Recent results on neutrino oscillations from NOvA

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Neutrinos oscillations

- Neutrinos change flavour as they travel
  - Nobel Prize 2015 for Kajita-san (SK) and Art McDonald (SNO)
- Oscillations depend on
  - Travel distance and energy of neutrinos
  - 3 angles of "rotation": θ_{12}, θ_{13} and θ_{23}
  - 2 differences of mass squared: Δm^2_{32} and Δm^2_{12}
  - 1 phase: δ_{CP}
  - Matter density (through the MSW effect)

- 3 neutrinos leading order disappearance probability:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \frac{1.27 \Delta m^2_{32} L}{E}$$

$$\Delta m^2_{32} = m^2_2 - m^2_3$$

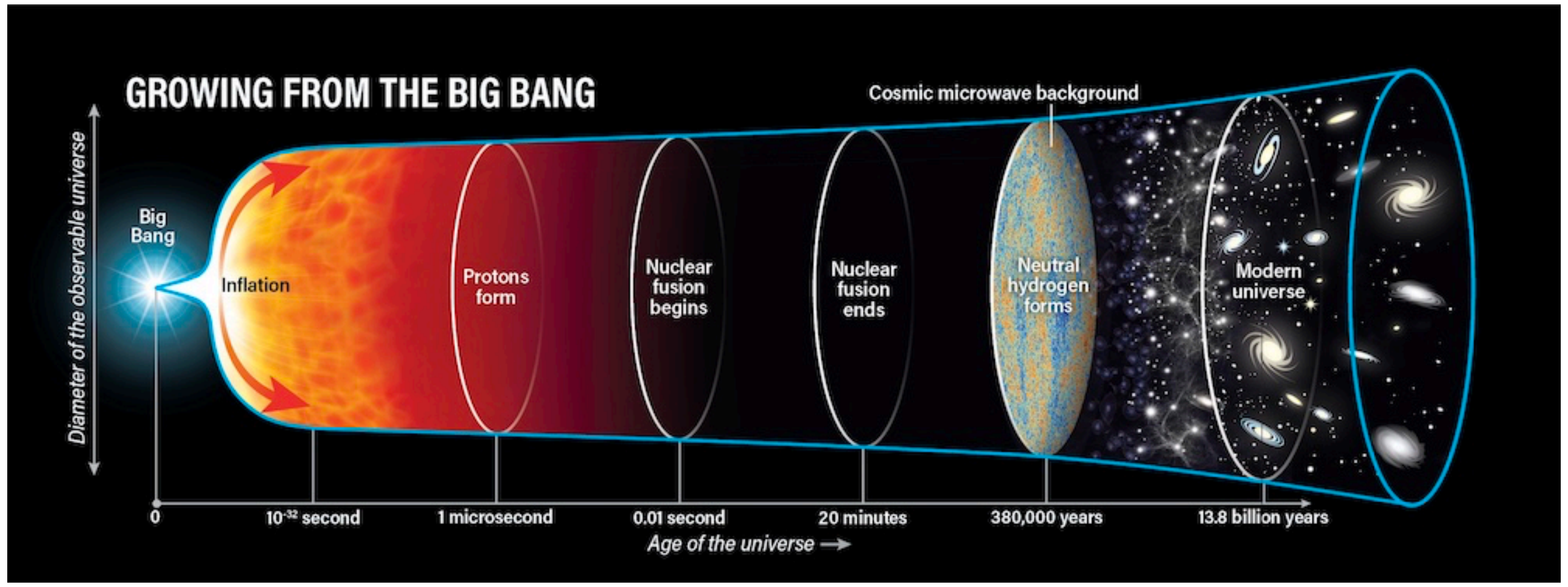
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric, beam}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{reactor, beam}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, reactor}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

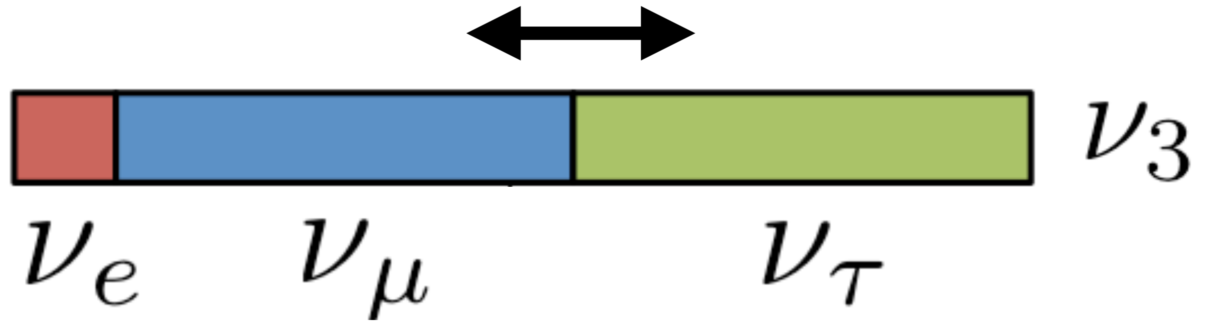
$$s_{ij} = sin\theta_{ij}$$

$$c_{ij} = cos\theta_{ij}$$

Neutrinos oscillations

- Unknowns left to discover/measure
  - θ_{23} octant / maximal mixing: is $\sin^2\theta_{23} = 0.5$?
  - Mass ordering: sign of Δm^2_{32}?
  - Charge parity violation: is $\delta_{CP} \neq 0$?





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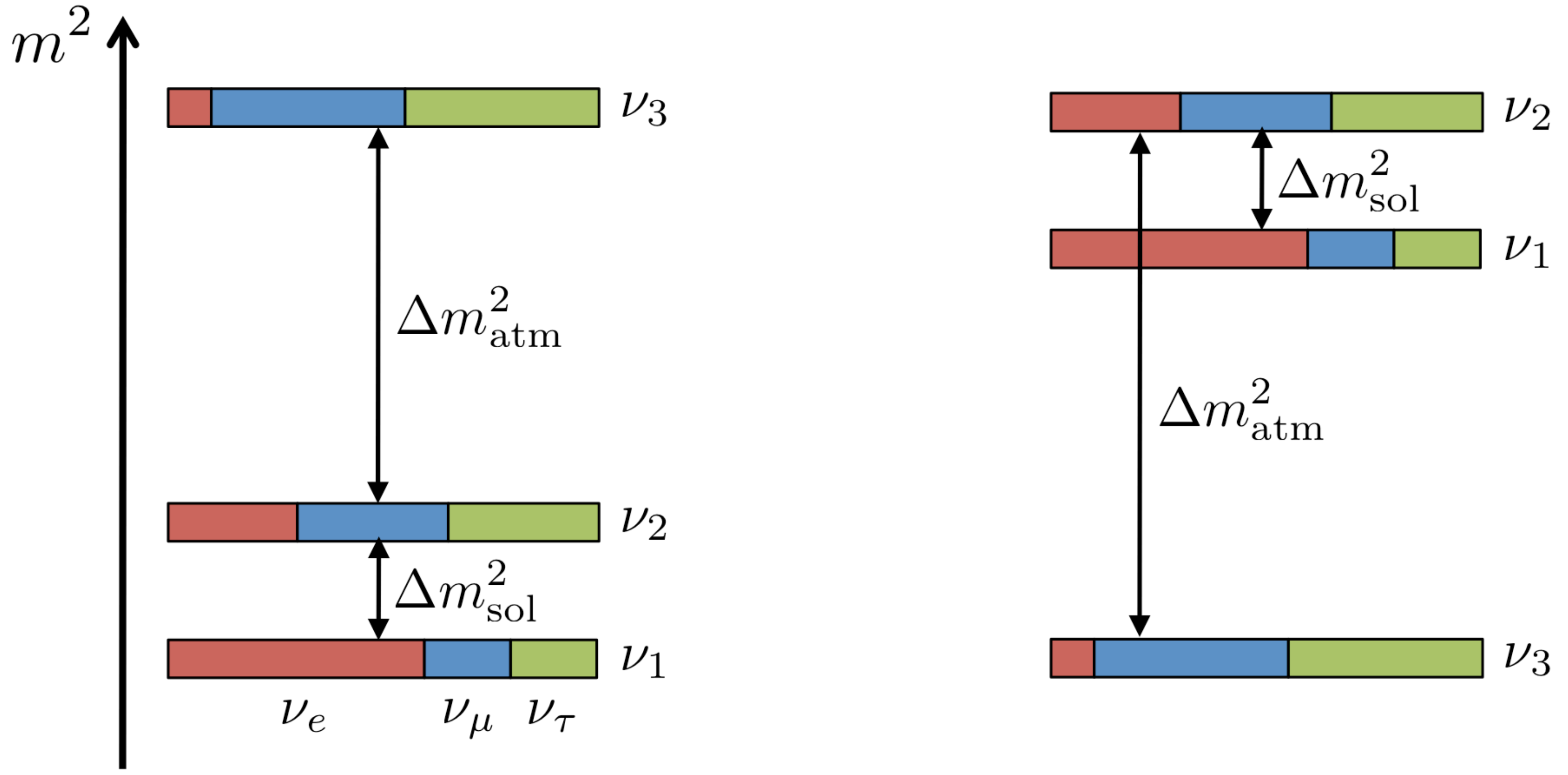


Normal ordering

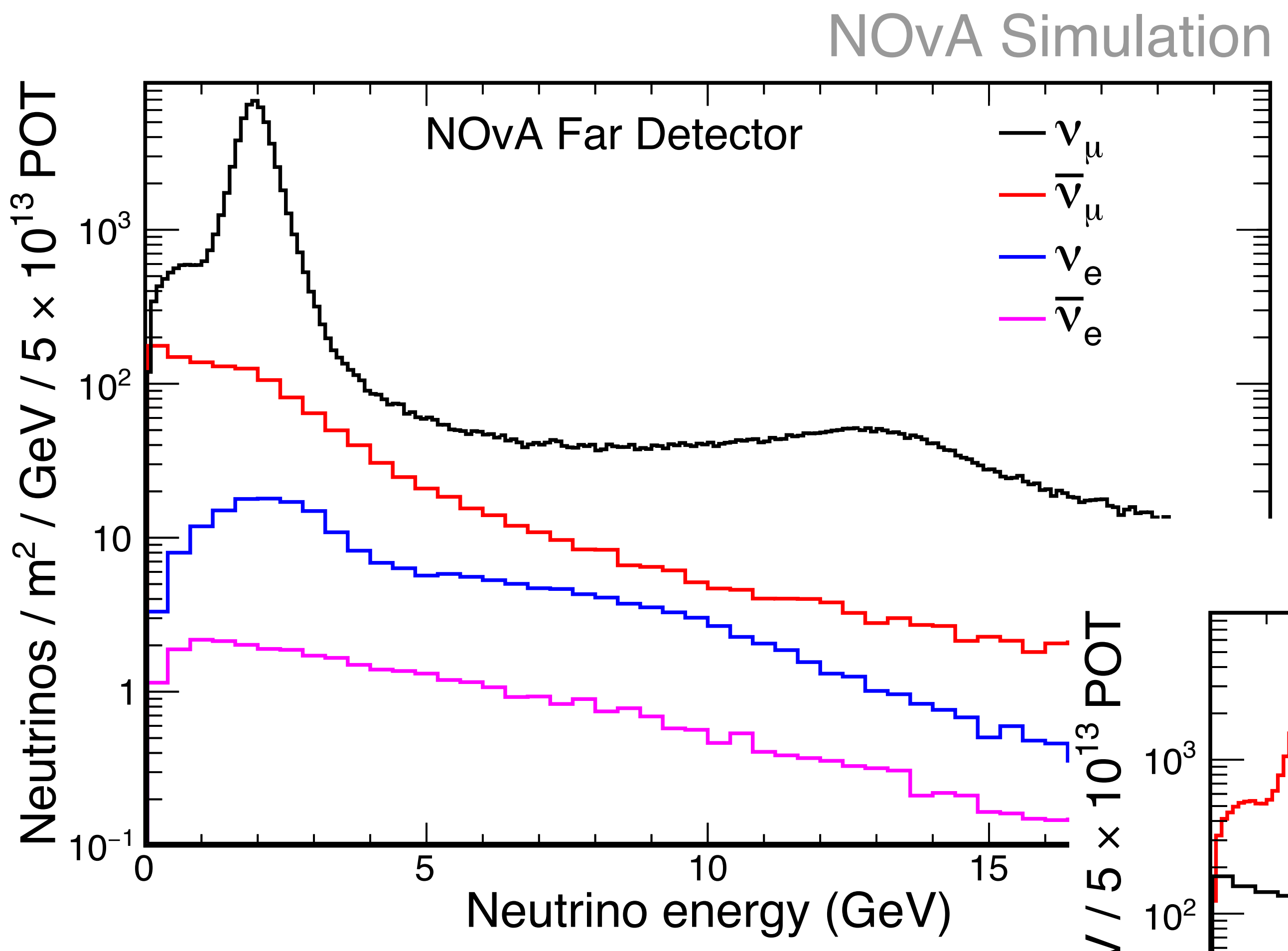
Inverted ordering

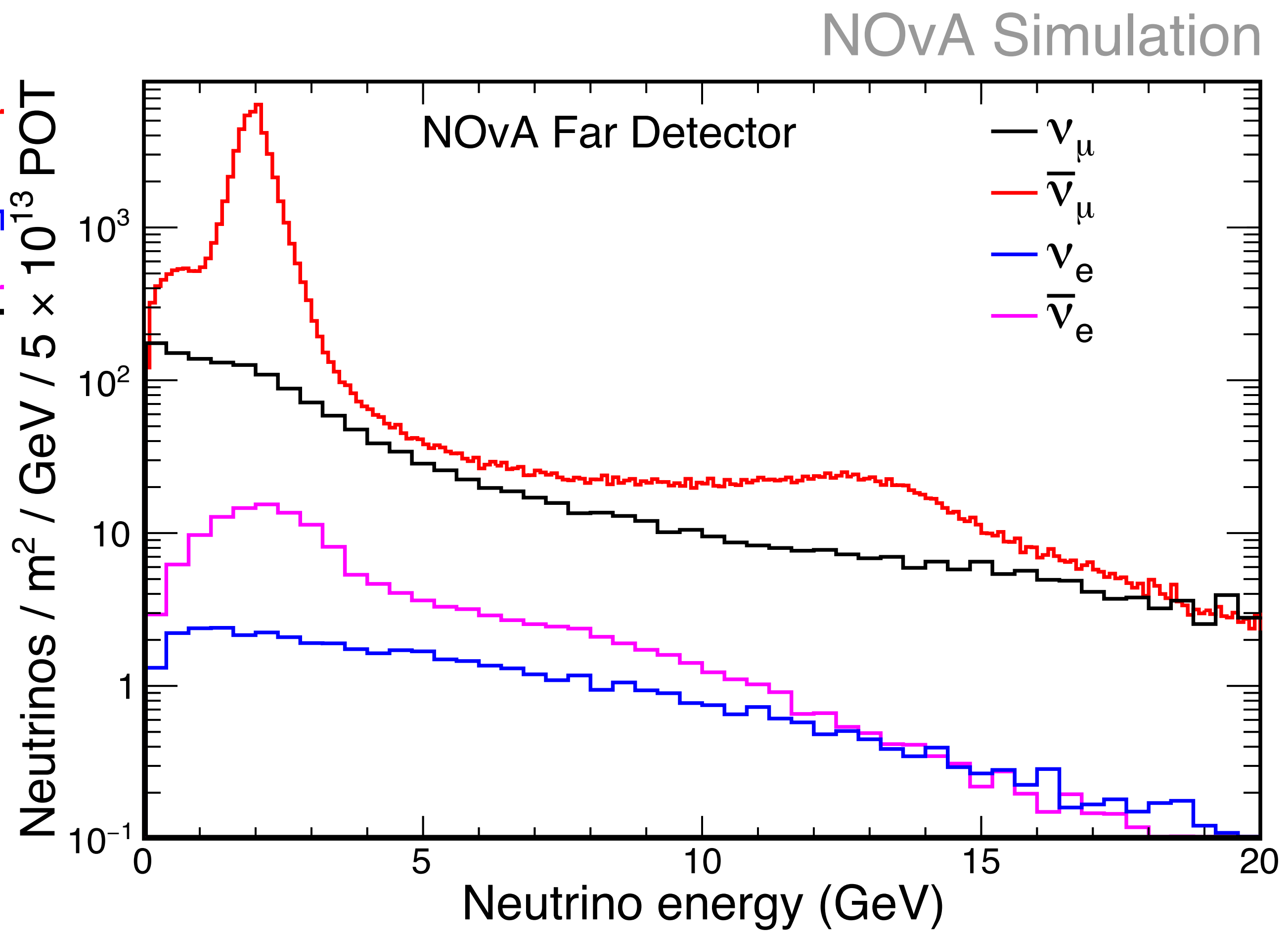
NOvA experiment

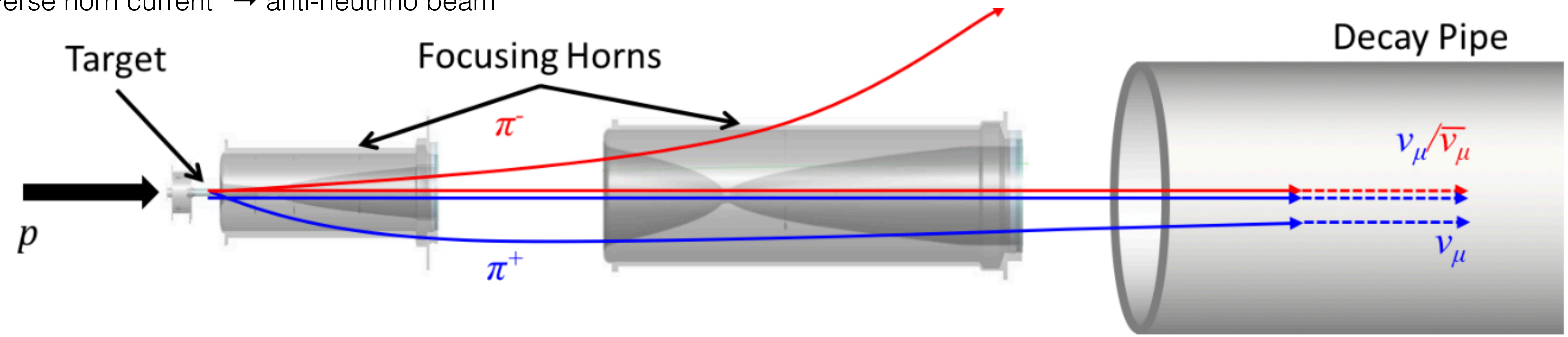
- NOvA (NuMI Off-axis electron-ν Appearance experiment)
  - Long baseline neutrino experiment
  - Taking data since 2014, ~250 physicists
  - Aims to measure ν_μ disappearance and ν_e appearance in a ν_μ beam
- 3 parts
  - NuMI proton accelerator, target and neutrino beam line producing a 2 GeV ν_μ beam (km 0) @ Fermilab
  - Near detector (300 tonnes of liquid plastic scintillator, 1 km away) @ Fermilab
  - Far detector (14 ktonnes, 810 km away) @ Ash River

NuMI beam

- NuMI proton accelerator
  - Capable of delivering ~850 kW (current record at 893 kW) of 120 GeV protons
  - Collimated to a 1m graphite target
- Produces a lot of π, which decay into ν_μ
  - π propagate in an intense magnetic field produced by the horns and decay in the 675 m decay pipe
- Detectors sit 14 mrad from the beam axis and see ν_μ of energy 2 GeV (off-axis effect)
- Horn current can be inverted:
  - FHC “forward horn current” → neutrino beam
  - RHC “reverse horn current” → anti-neutrino beam

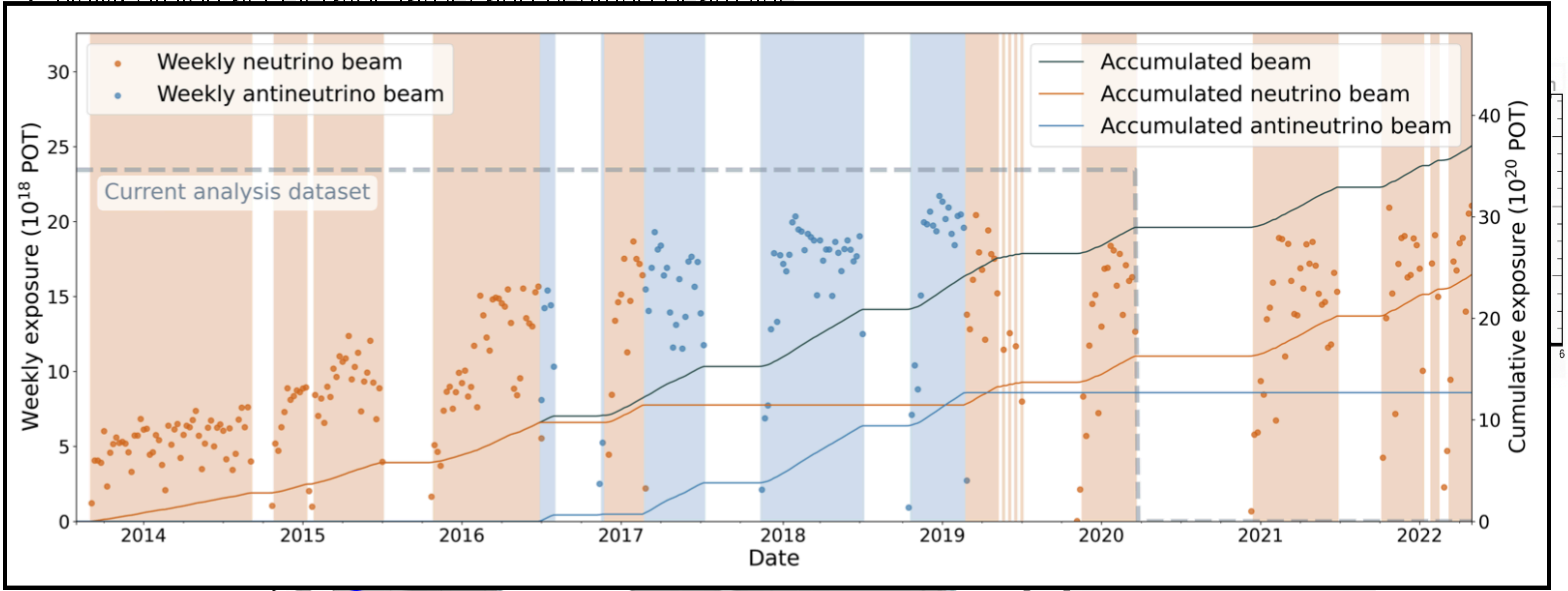






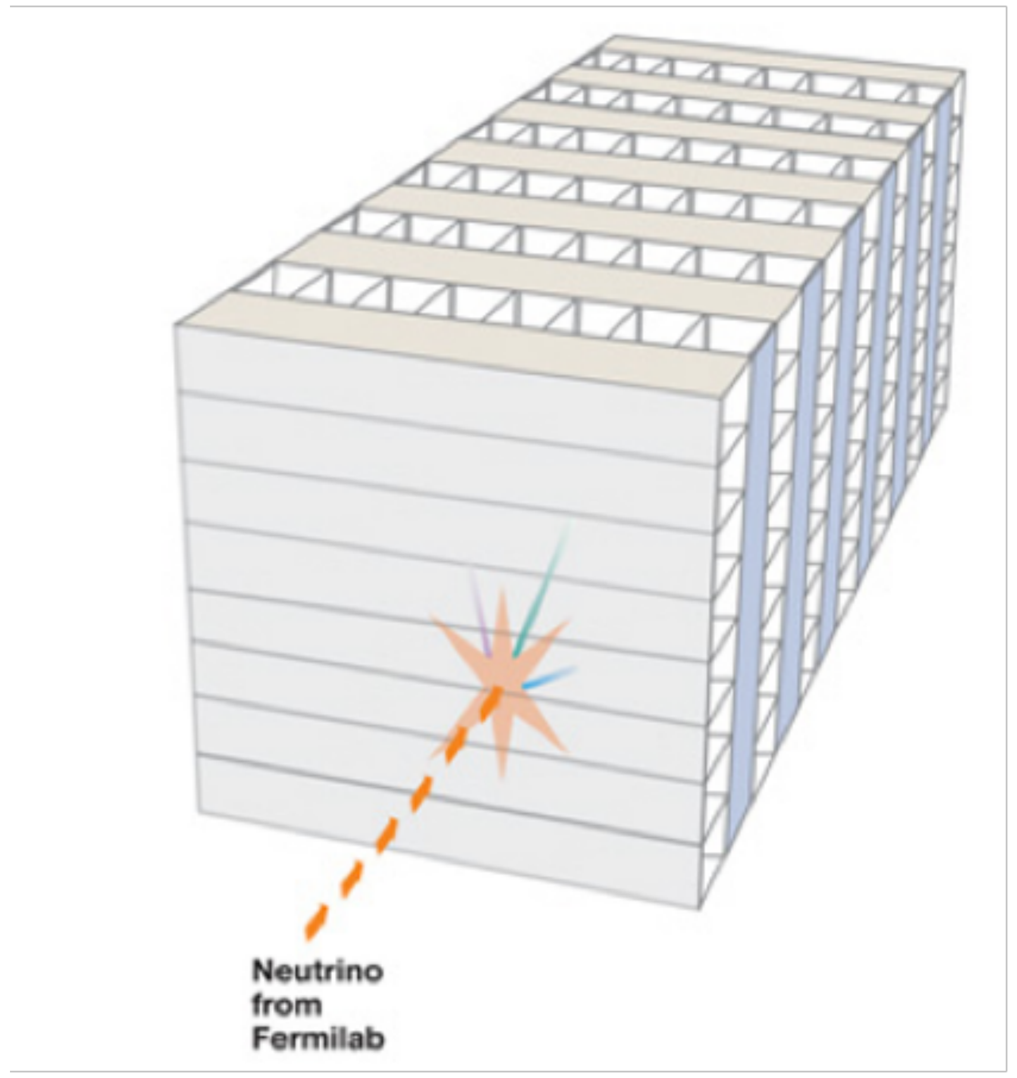
NuMI beam

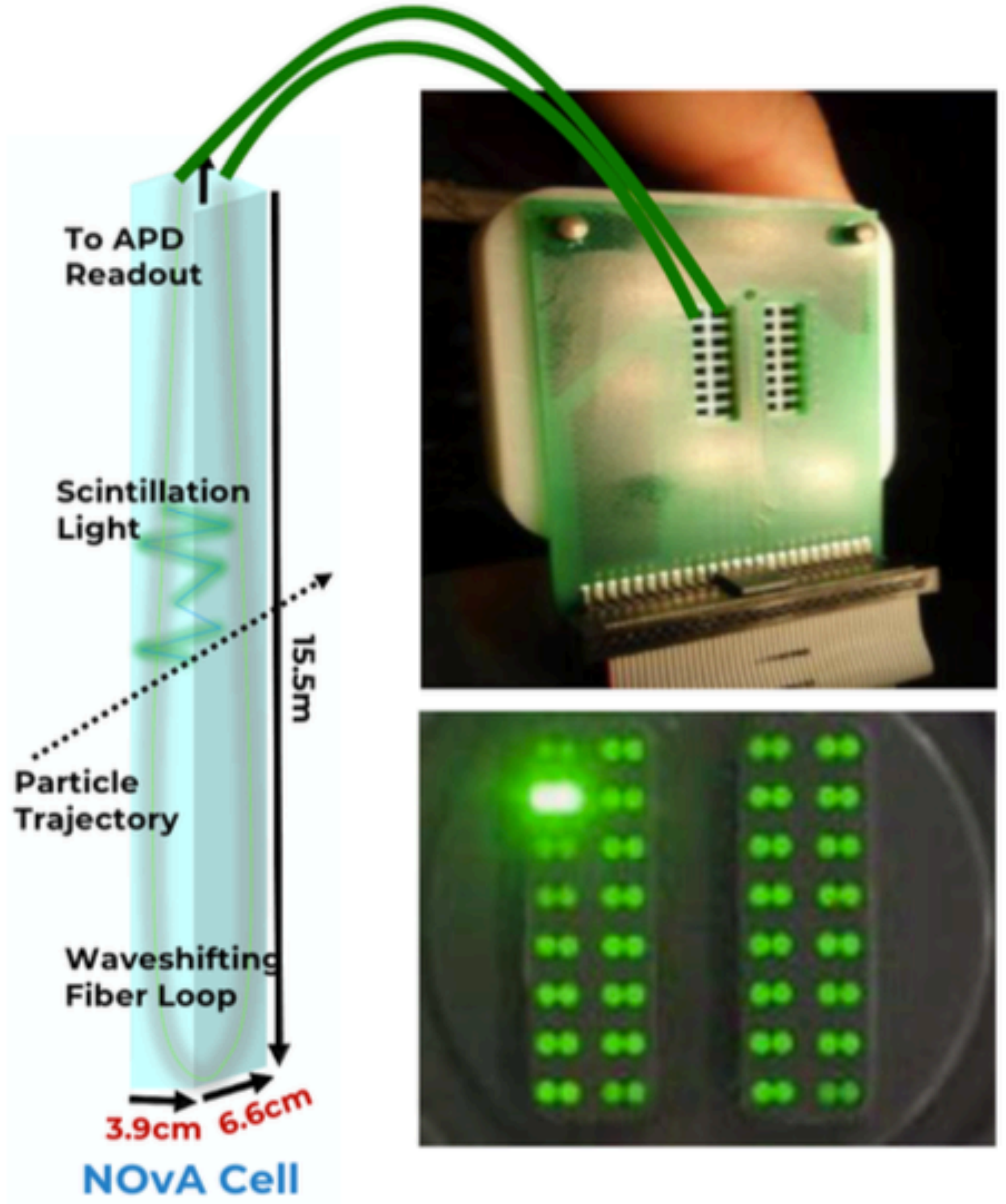
- NuMI proton accelerator, target and neutrino beam line



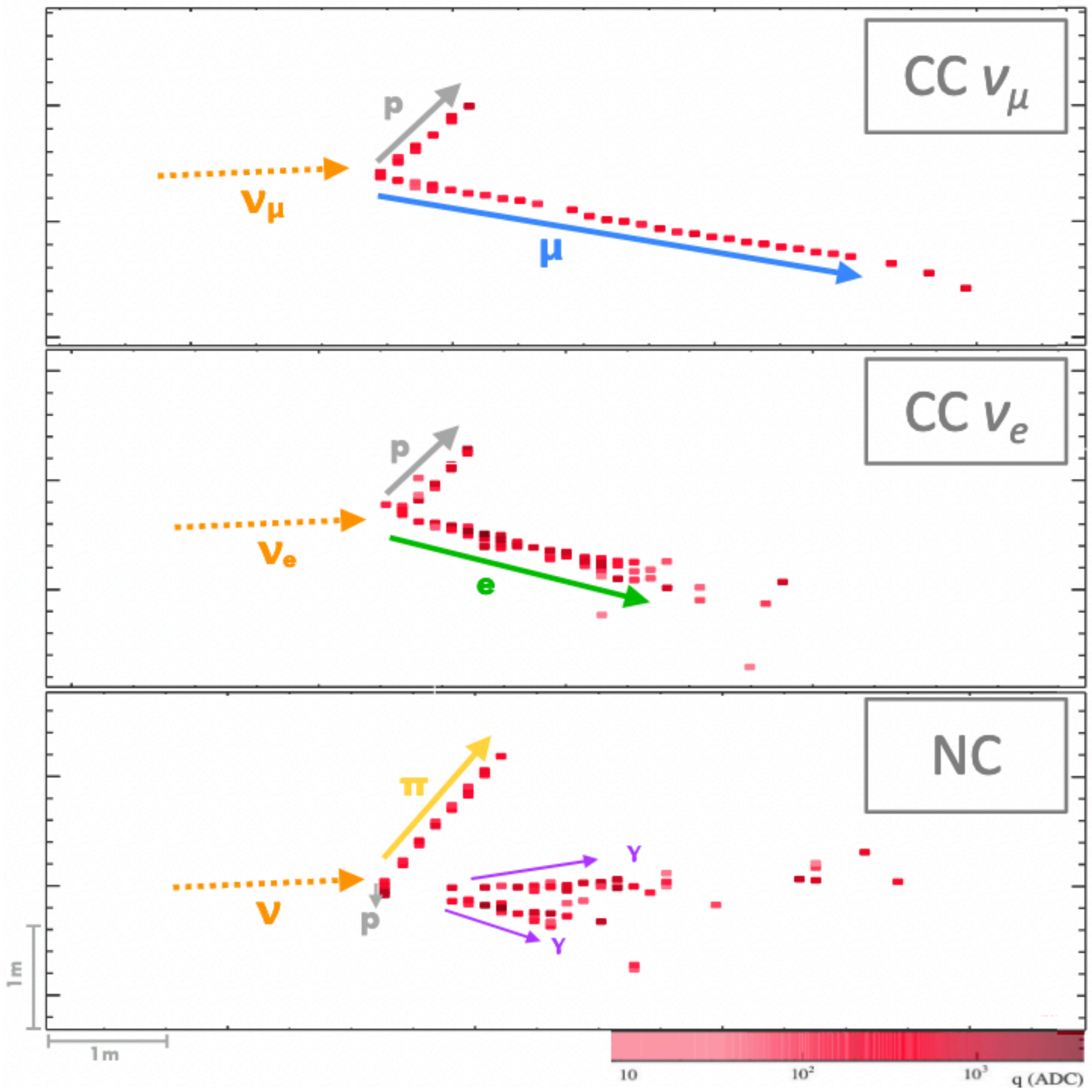
NOvA detectors

- Near and far detectors are functionally identical (km 1 and 810)
  - Tracking calorimeters
    - Extruded plastic cells filled with liquid scintillator
    - Alternate in vertical and horizontal position
  - Wavelength shifting fibre running through each cell
  - Avalanche Photodiode readout

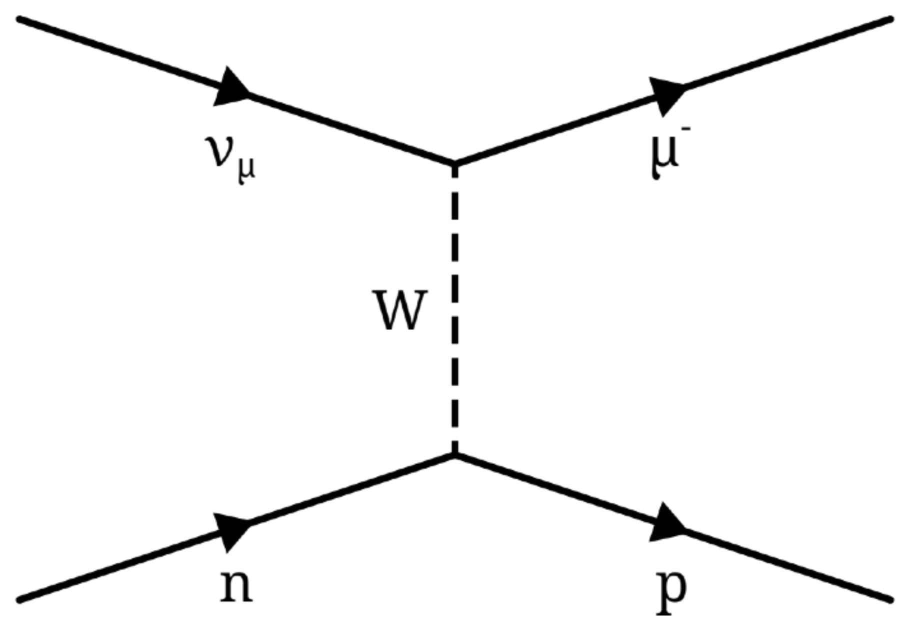




NOvA events



- Neutrino oscillation formula needs
  - ν flavour
  - L
  - E_ν

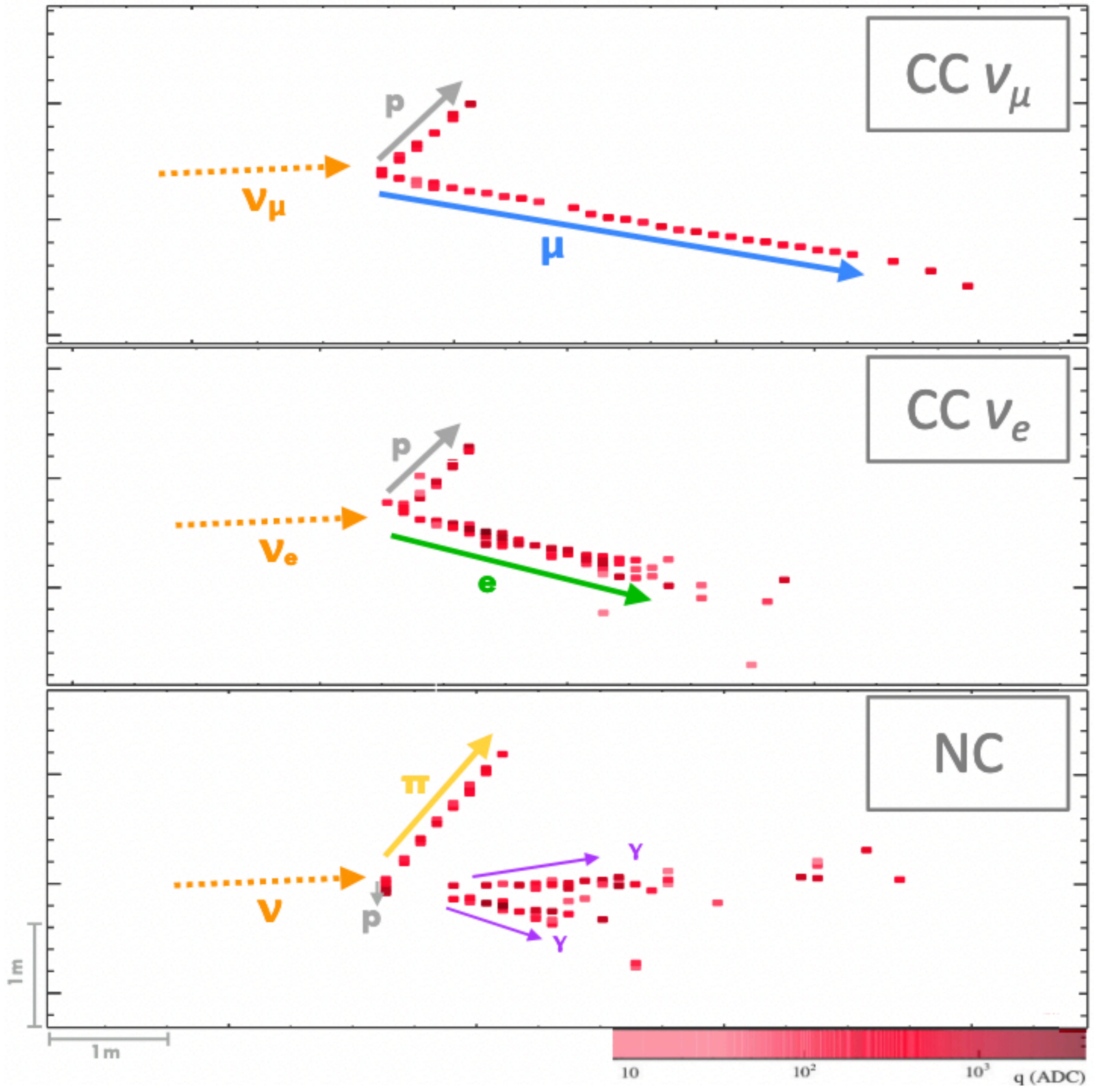


- Detailed images of the neutrino Charged Current (CC) events @ NOvA allows:
  - Event classification → Convolutional Neural Network
  - Energy reconstruction

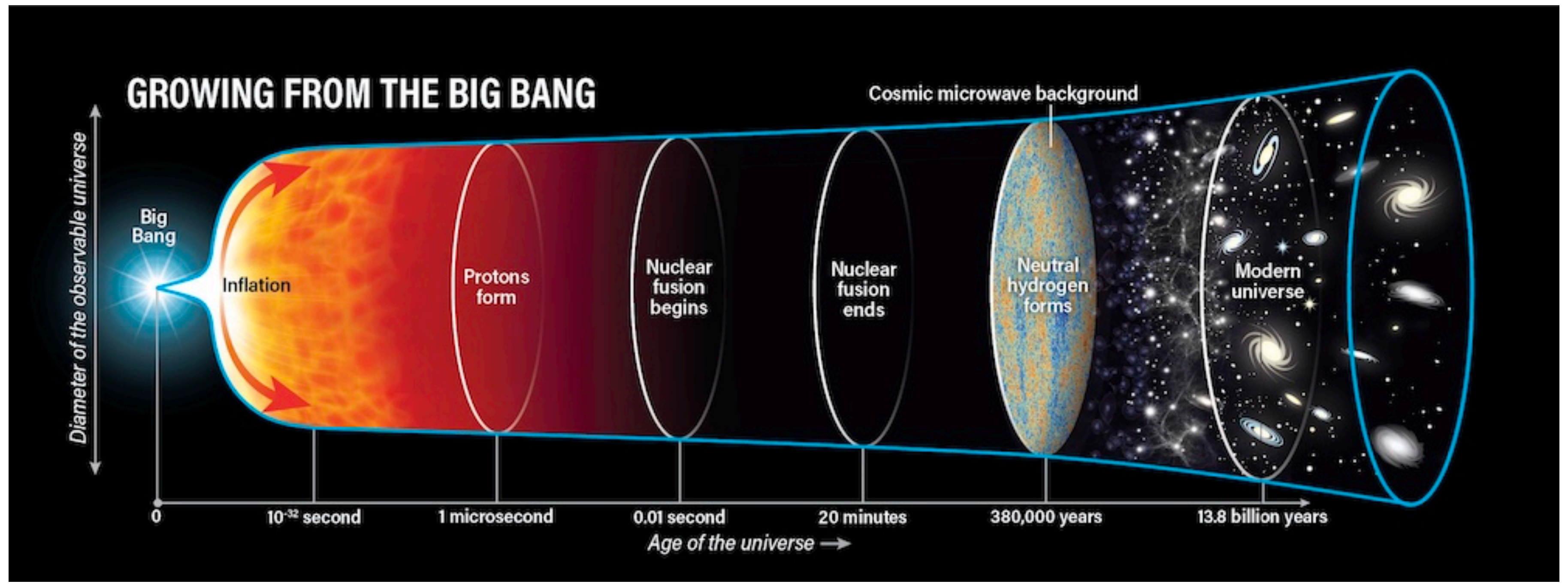
Imperial College London

Energy reconstruction

- Muon neutrinos CC: $E_{\nu_\mu} = E_{Had} + E_\mu$ (calorimetry and range) energy resolution: 9%
- Electron neutrinos CC: $E_{\nu_e} = f(E_{Had}, E_{EM})$ (both with calorimetric estimation) average energy resolution: 11%
- NC interactions: Calorimetry (14~17% resolution)

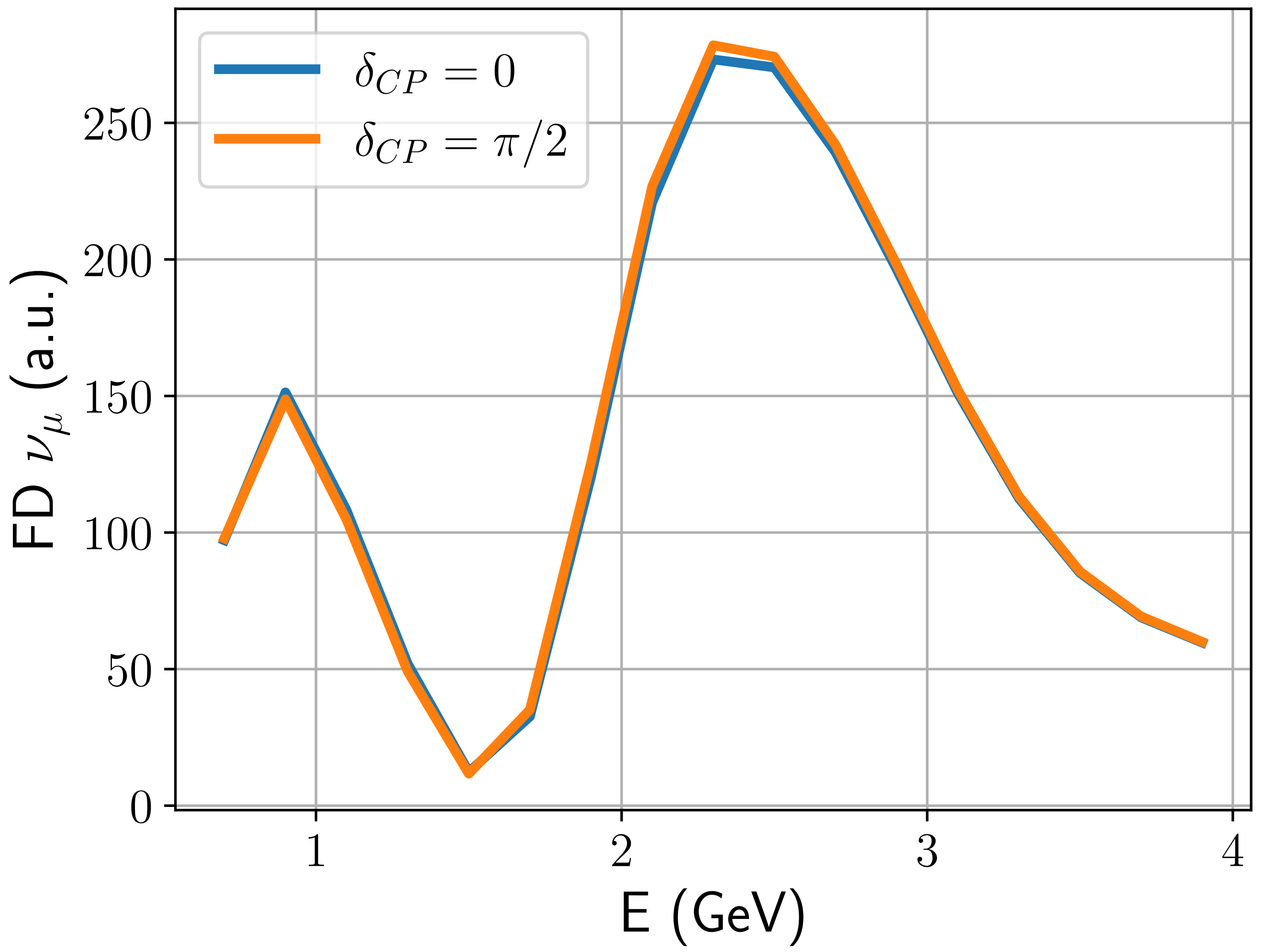


Why NOvA?
Far Detector True E_ν “mock study”



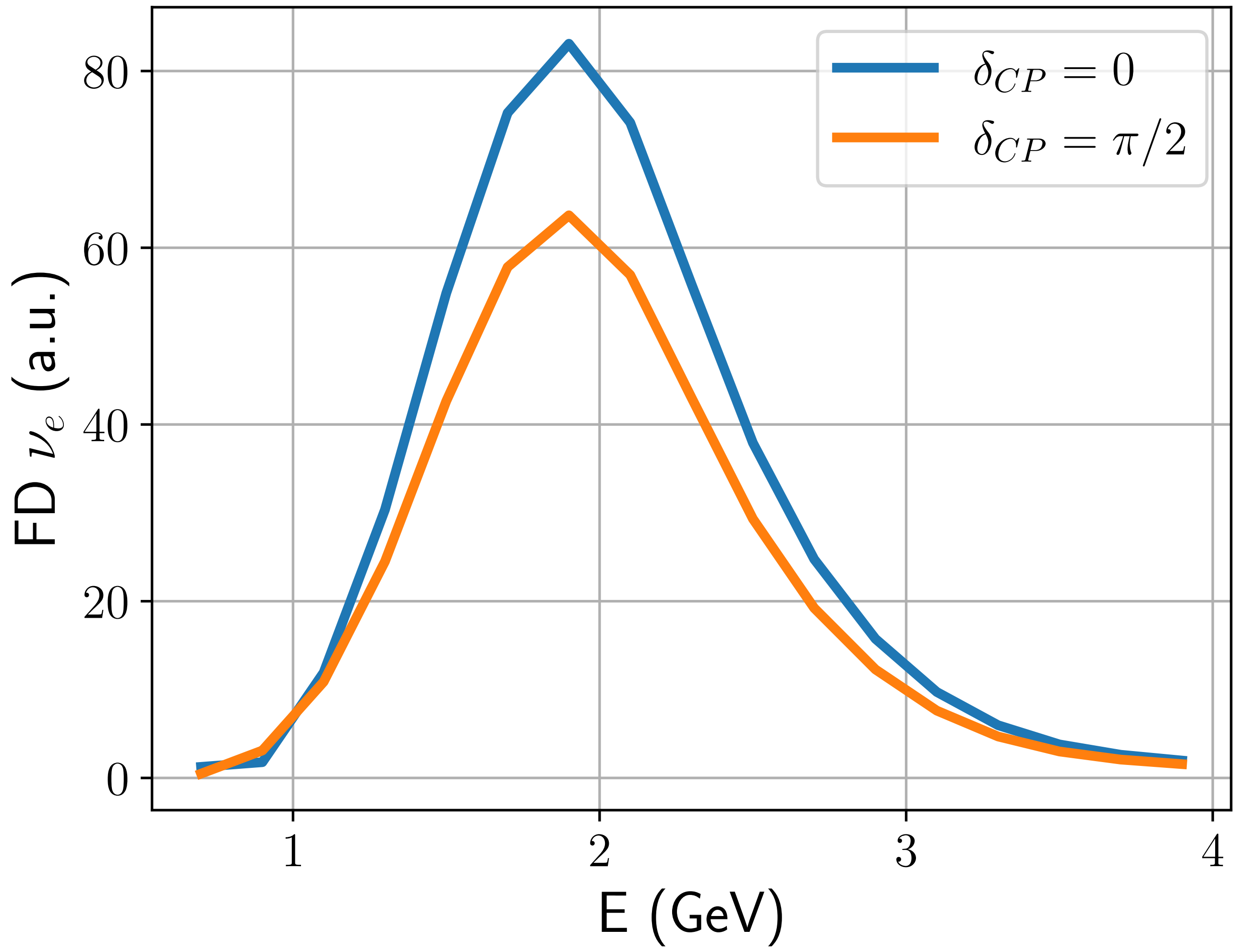
- Effect of δ_{CP}
  - No effect on the ν_μ spectra
    - Tiny effect due to matter effect
  - $\nu_\mu \rightarrow \nu_e$ oscillations are reduced compared to the anti-neutrino equivalent at maximal CP violation

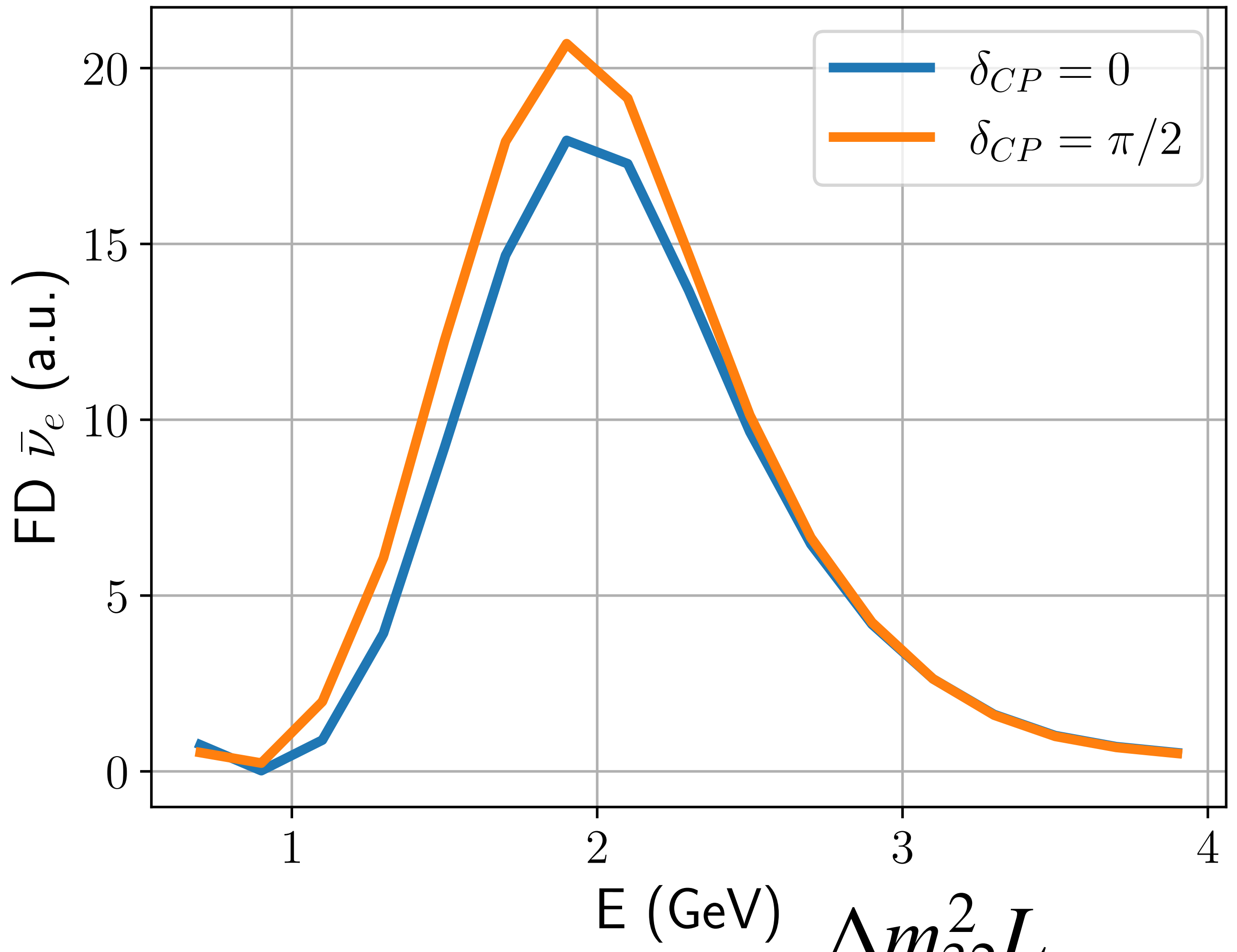
$$\Phi_{\nu_\mu} \times \sigma_{\nu_\mu} \times P(\nu_\mu \rightarrow \nu_\mu)$$



$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \frac{1.27\Delta m^2_{32} L}{E}$$

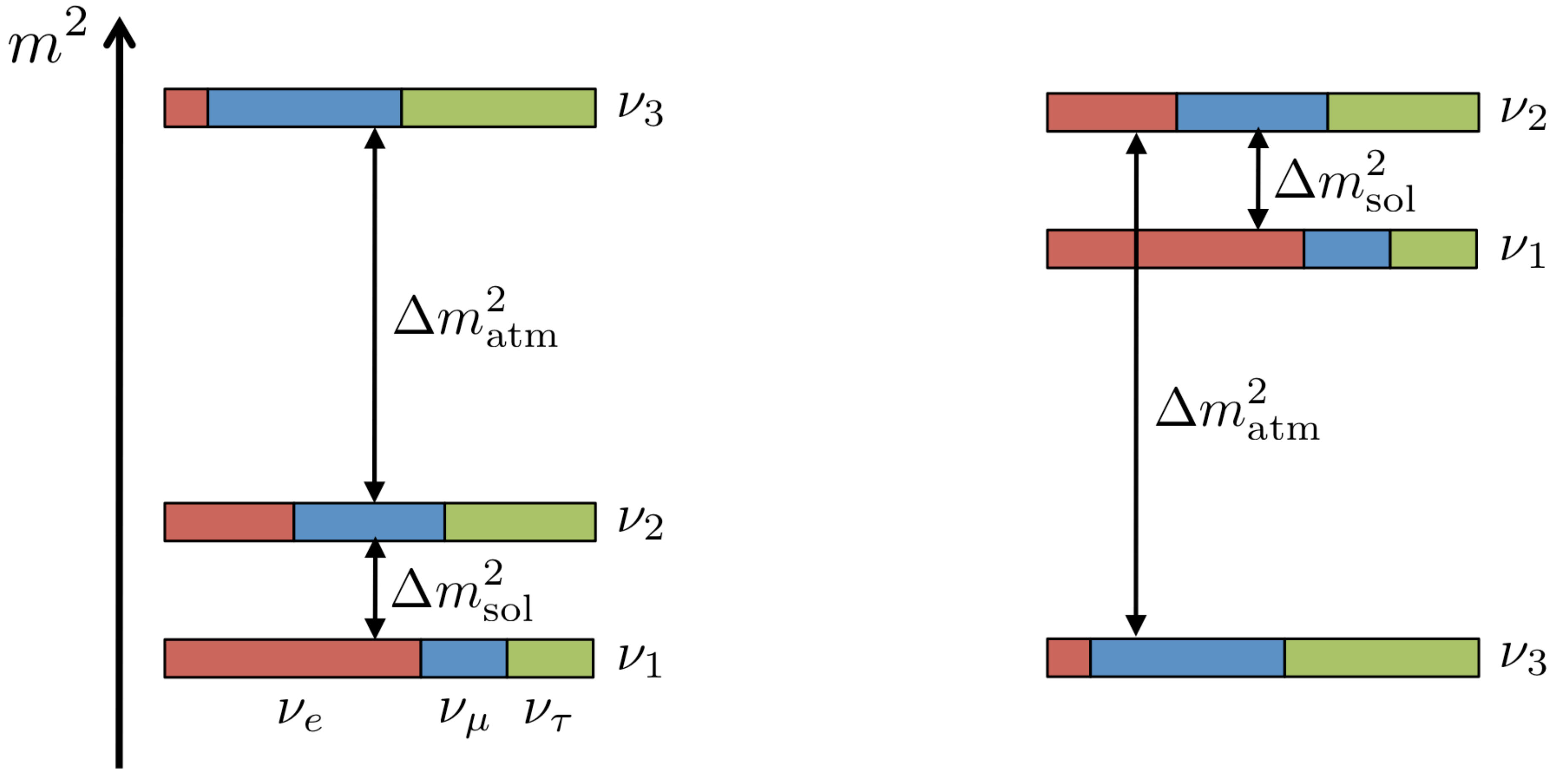
$$\Phi_{\nu_\mu} \times \sigma_{\nu_e} \times P(\nu_\mu \rightarrow \nu_e)$$





$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin \frac{\Delta m^2_{32} L}{4E} + f(\delta_{CP})$$

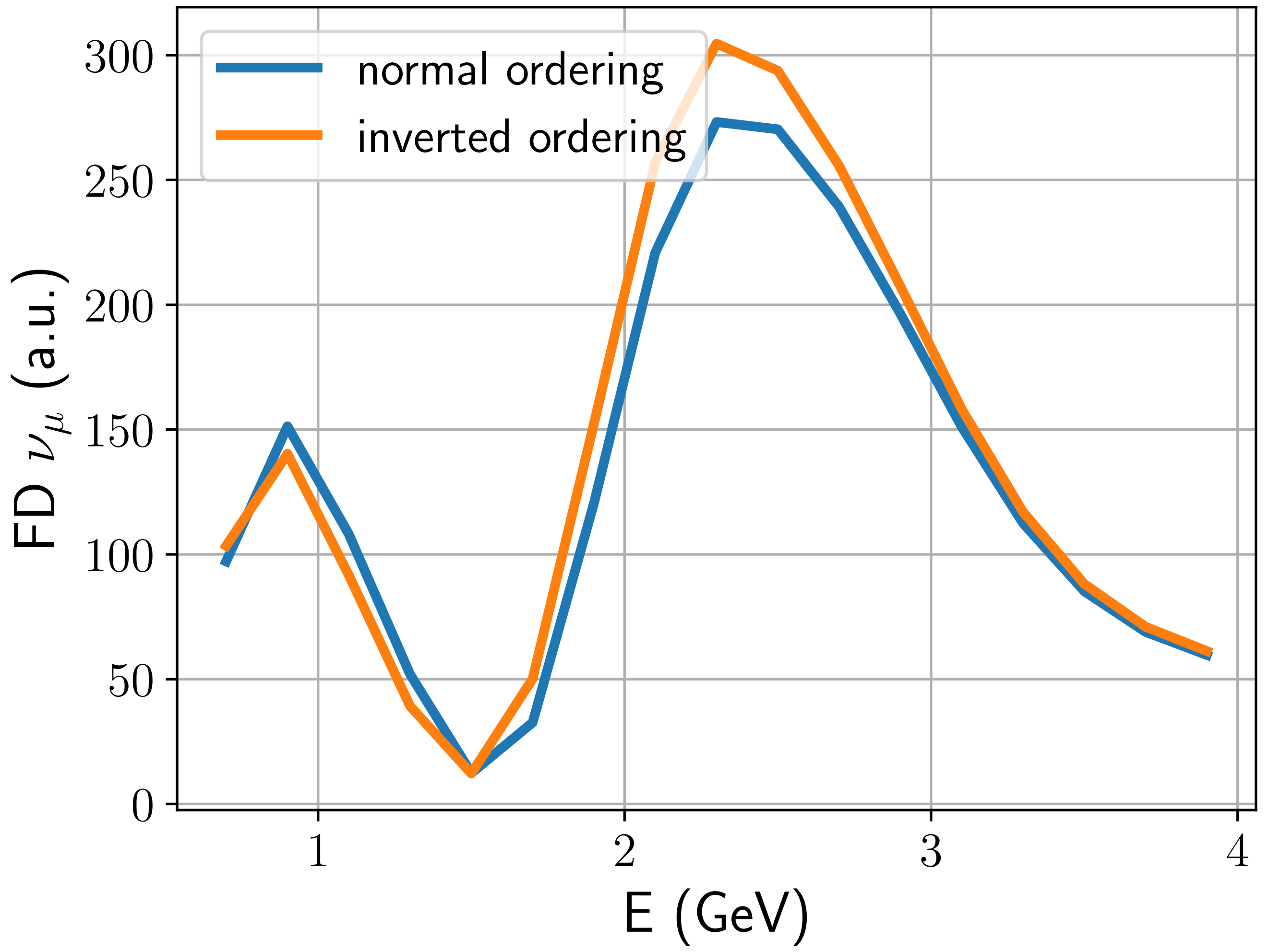
Why NOvA?
Far Detector True E_ν samples

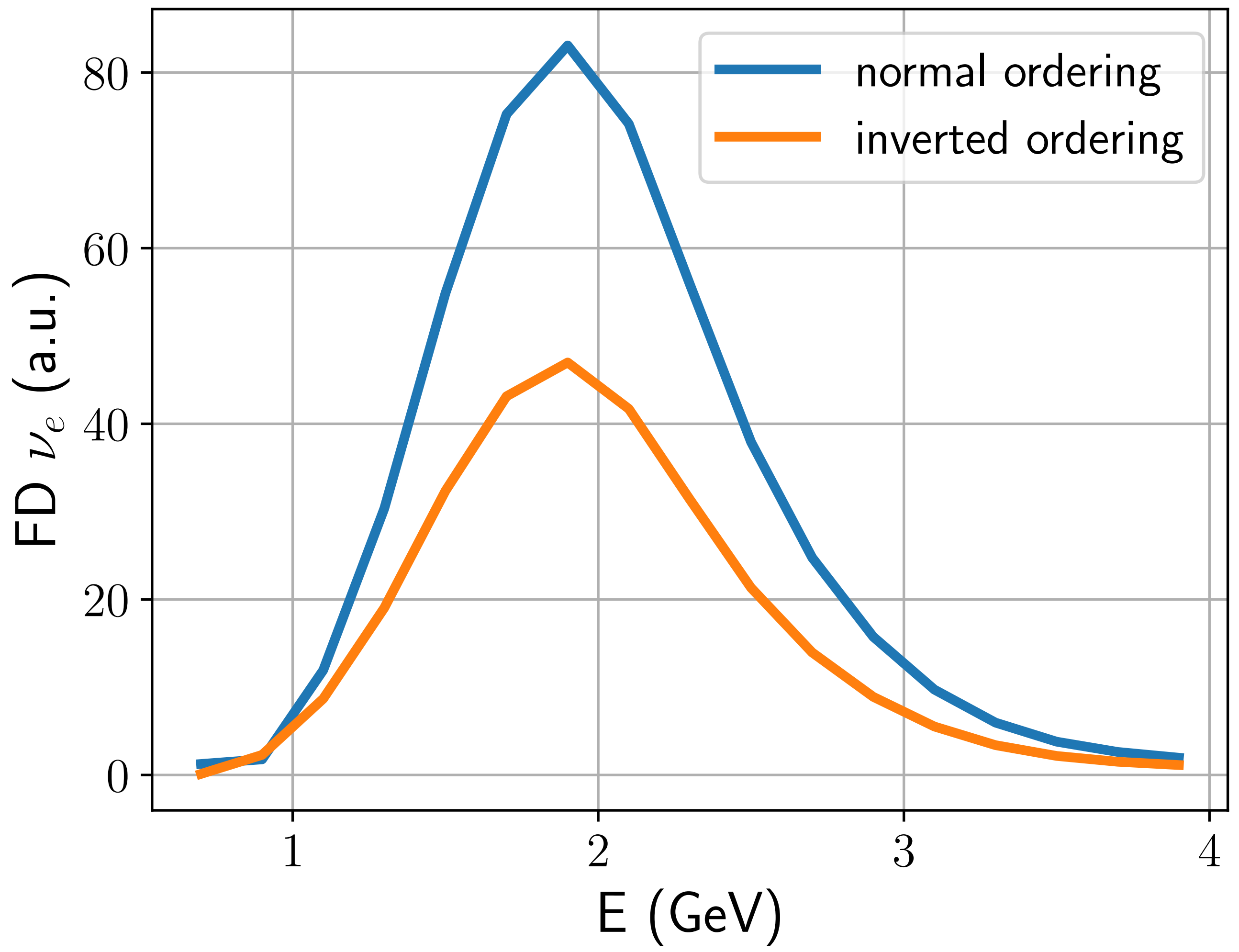


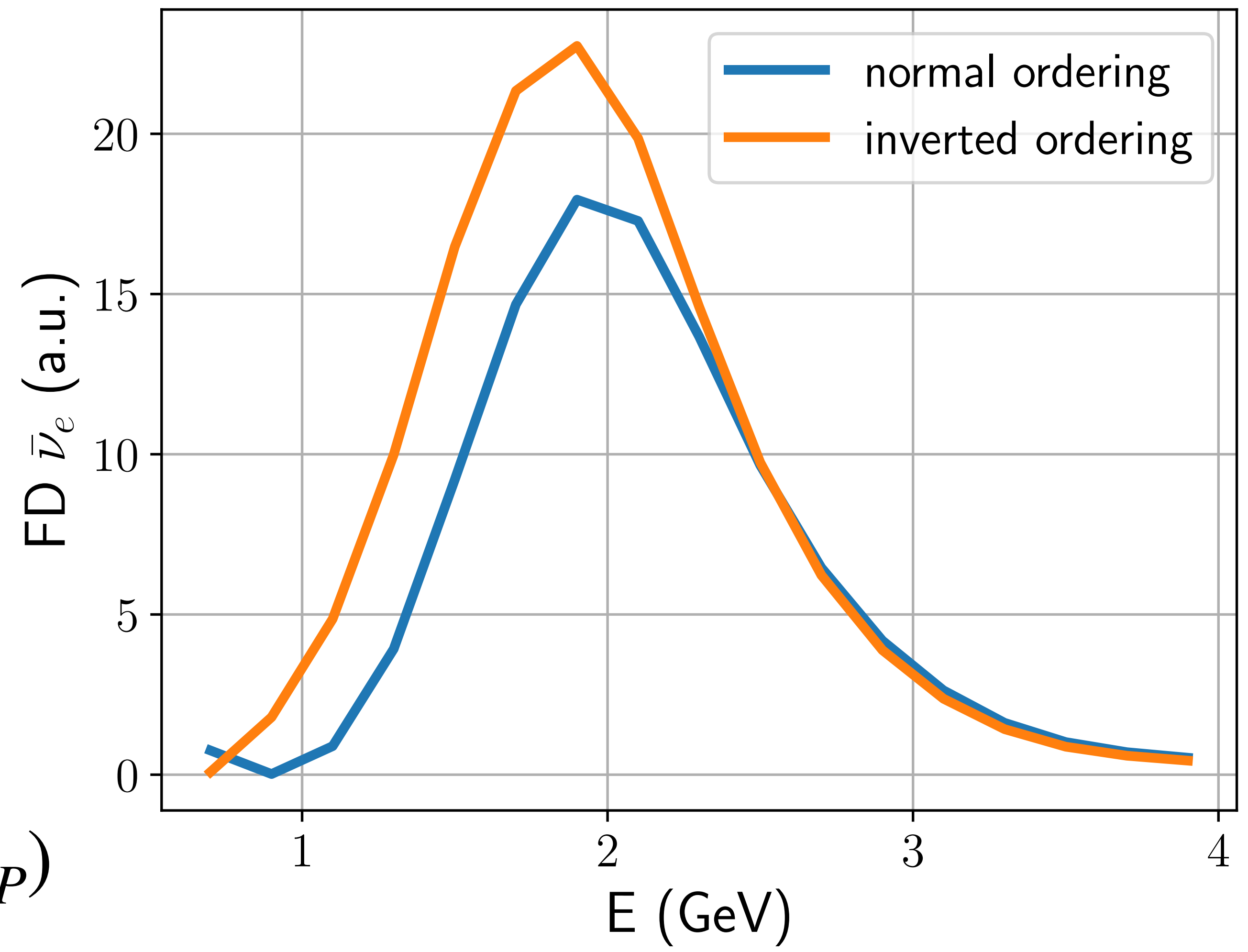
Normal ordering

Inverted ordering

- Effect of the mass ordering
  - ν_μ channel (FHC/RHC): moves the oscillation dip a bit
    - Disappearance sensitive to $|\Delta m^2_{32}|$
  - ν_e channel: changes the normalisation in opposite way for FHC/RHC
    - Appearance sensitive to Δm^2_{32} via matter effect







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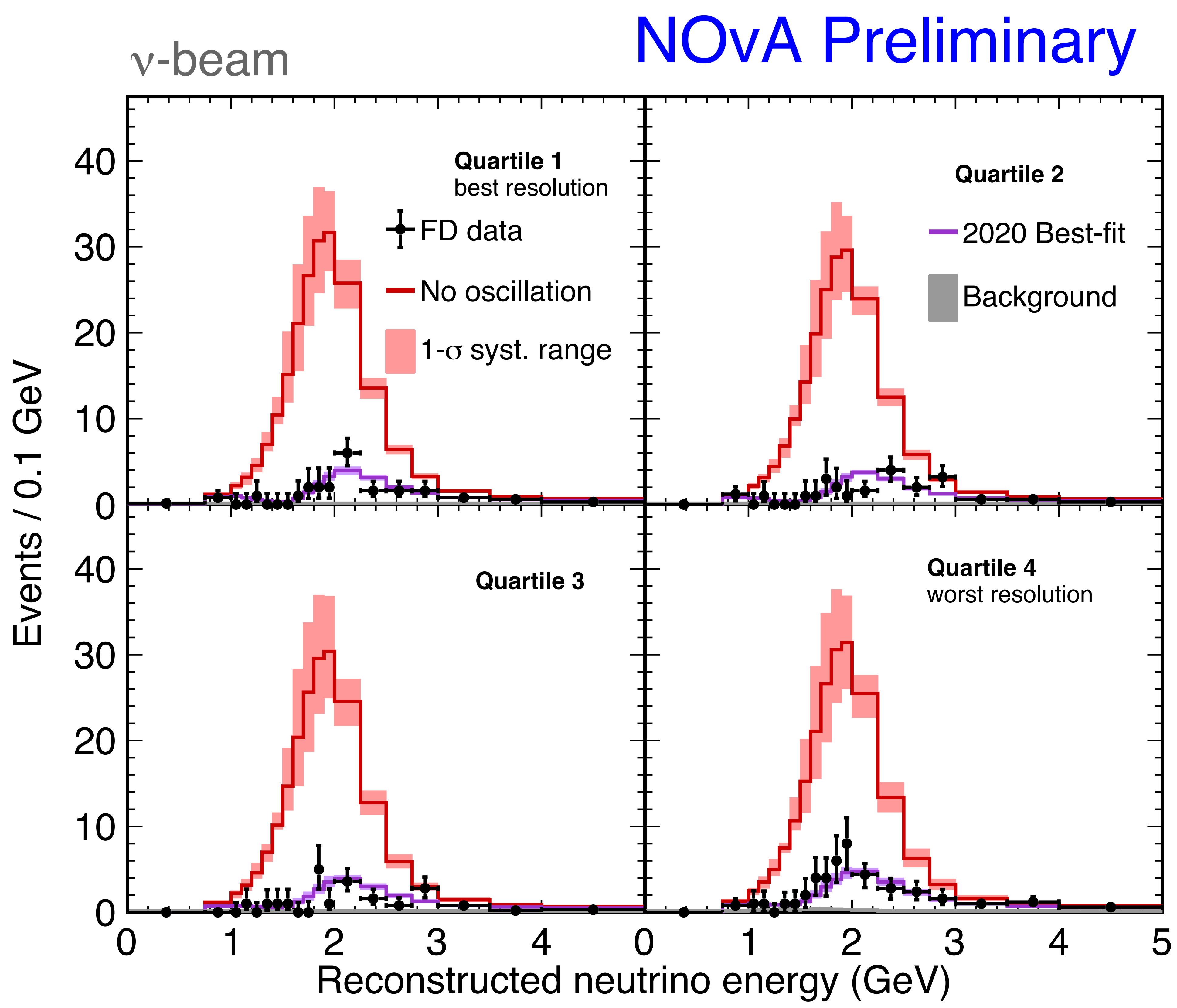
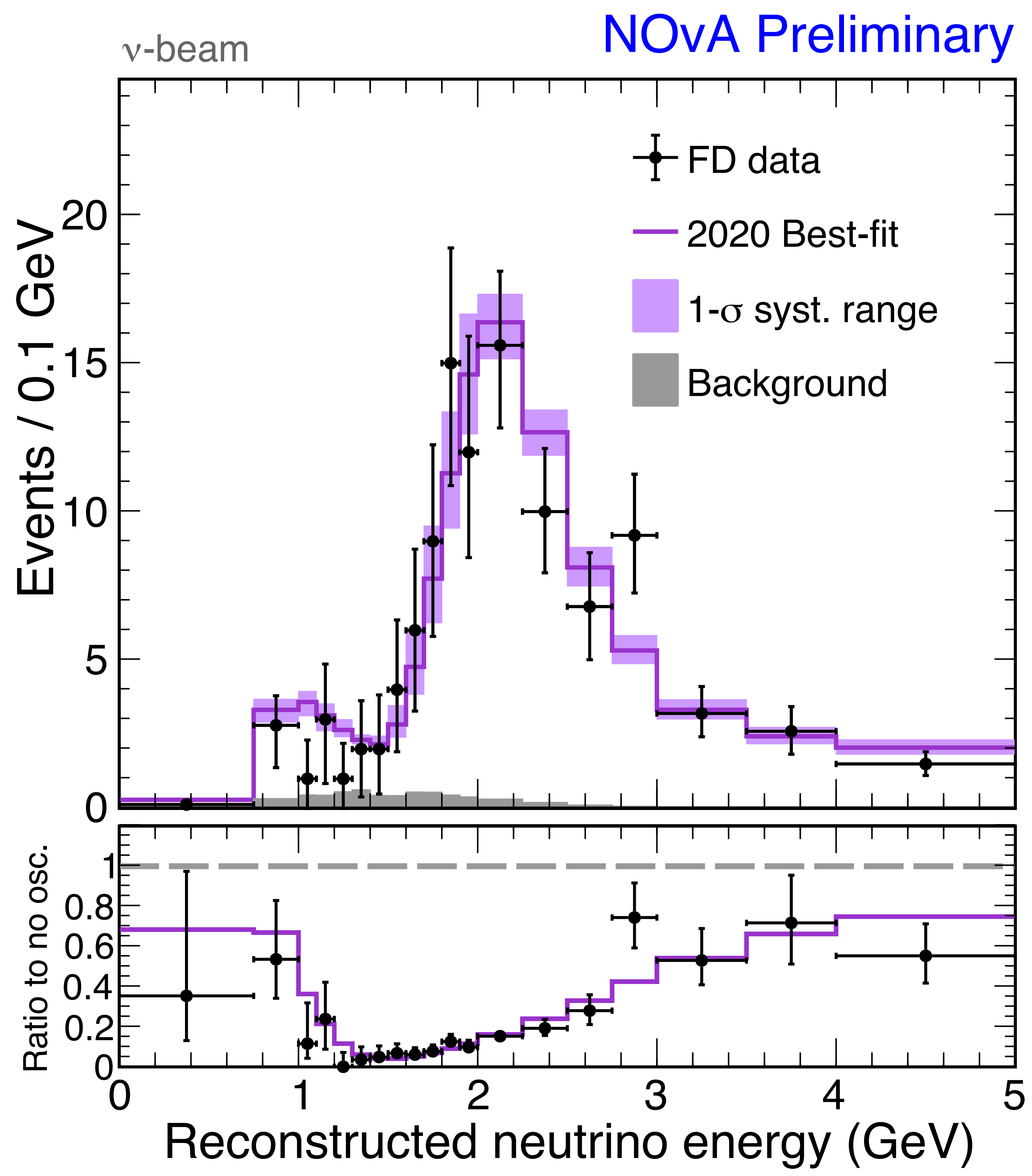
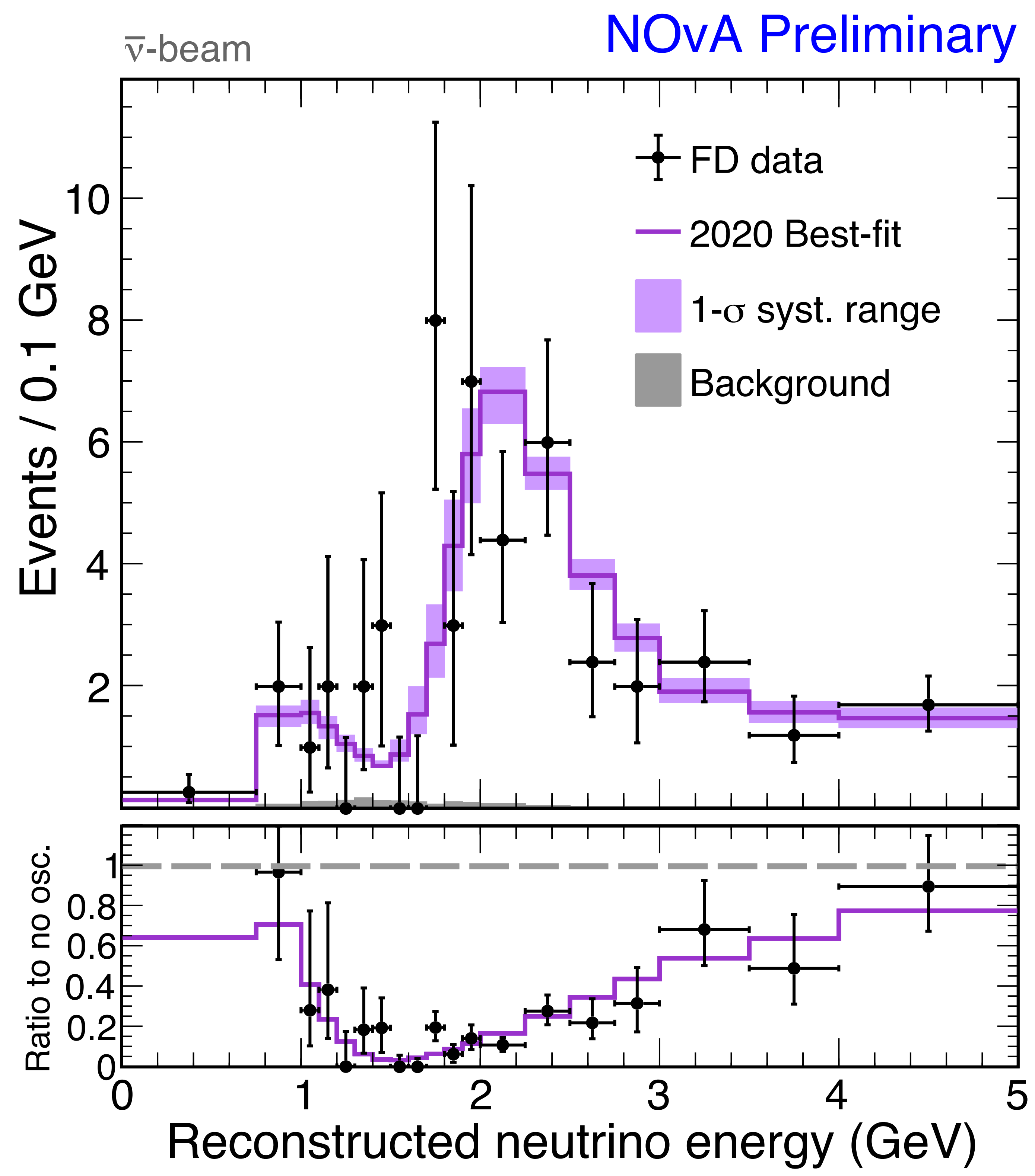
Extrapolation
Simplified view

- Makes extensive use of the functionally identical detectors
  - Basic idea is to unfold the ND spectra to true energy, add oscillation, corrections (beam divergences etc.), and fold it again to the FD
- Able to drastically reduce systematic uncertainties

Far detector ν_μ samples





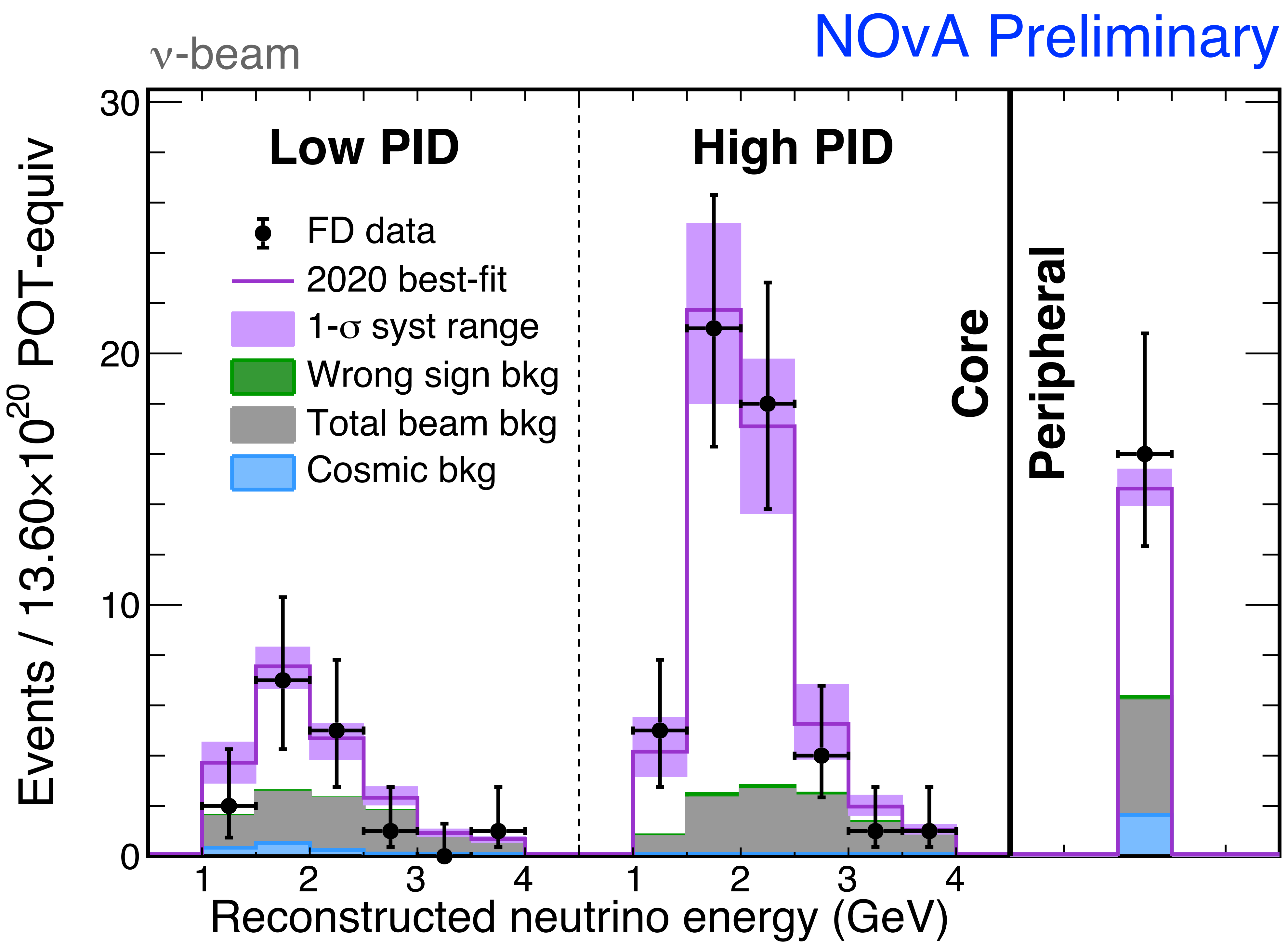


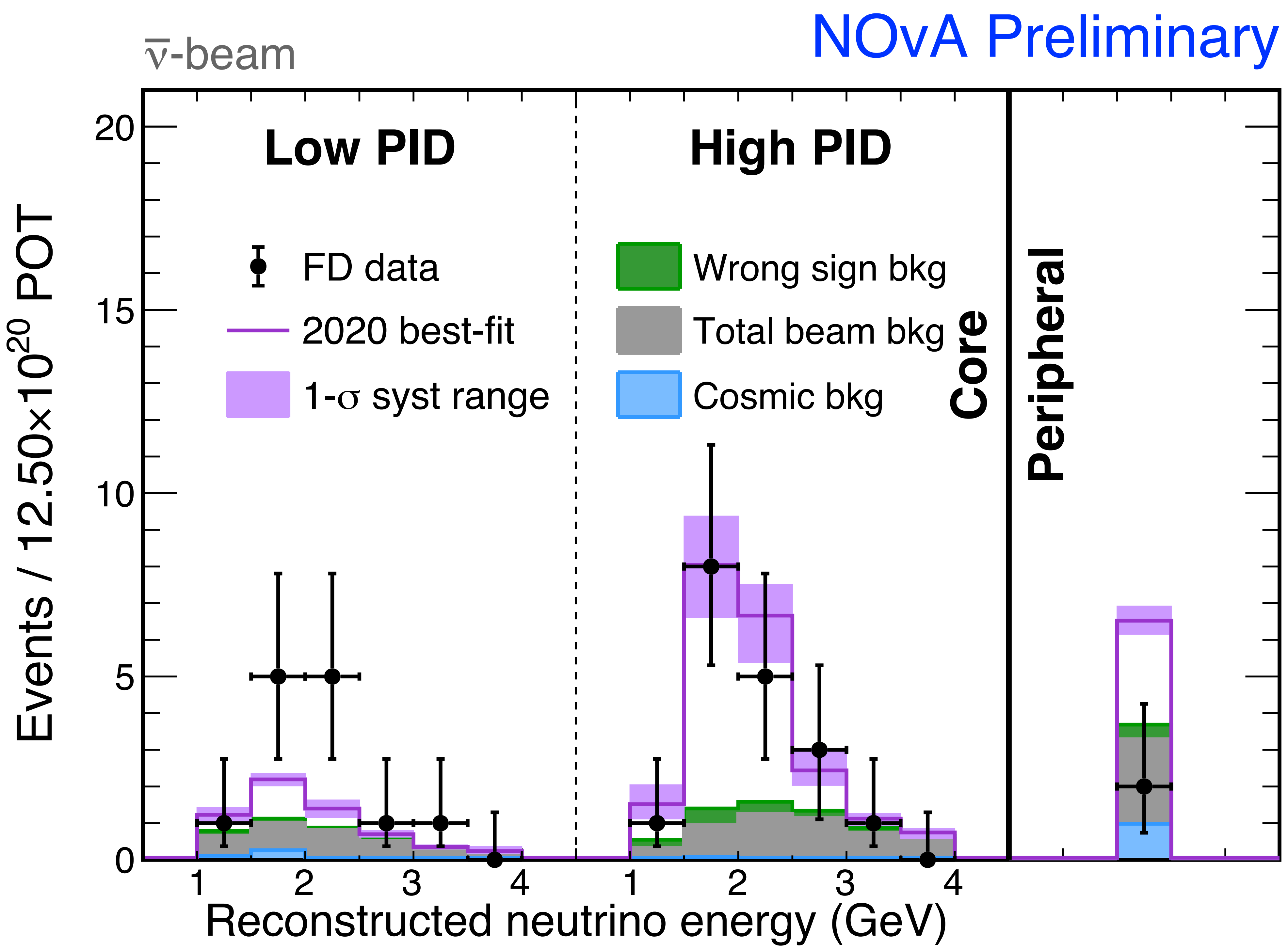
- Fitted: E_{Had} fraction quantile
- Muon |pT| bins are extrapolated separately

- Typical dip for the disappearance of (anti-)ν_μ
  - FHC observed: 211 ν_μ (BG: 8.2)
  - RHC observed:105 ν_μ (BG: 2.1)

Far detector ν_e samples

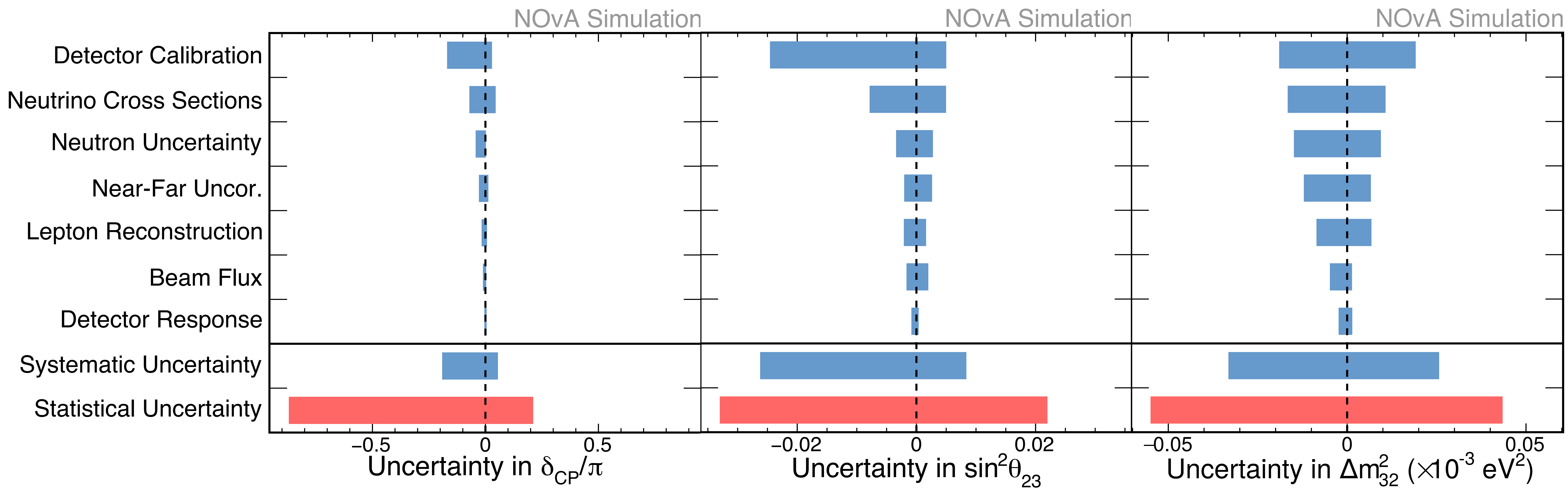
- Split by PID score from a convolutional neural network
  - FHC observed: 82 (BG: 26.8)
  - RHC observed: 33 (BG: 14)





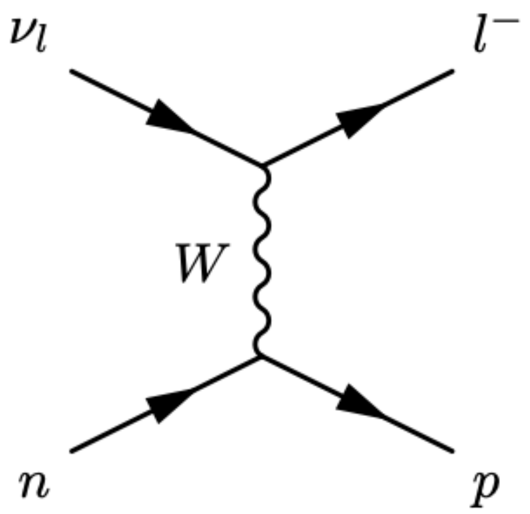
FD systematics

- ν_e samples are statistically limited → effect of systematics on δ_{CP} and θ_{13} is negligible
- Main effects for ν_μ samples
  - Calibration and neutrino cross section

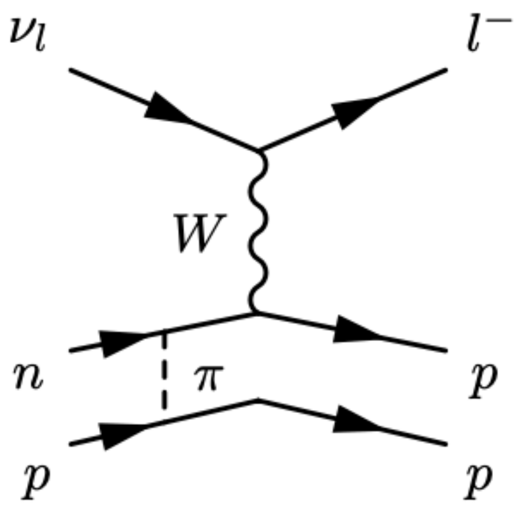


Cross section systematics

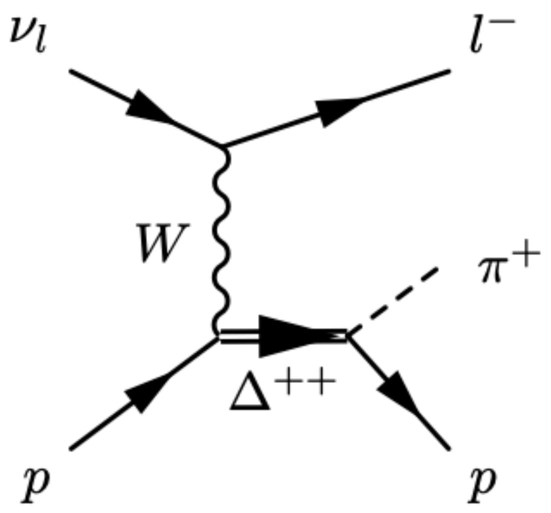
- (Should be) every LBL neutrino physicist's nightmare
  - A lot of unanswered questions that have a high impact on long baseline neutrino experiments
- NOvA uses GENIE v3.0.6 as neutrino nucleus interaction generator
  - Tuned by the GENIE collaboration and us (so-called N1810j_0211a - "NINJA" tune)
    - Z-expansion Quasi-Elastic Form Factor
  - Extra systematics
    - Low Q^2 suppression
    - Multi nucleon knockout (2p2h/MEC)
    - Final State Interactions (FSI)



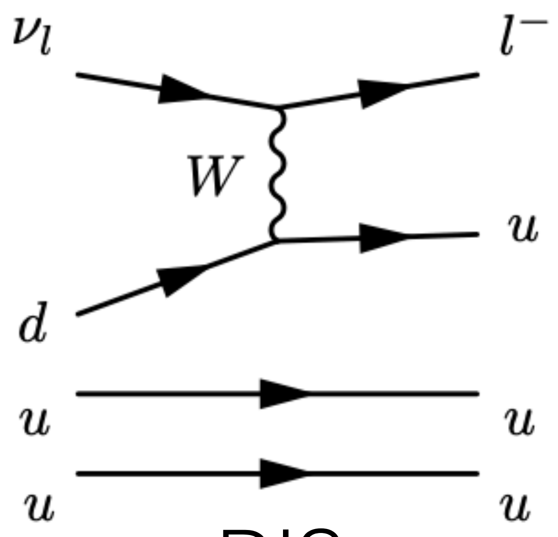
QE



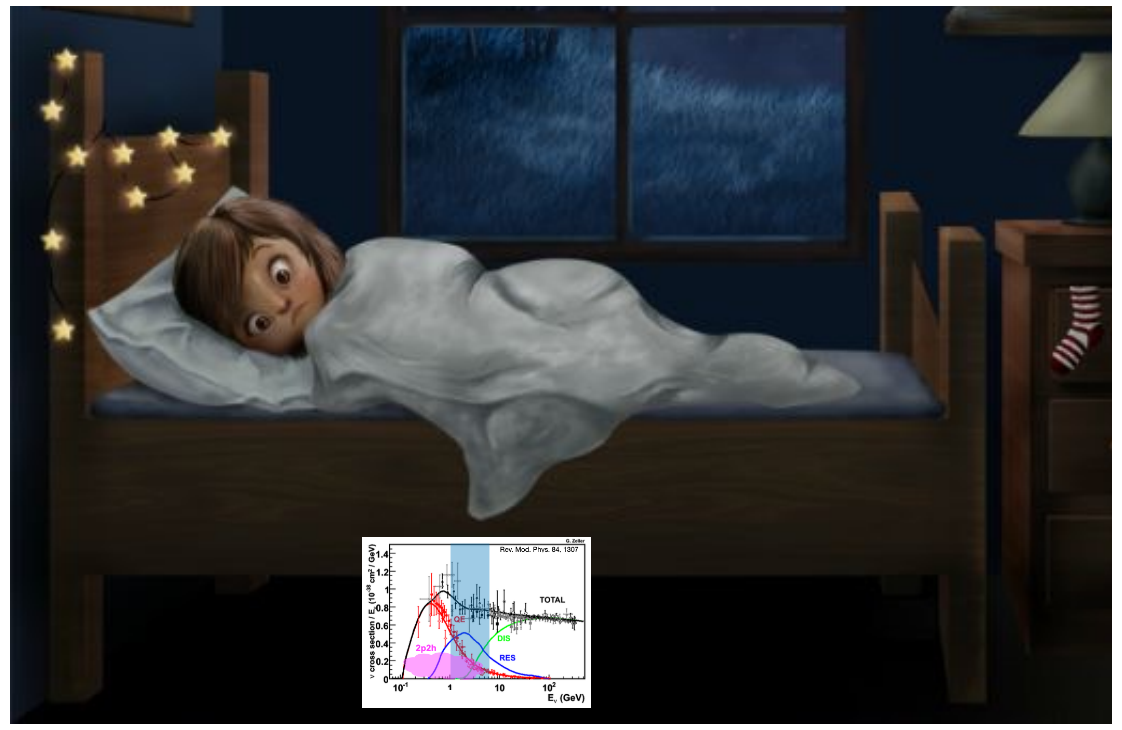
MEC

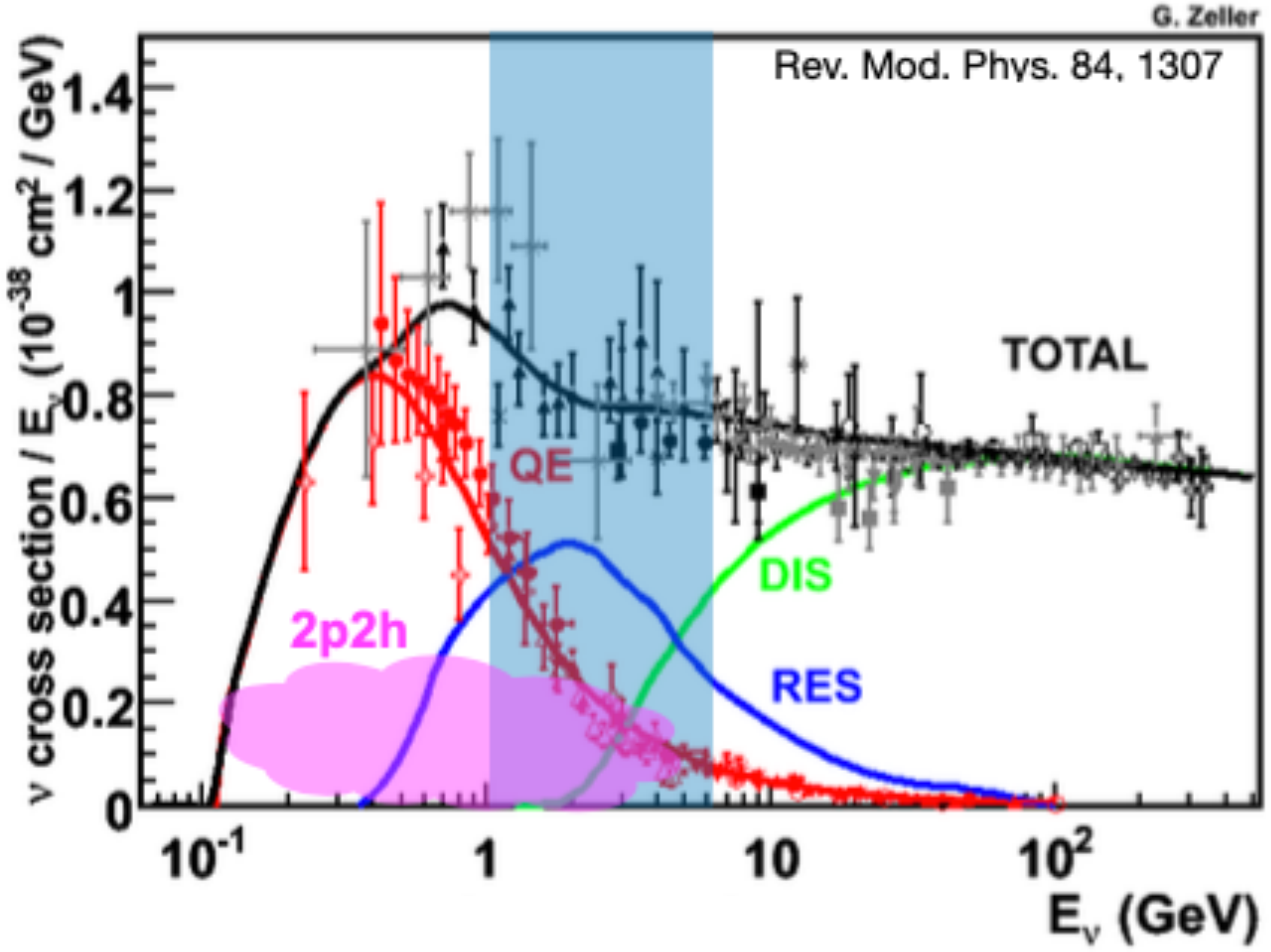


RESπ



DIS

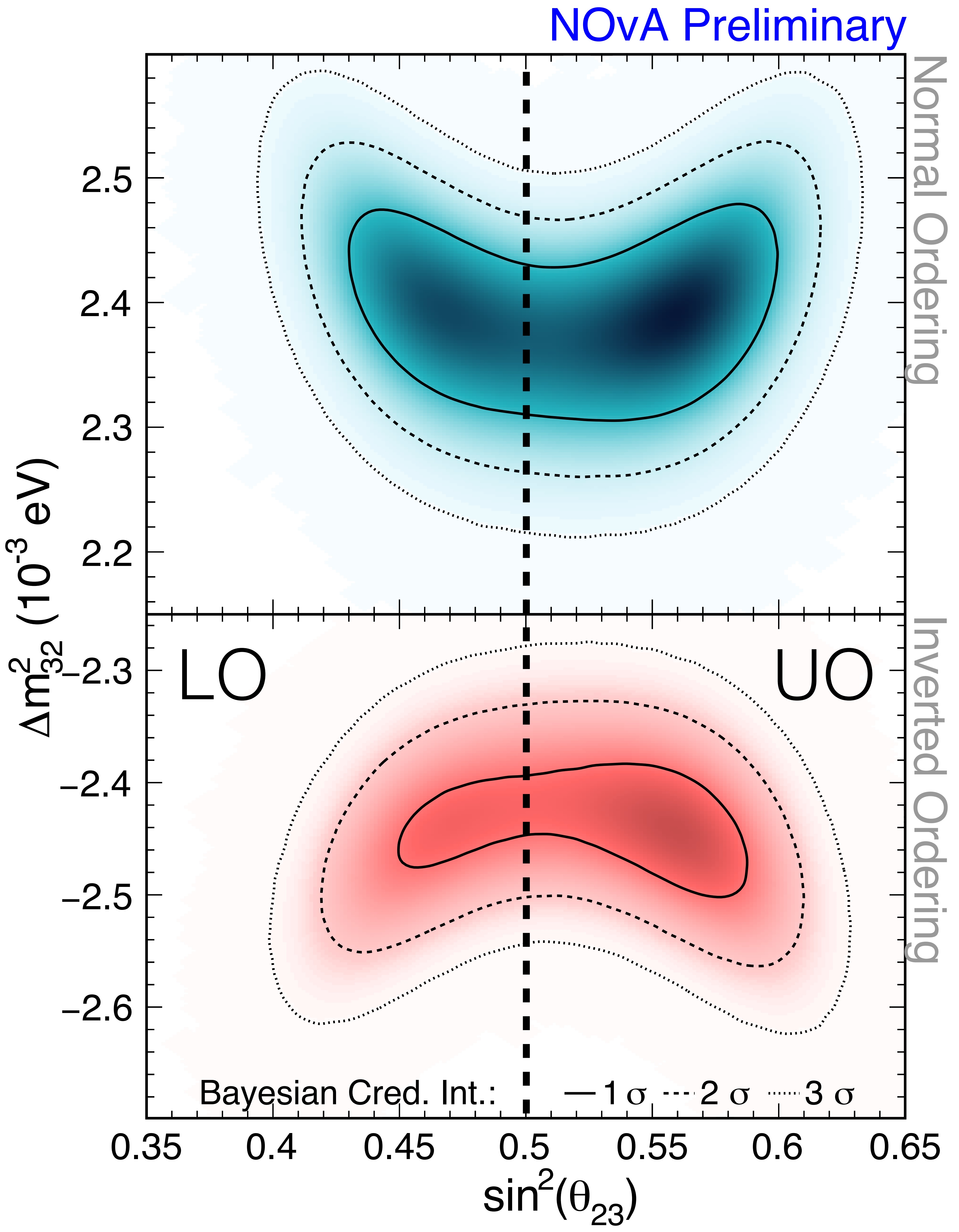




Disappearance parameters

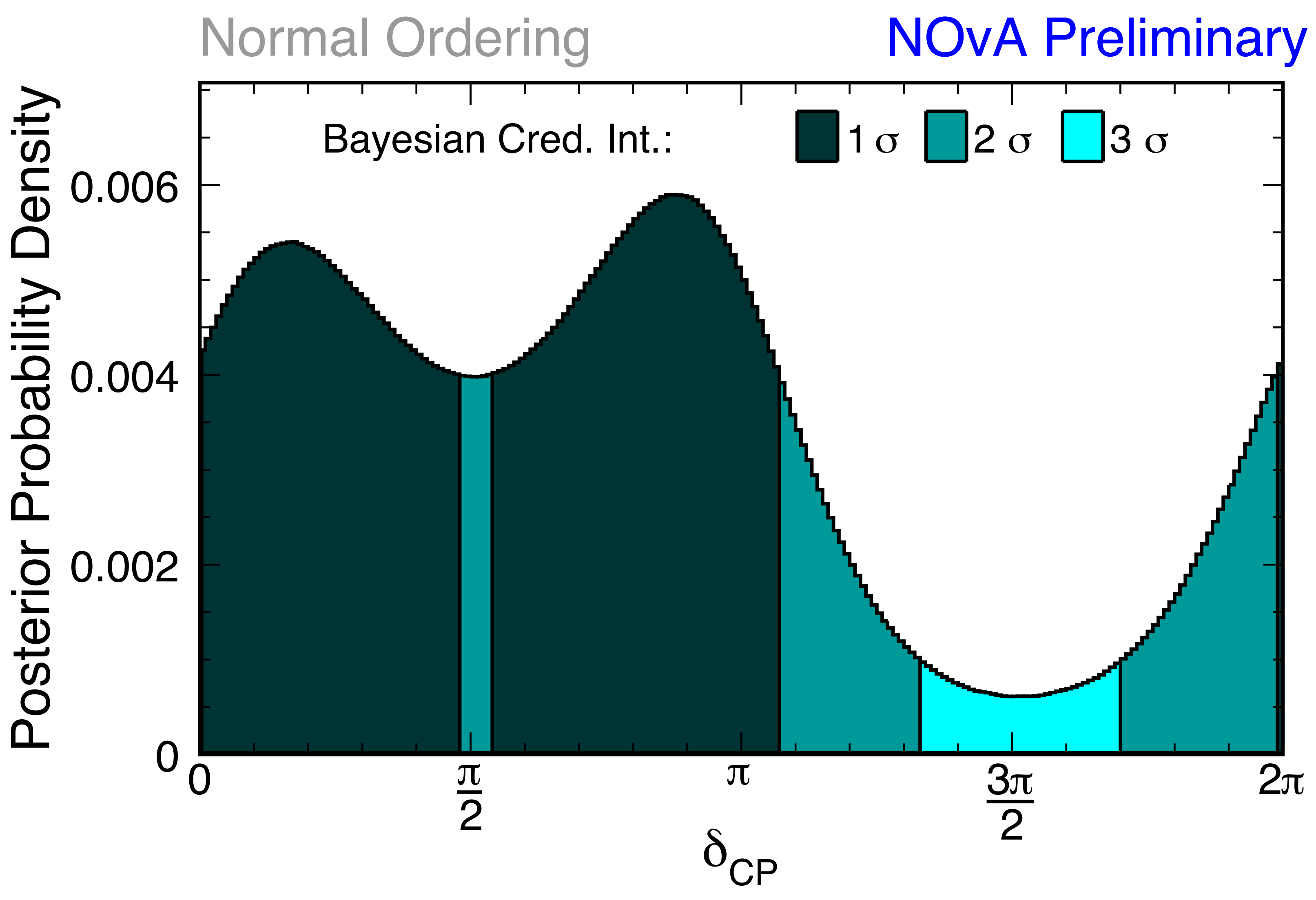
- "Disappearance parameters" = θ_{23} and Δm^2_{32} (i.e. typical atmospheric parameters first seen by SK)
- Weak preference in upper octant normal mass ordering
- Bayes factor (ratio of steps):
  - $\mathrm{BF}_{\frac{NO}{IO}} = 2.1$
  - $\mathrm{BF}_{\frac{UO}{LO}} = 1.7$

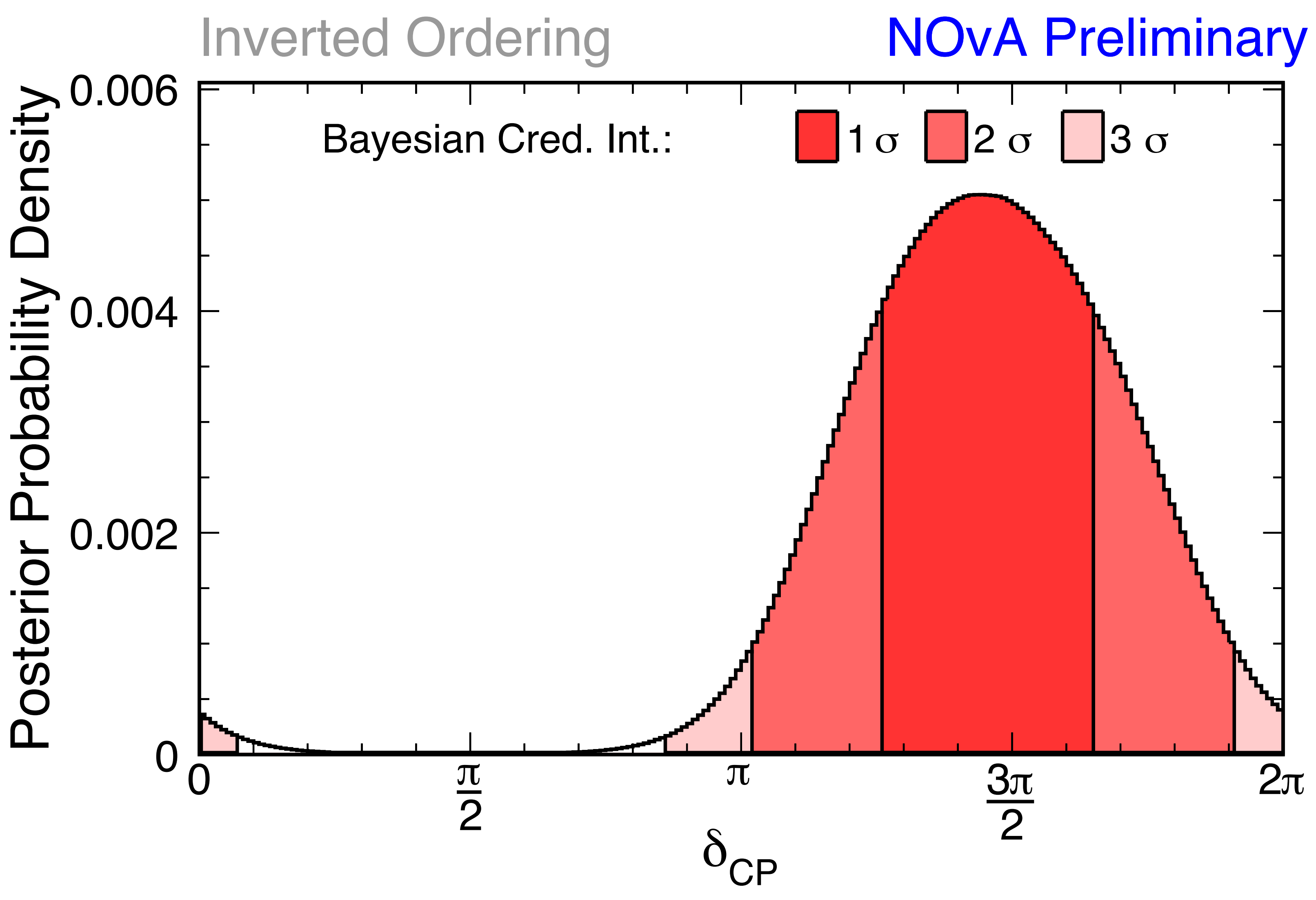
		Mass ordering		Total
		Normal	Inverted	
Octant	Upper	41.7%	20.9%	62.6%
	Lower	25.8%	11.5%	37.4%
Total		67.5%	32.5%	100%



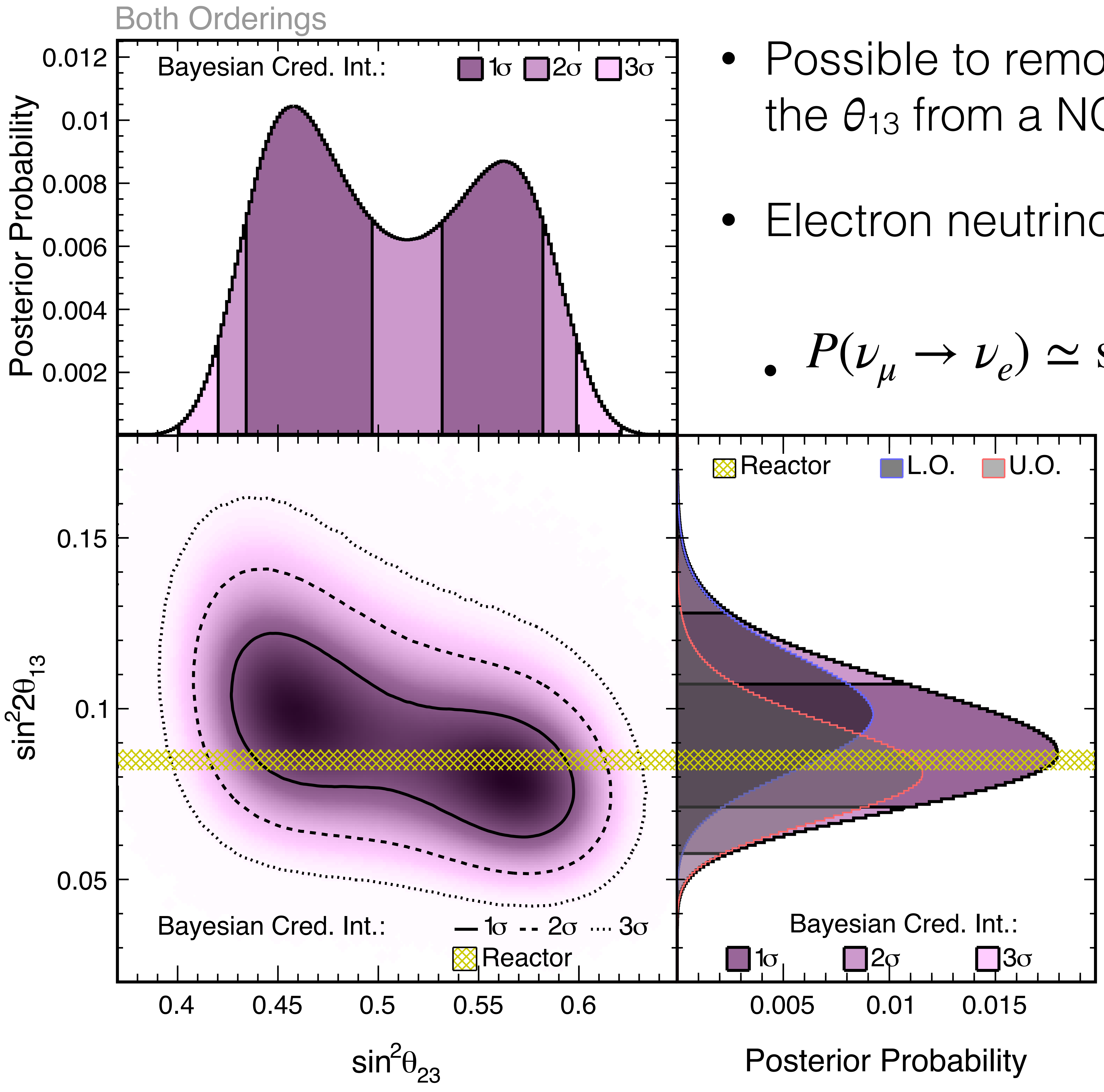
Appearance parameters

- "Appearance parameters" = θ_{13} and δ_{CP}, although they can't be observed without disappearance parameters…
- Strong correlation between mass hierarchy and δ_{CP}
  - Normal ordering: δ_{CP} = 1.5 π outside the 2 σ credible intervals (CI)
  - Inverted ordering: δ_{CP} = 0.5 π outside the 3 σ CI





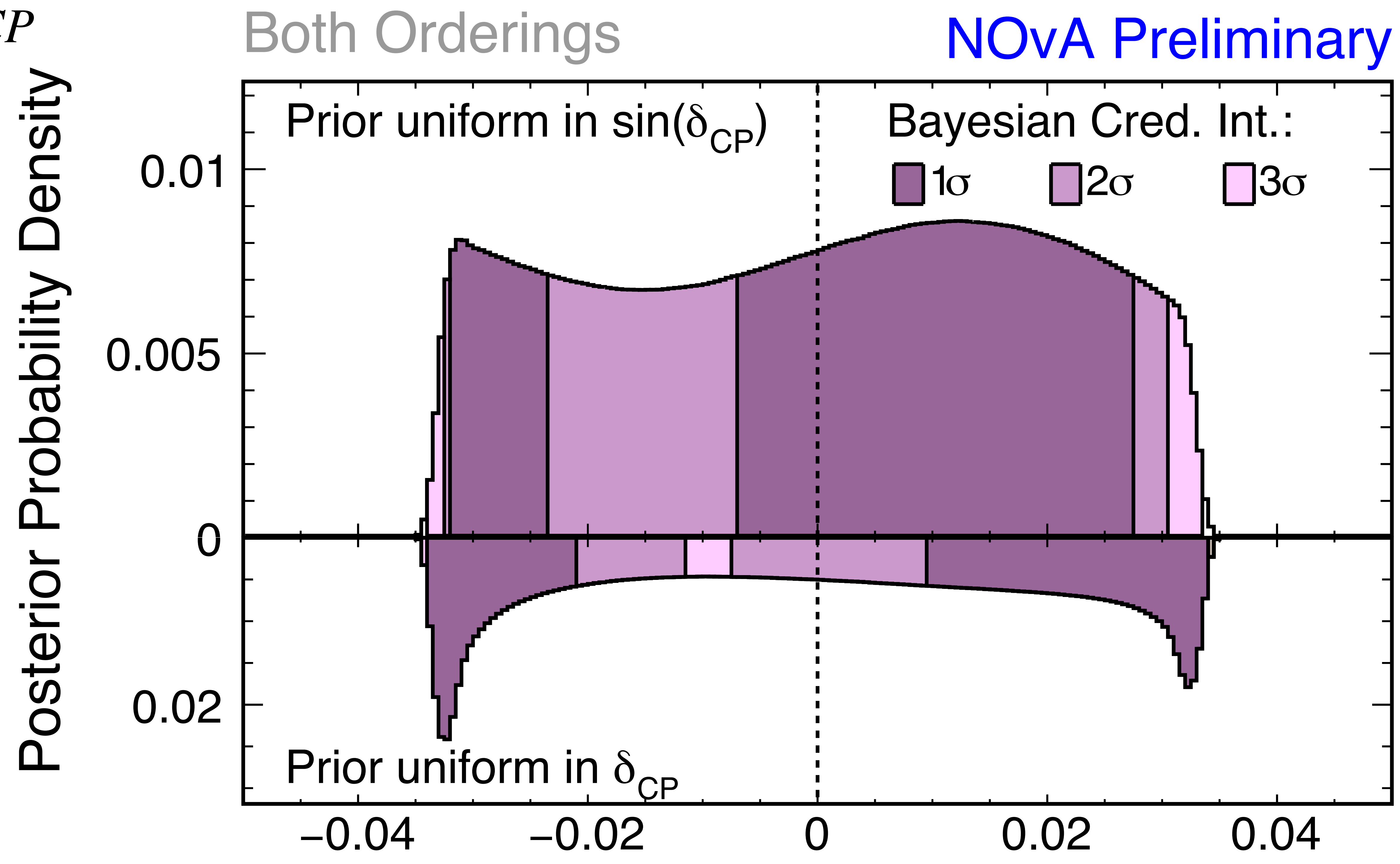
NOvA's own θ_{13} parameter measurement



- Possible to remove the reactor constraint and check the posterior of the θ_{13} from a NOvA only fit
- Electron neutrino appearance probability is:
  - $P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin\frac{\Delta m^2_{32}L}{4E} + f(\delta_{CP})$
- So θ_{23} (from ν_μ survival probability) and θ_{13} (from ν_e appearance probability) should be anti-correlated
- ν_e disappearance (reactor neutrino) and ν_e appearance data (NOvA) have high degree of consistency

Jarlskog invariant

- Jarlskog invariant is a measure of CP violation, independent of the PMNS parameterisation
  - $J = \cos\theta_{12}\cos^2\theta_{13}\cos\theta_{23}\sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta_{CP}$
- Basic idea:
  - J = 0 → CP is conserved
  - J ≠ 0 → CP is violated
- NOvA has weak sensitivity to J, so the choice of prior matters
  - Flat prior in $\sin\delta_{CP}$ (related to what we see)
  - Flat prior in δ_{CP} → J ≠ 0 more preferred
- $\mathrm{BF}_{\frac{J\neq 0}{J=0}} = 1.5$ (from the Savage-Dickey method)



Conclusion

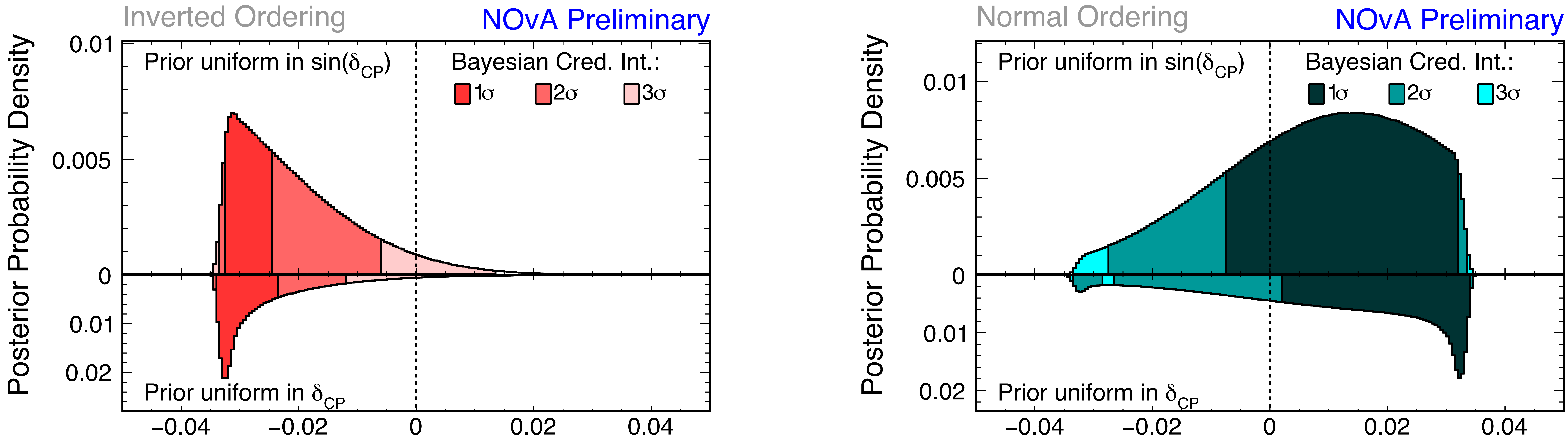
- Analysis of the NOvA data shows
  - No deviation from PMNS 3 neutrino flavour model
  - Marginal preference for the upper octant of θ_{23} and normal neutrino mass ordering
  - No hints of CP violation in the neutrino sector
- Future of NOvA
  - More POT: we analysed 26×10^{20} POT, collected 12×10^{20} since 2020 dataset, and should get around 60×10^{20} by the end of NOvA
  - Test beam
  - Joint analysis with T2K

Thanks for your attention!

Backup

Jarlskog invariant

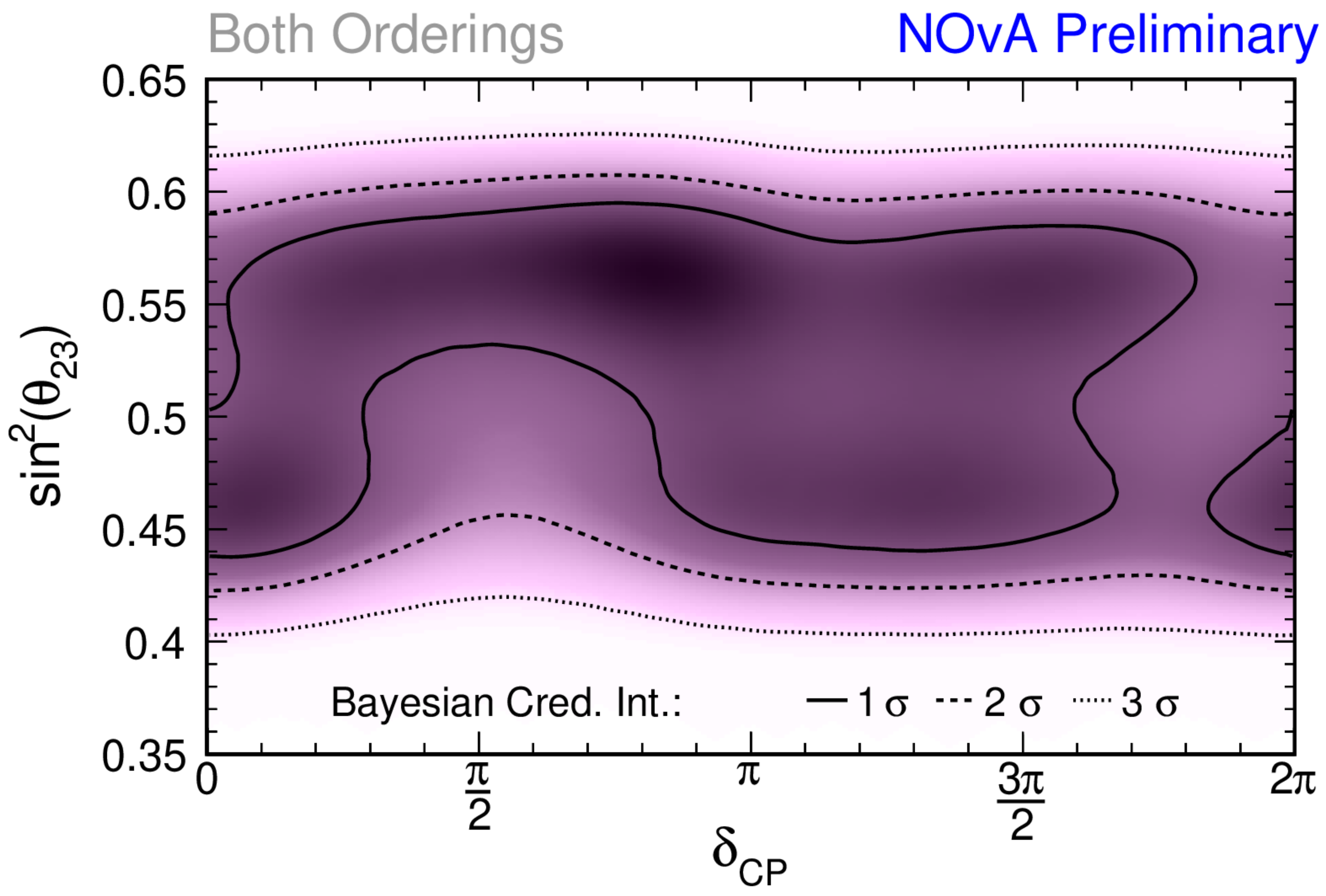
- Sign of J is governed by the sign of $\sin \delta_{CP}$
  - In inverted ordering: 2 σ exclusion of J = 0
  - In normal ordering no exclusion of J = 0



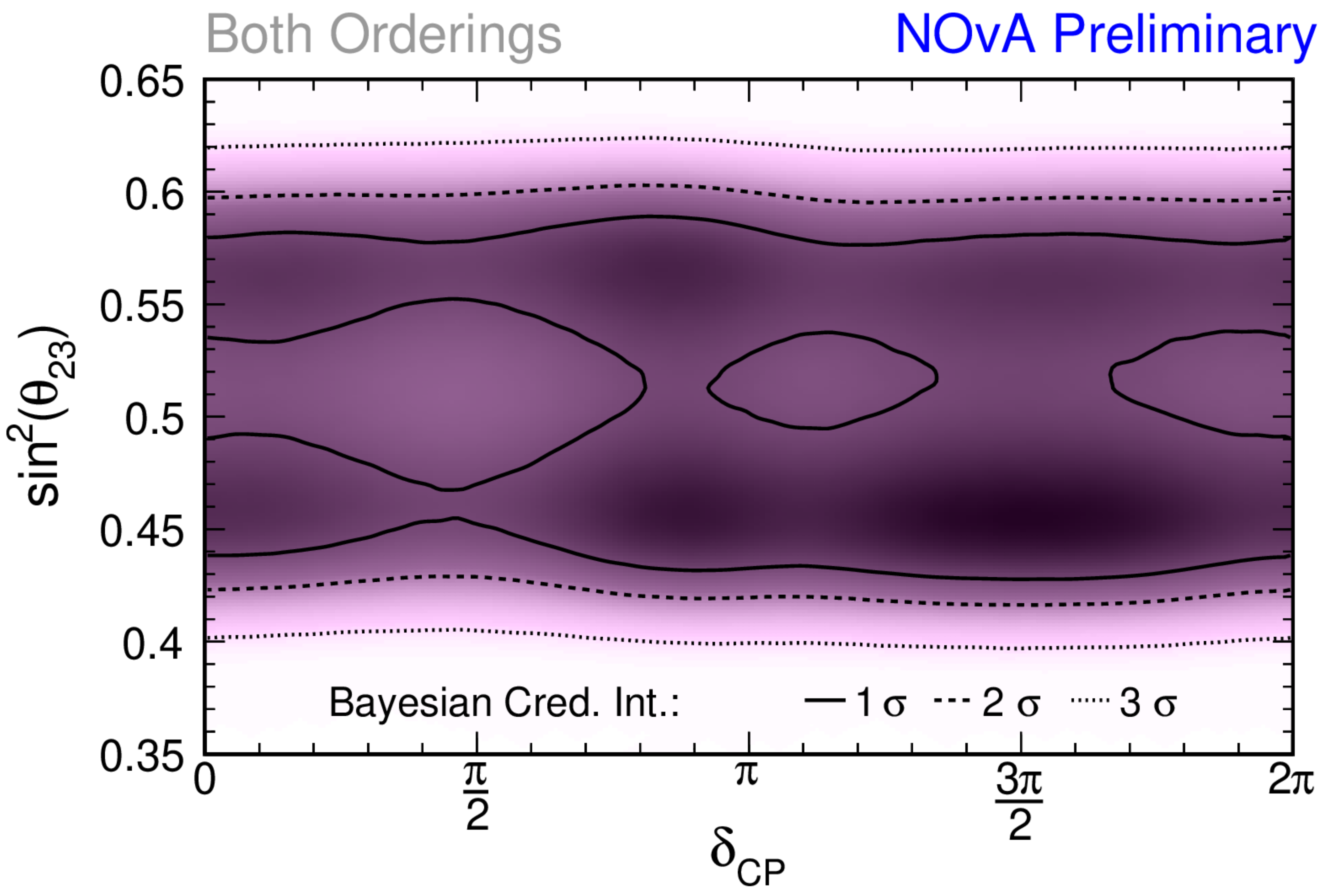
Reactor constraint

- Typically long baseline neutrino experiment use the reactor neutrino experiment's measurement on θ_{13} to enhance their sensitivity to δ_{CP}

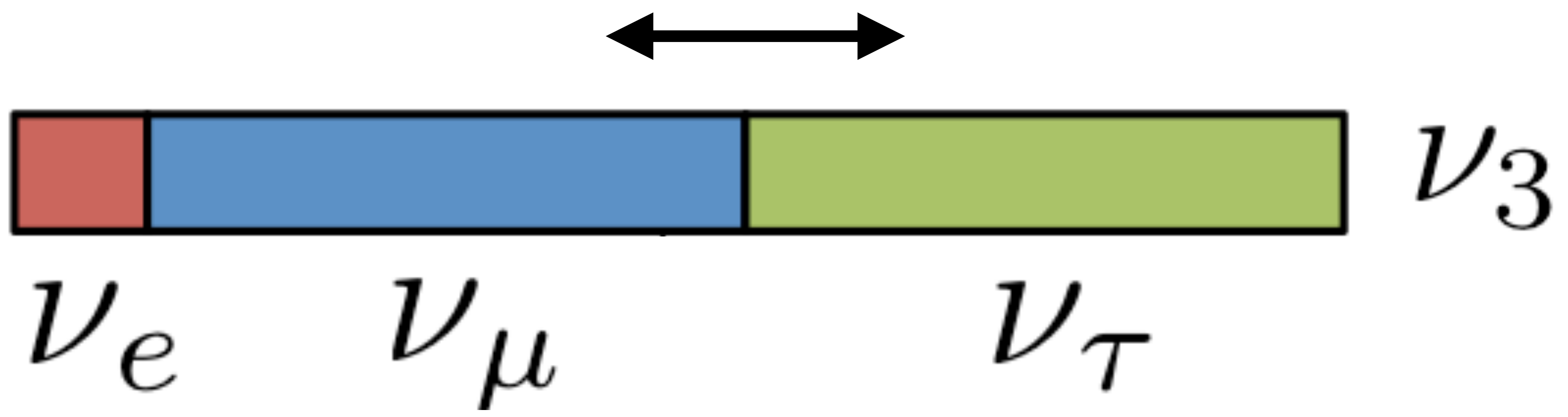
With reactor constraint



Without reactor constraint

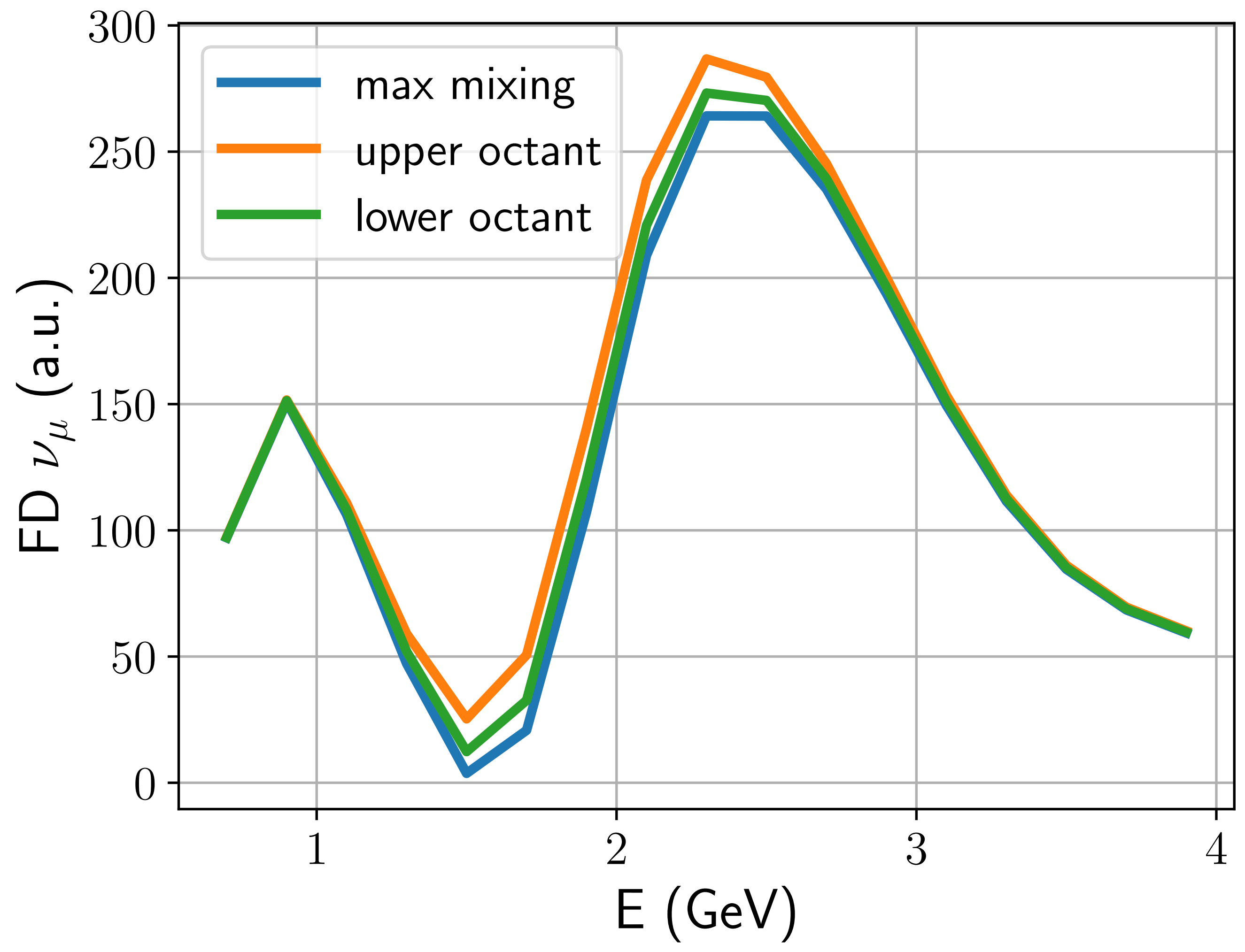


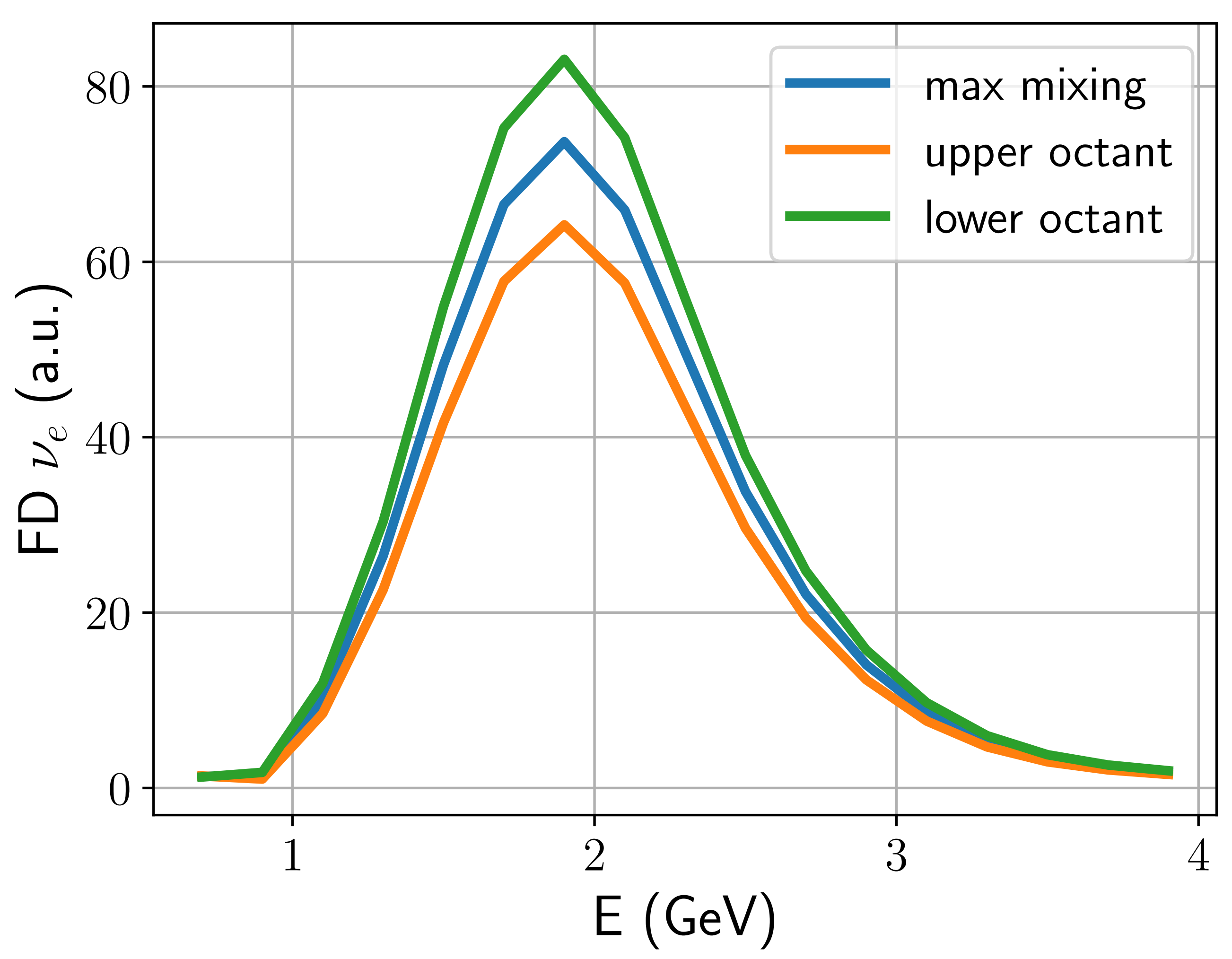
Why NOvA?
Far Detector True E_ν samples



- Effect of the octant (θ_{23} bigger or smaller than 45°)
  - Same effects in FHC/RHC
  - ν_μ channel:
    - Maximal disappearance at θ_{23} = 45° any movement away from that → ν_μ disappear less
      - Disappearance $\propto \sin^2 2\theta_{23}$
  - ν_e channel:
    - Sensitive to octant
      - Appearance $\propto \sin^2 \theta_{23}$

True variables





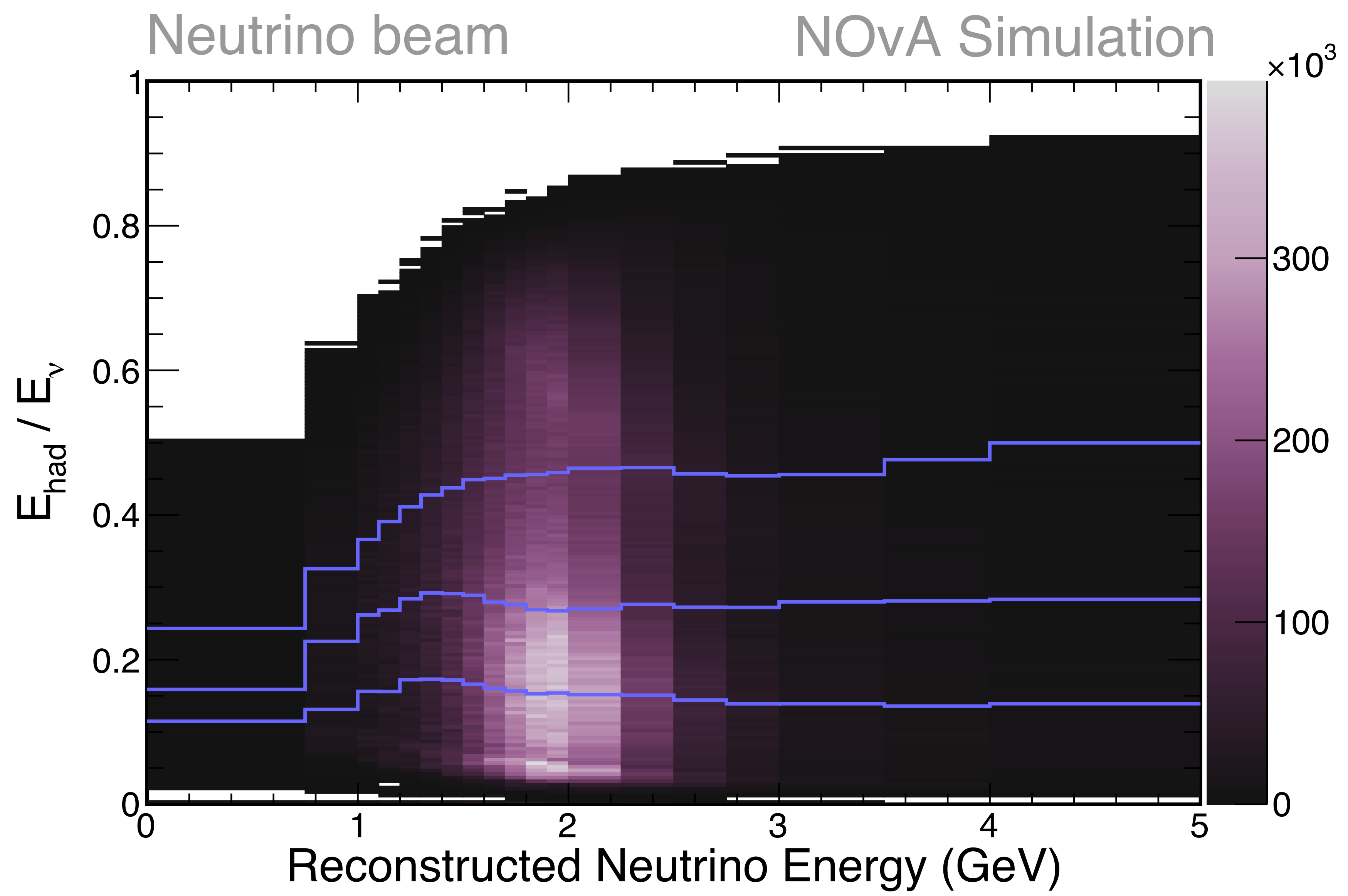
$$P(\nu_\mu \rightarrow \nu_\mu) \times \sigma_{\nu_\mu} \times \Phi_{\nu_\mu}$$

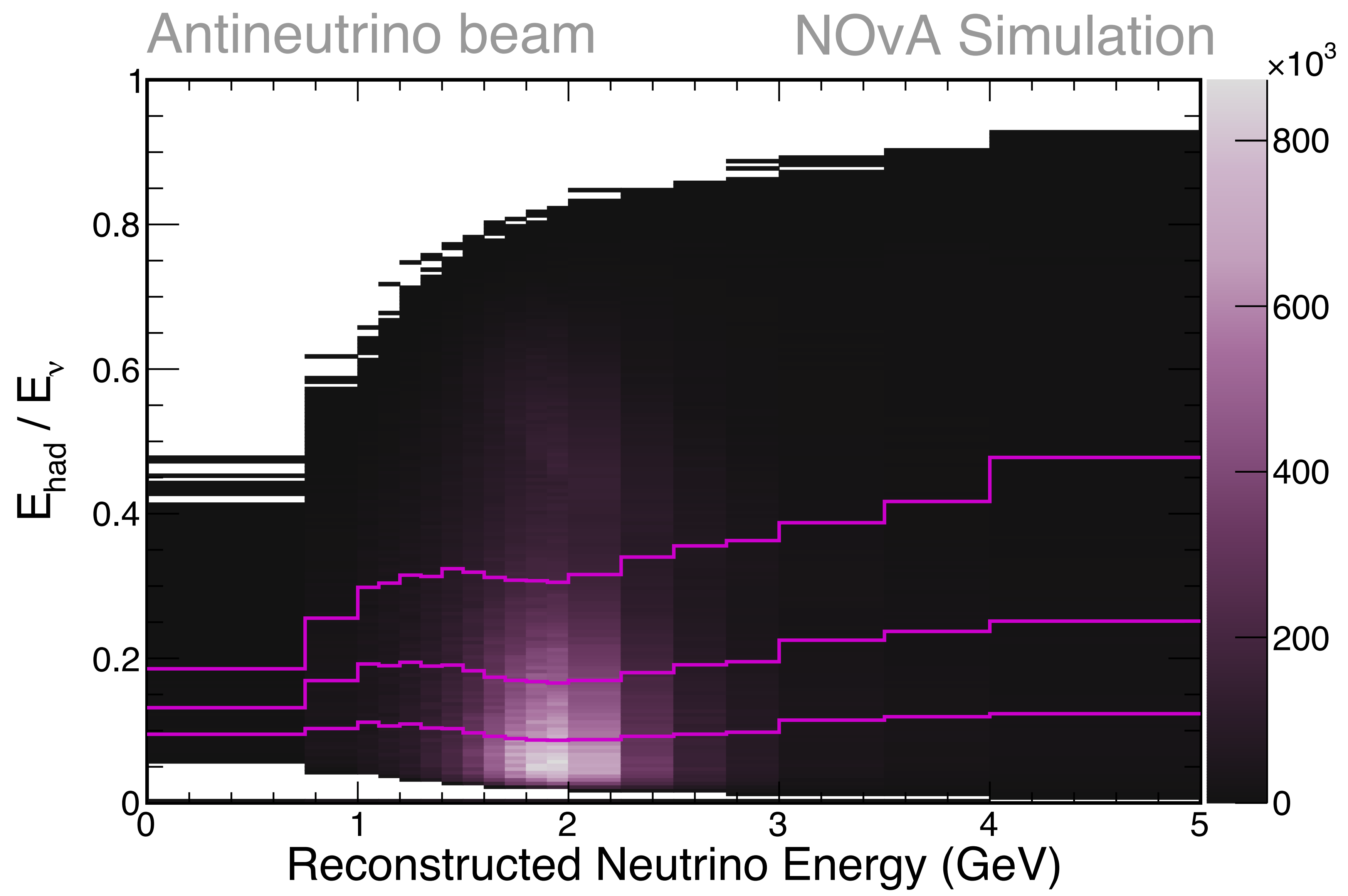
$$P(\nu_\mu \rightarrow \nu_e) \times \sigma_{\nu_e} \times \Phi_{\nu_\mu}$$

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \frac{1.27\Delta m^2_{32} L}{E}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin \frac{\Delta m^2_{32} L}{4E} + f(\delta_{CP})$$

E_{Had} extrapolation

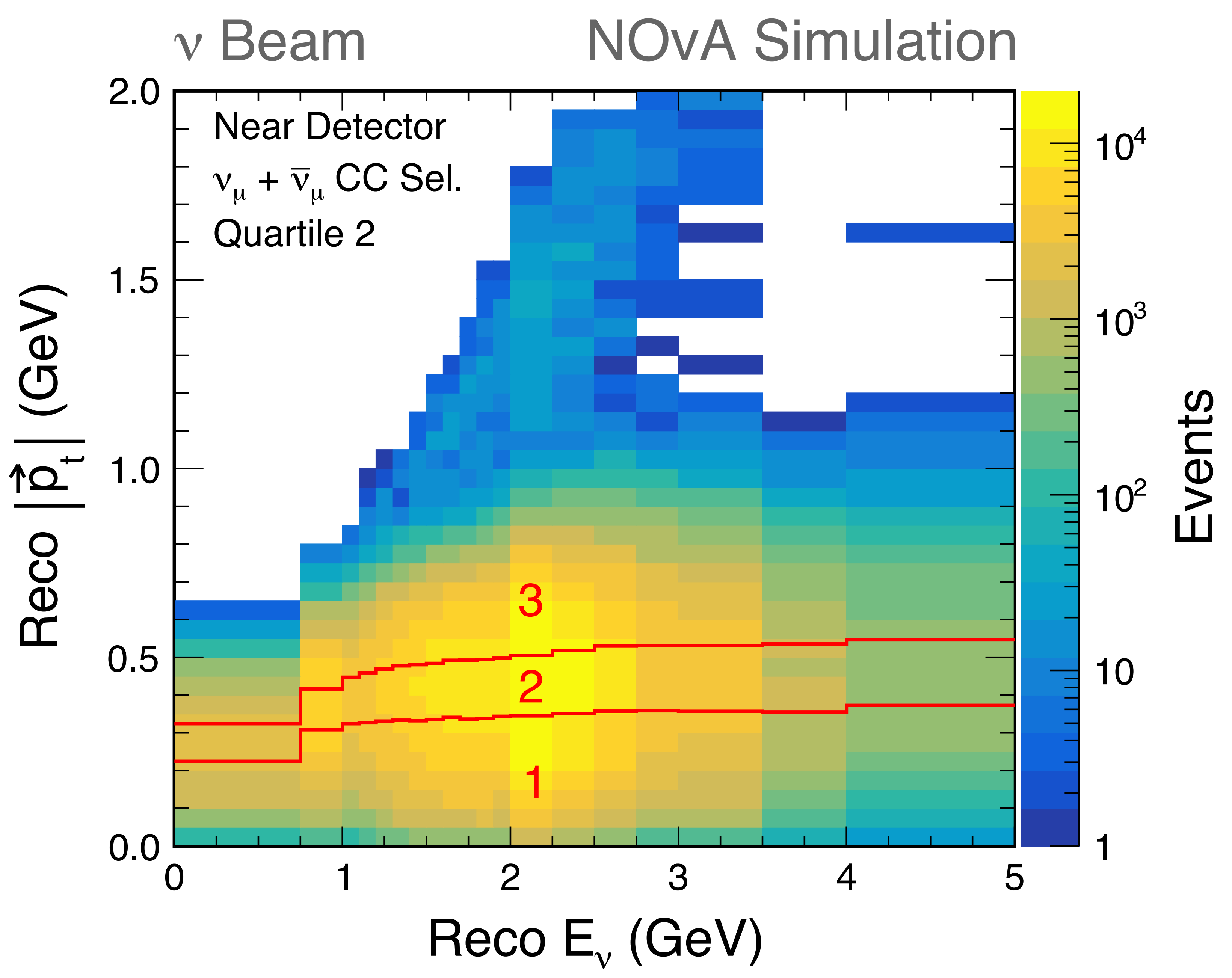


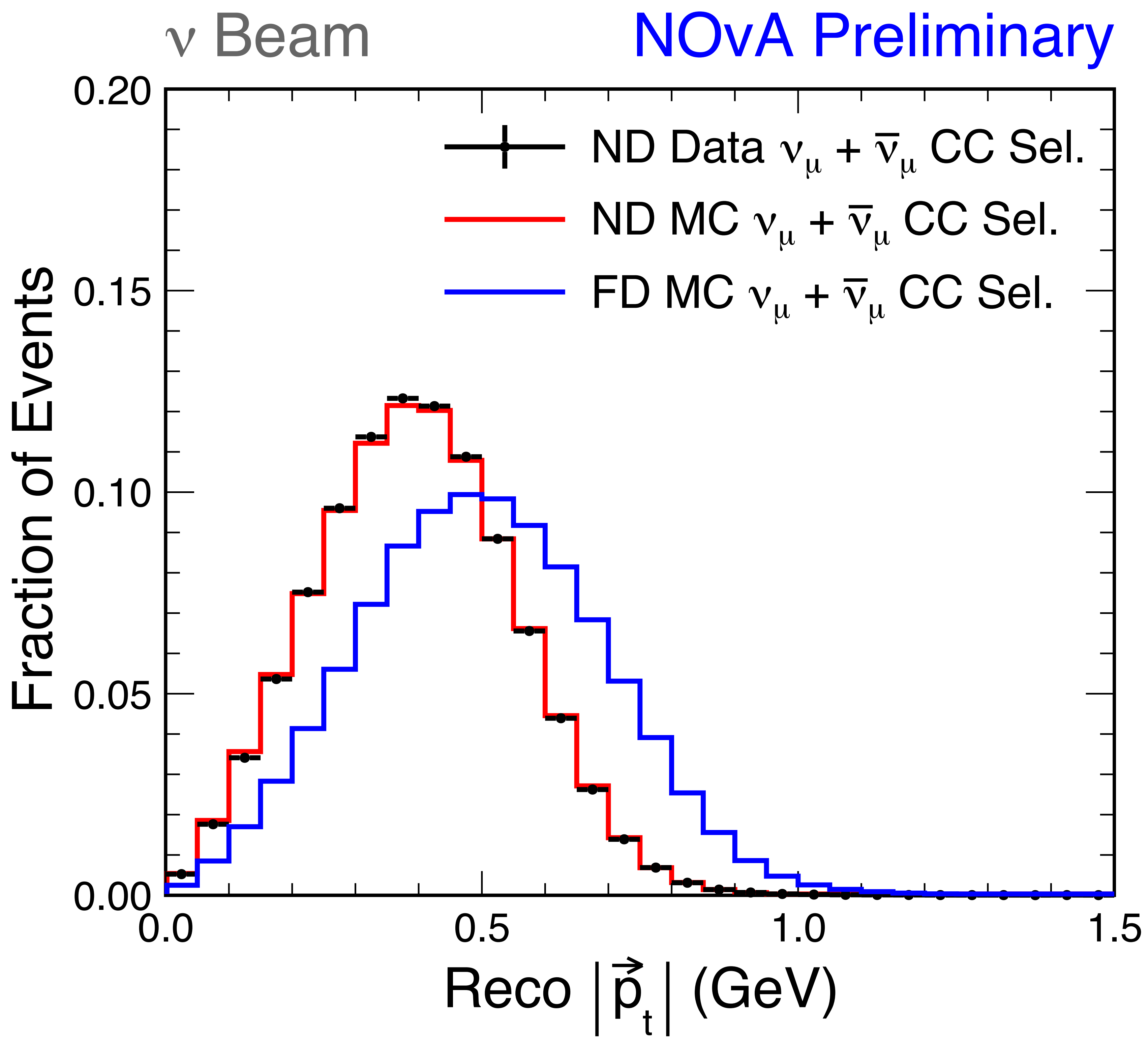


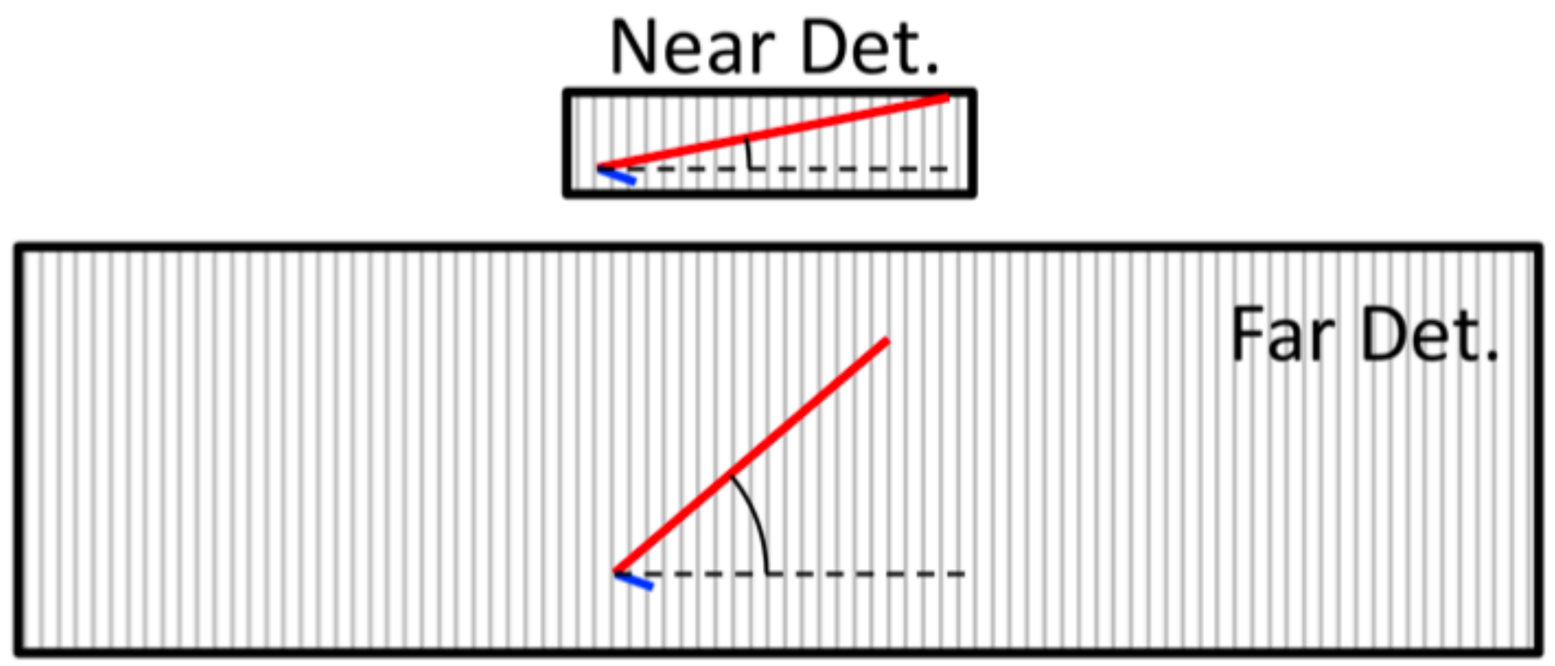
- Energy reconstruction depends on the hadronic energy fraction
- Split the hadronic energy fraction in quartiles
- Extrapolate ND → FD each of them independently

p_T extrapolation

- ND and FD have different sizes
  - Transverse muon momentum is different
- Separate into 3 p_T bins and extrapolate each of them independently

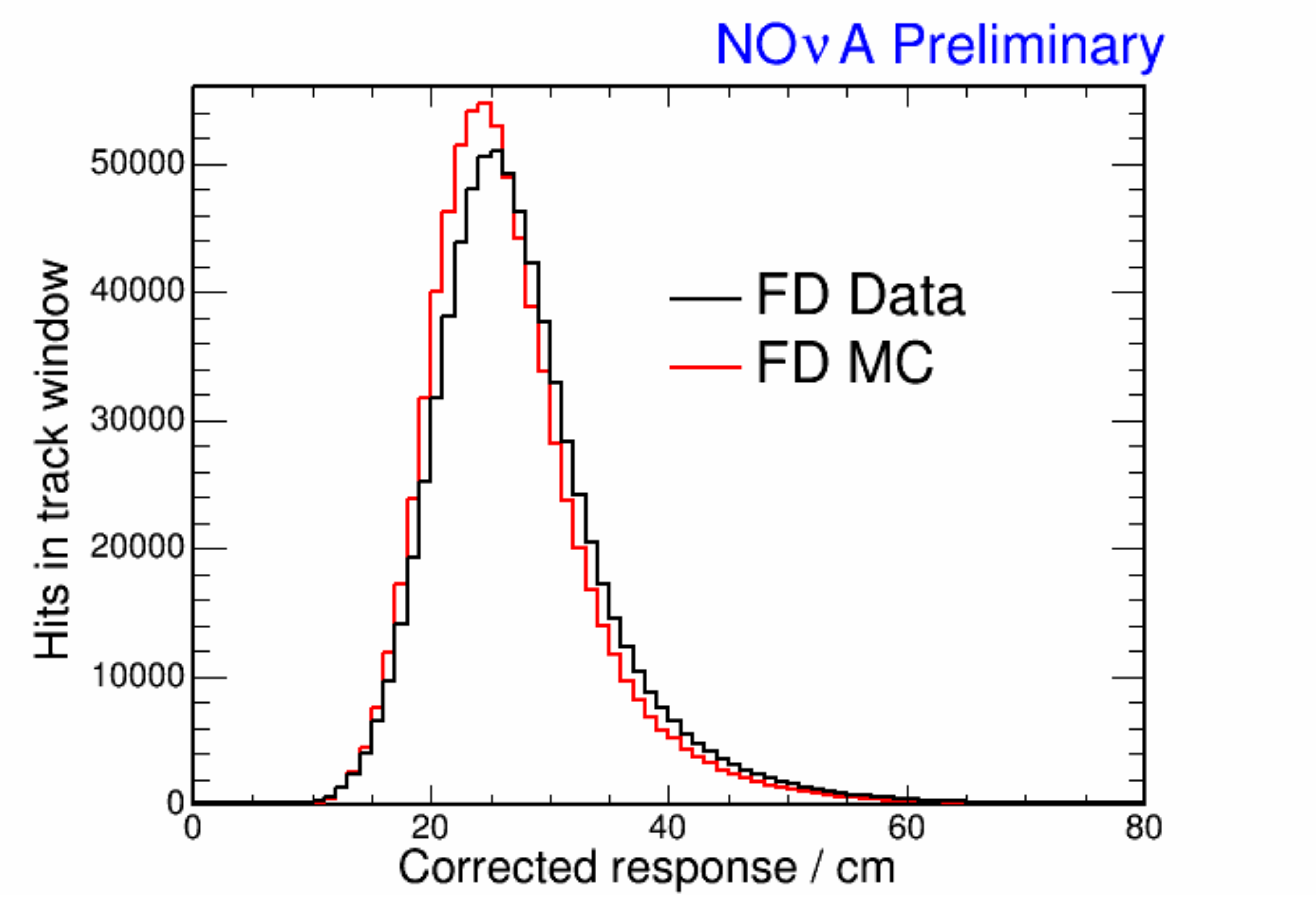


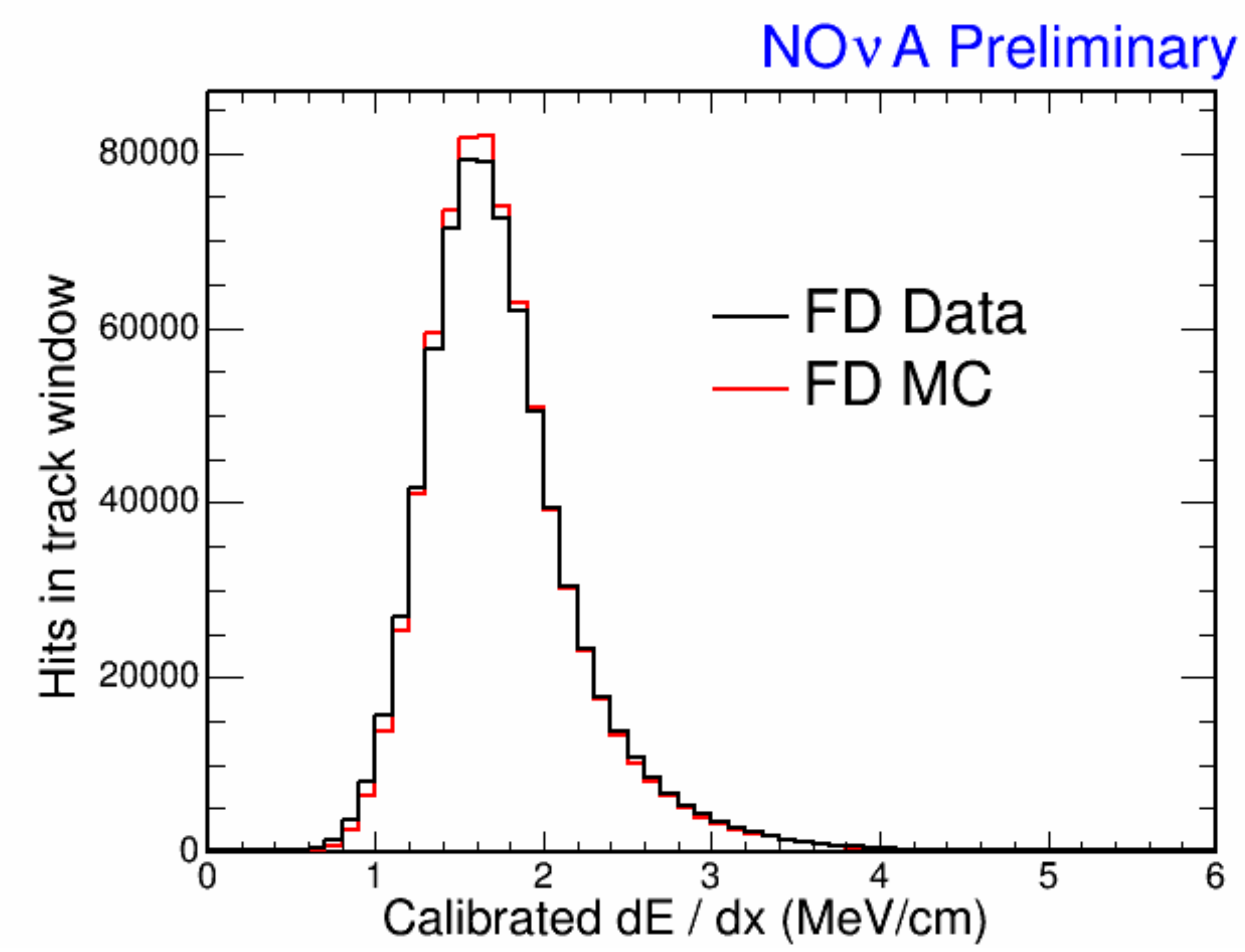




Detector Calibration

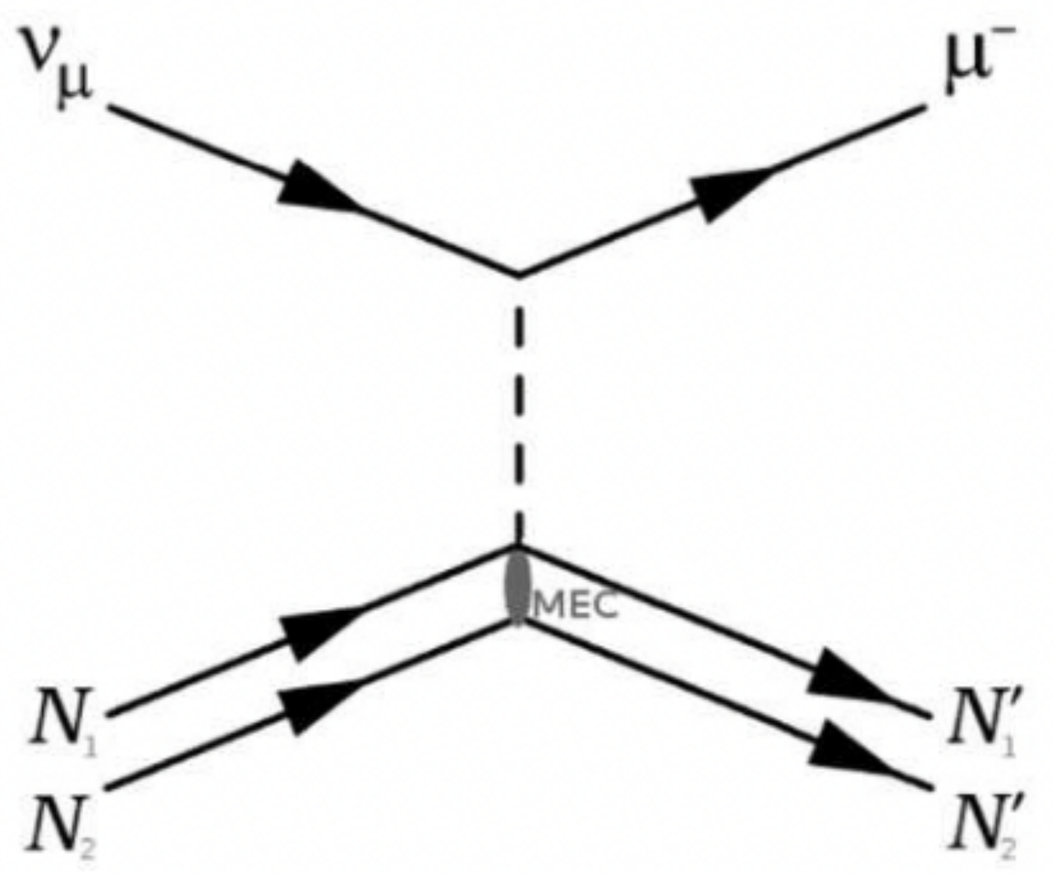
- Done with cosmic muons
  - Select stopping muons
  - Measure distance from the end of the track
  - Compare dEdx for MC and data and adjust
- Note these are plots from 2017! Got better since
- Limitation
  - Hadronic energy deposition is quite different from MIP!
- Hoping that the test beam can help us

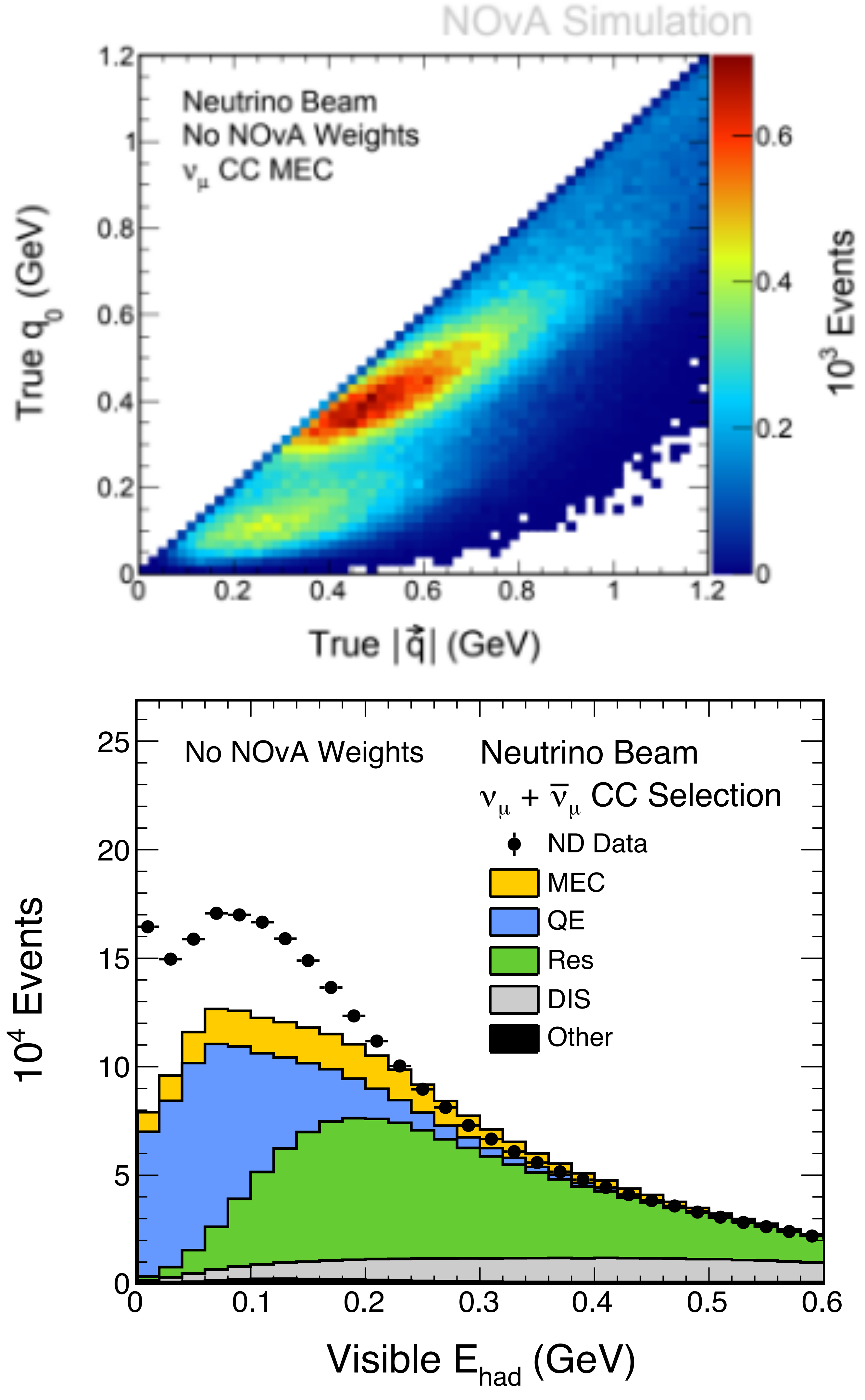




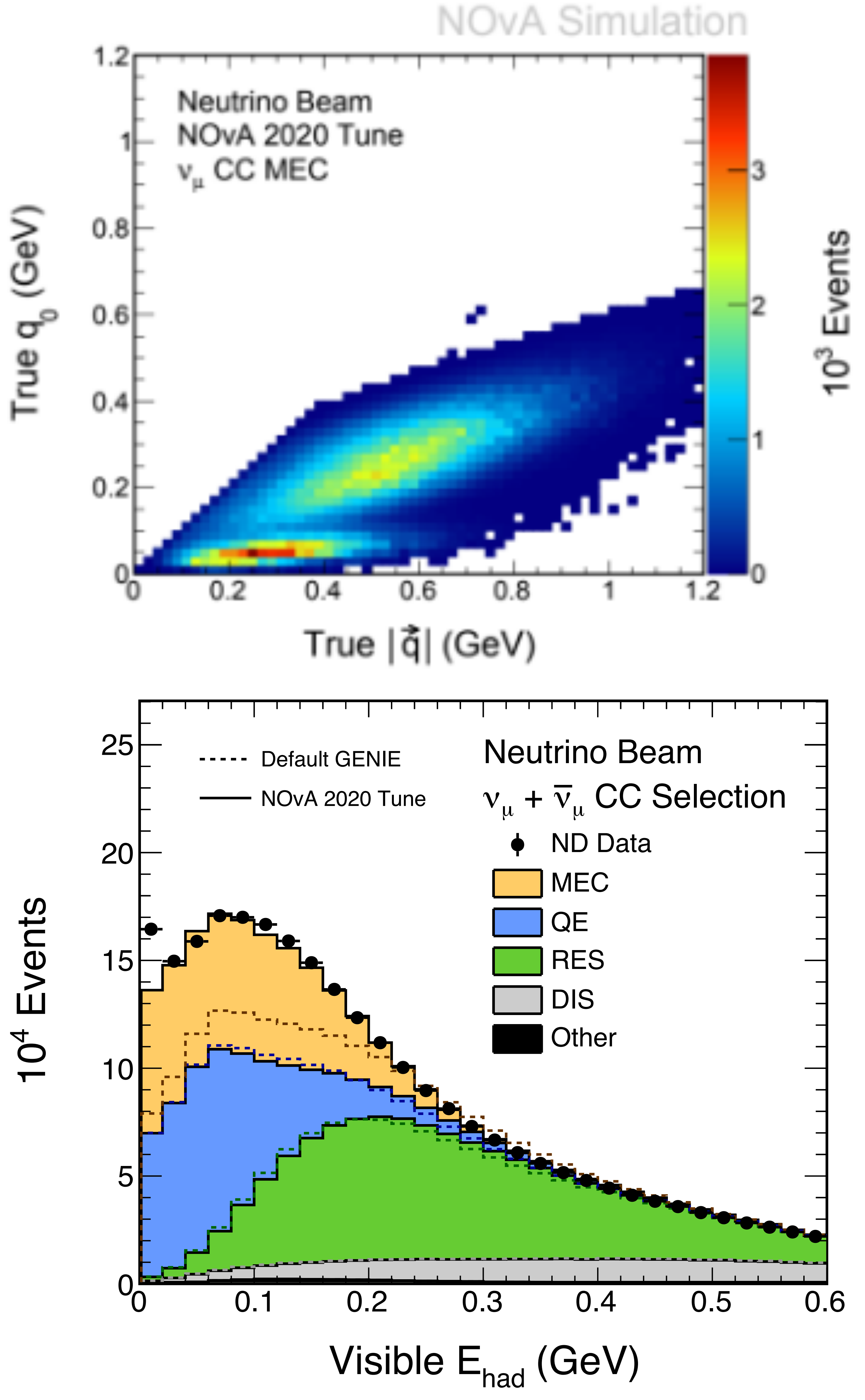
Multi-nucleon knockout

- σ_{MEC} needs a huge increase to agree with ND data
  - Not theory motivation
- "Good" answer requires a lot of work from both phenomenology and experiment data





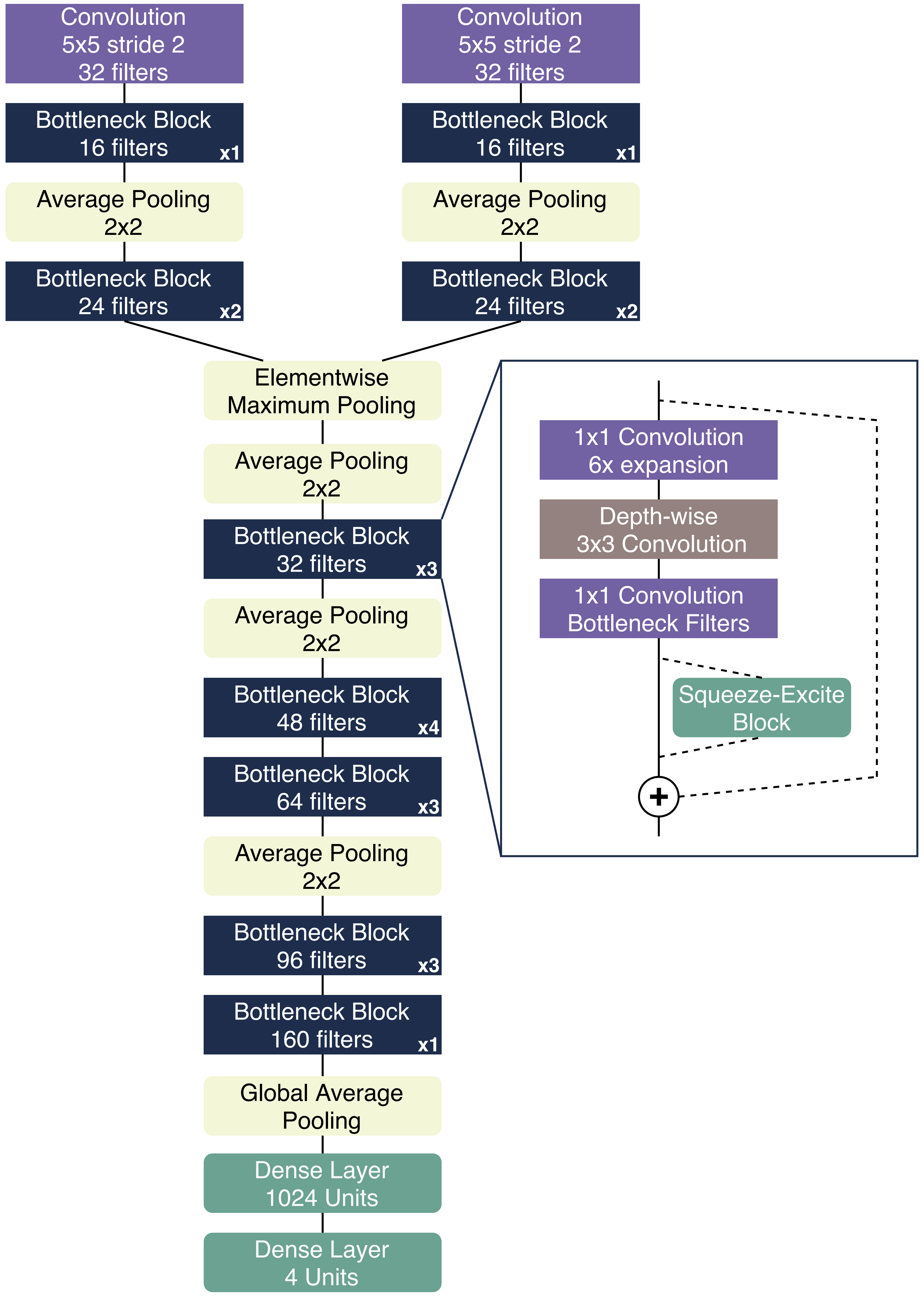
GENIE



NOvA's GENIE

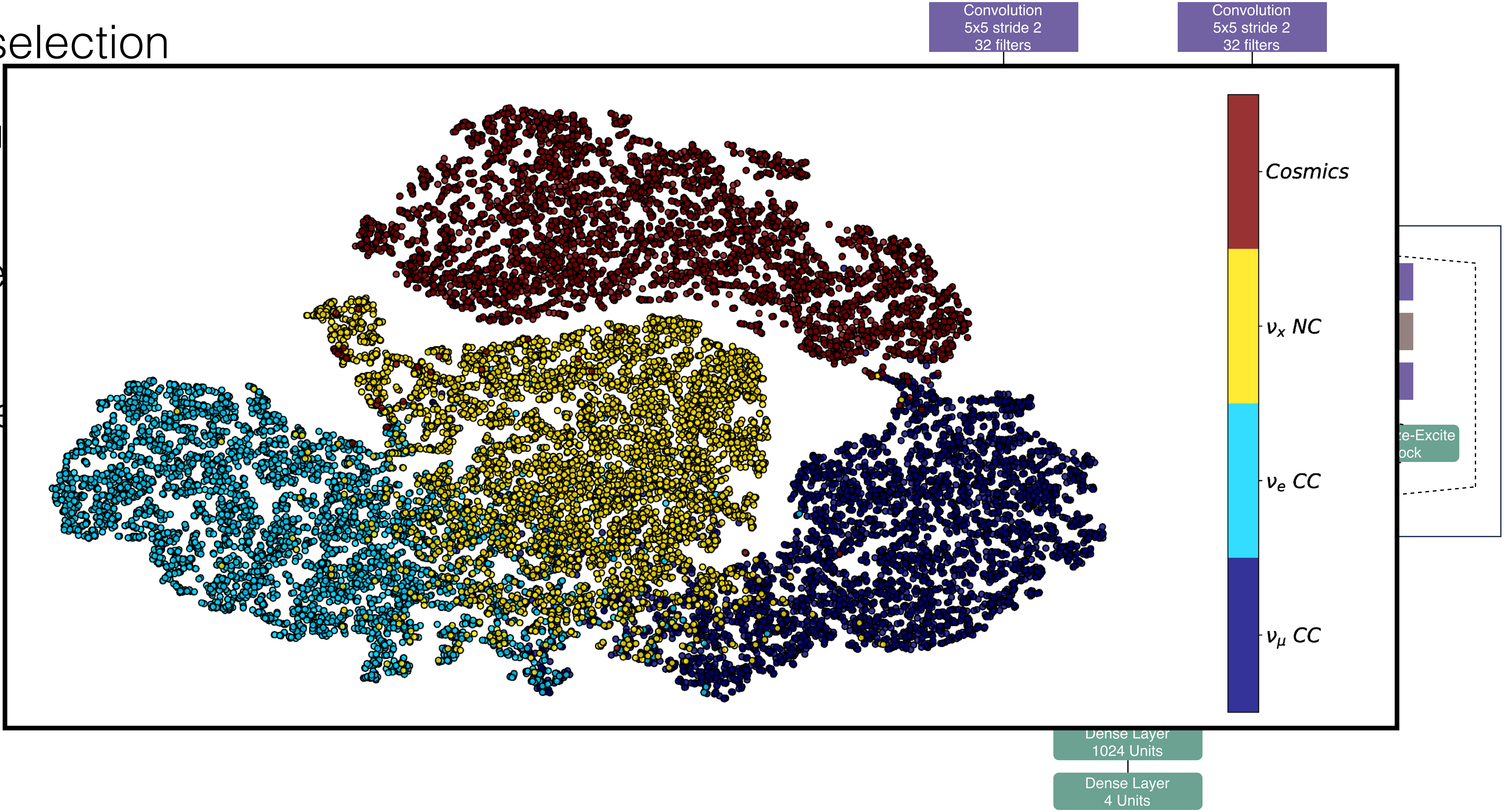
Event classification

- Preselection
  - Quality cut (detector was running normally)
  - Contained cut (nothing seems to be exiting the detector)
  - Cosmic rejection Boosted Decision Tree (the event doesn't look like a cosmic ray)
- PID with Convolutional Neural Network (CNN)
  - Topology-based algorithm
  - High purity samples



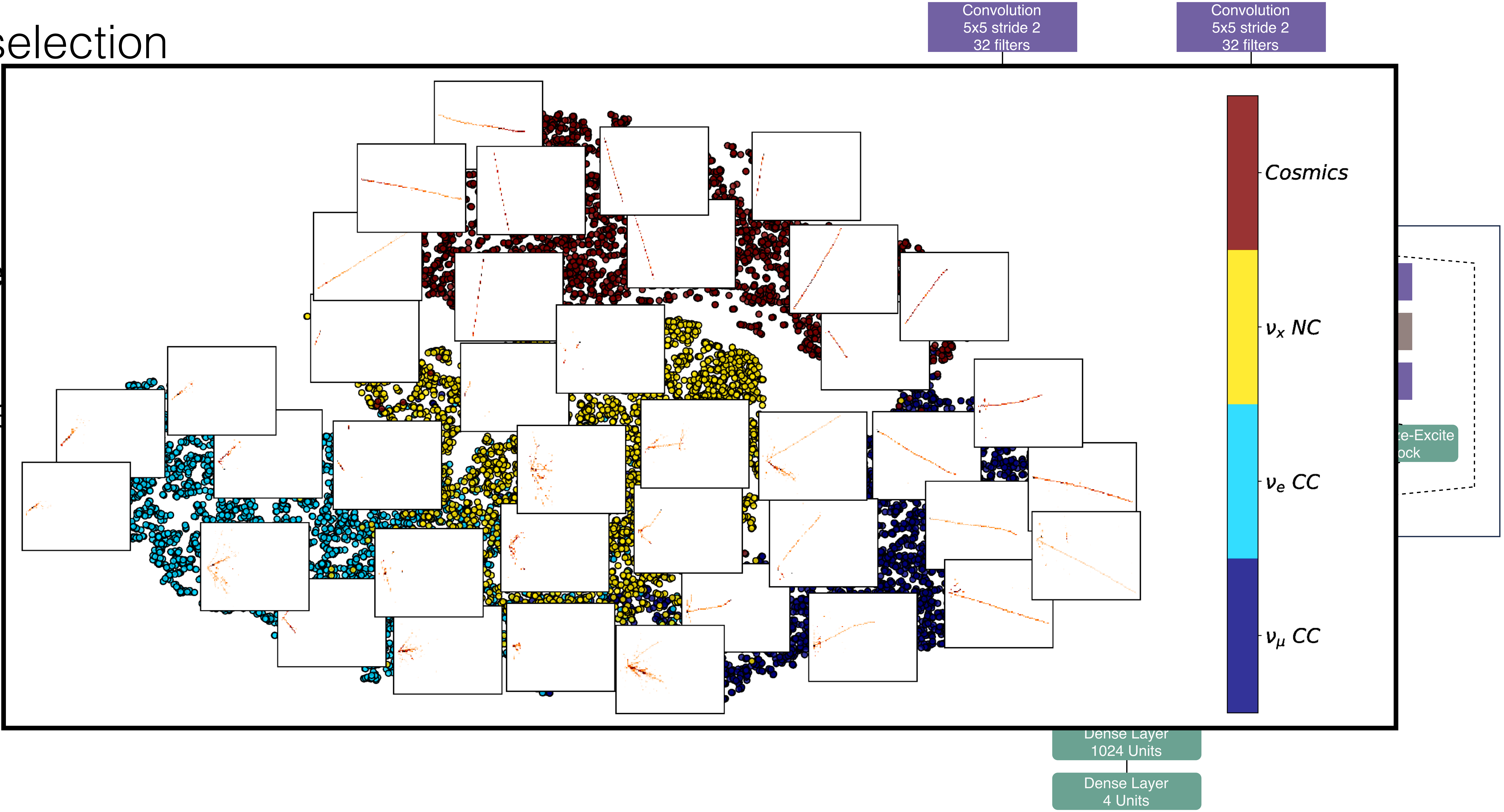
Event classification

- Preselection
  - Qu
  - Co
    the
  - Co
    eve
- PID
  - Co



Event classification

- Preselection
  - Qu
  - Co the
  - Co eve
- PID
  - Co



CVN confusion