Search for CP-violating Non-standard Interactions at the NOvA Experiment

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On Behalf of the NOvA Collaboration
Sept 2, 2022

NOvA Experiment

- Neutrino oscillation
- Charge parity (CP) violation
- Neutrino mass ordering
- Physics beyond the Standard Model

NOvA Experiment

- Neutrino oscillation
- Charge parity (CP) violation
- Neutrino mass ordering
- Physics beyond the Standard Model

→ Non-standard Interactions

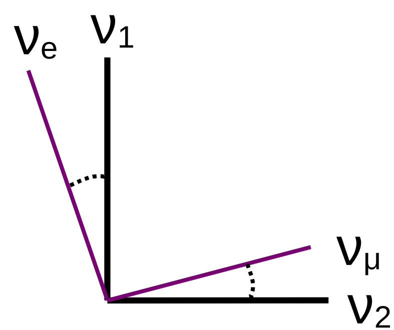
Neutrino Oscillation

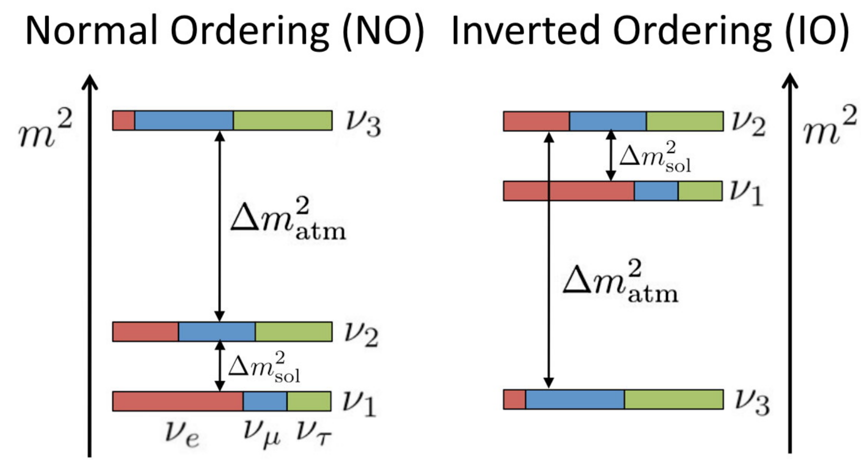
- As neutrinos propagate, they change flavor
- A direct consequence of neutrino masses
  - One of the few unexplained hiccups in the standard model

Next slide: The model

Oscillation Model

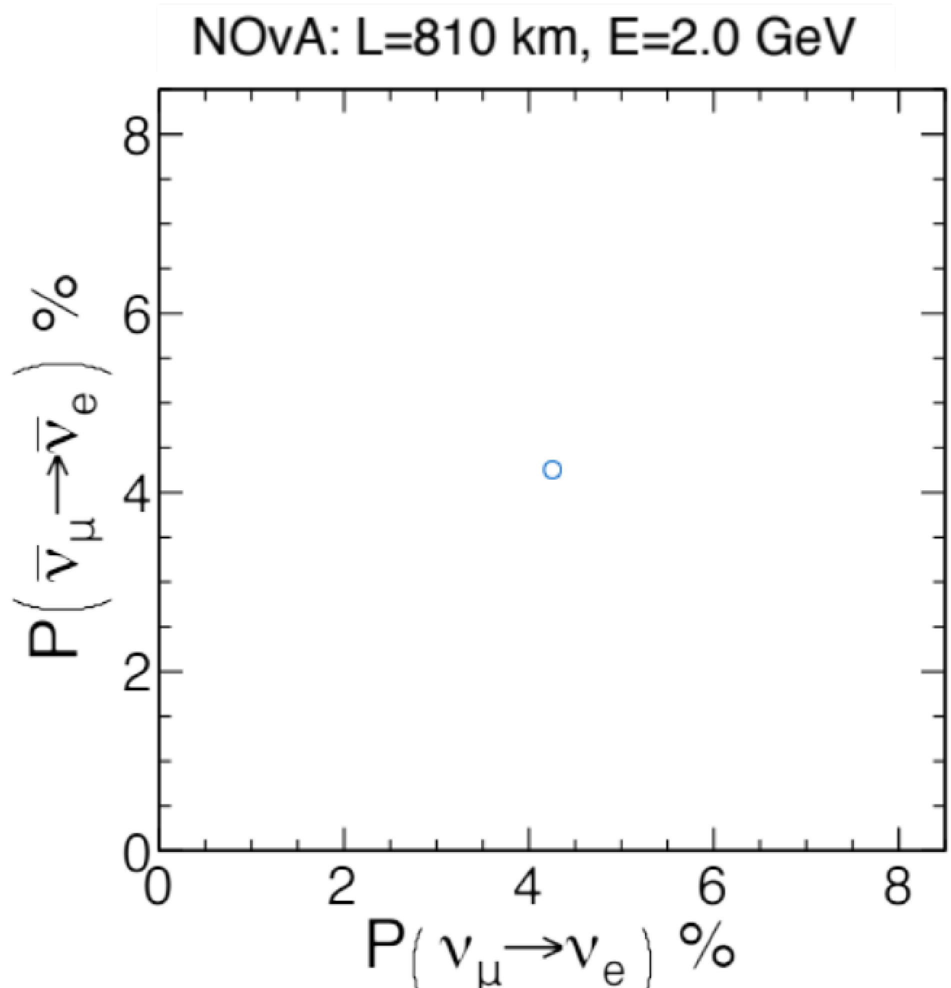
$$\mathcal{H} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger$$



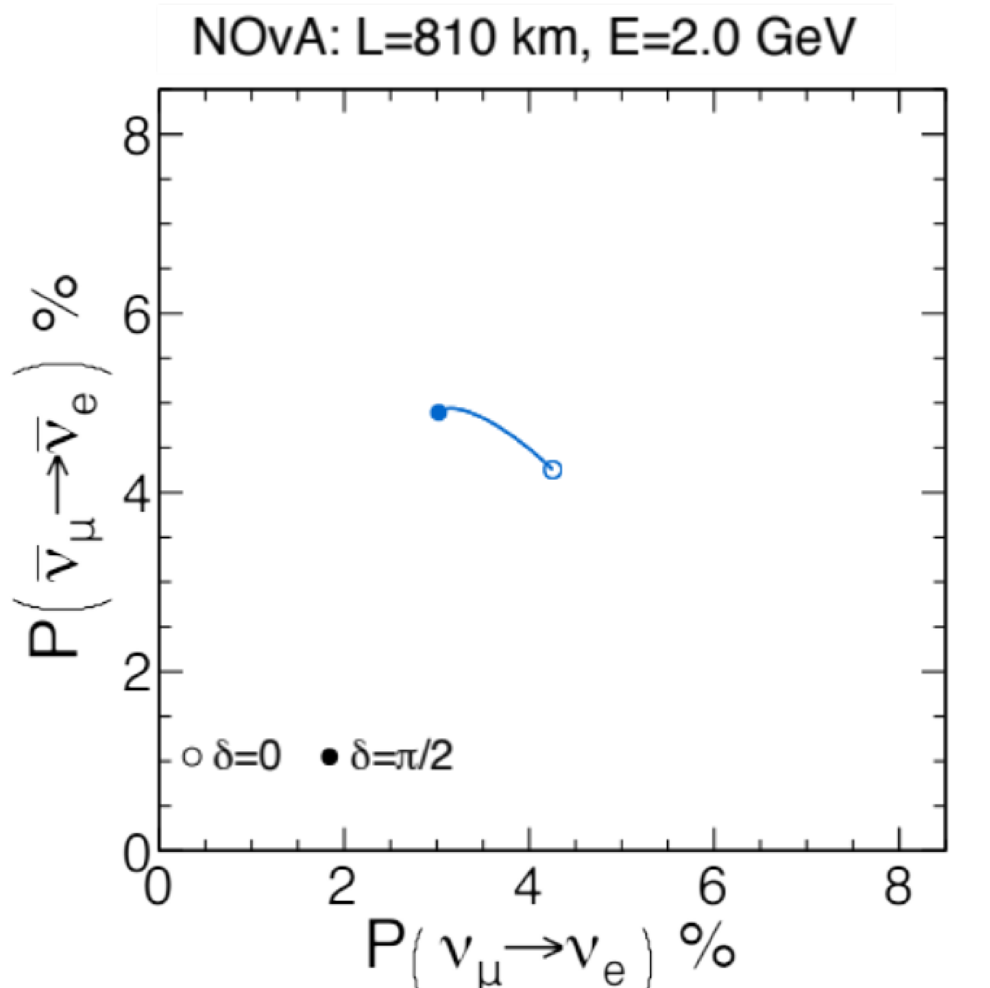


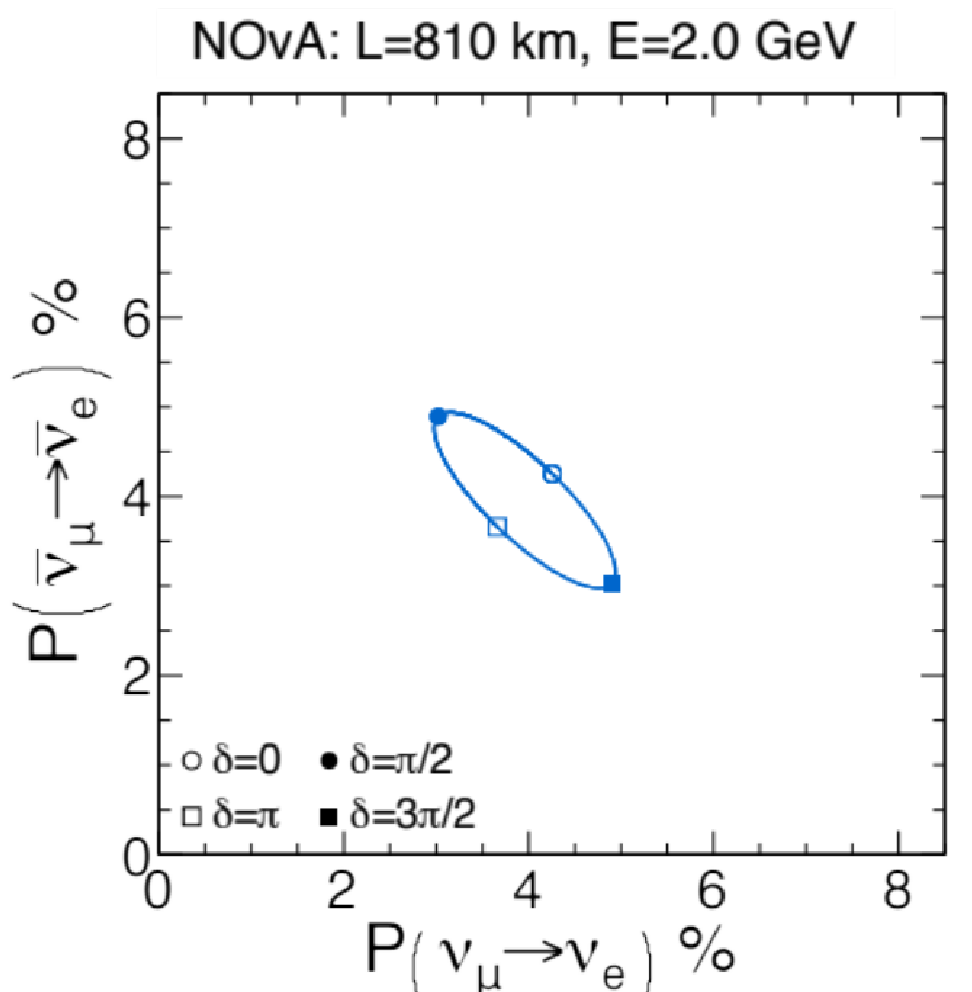
Courtesy of the JUNO collaboration

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta_{cp}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



NOvA: L=810 km, E=2.0 GeV
8
6
4
2
0
0
2
4
6
8
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ %
$P(\nu_\mu \rightarrow \nu_e)$ %

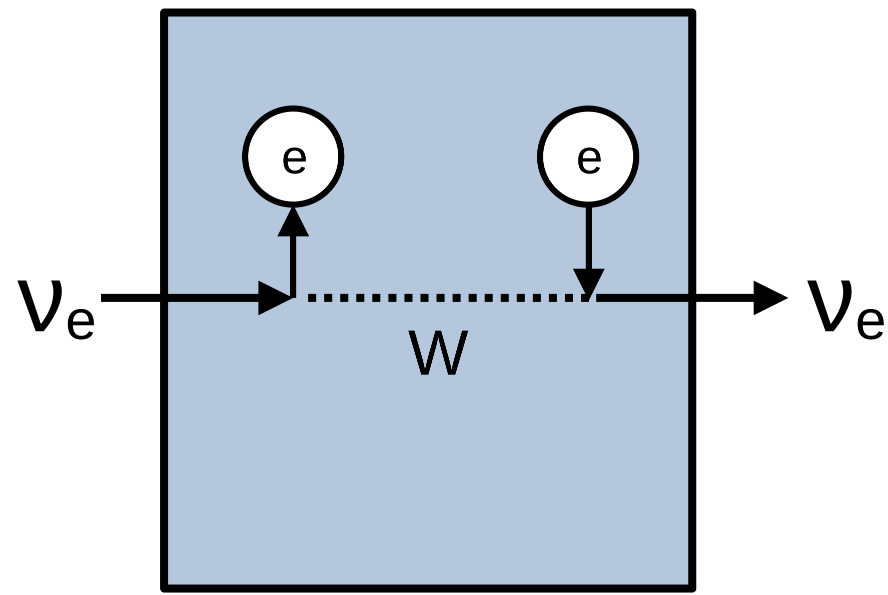

NOvA: L=810 km, E=2.0 GeV
P(ν̄μ→ν̄e) %
P(νμ→νe) %
δ=0
δ=π/2
0
2
4
6
8


NOvA: L=810 km, E=2.0 GeV
P(ν̄μ→ν̄e) %
P(νμ→νe) %
0
2
4
6
8
○ δ=0
● δ=π/2
□ δ=π
■ δ=3π/2

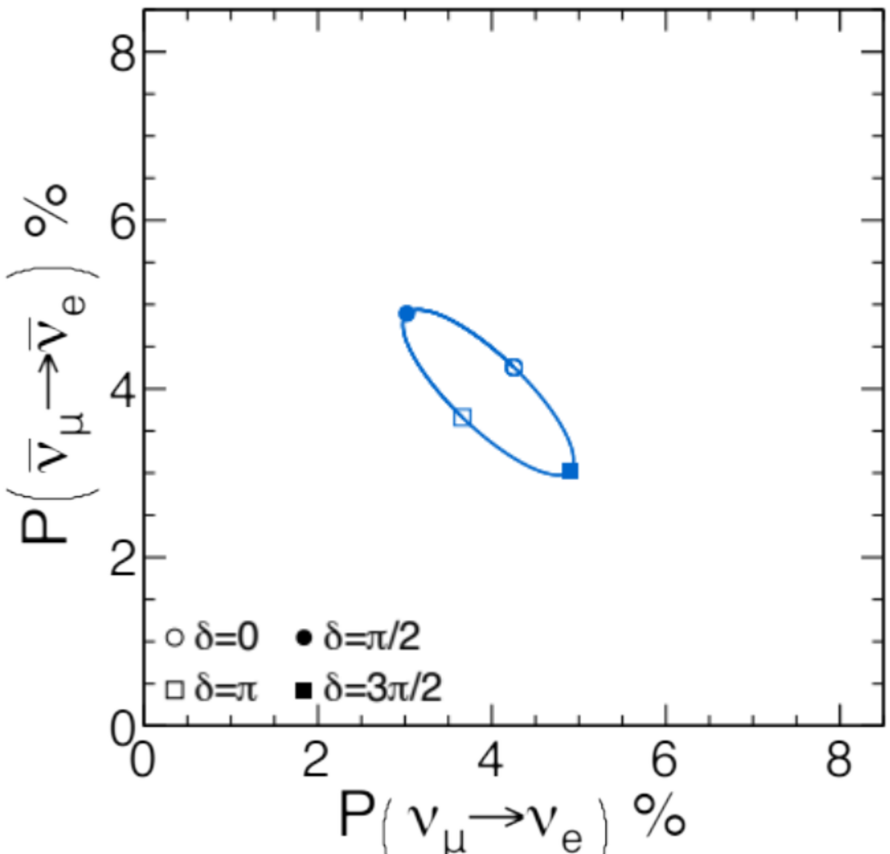
Matter Effects

Mikheyev–Smirnov–Wolfenstein (MSW) Effect

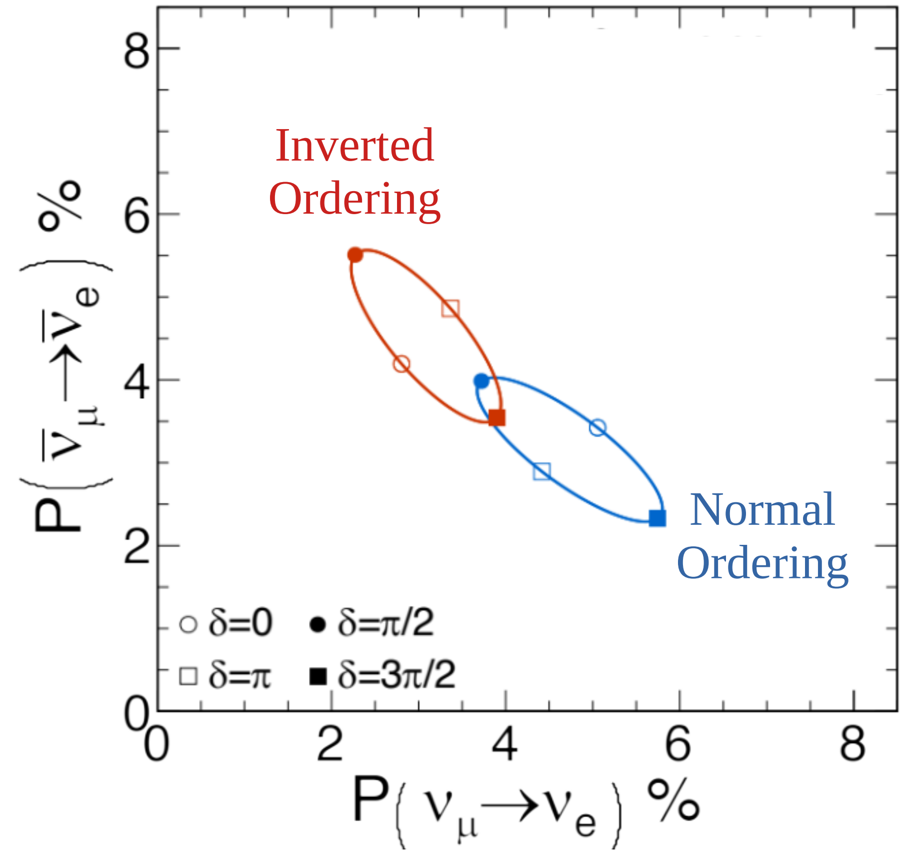
- ν_e different from ν_μ and ν_τ in matter
- ν_e scatters coherently against matter's electron cloud
  - Similar to how light scatters, causing refraction
- Reversed for anti-neutrinos



No Matter Effect



With Matter Effect



Matter Effect Model

$$\mathcal{H} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger + V \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V = V_e - V_{other} = \sqrt{2} G_F n_e$$

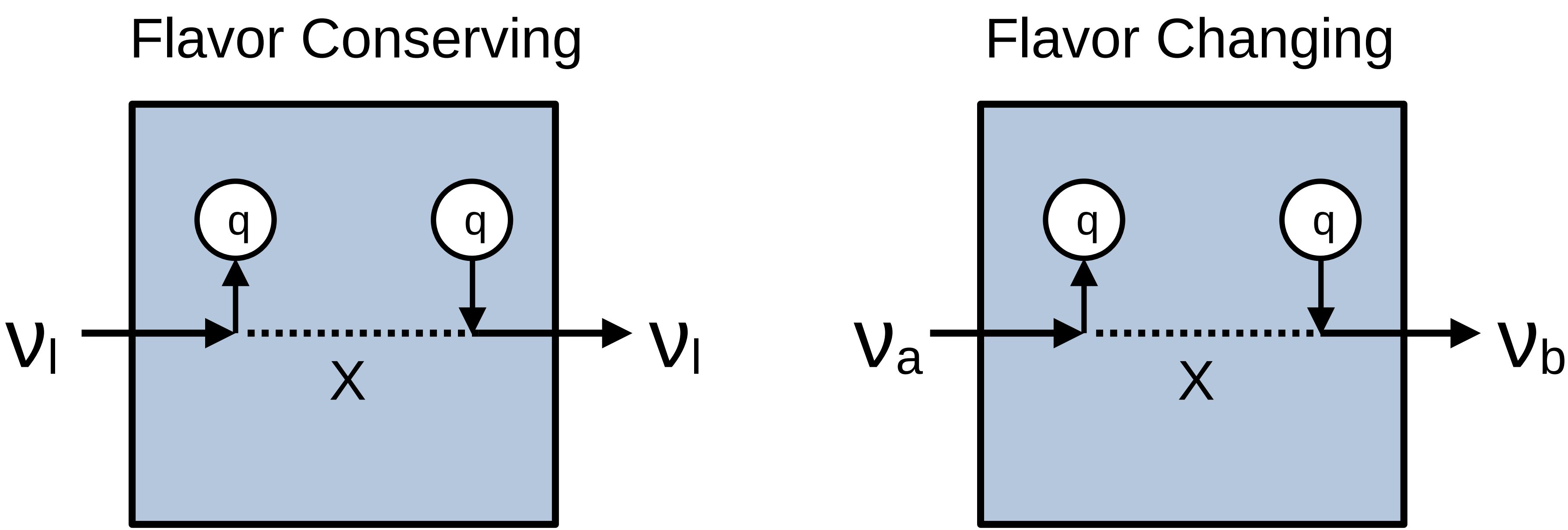
Density of electron cloud
which can change based on position.
Ultimately leads to resonances when
oscillation frequency ~ MSW frequency

arXiv:hep-ph/0305106

Non-Standard Interactions

Non-Standard Interactions (NSI)

- NSI are an BSM extension of the standard matter effect



q = constituents of matter: electrons, up/down quark

Non-Standard Interactions (NSI)

- Effective approach

$$\mathcal{H} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} U^\dagger + \sum_f V_f \begin{bmatrix} \delta_{ef} + \varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau} \\ \varepsilon^{f\,*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau} \\ \varepsilon^{f\,*}_{e\tau} & \varepsilon^{f\,*}_{\mu\tau} & \varepsilon^f_{\tau\tau} \end{bmatrix}$$

f = e, u, d

Non-Standard Interactions (NSI)

- Off-diagonal terms can be complex
  - Complex phases $\delta_{\alpha\beta}$

$$\mathcal{H} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} U^\dagger + \sum_f V_f \begin{bmatrix} \delta_{ef} + \varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau} \\ \varepsilon^{f\,*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau} \\ \varepsilon^{f\,*}_{e\tau} & \varepsilon^{f\,*}_{\mu\tau} & \varepsilon^f_{\tau\tau} \end{bmatrix}$$

f = e, u, d

$$\varepsilon^f_{\alpha\beta} = \left|\varepsilon^f_{\alpha\beta}\right| e^{i\delta^f_{\alpha\beta}}$$

Experimental Simplification

$$\mathcal{H} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} U^\dagger + \sum_f V_f \begin{bmatrix} \delta_{ef} + \varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau} \\ \varepsilon^{f\,*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau} \\ \varepsilon^{f\,*}_{e\tau} & \varepsilon^{f\,*}_{\mu\tau} & \varepsilon^f_{\tau\tau} \end{bmatrix}$$

Redefine sum of matrices to single effective matrix

Experimental Simplification

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Redefine sum of matrices to single effective matrix

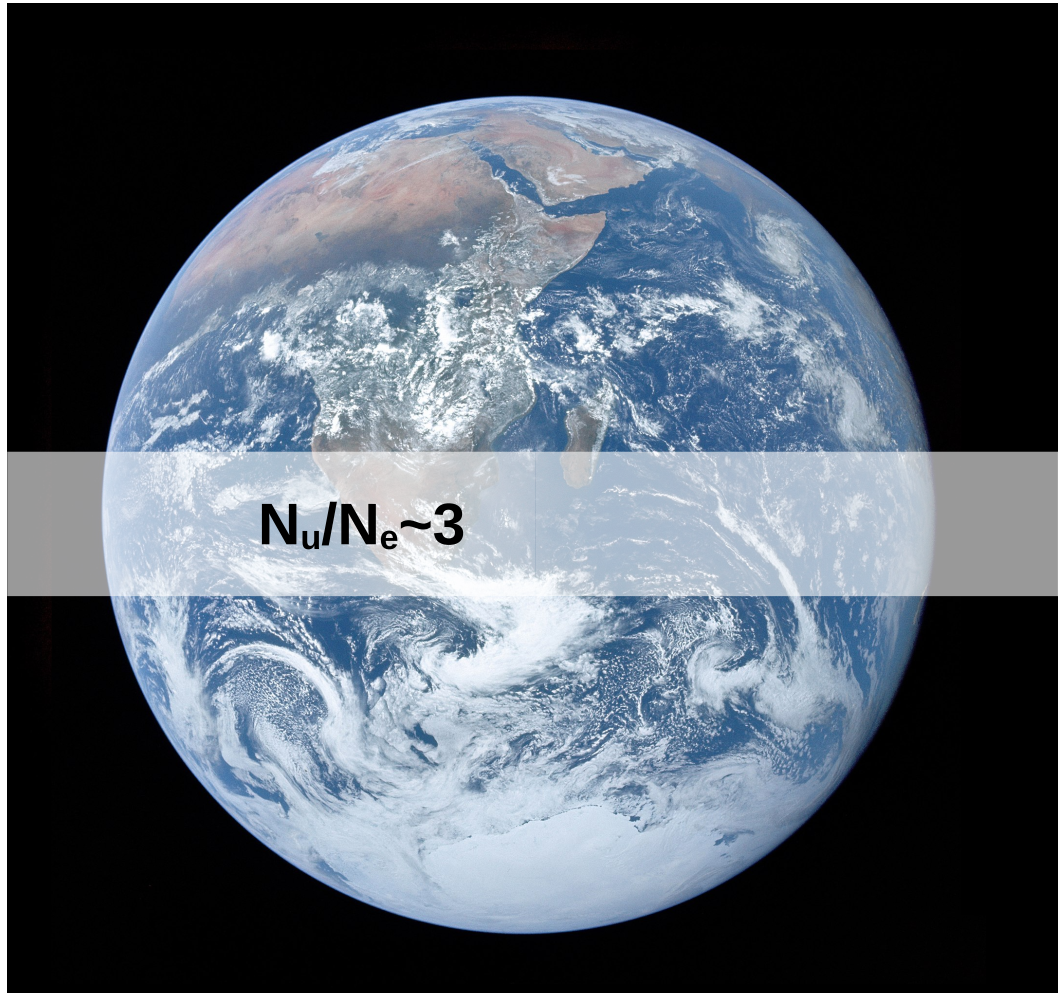
$$\mathcal{H} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger + V \begin{pmatrix} \delta_e + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ (\varepsilon_{e\mu})^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ (\varepsilon_{e\tau})^* & (\varepsilon_{\mu\tau})^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

Where $\varepsilon = 1 \rightarrow$ same size as MSW effect

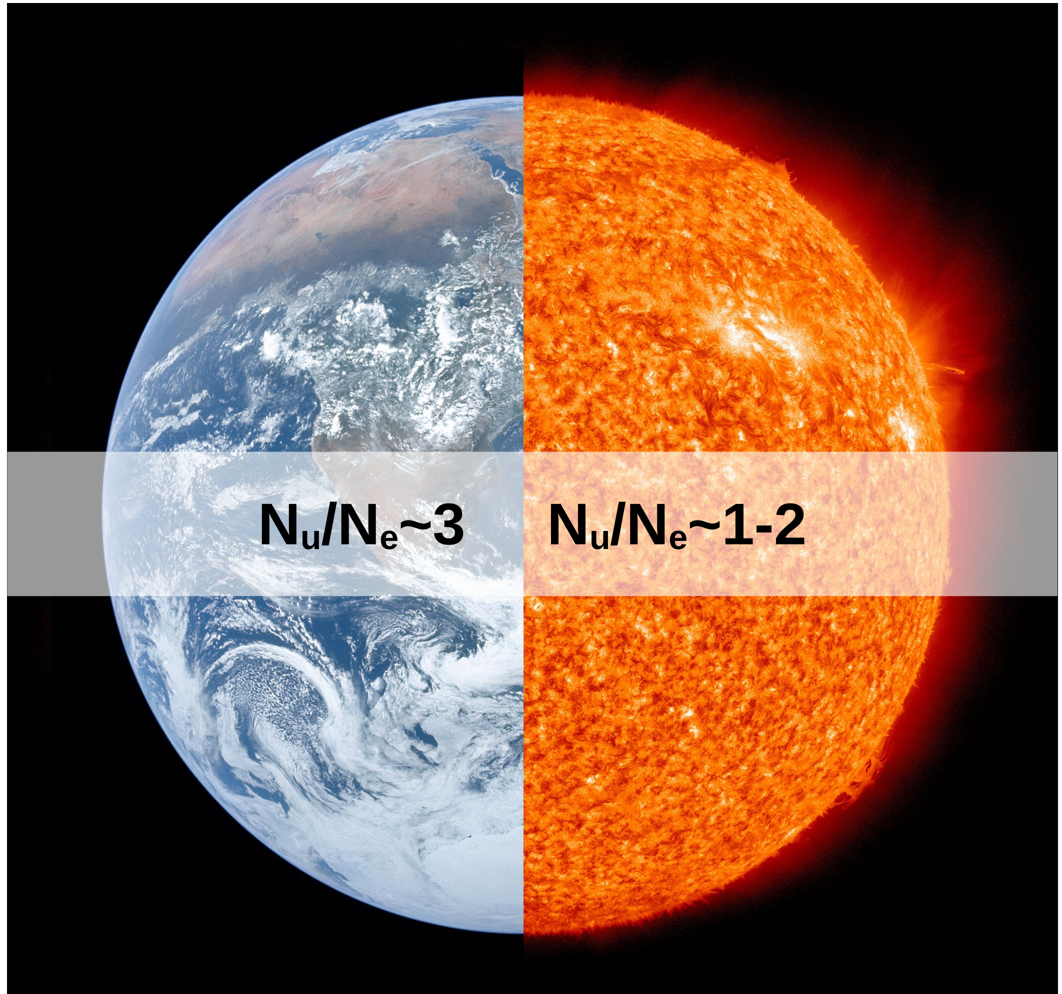
Assume all NSI comes from electrons

and correct if theory says up or down quark.

Correction Factors



Careful



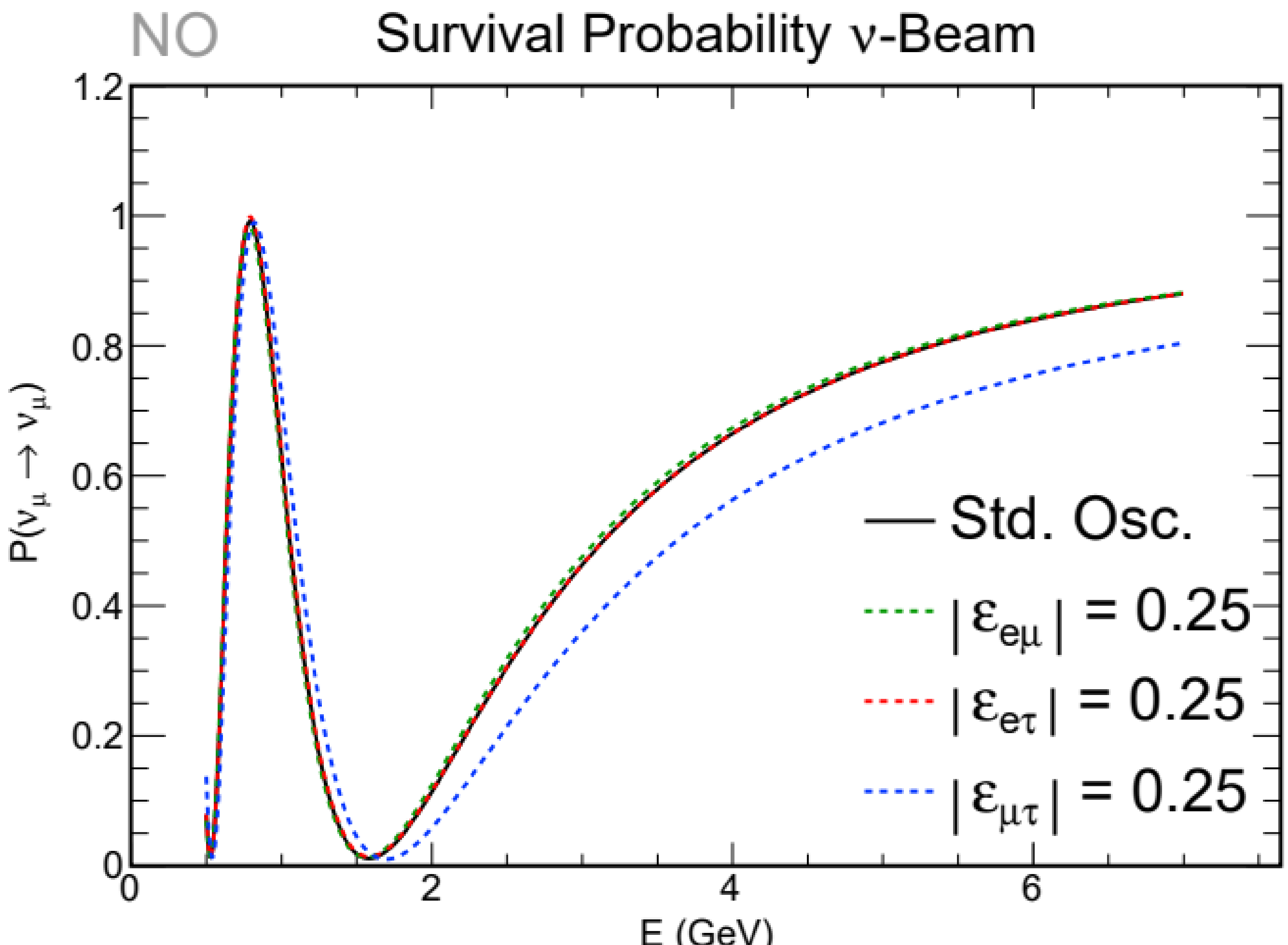
Non-Standard Interactions (NSI)

$$\mathcal{H} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger + V \begin{pmatrix} \delta_e + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ (\varepsilon_{e\mu})^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ (\varepsilon_{e\tau})^* & (\varepsilon_{\mu\tau})^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

- Off-diagonal terms can be written with a CP violating phase

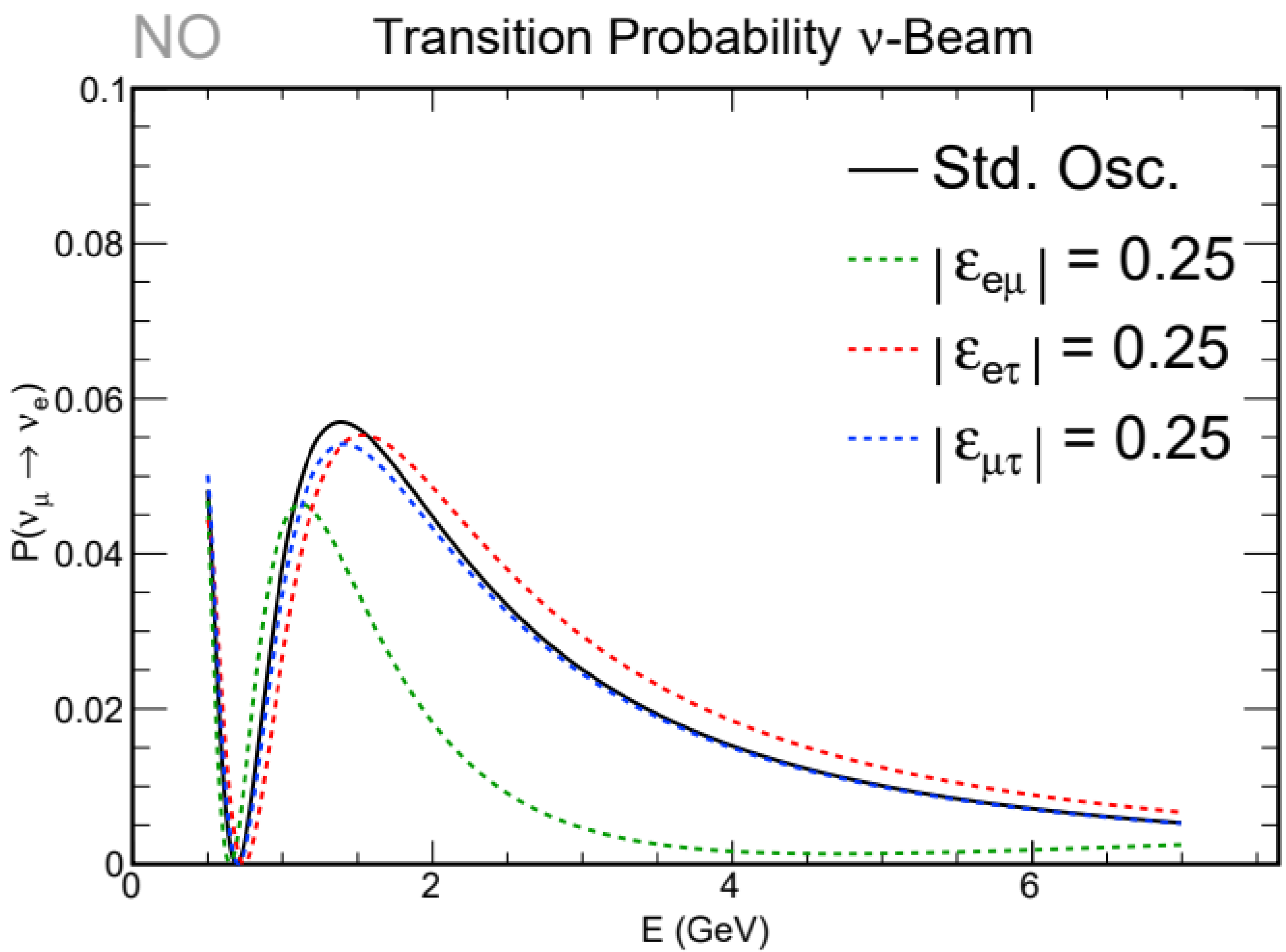
$$\varepsilon_{\alpha\beta} = \left|\varepsilon_{\alpha\beta}\right| e^{i\delta_{\alpha\beta}}$$

Effect of Each Parameter



$L = 810$ km
$\rho = 2.74$ g/cm^3
$\sin^2(\theta_{12}) = 0.304$
$\sin^2(\theta_{13}) = 0.0218$
$\sin^2(\theta_{23}) = 0.56$
$\Delta m^2_{21} = 7.54 \times 10^{-5}$ eV^2
$\Delta m^2_{32} = 2.41 \times 10^{-3}$ eV^2 (NO)
$\delta_{CP} = 0.82\pi$

Effect of Each Parameter



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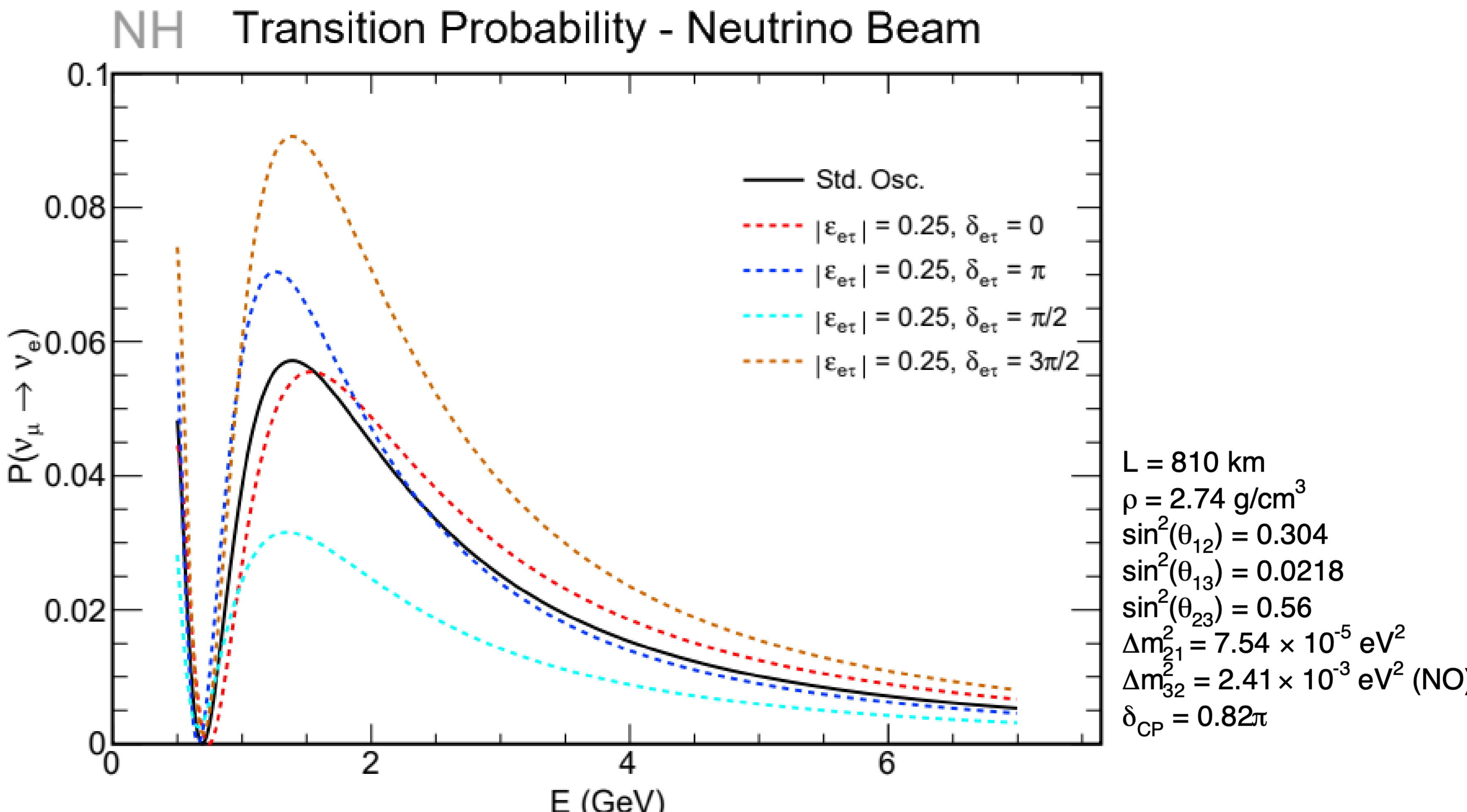
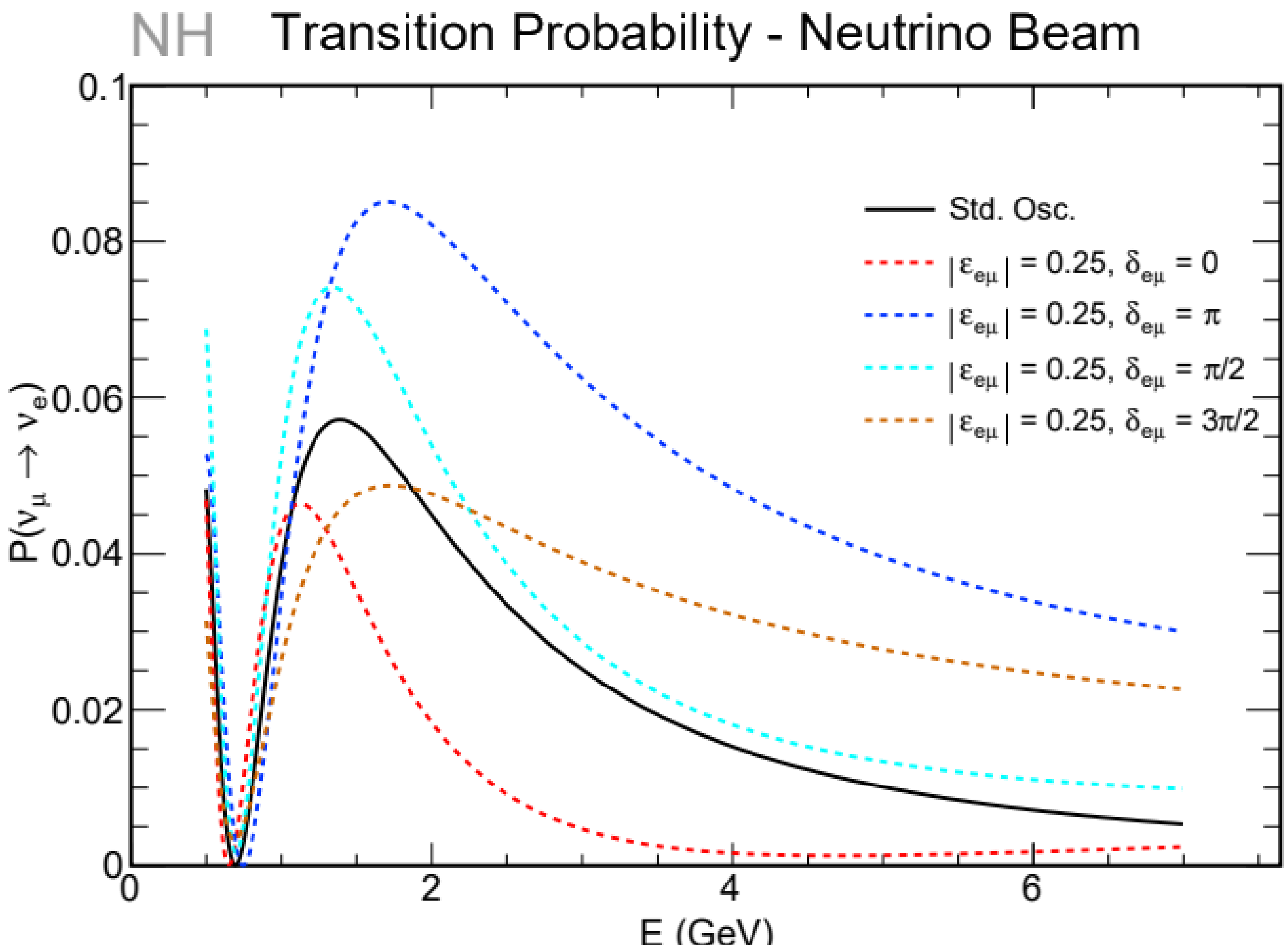
Effect of Phase: eτ sector



Effect of Phase: eμ sector



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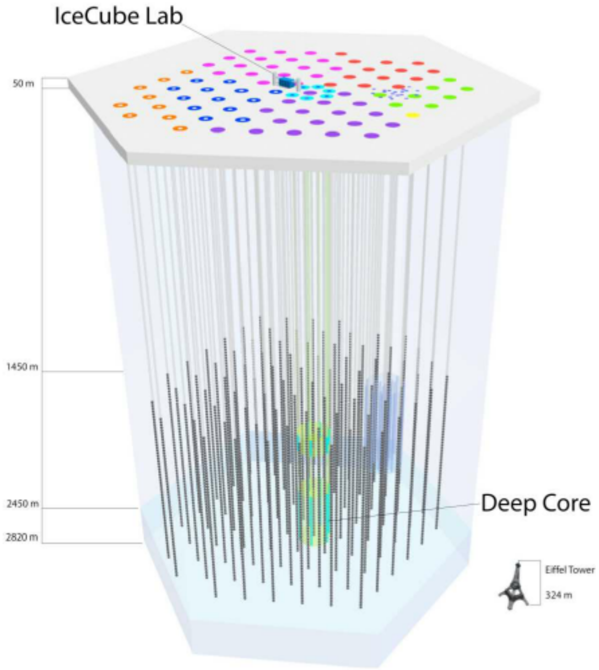
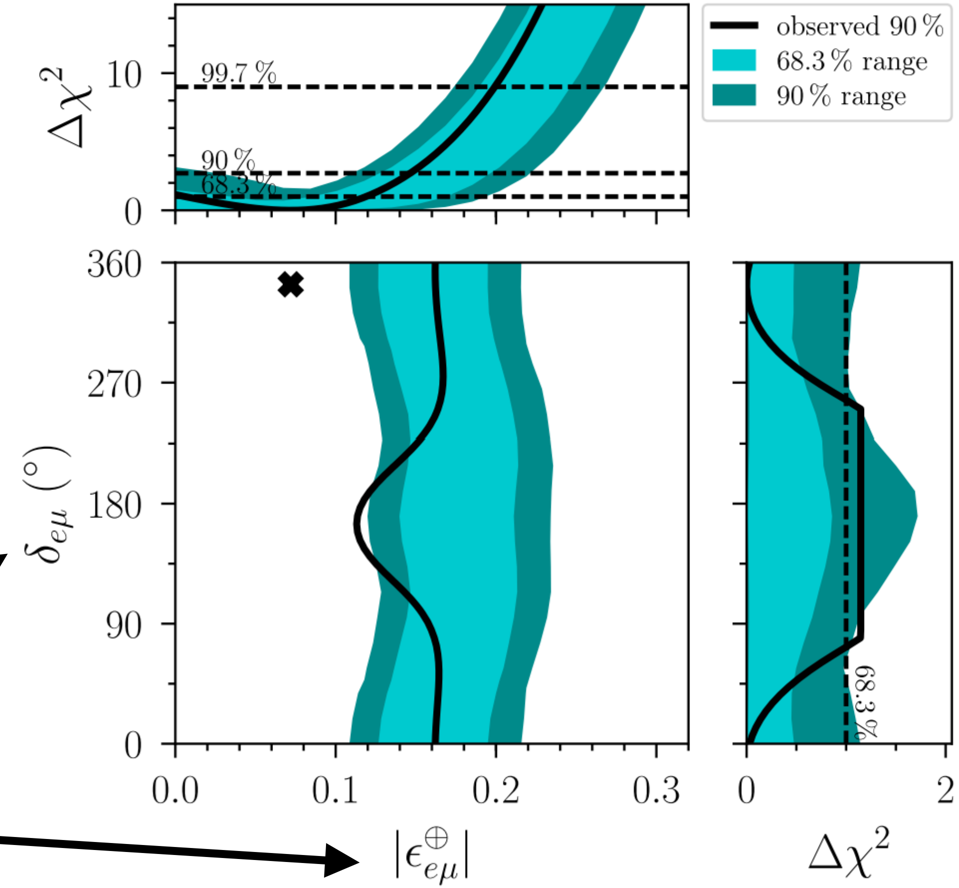
$\delta_{CP} = 0.82\pi$

What we know

Icecube



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

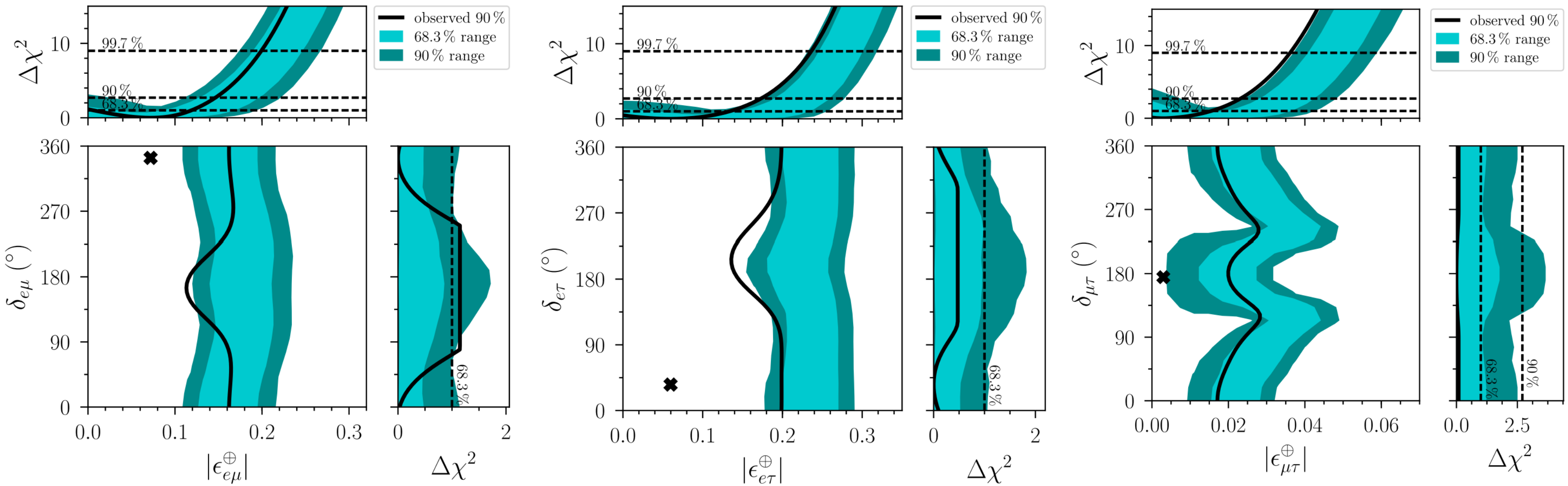


Phys. Rev. D104(Oct, 2021) 072006

Icecube

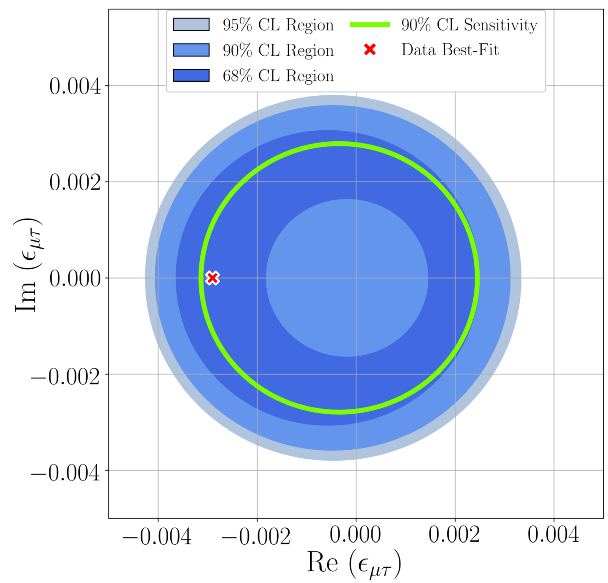
- Very tight constraints on NSI using atmospheric neutrinos
- Assumes $\delta_{CP} = 0$

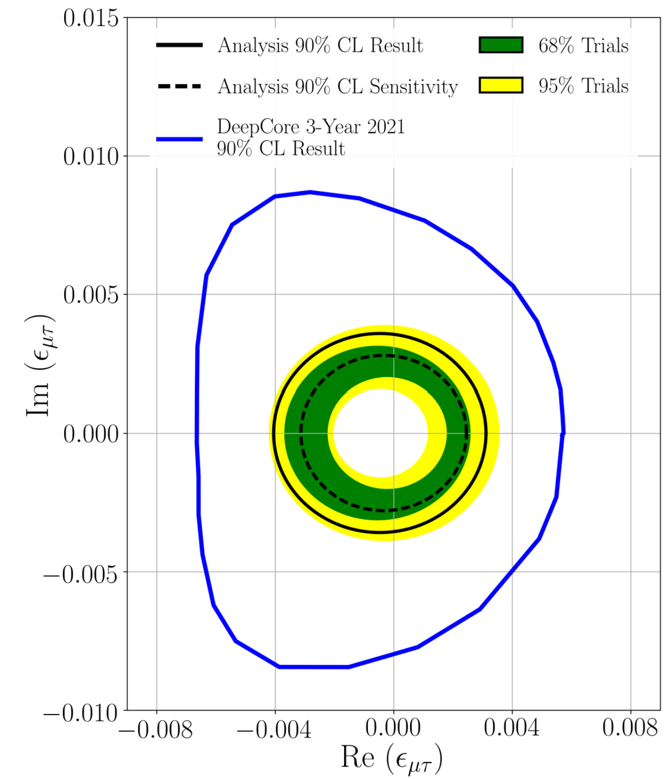
Phys. Rev. D104(Oct, 2021) 072006



Icecube: Tighter μτ Limits

- Measuring $Re(\varepsilon_{\mu\tau})$ & $Im(\varepsilon_{\mu\tau})$
- Using up to TeV level neutrinos





Phys. Rev. Lett. 129, 011804

δ_{CP} and $\delta_{e\tau}$

- $P(\nu_\mu \to \nu_e)$

  $\sim \sin\delta_{CP}$ & $\cos\delta_{CP}$ terms

  $\sim \varepsilon_{e\tau}\sin(\delta_{CP} + \delta_{e\tau})$, $\varepsilon_{e\tau}\cos(\delta_{CP} + \delta_{e\tau})$

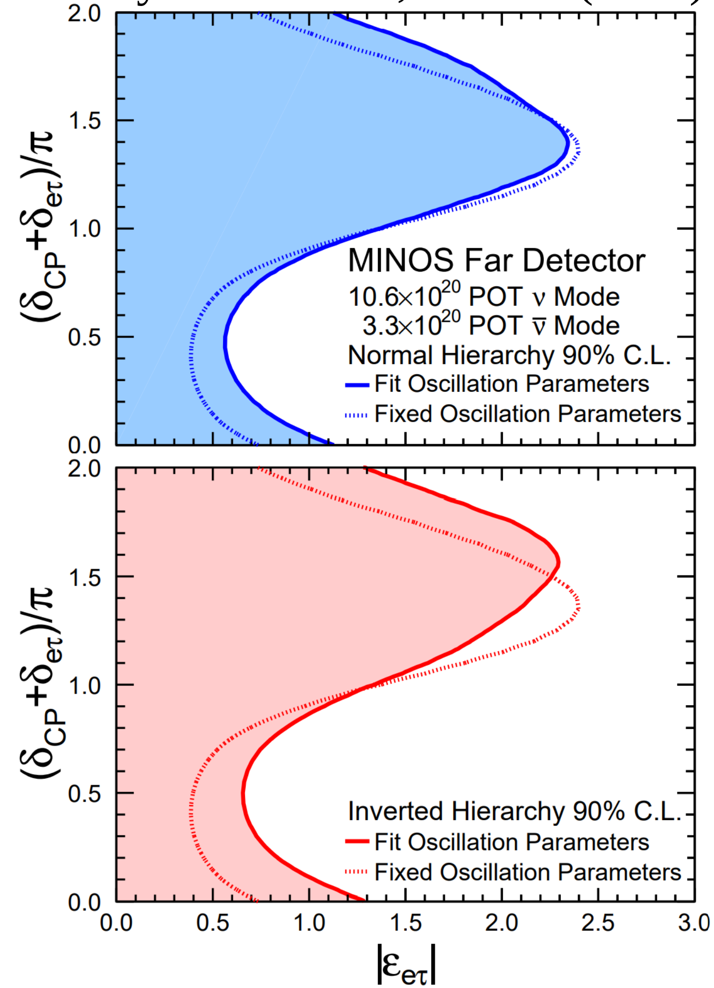
- A $\varepsilon_{e\tau}$ grows, $\delta_{CP} + \delta_{e\tau}$ terms become dominant effect
  - Similar in $\varepsilon_{e\mu}$

Phys.Rev.D77:013007,2008

MINOS

- Measure vs $\delta_{cp}+\delta_{e\tau}$
  - Largest terms are proportional to $\varepsilon_{e\tau}\cos(\delta_{cp}+\delta_{e\tau})$
  - Profile over the difference $\delta_{cp}-\delta_{e\tau}$

Phys. Rev. D 95, 012005 (2017)

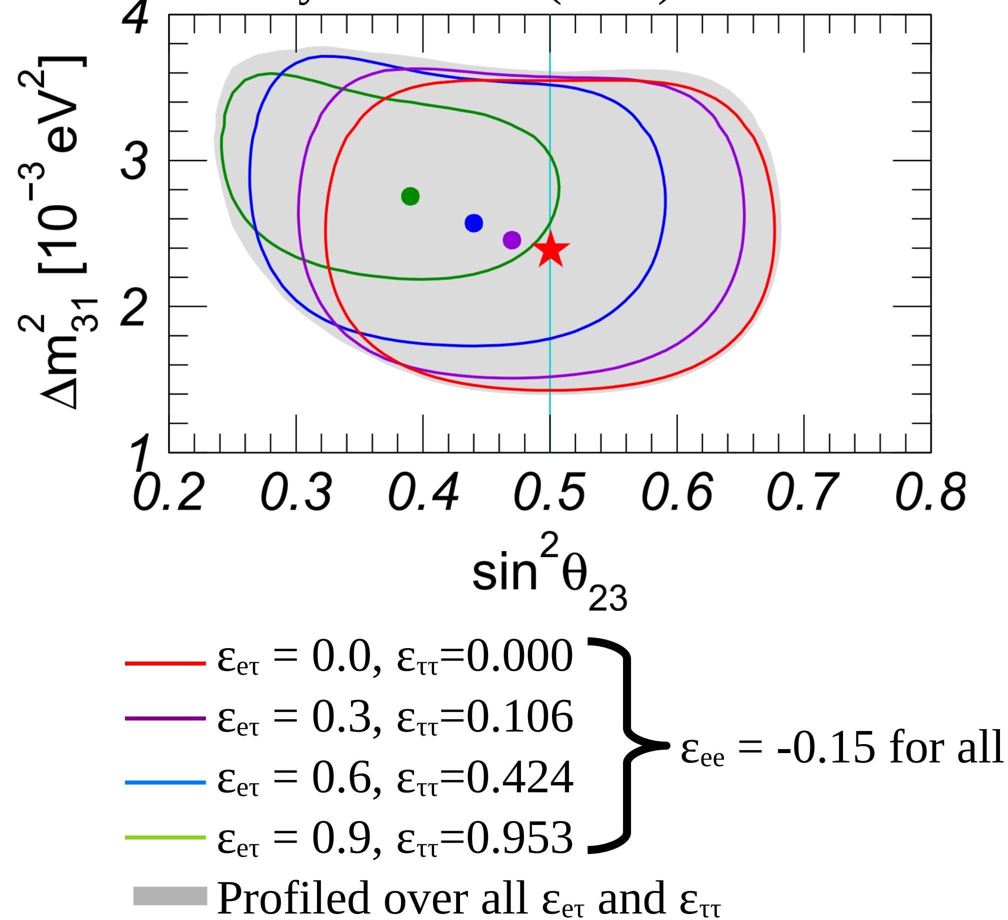


NSI's Effects on Standard Neutrino Oscillation Results

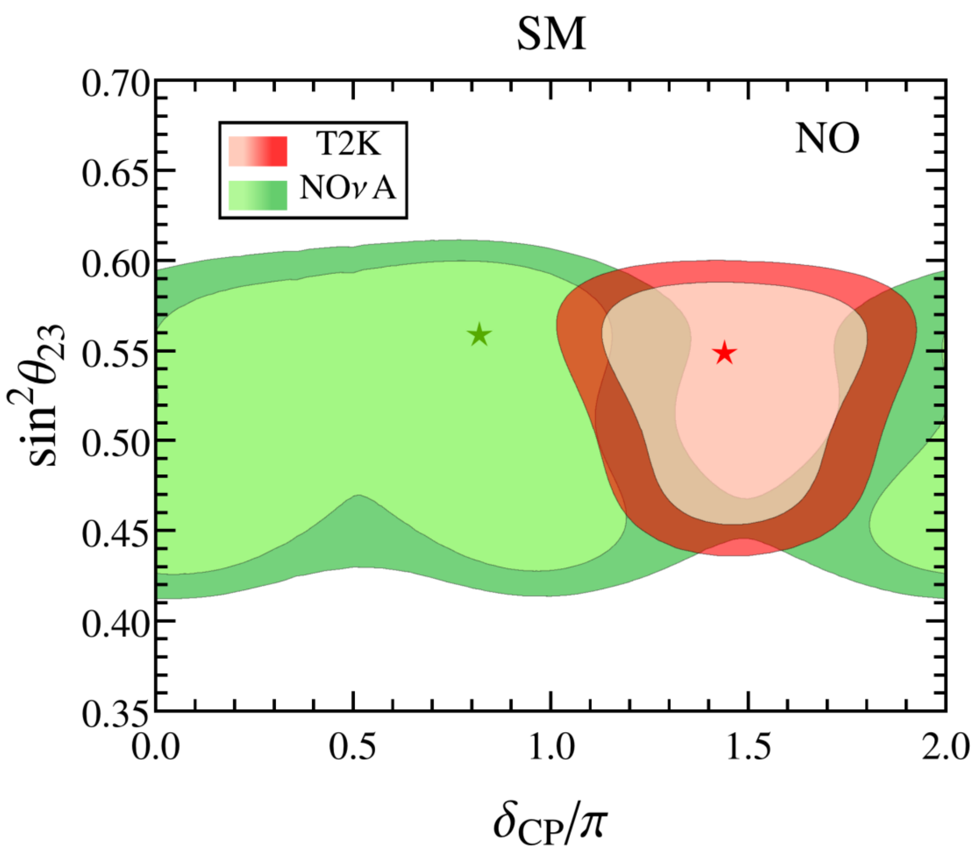
Effect on Std. Osc. Parameters

- Presence of NSI can bias interpretation of std. osc. parameters

Phys.Rev. D70 (2004) 111301

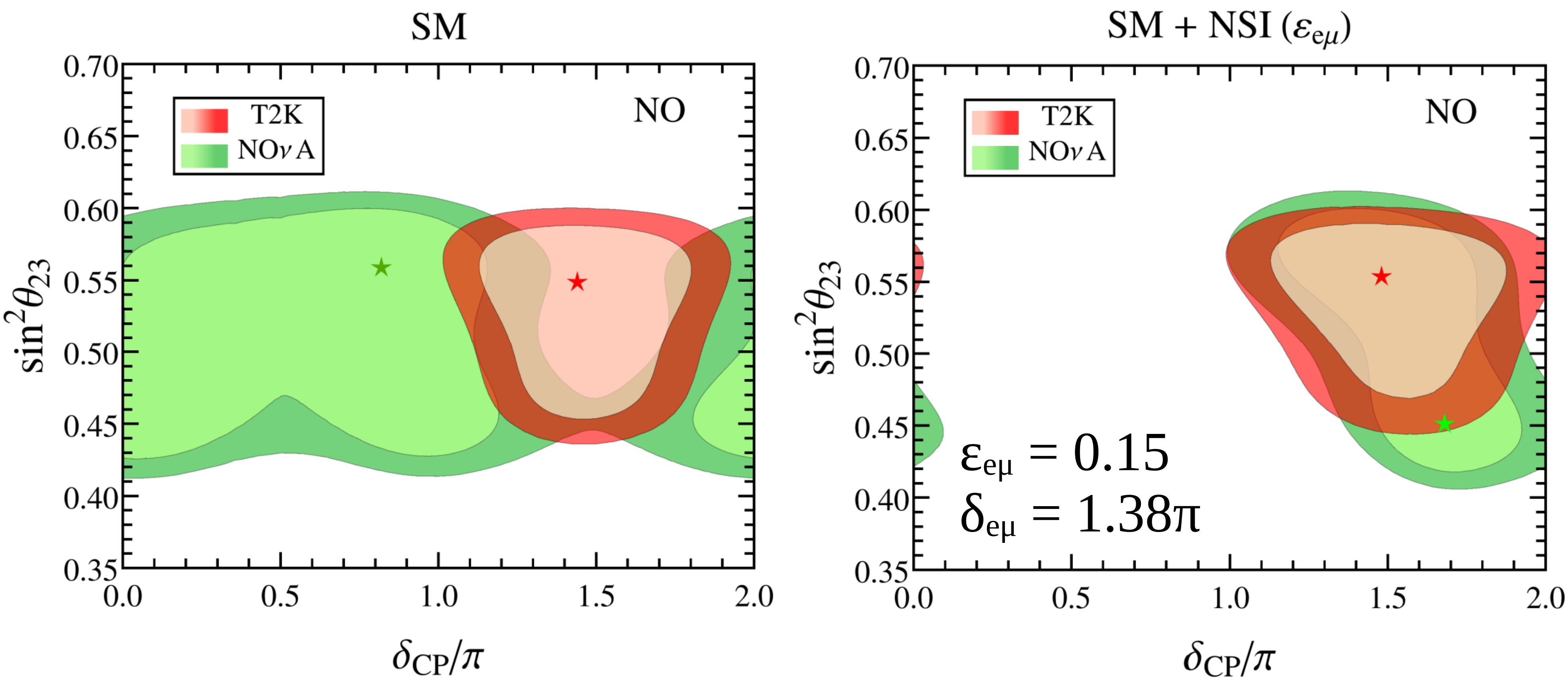


T2K-NOvA + NSI



Phys. Rev. Lett. 126, 051802 (2021)

T2K-NOvA + NSI



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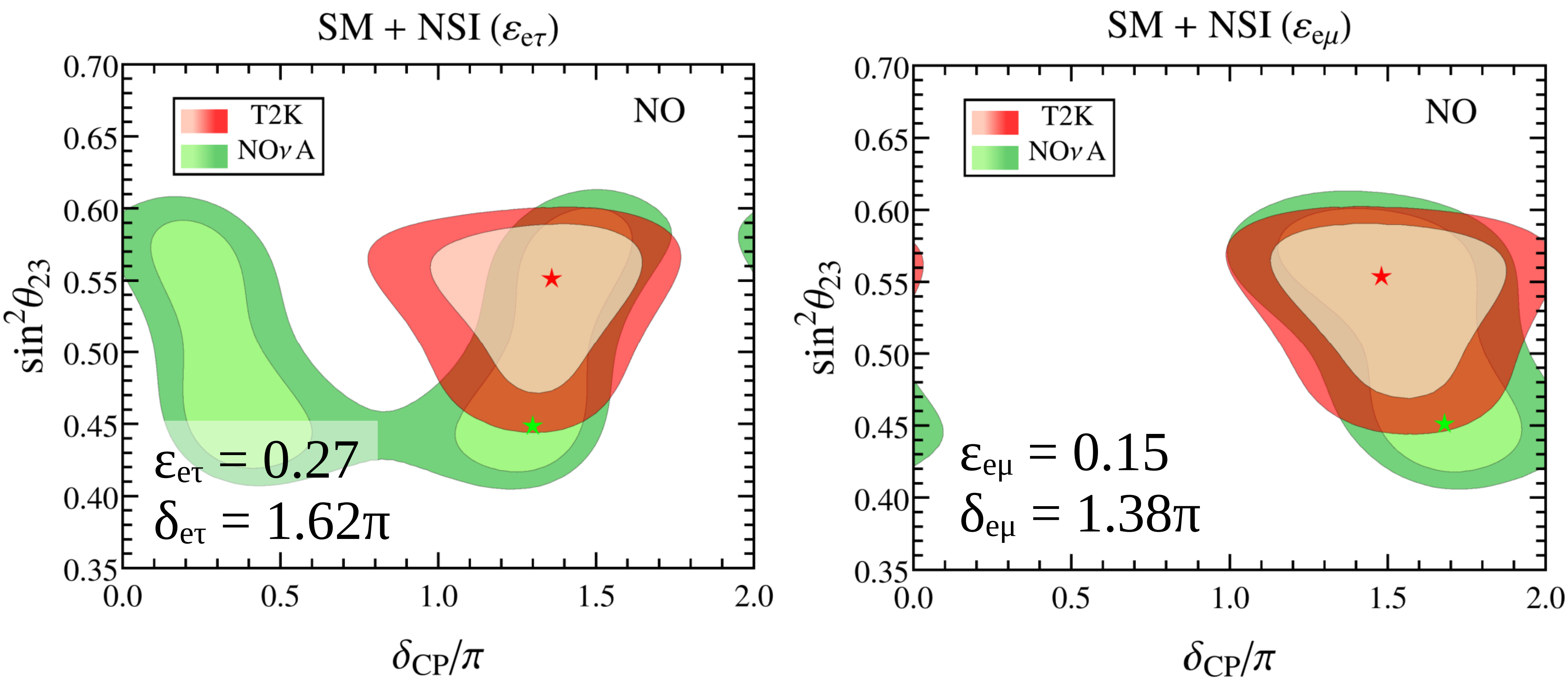
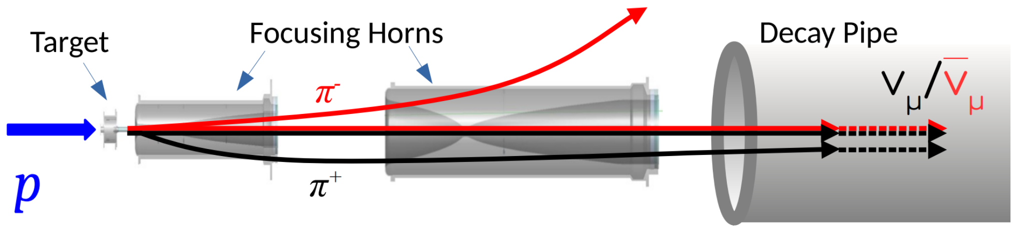
T2K-NOvA + NSI

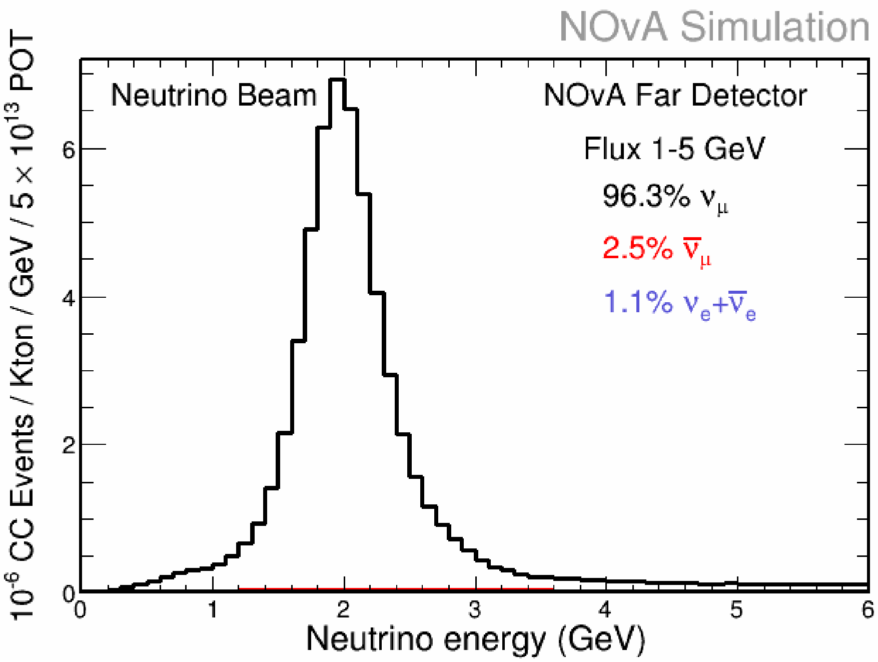


Phys. Rev. Lett. 126, 051802 (2021)

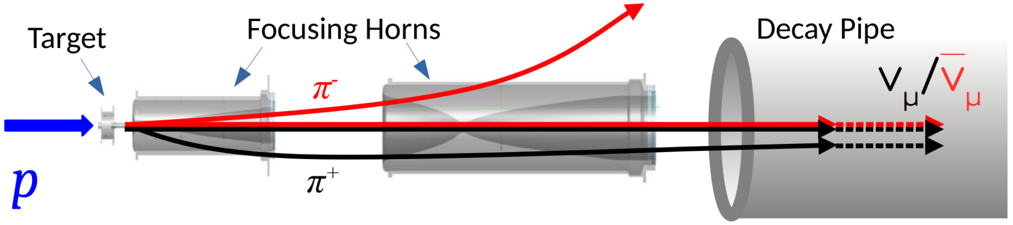
Measuring NSI at the NOvA Experiment

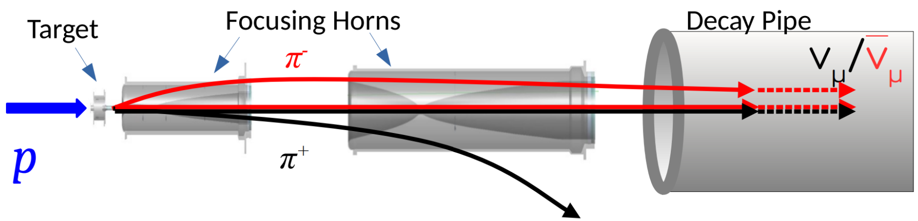
Neutrino Flux from NuMI beam

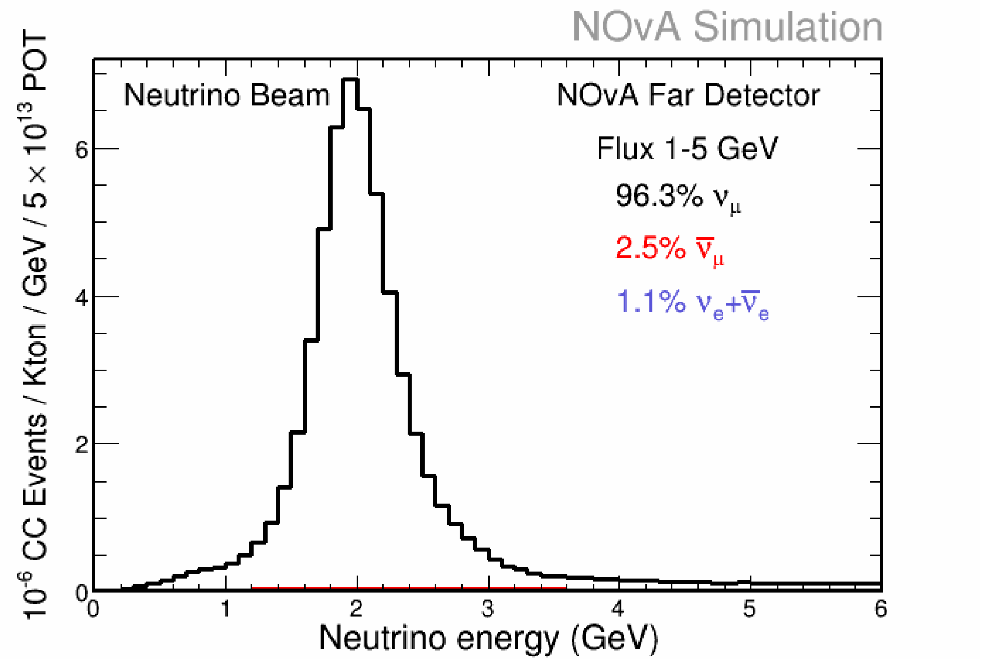


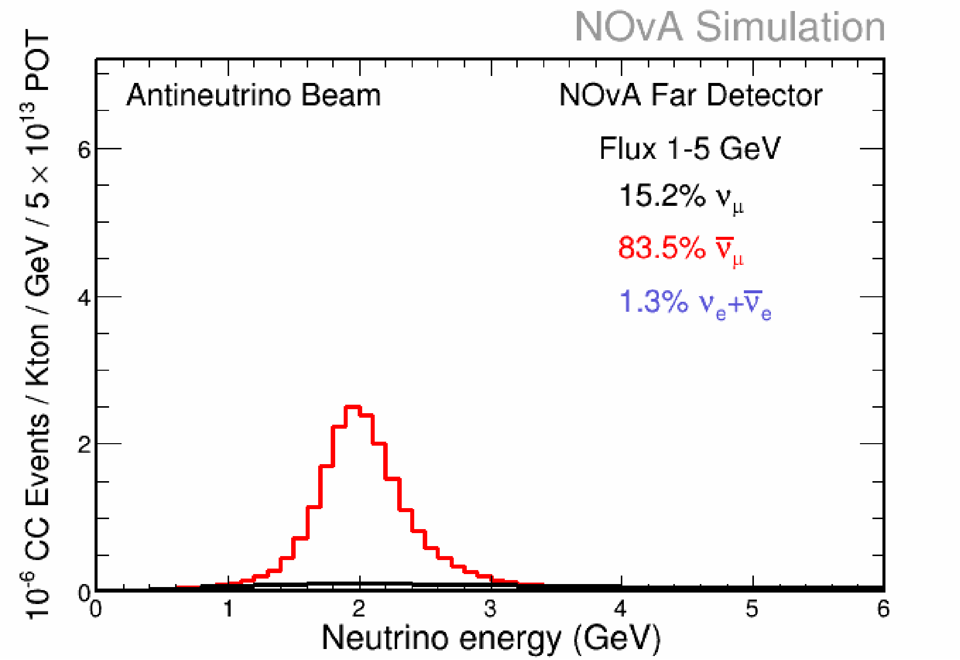


Neutrino Flux from NuMI beam

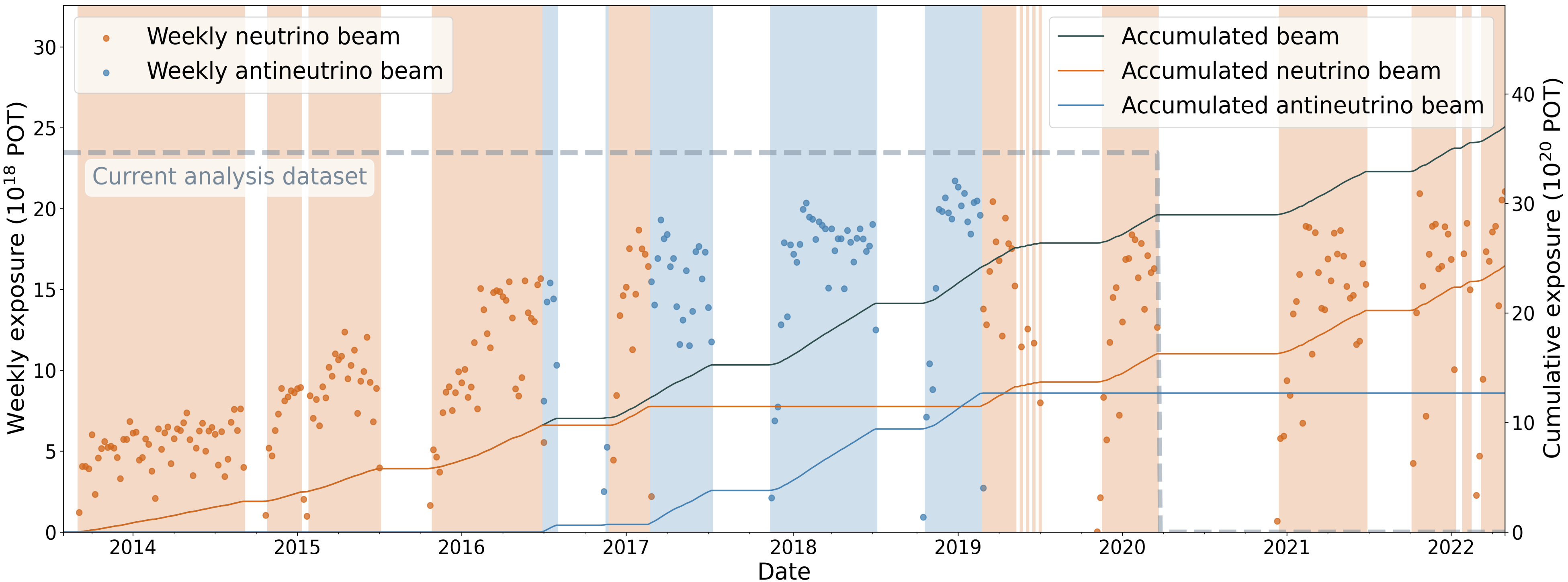






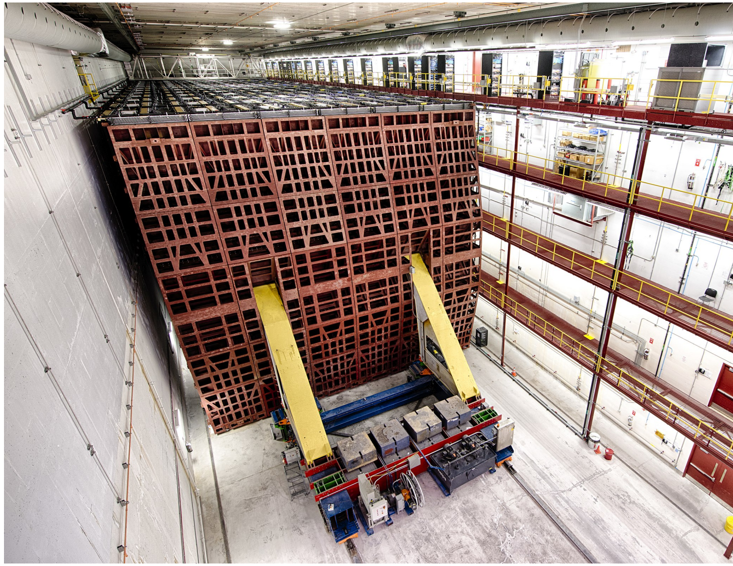


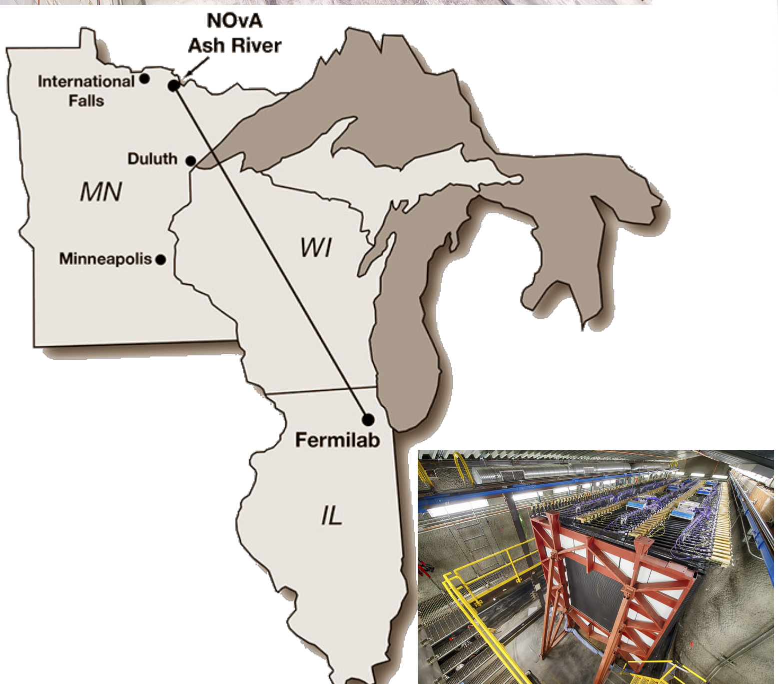
Protons on Target

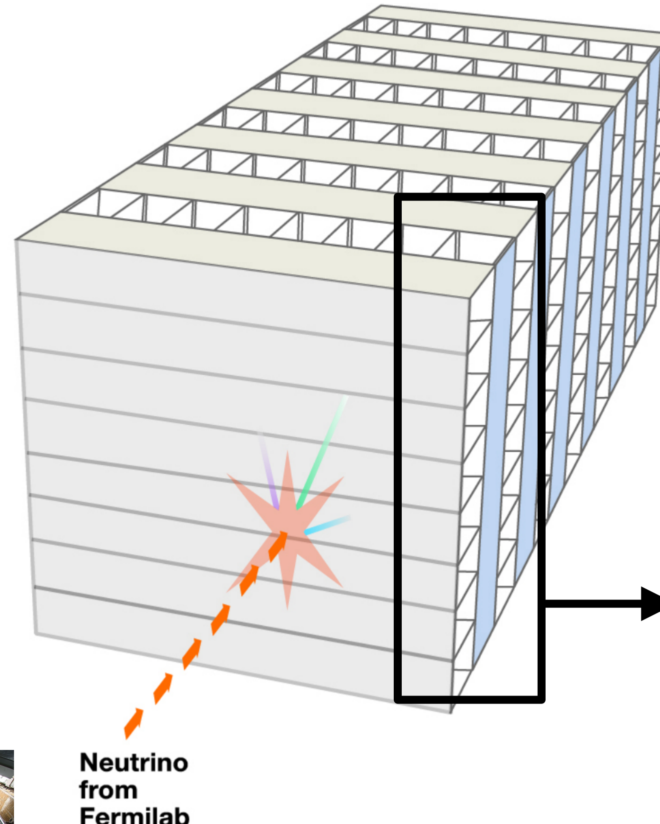


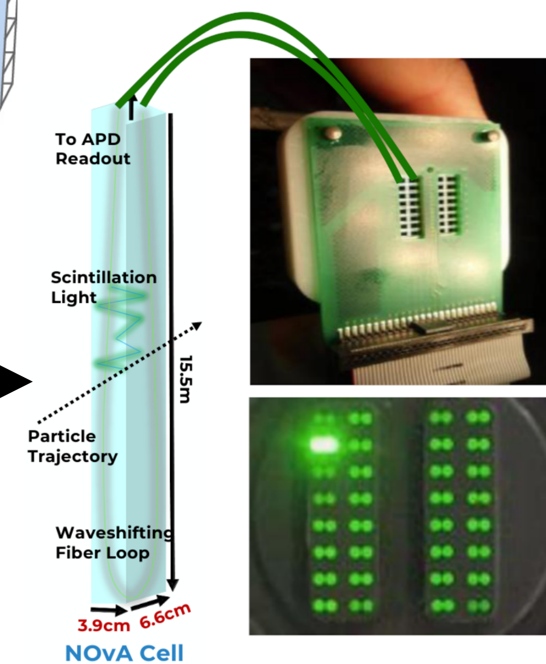
13.6×10^{20} POT ν 12.5×10^{20} POT $\bar{\nu}$

NOvA Experiment



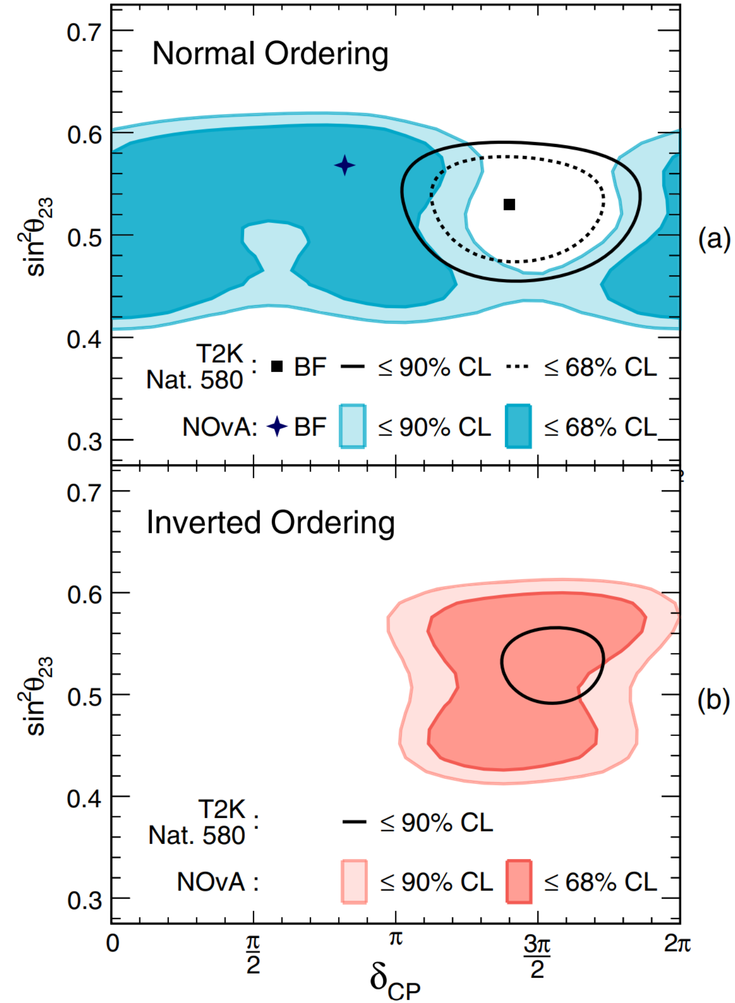






Reminder of Std. Osc. Result

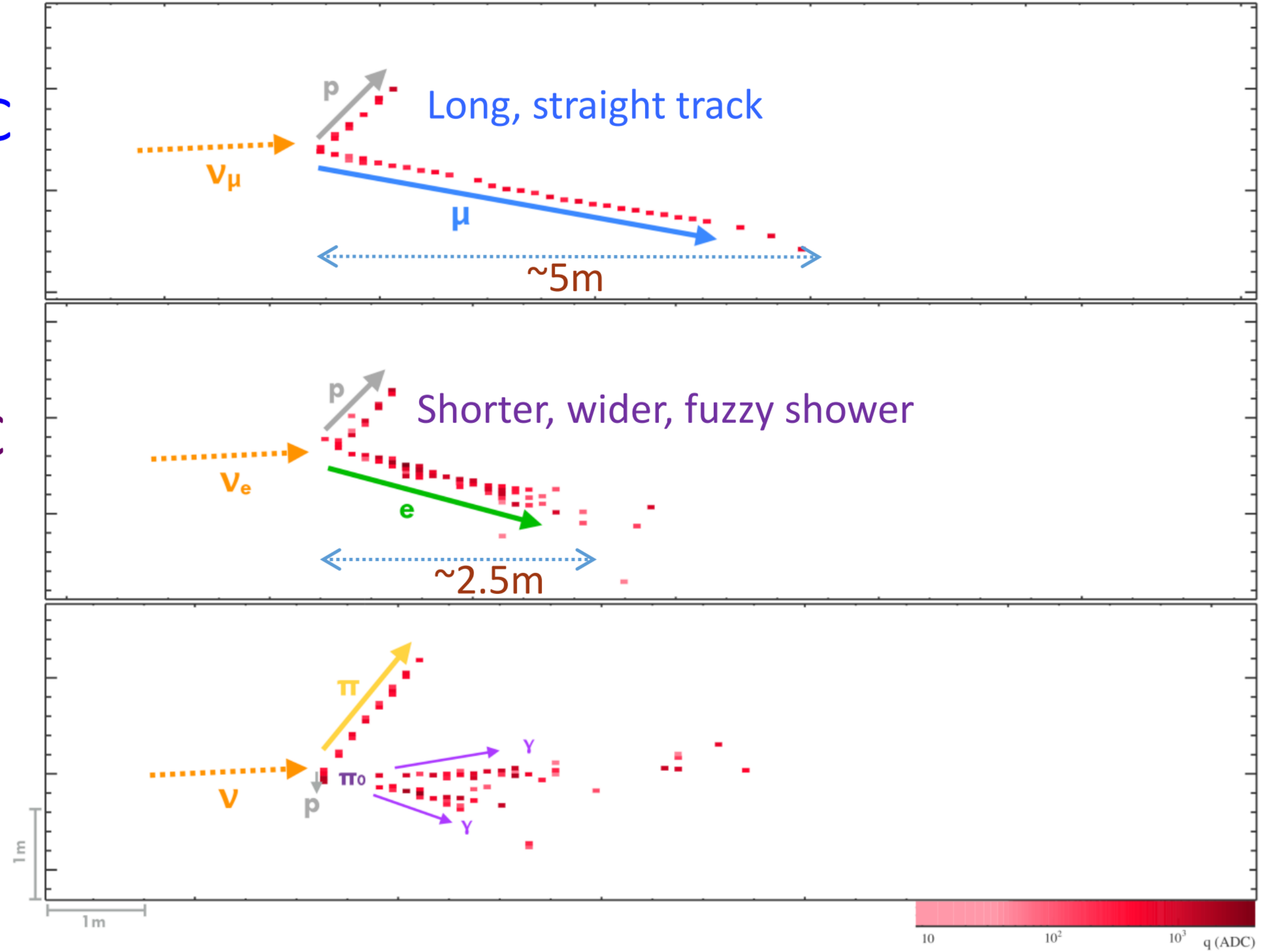
- Published August 1st, 2022
  - *Improved measurement of neutrino oscillation parameters by the NOvA experiment*
  - Phys. Rev. D 106, 032004
- Today's results are an NSI extension of the previous measurement



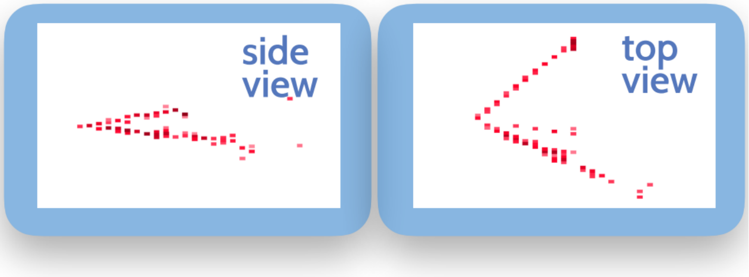
ν_μ CC

ν_e CC

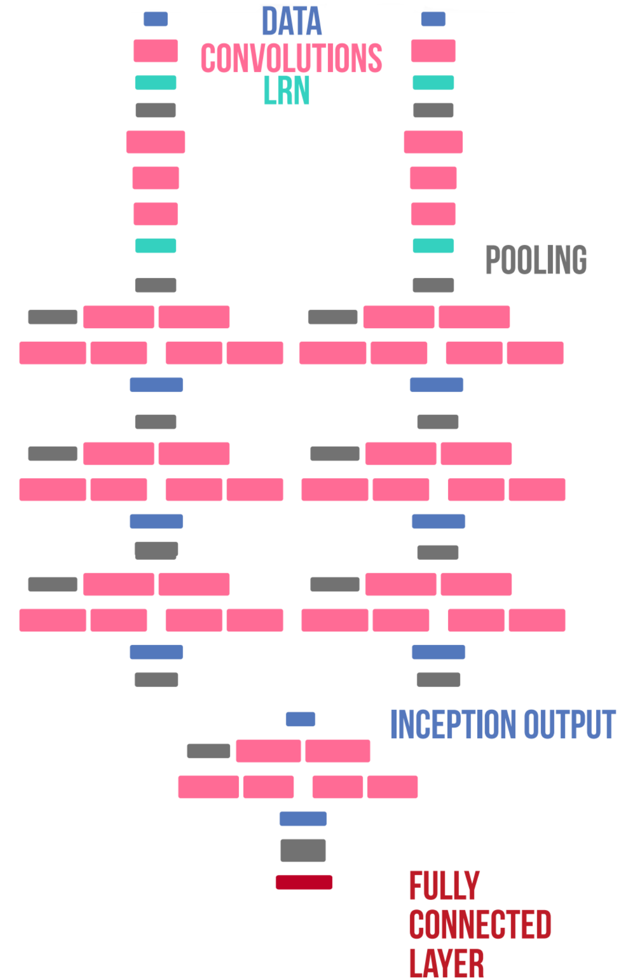
NC



Finding Neutrinos w/ CNNs

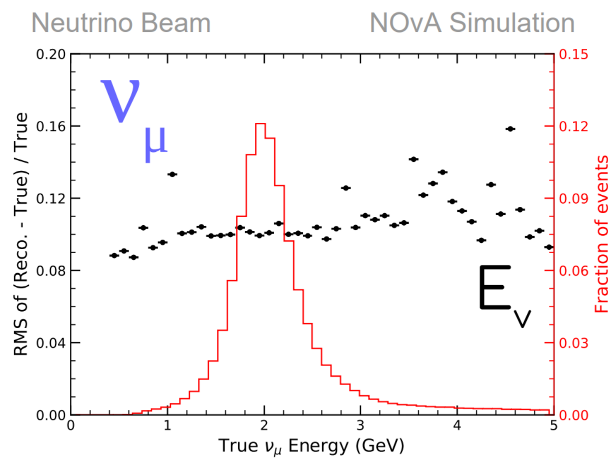


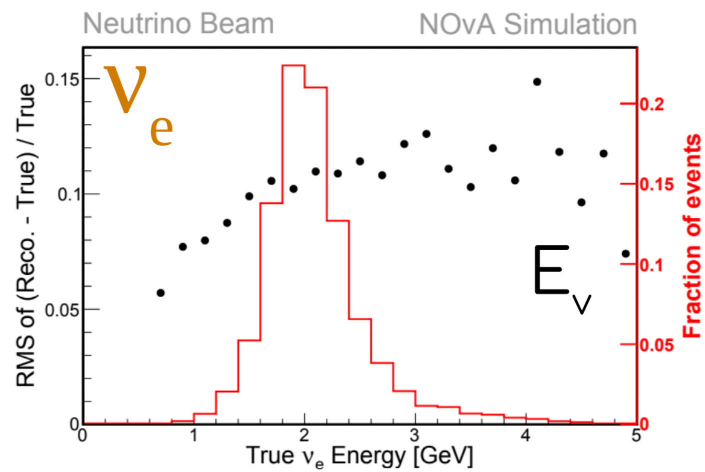
- 3rd generation
- Data-driven validation
- Increases effective exposure



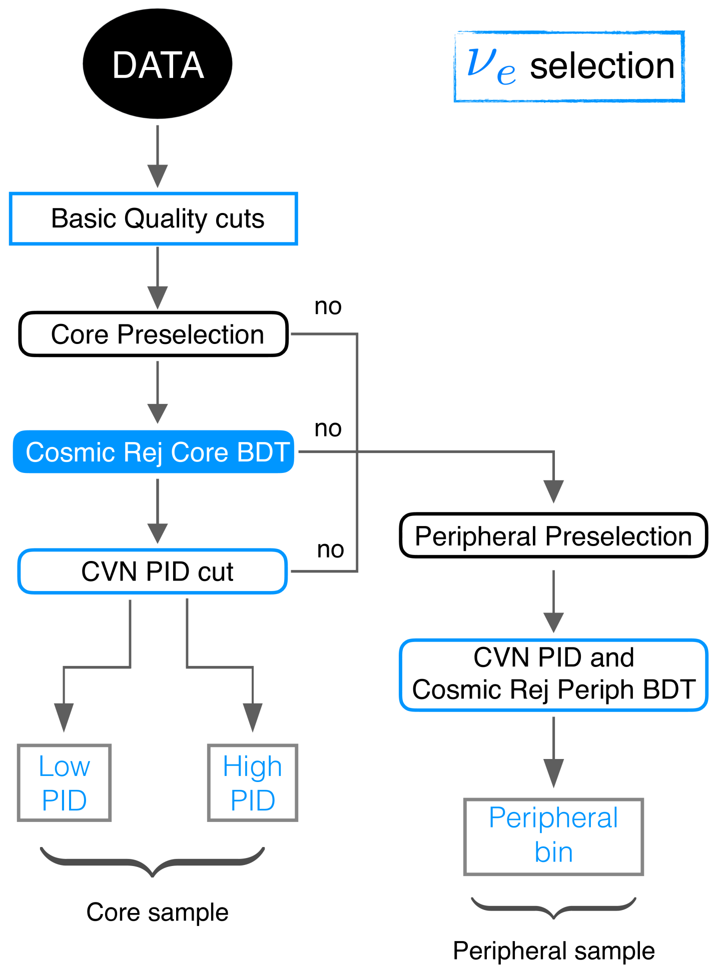
Energy Estimation

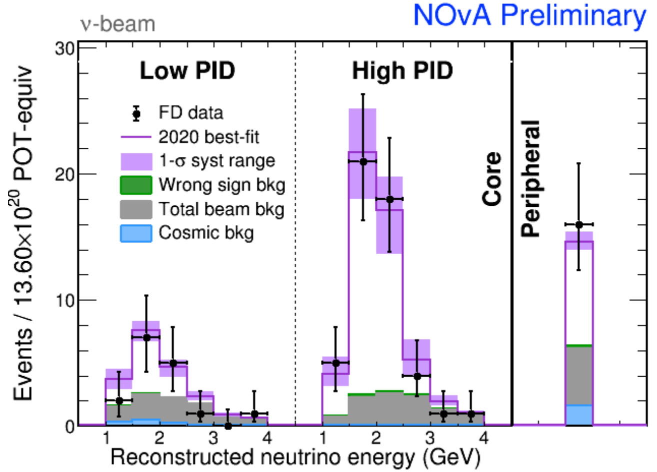
- $E_\nu \leftarrow E_l$ & $E_{hadronic}$
  - $<E_l> \sim 3\%$
  - $<E_{hadronic}> \sim 30\%$
- $<E_\nu> \sim 9\% \ (\nu_\mu)$
- $<E_\nu> \sim 11\% \ (\nu_e)$

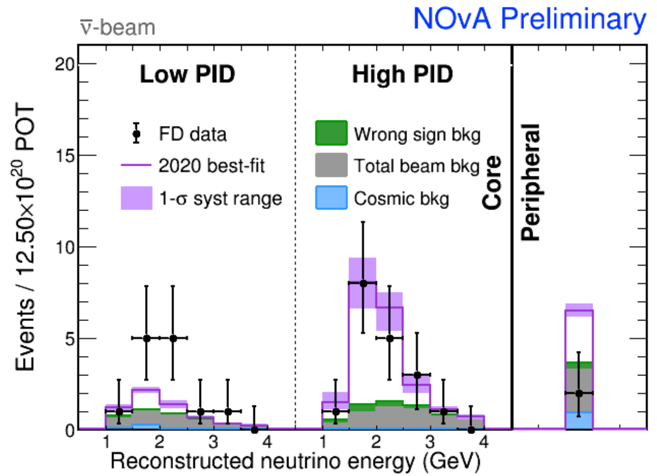




ν_e Reconstructed Spectra

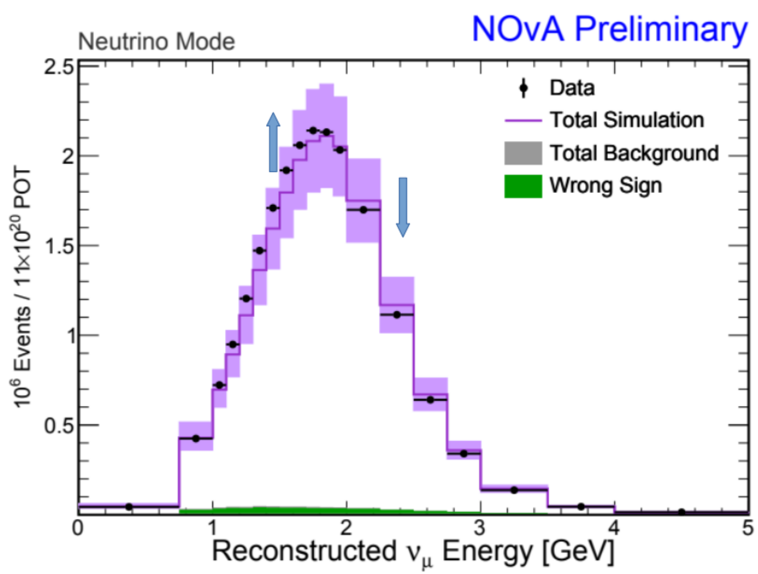






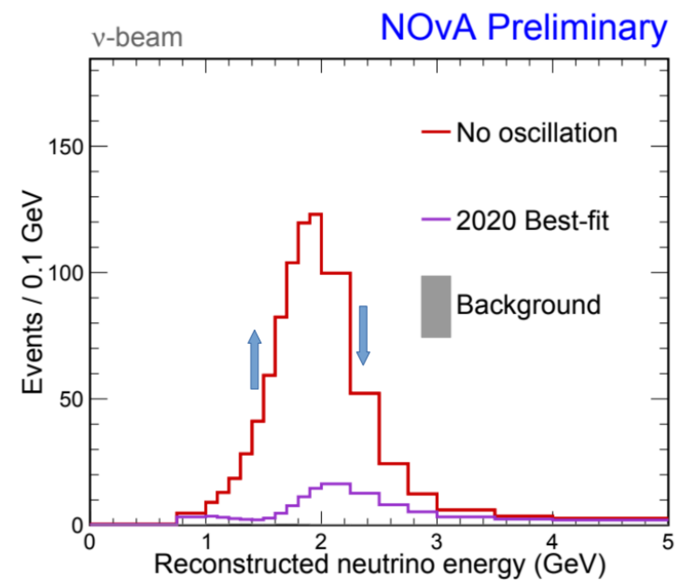
ND Extrapolation

Extrapolating ND → FD mitigates both "known" and "unknown" effects



"Extrapolation"

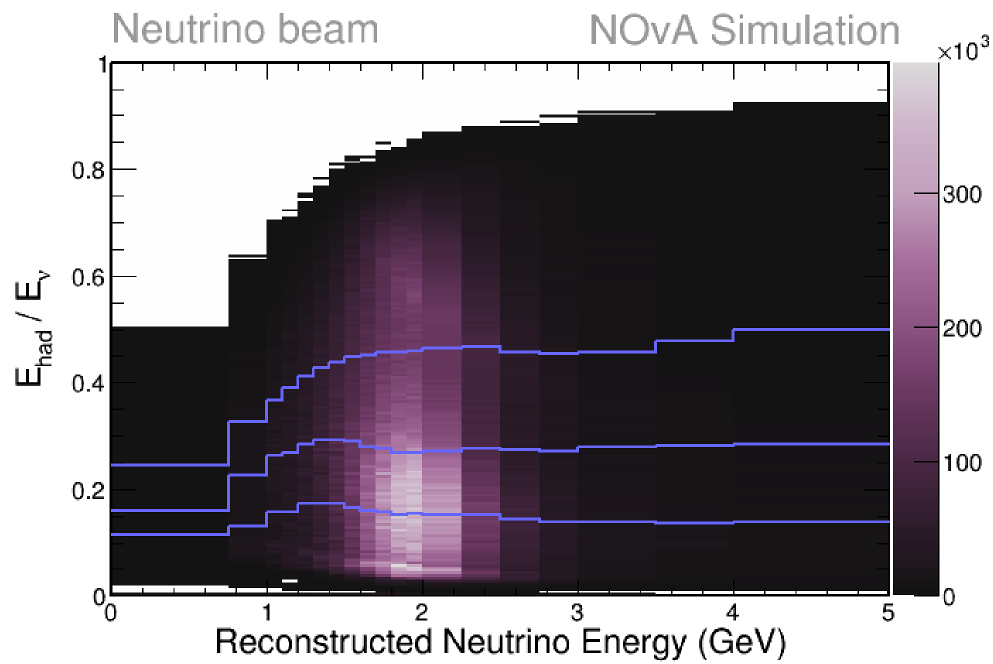
(account for beam divergence, detector size difference, etc. w/ MC)



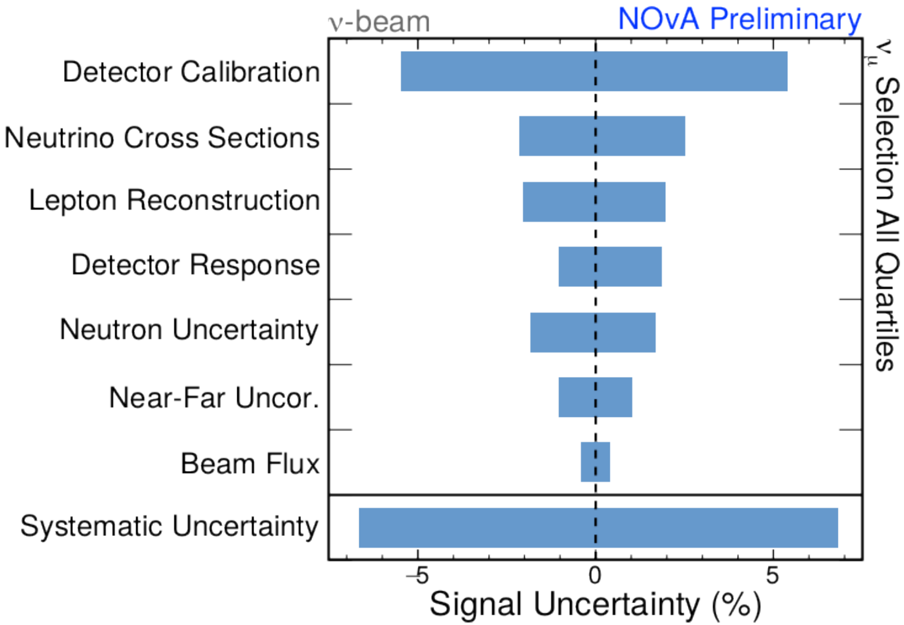
Slide courtesy of Jeremy Wolcott's 2020-09-18 W&C

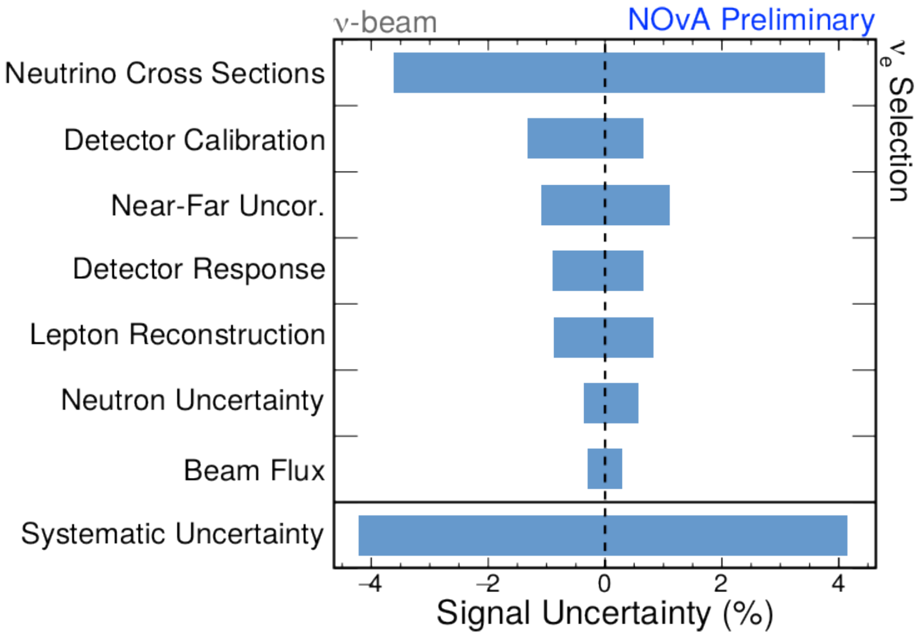
ND Data Exploitation

- Data is split into 4 quartiles based on hadronic energy fraction
  - <E_ν> better for low fraction
- Within each quartile, data is further split into bins of P_T
  - Helps with controlling differences between ND and FD acceptance



Final Systematic Uncertainty





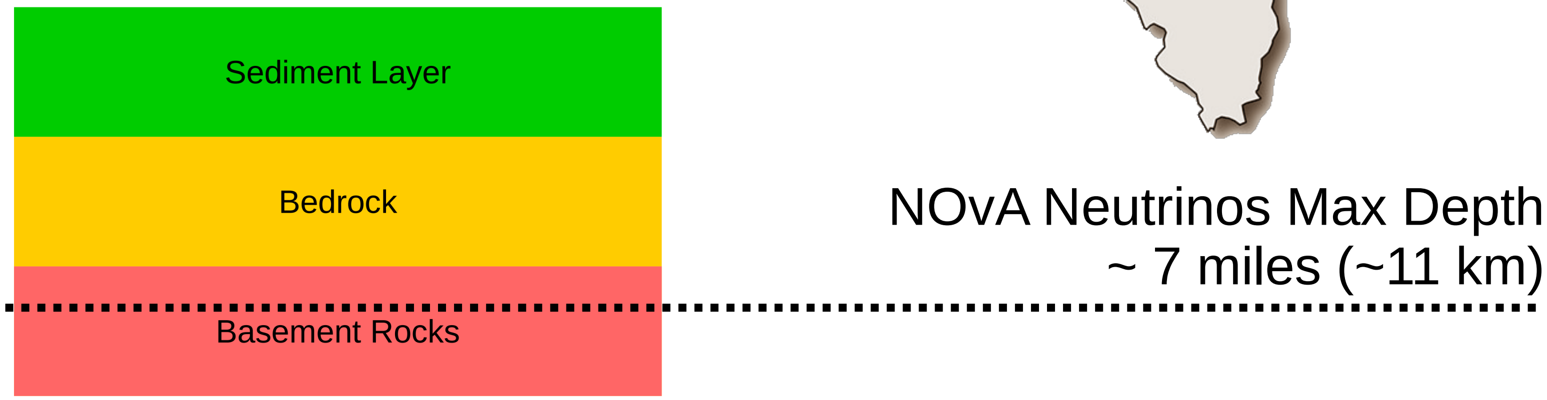
- Statistical uncertainty ~10%

NSI and the Analysis

- Need to be careful with two components when measuring NSI
- Rock density
- Constraints used for nuisance parameters

ρ Intro

- Density important to NSI
  - Signal ~ ε * ρ
- Neutrinos go up to 11km underground



NOvA Neutrinos Max Depth
~ 7 miles (~11 km)

CRUST Model

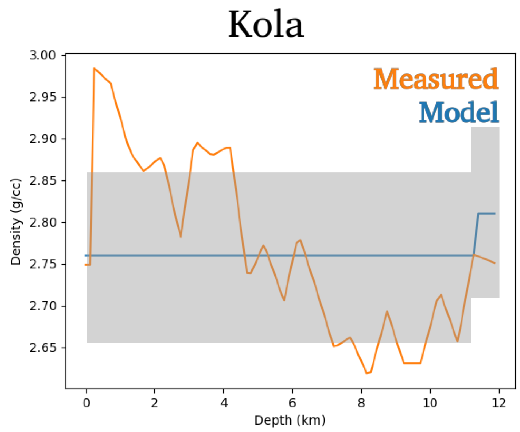
- Model of crust densities
- 1x1 degree longitude and latitude resolution
  - 12 chunks between Fermilab and Ash River
- Predicts an average density of 2.74 g/cm^3

Laske, G., Masters., G., Ma, Z. and Pasyanos, M., Update on CRUST1.0 - A 1-degree Global Model of Earth's Crust, Geophys. Res. Abstracts, 15, Abstract EGU2013-2658, 2013.
http://igppweb.ucsd.edu/~gabi/rem.html

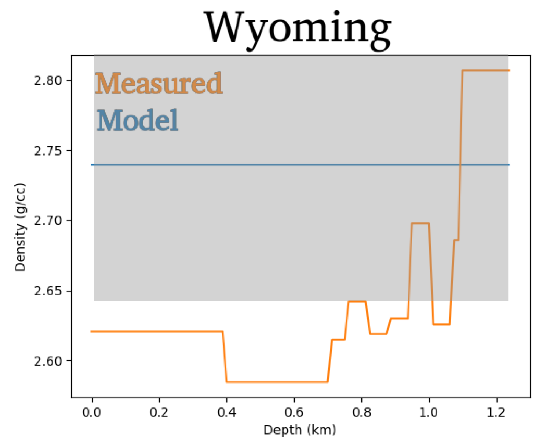
ρ Update: Uncertainty

- Compare CRUST model to real data
- Kola bore – deepest bore
- Wyoming oil bore – geologically similar

- Also direct bores from the MINOS cave
- 3.7% uncertainty



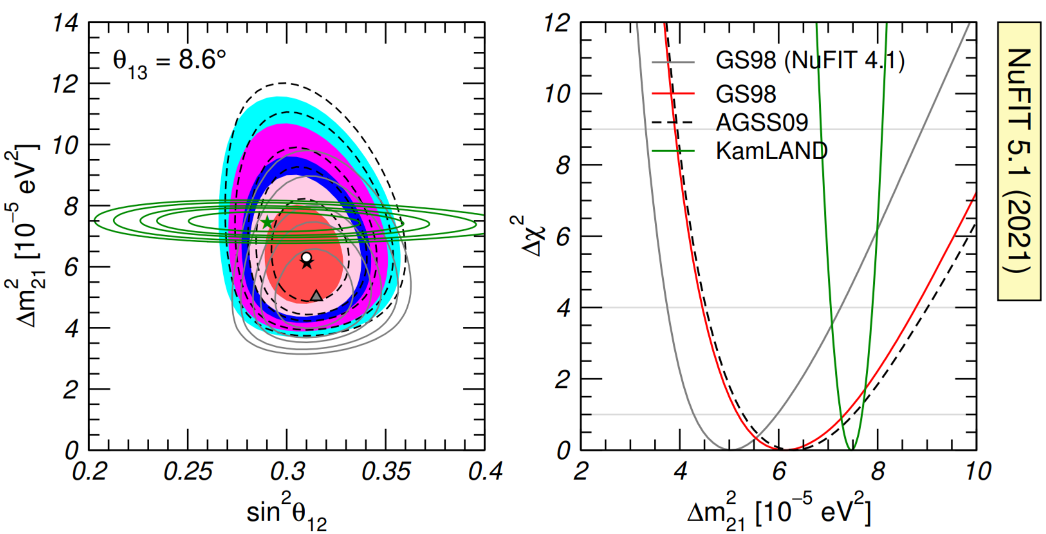
Kola Data: Acta Geodyn. Geomater., Vol. 11, No. 2 (174), 165–174, 20141



Wyoming Data: L.A. Beyer and F.G. Clutsom, Density and porosity of oil reservoirs 1055 and overlying formations from borehole gravity measurements, Gebo Oil 1056 Field, Hot Springs County, Wyoming, Report, 1978 doi:10.3133/oc88

Constraints

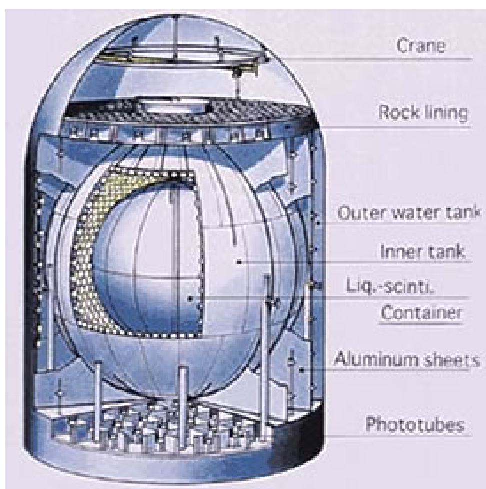
- NOvA is insensitive to some oscillation parameters
  - External sources are used to constrain those parameters
    - e.g. Particle Data Group or NuFit
- Combine results from various experiments

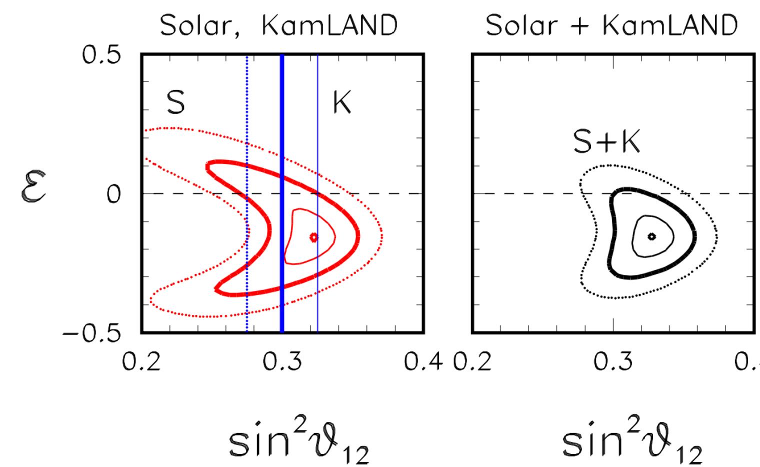


Universe 2021, 7, 459

NSI Effects

- In principle, NSI could effect the measurement of certain parameters
  - e.g. Solar + KamLAND prefer NSI at 1.9 sigma

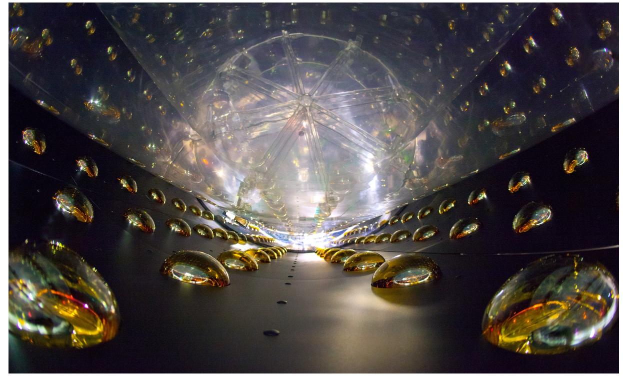


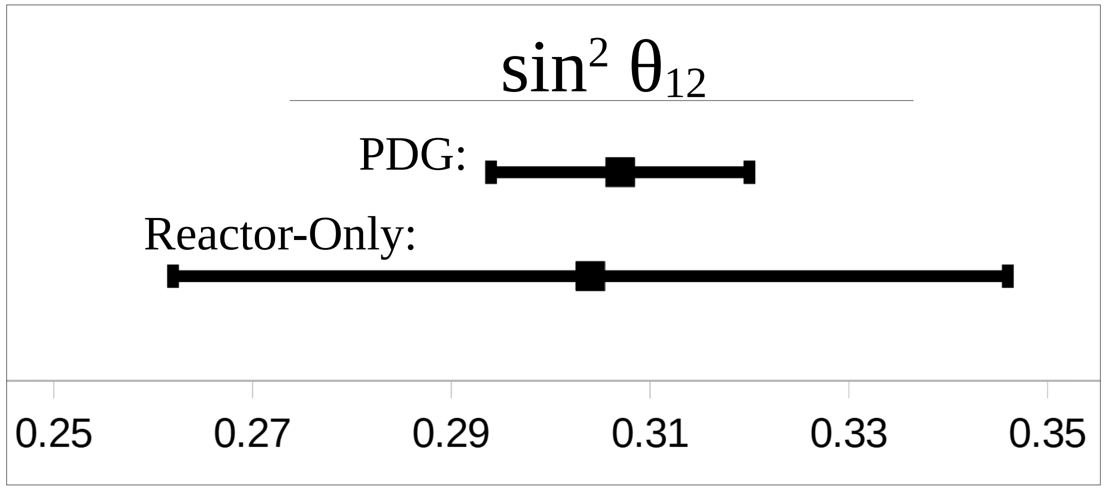


Phys.Rev.D83:101701,2011

Reactor-only Constraints

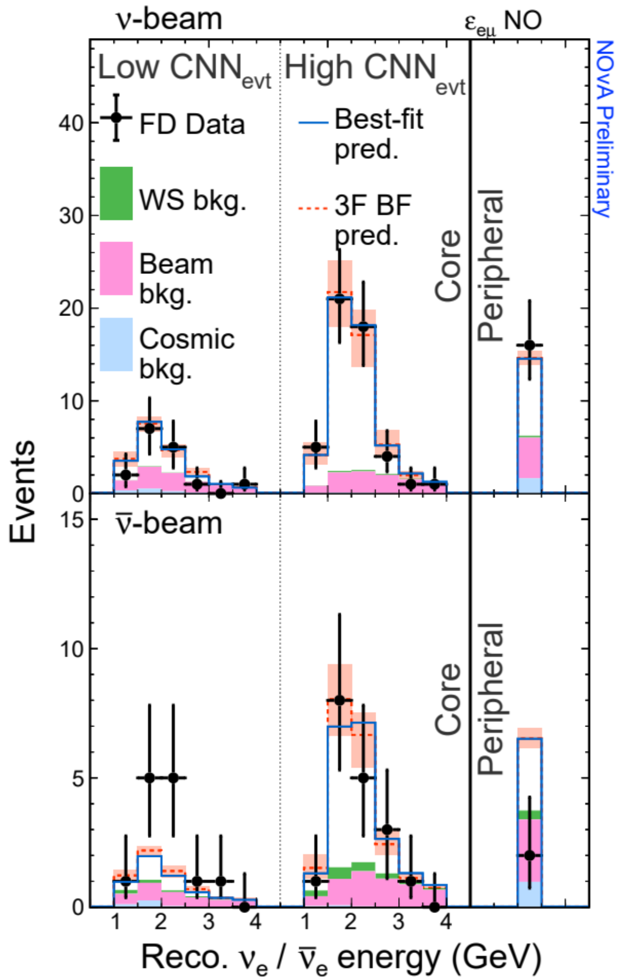
- Rely only on reactor experiments
  - Daya Bay, RENO, Chooz and KamLAND
- Δm^2_{21} (10^{-5}eV^2) = 7.54 ±0.19
  - PDG: 7.53 ± 0.18
- $\sin^2\theta_{12}$ = 0.304 ± 0.042
  - PDG: 0.307 ± 0.013
- $\sin^2\theta_{13}$ = 0.0218 ± 0.0007





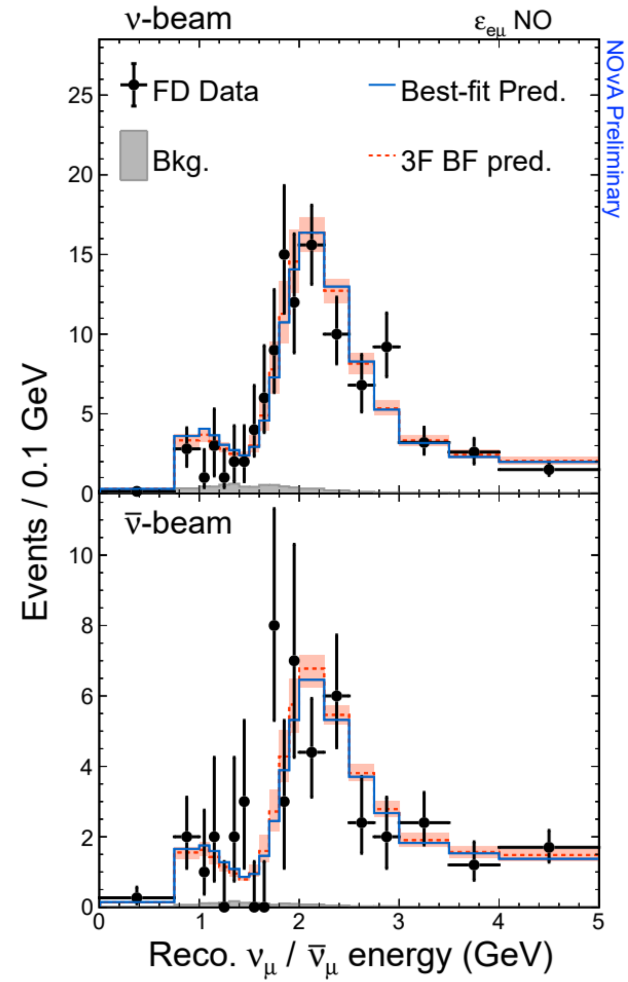
Results

eμ Spectra

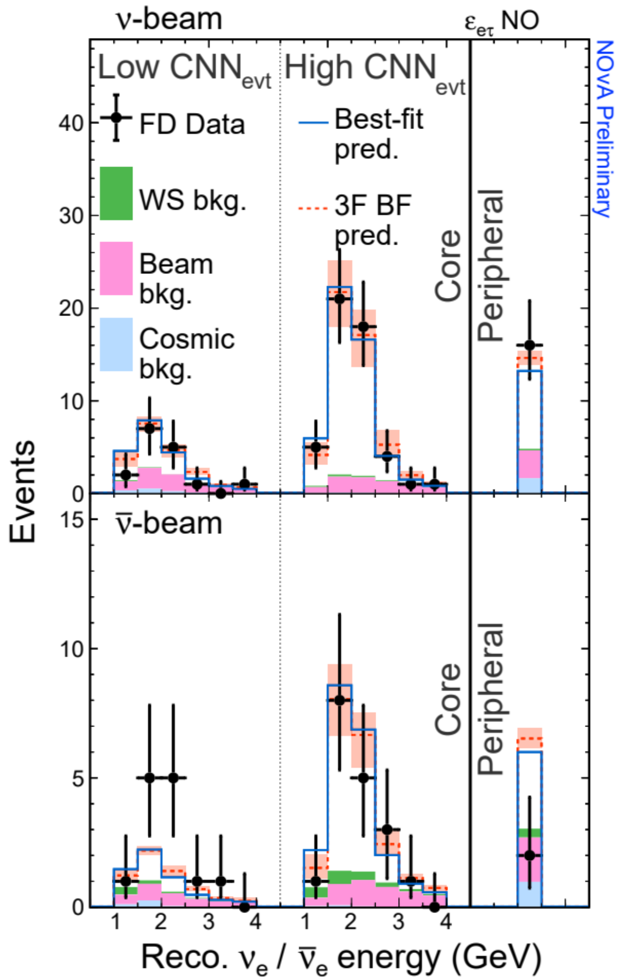


NSI *not* needed to explain NOvA spectra.

χ2 improvement only ~0.65 for 2 additional parameters.

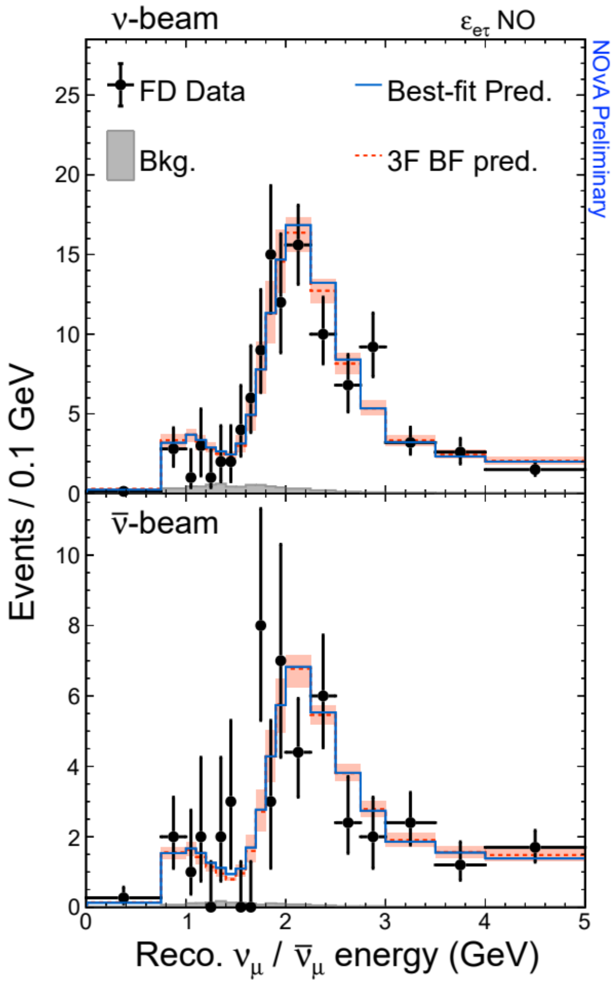


eτ Spectra

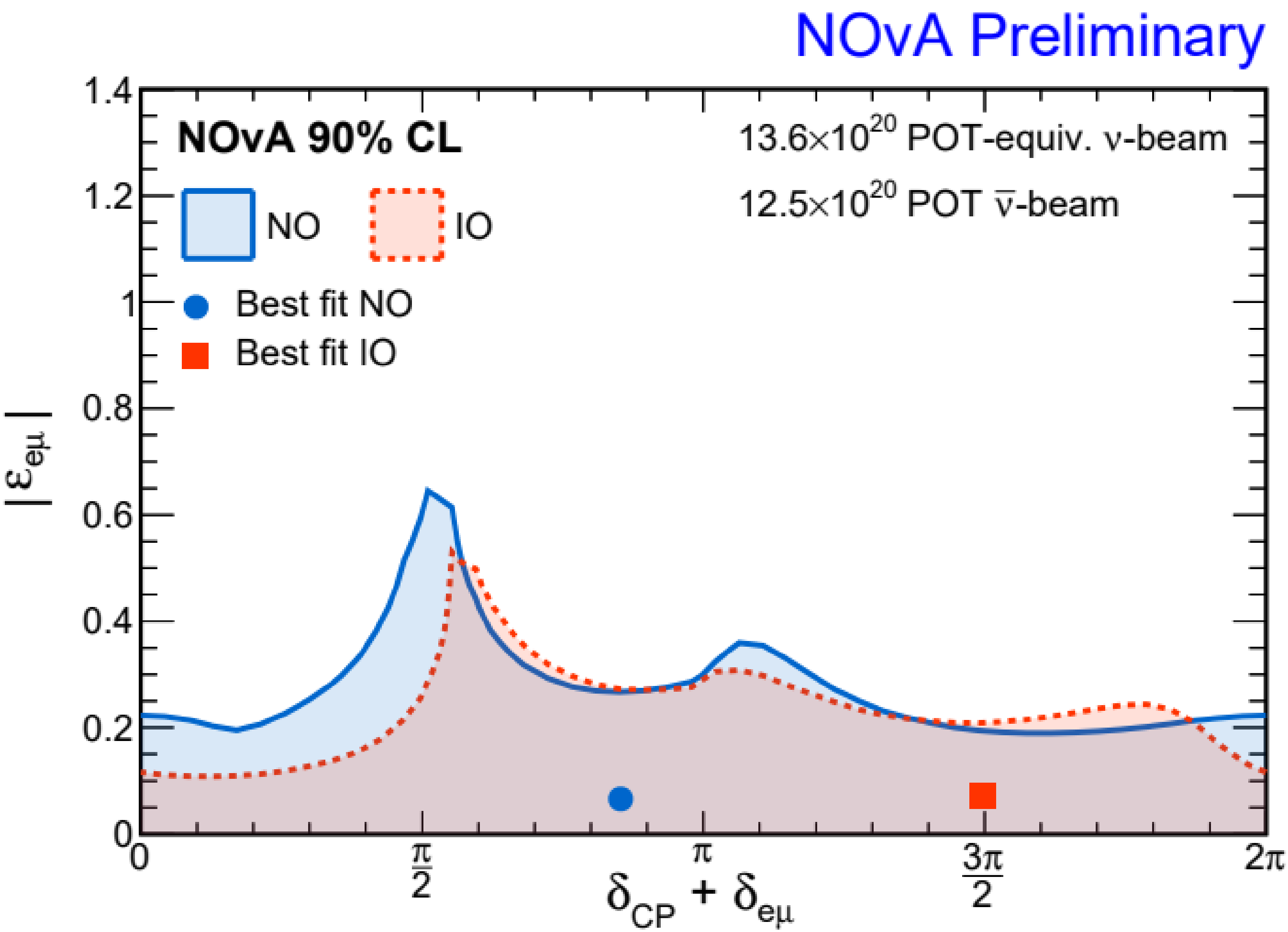


NSI *not* needed to explain NOvA spectra.

χ2 improvement only ~0.65 for 2 additional parameters.

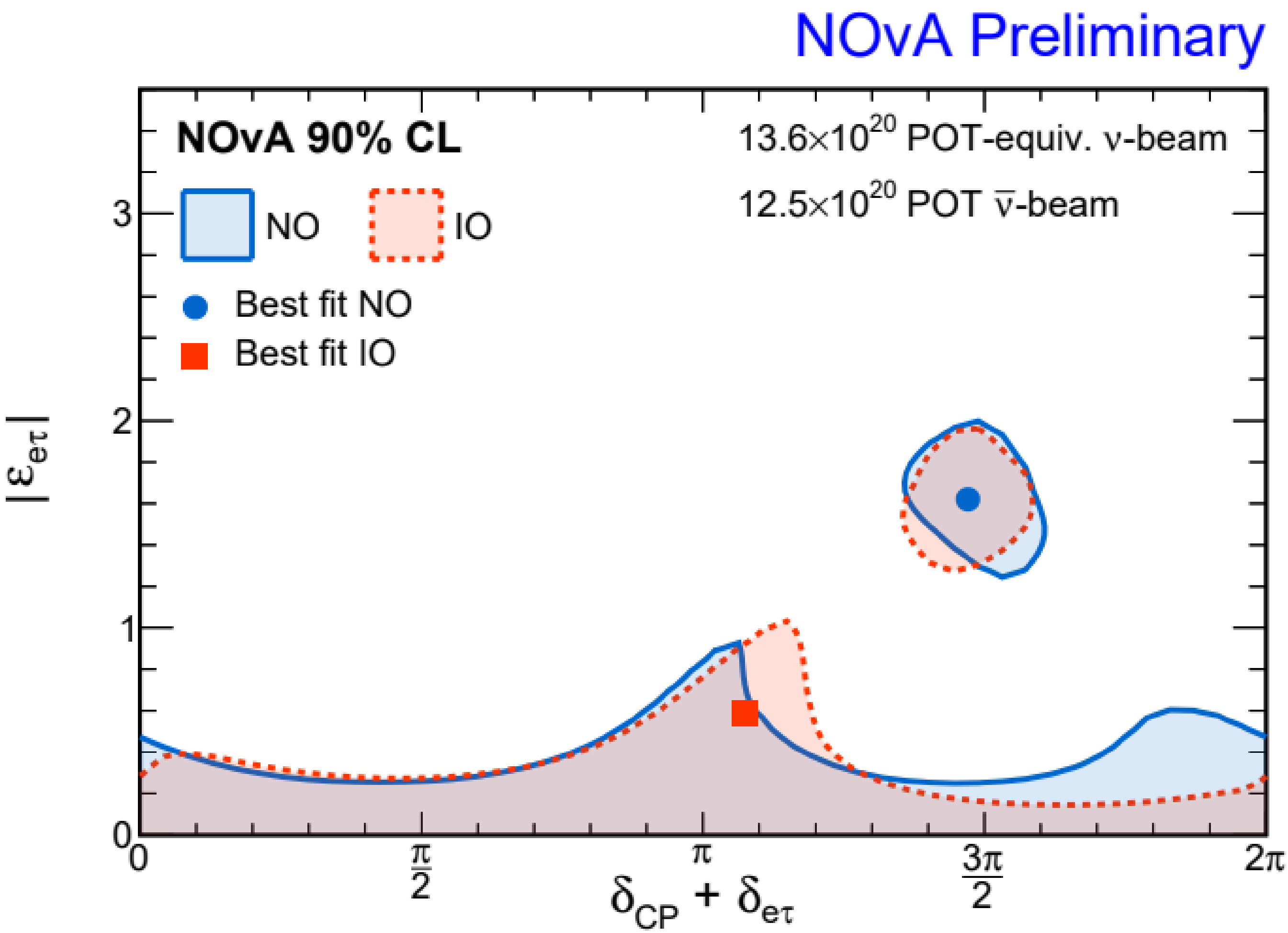


eμ Result



$\varepsilon_{e\mu} < \sim 0.3$

eτ Result

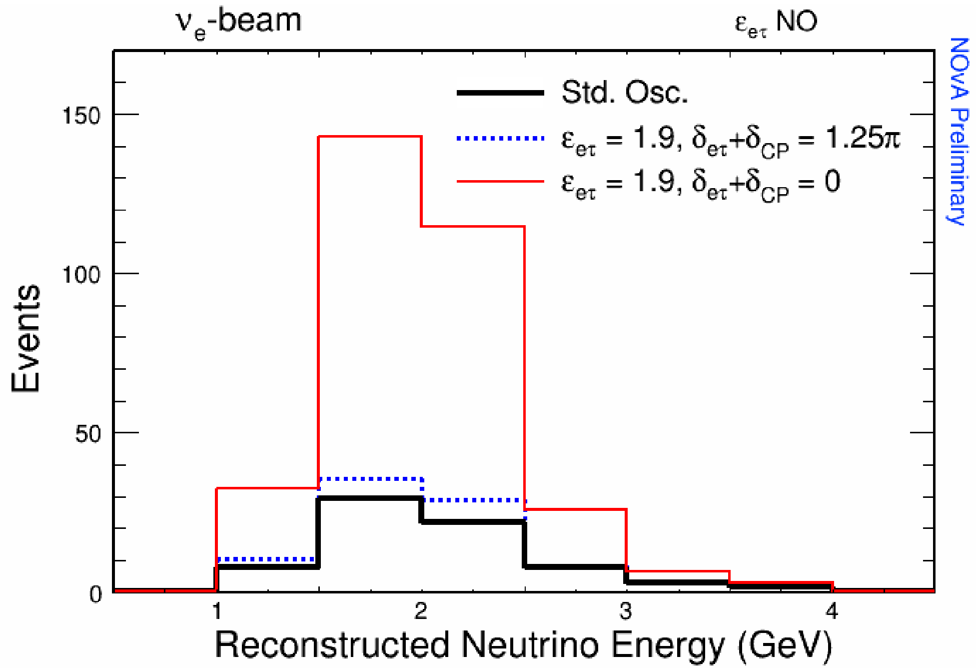


$\varepsilon_{\mu\tau} < \sim 0.4$ for most of phase space.

Upper region due to degeneracy.

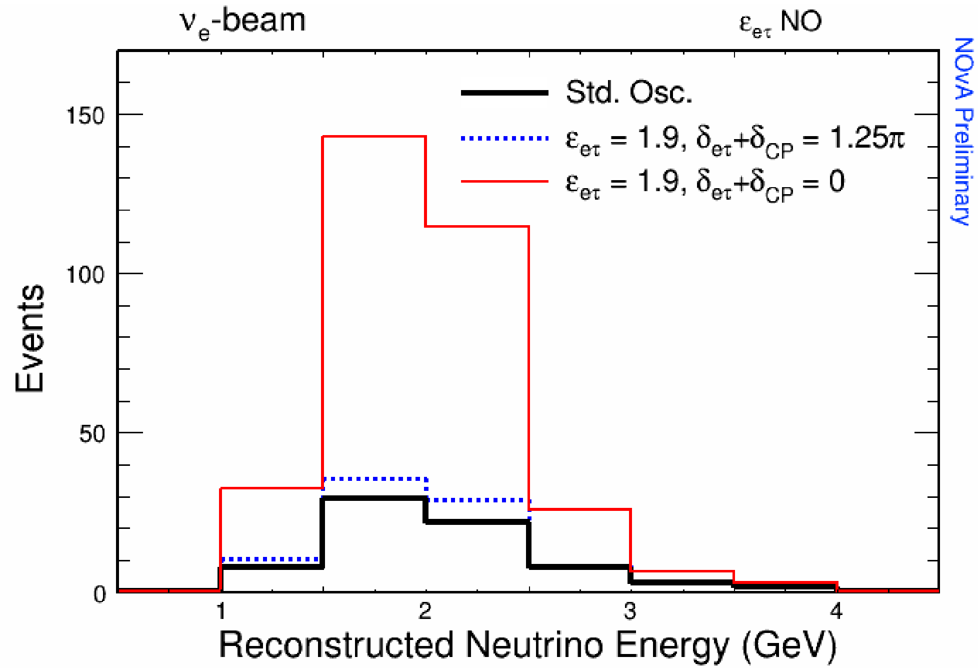
Degeneracy

Neutrino Mode

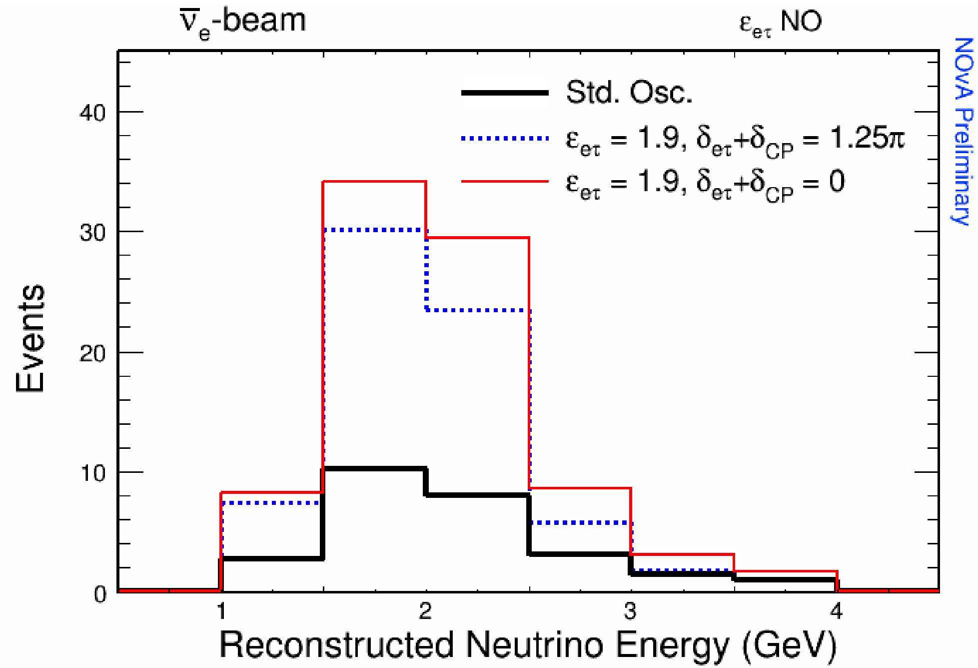


Degeneracy

Neutrino Mode

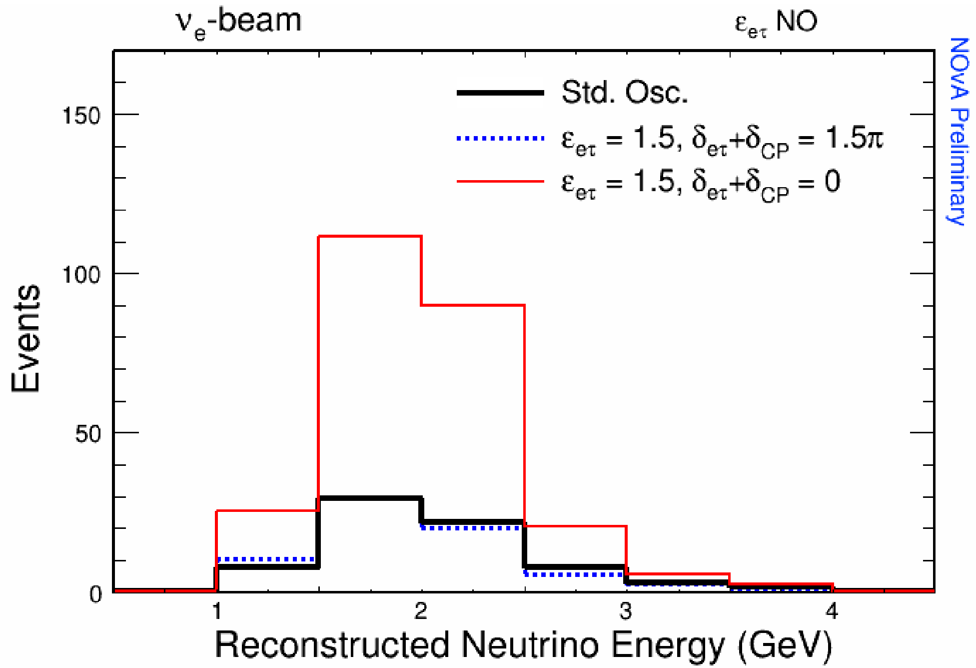


Anti-neutrino Mode

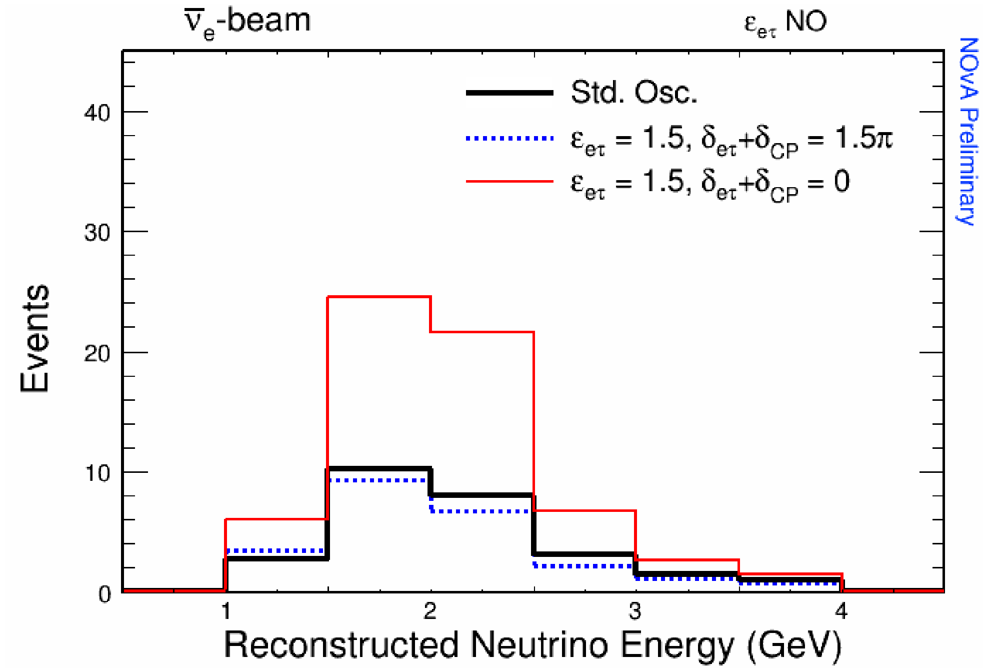


Dual Degeneracy

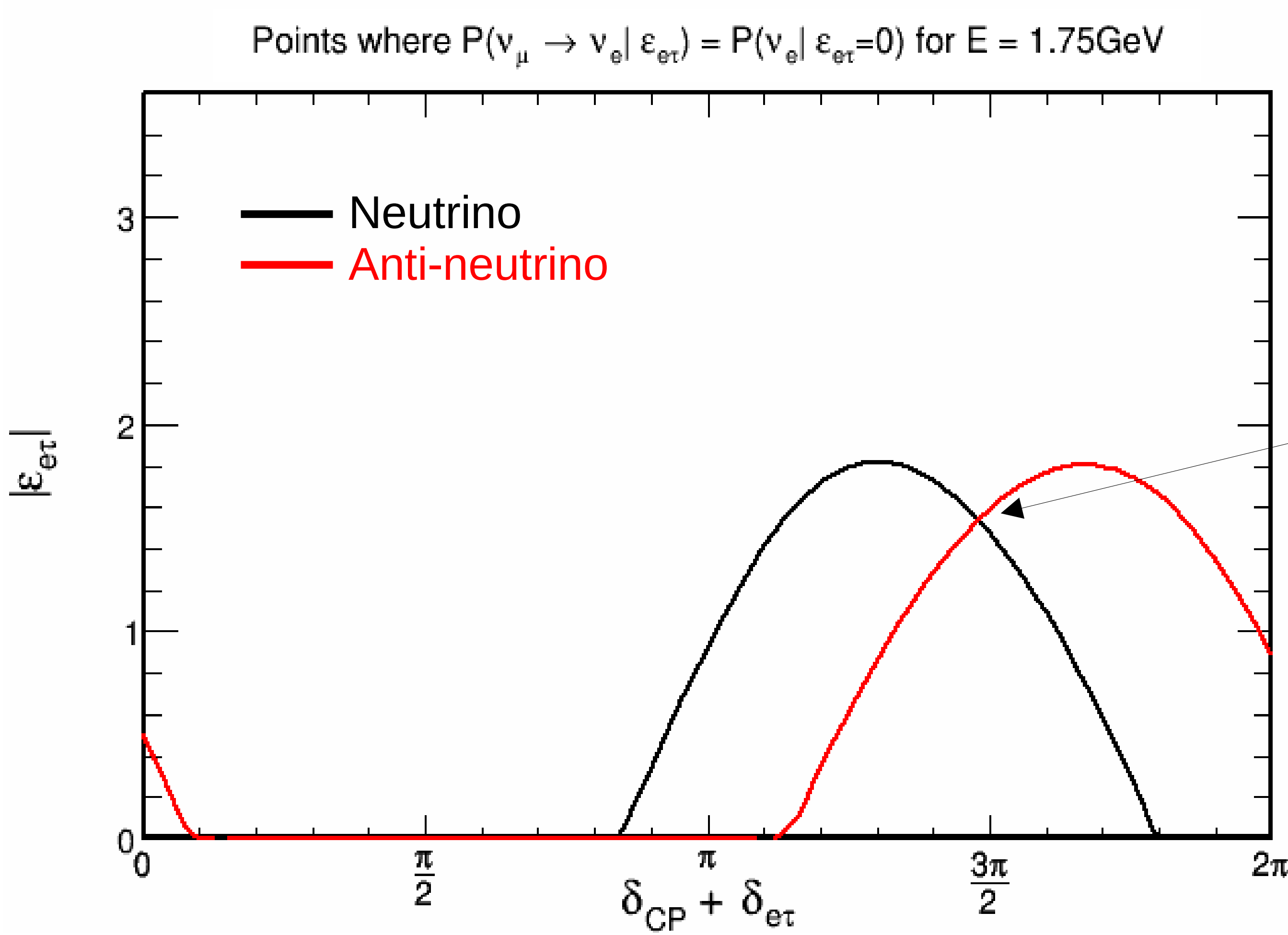
Neutrino Mode



Anti-neutrino Mode

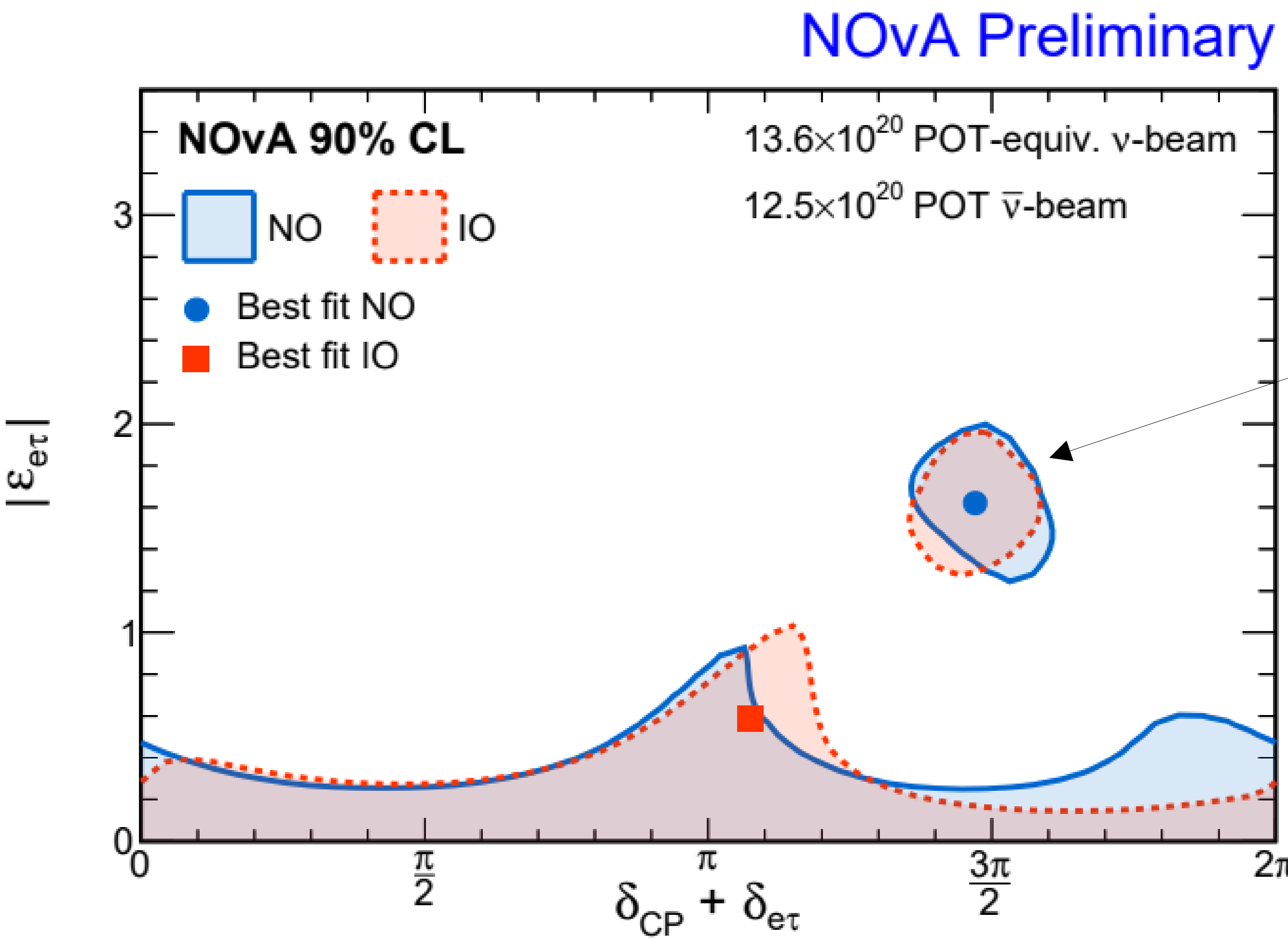


Degeneracy vs Delta



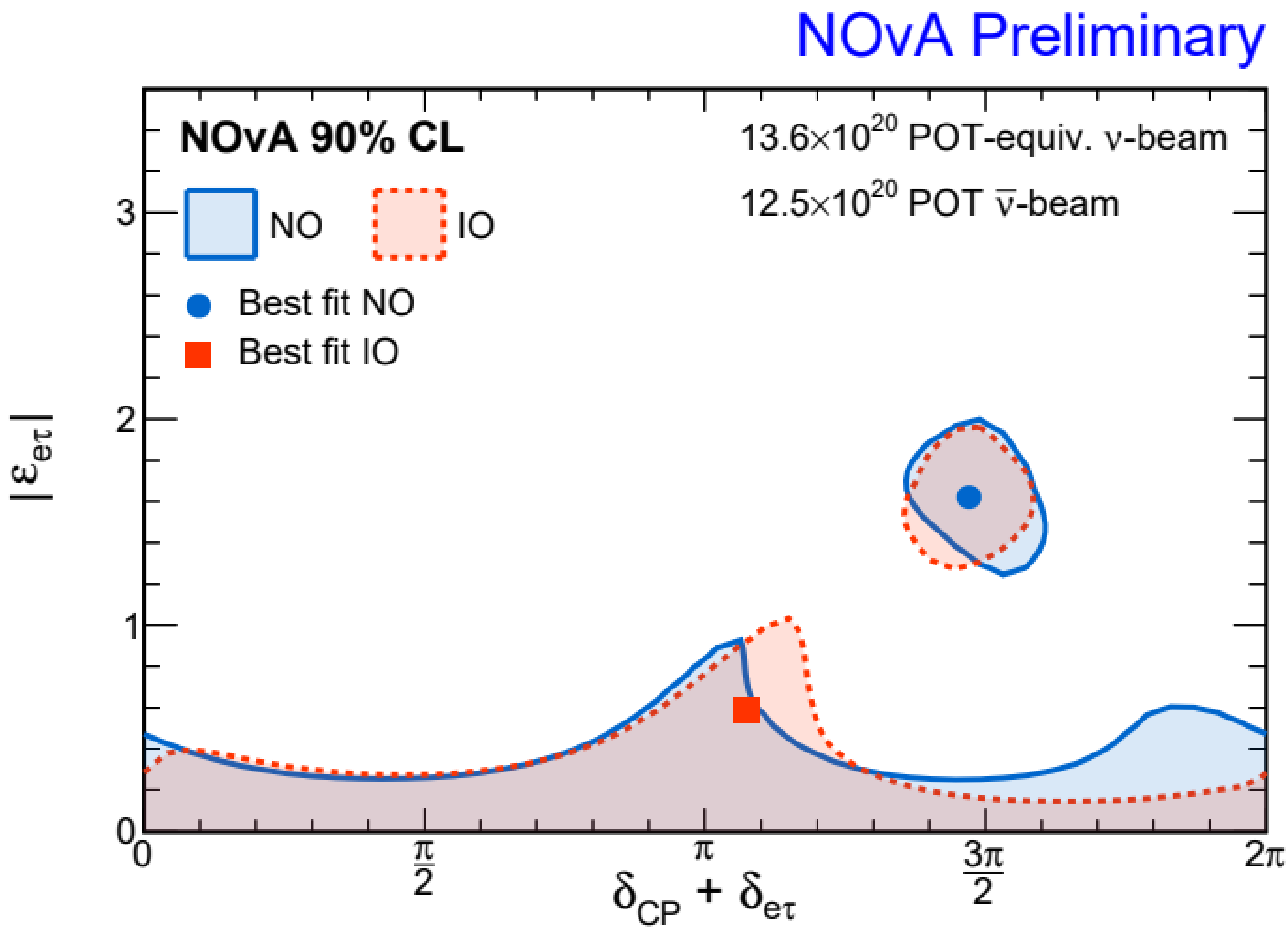
Would expect a loss in sensitivity here

eτ Result

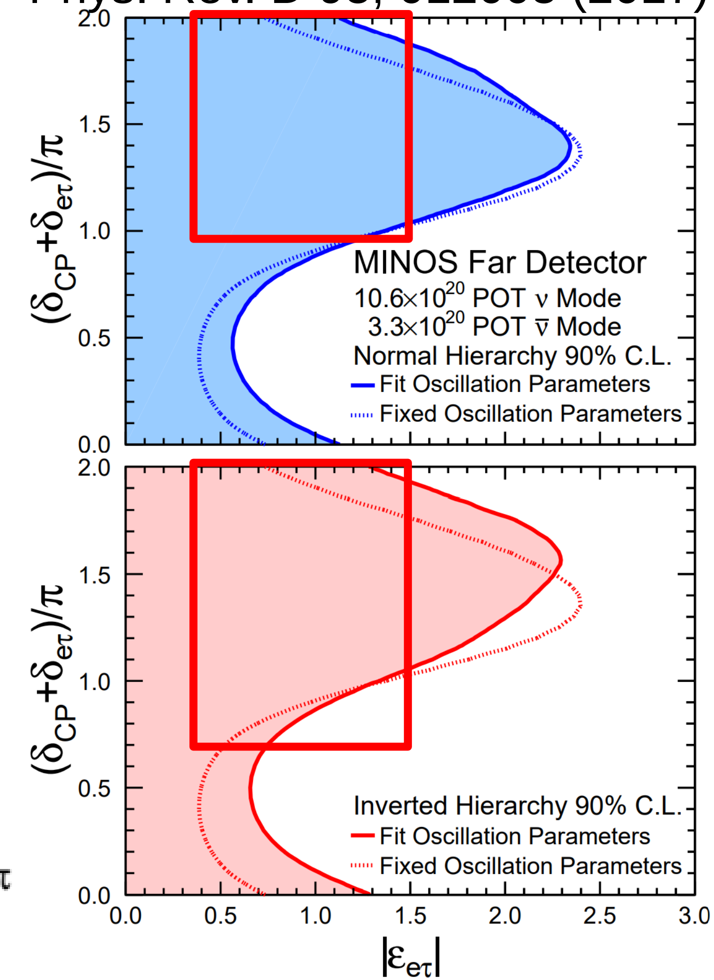


Additional contour at high $\varepsilon_{e\tau}$ due to this dual degeneracy

eτ Result: Comparison to Minos

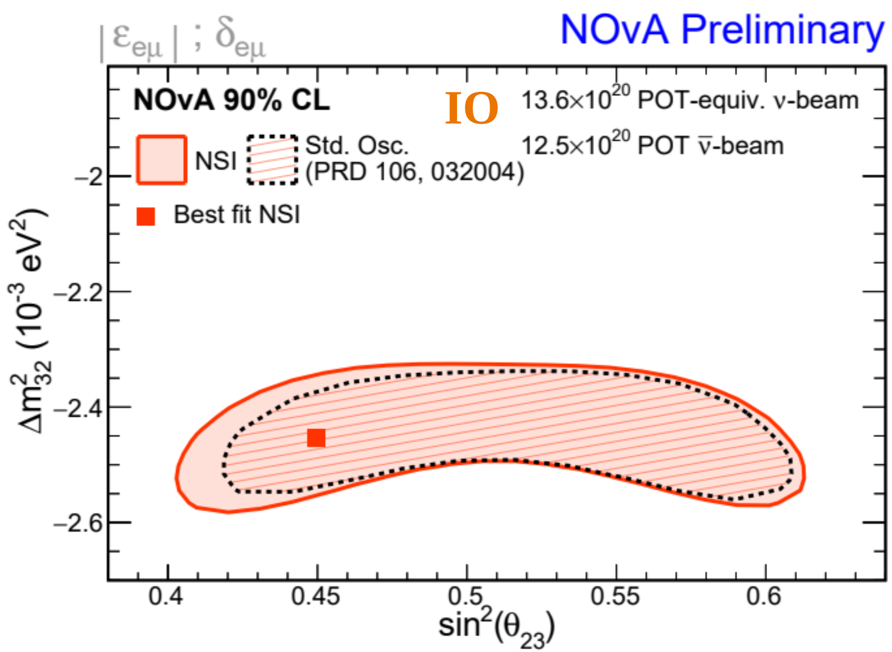


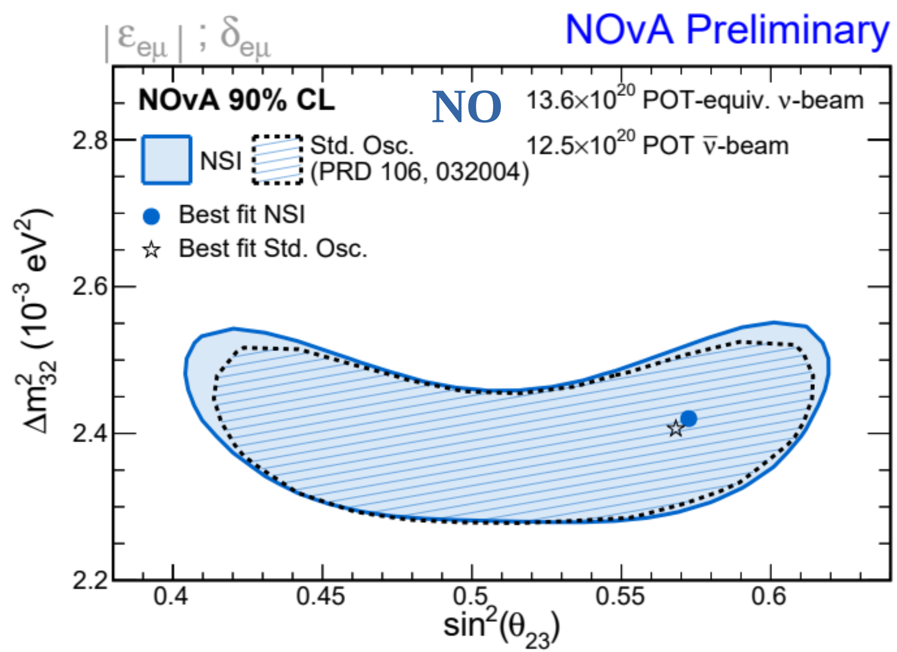
Phys. Rev. D 95, 012005 (2017)



Effect of NSI on Standard Oscillation Parameters

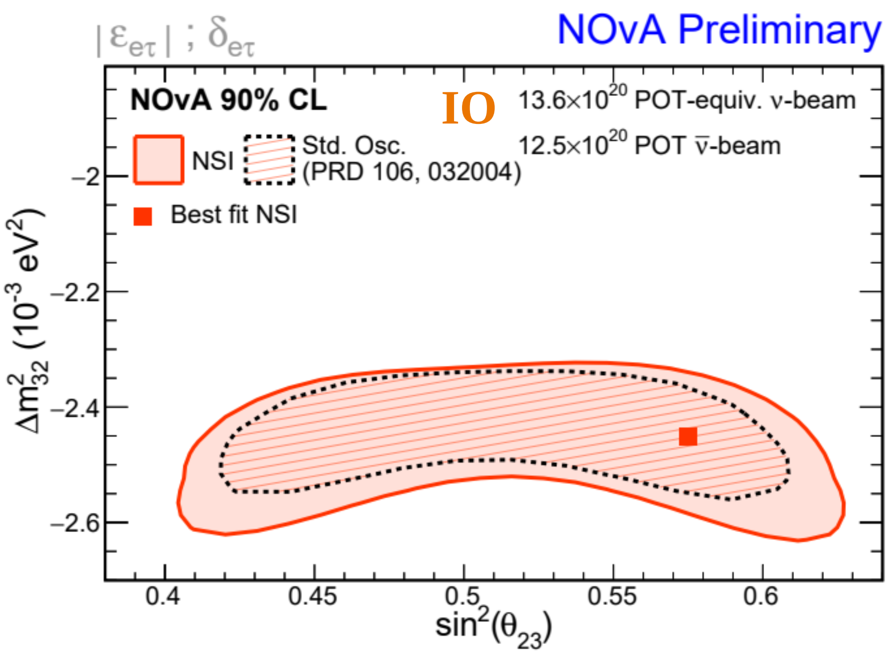
Δm^2_{32} vs $\sin^2\theta_{23}$ with eμ model

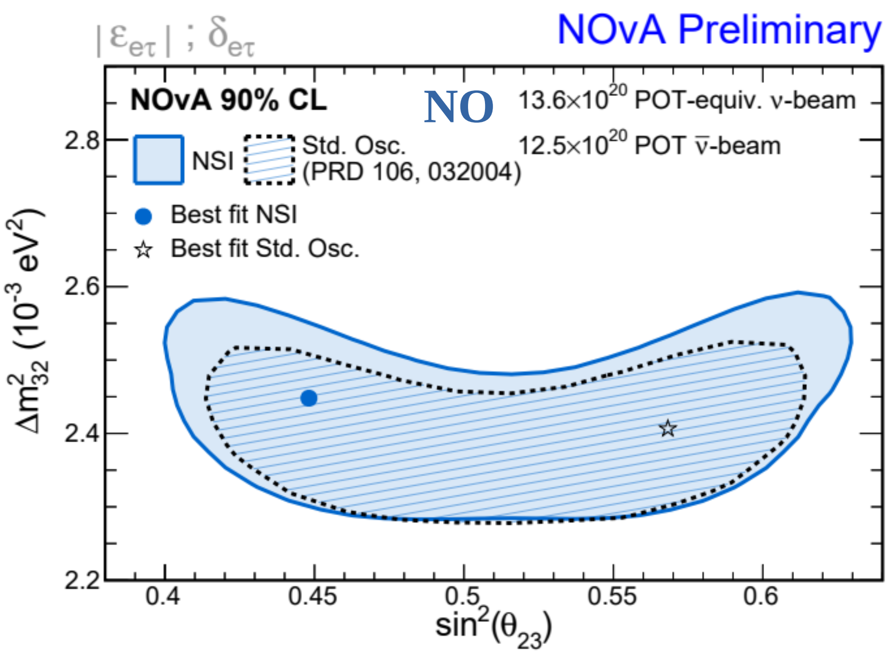




ν_μ disappearance unaffected by NSI

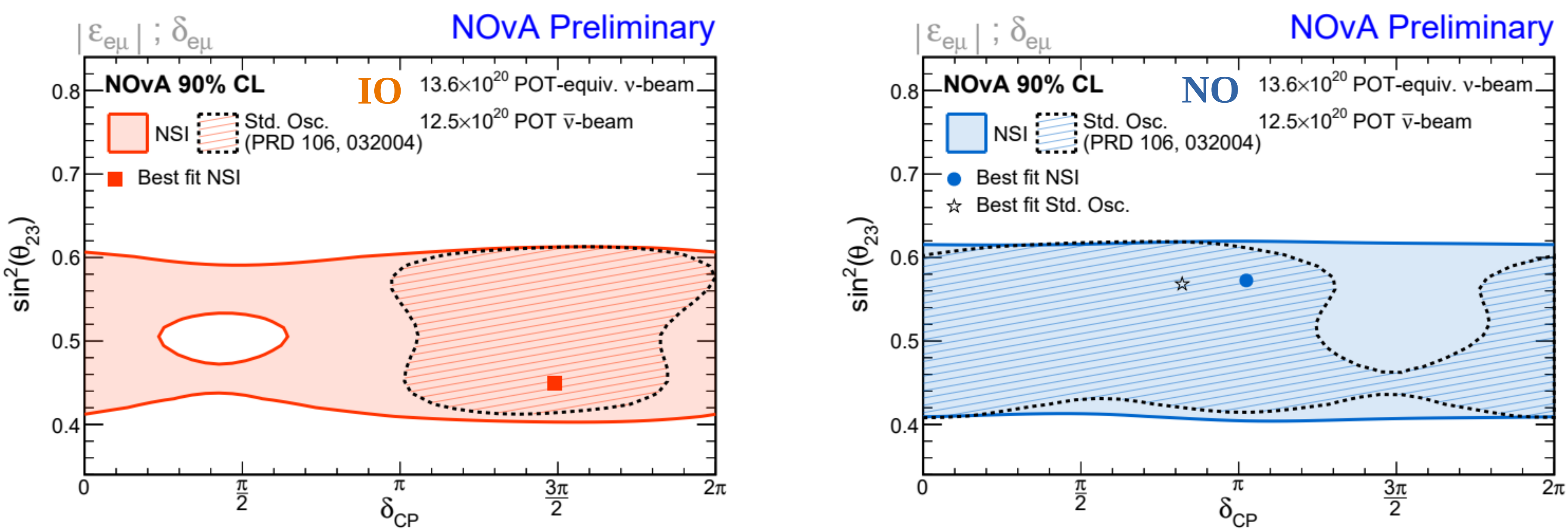
Δm^2_{32} vs $\sin^2\theta_{23}$ with $e\tau$ model





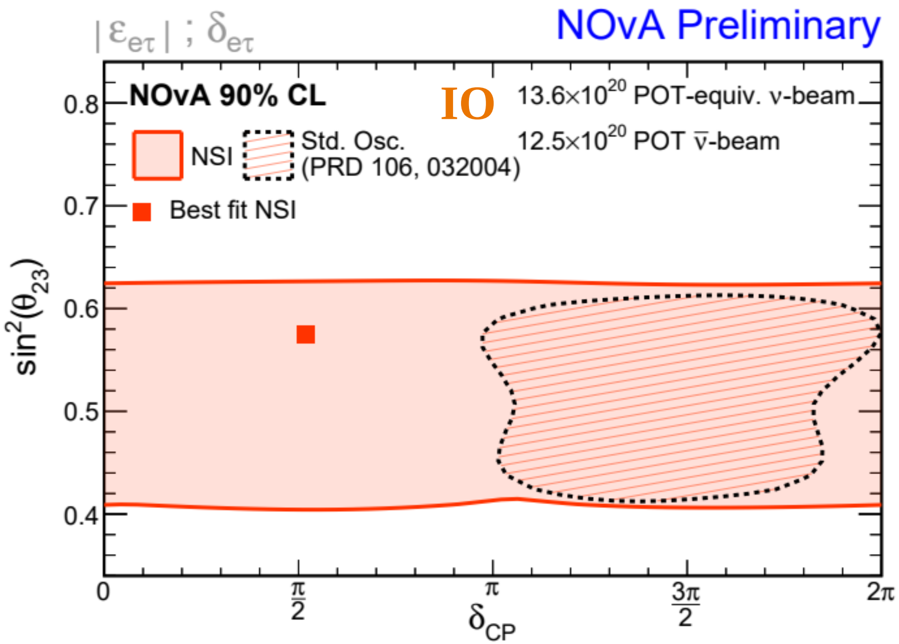
ν_μ disappearance unaffected by NSI

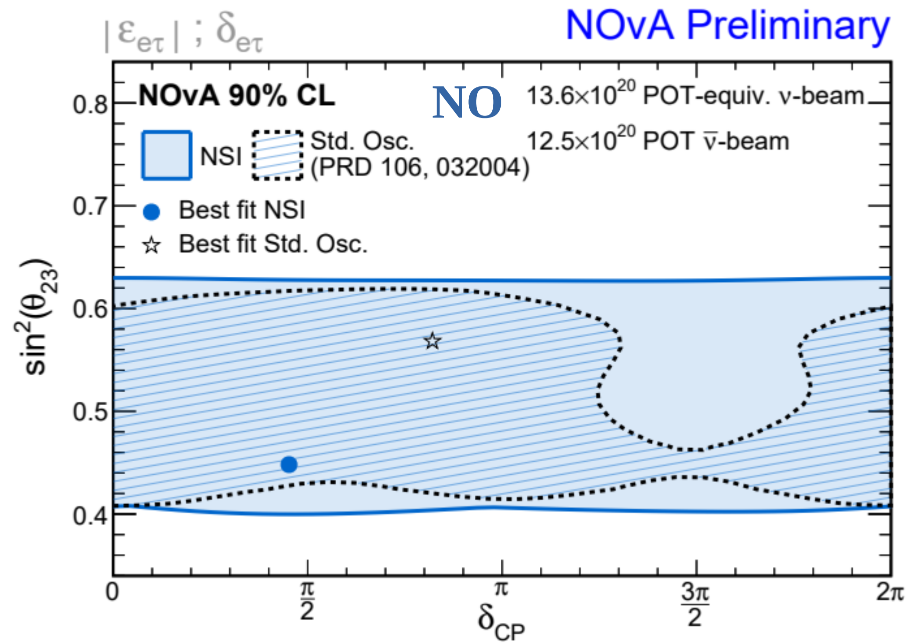
$\sin^2\theta_{23}$ vs δ_{CP} with eμ model



ν_e appearance affected by non-zero NSI

$\sin^2\theta_{23}$ vs δ_{CP} with eτ model





ν_e appearance affected by non-zero NSI

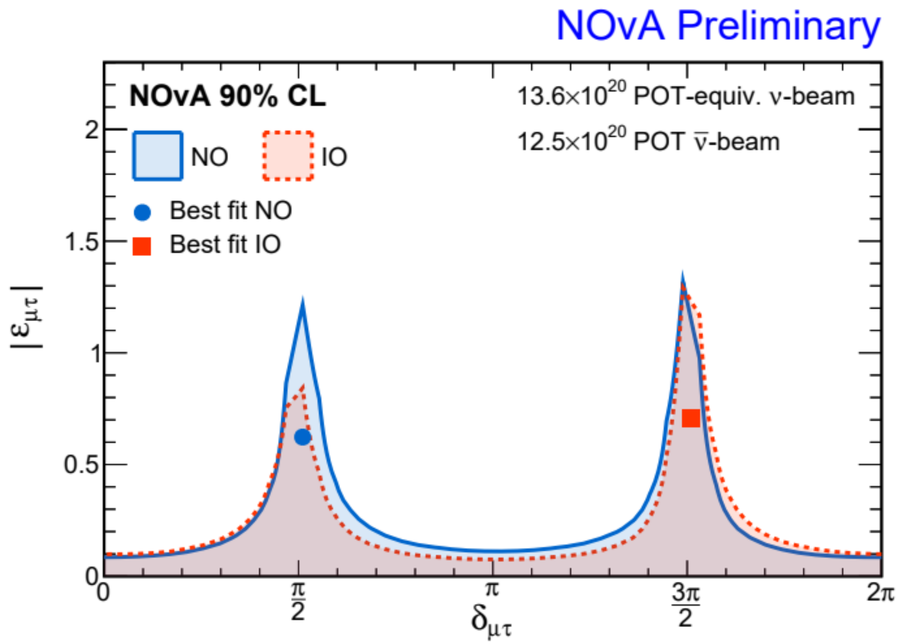
Conclusion

- NOvA alone doesn't need NSI to explain spectra
- $\varepsilon_{e\mu} < 0.3$
- $\varepsilon_{e\tau} > 0.4$ ruled out for most of phase space
  - High $\varepsilon_{e\tau}$ degeneracy
- δ_{CP} measurements difficult with non-zero NSI

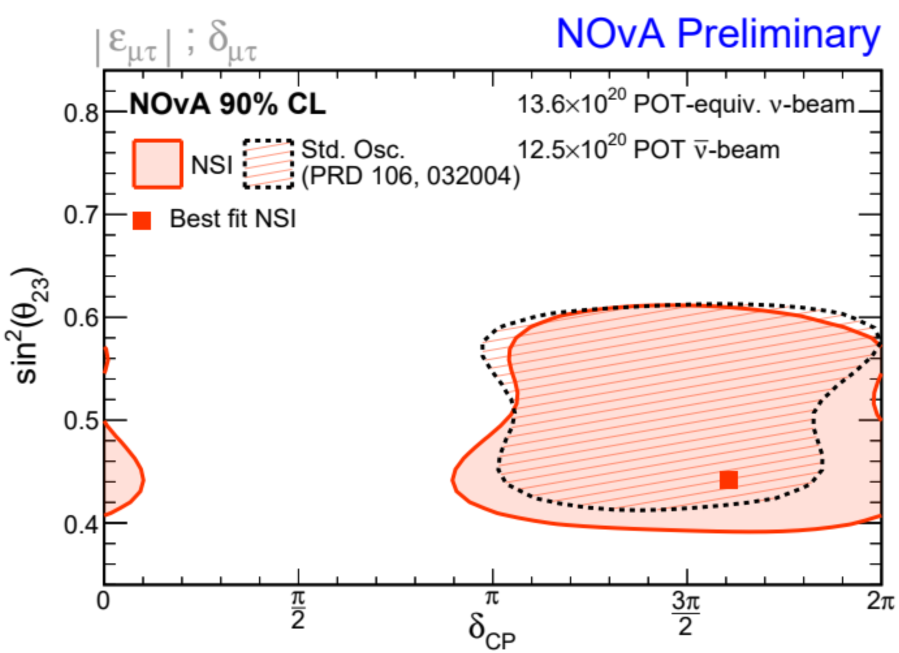
Thank you

Backup Slides

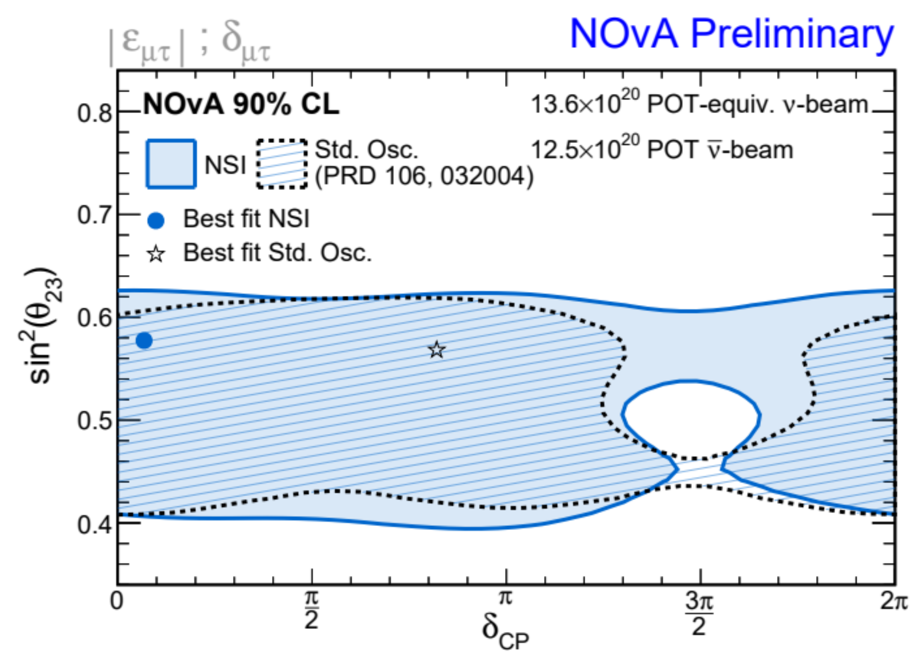
MuTau



NOvA Preliminary
NOvA 90% CL
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
NO
IO
Best fit NO
Best fit IO
|ε_μτ|
δ_μτ

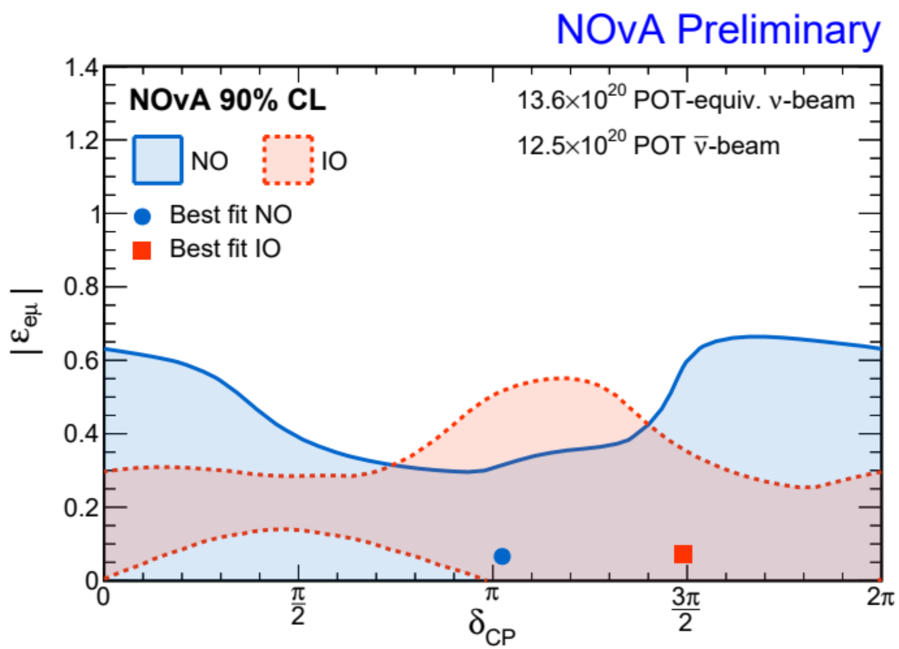


|ε_μτ| ; δ_μτ
NOvA Preliminary
NOvA 90% CL
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
NSI
Std. Osc. (PRD 106, 032004)
Best fit NSI
sin²(θ23)
δCP

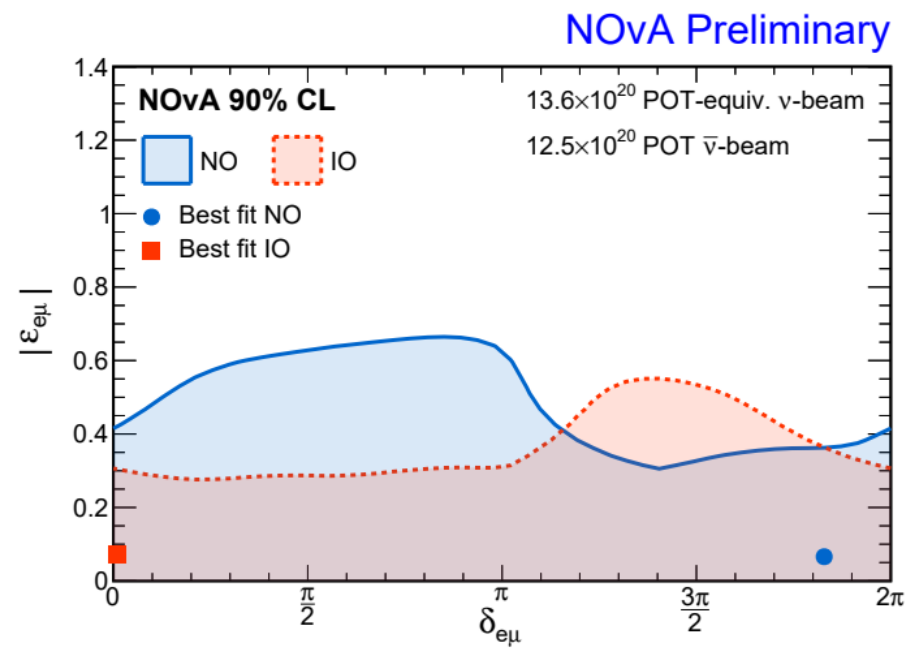


|ε_μτ| ; δ_μτ
NOvA Preliminary
NOvA 90% CL
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
NSI
Std. Osc. (PRD 106, 032004)
Best fit NSI
Best fit Std. Osc.
sin²(θ23)
δCP

EMu

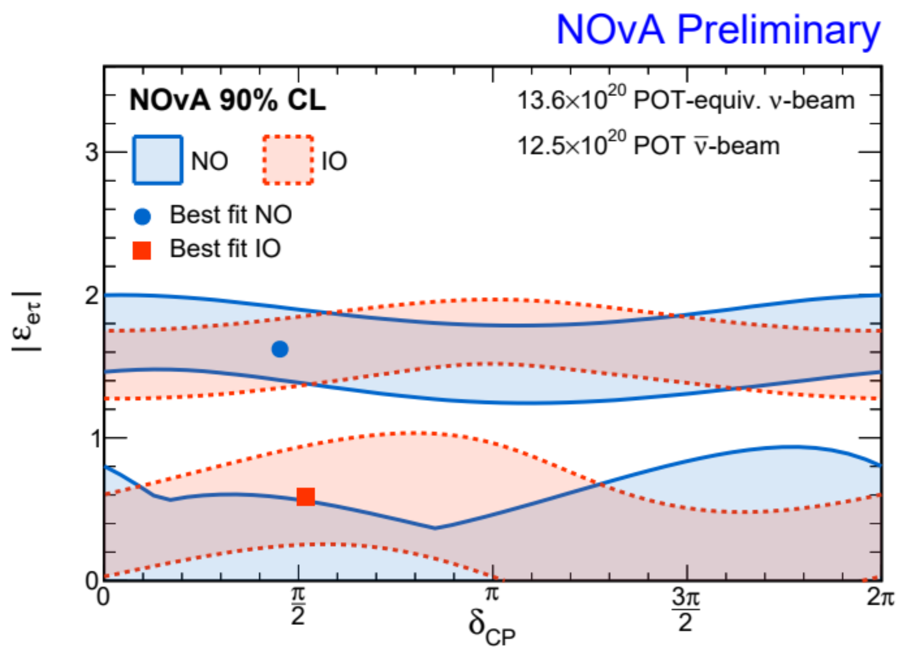


NOvA Preliminary
NOvA 90% CL
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
NO
IO
Best fit NO
Best fit IO
|ε_eμ|
δ_CP

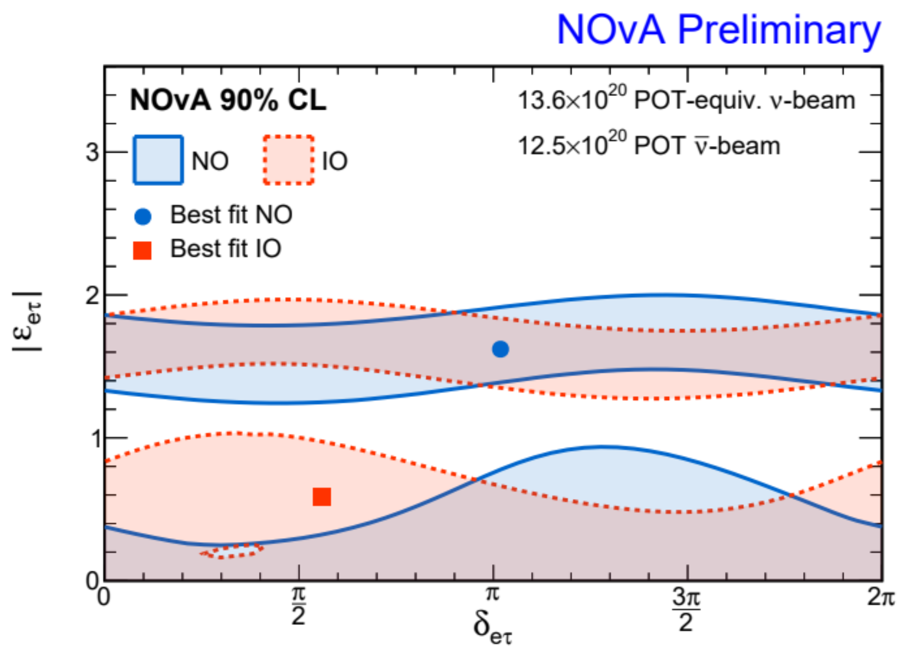


NOvA Preliminary
NOvA 90% CL
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
NO
IO
Best fit NO
Best fit IO
|ε_eμ|
δ_eμ

ETau

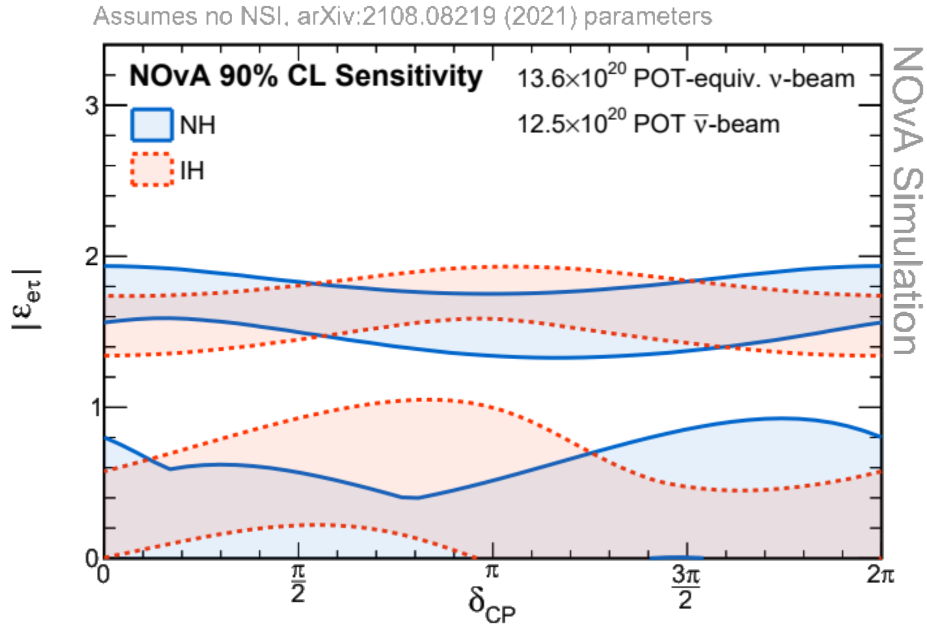


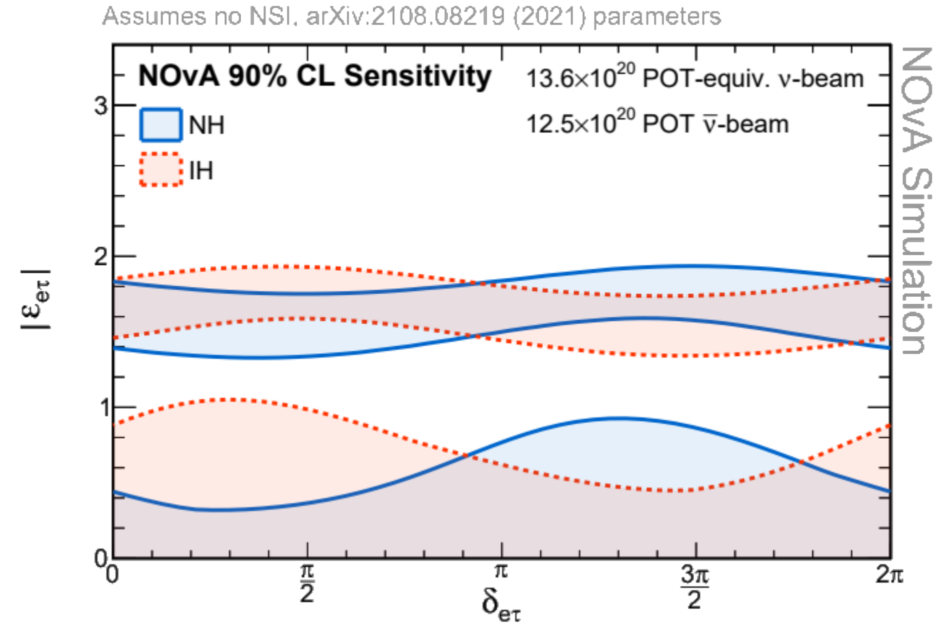
NOvA Preliminary
NOvA 90% CL
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
NO
IO
Best fit NO
Best fit IO
|ε_eτ|
δ_CP



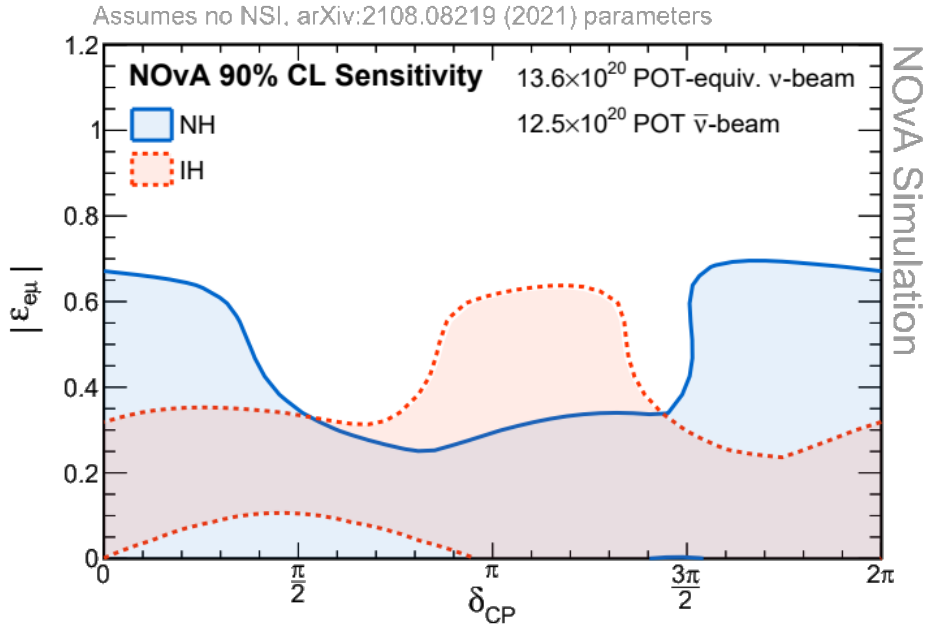
NOvA Preliminary
NOvA 90% CL
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
NO
IO
Best fit NO
Best fit IO
|ε_eτ|
δ_eτ

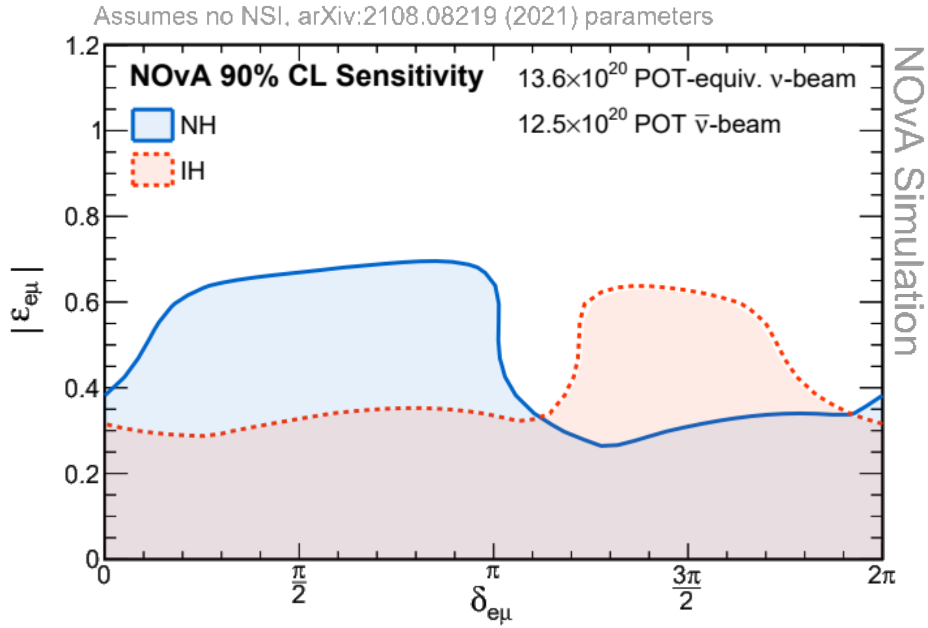
Sensitivity





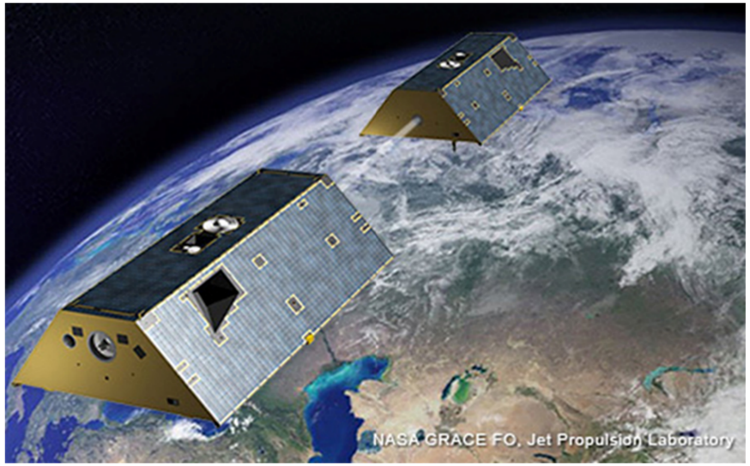
Sensitivity

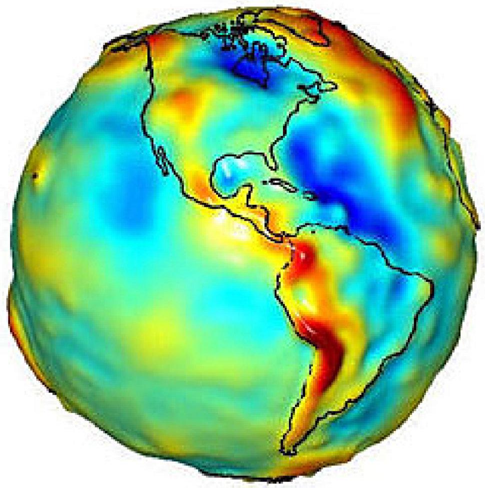




Measuring ρ

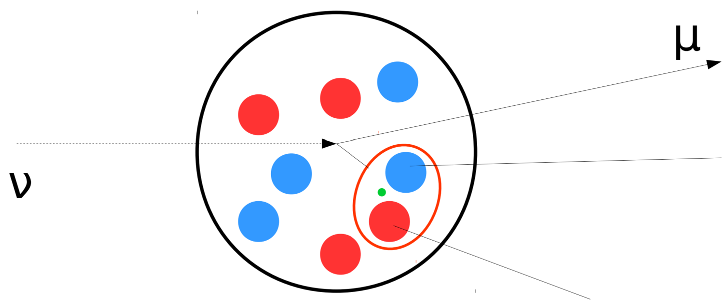
- Seismology
  - Depth = 0km-R_{earth}
- Gravity
  - Depth = 0km-moho (35km)
  - Uses assumptions based on seismology data
- Direct bores
  - 1-3 km fracking bore holes
  - 12km superdeep record

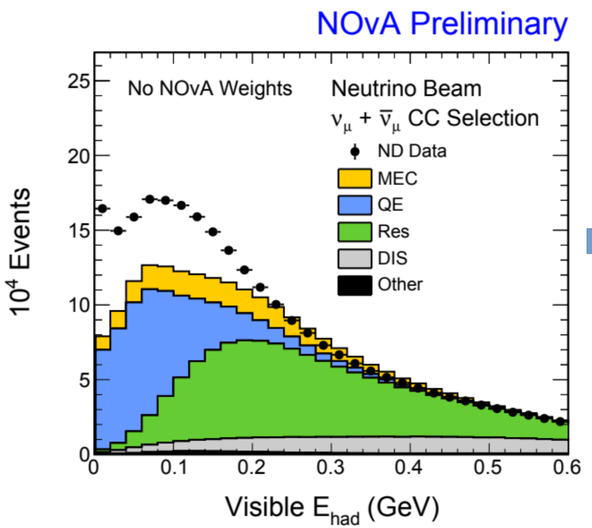


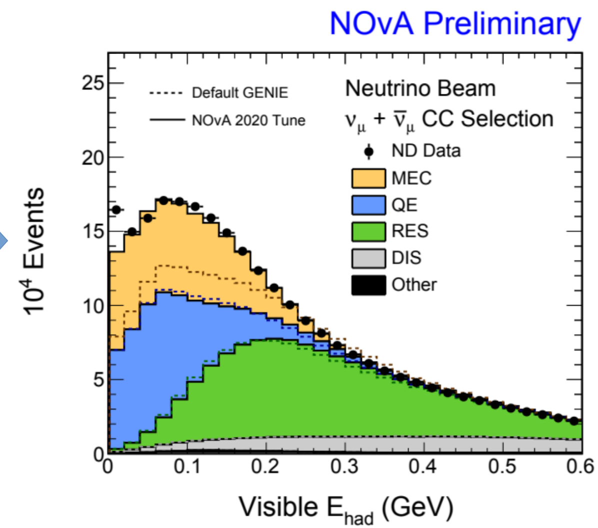


MEC Model

- Valencia MEC tuned to data
- NN/PP vs NP vs MINERvA systematics

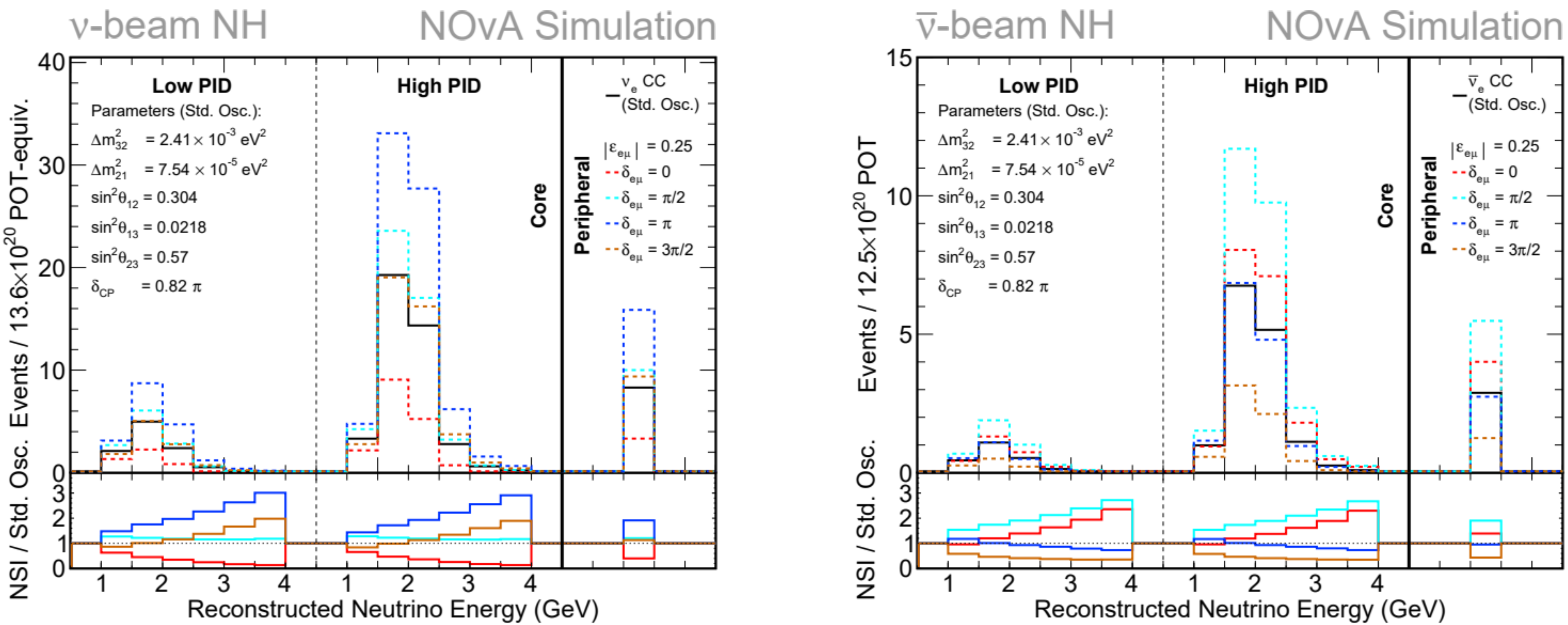






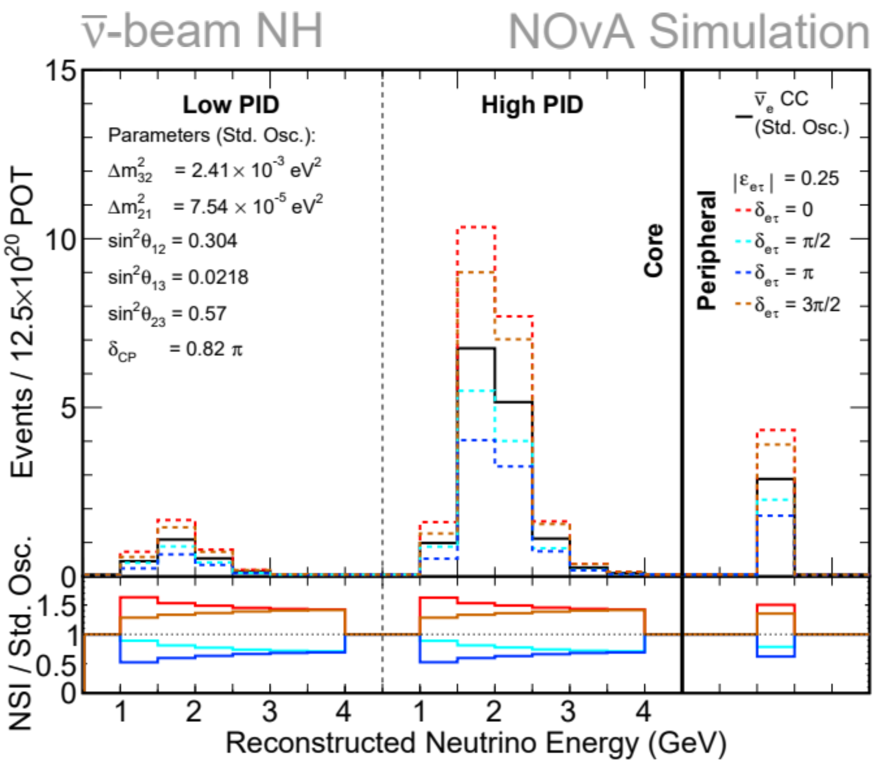
Effect of NSI on Reconstructed Spectra

eμ

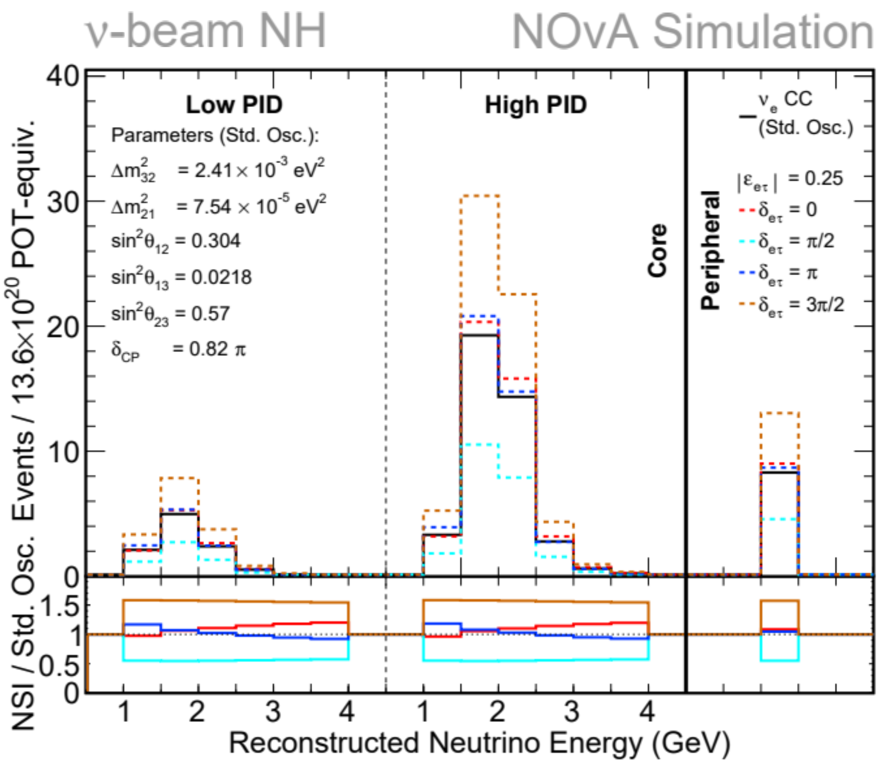


ν-beam NH
NOvA Simulation
Low PID
High PID
Core
Peripheral
Parameters (Std. Osc.):
Δm²32 = 2.41 × 10⁻³ eV²
Δm²21 = 7.54 × 10⁻⁵ eV²
sin²θ12 = 0.304
sin²θ13 = 0.0218
sin²θ23 = 0.57
δCP = 0.82 π
νe CC (Std. Osc.)
|εeμ| = 0.25
δeμ = 0
δeμ = π/2
δeμ = π
δeμ = 3π/2
Events / 13.6×10²⁰ POT-equiv.
NSI / Std. Osc.
Reconstructed Neutrino Energy (GeV)
ν̄-beam NH
NOvA Simulation
Low PID
High PID
Core
Peripheral
Parameters (Std. Osc.):
Δm²32 = 2.41 × 10⁻³ eV²
Δm²21 = 7.54 × 10⁻⁵ eV²
sin²θ12 = 0.304
sin²θ13 = 0.0218
sin²θ23 = 0.57
δCP = 0.82 π
ν̄e CC (Std. Osc.)
|εeμ| = 0.25
δeμ = 0
δeμ = π/2
δeμ = π
δeμ = 3π/2
Events / 12.5×10²⁰ POT
NSI / Std. Osc.
Reconstructed Neutrino Energy (GeV)

eτ



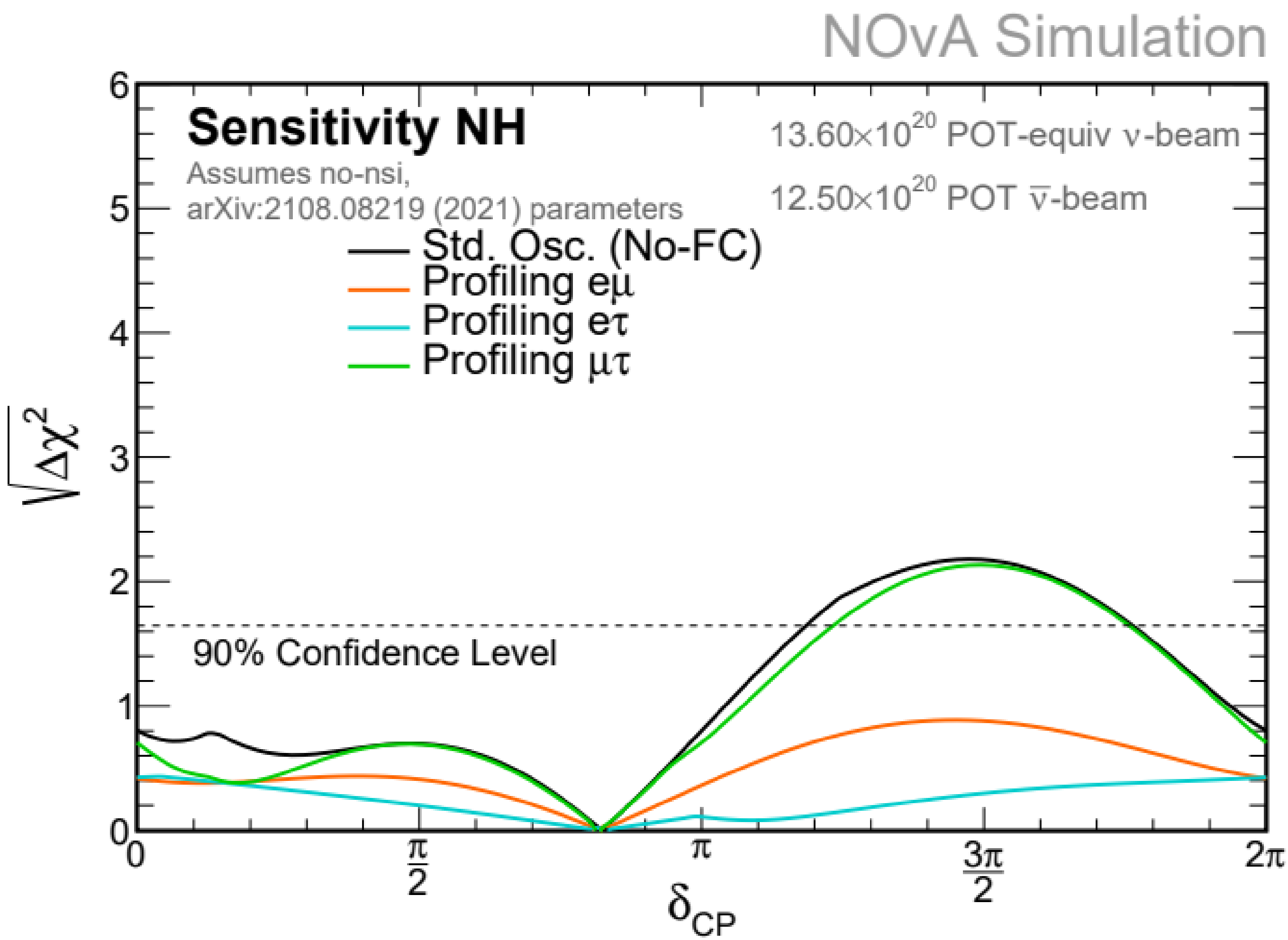
$\bar{\nu}$-beam NH
NOvA Simulation
Low PID
High PID
Parameters (Std. Osc.):
Δm^2_{32} = 2.41 × 10^{-3} eV^2
Δm^2_{21} = 7.54 × 10^{-5} eV^2
$\sin^2\theta_{12}$ = 0.304
$\sin^2\theta_{13}$ = 0.0218
$\sin^2\theta_{23}$ = 0.57
δ_{CP} = 0.82 π
Core
Peripheral
$\bar{\nu}_e$ CC (Std. Osc.)
$|\varepsilon_{e\tau}|$ = 0.25
$\delta_{e\tau}$ = 0
$\delta_{e\tau}$ = π/2
$\delta_{e\tau}$ = π
$\delta_{e\tau}$ = 3π/2
Events / 12.5×10^{20} POT
NSI / Std. Osc.
Reconstructed Neutrino Energy (GeV)



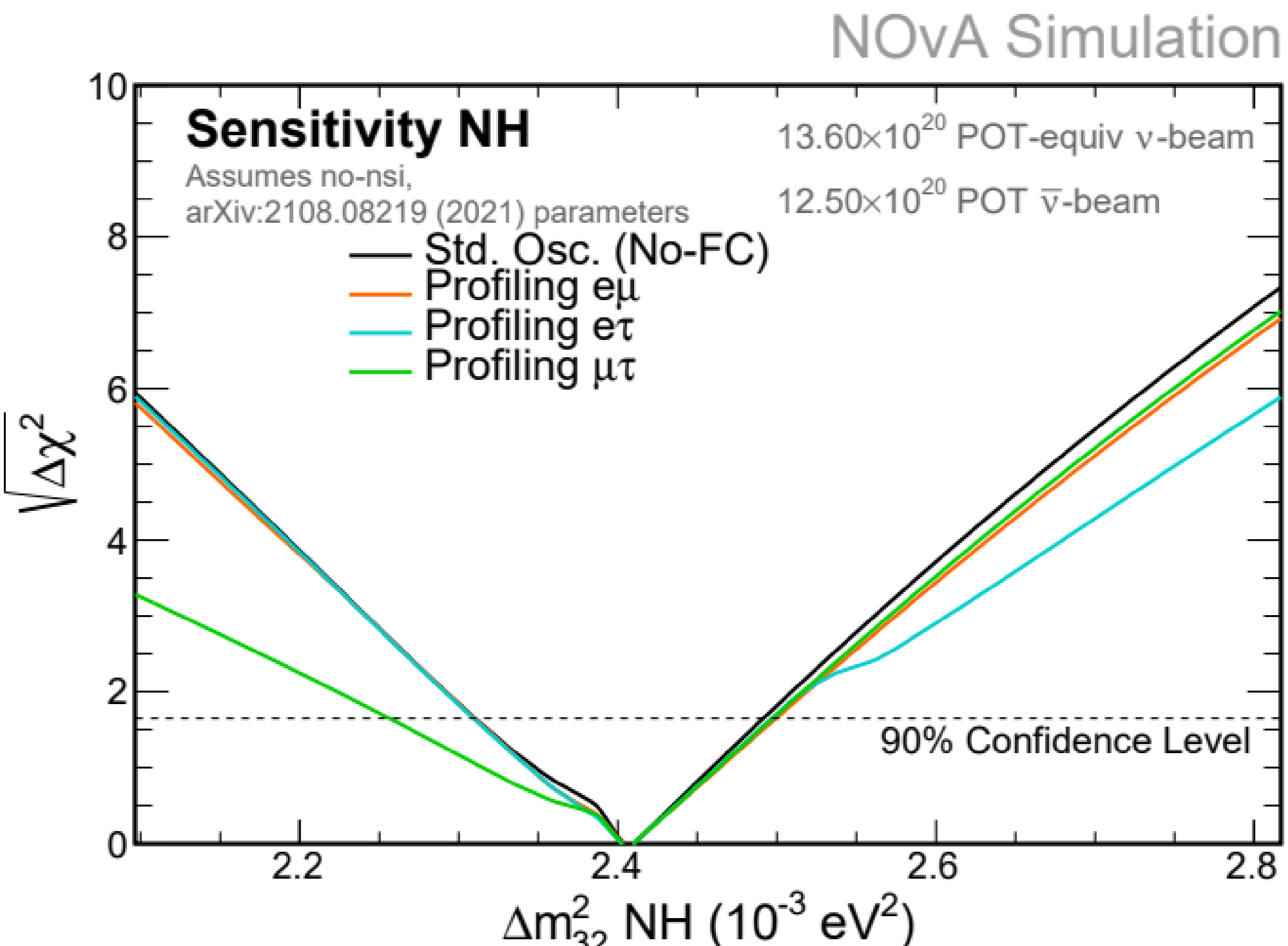
ν-beam NH
NOvA Simulation
Low PID
High PID
Parameters (Std. Osc.):
Δm^2_{32} = 2.41 × 10^{-3} eV^2
Δm^2_{21} = 7.54 × 10^{-5} eV^2
$\sin^2\theta_{12}$ = 0.304
$\sin^2\theta_{13}$ = 0.0218
$\sin^2\theta_{23}$ = 0.57
δ_{CP} = 0.82 π
Core
Peripheral
ν_e CC (Std. Osc.)
$|\varepsilon_{e\tau}|$ = 0.25
$\delta_{e\tau}$ = 0
$\delta_{e\tau}$ = π/2
$\delta_{e\tau}$ = π
$\delta_{e\tau}$ = 3π/2
Events / 13.6×10^{20} POT-equiv.
NSI / Std. Osc.
Reconstructed Neutrino Energy (GeV)

Sensitivities

δ_{CP}

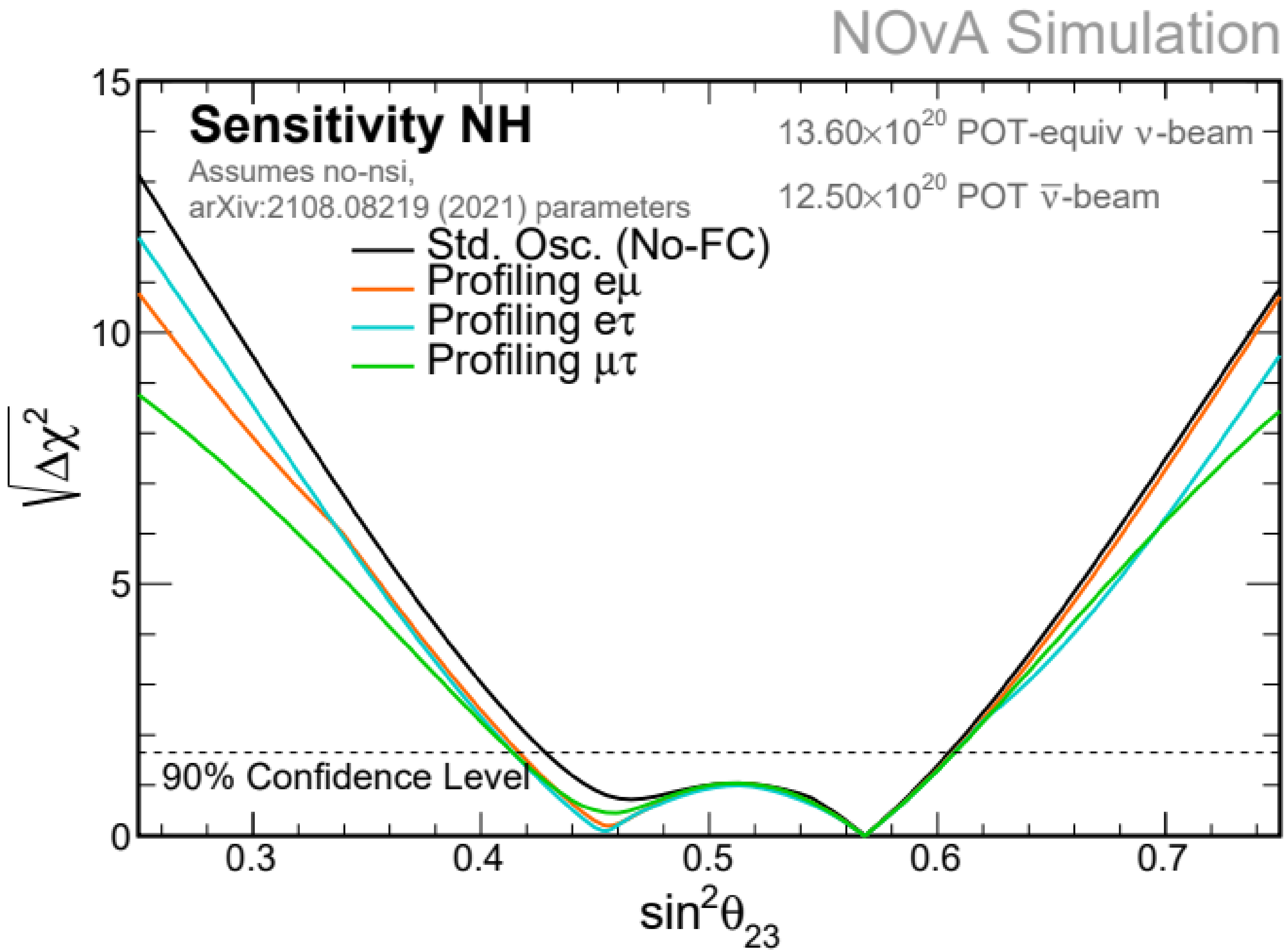

NOvA Simulation
Sensitivity NH
Assumes no-nsi,
arXiv:2108.08219 (2021) parameters
13.60×10^20 POT-equiv ν-beam
12.50×10^20 POT ν̄-beam
Std. Osc. (No-FC)
Profiling eμ
Profiling eτ
Profiling μτ
90% Confidence Level
√Δχ²
δCP
0
π/2
π
3π/2
2π
0
1
2
3
4
5
6

Δm^2_{32}

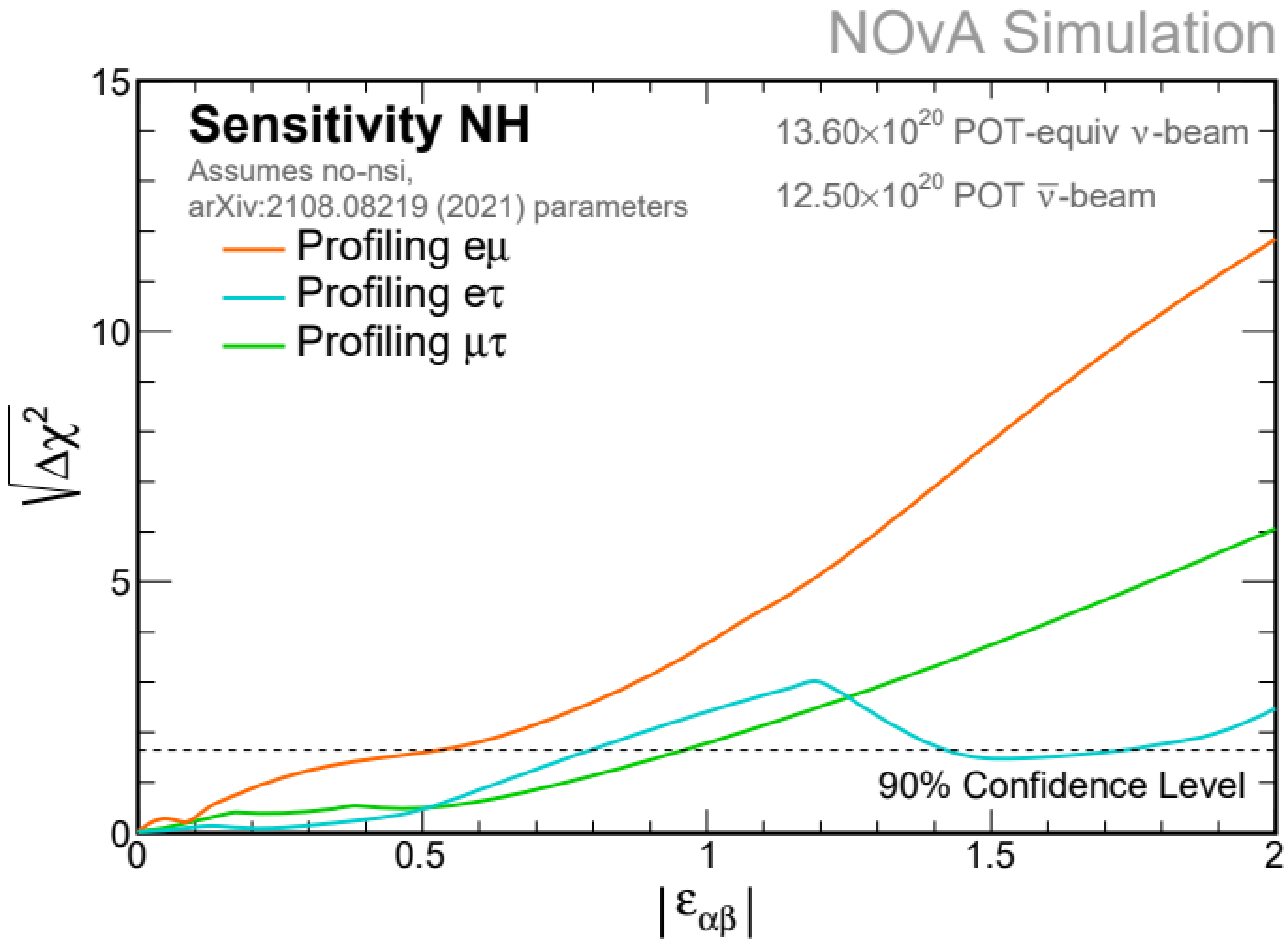


NOvA Simulation
Sensitivity NH
Assumes no-nsi,
arXiv:2108.08219 (2021) parameters
13.60×10^20 POT-equiv ν-beam
12.50×10^20 POT ν̄-beam
Std. Osc. (No-FC)
Profiling eμ
Profiling eτ
Profiling μτ
90% Confidence Level
√Δχ²
Δm²32 NH (10^-3 eV²)
0
2
4
6
8
10
2.2
2.4
2.6
2.8

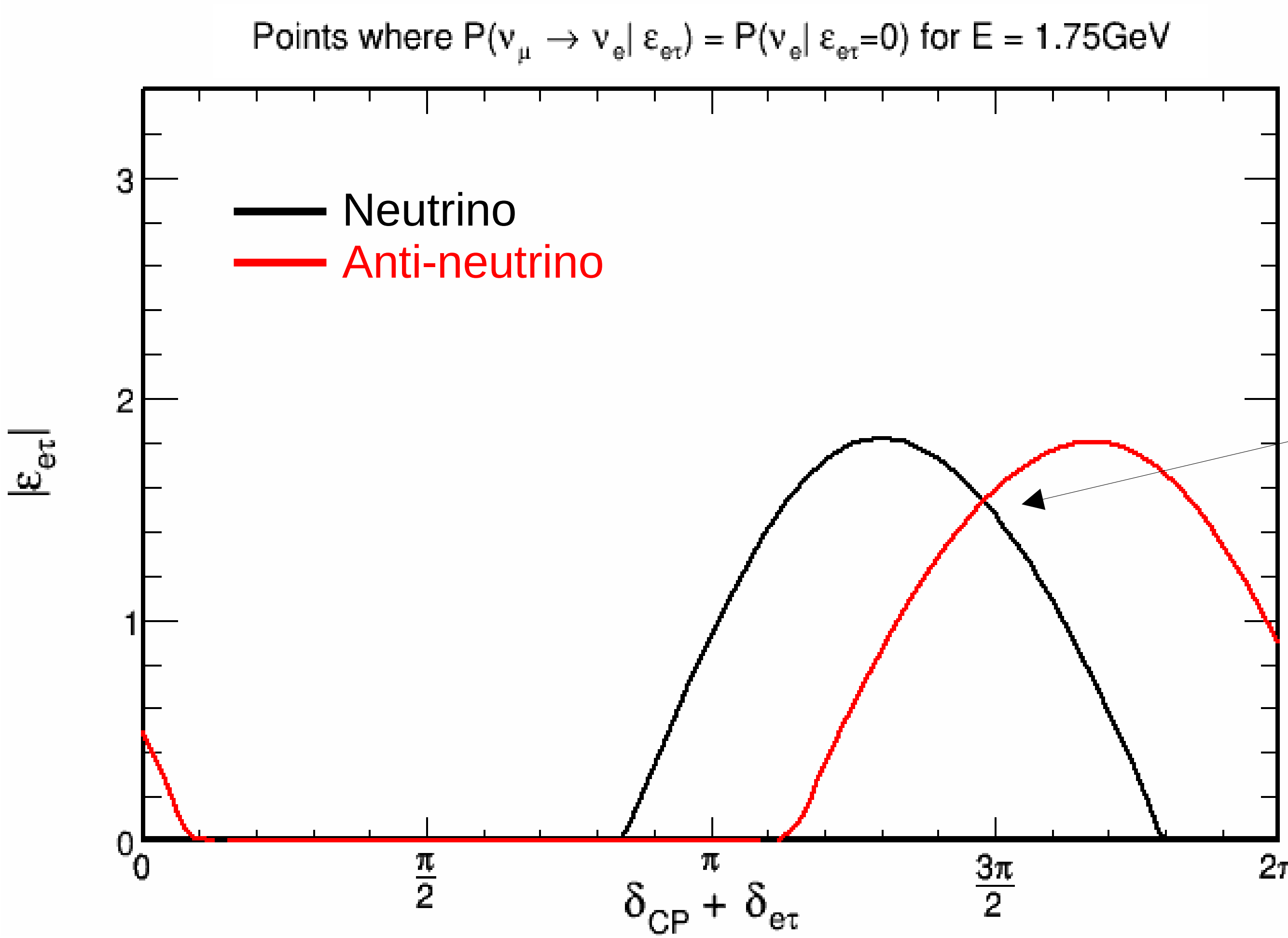
$\sin^2\theta_{23}$



$\varepsilon_{\alpha\beta}$

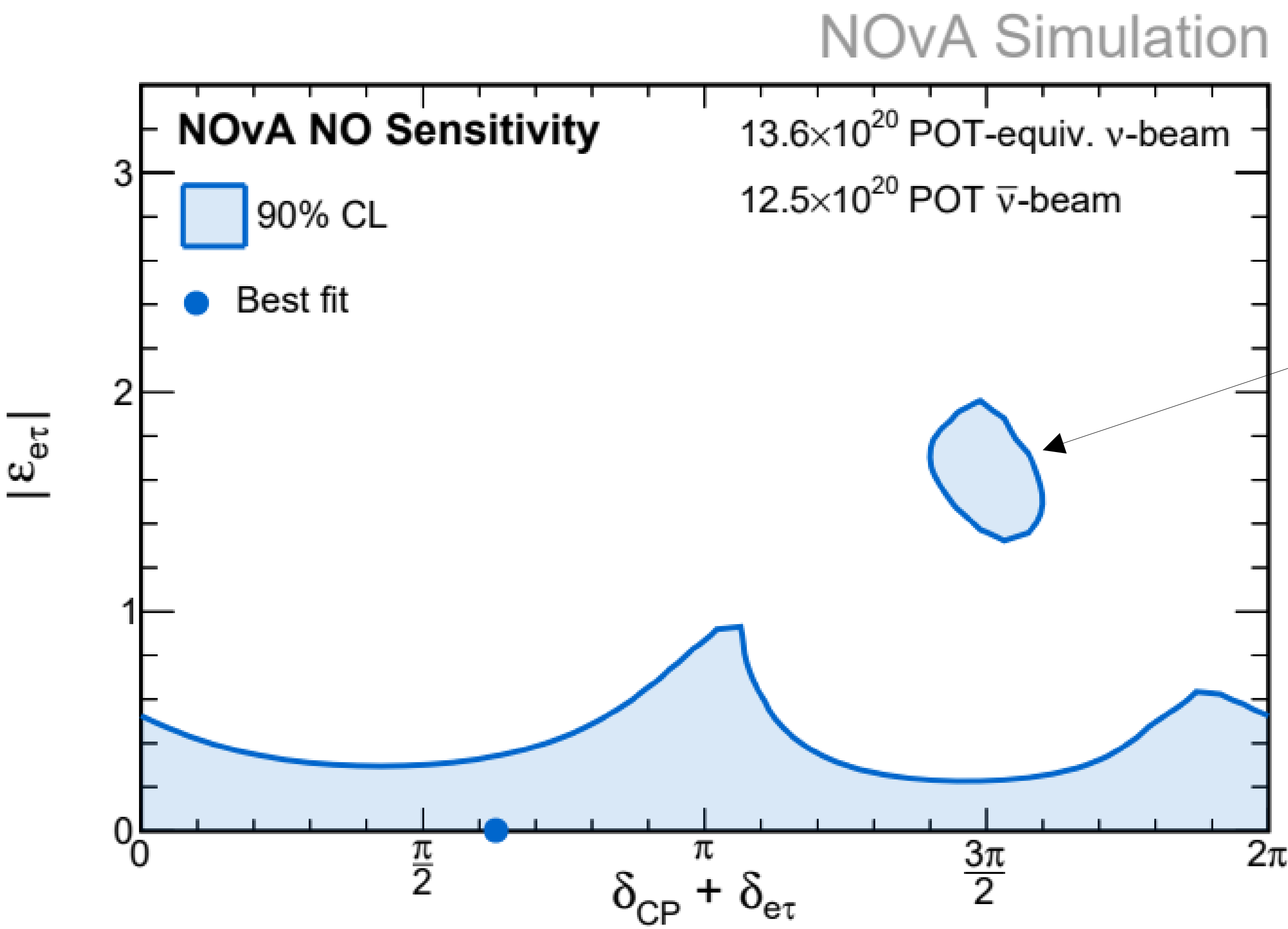


Degeneracy vs Delta



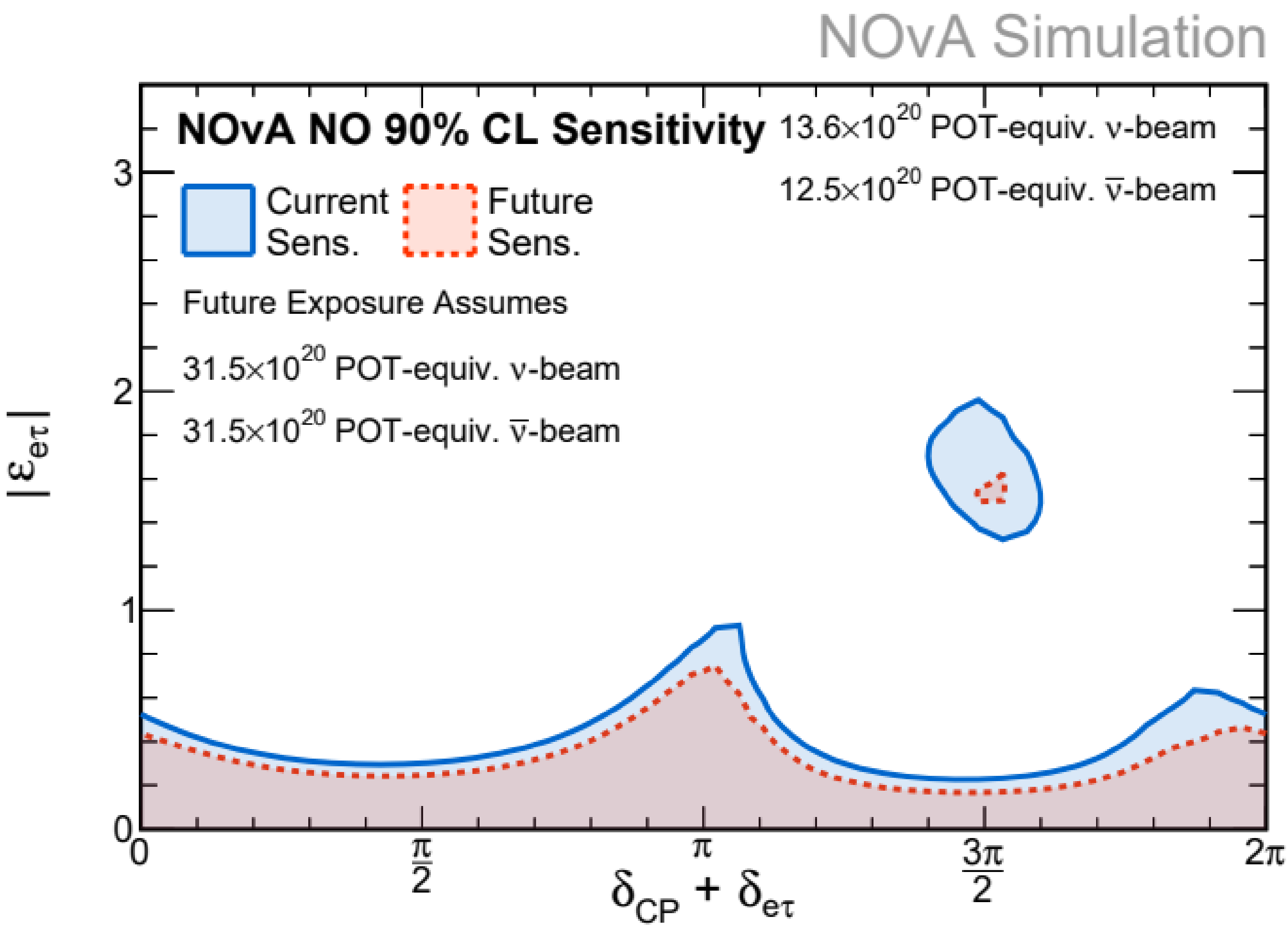
Would expect a loss in sensitivity here

eτ Sensitivity



Loss in sensitivity at high $\varepsilon_{e\tau}$ due to this dual degeneracy

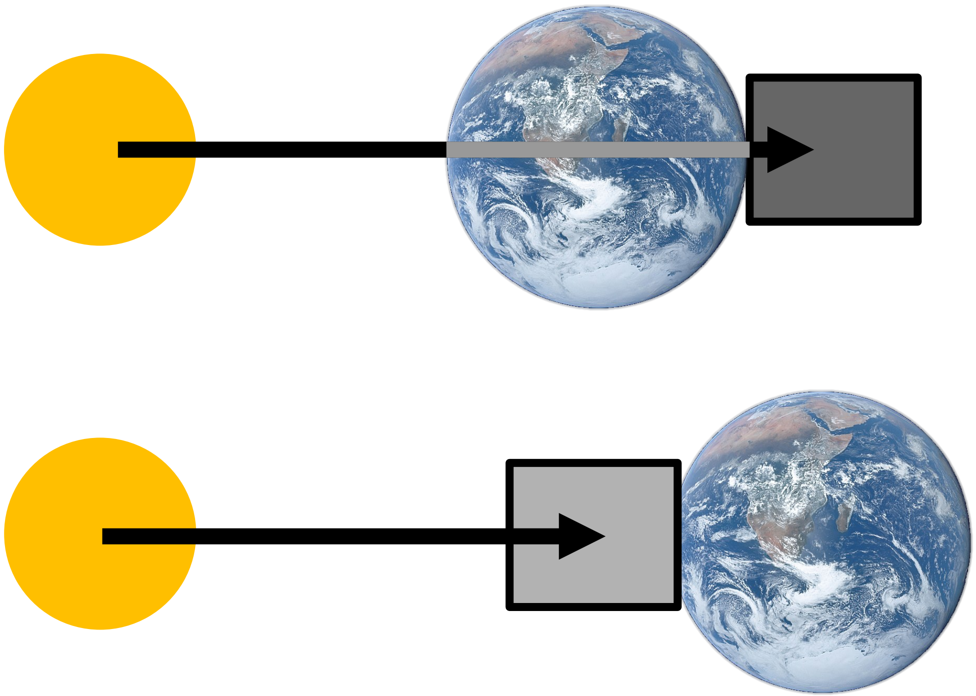
Future eτ Sensitivity

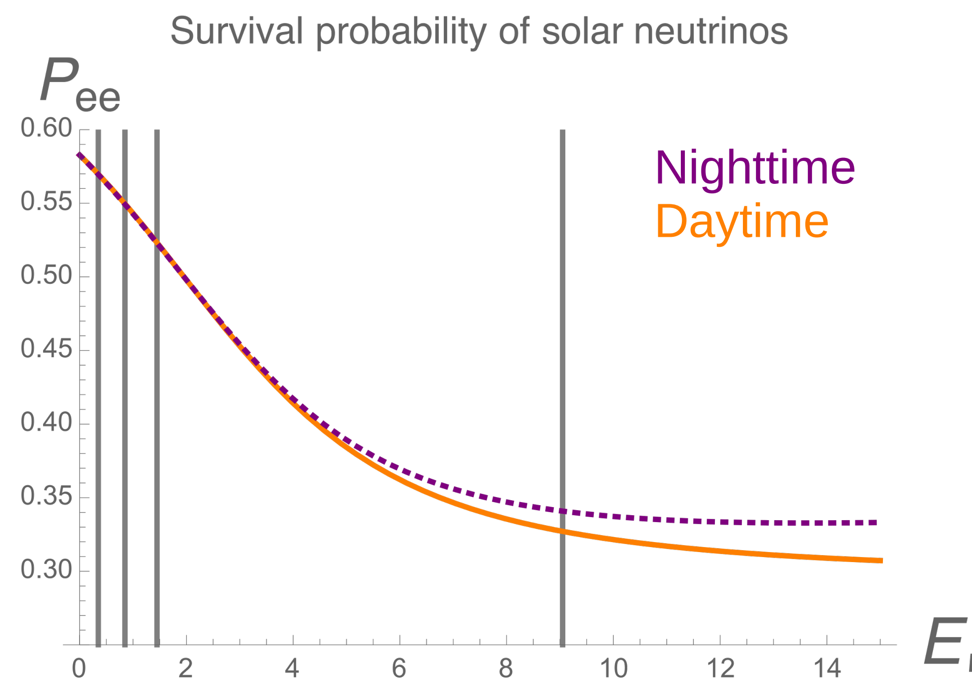


Future statistics not quite enough to remove high $\varepsilon_{e\tau}$ band.

Looking into additional improvements to the analysis

Mikheyev–Smirnov–Wolfenstein (MSW) Effect





Next slide: The math view

NSI in the Sun