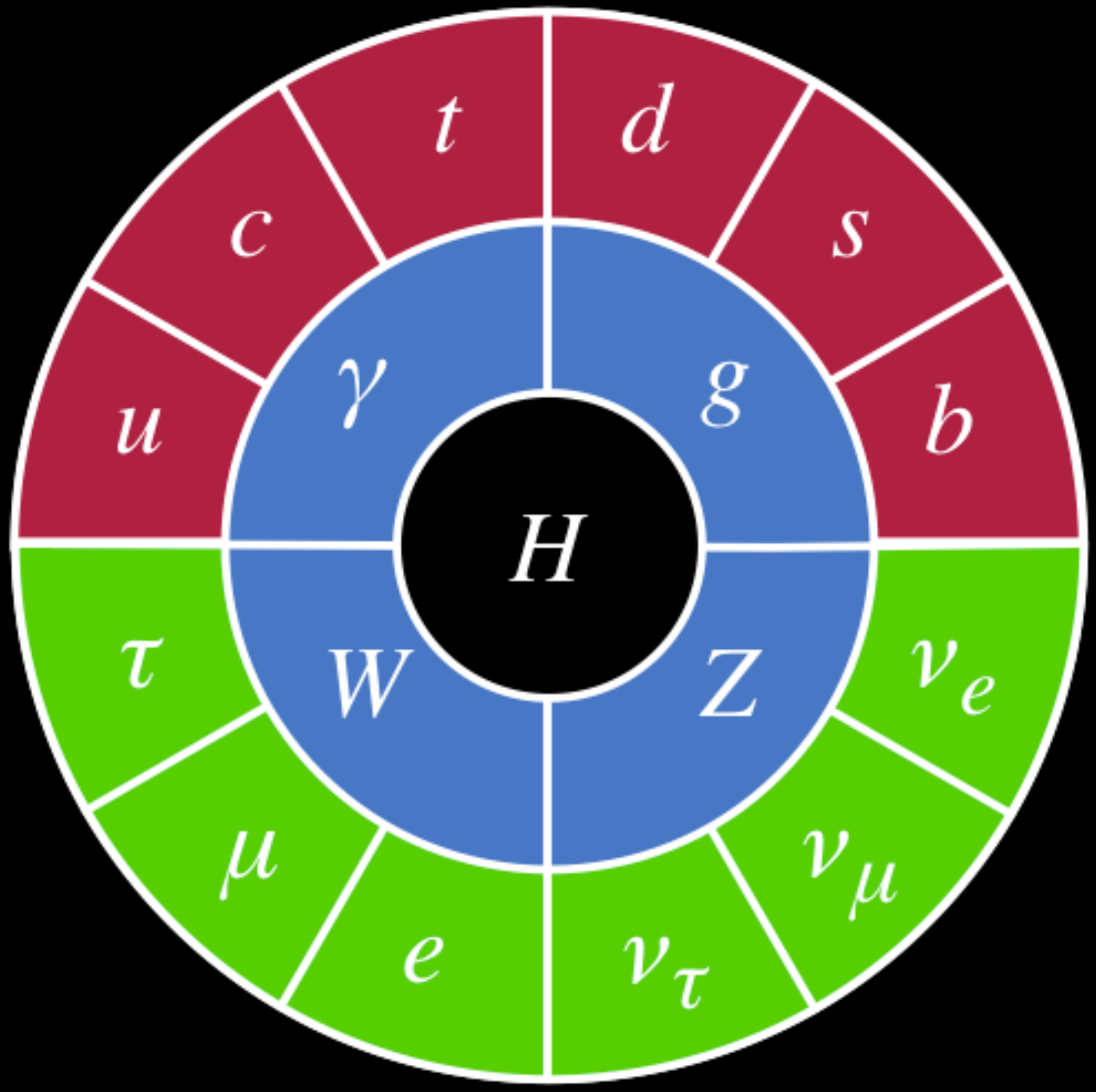
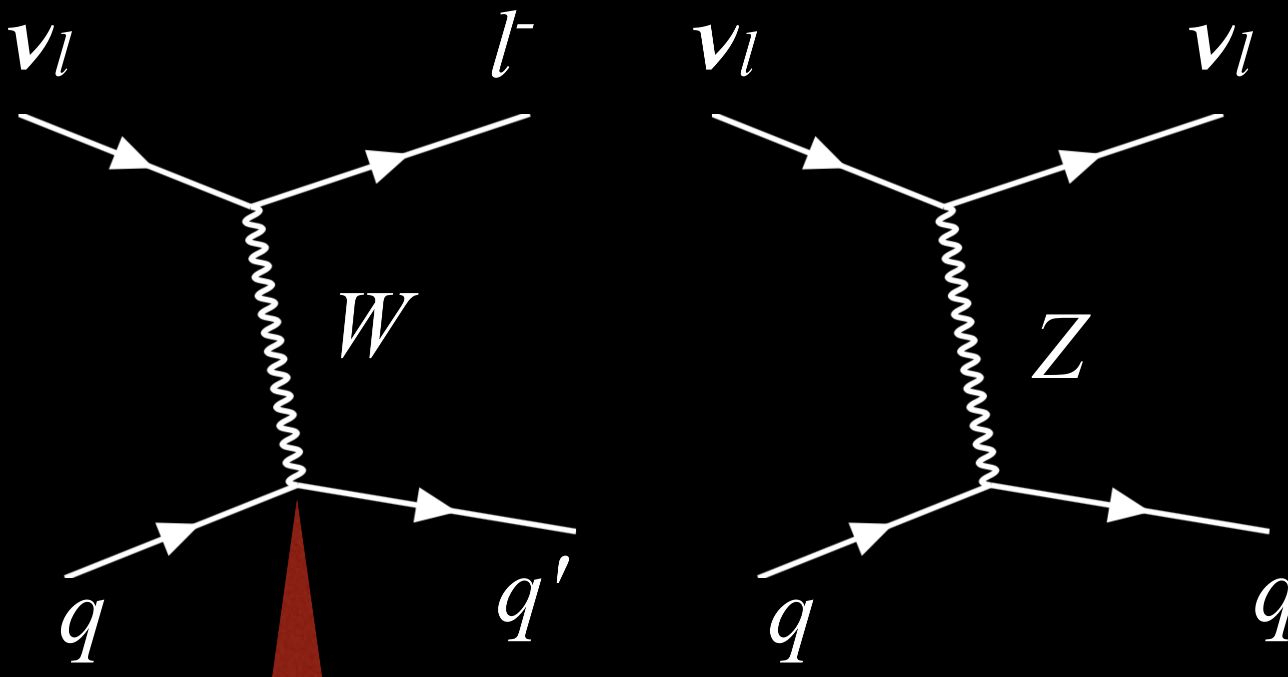
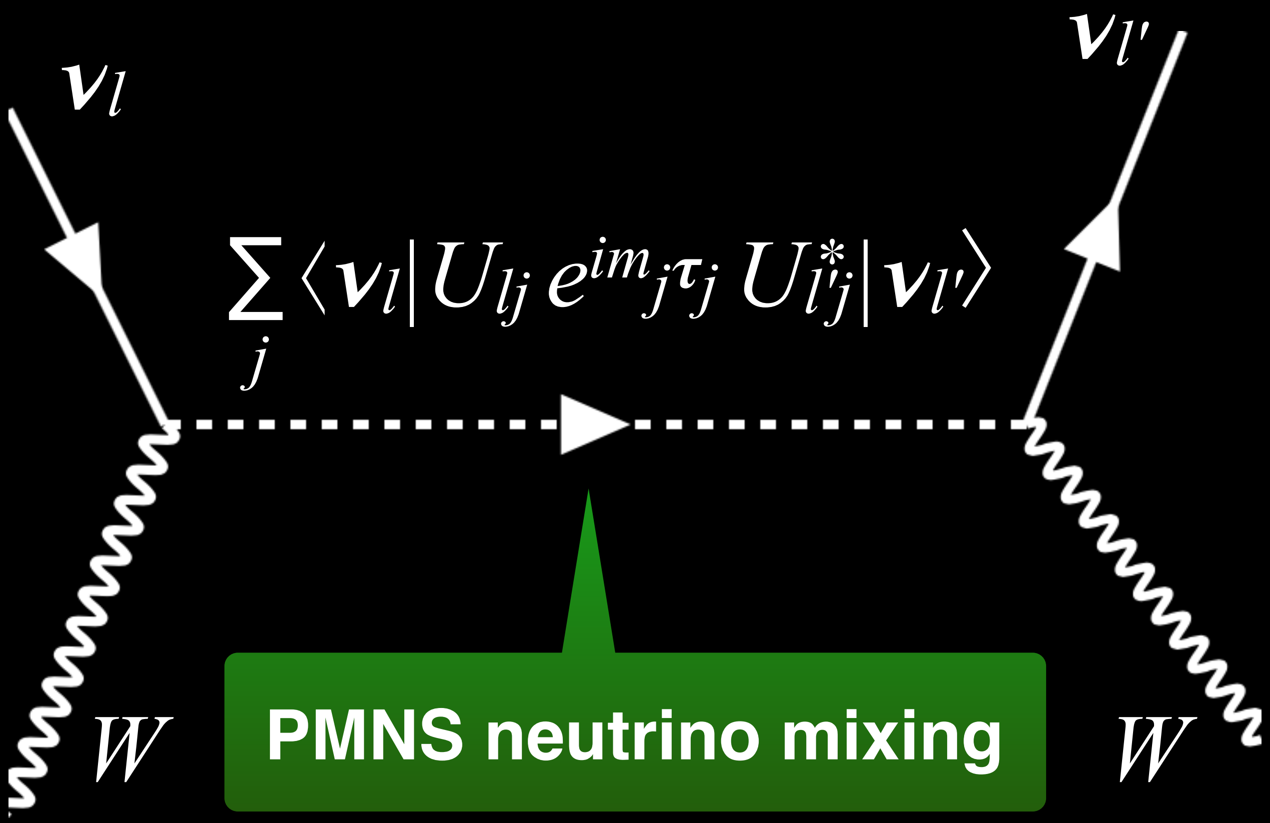
Neutrino





CKM quark mixing



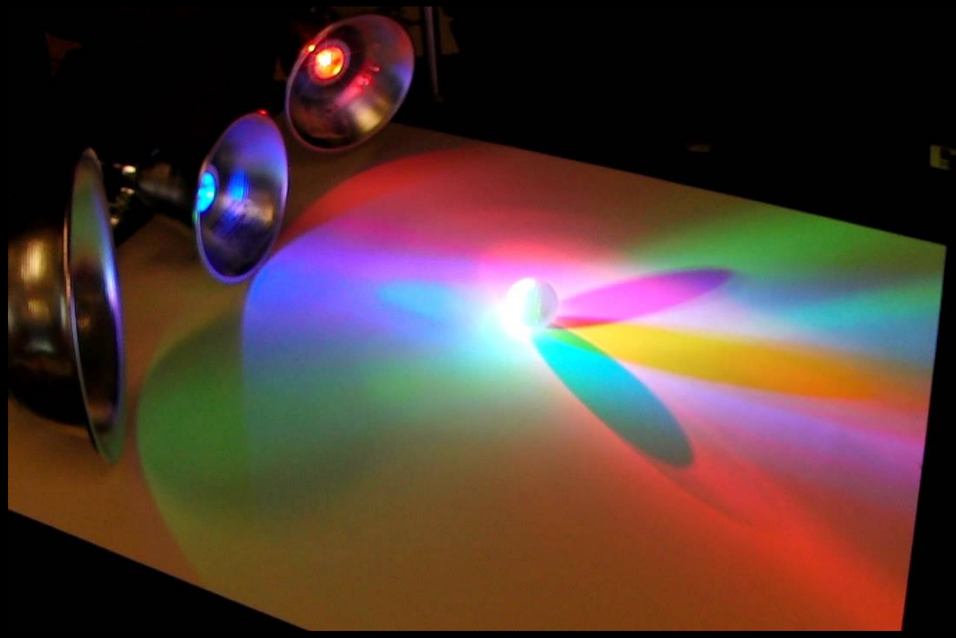
$$\sum_j \langle \nu_l | U_{lj}\, e^{i m_j \tau_j}\, U^*_{l'j} | \nu_{l'} \rangle$$

PMNS neutrino mixing

Neutrino

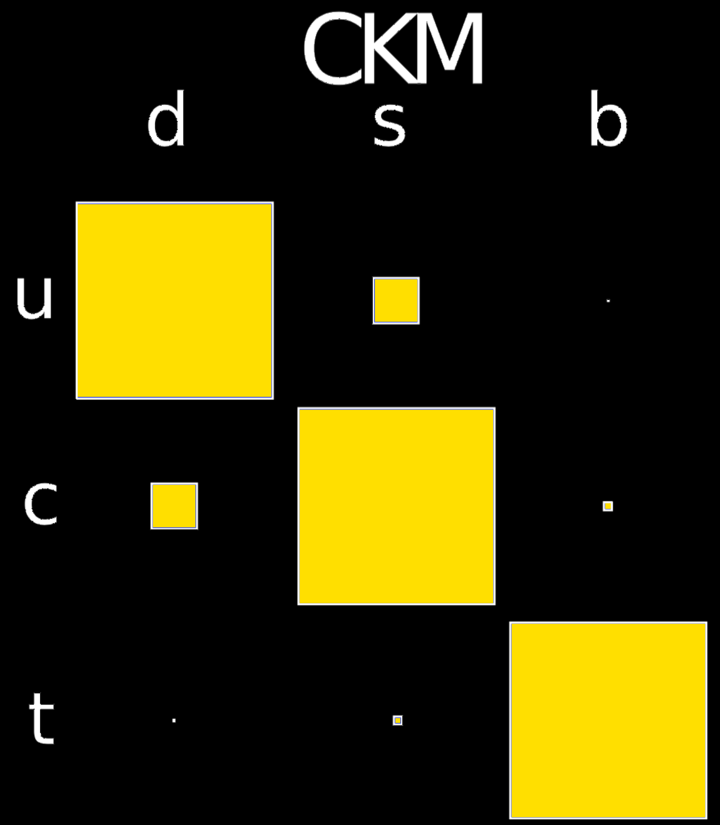
- Neutrinos mix, just like quarks?

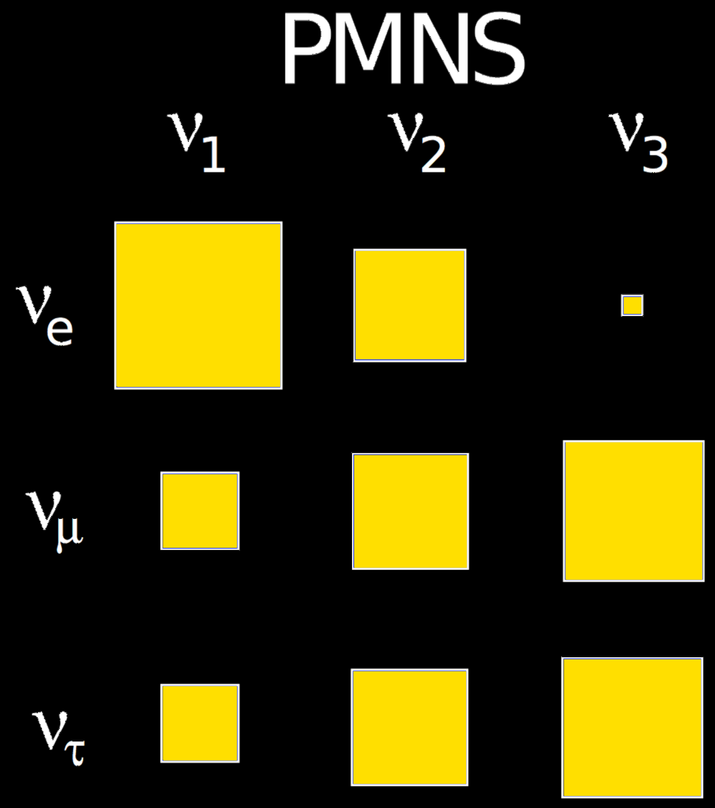
$$|\nu_l\rangle = \sum_i U^*_{li}|\nu_i\rangle \quad l=e,\mu,\tau \quad i=1,2,3$$



- PMNS matrix like CKM matrix?

- Unlike the quarks, neutrino mixing are large





Neutrino

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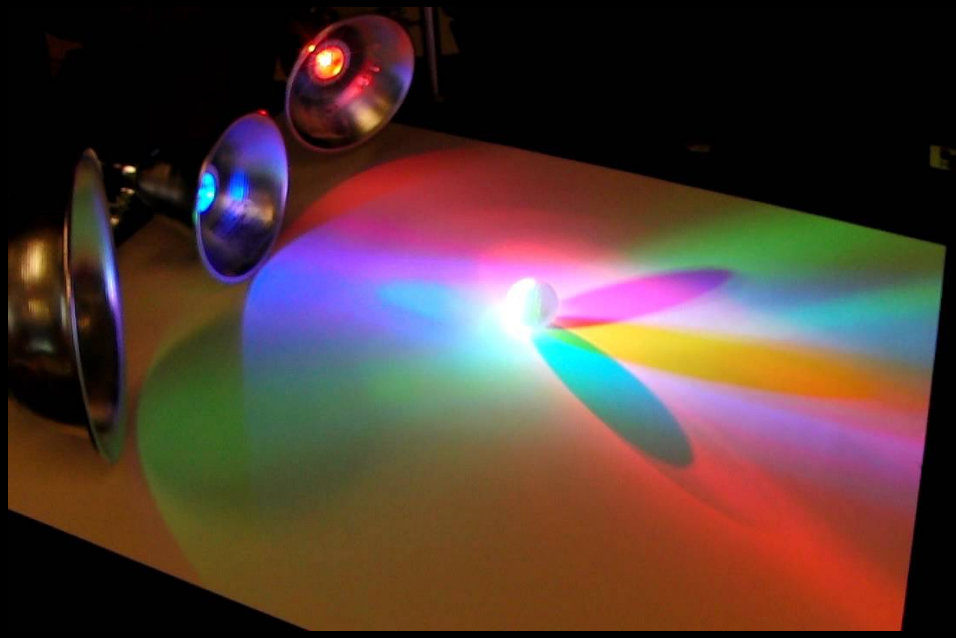
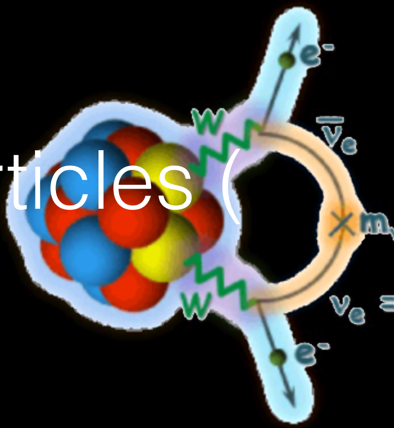


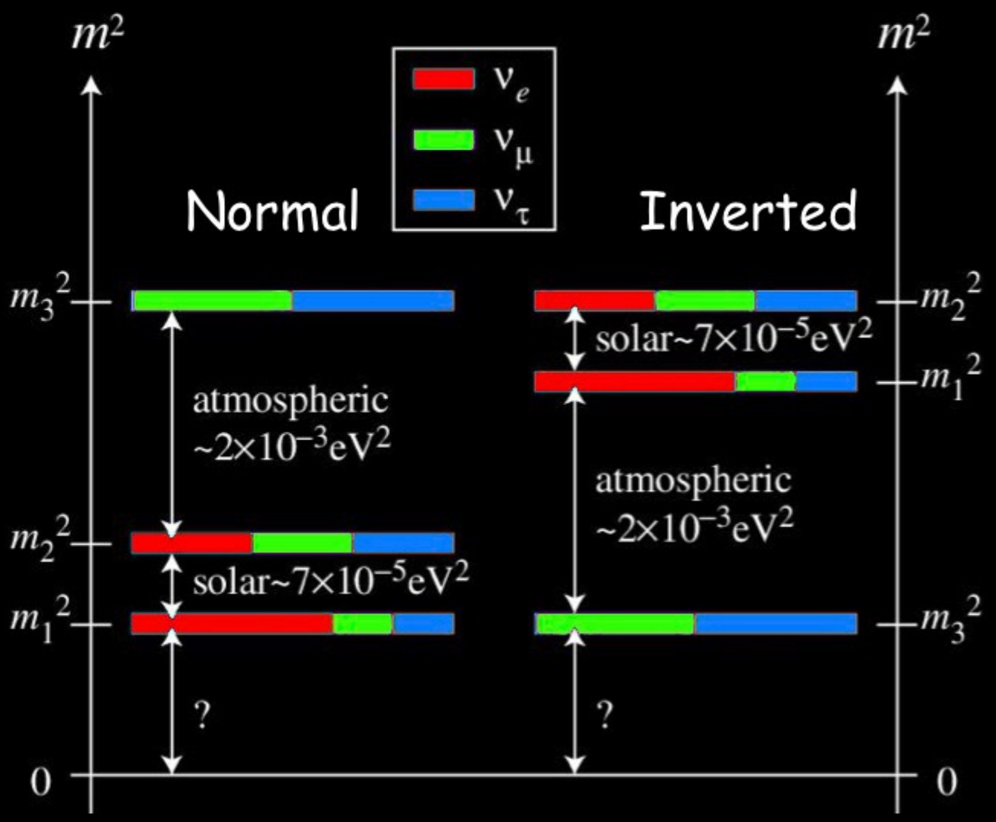
- PMNS matrix like CKM matrix?
- Unlike the quarks, neutrino mixing are large
- Open neutrino questions:

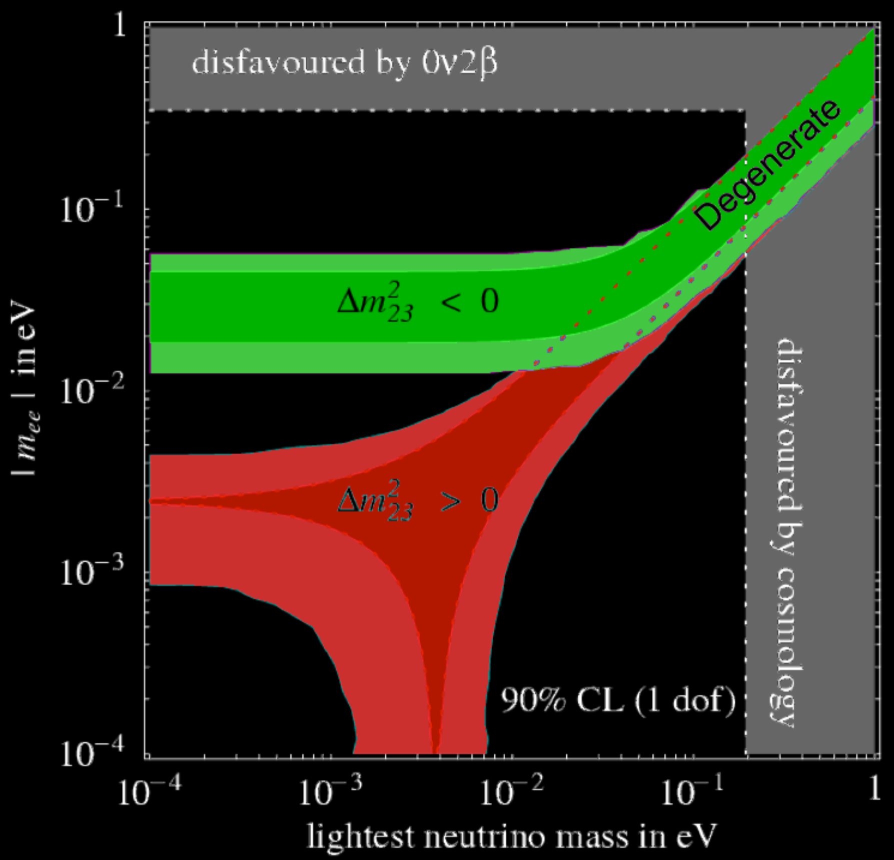
Dirac or Majorana? • Absolute masses • Mass ordering • CP-violation • Random mixing parameters or patterns? • Just 3 neutrino types?

Why hierarchy?

- Is the most electron-like state lightest?
- i.e. Does the pattern of the masses match the charged leptons?
- Are neutrinos Majorana particles ($\nu = \bar{\nu}$)?
- Observation of $0\nu\beta\beta$ would be proof they are
- Impact of IH determination: lack of $0\nu\beta\beta$ implies Dirac nature







Why CP-violation?

- Does e.g. P($\nu_{\mu}\rightarrow\nu_{e}$) = P($\overline{\nu_{\mu}}\rightarrow\overline{\nu_{e}}$)?
- Insight into fundamental symmetries of the lepton sector

- Why is the universe not equal parts matter and antimatter?
- Sakharov conditions: Baryon number violation • Out of thermal equilibrium • C and CP violation

- CPV in the Standard Model, eg for K and B mesons, but too small
- “Leptogenesis”: generate asymmetry in neutrinos, transfer to baryons

- Require **neutrino appearance** experiment to discover

Mixing patterns

- Only a small fraction of ν_e in $|\nu_3\rangle$

  (the famous $\mathrm{Sin}^2 2\theta_{13}$)
- The remainder is split about 50/50 ν_μ/ν_τ ($\mathrm{Sin}^2\theta_{23}$)
- Accident? Or a sign of underlying structure?

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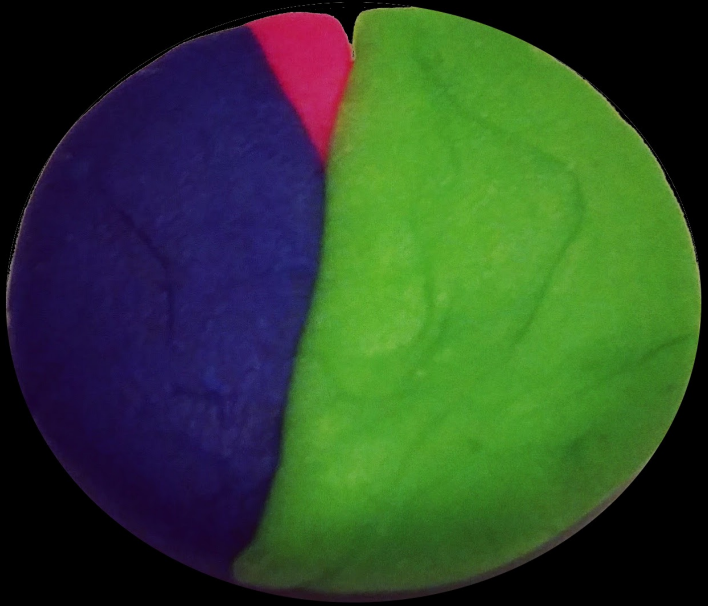
- The remainder is split about 50/50 ν_μ/ν_τ ($\mathrm{Sin}^2\theta_{23}$)
- Accident? Or a sign of underlying structure?

- Is θ_{23} exactly 45°?
- If not, it is

➡ $< 45^\circ$ $|\nu_3\rangle$ more ν_τ, like in quarks

➡ $> 45^\circ$ $|\nu_3\rangle$ more ν_μ, unlike quarks



Fermilab accelerator complex

- Neutrinos produced at Main Injector (**NuMI**)

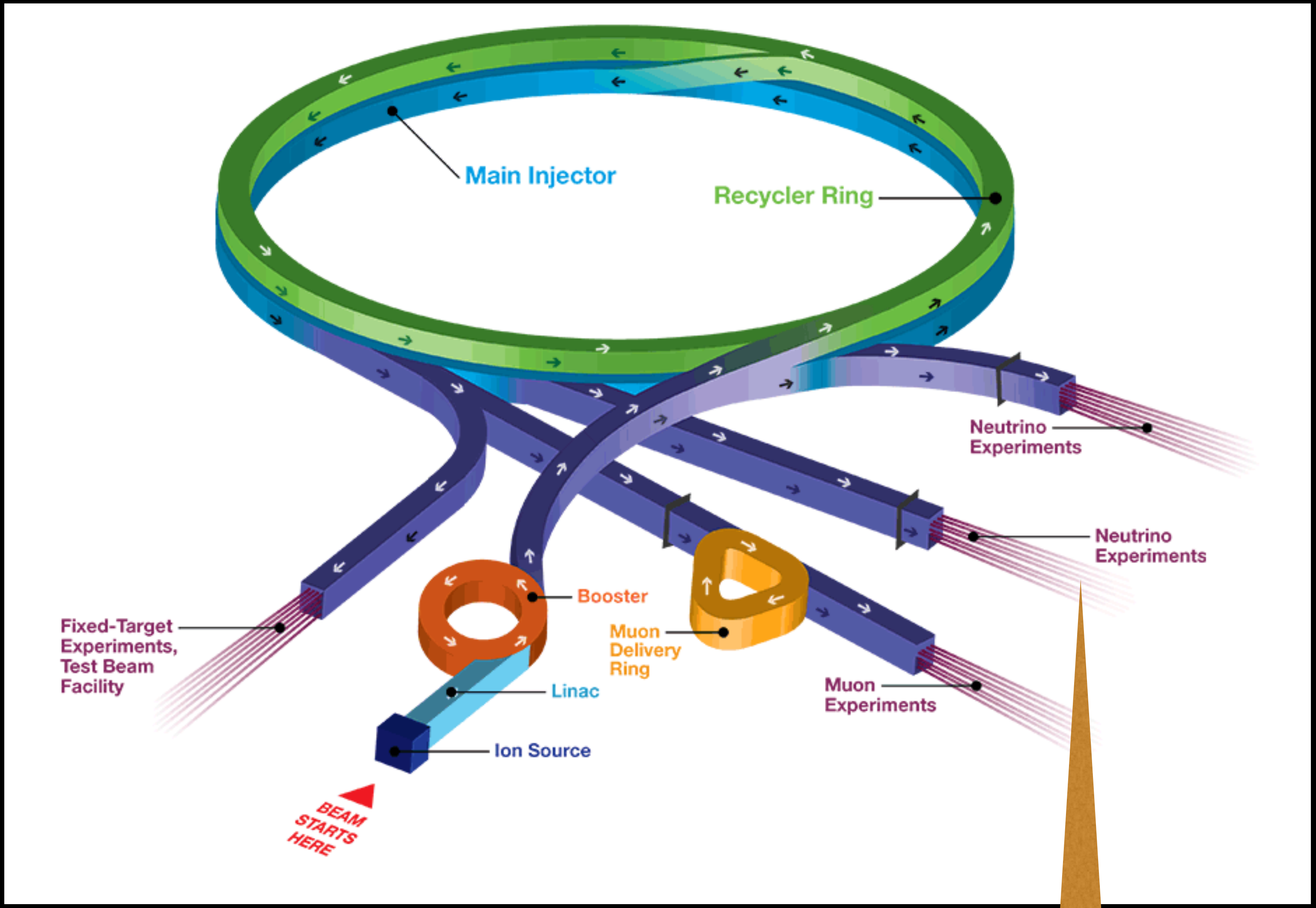
➡ Linac 750 keV

➡ Booster 400 MeV

➡ Recycler 8 GeV

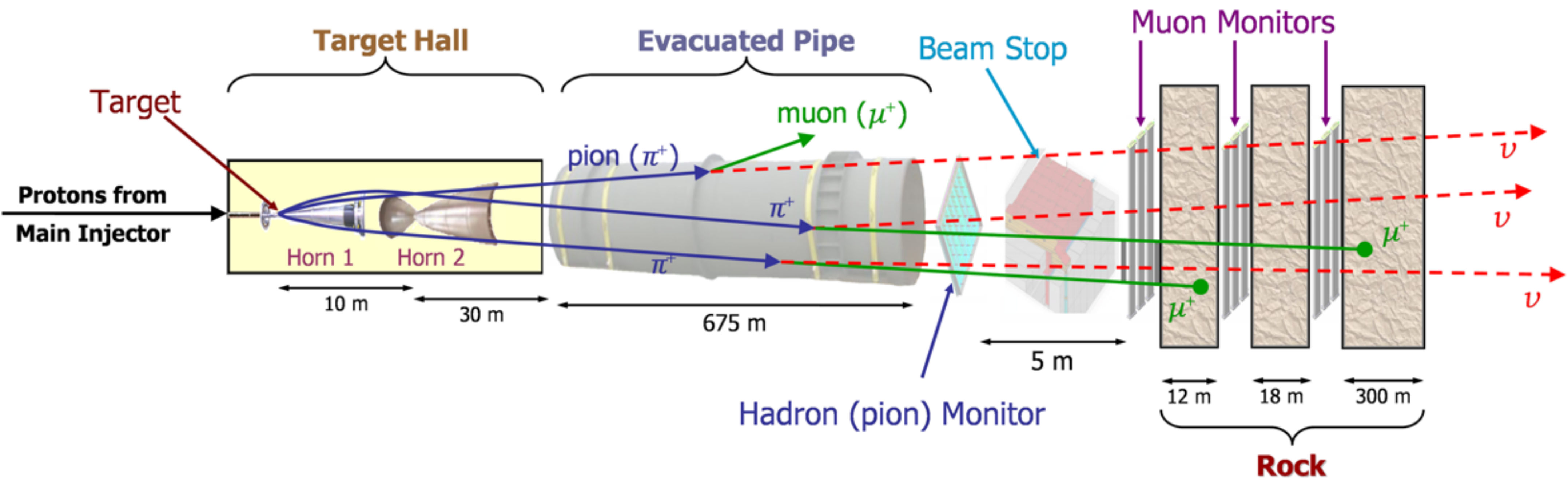
➡ NuMI 120 GeV

➡ to Carbon target



Line to High Energy Neutrino Experiments

The NuMI beam



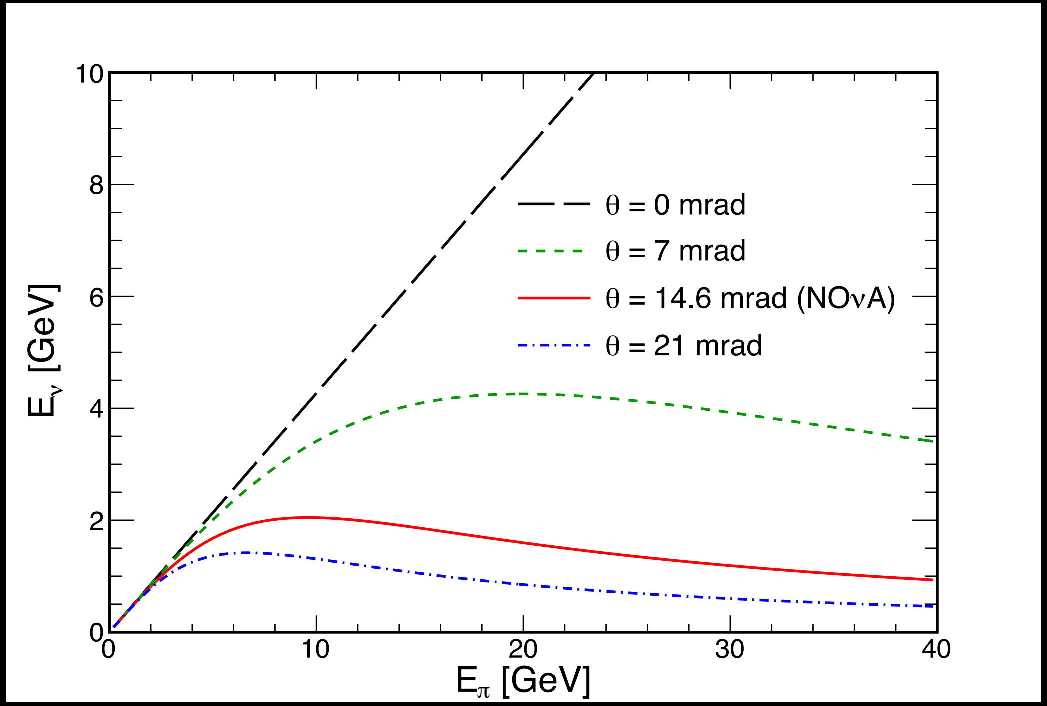
- 120 GeV protons from MI to Carbon target
- Produce mainly pions and kaons
- Focused by two magnetic horns
- Allow us to select charge sign for (anti)neutrinos
- Neutrinos produced every 1.3 sec in a spill with 6 doubled bunches 10 μs time window
- NuMI designed to provide for NOvA 700kW beam, producing 6×10^{20} POT/year

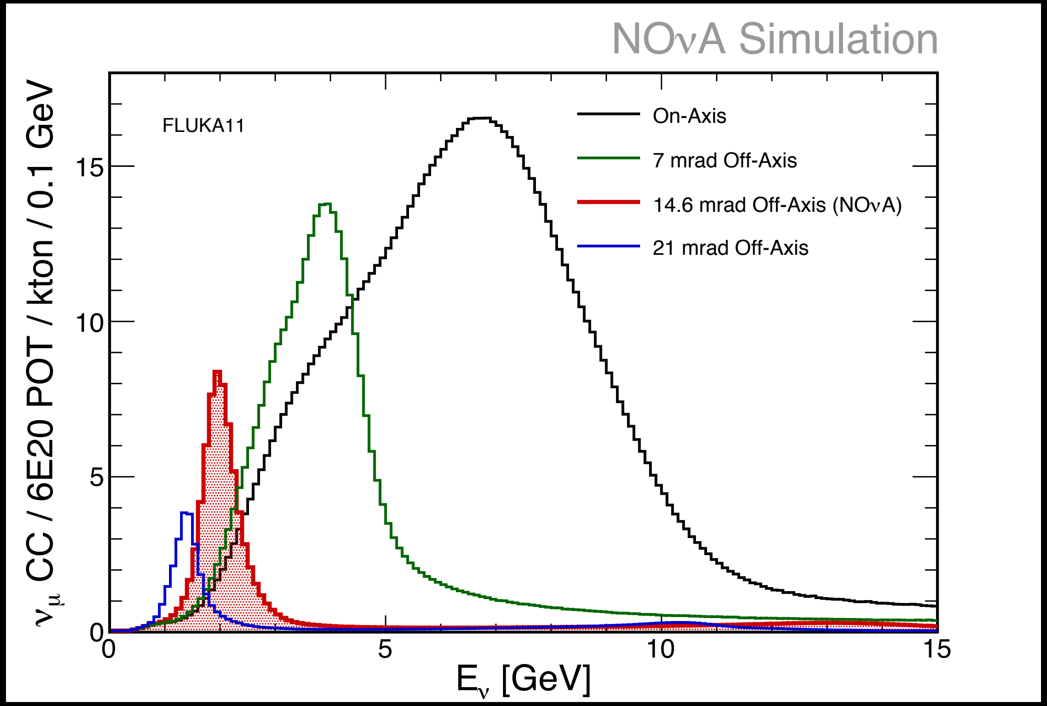
NuMI off-axis beam

- NOvA detectors are sited 14 mrad off the NuMI beam axis

- With the medium-energy NuMI tune, yields a narrow 2-GeV spectrum at the NOvA detectors

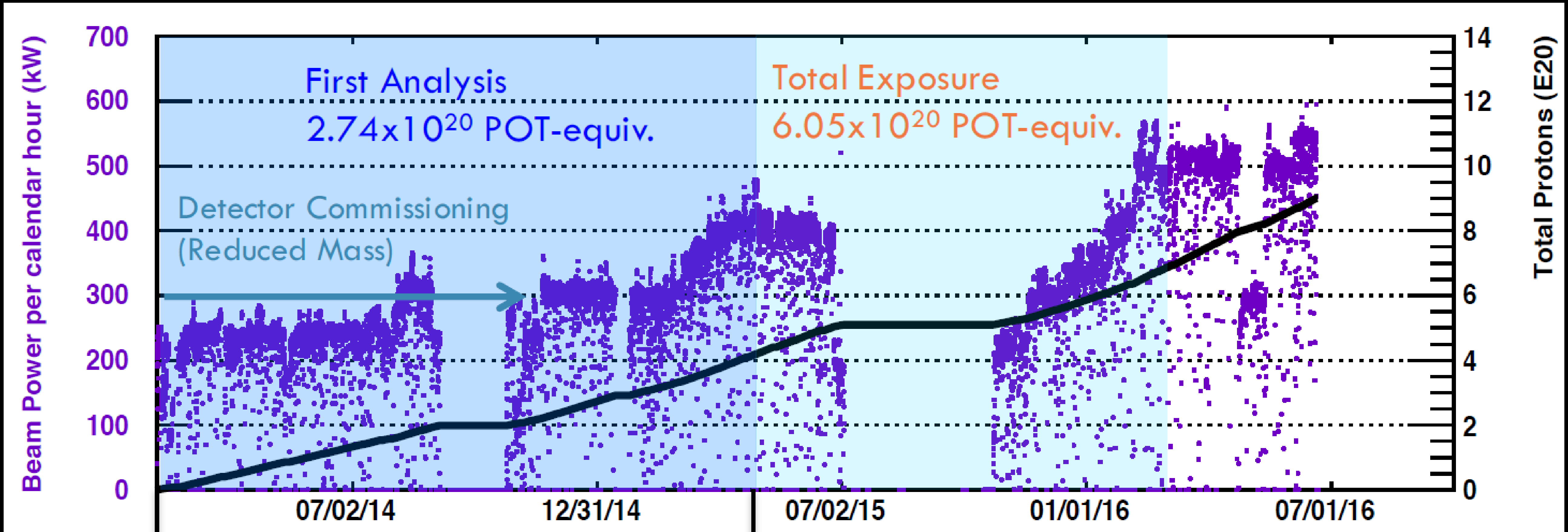
➡ Reduces NC and ν_e CC backgrounds in the oscillation analyses while maintaining high ν_μ flux at 2 GeV





Beam status

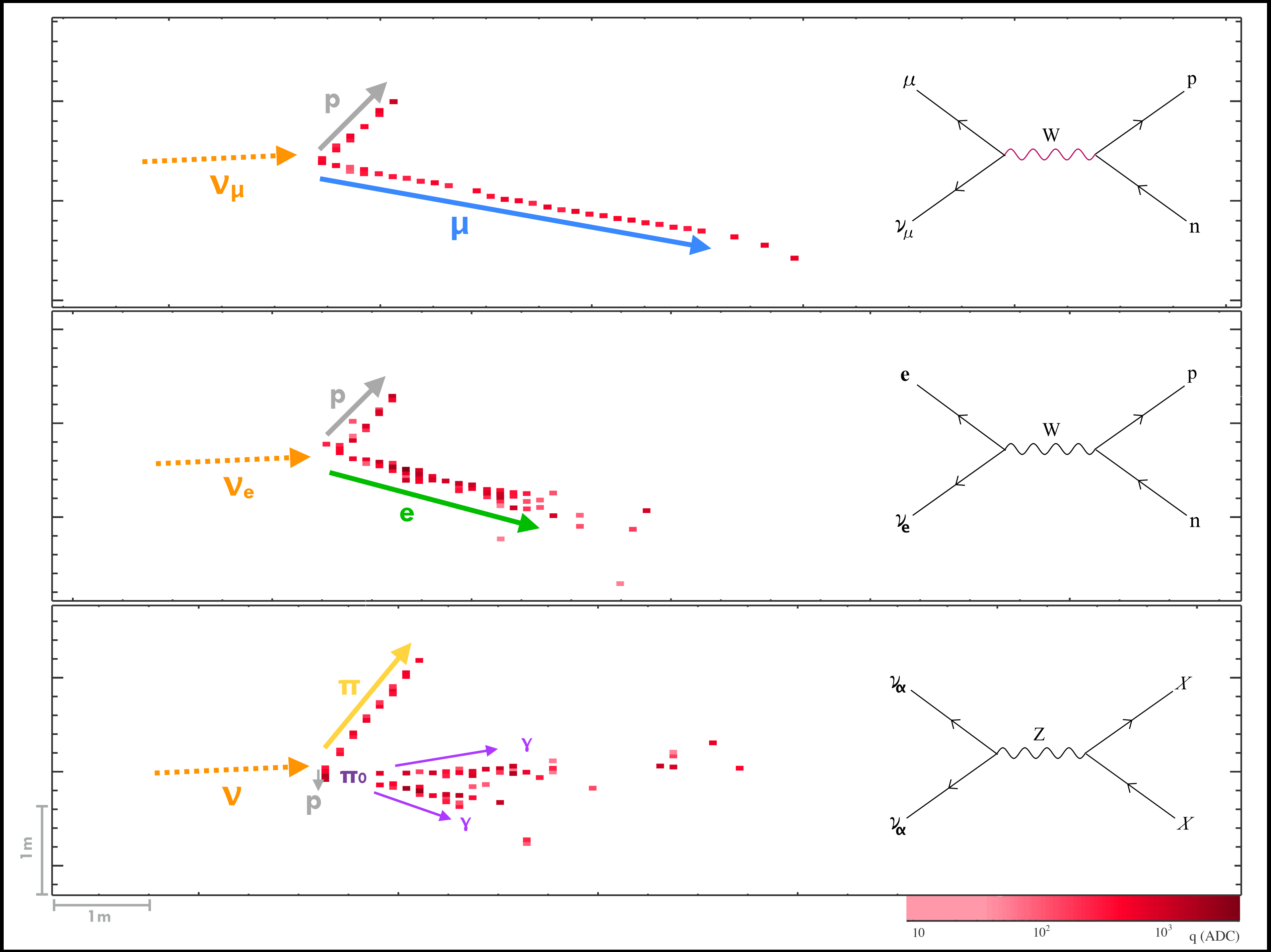
- Data from Feb 6, 2014 – May 2, 2016
- Achieved the 700kW design goal
- Have now about 9e20 POT neutrinos
- Switched to antineutrino mode from Feb 20th, 2017



$\nu_\mu \longrightarrow \nu_\mu$: Phys.Rev.D93.051104

$\nu_\mu \longrightarrow \nu_e$: PRL.116.151806

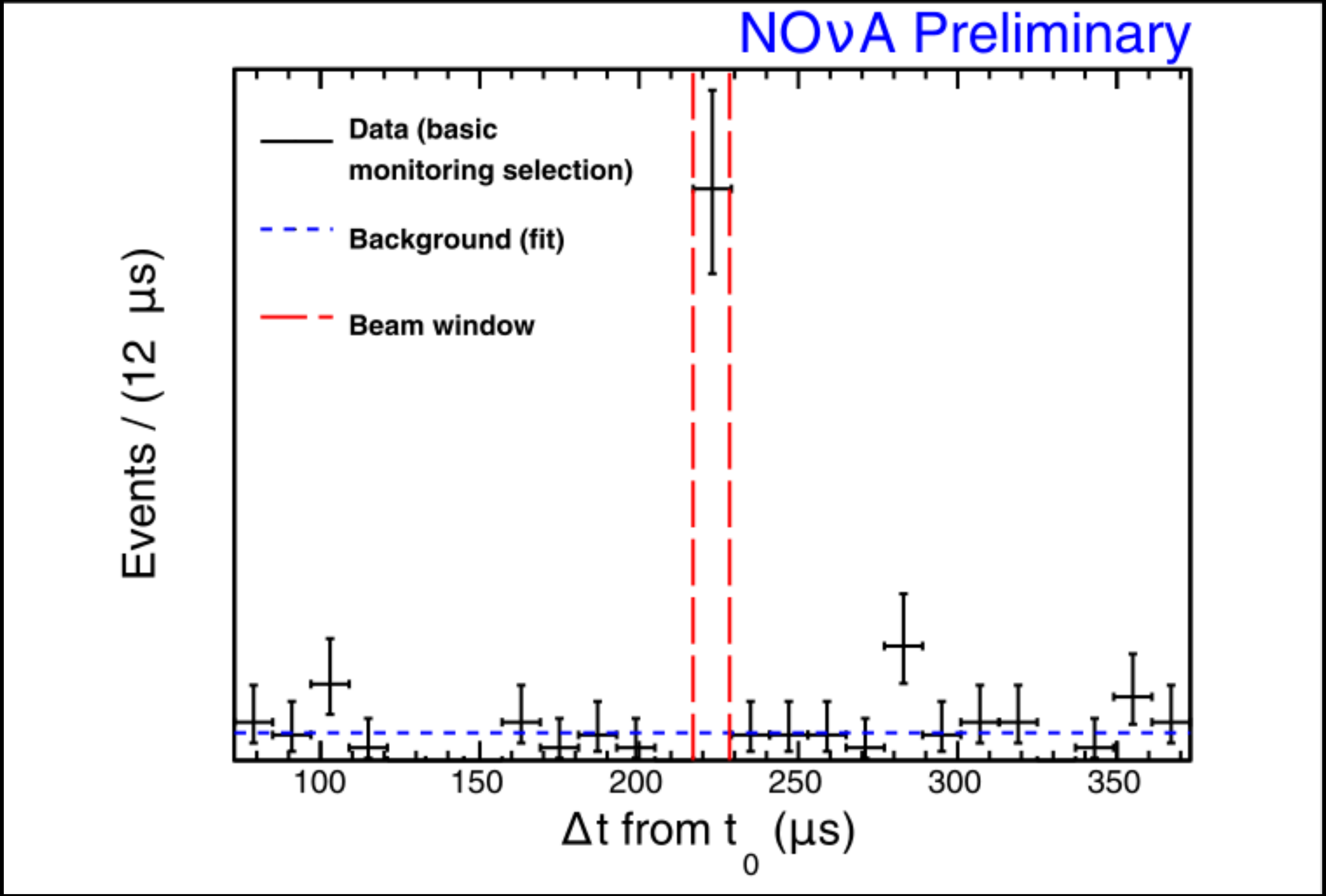
Event topologies



- Very good granularity
- X0 = 38 cm (6 cell depths, 10 cell widths)

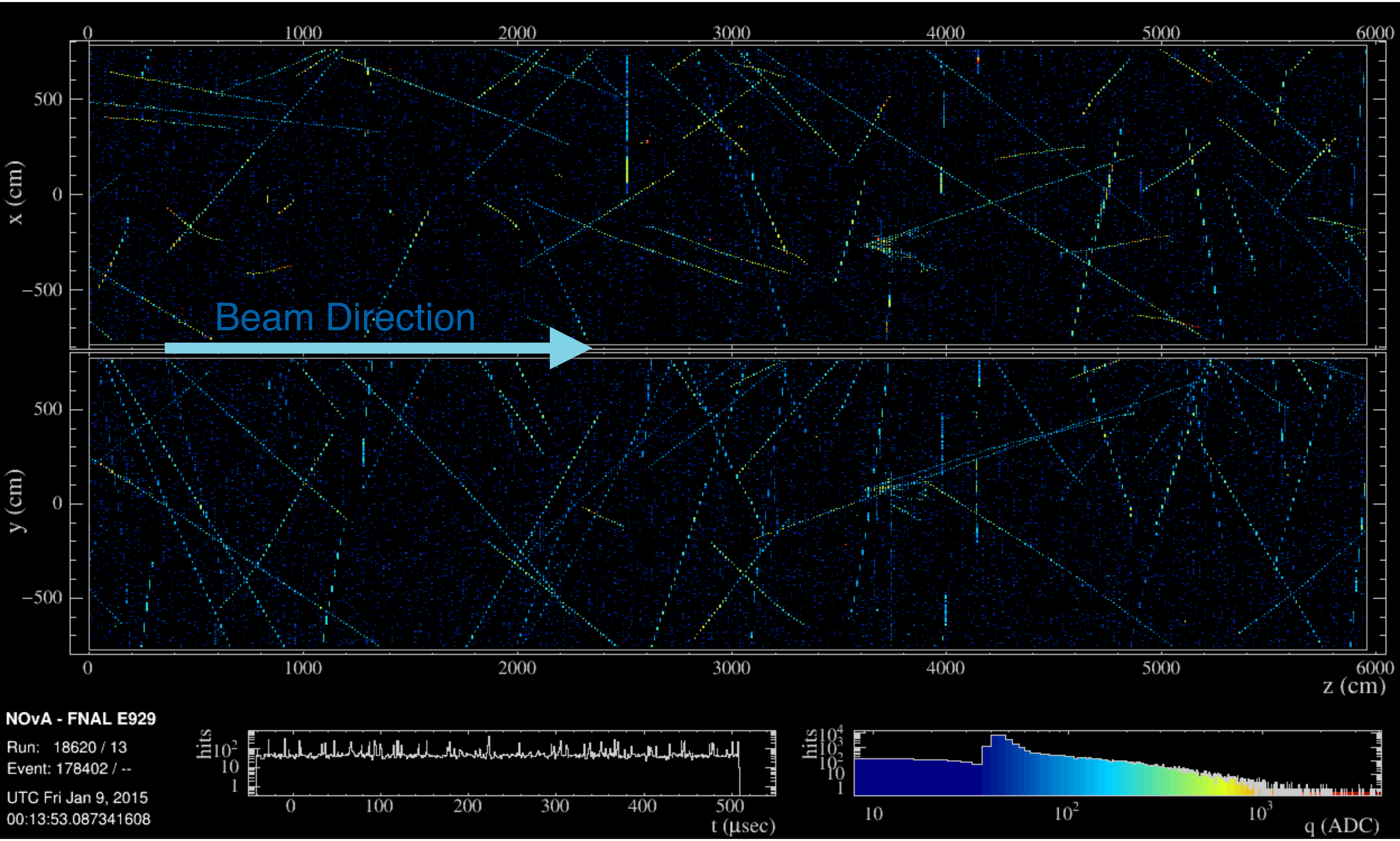
FD Beam Peak

- Trigger structure: 550 μs window, NuMI neutrinos arrive for 10 μs starting at 218 μs



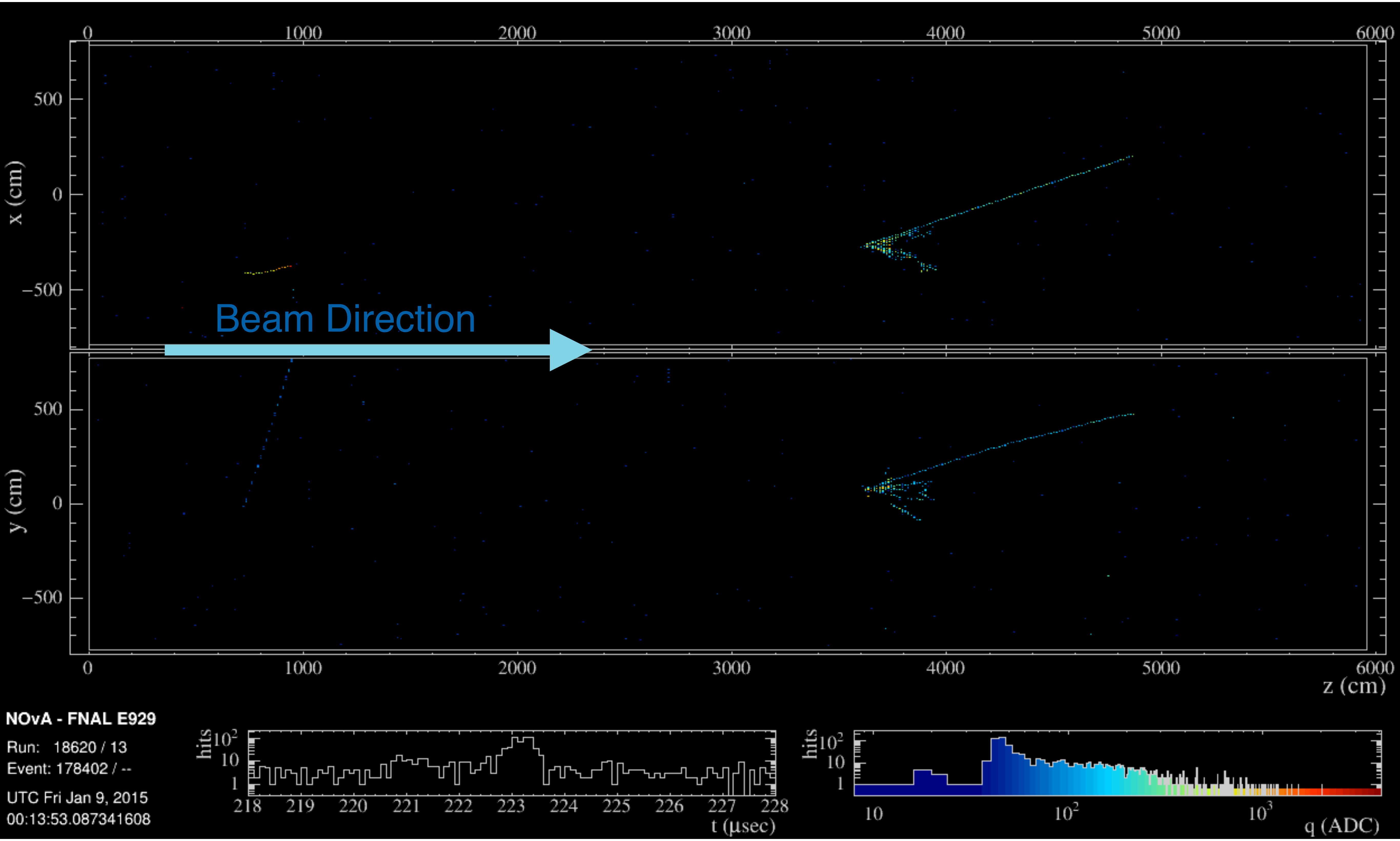
Cell hits colored by charge deposition

Far Detector 550 μs Readout Window



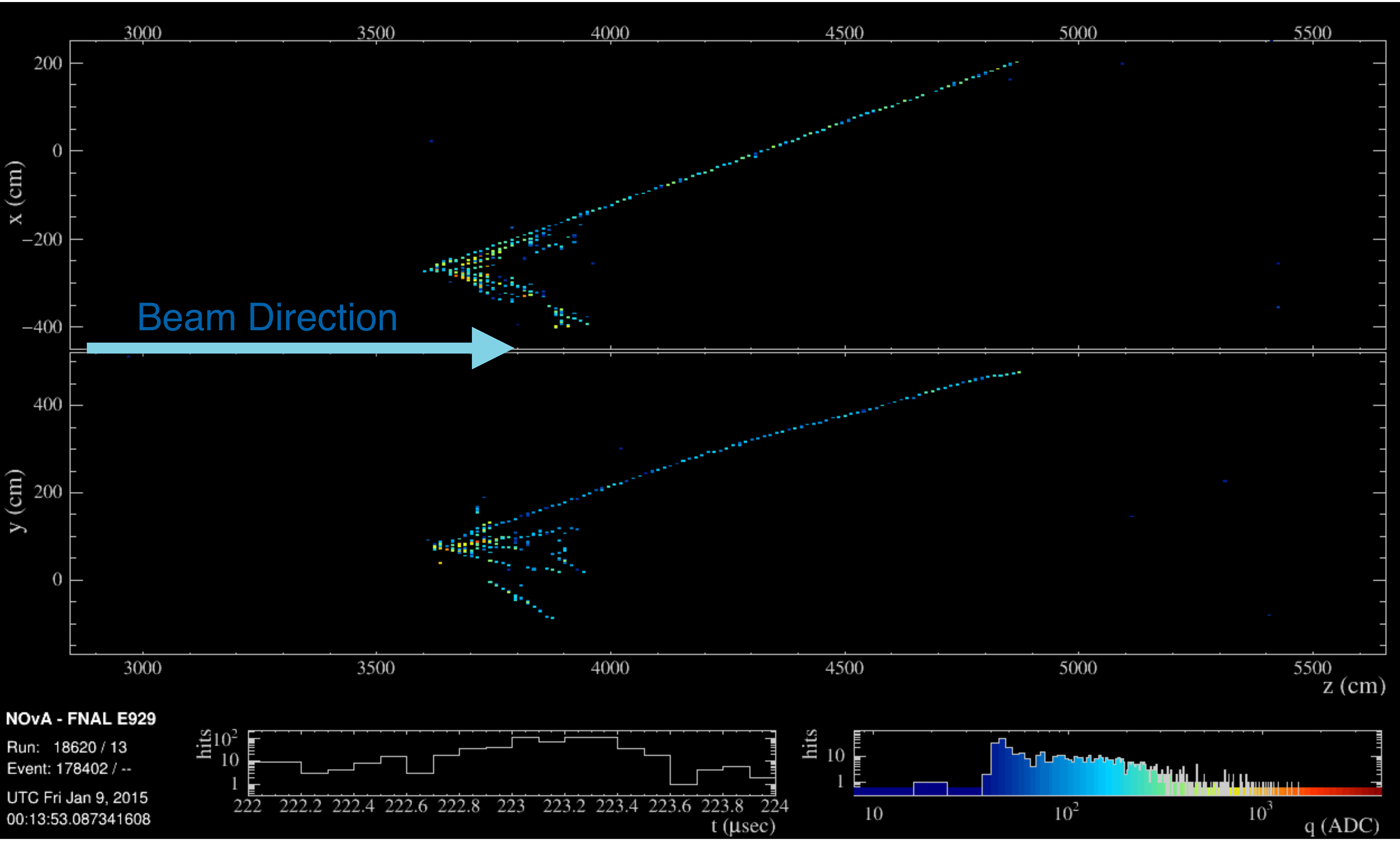
Far Detector 10 µs NuMI Beam Window

Cell hits colored by charge deposition



Far Detector Neutrino Interaction

Cell hits colored by charge deposition



Beam Direction

NOvA - FNAL E929

Run: 18620 / 13

Event: 178402 / --

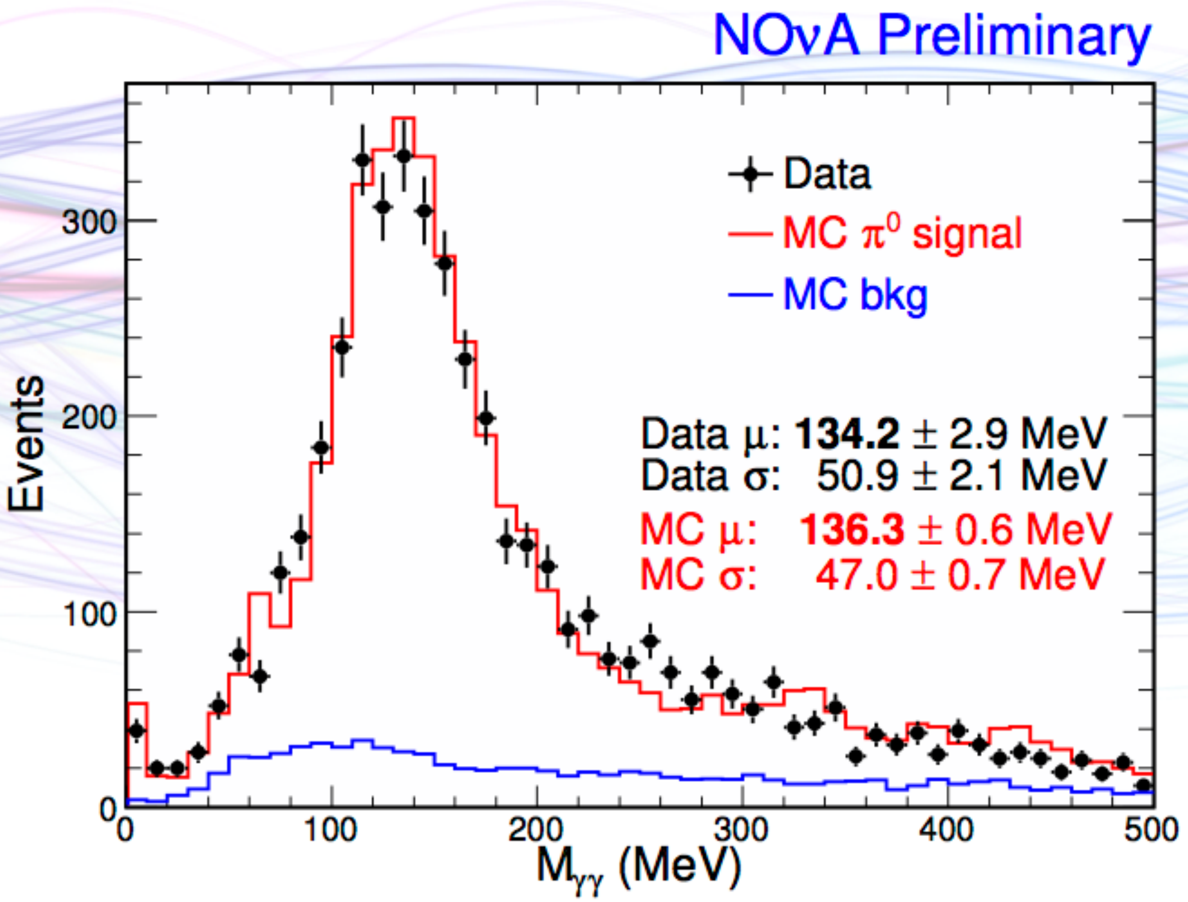
UTC Fri Jan 9, 2015

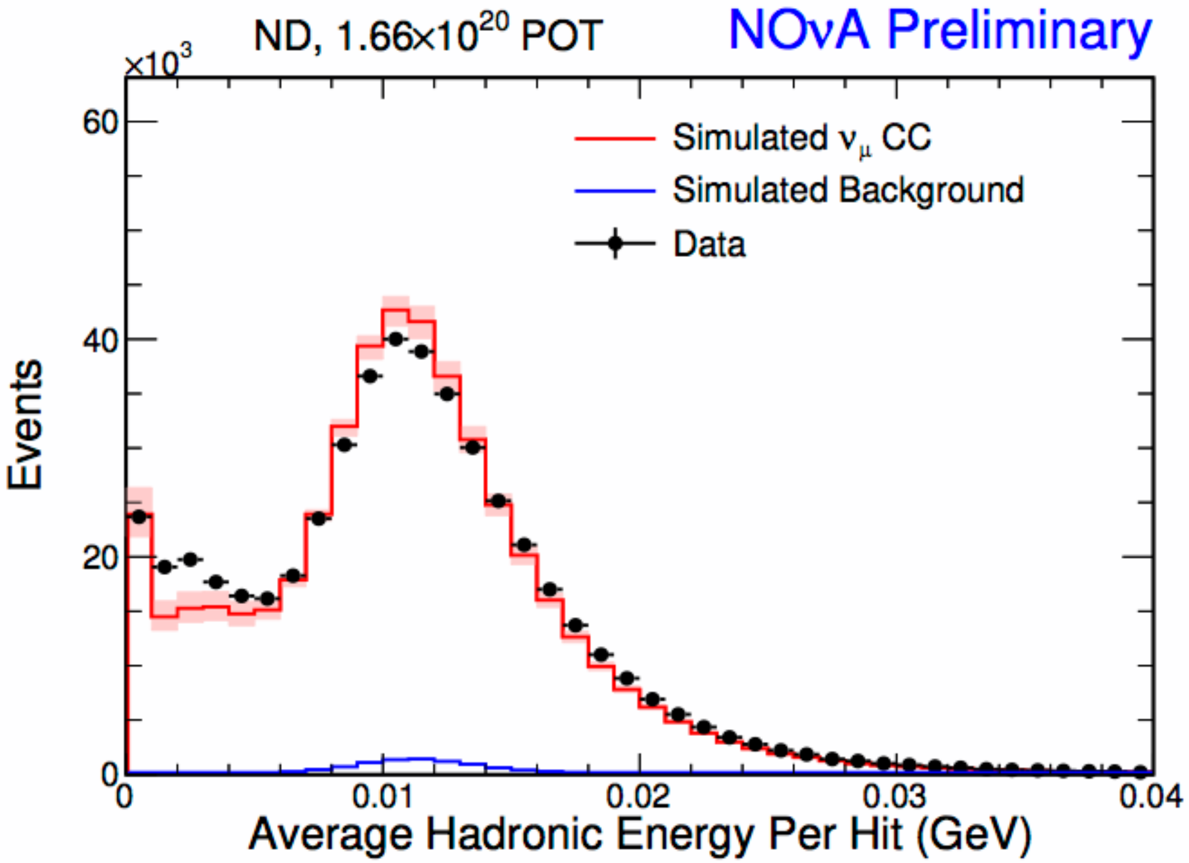
00:13:53.087341608

Numu disappearance

Calibration and energy scale

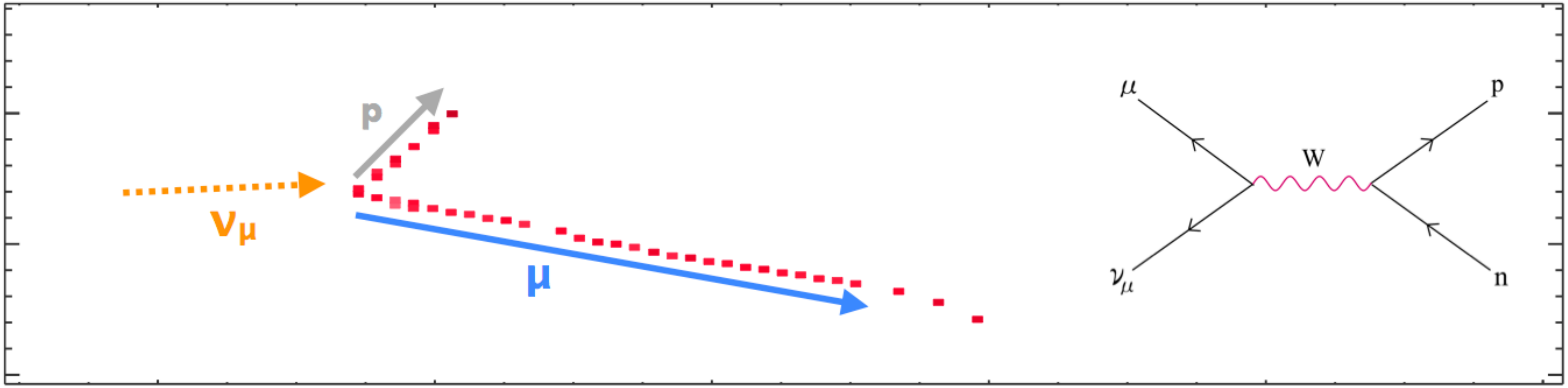
- Response varies substantially along cell due to light atten.
- Use cosmic ray muons as a standard candle to calibrate every channel individually
- Use *dE*/*dx* near the end of stopping muon to set abs. scale
- Multiple calibration x-checks
  - Beam muon dE/dx
  - Michel energy spectrum
  - π^0 mass peak
  - Hadronic energy/hit
- Take 5% abs. and rel. errors on energy scale





Principle of the ν_μ measurement

- Separate ν_μ CC interactions from backgrounds
  - Long muon track with distinctive dE/dx easy to spot
- Extrapolate observed ND spectrum to make FD unosc. prediction
- Measure shape of ν_μ deficit in the FD



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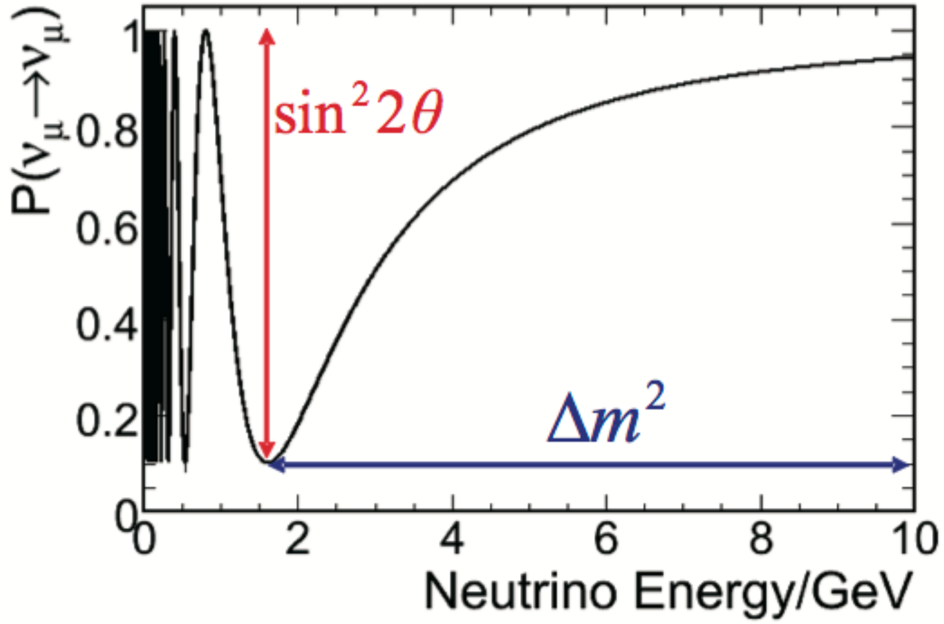


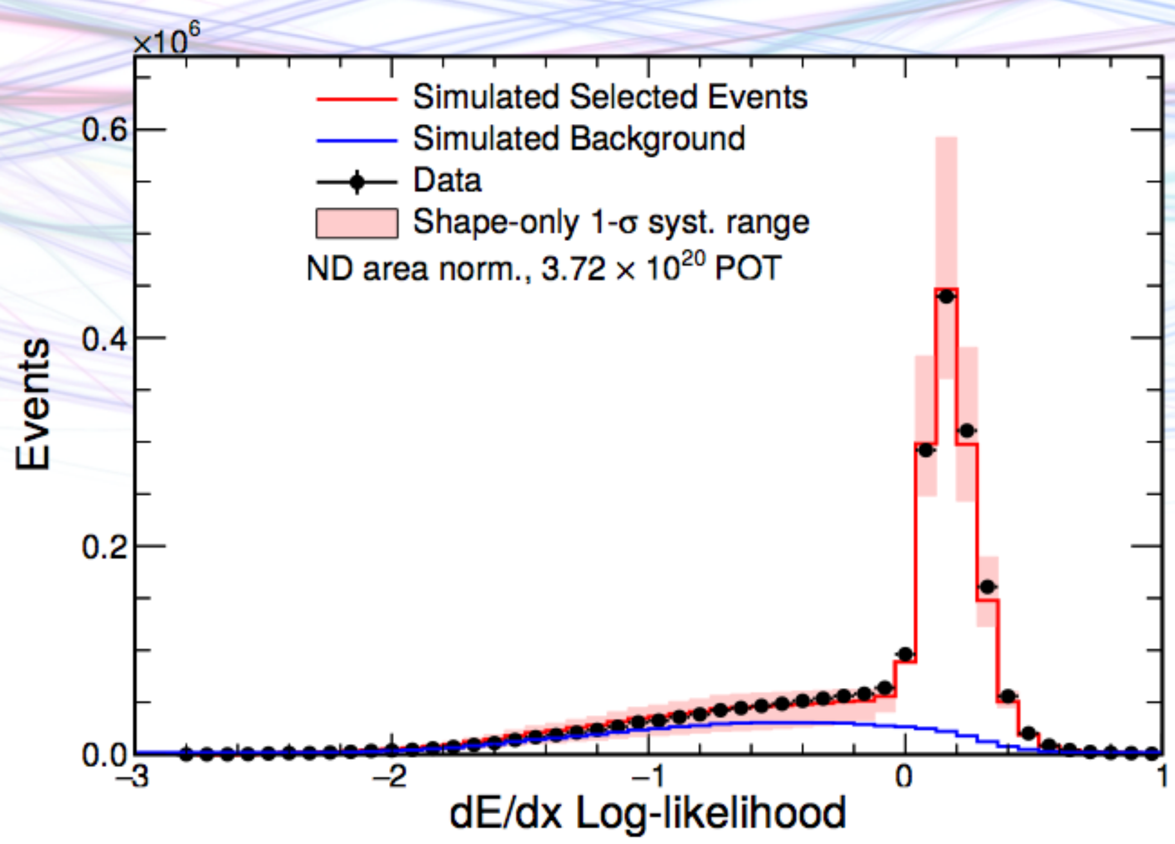
- Two flavor approx. works well here
- $P_{\mu\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$
- $\theta_{23} \approx 45^\circ \rightarrow$ almost all ν_μ expected to disappear at oscillation max.

Selecting muon neutrinos

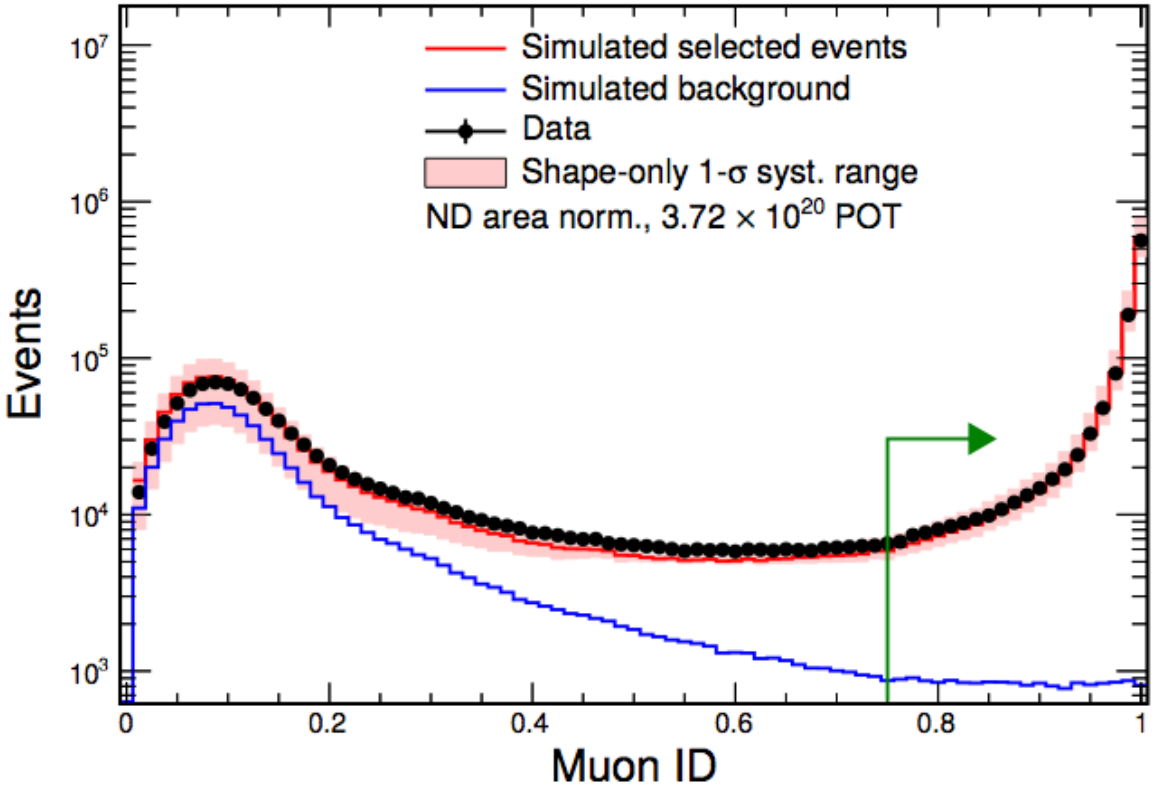
- Basic containment cuts requiring no activity close to detector walls

- kNN-based ν_μ classifier using 4 inputs
  - Track length
  - dE/dx
  - Scattering
  - Fraction of planes that have track-only

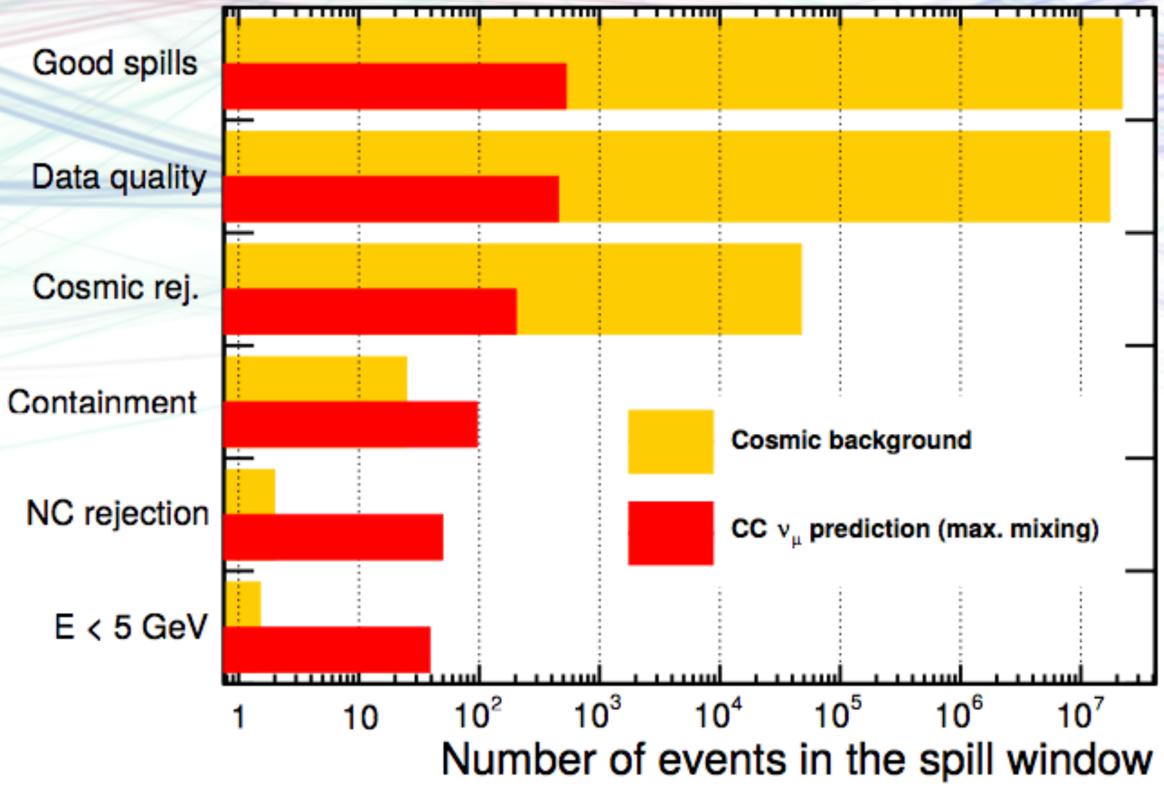
- Selection 81% efficient for ν_μ signal, 95% pure

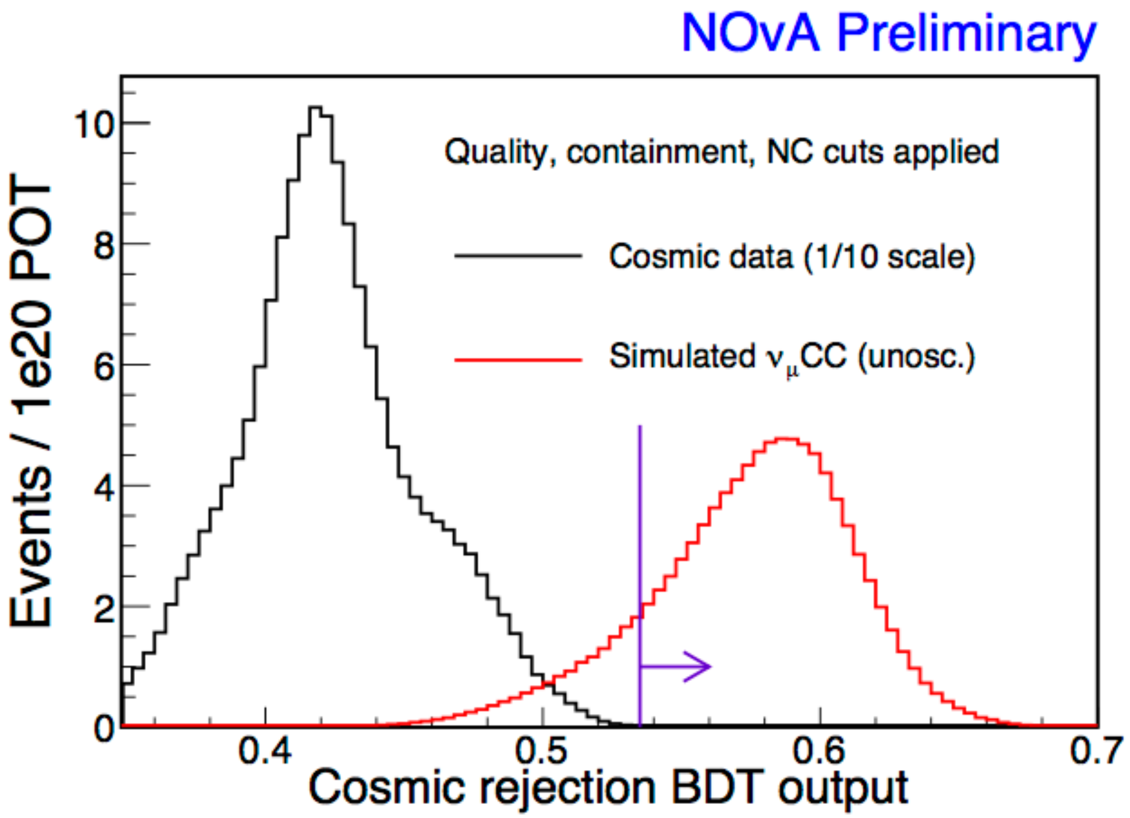


NOvA Preliminary



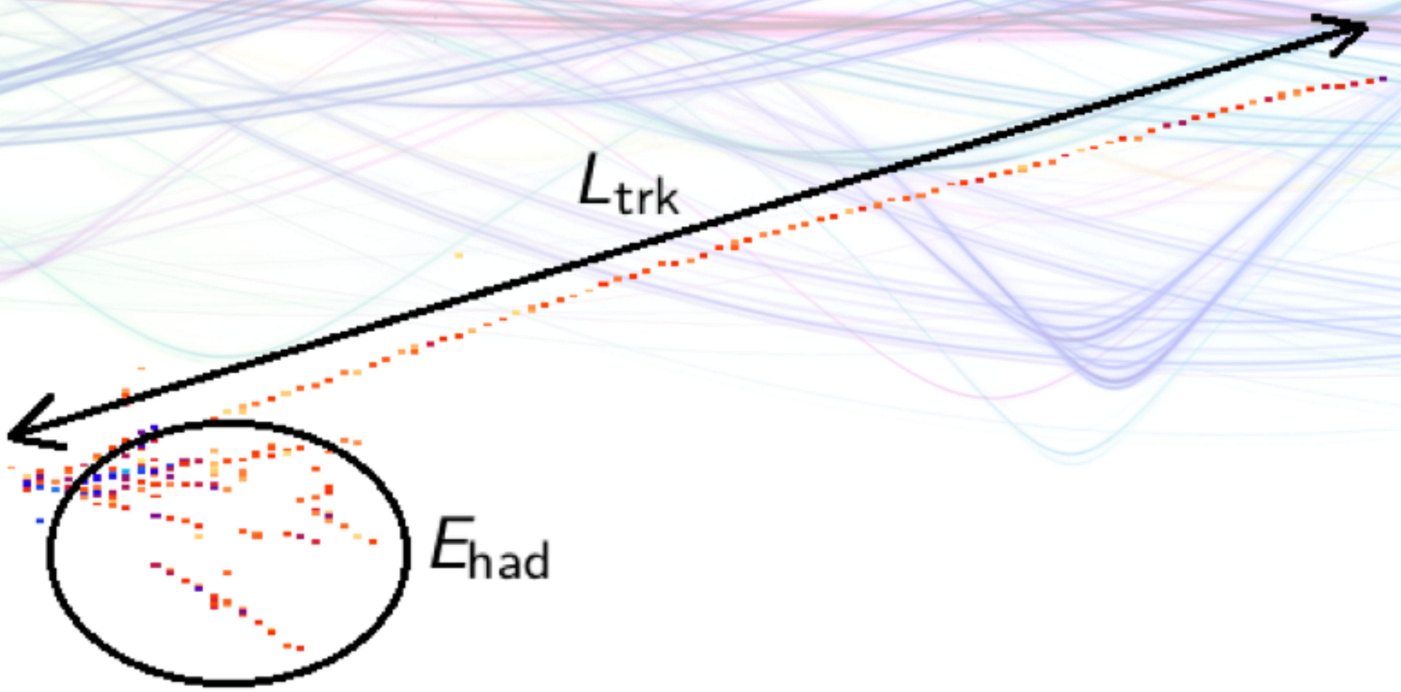
Cosmic rejection for ν_μ analysis





- 10μs spill window at $\sim$ 1Hz gives 10^5 rejection
- Cosmic background rate measured from data adjacent in time to the beam spill window
- Additional factor 10^7 from event topology plus boosted decision tree based on
  - Track direction
  - Track start and end points
  - Track length
  - Energy
  - Number of hits

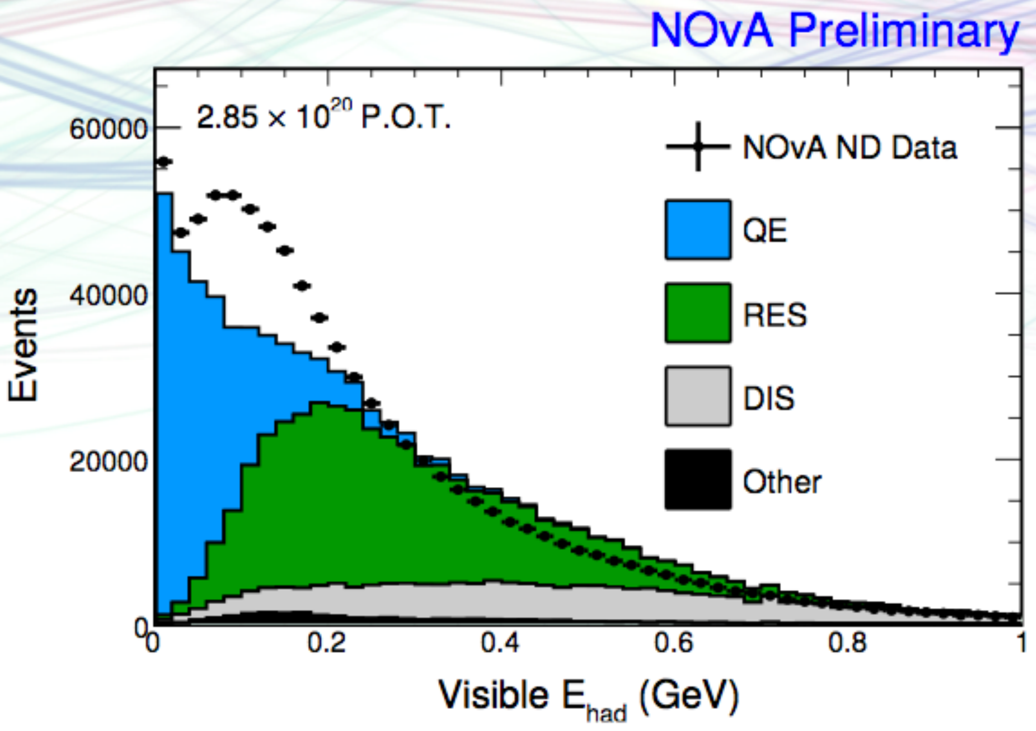
Muon neutrino energy reconstruction



- Estimate energy of selected events to trace out oscillation structure
- Known muon dE/dx → $E_\mu = f(L_{\text{trk}}) \sim k \times L_{\text{trk}}$
- Hadronic part of the event estimated calorimetrically

- $E_\nu = f(L_{trk}) + E_{\text{had}}$
- Achieve 7% energy resolution

Nuclear correlations



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- MINERvA report similar excess in their data[1]

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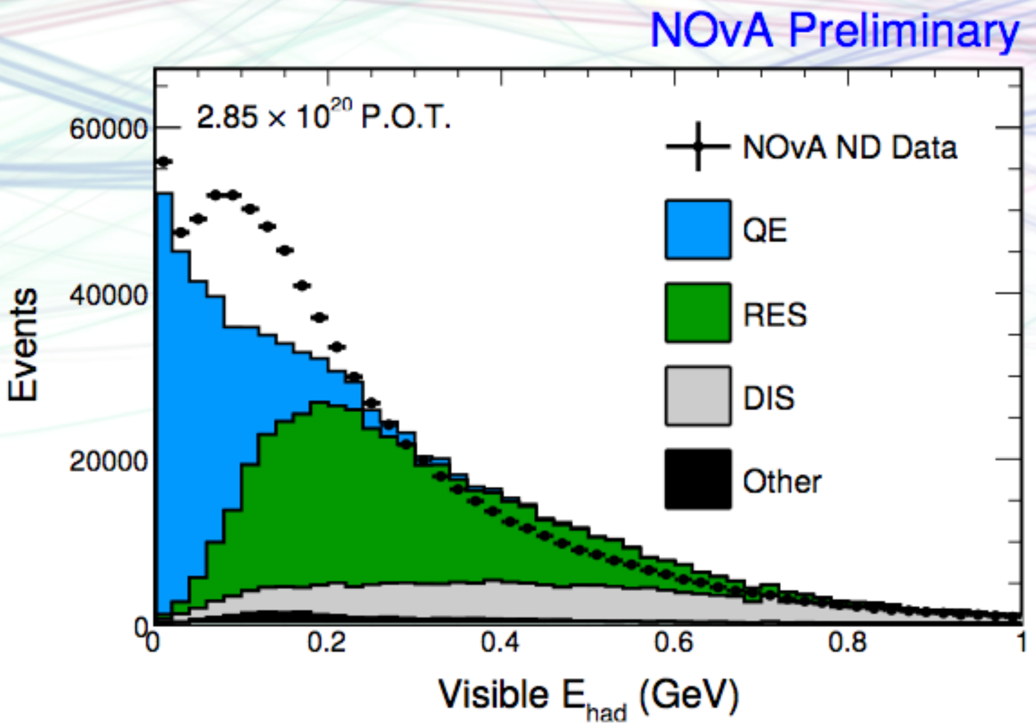

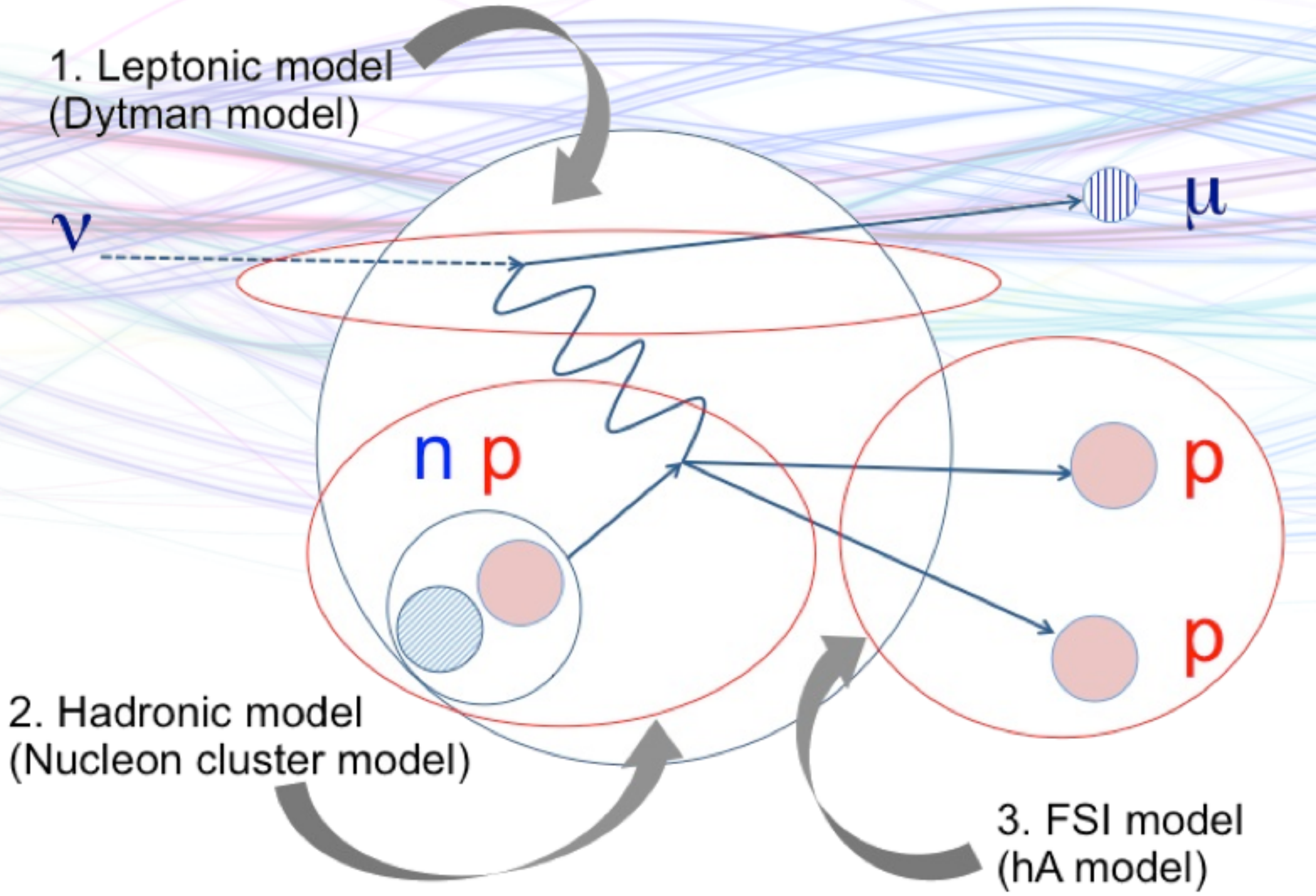

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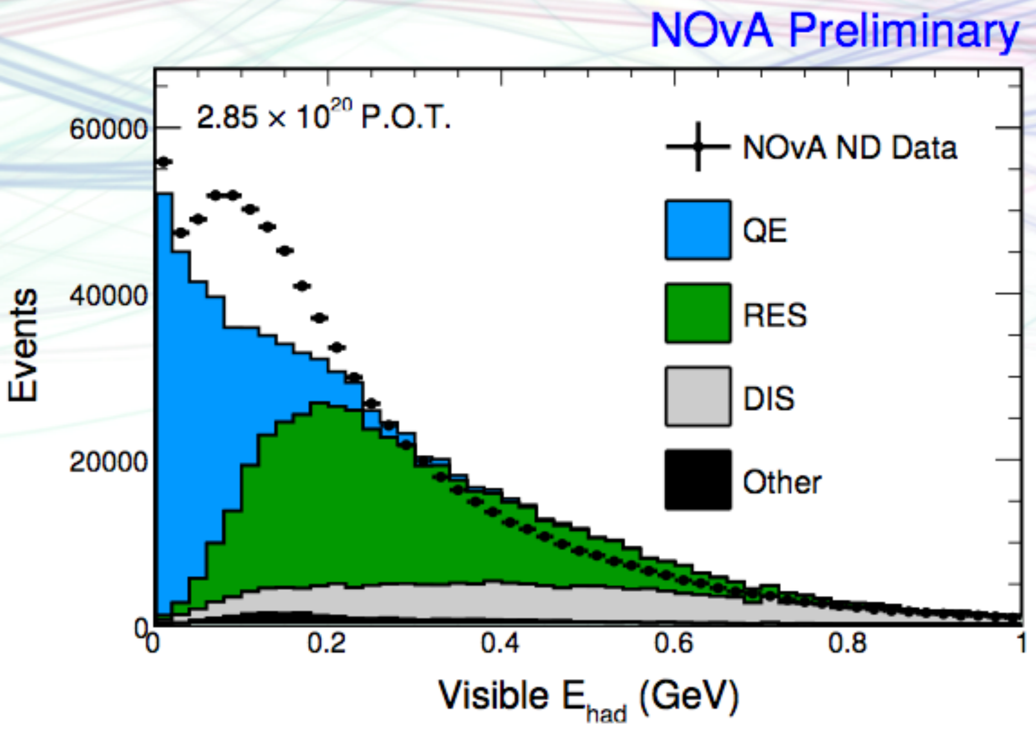

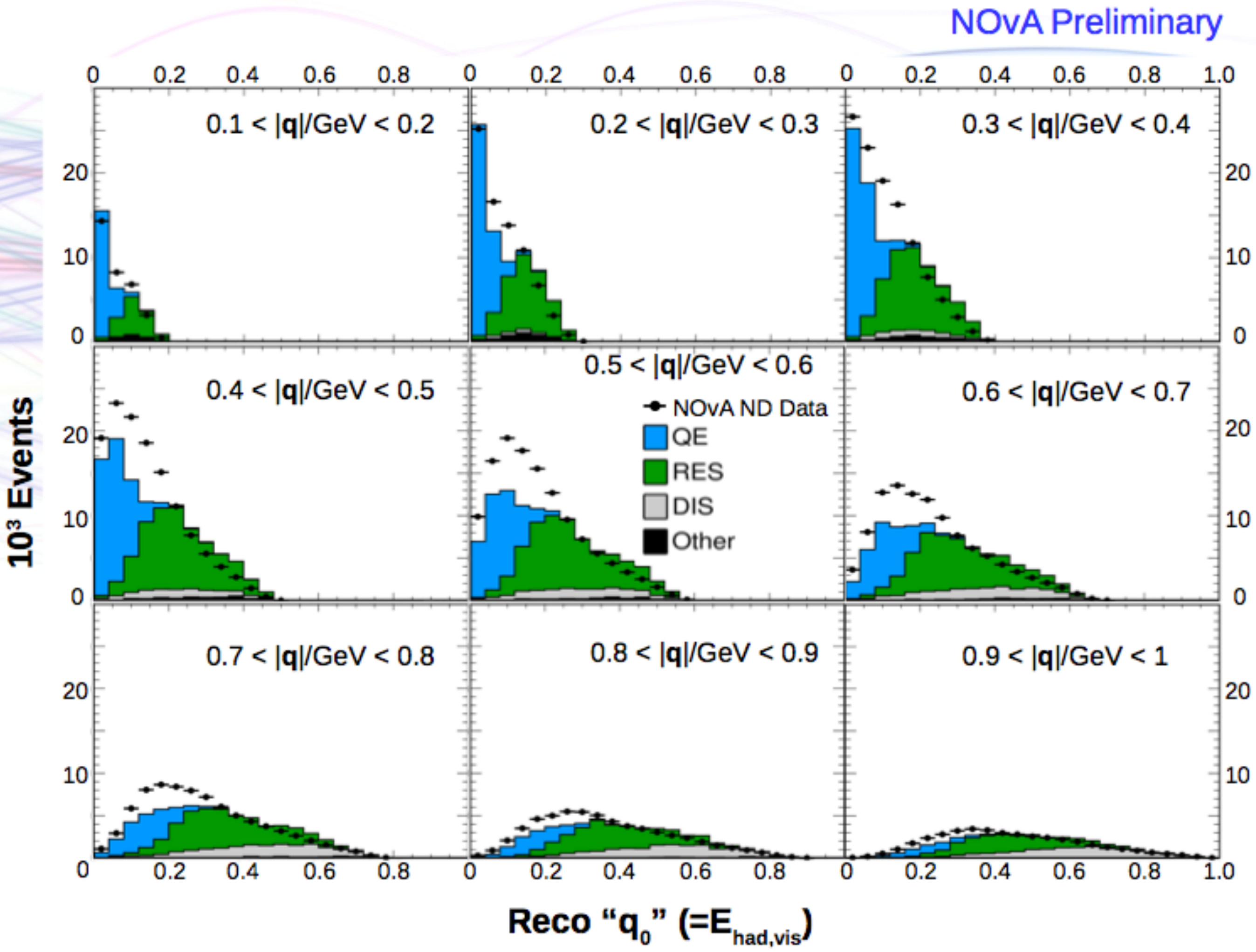

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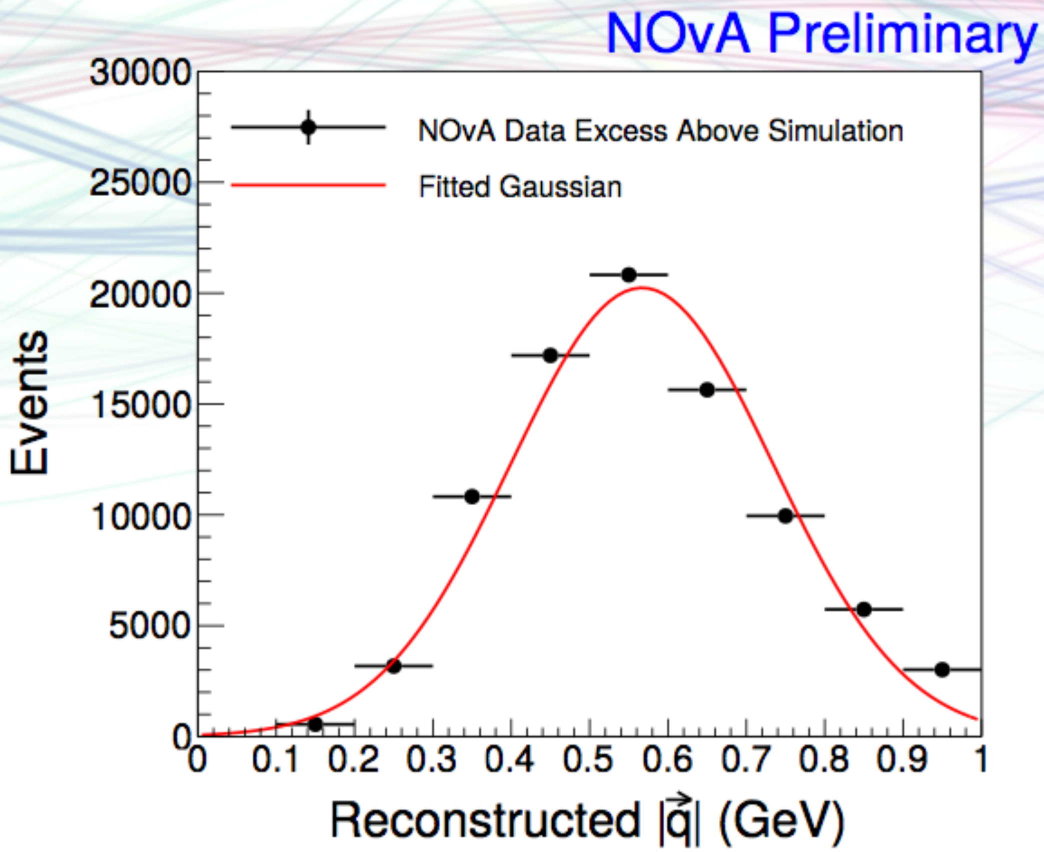

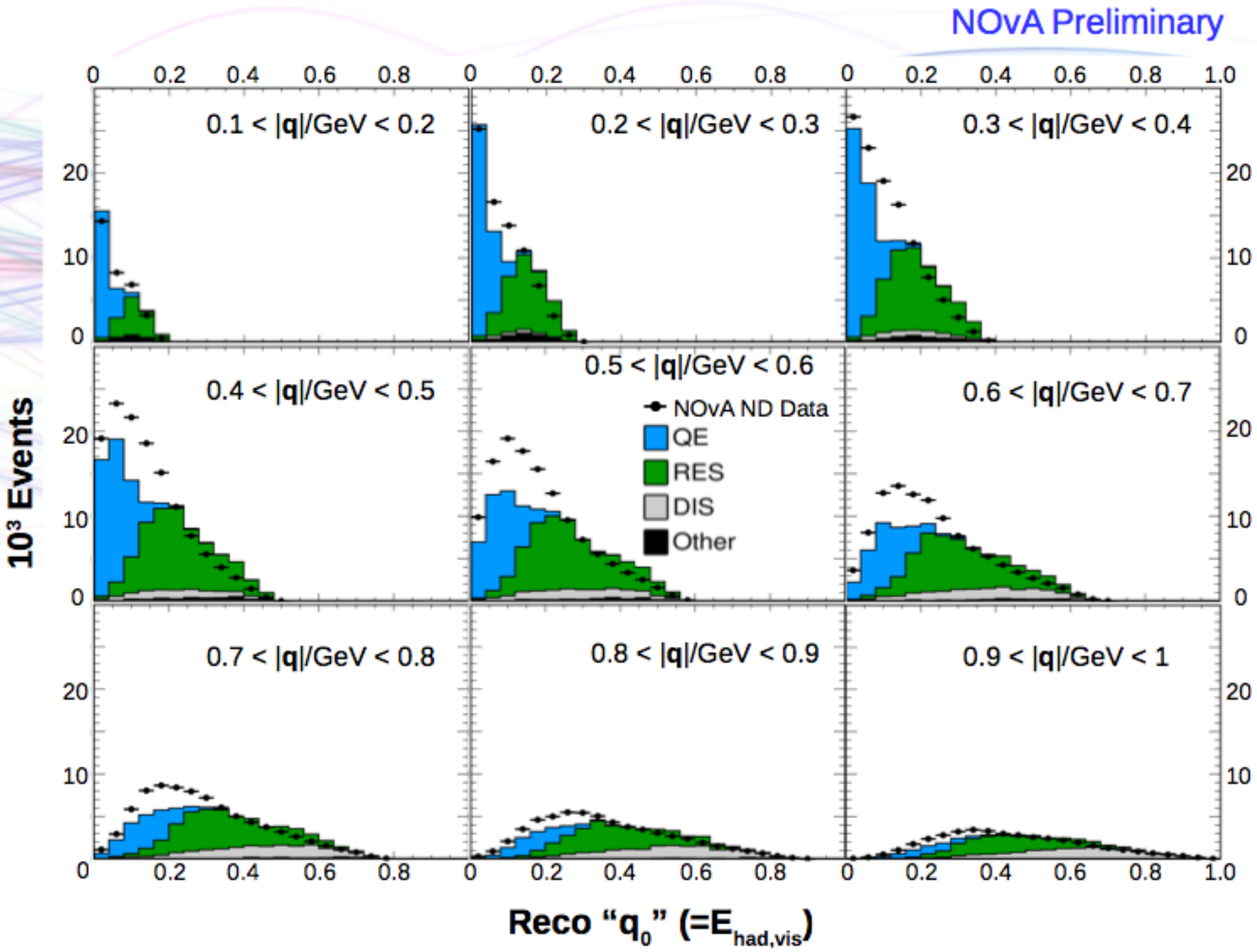

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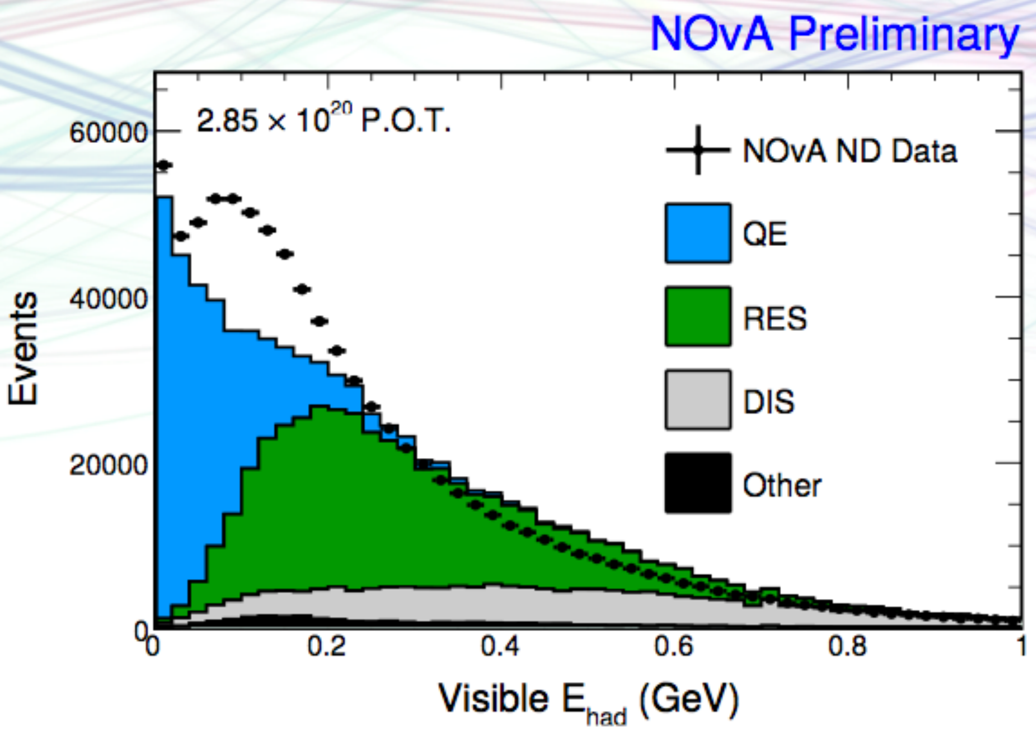

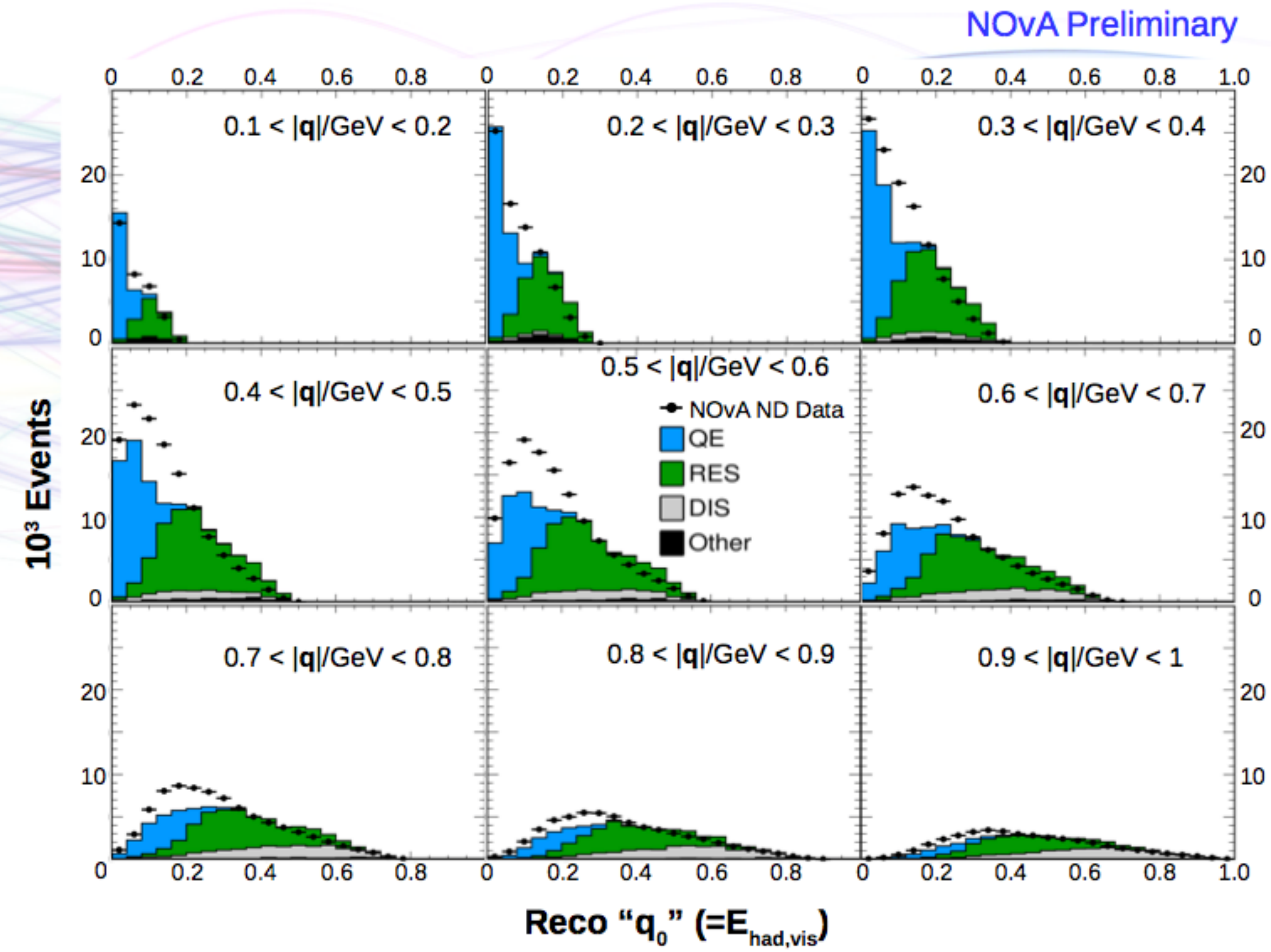

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- Reweight to match observed excess as a function of $\vec{p}$ transfer
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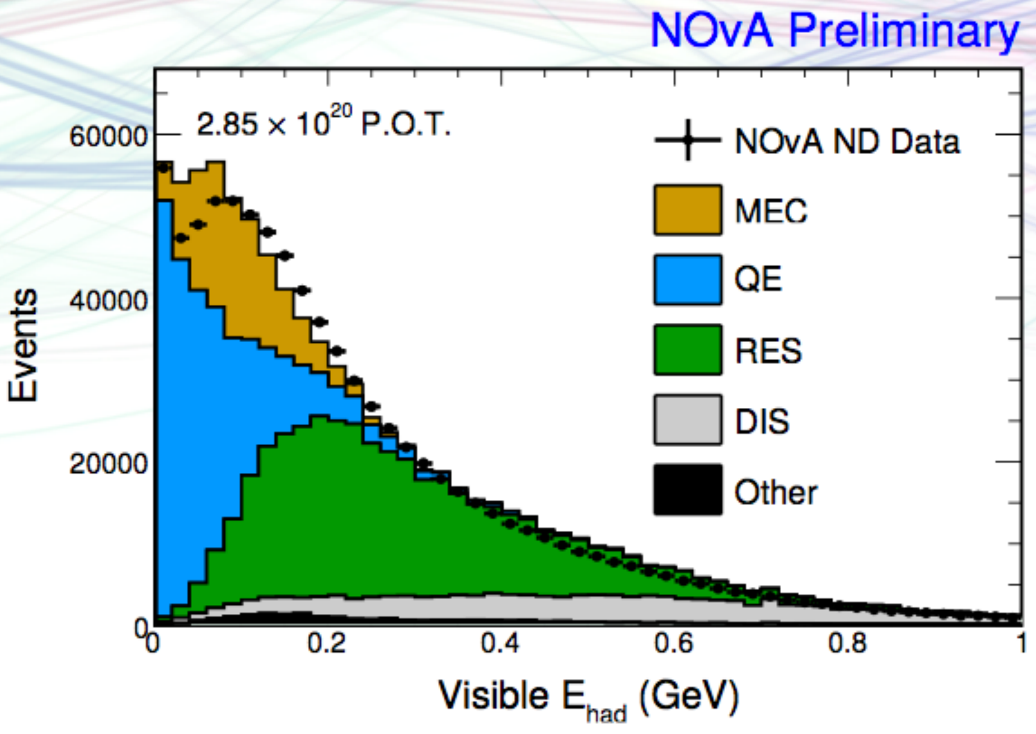

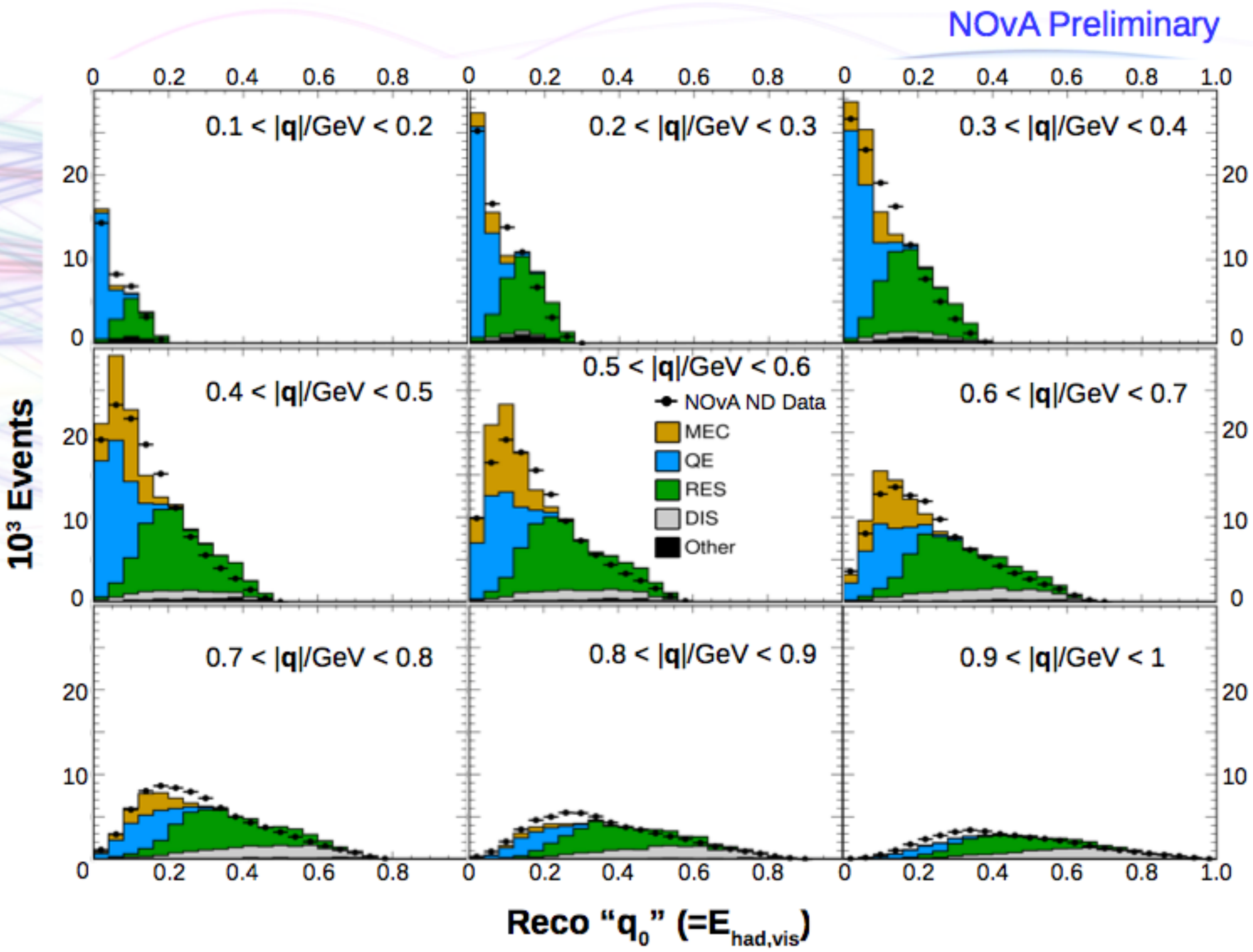

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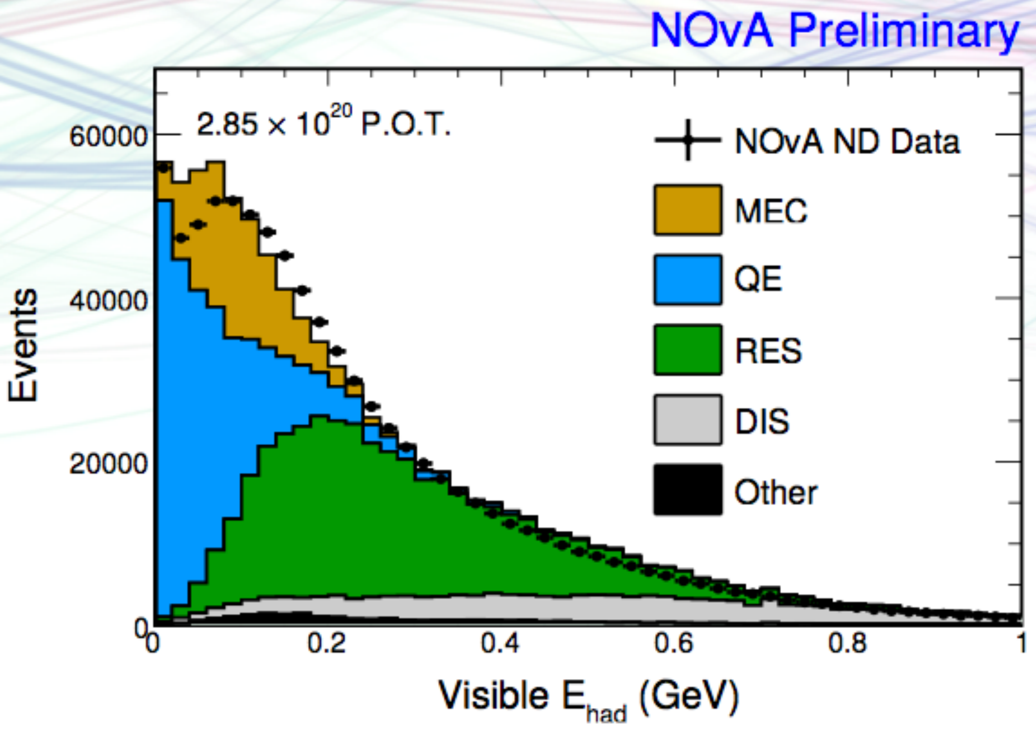

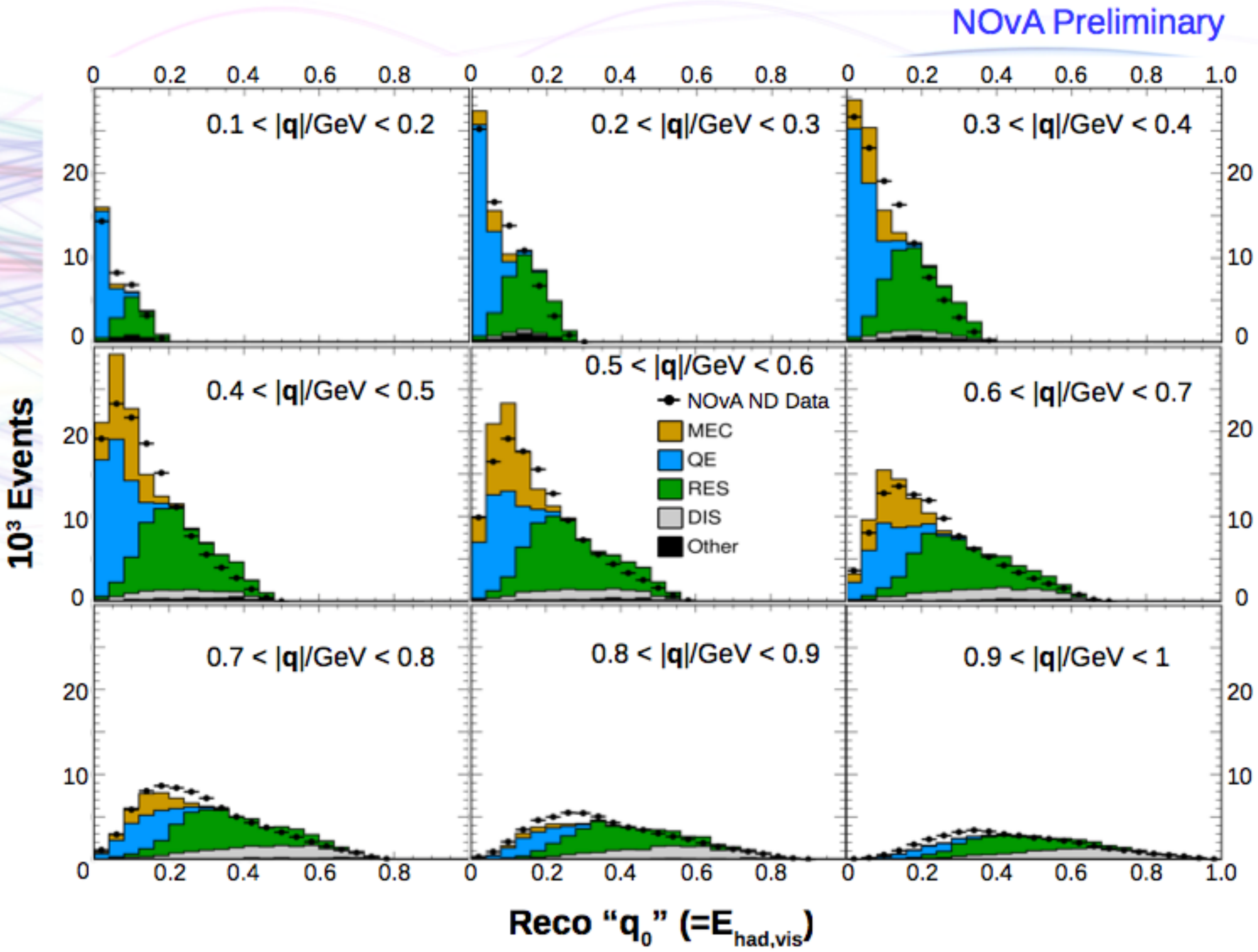

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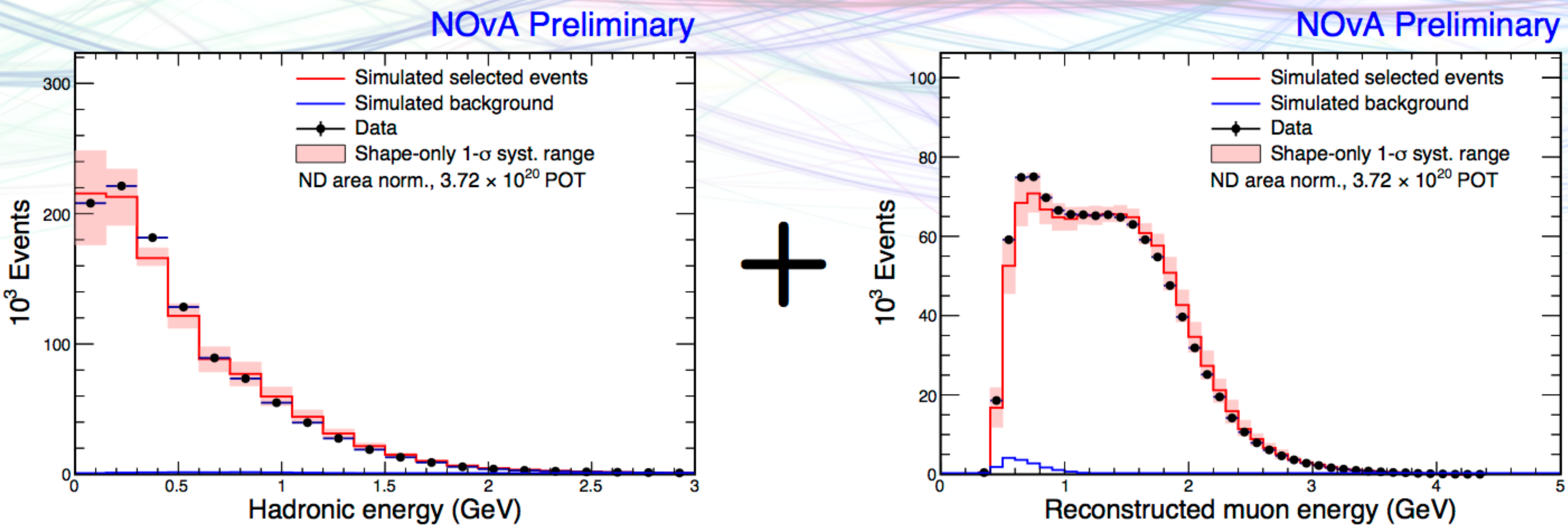
Muon neutrino energy reconstruction



- Good data/MC agreement for muon neutrino selected events
- Hadronic energy scale uncertainty improved to 5%

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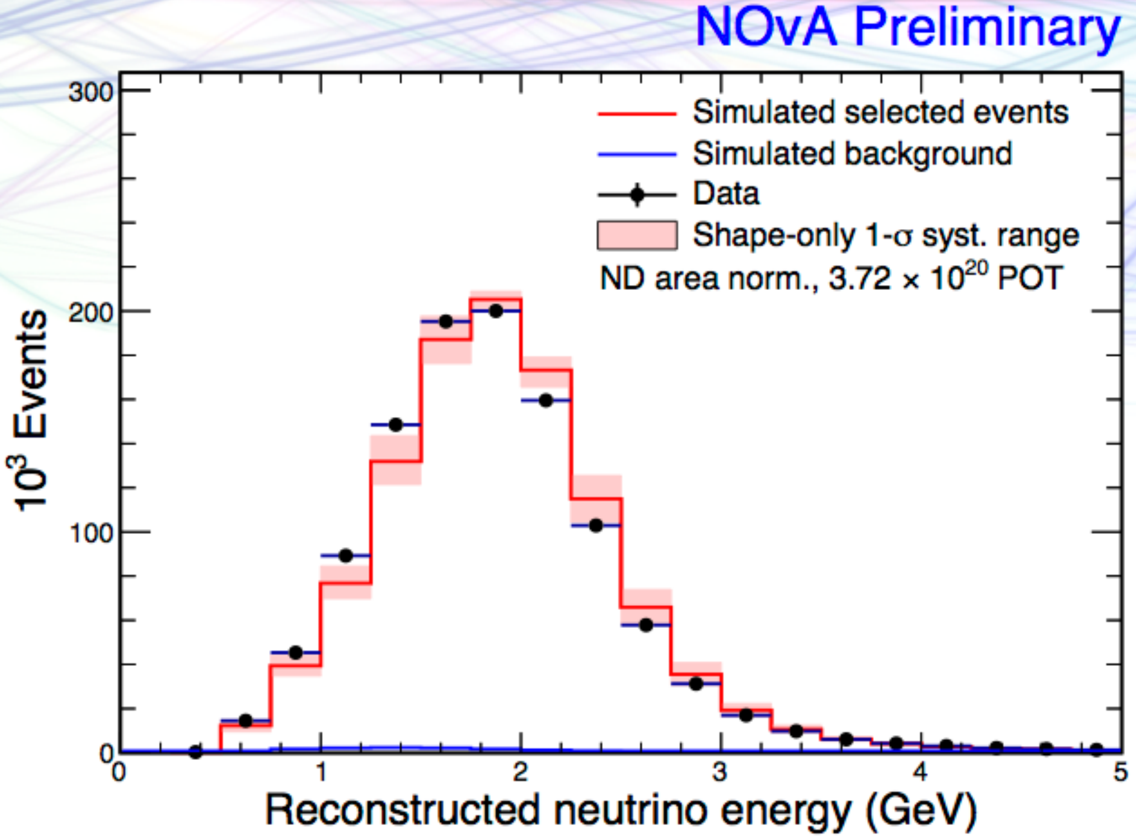

- Good data/MC agreement for muon neutrino selected events
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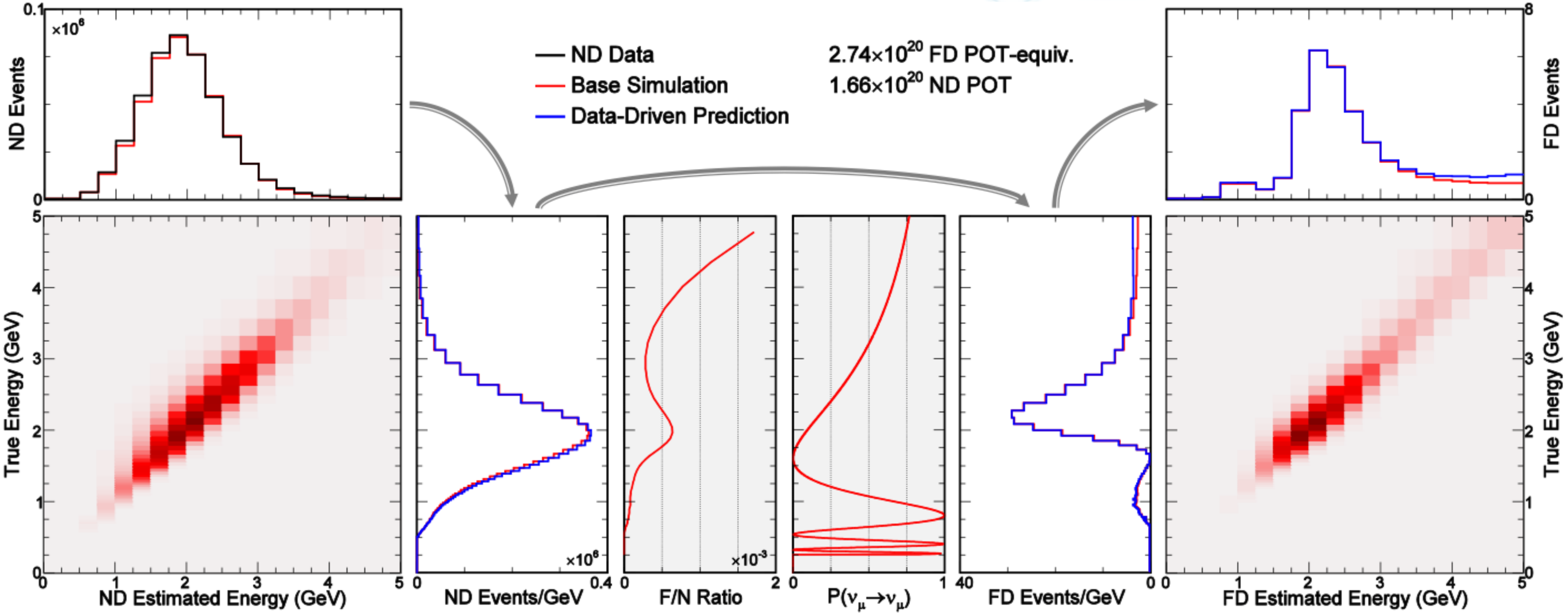
- Use ND data to predict FD neutrino spectrum

Extrapolation procedure

- Translate ND observations to true energy
- Transport to far detector and oscillate
- Smear back to reco energy

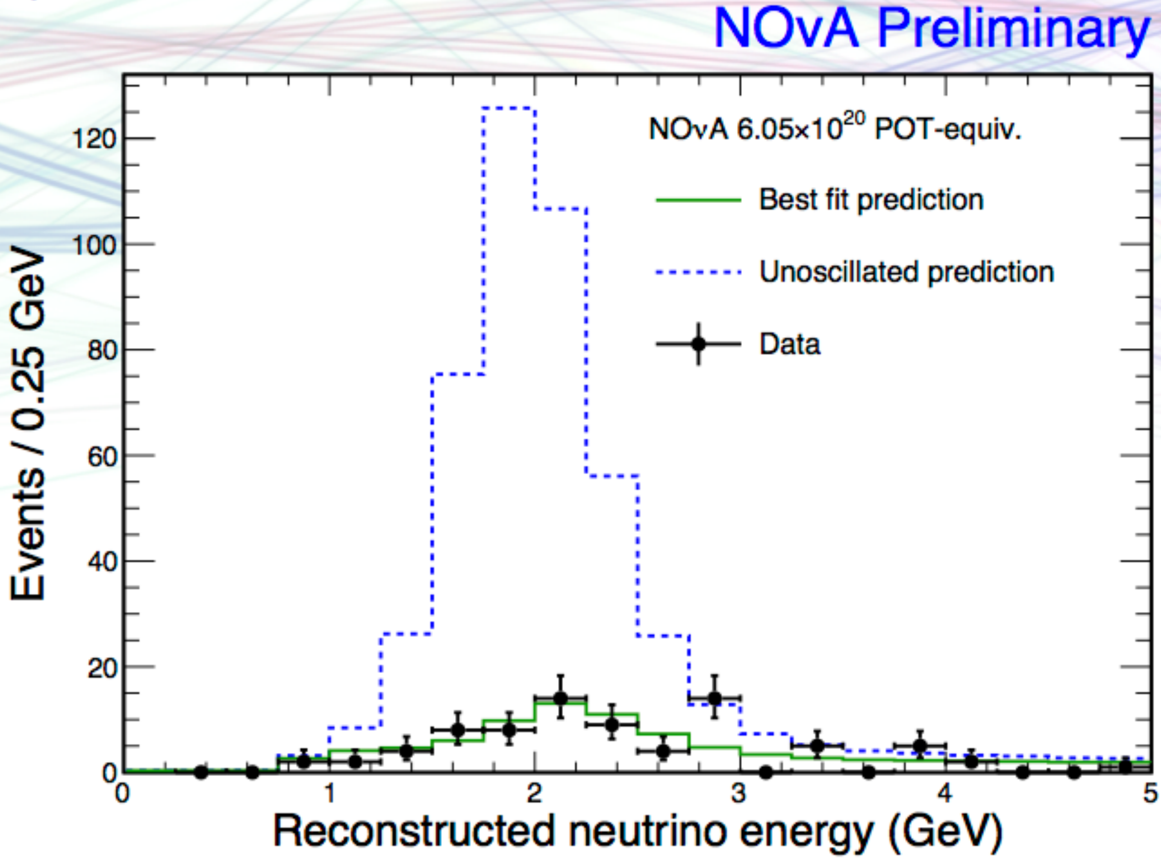


Systematic uncertainties

Source of uncertainty	Fractional uncertainty $\sin^2\theta_{23}$ ($\pm$%)	Fractional uncertainty Δm^2_{32} ($\pm$%)
Normalization	1.0	0.2
Muon E scale	2.2	0.8
Calibration	2.0	0.2
Relative E scale	2.0	0.9
Cross sections + FSI	0.6	0.5
Osc. parameters	0.7	1.5
Beam backgrounds	0.9	0.5
Scintillation model	0.7	0.1
Total systematic	3.4	2.4
Statistical uncertainty	4.1	3.5

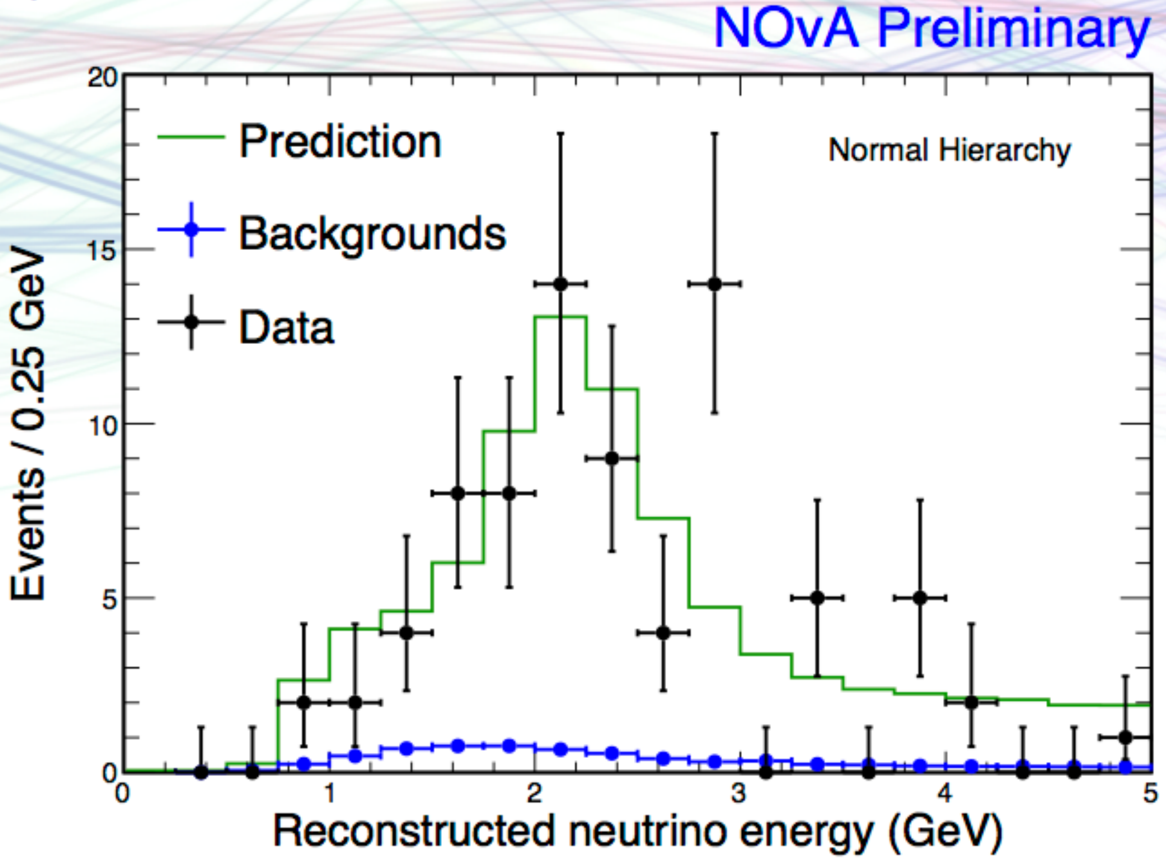
- Consider multiple possible sources of systematic error
- Propagate effect of each through extrapolation
- Include as pull terms in fit
- Quoting increase (in quadrature) of measurement error

ν_μ disappearance results



- Expect 473 FD ν_μ CC events with no oscillation
- Observe 82 (inc. 3.7 beam bkg. and 2.9 cosmic)

ν_μ disappearance results



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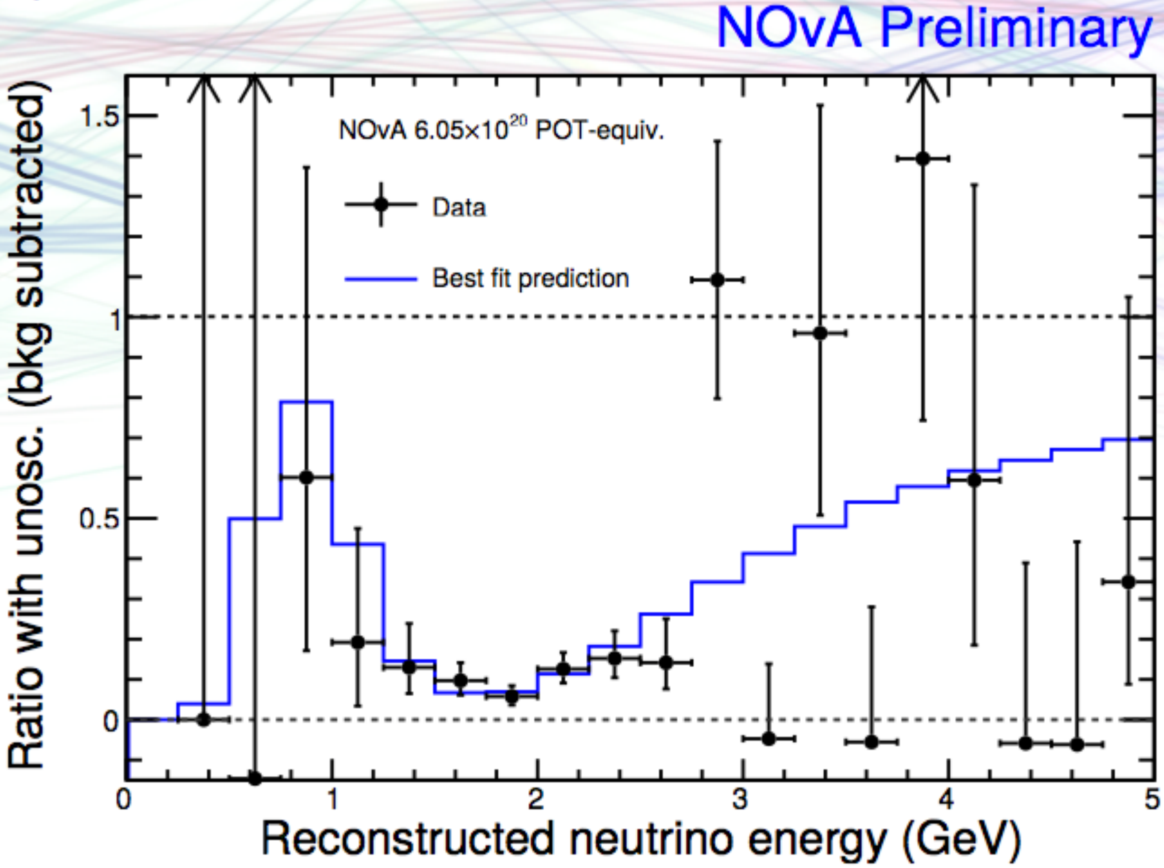

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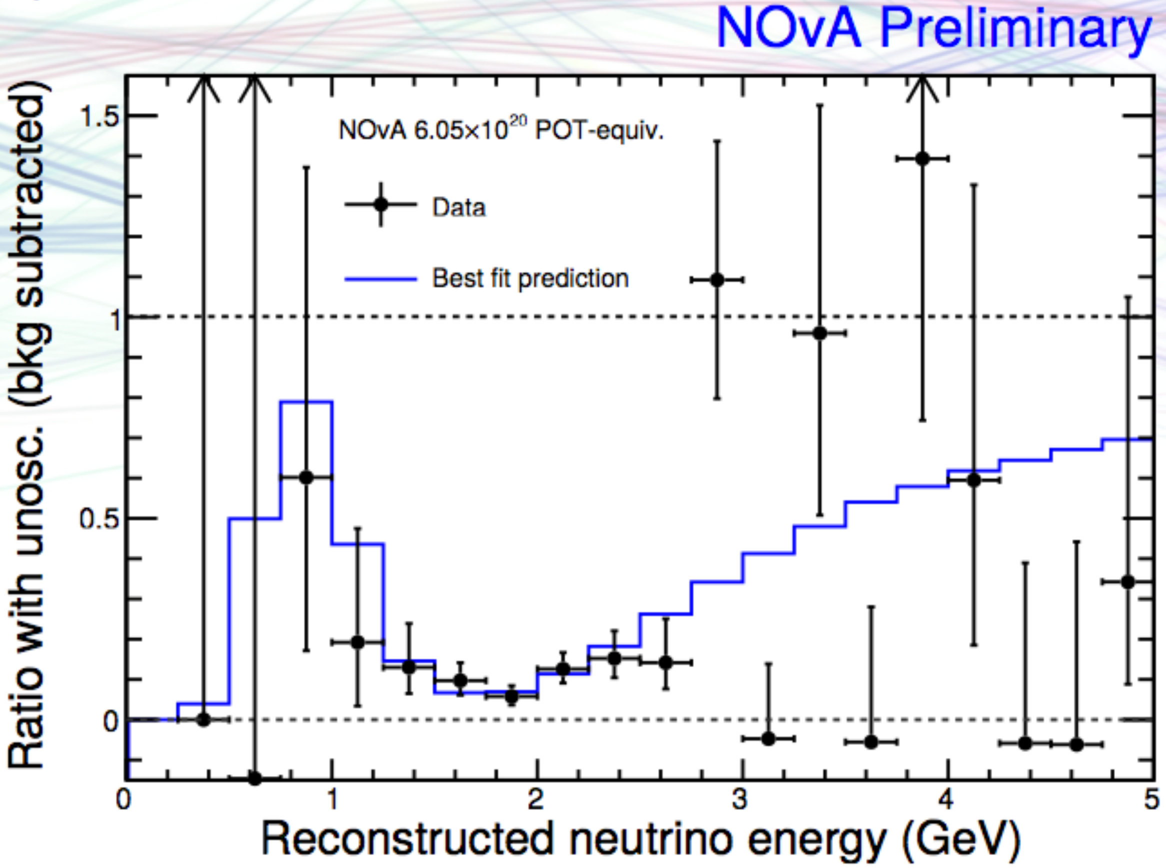

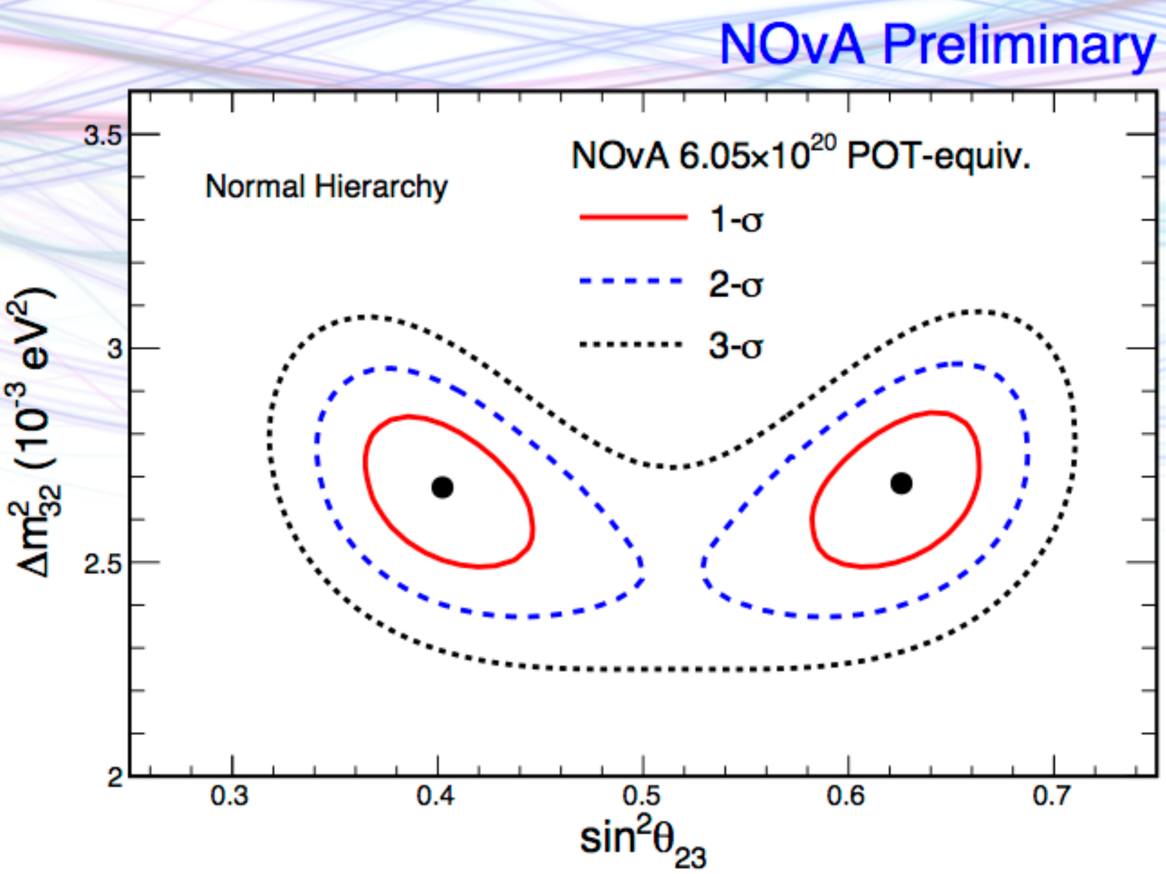

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- Maximal mixing excluded at 2.5σ (FC corrections in progress)

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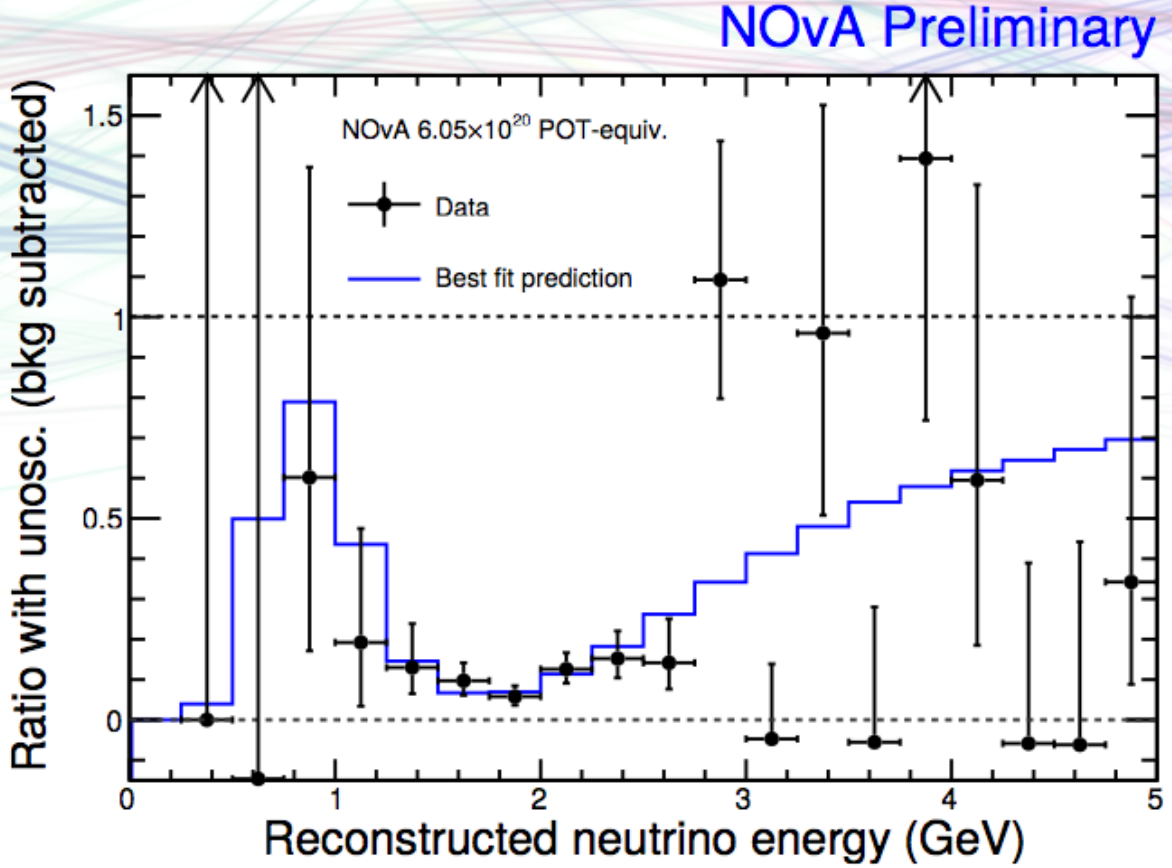

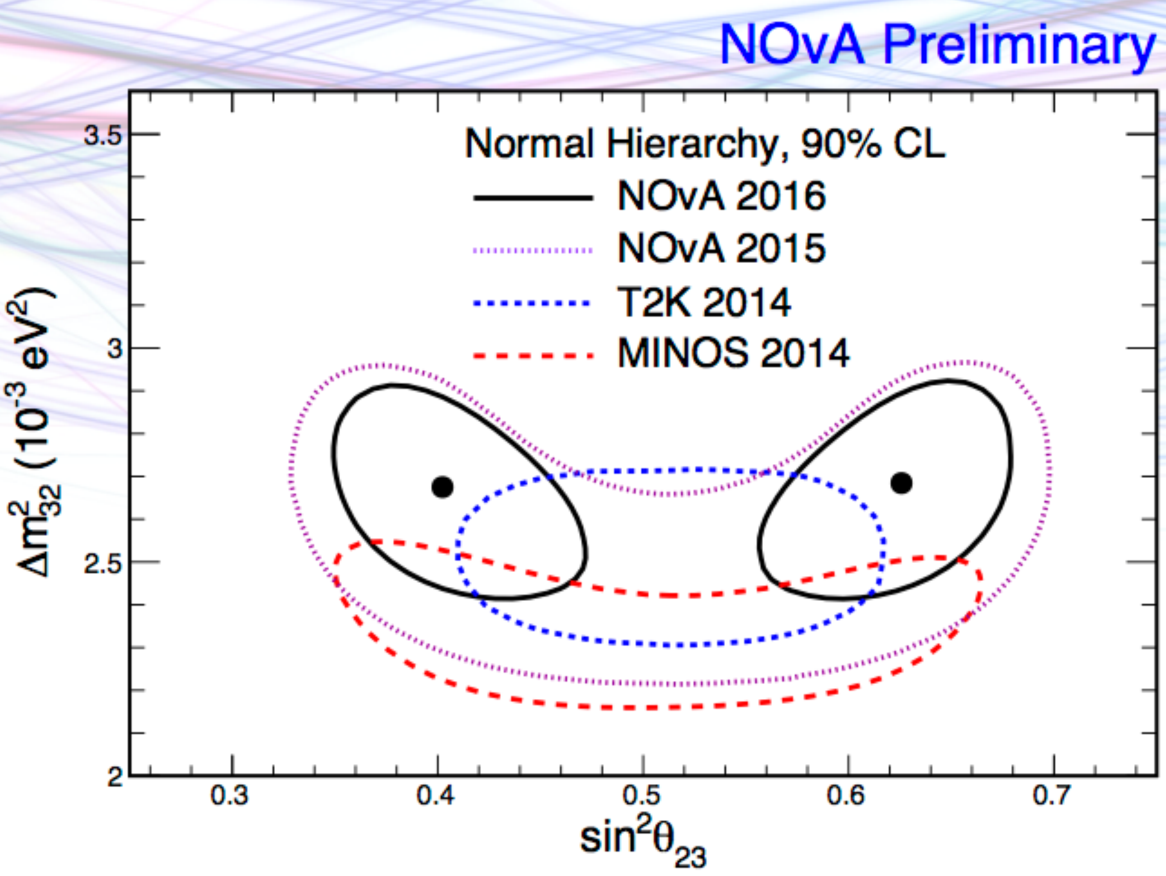

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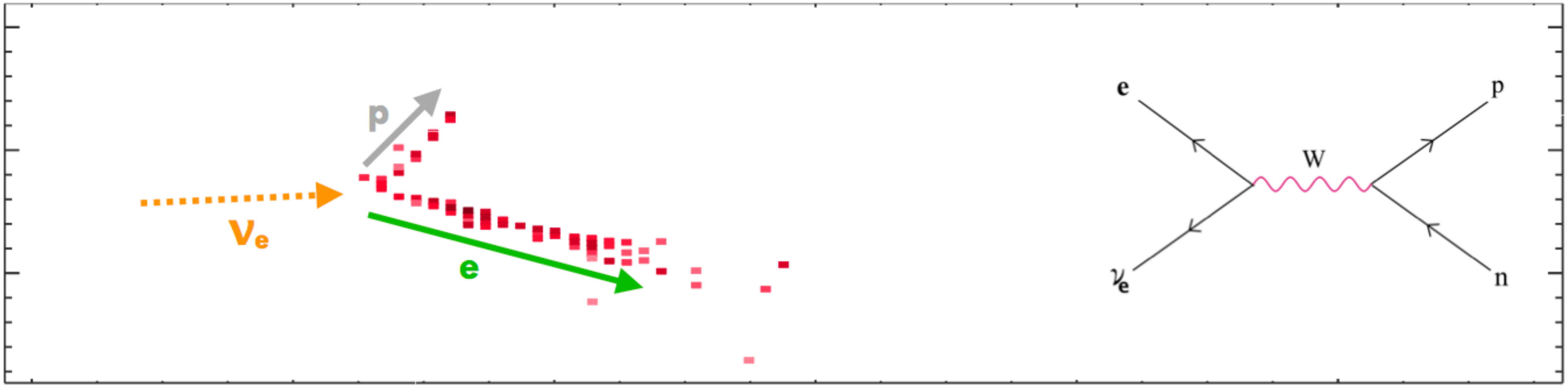
Nue appearance

Principle of the ν_e measurement

- Separate ν_e CC interactions from beam backgrounds
    - Harder problem than ν_μ CC selection
- Evaluate remaining backgrounds in ND
    - Intrinsic beam ν_e
    - Neutral currents
    - ν_μ CC – mostly oscillates away
- An excess in the FD is the sign of $\nu_\mu \to \nu_e$ oscillations



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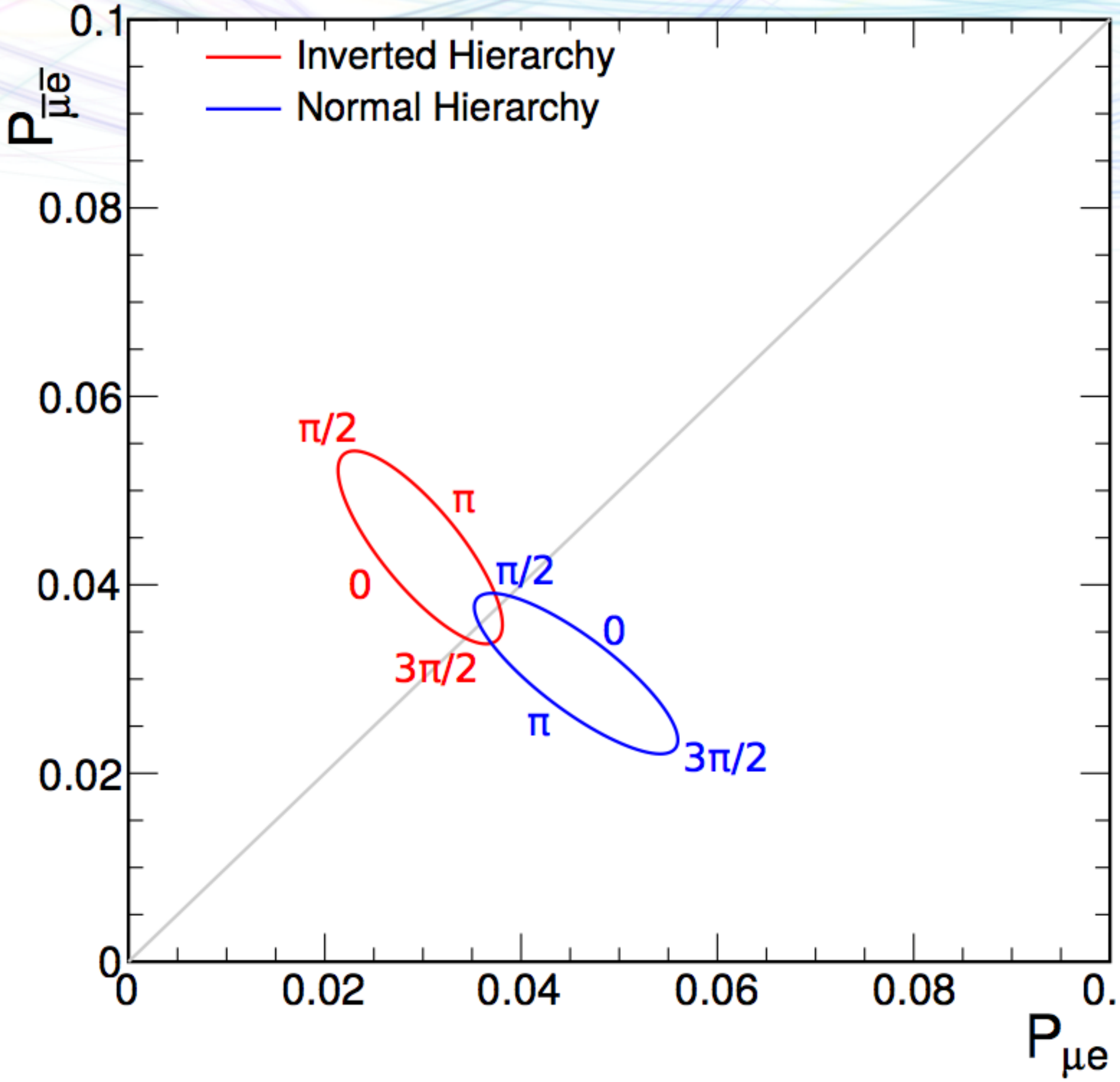
- $P_{\mu e} \approx \sin^2 2{\color{red}\theta_{13}} \sin^2 {\color{red}\theta_{23}} \sin^2\left(\frac{{\color{red}\Delta m^2_{32}} L}{4E}\right) + f({\color{green}\mathrm{sign}(\Delta m^2_{32})}) + f({\color{blue}\delta_{CP}})$
- θ_{13} only 8.5° degrees, most ν_μ go to ν_τ instead
- Look for deviations due to hierarchy (matter effects) and CP-violation

Principle of the ν_e measurement

- To first order, NOvA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ evaluated at 2GeV
- These depend differently on sign(Δm^2_{32}) and δ_{CP}



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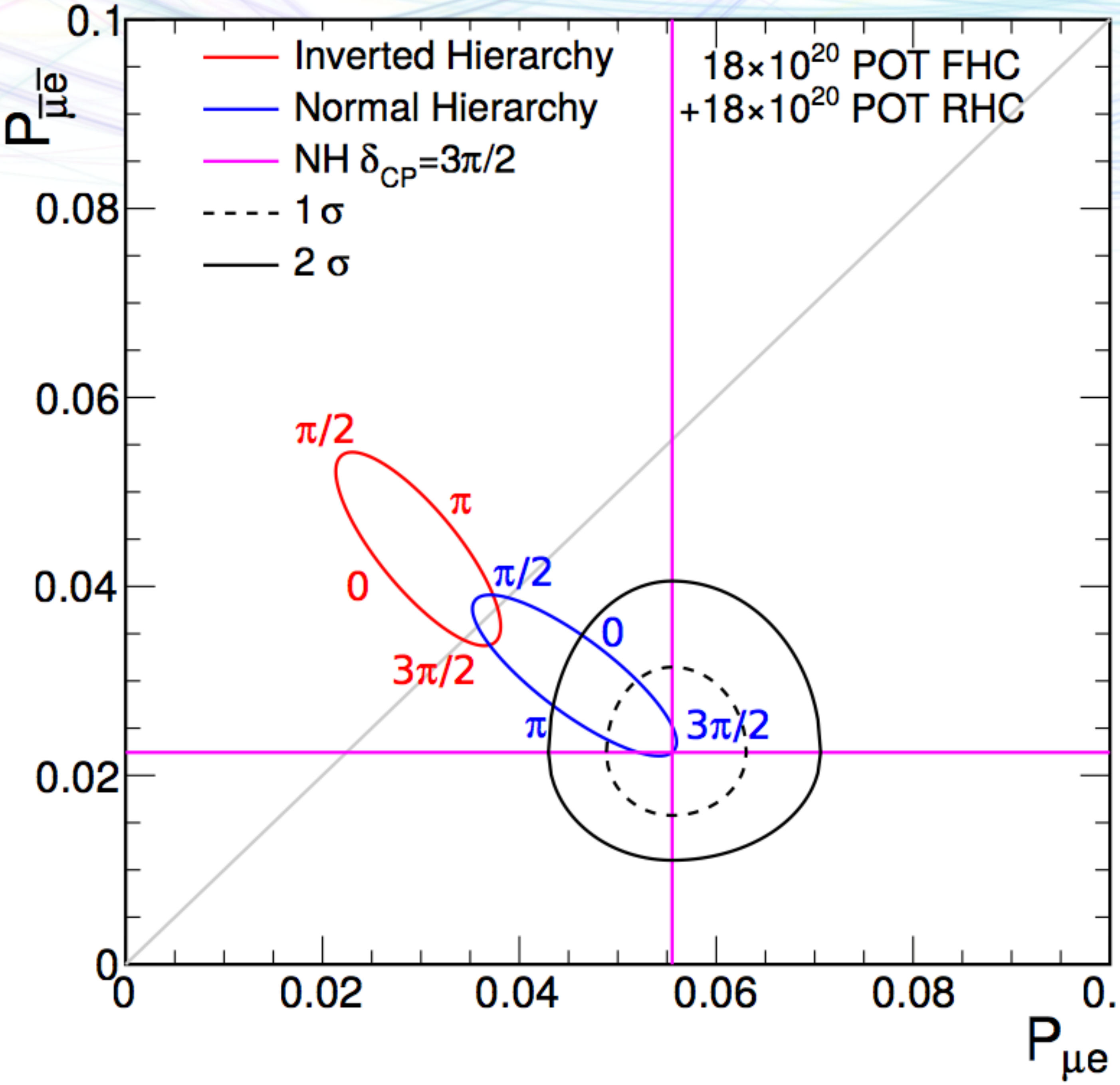

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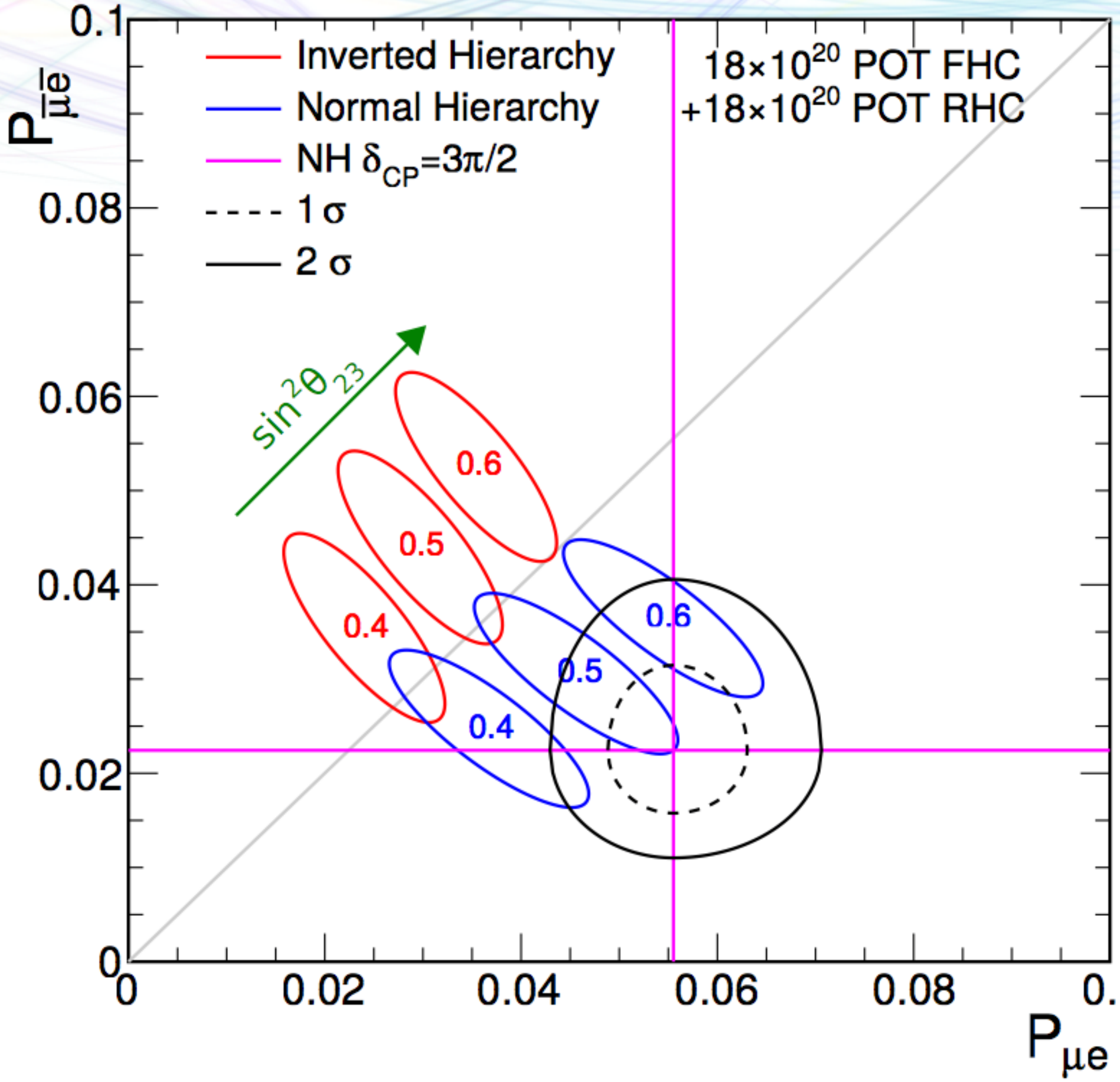
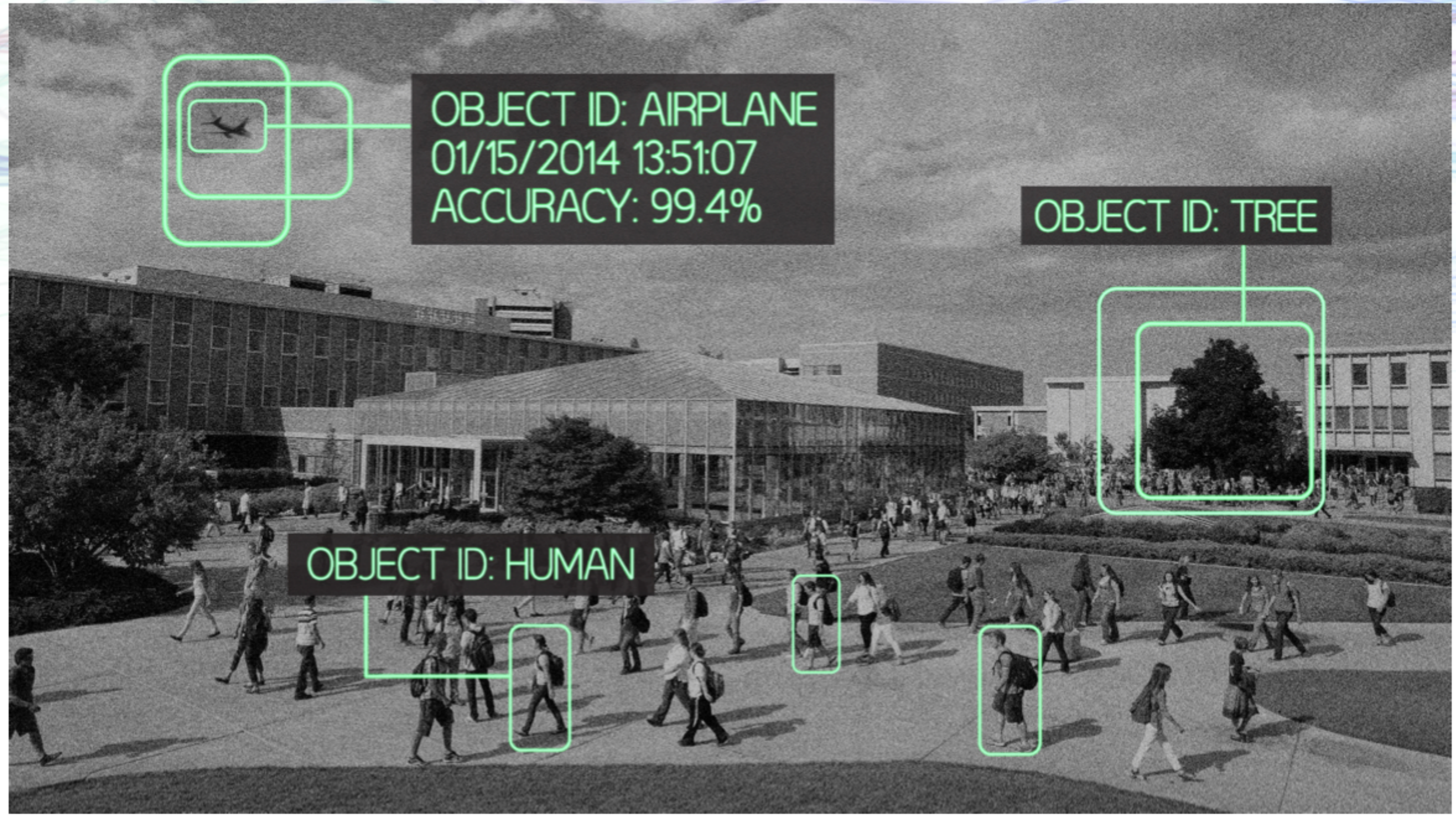
- P also $\propto \sin^2\theta_{23}$



Convolution Neural Networks



- Recent advances in machine learning/computer vision
- Achieving near-human performance on image classification tasks
- Why not classify event-displays?

Convolution Neural Networks

$$\frac{1}{8}\begin{bmatrix} -1 & -1 & -1 \\ -1 & +8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$

Edge-detection kernel

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- **CNN** – deep neural network, inputs are the pixels of the image
- Take advantage of translational invariance → convolutions

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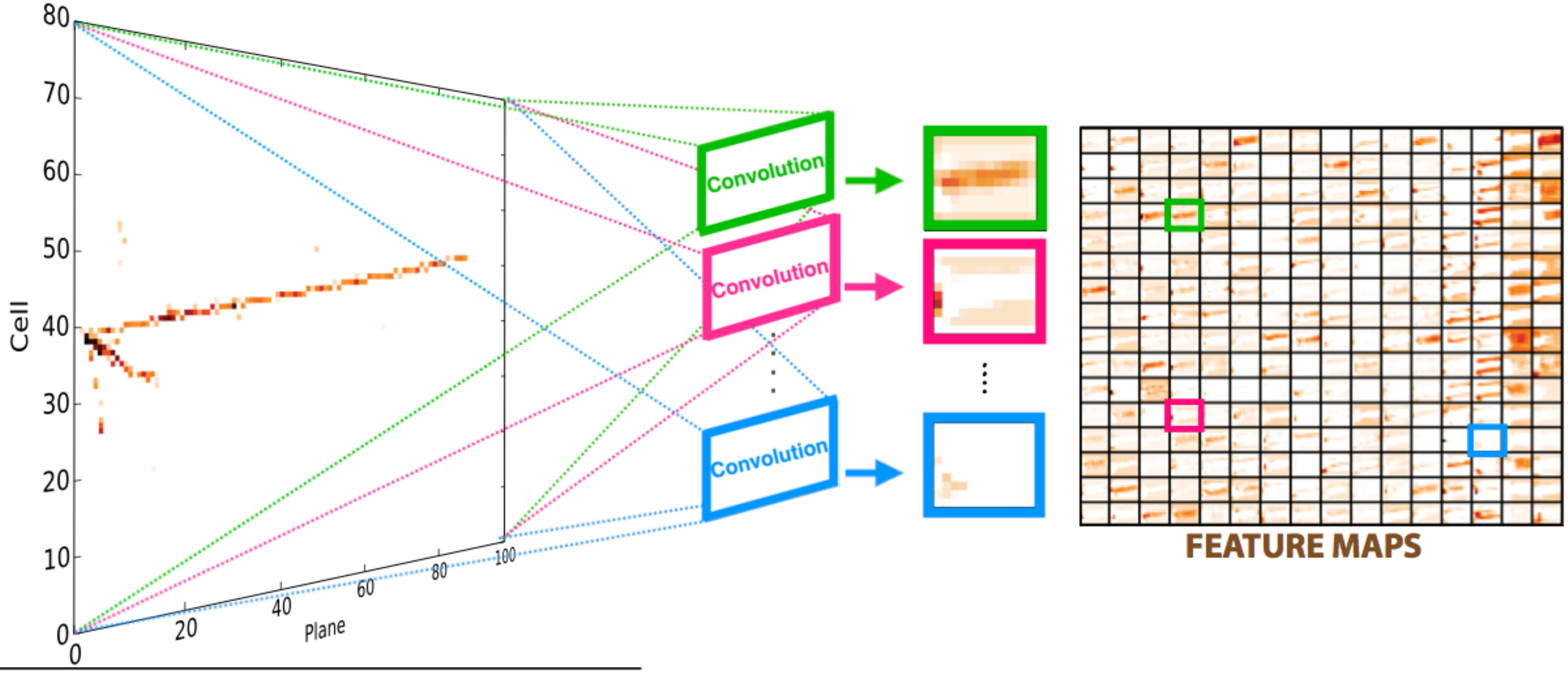
Selecting electron neutrinos – CVN

- **C**onvolutional **V**isual **N**etwork (CVN)
- Early layers perform convolutions to pick out abstract features
- Fully-connected final layers
- Trained using FNAL's Wilson Cluster GPUs
- Statistical power equivalent to 30% more exposure than previous IDs



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arXiv:1604.01444

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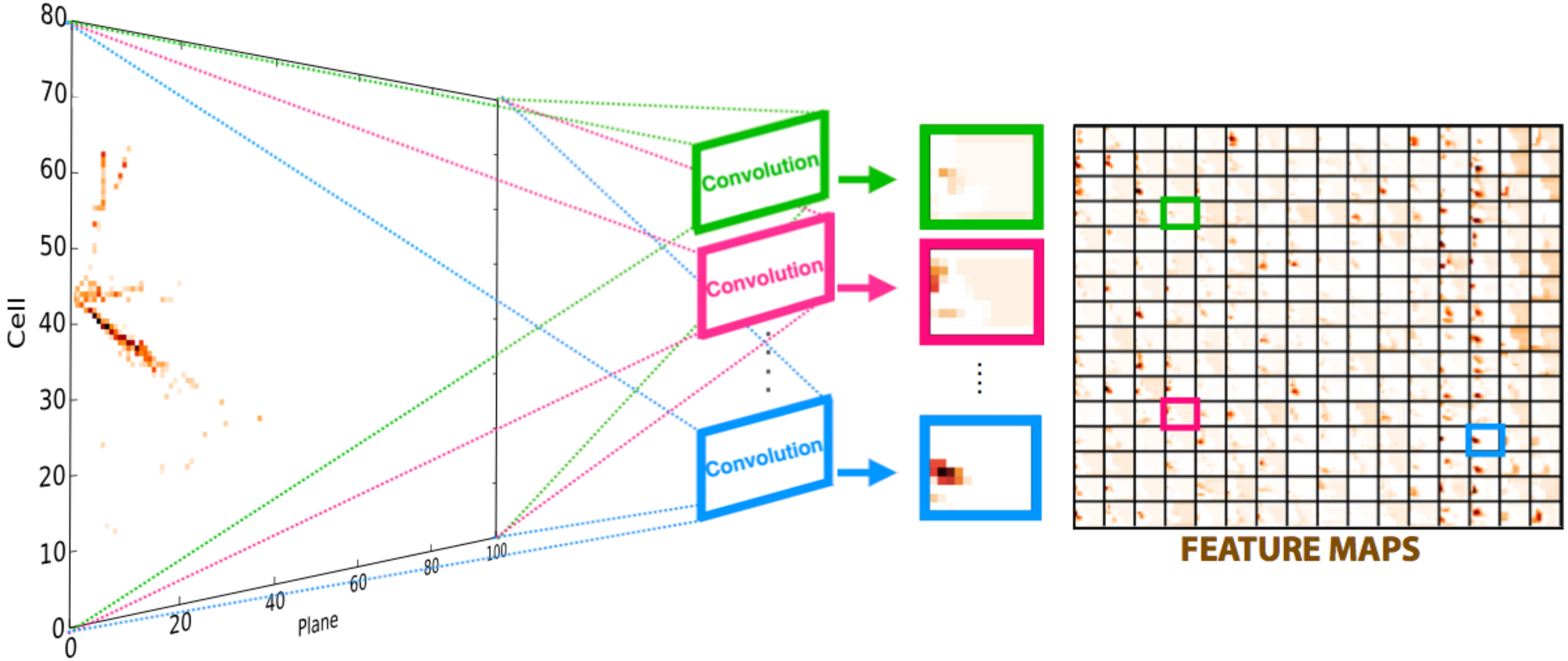

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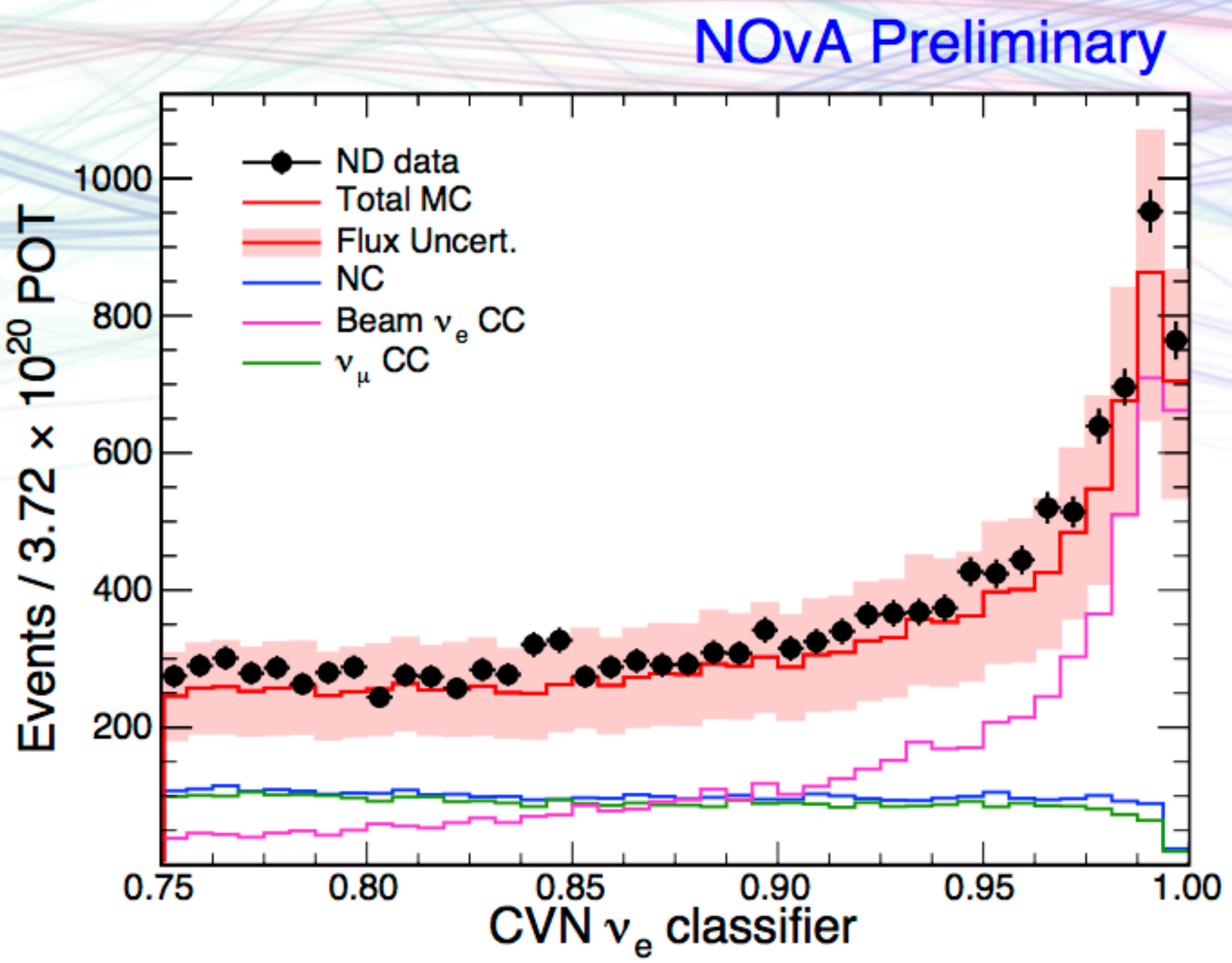
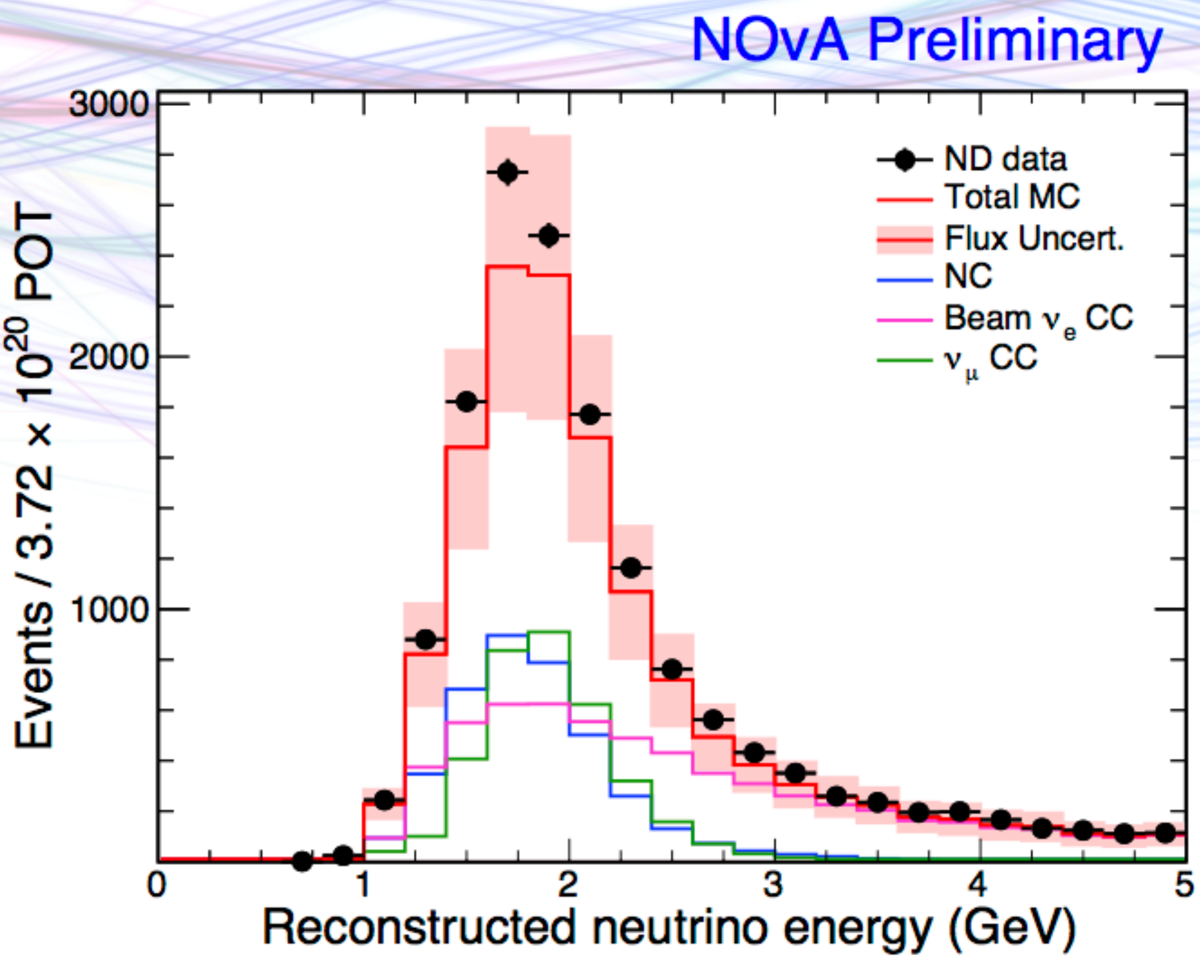
Selecting electron neutrinos – CVN



NOvA Preliminary



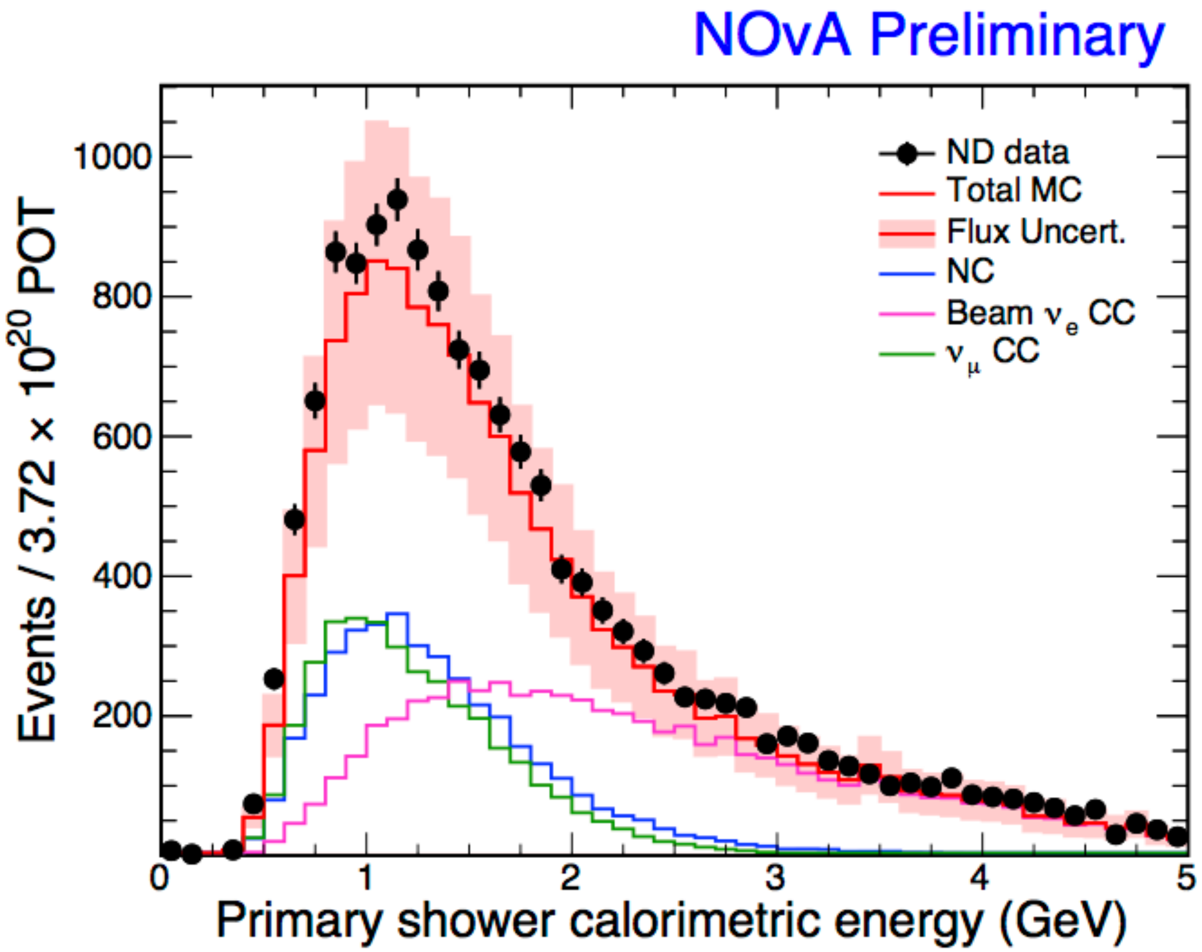
NOvA Preliminary

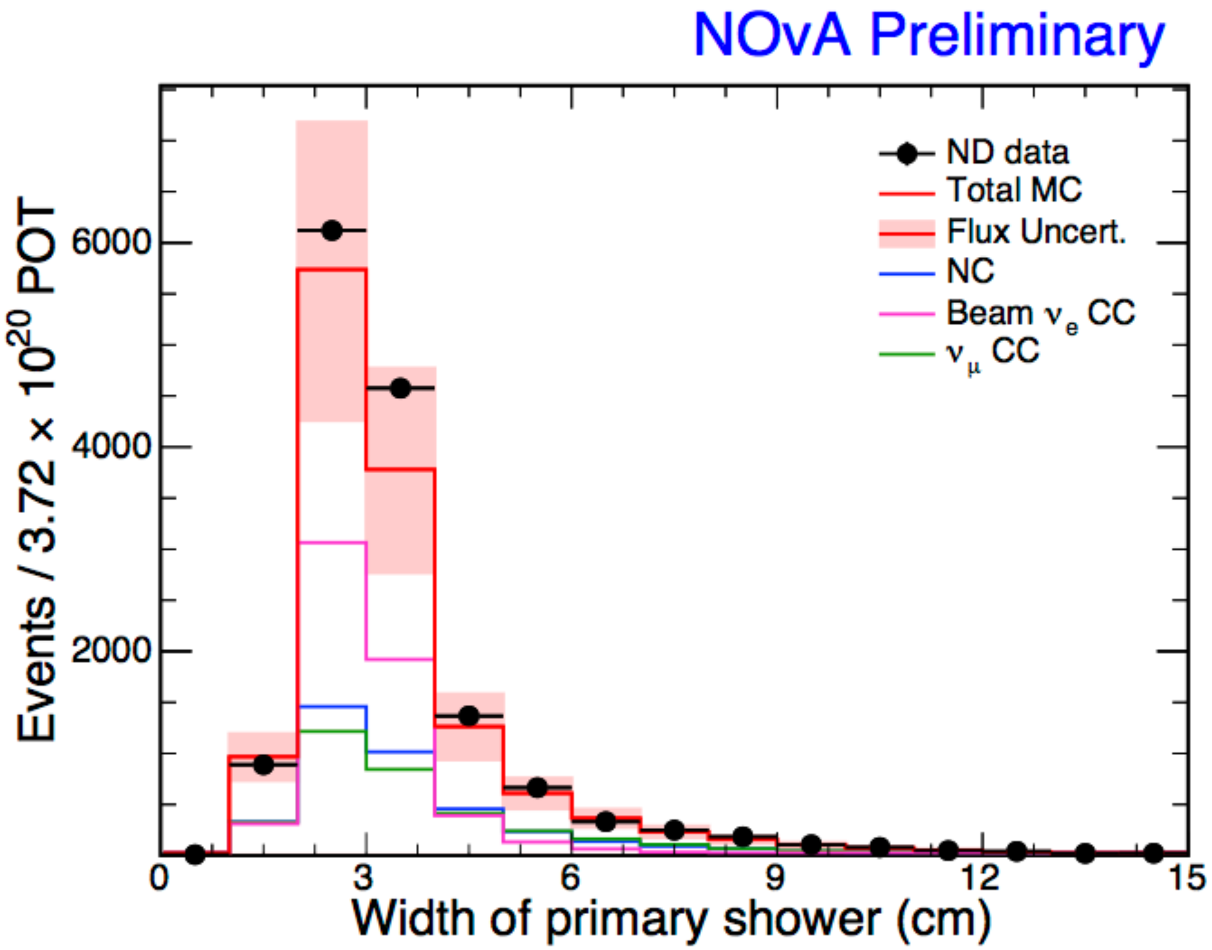
- 73% ν_e signal efficiency, 76% purity
- Loosen PID cut to maximize $s/\sqrt{s+b}$
- Analyze in 3 PID × 4 energy bins

Selector checks

- CVN subjected to the same (or greater) scrutiny than past PIDs

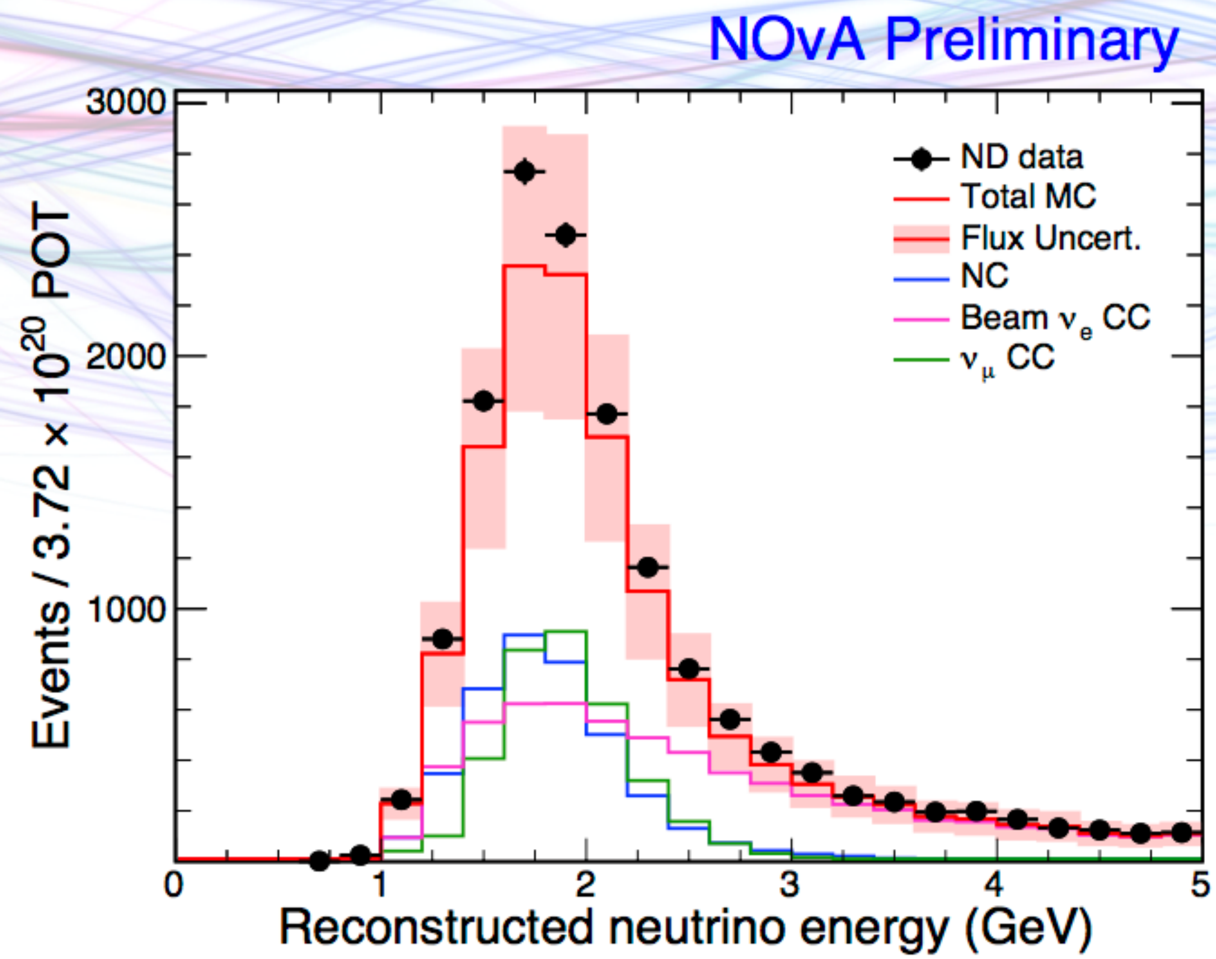
- ND data/MC is good
- Better cosmic rejection and similar systematics to other PID options





ND decomposition

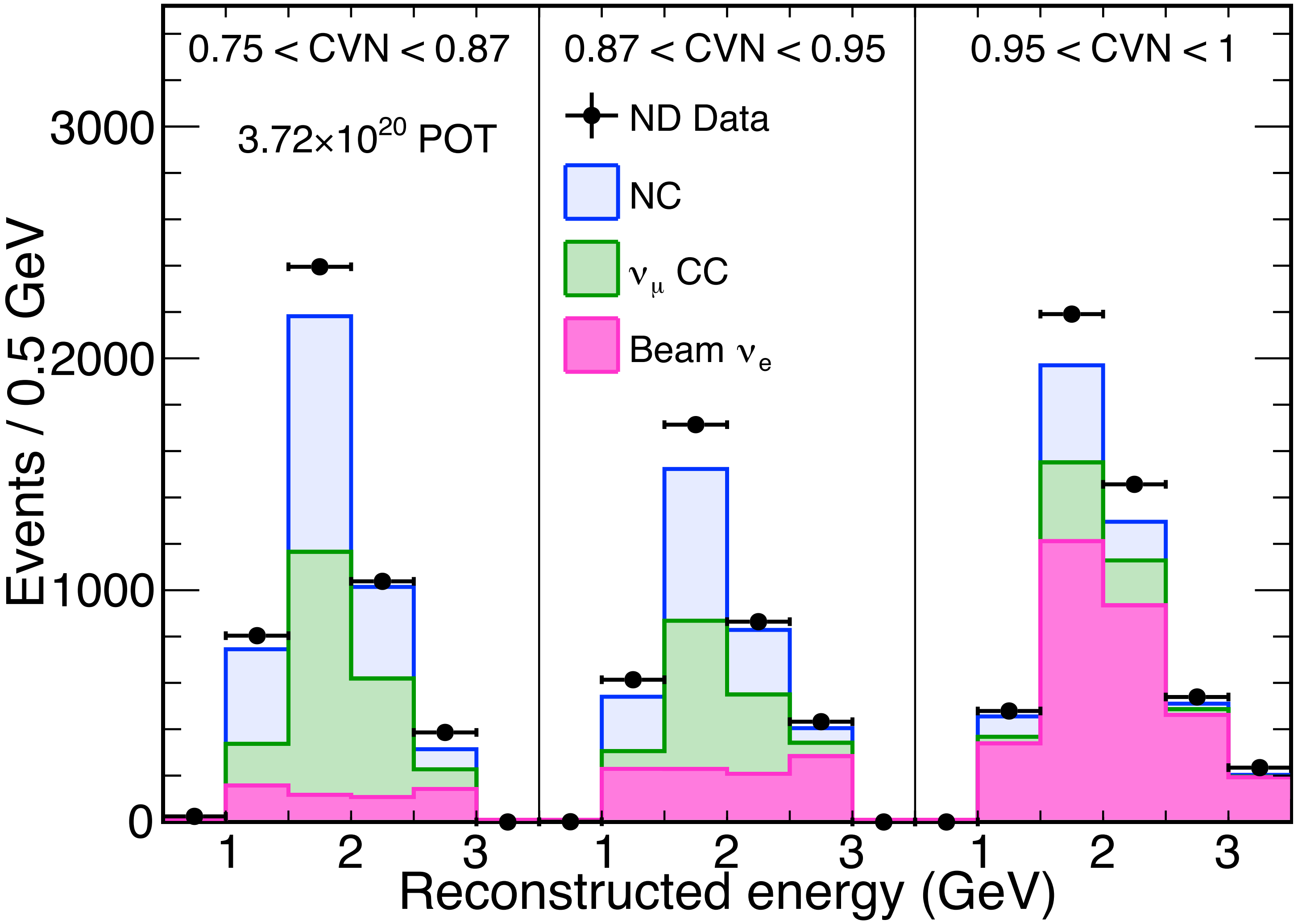
- Use ND data to predict FD backgrounds
  - Beam ν_e CC
  - NC
  - ν_μ CC
- $\sim$ 10% excess of data over MC



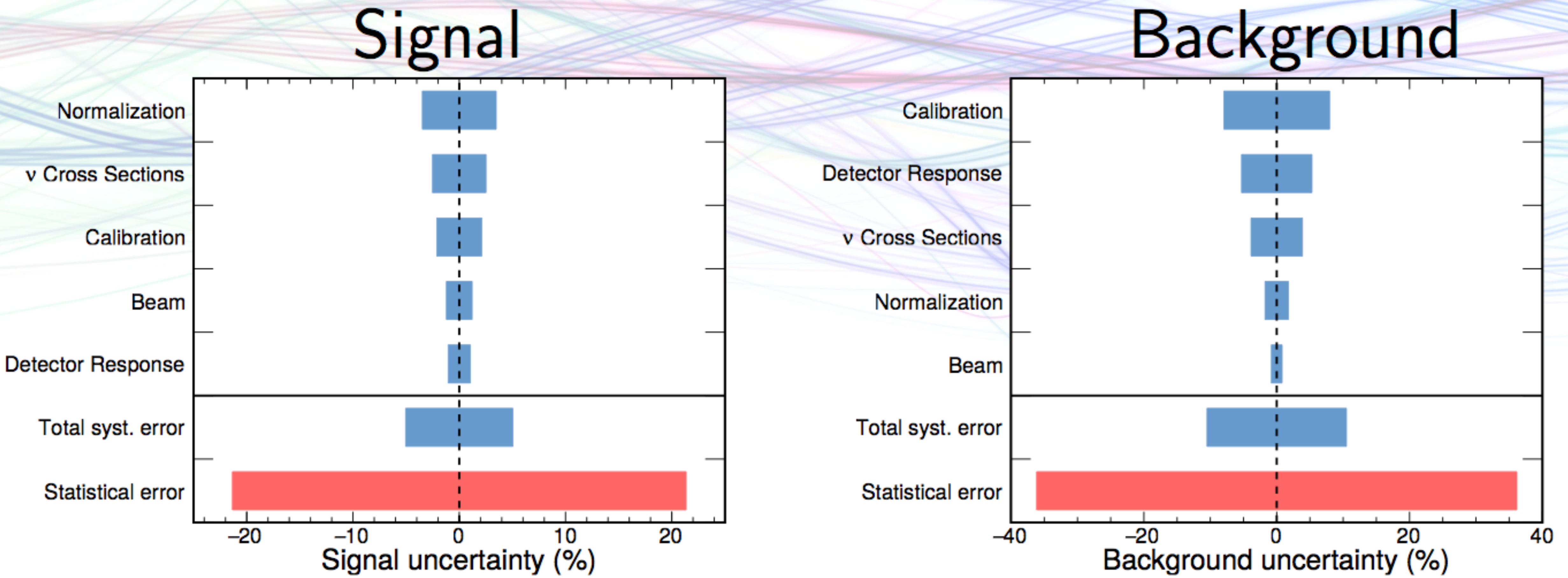
- How to divide between the components?
- *e.g.* most ν_μ CC oscillate away before FD

Data Driven Background Corrections

- ν_e CC selection in the ND picks out FD backgrounds
  - beam ν_e CC
  - ν_μ CC
  - NC
- ~10% excess of data over MC in the ND
- Extrapolate data/MC differences to adjust FD prediction
- Each component oscillates differently
- Must decompose the data into constituent components



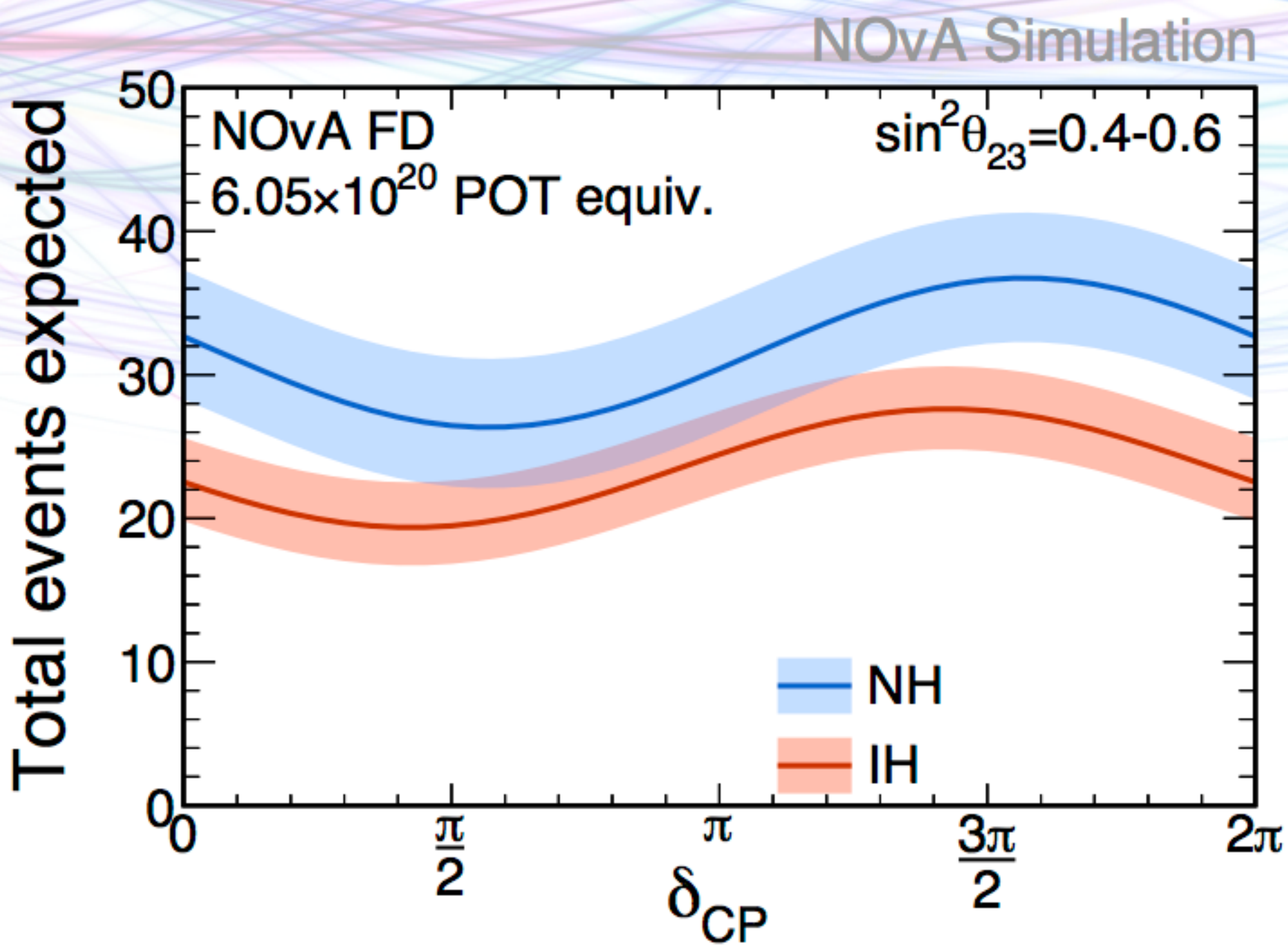
Systematics



- Considered multiple possible sources of systematic error
- Propagate shifts through to update FD prediction

- Total ∼ 5% error on signal, 10% on bkg.
- Fit nuisance parameters as pull terms
- Dominated by statistical error

Event count expectations



Total prediction

NH $\frac{3\pi}{2}$	IH $\frac{\pi}{2}$	$\sin^2\theta_{23} = 0.5$
36.4	19.4	±5% syst.

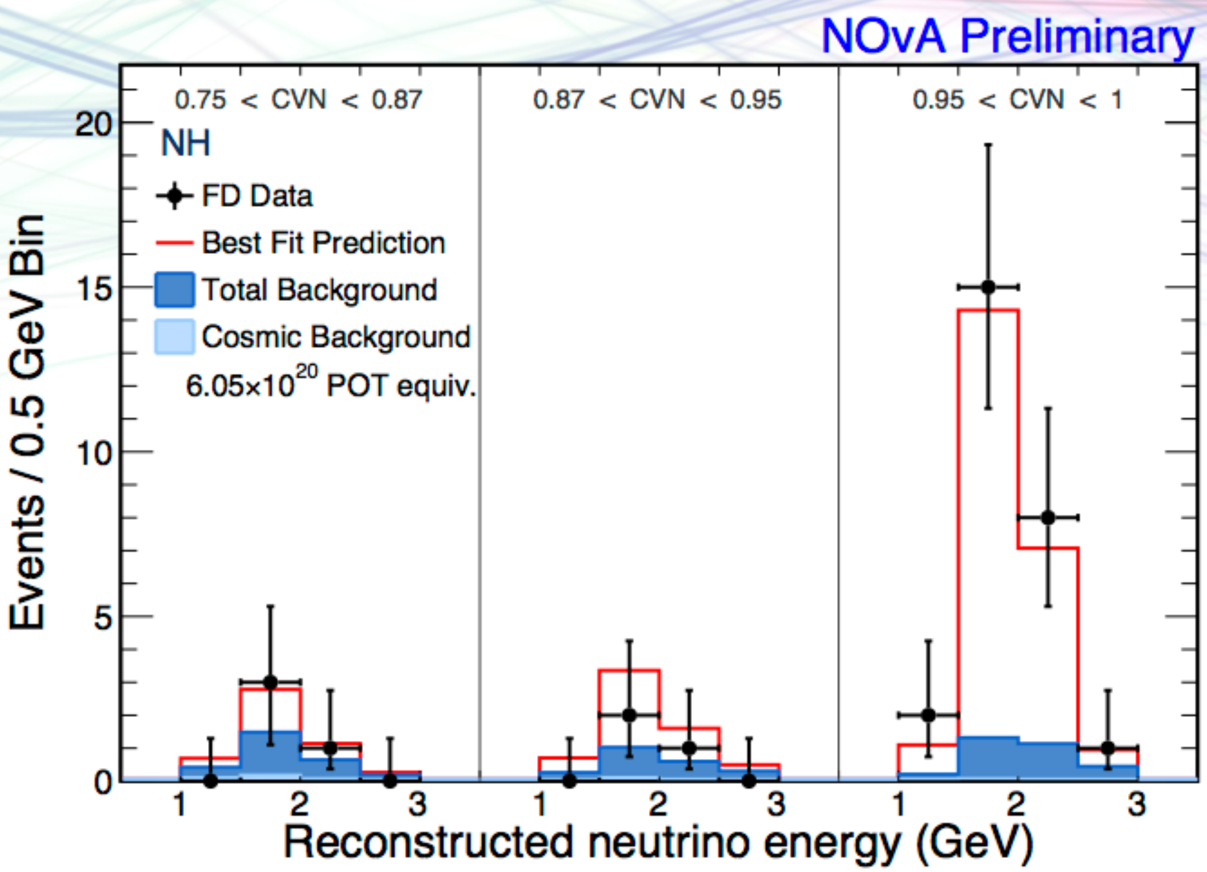
$$P_{\nu_\mu\to\nu_e} \propto \sin^2\theta_{23}\sin^2 2\theta_{13}$$

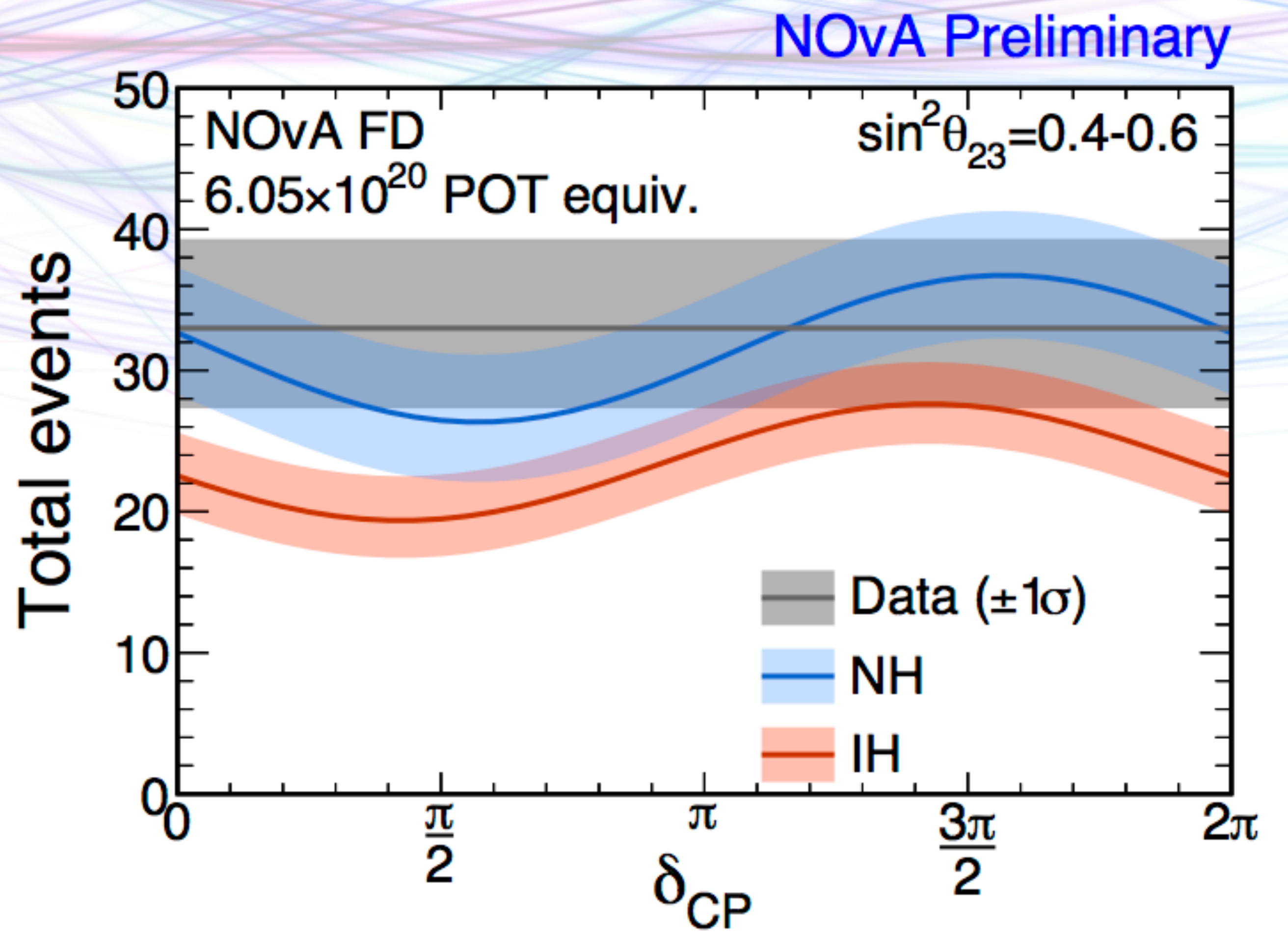
Background components

Total bkg	NC	beam ν_e	ν_μ CC	ν_τ CC	cosmics	
8.2	3.7	3.1	0.7	0.1	0.5	±10% syst.

Essentially independent of oscillation parameters

ν_e appearance results



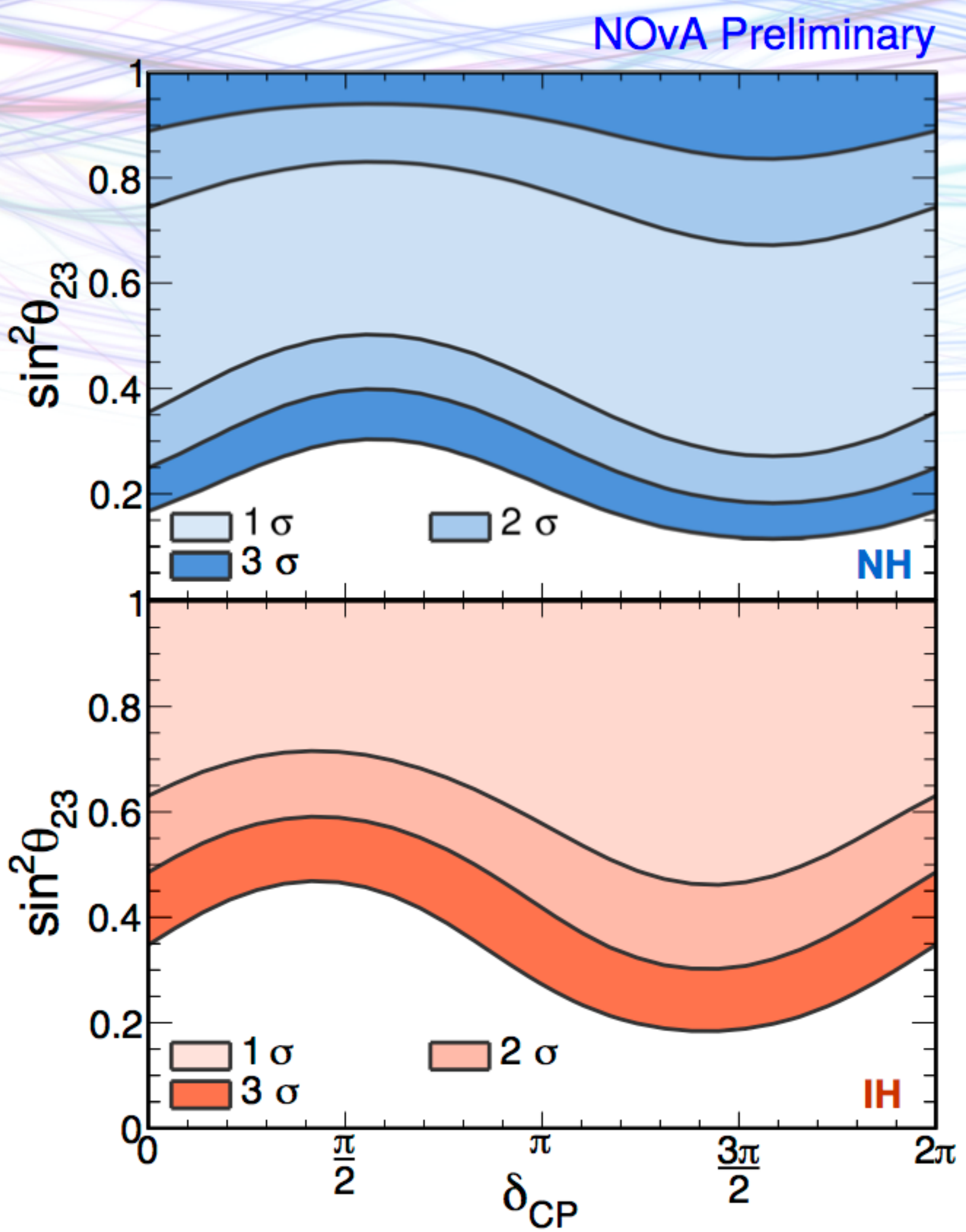


- Observe **33** events passing ν_e selection
- On 8.2 background
- Towards the higher end of expectations

Previous result PIDs: LID(LEM) sees 34(33) events on bkg. of 12.2(10.3)

ν_e fit results

- Constrain θ_{13} to reactor average $\sin^2 2\theta_{13} = 0.085 \pm 0.005$



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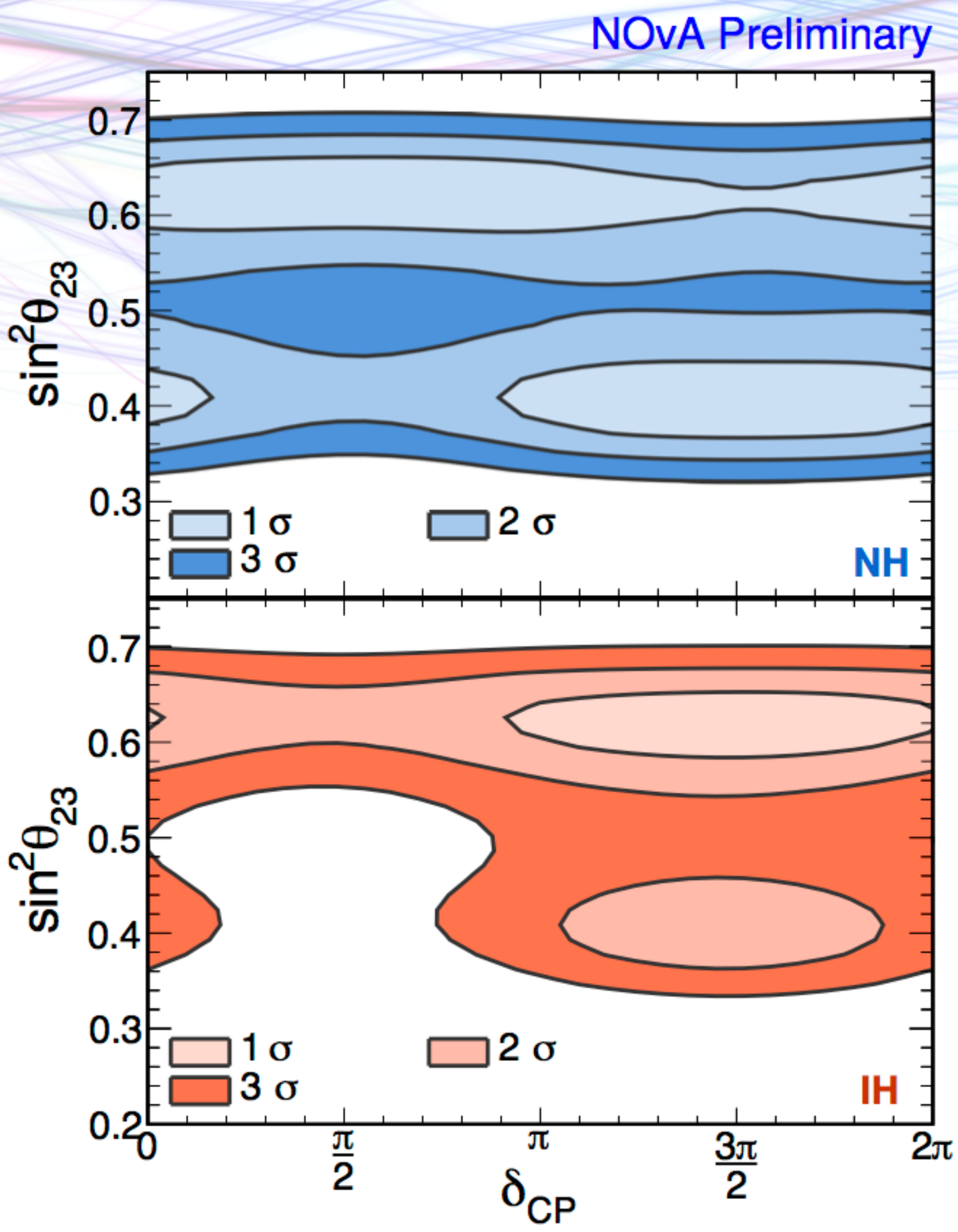
- Constrain θ_{13} to reactor average $\sin^2 2\theta_{13} = 0.085 \pm 0.005$
- Add $\Delta m^2_{32}/\theta_{23}$ results from ν_μ analysis
- Not a full joint fit. No syst./osc. param correlations. No FC.



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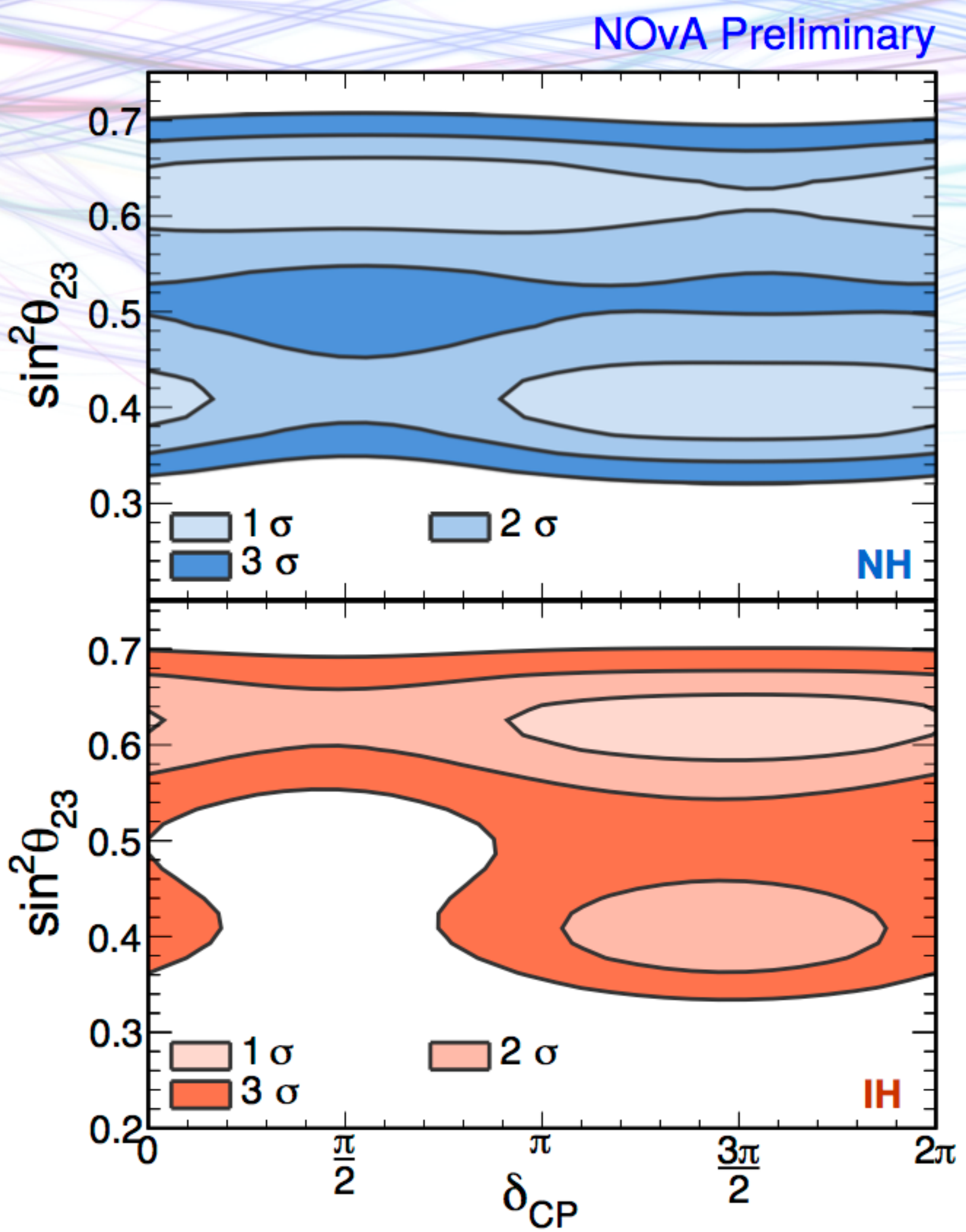
- Prefer NH, not statistically significant $\Delta\chi^2 = 0.46$
- Exclude region in IH, lower octant, around $\delta_{CP} = \pi/2$ at 3σ



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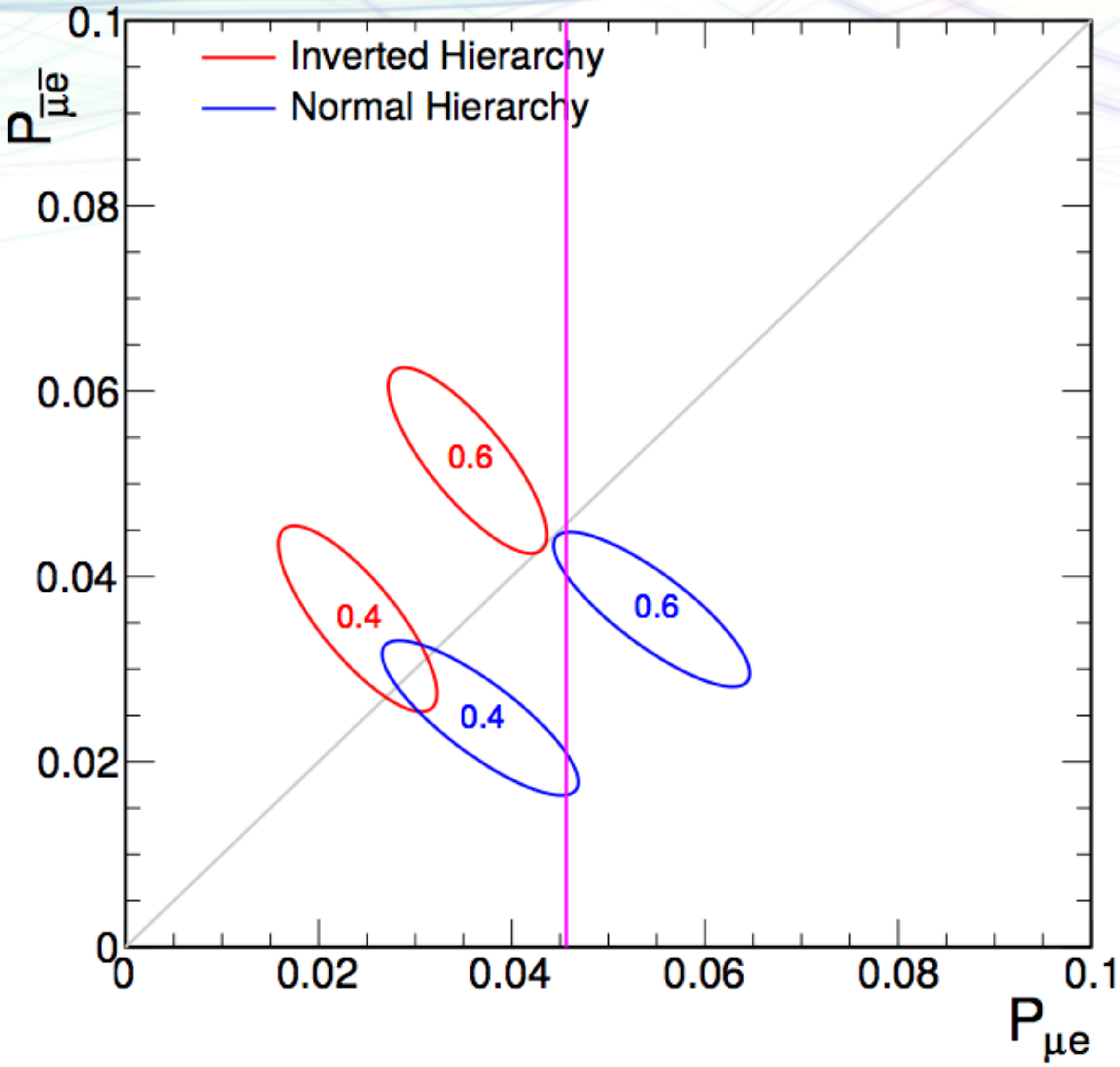

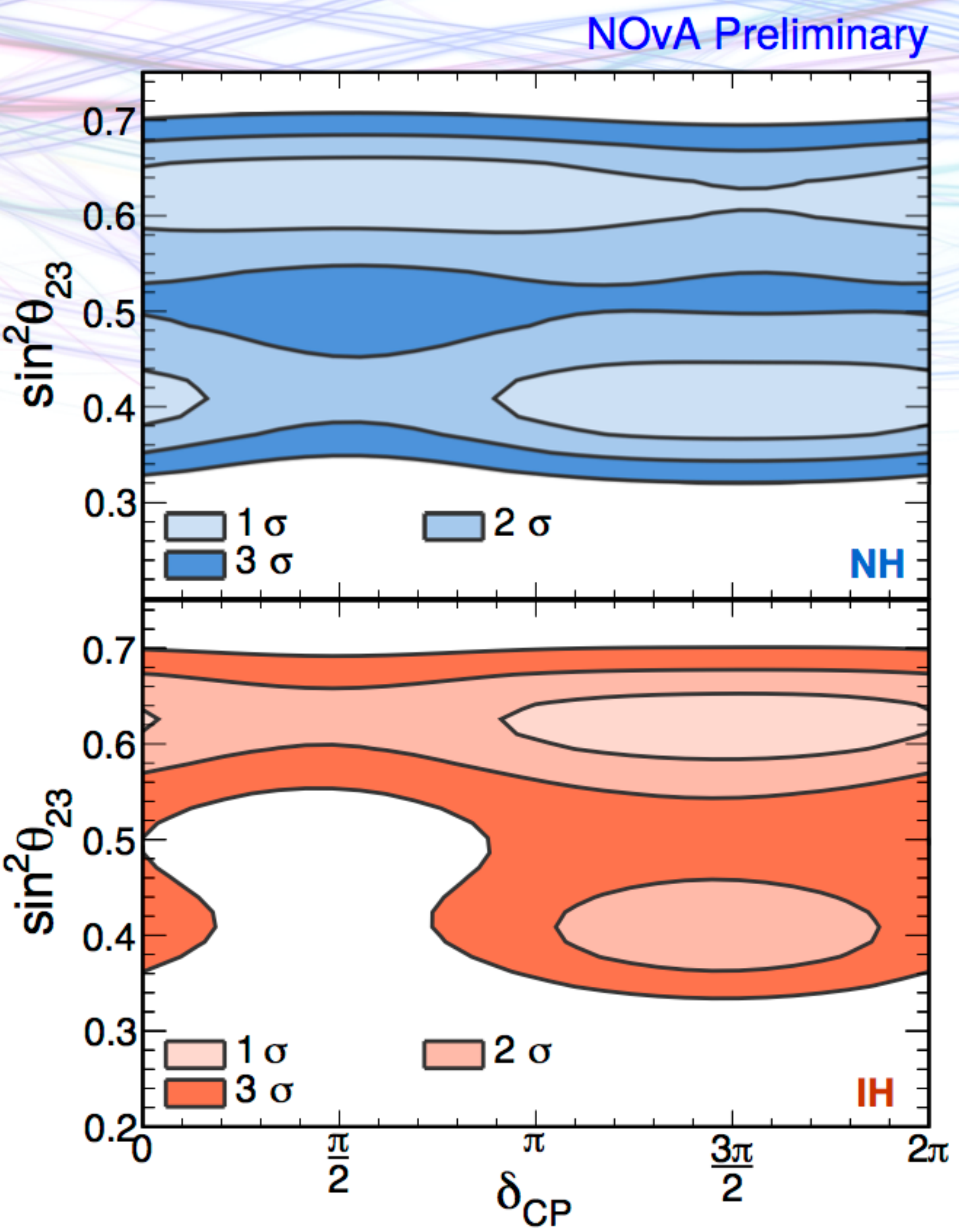

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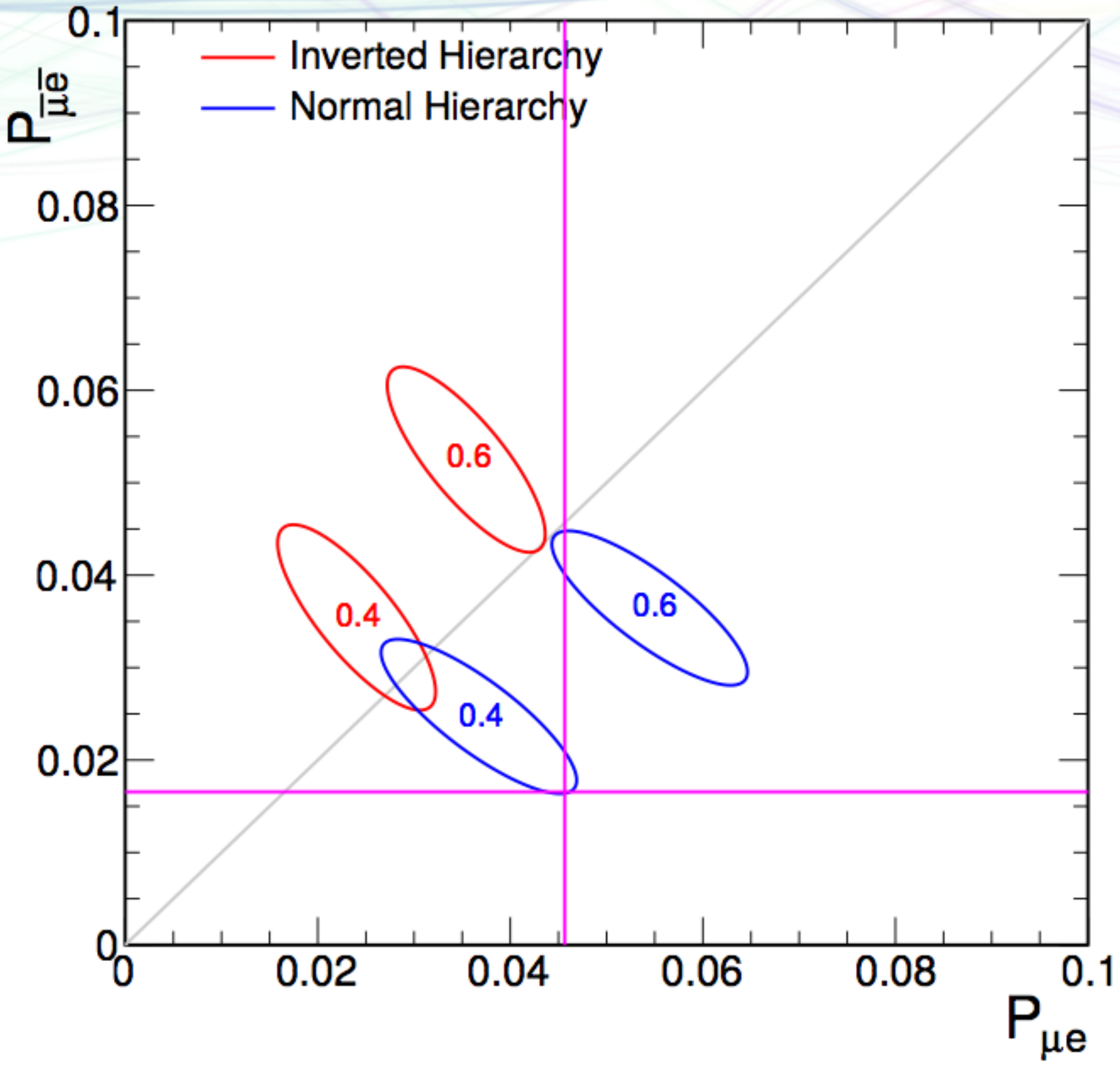

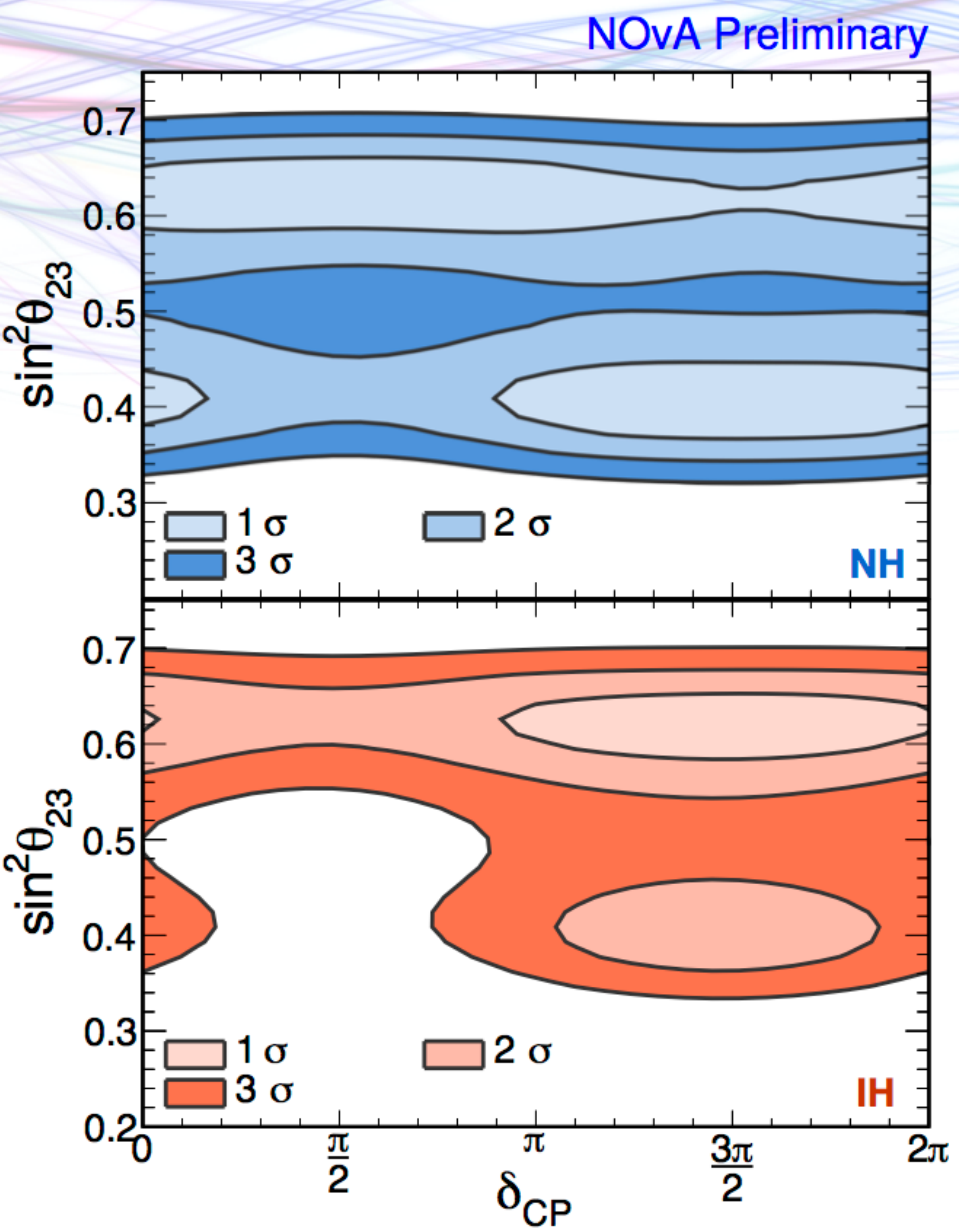

- Antineutrino data will help to resolve degeneracies
- $> 2\times$ difference in $\bar{\nu}_e$ rate between solutions

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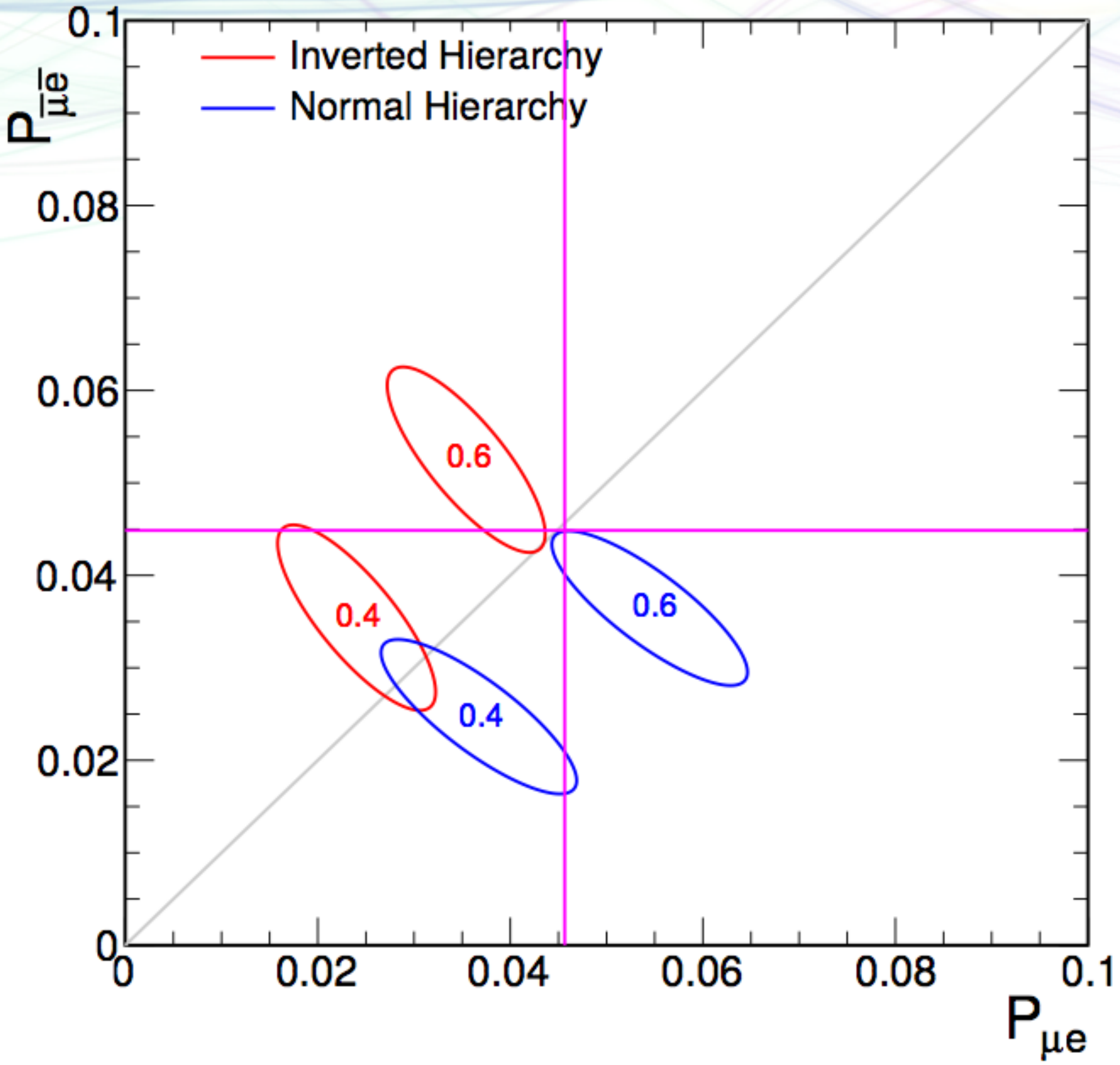

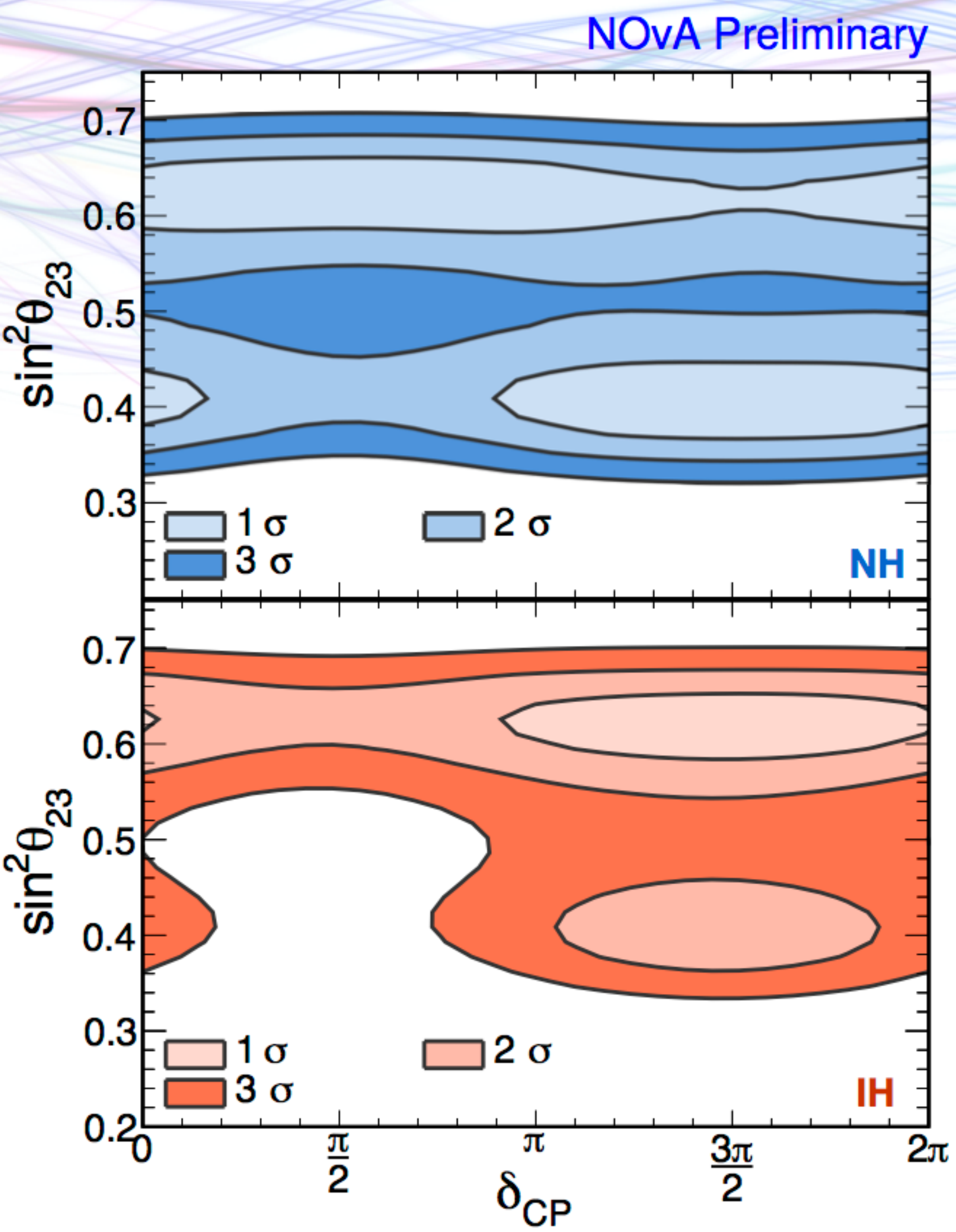

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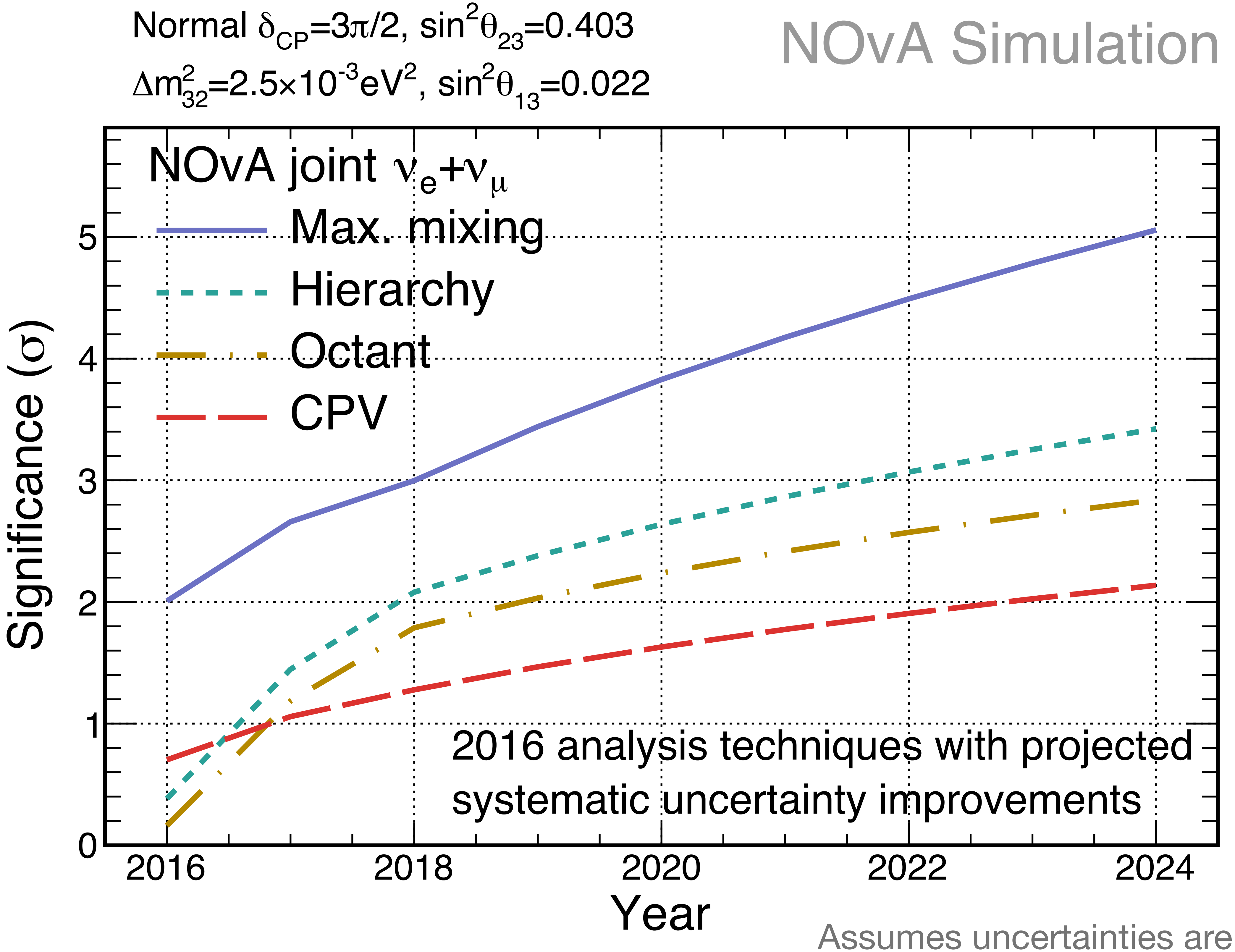
Looking ahead



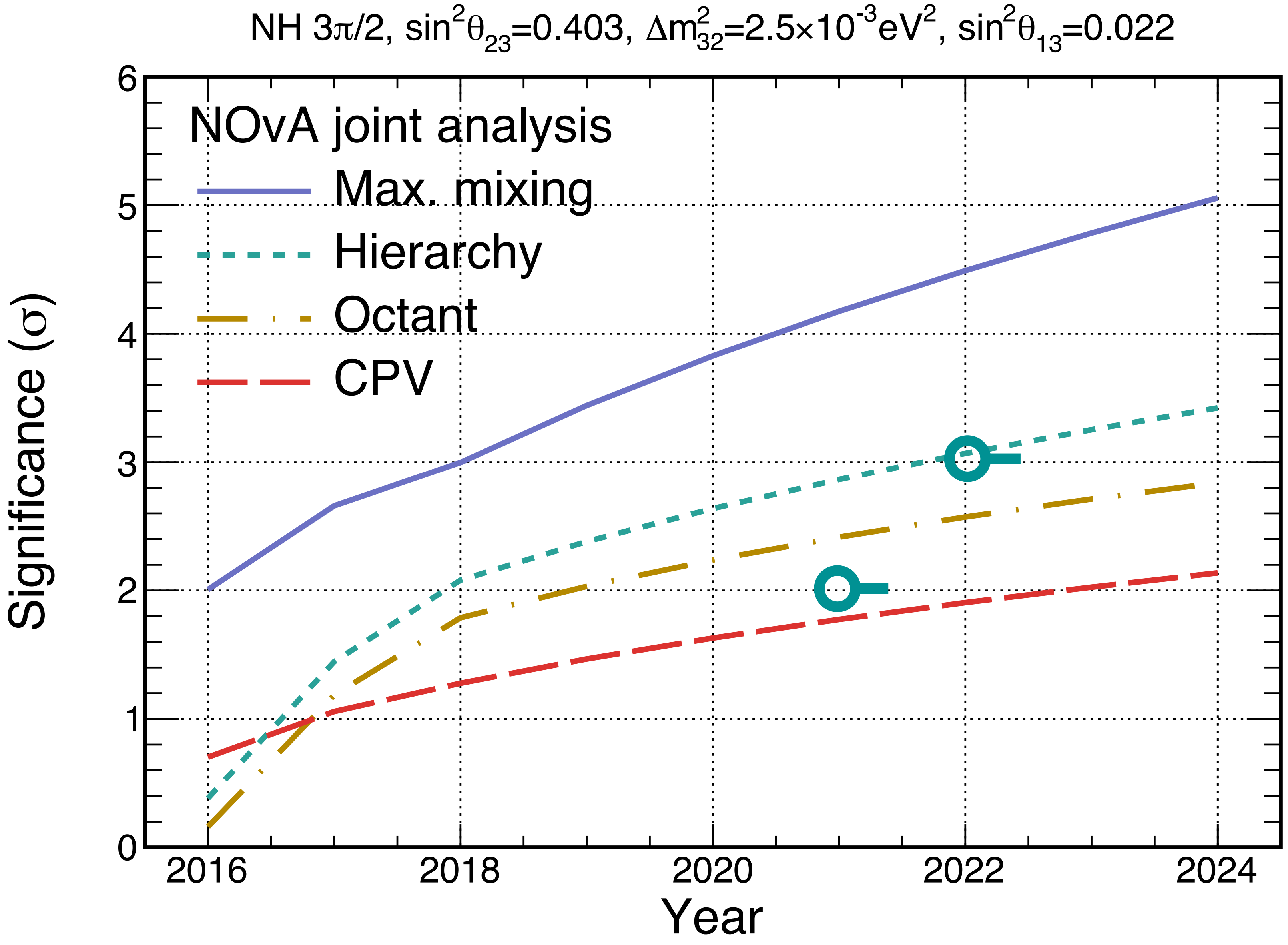
Projected NOvA physics reach

50/50 run plan for normal hierarchy lower octant

Assumes uncertainties are reduced to
- 2% signal / 5% background for electron neutrinos
- 2% muon energy scale, 3% hadronic energy, ~0% NC backgrounds for muon neutrinos

Competition

This opportunity is not unique to Fermilab. There are several projects hoping to capitalize on this opportunity.



Both **JUNO** and **ORCA** have construction underway.
Nearly identical schedules for mass hierarchy reach:

- 2σ in 2021
- 3σ in 2022

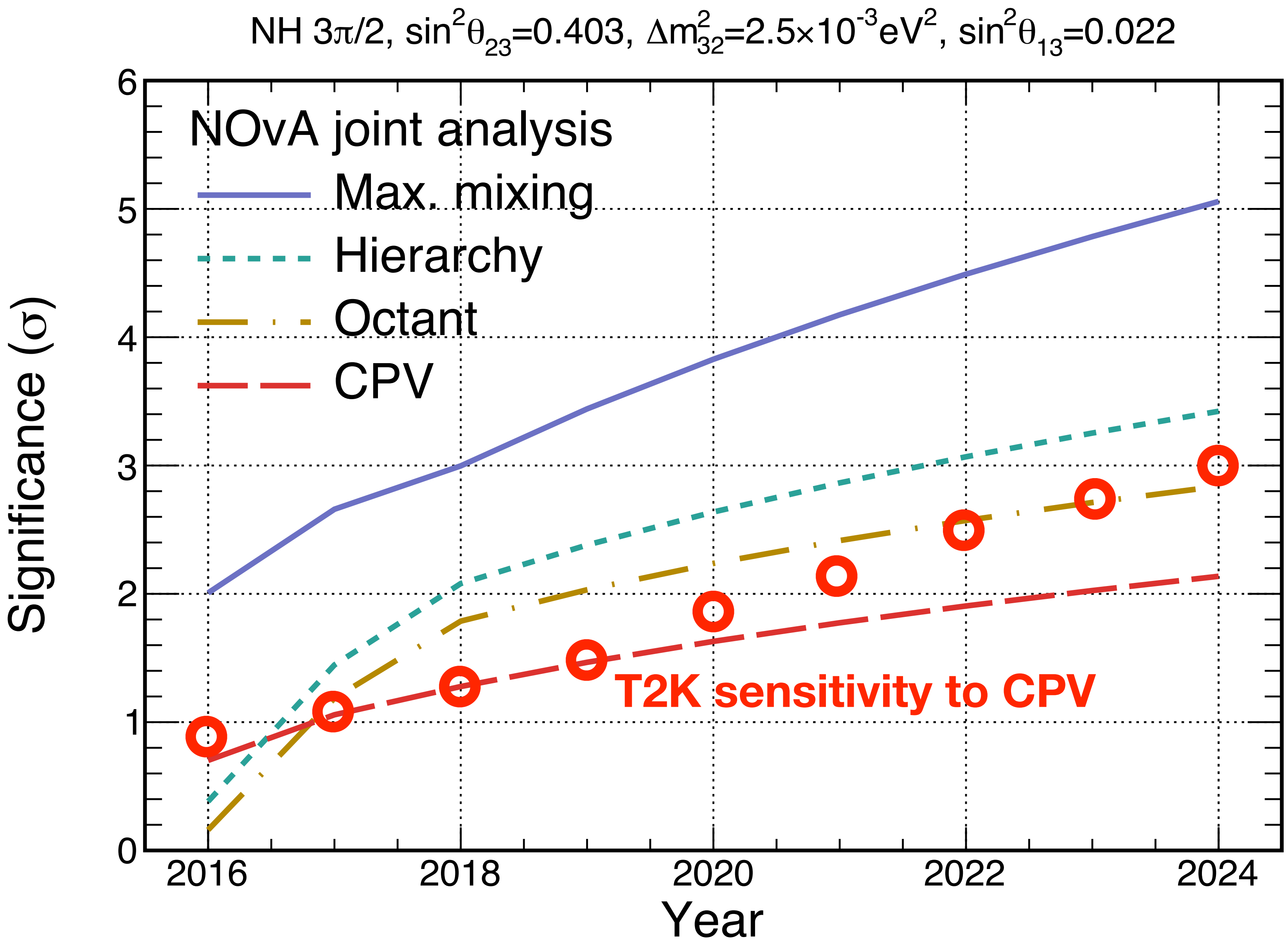
A Super-K + T2K combination gives roughly 2σ

Other competition from, global fits, and cosmology fits.

Competition

T2K has proposed an extended run to get 3σ sigma evidence for CPV

(arXiv:1607.08004v1 [hep-ex] 27 Jul 2016)



Until 2020 NOvA running flat-out and T2K have same CPV reach.

T2K beam power ramps from current 420 kW to 770 kW by 2020 (surpassing NuMI power) and then to 1.1+ MW by 2023. Assumes 5 months / year beam allocation for T2K

This plus analysis improvements drives the CPV reach of T2K to 3 sigma in 2024.