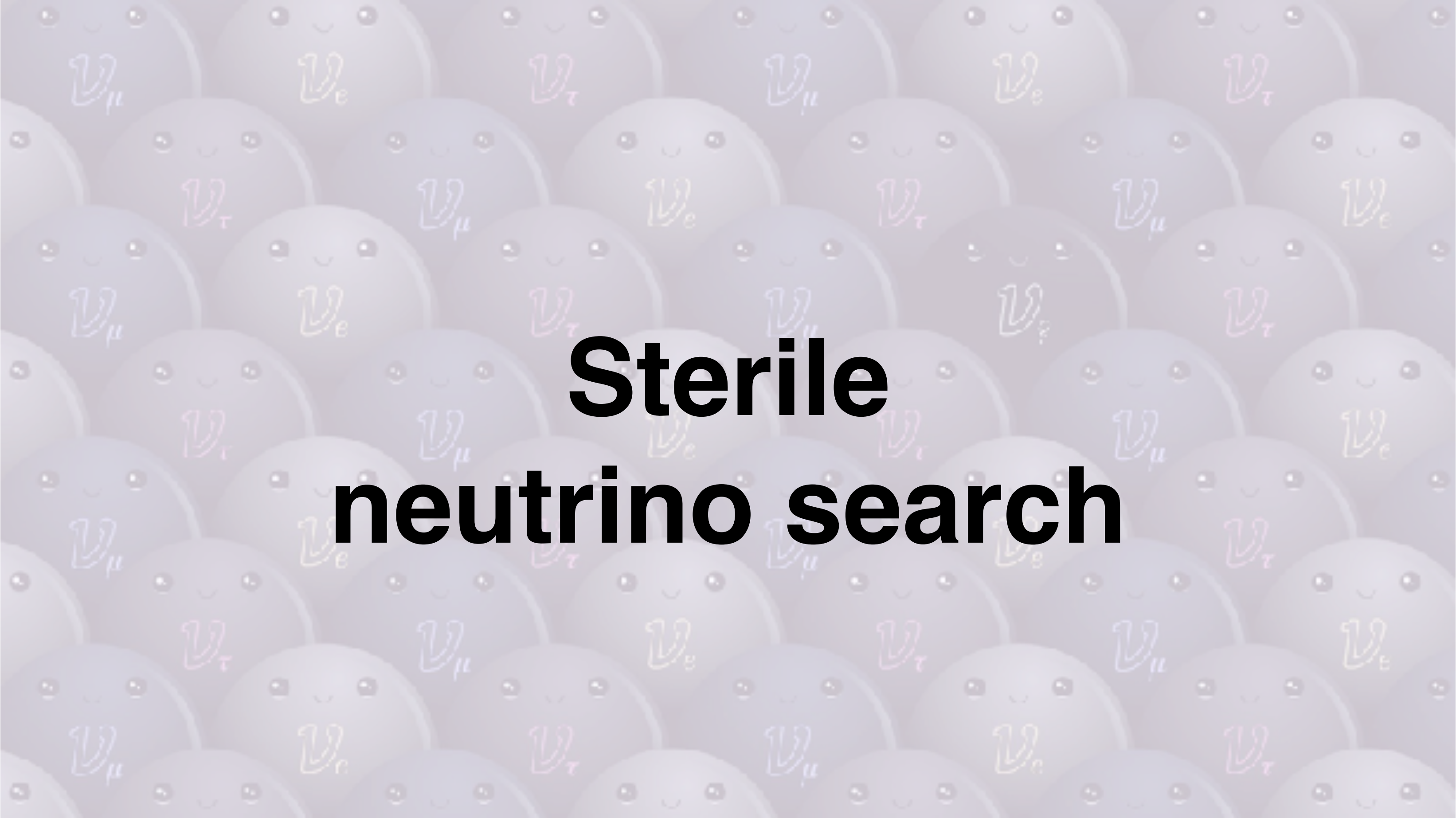
Queen Mary
University of London

Neutrino oscillation analyses (and much more) at the NOvA experiment

Dr Linda Cremonesi

University of Warwick Seminar
17th November 2022

Outline



All images produced by Sandbox Studio, Chicago

Sandbox Studio, Chicago

Neutrinos

Blink 182 - All the small things

Neutrinos

Extremely small mass

1 million times smaller than an electron

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Very abundant

~65 billion neutrinos going through your thumb every second

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Interact only via the weak force

In your lifetime you will on average interact with 1 neutrino

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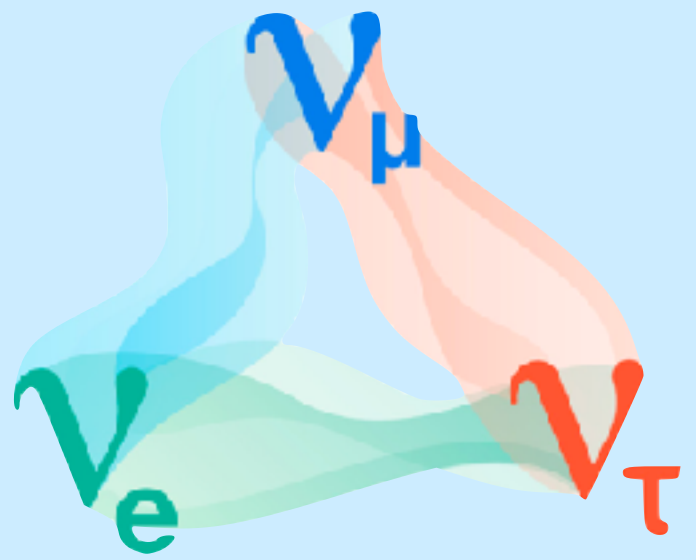
Change flavour when they propagate



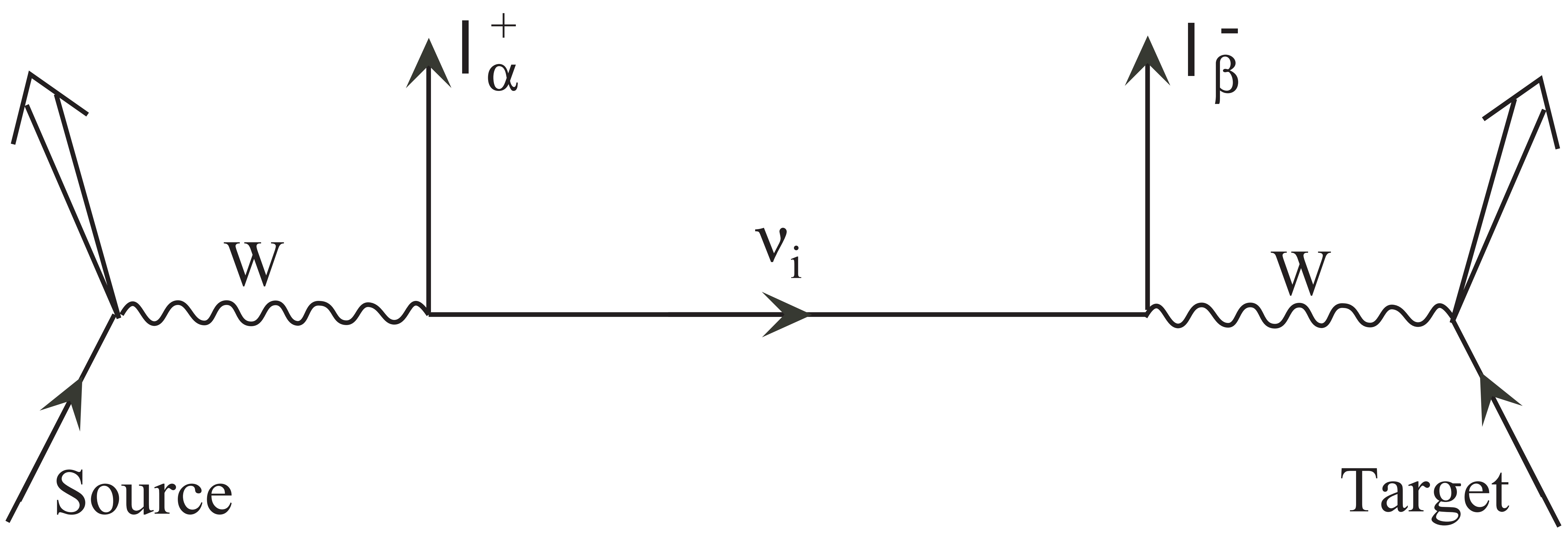
Neutrino flavour oscillations

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

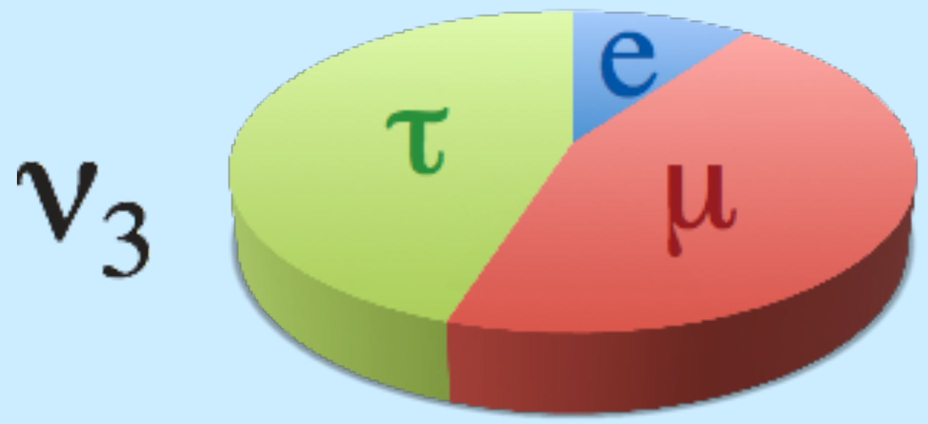
δ : CP-violating phase
α, β : Majorana phases

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

New symmetry?

How much do neutrinos mix?



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

Big questions

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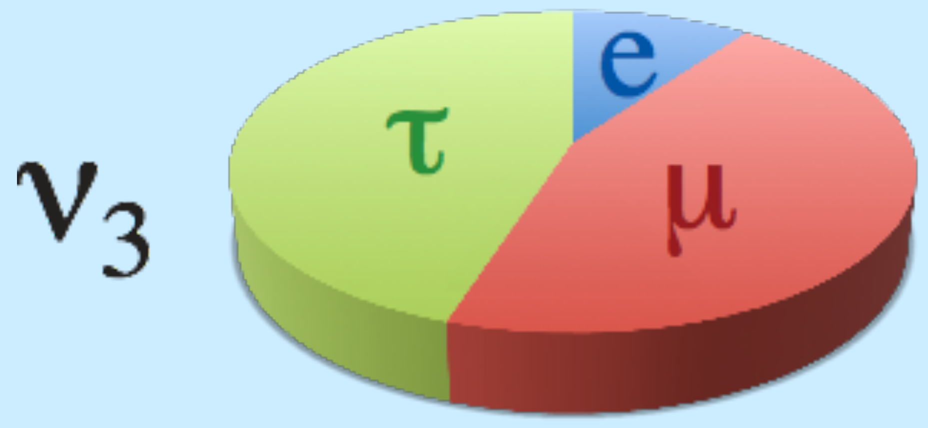

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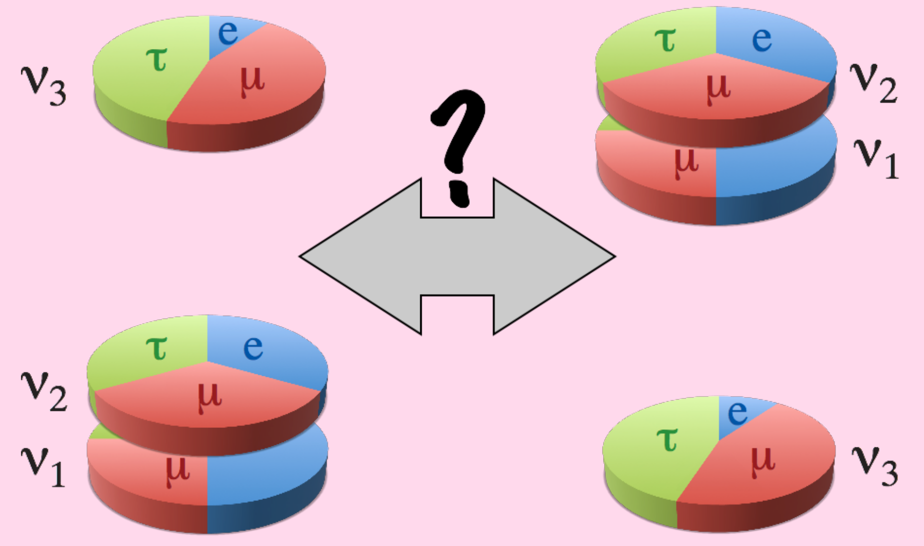
Majorana?

Which is the lightest neutrino?

Grand Unified Theories



Normal Ordering

Inverted Ordering

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

Big questions

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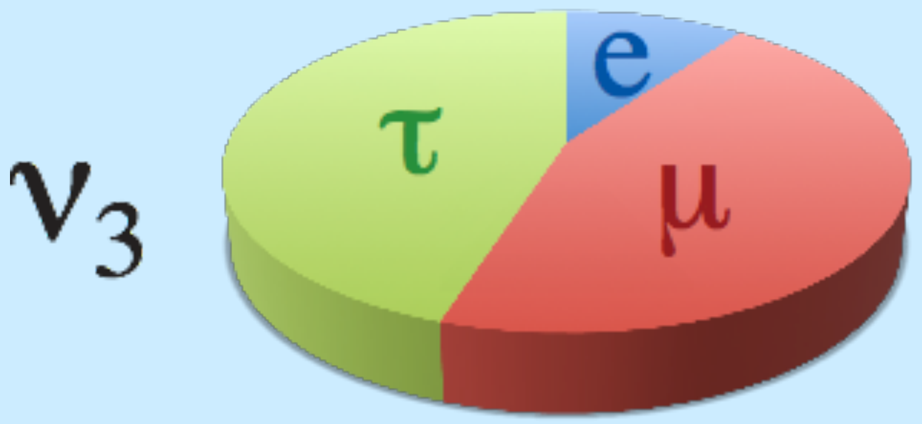

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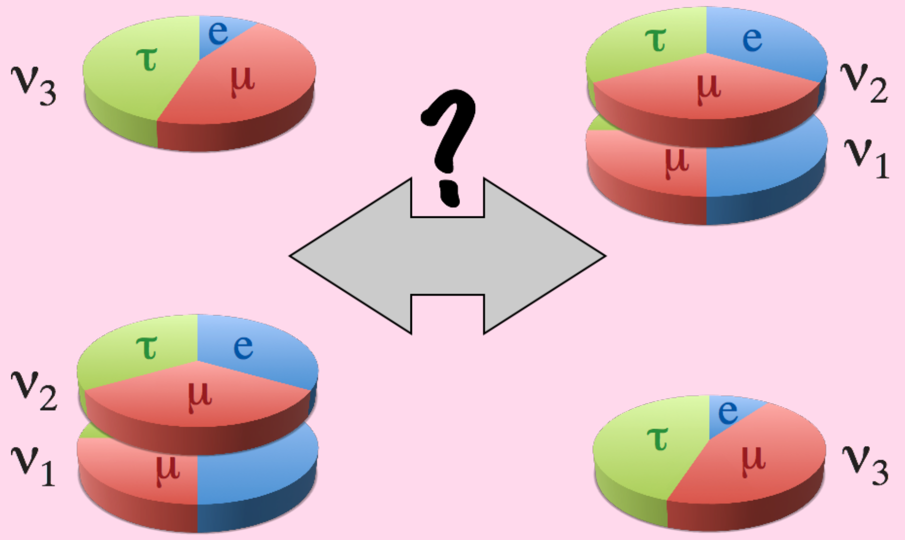
Grand Unified Theories



Normal Ordering

Inverted Ordering

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

Do neutrinos and antineutrinos oscillate in the same way?

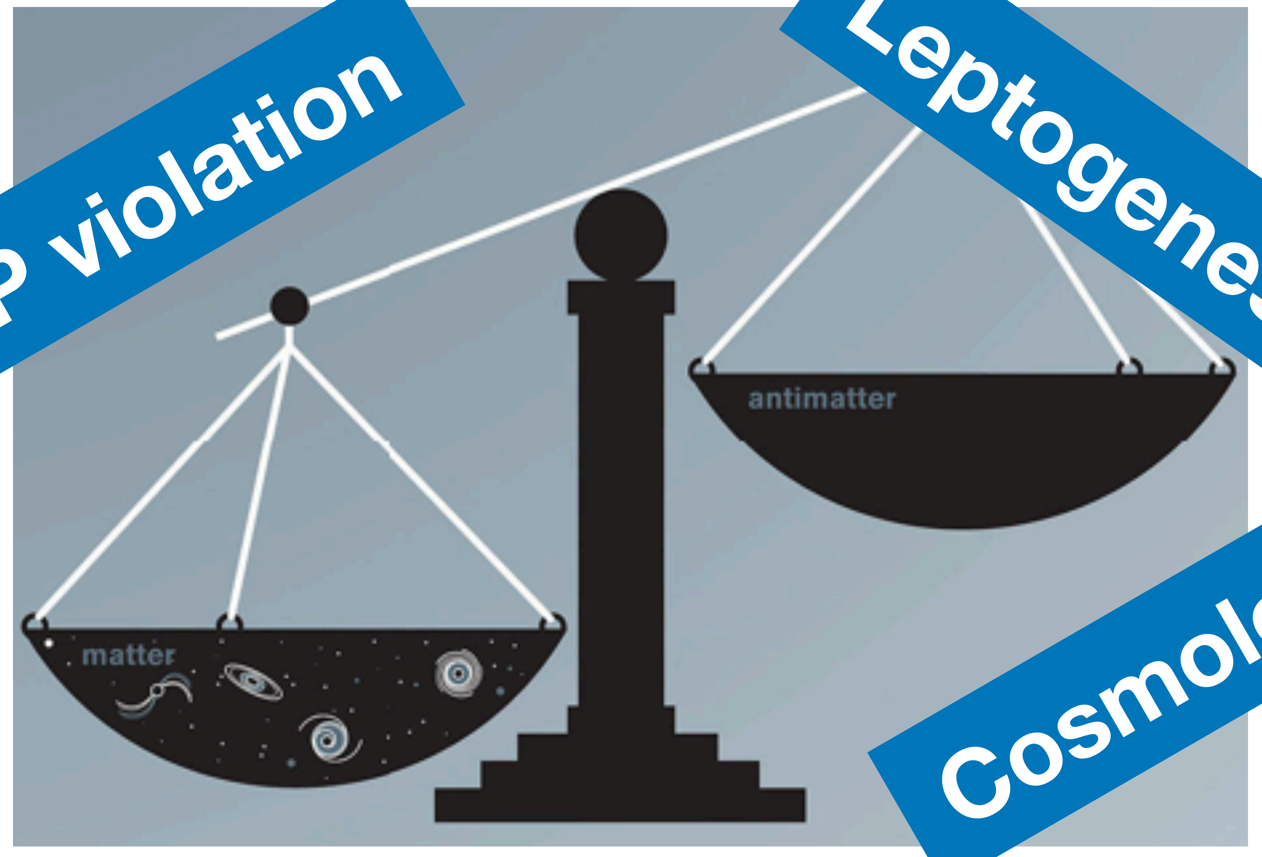
Jargon alert: is $\delta_{CP} \neq 0$?

?

CP violation

Leptogenesis

Cosmology



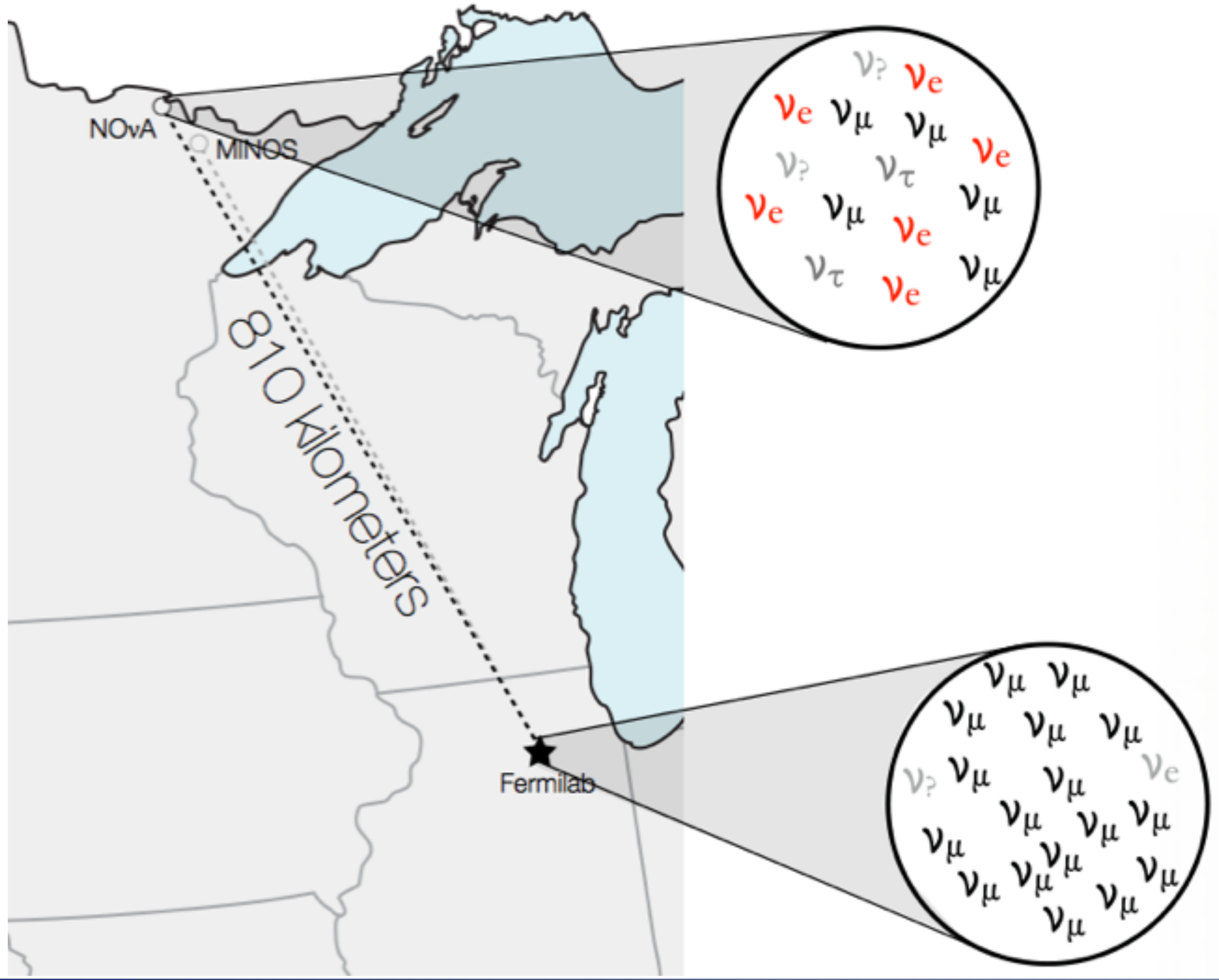
NOvA

The Proclaimers - I'm gonna be

266 scientists and engineers from 48 institutions in eight countries.

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.



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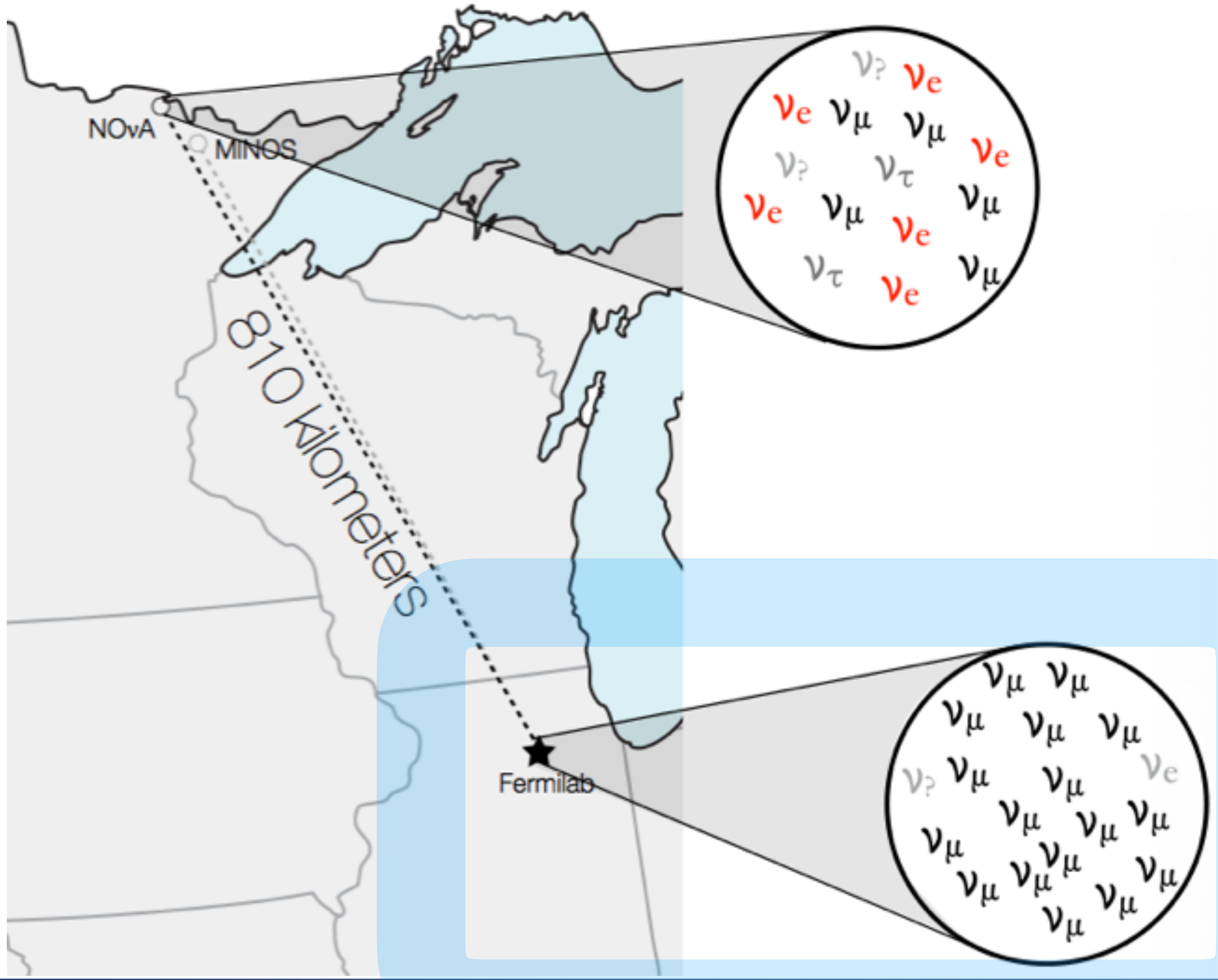
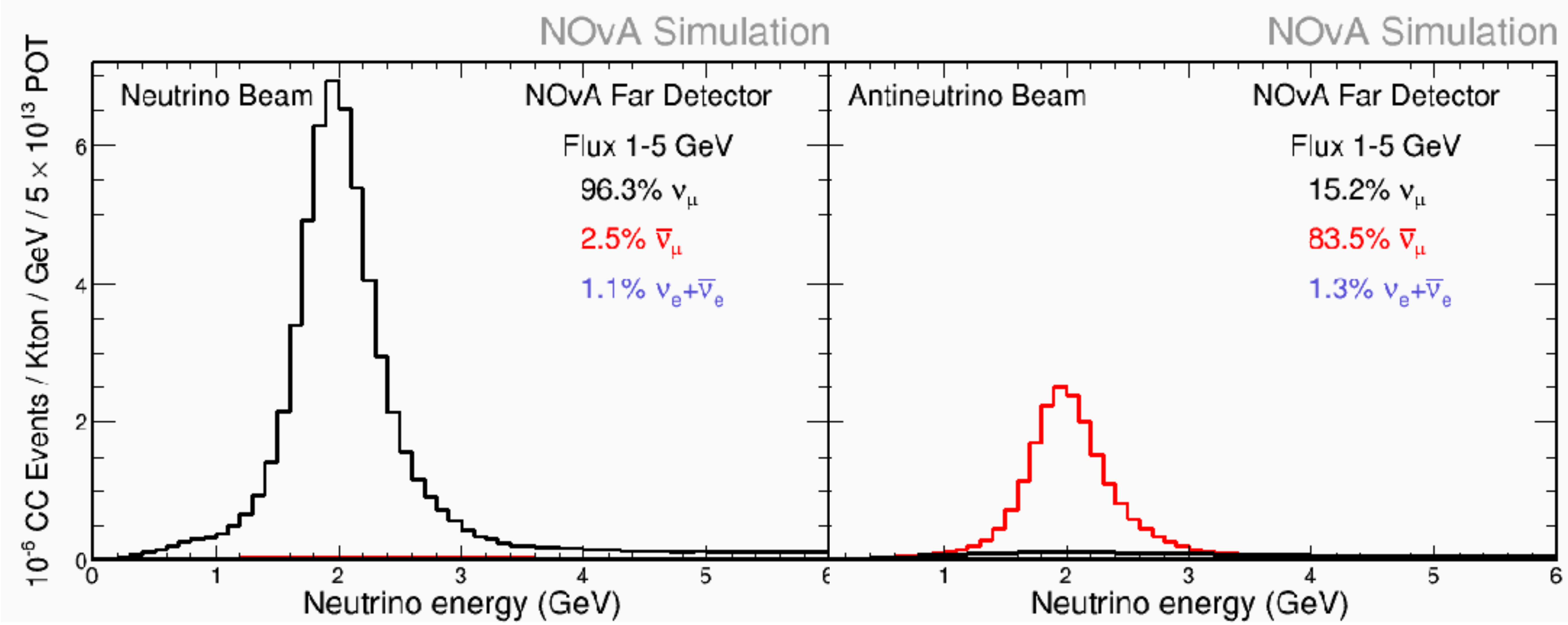
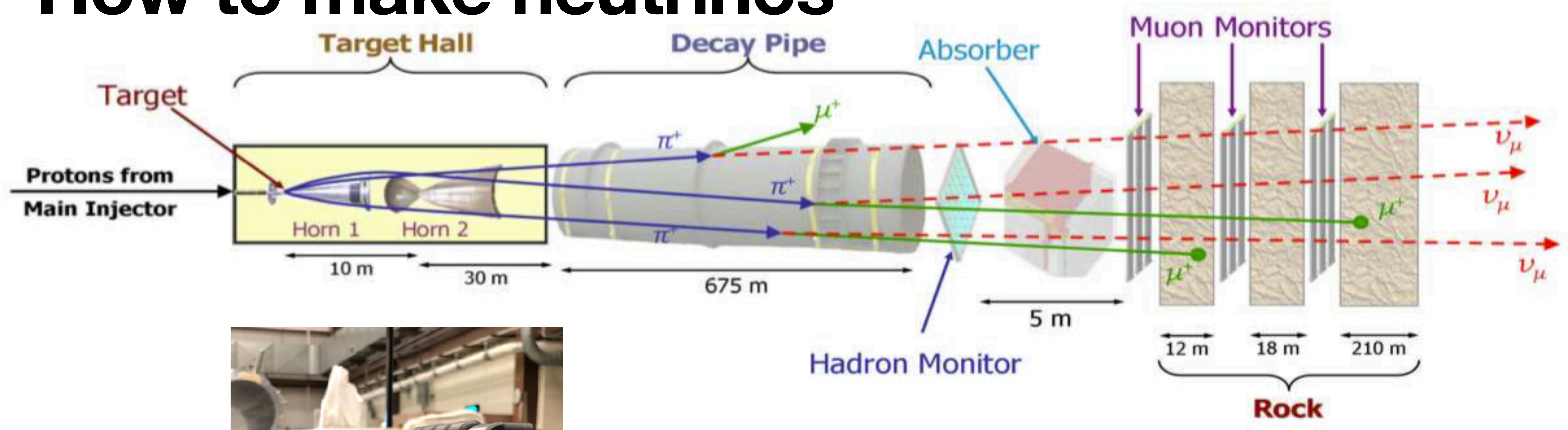


- High neutrino flux at Near Detector:
  - used as control for the oscillation analyses,
  - provides a rich data set for measuring cross sections.
- ND located 1km from the NuMI beam target.



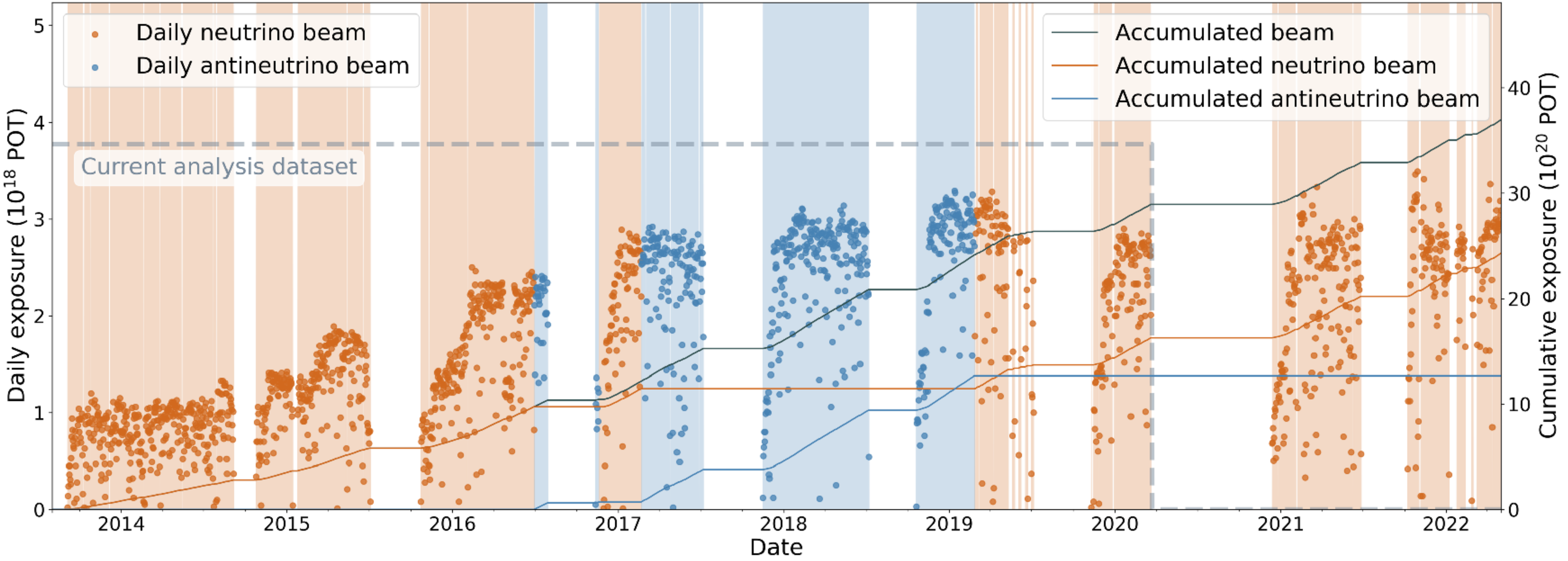
How to make neutrinos




MW-capable target

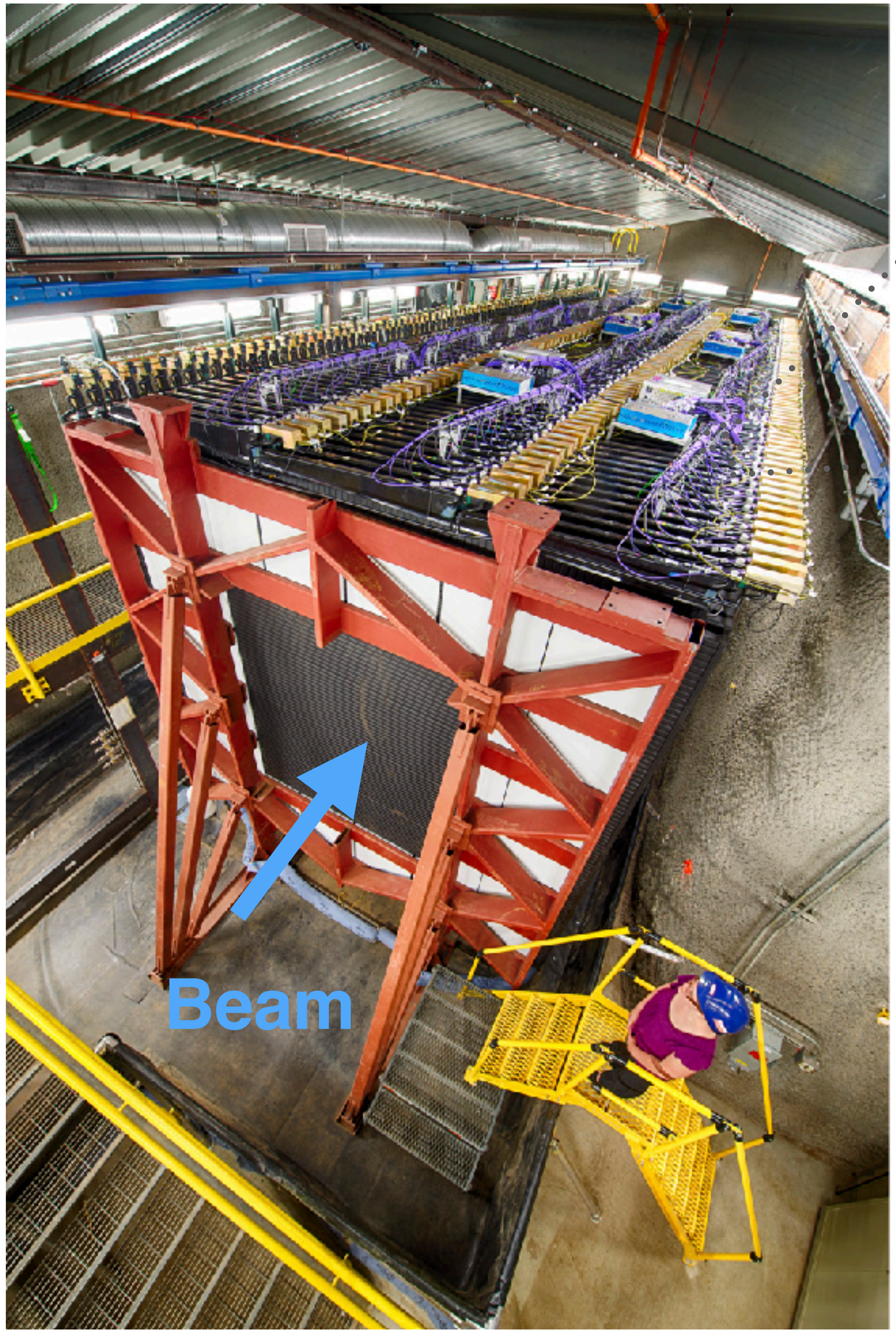

MW-capable horn

NOvA exposure to NuMI beam

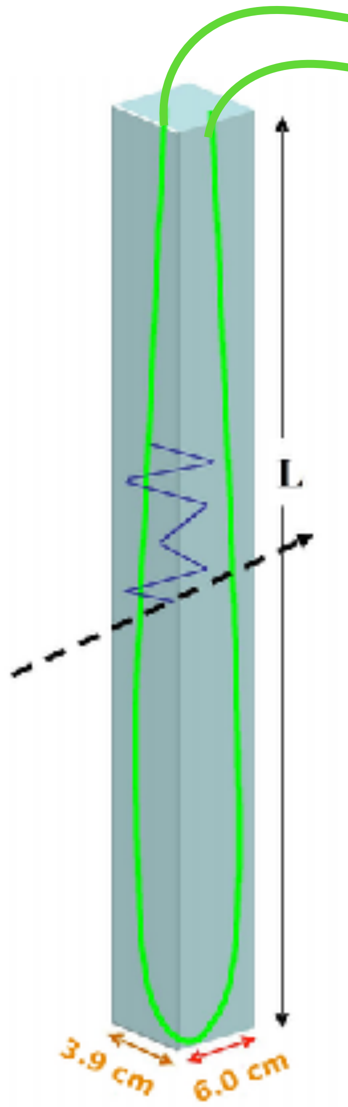


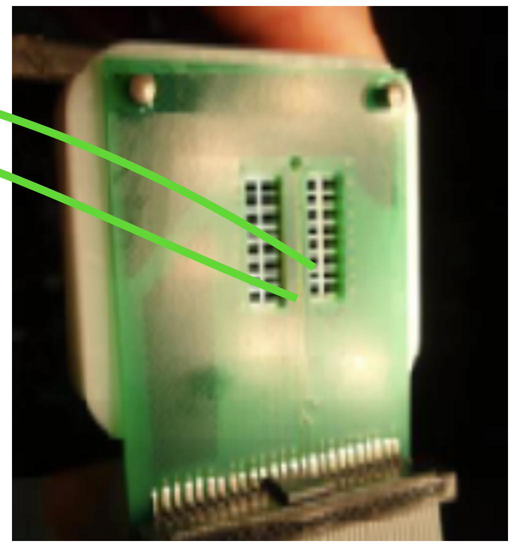
- NuMI running at ~750kW since 2019. NuMI power record of 893 kW.
- Total protons-on-target: 37 x 10^{20}

NOvA Detectors

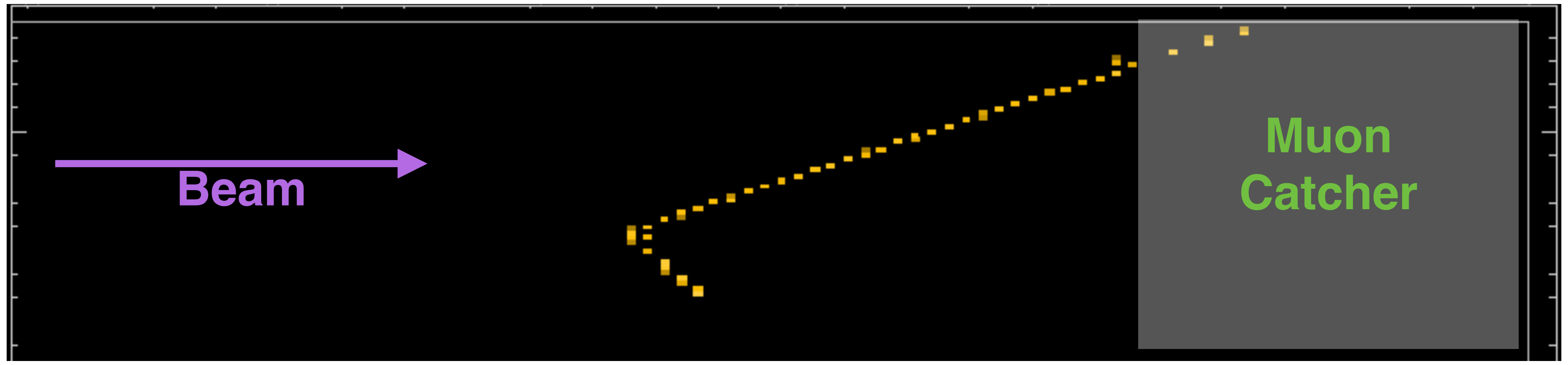


Alternating planes allow for 3D reconstruction





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

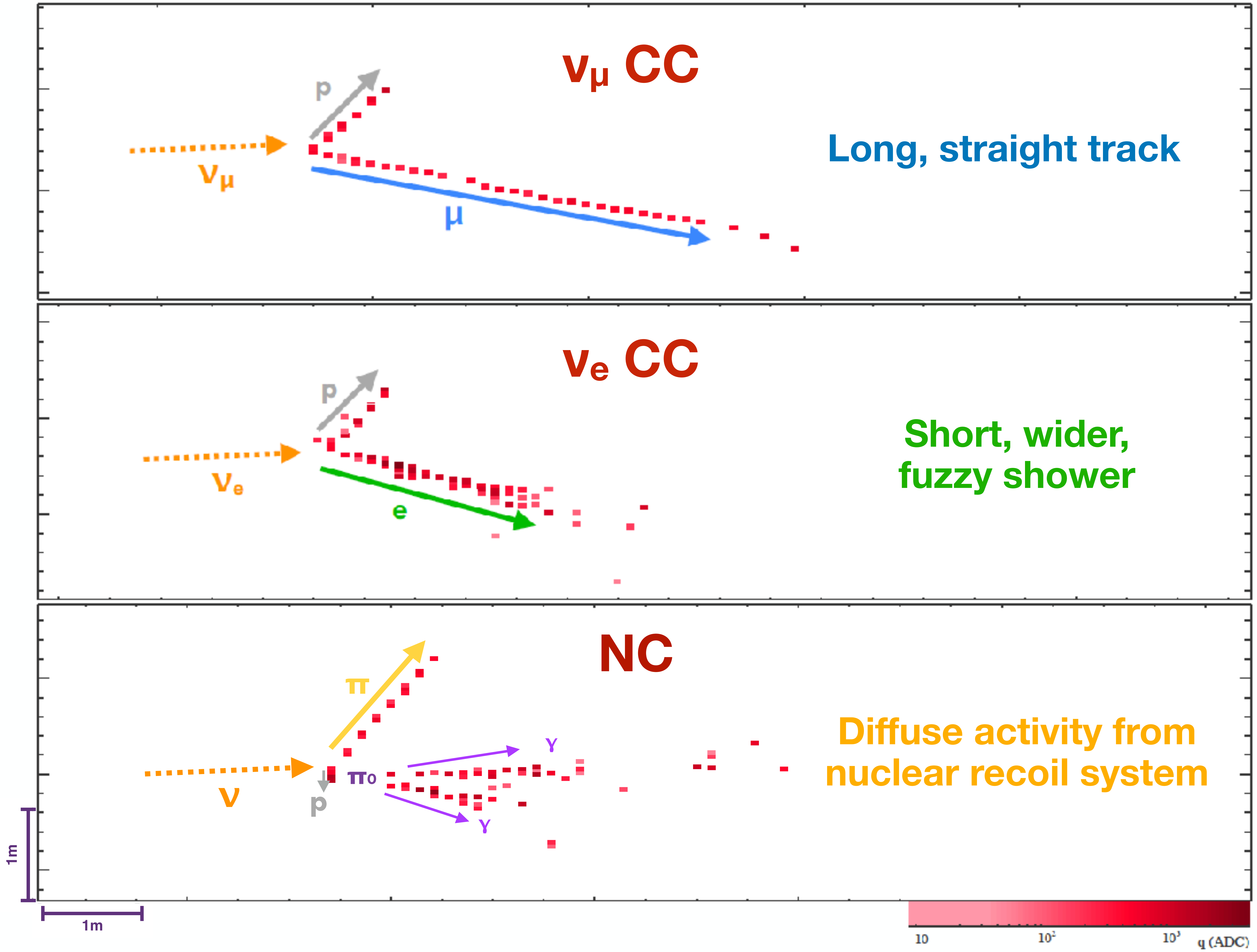


- Tracking calorimeter
- Extruded plastic cells, filled with liquid scintillator
- 0.17 X_0 per layer
- Near detector:
  - 300 tons, 1km from the target
  - Huge statistics: >1M ν_μ CC selected events

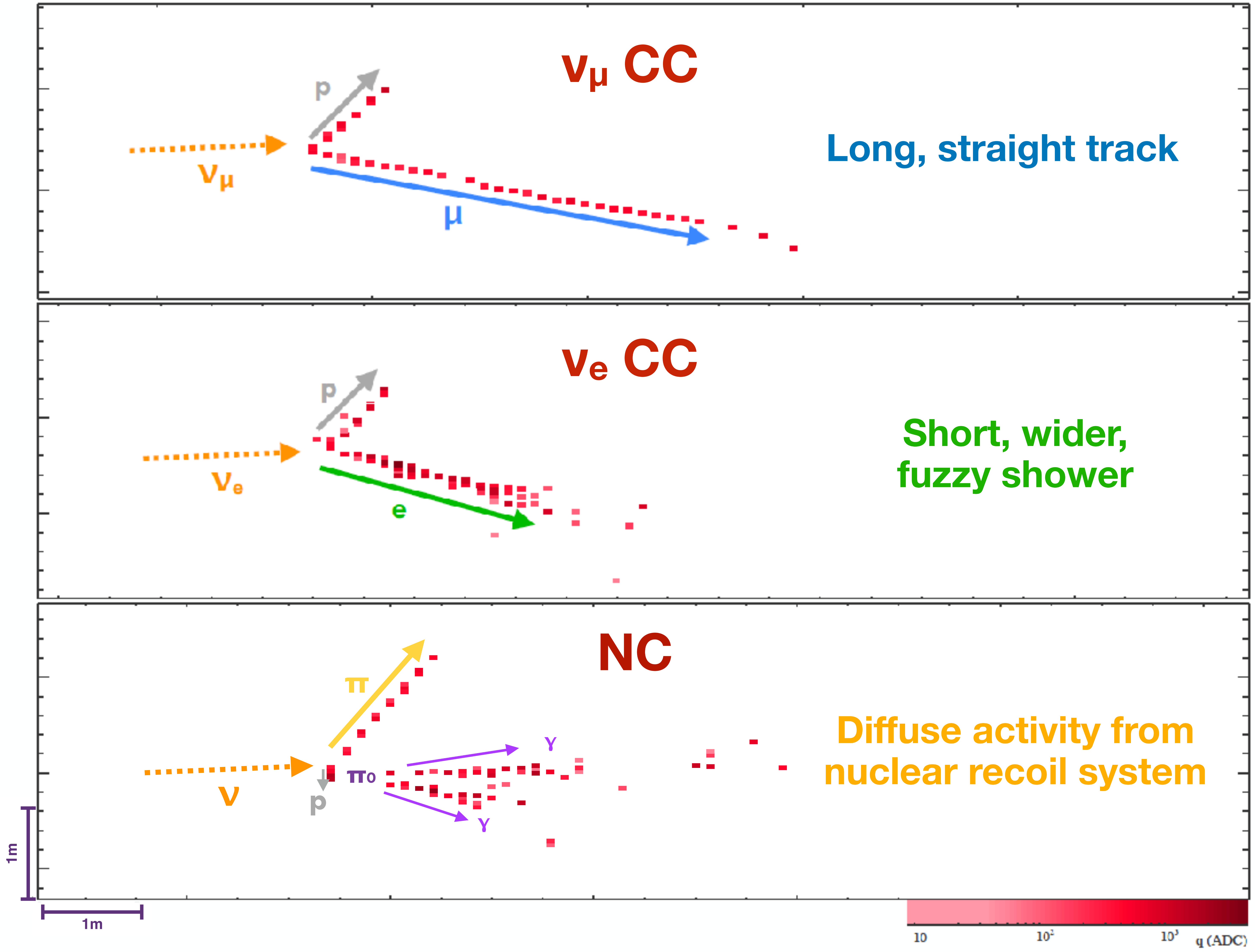
14,000 ton Far Detector

14,000 ton Far Detector

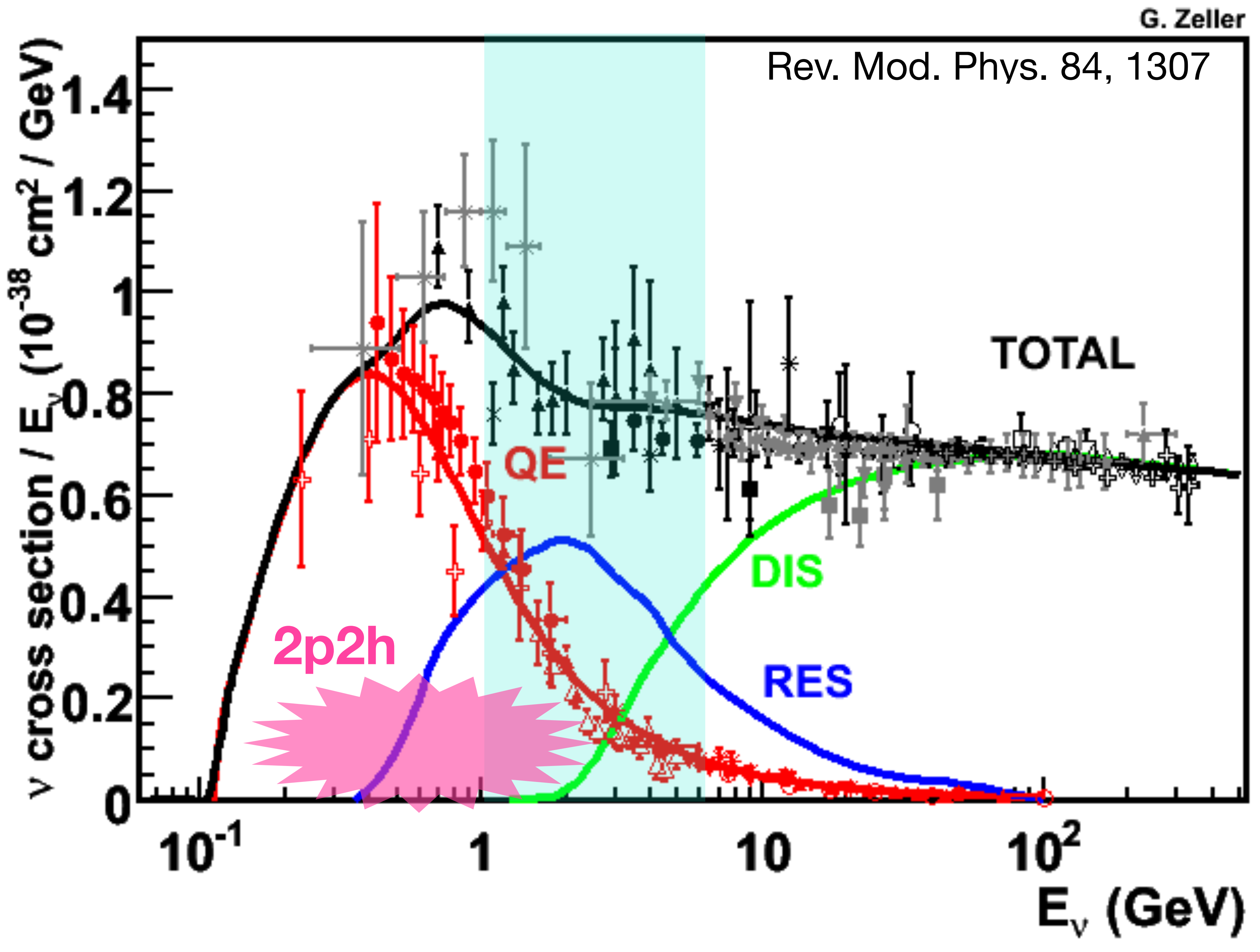
Detailed event images

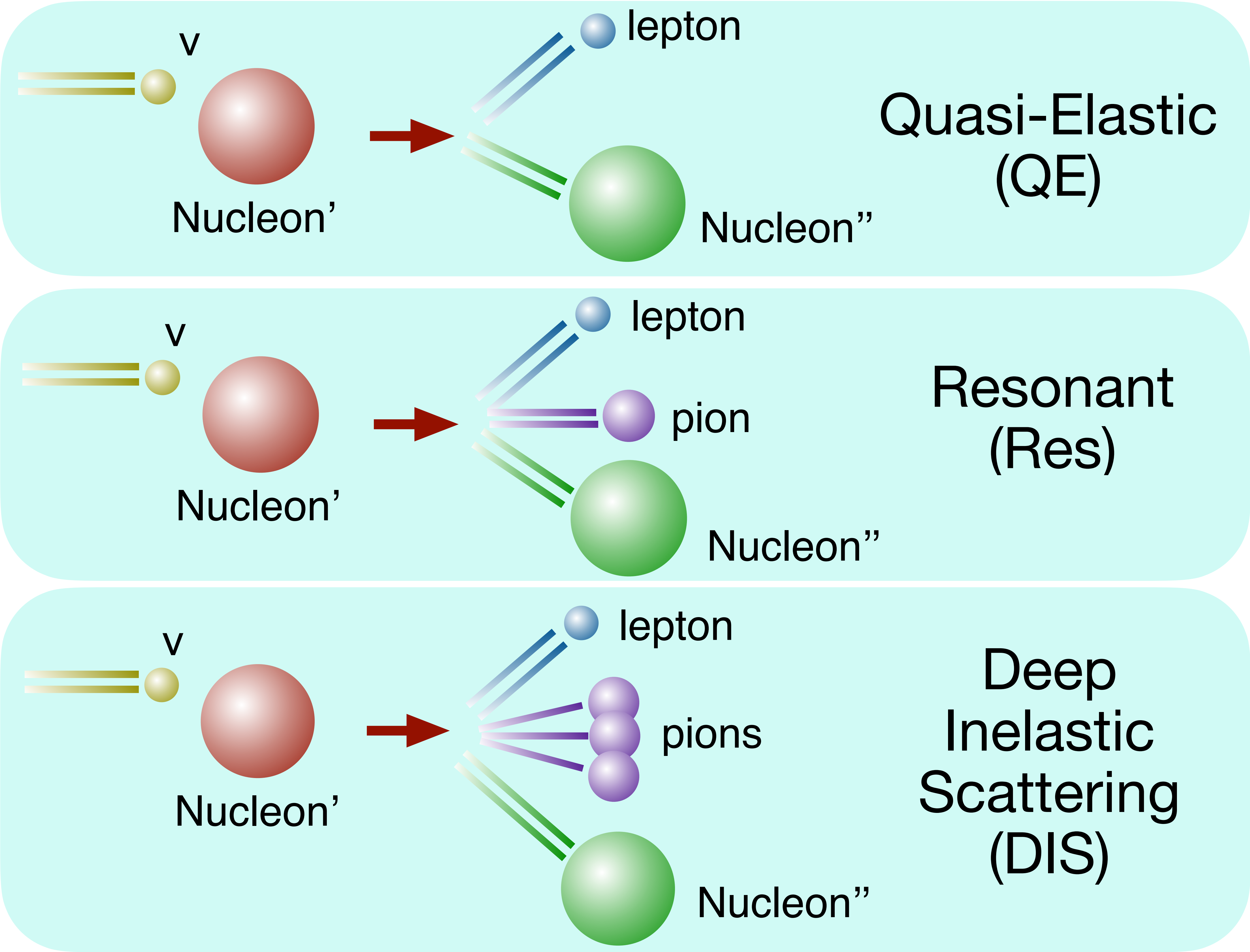


Detailed event images



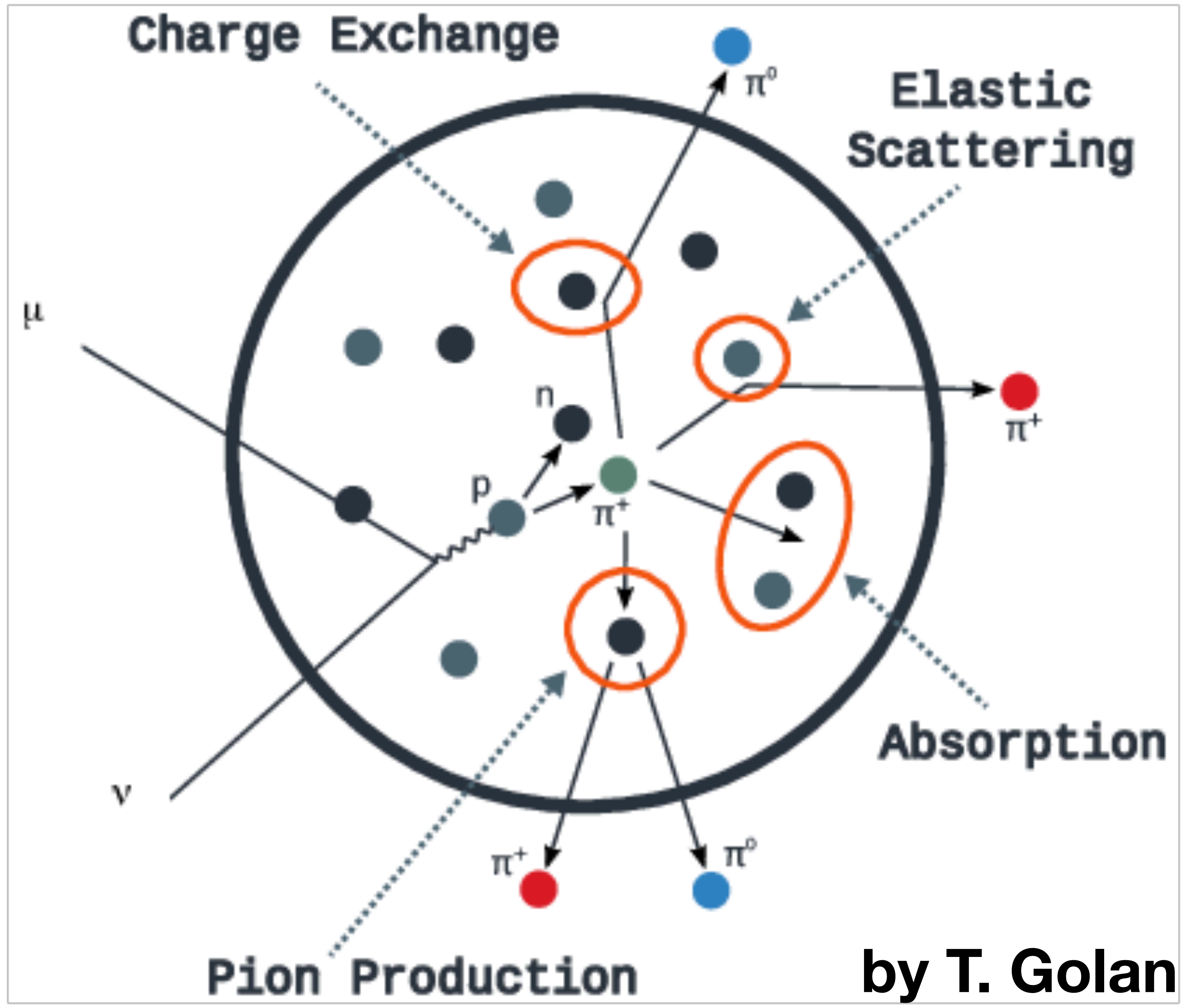
Neutrino CC interactions at NOvA

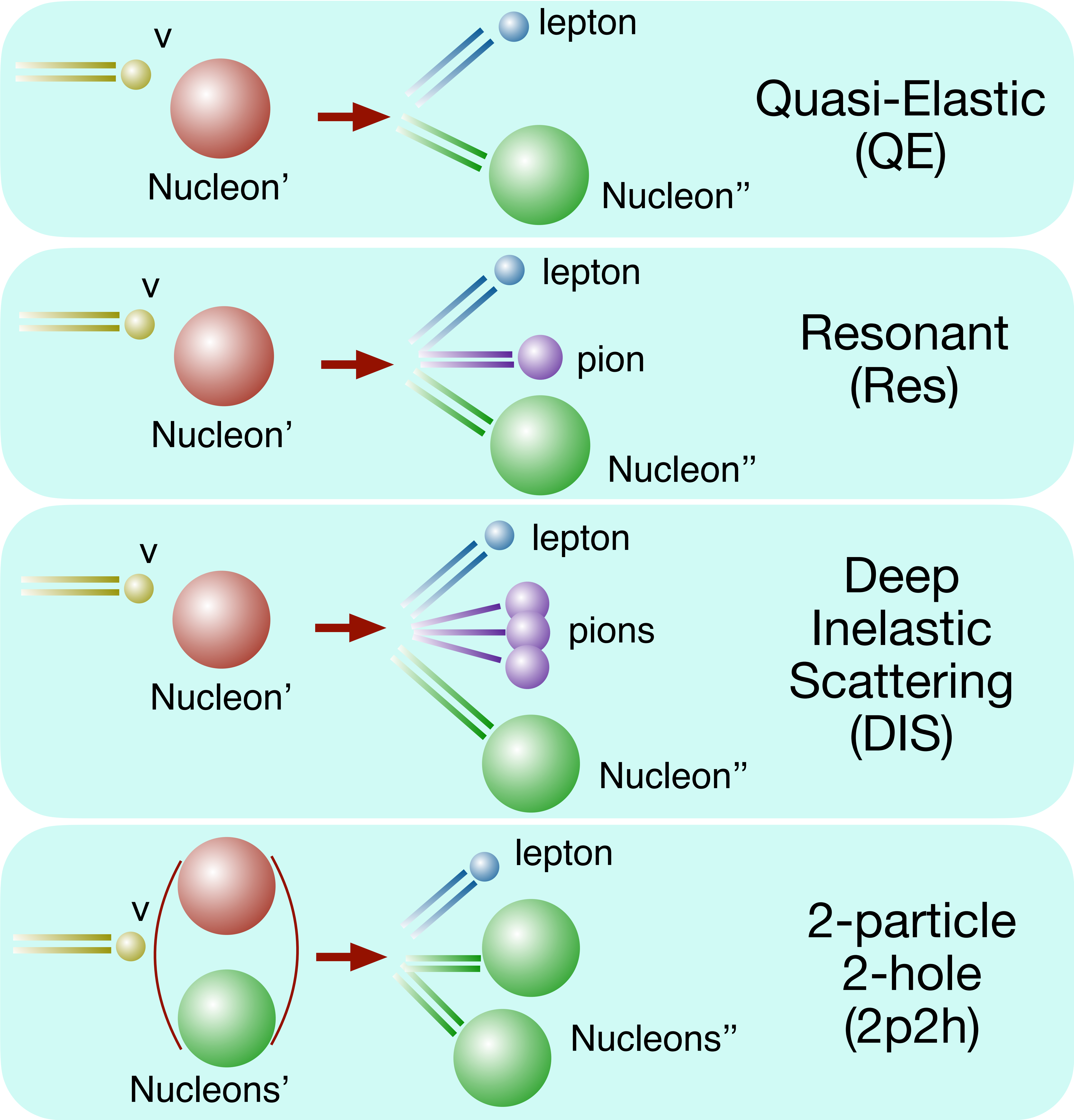




- NOvA flux peaks between 1 and 5 GeV: it sits in the transition region between different neutrino interaction processes.

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

Neutrino interactions

How to measure neutrino oscillations

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

Oscillated Neutrinos

How to measure neutrino oscillations

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

Oscillated Neutrinos

Neutrino flux

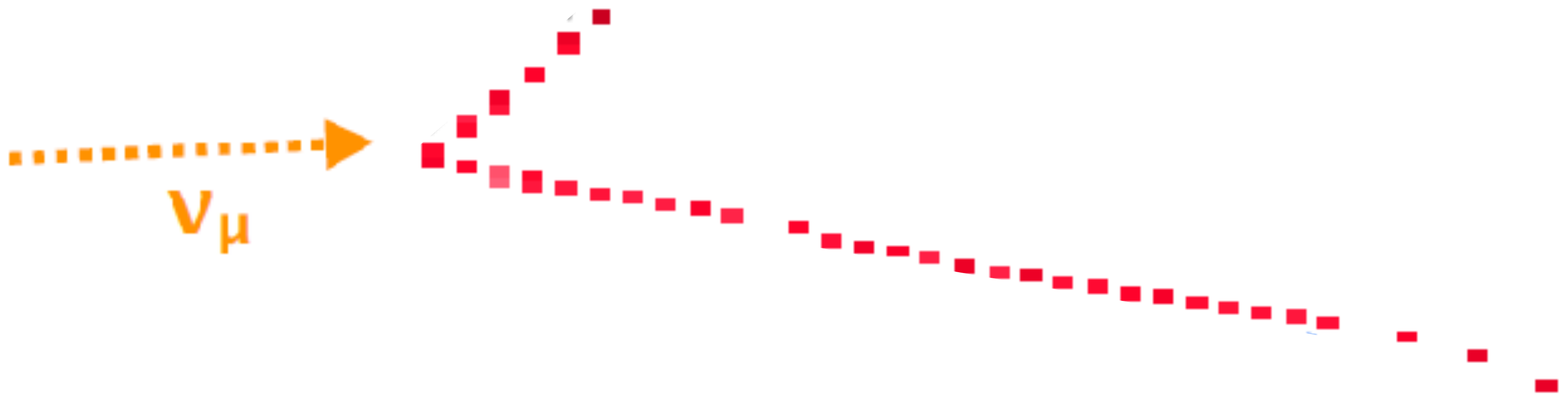
How to measure neutrino oscillations

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

Oscillated Neutrinos

Neutrino flux

Neutrino interactions



How to measure neutrino oscillations

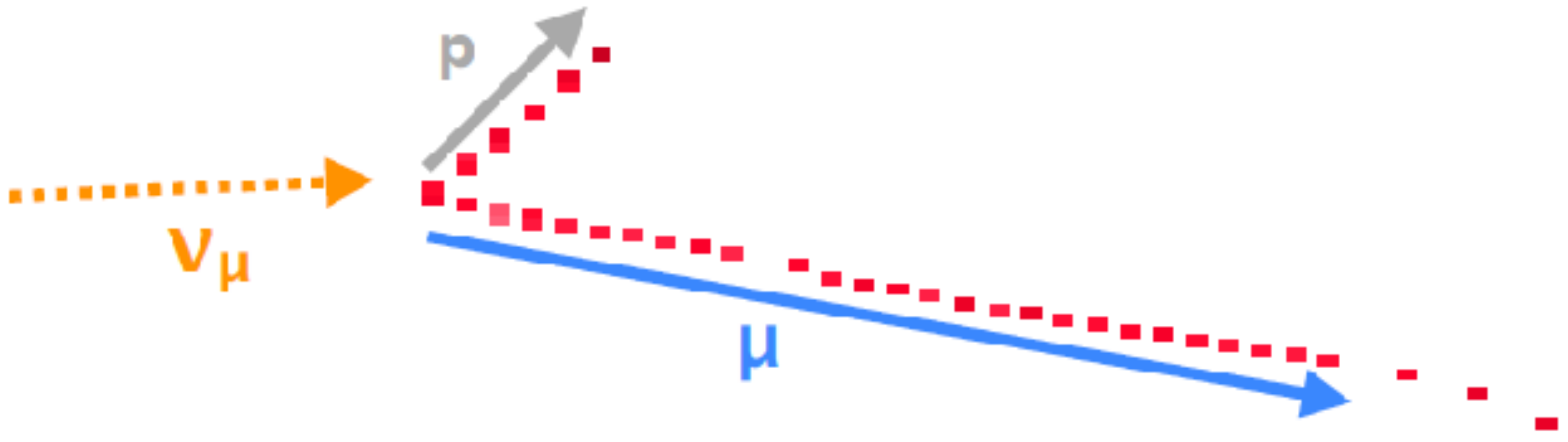
$$N \approx \Phi(E_\nu) \otimes \sigma(k, k') \otimes \epsilon \otimes P(\nu_\alpha \rightarrow \nu_\beta)$$

Oscillated Neutrinos

Neutrino flux

Neutrino interactions

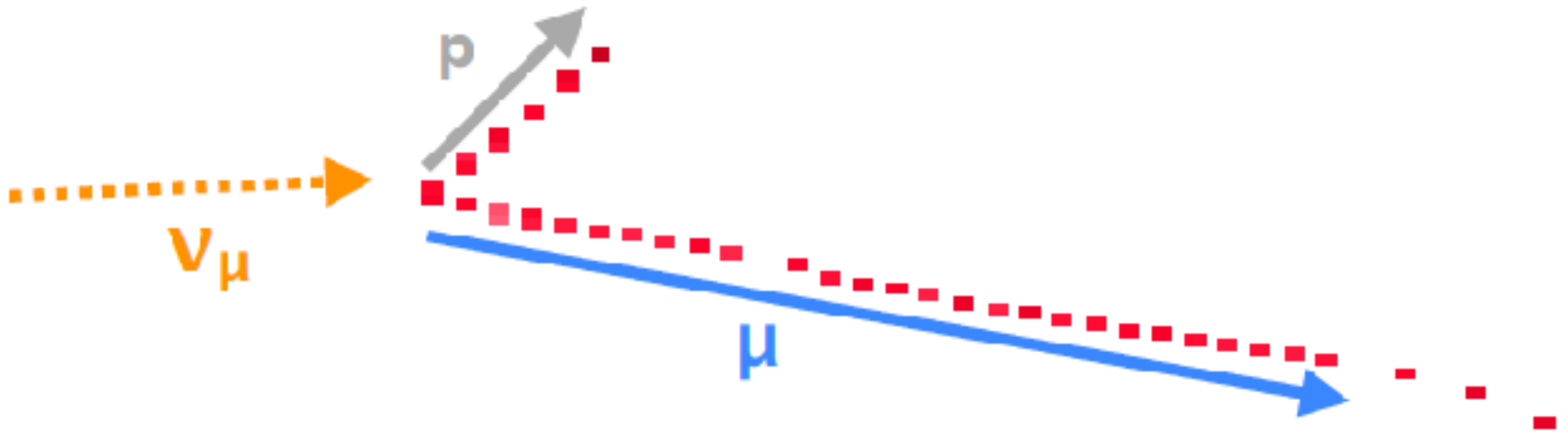
Detector response

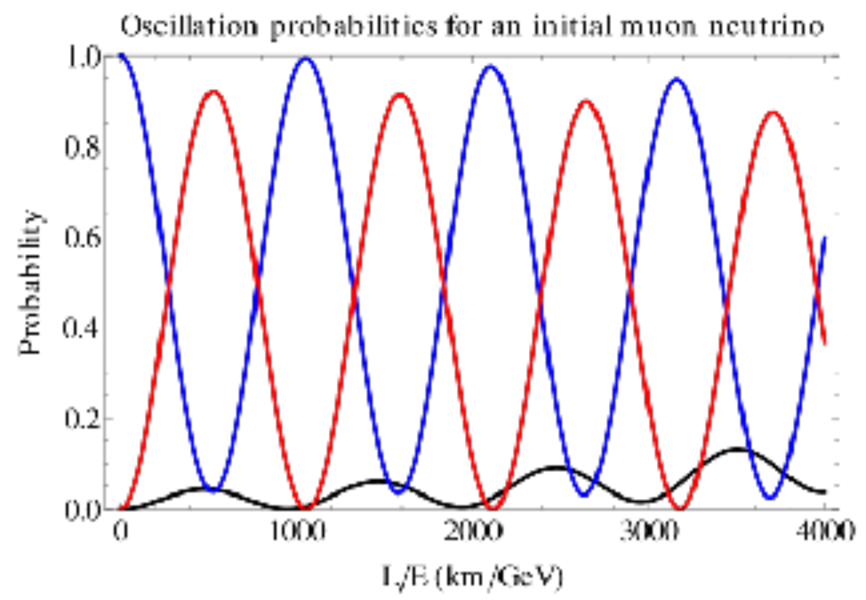


How to measure neutrino oscillations

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

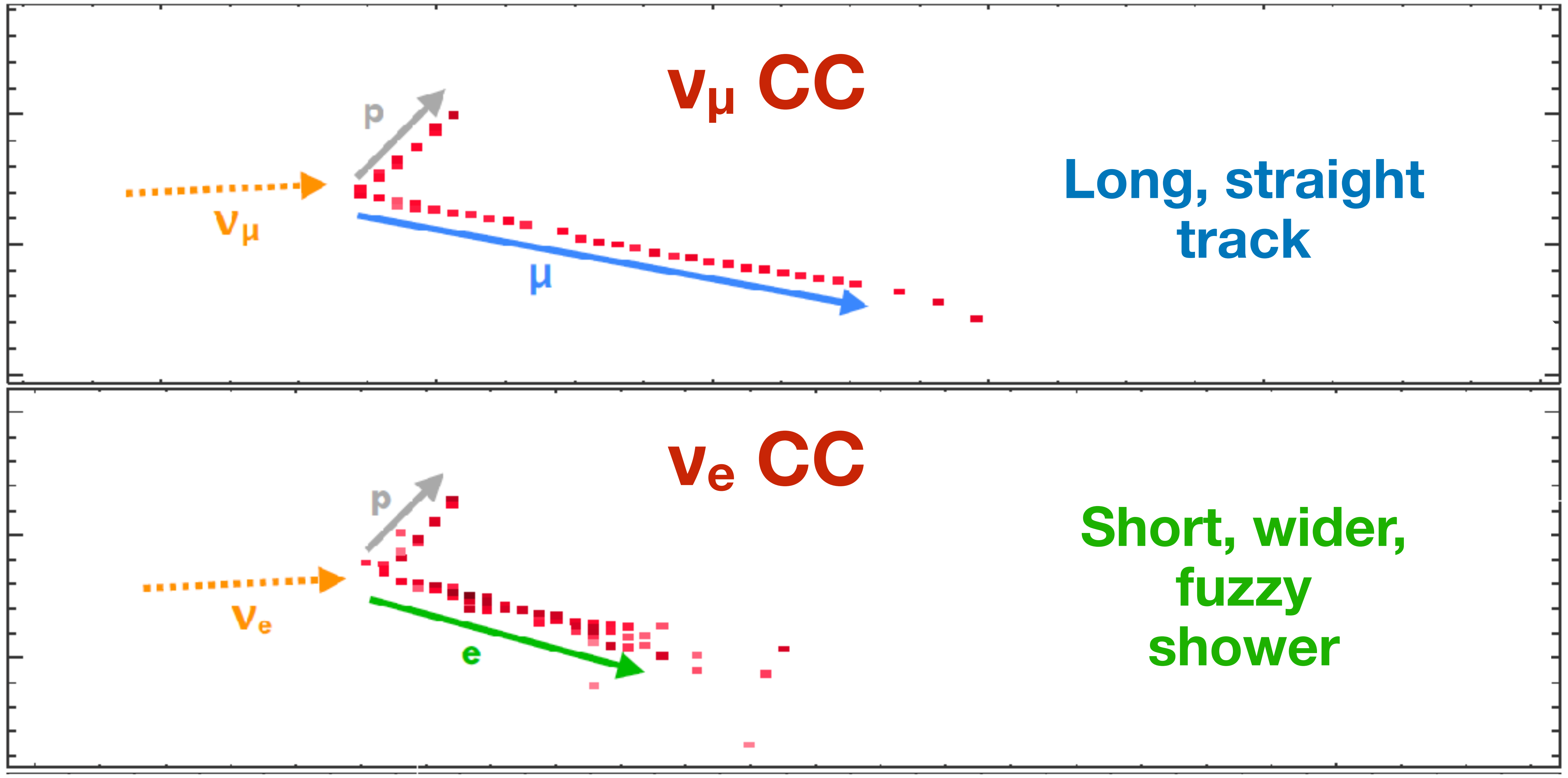
- N: Oscillated Neutrinos
- $\Phi(E_\nu)$: Neutrino flux
- $\sigma(k, k')$: Neutrino interactions
- ϵ: Detector response
- $P(\nu_\alpha \rightarrow \nu_\beta)$: Oscillation probability

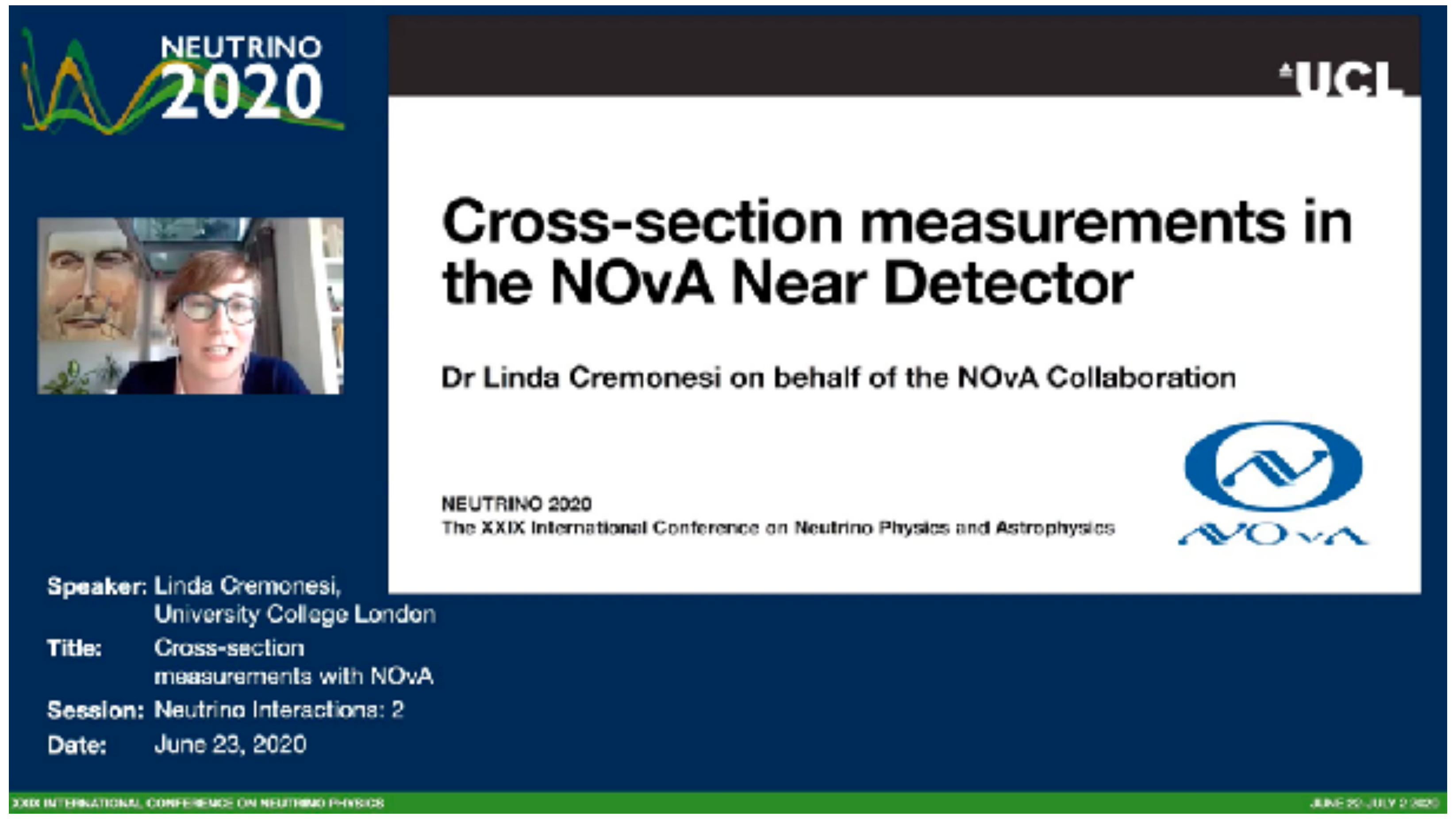




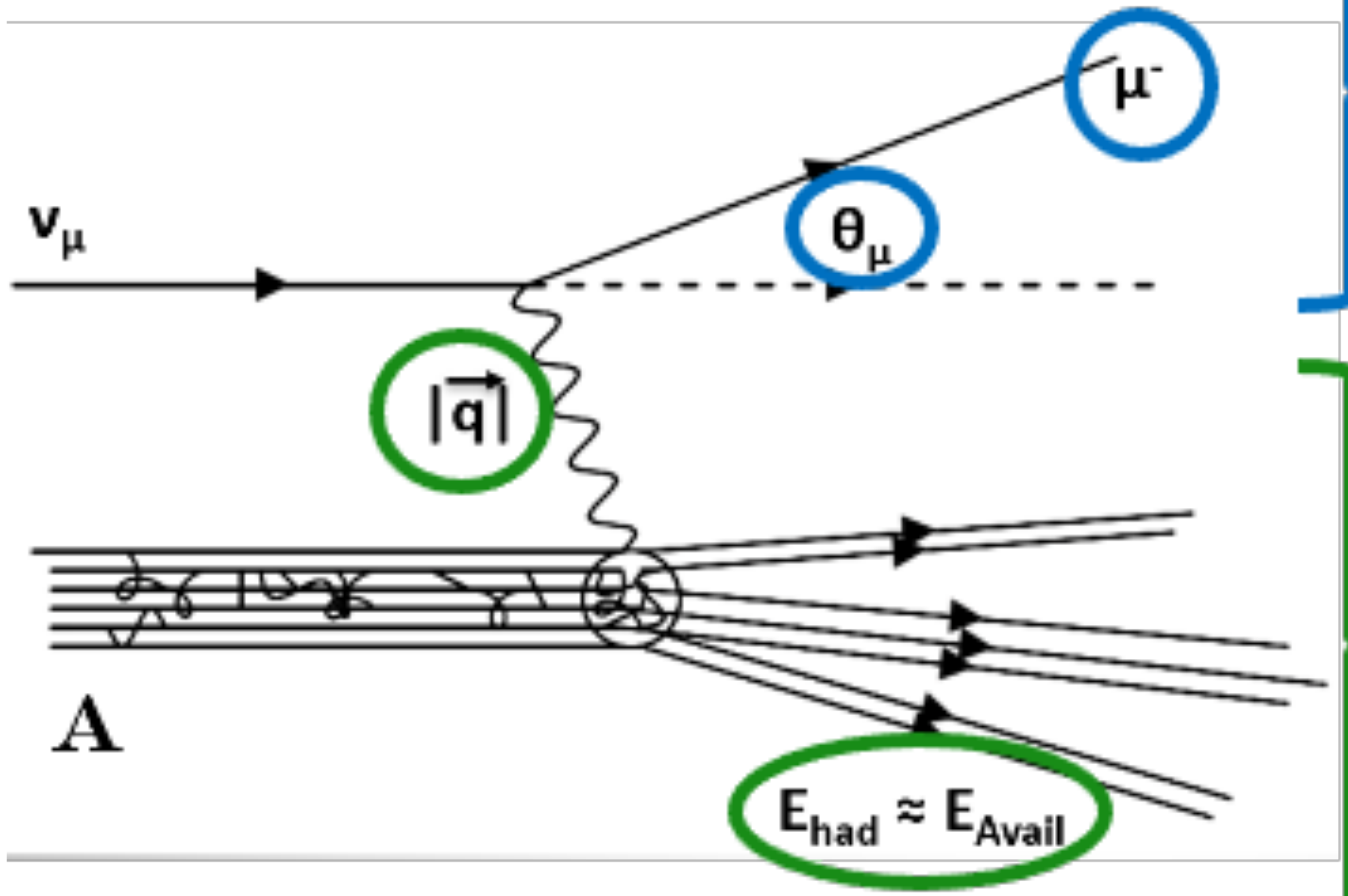
NOvA cross-section programme

- 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 in the next slide





Two new ν_μ double-differential results



Muon System ⇨ Energy vs angle

Exclusive
Select only events with low hadronic energy

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

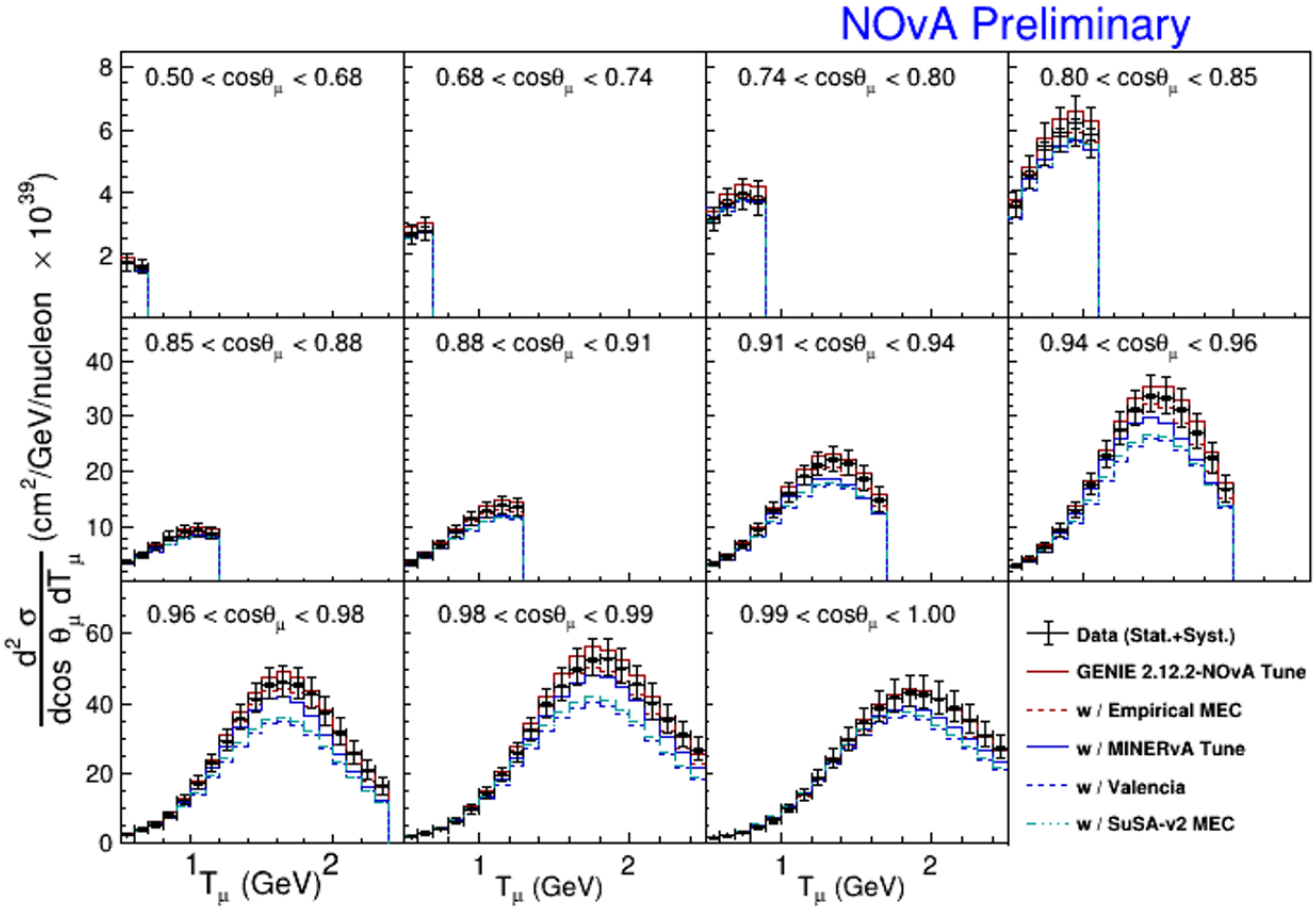
Inclusive
Select all ν_μ CC events

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)

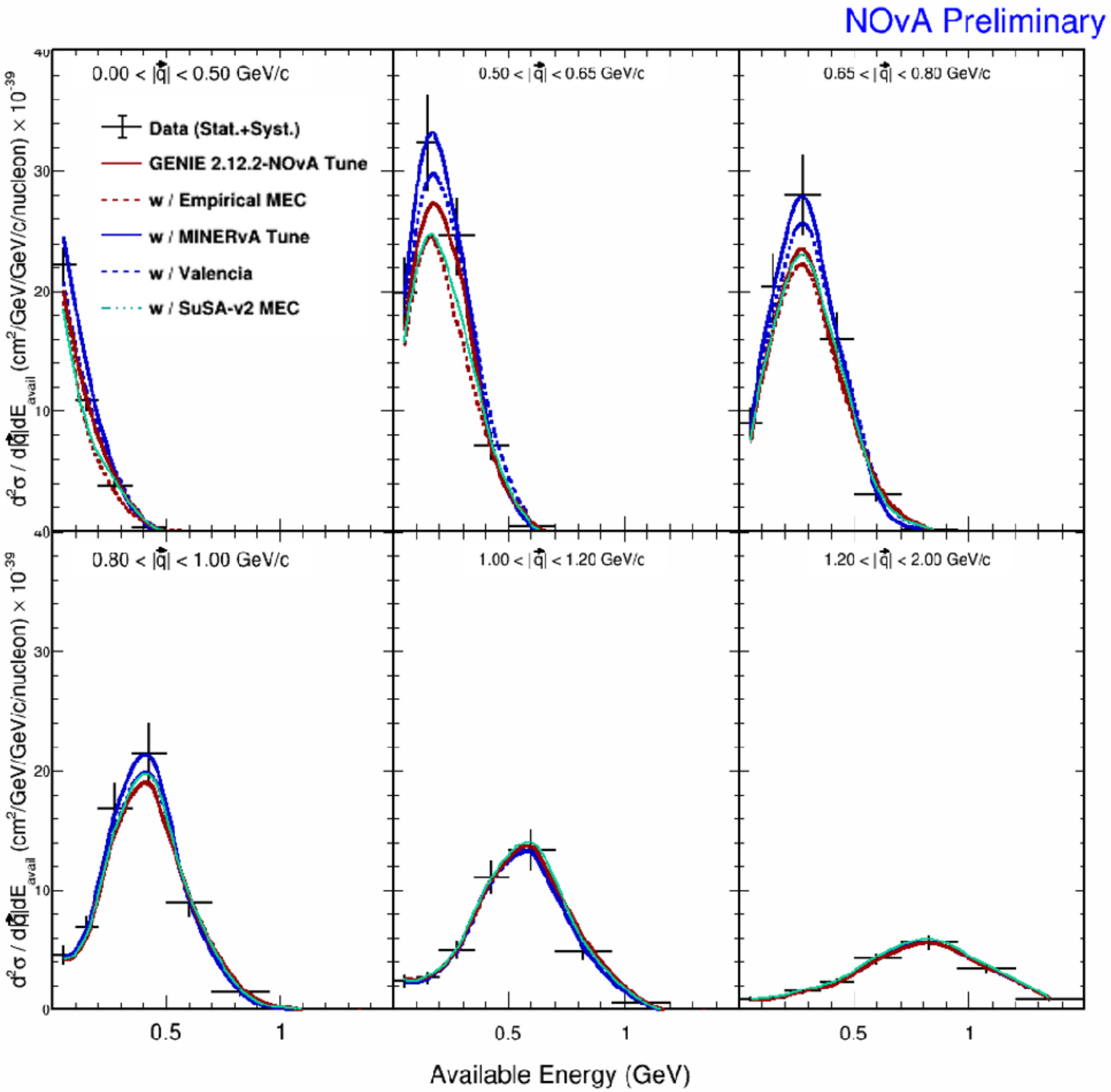


Hadronic System

ν_μ CC interactions:

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

Sandbox Studio, Chicago

Neutrino oscillations

David Bowie - Changes

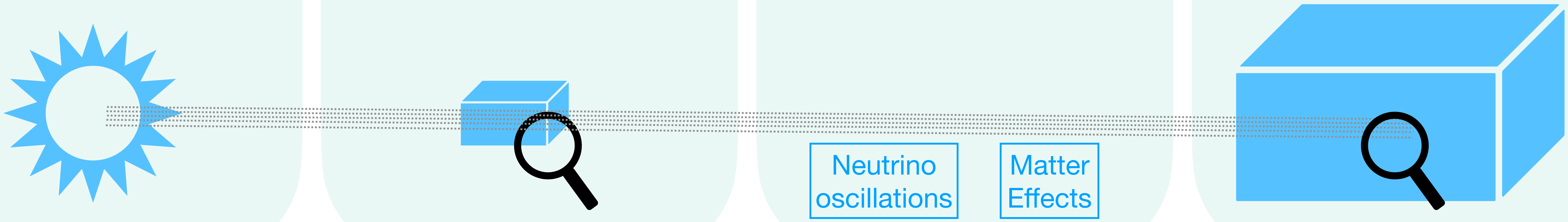
How most neutrino oscillations experiments work

Produce neutrinos

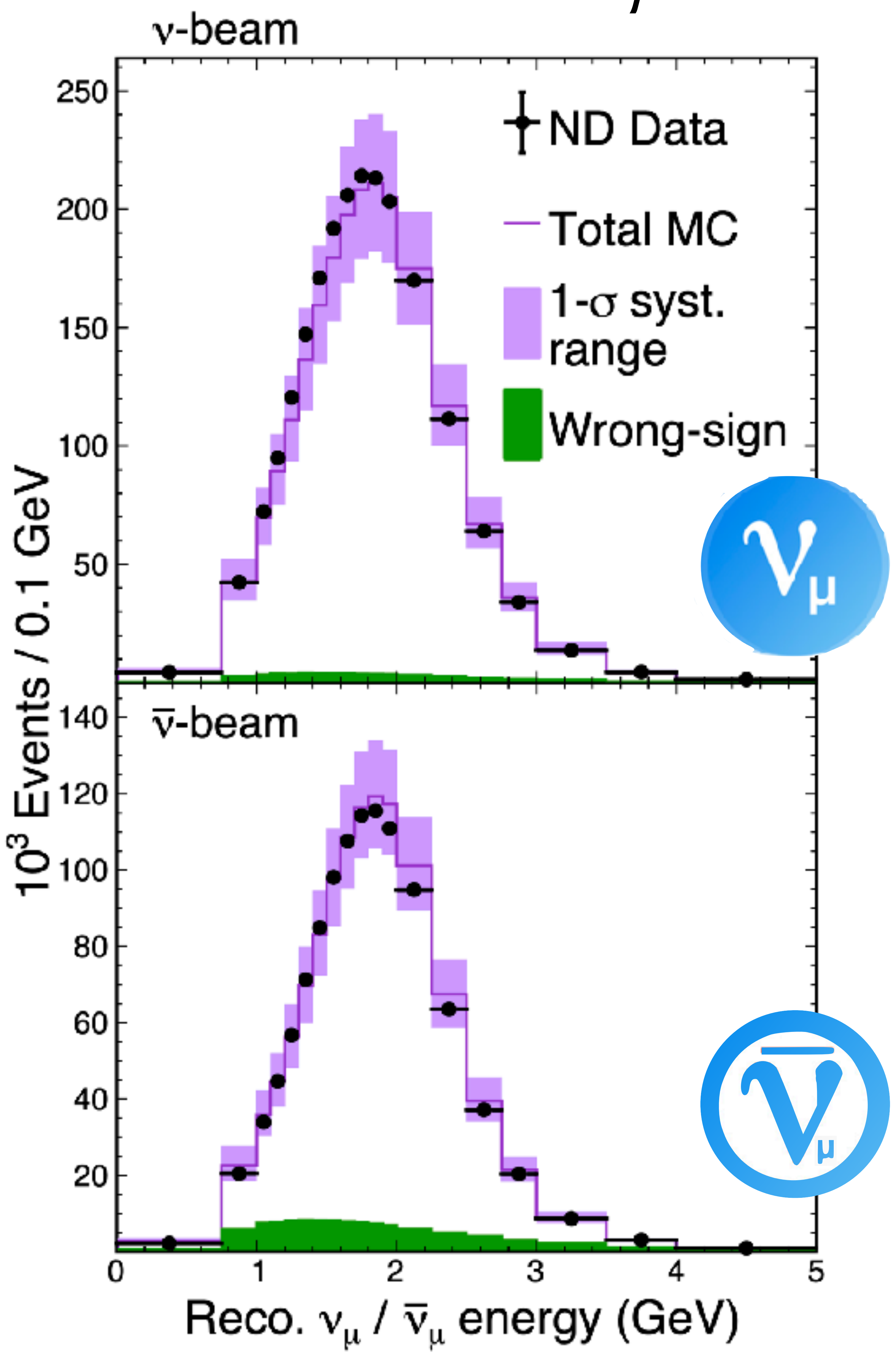
Check what you produced
[optional]

Propagate!
[a few km
to a few kpc]

Check what gets to the other side

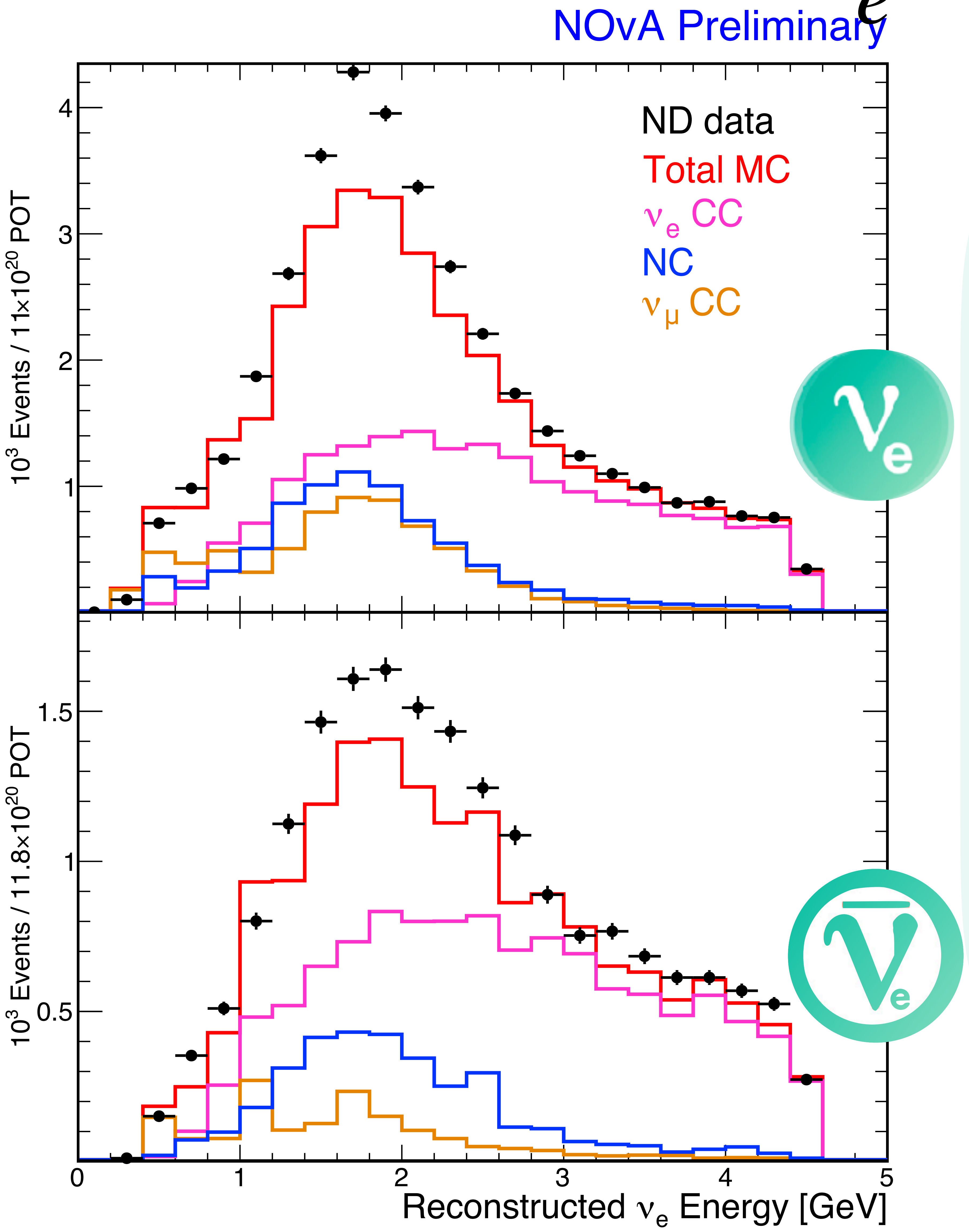


Near detector ν_μ spectra



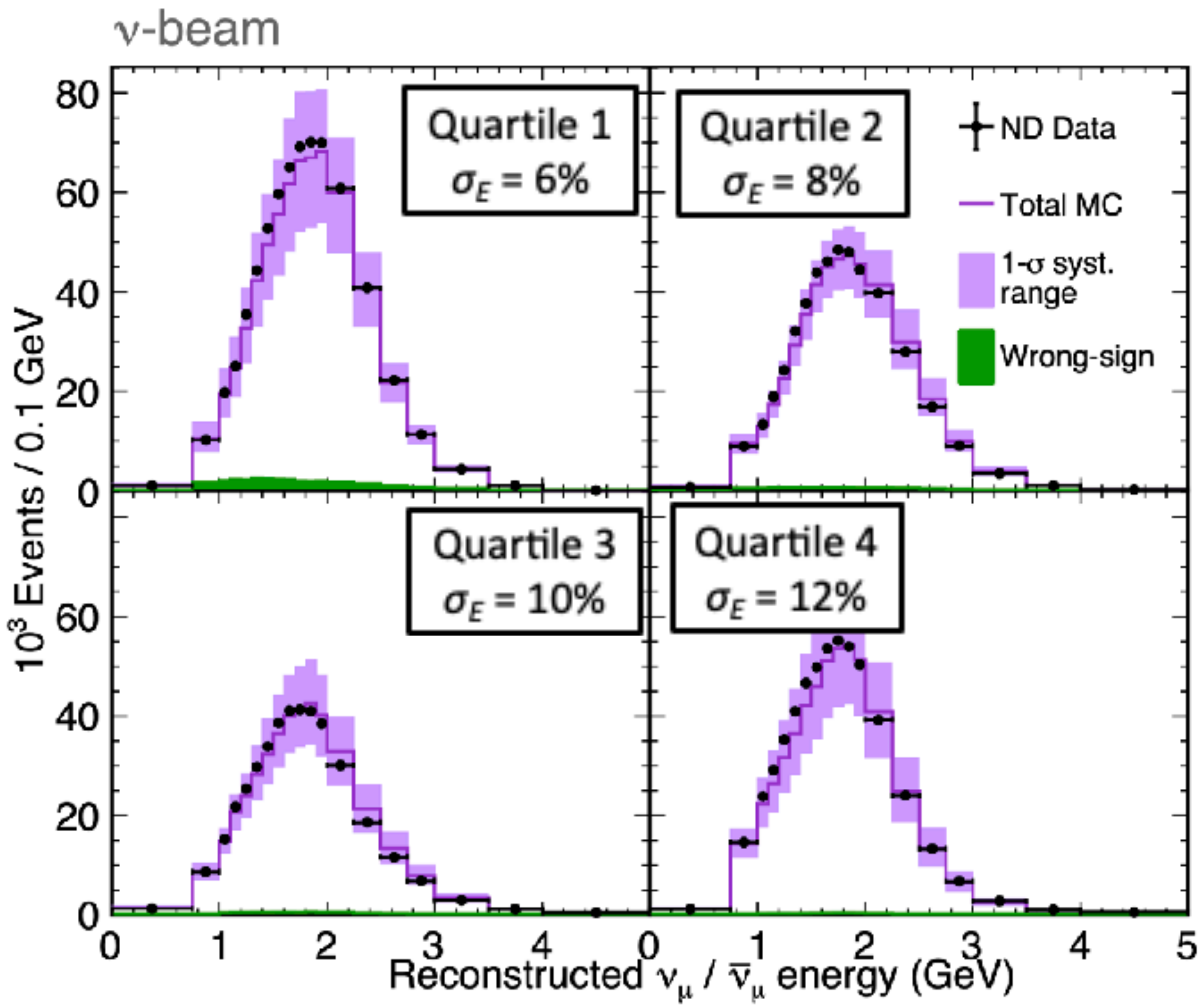
- Band around the MC shows the large impact of flux and cross-section uncertainties in only a single detector.
- We use this sample to predict both ν_μ and ν_e signal spectra at the Far Detector.
- Appearing ν_e's are still ν_μ's at the ND

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.

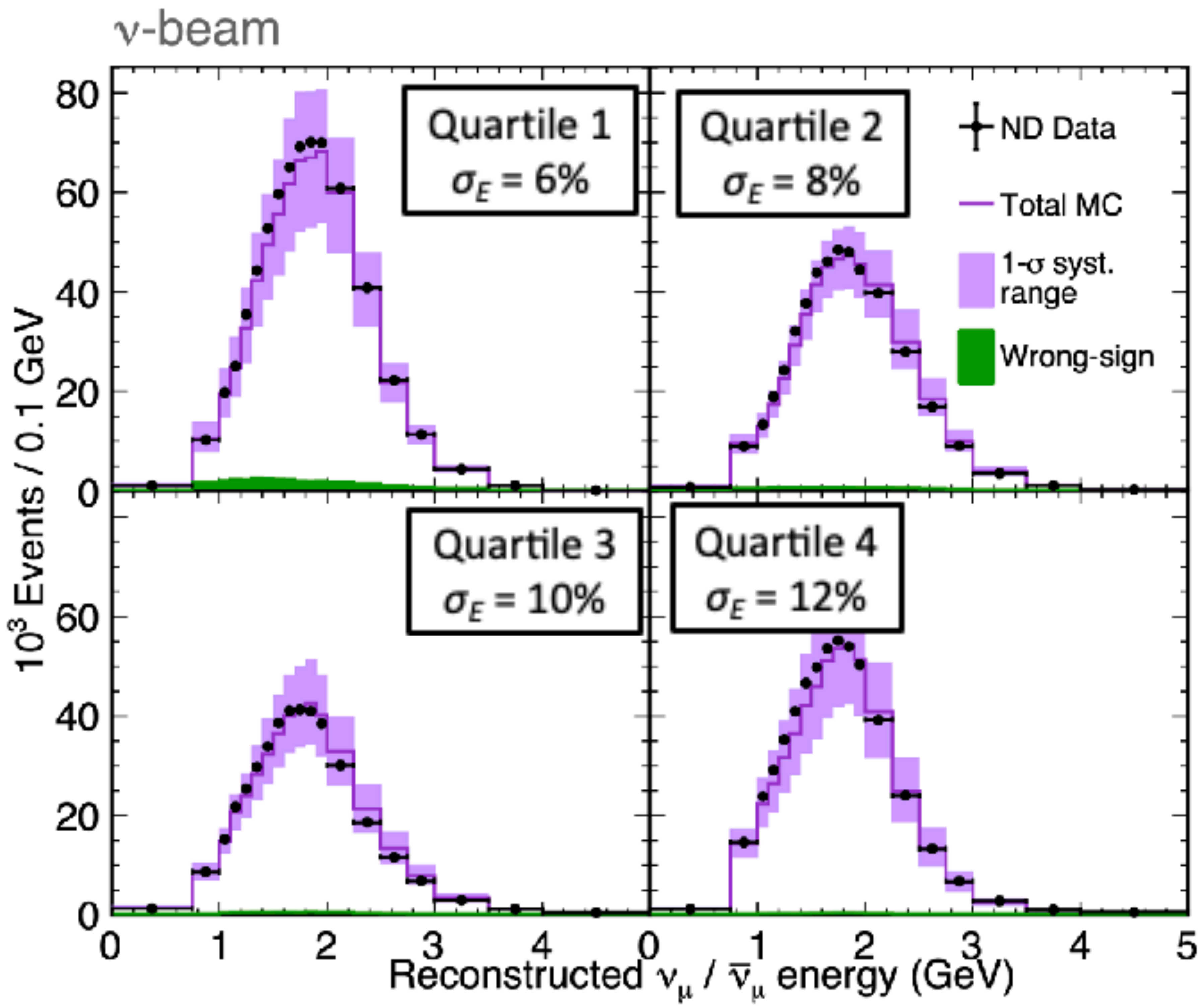
Enhancing sensitivity to oscillations

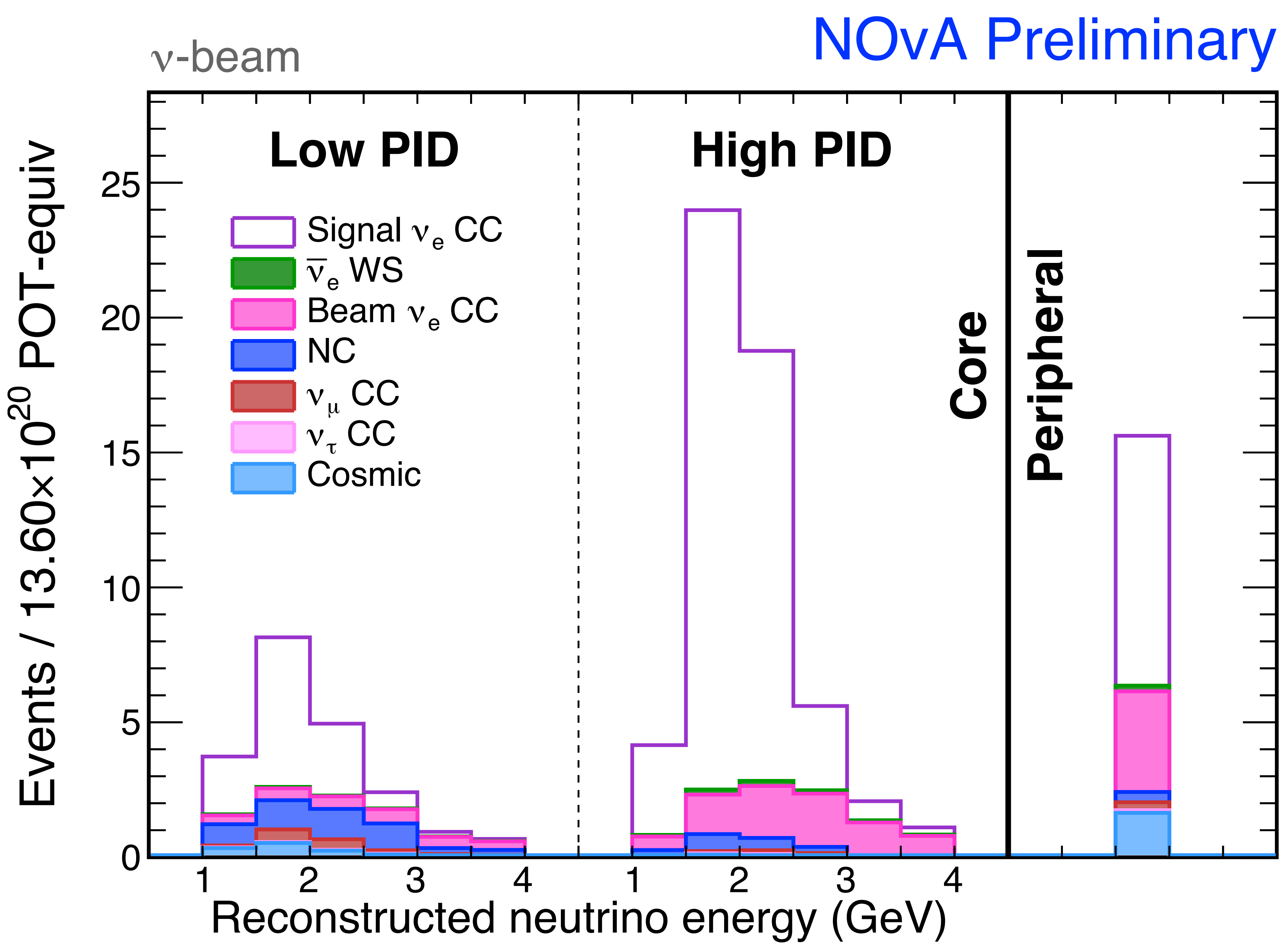


ν_μ sample

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

Enhancing sensitivity to oscillations





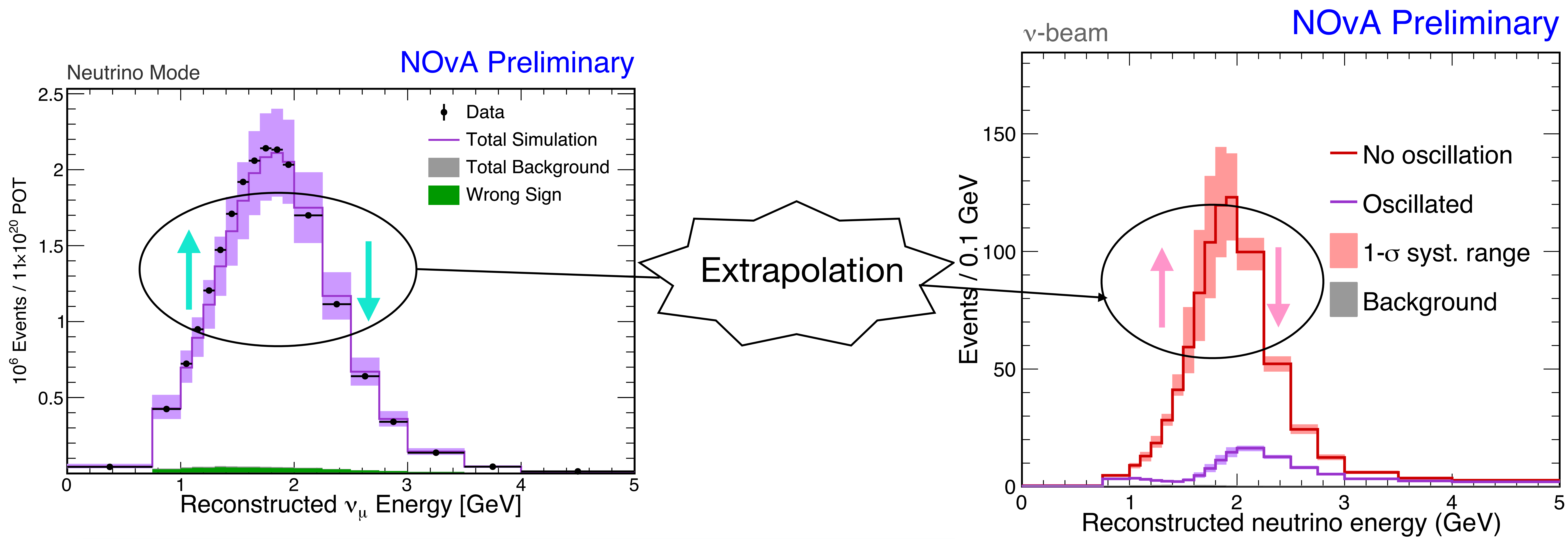
ν_μ sample

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

ν_e sample

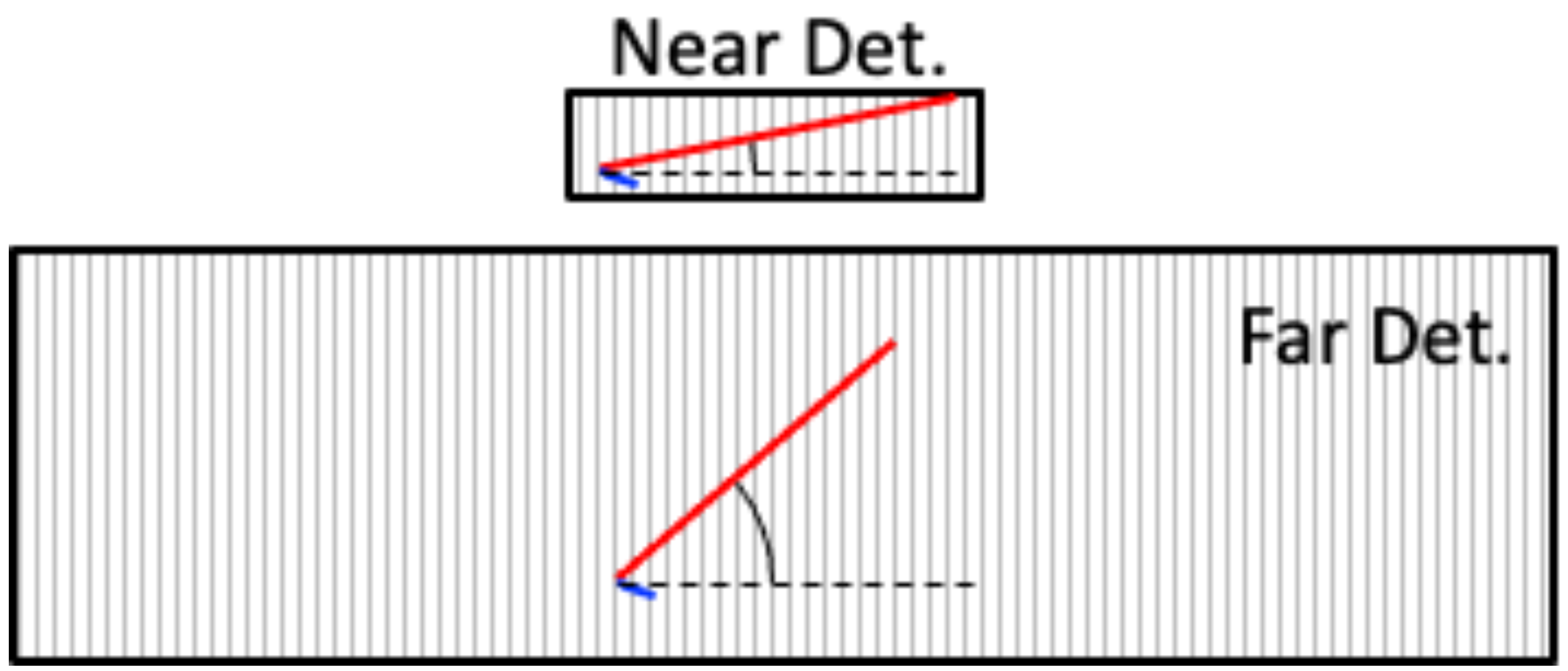
- Sensitivity depends primarily on separating signal from background.
- Peripheral sample:
  - Captures high-PID events which might not be contained close to detector edges.
  - No energy binning.

Extrapolating from near to far detector



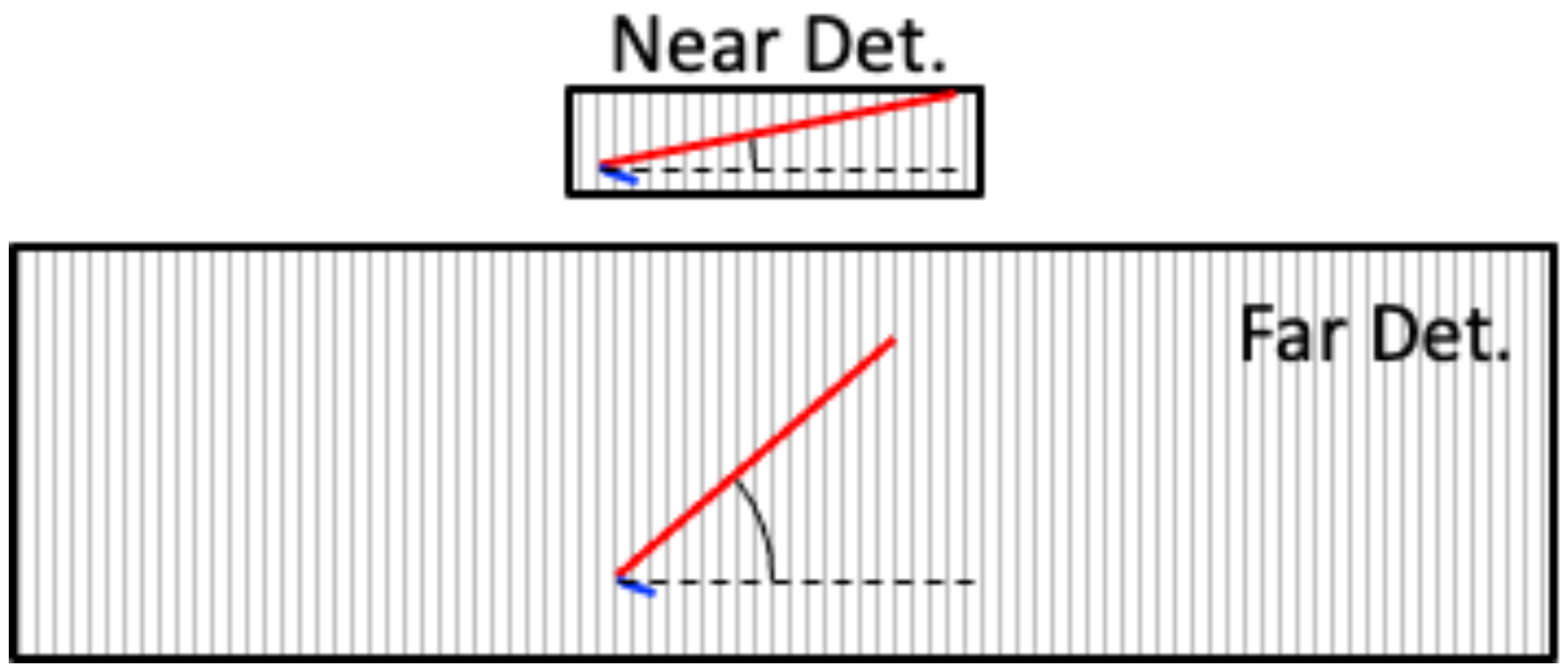
- Observe data-MC differences at the ND, use them to modify the FD MC.
  - Extrapolation performed in the analysis binning of energy + (resolution or PID).
- Significantly reduces the impact of uncertainties correlated between detectors
  - Especially effective at rate effects like the flux (7% → 0.3%).

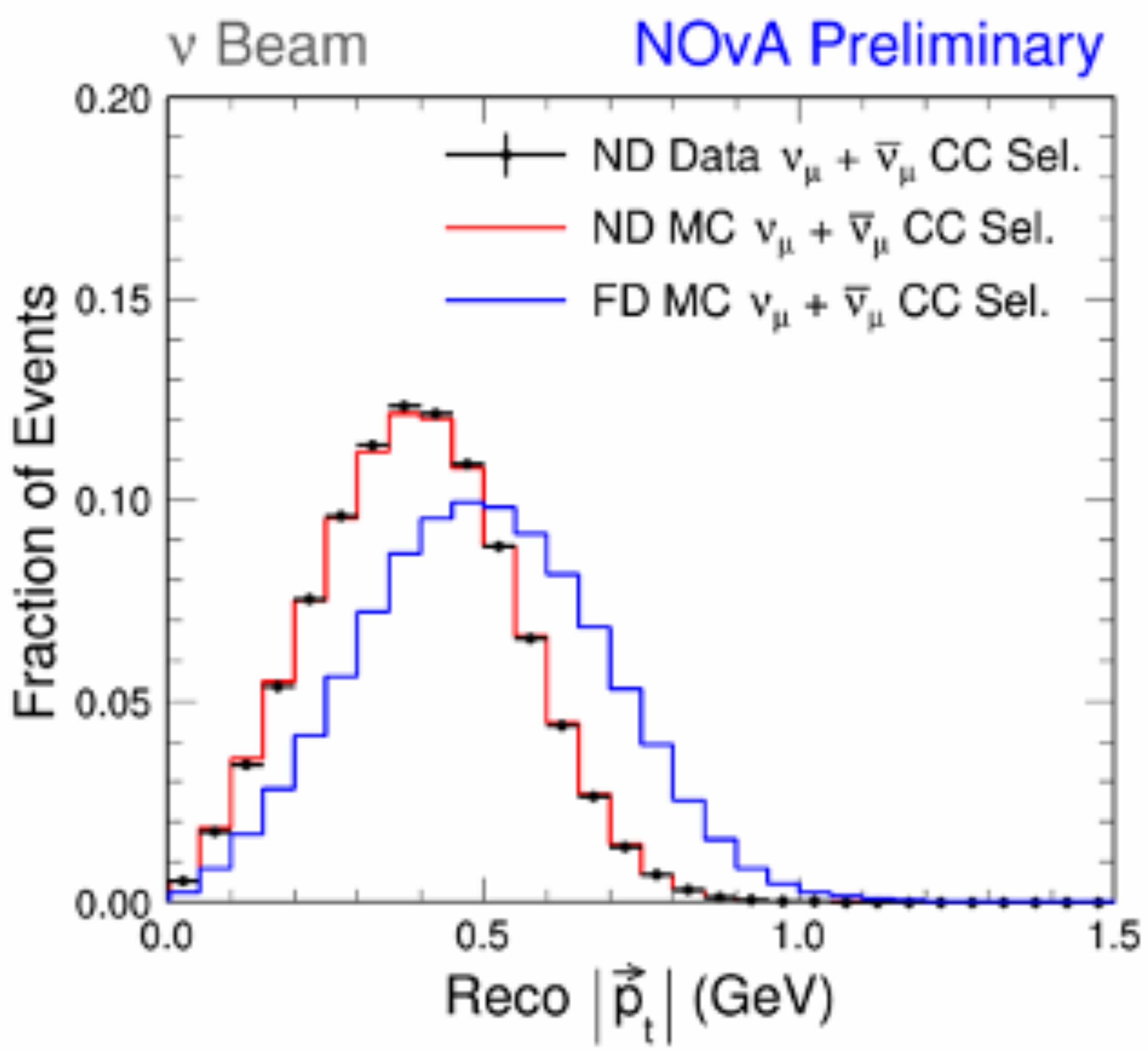
Extrapolating kinematics



- 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.

Extrapolating kinematics

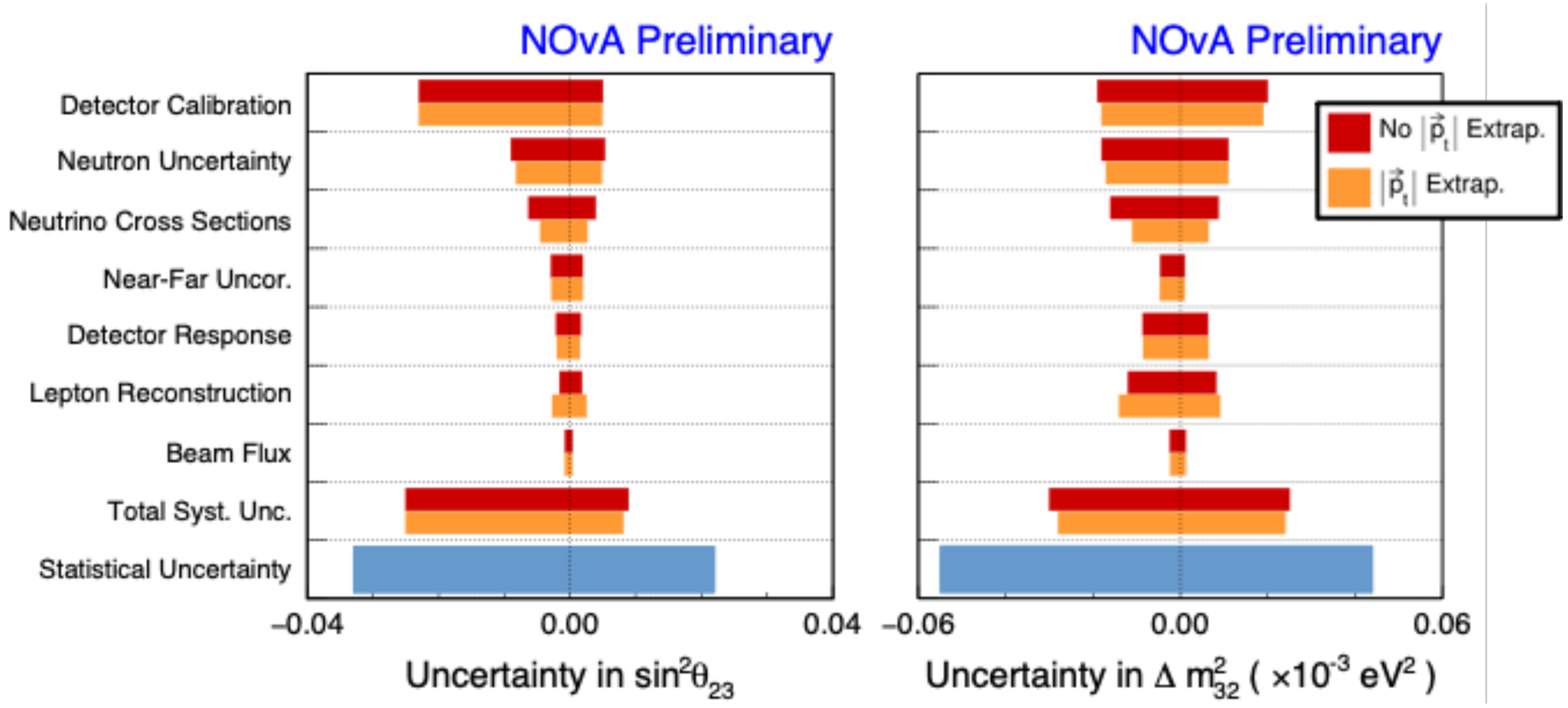




- Containment limits the range of lepton angles more in the Near Detector than in the Far.
- The ND is 1/5 the size of the FD.

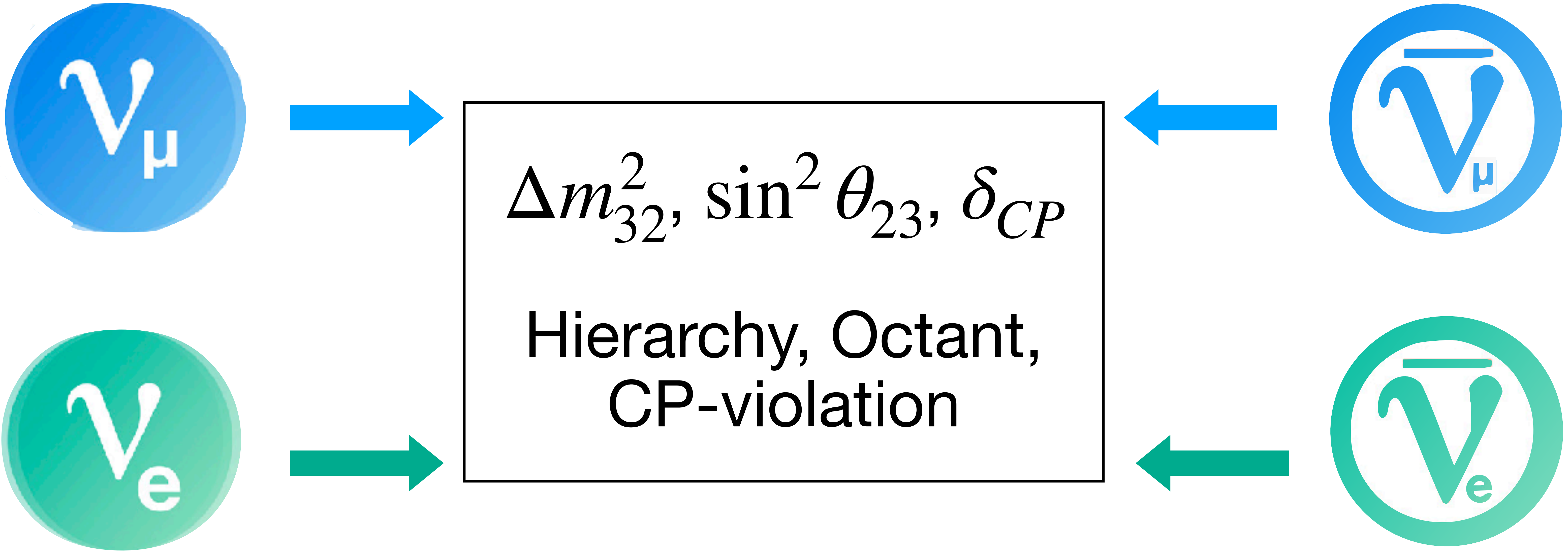
- Mitigate by extrapolating in bins of lepton transverse momentum, pt
- Split the ND sample into 3 bins of pt, extrapolate each separately to the FD.
  - Effectively "rebalances" the kinematics to better match between the detectors.
  - Re-sum the pt bins before fitting.

Systematics uncertainties with pt extrapolation



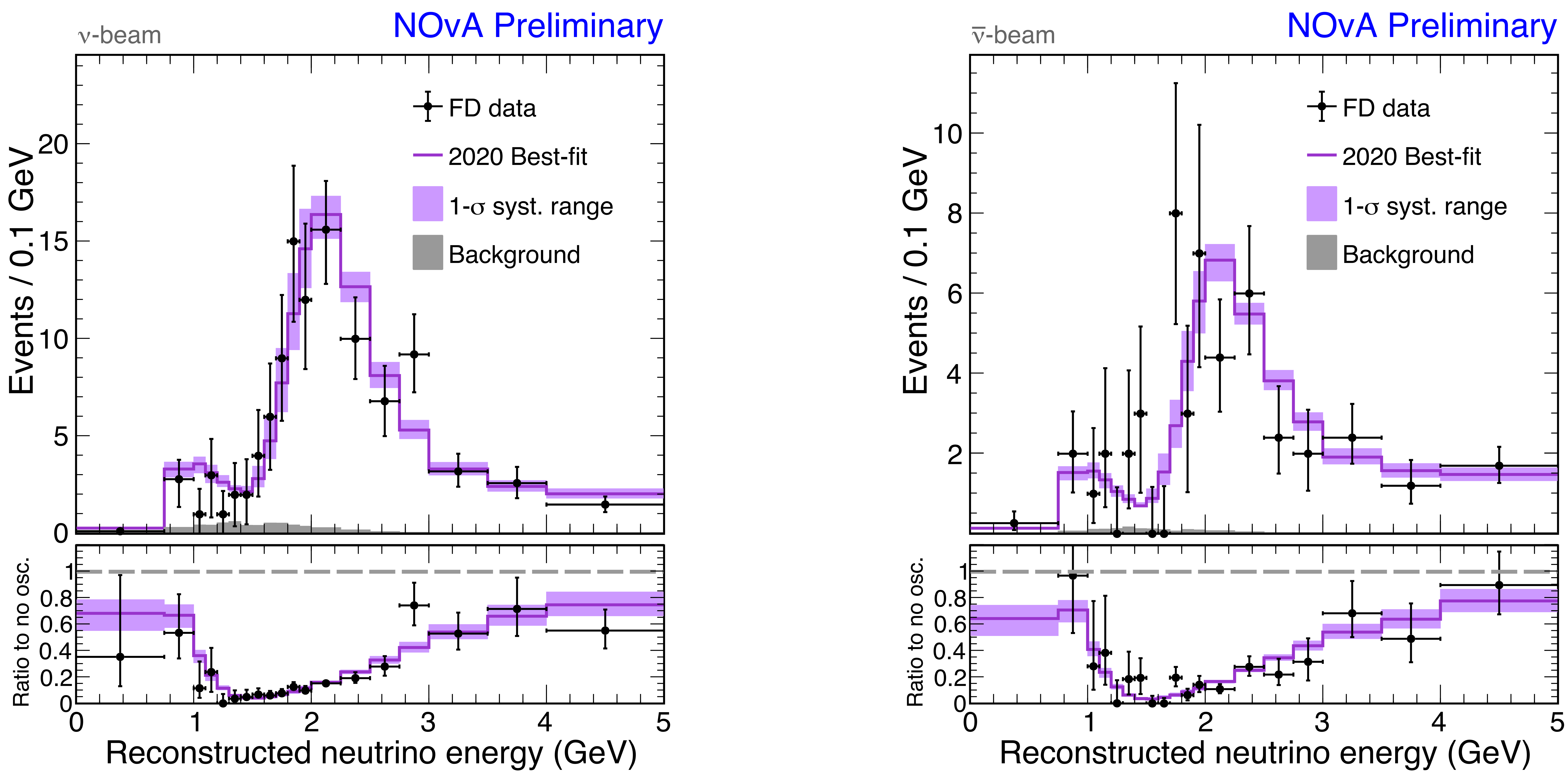
- Increased robustness also leads to a 30% reduction in cross section uncertainties.
  - Slightly increase the sensitivity to well-understood systematics on lepton reconstruction.
- Overall systematic reduction is 5-10%,
- The largest systematics come from the detector energy scale.

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



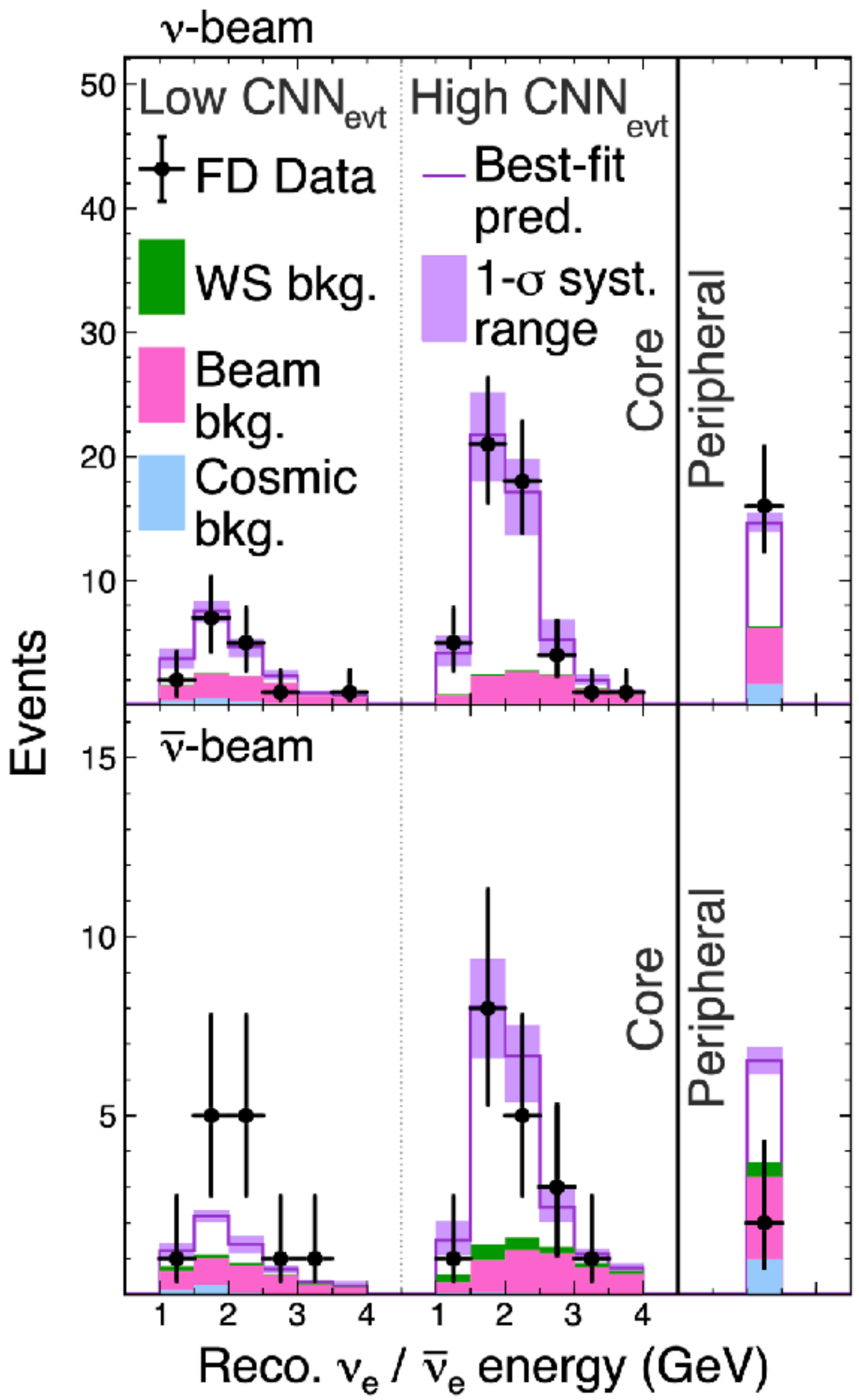
211 events, 8.2 background

105 events, 2.1 background

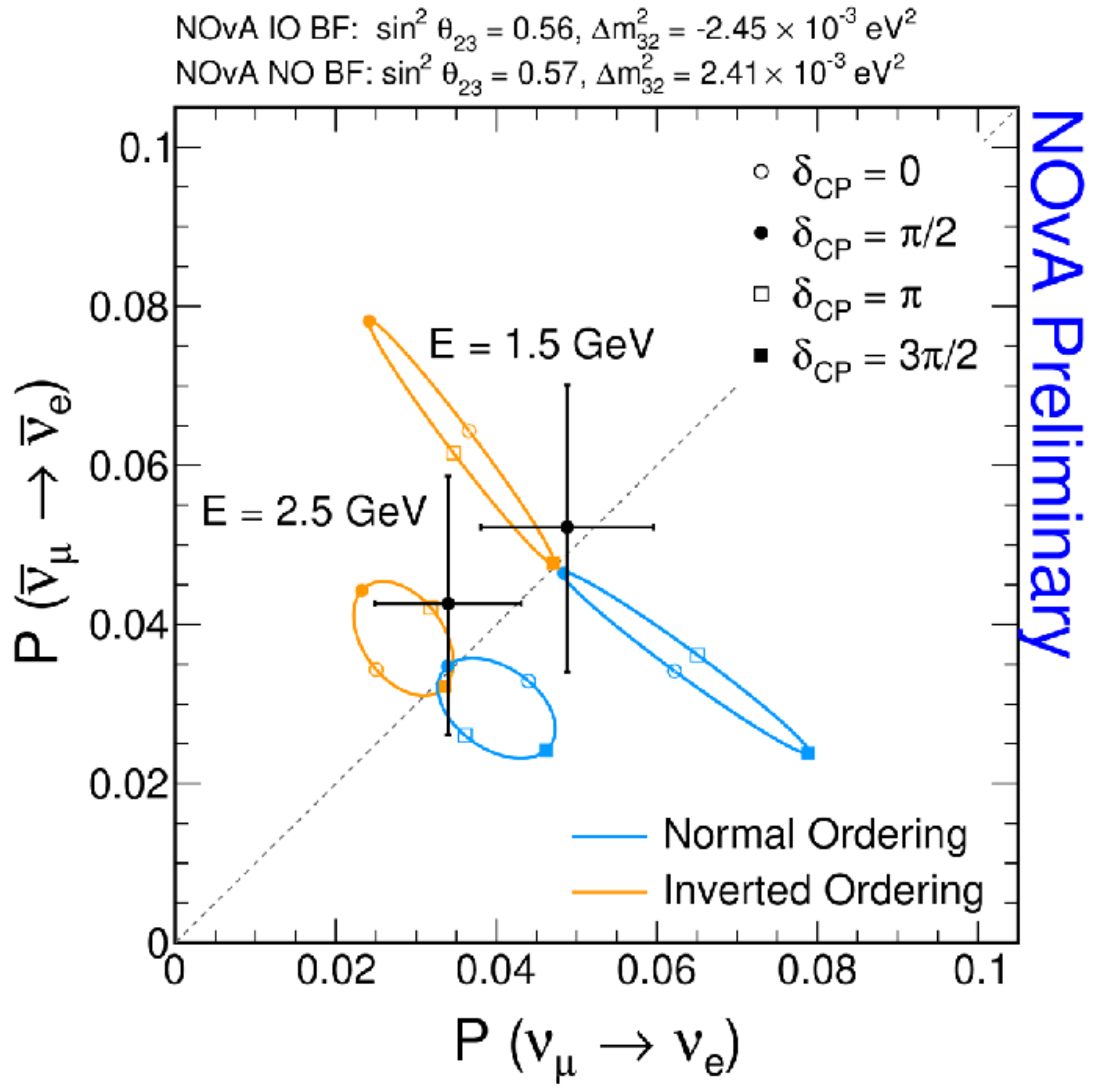
$\nu_e/\bar{\nu}_e$ data at the far detector

82 ν_e candidates, 27 background

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

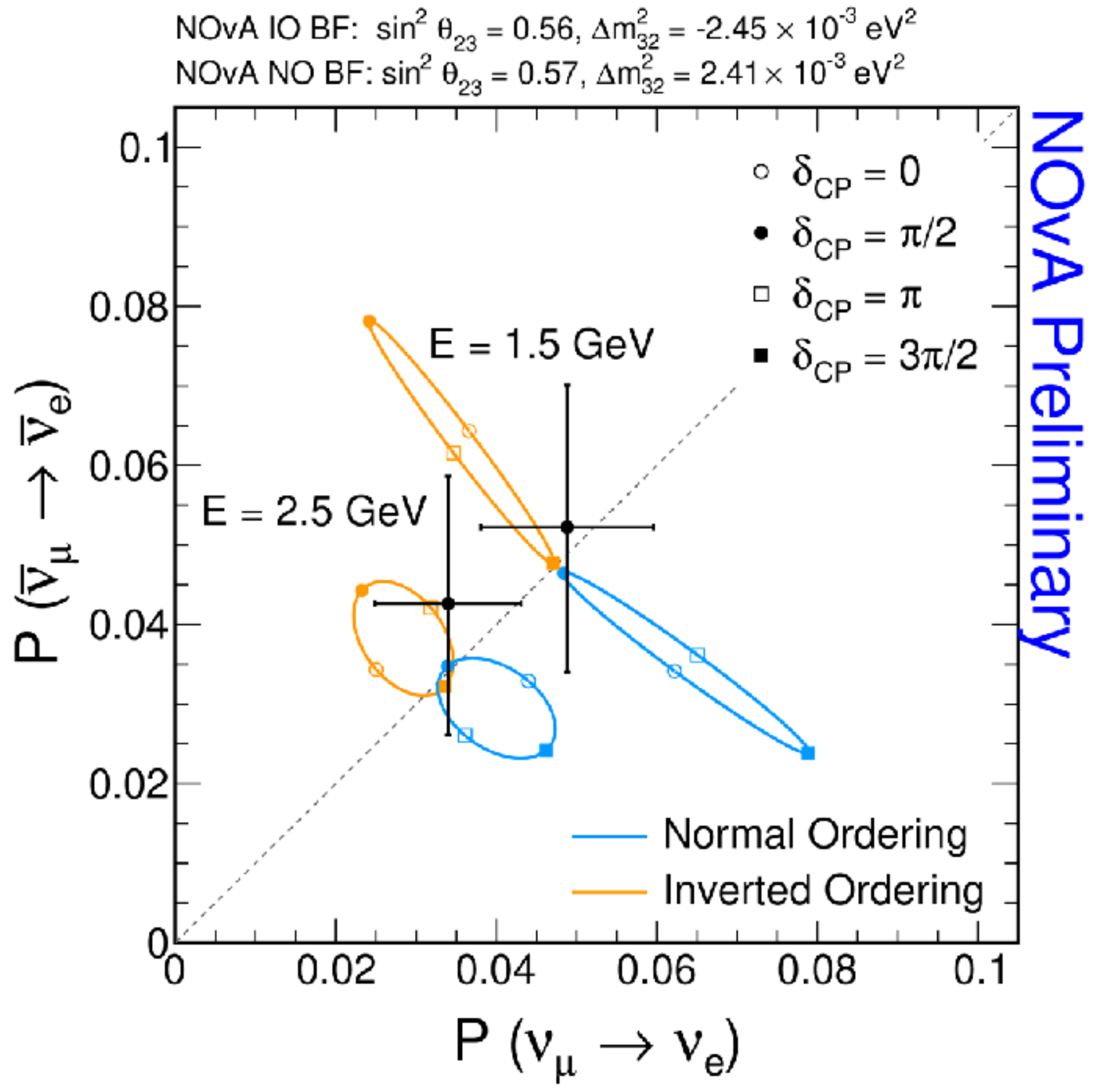


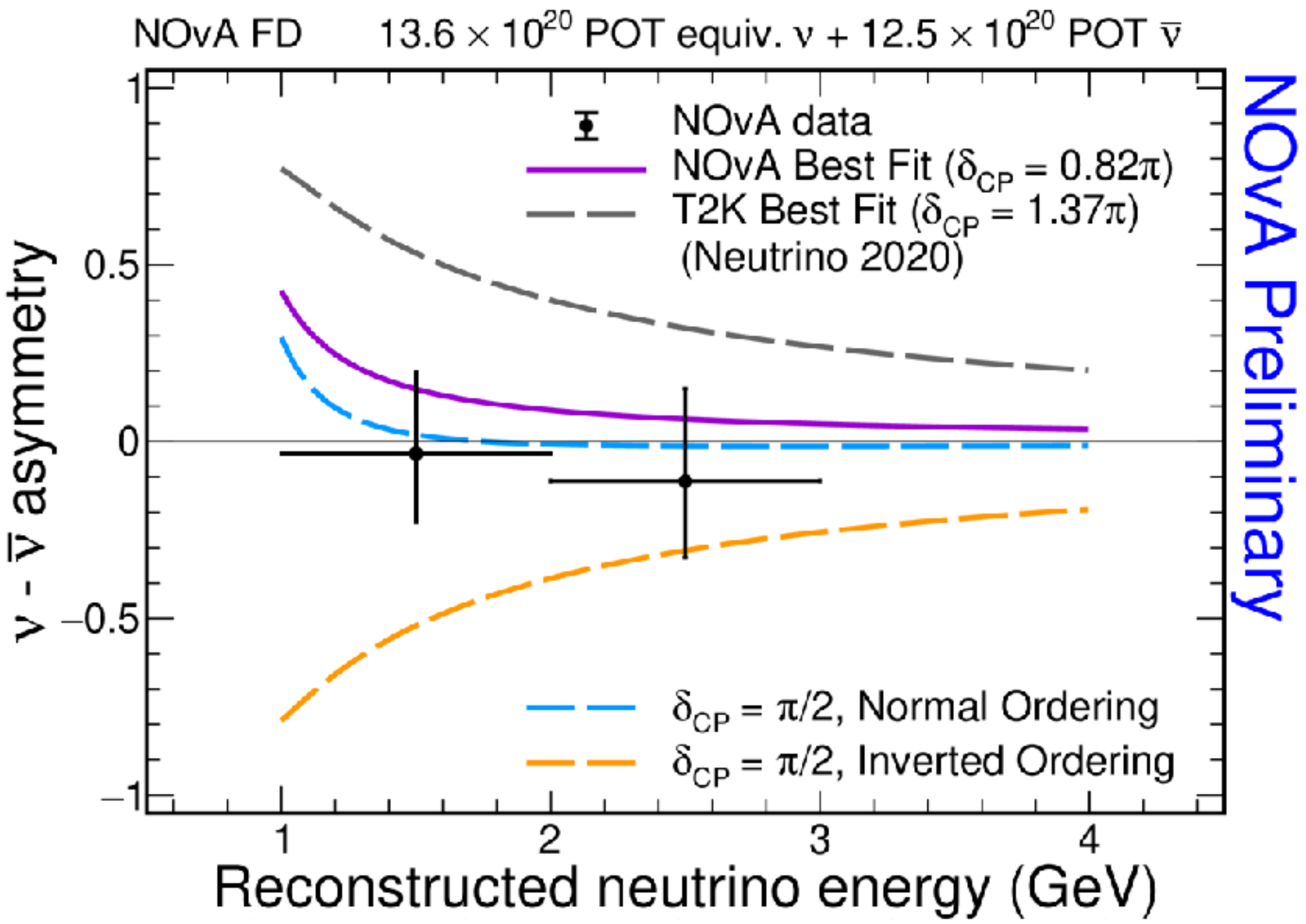
Appearance



NOvA IO BF: sin² θ23 = 0.56, Δm²32 = -2.45 × 10⁻³ eV²
NOvA NO BF: sin² θ23 = 0.57, Δm²32 = 2.41 × 10⁻³ eV²
NOvA Preliminary
δCP = 0
δCP = π/2
δCP = π
δCP = 3π/2
E = 1.5 GeV
E = 2.5 GeV
Normal Ordering
Inverted Ordering
P (ν̄μ → ν̄e)
P (νμ → νe)
0
0.02
0.04
0.06
0.08
0.1

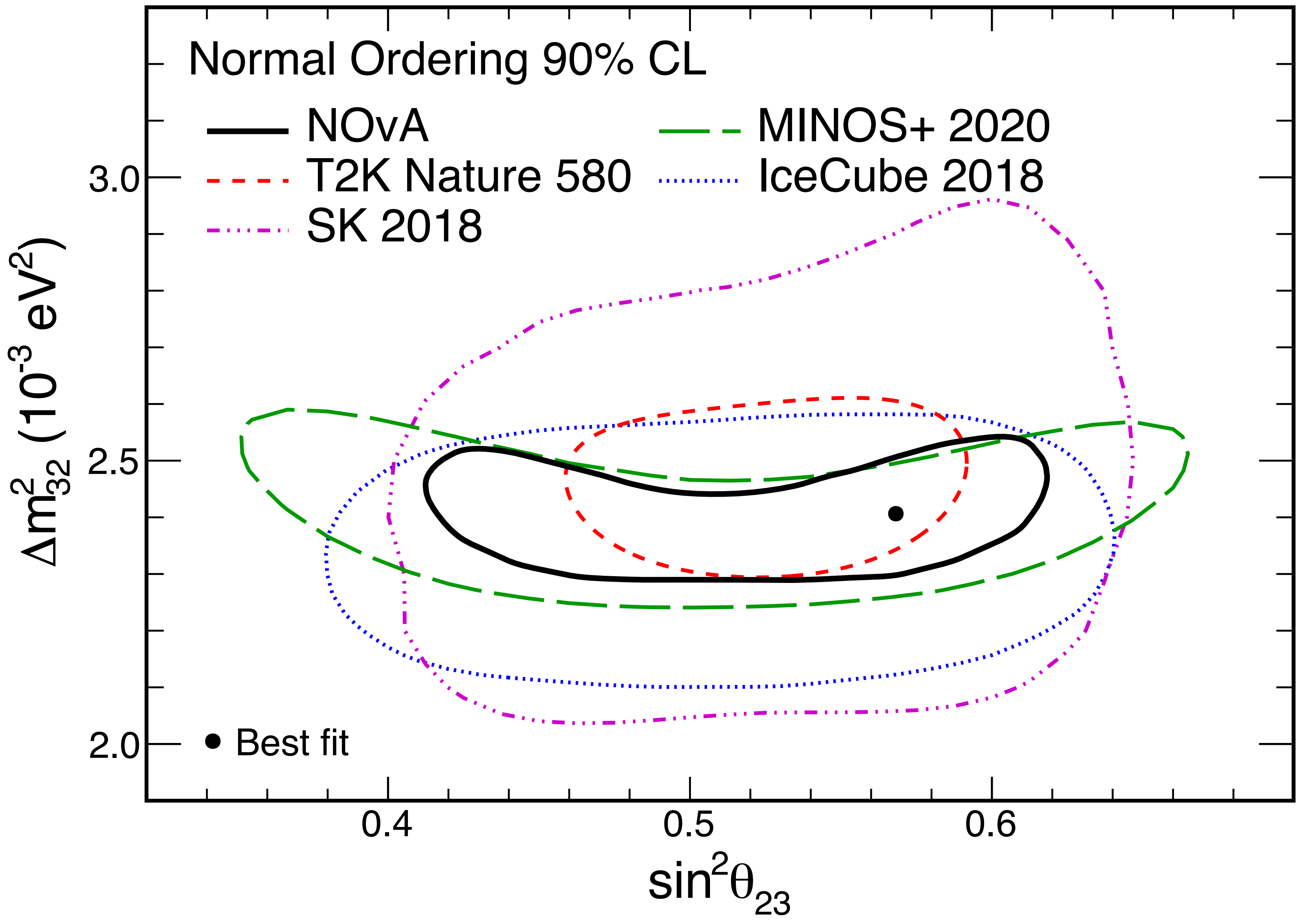
Appearance

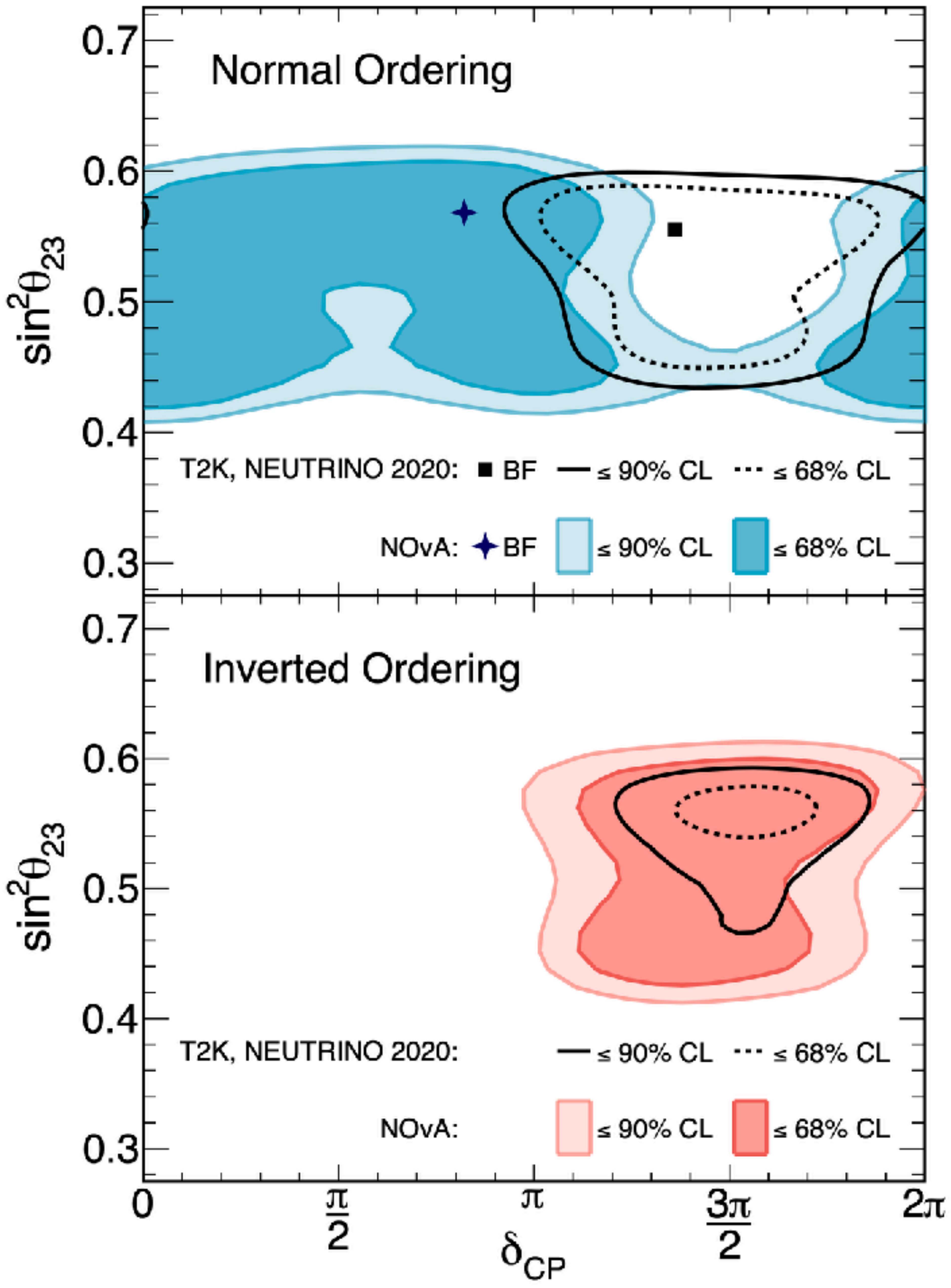




- Appearance asymmetry: $\dfrac{P(\nu_e) - P(\bar{\nu}_e)}{P(\nu_e) + P(\bar{\nu}_e)}$
- Asymmetry consistent with zero to 25% precision
- Disfavours mass ordering-δ_{CP} combinations with large asymmetry

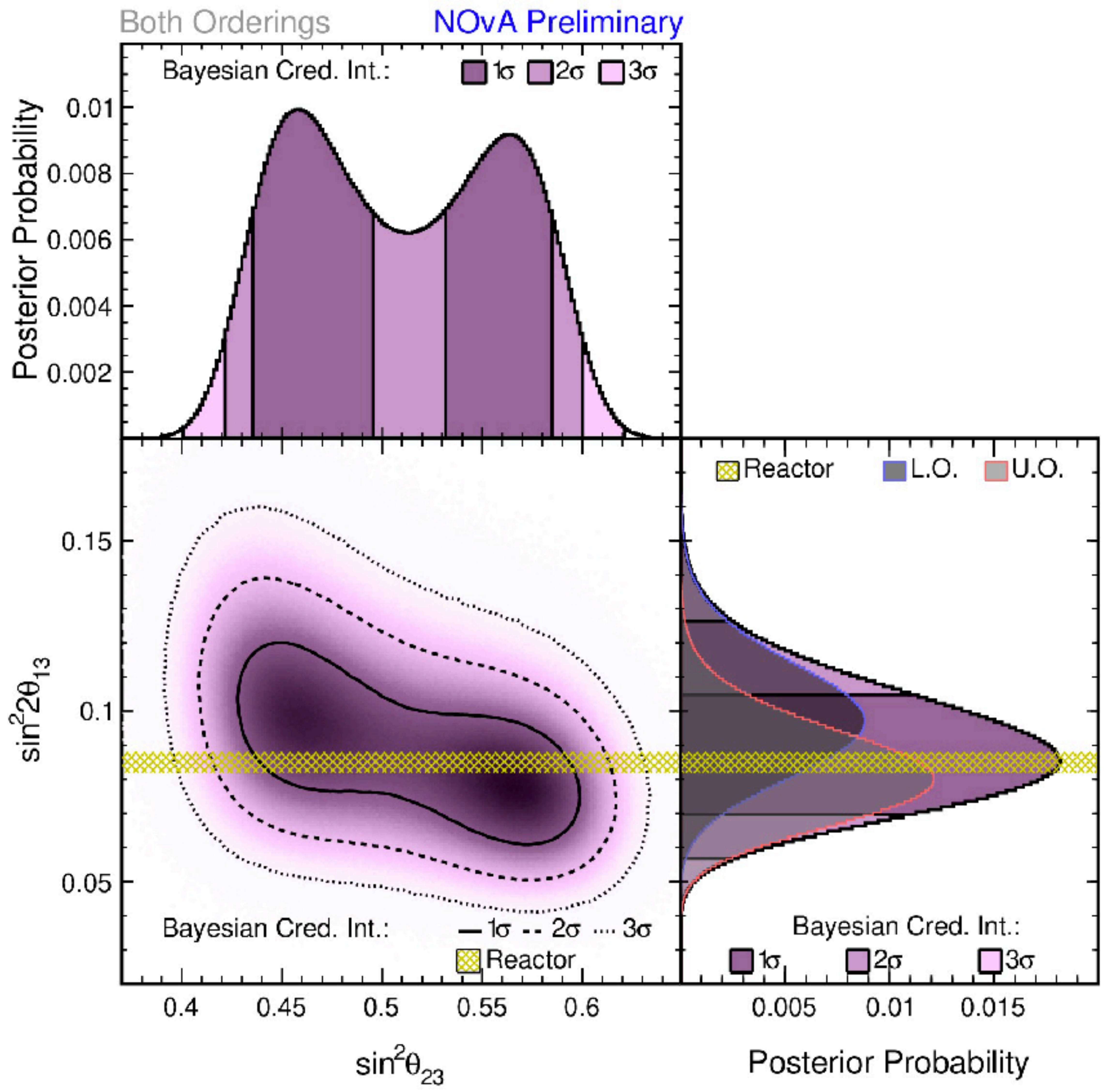
3-flavour fit results





- Exclude IO, $\delta_{CP} = \pi/2$ at $> 3\ \sigma$
- 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
- 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

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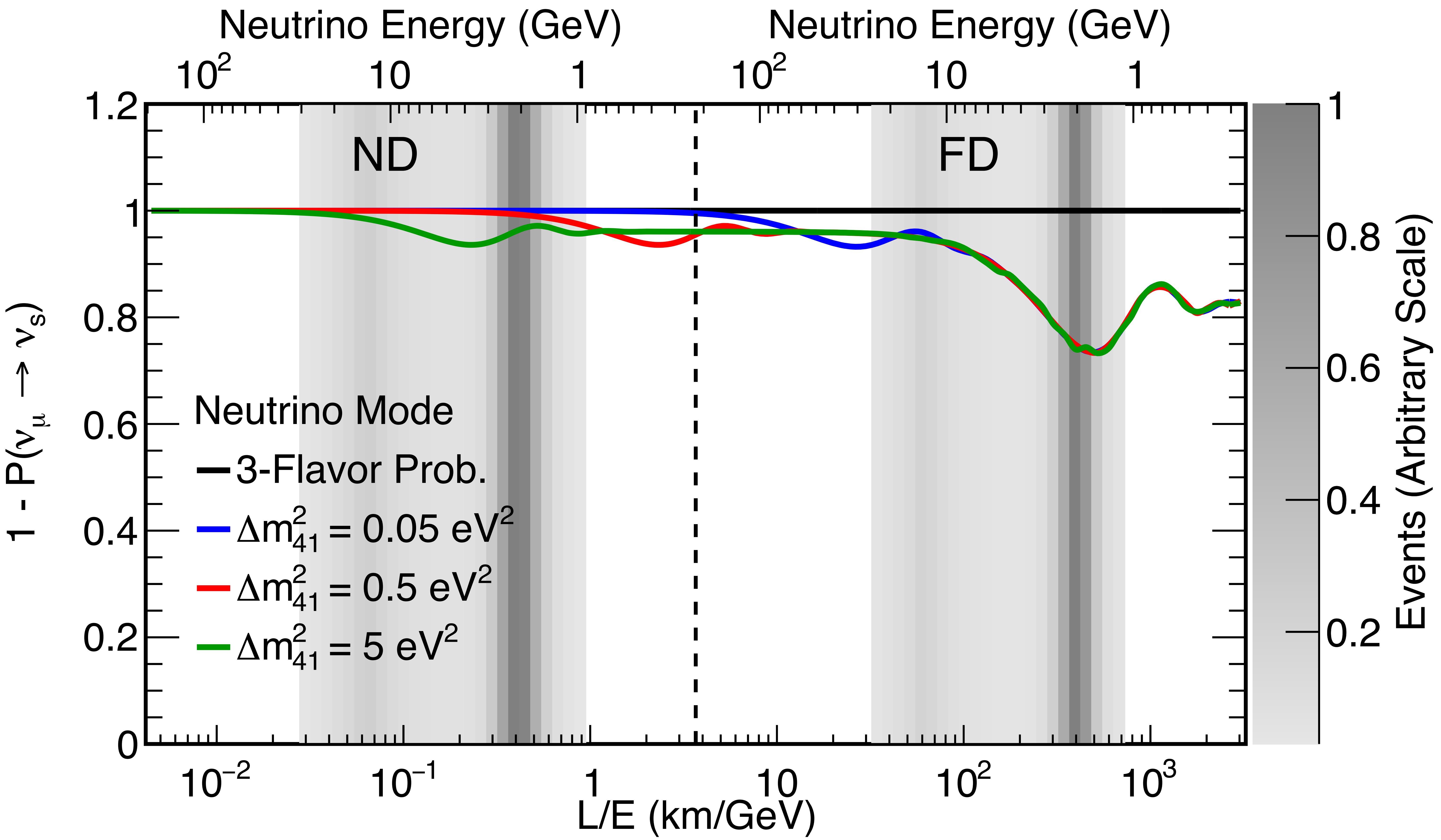
Sterile Neutrino Search

Queen - I'm the invisible man

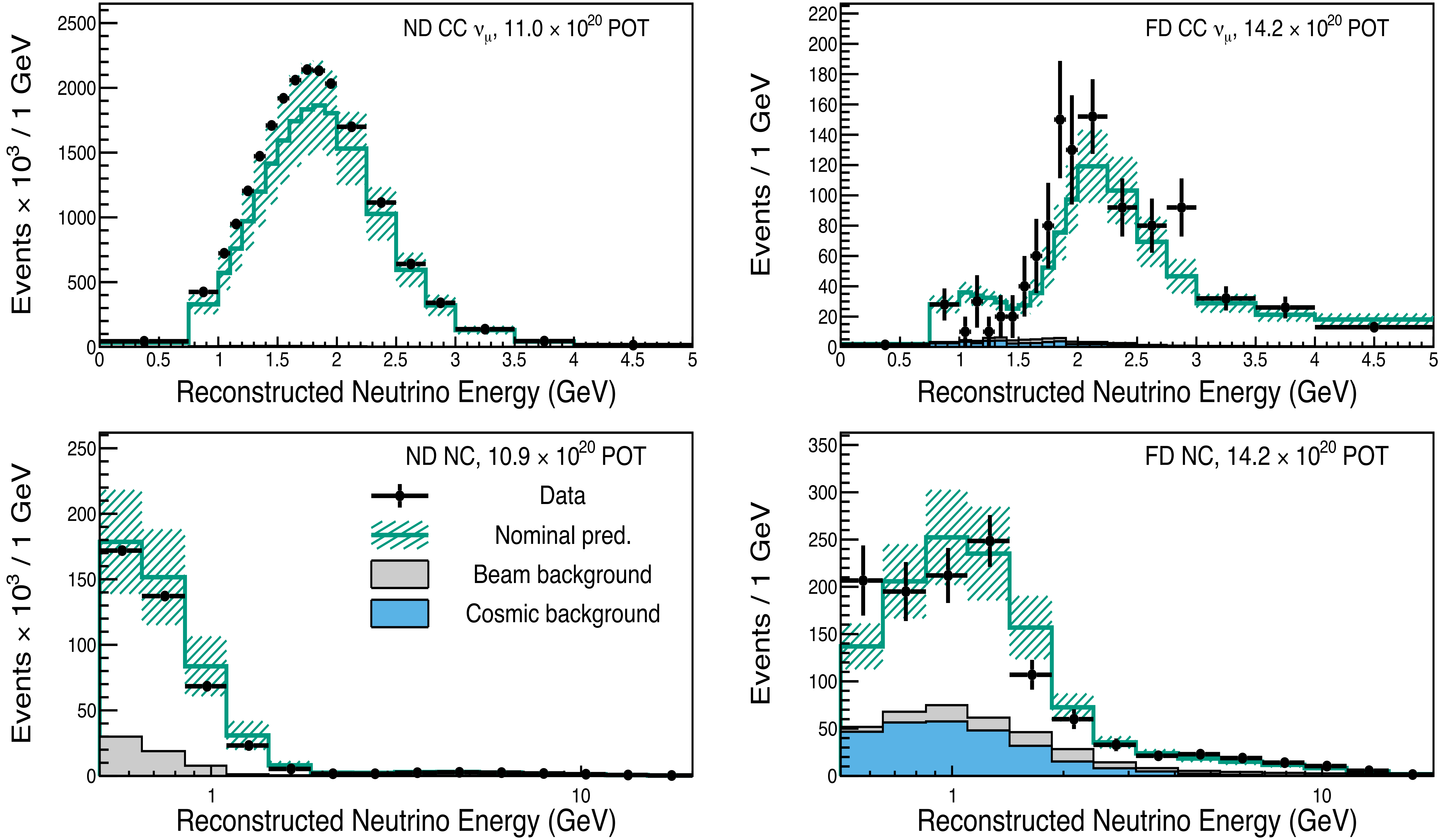
Sterile neutrino search

- 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



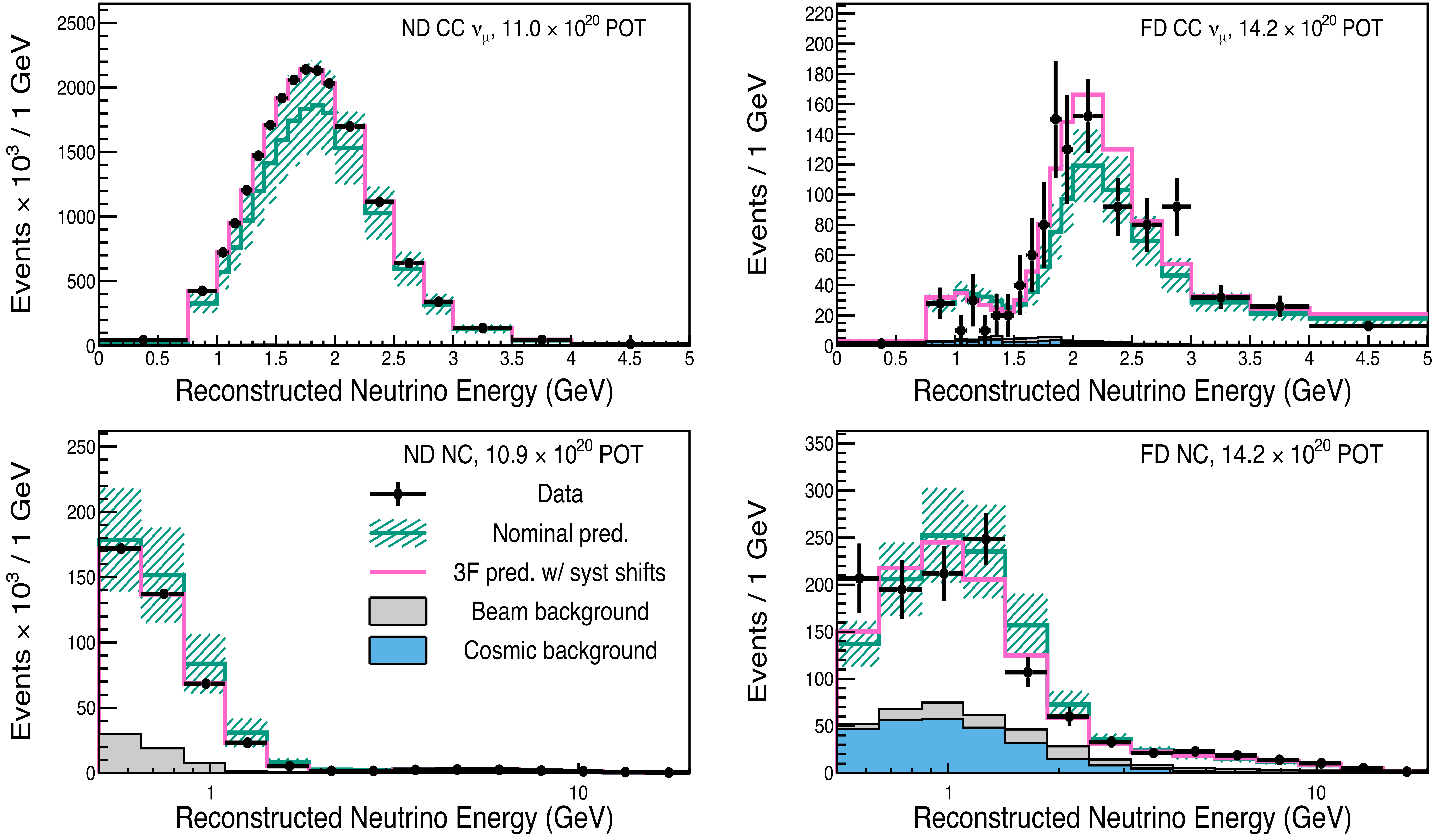
Phys.Rev.Lett. 127 (2021) 20, 201801
Phys.Rev.D 96 (2017) 7, 072006

Spectra used in sterile ν search



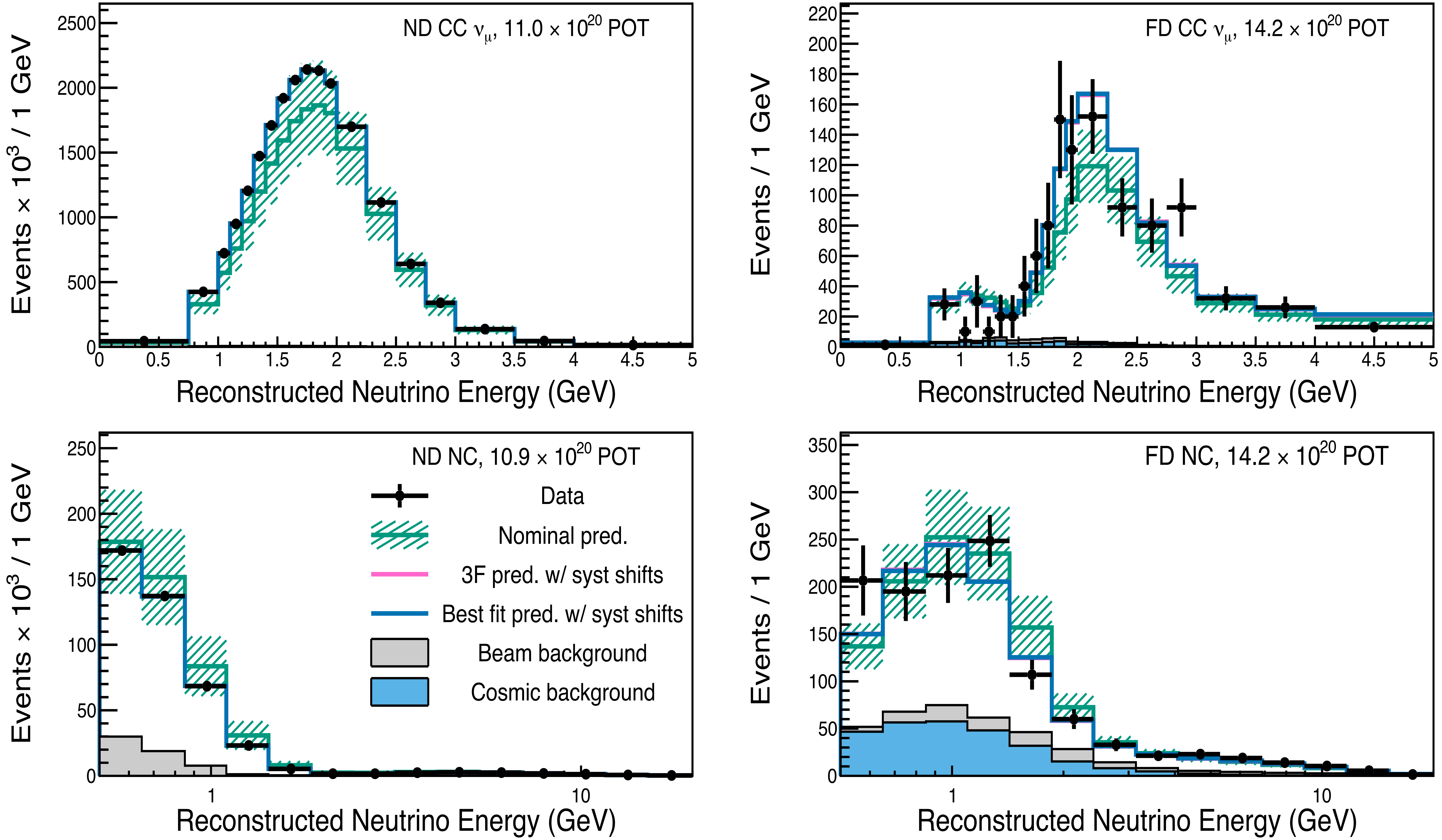
Pre-fit MC distributions (data-driven 2p2h tune not included in this analysis)

Spectra used in sterile ν search



3-Flavour hypothesis with systematic pulls included here

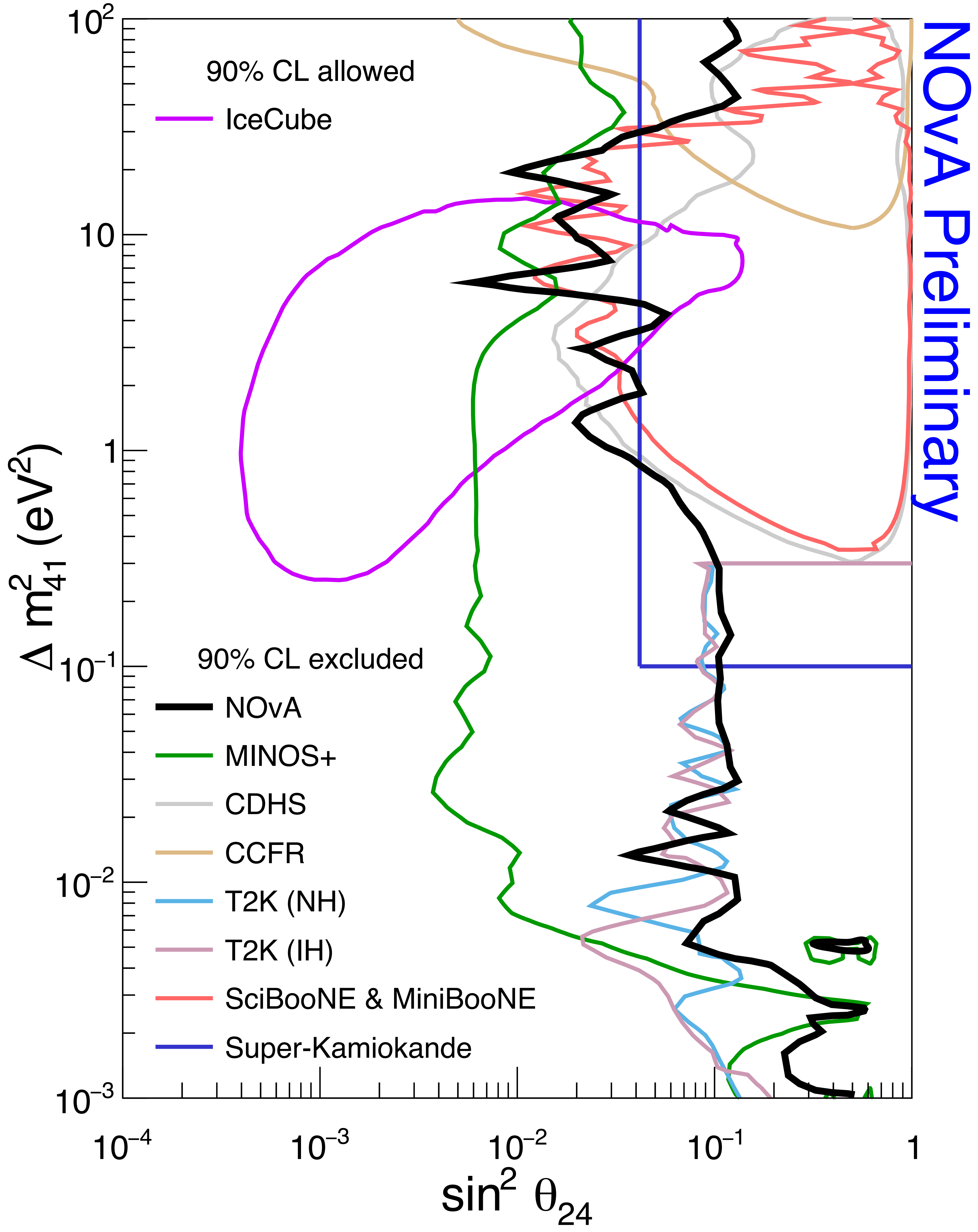
Spectra used in sterile ν search



Full best-fit for sterile neutrinos included here

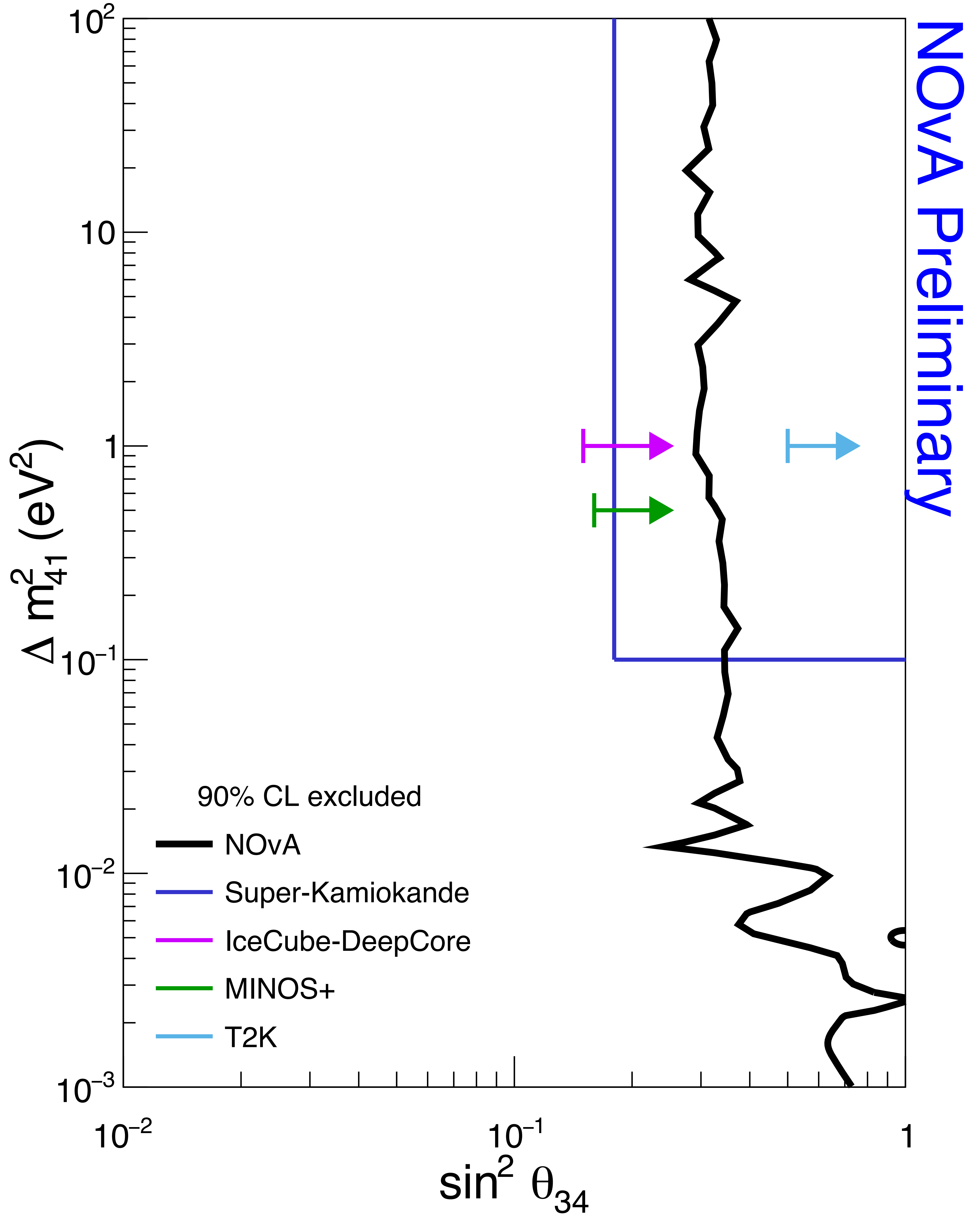
Sterile neutrino search results

- 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}



Sandbox Studio, Chicago

Future

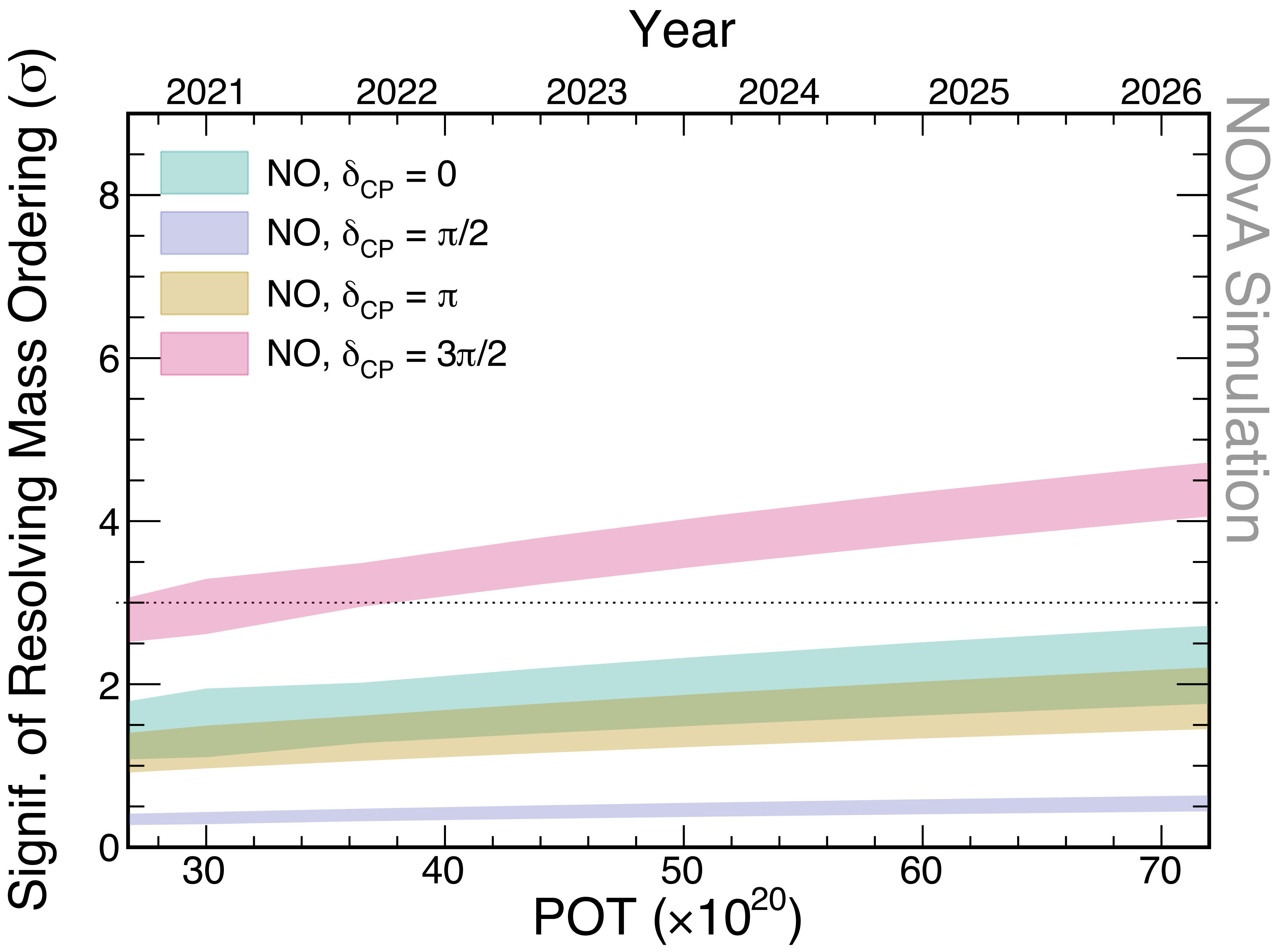
Journey - Don't stop believin'

Looking at the future

- Many NOvA analyses are limited by calibration and detector response uncertainties.
- The NOvA Test Beam experiment, currently in-progress, aims 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.

Future Prospects

- 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



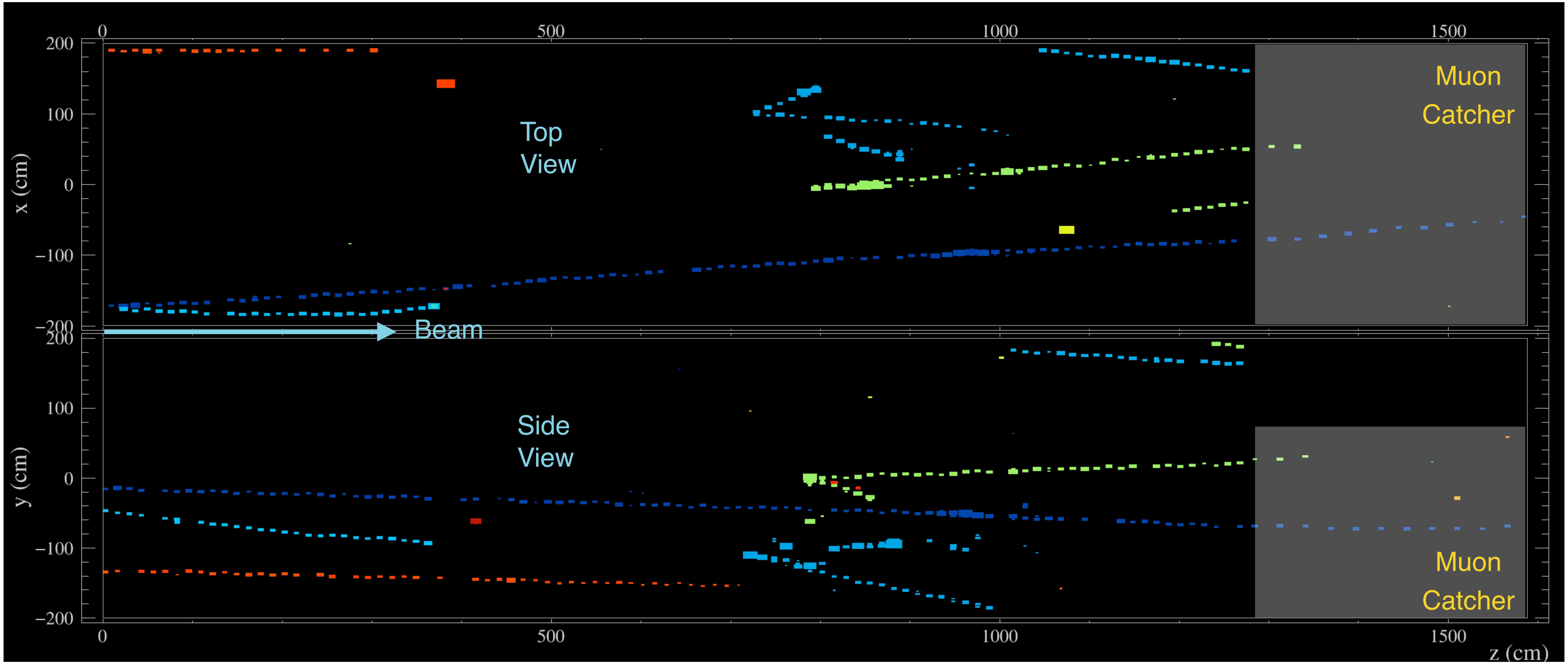
- Watch this space for:
  - NOvA-T2K joint fit
  - Further tests of alternative models (e.g. NSI)
  - Antineutrino beam cross section measurements

- Things I didn't cover:
  - NSI analyses
  - Exotics analysis

Thank you!

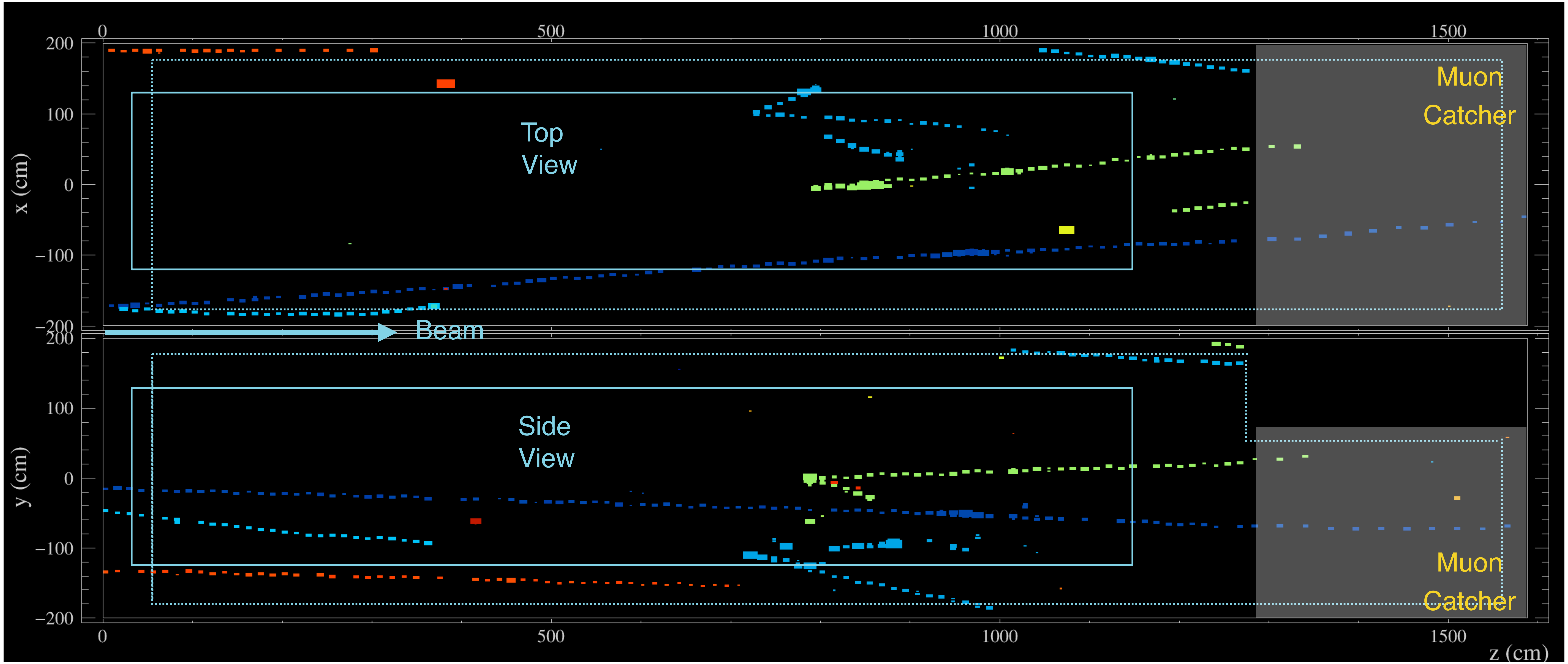
BACK UP

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

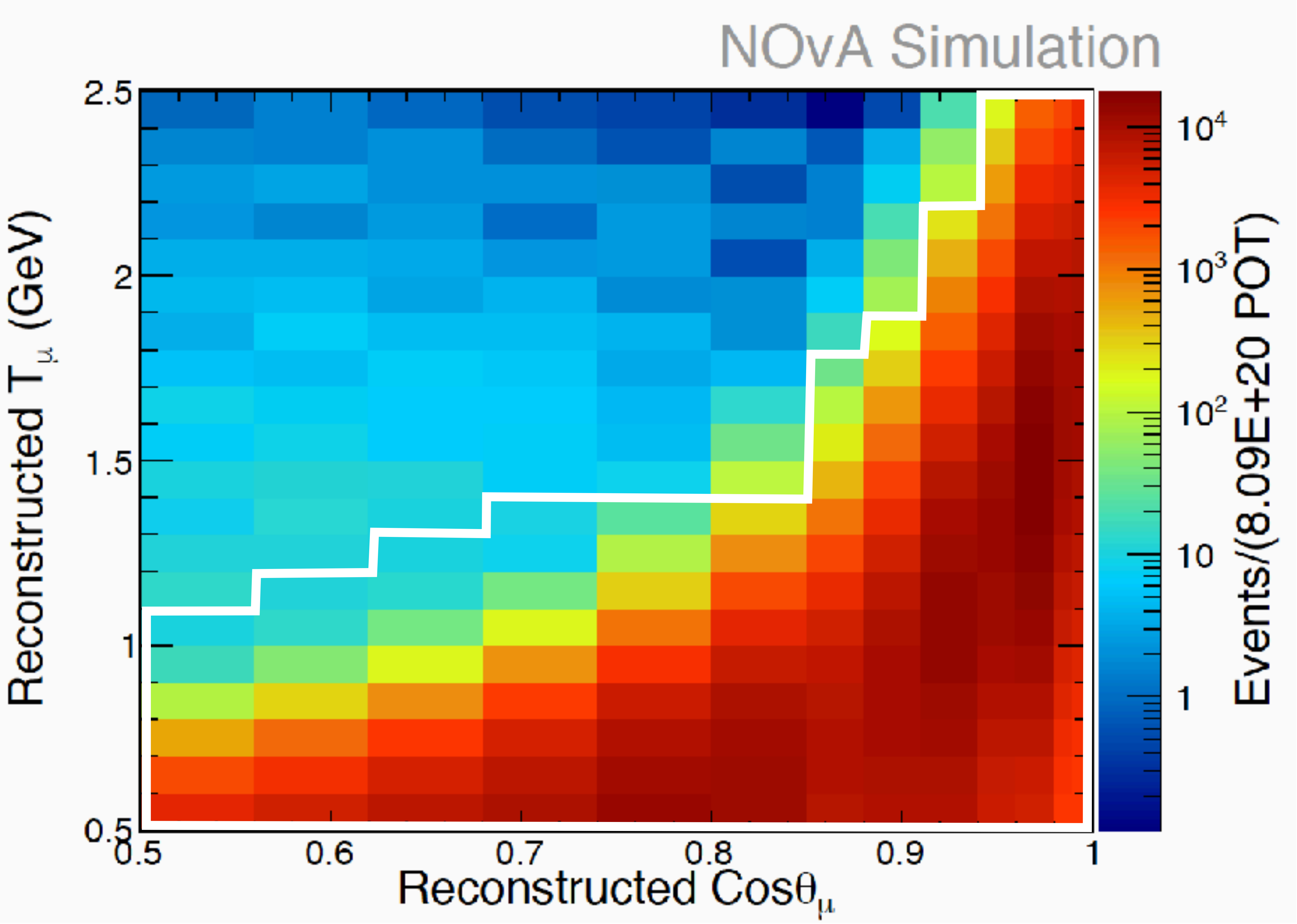


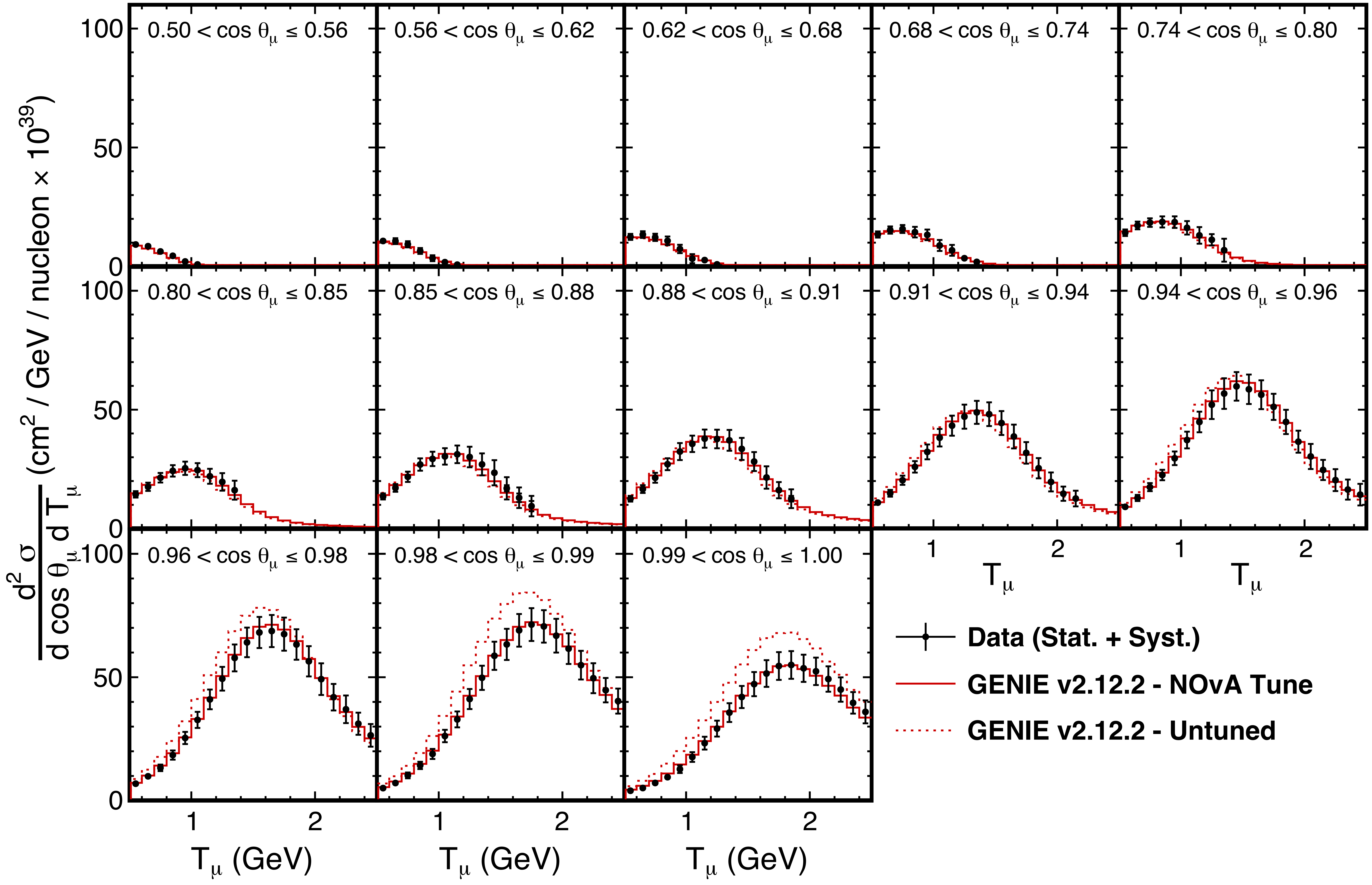
- Fiducial volume is the solid blue box, and excludes the muon catcher.
- The containment volume (blue dashed line) is defined by projected distance to the closest edge of the detector. Events with hadronic activity in or near the muon catcher are excluded.

Measurement strategy

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

- 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}.





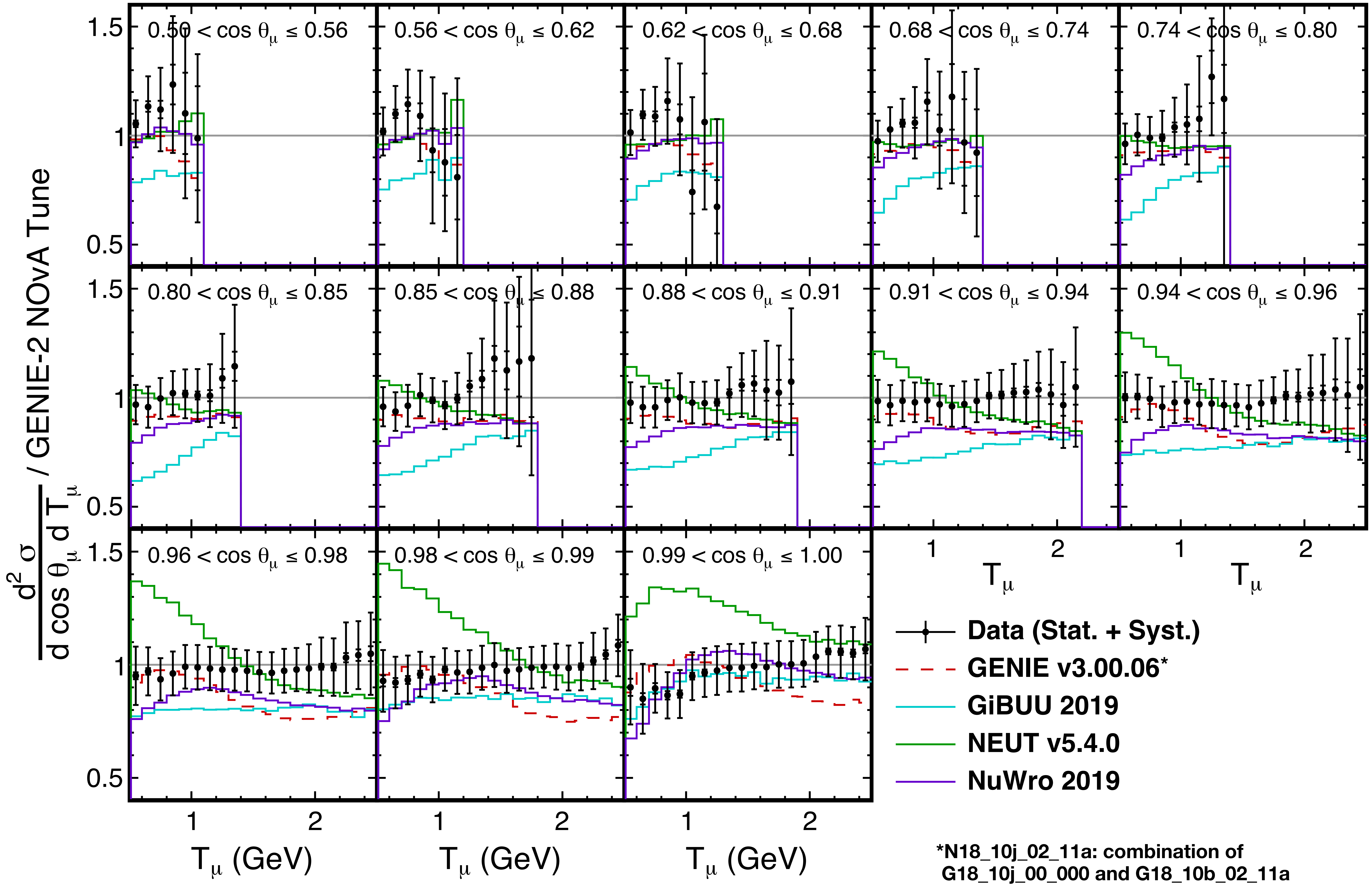
ν_μ CC inclusive double-differential measurement

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

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

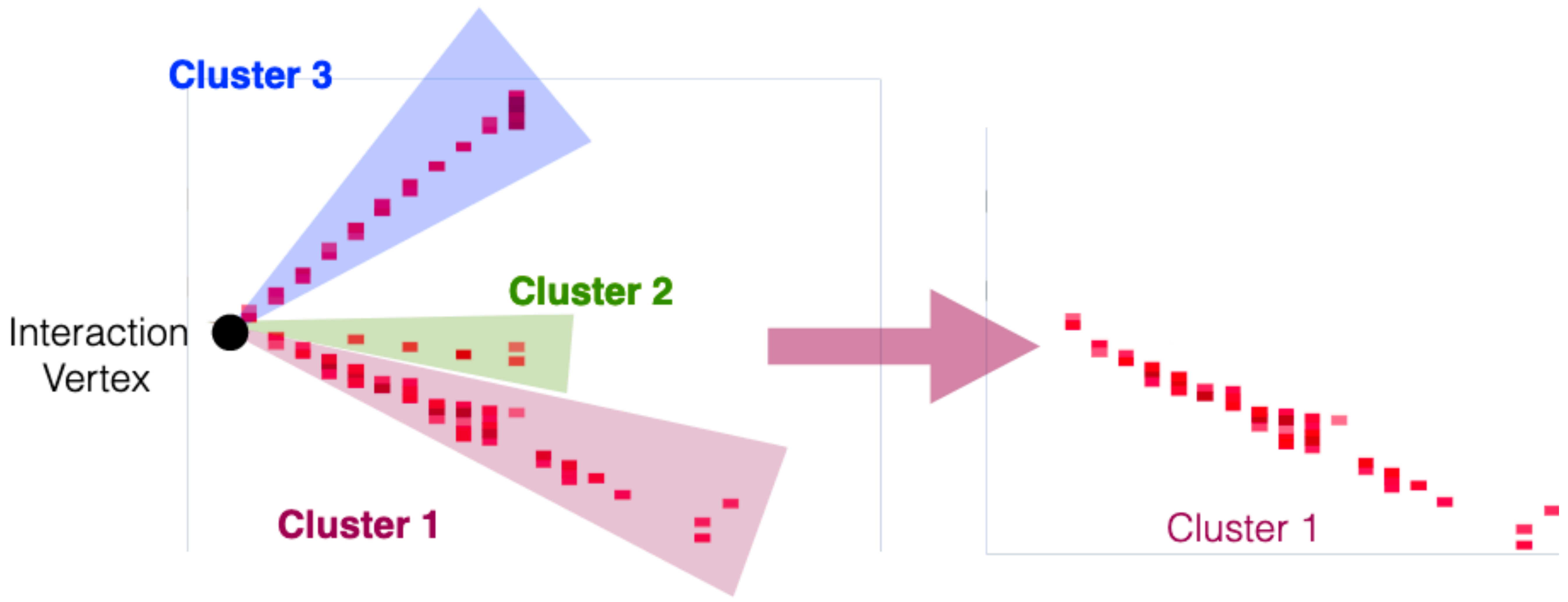


*N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a

- 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



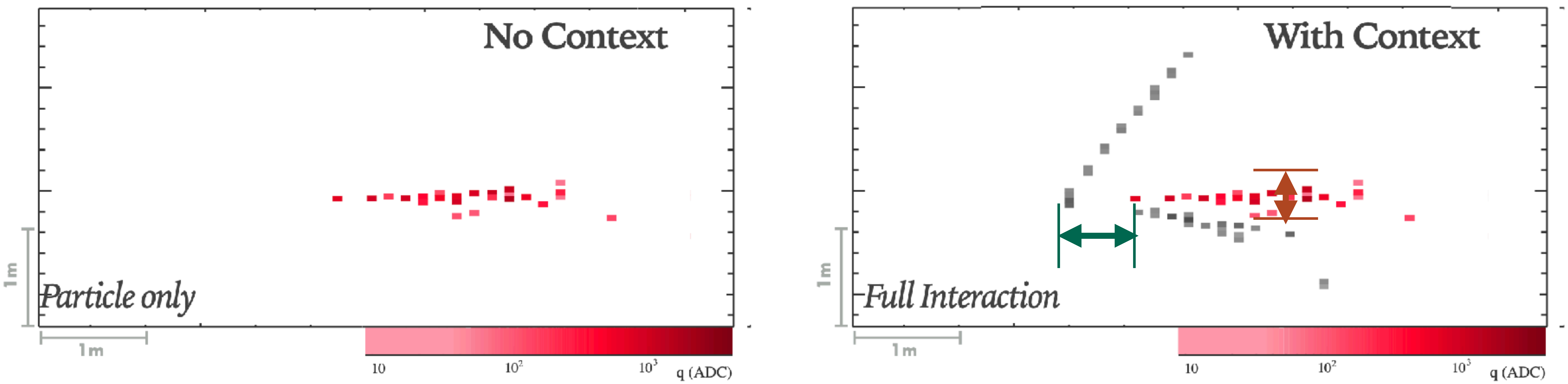
Single particles are separated using geometric reconstruction methods

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



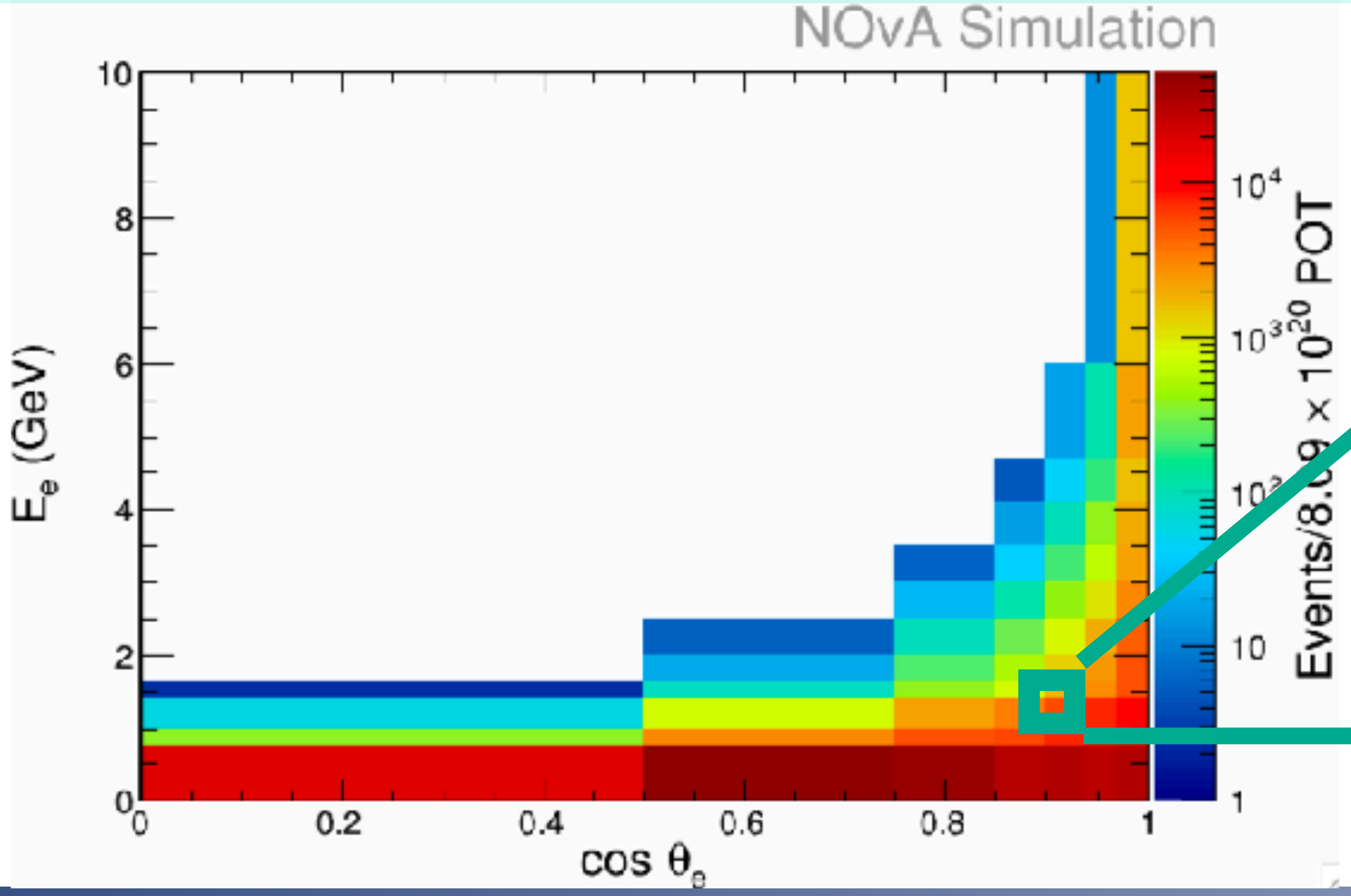
First ν_e CC double differential measurement

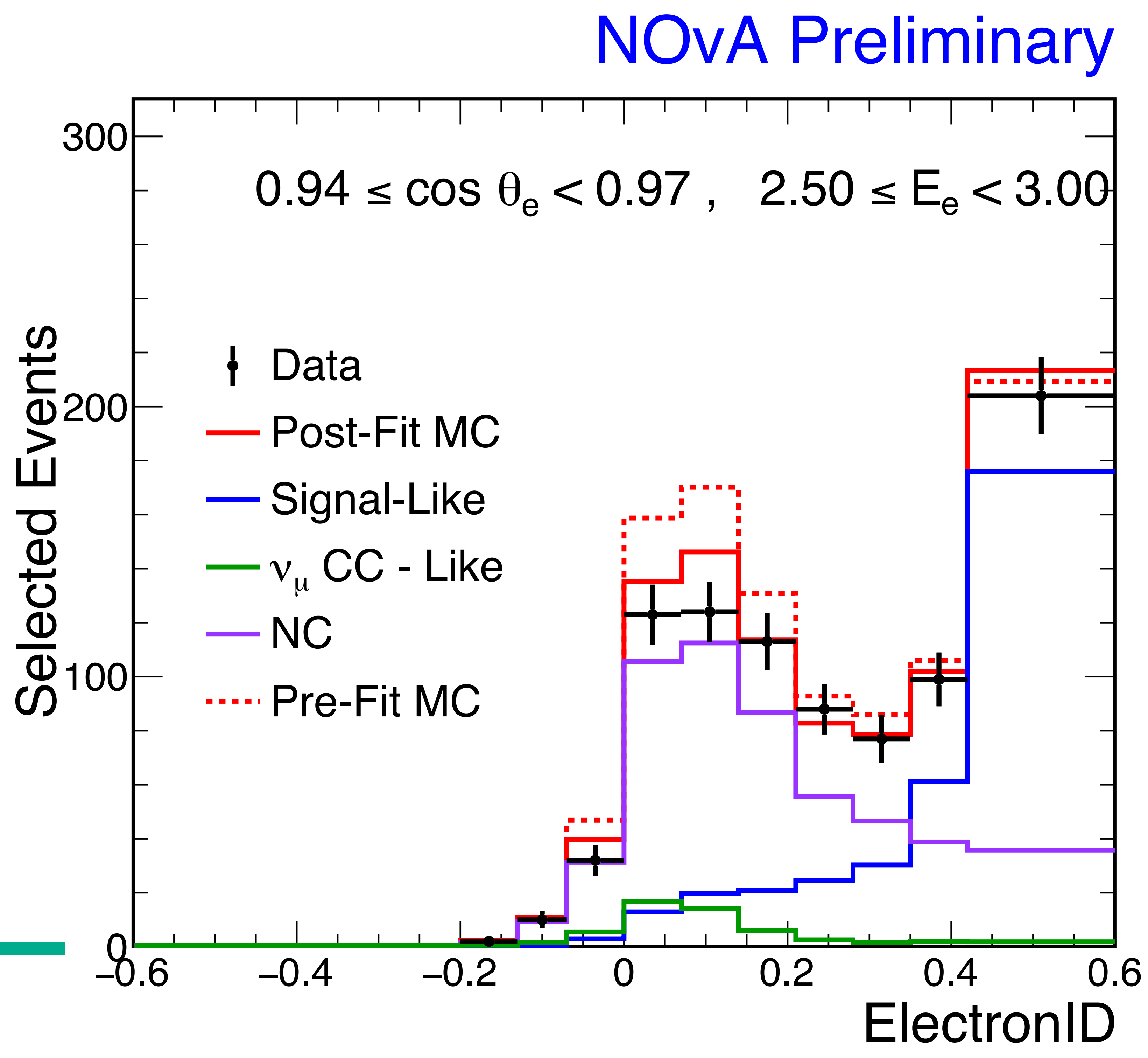
$$\left(\frac{d^2\sigma}{d\cos\theta_e dE_e}\right)_i = \sum_j \left(\frac{U_{ij}^{-1}(N^{\rm sel}(\cos\theta_e, E_e)_j - N^{\rm bkg}(\cos\theta_e, E_e)_j)}{N_{\rm t}\Phi\epsilon(\cos\theta_e, E_e)_{ik}\Delta\cos\theta_{e_i}\Delta E_{e_i}}\right)$$

- 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.

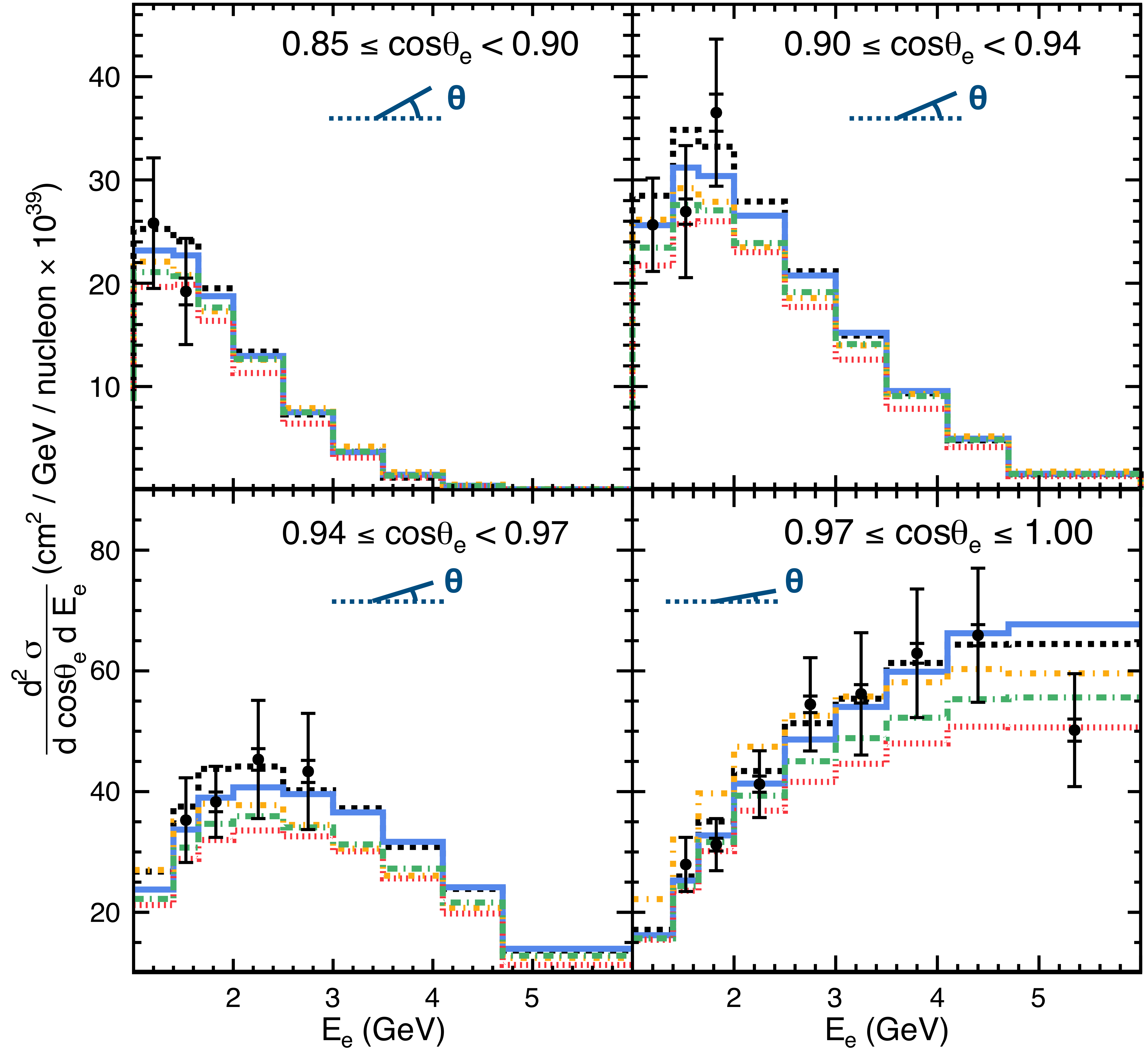
$$\chi^2 = (x_i - \mu_i)^T V_{ij}^{-1} (x_j - \mu_j)$$

i = (E_e , cos θ_e , ElectronID)





First ν_e CC inclusive double-differential measurement



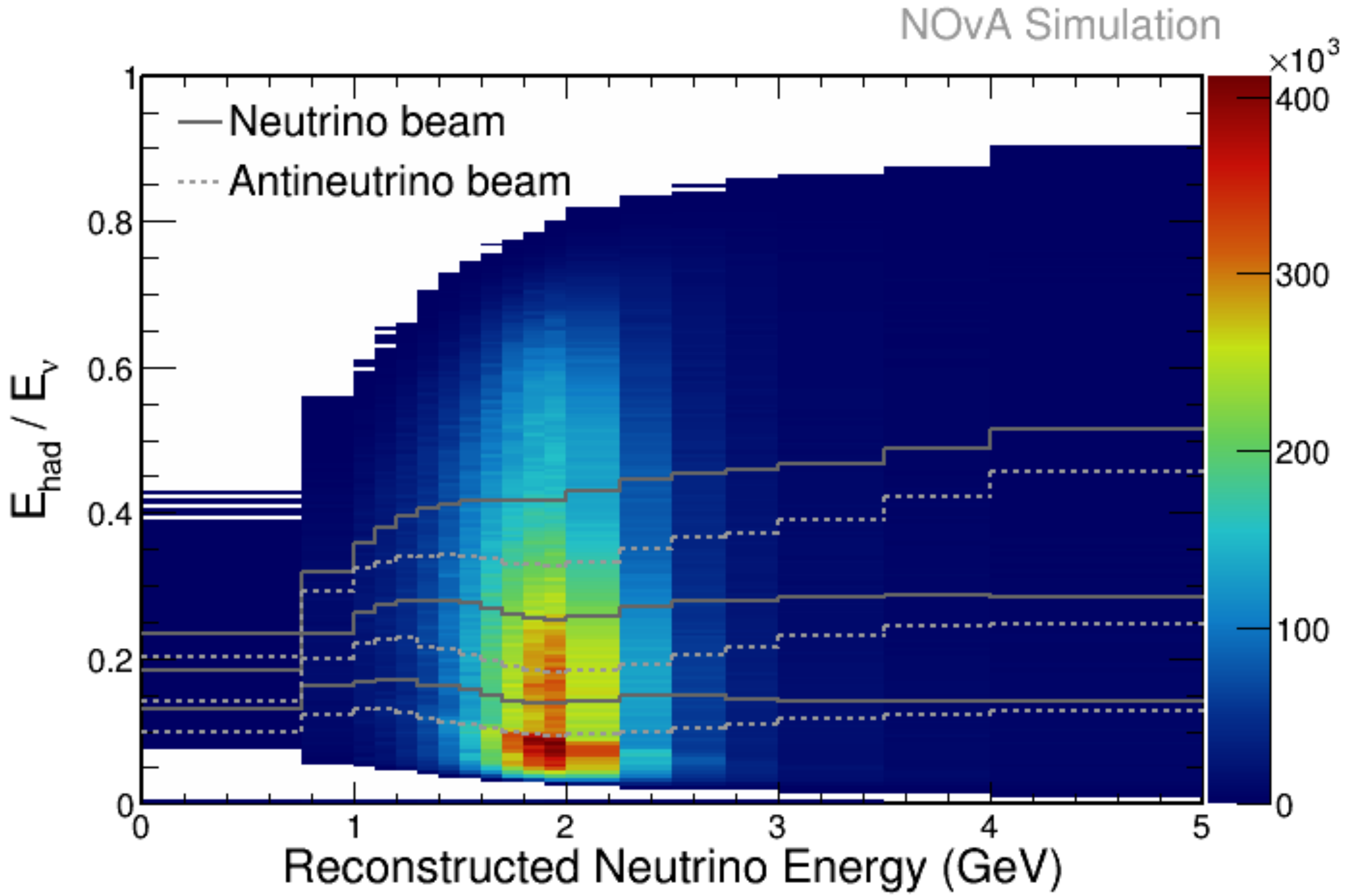
https://arxiv.org/abs/2206.10585
Accepted by PRL

- 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**

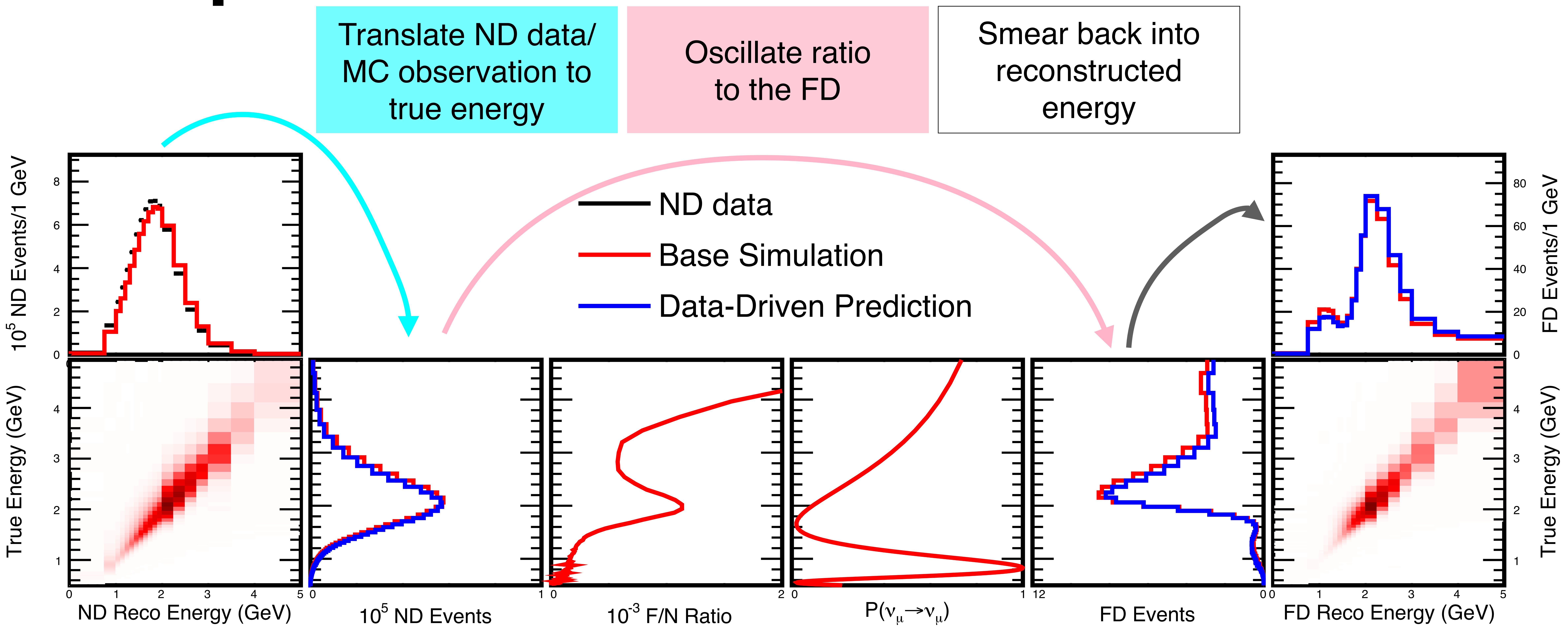
ν_μ energy resolution quartiles

- 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.



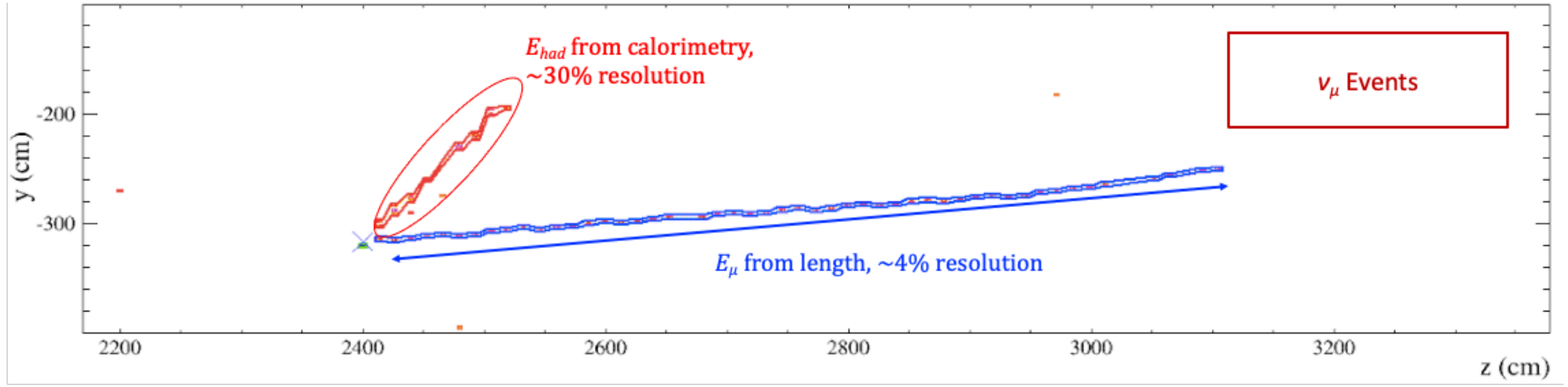
https://doi.org/10.1103/PhysRevD.106.032004

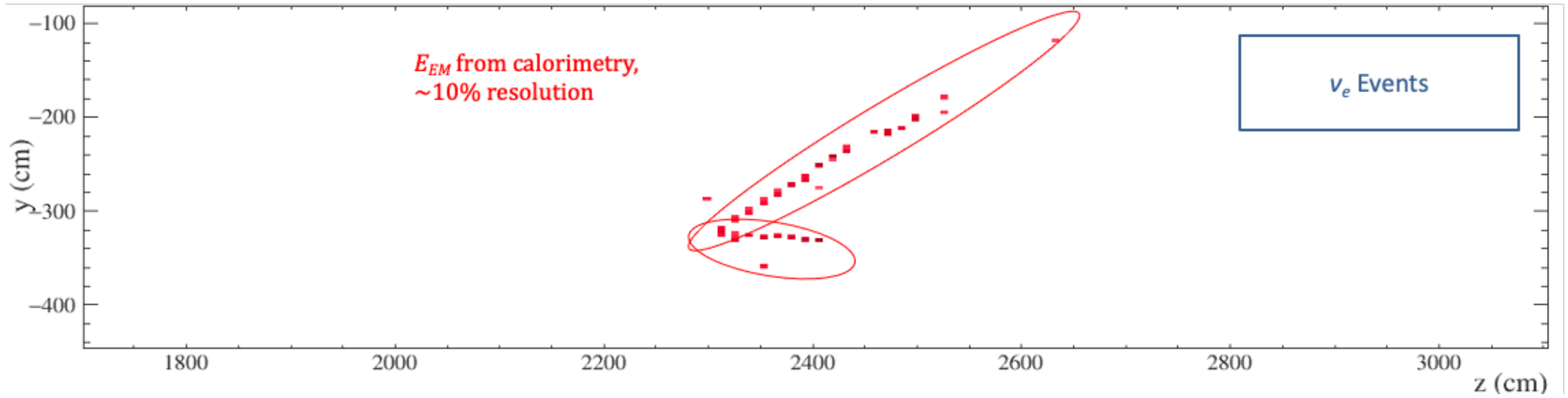
Extrapolation



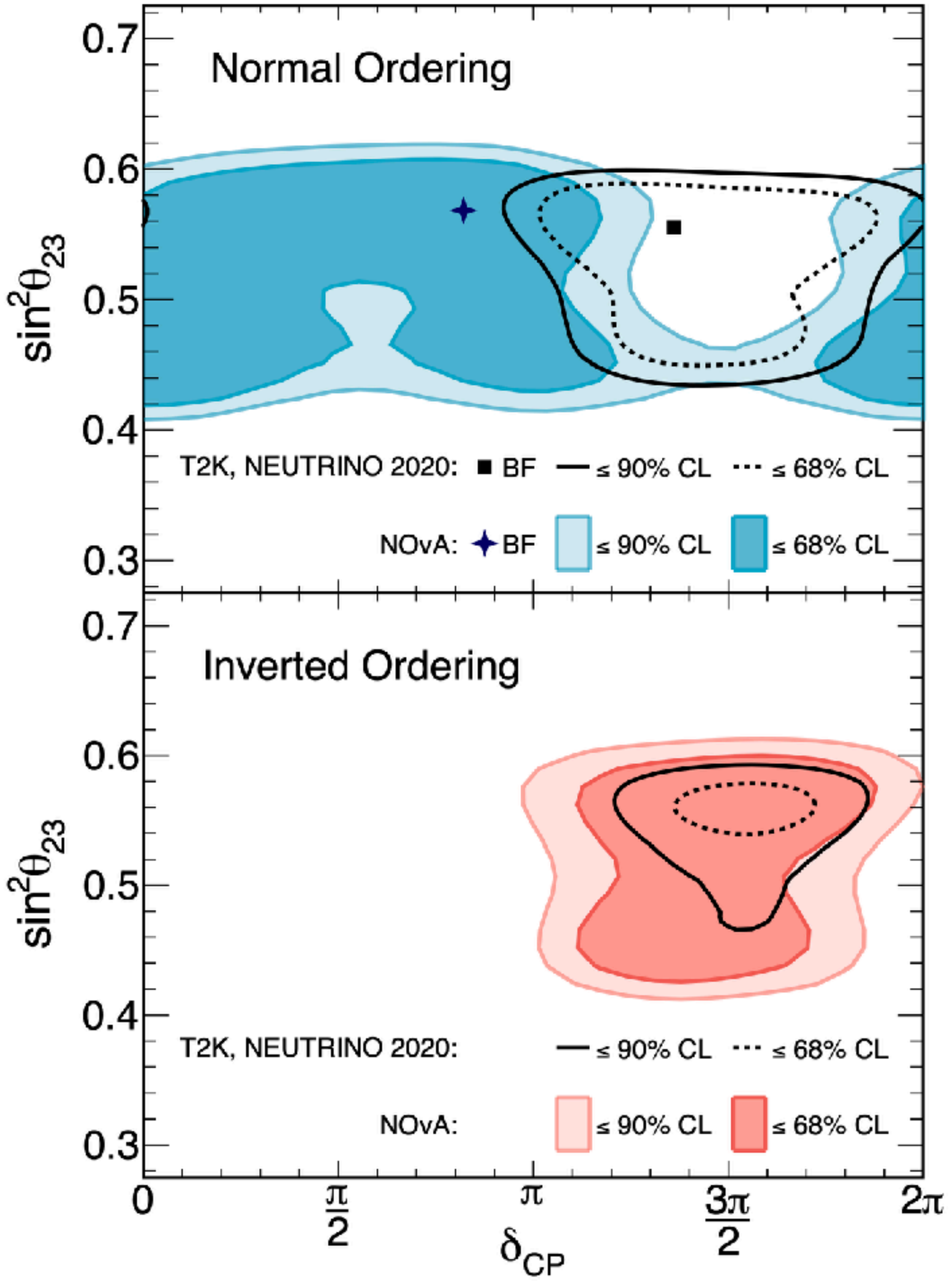
- Since NOvA has functionally similar Near and Far Detectors the flux combined with the cross sections uncertainties largely cancel.

Energy reconstruction

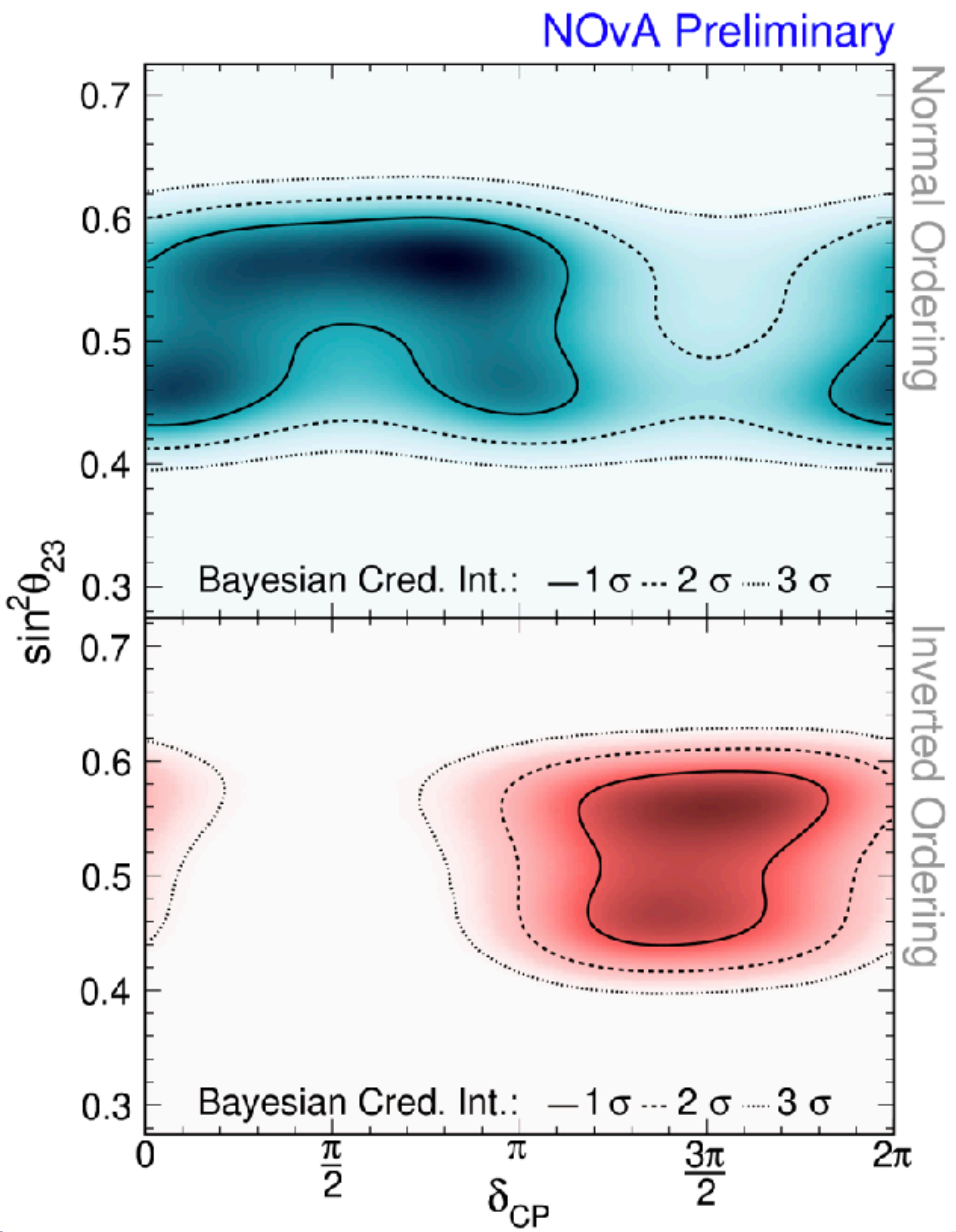


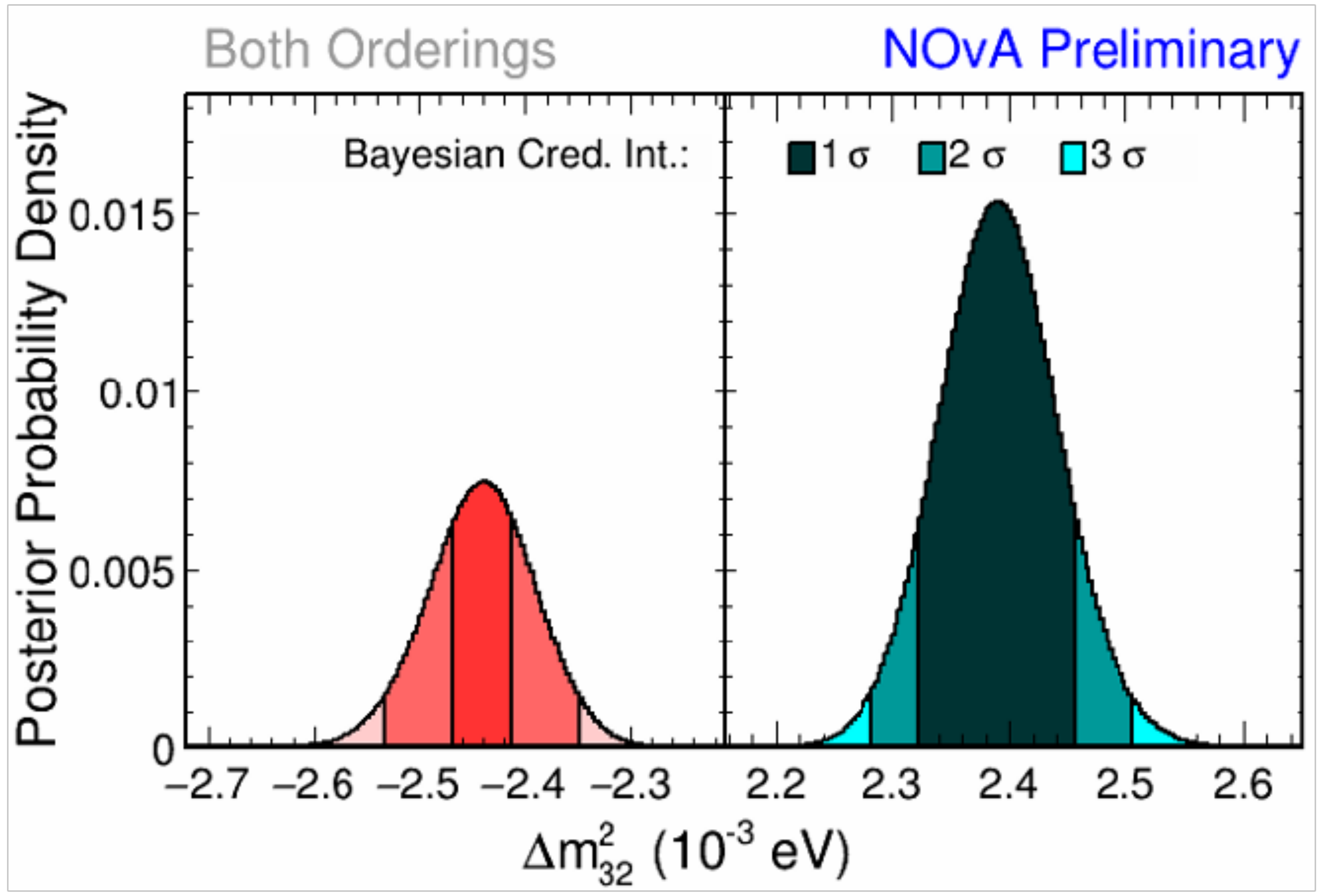


3-flavour fit results

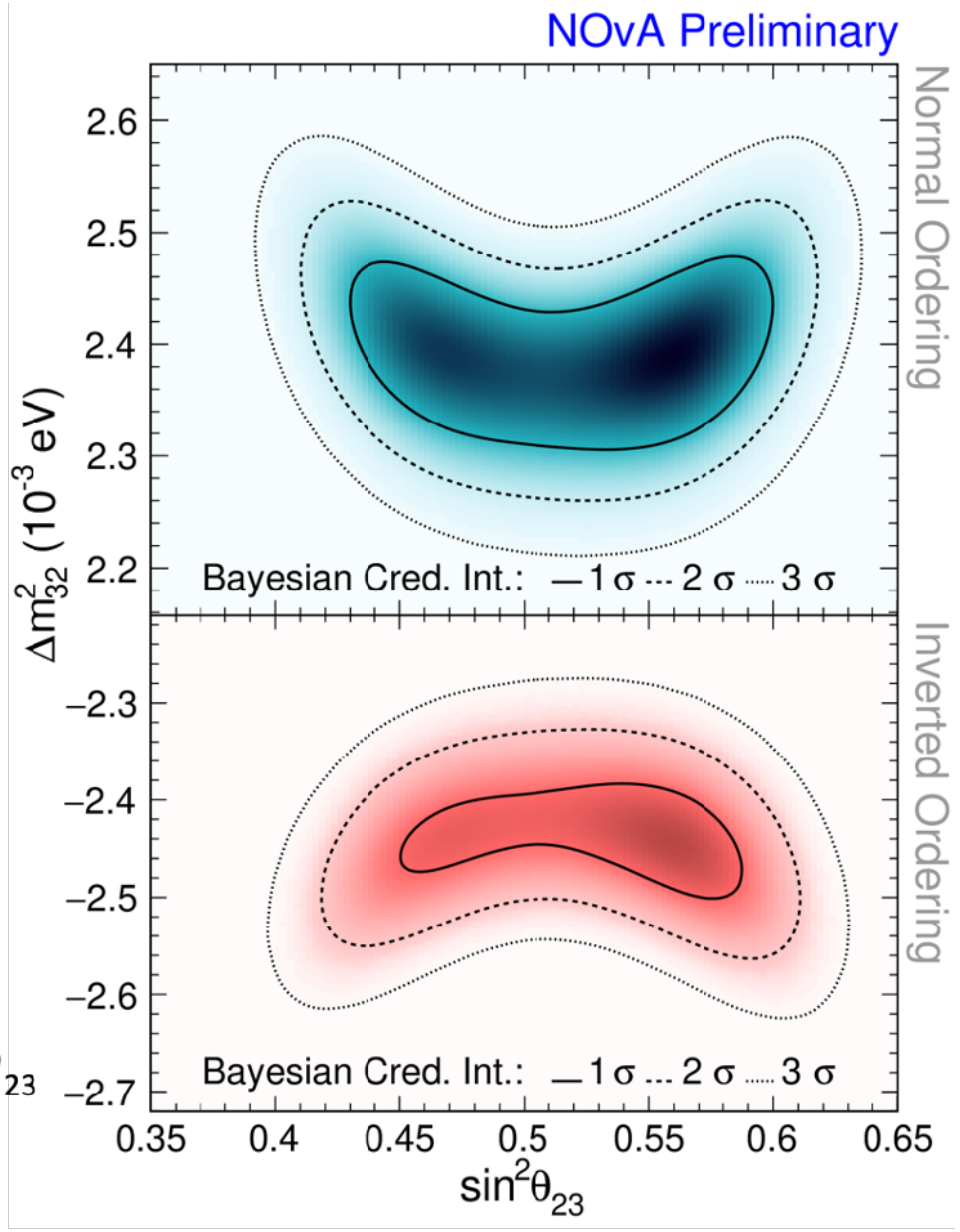


- Exclude IO, $\delta_{CP} = \pi/2$ at $> 3\ \sigma$
- Significant progress on joint fit with T2K
  - (coming soon)

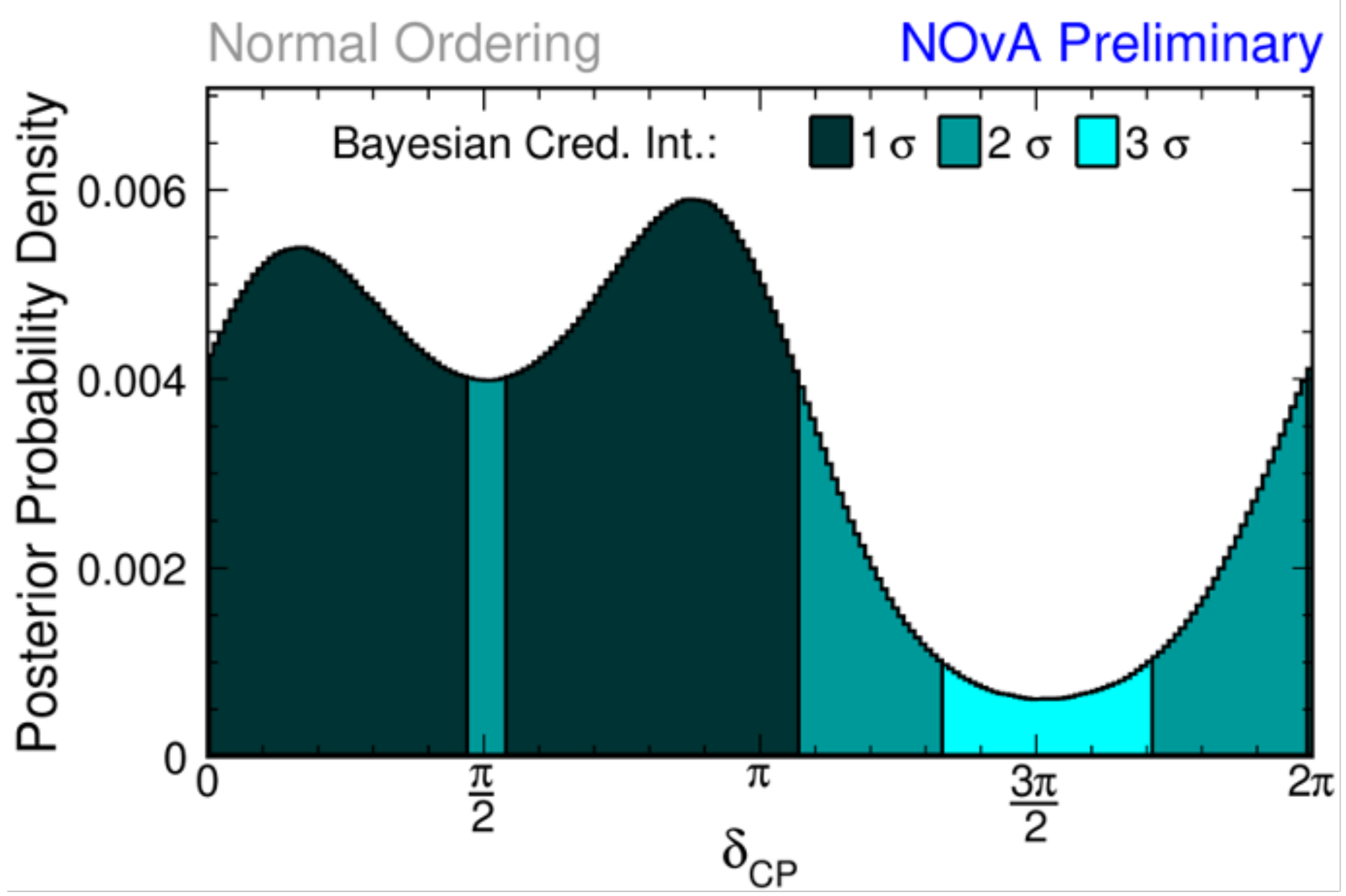


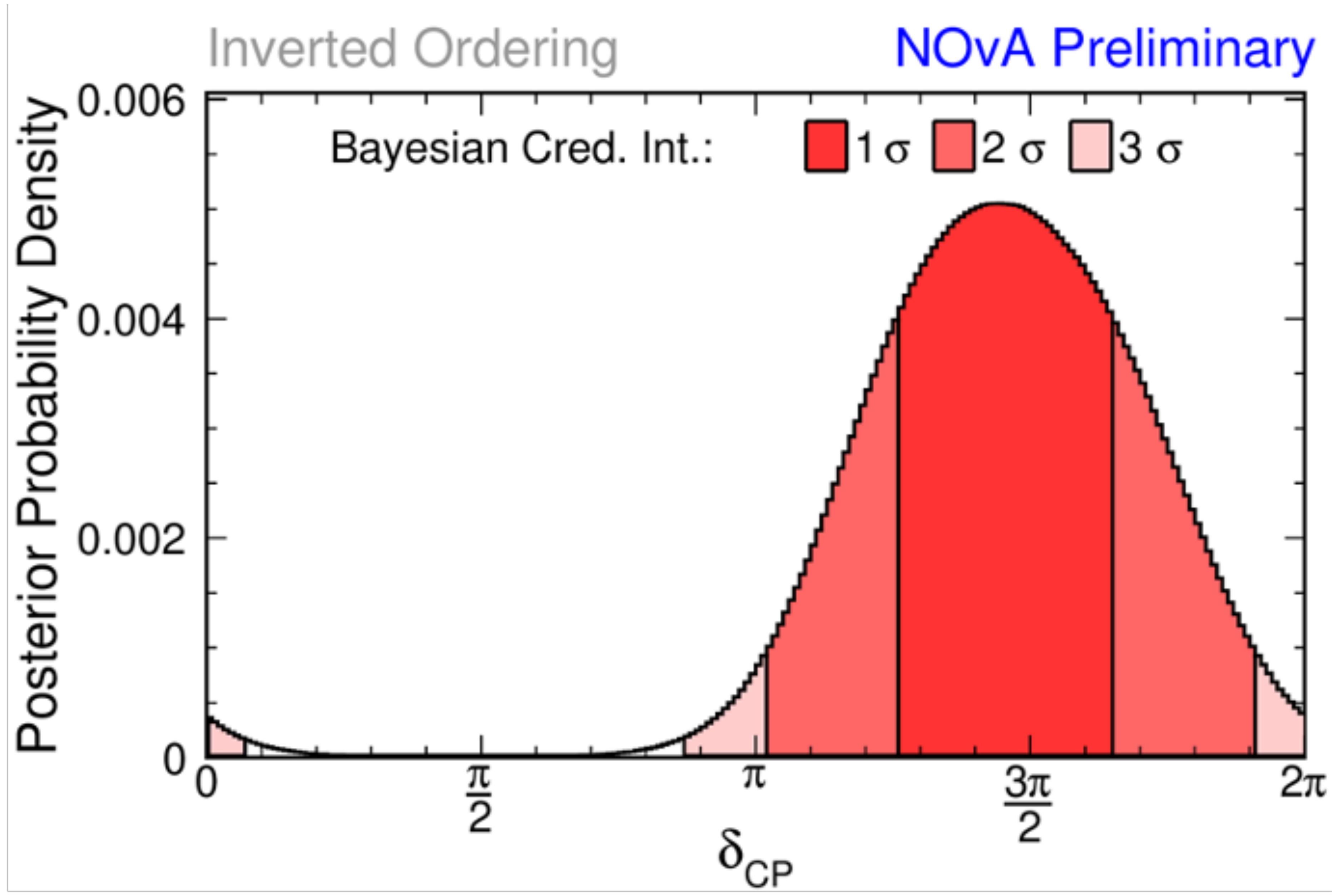


Posterior Probability	Lower Octant	Upper Octant	Sum
Normal Ordering	0.26	0.42	0.68
Inverted Ordering	0.11	0.21	0.32
Sum	0.37	0.63	1.00

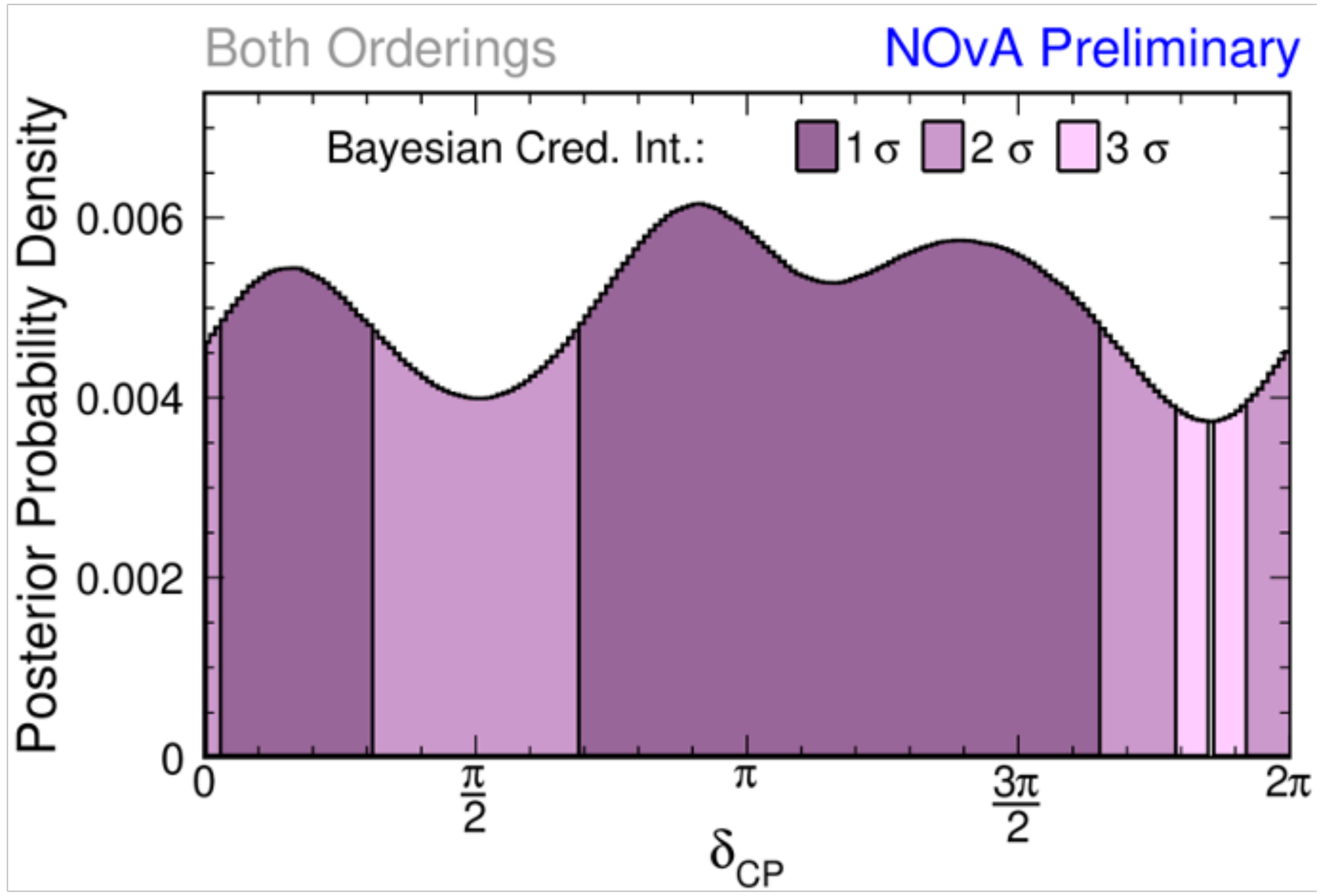


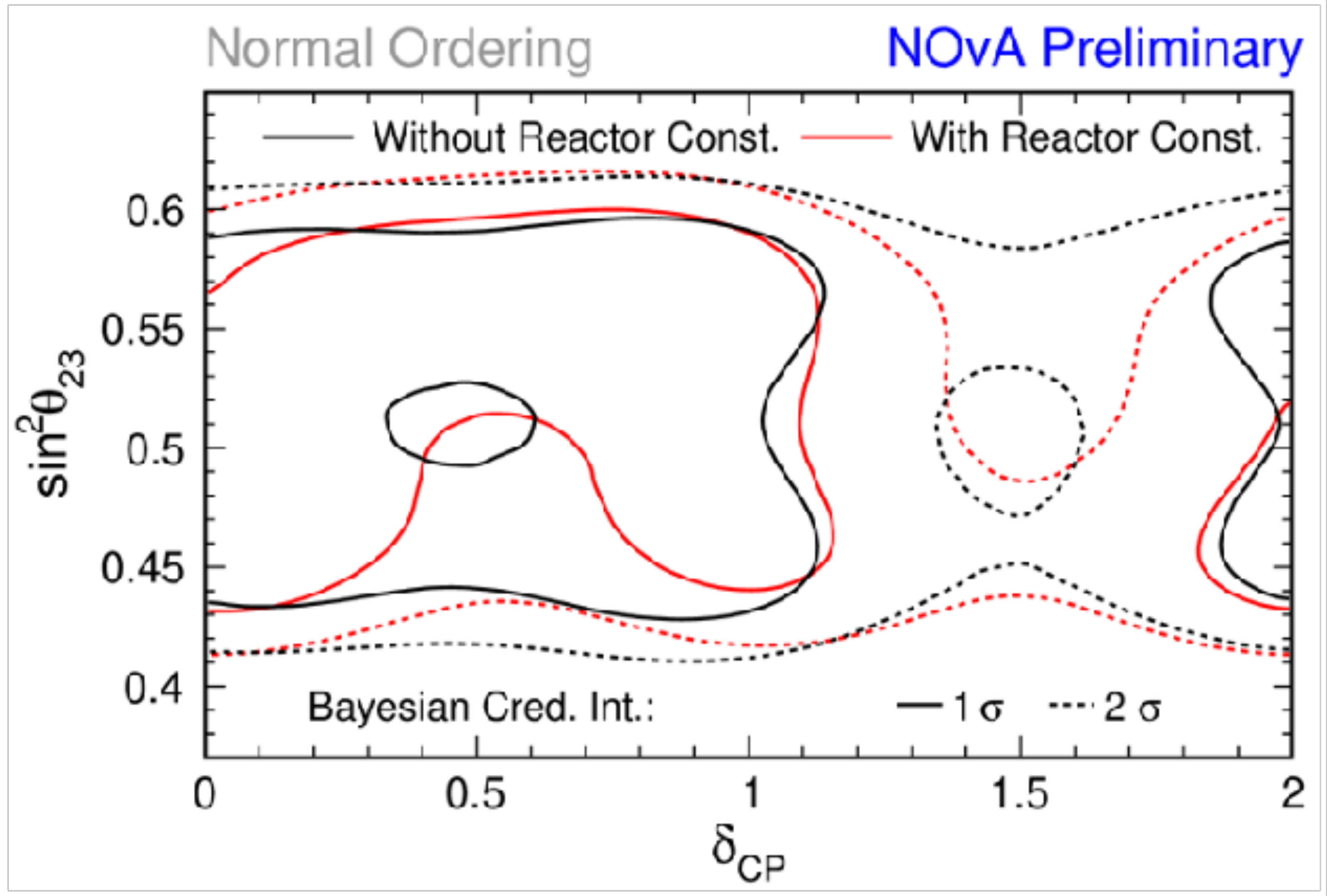
- Weak preference for upper octant of θ_{23} and Normal Mass Ordering.

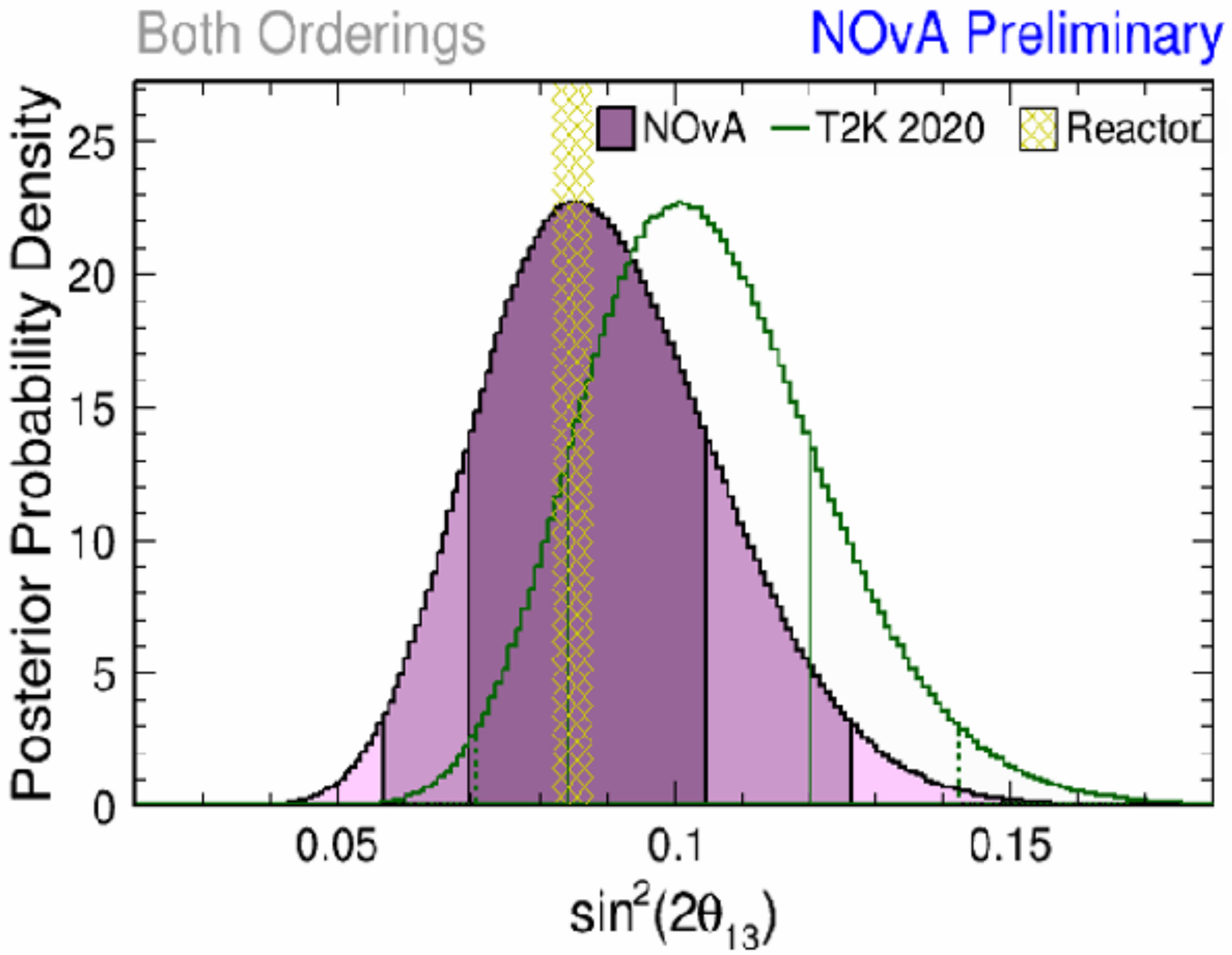




- CP violation more probable in the Inverted Mass Ordering.
- 3π/2 disfavoured in the Normal Ordering at more than 2σ Credible Interval.
- When both orderings taken into the account, no strong preference for *δ*.







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