# Nuclear Effects

## *It's 5am. Do you know where that nuclear model came from?*

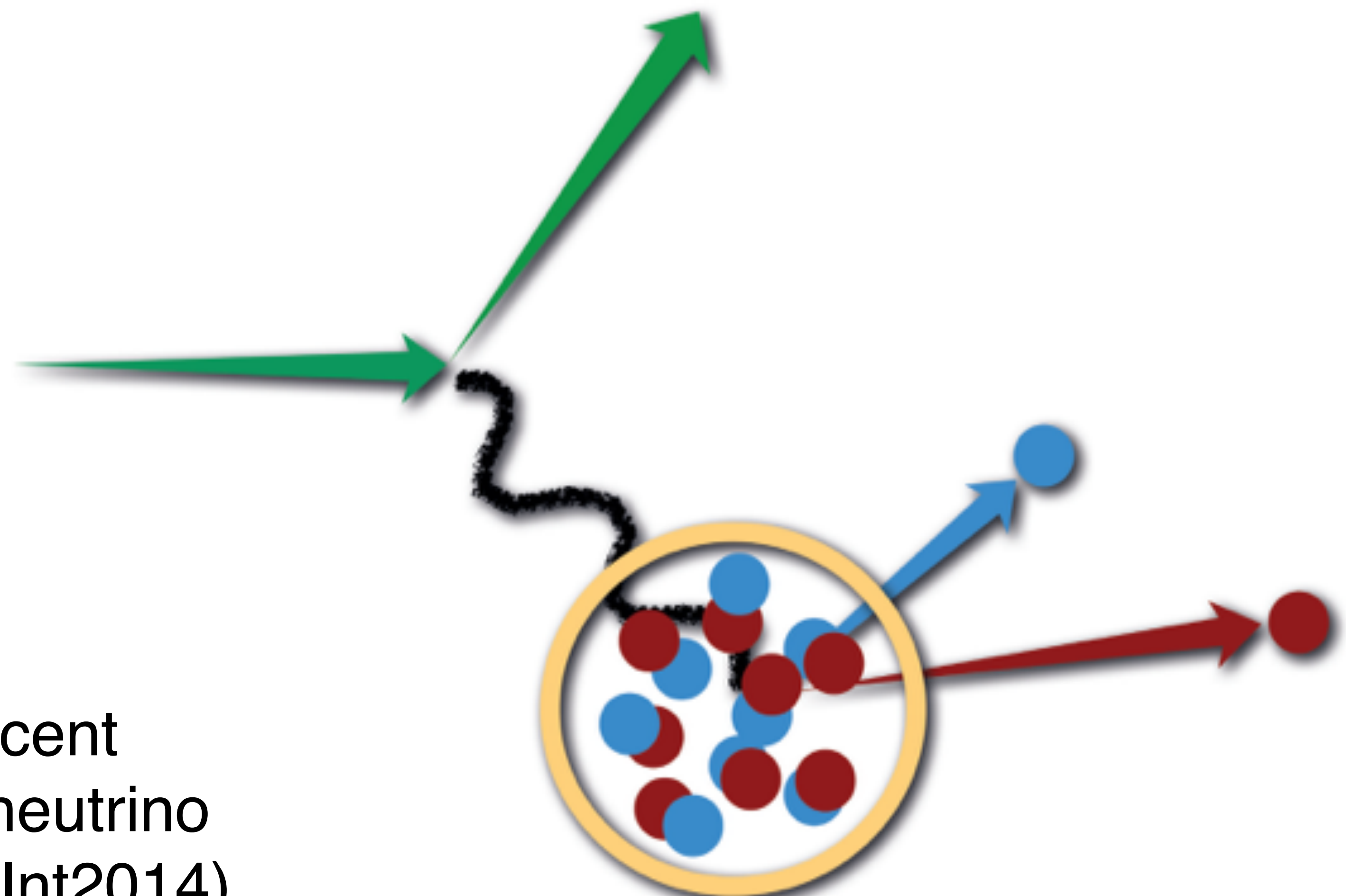


Image from recent workshop on neutrino scattering (NuInt2014)

Kendall Mahn, Luke Pickering
Michigan State University

# An overly generic oscillation analysis

$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

Far detector rate used to determine oscillation (P)

- Flux ($\Phi$), cross section processes (σ), efficiency ($\epsilon$)
- Correct association of reconstructed objects to true kinematics of an event (R)

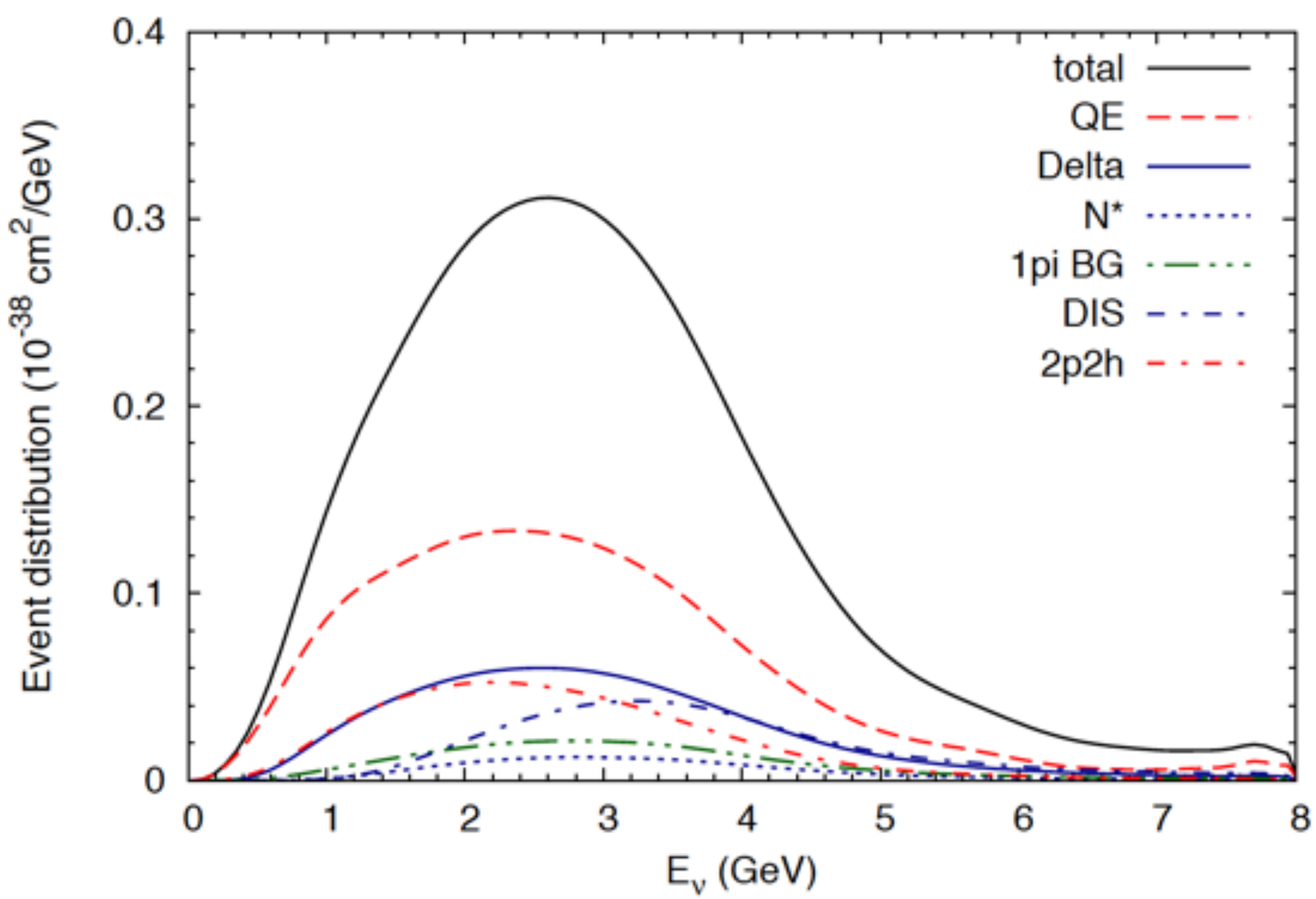
# An overly generic oscillation analysis

$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

$$N_{ND}^{\alpha}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(\mathbf{p}_{true}) \times \epsilon_\alpha(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})|,$$

Near detector measures rate:

- Multiple energies result in multiple processes (and physics effects)
- Inherent degeneracy between flux and cross section




*U. Mosel, AIP Conf. Proc. 680, 020009 (2015)*

# NUCLEAR EFFECTS AND HOW THEY HURT YOU

- Nuclear effects:
  - **Initial state**: Unknowable event-by-event Fermi motion.
  - **Changing rates**: Pauli blocking, RPA/binding energy
  - **New components**: multi-nucleon QE-like
    - You and who's multi-nucleon single pion model…?
  - **Final state**:
    - Obscures primary interaction—no way to access CCQE, RESpi.
    - Shuffles hadronic energy to and from neutrals—event-by-event neutrino energy estimation becomes model dependent.
      - What about when the nucleus isn't iso-scalar?
- Through all this what we **need** is ETrue(EVisible).

# Nuclear effects *matter*

We know from current experiments that studies with a single model is **insufficient**

- Dependance of model in efficiency, event selection…

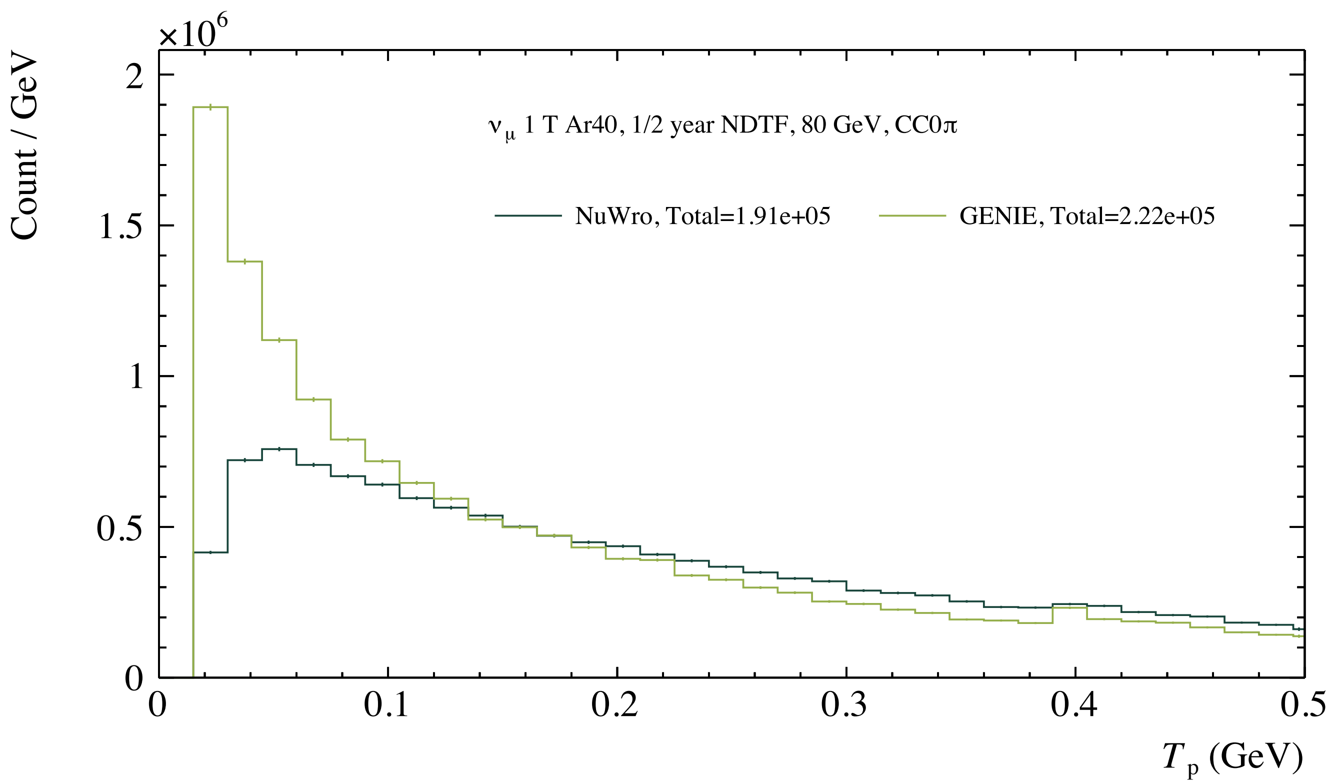
We are claiming our ND will mitigate/measure some of these effects

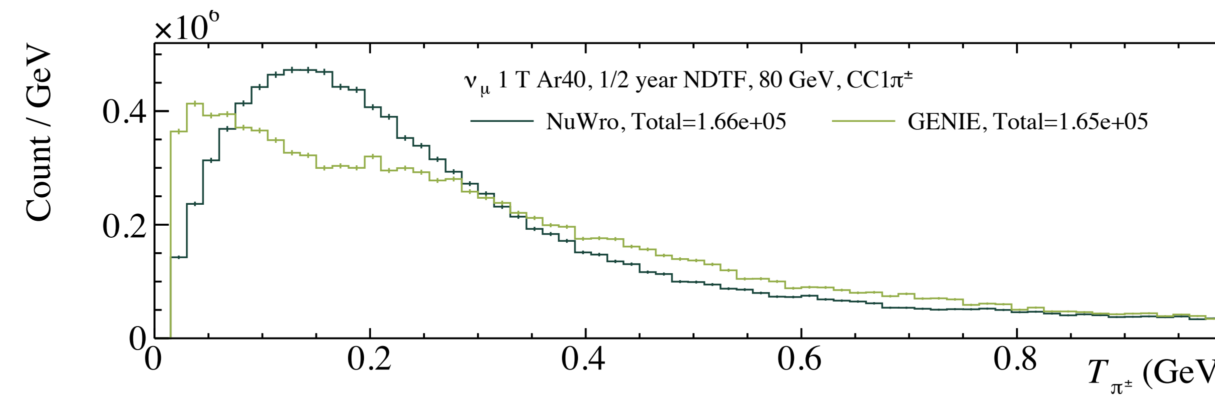
- Provocative: Let's prove it. We have alternate models (see following slides) let's use them in ND design analyses to show we can extract the nuclear physics or be insensitive

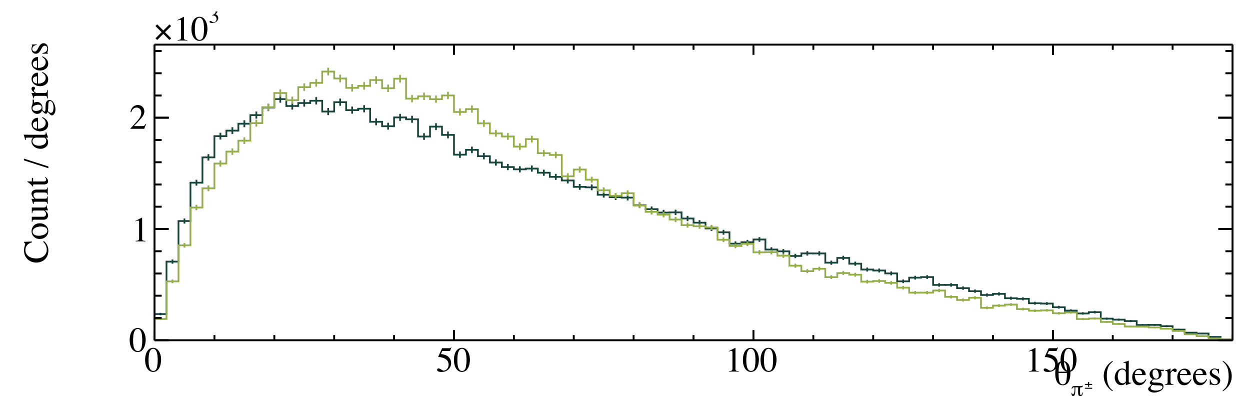
- Being specific about WHAT EFFECTS we will measure will also let us understand strengths/weaknesses of different approaches

*Ideas follow for some specific studies, tools*

# Threshold effects *matter*

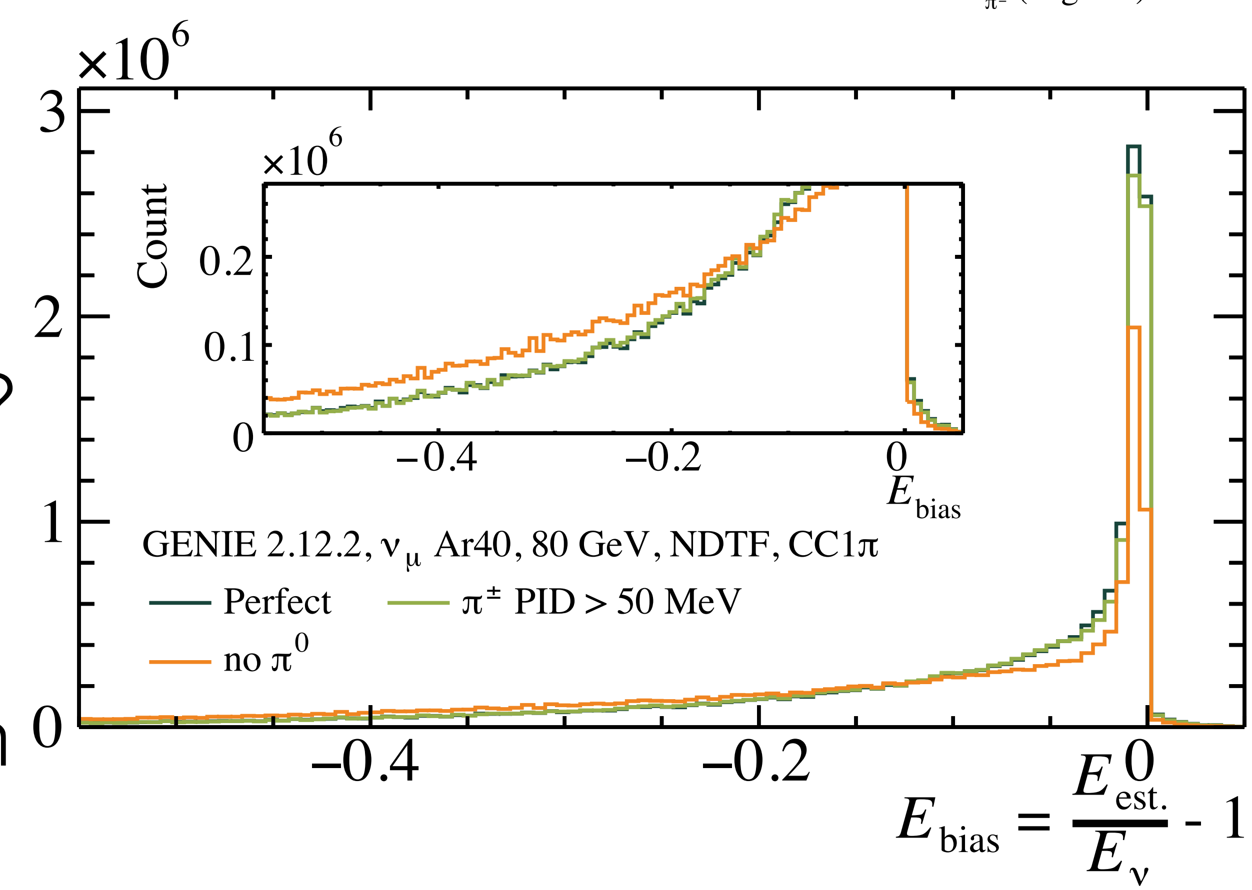


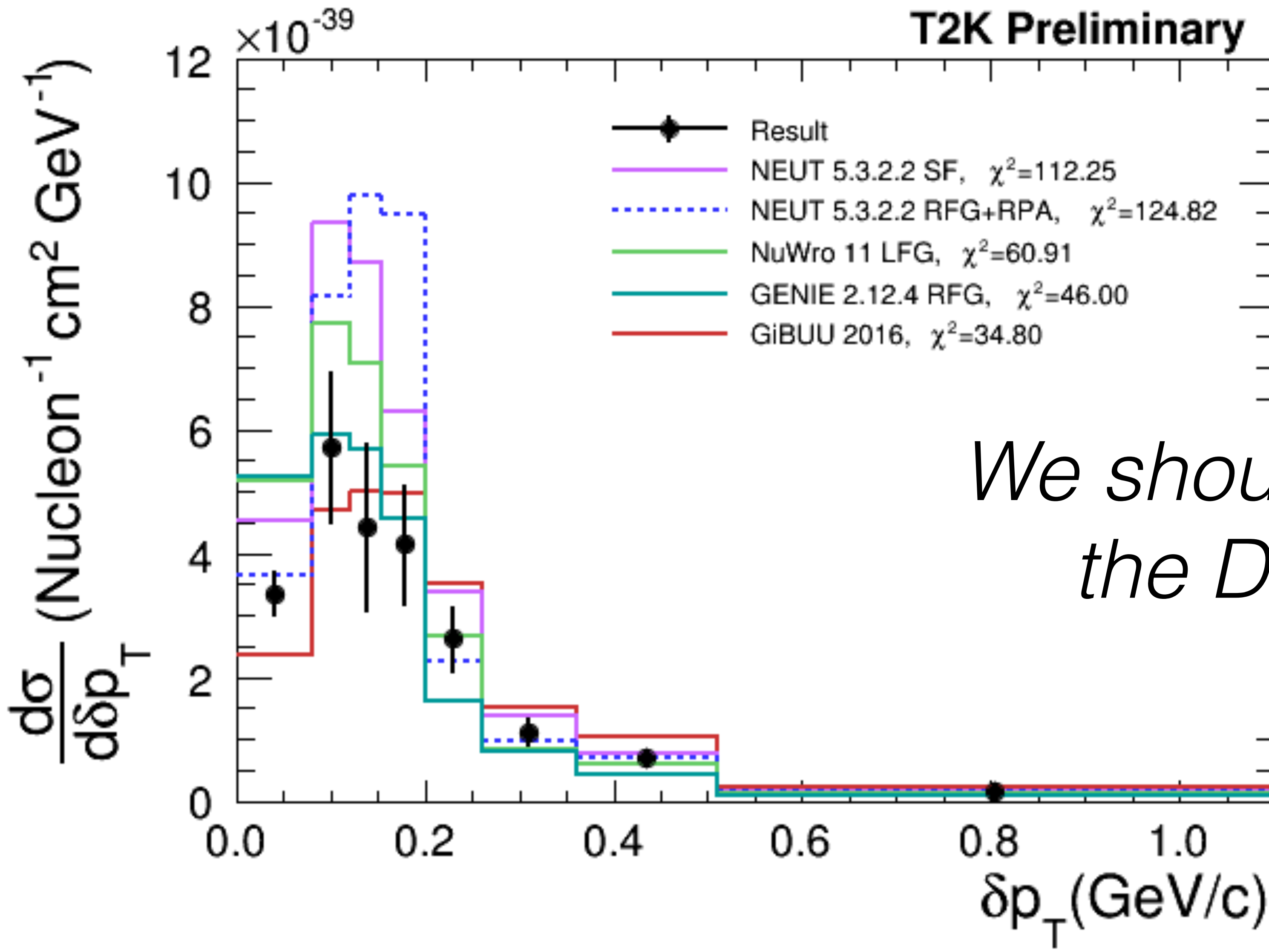




What is the impact of threshold on the analysis?

- How much energy are we losing? -> Ebias and how it changes
- What model information (or model discrimination) do we gain at lower KE protons, pions?



# Threshold effects *matter*




*We should just make this plot for the DUNE flux and various thresholds*

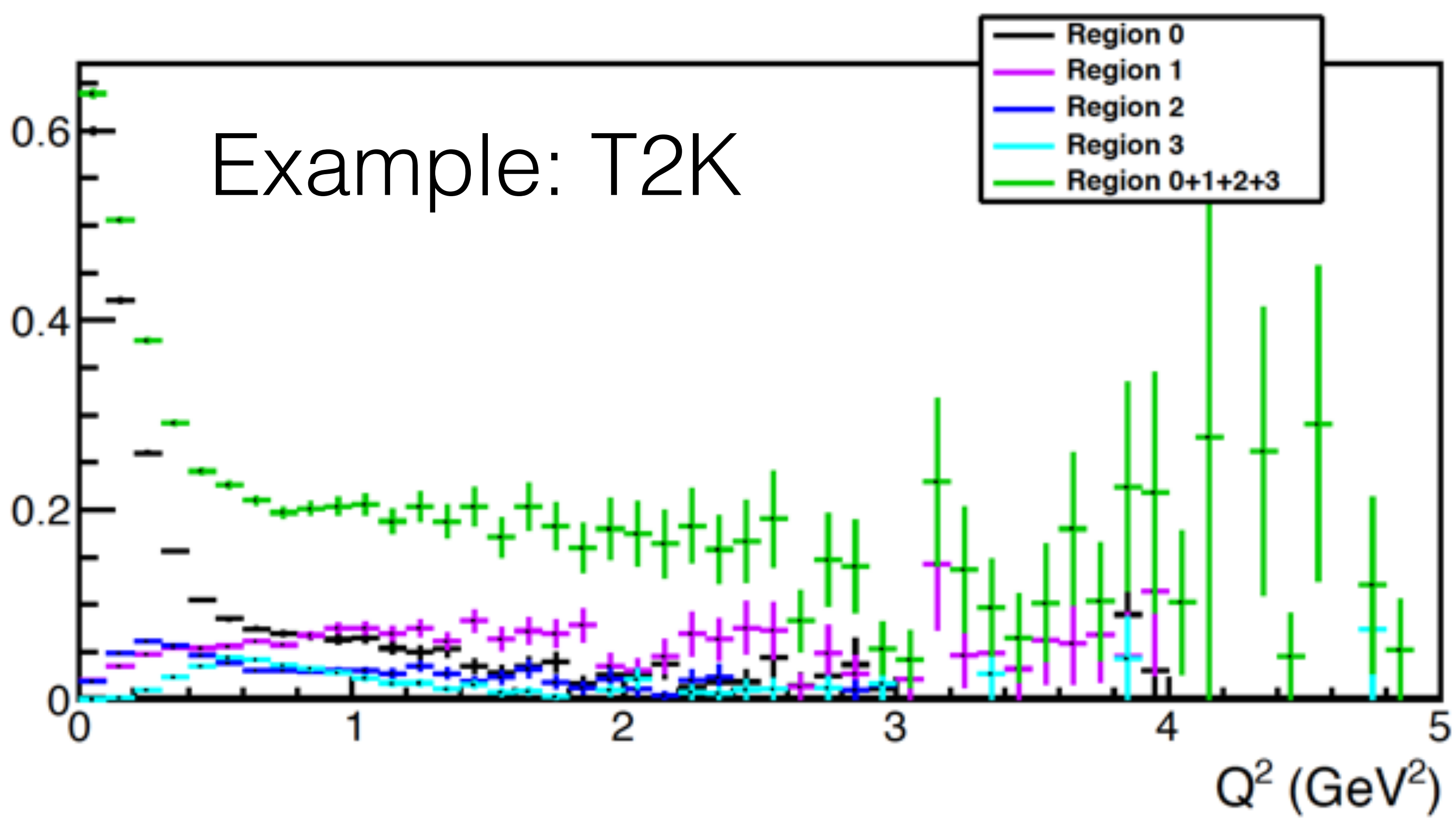
"Transverse variables" are sensitive to nuclear effects

- T2K data inconsistent with current models, what if we weren't limited in proton acceptance, resolution and threshold?

# Efficiency *matters*

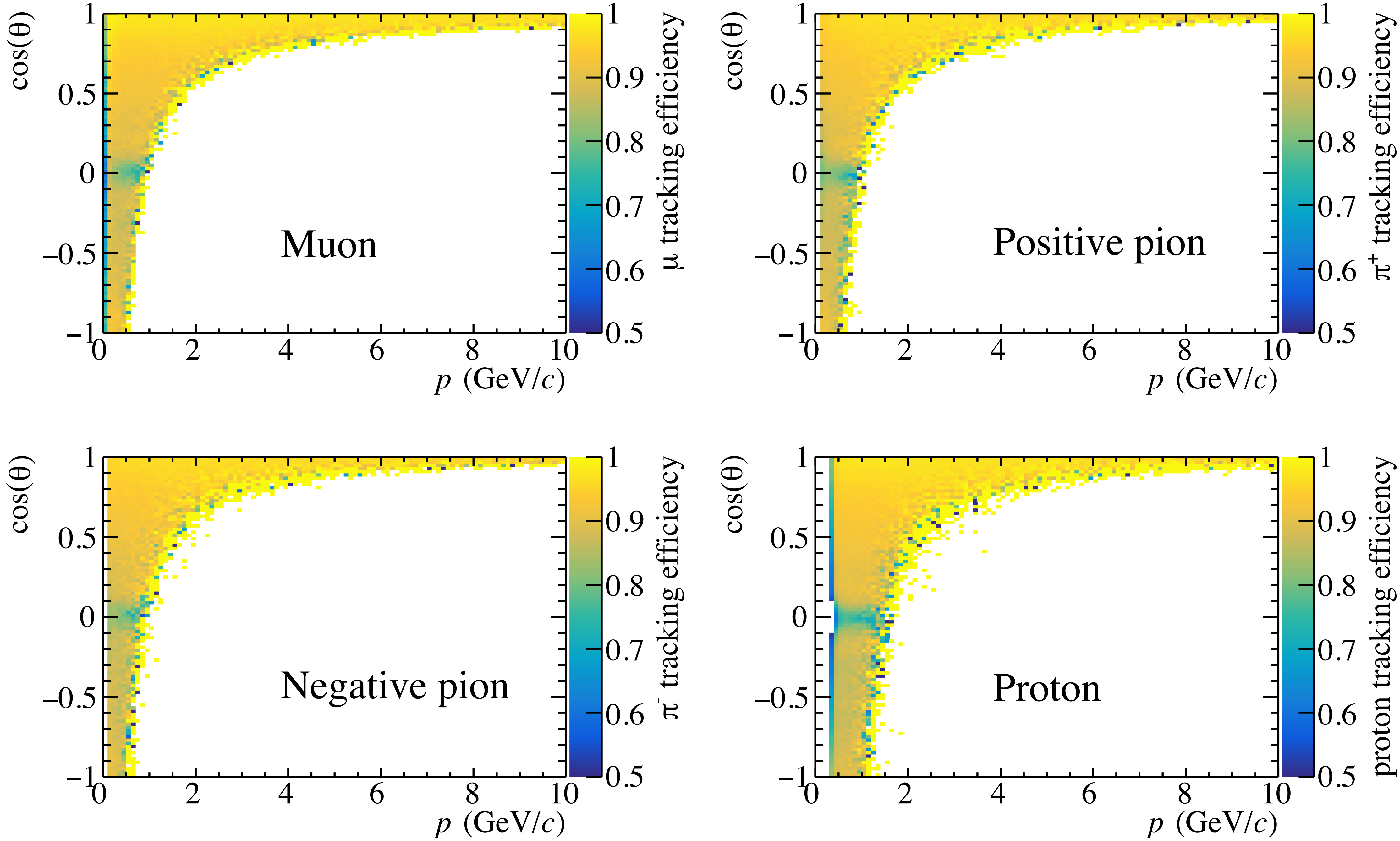
Model dependance of the efficiency at the ND creates bias

- Example (C. Zhang, BNL): Angle of track relative to wire planes “If this angle is small (<~7.5 degrees), we have a ambiguity problem, because lots of electrons will arrive at the wire planes at the same time.



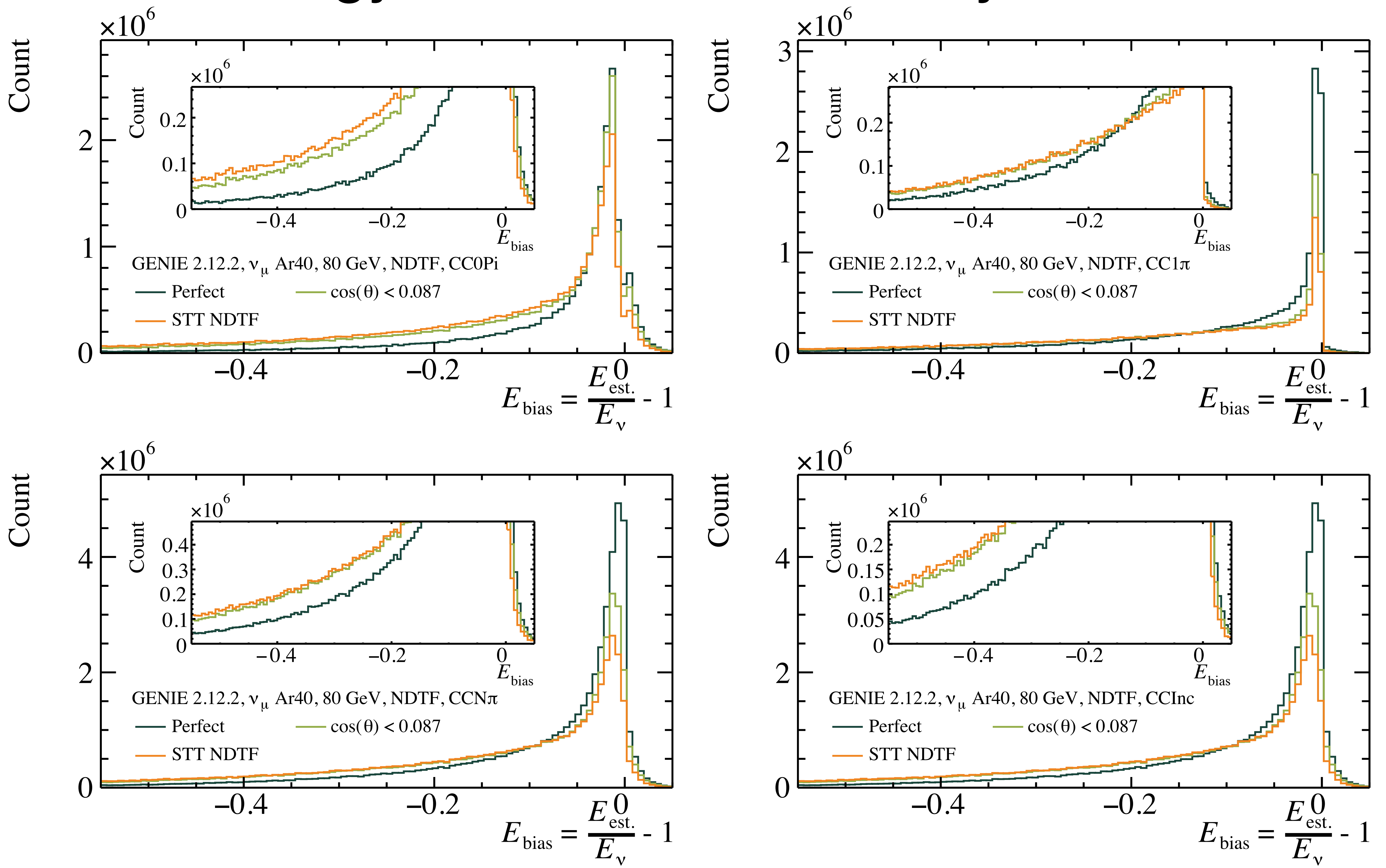

*. Can we articulate how close we can get to 4π acceptance for each configuration?*

# Example — NDTF STT Efficiency

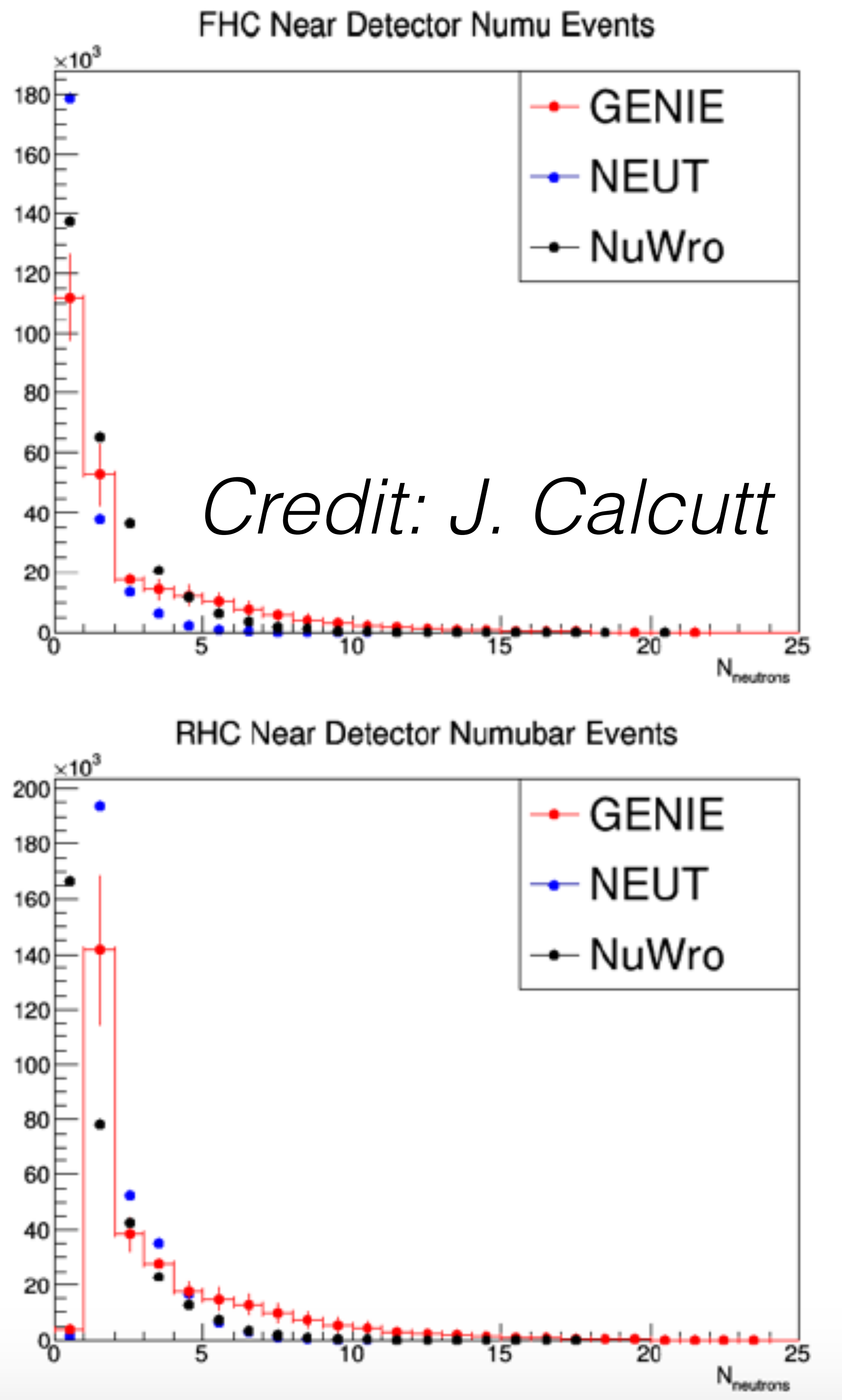



- NDTF Reconstruct: Require 12 straw hits.
- Apply efficiency particle-by-particle to final state generator events
- Can apply smearing similarly, but not considered here.

# Energy bias: Polar Efficiency effects

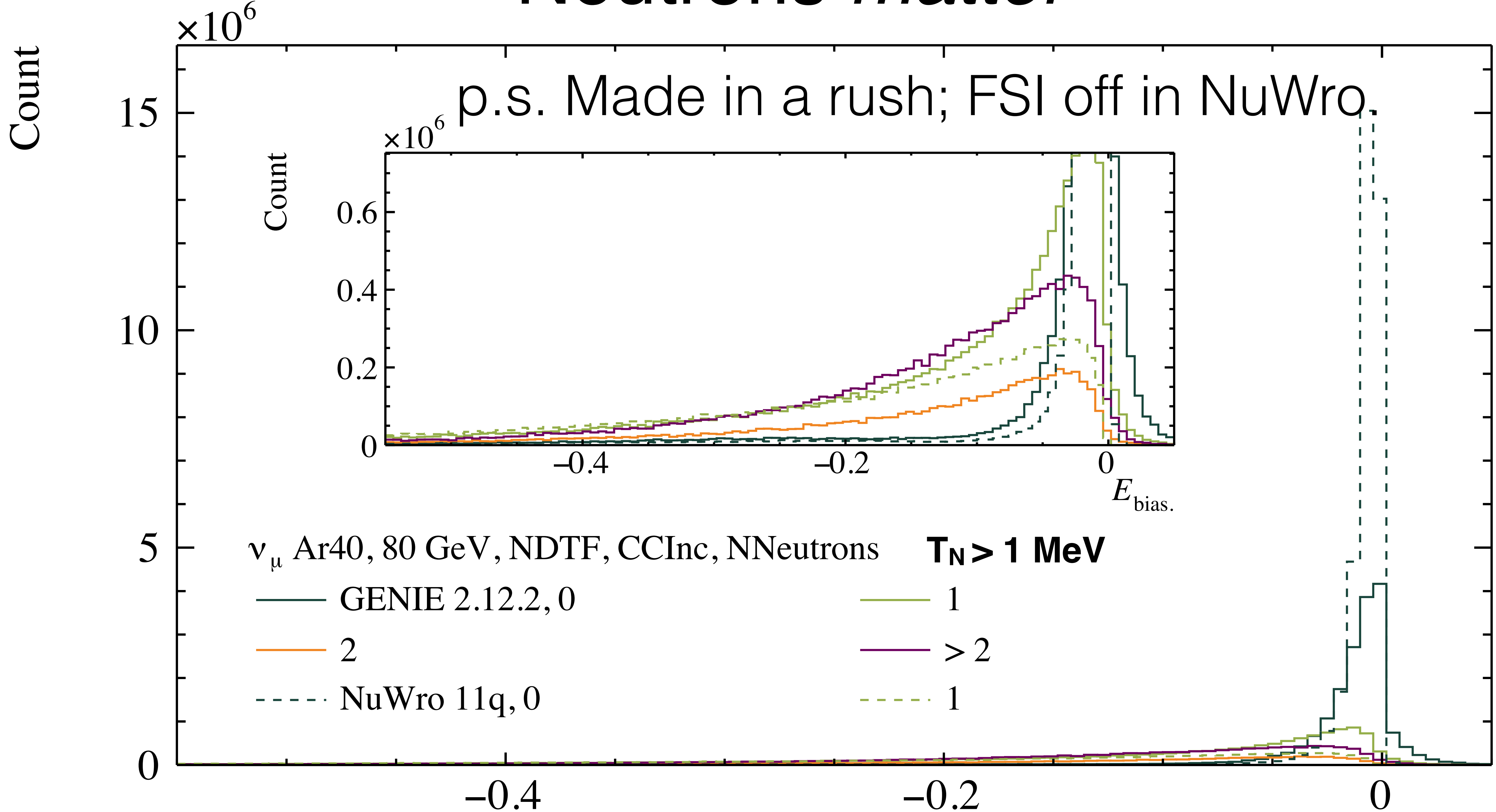


# Neutrons *matter*




- For CC0$\pi$ events on DUNE, signifiant fraction of energy carried away by neutrons, quite different for neutrinos vs. antineutrino events
- Significant model spread, would be nice to have some data…

# Neutrons *matter*




GENIE neutron multiplicity somewhat correlated with bias. $E_{\text{bias.}} = \dfrac{E_{\text{est.}}}{E_{\nu}} - 1$

*Feasibility: are there significant surrounding material neutron issues?*

# Nuclear targets *matter*

Likely, our nuclear model of Ar will be an effective theory bootstrapped from nuclear models on lighter targets

- High value if (enough stats) for He (fully calculatable), Some value of C (suffers from its own problems of mis-modelling, but more beam energies)

- Easy event rate plot: How long would we need to run with GaHe detector to get enough statistics to measure MAQE? or measure a simplified expected He nuclear effect?

- Difficulty with C: T2K analysis comparing C vs. O has 2% systematic uncertainty on separating nearby layers from detector/cross section model.

*What specifically does an alternate target gain us? At what level do we expect a difference to be visible?*

# Summary

**When we say we measure nuclear effects, what do we mean?**

- Let’s make sure the detector response is as uniform and low/broad as possible

**Will our measurements of nuclear effects be robust against alternate models?**

- We have alternate models available to us (NEUT, GiBUU, GENIE, NuWro and each have various theory-inspired changes). We are happy to share!

**What physics do we believe we will isolate from alternate target material and why?**

- Alternate models also can be projected to show size of expected/possible effects.

WE APOLOGISE FOR ANY INCONVENIENCE

# THANK YOU

# Backup slides

# Example: Limit of ND, Final State Interactions

| True Topology | CC-inclusive | CC0$\pi$-like | CC1$\pi^+$-like | CCOther-like |
|---|---|---|---|---|
| CC0$\pi$ | 51.5% | 72.4% | 6.4% | 5.8% |
| CC1$\pi^+$ | 15.0% | 8.6% | 49.2% | 7.8% |
| CCOther | 24.2% | 11.5% | 31.0% | 73.6% |
| non-$\nu_\mu$ CC | 4.1% | 2.3% | 6.8% | 8.7% |
| Out of FGD1 FV | 5.2% | 5.2% | 6.6% | 4.1% |

Good: Selection of samples according to “final state topology”, can be pure!

*Benefit of ND with: good particle identification, lack of dead (no instrumentation) regions, timing and vertex information*

Bad: Final state interactions migrate events between observable final states.

Different flux at ND and FD due to oscillation changes this rate

*A correct FSI model is needed to extract oscillation probabilities. ND helps but doesn’t “solve” this problem.*

# Energy estimators // Energy Reconstruction

$$E_\nu^{cal} = \epsilon_n + E_\ell + \sum_i (E_{\mathbf{p}'_i} - M) + \sum_j E_{\mathbf{h}'_j}$$

Calorimetric estimation of energy depends on:

1. Nuclear properties/cross section model (separation energy epsilon n)
2. Kinetic energy of nucleons (Ep-M) (since ejected from nucleus)
3. Total energy of the mesons (Eh) (since produced in the process)

Low threshold is important to get all mesons, nucleons

Neutrons and proton mis-reconstruction is important

Understanding response of detector to particles is crucial

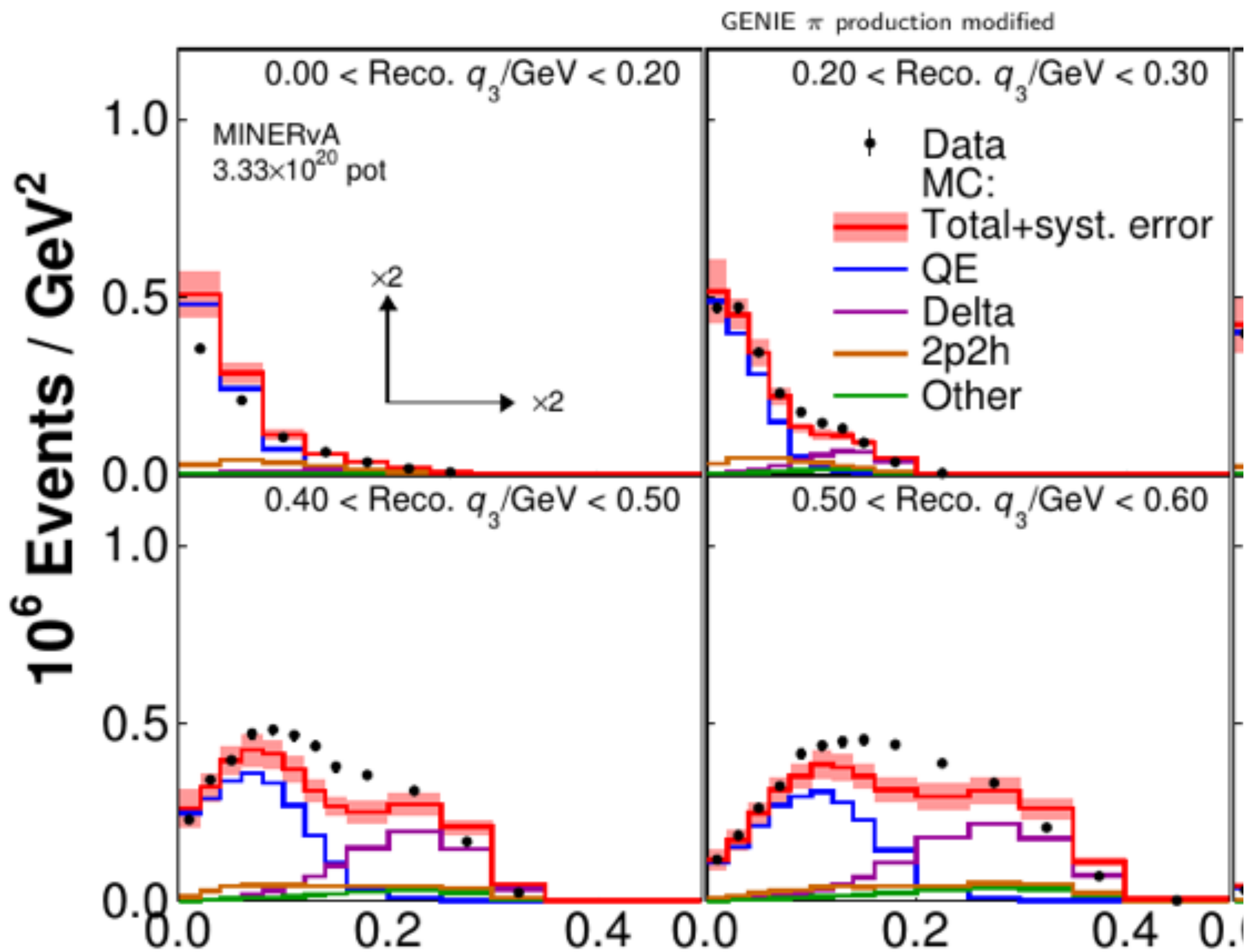
# Inactive ("dead") material

Lots of neutrino interactions in concrete, sand, **magnet** and dead material of detector (~5% p7)

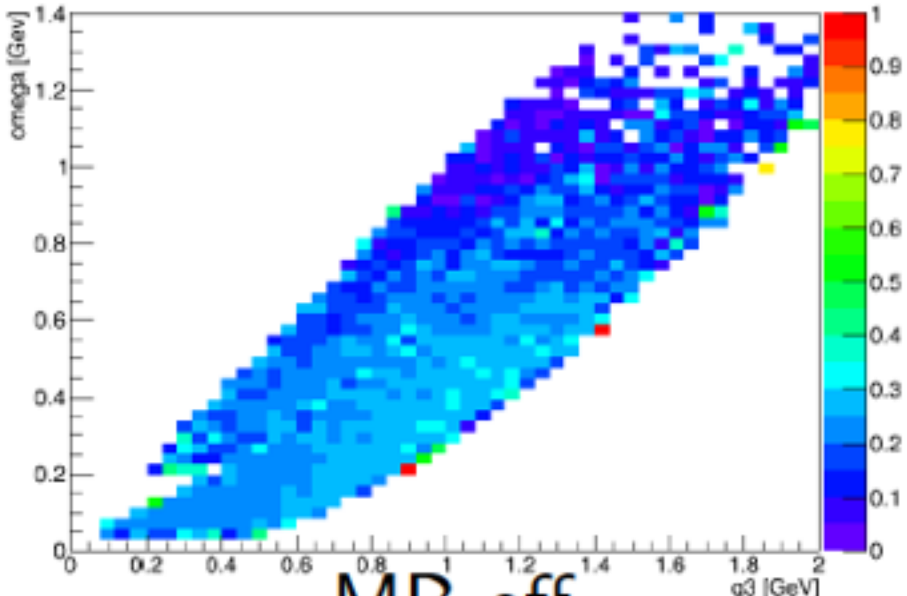
*Improved with better global timing across the detector (is it entering or exiting?) but always an issue at some level (glue, bar coating, electronics, central cathode)*

Fully active targets or fiducial volume can reduce this, see NOvA or MINERvA (PRL 116, 071802, plot from NuInt2015)

Take careful measurements of the detector as built.

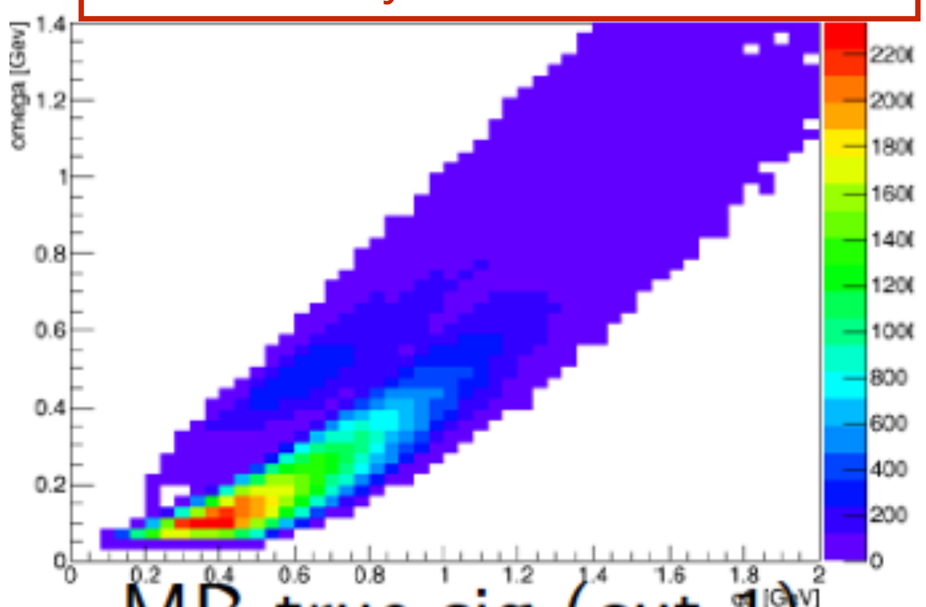


# Acceptance




MB eff.

Preliminary: TENSIONS2016

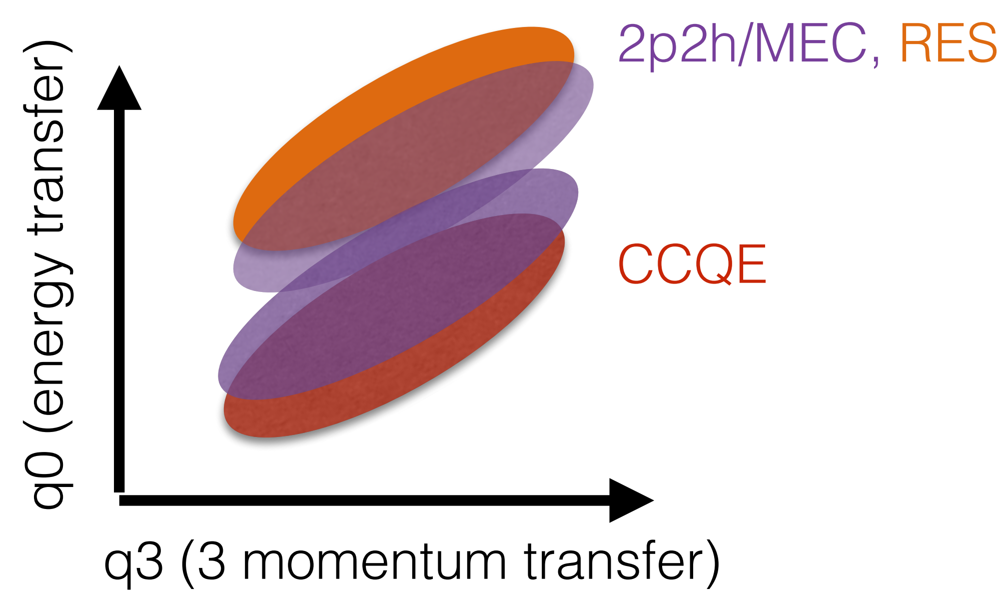



MB true sig (cut 1)

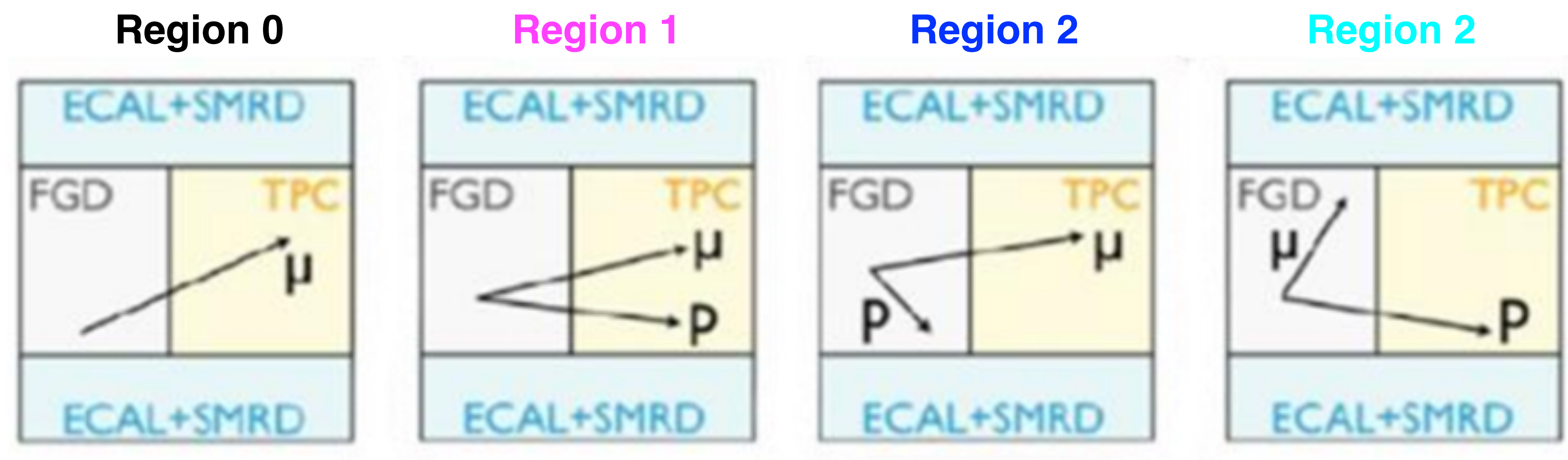
MiniBooNE detector (4π, Cherenkov)

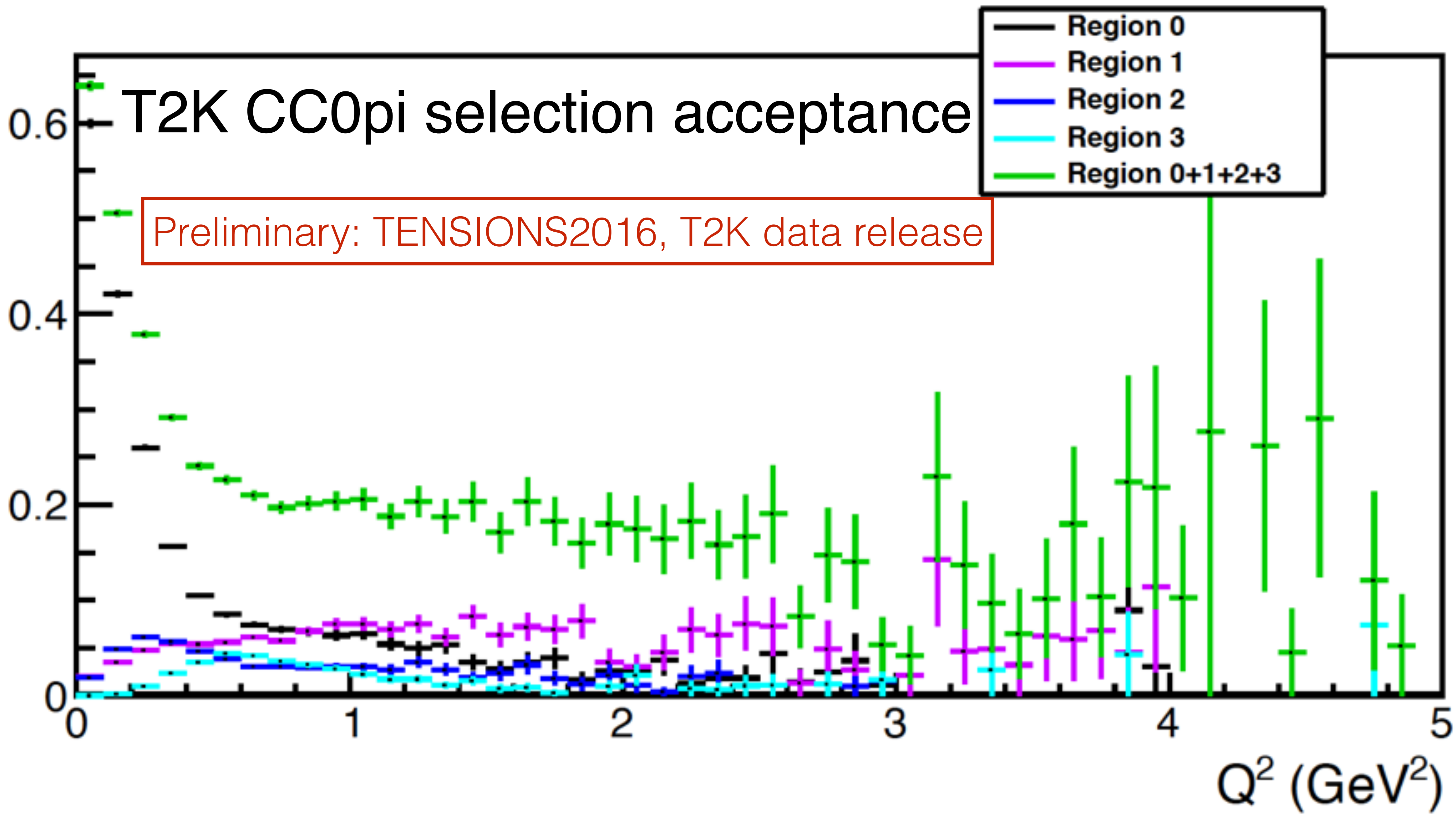
- Efficiency quite flat in cross section physics of interest: q0-q3, $Q^2$

- Accepts most momentum and all angle. Limited from muon range, which is “easy” to measure




*Changing efficiency can couple to cross section model and increase systematic uncertainty*

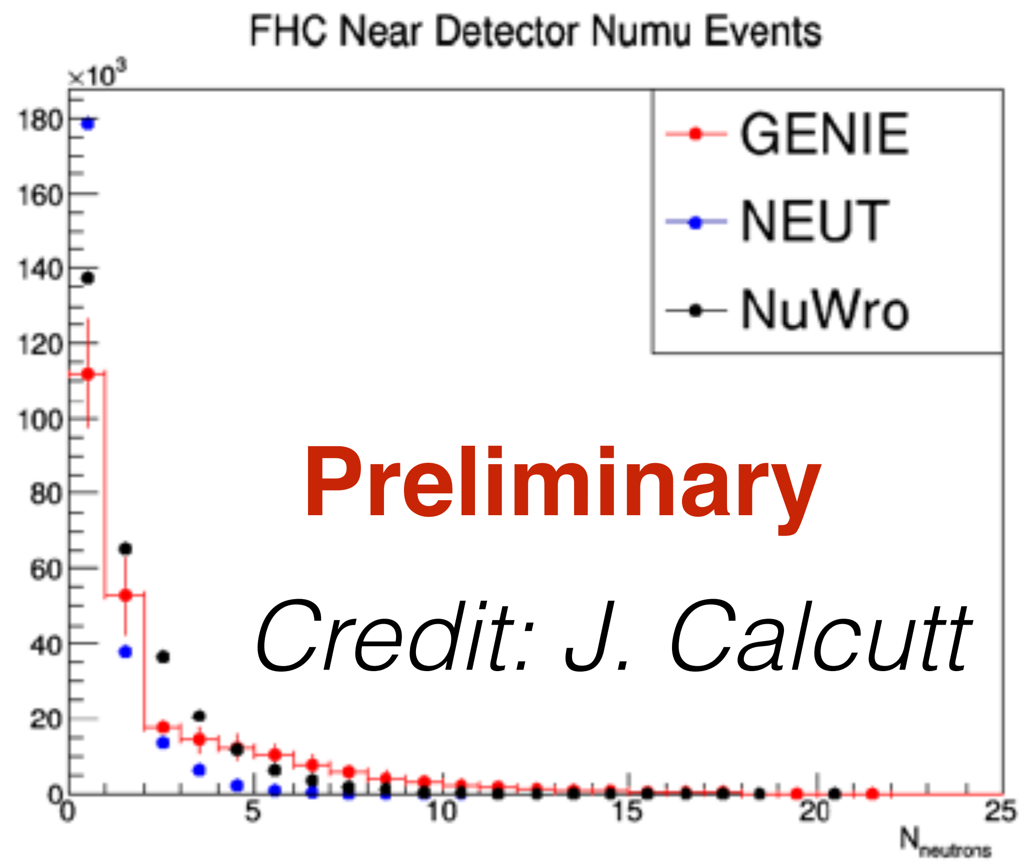

Region 0
Region 1
Region 2
Region 2
ECAL+SMRD
FGD
TPC
μ
p
ECAL+SMRD

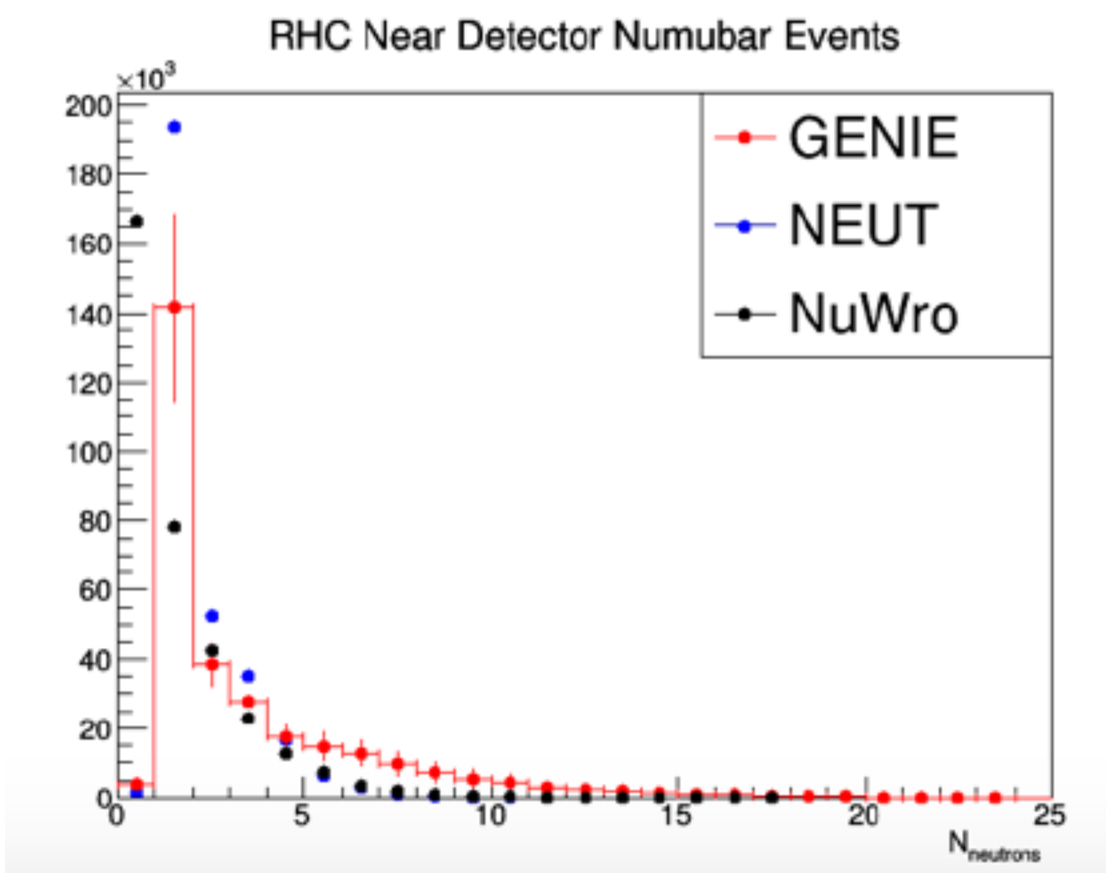

T2K CC0pi selection acceptance
Preliminary: TENSIONS2016, T2K data release
Region 0
Region 1
Region 2
Region 3
Region 0+1+2+3
0.6
0.4
0.2
0
0
1
2
3
4
5
$Q^2$ (GeV$^2$)

# Summary

- **ND are powerful piece of an oscillation analysis**
  - ~3% uncertainties in extrapolation
- **In addition to ND, oscillation analysis will needs flux model, cross section theory and modelling, and additional dedicated measurements**
- **I want my near detector to do everything! Give me:**
  - Excellent PID, sign selection, fully active target material, 4pi acceptance
  - Neutron identification
  - Alternate target materials

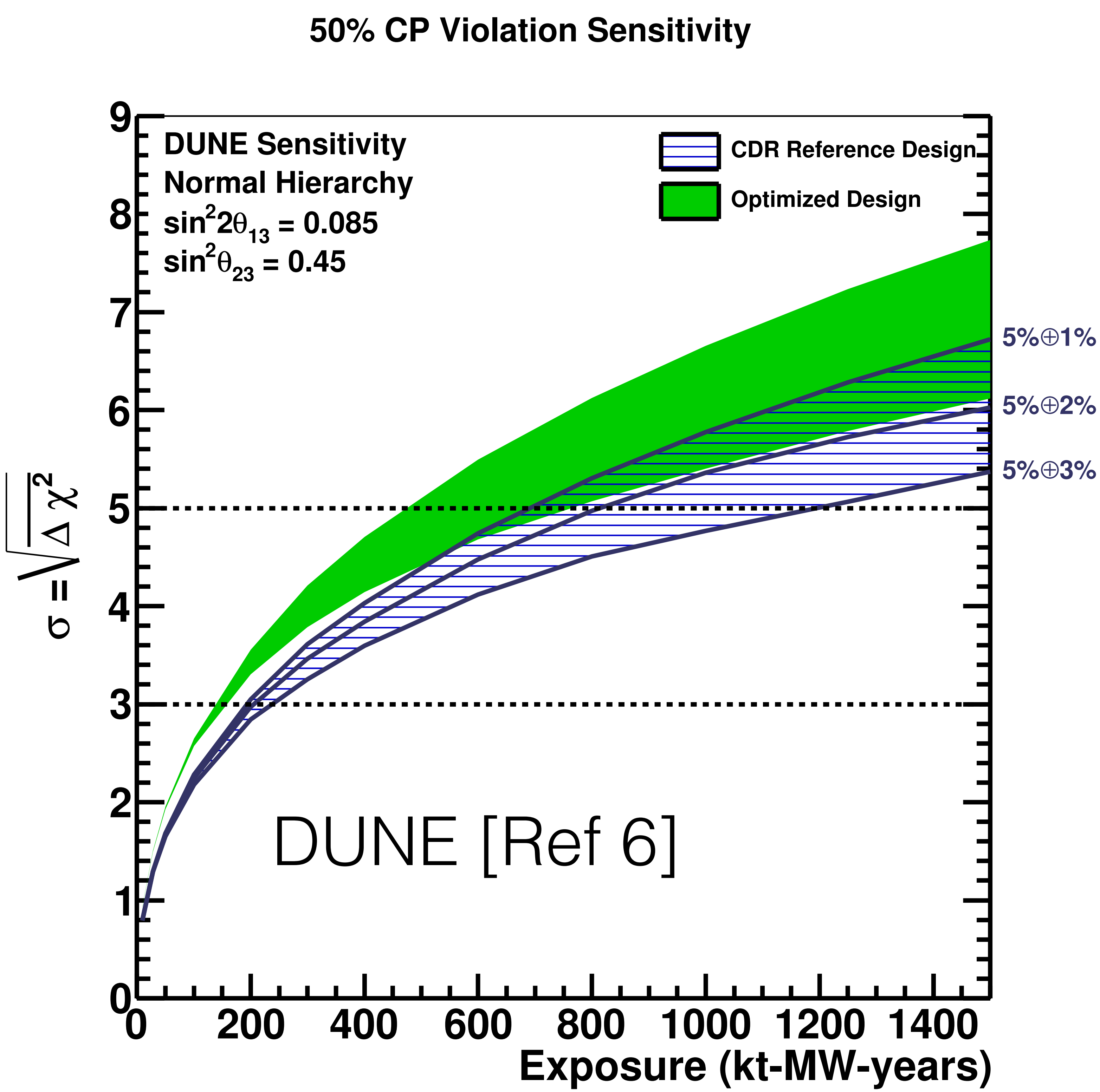
# Another pitfall: Role of neutrons




- For CC0π events on DUNE, signifiant fraction of energy carried away by neutrons
- Significant model spread
- Theory: need semi-inclusive prediction of neutrons
- Experiment: Need validation of those models. **Crucial role of experiments like ANNIE**

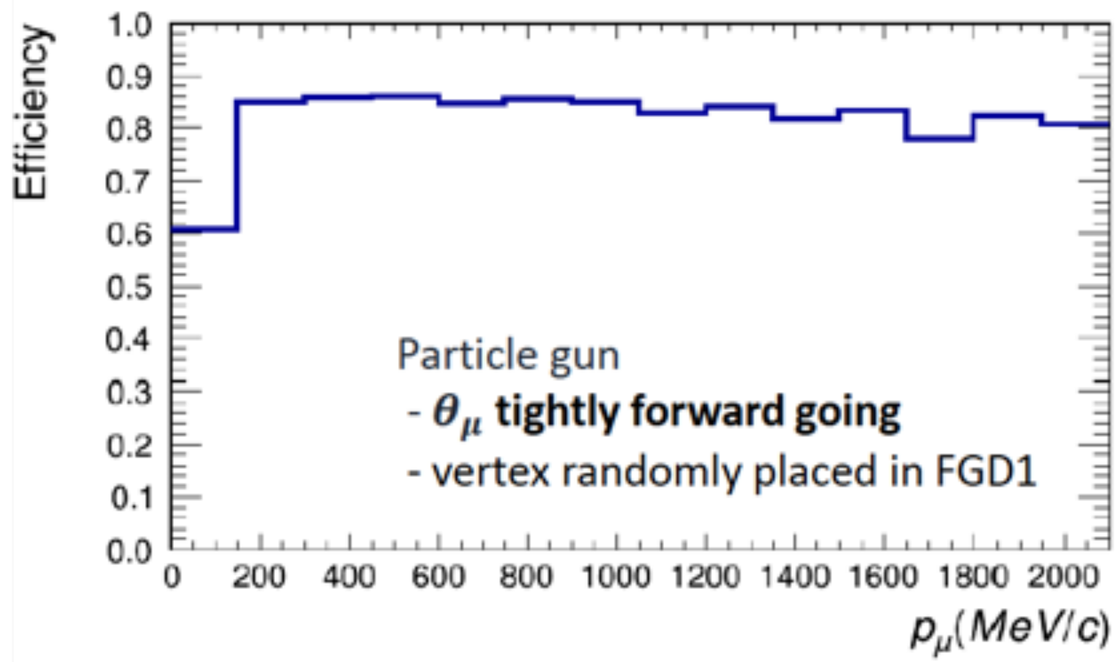
# How well do we need to know ν-A?

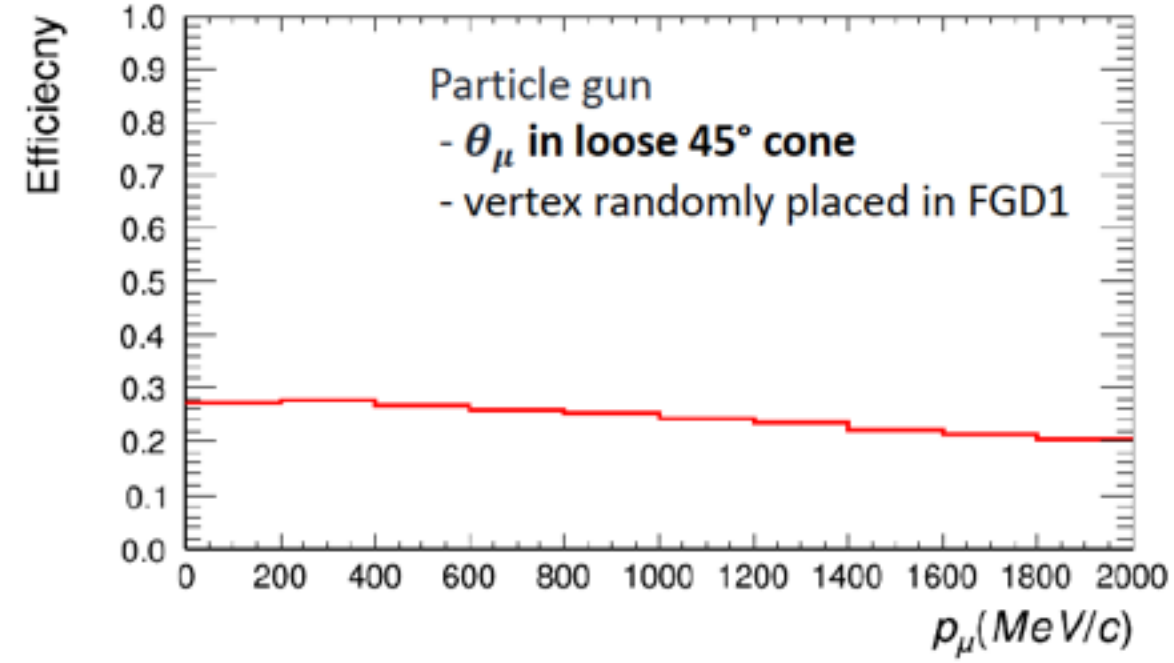



| | $\nu_e$ | $\bar{\nu}_e$ |
|---|---|---|
| **T2K Ref [7]** | 5.4% (>3.9%) | 6.2% (>4.1%) |
| **NOvA Ref [8]** | 17.6% (14.0%) | - |

# Model dependence? Efficiency Calculation

- **Example 1** – want to measure $p_\mu$ for single muons using TPC.
  - The efficiency is very dependent on the underlying $\theta_\mu$ distribution.
  - The underlying $\theta_\mu$ distribution depends on the neutrino scattering model




- **Solution** – Build efficiency in bins of $p_\mu, \theta_\mu$
  – Restrict $p_\mu, \theta_\mu$ phase space to regions of high (flat) $\epsilon$

- Problem becomes more complicated with multiple particles

*Credit: S. Dolan, T2K-XSEC workshop and State of Nu-tion speaker*