

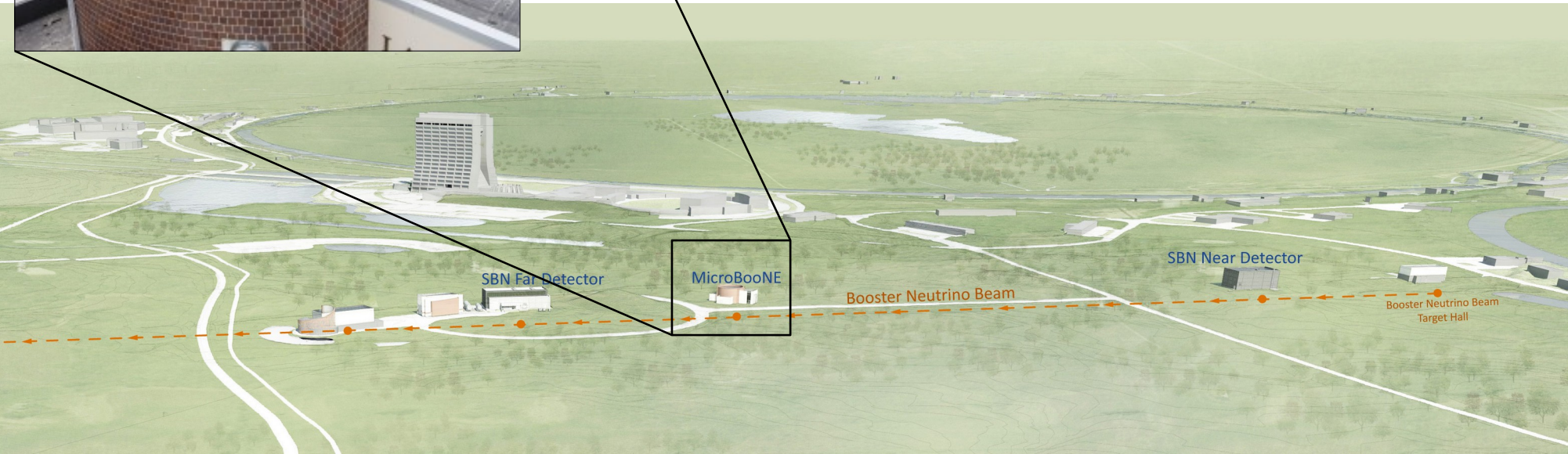
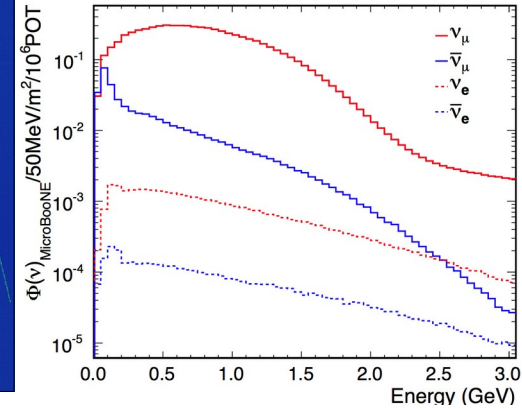
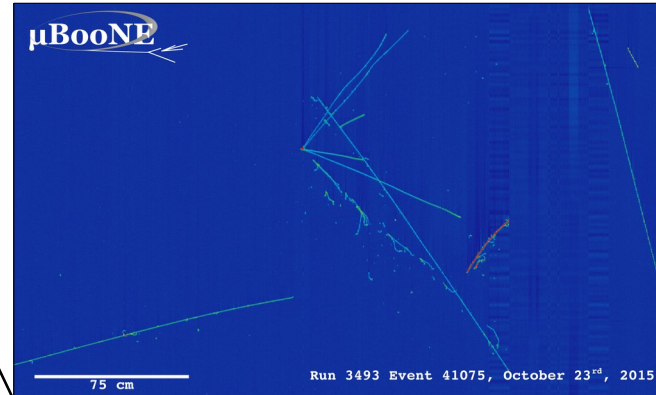
Kinematic Imbalance Measurements with pionless events at MicroBooNE

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NuInt 2024, Sao Paulo, Brazil

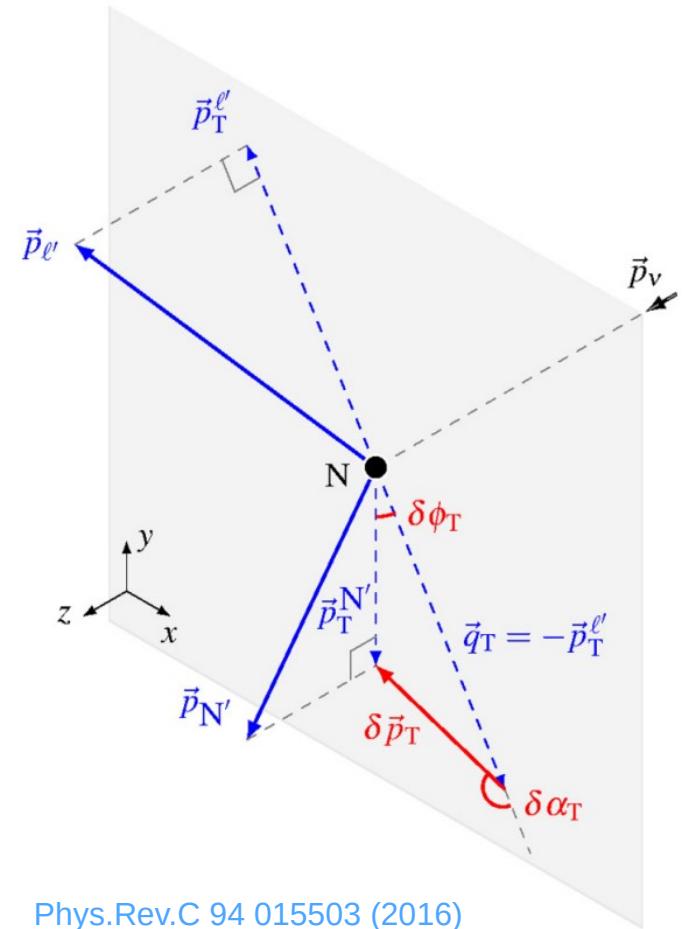


MicroBooNE



Transverse Kinematic Imbalance

- We know the initial momentum perpendicular 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)



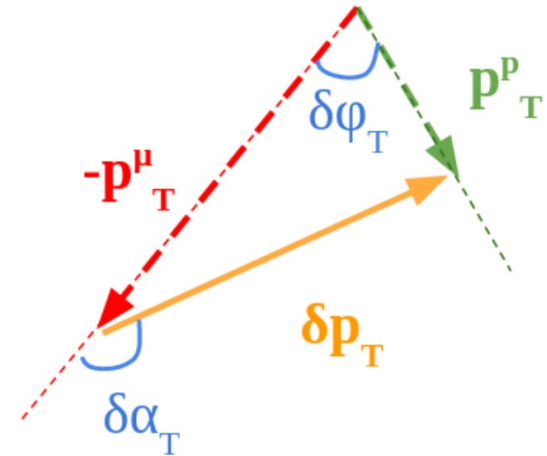
What does δp_T mean?

- 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



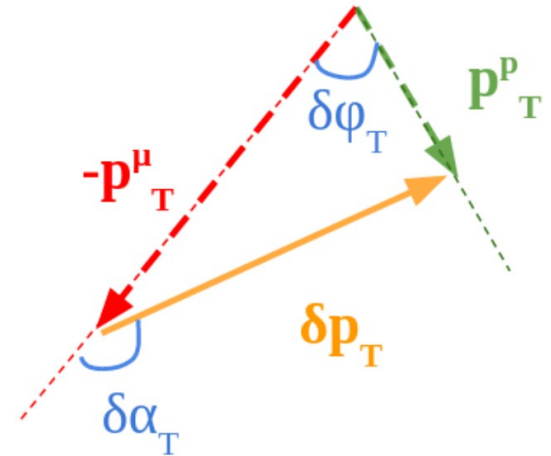
What does $\delta\alpha_T$ mean?

- $-p_T^\mu$ 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 momentum 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:

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

$$B = 30.9 \text{ MeV}$$



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

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



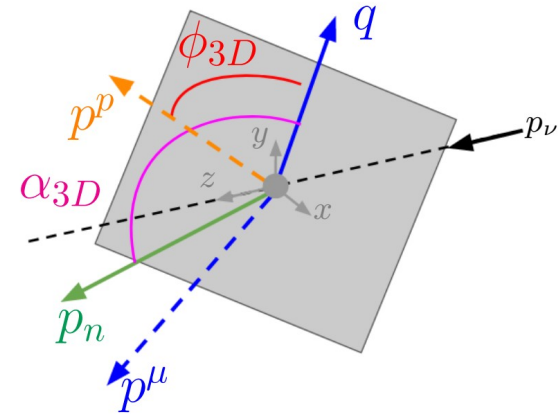
Generalised Kinematic Imbalance

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

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

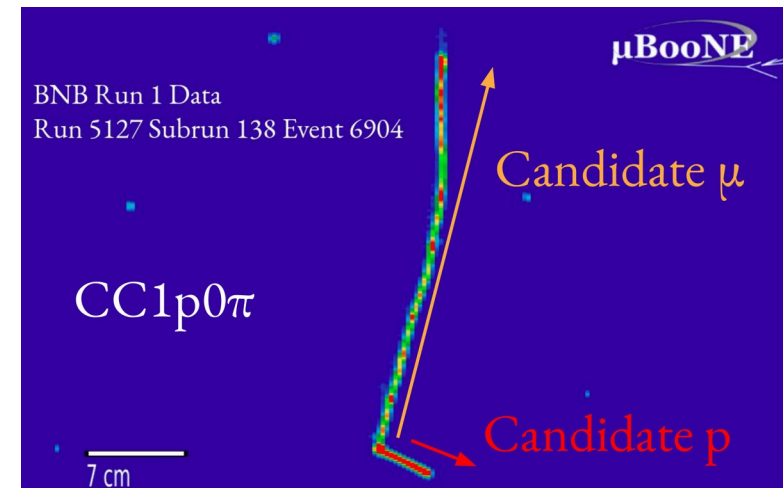
$$\alpha_{3D} = \cos^{-1} \left(\frac{\vec{q} \cdot \vec{p}_n}{|\vec{q}| |\vec{p}_n|} \right)$$

- 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



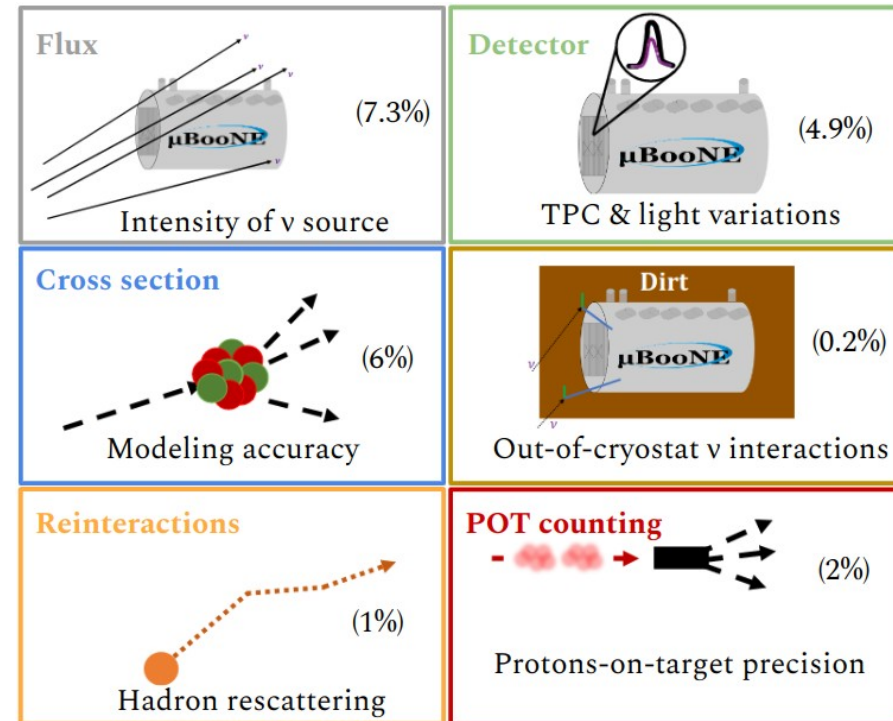
Signal Definition

- 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

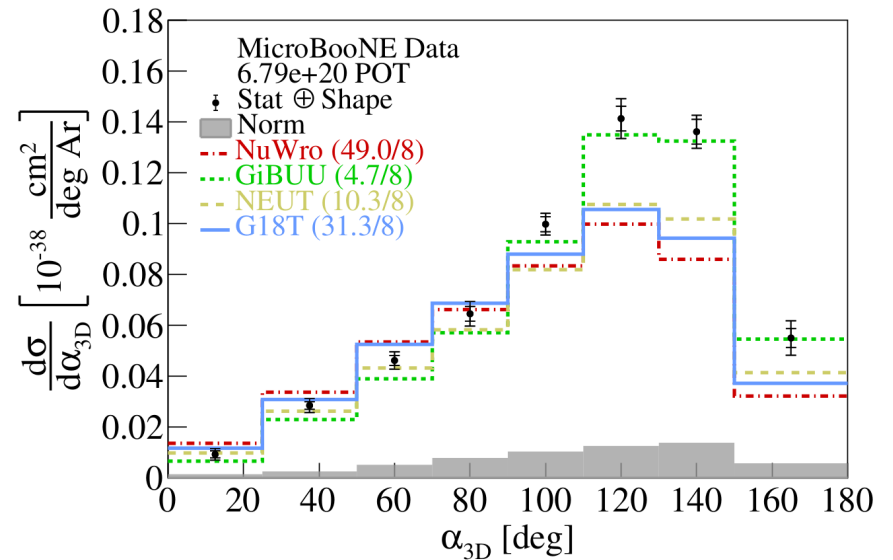
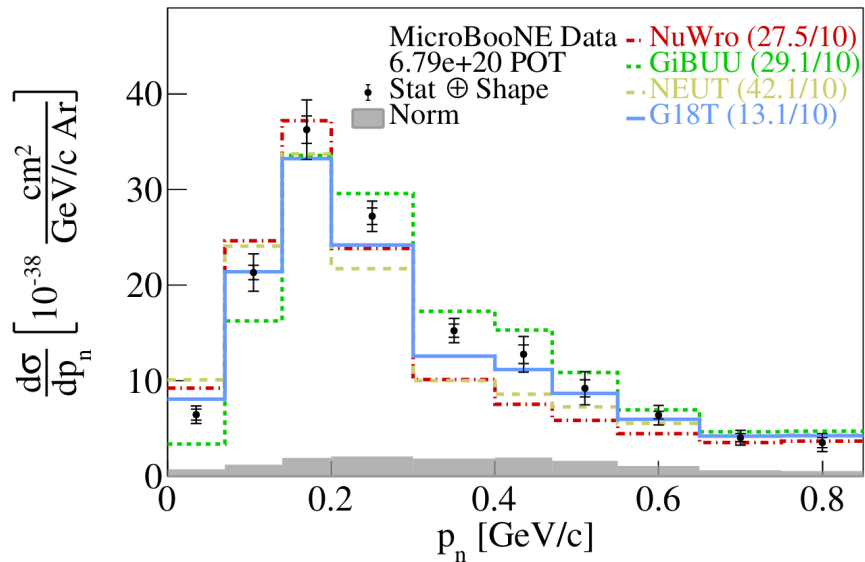
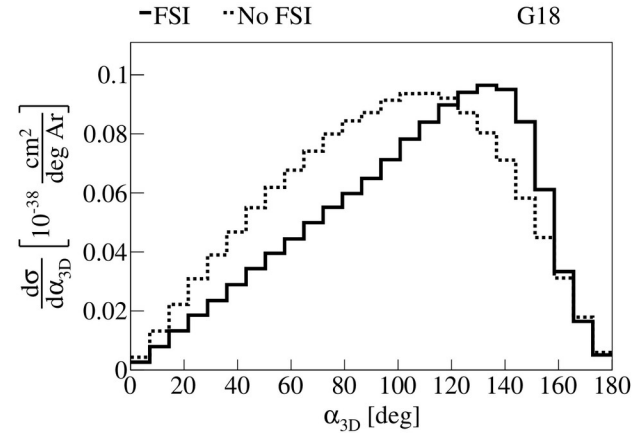
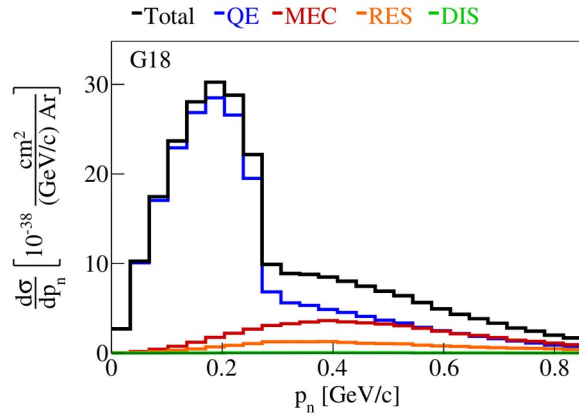
- Select events with:
 - One muon-like track
 - One proton-like track
 - Nothing else
- Estimate uncertainties on *predicted event rate*
 - This includes flux normalisation and shape
 - Does not include signal uncertainties, other than impact on smearing/efficiency
- Transform to regularised space
 -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



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

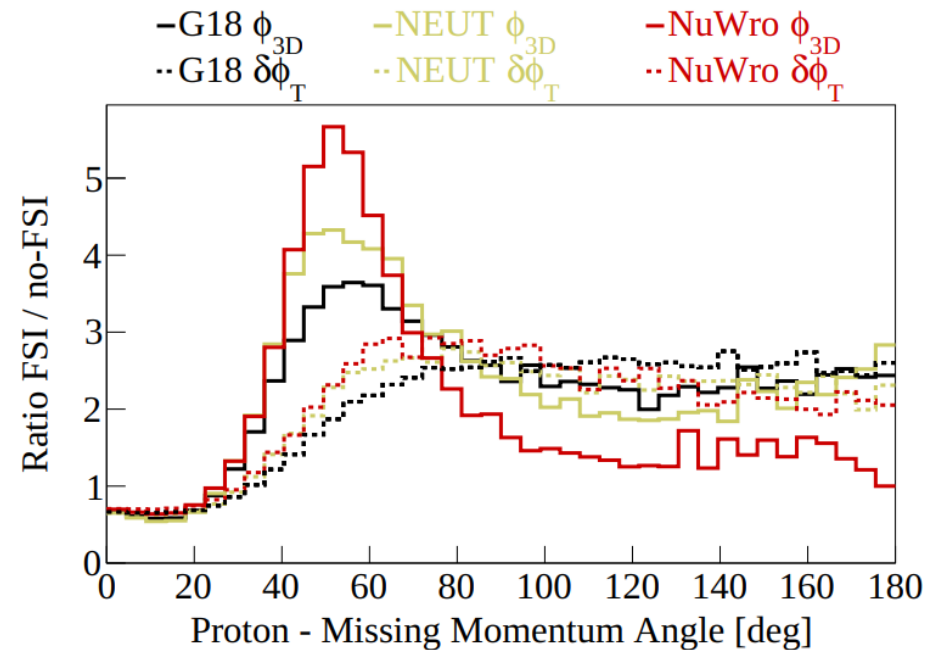
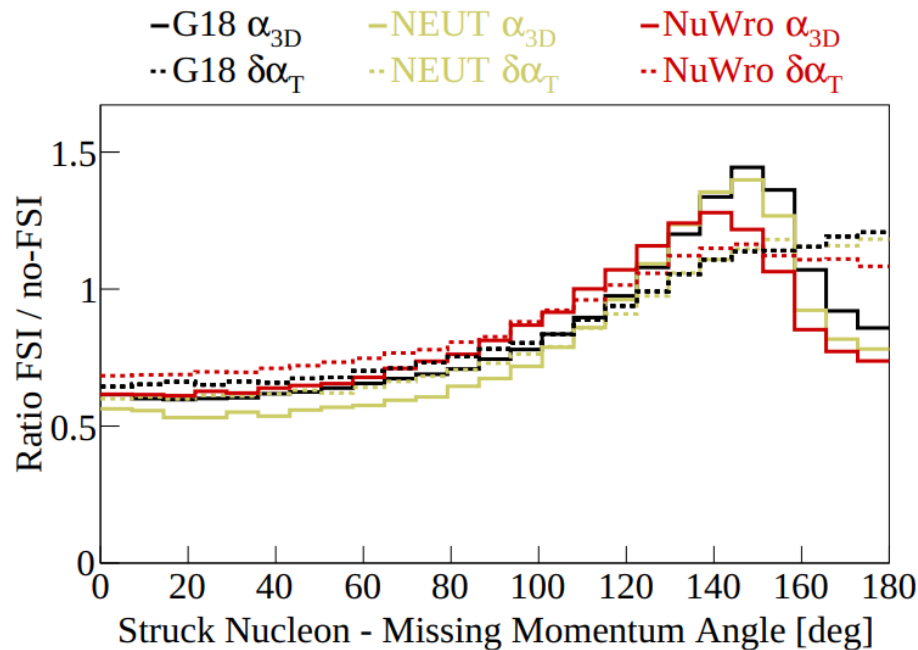


Data!



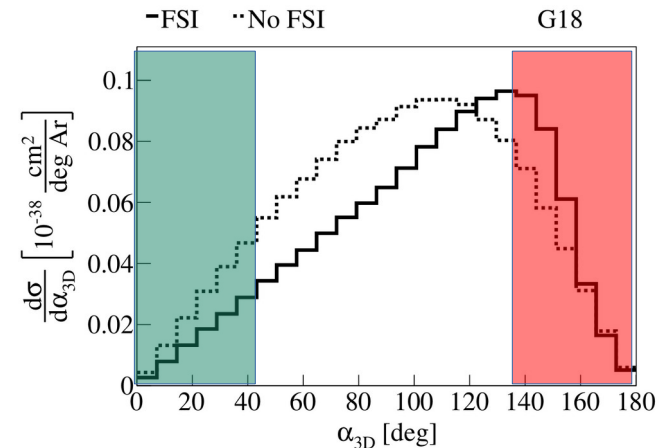
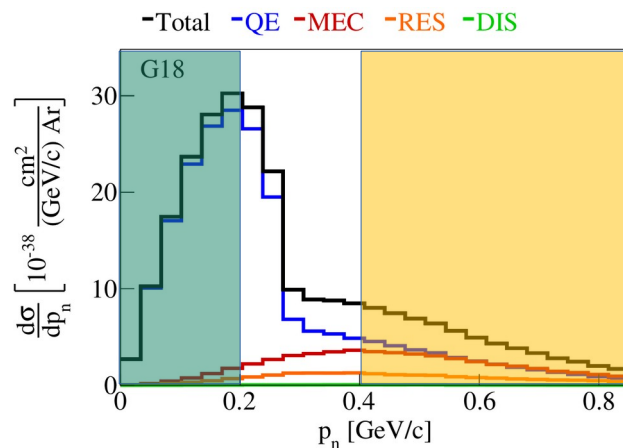
FSI sensitivity

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



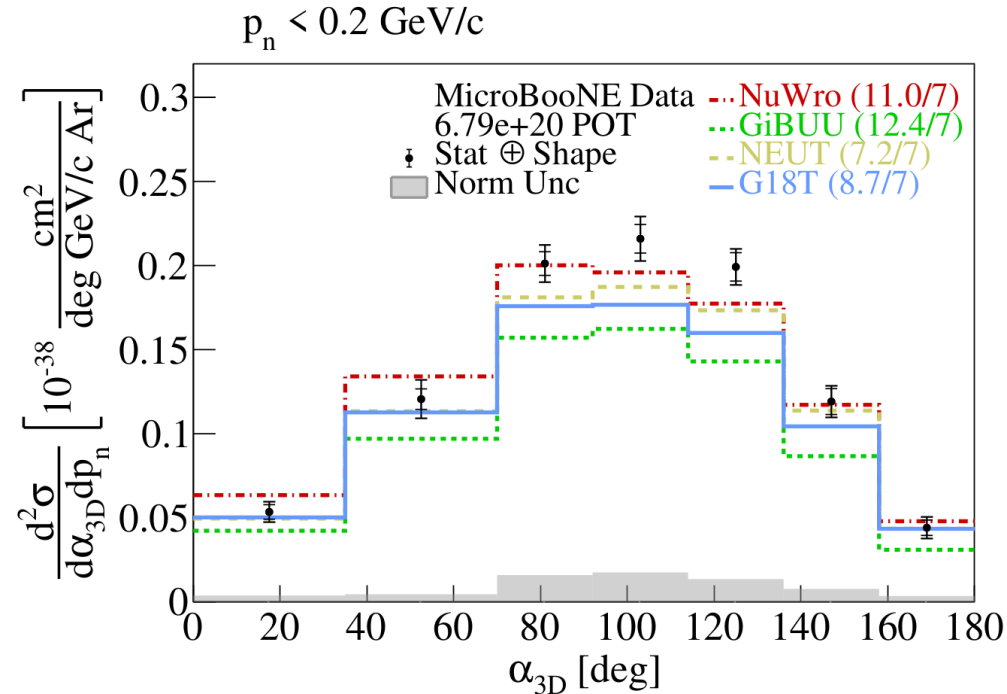
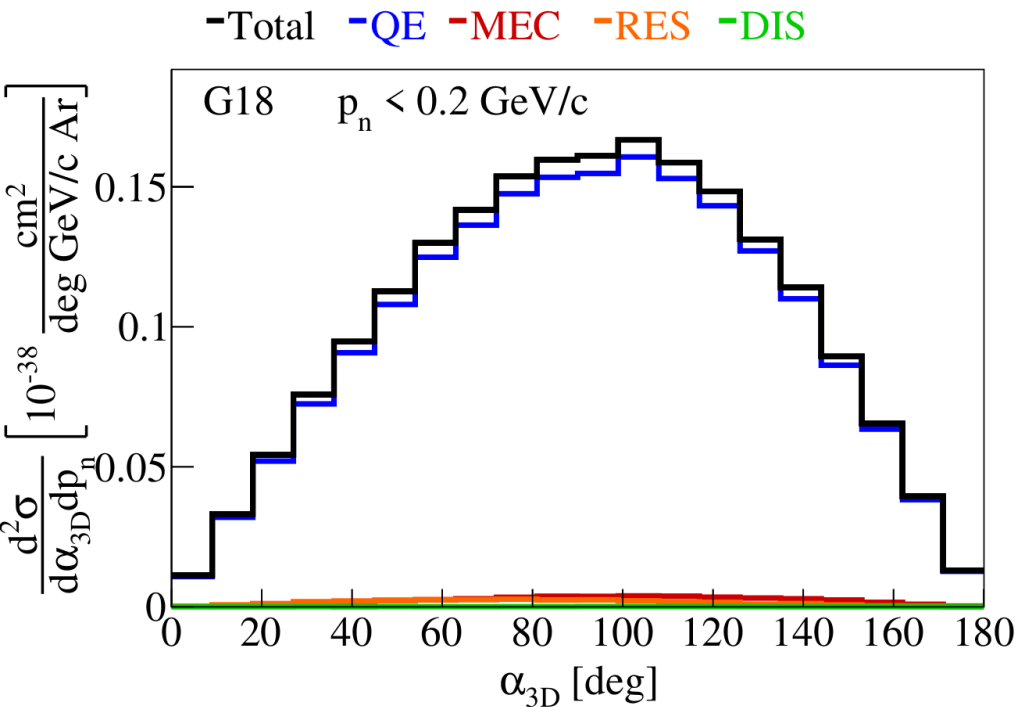
Multi-differential measurement

- 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



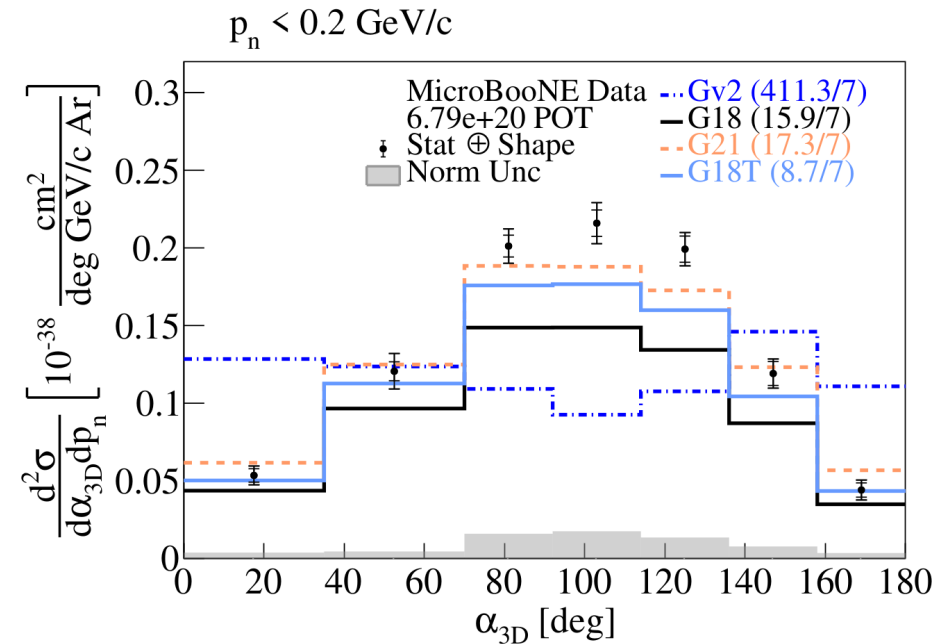
Low missing momentum

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



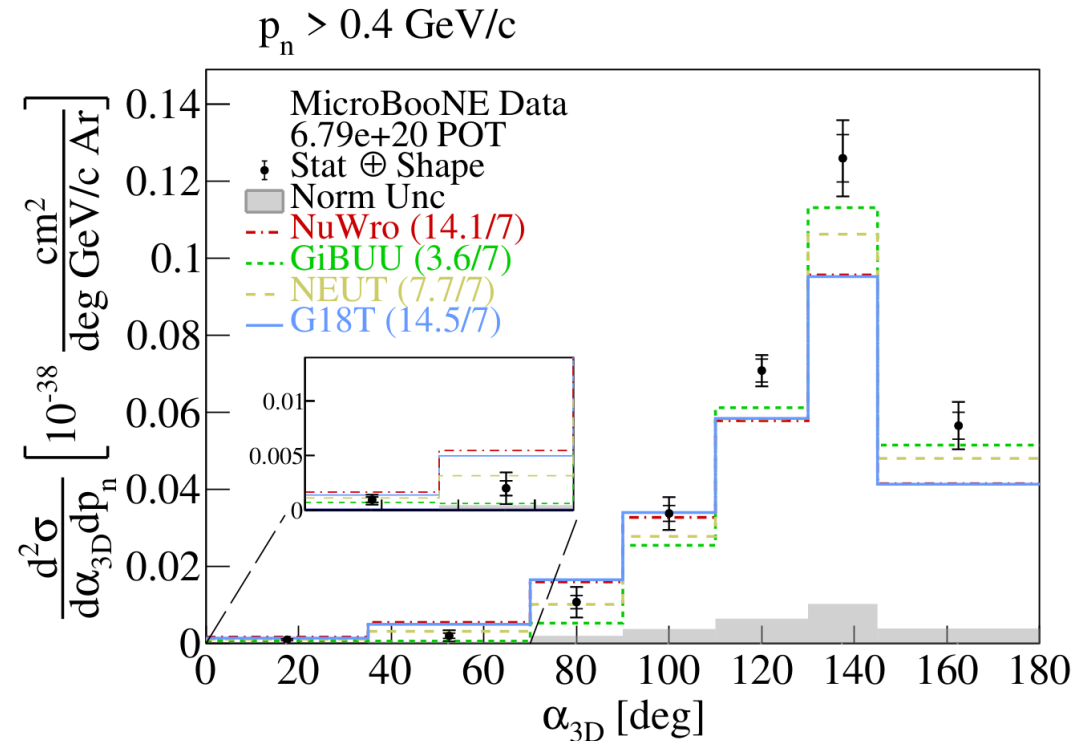
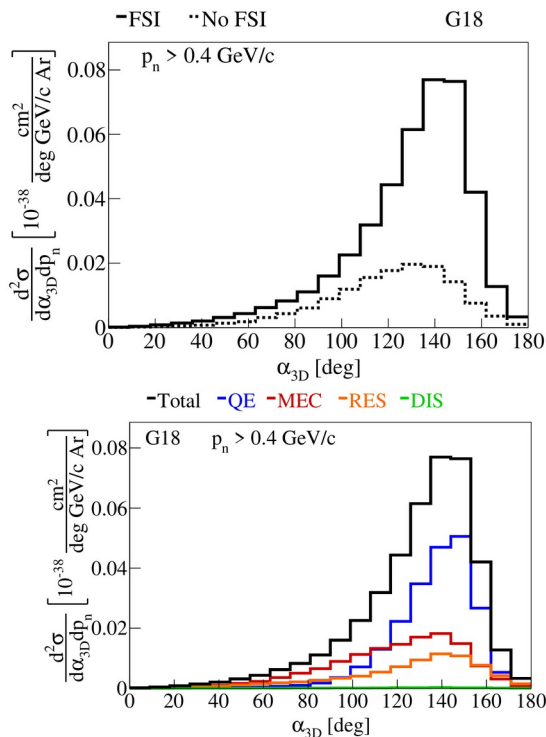
The last word on GENIE v2?

- 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



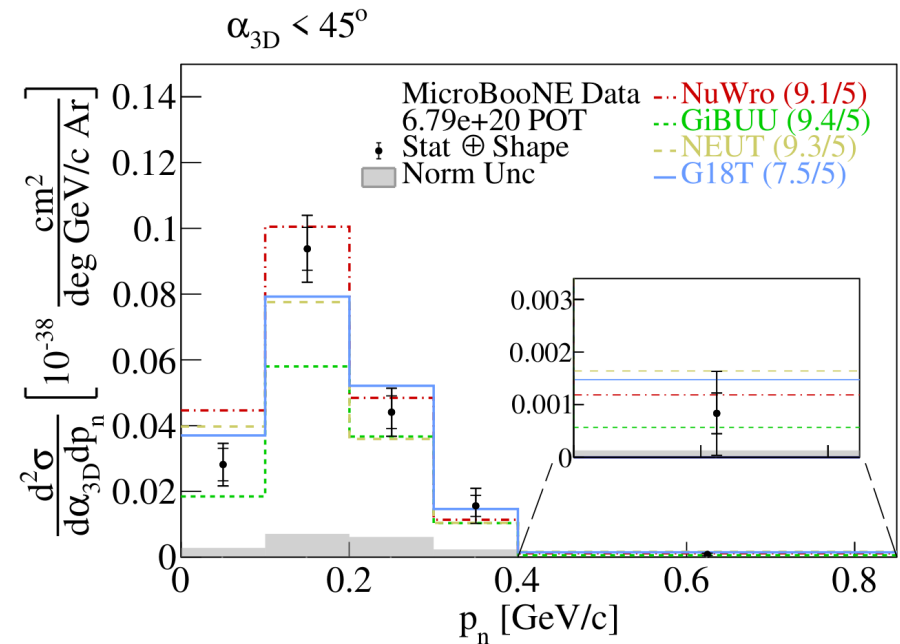
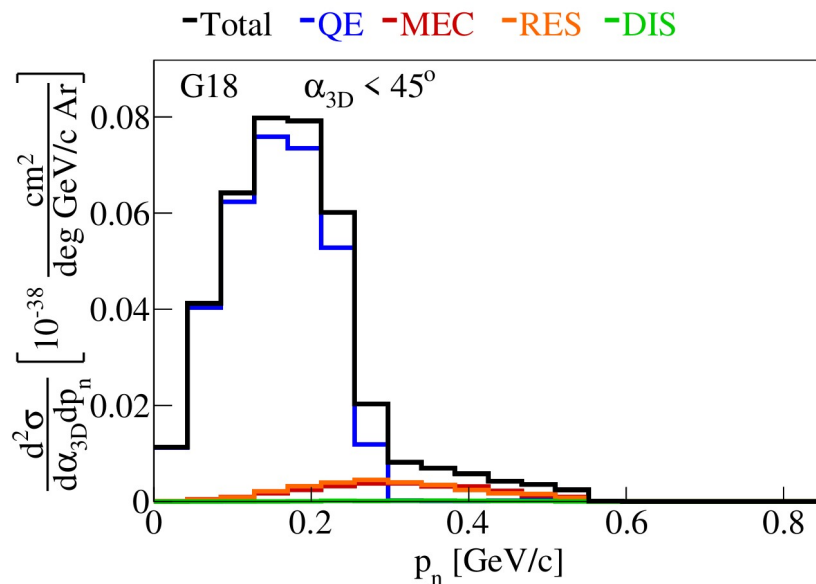
High missing momentum

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



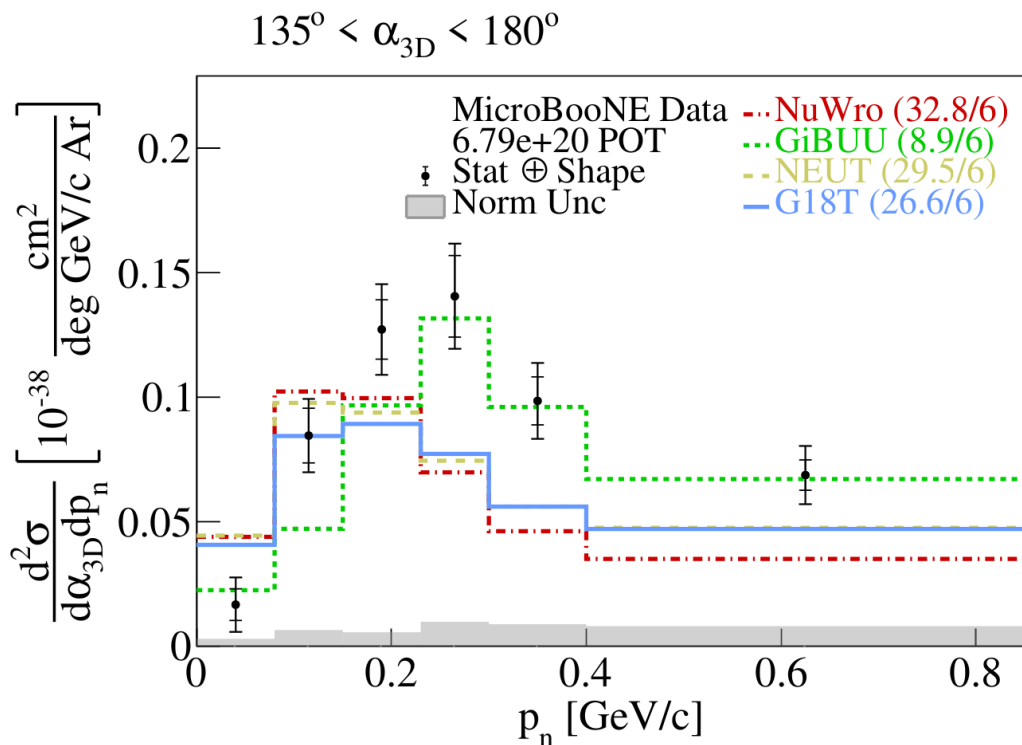
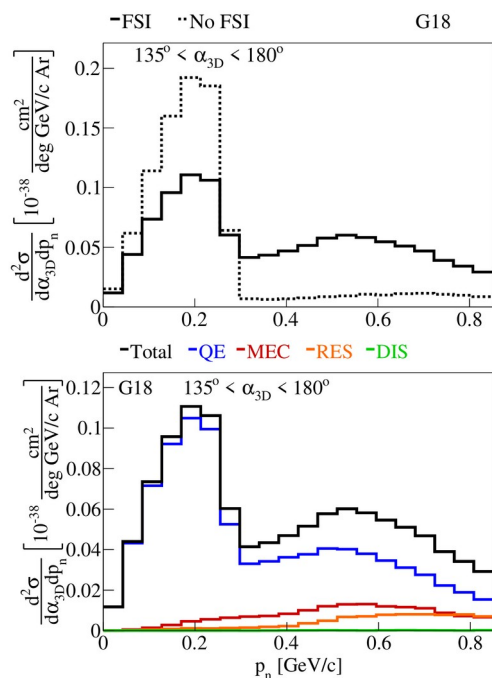
LOW-FSI

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

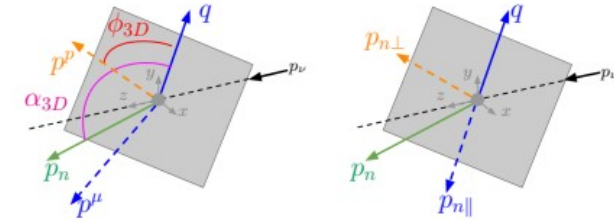
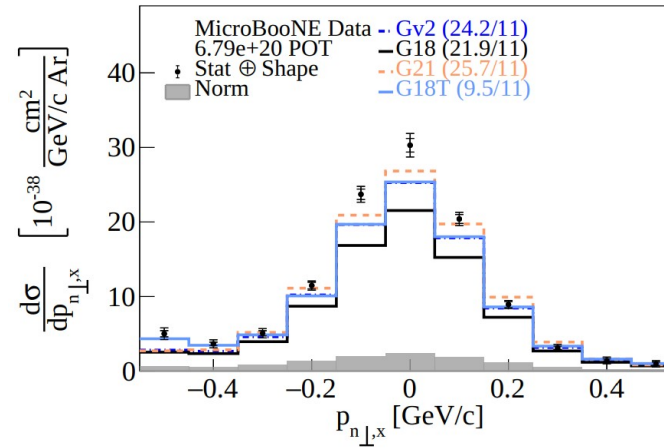
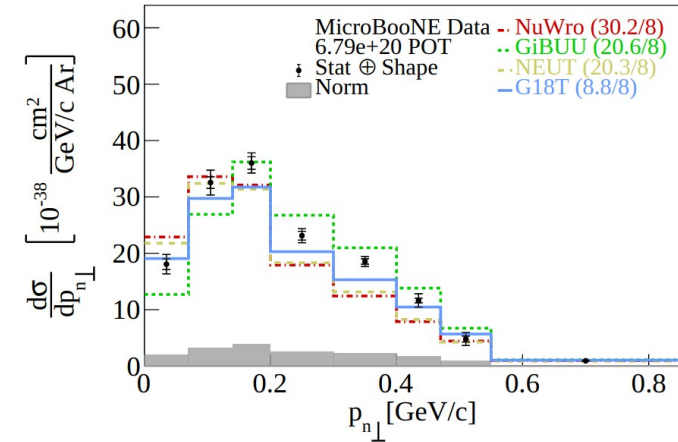
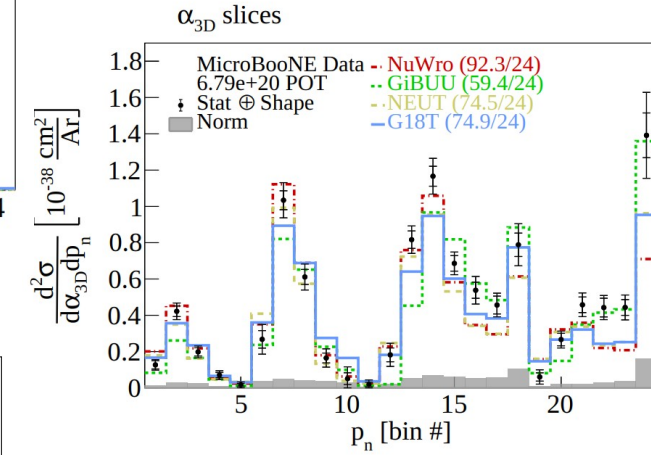
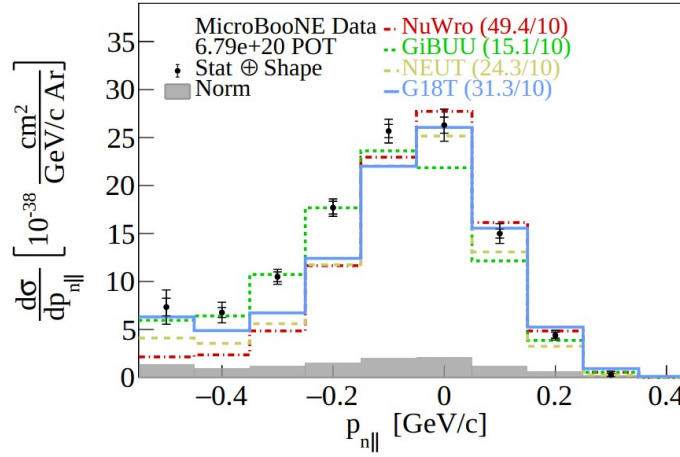
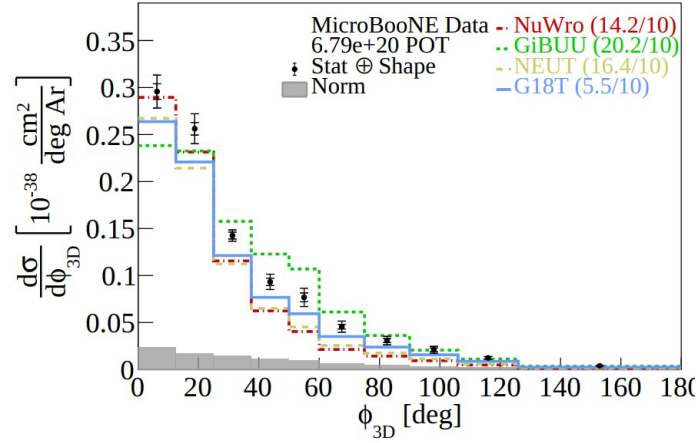


High-FSI

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



More...



Summary

- Generalising kinematic imbalance variables enhances sensitivity to FSI, Fermi motion, and MEC events
 - These apply to any final state – we started with $CC0\pi1p$
- 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!)

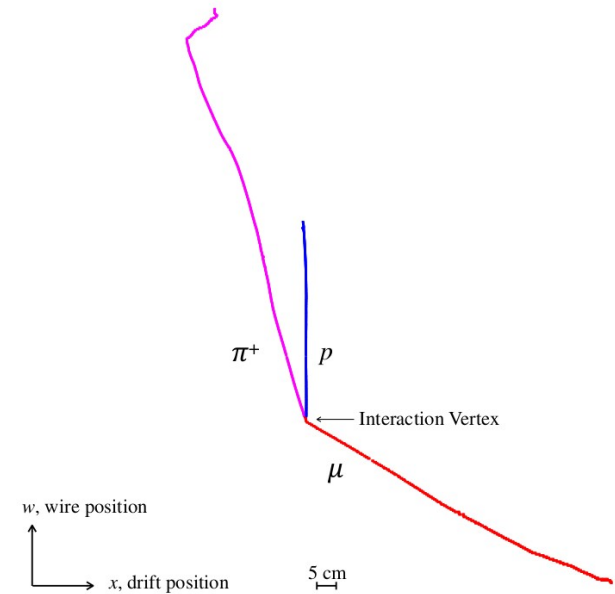


Backup slides



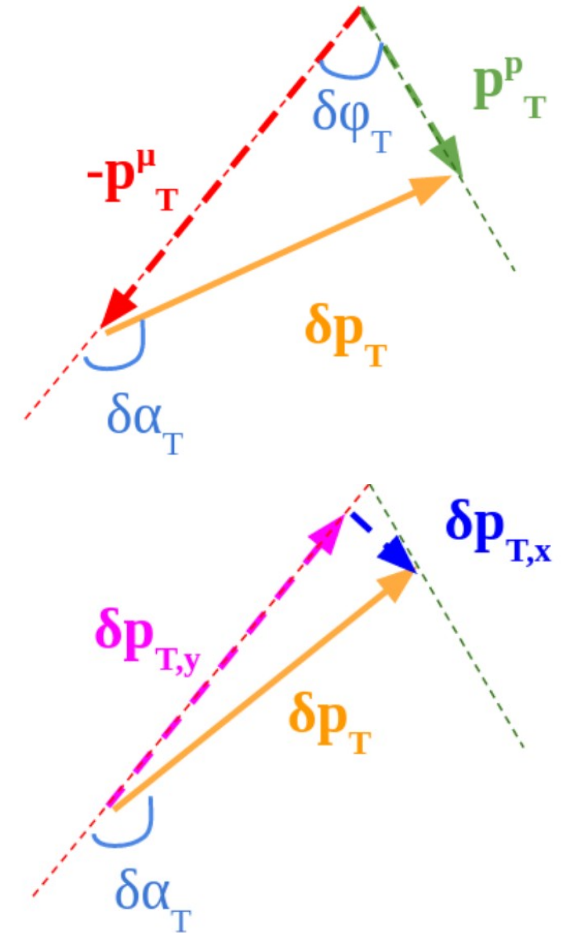
Reconstruction

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



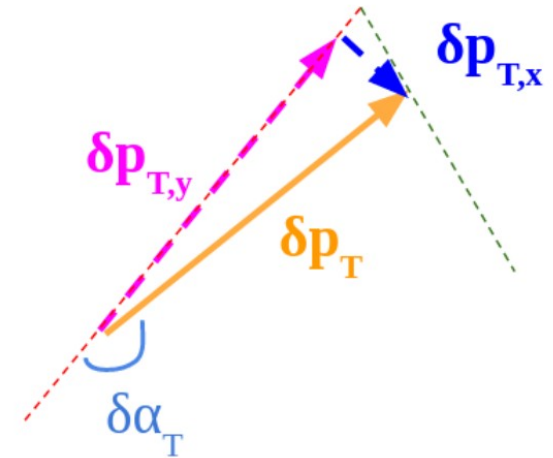
Projection variables

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



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

- 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

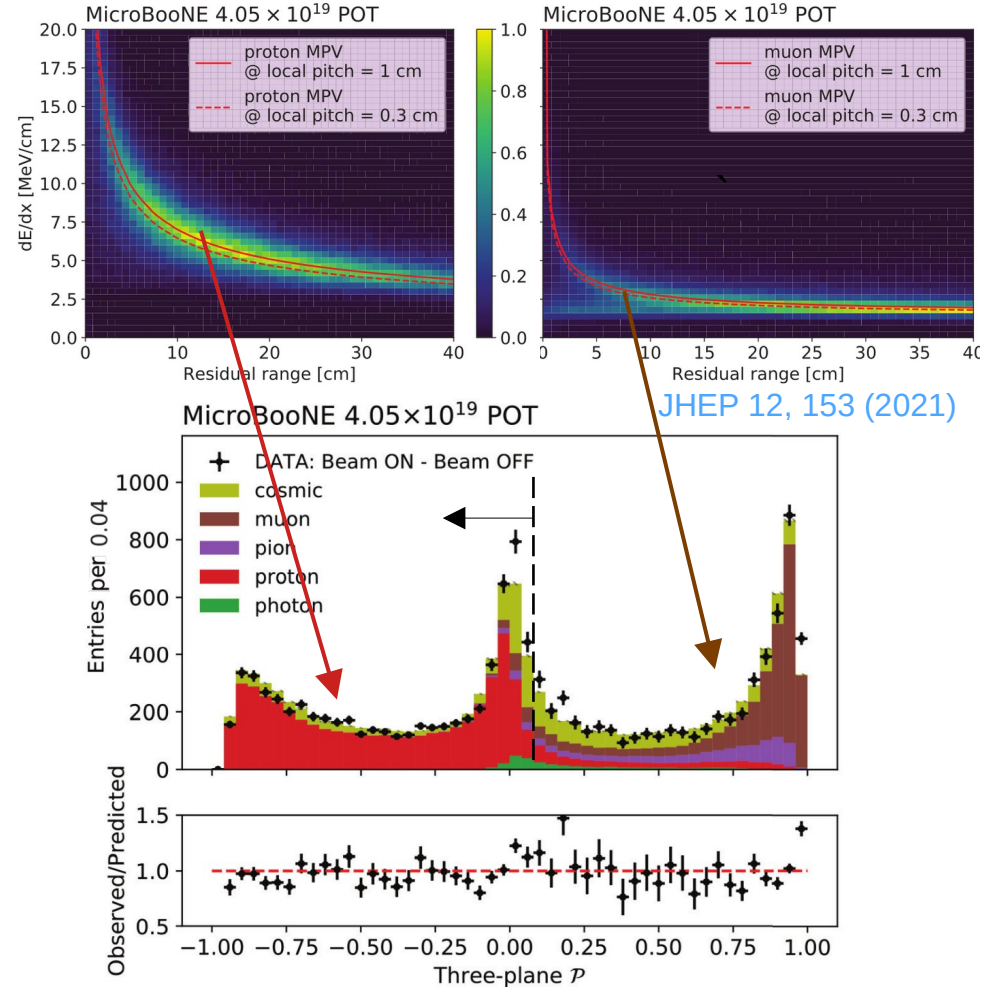
$$p_{n\perp} = \sqrt{(p_{n\perp,x})^2 + (p_{n\perp,y})^2} = |p_n| \sin(\alpha_{3D}),$$

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



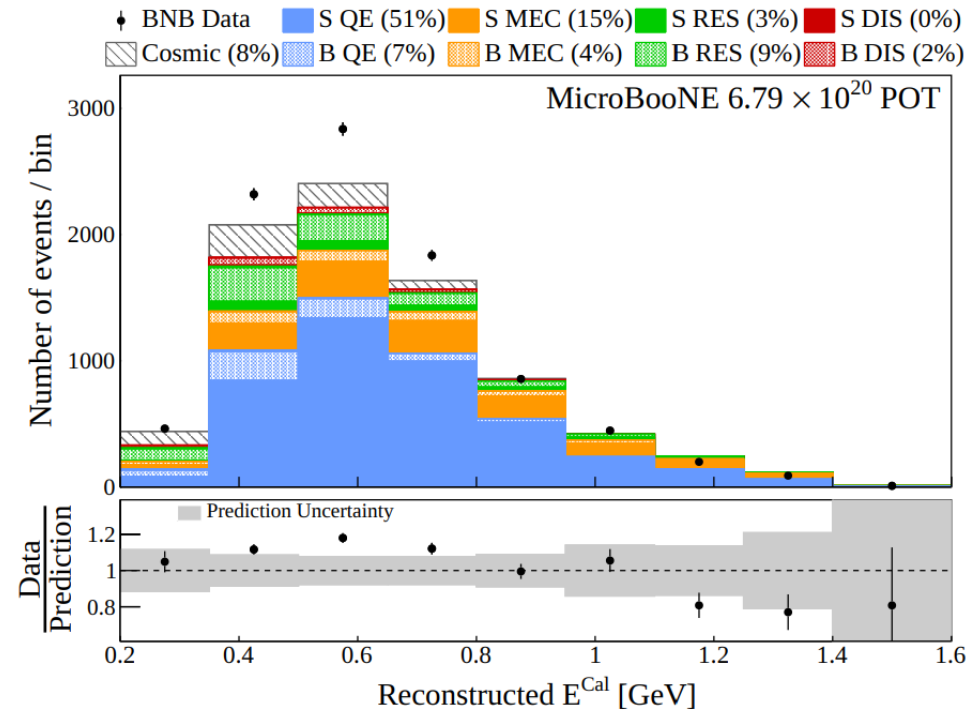
Particle Identification

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



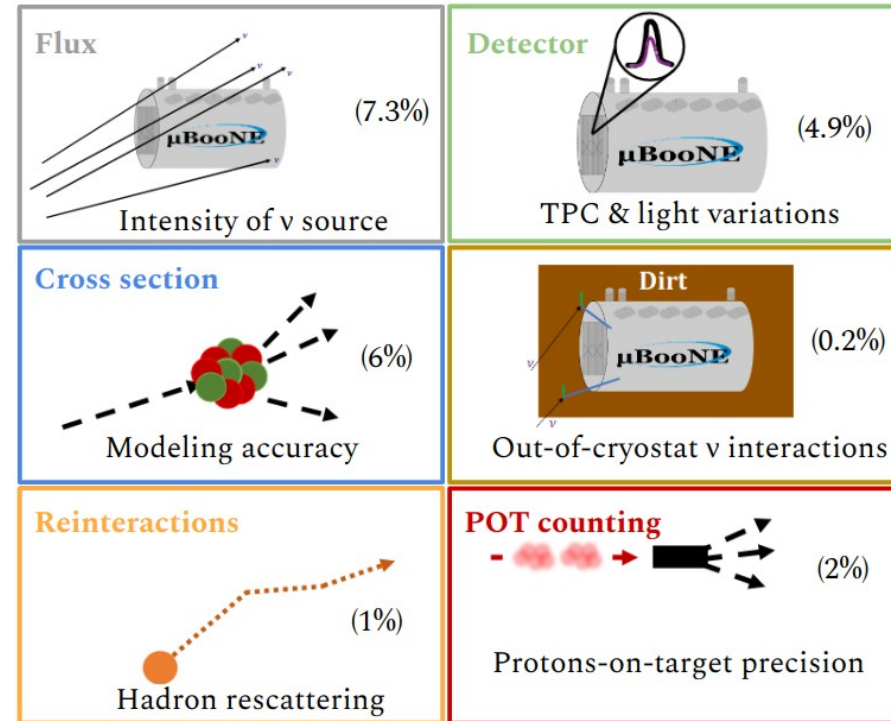
Final Event Sample

- 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

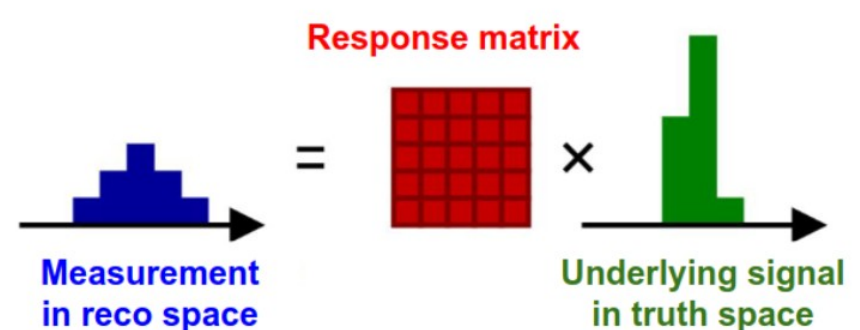
- Vary all systematic parameters in MC, to produce covariance matrix for predicted event rate
- Assume this covariance matrix applies to the data
 - This requires “reasonable” data/MC agreement to hold
- For signal interaction modelling, only vary the impact on efficiency and smearing
- Divide by assumed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

$$M_i = \sum_j R_{ij} \cdot S_j + B_i$$


The diagram illustrates the unfolding process. On the left, a blue histogram represents the 'Measurement in reco space'. This is followed by an equals sign. In the center is a red grid representing the 'Response matrix'. To the right of the grid is a multiplication symbol (×) and a green histogram representing the 'Underlying signal in truth space'. The entire equation is visually represented as: Measurement in reco space = Response matrix × Underlying signal in truth space.



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!

$$M_i = \sum_j R_{ij} \cdot S_j + B_i$$
