DUNE long baseline oscillation analysis Overview and plans

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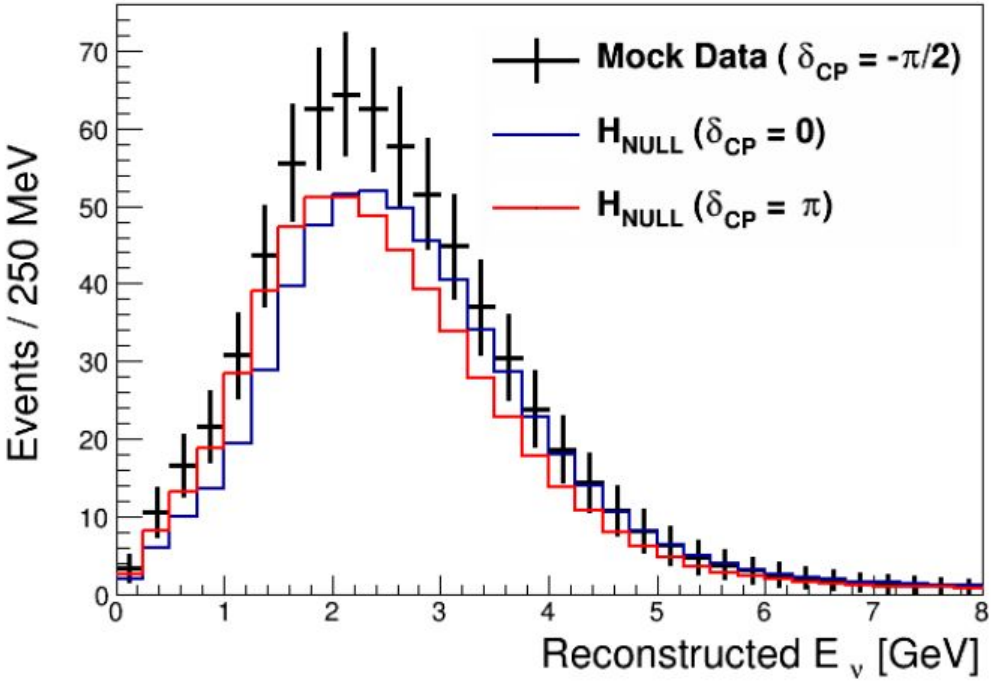
15 October, 2018

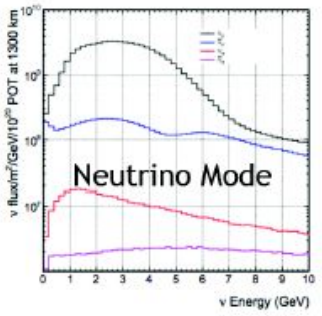
Sensitivity determination: δ_{CP}

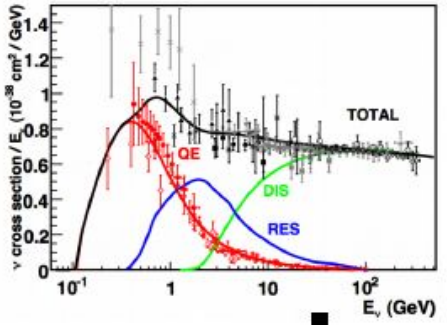
- Create "test" set of far detector samples with some set of oscillation parameters
- Create another set with null hypothesis ($\delta_{CP} = 0,\pi$)

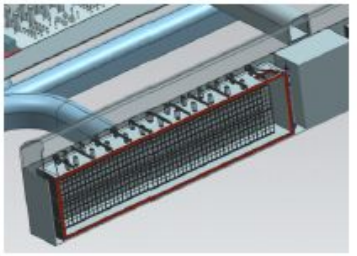


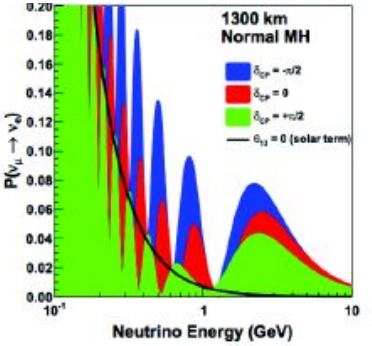
- Incorporate near detector samples to constrain systematics
- Adjust parameters (within uncertainties) on null samples until χ^2 with test sample is minimized

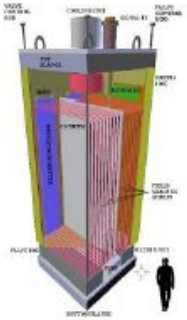
Joint ND+FD analysis

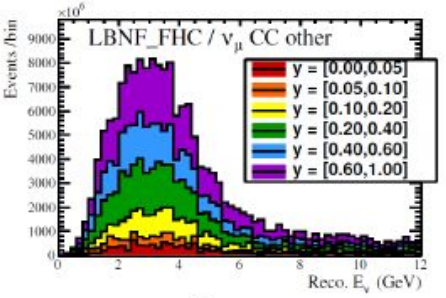


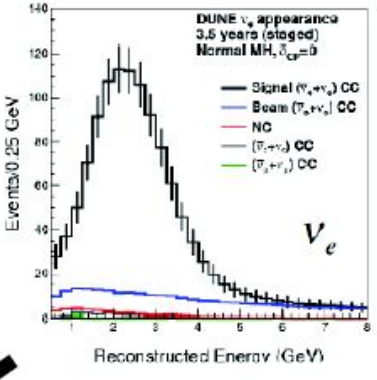


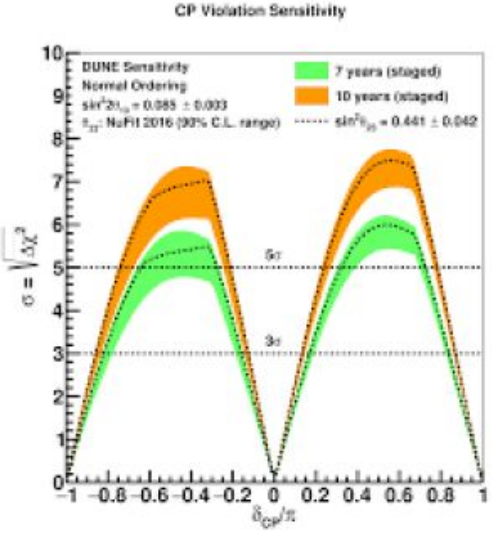




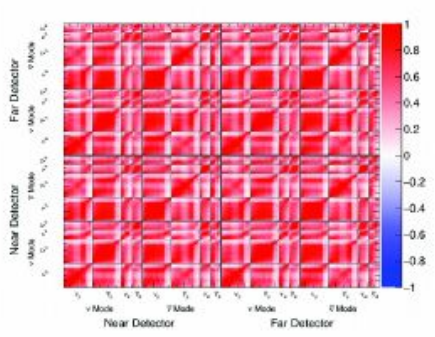






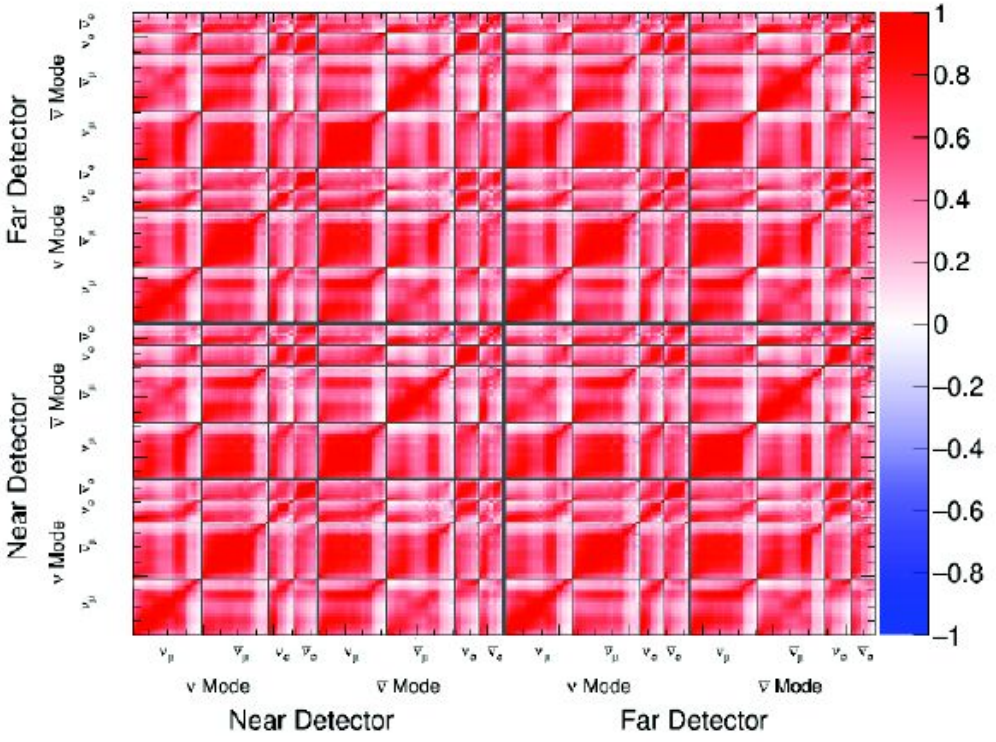


$$\sqrt{\Delta\chi^2}$$



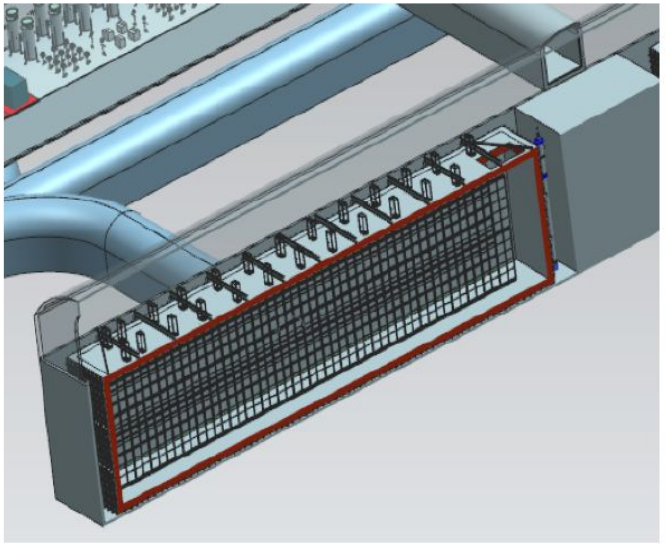
Flux uncertainties

- Approach built on experience from NOvA, MINERvA
- Hadron production and beam focusing uncertainties
  - Describes ν_μ and ν_e
  - ND and FD
  - Neutrino and antineutrino
  - In progress: off-axis angles



Detector systematics

- Uncertainty on relationship between true neutrino energy and detector observables
  - Largely uncorrelated between ND and FD
- Challenging to assess because
  - No actual detector to study
  - ProtoDUNE just turned on
  - Near detector is just concept
- But easy to implement in fitter
- Expect input from ProtoDUNE, MicroBooNE soon



Cross section uncertainties

- Challenging to implement
  - Affect analysis in non-trivial ways
  - Parameter changes affect all samples
  - Some adjustments require “reweighting zero”
  - Many necessary uncertainties are not implemented in GENIE
- Developed “DUNE-reweight”
  - Code ART derived from T2K and MINERvA experience
  - Expands on existing GENIE reweighting to implement many important new uncertainties

DUNE-reweight

Uncertainty	Mode	Description
M_A^{QE} →z exp.	1p1h/QE	D_2 constraint
BeRPA	1p1h/QE	RPA/nuclear model suppression
E_b	1p1h/QE	Shift in nuclear model removal energy
MnvaTune1	2p2h	Strength into (nn)pp only
MnvaTune2	2p2h	Strength into np pairs only
MnvaTune3	1p1h/QE+2p2h	Strength into 1p1h vs. 2p2h
ArC2p2h	2p2h Ar/C scaling	Electron scattering SRC pairs
E_{2p2h}	2p2h	Energy dependence
M_A^{res}, C_5^A	RES	Single pion form factors
$I_{1/2}$ bkg	RES	Non-resonant background
Low Q^2 1π	RES	Low Q^2 (empirical) suppression
MK model	RES	Alternate strength in W
GENIE FSI	all	Nominal FSI
E_{avail}/q_0	all	Extreme FSI-like variations
NC/multi-π 50%	CC/NC with > 1 pion	Increased uncertainty
ν_e/ν_u	ν_e	Large uncertainty since ν_e unique phase space
$\nu_e/\overline{\nu}_e$ norm	ν_e,$\overline{\nu}_e$	McFarland&Day, PRD86 053003

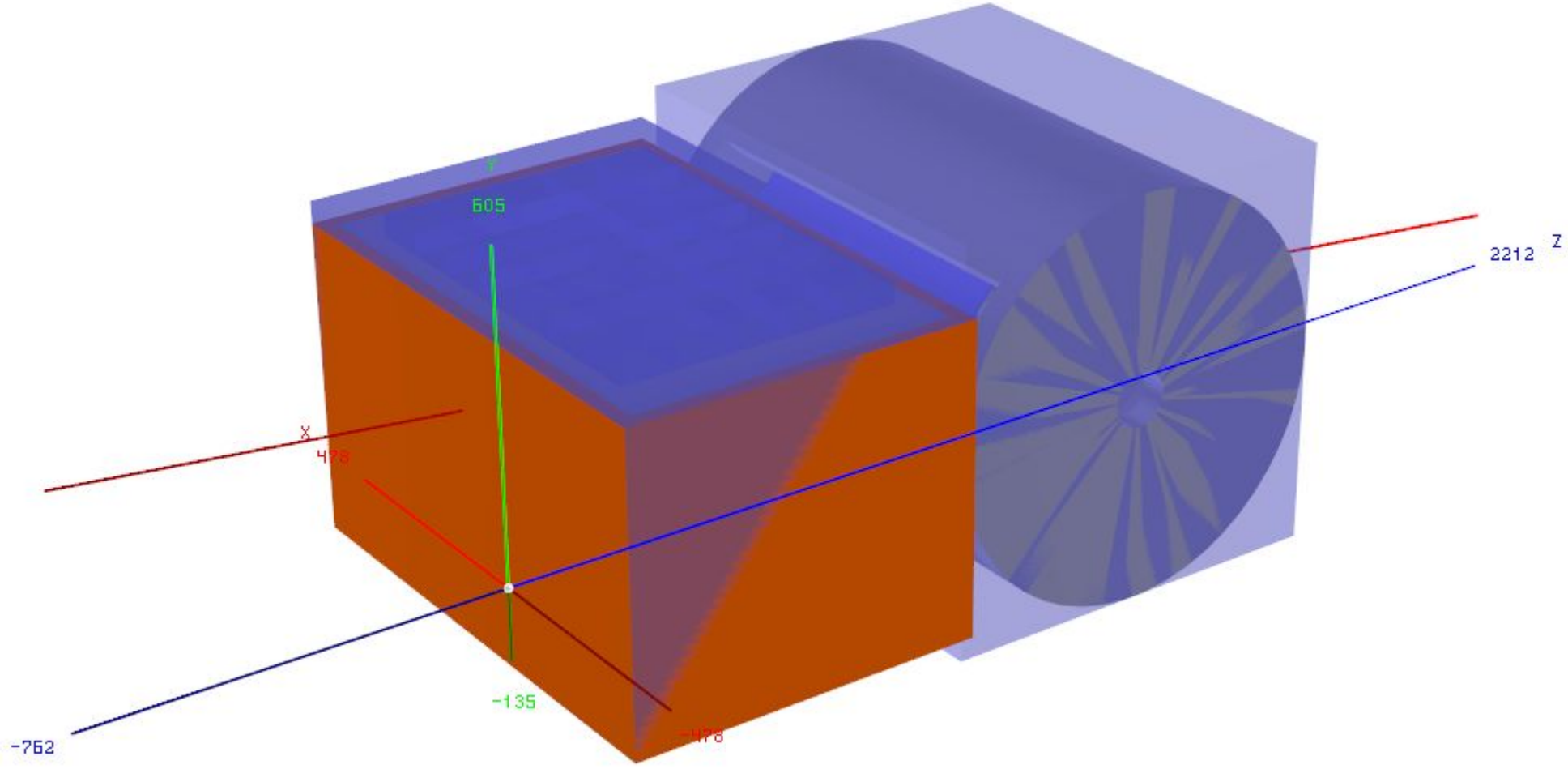
Existing GENIE dial new error

Norm error based on GENIE/Data

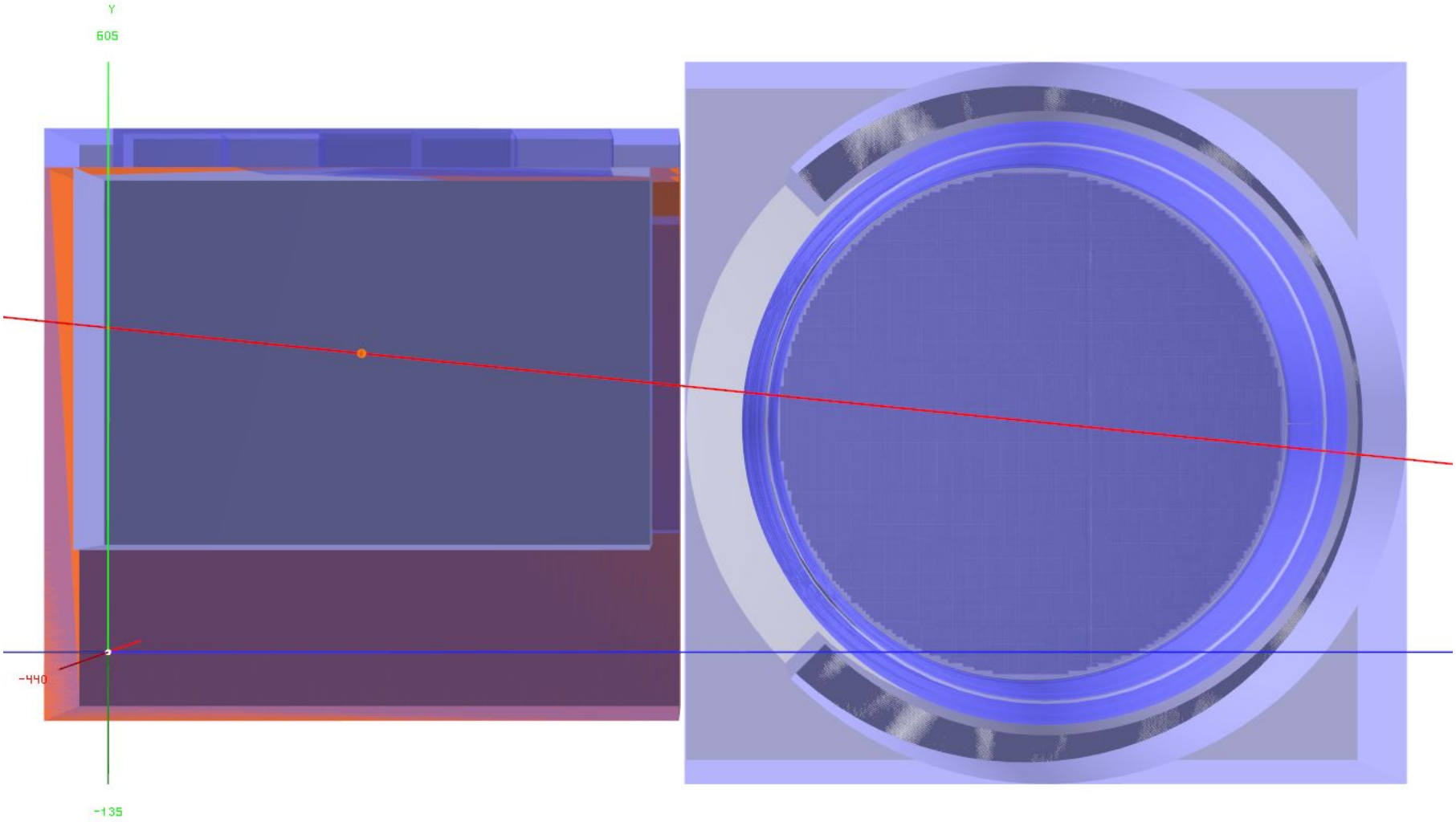
Nuclear model uncertainties in Q^2 or q_0- q_3

Kevin McFarland

Near detector concept: Modular LAr TPC & Magnetized high-pressure gas Ar TPC

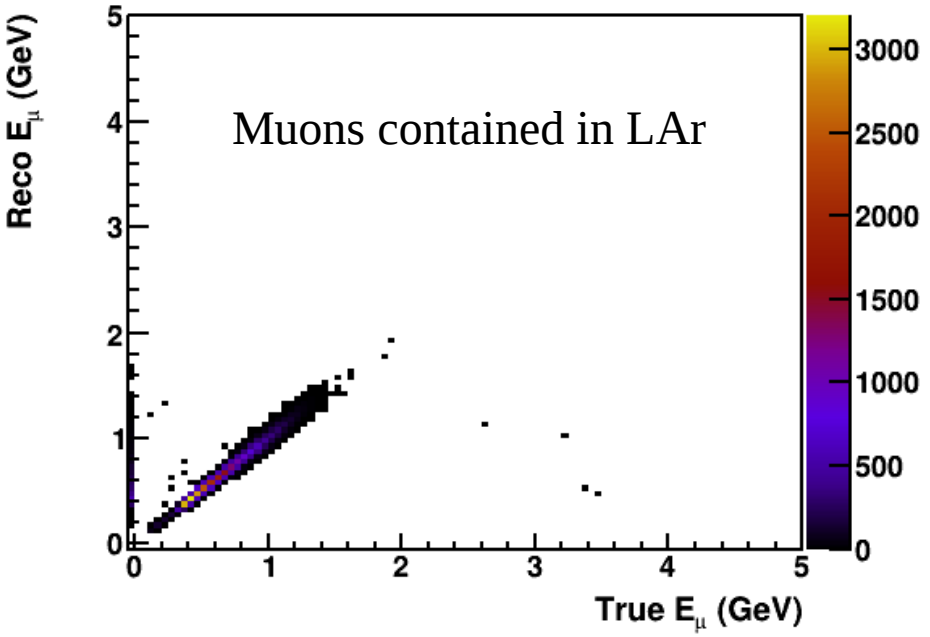


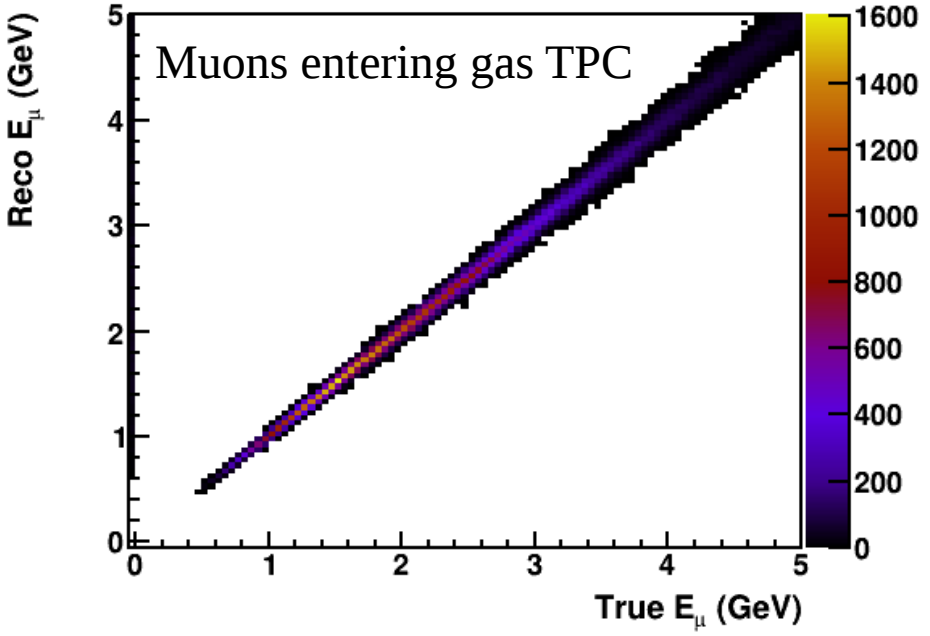
Near detector concept: Modular LAr TPC & Magnetized high-pressure gas Ar TPC



Parameterized “reconstruction” based on Geant4 energy deposits

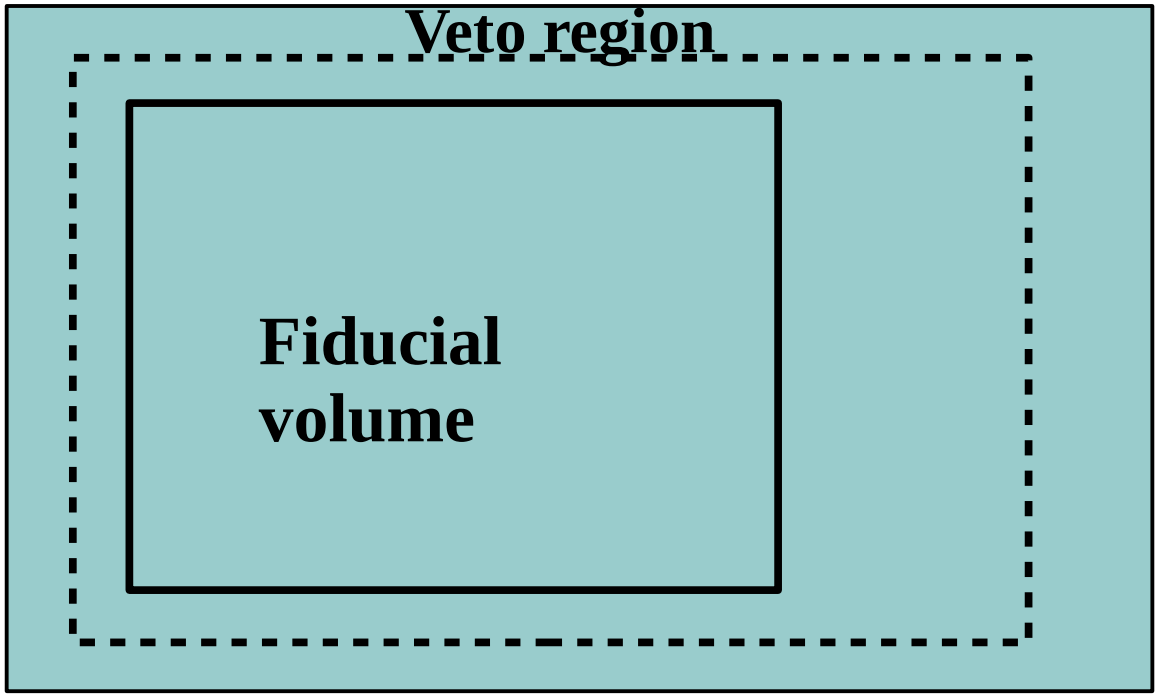
- Simulate muon acceptance and reconstruction smearing:
  - Contained in active LAr – by range
  - Matched to gas TPC – by curvature

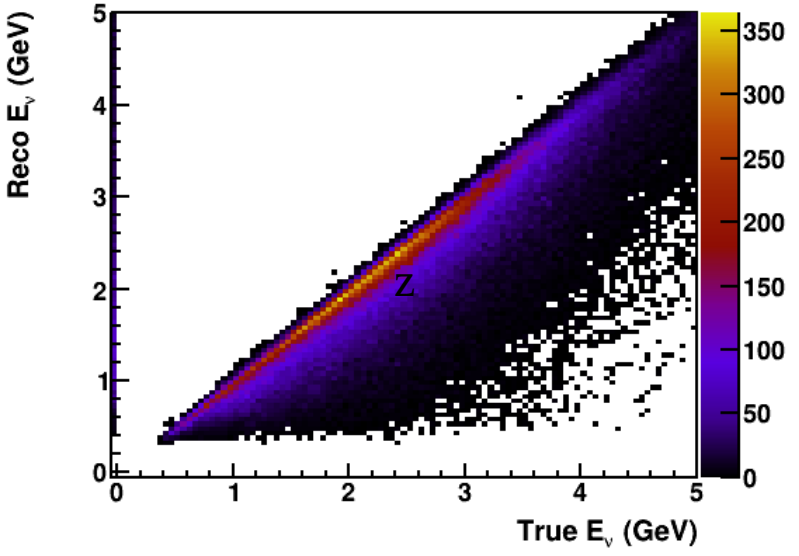




Parameterized “reconstruction” based on Geant4 energy deposits

- Simulate calorimentric hadronic energy reconstruction by looking at true energy deposits in active LAr

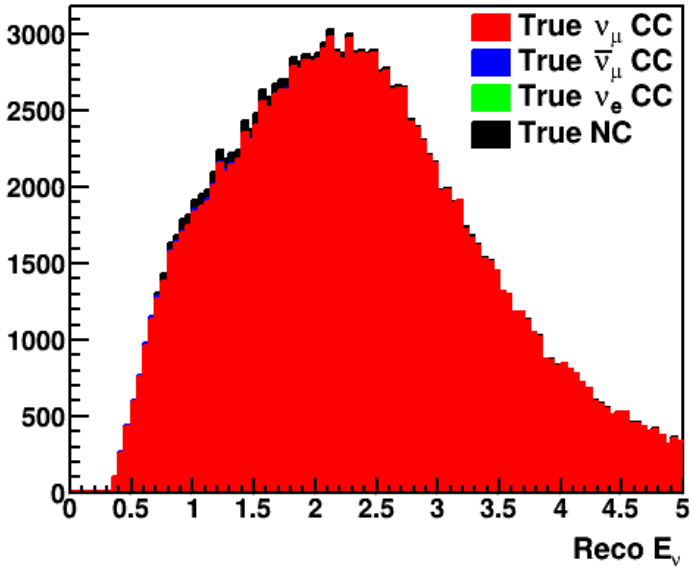




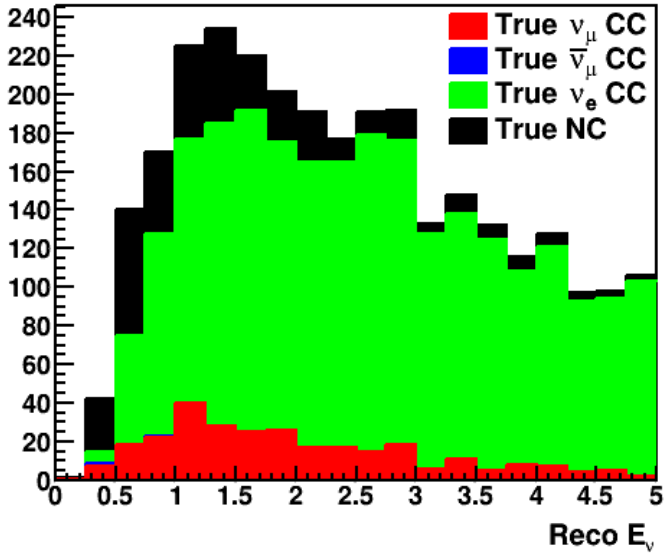
- Reject events with too much energy in veto region → good hadron containment

Form reconstructed samples

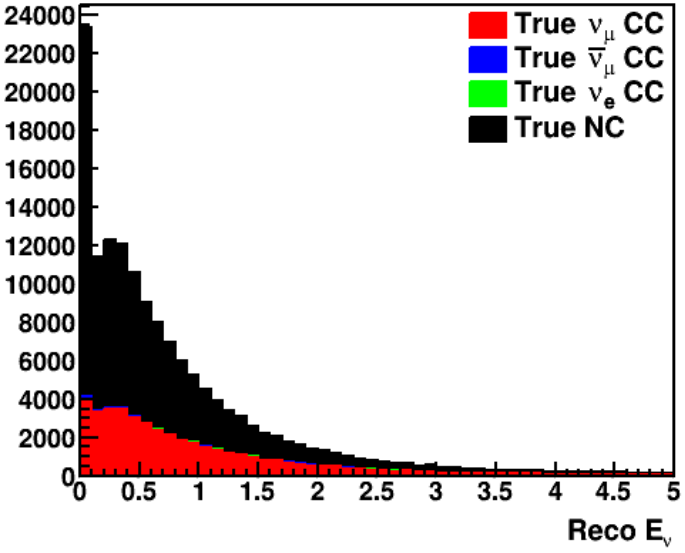
Reco ν_μ CC



Reco ν_e CC



Reco NC



- Preliminary pseudo-reconstruction and event classification
- Based on track length, dE/dx profile, γ conversion distance, etc.

Summary of ND work

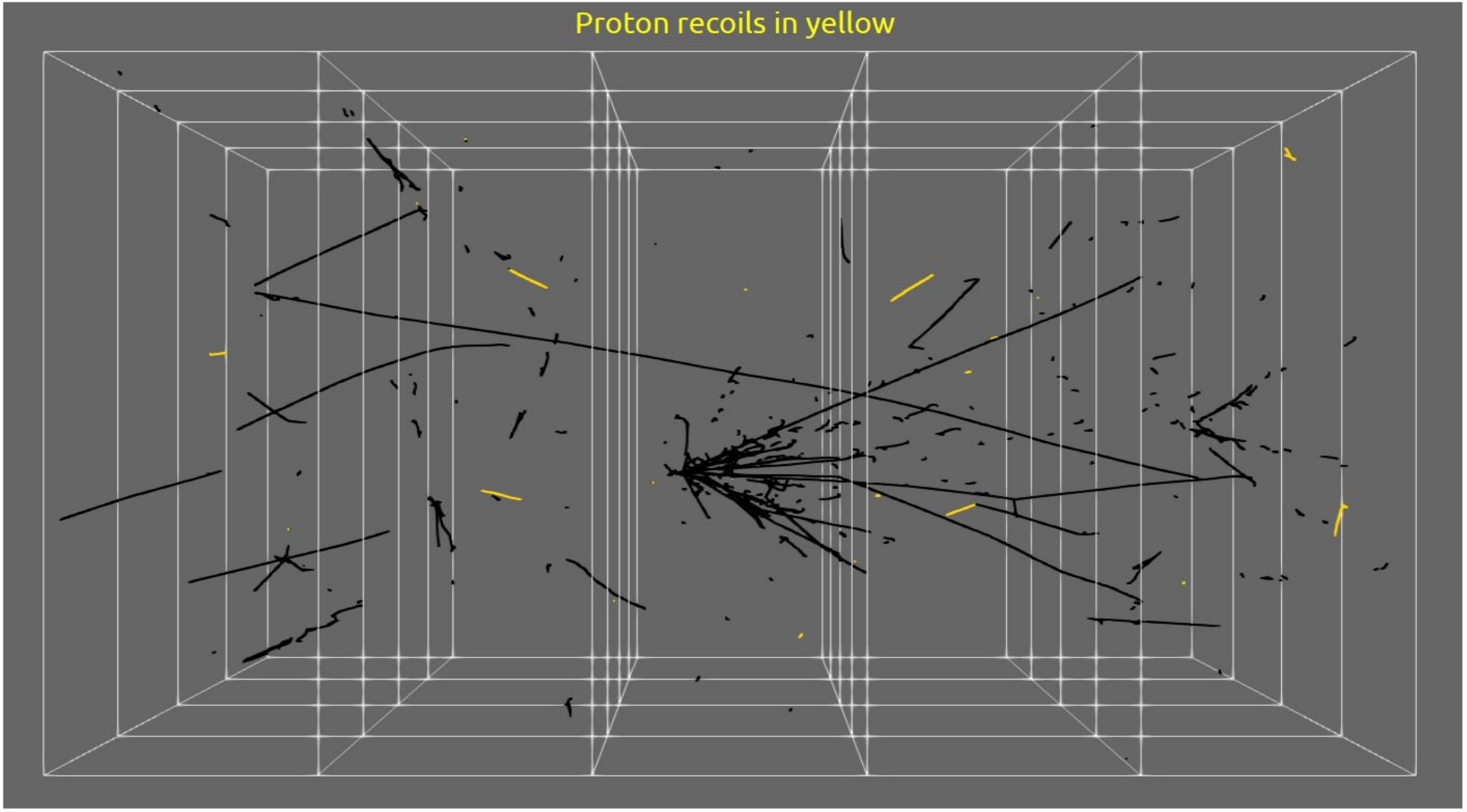
- Liquid argon samples
  - Geometry, event generation, “reconstruction” done
  - Fully integrated with DUNE-reweight and fitting software
  - Improvements to event selection, additional analysis samples ongoing
  - Detector systematics to be added
- Gas argon samples
  - Lower thresholds and rates
  - Geometry built, event generation tested
  - DUNE-reweight, fitting integration shared with LAr
  - “Reconstruction”, sample selection in progress
- Off-axis samples
  - Code is written and being tested
  - Needs to be integrated with fitting software

Backups

Neutron reconstruction

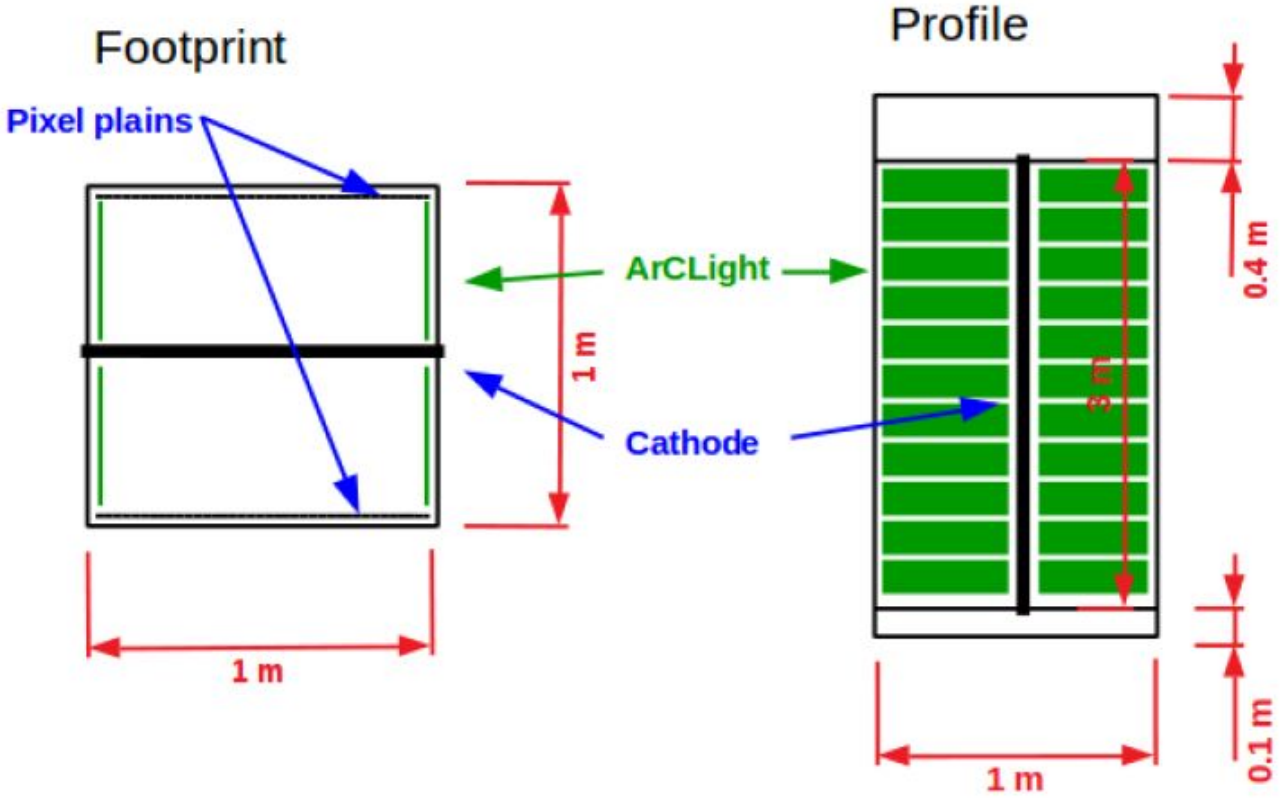
- Neutron reconstruction is difficult
- For neutrons of 10s to 100s MeV kinetic energy, identification is possible through neutron-proton “elastic” scattering of bound proton
- Must constrain uncertainties on neutron production at near detector:
  - Tagging neutrons in LAr
  - Possible energy measurement from time-of-flight in fast 3DST or ECal
  - Detailed measurements of protons → constraints on neutrons

Example LAr ND beam spill



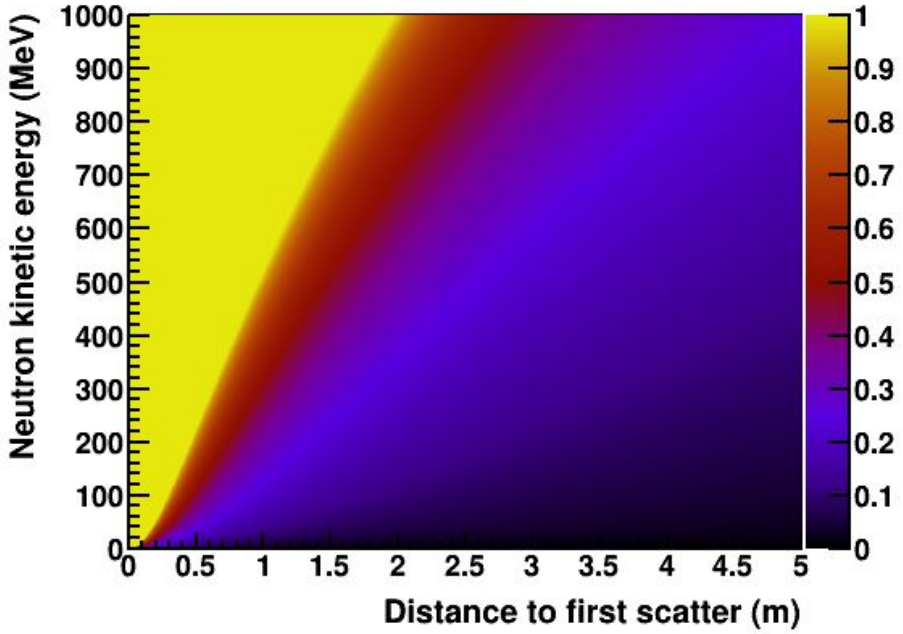
Neutron association is challenging in high-rate environment

- Near detector design includes modular light readout
- Fast component scintillation light with $\tau \sim 6$ ns

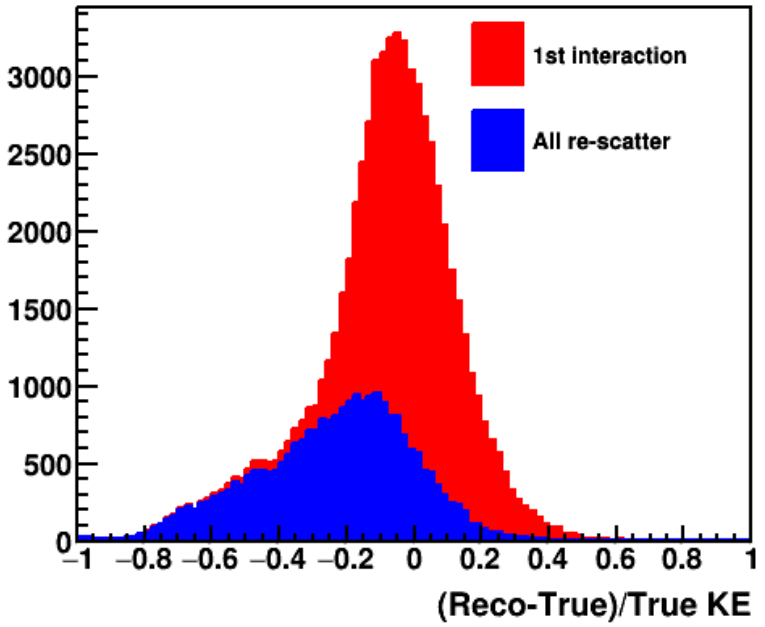


- Tiled light detectors within a module give O(30 cm) position resolution to optical signals
- Allows for associating neutron recoil signals to neutrino interactions using timing

Neutron measurements with TOF

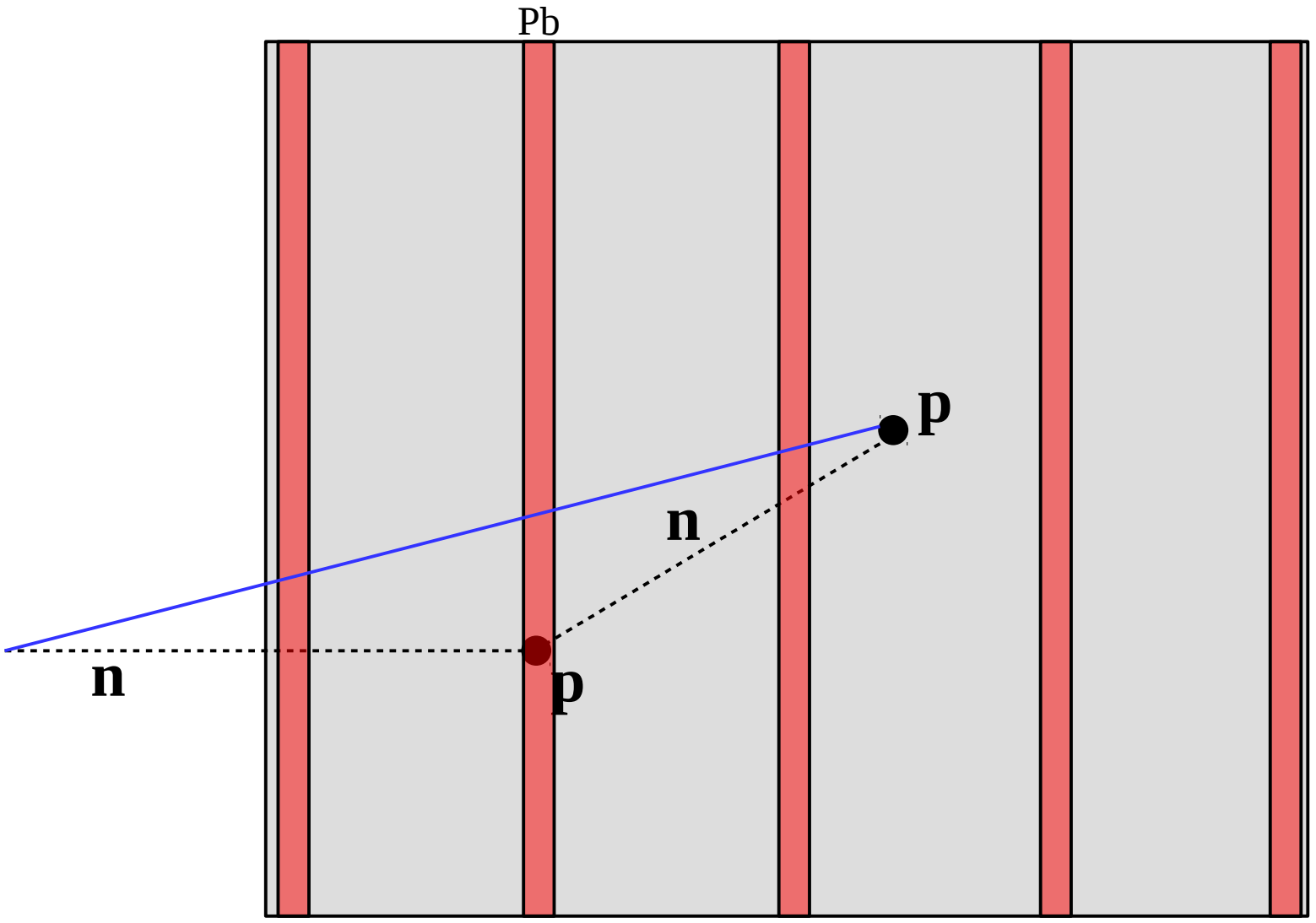


100 MeV neutron, 100cm to scatter
0.7ns timing resolution
CH+Pb ECal



- Neutron kinetic energy resolution from TOF is ~20% at 100 MeV for neutrons with 100cm lever arm
- Can potentially achieve ~30-50% efficiency

Misreconstruction of energy



Underestimate distance traveled by neutron

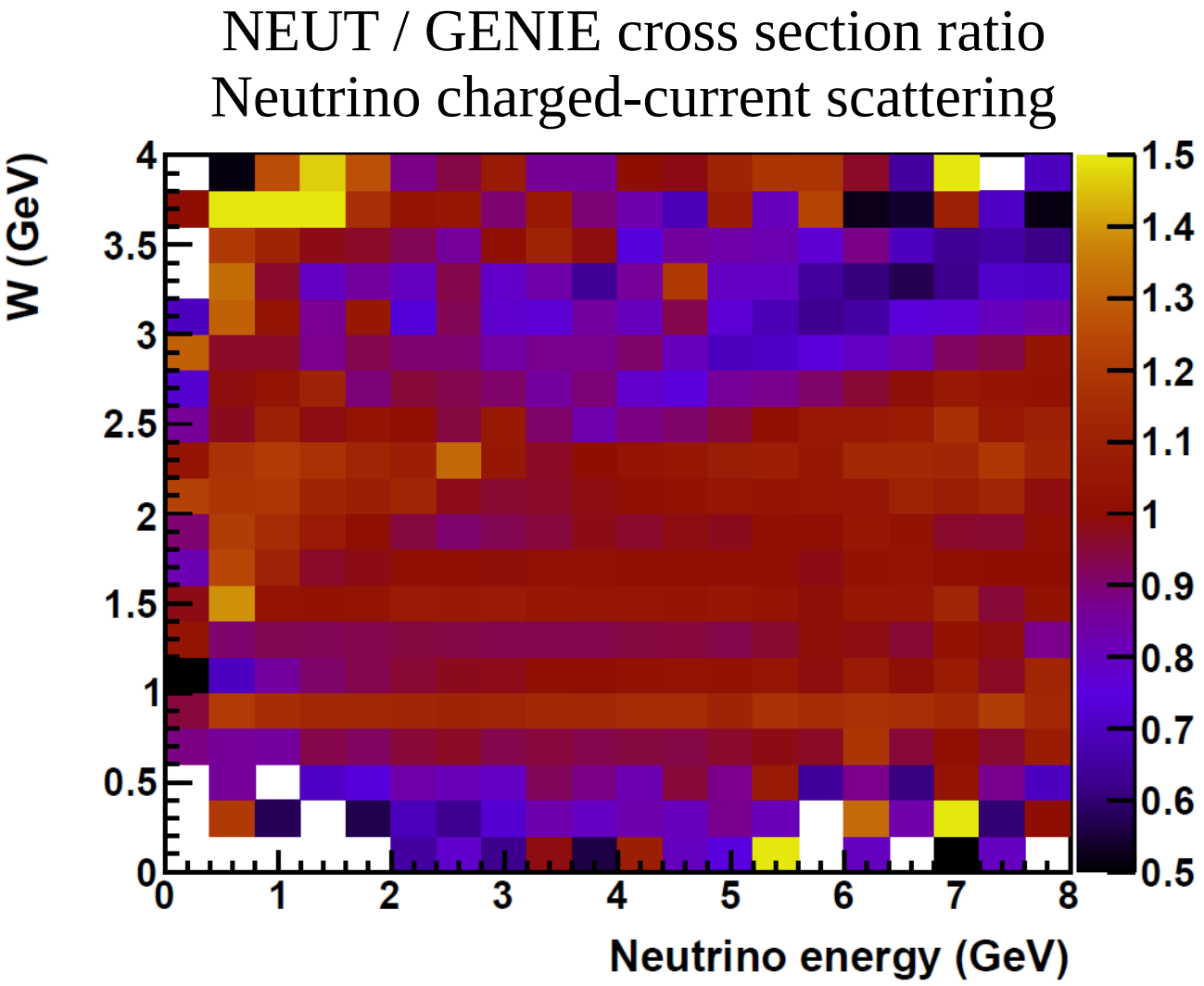
Second neutron is slower, so time will be overestimate of initial neutron's energy

$\beta = d/t \rightarrow$ underestimate energy

Use of other neutrino event generators

- Test that cross section systematics cover differences between generators
- Generate mock data based on other generators (NEUT, NuWro, GiBUU) from existing samples by reweighting
- Modified E_{rec} vs. E_{true} relationship, with other observables kept fixed on-axis
- Currently not possible to do full simulations with other generators
  - Long term goal: develop tools to do this

Example: Reweight to NEUT



- Fast, easy to implement reweighting to another generator based on truth-level kinematics
- Caveat: Projects away any differences in other quantities

Planned fake data studies

Fake data studies

NuWro	all+FSI	Similar underlying model with different FSI
NEUT SF	QE+FSI	SF with different FSI, no 2p2h
Alternate GENIE		
GENIE hN2015	all	Different FSI within the context of GENIE
Z-EXP	QE	Alternate non-dipole form factors
DUNE PRISM	all	Probes Erec-Etrue response function.