arXiv:2310.06082

Kinematic Imbalance Measurements with pionless events at MicroBooNE

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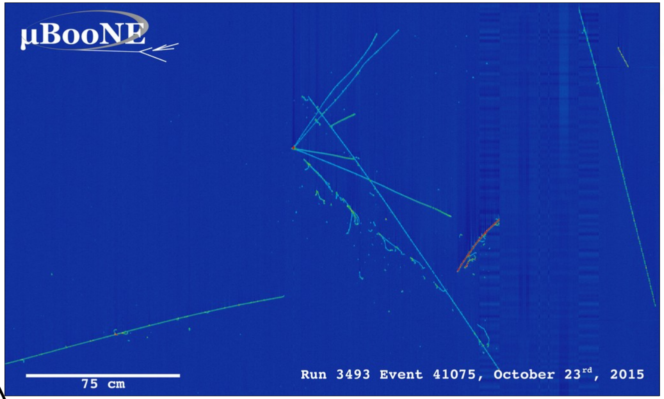
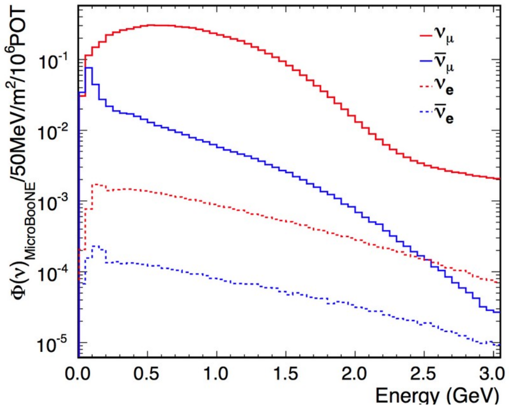
NuInt 2024, Sao Paulo, Brazil

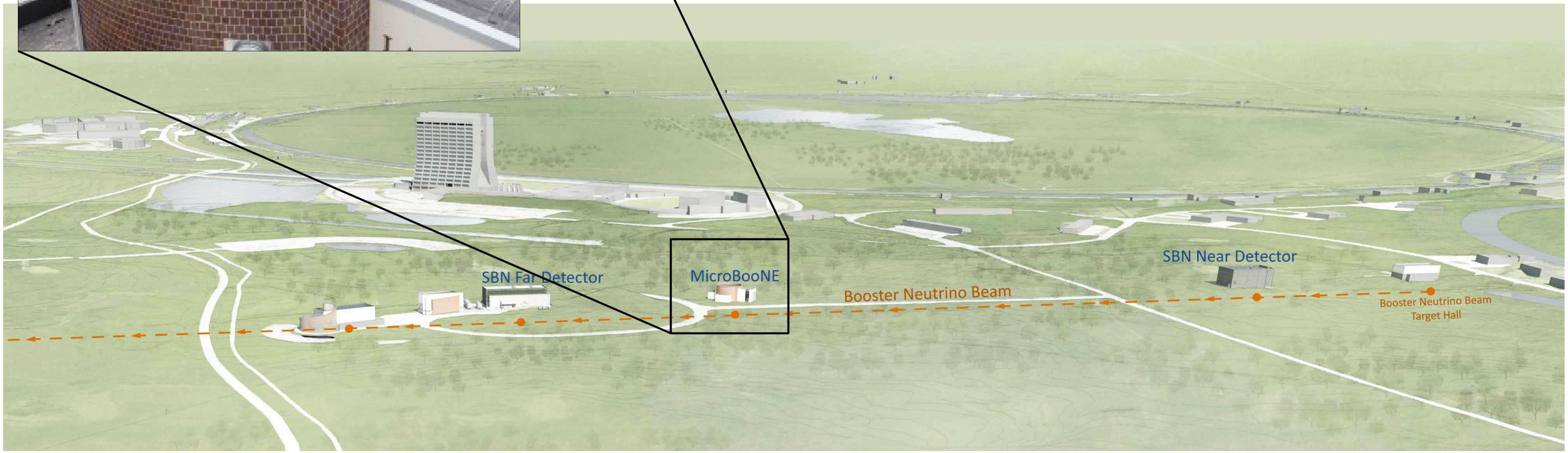
MicroBooNE



μBooNE
75 cm
Run 3493 Event 41075, October 23rd, 2015



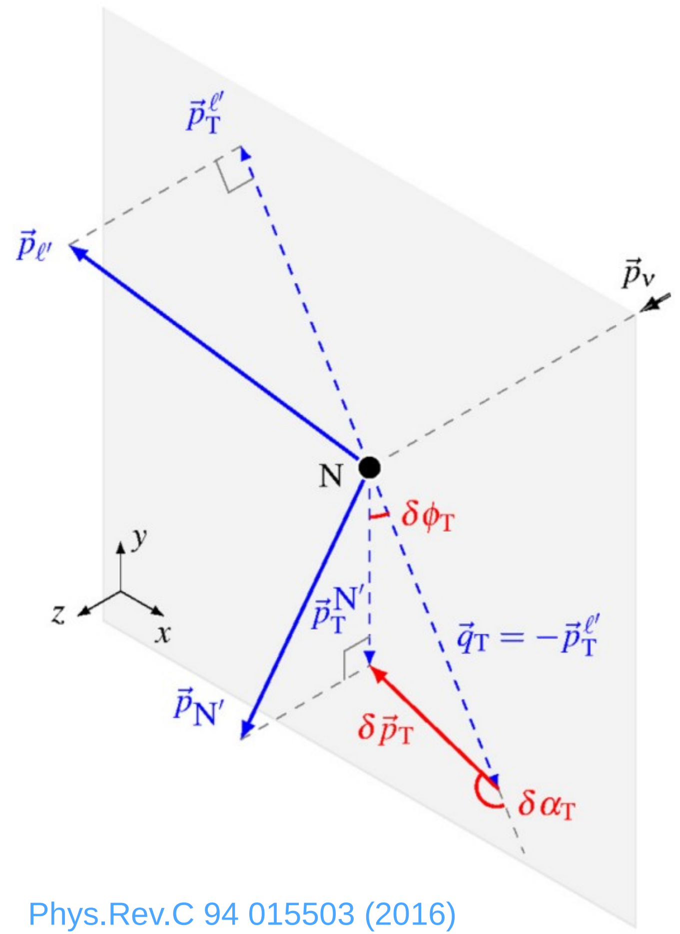
$\Phi(\nu)_{MicroBooNE}/50MeV/m^2/10^6POT$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.0 0.5 1.0 1.5 2.0 2.5 3.0
Energy (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$



SBN Far Detector
MicroBooNE
Booster Neutrino Beam
SBN Near Detector
Booster Neutrino Beam Target Hall

Transverse Kinematic Imbalance

- We know the initial momentum perpendidular to the beam is zero
- Measuring non-zero transverse momentum tells us about *missing momentum*
- Three primary variables measured:
  - δp_T
  - $\delta \alpha_T$
  - $\delta \phi_T$



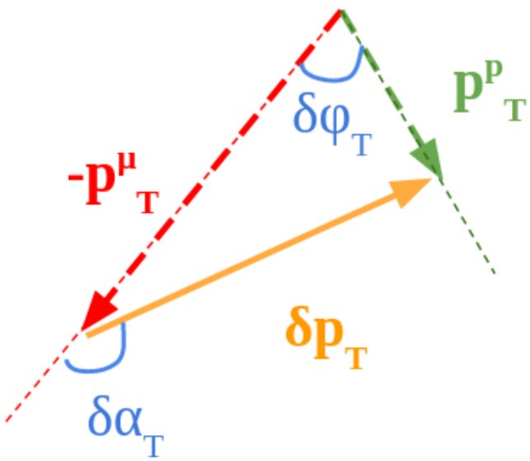
Phys.Rev.C 94 015503 (2016)

What does δp_T mean?

- Non-zero value is due to missing momentum
  - δp_T is the negative of the missing momentum
- In the absence of FSI, this will be the (transverse) momentum of the struck nucleon

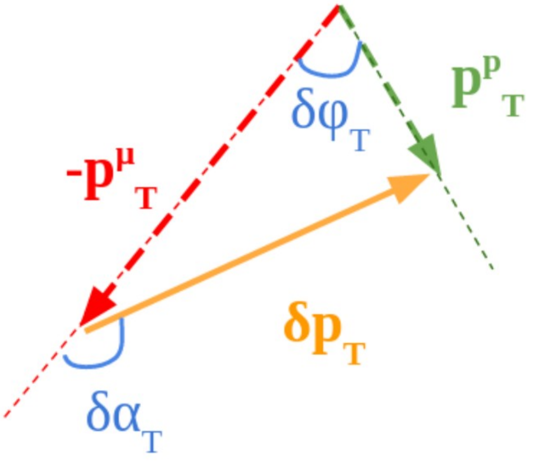
What does $\delta\alpha_T$ mean?

- $-p^{\mu}_T$ is the transverse momentum transfer
  - $\delta\alpha_T$ is the angle between the momentum transfer and the missing momentum (δp_T)
  - In the transverse plane
- In the absence of FSI, this is the angle between momtentum transfer and initial state nucleon direction
  - And there should be no directional preference



What does $\delta\phi_T$ mean?

- Similarly, $\delta\phi_T$ is the angle between the momentum transfer and the total hadron momentum
  - Or the leading proton momentum, depending on your choice



What transverse variables miss

- All these variables are 2D projections of a 3D system
- Sometimes that 3rd dimension contains a lot of additional information!

Longitudinal component

- We know more than the initial transverse momentum
- We know (near enough) the neutrino mass is zero
- And therefore we have *two measures* of the neutrino energy – energy and momentum should be equal
- Assuming there is no missing momentum/energy:

$$E_\nu = E_\mu + K_p + B = p_L^\mu + p_L^p$$

B = 30.9 MeV

Longitudinal missing momentum

- If the nuclear recoil carries away all missing momentum, there is negligible missing energy

Neutrino energy estimate

$$E_{\text{cal}} = E_\mu + K_p + B$$

Longitudinal missing momentum

$$p_L = p_L^\mu + p_L^p - E_{\text{cal}}$$

Estimated momentum transfer

$$\vec{q} = E_{\text{cal}}\hat{z} - \vec{p}_\mu$$

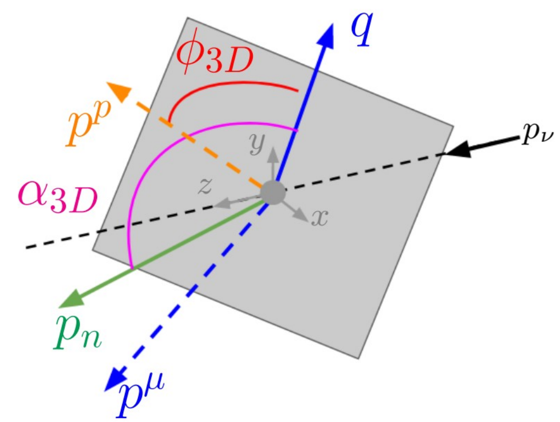
Generalised Kinematic Imbalance

$$p_n = |\vec{p}_n| = \sqrt{p_L^2 + \delta p_T^2}$$

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

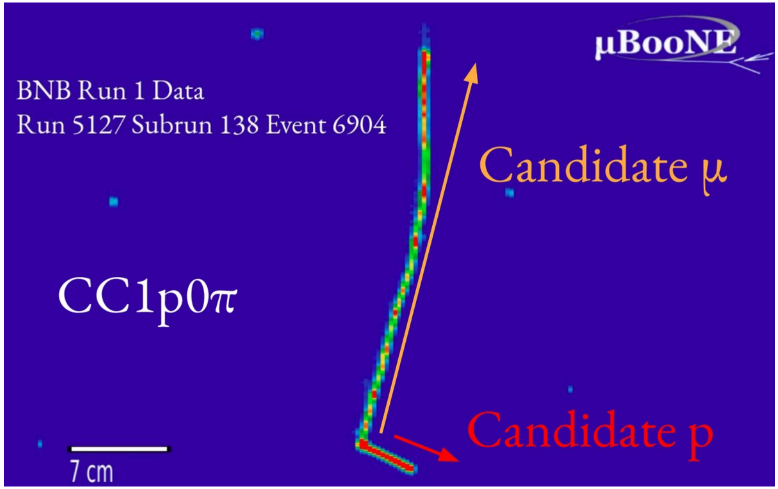
$$\alpha_{3D} = \cos^{-1}\left(\frac{\vec{q}\cdot\vec{p}_n}{|\vec{q}||\vec{p}_n|}\right)$$

- All built as direct analogues of the transverse equivalents
- Note, these are well-defined even if our assumptions are wrong
  - And in fact, there's physics to be seen when our assumptions fail



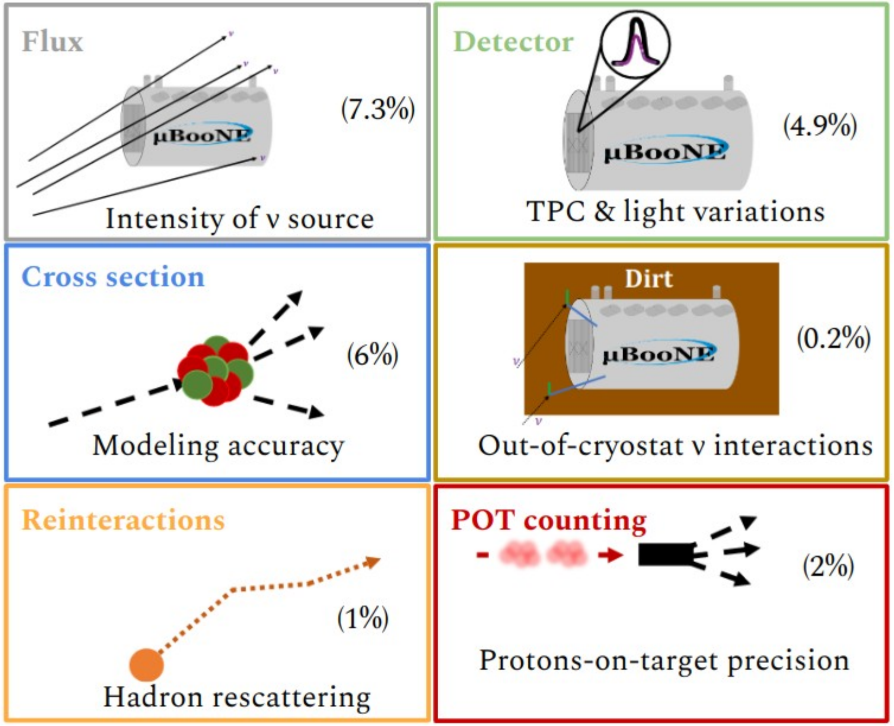
Signal Definition

- We measure these with the simplest topology we can: one muon, one proton
  - Also happens to be a very common topology…
- Specifically:
  - One muon (100 MeV/c – 1200 MeV/c)
  - One proton (300 MeV/c – 1000 MeV/c)
  - No charged pions over 70 MeV/c
  - No neutral pions or heavier mesons
  - Any number of neutrons
- Low thresholds due to reconstruction
- High limits due to containment and re-interactions



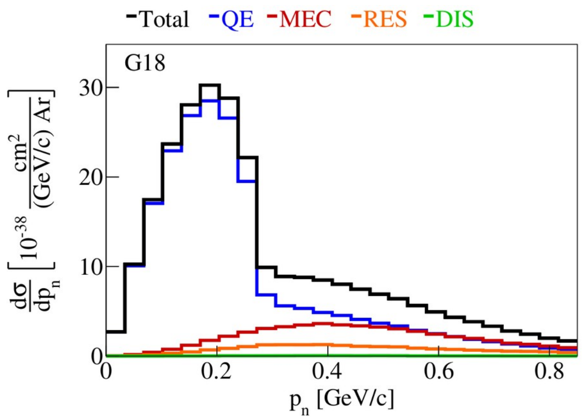
How we make the measurement

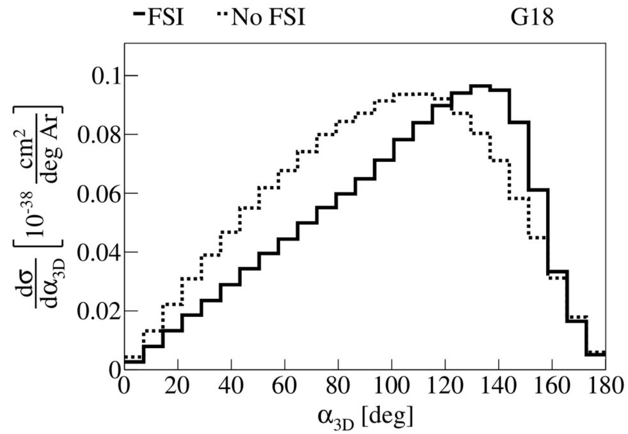
- Select events with:
  - One muon-like track
  - One proton-like track
  - Nothing else
- Estimate uncertainties on *predicted event rate*
  - This includes flux normalisation and shape
  - Does not include signal uncertainties, other than impact on smearing/efficiency
- Transform to regularised space
  - And include matrix that converts truth space to regularised space
- Scale for exposure (flux, targets)

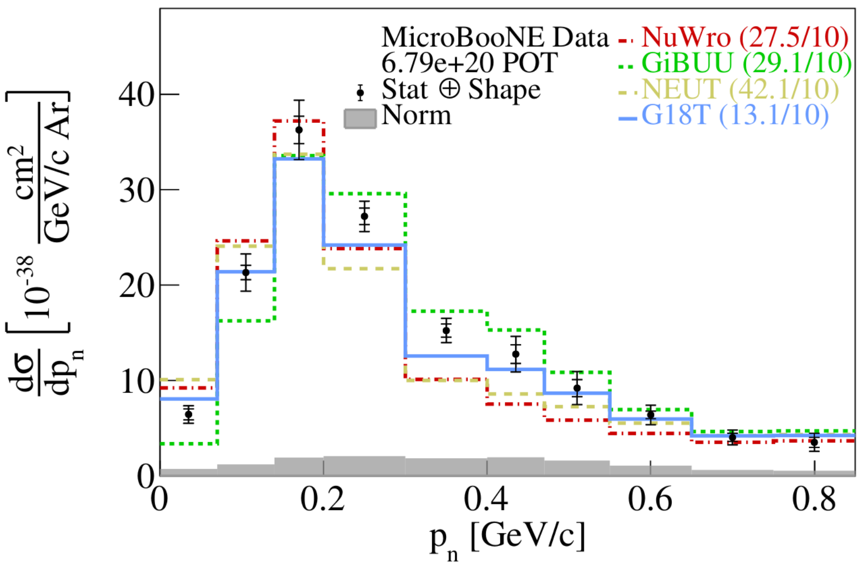


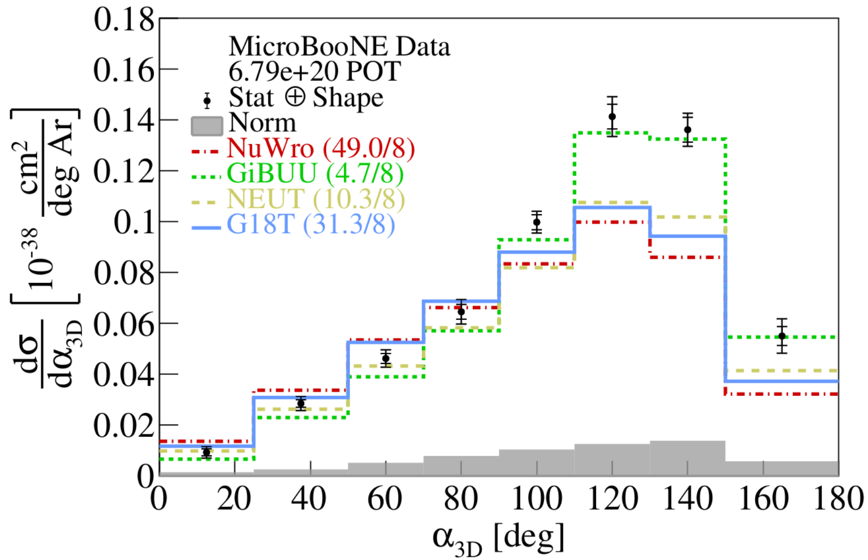
$$N_{pred}(x_r) = \sum_t U_{tr} \int \phi(E_\nu)\, \sigma(E_\nu, x_t)\, dE_\nu + B_r$$

Data!


Total QE MEC RES DIS
G18
$\frac{d\sigma}{dp_n}$ $[10^{-38} \frac{cm^2}{(GeV/c)\ Ar}]$
p_n [GeV/c]

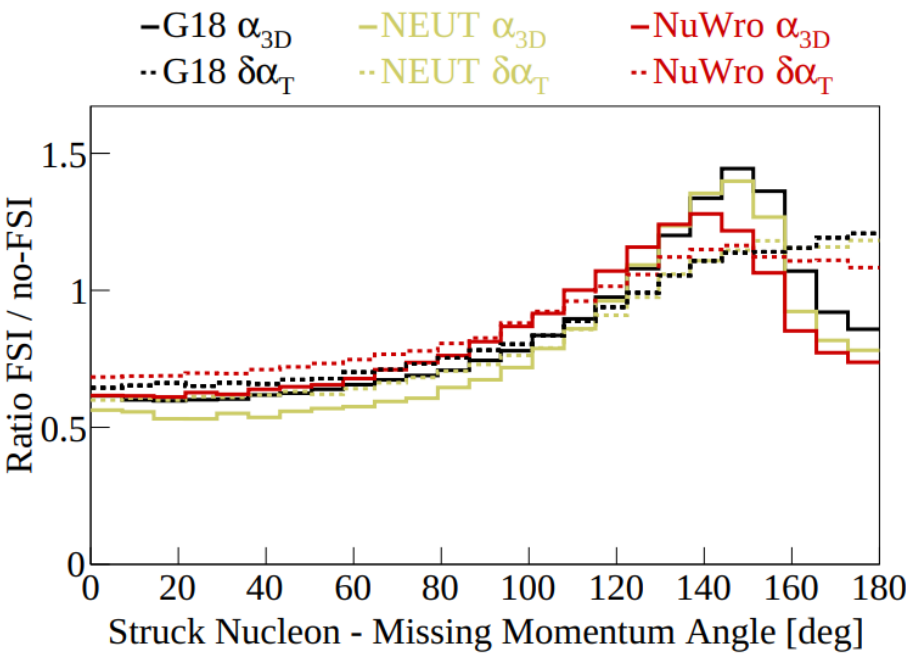

FSI No FSI G18
$\frac{d\sigma}{d\alpha_{3D}}$ $[10^{-38} \frac{cm^2}{deg\ Ar}]$
α_{3D} [deg]

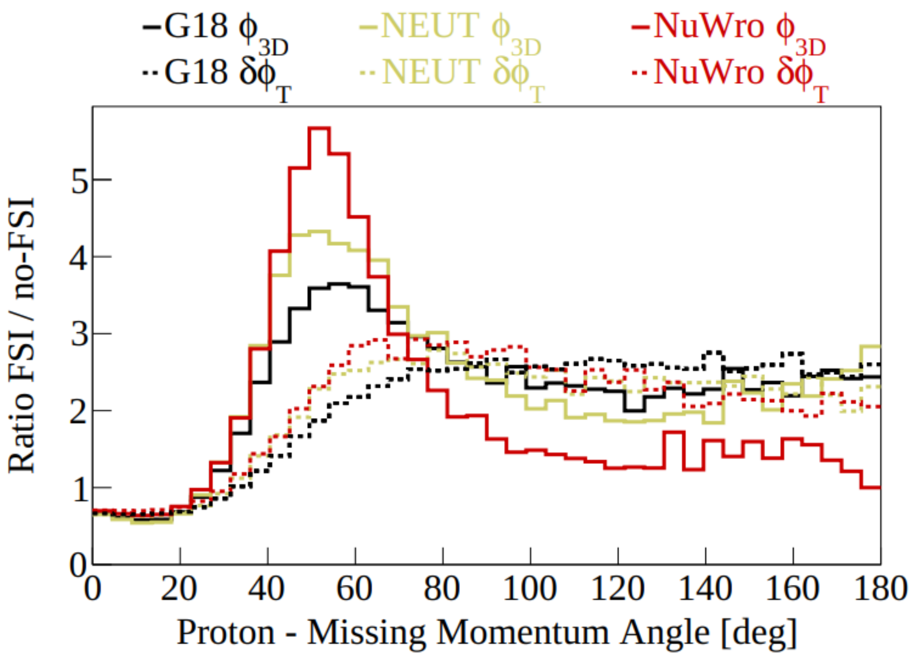

MicroBooNE Data
6.79e+20 POT
Stat ⊕ Shape
Norm
NuWro (27.5/10)
GiBUU (29.1/10)
NEUT (42.1/10)
G18T (13.1/10)
$\frac{d\sigma}{dp_n}$ $[10^{-38} \frac{cm^2}{GeV/c\ Ar}]$
p_n [GeV/c]


MicroBooNE Data
6.79e+20 POT
Stat ⊕ Shape
Norm
NuWro (49.0/8)
GiBUU (4.7/8)
NEUT (10.3/8)
G18T (31.3/8)
$\frac{d\sigma}{d\alpha_{3D}}$ $[10^{-38} \frac{cm^2}{deg\ Ar}]$
α_{3D} [deg]

FSI sensitivity

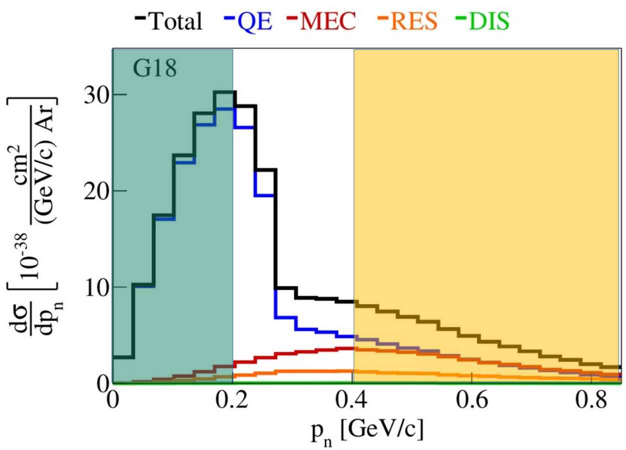
- Comparing ratios with and without FSI
- Generalised variables have more sensitivity to the presence, and details, of FSI

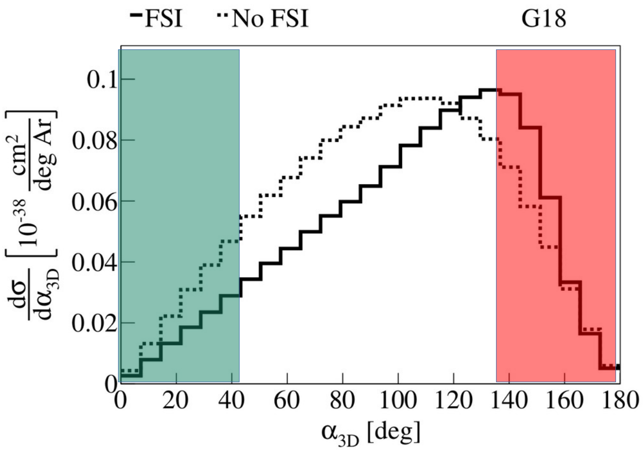




Multi-differential measurement

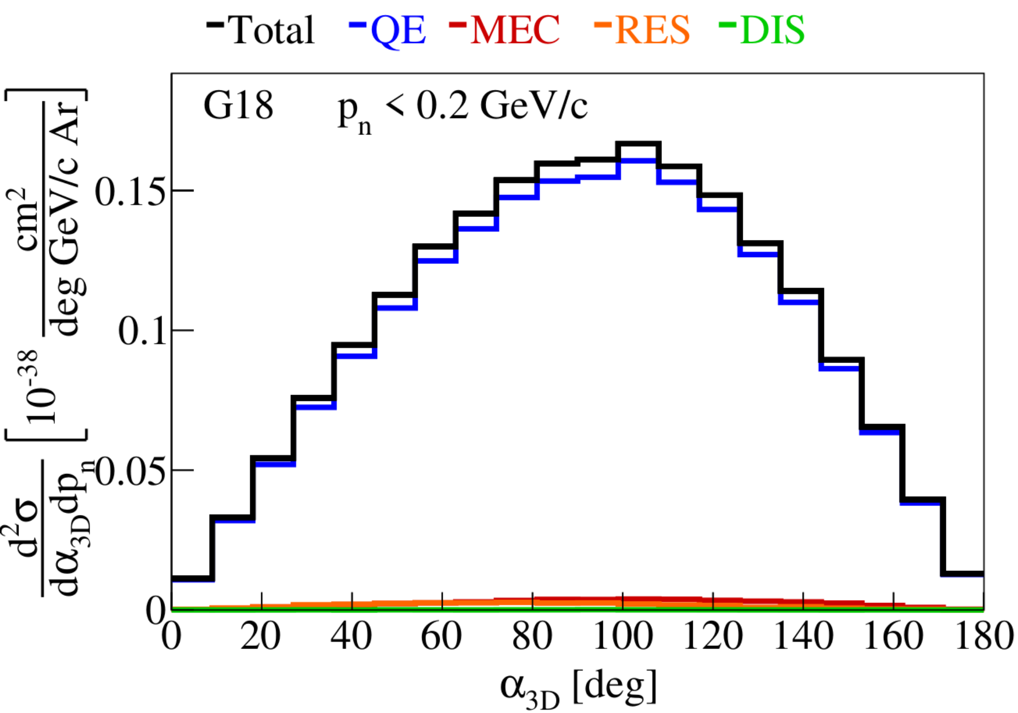
- TKI measurements more powerful when we measure δp_T and $\delta \alpha_T$ simultaneously
- Follow the same strategy here – isolate FSI, MEC, and Fermi motion separately

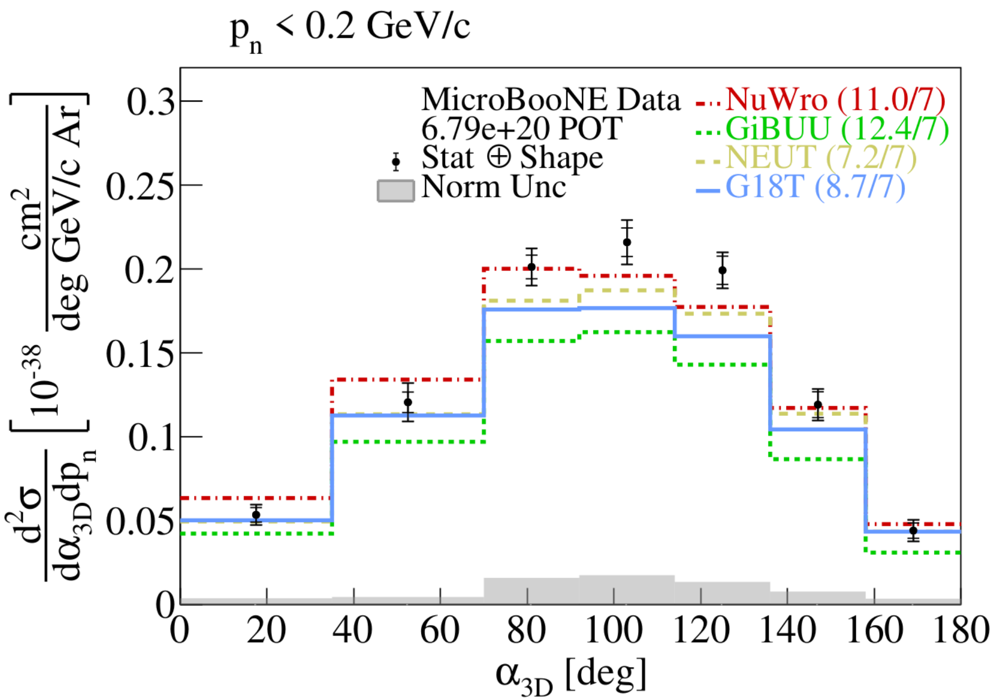




Low missing momentum

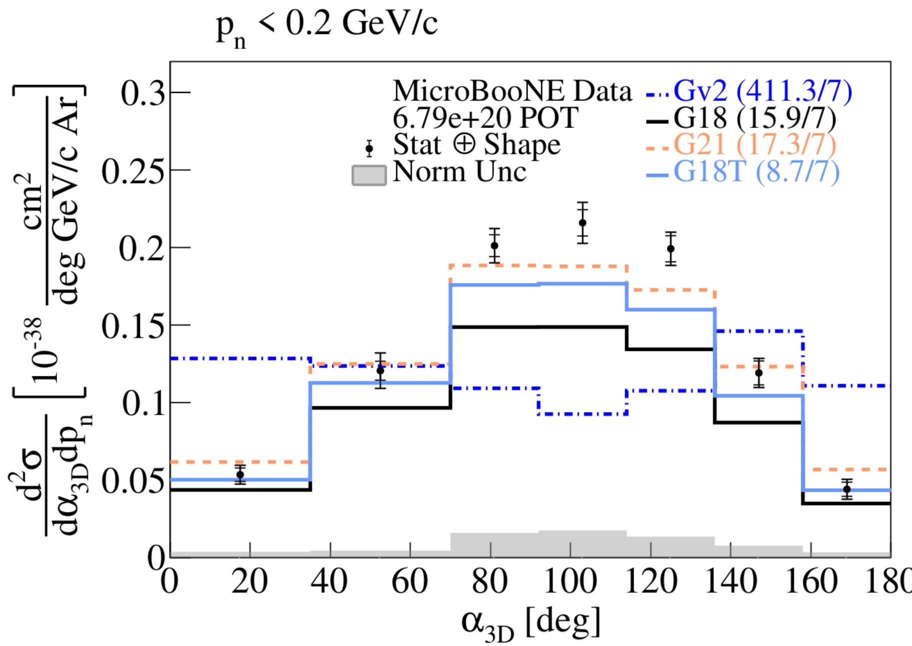
- Minimal FSI, highly pure QE sample
- No direction preference – sin curve shape from phase space





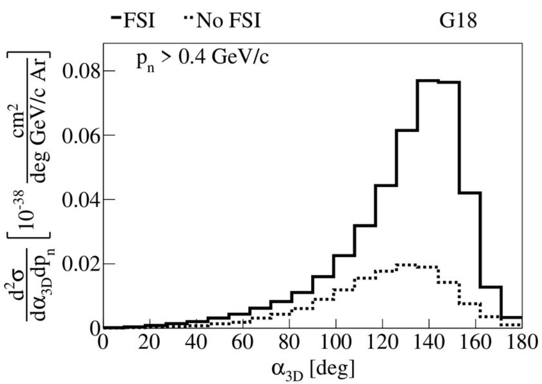
The last word on GENIE v2?

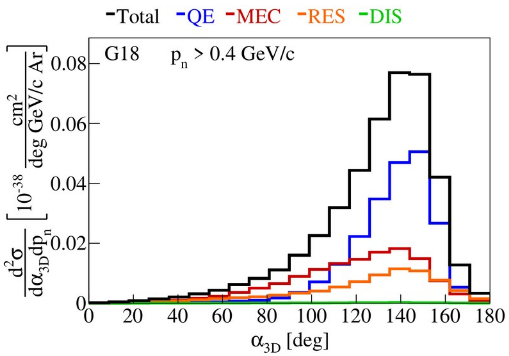
- GENIE v2 has a number of bugs, which aren't hugely obvious when measuring inclusive muon kinematics
- These variables are *extremely* sensitive to unphysical effects!
- GENIE v2 should probably be resigned to history

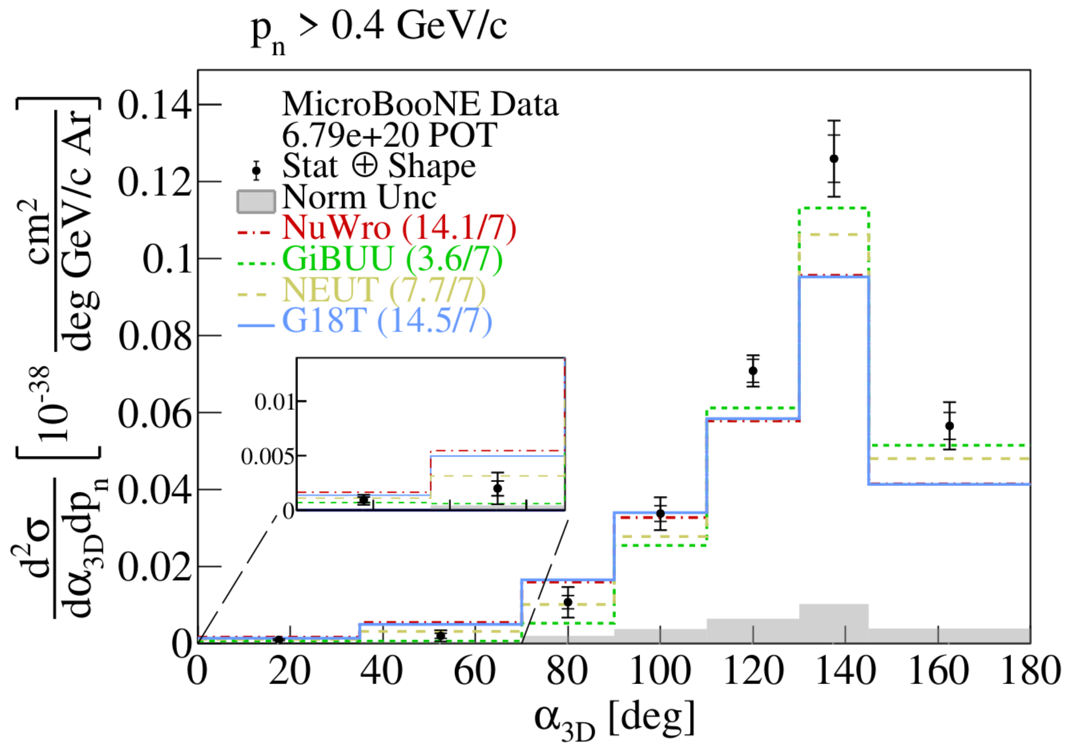


High missing momentum

- High α – FSI has x4 impact on the cross section
  - Mainly QE events with proton FSI
- Low α – MEC-dominated (50-75% pure MEC)

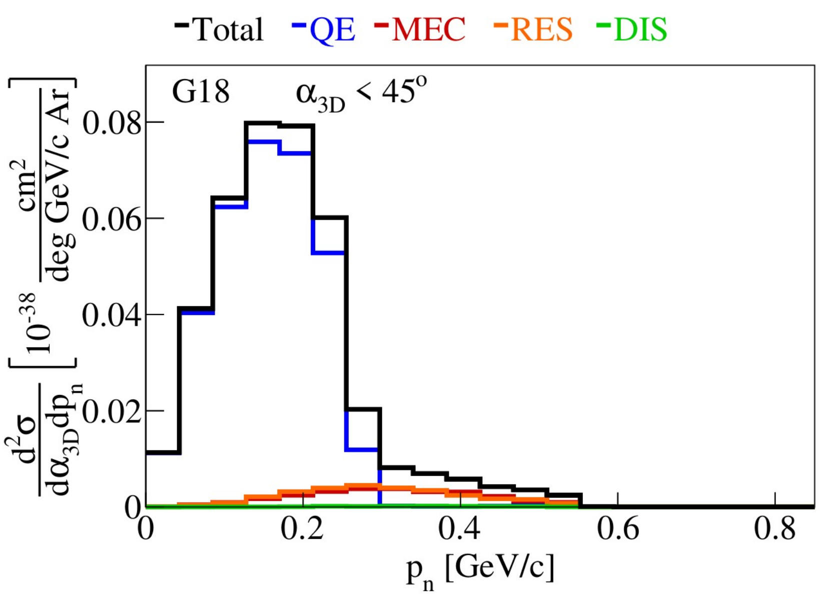


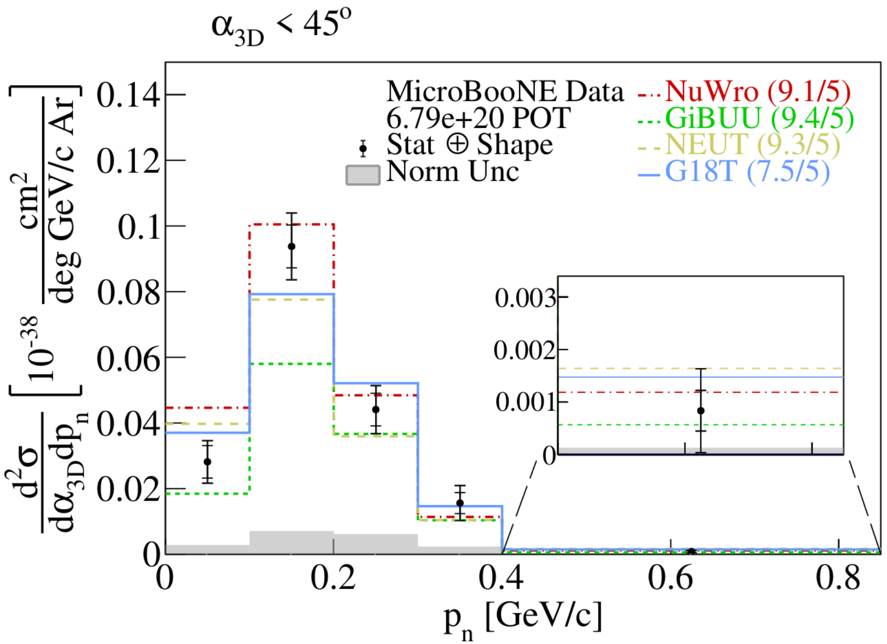




Low-FSI

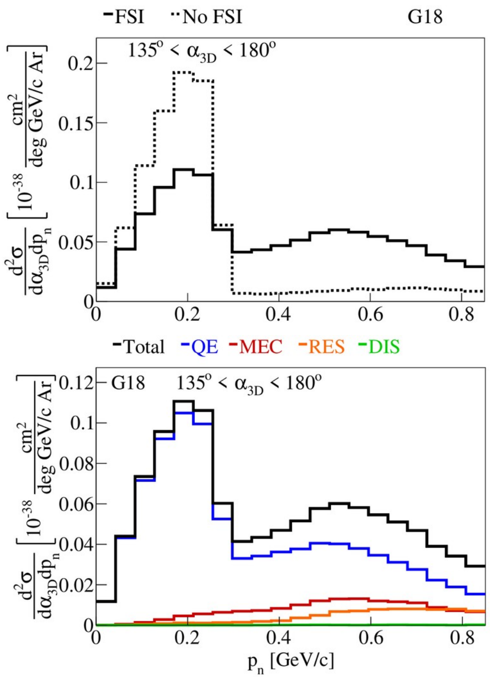
- Clean QE peak
- Tail is a mix of RES (plus π-abs) and MEC events
  - Limited stats due to cutting hard on α_{3D}

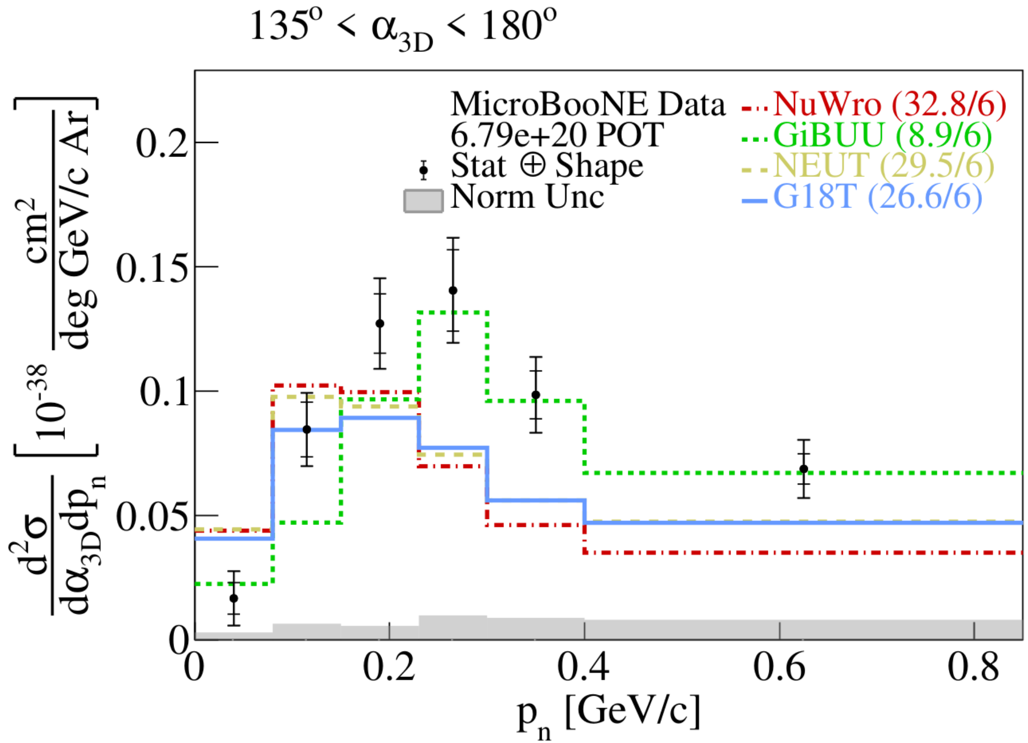




High-FSI

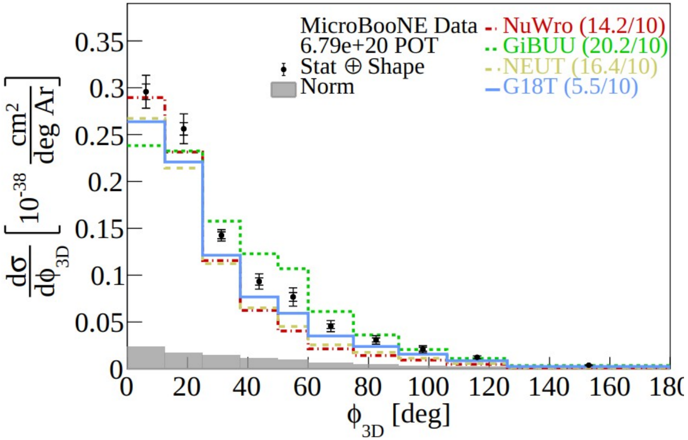
- High-p_n tail dominated by FSI
- QE peak reduced considerably by FSI
- Statistics plus resolution wash out double-peak structure currently

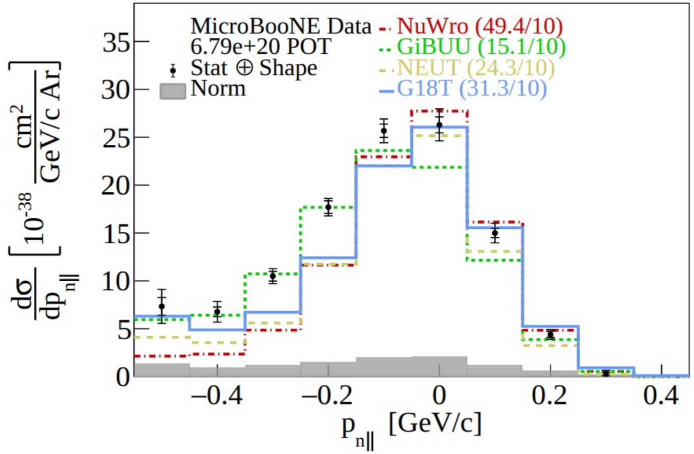


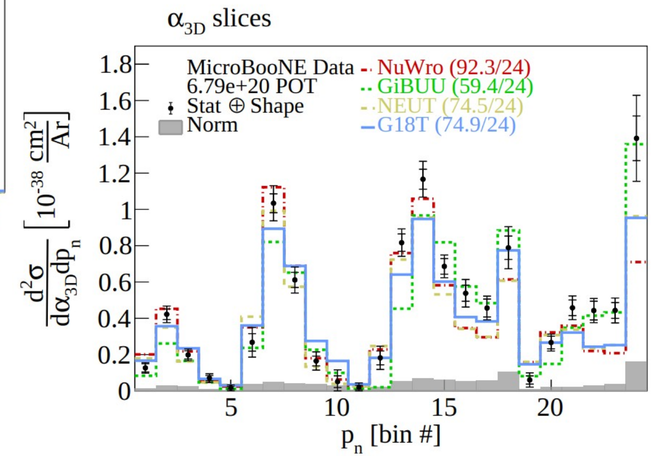


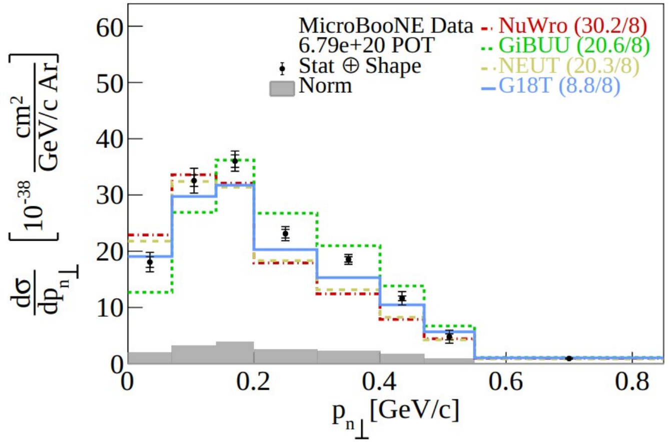
More...

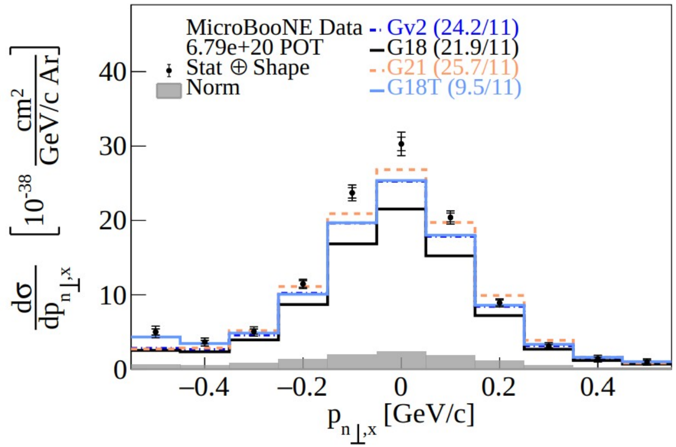
arXiv:2310.06082

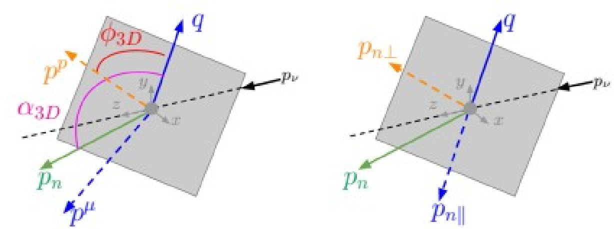












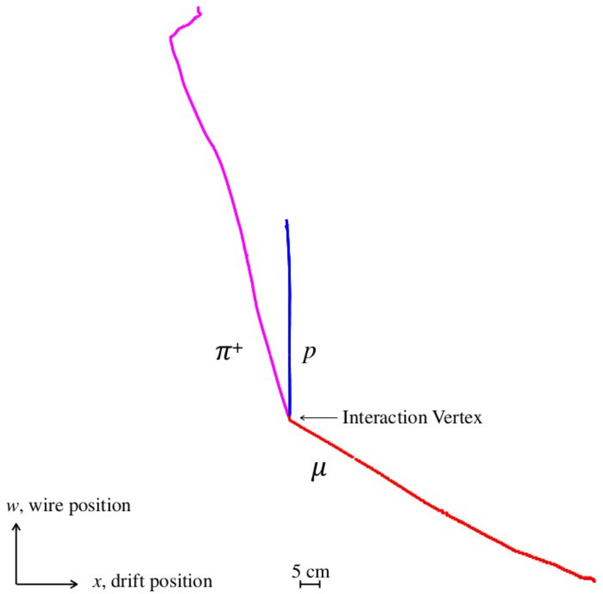
Summary

- Generalising kinematic imbalance variables enhances sensitivity to FSI, Fermi motion, and MEC events
  - These apply to any final state – we started with CC0π1p
- Multi-differential measurements provide additional sensitivity
- Primary conclusions:
  - GENIE G18 does best in low-FSI regions
  - GiBUU does best in high-FSI regions
- Limitations to the analysis:
  - We have more data to analyse!
  - No correlations between observables (see next talk!)

Backup slides

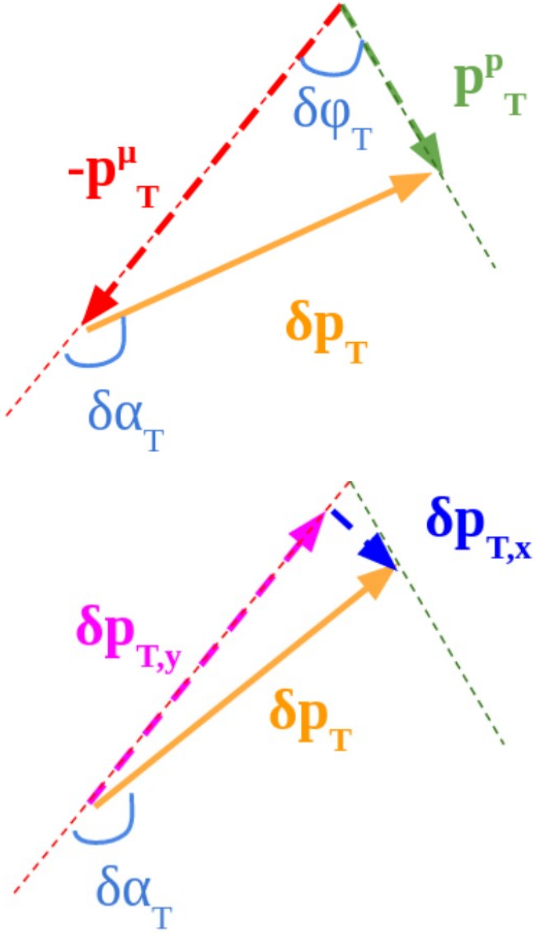
Reconstruction

- Pandora multi-algorithm toolkit
- Rejects obvious cosmic ray muons
- Reconstructs remainder under neutrino assumption
- Produces “slices”, and selects the most neutrino-like slice



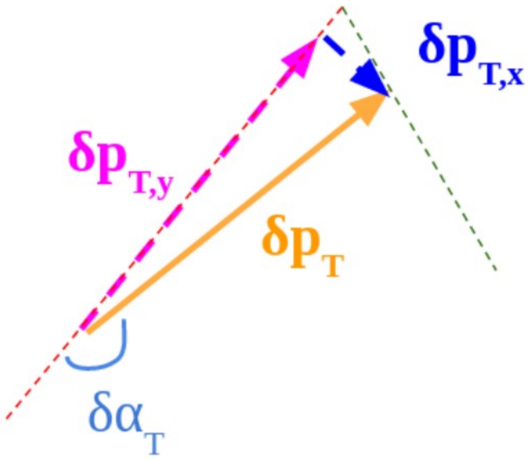
Projection variables

- Also measure $\delta p_{T,x}$ and $\delta p_{T,y}$
- $\delta p_{T,x}$ also known as δp_{TT}



δp_{TT}, $\delta p_{T,x}$, $\delta p_{T,y}$?

- These variables are the projections of δp_T parallel and perpendicular to the momentum transfer
- The final state hadrons boosted along the momentum transfer, so x should be symmetric and y will have an asymmetry



Generalised Kinematic Imbalance

- Projection variables work the same way
- Now there are two perpendicular components
- Fairly arbitrarily, we place one (x) in the transverse plane

$$p_{n\perp,x} = (\hat{q}_T \times \hat{z}) \cdot \vec{p}_n,$$

$$p_{n\perp,y} = (\hat{q} \times (\hat{q}_T \times \hat{z})) \cdot \vec{p}_n,$$

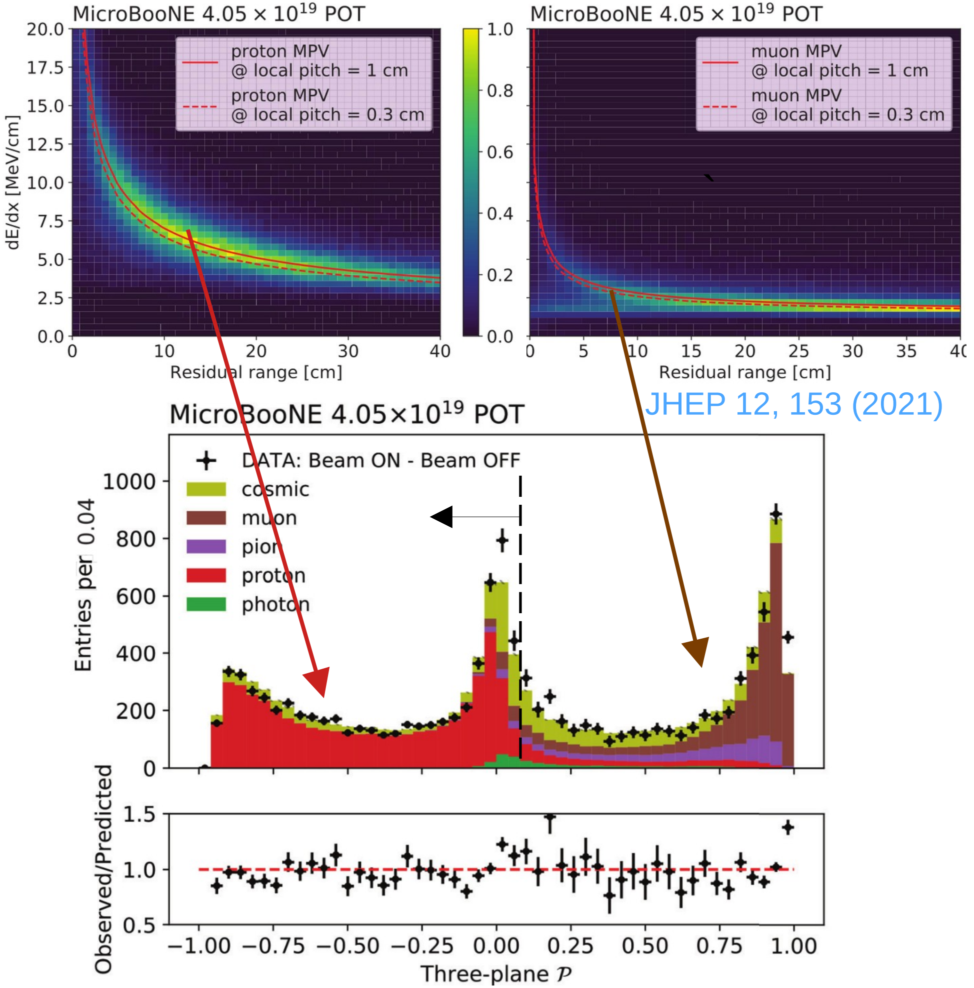
These cross products produce unit vectors pointing in the right direction

$$p_{n\perp} = \sqrt{(p_{n\perp,x})^2 + (p_{n\perp,y})^2} = |p_n| \sin(\alpha_{3D}),$$

$$p_{n||} = \hat{q} \cdot \vec{p}_n = |p_n| \cos(\alpha_{3D}).$$

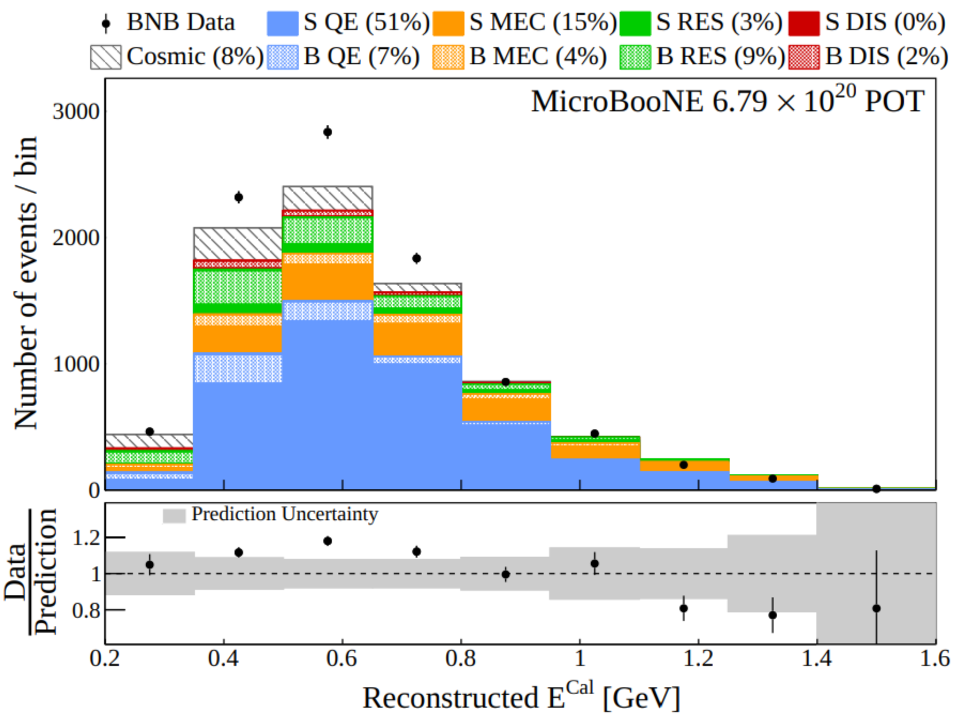
Particle Identification

- dE/dx measured vs distance from end point
- Compared to predictions from muon and proton
- Use all three planes, produce log likelihood ratio



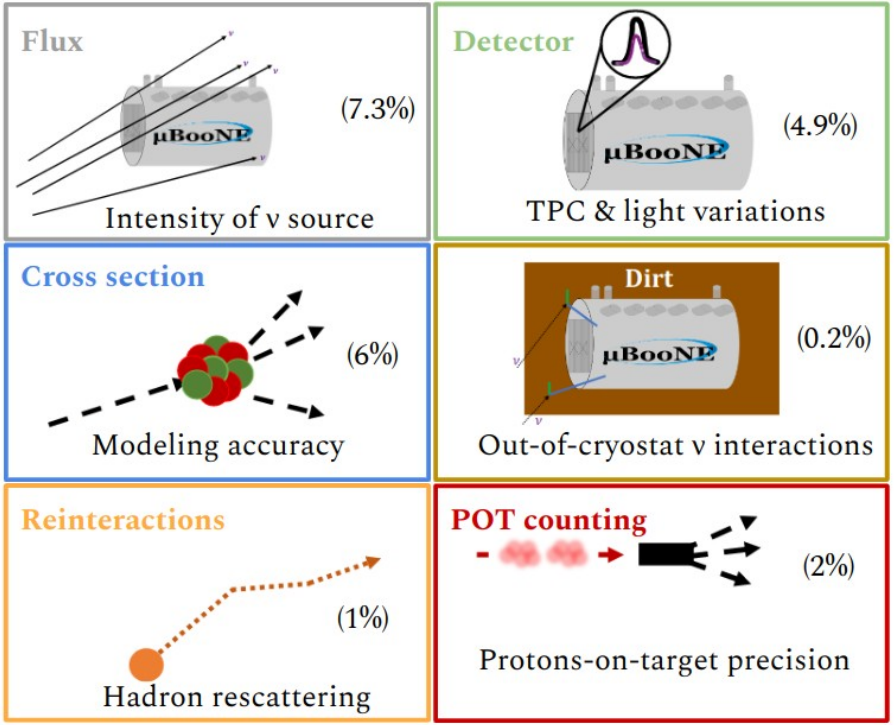
Final Event Sample

- All particles required to stop in the detector
  - Necessary for resolution
- 9,051 events selected
- 70% purity
- Most common backgrounds are 2-proton events with a missed proton



Uncertainties

- Vary all systematic parameters in MC, to produce covariance matrix for predicted event rate
- Assume this covariance matrix applies to the data
  - This requires “reasonable” data/MC agreement to hold
- For signal interaction modelling, only vary the impact on efficiency and smearing
- Divide by assumed integrated flux – all uncertainties are in the numerator
  - Including flux shape uncertainties

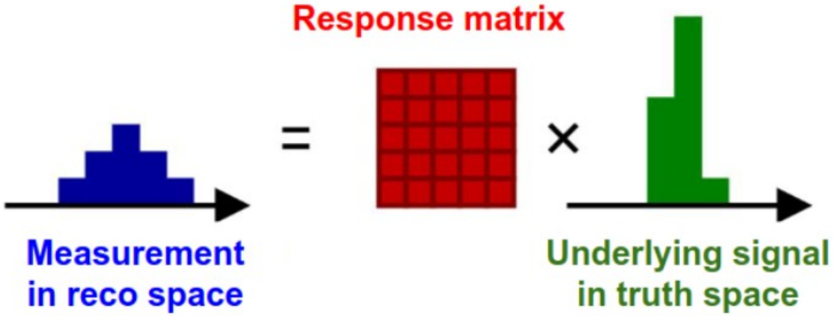


Unfolding

JINST 12, P10002 (2017)

- Wiener-SVD unfolding used
  - From signal processing – treat uncertainties as “noise”
- Method provides “additional smearing matrix” to smear predictions into regularised space
- Our resolution is good, so truth, reco, and regularised spaces look very similar!

$$M_i = \Sigma_j \; R_{ij} \bullet S_j + B_i$$



Unfolding

JINST 12, P10002 (2017)

- Wiener-SVD unfolding used
  - From signal processing – treat uncertainties as "noise"
- Method provides "additional smearing matrix" to smear predictions
  - An artefact of regularising
- Allows preservation of χ^2 from reco space to regularised space
- Our resolution is good, so truth, reco, and regularised spaces look very similar!

$$M_i = \Sigma_j \; R_{ij} \bullet S_j + B_i$$