Neutrino RG Running in Oscillation Experiments

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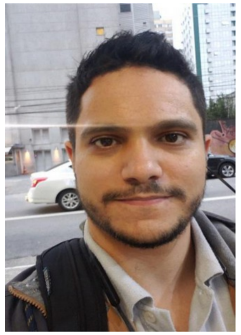


Pedro Pasquini

孔垂范

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

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

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

νSTEP 2025 @ Beijing

October 25, 2025

李政道研究所 Tsung-Dao Lee Institute

Outline

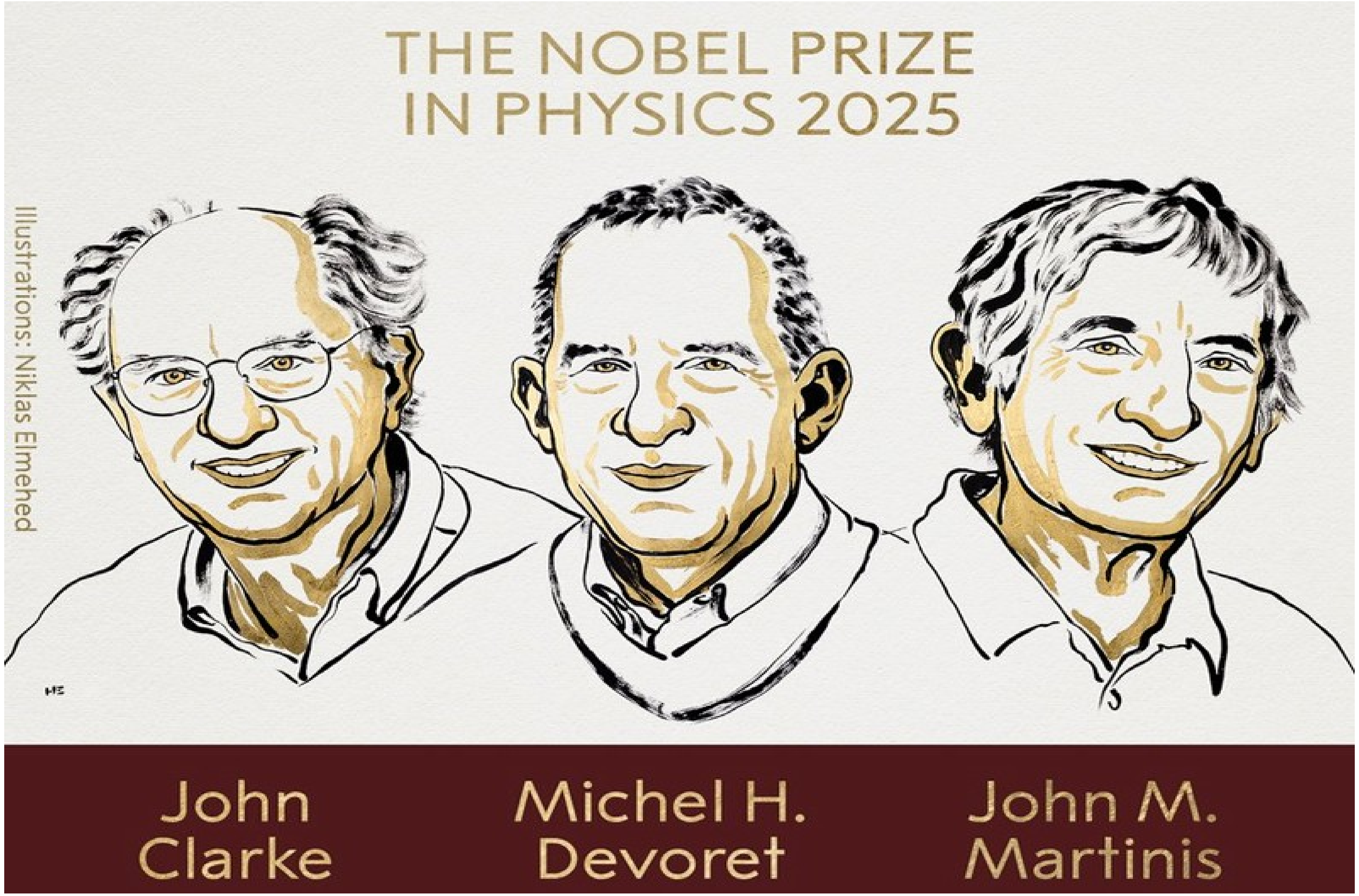
1) Overview of CP Status

2) RG Running vs CP

3) Zero-Distance Effect @ Short Baseline

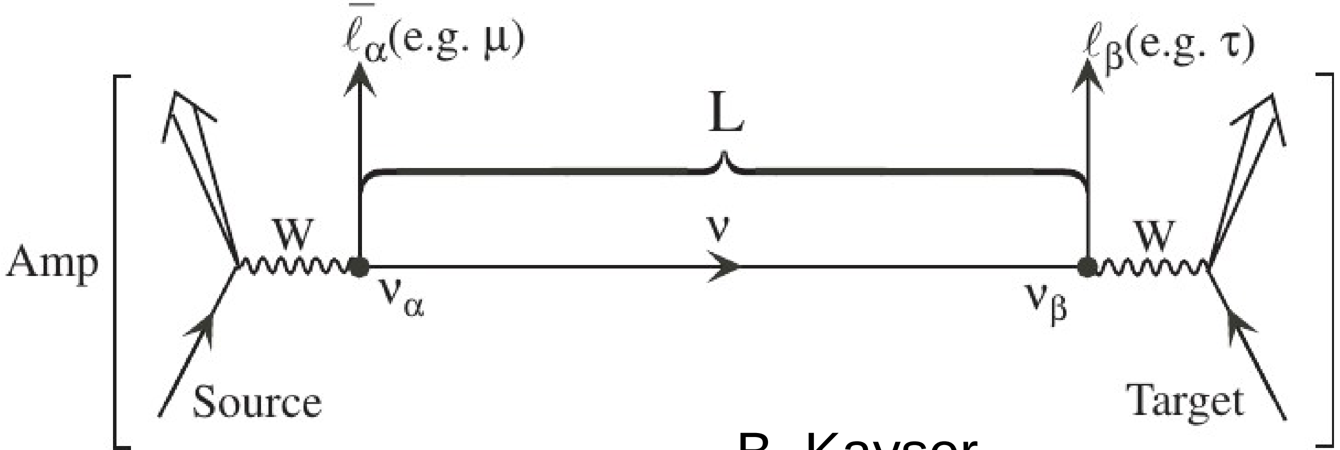
4) Summary

Nobel Prize in Physics 2025

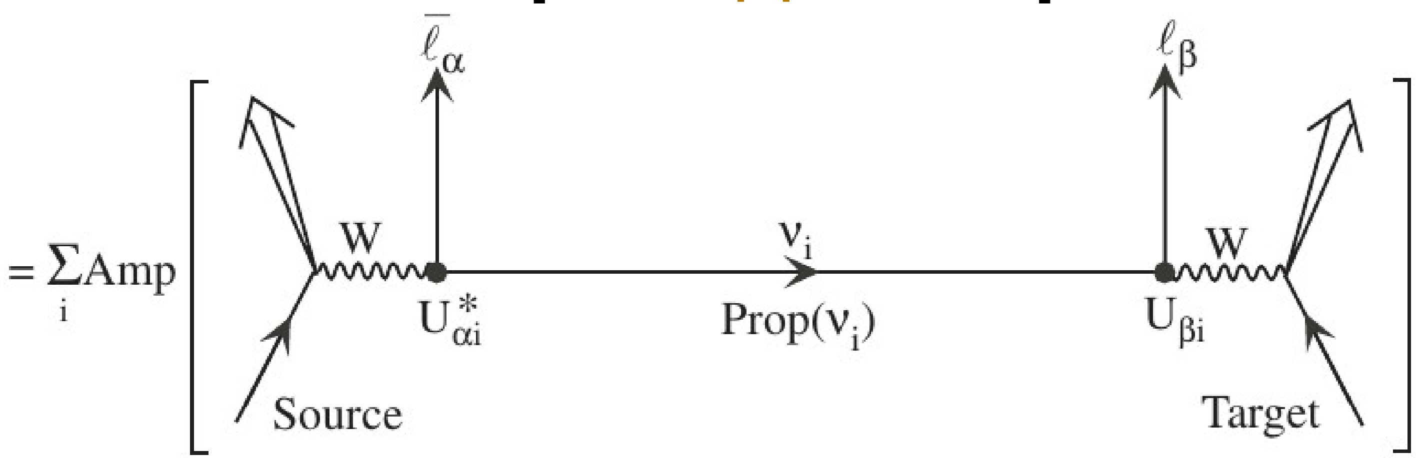


Macroscopic quantum phenomena

ν Oscillation as Macroscopic QM Pheno



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



ν oscillation is essential quantum interference @ macroscopic scales!

Reactor: O(1~10) km

Accelerator: O(100~1000) km

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

Solar: O(10^5) km

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

3ν Oscillation & PMNS Matrix

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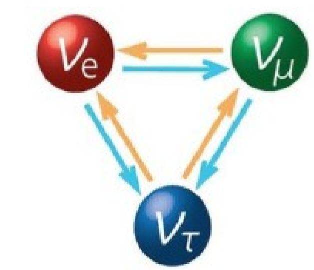
$$\mathrm{U}_{\mathrm{PMNS}} = \mathcal{P} \begin{pmatrix} c_s c_r & s_s c_r & s_r e^{-i\delta_D} \\ -s_s c_a - c_s s_a s_r e^{i\delta_D} & +c_s c_a - s_s s_a s_r e^{i\delta_D} & s_a c_r \\ +s_s s_a - c_s c_a s_r e^{i\delta_D} & -c_s s_a - s_s c_a s_r e^{i\delta_D} & c_a c_r \end{pmatrix} \mathcal{Q}$$



with $\mathcal{P} \equiv \mathrm{diag}(e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3})$ & $\mathcal{Q} \equiv \mathrm{diag}(e^{i\delta_{M1}}, 1, e^{i\delta_{M3}})$
[$(s, a, r) \equiv (12, 23, 13)$ 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

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IC19 without SK atmospheric data

	Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$0.430 \to 0.596$	$0.562^{+0.012}_{-0.015}$	$0.437 \to 0.597$
$\theta_{23}/^\circ$	$48.5^{+0.7}_{-0.9}$	$41.0 \to 50.5$	$48.6^{+0.7}_{-0.9}$	$41.4 \to 50.6$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$0.02023 \to 0.02376$	$0.02224^{+0.00056}_{-0.00057}$	$0.02053 \to 0.02397$
$\theta_{13}/^\circ$	$8.52^{+0.11}_{-0.11}$	$8.18 \to 8.87$	$8.58^{+0.11}_{-0.11}$	$8.24 \to 8.91$
$\delta_{CP}/^\circ$	177^{+19}_{-20}	$96 \to 422$	285^{+25}_{-28}	$201 \to 348$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.534^{+0.025}_{-0.023}$	$+2.463 \to +2.606$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \to -2.438$

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

Daya Bay heralded a new era of precision measurement in 2012!

Kam-Biu Luk @ Neutrino 2022

CP Measurement

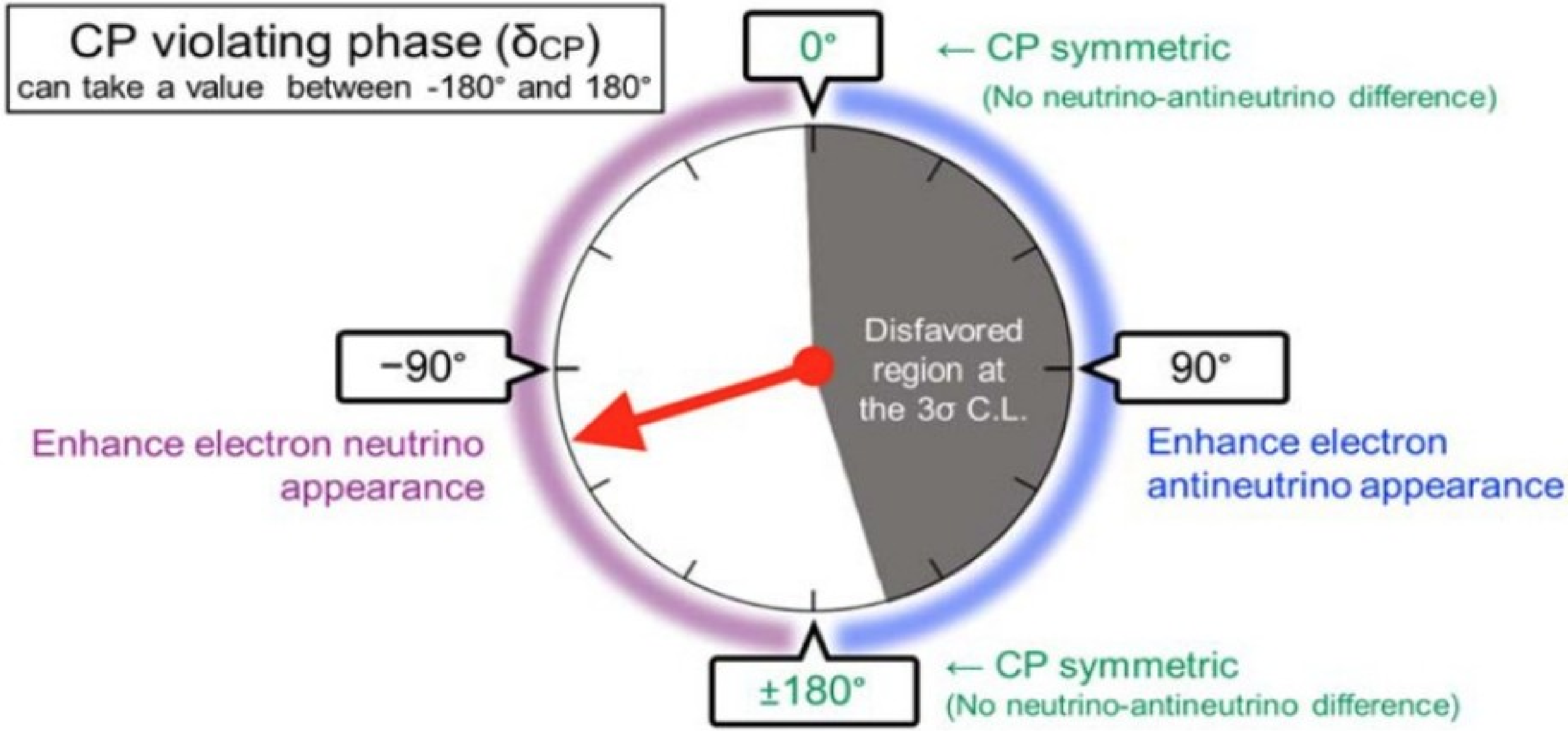
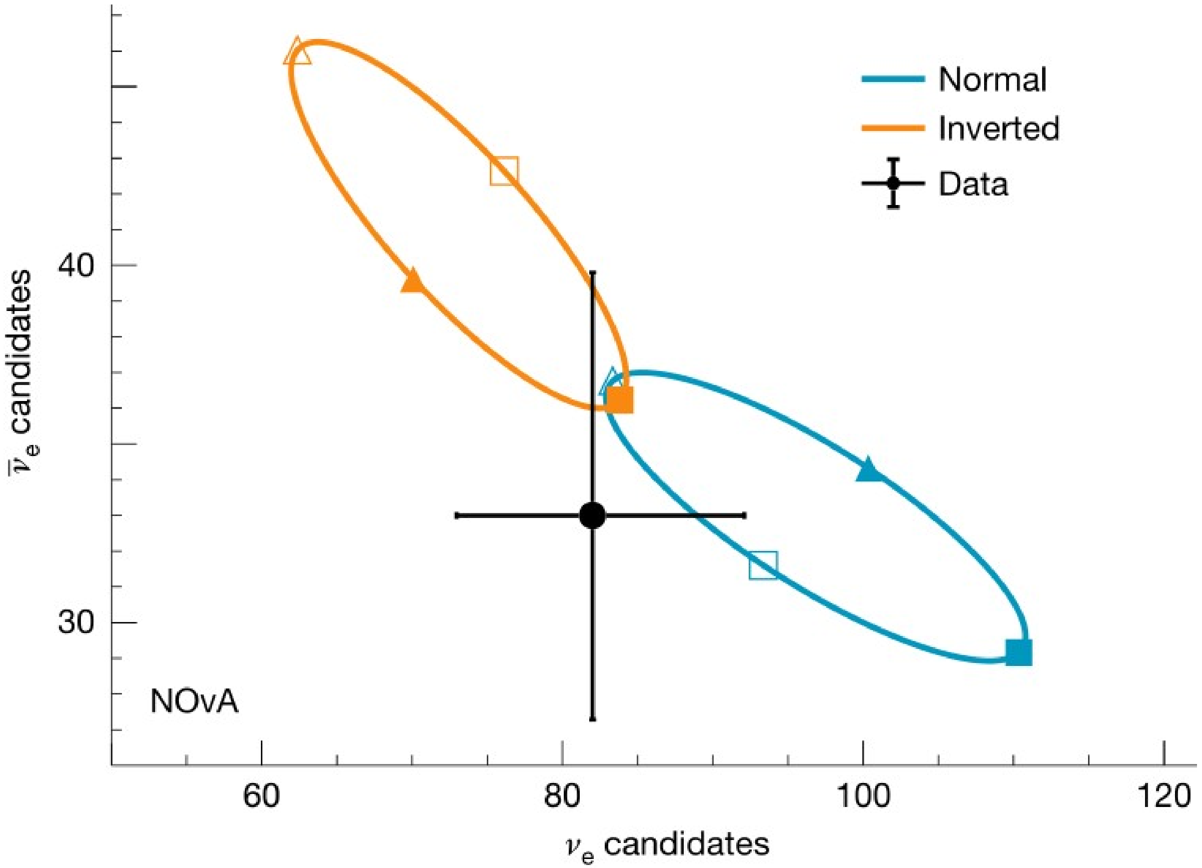


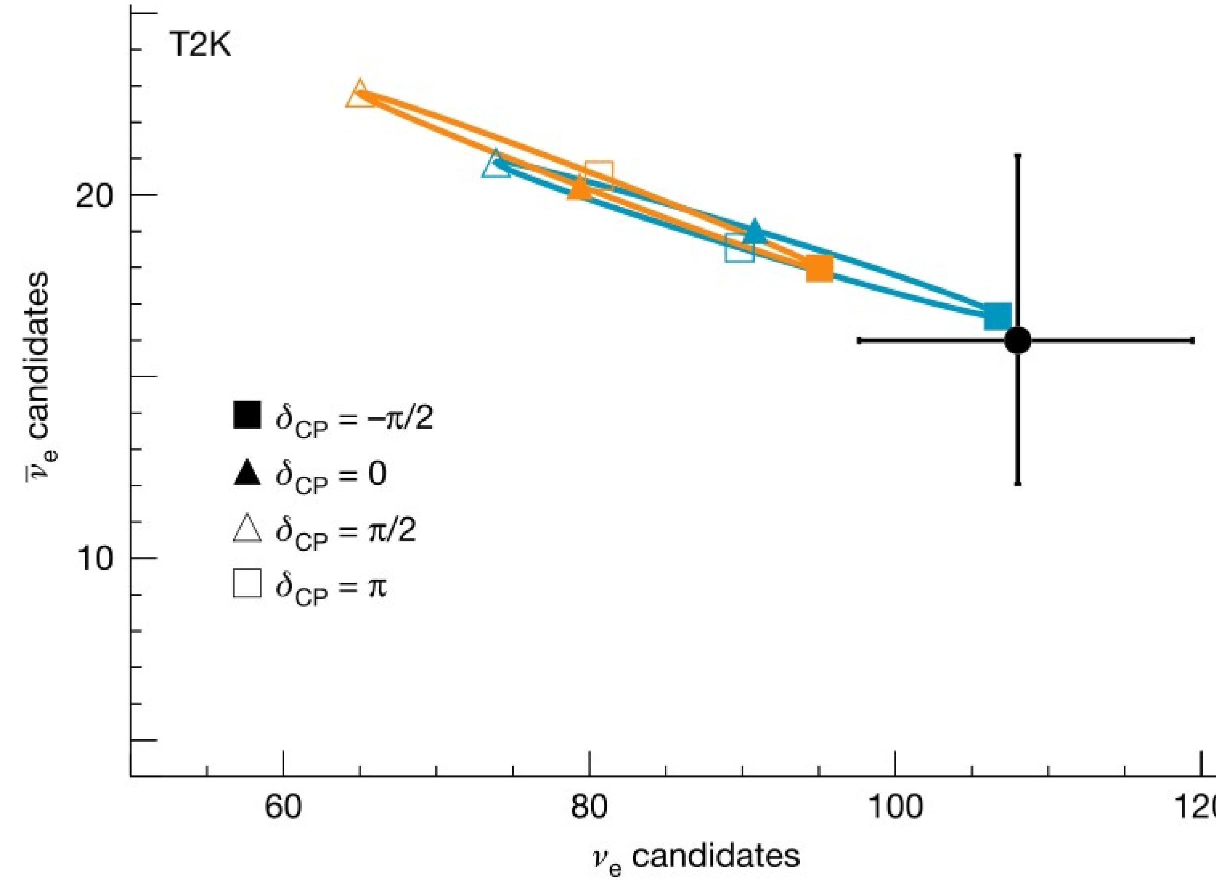
Fig.1 The arrow indicates the value most compatible with the data. The gray region is disfavored at 99.7% (3σ) confidence level. Nearly half of the possible values are excluded.

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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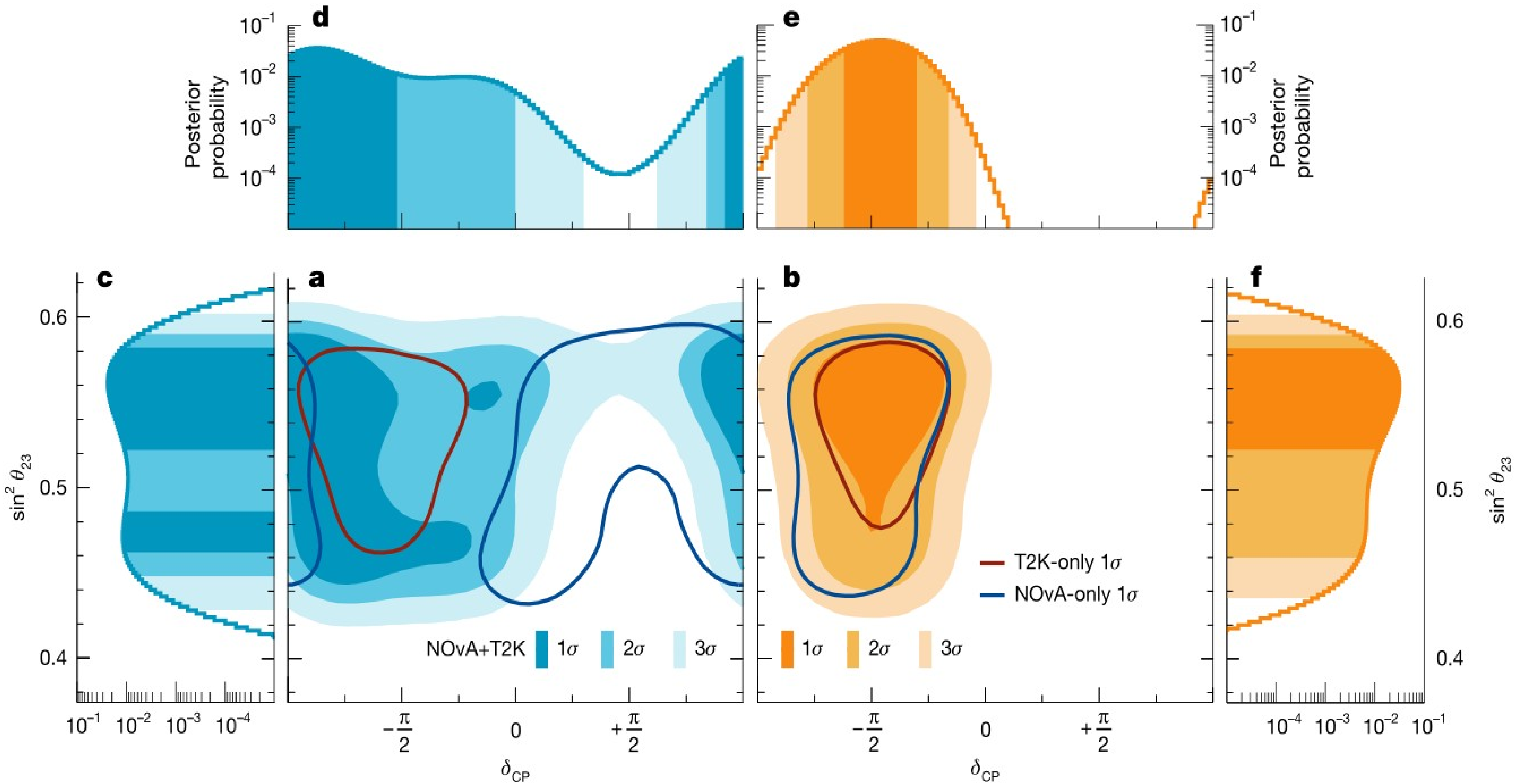

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CP from Global Fit

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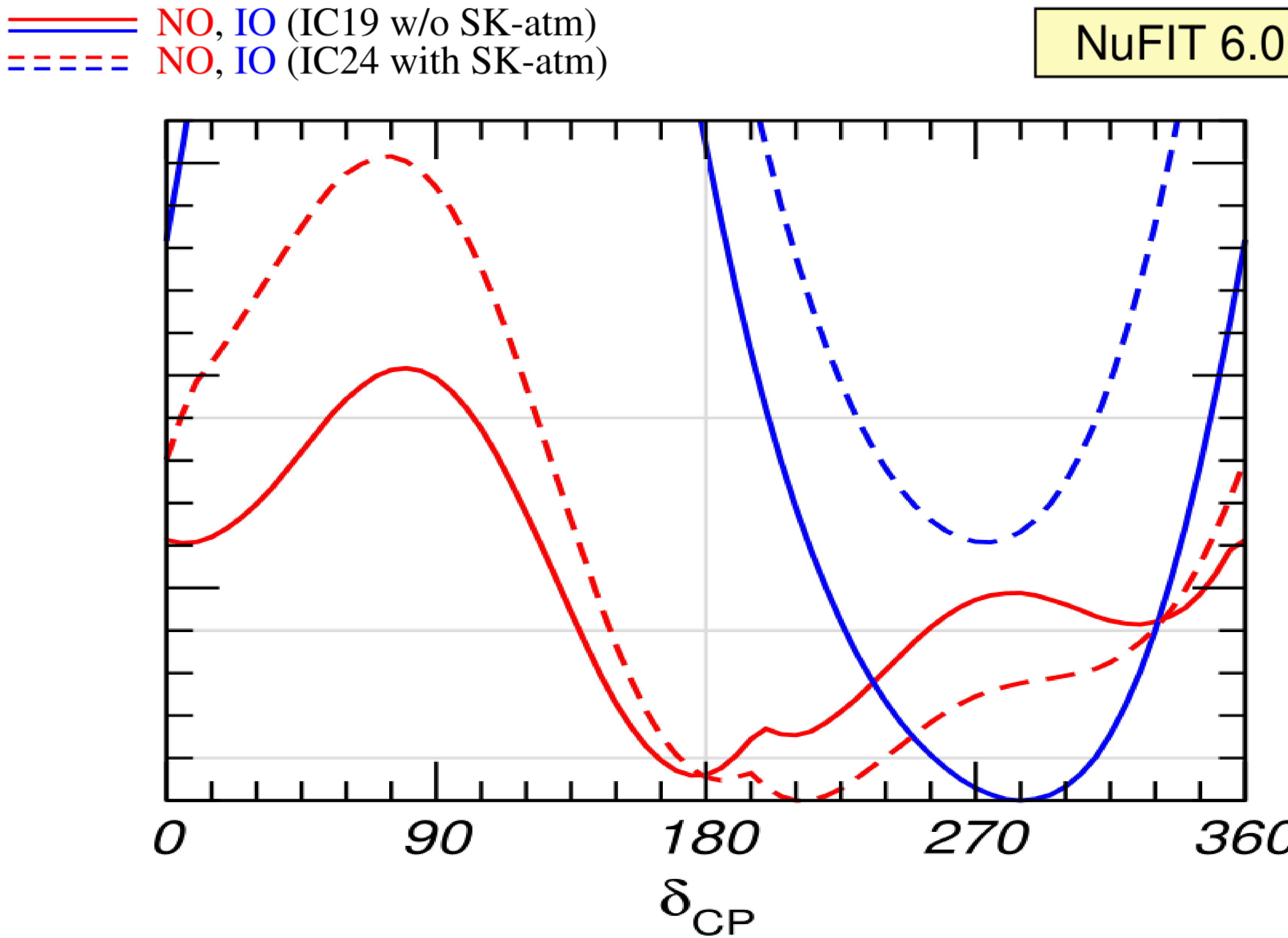
NuFIT 6.0 (2024)



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Two Mixing Matrices in ν Oscillation

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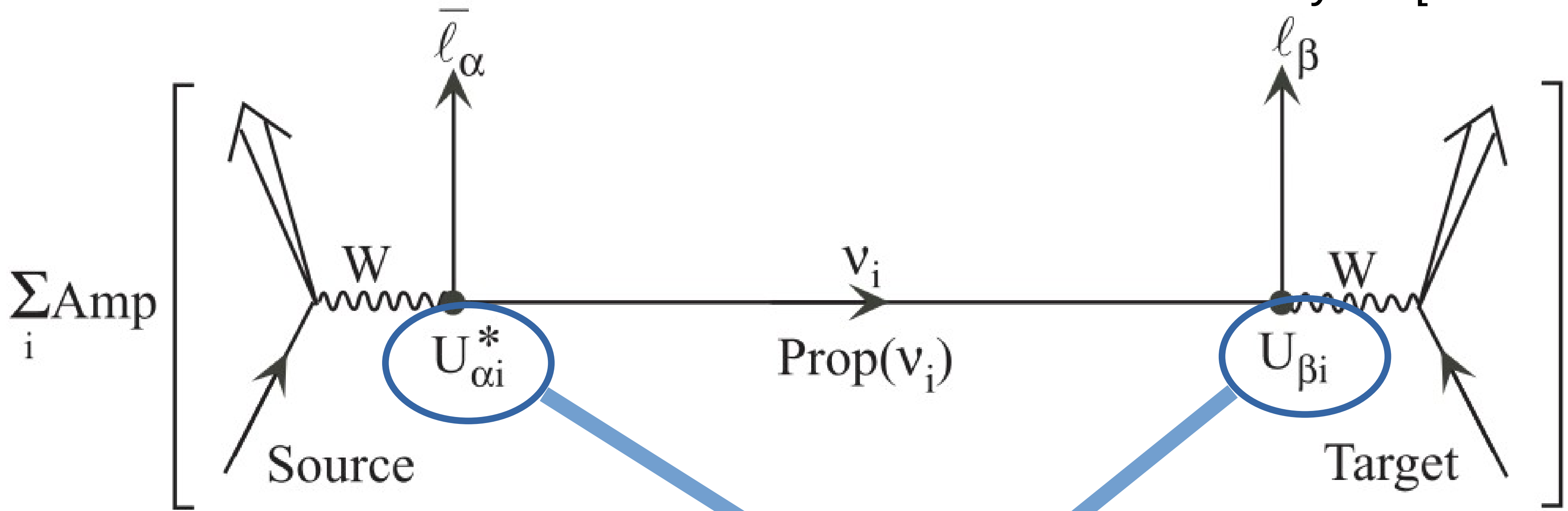
B. Kayser [arXiv:hep-ph/0506165]



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

Should they be the same?

Accelerator ν Experiments

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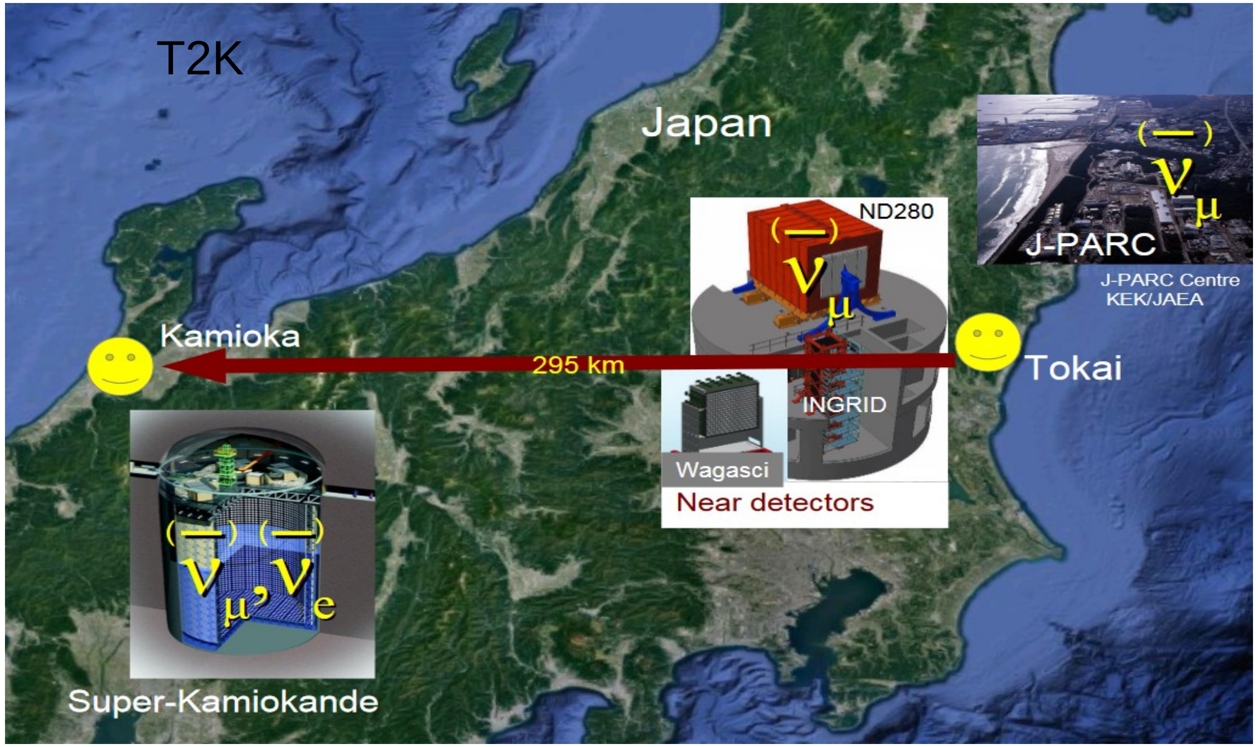

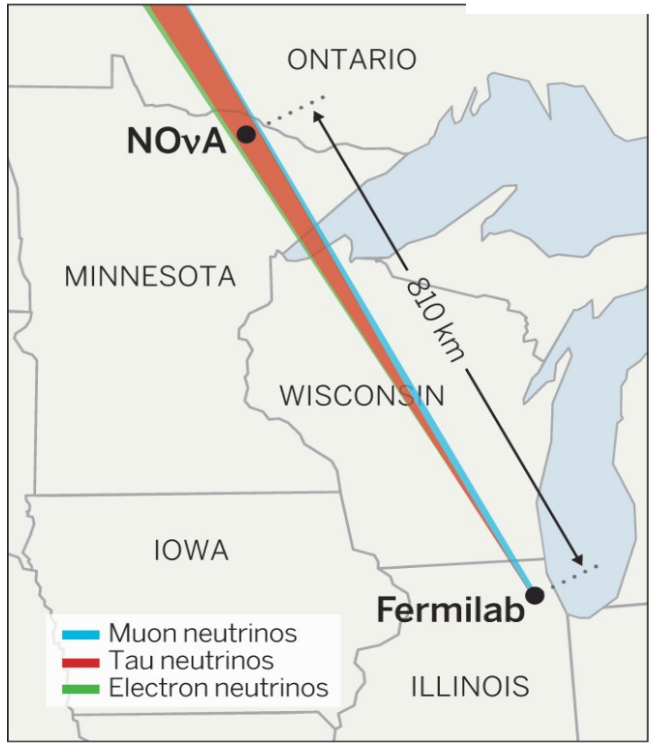

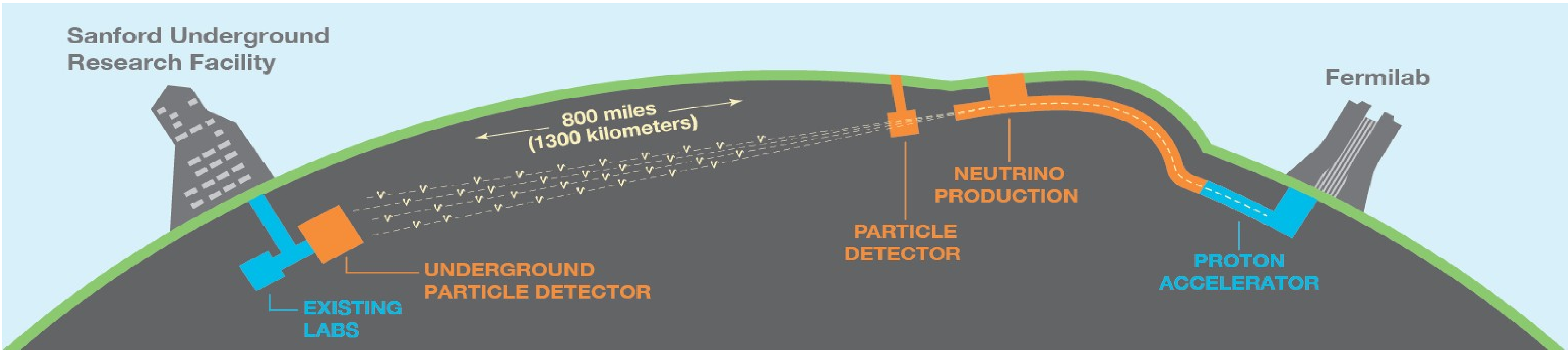

Production vs Detection

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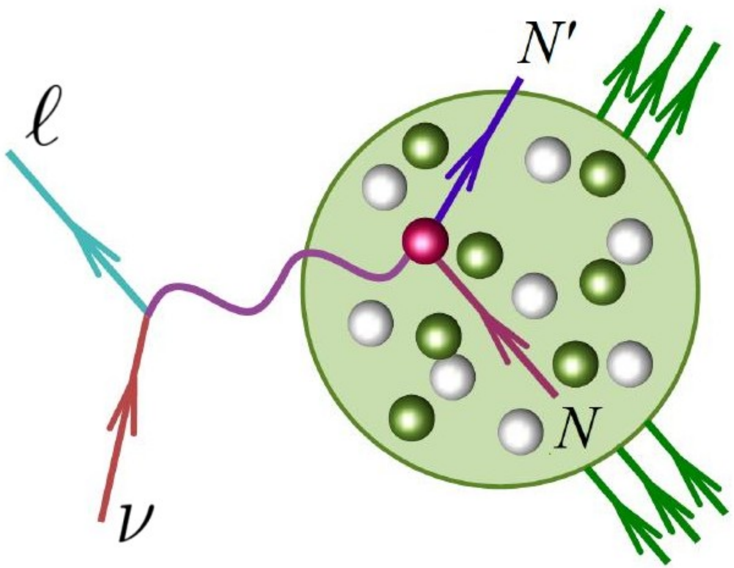
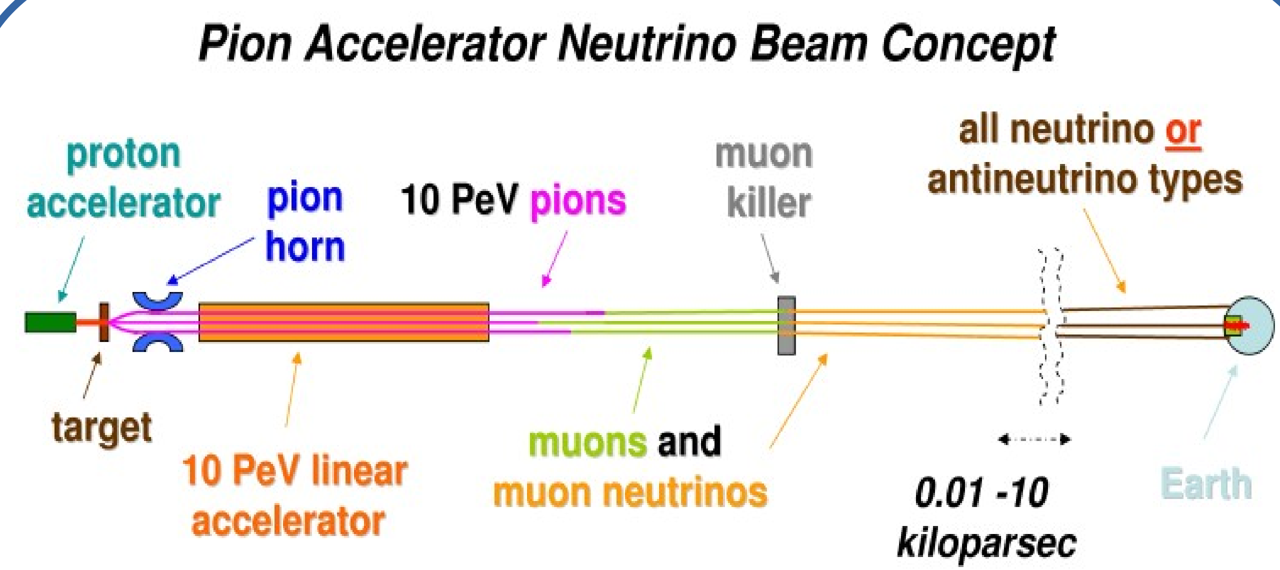
$$\mathcal{A}^{\rm osc}_{\beta\alpha} \equiv \sum_i U_{\beta i} e^{-i\frac{m_i^2}{2E_\nu}L} U^*_{\alpha i}$$

$Q_d^2 \approx ?$

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

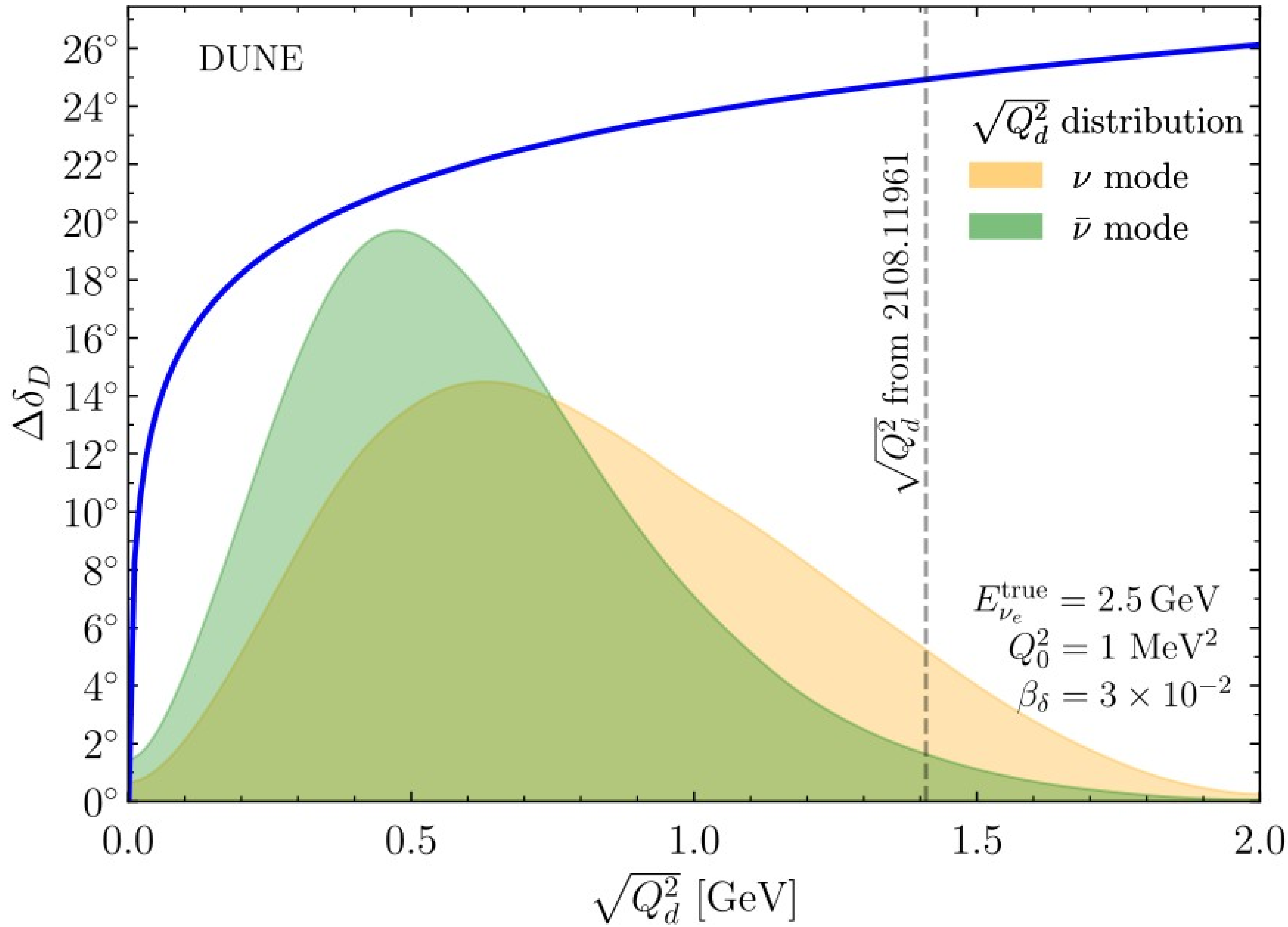


Detection: ES, RES, DIS



Production: π, μ, K decays

Mismatched Momentum Transfer



Mismatched Mixing Matrices from RG

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

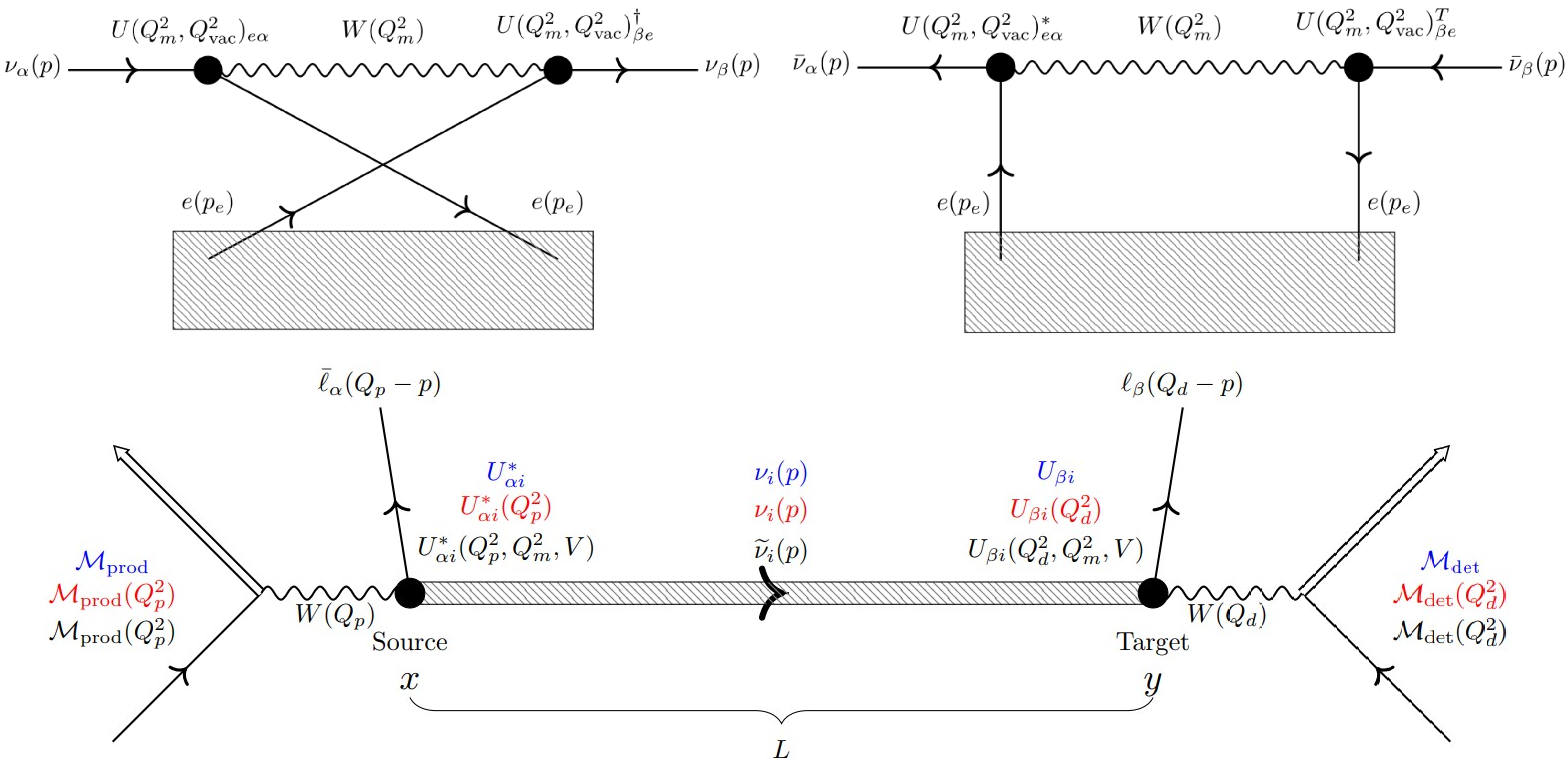
$$\theta_{ij}(Q^2) \equiv \theta_{ij}(Q_0^2) + \beta_{ij} \ln\left(\left|\frac{Q^2}{Q_0^2}\right|\right)$$

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

The mixing matrices needs not to be the same!

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

Momentum Transfer in Matter Effect



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

Energy Reconstruction @ DUNE

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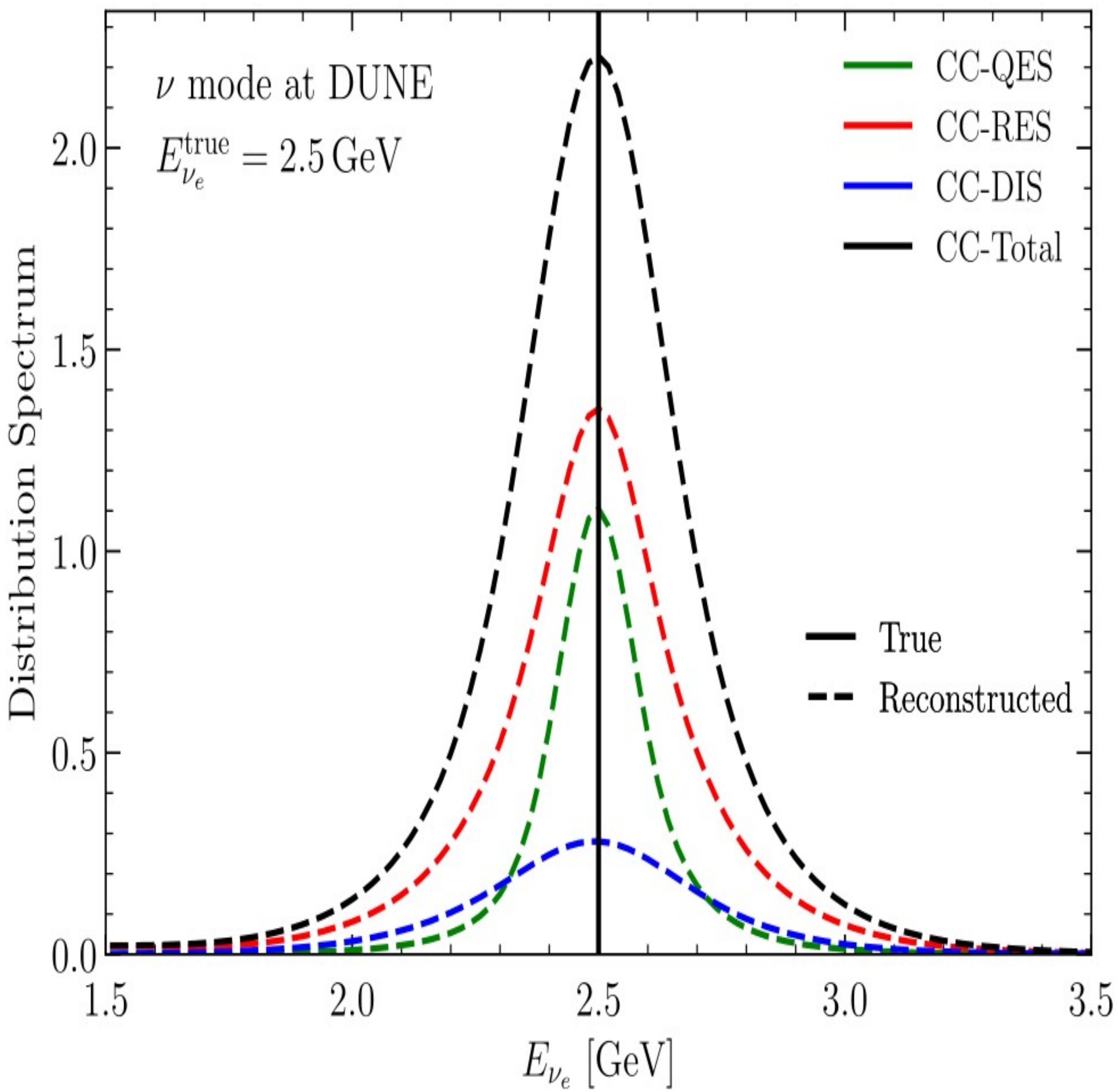
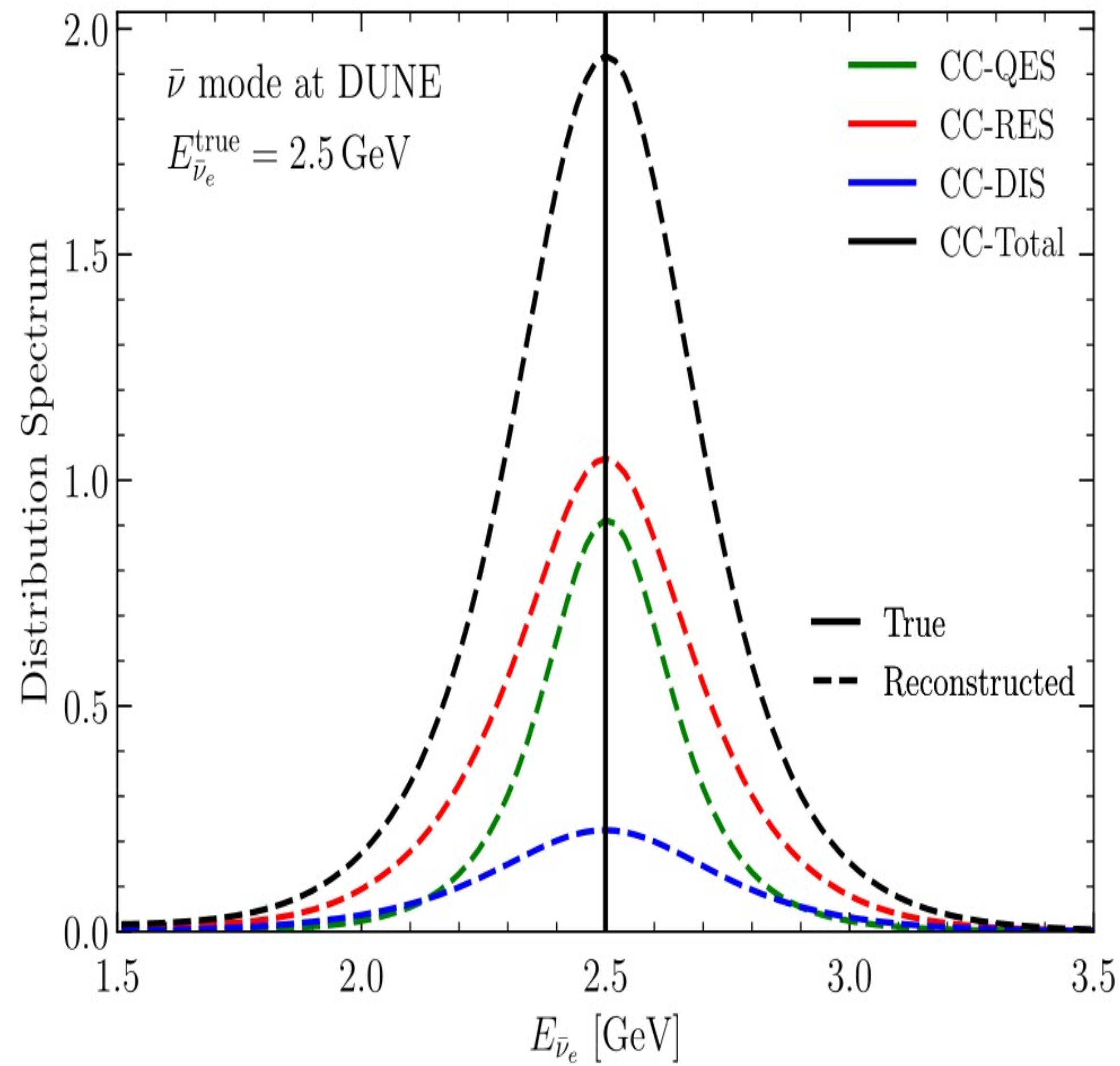
$$E_\nu^{\rm rec} = E_\ell^{\rm rec} + E_{\rm had}^{\rm rec}$$

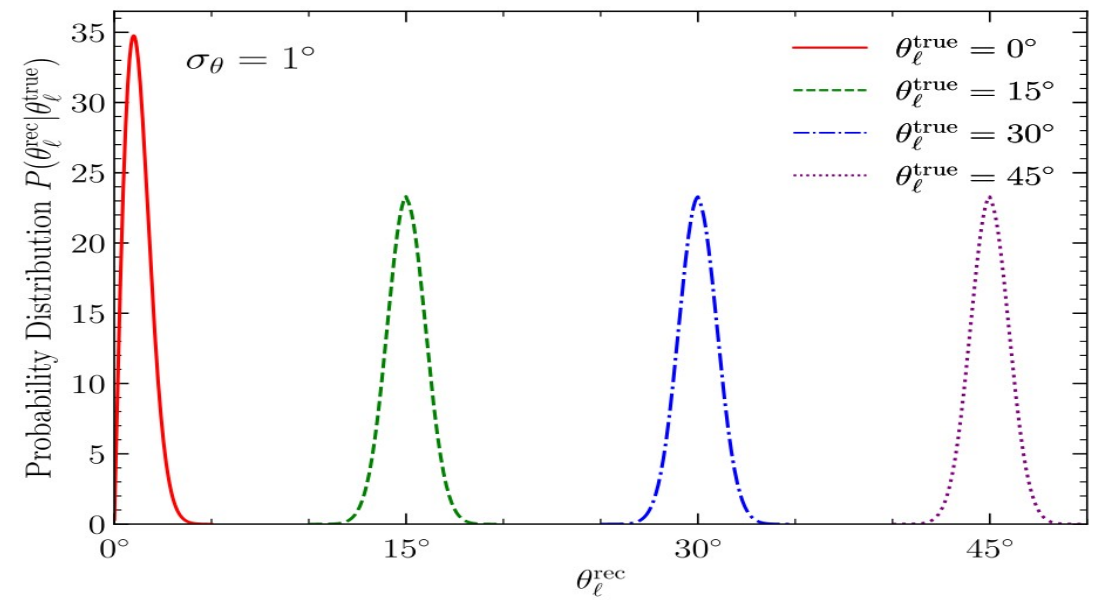


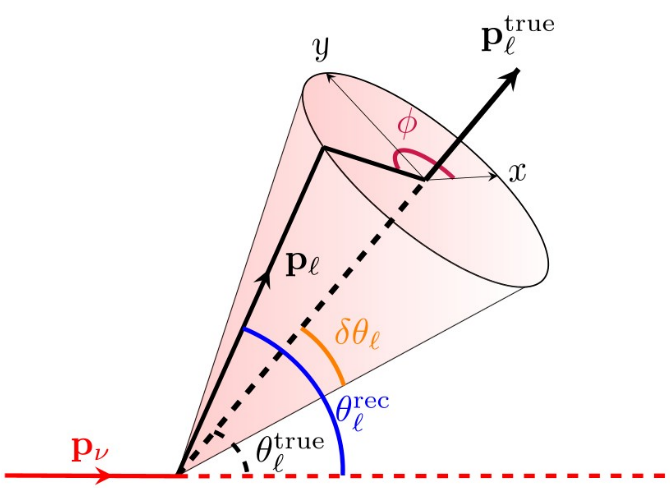


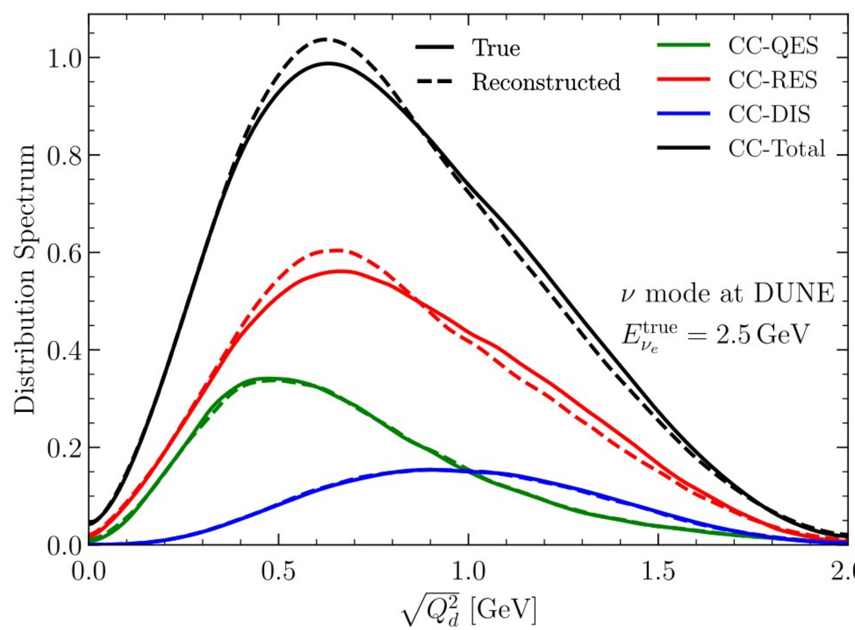
Momentum Transfer Reconstruction

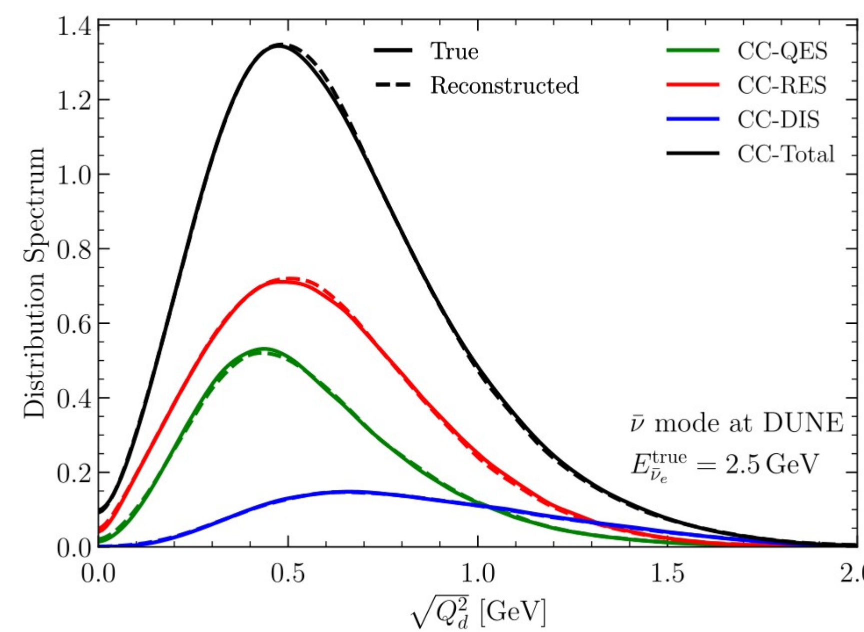
$$Q^2_{\rm rec} \equiv \left|(p_\nu^{\rm rec} - p_\ell^{\rm rec})^2\right| = 2E_\nu^{\rm rec}\left(E_\ell^{\rm rec} - |\boldsymbol{p}_\ell^{\rm rec}|\cos\theta_\ell^{\rm rec}\right) - m_\ell^2$$

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









Extended GLoBES Simulation

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

Single GLoBES

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

Implement momentum transfer by hand

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

4D transfer table

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

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

Degeneracy with CP Phase

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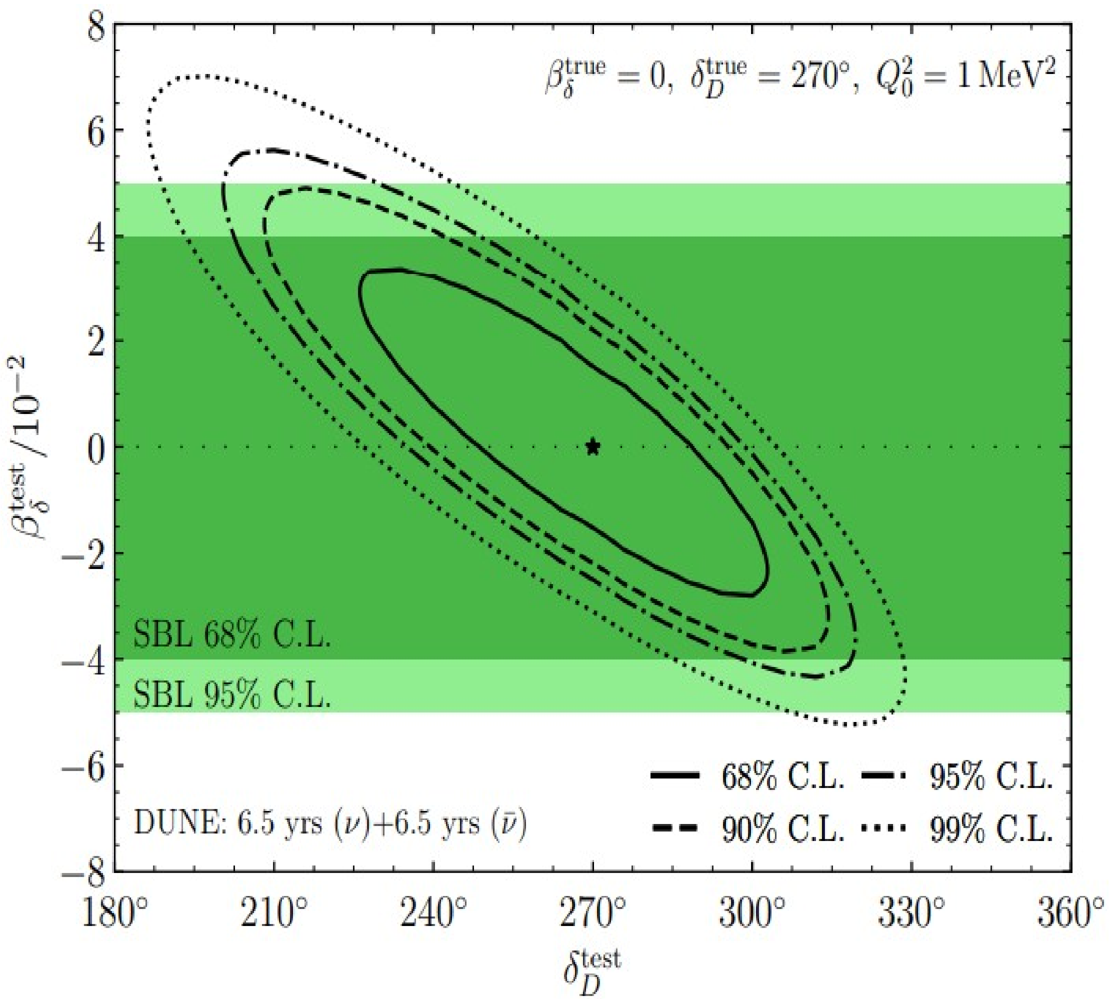
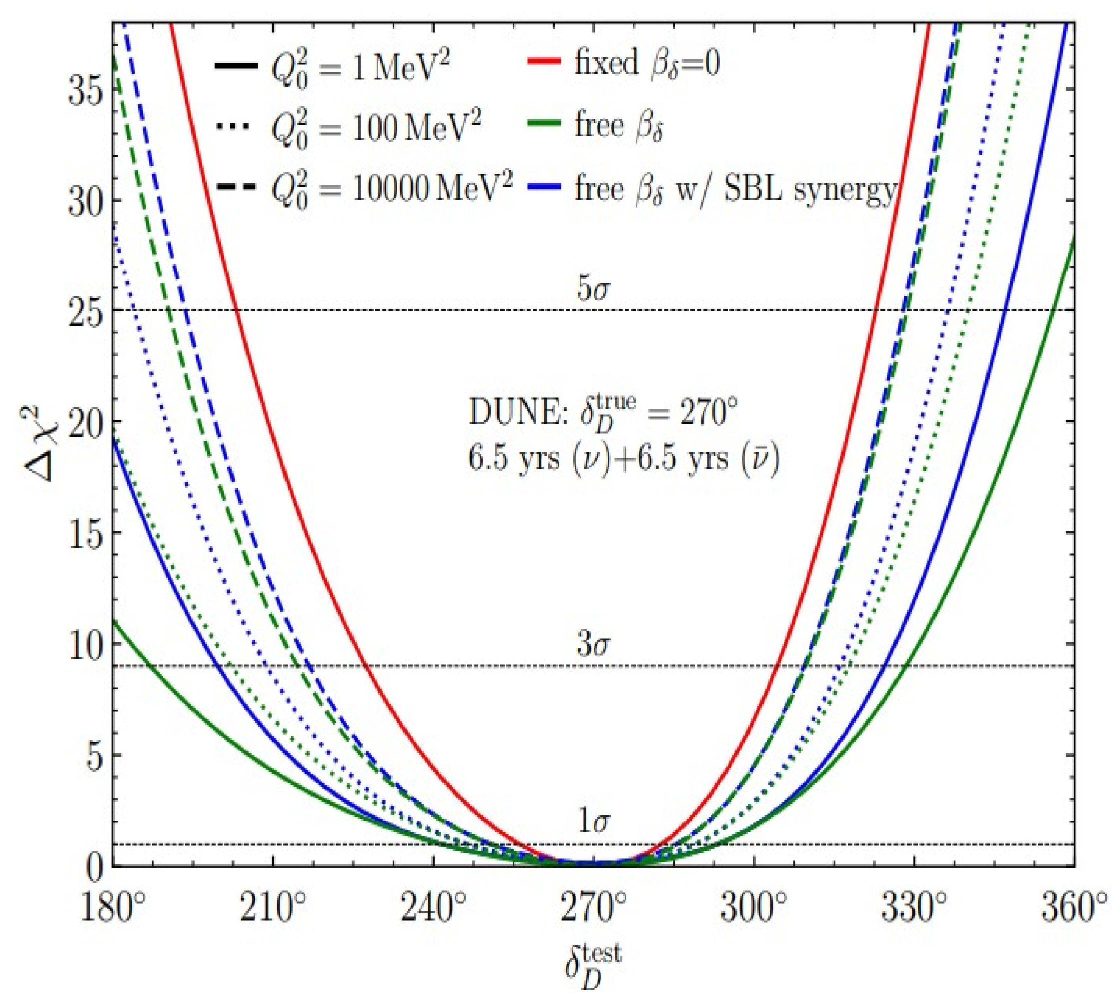
$$\mathcal{A}^{\rm osc}_{\beta\alpha} = U_{\beta i}(Q_d^2) e^{-iL\frac{m_i^2}{2E_\nu}} U^*_{\alpha i}(Q_p^2) \qquad \delta_D(Q^2) \equiv \delta_D(Q_0^2) + \beta_\delta \ln\left(\left|\frac{Q^2}{Q_0^2}\right|\right)$$





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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-unitary mixing!

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

Existing Short-Baseline Experiments

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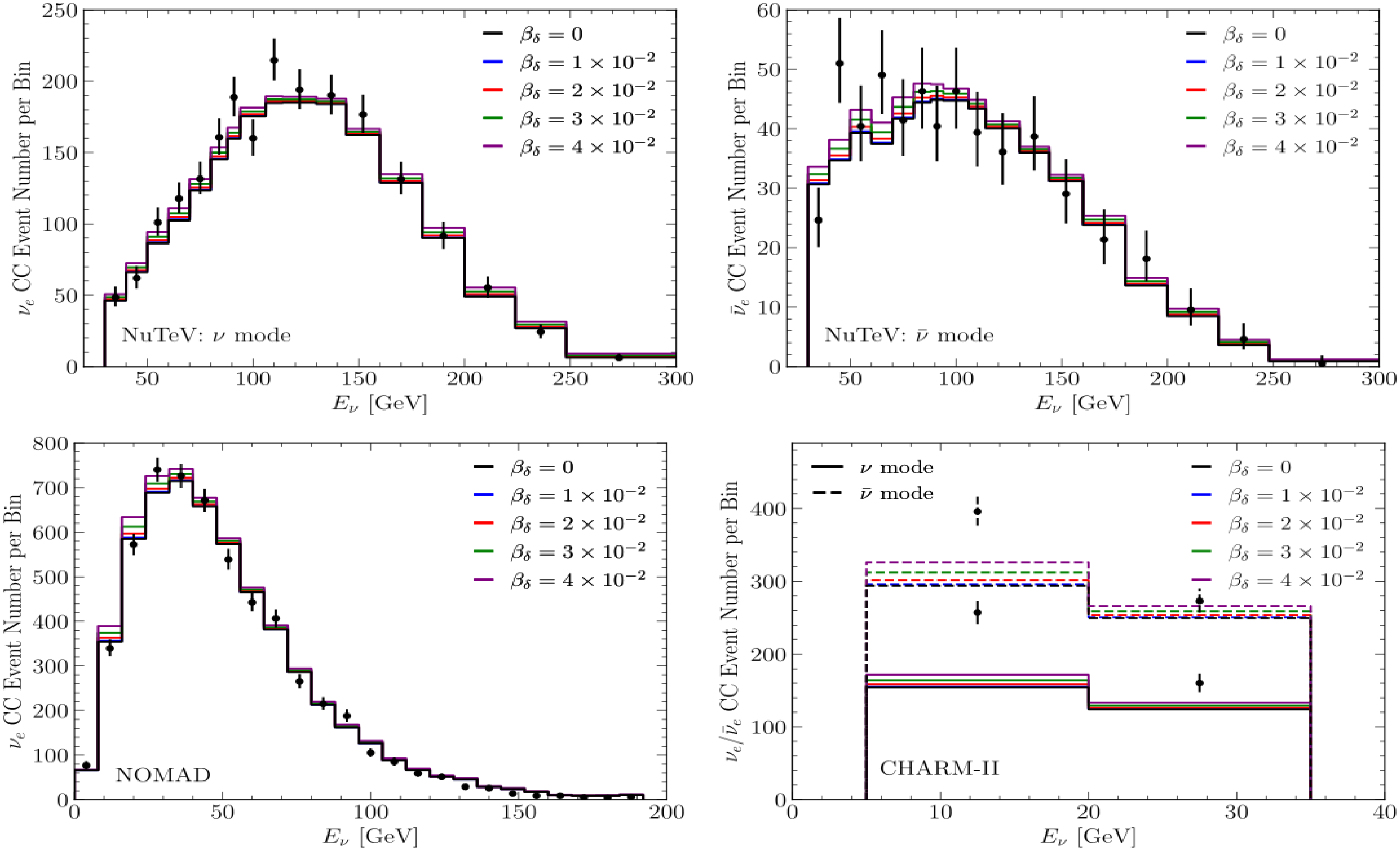

Constraint @ Short-Baseline Experiments

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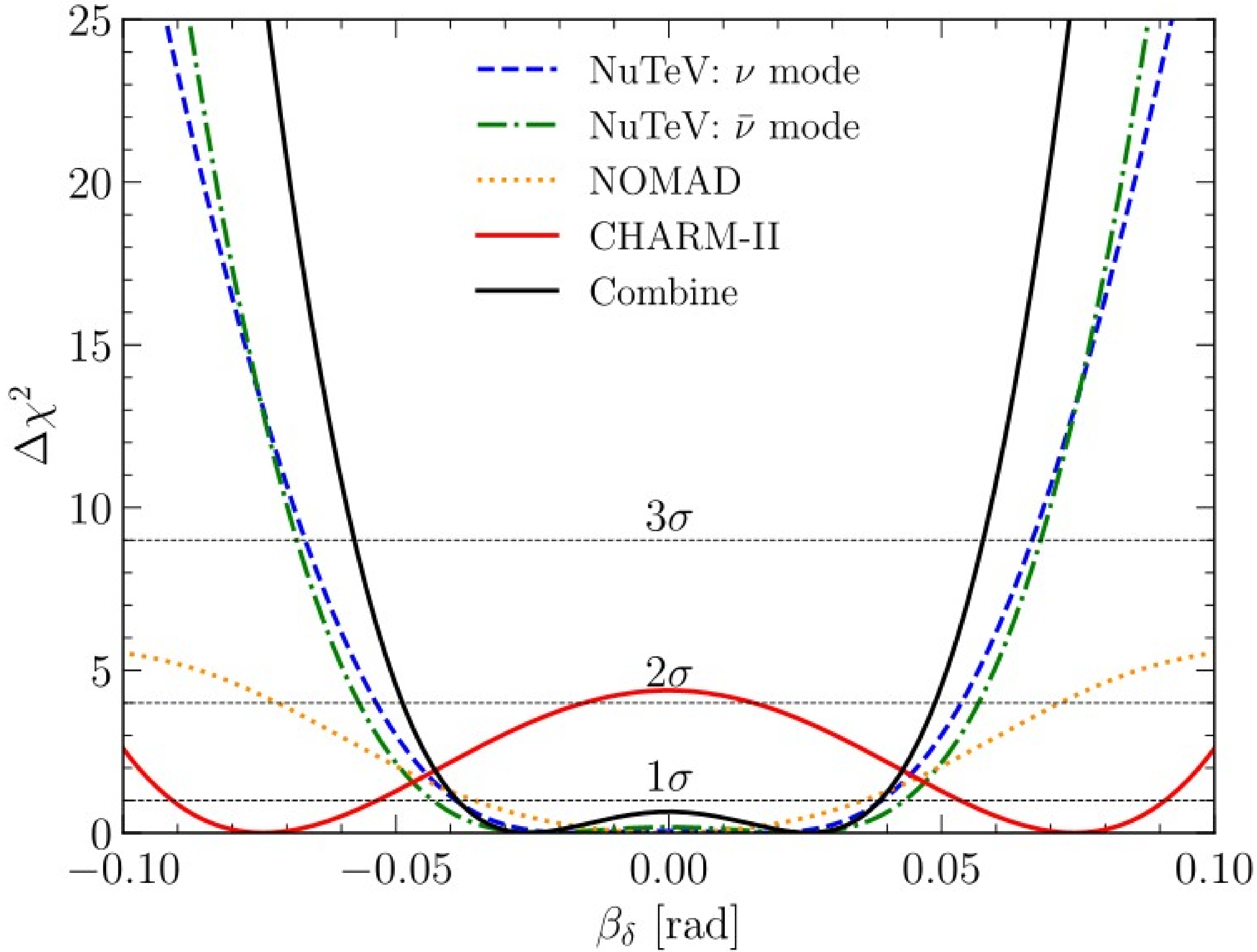

Momentum Transfer for Reactor ν

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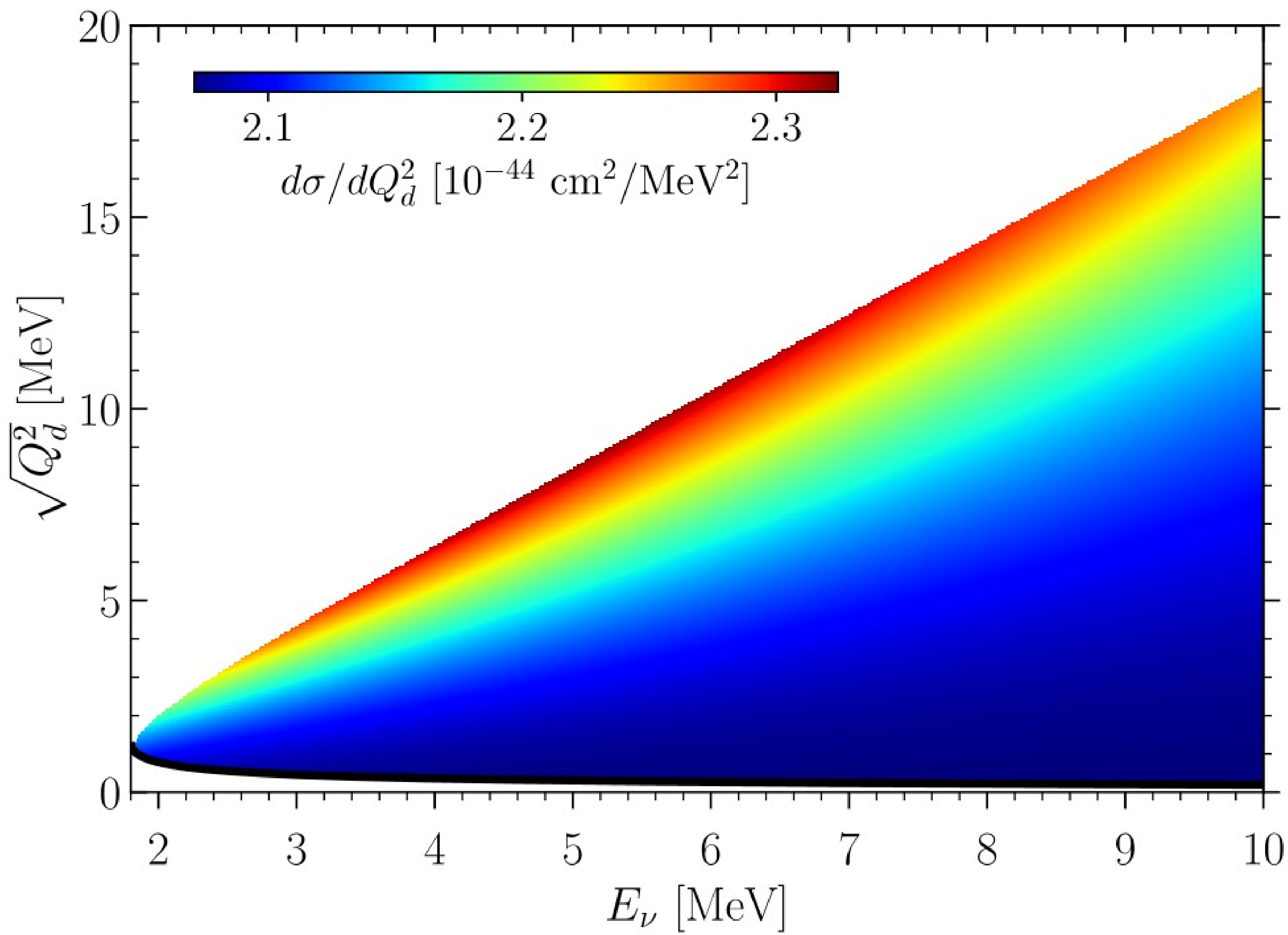
$$Q_p^2 \approx 1.67\,\mathrm{MeV}^2 \qquad Q_d^2 \approx \mathcal{O}(10^{-2} \sim 10^2)\,\mathrm{MeV}^2$$



CP RG Running for Reactor ν Osc

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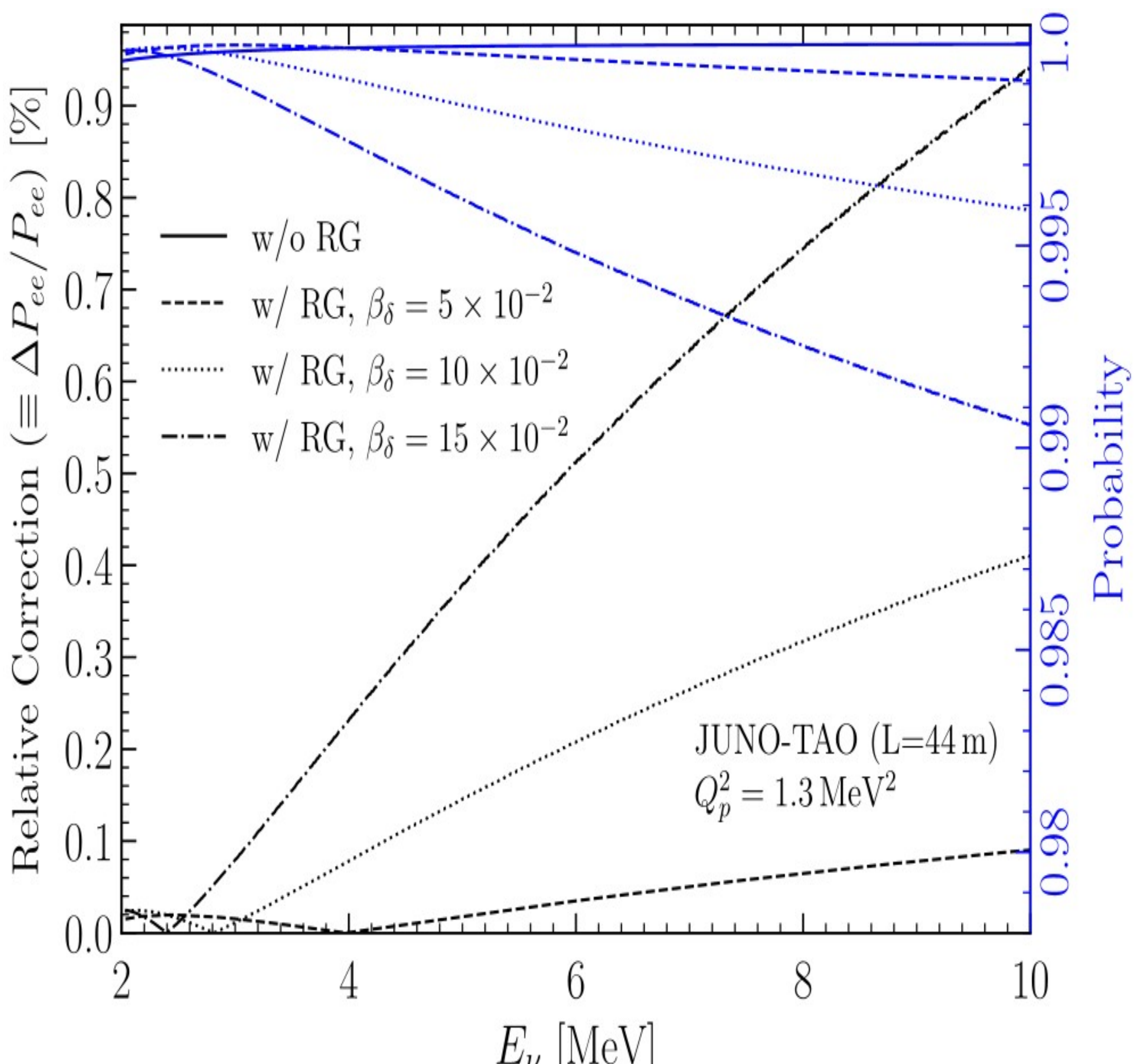
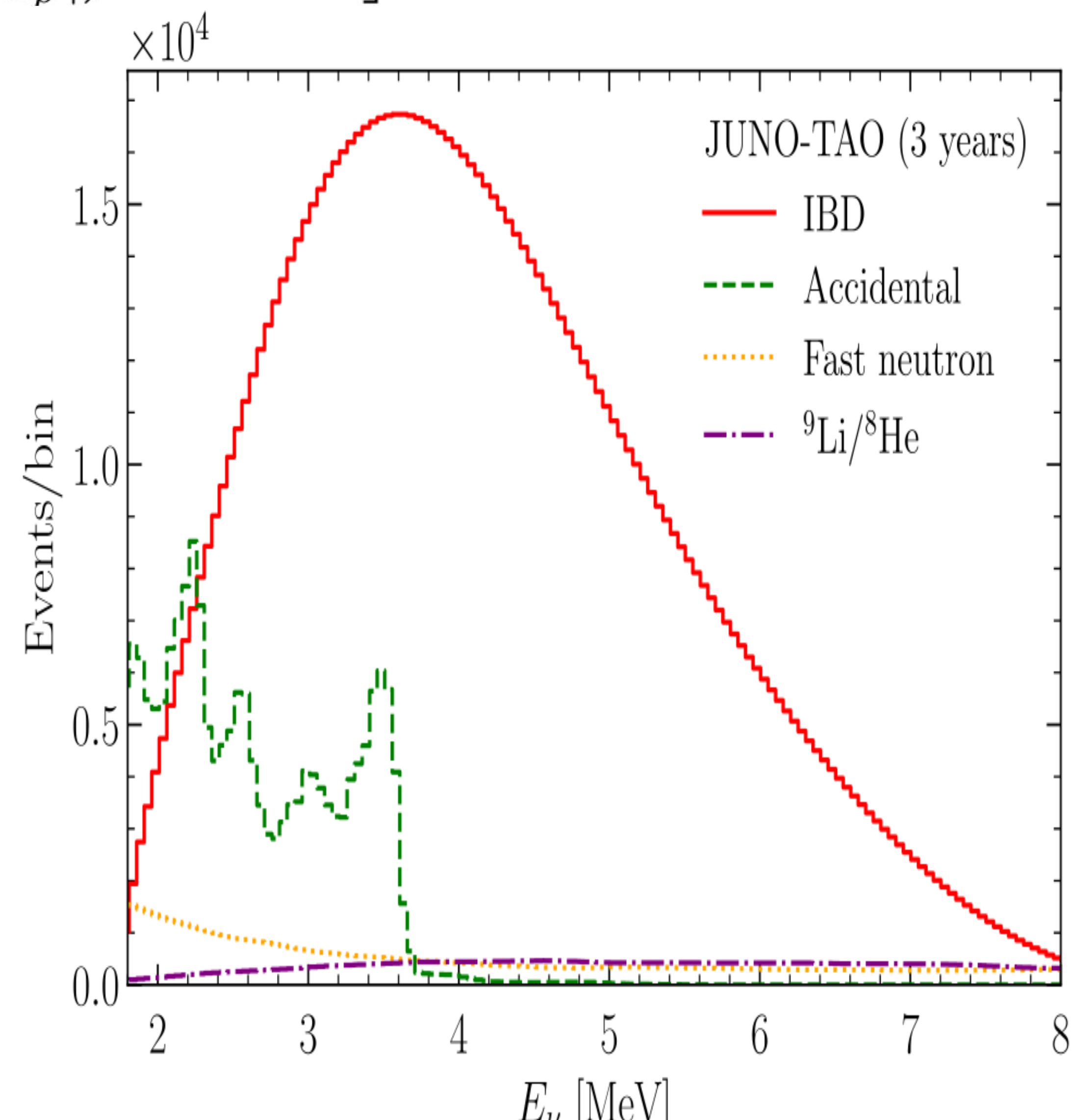
$$1 - P_{\rm ee}(Q^2_{d,p}) \approx \left[\frac{1}{2}\ln\left(\left|\frac{Q^2_d}{Q^2_p}\right|\right)\sin 2\theta_{13}\beta_\delta\right]^2$$





Zero Distance Effect

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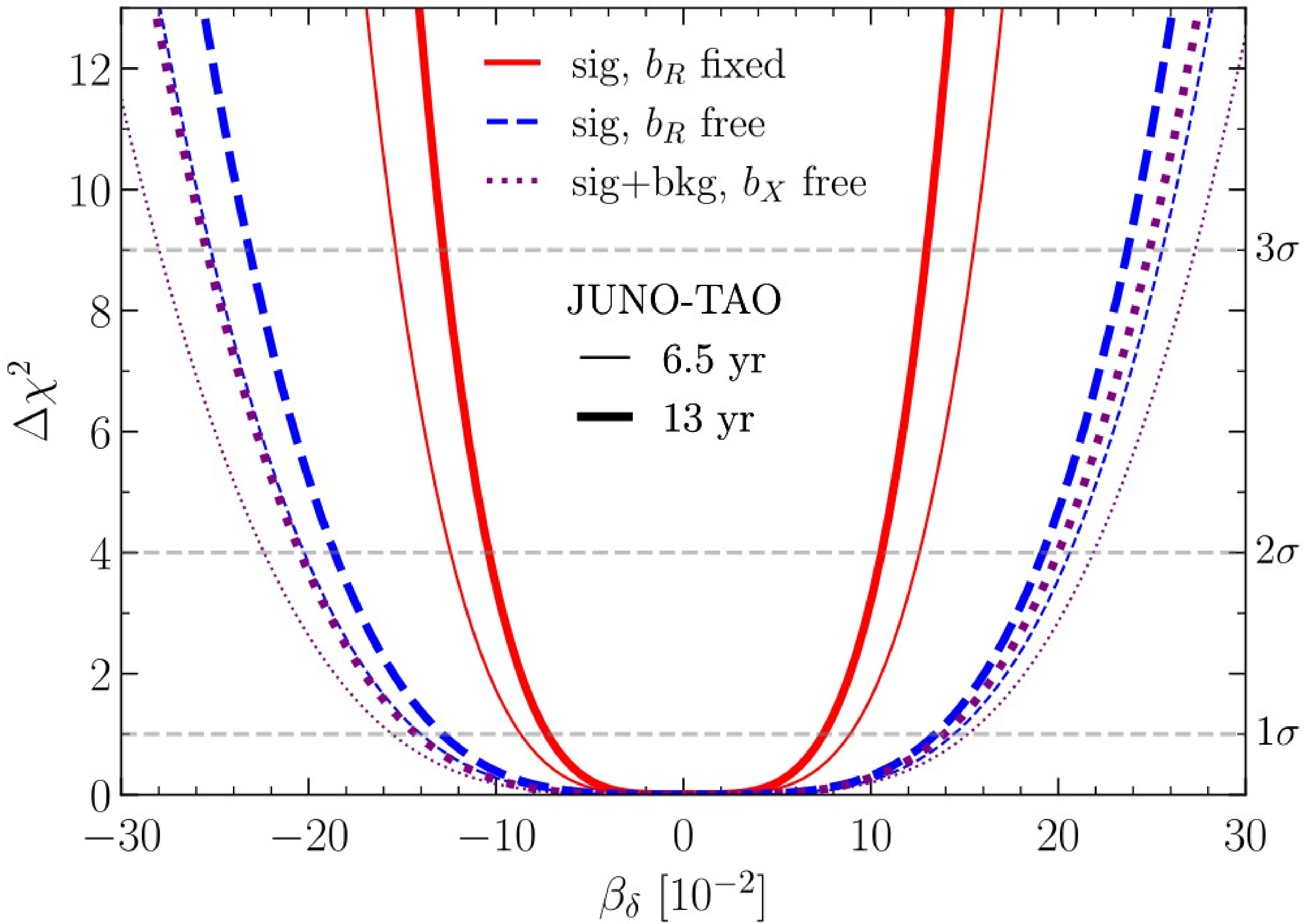
$$\overline{P}_{ee}(E_\nu) \equiv \int P_{ee}(Q^2_{p,d}) \frac{1}{\sigma} \frac{d\sigma}{dQ^2_d} dQ^2_d$$



Summary

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

  Effective non-unitary mixing.

  Zero-distance effect.

- **RG running can interfere with CP**

  Accelerator exps: DUNE ...

  Reactor exps: JUNO

- **Short-baseline experiments for constraints**

  High-Energy: NuTeV, NOMAD, CHARM-II

  Low-Energy: JUNO-TAO

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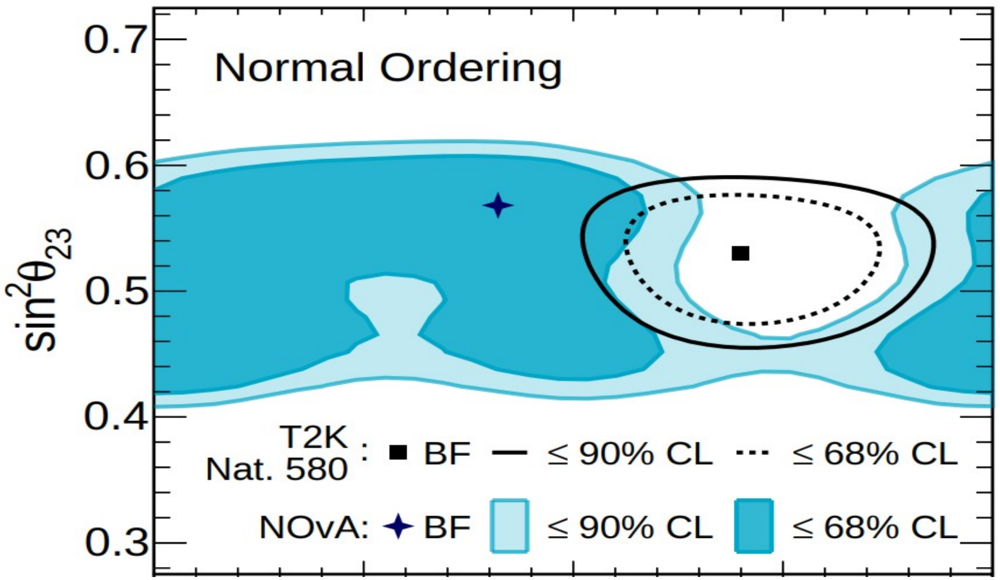
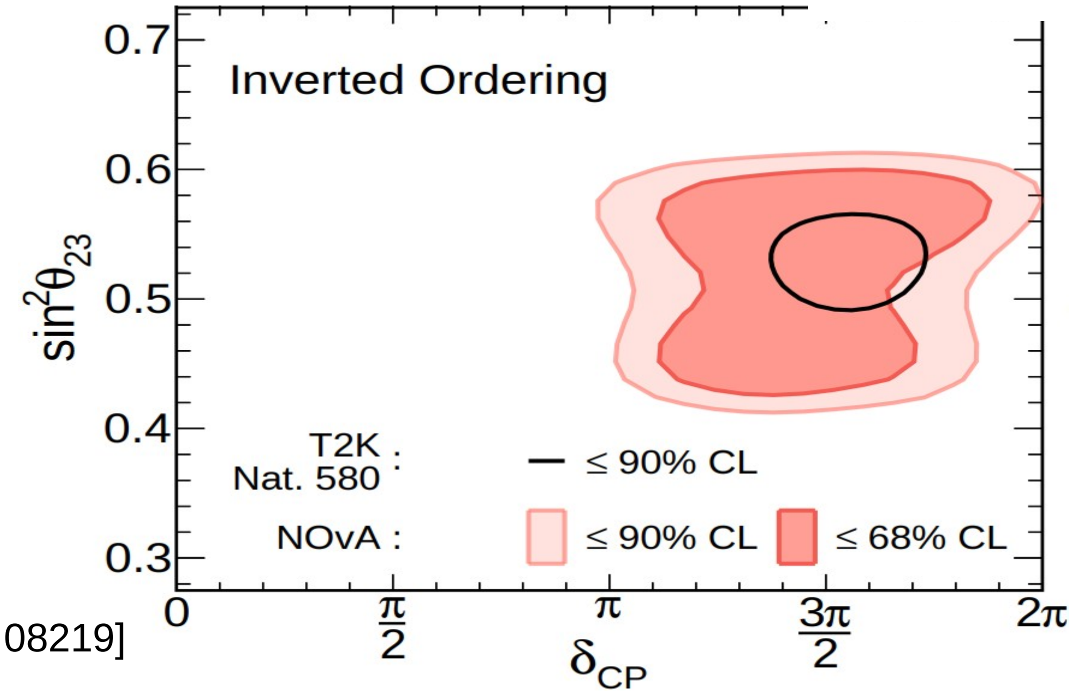
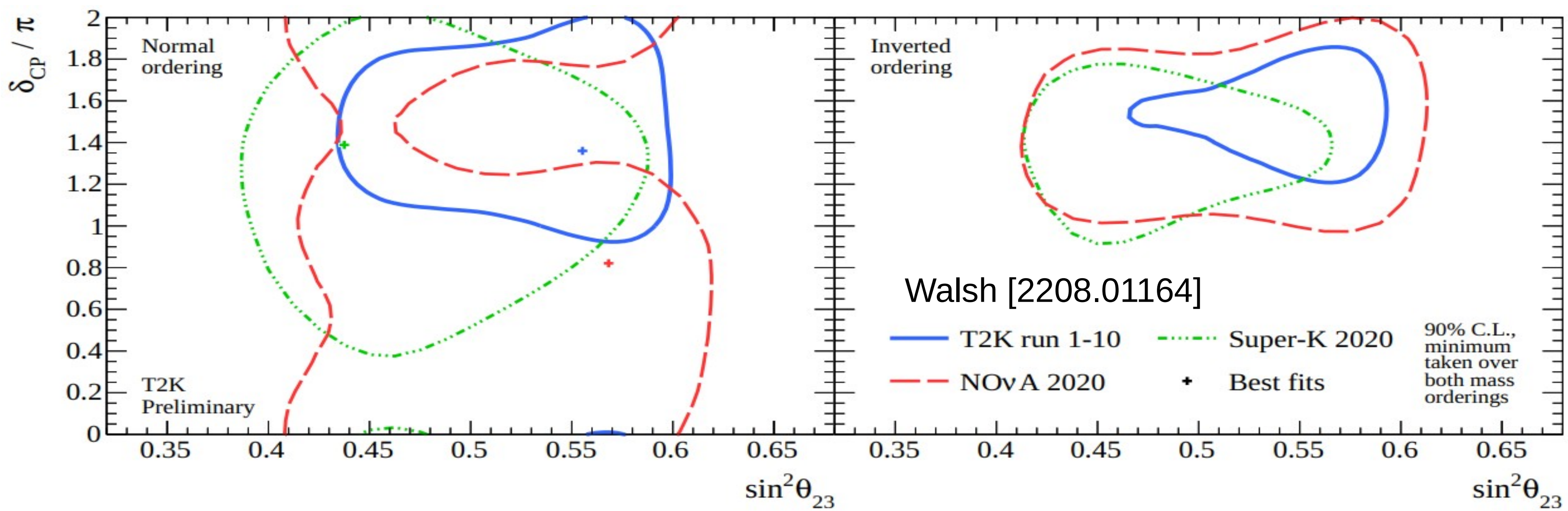
Thank You

T2K vs NOvA





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



T2K+NOvA Constraint on Δm^2_{32}

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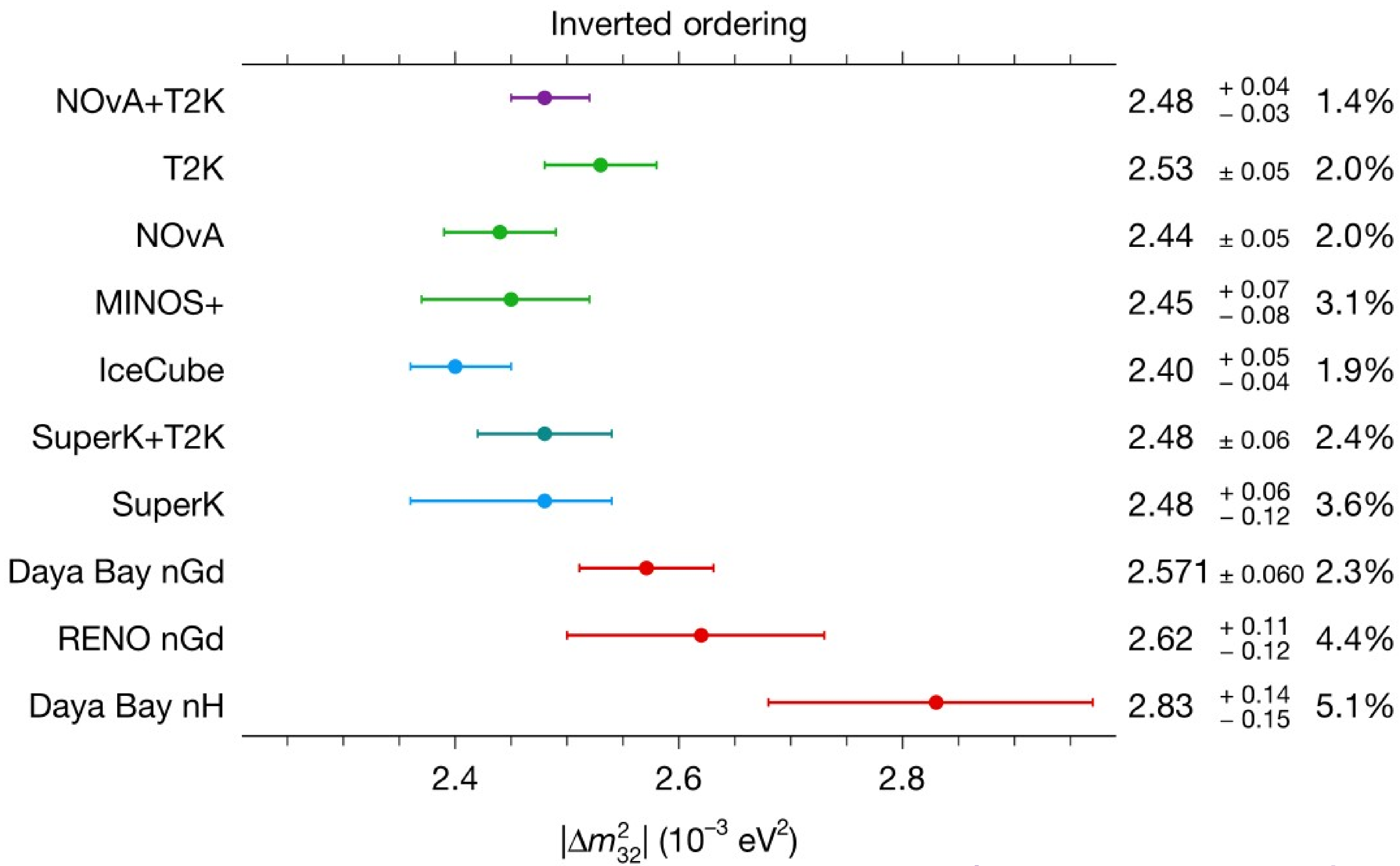

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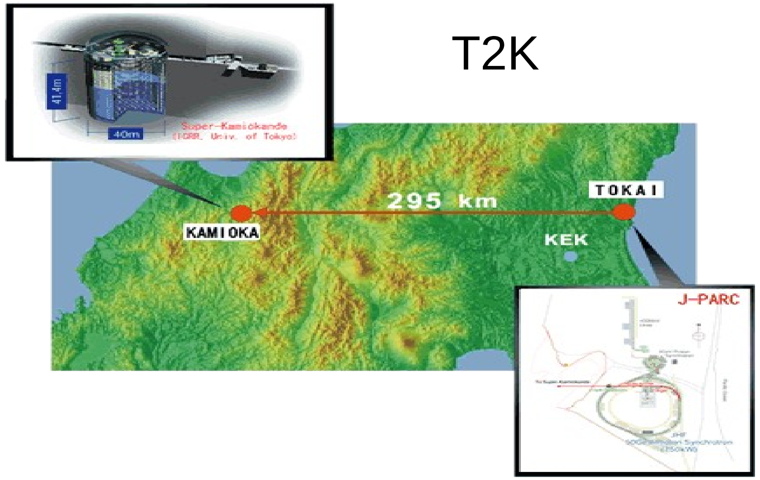
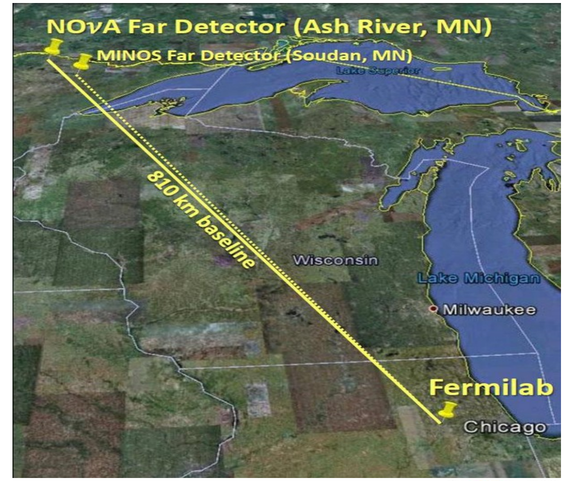
Future Accelerator Exps



T2K



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

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

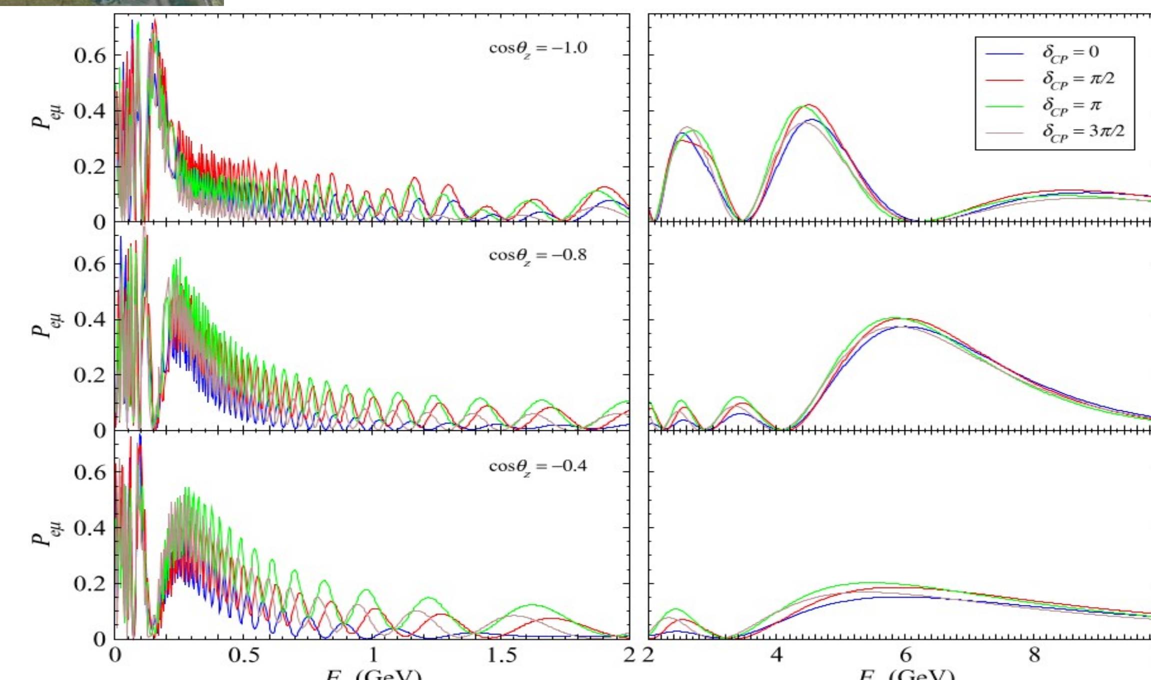
- In China?

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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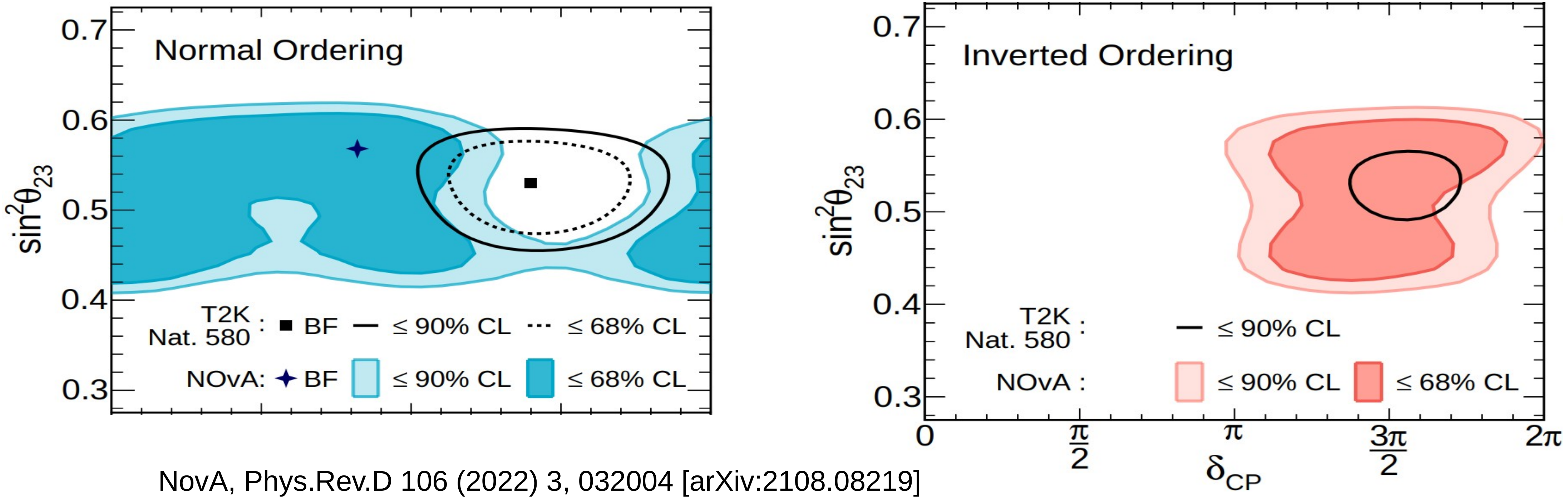

NovA, Phys.Rev.D 106 (2022) 3, 032004 [arXiv:2108.08219]

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

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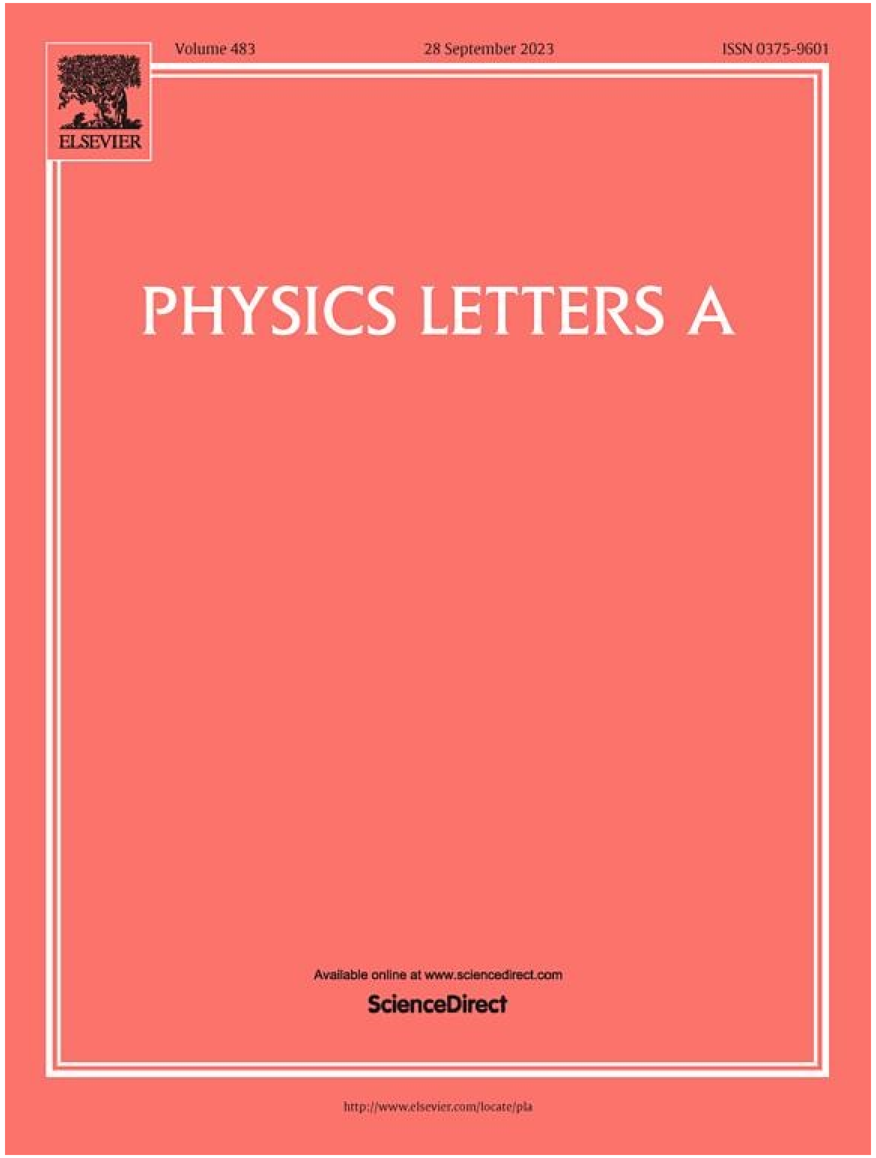

Aims & Scope

- Nonlinear science,
- Statistical physics,
- Mathematical and computational physics,
- AMO and physics of complex systems,
- Plasma and fluid physics,
- Optical physics,
- General and cross-disciplinary physics,
- Biological physics and nanoscience,
- Astrophysics, Particle physics and Cosmology.