More Independent CPV Measurements

Dual Calorimetry in Liquid Argon TPC

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

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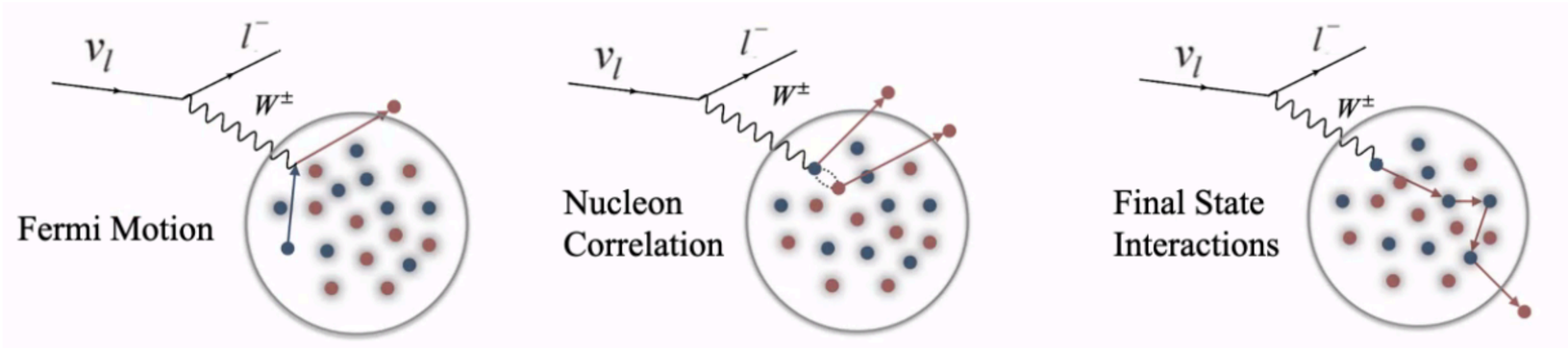
LBL Biweekly
Aug 19

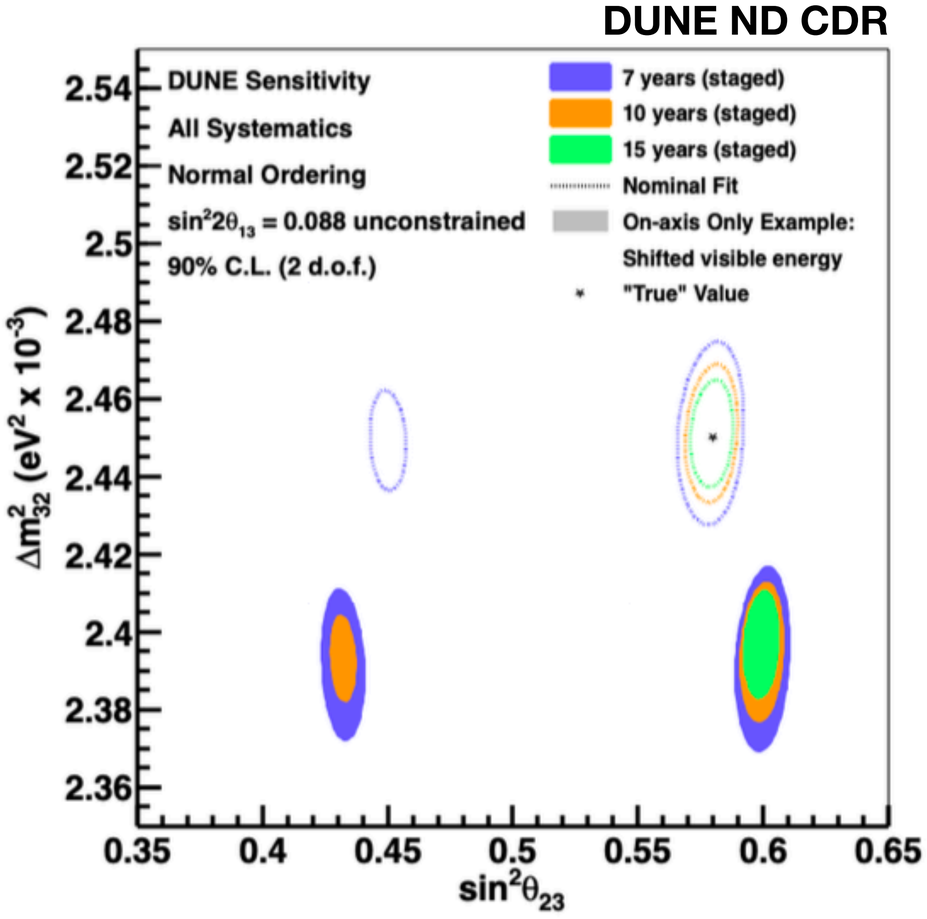
Stony Brook University

The Well-known Bias

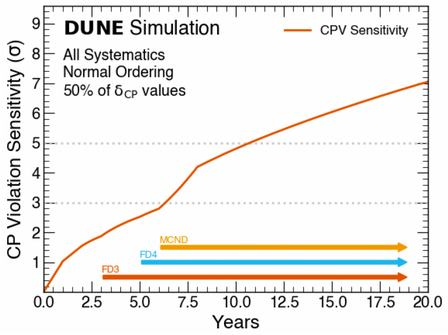
- In standard OA, a lot of uncertainties come from Xsec systematics
  - **It is non-perturbative QCD! Many unknowns in neutrino-nucleus interaction model**, e.g., initial/final state interaction, nucleon correlation
  - Neutrino mixing parameters are constrained by fitting MC to data
  - Because cross section models are not incomplete, this results in model tuning, which could produce biased results
  - Standard OA performs many fake data studies to take this into account
- Tension b/t **T2K & NOvA - model biases may be at play!**

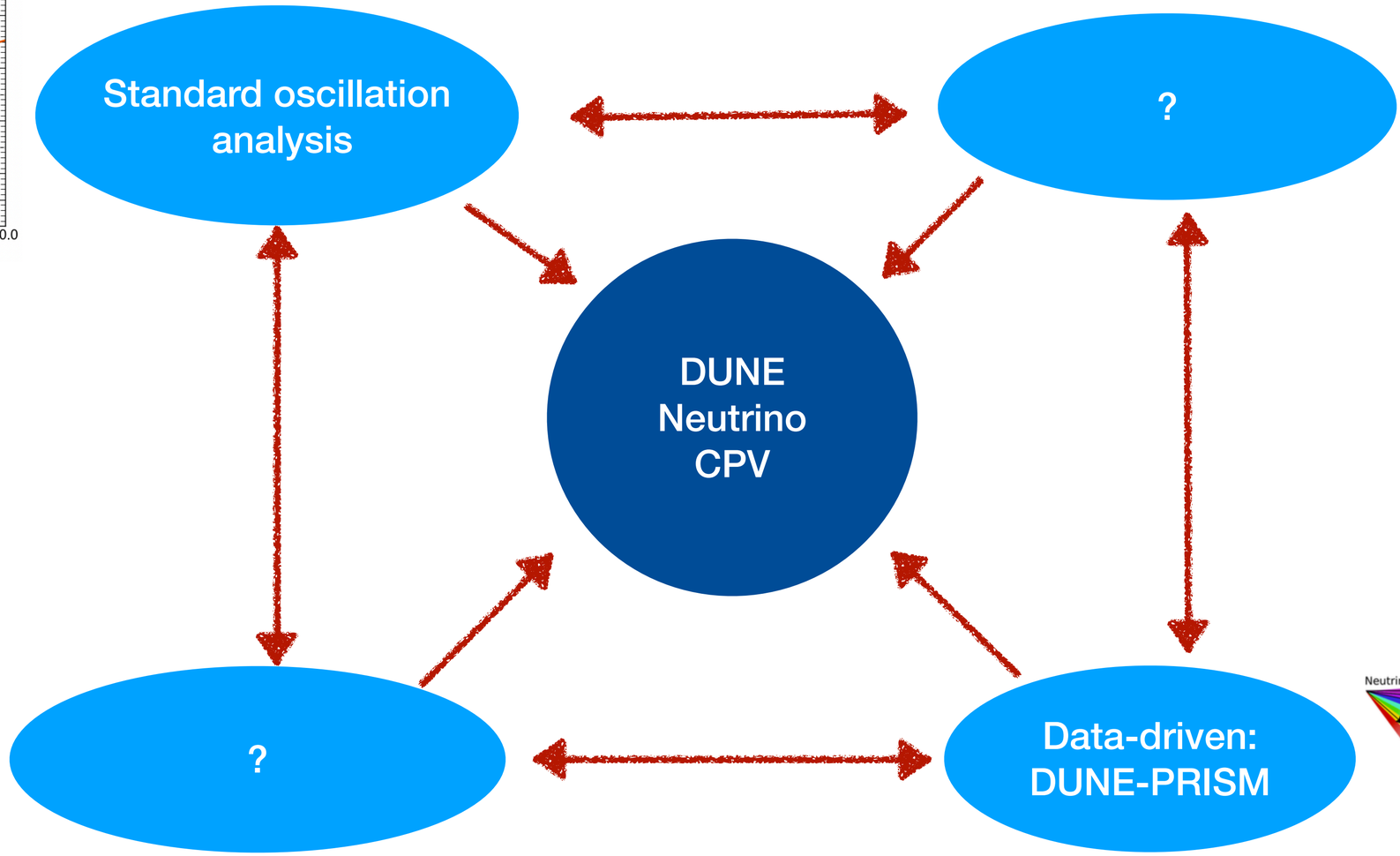
- **Important for DUNE to have as many as possible *independent* probes to neutrino oscillation**

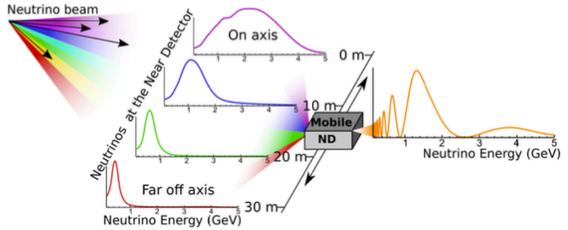




Multiple Roads to Neutrino CPV







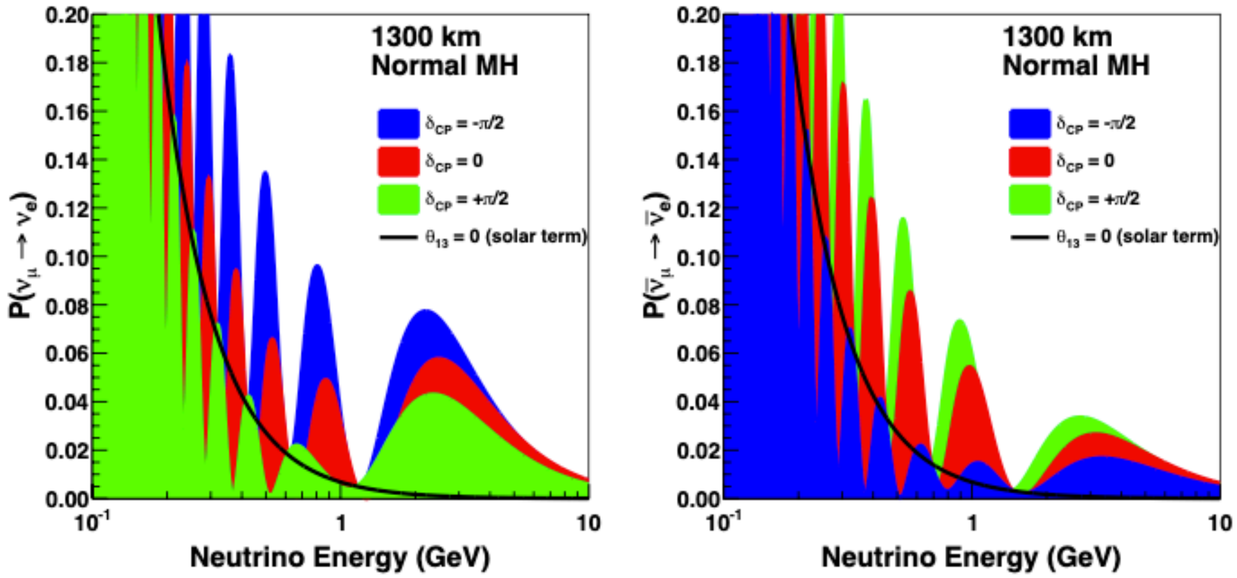
DUNE Offers More Probes for CPV

2nd CPV: arXiv

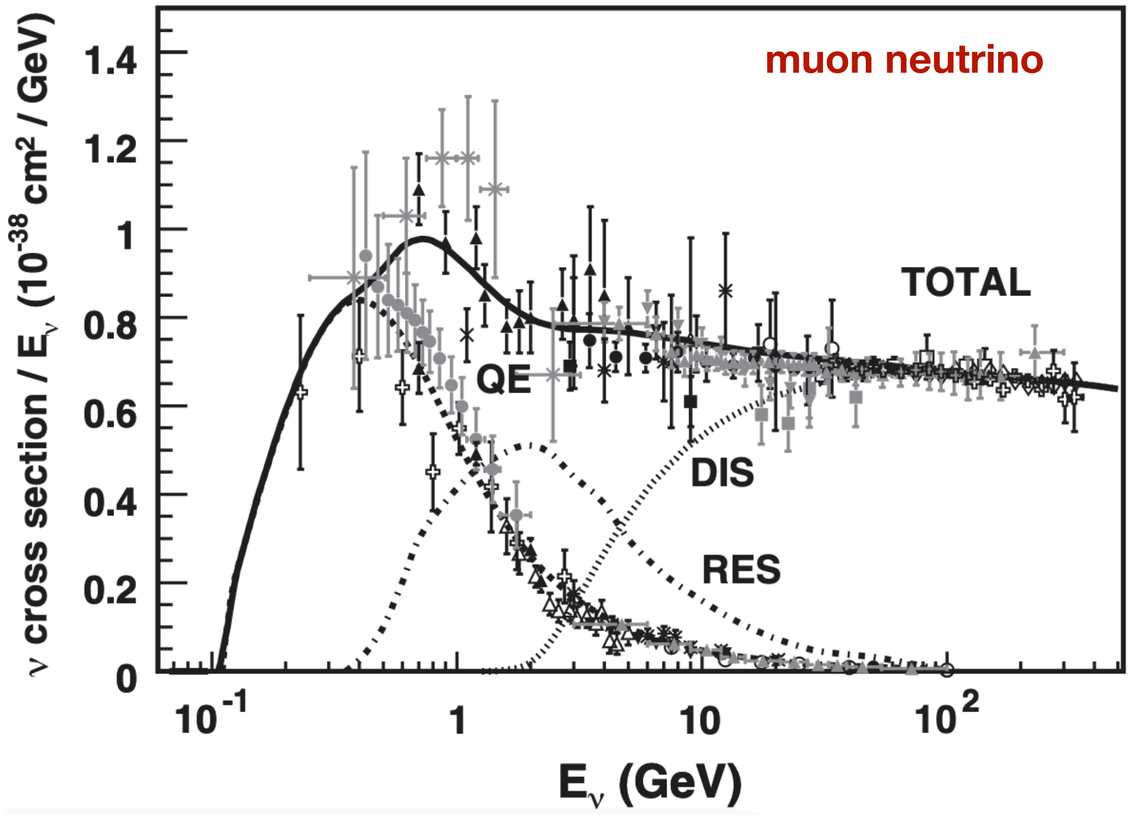
PHYS. REV. D 103, 116003 (2021)

Wide-band beam offers access to the 2nd oscillation peak

- **An independent CPV measurement for free!**
  - Stronger CPV effect @2nd peak
  - Lower energy region: very different interaction processes and systematics
  - **Measuring CP independently with two oscillation peaks is a unique capability of DUNE - should not give up**
- Statistics is low (can't help much), but **finer energy resolution could help resolve the 2nd peak structure**
  - Offered by an enhanced light detection system in Phase II FD3

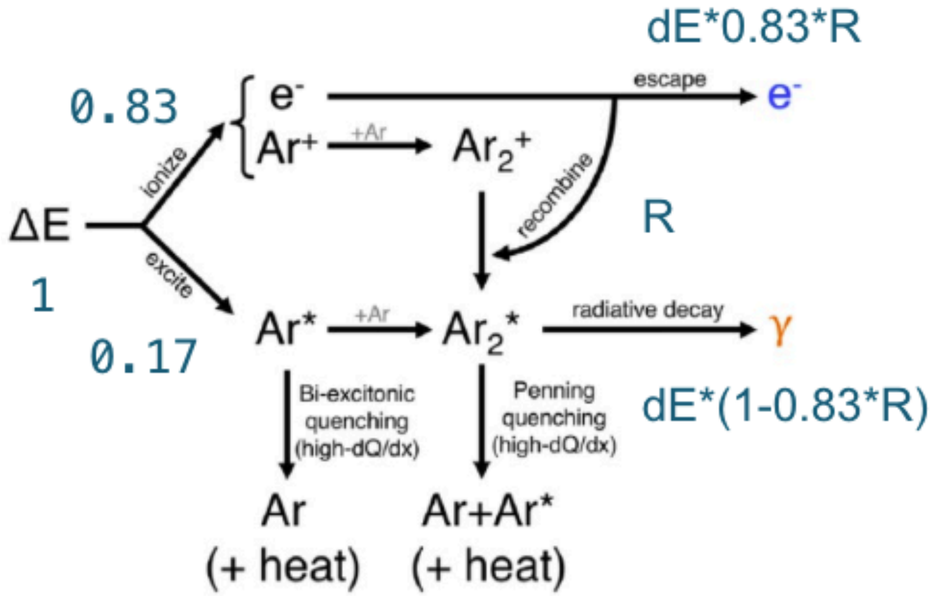


DUNE FD TDR: physics



A Genie-edepsim Study of GeV ν_e CC Events in a LAr Bath (200m long each dimension)

- **Done in the context of Phase II FD3 APEX - many details omitted in this talk (see paper later)**
- **Energy deposition into charge (Q), light (L), detection threshold**
  - Applied realistic charge (dQ/dx) and light (dL/dx) yield from dE/dx
    - dQ: Birks model
    - dL = dE - dQ
    - Used a benchmark mean light yield for FD3: 180 PE/MeV
  - Applied detection thresholds: 75 keV



$$dQ = 0.83 \times dE \times (1 - r)$$

$$1 - r = \frac{0.8}{1 + k_Q dE/dx}.$$

$$k_Q = 0.0972\ \mathrm{g/MeV\,cm^2}$$

@500V/cm

Apply the light yield: 180PE/MeV, the number of PE for an event would be:

N_{PE} = L*180

Apply the fluctuation, the detected photon number would be:

N_{PE_rand} = Gaussian(N_{PE},$\sqrt{N_{PE}}$)

The detected energy in light:

$L_{detected}$ = N_{PE_rand} *180(PE/MeV)

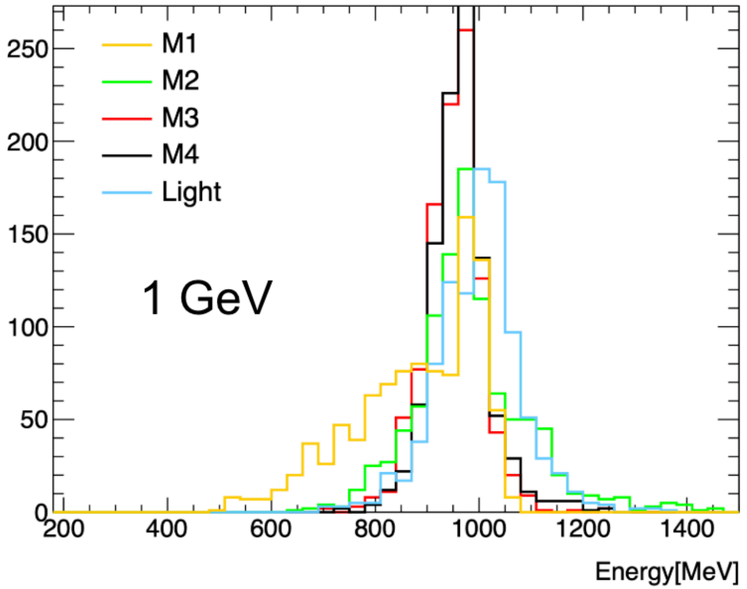
Combined with charge energy, the detected energy in total:

E_{LQ} = $L_{detected}$ + Q

GeV Event Reconstruction and Energy Resolution

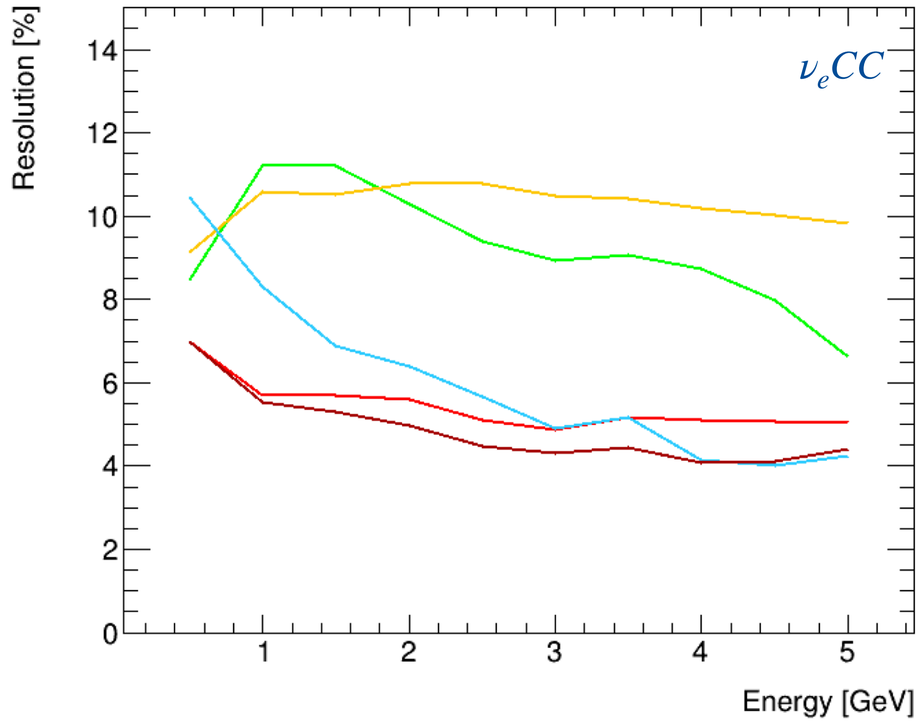
Five different methods of energy reconstruction

1. Charge calorimetry: $E_\nu = Q_{tot}/0.58$
2. Separate lepton/hadron :
   $1/(1+\alpha)E_\nu = (Q_{lep} + Q_{\pi_0})/0.66 + (Q_{had})/0.37$
3. Separate tracks/dots
   $1/(1+\alpha)E_\nu = E_{track} + E_\mu + (Q_{lep\_dots} + Q_{\pi_0\_dots})/0.24 + (Q_{had\_dots})/0.57$
4. + Individual PID;
   neutron, charged pion
5. Light: $E_\nu = L_{tot}/0.42$



Resolution is rms/E ;

1. **Charge calorimetry: 10.5% @1GeV**
2. **Separate lepton/hadron: 11.2% @1GeV**
3. **Separate tracks/dots: 5.7% @1GeV**
4. **Individual PID: 5.5% @1GeV**
5. **Light: 8.2% @1GeV**



Light Helps GeV Event Reconstruction

- **Light offers** an **independent calorimetry** with **comparable or better energy resolution** (8%@1GeV) to charge calorimetry
  - **Rely less on PID,** less affected by complicated hadronic system…

N.B. Adding light to charge only recovers the deposited E (with long tails…), but doesn't help reconstruction because resolution is dominated by PID —> not the case for lower E

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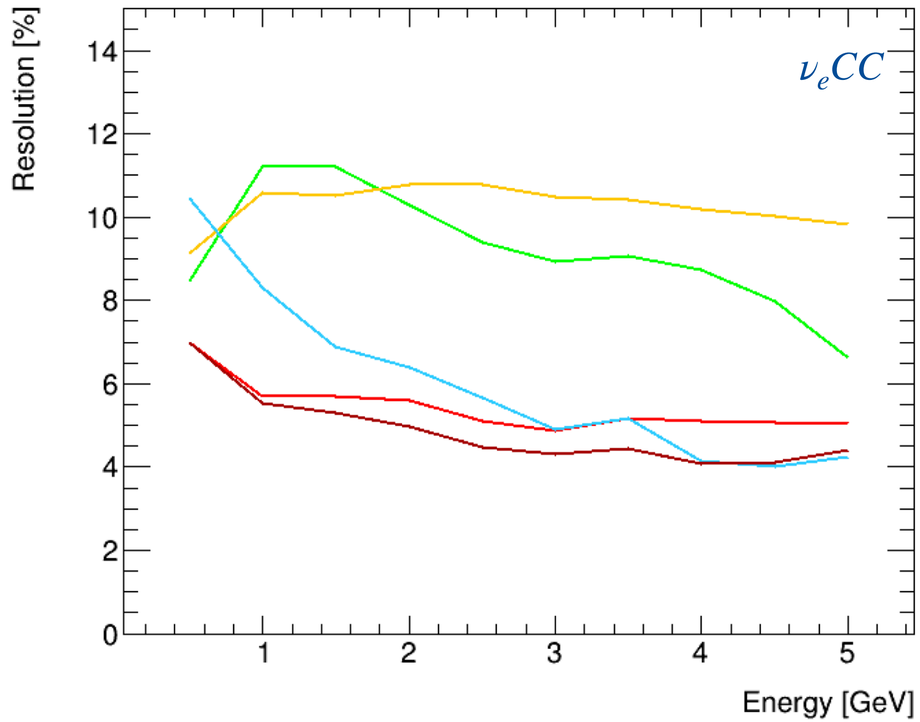
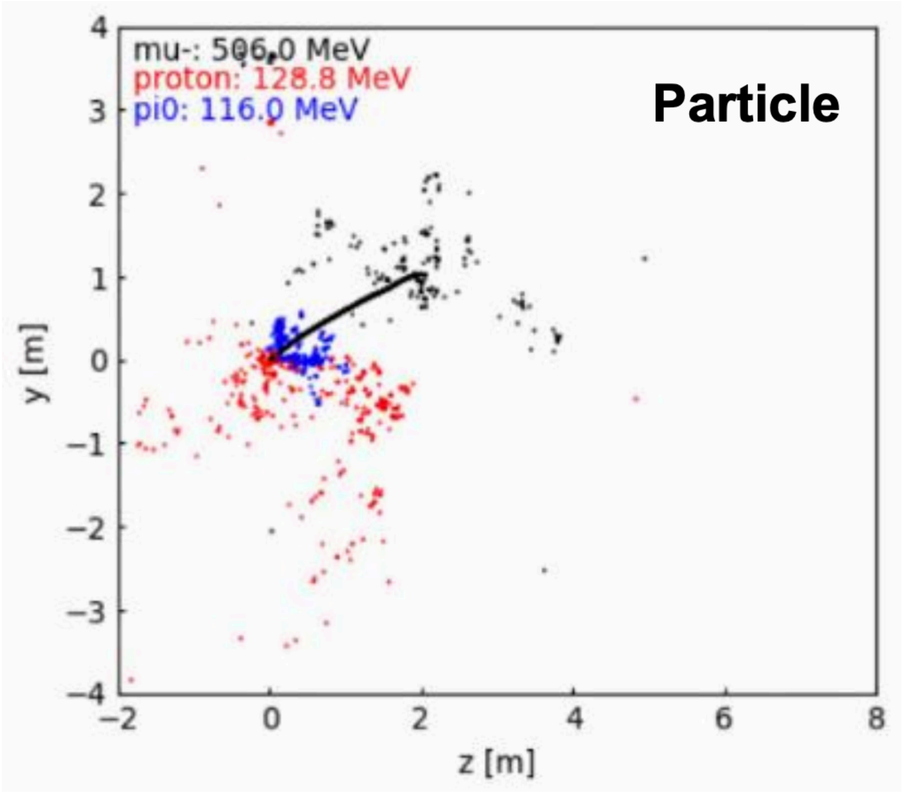


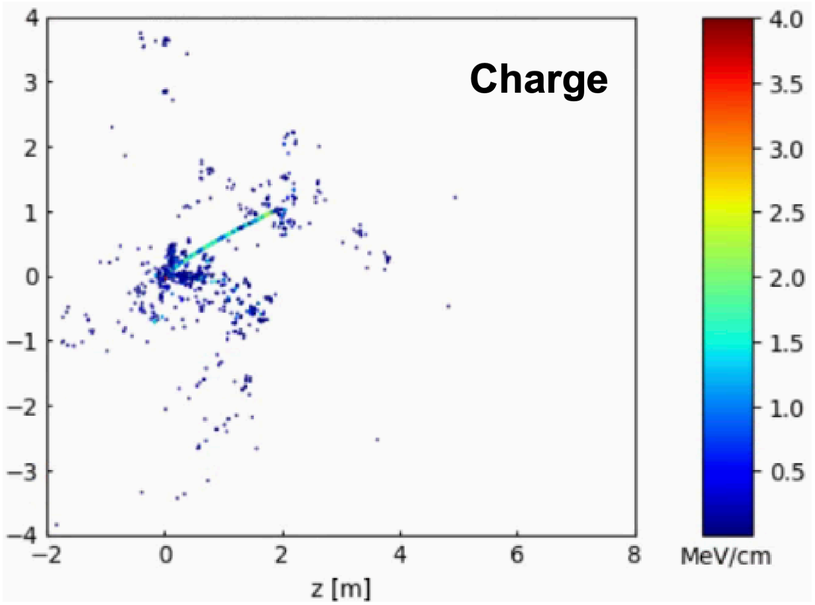
Energy resolution in DUNE VD TDR

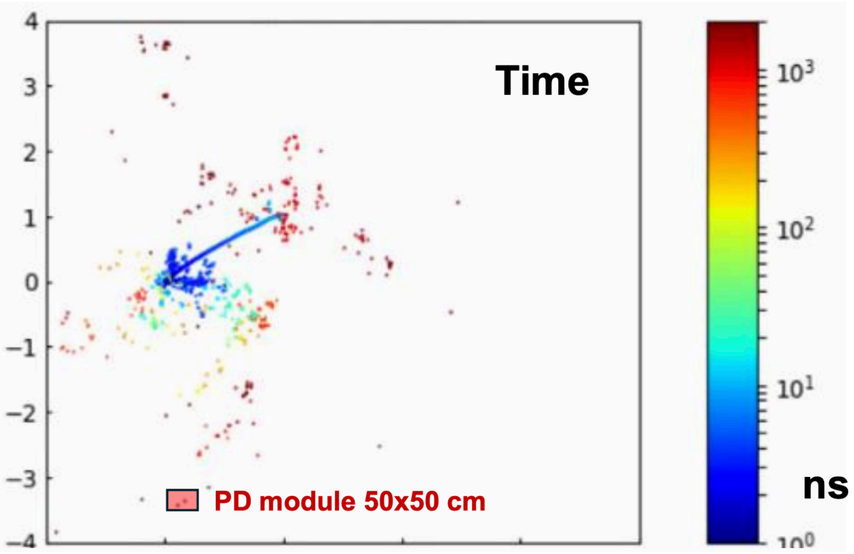
Event hypothesis	Vertical Drift	Horizontal Drift
ν_μ CC with contained μ track	21%	18%
ν_μ CC with exiting μ track	19%	20%
ν_e CC	14%	13%

Light Helps GeV Event Reconstruction

- **Light** info (**timing**, position, etc) **helps charge PID and charge-based reconstruction**
  - **Identify μ/π decay/capture**
  - Tag **neutron** propagation with timing (up to μs), n-capture tagging with PDS + TPC
  - Reconstruct track/event **direction** for background rejection





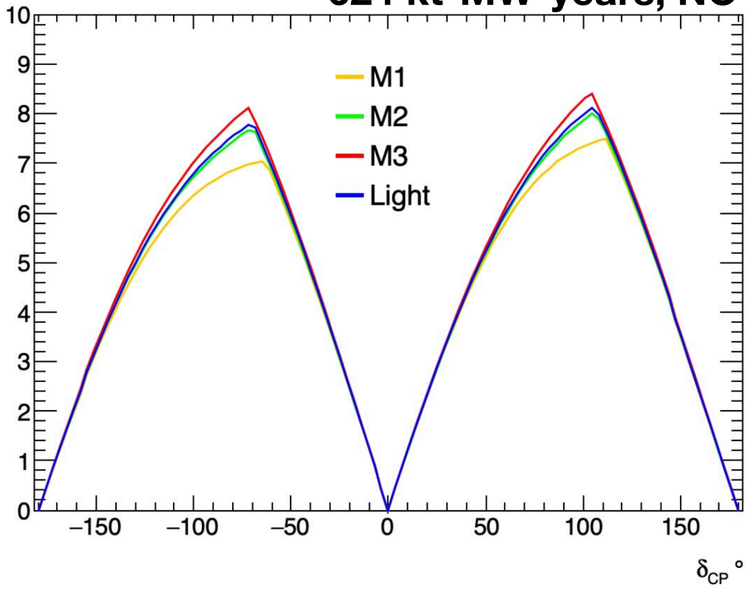


How Light Helps Independent CPV Measurement

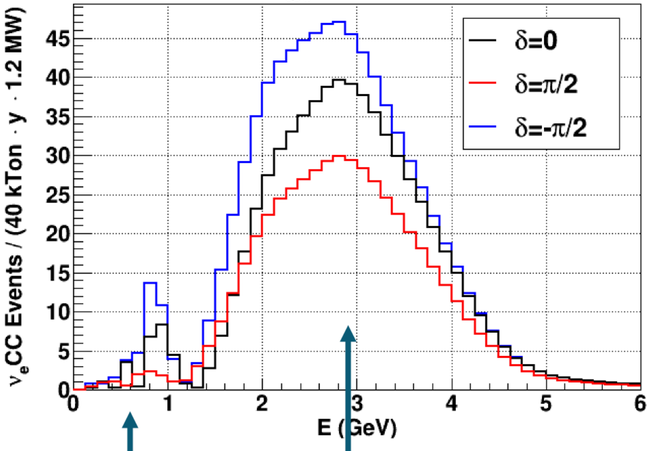
- Use new energy smearing for ν_e and $\bar{\nu}_e$ signal in DUNE GLoBES
  - Main contribution to the CP sensitivity is from 1st oscillation peak - insensitive to energy resolution

- **Better energy resolution will improve the CPV significance at 2nd oscillation peak (M1 → M2 → M3)**
  - **Light assisted charge PID helps improve energy resolution**
- **Light calorimetry alone provides another independent CPV measurement**

624 kt-MW-years, NO



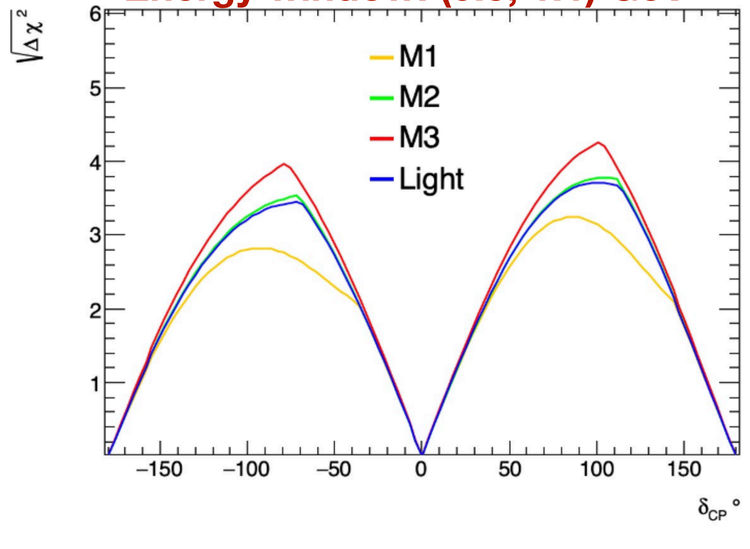
True DUNE spectra at FD (NO)
Perfect energy reconstruction



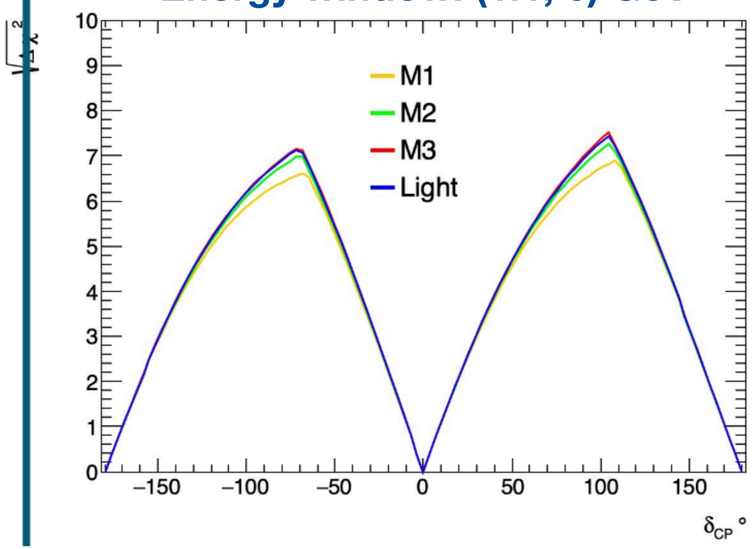
1st oscillation peak

2nd oscillation peak

Energy window: (0.5, 1.1) GeV



Energy window: (1.1, 6) GeV



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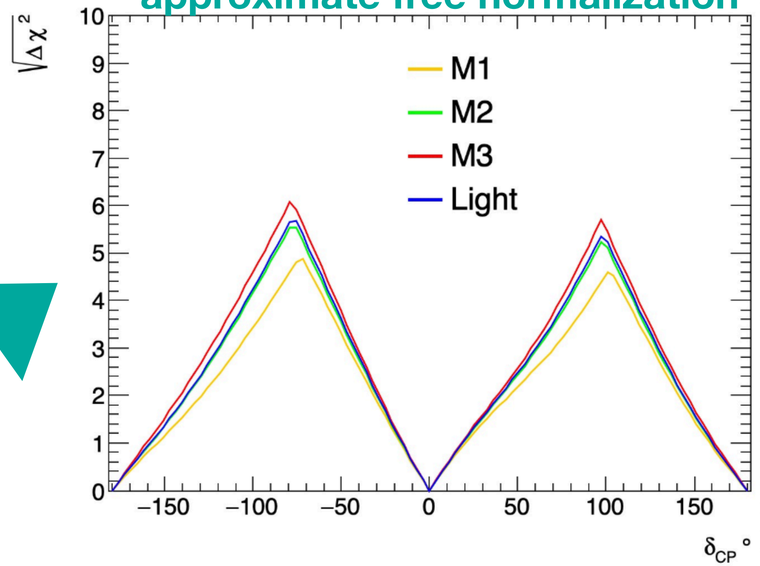
- **Better energy resolution will improve the CPV significance at 2nd oscillation peak (M1 → M2 → M3)**
  - **Light assisted charge PID helps improve energy resolution**
- **Light calorimetry alone provides another independent CPV measurement**
- **Better resolution improve the contribution from spectra shape**

Shape-only sensitivity: approximate free normalization



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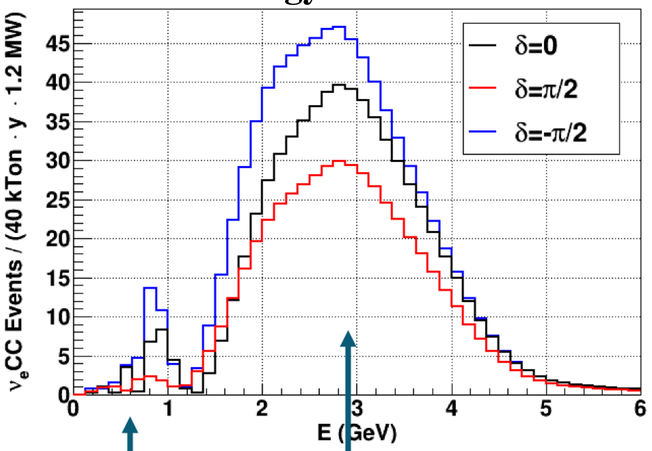
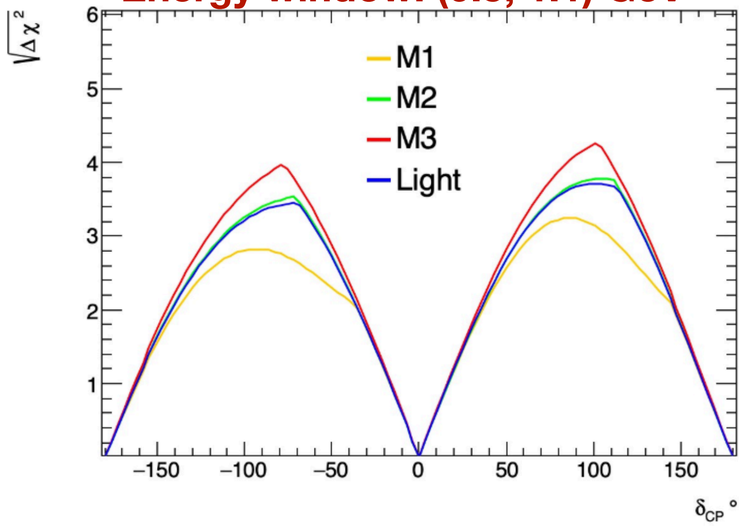


1st oscillation peak

2nd oscillation peak

Energy window: (0.5, 1.1) GeV



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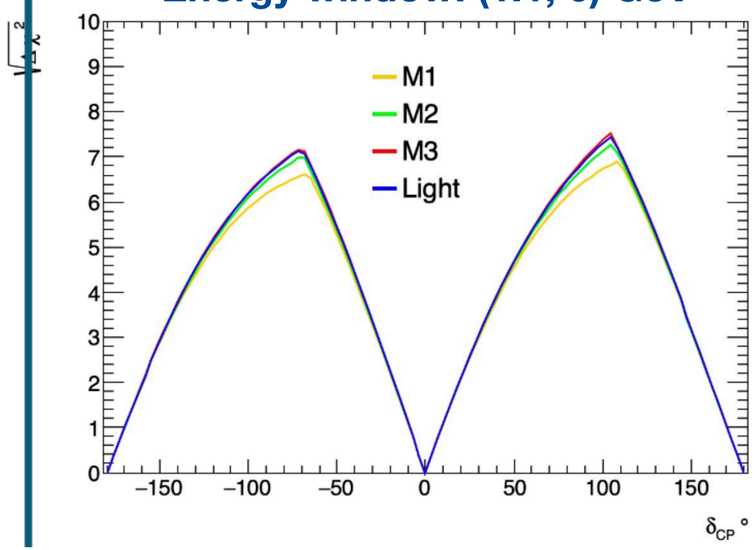

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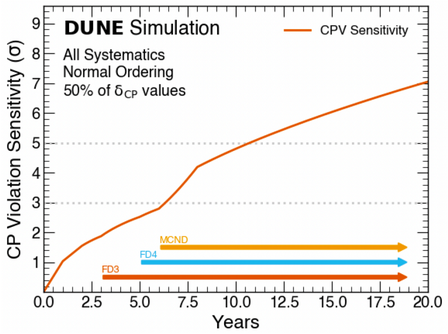
Multiple Roads to Neutrino CPV



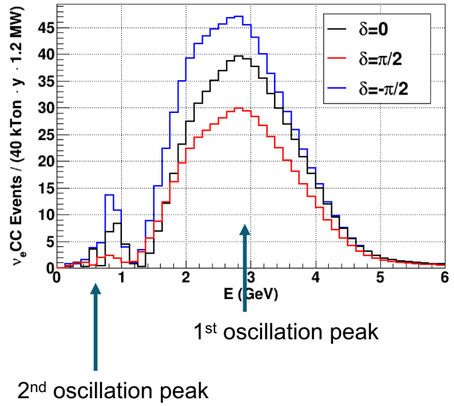
Standard oscillation analysis

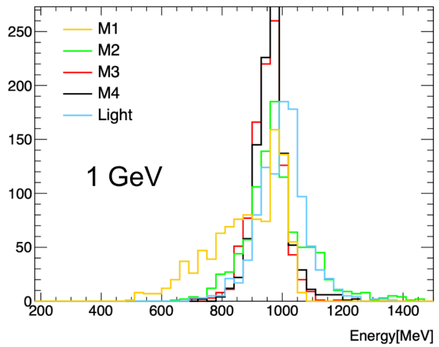
CPV@2nd oscillation peak

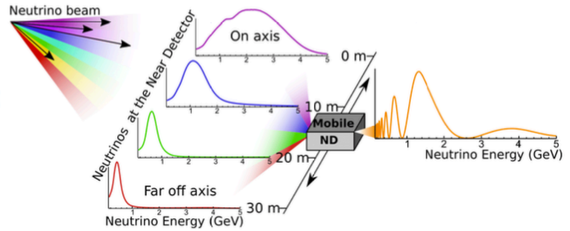
DUNE Neutrino CPV

Pure light calorimetry

Data-driven: DUNE-PRISM







New CPV Analyses and Plans

- **Propose new CPV analyses**
  - One analysis offers an **independent probe** - expect comparable sensitivity to main OA
    - **Light calorimetry only analysis** @ full oscillation spectrum (1st & 2nd osc peaks)
  - Two analyses where sensitivity improves with better E resolution via **light-assisted charge PID**
    - **2nd oscillation peak analysis**
    - **Shape-only analysis**: free normalization/shape-only chi2
- Need to develop light sim & reco
  - More detailed light simulation
  - Further develop light-assisted event reconstruction
  - Develop good energy estimators based on light yield map for GeV neutrino events
- Possible synergy with standard OA or PRISM analysis
  - Linear combination of PRISM data can produce the 2nd osc peak well
  - **Need standard OA inputs**