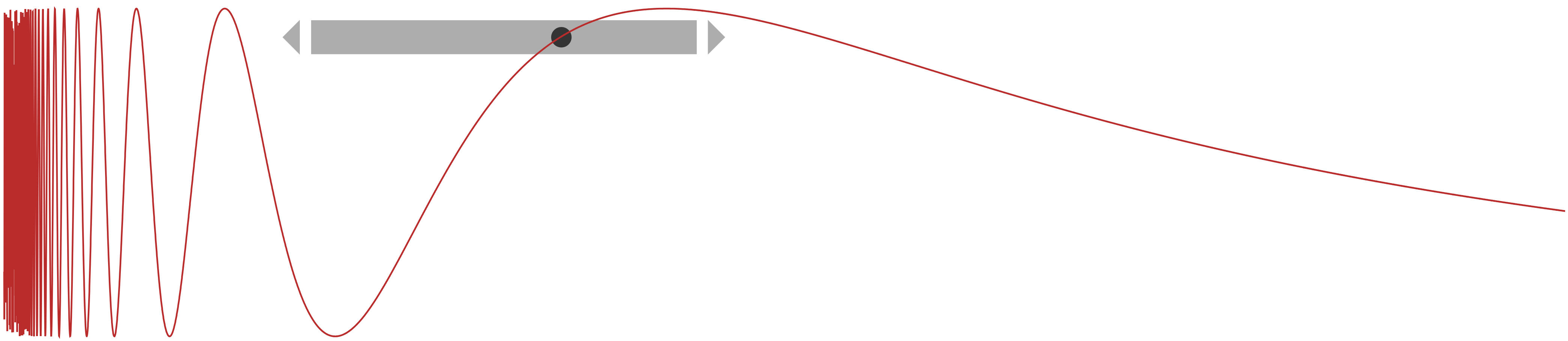
RECENT RESULTS FROM NOvA



Jeremy Wolcott
Tufts University
[on behalf of the NOvA collaboration]

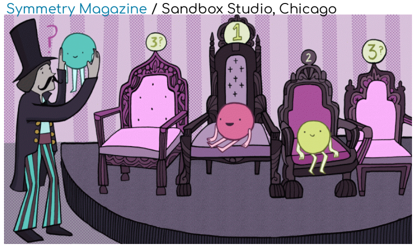
NuFact 2022
August 1, 2022

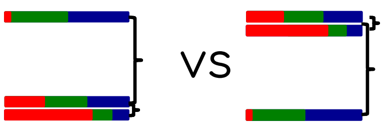
Tufts UNIVERSITY

[DOE award #DE-SC0019032]

ν questions

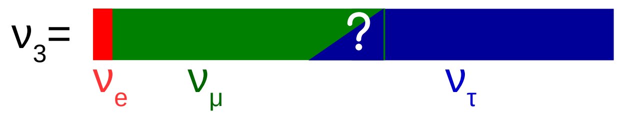
Symmetry Magazine / Sandbox Studio, Chicago





Which way are the **neutrino states ordered?**

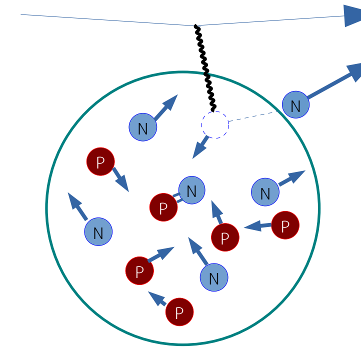
Do ν_μ/ν_τ **mix equally** into the ν mass states?



Are there **light sterile neutrinos?**

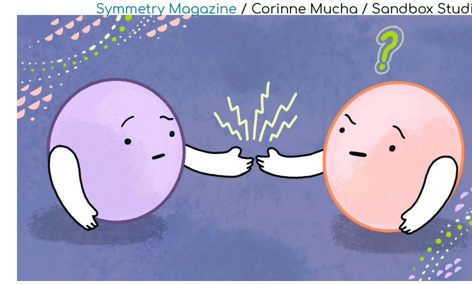
$$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$$

Do neutrinos exhibit **CP violation?**



Is our picture of **neutrino scattering** sufficient?

Symmetry Magazine / Corinne Mucha / Sandbox Studio

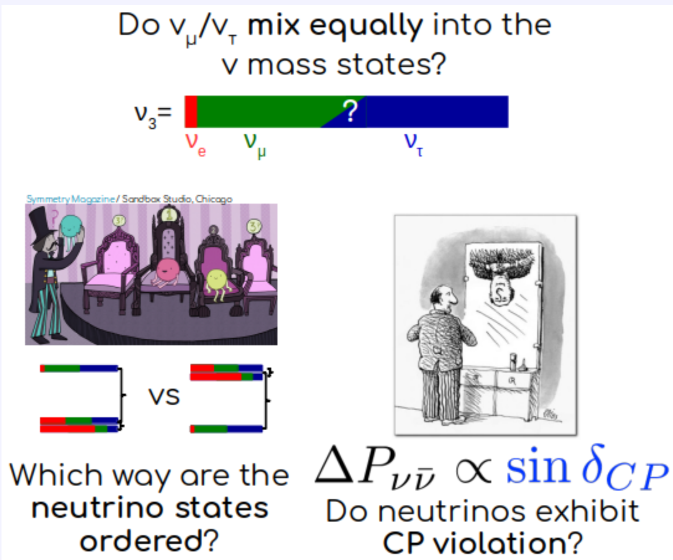


$$H = UH_0U^\dagger + H_{matter}$$

$$\ldots + H_{NSI}??$$

Do we fully understand **neutrino propagation in matter?**

ν questions: meta



① What can we learn by constraining 3-flavor oscillation parameters?

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}=\begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

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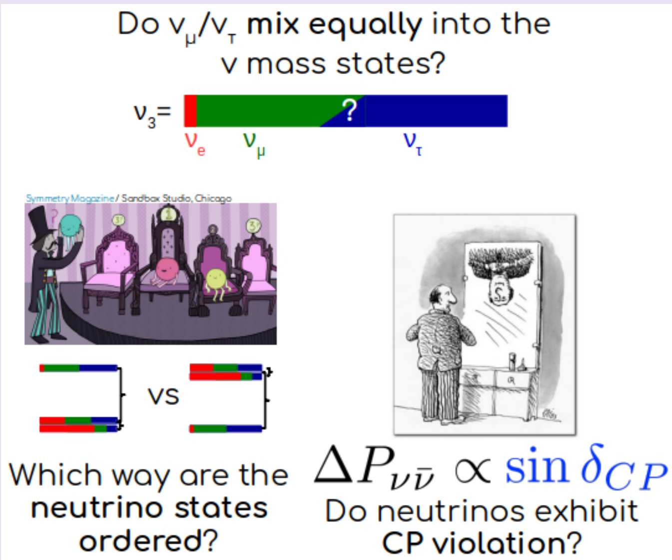

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② Is the 3-flavor oscillation model complete?

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{bmatrix}$$

$$\mathcal{H} = \frac{1}{2E}\left[U_{PMNS}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger_{PMNS} + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

ν questions: meta

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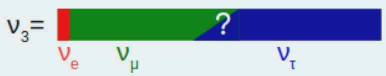

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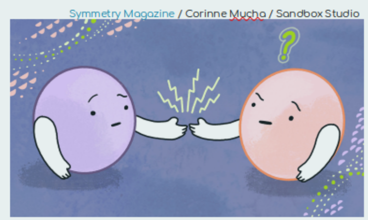

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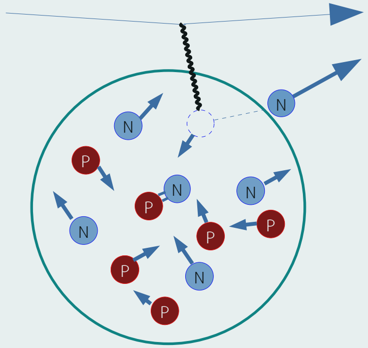

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③ Are interesting physics being hidden (or exposed!) by our "heavy" nuclear media?

ν questions: meta

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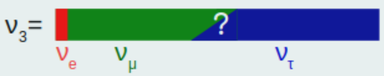
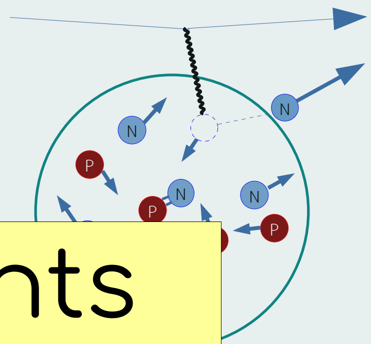


Which way **neutrino order**

Are there **light sterile neutrinos?**



ure of attering nt?

New-in-2022 measurements by NOvA engage all of these

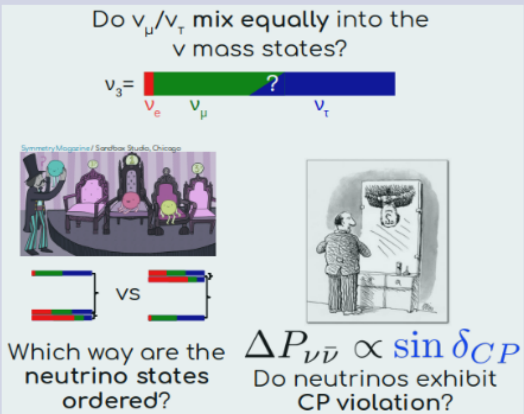
① Wh constraining 3-flavor oscillation parameters?

Do we fully understand **neutrino propagation in matter?**

② Is the 3-flavor oscillation model complete?

③ Are interesting physics being hidden (or exposed!) by our "heavy" nuclear media?

ν questions: meta



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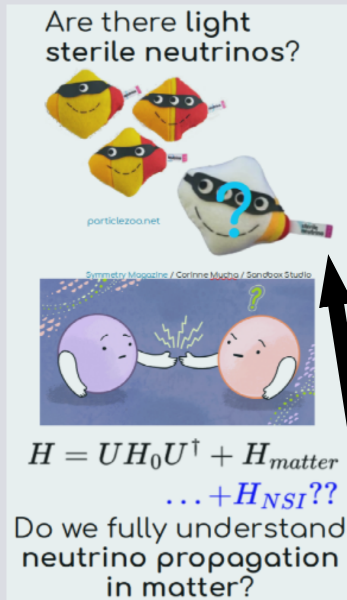

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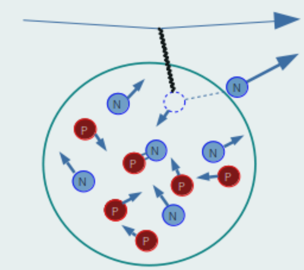

Is our picture of neutrino scattering sufficient?

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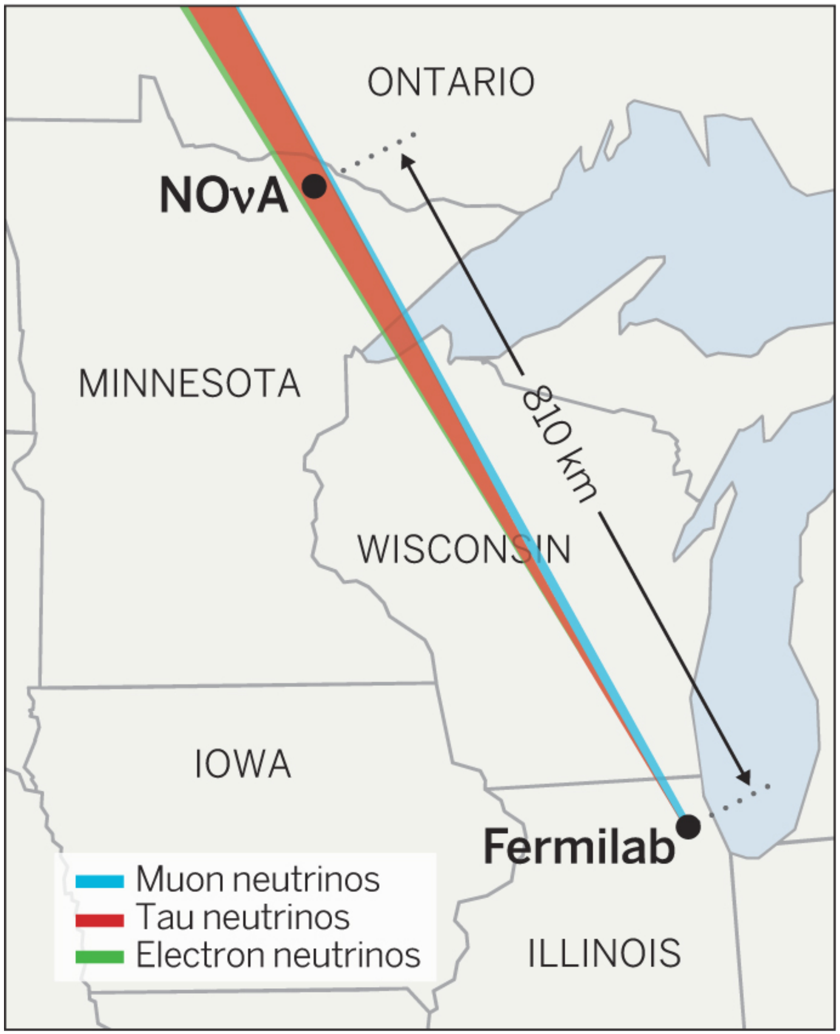
Two ν_μ CC cross section measurements

Bayesian look at 3-flavor model constraints

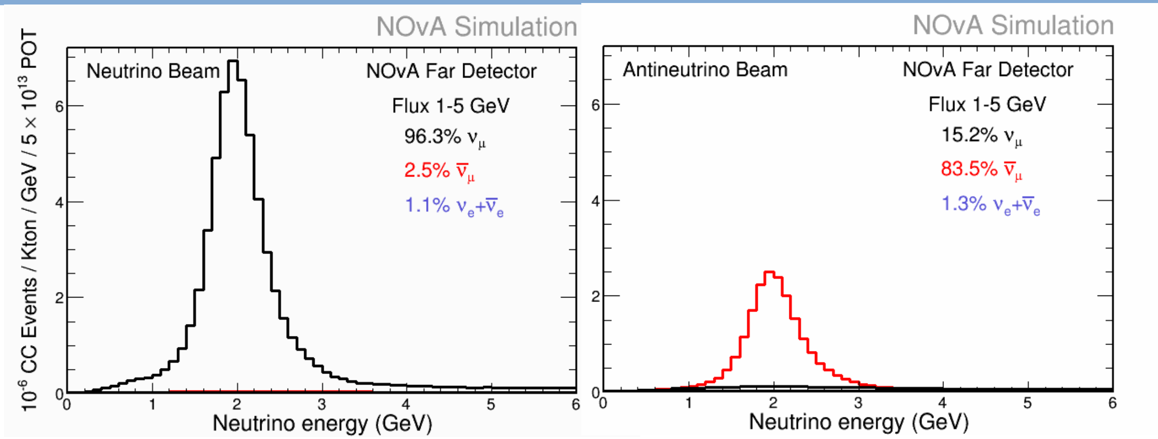
Search for nonstandard interactions

Search for sterile neutrinos

NOvA: neutrinos

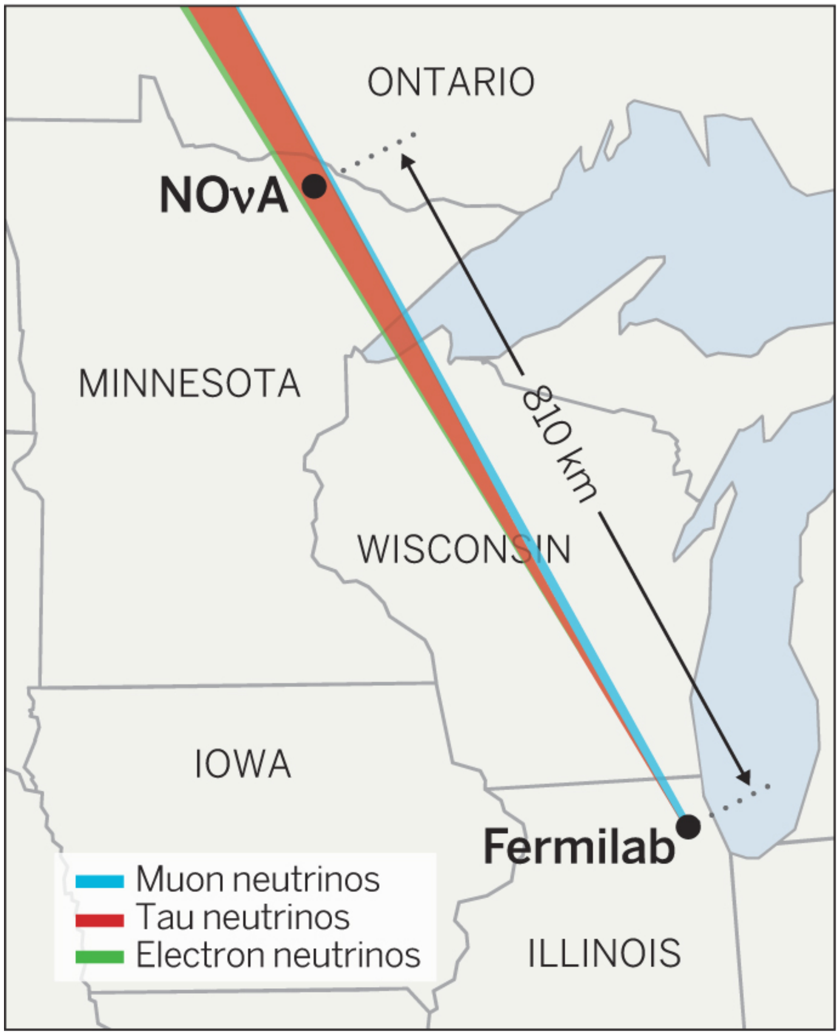


K. ENGMAN/SCIENCE 345, 6204



23.2×10^{20} (neutrino mode) + 12.7×10^{20} (antineutrino mode) POT recorded so far

NOvA: neutrinos



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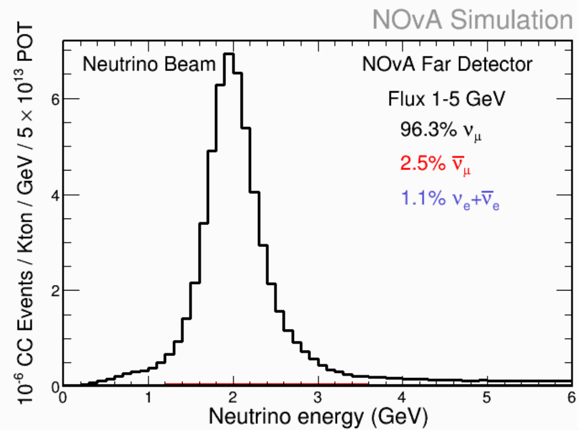
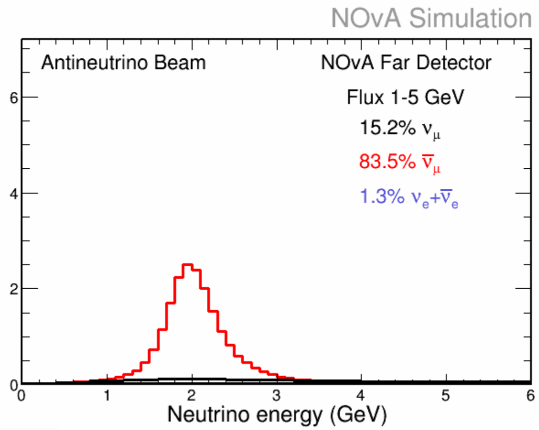




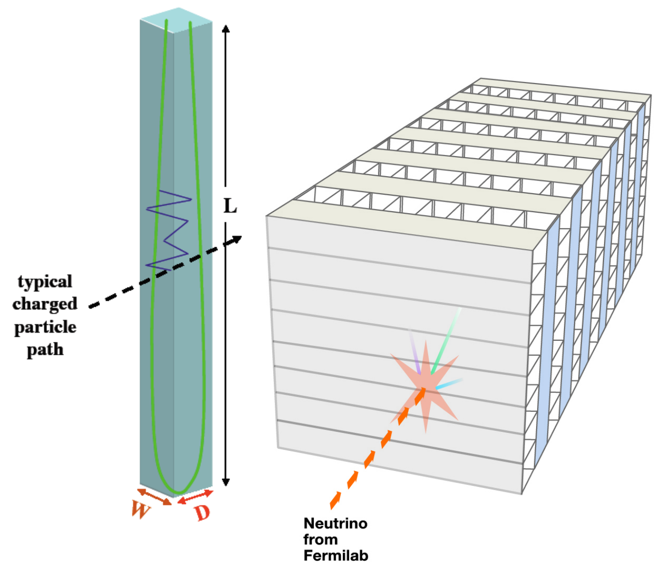
23.2×10^{20} + 12.7×10^{20} POT recorded so far
(neutrino mode) (antineutrino mode)

MW-capable target (installed 2019)

MW-capable horn (installed 2020)

2021-2022:
Record year for peak intensity & total exposure

NOvA: detectors

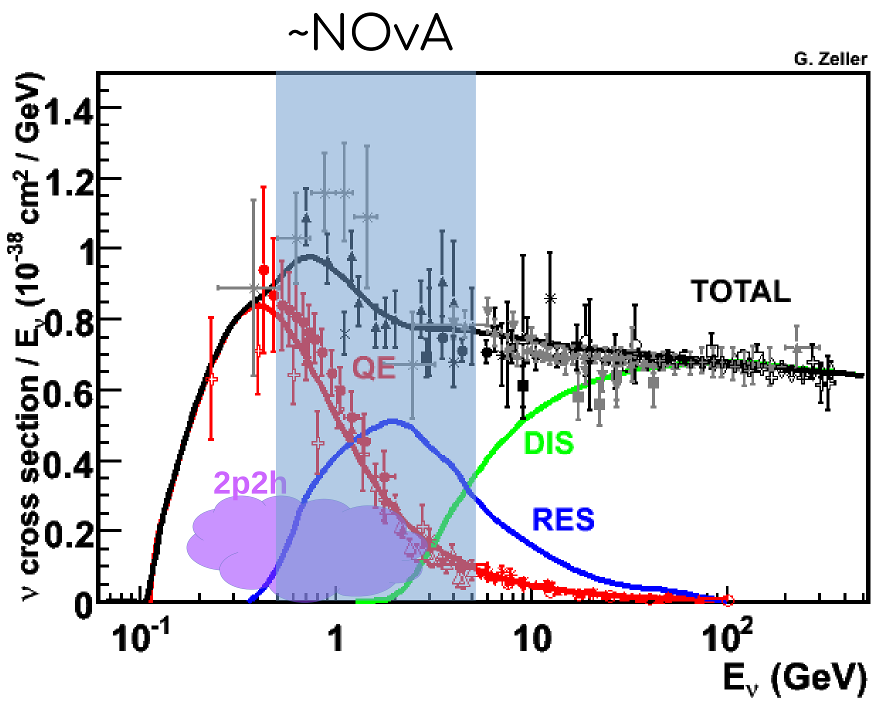


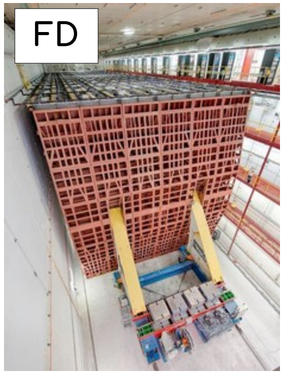
- Two hydrocarbon-based tracking calorimeters
  - Extruded plastic cells, ~4x6cm
  - Fill: mineral oil doped with pseudocumene scintillator

  → each cell **~1/6 X_0 deep**

- Alternating **stereoscopic planes** (90° rotation)

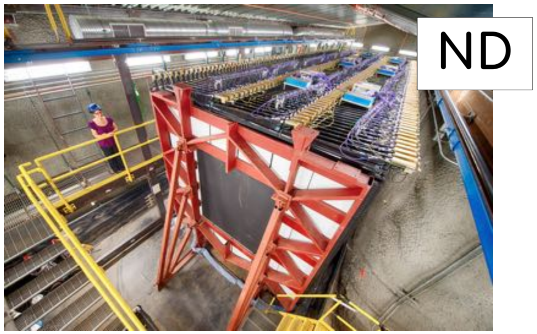
NOvA: detectors

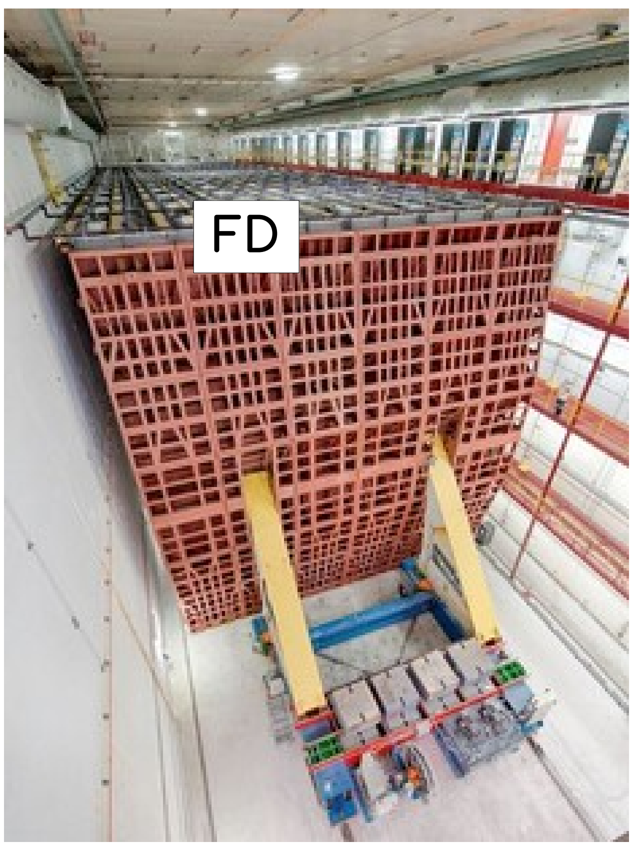


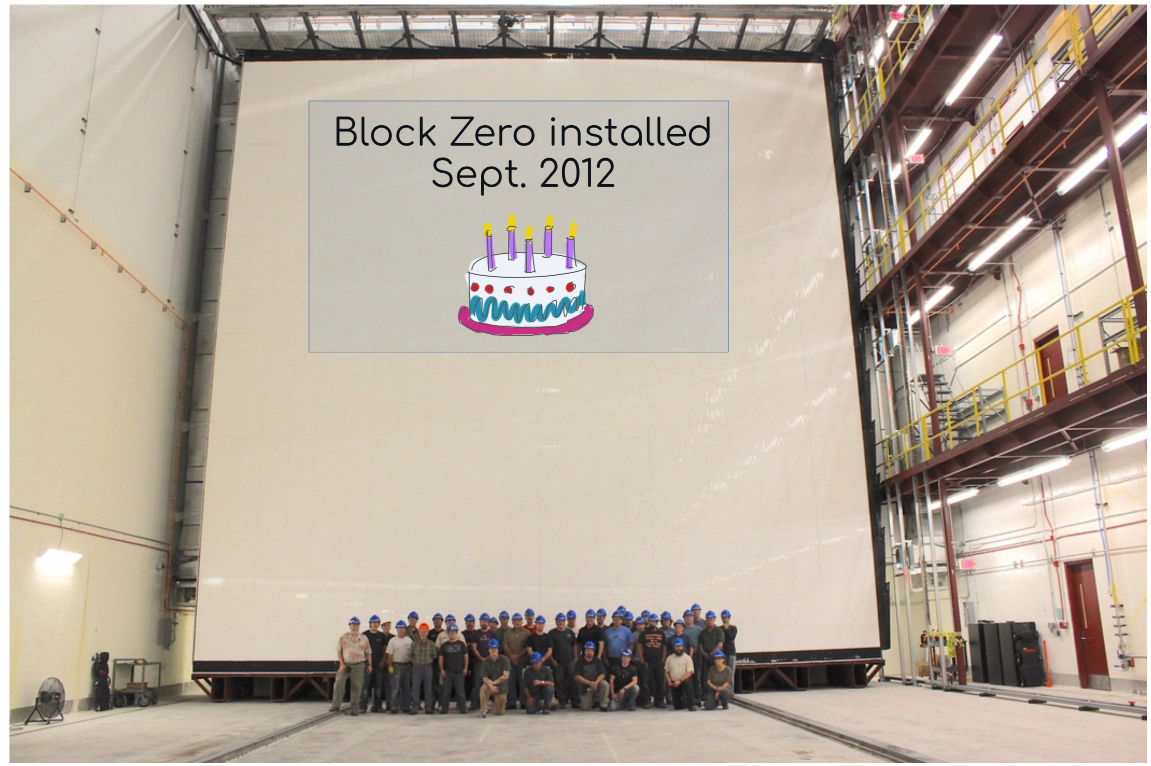


- 300 ton Near Detector at Fermilab
  - ~1 km from neutrino production point
- Millions of ν_μ CC and tens of thousands of ν_e CC interactions in "crossover" energy region
  → Study all interaction types & ^{12}C nuclear effects with huge statistics

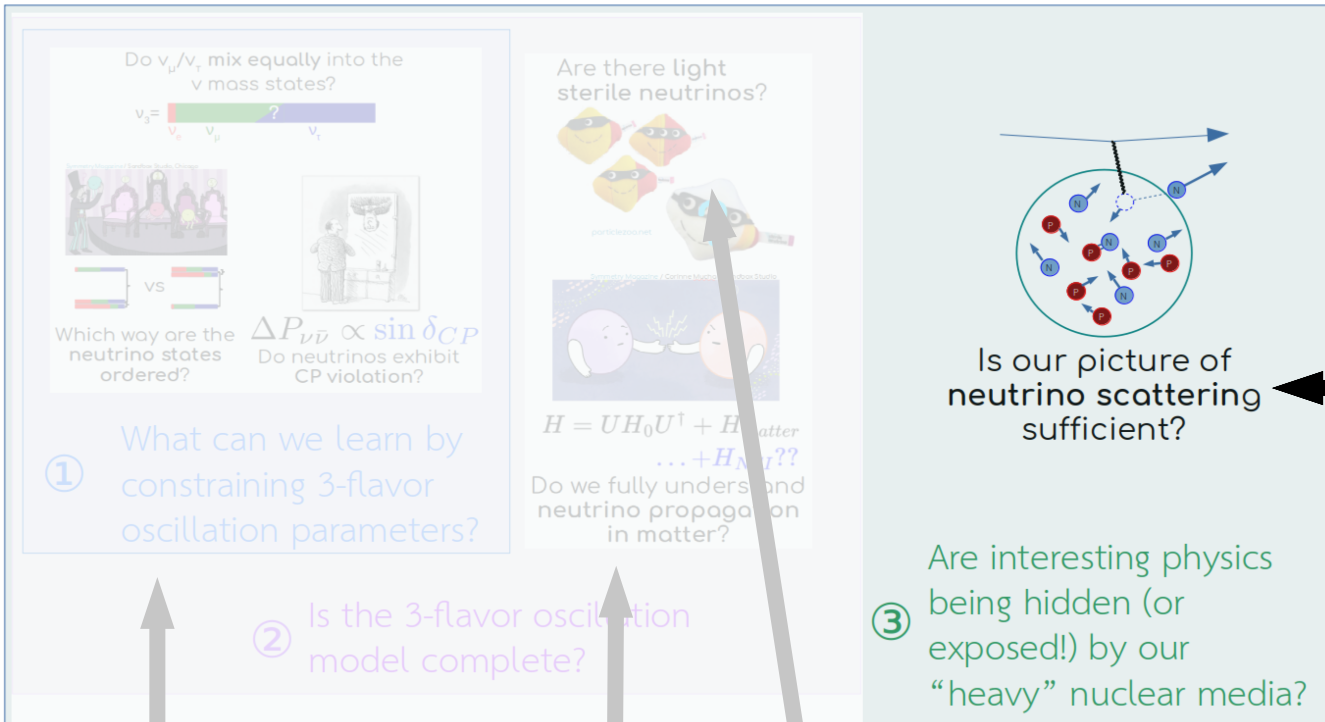
NOvA: detectors







- 14,000 ton Far Detector in Ash River
  - Highly sensitive to ν_μ CC, ν_e CC, NC



Two ν_μ CC cross section measurements

(use Near Detector exclusively)

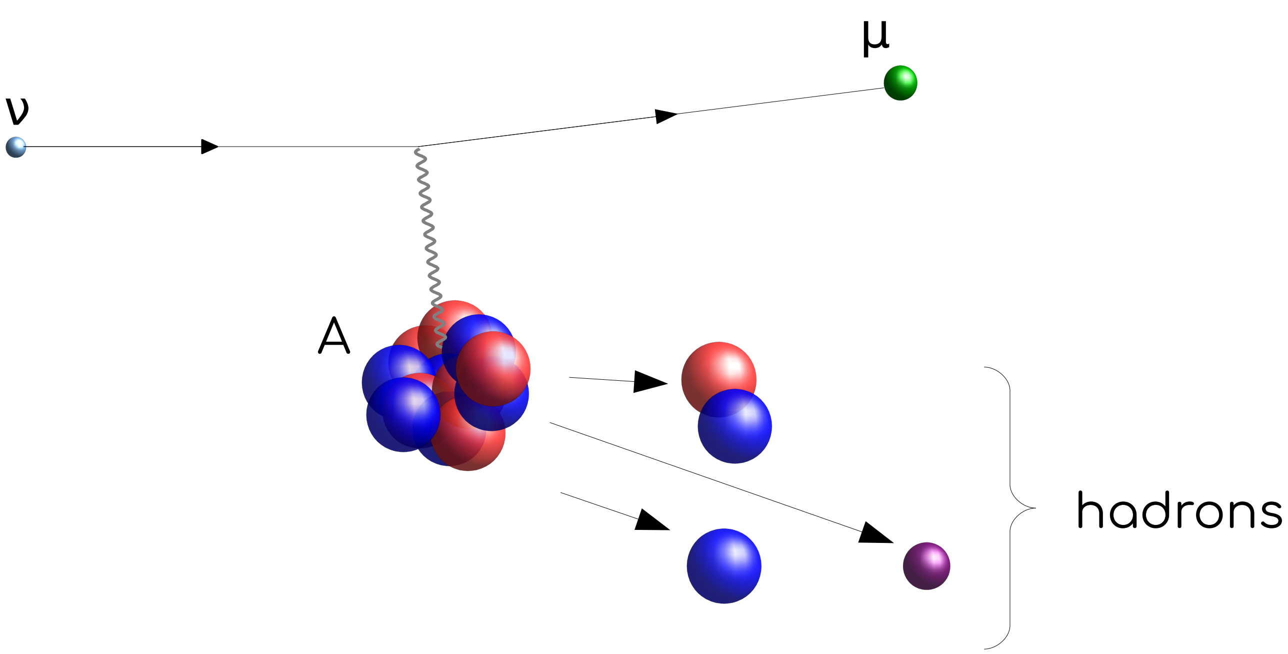
Bayesian look at 3-flavor model constraints

Search for nonstandard interactions

Search for sterile neutrinos

ν interactions measurements

Examine ν_μ CC interactions from different 'directions':



ν interactions measurements

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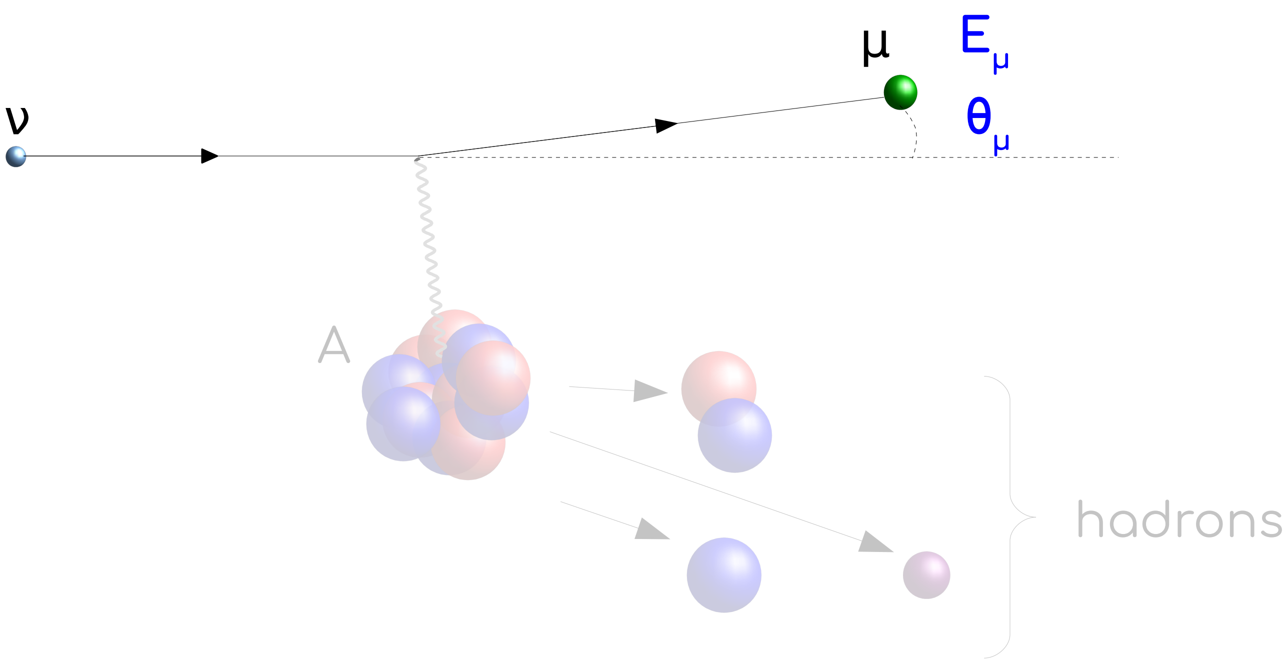
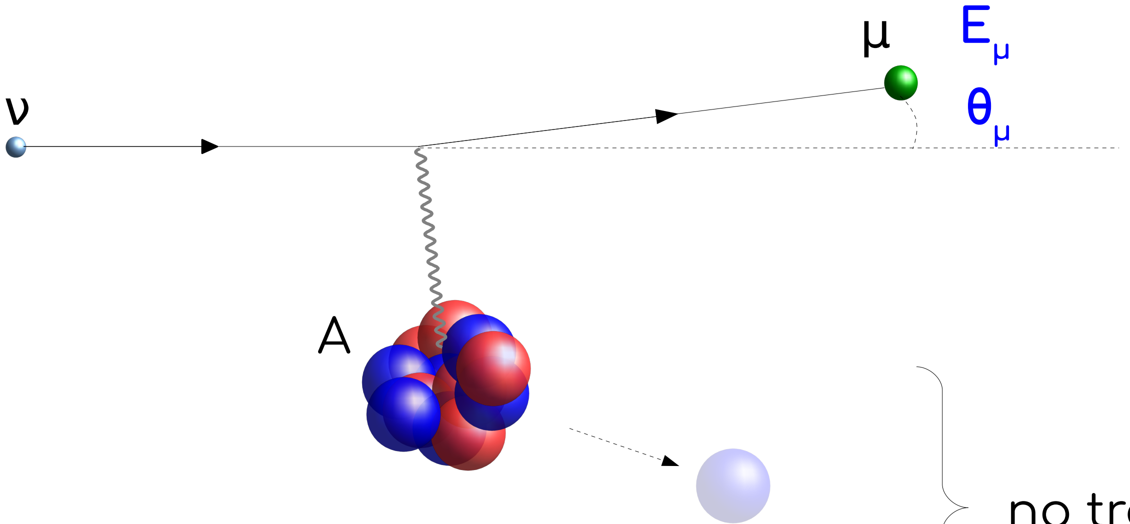


1. Fate of the outgoing muon

measure **energy, angle**
(good resolution)

ν interactions measurements

Examine ν_μ CC interactions from different 'directions':



no trackable hadrons

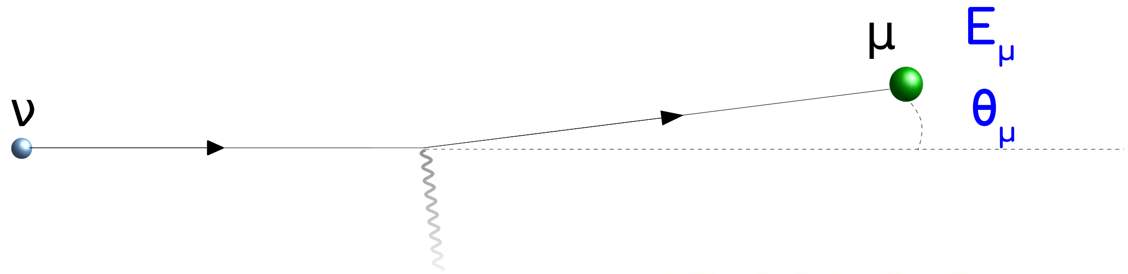
($KE_p \leq 200$ MeV;
$KE_\pi \leq 175$ MeV)

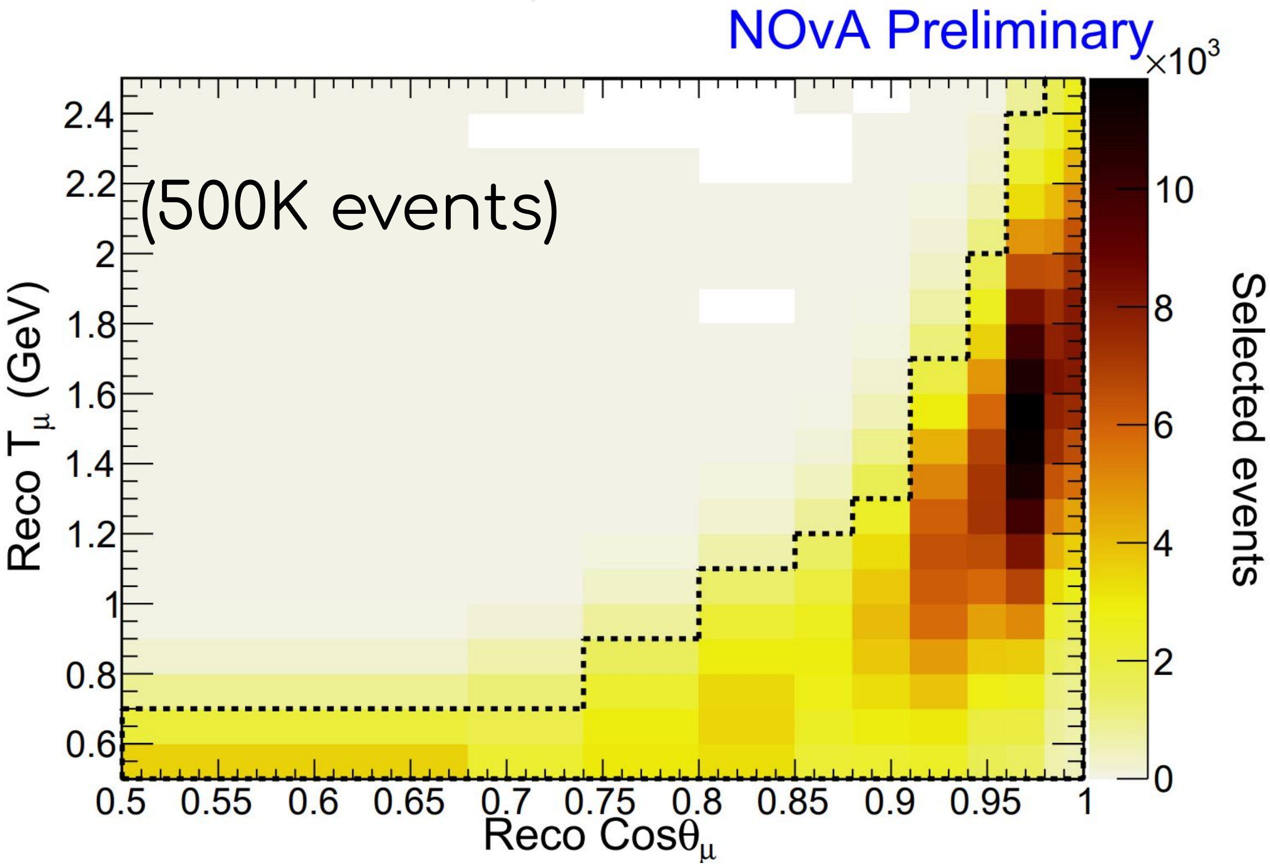
1. Fate of the outgoing muon

measure **energy, angle** (good resolution)

Exclusive measurement:
low hadronic energy
(no hadronic tracks)

ν_μ CC: muon system





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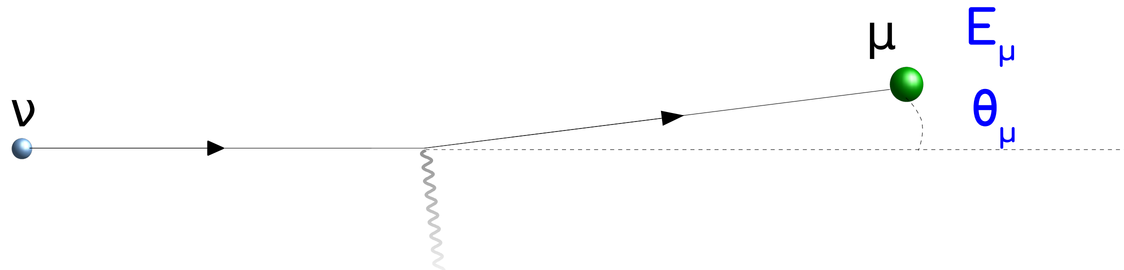
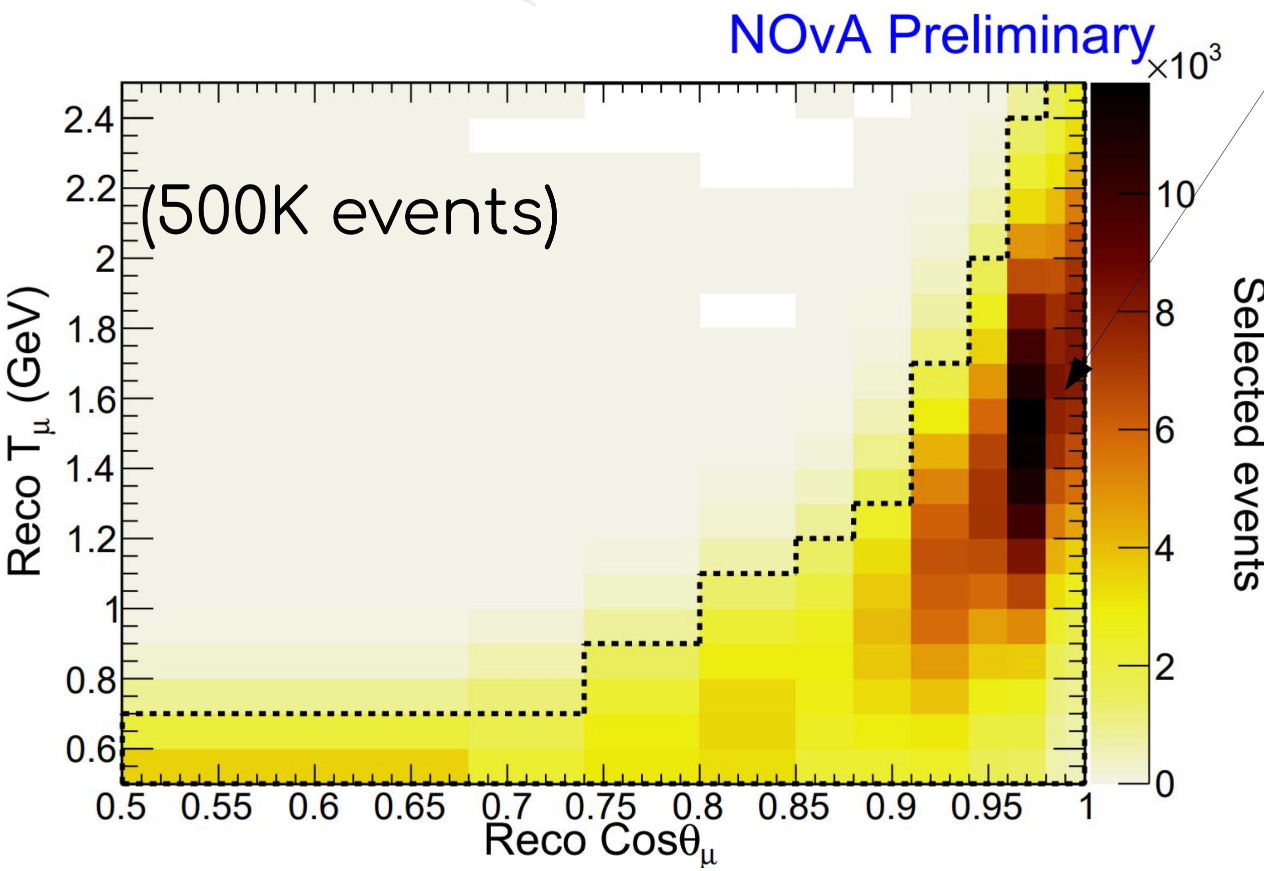
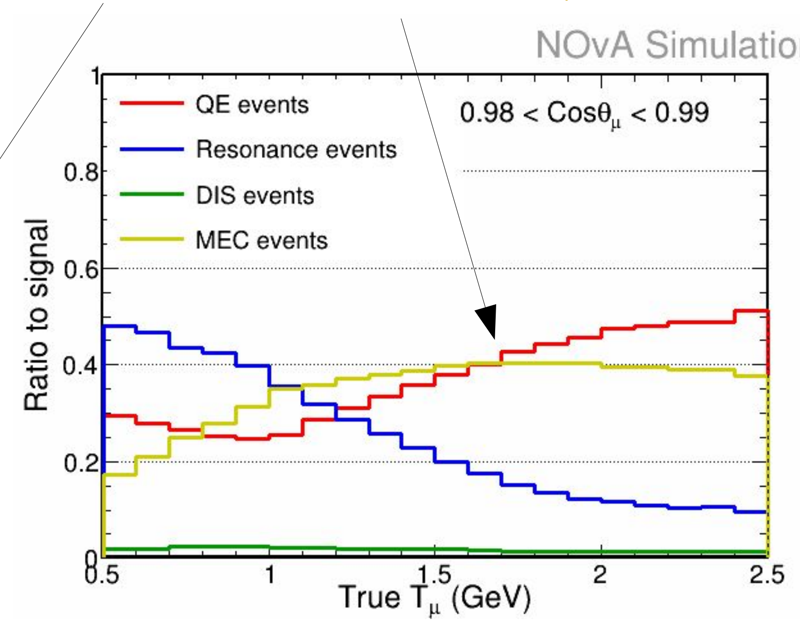
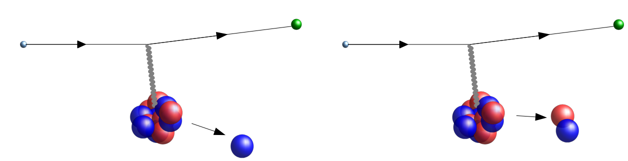




Forward, energetic muon
→ enhanced elastic, 2p2h



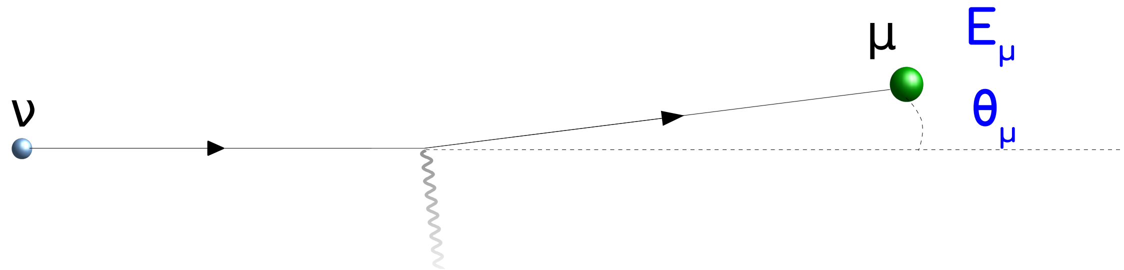


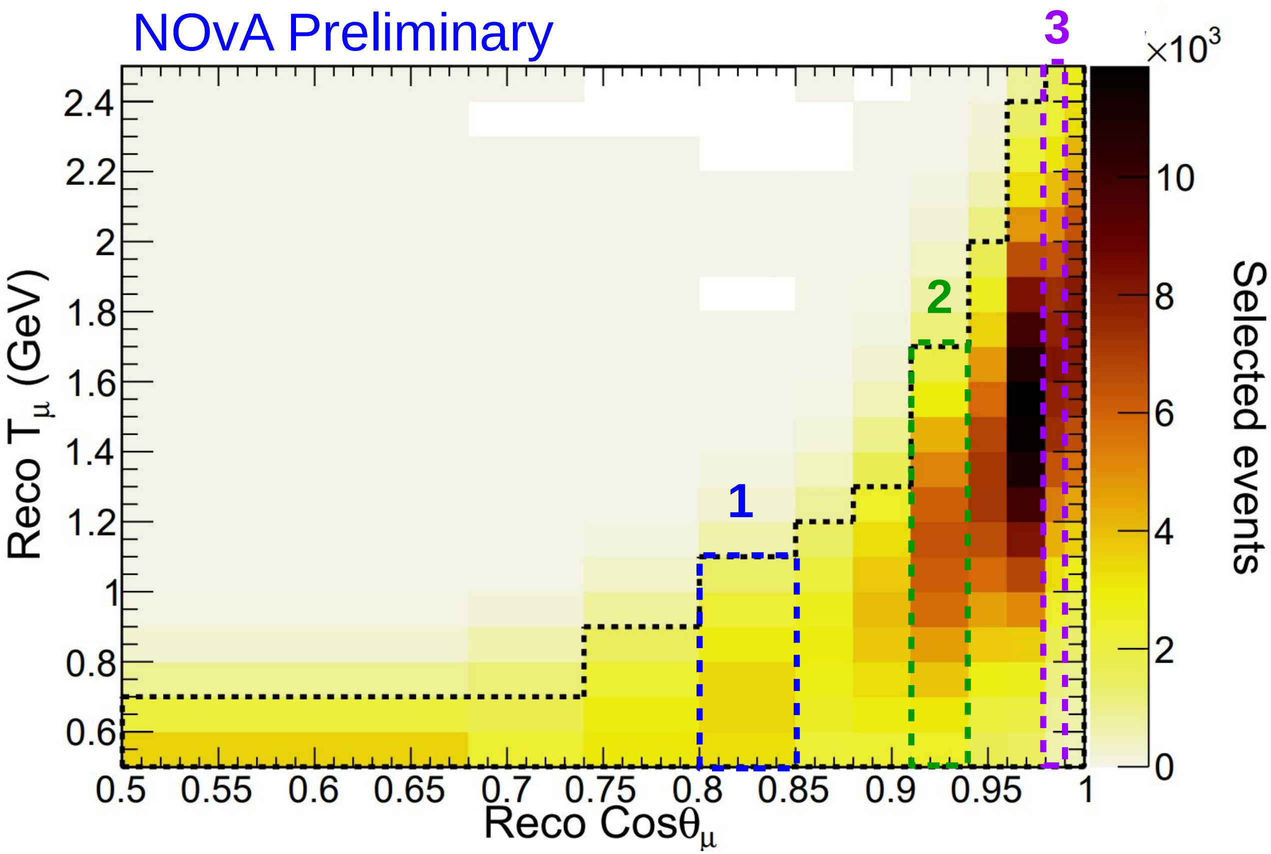
Quasielastic
(1 nucleon)

2p2h
(2 nucleons)

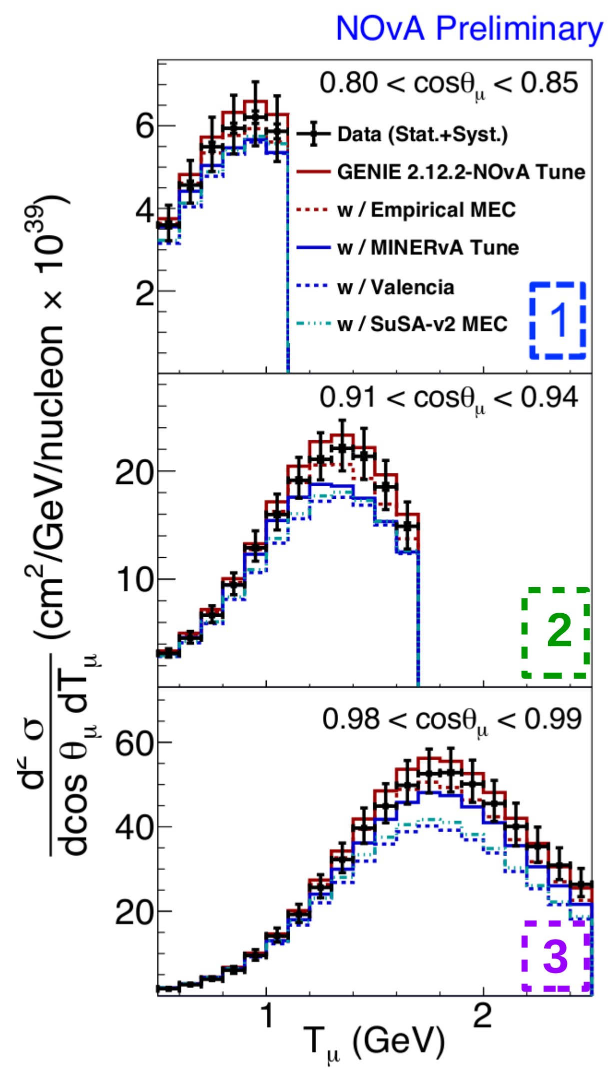
Very sensitive to
nuclear initial state

ν_μ CC: muon system

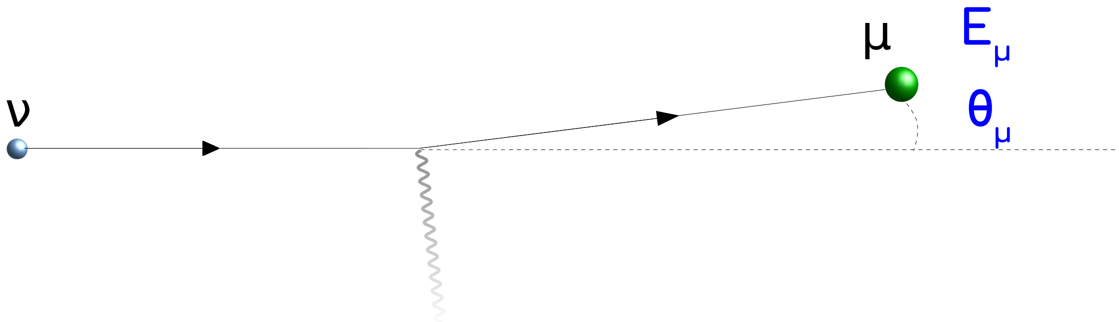




Analyze in terms of 2p2h model:



ν_μ CC: muon system

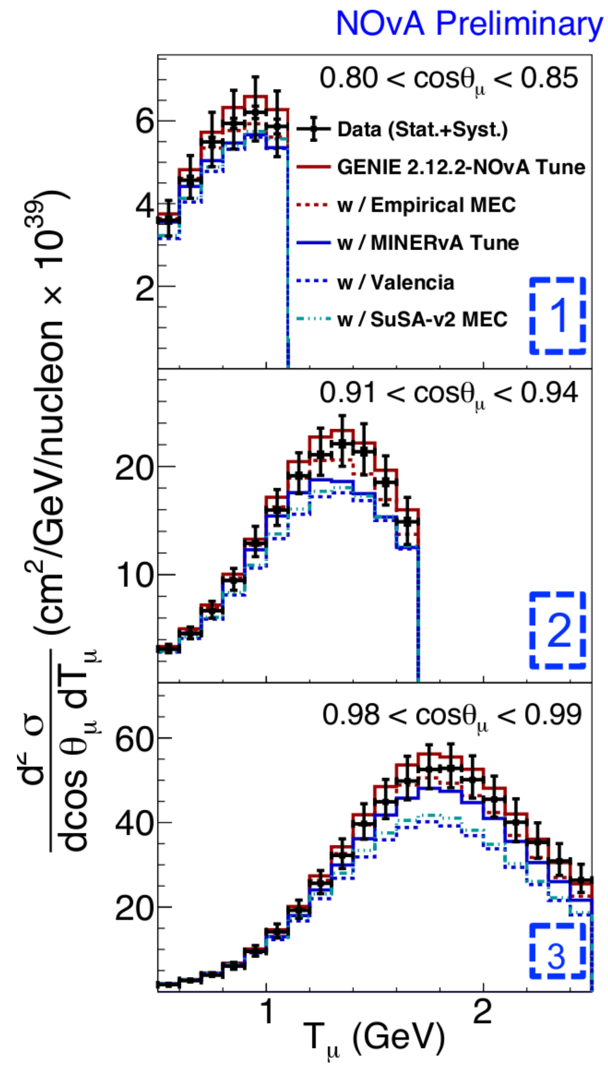


2p2h model	χ^2 (115 d.o.f.) (includes 11 $\cos\theta_\mu$ slices)
GENIE 2.12.2 + NOvA tune	200
Empirical MEC	190
València + MINERvA tune	340
València	630
SuSA v2	620

Tuned: GENIE 2.12.2 + NOvA tune, Empirical MEC, València + MINERvA tune

Pure theory: València, SuSA v2

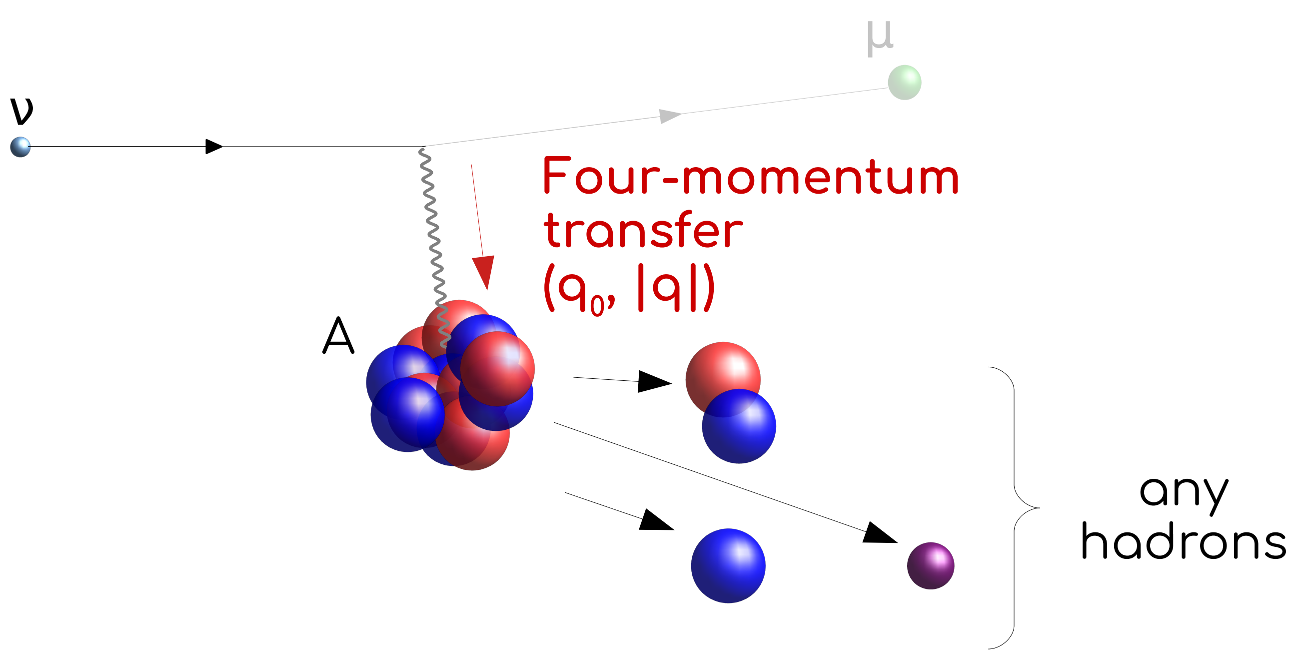
Analyze in terms of 2p2h model:



- Tuned 2p2h "models" describe data better than pure theory
- No 2p2h model yields good agreement
  - València QE model (local Fermi gas) is used in all preds.
  - **Interplay with QE model is important!**

ν_μ CC: hadron system

Examine ν_μ CC interactions from two 'directions':



1. Fate of the outgoing muon

measure **energy**, angle (good resolution)

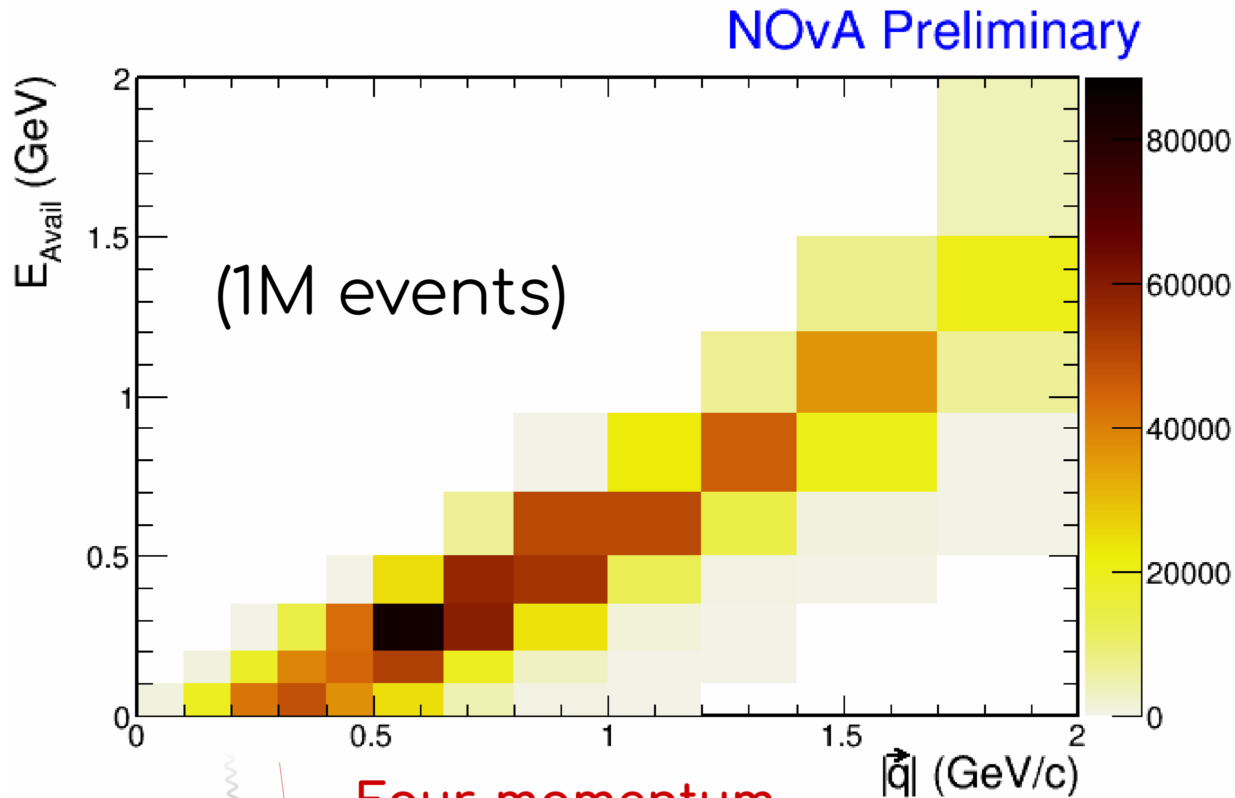
Exclusive measurement: **low hadronic energy**

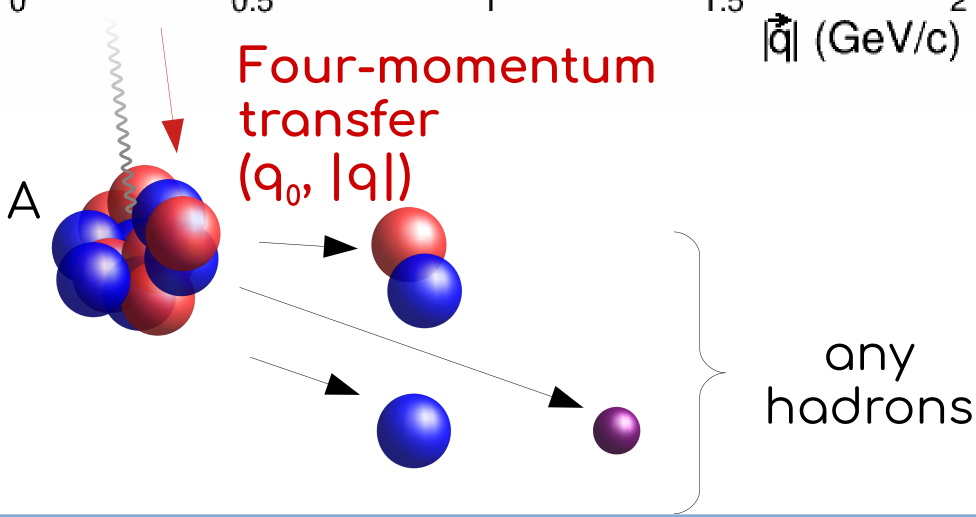
2. Hadron system response

measure **"visible" hadronic energy, three-momentum xfer**

Inclusive measurement **(within phase space)**

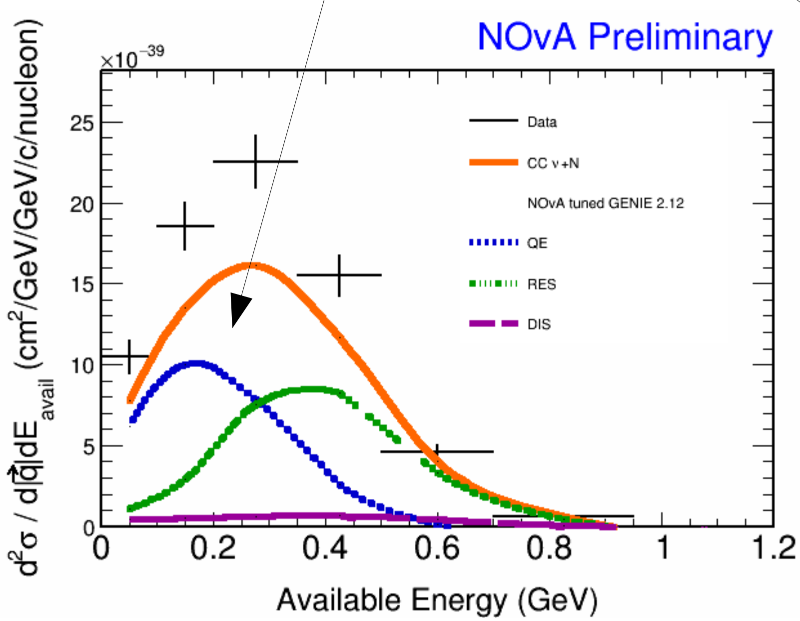
ν_μ CC: hadron system

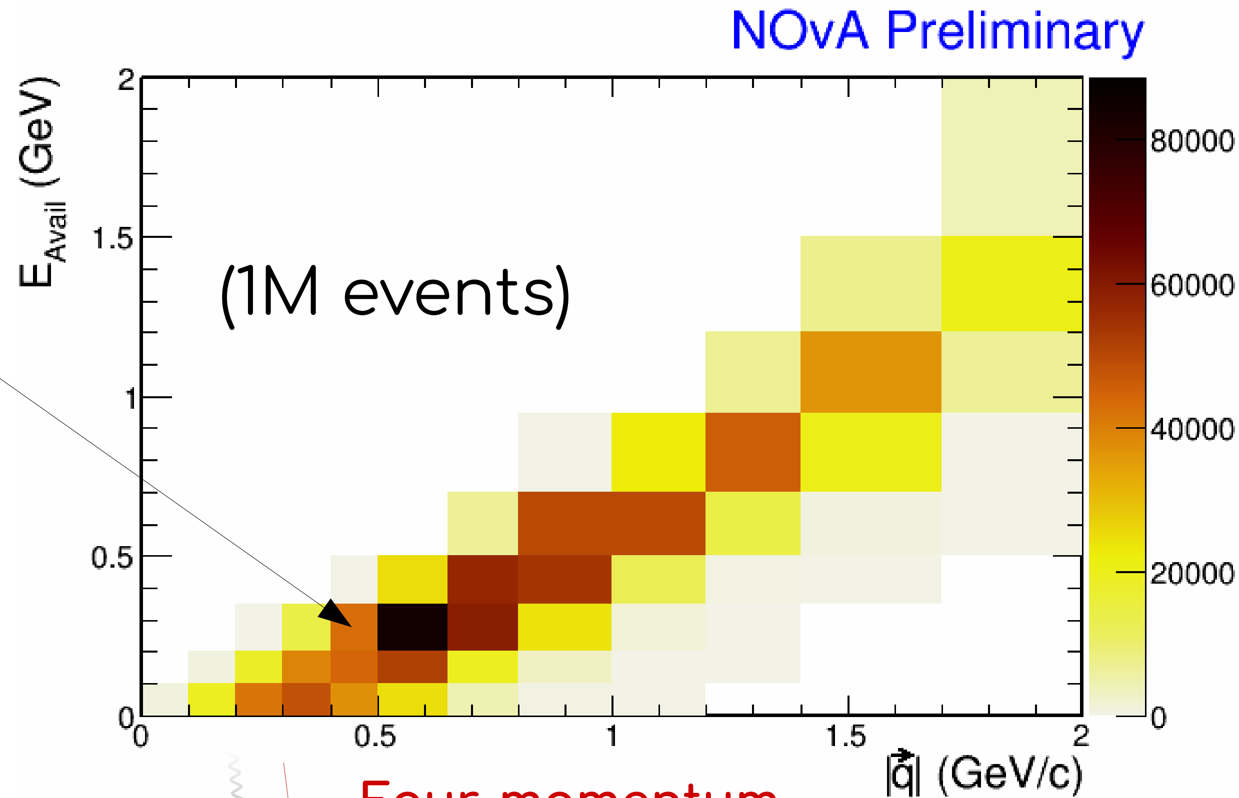


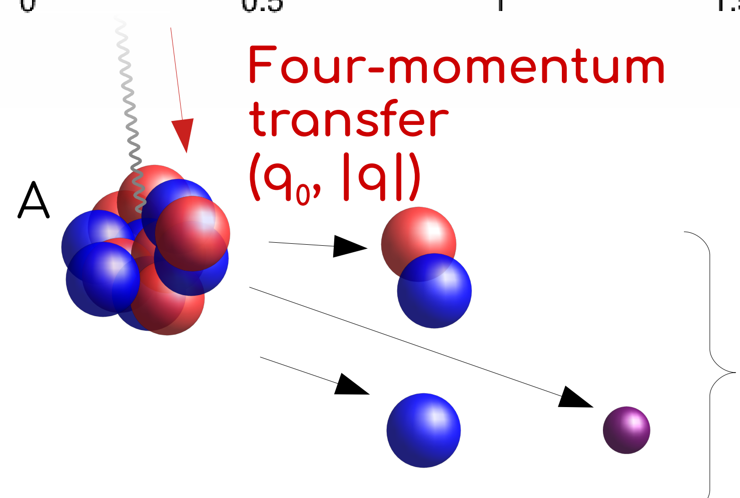


ν_μ CC: hadron system

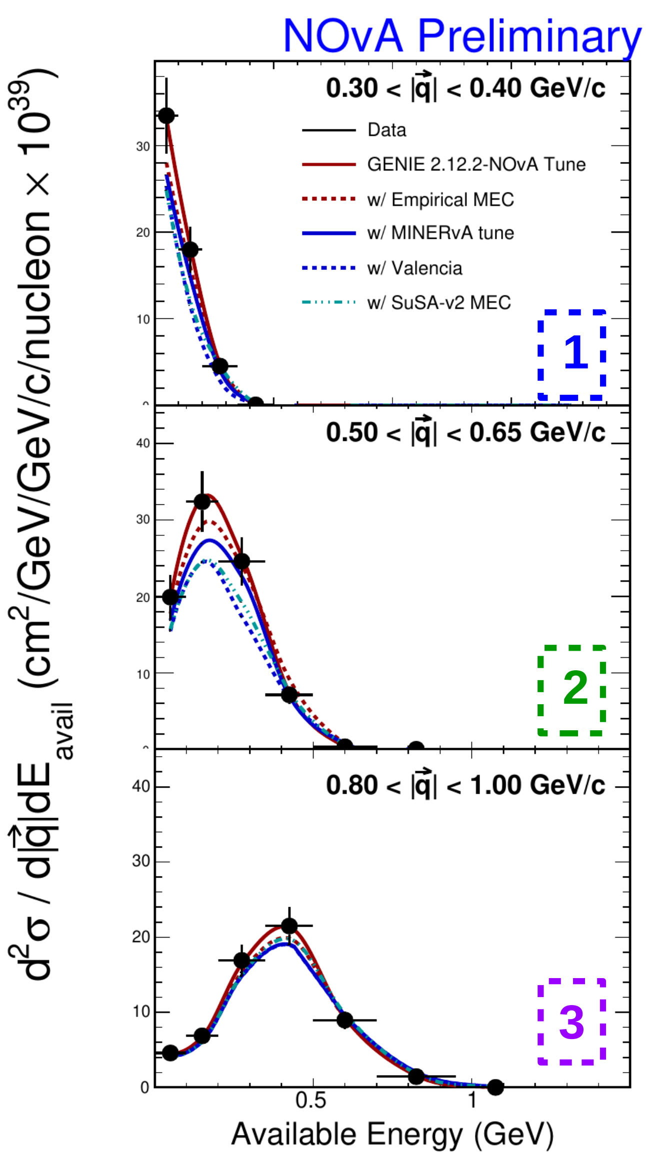
Low energy & momentum xfer
→ enhanced elastic, 2p2h.
(Inelastic stuff higher)

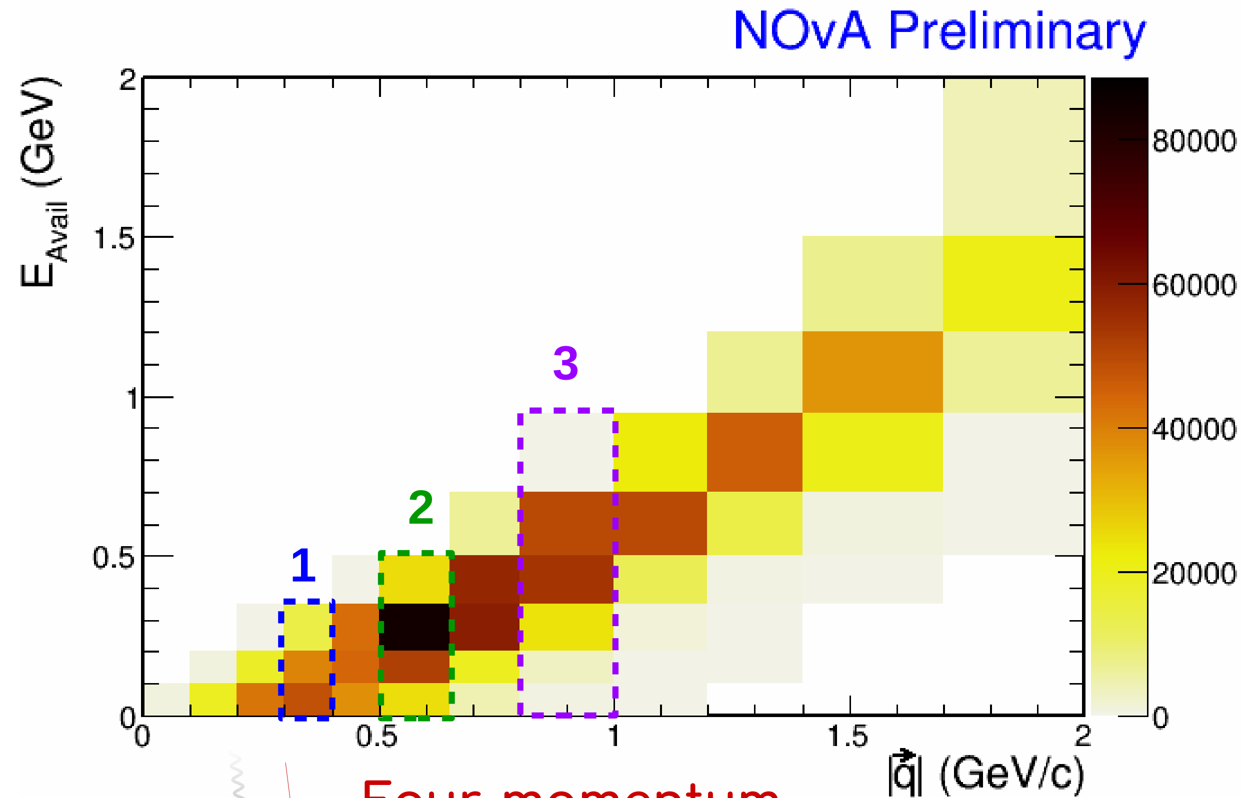


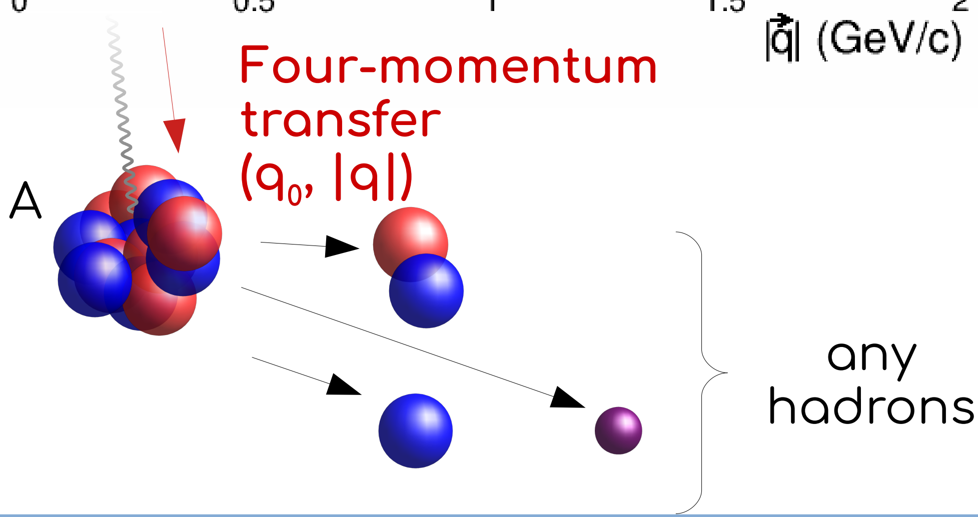




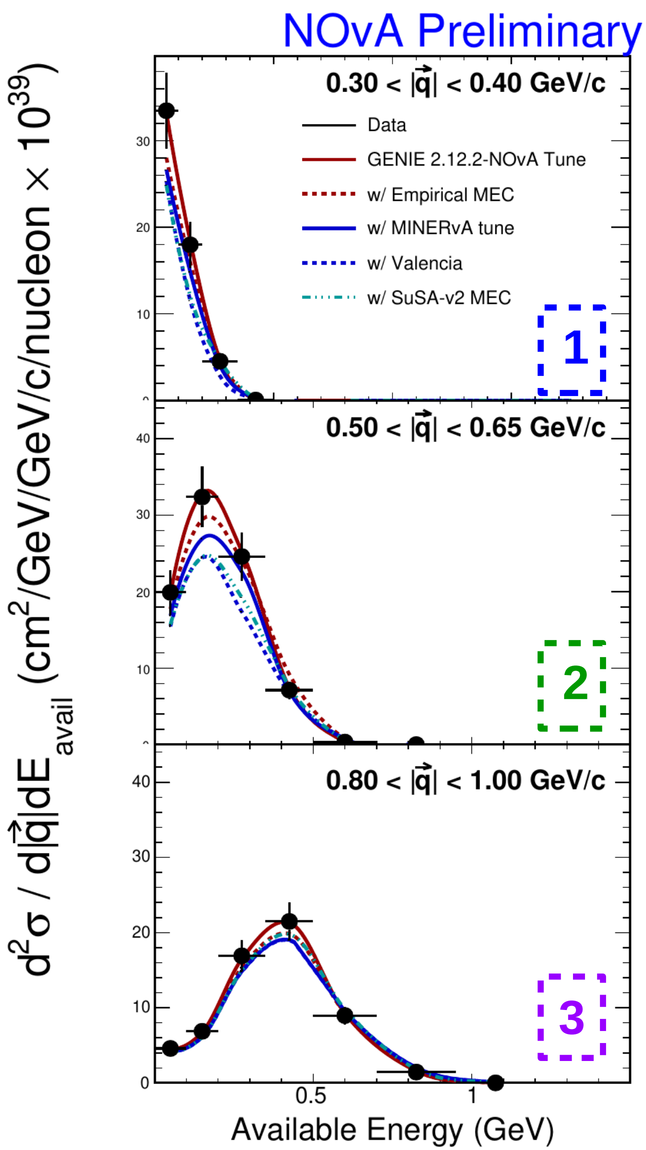
ν_μ CC: hadron system







ν_μ CC: hadron system

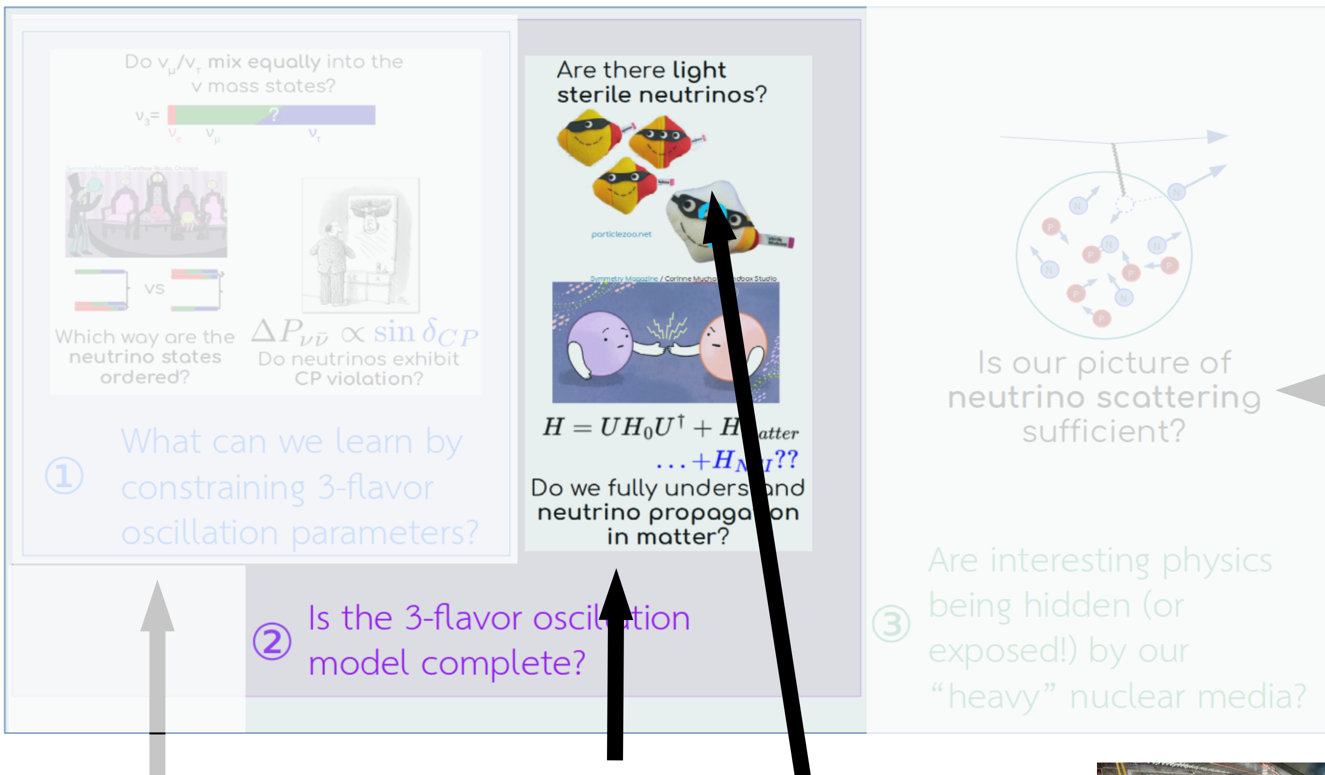


2p2h model	χ^2 (67 d.o.f.) (includes 12 |q| slices)	
GENIE 2.12.2 + NOvA tune	560	Tuned
Empirical MEC	910	Tuned
València + MINERvA tune	970	Tuned
València	1900	Pure theory
SuSA v2	1000	Pure theory

- Significant discrepancies from inelastic (RES, DIS) processes in this inclusive sample
  - Inelastic processes at higher energy, momentum xfers
  - **Base agreement is poor** (see backup)
- Wide variation across 2p2h models
  - QE/2p2h interplay significant here too
- χ^2s above include conservative detector response uncertainties
  - NOvA Test Beam program expected to help mitigate in future; see M. Wallbank in WG1 on Friday

ν_μ CC: takeaways

- Significant data-theory discrepancies for ν-^{12}C at 2 GeV
  - Elastic region: cannot be resolved by theory 2p2h models alone
  - Rich pion production region remains underexplored, poorly predicted
  - **NOvA oscillation measurements require robust uncertainties** (see Kirk Bays' talk in WG1+2 on Tuesday)
- High-stats measurements from NOvA probe both lepton & hadron systems in ν_μ CC interactions
  - Data releases in progress
- $\bar{\nu}_\mu$ & $\bar{\nu}_e$ inclusive, and numerous exclusive-channel measurements, just around the corner!
  - See, e.g., F. Gao's talk in WG2 on Friday

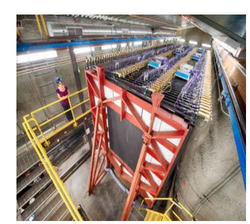


Two ν_μ CC cross section measurements

Bayesian look at 3-flavor model constraints

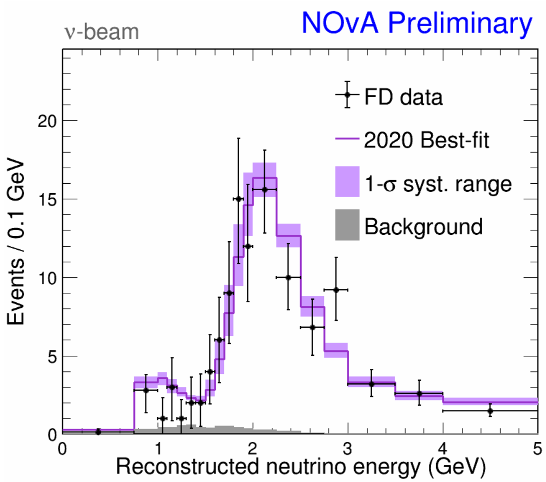
Search for nonstandard interactions

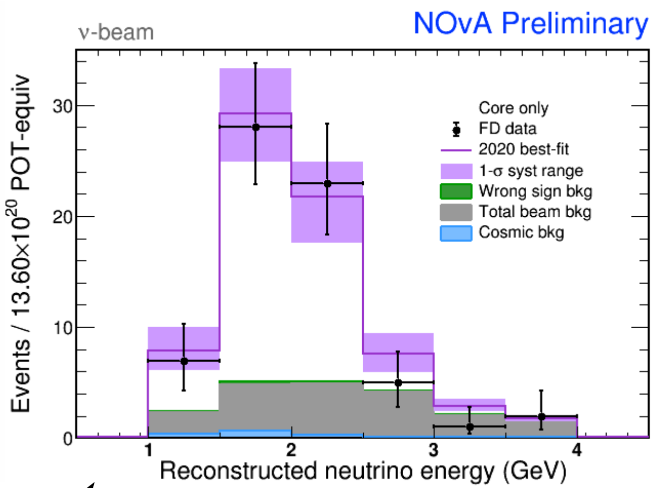
Search for sterile neutrinos

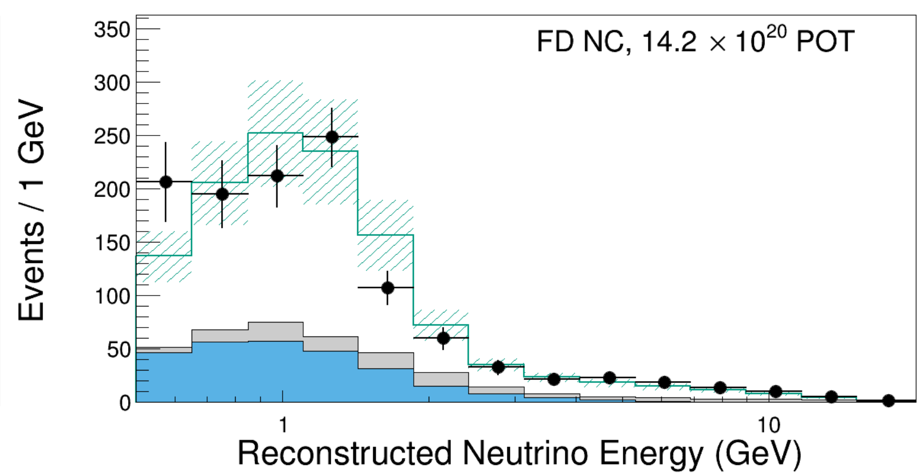


(use both Near & Far Detectors)

Far Detector data







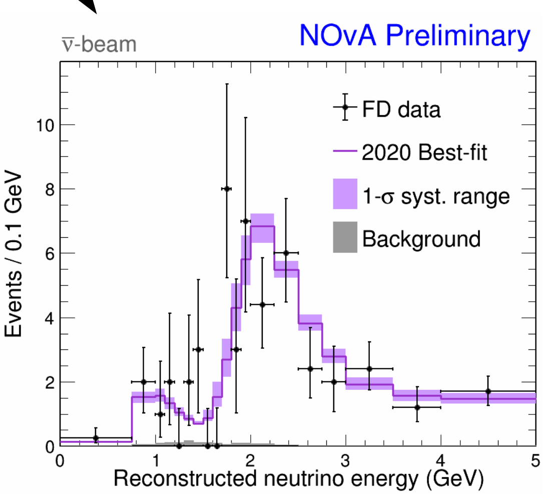
211 ν_μ cand.

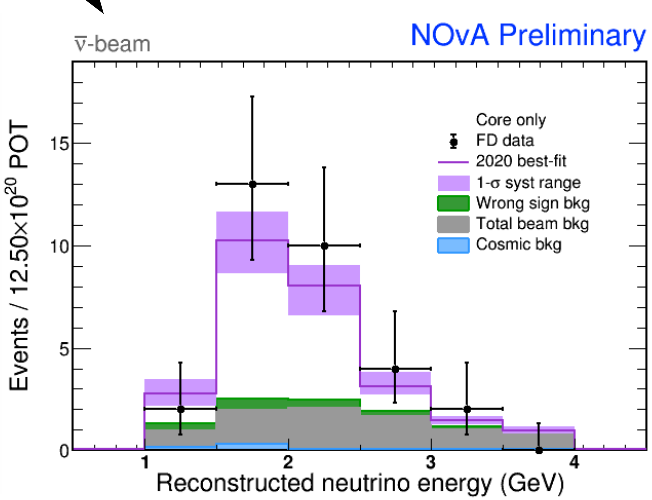
105 $\bar{\nu}_\mu$ cand.

82 ν_e cand.

33 $\bar{\nu}_e$ cand.

469 NC cand.





(plus ~4M $\nu_\mu + \bar{\nu}_\mu$,
50K $\nu_e + \bar{\nu}_e$,
100K NC
in the Near Detector)

… the 3-flavor model
describes them all pretty well …

Sterile neutrinos?

Adding one more neutrino
makes phenomenology much richer:

ν_μ CC disappearance

3-flavor-only

$$P(\nu_\mu \to \nu_\mu) \approx \boxed{1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31}} + 2\sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{24} \sin^2 \Delta_{41}.$$

NC disappearance

$$1 - P(\nu_\mu \to \nu_s) \approx \boxed{1} - \cos^4 \theta_{14} \cos^2 \theta_{34} \sin^2 2\theta_{24} \sin^2 \Delta_{41} - \sin^2 \theta_{34} \sin^2 2\theta_{23} \sin^2 \Delta_{31} + \frac{1}{2} \sin \delta_{24} \sin \theta_{24} \sin 2\theta_{23} \sin \Delta_{31}.$$

Sterile neutrinos?

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makes phenomenology much richer:

ν_μ CC disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31} + 2\sin^2 2\theta_{23} \boxed{\sin^2 \theta_{24}} \sin^2 \Delta_{31} - \boxed{\sin^2 2\theta_{24}} \sin^2 \Delta_{41} .$$

At NOvA, additional mixing driven by two angles and one phase

NC disappearance

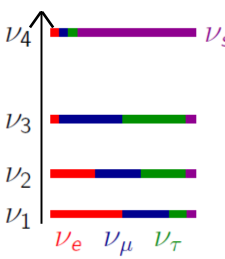
$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4 \theta_{14} \boxed{\cos^2 \theta_{34} \sin^2 2\theta_{24}} \sin^2 \Delta_{41} - \boxed{\sin^2 \theta_{34}} \sin^2 2\theta_{23} \sin^2 \Delta_{31} + \frac{1}{2} \boxed{\sin \delta_{24} \sin \theta_{24}} \sin 2\theta_{23} \sin \Delta_{31} .$$

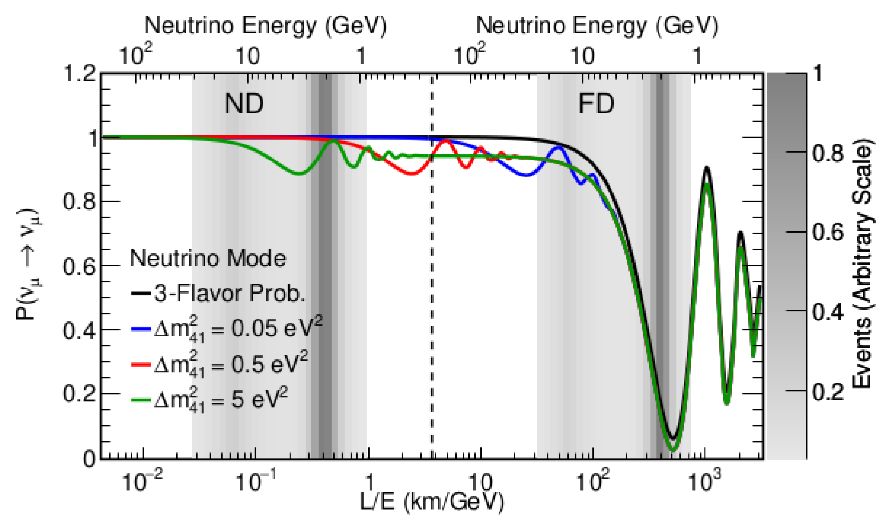
[Note: approximations for illustration only. Actual analysis uses full oscillation probabilities.]

Sterile neutrinos?

- **Search for sterile ν:**
  - Search for **one additional neutrino** (3+1 model)
  - Include **NC & ν_μ CC** interactions
  - Probe **wide Δm^2_{41} range:**
    - Fit ND+FD spectra simultaneously
    - Use covariance matrix to capture ND-FD correlations
    - Dedicated systematics to reduce dependence on (possibly oscillated) neutrino data

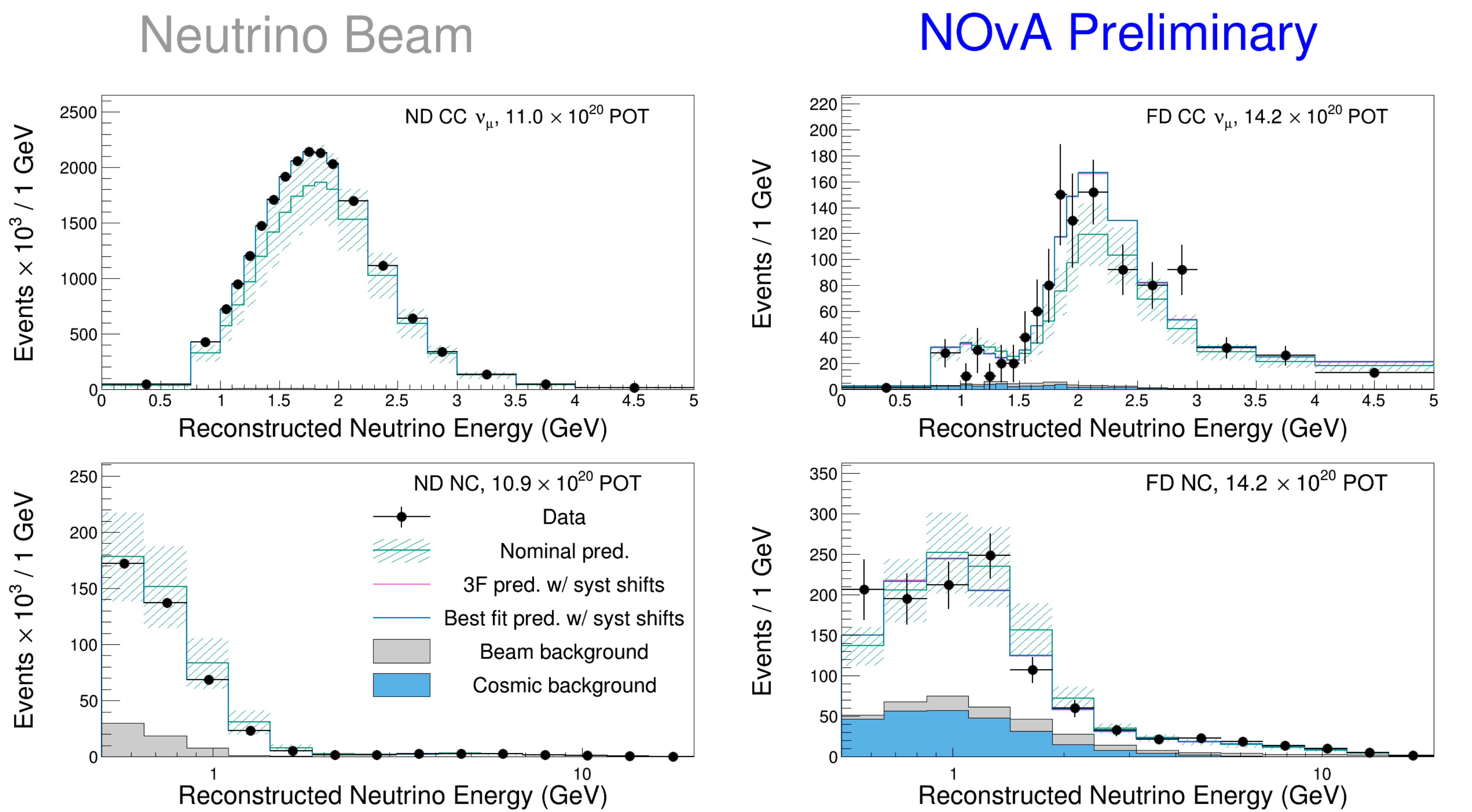
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$





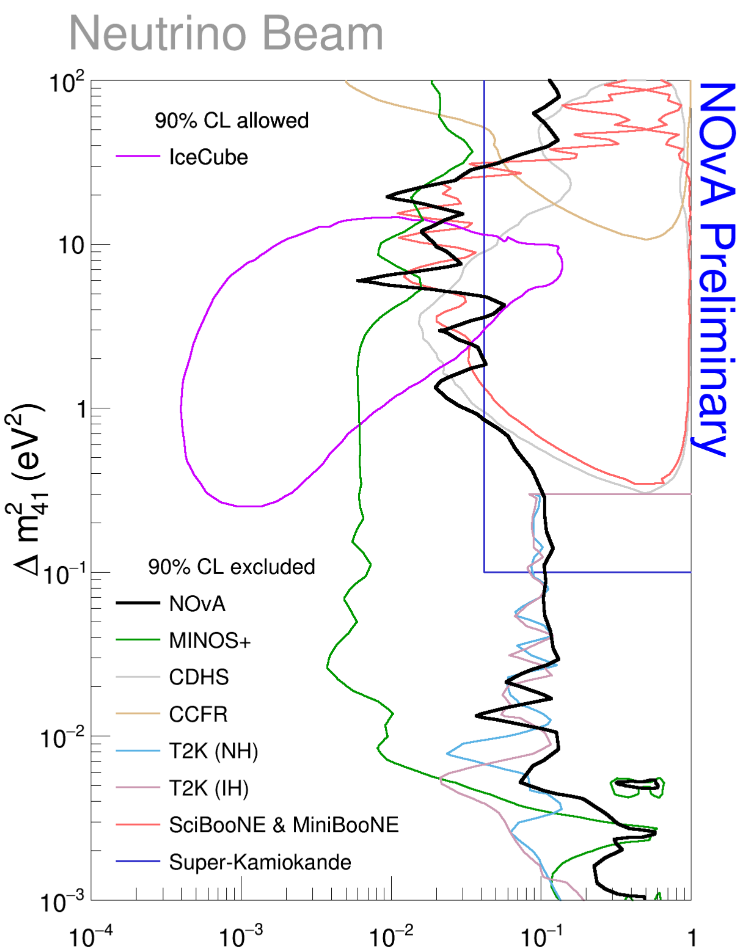
Previous work from NOvA:
PRL 127, 201801 (2021)
PRD 96, 072006 (2017)

Sterile neutrinos?: data



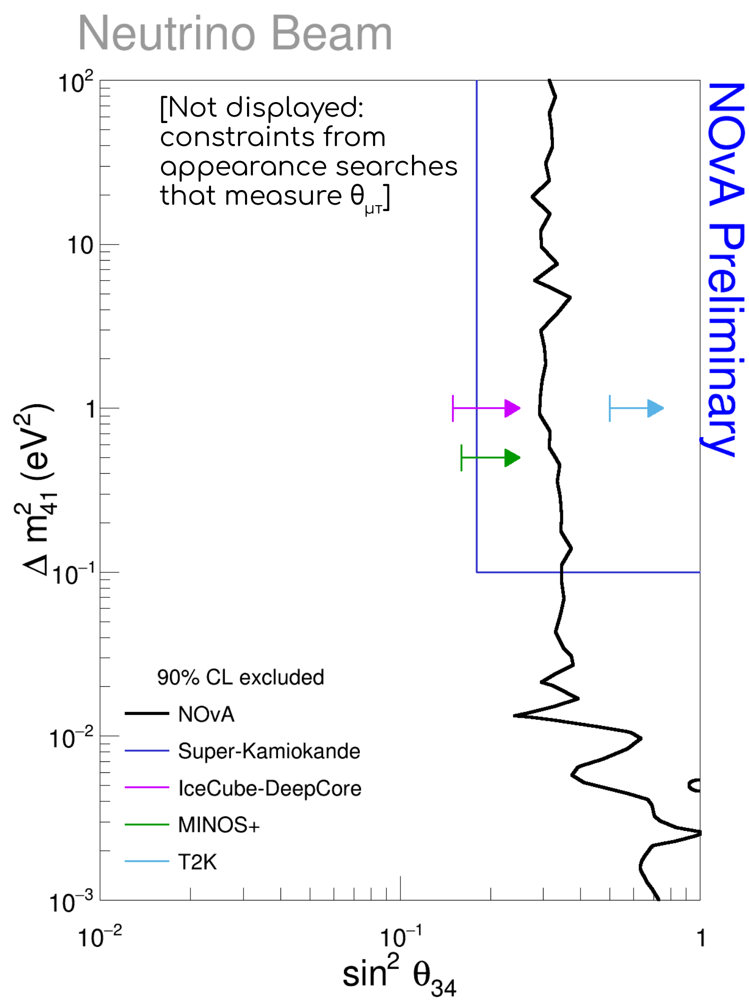
3-flavor (null sterile oscillations) and 3+1 best fits are ~identical

Sterile neutrinos?: results



Competitive limits on θ_{24} at Δm^2_{41} ~ 10 eV^2

(need both dets., both CC&NC for sensitivity across all Δm^2_{41})



New constraints on θ_{34}

(sensitivity mainly via NC channel)

Sterile neutrinos: takeaways

- No evidence for sterile neutrinos in NOvA data
- New constraints on 3+1 models:
  - In interesting region of θ_{24} space
  - Across broad swath of θ_{34}
- See V Hewes's talk in WG1 tomorrow for more details

Nonstandard interactions?

- Search for nonstandard interactions (NSI):

$$\mathcal{H} = U\mathcal{H}_0 U^\dagger + \mathcal{H}_{matter} + \mathcal{H}_{NSI}$$

  - Consider extra terms in Hamiltonian analogous to MSW effect
  - Exploit long (810km) NOvA baseline & associated strong matter effects
  - Use ν_μ, $\bar{\nu}_\mu$ disappearance and ν_e, $\bar{\nu}_e$ appearance spectra

Nonstandard interactions?

Adding **additional terms** to matter potential
analogous to MSW effect
results in many parameters in the Hamiltonian:

$$\mathcal{H} = \frac{1}{2E}\left[U_{PMNS} \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger_{PMNS} + a \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix} \right]$$

3-flavor-only

$a \equiv 2\sqrt{2} G_F N_e E$ [*Wolfenstein matter potential*]

$$\varepsilon_{\alpha\beta} = \left|\varepsilon_{\alpha\beta}\right| e^{i\delta_{\alpha\beta}}$$

Nonstandard interactions?

Adding **additional terms** to matter potential **analogous to MSW effect** results in many parameters in the Hamiltonian:

$$\mathcal{H} = \frac{1}{2E}\left[U_{PMNS}\begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{PMNS} + a\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

$a \equiv 2\sqrt{2}G_F N_e E$ [*Wolfenstein matter potential*]

Two categories of parameters:

$$\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}|e^{i\delta_{\alpha\beta}}$$

On-diagonal: "NSI effective Δm^2s" (real-valued)

→ neglected in this analysis (limited sensitivity)

Nonstandard interactions?

Adding **additional terms** to matter potential
analogous to MSW effect
results in many parameters in the Hamiltonian:

$$\mathcal{H} = \frac{1}{2E}\left[U_{PMNS}\begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{PMNS} + a\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

$a \equiv 2\sqrt{2}G_F N_e E$ [*Wolfenstein matter potential*]

Two categories of parameters:

$$\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}|e^{i\delta_{\alpha\beta}}$$

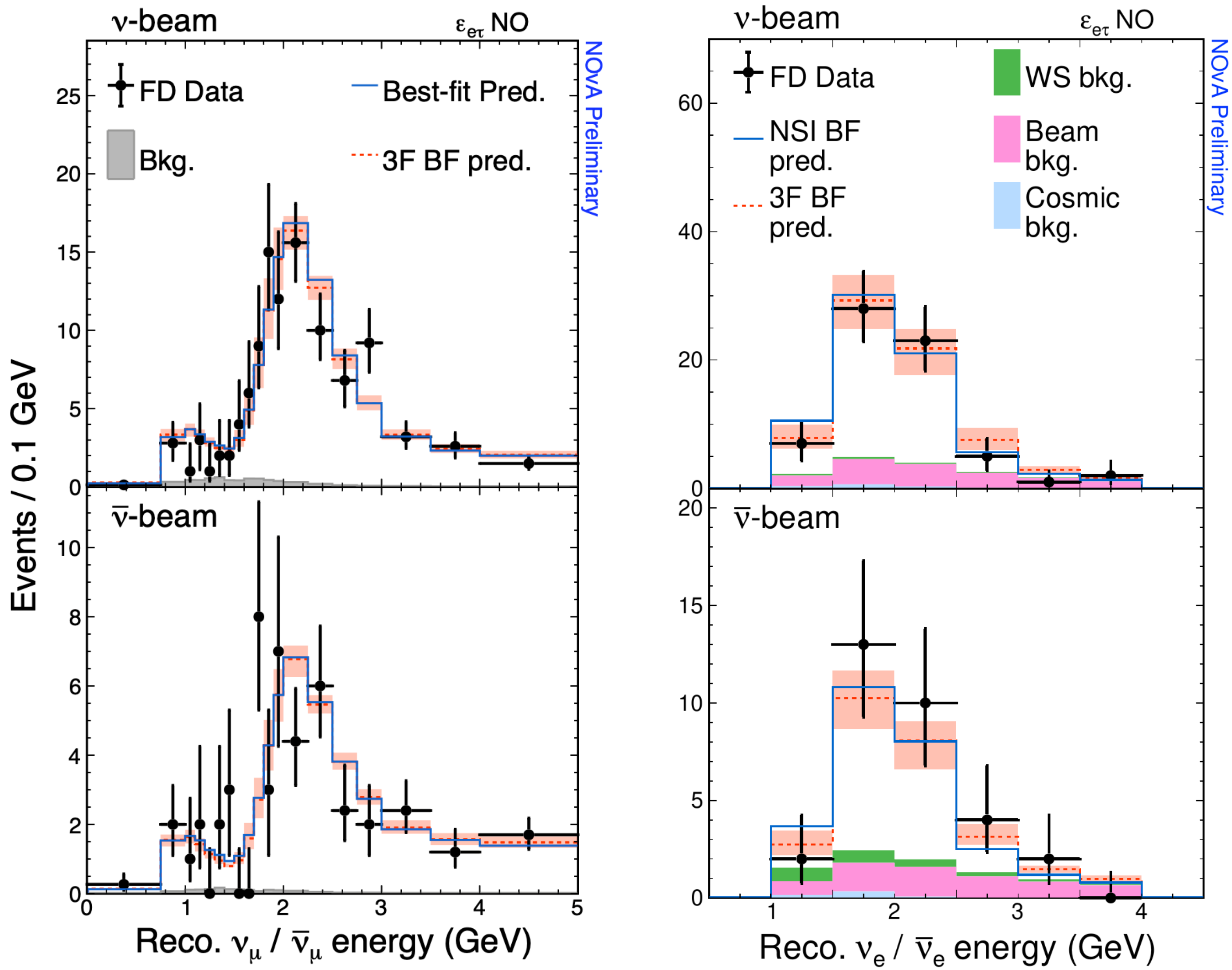
On-diagonal: "NSI effective Δm^2s" (real-valued)

neglected in this analysis (limited sensitivity)

Off-diagonal: "NSI effective mixing angles" (may be complex)

→ fit these individually (but always simultaneous w/ std. osc)

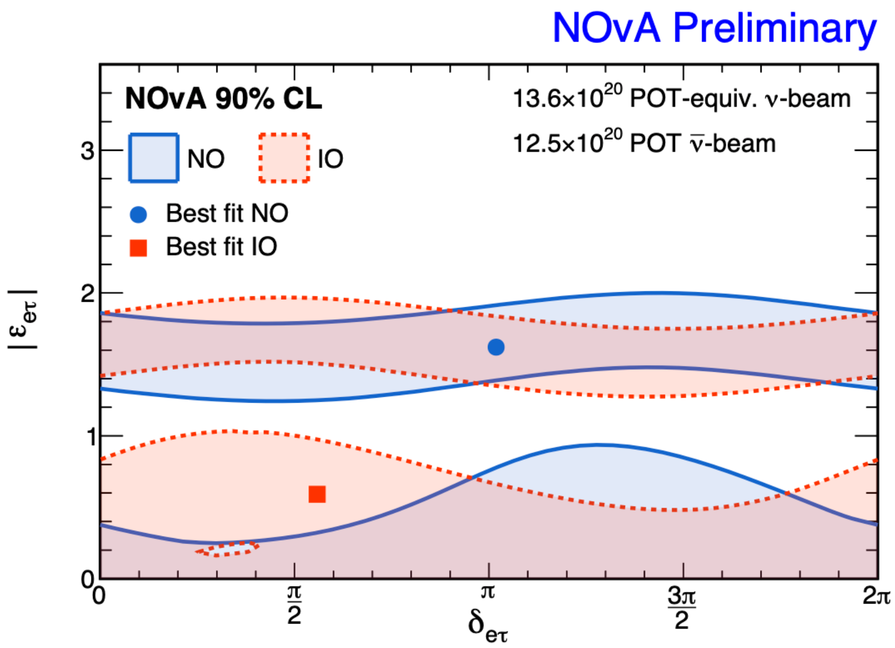
NSI?: data

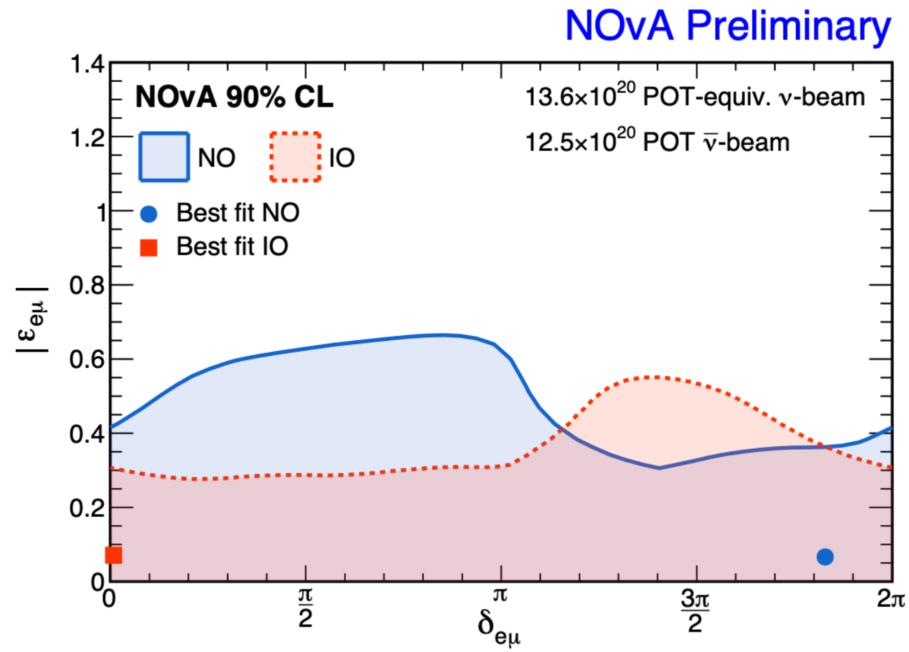


[$\varepsilon_{e\mu}$, $\varepsilon_{\mu\tau}$ similar]

3-flavor (all $\varepsilon_{\alpha\beta}$=0) and NSI best fits are ~identical

NSI?: results

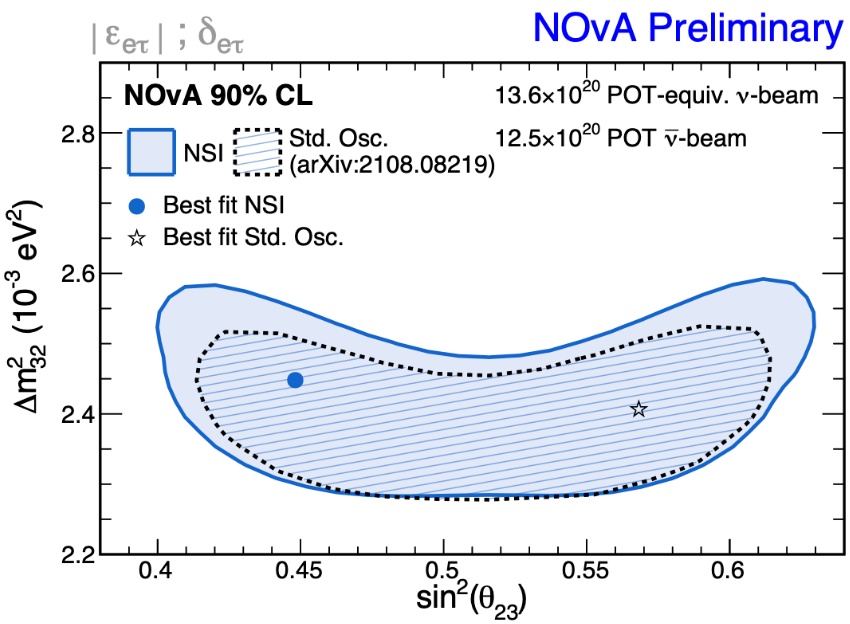


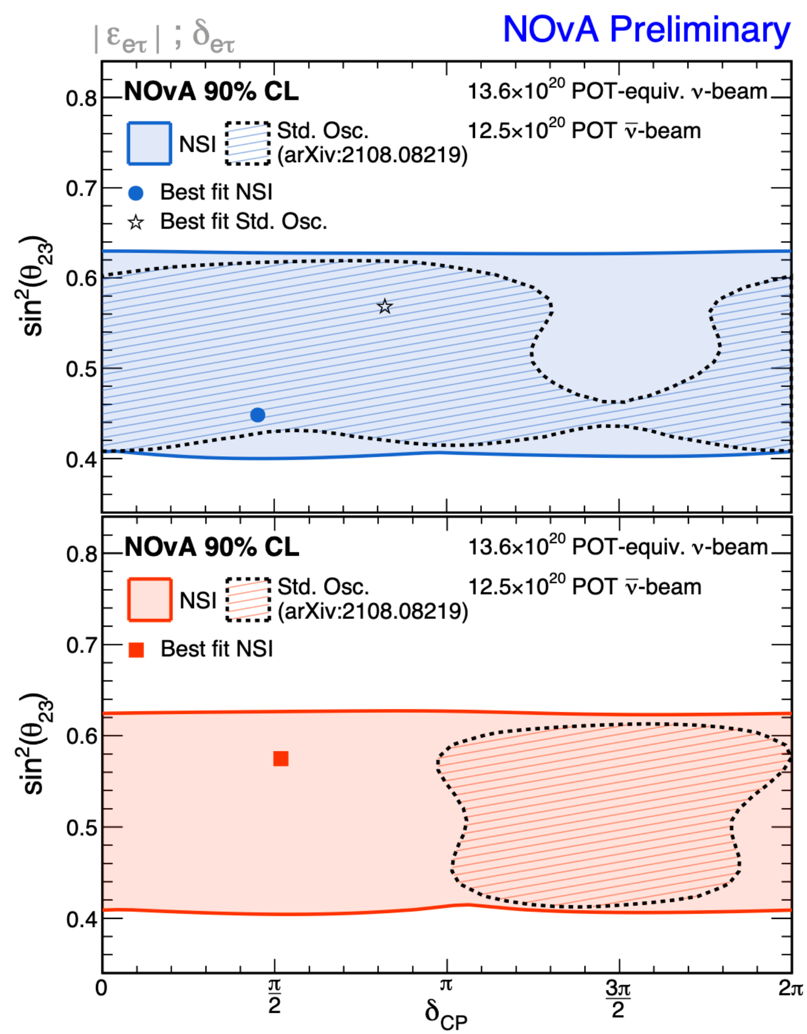


Data is consistent with many values of NSI parameters.

Rule out some $|\varepsilon_{\alpha\beta}|$, but phases are unconstrained

NSI: collateral impacts



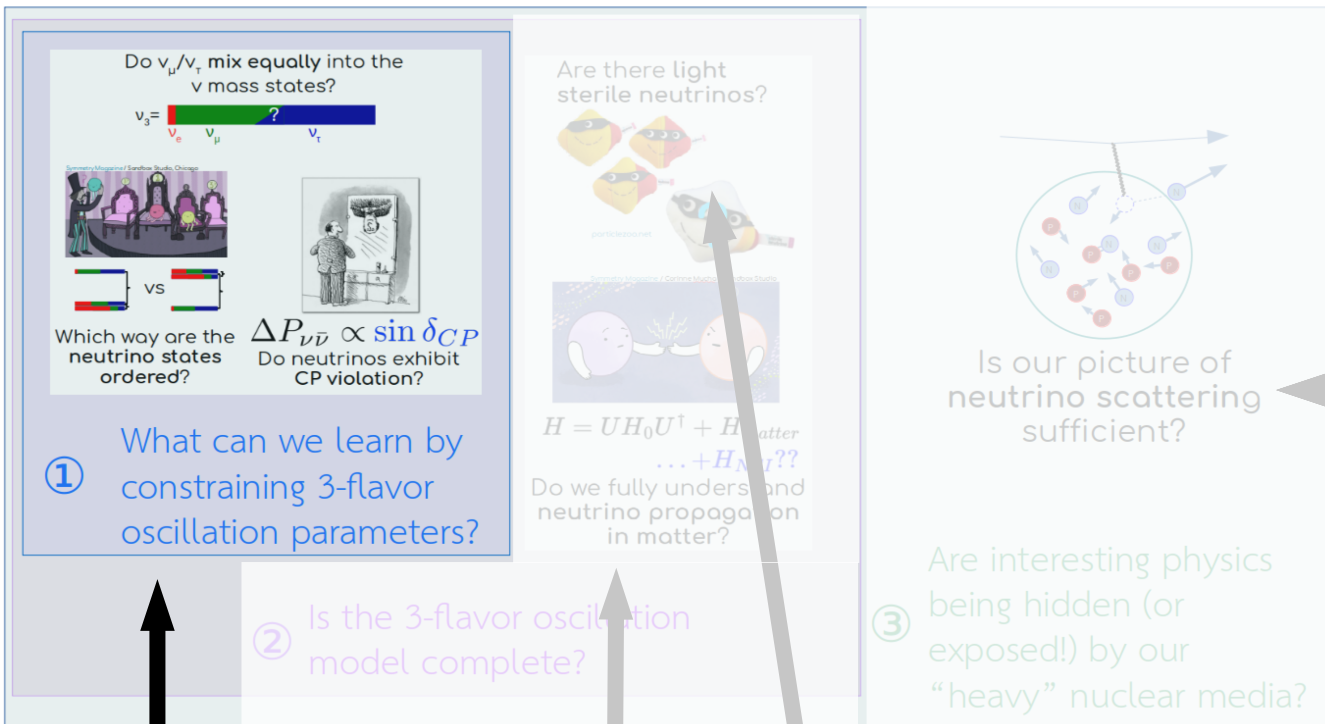


<u>If</u> we admit the possibility of NSI, however,

ν_e appearance conclusions (esp. mass hierarchy and δ_{CP}) are significantly weakened

NSI: takeaways

- Addition of NSI does not improve description of NOvA data
- "Large" NSI parameter values excluded at 90% CL:
  - $|\varepsilon_{e\mu}| \gtrsim 0.6$
  - $1.0 \lesssim |\varepsilon_{e\tau}| \lesssim 1.2$ and $|\varepsilon_{e\tau}| \gtrsim 2.0$
  - All values of phases compatible with current data
- Allowing the possibility of NSI affects "standard oscillation" parameter inferences
  - Minor weakening of atmospheric parameter measurements
  - Mass hierarchy and δ_{CP} sensitivity effectively wiped out
- Again V Hewes's talk in WG1 will also discuss

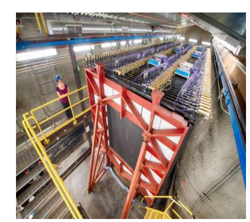


Two ν_μ CC cross section measurements

Bayesian look at 3-flavor model constraints

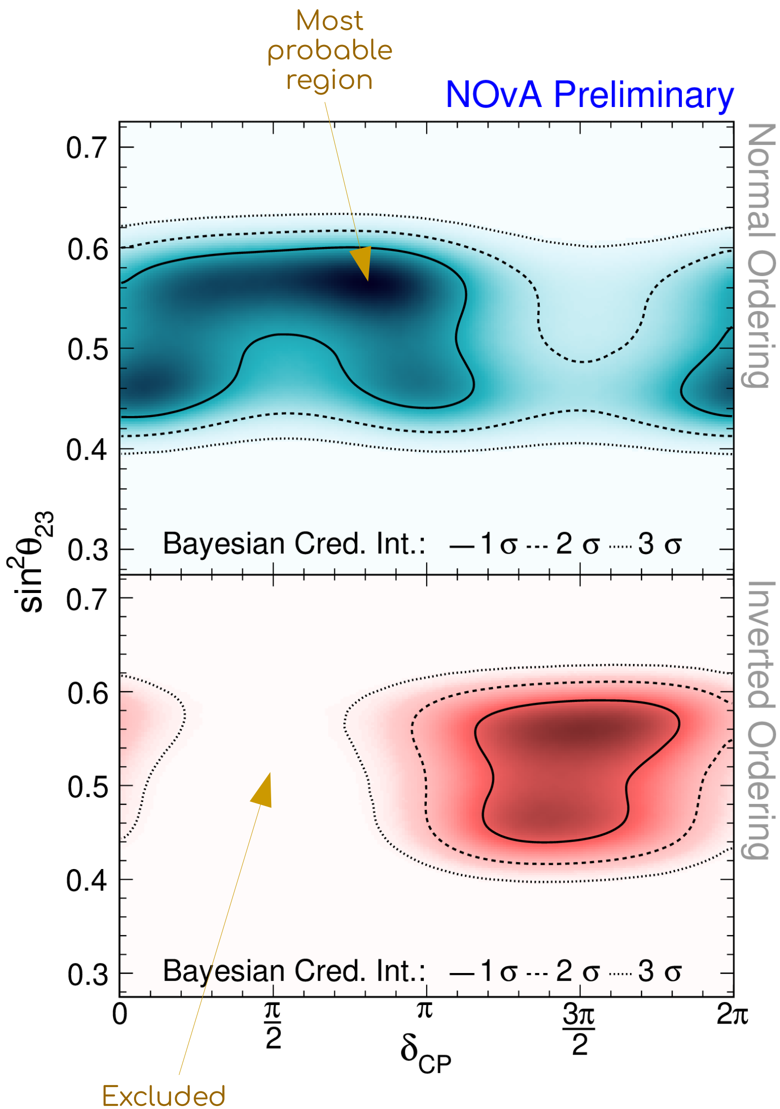
Search for nonstandard interactions

Search for sterile neutrinos



(use both Near & Far Detectors)

PMNS measurements



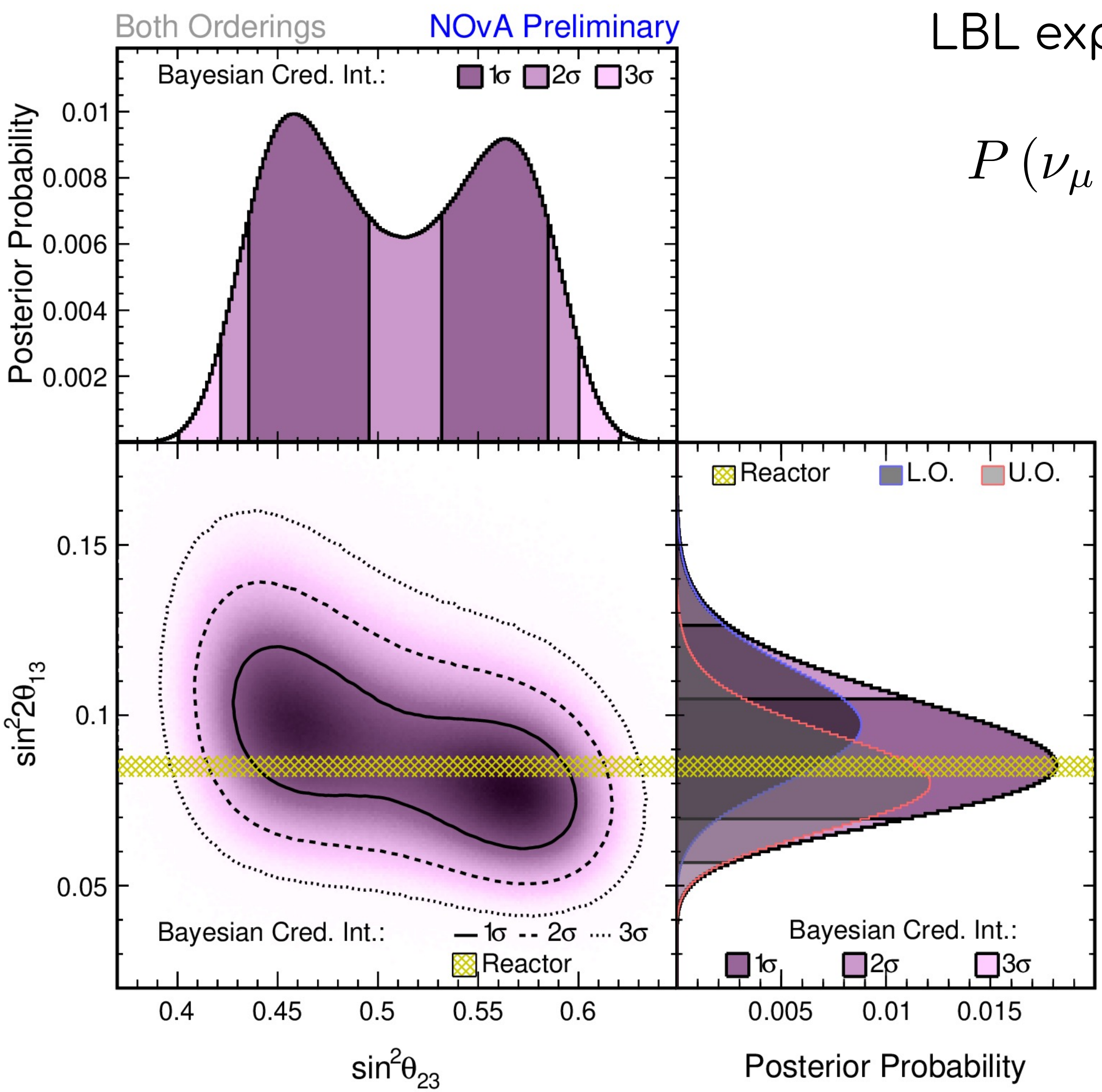
New Bayesian analysis
has similar top-line conclusions as previous:

Weak preferences for Normal Ordering, Upper θ_{23} Octant

Rule out (> 3σ) combination (IO, $\delta_{CP}=\pi/2$)

… but it also allows us to drill deeper…

PMNS measurements



LBL expts can't measure θ_{23} octant alone:

$$P(\nu_\mu \to \nu_e) \approx \underbrace{\sin\theta_{23}\sin 2\theta_{13}}_{\text{correlated at first order!}} \sin\Delta_{31} + \ldots$$

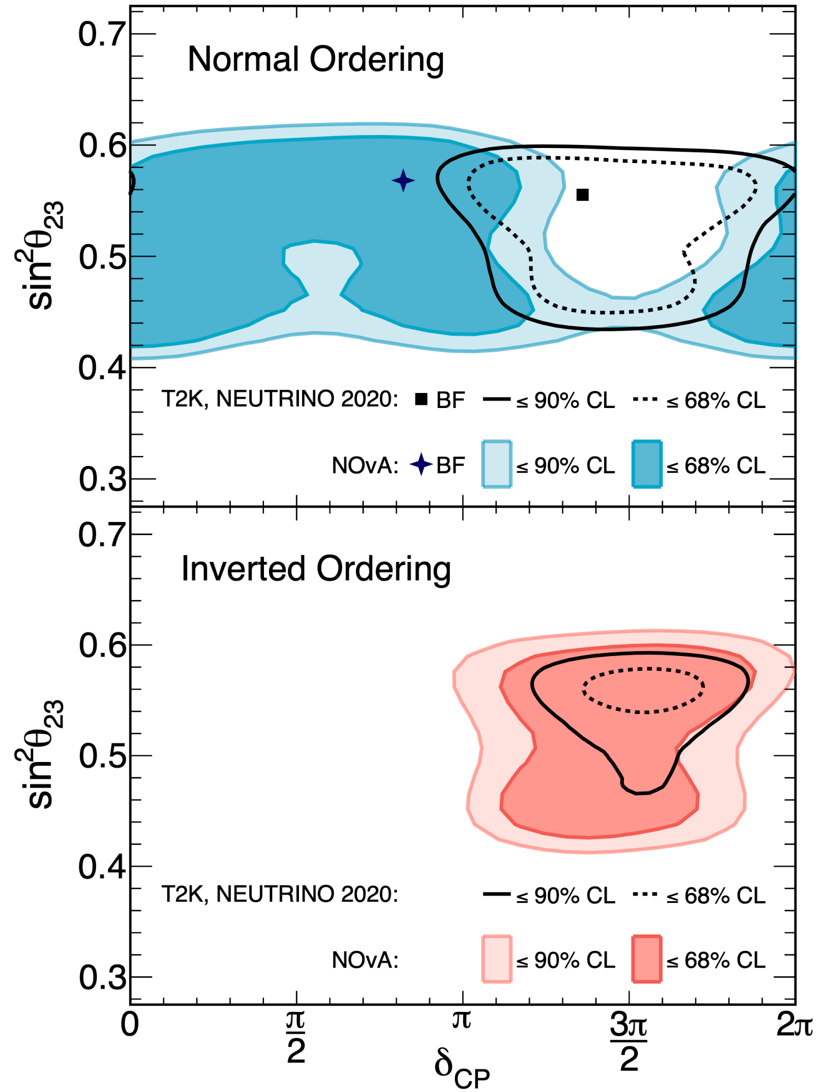
Bayesian analysis enables **first NOvA-only measurement of θ_{13}**:

- Strong correlations with θ_{23} (as expected)
- Very good agreement with reactor value!
- (weak) θ_{23} octant preference driven by reactor constraint

$$\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$$

PMNS measurements

- NOvA, T2K data preferences broadly compatible
  - Most probable regions (in NO) distinct, but significant 1σ contour overlap
  - IO surfaces very similar
- Official joint fit results expected later in 2022



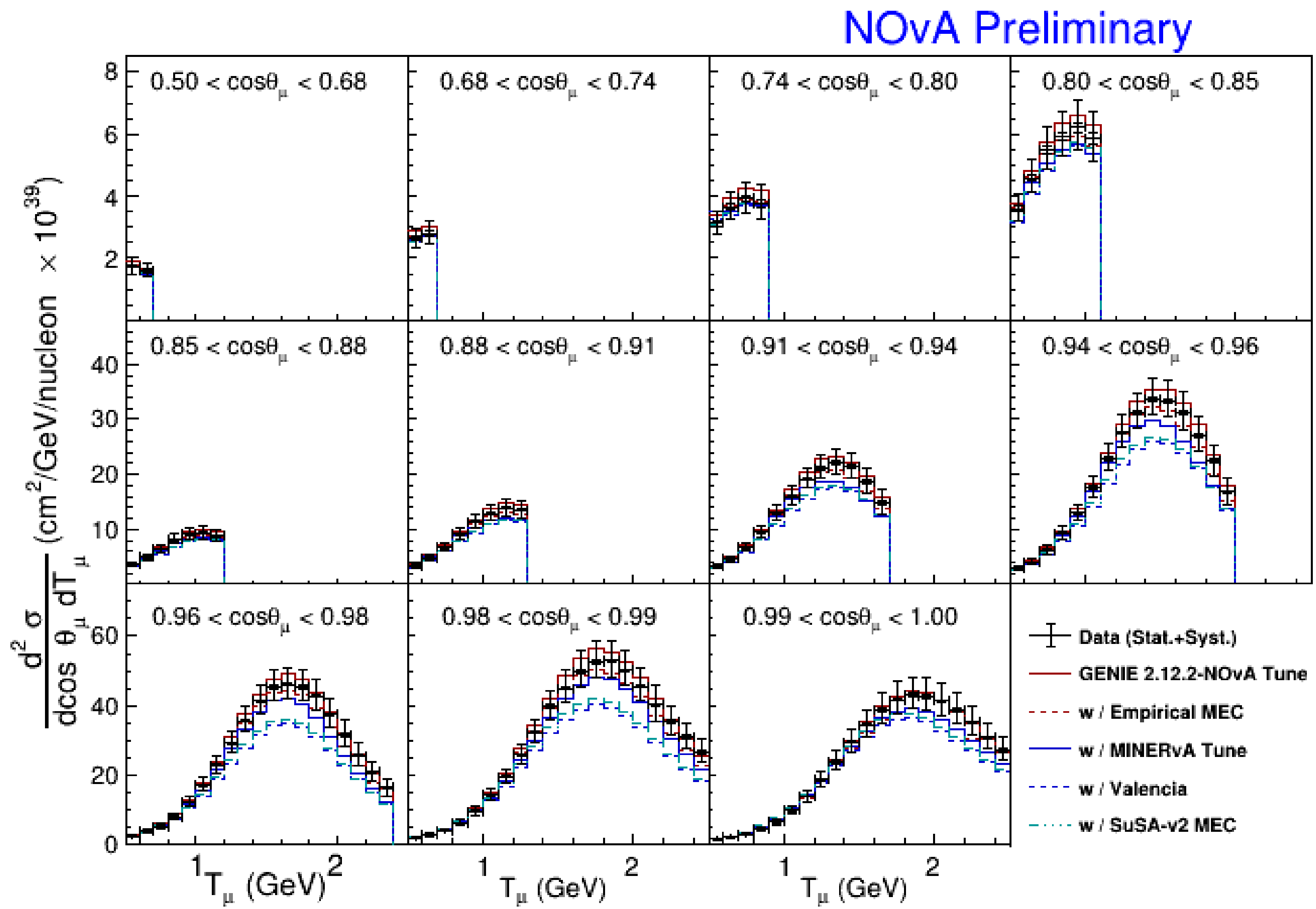
PMNS: takeaways

- Weak indications for upper θ_{23} octant, normal hierarchy
- PMNS model is holding up well to deeper scrutiny
  - First NOvA-only θ_{13} result is consistent w/ reactors
  - NOvA & T2K have broadly compatible PMNS results
  - Bayesian result enables other new inferences too! (e.g.: Jarlskog invariant—see backups)
- See R. Sharma's talk in WG1 on Friday for more

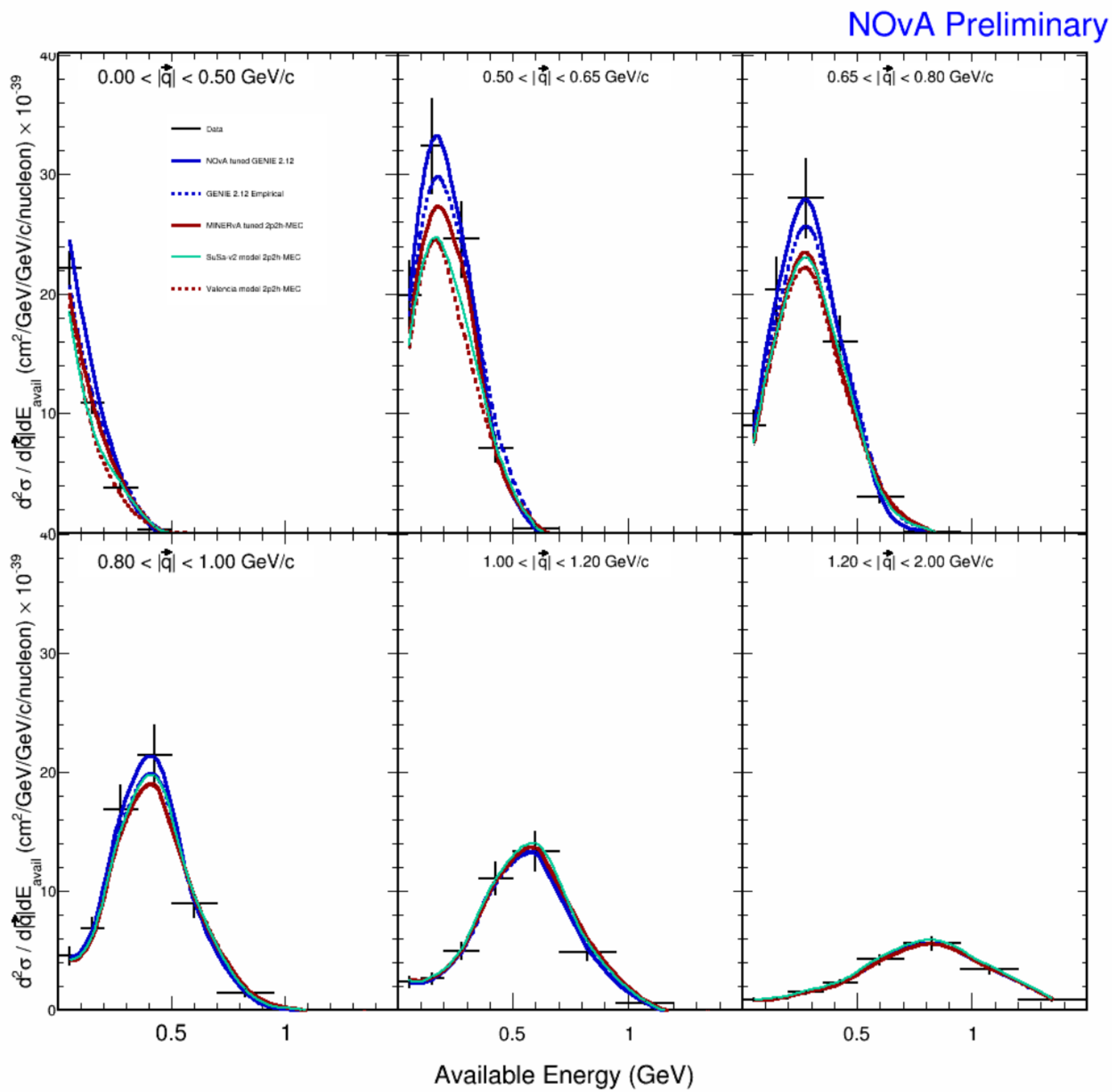
Summary

- Significant NOvA data-theory discrepancies in scattering measurements
- PMNS oscillation model holding up to increased scrutiny
  - No sign of sterile neutrino
  - NSI do not improve description of data
  - Good agreement with other PMNS measurements (T2K; reactors)
- Plethora of new NOvA results around the corner!
  - About 50% of expected data collection still to come

Overflow

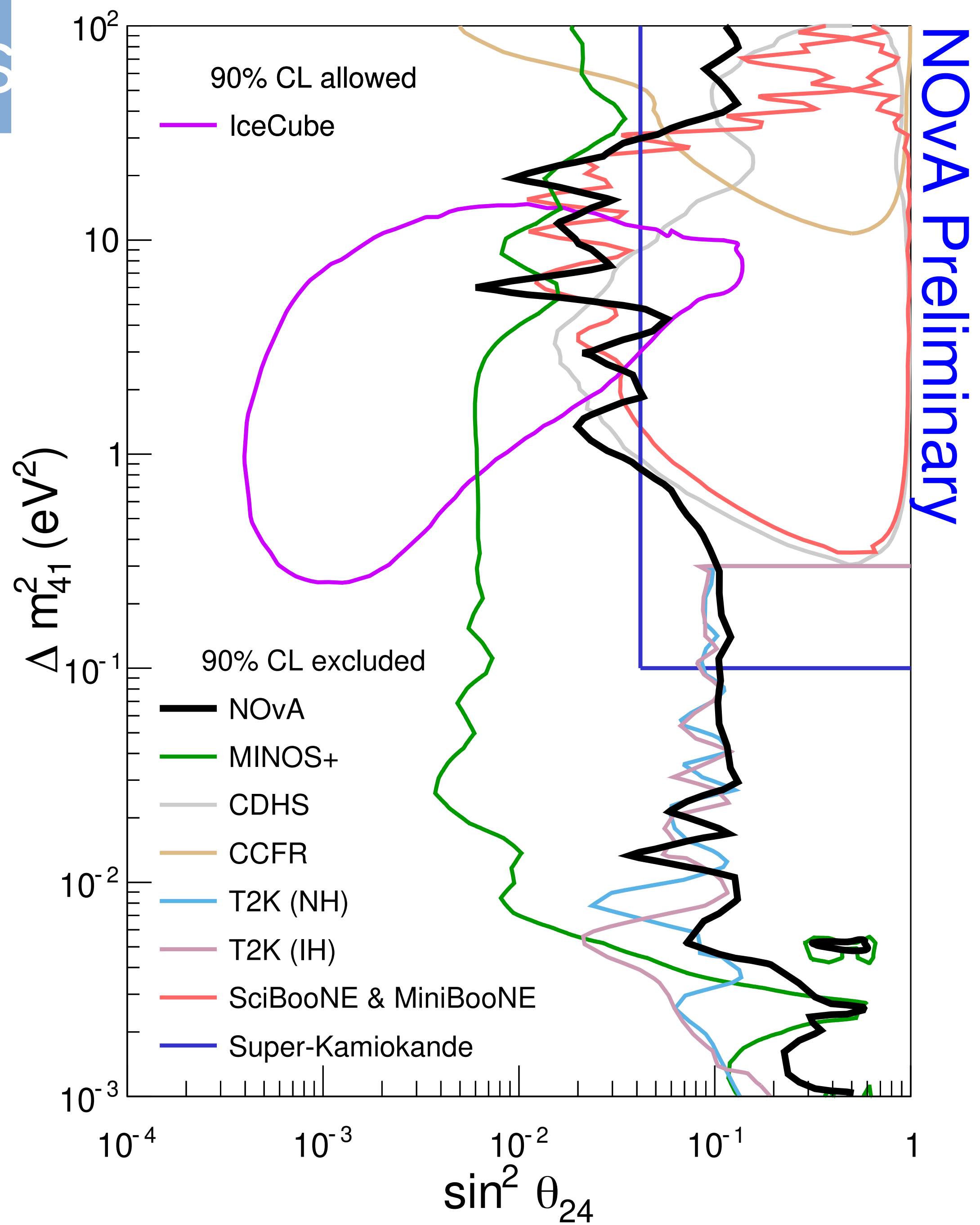

NOvA Preliminary
0.50 < cosθμ < 0.68
0.68 < cosθμ < 0.74
0.74 < cosθμ < 0.80
0.80 < cosθμ < 0.85
0.85 < cosθμ < 0.88
0.88 < cosθμ < 0.91
0.91 < cosθμ < 0.94
0.94 < cosθμ < 0.96
0.96 < cosθμ < 0.98
0.98 < cosθμ < 0.99
0.99 < cosθμ < 1.00
Data (Stat.+Syst.)
GENIE 2.12.2-NOvA Tune
w / Empirical MEC
w / MINERvA Tune
w / Valencia
w / SuSA-v2 MEC
$\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}$ (cm^2/GeV/nucleon × 10^{39})
T_μ (GeV)

ν_μ CC: hadron system

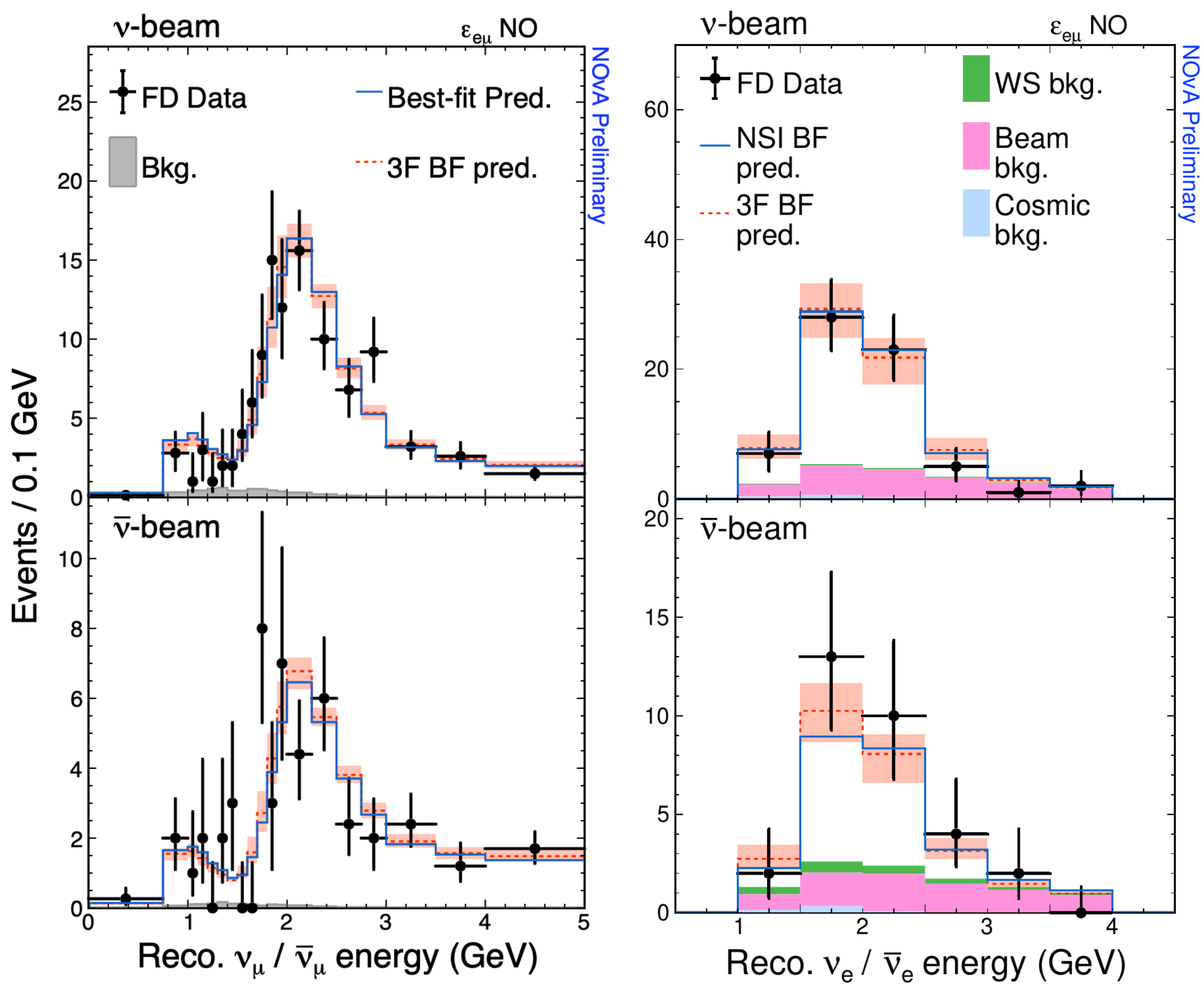


Other sterile neutrino searches

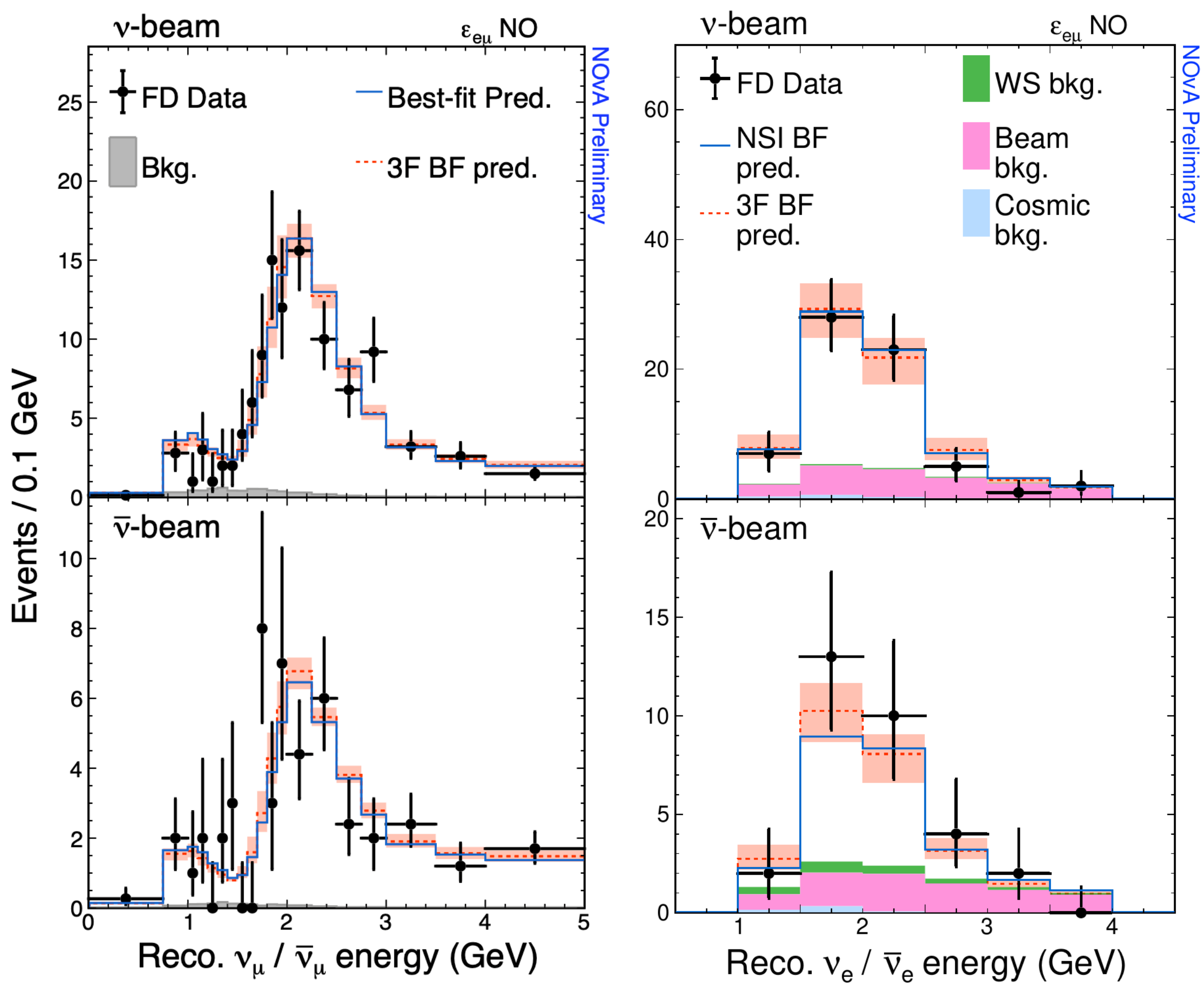
- Citations:
  - SK: K. Abe et al. (Super-Kamiokande), Phys. Rev. D 91, 052019 (2015)
  - CDHS: F. Dydak et al. (CDHSW), Phys. Lett. B 134, 281 (1984)
  - CCFR: I.E. Stockdale et al. (CCFR), Phys. Rev. Lett. 52, 1384 (1984)
  - SciBooNE: K. B. M. Mahn et al. (SciBooNE, MiniBooNE), Phys. Rev. D 85, 032007 (2012)
  - MINOS+: P. Adamson et al. (MINOS+) Phys. Rev. Lett. 122, 091803 (2019)
  - T2K: K. Abe et al. (T2K) Phys. Rev. D 99, 071103(R) (2019)
  - IceCube: M. G. Aartsen et al. (IceCube), Phys. Rev. Lett. 125, 141801 (2020)



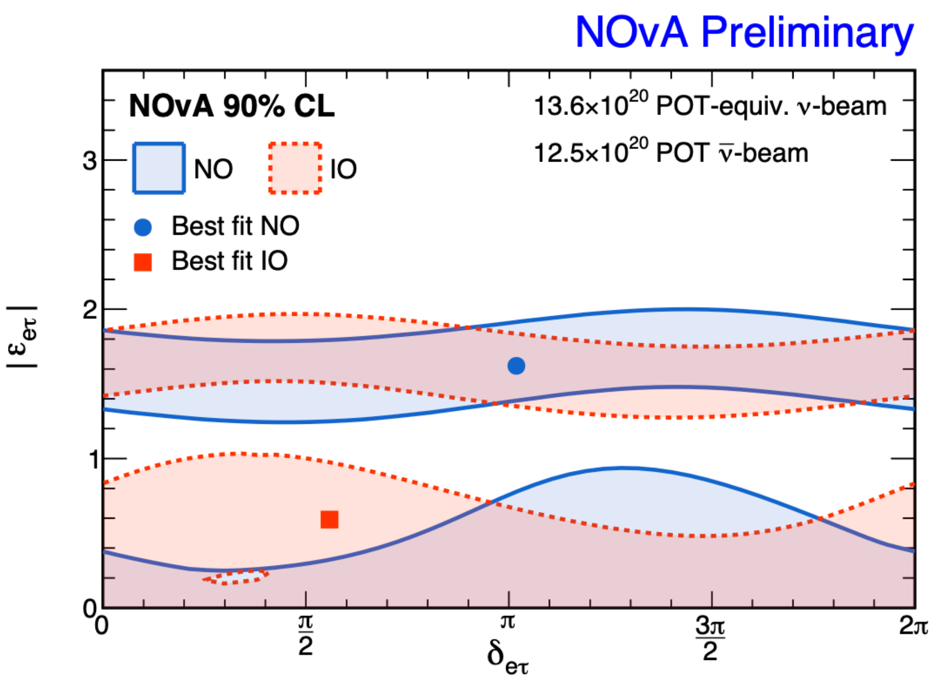
Other NSI spectra: $\varepsilon_{e\mu}$

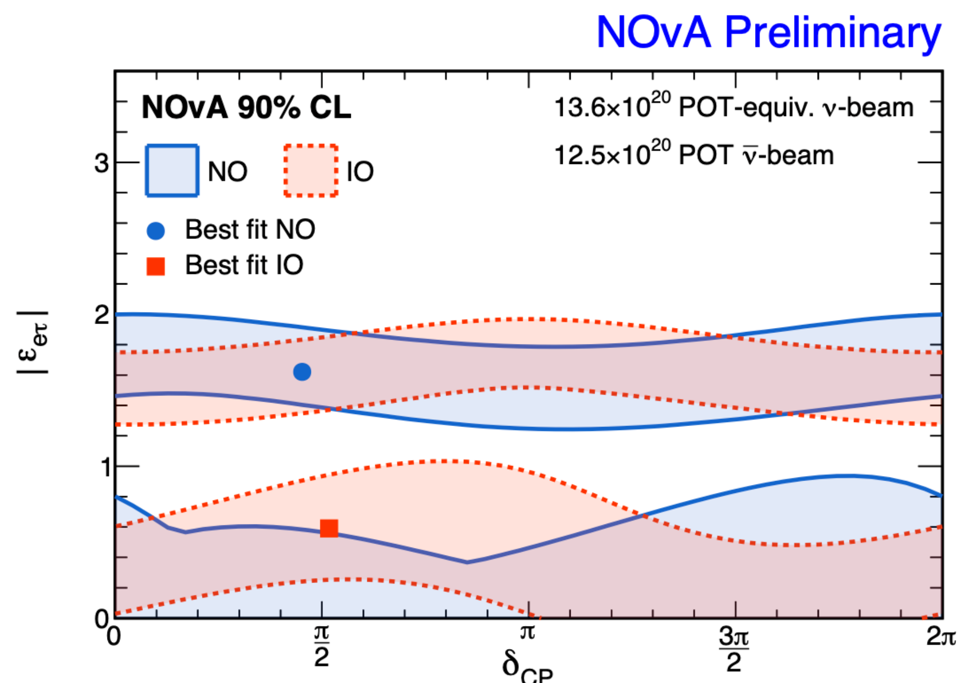


Other NSI limits: $\varepsilon_{e\mu}$



About that "upper band"...





The oscillation probability has terms proportional to

$$|\epsilon_{e\tau}|\cos\left(\delta_{CP}+\delta_{e\tau}\right)$$

This term dominates in the intermediate $|\varepsilon_{e\tau}|$ region,

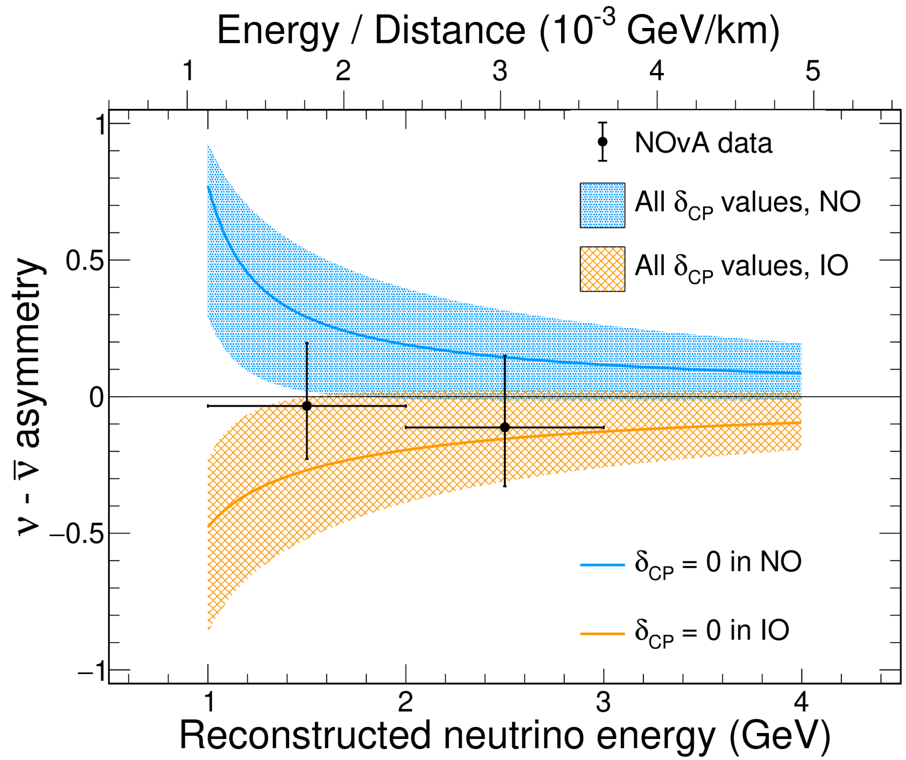
but **$(\delta_{CP} + \delta_{e\tau}) = n\pi/2$ makes the cosine term vanish,**

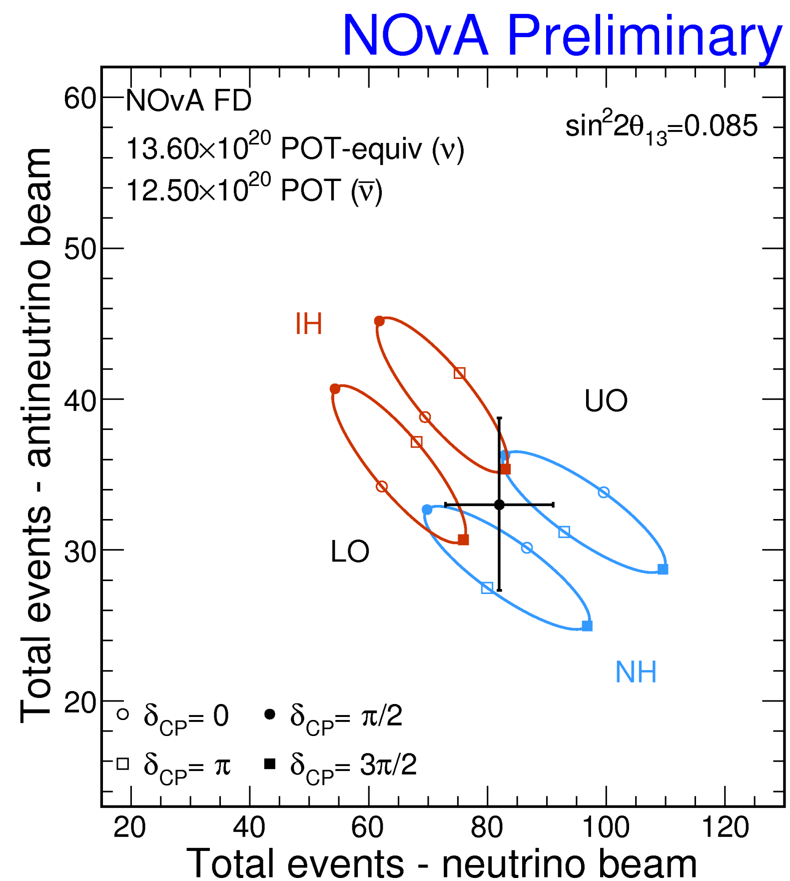
which makes prob reduce to ~3-flavor.

When we profile over one of the two δs, the best-fit for the other δ always forces their sum to nπ/2, in order to be compatible with the data (which is compatible with 3-flavor-only).

At lower and higher $|\varepsilon_{e\tau}|$, other terms in the probability dominate (and are not reducible to the 3-flavor-only case even at $(\delta_{CP} + \delta_{e\tau}) = n\pi/2$).

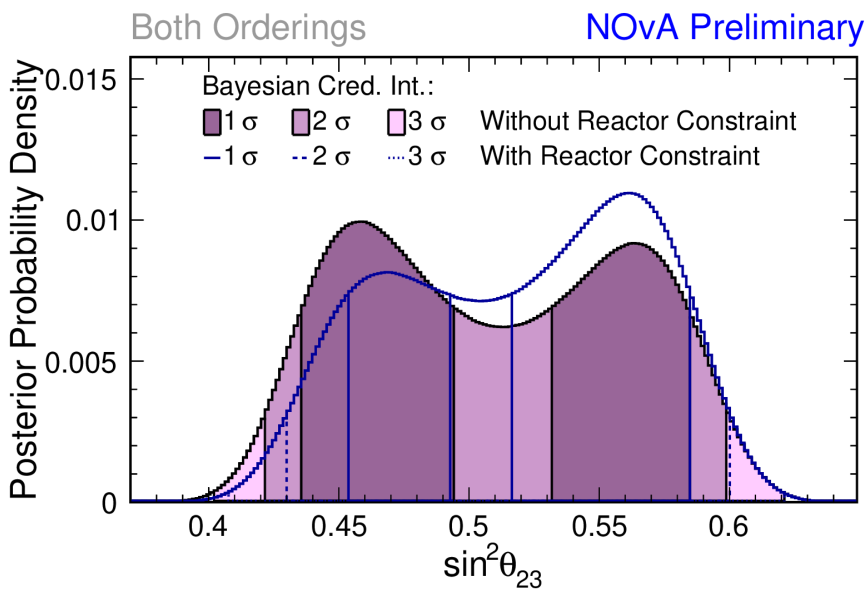
PMNS measurements



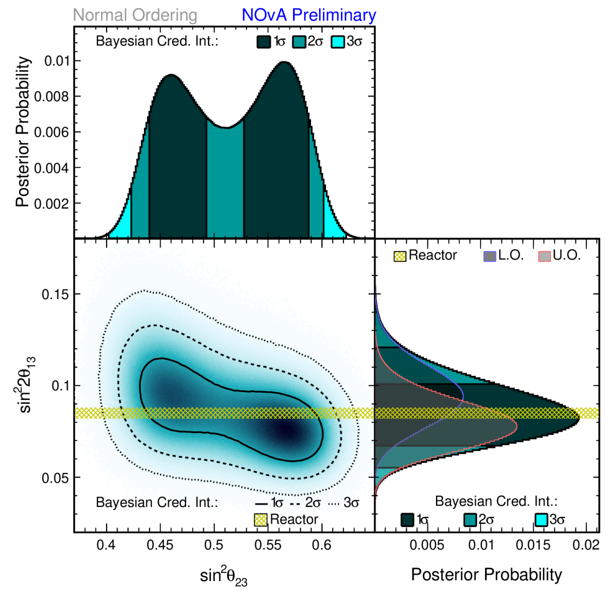


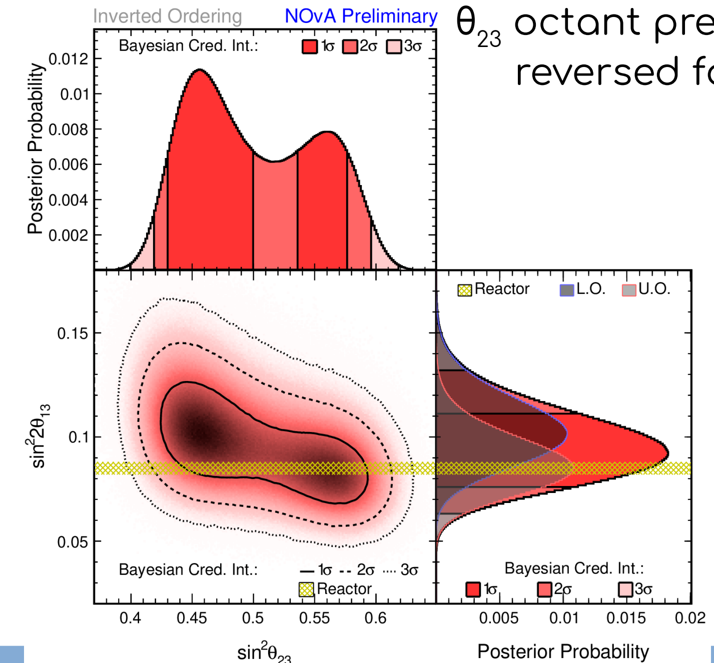
Data consistent with **no $\nu_e - \bar{\nu}_e$ asymmetry** at 20-25% level → best fit **in the middle of PMNS parameter space**

NOvA-only θ_{13}



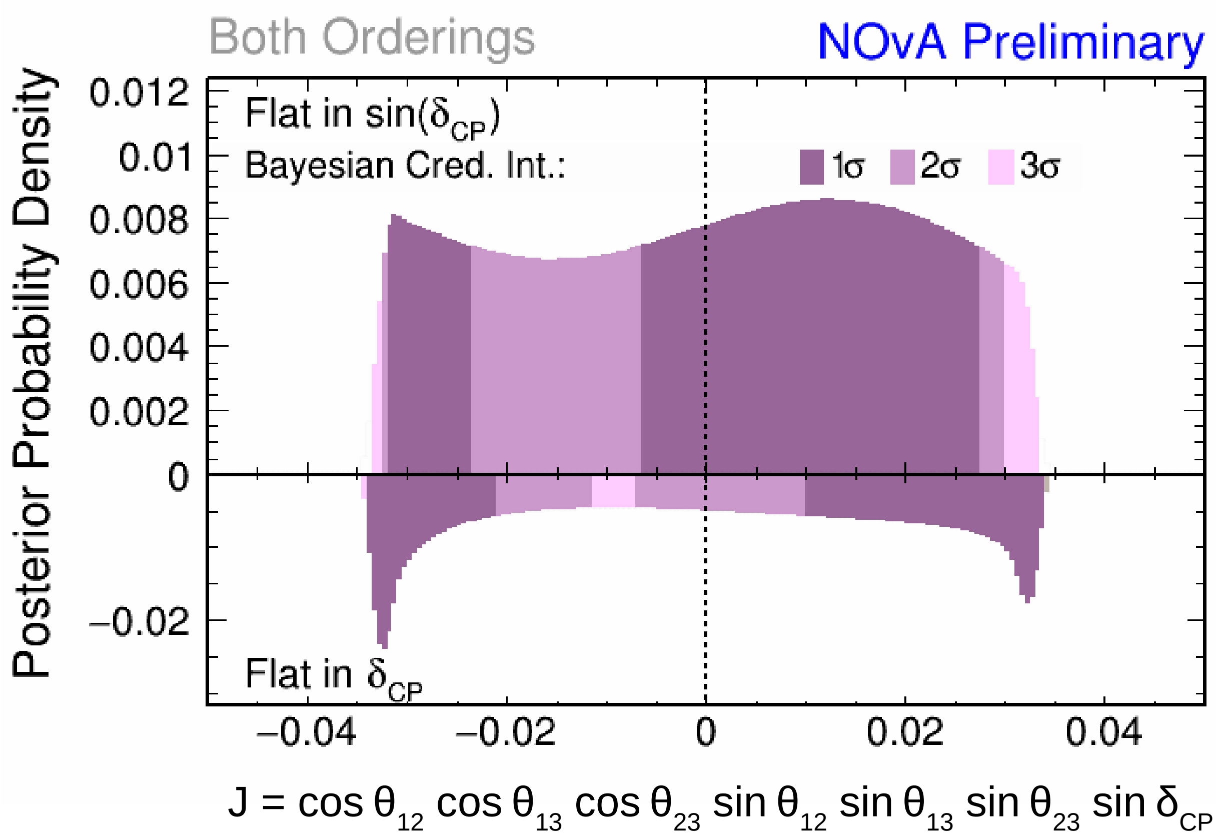
Prefer lower θ_{23} octant with free θ_{13}, upper octant when constrained.





θ_{23} octant preference reversed for IO

Jarlskog invariant



Jarlskog invariant: measures of CP-violation independent of parametrization

Unlike other NOvA measurements (except δ_{CP}), J depends on prior:
Flat in sin δCP (upper half of plot) ↔ data preference
Flat in δCP (lower half of plot) ↔ bias away from minimal CPV (theory motivated)

Future

- Only ~halfway done data taking
  - Stat. unc. ~ syst unc. for Δm^2_{32}, $\sin^2\theta_{23}$ by end of run
  - Mass ordering resolution possible depending on true value
- Test beam program in full swing (see M. Wallbank in WG1 on Friday)
- Many improvements to oscillation analyses, new cross section measurements & exotic searches in progress!

(Stats. only, but systs. ~inconsequential at full exposure. Assumes NOvA 2020 best fit for atmo. params)