Overview of next-generation oscillation experiments

Callum Wilkinson

Thanks to Stephen Dolan, Luke Pickering, Patrick Stowell and Clarence Wret for material

accelerator long-baseline

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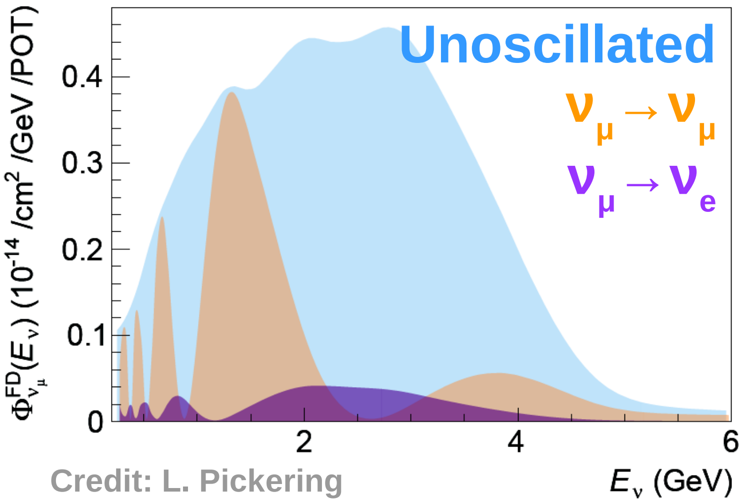
BERKELEY LAB

Accelerator neutrino experiments

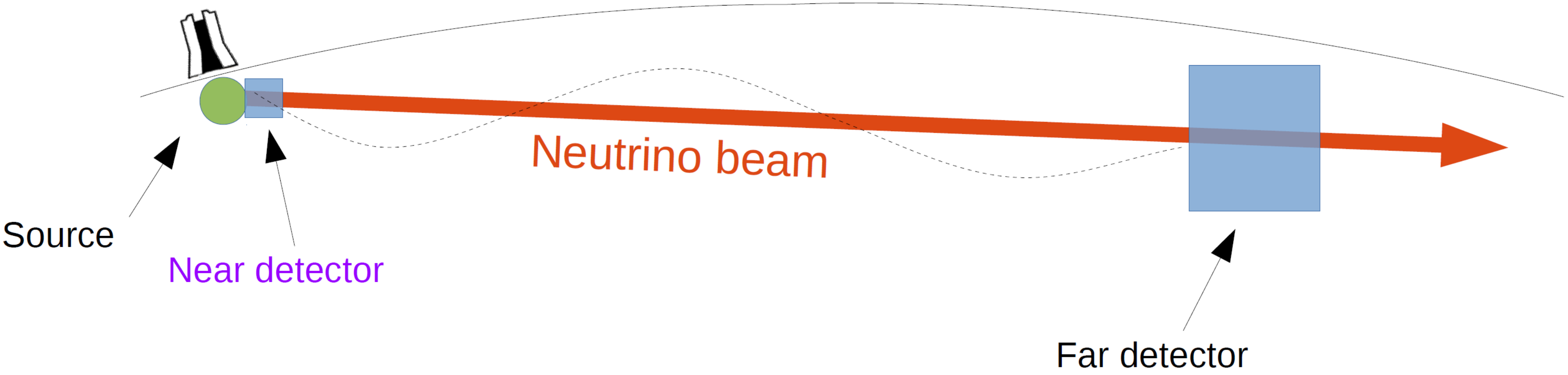
$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\int dE\ \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(E_\nu; \nu_A \to \nu_B)}_{\text{Far}}$$



Credit: L. Pickering

- Complex inference of **oscillation probability** from measured **event rate**
- Near detector to constrain **neutrino flux** and **cross-section** models/systematics
- Different near and far detector fluxes mean uncertainties do not neatly cancel
- **Detector smearing** introduces further ambiguities at both near and far detectors

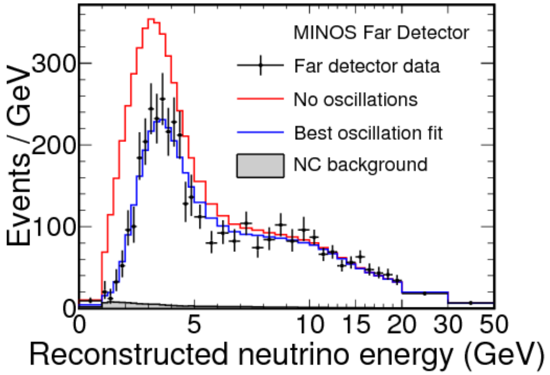
Accelerator neutrino experiments



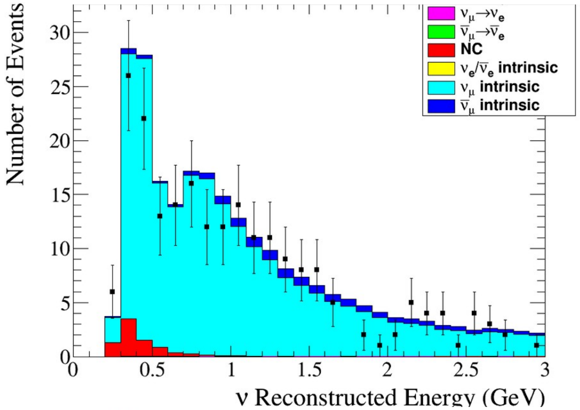
- Δm^2_{32} sets P_{max}~500 L/E_ν (km/GeV)
- Trade-off between L and E:
  - $R \sim 1/L^2$
  - $R \sim E_\nu$
  - Matter effect increases with E
- Choice of detector technology important for E_ν reconstruction and resolution

Accelerator neutrino experiment history

	Name	**L (km)**	**Peak E_ν (GeV)**	**Year (projected)**	**FD mass**
Past	K2K	250	1	1999-2004	22.5 kt
	MINOS	735	3	2005-2012	5.4 kt
	OPERA	732	17	2008-2012	1.35 kt
Present	T2K	295	0.6	2010-(202?)	27.2 kt
	NOvA	810	2	2013-(202?)	14 kt
Future	DUNE	1285	2.5	(2031-204?)	40 kt
	Hyper-K	295	0.6	(2028-204?)	187 kt



Past



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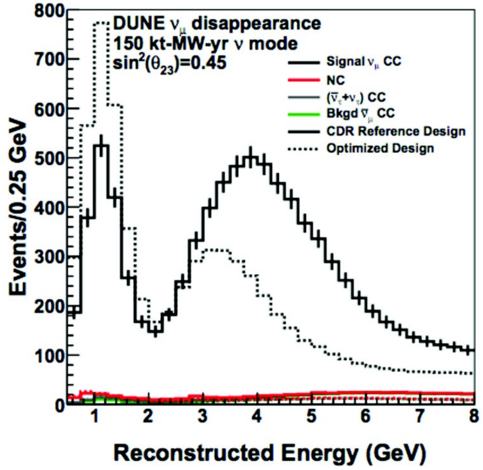
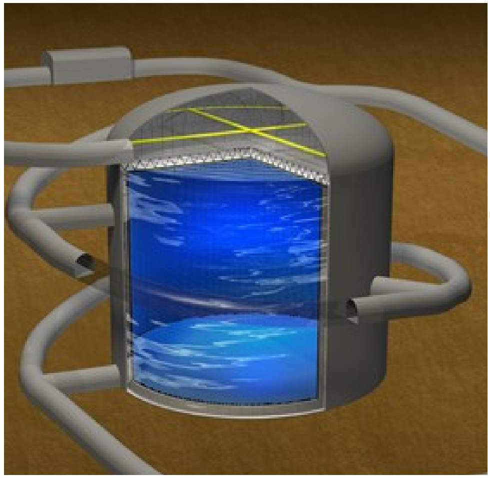
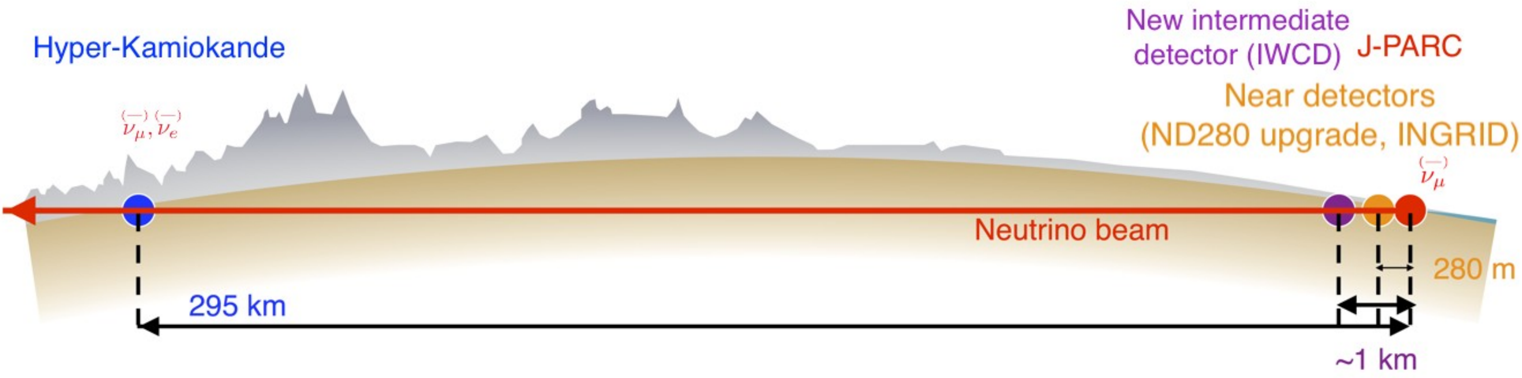
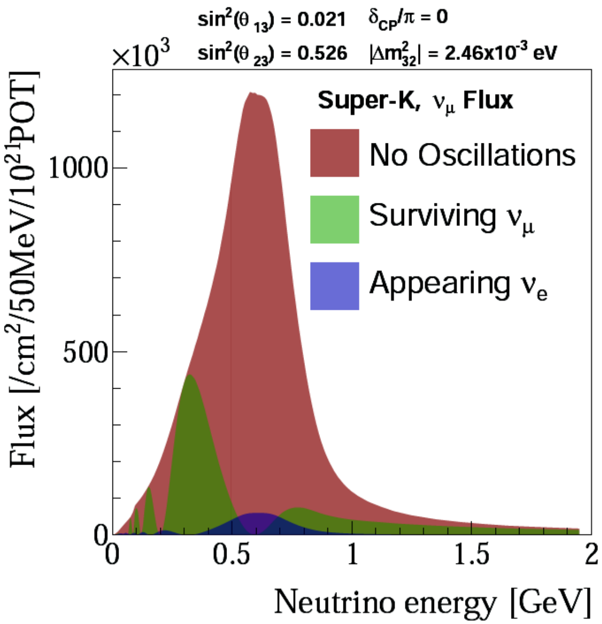


Future

Hyper-K overview





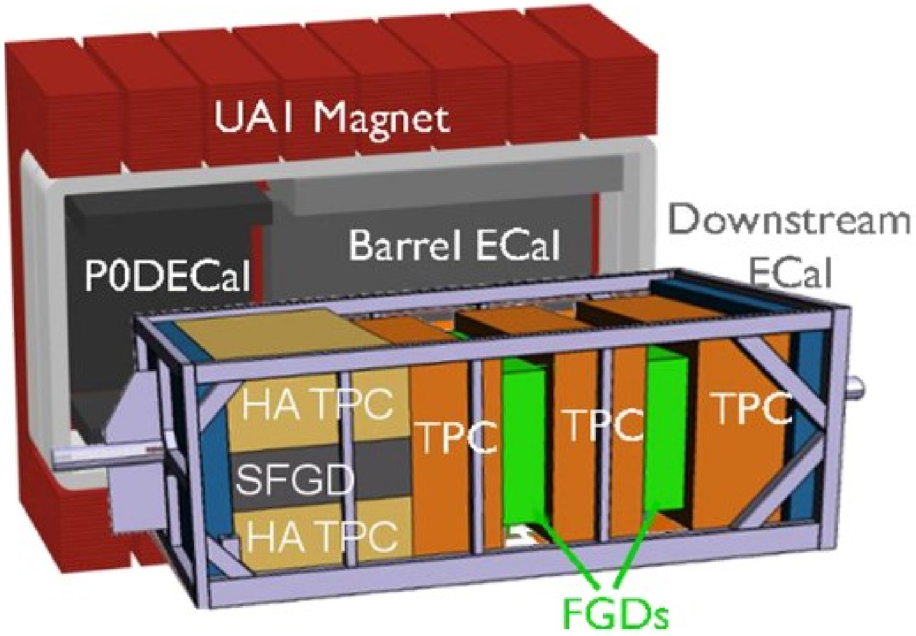


Credit: L. Pickering

- L ≈ 295 km; $E_\nu \approx$ 0.6 GeV (*narrow band*); water Cherenkov detector
- Significant upgrade to T2K design:
  - 1.3 MW beam
  - Upgraded near detector complex
  - 187 kt FV tank (~7x Super-K FV)
- Civil construction underway, physics ~2028

Hyper-K near detector

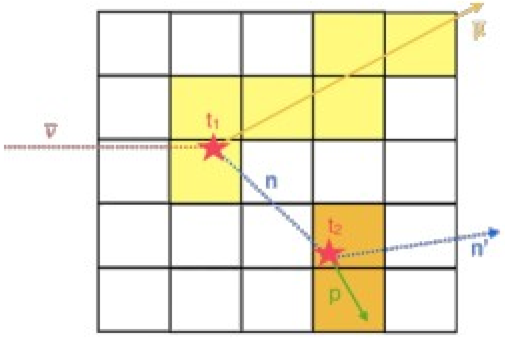
2.5° off axis



Upgraded (T2K) ND280:

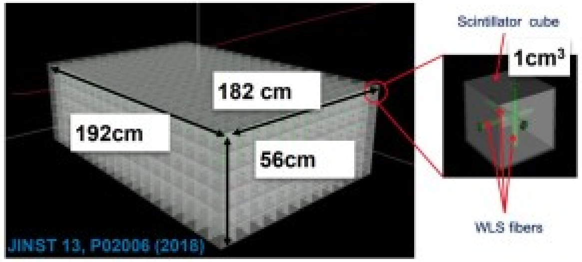
- High resolution SFGD
- Improved angular acceptance
- Neutron tagging capabilities

+Intermediate Water Cherenkov Detector (IWCD)



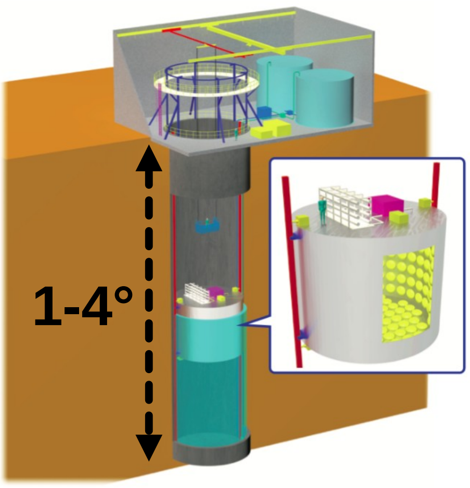
Neutron measurements

Phys. Rev. D **101**, 092003
Phys. Rev. D **110**, 032019

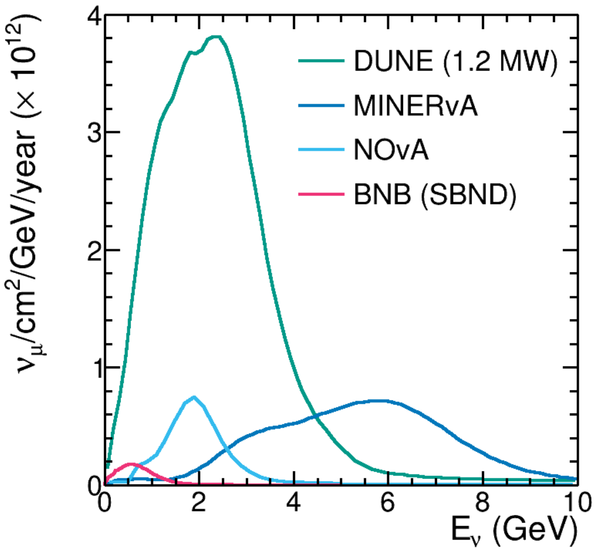


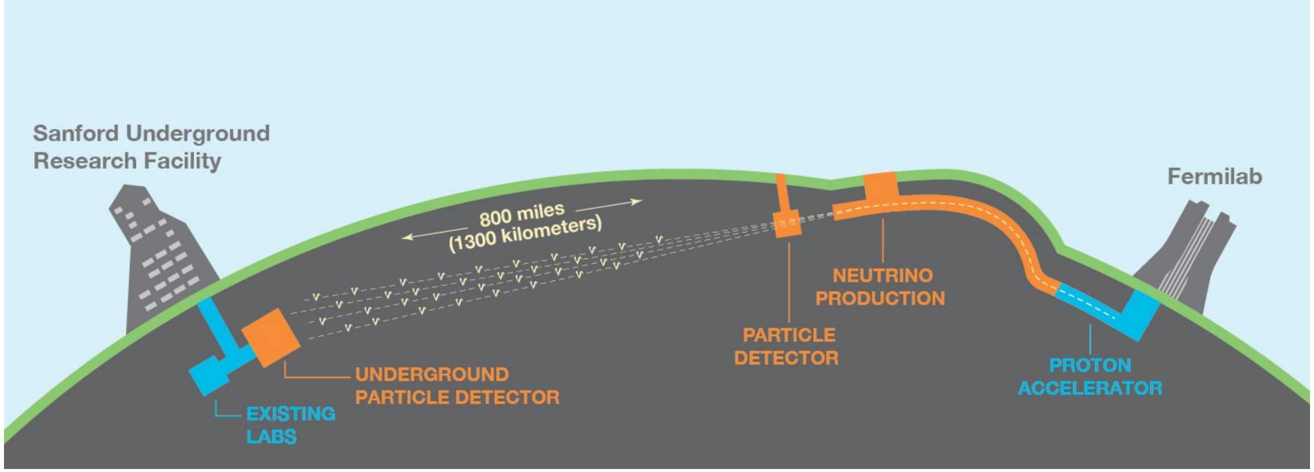
Super-fine granularity

JINST **13**, P02006



DUNE overview





- L ≈ 1285 km; $E_\nu \approx$ 2.5 GeV (*broad band*); liquid argon time projection chamber (LArTPC)
- High-intensity neutrino beam (1.2 → 2.4 MW)
- Near detector system at Fermilab
- 4 x 17 kt LAr far detector modules at SURF

DUNE near detector

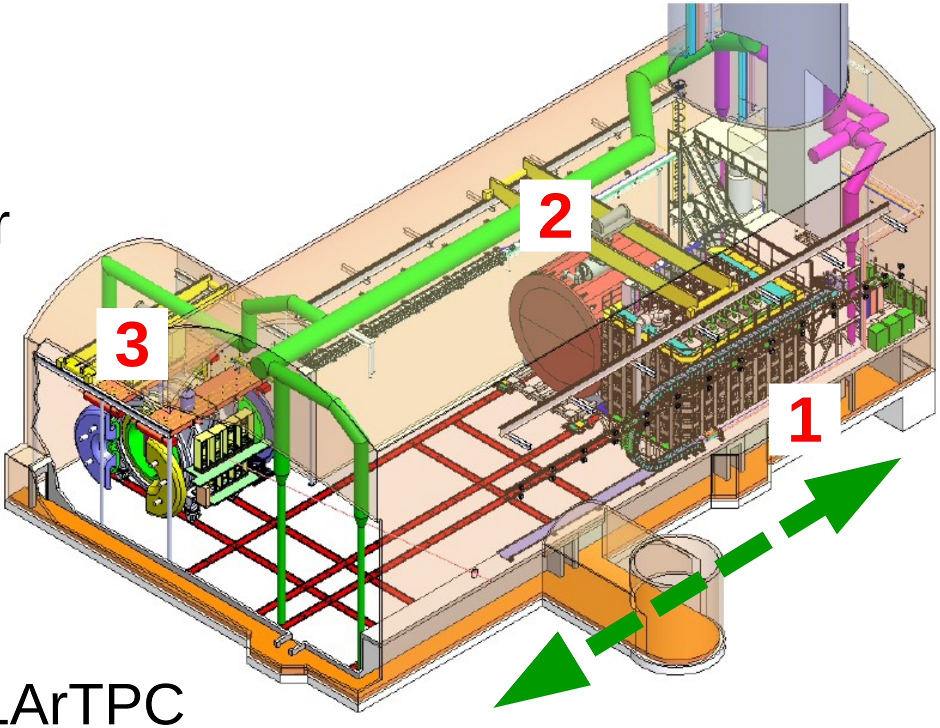
Moveable

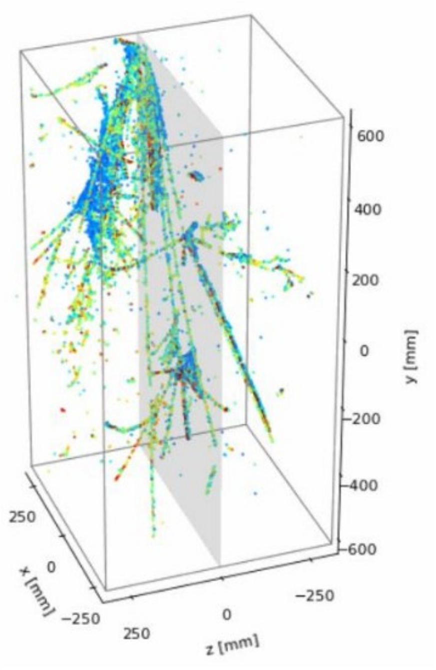
Three major components:

1 – Pixelated 150 t LArTPC

2 – Downstream magnetized tracker

3 – SAND: dedicated beam monitor

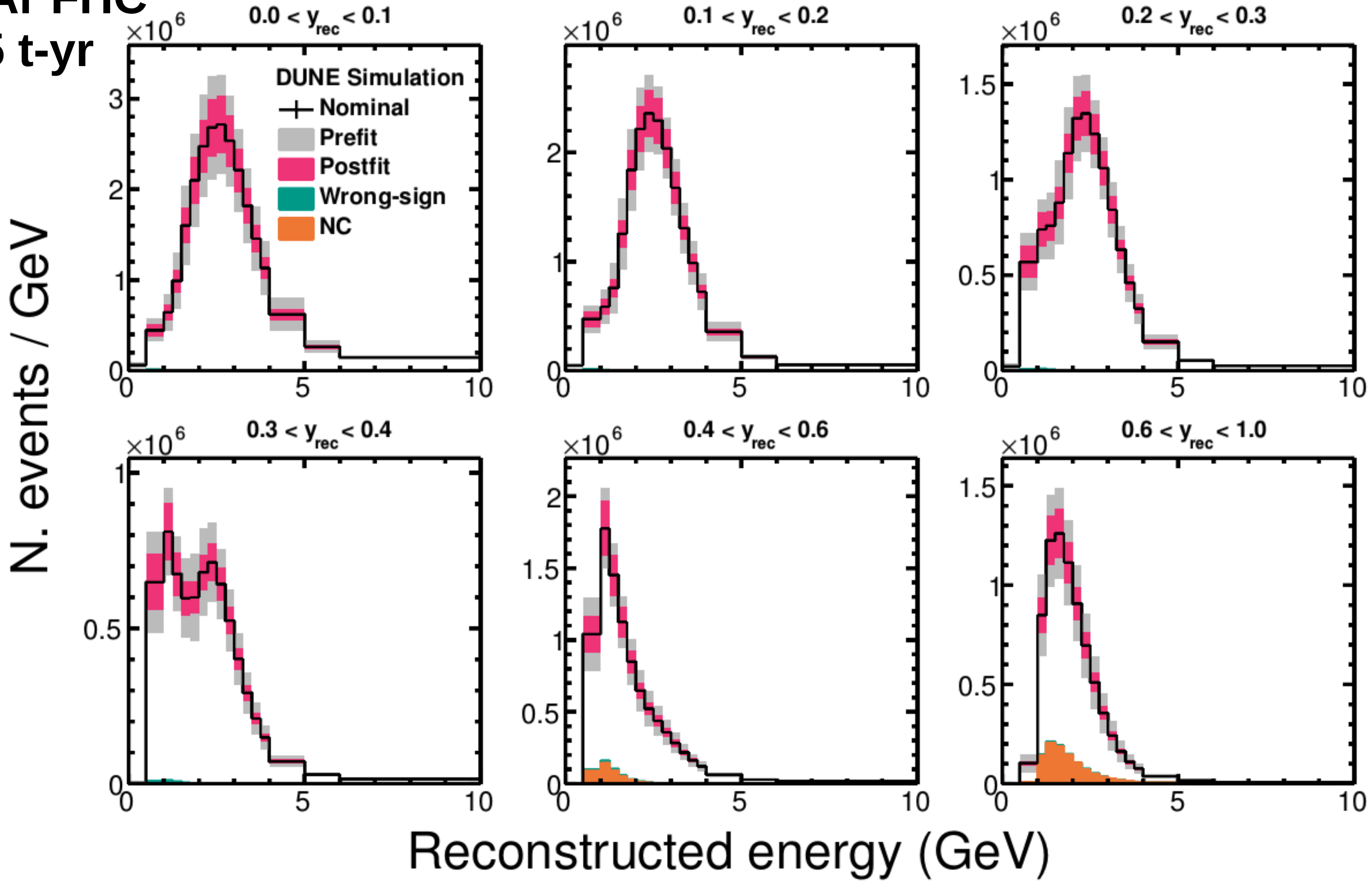




- High resolution core LArTPC
- Off-axis movement accesses different fluxes
- Some neutron detection abilities with SAND
- Magnet allows separation/constraint of $\nu/\bar{\nu}$
- Able to tolerate high rate environment

A high-rate environment?

≈100 million events/year in the DUNE ND LArTPC

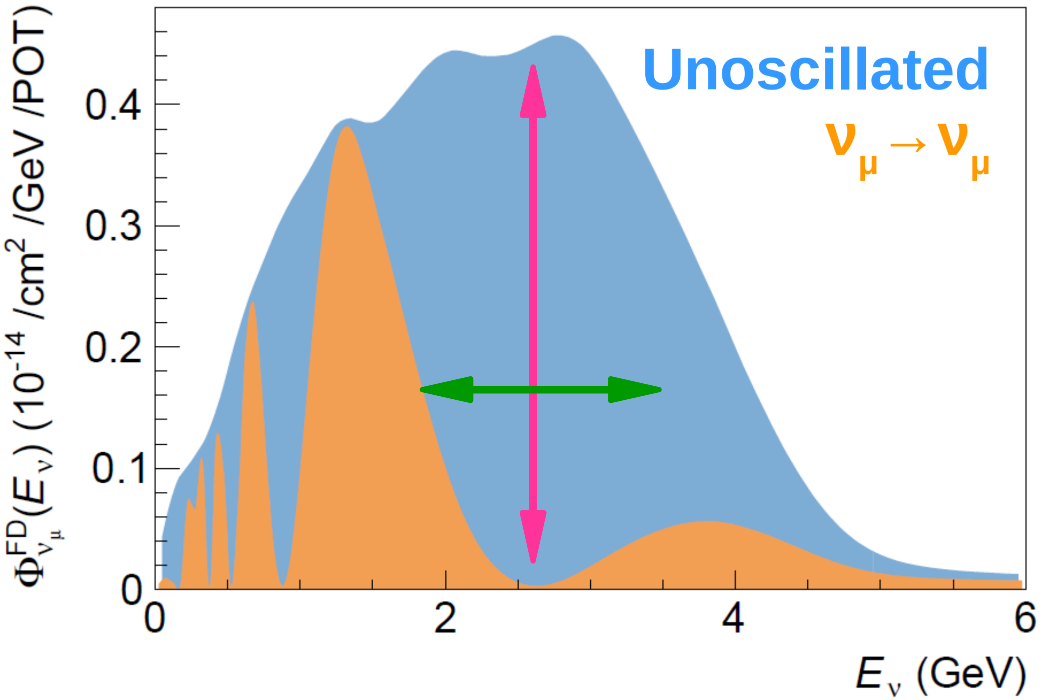


ND-LAr FHC
105 t-yr

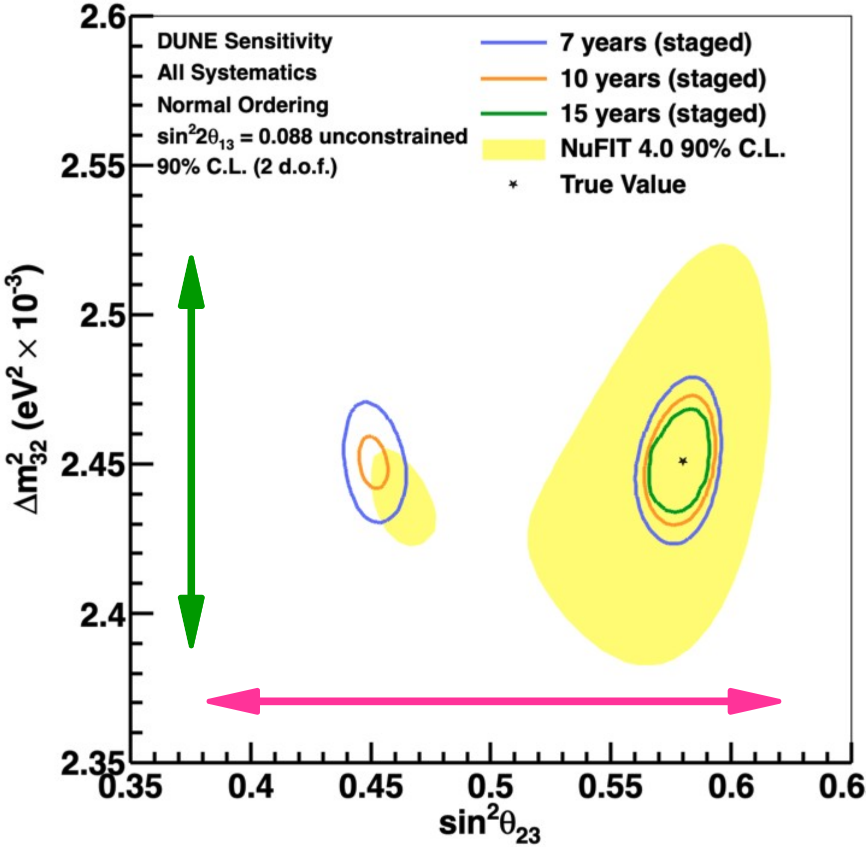
Measurement aims: disappearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) = 1 - \underline{\left(\cos^4\theta_{13}\,\underline{\sin^2 2\theta_{23}} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)}\,\underline{\sin^2\Phi_{32}} + \ldots$$

$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji} L}{E_\nu}$$



90% confidence



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Measurement aims: MO and CPV

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Phi_{31}-aL)}{(\Phi_{31}-aL)^2}\Phi_{31}^2$$

$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Phi_{31}-aL)}{\underline{(\Phi_{31}-aL)}}\Phi_{31}\frac{\sin(aL)}{(aL)}\Phi_{21}\underline{\cos(\Phi_{31}\,\underline{\pm}\,\delta_{\rm CP})}$$

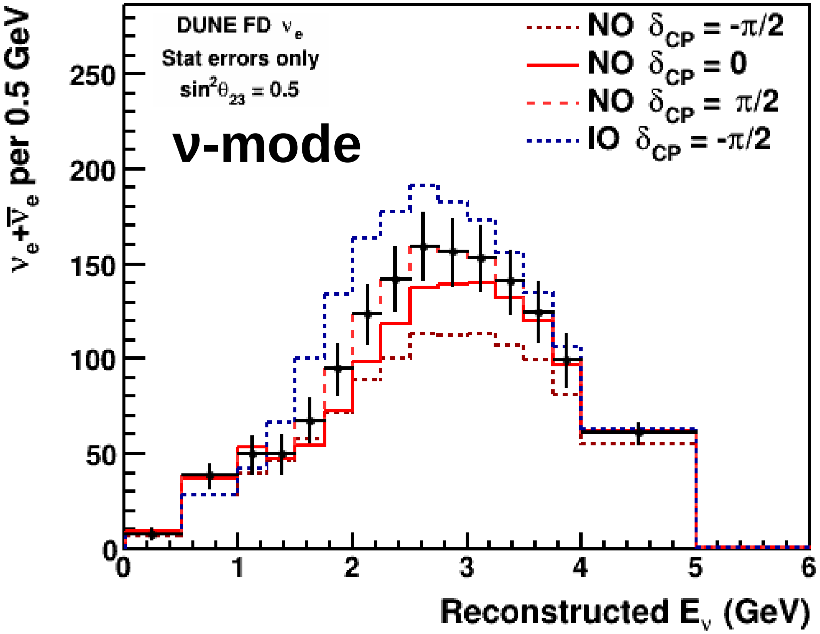
$$+\ldots$$

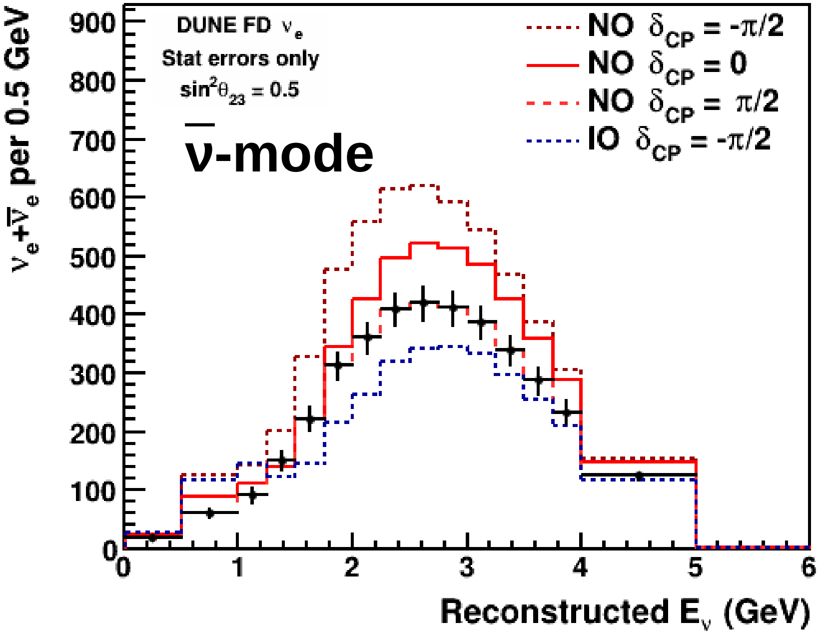
$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji}L}{E_\nu} \qquad a = \underline{\pm}\frac{G_{\rm F}N_e}{\sqrt{2}}$$

Sign change for ν_e and $\overline{\nu}_e$

Interplay between MO and $\delta_{\rm CP}$

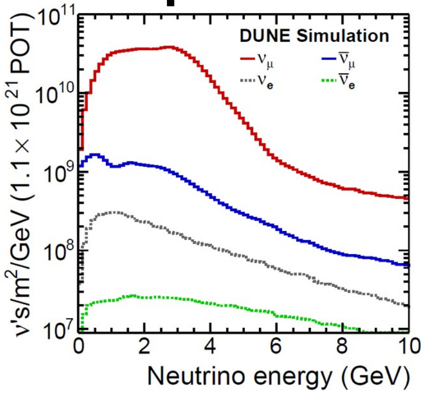
Matter effect increases with E_ν, Enhances MO sensitivity





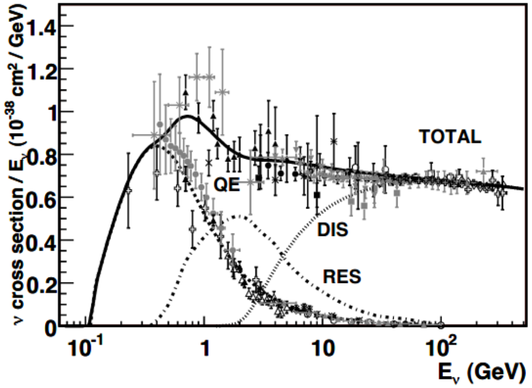
Sketch of an oscillation analysis

Flux prediction

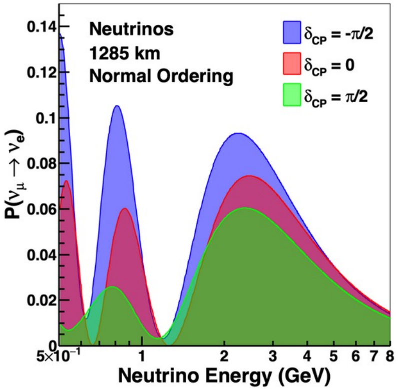


X

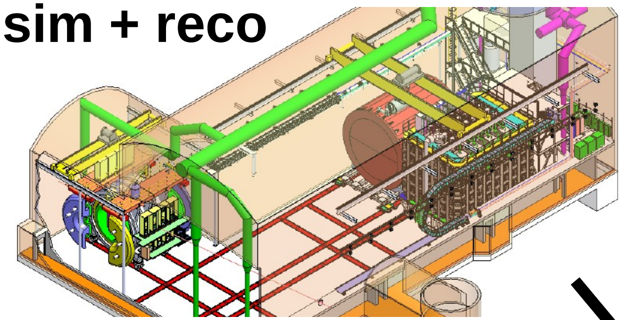
Interaction model



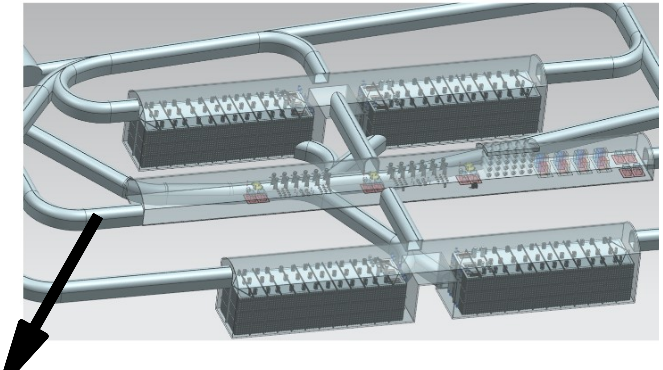
Oscillations



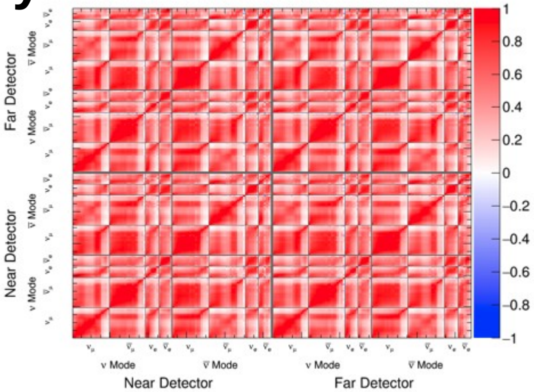
ND sim + reco



FD sim + reco



Systematic uncertainties



Fitting framework

$$\chi^2(\vec{\vartheta},\vec{x}) = 2\sum_i^{N_{\text{bins}}}\left[M_i(\vec{\vartheta},\vec{x}) - D_i + D_i\ln\left(\frac{D_i}{M_i(\vec{\vartheta},\vec{x})}\right)\right] + \sum_j^{N_{\text{systs}}}\left[\frac{\Delta x_j}{\sigma_j}\right]^2$$

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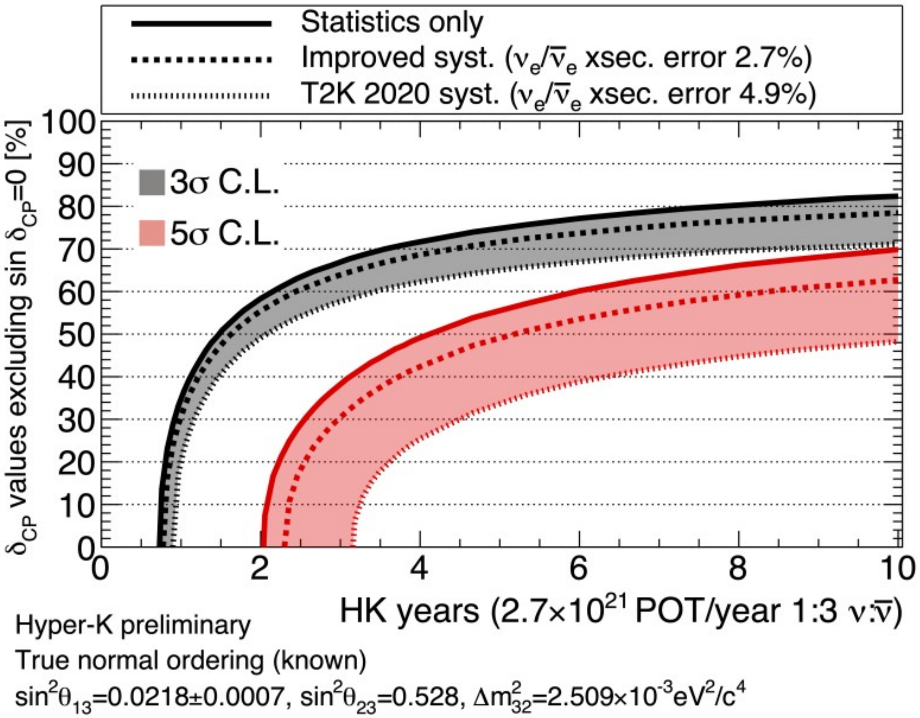
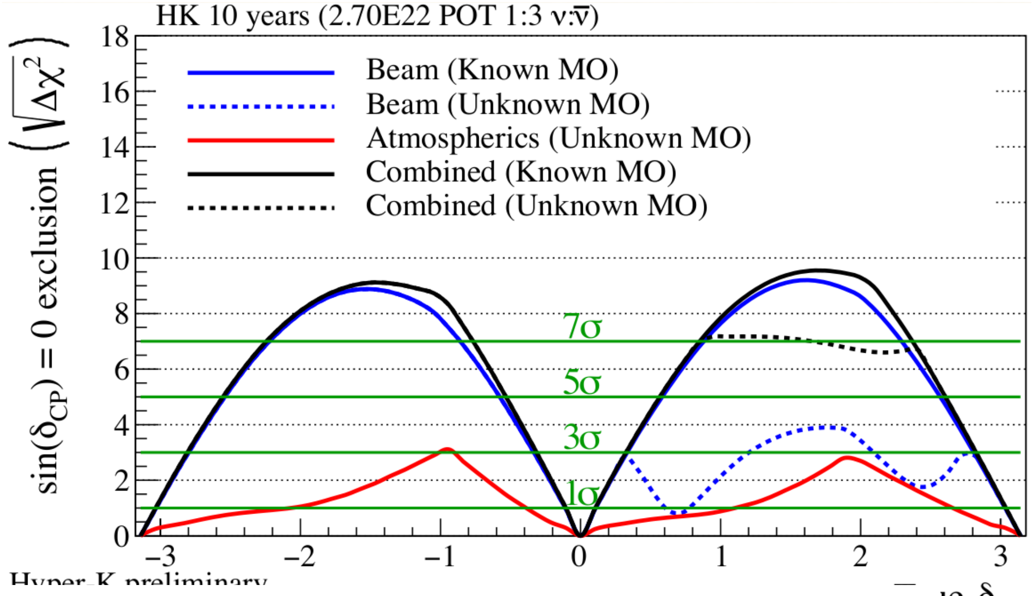
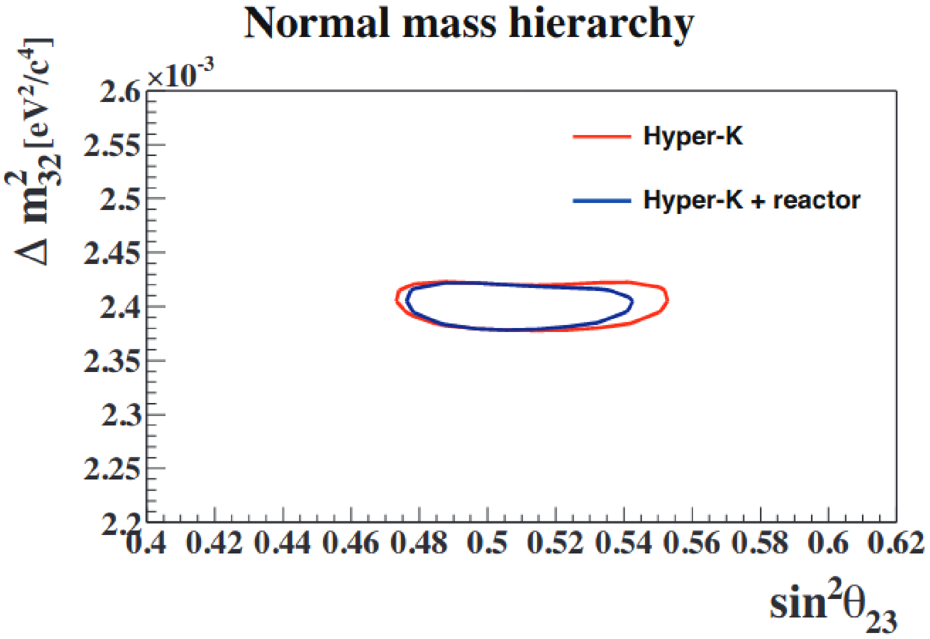
PRD 105 (2022) 7, 072006

Hyper-K sensitivity projections



**Snowmass year = 10^7 s*





- Strong CPV constraint – MO from atmospherics or other experiments
- >3σ CPV, 50% δ_{CP} values in 2 years
- >5σ CPV, 50% δ_{CP} values in 5 years
- Precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}

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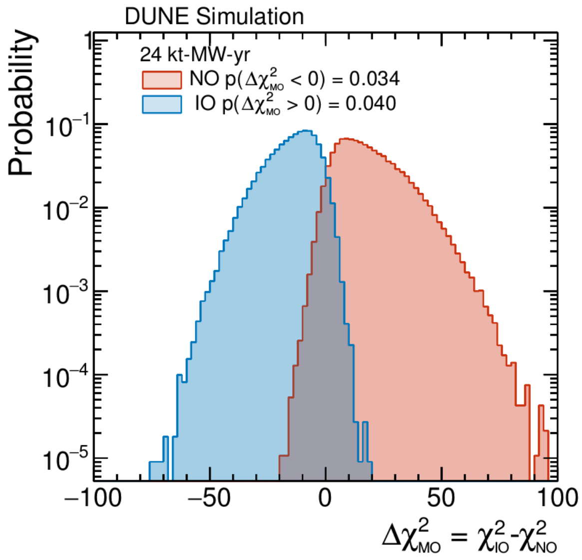
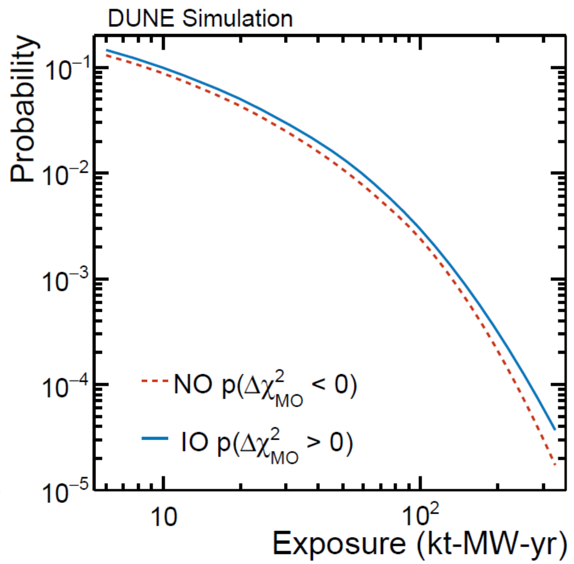
DUNE sensitivity projections



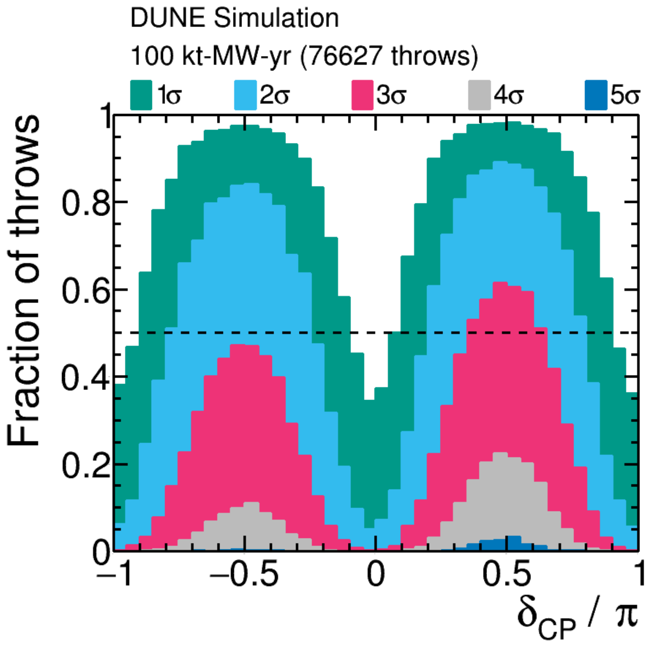


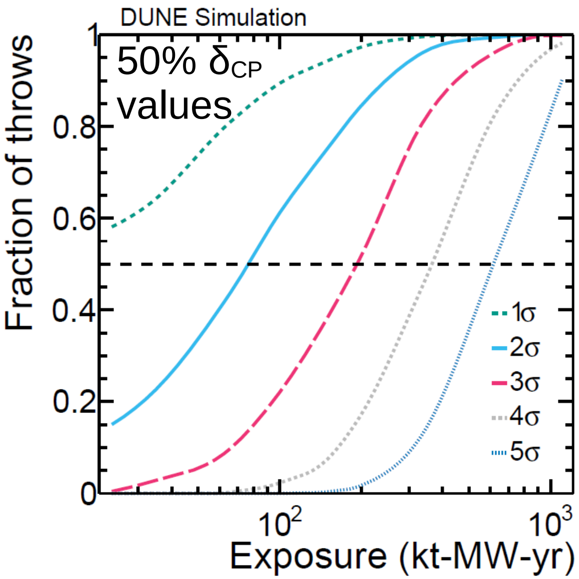
Phase I:

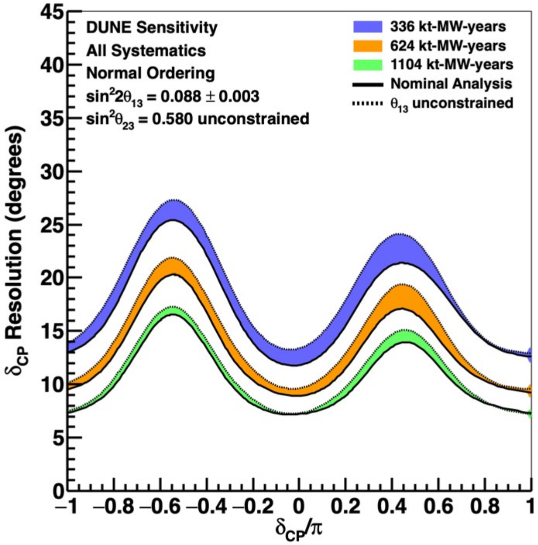
- MO to >5σ
- 3σ CPV if $\delta_{CP} \pm\pi/2$

Phase II:

- >5σ CPV, >50% δ_{CP} values
- >3σ CPV, >75% δ_{CP} values
- Precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}







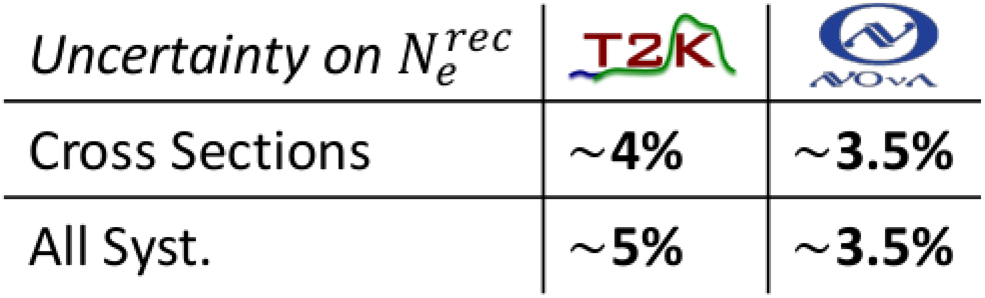
Fantastic, I’m sold!

What are the limiting systematics?

- Current experiments are statistics limited ~100 FD ν_e events
- DUNE+HK will be systematics limited ~1000 FD ν_e events
- **Cross-section systematics are dominant systematic now**
- DUNE/HK: need residual ND→FD uncertainties ≈percent level

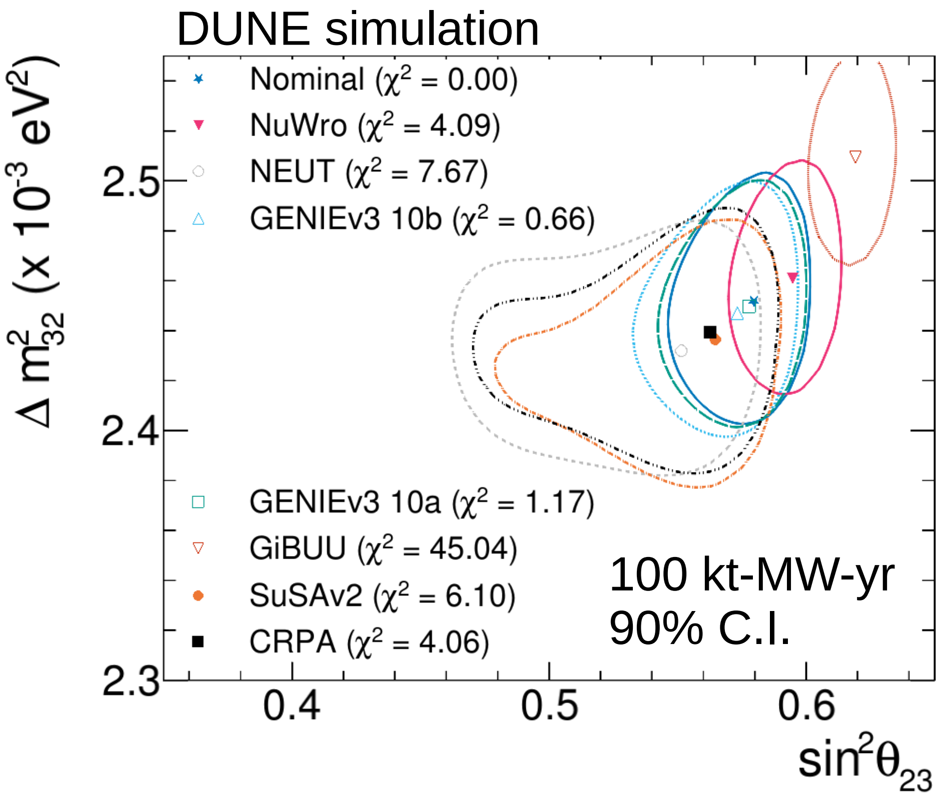
Current systematic uncertainties

(Table from S. Dolan's NuFact talk)



Uncertainty on N_e^{rec}	T2K	NOvA
Cross Sections	~**4%**	~**3.5%**
All Syst.	~**5%**	~**3.5%**

How limiting?



- DUNE example: ND+FD fit with full* systematic uncertainty model
- Alternative model choice leads to out of model biases
- If we were operating DUNE now, this **would be** limiting

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What about the near detectors???

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

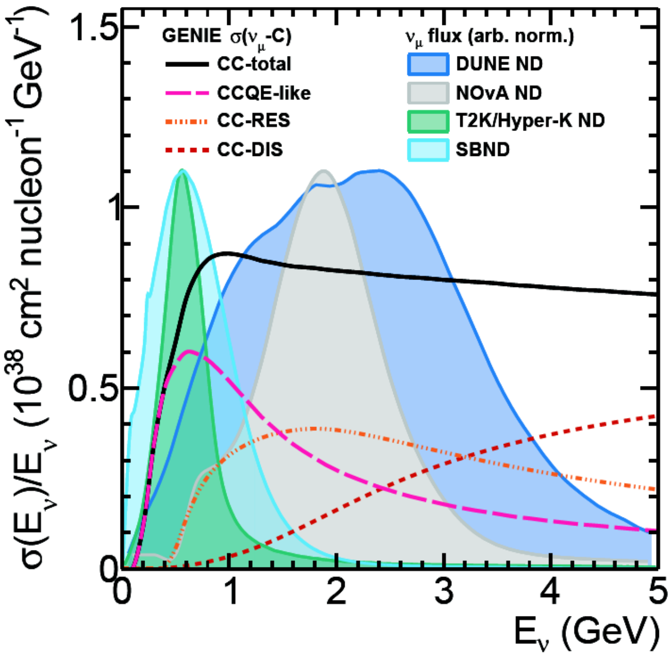
$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\int dE\ \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(E_\nu; \nu_A \rightarrow \nu_B)}_{\text{Far}}$$

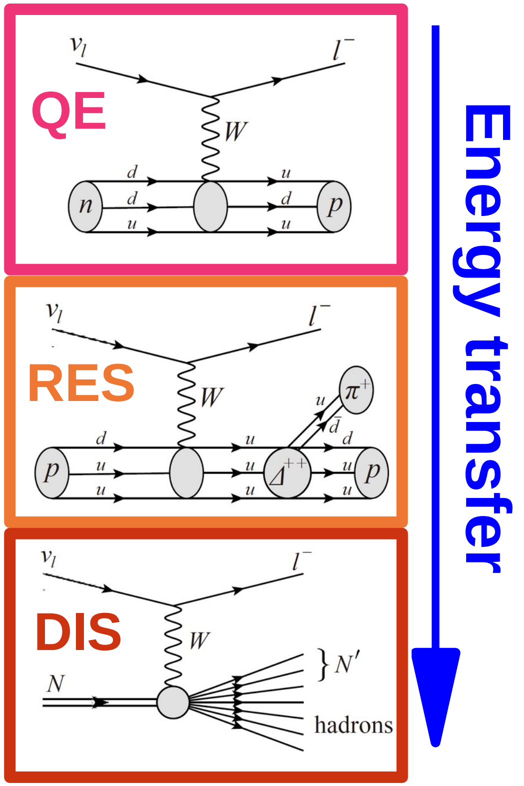
- Ambiguities between cross-section and flux uncertainties
- Different fluxes between near and far
- Imperfect and non-identical ND and FD
- **Missing degrees of freedom!** Model differences cannot be covered by systematics in the base model

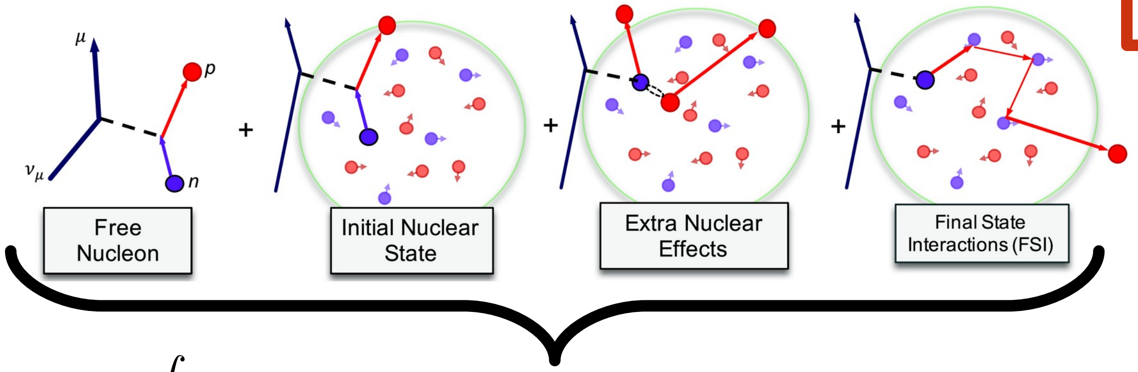
So what do we need to model?

Key issues:

- E_ν dependence
- E_ν reconstruction
- ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$
- Extrapolation out of detector acceptance

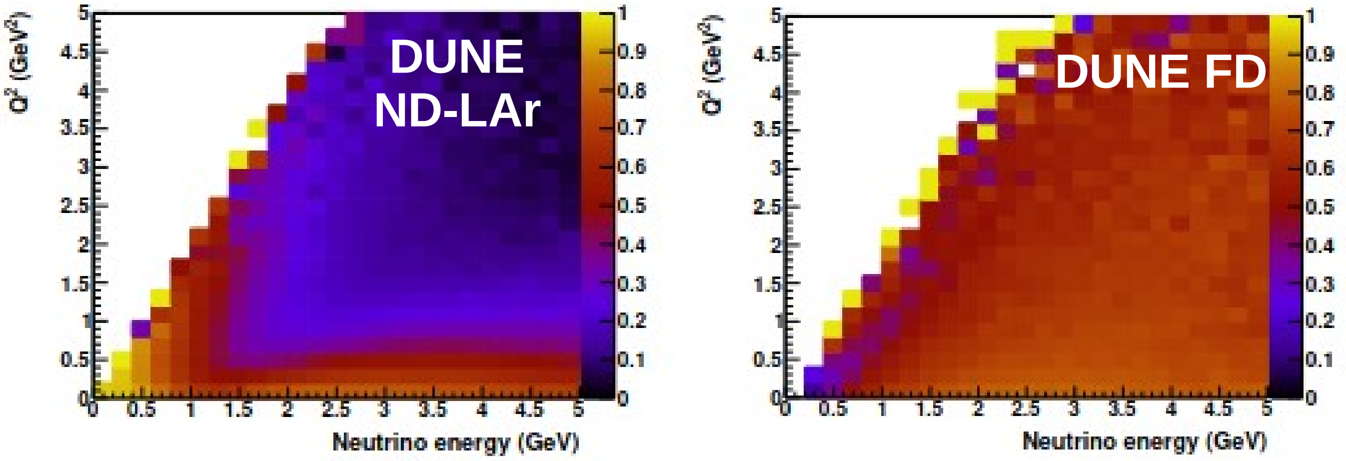






$$R(\vec{\mathbf{x}}) = \int dE\ \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(E_\nu; \nu_A \to \nu_B)$$

Extrapolation out of detector acceptance

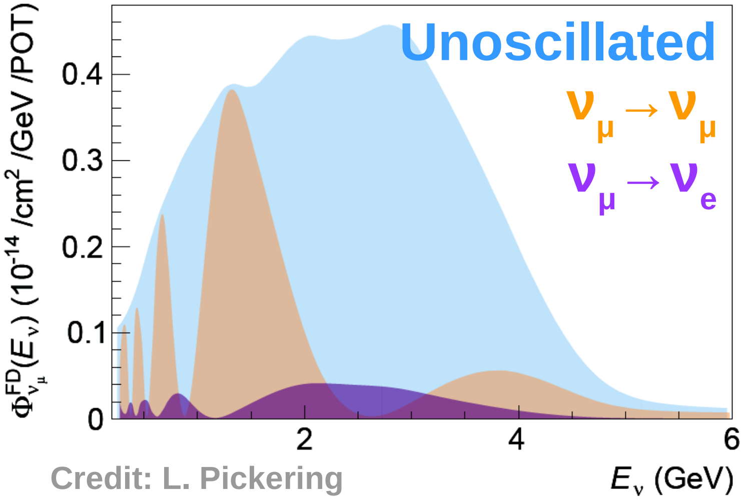


arXiv:2203.06281

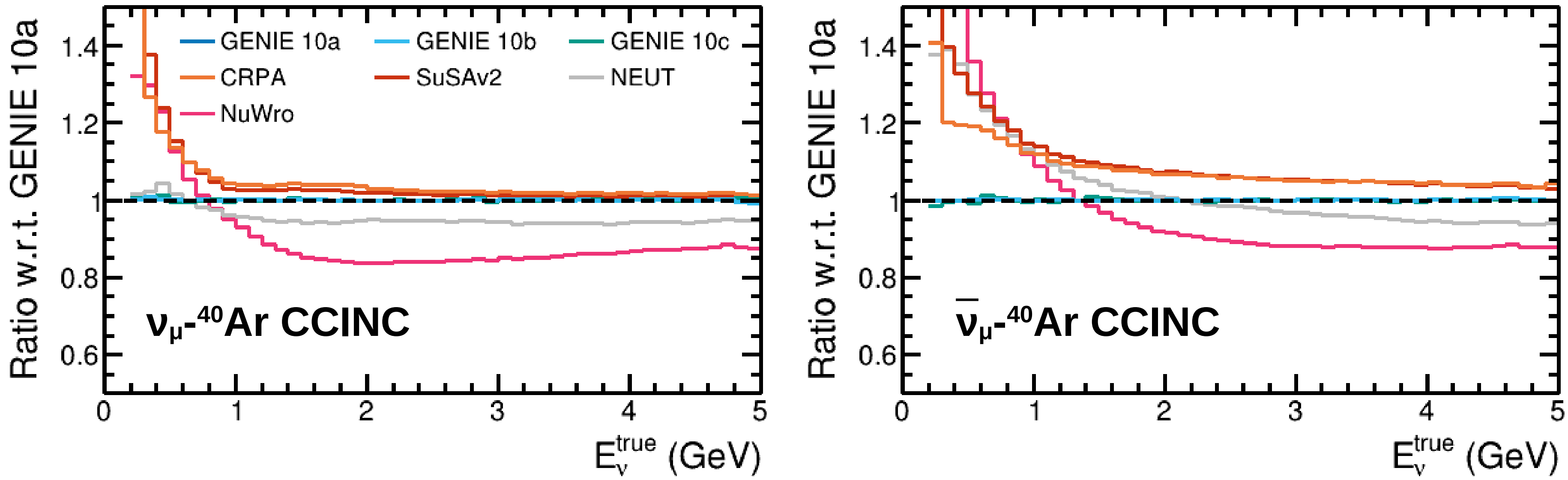
- ND and FD acceptances are different even if designs are similar → detector size, pile-up
- Implicit trust in model and uncertainties to extrapolate to the additional phase-space

E_ν dependence

- Different ND and FD fluxes: ND → FD extrapolation relies on E_ν dependence
- Differences between current models +inconsistent between ν_μ and $\bar{\nu}_\mu$
- True for both HK and DUNE



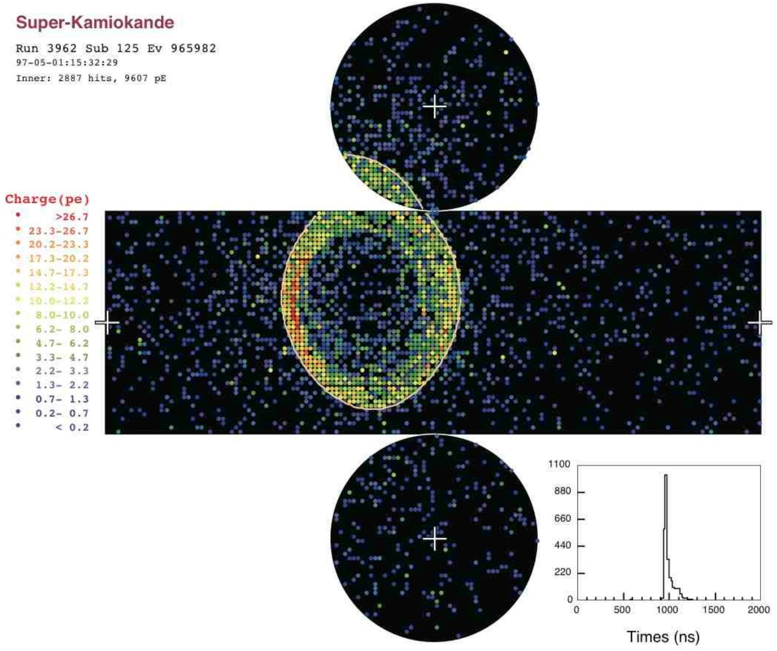
Credit: L. Pickering



E$_\nu$ reconstruction methods

(1) **Leptonic** variables only:

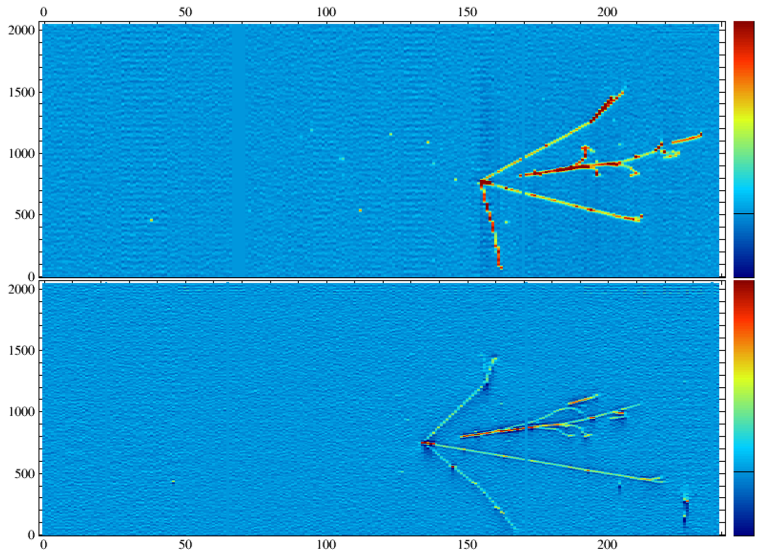
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$



Water Cherenkov: T2K, Hyper-K

(2) **Leptonic** and **hadronic** information:

$$E_\nu = E_\mu + E_{\text{had}}$$



Tracking calorimeter: NOvA;
Liquid Argon TPCs: DUNE

E_ν reconstruction methods

(1) **Leptonic** variables only:

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

- CC0π
- Non-CCQE contributions
- Pion production < threshold
- Pion prod. + absorption rate
- Smearing from nuclear model

(2) **Leptonic** and **hadronic** information:

$$E_\nu = E_\mu + E_{\mathrm{had}}$$

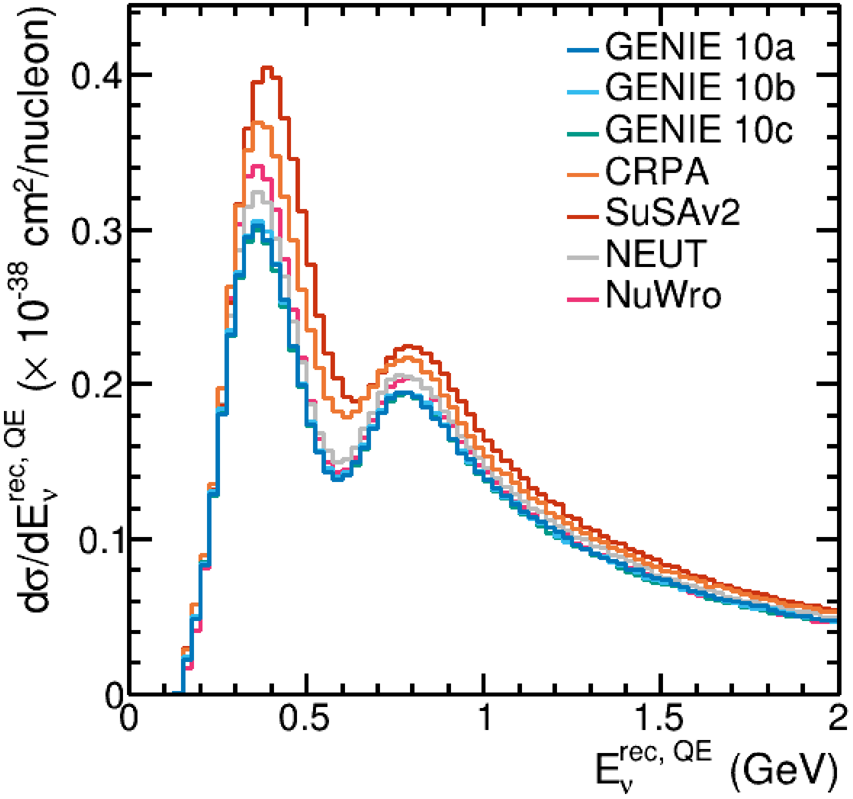
- CC-inclusive
- Pion production rate below experimental threshold
- Neutral energy fraction
- Nuclear model initial and final state effects

+ E_ν dependence for all of the above!

E_ν reconstruction status

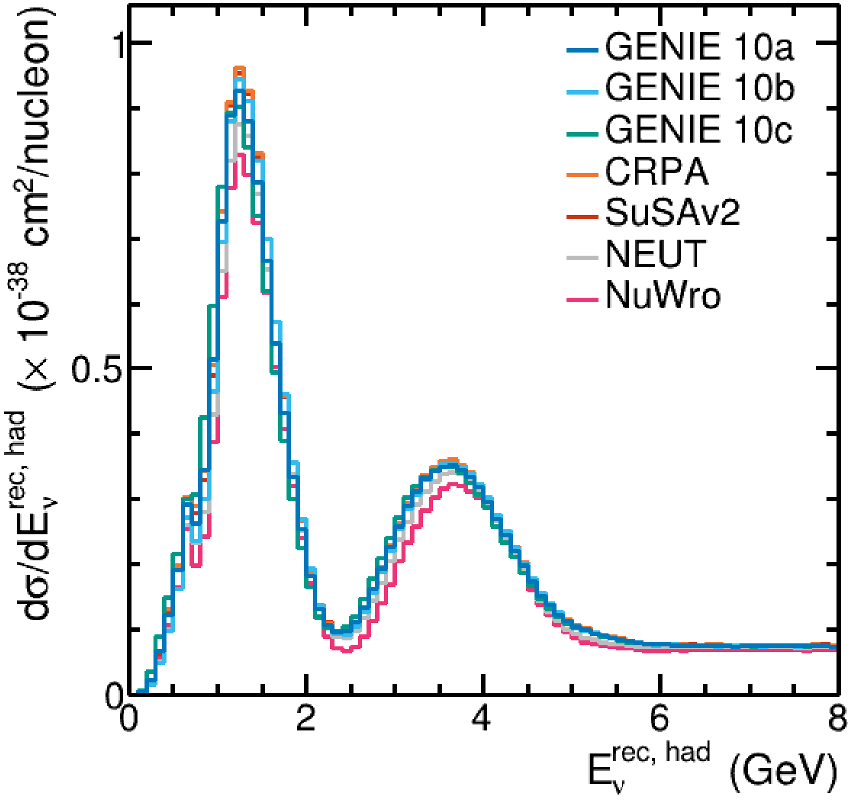
Hyper-K FHC ν_μ CC0π

Perfect lepton reconstruction

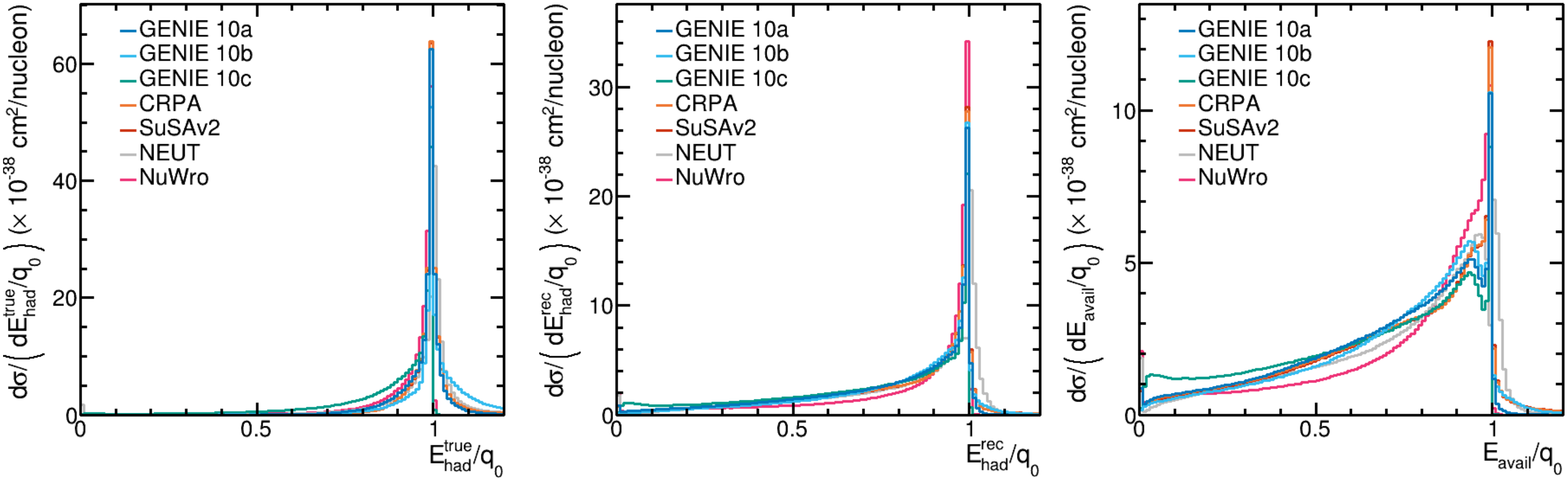


DUNE FHC ν_μ CCINC

Perfect reconstruction of all particles except neutrons



How well do we model E_{had}?



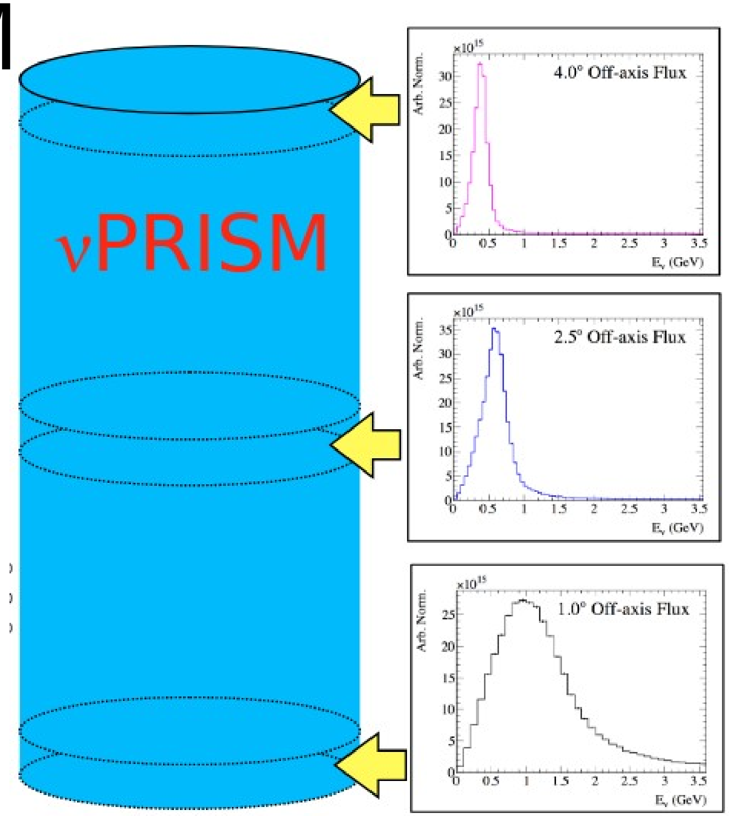
$$E_{\mathrm{had}}^{\mathrm{true}} = \Big(\sum_{i=n,p} E_{\mathrm{kin}}^{i} \Big) + \Big(\sum_{i=\pi^{\pm},\pi^{0},\gamma,K^{0},K^{\pm}} E_{\mathrm{total}}^{i} \Big)$$

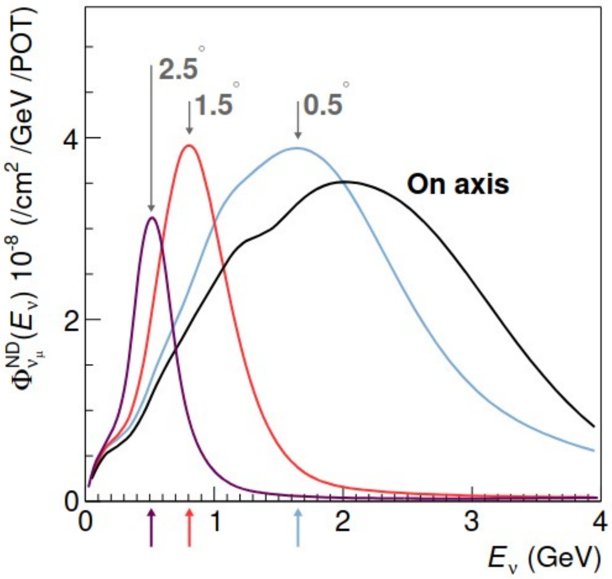
$$E_{\mathrm{had}}^{\mathrm{reco}} = \Big(\sum_{i=p} E_{\mathrm{kin}}^{i} \Big) + \Big(\sum_{i=\pi^{\pm},\pi^{0},\gamma,K^{0},K^{\pm}} E_{\mathrm{total}}^{i} \Big)$$

$$E_{\mathrm{avail}} = \Big(\sum_{i=p,\pi^{\pm}} E_{\mathrm{kin}}^{i} \Big) + \Big(\sum_{i=,\pi^{0},\gamma,K^{0},K^{\pm}} E_{\mathrm{total}}^{i} \Big)$$

Tackling E_ν dependence: PRISM

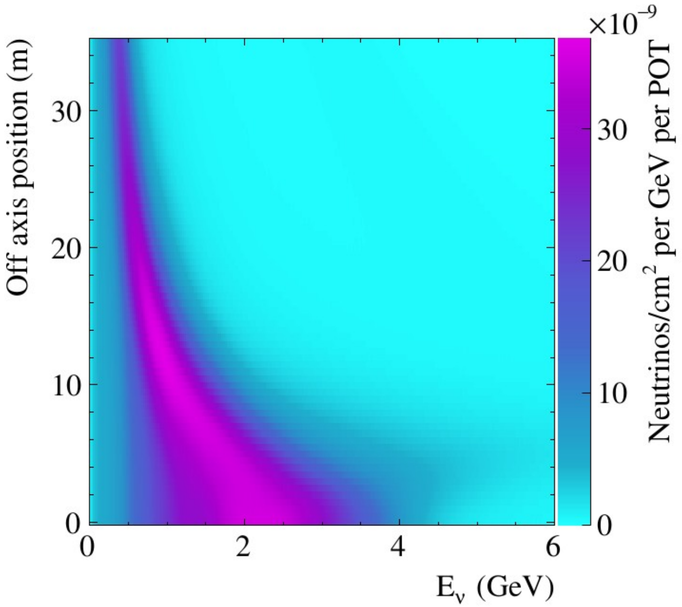
- Moving away from the beam axis reduces the flux width and peak E_ν
- Possible with IWCD for HK and the off-axis movement of the DUNE ND
- Adds important information to break flux*XSEC degeneracy!
- But each flux is still extended and complex, still not a trivial problem



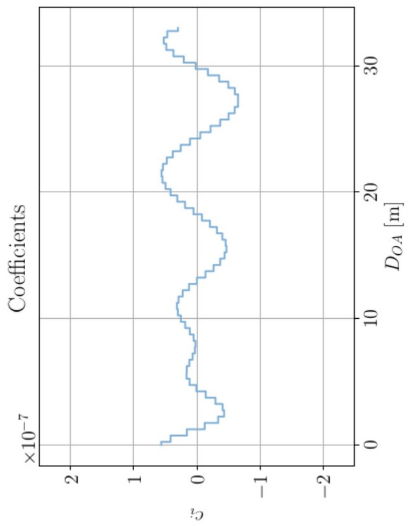


Instruments **5**, *no. 4, p31, 2021*

PRISM linear combination analyses



X



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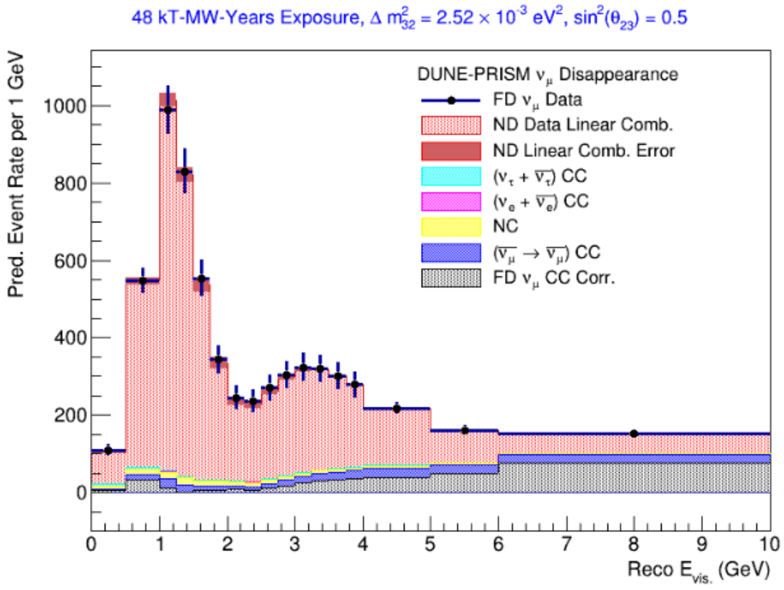
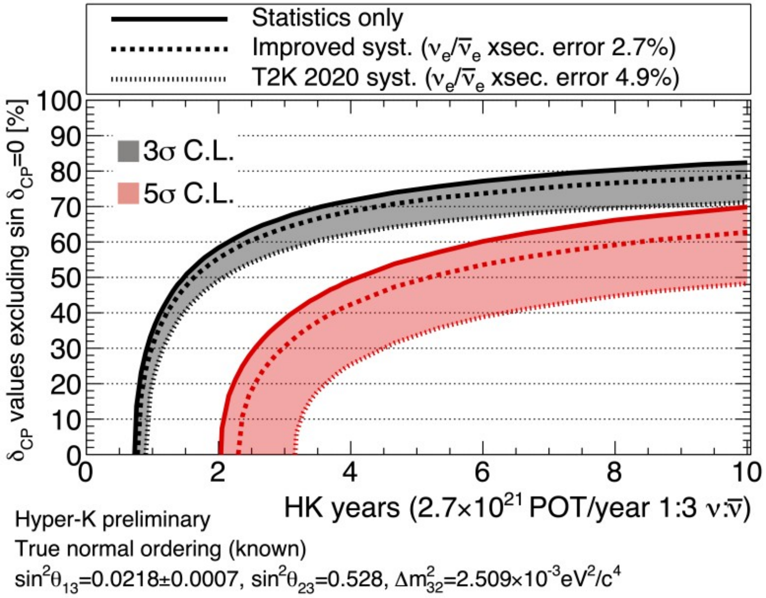
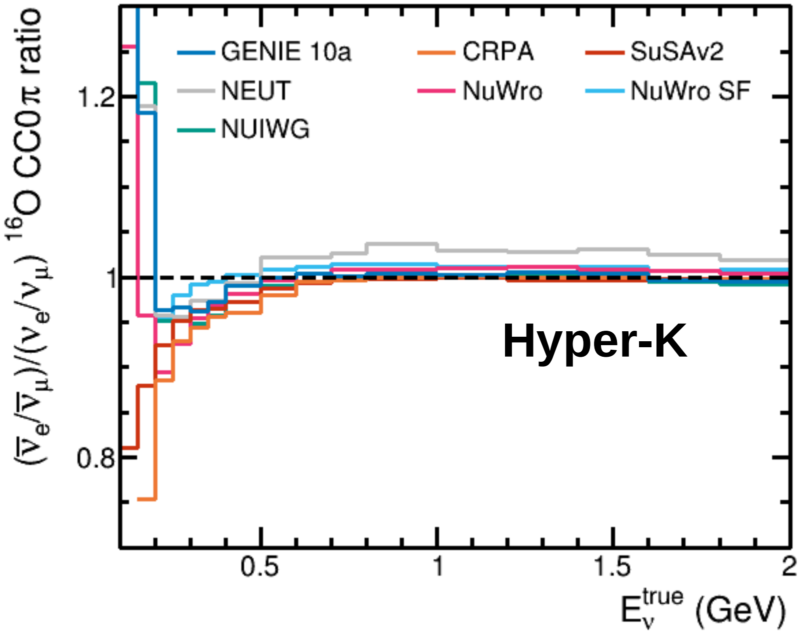


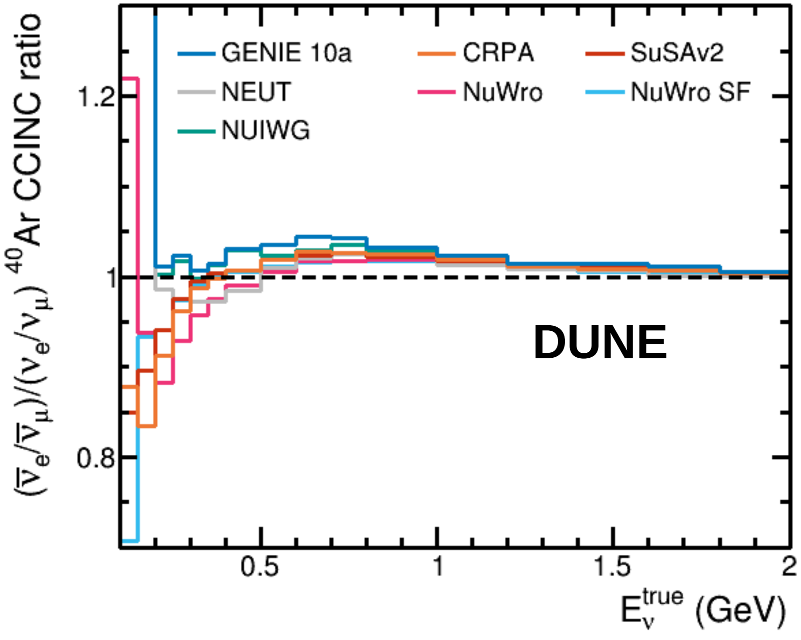
- Linear combinations of off-axis data approximate the oscillated FD flux
- *Reduces* cross-section model dependence
- **But** the overall sensitivity likely to be lower (subdividing ND statistics, complex flux uncertainty)
- Unclear what the remaining XSEC uncertainties are → stress on different parts of the model/phase space

ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$

- ND ν_e and $\bar{\nu}_e$ rates are low, ND vs FD fluxes very different
- PRISM less useful for ν_e due to different production kinematics
- HK and DUNE likely to rely on theory, HK explicitly show impact
- Current generator implementations differ by more than assumed uncertainties







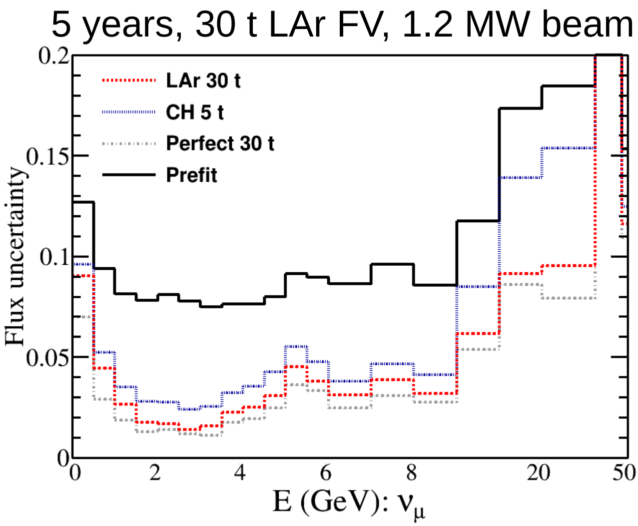
ND standard candles?

With large ND event rates, possible to utilize (faint) standard candles:

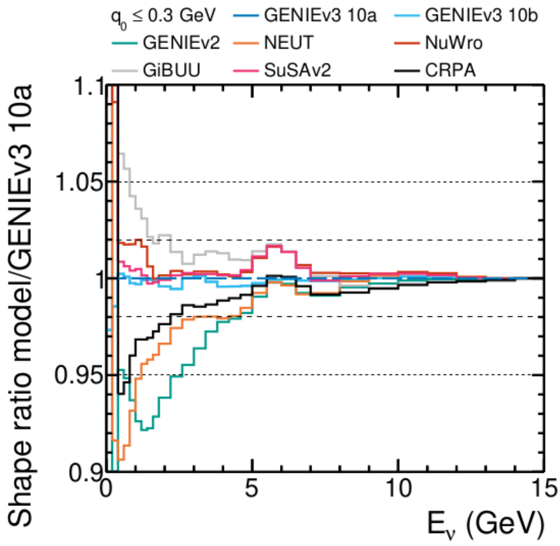
- ν+e → ν+e elastic scattering
- Inverse muon decay: $\nu_\mu + e \rightarrow \mu + \nu_e$
- The low-ν technique
- Isolating hydrogen events
- Coherent pion scattering

Rely on: a known cross section and/or isolating a region of phase space

New/extra challenges for systematic modeling



PRD 101, 032002 (2020)



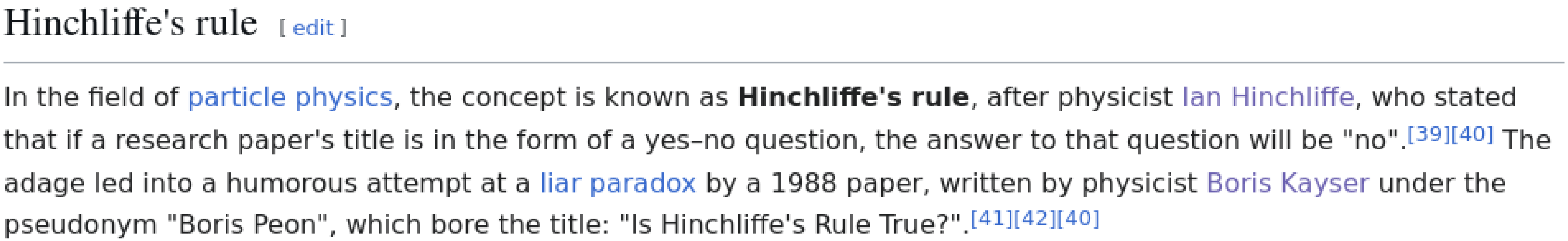
EPJC 82 (2022) 9, 808

Do we have a path to precision?

Maybe? But not a purely experimental one...

Needs:

- A theoretically consistent XSEC model, implemented in a generator
- A robust uncertainty model
- Dedicated measurement programs
- Improved near detectors



Hinchliffe's rule [edit]

In the field of particle physics, the concept is known as **Hinchliffe's rule**, after physicist Ian Hinchliffe, who stated that if a research paper's title is in the form of a yes–no question, the answer to that question will be "no".[39][40] The adage led into a humorous attempt at a liar paradox by a 1988 paper, written by physicist Boris Kayser under the pseudonym "Boris Peon", which bore the title: "Is Hinchliffe's Rule True?".[41][42][40]

https://en.wikipedia.org/wiki/Betteridge's_law_of_headlines

Ultimate precision: joint fits

- Unless HK+DUNE expose significant new physics*, their joint fit will be the legacy precision oscillation measurement
- No longer adequate to consider parameters “effective” with the freedom we currently allow
- A-scaling will be a significant challenge/need
- Consistent model which is precise over a broader E_ν range
- Others?

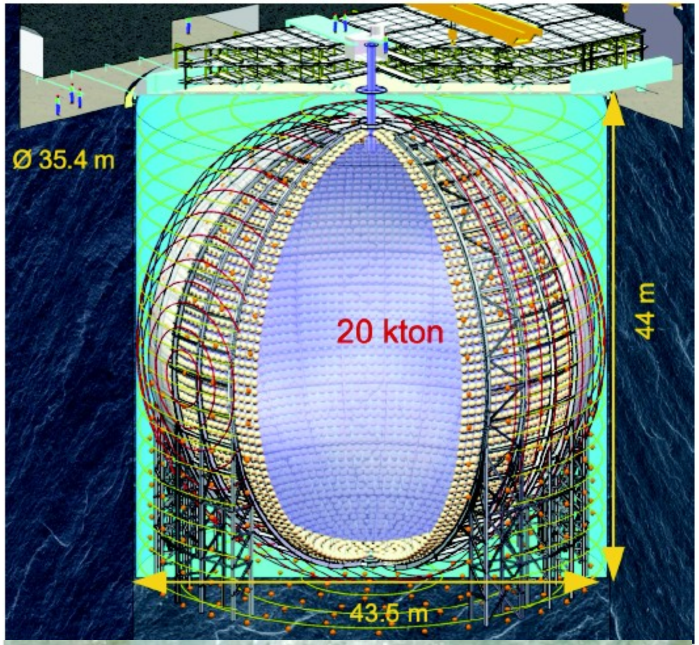
**Of course, if they do uncover new physics, the same issues will just be more urgent*

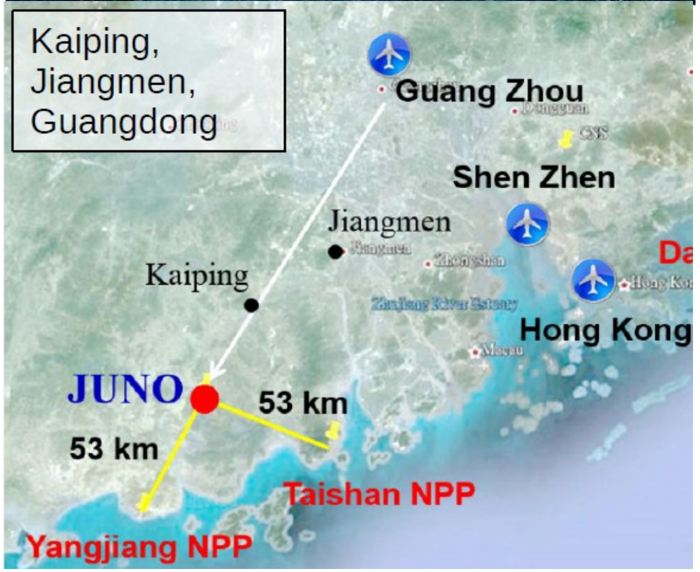
Concluding thoughts

- DUNE and HK promise precision oscillation measurements
- Cross-section systematics will be limiting without significant improvements to the current situation
- A high-performance ND helps constrain the problem, and offers new opportunities!
- But, more sophisticated theory and complete uncertainty models are also essential
- <u>A strong relationship between measurement and theory is the only way to achieve precision</u>

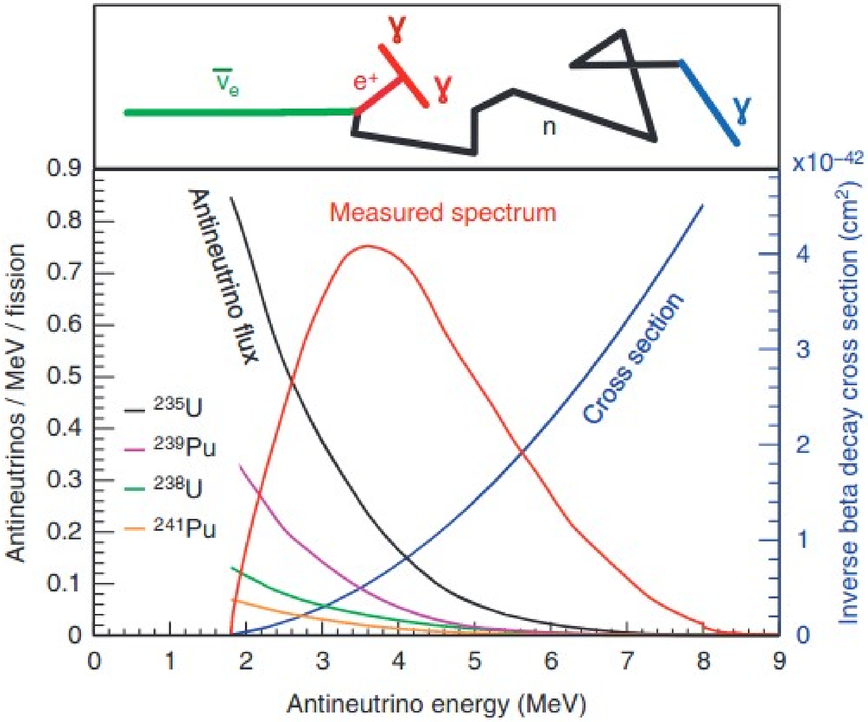
Backup

JUNO: Jiangmen Underground Neutrino Observatory





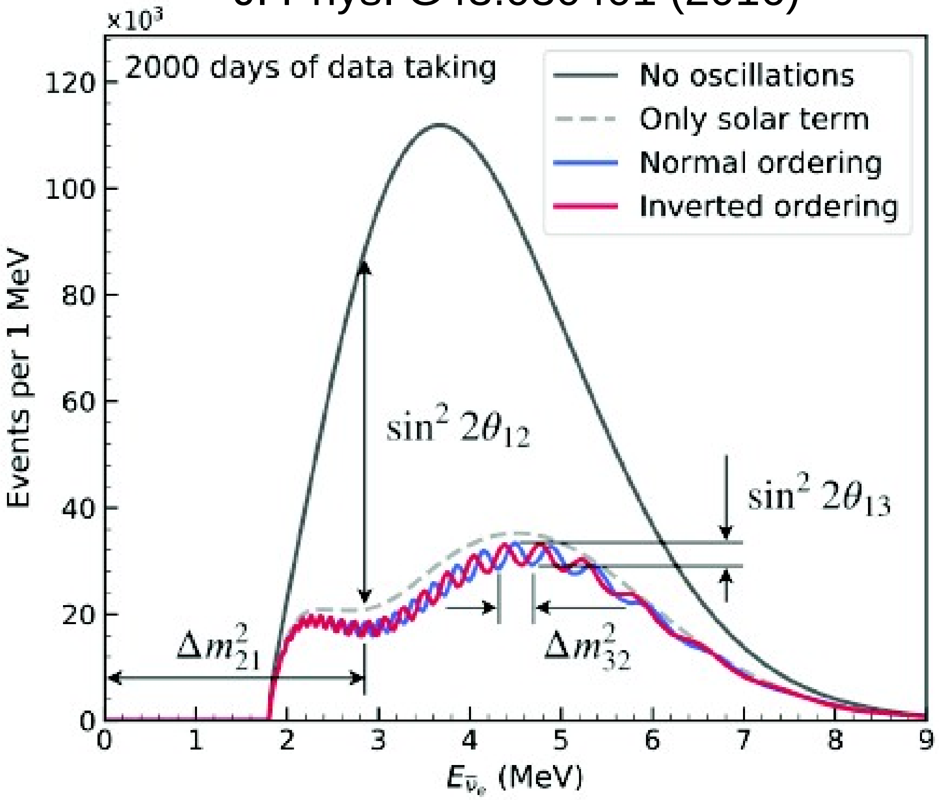
- Reactor antineutrino experiment
- 20 kt liquid scintillator detector ~50 km from 2x ~20 GW reactor complexes
- 75% photocathode coverage → 3%/√E energy resolution
- Construction ongoing, data taking 2023

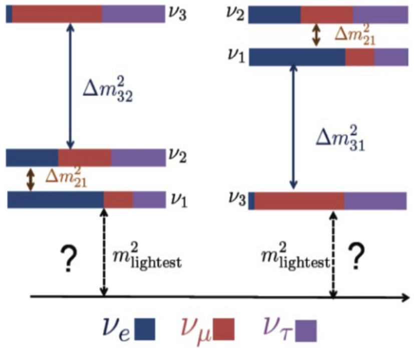


Reactor neutrino future - JUNO

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \left(\underline{\cos^2\theta_{12}\sin^2\Phi_{31} + \sin^2\theta_{12}\sin^2\Phi_{32}}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Phi_{21}$$

J. Phys. G43:030401 (2016)

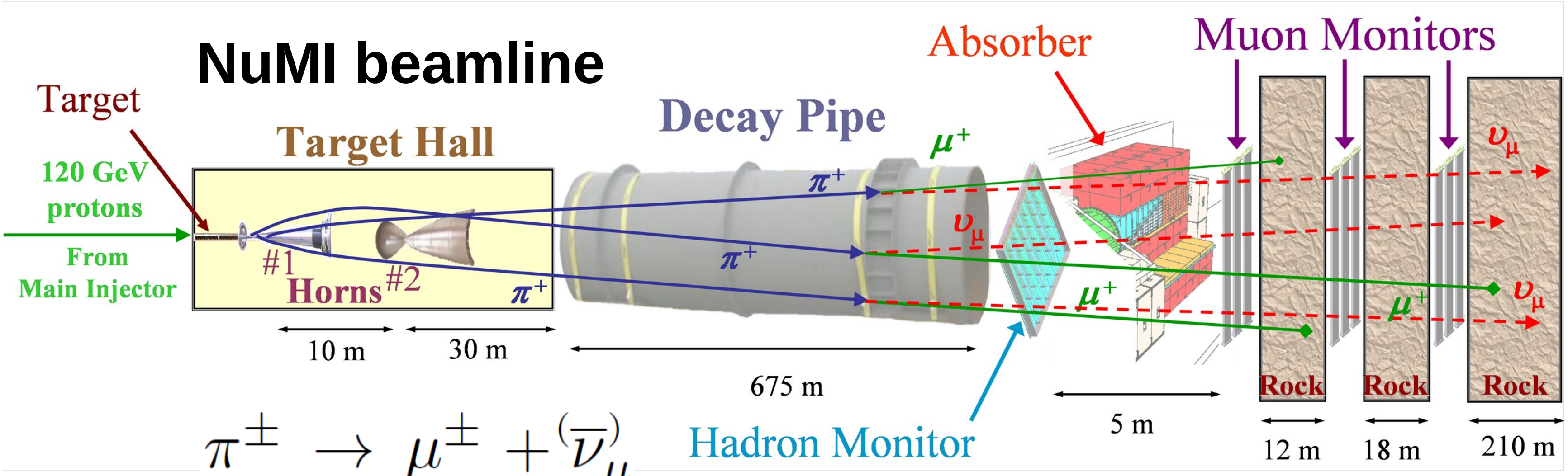




$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji} L}{E_\nu}$$

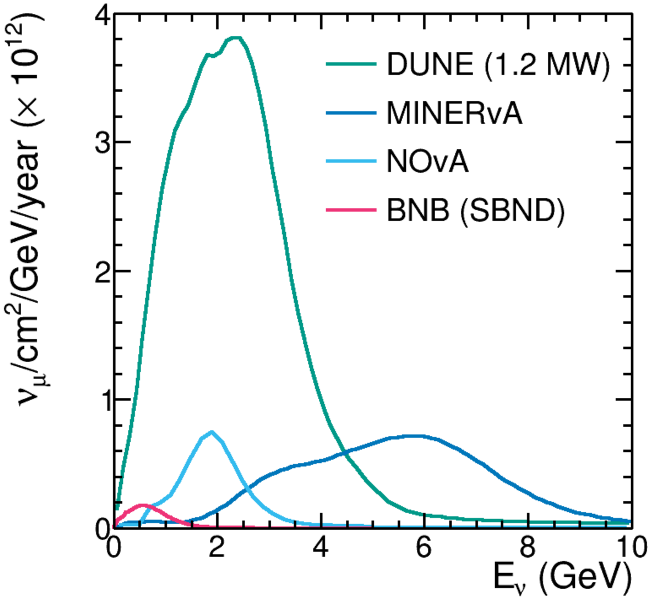
- High-precision measurements on “solar terms” $\sin^2\theta_{12}$ and Δm^2_{21}
- At long baselines, NO/IO spectra differ due to competing Φ_{31} and Φ_{32} terms
- ***But***, clearly very sensitive to energy scale and resolution

Accelerator neutrino beams



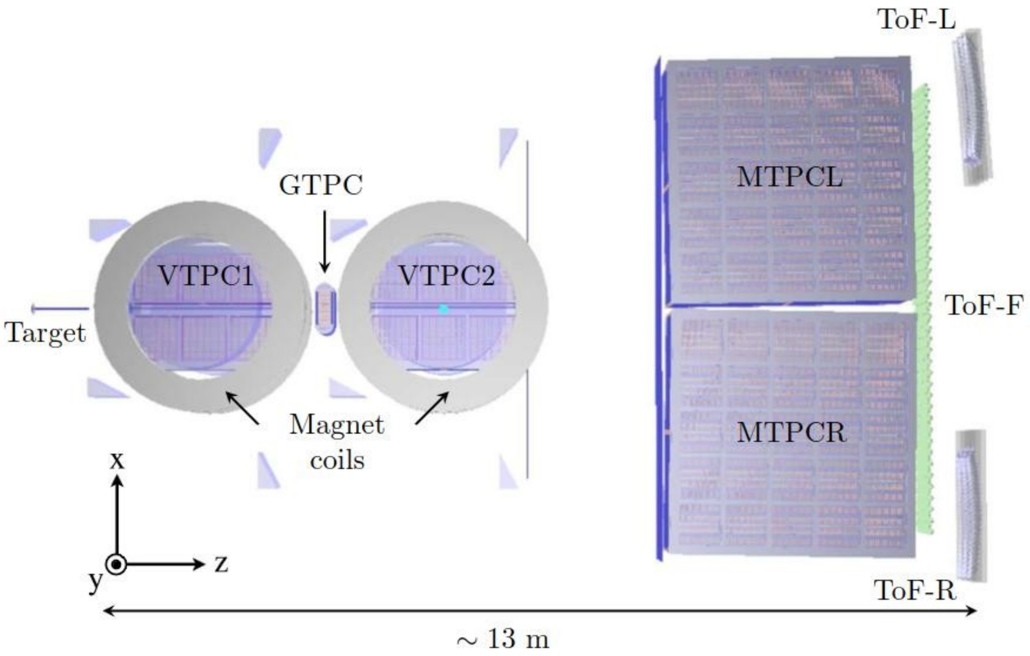
$$\pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$$

- O(10-100) GeV primary proton beams
- O(10 GeV) secondary pions and kaons
- Focused with electromagnetic horns
- *But still cover a broad E_ν range*



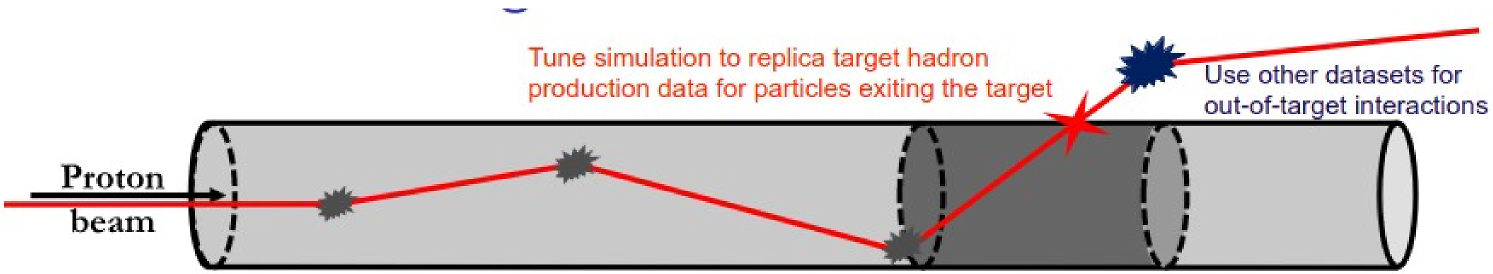
Accelerator neutrino flux uncertainty

- Dedicated hadron production measurements at fixed target beam facilities:
  - Thin target
  - Replica target
- Example: NA61/SHINE*, used for T2K → **5-10% uncertainties**



Eur. Phys. J. C76, 617 (2016)

Eur. Phys. J. C79, 100 (2019)

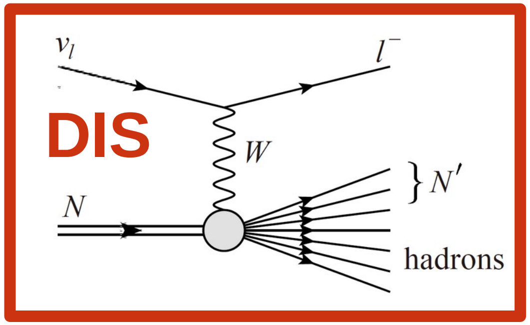


Tune simulation to replica target hadron production data for particles exiting the target

Use other datasets for out-of-target interactions

The low-ν method [1,2]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_0} = \frac{G_\mathrm{F}^2 M}{\pi}\int_0^1 \left(F_2 - \frac{q_0}{E_\nu}\left[F_2 \mp xF_3\right] + \frac{q_0}{2E_\nu^2}\left[\frac{Mx(1-R_\mathrm{L})}{1+R_\mathrm{L}}F_2\right] + \frac{q_0^2}{2E_\nu^2}\left[\frac{F_2}{1+R_\mathrm{L}} \mp xF_3\right]\right)\mathrm{d}x$$

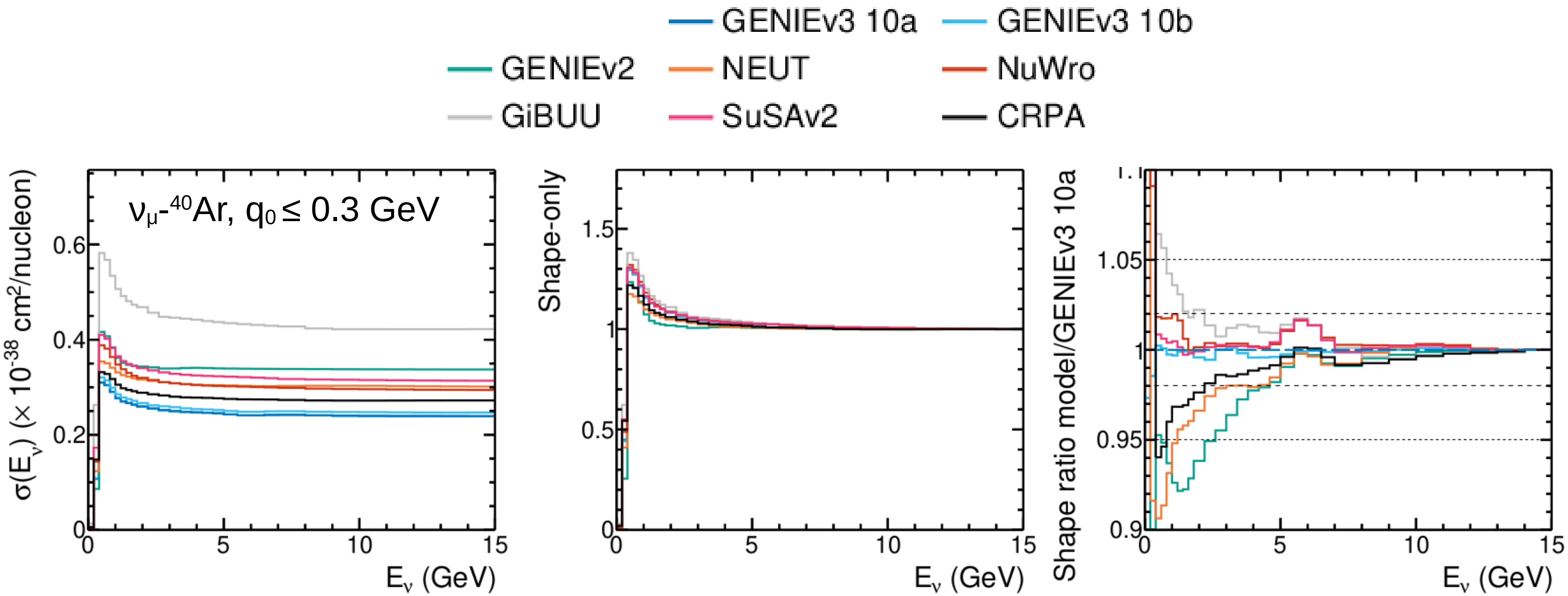


- Comes from the observation that if $q_0/E_\nu \ll 1$, the cross section is approximately constant with E_ν
- The rate as a function of E_ν gives acces to the flux *shape*
- Very closely linked to the “low-y” ($y = q_0/E_\nu$) method [2]

[1] S. R. Mishra in Workshop on Hadron Structure Functions and Parton Distributions, 84 , p84. World Scientific, 1990

[2] R. Belusevic and D. Rein Phys. Rev. D 38 (1988) 2753–2757

Is the low-q_0 cross section well described?



Compare a variety of new/commonly used generator models

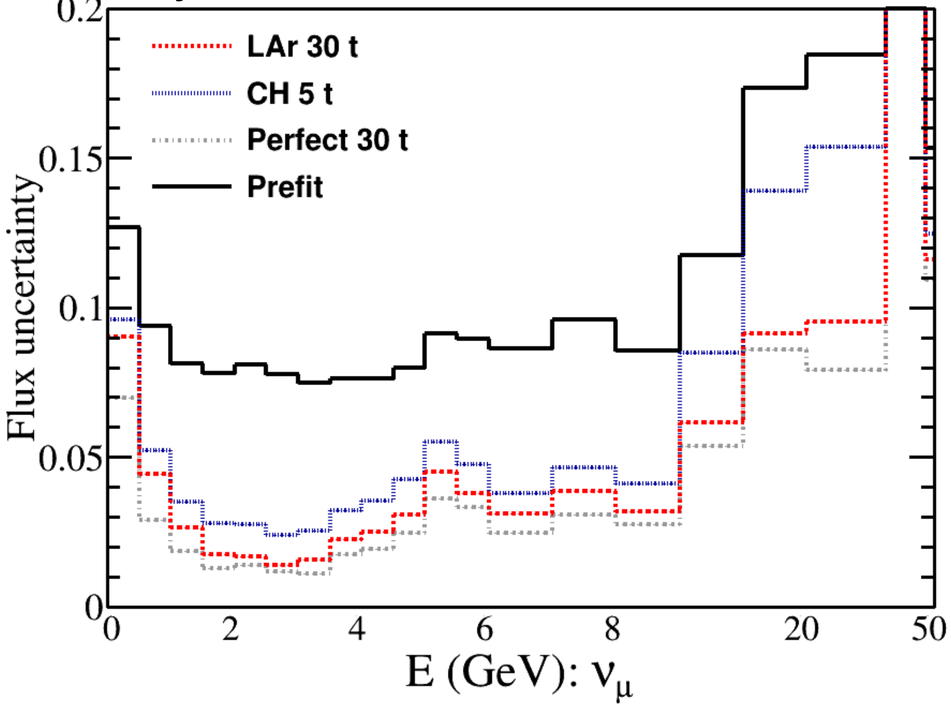
Normalize to a fixed point at high energy – where q_0/E_ν corrections are smallest

Take a ratio w.r.t a reference model

Neutrino-electron elastic scattering

- The known, but small, cross section can be used to constrain the flux. ~5000 LAr ND events/year
- A powerful additional tool for achieving DUNE's sensitivities, and resolving flux ↔ cross section ambiguities

5 years, 30 t LAr FV, 1.2 MW beam



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$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}}$$

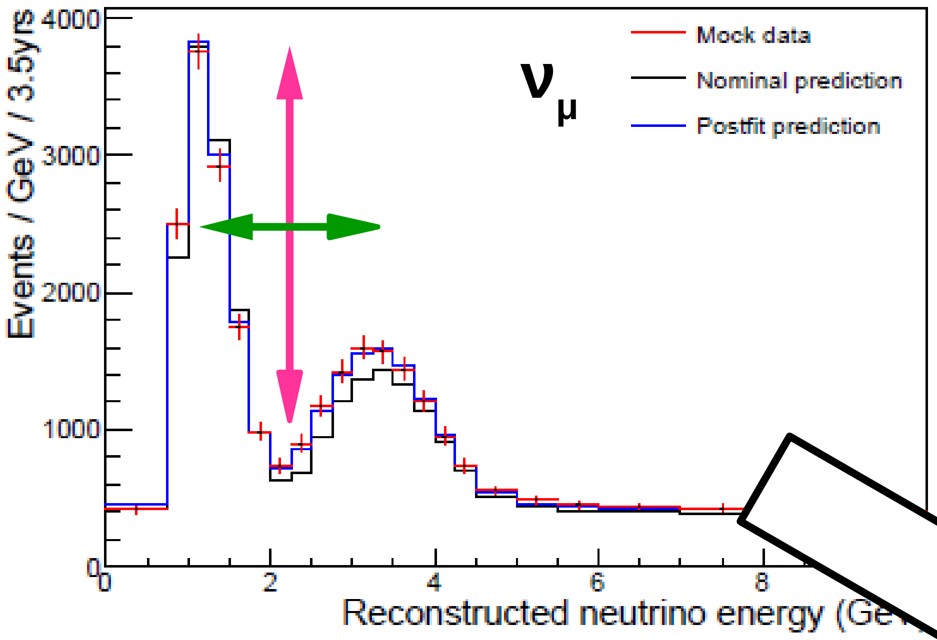
- Strong normalization contraint due to known XSEC
- Weak shape constraint due to detector smearing and beam divergence

Few-GeV cross-section models

A variety of model predictions are on the market – use a variety to investigate potential for bias:

- **GENIEv2** – used in many published results
- **GENIEv3 10a** and **GENIEv3 10b** – currently used by many active experiments (10a vs 10b have different FSI models)
- **SUSAv2** and **CRPA**: state-of-the-art nuclear response modeling for pionless events (implemented in GENIE ~v3.2.0)
- **NEUT**: used by T2K
- **NuWro**: performs well w.r.t. world cross-section data
- GiBUU: sophisticated hadron-transport, different neutrino–nucleon model, also performs well in world data comparisons

Bias studies: cross-section mismodeling



- Shift 20% of proton energy to neutrons (for all E_ν)
- Subtle impact on spectra, but large bias in oscillation parameters

90% confidence