Improved Neutrino Energy Estimation in Neutral Current Interactions and Prospects for Sterile Neutrino Searches

Andrew P. Furmanski, Christopher Hilgenberg

DPF 2021

UNIVERSITY OF MINNESOTA

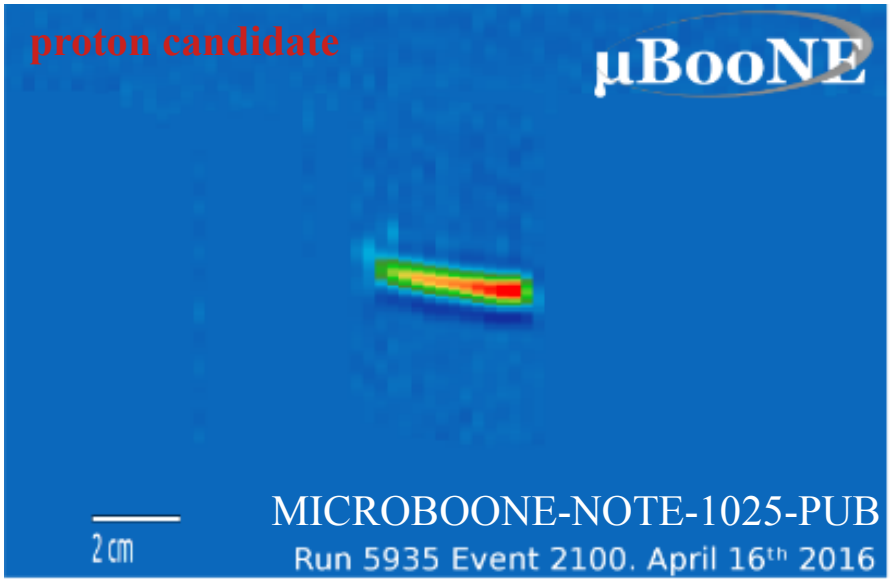
Outline

- NC scattering at the Short-Baseline Neutrino Program (SBN)
- NC neutrino energy reconstruction
  - Calorimetry only
  - Final state (FS) kinematics
- SBN sterile neutrino search sensitivity using NC

See Furmanski and Hilgenberg, Phys. Rev. D 103, 112011 (2021)

E_ν Reconstruction in NC Scattering

- Typically rely on calorimetry alone
- Performance of liquid argon time projection chambers motivates new method
  - Technology used in SBN/DUNE
  - Use FS kinematics
  - Analogous to CCQE scattering using outgoing lepton kinematics



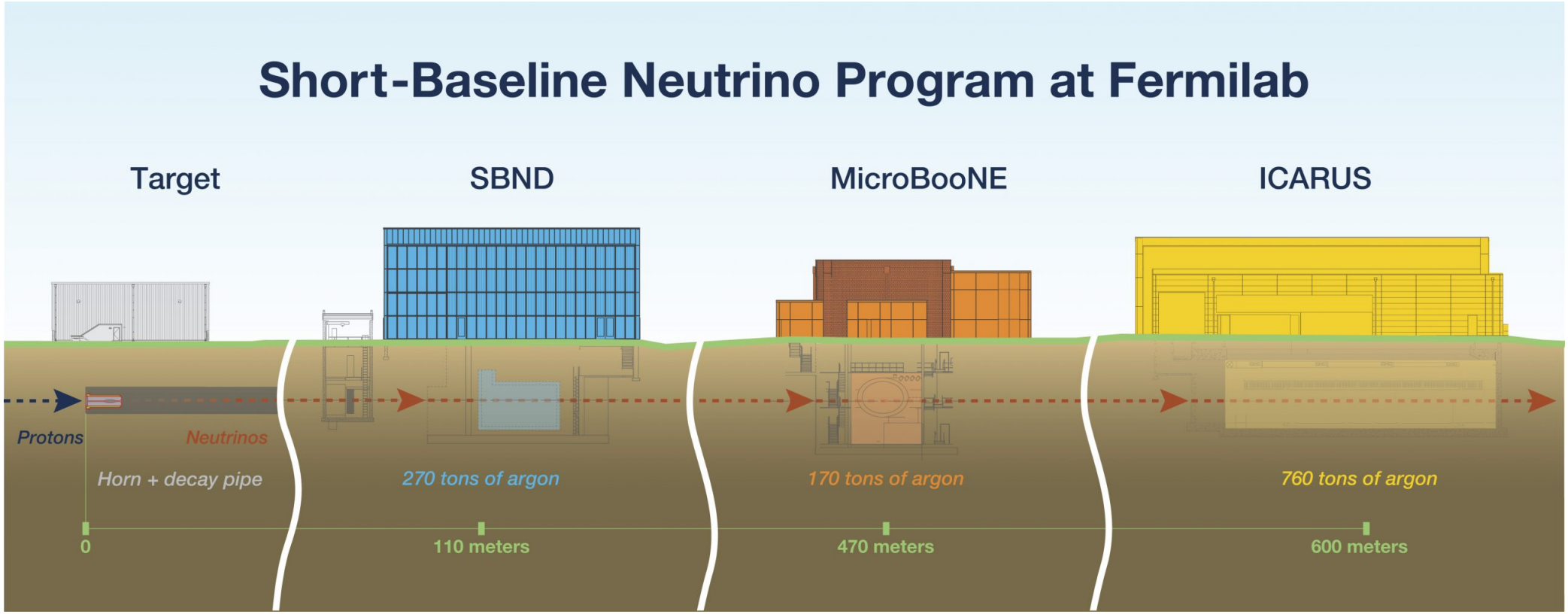
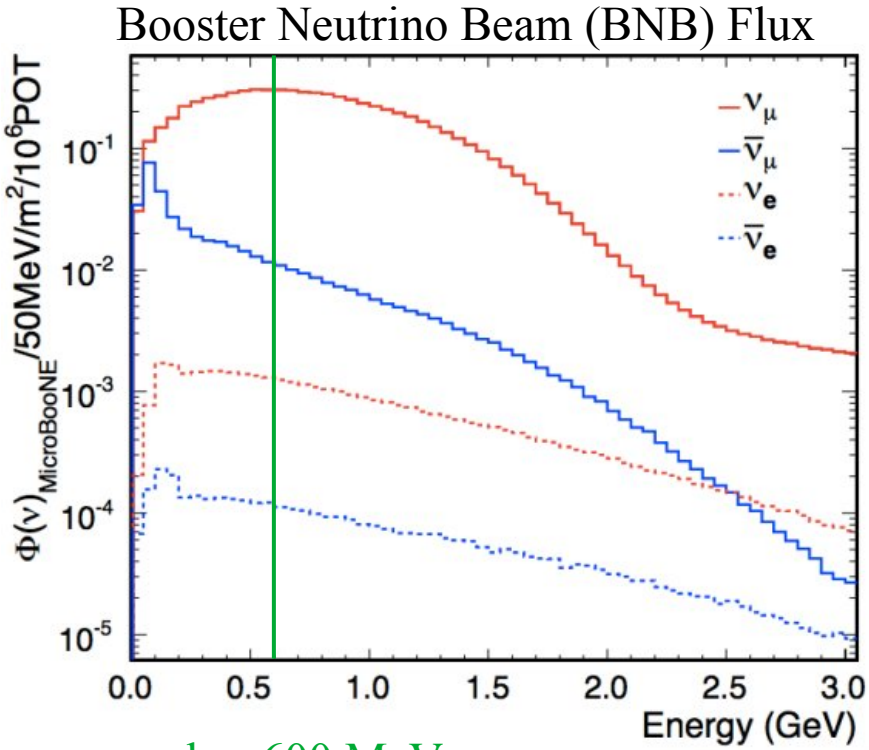


Image credit: Fermilab

Toy Study



peak ~ 600 MeV

- BNB-like flux [1]
- Generator level analysis
- GENIE [2] v3.00.06 with G1810a0211a
- 5 million ν_μ & $\bar{\nu}_\mu$ interactions on Ar for each SBN-like detector

1. arXiv:1503.01520
2. NIM A 614,87 (2010)

Assumed Performance

- Cheated reconstruction with Guassian resolution
- Neutron tagging
  - T threshold*: 50 MeV
  - 50% efficiency
- $\pi^{+/-}$ indistinguishable from μ's

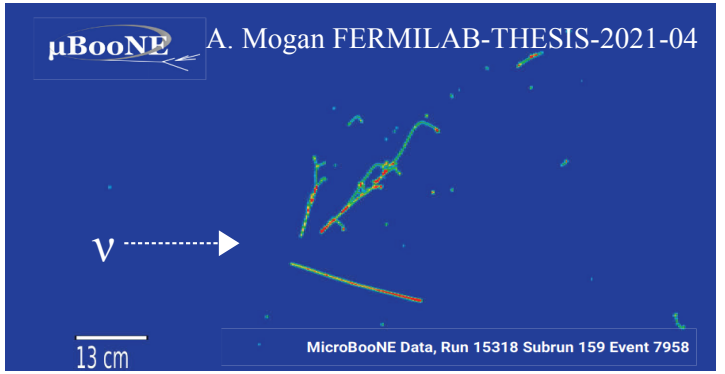
Species	Threshold* [MeV]	Energy Resolution	Angular Resolution [deg]
p [10] [11]	25-50	60 MeV	5-10
$\pi^{+/-}$ [12] [13]	10-20	10-20%	2-5
γ [14]	30	10-20%	5-10

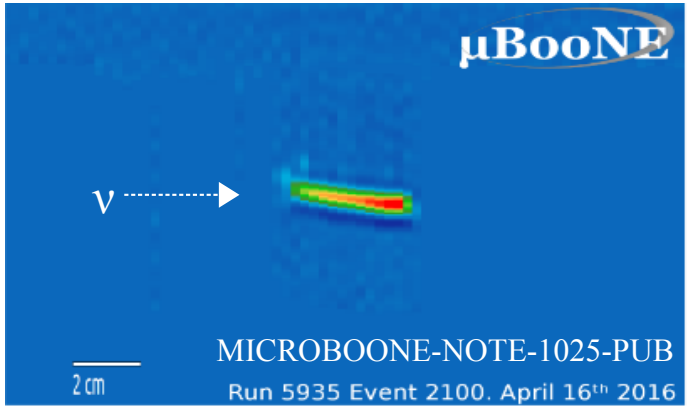
*threshold applied to true kinetic energy

10. Phys. Rev. D 89, 112003 (2014)
11. Phys. Rev. D 102, 112013 (2020)
12. Phys. Rev. Lett. 125, 201803 (2020)
13. Phys. Rev. Lett. 123, 131801 (2019)
14. JINST 15 P02007 (2020)

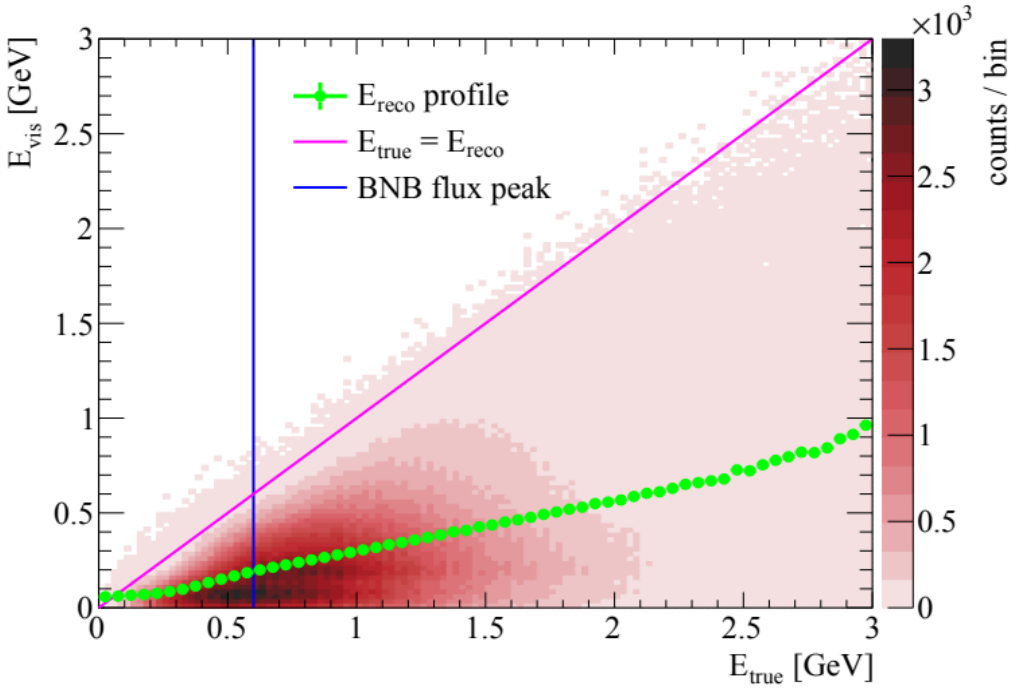
Event Selection

- NC0$\pi^{\pm}$
  - No leptons or $\pi^{\pm}$ above threshold
- NC1p with n-tagging
  - Single p above threshold only
  - Elastic scattering dominant
  - Reject if n-tagged





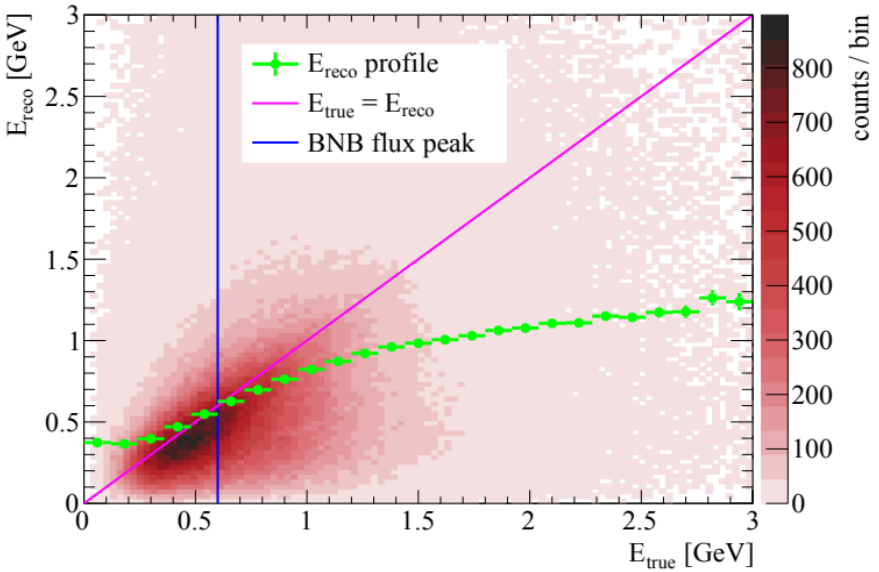
E_ν from Visible Energy



- $E_\nu > E_{vis} = \Sigma_i E_{had,i}$
- MC corrections required
- Method used in organic scintillator based experiments
  - NovA [1][2]
  - MINOS/ MINOS+ [3]

1. Phys. Rev. D 96,072006 (2017)
2. S. Yang, Ph.D. Thesis, Cincinnati U. (2019)
3. Phys. Rev. Lett. 122, 091803 (2019)

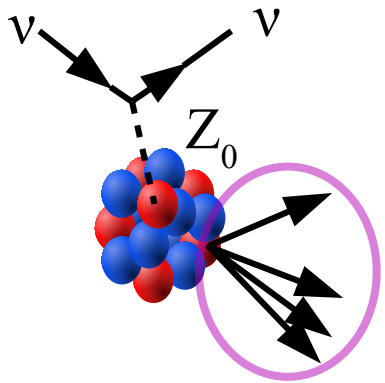
E_ν from Final State Kinematics



- Scatter off free nucleon at rest
- E_ν uniquely determined
- MC corrections not required

FS hadronic system with

- Total energy E_h
- Total momentum p_h
- Angle w.r.t. beam θ_h



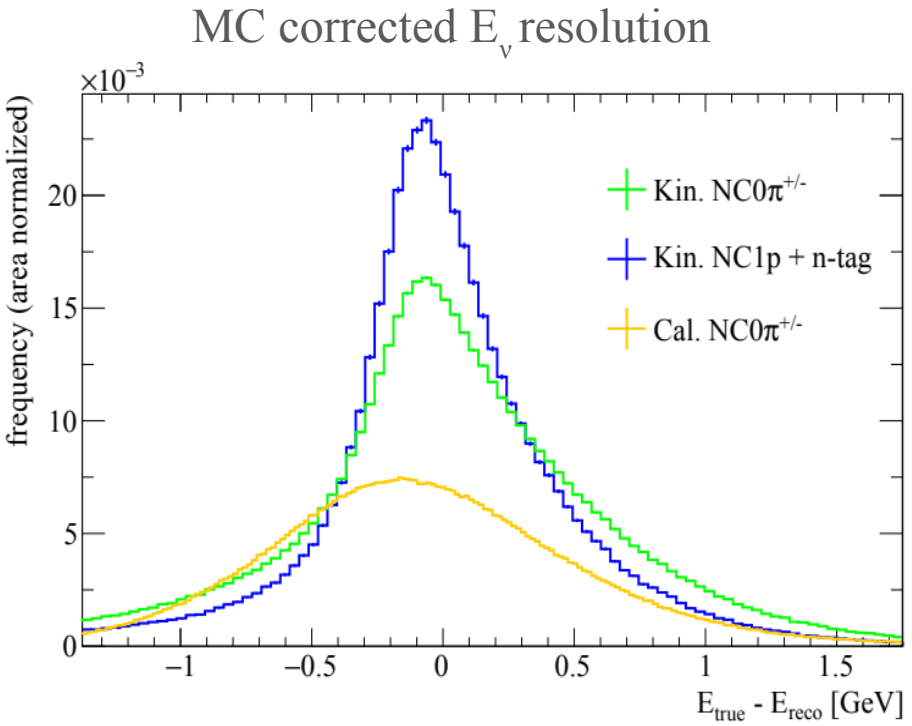
$$E_\nu = \frac{p_h^2 - (E_h - m_N)^2}{2(m_N + p_h \cos\theta_h - E_h)}$$

Performance

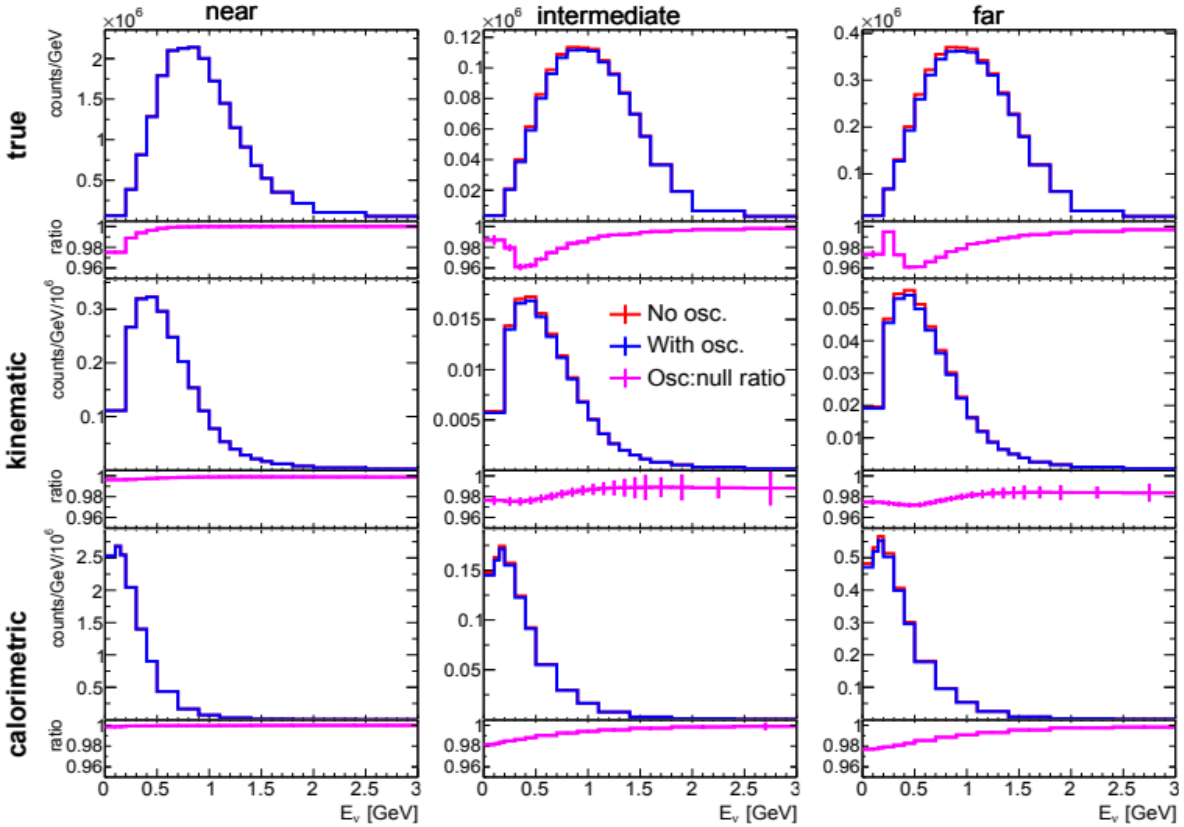
Method / Selection	Integrated Efficiency[%]
Cal NC0$\pi^{+/-}$	45
Kin NC0$\pi^{+/-}$	35
Kin NC1p + n-tag	15

kinematic vs. calorimetric (corrected)

- 75% lower bias
- 45% lower FWHM
- 10% lower efficiency



Probing the 3+1 Model with νNC



$$P_{\nu_\mu \to \nu_s} = \sin^2 2\theta_{\mu s} \sin^2\left(1.27 \Delta m^2_{41} \frac{L}{E_\nu}\right)$$

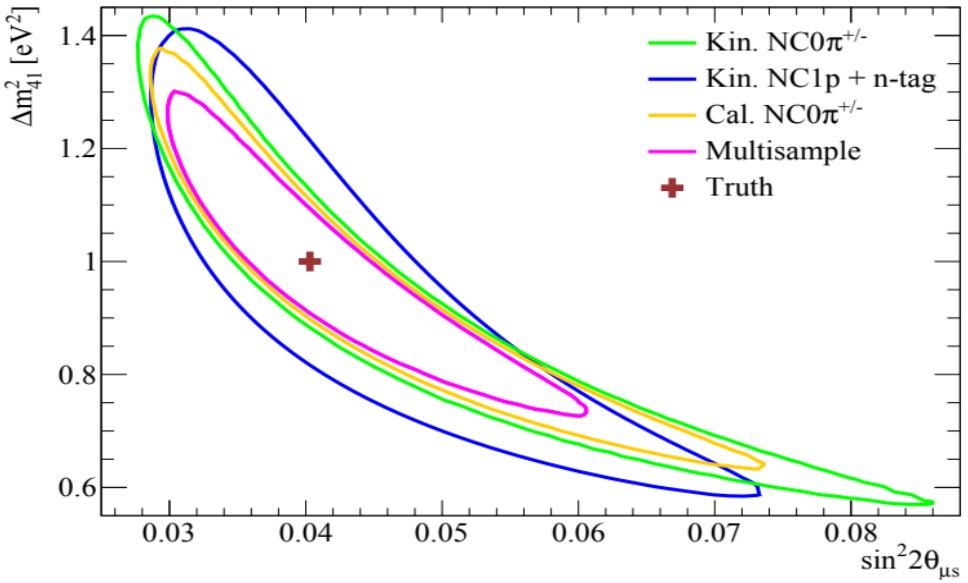
Signal: disappearance of *any* active flavors

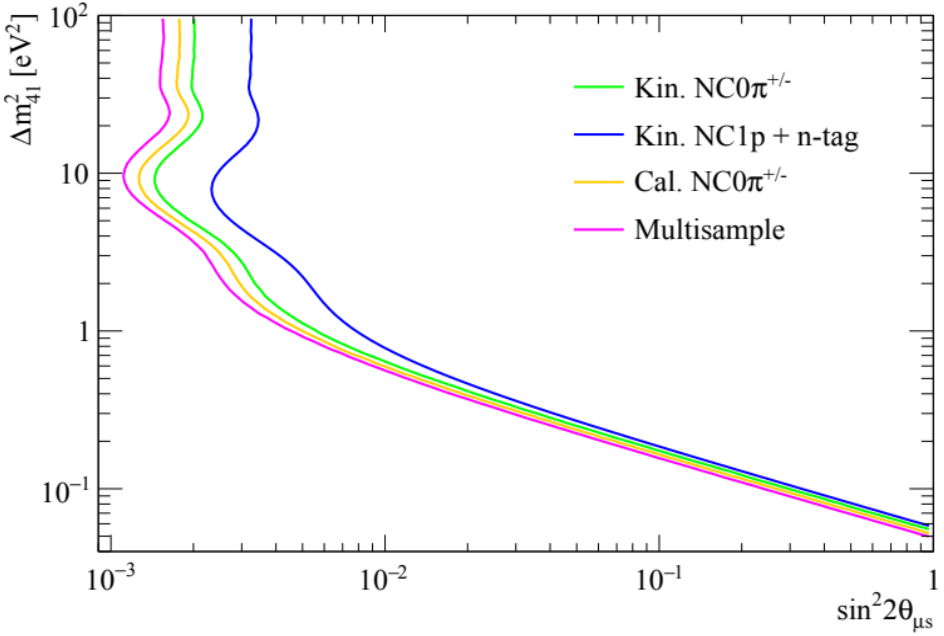
$\sin^2 2\theta_{\mu s} = 0.04$

$\Delta m^2_{41} = 1.00\ \text{eV}^2$

at fixed, ideal baseline

3+1 Sensitivity via NC Disappearance





- Maintain statistics but add shape information
- Multisample method: Kin. NC1p + n-tag $\oplus$ Kin. NC0$\pi^{+/-}$ $\oplus$ Cal. NC0$\pi^{+/-}$

Summary and Next

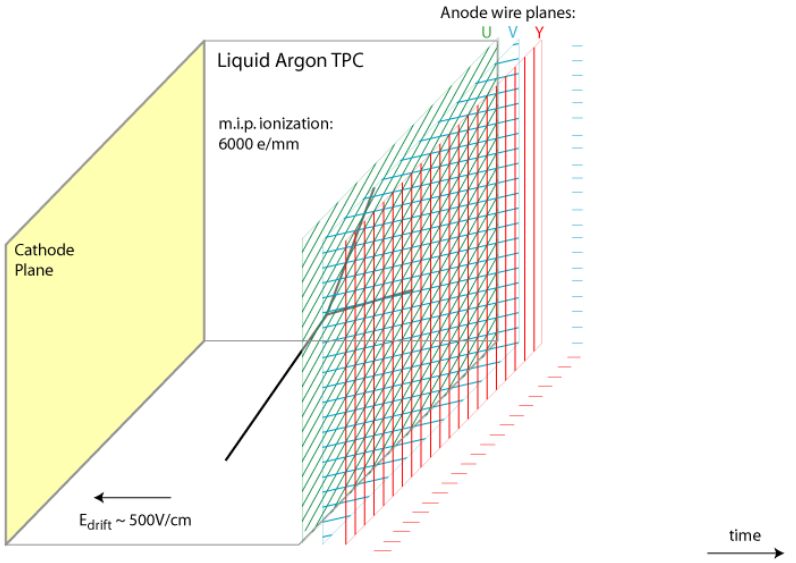
- Kinematic method performs favorably at BNB energies compared to calorimetric method
- NC disappearance is interesting channel for sterile search at SBN with kinematic method improving sensitivity
- Introduce method to SBN experiments
  - Test method with MicroBooNE data
  - Incorporate into SBN oscillation analyses

See Furmanski and Hilgenberg, Phys. Rev. D 103, 112011 (2021)

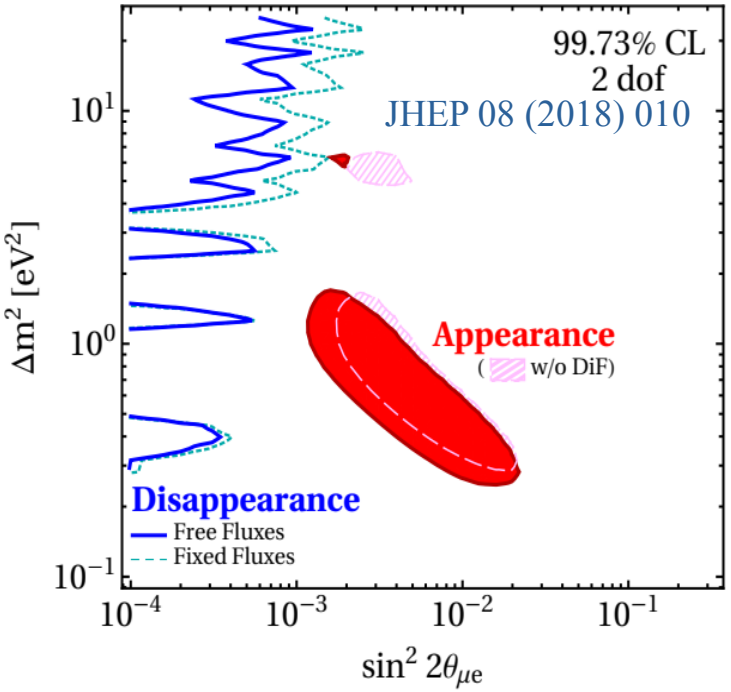
backup

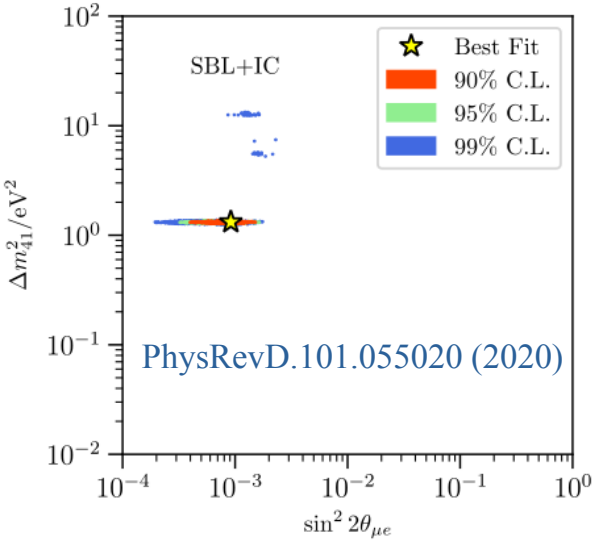
Liquid Argon Time Projection Chambers

- mm^3 spatial resolution
- Full sampling calorimetry
- Tens of MeV thresholds
- Used in accelerator neutrino experiments
  - ICARUS
  - ArgoNeuT
  - MicroBooNE
  - **SBN**
  - DUNE

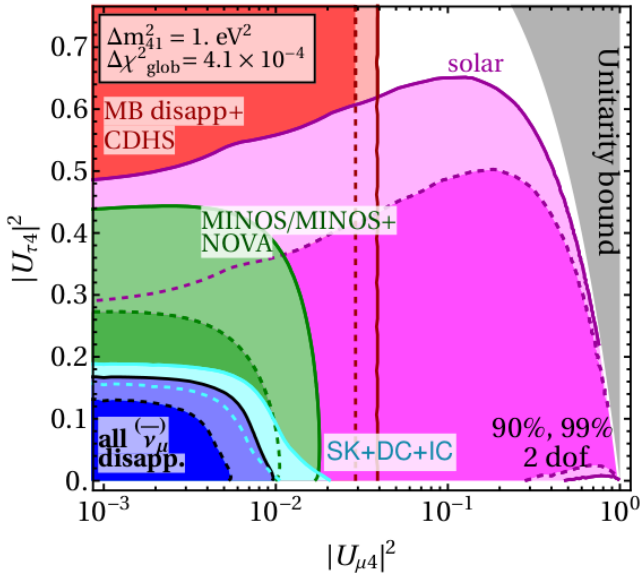


3+1 Global Analyses



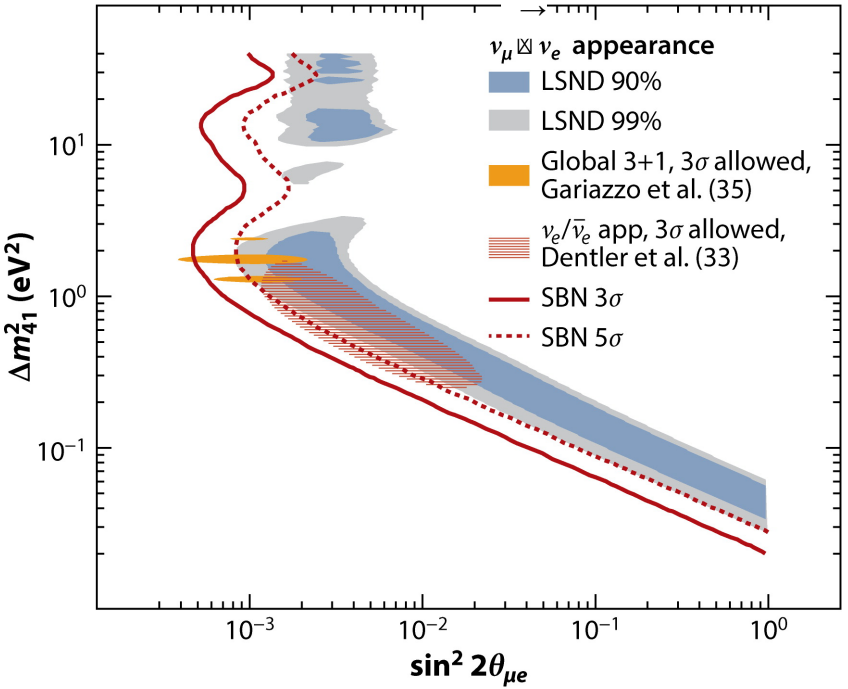


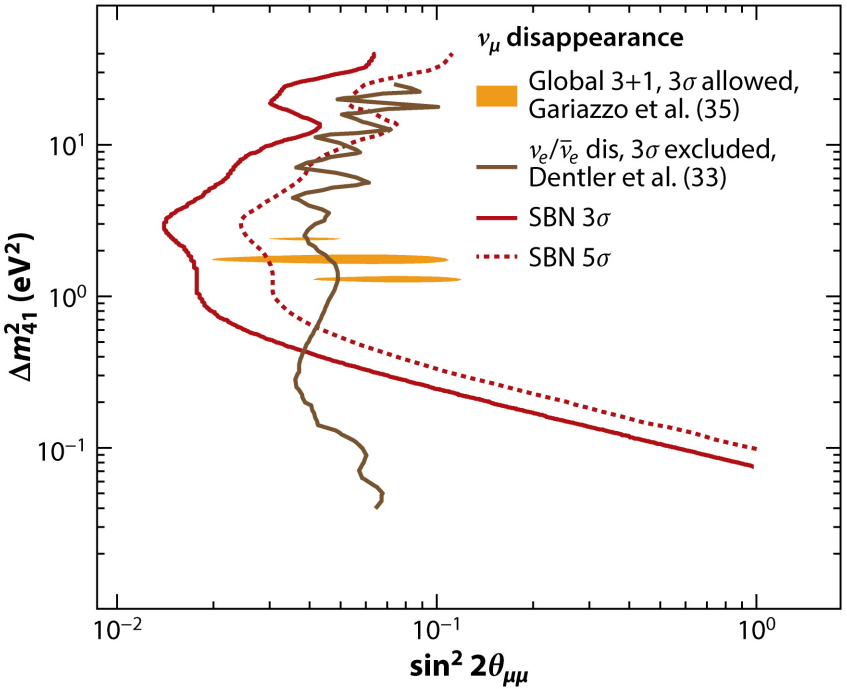
JHEP 08 (2018) 010



- 4.7σ tension between appearance/disappearance data sets (probe $|U_{e4}|$ and $|U_{\mu 4}|$)
- $|U_{\tau 4}|$ poorly constrained, most stringent from IceCube

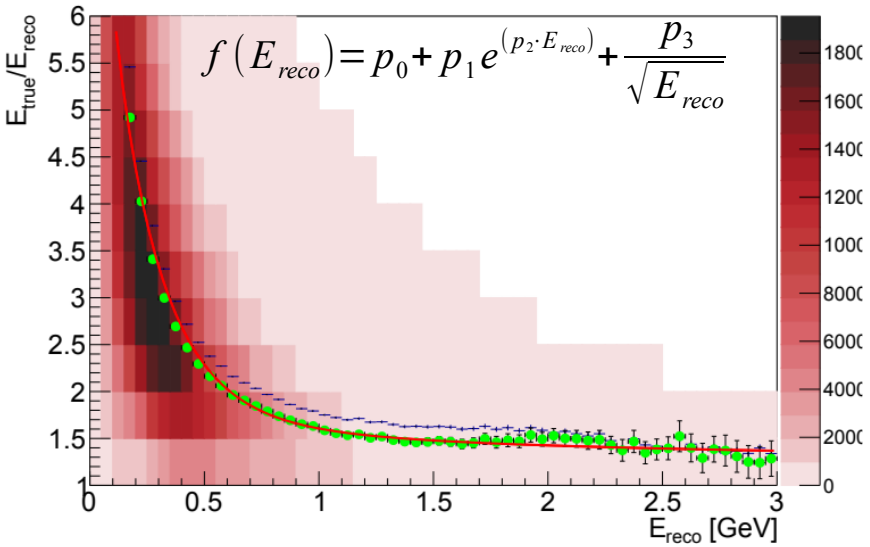
SBN 3+1 Sensitivity via CC



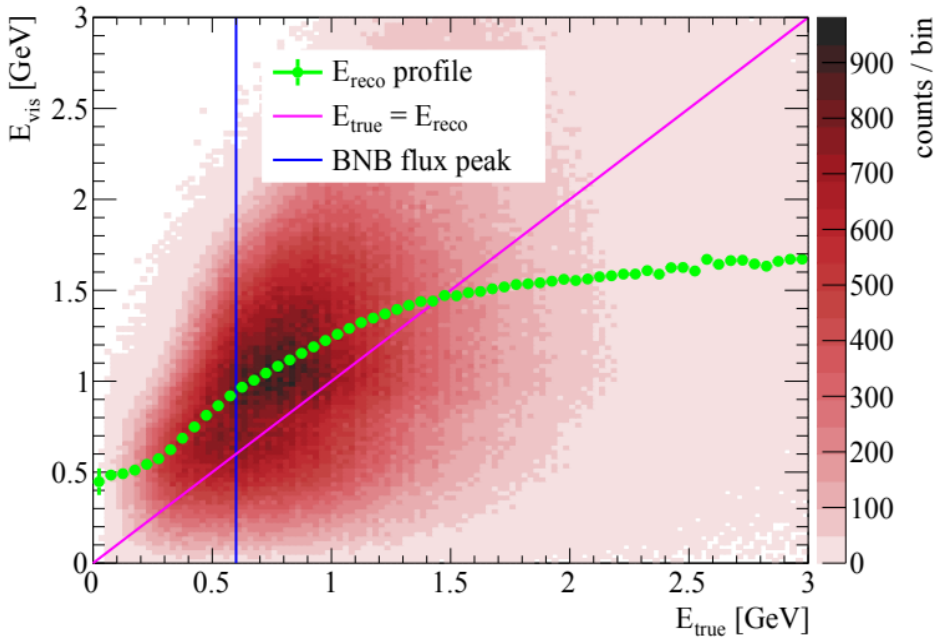


Machado PAN, et al. 2019.
Annu. Rev. Nucl. Part. Sci. 69:363–87

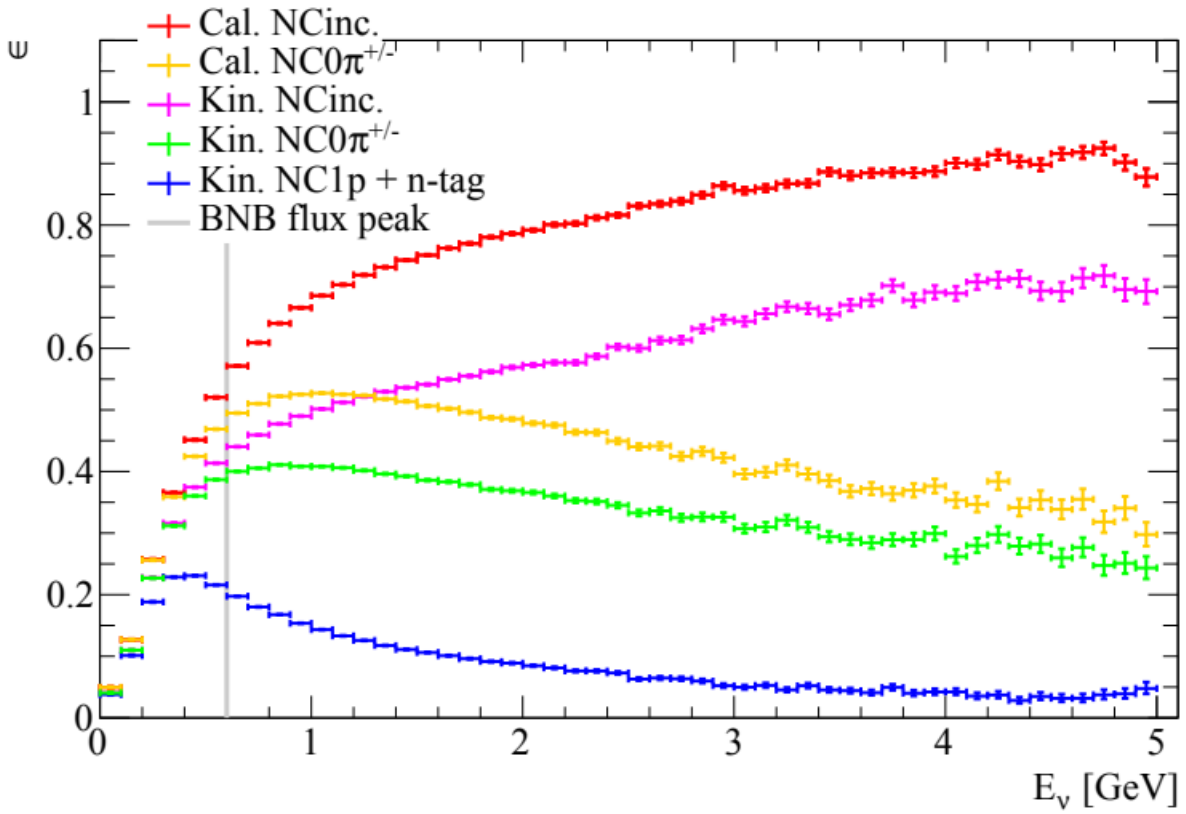
MC Correction for Cal. Method



- Experiments **do not** assume $E_{vis} \sim E_{\nu}$
- MC templates or unfolding employed



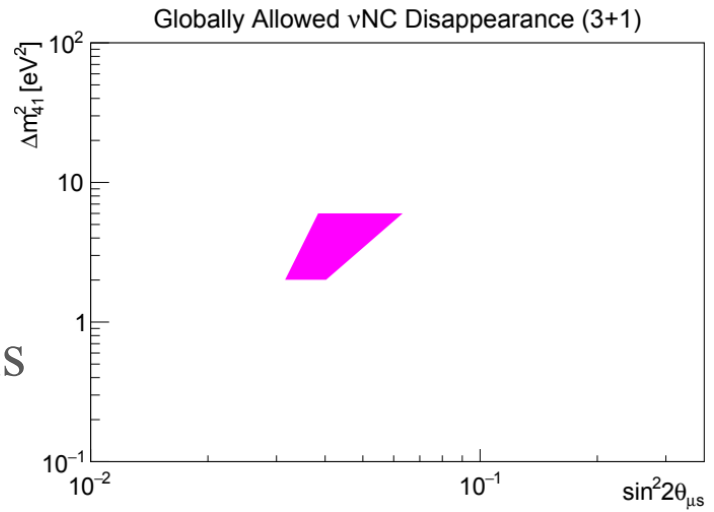
Efficiencies



Method / selection	Integrated Efficiencies [%]
Cal NCinc	60
Cal NC0$\pi^{+/-}$	47
Kin NCinc	45
Kin NC0$\pi^{+/-}$	37
Kin NC1p + n-tag	16

Deriving a Globally Allowed Region in ($\sin 2\theta_{\mu s}$, Δm_{41}^2) Space

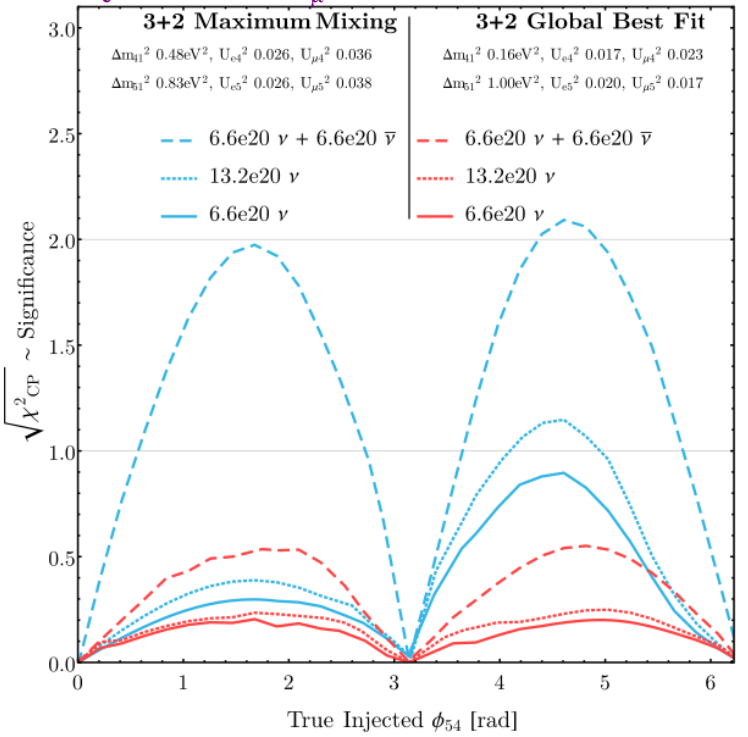
- At short baselines, mixing angle determined by $|U_{\mu 4}|$,$|U_{s4}|$
  - $|U_{s4}|$ calculated from unitarity condition
- PhysRevD 101.055020 provides a table with 3+1 PMNS element values in 90% C.L. intervals
  - Includes statistical and systematic uncertainties
  - Values given for two values of Δm_{41}^2: 2 and 7 eV^2
  - Yields 4 points in parameter space



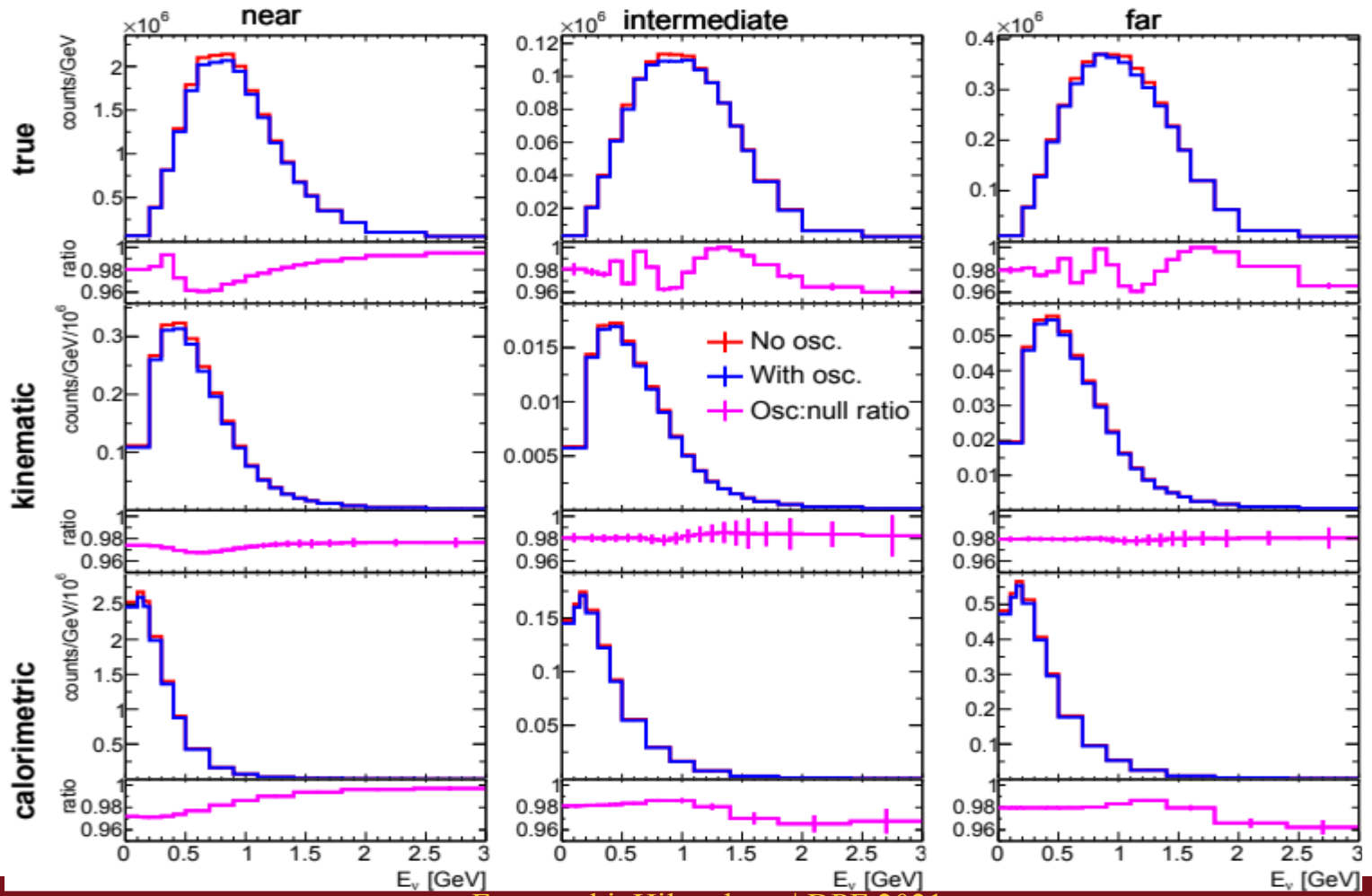
Aside: 3+2 and 3+3 Models

- 3+1 sensitivity provides a convenient benchmark
- Additional parameters w.r.t. 3+1
  - 3+2: 2 matrix elements, 1 mass splitting, 1 CPV phase
  - 3+3: 4 matrix elements, 2 mass splittings, 3 CPV phases
- Global analyses prefer mass splittings O(1 eV^2) for 3+1, 3+2, 3+3
- See Phys Rev D 96.055001 for an SBN sensitivity analysis for each model
- Bottom line: νNC disappearance analysis at SBN could extend SBN's reach to cover 3+2 and 3+3 phase space, even CPV

ν_e dis/app + ν_μ dis joint fit (no νNC dis)



E_ν Spectra*: $\sin^2 2\theta_{\mu s} = 0.04$, $\Delta m^2_{41} = 7.00\ eV^2$



*fixed, ideal baseline

Calculating Sensitivities

- Use binned Poisson likelihood (L)
  - N^{exp} → null hypothesis
  - N^{obs} → measurement
- Index runs over bins of reconstructed energy, all detectors
- Construct log likelihood ratio (-2lnλ)
  - Asimov data set (global min χ^2) in denominator
- Assume Wilk's theorem applies to obtain significance (σ)

$$L = \prod_i^N \frac{(N_i^{exp})^{N_i^{obs}}}{N_i^{obs}!} e^{-N_i^{exp}}$$

$$-2\ln\lambda = 2\sum_i^N \left[N_i^{exp} - N_i^{obs} + N_i^{obs} \ln \frac{N_i^{obs}}{N_i^{exp}} \right]$$

$$\Delta\chi^2 = \chi^2_{test} - \chi^2_{Asimov}$$

$$\sigma = \sqrt{\Delta\chi^2} = \sqrt{-2\ln\lambda}$$