

Новые результаты по нейтринным осцилляциям в эксперименте NOvA

Олег Самойлов (ЛЯП ОИЯИ)

Семинар ЛЯП по физике нейтрино и астрофизике
19 января 2018 г.

Latest Oscillation Results from NOvA

Презентован 12 января 2018 г.
в Фермилабе (JETP seminar)



Alexander Radovic
College of William and Mary

Latest Oscillation Results from NOvA

Conclusions

A. Radovic, JETP January 2018

- At 8.85×10^{20} POT, NOvA finds:
 - **Muon neutrinos disappear:** Competitive measurement of Δm^2_{32} , new analysis prefers mixing near-maximal.
 - **Electron neutrinos appear:** Inverted Hierarchy at $\delta_{CP} = \pi/2$ disfavored at greater than 3σ . Approaching 2σ IH rejection.
 - **Excellent detector and beam performance.**
 - **Significant improvement in our analysis tools.** Expected to continue, benefiting from efforts like the NOvA test beam.
- Looking forward to opening the box on our first antineutrino data this summer! Expect NOvA to continue to contribute to key questions:
 - Is δ_{CP} nonzero?
 - What is the mass hierarchy?

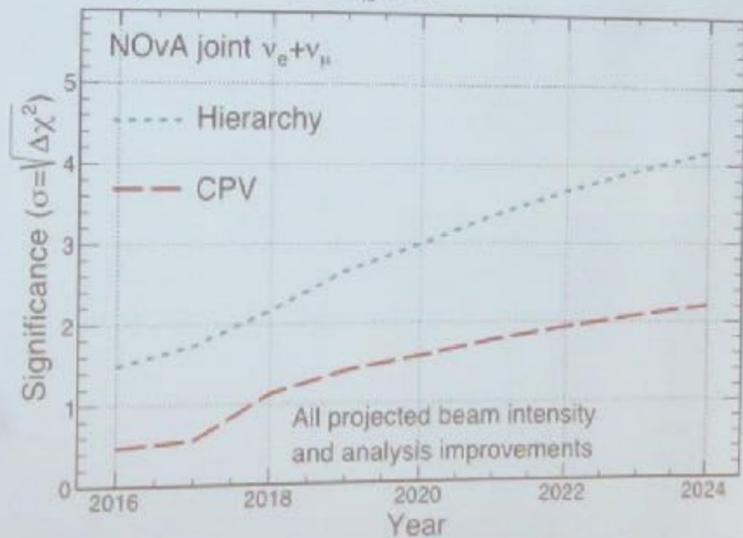
The Future

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Normal $\delta_{CP} = 3\pi/2$, $\sin^2 \theta_{23} = 0.500$
 $\Delta m^2_{32} = 2.45 \times 10^{-3} \text{eV}^2$, $\sin^2 2\theta_{13} = 0.082$

NOvA Simulation

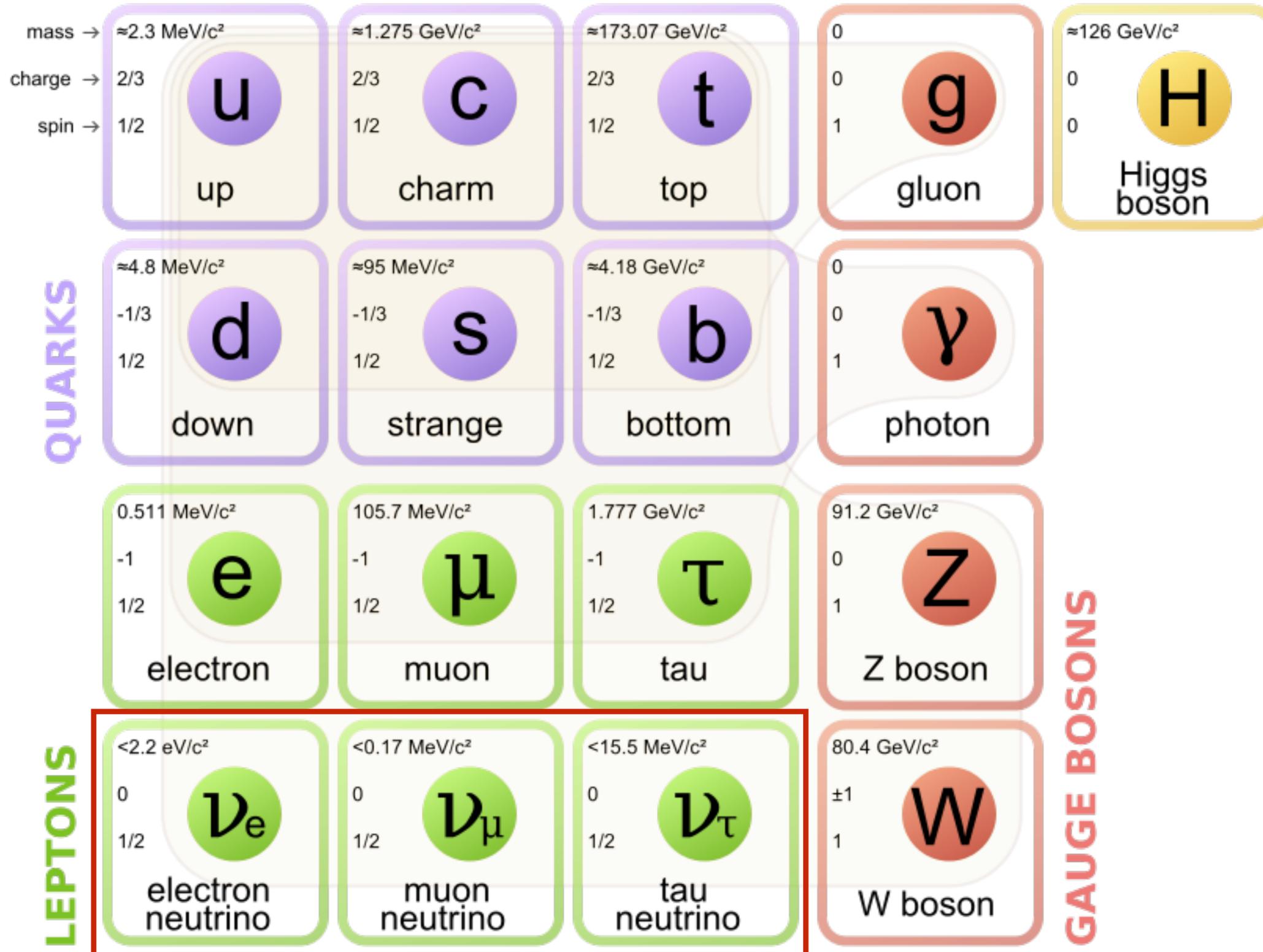


Главные результаты 2017 года

- ✓ $8,85 \times 10^{20}$ протонов-на-мишень ускорительного комплекса NuMI в пучке мюонного нейтрино дают следующие результаты
- ➔ В моде исчезновения мюонного нейтрино: улучшение измерения Δm^2_{32} , новый результат близок к максимальному смешиванию угла θ_{23} .
- ➔ В моде появления электронного нейтрино: обратная иерархия для $\delta_{CP} = \pi/2$ исключается также на уровне 3σ . Новые результаты приближаются в исключении обратной иерархии на уровне 2σ для всей области параметров фазы CP-четности.
- ➔ Получены значительные улучшения в описании работы детекторов и нейтринного пучка
- ➔ NOvA в хорошей форме для получения новых результатов по антинейтринной моде этим летом (NEUTRINO-2018).
- ➔ В настоящее время NOvA (на ряду с T2K) является ключевым “игроком” в разрешении вопросов определения параметра нарушения CP-симметрии в лептонном секторе и иерархии масс нейтрино

**У кого интерес разгорелся –
детали...**

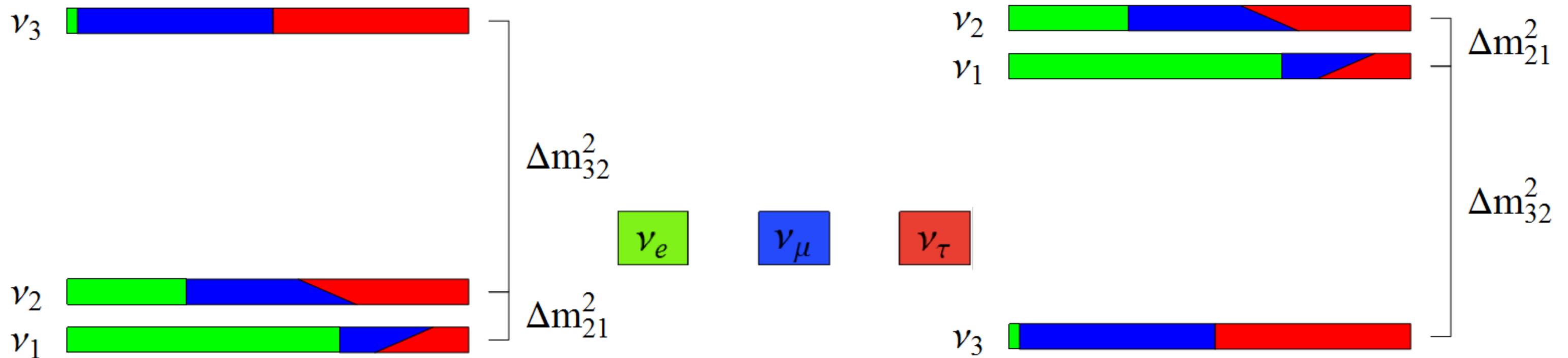
Neutrino Oscillations



Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^* \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

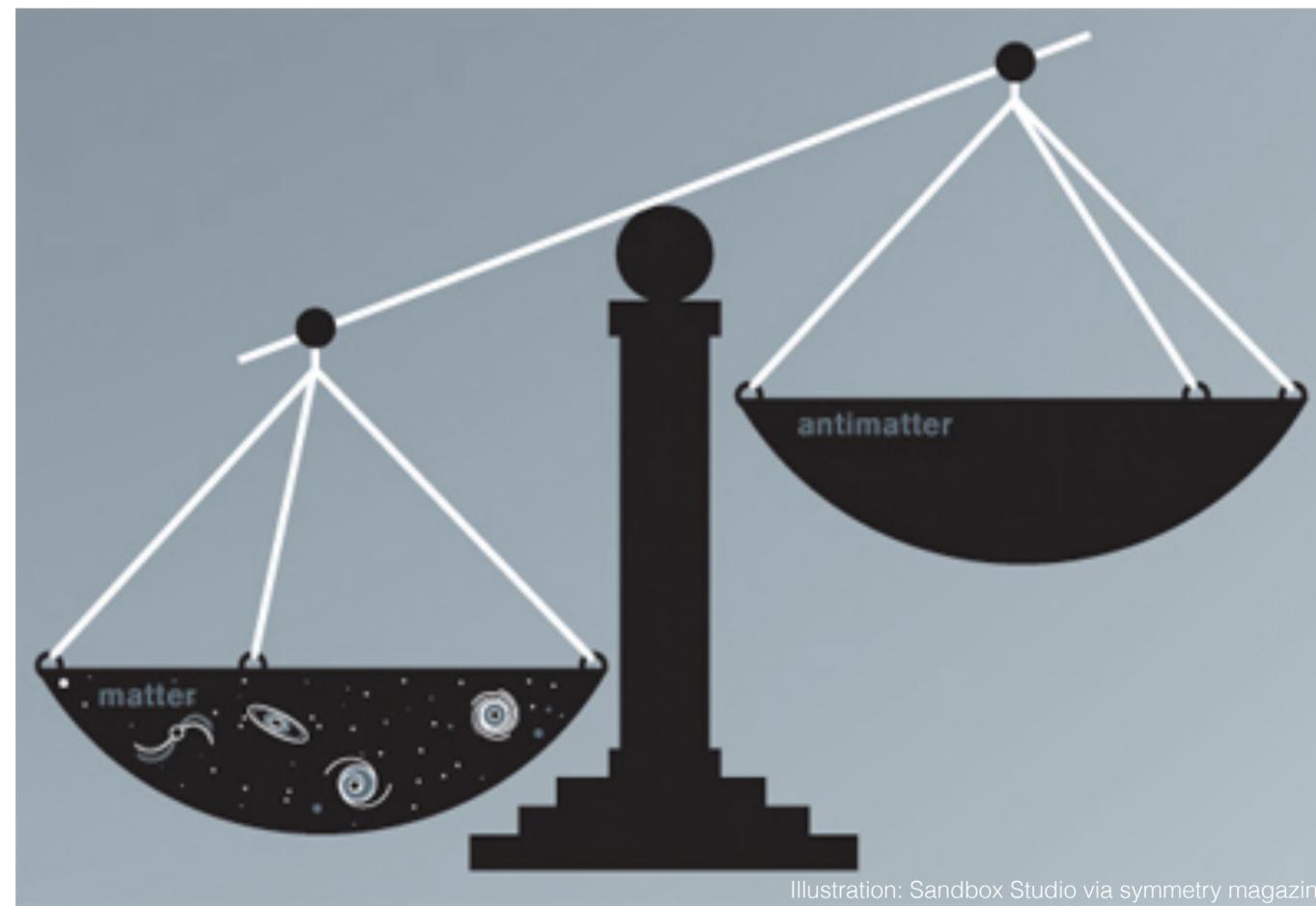
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$



Why Study Neutrino Oscillations?

Neutrino oscillations raised as many questions as it answered:

- Why is lepton sector mixing much larger than quark sector mixing? Is θ_{23} maximal?
- What is the hierarchy of neutrino masses?
- Is there CP violation in the lepton sector?

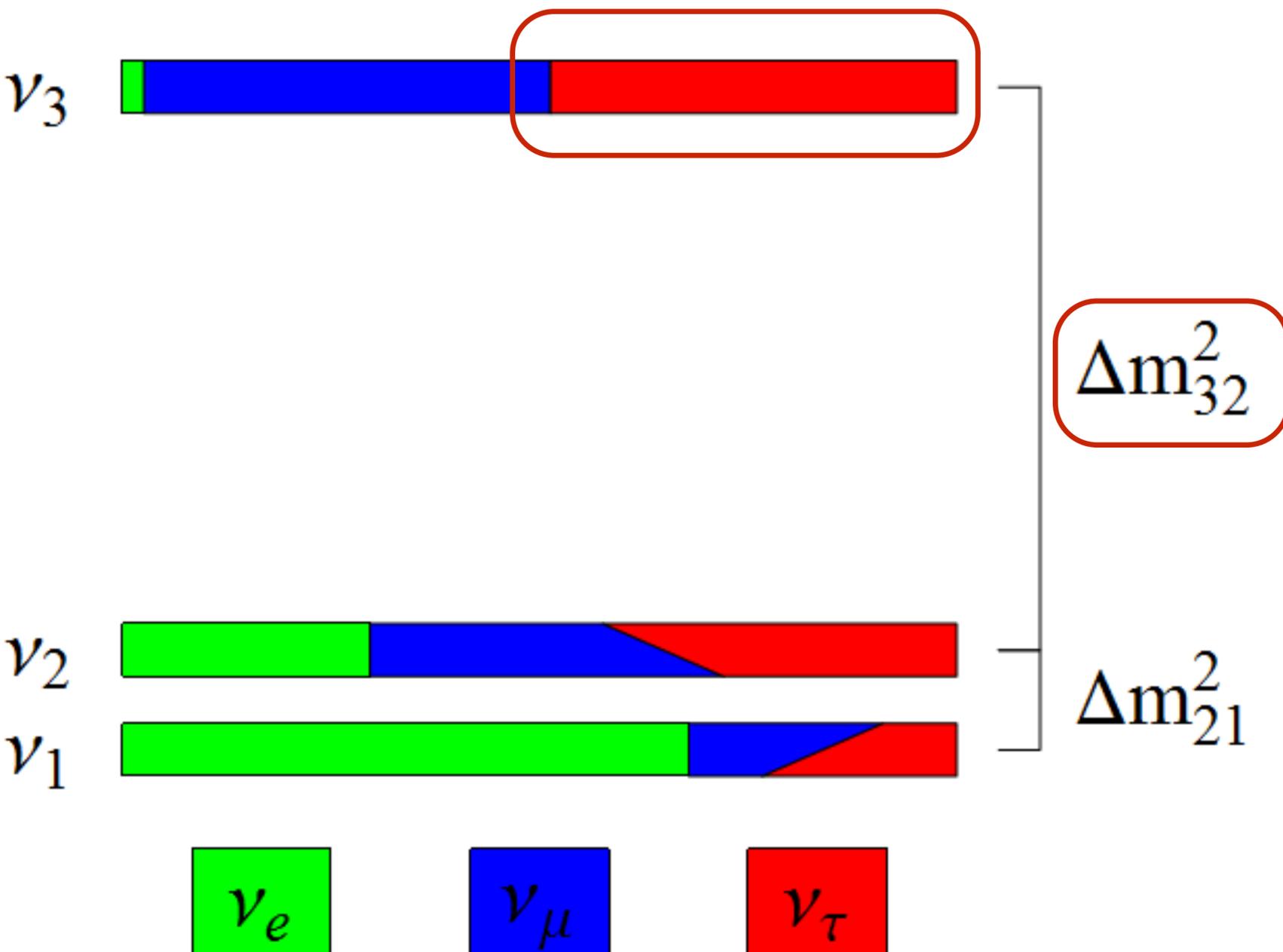


NOvA Physics Goals

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Precise measurements:
 Δm_{32}^2 and $\sin^2(2\theta_{23})$ for
neutrinos and antineutrinos

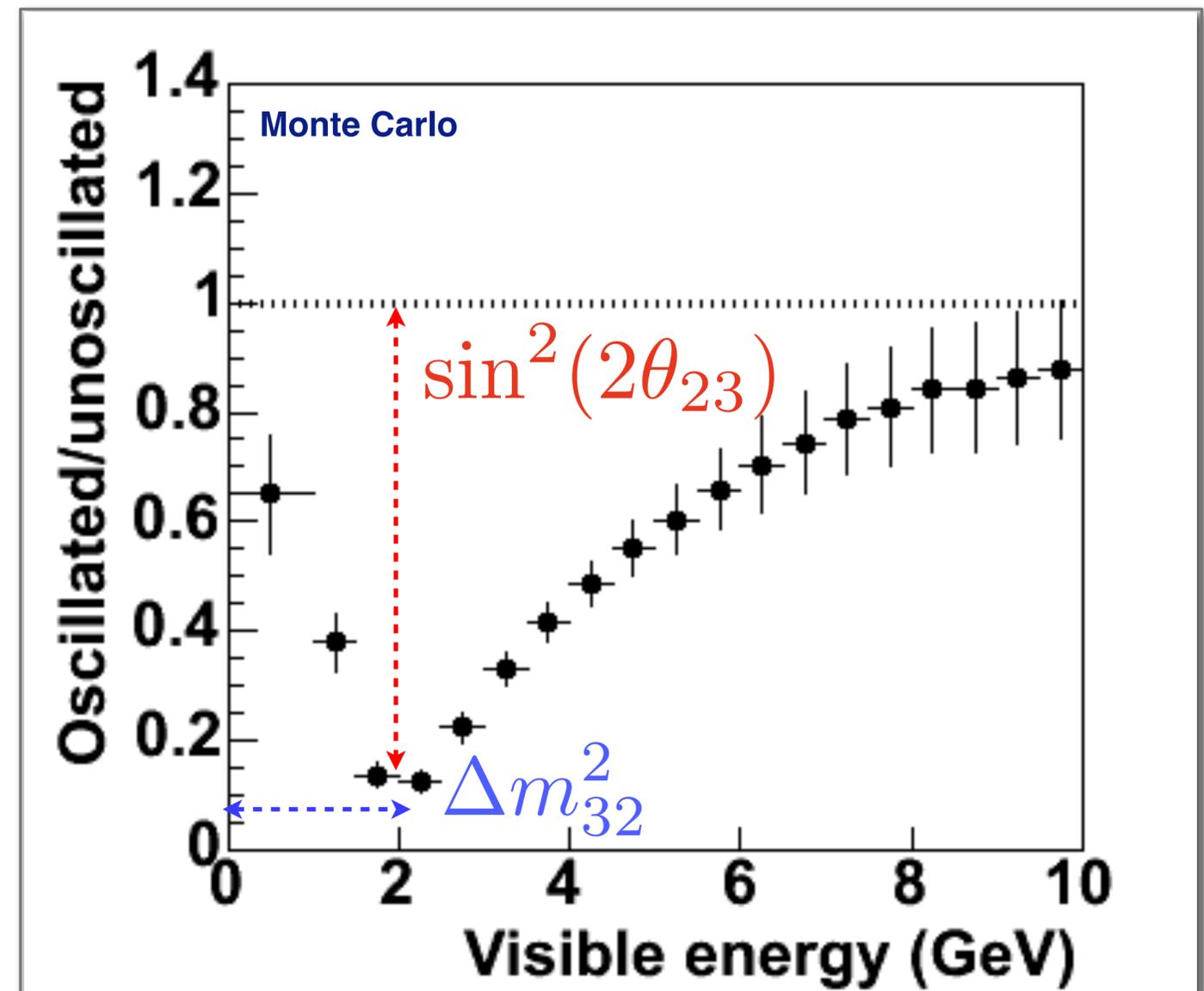
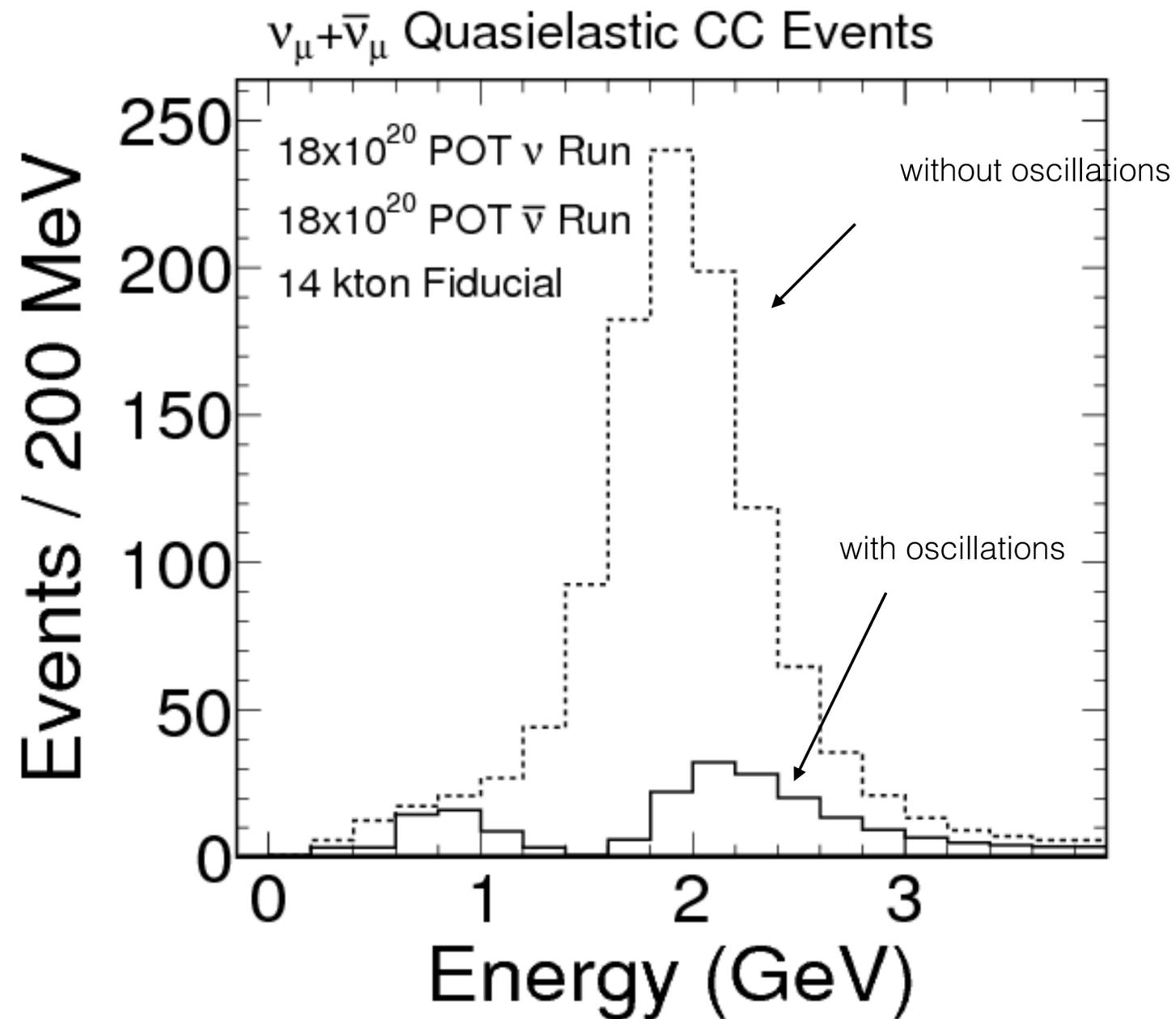
Strong Constraints on:
 θ_{23} octant

δ_{cp}

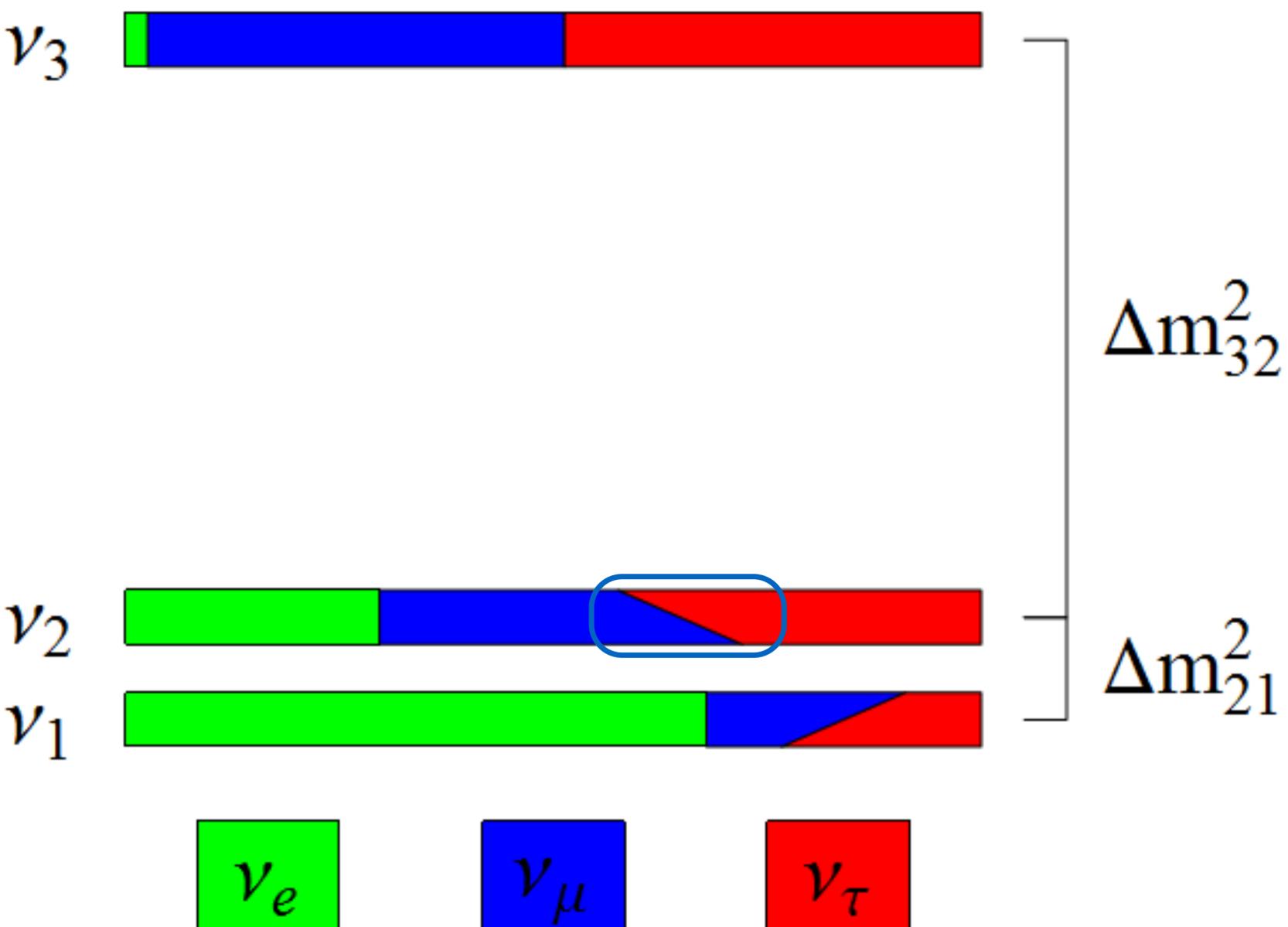
mass hierarchy

ν_μ Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m_{atm}^2 L}{E}\right)$$



NOvA Physics Goals



Precise measurements:
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Strong Constraints on:
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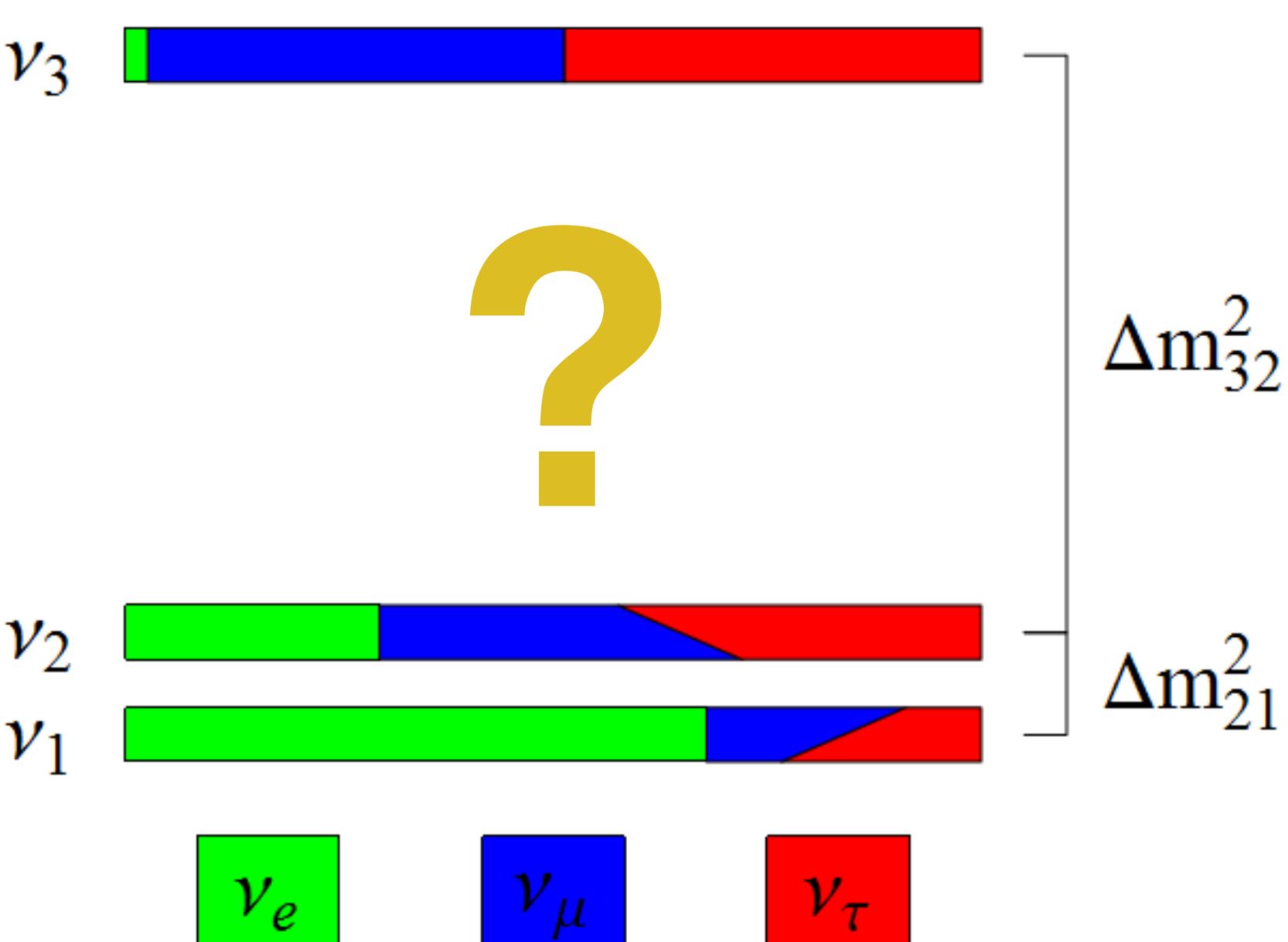
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NOvA Physics Goals

12



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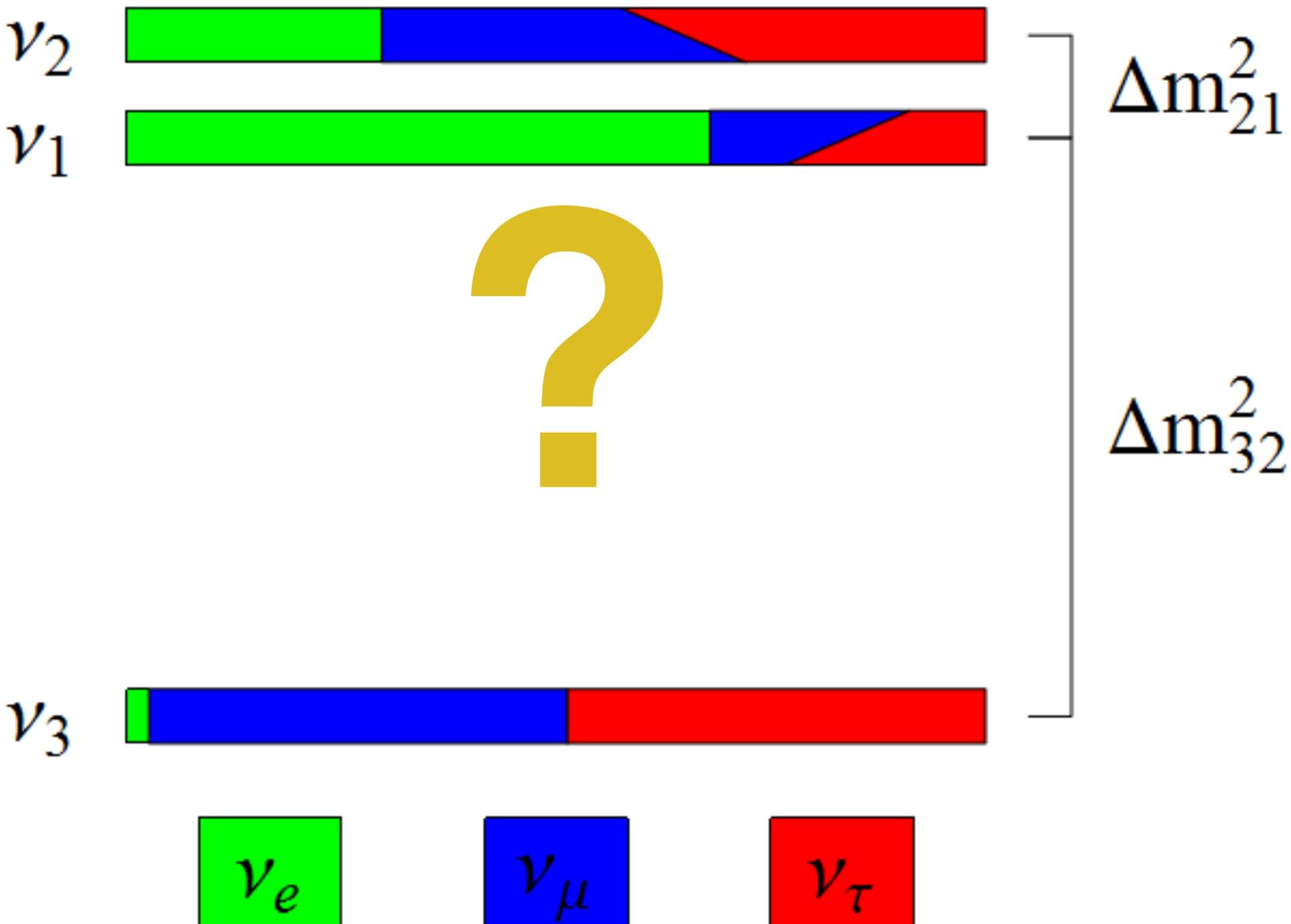
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NOvA Physics Goals

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 Δm_{32}^2 and $\sin^2(2\theta_{23})$ for
neutrinos and antineutrinos

Strong Constraints on:
 θ_{23} octant
 δ_{cp}
mass hierarchy

ν_e Appearance

By measuring beam muon neutrinos which have oscillated to electron neutrinos we gain the power to constrain:

θ_{23} octant

δ_{cp}

mass hierarchy

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i \left(\frac{\Delta m_{32}^2 L}{4E} + \delta_{cp} \right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

Solar term contributes
<1% at ~ 400 L/E

ν_e Appearance

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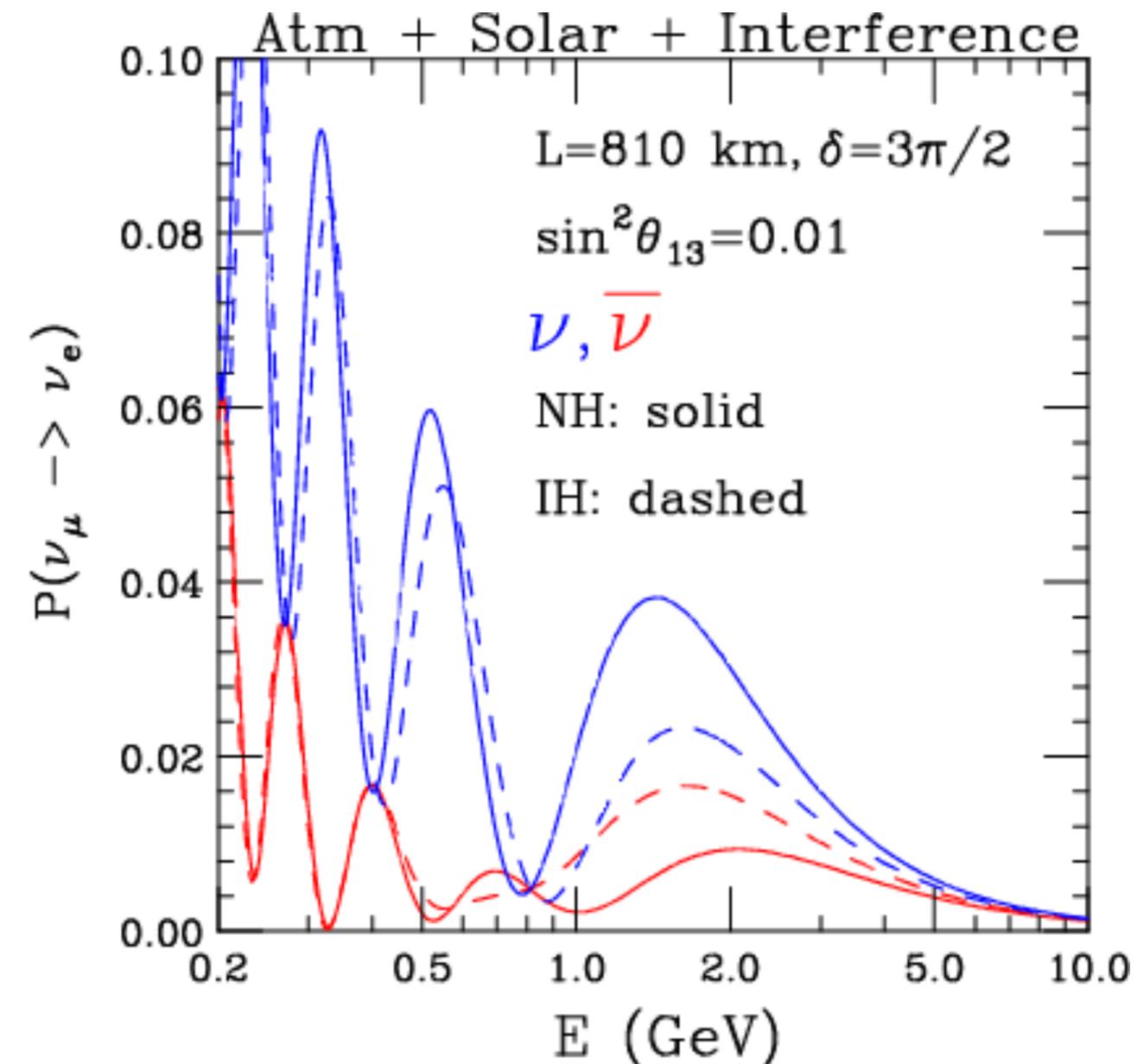
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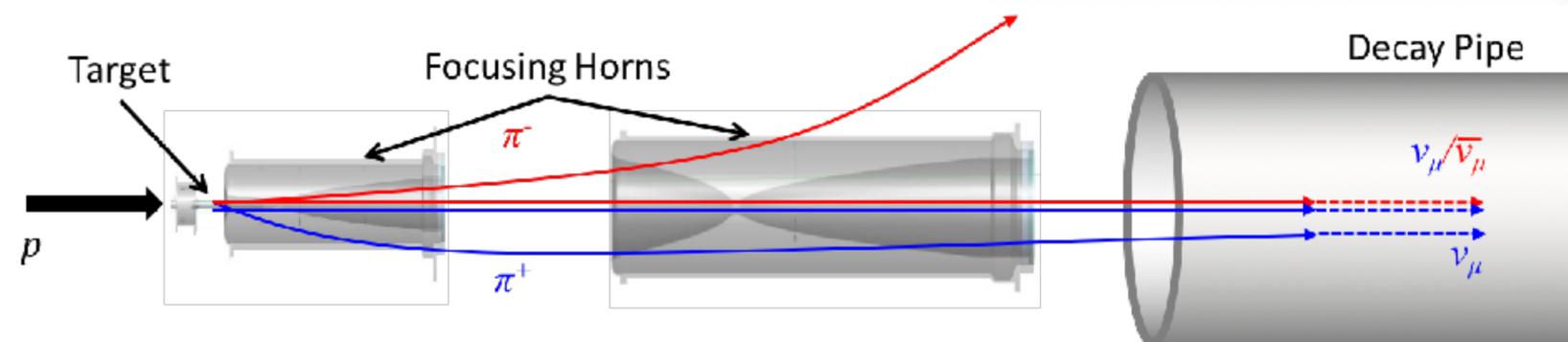
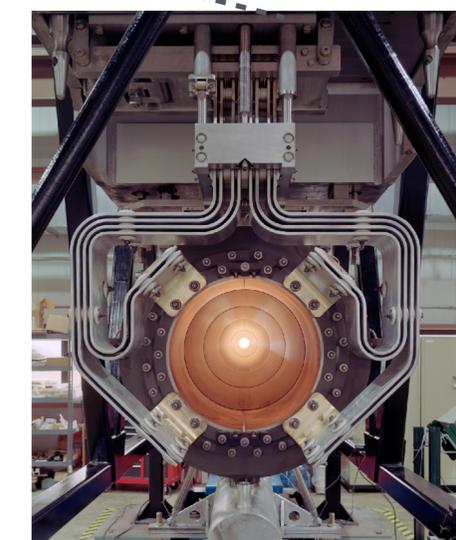
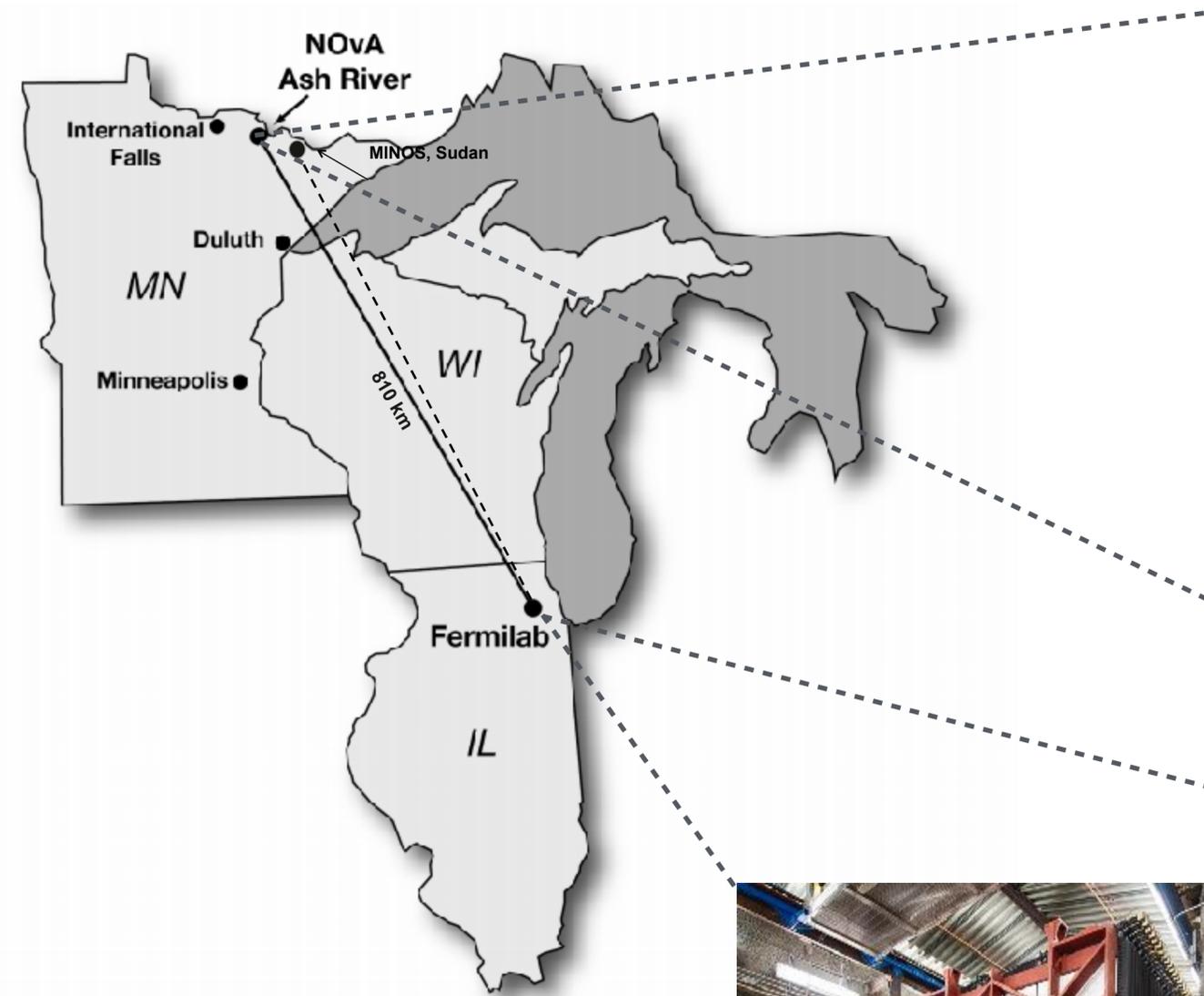
Electron neutrinos experience an extra interaction as they pass through matter, modifying oscillation probabilities, giving us a window into the mass hierarchy.



NuMI Off-axis ν_e Appearance



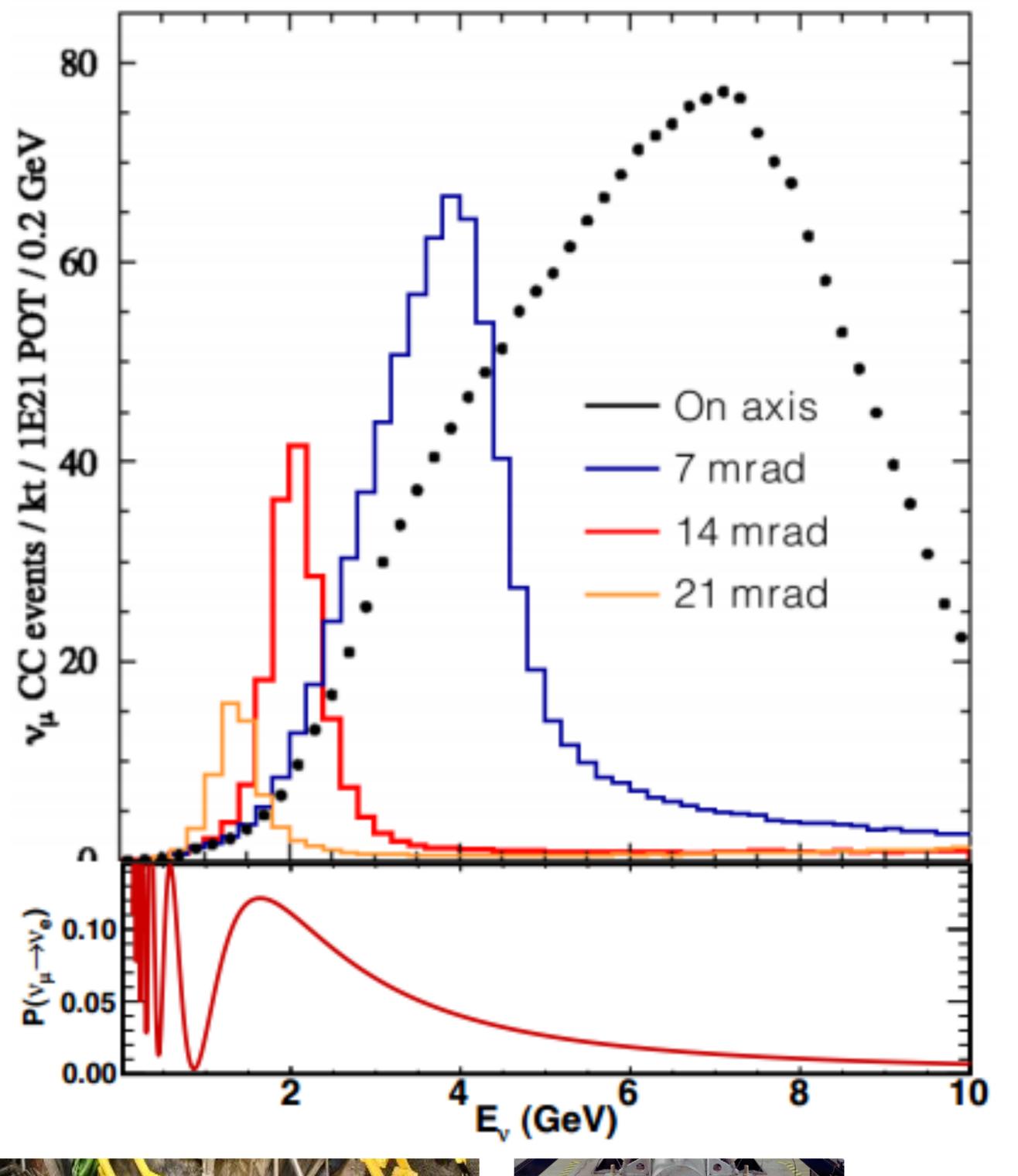
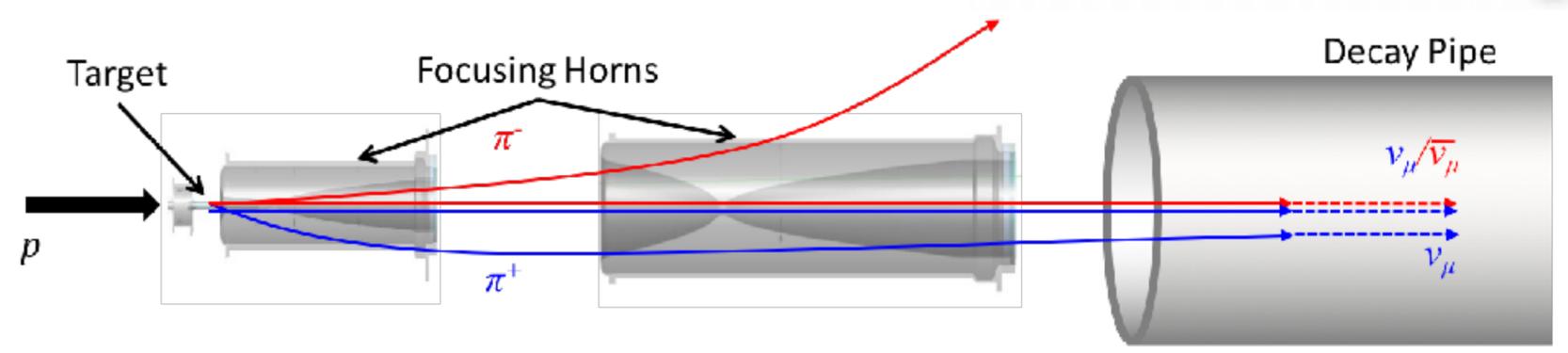
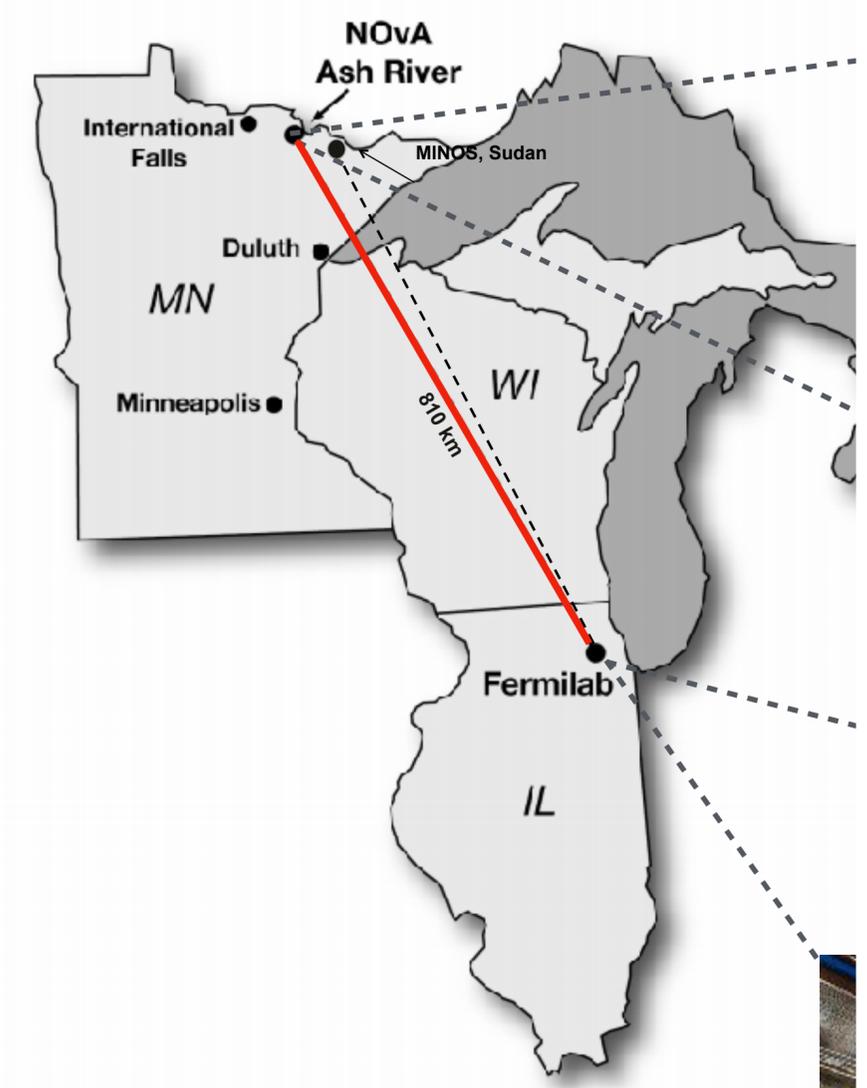
Studying oscillations over a 810km baseline with two functionally identical detectors and the worlds most powerful muon neutrino beam, NuMI.



NuMI Off-axis ν_e Appearance



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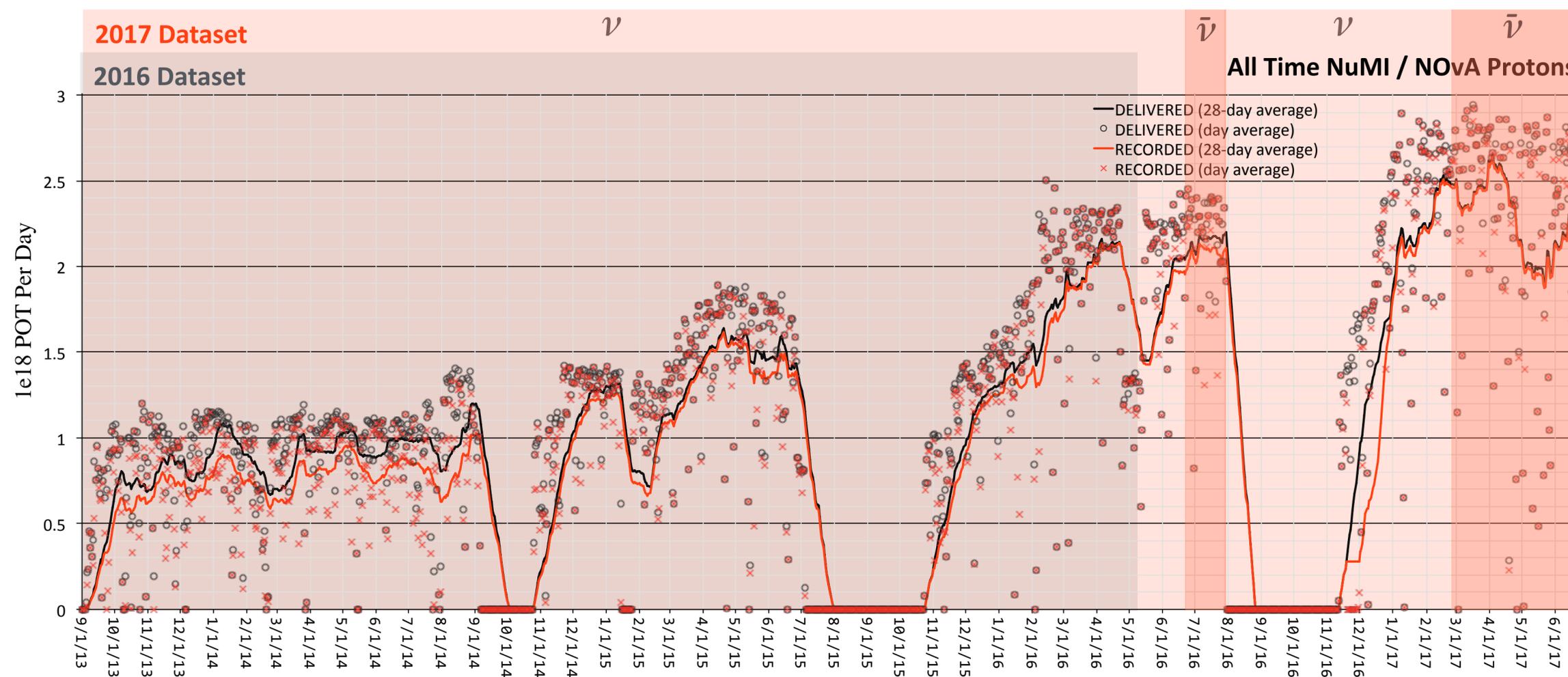
Beam Exposure

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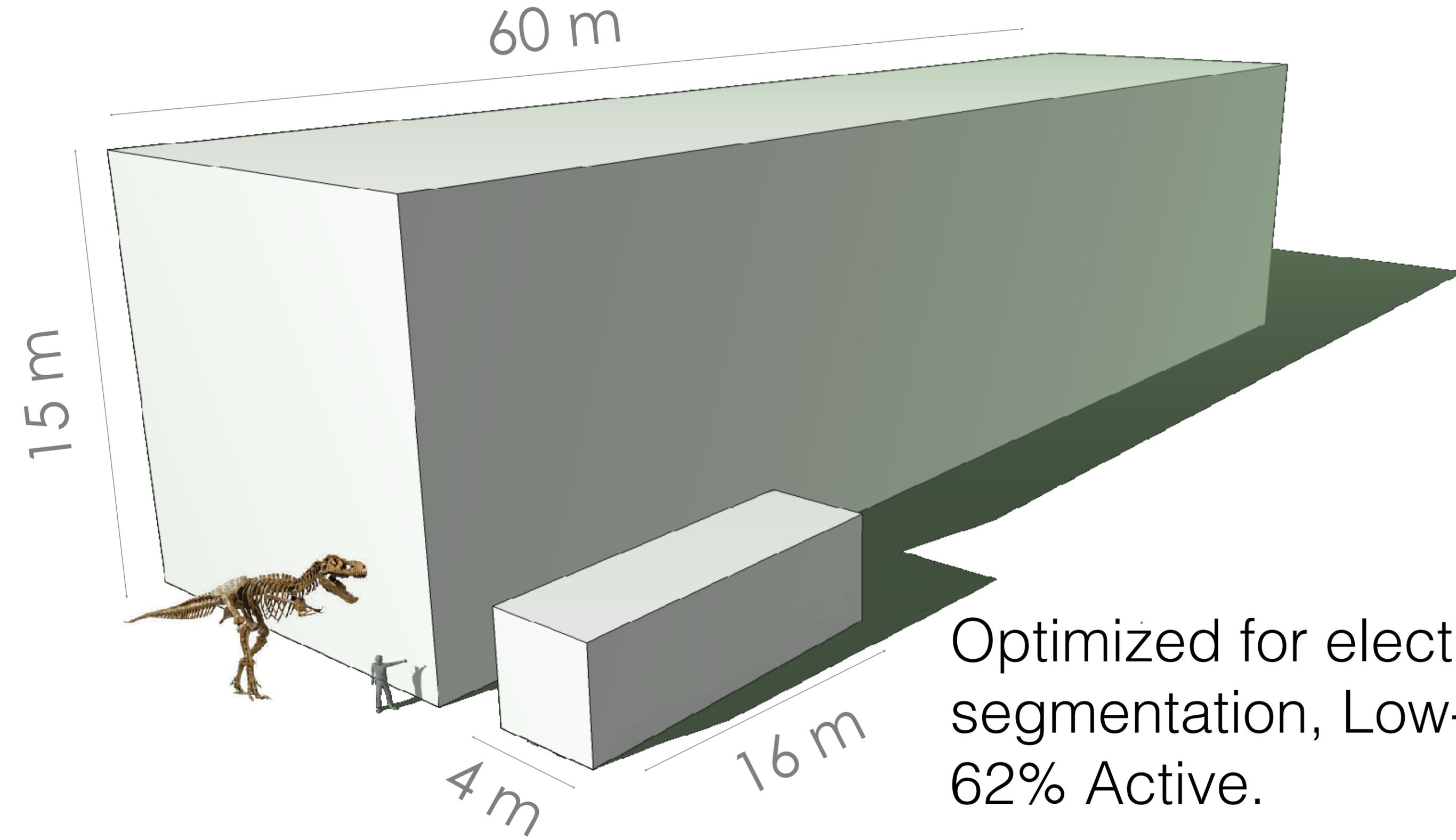


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- 8.85×10^{20} POT in 14 kton equivalent detector
 - 50% more exposure than the 2016 analysis
- Currently running in anti-neutrino mode
- Running at 700 kW design goal since June 2016!

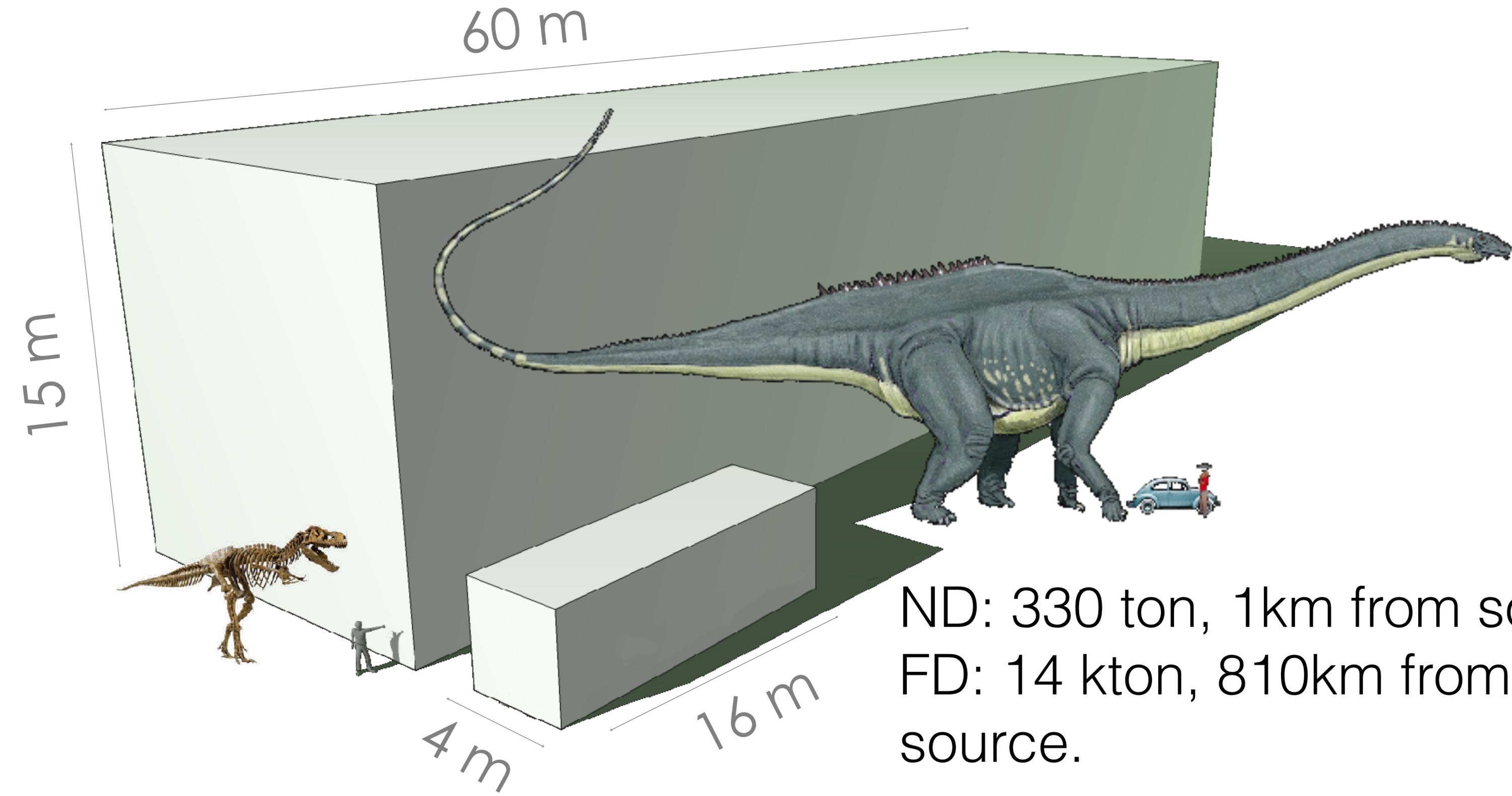


The NOvA Detectors



Optimized for electron ID, fine segmentation, Low-Z, and 62% Active.

The NOvA Detectors

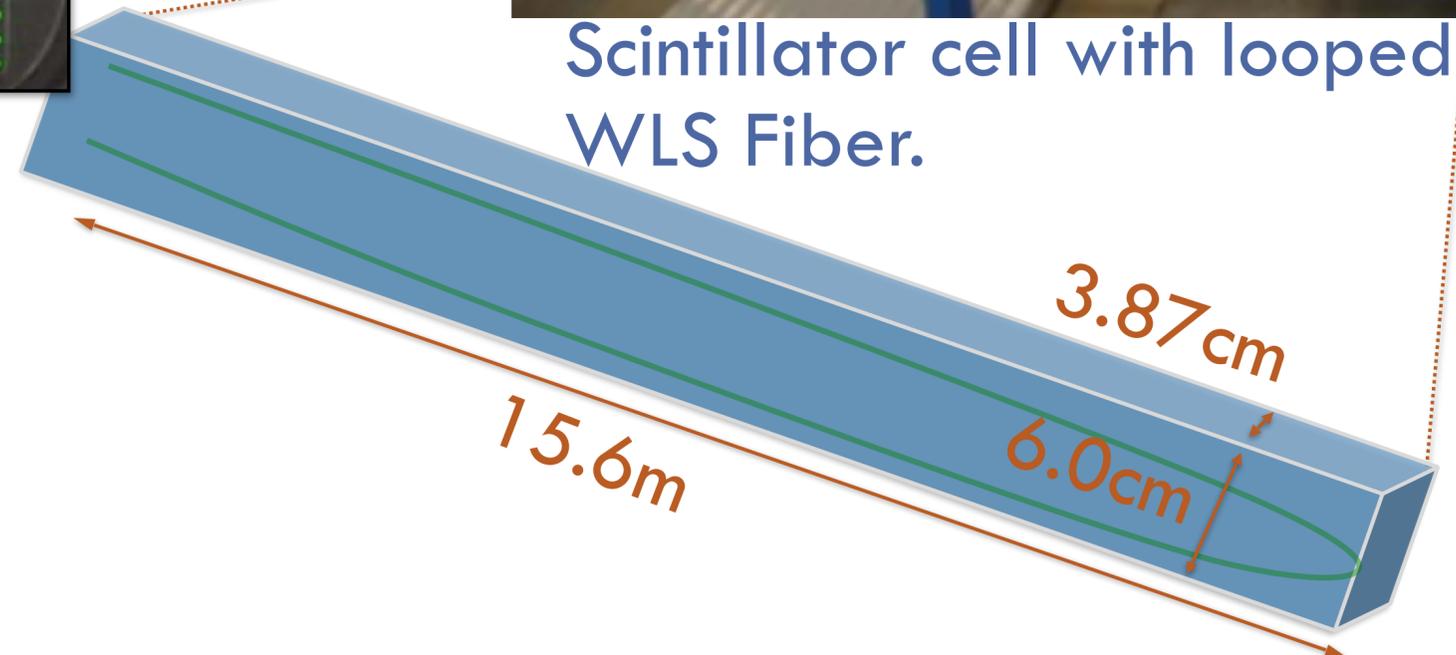
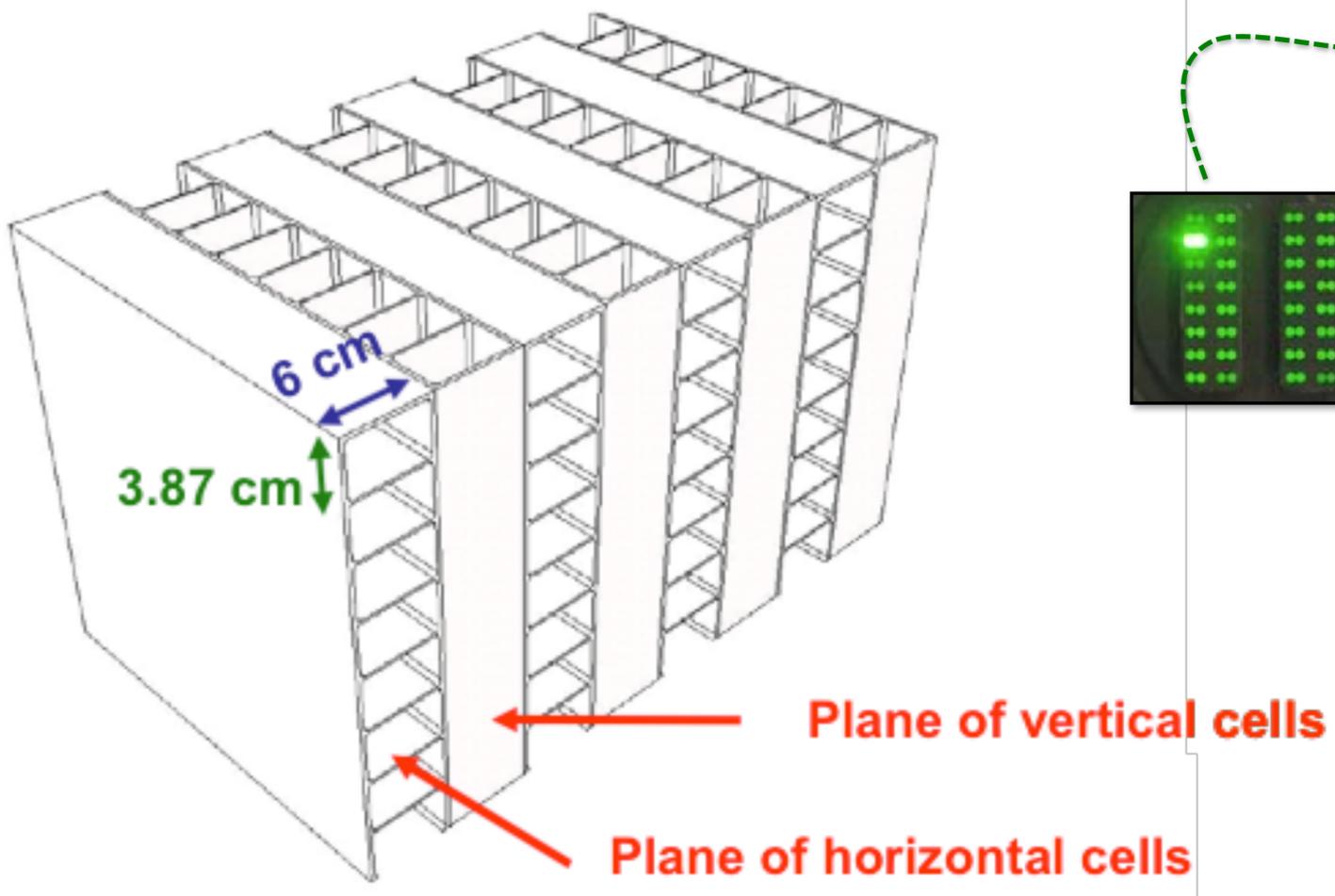
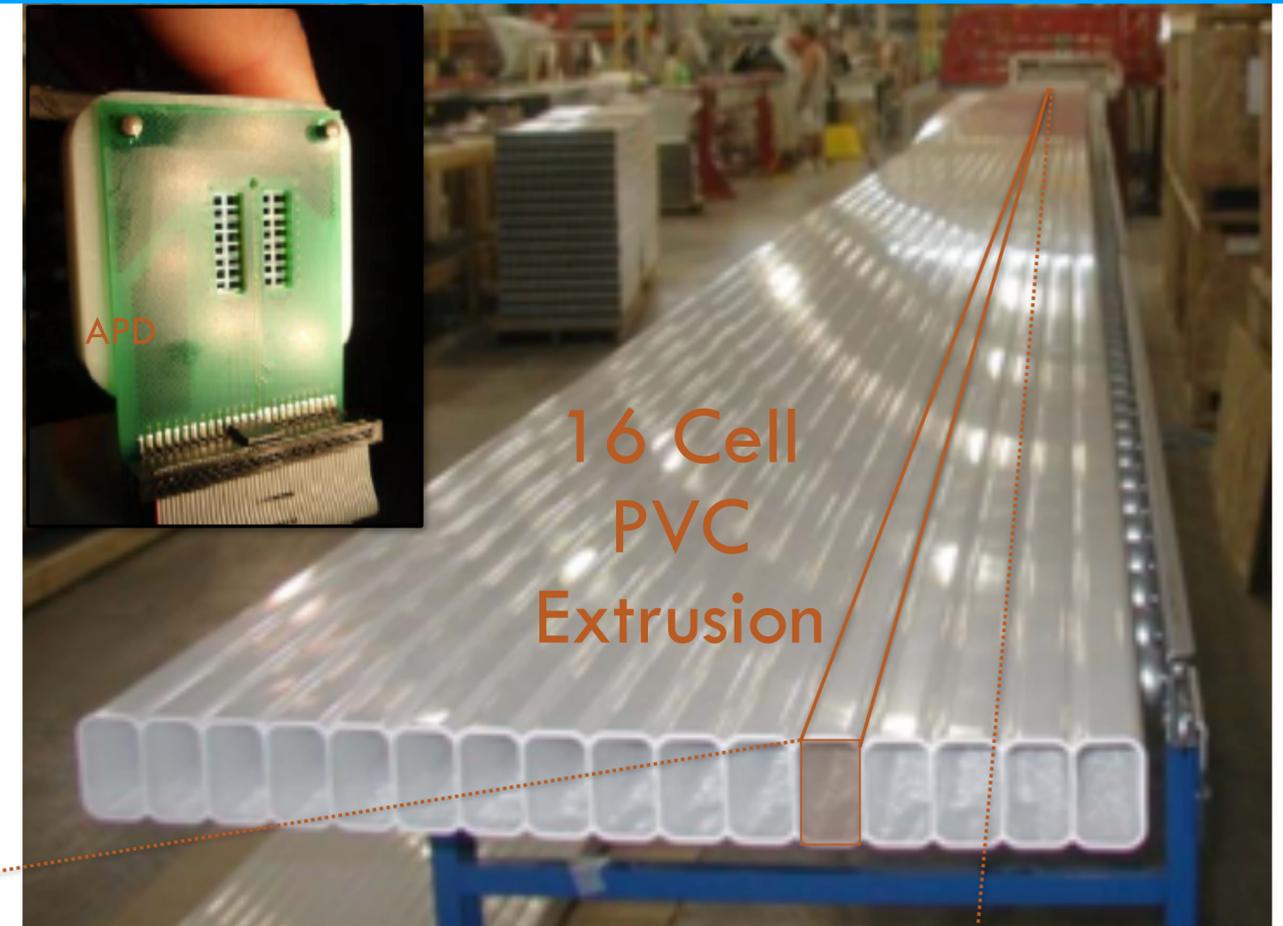


ND: 330 ton, 1km from source.
FD: 14 kton, 810km from source.

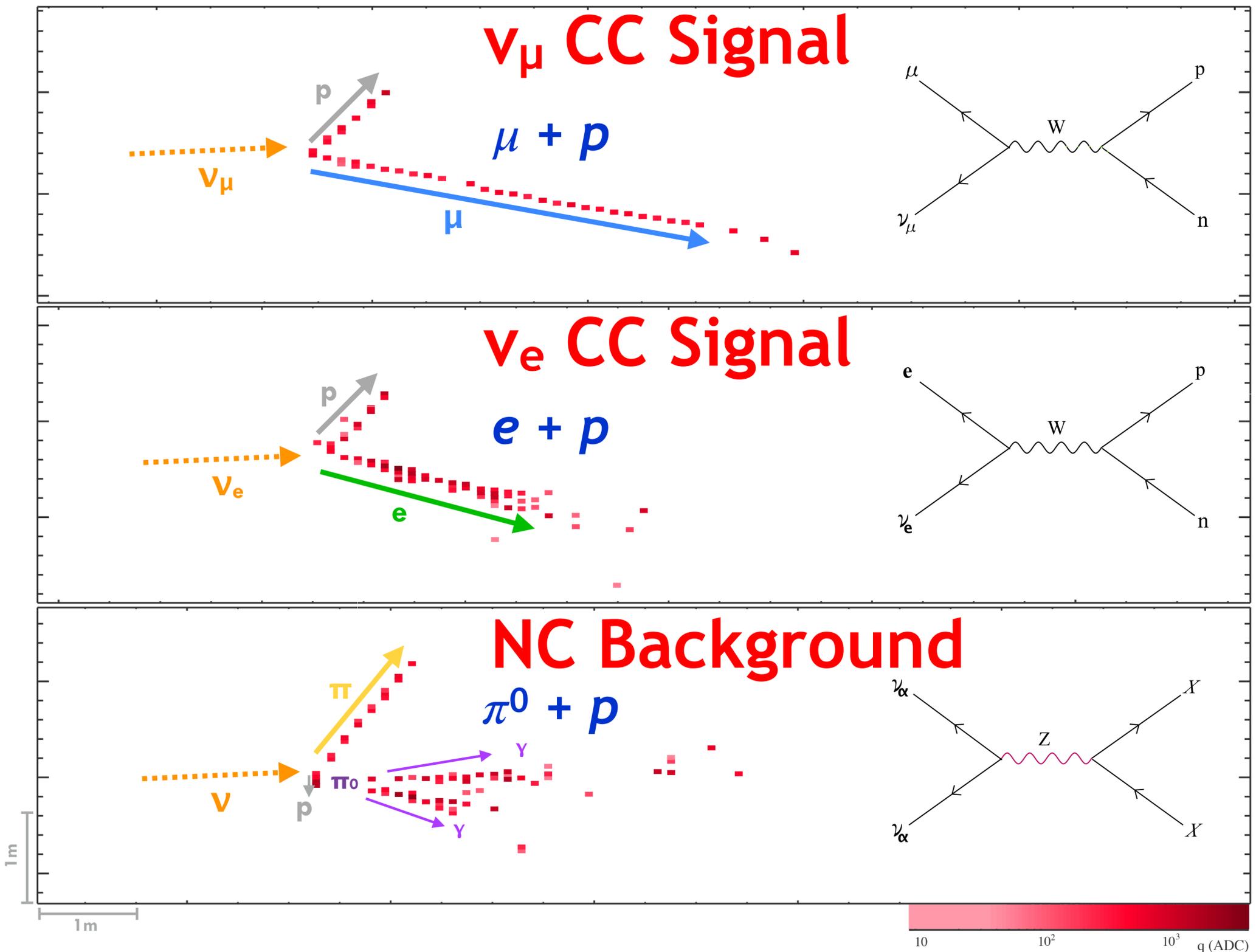
Detector Technology



- PVC extrusion + Liquid Scintillator
 - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
 - FD has ~344,000 channels
 - muon crossing far end ~40 PE
- Layered planes of orthogonal views



NOvA Event Topologies



1 radiation length = 38cm (6 cell depths, 10 cell widths)

What's New?

- **More data**, 50% more than our last oscillation update.
- **Improved analysis**, continued use of deep learning tools for our appearance and now also for our disappearance measurements. Binning in energy resolution that better exploits the information in the existing data.
- **Retuned cross section modeling**, continued development of how we treat cross sections including crucial multi-nucleon effects.
- **Detector simulation improvements**, dramatically reducing some of our largest uncertainties in previous measurements.
- **Data driven flux estimates**, developed by MINERvA.

Deep Learning Inspired PID: ν_e & ν_μ Selection

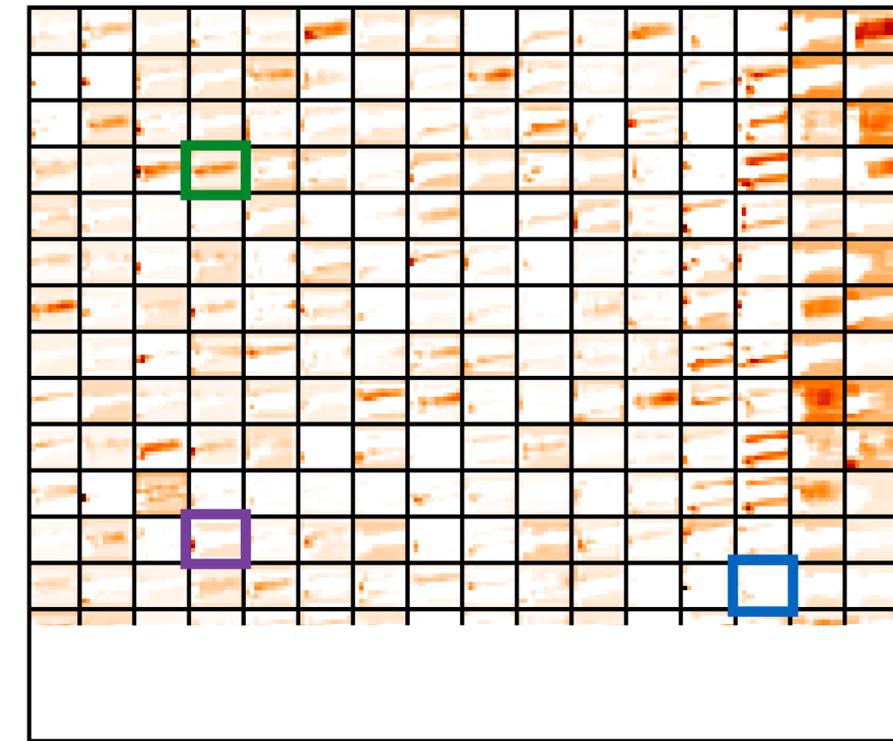
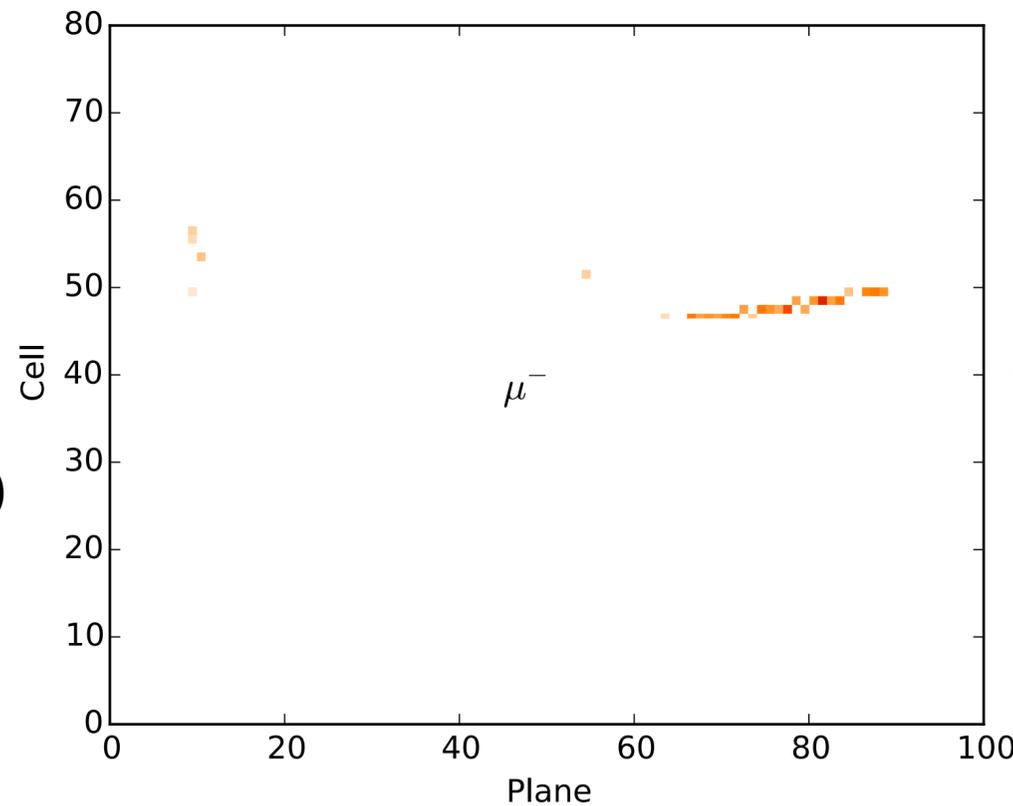
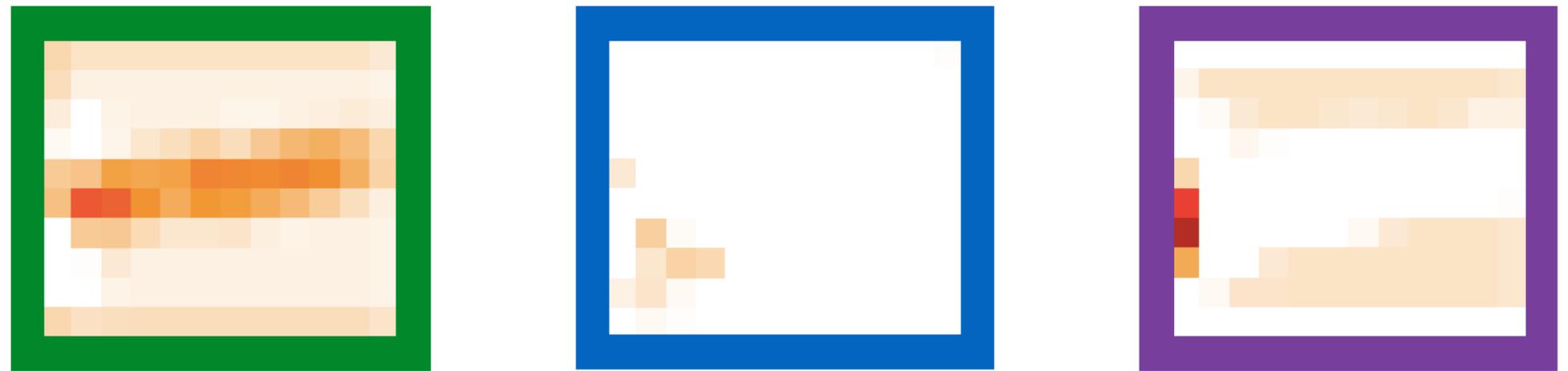
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Previously only used for our ν_e analysis, now our ν_μ analysis also features the same event selection technique based on ideas from computer vision and deep learning.

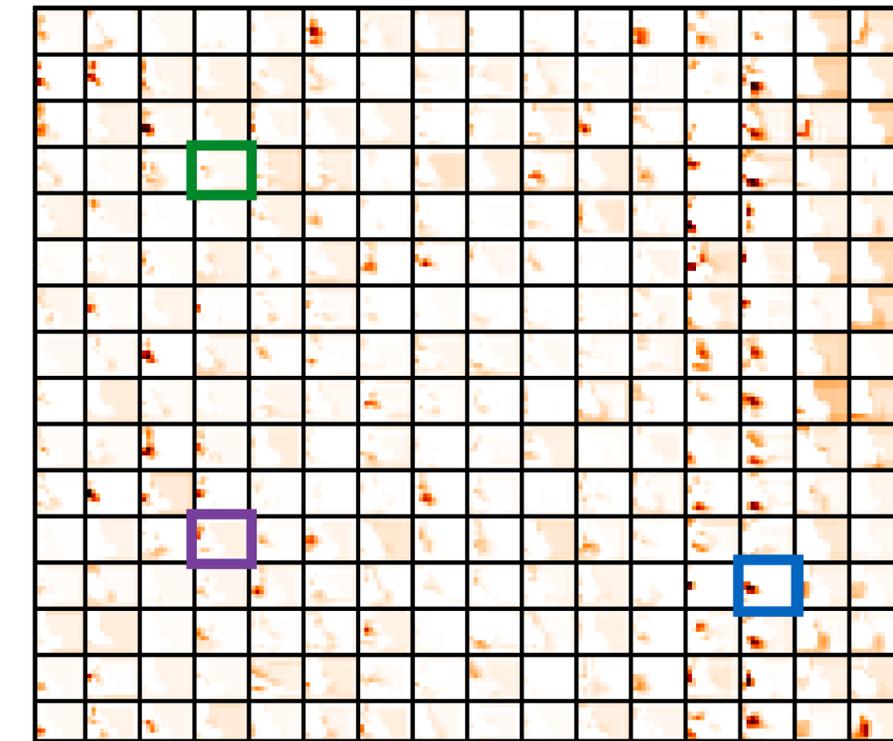
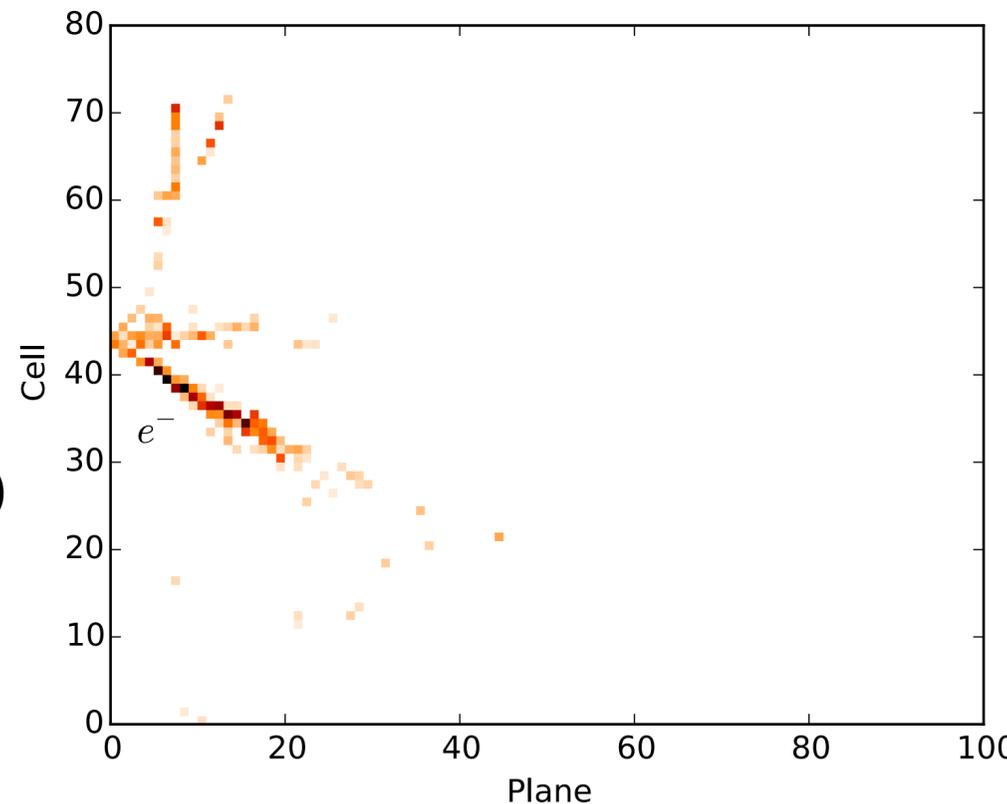
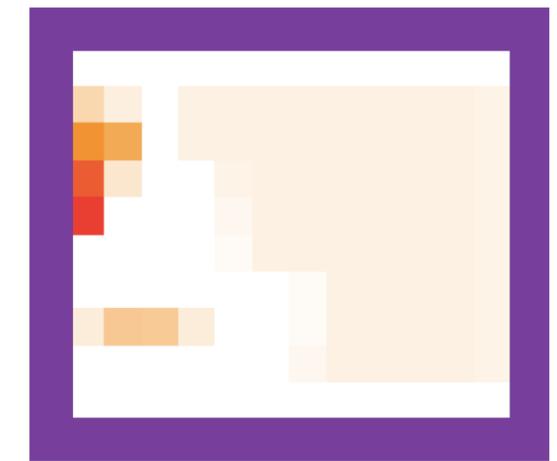
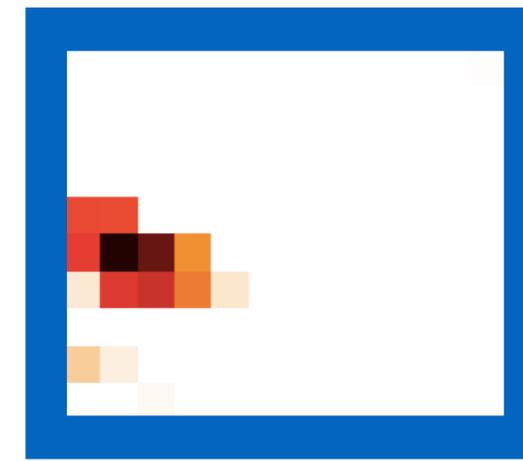
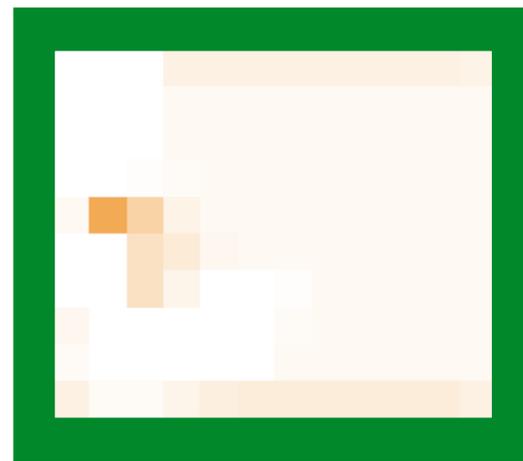
Additionally now used to reclaim a new class of previously rejected ν_e events.



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Simulation

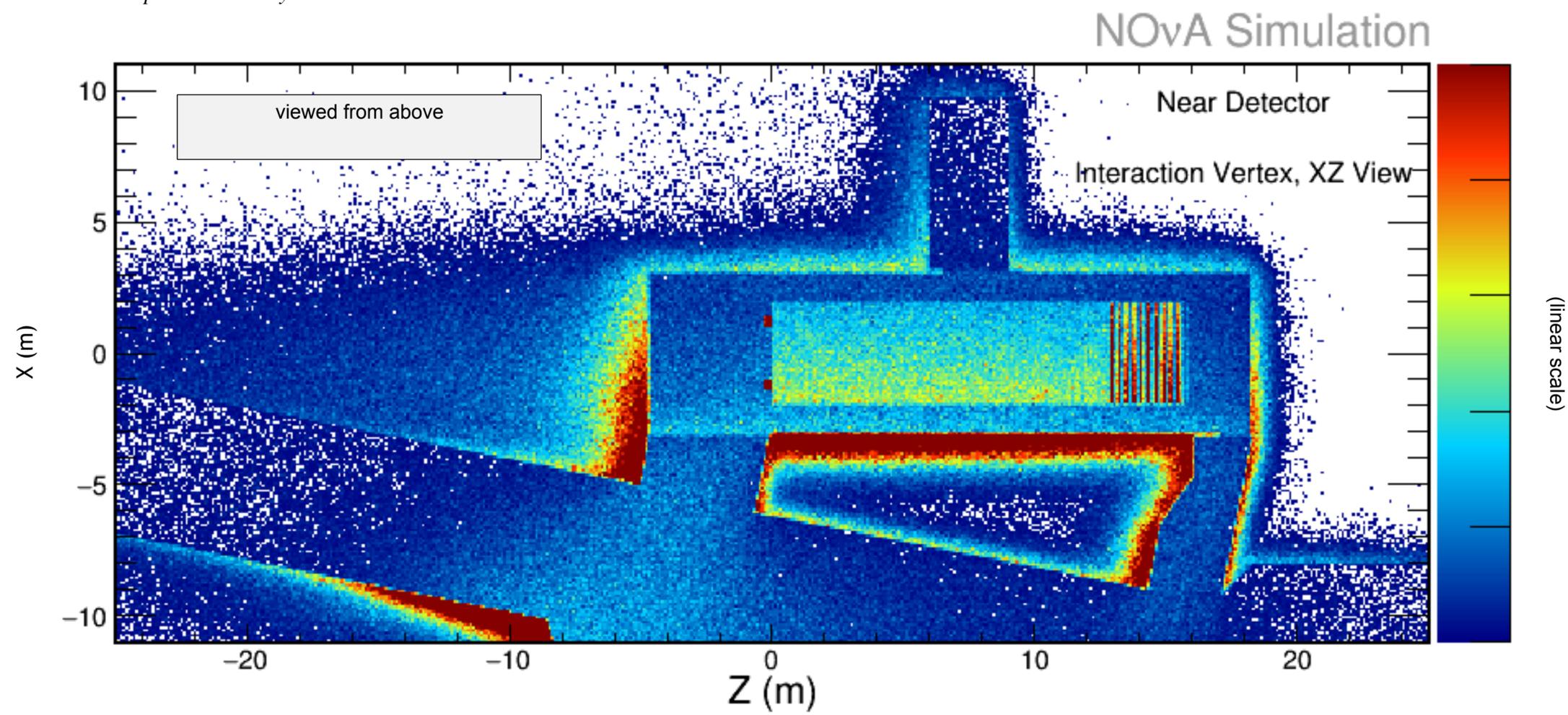
26



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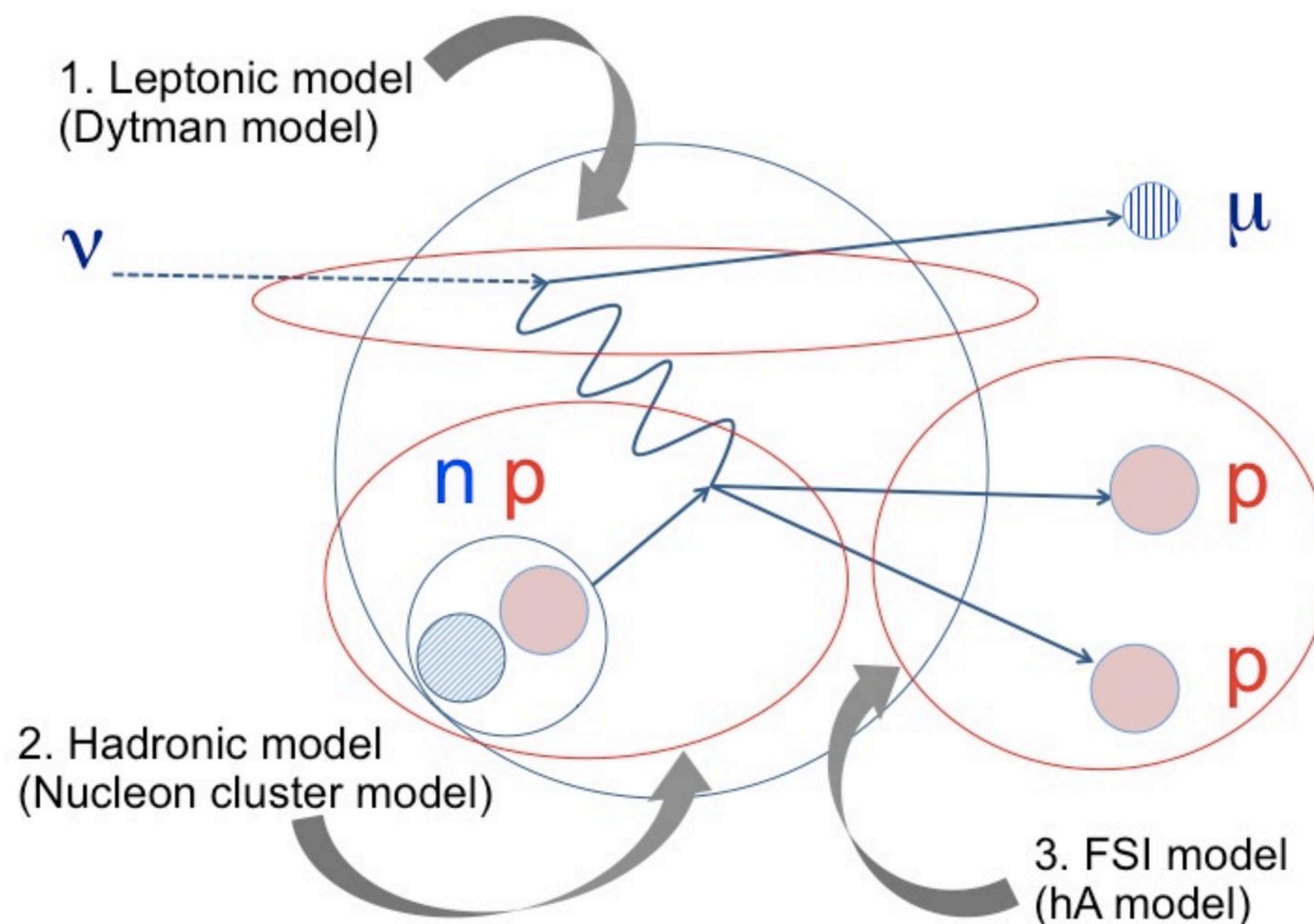
- Beam hadron production, propagation, neutrino flux: **GEANT4/External Data**
- Cosmic ray flux: **Data Triggers**
- Neutrino Interactions and FSI modeling: **GENIE v2.12.2**
- Detector Simulation: **GEANT4**
- Readout electronics and DAQ: **Custom simulation routines**

Simulation: Locations of neutrino interactions that produce activity in the Near Detector



Retuned Interaction Modeling

- Nuclear effects on the initial state (nuclear charge screening/"RPA" effect) and reactions themselves (multi-nucleon ejection e.g. 2p2h via Meson Exchange Currents (MEC)) remain important components of our interaction model, particularly of the hadronic energy component of our interactions.
- Theory for these effects and how they fit together remains incomplete and model evidence ambiguous.
- Important that we not just have the best possible central value tune, but also appropriately conservative uncertainties.

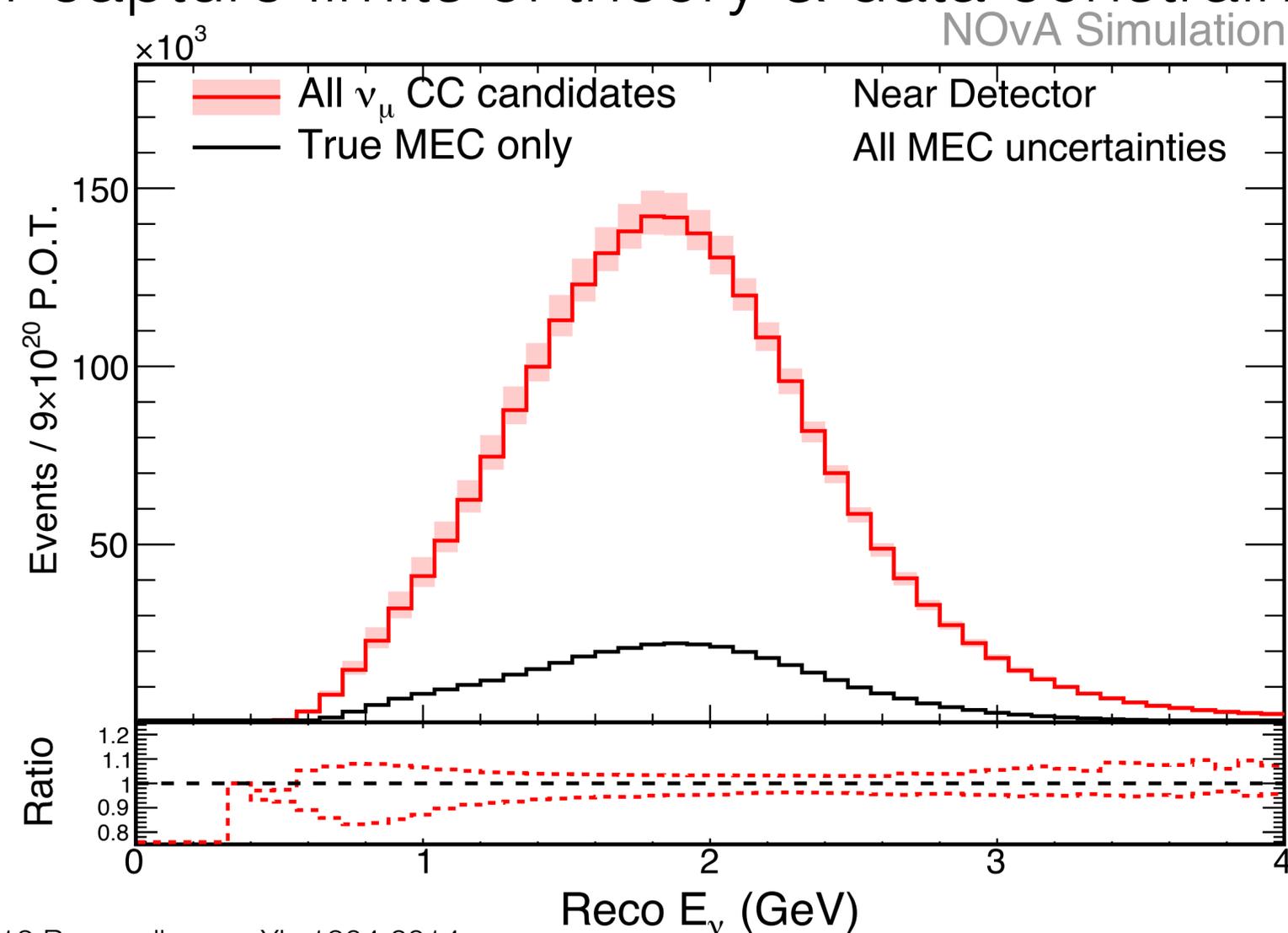
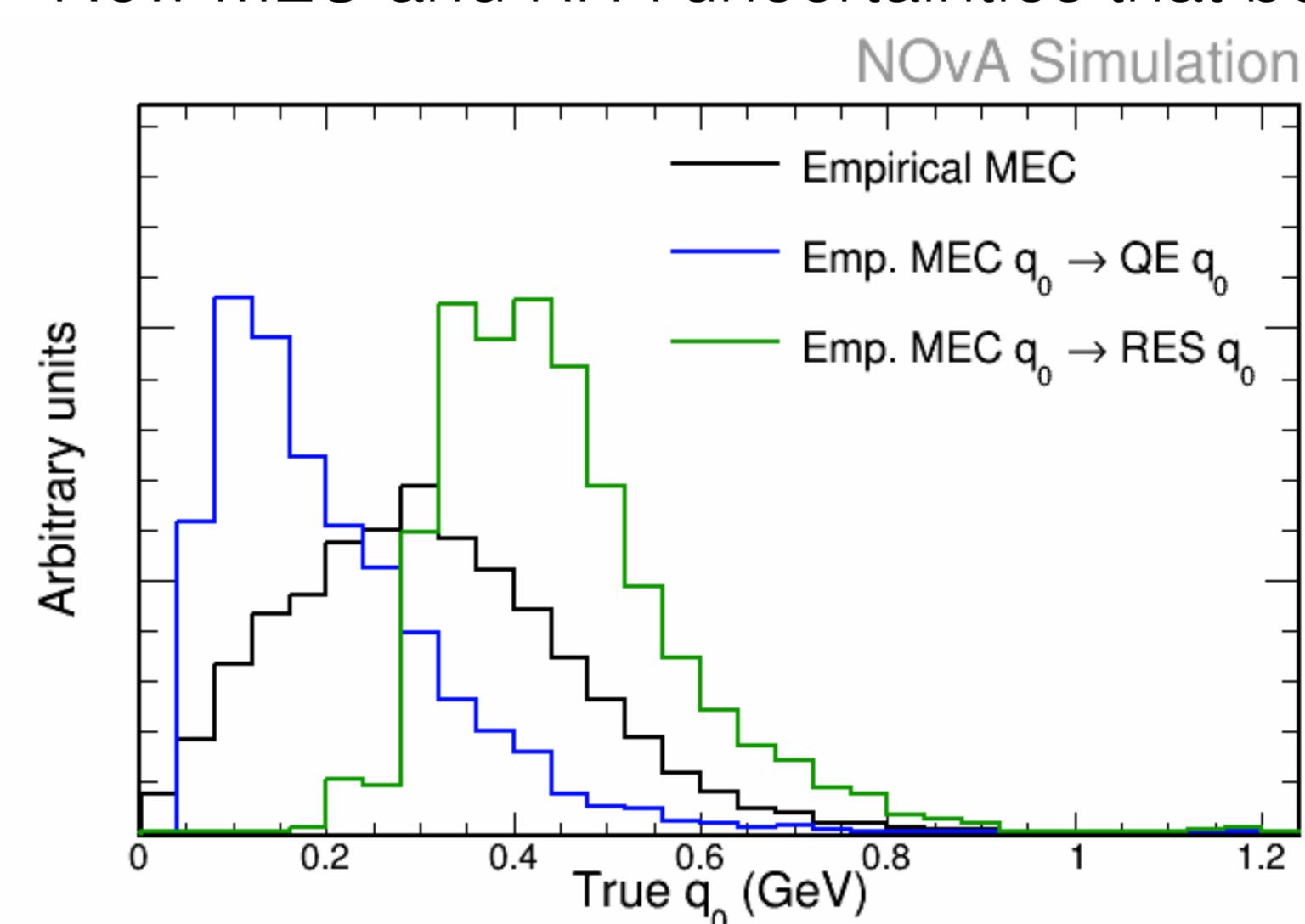


"Meson Exchange Current (MEC) Models in Neutrino Interaction Generators"
AIP Conf.Proc. 1663 (2015) 030001
Teppei Katori

Retuned Interaction Modeling



- Continue to tune MEC to match the excess in our data, now fit using default empirical MEC's* model for energy transfer to the hadronic system (q_0).
- QE RPA from the Valencia group via Richard Gran** now included in central value tune.
- New MEC and RPA uncertainties that better capture limits of theory & data constraints.



* "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators", Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014

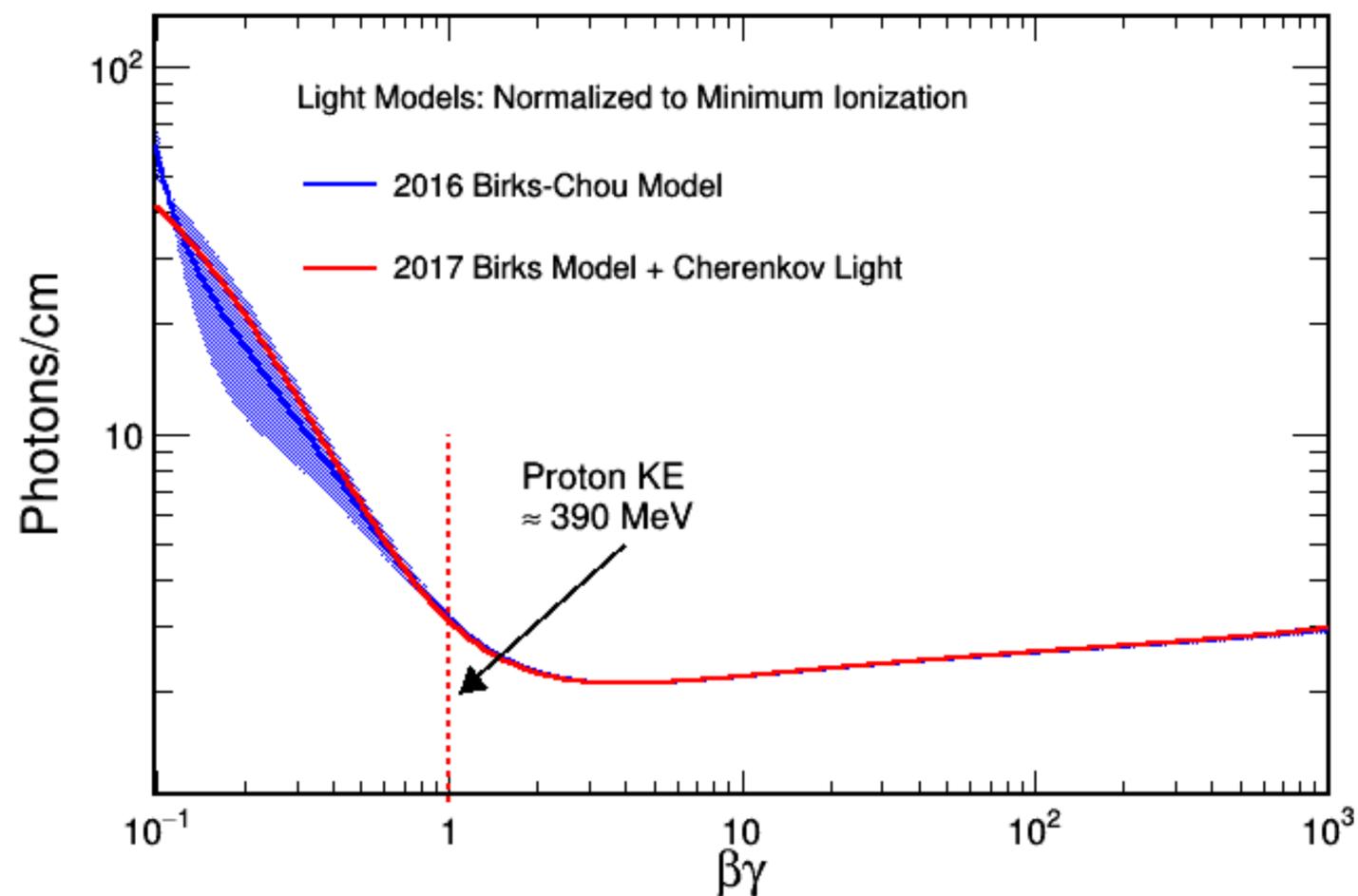
** "Model uncertainties for Valencia RPA effect for MINERvA", Richard Gran, FERMILAB-FN-1030-ND, arXiv:1705.02932

Improved Detector Simulation

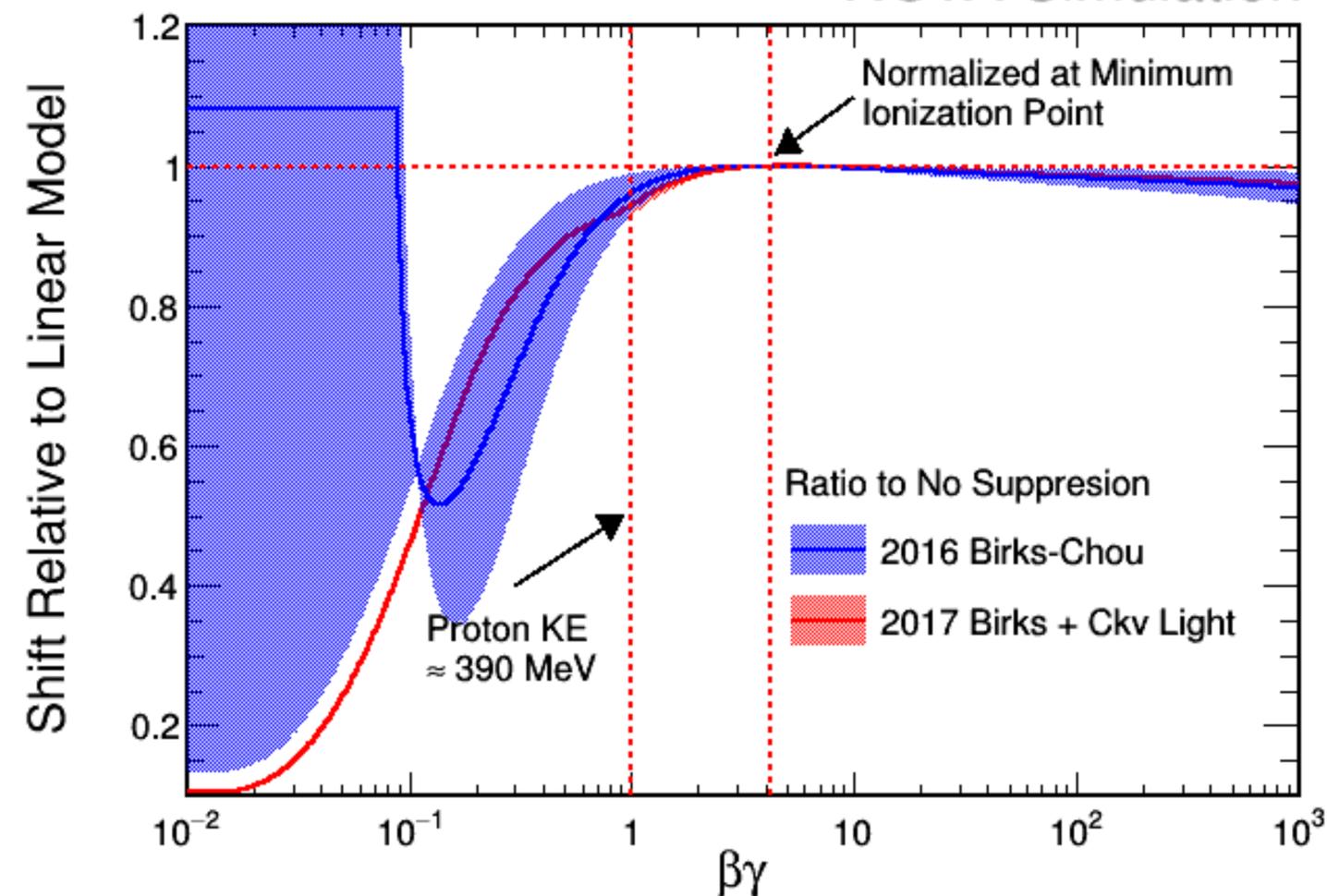


- Previously detector response uncertainties were some of our largest. Reduced by an order of magnitude in new detector simulation, driven by addition of cherenkov light.
- Absorbed and re-emitted Cherenkov light is a small but important in modeling the detector response to hadronic activity.
- Expected energy resolution for ν_μ CC events moves from 7% to 9%.

NOvA Simulation



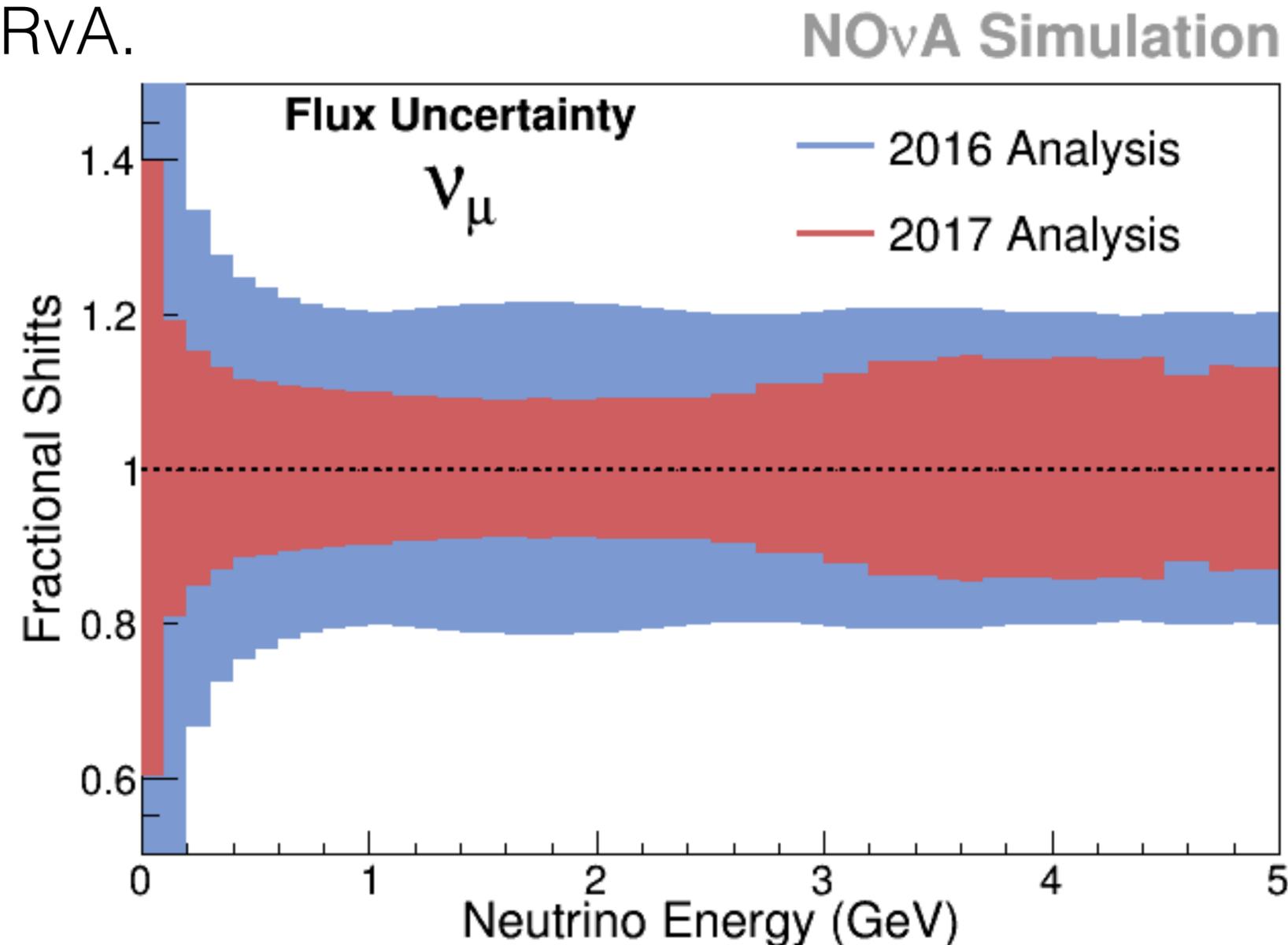
NOvA Simulation



New Flux



- A new data driven flux, Package to Predict the FluX (**PPFX**), based on thin target hadron production data from NA49 and MIPP.
- Comes with greatly reduced flux uncertainties.
- Pioneered at MINERvA.

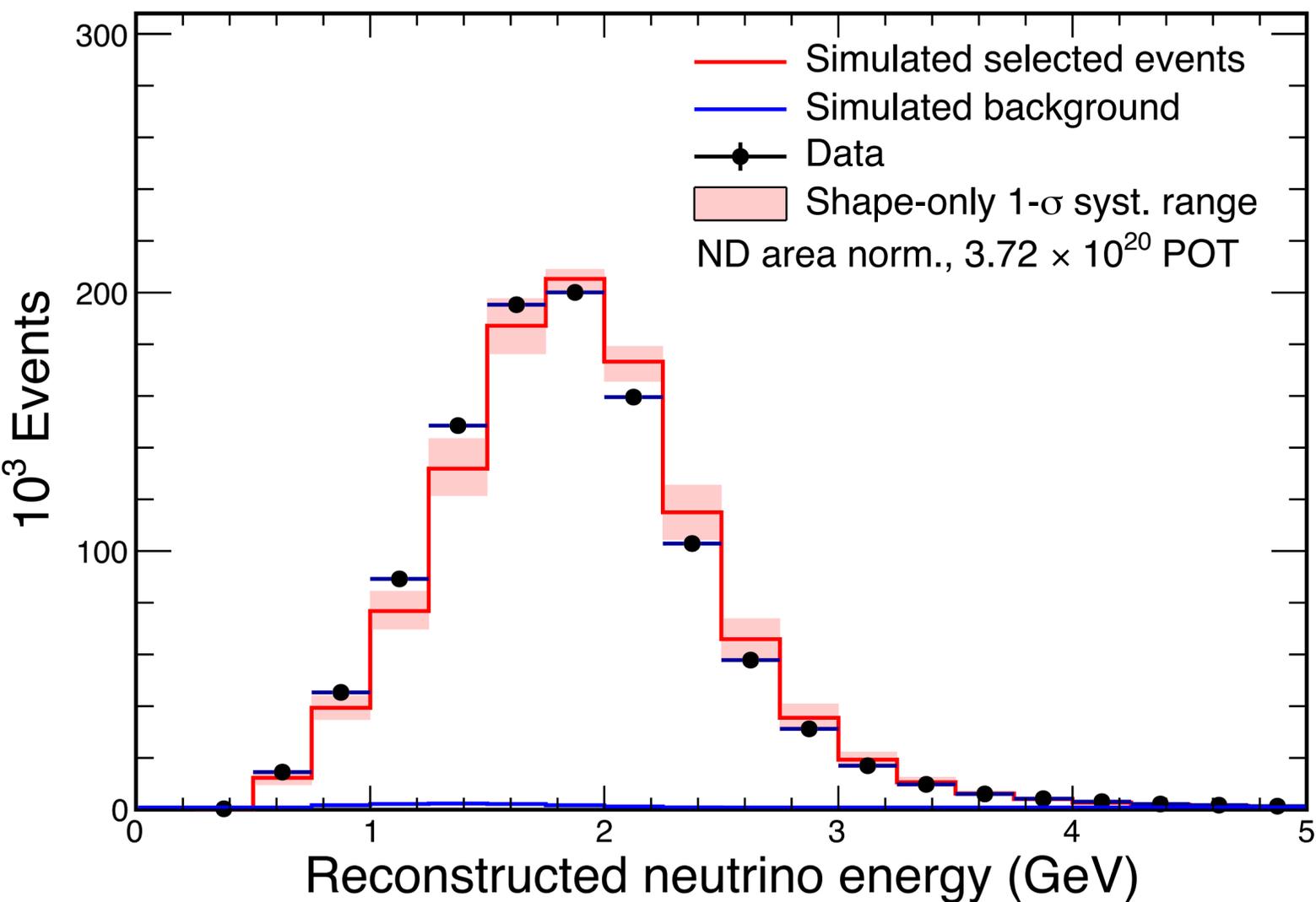


“Neutrino Flux Predictions for the NuMI Beam”
MINERvA Collaboration (L. Aliaga et al.)
Phys.Rev. D94 (2016) no.9, 092005

Simulation



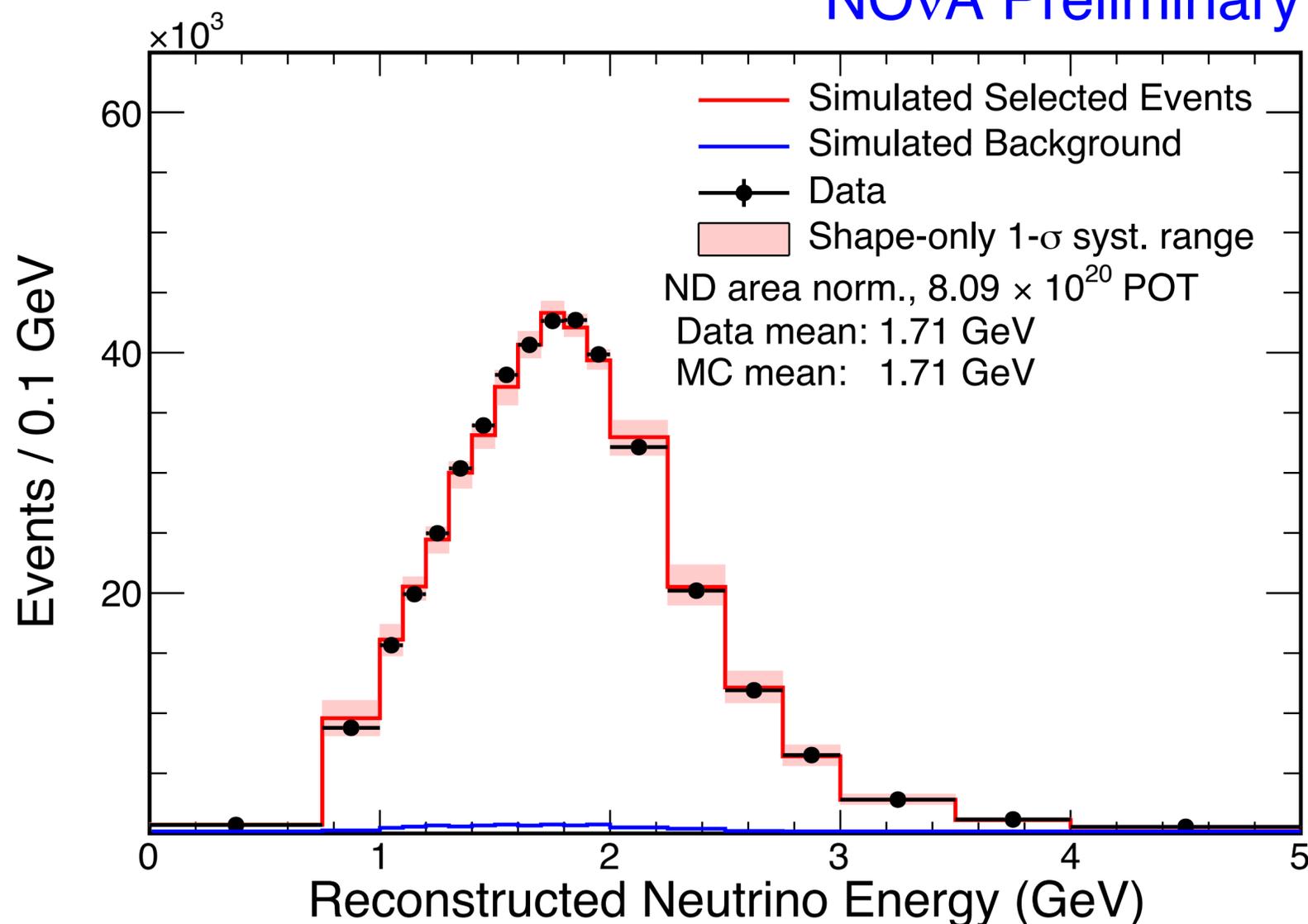
NOvA Preliminary



Old



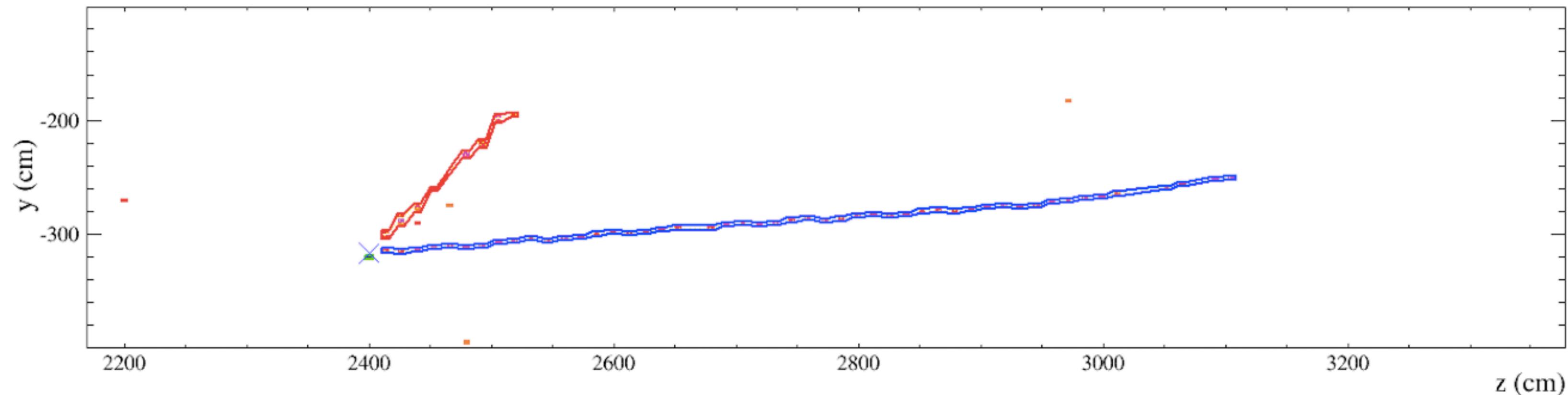
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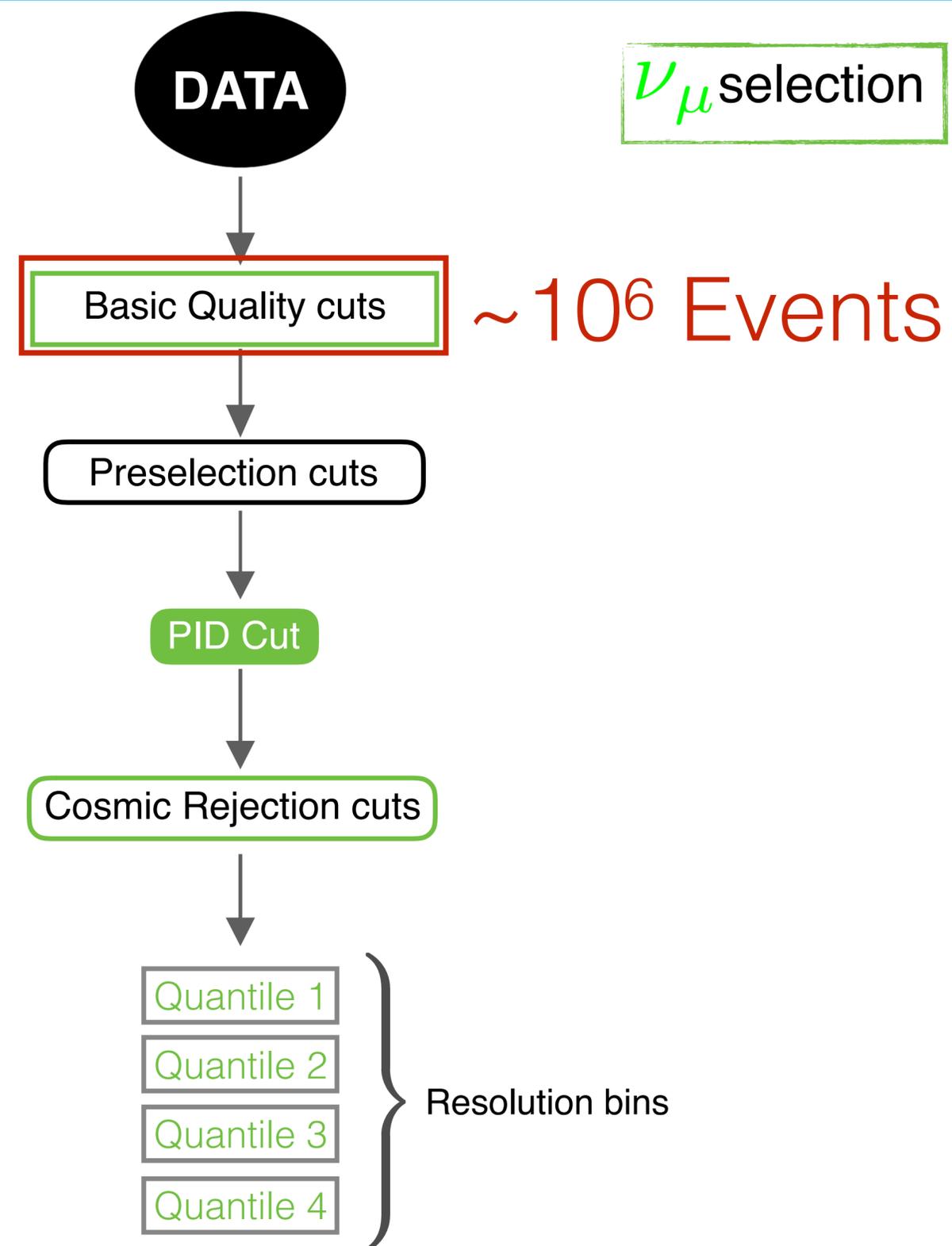
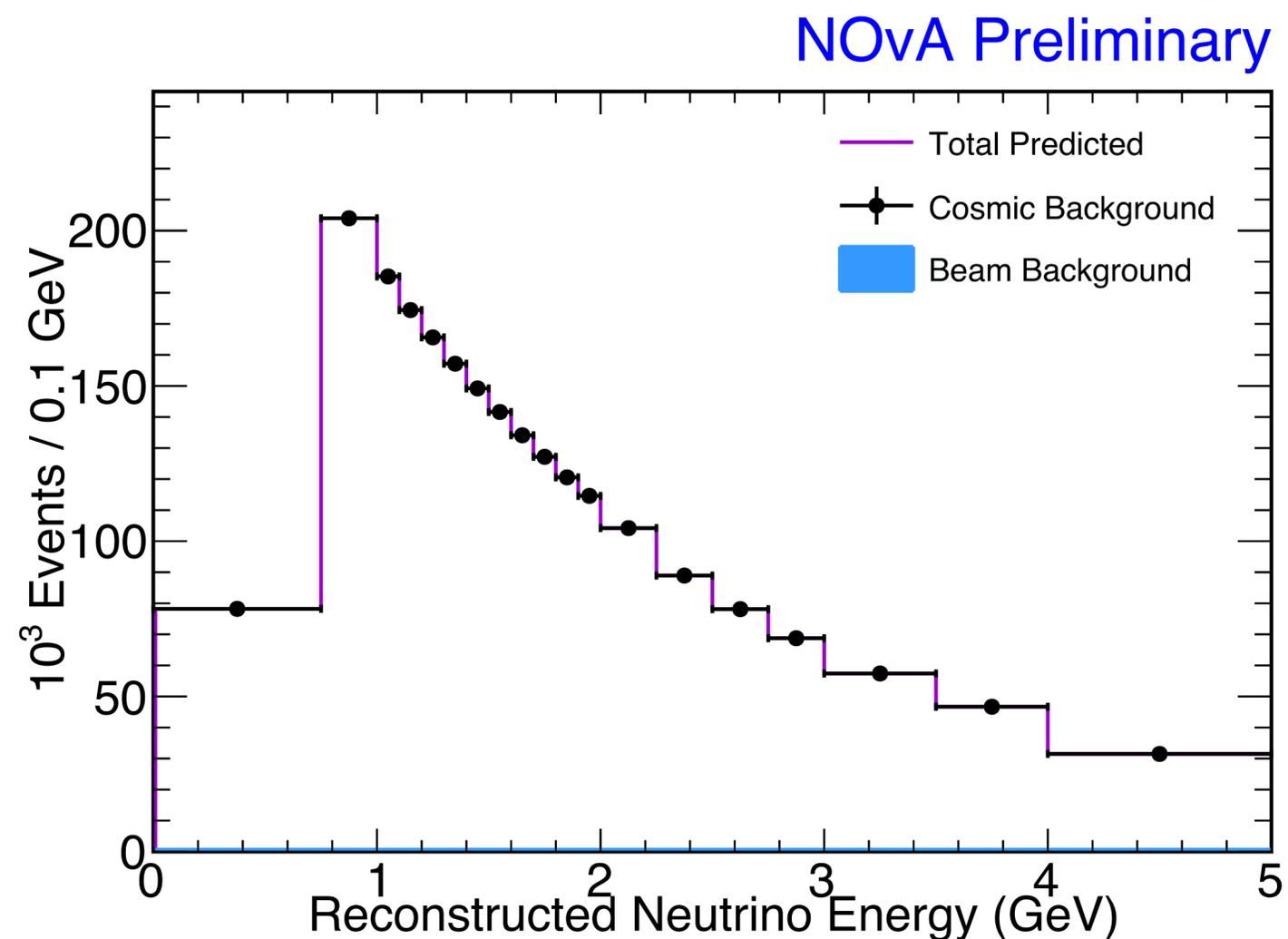
ν_μ Disappearance

1. Select, measure & characterize ND and FD ν_μ events.
2. Extrapolate beam expectation to FD and measure cosmic expectation from FD data out of the beam spill window.
3. Compare measured FD energy spectra to expectation.



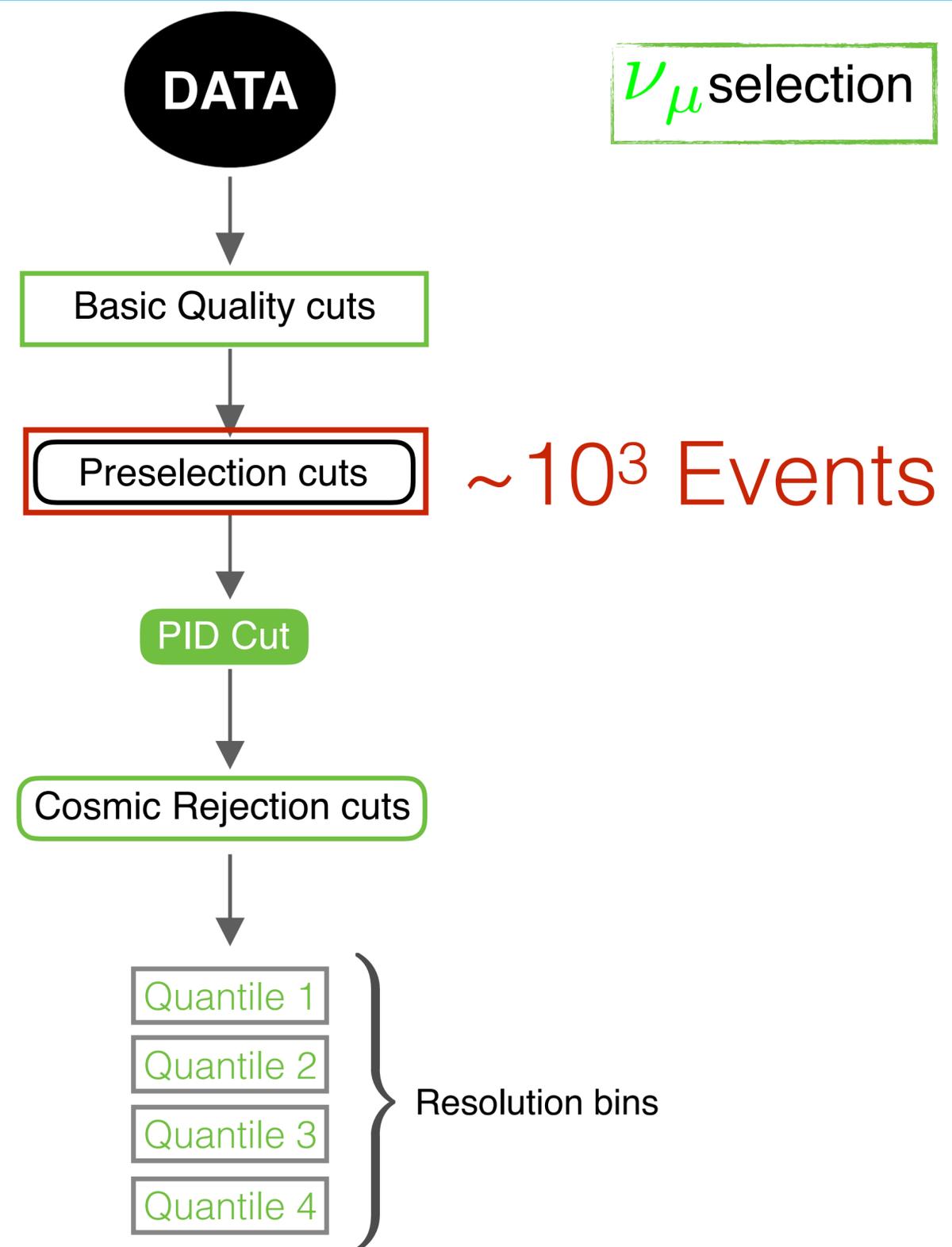
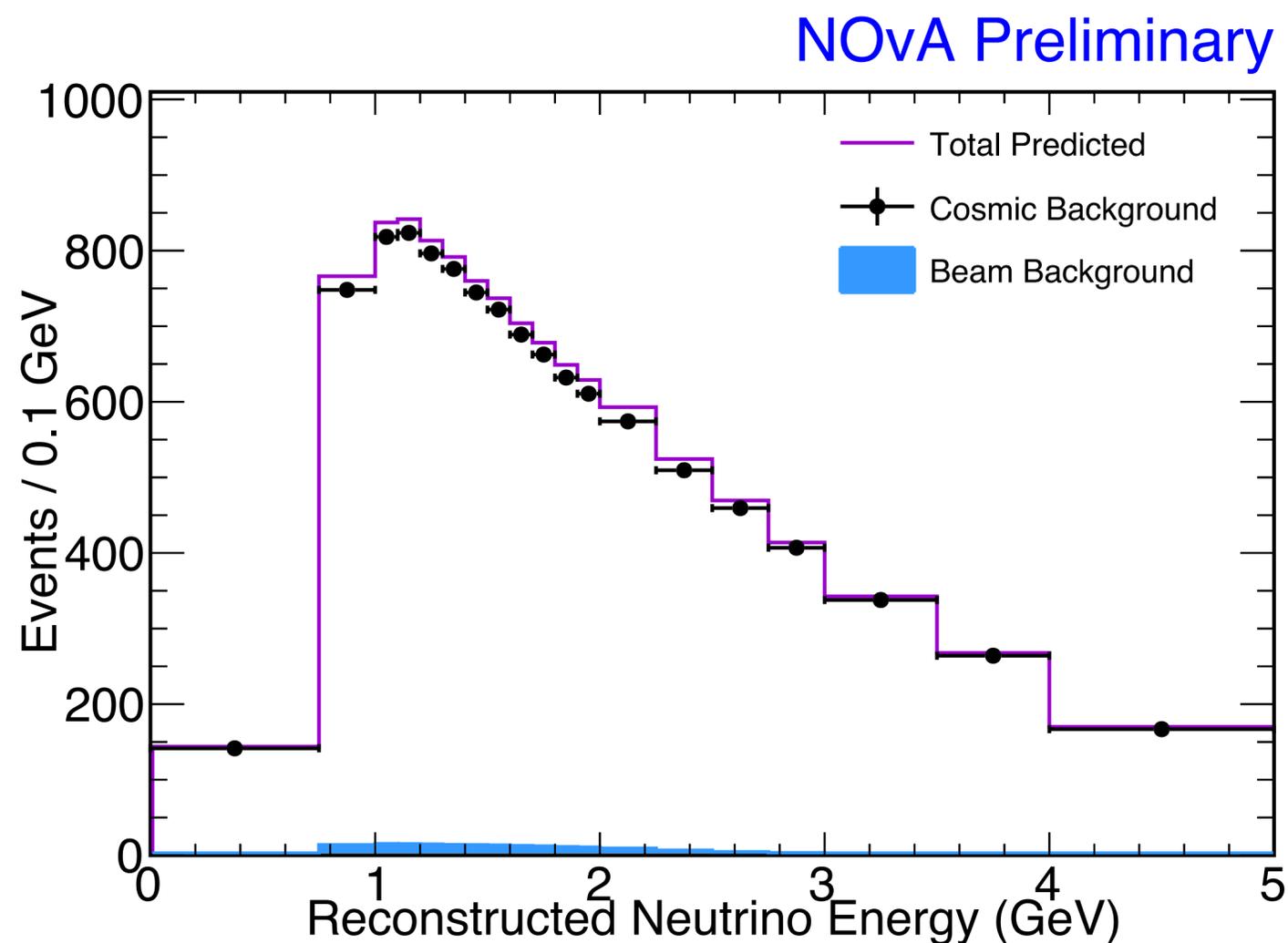
Improved ν_μ Selection

Even with excellent timing resolution cosmogenic activity at the Far Detector remains a challenging background due to raw rate.



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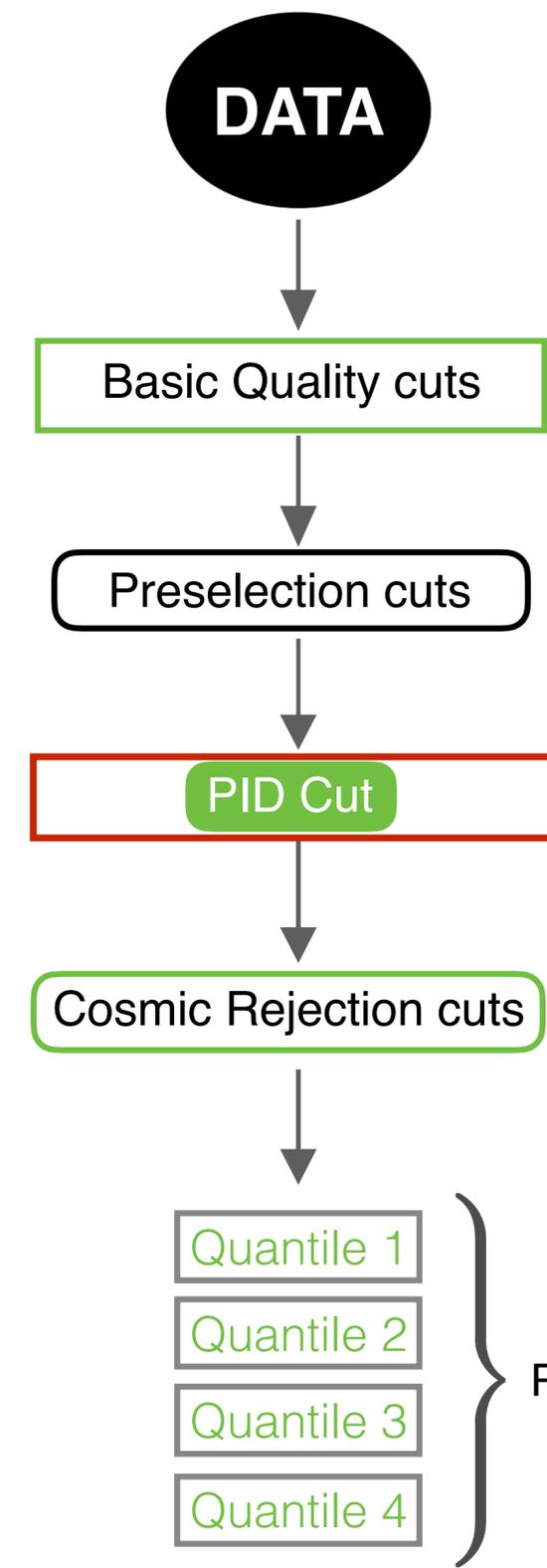


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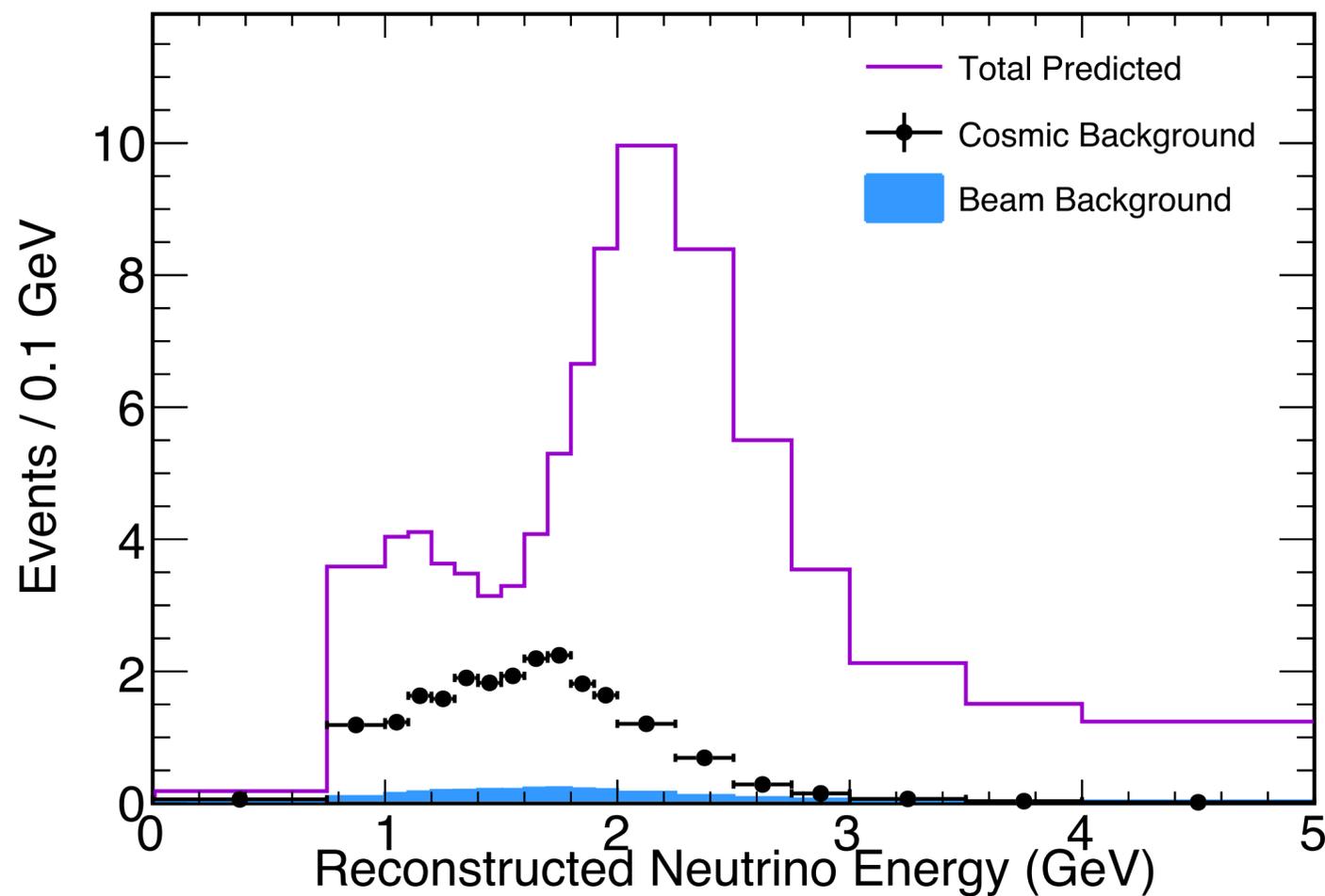


- New selection using CVN, a retuned cosmic rejection BDT, and a new PID cut
- Equivalent background rejection with 11% more signal selected.

ν_μ selection



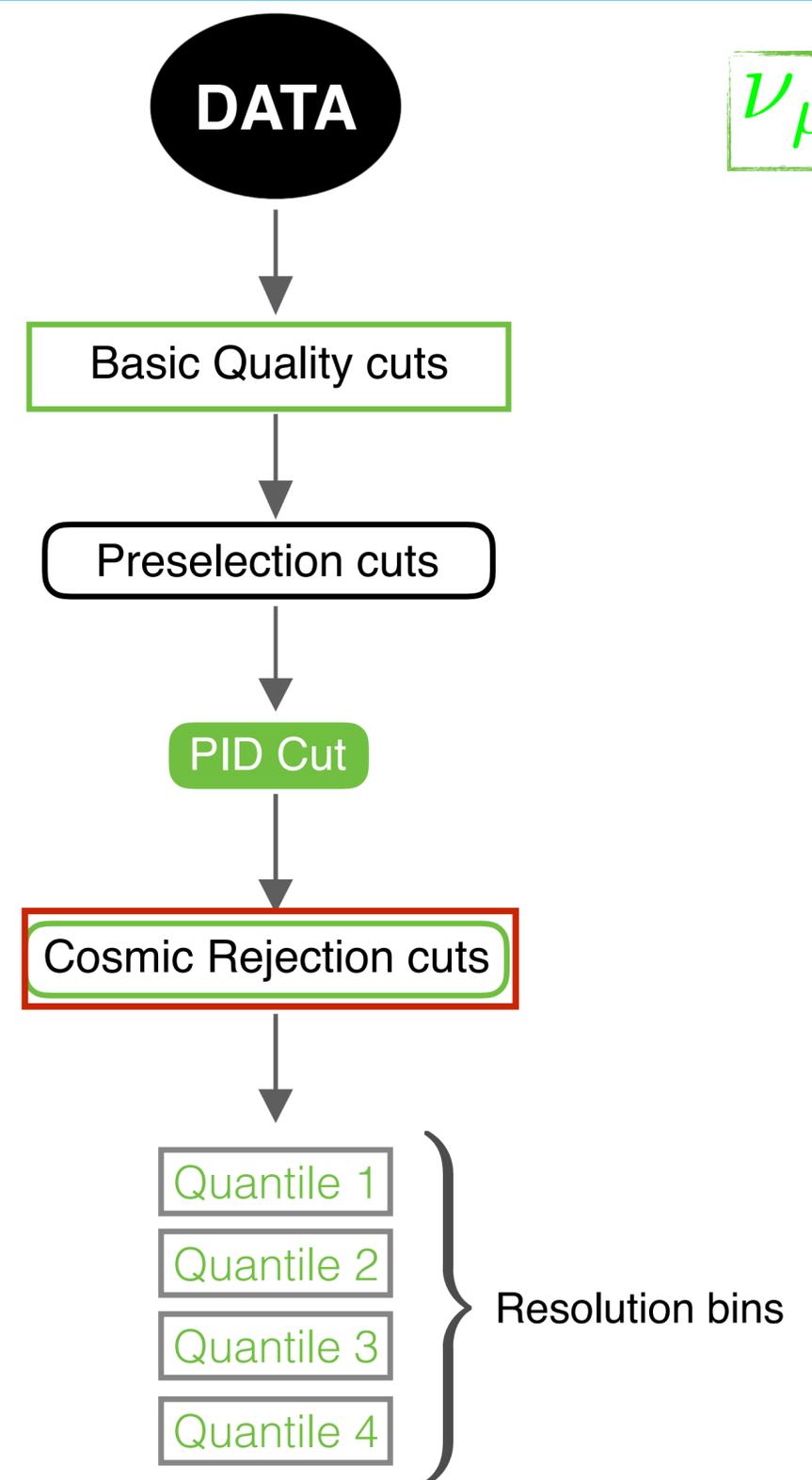
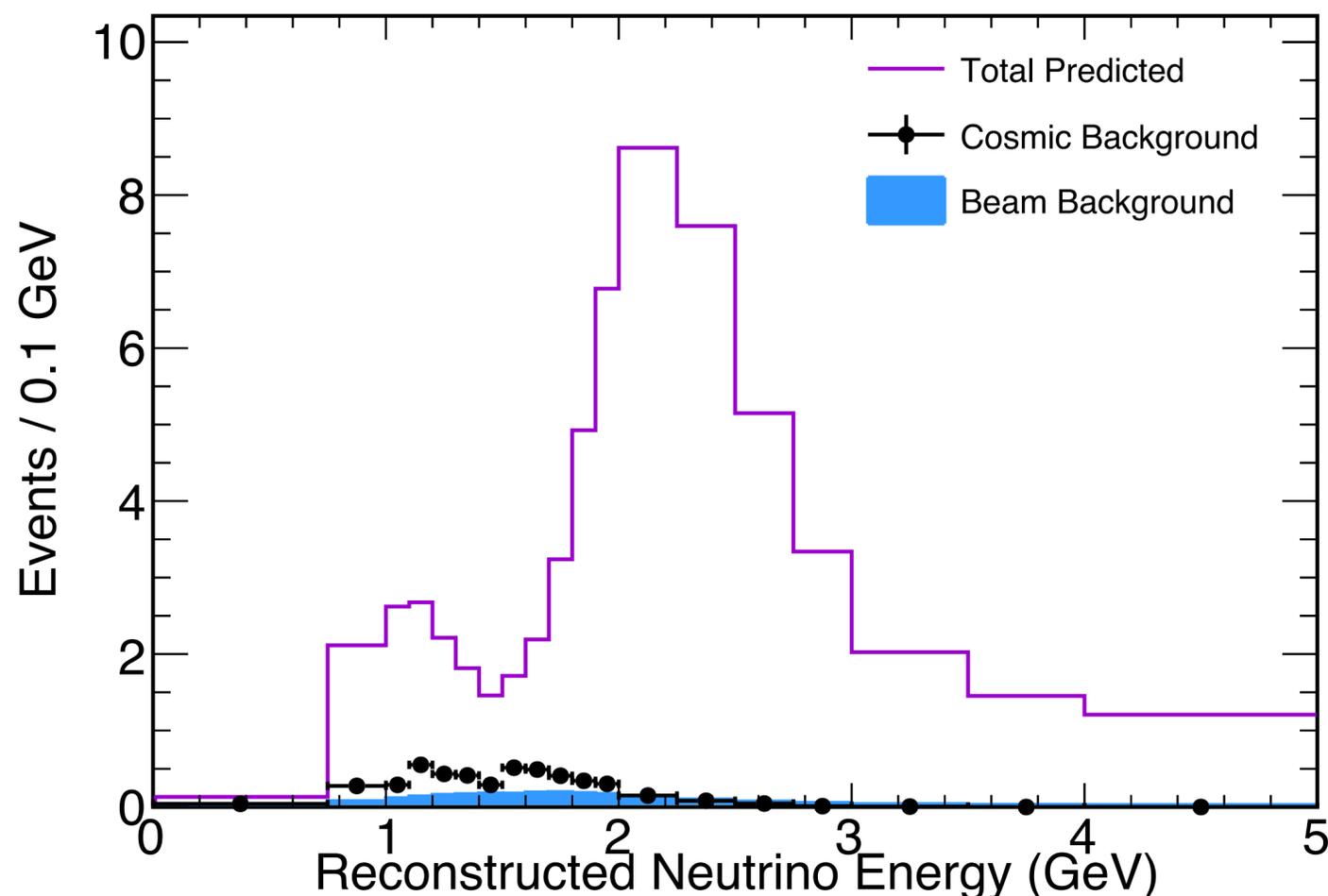
NOvA Preliminary



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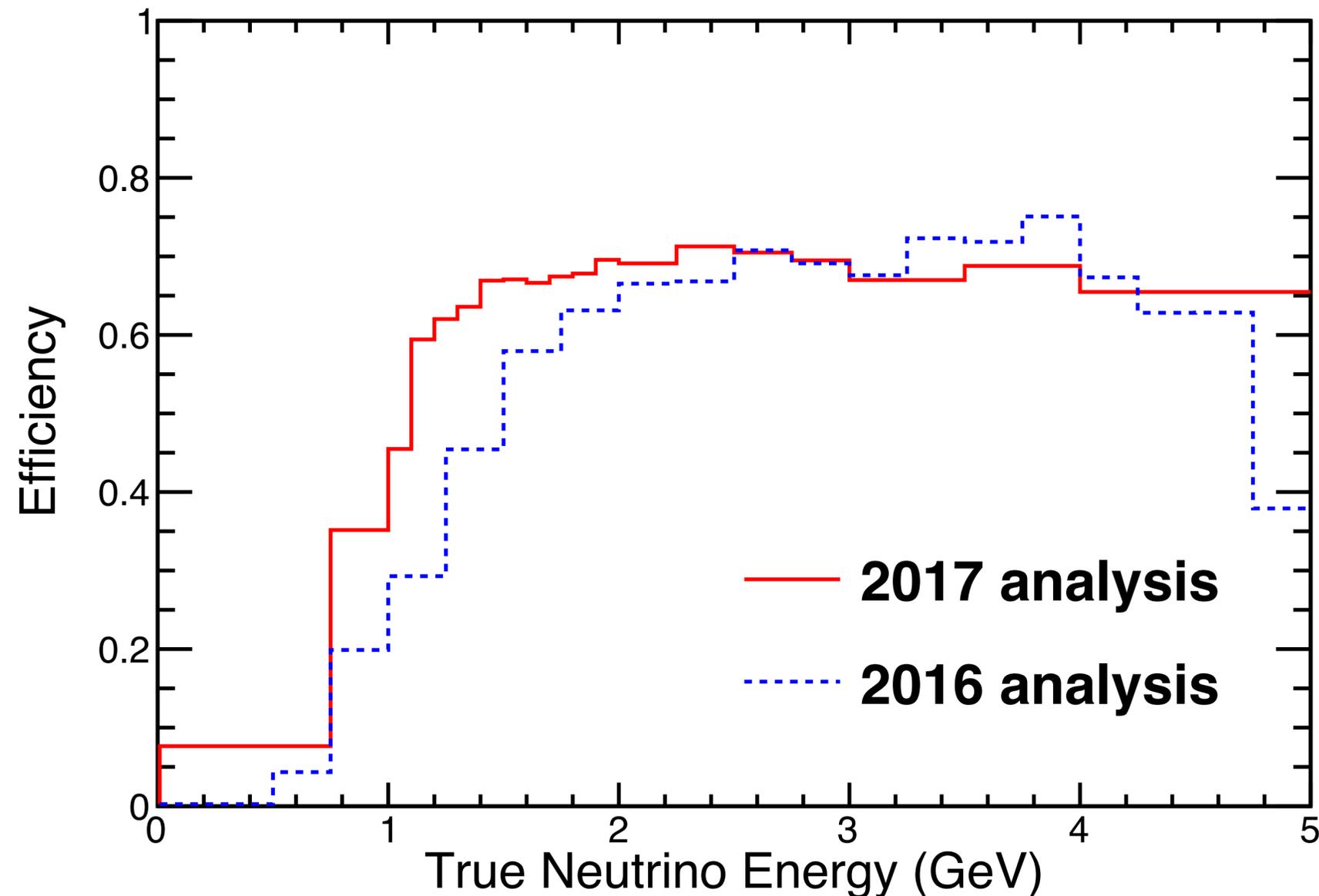
NOvA Preliminary



ν_μ selection

Improved ν_μ Selection

- Improvement is most pronounced in key low energy region.
- Expected overlap between old and new PIDs is consequentially low, particularly in cosmic background events.



Cosmic Background Prediction

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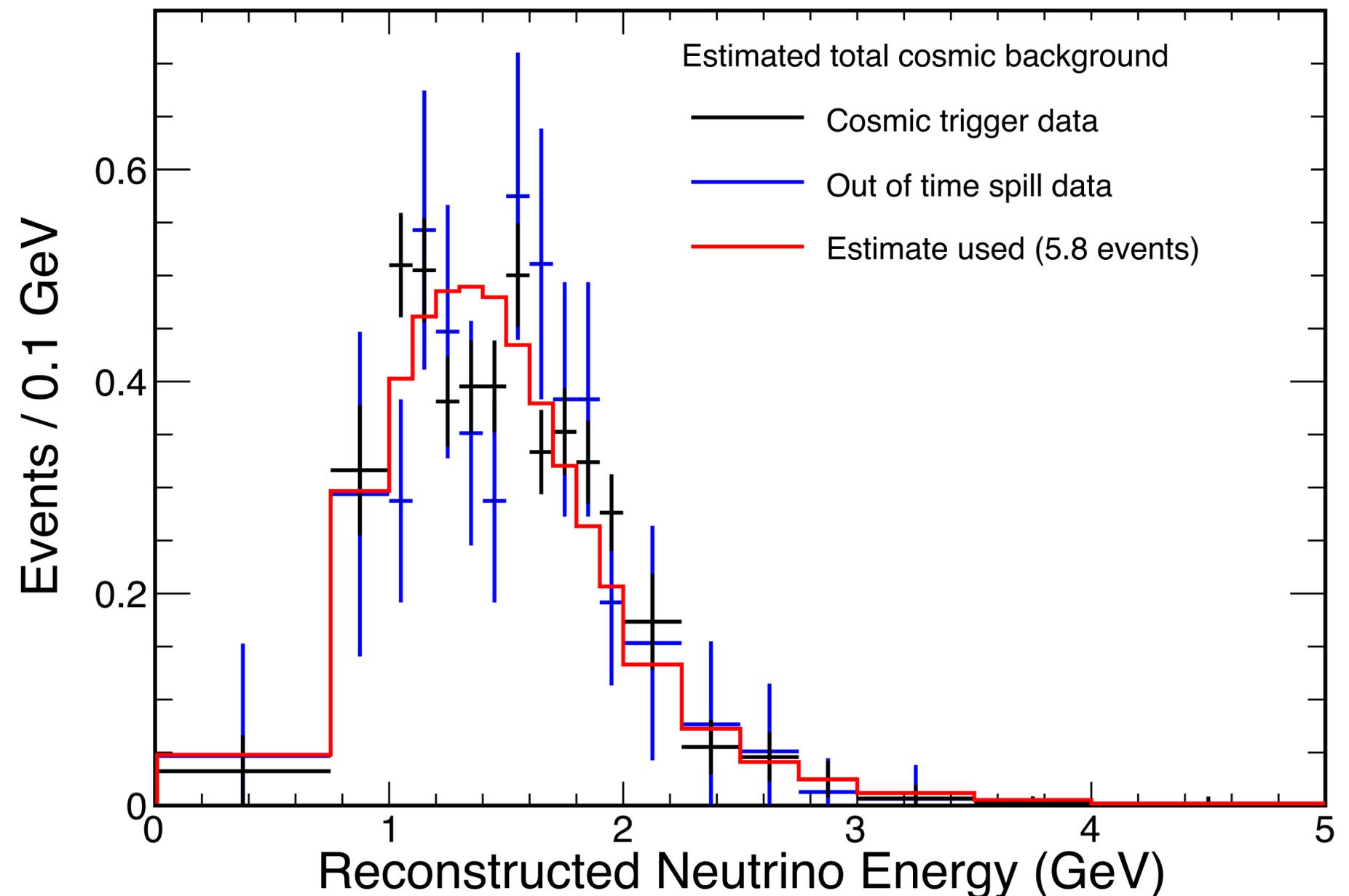


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- Cosmic backgrounds are characterized using cosmic activity recorded out of the beam spill.

NOvA Preliminary

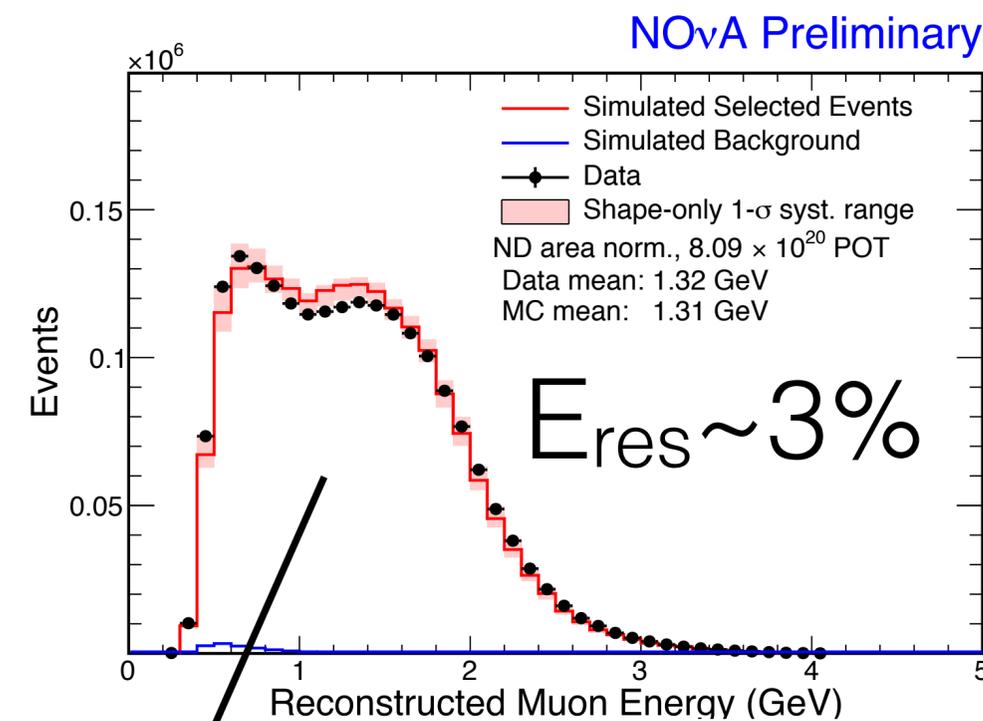
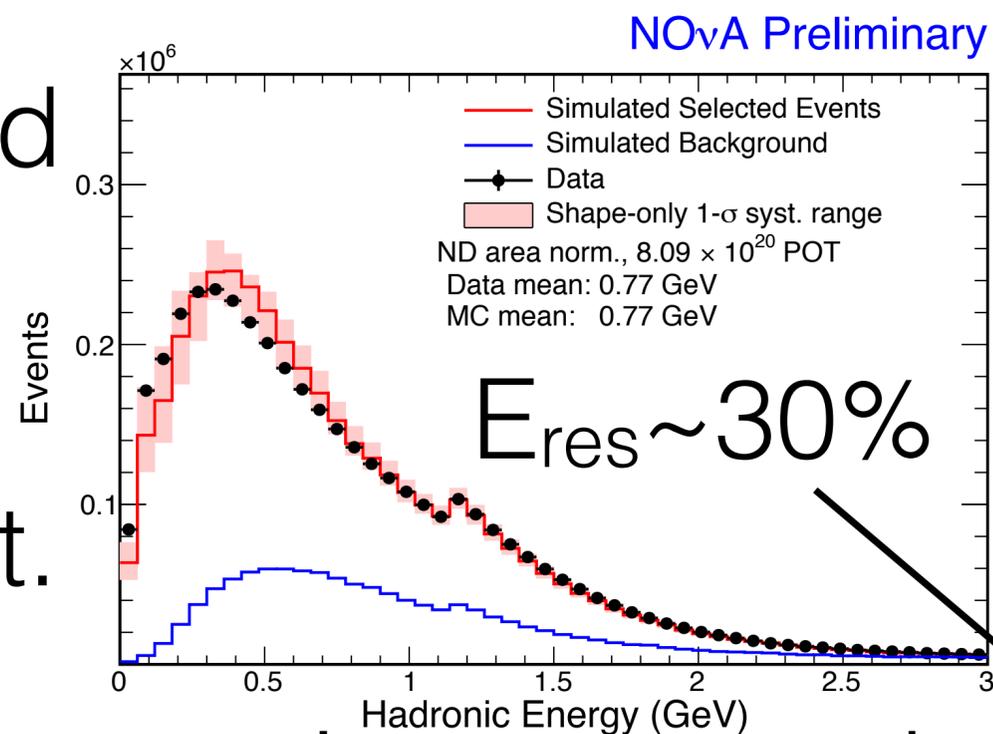
- Final cosmic rate comes from cosmic activity recorded adjacent to the beam spill, ensuring perfectly matched detector performance.



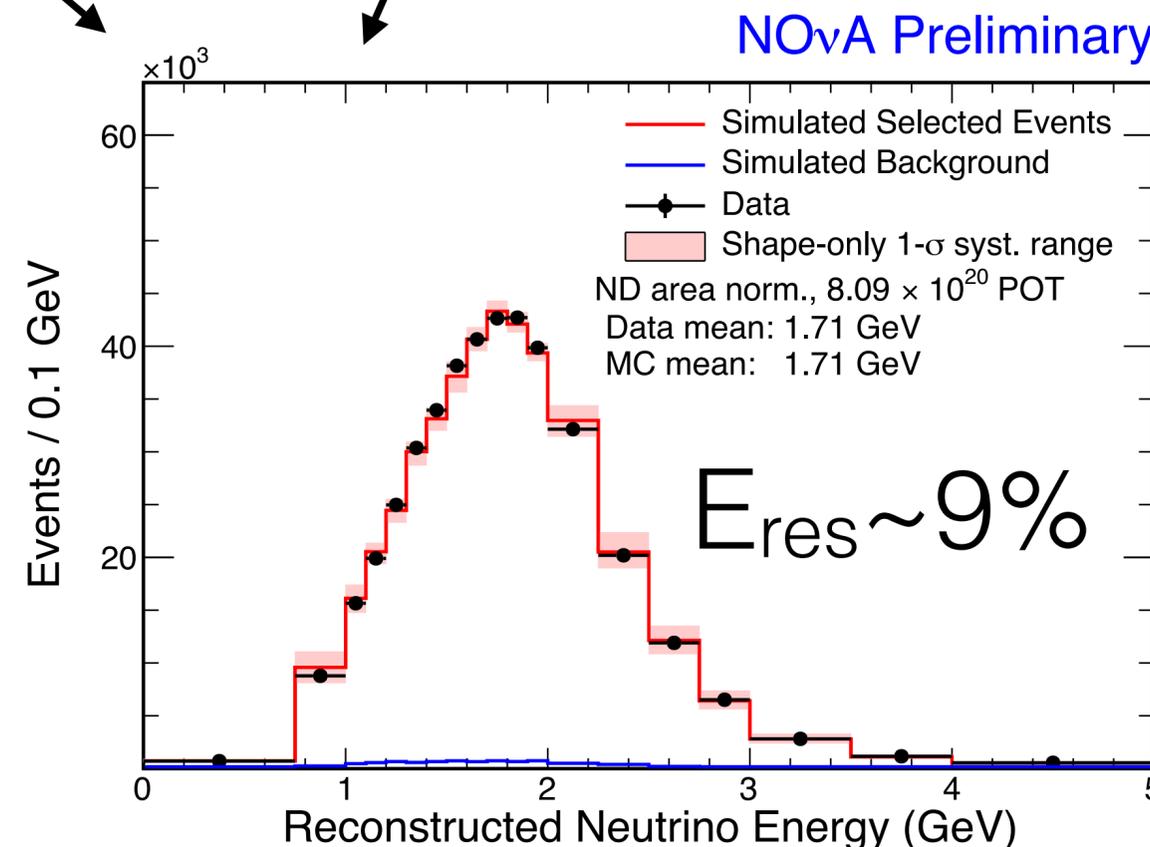
ν_μ Energy Estimation



- Final reconstructed energy combines E_{had} and E_μ via a piecewise linear fit.



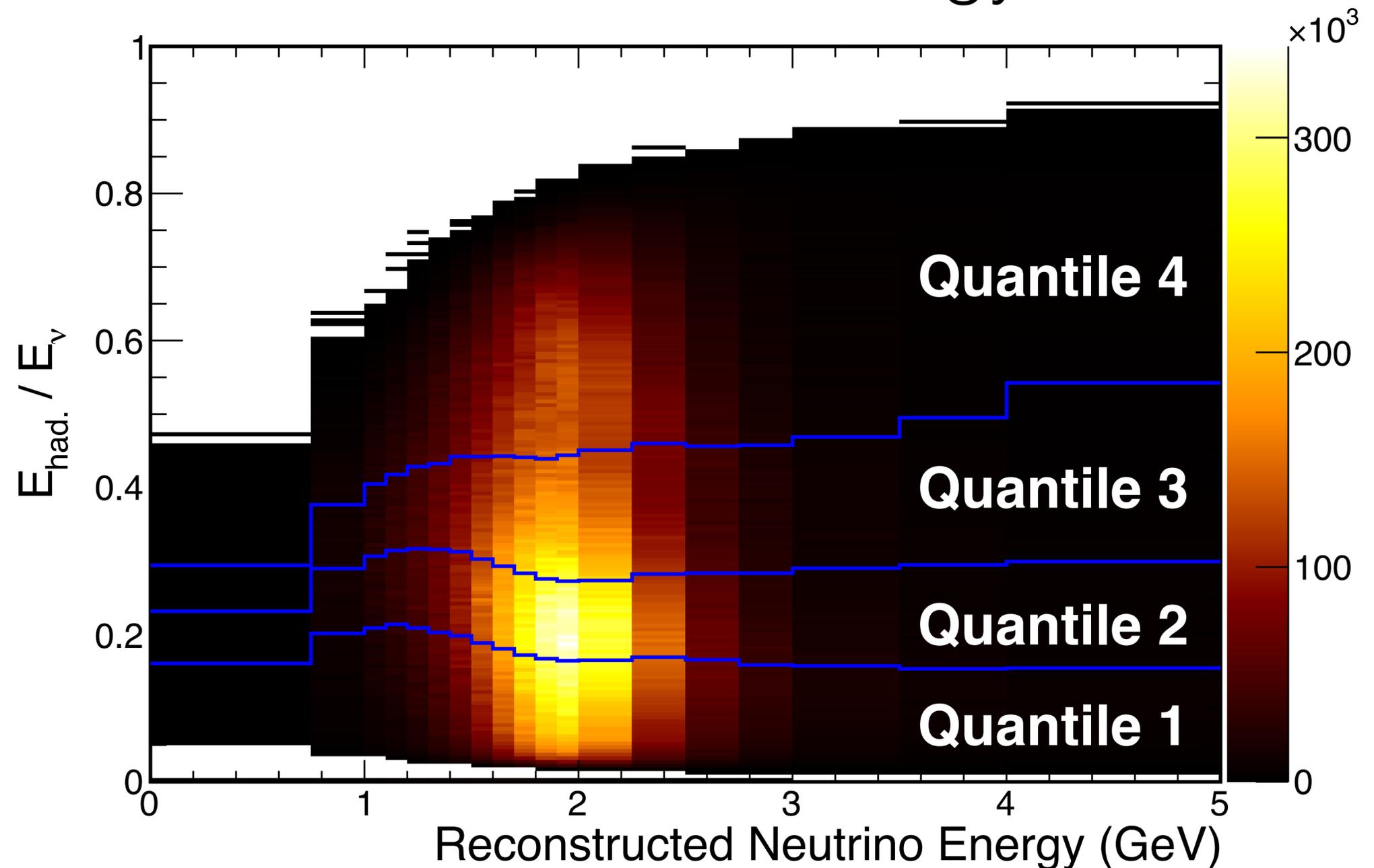
- Observed ND spectrum is converted to true energy using MC expectation, extrapolated to FD using a Far/Near flux ratio, and then converted to an expected reconstructed energy spectra.



Resolution Bins



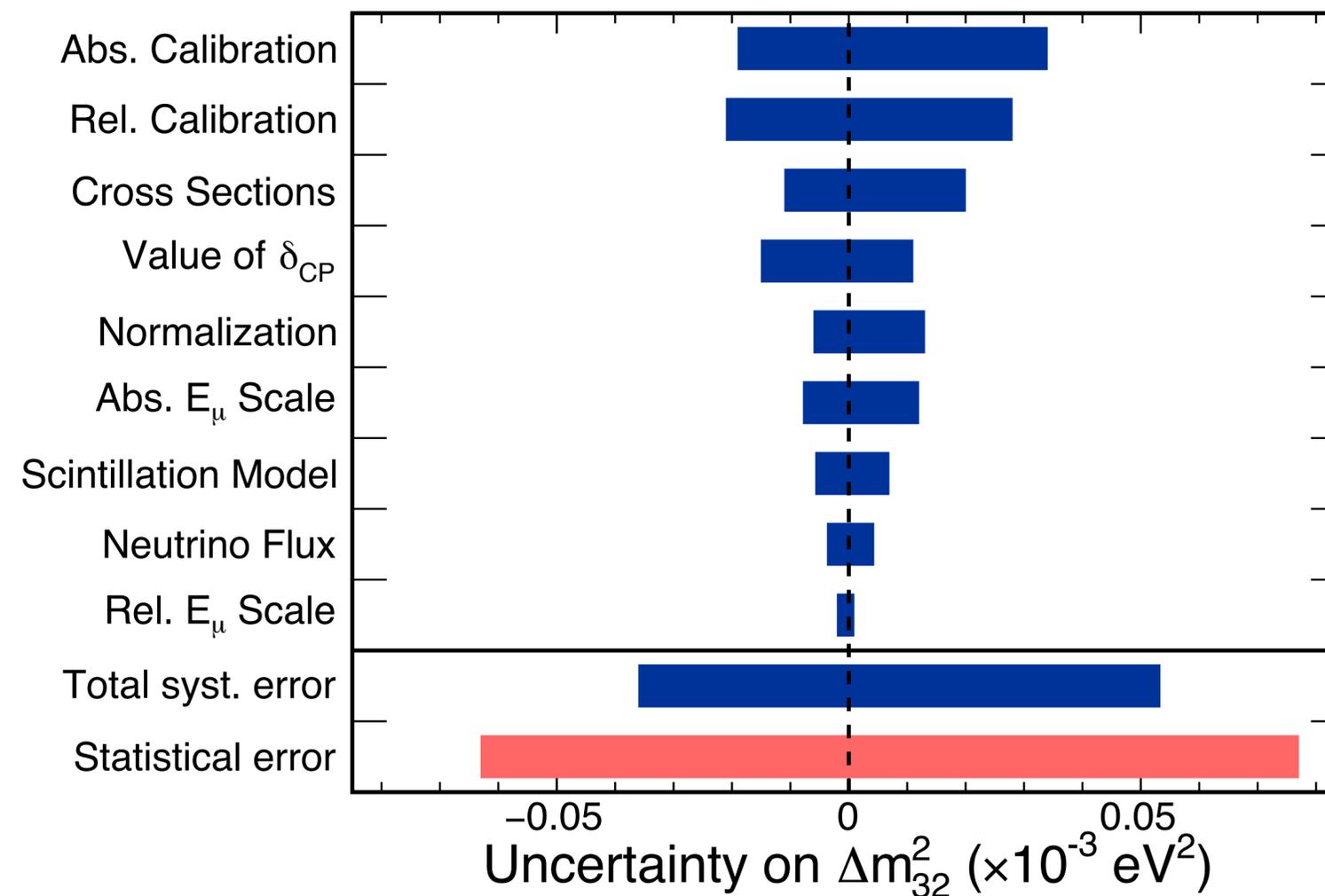
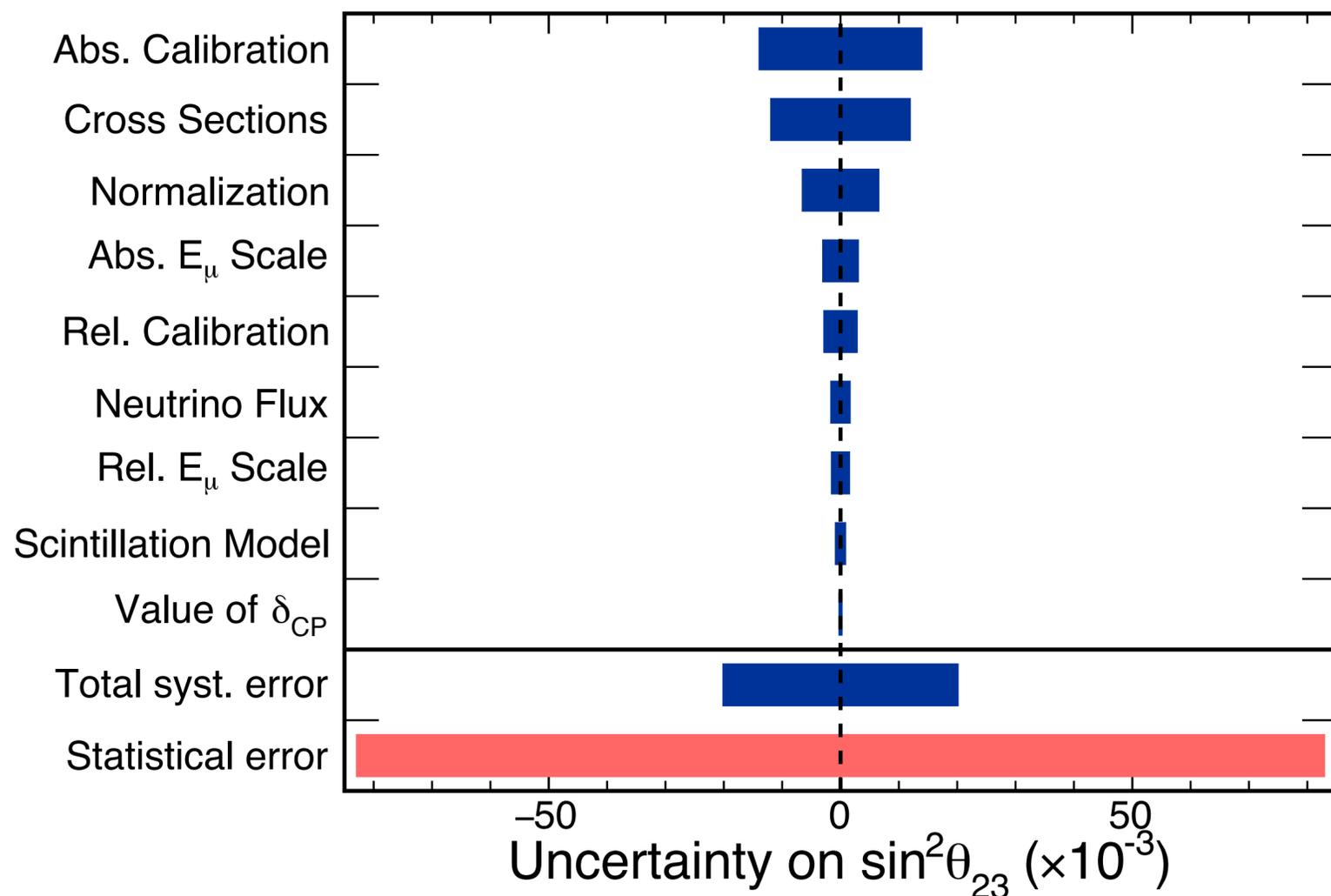
- Four bins of equal populations in FD, split in hadronic energy fraction as a function of reconstructed neutrino energy.
- Resolution varies from $\sim 6\%$ to $\sim 12\%$ from the best to worst resolution bins.



ν_μ Systematics



- Systematics were assessed by generating sets of shifted MC.
- Those shifted datasets were used instead of our nominal MC to assess the impact on our final result.



ν_μ FD Selected Sample

In the absence of oscillations we expect 763 events. **126 were observed.**

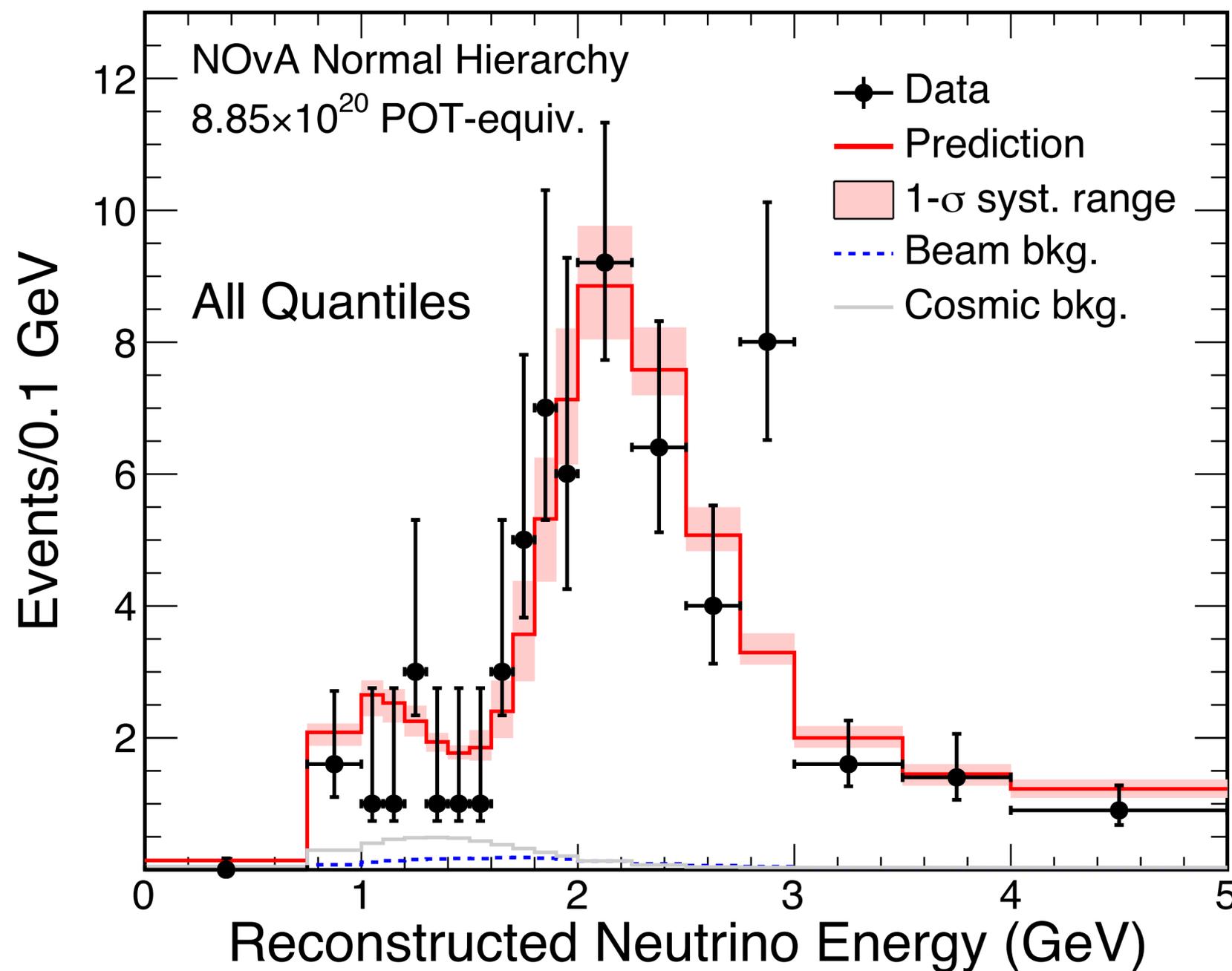
	Total Observed	Expectation at Best Fit	Total Background	Cosmic	Neutral Current	Other Beam
All Q Events	126	129	9.24	5.82	2.50	0.96

ν_μ FD Selected Sample

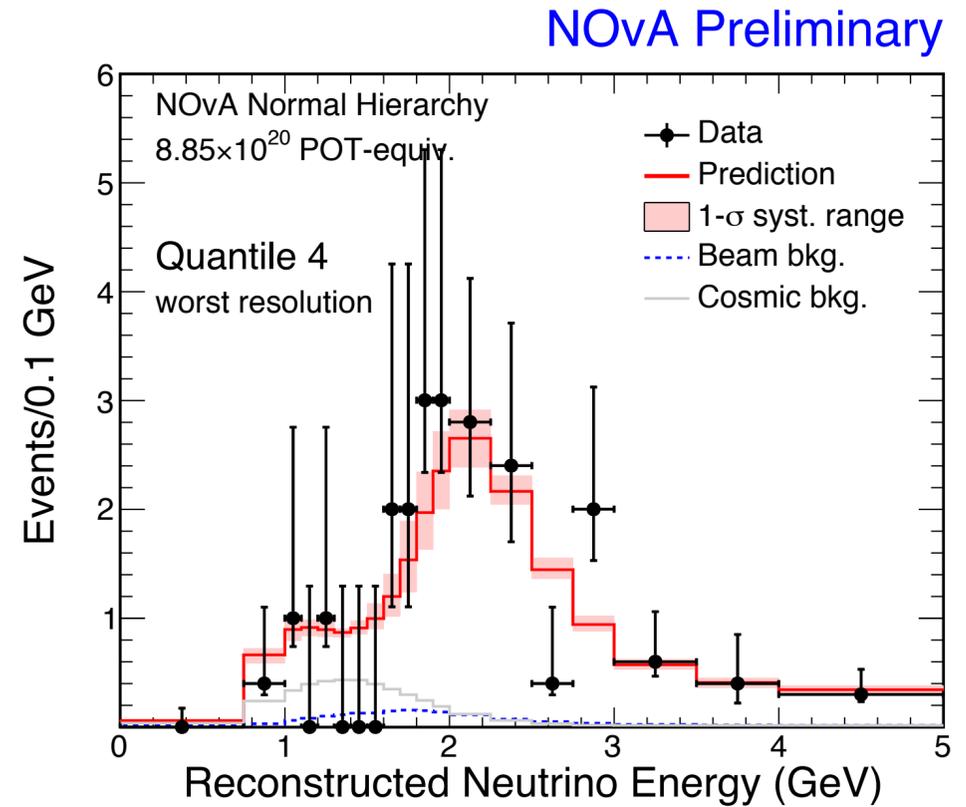
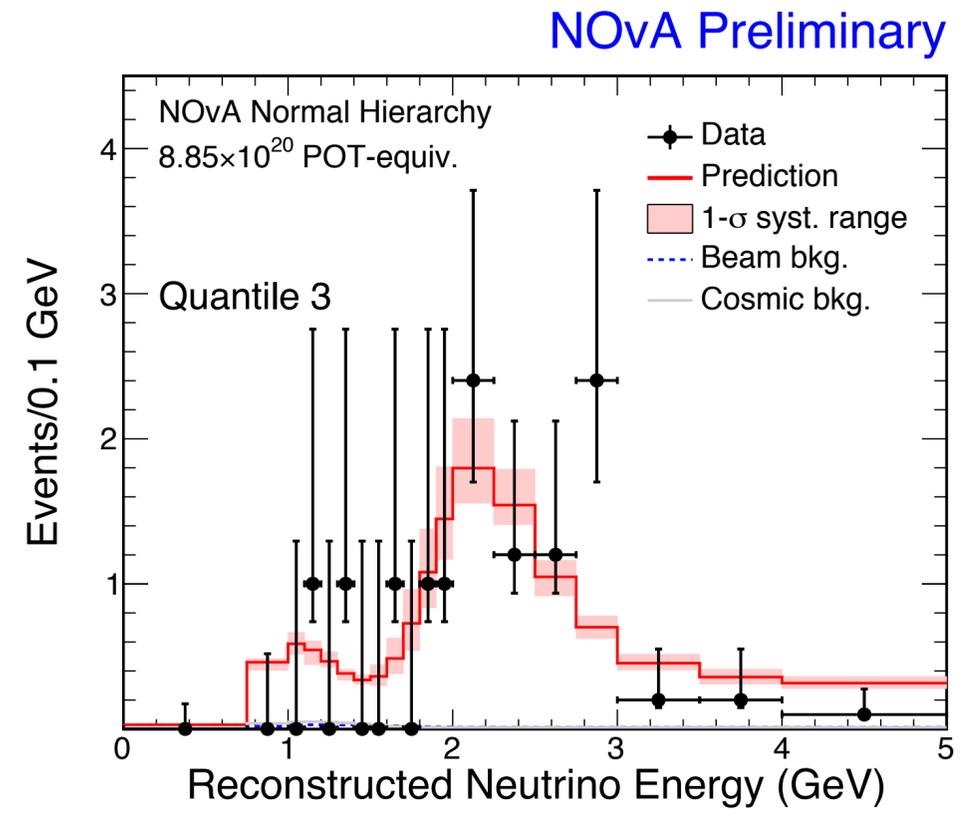
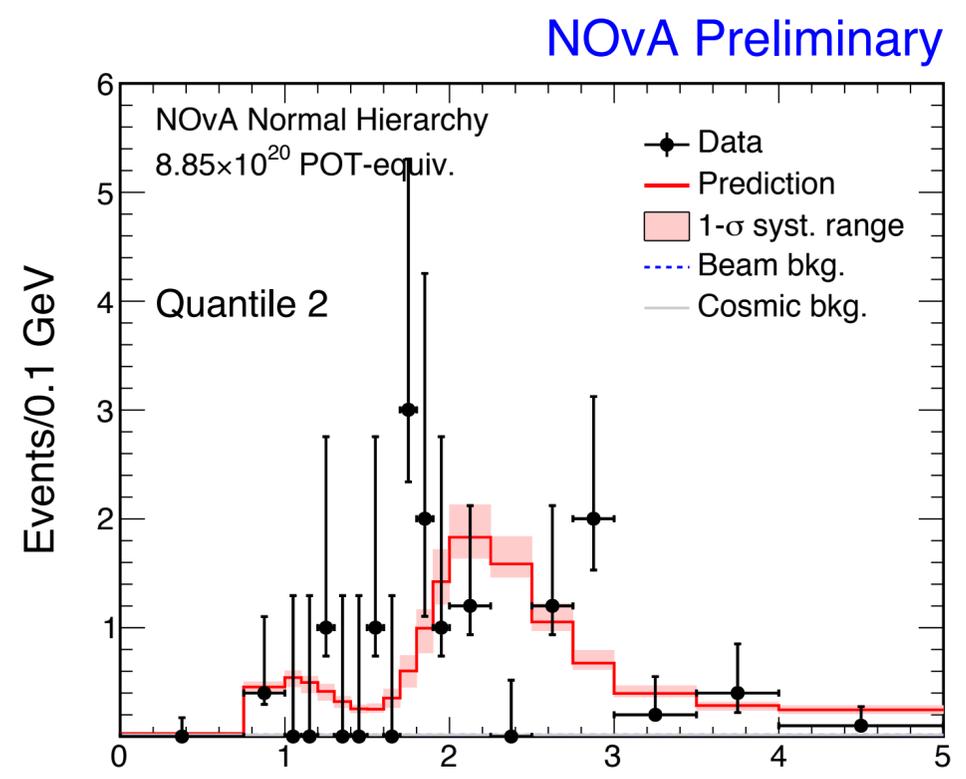
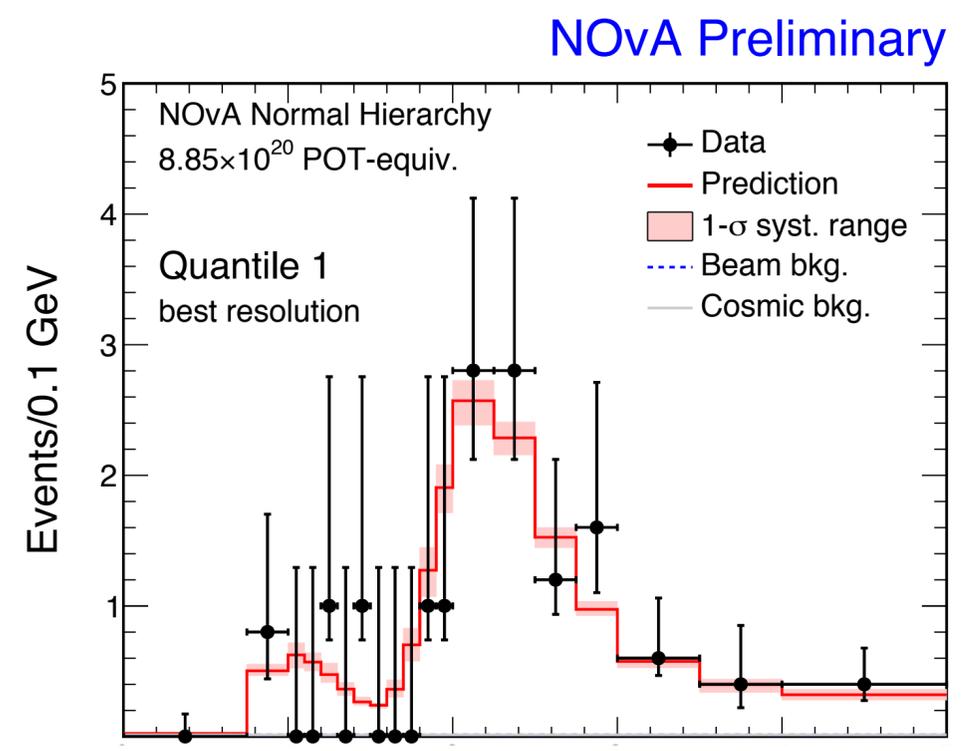


In the absence of oscillations we expect 763 events. **126 were observed.**

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ν_μ FD Selected Sample



ν_μ Result

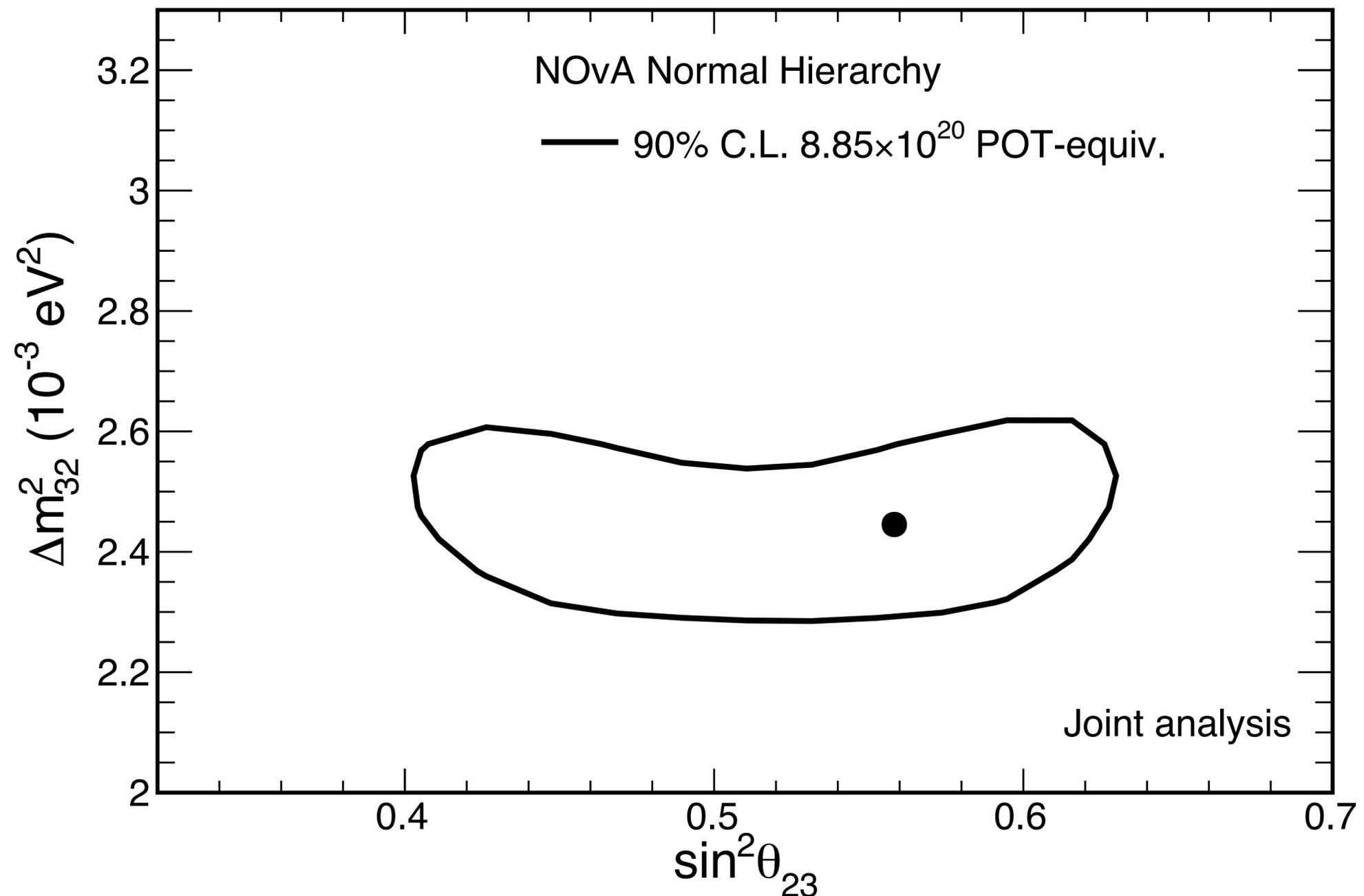
- Full joint fit with appearance analysis. Feldman Cousins corrections in 2D & 1D limits.
- All systematics, oscillation pull terms shared.
- Constrain θ_{13} using world average from PDG, $\sin^2 2\theta_{13} = 0.082$

NOvA Preliminary

Best fit:

$$\Delta m_{32}^2 = 2.444^{+0.079}_{-0.077} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{23} = 0.558^{+0.041}_{-0.033}$$



Atmospheric Mixing and World Constraints

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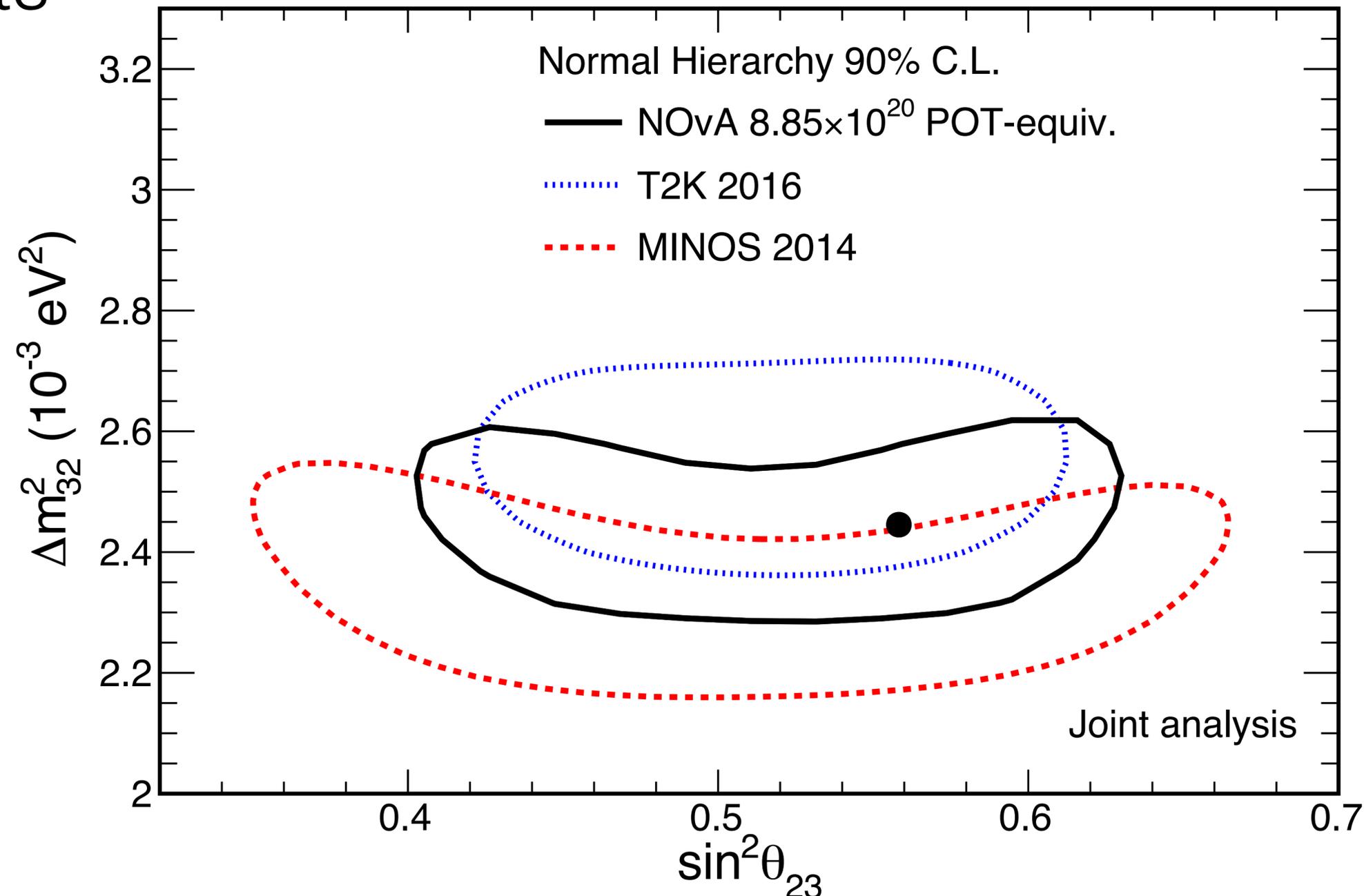
- Consistent with world expectation.
- Competitive measurements of Δm^2_{32} .

NOvA Preliminary

Best fit:

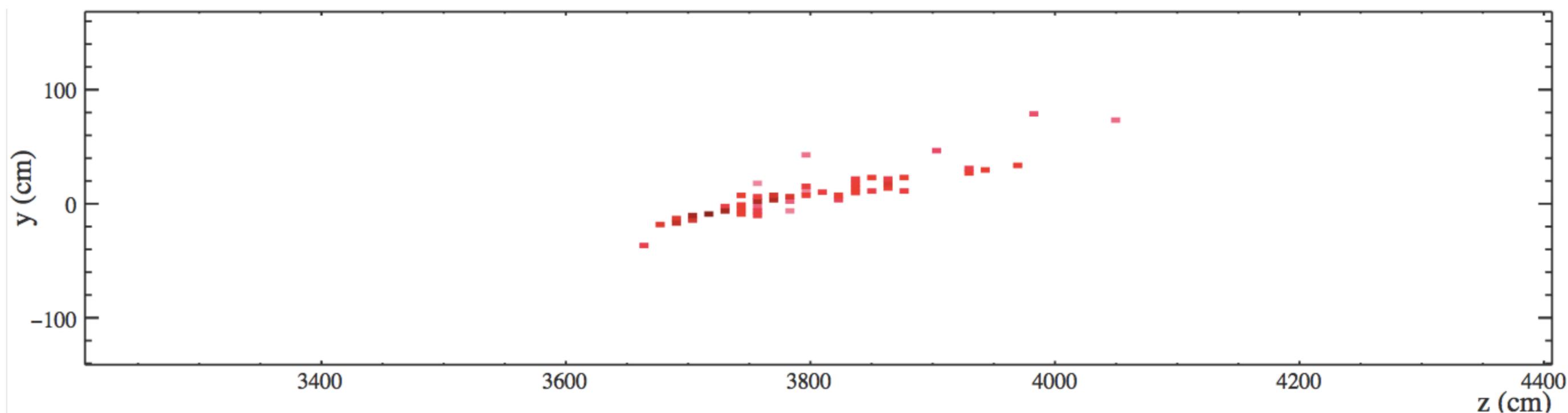
$$\Delta m^2_{32} = 2.444^{+0.079}_{-0.077} \times 10^{-3} \text{ eV}^2$$

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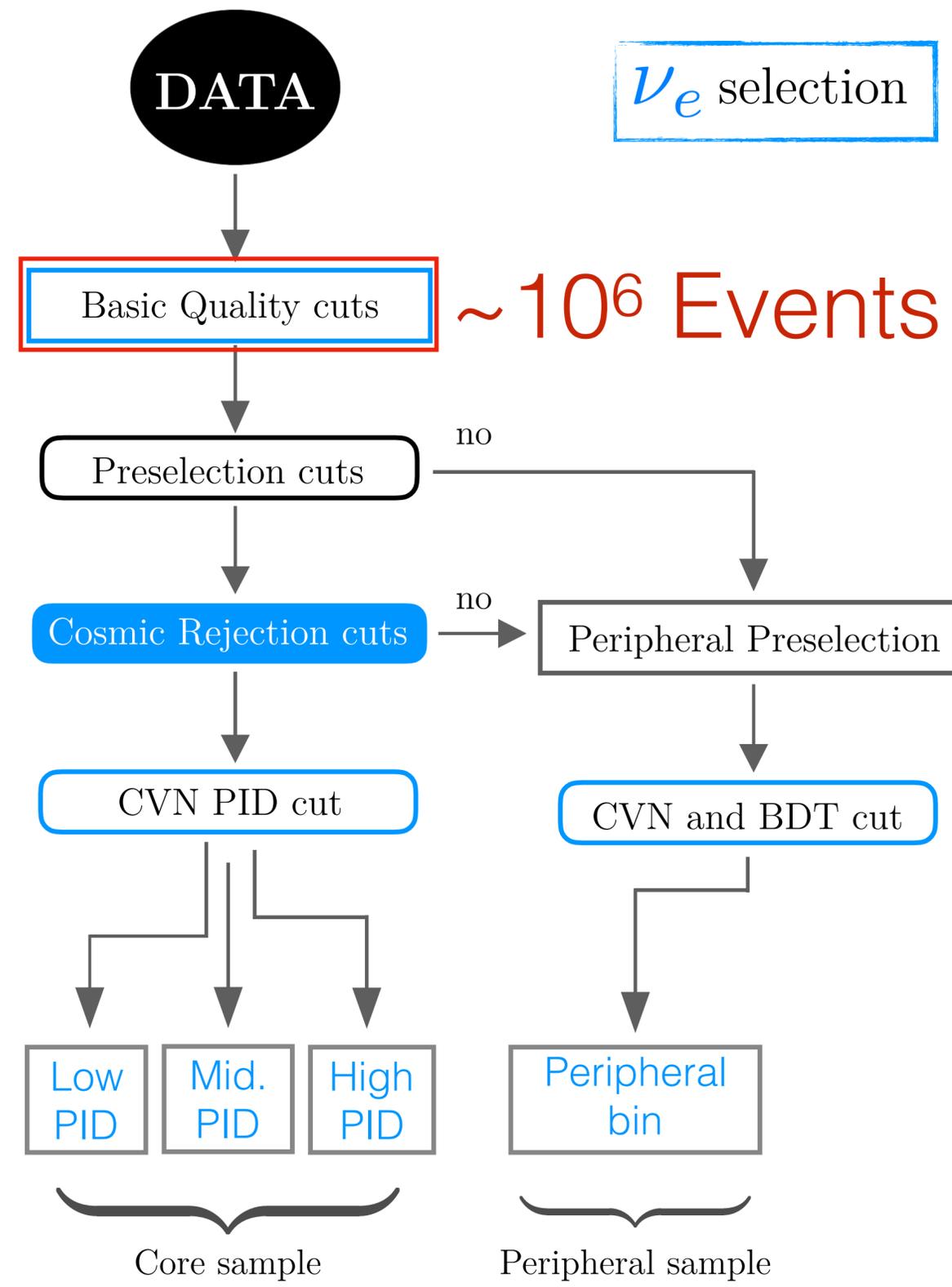
ν_e Appearance

1. Measure ND and FD ν_e and ν_μ Selected Spectra
2. Break down ND ν_e selected events to separately extrapolate background components.
3. Extrapolate ND ν_μ selected events estimate signal at the FD. Use FD data from outside of the beam spill to estimate cosmic backgrounds.
4. Compare measured FD to expectation.

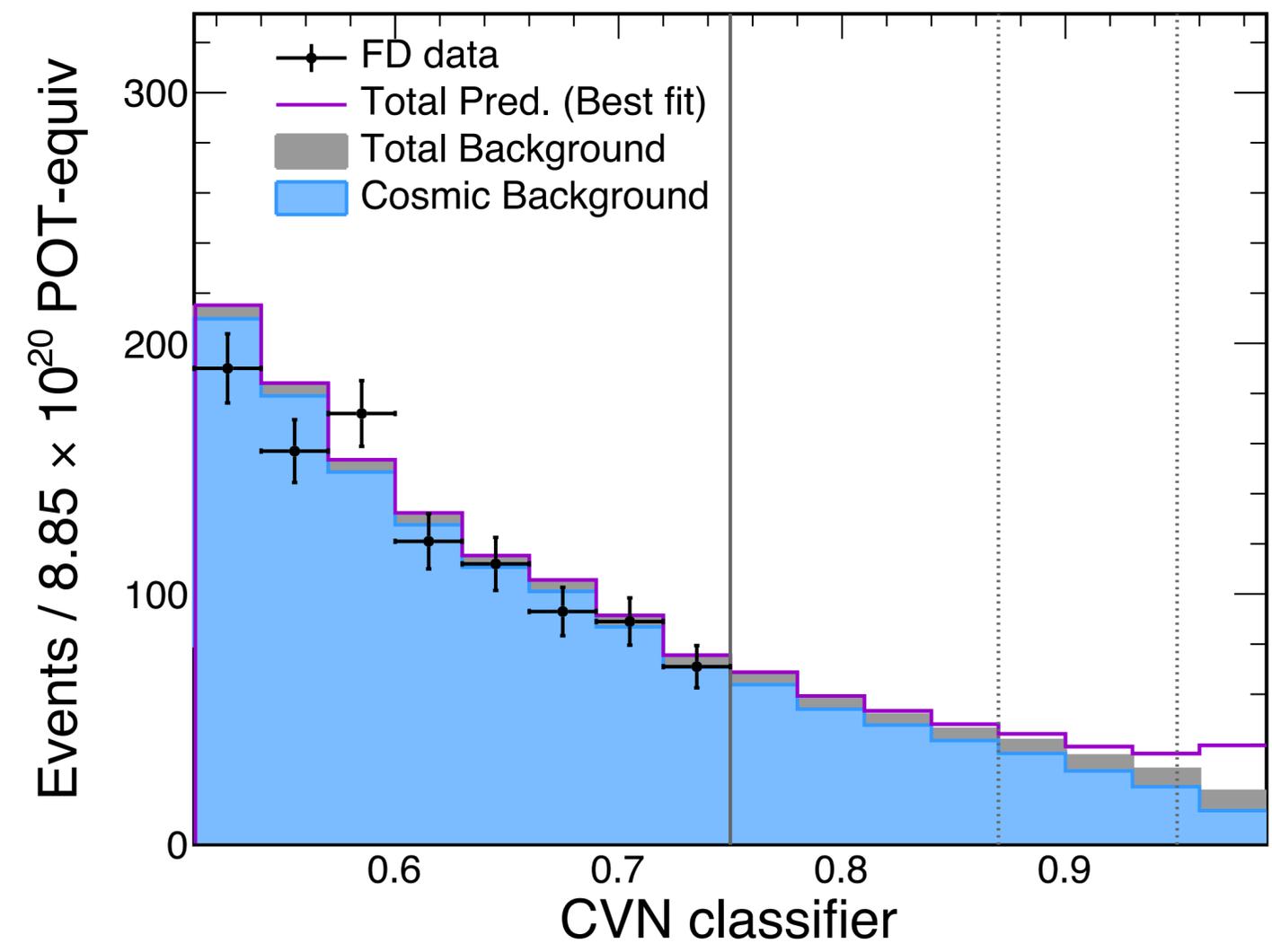


ν_e Selection

Optimized to maximally exploit the power of our our CVN ID. Select down to low PID values to recover as many signal events as possible. Binning in PID to retain the full power of the high purity subsample of events.

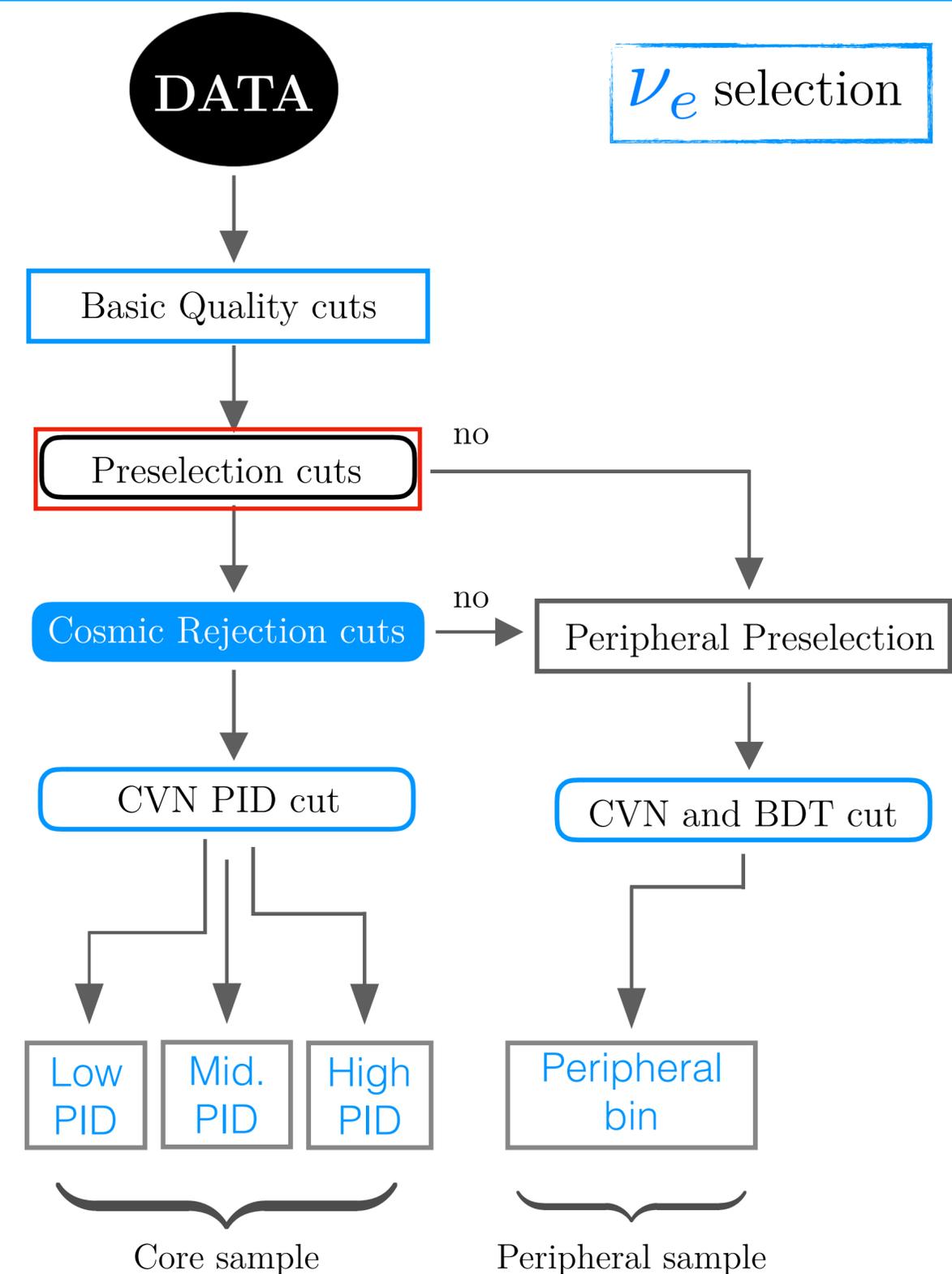
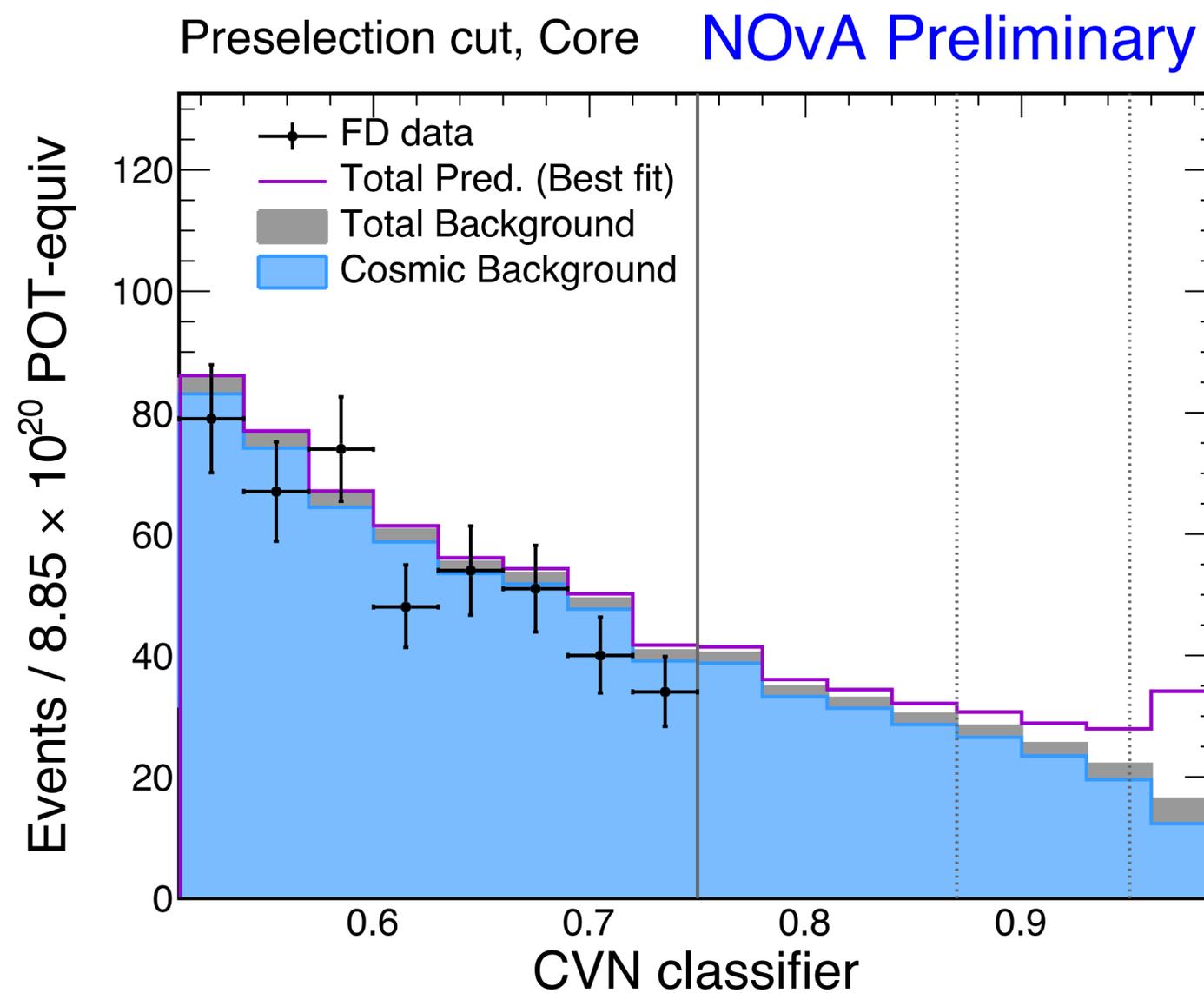


Basic cuts NOvA Preliminary



ν_e Selection

Optimized to maximally exploit the power of our our CVN ID. Select down to low PID values to recover as many signal events as possible. Binning in PID to retain the full power of the high purity subsample of events.



ν_e Selection

Optimized to maximally exploit the power of our our CVN ID. Select down to low PID values to recover as many signal events as possible. Binning in PID to retain the full power of the high purity subsample of events.

DATA ν_e selection

Basic Quality cuts

 $\sim 10^4$ Events

Preselection cuts

Cosmic Rejection cuts

Peripheral Preselection

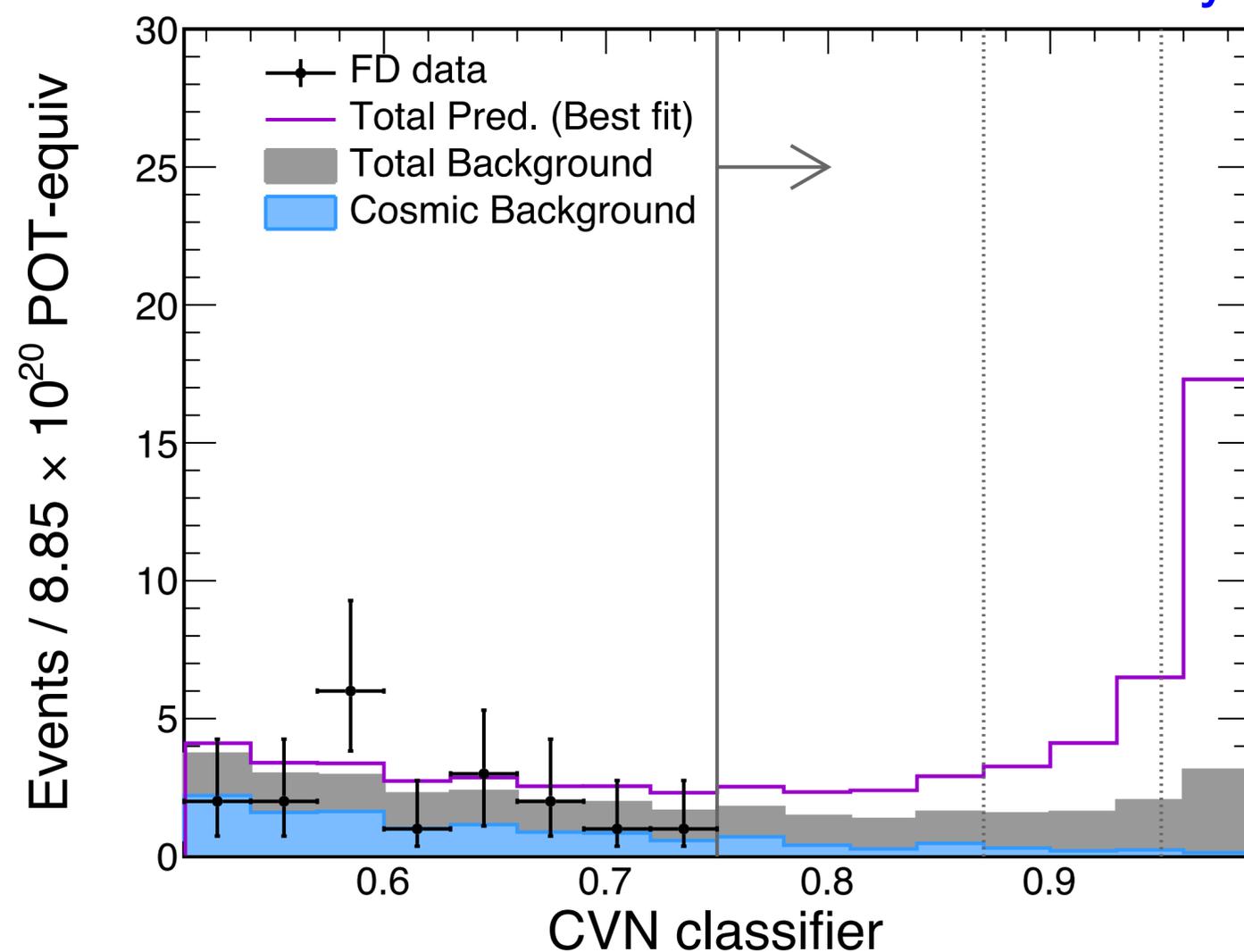
CVN PID cut

CVN and BDT cut

Low
PIDMid.
PIDHigh
PIDPeripheral
bin

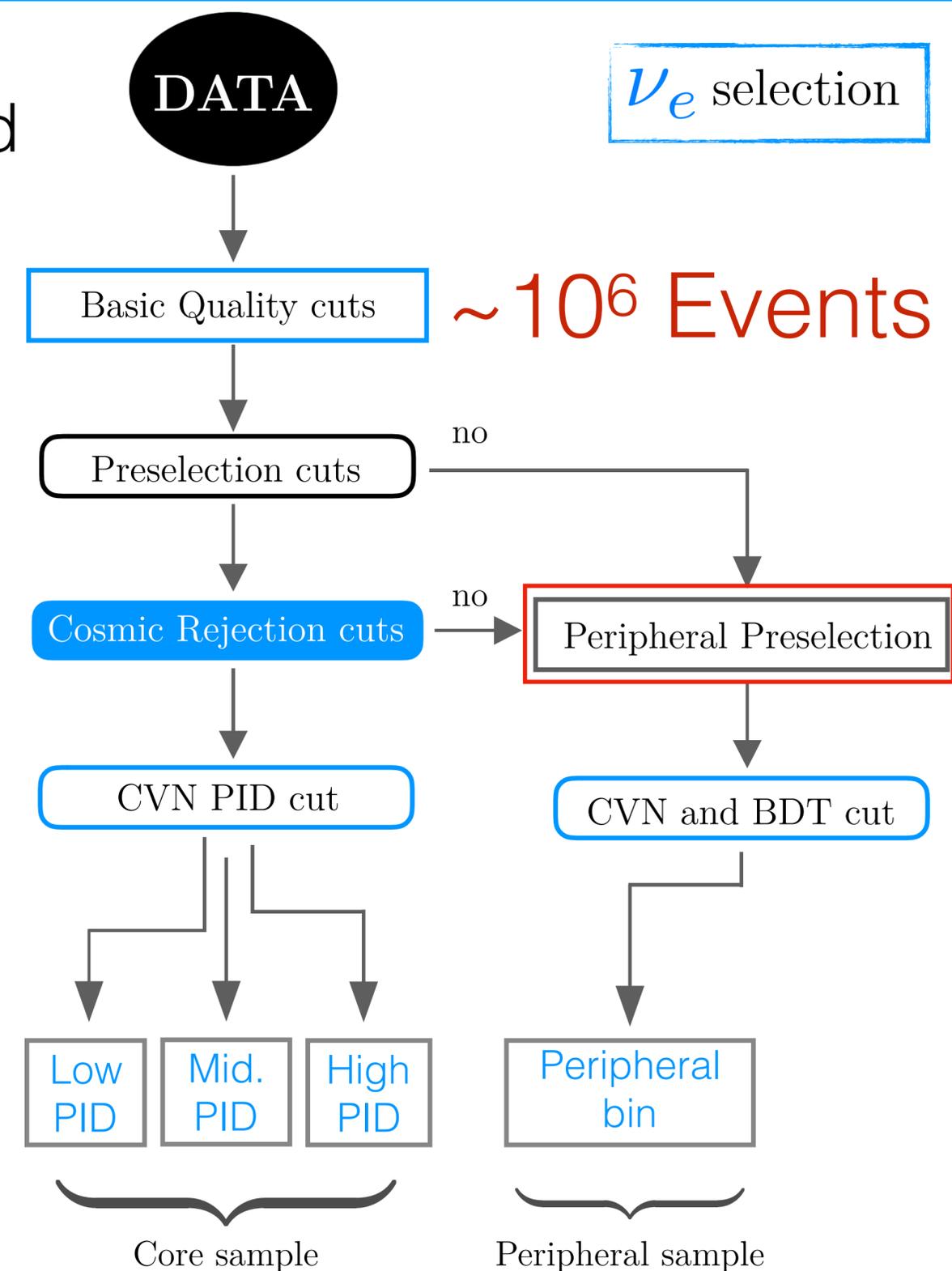
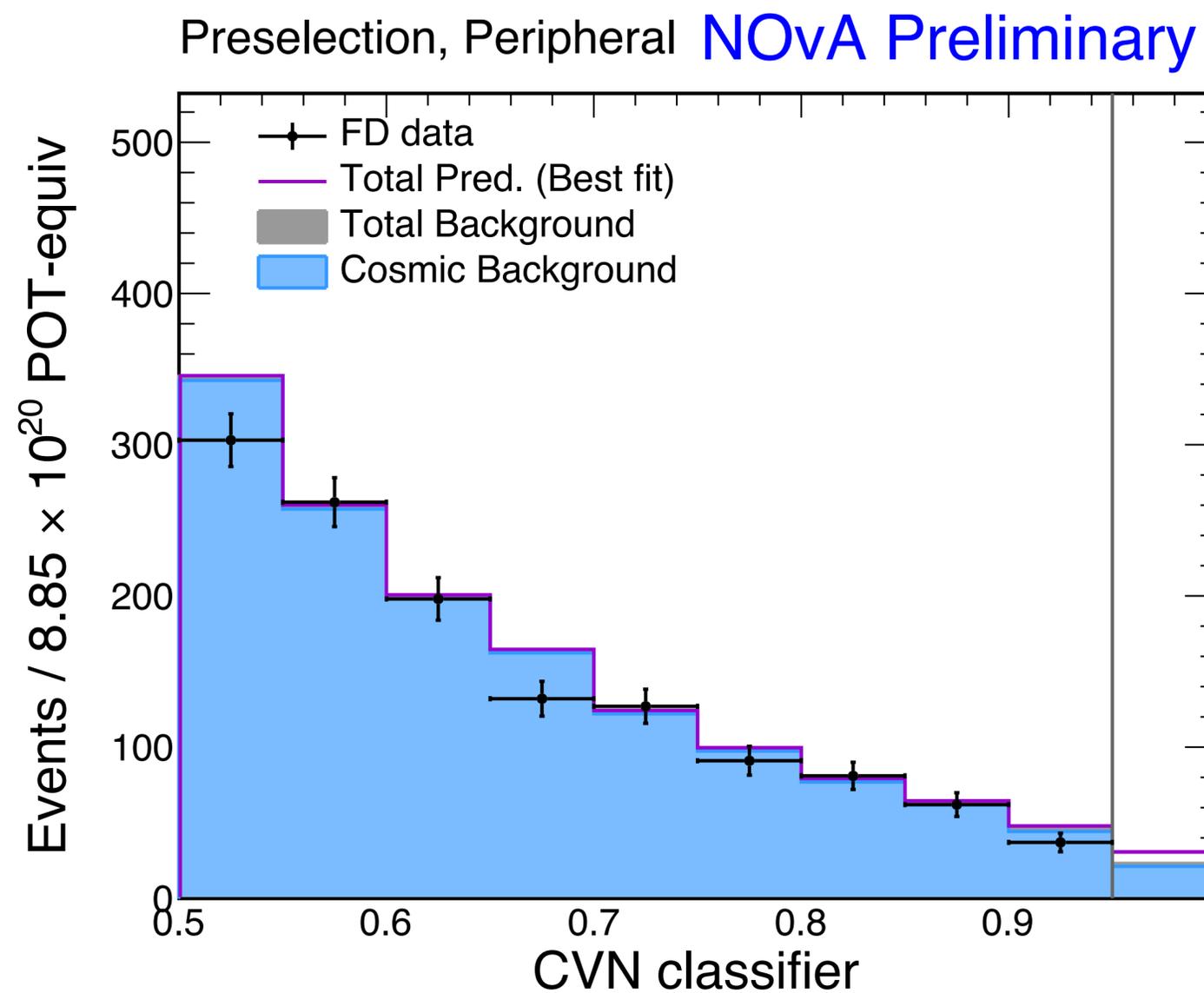
Core sample

Peripheral sample

Full Preselection, Core **NOvA Preliminary**

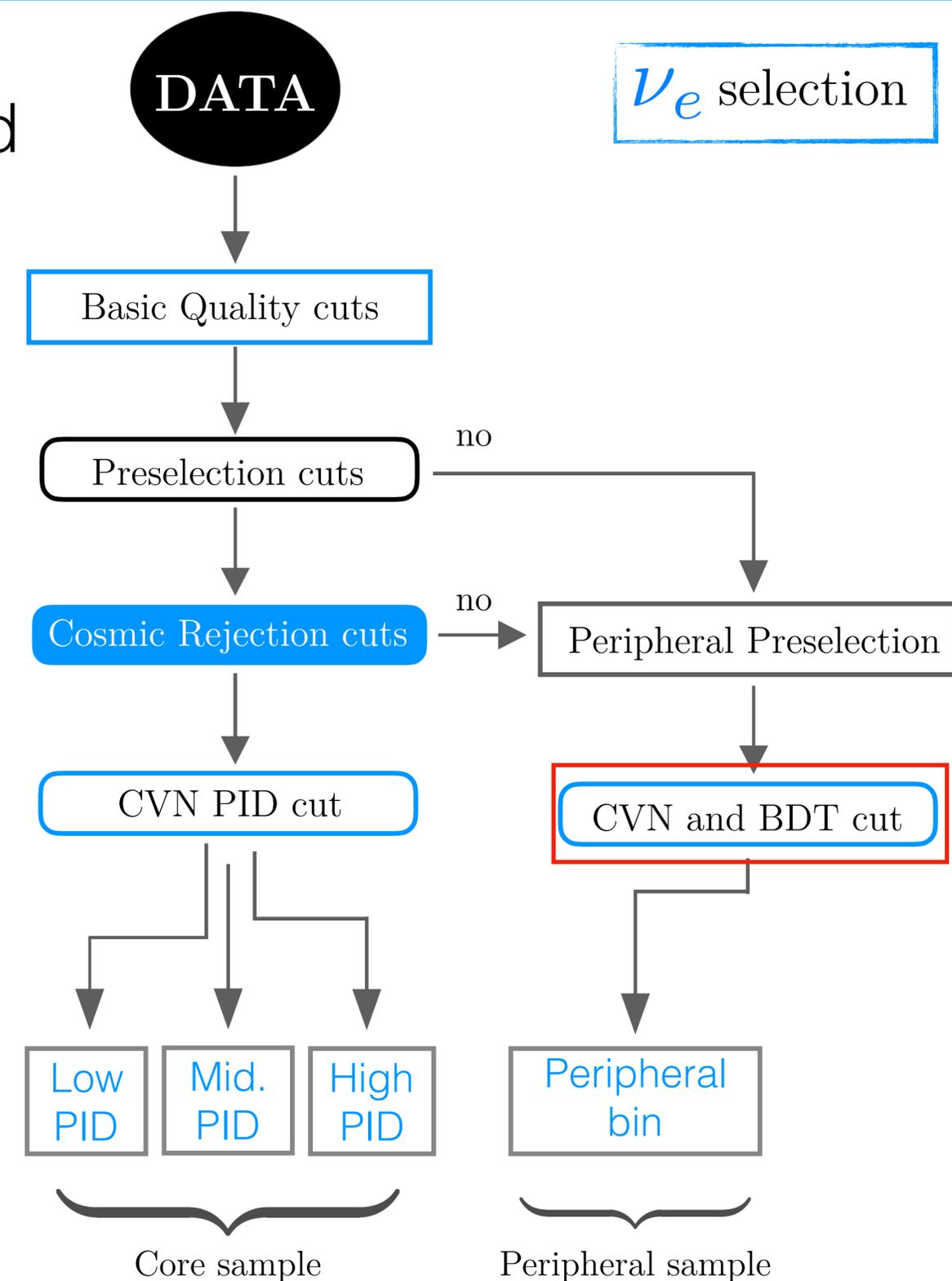
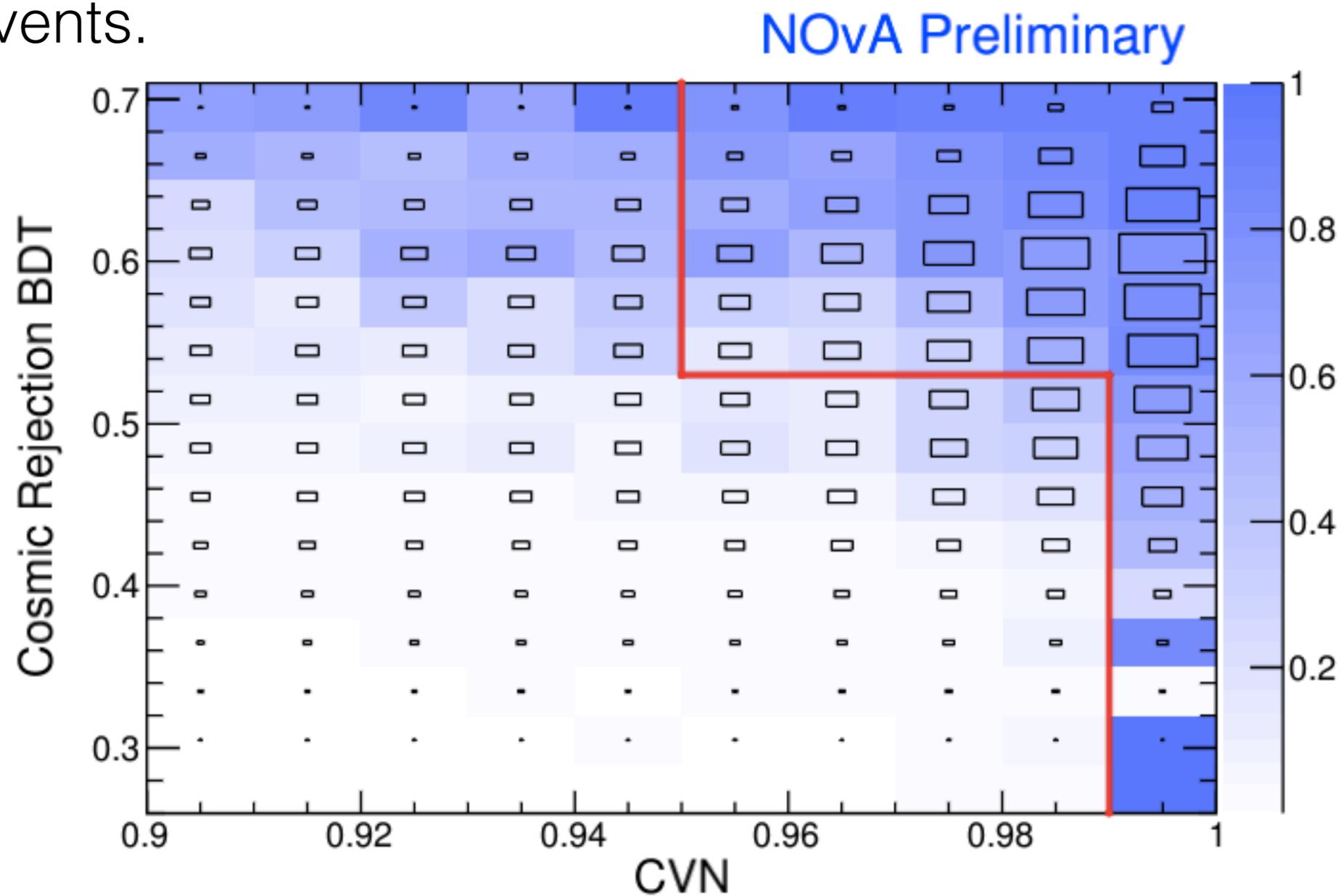
ν_e Selection

Harsh cosmic rejection cuts also reject some signal events. The addition of a new cosmic rejection BDT and a tight cut on CVN allow us to reclaim some of those events.



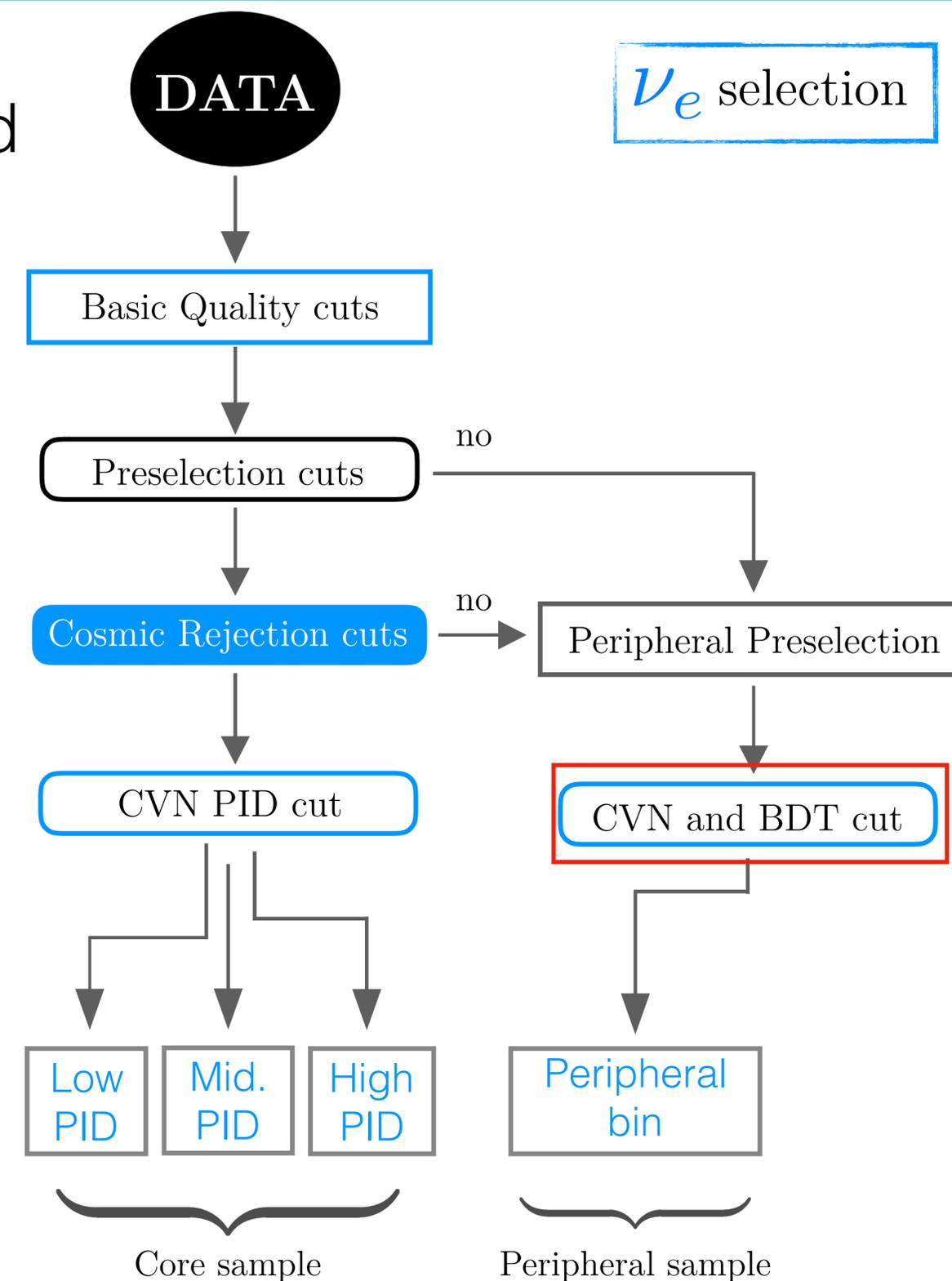
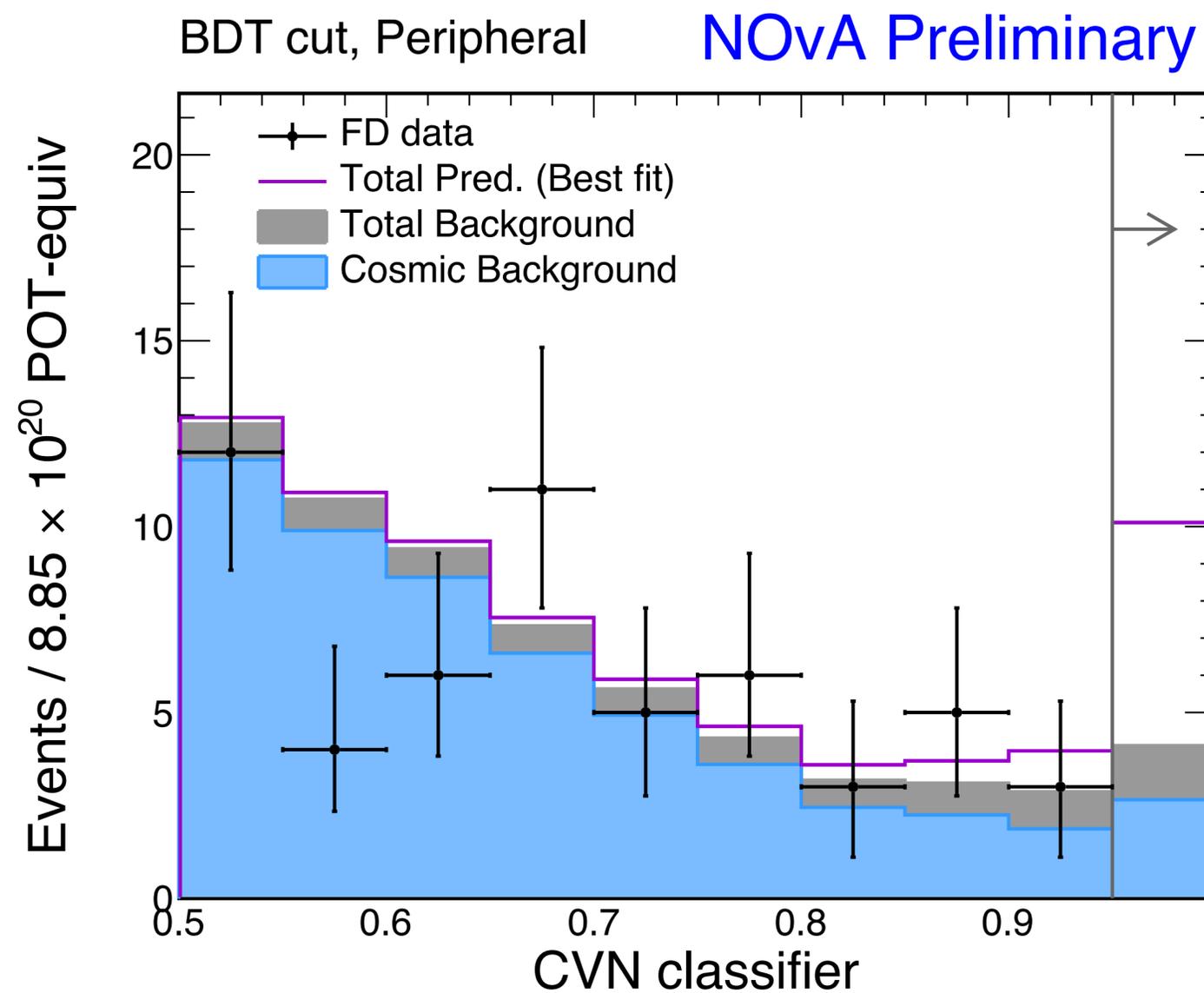
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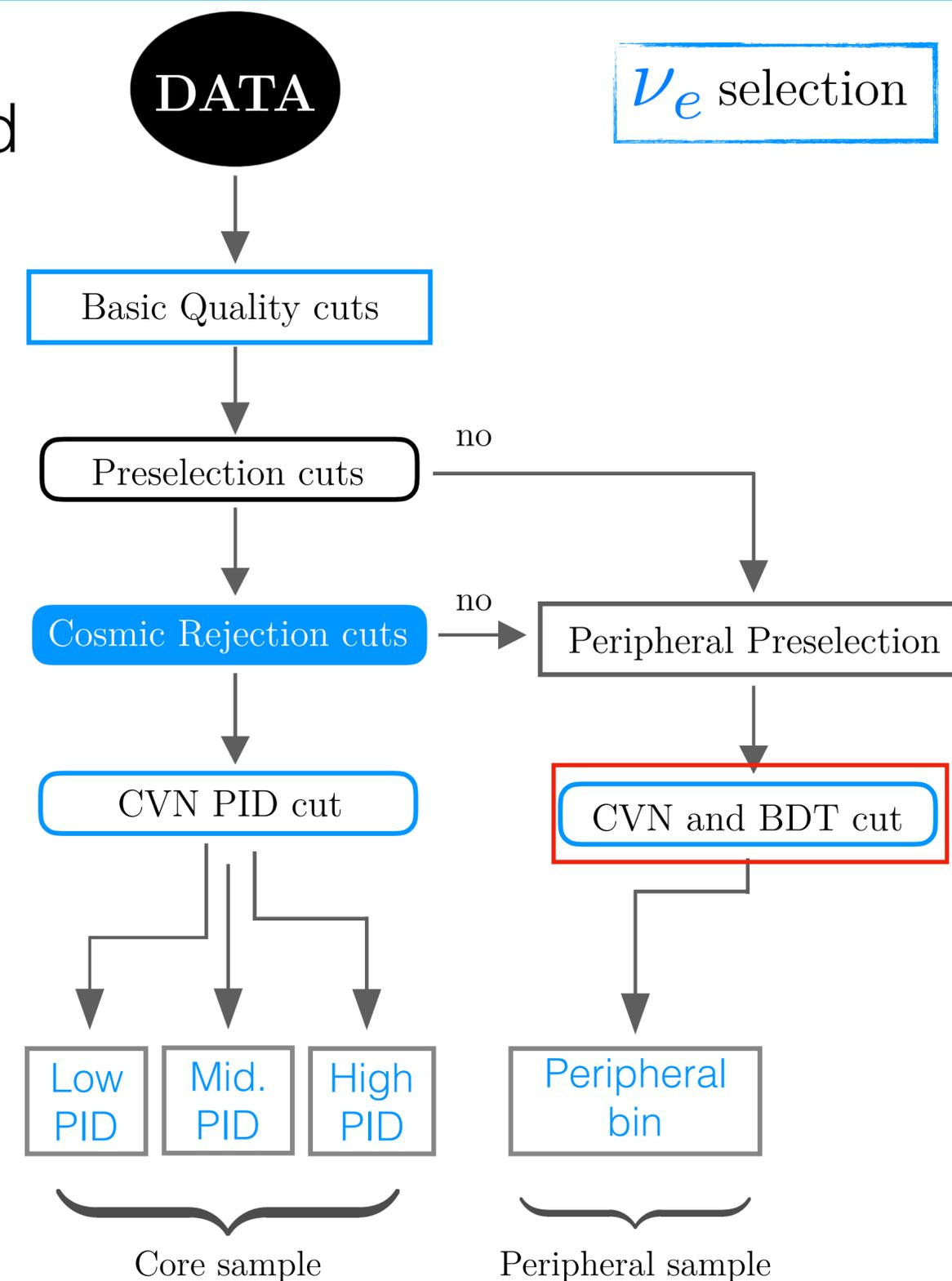
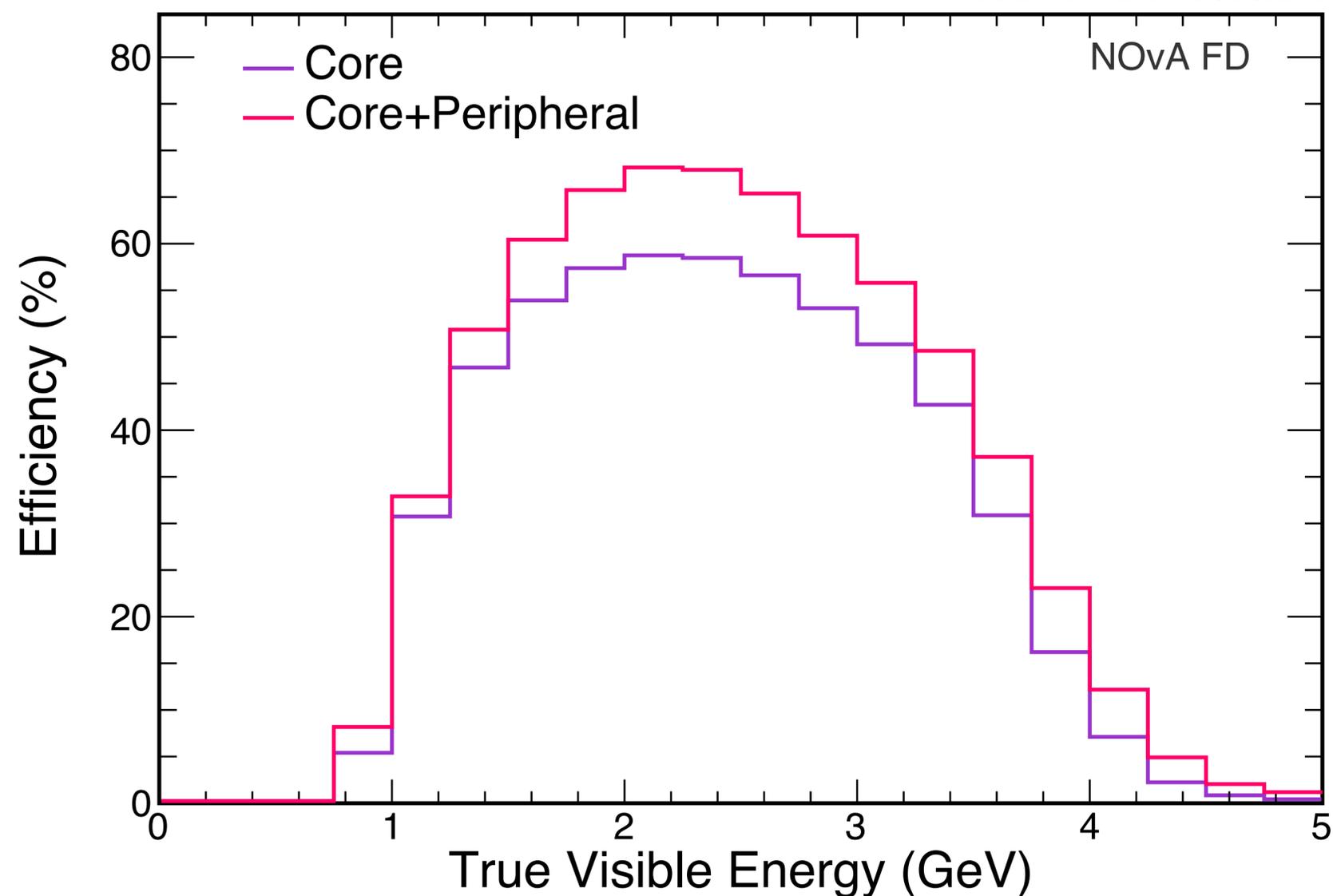


ν_e Selection

Harsh cosmic rejection cuts also reject some signal events. The addition of a new cosmic rejection BDT and a tight cut on CVN allow us to reclaim some of those events.

NOvA Simulation

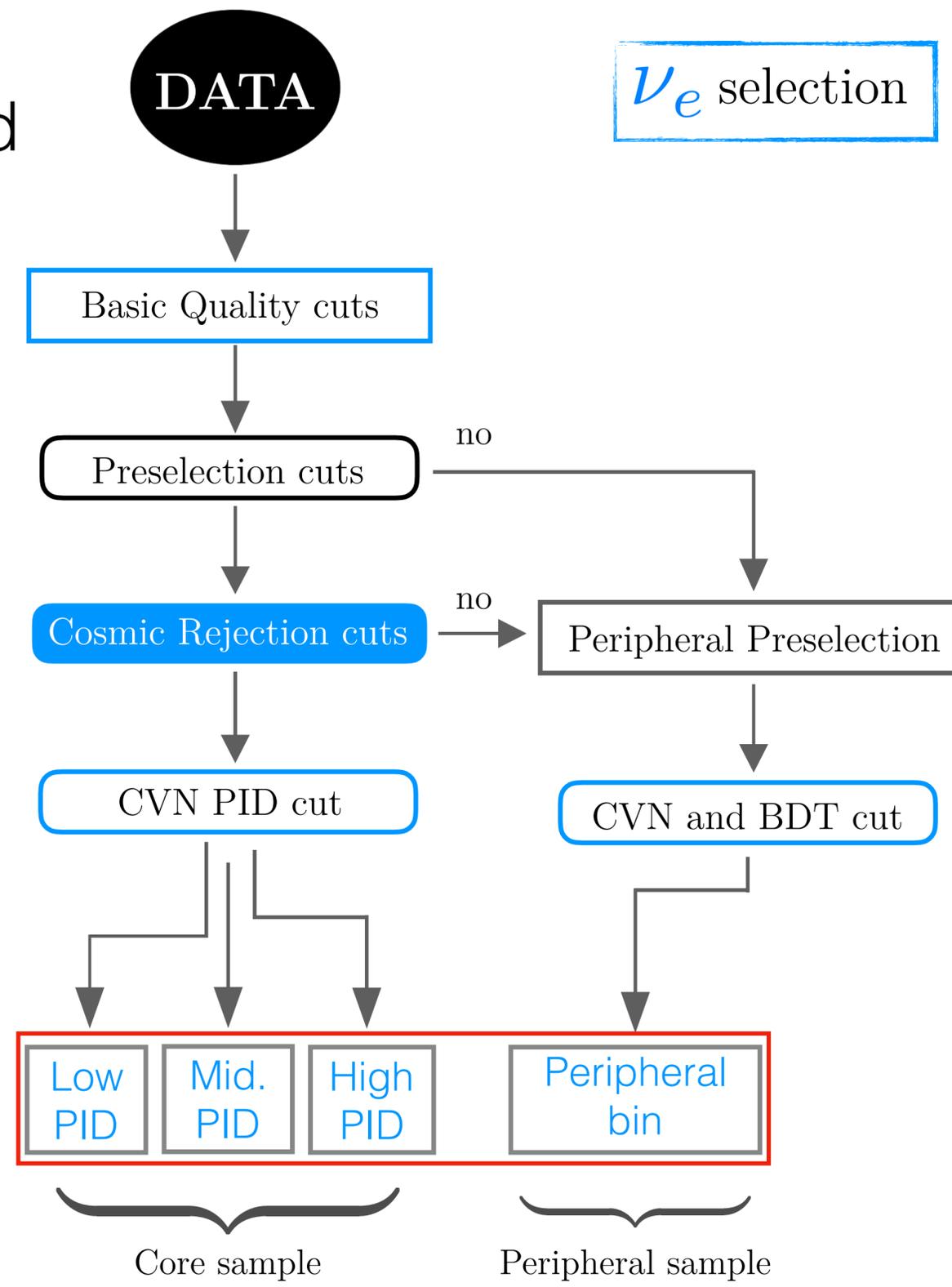
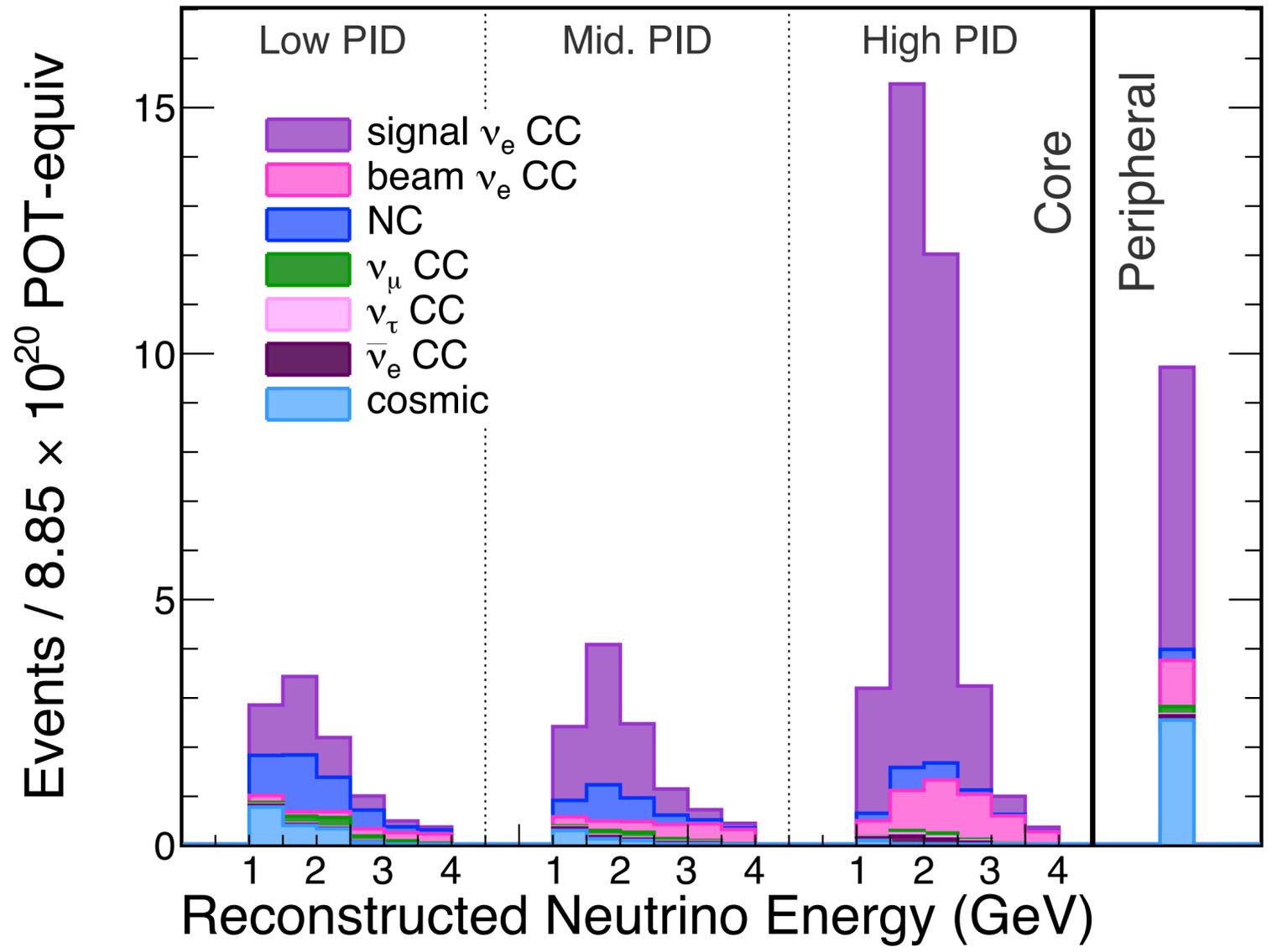
NOvA FD



ν_e Selection

Harsh cosmic rejection cuts also reject some signal events. The addition of a new cosmic rejection BDT and a tight cut on CVN allow us to reclaim some of those events.

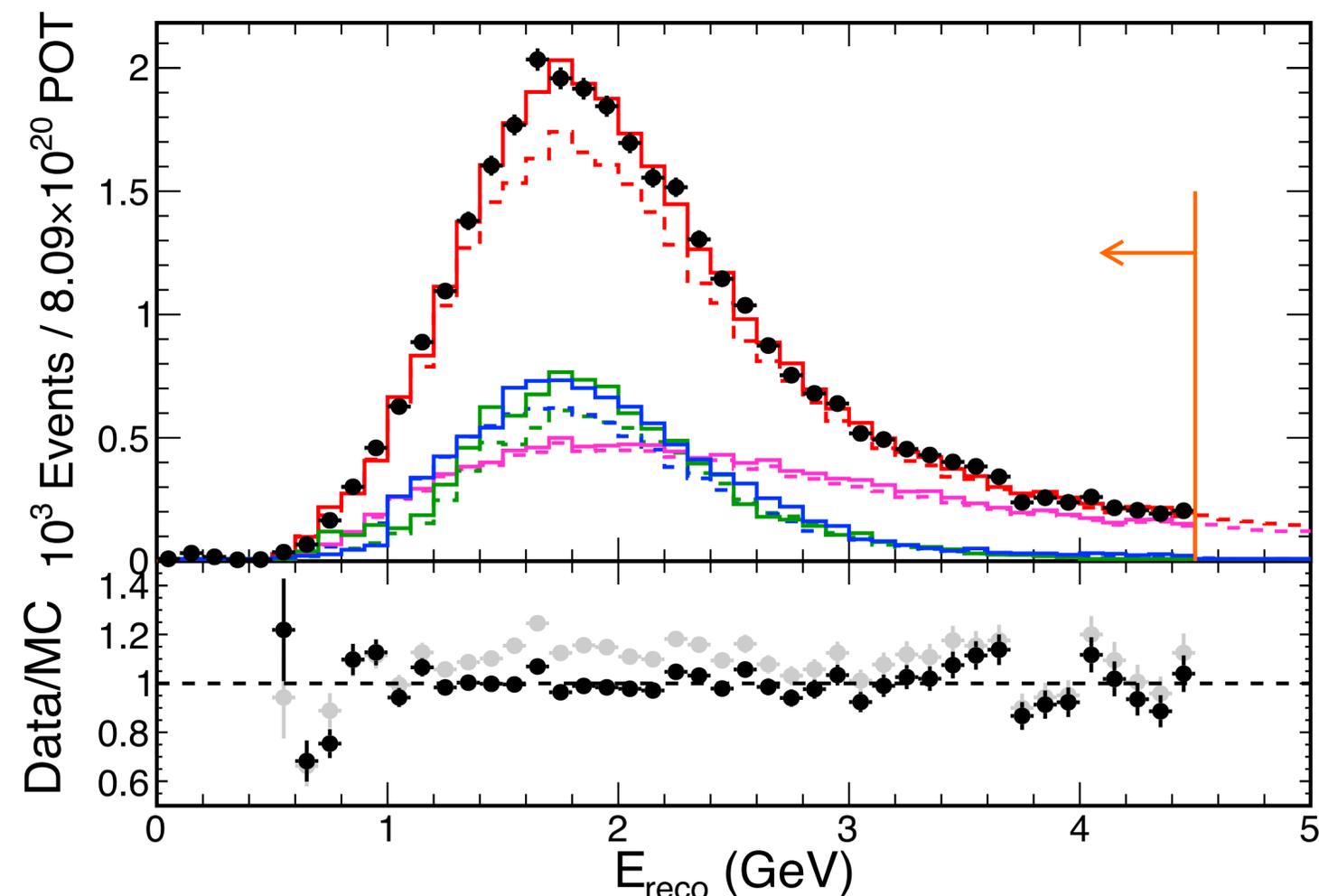
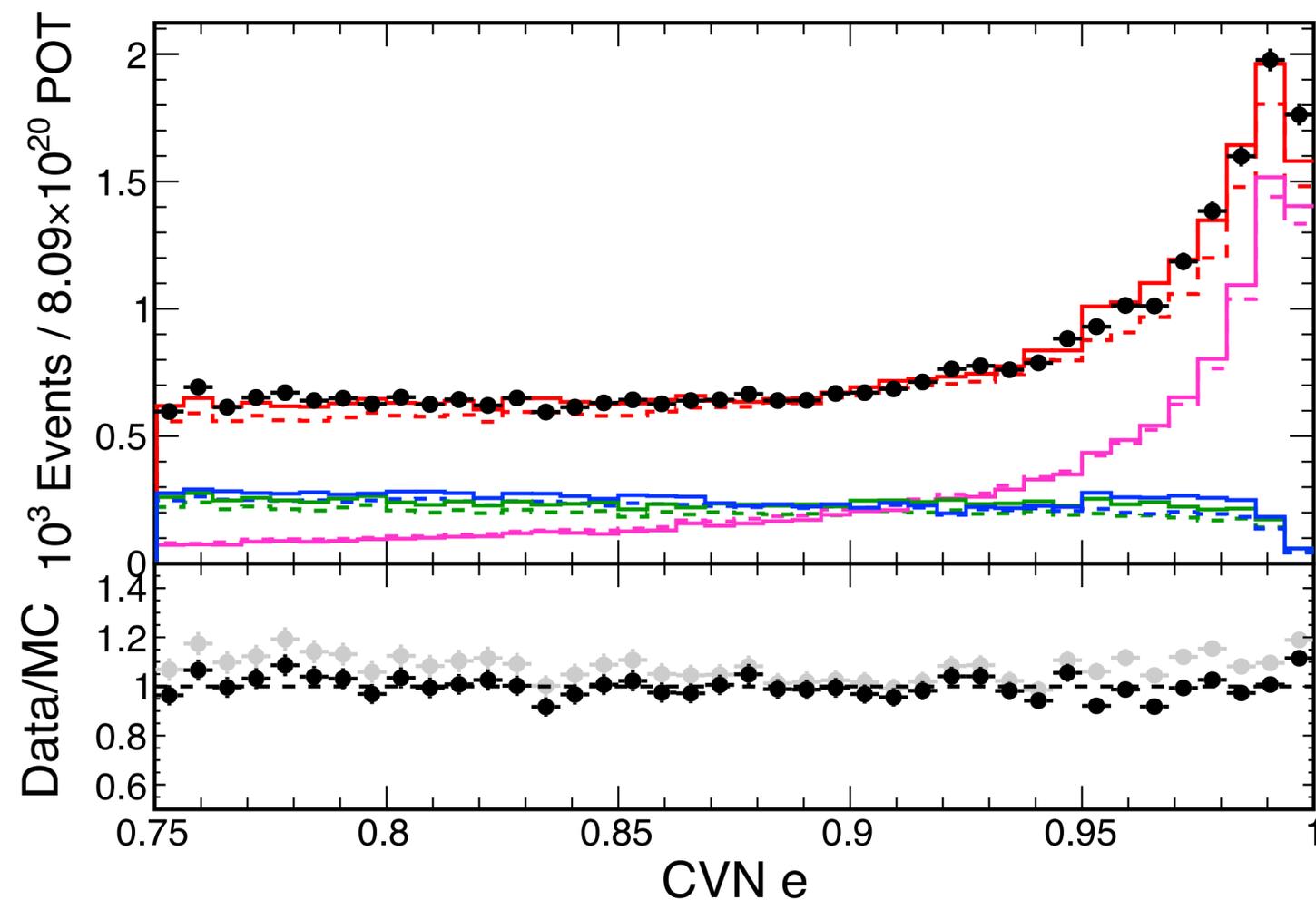
NOvA Preliminary



ν_e ND Selected Sample



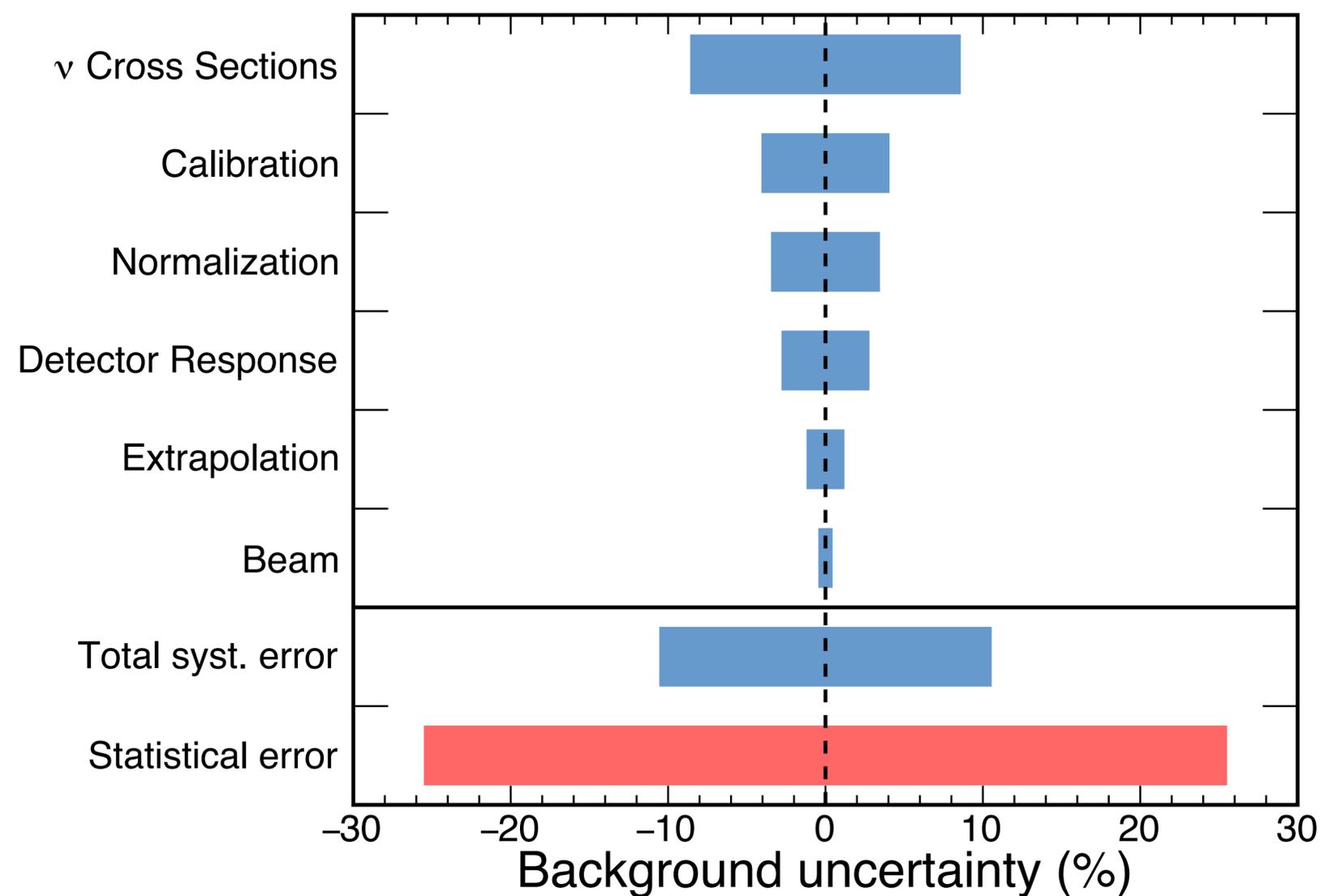
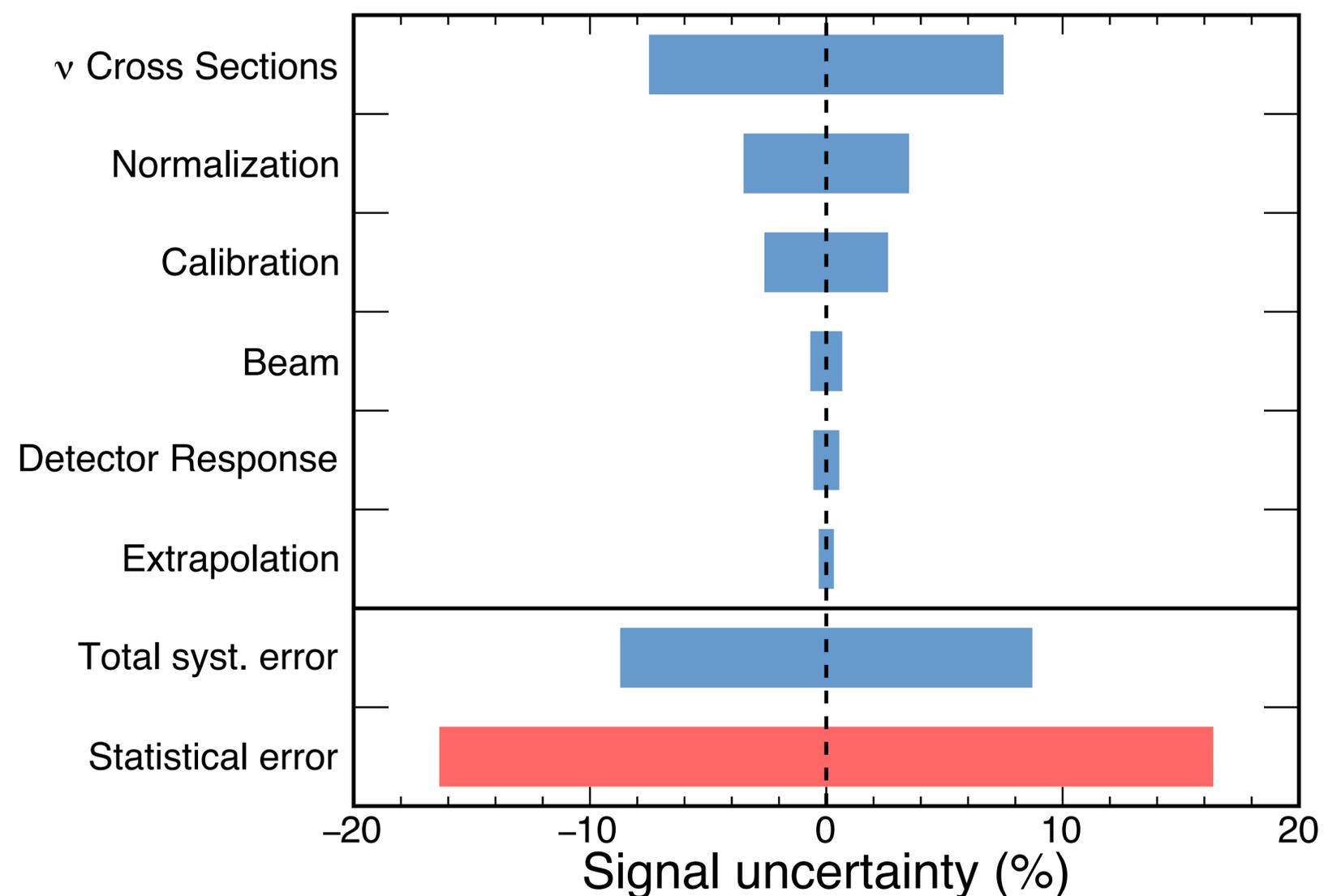
- Signal prediction from the ND selected ν_μ spectra used in disappearance analysis.
- Background prediction from ND selected ν_e data, data driven breakdown of the sample in order to extrapolate each component separately.
- Final background correction: beam ν_e up by 1%, NC up by 20%, ν_μ CC up by 10%.



ν_e Systematics



- As in ν_μ systematics were assessed by generating sets of shifted MC.
- Those shifted datasets were used instead of our nominal MC to assess the impact on our final result.



ν_e FD Predicted Sample

- Extrapolate each component in bins of energy and CVN output.
- Expected event counts depend on oscillation parameters.

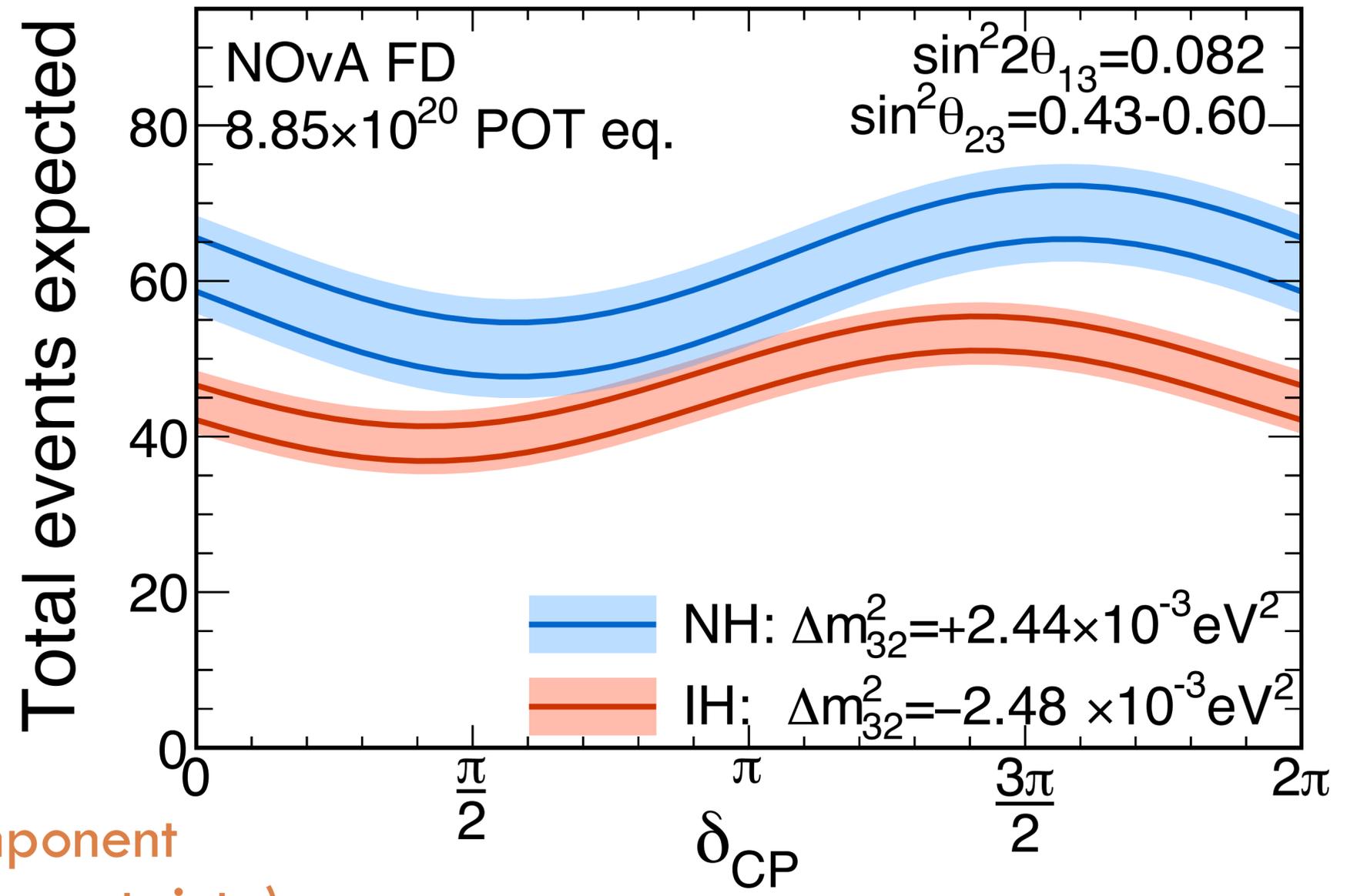
Signal events
($\pm 9\%$ systematic uncertainty):

NH, $3\pi/2,$	IH, $\pi/2,$
48	20

Background by component
($\pm 10\%$ systematic uncertainty):

Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
20.5	6.6	7.1	1.1	0.3	4.9

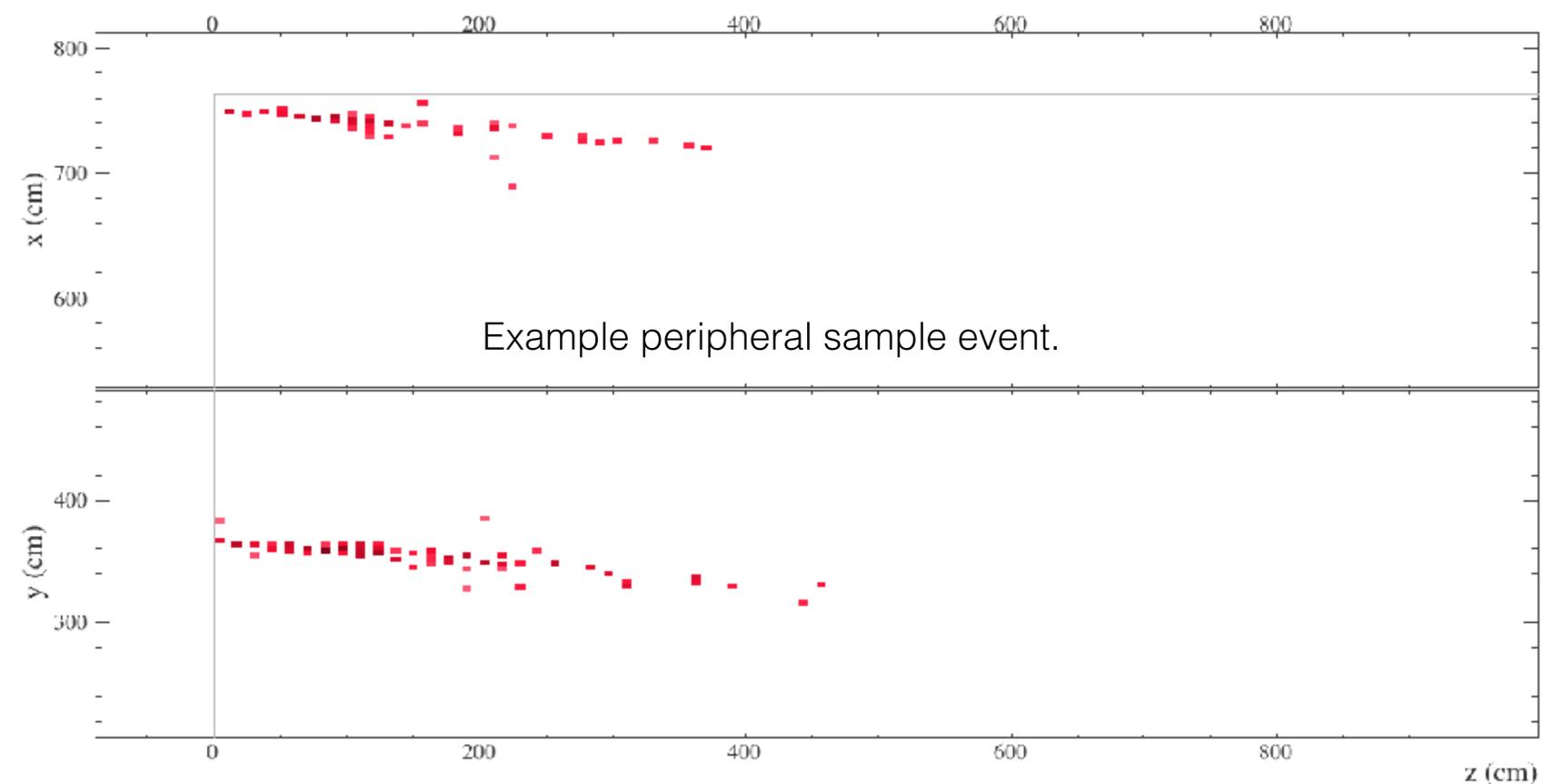
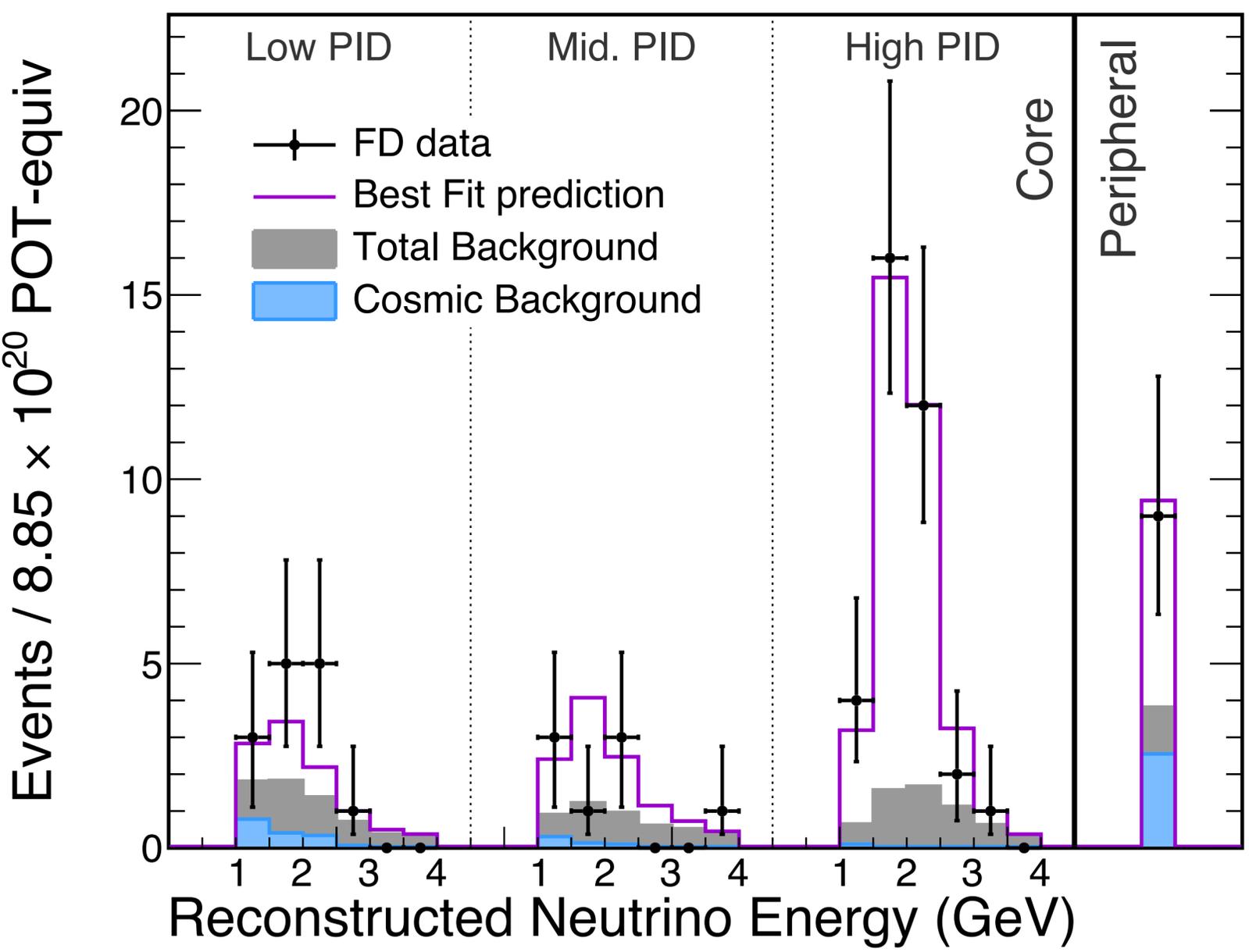
NOvA Simulation



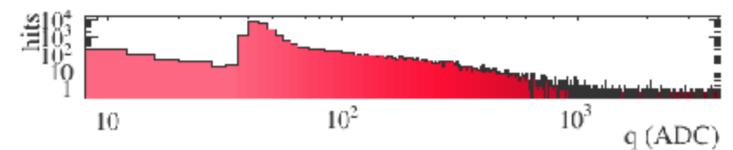
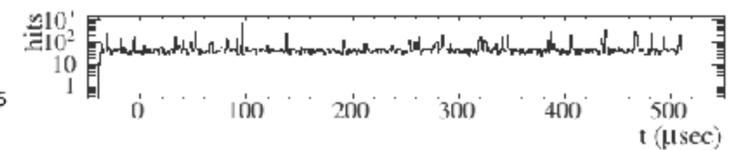
ν_e FD Selected Sample

Observe **66 events in FD**. Background Expectation 20.5 ± 2.5 .

NOvA Preliminary



NOvA - FNAL E929
Run: 19348 / 58
Event: 832917 / --
UTC Wed Apr 15, 2015
16:36:45.989739568

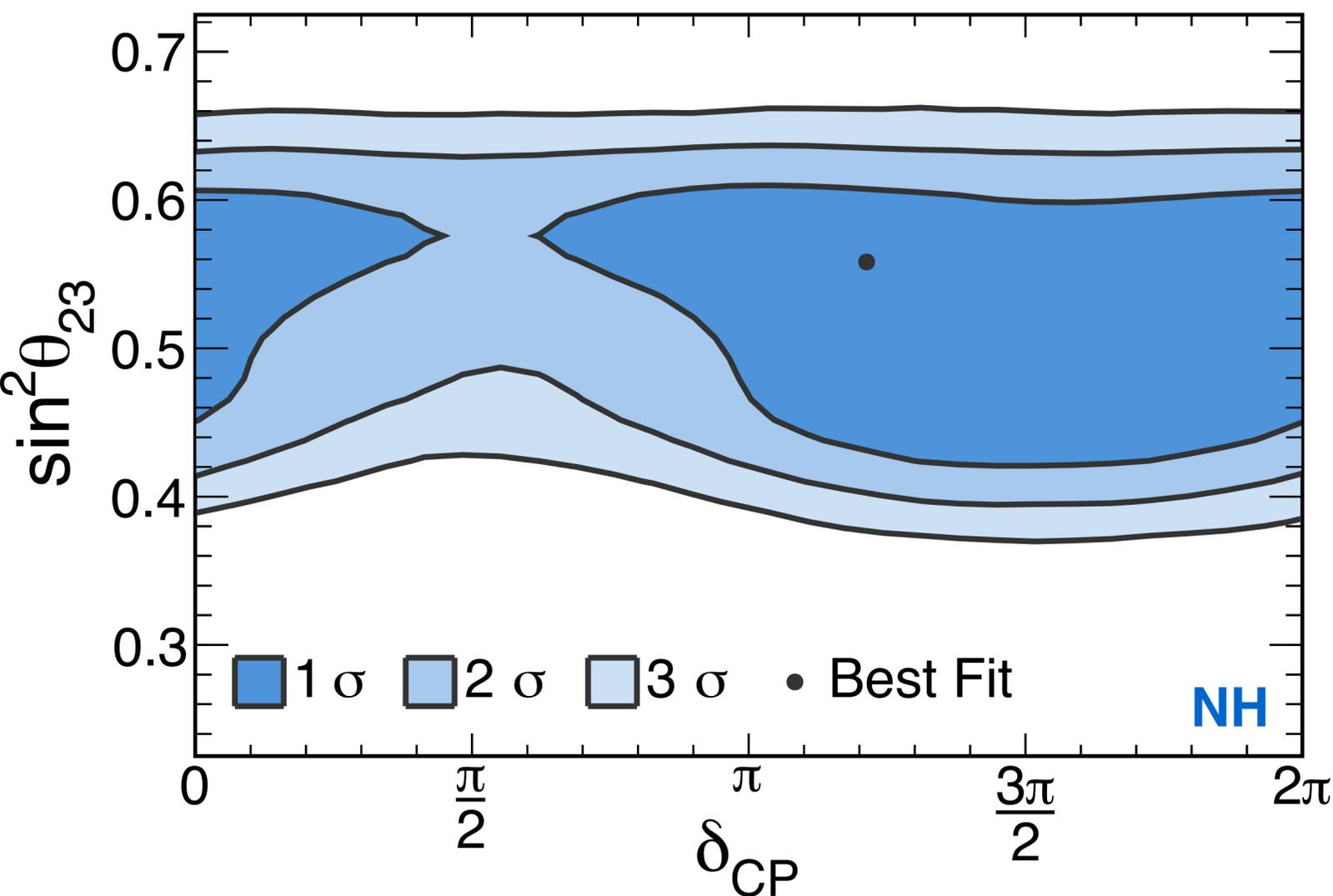


Joint Best Fits

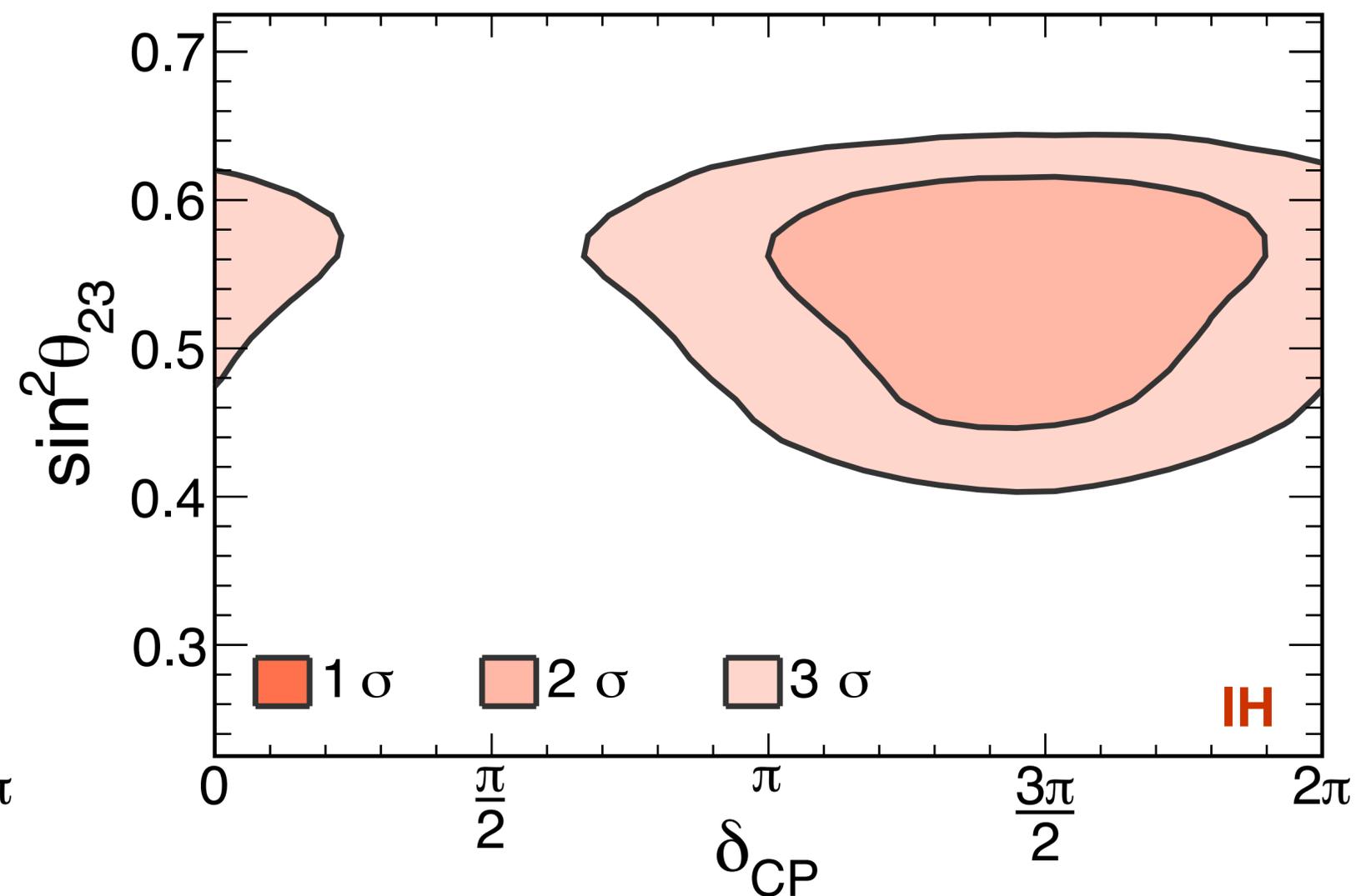


- Full joint fit with disappearance analysis. Feldman Cousins corrections in 2D & 1D limits.
- All systematics, oscillation pull terms shared.
- Constrain θ_{13} using world average from PDG, $\sin^2 2\theta_{13} = 0.082$

NOvA Preliminary



NOvA Preliminary

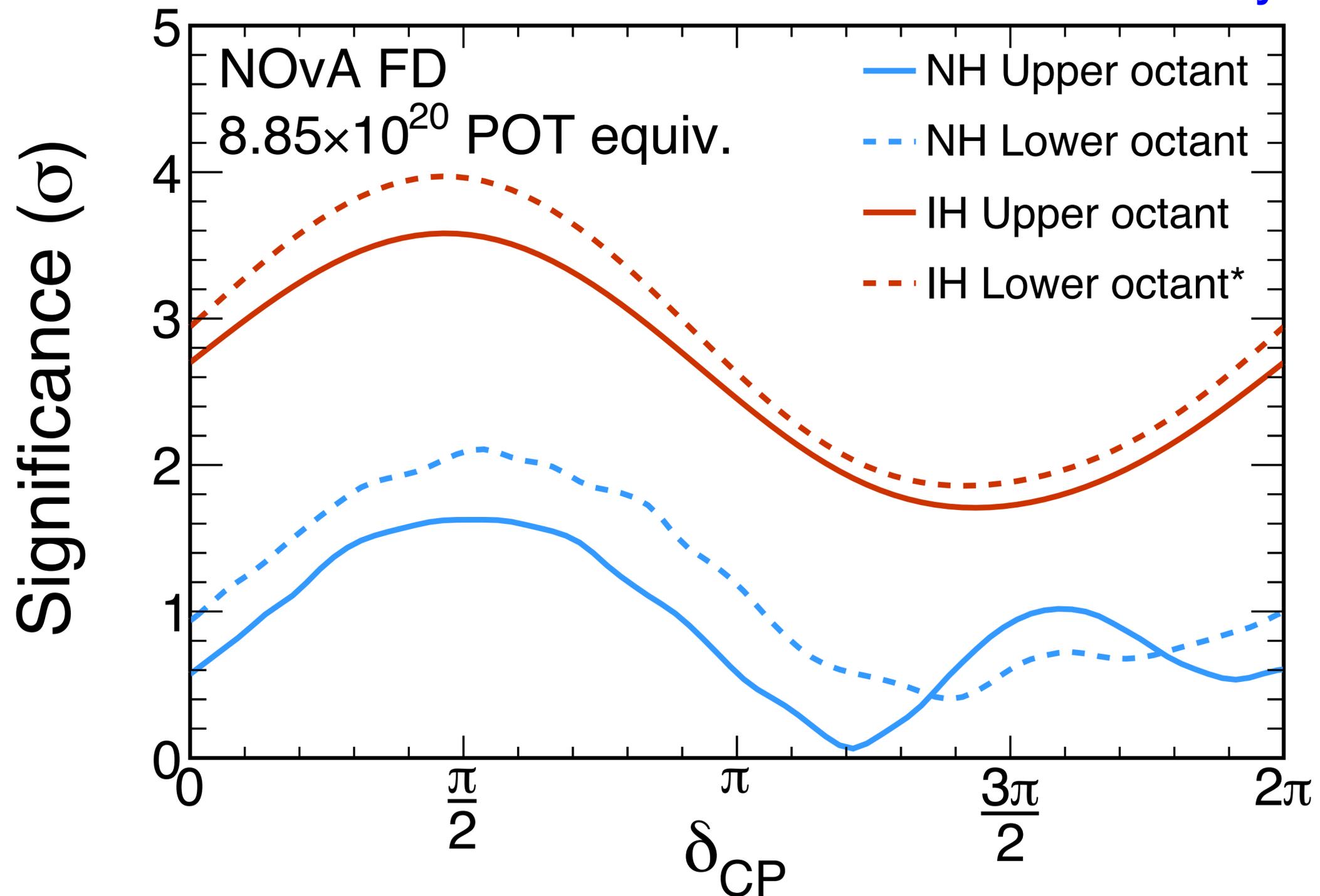


Joint Best Fits

NOvA Preliminary

IH at $\delta_{CP} = \pi/2$
disfavored at greater
than 3σ .

Approaching IH
rejection at 2σ .

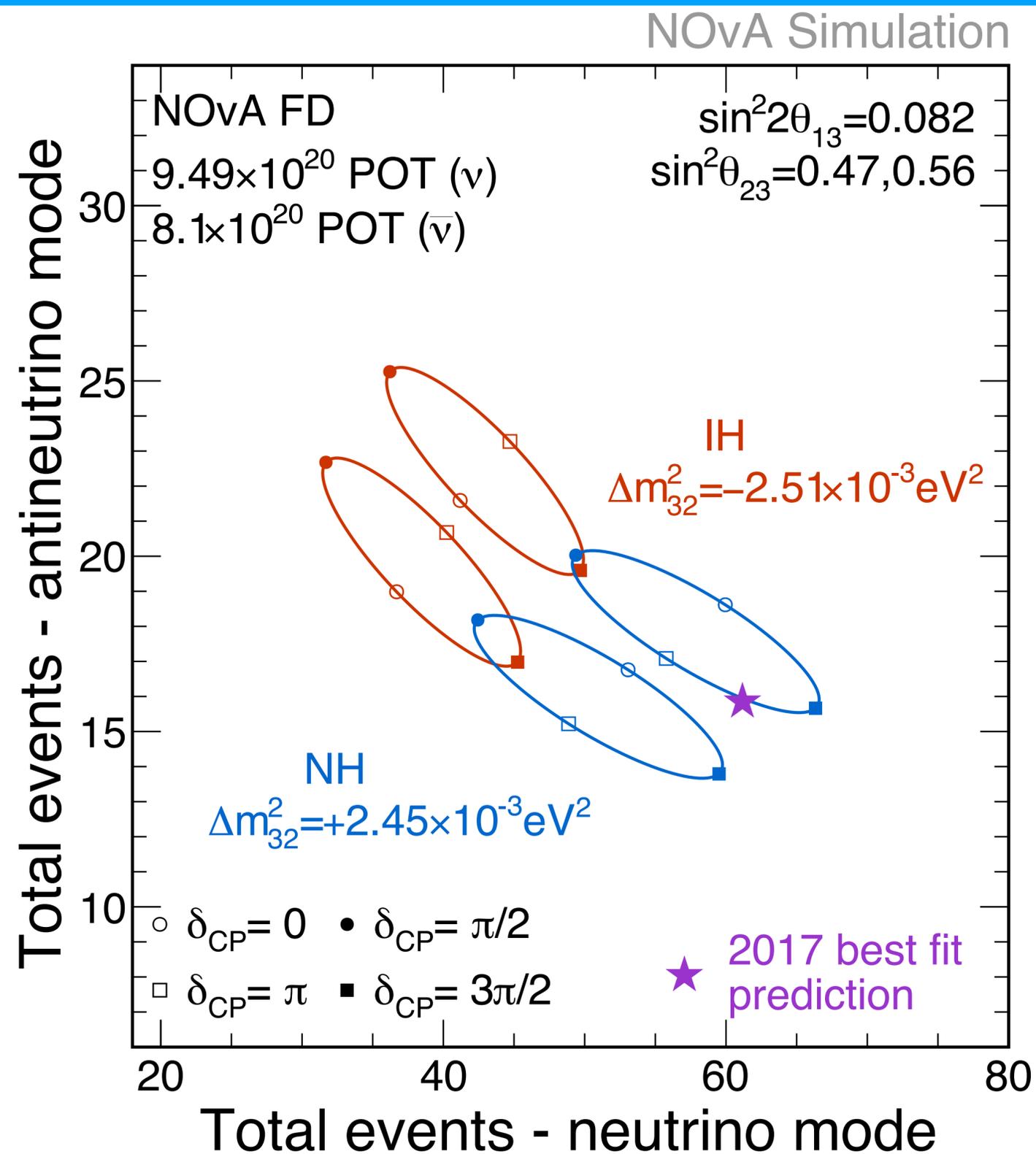


The Future

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The Future

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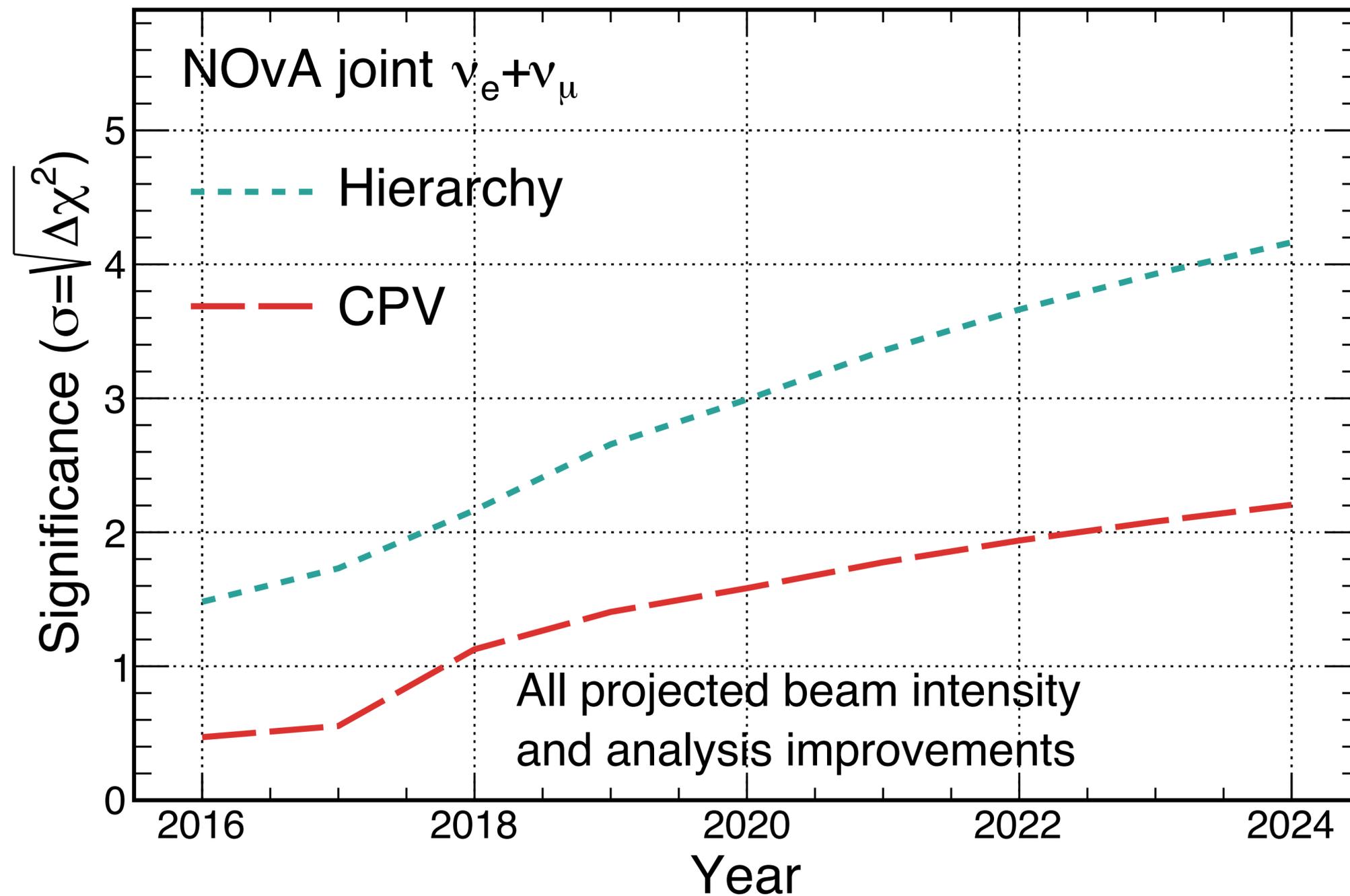


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Normal $\delta_{CP}=3\pi/2$, $\sin^2\theta_{23}=0.500$

$\Delta m_{32}^2=2.45\times 10^{-3}\text{eV}^2$, $\sin^2 2\theta_{13}=0.082$

NOvA Simulation



Conclusions

- At 8.85×10^{20} POT, NOvA finds:
 - **Muon neutrinos disappear:** Competitive measurement of Δm^2_{32} , new analysis prefers mixing near-maximal.
 - **Electron neutrinos appear:** Inverted Hierarchy at $\delta_{cp} = \pi/2$ disfavored at greater than 3σ . Approaching 2σ IH rejection.
- **Excellent detector and beam performance.**
- **Significant improvement in our analysis tools.** Expected to continue, benefiting from efforts like the NOvA test beam.
- Looking forward to opening the box on our first antineutrino data this summer! Expect NOvA to continue to contribute to key questions:
 - Is δ_{cp} nonzero?
 - What is the mass hierarchy?

JINR contribution to NOvA

Name	Laboratory	Tasks	FTE	Name	Laboratory	Tasks	FTE
Allakhverdian, V.	DLNP	ND Physics, s-quark prop	0.4	Kuznetsov, E.	LIT	Computing, hardware	0.1
Amvrosov, V,	DLNP	Numu oscillation analysis	0.1	Matveev, V.	BLTP	Theory, Coll management	0.1
Anfimov, N.	DLNP	Det operations, test stand	0.3	Morozova, A.	DLNP	Exotics, CR muons	0.3
Antoshkin, A.	DLNP	Det operations, test stand	0.3	Naumov, V.	BLTP	Osc and cross sec theory	0.3
		Exotics, slow monopoles	0.3	Olshevskiy, A.	DLNP	Coll and JINR manag, IBrep	0.5
		Det control, ROC-liaison	0.1	Petrova, O.	DLNP	Exotics, CR muons	0.7
Balashov, N.	LIT	Computing	0.3			Det sim, cross sec calc	0.3
Baranov, A.	LIT	Computing, Cloud	0.1	Samoylov, O.	DLNP	Det sim, co-convener	0.5
Bolshakova, A.	DLNP	Reco, Proton ID	0.5			Det control, ROC-manag	0.3
		Det sim, ADC thresholds	0.5			JINR ana coordinations	0.1
Bilenky, S.	BLTP	Oscillation theory	0.1			Coll manag, deputy at JINR	0.1
Dolbilov, A.	LIT	Computing, network support	0.1	Sheshukov, A.	DLNP	DAQ, software dev/support	0.3
Kakorin, I.	VLHEP	Det sim, GENIE	0.5			DDT, supernova trigger dev	0.3
Klimov, O.	DLNP	Reco, Proton ID	0.6			Exotics, supernova detect	0.3
Kolupaeva, L.	DLNP	Nue oscillation analysis	0.8			Det control, ROC software	0.1
		Software, release manag	0.2	Sotnikov, A.	DLNP	Det operations, test stand	0.1
Kullenberg, K.	DLNP	ND Physics, con pion	0.6	Velikanova, D.	DLNP	Det operations, test stand	0.1
Kuzmin, K.	BLTP	Det sim, cross sec theory	0.1	TOTAL 24			10.3

NOvA работает, следите за обновлениями



- ❖ В 2017 году группой было представлено:
 - 11 докладов на конференциях ICRC, NEC, AYSS, “Ломоносов” МГУ;
 - 4 семинара ЛЯП;
 - 9 постеров на ПКК по ФЭЧ.
 - Опубликовано 2 индивидуальные статьи;
 - В печати 4 тезисов конференций.
- ❖ Следите в начале 2018 года:
 - Семинар ЛЯП по новым осцилляционным результатам 19 января 2018 (О.Б.Самойлов);
 - 11 постеров на 48 ПКК по ФЭЧ;
 - Пленарный доклад Людмилы Колупаевой на NuHorizon-2018;
 - Новые осцилляционные результаты, включающей антинейтринную моду в мае 2018;
 - Пленарный доклад Олега Самойлова на QUARKS-2018;
 - Участие с результатами анализов Л.Колупаевой и А.Шешукова на NEUTRINO-2018
 - Участие с докладом про обновление цепочки моделирования нейтринных событий и отклика детекторов О.Самойлова на SNRP-2018
 - и другие новости NOvA.