Multi-Proton Zero Pion Cross-Section Measurement with the NuMI Beam

Jack Smedley

ICARUS Collaboration Meeting

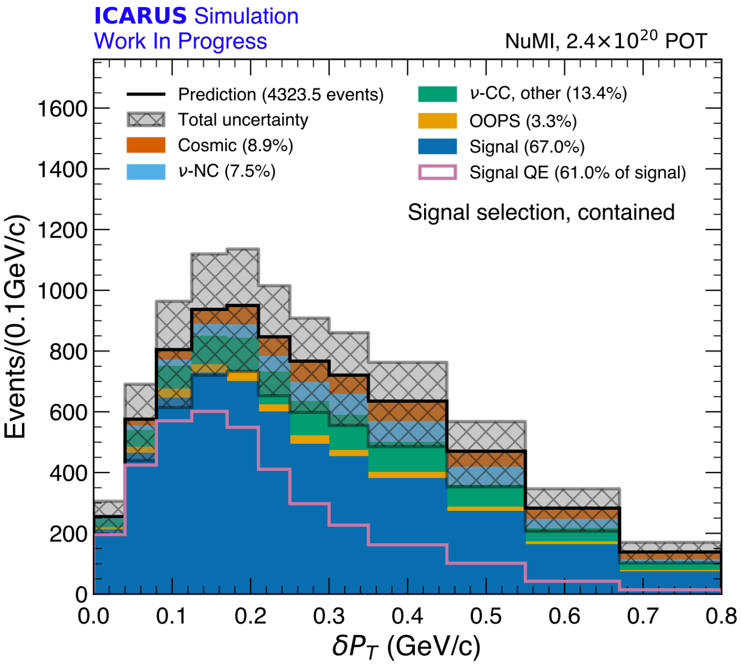
Monday, October 14, 2024

UNIVERSITY of ROCHESTER

Imaging Cosmic And Rare Underground Signals

Why Multi-Proton?

- We just heard from Jaesung about the ν_μCCNp0π (N>0)
- Focus on QE-like signal definitions is popular in the field for probing the dominant interaction mode for accelerator neutrino experiments



[B. Howard and J. Kim, docdb 37241]

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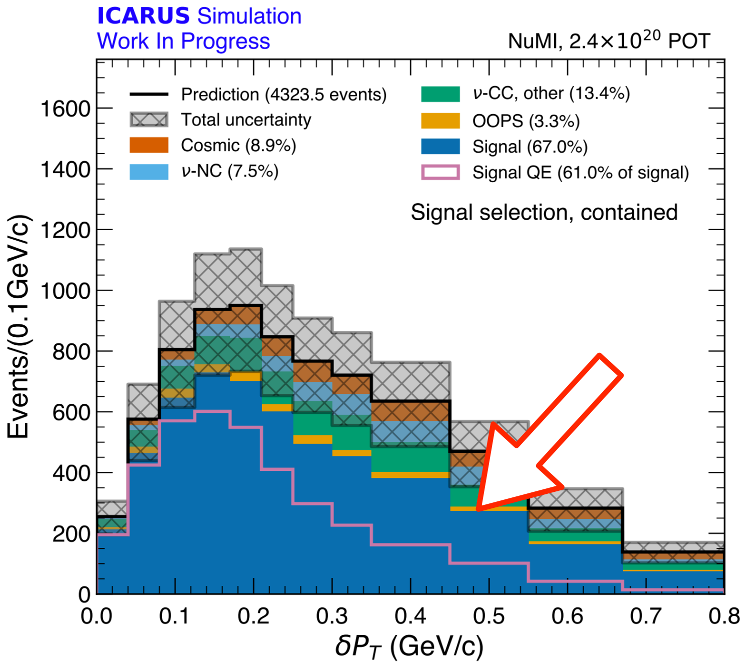
- Focus on QE-like signal definitions is popular in the field for probing the dominant interaction mode for accelerator neutrino experiments
- As measurements and modeling have improved for QE, the ***non-QE*** components that come along for the ride are still very uncertain!



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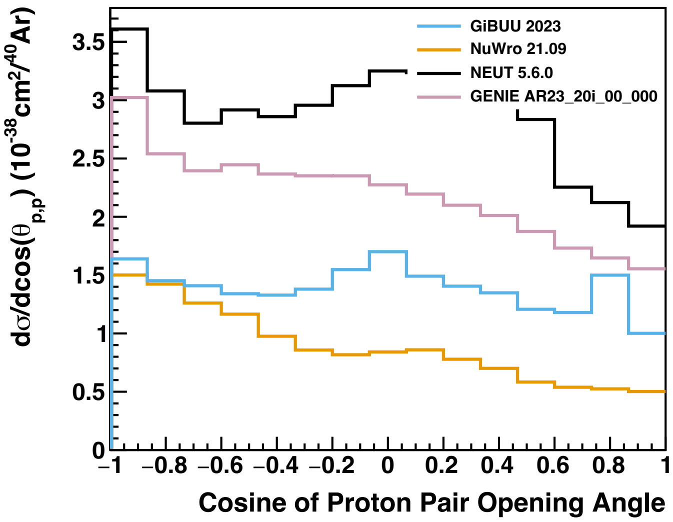

- Selecting for ν_μCC>1p0π events directly enhances these non-QE interactions
- Sensitivity to processes like 2p2h and pion absorption via final state interactions (FSI), for which we know our models are not sufficient

Differential cross section for multi-proton events extracted from truth-level generator comparisons with the ICARUS NuMI flux

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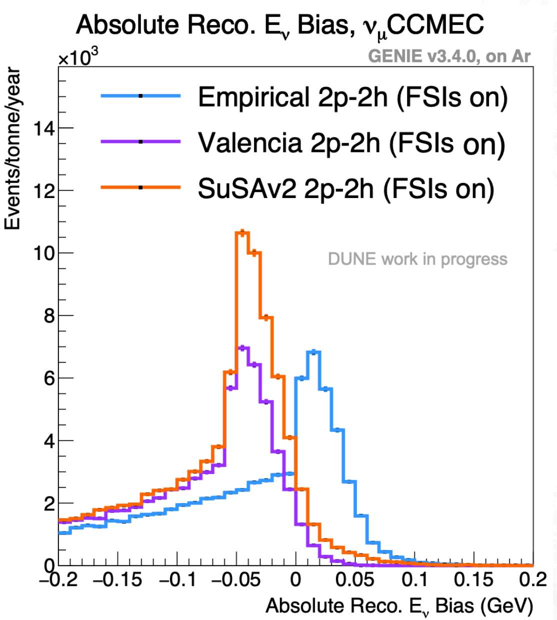


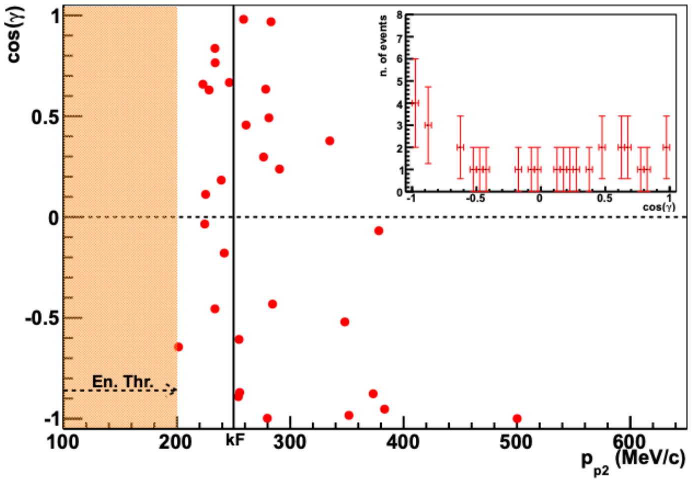
L. Bathe-Peters, Jan 24 DUNE CM

- Selecting for ν_μCC>1p0π events directly enhances these non-QE interactions
- Sensitivity to processes like 2p2h and pion absorption via final state interactions (FSI), for which we know our models are not sufficient
- Getting this right matters! Interaction model uncertainties only become more relevant as we enter the high-stats era of neutrino oscillation physics!

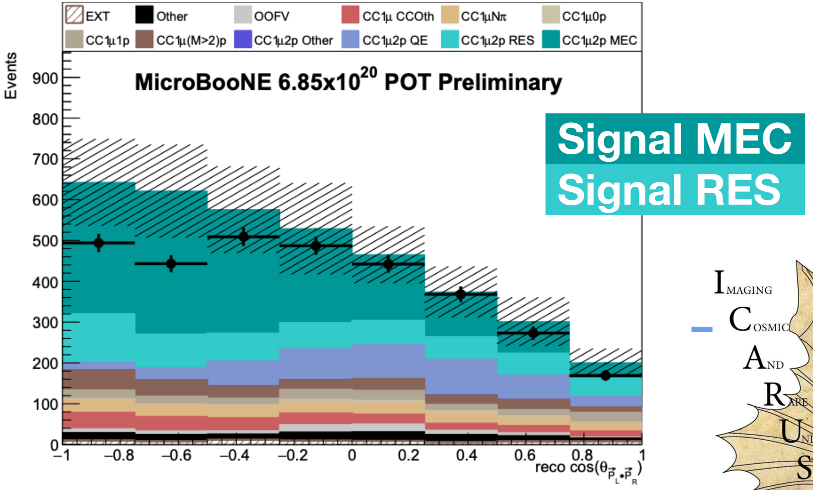
Literature Review

- One result on multi-nucleon production in argon has been published, a 2014 ArgoNeut paper that identified just 30 events
- Similar analyses now in development by μBooNE and SBND using the BNB flux
  - Smaller resonant pion absorption contribution due to lower neutrino energy, results will be very complimentary with an ICARUS NuMI measurement!

ArgoNeut Result

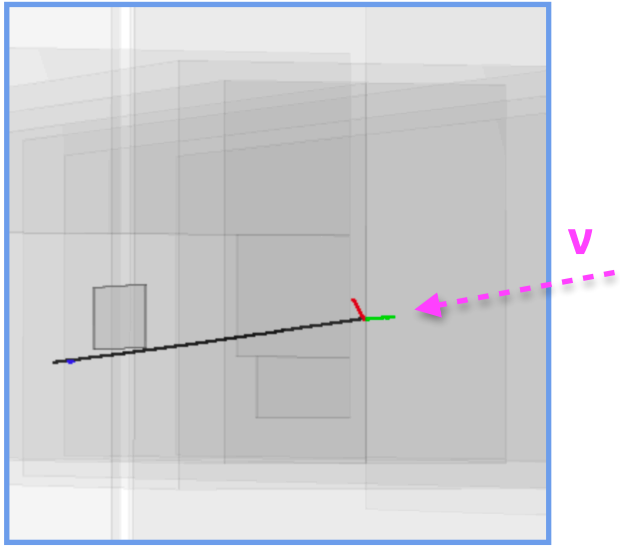


μBooNE Tech Note



ν_μCC>1p0π Signal Defintion

- **A subset of the Np analysis, with the exception of a wider proton momentum range!**
- ν_μCC or anti-ν_μCC in FV
- p_μ > 226MeV/c, ~50cm in LAr
- At least two protons with p_p from 350MeV/c to 2GeV/c
  - 350MeV/c corresponds to ~3.75cm in LAr
  - Efficiency beyond 2GeV/c is negligible
- Any number of neutrons or below-threshold protons
- Exactly zero pions



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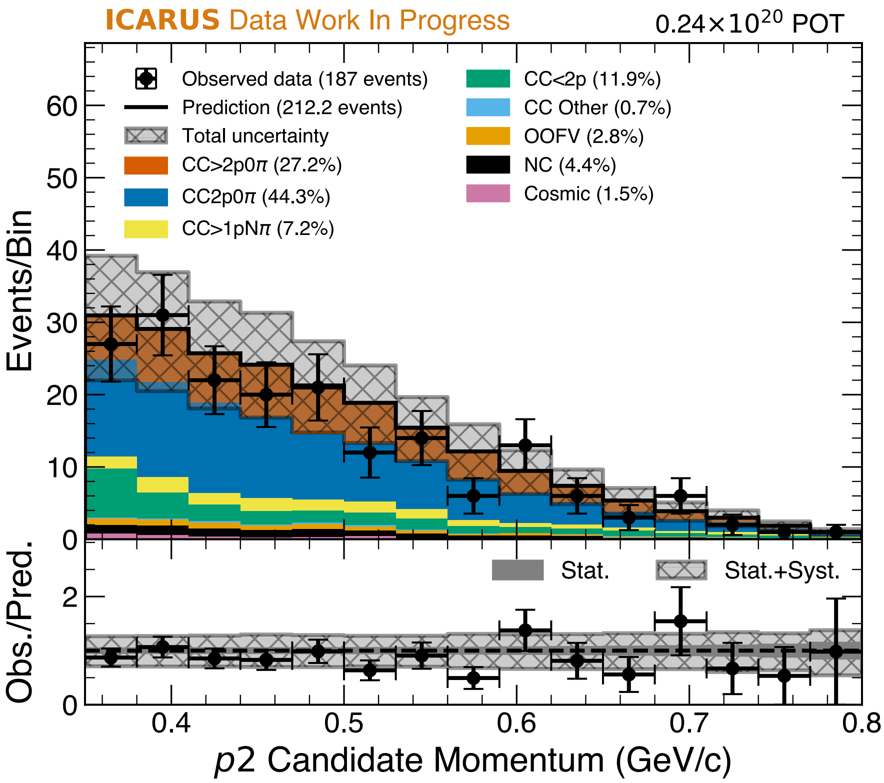
Event Selection

- Event is not a “Clear Cosmic” and has a vertex in the FV
- A reconstructed muon candidate, defined the same as other analyses
- At least two reconstructed proton candidates, *defined more loosely for improved efficiency in low proton momentum*
  - Reco momentum between 350 MeV/c and 2GeV/c
  - Proton χ^2 PID score < 50, no cut on muon χ^2 PID
  - No cut on Pandora track score
- No other primary tracks or shower exceeding 15cm or the leading proton length

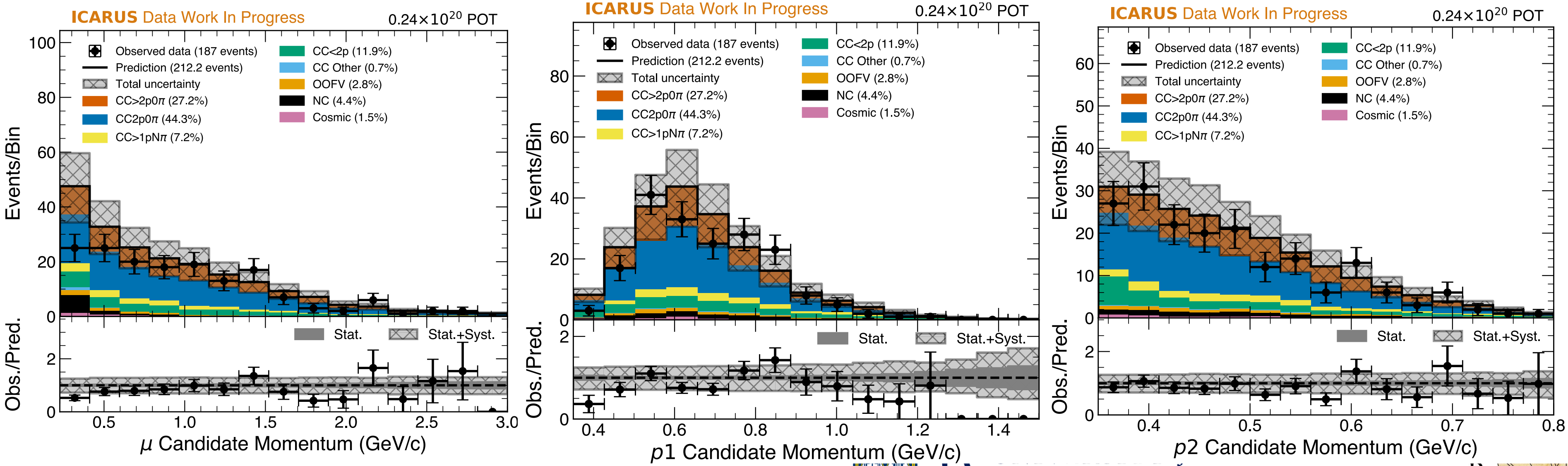
Selection Performance

- Shown as a function on sub-leading proton momentum
- Data points are 10% of Run1+Run2 (sampled from the same 15% shown by Jaesung), MC is scaled to match exposure
  - *Note that we don't expect perfect agreement, the models are wrong!*
- Error bands are the complete set of flux, GENIE, GEANT4, and detector uncertainties
- 71% signal purity, 44% 2p and 27% >2p



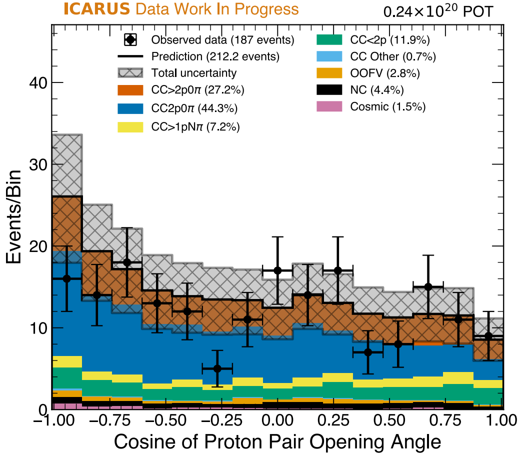
Low Level Observables

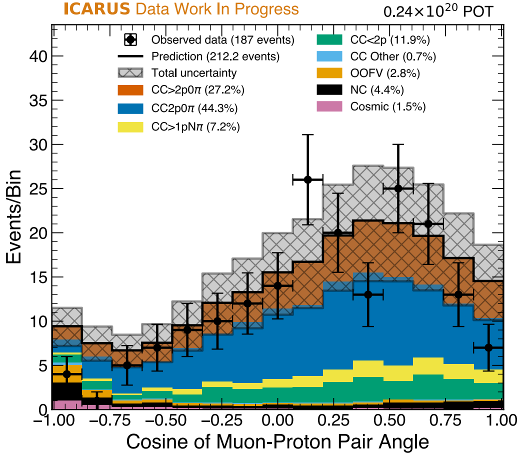
- Data-MC agreement looks as good as can be expected
  - GENIE's “model” for the sub-leading proton momentum, is at best arbitrary
- No obvious POT accounting issues or other red flags

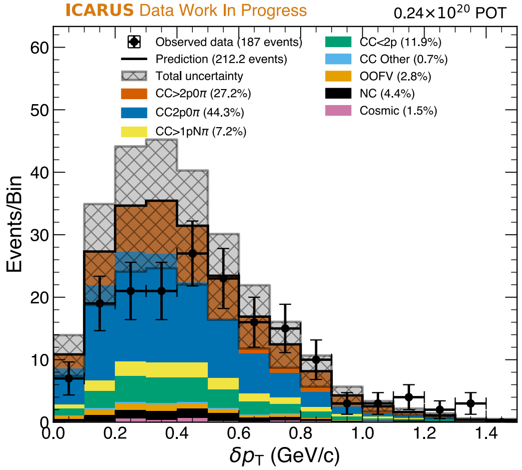


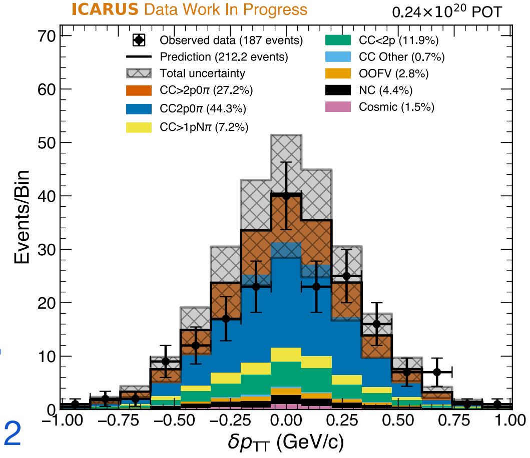
High Level Observables

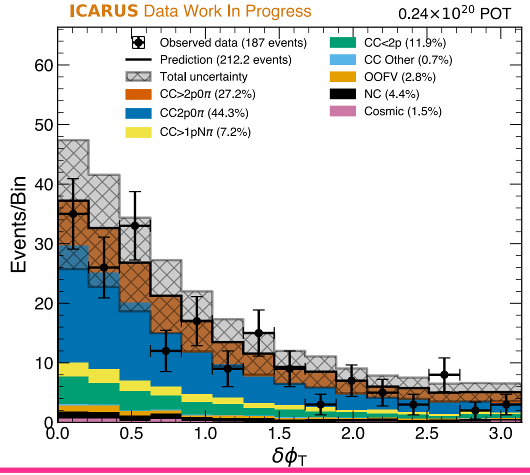
Opening Angles

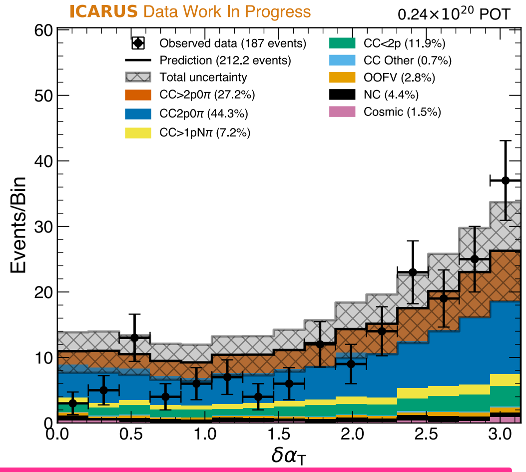




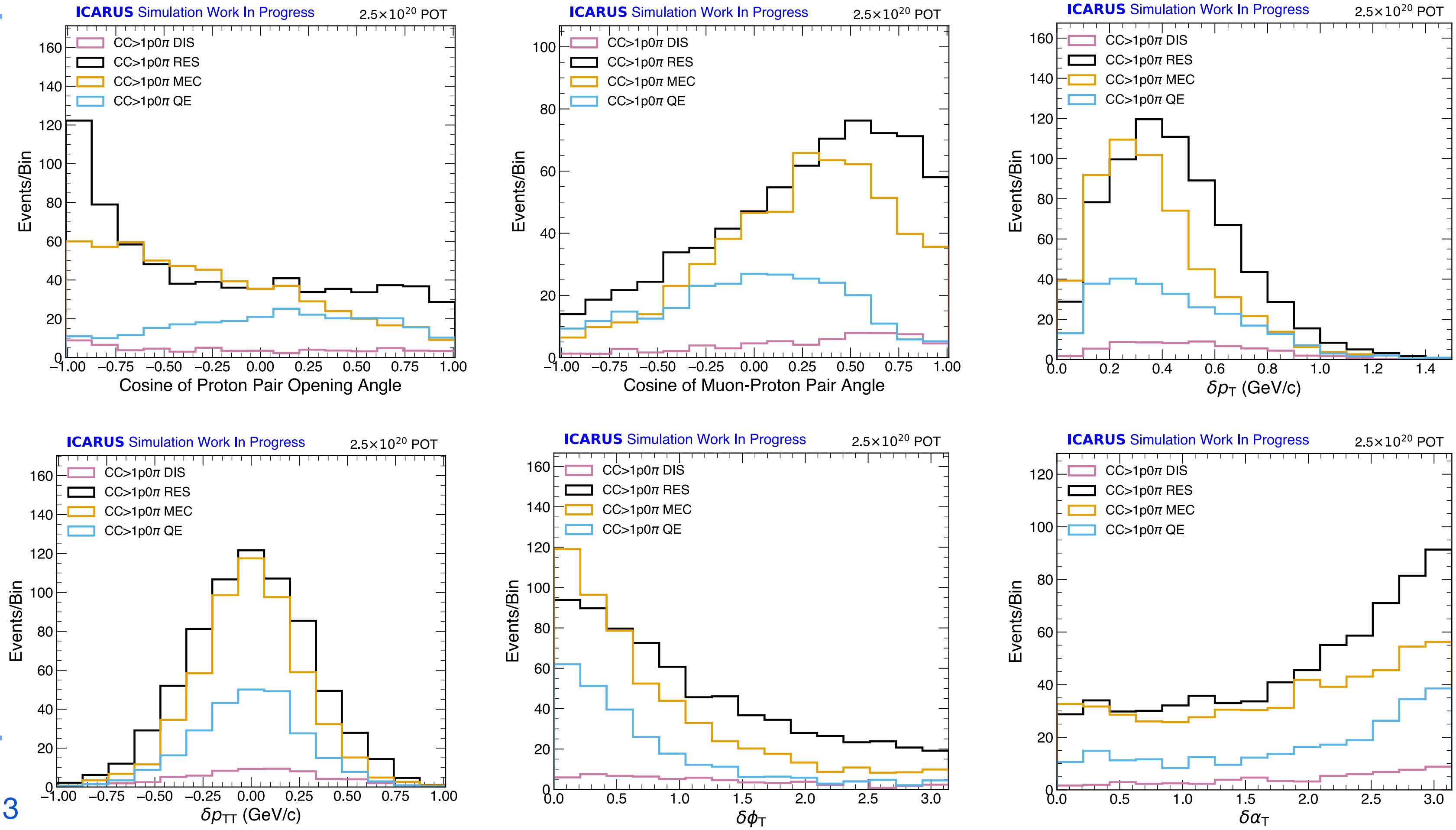




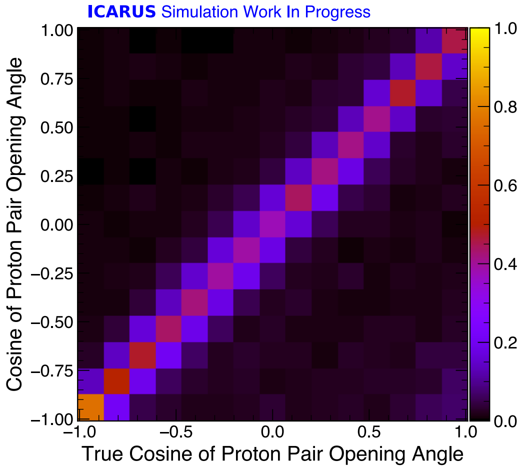


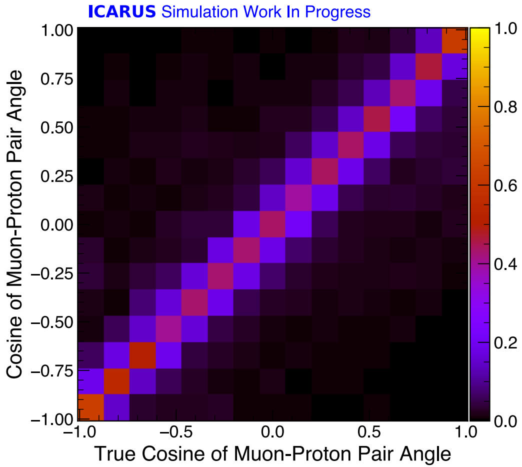


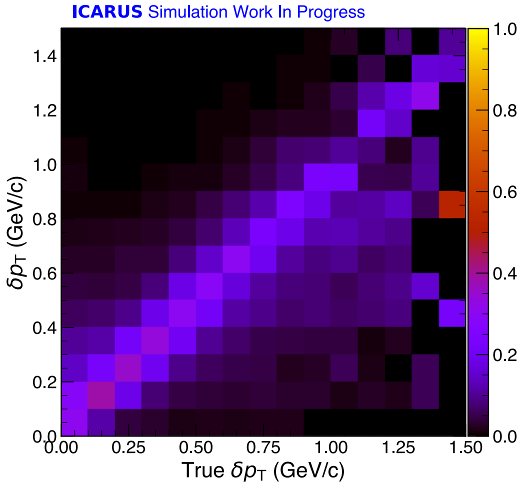
Transverse Kinematic Imbalance variables defined out of the muon and the leading two protons

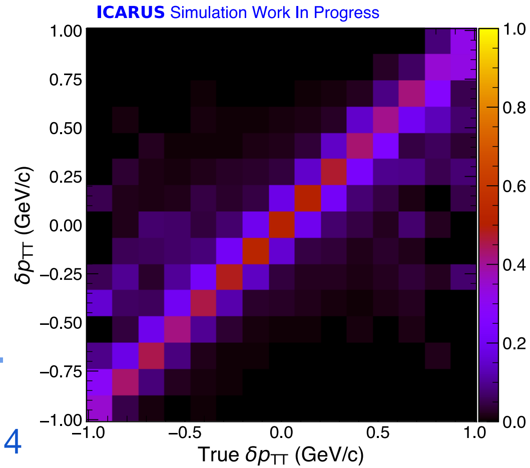


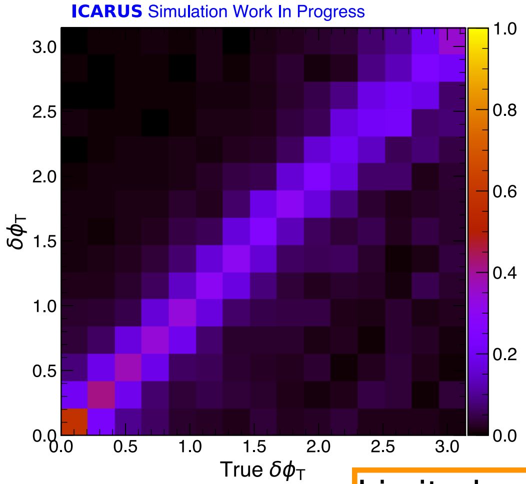
All signal events broken down by interaction mode

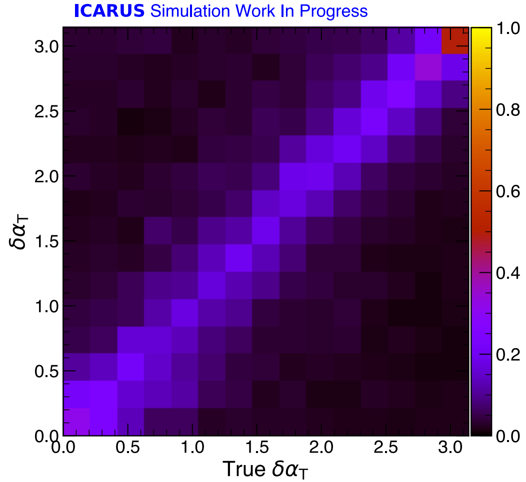










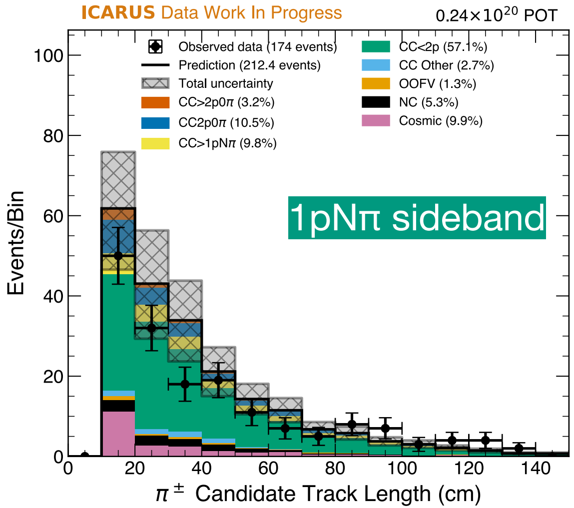


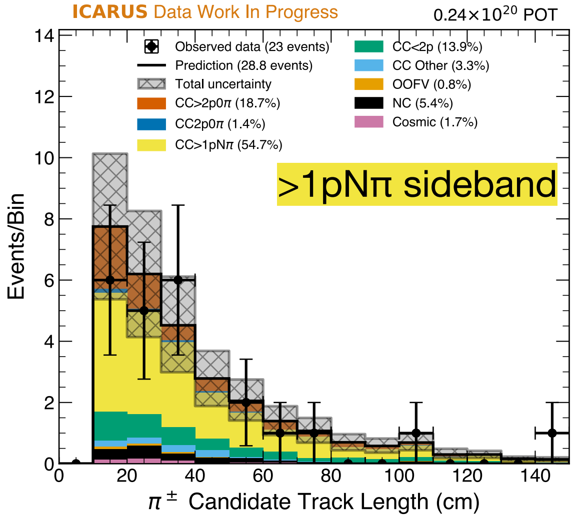
Column-normalized smearing

Limited resolution due to MCS muon momentum!

Control Samples

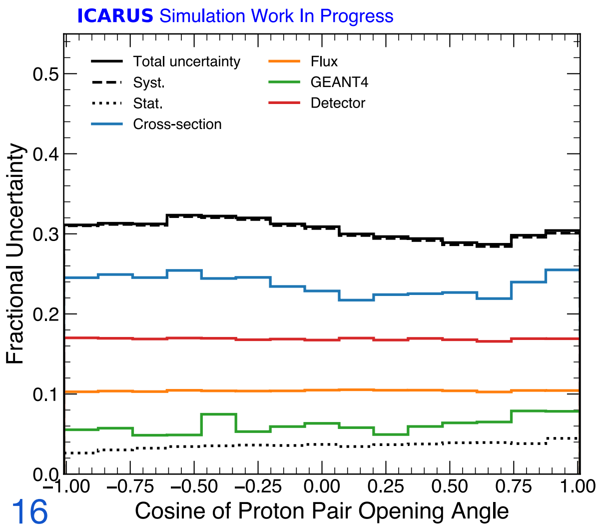
- The leading background contributor is CC<2p events, mostly selected due to post-FSI strong interactions in the argon knocking out additional protons
- Followed by CC>1pNπ events, where a pion was missed in the event
- Both can be constrained with pion sidebands, with ν_μCC1pNπ and ν_μCC>1pNπ selections respectively
- Selecting events events with an additional MIP-like track and sorting into one selection the other depending on the number of reconstructed protons





Uncertainty and Efficiency

- All systematics are currently shared with the Np analysis
    - Detector uncertainties were assessed independently for this sample as a cross-check and found to be consistent
- Dominant uncertainties on the *prediction* come from the signal modeling
- This largely cancels in the efficiency correction, not impacting the measurement



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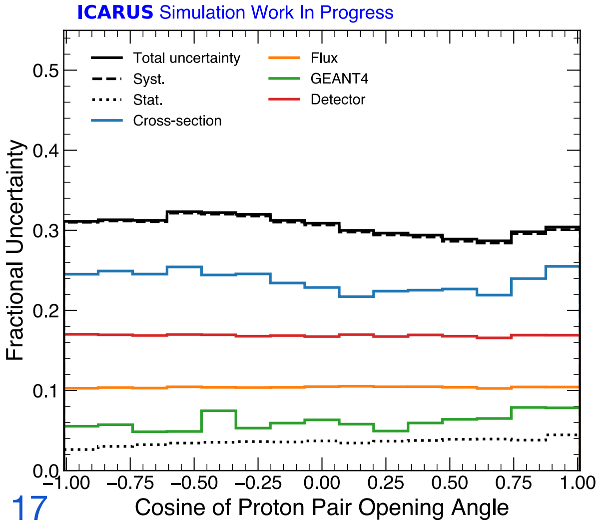

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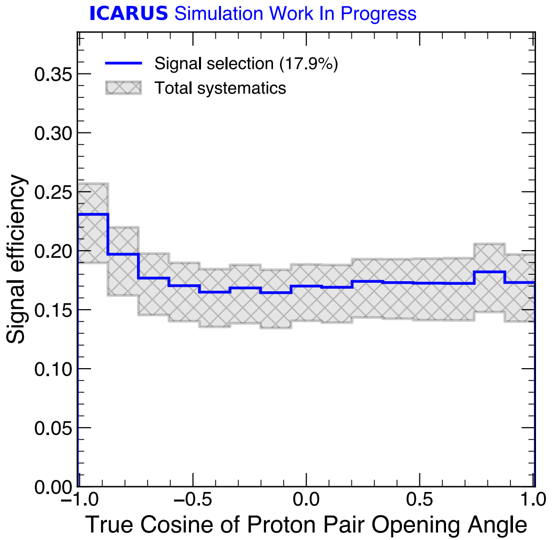
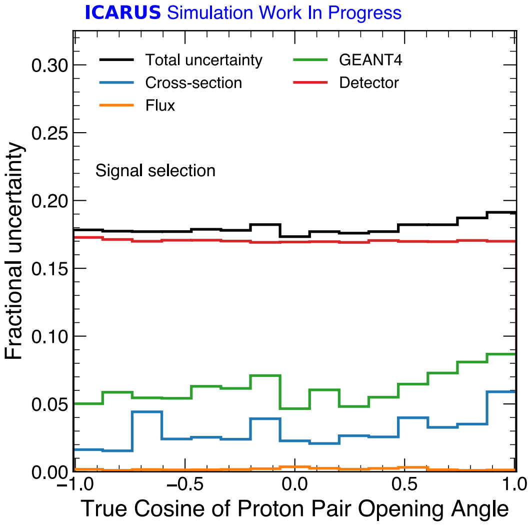




Uncertainty on the **efficiency**

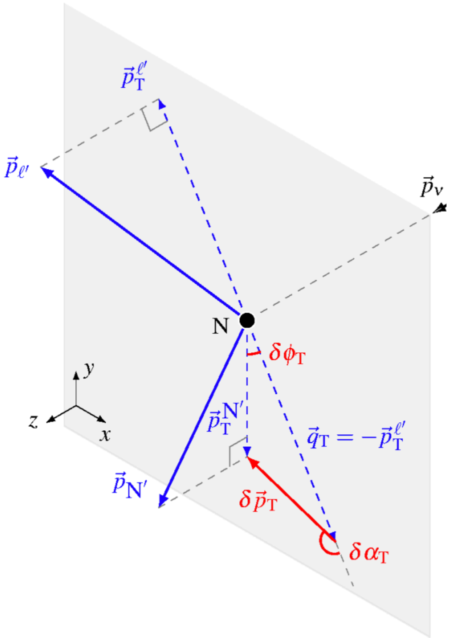
Conclusions and Next Steps

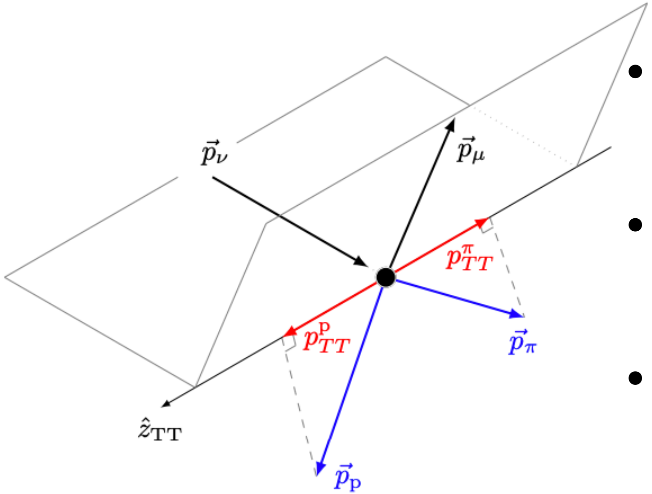
- Selections and systematic assessments for the NuMI multi-proton measurement are in a very mature state
- 10% data looks promising, agreement with MC is as good as can be expected and no red flags were found
- Analysis proposal document has been reviewed by the committee, and a technical note is being drafted
  - Aiming to complete the tech note and request sideband unblinding ***this fall!***

Stay tuned!

Backup

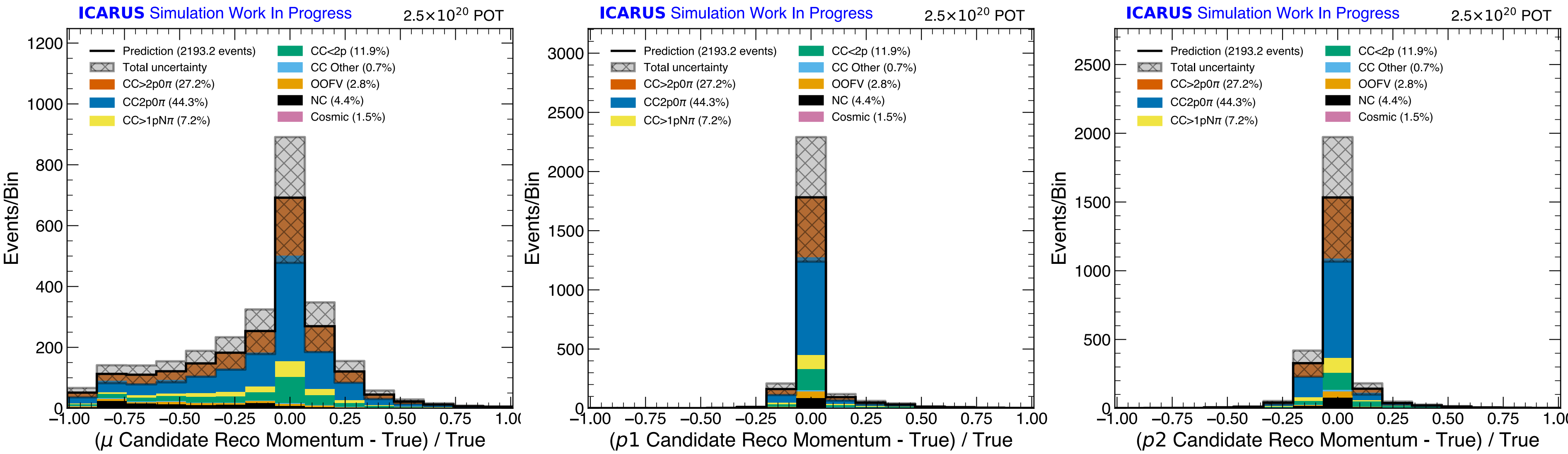
TKI Definitions





- All defined with respect to the muon and the leading two protons
- δpT - Single-transverse momentum imbalance, sum of momentum transverse to neutrino direction
- δαT - Transverse boosting angle, indicated if FSI is boosting with or against lepton direction
- δϕT - Transverse opening angle, measured between the muon and the hadronic system
- δpTT - Double-transverse momentum imbalance, sum of momentum transverse to neutrino direction ***and*** muon direction

Momentum Residuals



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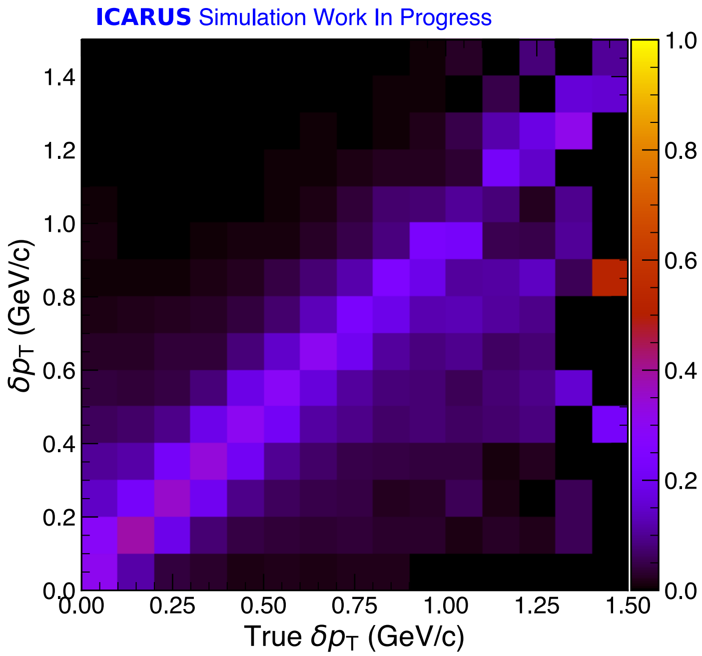
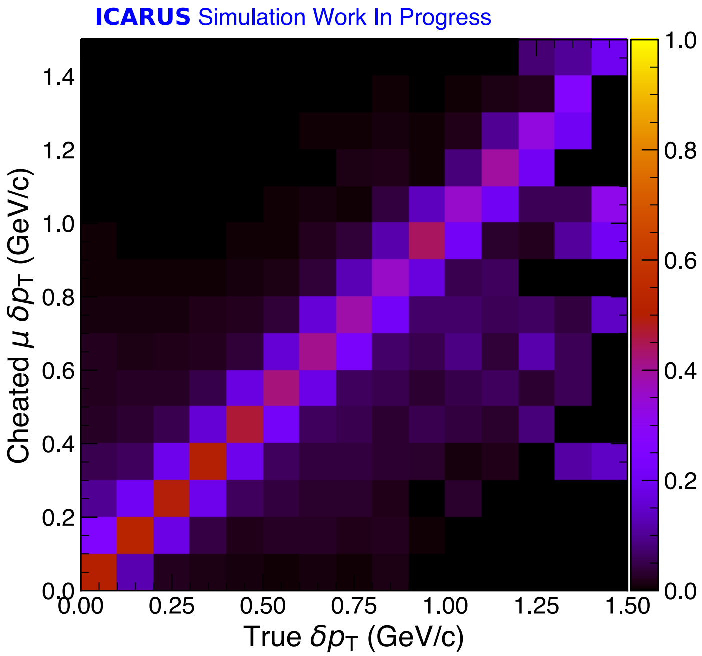
Assessing the Impact of MCS

- < 30% of the selected events have a contained muon
- We can test the impact of muon momentum mis-estimation on observables by cheating muon truth information into the reconstructed variables

Transverse momentum imbalance





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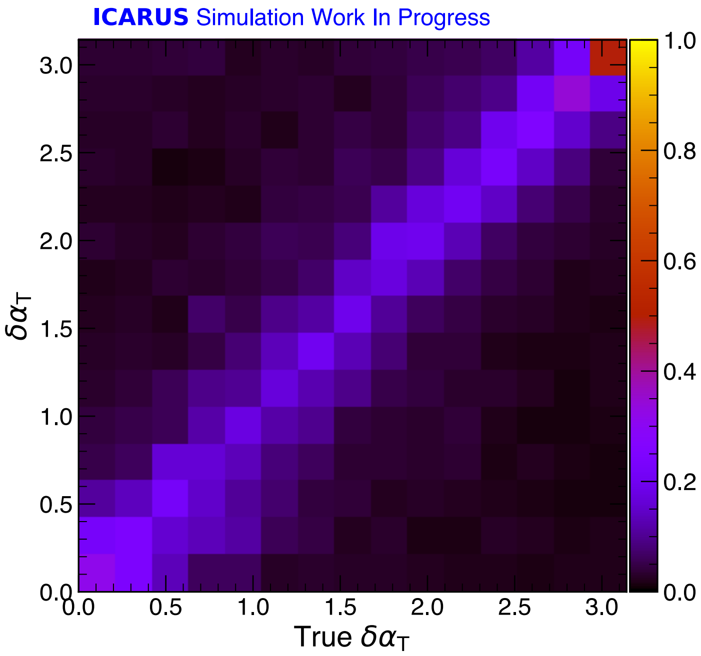
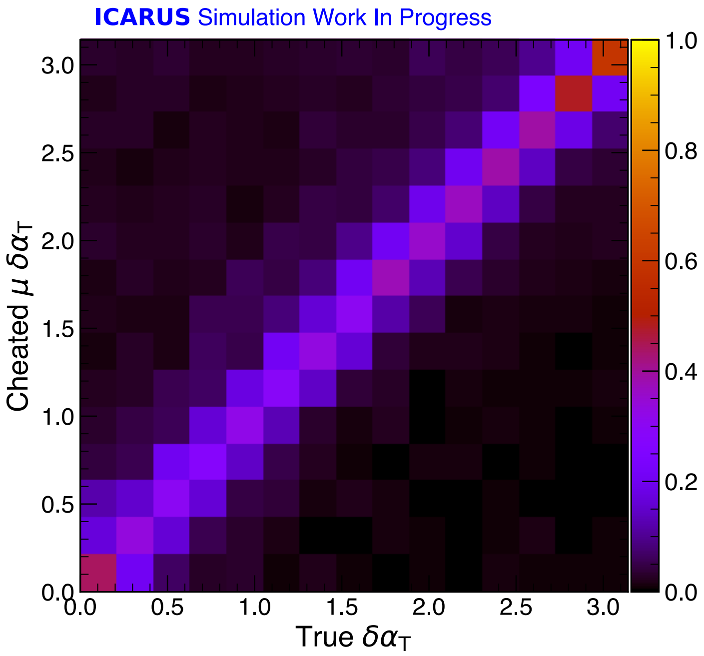
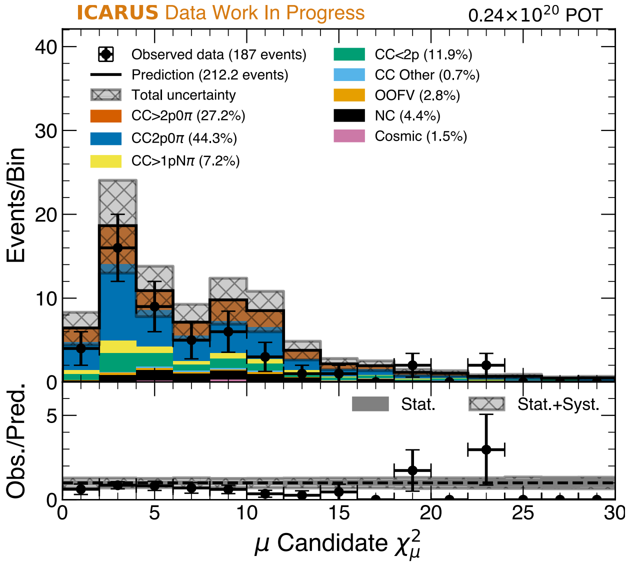
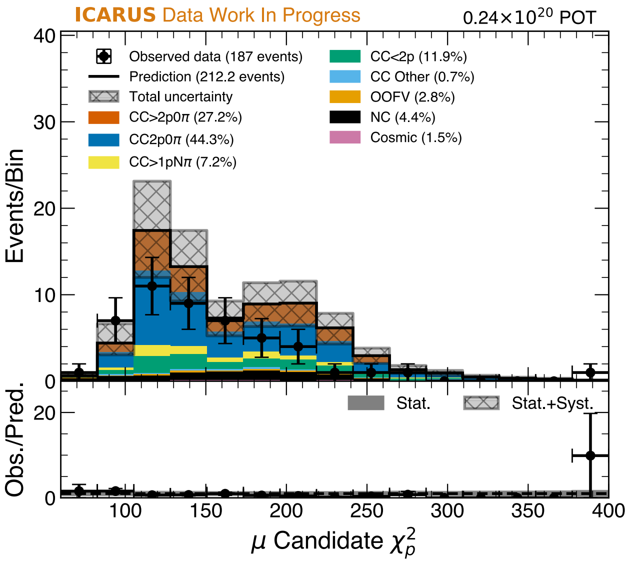
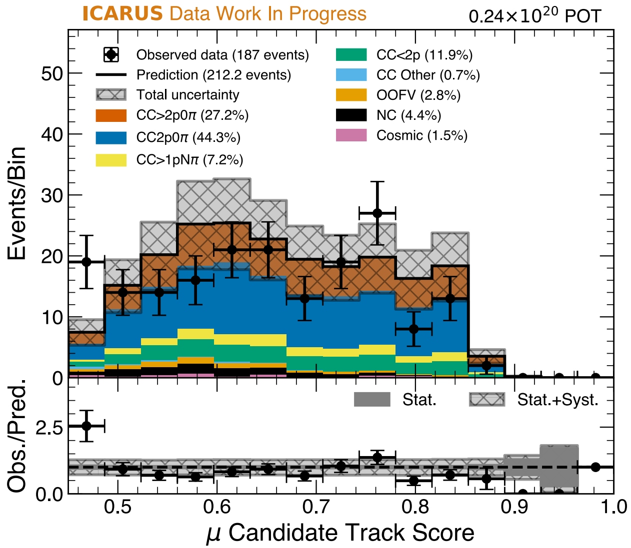




Selection Variables







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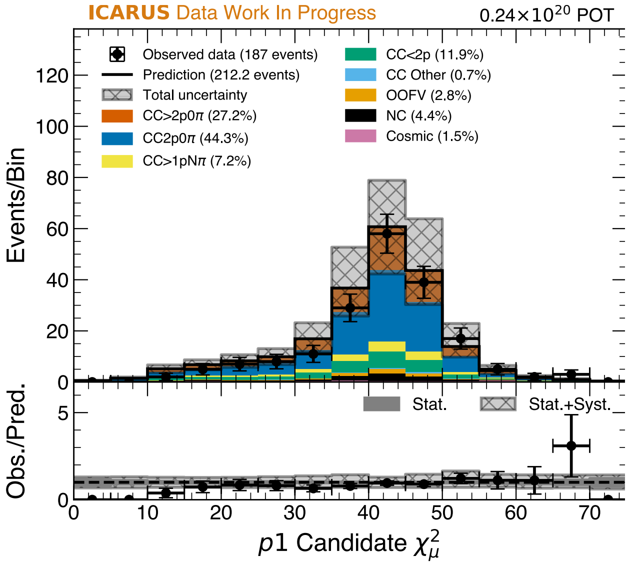

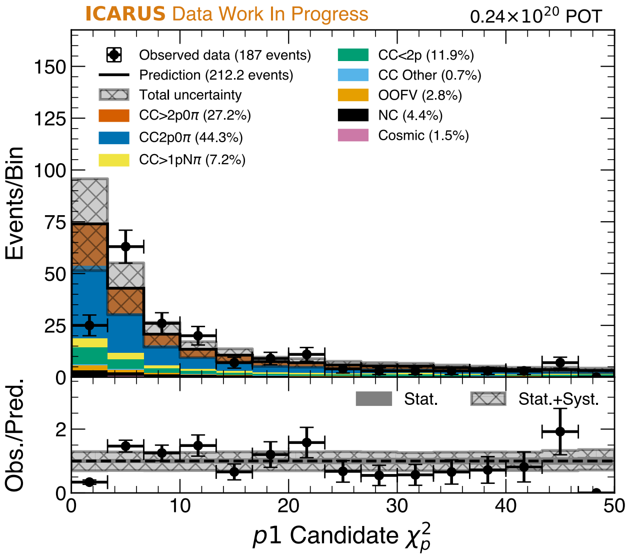

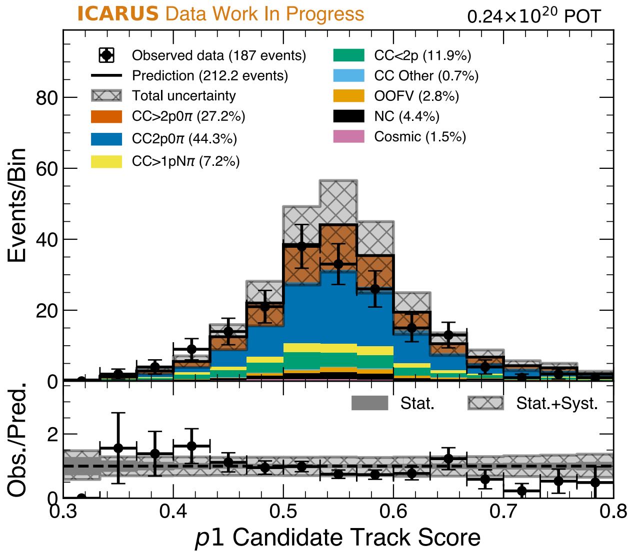

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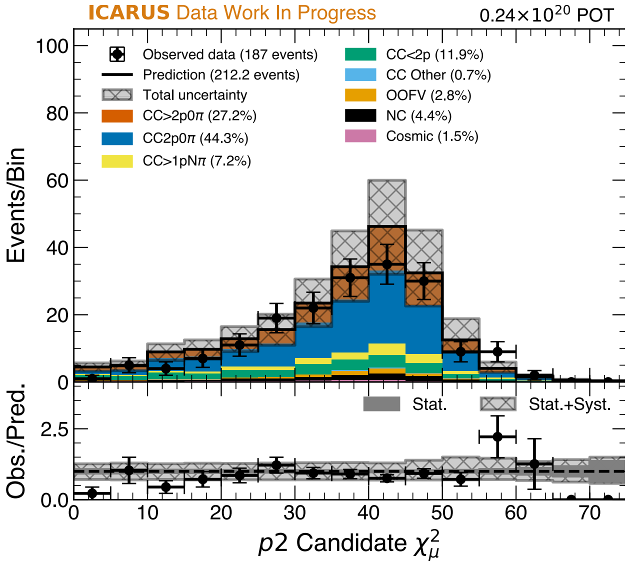
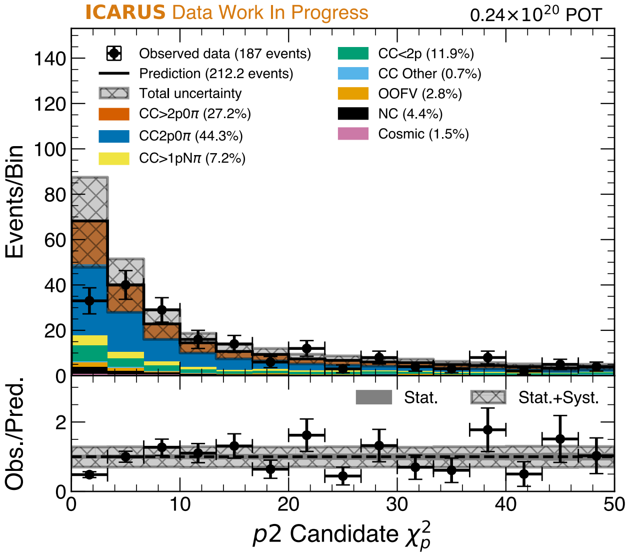
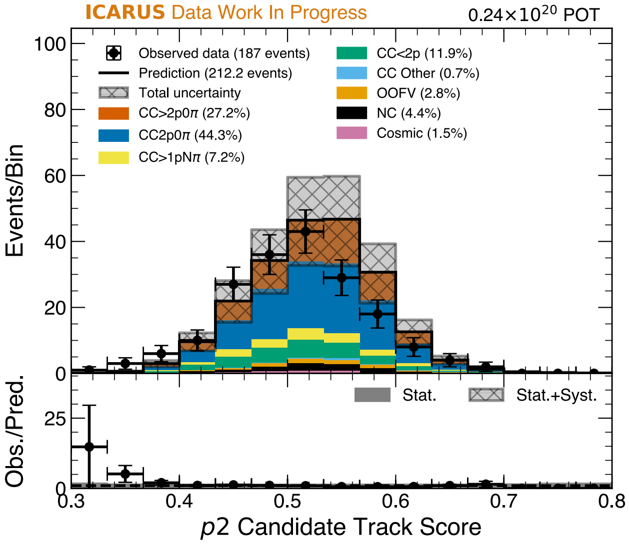




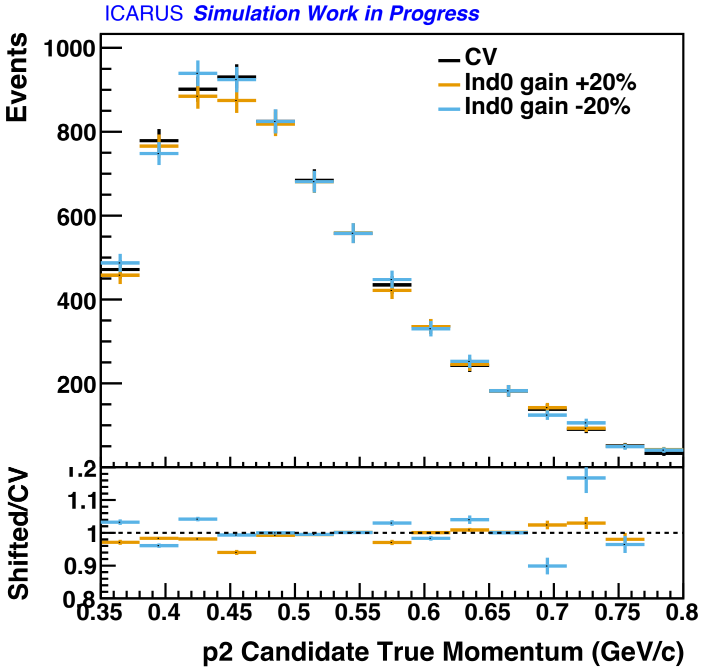


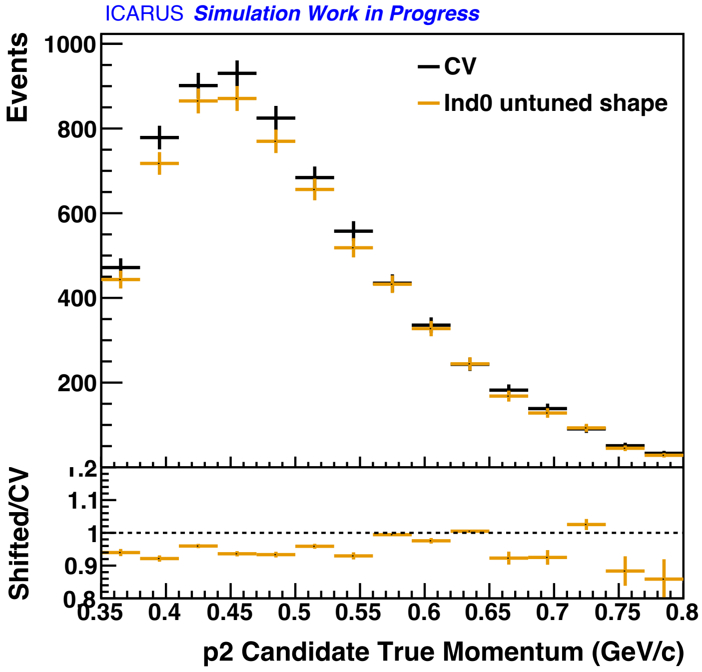
Detector Variation Studies

- I generated many GENIE events and filtered for Np (Bruce+Jaesung's signal) and/or multi-proton events (my signal) to be used as common inputs to detector variation samples for both analyses
    - ~50k multi-proton events and >100k Np events
- I've evaluated the impact of several different detector effects on the multi-proton selection, consistent with what was done for Gray's di-muon search and earlier detector systematics studies for the Np XS
- Some of these variations are known to be ***overly conservative***!
    - Some variations still need to be checked for this analysis, including the effect of the light level on trigger efficiency
- For reference the general process, icaruscode version, and fcls used are all documented in these notes (docdb 37753)

Detector Variation Studies

- No surprises, no obvious shape effects, and importantly *no observed differences from the findings of the very similar Np analysis*!
  - If this holds true for the remaining detector effects, then these analyses will share a common set of detector systematics





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