New Oscillation Results from the NOvA Experiment

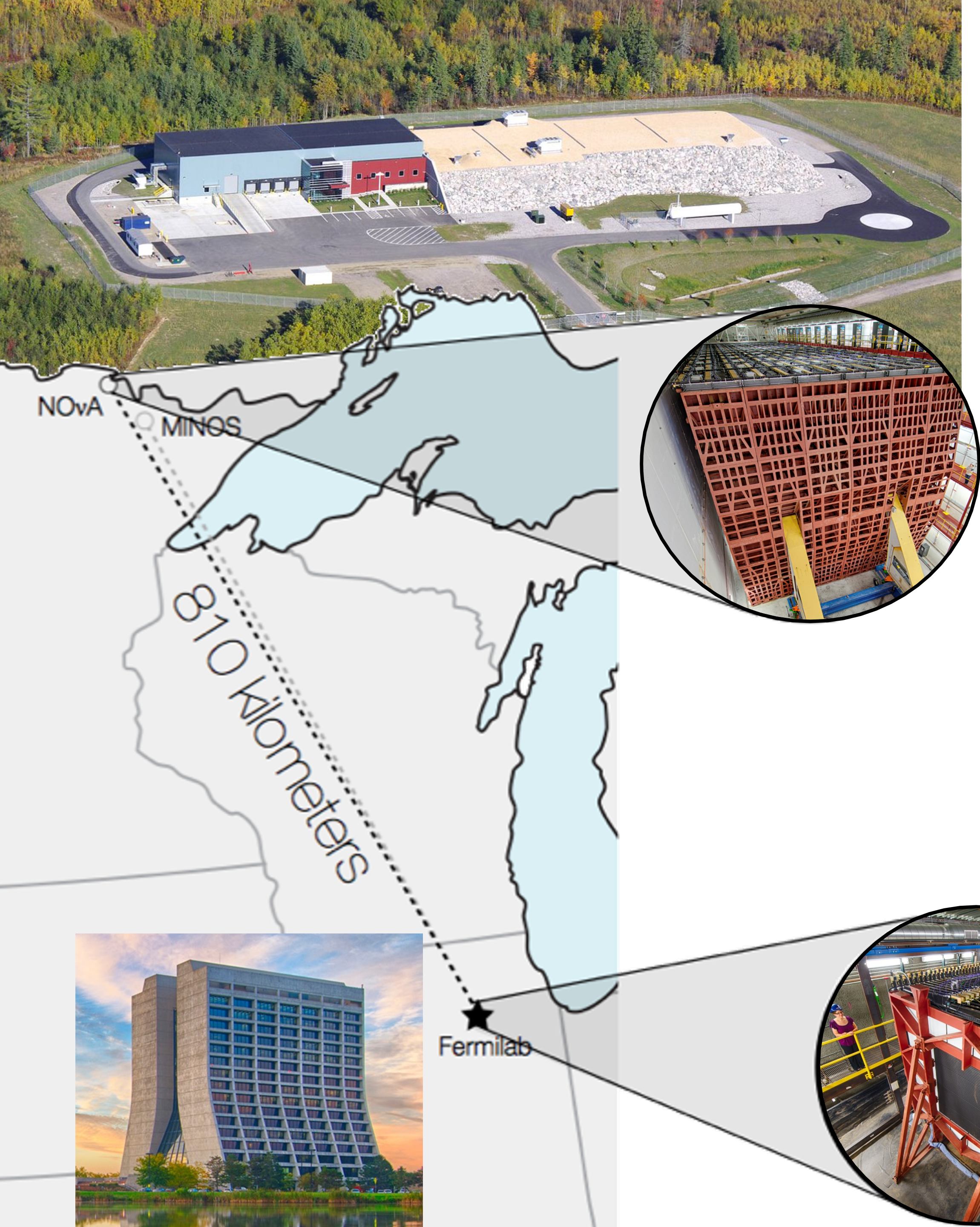
Alex Himmel, Fermilab
for the NOvA Collaboration

NOvA

Fermilab

NEUTRINO 2020

July 2nd, 2020

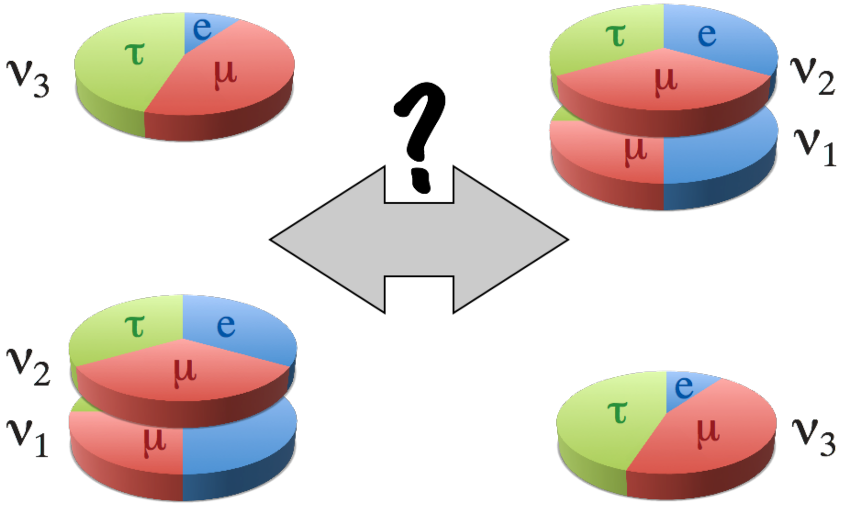


The NOvA Experiment

- Long-baseline neutrino oscillation experiment
- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.

Take a tour in VR!

NOvA Physics



- Atmospheric sector oscillations:
  - $\Delta m^2{}_{32}$, $\sin^2\theta_{23}$, δ_{CP}
- Key open questions in oscillations:
  - Is the neutrino mass hierarchy normal or inverted?
  - Is CP violated in the neutrino sector?
  - Is θ_{23} mixing maximal?
    - ν_μ-ν_τ symmetry
    - If not, what is the octant of θ_{23}?

NOvA Physics

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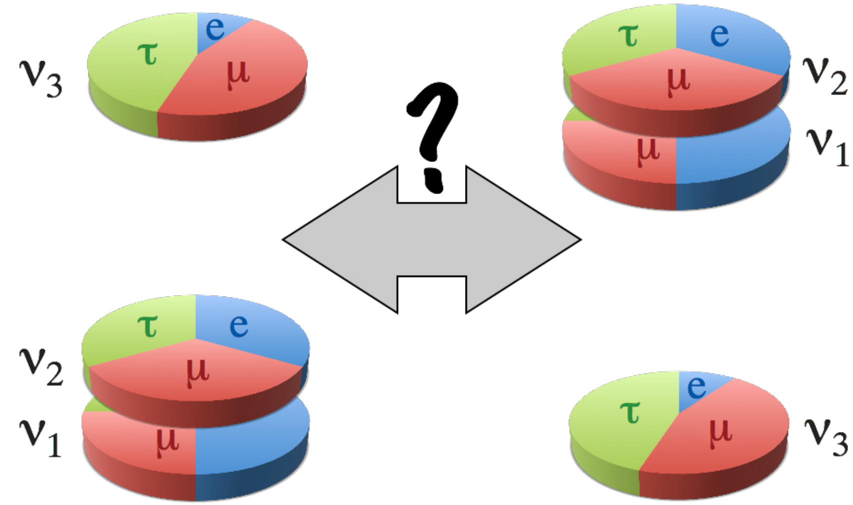
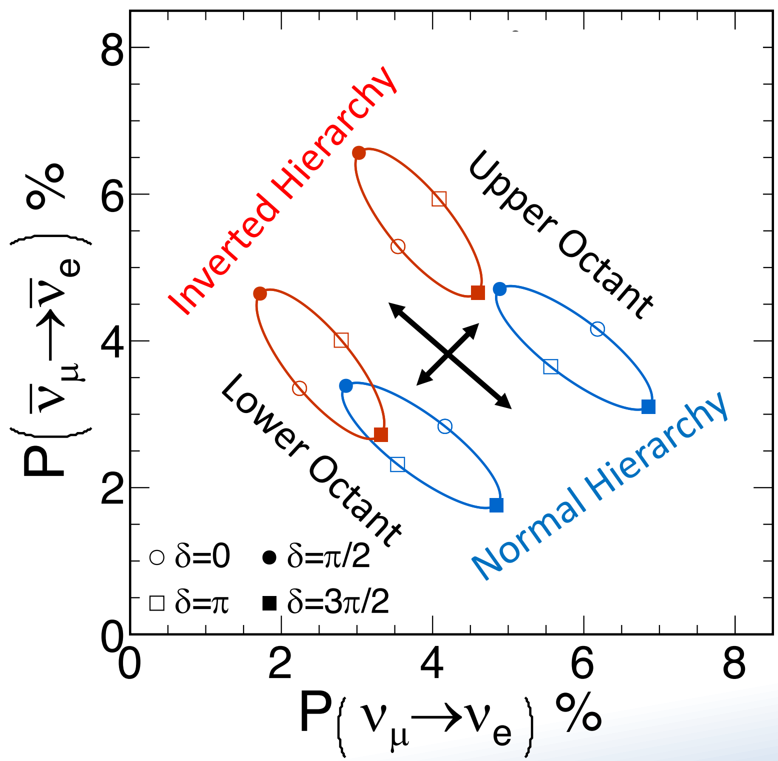
  - Is CP violated in the neutrino sector?
  - Is θ_{23} mixing maximal?
    - ν_μ-ν_τ symmetry
    - If not, what is the octant of θ_{23}?
- Disentangle by measuring…
  - disappearance $P(\nu_\mu \rightarrow \nu_\mu)$ and appearance $P(\nu_\mu \rightarrow \nu_e)$
  - in neutrinos and antineutrinos
  - over long baselines to separate hierarchy and δ effects.





NOvA Physics Beyond 3-flavor

Astrophysics Cross Sections Sterile and BSM

Neutrino 2020 Talks

- Cross-section measurements with NOvA
  - Linda Cremonesi

Papers since NEUTRINO 2018

- Observation of seasonal variation of atmospheric multiple-muon events in the NOvA Near Detector, Phys.Rev.D 99 (2019) 12, 122004
- Search for Multi-Messenger Signals in NOvA Coincident with LIGO/Virgo Detections, Phys.Rev.D 101 (2020) 112006
- Supernova neutrino detection in NOvA, arXiv: 2005.07155 [physics.ins-det]

- Measurement of Neutrino-Induced Neutral-Current Coherent π^0 Production in the NOvA Near Detector, Accepted to PRD, arXiv: 1902.00558 [hep-ex]
- Adjusting Neutrino Interaction Models and Evaluating Uncertainties using NOvA Near Detector Data, arXiv: 2006.08727 [hep-ex]

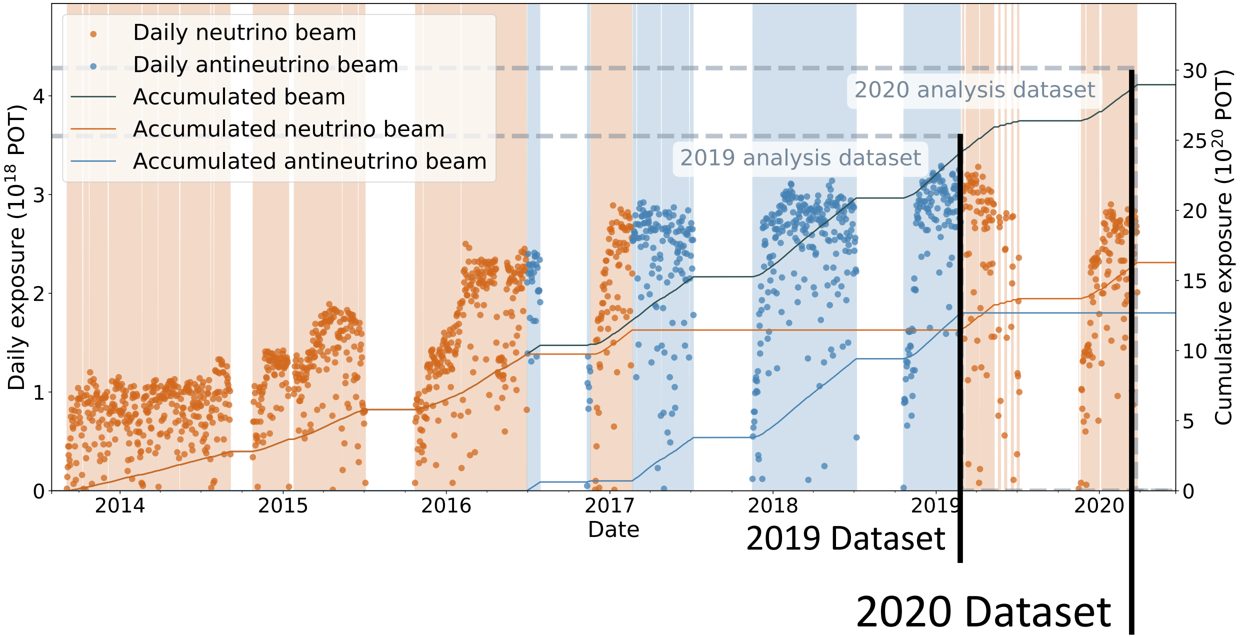
Neutrino 2020 Posters

- 358. Astrophysics with NOvA, Matt Strait & Oleg Samoylov
- 550. Galactic Supernova Neutrinos, Justin Vasel, Andrey Sheshukov, Alec Habig

- 555. Event Selection and Systematics, Adam Lister & Anne Norrick
- 442. Sterile Neutrino Search via NC Disappearance with Antineutrinos, Mike Wallbank
- 431. Poisson Likelihood Covariance Technique for 3+1 Sterile Searches, Jeremy Hewes
- 541. Neutrino Tridents, Erica Smith & Kelli Michaels

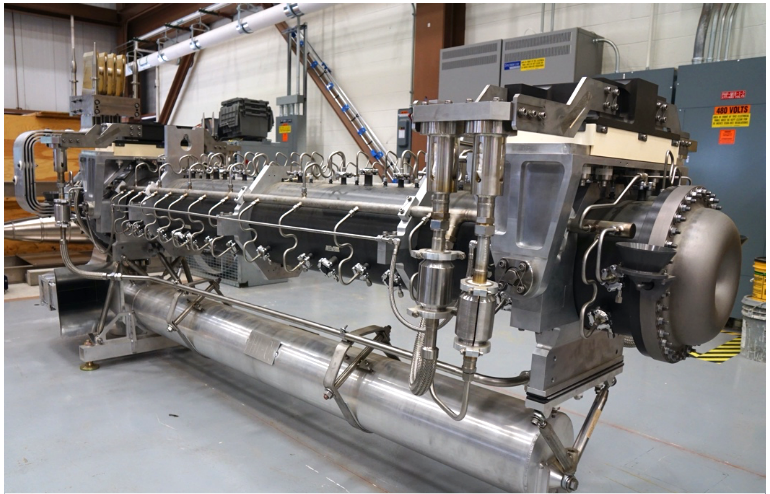
- 398. Inclusive CC ν_μ , Connor Johnson
- 505. Inclusive CC ν_e, Matt Judah
- 228. CC $\nu_\mu\pi^\pm$, Cathal Sweeney

The NuMI Beam



- Typically ~670 kW
- Peaks >750 kW
- 50% more neutrino beam data in this analysis

MW-capable target

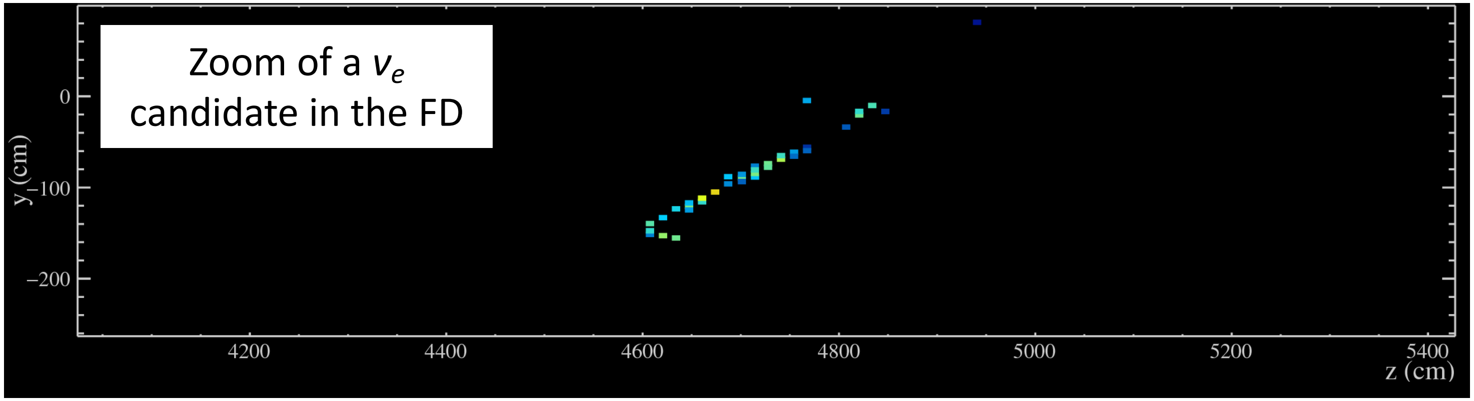


MW-capable horn

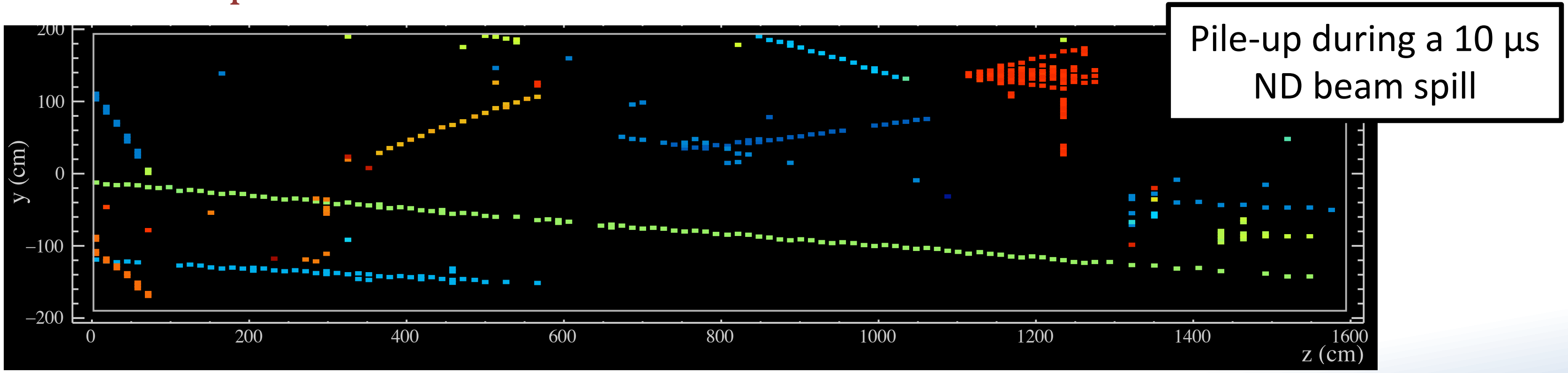
- Working towards 900+ kW
  - Upgrading the NuMI beamline components
  - Allows gradual increase in power up to 850 kW with faster cycle times
  - Early PIP-II upgrades allow 900+ KW

The NOvA Detectors

- Segmented liquid scintillator detectors provide 3D tracking and calorimetry
- Optimized for electron showers: ~6 samples per X_0 and ~60% active



- Good time resolution (few ns) and spatial resolution (few cm)
  - Allows clear separation of individual interactions



How to Measure Oscillations

Observe flavor change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections, and detector response.

How to Measure Oscillations

Neutrino ID

Reconstruction

Observe flavor change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections, and detector response.

Extrapolation

Models

How to Measure Oscillations

Neutrino ID

Reconstruction

Observe flavor change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections, and detector response.

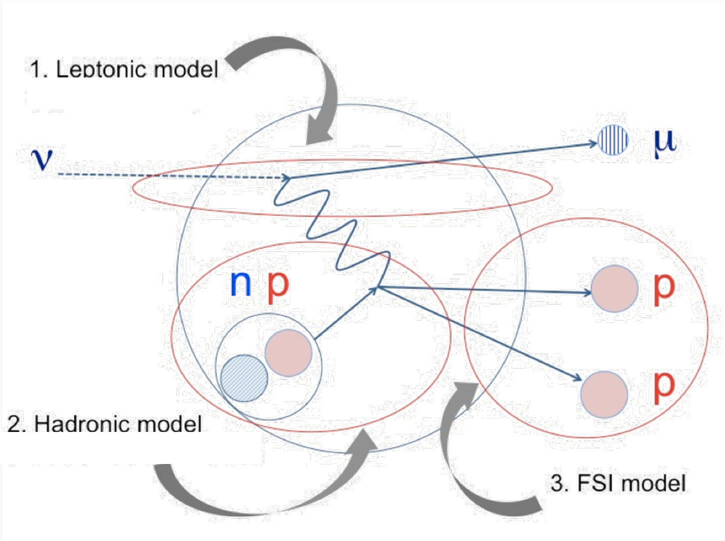
Extrapolation

Models

Updated for 2020

Neutrino Interaction Model

- Constantly evolving understanding of ν interactions.
- Upgrade to GENIE 3.0.6 → freedom to choose models
- Chose the most "theory-driven" set of models plus GENIE's re-tune of some parameters*.
- Some custom tuning is still required.
  - Substantially less than was needed with GENIE 2.12.2, which required tweaks to most models.

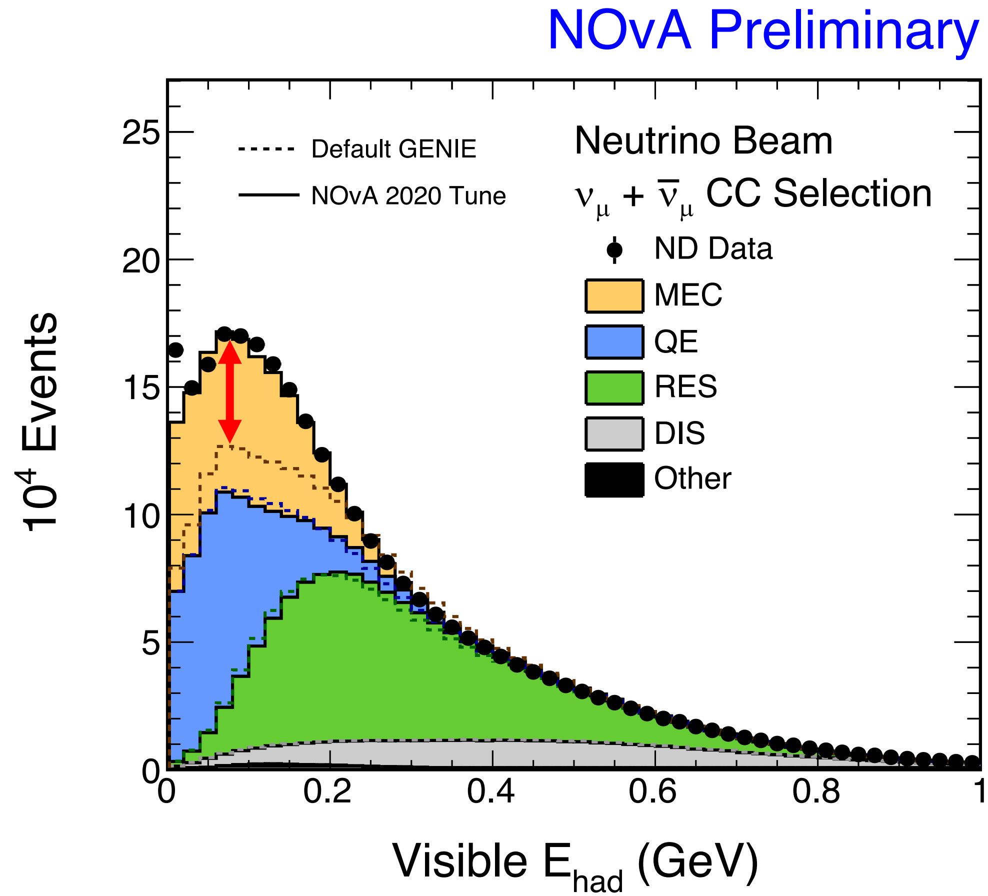


Process	Model	Reference
Quasielastic	Valencia 1p1h	J. Nieves, J. E. Amaro, M. Valverde, Phys. Rev. C 70 (2004) 055503
Form Factor	Z-expansion	A. Meyer, M. Betancourt, R. Gran, R. Hill, Phys. Rev. D 93 (2016)
Multi-nucleon	Valencia 2p2h	R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas, Phys. Rev. D 88 (2013)
Resonance	Berger-Sehgal	Ch. Berger, L. M. Sehgal, Phys. Rev. D 76 (2007)
DIS	Bodek-Yang	A. Bodek and U. K. Yang, NUINT02, Irvine, CA (2003)
Final State Int.	hN semi-classical cascade	S. Dytman, Acta Physica Polonica B 40 (2009)

* We call our tune N1810j_0211a, and it is built by starting with G1810b_0211a and substituting the Z-expansion form factor for the dipole one. This combination was not available in the 3.0.6 release, but it may be available in future versions.
Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001

Neutrino Interaction Model

- 2p2h *or* Meson Exchange Current *or* Multi-nucleon Interactions:
  - Disagreement of models with multiple experiments well-known
  - Tuned to **NOvA ND data** with two 2D gaussians in q_0-$|\vec{q}|$ space.
  - Generous systematics covering normalization and kinematic shape
- Final State Interactions
  - Used **external π-scattering data** primarily to set uncertainties
  - Required adjusting central value, change in overall xsec was small.

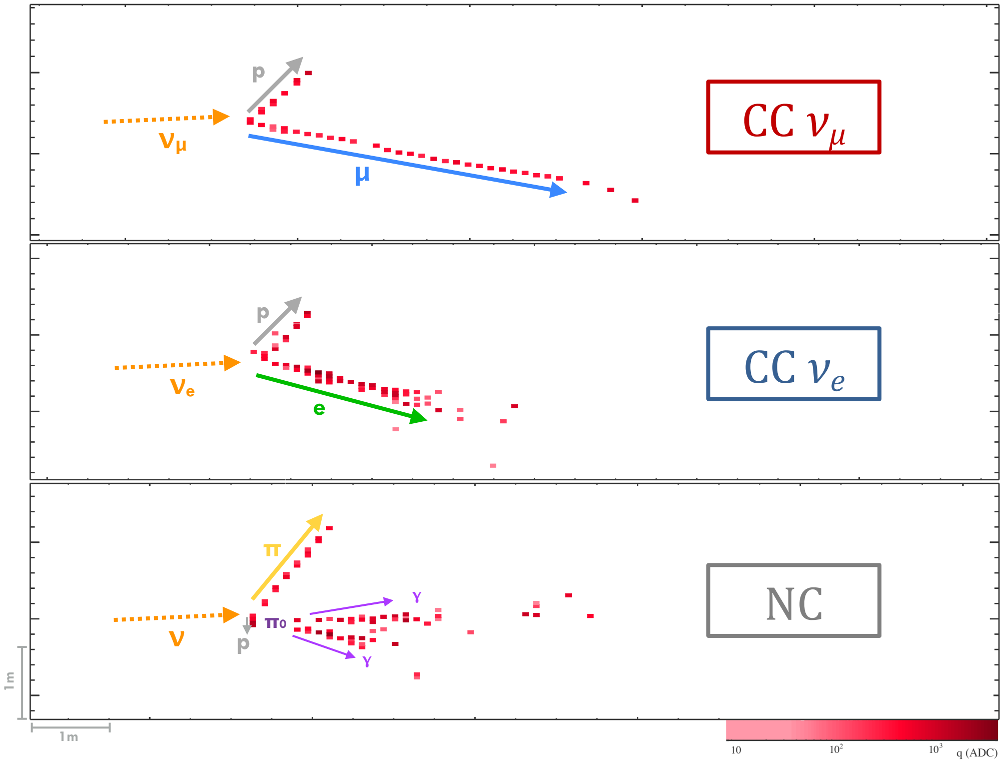


Posters

67. Cross section adjustments for 2p2h
    - Maria Martinez Casales

352. Central value tuning and uncertainties for the hN FSI model in GENIE 3
    - Michael Dolce, Jeremy Wolcott, Hugh Gallagher

Selecting and Identifying Neutrinos



- Identify neutrino flavor using a **convolutional neural network.**
  - A deep-learning technique from computer vision
  - New, faster network for 2020.
- Before main PID:
  - Events are contained in the detector
  - CC ν_μ require a well-reconstructed μ track
  - Reject cosmic rays with BDTs
- Performance relative to preselection:
  - ν_μ: ~90% efficient, 99% bkg. rejection
  - ν_e: ~80% efficient, 80% bkg. rejection
- Validate performance against data-driven control samples in both detectors.

Posters

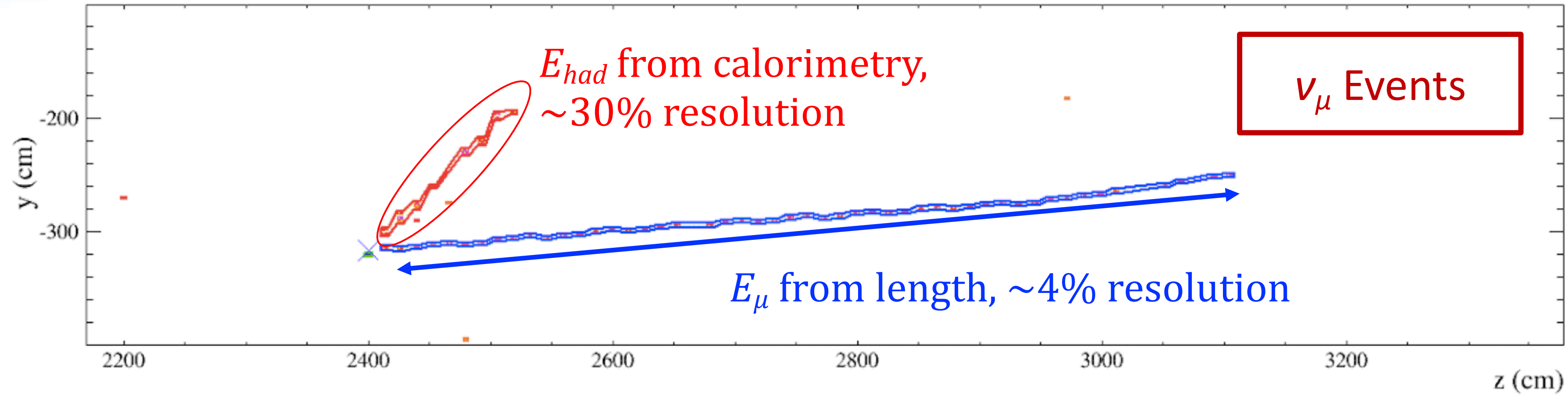
182. Improvements and New Applications of Machine Learning
   – Ashley Back & Micah Groh

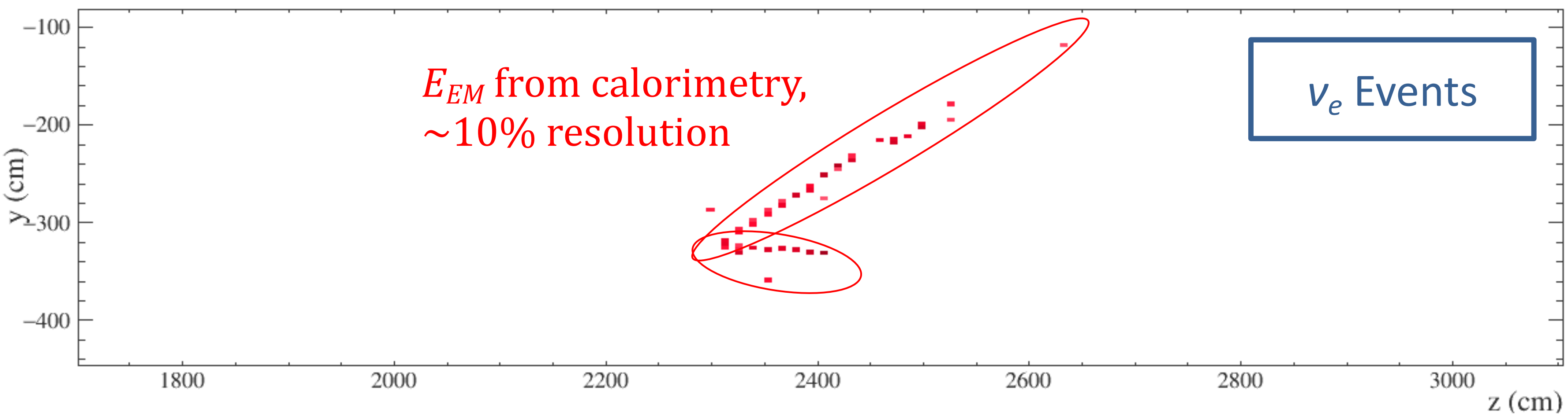
120. Data-Driven cross checks for ν_e selection efficiency in NOvA
   – Anna Hall & Liudmila Kolupaeva

258. Data-Driven Wrong-Sign Background Estimates
   – Abhilash Yallappa Dombara

First CNN in HEP result: A. Aurisano, et al. JINST 11 (2016) 09, P09001

Energy Reconstruction



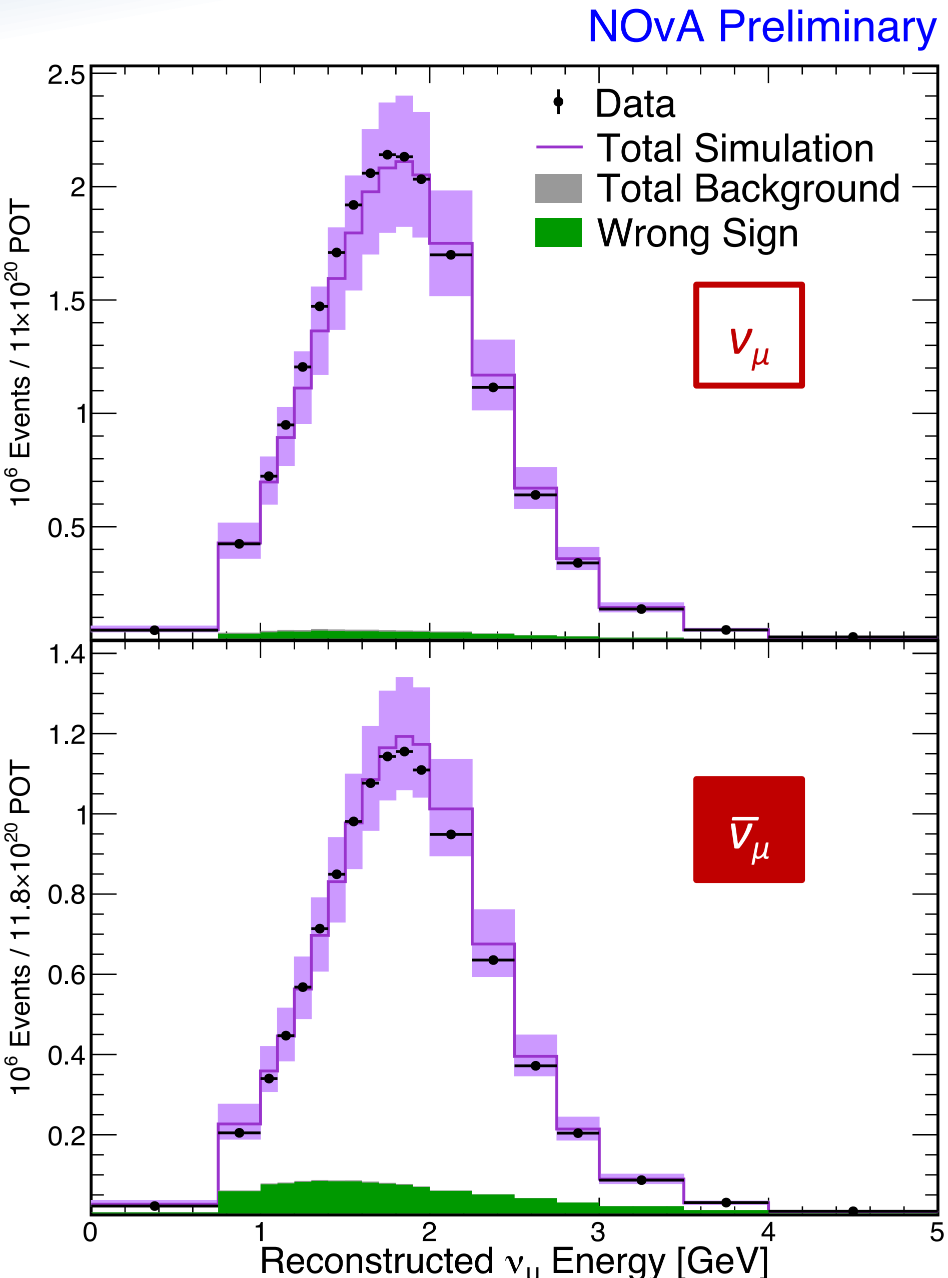


Posters

268. Neutrino Energy Estimation in the NOvA Experiment

– Nitish Nayak

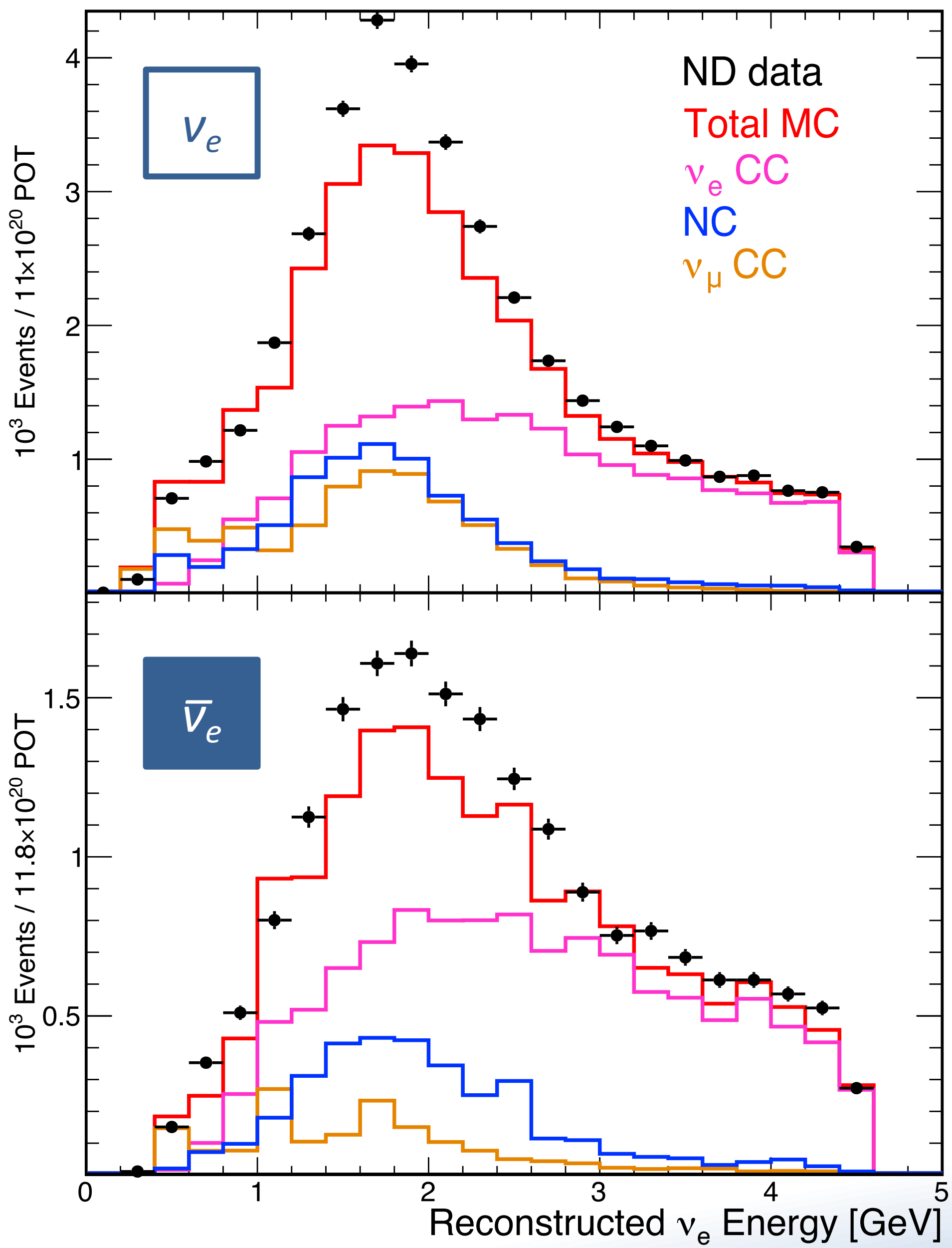
Near Detector ν_μ Spectra



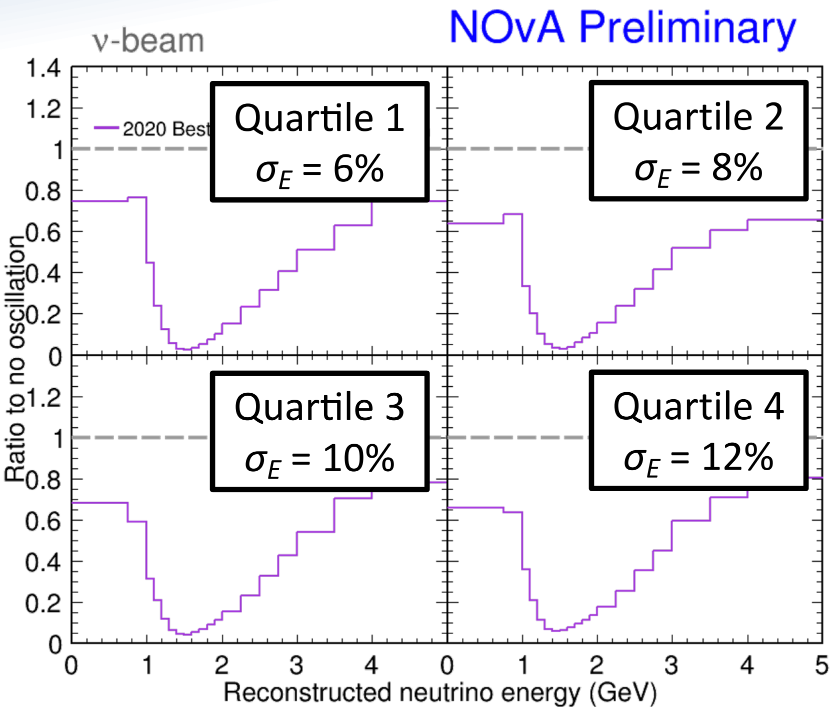
- Band around the MC shows the large impact of flux and cross-section uncertainties in only a single detector.
- We use this sample to predict both ν_μ and ν_e signal spectra at the Far Detector.
  - Appearing ν_e's are still ν_μ's at the ND

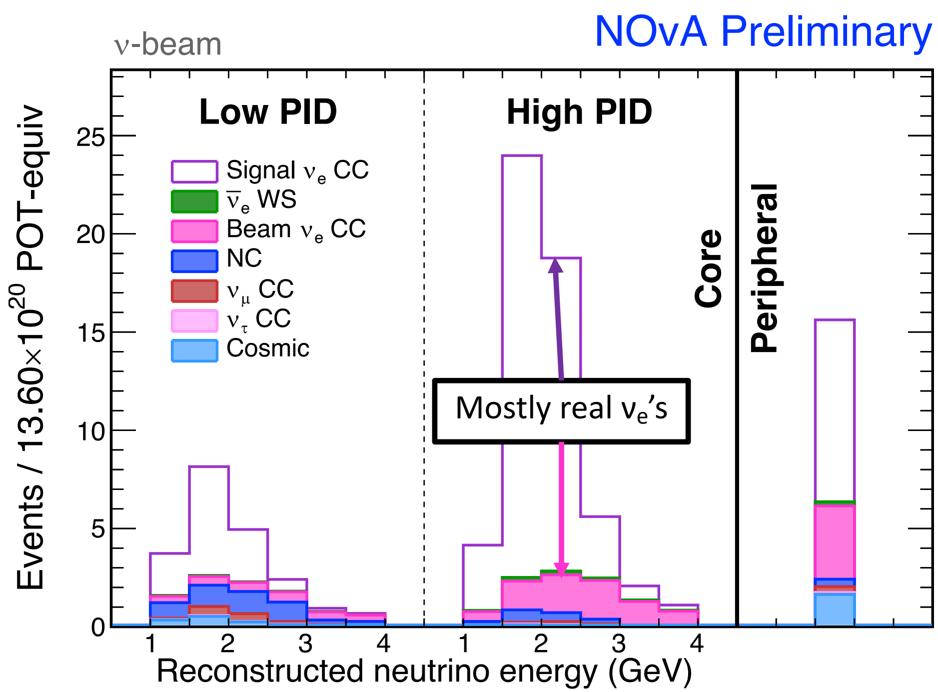
Near Detector ν_e-like Spectra

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



Enhancing Sensitivity to Oscillations





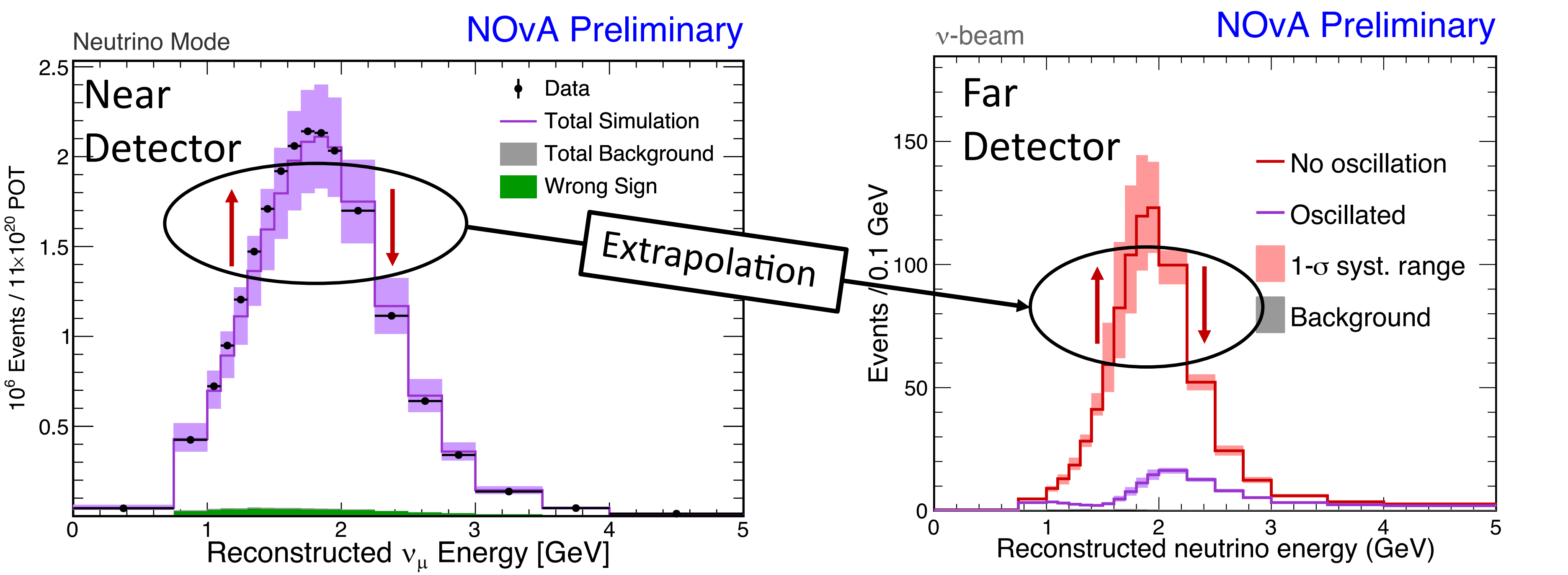
ν_μ sample

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

ν_e sample

- Sensitivity depends primarily on separating signal from background.
- Bin by *purity* → bins of low & high PID
- Peripheral sample:
  - Captures high-PID events which might not be contained close to detector edges.
  - No energy binning.

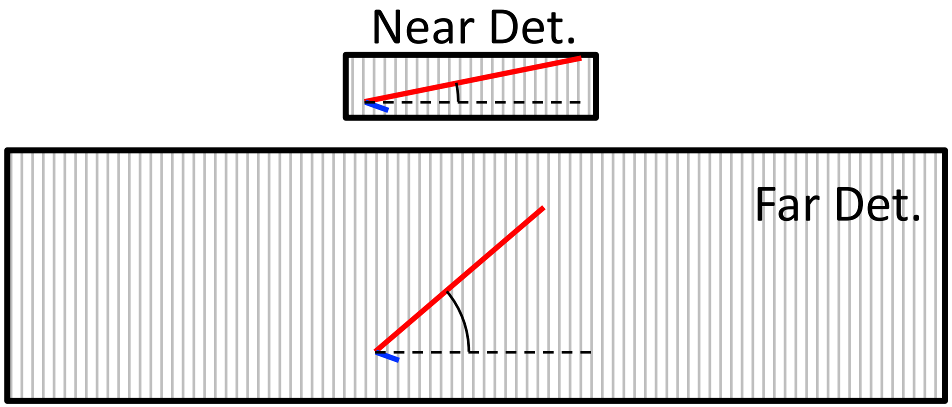
Extrapolating from Near to Far Detector

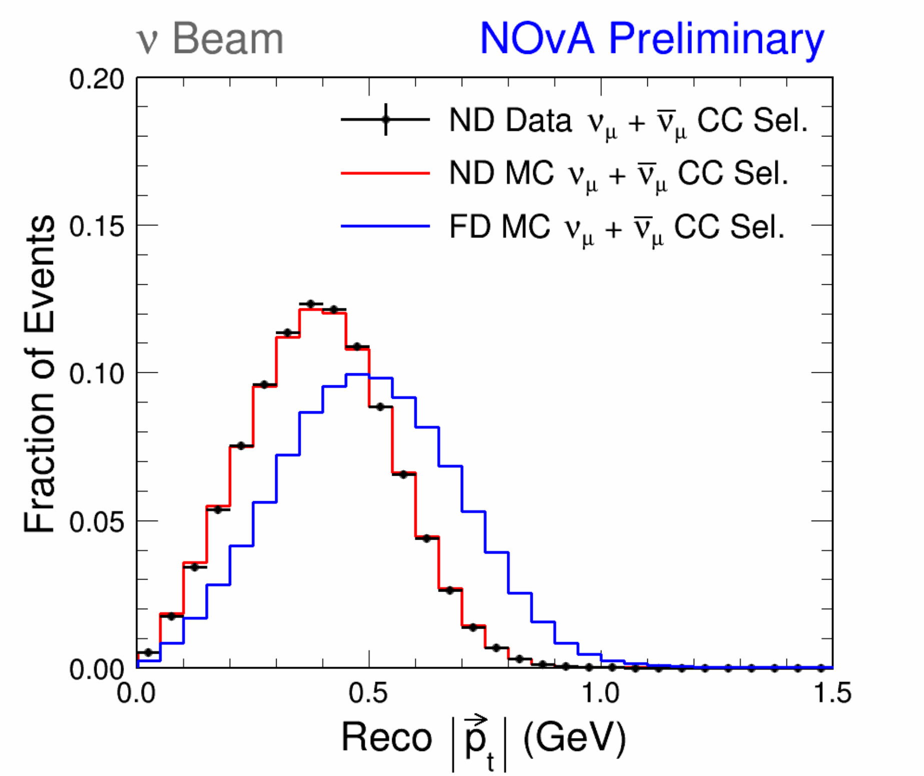


- Observe data-MC differences at the ND, use them to modify the FD MC.
  - Extrapolation performed in the analysis binning of energy + (resolution or PID).
- Significantly reduces the impact of uncertainties correlated between detectors
  - Especially effective at rate effects like the flux (7% → 0.3%).

Extrapolating Kinematics

- Containment limits the range of lepton angles more in the Near Detector than in the Far.
  - The ND is 1/5 the size of the FD.
- Mitigate by extrapolating in bins of **lepton transverse momentum, p_t**
  - Transverse to the ν-beam direction ≈ the central axis of the detectors
- Split the ND sample into 3 bins of p_t, extrapolate each separately to the FD.
  - Effectively "rebalances" the kinematics to better match between the detectors.
  - Re-sum the p_t bins before fitting.

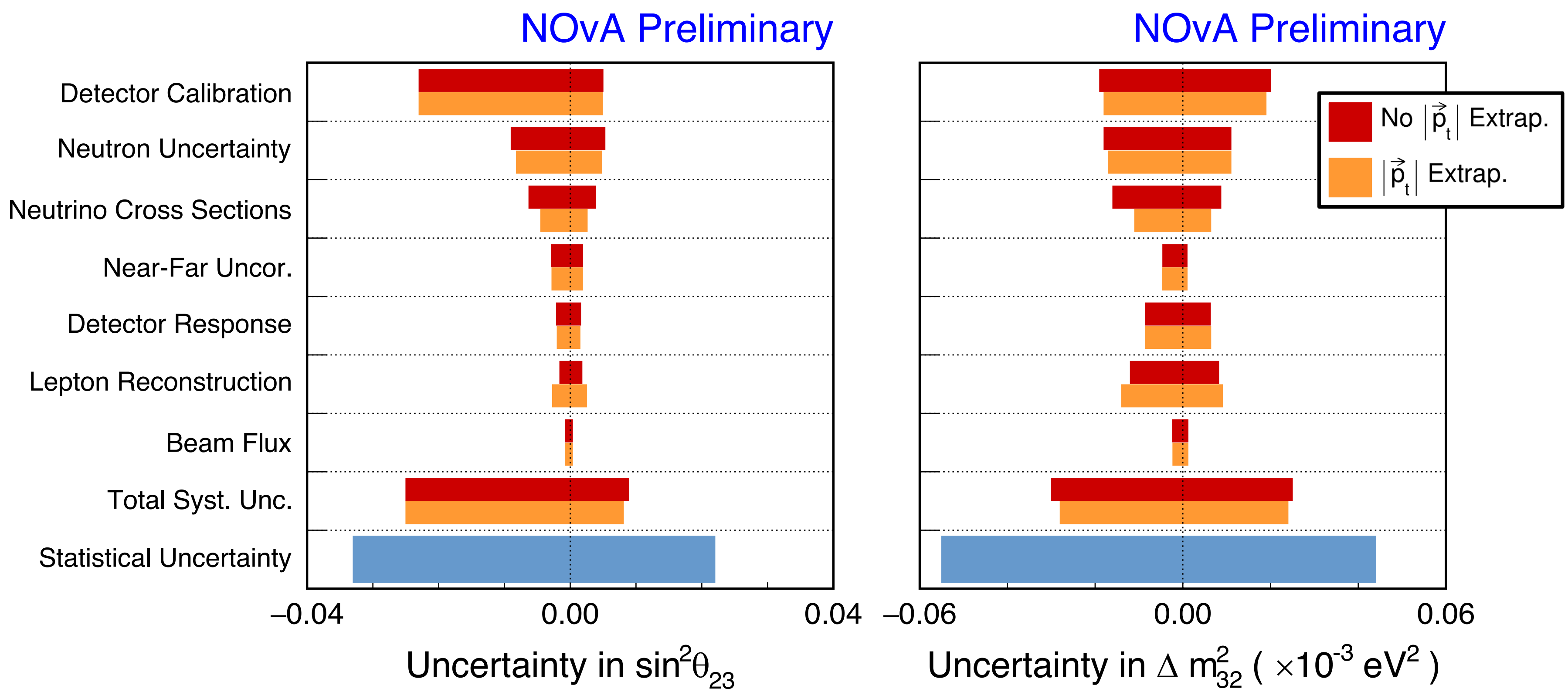




Posters

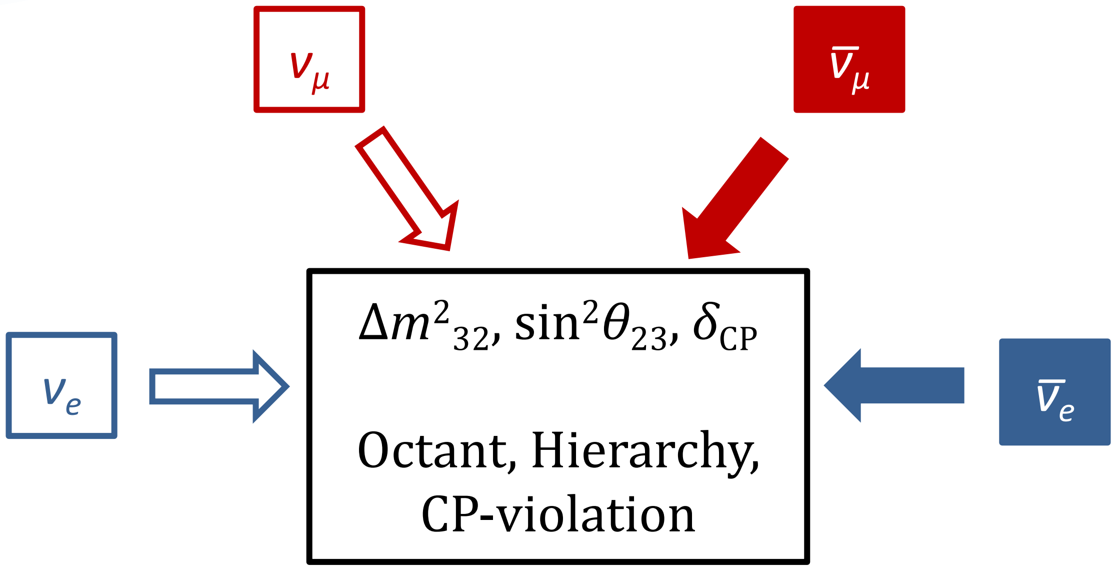
354. Near-to-Far Extrapolation in Transverse Momentum at NOvA
   – Aaron Mislivec

Systematic Uncertainties with p_t Extrapolation



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

Oscillation Fit



- Simultaneous fit of all samples, reactor-constrained $\sin^2 2\theta_{13} = 0.085 \pm 0.003$.
- We perform a frequentist analysis and use the Feldman-Cousins method to ensure proper coverage in all contours and intervals.

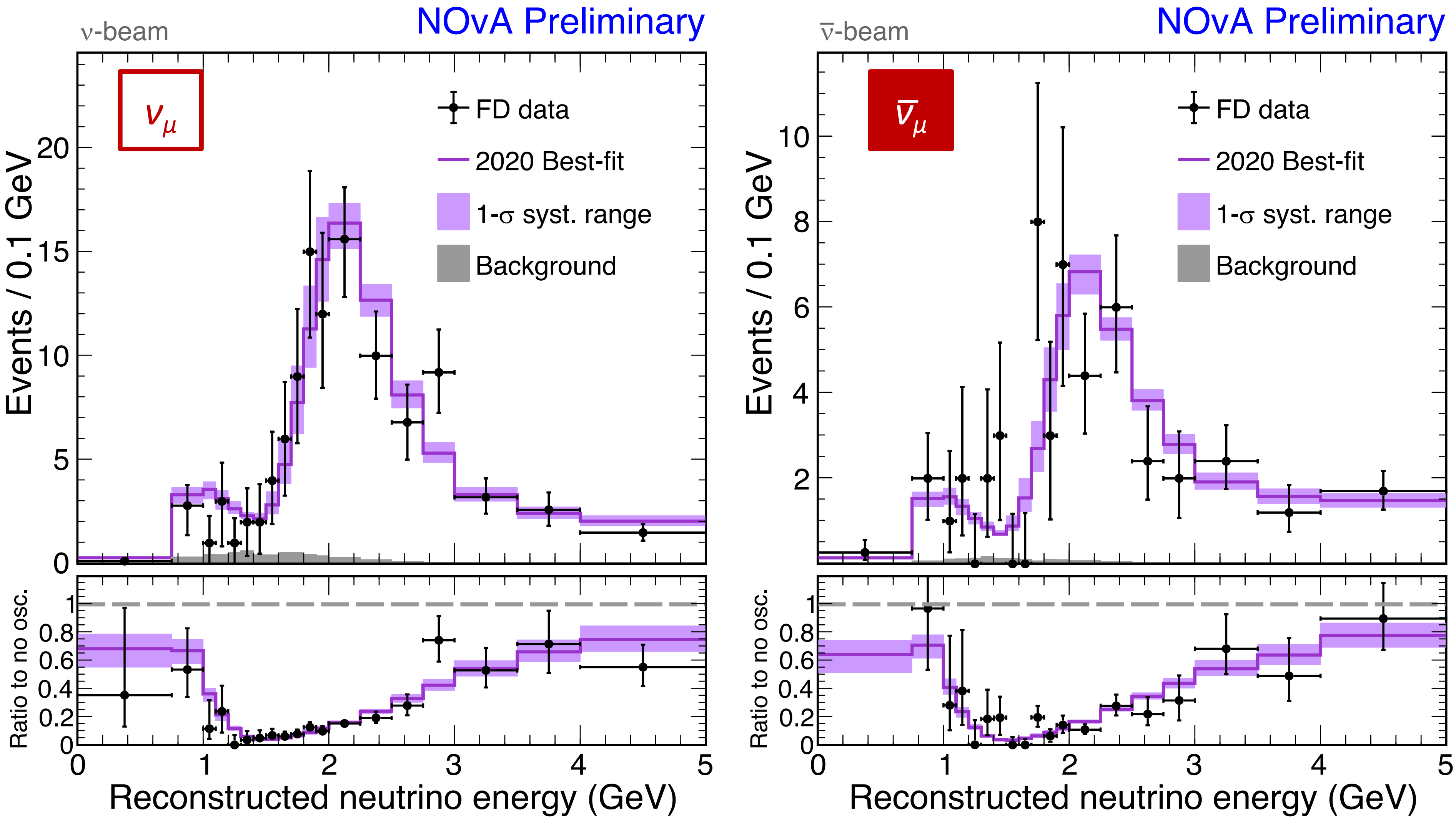
Posters

262. Accelerating Calculation of Confidence Intervals for NOvA's Neutrino Oscillation Parameter Estimation with Supercomputers
   – Steven Calvez, Tarak Thakore

SciDAC Scientific Discovery through Advanced Computing

NERSC National Energy Research Scientific Computing Center

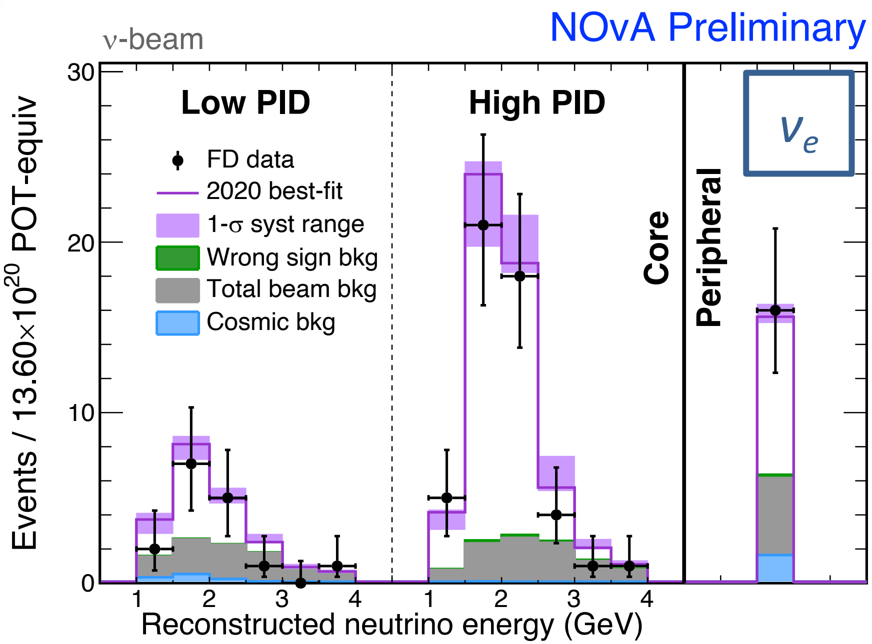
ν_μ and $\bar{\nu}_\mu$ Data at the Far Detector

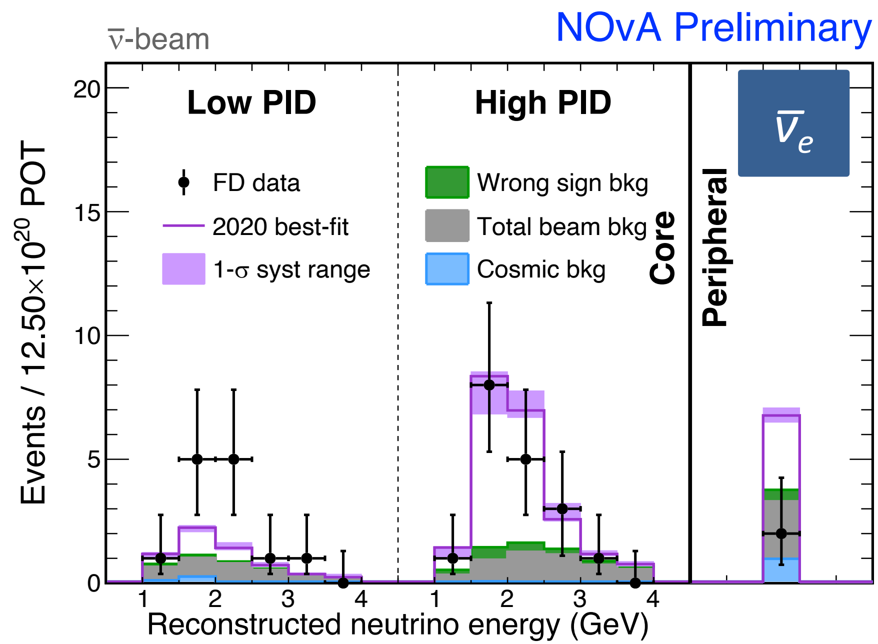


211 events, 8.2 background

105 events, 2.1 background

ν_e and $\bar{\nu}_e$ Data at the Far Detector



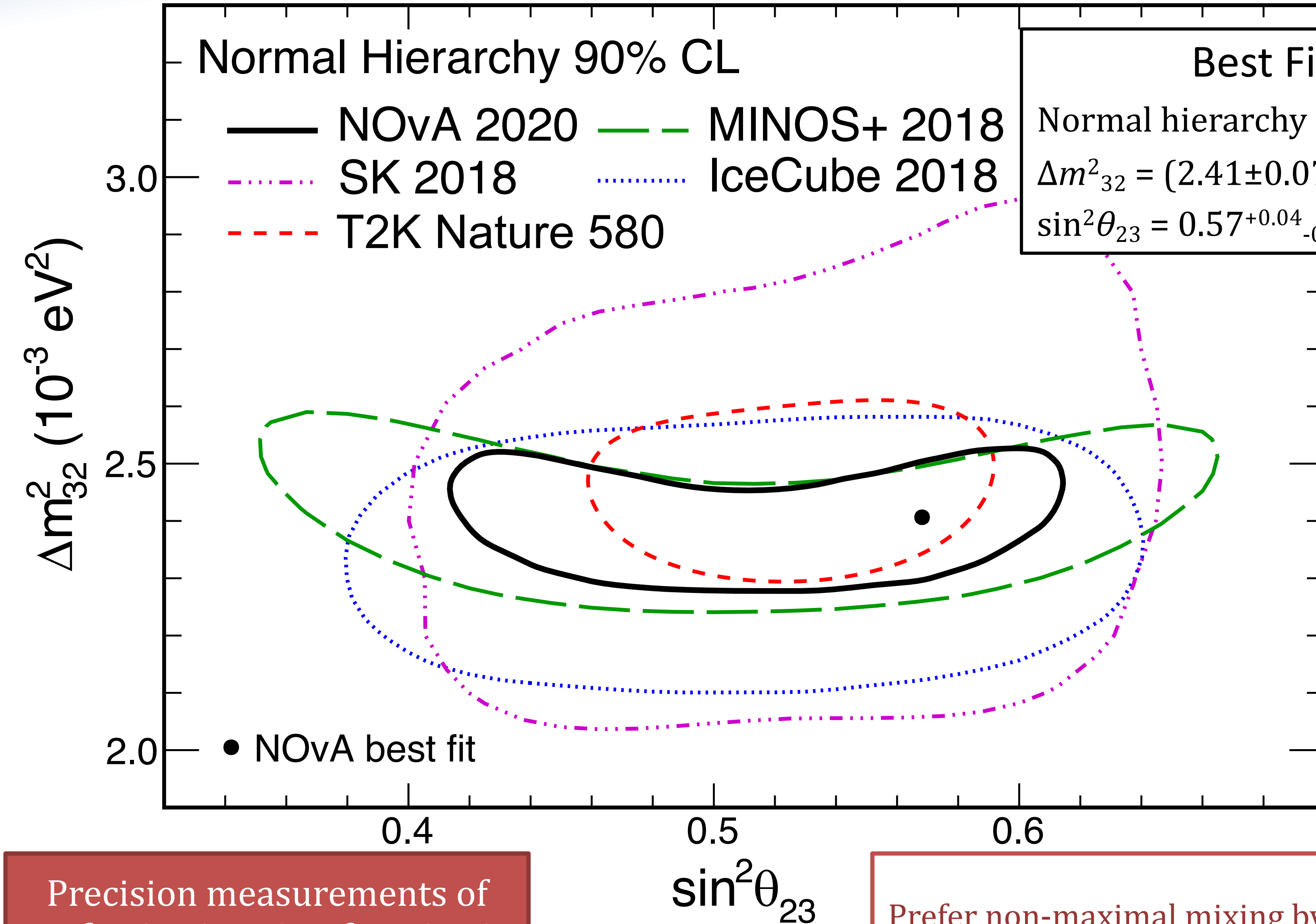


Total Observed	**82**	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

Total Observed	**33**	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

>4σ evidence of $\bar{\nu}_e$ appearance

NOvA Preliminary



Best Fit

Normal hierarchy

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

Precision measurements of Δm^2_{32} (3%) and $\sin^2\theta_{23}$ (6%).

Prefer non-maximal mixing by 1.1σ.

NOvA Preliminary

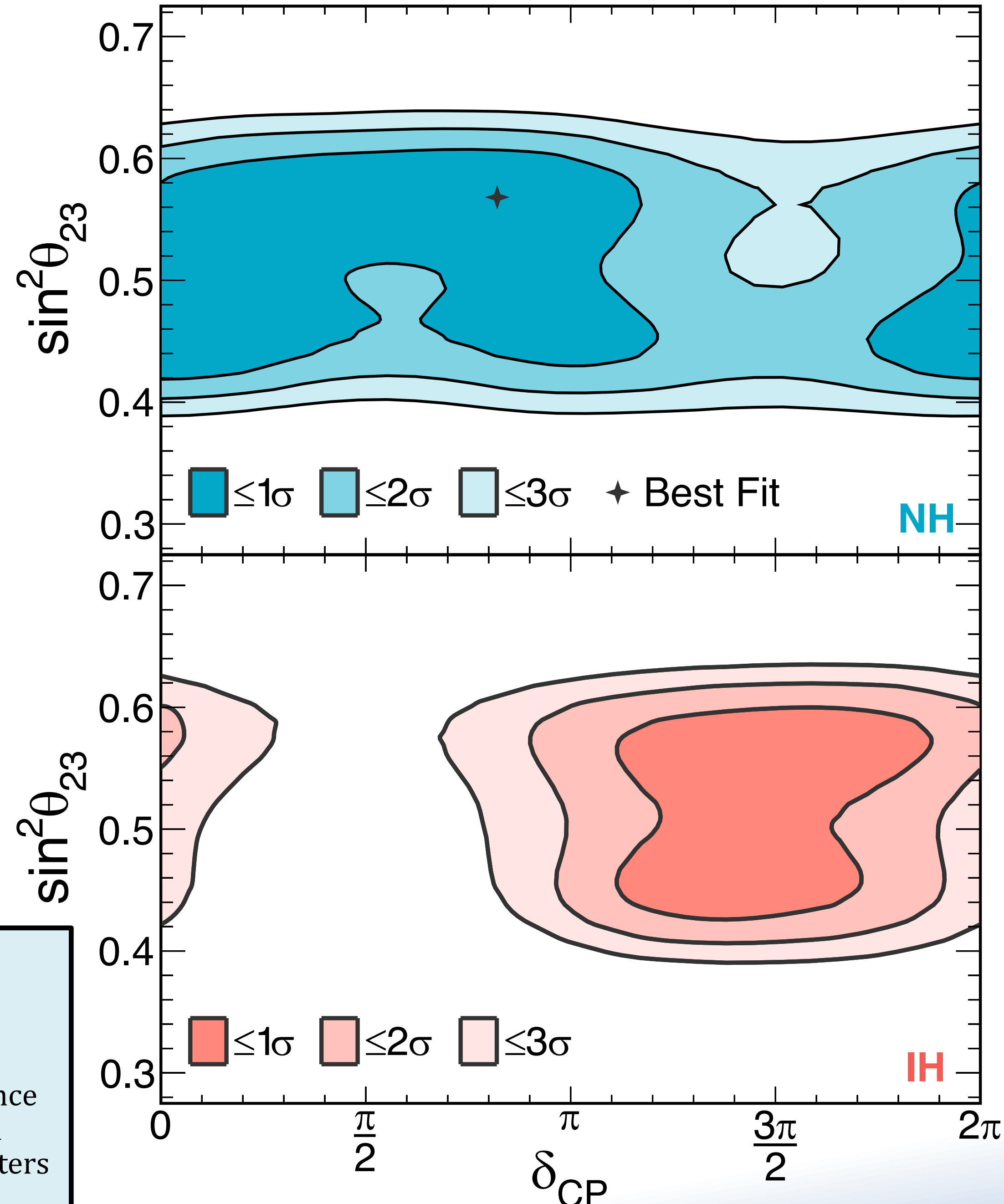
Best Fit

Normal hierarchy

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

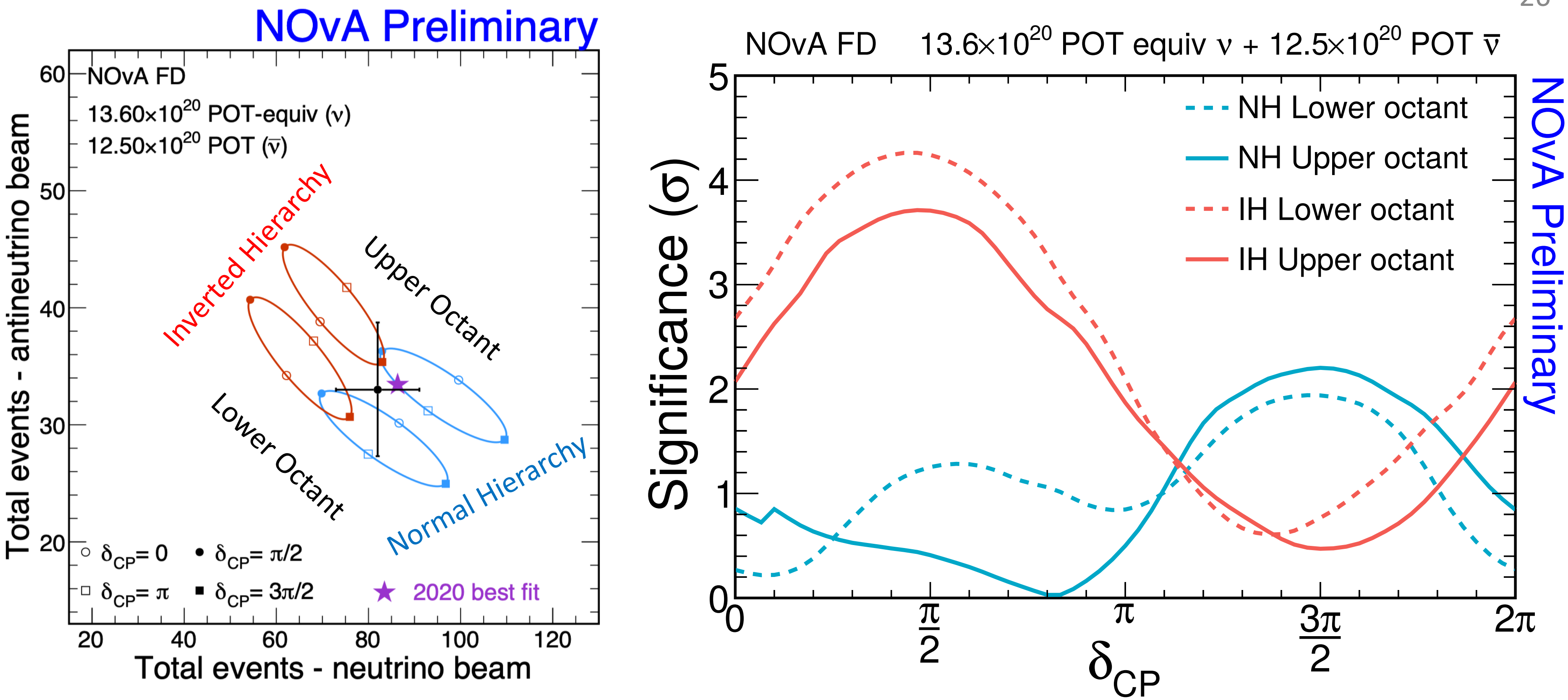
$\delta = 0.82\pi$



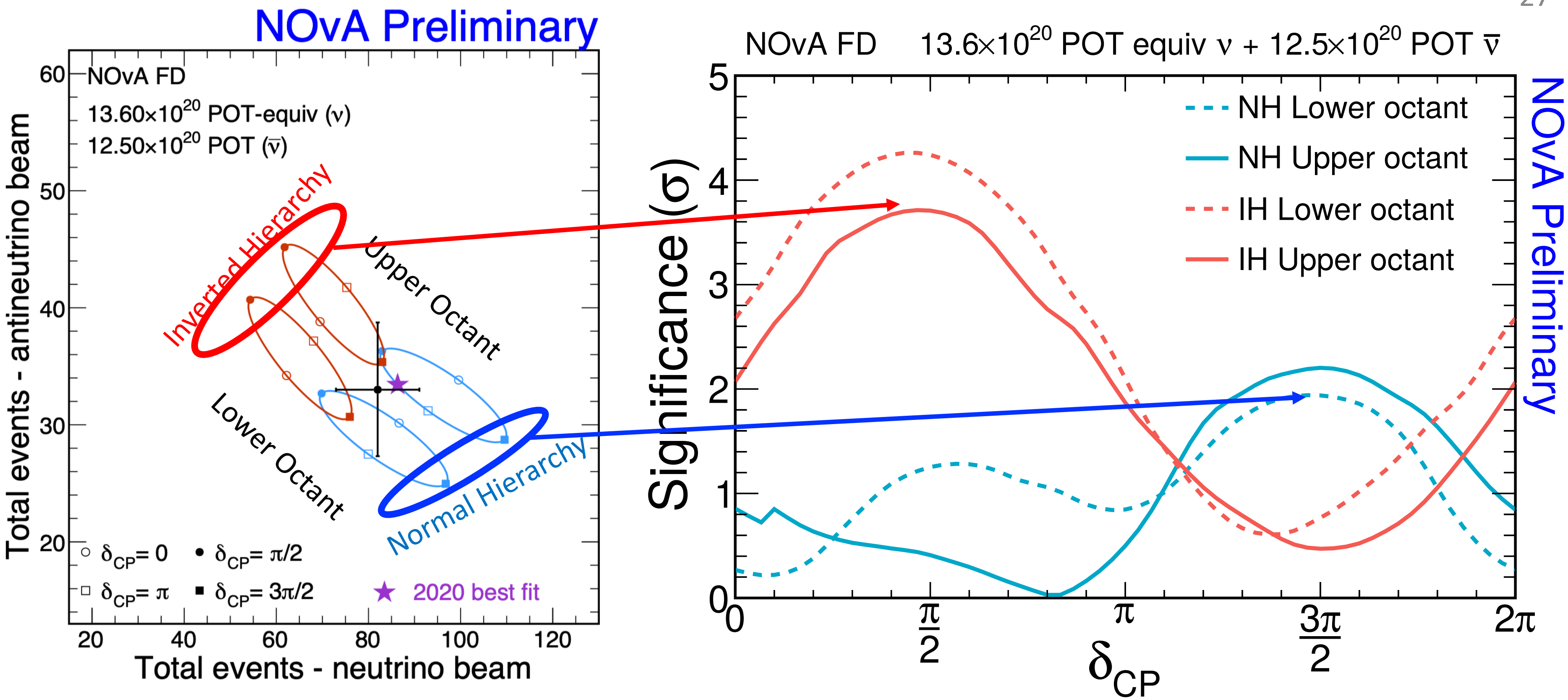
Posters

83. Long-baseline neutrino oscillation results from NOvA
   – Liudmila Kolupaeva & Karl Warburton

262. Accelerating Calculation of Confidence Intervals for NOvA's Neutrino Oscillation Parameter Estimation with Supercomputers
   – Steven Calvez, Tarak Thakore



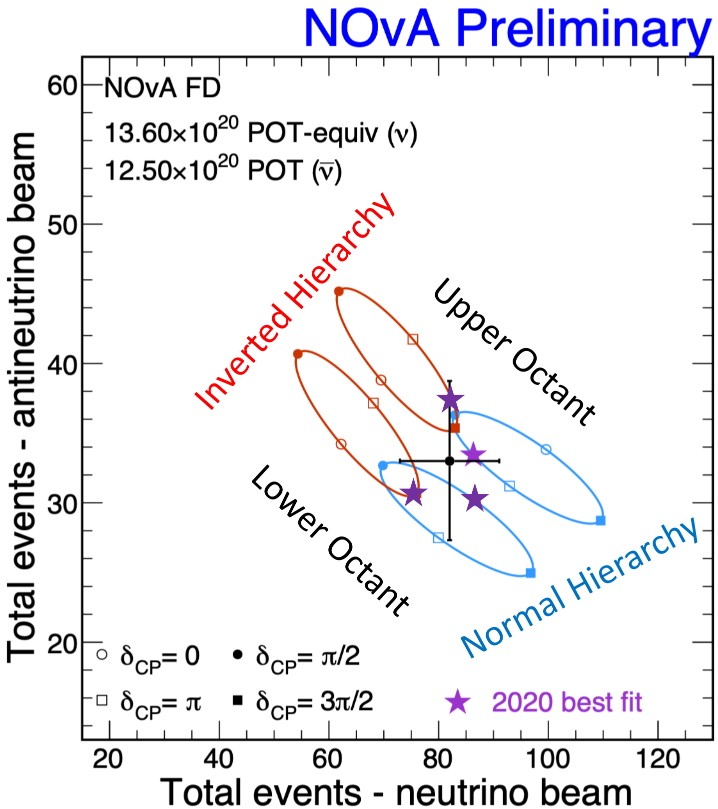
- We see no strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$

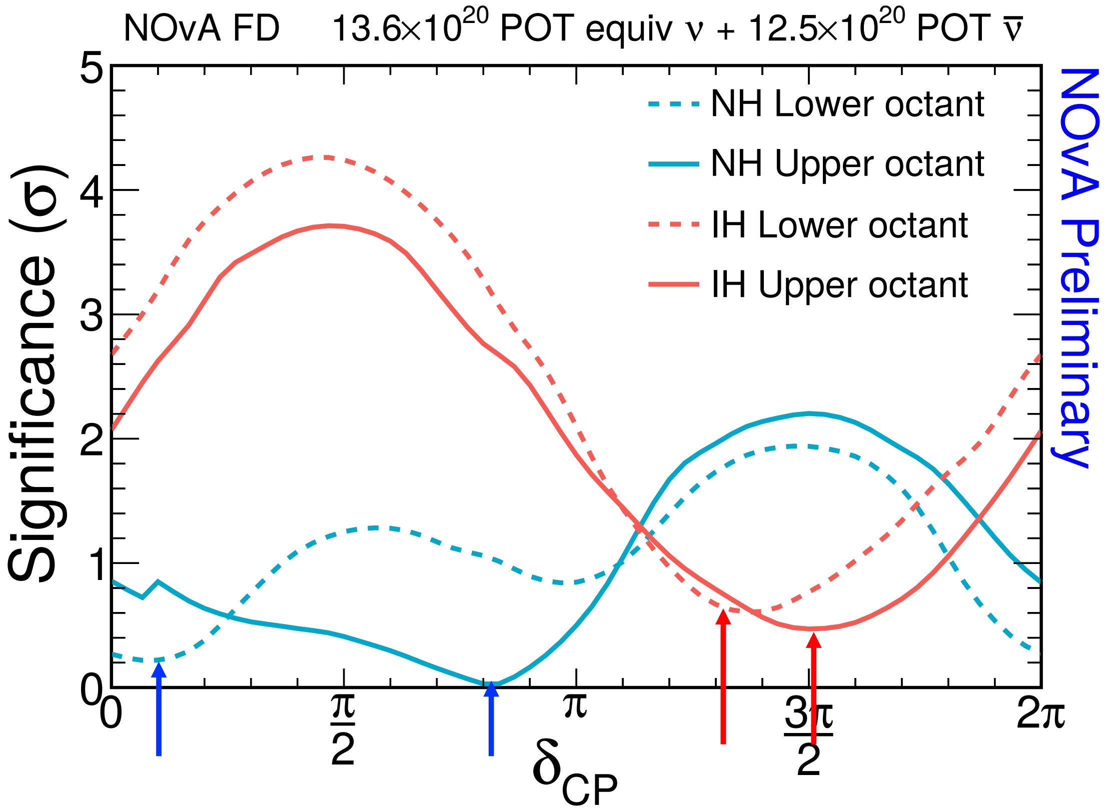


- We see no strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$
- Disfavor hierarchy-δ combinations which would produce that asymmetry

Exclude IH $\delta = \pi/2$ at $>3\sigma$

Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$





- We see no strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$
- Disfavor hierarchy-δ combinations which would produce that asymmetry
- Consistent with hierarchy-octant-δ combinations which include some "cancellation."
  - Since such options exist for both octants and hierarchies, results show no strong preferences.

Exclude IH $\delta = \pi/2$ at $>3\sigma$

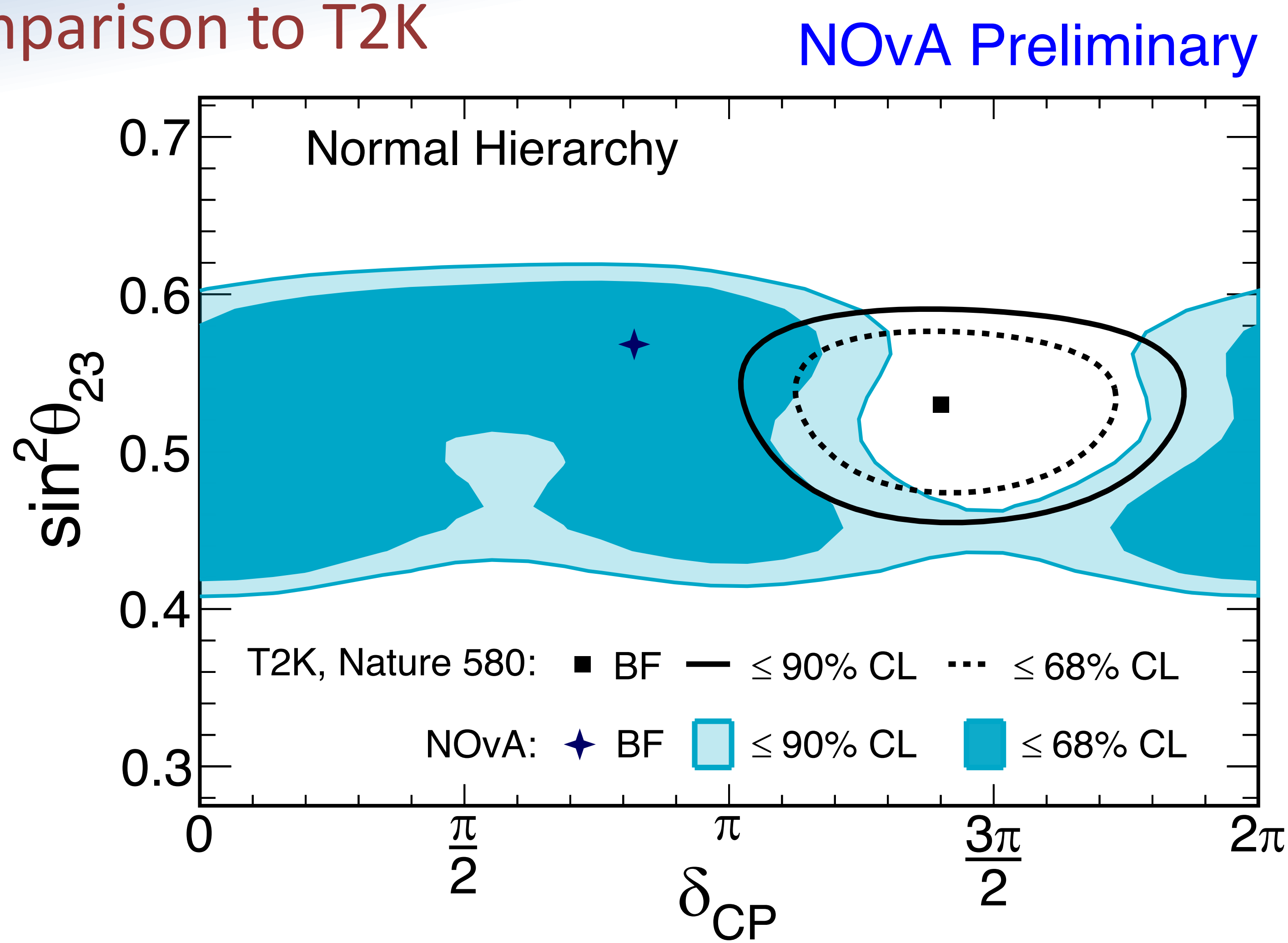
Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Prefer...

Normal Hierarchy at 1.0σ

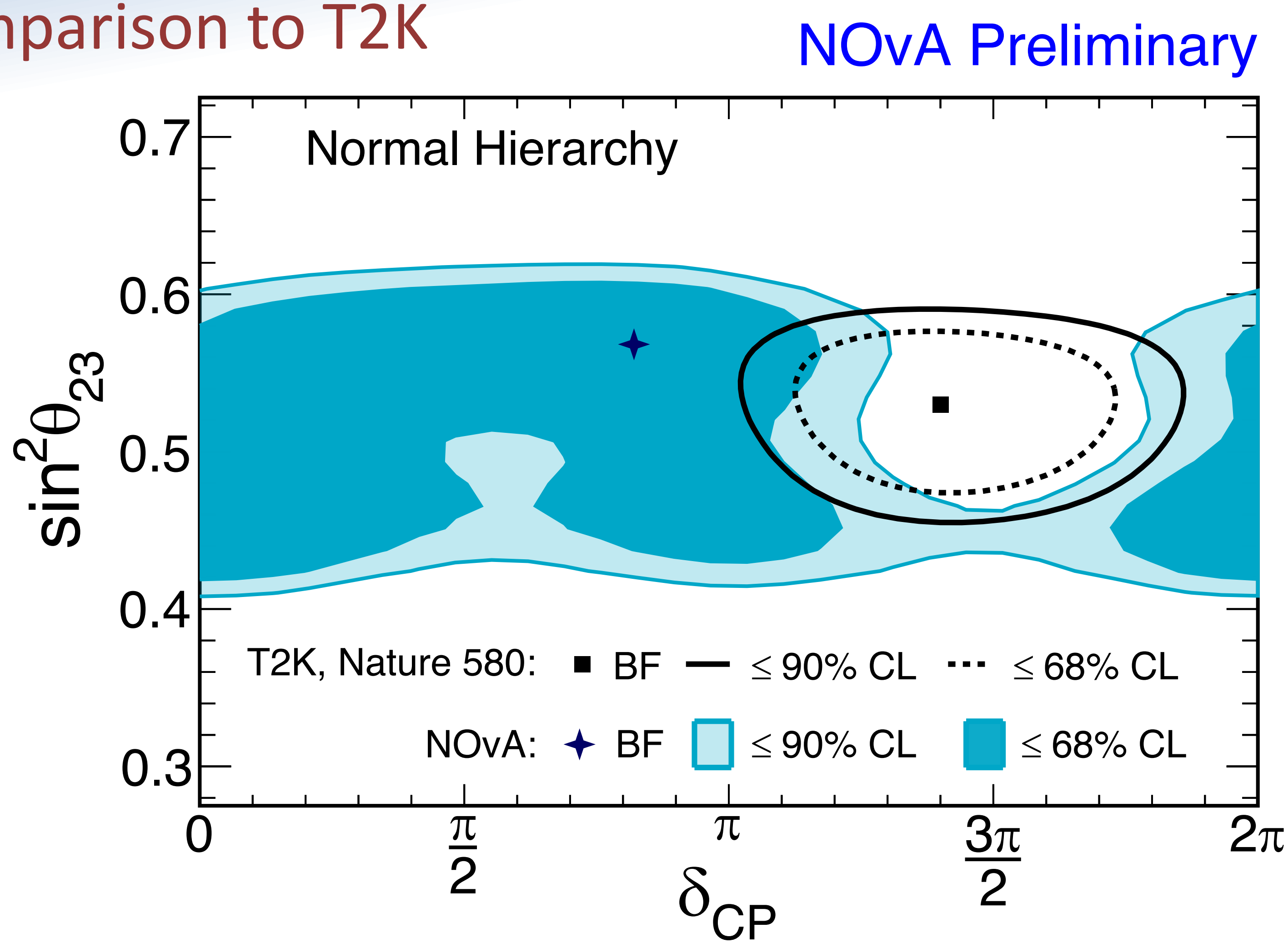
Upper Octant at 1.2σ

Comparison to T2K



- Clear tension with T2K's preferred region.
- Quantifying consistency requires a joint fit of the data from the two experiments, which is already in the works.
  - Semi-annual workshops, regular joint group meetings, and a signed joint agreement.

Comparison to T2K



Conclusions

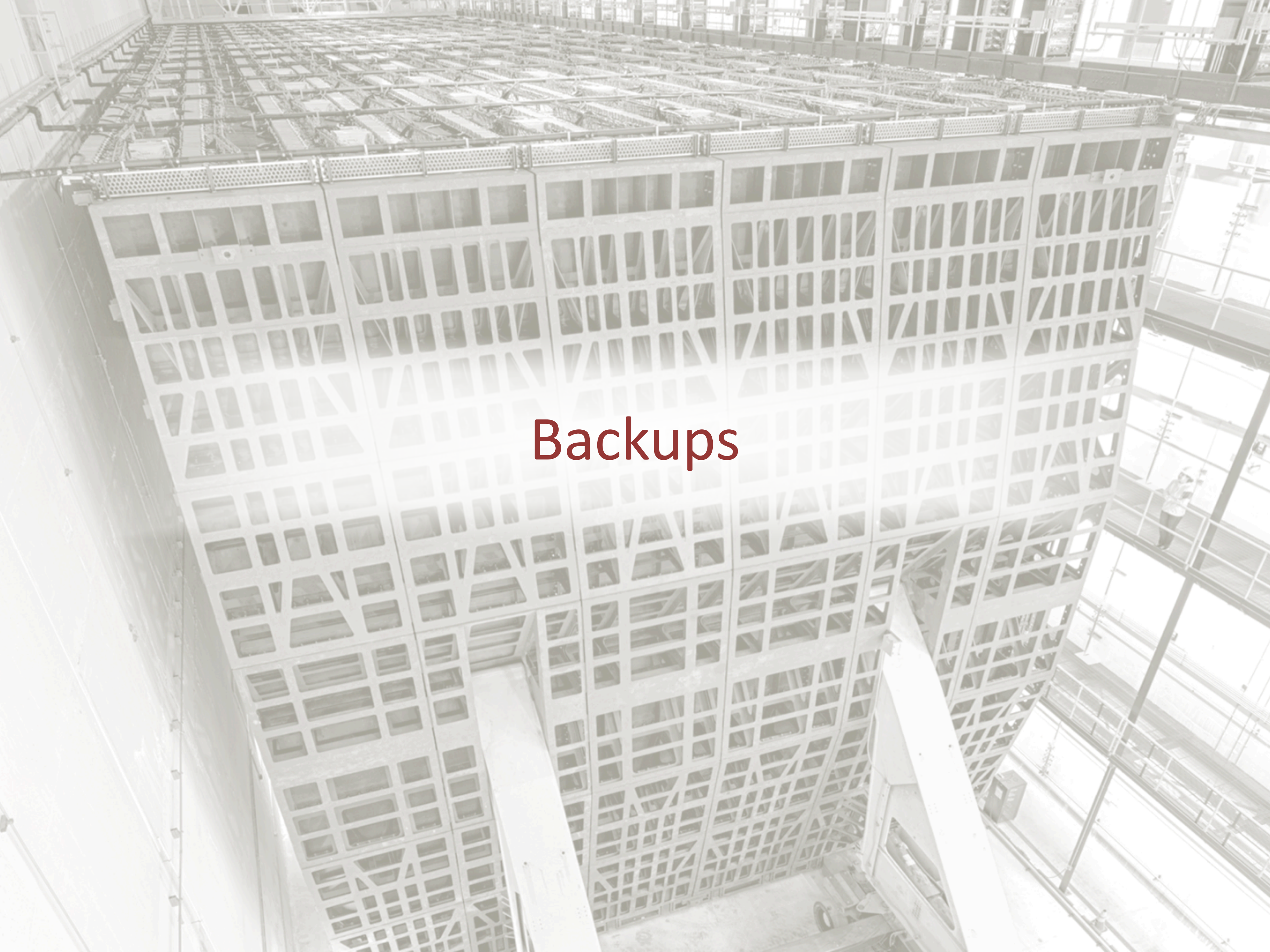
- We present an updated neutrino oscillation analysis with:
  - 50% more neutrino beam data,
  - updated simulation and reconstruction, including a new GENIE 3 cross-section model,
  - updated extrapolation which mitigates differing detector acceptances.
- New 3-flavor oscillation results:
  - $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$
  - $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$
  - exclude IH, $\delta = \pi/2$ at $> 3\sigma$,
  - disfavor NH, $\delta = 3\pi/2$ at $\sim 2\sigma$.
- Looking ahead:
  - We can reach 3σ hierarchy sensitivity for 30-50% of δ values, with the full dataset and an upgraded beam.
  - Plan to reduce our largest systematics, those related to detector energy scale, with the results of our test beam experiment.

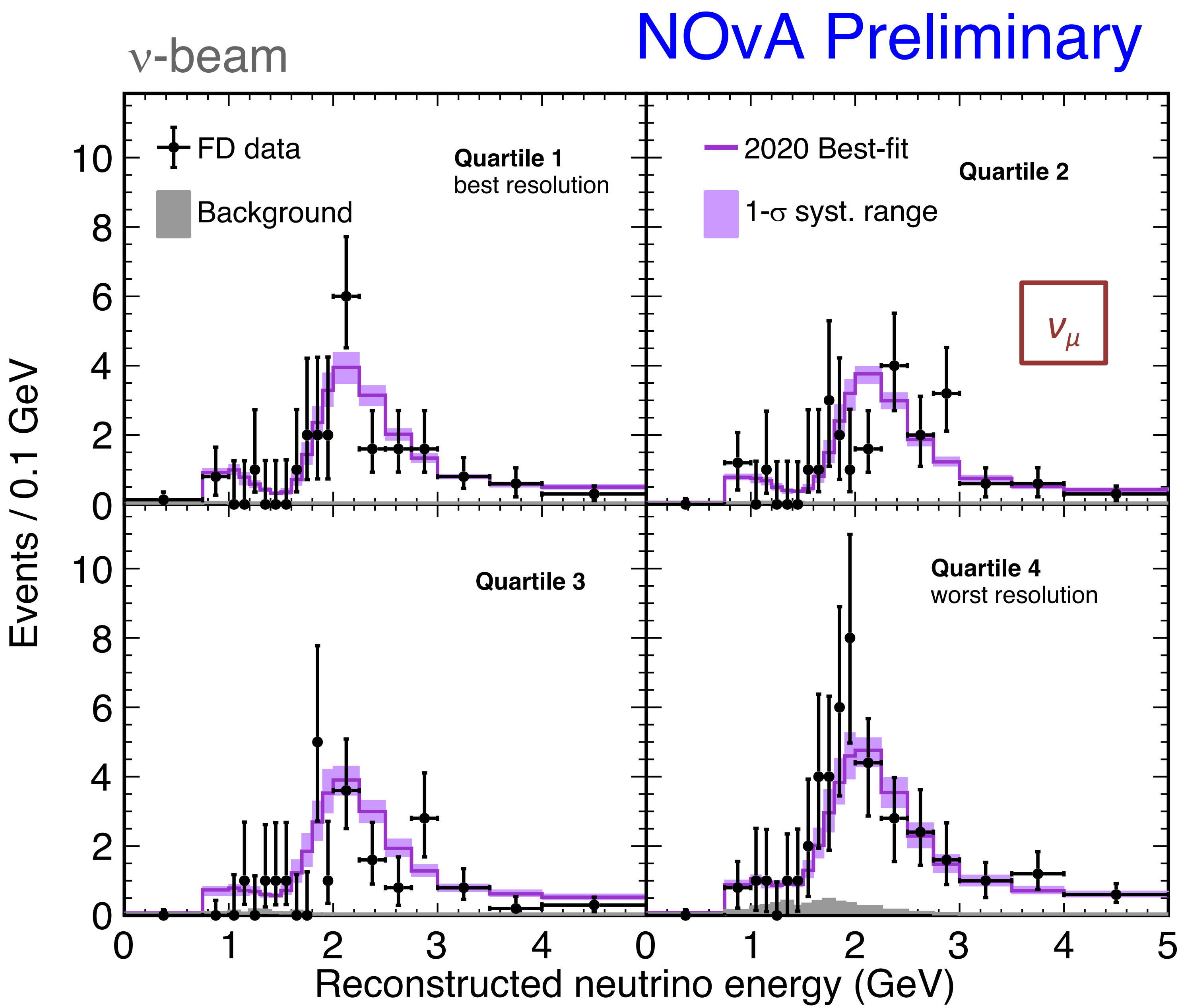
Posters

314. Design and Operation of a Charged Particle Beamline
  - David Duenas Tonguino, Mike Wallbank, Alex Sousa, Andrew Sutton, Teresa Lackey

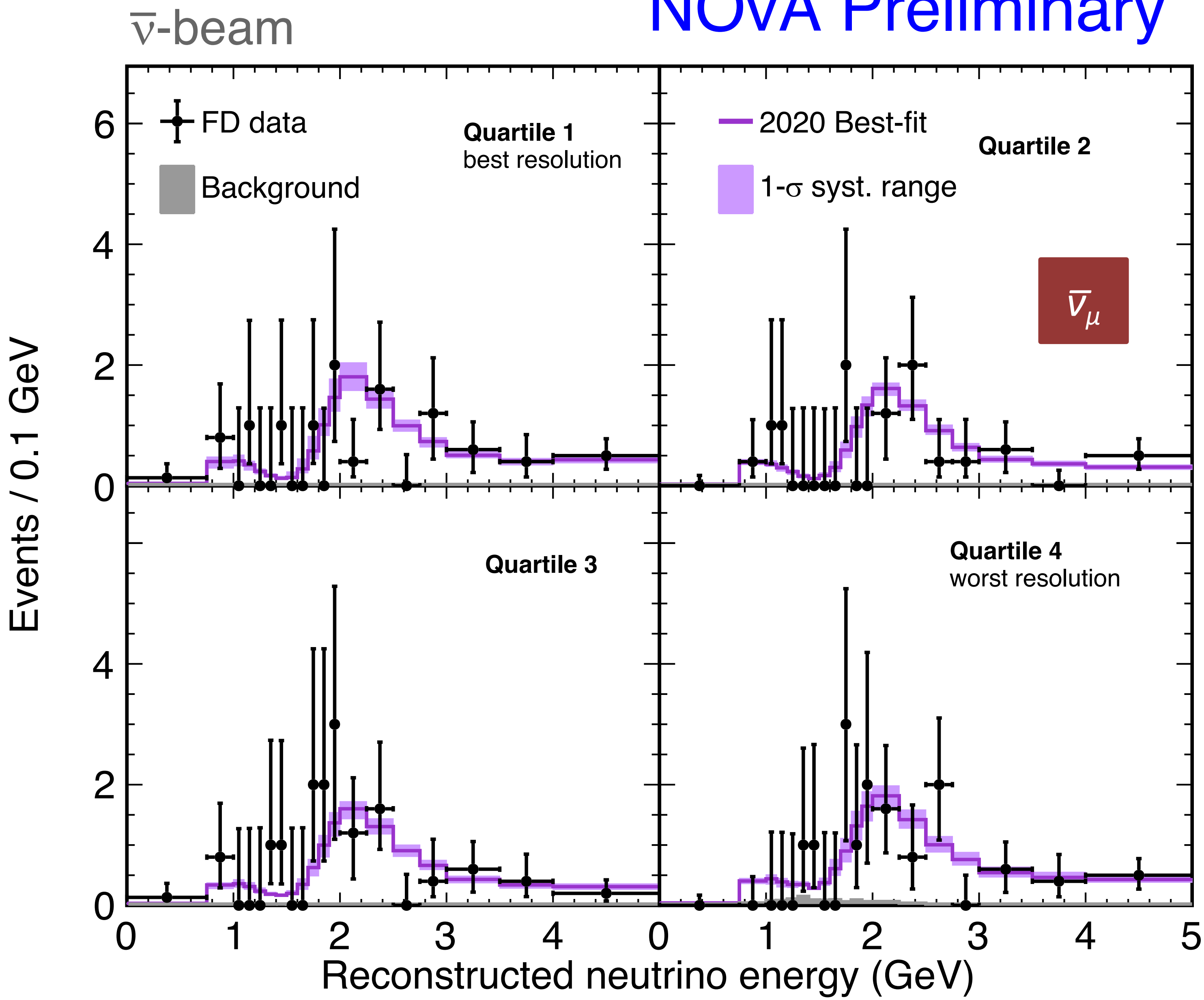
Questions?

Backups

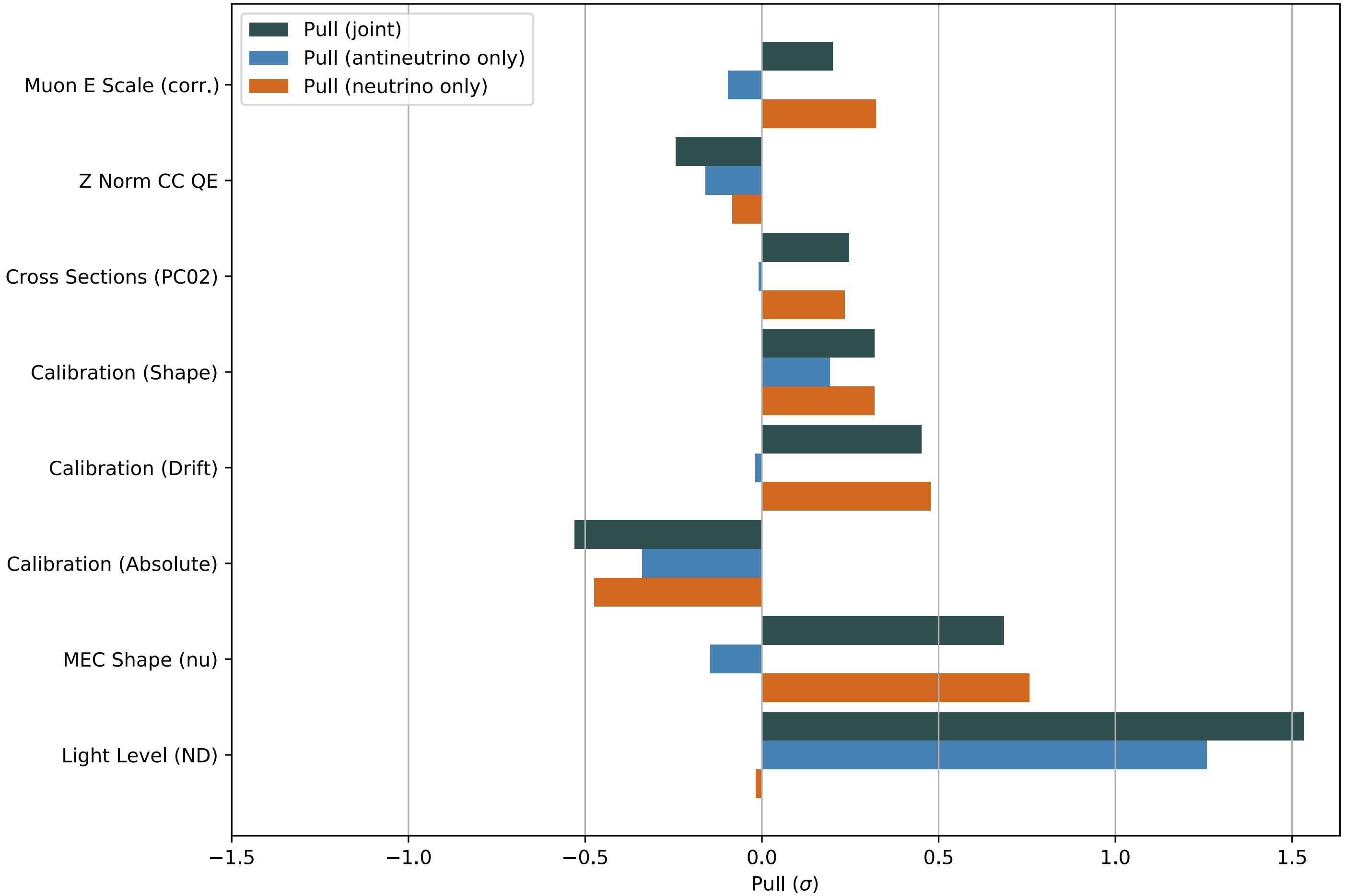



NOvA Preliminary
ν-beam
FD data
Background
2020 Best-fit
1-σ syst. range
Quartile 1
best resolution
Quartile 2
Quartile 3
Quartile 4
worst resolution
ν_μ
Events / 0.1 GeV
Reconstructed neutrino energy (GeV)

NOvA Preliminary

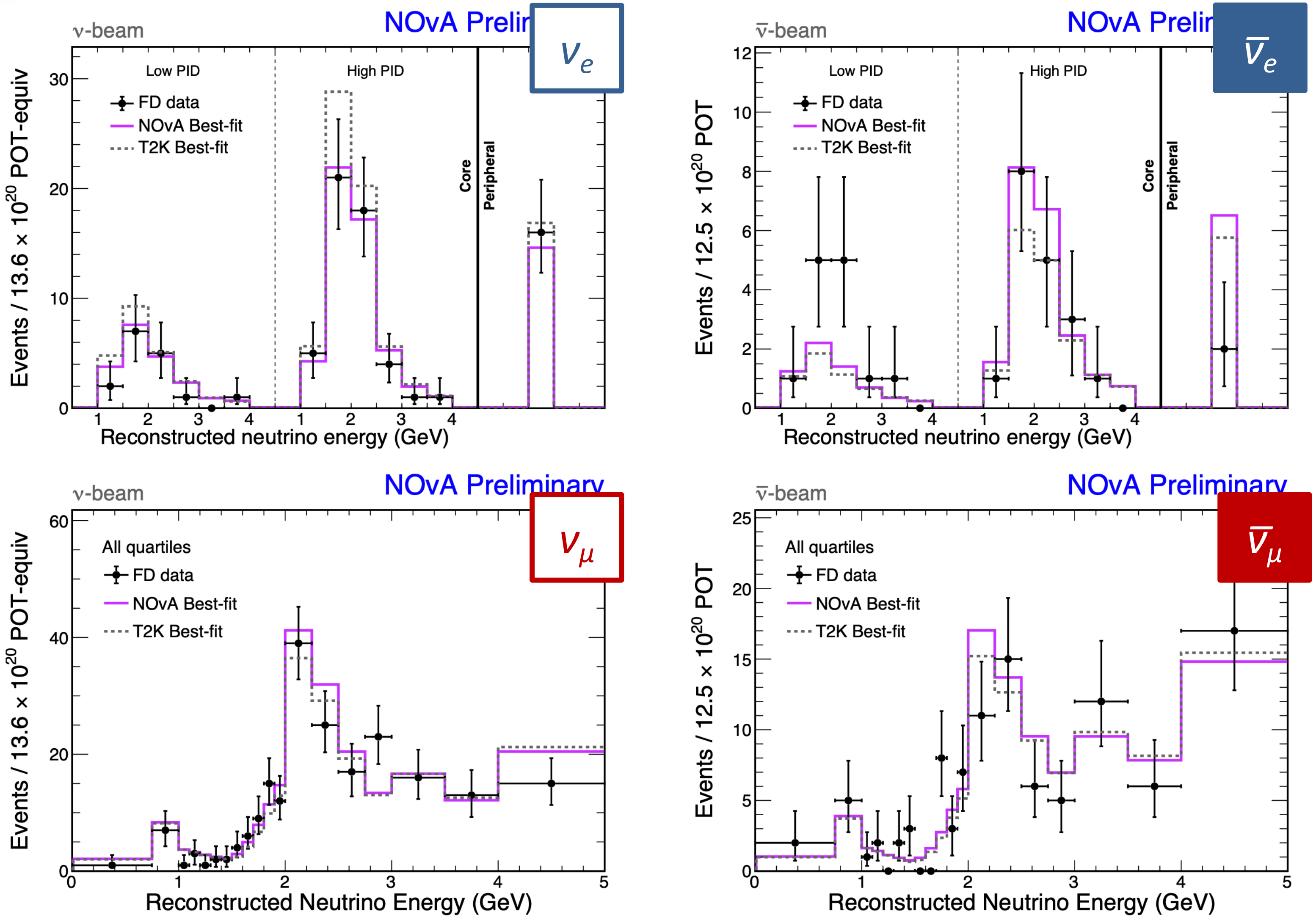


Pulls in the Fit



- Largest pulls also correspond to some of our known most important systematics:
  - Detector light model and energy scale (calibration)
  - Multi-nucleon cross section
- We see examples where a pull comes primarily from the neutrino or antineutrino beam, but generally do not see *contradictory* pulls.

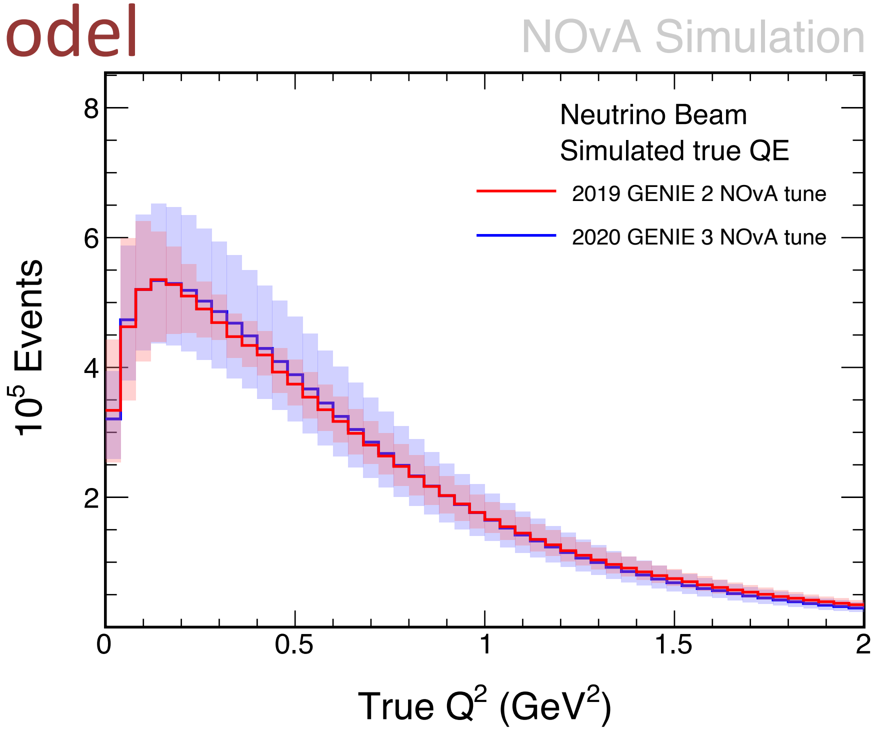
Spectra with NOvA and T2K Best Fits



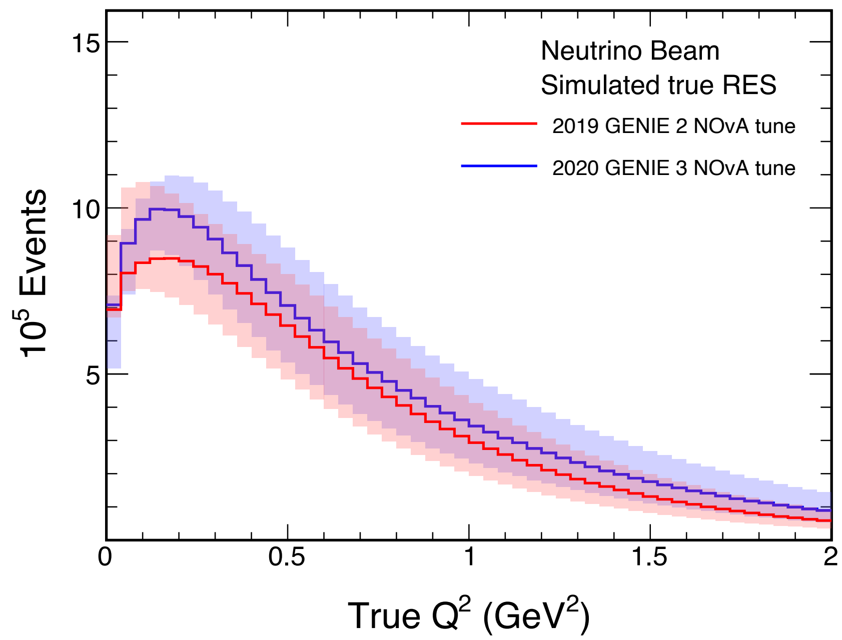
- Both best fits also include minimization of our systematic uncertainties.

2020 vs. 2017 Cross Section Model

- The QE central value is quite similar, but the expanded uncertainty due to the Z-expansion is apparent.

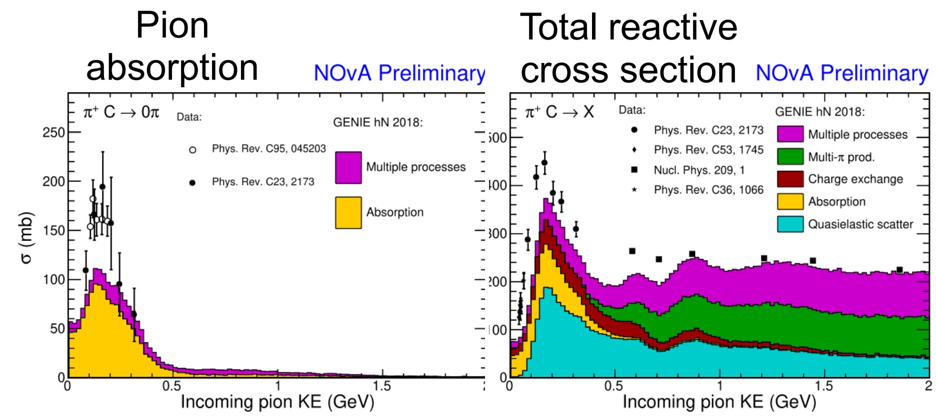


- In resonance, the uncertainty remains similar, the but the central value has changed.
- New model, Berger-Seghal, plus the global retune to scattering data.

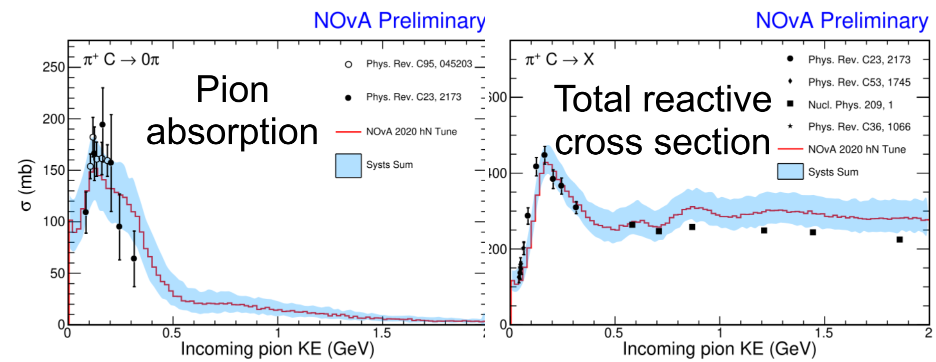


hN2018 FSI tuning

- New FSI model in GENIE 3.0.6: semi-classical cascade, “hN”
  - Propagates hadrons through nucleus in finite steps
  - Simulates interactions according to probabilities derived from Oset et al. quantum model*
  - Tuned using external pion scattering data, which is related to intranuclear probabilities using amplitudes from Oset model
- Old model (“hA”) simply assumes hadron scattering data applies directly to FSI



... but hN2018 agrees poorly with pion scattering data on carbon.

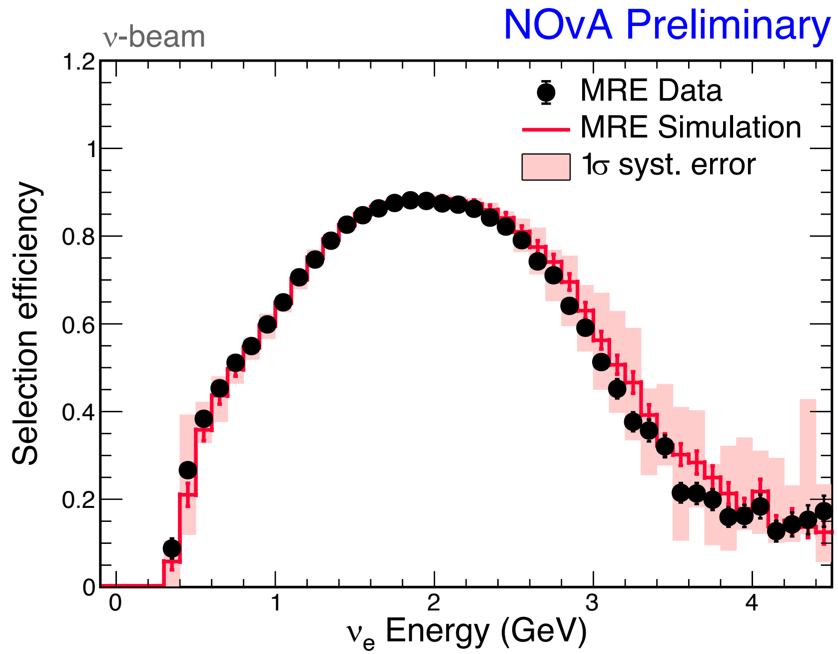


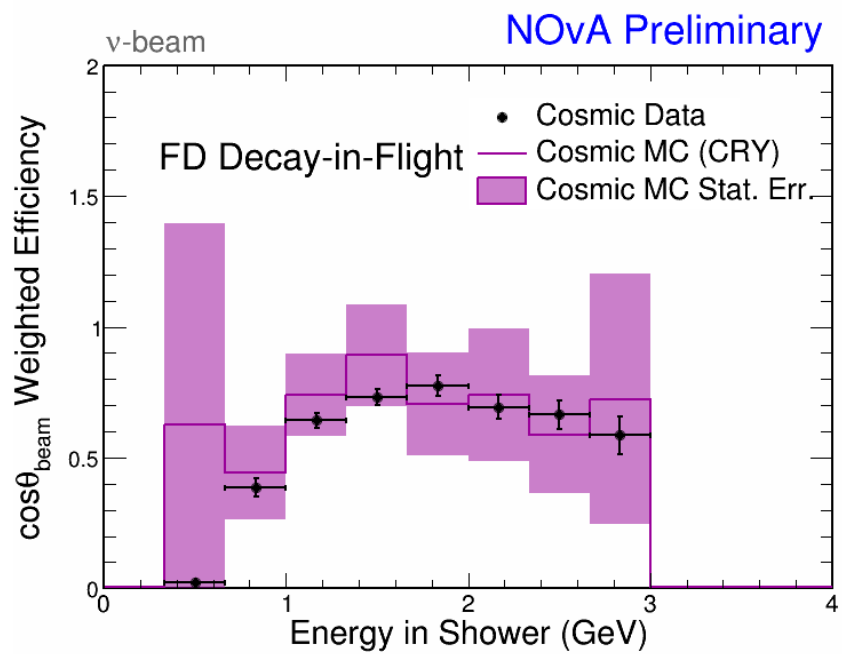
We retune hN2018 and develop systematics based in part on similar work by T2K†

* L. L. Salcedo et al. Nucl. Phys. A484: 557 (1988).
† E.S. Pinzon Guerra et al. Phys Rev. D99: 052007 (2019).

Selection: Validating Performance

- Examine PID efficiency relative to pre-selection.
  - Specifically target the behavior of the PID.
- ND: mixed data-MC sample
  - Mix simulated electrons and real hadronic showers
- FD: decay-in-flight electrons
  - Real electron showers from cosmic muons which decay

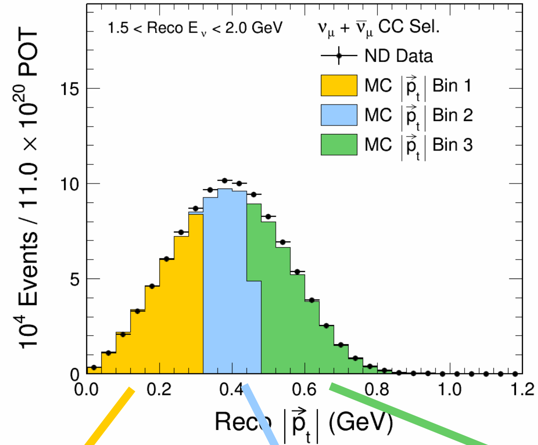




Posters

120. Data-Driven cross checks for ν_e selection efficiency in NOvA
   - Anna Hall

258. Data-Driven Wrong-Sign Background Estimates
   - Abhilash Yallappa Dombara



- Create 3 energy spectra, one for each p_t bin.
- Each spectra gets its own extrapolation.
- Predictions are summed before fitting.