Cross-section measurements at T2K

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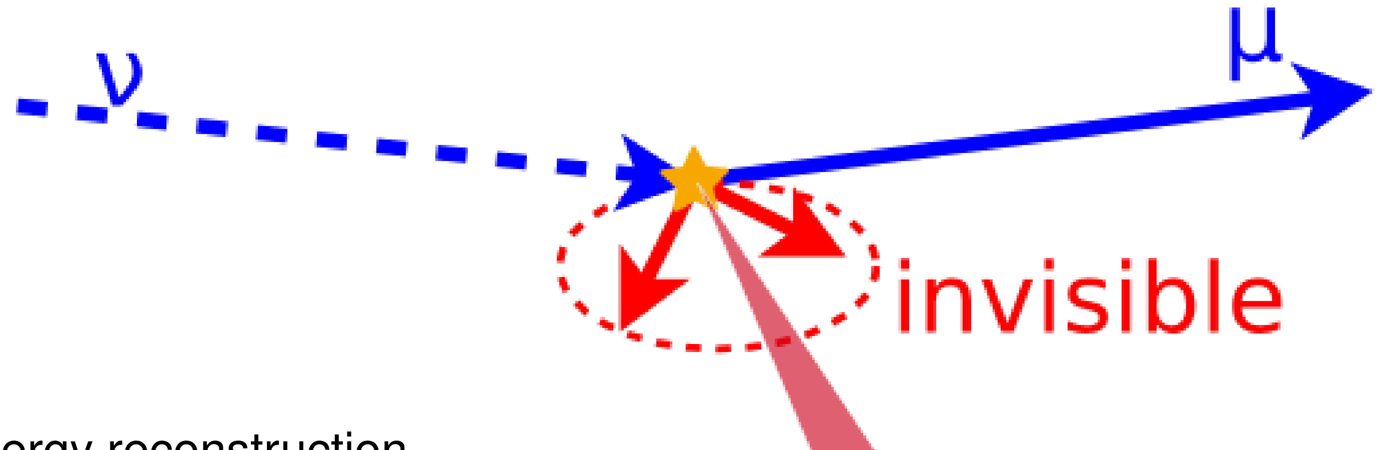
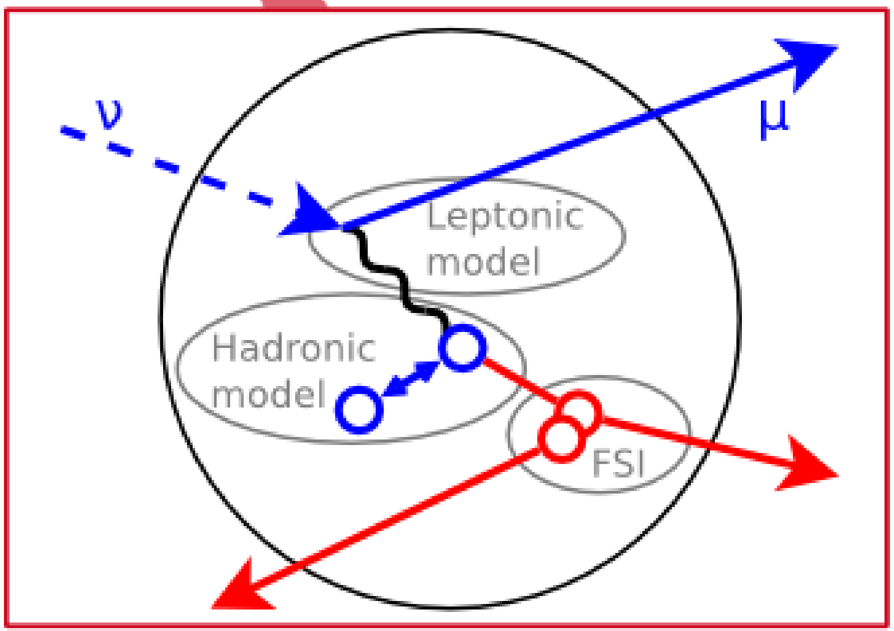
The T2K experiment
Tokai To Kamioka

- 300 km baseline, neutrino beam experiment
- Super-Kamiokande, 50 kt water, Cherenkov ring detector
- First to see ν_e appearance in ν_μ beam
- Hints at Normal Mass Hierarchy, maximal CP-violation
- See talk "Recent Results from T2K" by Simon Bienstock on Tuesday

Why cross sections?
Nuclear effects

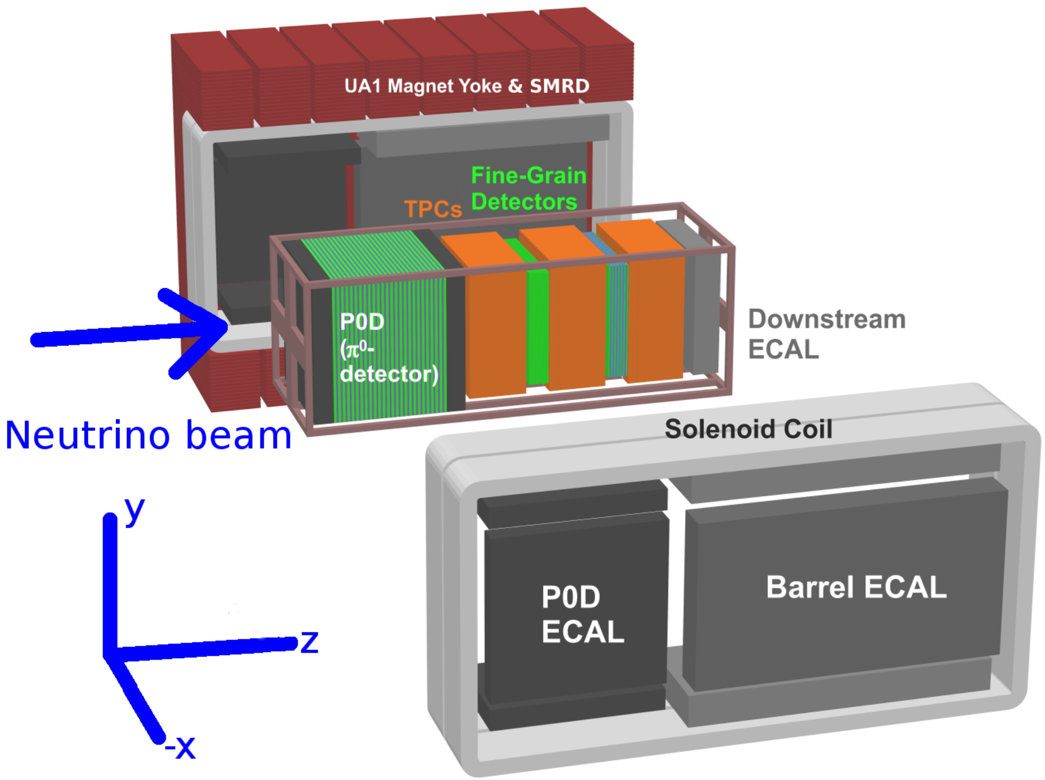


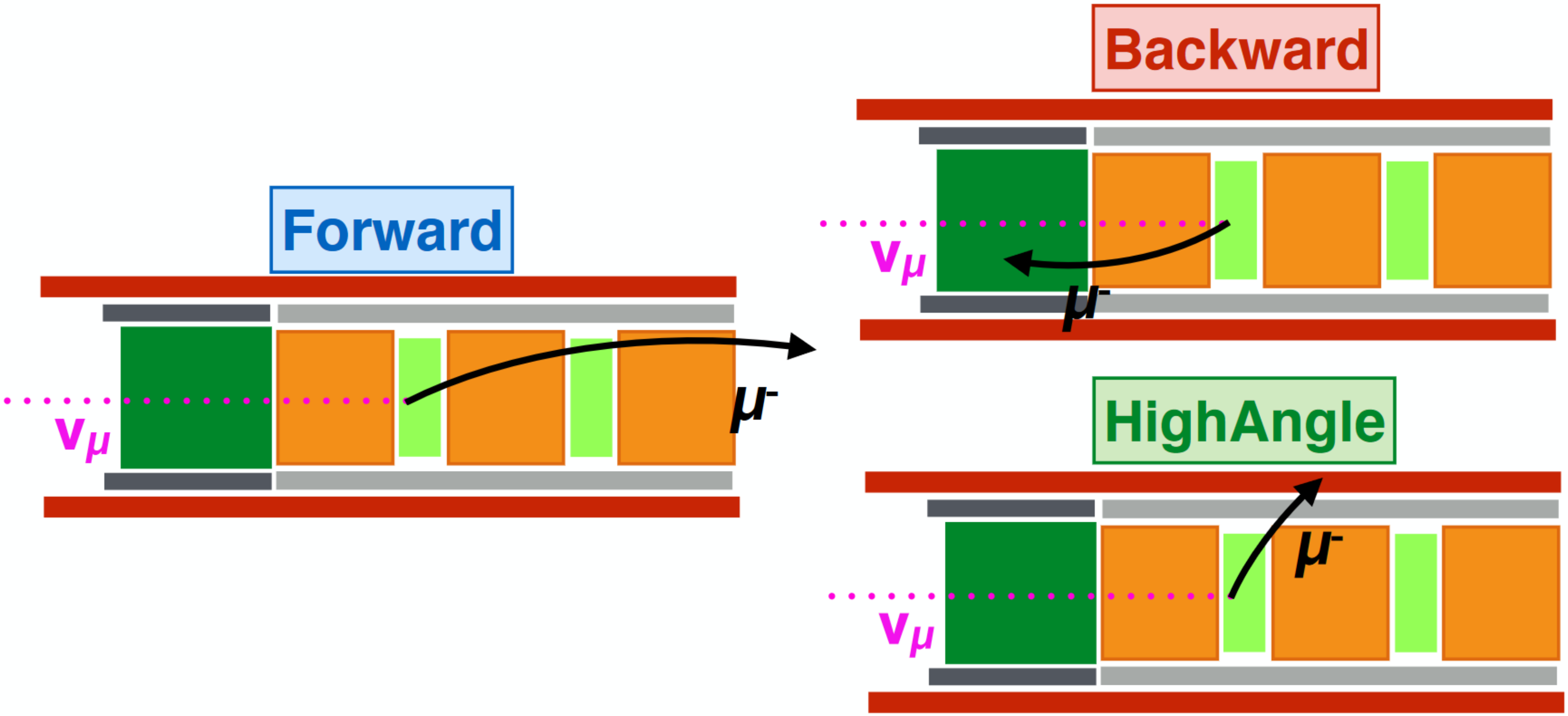
- Kinematic ν energy reconstruction
- Particle momentum under detection threshold $\Rightarrow$ invisible
- Correction using nuclear interaction models
- Source of systematic uncertainties
- Really interesting physics!



Near Detector ND280

- 280 m downstream from graphite target
- Characterises un-oscillated neutrino beam
- Cross-section measurements on different materials
- Designed for interactions in solid, scintillating detectors (e.g. Fine Grained Detectors, FGDs) and passive water targets
- Particle identification in three large Time Projection Chambers (TPCs)
- Inner detectors surrounded by Electromagnetic Calorimeters (ECALs)

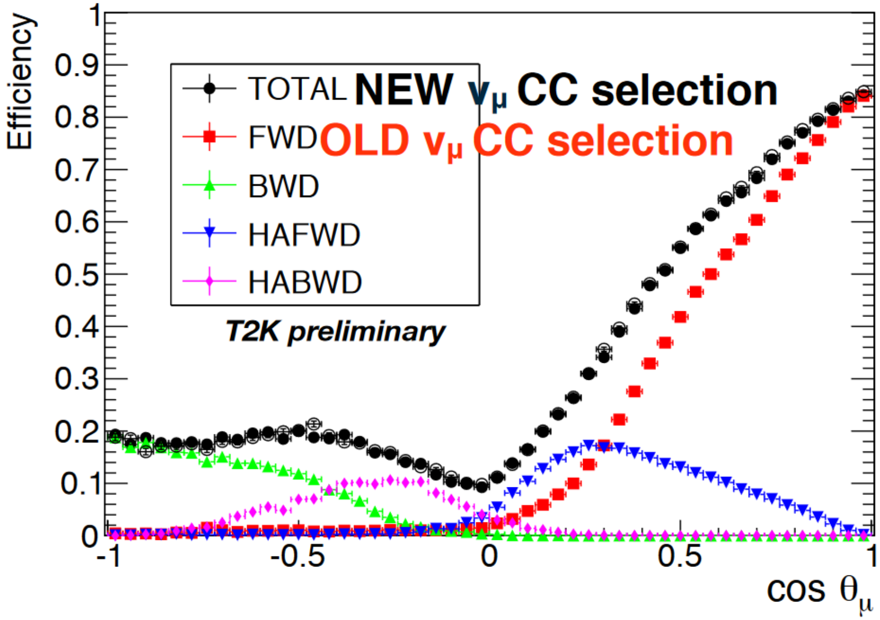




- Double-differential CC inclusive: $\nu_\mu + A \rightarrow \mu^- + X$, binned in p_μ and $\cos(\theta_\mu)$
- Target material: FGD1, plastic (C[86%], H[7%], O[4%], Ti[2%], Si[1%])[1]

[1] mass fractions

4π Charged Current inclusive measurement
Efficiencies and purities

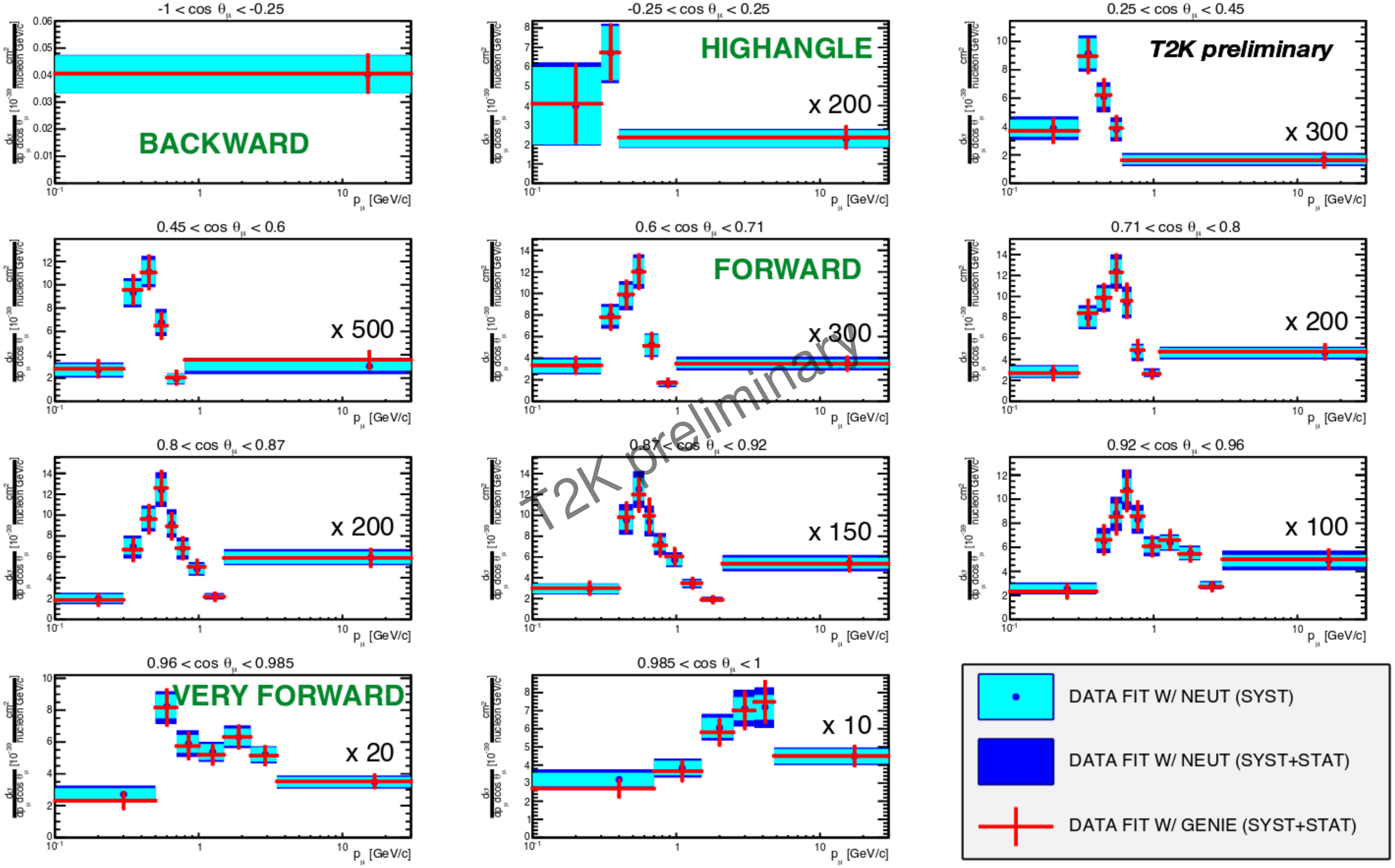


Purities	FWD	BWD	HAFWD	HABWD
ν_μ CC	89%	73%	82%	79%
$\bar{\nu}_\mu$ / ν_e / $\bar{\nu}_e$ CC or NC	6%	2%	6%	3%
Out of FV	4%	22%	11%	17%
Sand μ	1%	2%	1%	1%

(HA = High Angle)

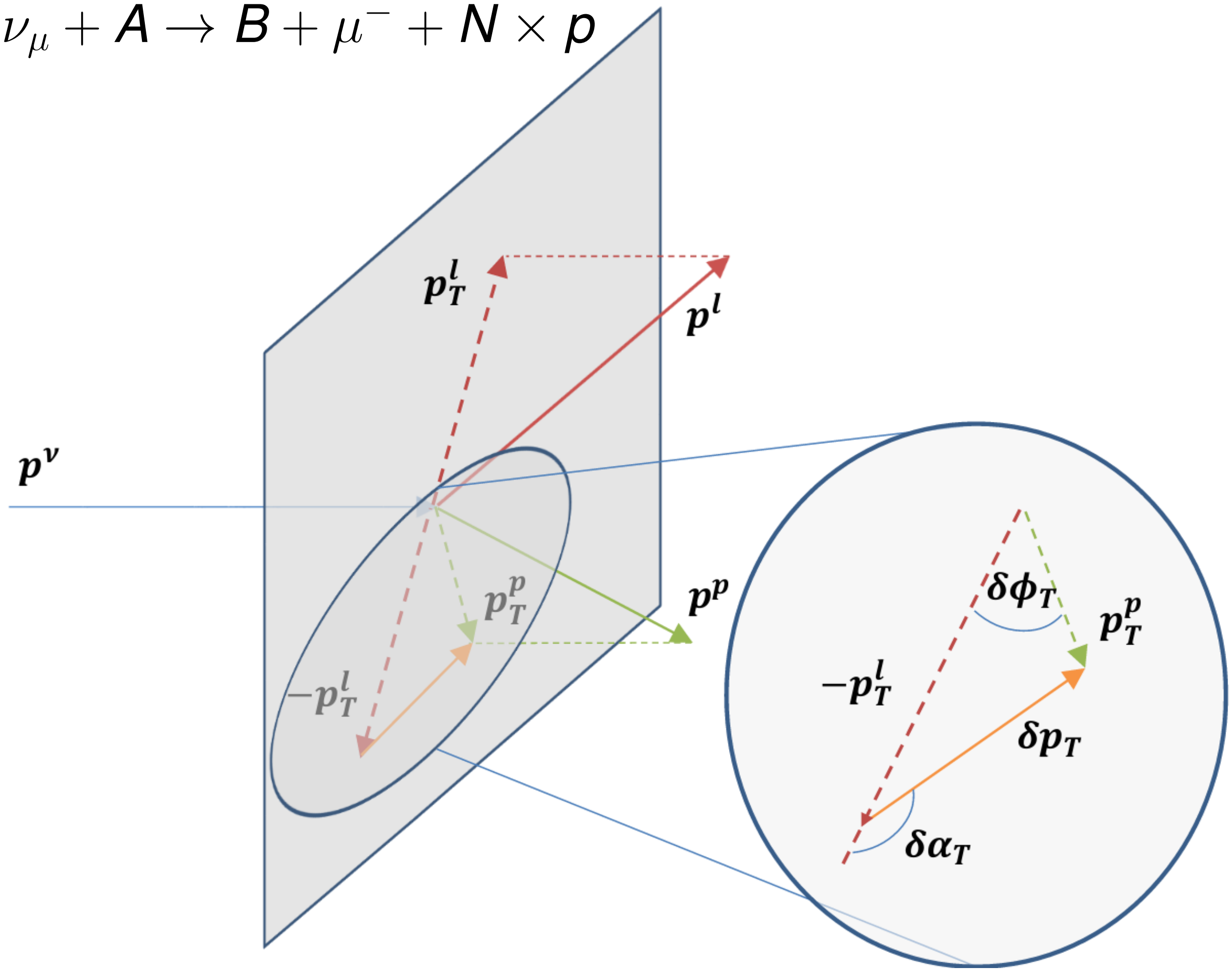
- Different acceptances of near and far detector cause systematic uncertainties
  - Super Kamiokande is symmetric, homogeneous
    - Full 4π acceptance
  - ND280 is “more complicated”
    - Used to be sensitive to forward-going muons only
- New 4π selection fixes this
  - Now can see “everything”
  - Backward efficiency lower than forward

4π CC inclusive measurement
Results



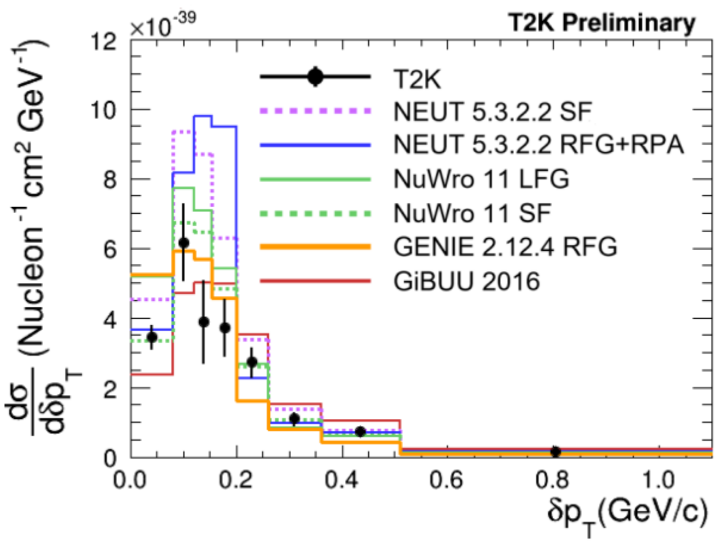
Transverse variable measurement
Charged Current $0\pi + Np$ on plastic (FGD1)

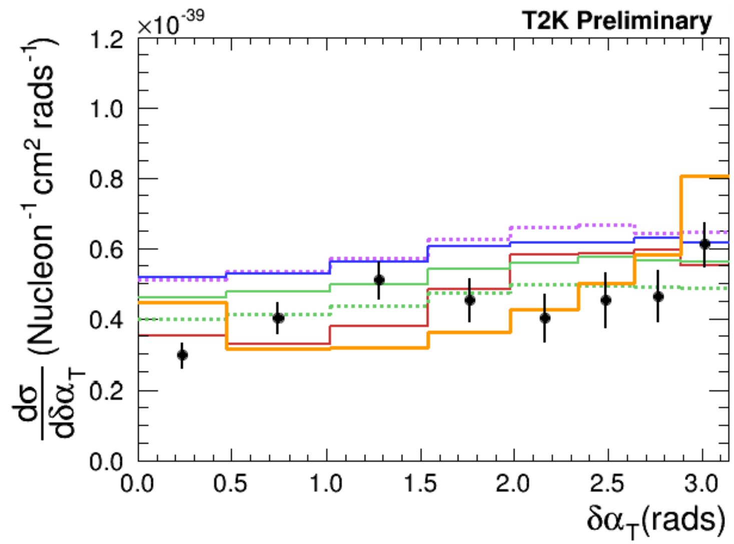
$$\nu_\mu + A \rightarrow B + \mu^- + N \times p$$

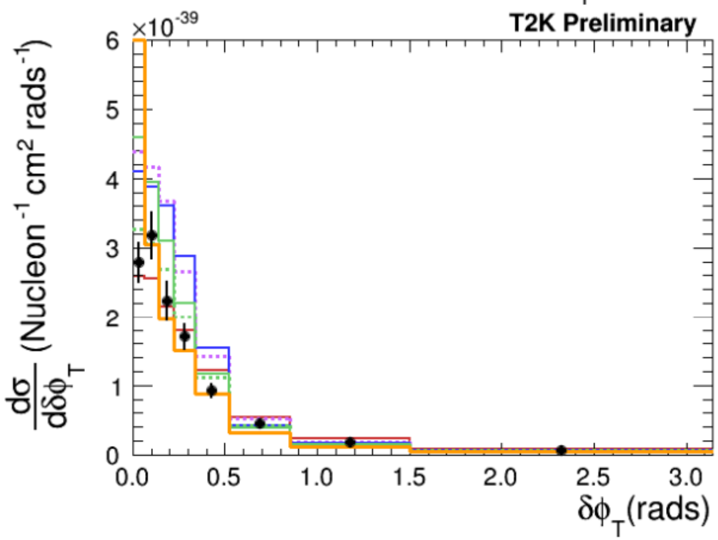


- Proton kinematics offer additional insight into neutrino interactions
- QE interaction with nucleon at rest should produce balanced transverse momentum
- All deviations from balance indicate nuclear effects
- Signal definition:
  - $p_\mu > 250\,\text{MeV}/\text{c}$
  - $\cos(\theta_\mu) > -0.6$
  - $450\,\text{MeV}/\text{c} < p_p < 1000\,\text{MeV}/\text{c}$
  - $\cos(\theta_p) > 0.4$

Transverse variable measurement
Results





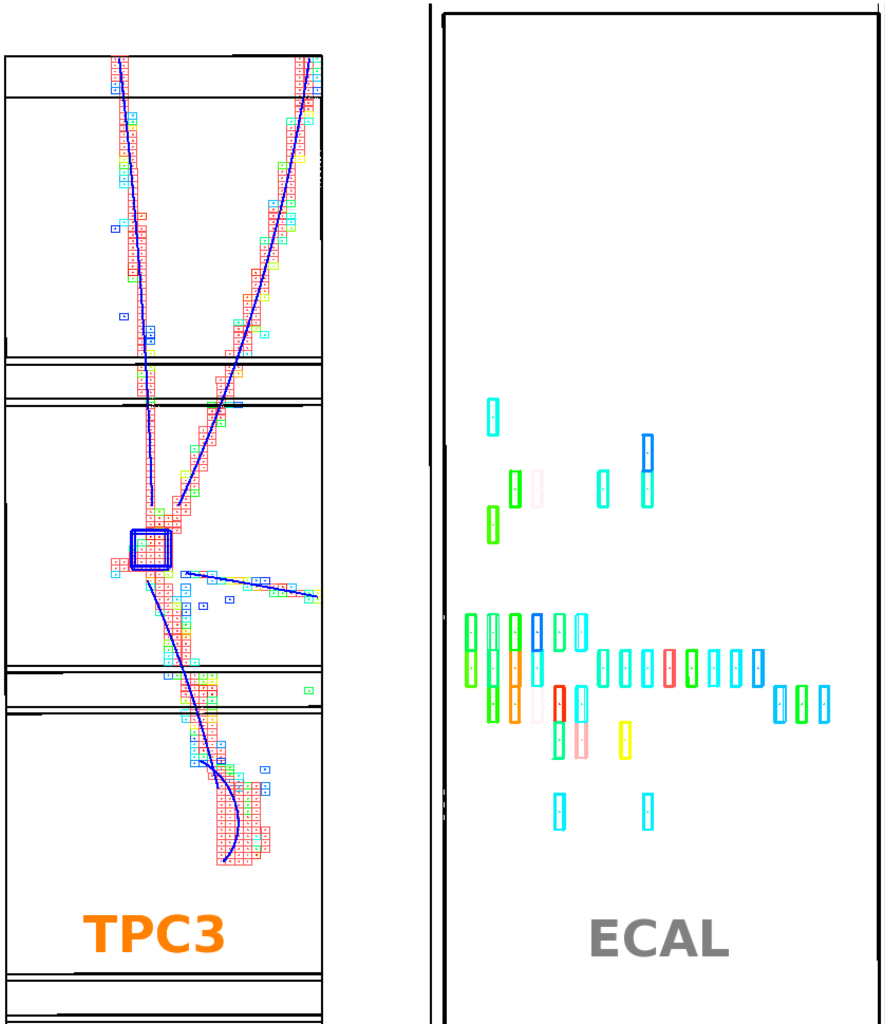


Generator Comparisons

- Plenty of separation
- Result disfavours a `Fermi cliff' in δp_T
- GENIE shape in first bin of each STV related to FSI model
- Nuclear effect isolation

Gas interactions

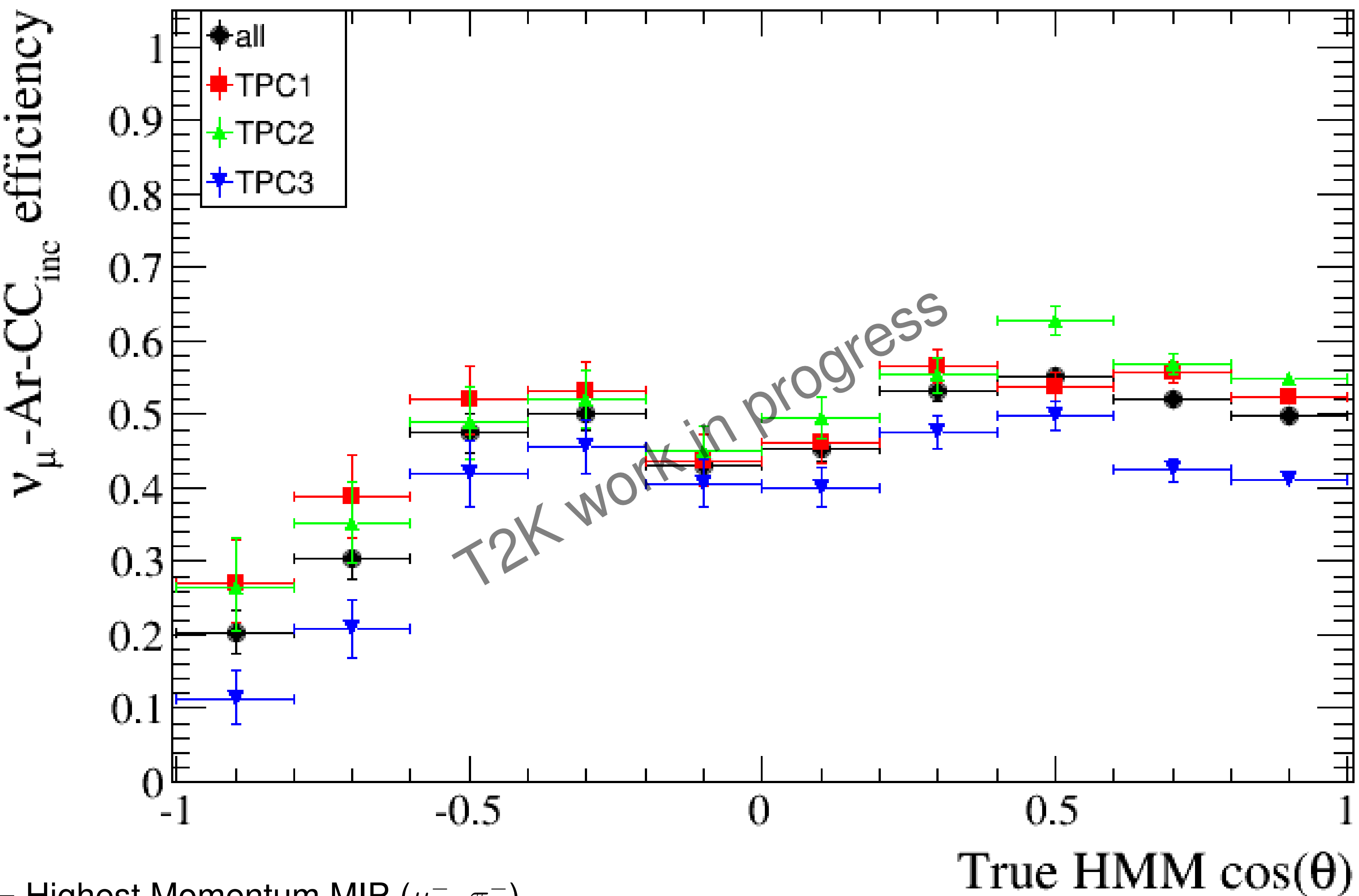
Lowering the threshold



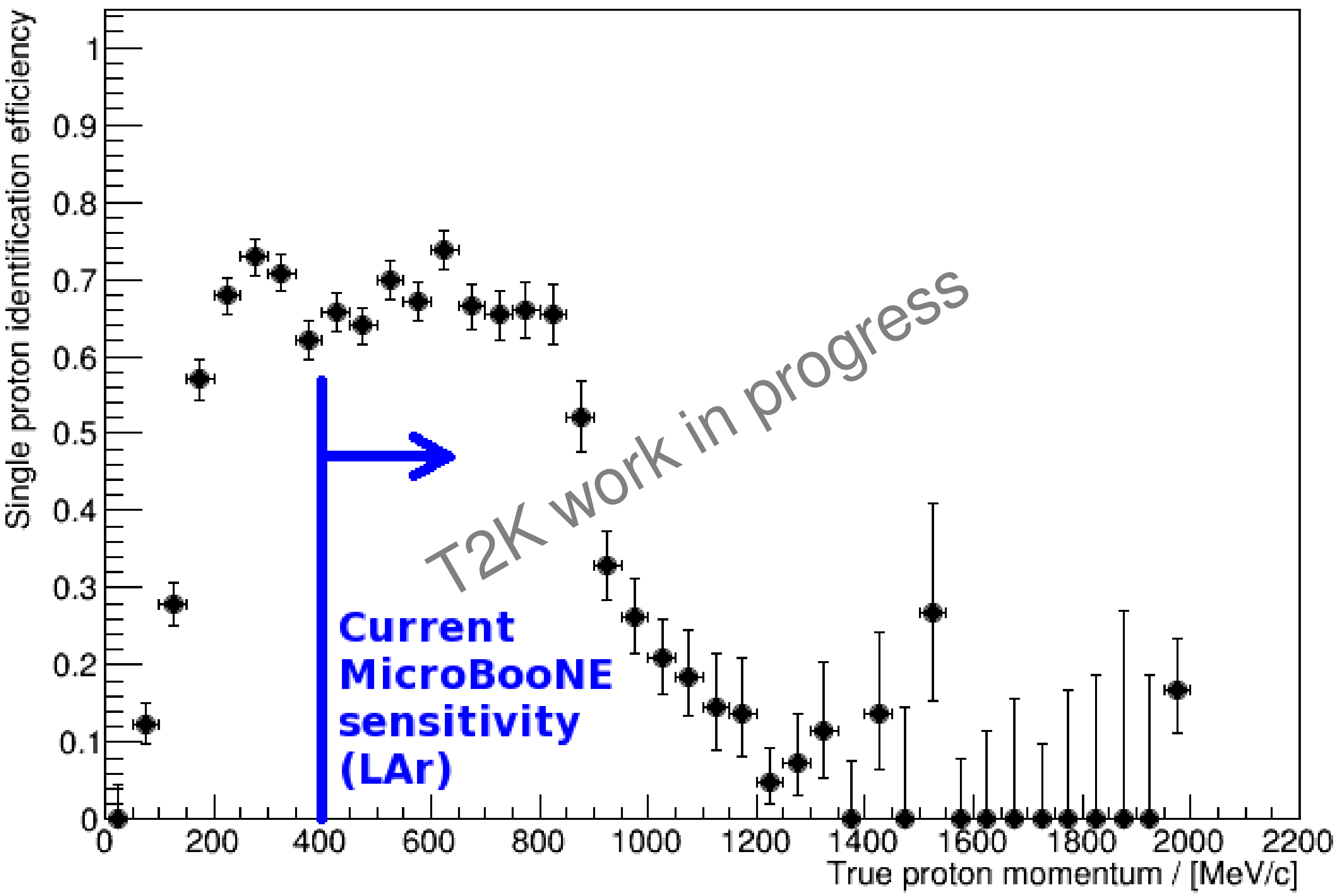
- CC inclusive: $\nu_\mu + A \to \mu^- + X$
- Target material: "T2K gas" (Ar[95%], CF4[3%], iC4H10[2%])[a]
- Active, low density target
  - ⊕ Low particle detection threshold
  - ⊖ Low statistics
- Primary design goal of TPCs was identifying particles from FGDs
  - A/V not ideal
  - Dead volumes inside TPCs
- Needed complete rewrite of reconstruction software
- Challenging but worthwhile

[a] volume fractions

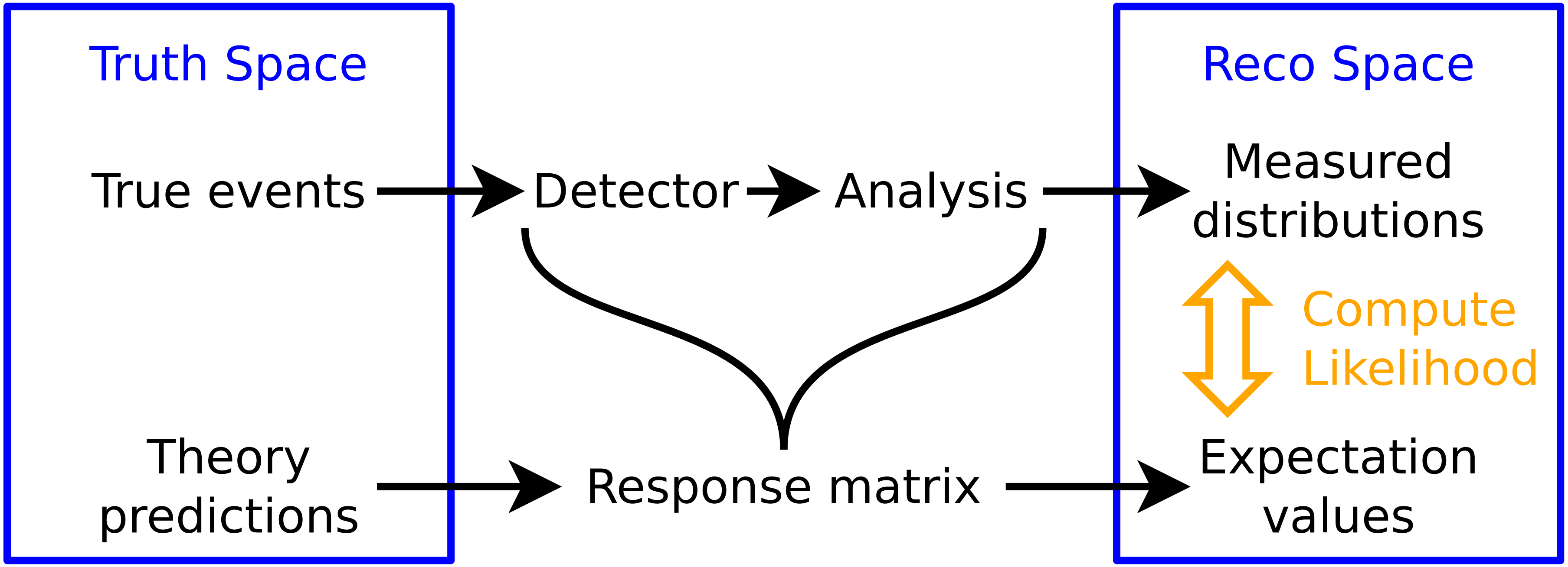
Gas interactions
MIP efficiencies



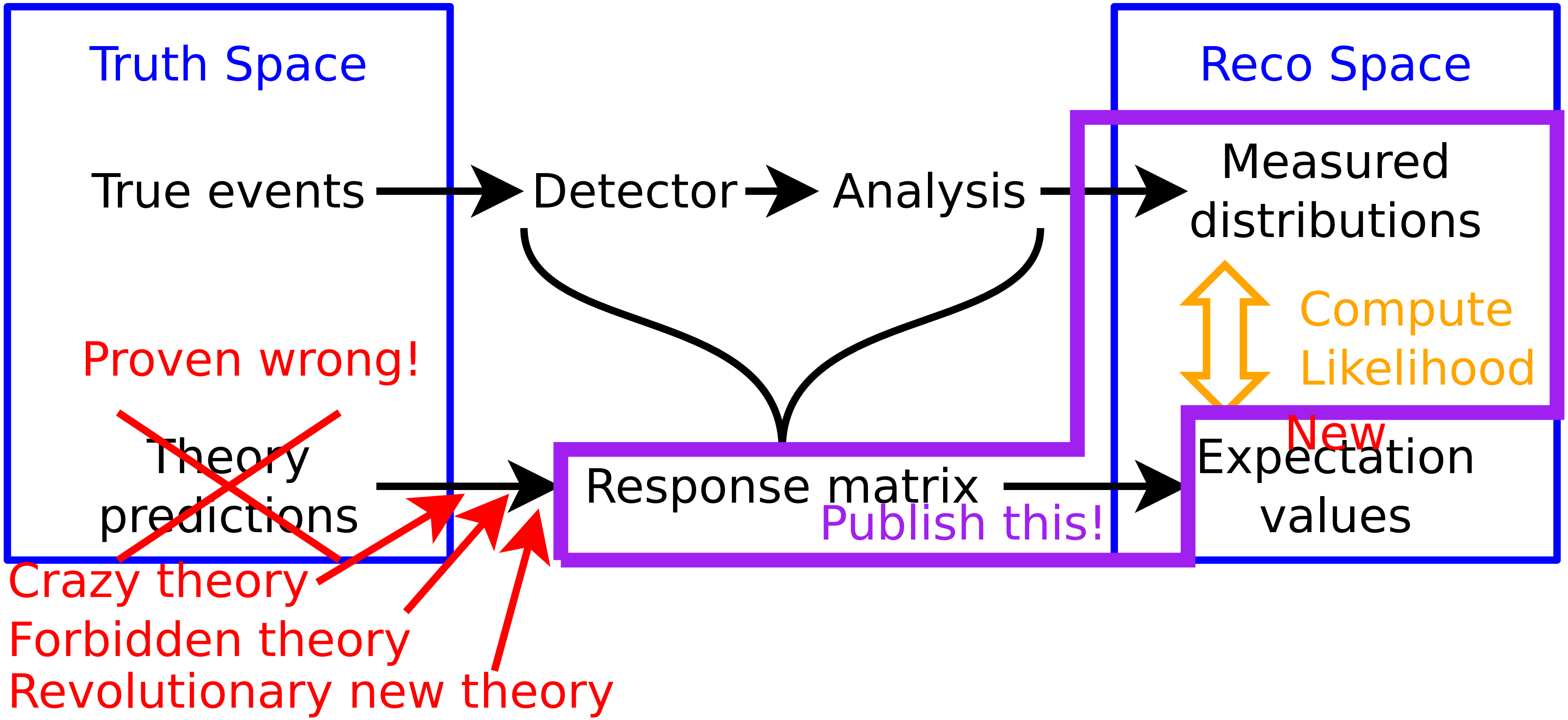
HMM = Highest Momentum MIP (μ^-, π^-)



- Very basic PID based on TPC dE/dx and momentum



- Low statistics and complicated efficiencies make unfolding difficult
  - Efficiency depends on muon momentum, muon angle, additional particles at the vertex, ...
- Will try "forward-folding" approach
  - Use response matrix to bring theory to reco space



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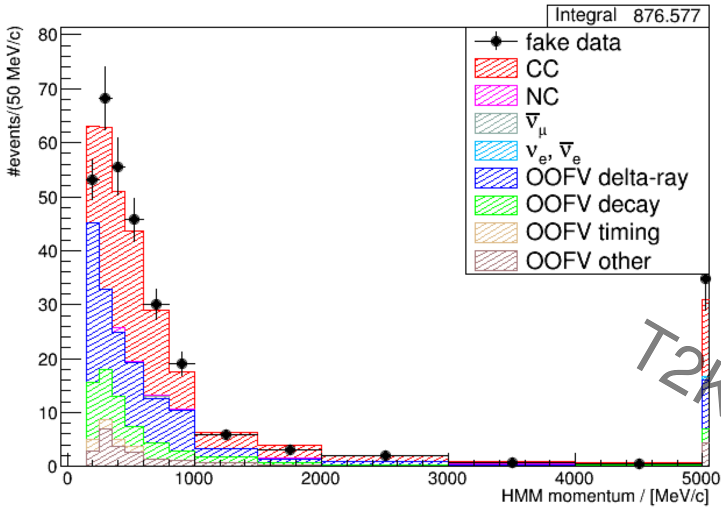
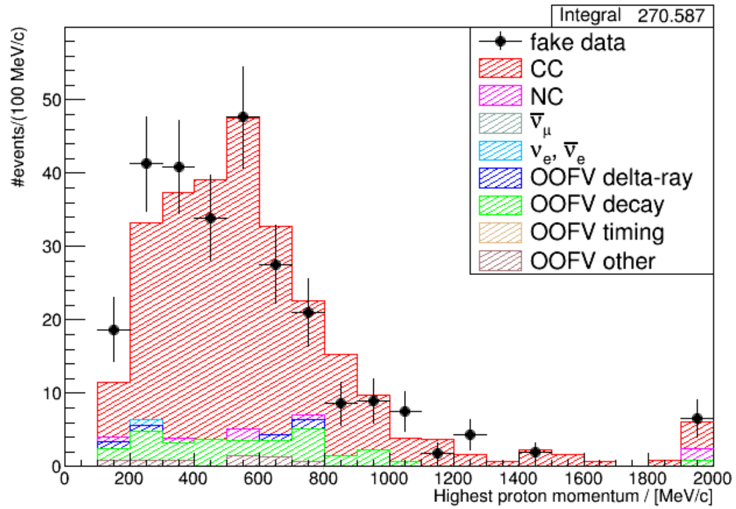
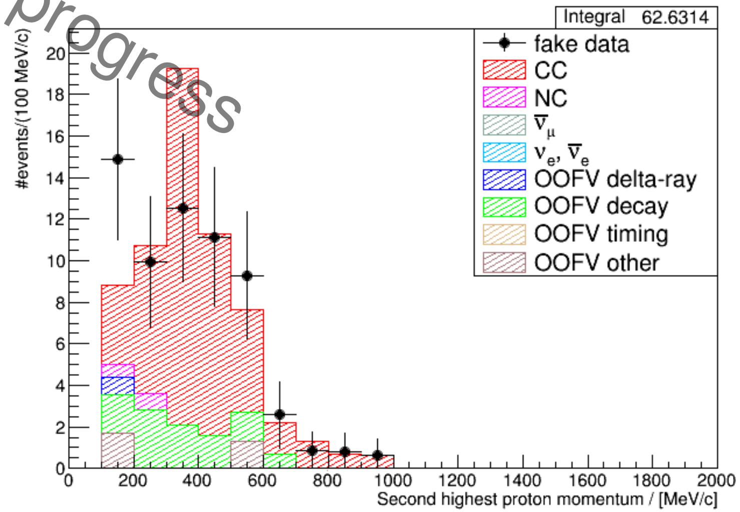
Gas interactions
MC studies





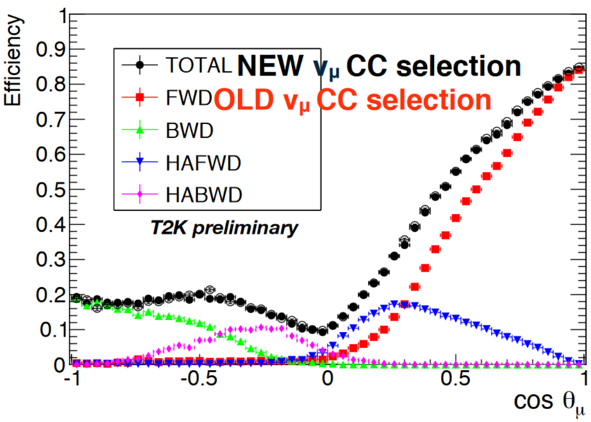
T2K work in progress

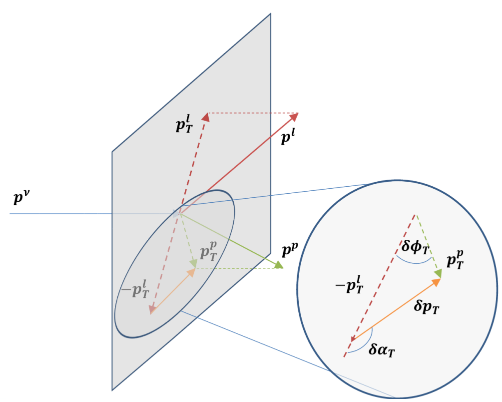
- Data not unblinded yet
- Compare Genie 2.8.0 (fake data) with Neut 5.3.2 (stacked histograms)
- Area normalised
- Efficiency and purity $\sim 50\%$
- Huge increase of purity when looking at identified protons w/ $p_{\text{reco}} > 100\,\text{MeV/c}$

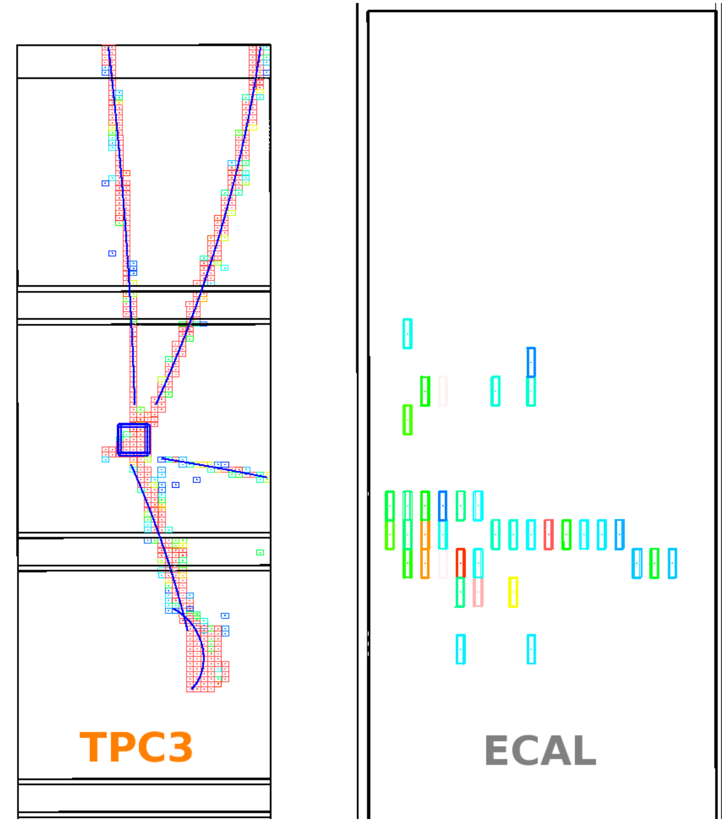


Conclusion and Outlook

- T2K cross-section program is progressing nicely
  - Not covered here: Water target[2], ν_e, $\bar{\nu}_\mu$, ratios...
  - Even more: INGRID, WAGASCI, Emulsions...
- Pushing the limits of our detectors
  - Improving old measurements
  - Trying new measurements
- Proton kinematics open up a new window to nuclear effects
- Gaseous TPC will offer unprecedented look at low-momentum particles







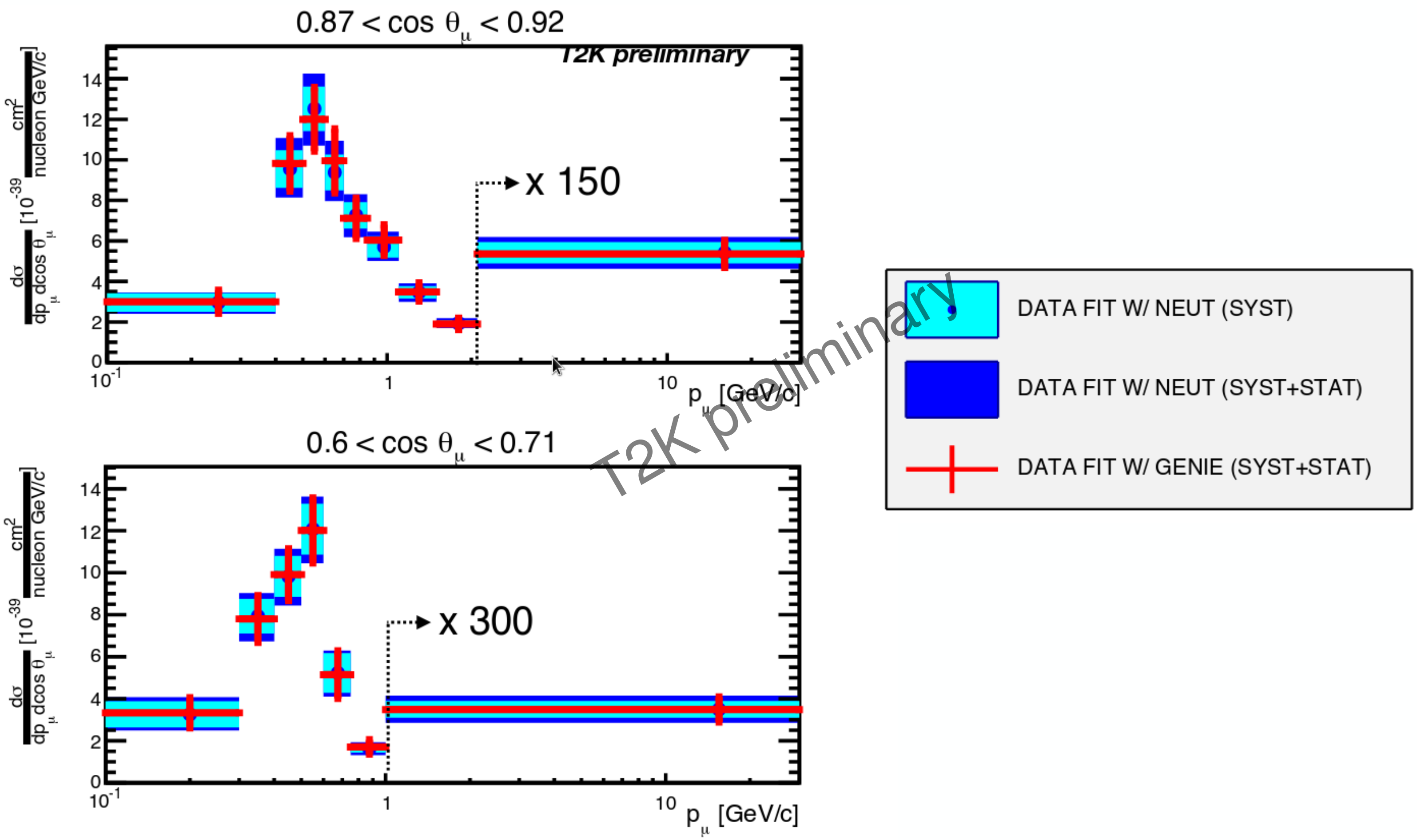
[2]K. Abe et al. (T2K Collaboration) Phys. Rev. D 95, 012010 Published 26 January 2017

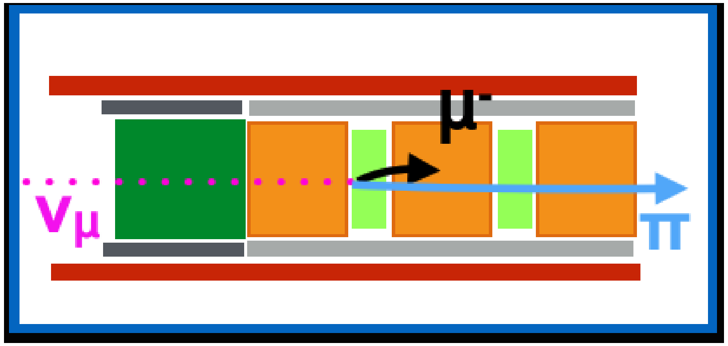
Thank you!

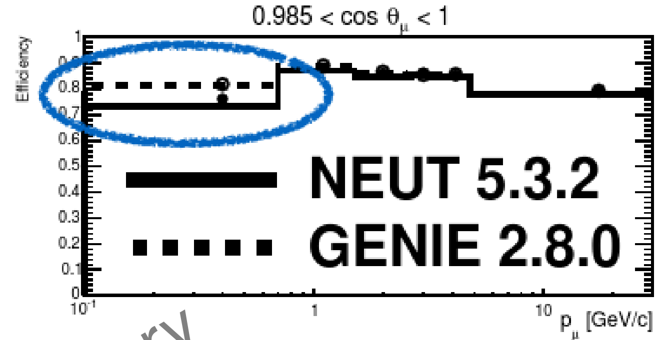
Backup

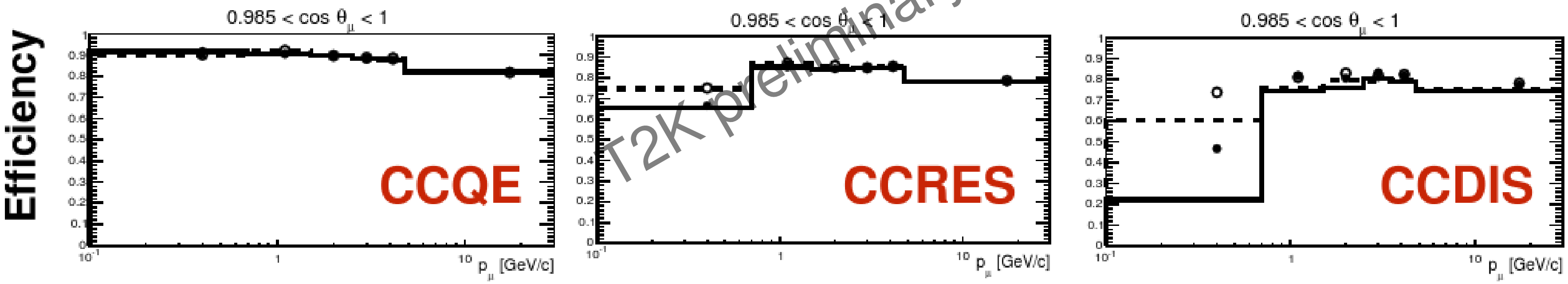
4π CC inclusive measurement
Result details

- Robust cross-section measurement (same results with two models).

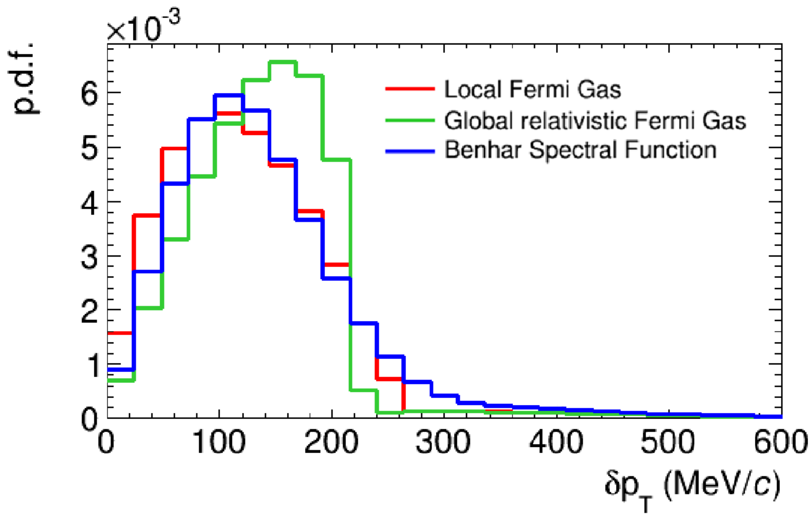


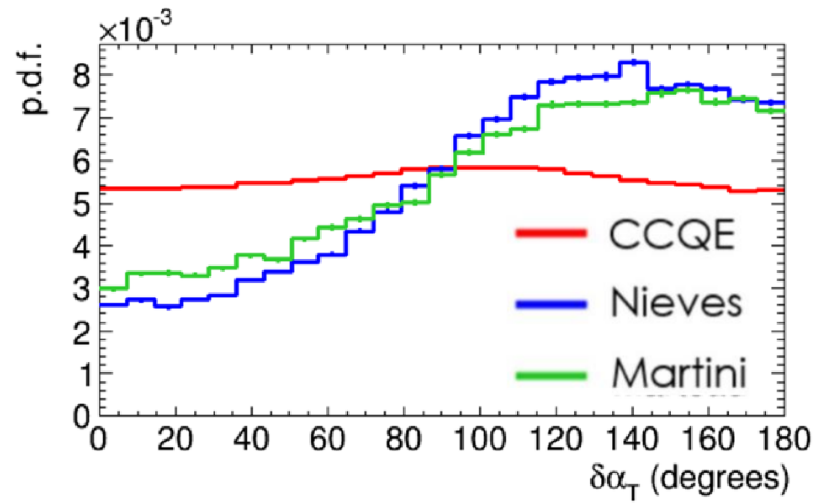


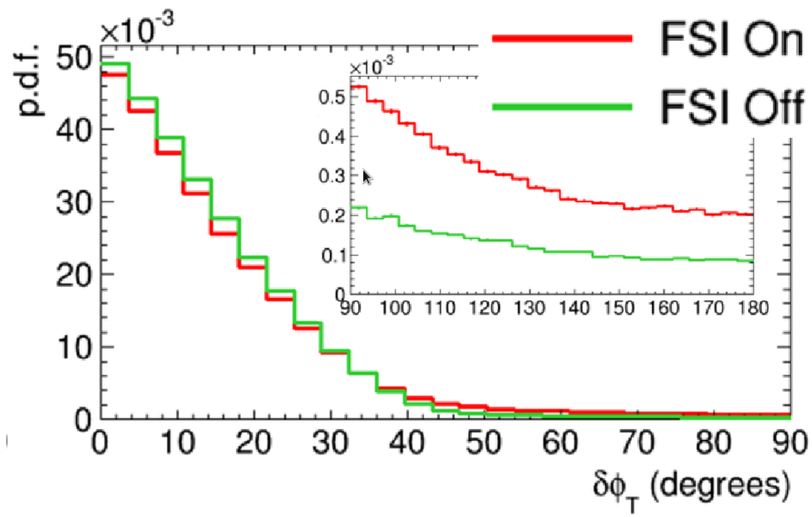




- Model dependence for forward going, low-momentum muons
- Higher momentum pions misidentified as muons
- Pion distribution differs between generators
- WIP







- Distributions sensitive to multiple nuclear effects
- Bonus points: Not affected by M_A
  - See “MiniBooNE M_A puzzle”

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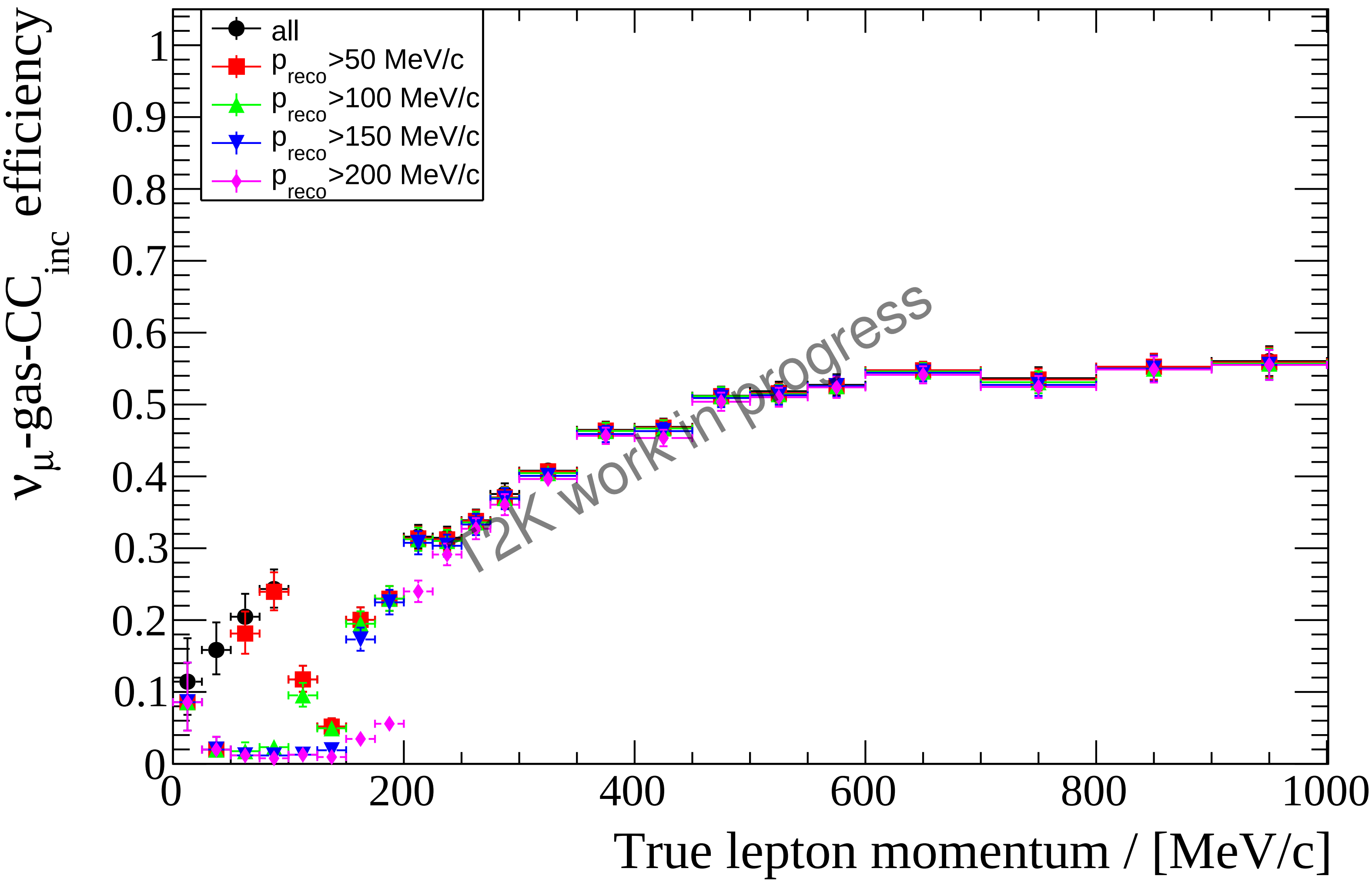
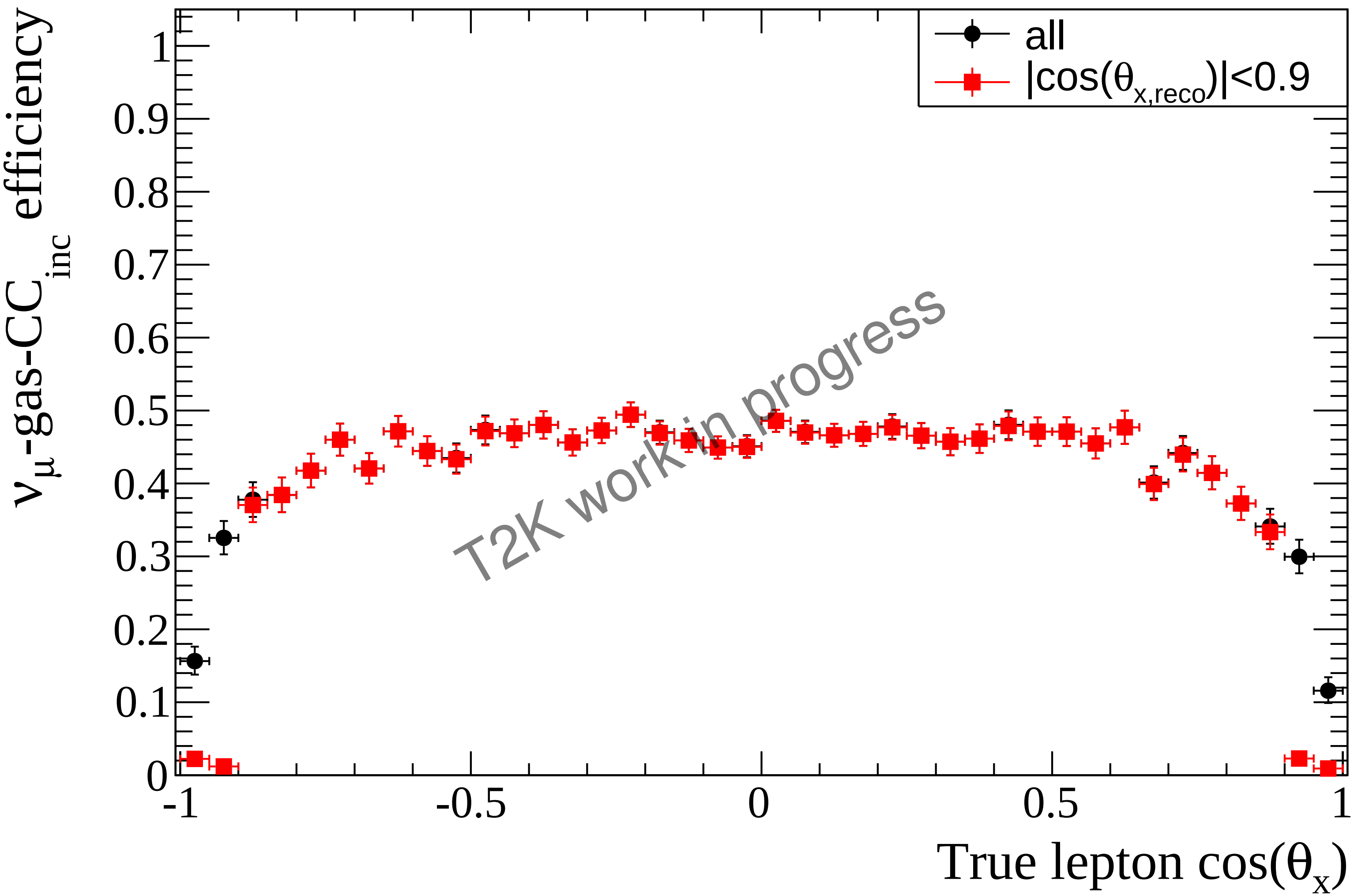
Gas Interaction
Muon efficiency vs momentum

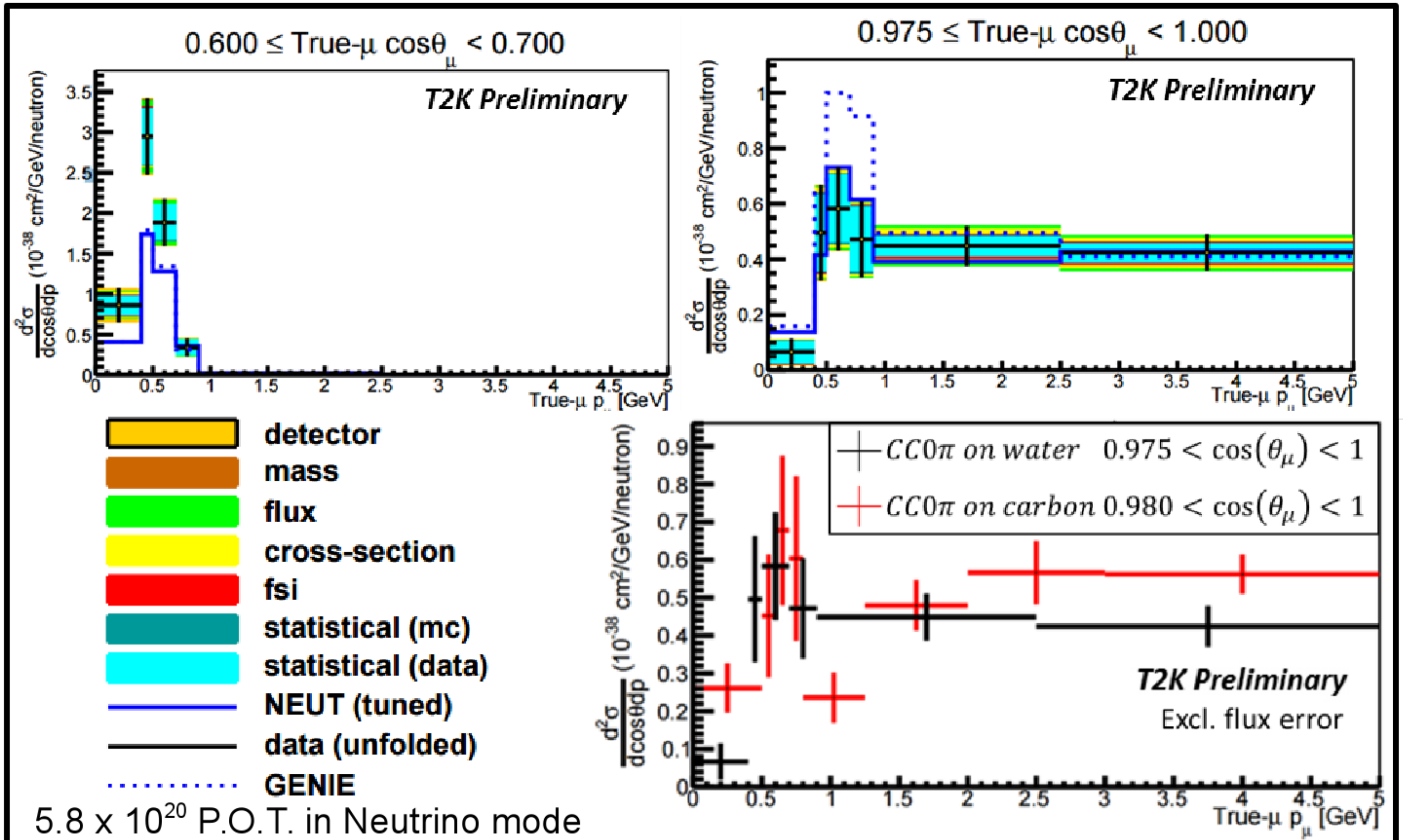


Gas Interaction
Muon efficiency vs drift direction



P0D CC0π on Water

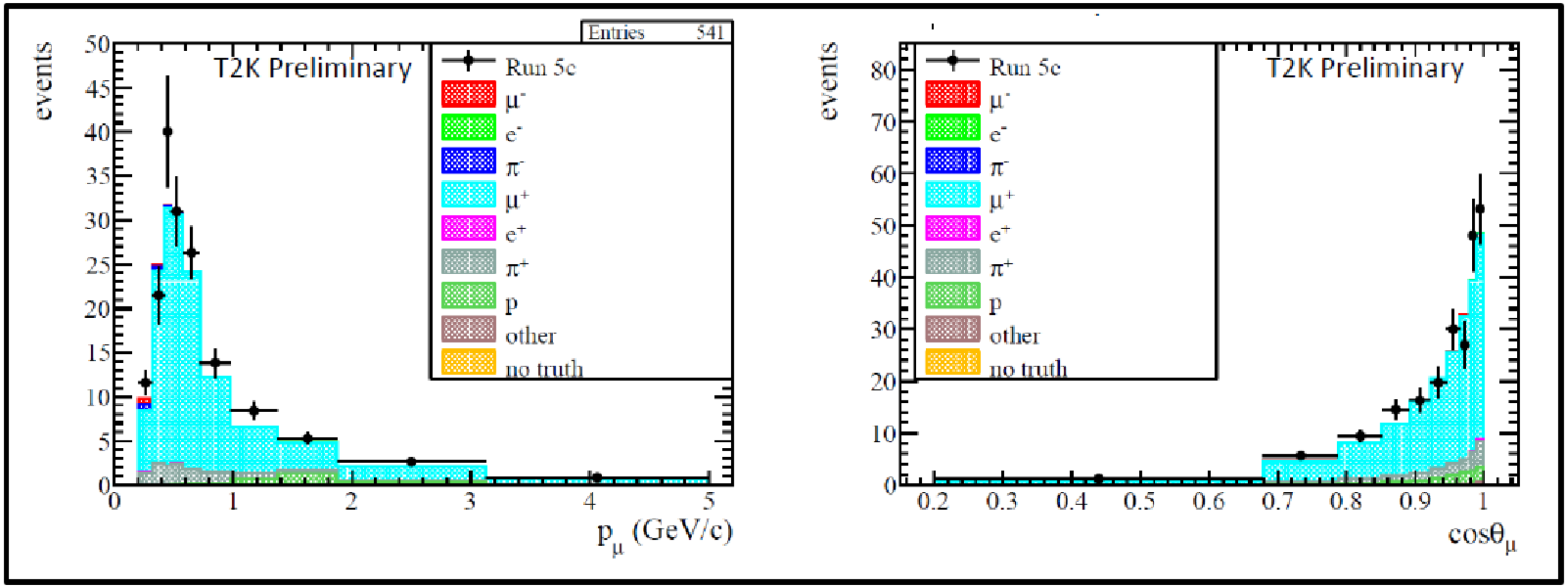
- **Result:** Flux-integrated double-differential **CC0π** cross section on water in final state muon kinematic variables [p_μ, $\cos(\theta_\mu)$]



Antineutrinos @ ND280

Select highest momentum positive track (μ^+) from FGD-TPC:

- Quality cuts, particle ID, and veto cuts are then applied
- A control sample is used to minimize protons
  - Can be difficult to distinguish from muons at 1 – 2 GeV

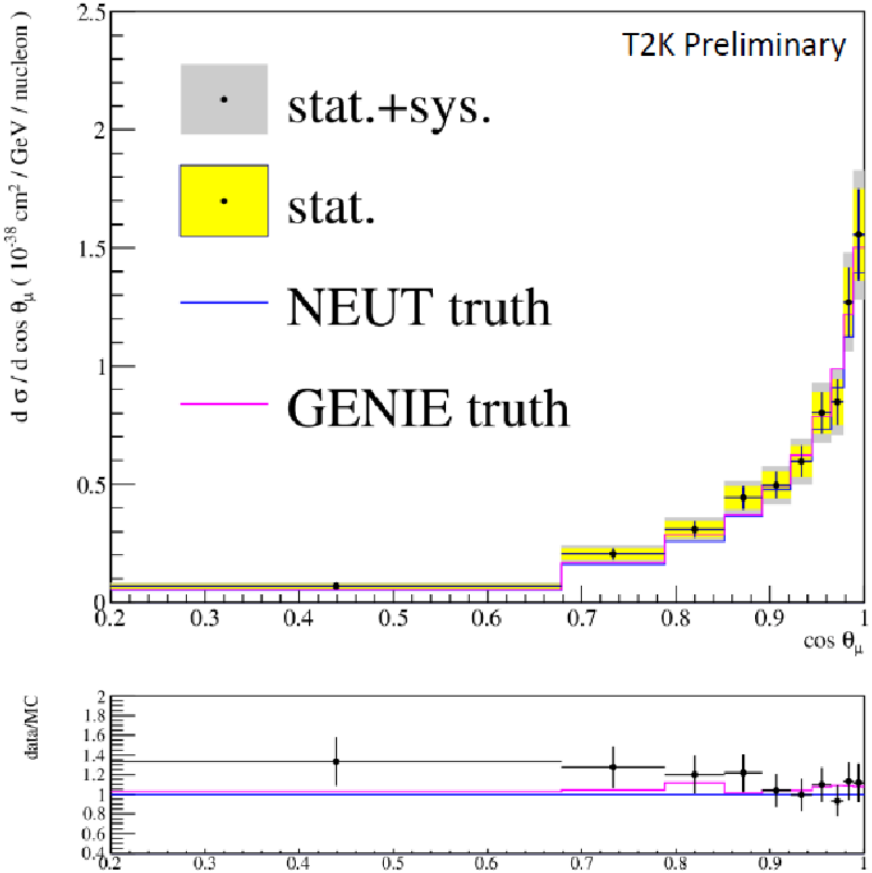


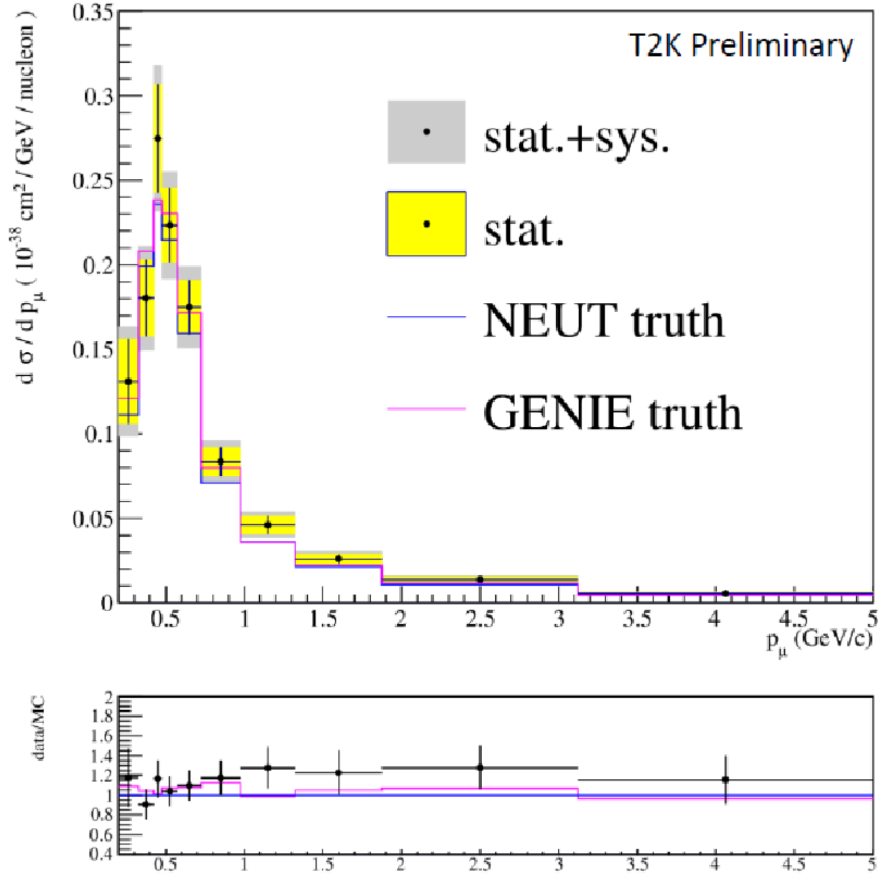
4.29×10^{19} P.O.T. in Antineutrino mode

$\bar{\nu}_\mu$ CC-Inclusive on Carbon

The University Of Sheffield.

Analysis uses FGD1 data in RHC ($\bar{\nu}$) mode





Good agreement w/ both NEUT & GENIE

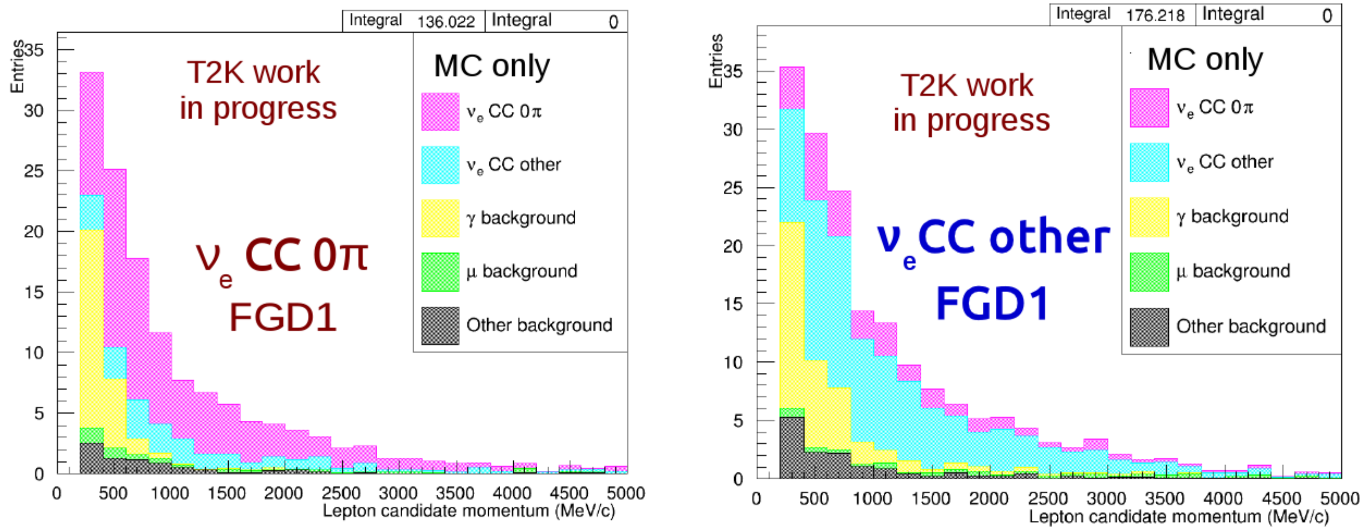
4.29×10^{19} P.O.T. in Antineutrino mode

Splitting ν_e CC events into ν_e CC 0π and ν_e CC other sub-samples

Split ν_e CC sample according to the particles that exit the nucleus (**i.e. after FSI**)

*** Michel/delayed electrons** *** track multiplicity (+ TPC PID)**

ν_e CC 0π (no mesons exit nucleus) **ν_e CC other** (Any ν_e CC that is not CC 0π)



ν – beam selection: T2K Run 2010 – 2013 (~6×10^{20} POT ν – beam)

NOTE: plot does not include recent run period → increased stats for measurement