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Sunday 15th September

NuFACT 2024 Satellite Workshop:
Multi-experiment oscillation analysis

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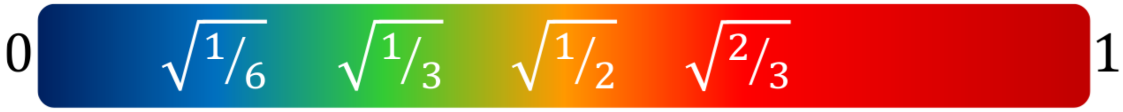
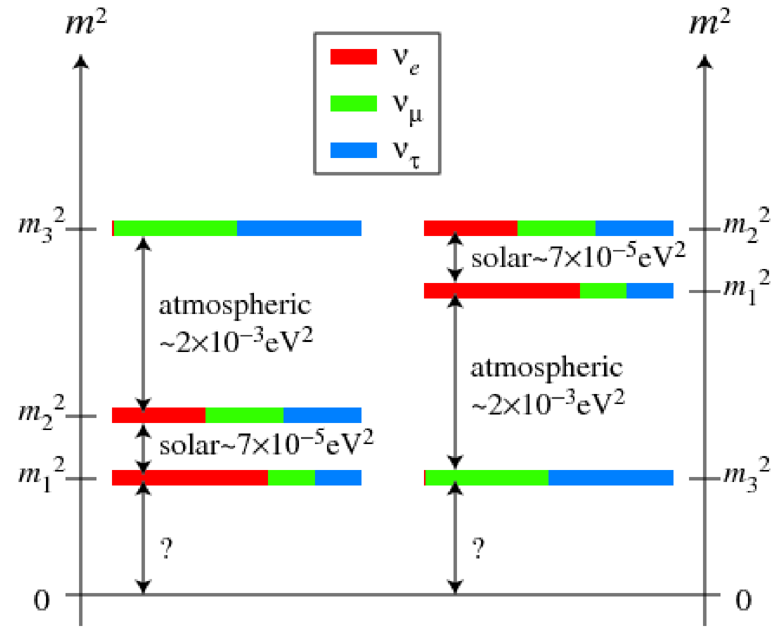
Neutrino oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





What do we know (PDG 23)?

- $\sin^2\theta_{23} = 0.455 \pm 0.018$
- $\sin^2\theta_{13} = 0.0223 \pm 0.0007$
- $\sin^2\theta_{12} = 0.303 \pm 0.13$
- $|\Delta m^2_{32}| = (2.45 \pm 0.03) \times 10^{-3}\ \mathrm{eV}^2$
- $\Delta m^2_{21} = (7.36 \pm 0.16) \times 10^{-5}\ \mathrm{eV}^2$

What don't we know?

- Do neutrinos violate CP?
- Is $m_3 > m_2$? (Mass Ordering)
- Is $\theta_{23} > 45^o$? (Octant)
- What is the value of m_1?
- Are neutrinos Majorana particles?
- New physics?

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Neutrino oscillation

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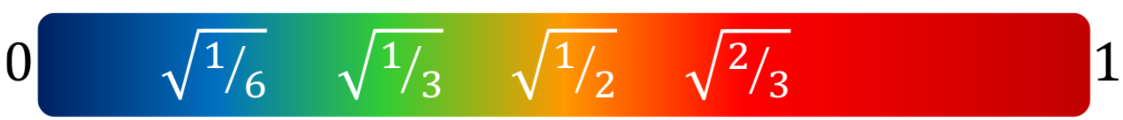

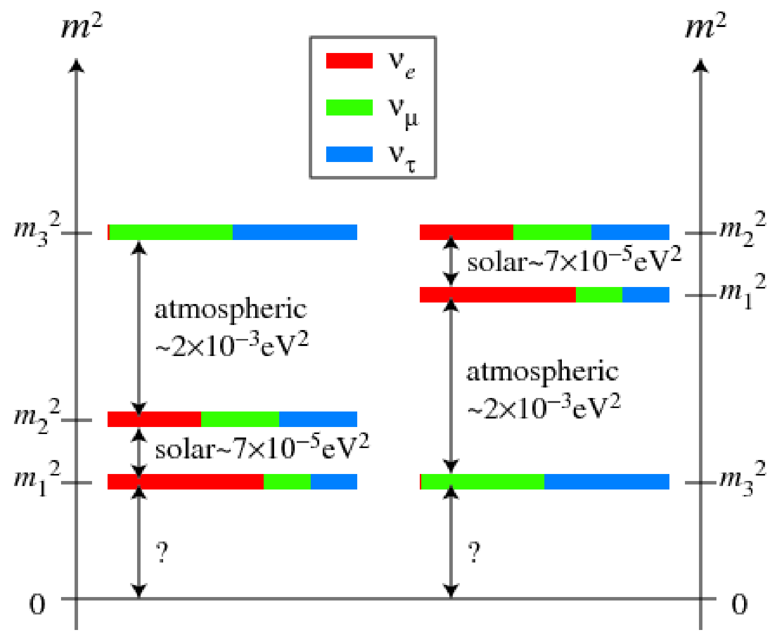

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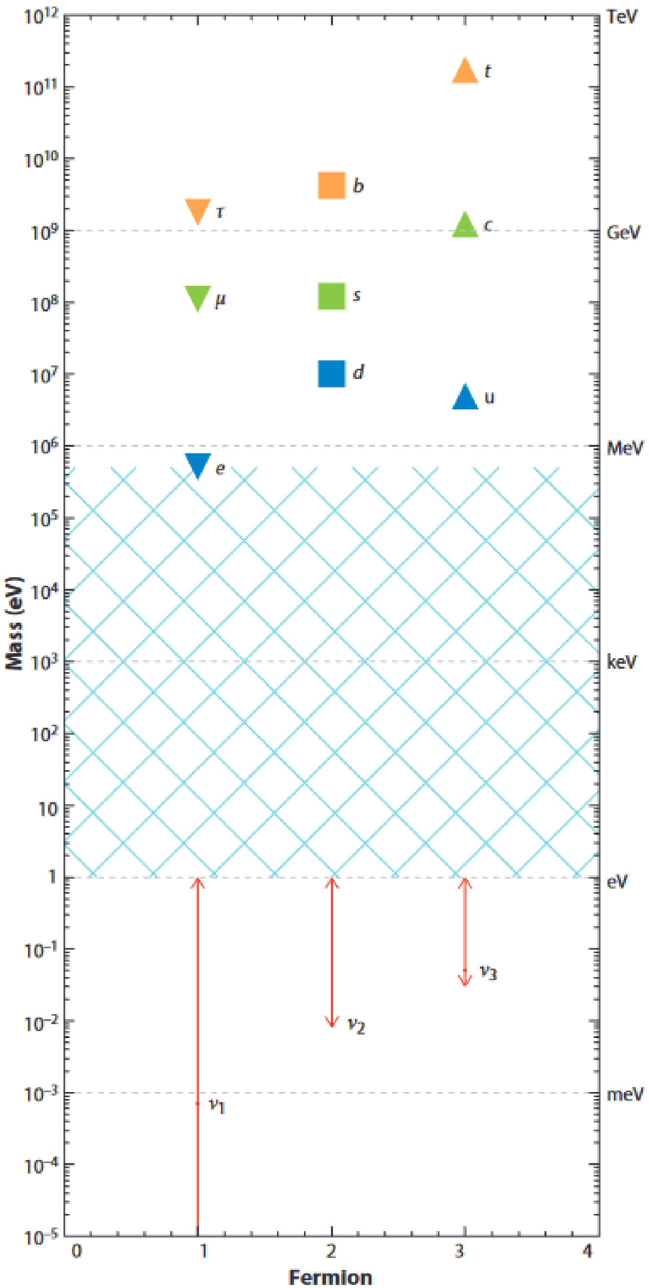
Massive Neutrinos

- Neutrino oscillation implies neutrinos have mass
- Mass generation mechanism unknown
  - Majorana or Dirac
  - Tree-level or loop
  - New particles (scalar, fermion etc.)
- Neutrino masses are tiny



Following taken from Annu. Rev. Nucl. Part. Sci. 2016.66:197-217

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Neutrino mass models - Dirac

- Add ν_R SU(2) singlet to the SM
- Dirac mass term exists, but why are the neutrino masses so small?
  - Extra dimensions
  - New symmetries that forbid tree-level mass terms
- ν_R can (must) have a Majorana mass term as well,

$$\mathcal{L}_\nu = M_{ij}\nu_R^i \nu_R^j$$

Neutrino mass models - Majorana

- Add N new, massive right-handed neutrinos, ν_R, with mass matrix M_N

$$\mathcal{L}_{Dirac} = m_D \nu_L \nu_R \quad \text{and} \quad \mathcal{L}_{Majorana} = M_N \nu_R \nu_R$$

$$m_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

- New mass scale not related to EWSB and Higgs
- 3x3 active neutrino mixing matrix a subset of (3+N) x (3+N) matrix
  - PMNS matrix may not be unitary

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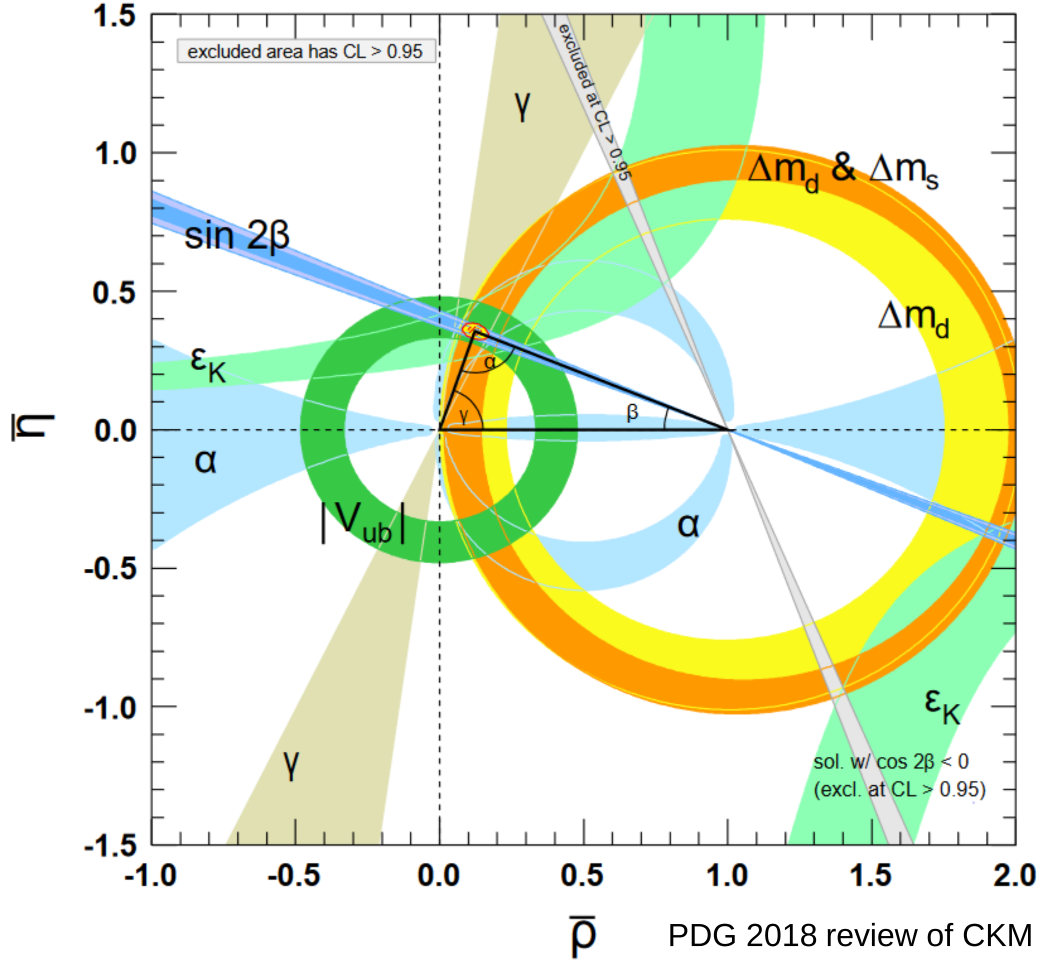
Unitarity measurements

- Non-unitarity not seen in quarks (yet)
- Would indicate new physics
  - Generic search (steriles, neutrino decay, NSIs etc.)
- Requires **over-constraint** of PMNS parameters



PDG 2018 review of CKM matrix

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Unitarity measurements in PMNS

- Many contributions
  - Daya Bay
  - JUNO
  - SNO
  - Hyper-K / DUNE
  - DUNE / Hyper-K / IceCube

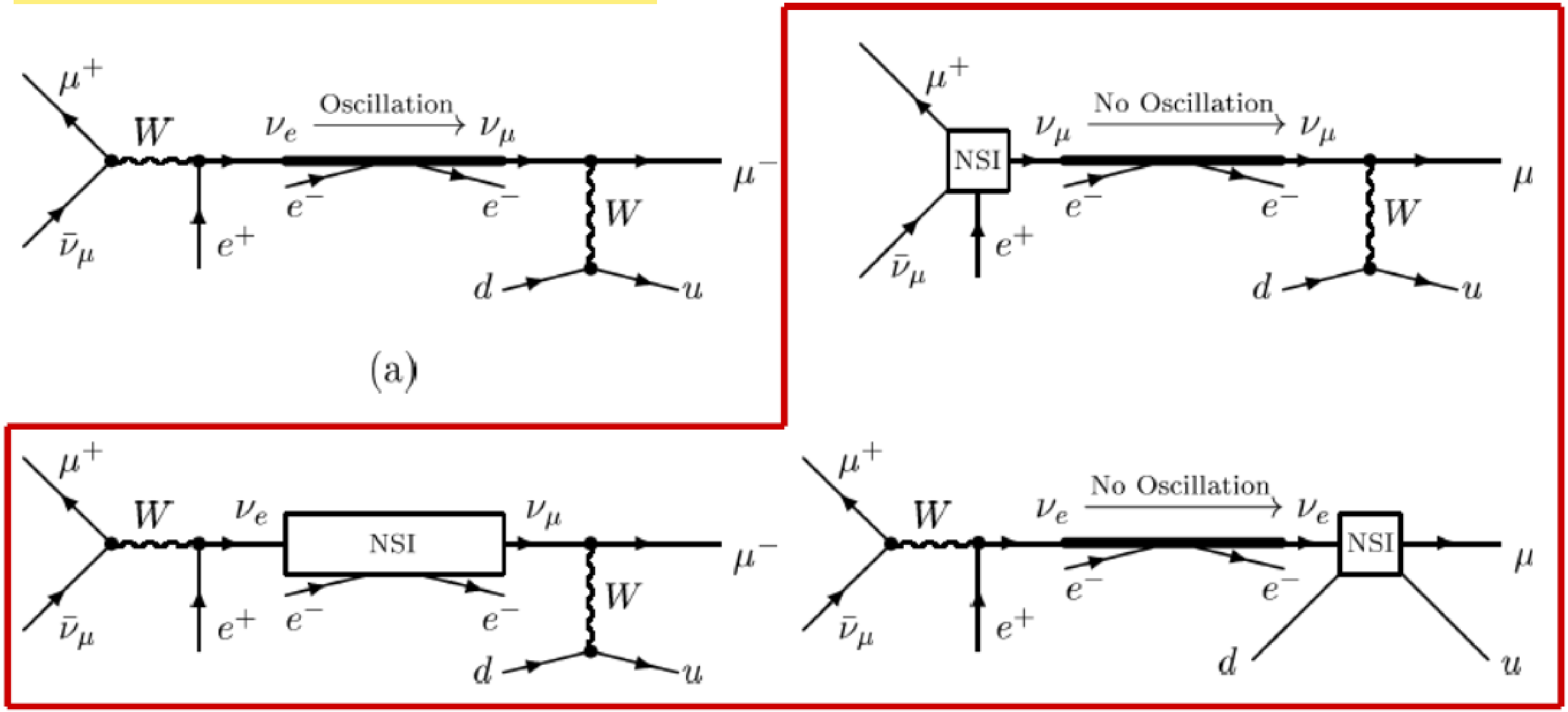
Experiment	Measured quantity with unitarity
Reactor SBL $(\overline{\nu}_e \to \overline{\nu}_e)$	$4\|U_{e3}\|^2 \left(1 - \|U_{e3}\|^2\right) = \sin^2 2\theta_{13}$
Reactor LBL $(\overline{\nu}_e \to \overline{\nu}_e)$	$4\|U_{e1}\|^2\|U_{e2}\|^2 = \sin^2 2\theta_{12} \cos^4 \theta_{13}$
SNO $(\phi_{CC}/\phi_{NC}$ Ratio)	$\|U_{e2}\|^2 = \cos^2 \theta_{13} \sin^2 \theta_{12}$
SK/T2K/MINOS $(\nu_\mu \to \nu_\mu)$	$4\|U_{\mu 3}\|^2 \left(1 - \|U_{\mu 3}\|^2\right) = 4 \cos^2 \theta_{13} \sin^2 \theta_{23} \left(1 - \cos^2 \theta_{13} \sin^2 \theta_{23}\right)$
T2K/MINOS $(\nu_\mu \to \nu_e)$	$4\|U_{e3}\|^2\|U_{\mu 3}\|^2 = \sin^2 2\theta_{13} \sin^2 \theta_{23}$
SK/OPERA $(\nu_\mu \to \nu_\tau)$	$4\|U_{\mu 3}\|^2\|U_{\tau 3}\|^2 = \sin^2 2\theta_{23} \cos^4 \theta_{13}$

S. Parke, M. Ross-Lonergan, Phys. Rev. D 93, 113009 (2016)

NSIs interfere with Oscillations

the "golden" oscillation channel

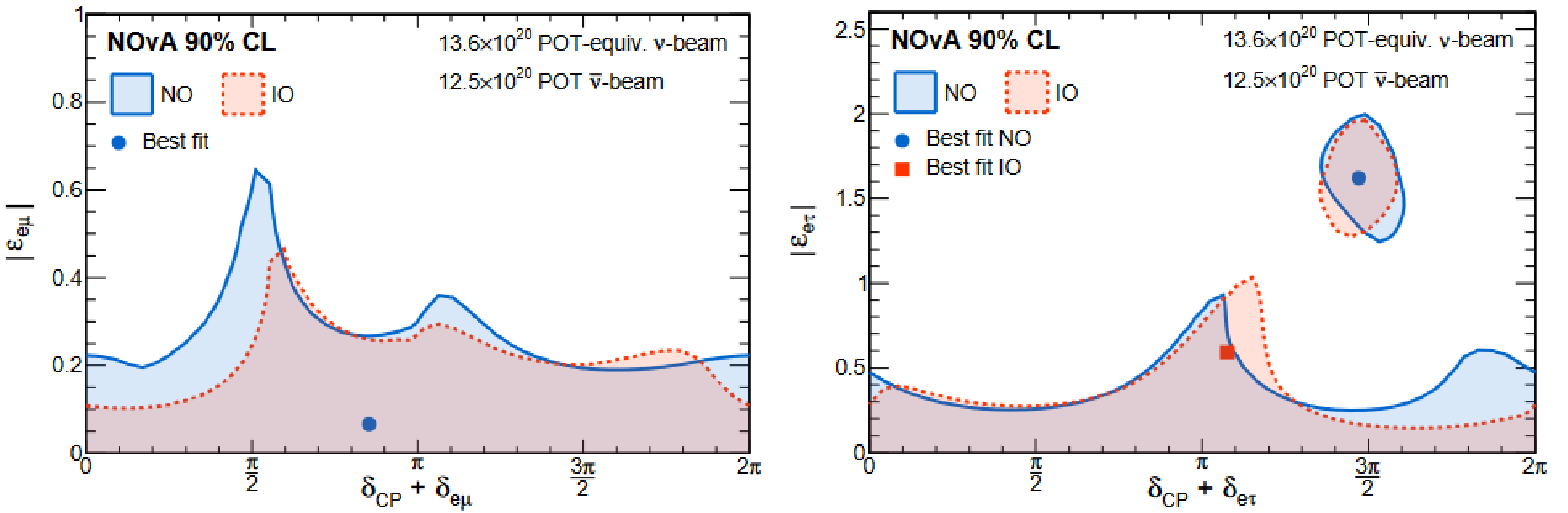
NSI contributions to the "golden" channel



interference in oscillations ~ε ↔ FCNC effects ~ε²

NOvA NSI results

- Measuring disappearance of muon (anti)neutrinos and appearance of electron (anti)neutrinos
- Looking for phase and size of NSI in $e \to \mu$ and $e \to \tau$



https://arxiv.org/abs/2403.07266

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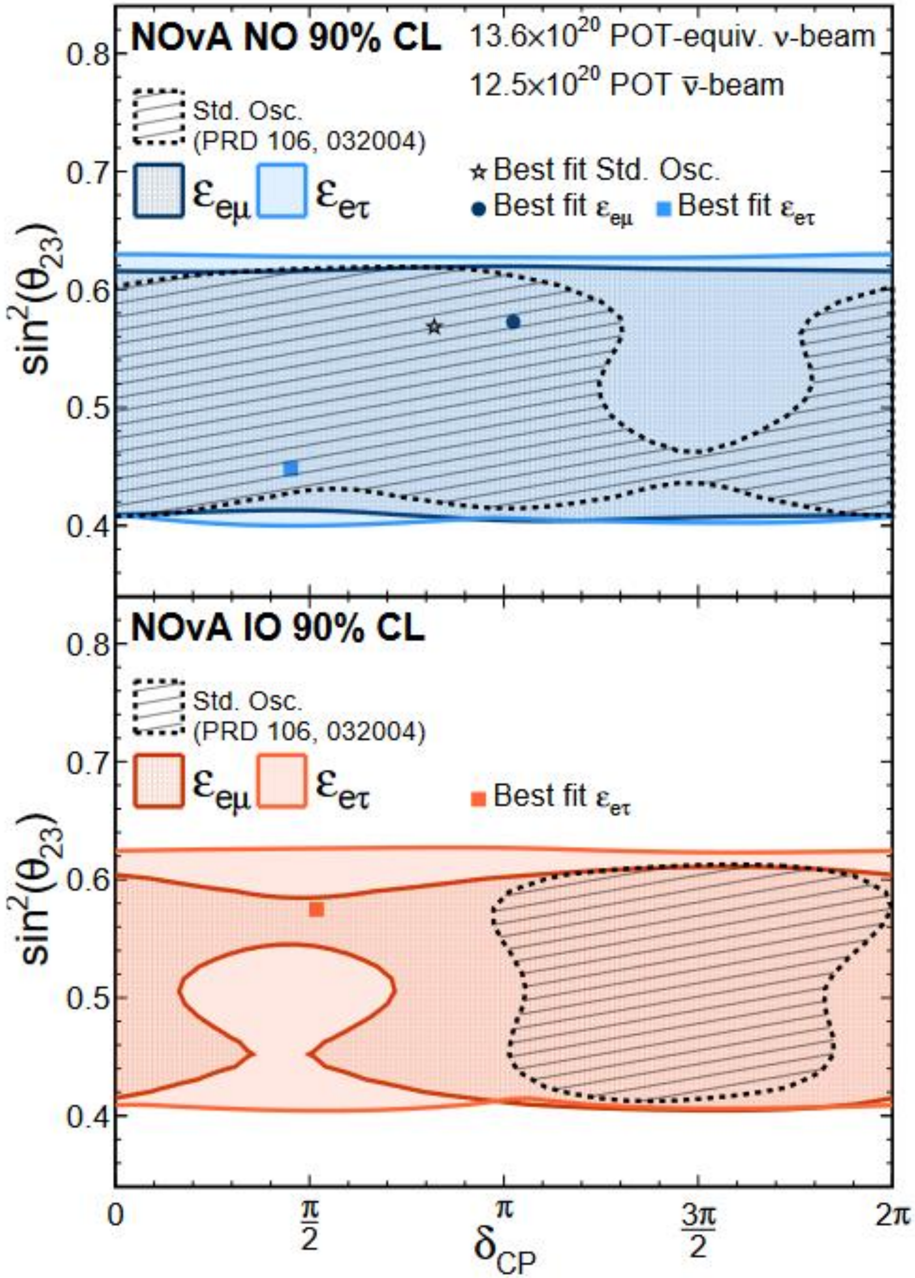
NOvA NSI results

- Impact on PMNS δ_{CP}

- At single experiment including NSI removes almost all sensitivity to CP violating phase in standard PMNS matrix
  - Effects are degenerate!



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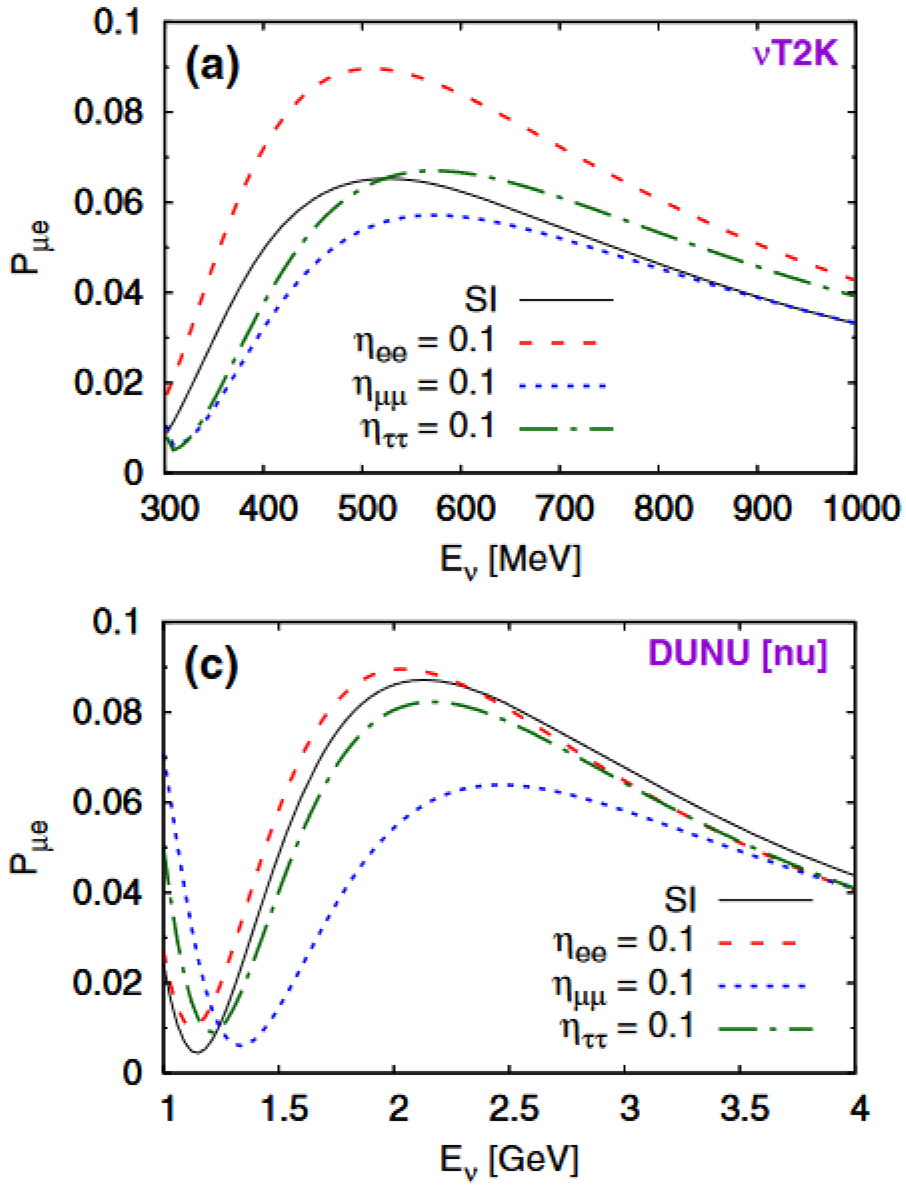
Multi-experiment NSI

- T2K neutrinos travel 295km
- DUNE neutrinos travel 1300km
- See different NSI terms have different effects
  - Combining data from multiple experiments allows us to (re)gain sensitivity
  - Many talks next week look at this

From PhysRevLett.122.211801



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Recent multi-experiment analyses

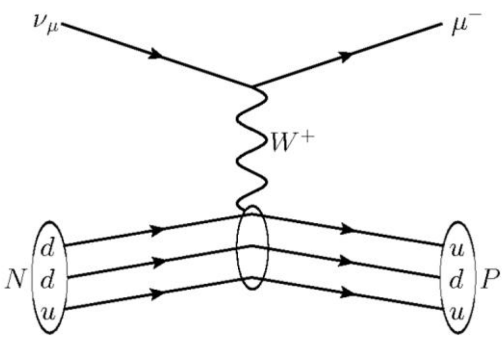
- CMS + ATLAS Higgs combinations
  - Similar detectors and physics but different analysis methods, different model choices, different samples
- T2K + NOvA
  - Similar physics and samples, but very different detectors and analysis methods
- T2K + SK
  - Combined “same” detector but using different physics samples and different analysis methods
- Hopefully we can learn from these experiments!

Summary

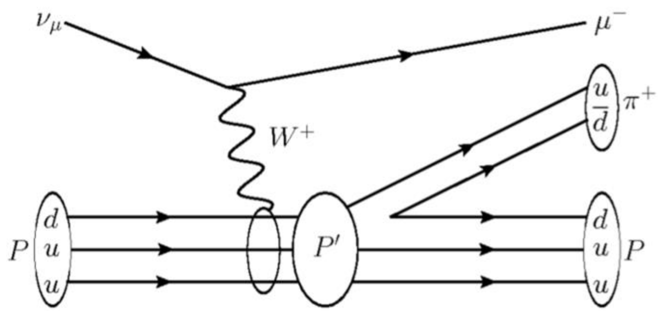
- Next generation of experiments aim for precision neutrino physics
  - Direct searches for new physics, unitarity of PMNS
  - Not clear that there will be any next-to-next gen experiments…
- PMNS unitarity and other BSM searches require combined analysis
  - Need reactor and atmospheric, not just beam
- T2K + NOvA analysis took 8 years from initial discussion until first result
  - Combination analyses are hard!
- **Goal for workshop:**
  - Start (hopefully regular) discussion between experiments to make combinations easier
  - Get ideas for ways to work together in future

Backups

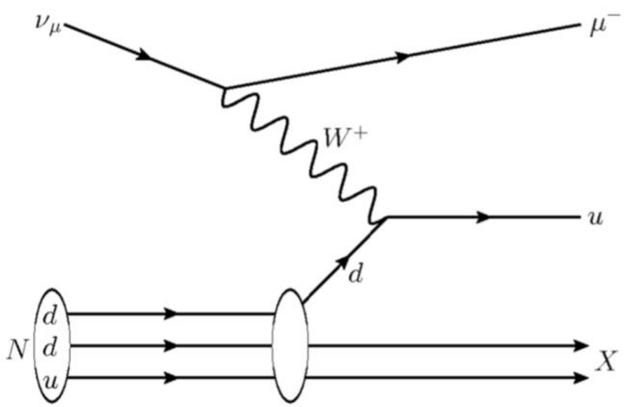
Neutrino cross-section measurements



Quasi-elastic (QE)



Single pion production (RES)



Inelastic Scattering

- Characterised by particles in final state
  - Only lepton + nucleon = quasi-elastic
  - Single pion = Resonant or coherent pion production
  - Multiple pions = Shallow / deep inelastic scattering

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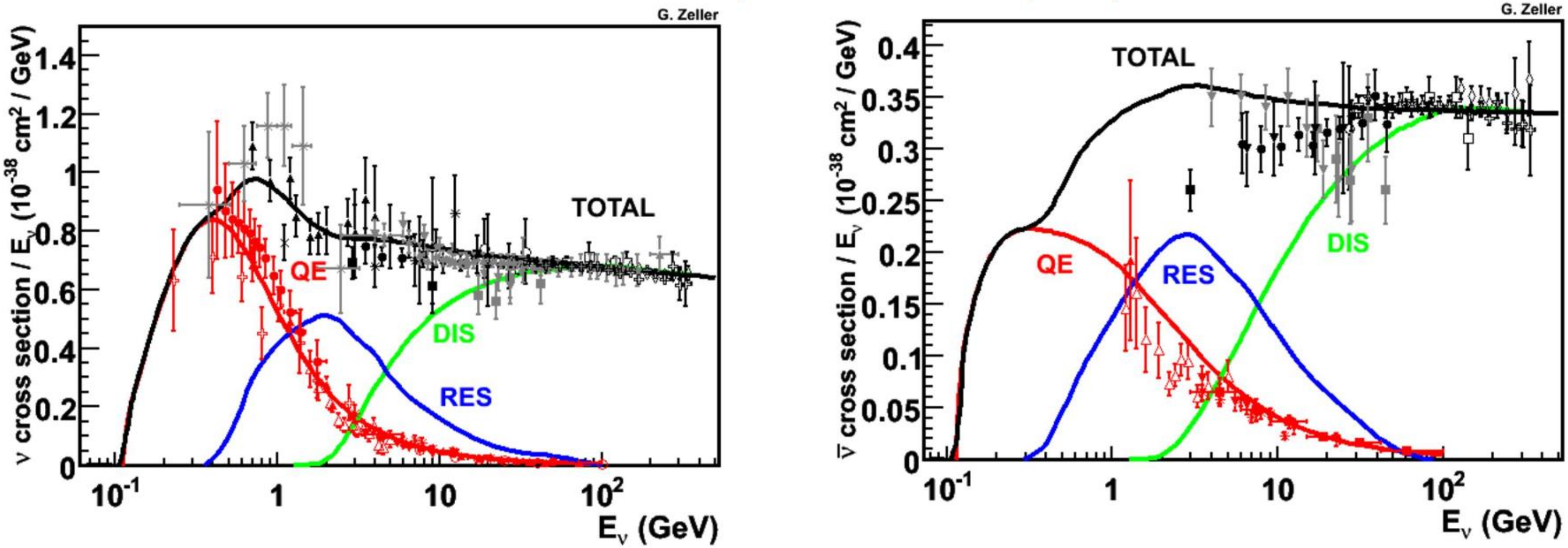
Neutrino cross-section measurements

Rev. Mod. Phys. 84, 1307–1341 (2012)



- High energy – DIS dominates, perturbative theories work, data and theory agree
- Lower energy (~1 GeV neutrino energy) – data and theory disagree more

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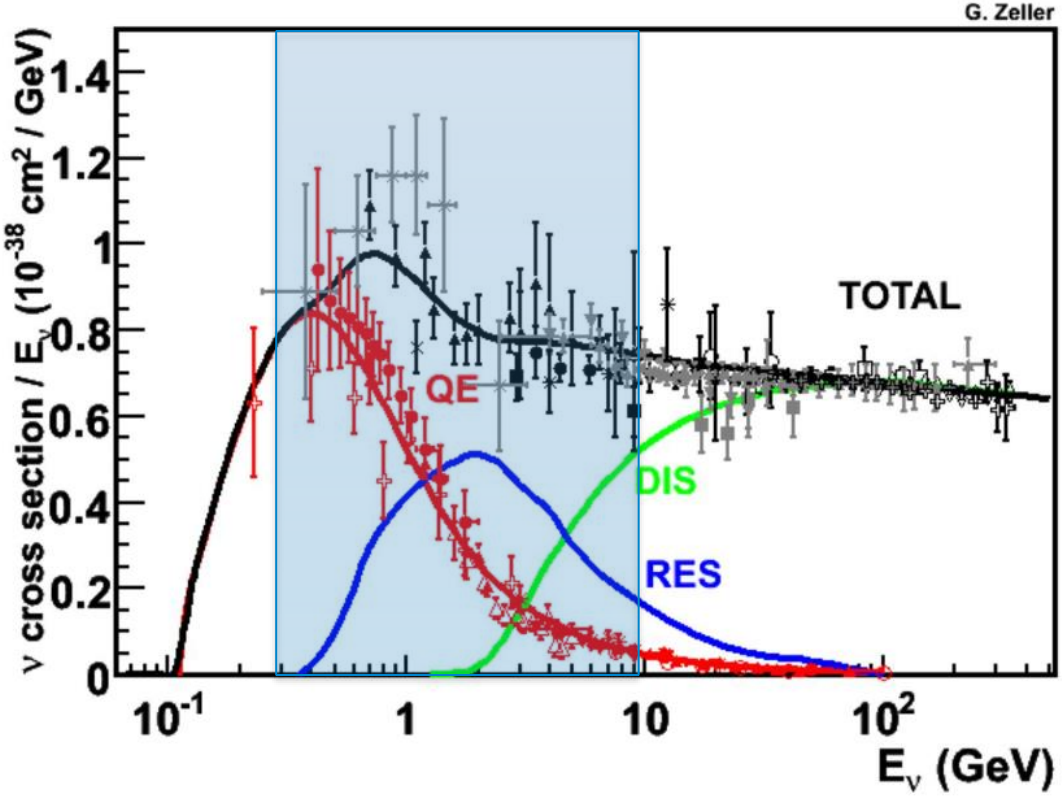
Neutrino cross-section measurements

- Neutrino oscillations depend on L(km)/E(GeV)

- Earth-based long-baseline experiments have to have neutrino energies <10 GeV

- Lots of work still to do to understand these cross-sections



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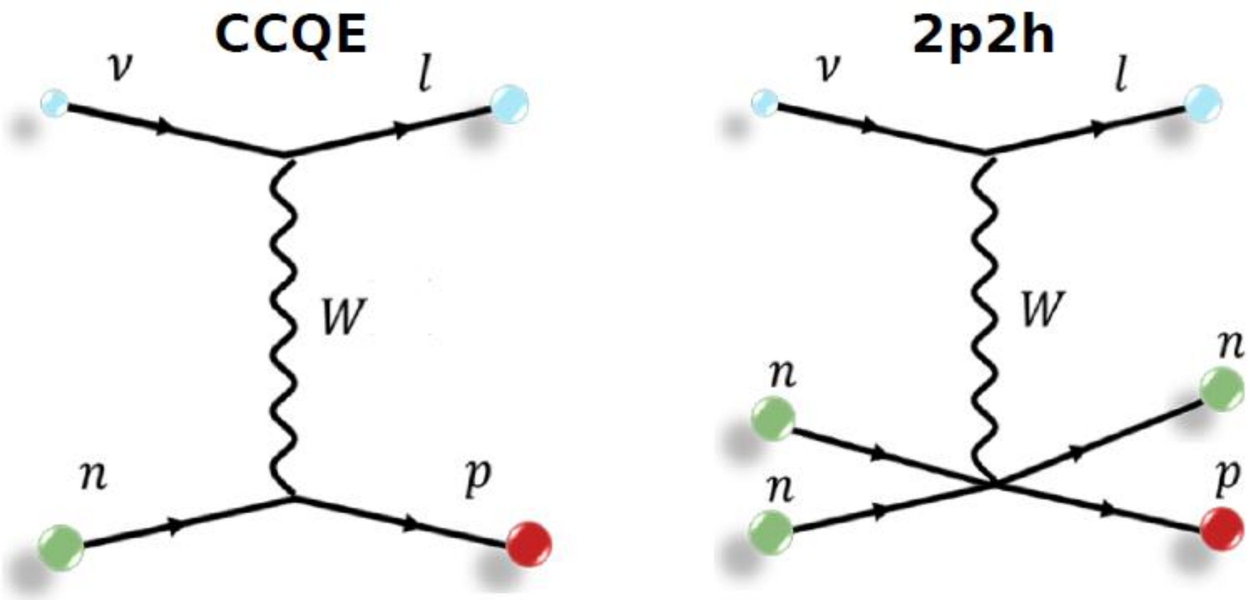
Example – 2p2h interactions



- Similar to CCQE
- Neutrino interacts with correlated pair of nucleons – invisible to detector

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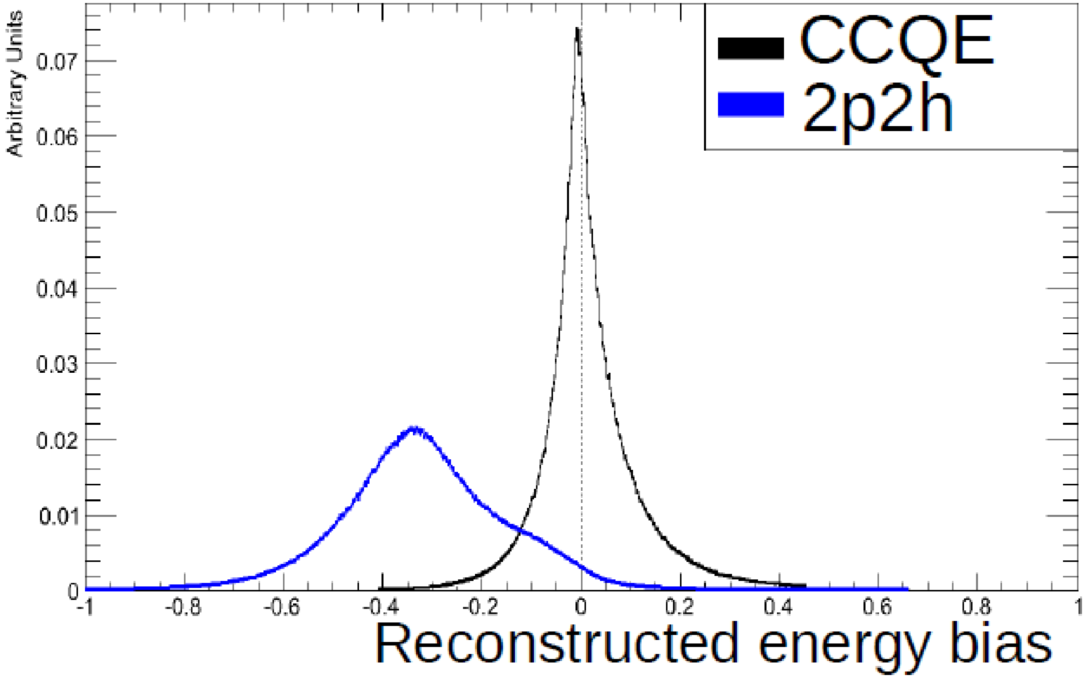
Example – 2p2h interactions



- Reconstructed neutrino energy is biased, leads to bias in oscillation parameters
- Requires improved experimental measurements or theoretical models

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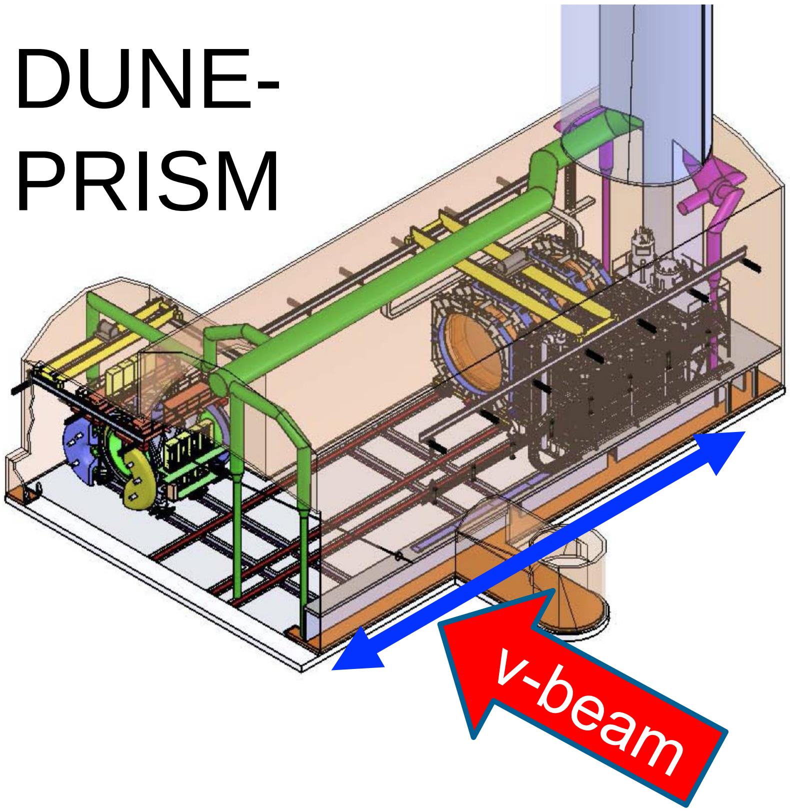
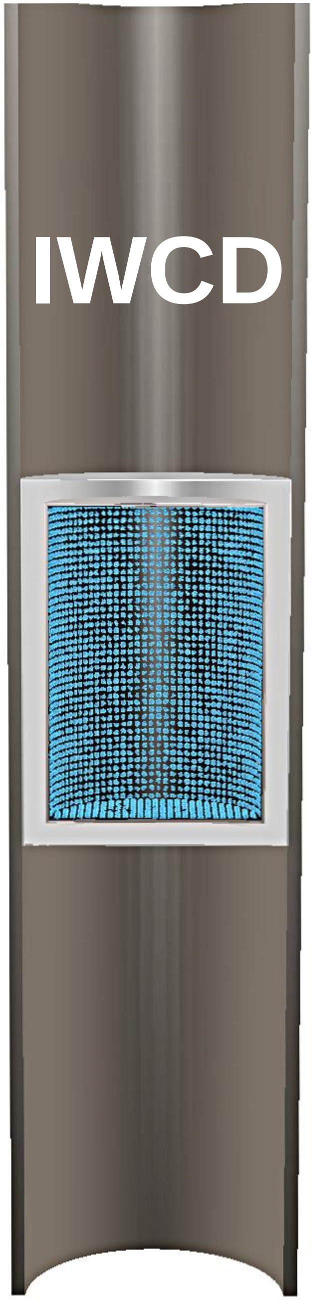
DUNE-PRISM and IWCD/NuPRISM



- Near / intermediated detectors for DUNE / HK
- Span a range of angles off the centre of the neutrino beam
  - DUNE-PRISM – horizontal, ~35m
  - IWCD – vertical, ~50m



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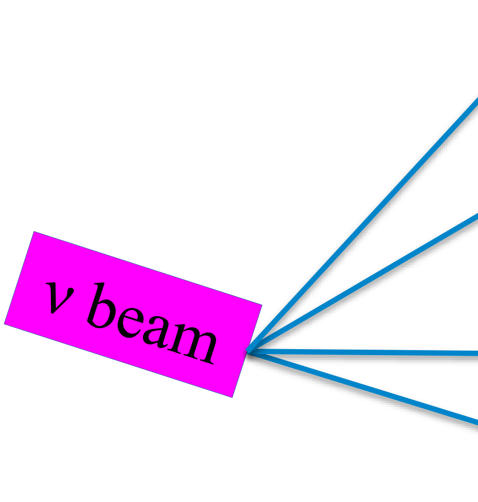
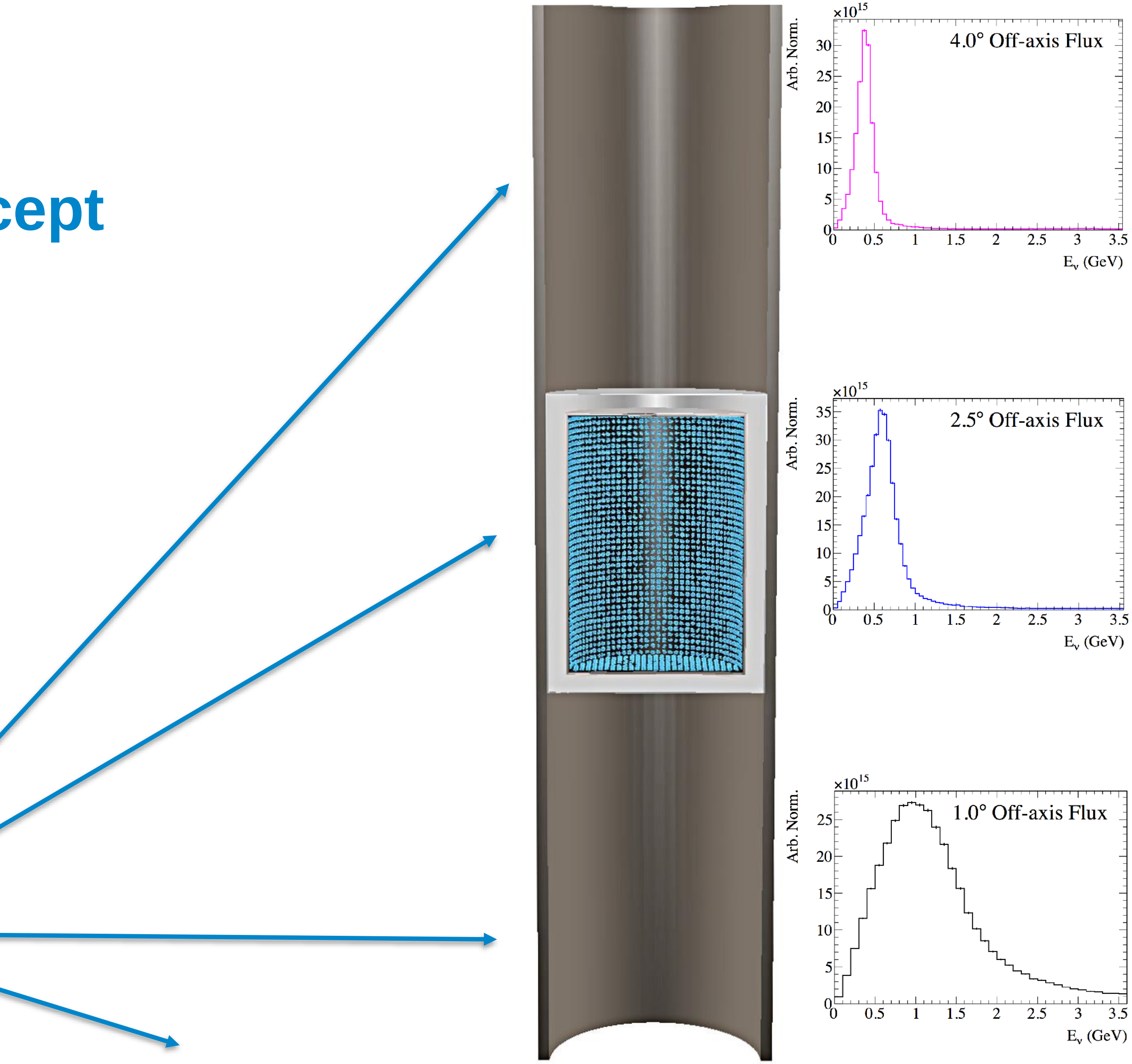
PRISM concept

- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position





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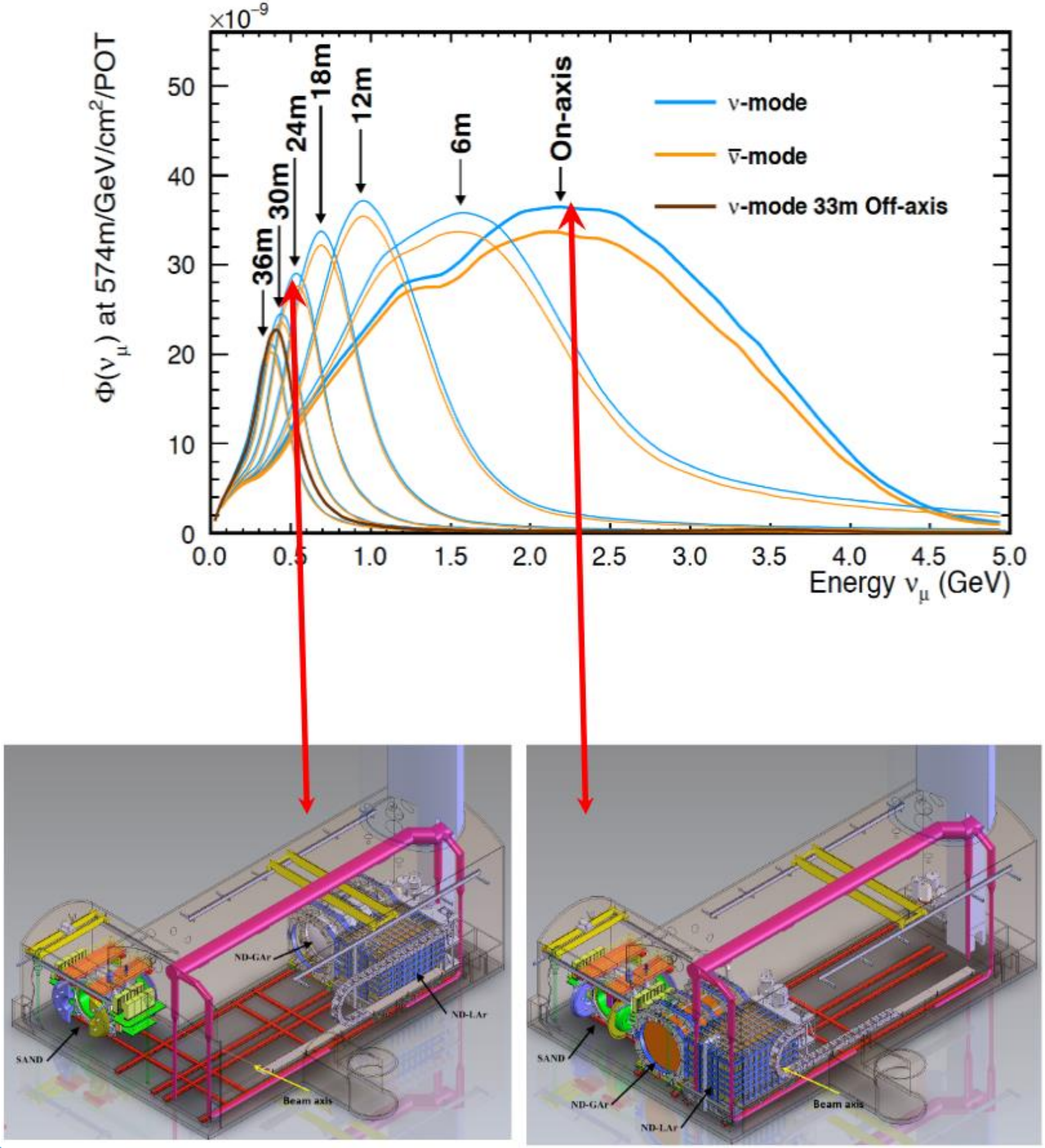

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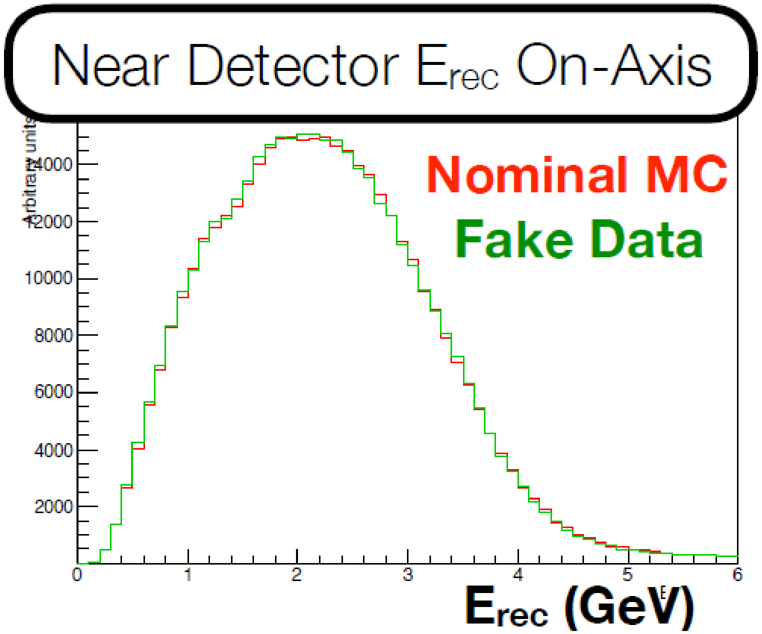
PRISM benefits - 1

DUNE study - C. Vilela, G. Yang



- Near detector along same axis as far detector
  - Tunes MC (red) to match near detector data (green)

PRISM benefits - 1

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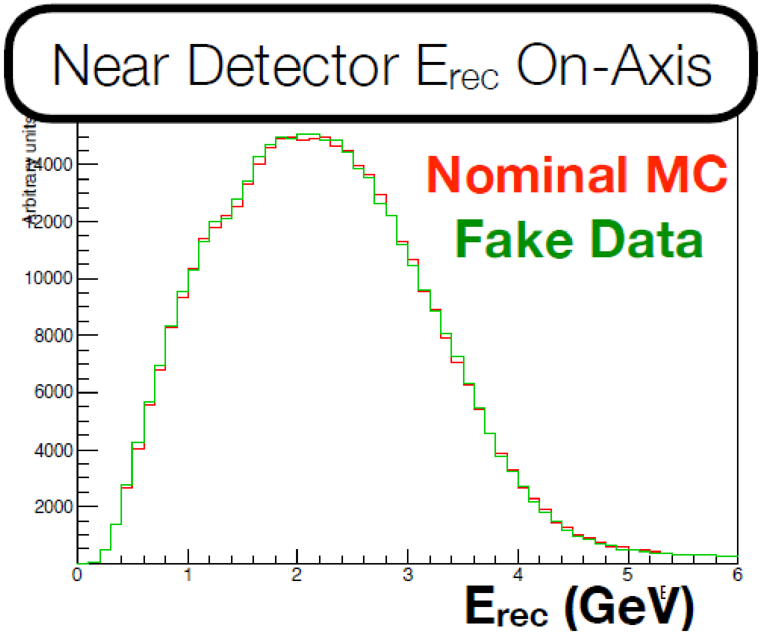

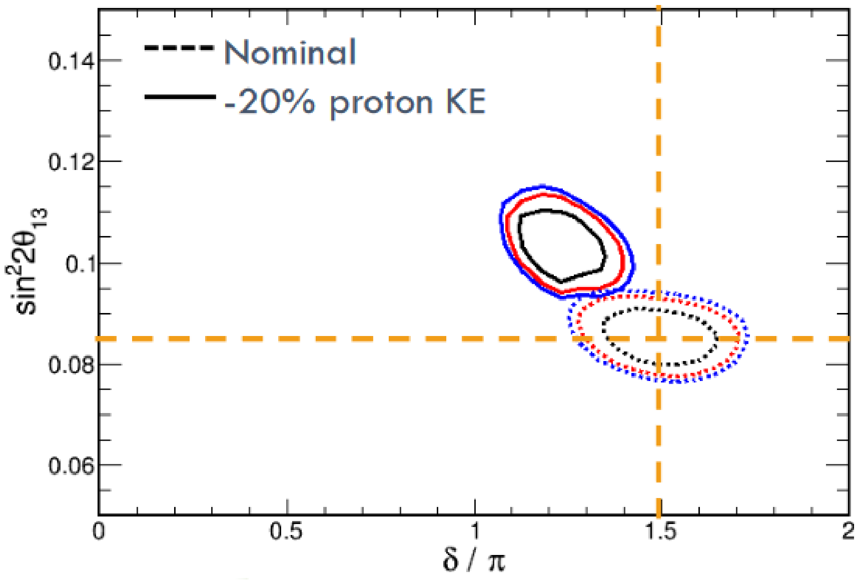

- Near detector along same axis as far detector
  - Tunes MC (red) to match near detector data (green)
  - Can associate data-MC differences to wrong model – biased oscillation measurement

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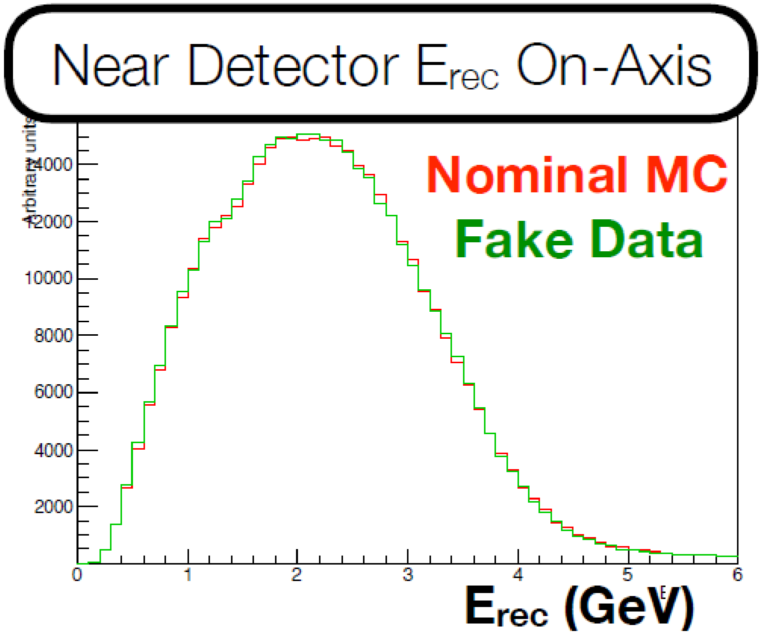
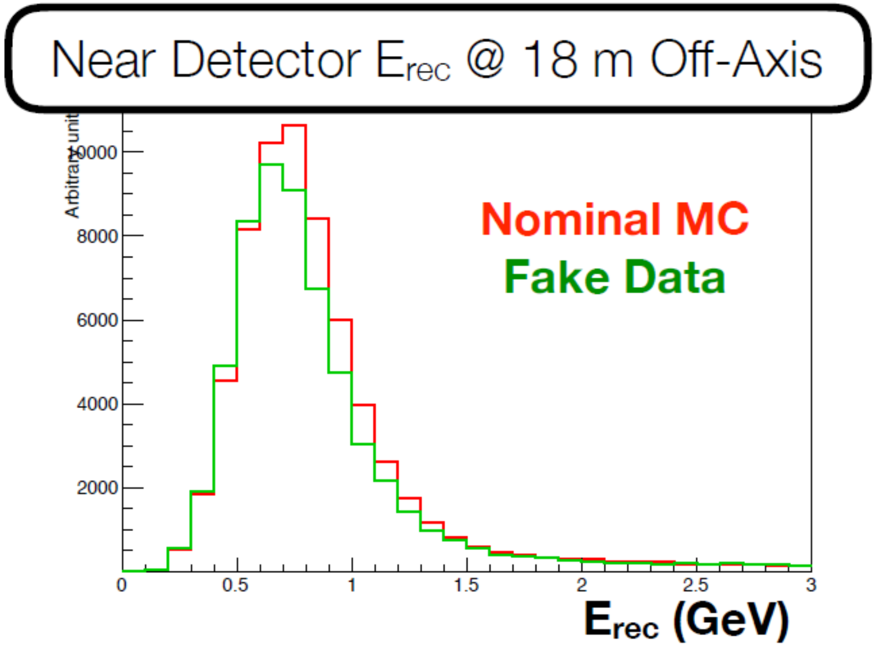
PRISM benefits - 1

DUNE study - C. Vilela, G. Yang





- Test MC tuning (green) by comparing to data (red) at point further off-axis (left plot)
- Clearly see model does not agree – model tuning wrong / model incomplete

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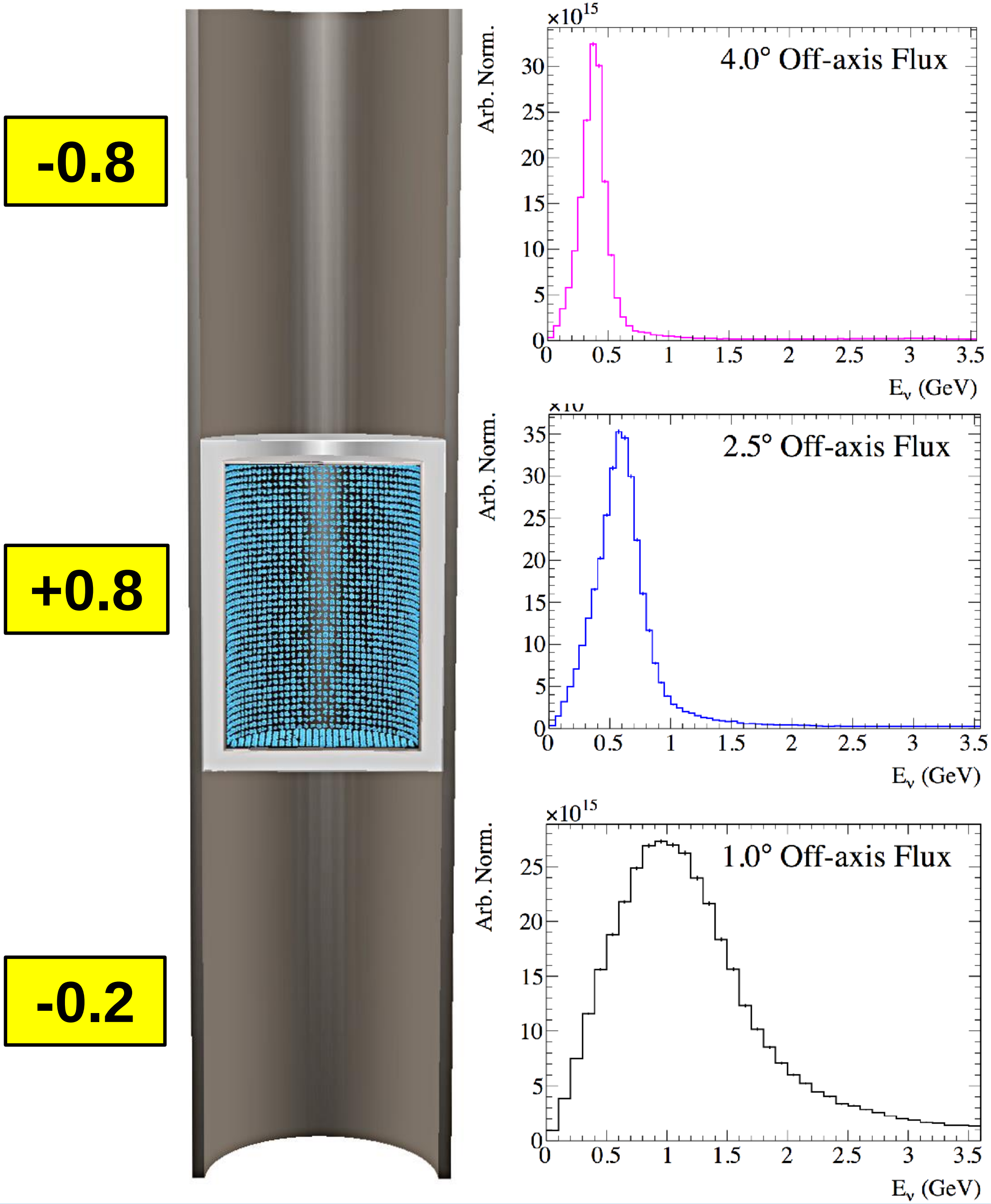
PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’



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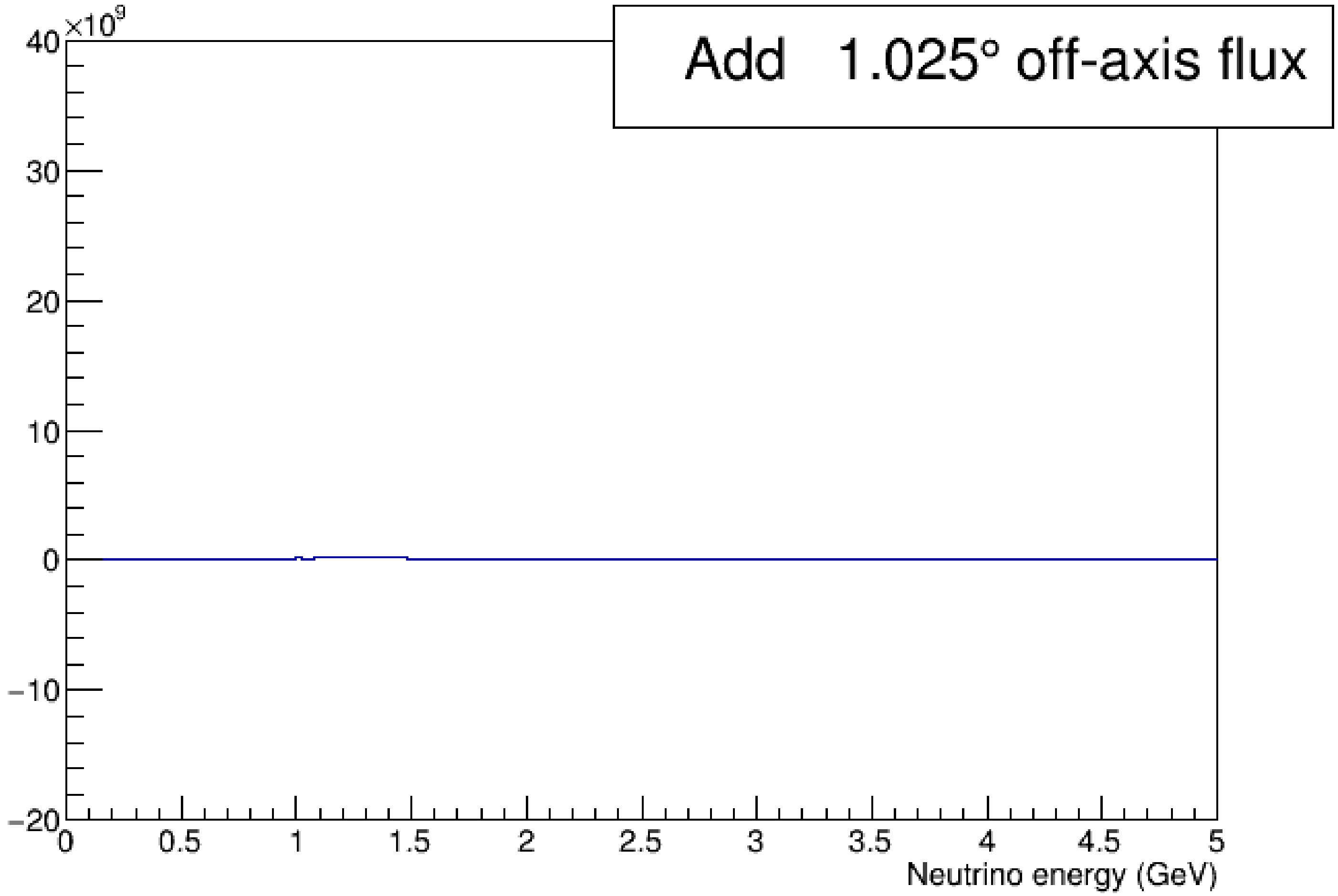

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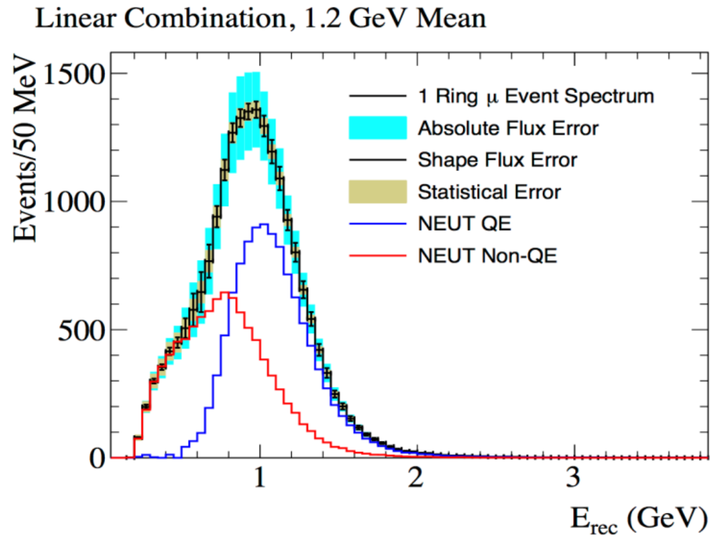
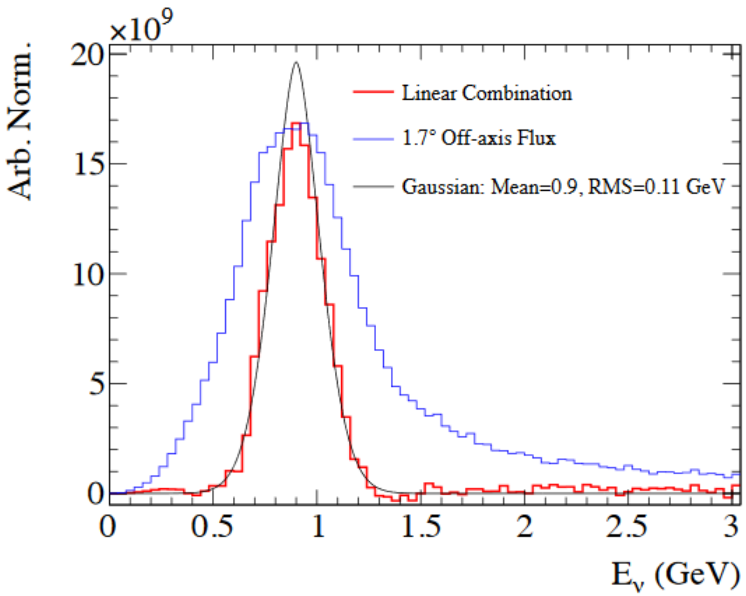
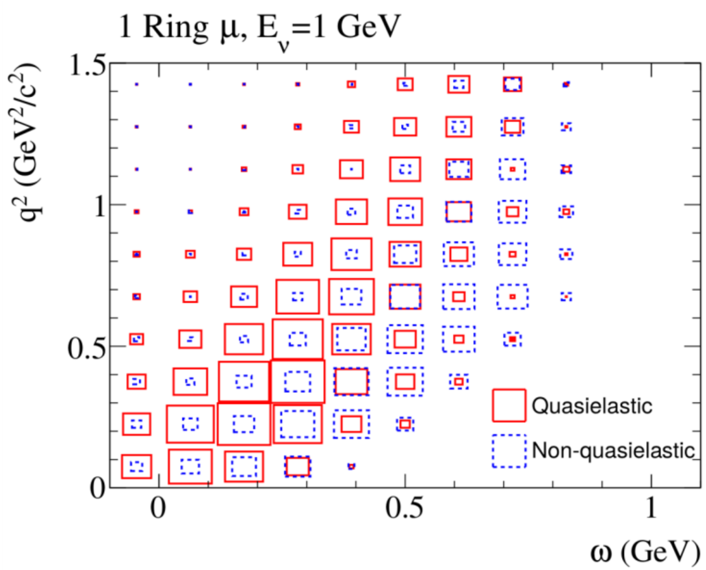
PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis 'slices'
- Produce Gaussian energy distribution







- Measure at a known energy
- Map out true-reco relationship
- Energy range determined by off-axis range