How the ND affects DUNE physics and why DUNE needs ND-GAr

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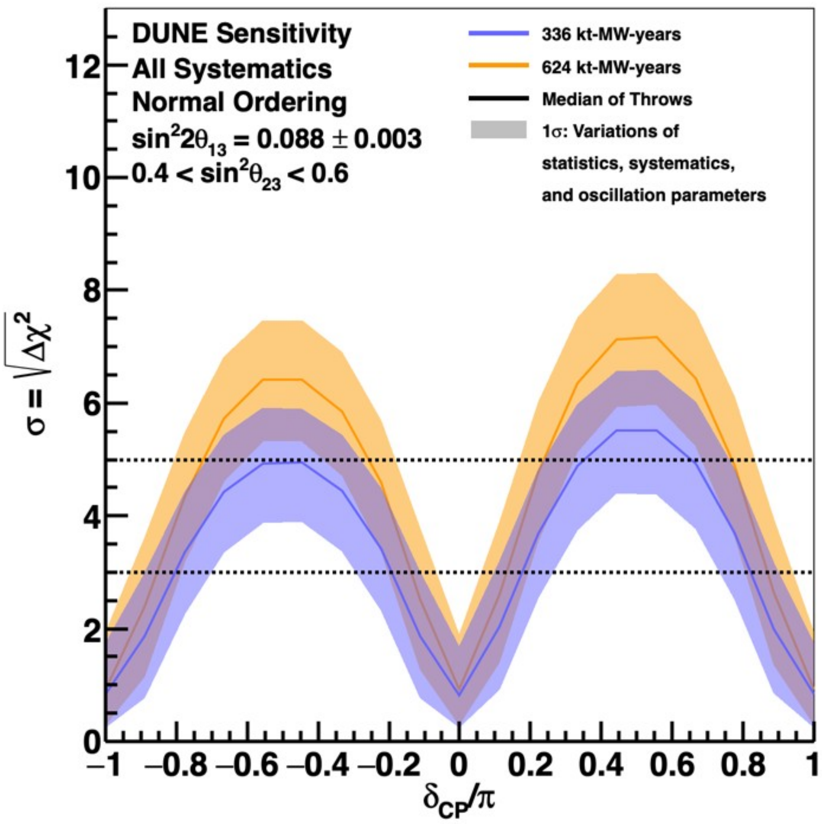
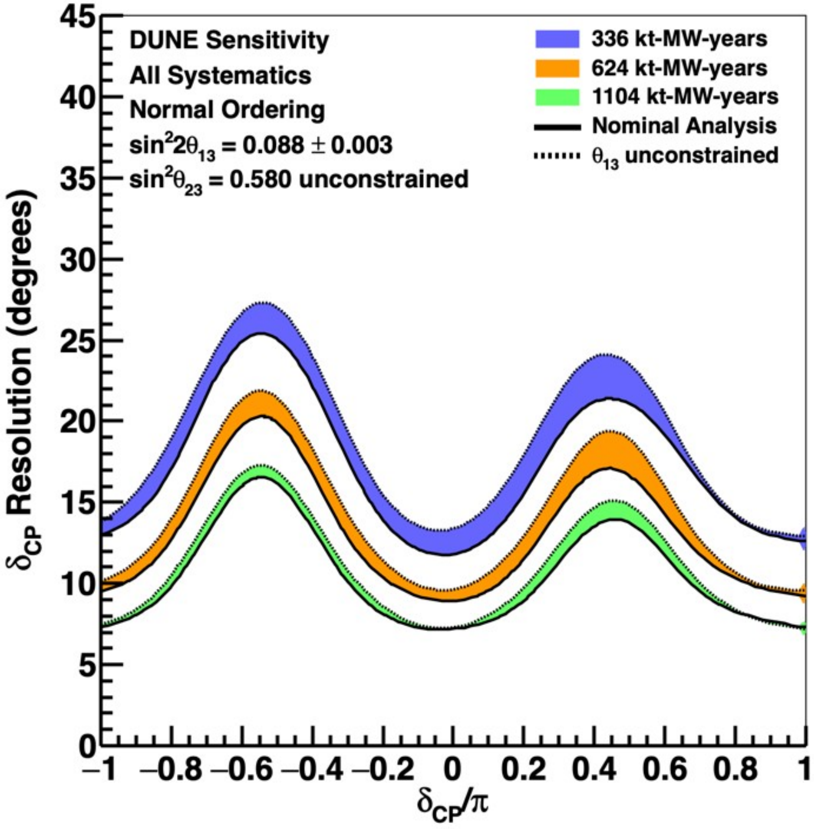
University of Rochester
Fermilab PAC meeting
18 November, 2021

DUNE oscillation physics goals


CP Violation Sensitivity

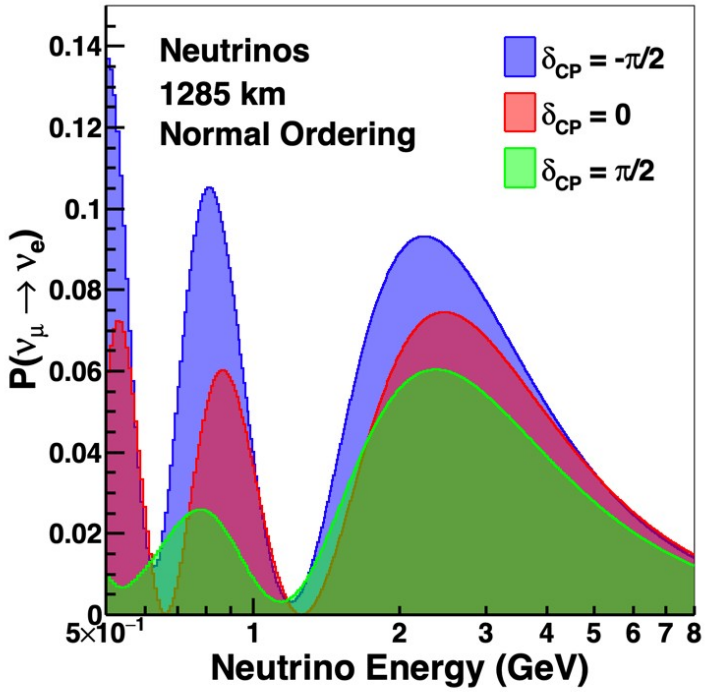


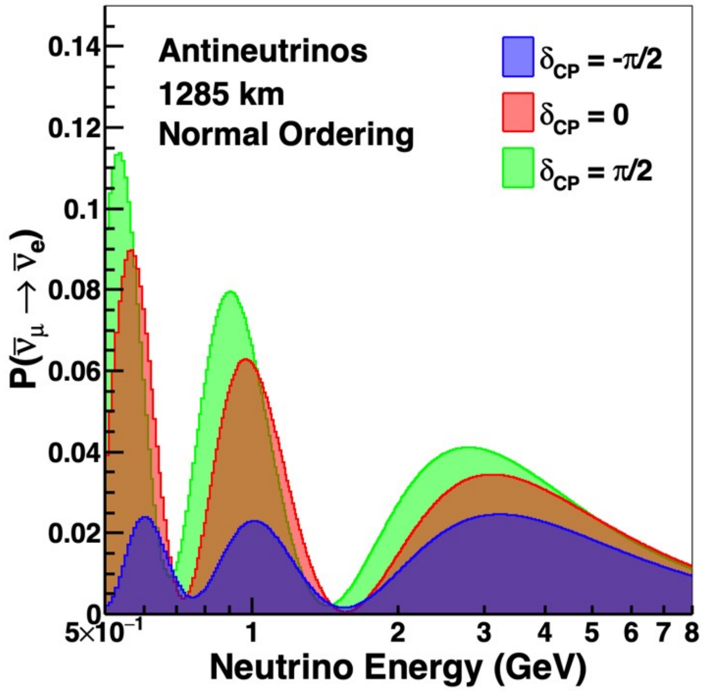
- Primary long-term physics goals:
  - Observe CP violation at 5σ (3σ) over 50% (75%) of δ_{CP} values
  - Make world-leading precision measurements of long-baseline oscillation parameters, including the mass ordering and δ_{CP}

Outline

- How to measure neutrino oscillations, and the role of the Near Detector
- Extracting oscillation parameters from DUNE data
- Requirements for a more capable near detector
- ND-GAr design
- Timescale: when ND-GAr becomes important

CP-violation and mass ordering affect (anti)neutrino oscillations





- Mass ordering and CP violation both enhance ν_e appearance and suppress $\bar{\nu}_e$ appearance, or vice versa
- Mass ordering effect is huge at the first maximum → removes degeneracy with CP violation and both can be measured

Measuring an oscillation probability

$$P(\nu_\mu \rightarrow \nu_e) = \frac{\Phi_e^{FD}(E_\nu)}{\Phi_\mu^{ND}(E_\nu)}$$

- Oscillation probability is essentially the ratio of the ν_e flux at the FD to the ν_μ flux at the beam source (~ND)

Measuring an oscillation probability

$$P(\nu_\mu \rightarrow \nu_e) = \frac{\Phi_e^{FD}(E_\nu)}{\Phi_\mu^{ND}(E_\nu)}$$

$$N_e^{FD}(E_\nu) = \Phi_e^{FD}(E_\nu) \times \sigma_e(E_\nu) \times \epsilon_e^{FD}(E_\nu)$$

- But we actually measure an event rate, which is the product of the flux (Φ), cross section (σ), and detector acceptance and efficiency (ε), which all depend on E_ν, and all have significant uncertainties

Measuring an oscillation probability

$$P(\nu_\mu \rightarrow \nu_e) = \frac{\Phi_e^{FD}(E_\nu)}{\Phi_\mu^{ND}(E_\nu)}$$

$$N_e^{FD}(E_\nu) = \Phi_e^{FD}(E_\nu) \times \sigma_e(E_\nu) \times \epsilon_e^{FD}(E_\nu)$$

$$N_e^{FD}(E_{rec}) = \int dE_\nu \mathbf{D}^{FD}(E_\nu \rightarrow E_{rec}) \Phi_e^{FD}(E_\nu) \times \sigma_e(E_\nu) \times \epsilon_e^{FD}(E_\nu)$$

- And we don’t actually measure E_ν, we measure some reconstructed energy, which is smeared by a matrix (**D**) that relates true to reconstructed energy

Measuring an oscillation probability

$$P(\nu_\mu \rightarrow \nu_e) = \frac{\Phi_e^{FD}(E_\nu)}{\Phi_\mu^{ND}(E_\nu)}$$

$$N_e^{FD}(E_\nu) = \Phi_e^{FD}(E_\nu) \times \sigma_e(E_\nu) \times \epsilon_e^{FD}(E_\nu)$$

$$\frac{N_e^{FD}(E_{rec})}{N_\mu^{ND}(E_{rec})} = \frac{\int dE_\nu \mathbf{D}^{FD}(E_\nu \rightarrow E_{rec})\Phi_e^{FD}(E_\nu) \times \sigma_e(E_\nu) \times \epsilon_e^{FD}(E_\nu)}{\int dE_\nu \mathbf{D}^{ND}(E_\nu \rightarrow E_{rec})\Phi_\mu^{ND}(E_\nu) \times \sigma_\mu(E_\nu) \times \epsilon_\mu^{ND}(E_\nu)}$$

- We make the analogous measurement at the LAr ND to largely cancel uncertainties, but with several critical caveats

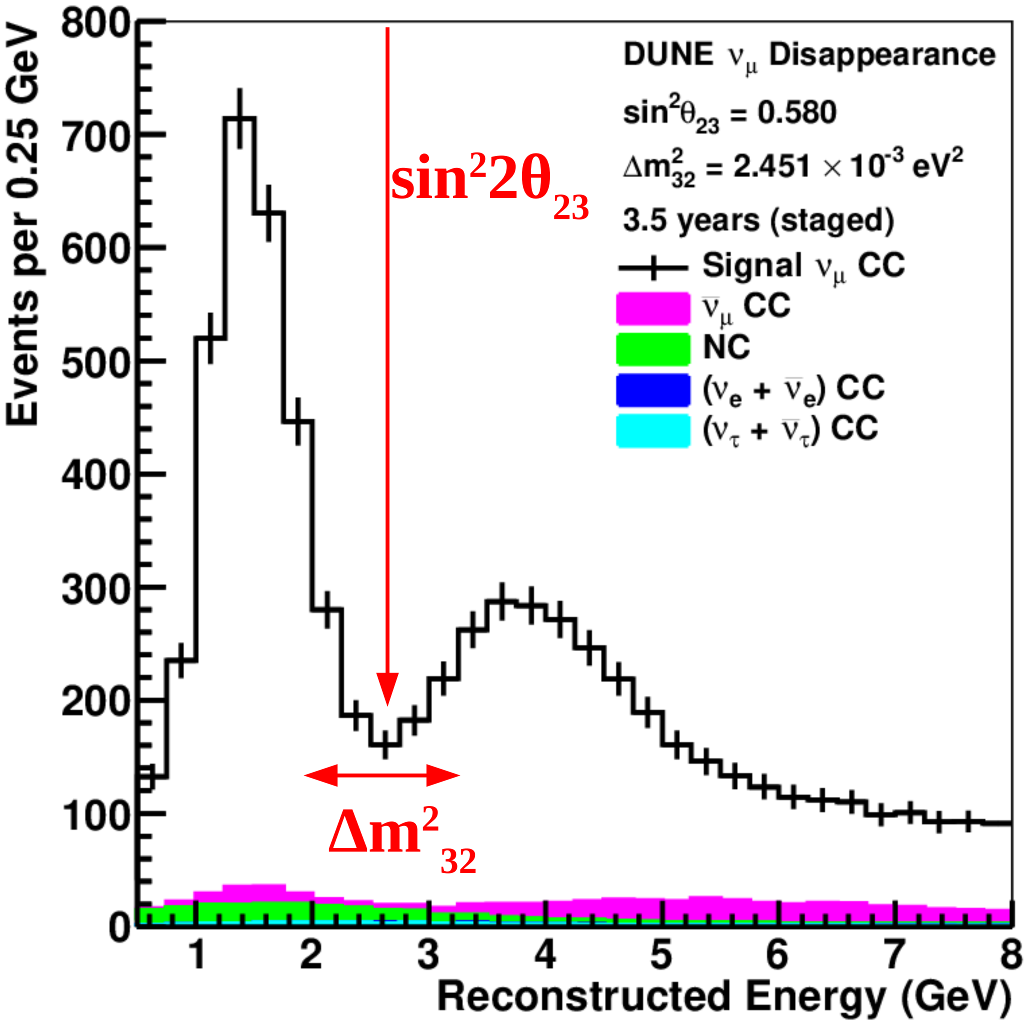
Percent-level effects are critical for DUNE’s long-term physics

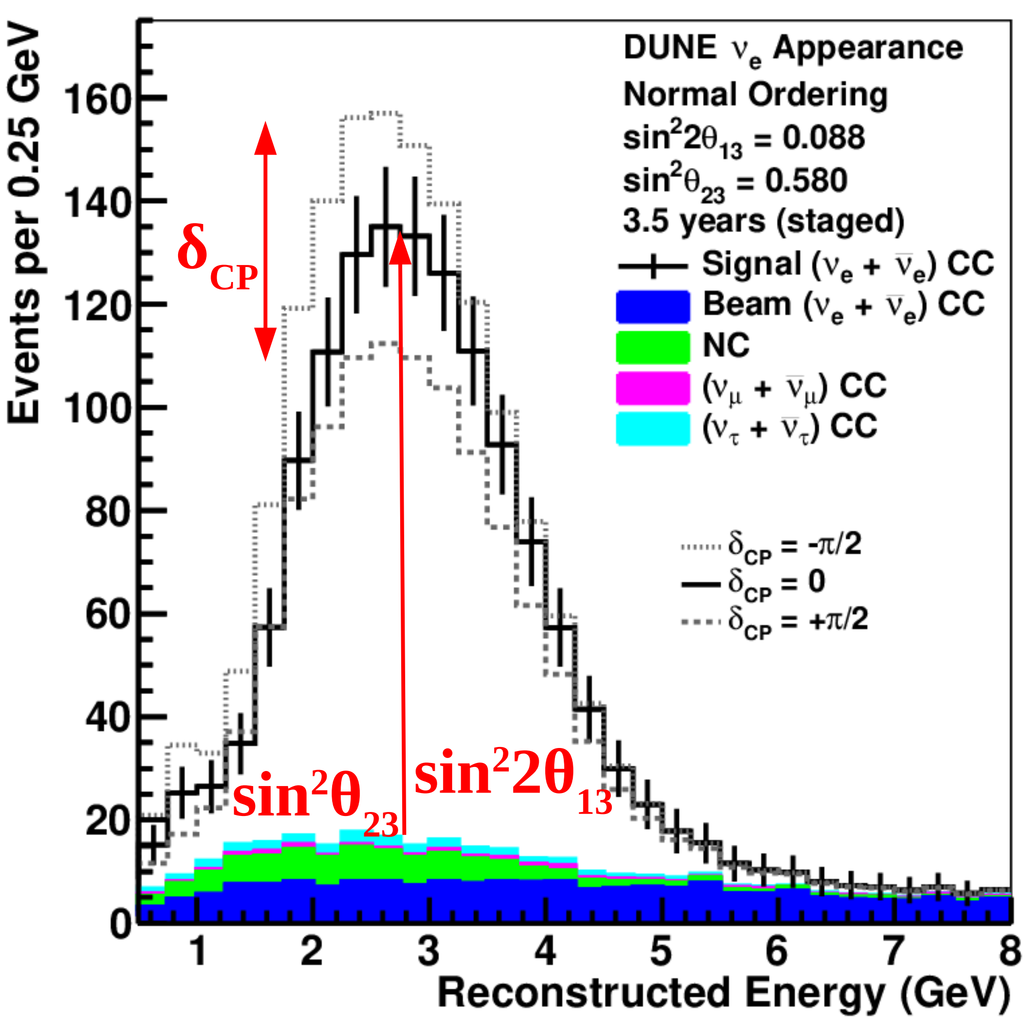
$$\frac{N_e^{FD}(E_{rec})}{N_\mu^{ND}(E_{rec})} = \frac{\int dE_\nu \boxed{\mathbf{D}^{FD}(E_\nu \to E_{rec})} \Phi_e^{FD}(E_\nu) \times \boxed{\sigma_e(E_\nu)} \times \boxed{\epsilon_e^{FD}(E_\nu)}}{\int dE_\nu \boxed{\mathbf{D}^{ND}(E_\nu \to E_{rec})} \Phi_\mu^{ND}(E_\nu) \times \boxed{\sigma_\mu(E_\nu)} \times \boxed{\epsilon_\mu^{ND}(E_\nu)}}$$

- For precision measurement, it is not sufficient to simply measure this ratio, must also separately constrain
  - Acceptance is different at the near detector
  - Cross section differences due to available phase space from lepton mass effects
  - $E_\nu \to E_{rec}$, which depends on detector response and also on exclusive cross sections (i.e. composition and kinematics of final-state hadrons)
  - All of this depends on neutrino energy → different fluxes (due to oscillations) means a different integral

Oscillations affect FD E_{rec} spectra

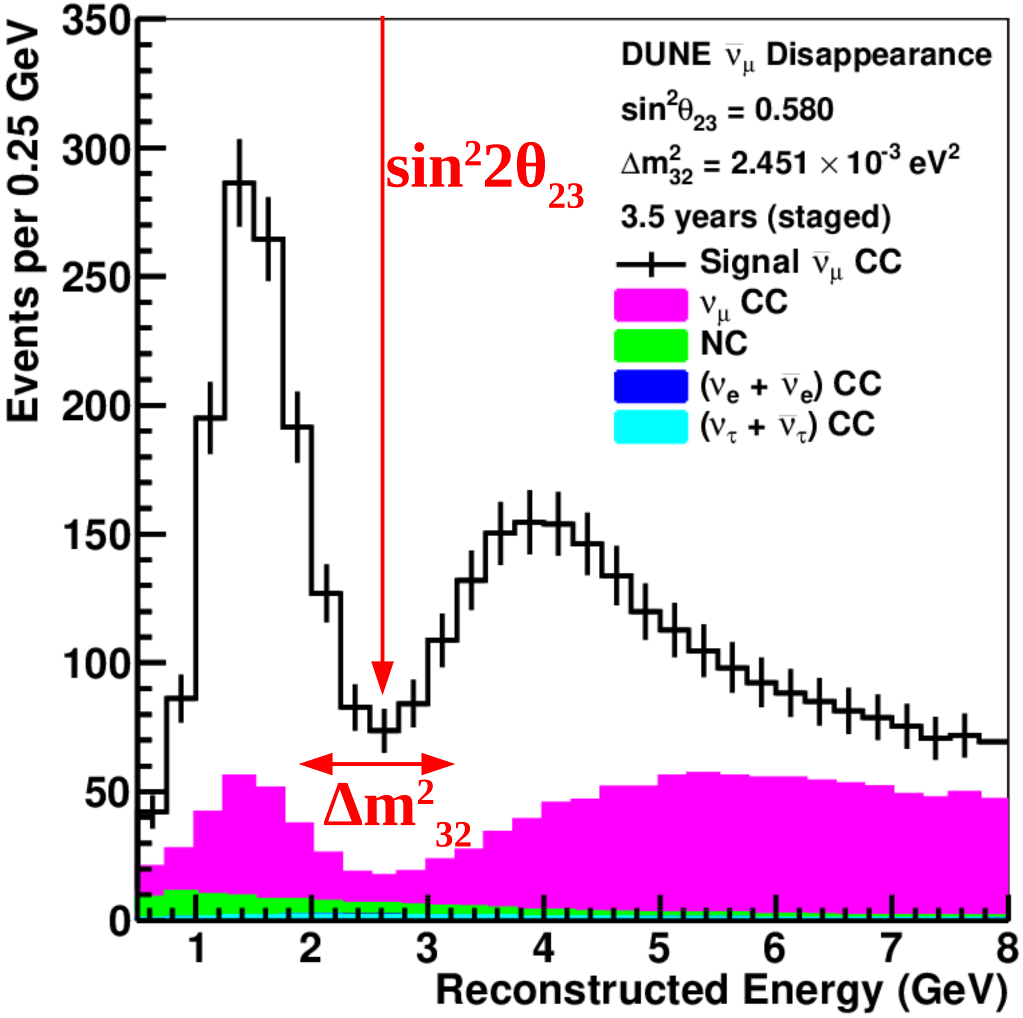
FHC = neutrinos

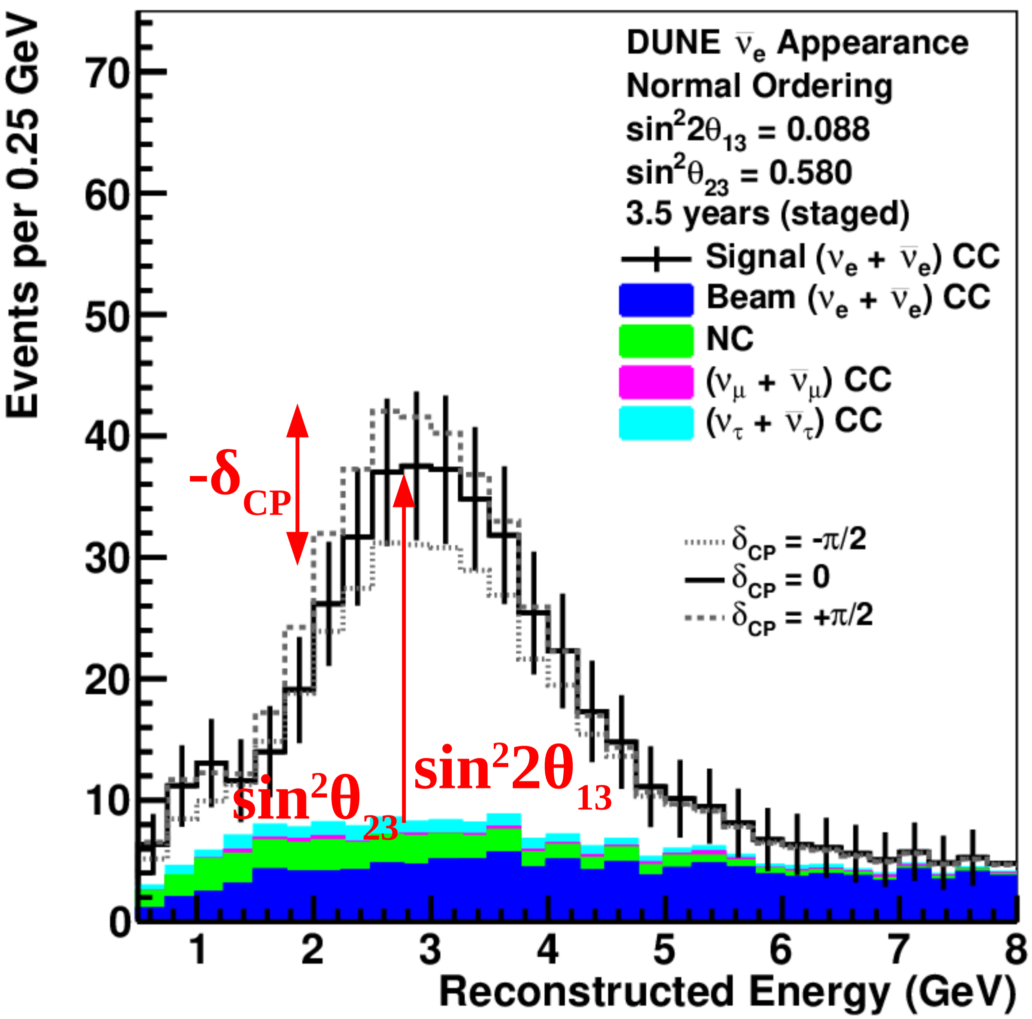




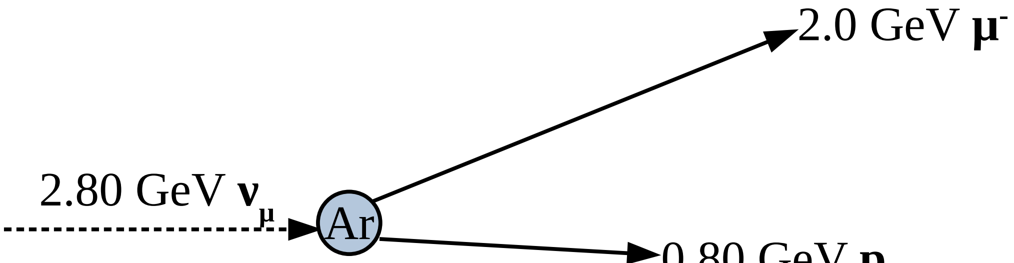
Oscillations affect FD E_{rec} spectra

RHC = antineutrinos

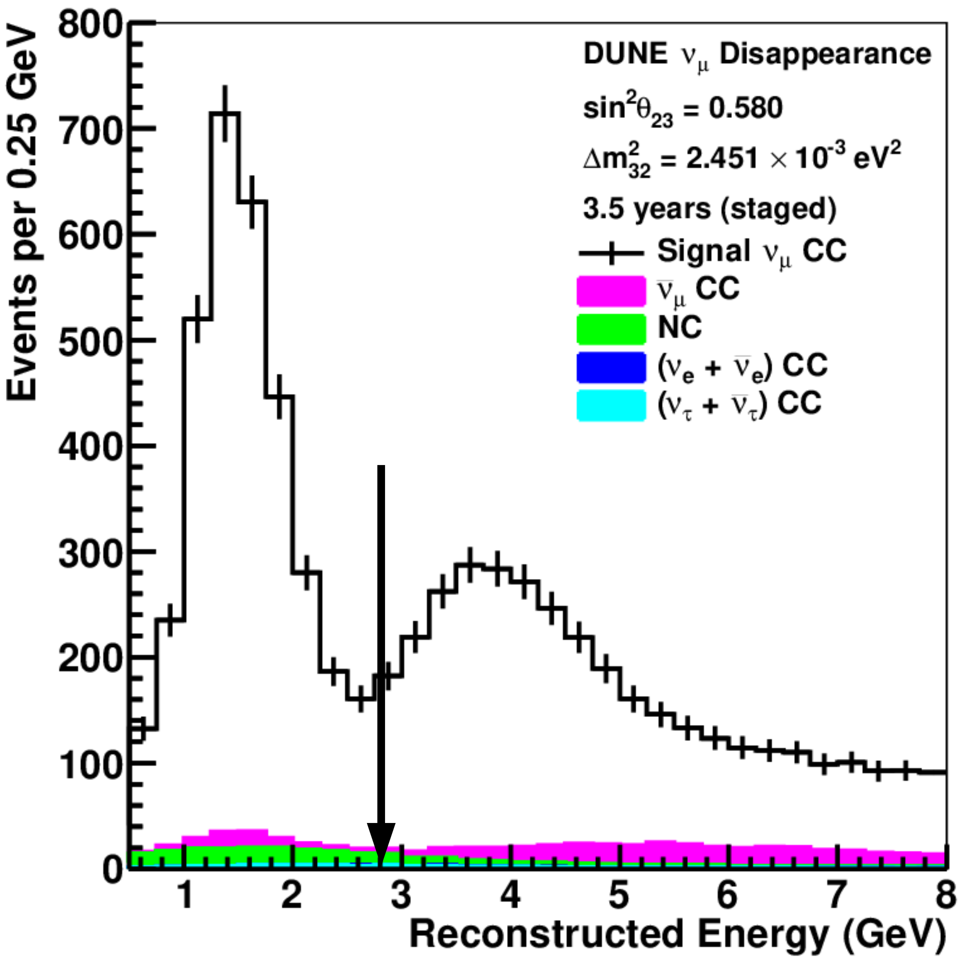




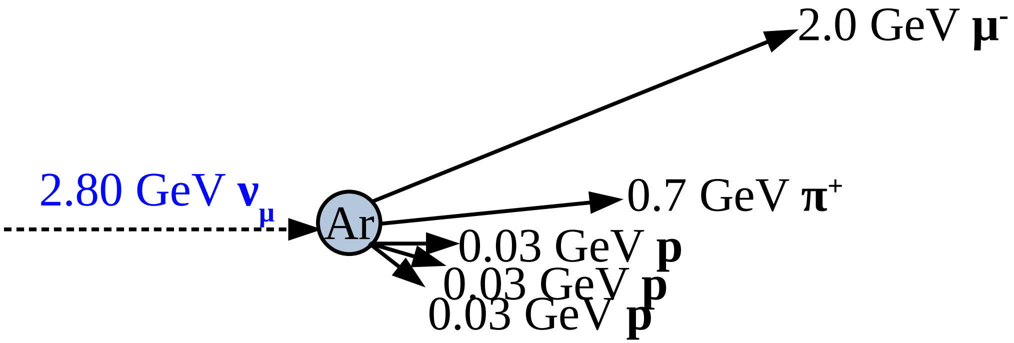
Cross section uncertainties affect reconstructed energy



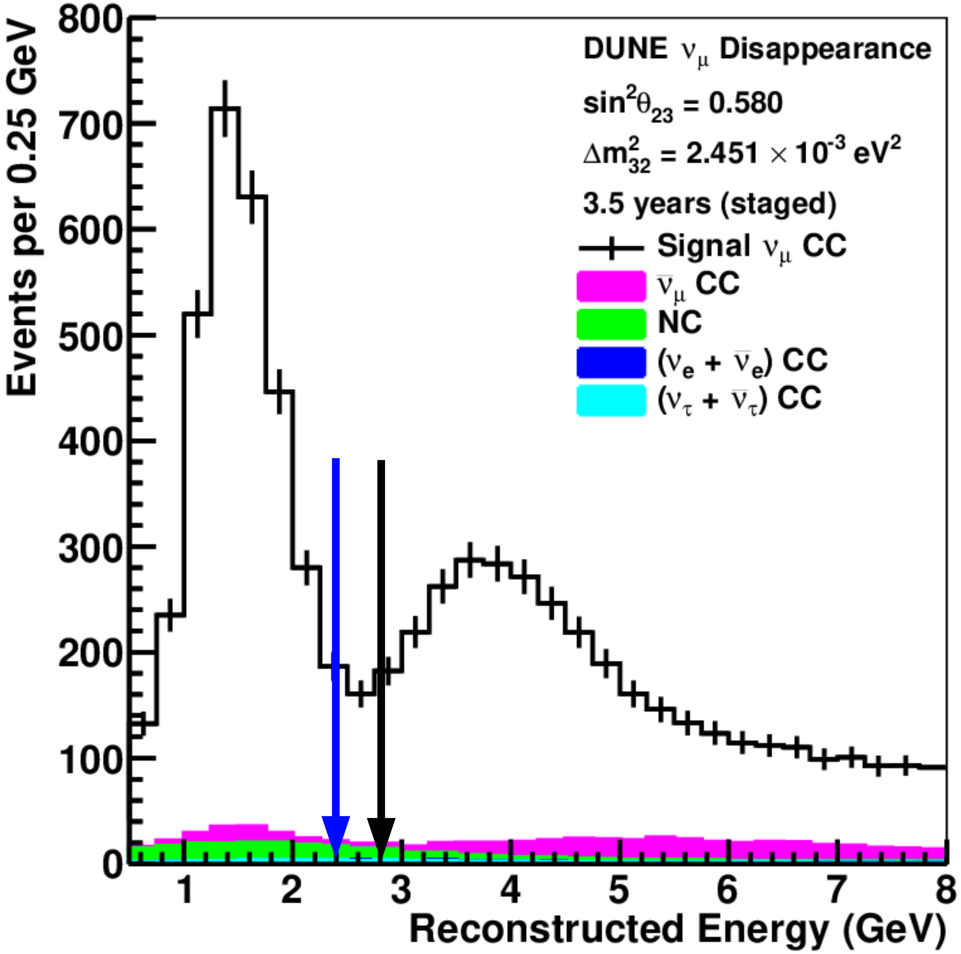
- Depending on the interaction process, it might be that all of the final-state particles are visible, above threshold, and easily reconstructed



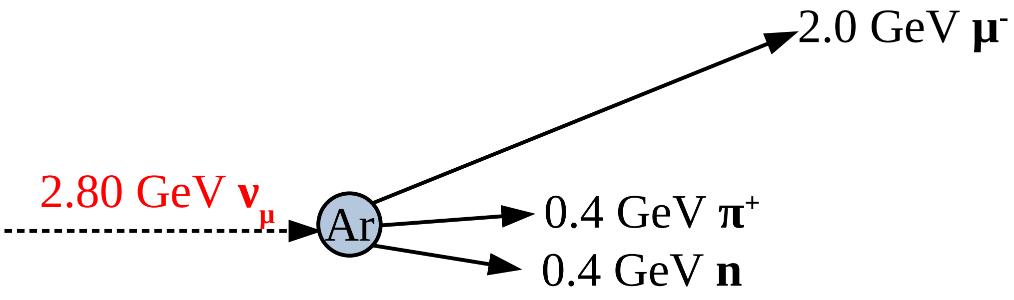
Cross section uncertainties affect reconstructed energy



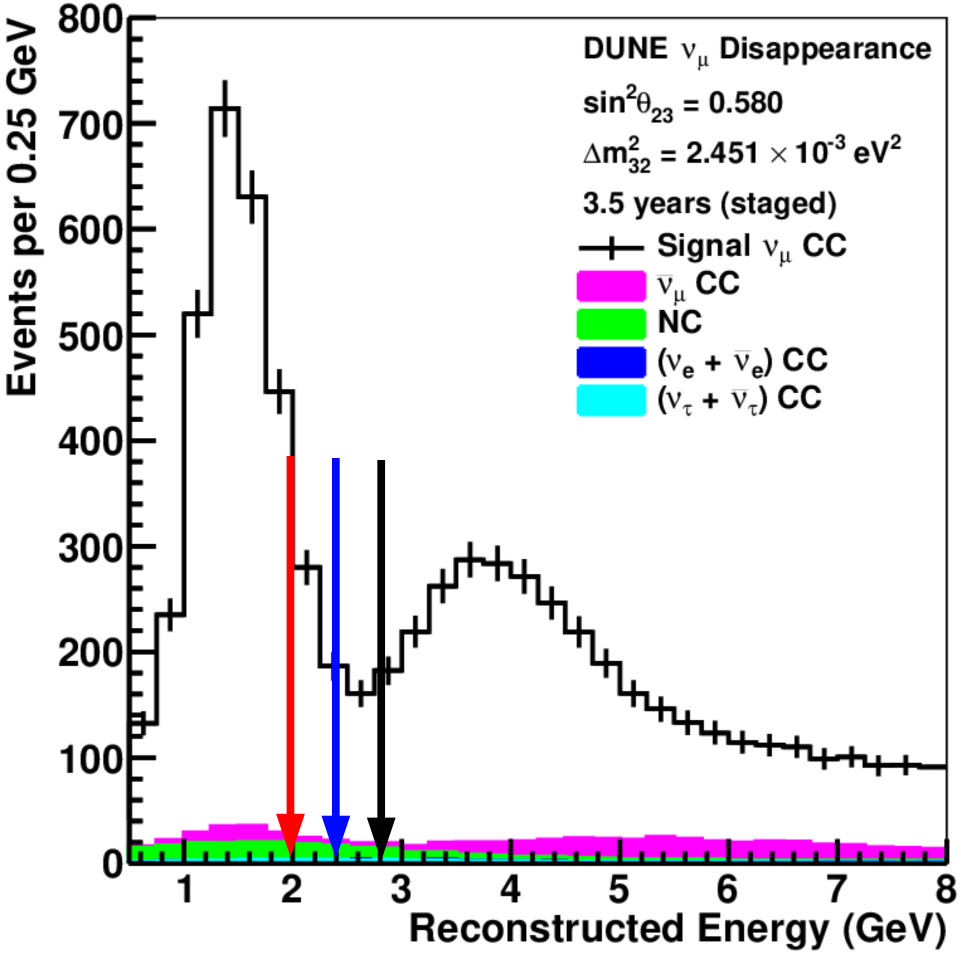
- But charged pion rest masses are typically not seen, and hadronic showers have large stochastic fluctuations in visible energy
- Due to FSI, several soft protons may be ejected, which are below tracking threshold, and affected by large recombination in LAr



Cross section uncertainties affect reconstructed energy

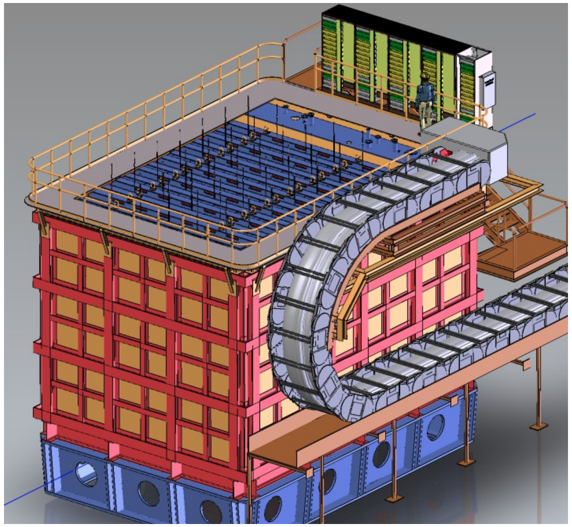


- Neutrons may not be detected at all, or may initiate a hadronic shower
- As a result, the same neutrino can have very different reconstructed energy depending on the specific interaction process and the final-state kinematics



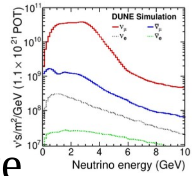
Oscillation analysis with ND-LAr

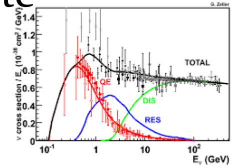
ND-LAr data

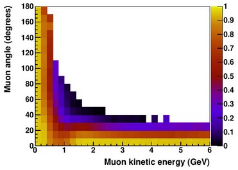


extrapolate

Flux model
Interaction model
Detector model

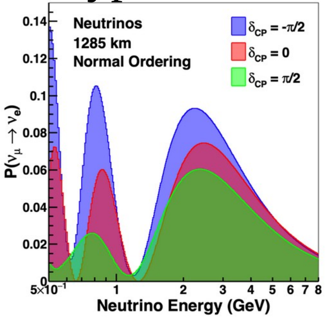




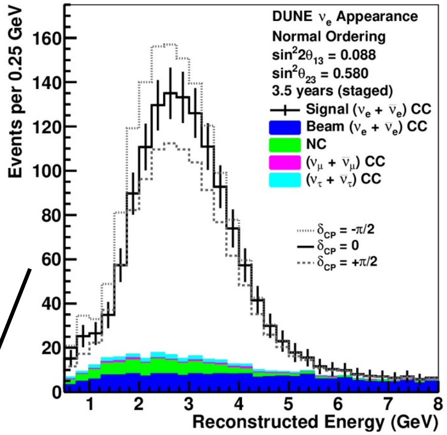


x

Oscillation hypothesis



FD prediction



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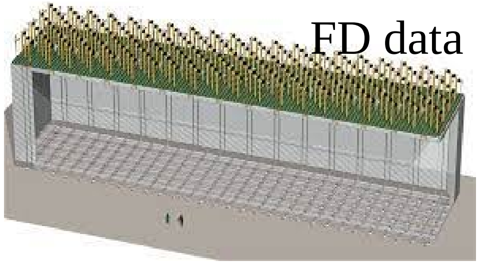
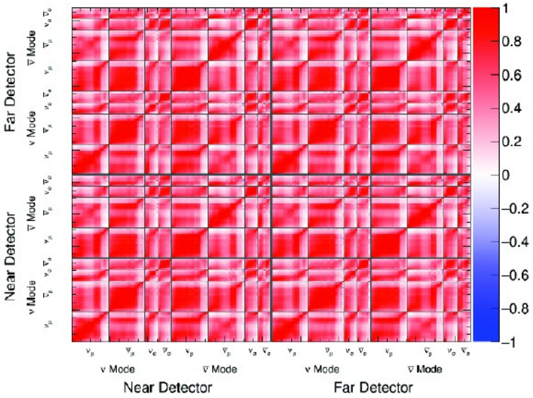
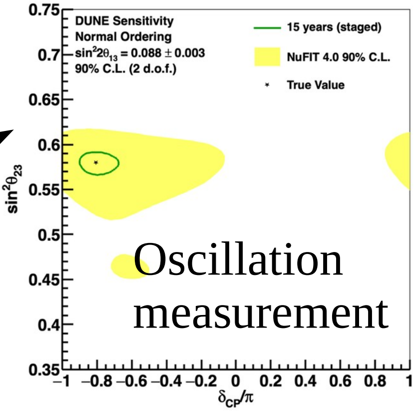




Systematics

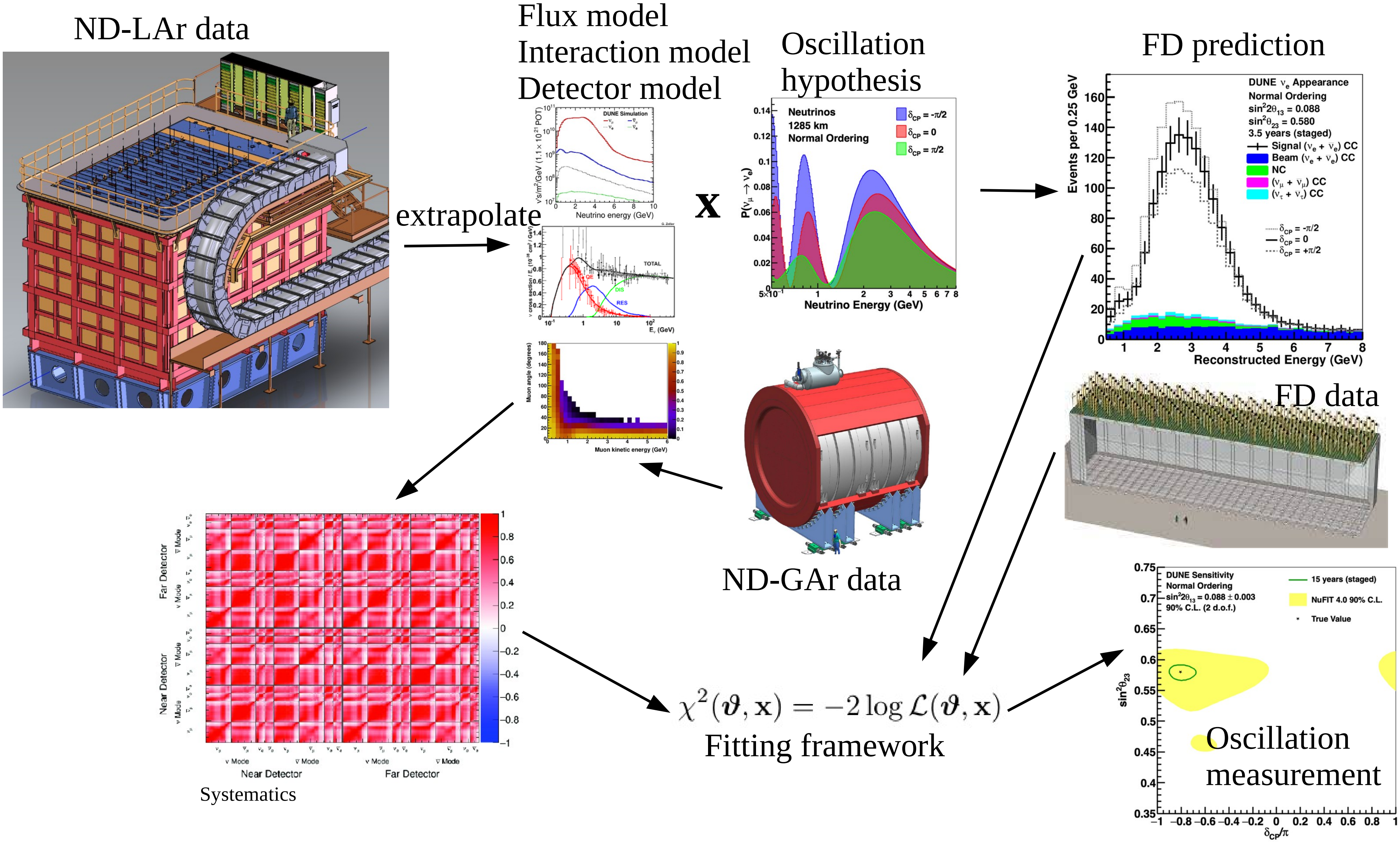
$$\chi^2(\boldsymbol{\vartheta}, \mathbf{x}) = -2\log\mathcal{L}(\boldsymbol{\vartheta}, \mathbf{x})$$

Fitting framework



Oscillation measurement

Oscillation analysis with ND-GAr



ND-LAr data

extrapolate

Flux model
Interaction model
Detector model

x

Oscillation hypothesis

FD prediction

ND-GAr data

FD data

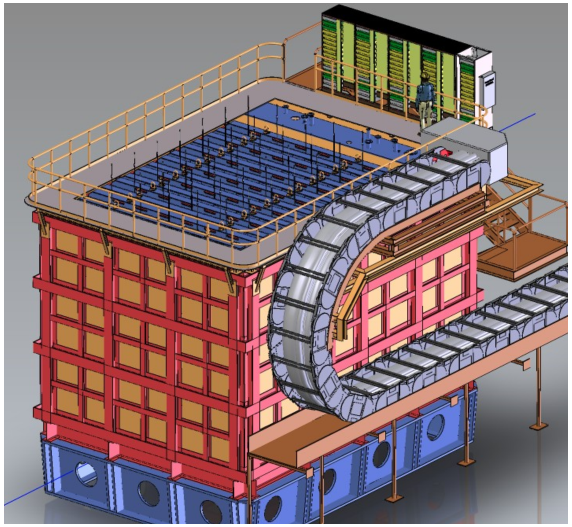
Systematics

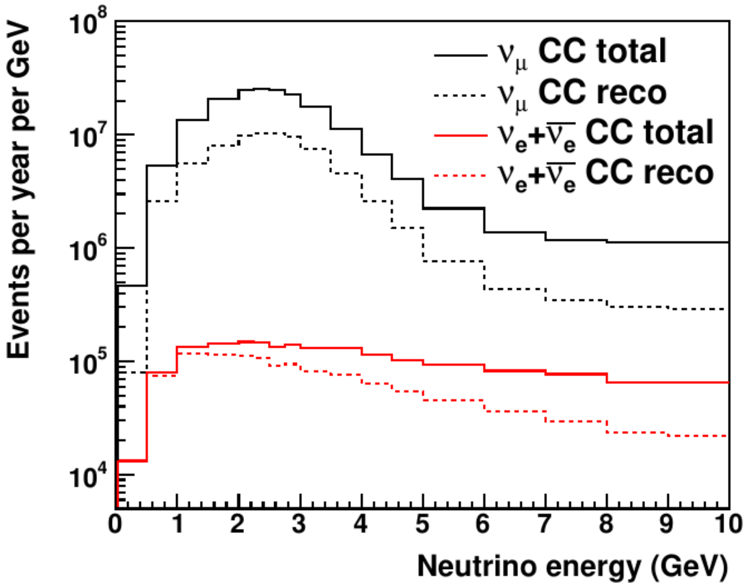
$$\chi^2(\boldsymbol{\vartheta}, \mathbf{x}) = -2\log\mathcal{L}(\boldsymbol{\vartheta}, \mathbf{x})$$

Fitting framework

Oscillation measurement

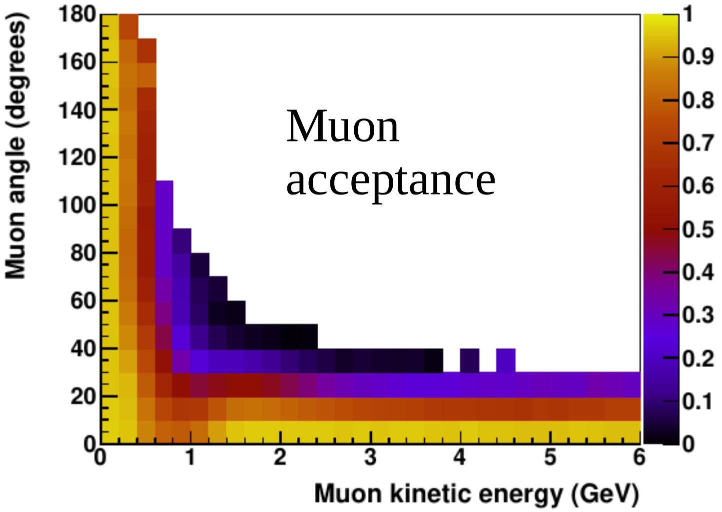
ND-LAr is critical for predicting the FD-LAr spectra

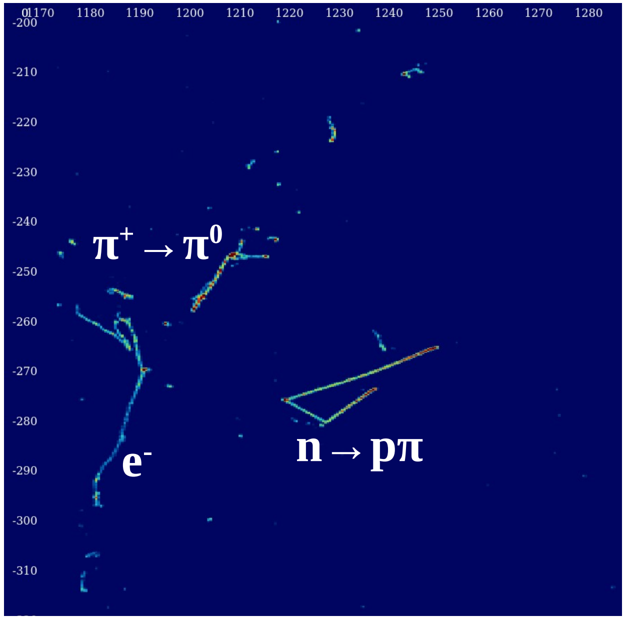




- ND-LAr gives us a direct measurement of neutrino interactions in LAr
  - Same beam
  - Same target
  - Very similar detector response
- Can be extrapolated to the FD, especially using PRISM off-axis measurements
- ND-LAr will accumulate ~50M interactions per MW-yr → can study these events in great detail

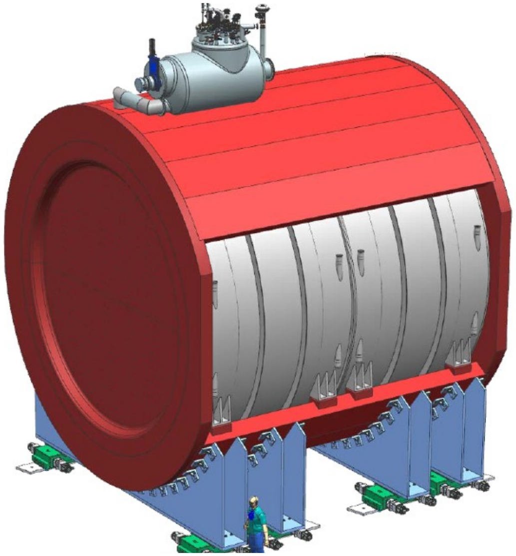
ND-LAr has several key limitations that make extrapolation challenging

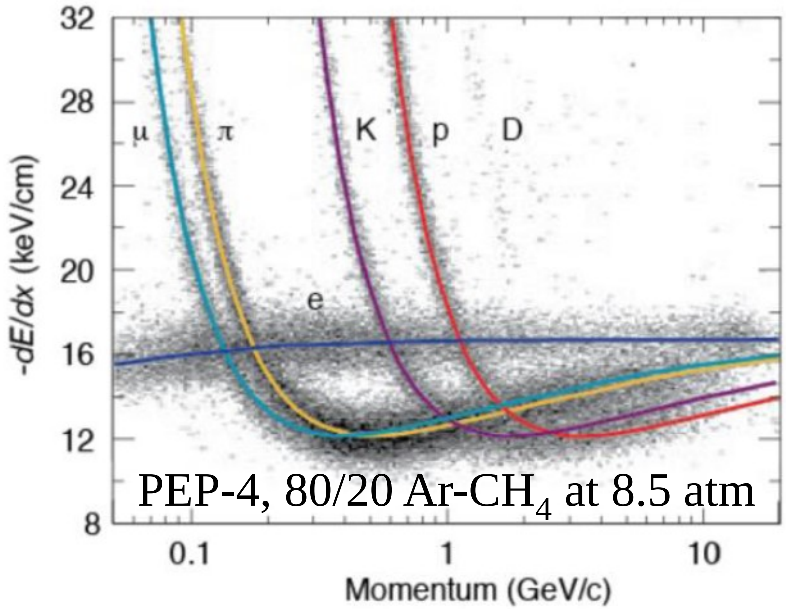




- ND-LAr is not a 4π detector
  - FD has ~uniform acceptance, so corrections are required
- ND-LAr has relatively high thresholds to protons
  - Nuclear effects modify E_{rec}, but produce very soft nucleons
- ND-LAr is relatively dense
  - Hadrons typically scatter, showers make exclusive measurements of hadrons difficult

Requirements to constrain critical 2nd-order effects in ND-LAr

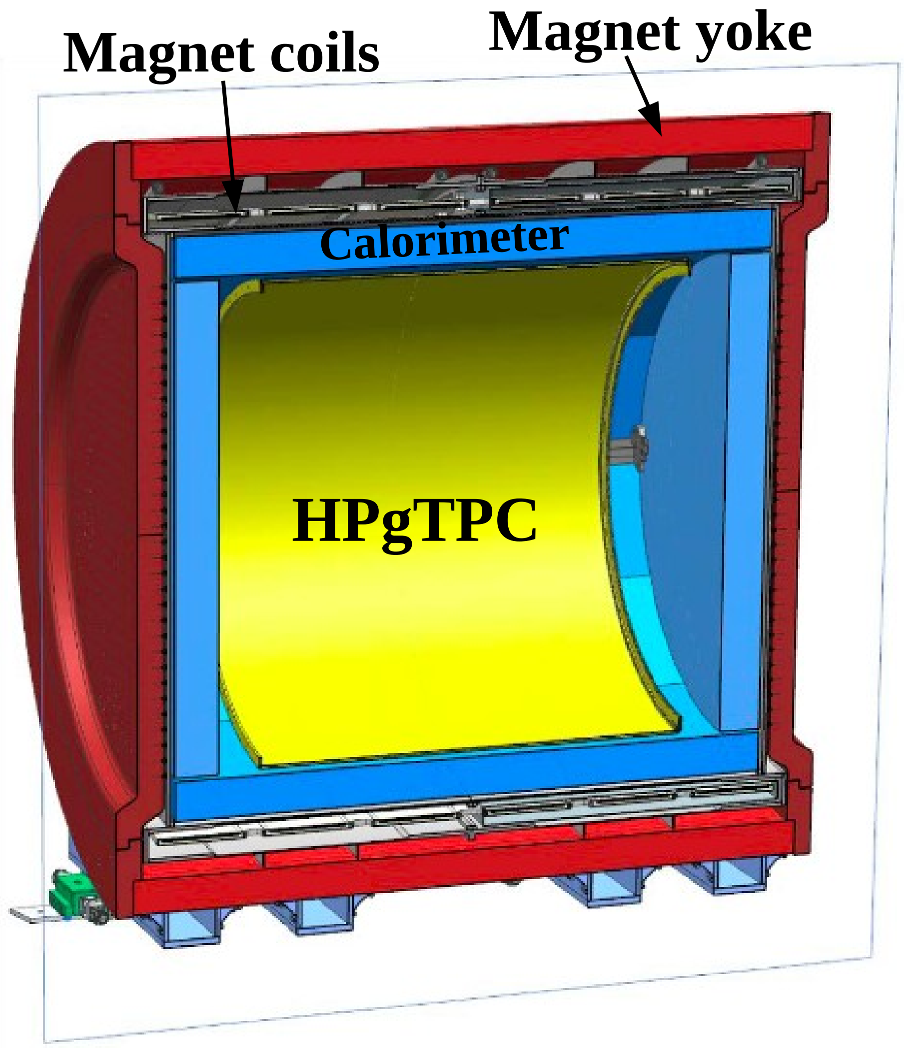




PEP-4, 80/20 Ar-CH$_4$ at 8.5 atm

- Argon target
  - Uncertainties due to A-extrapolation would dwarf any constraints
- 4π acceptance
  - Directly measure the acceptance in ND-LAr by comparing with a 4π detector with the same nuclear target
- Long interaction lengths, low thresholds, excellent hadron PID
  - Cleanly separate exclusive final states and measure hadron kinematics

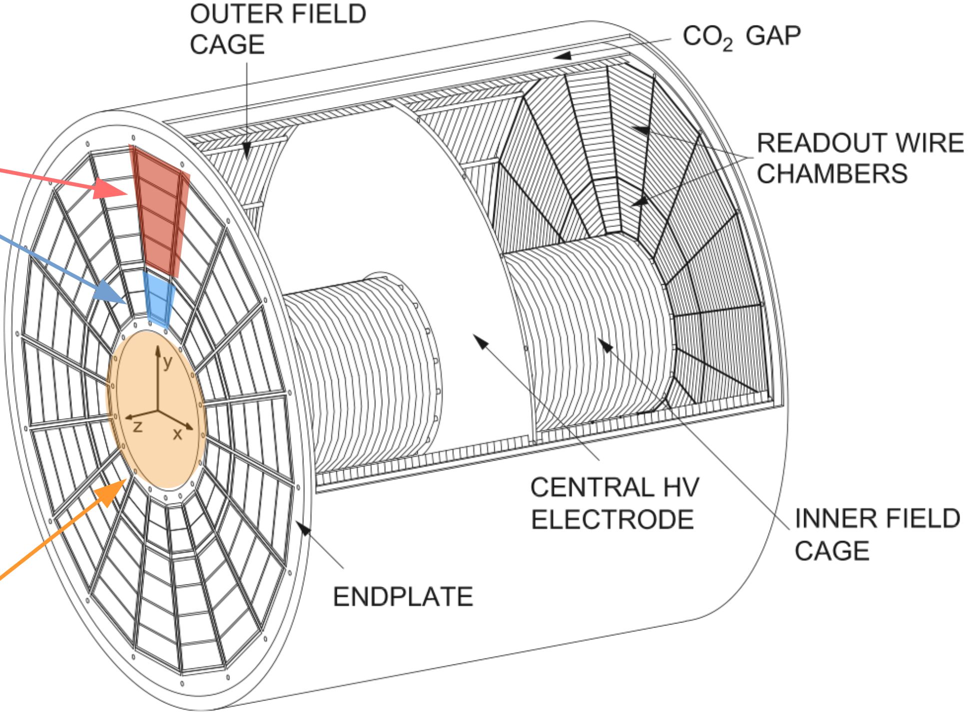
ND-GAr concept: magnetized gas TPC + calorimeter



- High-pressure gaseous argon TPC (**HPgTPC**)
  - 10bar Ar gas mix
  - O(1 ton) fiducial mass
- **Calorimeter** based on CALICE R&D
- **Magnet**: solenoid with partial return yoke (SPY)
  - 0.5 T central field
  - Acts as a pressure vessel for HPgTPC

HPgTPC concept: based on ALICE

- 5m length + 5m diameter
- Option to re-use existing ALICE outer and inner readout chambers, or build new ones
- New systems required:
  - Field cage & HV feedthrough
  - Pressure vessel
  - Central readout chamber x2



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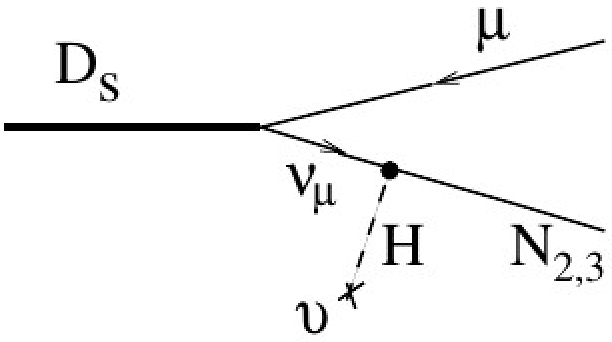
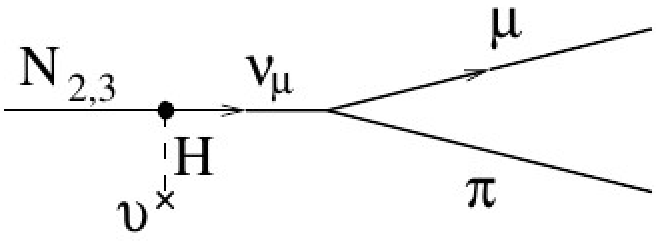
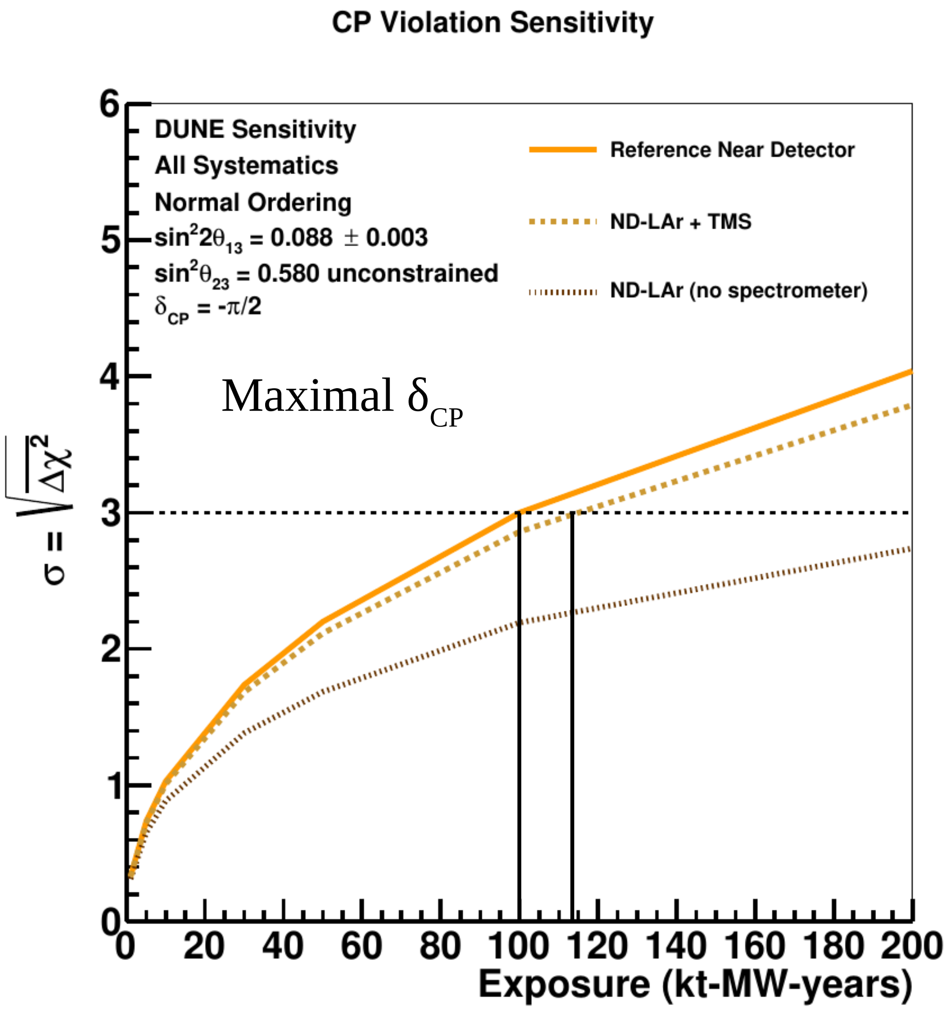
Broadening the DUNE physics program: BSM searches





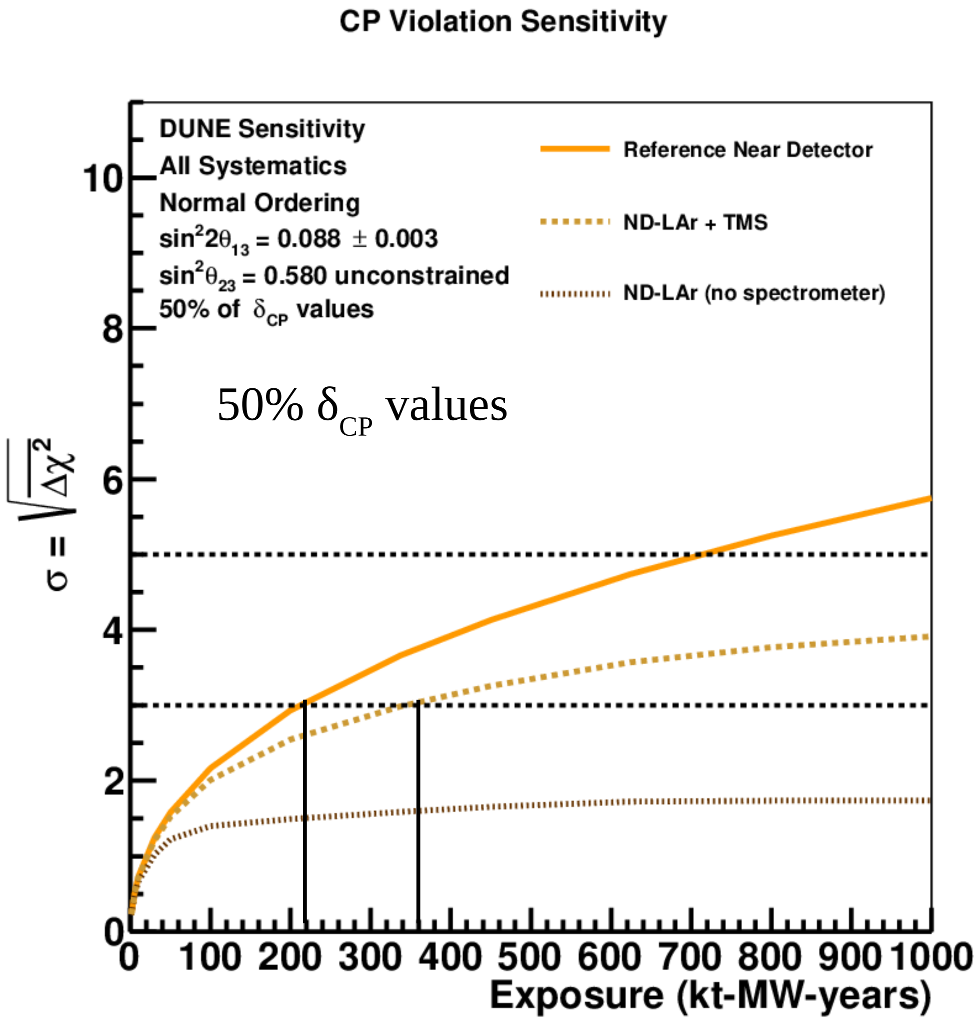
- Neutral particles (e.g. HNL, production & decay above) produced in the beamline can **decay** in the ND
- Signal rate scales with *volume*, but backgrounds from SM neutrino interactions scale with *mass* → a low-mass detector is a huge win
- Low threshold of ND-GAr will also reject neutrino backgrounds with nuclear break-up

ND-GAr constraints are not needed for 3σ maximal CPV measurement



- Early physics milestones (mass ordering & maximal CPV) are limited by FD statistics
- Sufficient to model the extrapolation to the FD, and eat a systematic
- Delay in 3σ observation of maximal CPV ($\delta = -\pi/2$) due to not having ND-GAr is ~15%

ND-GAr is critical for measuring CPV over 50% of δ_{CP} values

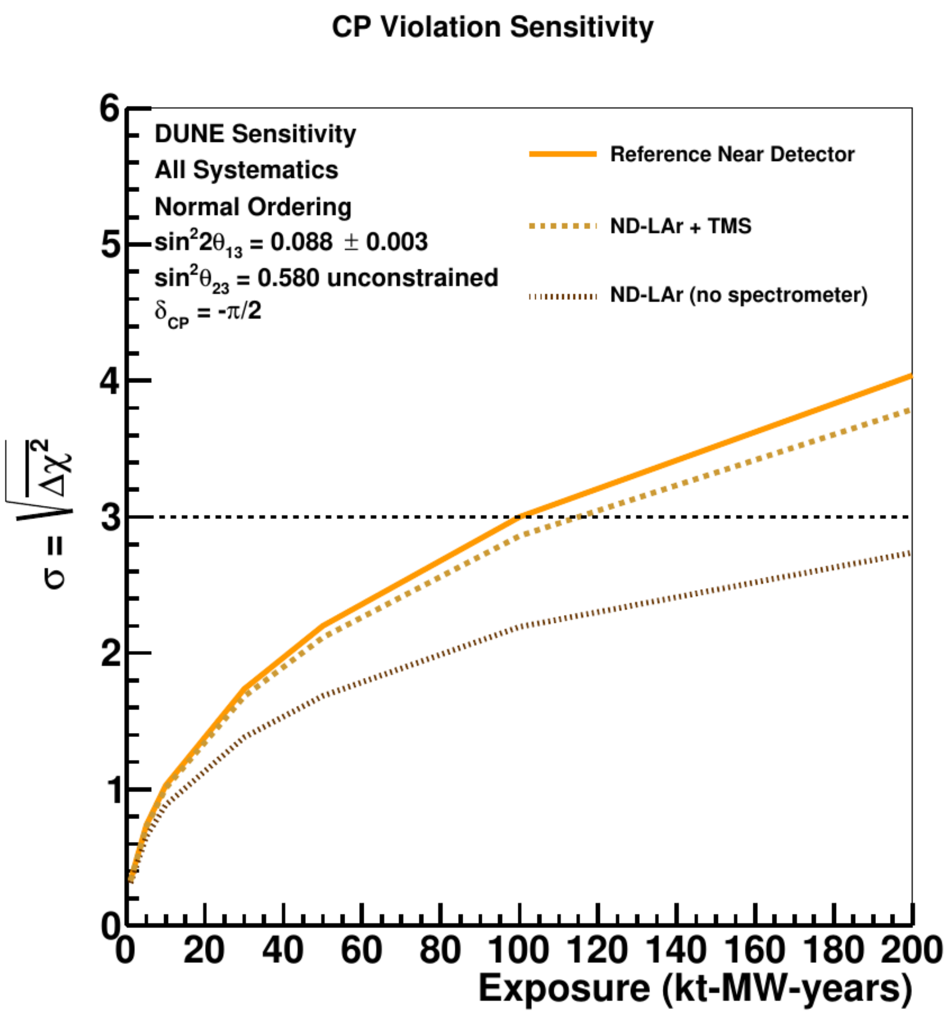


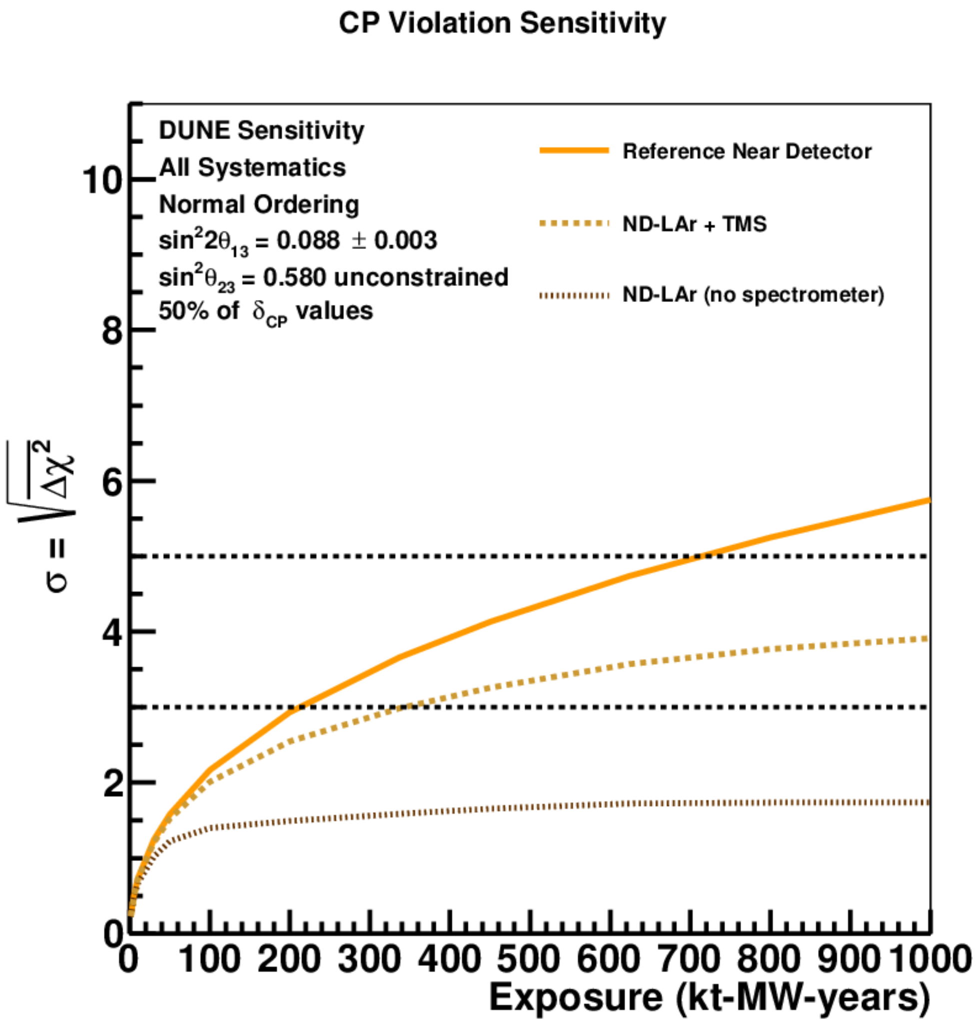
- Longer-term physics goal → higher precision measurements
- Required systematics become more stringent, and it is no longer sufficient to model 2nd-order effects
- ND-GAr constraint reduces the exposure required for 3σ by ~50%, and is required to ever reach 5σ

Summary

- Near Detector is critical for constraining systematic uncertainties in DUNE
- ND-LAr is fundamental → extrapolate ND data to FD
- But extrapolating ND→FD requires models, and constraining this model space requires a more capable argon near detector with 4π acceptance, low thresholds, long interaction lengths, and superior PID → ND-GAr
- Staging is feasible because precision constraints are not required until ~200 kt-MW-yrs FD exposure

Thank you


CP Violation Sensitivity
DUNE Sensitivity
All Systematics
Normal Ordering
$\sin^2 2\theta_{13} = 0.088 \pm 0.003$
$\sin^2\theta_{23} = 0.580$ unconstrained
$\delta_{CP} = -\pi/2$
Reference Near Detector
ND-LAr + TMS
ND-LAr (no spectrometer)
$\sigma = \sqrt{\Delta\chi^2}$
0
1
2
3
4
5
6
0
20
40
60
80
100
120
140
160
180
200
Exposure (kt-MW-years)


CP Violation Sensitivity
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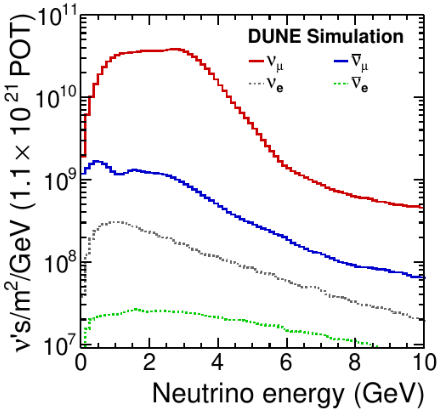
Reference Near Detector
ND-LAr + TMS
ND-LAr (no spectrometer)
$\sigma = \sqrt{\Delta\chi^2}$
0
2
4
6
8
10
0
100
200
300
400
500
600
700
800
900
1000
Exposure (kt-MW-years)

Backups

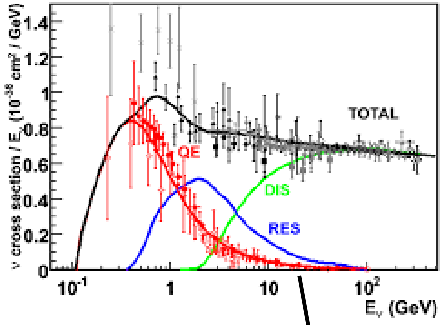
How the oscillation analysis works

Flux model



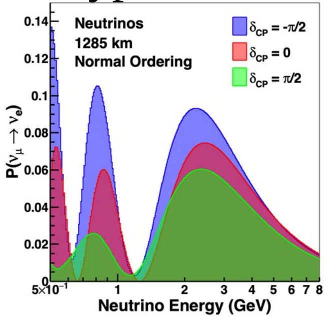
x

Interaction model
Detector model

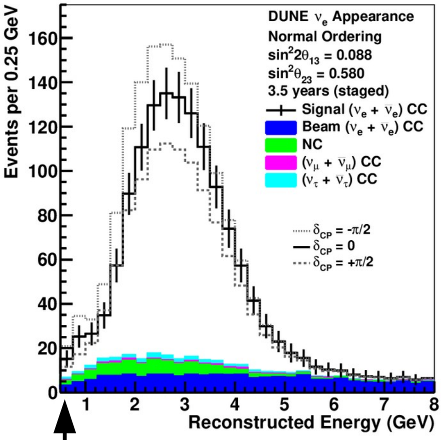


x

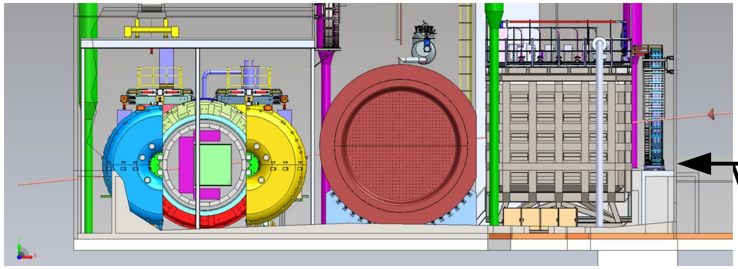
Oscillation hypothesis



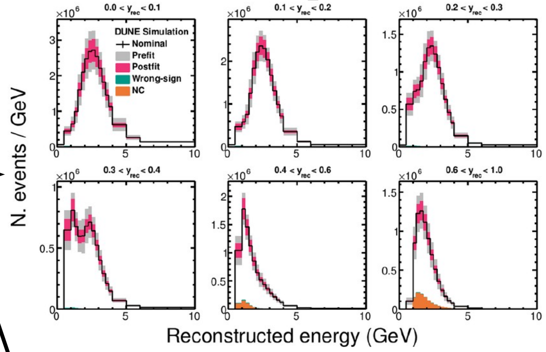
FD prediction



ND data



ND prediction



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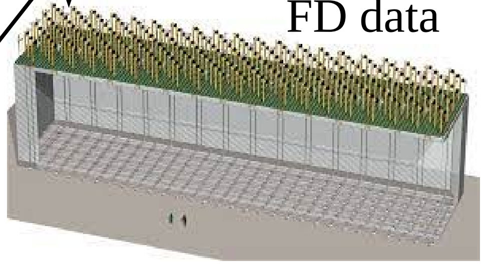
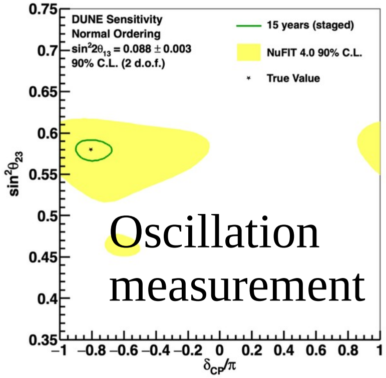


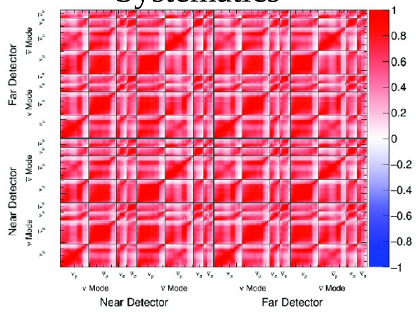


Oscillation measurement

$$\chi^2(\boldsymbol{\vartheta}, \mathbf{x}) = -2\log\mathcal{L}(\boldsymbol{\vartheta}, \mathbf{x})$$

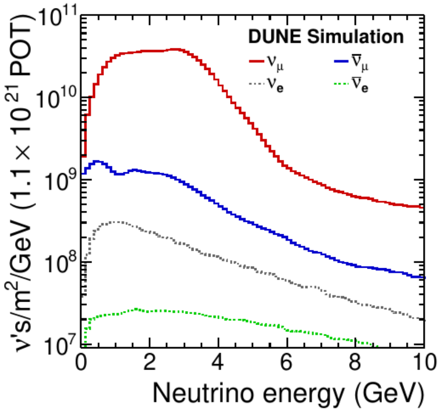
Fitting framework

Systematics



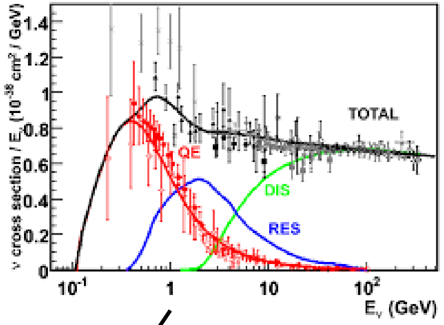
Oscillation analysis with no ND

Flux model



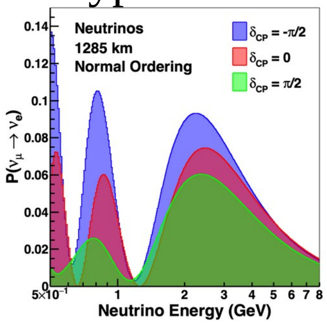
x

Interaction model
Detector model

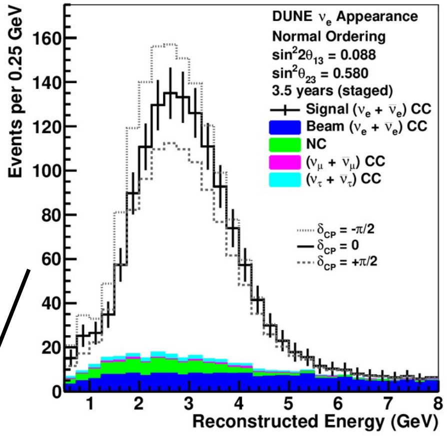


x

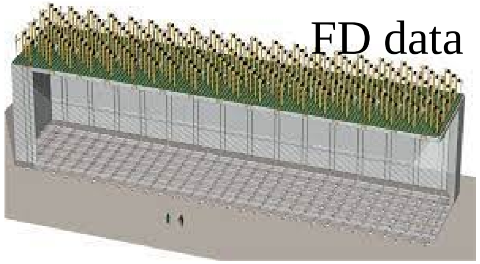
Oscillation hypothesis

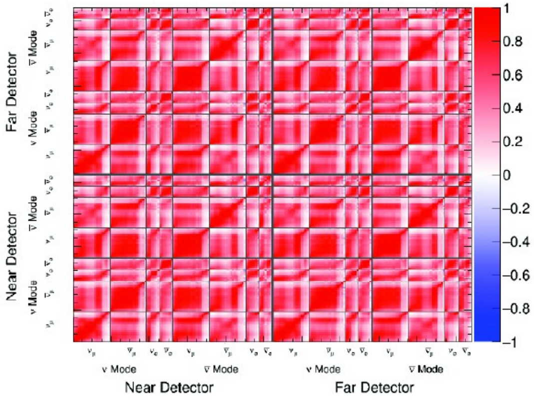


FD prediction



FD data

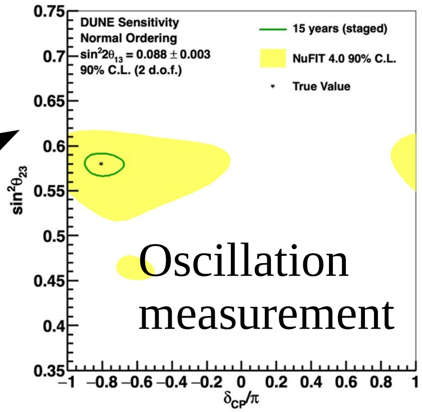




Systematics

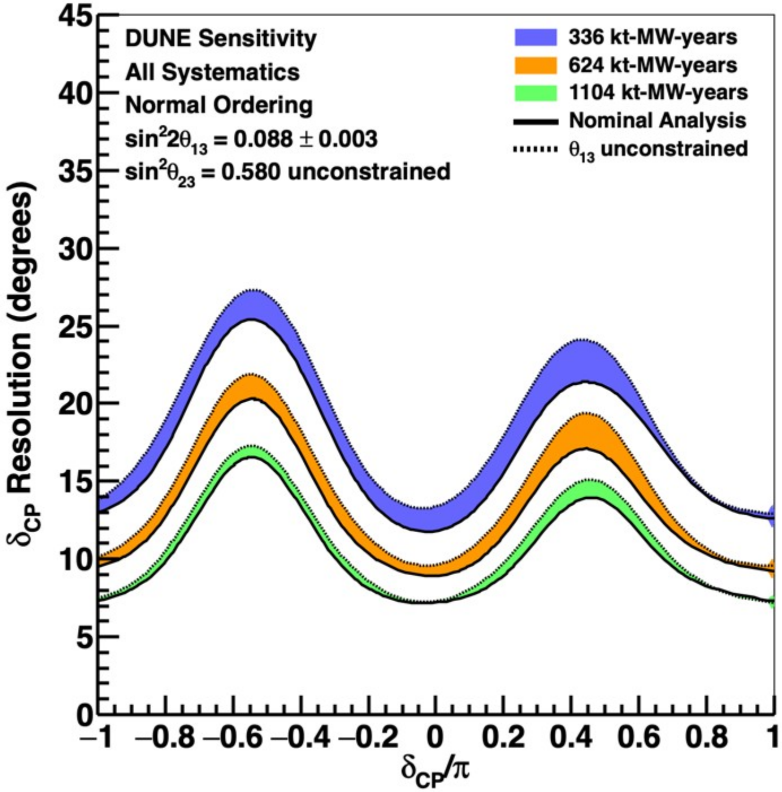
$$\chi^2(\boldsymbol{\vartheta}, \mathbf{x}) = -2\log\mathcal{L}(\boldsymbol{\vartheta}, \mathbf{x})$$

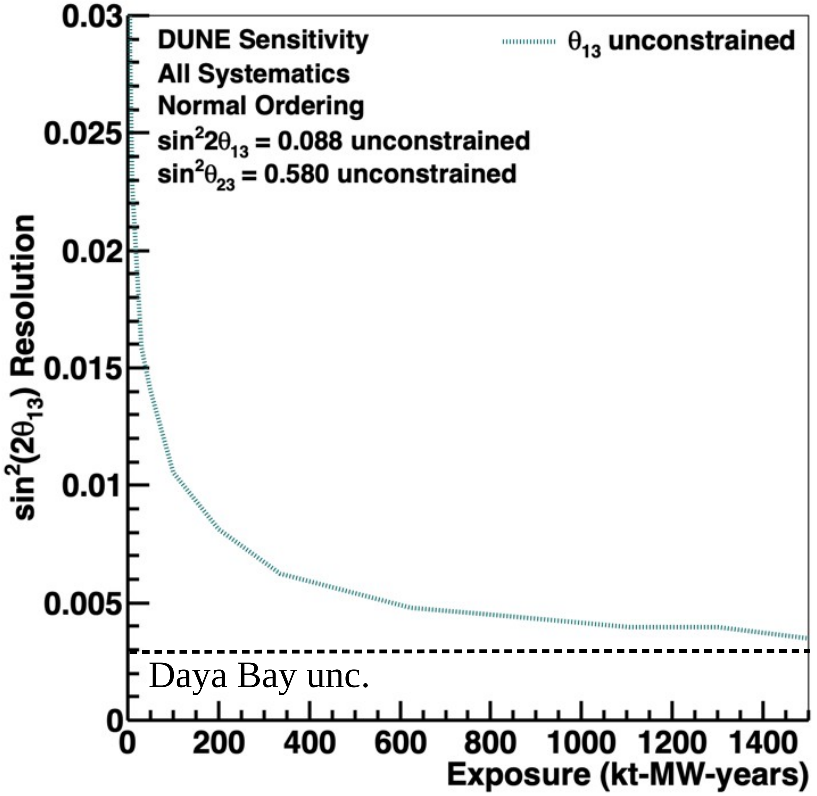
Fitting framework



Oscillation measurement

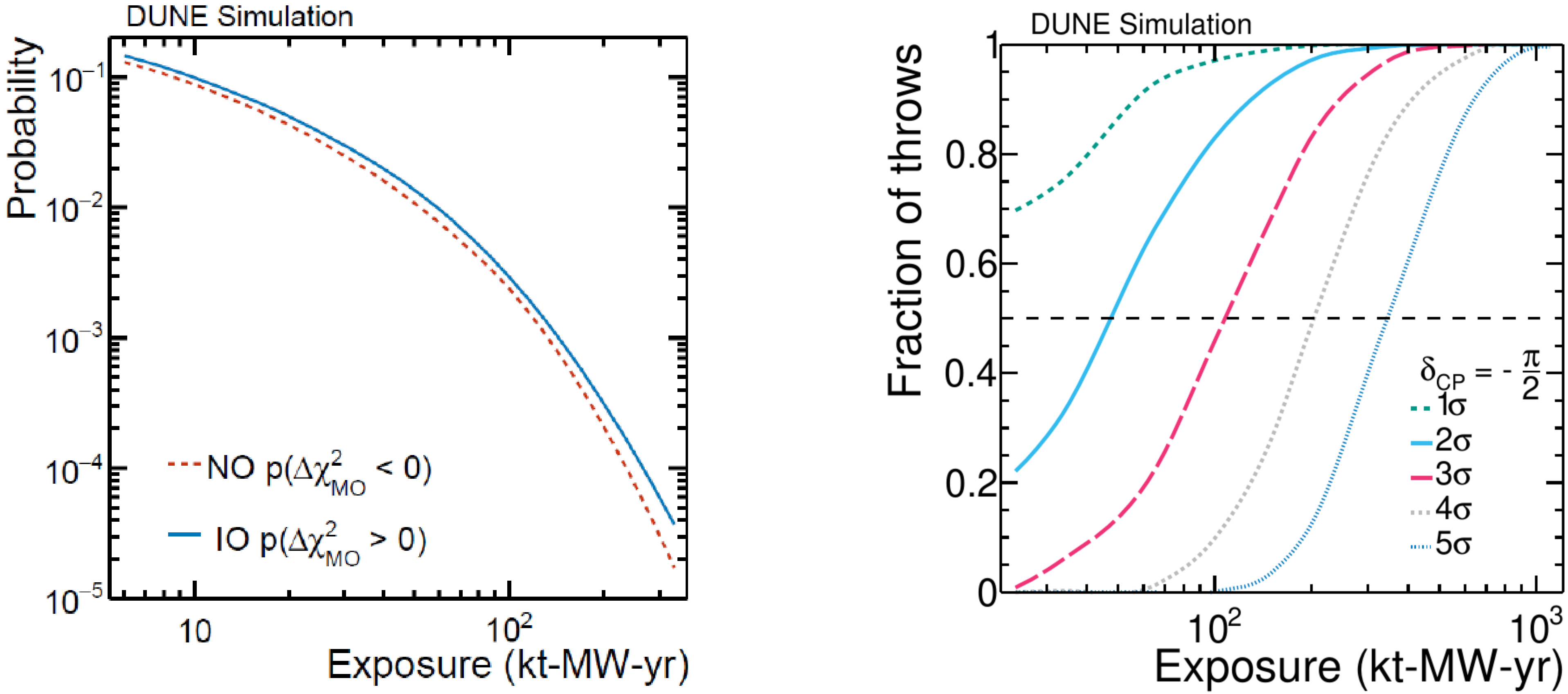
Physics goals: long-term





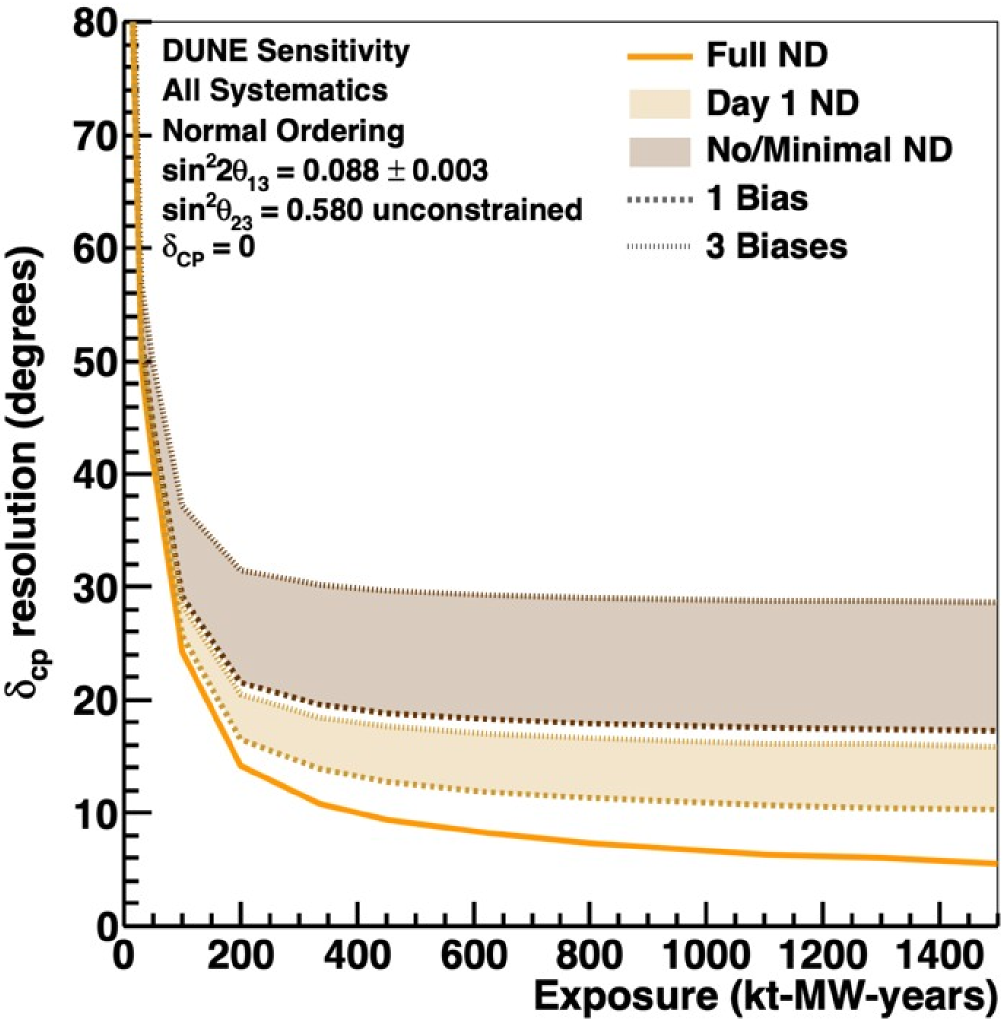
- Precision oscillation physics: 10-15° measurement of δ_{CP}, world-leading θ_{23} and Δm^2_{32}, θ_{13} competetive with reactor experiments
- These goals require >600 kt-MW-yrs exposure, and few-percent systematic constraints from highly-capable near detector

Physics goals: short-term



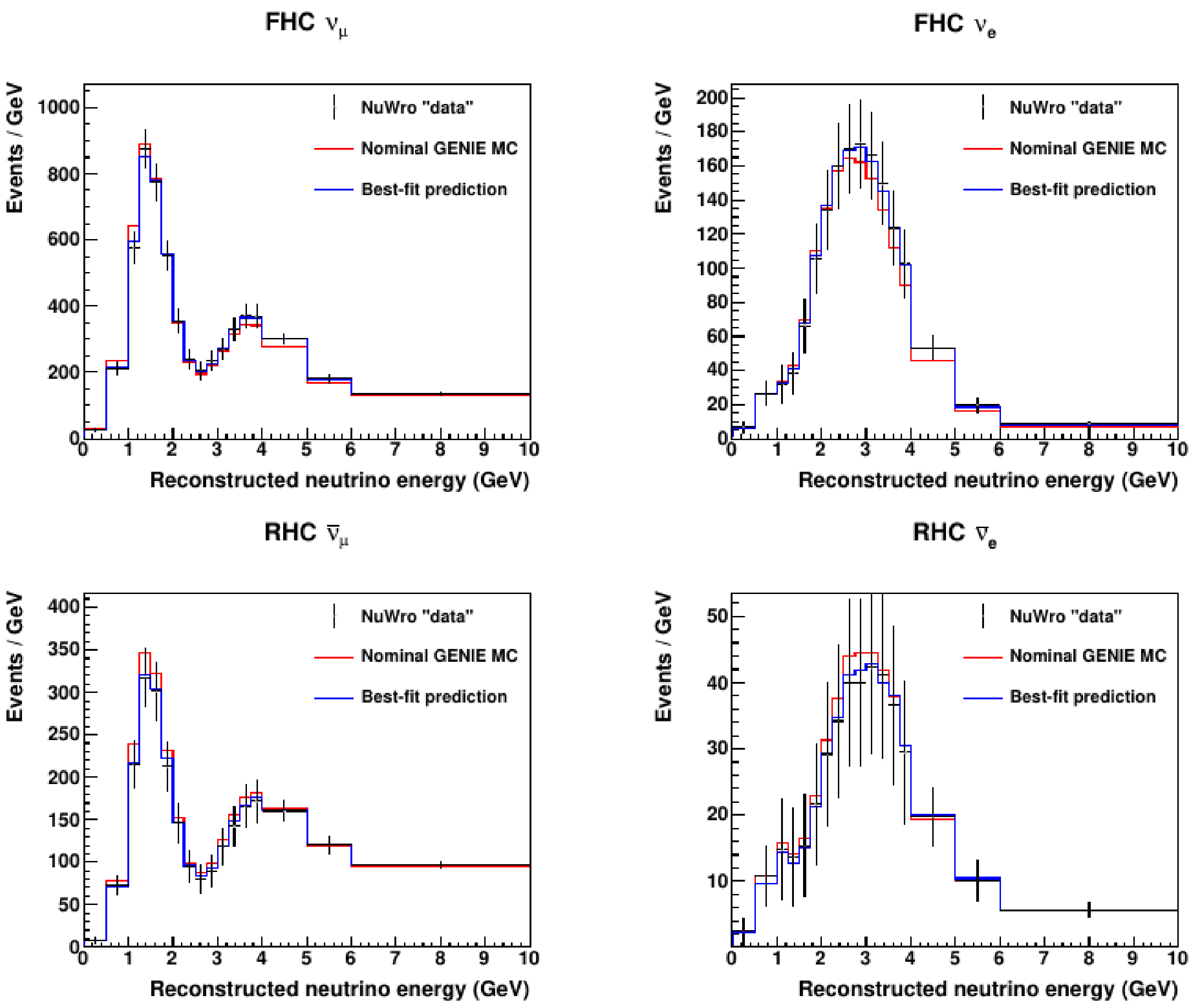
- DUNE can measure the mass ordering unambiguously (<1% mis-ID) with ~50 kt-MW-yrs exposure, and is sensitive to maximal CPV at 3σ with ~100 kt-MW-yrs
- Required systematic constraints are similar to existing experiments, and can be achieved with ND-LAr + TMS

Out-of-model effects limit δ resolution at ~200 kt-MW-yrs



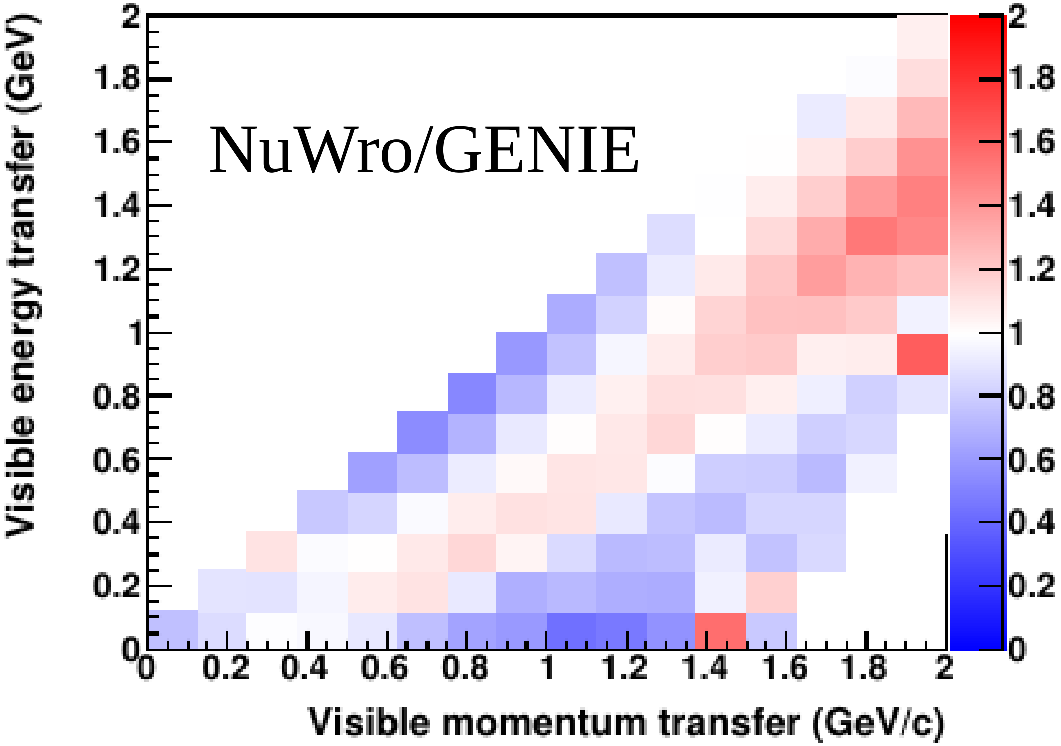
- Biases from modeling effects are taken as additional uncertainties on the measured value of δ_{CP}
- These biases can be mitigated with additional ND measurements
- For very short exposures < 100 kt-MW-yrs, we are statistics limited and the bias can be adequately mitigated with ND-LAr+TMS

Out-of-model systematics with mock data: NuWro sample



- FD is easily able to fit the NuWro mock data, but best-fit gets δ wrong by ~17°
- This is small compared to early resolution (~30-60°), but not small compared to ultimate resolution (7-15°)

Mitigating this 17° bias with D1ND



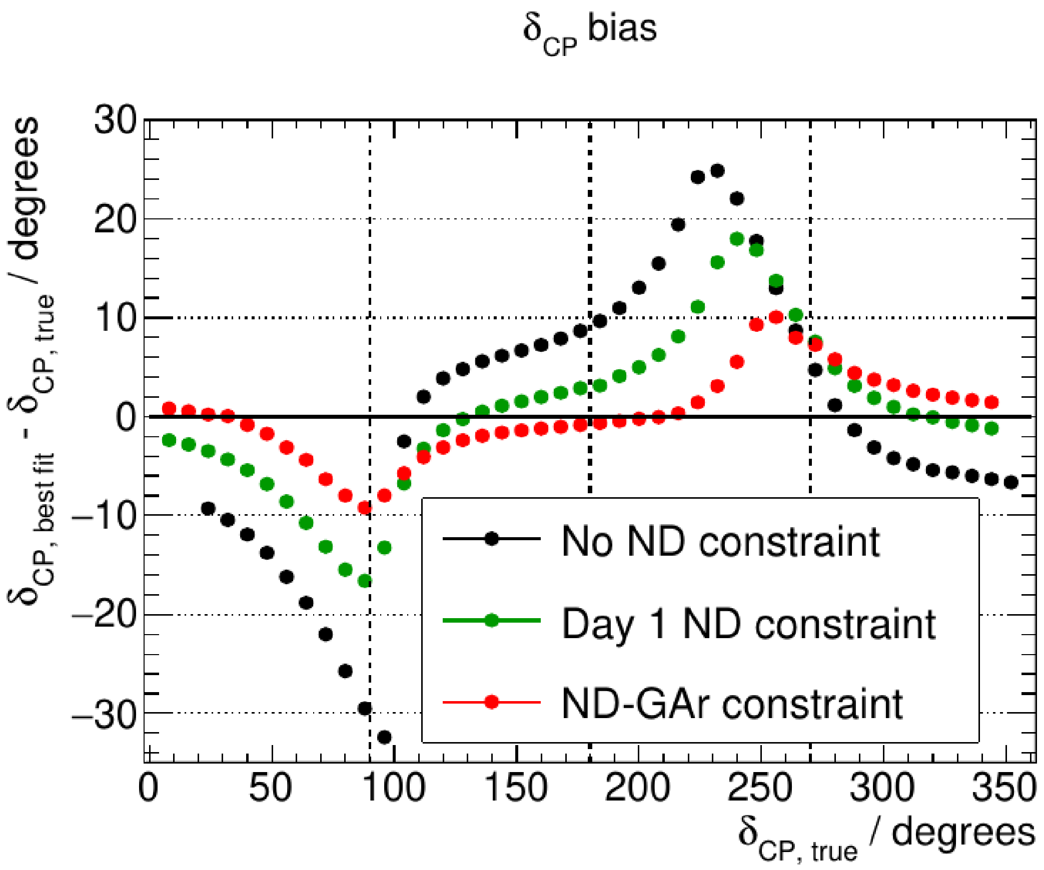
$$E_{vis} = T_p + E_\pi$$

$$Q^2 = 2E_\nu(E_{lep} - p_{lep}\cos\theta_{lep}) - m_{lep}^2$$

$$p_{vis} = \sqrt{Q^2 + E_{vis}^2}$$

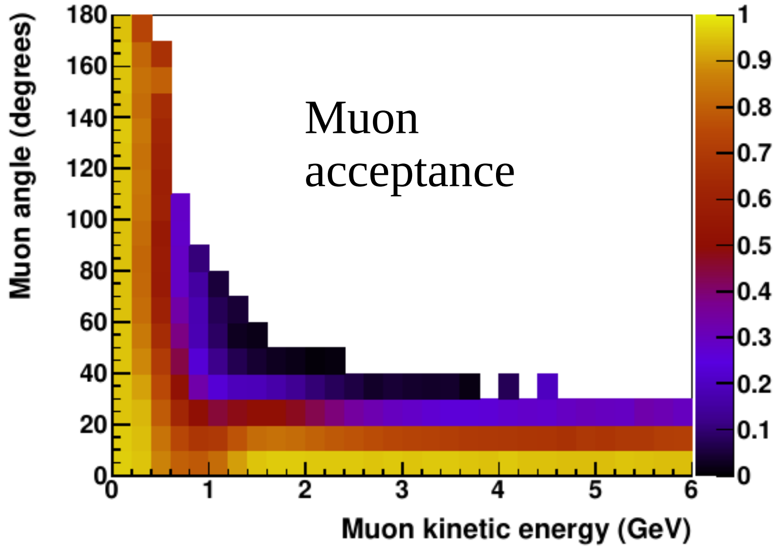
- Measure CC events in a 2D kinematic space: “E_{vis}” & “p_{vis}”
- Hadronic system is required to be contained in LAr
- Muon is measured by range in LAr + spectrometer (TMS)
- ND “data” / GENIE is used to generate weights that are applied to FD prediction

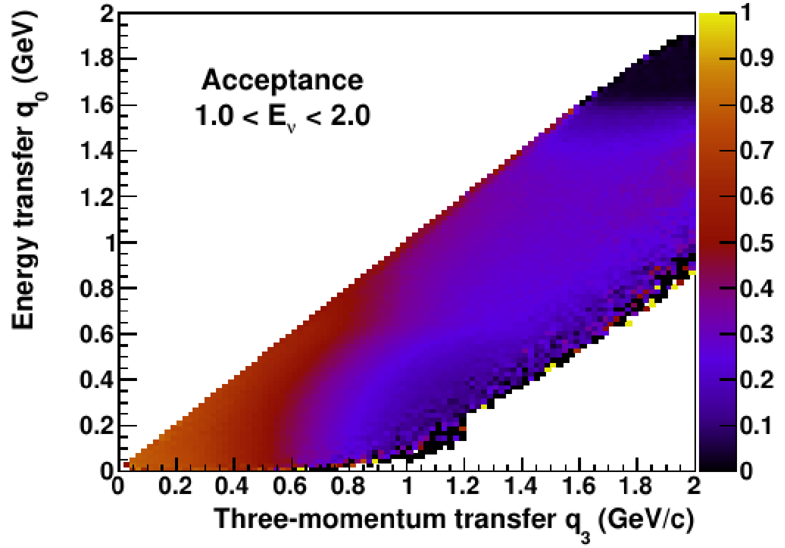
Reduced bias with ND-derived weights to FD prediction



- Use of ND data reduces bias from ~17° to ~9° (D1ND) to <4° (Full ND)
- This bias is treated as an additional systematic added in quadrature to CPV sensitivities

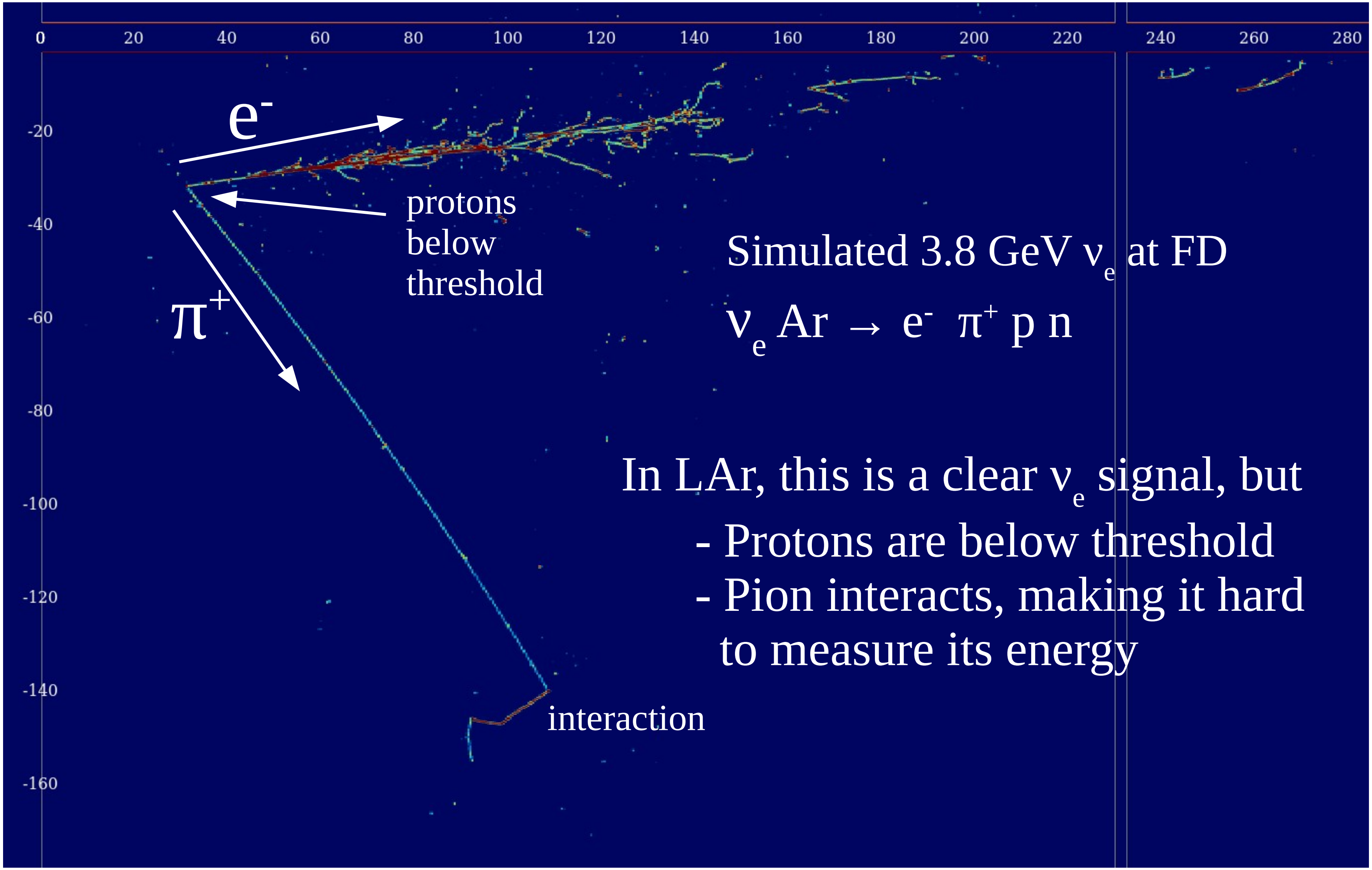
ND-LAr is not a 4π detector





- Muons travel ~5m/GeV in LAr
- In FD, muons are mainly reconstructed by range
- Containing a 3 GeV muon would require a >15m detector
    - Channel count O(100s million)
    - Much larger conventional facilities
- We rely on sampling the kinematic phase space (ε > 0 everywhere), but we must correct for the non-uniform acceptance

Energy reconstruction is sensitive to the final state kinematics



Simulated 3.8 GeV ν_e at FD

$\nu_e \, \mathrm{Ar} \rightarrow e^- \, \pi^+ \, p \, n$

In LAr, this is a clear ν_e signal, but

- Protons are below threshold
- Pion interacts, making it hard to measure its energy

ND-GAr drift and gas mixture

- Drift distance of 2.5 m for two-side readout, or 5 m for single-side readout
- Gas mixture still being optimized, but for 90% Ar + 10% CH_4 at 10 atm:
  - ~1 ton fiducial mass
  - ~1.6M ν_μ CC interactions per year at 1.2 MW
  - ~28k ν_e CC interactions per year at 1.2 MW
  - 97% of neutrino interactions on argon
  - Electric field of 400 V/cm → drift velocity of ~3 cm/μs

Expected event rates in ND-GAr

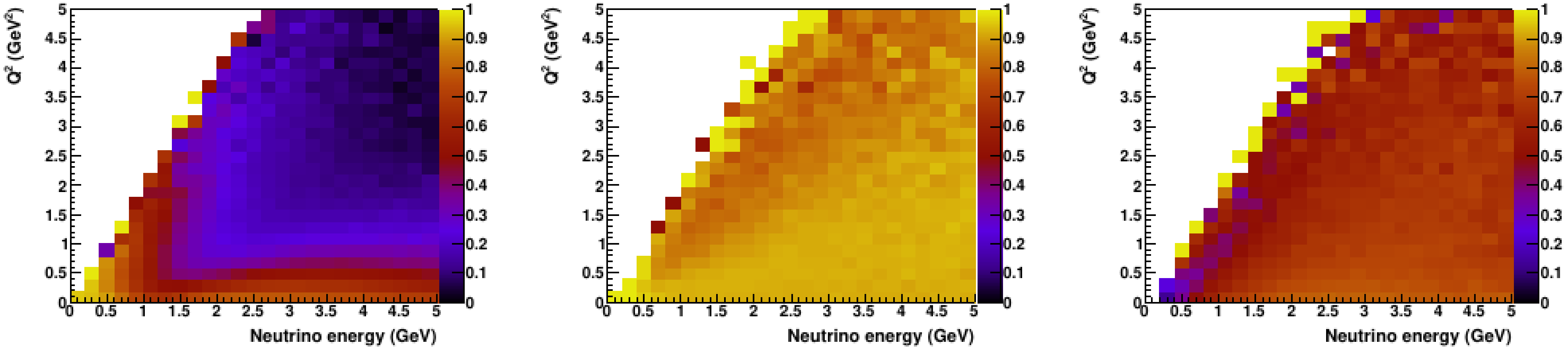
FHC Beam		**RHC Beam**	
Process	**Events/ton/yr**	**Process**	**Events/ton/yr**
All ν_μ-CC	1.64×10^6	All $\bar{\nu}_\mu$-CC	5.26×10^5
CC 0π	5.85×10^5	CC 0π	2.36×10^5
CC $1\pi^\pm$	4.09×10^5	CC $1\pi^\pm$	1.51×10^5
CC $1\pi^0$	1.61×10^5	CC $1\pi^0$	4.77×10^4
CC 2π	2.10×10^5	CC 2π	5.21×10^4
CC 3π	9.28×10^4	CC 3π	1.66×10^4
CC K_s	1.20×10^4	CC K_s	2.72×10^3
CC $K^\pm$	4.57×10^4	CC $K^\pm$	4.19×10^3
CC other	1.27×10^5	CC other	1.62×10^4
All $\bar{\nu}_\mu$-CC	7.16×10^4	All ν_μ-CC	2.72×10^5
All NC	5.52×10^5	All NC	3.05×10^5
All ν_e-CC	2.85×10^4	All ν_e-CC	1.84×10^4
$\nu e \to \nu e$	170	$\nu e \to \nu e$	120

Expected performance of ND-GAr

Parameter	Value	Comments
Single hit resolution $\sigma_\perp$	250 μm	*$\perp$ to TPC drift direction
Single hit resolution $\sigma_\parallel$	1500 μm	*$\|$ to TPC drift direction
Two-track separation	1 cm	*
$\sigma(dE/dx)$	5%	*
μ reconstruction: σ_p/p	(2.9%, 14%)	(core, tails), ν_μ CC events, LBNF flux
μ σ_p/p vs. track length	(10%, 4%, 3%)	(core),(1,2,3 m), ν_μ CC events, LBNF flux
Angular resolution	0.8°	ν_μ CC events, LBNF flux
Energy scale uncertainty	$\lesssim$ 1%	*(by spectrometry)
Proton detection threshold	5 MeV	kinetic energy
ECAL energy resolution	$6\%/\sqrt{E(\text{GeV})} \oplus 1.6\%/E(\text{GeV}) \oplus 4\%$	
ECAL pointing resolution	10° at 500 MeV	

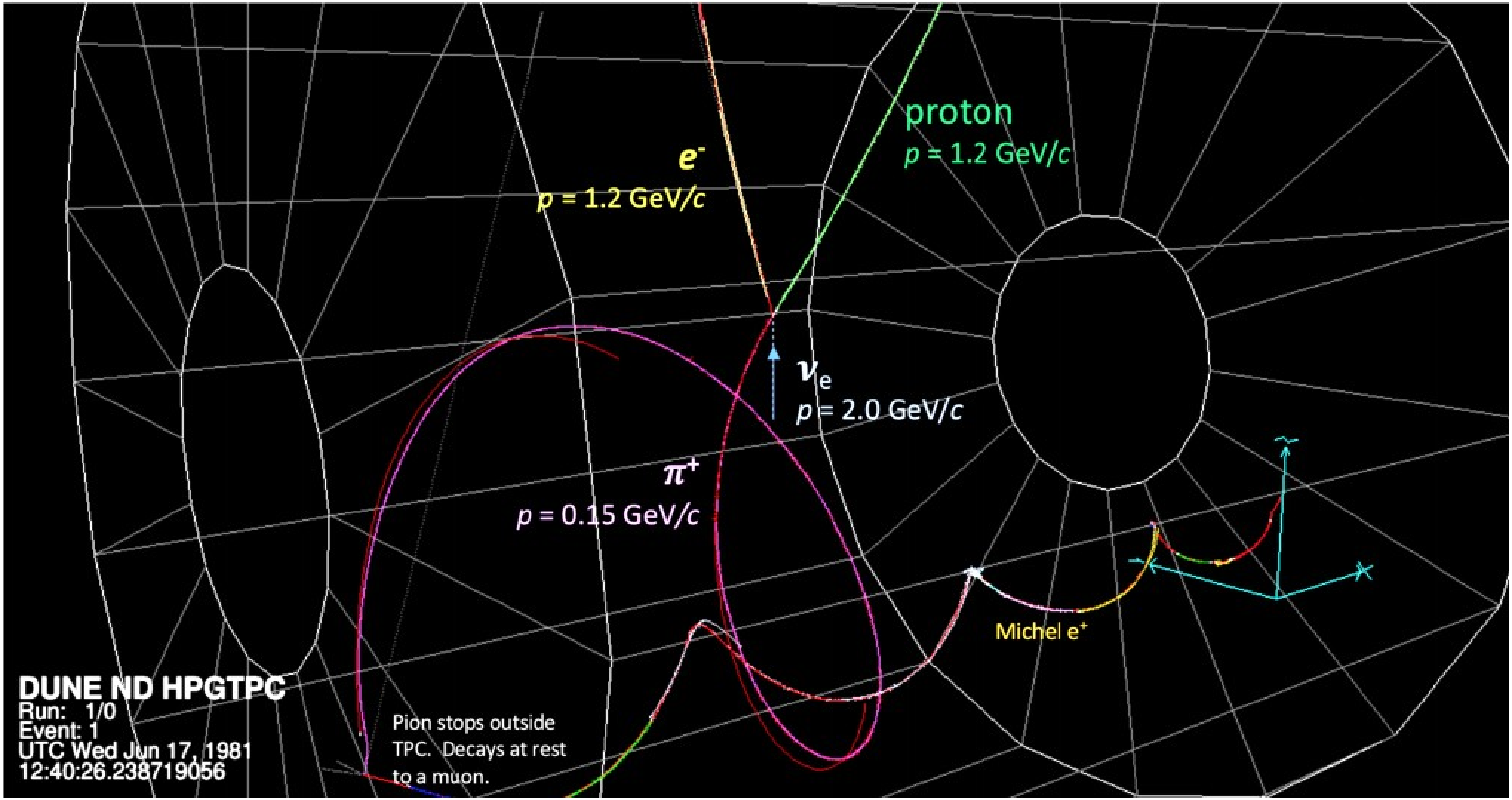
*based on extrapolation from ALICE and/or PEP-4

ν_μ CC acceptance in ND-LAr, ND-GAr, FD1-HD



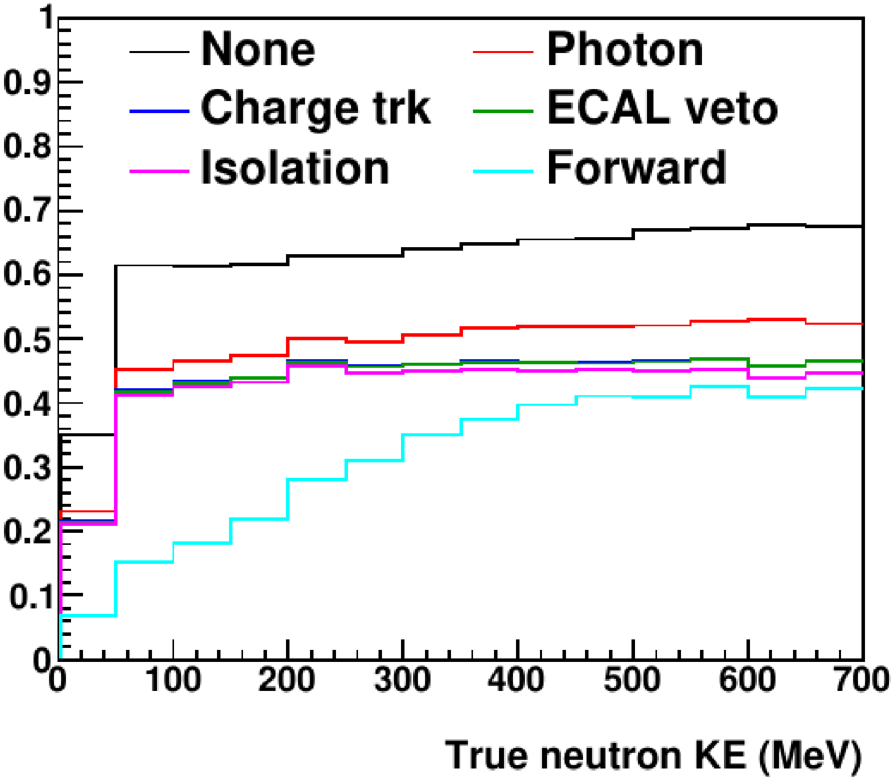
- FD has uniform acceptance over broad range of neutrino energy and four-momentum transfer (plot at right shows acceptance for reconstruction by range)
- ND-GAr has similar uniformity, higher overall acceptance
- ND-LAr has a cut-out that corresponds to high-angle muons with enough energy to exit detector

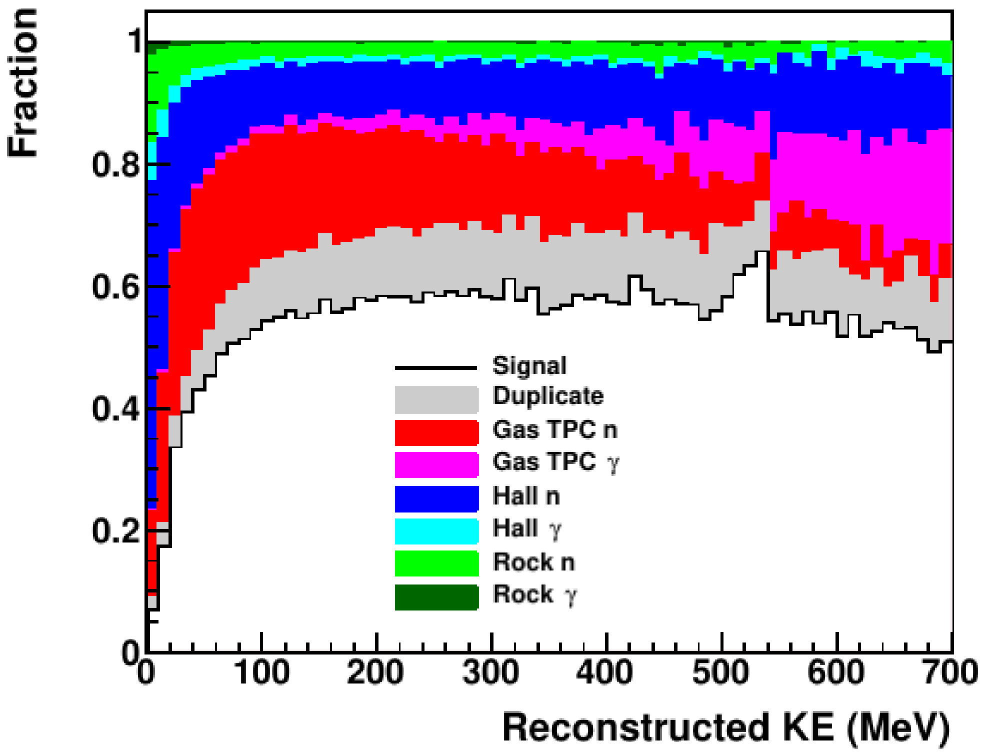
ν_e CC event display in ND-GAr



Pion stops outside TPC. Decays at rest to a muon.

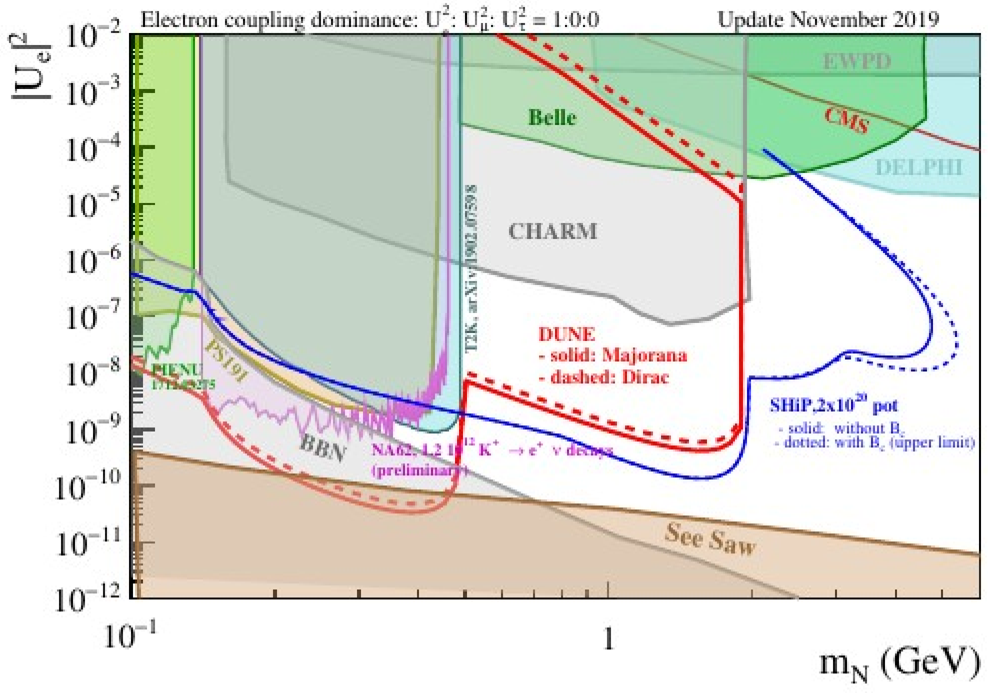
Neutron reconstruction in ND-GAr ECAL using time-of-flight

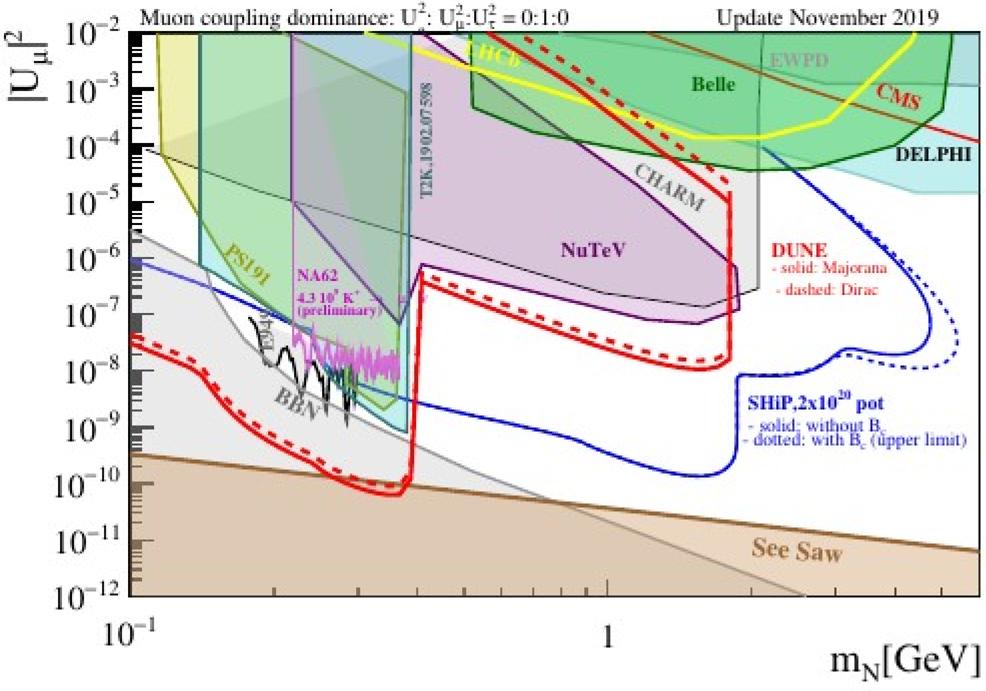




- Potential to measure neutrons from ν-Ar interactions directly using TOF in ND-GAr ECAL has been demonstrated with simulation
- For RHC inclusive antineutrino scattering, can achieve >50% purity with >40% efficiency; better performance can be achieved for some exclusive final states

Sensitivity to HNL with DUNE ND





- DUNE sensitivity (in red), compared with existing limits (shaded) and proposed SHiP experiment