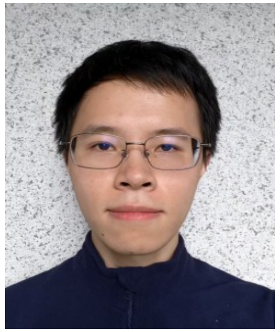
Disentangle RG Running Parameters & Distinguish Dirac vs Majorana @ JUNO



Joao Pinheiro

覃少洋

Shao-Feng Ge

葛韶锋

SFG, Joao Pinheiro, Shaoyang Qin [2606.24560]

see also **SFG**, Chui-Fan Kong, Pedro Pasquini [PRD, 2310.04077, 2411.18251]

SHANGHAI JIAO TONG UNIVERSITY

NOPP @ IHEP

August 14, 2026

Tsung-Dao Lee Institute

ν Oscillation as 1st New Physics

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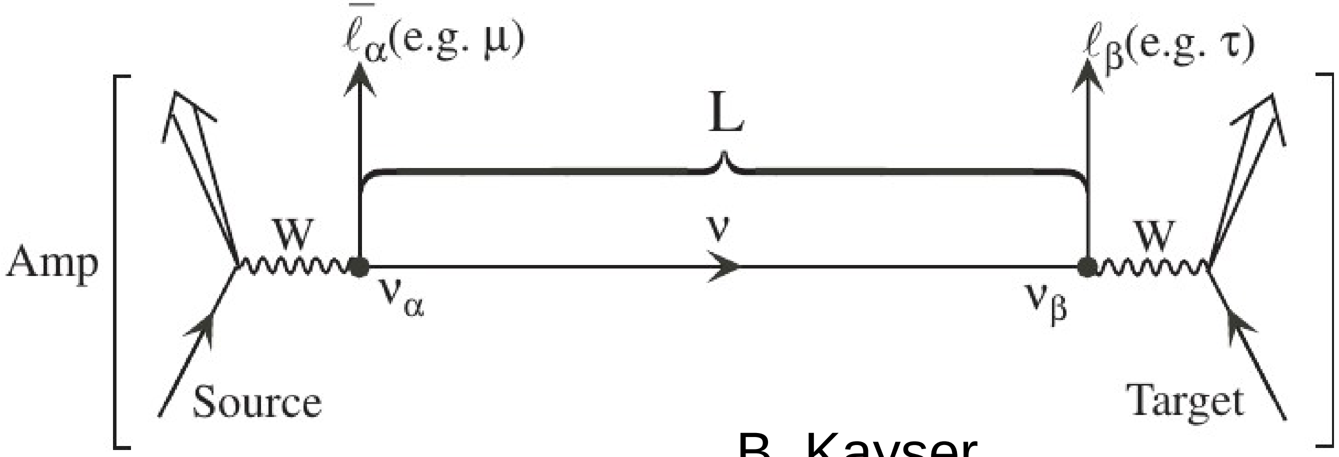
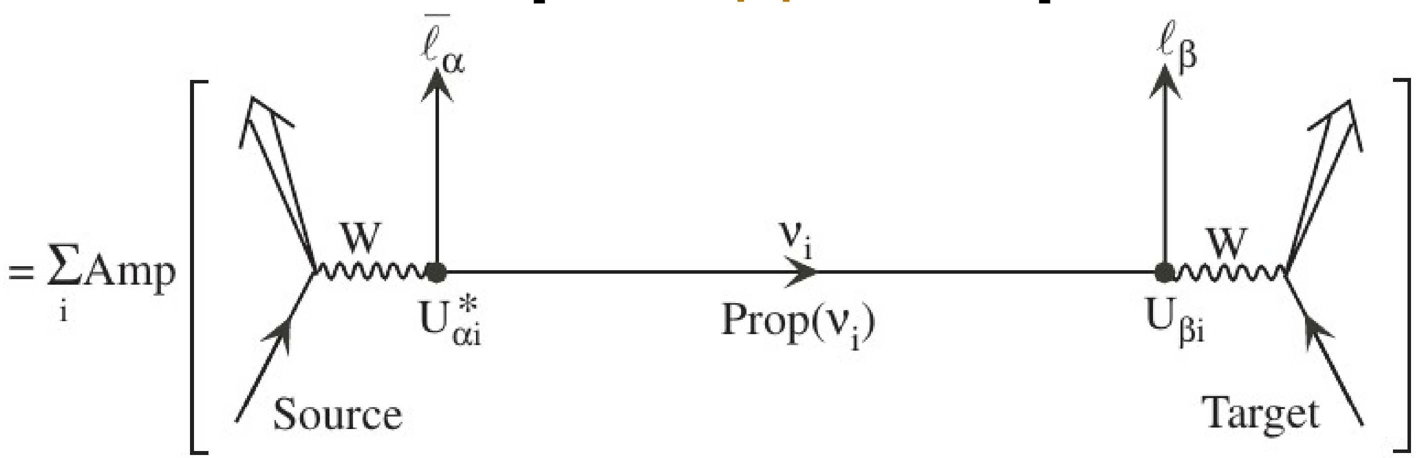


B. Kayser
[arXiv:hep-ph/0506165]



Reactor: O(1~10) km

Accelerator: O(100~1000) km

Atmospheric: O(10^3~10^4) km

Solar: O(10^5) km

ν oscillation is essential quantum interference @ macroscopic scales!

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i \to \boxed{\sum_i U_{\alpha i} e^{i(E_i t - \vec{P}_i \cdot \vec{x})} \nu_i} = \boxed{\sum_i U_{\alpha i} P_i U^\dagger_{\beta i} \nu_\beta} \equiv \sum_\beta A_{\alpha\beta} \nu_\beta$$

3ν Oscillation & PMNS Matrix

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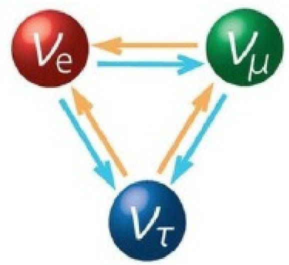
$$\mathrm{U}_{\mathrm{PMNS}} = \mathcal{P} \begin{pmatrix} c_s c_r & s_s c_r & s_r e^{-i\delta_{\mathrm{D}}} \\ -s_s c_a - c_s s_a s_r e^{i\delta_{\mathrm{D}}} & +c_s c_a - s_s s_a s_r e^{i\delta_{\mathrm{D}}} & s_a c_r \\ +s_s s_a - c_s c_a s_r e^{i\delta_{\mathrm{D}}} & -c_s s_a - s_s c_a s_r e^{i\delta_{\mathrm{D}}} & c_a c_r \end{pmatrix} \mathcal{Q}$$



with $\mathcal{P} \equiv \mathrm{diag}(e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3})$ & $\mathcal{Q} \equiv \mathrm{diag}(e^{i\delta_{\mathrm{M1}}}, 1, e^{i\delta_{\mathrm{M3}}})$

$[(s, a, r) \equiv (12, 23, 13)$ for (**solar, atmospheric, reactor**) angles$]$

$$\begin{aligned} \mathrm{P}(\nu_\alpha \to \nu_\beta) &= |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2 \\ &= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E}) \\ &\quad + 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E}) \end{aligned}$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j \qquad \Delta m^2_{ij} \frac{L}{4E} = 1.27\, \Delta m^2_{ij}(\mathrm{eV}^2) \frac{L\,(\mathrm{km})}{E\,(\mathrm{GeV})}$$

ν Oscillation Parameters

NuFIT 6.1 (2025)

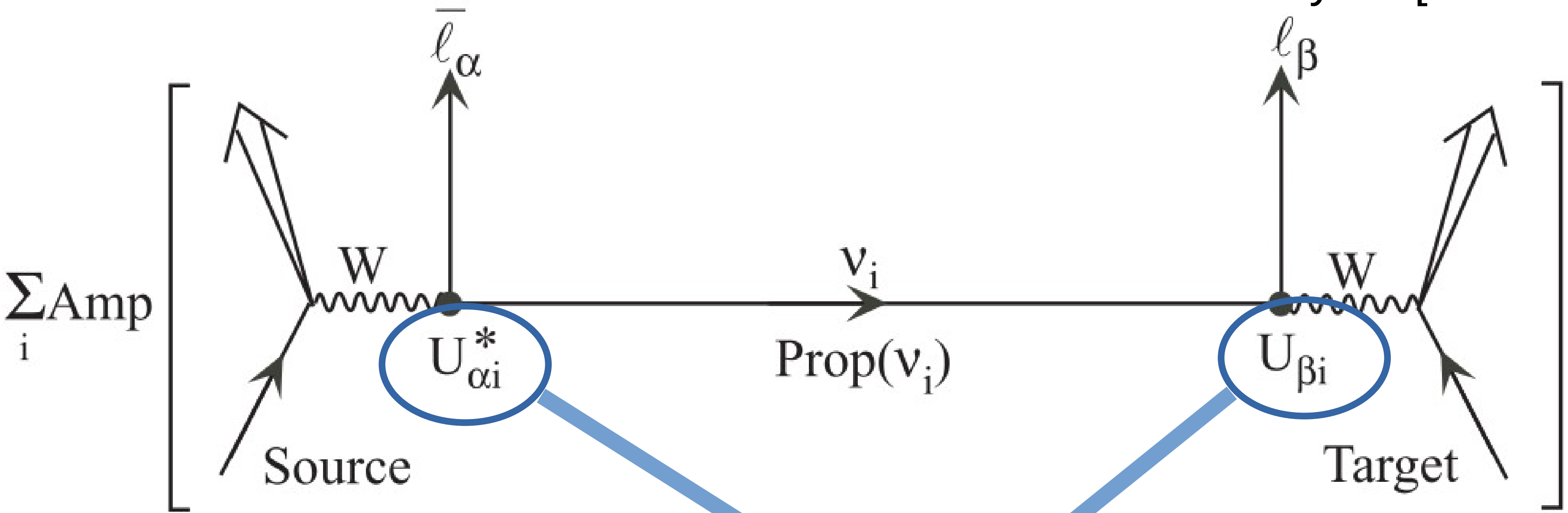
IC23 without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 1.5$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \to 0.3295$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \to 0.3295$
$\theta_{12}/^\circ$	$33.76^{+0.42}_{-0.41}$	$32.54 \to 35.03$	$33.76^{+0.42}_{-0.41}$	$32.54 \to 35.03$
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.014}$	$0.432 \to 0.587$	$0.555^{+0.013}_{-0.016}$	$0.437 \to 0.590$
$\theta_{23}/^\circ$	$43.27^{+1.0}_{-0.82}$	$41.11 \to 50.02$	$48.15^{+0.75}_{-0.92}$	$41.40 \to 50.21$
$\sin^2\theta_{13}$	$0.02249^{+0.00057}_{-0.00057}$	$0.02070 \to 0.02420$	$0.02261^{+0.00056}_{-0.00056}$	$0.02091 \to 0.02433$
$\theta_{13}/^\circ$	$8.62^{+0.11}_{-0.11}$	$8.27 \to 8.95$	$8.65^{+0.11}_{-0.11}$	$8.31 \to 8.97$
$\delta_{\rm CP}/^\circ$	207^{+23}_{-20}	$114 \to 405$	283^{+24}_{-28}	$202 \to 347$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.537^{+0.094}_{-0.10}$	$7.236 \to 7.823$	$7.537^{+0.094}_{-0.10}$	$7.236 \to 7.822$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.521^{+0.026}_{-0.018}$	$+2.454 \to +2.592$	$-2.500^{+0.024}_{-0.023}$	$-2.569 \to -2.430$

Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Pinheiro & Schwetz [2410.05380]
See also [2601.09791]

Two Mixing Matrices in ν Oscillation

B. Kayser [arXiv:hep-ph/0506165]



$$\mathcal{A}^{\rm osc}_{\beta\alpha} \equiv \sum_i U_{\beta i} e^{-i\frac{m_i^2}{2E_\nu}L} U^*_{\alpha i}$$

The same set of mixing parameters appear at two different places.

Unitarity

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$$\mathcal{A}^{\mathrm{osc}}_{\beta\alpha} \equiv \sum_i U_{\beta i} e^{-i\frac{m_i^2}{2E_\nu}L} U^*_{\alpha i}$$

- **Oscillation Probability**

$$P_{\alpha\beta} \equiv |A_{\alpha\beta}|^2 = \left| \sum_{i=1}^{3} U_{\beta i} \exp\left(-i\frac{m_i^2 L}{2E_\nu}\right) U^*_{\alpha i} \right|^2$$

- **Unitarity**

$$P_{\alpha\beta}(L \to 0) \to |(UU^\dagger)_{\beta\alpha}|^2 = \delta_{\alpha\beta}$$

No transition can happen @ vanishing baseline!

Should they be the same?

Momentum Transfer for Reactor ν

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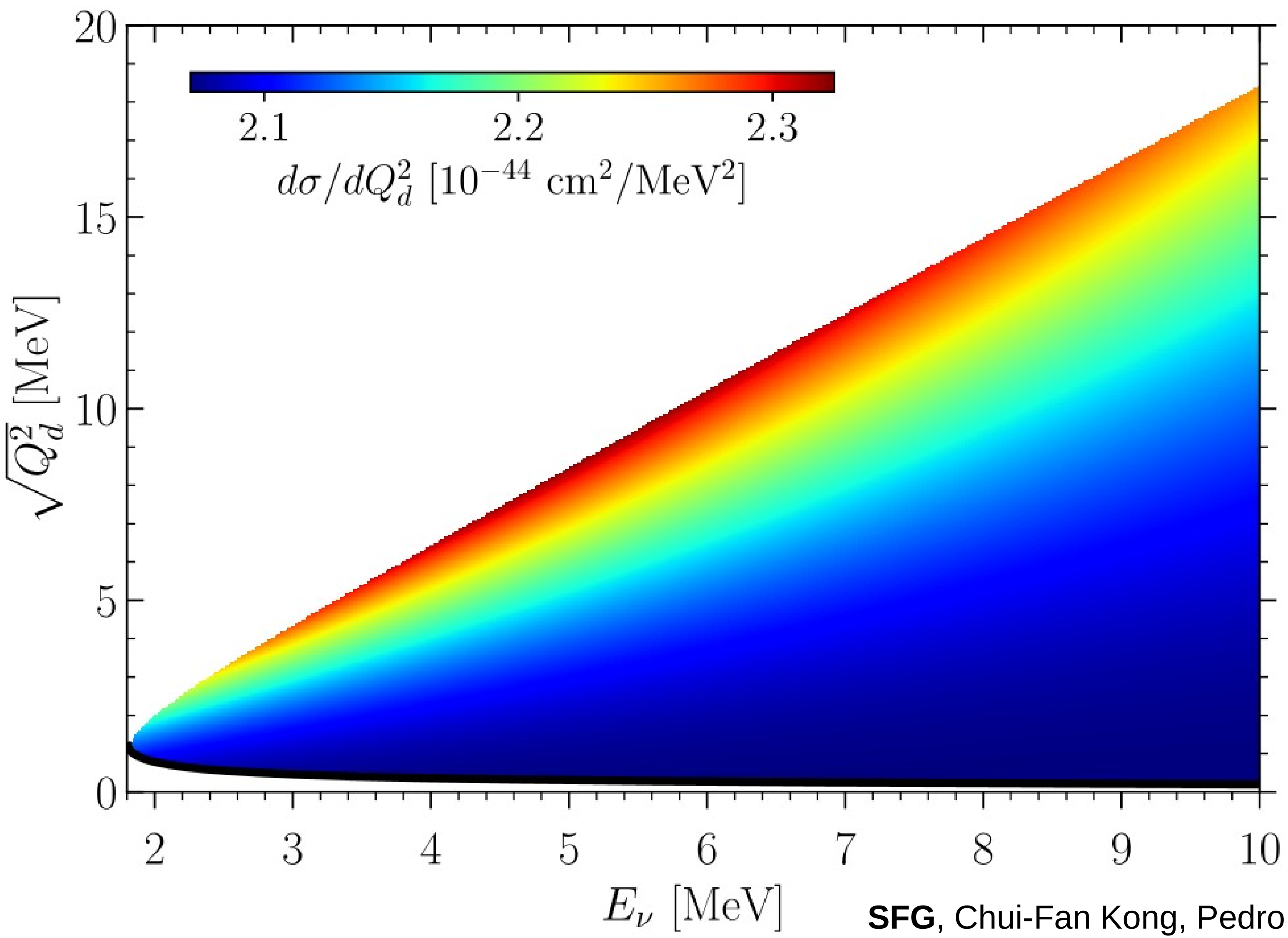
Beta Decay $Q_p^2 \approx 1.67\,\mathrm{MeV}^2$

$Q_d^2 \approx \mathcal{O}(10^{-2} \sim 10^2)\,\mathrm{MeV}^2$ **Inverse Beta Decay**



SFG, Chui-Fan Kong, Pedro Pasquini [PRD, 2411.18251]

Mismatched Mixing Matrices from RG

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$$\mathcal{A}^{\rm osc}_{\beta\alpha} \equiv \sum_i U_{\beta i} e^{-i\frac{m_i^2}{2E_\nu}L} U^*_{\alpha i}$$

$$\theta_{ij}(Q^2) \equiv \theta_{ij}(Q_0^2) + \beta_{ij} \ln\left(\left|\frac{Q^2}{Q_0^2}\right|\right)$$

$$\delta_D(Q^2) \equiv \delta_D(Q_0^2) + \beta_\delta \ln\left(\left|\frac{Q^2}{Q_0^2}\right|\right)$$

The mixing matrices needs not to be the same!

$$\mathcal{A}^{\rm osc}_{\beta\alpha} = U_{\beta i}(Q_d^2) e^{-iL\frac{m_i^2}{2E_\nu}} U^*_{\alpha i}(Q_p^2)$$

Zero Distance Effect

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$$\mathcal{A}^{\rm osc}_{\beta\alpha} = U_{\beta i}(Q_d^2) e^{-iL\frac{m_i^2}{2E_\nu}} U^*_{\alpha i}(Q_p^2)$$

$$\boxed{\frac{1}{E_\nu} \ll L \ll \frac{2E_\nu}{\Delta m^2_{ij}}}$$

Non-zero transition even in the zero distance limit!

$$P_{\alpha\beta} = \left| \left[U(Q_d^2) U^\dagger(Q_p^2) \right]_{\beta\alpha} \right|^2 \neq 0$$

Effective non-unitarity!

$$P_{ee}(Q^2_{d,p}) = 1 - \sin^2\left(\frac{\Delta\delta_D}{2}\right) \sin^2 2\theta_{13} \qquad P_{\mu e}(Q^2_{d,p}) = \sin^2\left(\frac{\Delta\delta_D}{2}\right) s^2_{23} \sin^2 2\theta_{13}$$

SFG, Chui-Fan Kong, Pedro Pasquini [PRD, 2411.18251]

CP RG Running for Reactor ν Osc

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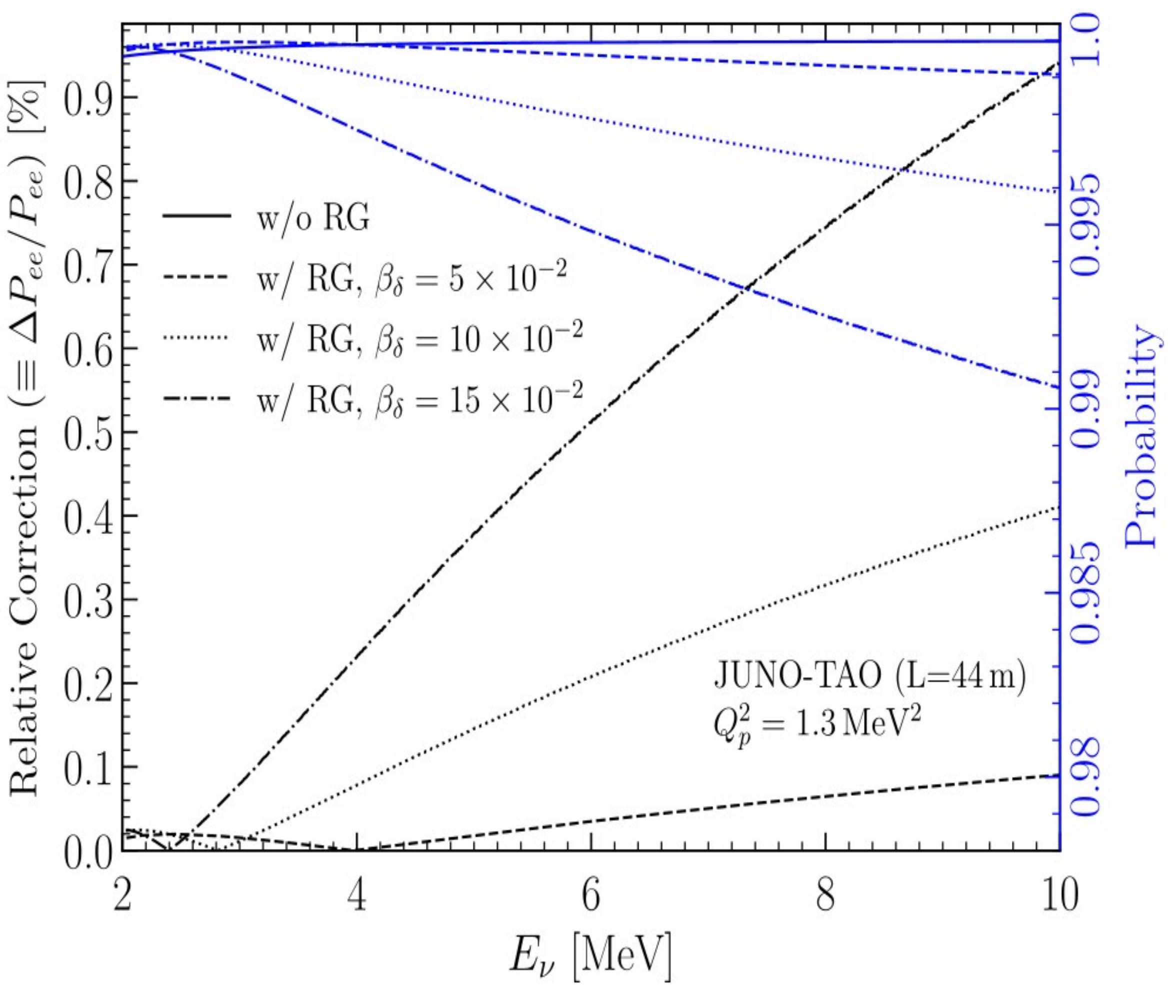
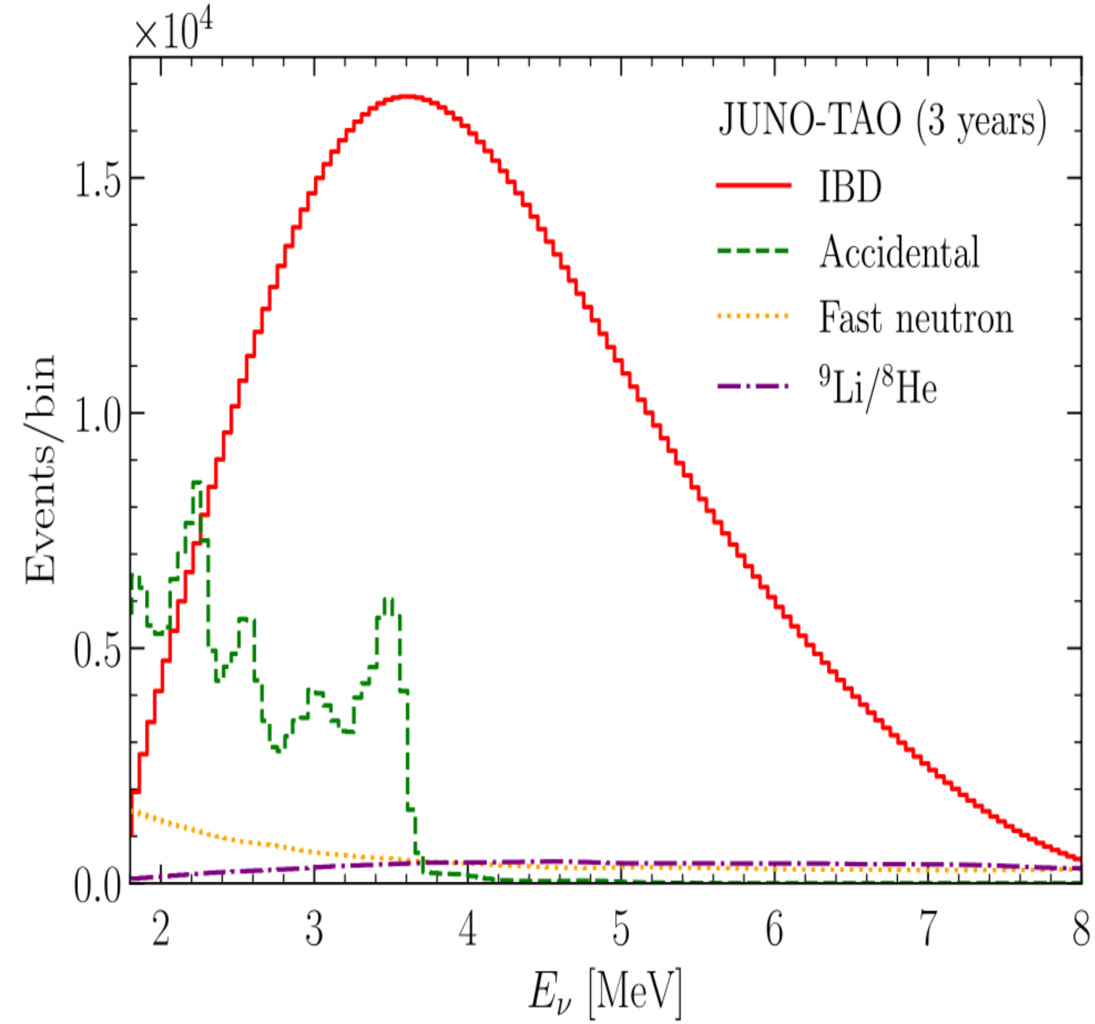
$$1 - P_{\rm ee}(Q^2_{d,p}) \approx \left[\frac{1}{2}\ln\left(\left|\frac{Q^2_d}{Q^2_p}\right|\right)\sin 2\theta_{13}\beta_\delta\right]^2$$





SFG, Chui-Fan Kong, Pedro Pasquini [PRD, 2411.18251]

CP RG Running Sensitivity @ JUNO-TAO

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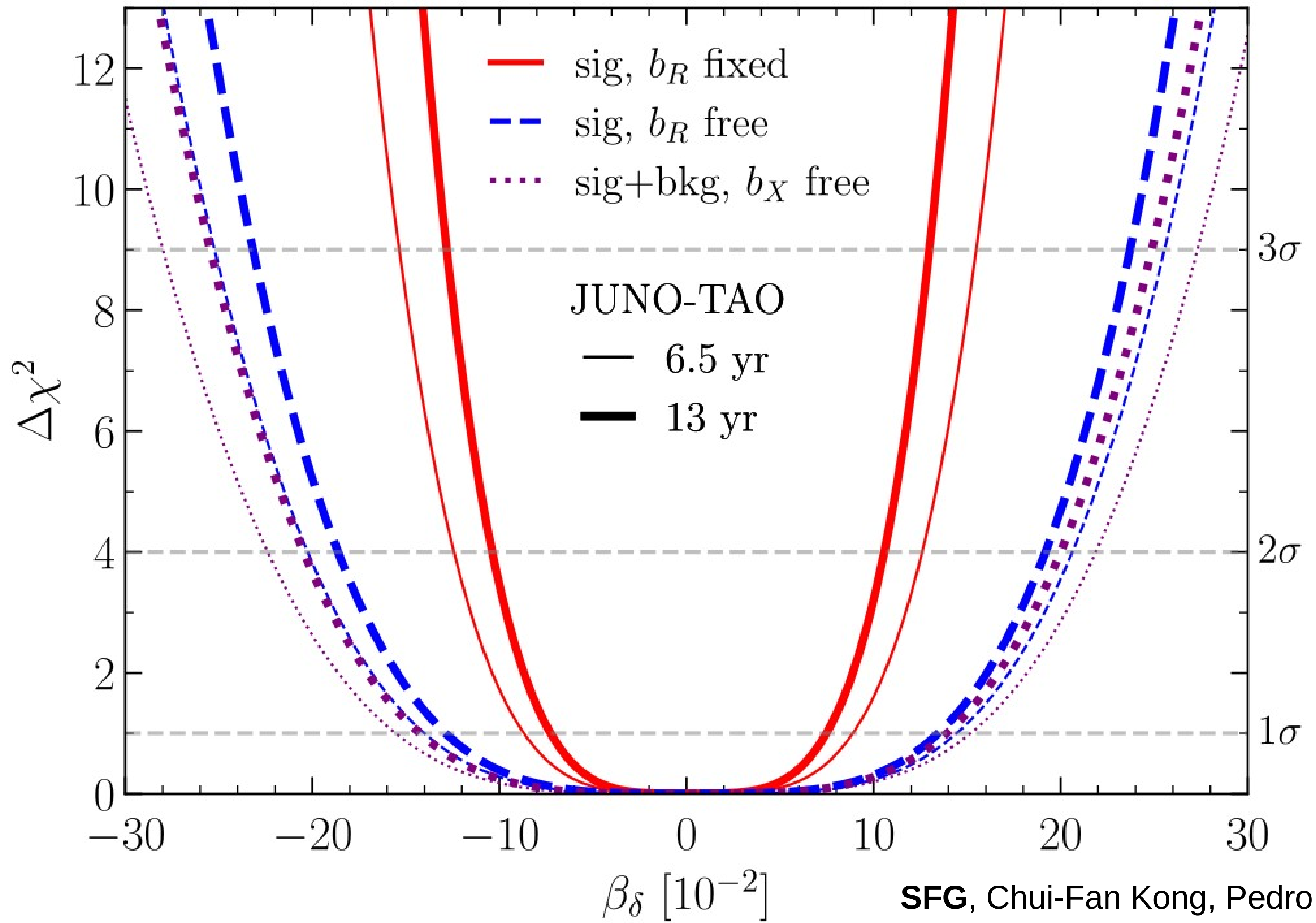
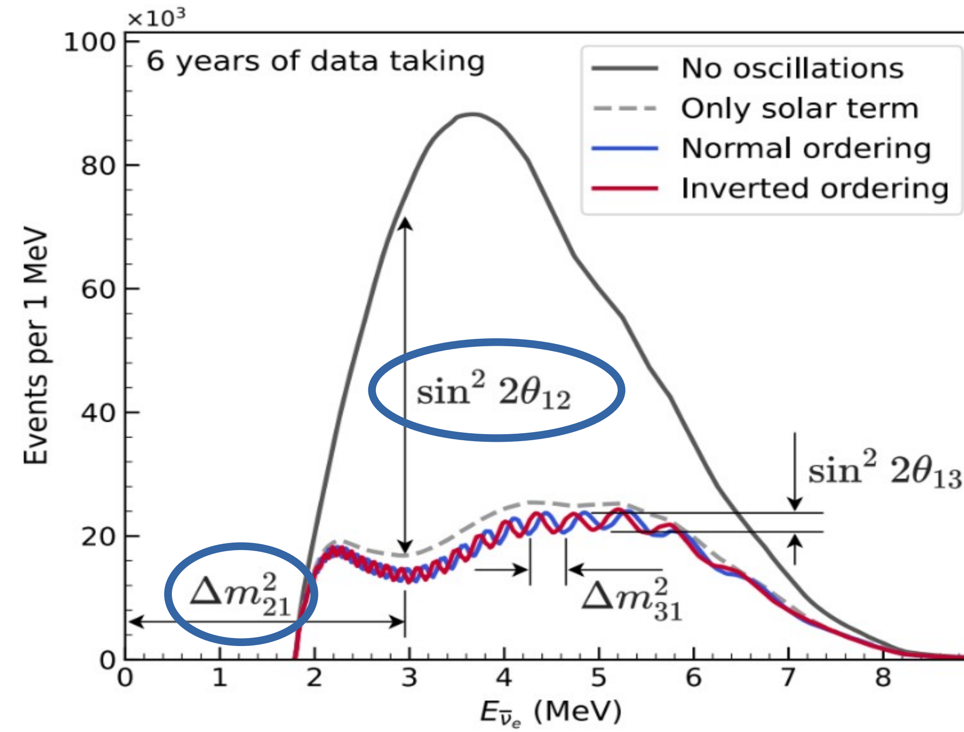
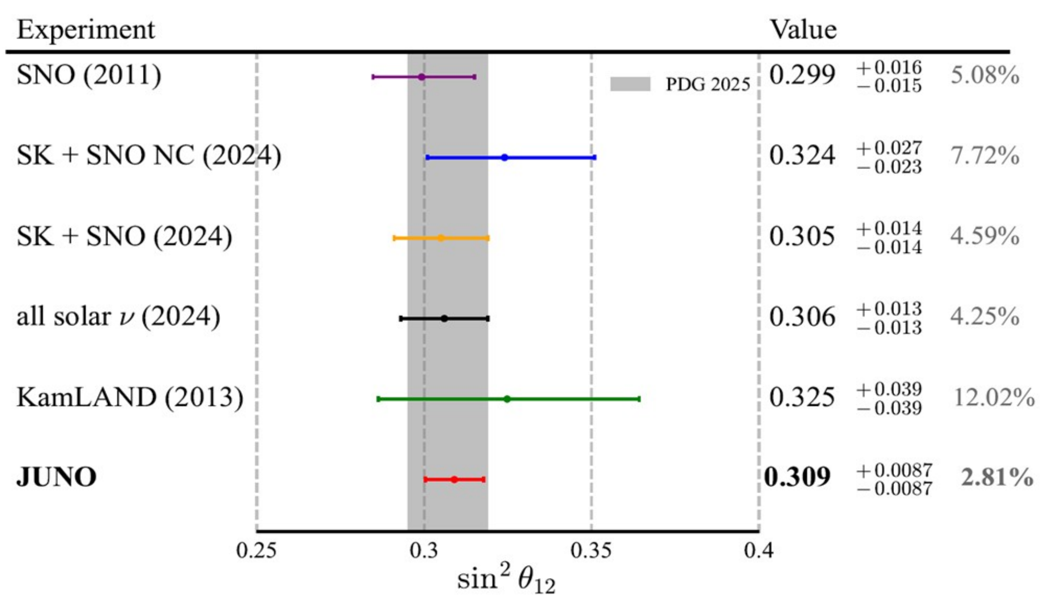
$$\overline{P}_{ee}(E_\nu) \equiv \int P_{ee}(Q^2_{p,d}) \frac{1}{\sigma} \frac{d\sigma}{dQ^2_d} dQ^2_d$$

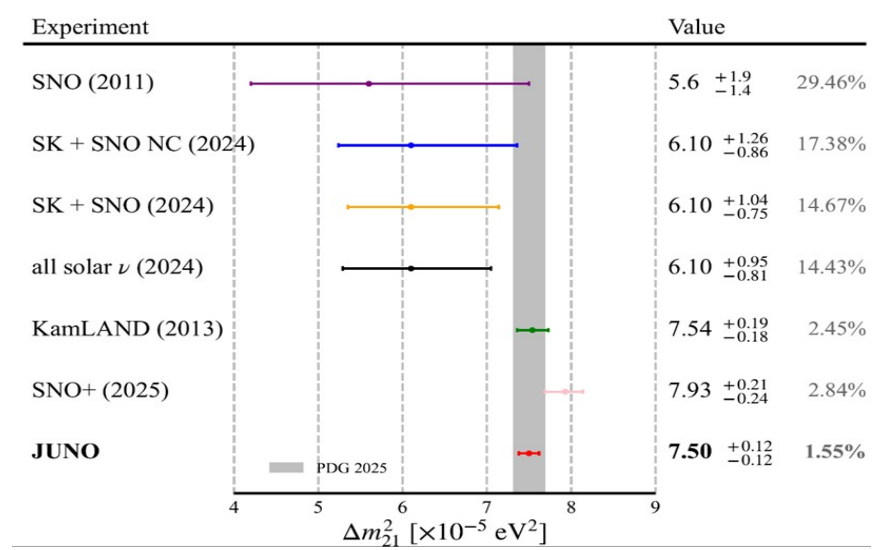


SFG, Chui-Fan Kong, Pedro Pasquini [PRD, 2411.18251]

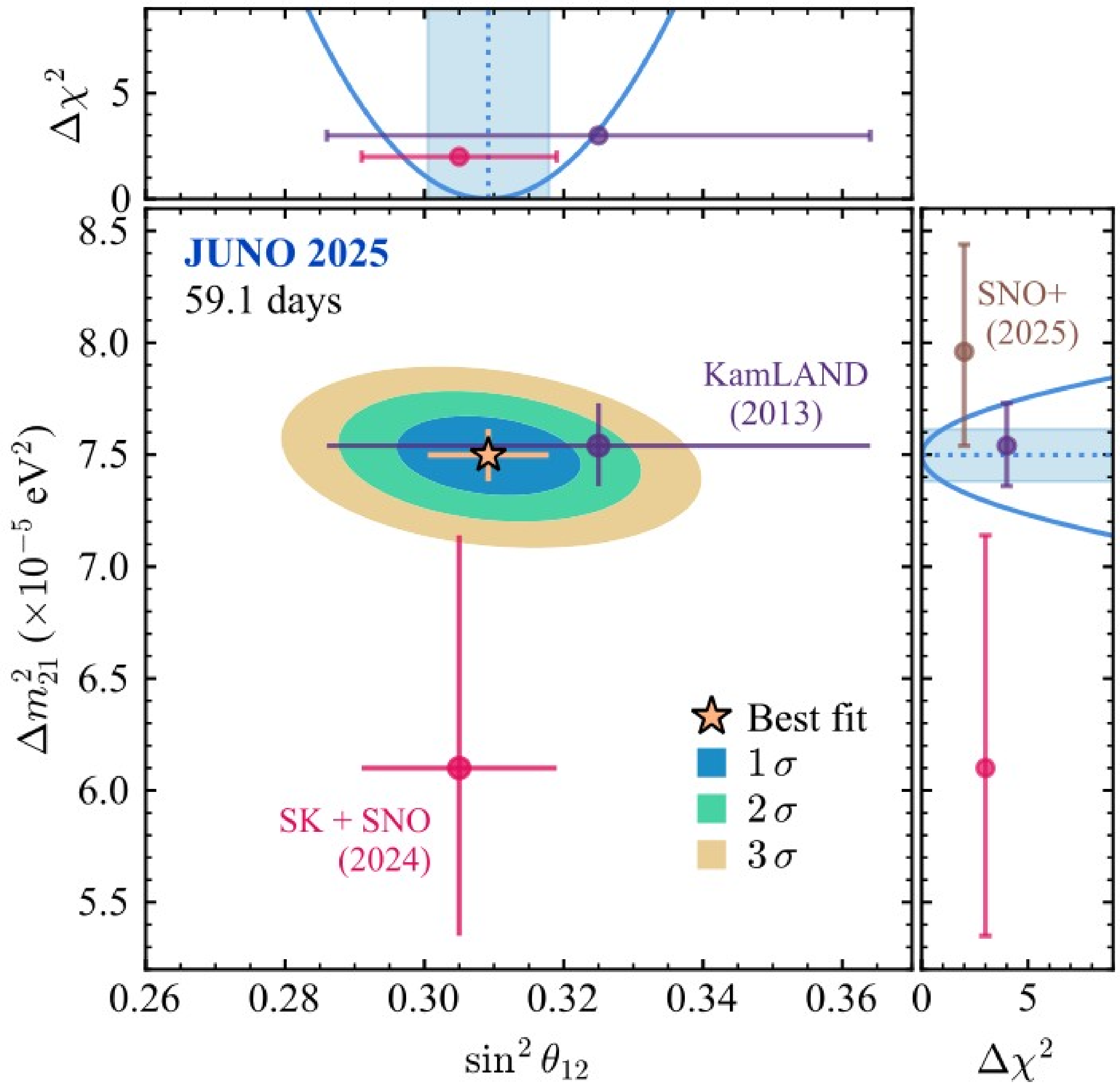
JUNO Experiment & 1st Data



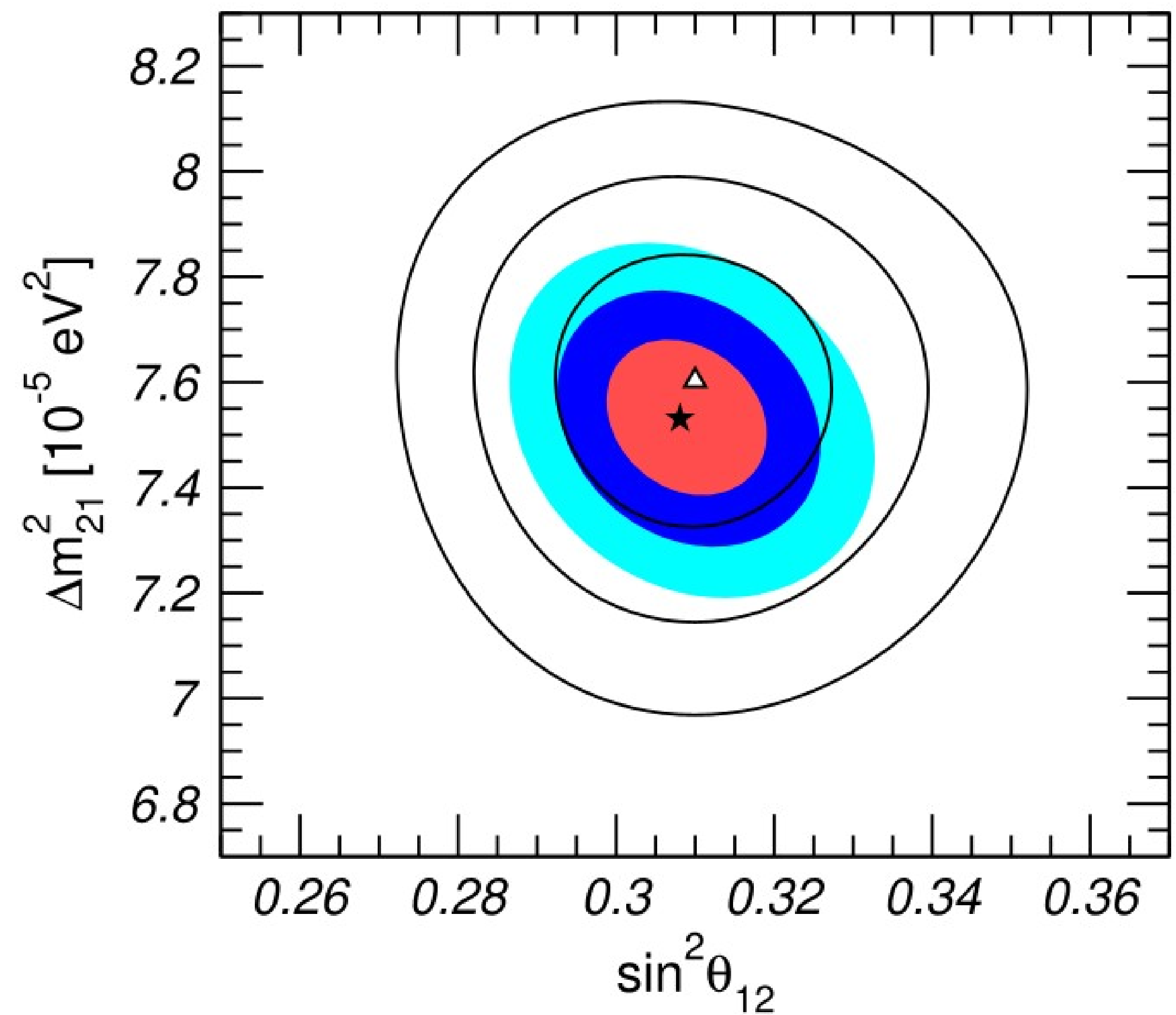




JUNO 1st Data



JUNO Collaboration [2511.14593]



NuFit [2601.09791]

Slow & Fast Modes @ JUNO

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$$P_{\alpha\beta} = \left| \sum_{i=1}^{3} U_{\beta i}(Q_d^2) \exp\left(-i \frac{m_i^2 L}{2E_\nu}\right) U^*_{\alpha i}(Q_p^2) \right|^2$$

$$U \equiv \mathcal{P} V \mathcal{Q}$$

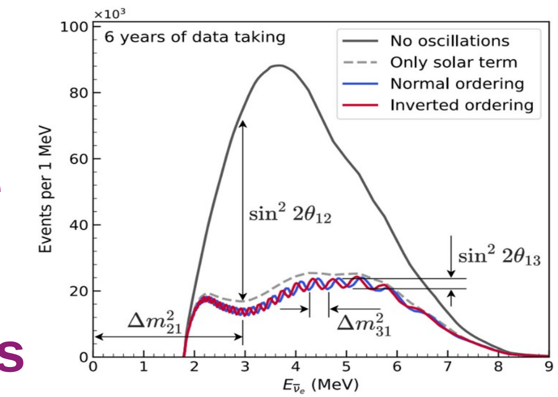
$$\mathcal{Q} \equiv \mathrm{diag}\{e^{i\delta_{\rm M1}/2}, 1, e^{i\delta_{\rm M3}/2}\}$$

- **Reactor ν Oscillation Probability**

$$\begin{aligned} P_{\overline{e}\overline{e}} \approx 1 &- 4c_r^4 c_s^2 s_s^2 (1 + \Delta\Theta_{21}) \sin^2(\Phi_{21} + \Delta\Phi_{21}) \\ &- 4c_r^2 s_r^2 c_s^2 (1 + \Delta\Theta_{31}) \sin^2(\Phi_{31} + \Delta\Phi_{31}) \\ &- 4c_r^2 s_r^2 s_s^2 (1 + \Delta\Theta_{32}) \sin^2(\Phi_{32} + \Delta\Phi_{32}) \end{aligned}$$

Slow Mode

Fast Modes



Correction comes from both amplitude & oscillation phases

Dirac

Majorana

$$\begin{aligned} \Delta\Theta_{21} &\equiv (\cot\theta_s - \tan\theta_s)\Delta\theta_s - 2\tan\theta_r \Delta\theta_r, \\ \Delta\Theta_{31} &\equiv -\tan\theta_s \Delta\theta_s + (\cot\theta_r - \tan\theta_r)\Delta\theta_r, \\ \Delta\Theta_{32} &\equiv \cot\theta_s \Delta\theta_s + (\cot\theta_r - \tan\theta_r)\Delta\theta_r, \end{aligned}$$

$$\begin{aligned} \Delta\Phi_{21} &\equiv -\frac{1}{4}\boxed{\Delta\delta_{\rm M1}}, \\ \Delta\Phi_{32} &\equiv -\frac{1}{2}\boxed{\Delta\delta_D} + \boxed{\frac{1}{4}\Delta\delta_{\rm M3}}, \\ \Delta\Phi_{31} &\equiv -\frac{1}{2}\boxed{\Delta\delta_D} - \boxed{\frac{1}{4}\Delta\delta_{\rm M1} + \frac{1}{4}\Delta\delta_{\rm M3}} \end{aligned}$$

CP phases do not appear, but their RG running parameters can!

Dirac vs Majorana

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- **Dirac neutrinos**

$$\mathrm{M}_\nu \equiv U_L \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} U_R^\dagger$$

$$U_L \equiv \mathcal{P}_L V_L \mathcal{Q}_L$$
$$U_R \equiv \mathcal{P}_R V_R \mathcal{Q}_R$$

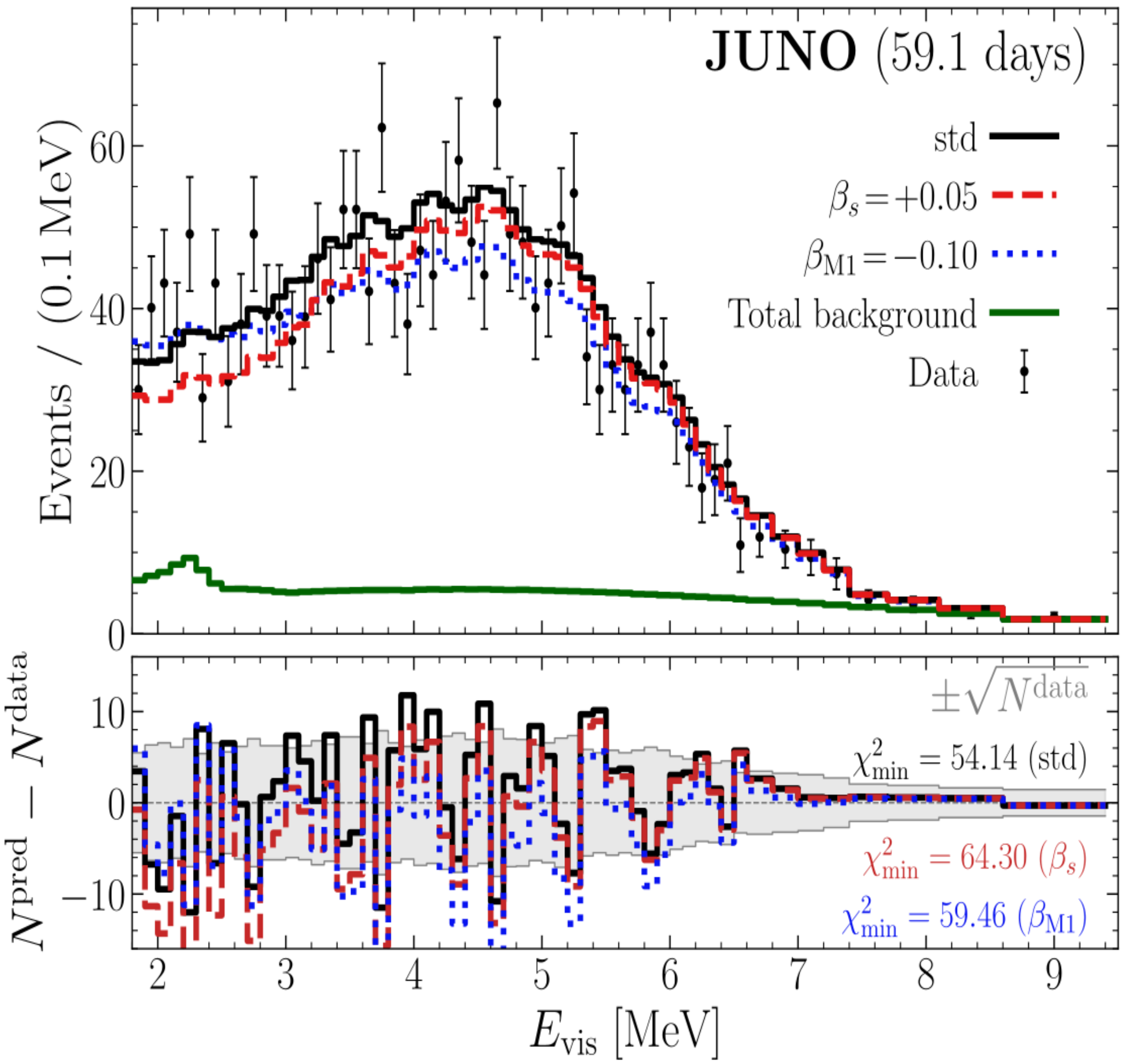
$$\mathrm{Q}_L \equiv \begin{pmatrix} e^{i\alpha_L} & & \\ & e^{i\beta_L} & \\ & & e^{i\gamma_L} \end{pmatrix} \qquad \mathrm{Q}_R \equiv \begin{pmatrix} e^{i\alpha_R} & & \\ & e^{i\beta_R} & \\ & & e^{i\gamma_R} \end{pmatrix}$$

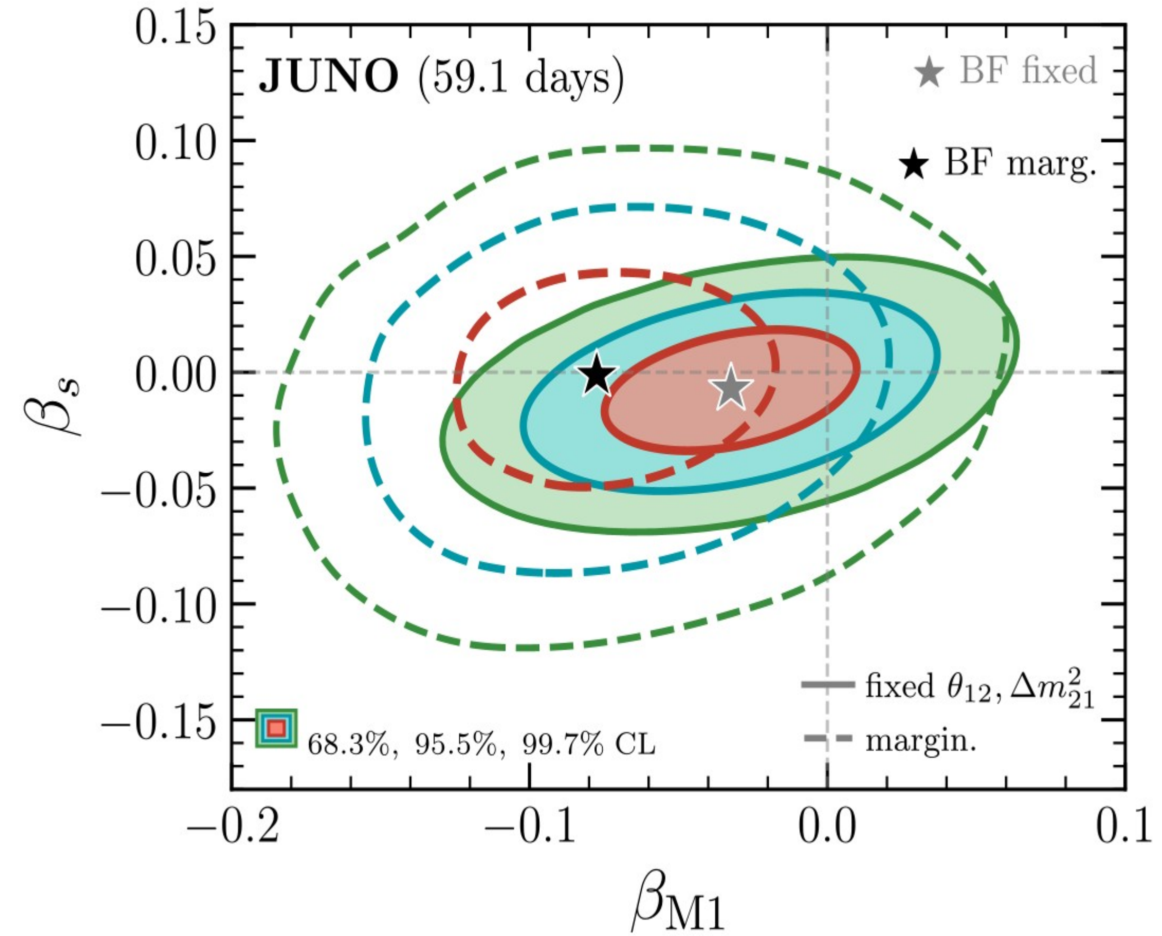
For Dirac neutrinos, there is no physical Majorana CP phase!

- **Majorana neutrinos**

$$U_L = U_R^* \quad \Rightarrow \quad \mathcal{Q}_L \ \& \ \mathcal{Q}_R \text{ are correlated!}$$

Slow Mode @ JUNO [1st Data]





Prefer a nonzero β_{M1}!

Prefer Majorana ν's?

Fast Modes @ JUNO

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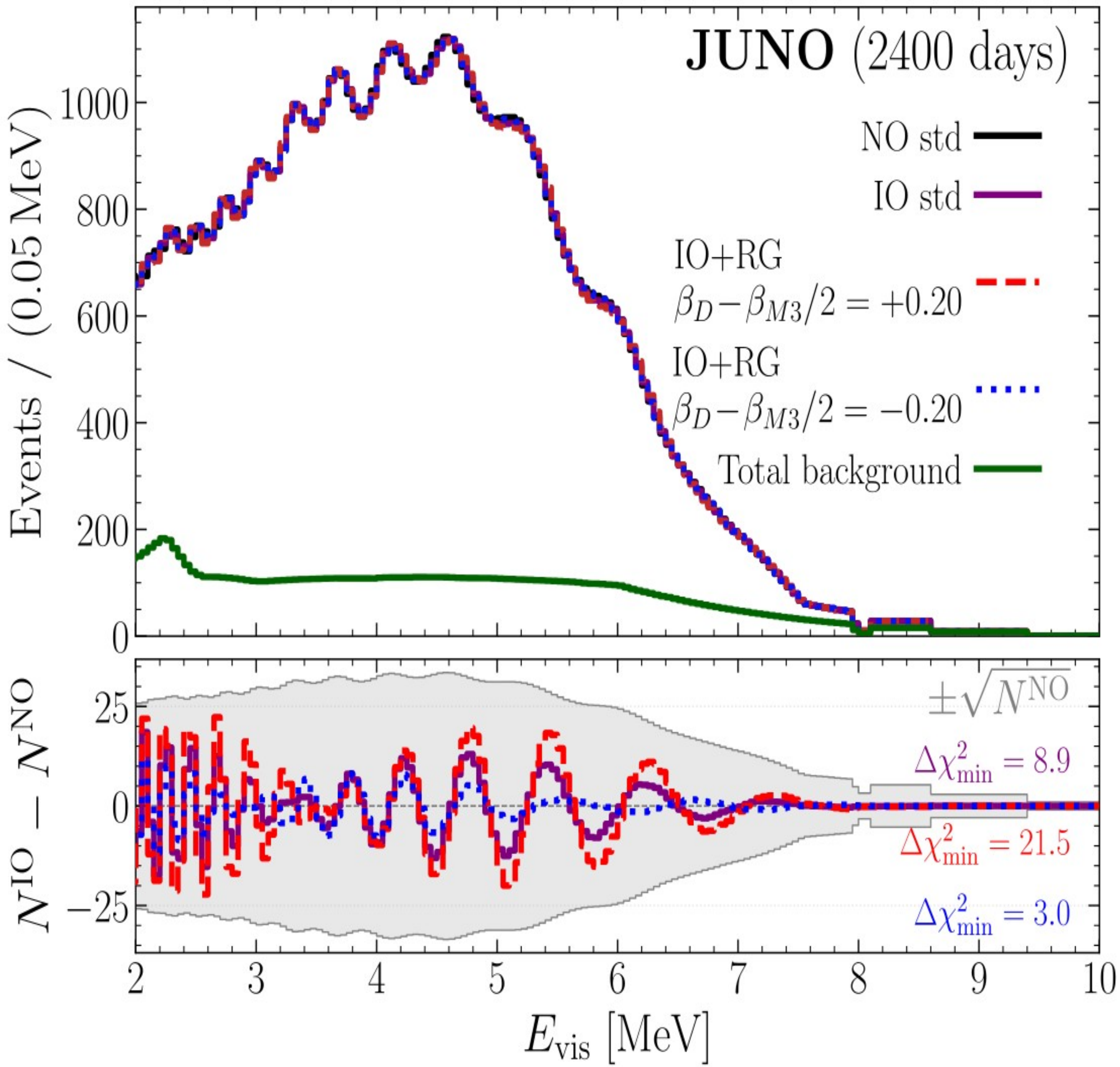

$$P^{\rm fast}_{\bar e\bar e} \propto \cos\left(2\Phi_{ee} \pm \Phi_\odot\right)$$

$$\Phi_{ee} \equiv \frac{\Delta m^2_{ee} L}{4E_\nu}$$

Normal
vs
Inverted

$$\text{NO:} \propto \cos\left(2|\Phi_{ee}| - 2\Delta\Phi_{ee} + \Phi_\odot - \Delta\Phi_\odot\right)$$

$$\text{IO:} \propto \cos\left(2|\Phi_{ee}| + 2\Delta\Phi_{ee} - \Phi_\odot + \Delta\Phi_\odot\right)$$

$$\Delta\Phi_{ee} \equiv \frac{1}{2}\Delta\delta_D + \frac{1}{4}c_s^2\Delta\delta_{\rm M1} - \frac{1}{4}\Delta\delta_{\rm M3}$$

$$\Delta\Phi_\odot \equiv \frac{\sin 2\theta_s \sin\Phi_{21}}{\cos^2\Phi_{21} + \cos^2 2\theta_s \sin^2\Phi_{21}}\Big[\cos\Phi_{21}\,\Delta\theta_s + \frac{1}{4}\cos 2\theta_s \sin 2\theta_s \sin\Phi_{21}\Delta\delta_{\rm M1}\Big]$$

RG interferes with mass ordering measurement

Restore MO Sensitivity with JUNO-TAO

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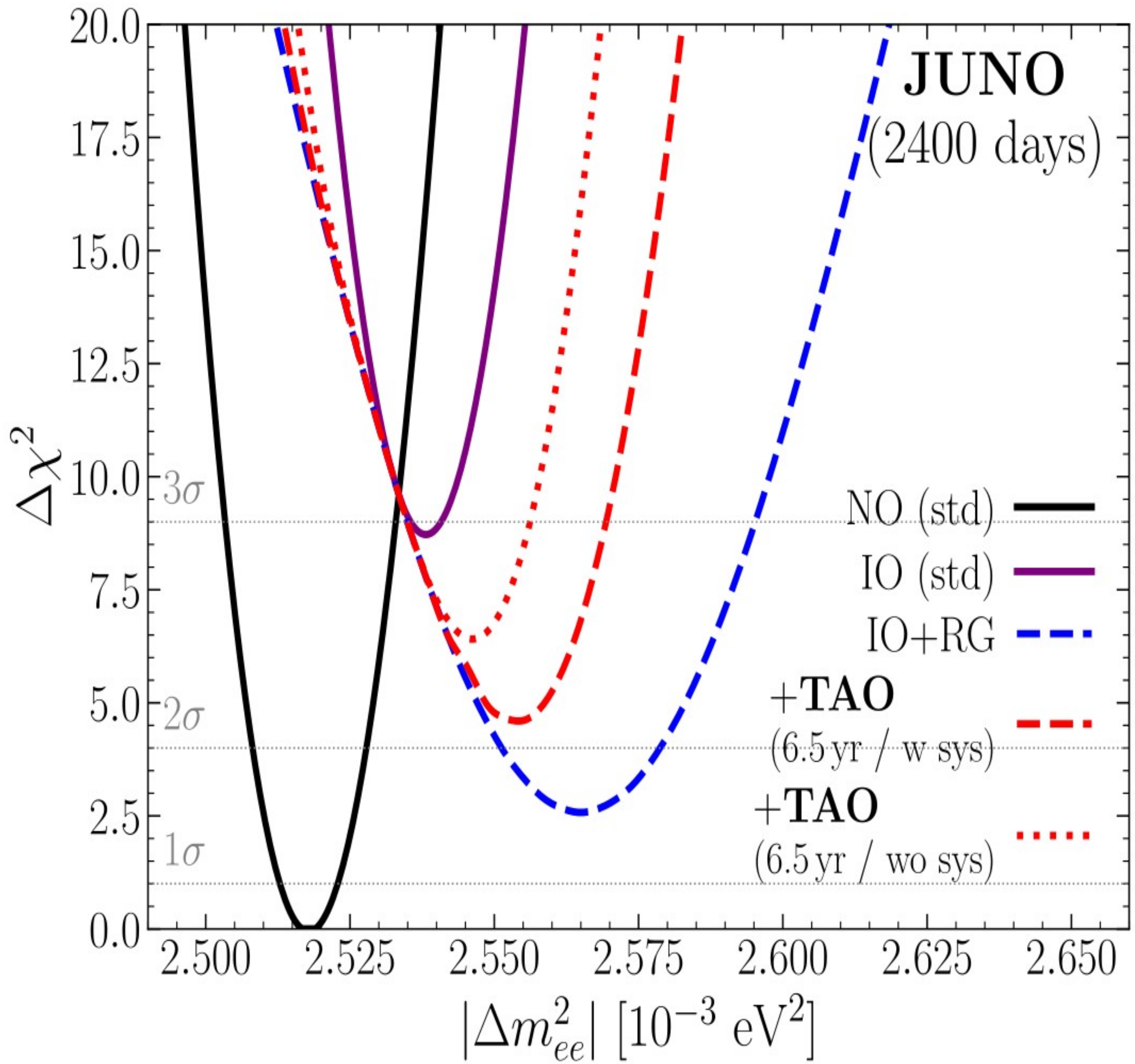

$$\Delta\Phi_\odot \equiv \frac{\sin 2\theta_s \sin\Phi_{21}}{\cos^2\Phi_{21} + \cos^2 2\theta_s \sin^2\Phi_{21}} \Big[\cos\Phi_{21} \Delta\theta_s + \frac{1}{4}\cos 2\theta_s \sin 2\theta_s \sin\Phi_{21} \Delta\delta_{\rm M1} \Big]$$

Slow Mode

$$\Delta\Phi_{ee} \equiv \frac{1}{2}\Delta\delta_D + \frac{1}{4} c_s^2 \Delta\delta_{\rm M1} - \frac{1}{4}\Delta\delta_{\rm M3}$$

$$P_{\bar e \bar e}(L \to 0) \approx 1 - \frac{1}{4}\sin^2(2\theta_r)\left(\Delta\delta_D - \frac{1}{2}\Delta\delta_{\rm M3}\right)^2$$

Zero Distance @ JUNO-TAO

Summary

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- **Mixing matrices @ production & detection need not to be the same!**

$$U(Q_p^2) \neq U(Q_d^2) \quad \Rightarrow \quad U(Q_p^2)U^\dagger(Q_d^2) \neq I$$

- **CP effects @ Reactor exp's (JUNO, TAO, Daya Bay)**

1. **Effective non-unitarity @ TAO**
2. **Distinguish Dirac vs Majorana with ν osc**

   JUNO 1st Data prefers nonzero β_{M1}
3. **Disentangle multiple RG @ JUNO**
4. **Interfere with mass ordering measurement**

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Thank You

CP Measurement

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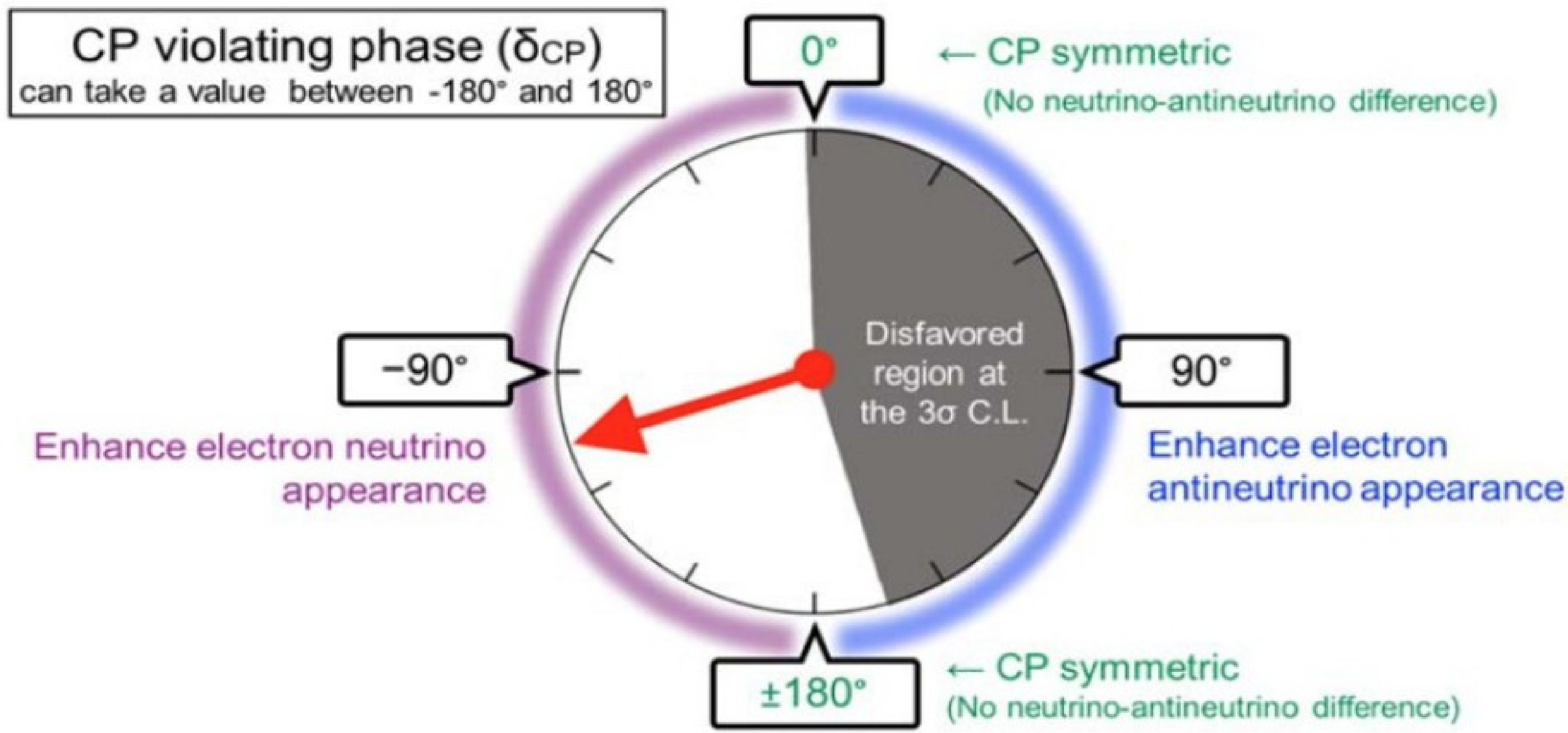
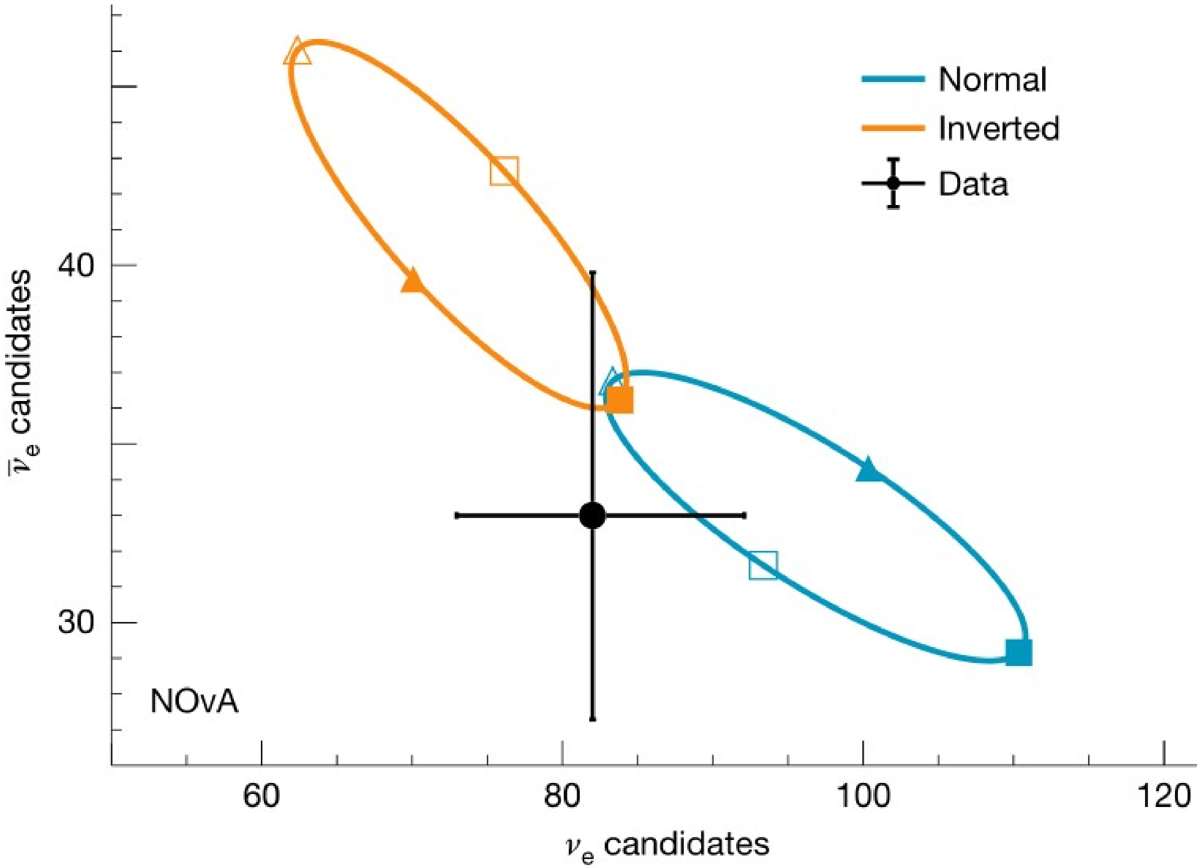


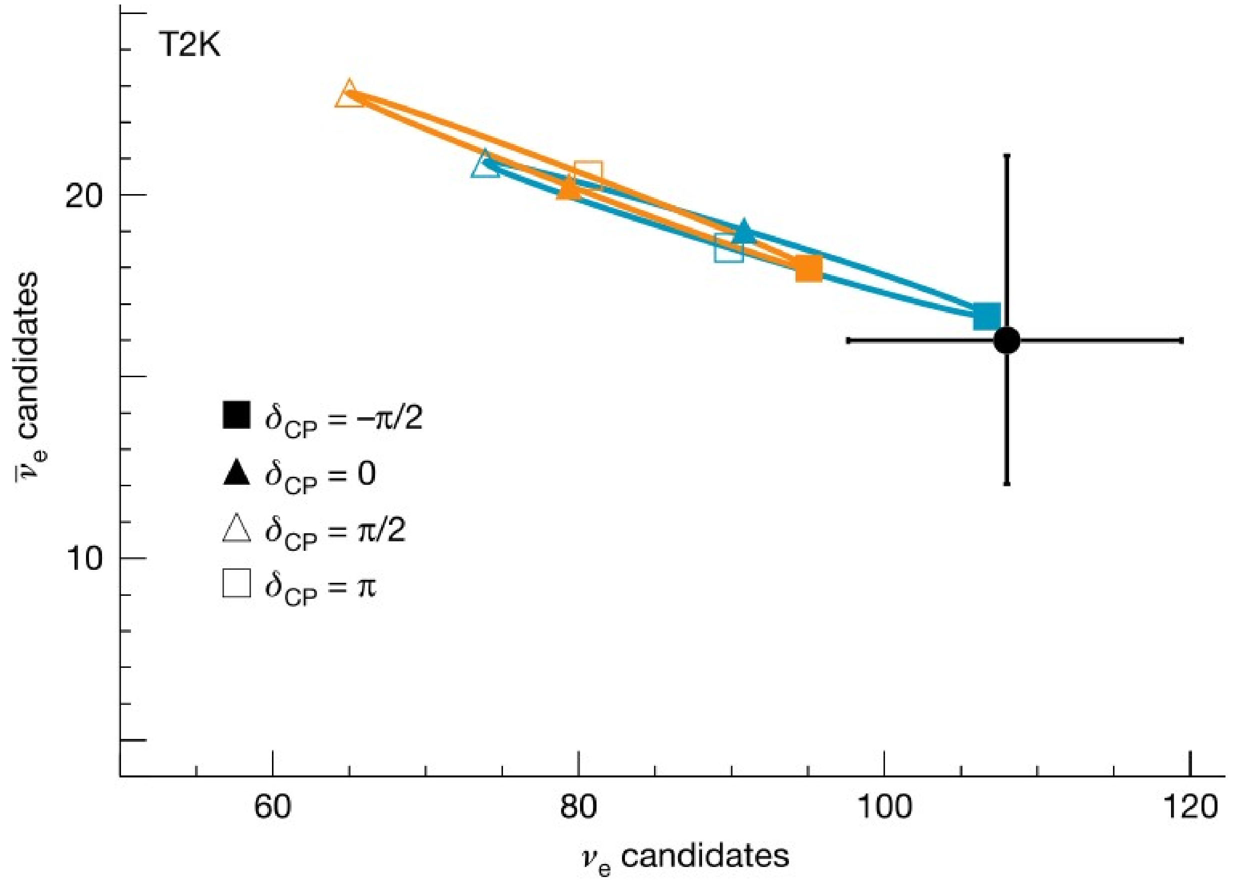
Fig.1 The arrow indicates the value most compatible with the data. The gray region is disfavored at 99.7% (3σ) confidence level. Nearly half of the possible values are excluded.

https://www.kek.jp/en/newsroom/attic/PR20200416_T2K_E.pdf

Nature vol. 580, pages 339-344(2020)

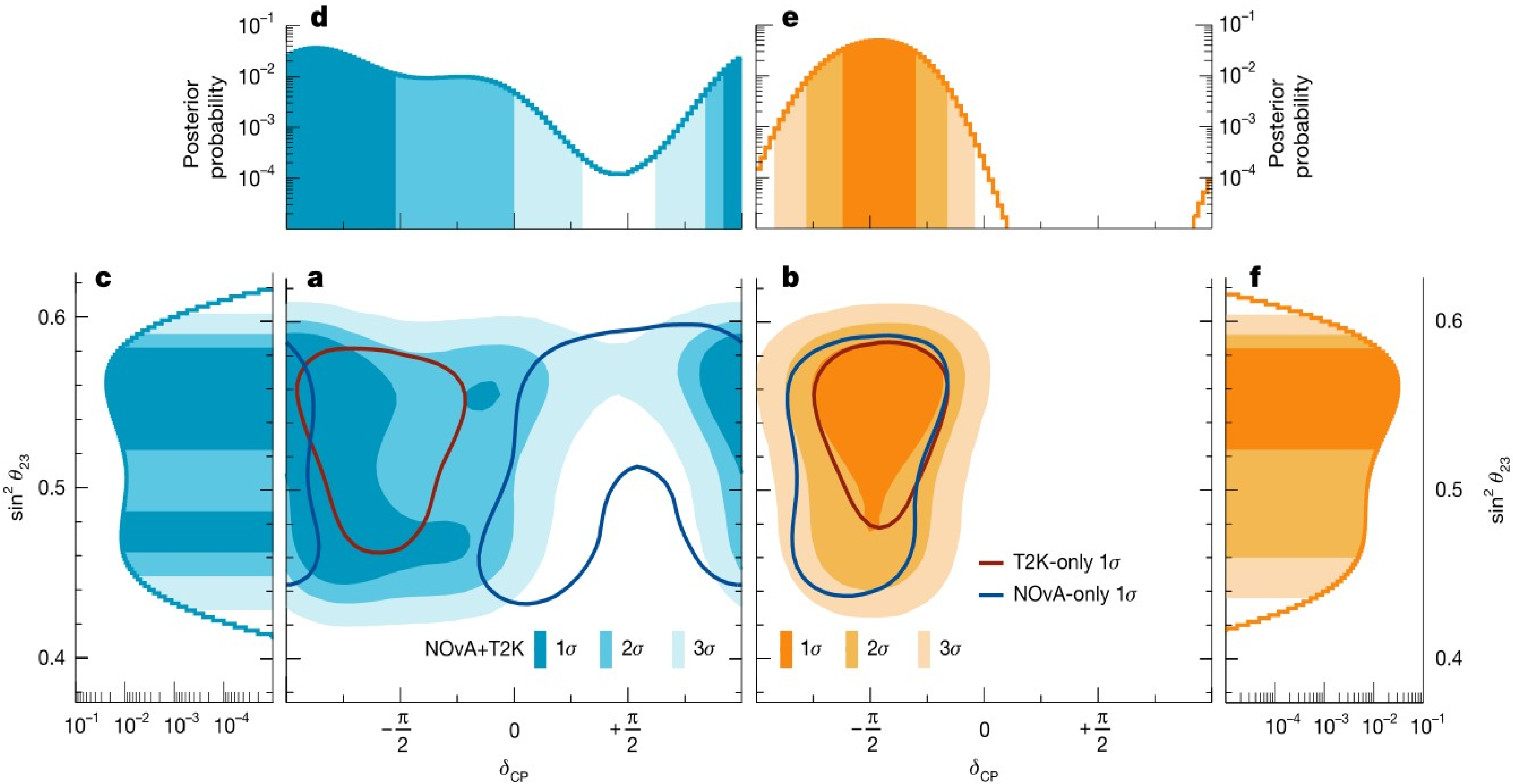
T2K vs NOvA





Nature Vol. 646, pp.818-824, on October 22, 2025

T2K+NOvA Joint Analysis



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CP from Global Fit

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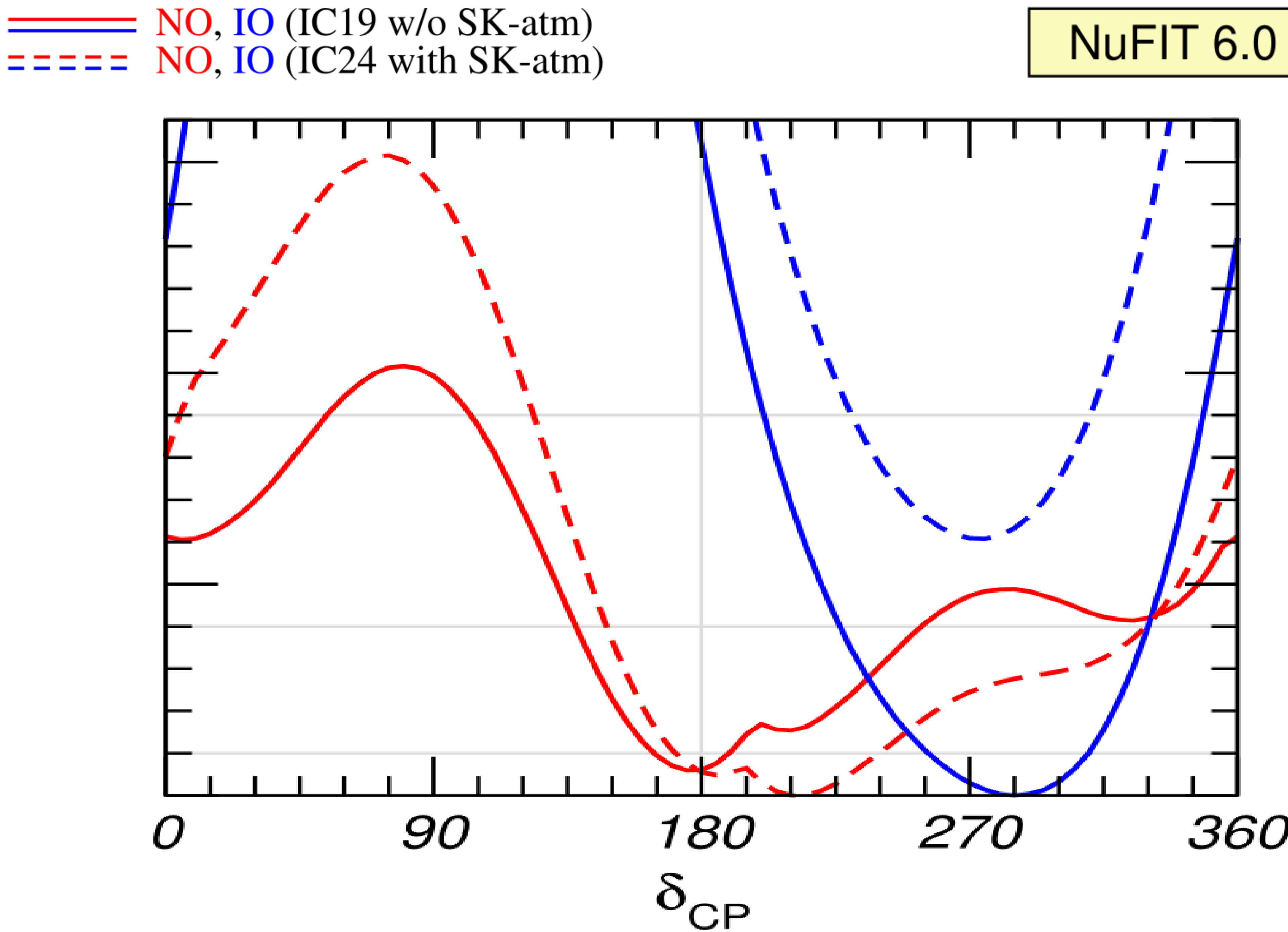

T2K+NOvA Constraint on Δm^2_{32}

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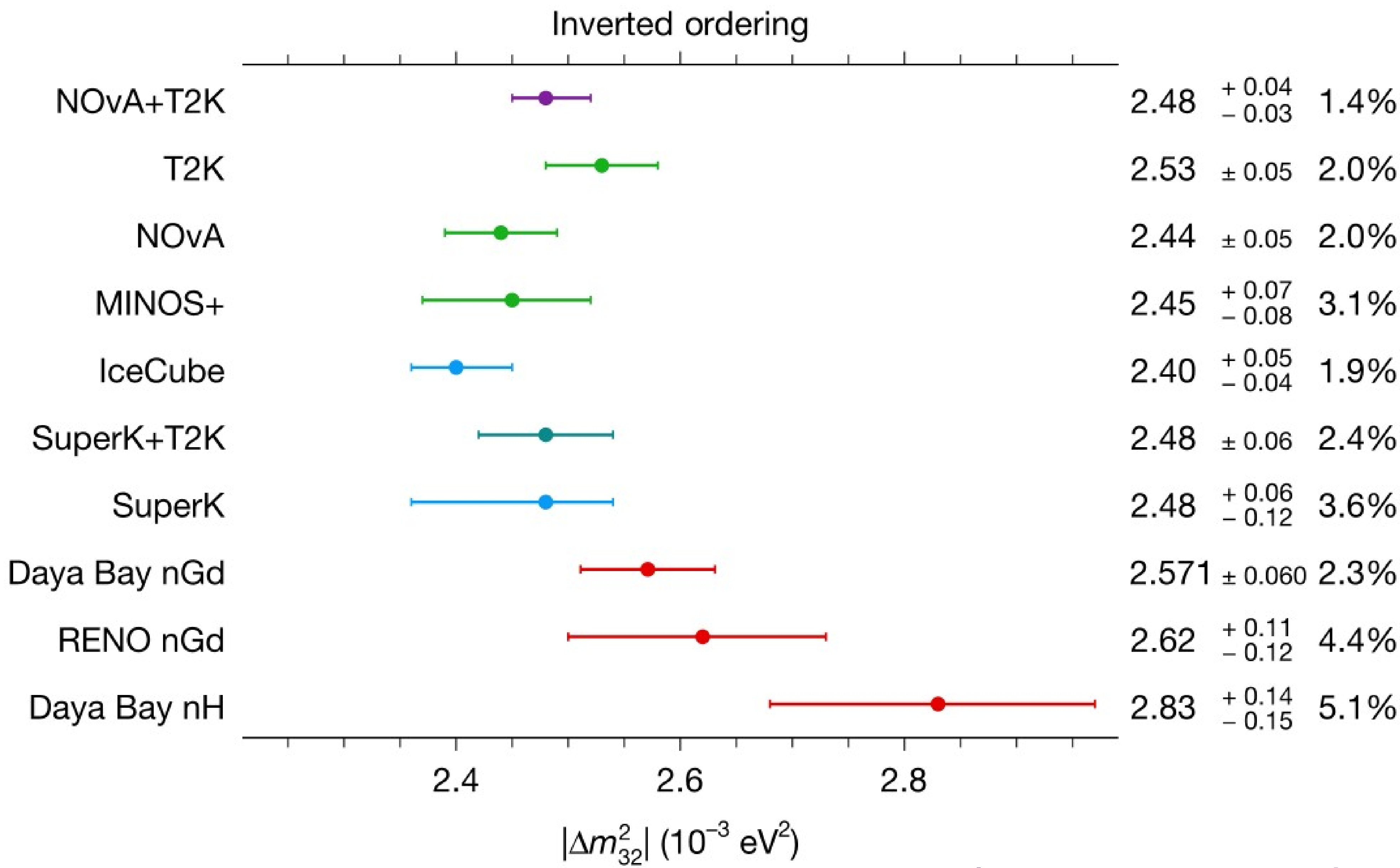
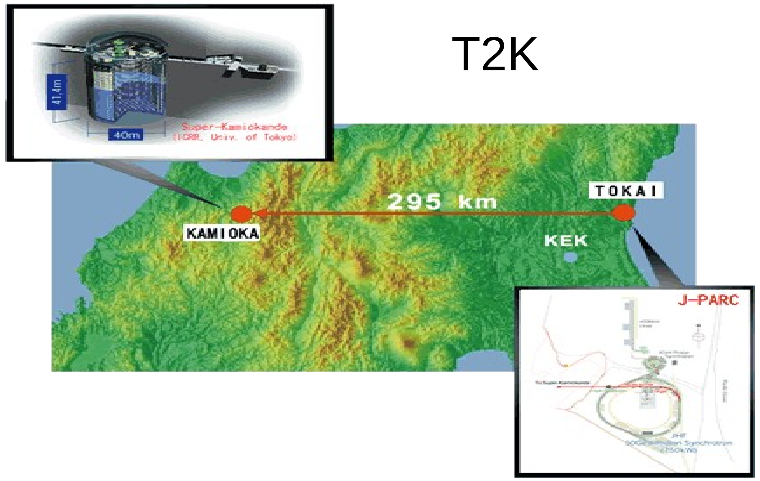
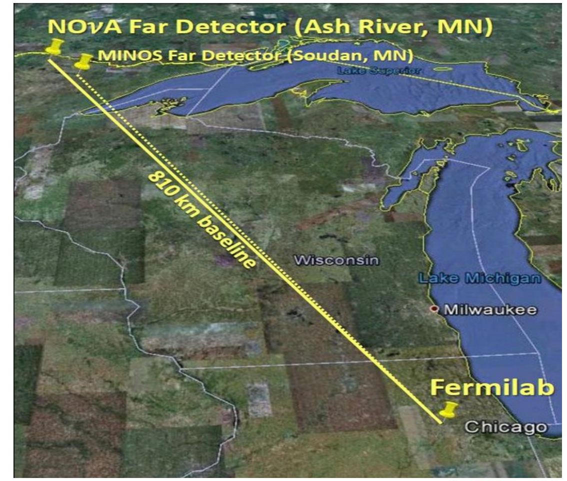


Nature Vol. 646, pp.818-824, on October 22, 2025

Future Accelerator Exps





- Flux upgrade: **T2K-II**, **NOνA-II**?
- Detector upgrade: **T2HK**
- Baseline upgrade: **T2KK**, **T2KO**
- **MOMENT**

Cao et al [1401.8125]
Tang et al [1909.01548]

- In China?

Tang, Vihonen & Xu [2202.13595]
Li et al [2204.11871, 2205.15350, 2301.02493]

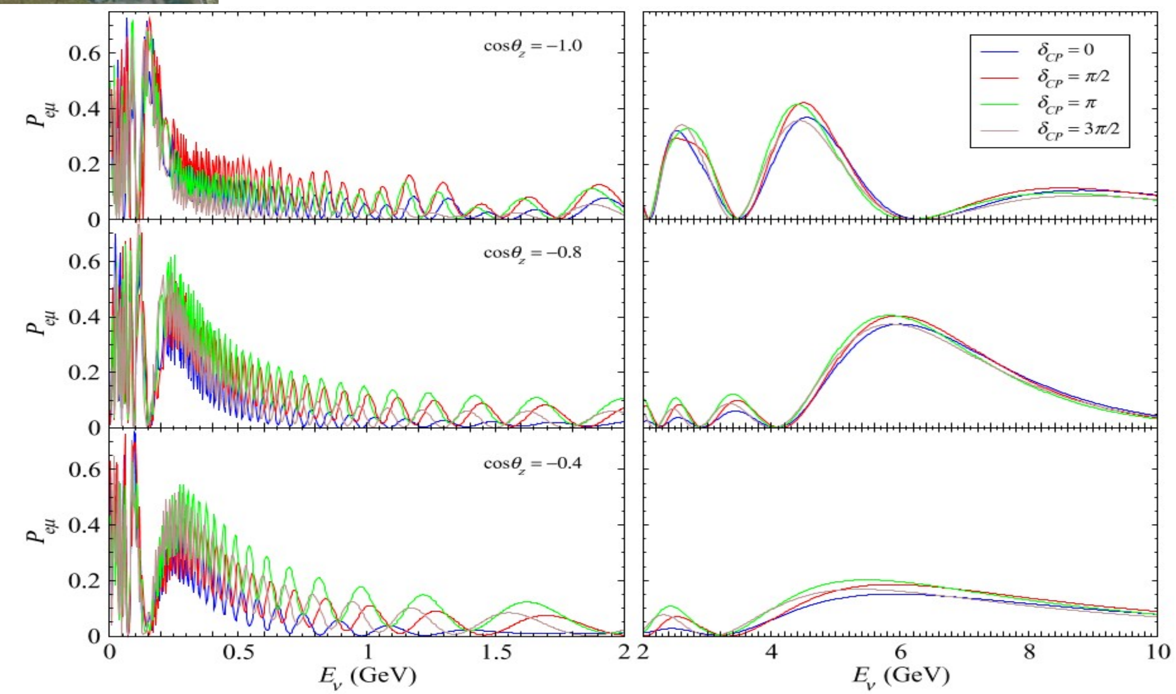
- Atmospheric

Super-PINGU: Razzaque & Smirnov [1406.1407]

JUNO: An et al [1507.05613], 2310.06281

DUNE: Kelly, Machado, Martinez-Soler, Parke & Perez-Gonzalez [1904.02751]

Super-ORCA: Hofestadt, Bruchner & Eberl [1907.12983]



Tension between T2K & NOvA

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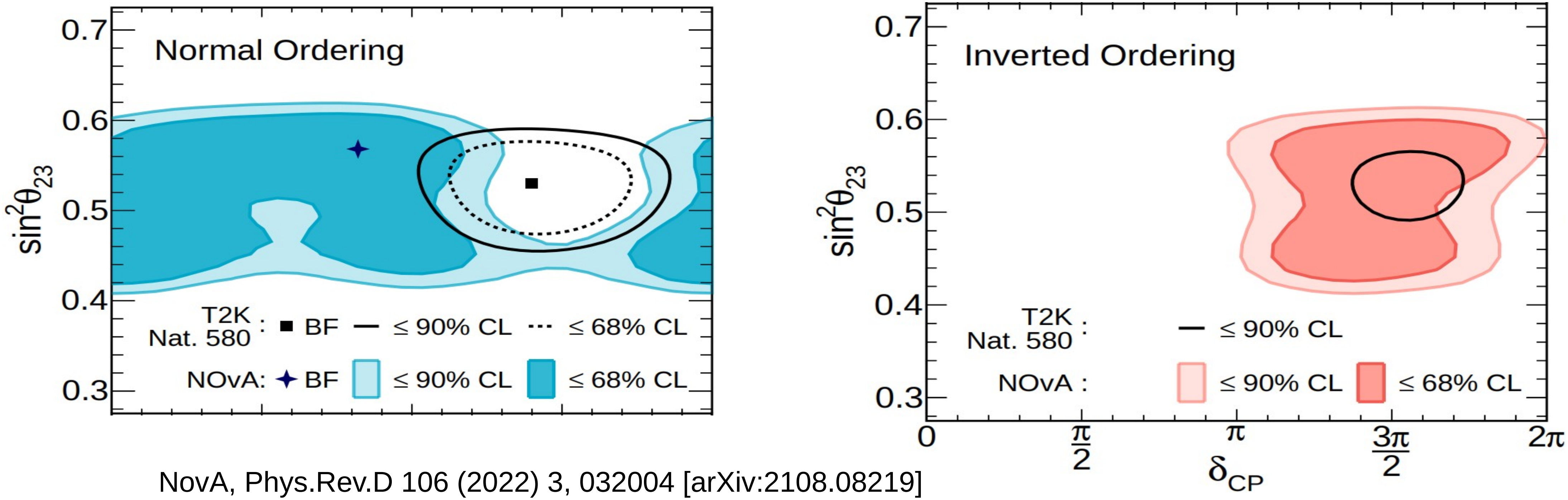

NovA, Phys.Rev.D 106 (2022) 3, 032004 [arXiv:2108.08219]

- **Non-Standard Interactions** — Denton, Gehrlein & Pestes [2008.01110]
- **Non-Unitary Mixing** — Rahaman, Razzaque & Sankar [2201.03250]
- **Lorentz Violation**
- **Sterile Neutrinos** — Chatterjee & Palazzo [2005.10338]

Confusion from New Physics

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- **Non-Standard Interactions**

$$\mathcal{H} \equiv \frac{1}{2\mathbf{E}_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_s^2 & \\ & & \Delta m_a^2 \end{pmatrix} U^\dagger + V_{cc} \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

Du, Li, Tang, Vihonen & Yu [2011.14292, 2106.15800]

Tang & Zhang [1705.09500]

Du, Li, Tang, Vihonen & Yu [2106.15800]

Scalar NSI: **SFG** & Parke [1812.08376]

Smirnov & Xu [1909.07505]

- **Non-Unitary Mixing**

$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}| e^{i\phi} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

SFG, Pasquini, Tortola & Valle [1605.01670]

Tang, Zhang & Li [1708.04909]

Hu, Ling, Tang & Wang [2008.09730]

- **Sterile neutrinos**

Chatterjee & Palazzo [2005.10338]

- **Lorentz violation**

Rahaman, Razzaque & Sankar [2201.03250]

- **Dark NSI**

Berlin [1608.01307]

Zhao [1701.02735]

Brdar, Kopp, Liu, Prass & Wang [1705.09455]

Liao, Marfatia & Whisnant [1803.01773]

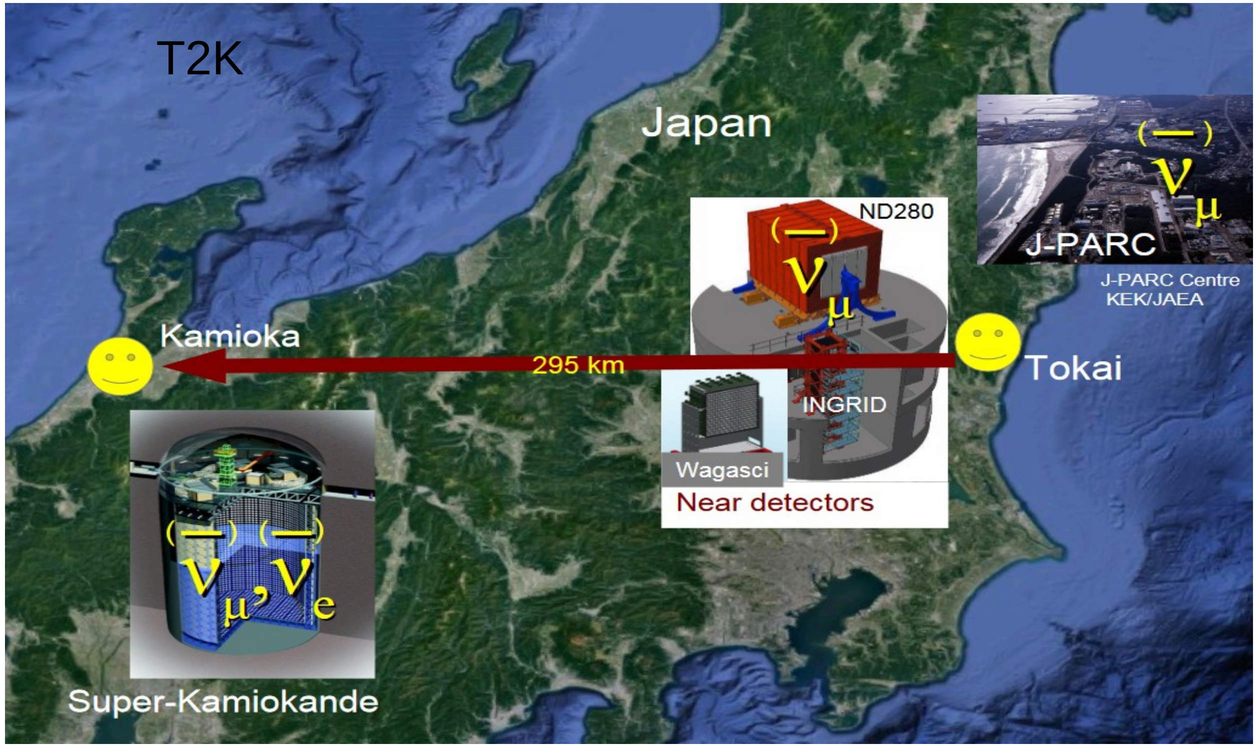
Chao, Hu, Jiang & Jin [2009.14703]

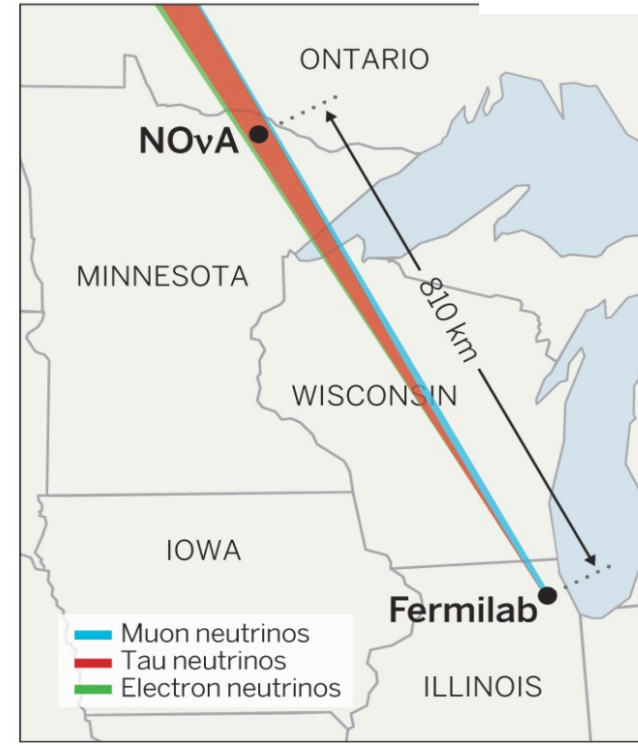
SFG, Murayama [1904.02518]

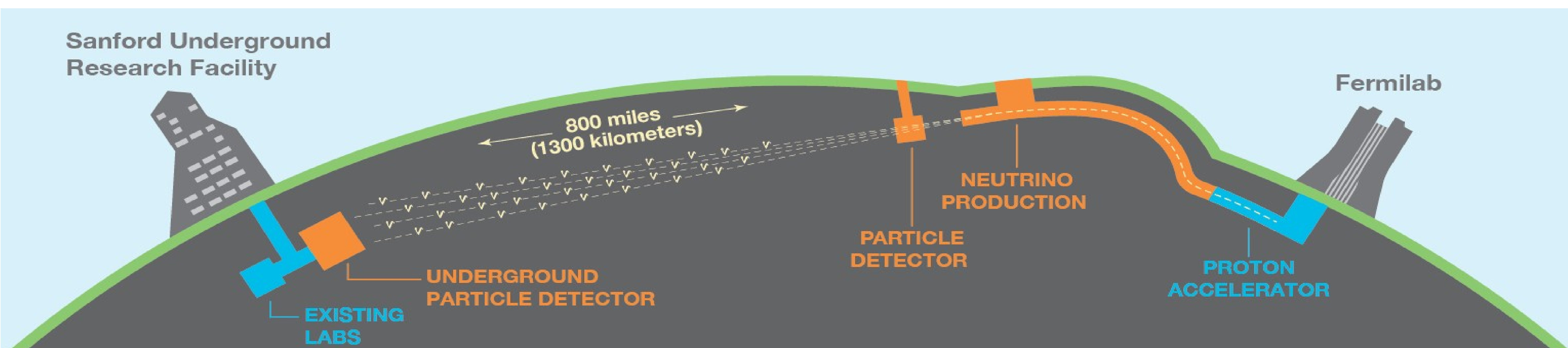
SFG, PoS NuFact2019 (2020) 108

SFG, J.Phys.Conf.Ser. 1468 (2020) 1, 012125

Accelerator ν Experiments





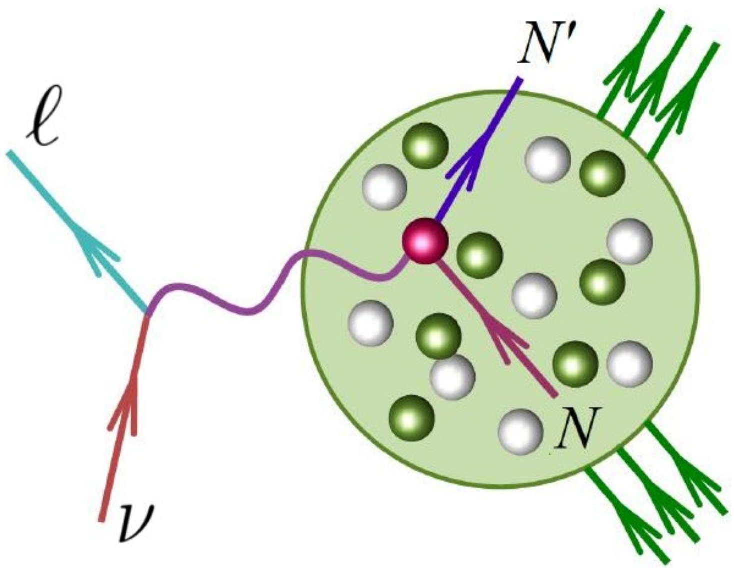


Production vs Detection

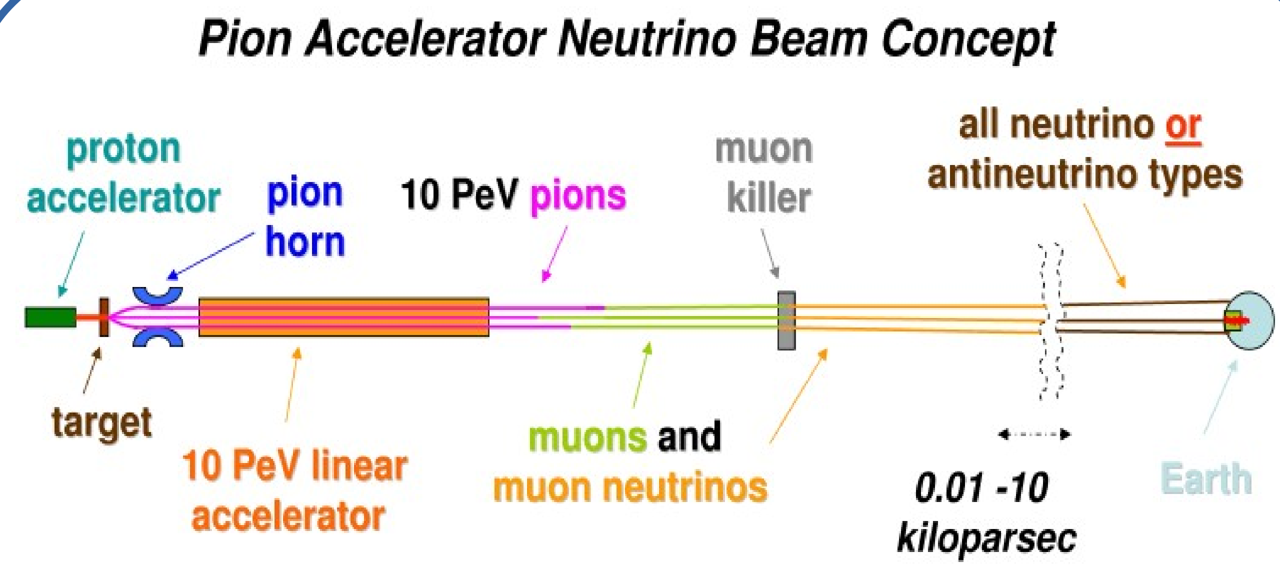
$$\mathcal{A}^{\rm osc}_{\beta\alpha} \equiv \sum_i U_{\beta i} e^{-i\frac{m_i^2}{2E_\nu}L} U^*_{\alpha i}$$

$Q_d^2 \approx ?$

$Q_p^2 \approx (100\,\mathrm{MeV})^2$



Detection: ES, RES, DIS



Production: π, μ, K decays

Mismatched Momentum Transfer

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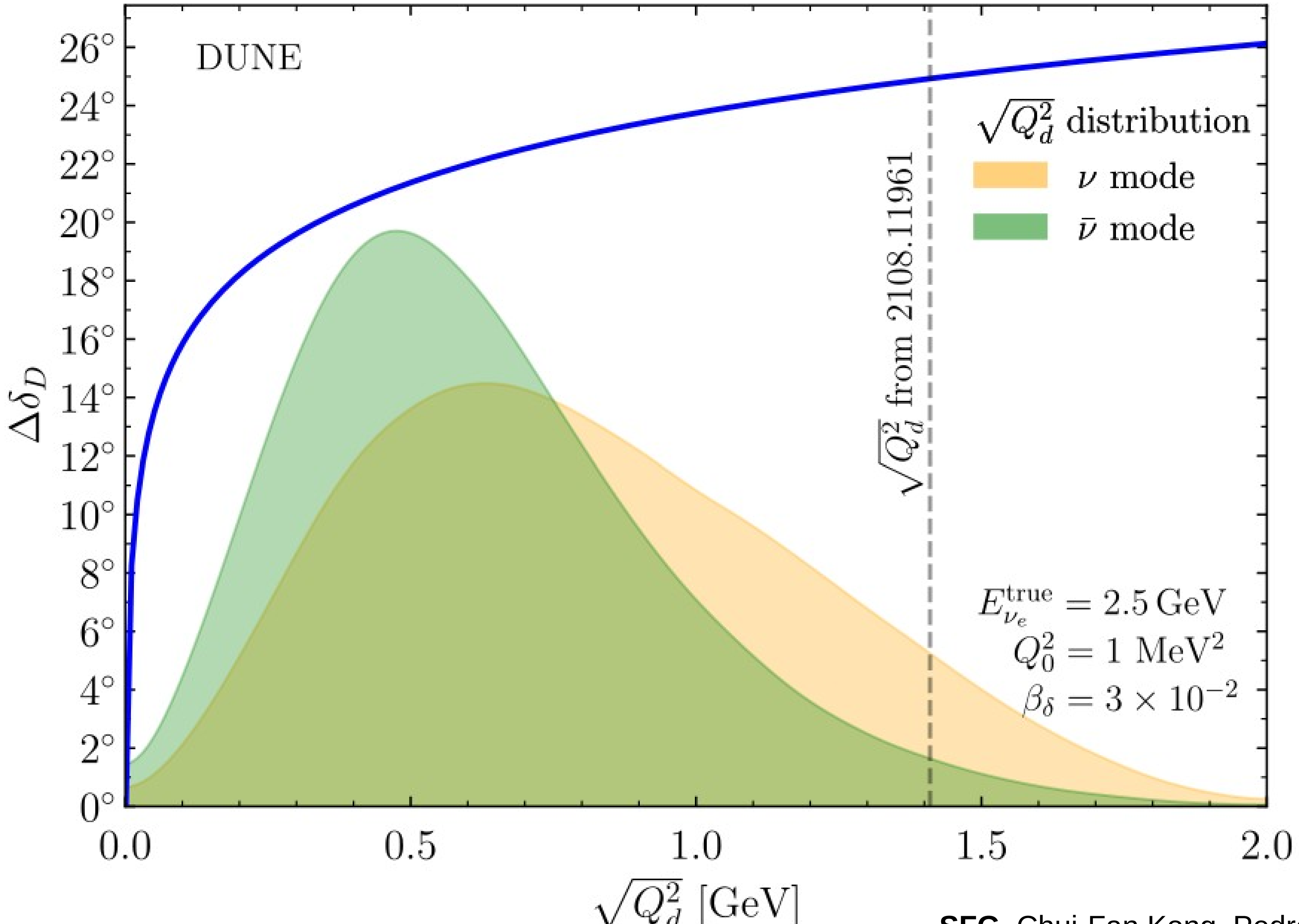
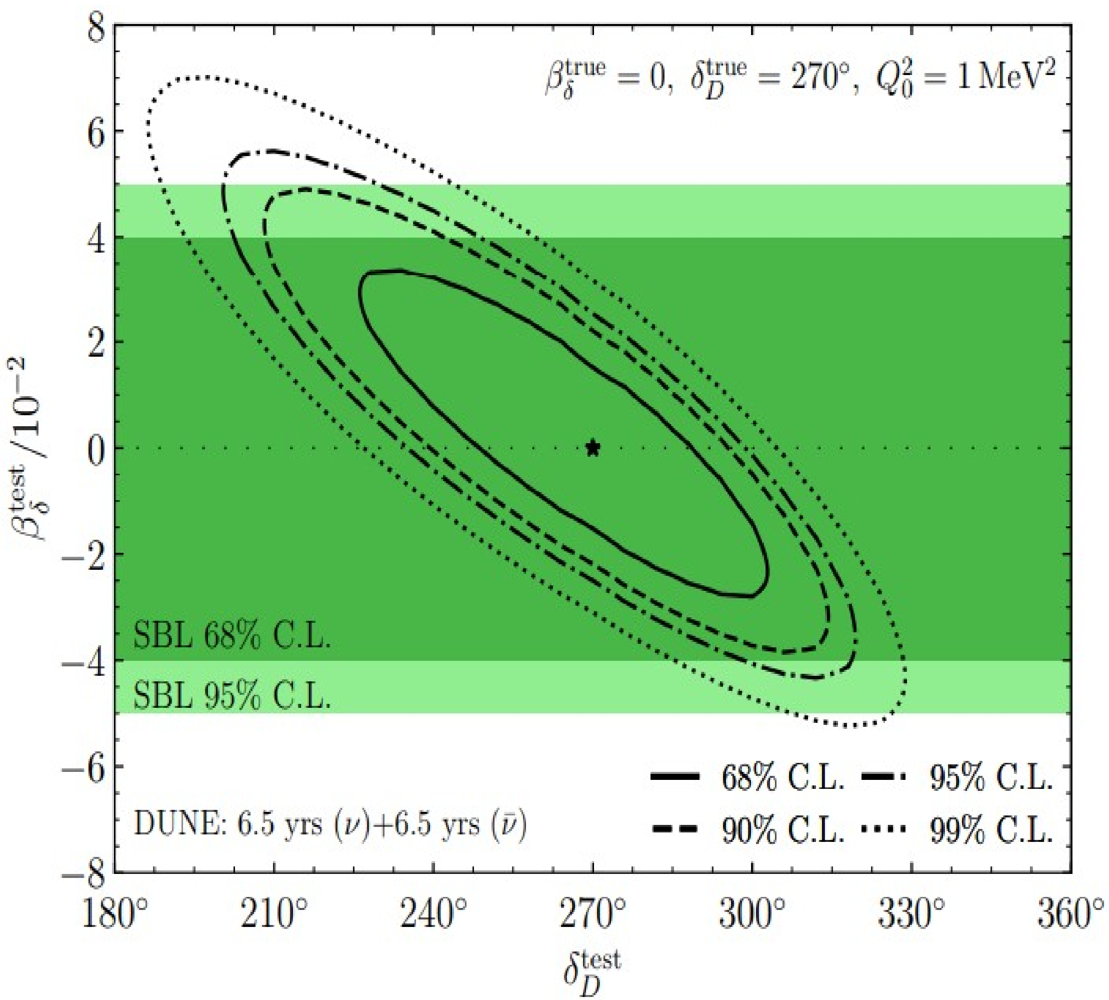
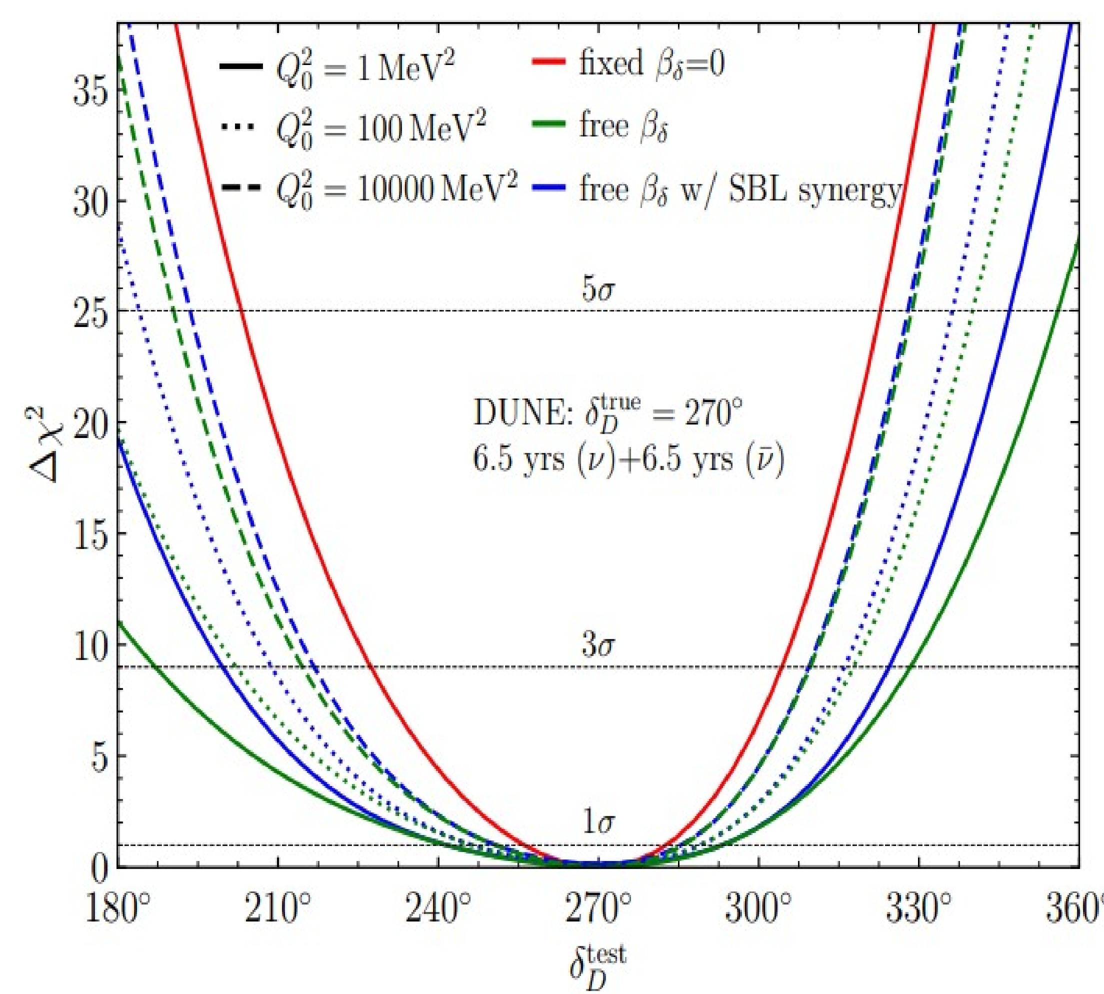


SFG, Chui-Fan Kong, Pedro Pasquini [**PRD, 2310.04077**]

Degeneracy with CP Phase

$$\mathcal{A}^{\rm osc}_{\beta\alpha} = U_{\beta i}(Q^2_d) e^{-iL\frac{m^2_i}{2E_\nu}} U^*_{\alpha i}(Q^2_p) \qquad \delta_D(Q^2) \equiv \delta_D(Q^2_0) + \beta_\delta \ln\left(\left|\frac{Q^2}{Q^2_0}\right|\right)$$





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Momentum Transfer in Matter Effect

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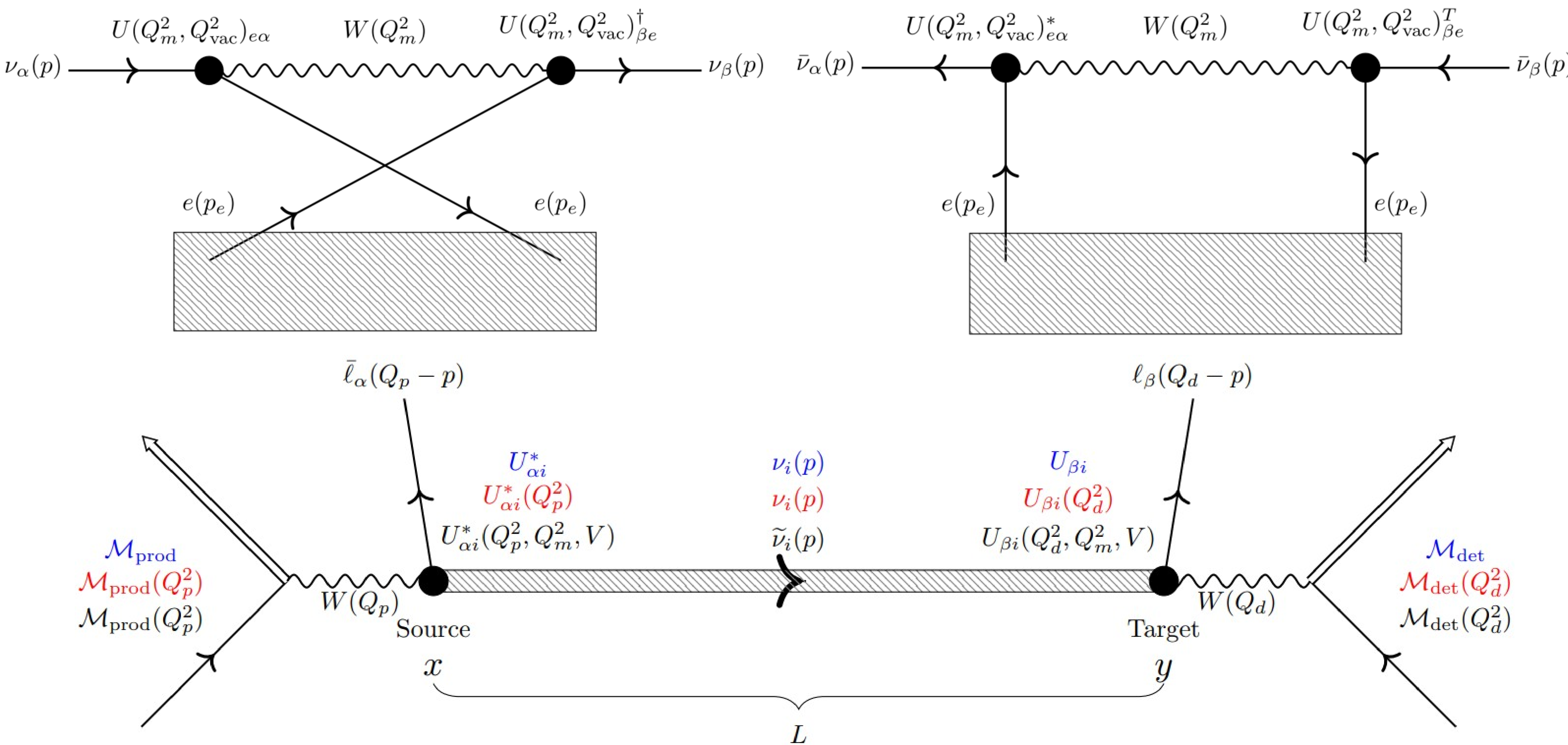

blue : vacuum w/o RG ruuning   red : vacuum w/ RG ruuning   black : w/ matter effect & RG ruuning

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Energy Reconstruction @ DUNE

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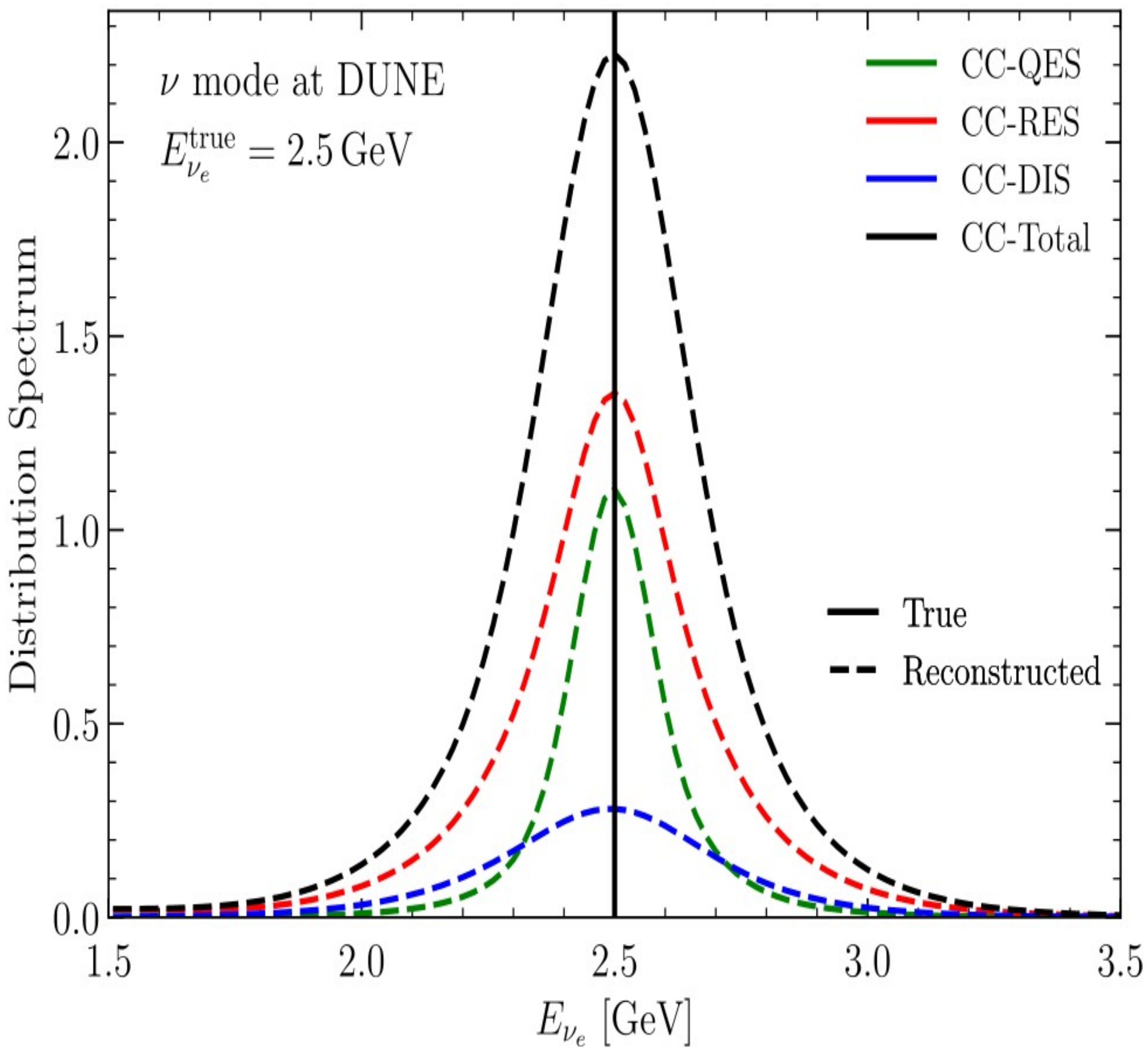
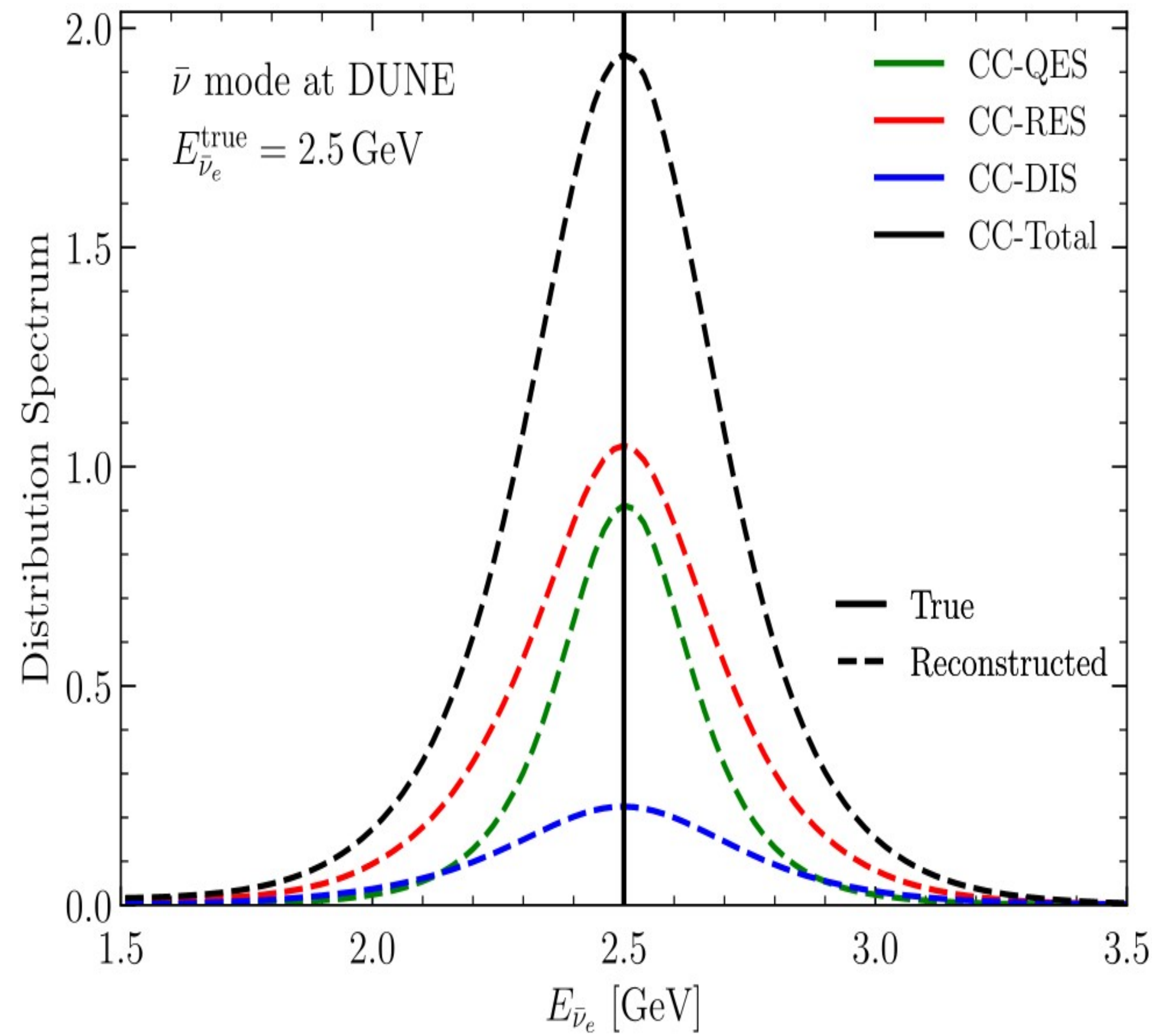
$$E_\nu^{\rm rec} = E_\ell^{\rm rec} + E_{\rm had}^{\rm rec}$$





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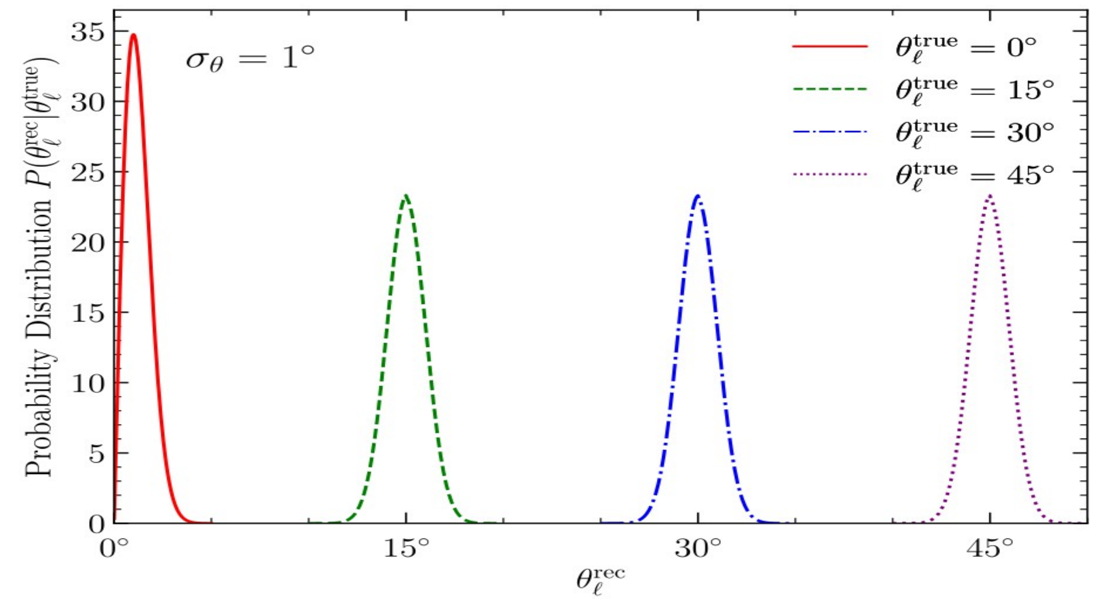
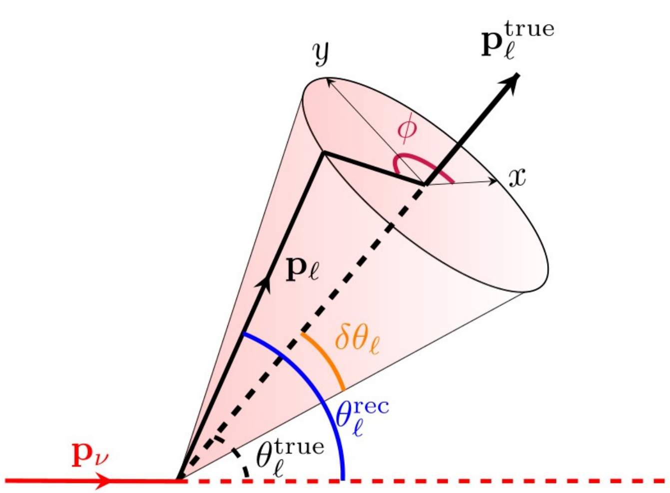
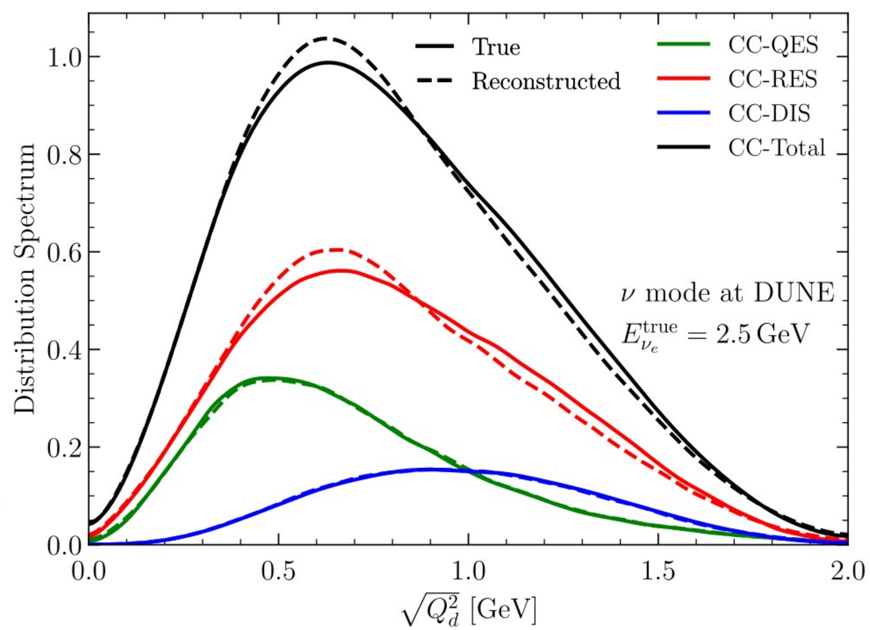
Momentum Transfer Reconstruction

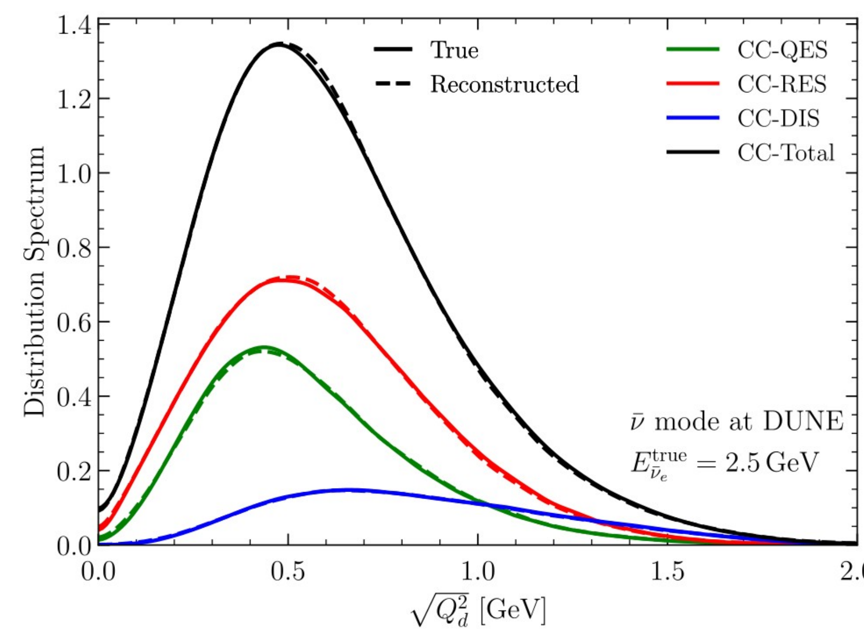
$$Q^2_{\rm rec} \equiv \left|(p_\nu^{\rm rec} - p_\ell^{\rm rec})^2\right| = 2E_\nu^{\rm rec}\left(E_\ell^{\rm rec} - |\boldsymbol{p}_\ell^{\rm rec}|\cos\theta_\ell^{\rm rec}\right) - m_\ell^2$$

Particle	Energy Resolution (σ/E) at DUNE
$\pi^\pm$	15%
$e^\pm/\gamma$	1.5%
p	$p < 400\,\mathrm{MeV/c}: 4\%$ $p > 400\,\mathrm{MeV/c}: 10\% \oplus 3.1\%/\sqrt{E}\,[\mathrm{GeV}]$
n	$40\%/\sqrt{E}\,[\mathrm{GeV}]$
other	$5\% \oplus 30\%/\sqrt{E}\,[\mathrm{GeV}]$









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Extended GLoBES Simulation

$$\left.\frac{dN^{\text{true}}}{dE_\nu^{\text{true},i}}\right|_{Q^2_{\text{true},j}} \equiv N^{\text{target}} \phi_\alpha(E_\nu^{\text{true},i}) P_{\alpha\beta}(E_\nu^{\text{true},i}, Q^2_{\text{true},j}) \sigma_\beta(E_\nu^{\text{true},i})$$

Single GLoBES

$$\text{GLB}_j: \quad N_i^{\text{GLB}_j} = \left.\frac{dN^{\text{true}}}{dE_\nu^{\text{true},i}}\right|_{Q^2_{\text{true},j}} \Delta E_i^{\text{true},i}$$

Implement momentum transfer by hand

$$N_{ij} \equiv N_i^{\text{GLB}_j} \times \left.\left(\frac{d\sigma_\beta}{\sigma_\beta dQ^2_{\text{true},j}}\right)\right|_{E_\nu^{\text{true},i}} \Delta Q^2_{\text{true},j}$$

4D transfer table

$$N_{i'j'} \equiv \sum_{ij} N_{ij} \times T'_{iji'j'} \equiv \sum_{ij} N_i^{\text{GLB}_j} \times T_{iji'j'}$$

$$T_{iji'j'} \equiv \left.\left(\frac{d\sigma_\beta}{\sigma_\beta dQ^2_{\text{true},j}}\right)\right|_{E_\nu^{\text{true},i}} \times \Delta Q^2_{\text{true},j} \times T'_{iji'j'} = \frac{\Delta N(E_\nu^{\text{true},i}, Q^2_{\text{true},j}; E_\nu^{\text{rec},i'}, Q^2_{\text{rec},j'})}{N_{\text{total}}(E_\nu^{\text{true},i})}$$

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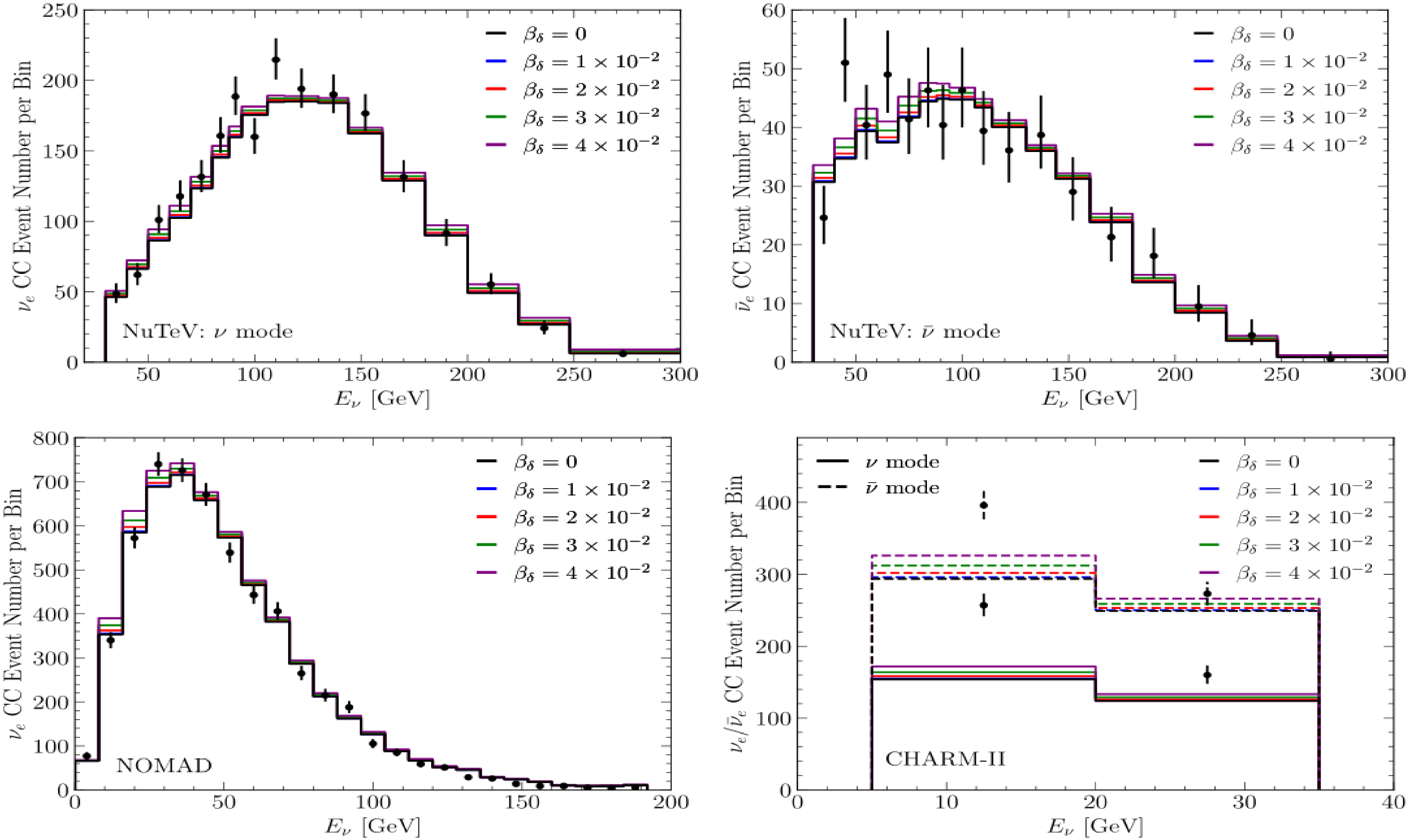
Existing Short-Baseline Experiments



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Constraint @ Short-Baseline Experiments

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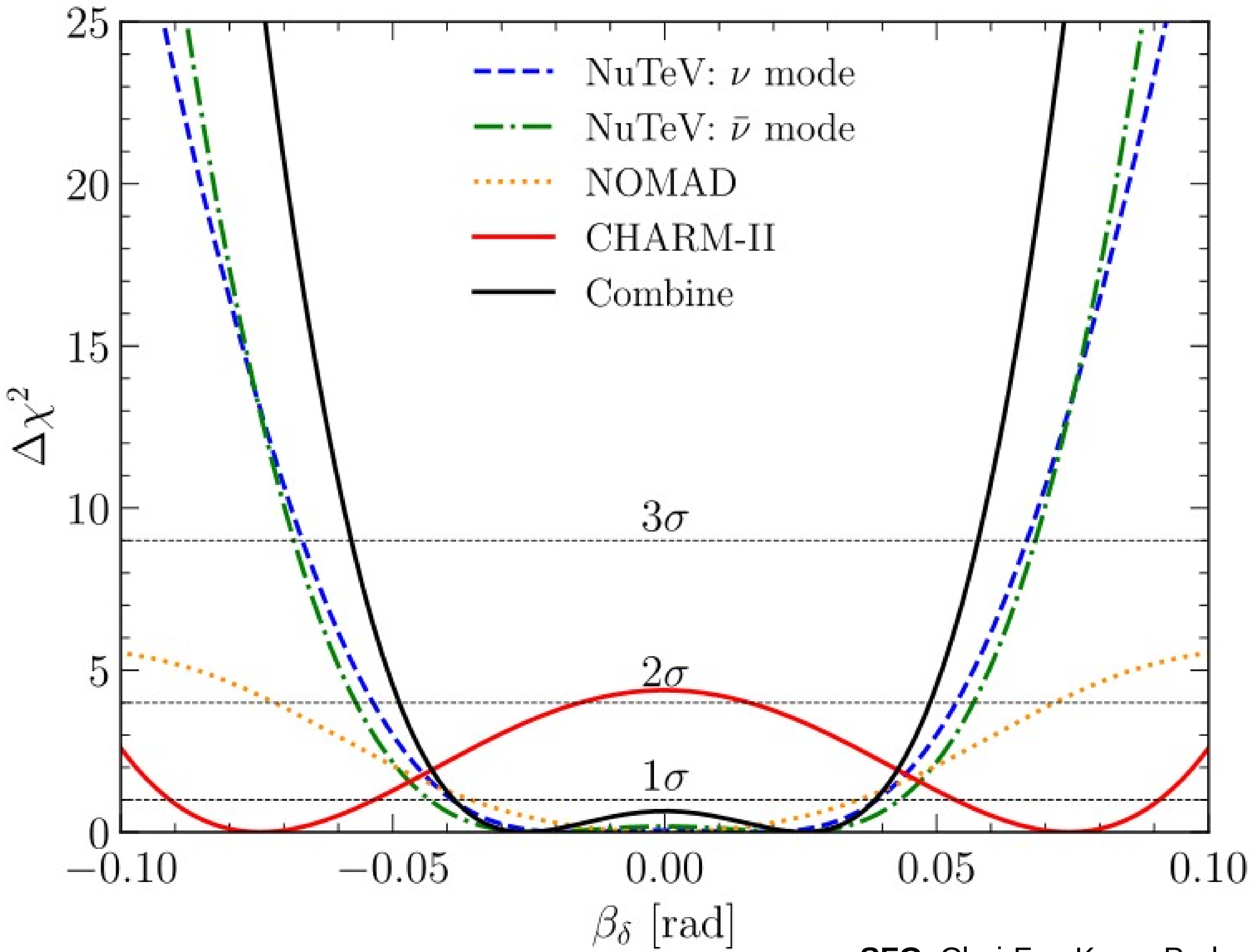

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