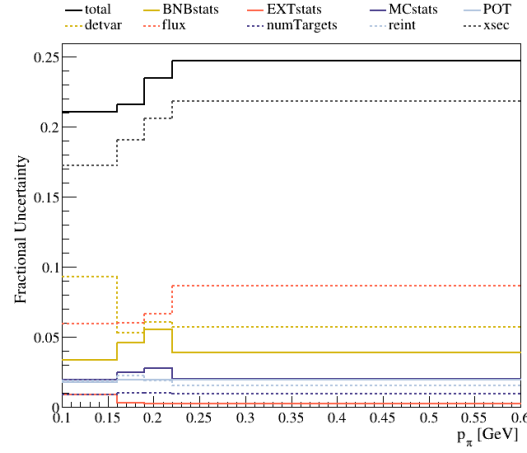
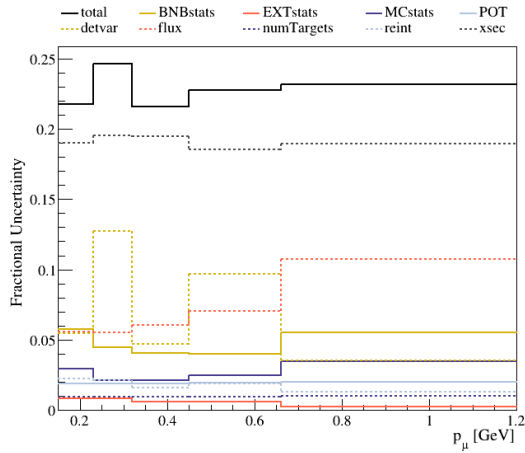
SYSTEMATIC UNCERTAINTIES



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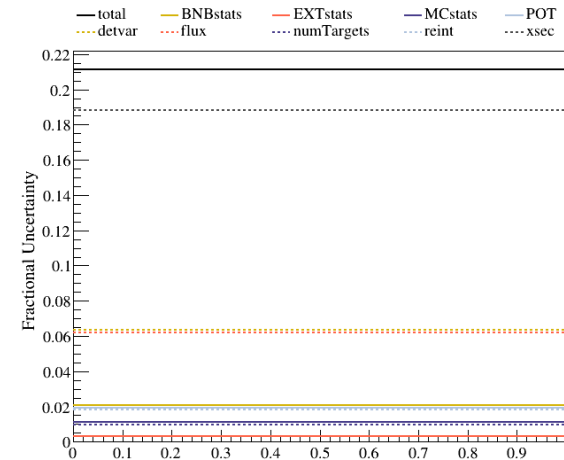
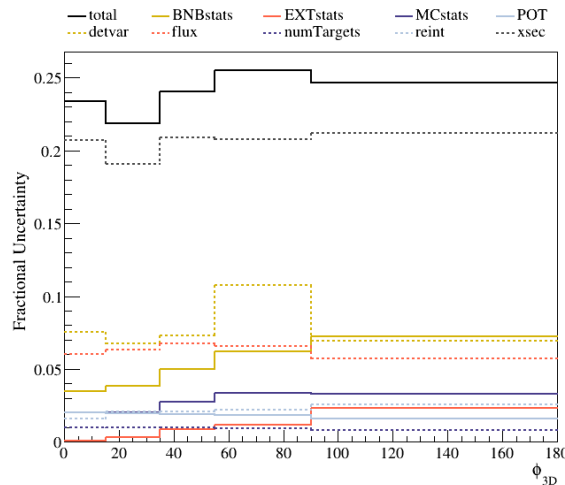
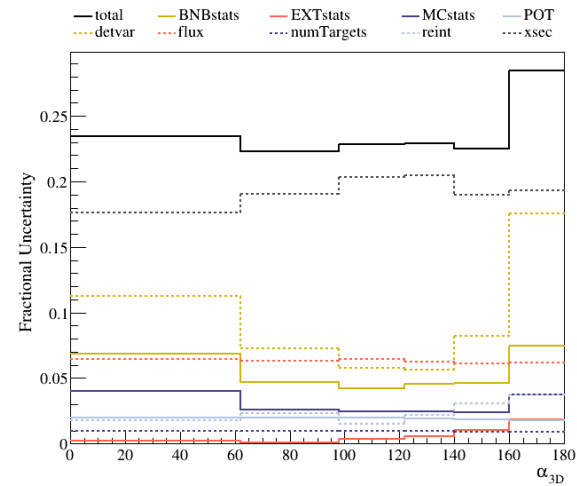
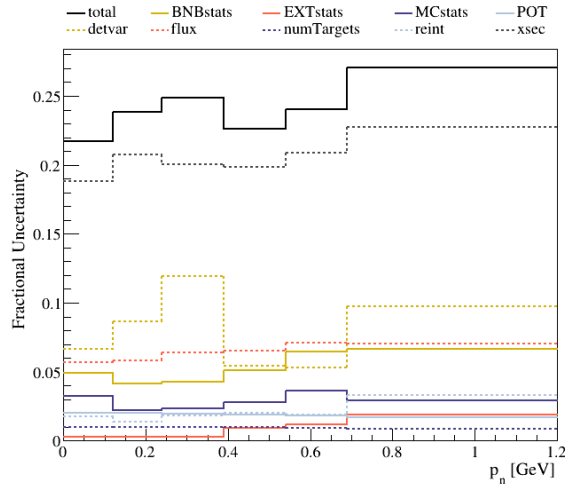
SYSTEMATICS

KINEMATIC VARIABLES



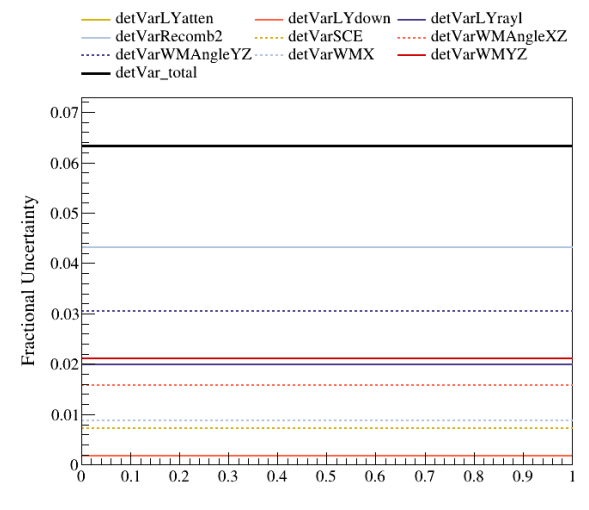
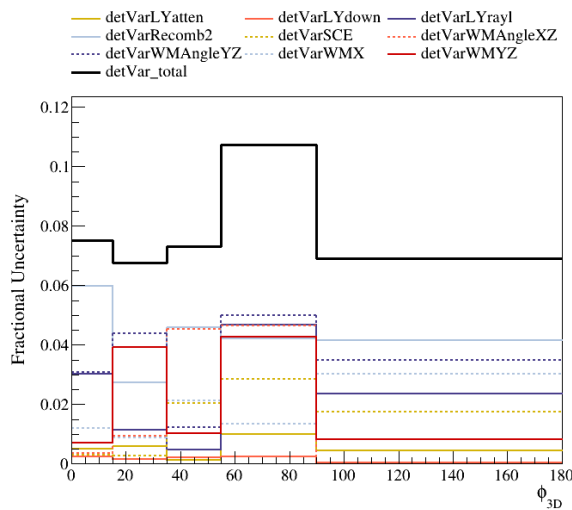
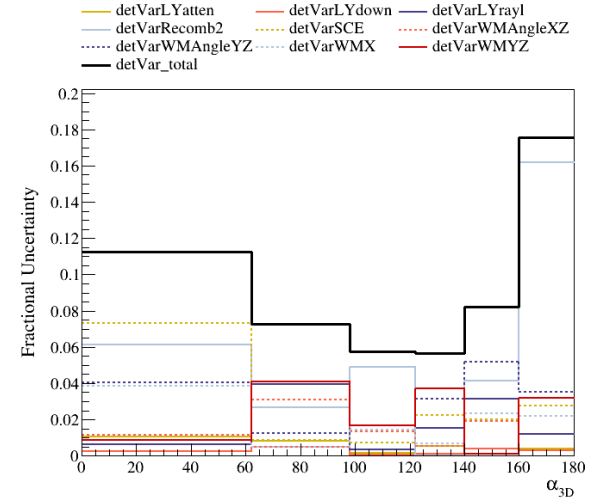
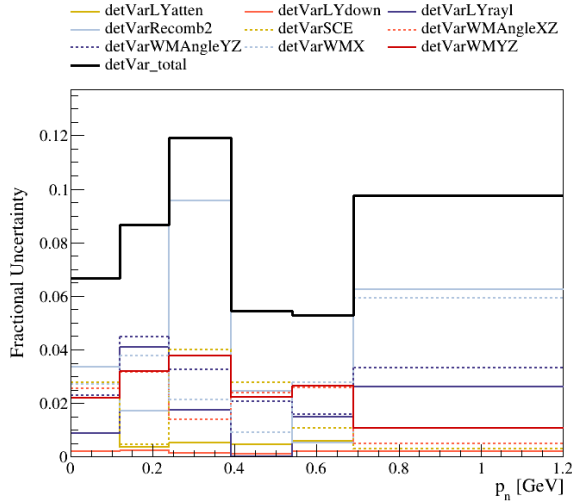
SYSTEMATICS

GKI VARIABLES



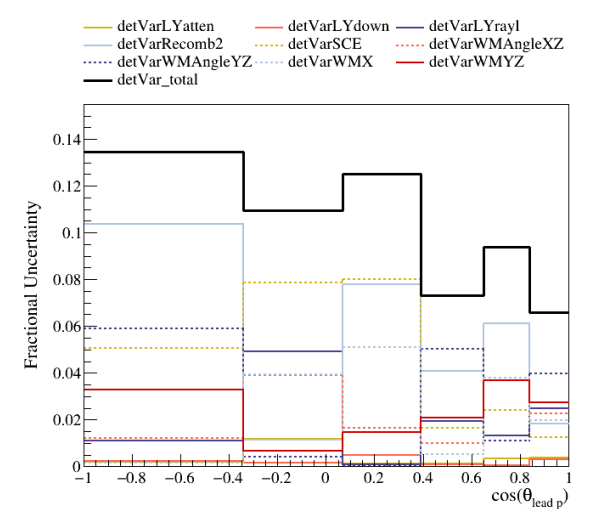
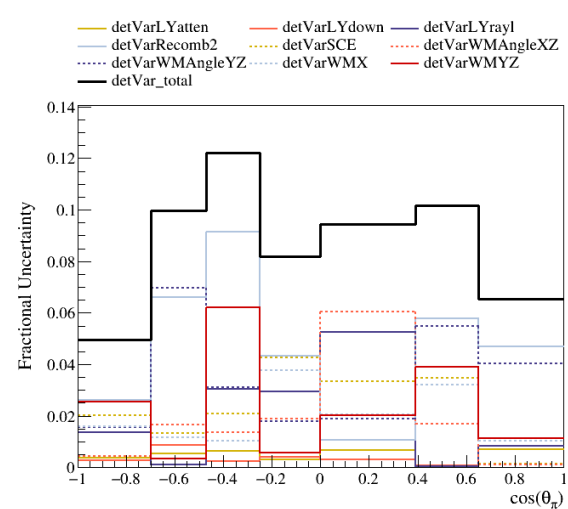
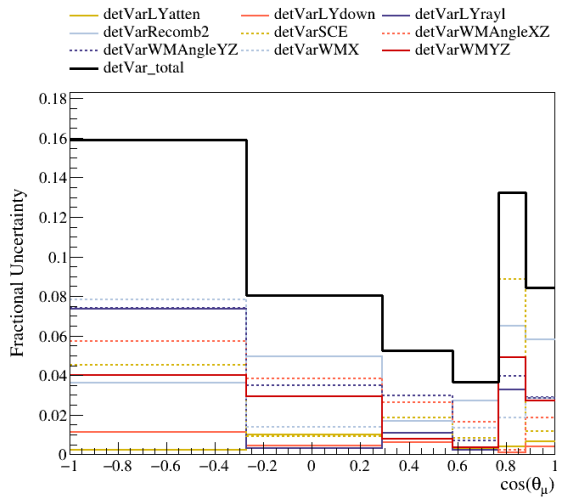
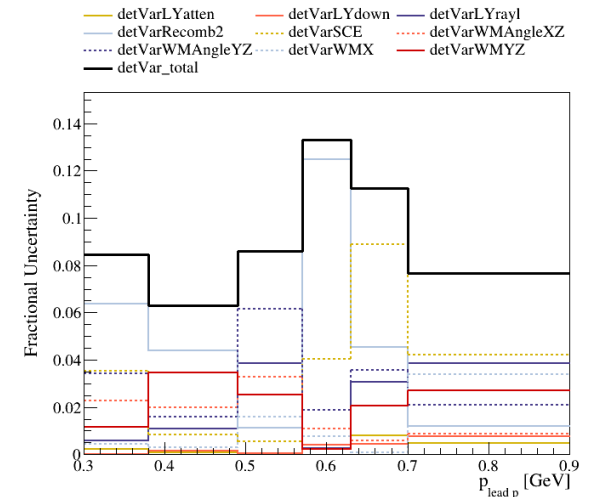
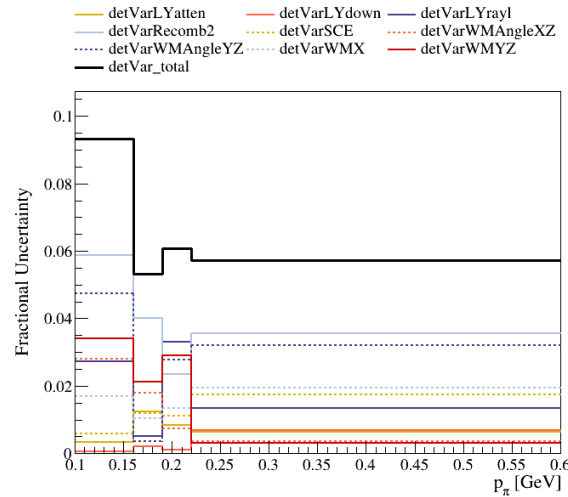
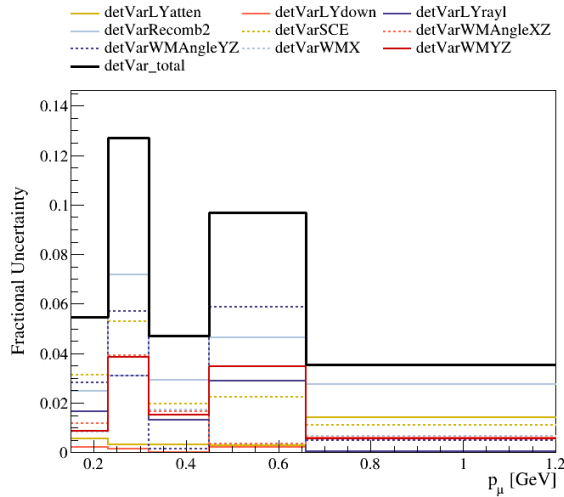
SYSTEMATICS – DETVARS

GKI VARIABLES



SYSTEMATICS – DETVARS

KINEMATIC VARIABLES



BACKUP SLIDES

UNFOLDING

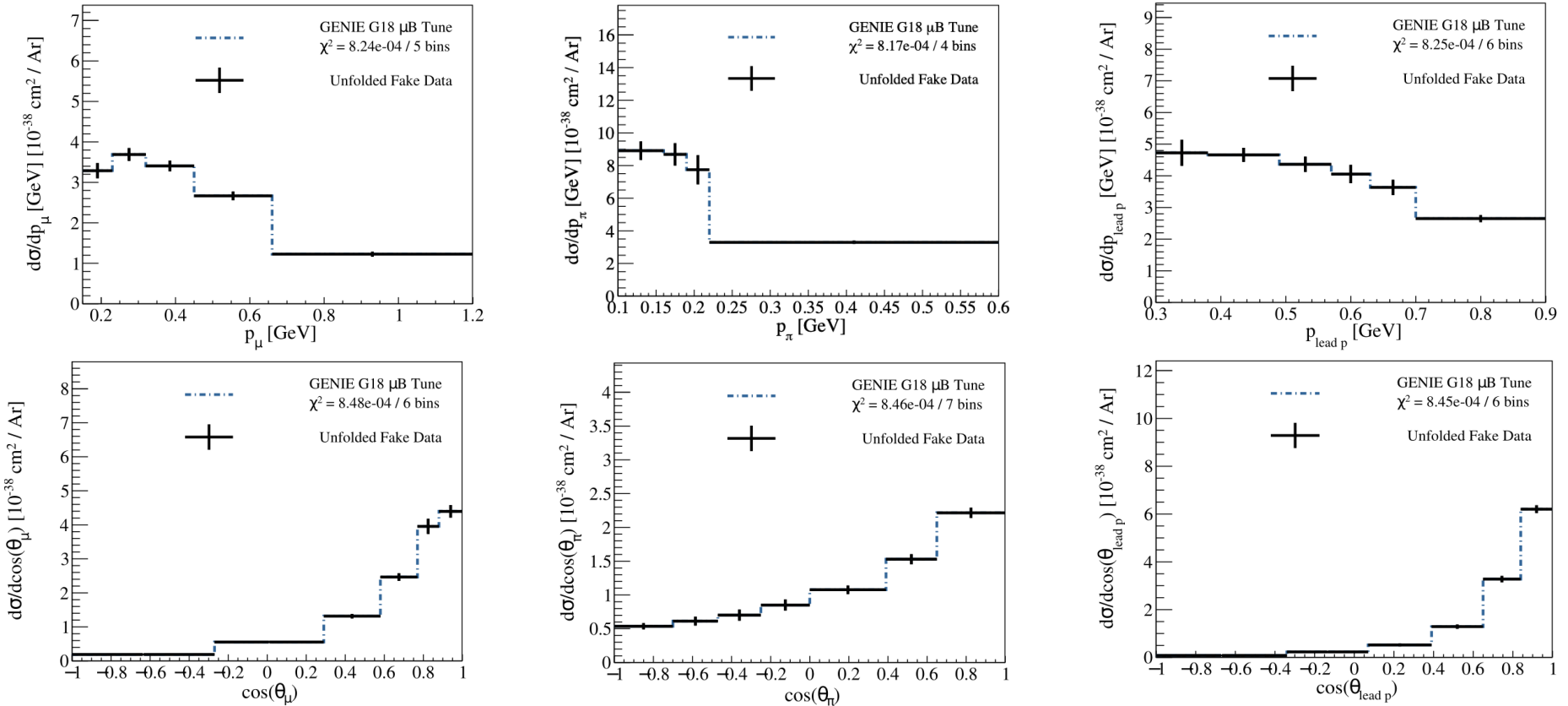


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CLOSURE TEST

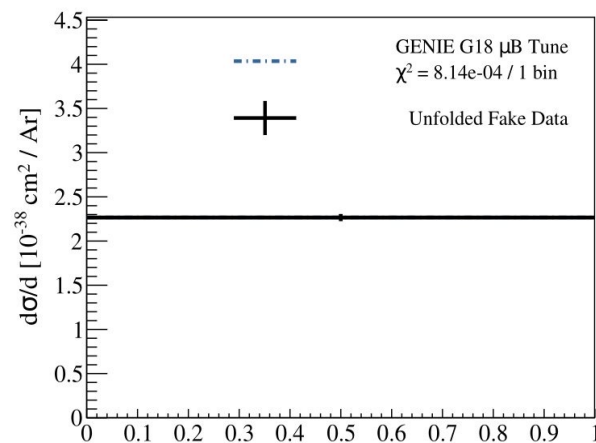
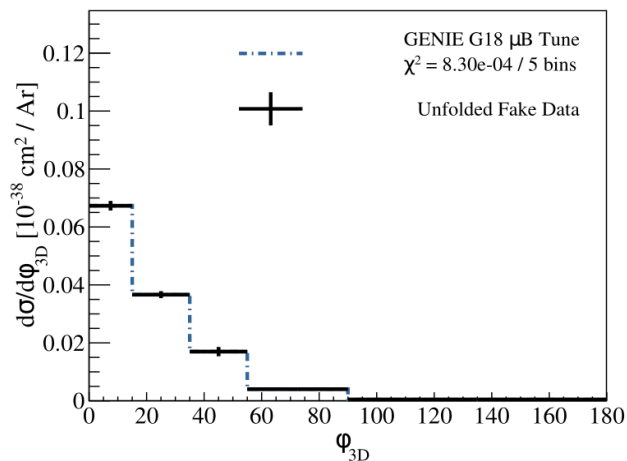
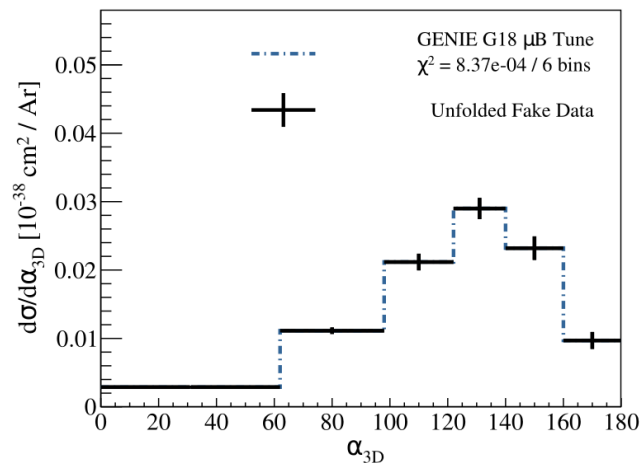
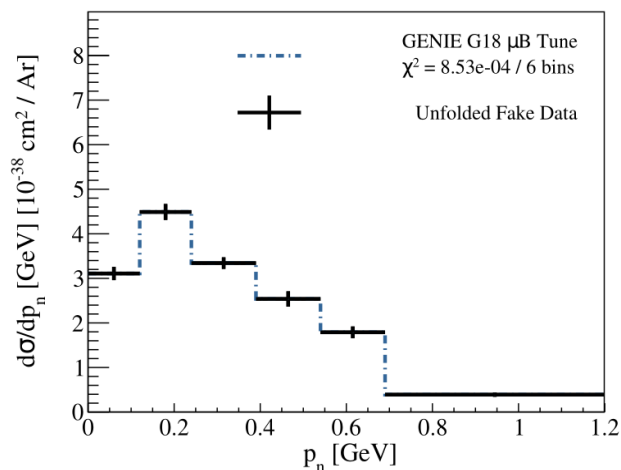
KINEMATIC VARIABLES

- After all the implementations in the code, the Closure test was repeated.
- Everything remains consistent.



CLOSURE TEST

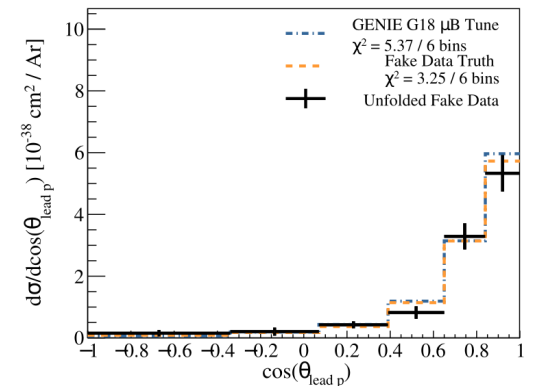
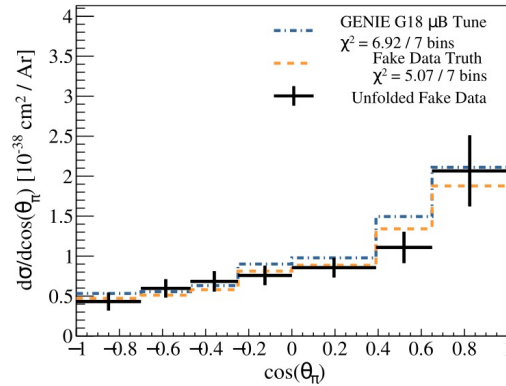
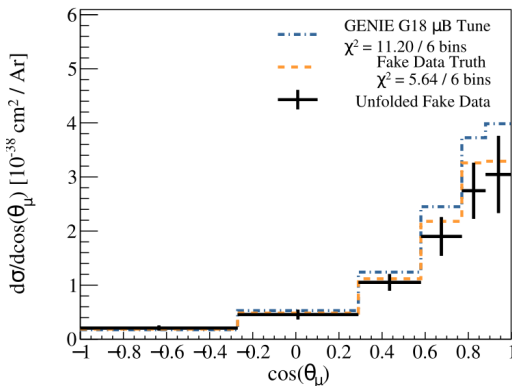
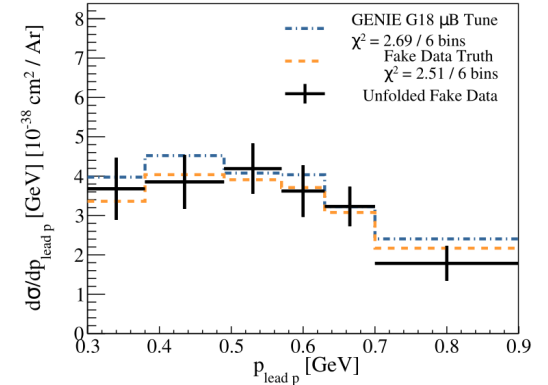
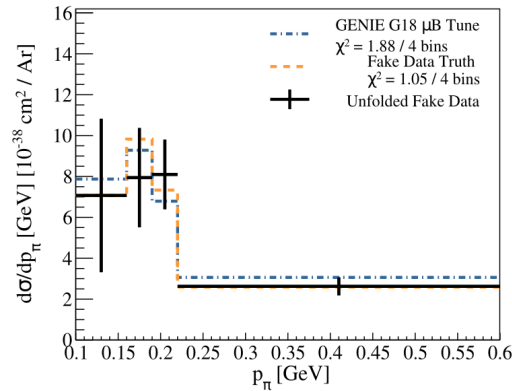
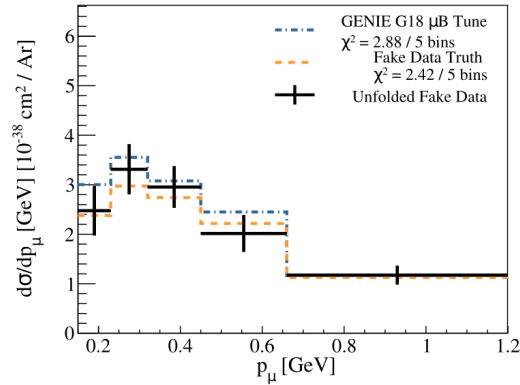
GKI VARIABLES



FAKE DATA STUDY

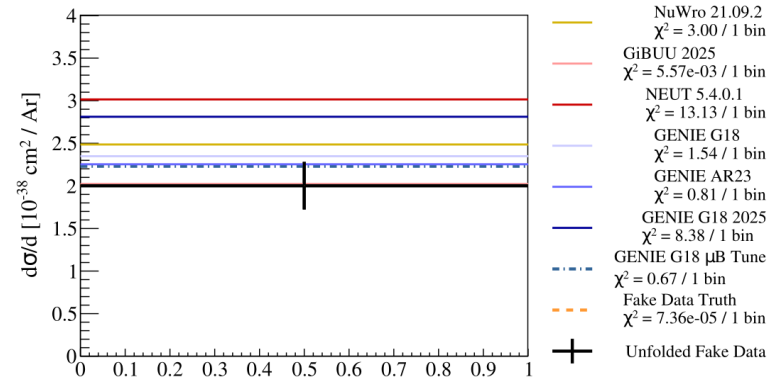
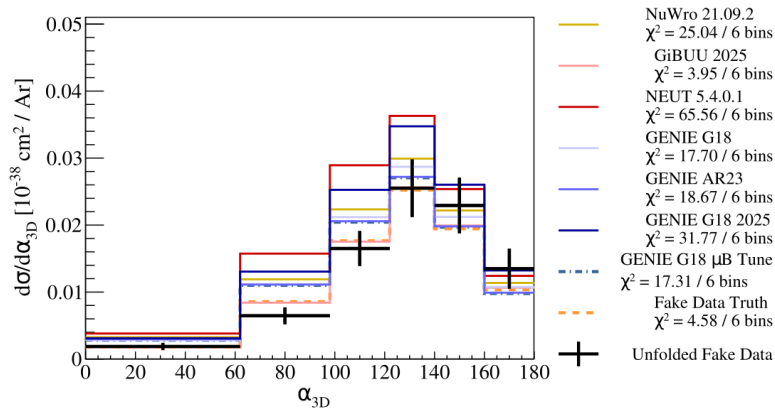
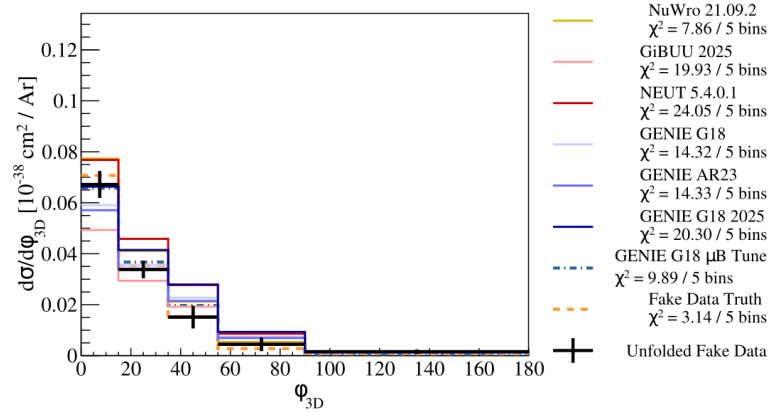
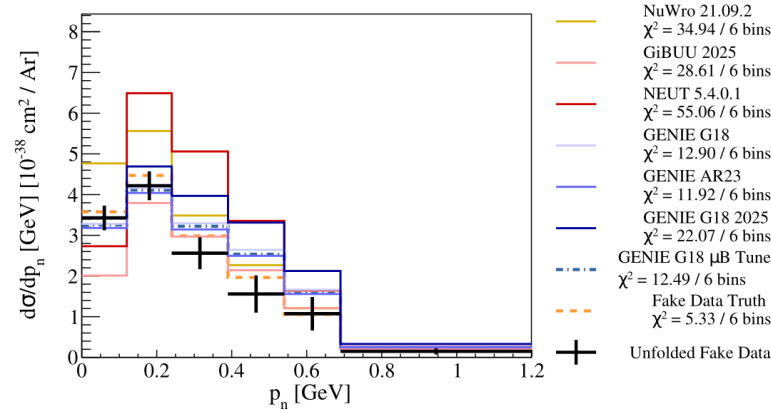
KINEMATIC VARIABLES

As for the Closure test, the Fake data study is consistent with the expected result, demonstrating that the Unfolded NuWRO Data is preferred over the GENIE CV.



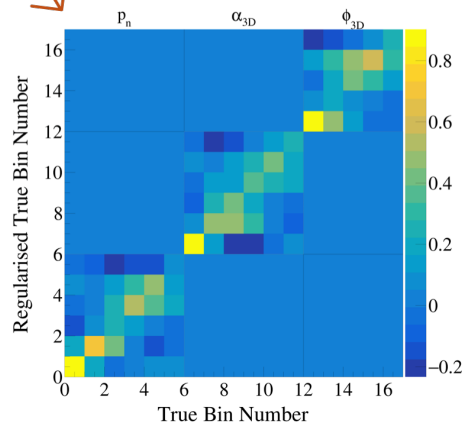
FAKE DATA STUDY

GKI VARIABLES

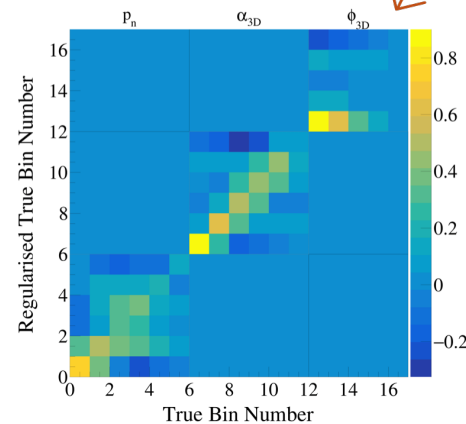


A_C MATRIX (FAKE DATA)

First-deriv
Norm_type=0

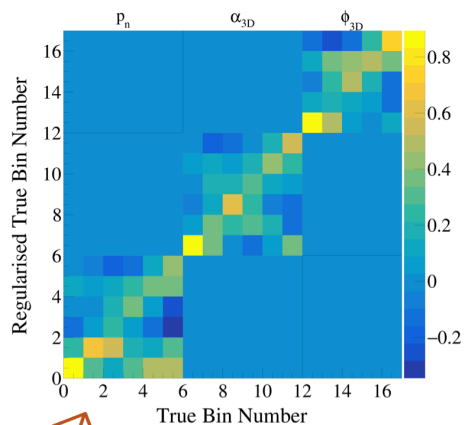


First-deriv
Norm_type=0.5

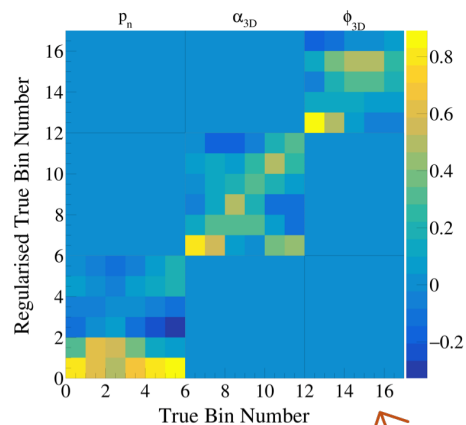


$$A_C = C^{-1} V_C W_C V_C^T C$$

$$C \rightarrow C \cdot \text{diag}\left(\frac{1}{(p_{\text{prior}})^{\text{Norm_type}}}\right)$$



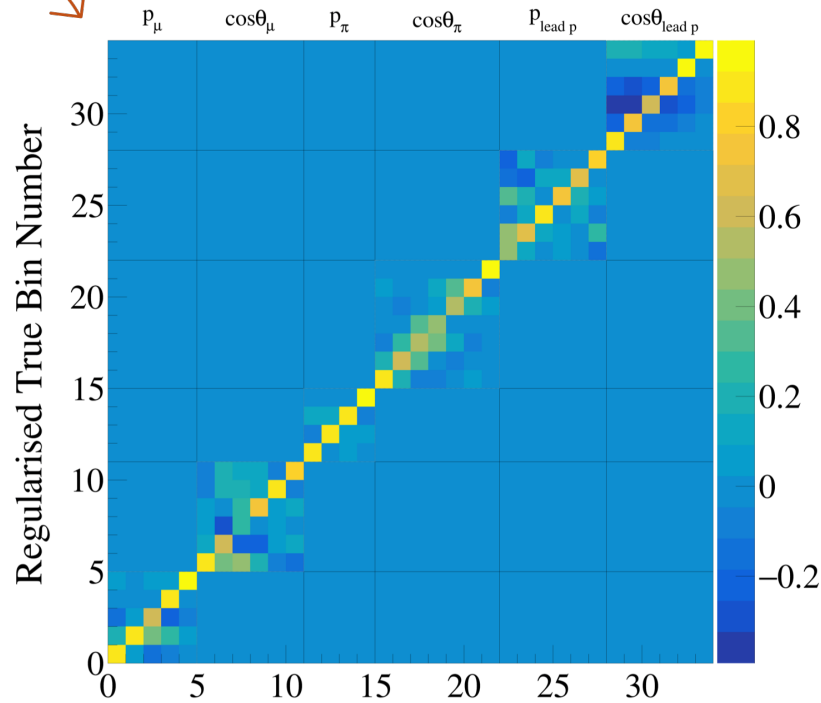
Second-deriv
Norm_type=0



Second-deriv
Norm_type=0.5

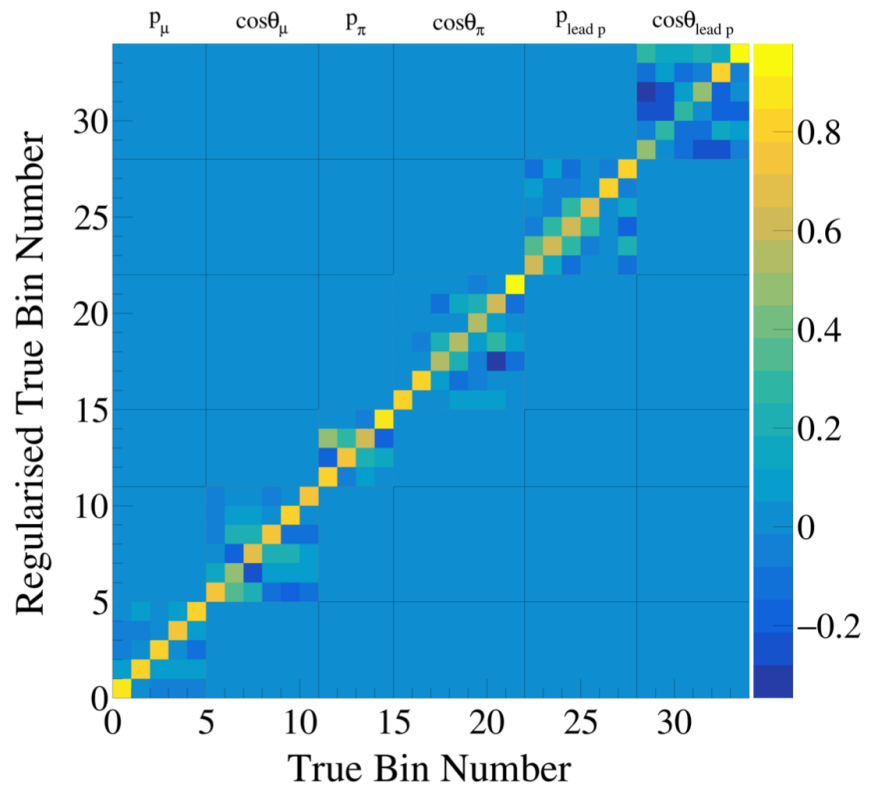
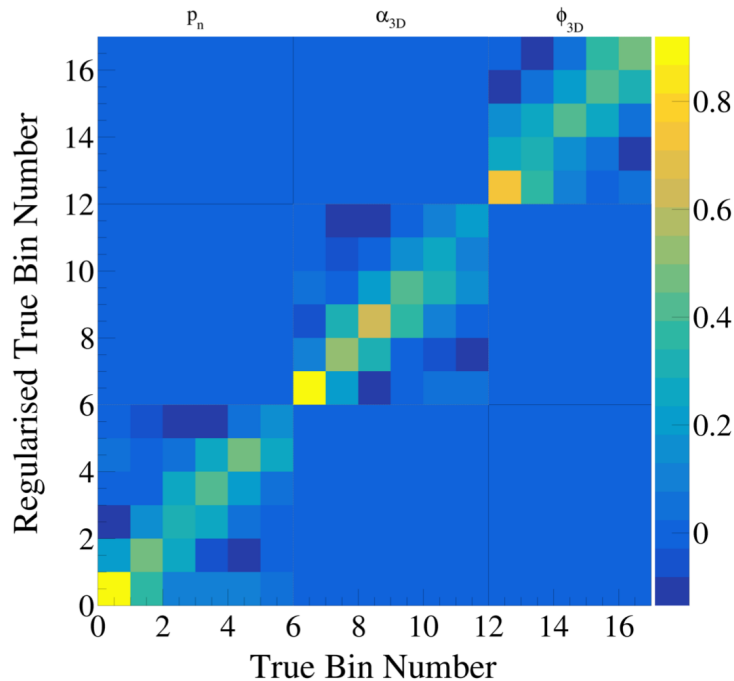
REGULARISATION MATRIX (FAKE DATA)

First-deriv
Norm_type=0

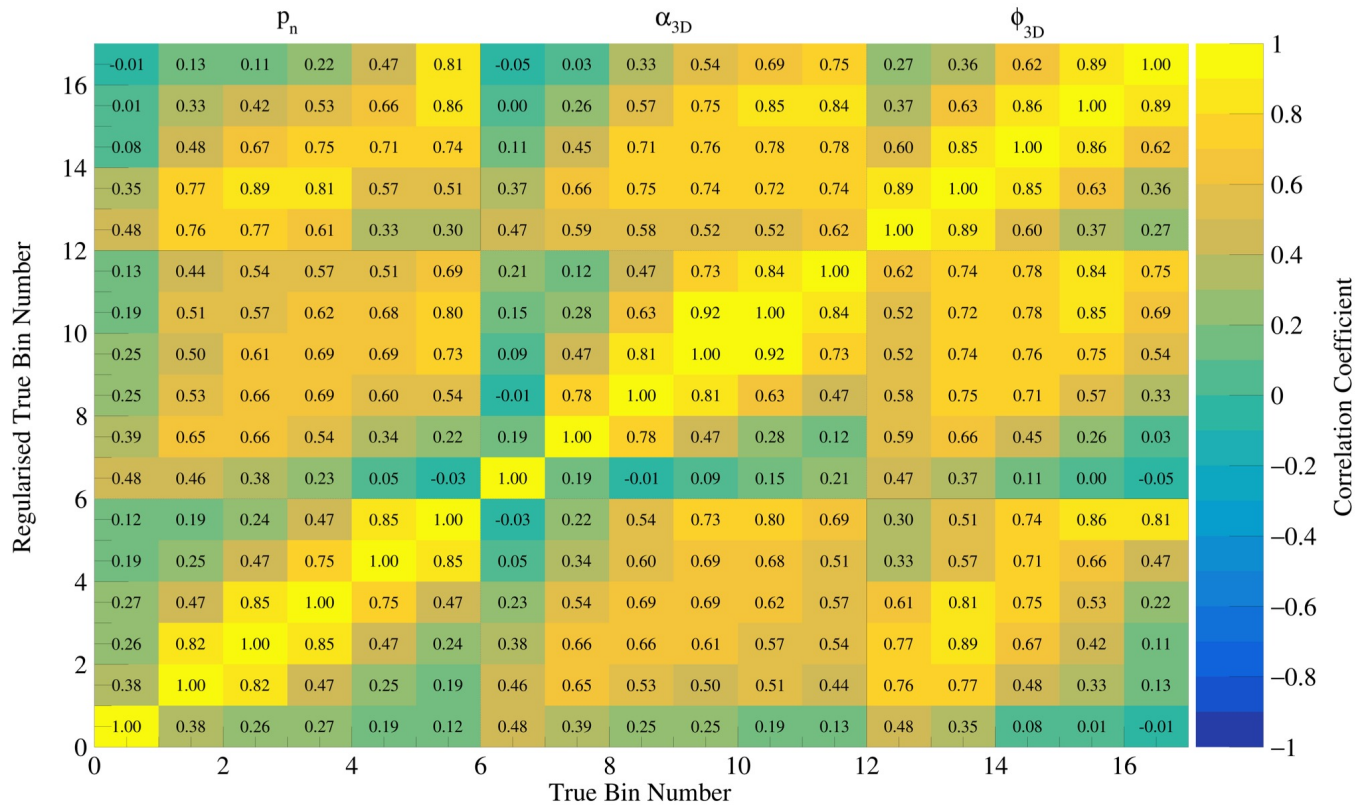


A_C MATRIX (DATA)

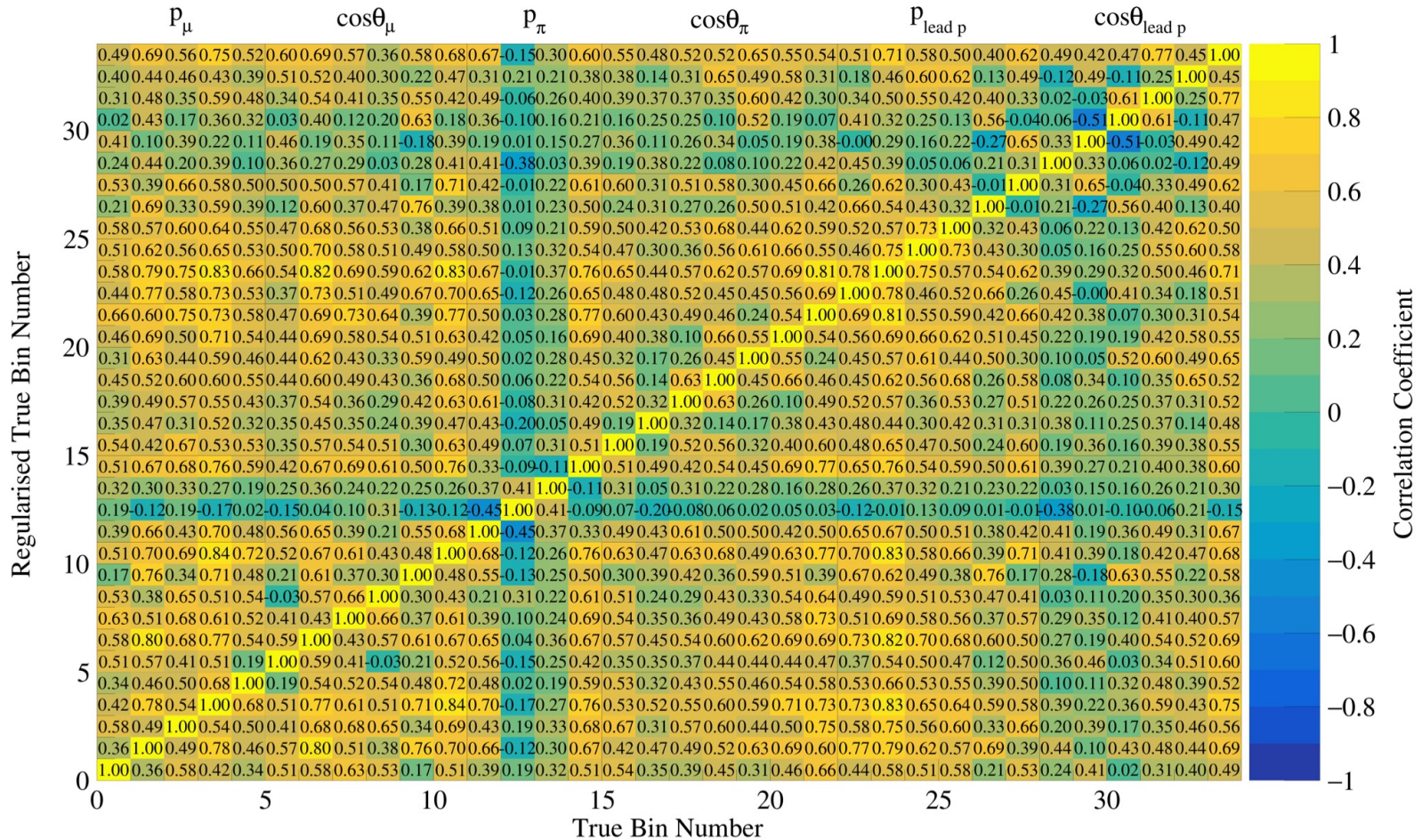
Wiener-SVD First derivative.



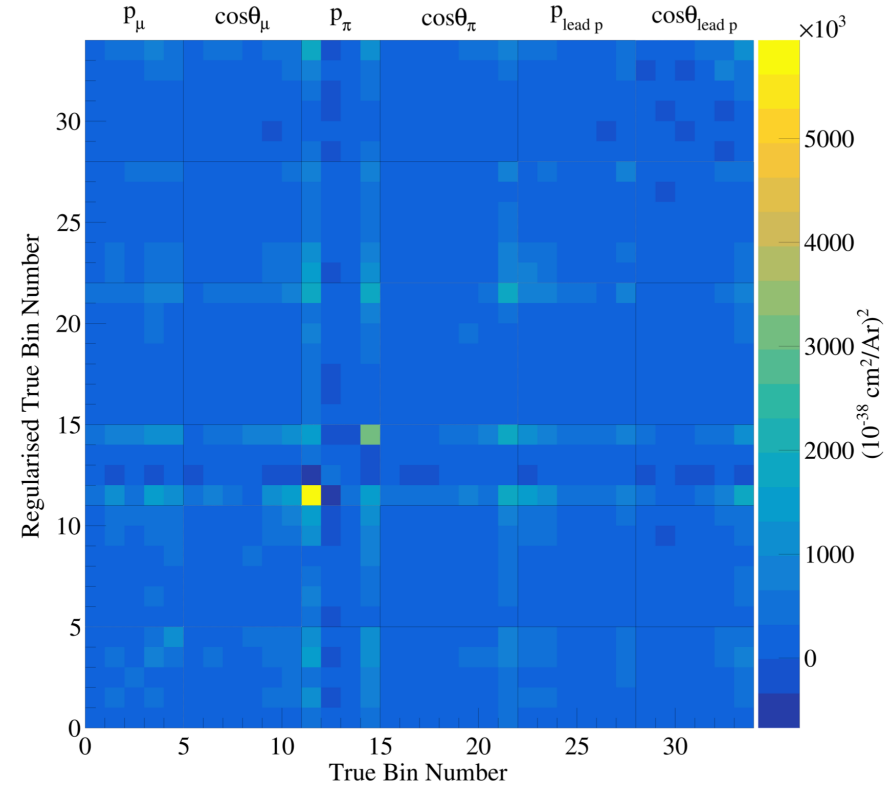
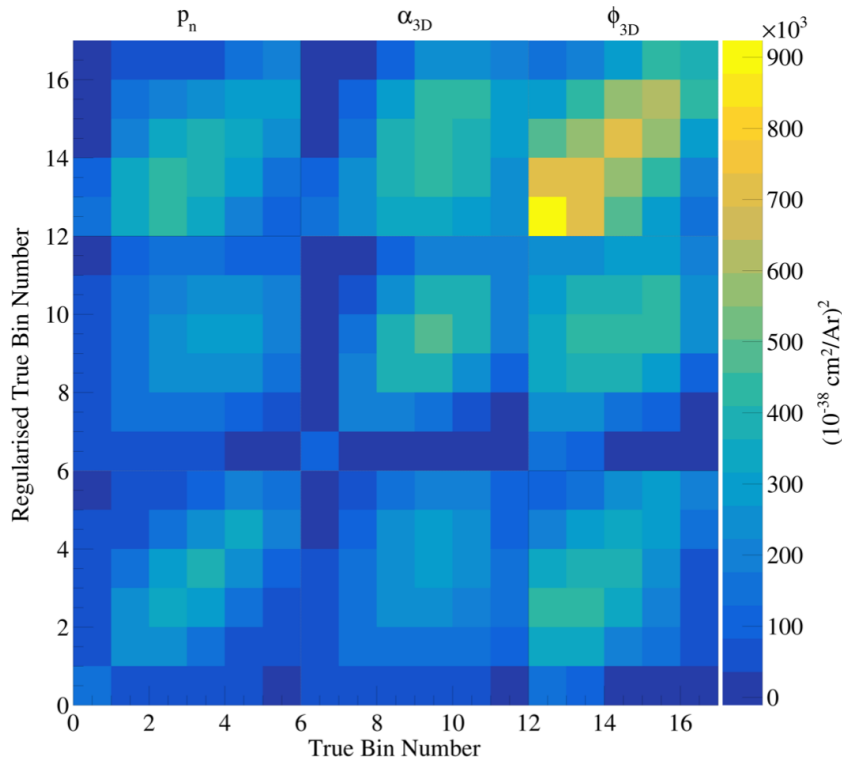
CORRELATION MATRIX (DATA)



CORRELATION MATRIX (DATA)



COVARIANCE MATRIX (DATA)



BACKUP SLIDES

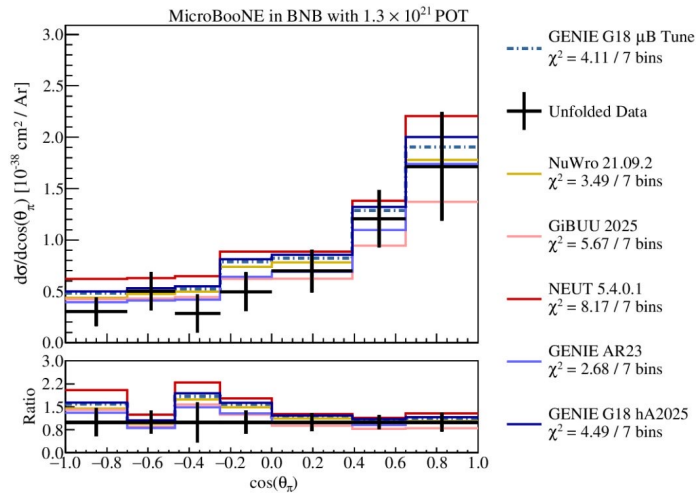
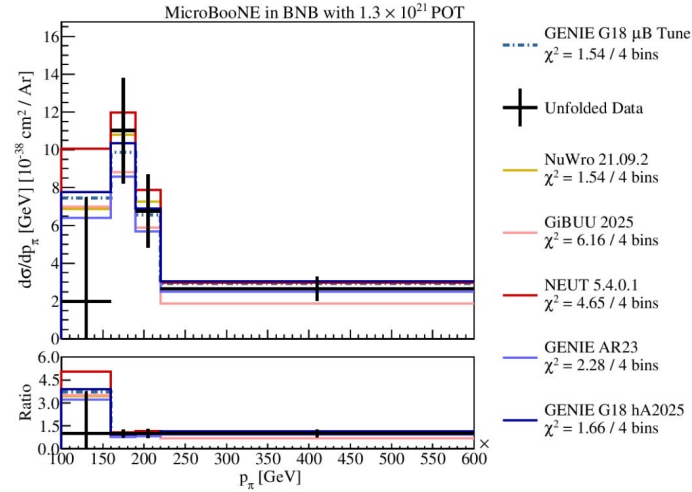
FSI VS NO-FSI



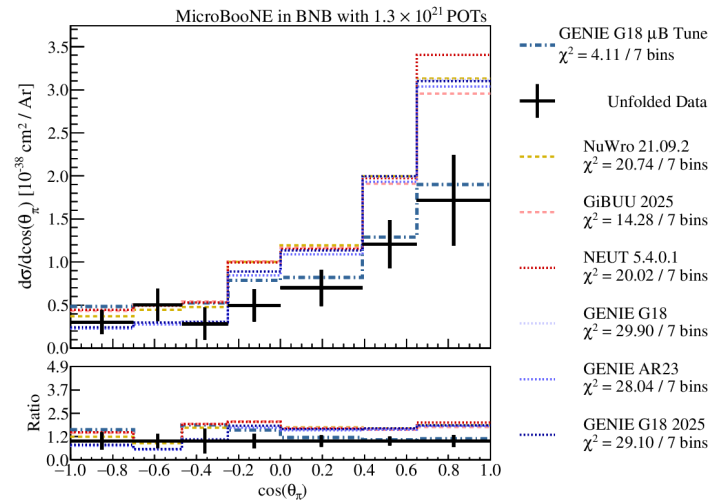
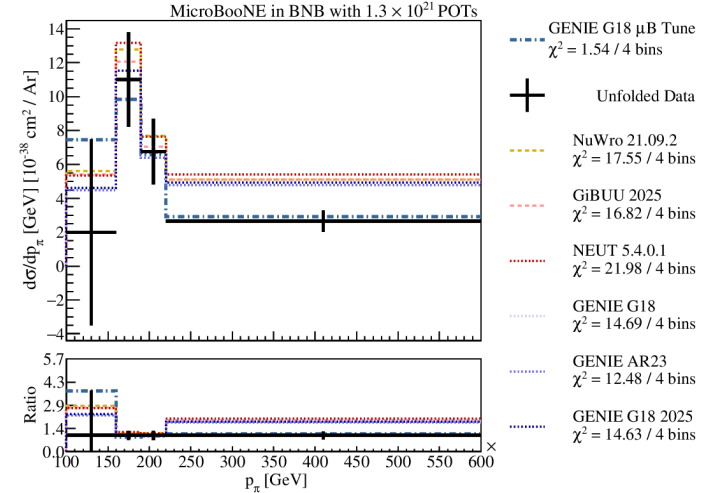
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KINEMATIC VARIABLES (PIONS)

WITH FSI

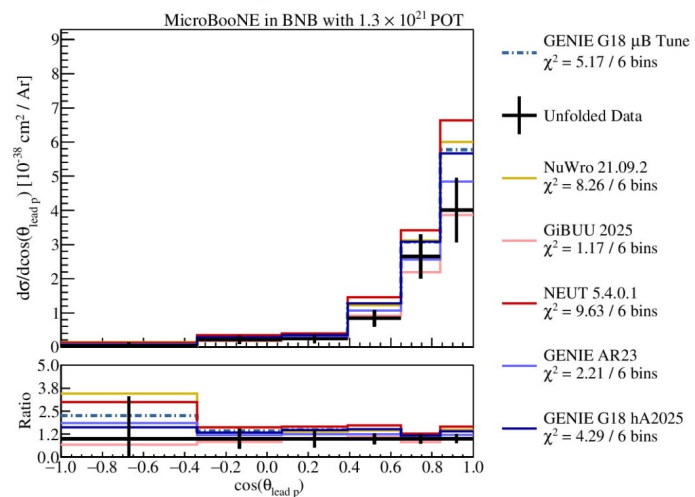
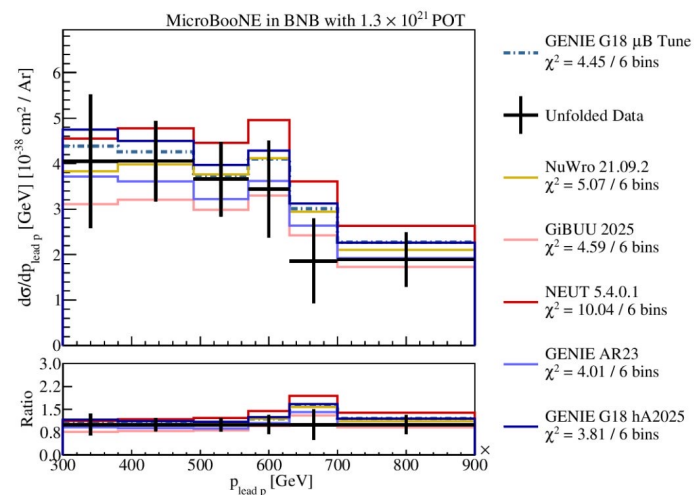


WITHOUT FSI

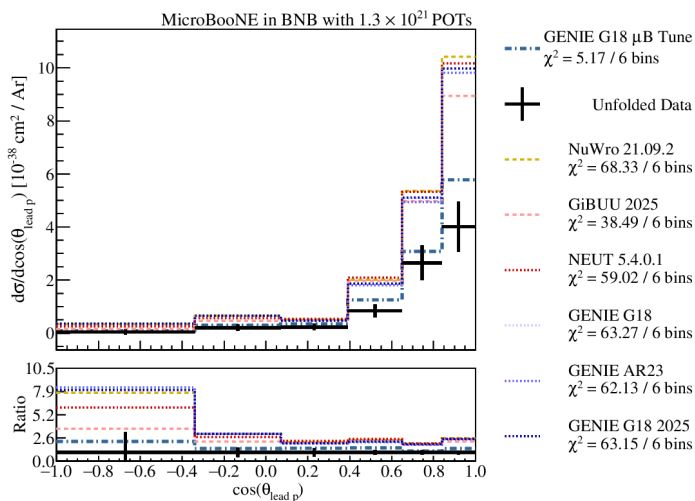
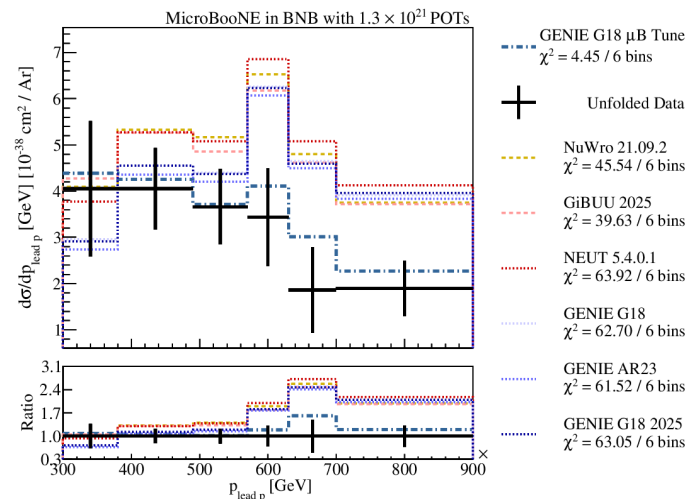


KINEMATIC VARIABLES (PROTONS)

WITH FSI

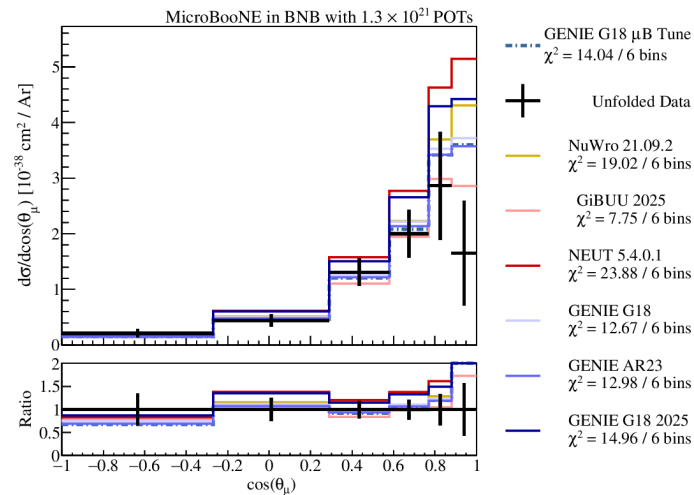
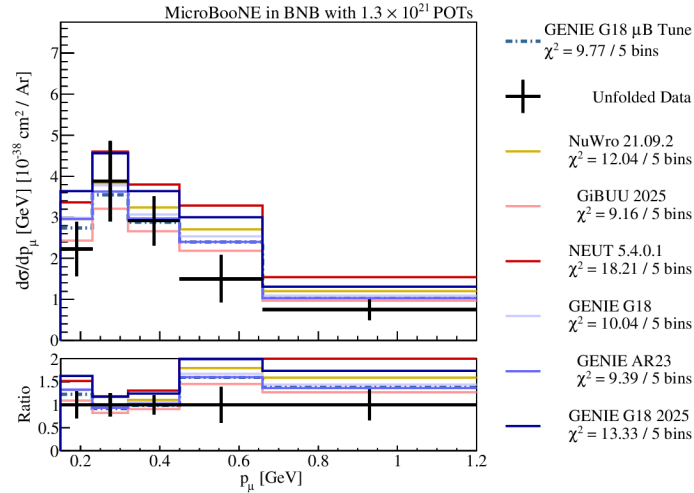


WITHOUT FSI

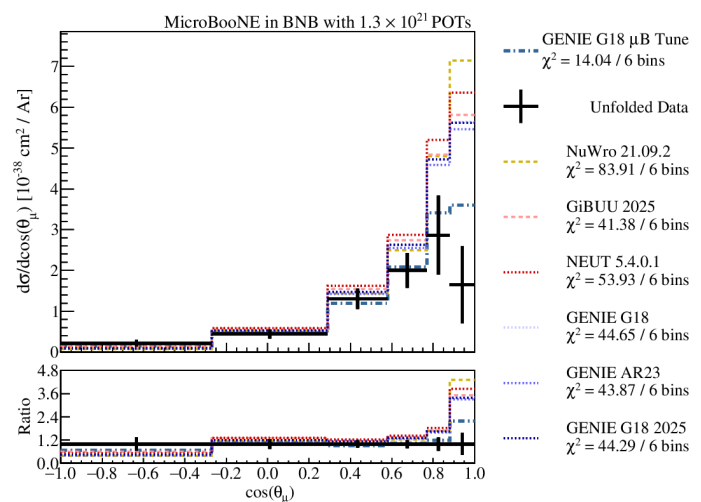
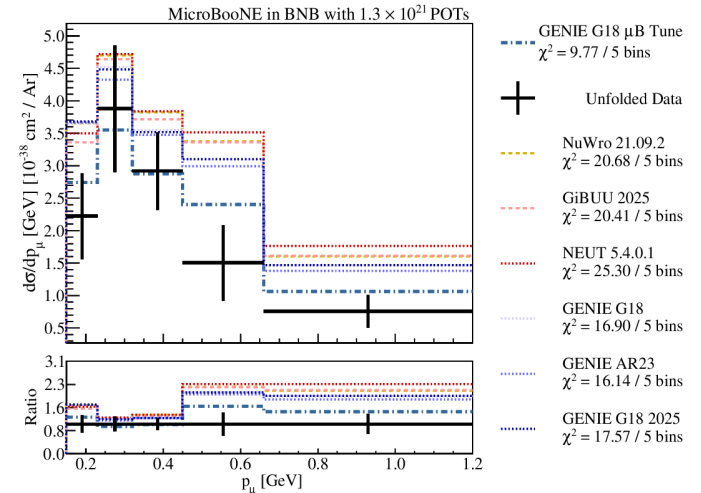


KINEMATIC VARIABLES (MUONS)

WITH FSI

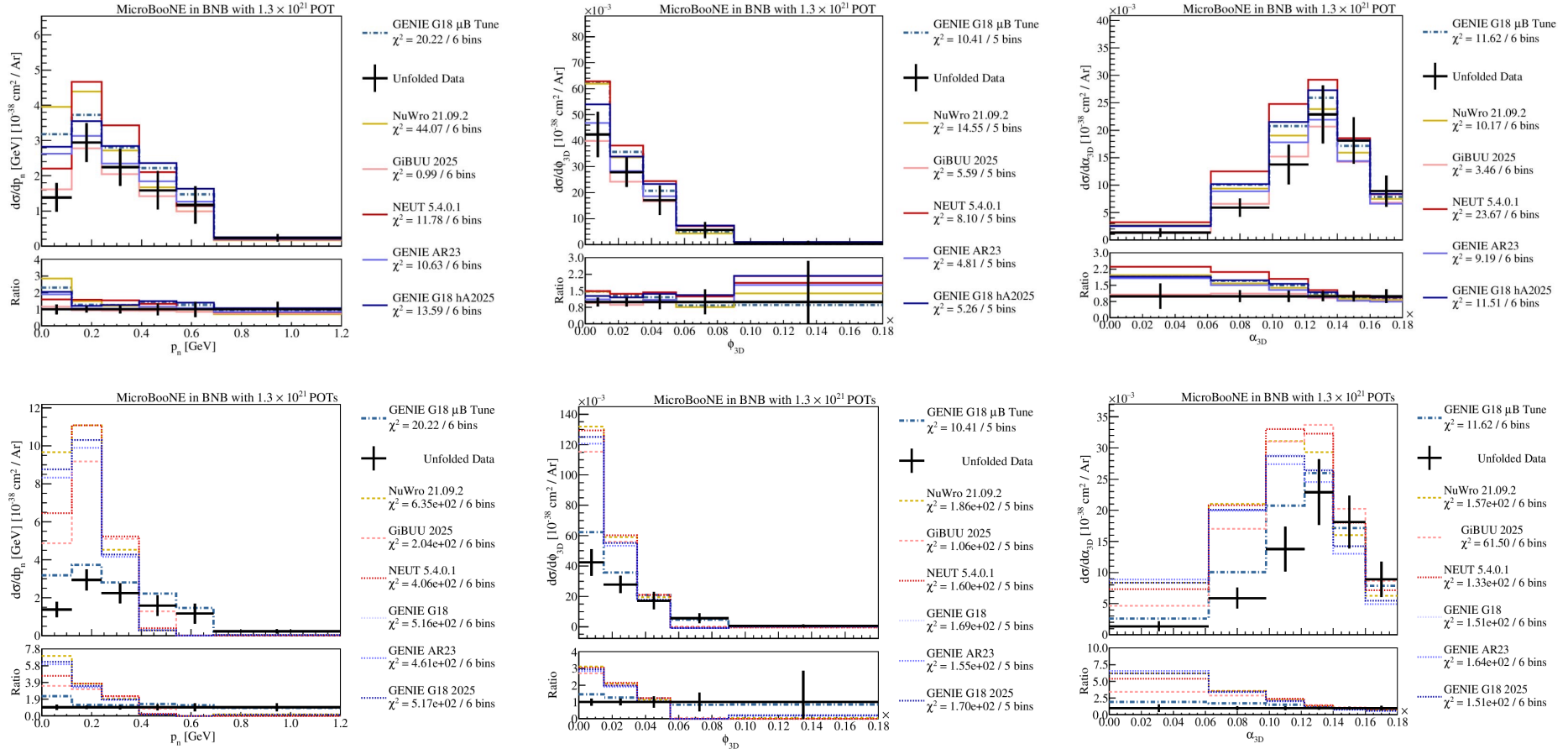


WITHOUT FSI



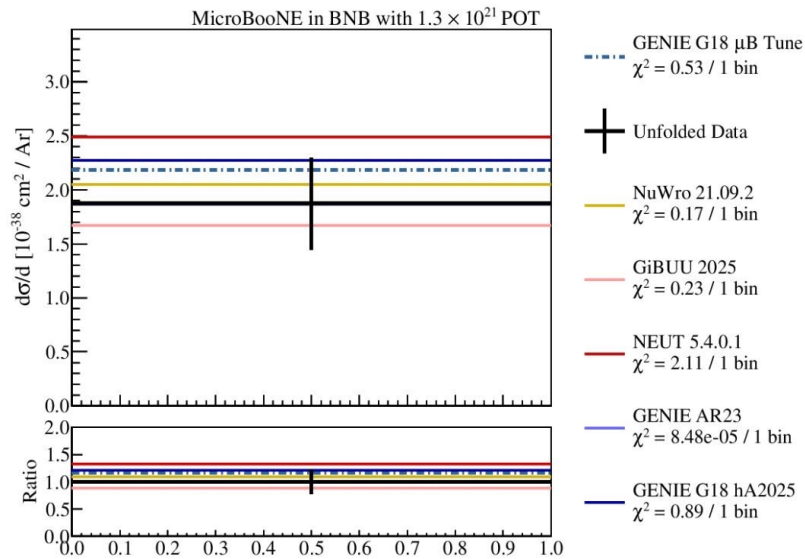
GKI VARIABLES

WITH FSI

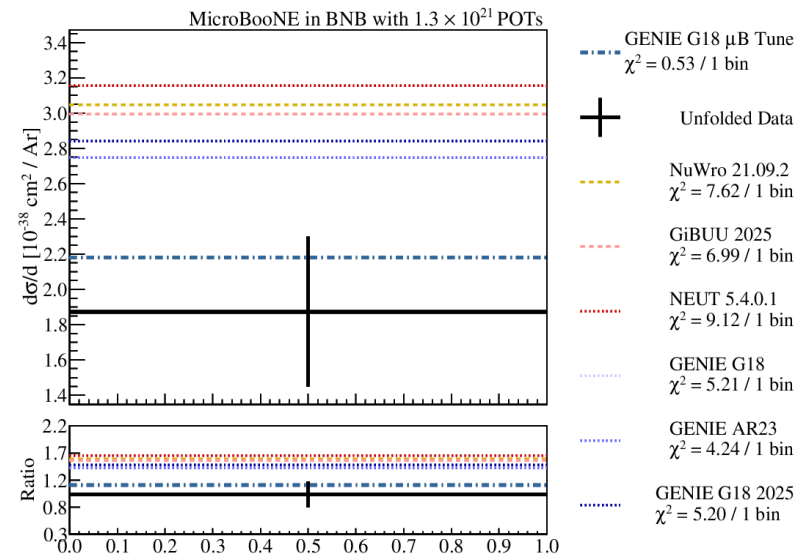


TOTAL

WITH FSI



WITHOUT FSI



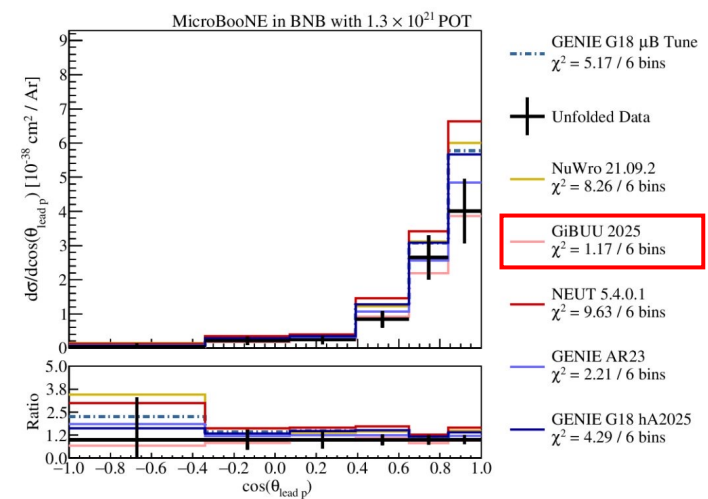
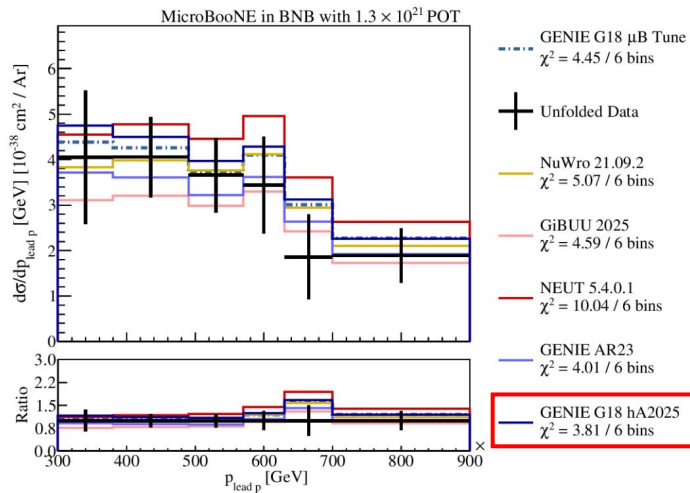
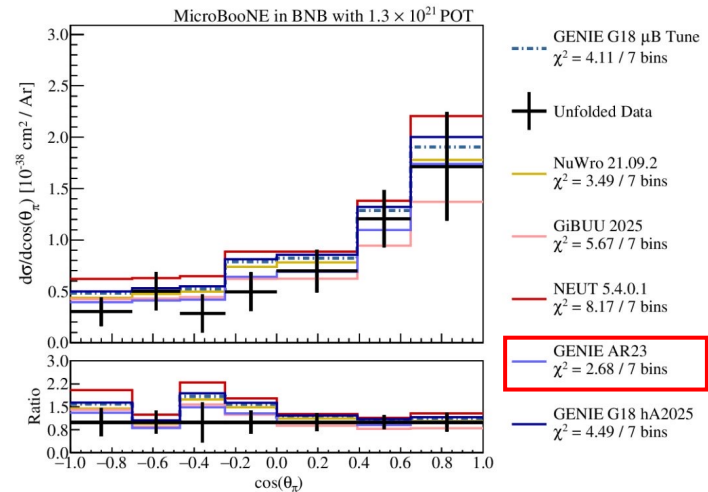
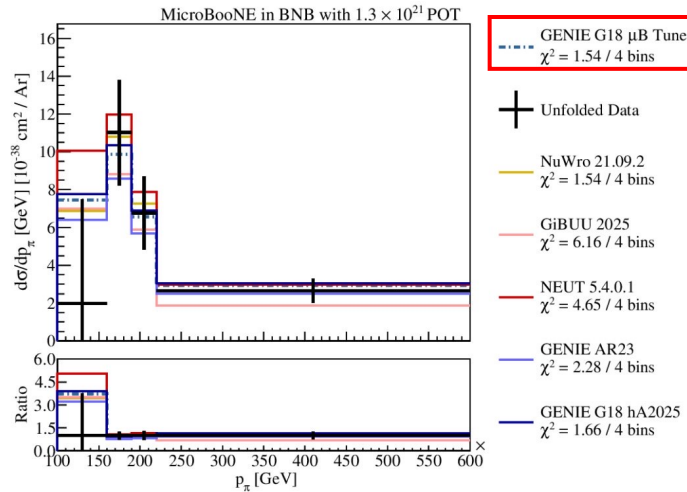
BACKUP SLIDES

RESULTS



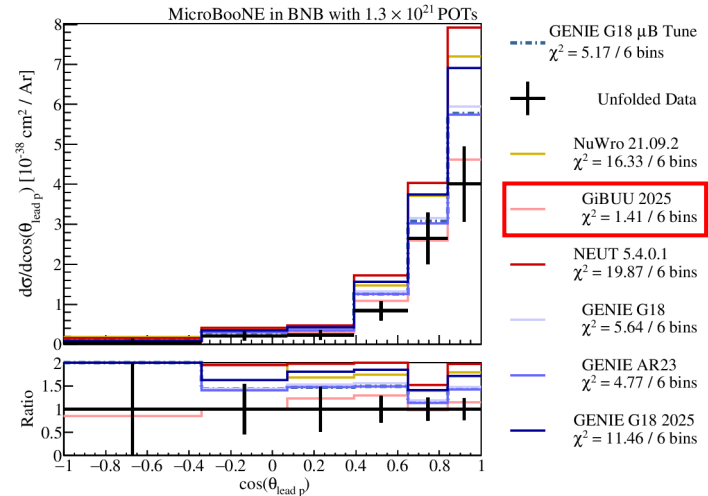
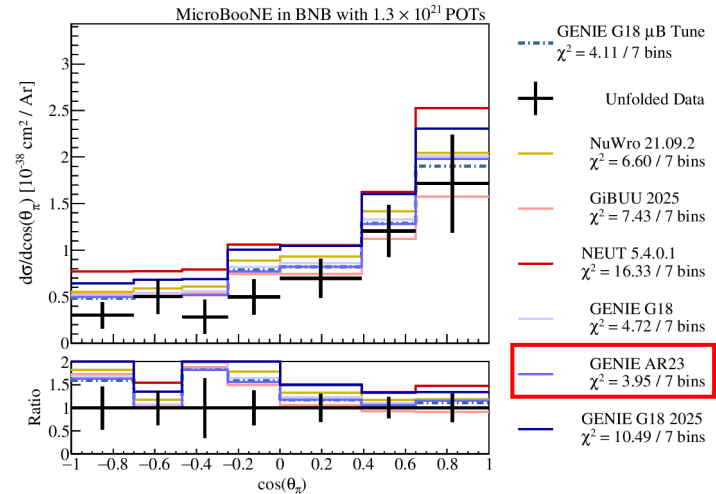
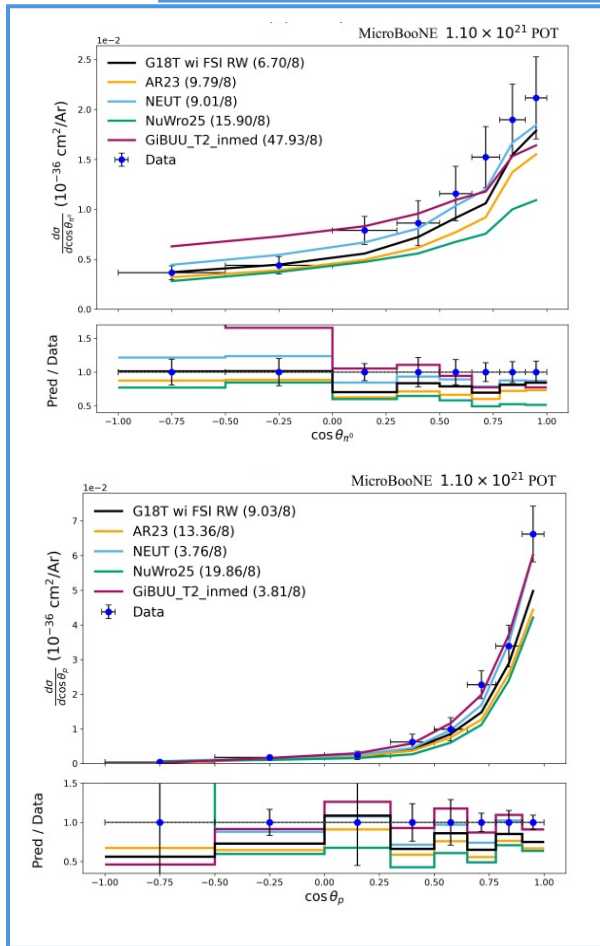
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KINEMATIC VARIABLES (π & lead p)



KINEMATIC VARIABLES (π & lead p)

MicroBooNE Document 46143-v6

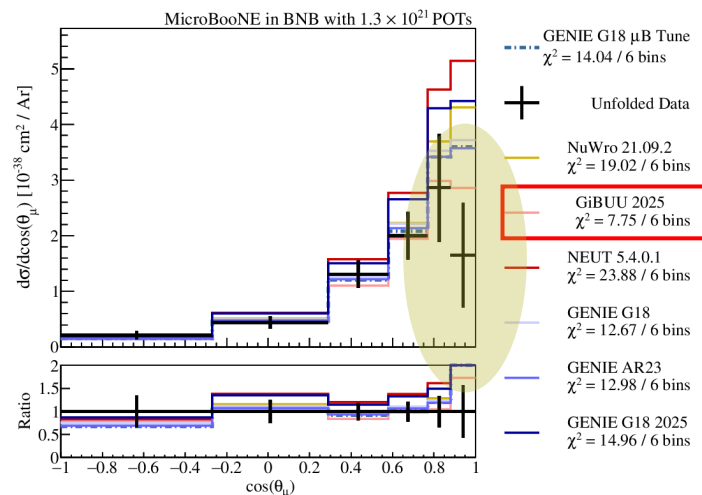
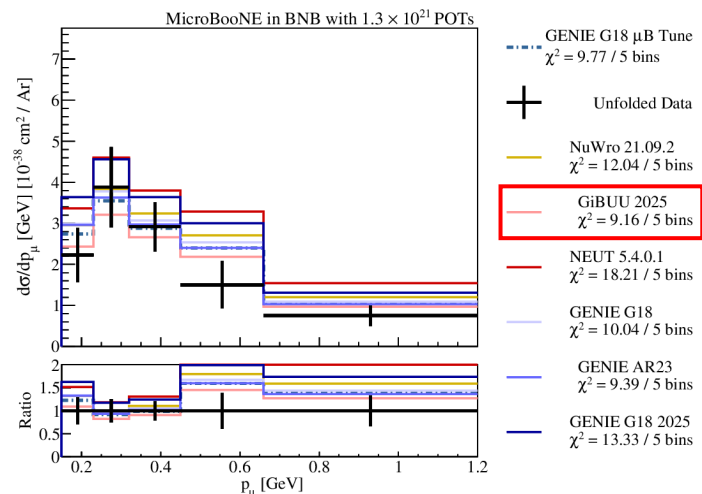
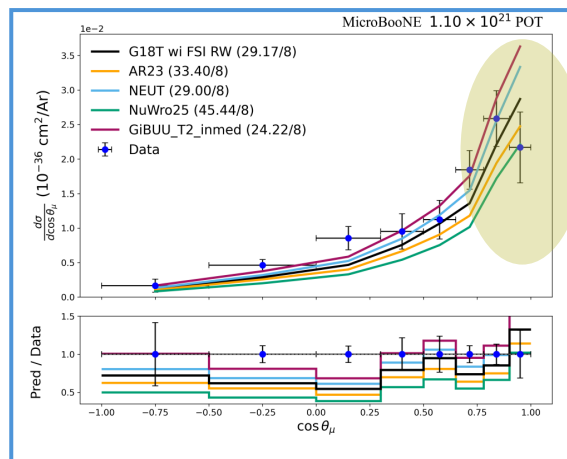


KINEMATIC VARIABLES (μ)

In terms of the muon kinematics general observed trend remains, and discrepancy with data observed in the forward direction (low- Q^2).

Effect generally associated to random phase approximation (RPA).

This was also seen in [MicroBooNE Document 46143-v6](#)

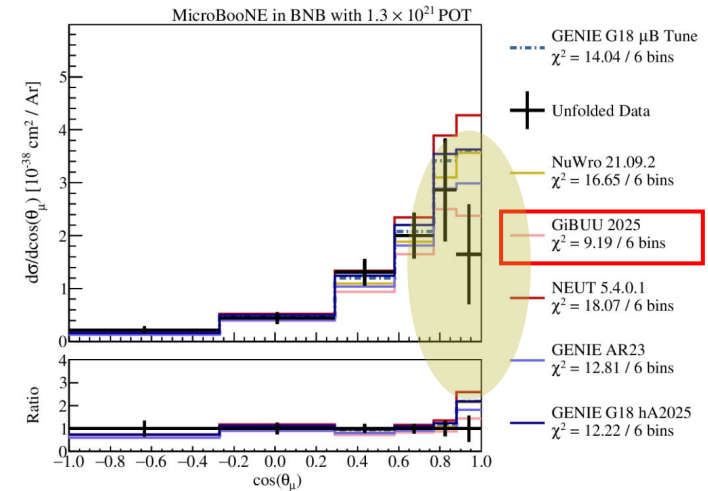
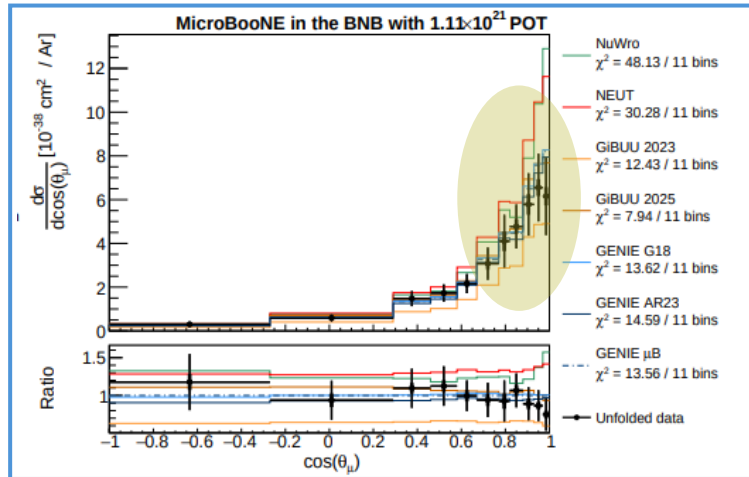
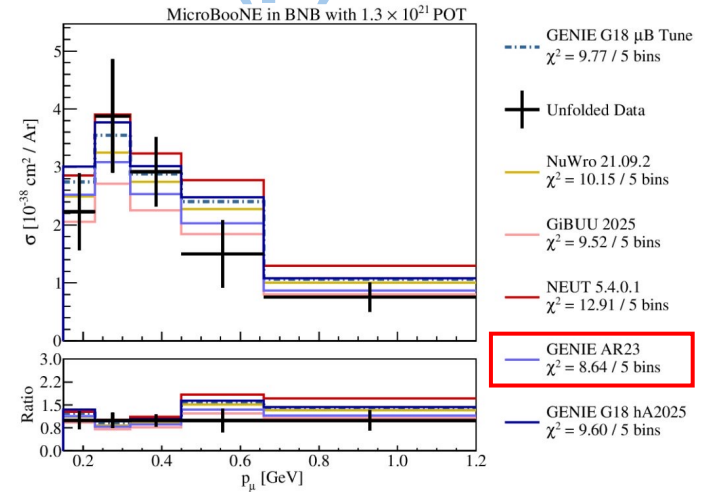


KINEMATIC VARIABLES (μ)

In terms of the muon kinematics general observed trend remains, and discrepancy with data observed in the forward direction (low- Q^2).

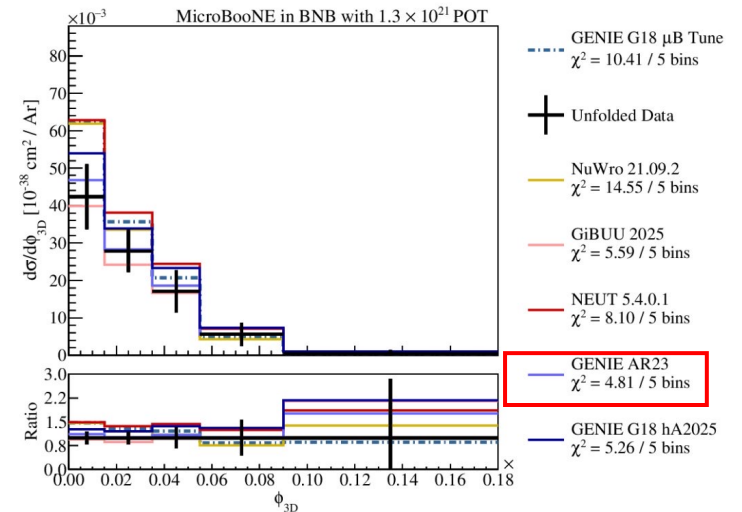
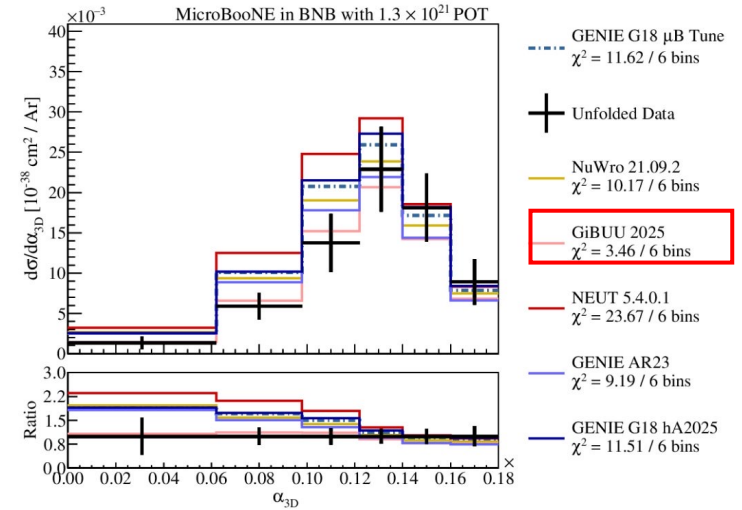
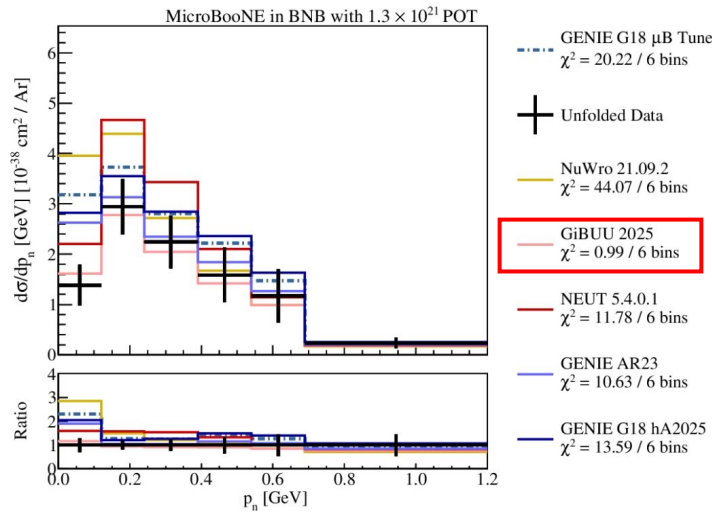
Effect generally associated to random phase approximation (RPA).

This was also seen in [MicroBooNE Document 46143-v6](#) and in [Phys. Rev. D 113, 032007 \(2026\)](#)



GKI OBSERVABLES

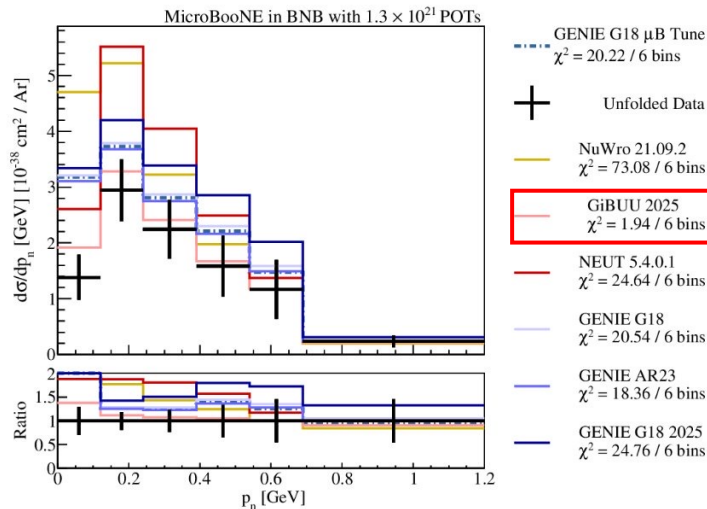
GiBUU provides the best overall description of the GKI observables.



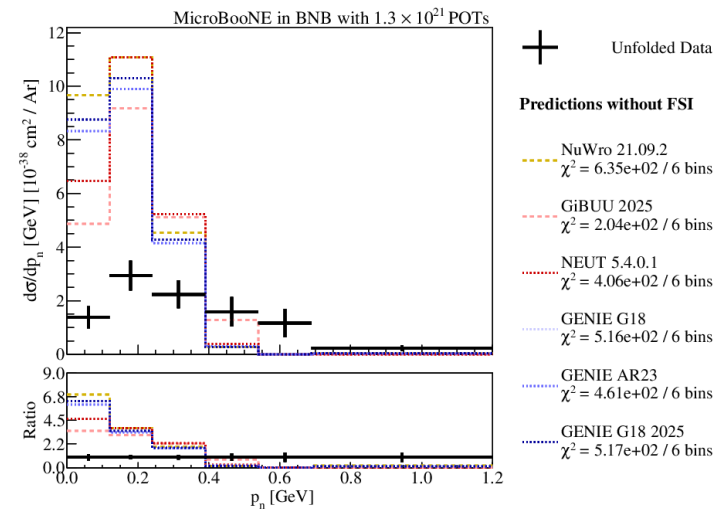
GKI OBSERVABLES

The removal of FSI produces a pronounced enhancement at low missing momentum together with a suppression of the high- p_n tail, indicating that rescattering processes generate additional momentum imbalance and populate the large- p_n region

WITH FSI



WITHOUT FSI

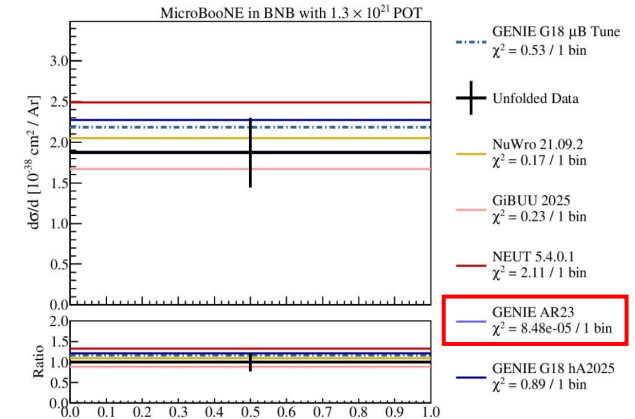


TOTAL CROSS-SECTION

The total measured cross-section is of:

$$\sigma = (1.873 \pm 0.085 \text{ (stat.)} \pm 0.416 \text{ (syst.)}) \times 10^{-38} \text{ cm}^2/\text{Ar}$$

SUMMARY TABLE



Observable	NDF	GENIE G18 μ B Tune	NuWro	GiBUU	NEUT	GENIE G18	GENIE AR23	GENIE G18 2025
p_μ	5	9.77	12.04	9.16	18.21	10.04	9.39	13.33
$\cos \theta_\mu$	6	14.04	19.02	7.75	23.88	12.67	12.98	14.96
p_π	4	1.54	2.84	4.14	8.75	1.7	1.56	4.95
$\cos \theta_\pi$	7	4.11	6.60	7.43	16.33	4.72	3.95	10.49
$p_{\text{lead } p}$	6	4.45	8.01	5.21	17.02	4.95	5.03	7.68
$\cos \theta_{\text{lead } p}$	6	5.17	16.33	1.41	19.87	5.64	4.77	11.46
p_n	6	20.22	73.08	1.94	24.64	20.54	18.36	24.76
α_{3D}	6	11.62	15.96	4.12	36.48	12.31	13.11	19.01
ϕ_{3D}	5	10.41	23.32	5.57	15.65	7.16	6.47	9.79
Total cross section	1	0.53	1.74	0.06	6.43	1	0.61	4.27

BACKUP SLIDES

GOLDEN PION SELECTION

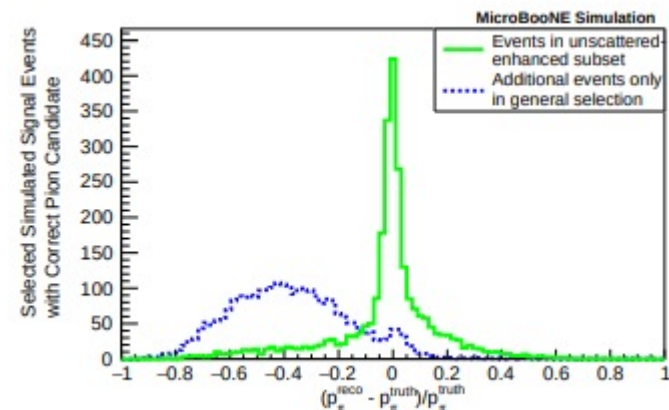


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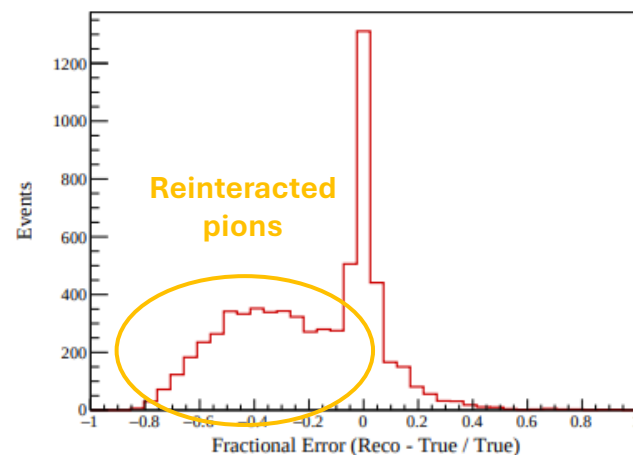
GOLDEN PION SELECTION

GIST BEHIND THIS SELECTION CUT

- Pion reconstruction when they reinteract is poor.
- P. Detje used a BDT to remove those reinteracting events
(/exp/uboone/app/users/jdetje/cc1pi_handover_57_2/Fe
bPeLEE4/goldenPion_BDT.root).
- Files reprocessed to include this again using the
ubcc1pi framework .



[J. P. Detje Paper](#)



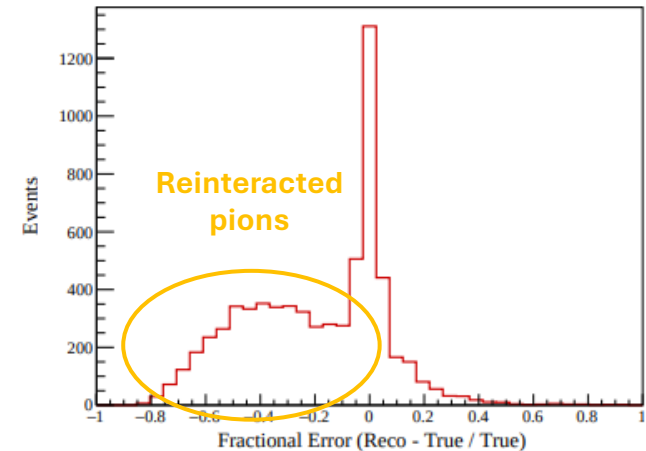
GOLDEN PION SELECTION

CONCERNS

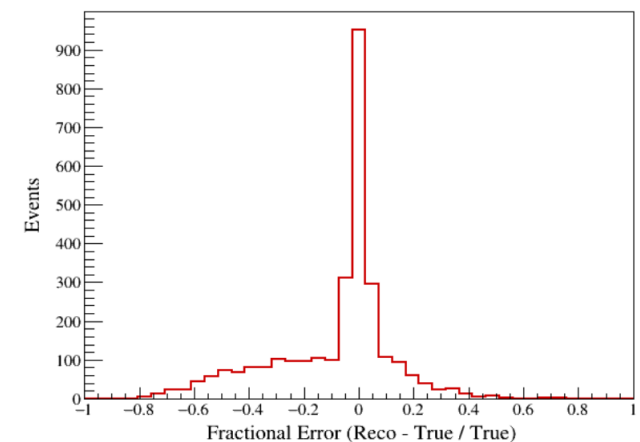
The BDT does cut out misreconstructed events. However:

- The statistic of the study are compromised:
 - # signal events: 1295 $\rightarrow$ 581
 - # selected events: 2112 $\rightarrow$ 911
 - Efficiency: 7.73 $\rightarrow$ 3.93%
 - Purity: 61.32 $\rightarrow$ 63.78%
- I have done series of investigations into whether the poor reconstruction of the non-golden pions has a significant impact on the response matrices of the variables of interest.

WITHOUT GOLDEN BDT SELECTION



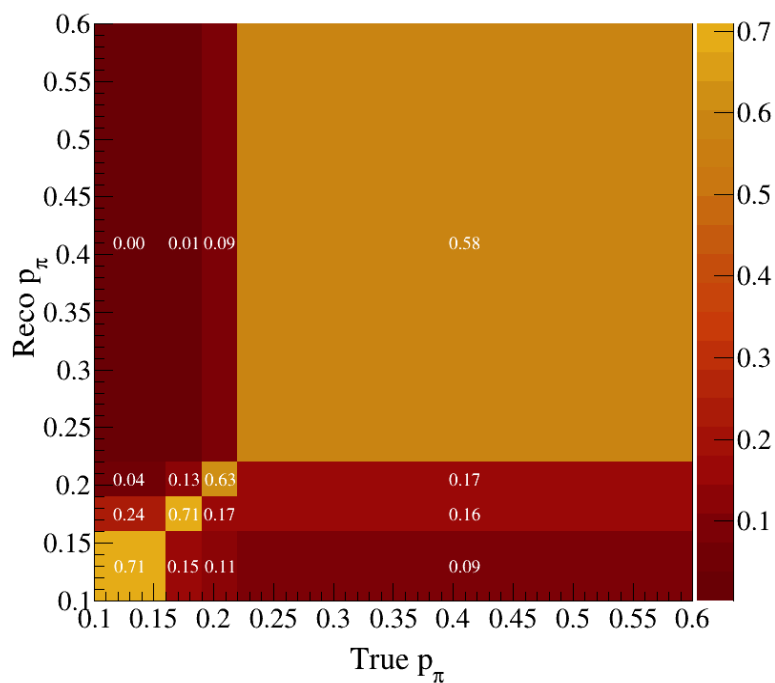
WITH GOLDEN BDT SELECTION



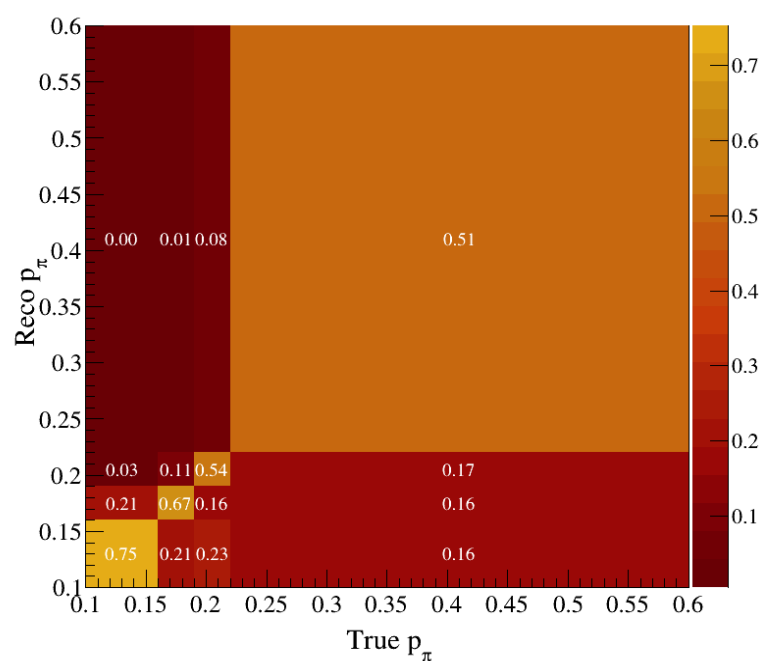
GOLDEN PION SELECTION

COMPARISON OF SELECTION

WITH GOLDEN BDT SELECTION



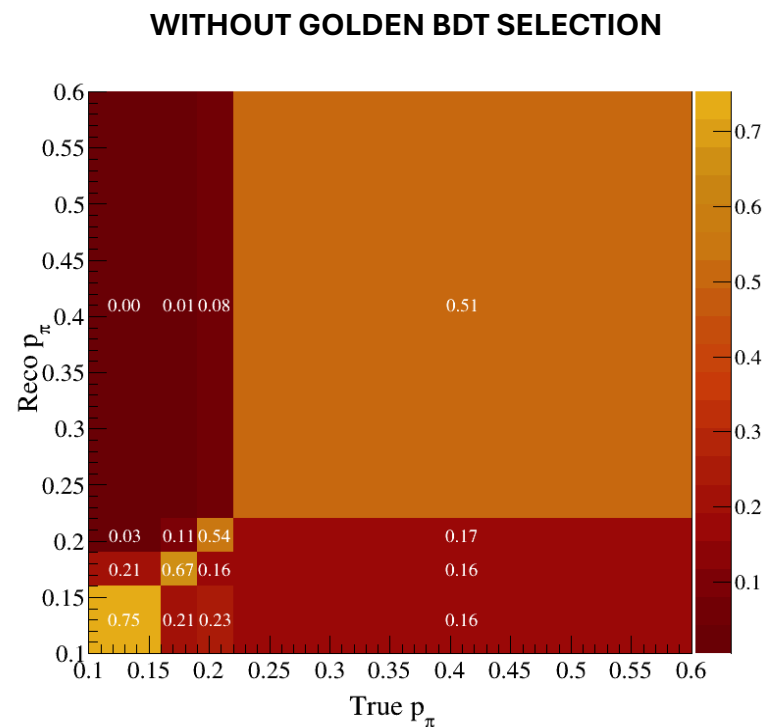
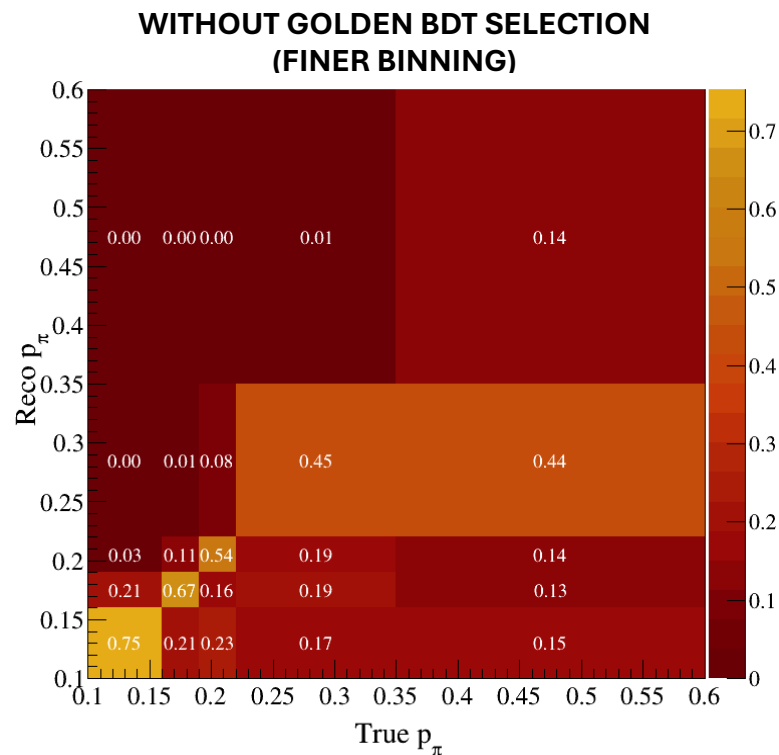
WITHOUT GOLDEN BDT SELECTION



GOLDEN PION SELECTION

COMPARISON OF SELECTION

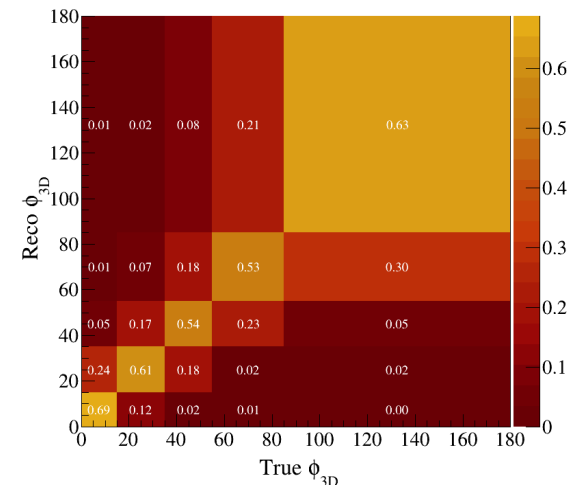
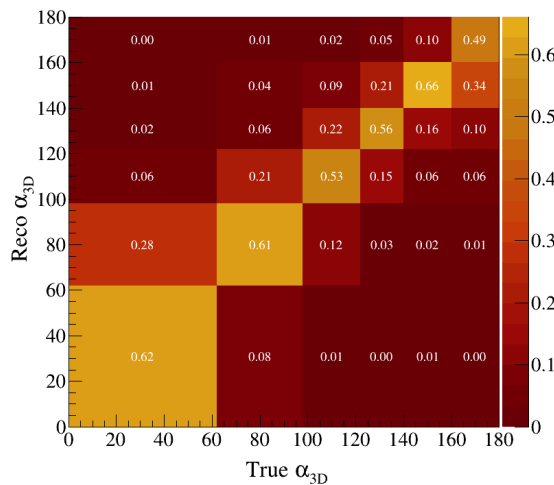
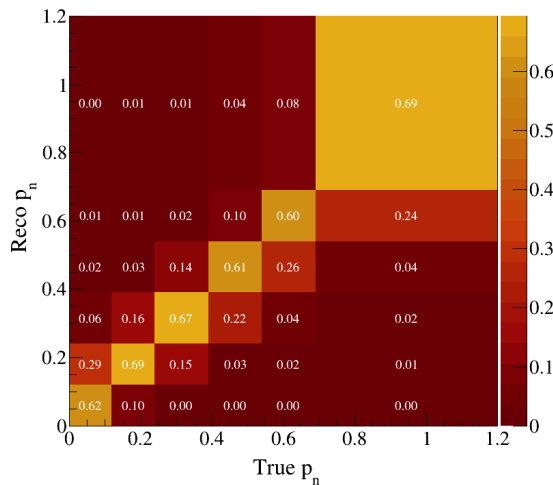
Finer bin studies highlighted the necessity to define the bin scheme such that all these high-energy pions fall into the same bin.



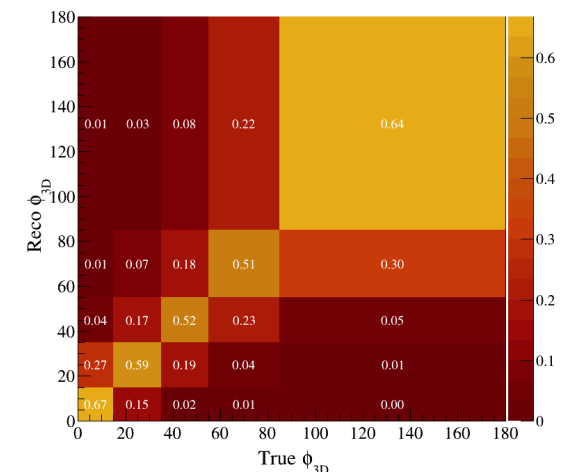
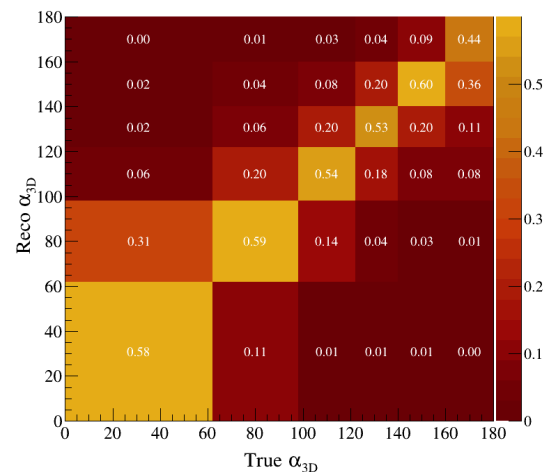
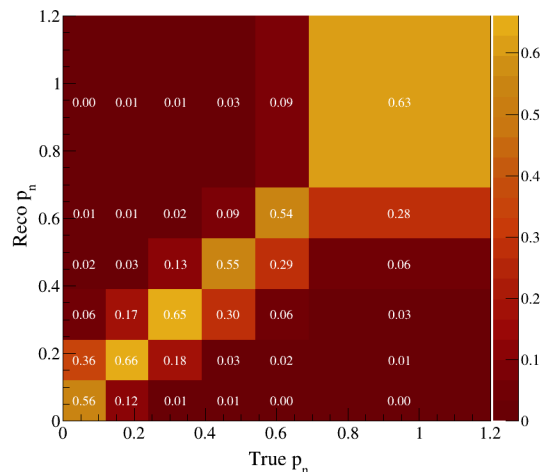
GOLDEN PION SELECTION

DOES IT AFFECT THE GKI VARIABLES?

WITH GOLDEN BDT

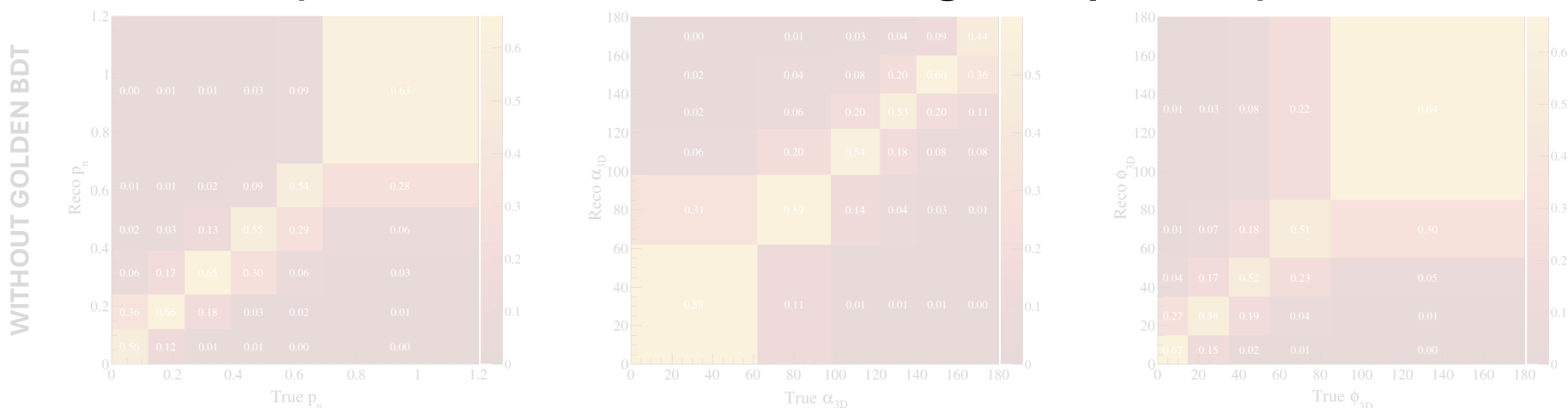
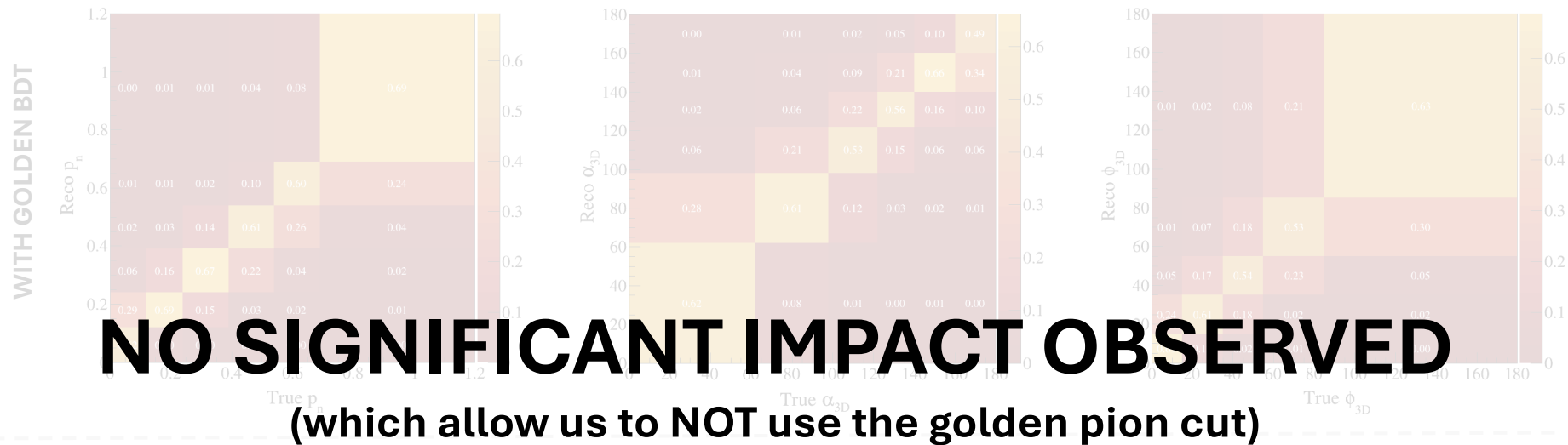


WITHOUT GOLDEN BDT



GOLDEN PION SELECTION

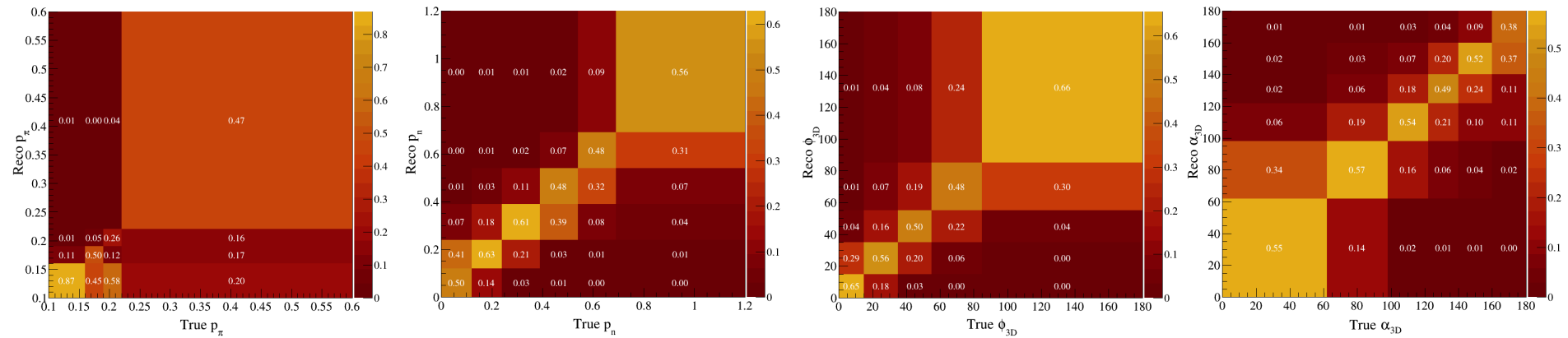
DOES IT AFFECT THE GKI VARIABLES



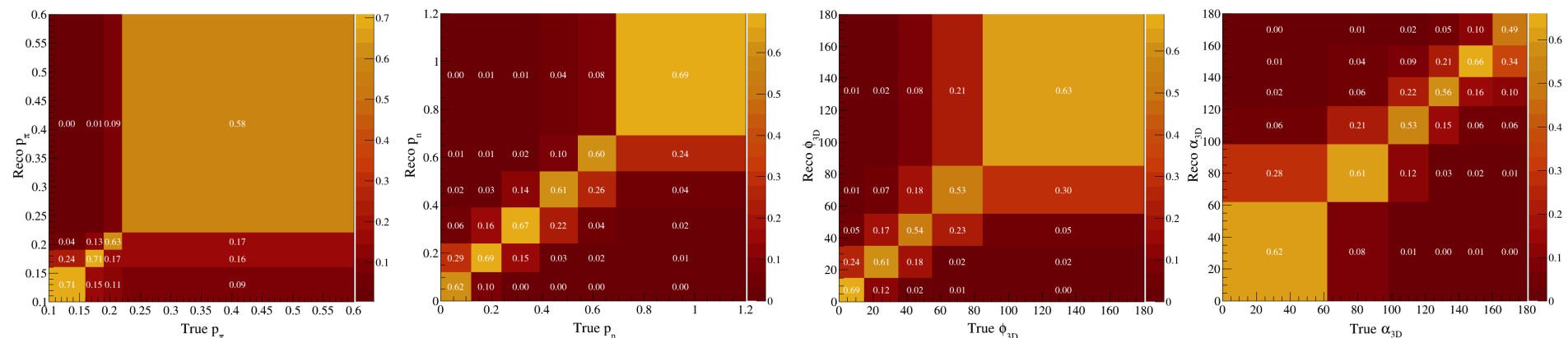
GOLDEN AND NOT GOLDEN PIONS

HOW DOES THE GOLDEN PION SELECTION AFFECT GKI VARIABLES?

EVENTS **NOT** PASSING THE GOLDEN BDT SELECTION (I.E., SCATTERING)



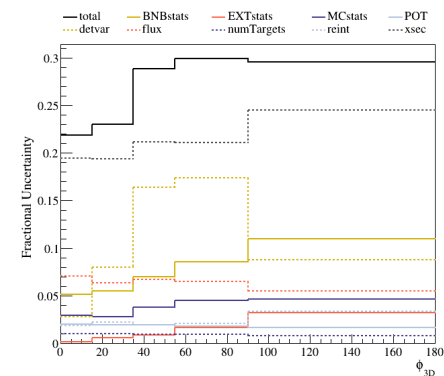
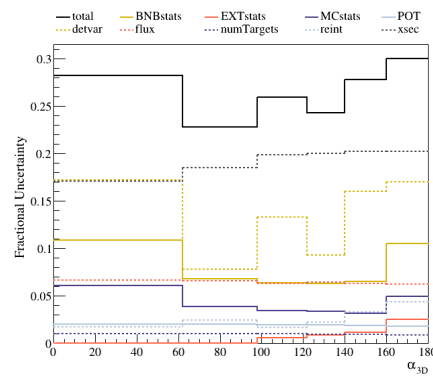
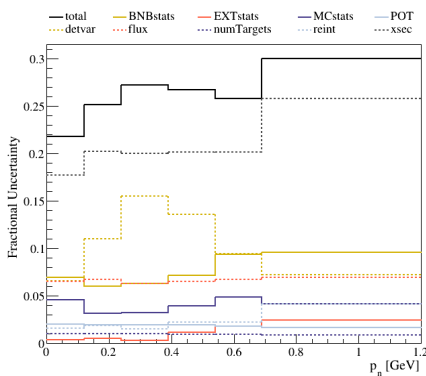
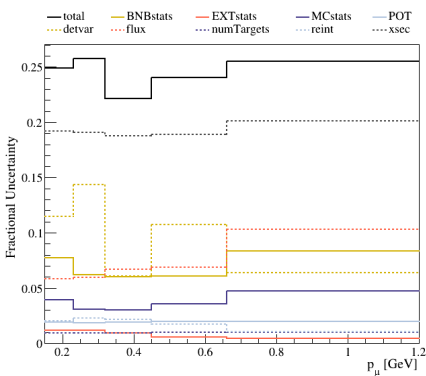
EVENTS PASSING THE GOLDEN BDT SELECTION (I.E., **NOT** SCATTERING)



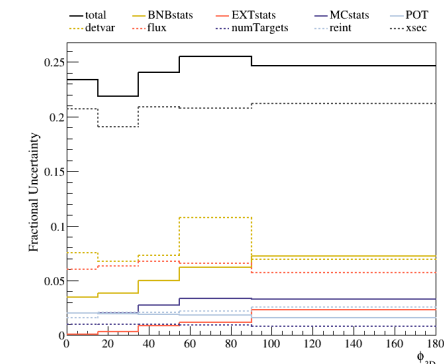
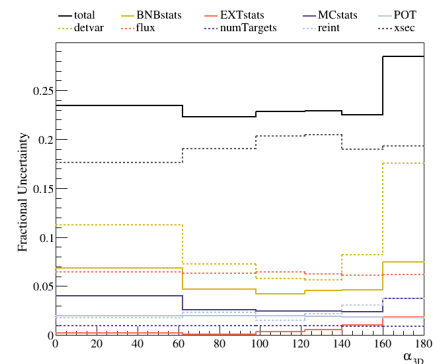
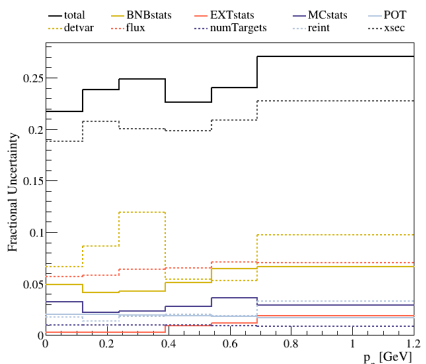
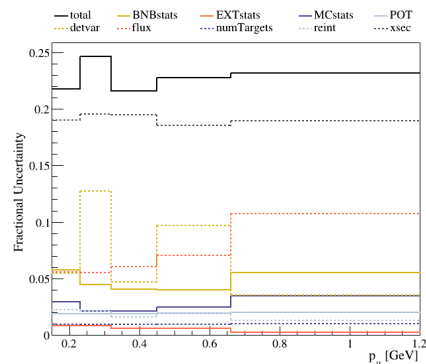
SYSTEMATICS

(NOT) REQUIRING GOLDEN PIONS IN THE SELECTION

WITH GOLDEN PIONS REQUIRED



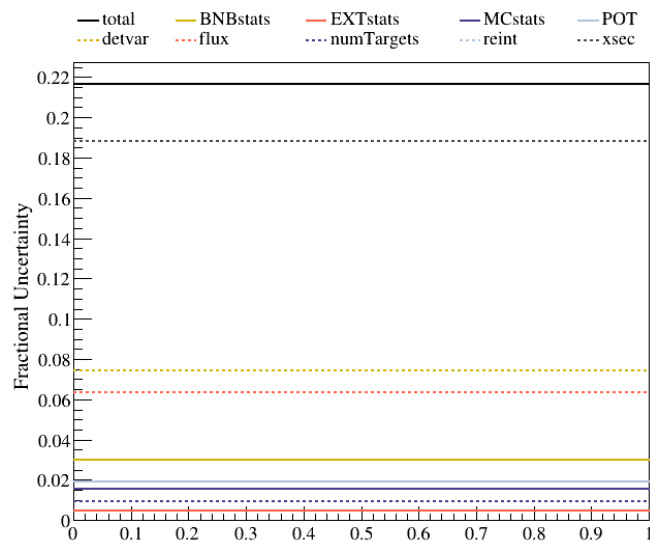
WITHOUT REQUIRING GOLDEN PIONS



SYSTEMATICS

(NOT) REQUIRING GOLDEN PIONS IN THE SELECTION

WITH GOLDEN PIONS REQUIRED



WITHOUT REQUIRING GOLDEN PIONS

