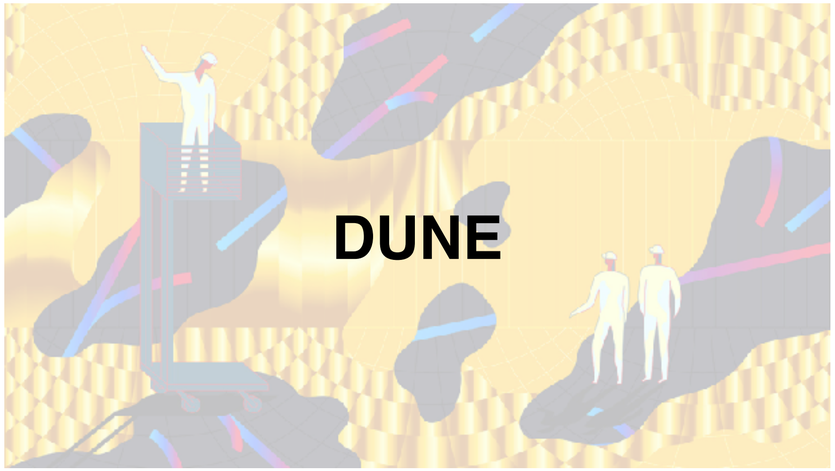
Queen Mary
University of London

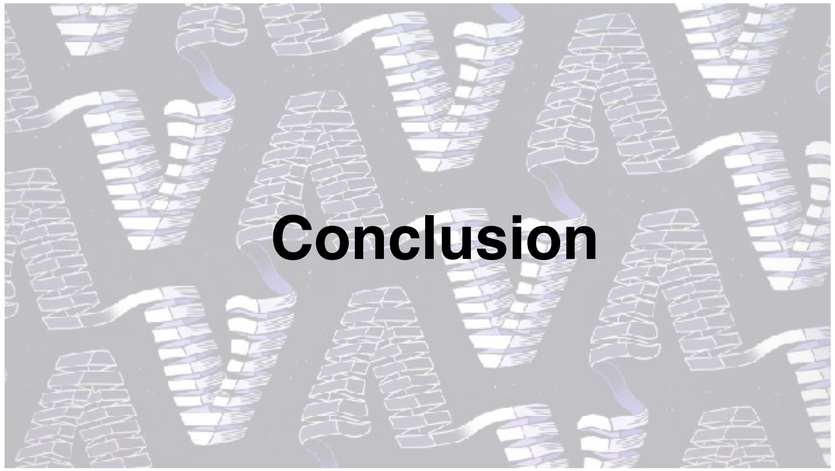
NOvA and DUNE

Dr Linda Cremonesi

UK HEP Forum 2022
Neutrinos: what? where from? and where to?

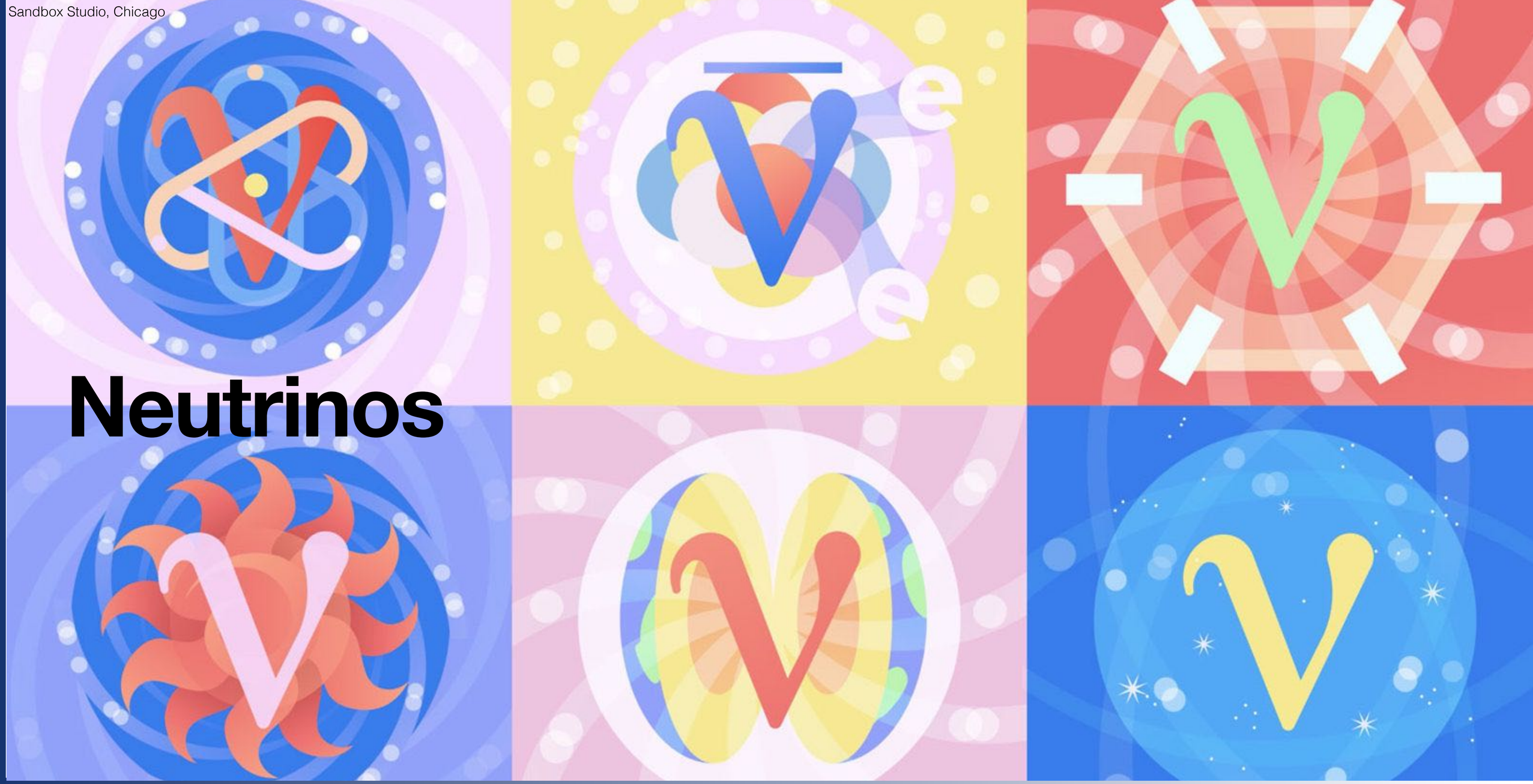
Outline





All images produced by Sandbox Studio, Chicago

Sandbox Studio, Chicago



Neutrinos

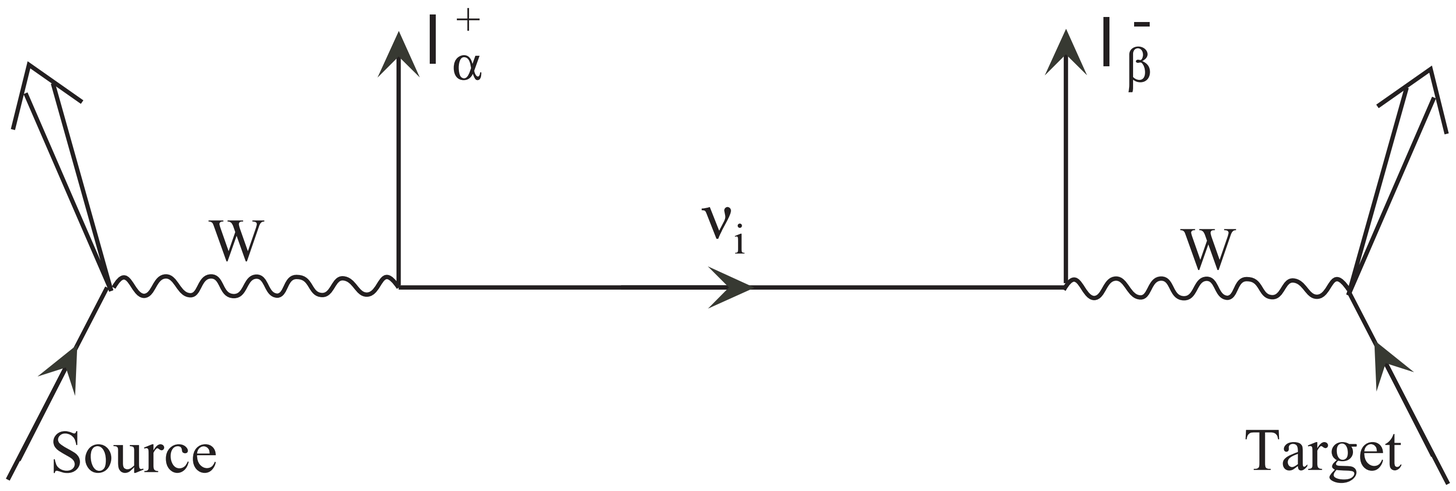
Neutrino flavour oscillations

Flavour eigenstates
ν_e, ν_μ, ν_τ

3x3 unitary matrix
PMNS matrix

Mass eigenstates
ν_1, ν_2, ν_3

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$



2015
Nobel Prize in Physics

PMNS Parametrisation - 3 flavours

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

θ_{ij} : the mixing angles

δ : CP-violating phase

α, β : Majorana phases

Atmospheric	"Reactor/LBL"	Solar
$\theta_{23} \sim 45^o$	$\theta_{13} \sim 8.5^o$	$\theta_{12} \sim 33^o$
$\Delta m^2_{32} \sim \pm 2.5 \times 10^{-3} eV^2$	$\delta_{CP}???$	$\Delta m^2_{12} \sim 7.5 \times 10^{-5} eV^2$

Big questions

How much do neutrinos mix?

Jargon alert: is θ_{23} maximal? Upper/Lower octant?

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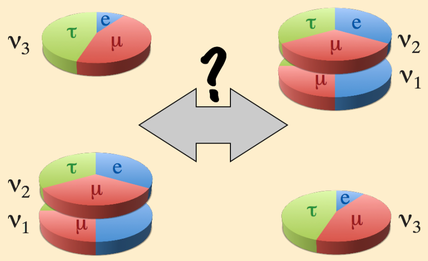
Which is the lightest neutrino?



Normal Ordering Inverted Ordering

Jargon alert: is $\Delta m^2_{32} \lessgtr 0$?

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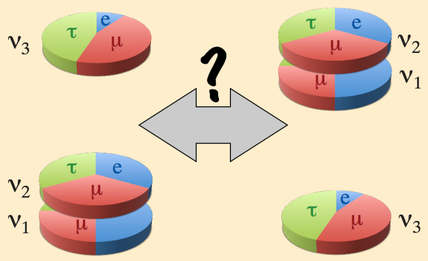

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Do neutrinos and antineutrinos oscillate in the same way?

?

Jargon alert: is $\delta_{CP} \neq 0$?

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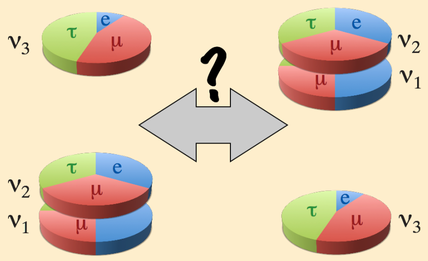

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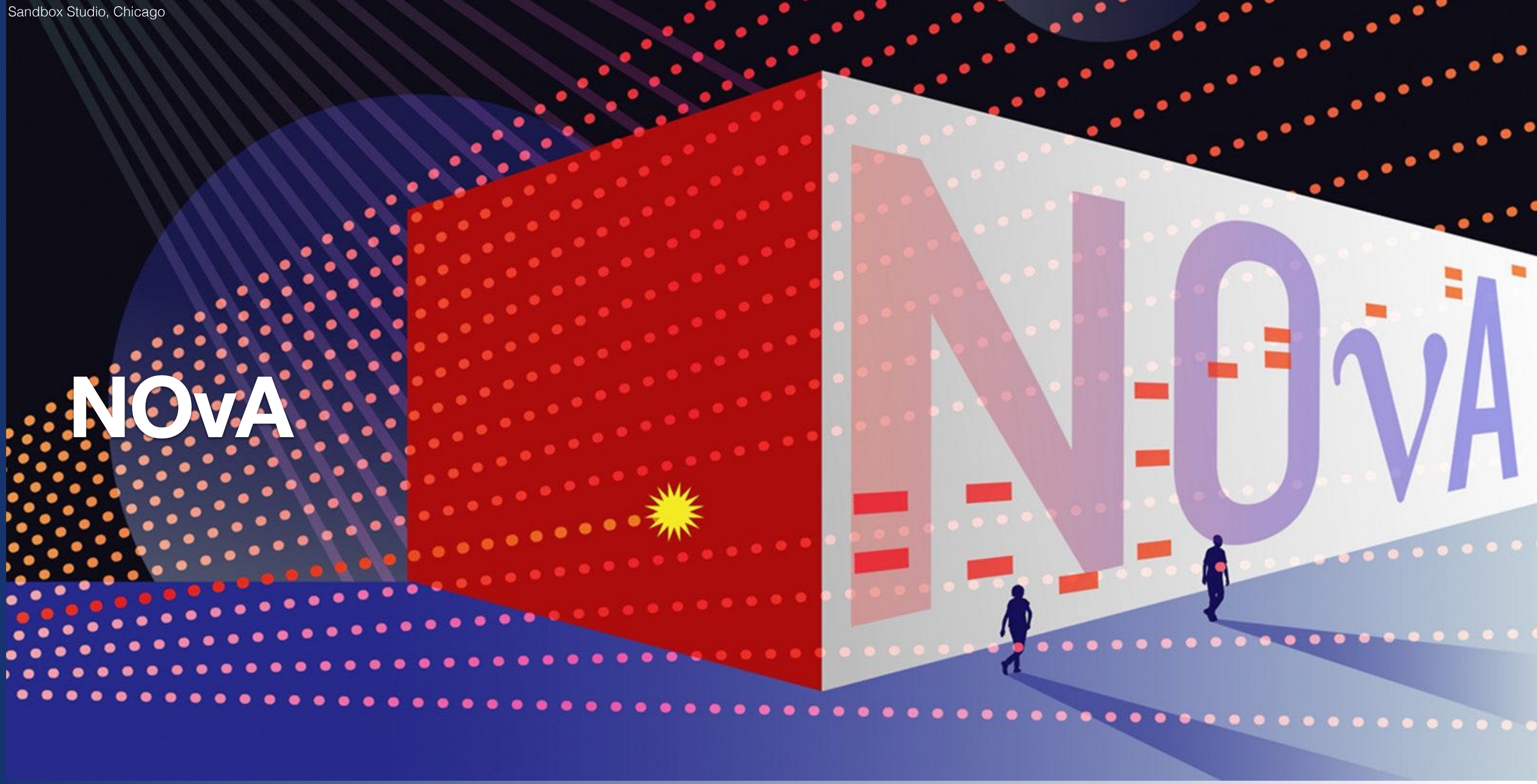
Jargon alert: is $\delta_{CP} \neq 0$?

Is there a light sterile neutrino?

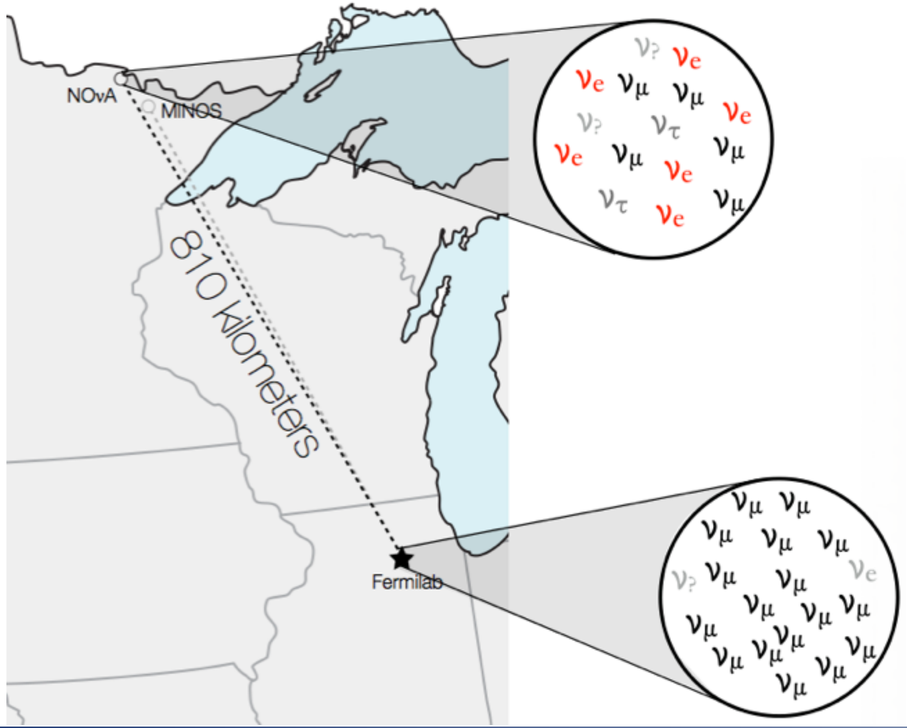
Jargon alert: ν_s ? ν_4 ?

Sandbox Studio, Chicago



The NOvA experiment

- NOvA is a long-baseline neutrino experiment:
  - 2 detectors, 14.6 mrad off-axis, 809 km apart.
  - Designed to measure for $\nu_\mu \rightarrow \nu_e$ oscillations: detectors provide excellent imaging of both ν_μ and ν_e CC events.
- NOvA can run in neutrino-mode or antineutrino-mode.



- High neutrino flux at Near Detector:
  - used as control for the oscillation analyses,
  - provides a rich data set for measuring cross sections.
- ND located 1km from the NuMI beam target.

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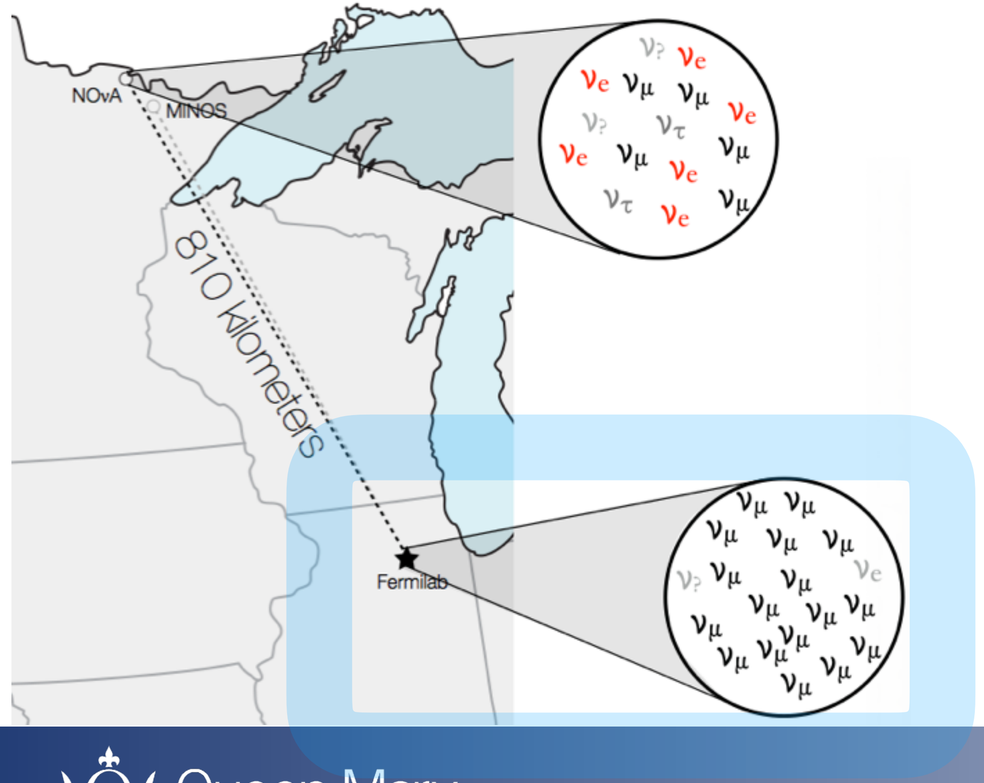
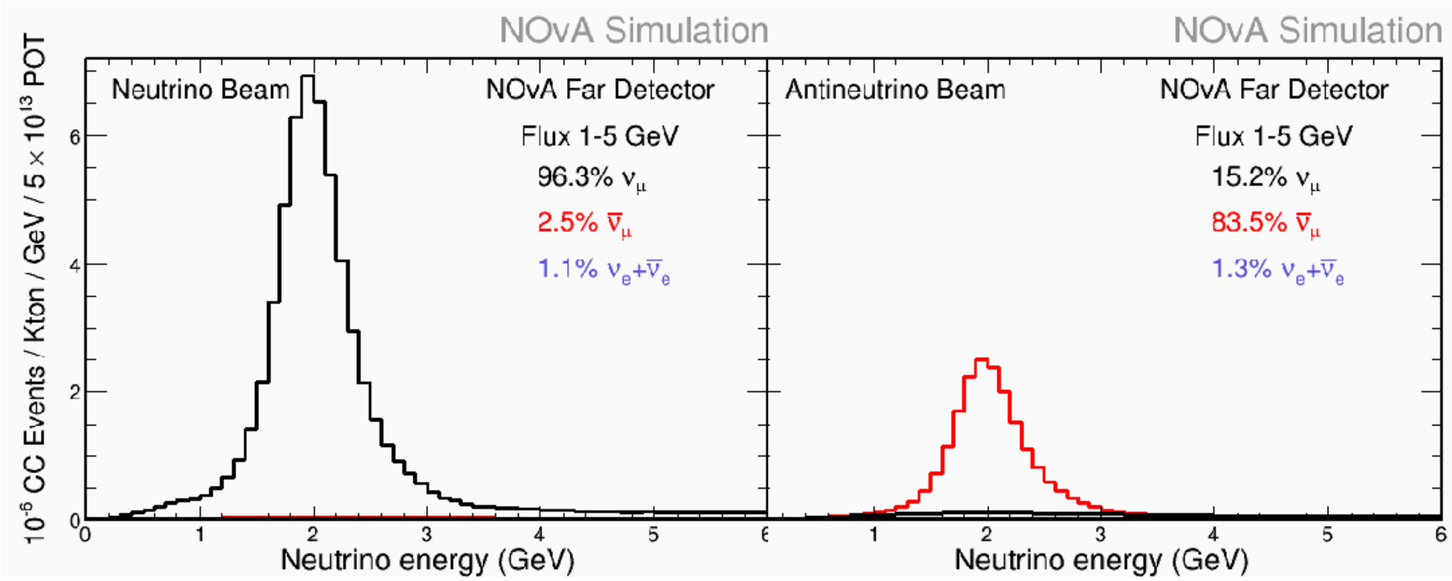
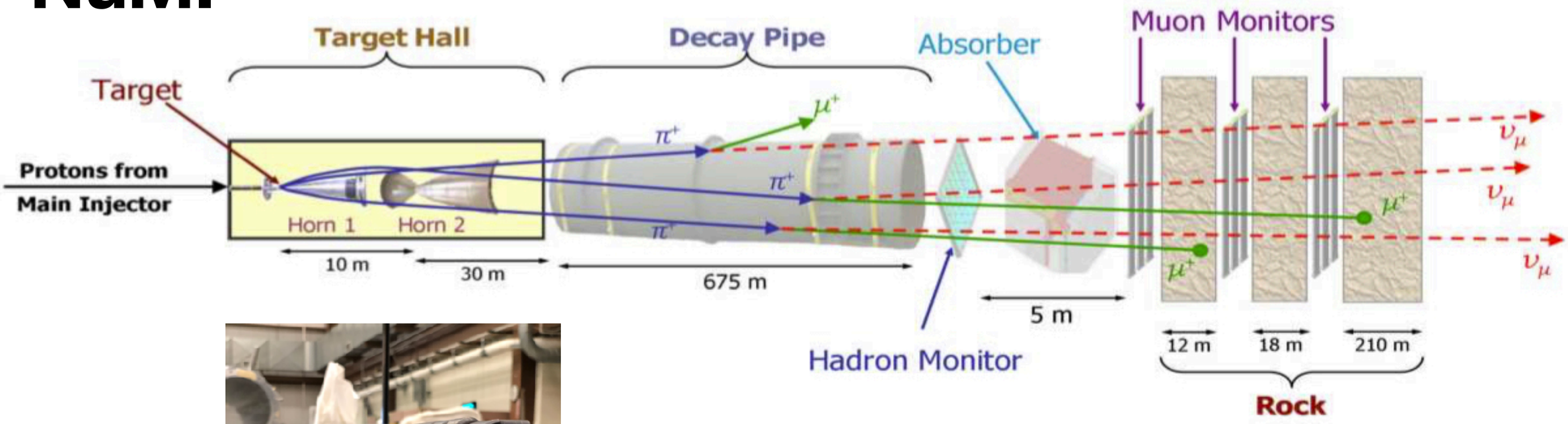
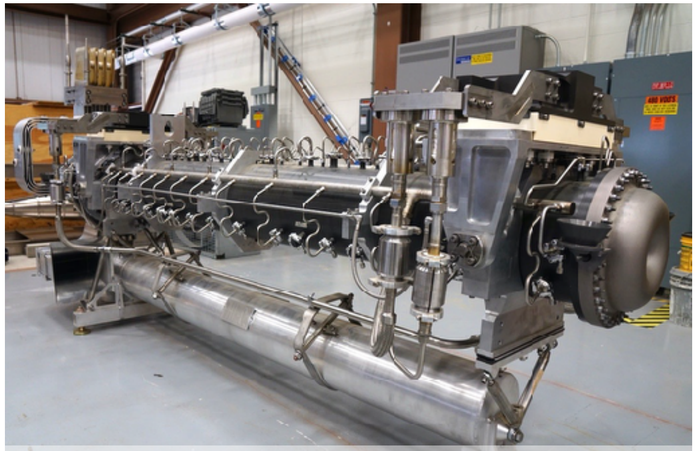




NuMI

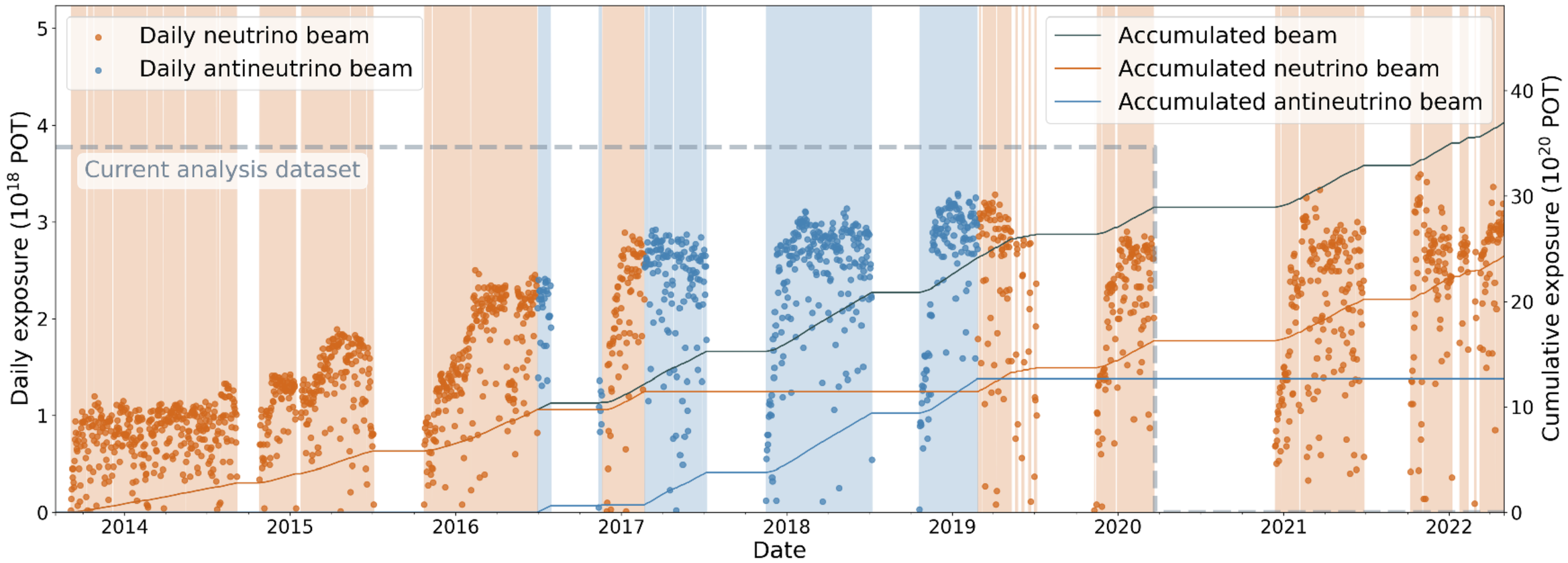


MW-capable target



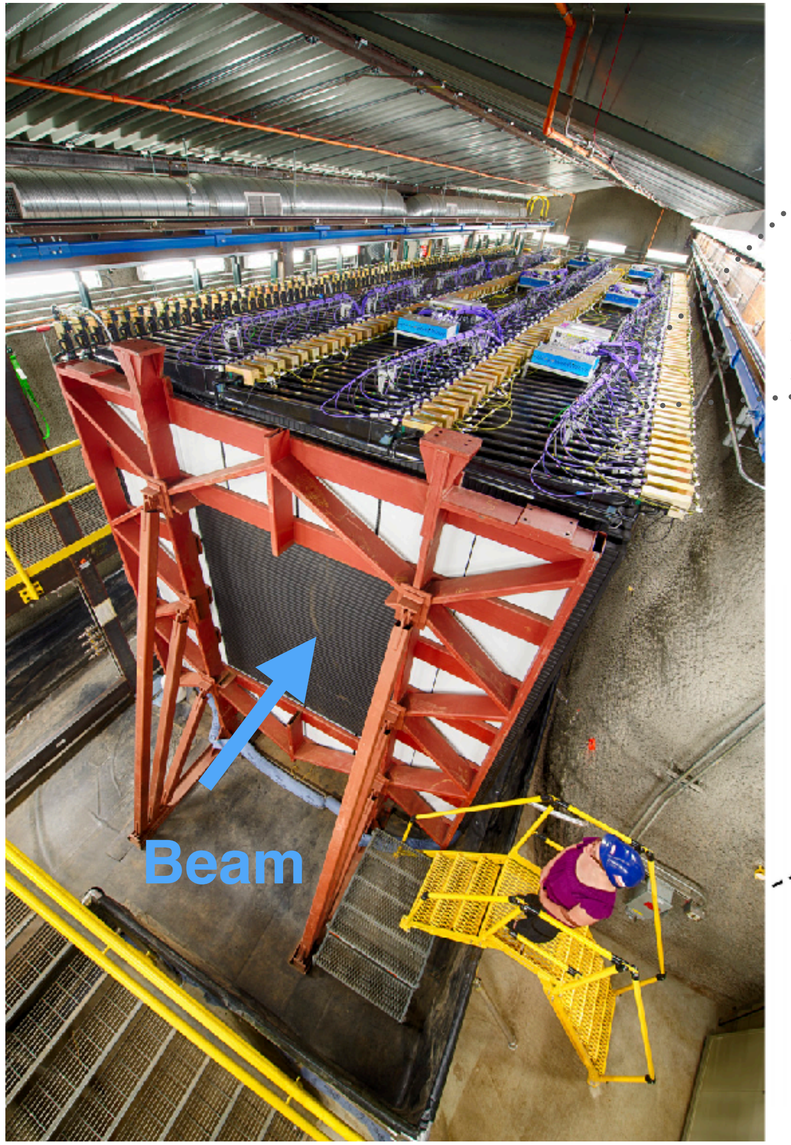
MW-capable horn

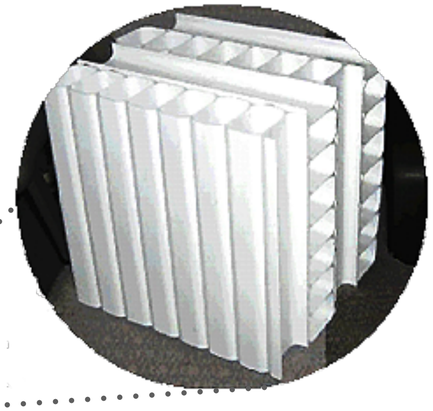
NOvA exposure to NuMI beam



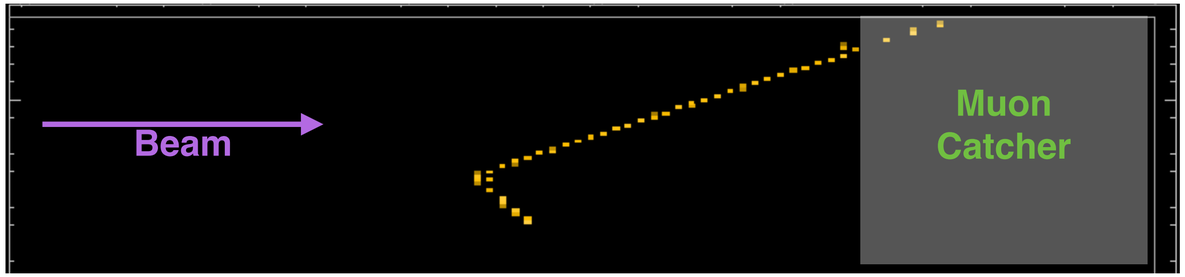
- NuMI running at ~750kW since 2019. NuMI power record of 893 kW.
- Total protons-on-target: 37 x 10^{20}

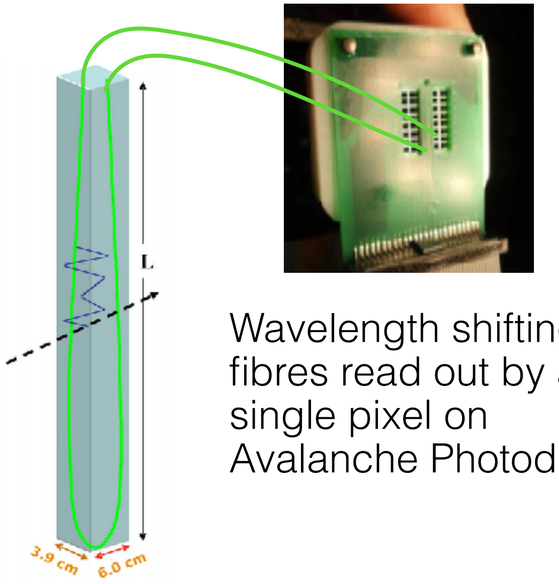
NOvA Detectors





Alternating planes allow for 3D reconstruction



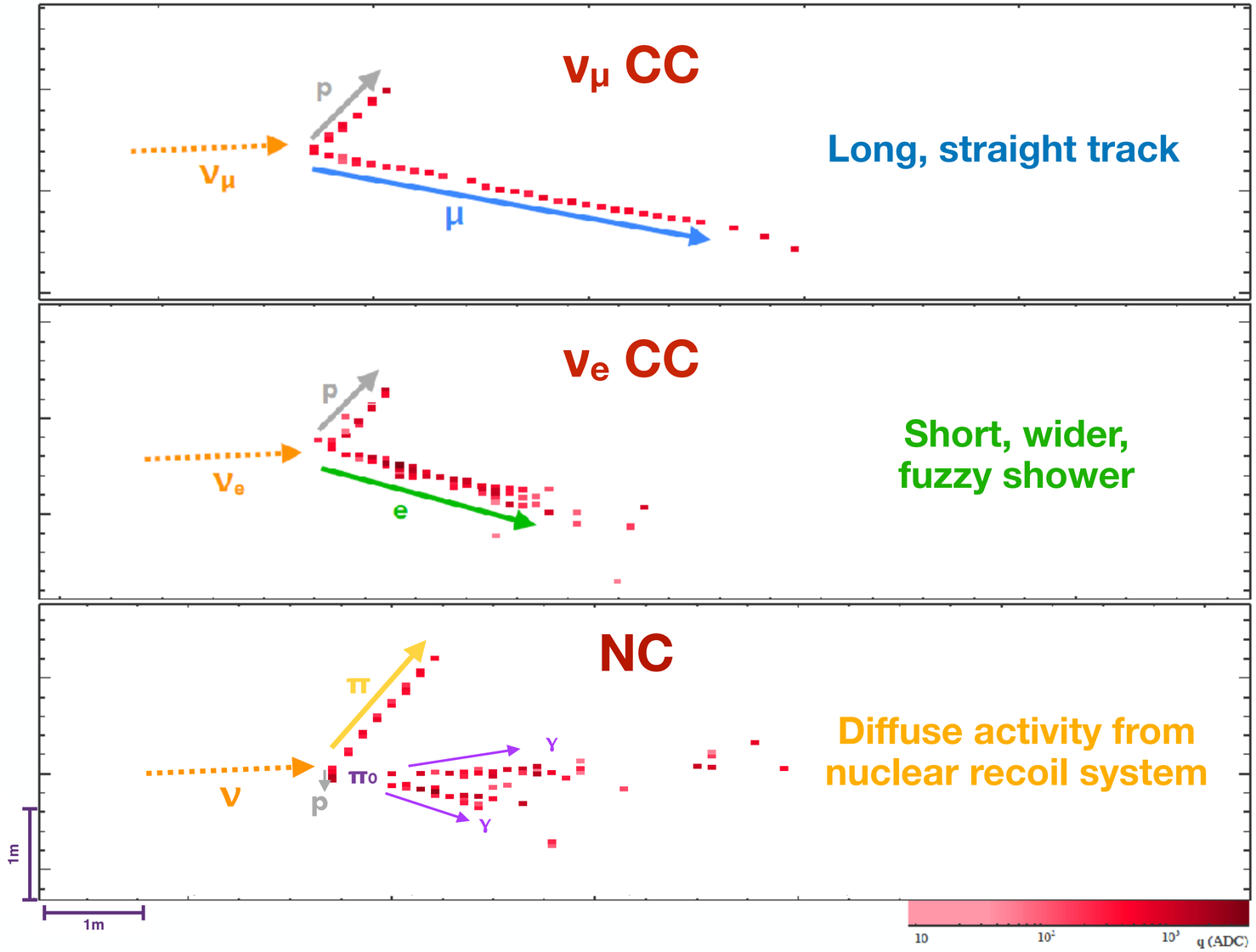


Wavelength shifting fibres read out by a single pixel on Avalanche Photodiode

- Tracking calorimeter
- Extruded plastic cells, filled with liquid scintillator
- 0.17 X_0 per layer
- Near detector:
  - 300 tons, 1km from the target
  - Huge statistics: >1M ν_μ CC selected events

14,000 ton Far Detector

Detailed event images



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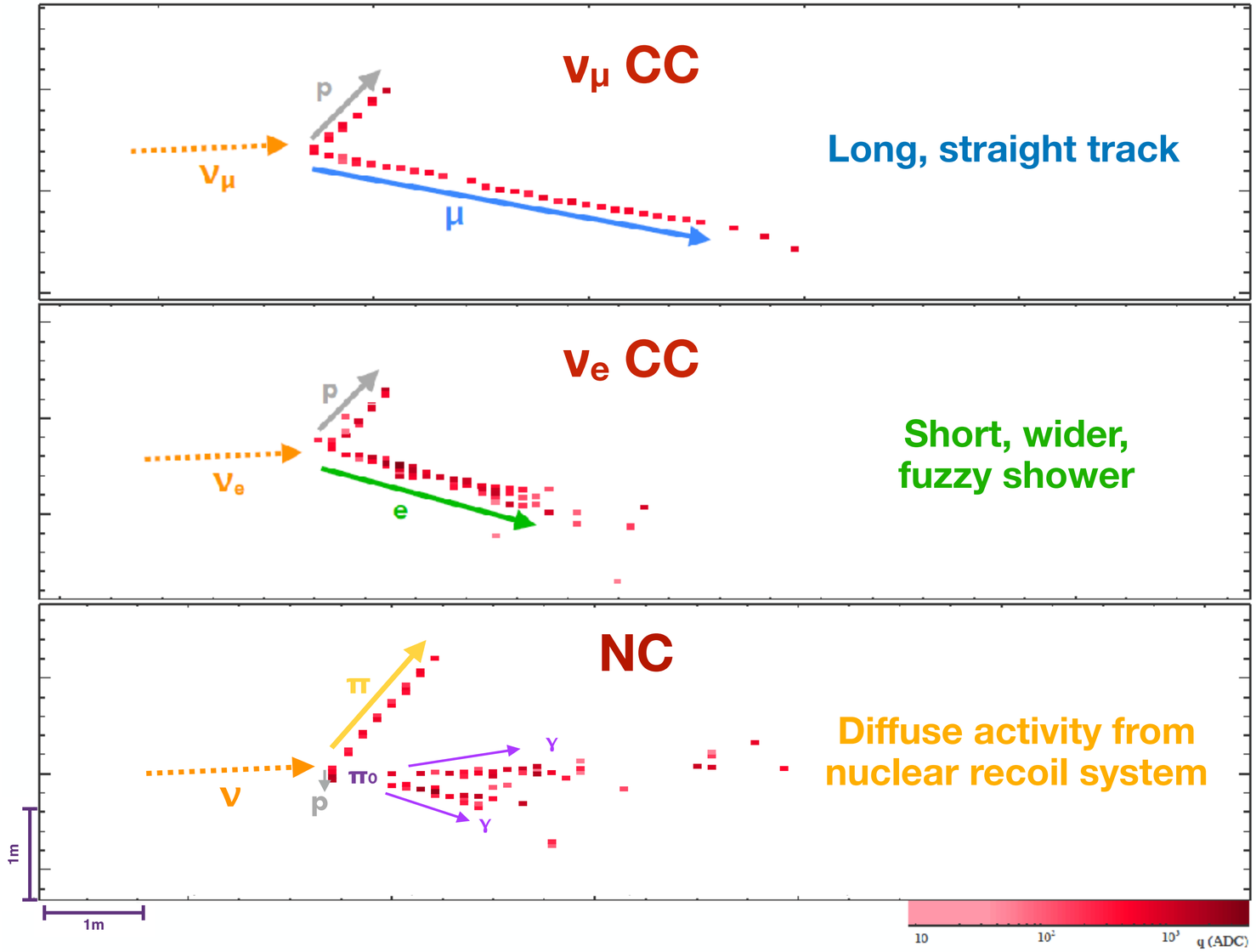
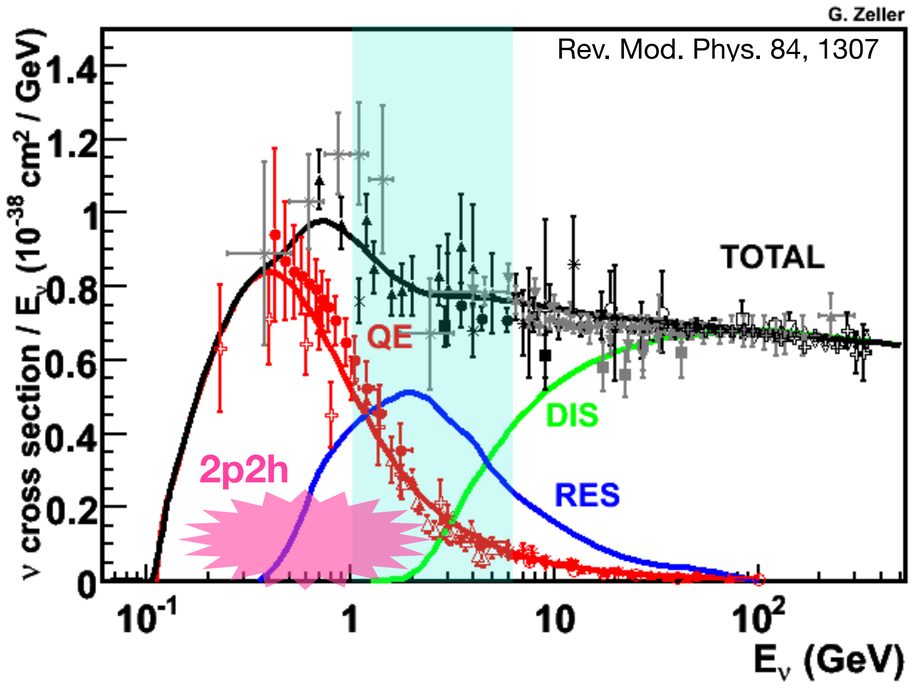
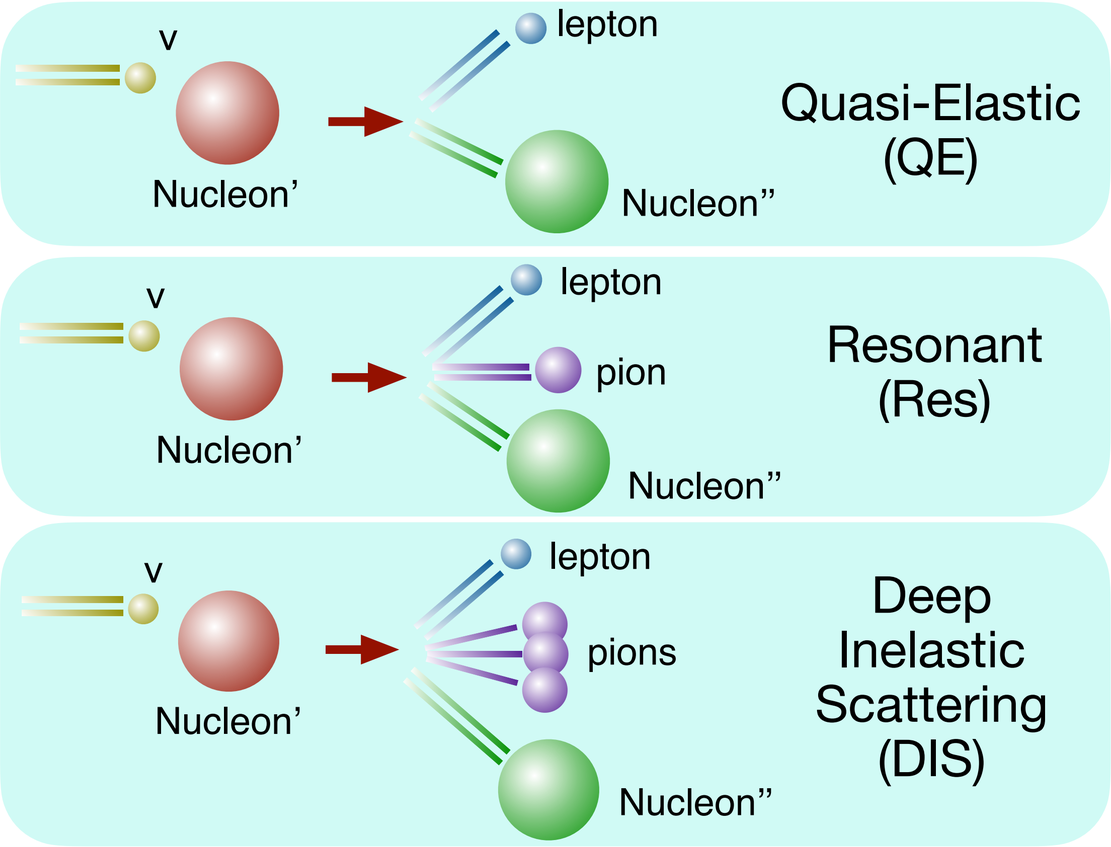


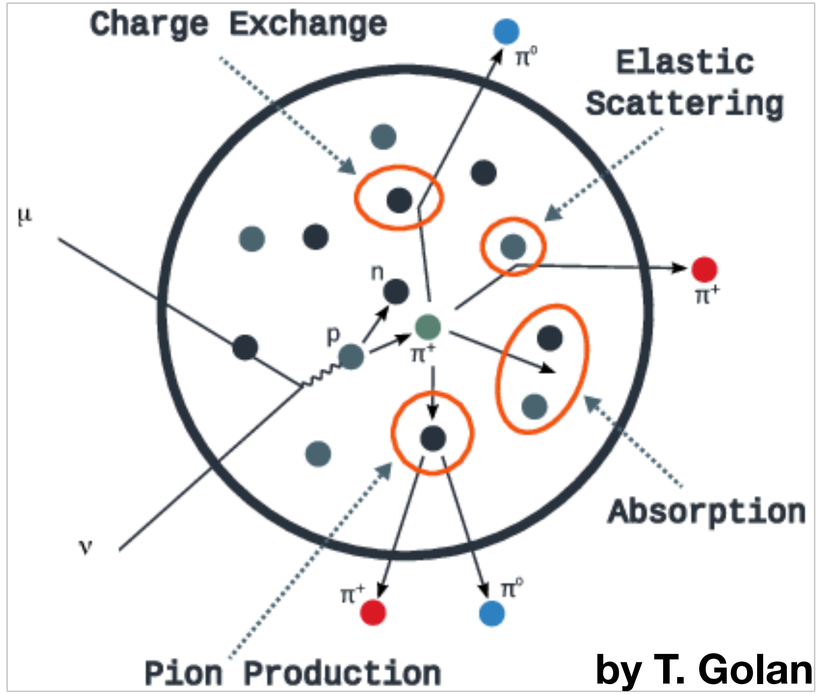
Neutrino CC interactions at NOvA

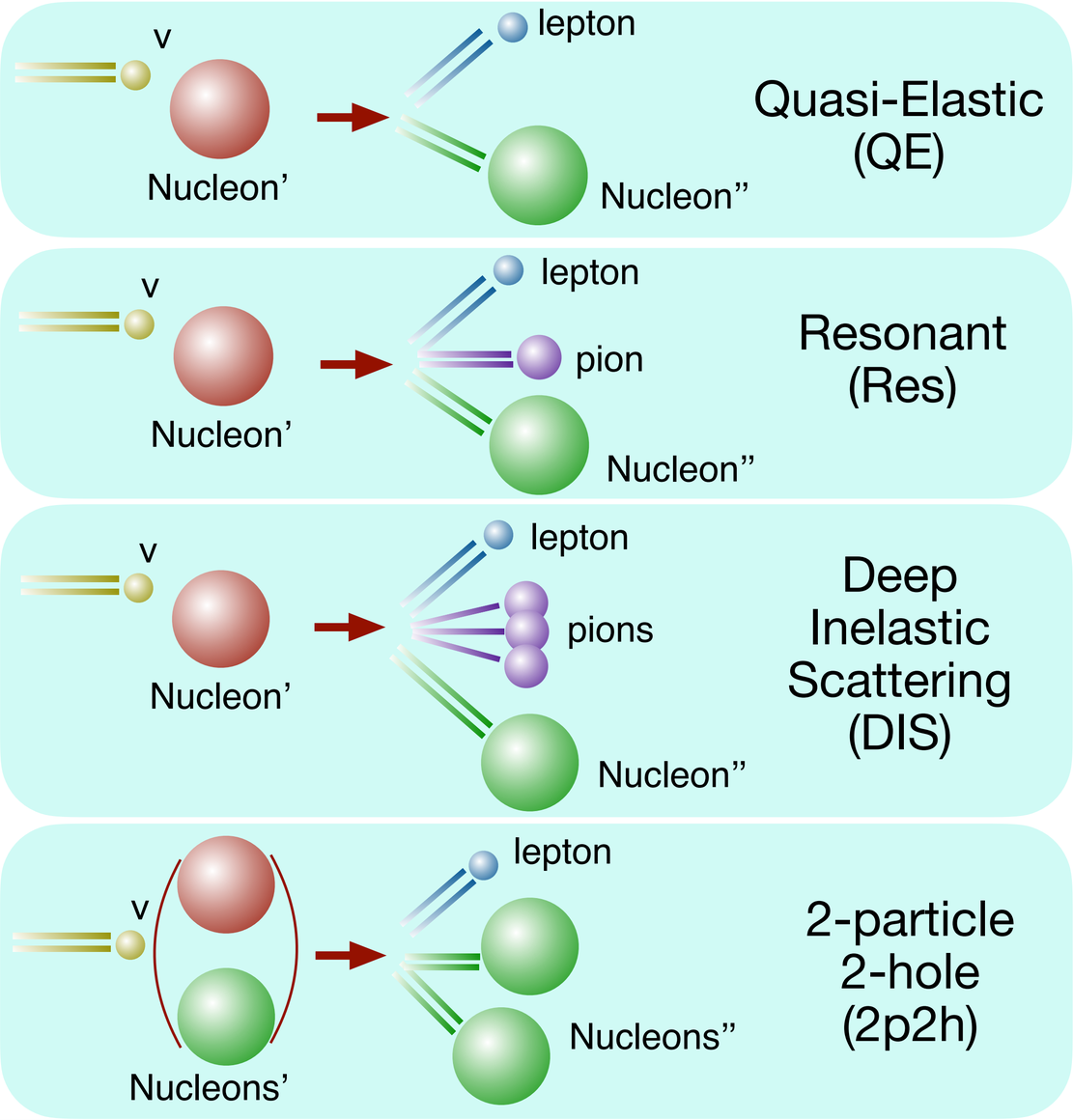




- NOvA flux peaks between 1 and 5 GeV: it sits in the transition region between different neutrino interaction processes.

Neutrino CC interactions at NOvA

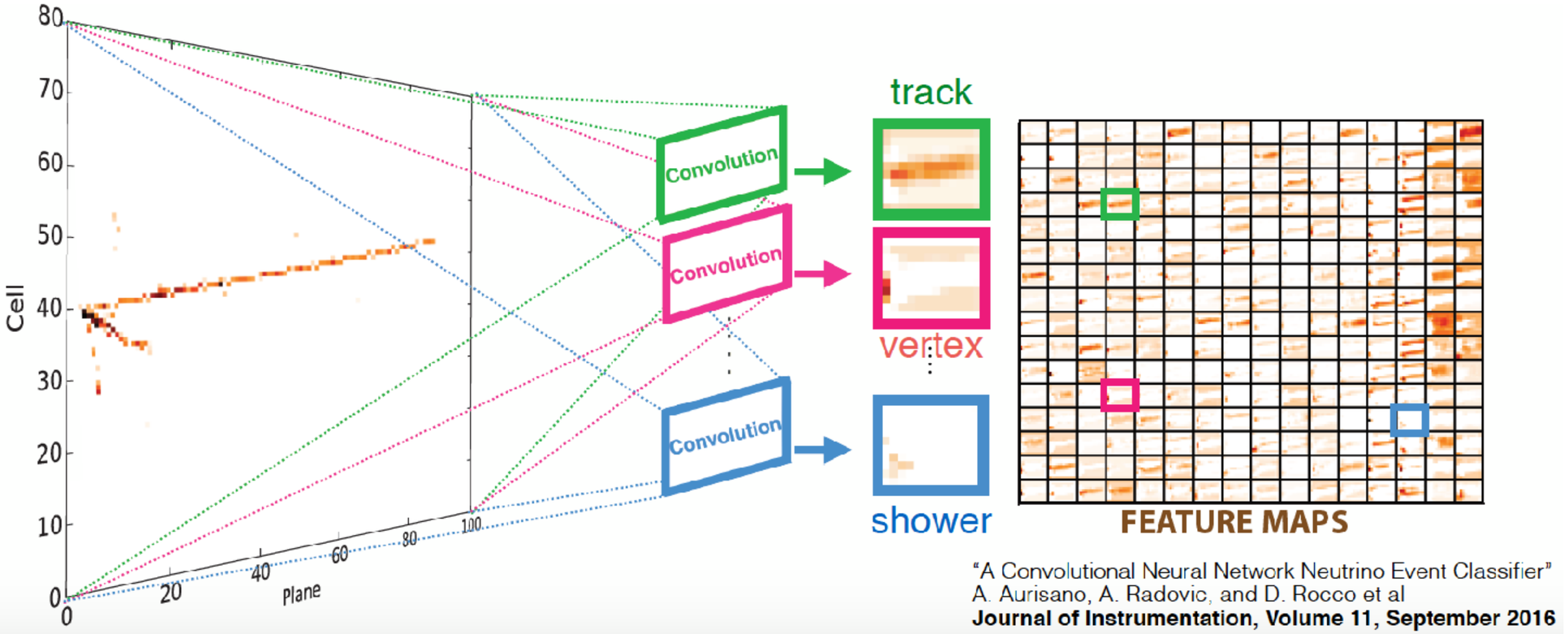




- Nuclear effects are significant
  - Contribution of axial part of weak interaction can only be studied w/ neutrinos
  - Better understanding important for reducing systematics on oscillation measurements

Deep learning

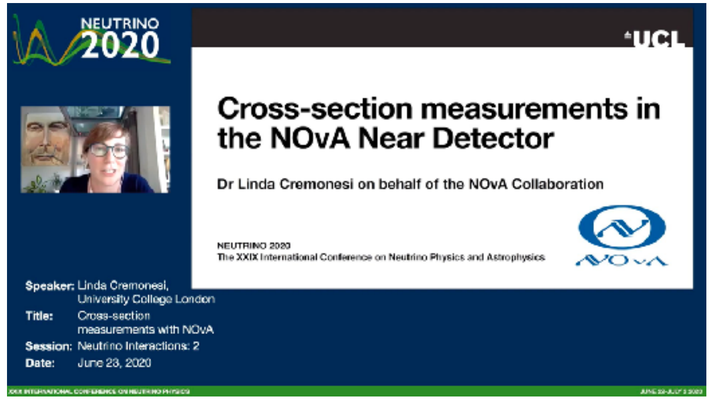
- Pioneering use of deep learning for image clarification in HEP
- Convolutional Neural Network used as a multi-classifier, assigning an ID: ν_μ, ν_e, NC, cosmic for each interaction
- Trained for neutrino and antineutrino beam separately.
- Cosmic data included in training.

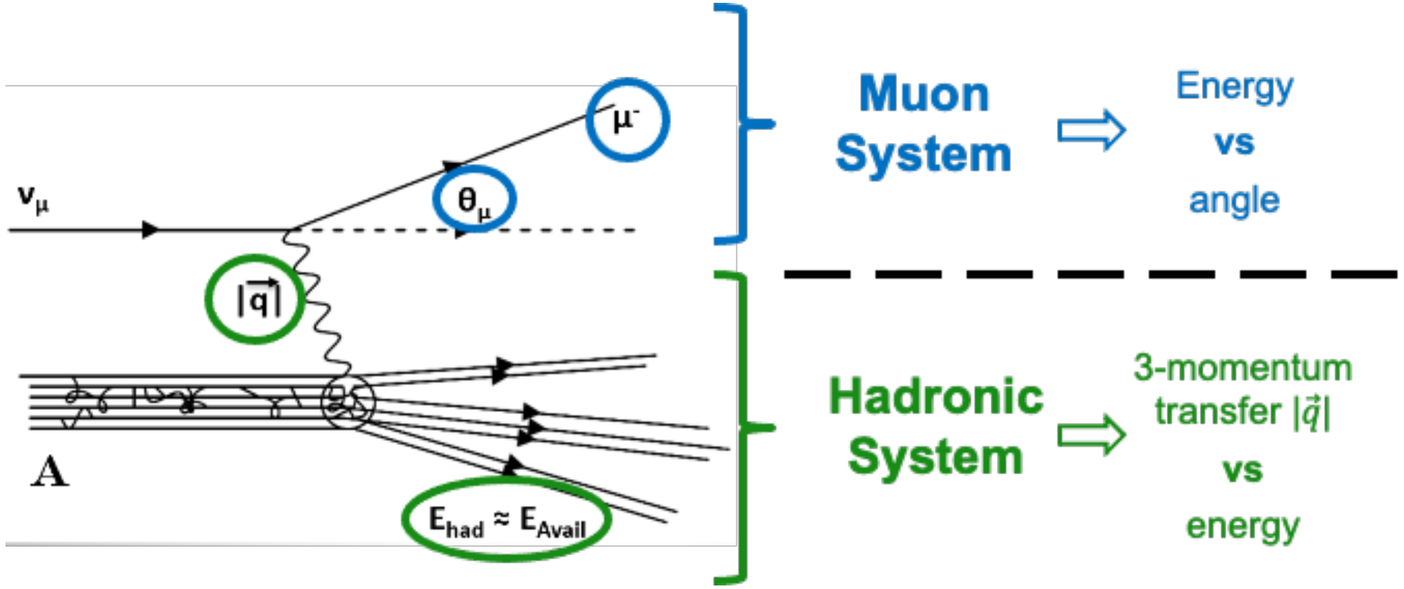


"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

NOvA cross-section programme

- Neutrino CC inclusive analyses presented at Neutrino2020
  - ν_μ CC inclusive
    arXiv: 2109.12220 (in PRD review)
  - ν_e CC inclusive
    arXiv: 2206.10585 (accepted by PRL)
- Antineutrino inclusive analyses to be released early next year
- Two more analyses released at Neutrino 2022 trying to better understand 2p2h
  - Muon system analysis: 115 muon kinematics points
  - Hadron system analysis: 67 hadron kinematics points
  - Uncertainties ~ 12% dominated by flux
  - Comparisons with various 2p2h models finds better agreement to tuned models.





NOvA neutrino oscillation analysis

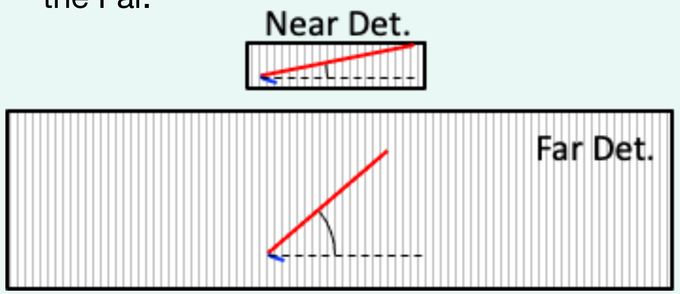
ND

- Binned by hadronic energy fraction (sensitivity of disappearance measurement comes from resolution)

- Binned by PID (sensitivity of appearance measurement driven by purity)

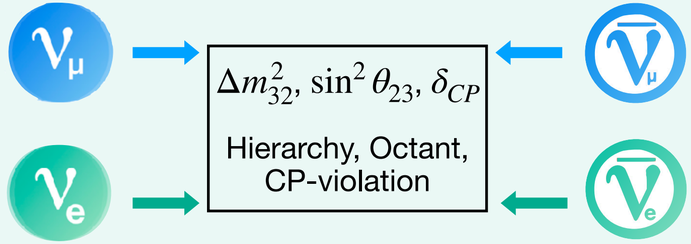
Extrapolation

- Containment limits the range of lepton angles more in the Near Detector than in the Far.



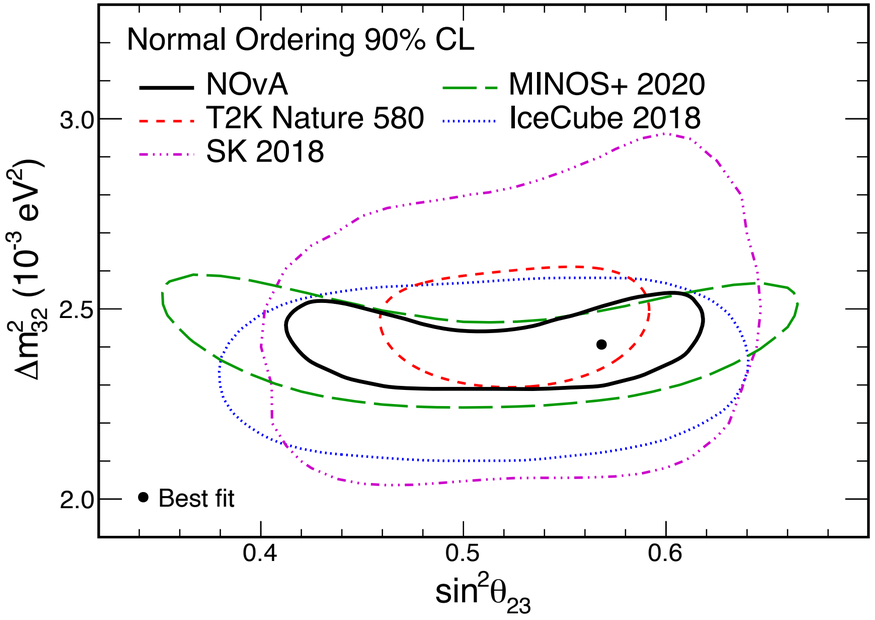
- Extrapolation in 3 bins of pT (lepton transverse momentum) for each energy bin
- Re-sum pT bins before fit

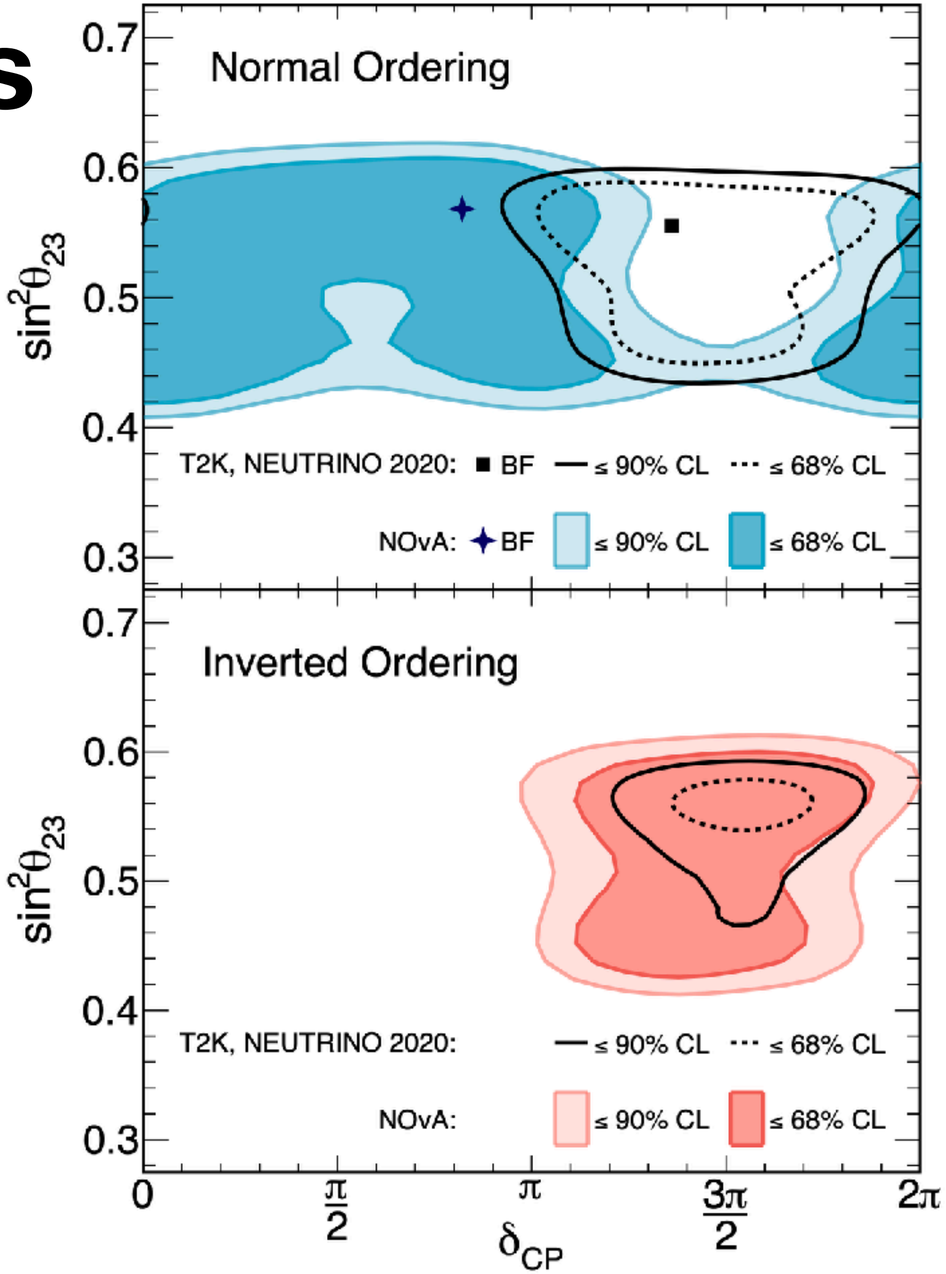
FD



- Simultaneous fit of all samples
- Two analysis:
  - A frequentist analysis with Feldman-Cousins method
  - A Markov Chain MC Baysian analysis

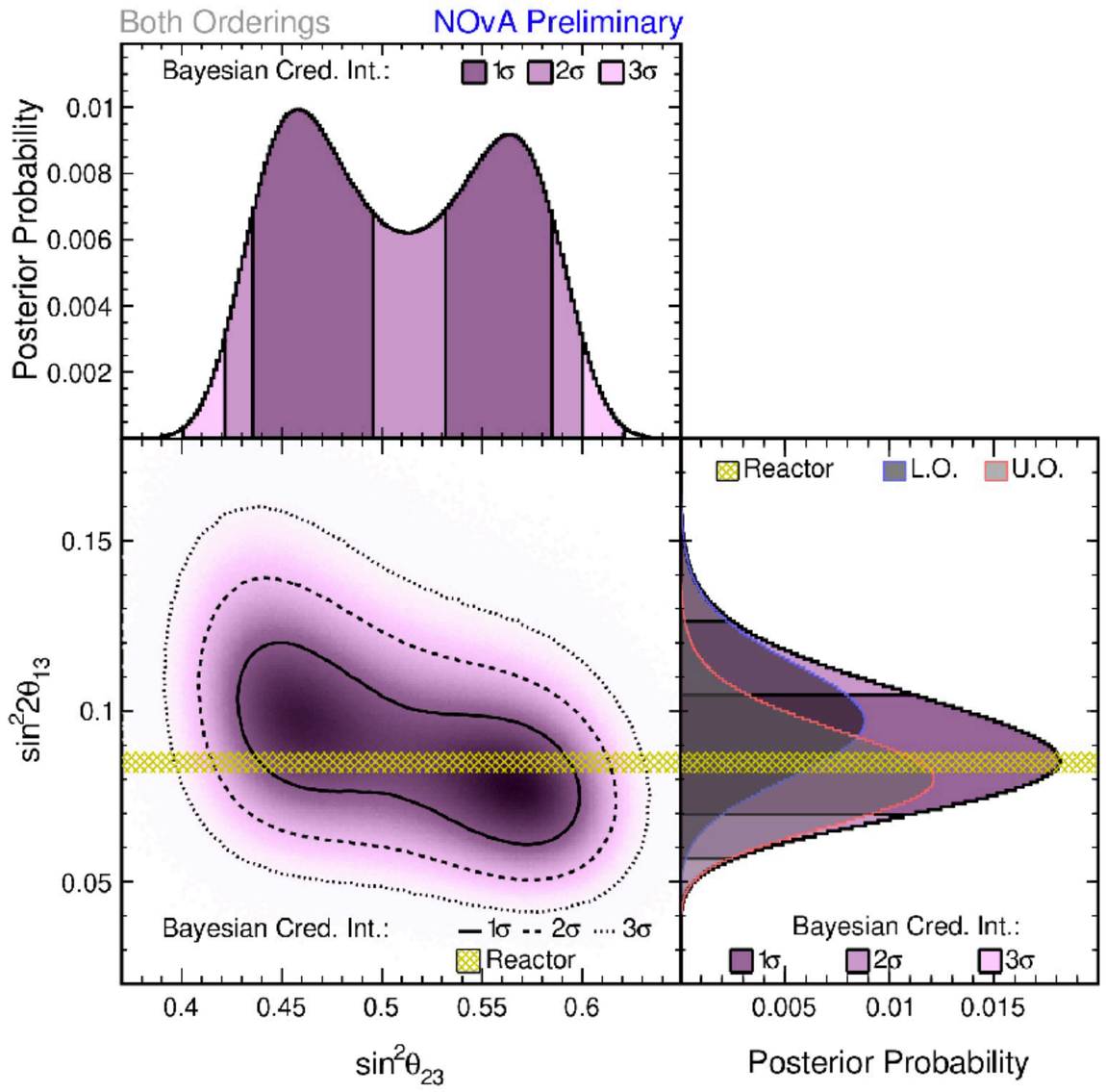
Neutrino oscillation results





- θ_{23} consistent with 45°
- Exclude IO, $\delta_{CP} = \pi/2$ at $> 3\ \sigma$
- Significant progress on joint fit with T2K (coming soon)
- Frequentist results: 10.1103/PhysRevD.106.032004 (Editors Choice and Featured in Physics article)

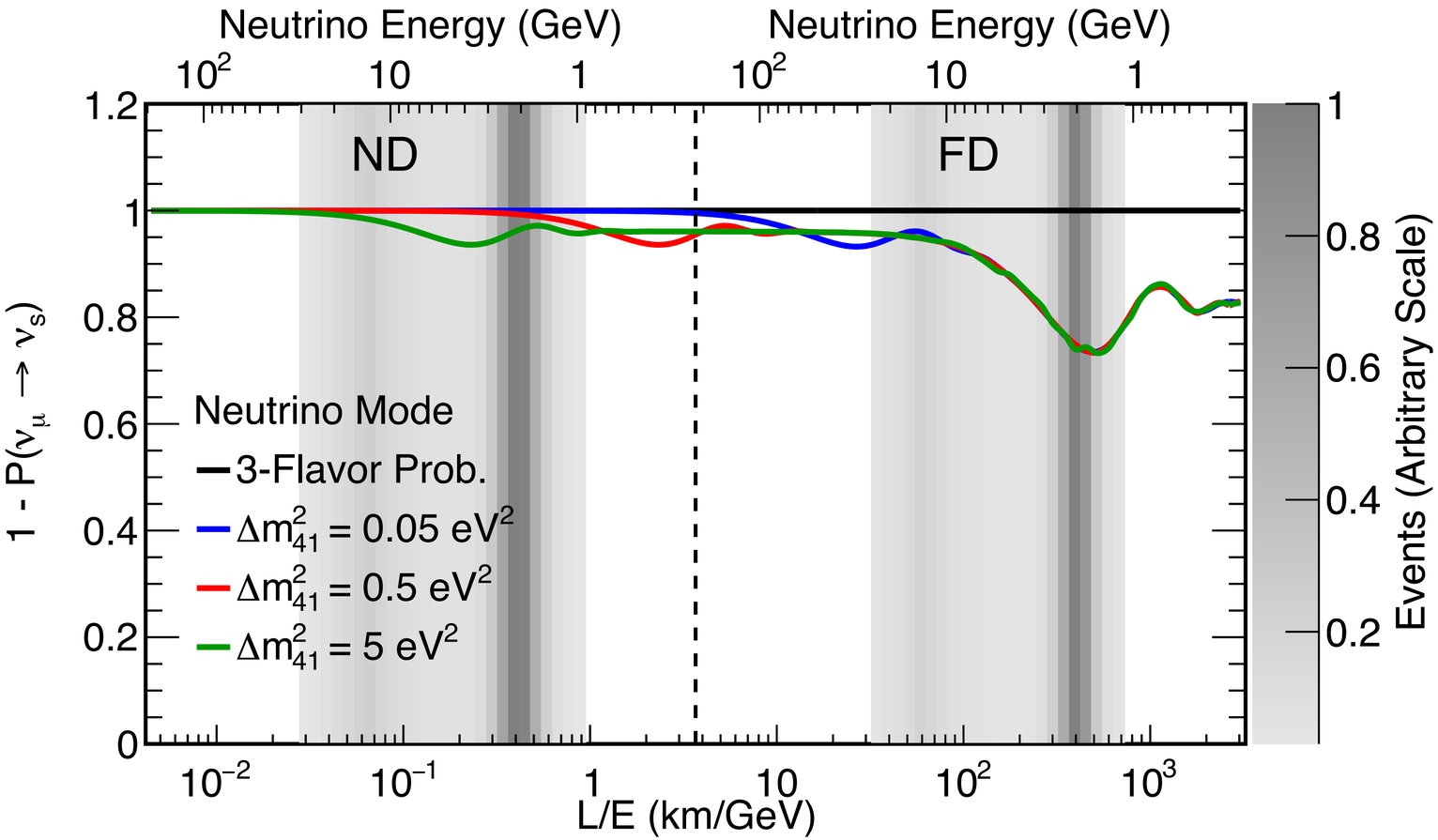
NOvA-only θ_{13} and θ_{23} results



- Baysian analysis (co-led by Artur Sztuc, UCL)
- Larger θ_{13} would favour lower octant for θ_{23} and vice versa
- Normally use reactor θ_{13} constraint in fit
- Here θ_{13} is measured by NOvA $\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$
- Consistent with reactor experiments
- Publication in preparation

Sterile neutrino search

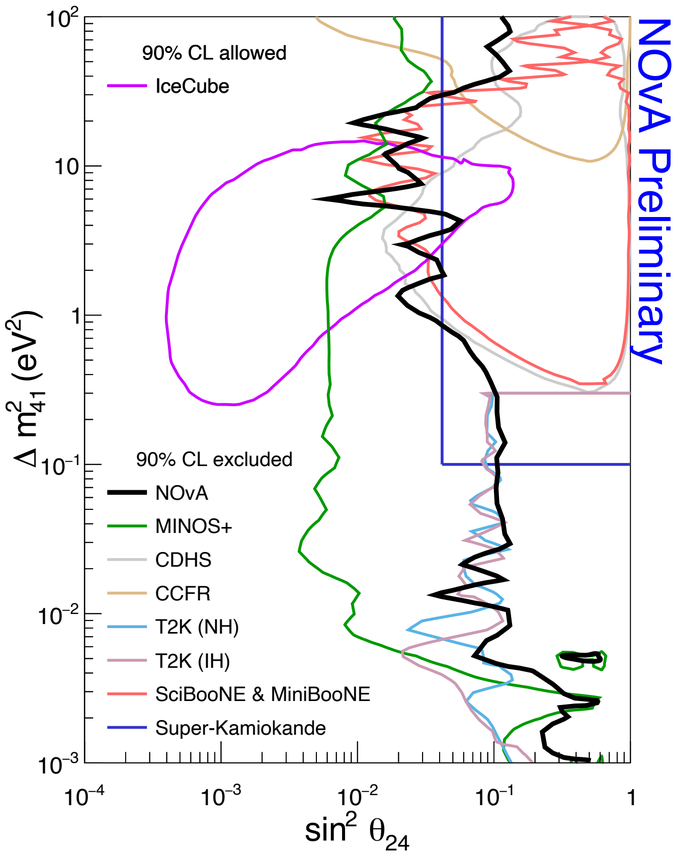
- Search for 4th, sterile, neutrino
- Analysis uses 3+1 fit sterile neutrino model to samples:
  - neutral current
  - ν_μ CC
- Oscillations allowed in both detector simultaneously

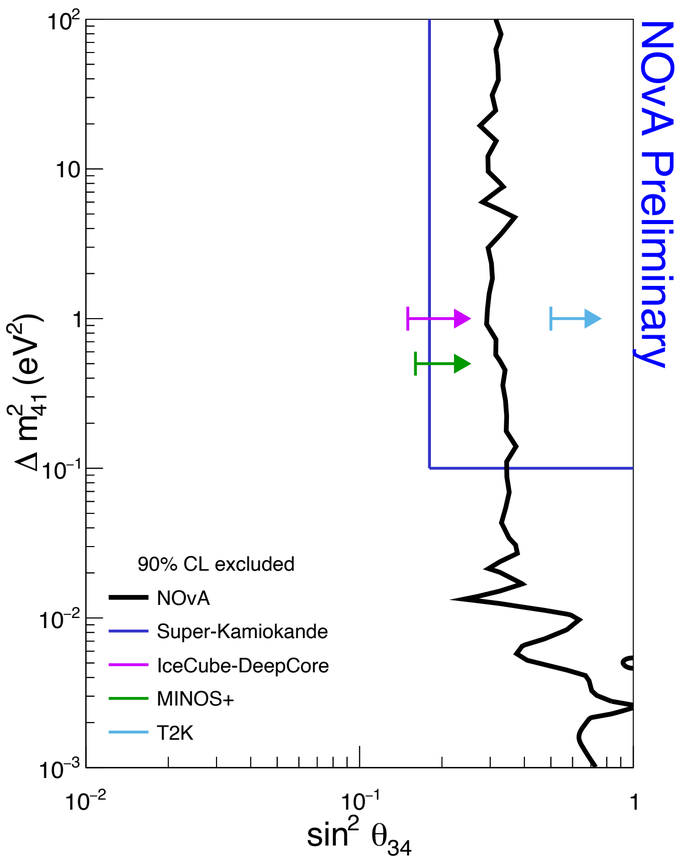


Phys.Rev.Lett. 127 (2021) 20, 201801
Phys.Rev.D 96 (2017) 7, 072006

Sterile neutrino search results

- Data shows no evidence for sterile neutrinos
  - Best fit at small θ_{24} and θ_{34} with low significance
- Competitive limits on θ_{24} for $\Delta m^2_{41} \sim 10\text{eV}^2$
- Analysis systematics limited at large Δm^2_{14} (Near det.) but less so for small Δm^2_{14} (Far det.)
- New constraints on θ_{34} (a measure of mixing between ν_τ and a sterile ν)
- Historically studied via ν_τ appearance searches at short baselines as $\theta_{\mu\tau}$
- NOvA's sensitivity comes from neutral current events
  - enhanced by constraints on θ_{24} from ν_μ charged current events
- Long-baseline providing sensitivity at small Δm^2_{41}





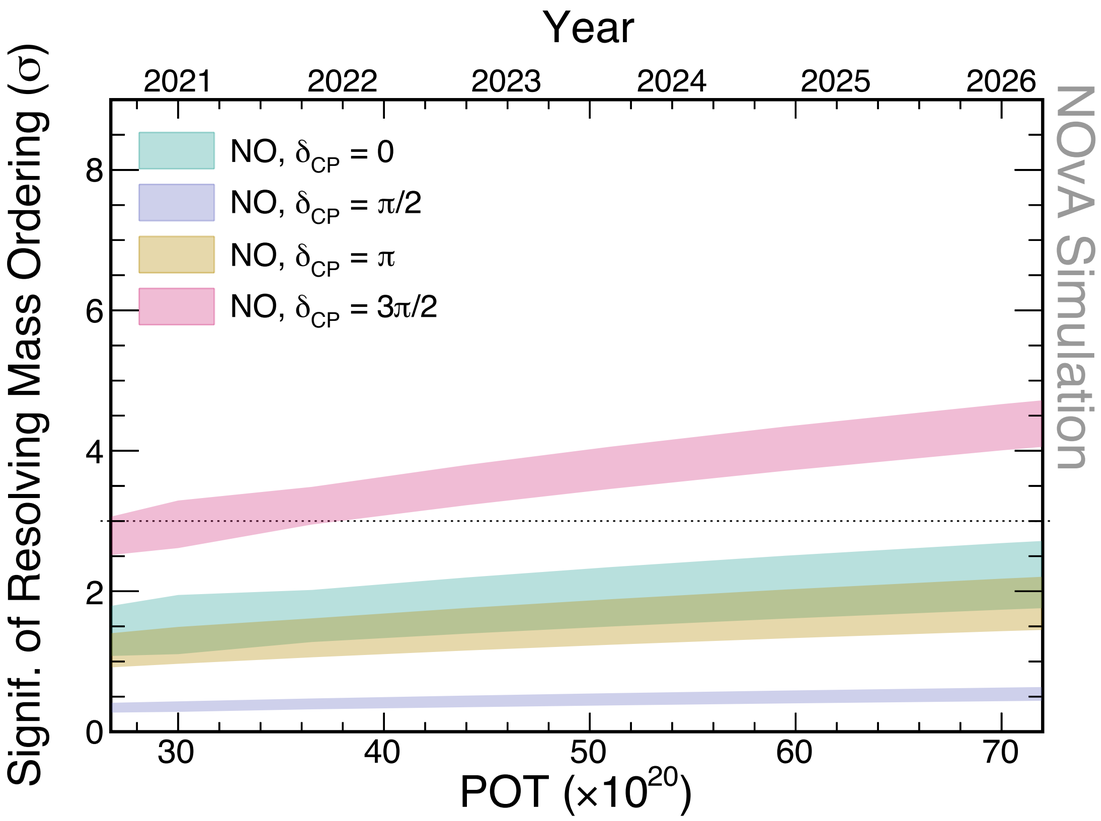
Looking at the future

- Many NOvA analyses are limited by calibration and detector response uncertainties.
- The NOvA Test Beam experiment just finished taking data. Our aim is to reduce the calibration and detector response uncertainties.
- The flux uncertainties for neutrino interaction analyses will be reduced with a neutrino-electron cross section measurement currently under development.

NOvA Future

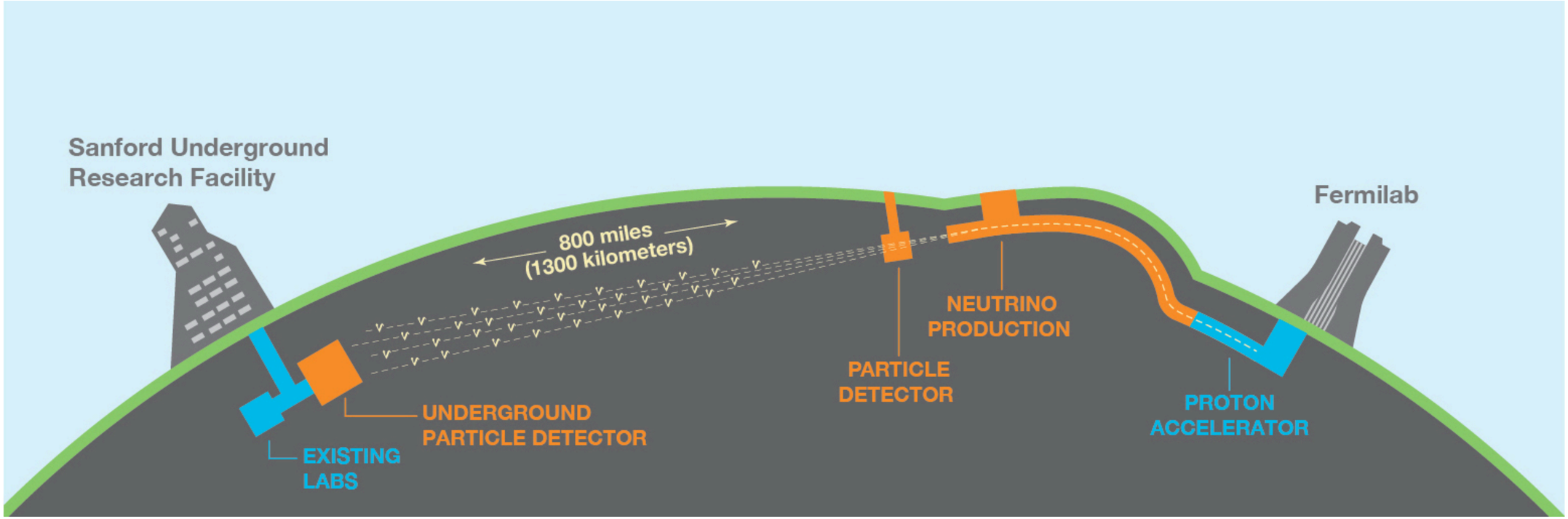
- Increasing sensitivity to mass ordering to come
  - Will more than double data set in both beams
  - –>3σ mass ordering sensitivity for 30-40% of δ-values
  - By run end, statistical errors still significantly larger than current systematics on ν_e appearance

- Watch this space for:
  - NOvA-T2K joint fit
  - Further tests of alternative models (e.g. NSI)
  - Antineutrino beam cross section measurements



Sandbox Studio, Chicago

DUNE: Physics Goals



Discovery sensitivity to CP violation, mass ordering, and θ_{23} octant.

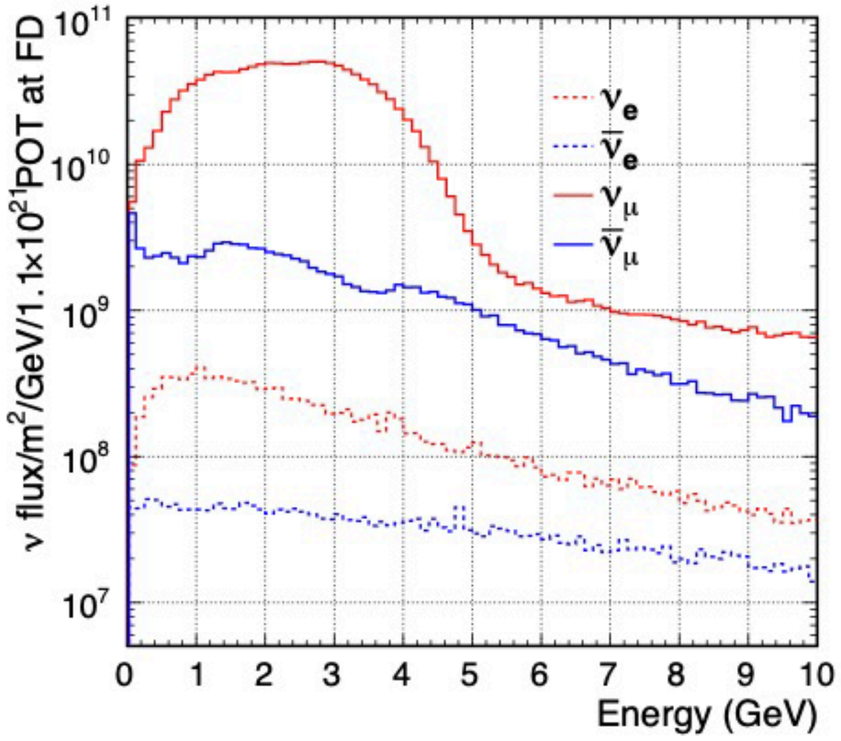
High-precision measurements of Δm^2_{32}, δ_{CP}, θ_{23}, θ_{13} in a single experiment.

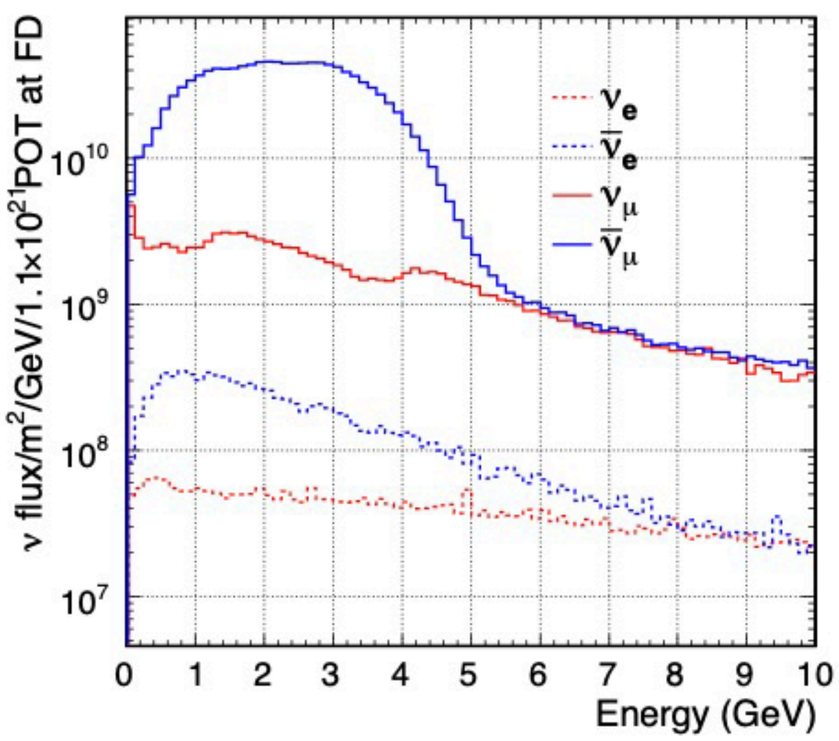
Sensitivity to MeV-scale neutrinos, such as from a galactic supernova burst.

Low backgrounds for sensitivity to BSM including baryon number violation.

DUNE Design: Wideband Beam

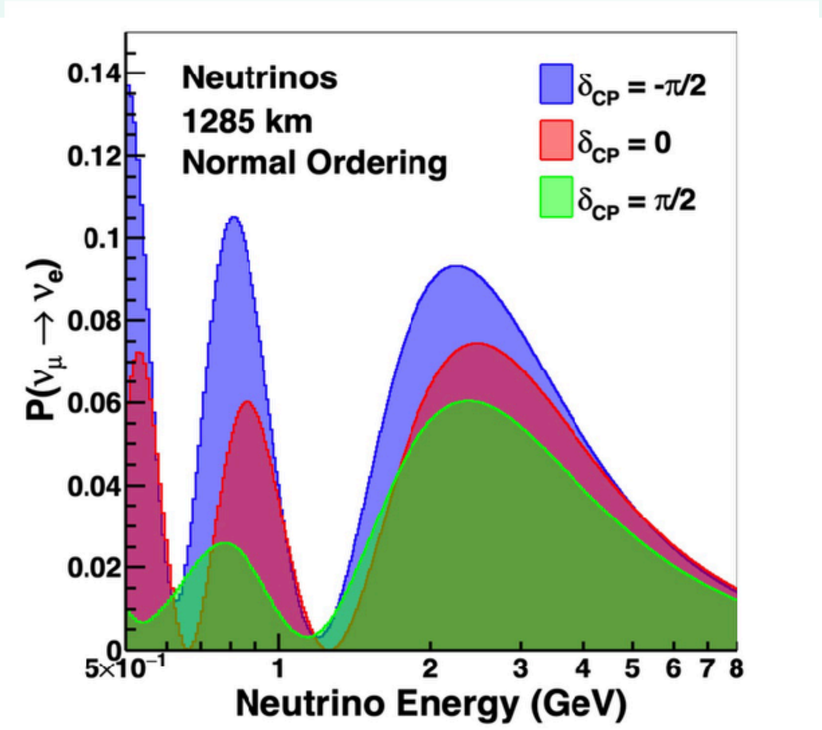
- The LBNF neutrino beam will provide neutrinos and antineutrinos with energies from 0-5+ GeV
- Simulated neutrino fluxes at the far detector are shown below.

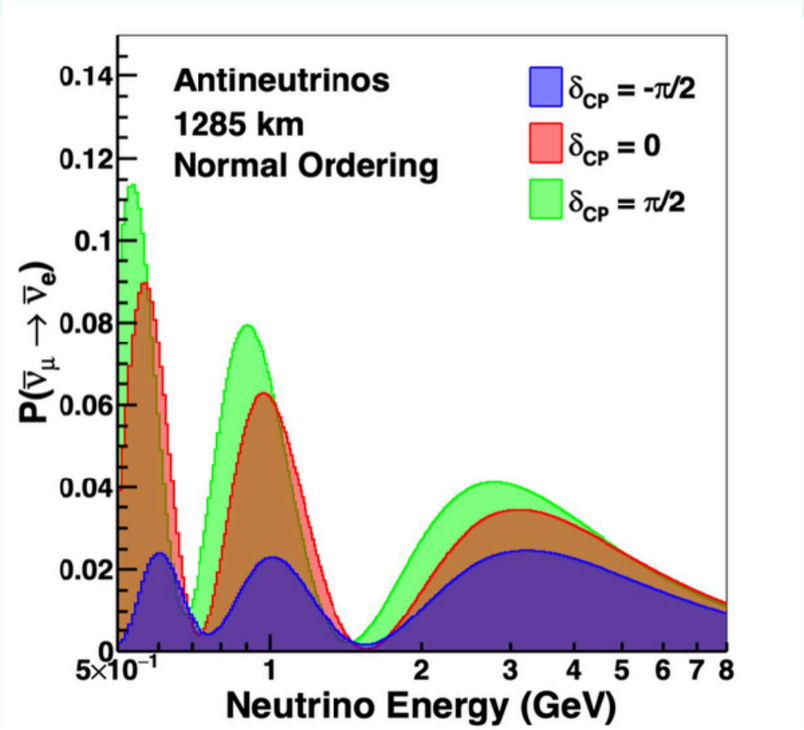




DUNE Design: 1300km Baseline

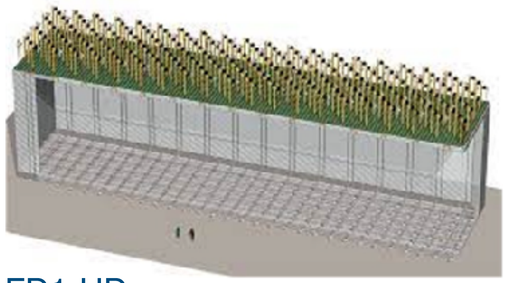
- The long baseline + wideband beam provide opportunity to unambiguously determine Mass ordering, δ_{CP}, θ_{23} octant from oscillation probability.
- DUNE has a unique ability to measure νe appearance as a function of L/E, over more than a full oscillation period



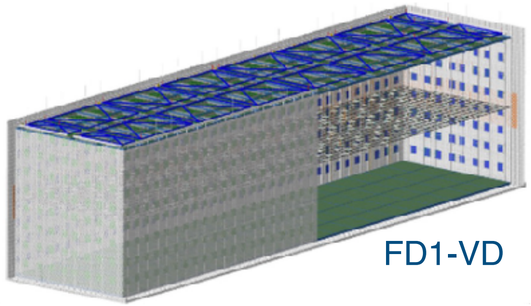


DUNE Design: Precision Reco

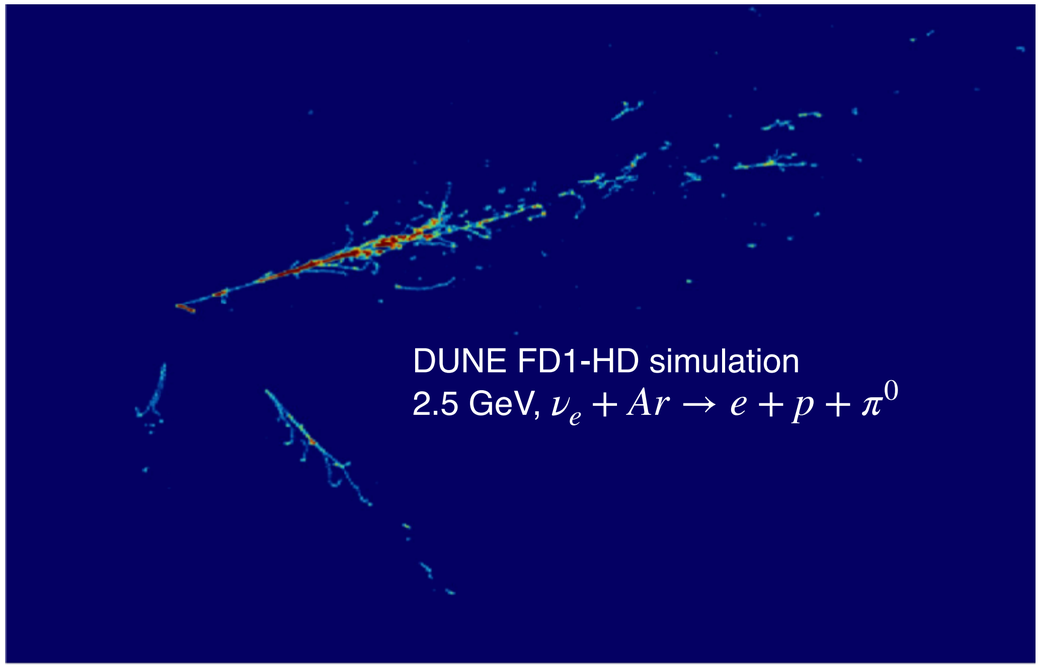
- The far detector must be able to identify flavour and reconstruct neutrino energy over the broad range over energies and interaction topologies provided by the beam.
- LAr TPC technologies fulfil both and scales to very large detector mass.
- DUNE will use a combination of horizontal drift and vertical drift modules.



FD1-HD

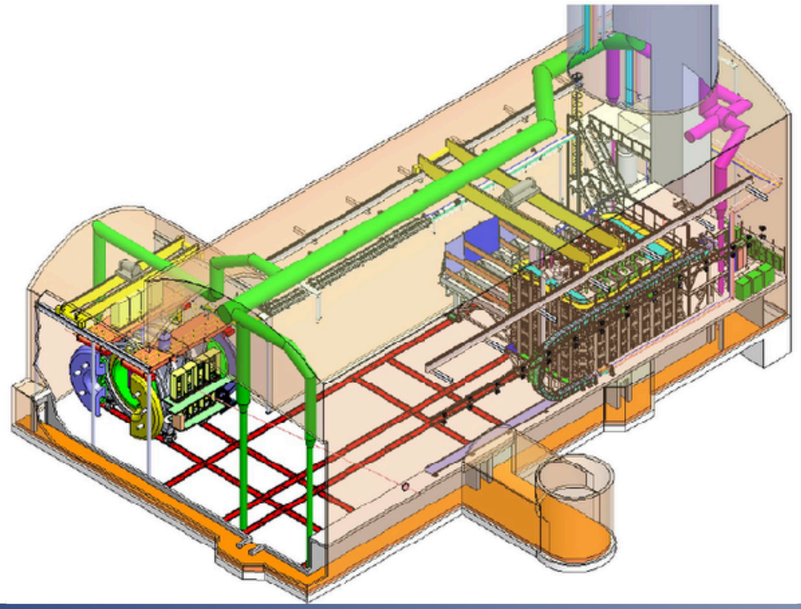


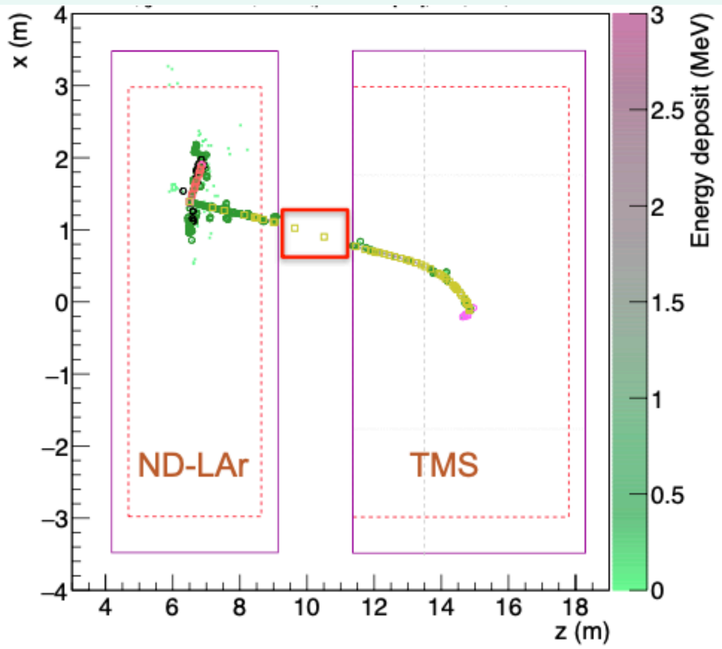
FD1-VD



DUNE Design: Systematics Control

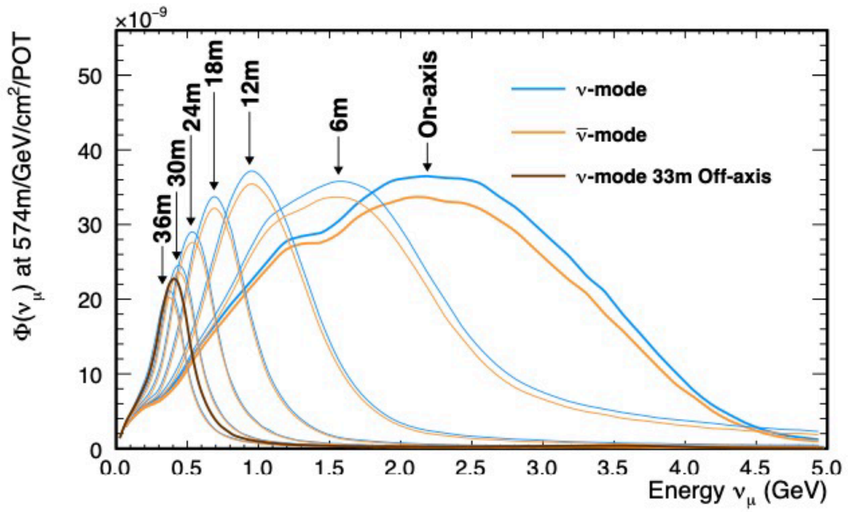
- DUNE Near Detector will measure the neutrino flux, neutrino interaction cross sections on Ar, and measure of LAr TPC response at few percent level.
- ND LAr is design similarly to FD with added modularity and pixelization to handle intense near source rate and sized to contain hadronic activity.
- Downstream systems measure muon momentum (TMS), flux (SAND) and provide additional interaction constraints.

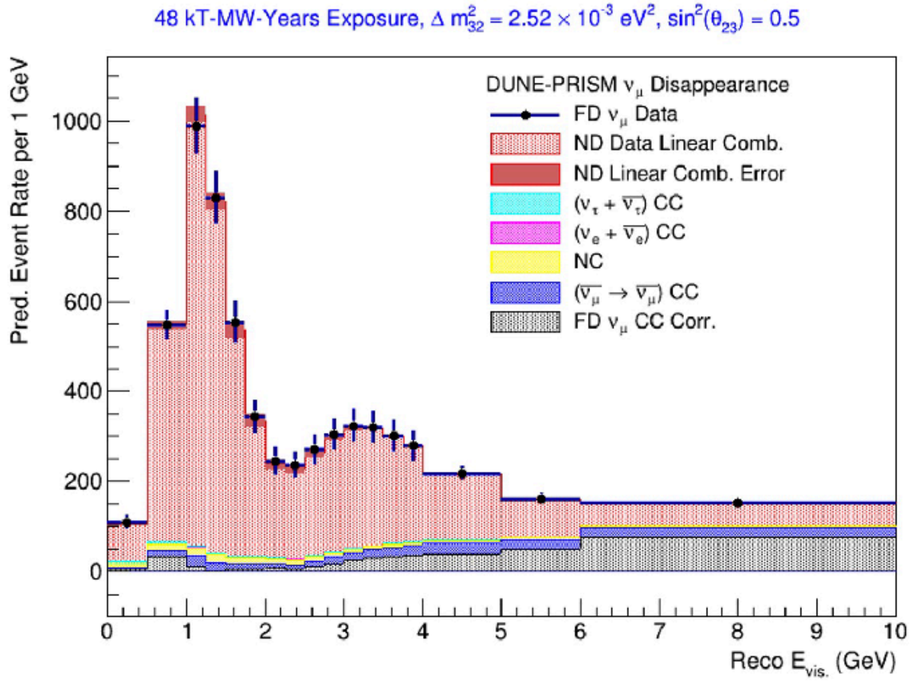




DUNE Design: PRISM

- ND-LAr + Spectrometer can be moved off-axis to enhance flux at lower energies.
- These samples allow one to build a linear combination to match FD oscillated specta and build analysis with minimal interaction modelling.





DUNE Plans and Installation

- DUNE construction is phased to provide continuous progress toward physics goals beginning this decade.

Phase I

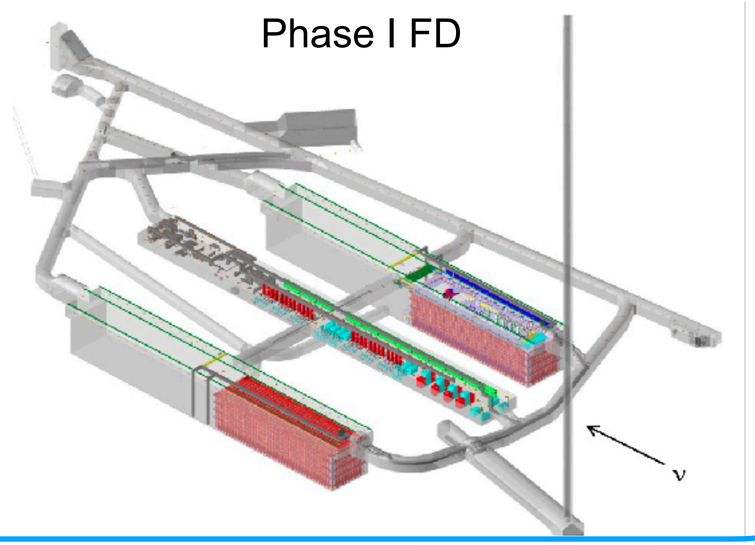
Ramp to 1.2 MW beam intensity

Two 17kt (10kt fid.) LAr TPC FD modules. One HD on VD.

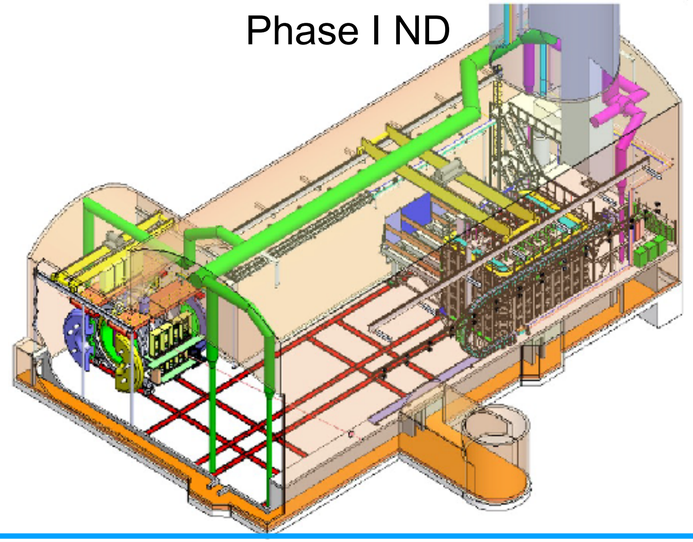
Near detector: ND-LAr + TMS (steel/scint. range stack) + SAND

Moveable to enable PRISM

Phase I FD



Phase I ND



DUNE Plans and Installation

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Two 17kt (10kt fid.) LAr TPC FD modules. One HD on VD.

Near detector: ND-LAr + TMS (steel/scint. range stack) + SAND

Moveable to enable PRISM

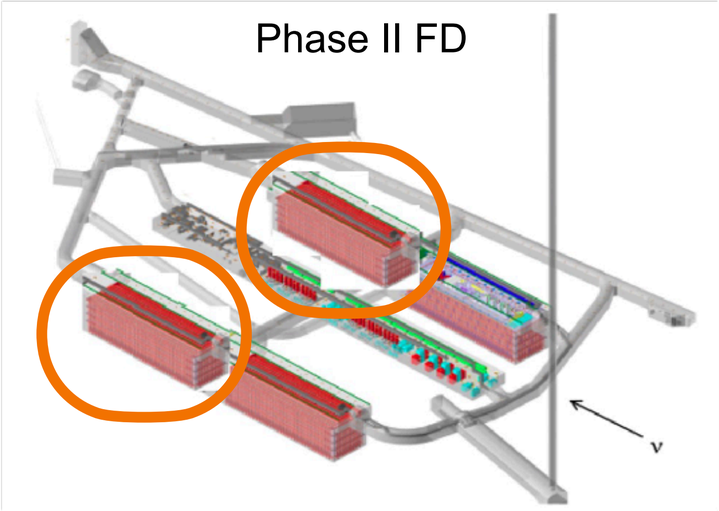
Phase II Upgrades

Proton beam increase to 2.4 MW

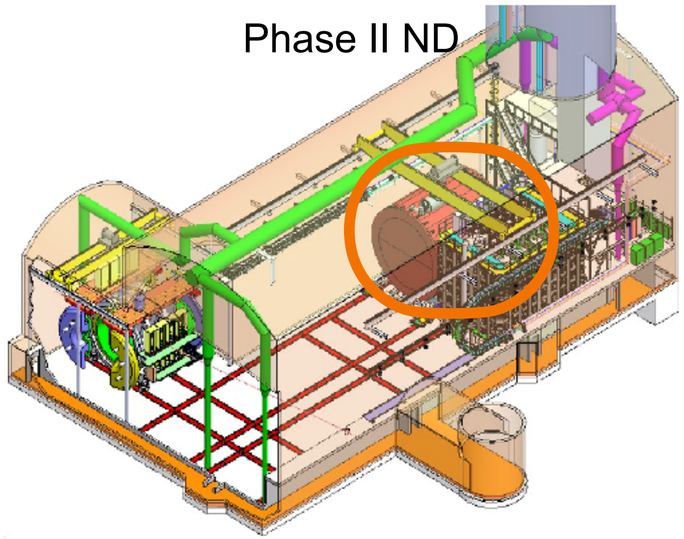
Four FD modules (3 LAr TPCs + 1 new tech)

TMS Upgraded to ND-GAr to provide enhanced ND interaction physics capabilities.

Phase II FD



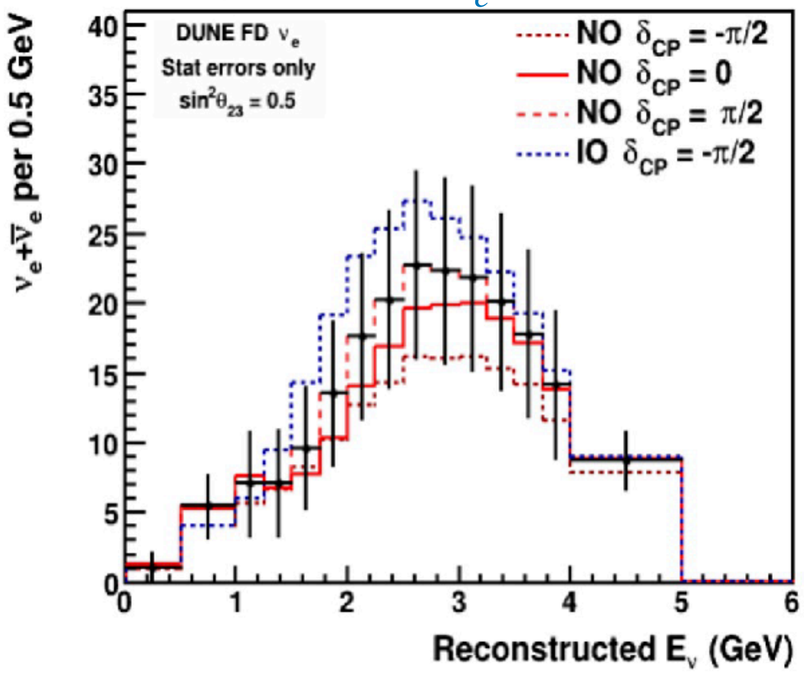
Phase II ND



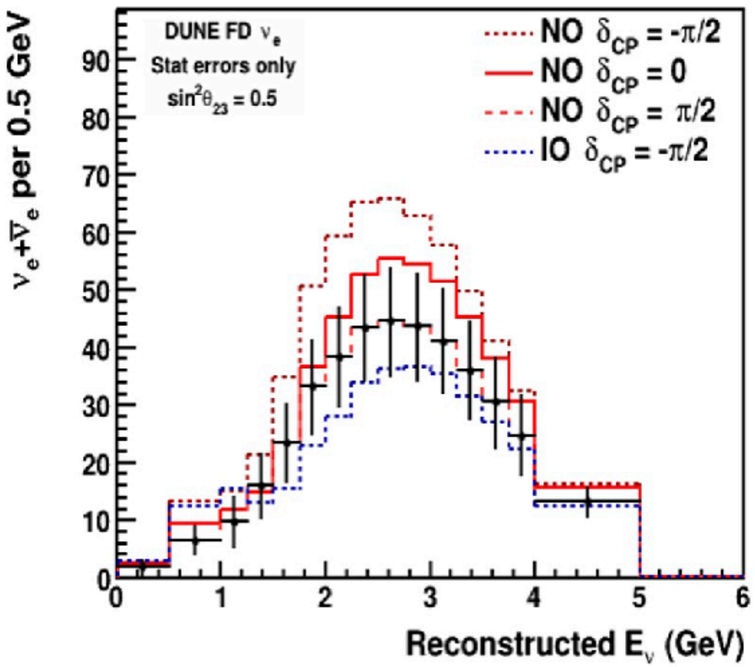
DUNE Physics: Mass ordering

- DUNE has unprecedented and unrivaled ability to definitively resolve the mass ordering independent of other experiments.
- 4 years of running with 2 FD modules in most conservative beam ramp to 1.2 MW provides clear discovery potential

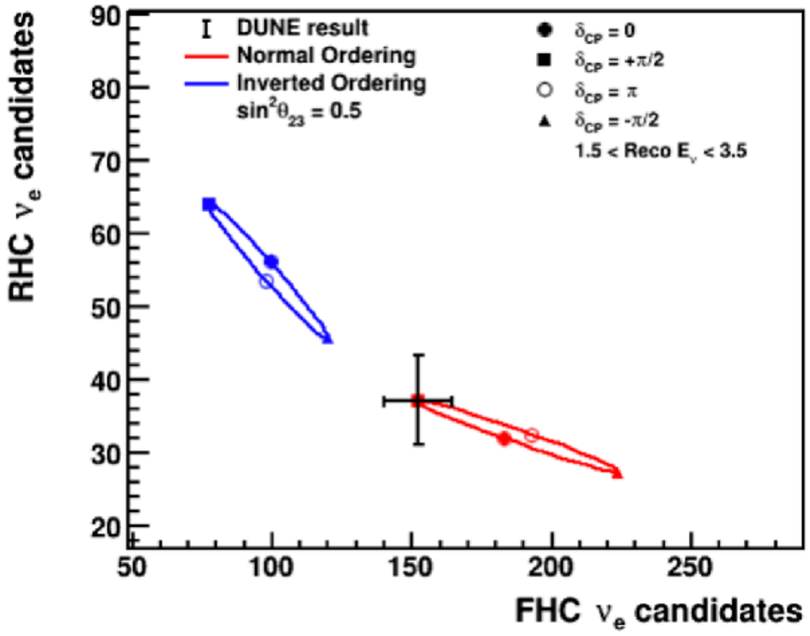
RHC ν_e



FHC ν_e

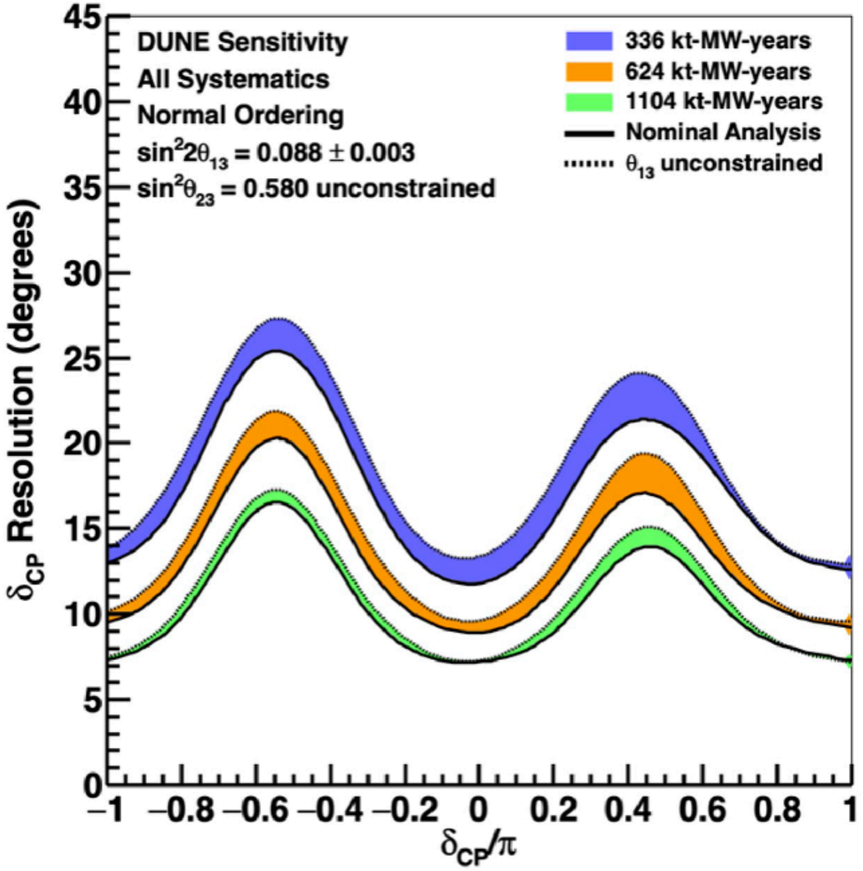


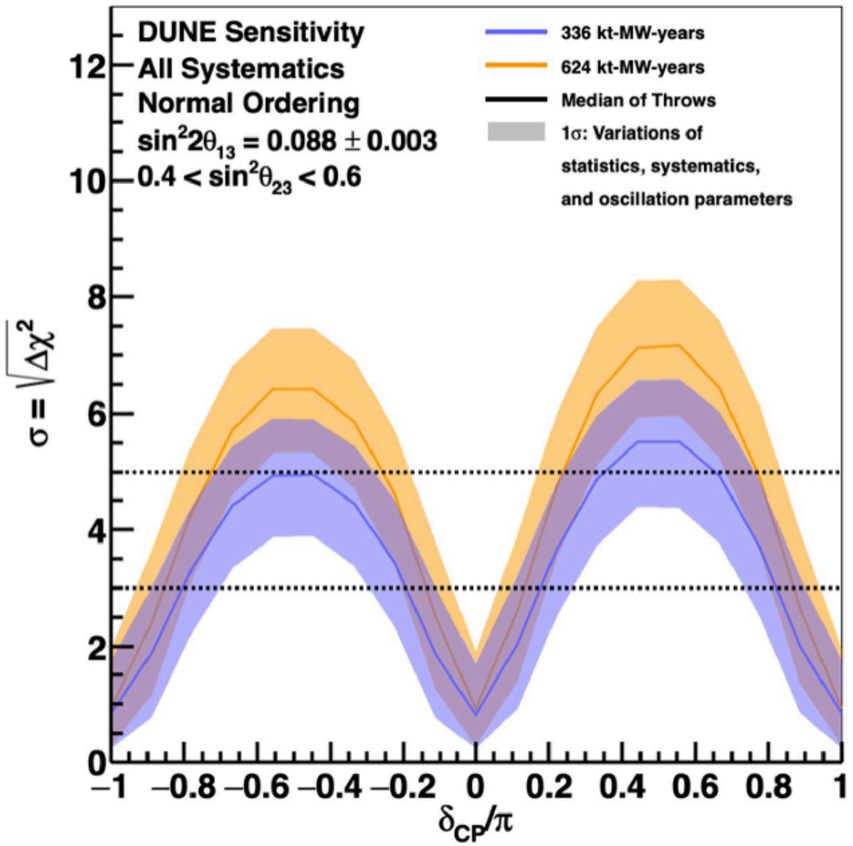
4 years with 20kt



DUNE Physics: CP violation

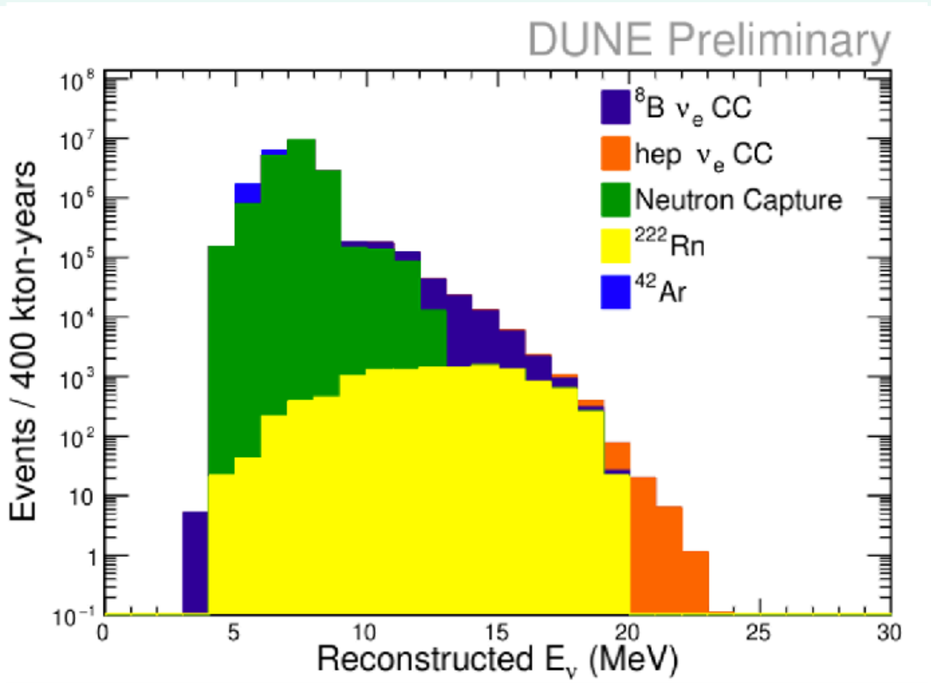
- 5σ discovery potential for CP violation over >50% of δ_{CP} values
- 7-16° resolution to δ_{CP}, with external input for only solar parameters.

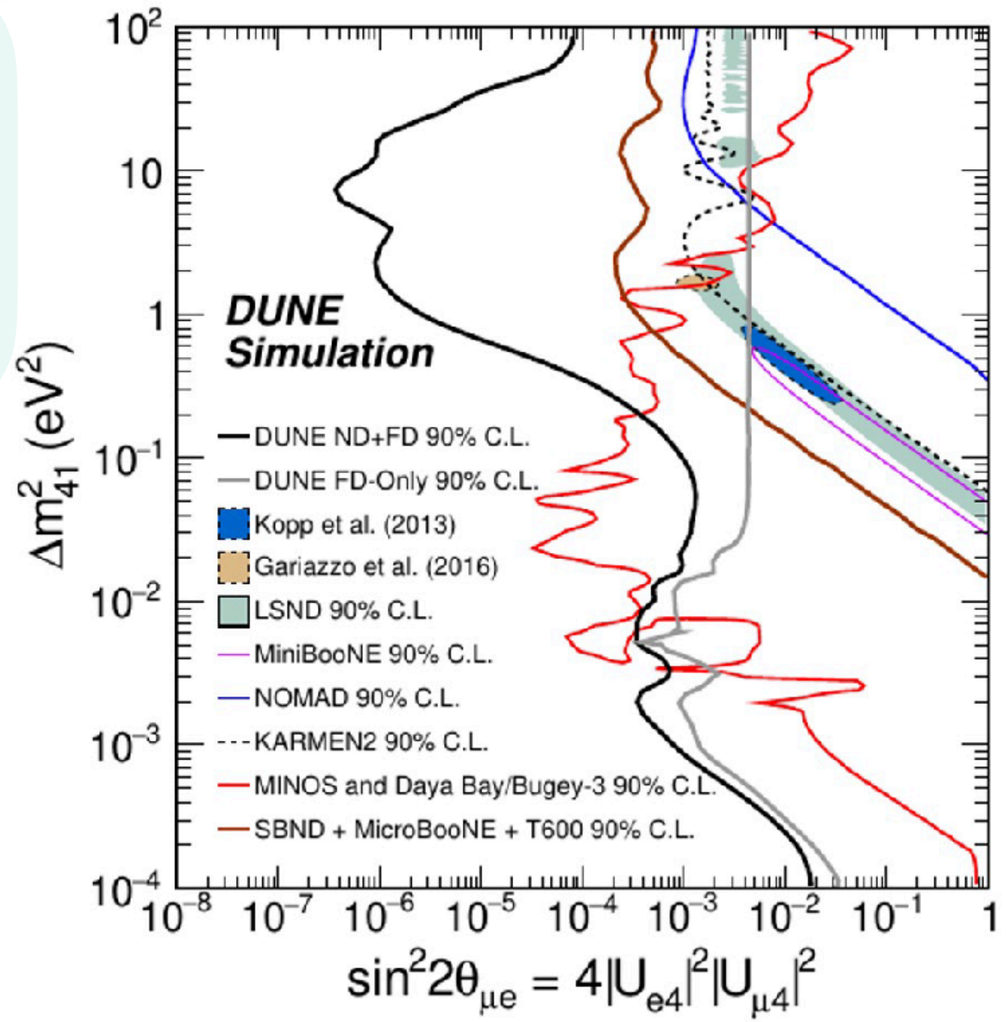




Additional Neutrino Physics

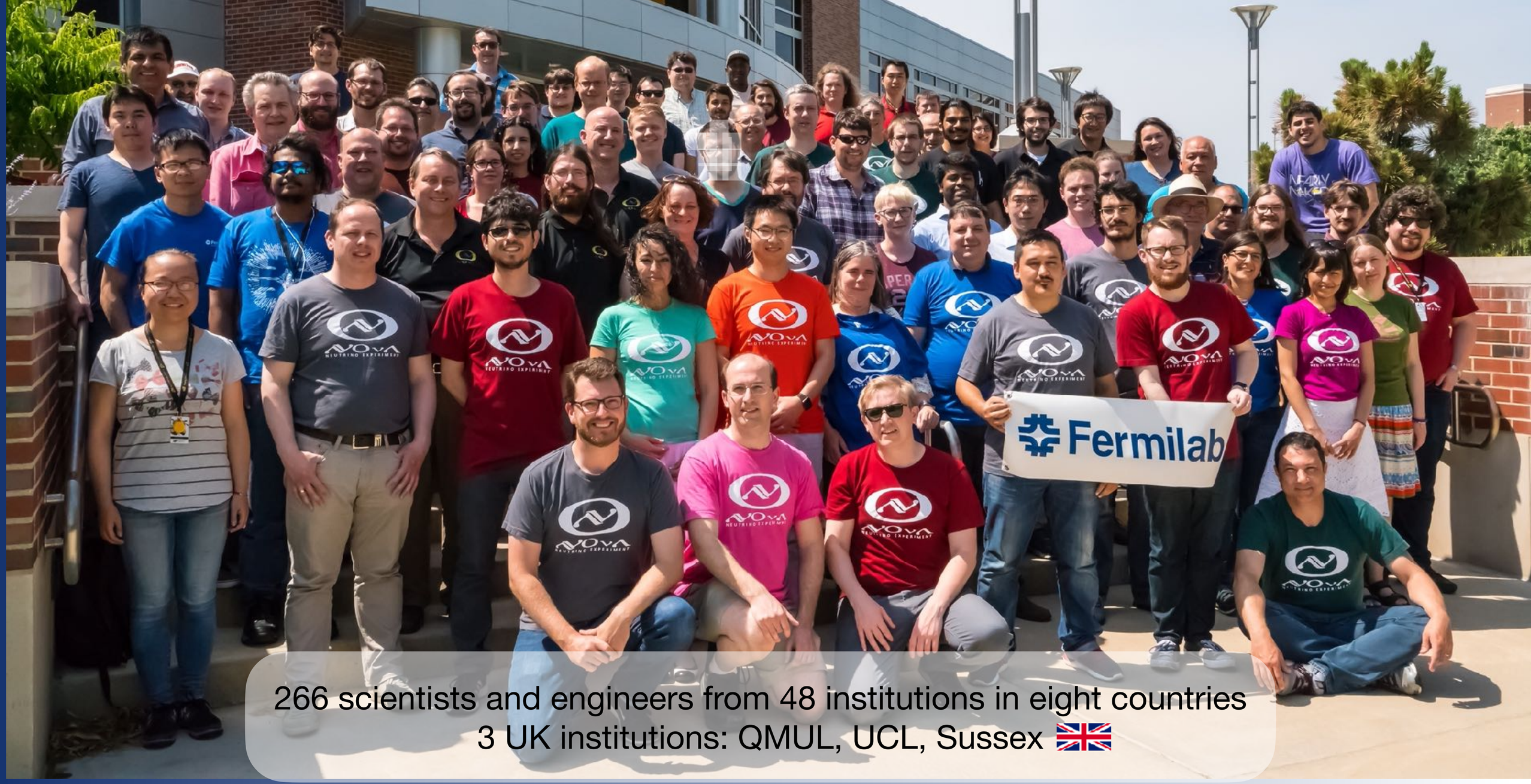
- DUNE will provide world leading precision on Δm^2_{32} and θ_{23}, allowing direct testing of PMNS unitarity.
- MeV-scale Physics
  - Galactic SNB will produce 1000s of events
  - Sensitivity to solar neutrinos in study.
  - Searches for NSI and sterile neutrinos.






Sandbox Studio, Chicago

Conclusions



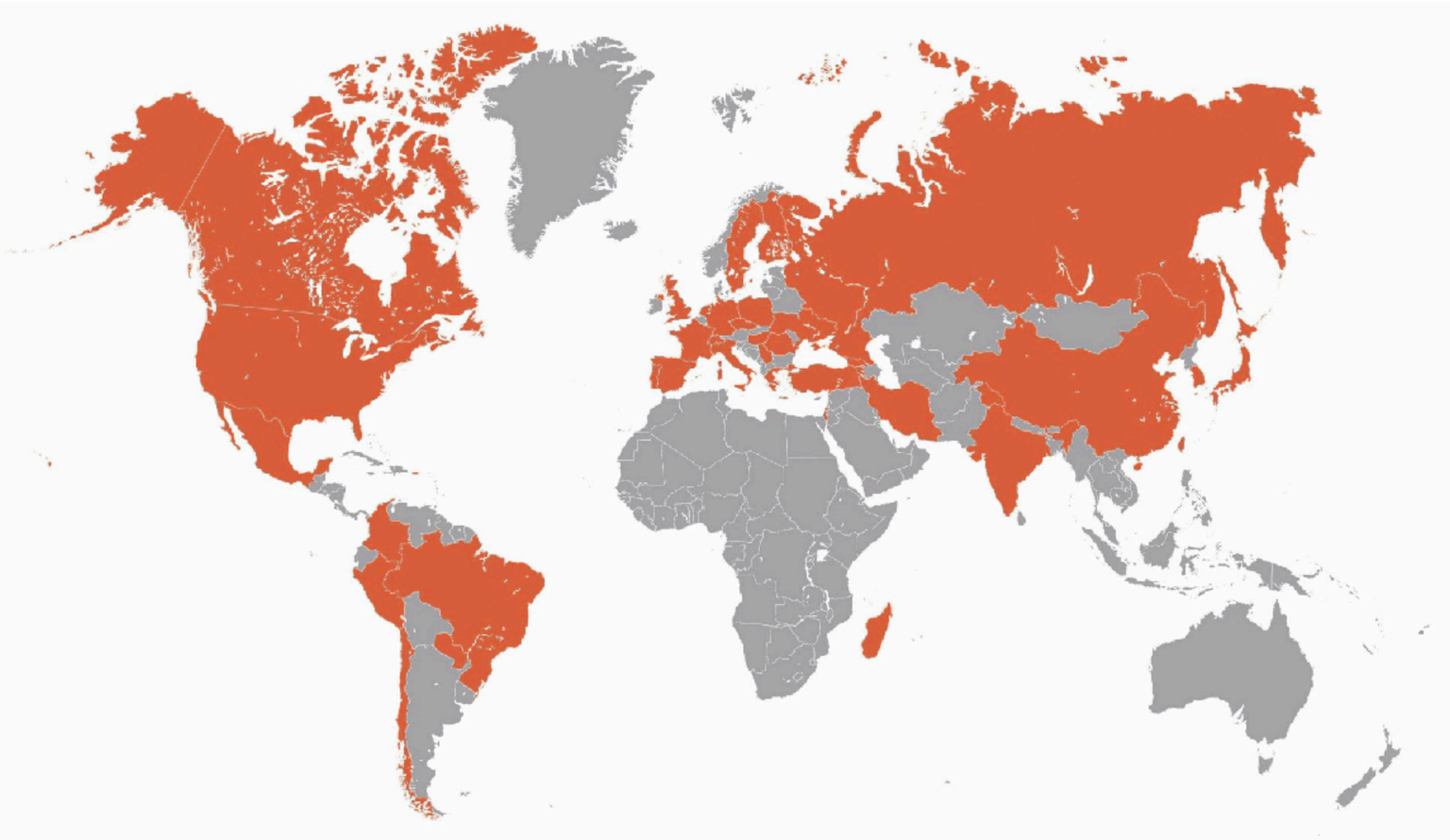
266 scientists and engineers from 48 institutions in eight countries
3 UK institutions: QMUL, UCL, Sussex

UK leadership in NOvA

- UK leadership:
  - 1+1 Analysis coordinator
  - 2 Analysis group conveners
  - 2 Technical group conveners
  - 3 Run Coordinators
- UK groups have made strong leading contributions to:
  - 3-flavour oscillations
  - ND analyses
  - Test beam programme
  - Computing groups
  - Detector calibration
  - Operations

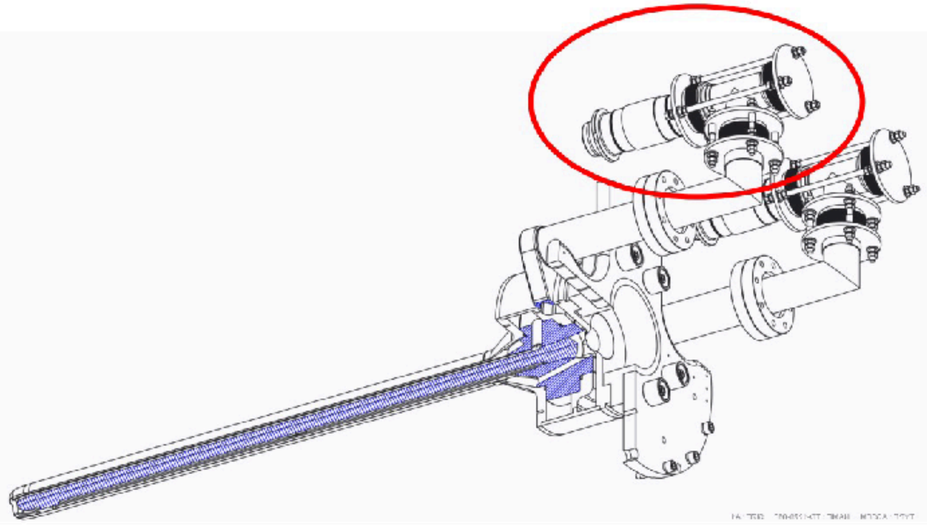
DUNE Collaboration

- DUNE is an international collaboration of >1300 scientists and engineers from 37 countries + CERN (and counting)



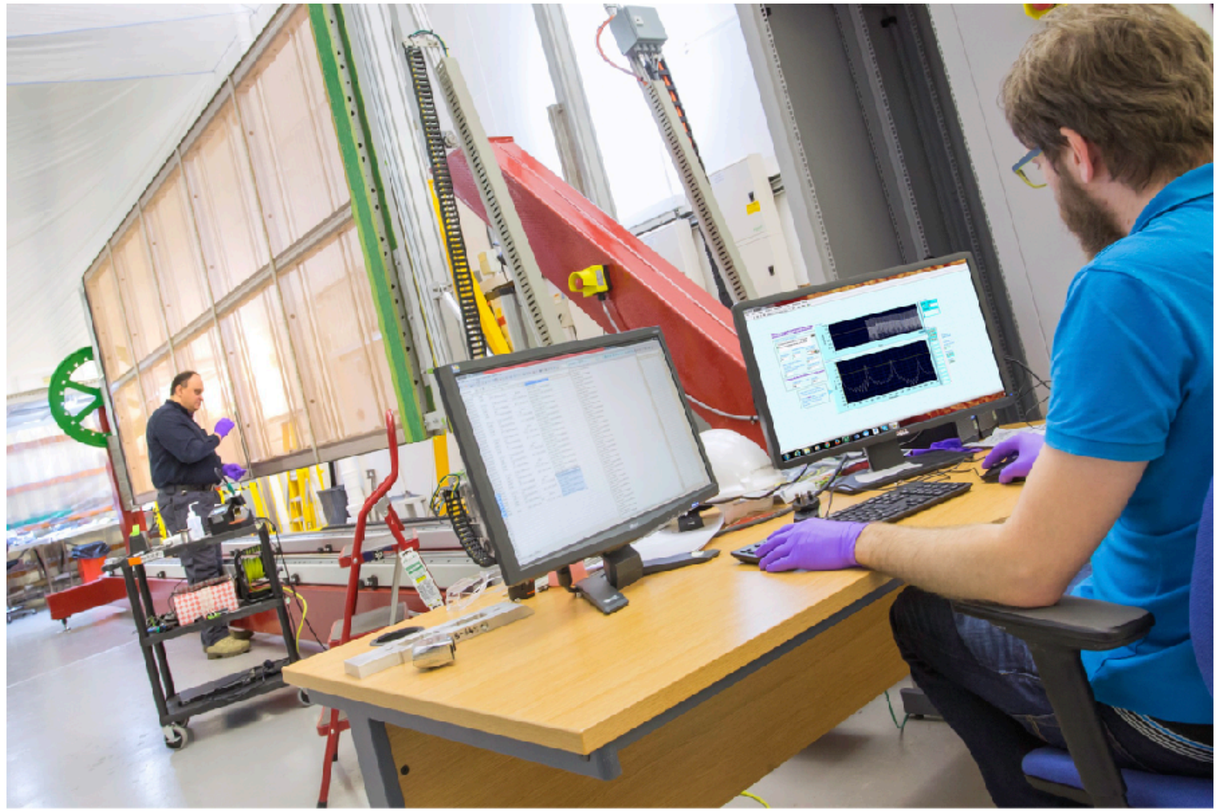
UK leadership in LBNF

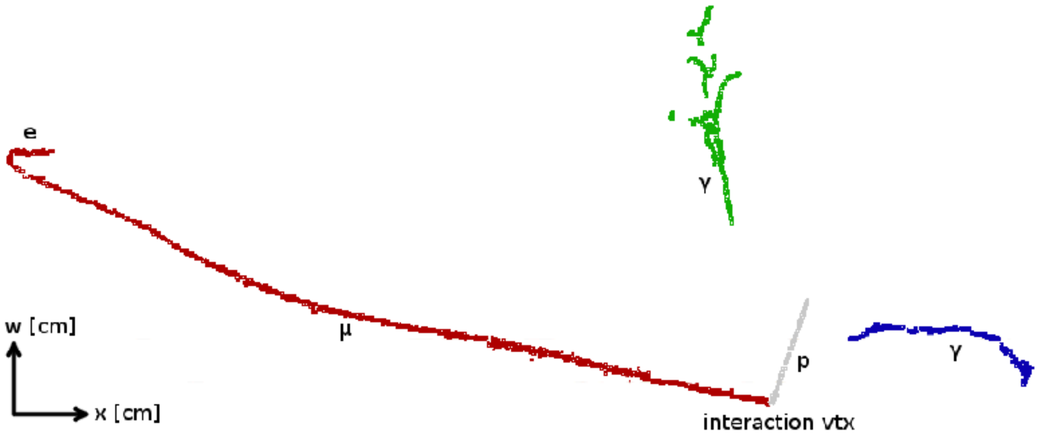
- Daresbury and RAL are world centres of accelerator expertise
- Producing RF cavities for the PIP-II upgrade for the LBNF 1.2 MW beam
  - And eventual 2.4 MW goal
- Delivering the LBNF proton target



UK leadership in DUNE

- UK is building the majority of readout planes (APAs) for the first 10 kt module
  - Major construction factory at Daresbury
- UK is providing the DAQ for the first two 10 kt modules
  - And contributing to ND DAQ
- UK is delivering Pandora reconstruction





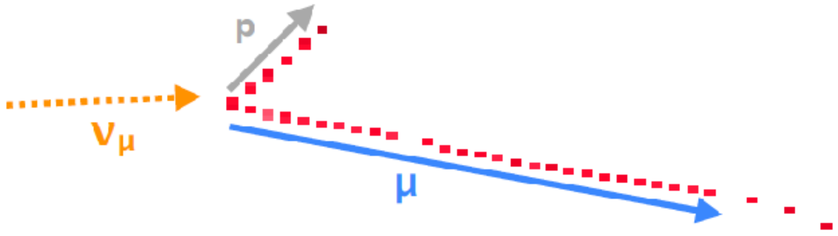
Thank you!

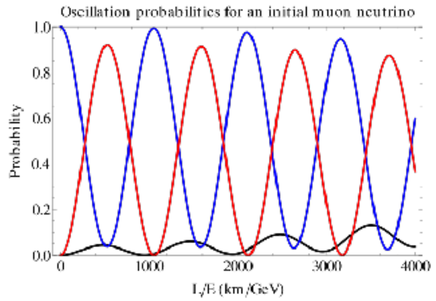
BACK UP

How to measure neutrino oscillations

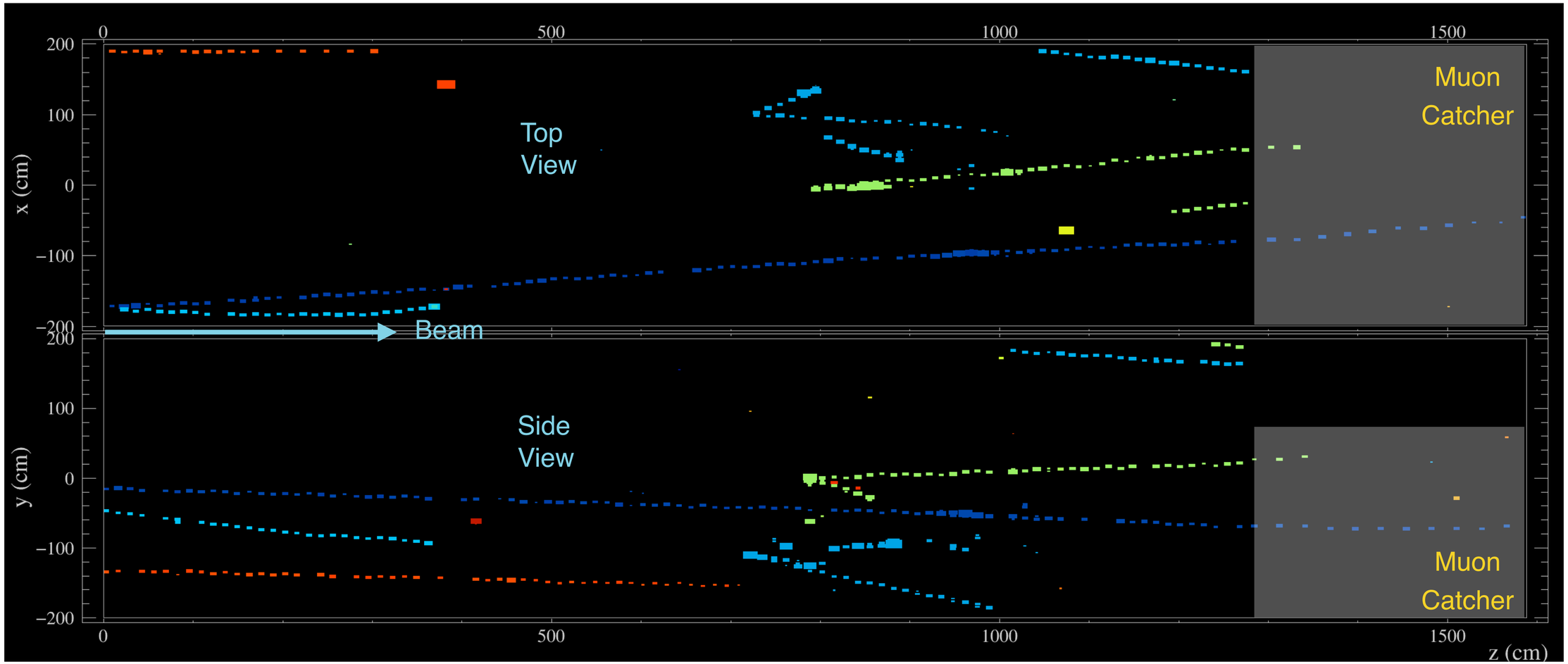
$$N \approx \Phi(E_\nu) \otimes \sigma(k, k') \otimes \epsilon \otimes P(\nu_\alpha \to \nu_\beta)$$

N	$\Phi(E_\nu)$	$\sigma(k, k')$	ϵ	$P(\nu_\alpha \to \nu_\beta)$
Oscillated Neutrinos	Neutrino flux	Neutrino interactions	Detector response	Oscillation probability



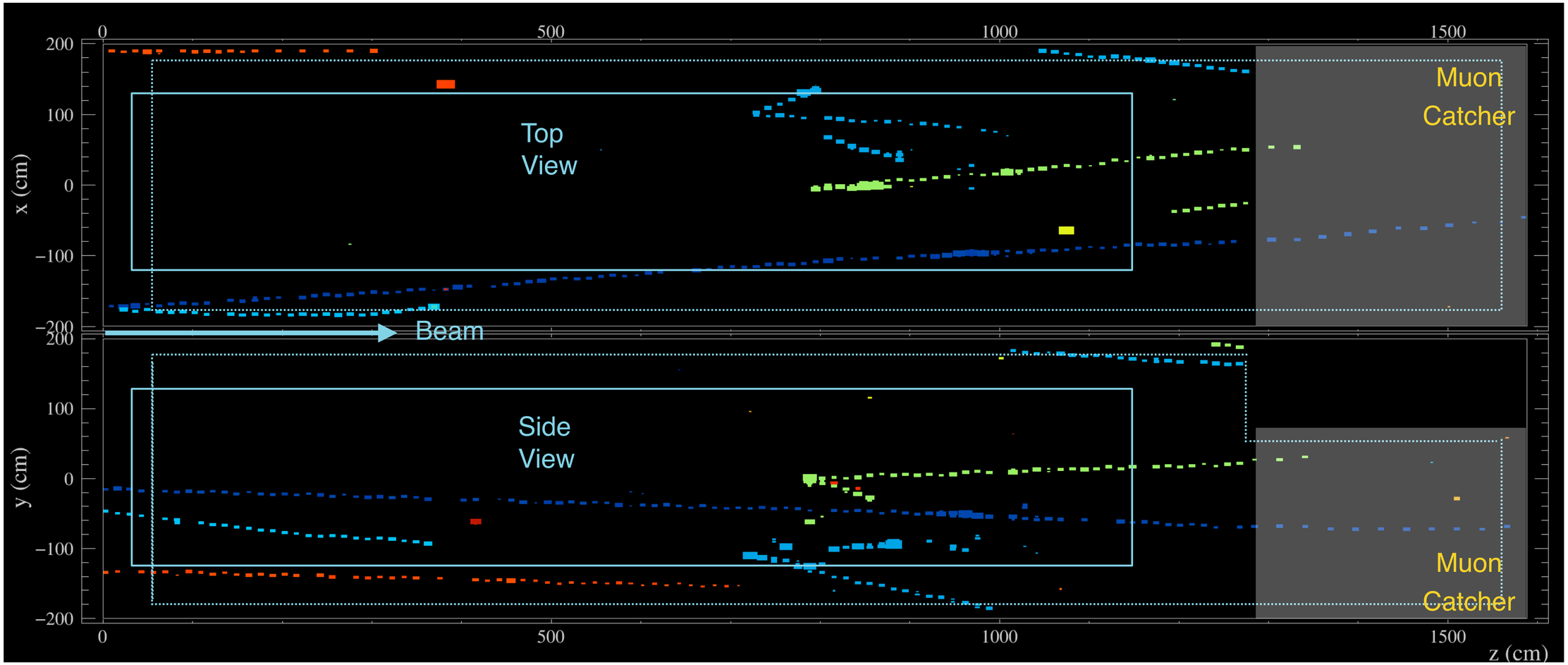


Reconstruction and pre-selection



- Hits associated in time and space are used to form a candidate interaction. Tracks and showers are reconstructed from these hits.
- The start of the reconstructed muon track is defined as the vertex of the interaction.

Reconstruction and pre-selection

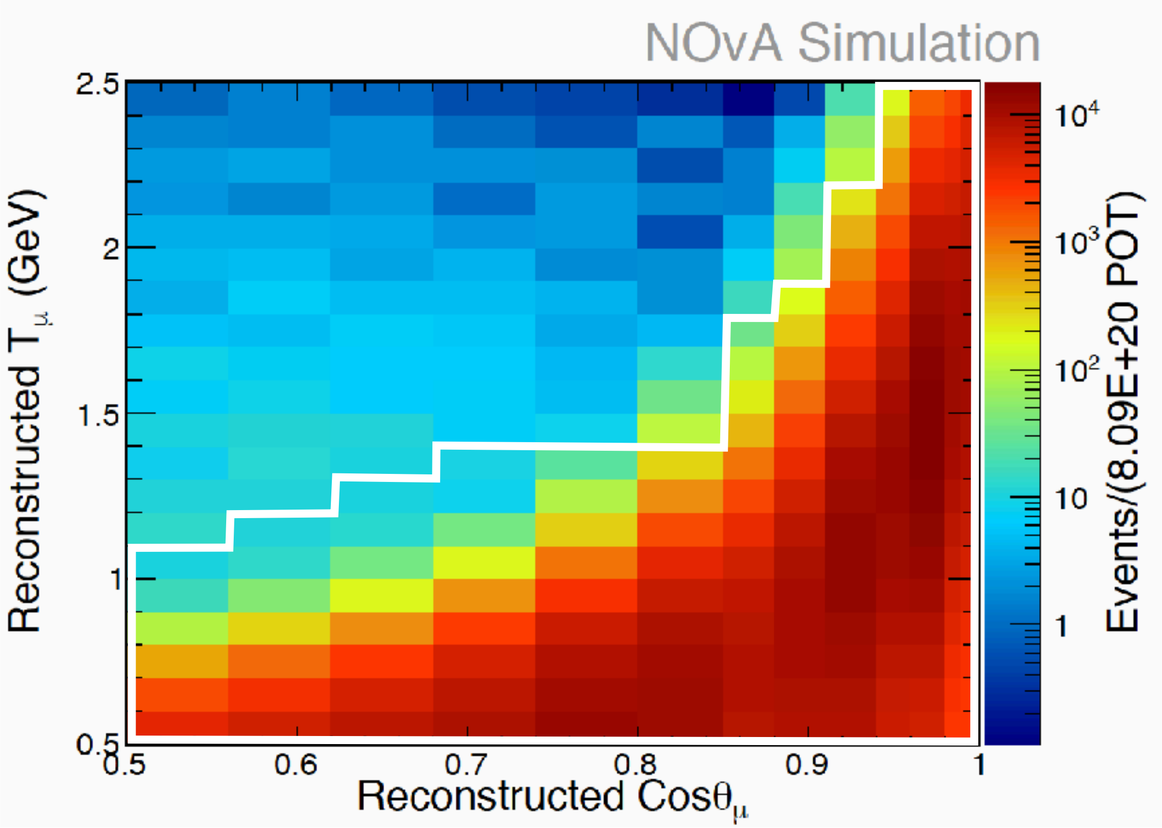


- Fiducial volume is the solid blue box, and excludes the muon catcher.
- The containment volume (blue dashed line) is defined by projected distance to the closest edge of the detector. Events with hadronic activity in or near the muon catcher are excluded.

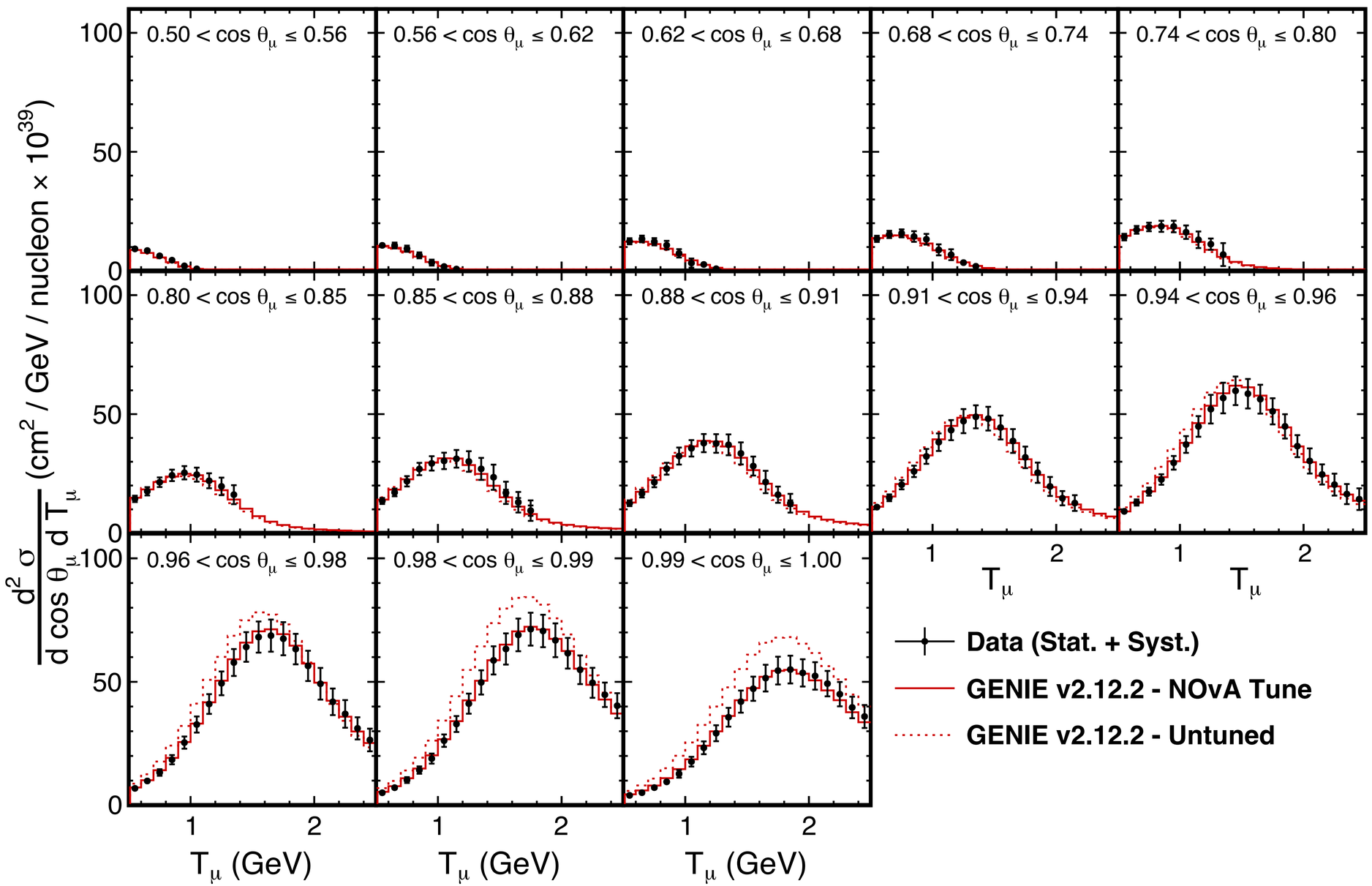
Measurement strategy

$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \sum_k \left(\frac{\sum_j U^{-1}_{ijk}(N^{\mathrm{sel}}(\cos\theta_\mu, T_\mu, E_{\mathrm{avail}})_j P(\cos\theta_\mu, T_\mu, E_{\mathrm{avail}})_j)}{N_{\mathrm{t}}\Phi\epsilon(\cos\theta_\mu, T_\mu, E_{\mathrm{avail}})_{ik}\Delta\cos\theta_{\mu_i}\Delta T_{\mu_i}}\right)$$

- Flux-averaged double differential cross section in 172 bins (white outline).
- Selection purity and efficiency corrections applied in 3D space (T_μ, $\cos\theta_\mu$, E_{avail}).
- E_{avail} (available energy): total energy of all observable final state hadrons.
- This reduces potential model dependence of the efficiency and purity corrections on the final-state hadronic system.
- Unfolded 3D result is then integrated over E_{avail}.



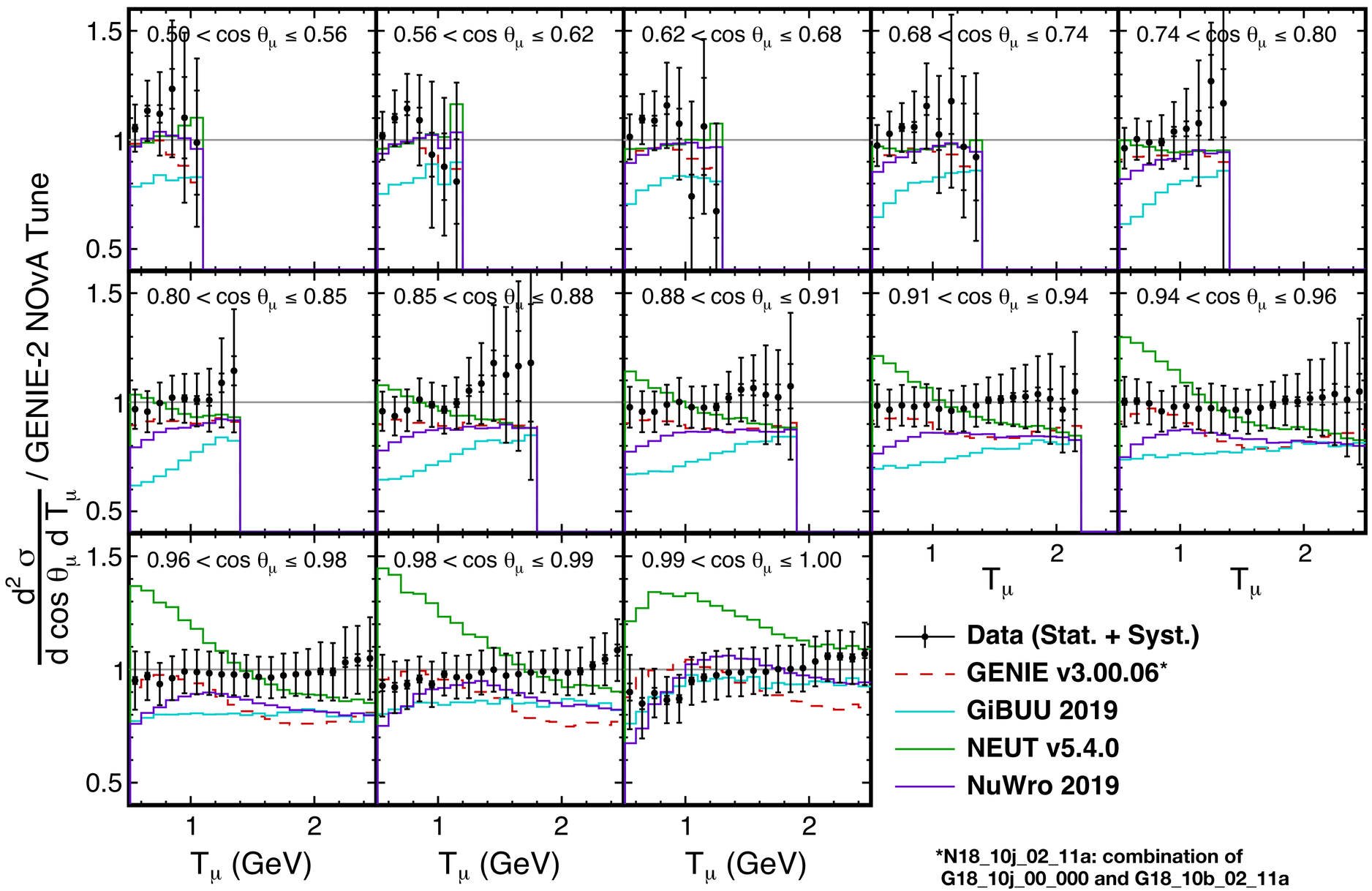
ν_μ CC inclusive double-differential measurement



https://arxiv.org/abs/2109.12220
in PRD review

- Cross section calculated at 172 kinematic points
- Good agreement between tuned/ untuned GENIE versions in high angle slices.
- At forward angle, where QE and MEC events dominate, the untuned GENIE 2 overshoots data.

ν_μ CC inclusive double-differential measurement



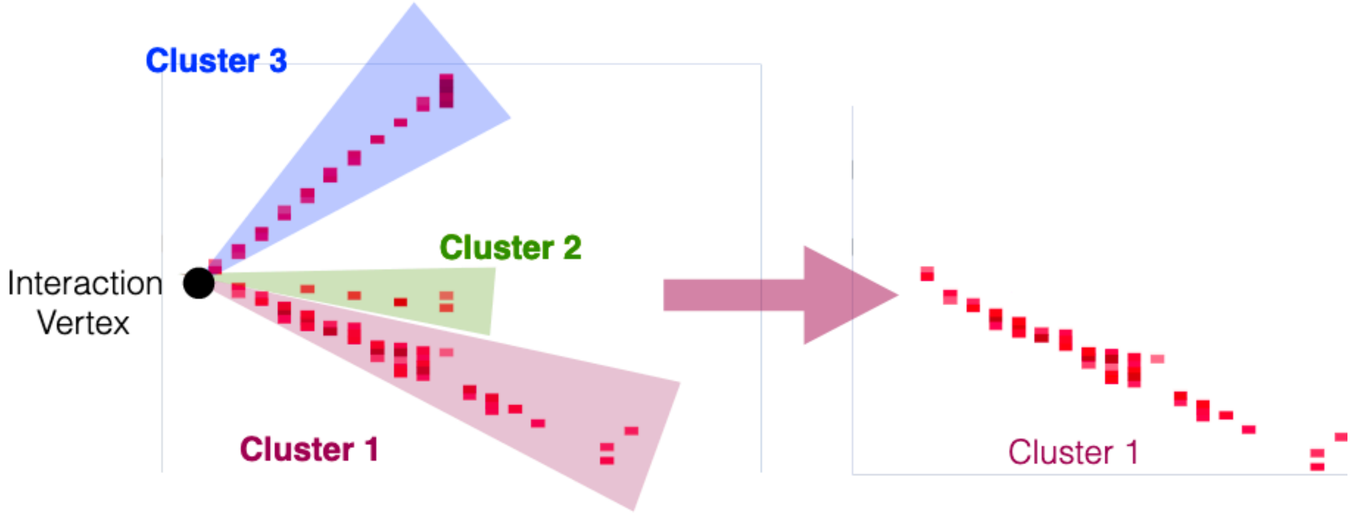
*N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a

https://arxiv.org/abs/2109.12220
in PRD review

- Out of the box generator comparisons.
- All generators reproduce well the shape of our data.
- We notice an overall normalisation difference in GiBUU.

Identifying electrons

- Single particle identification is done by a Deep Convolutional Network
- The network is trained using single particle simulated within the detector
  - Network “sees” two 2D views of the deposited energy by the single particle



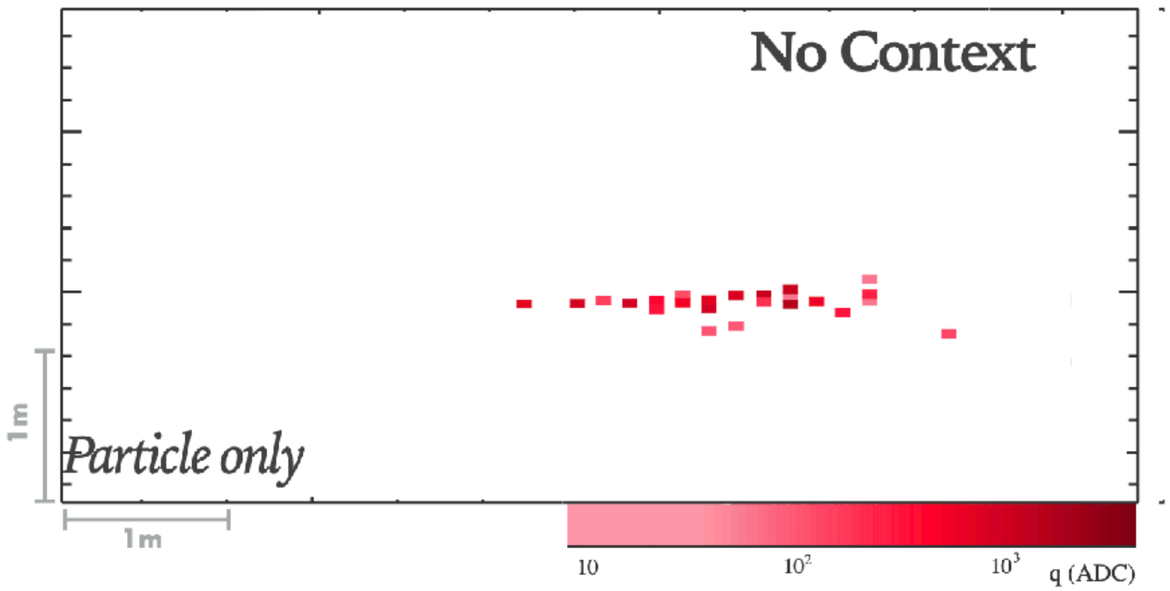
Single particles are separated using geometric reconstruction methods

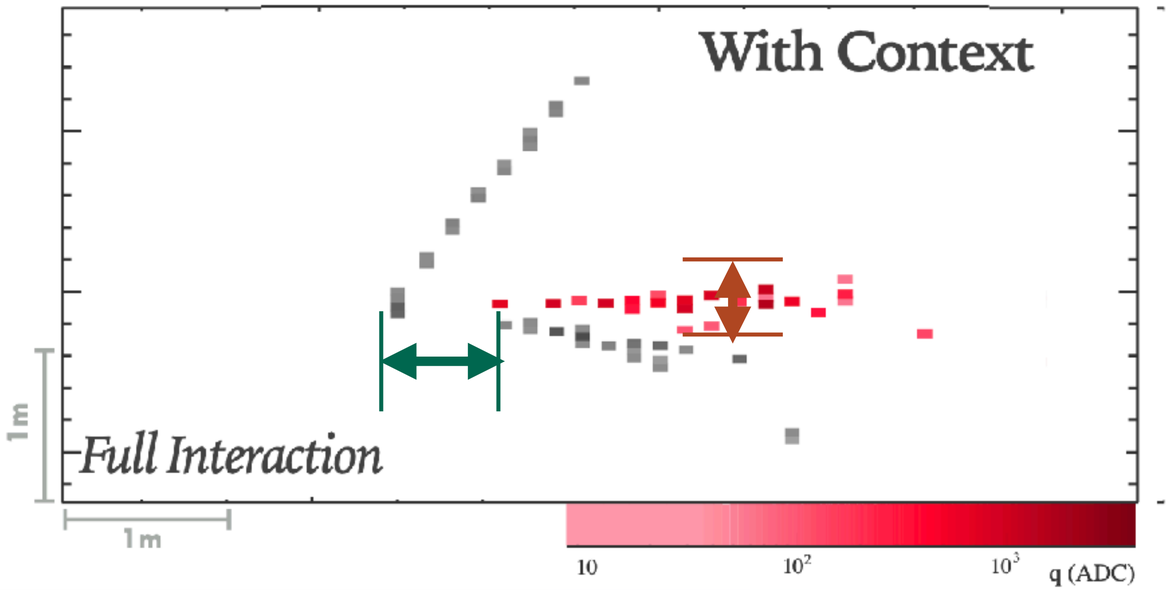
Each reconstructed particle is classified as:

- Electron
- Muon
- Pion
- Photon
- Proton

Identifying particles

- The task of classification can be aided by **providing context**
  - Analysis uses a Boosted Decision tree to distinguish electrons from other particles using:
    - The output of the deep convolutional network
    - Reconstructed shower width
    - Gap to reconstructed vertex





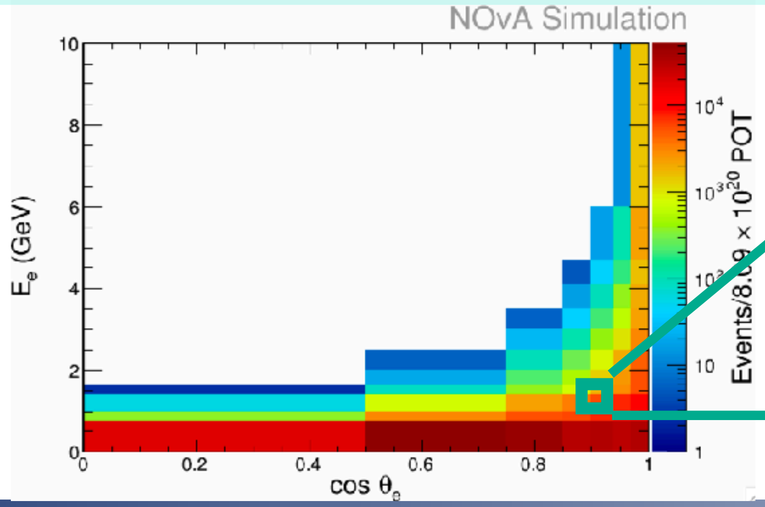
First ν_e CC double differential measurement

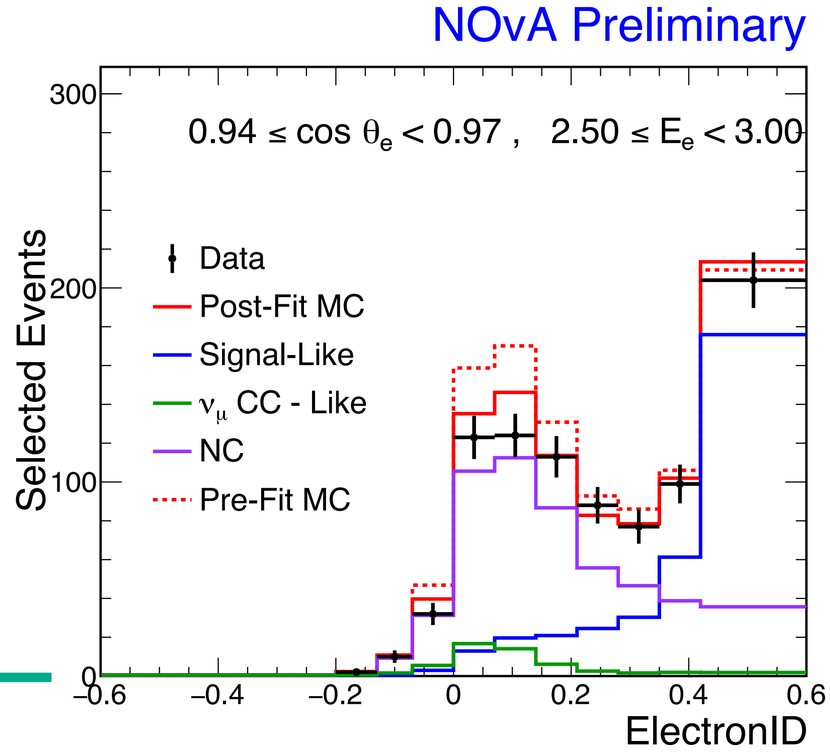
$$\left(\frac{d^2\sigma}{d\cos\theta_e dE_e}\right)_i = \sum_j \left(\frac{U_{ij}^{-1}(N^{\mathrm{sel}}(\cos\theta_e, E_e)_j - N^{\mathrm{bkg}}(\cos\theta_e, E_e)_j)}{N_{\mathrm{t}}\Phi\epsilon(\cos\theta_e, E_e)_{ik}\Delta\cos\theta_{e_i}\Delta E_{e_i}}\right)$$

- Flux-averaged double differential cross section as a function of the electron kinematics.
- Background estimate in each electron kinematic bin is done via a template fit of the ElectronID distribution.
- Uncertainties in templates shape are accounted for using a covariance matrix.

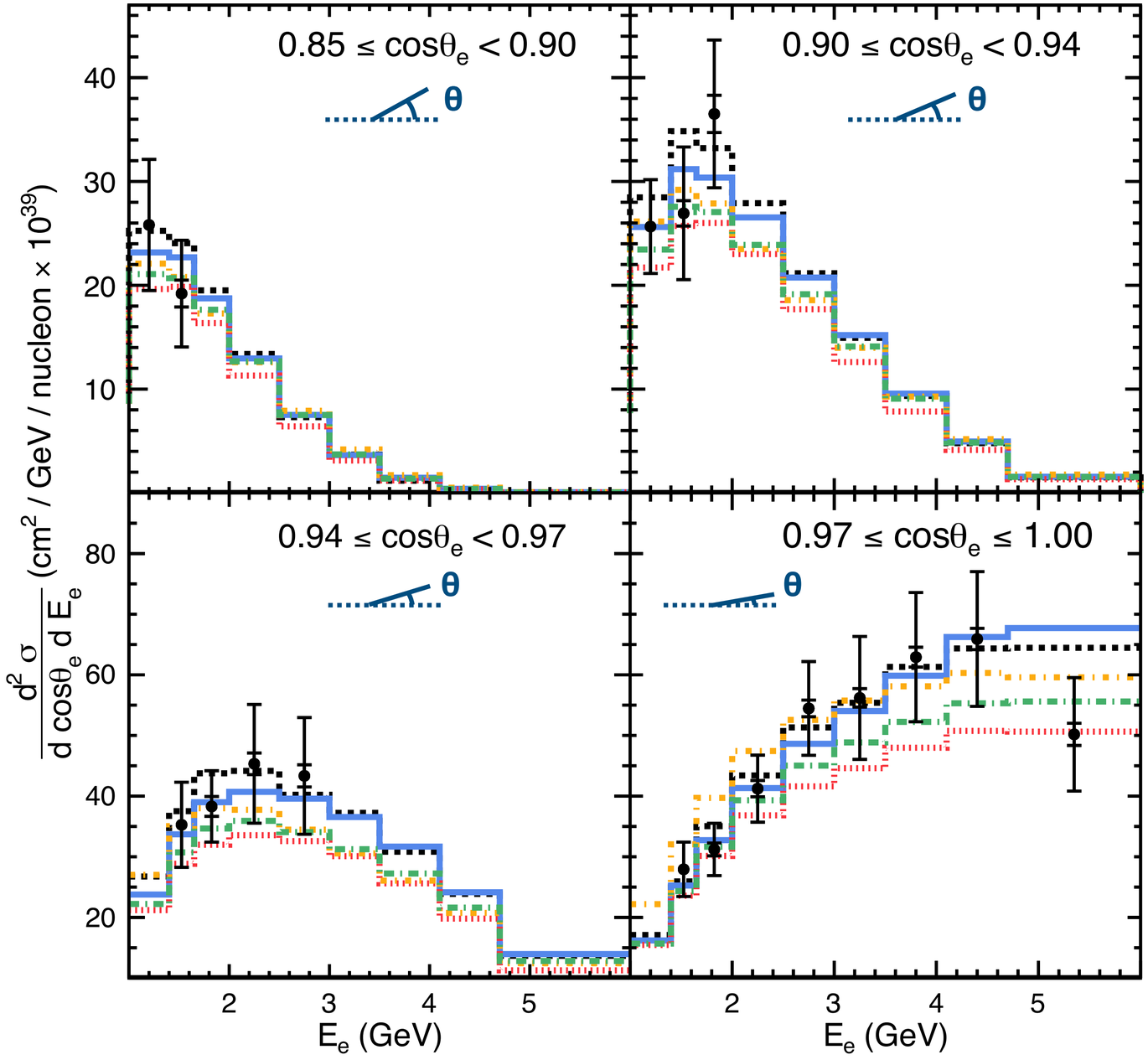
$$\chi^2 = (x_i - \mu_i)^T V_{ij}^{-1} (x_j - \mu_j)$$

i = (E_e , cos θ_e , ElectronID)





First ν_e CC inclusive double-differential measurement



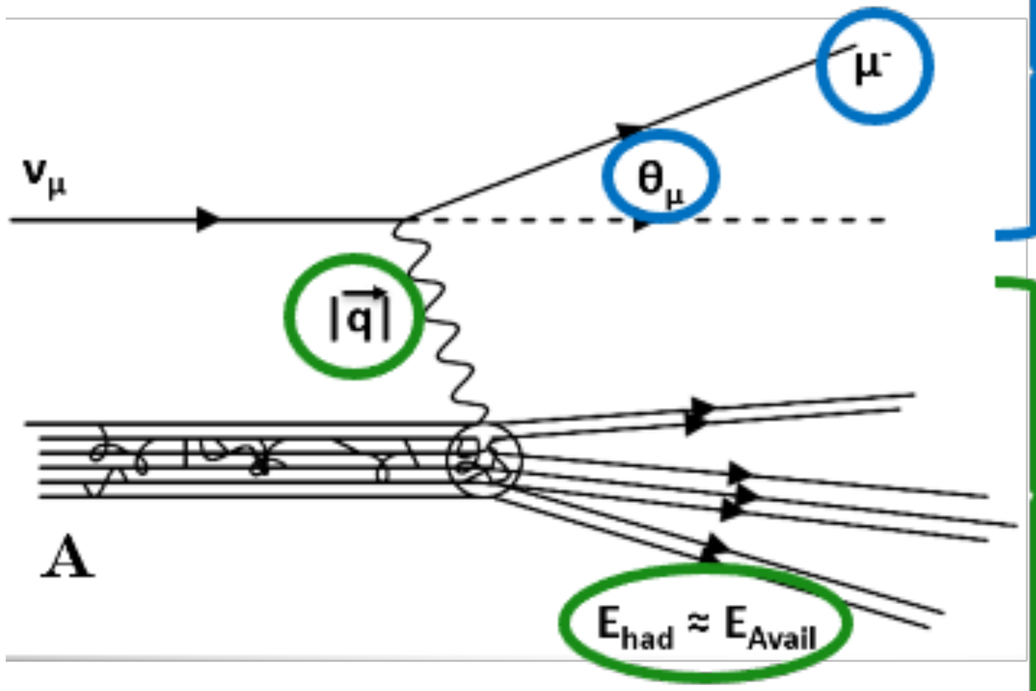
- Data (Stat. + Syst.)
- GENIE v2 - NOvA-tune
- GENIE v3*
- GiBUU
- NEUT
- NuWro

https://arxiv.org/abs/2206.10585
Accepted by PRL

- Out of the box generator comparison.
- Measurement in good agreement with generator predictions.

***N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a**

Two new ν_μ double-differential results



Muon System ⇨ Energy **vs** angle

<u>Exclusive</u>
Select only events with low hadronic energy

Hadronic System ⇨ 3-momentum transfer $|\vec{q}|$ **vs** energy

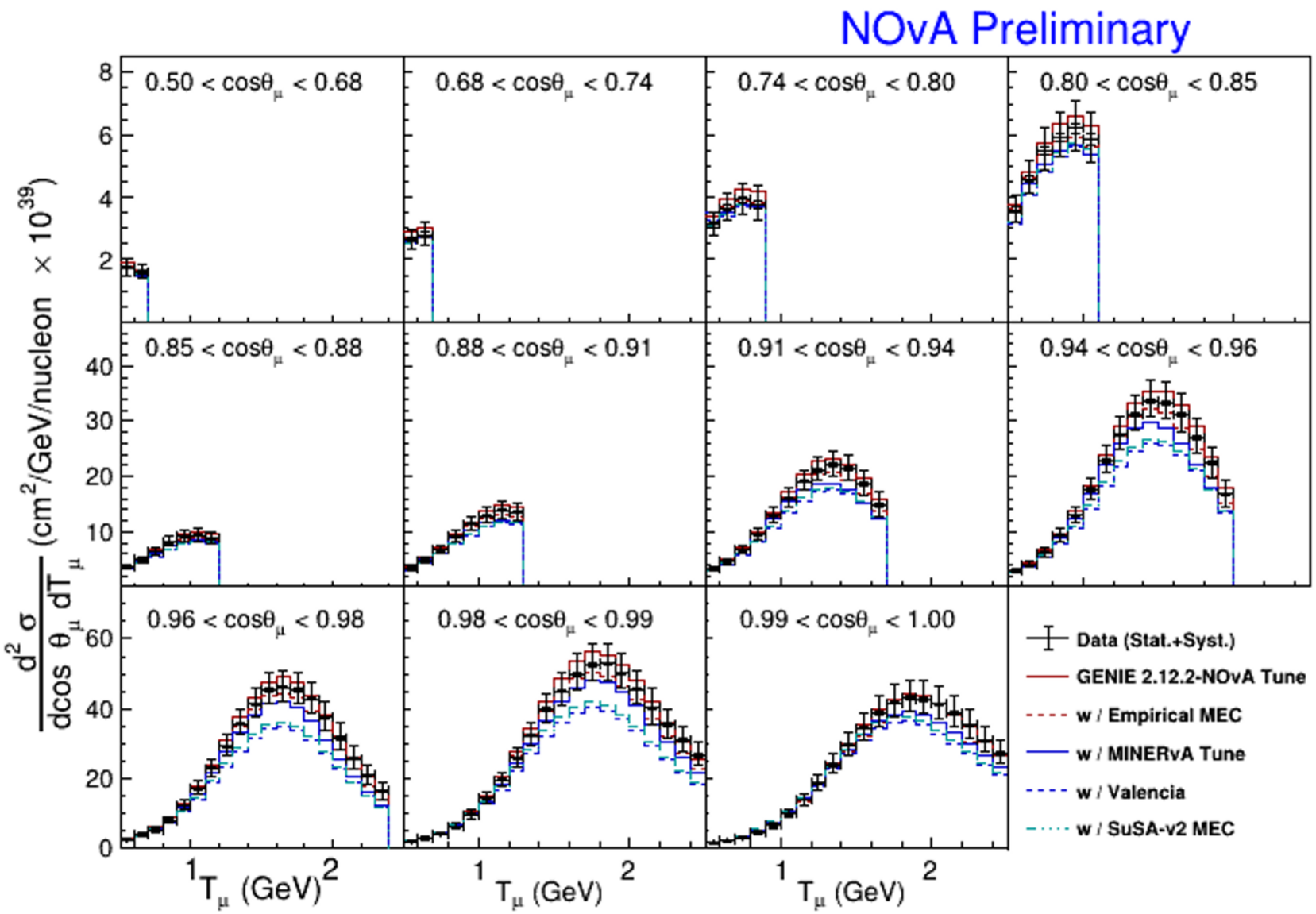
<u>Inclusive</u>
Select all ν_μ CC events

Muon System

ν_μ CC interactions:

- $T_p \leq 250$ MeV
- $T_\pi \leq 175$ MeV

- Events must have exactly one reconstructed track (low E_{had})
  - **Boosts 2p2h,** reduces DIS and RES
- Cross section reported at 115 kinematic points
- 12-15% uncertainty typically (dominated by flux systematic)

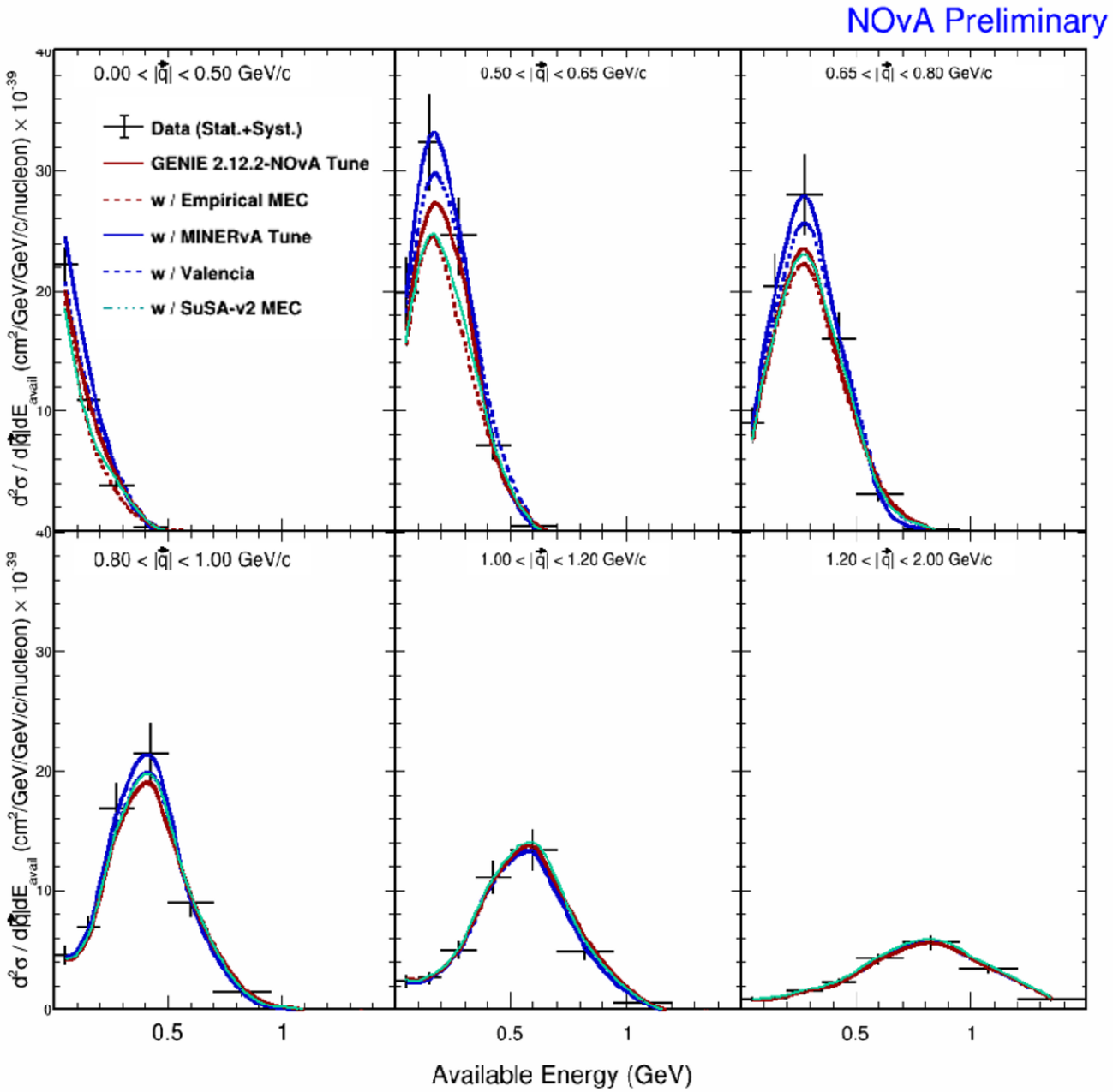


Hadronic System

ν_μ CC interactions:

- $|\vec{q}| \leq 2$ GeV/c
- $E_{Avail} \leq 2$ GeV

- Same selection as ν_μ CC inclusive analysis
- NOvA's first measurement in $|\vec{q}|$ and E_{Avail}
  - **2p2h concentrated at low values**
- Cross section reported at 67 kinematic points
- ~12% uncertainty typically (dominated by flux systematic)



Comparison of 2p-2h models to data

Large χ^2 values seen for all 2p2h models/tunes

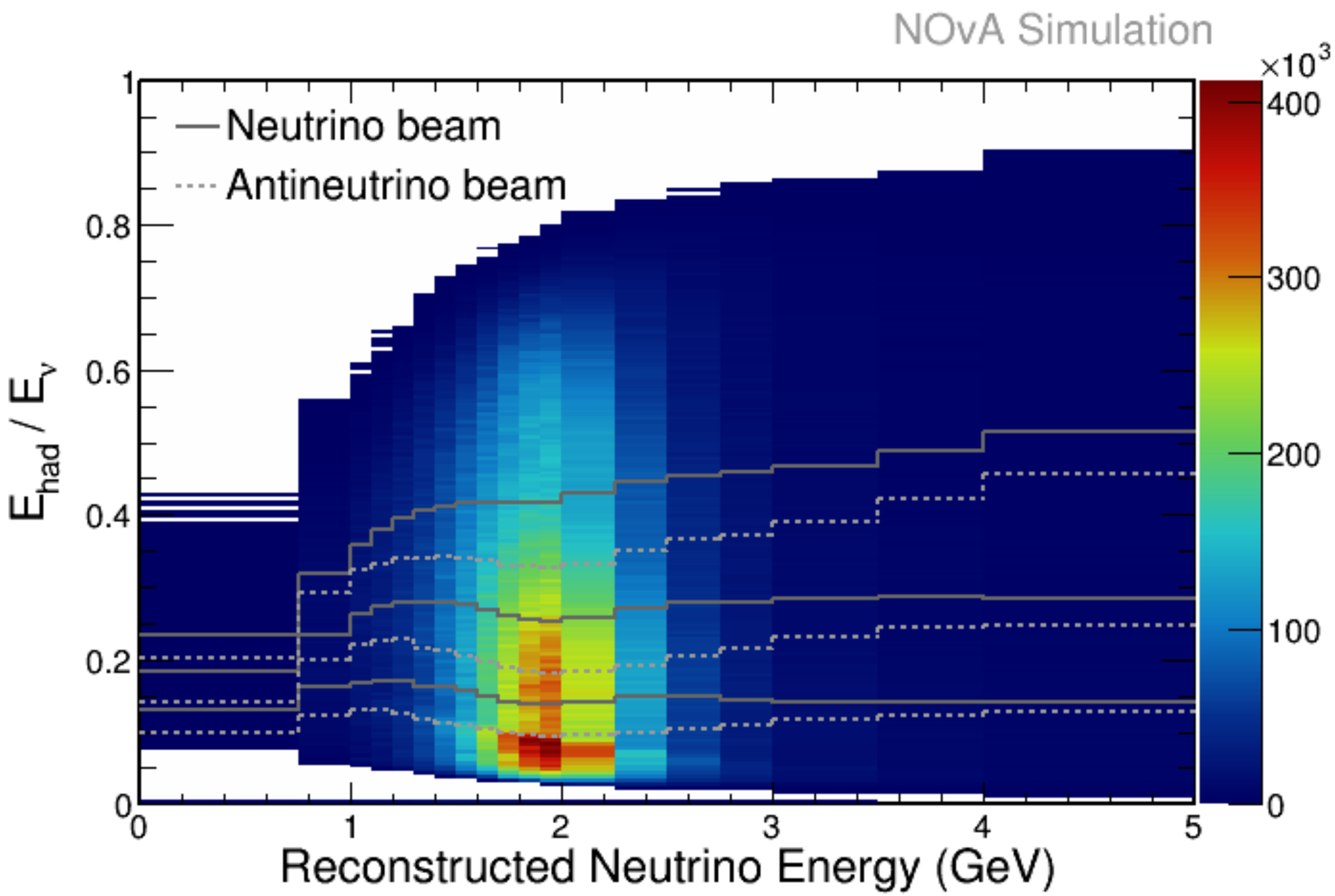
Tuned models match data better than Valencia/SuSA-v2

2p2h Model	Muon System χ^2 (115 d.o.f.)	Hadron System χ^2 (67 d.o.f.)
GENIE v2.12.2 - NOvA Tune	200	320
Empirical MEC	190	460
Valencia w/ MINERvA Tune	340	420
Valencia	630	910
SuSA - v2	620	590

- χ^2 calculated for data vs. simulation with the various 2p2h models using full covariance matrix
- Correlations between bins are dominant contribution to χ^2
- Data release for these high-statistics analyses coming soon
  - Can explore many aspects of generator models beyond 2p2h with this data

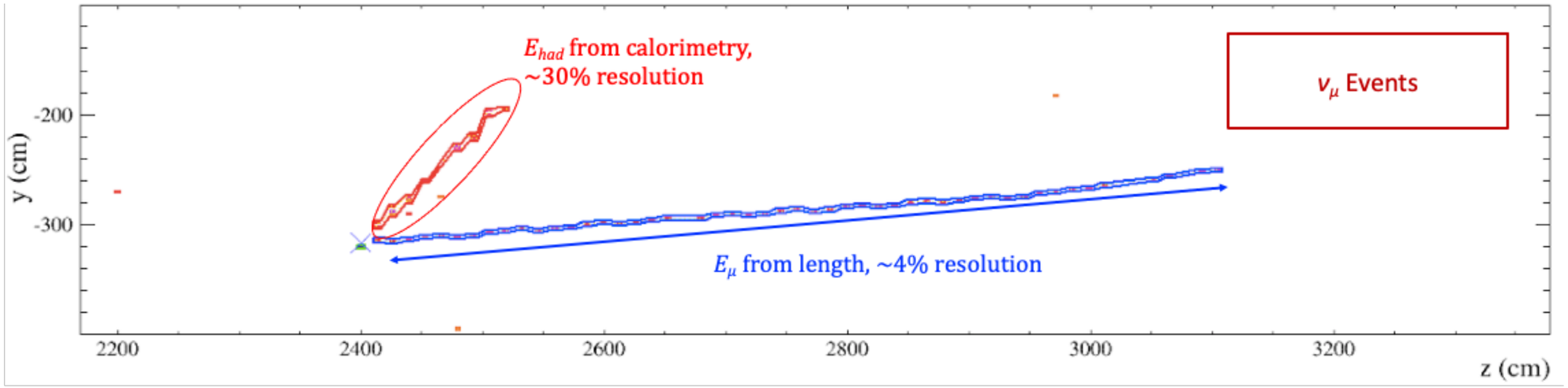
ν_μ energy resolution quartiles

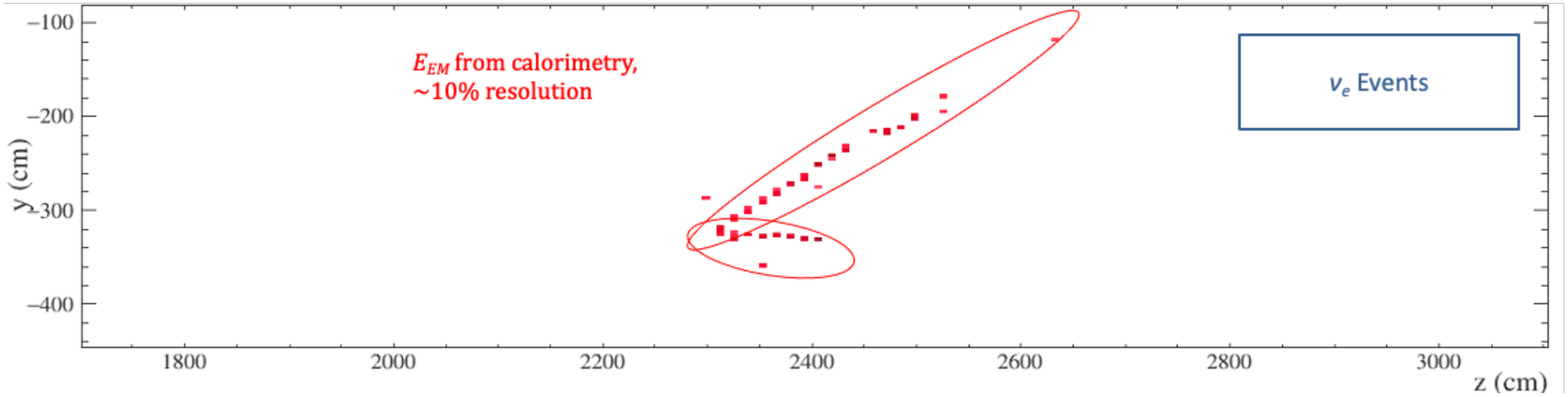
- The data is split in four equal populations (quartiles) of hadronic energy fraction as a function of reconstructed neutrino energy.
- Done separately for neutrino versus antineutrinos.
- Energy resolution varies from 5.8% (5.5%) to 11.7% (10.8%) for neutrino (antineutrino) beam.



https://doi.org/10.1103/PhysRevD.106.032004

Energy reconstruction



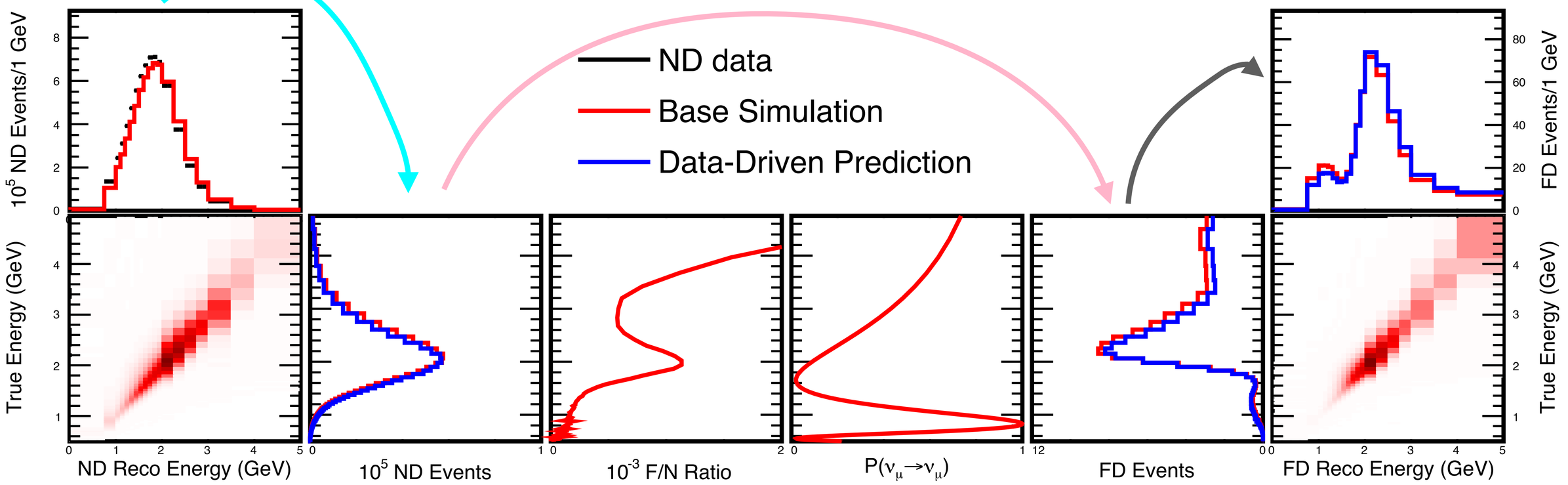


Extrapolation

Translate ND data/ MC observation to true energy

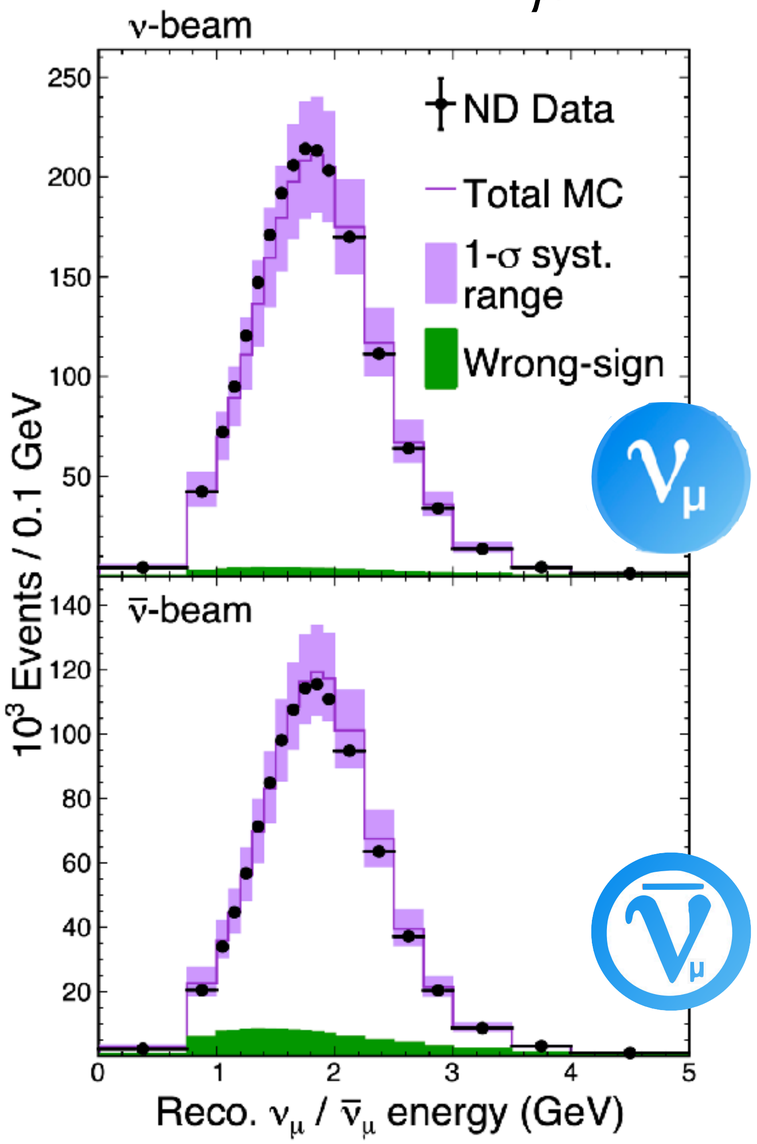
Oscillate ratio to the FD

Smear back into reconstructed energy



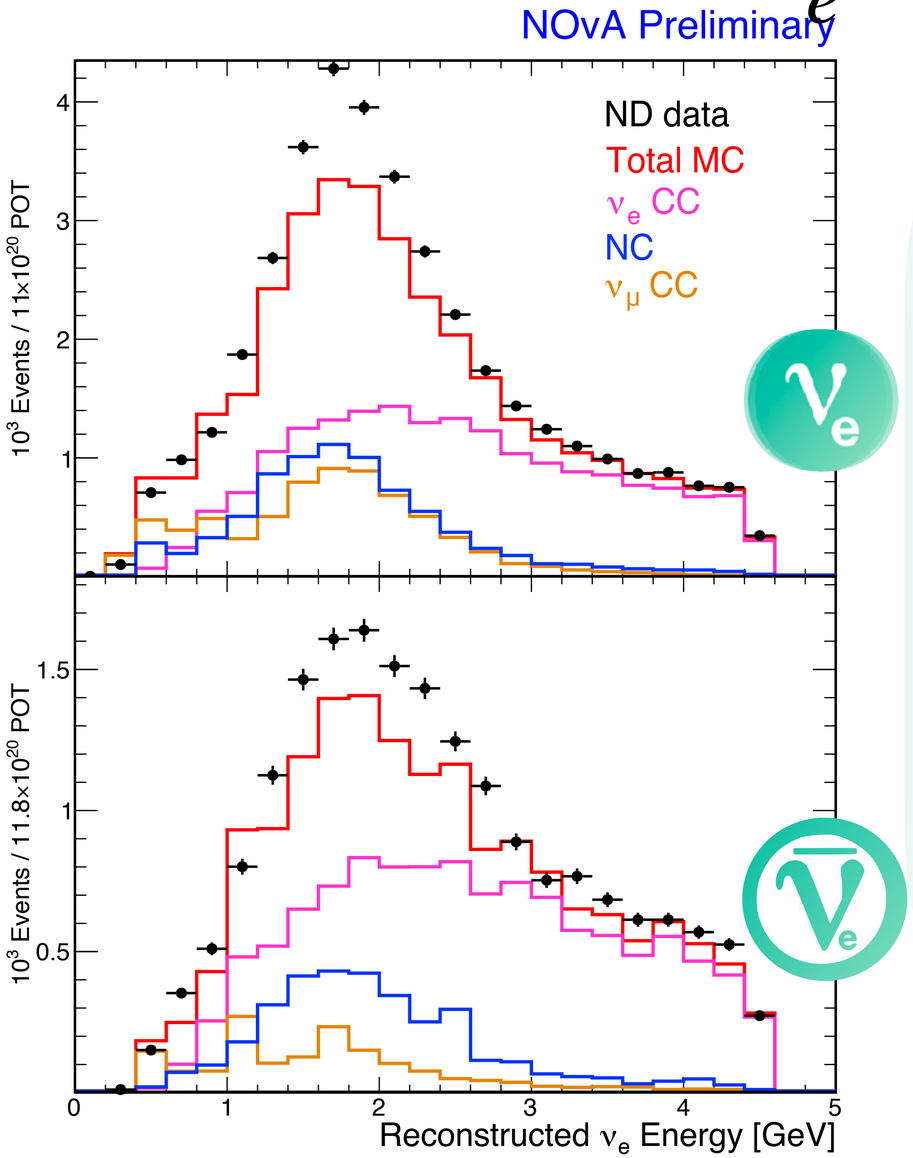
- Since NOvA has functionally similar Near and Far Detectors the flux combined with the cross sections uncertainties largely cancel.

Near detector ν_μ spectra



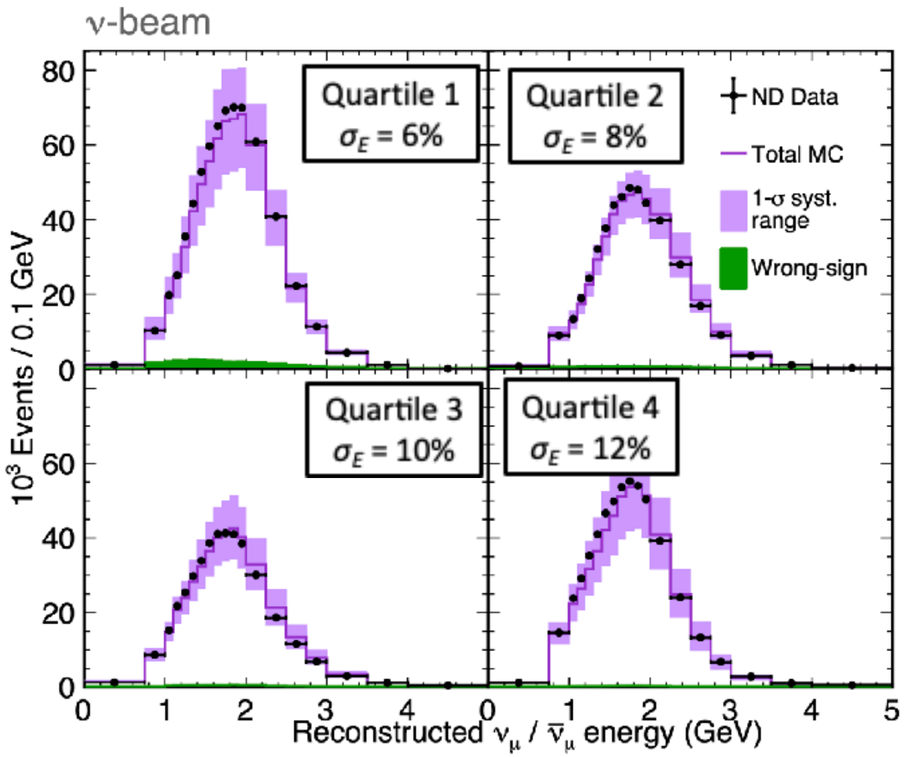
- Band around the MC shows the large impact of flux and cross-section uncertainties in only a single detector.
- We use this sample to predict both ν_μ and ν_e signal spectra at the Far Detector.
- Appearing ν_e's are still ν_μ's at the ND

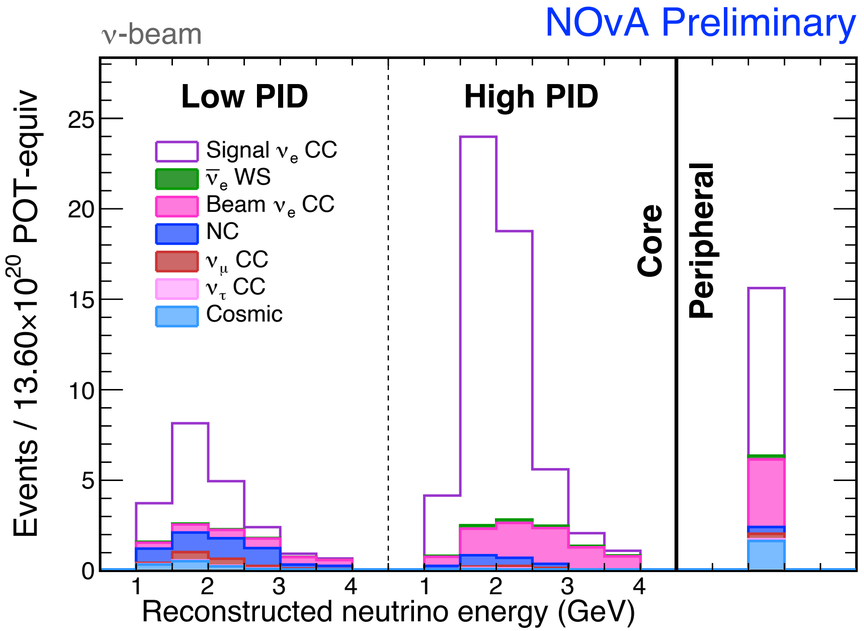
Near detector ν_e-like spectra



- The ND ν_e-like spectrum contains the background to the appearing ν_e's at the FD.
- Largest component is the irreducible $\nu_e/\bar{\nu}_e$ flux component.
  - 50% in neutrino-mode
  - 71% in antineutrino mode
- We use this sample to predict the background to ν_e appearance.

Enhancing sensitivity to oscillations





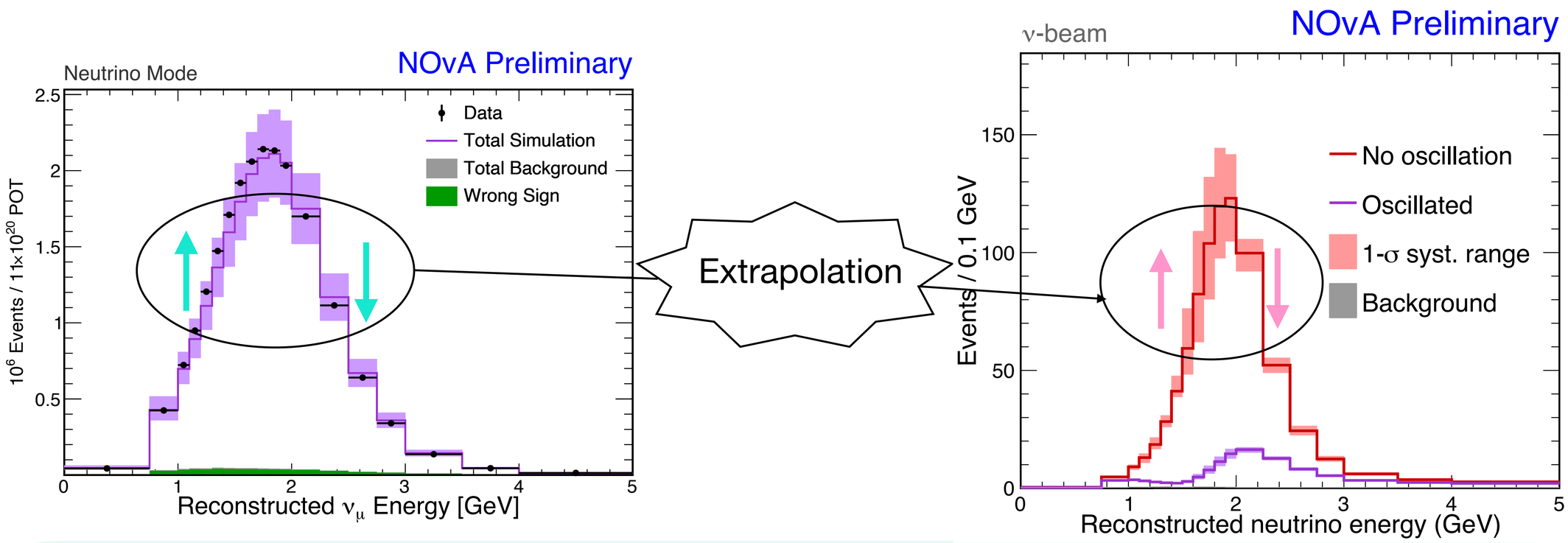
ν_μ sample

- Sensitivity depends primarily on the shape of the energy spectrum.
- Bin by energy resolution → bin by hadronic energy fraction

ν_e sample

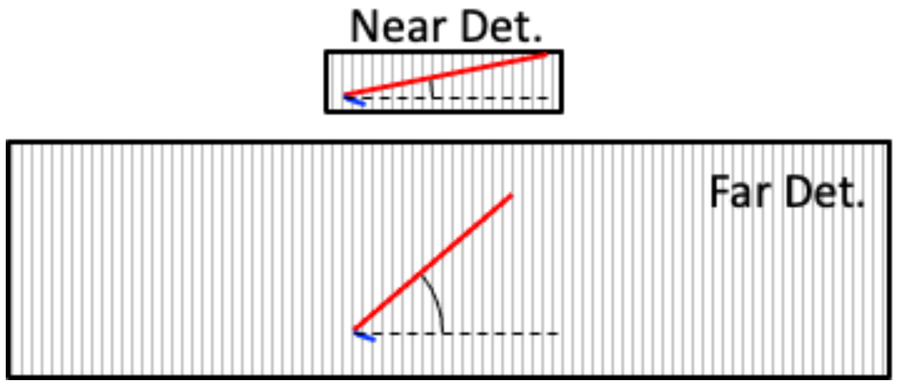
- Sensitivity depends primarily on separating signal from background.
- Peripheral sample:
  - Captures high-PID events which might not be contained close to detector edges.
  - No energy binning.

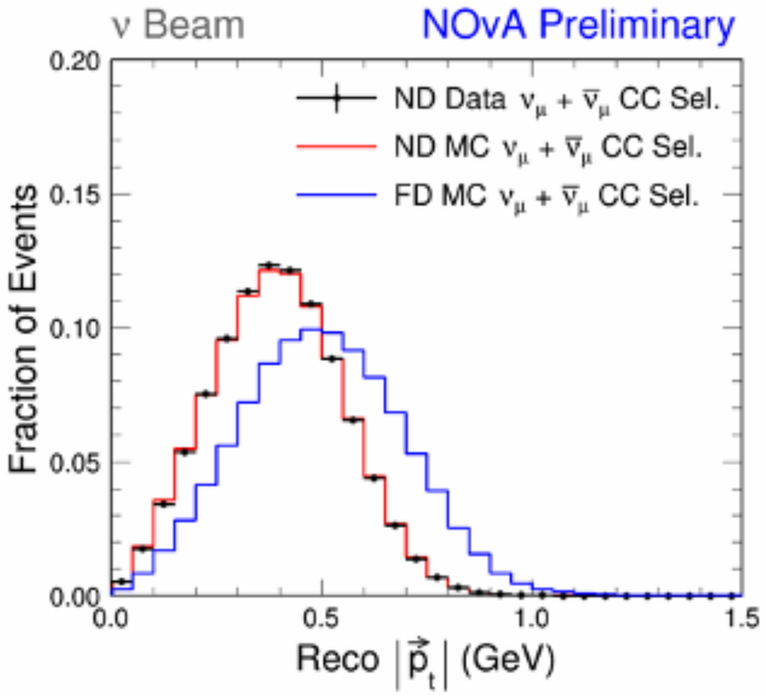
Extrapolating from near to far detector



- Observe data-MC differences at the ND, use them to modify the FD MC.
  - Extrapolation performed in the analysis binning of energy + (resolution or PID).
- Significantly reduces the impact of uncertainties correlated between detectors
  - Especially effective at rate effects like the flux (7% → 0.3%).

Extrapolating kinematics

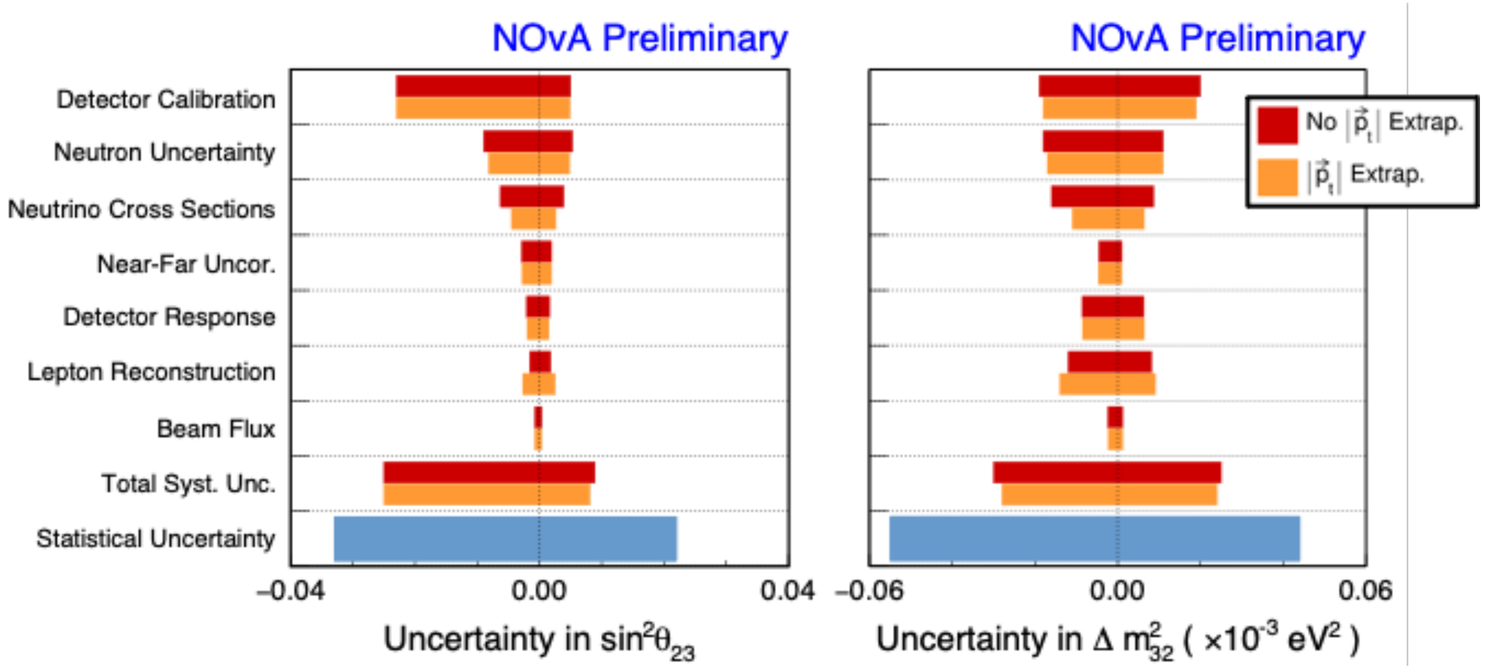




- Containment limits the range of lepton angles more in the Near Detector than in the Far.
- The ND is 1/5 the size of the FD.

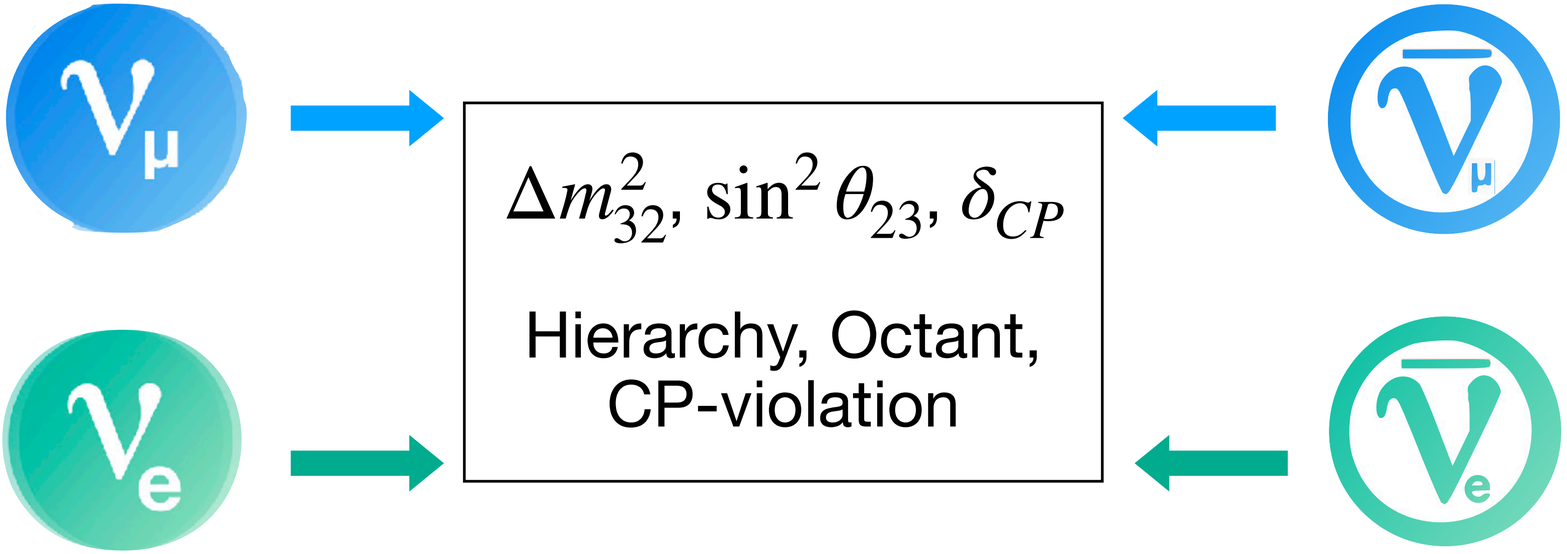
- Mitigate by extrapolating in bins of lepton transverse momentum, pt
- Split the ND sample into 3 bins of pt, extrapolate each separately to the FD.
  - Effectively “rebalances” the kinematics to better match between the detectors.
  - Re-sum the pt bins before fitting.

Systematics uncertainties with pt extrapolation



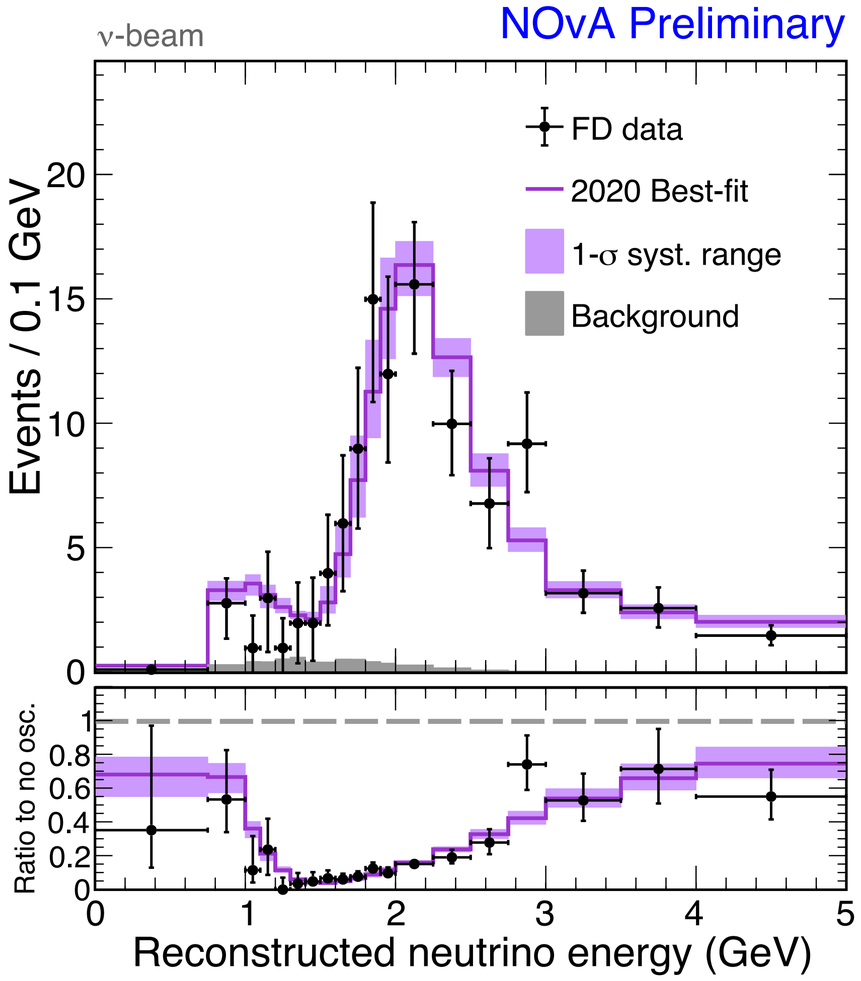
- Increased robustness also leads to a 30% reduction in cross section uncertainties.
  - Slightly increase the sensitivity to well-understood systematics on lepton reconstruction.
- Overall systematic reduction is 5-10%,
- The largest systematics come from the detector energy scale.

Oscillations fit

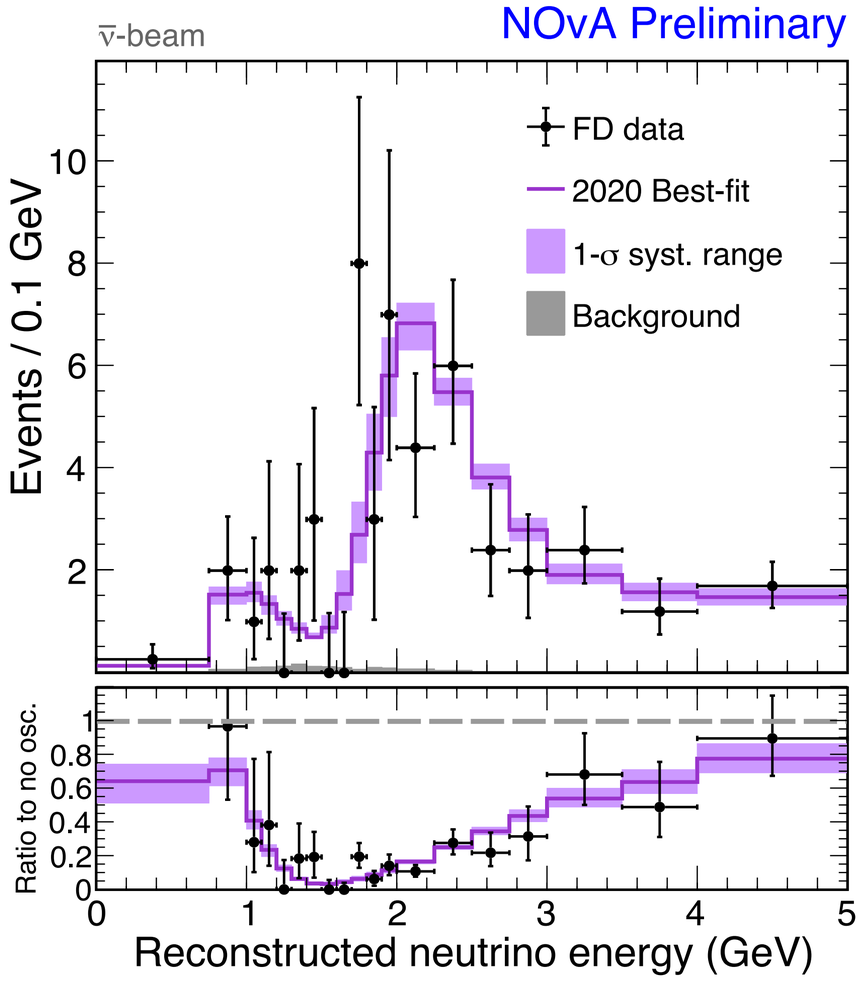


- Simultaneous fit of all samples
- We perform two analysis:
  - A frequentist analysis with Feldman-Cousins method (reactor-constrained $\sin^2 2\theta_{13} = 0.085 \pm 0.003$)
  - A Markov Chain MC Baysian analysis

$\nu_\mu/\bar{\nu}_\mu$ data at the far detector



211 events, 8.2 background

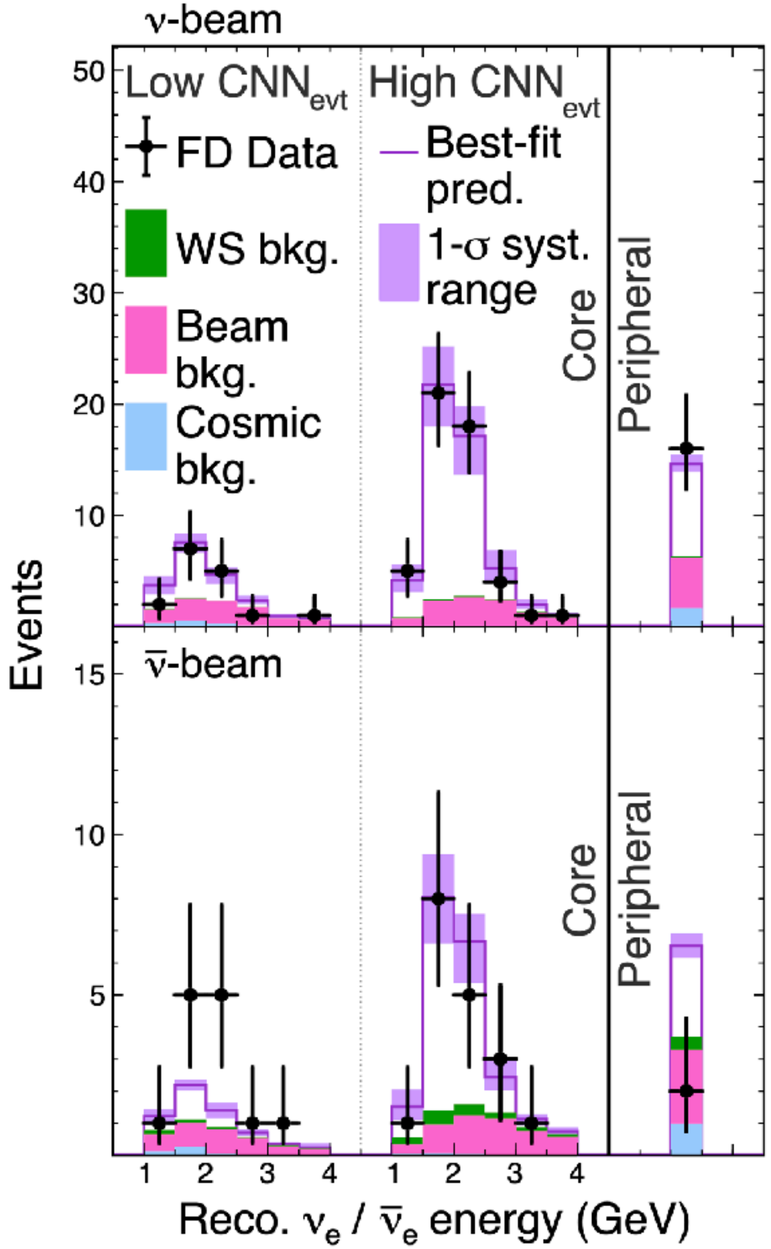


105 events, 2.1 background

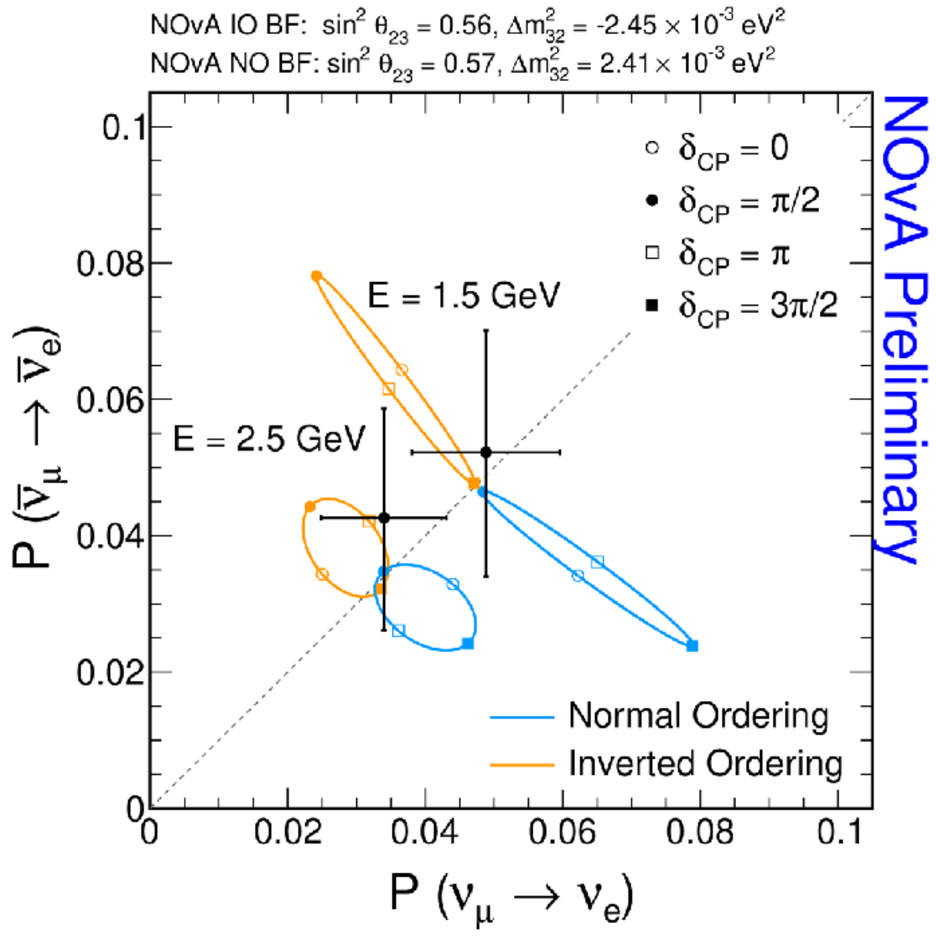
$\nu_e/\bar{\nu}_e$ data at the far detector

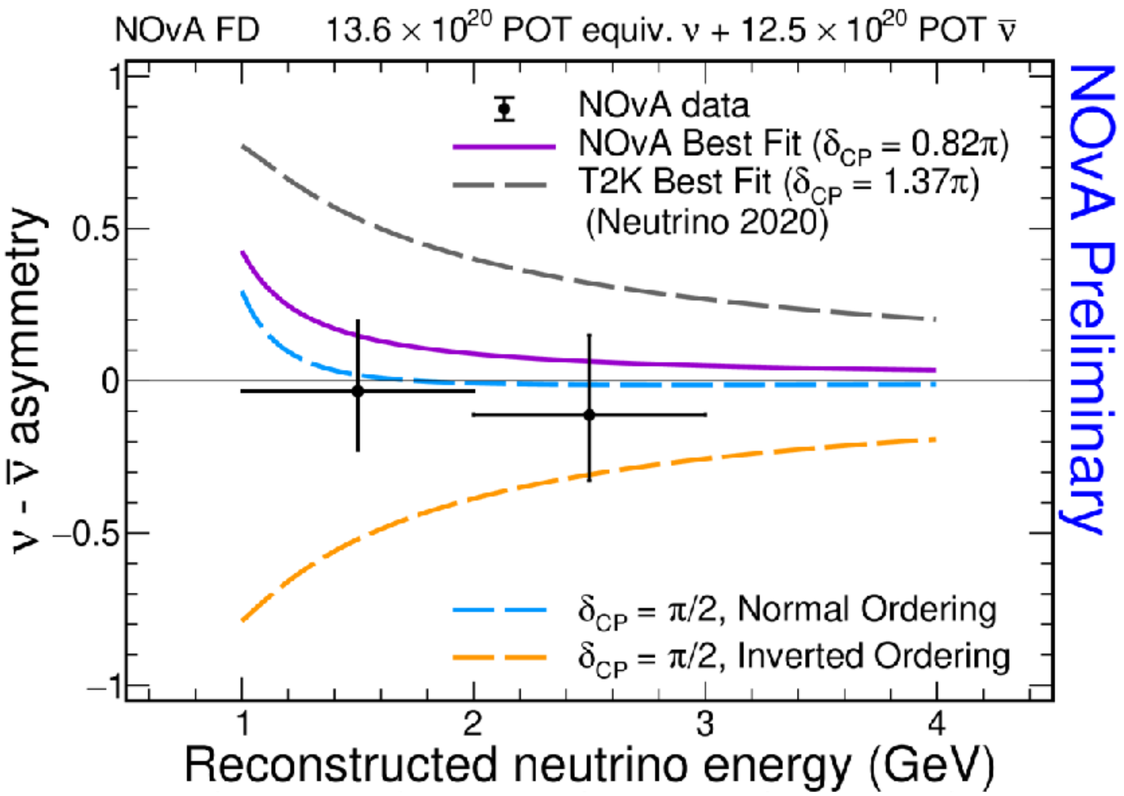
82 ν_e candidates, 27 background

33 $\bar{\nu}_e$ candidates, 14 background



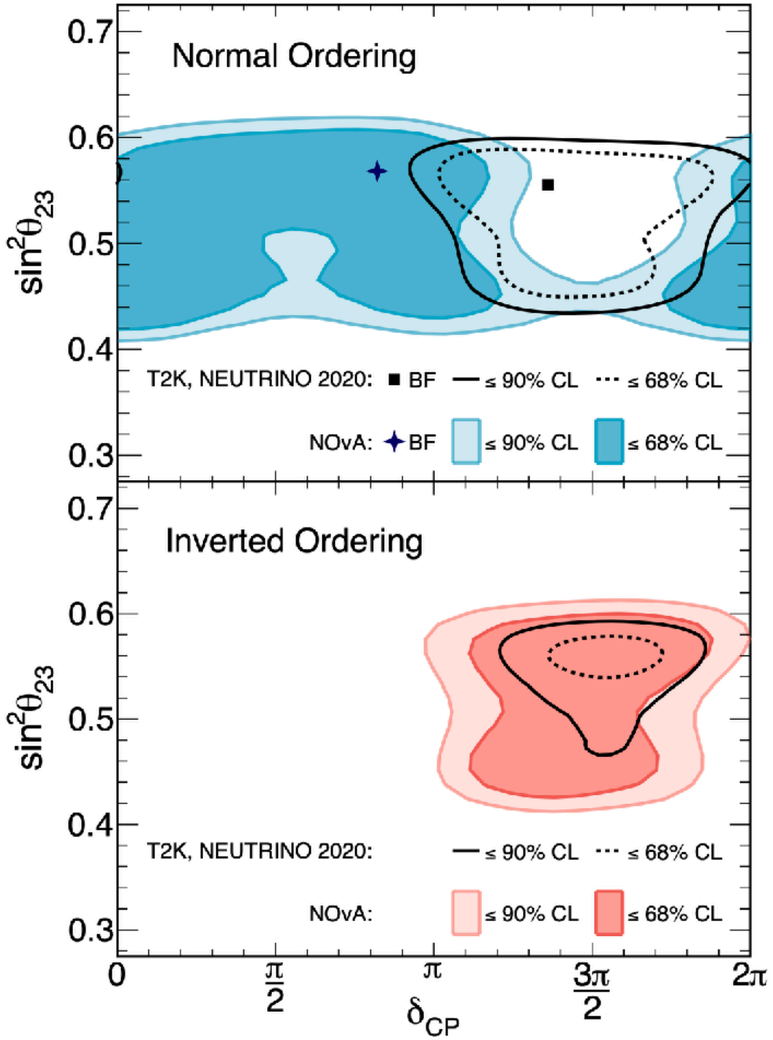
Appearance



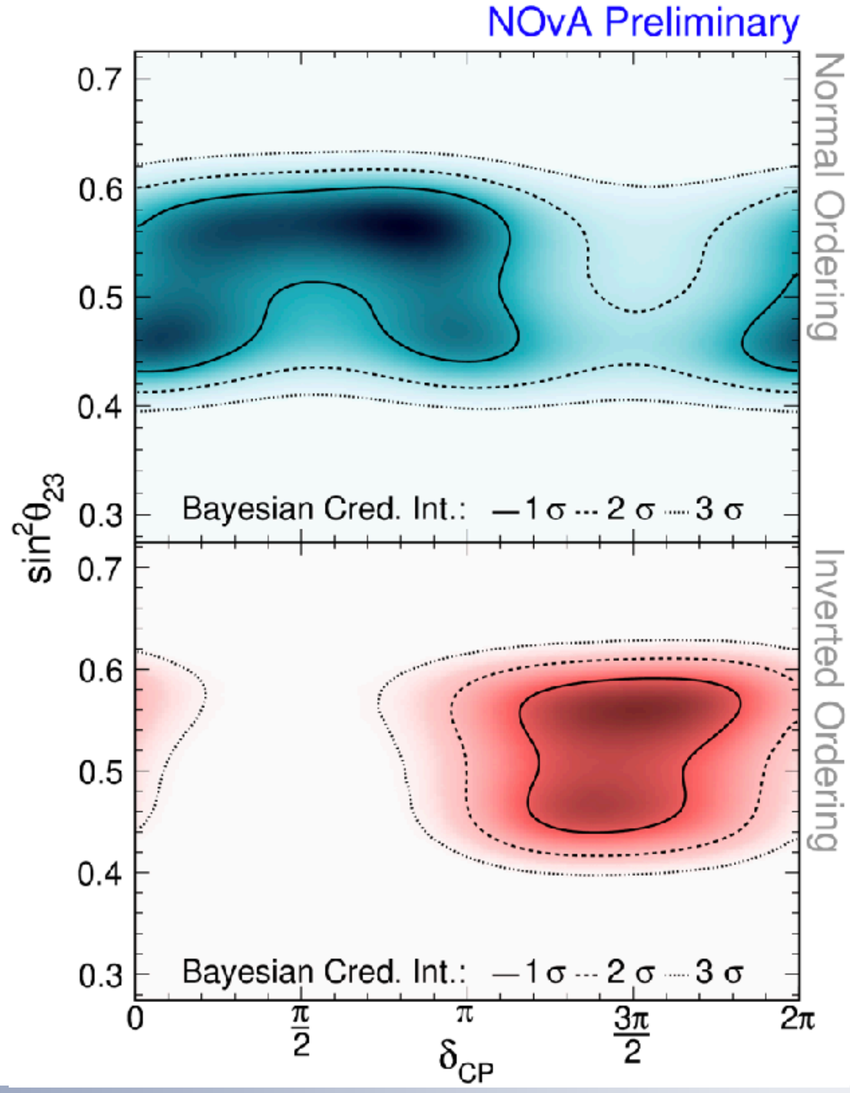


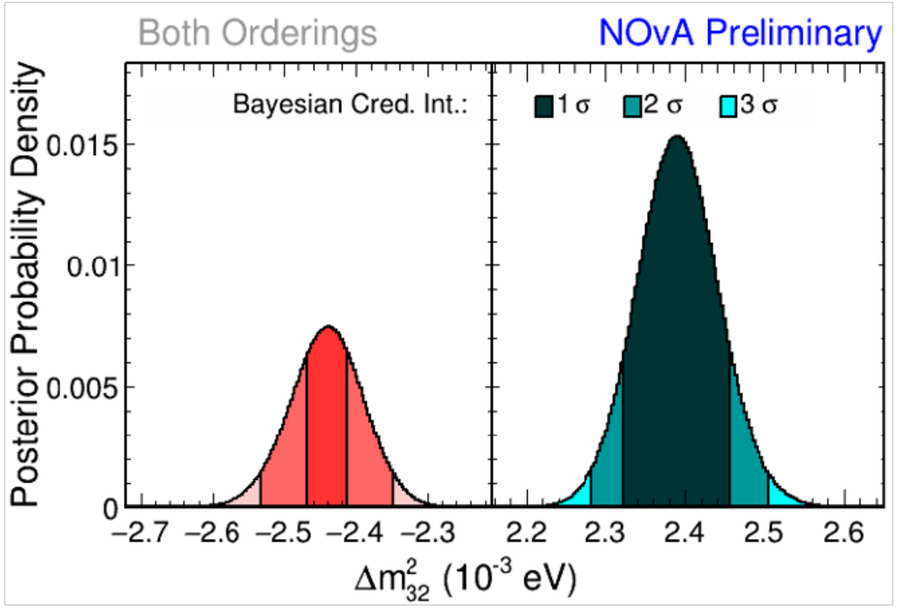
- Appearance asymmetry: $\dfrac{P(\nu_e) - P(\bar{\nu}_e)}{P(\nu_e) + P(\bar{\nu}_e)}$
- Asymmetry consistent with zero to 25% precision
- Disfavours mass ordering-δ_{CP} combinations with large asymmetry

3-flavour fit results



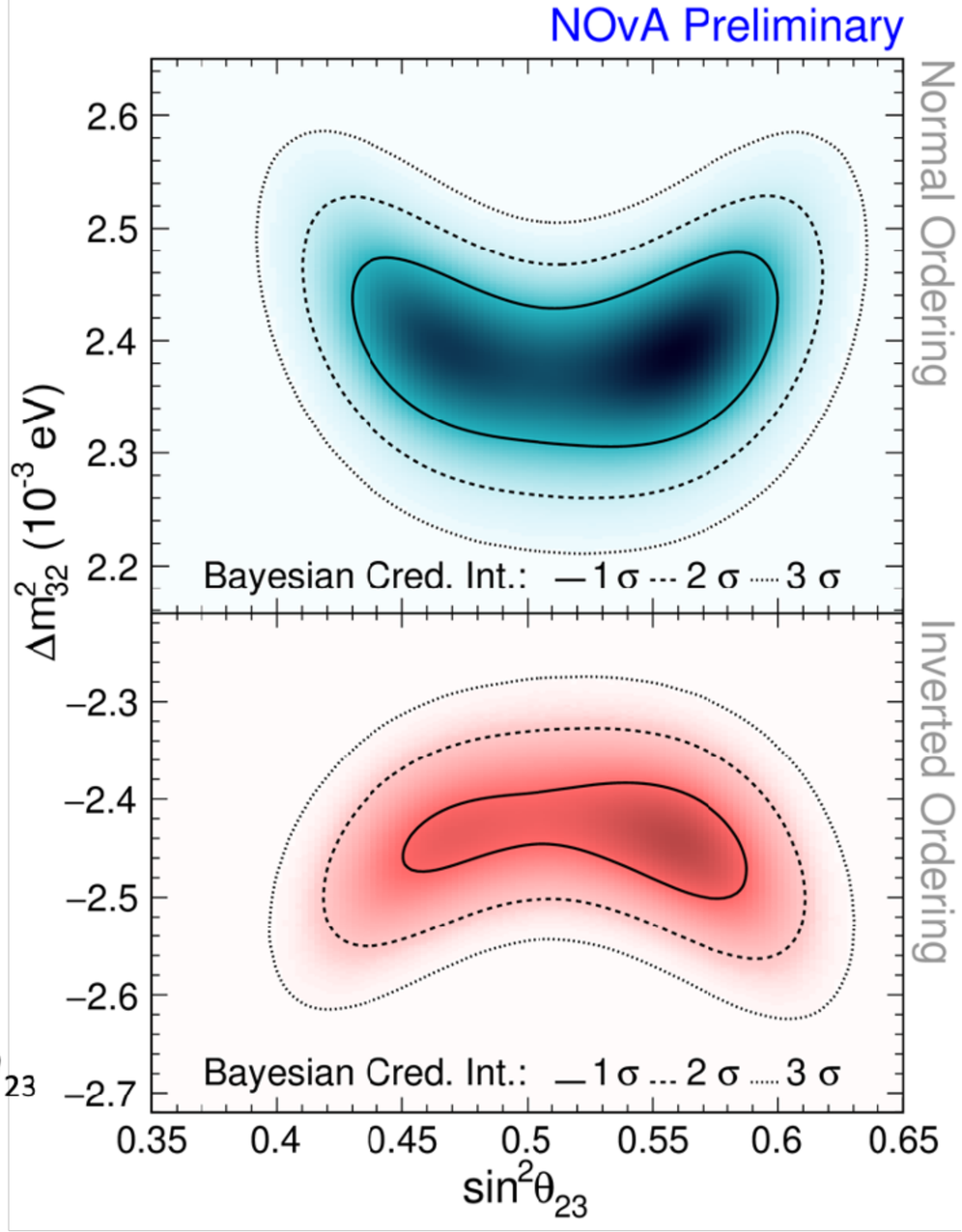
- Exclude IO, $\delta_{CP} = \pi/2$ at > 3 σ
- Significant progress on joint fit with T2K
  - (coming soon)

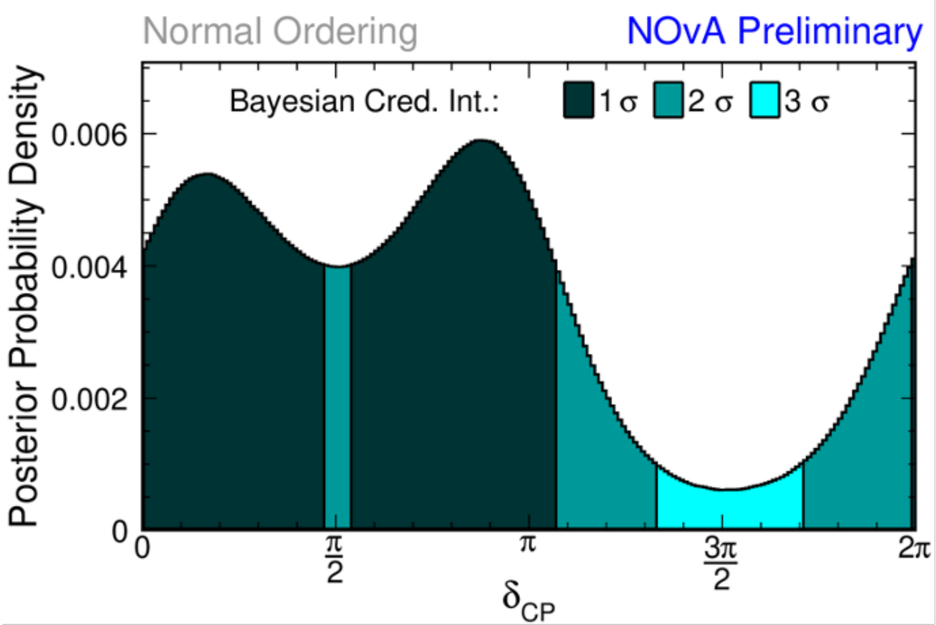


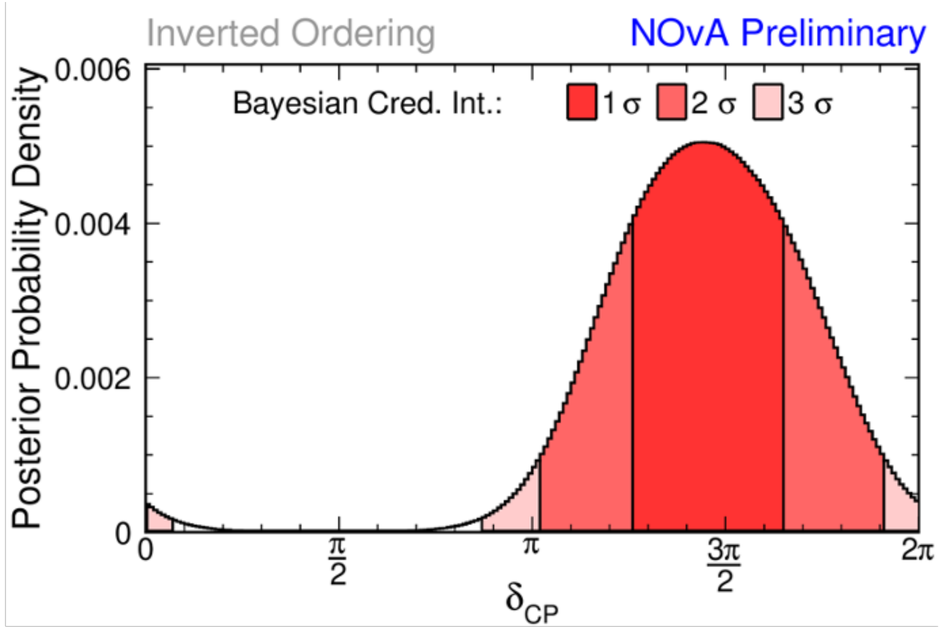


Posterior Probability	Lower Octant	Upper Octant	Sum
Normal Ordering	0.26	0.42	0.68
Inverted Ordering	0.11	0.21	0.32
Sum	0.37	0.63	1.00

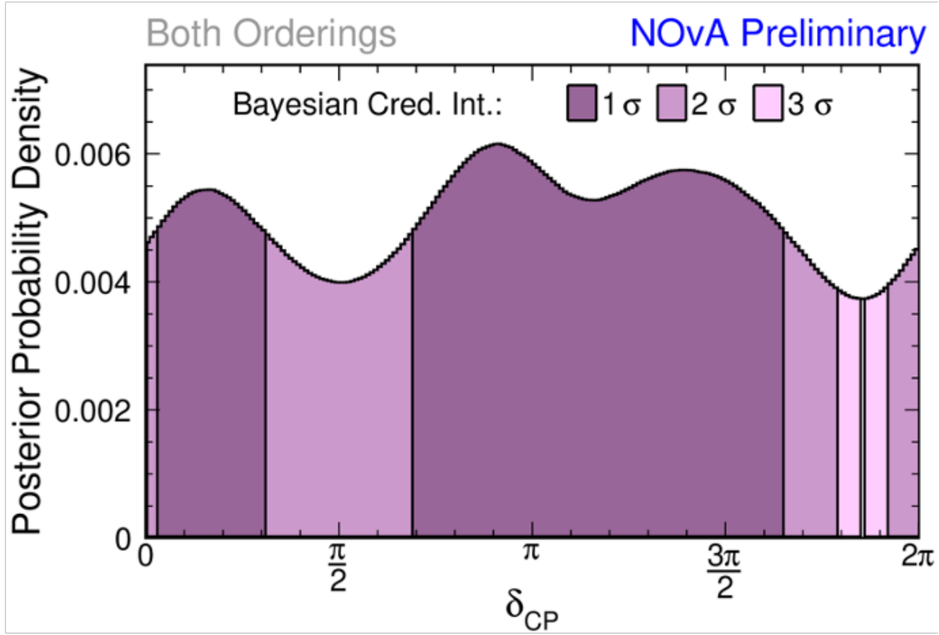
- Weak preference for upper octant of θ_{23} and Normal Mass Ordering.

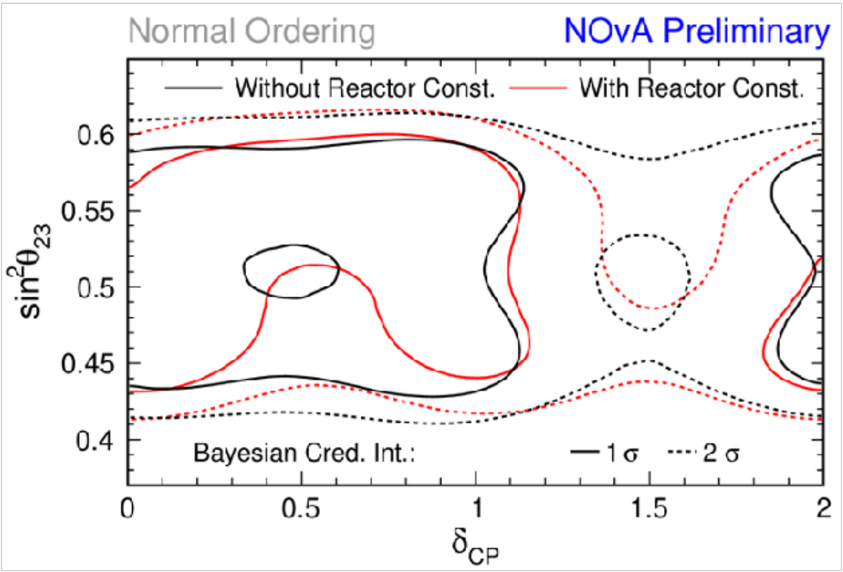


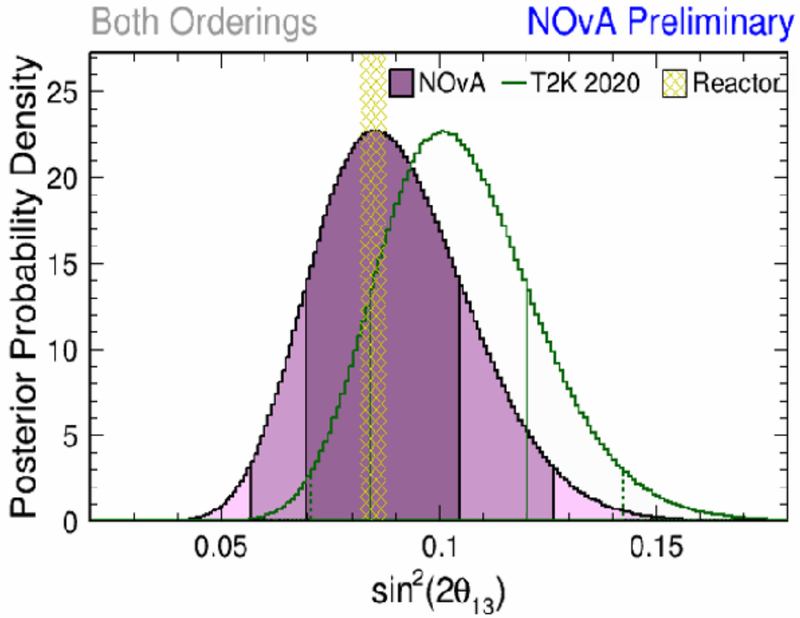




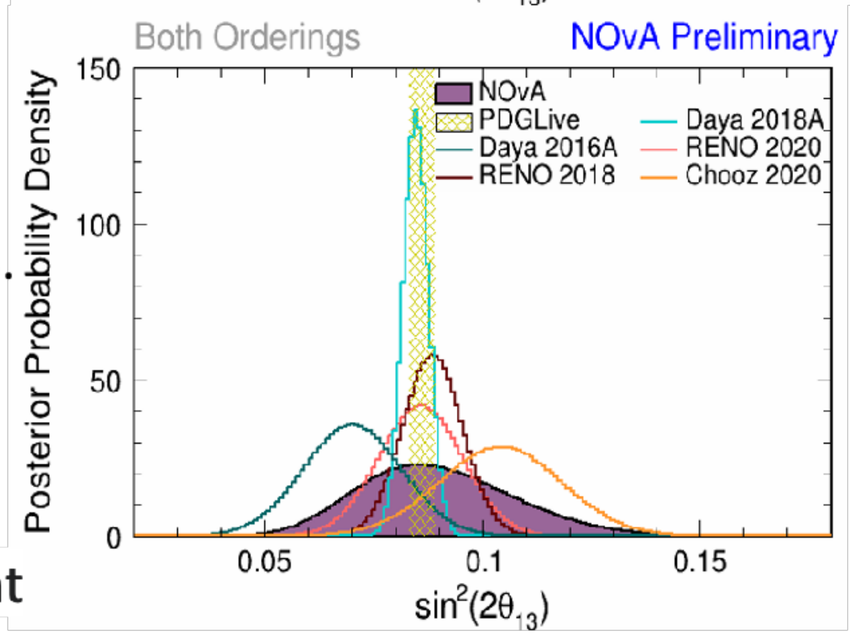
- CP violation more probable in the Inverted Mass Ordering.
- 3π/2 disfavoured in the Normal Ordering at more than 2σ Credible Interval.
- When both orderings taken into the account, no strong preference for δ.







- No tension between T2K and NOvA for θ_{13}.
- No tension between accelerator and reactor neutrino experiments.
- Long-distance $\nu_\mu \to \nu_e$ agree with short-distance $\bar{\nu}_e \to \bar{\nu}_e$.
- Higher preference for the Upper Octant with the Reactor Constraint



Jeff Hartnell, Neutrino 2022 NOvA

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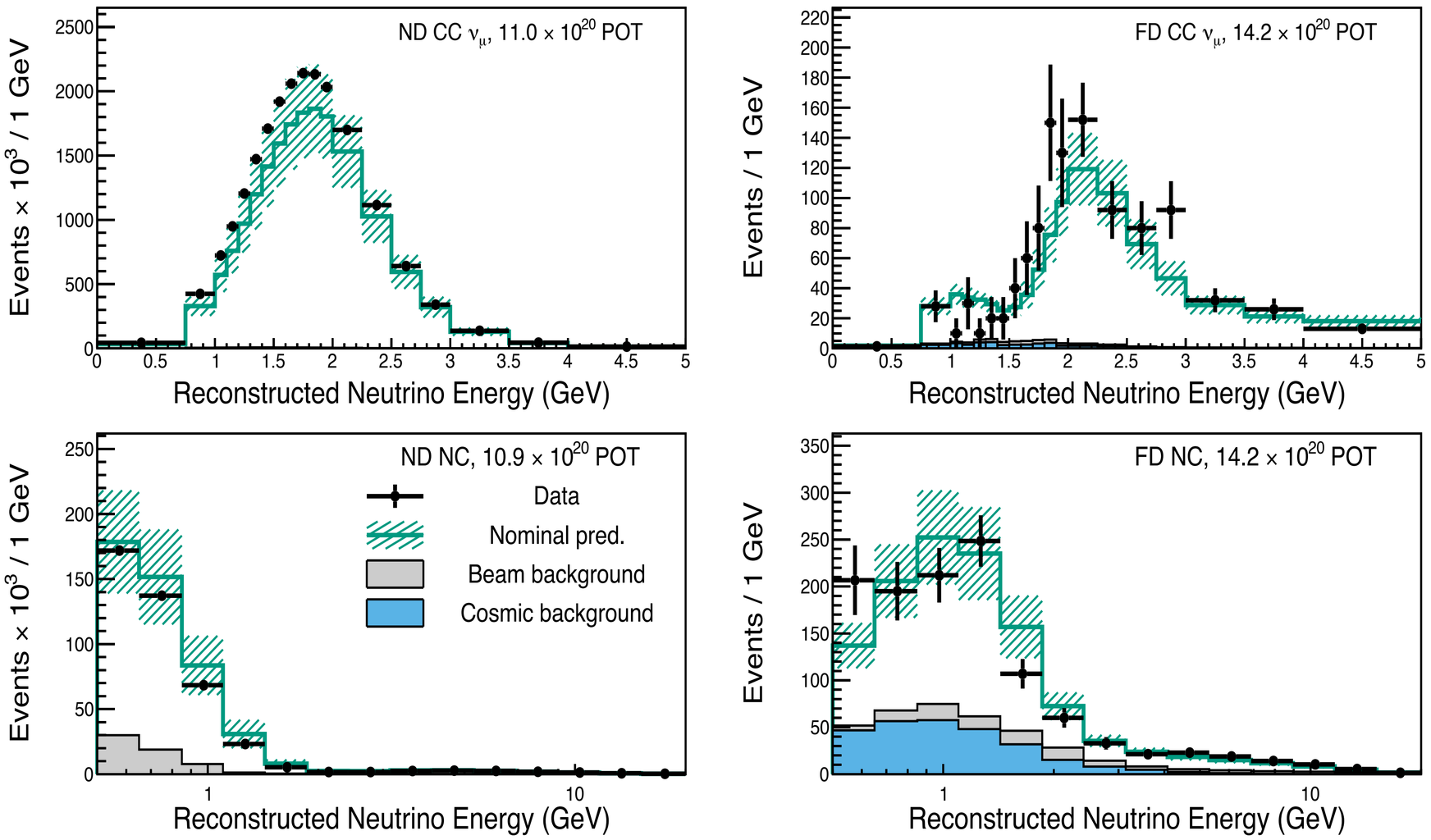
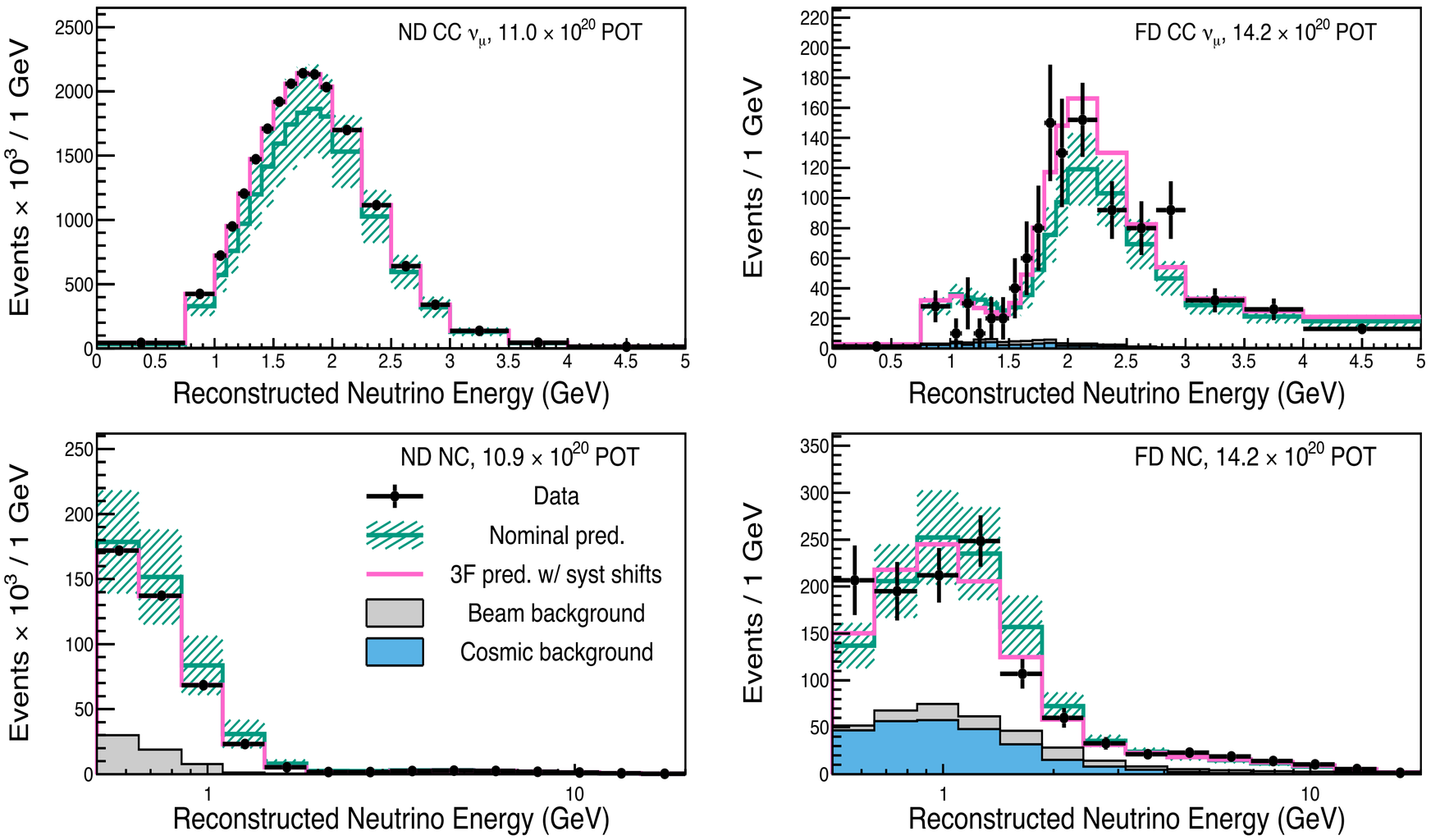
Spectra used in sterile ν search



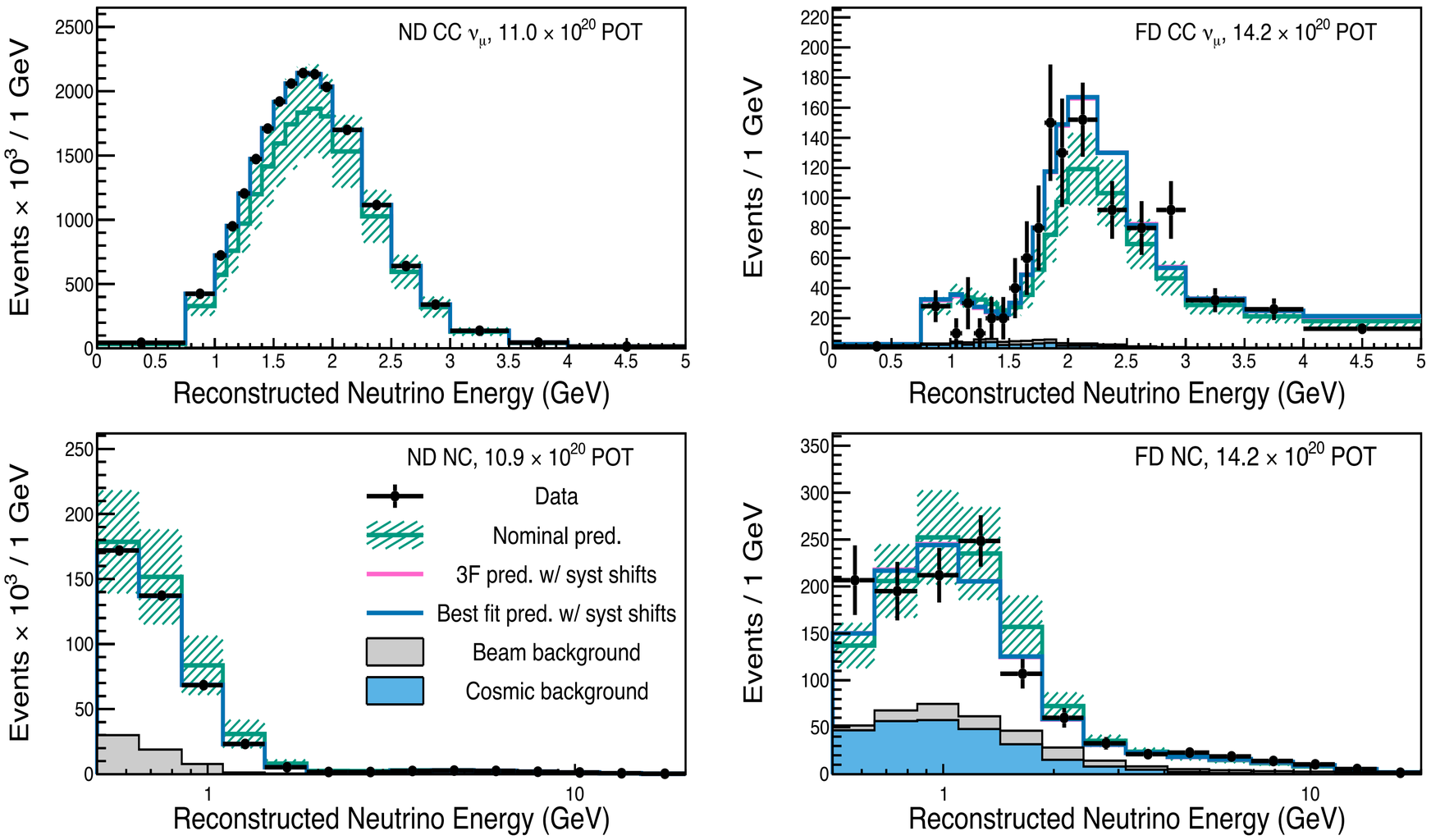
Pre-fit MC distributions (data-driven 2p2h tune not included in this analysis)

Spectra used in sterile ν search



3-Flavour hypothesis with systematic pulls included here

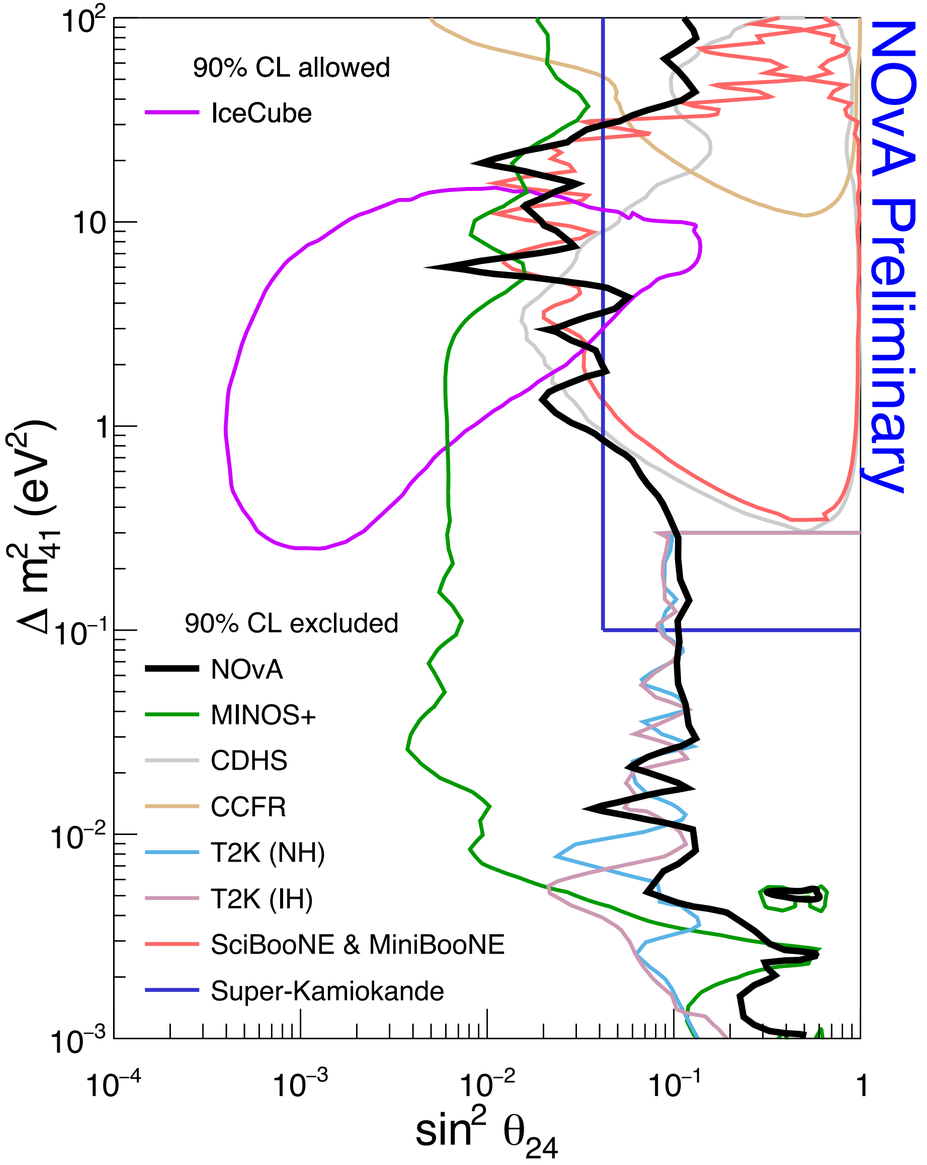
Spectra used in sterile ν search



Full best-fit for sterile neutrinos included here

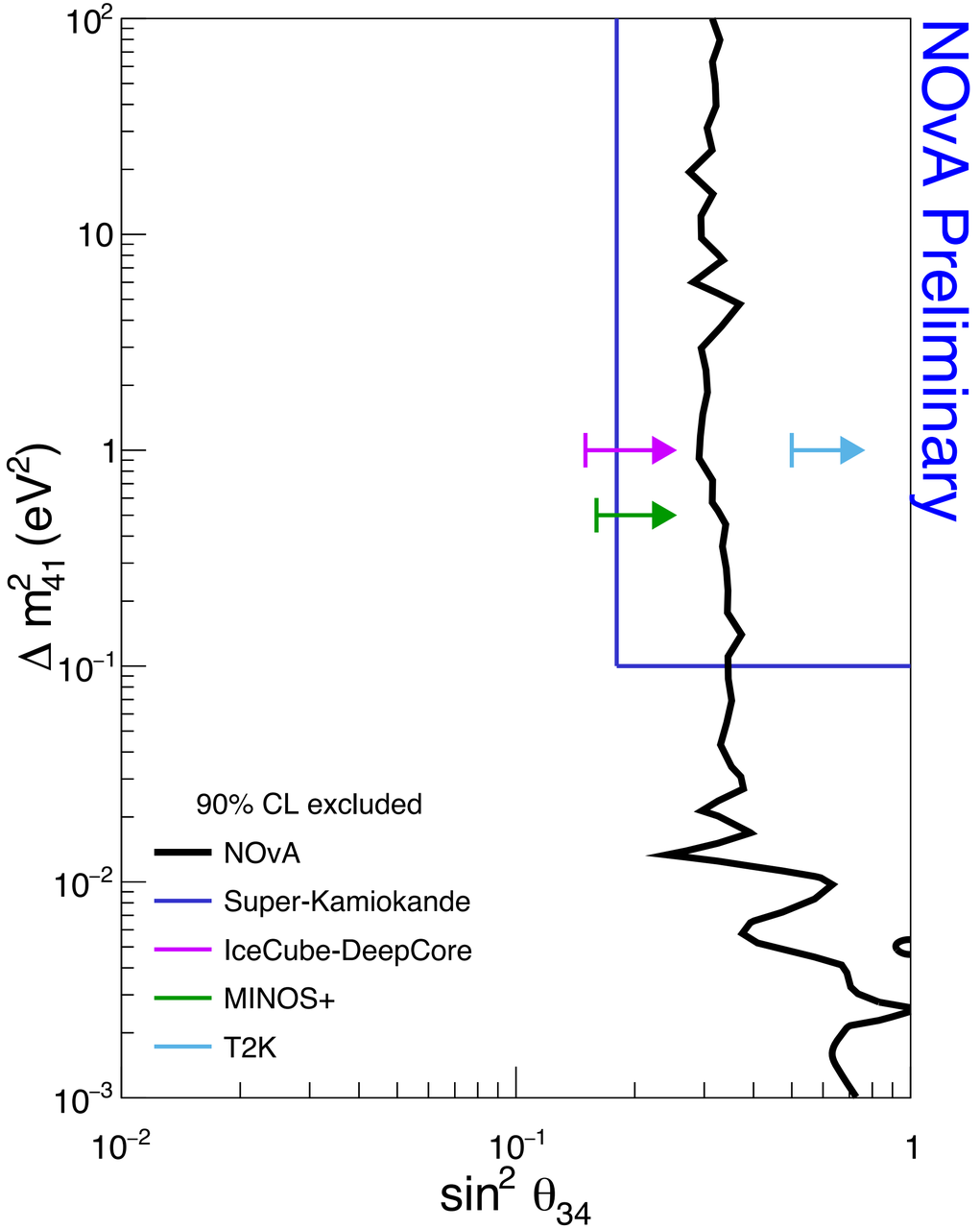
Sterile neutrino search results

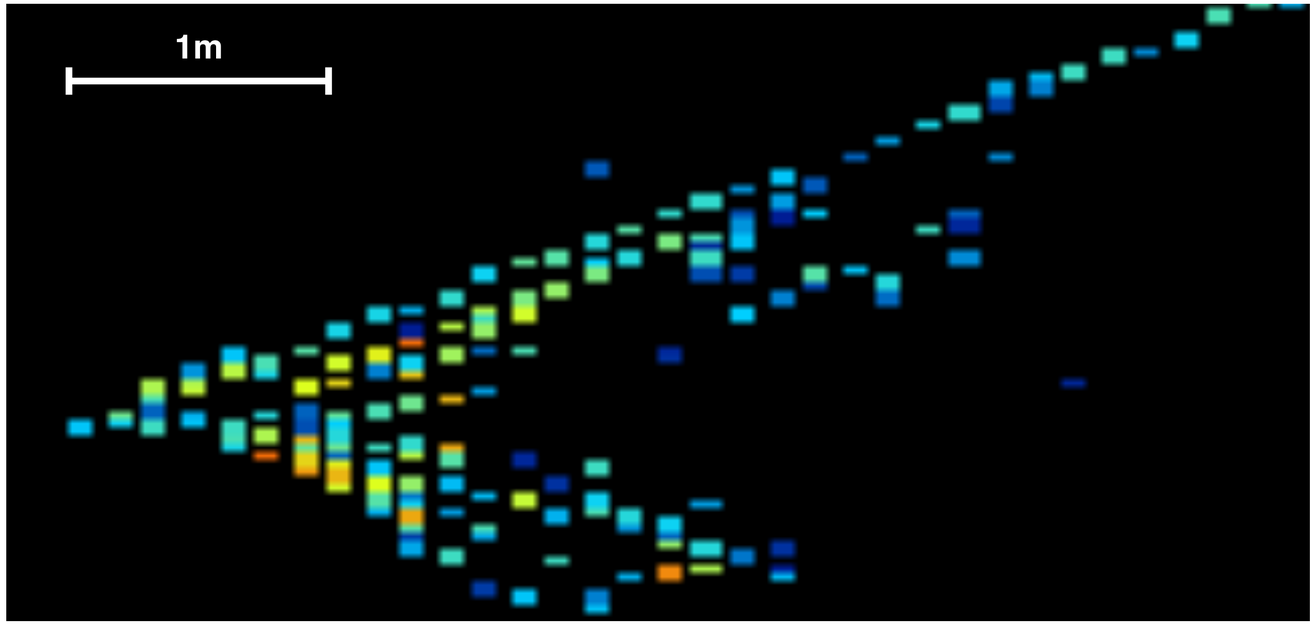
- Data shows no evidence for sterile neutrinos
  - Best fit at small θ_{24} and θ_{34} with low significance
- Competitive limits on θ_{24} for $\Delta m^2_{41} \sim 10\text{eV}^2$
- Goodness of fit:
  - χ2/d.o.f. = 56.4/66
- Analysis systematics limited at large Δm^2_{14} (Near det.) but less so for small Δm^2_{14} (Far det.)



θ_{34} results

- A measure of mixing between ν_τ and a sterile ν
- Historically studied via ν_τ appearance searches at short baselines as $\theta_{\mu\tau}$
- NOvA's sensitivity comes from neutral current events
  - enhanced by constraints on θ_{24} from ν_μ charged current events
- Long-baseline providing sensitivity at small Δm^2_{41}
- New constraints on θ_{34}

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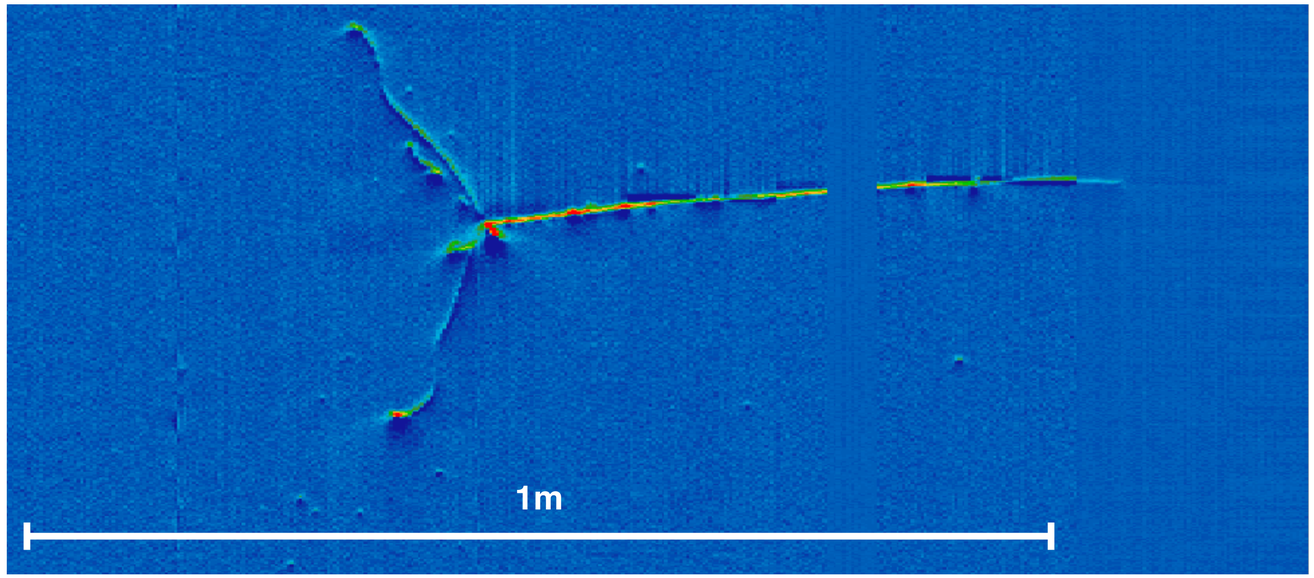
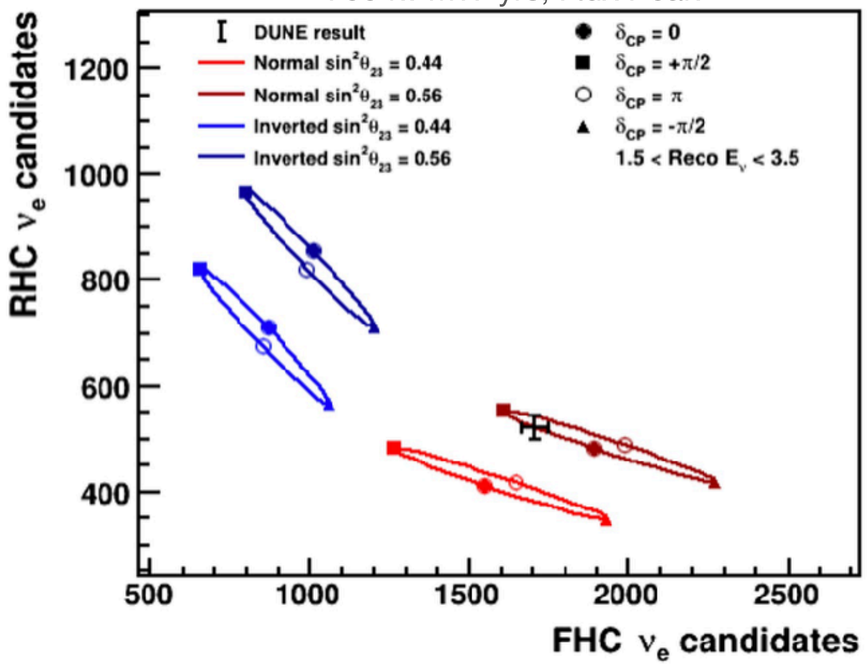

1m

DUNE Design: High Statistics

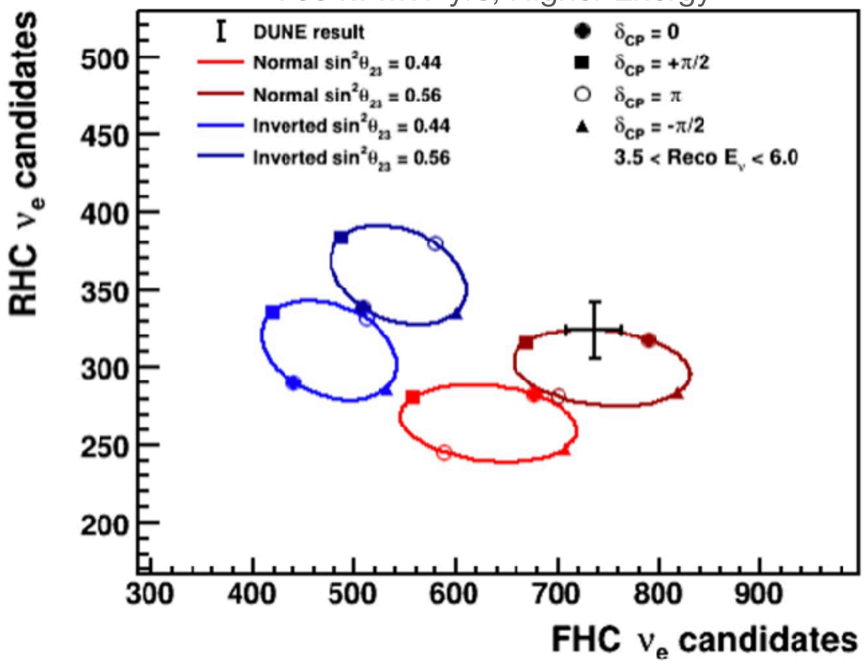
- DUNE's long-term goal is four 17 kt LAr TPC FD modules in beam from 2.4 MW Fermilab proton beam providing few percent level statistical uncertainties.

- Power of high stats with wide band LBL shown in bi-event plots.

700 kt-MW-yrs, Flux Peak

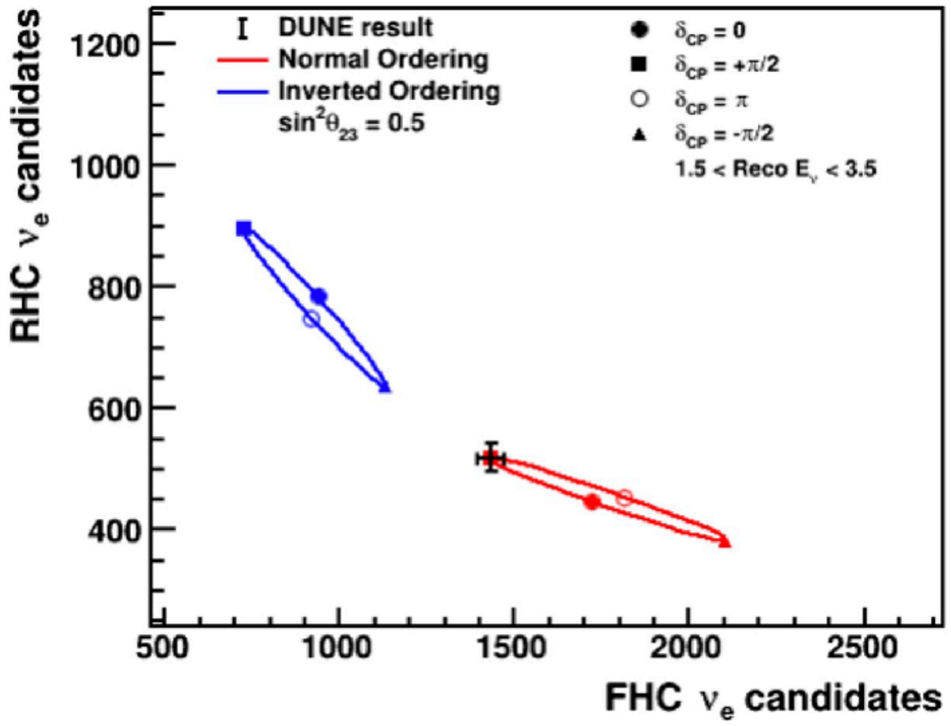


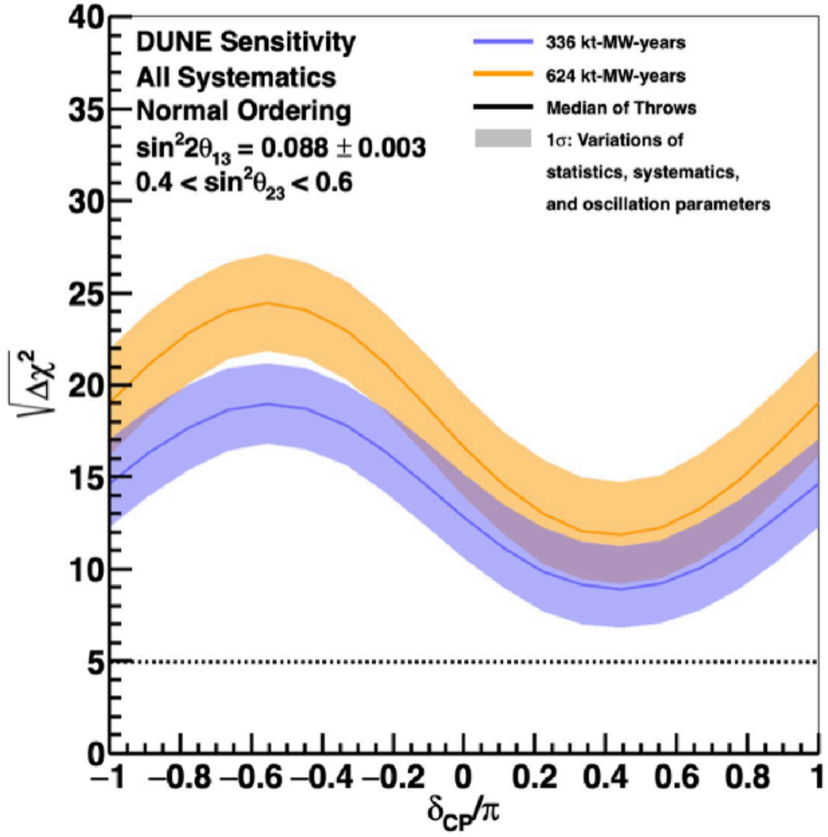
700 kt-MW-yrs, Higher Energy



DUNE Physics: Mass ordering

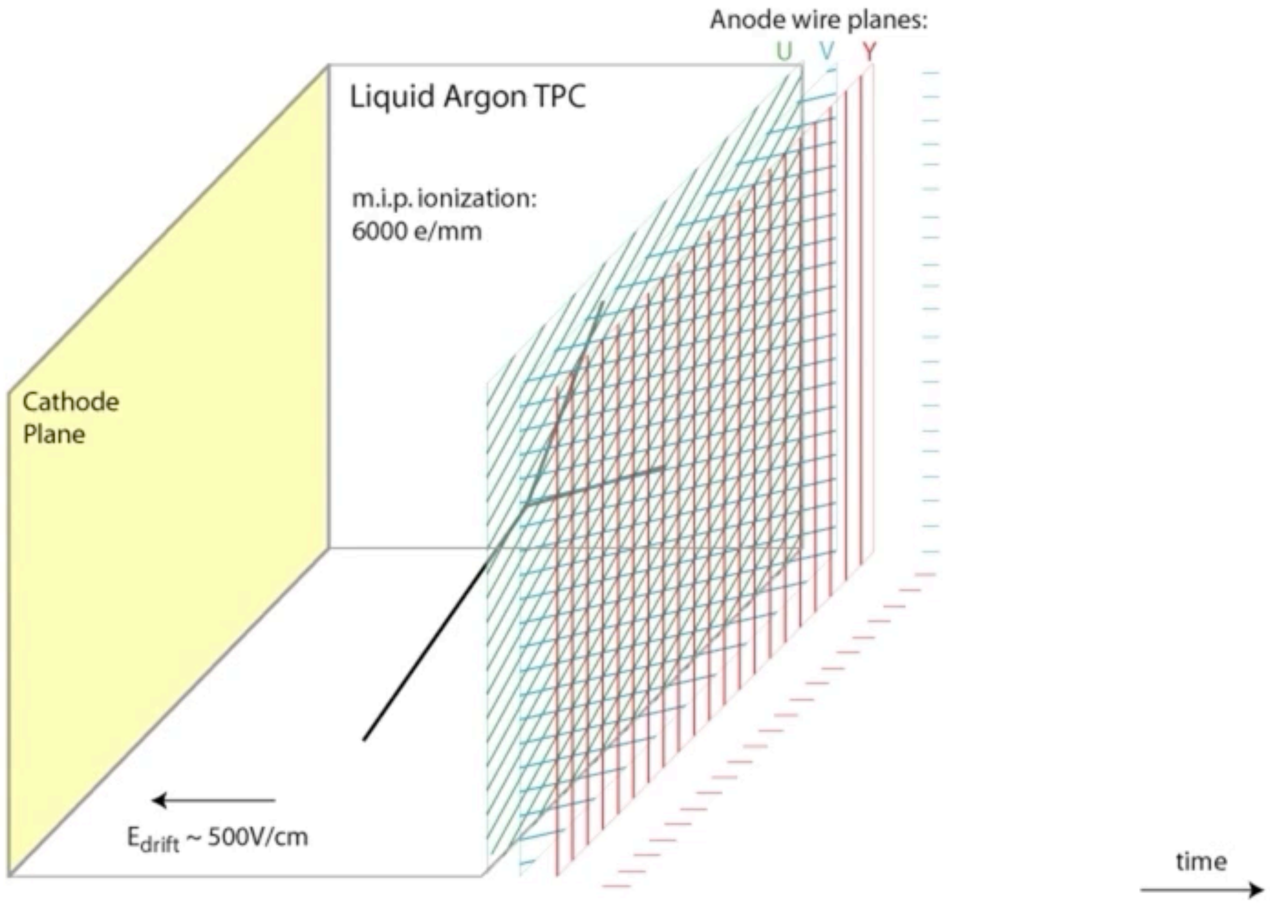
- Statistics from 6 years of full DUNE with 2.4 MW (800 kt-MWyrs total exposure) exploits enormous NO vs IO differences.
- DUNE maintains ability to definitively resolve the mass ordering regardless of the values of other parameters





Liquid argon TPC

- Argon is a noble element -> small electronegativity
- Liquid argon ~ 1000 times more dense than gas Argon -> increase likelihood of neutrino interactions
- Relatively inexpensive



Animation by Bo You (BNL)