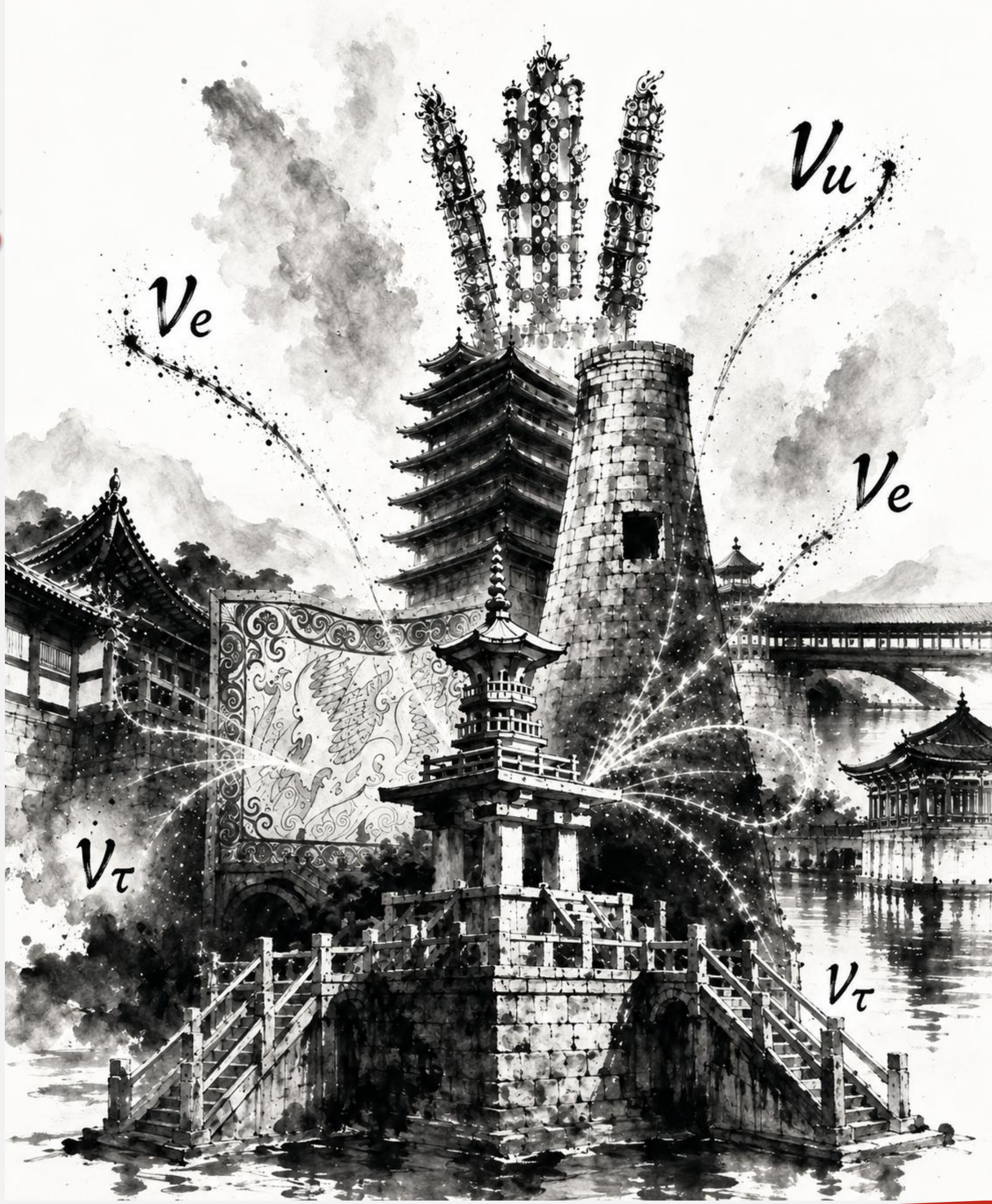
RG Running of Multiple Neutrino Mixing Parameters at Oscillation Experiments

Chui-Fan Kong
kongcf@ibs.re.kr
IBS-CTPU-PTC

Based on arXiv:2606.26720 [hep-ph]

In collaboration with:
Peter B. Denton (BNL), Shao-Feng Ge (TDLI & SJTU)
Pedro Pasquini (UNICAMP)



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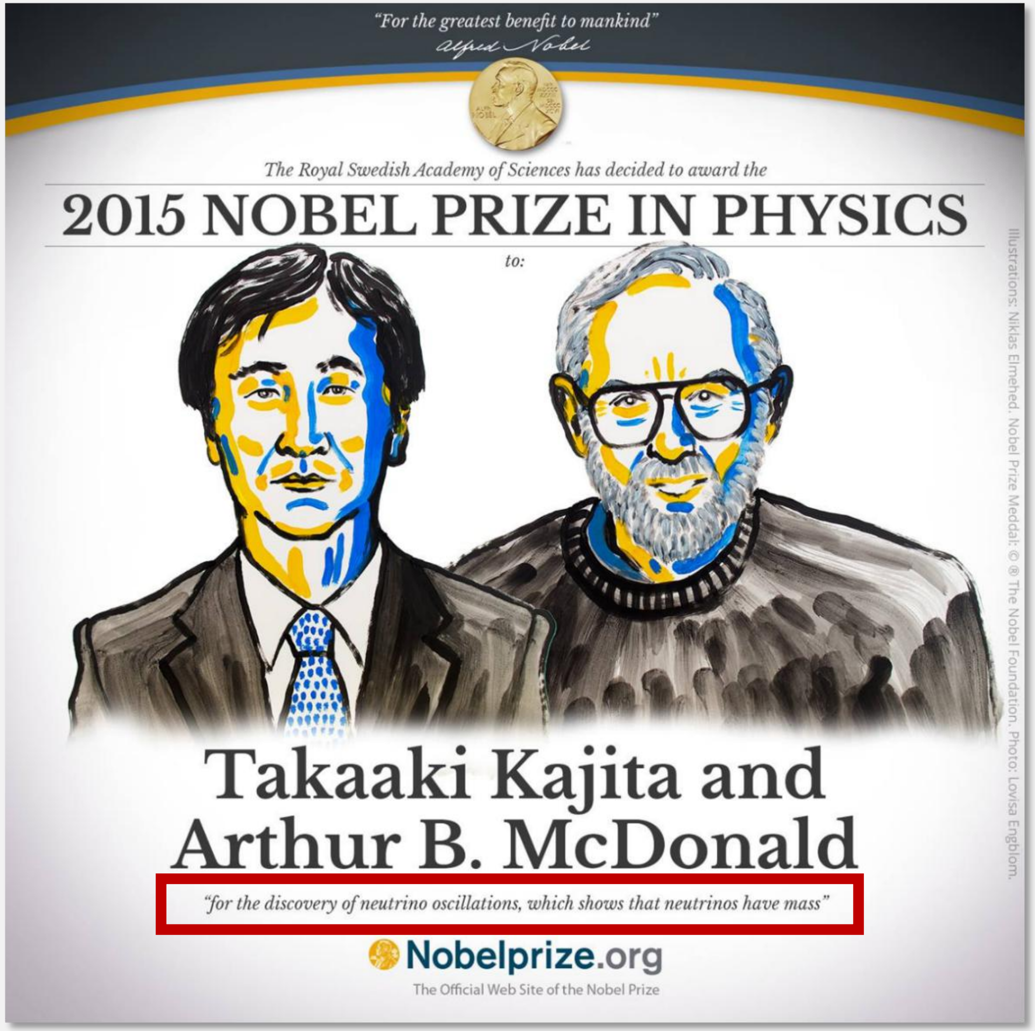
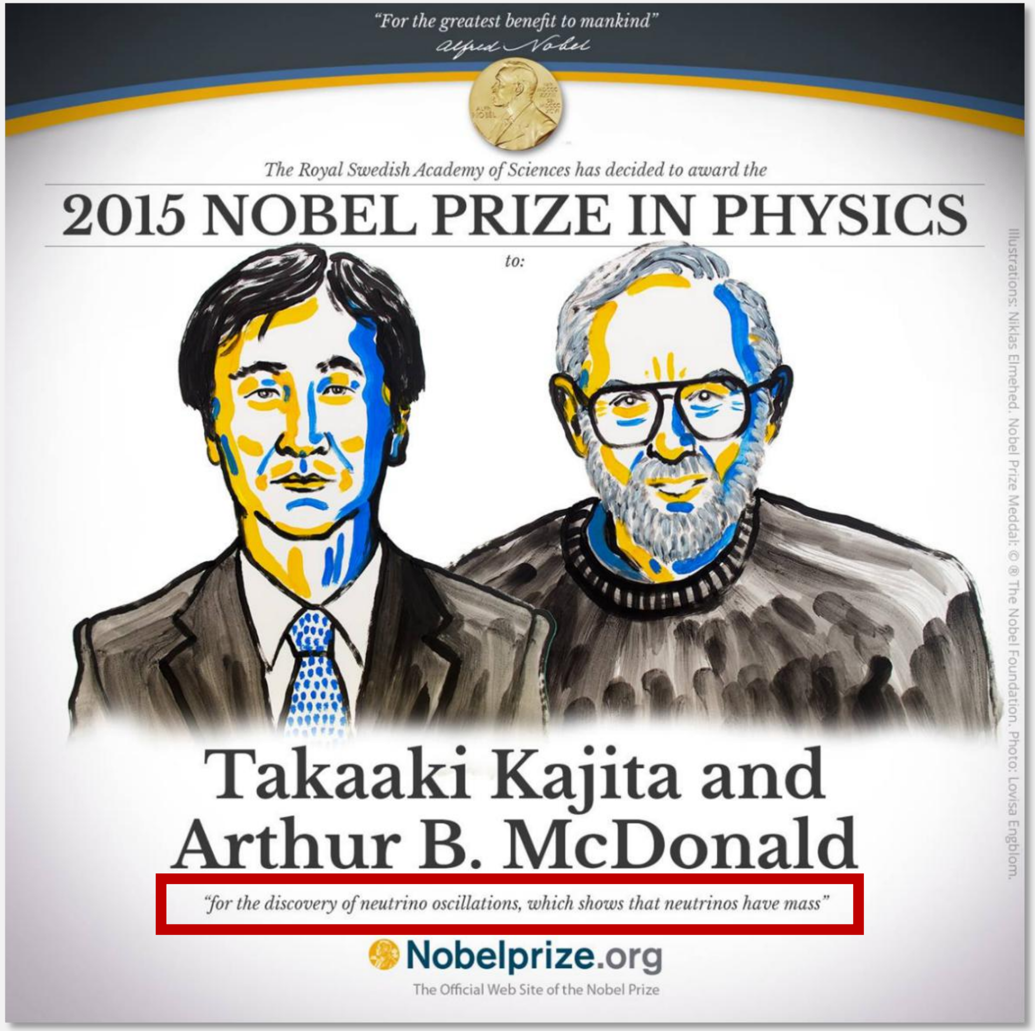


"for the discovery of neutrino oscillations, which shows that neutrinos have mass"



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Neutrino oscillation $\xrightarrow{\text{indicates}}$ New physics?!

Neutrino oscillation $\xleftarrow[\text{can be tested}]{}$ New physics?!

Outline

- Neutrino oscillation in a nutshell
- RG running effect on neutrino oscillation
- Experimental sensitivities

Neutrino oscillation in a nutshell

See also talks by Jose Valle and Byeongsu Yang

Neutrino Oscillation in A Nutshell

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Mixing:

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

flavor eigenstates ⟷ mixing matrix ⟷ mass eigenstates

Neutrino Oscillation in A Nutshell

Mixing:

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

flavor eigenstates $\xleftrightarrow{\text{mixing matrix}}$ mass eigenstates

source

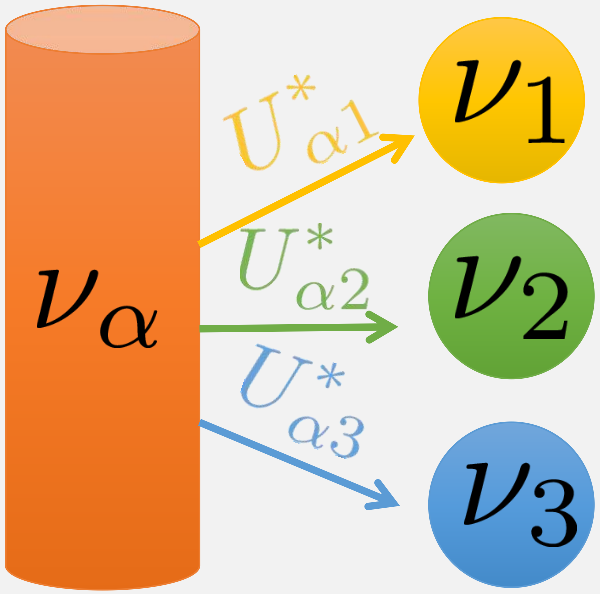
$$\alpha, \beta \in \{e, \mu, \tau\}$$

Neutrino Oscillation in A Nutshell

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

Production:

$$|\nu_\alpha\rangle = U^*_{\alpha 1}|\nu_1\rangle + U^*_{\alpha 2}|\nu_2\rangle + U^*_{\alpha 3}|\nu_3\rangle$$



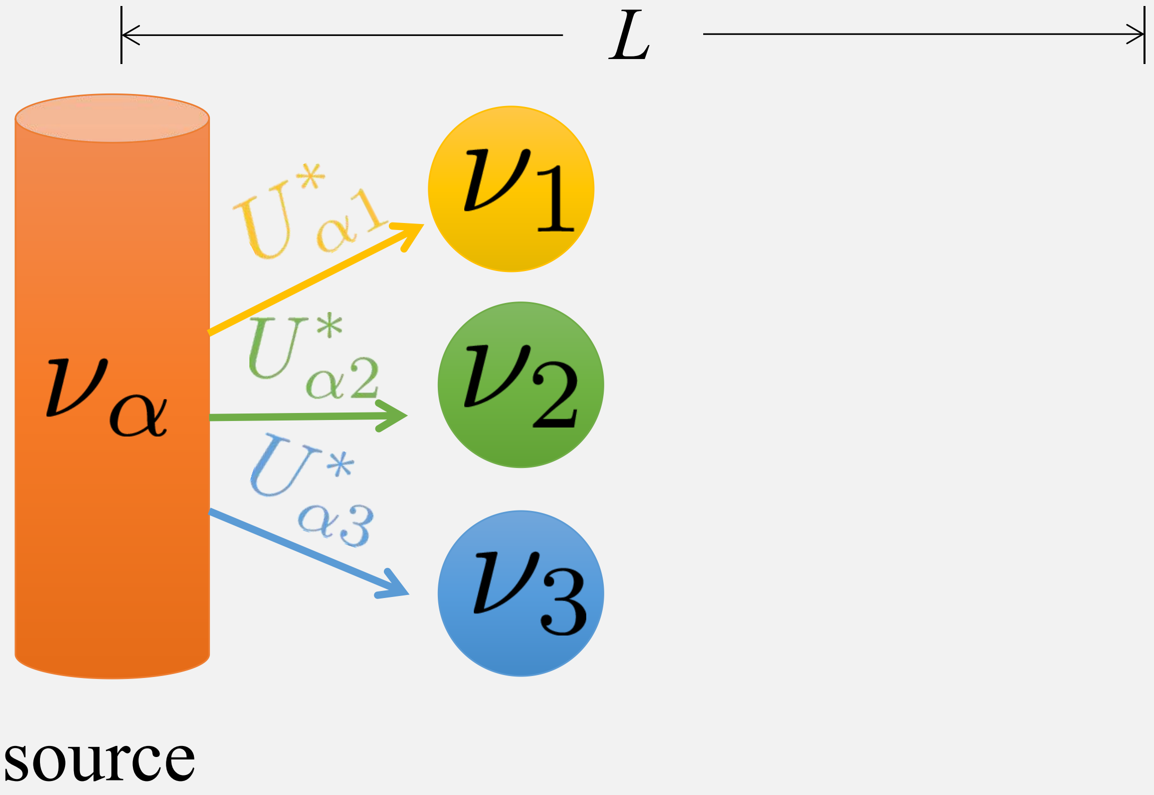
source

$$\alpha, \beta \in \{e, \mu, \tau\}$$

Neutrino Oscillation in A Nutshell

Propagation after a distance L:

ν_1	ν_2	ν_3
$e^{-i\frac{m_1^2}{2E}L}$	$e^{-i\frac{m_2^2}{2E}L}$	$e^{-i\frac{m_3^2}{2E}L}$



$\alpha, \beta \in \{e, \mu, \tau\}$

Neutrino Oscillation in A Nutshell

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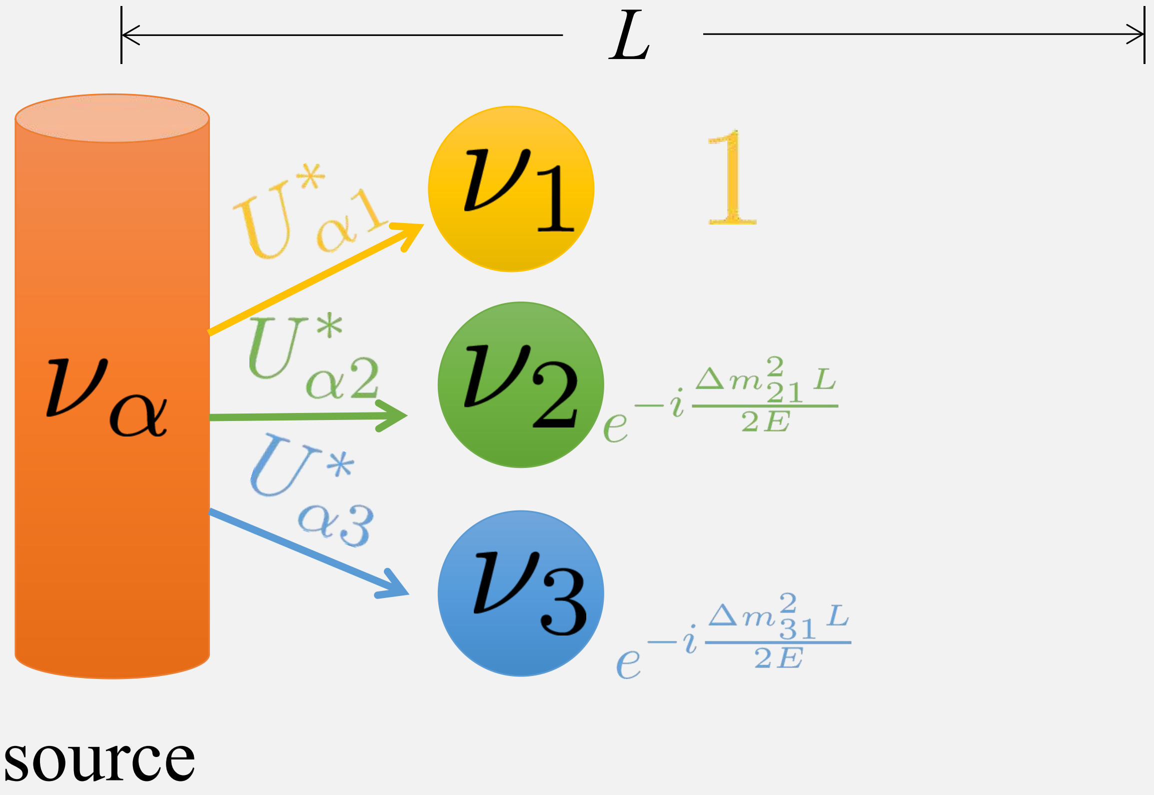
$[\Delta m_{21}^2 \equiv m_2^2 - m_1^2,$

$\Delta m_{31}^2 \equiv m_3^2 - m_1^2]$

Propagation after a distance L:

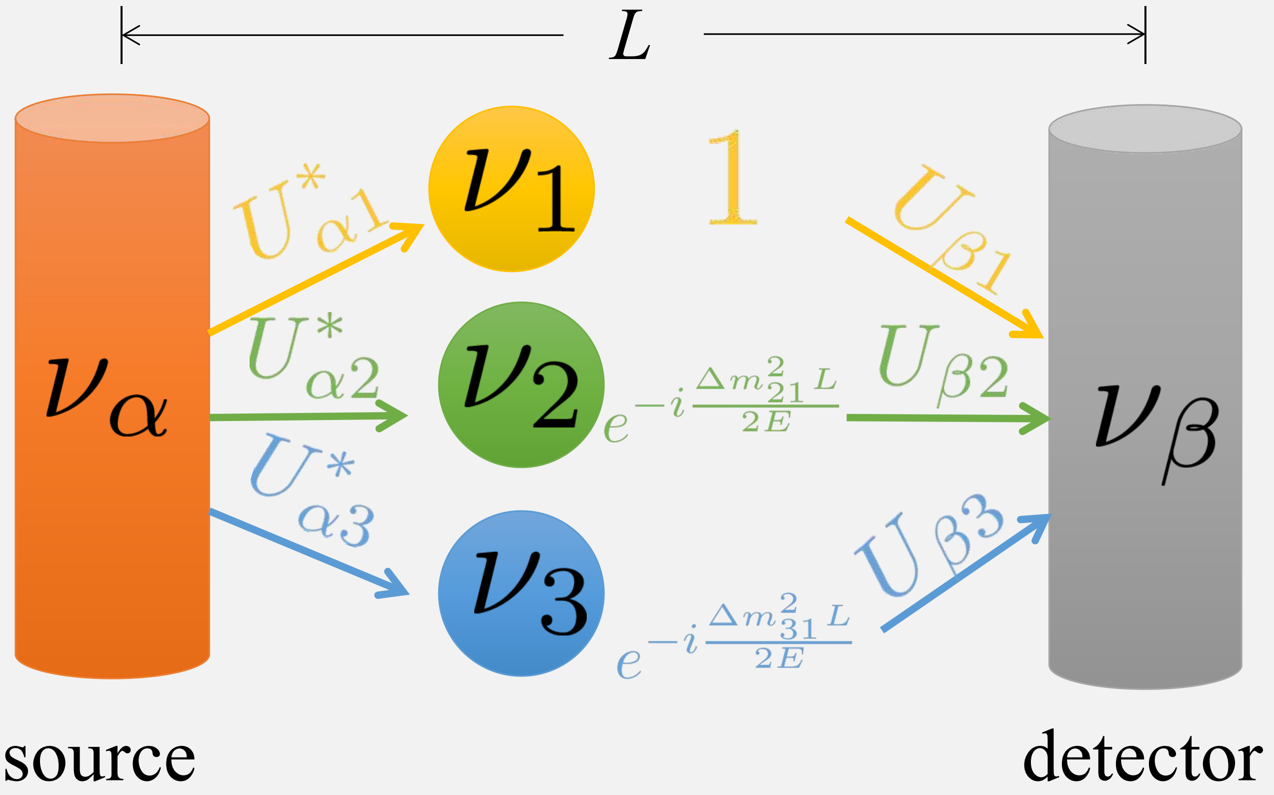
ν_1	ν_2	ν_3
$e^{-i\frac{m_1^2}{2E}L}$	$e^{-i\frac{m_2^2}{2E}L}$	$e^{-i\frac{m_3^2}{2E}L}$
$\downarrow$	$\downarrow$	$\downarrow$
1	$e^{-i\frac{\Delta m_{21}^2}{2E}L}$	$e^{-i\frac{\Delta m_{31}^2}{2E}L}$



$\alpha, \beta \in \{e, \mu, \tau\}$

Neutrino Oscillation in A Nutshell

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



Detection:

$$\langle \nu_\beta | = U_{\beta 1} \langle \nu_1 | + U_{\beta 2} \langle \nu_2 | + U_{\beta 3} \langle \nu_3 |$$

$$\alpha, \beta \in \{e, \mu, \tau\}$$

Neutrino Oscillation in A Nutshell

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

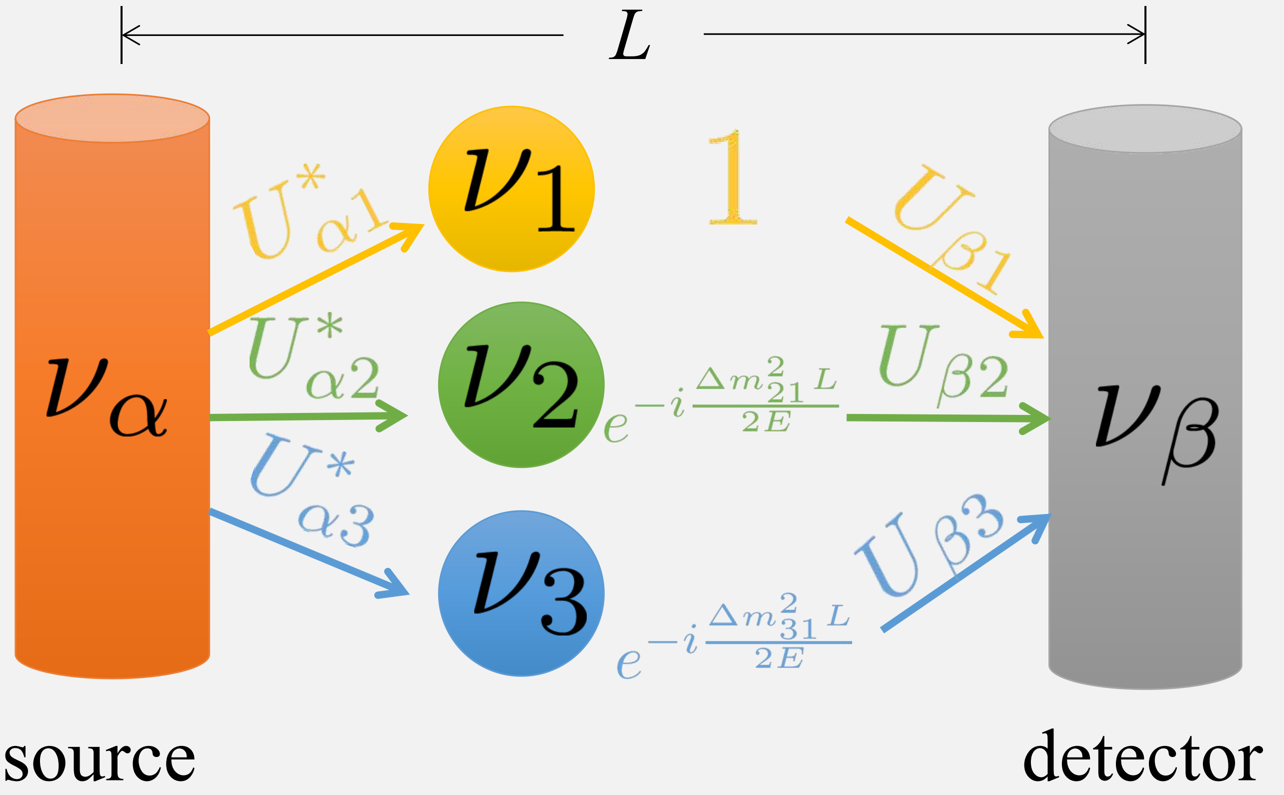
Production:

$$|\nu_\alpha\rangle = U^*_{\alpha 1}|\nu_1\rangle + U^*_{\alpha 2}|\nu_2\rangle + U^*_{\alpha 3}|\nu_3\rangle$$

Propagation: $1 \qquad e^{-i\frac{\Delta m^2_{21} L}{2E}} \qquad e^{-i\frac{\Delta m^2_{31} L}{2E}}$

Detection:

$$\langle\nu_\beta| = U_{\beta 1}\langle\nu_1| + U_{\beta 2}\langle\nu_2| + U_{\beta 3}\langle\nu_3|$$



$\alpha, \beta \in \{e, \mu, \tau\}$

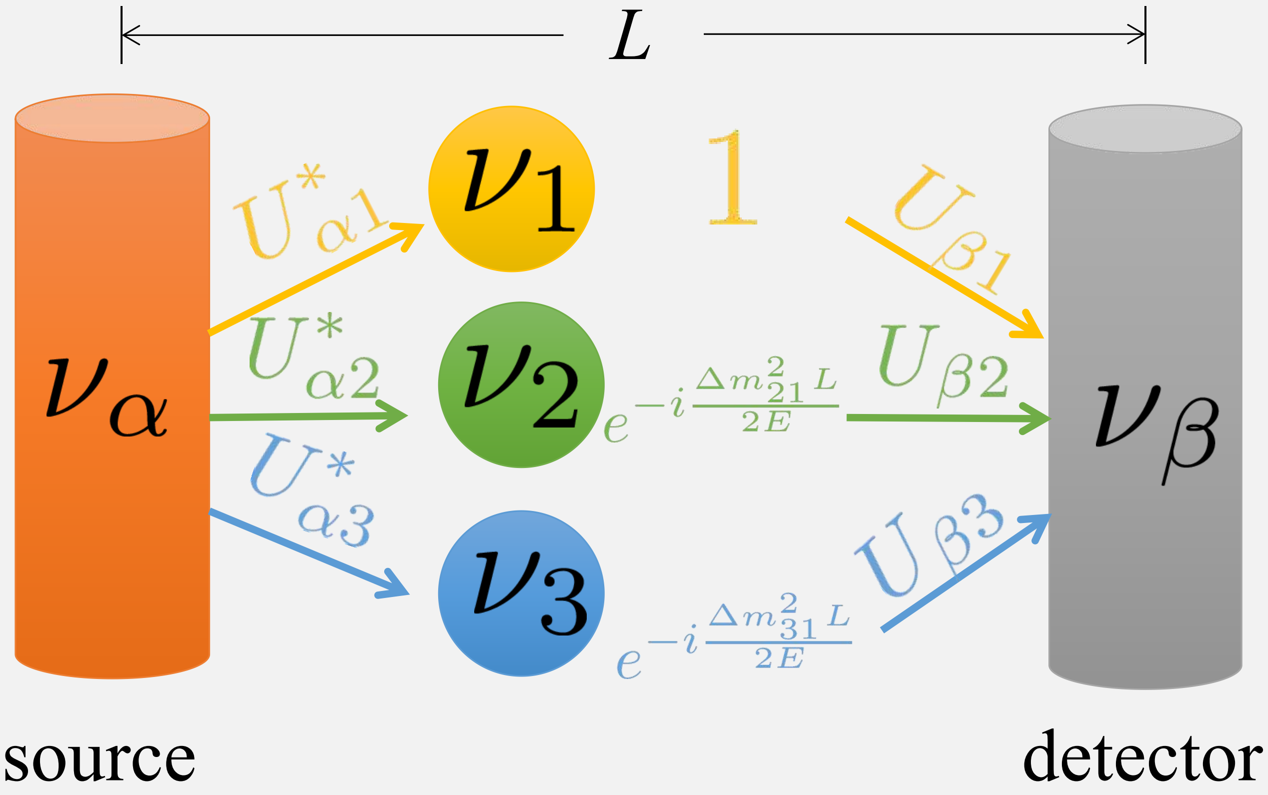
Neutrino Oscillation in A Nutshell

- Oscillation amplitude

$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = U^*_{\alpha 1} U_{\beta 1} + U^*_{\alpha 2} e^{-i\frac{\Delta m^2_{21}}{2E}L} U_{\beta 2} + U^*_{\alpha 3} e^{-i\frac{\Delta m^2_{31}}{2E}L} U_{\beta 3}$$

- Oscillation probability

$$P(\nu_\alpha \to \nu_\beta) = |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2$$



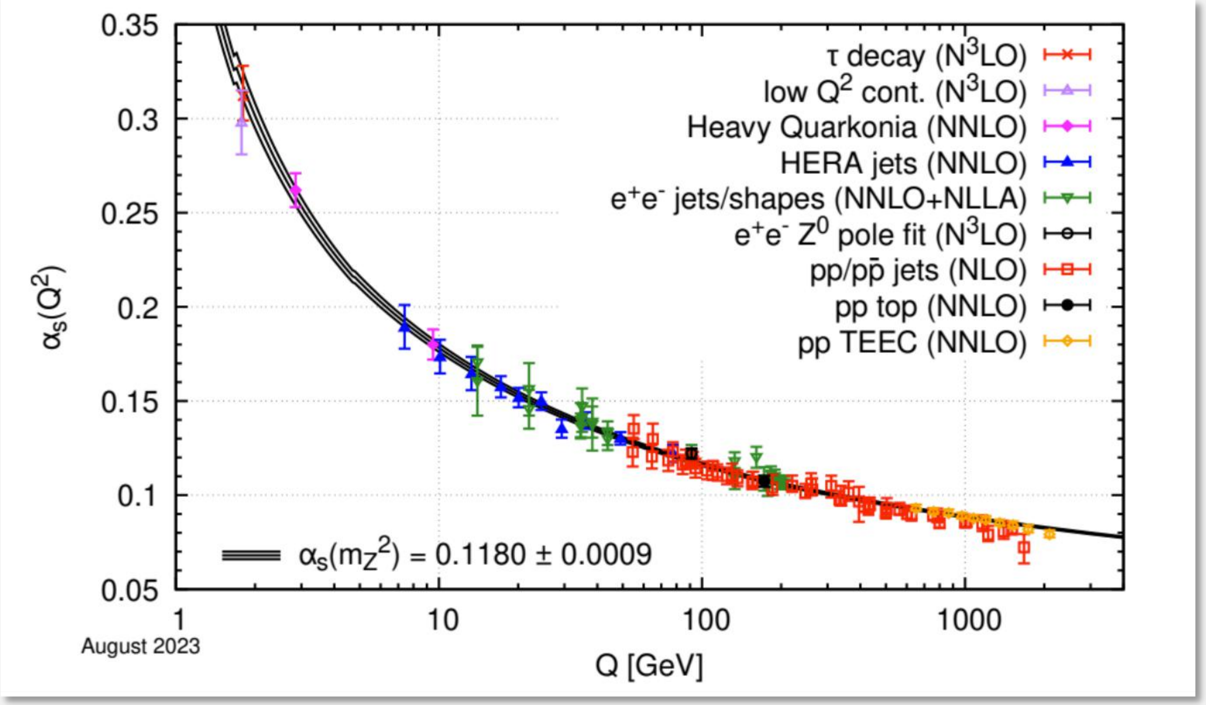
$\alpha, \beta \in \{e, \mu, \tau\}$

RG running effect on neutrino oscillation

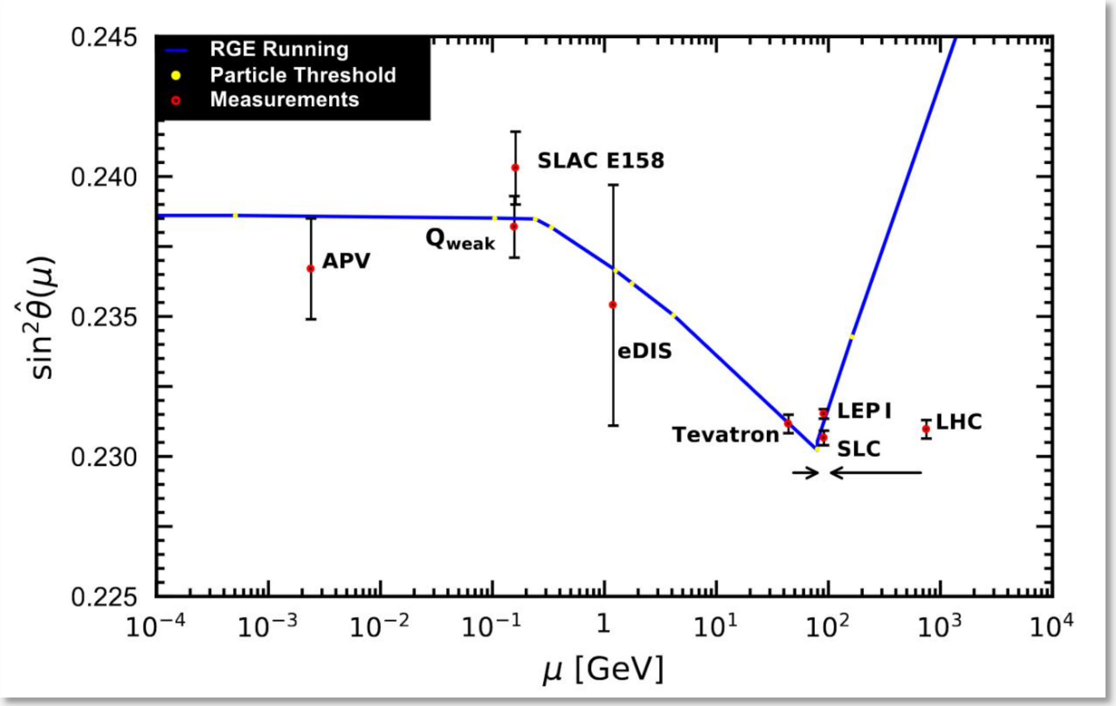
RG Running Effect

The **loop corrections** lead to RG running effect:

strong coupling constant



weak mixing angle



credit: Particle Data Group

RG Running Effect

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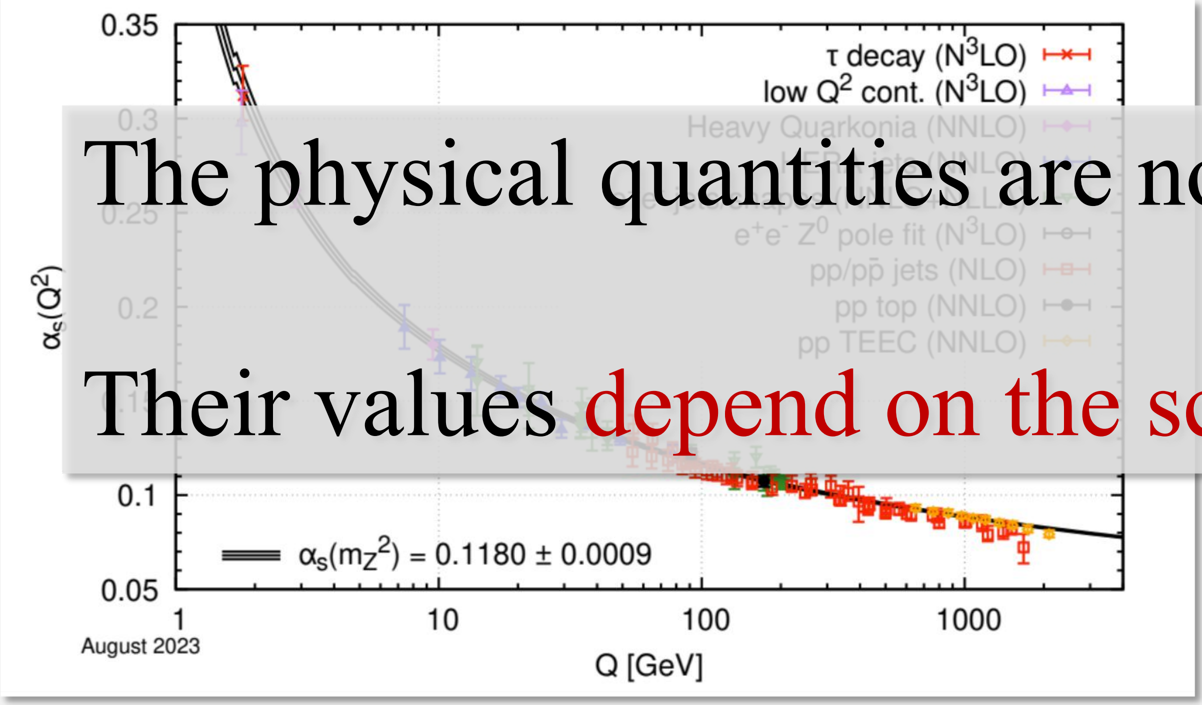
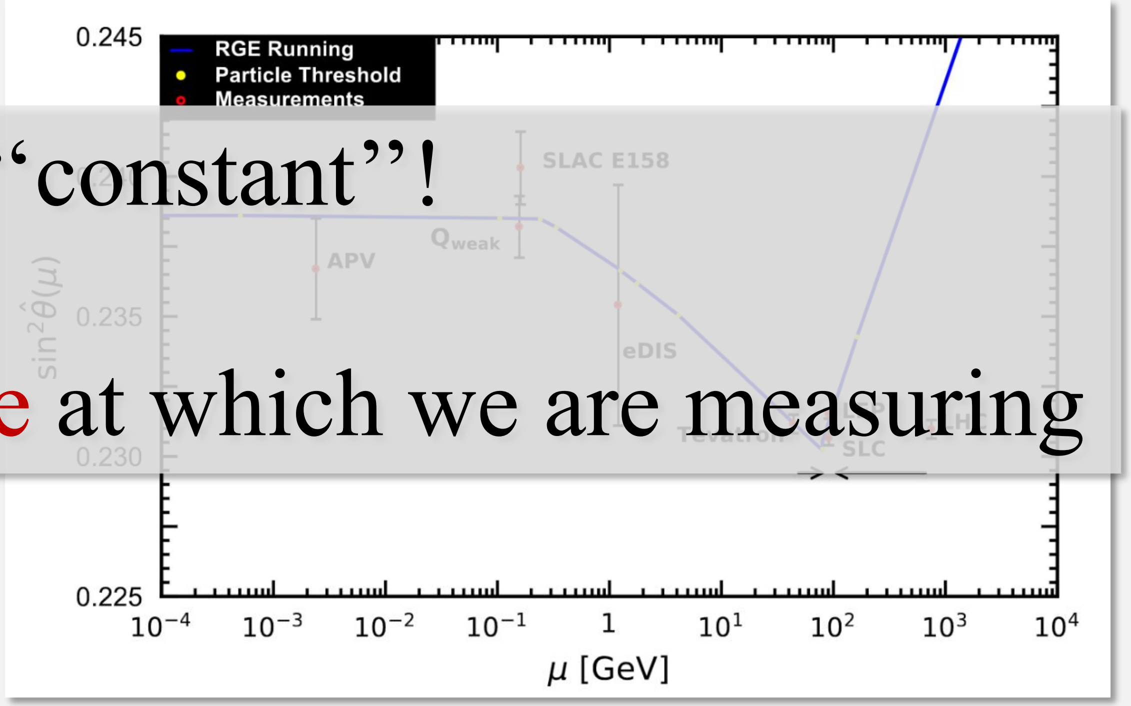


weak mixing angle



The physical quantities are not "constant"!

Their values depend on the scale at which we are measuring

credit: Particle Data Group

RG Running of Neutrino Mixing Parameters

What happens if neutrinos interact with new light degree of freedoms?

credit: symmetry

RG Running of Neutrino Mixing Parameters

What happens if neutrinos interact with new light degree of freedoms?

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Loop corrections can happen at low scales

RG Running of Neutrino Mixing Parameters

What happens if neutrinos interact with new light degree of freedoms?

credit: symmetry

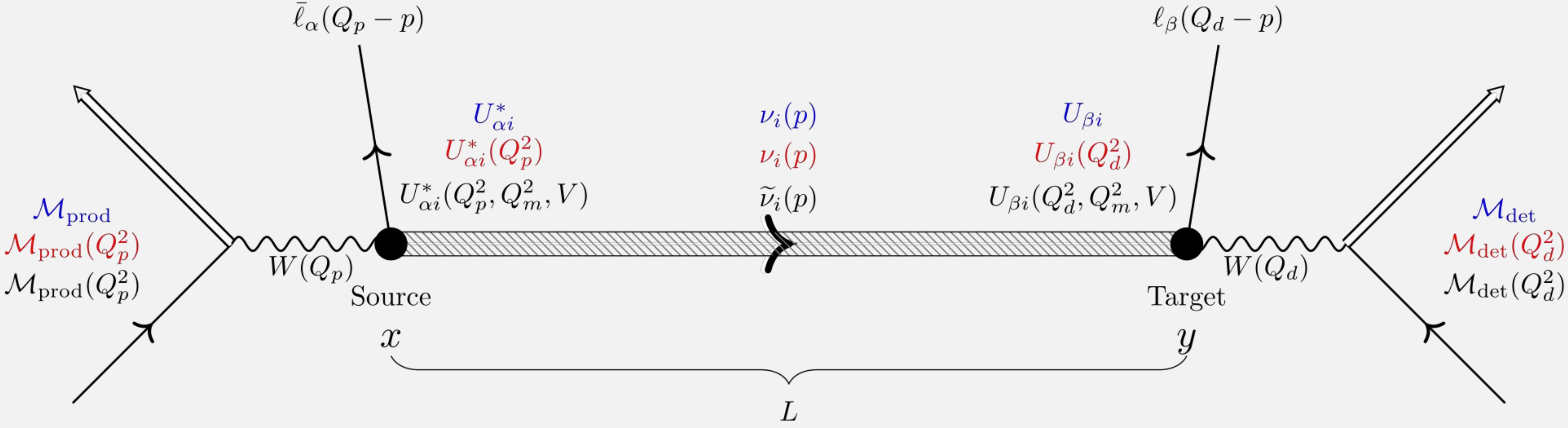
↓

Loop corrections can happen at low scales

↓

Neutrino mixing parameters become scale-dependent: $U \to U(Q^2)$

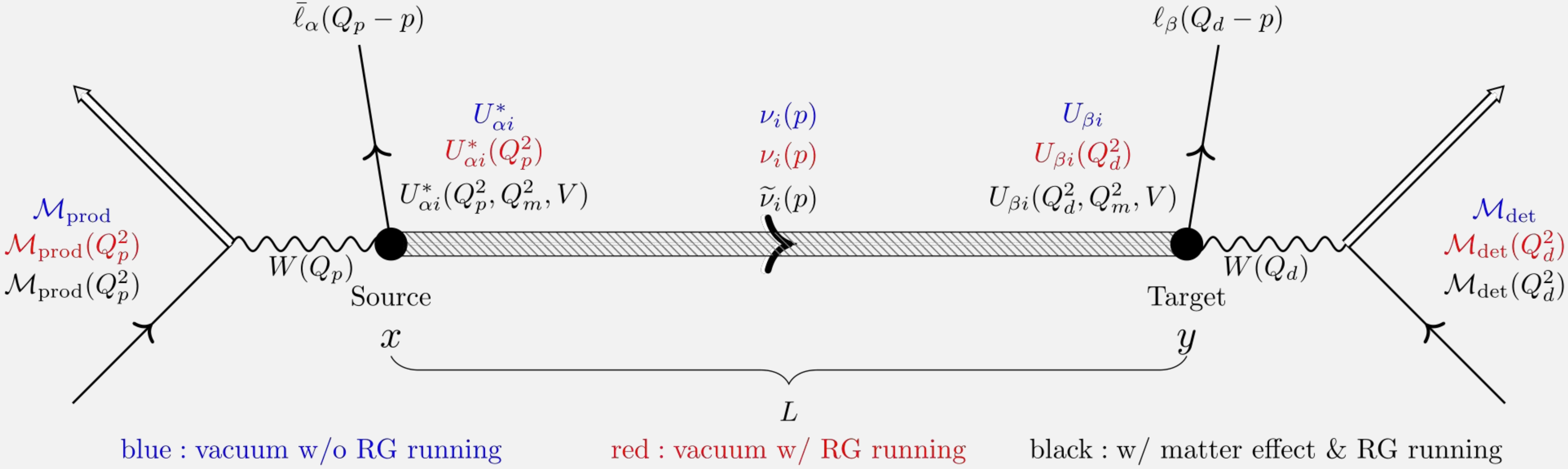
Oscillation w/ RG Running Effect



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

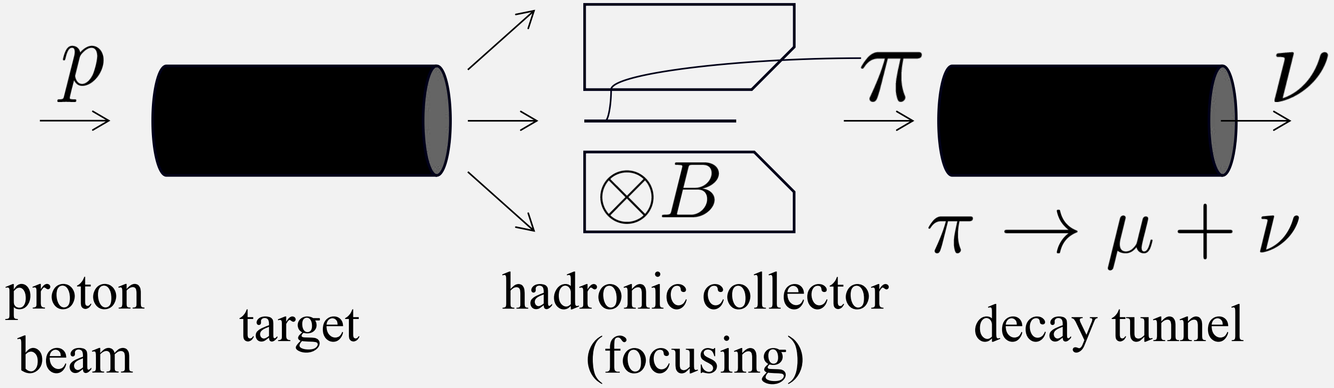
- w/o RG running: $\text{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i} e^{-im_i^2 \frac{L}{2E_\nu}} U_{\beta i}$
- w/ RG running: $\text{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i}(Q_p^2) e^{-im_i^2 \frac{L}{2E_\nu}} U_{\beta i}(Q_d^2)$

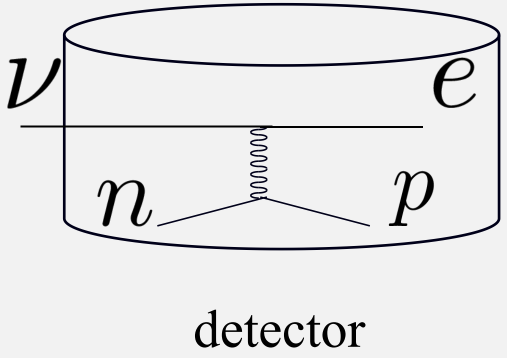
Oscillation w/ RG Running Effect



- w/o RG running: $\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i} e^{-i m_i^2 \frac{L}{2E_\nu}} U_{\beta i}$
- w/ RG running: $\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i \boxed{U^*_{\alpha i}(Q_p^2)} e^{-i m_i^2 \frac{L}{2E_\nu}} \boxed{U_{\beta i}(Q_d^2)}$

RG Running at Oscillation Experiments

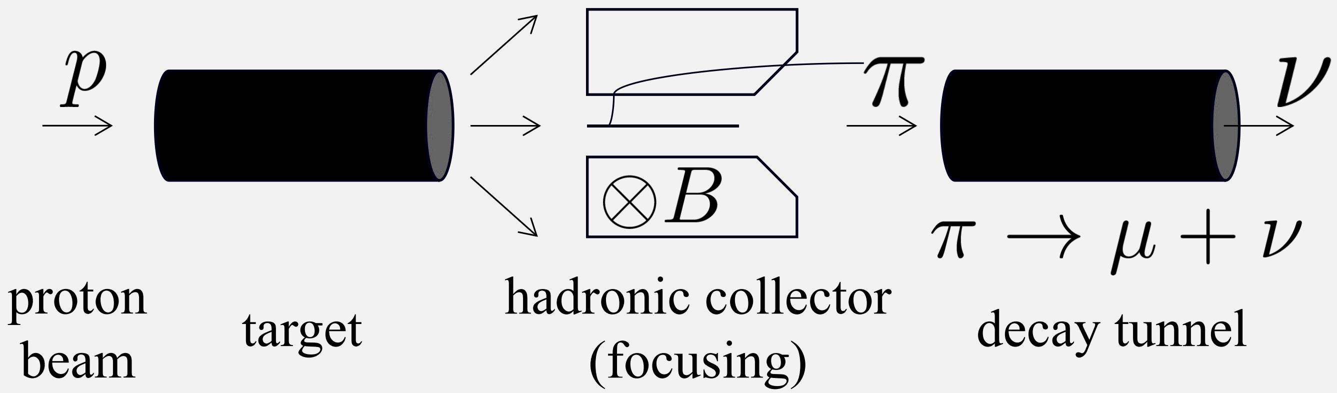


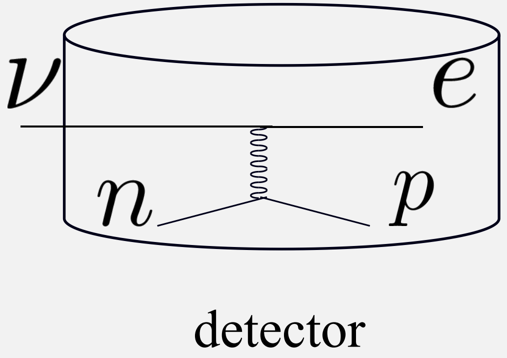


neutrino production
(particle decay)

neutrino detection
(scattering)

RG Running at Oscillation Experiments

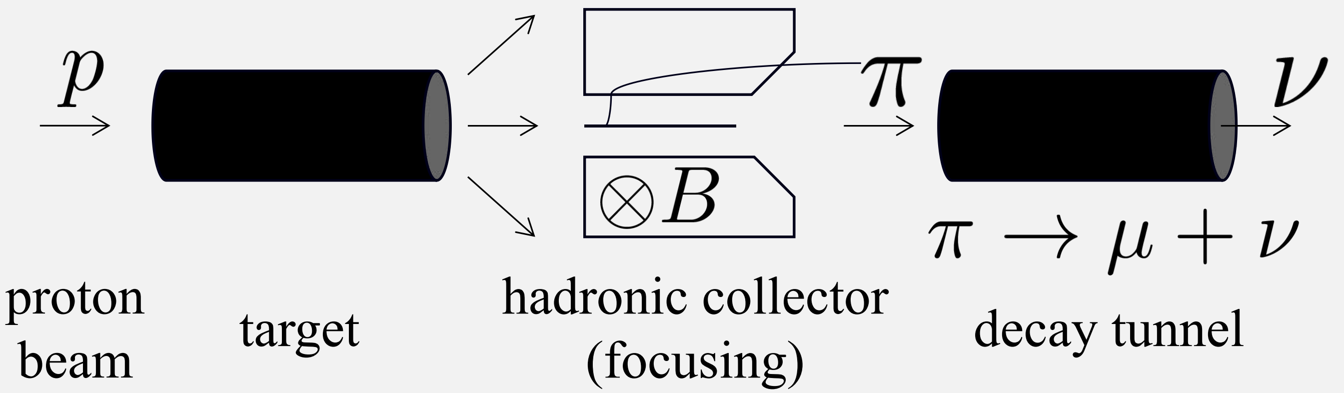


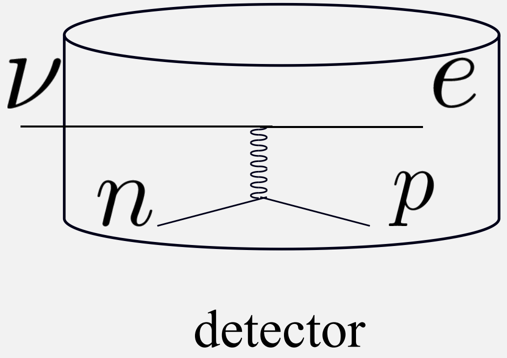


neutrino production
(particle decay)
$U(Q_p^2)$

neutrino detection
(scattering)
$U(Q_d^2)$

RG Running at Oscillation Experiments



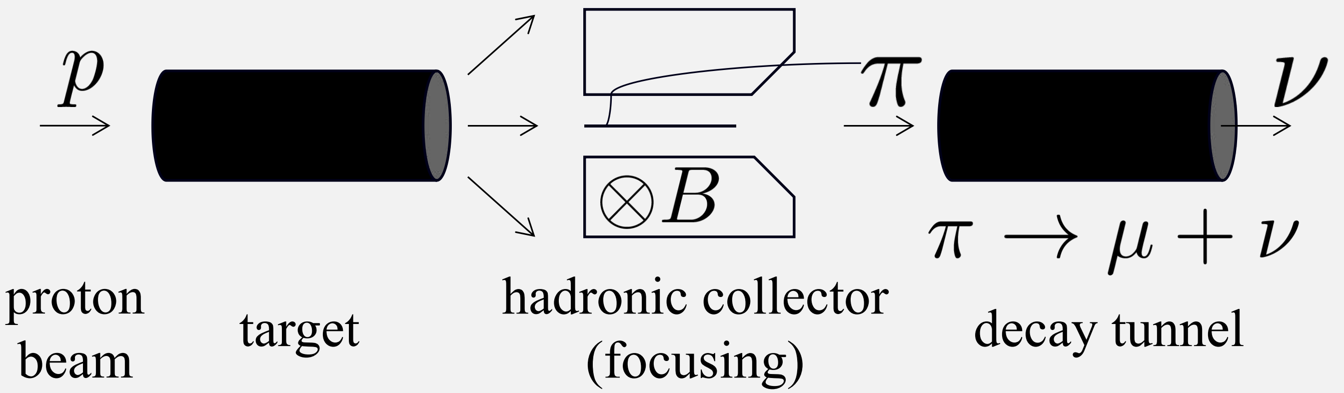


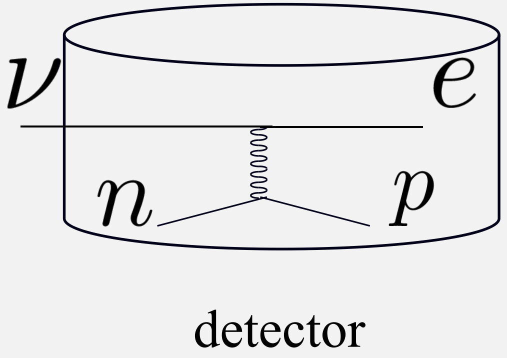
neutrino production
(particle decay)
$U(Q_p^2)$

$\neq$

neutrino detection
(scattering)
$U(Q_d^2)$

RG Running at Oscillation Experiments





neutrino production (particle decay)		neutrino detection (scattering)
$U(Q_p^2)$	$\neq$	$U(Q_d^2)$

$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i \boxed{U^*_{\alpha i}(Q_p^2)} e^{-i m_i^2 \frac{L}{2E_\nu}} \boxed{U_{\beta i}(Q_d^2)}$$

Experimental sensitivities

Parametrization

We take a model-independent parametrization

$$\frac{dX}{d\ln|Q^2|} = \beta_X$$

Solution:

$$X(Q^2) \approx X(Q_0^2) + \beta_X \ln\left(\left|\frac{Q^2}{Q_0^2}\right|\right)$$

For model-dependent case, refer to
K. S. Babu, V. Brdar, A. de Gouvêa, P. A.N. Machado, arXiv: 2108.11961

Parametrization

We take a model-independent parametrization

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

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

β parameters quantify the RG running effect

For model-dependent case, refer to
K. S. Babu, V. Brdar, A. de Gouvêa, P. A.N. Machado, arXiv: 2108.11961

Pheno Results: Zero-distance Effect

- w/o RG running effect:

$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_\mathrm{i} \mathrm{U}^*_{\alpha \mathrm{i}} e^{-\mathrm{i} m_\mathrm{i}^2 \frac{\mathrm{L}}{2\mathrm{E}_\nu}} \mathrm{U}_{\beta \mathrm{i}} \xrightarrow{\boxed{\mathrm{L}\to 0}} \sum_\mathrm{i} \mathrm{U}^*_{\alpha \mathrm{i}} \mathrm{U}_{\beta \mathrm{i}} = \delta_{\alpha\beta}$$

no flavor transition in the zero-distance limit!

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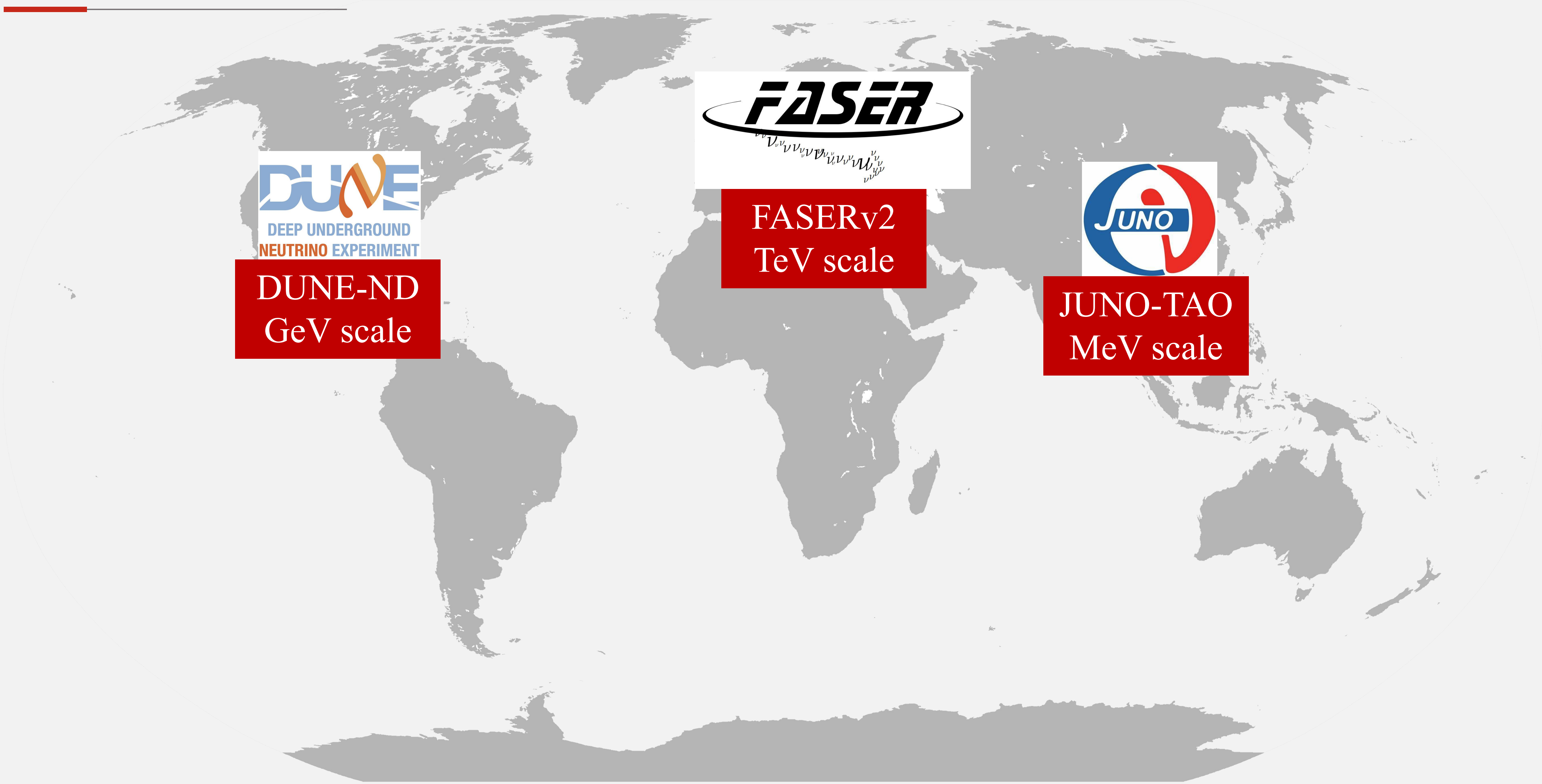
no flavor transition in the zero-distance limit!

- w/ RG running effect:

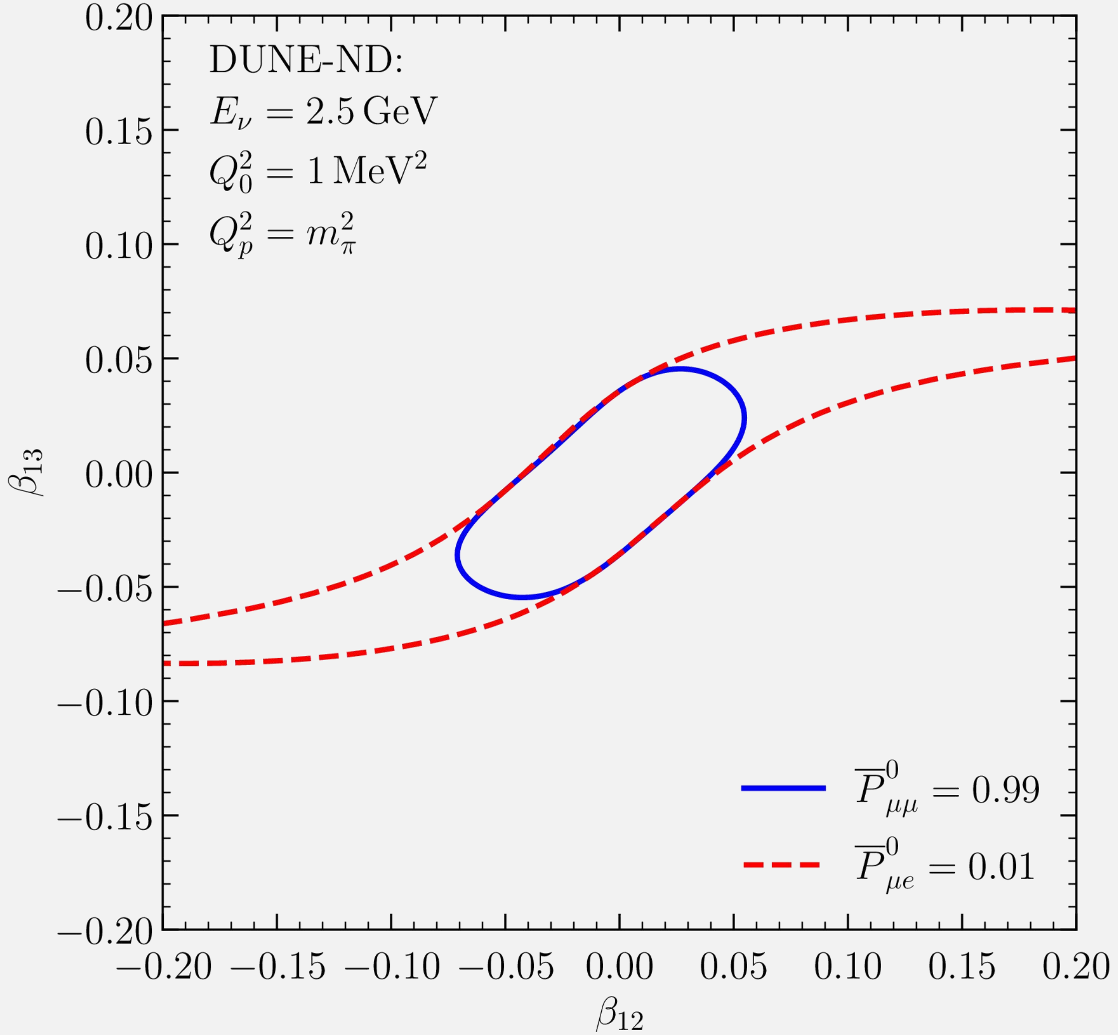
$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i}(Q_p^2) e^{-im_i^2 \frac{L}{2E_\nu}} U_{\beta i}(Q_d^2) \xrightarrow{\boxed{L\to 0}} \sum_i U^*_{\alpha i}(Q_p^2) U_{\beta i}(Q_d^2) \neq \delta_{\alpha\beta}$$

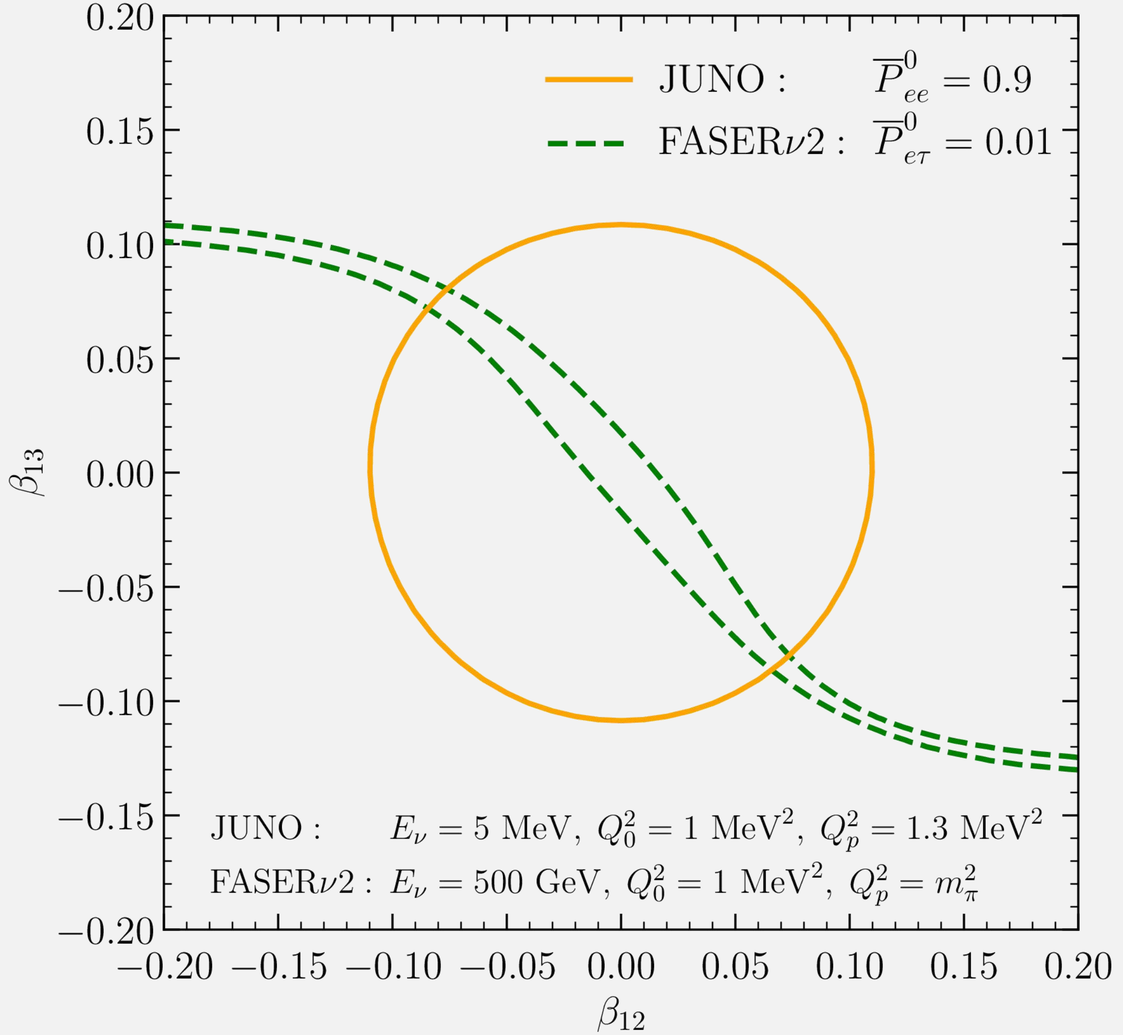
flavor transition in the zero-distance limit!

Pheno Results: Effect at Multiple Exps



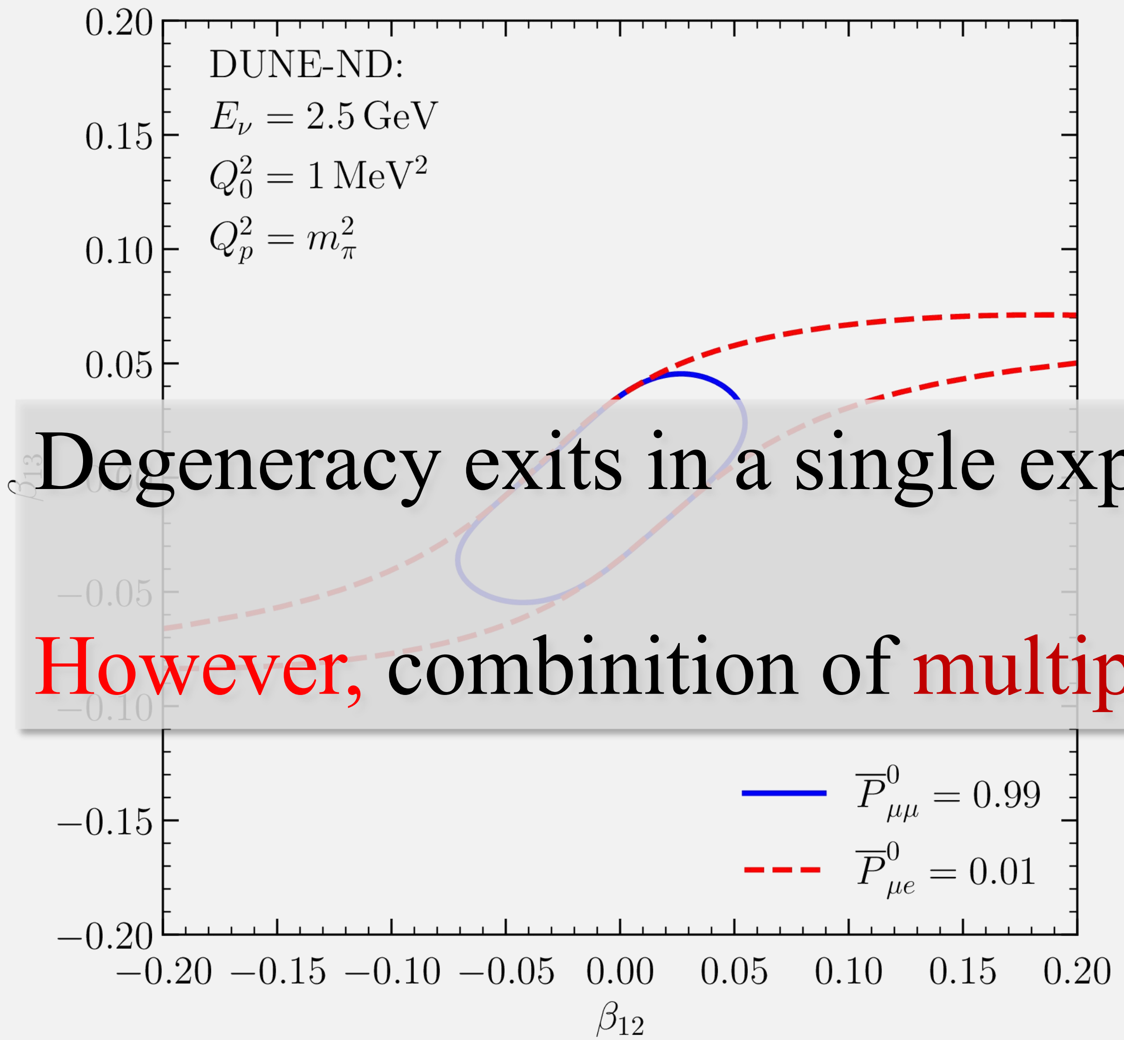
Pheno Results: Effect at Multiple Exps

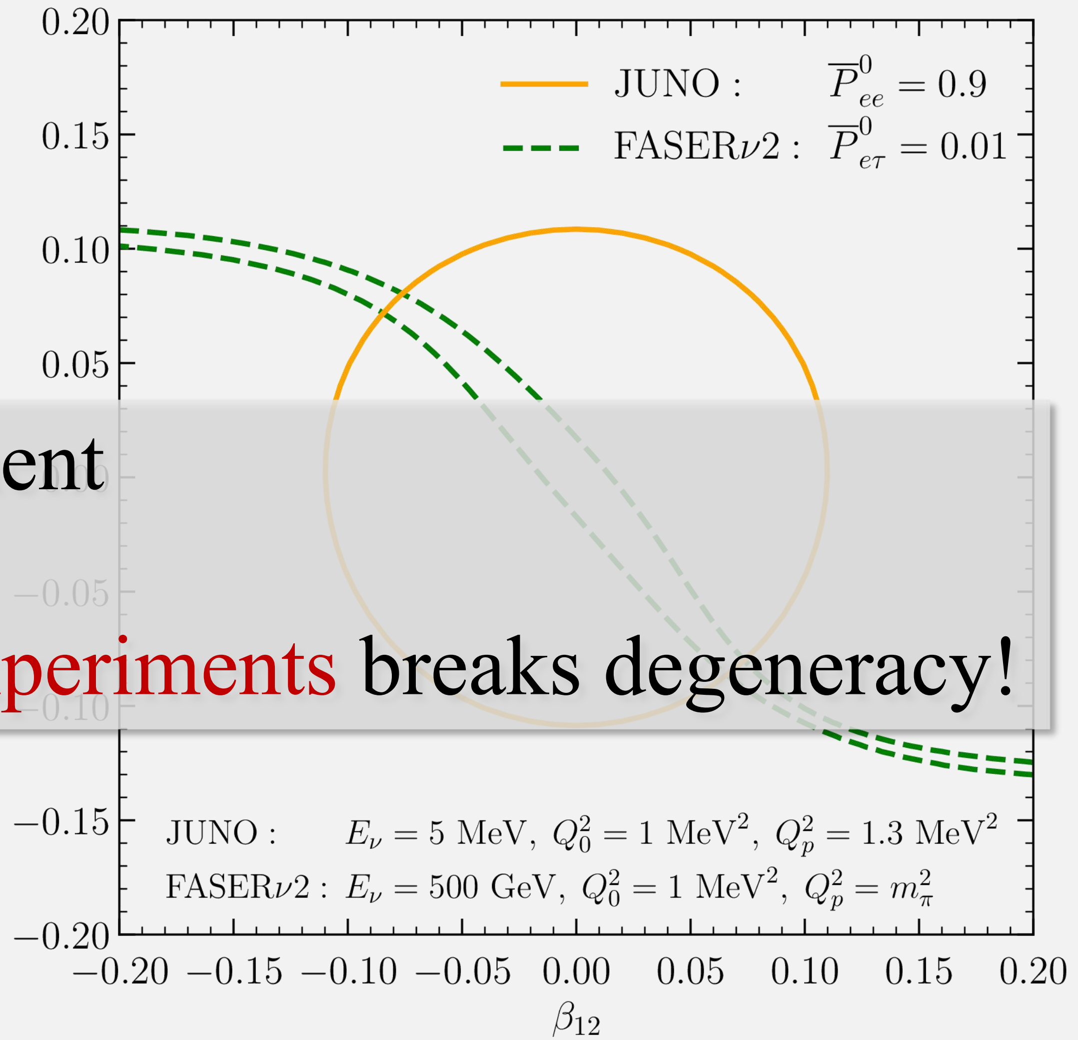




*Denton, Ge, **CFK**, Pasquini, arXiv: 2606.26720*

Pheno Results: Effect at Multiple Exps





Degeneracy exits in a single experiment

However, combinition of multiple experiments breaks degeneracy!

*Denton, Ge, **CFK**, Pasquini, arXiv: 2606.26720*

Pheno Results: Effect at Multiple Exps

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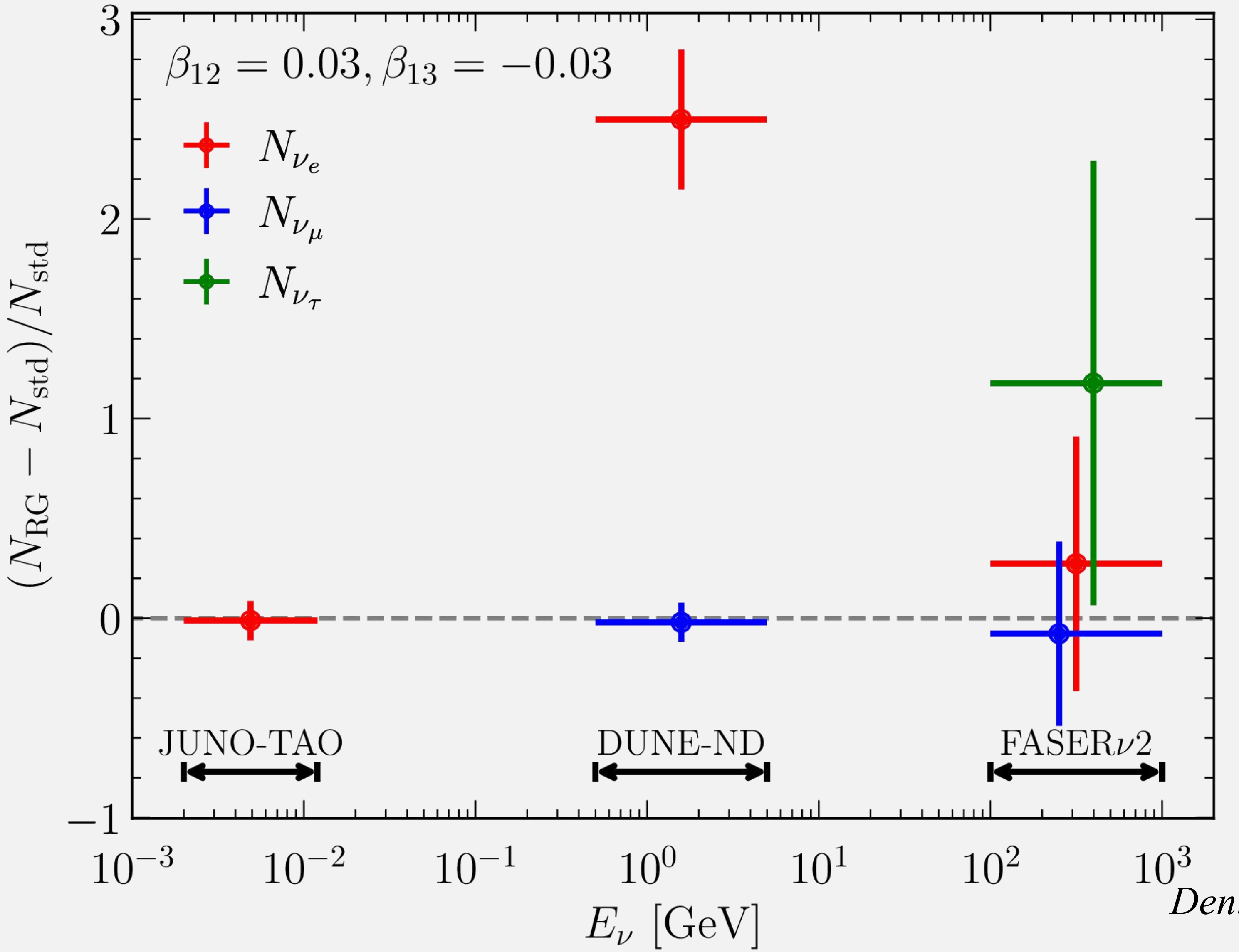
Exp.	Oscillation Channels	$\overline{\ln^2 \lvert Q_d^2\rvert/\lvert Q_p^2\rvert}$
JUNO-TAO	$\overline{\nu}_e \to \overline{\nu}_e$	5 $(E_\nu = 3.6\,\mathrm{MeV})$
DUNE-ND	$\nu_\mu \to \nu_{e,\mu}$ & $\overline{\nu}_\mu \to \overline{\nu}_{e,\mu}$ $\nu_e \to \nu_{e,\mu}$ & $\overline{\nu}_e \to \overline{\nu}_{e,\mu}$	12 $(E_\nu = 2.5\,\mathrm{GeV})$
FASERν2	$\nu_\mu \to \nu_{e,\mu,\tau}$ & $\overline{\nu}_\mu \to \overline{\nu}_{e,\mu,\tau}$ $\nu_e \to \nu_{e,\mu,\tau}$ & $\overline{\nu}_e \to \overline{\nu}_{e,\mu,\tau}$ $\nu_\tau \to \nu_{e,\mu,\tau}$ & $\overline{\nu}_\tau \to \overline{\nu}_{e,\mu,\tau}$	82 $(E_\nu = 0.5\,\mathrm{TeV})$

*Denton, Ge, **CFK**, Pasquini*
arXiv: 2606.26720

Pheno Results: Effect at Multiple Exps



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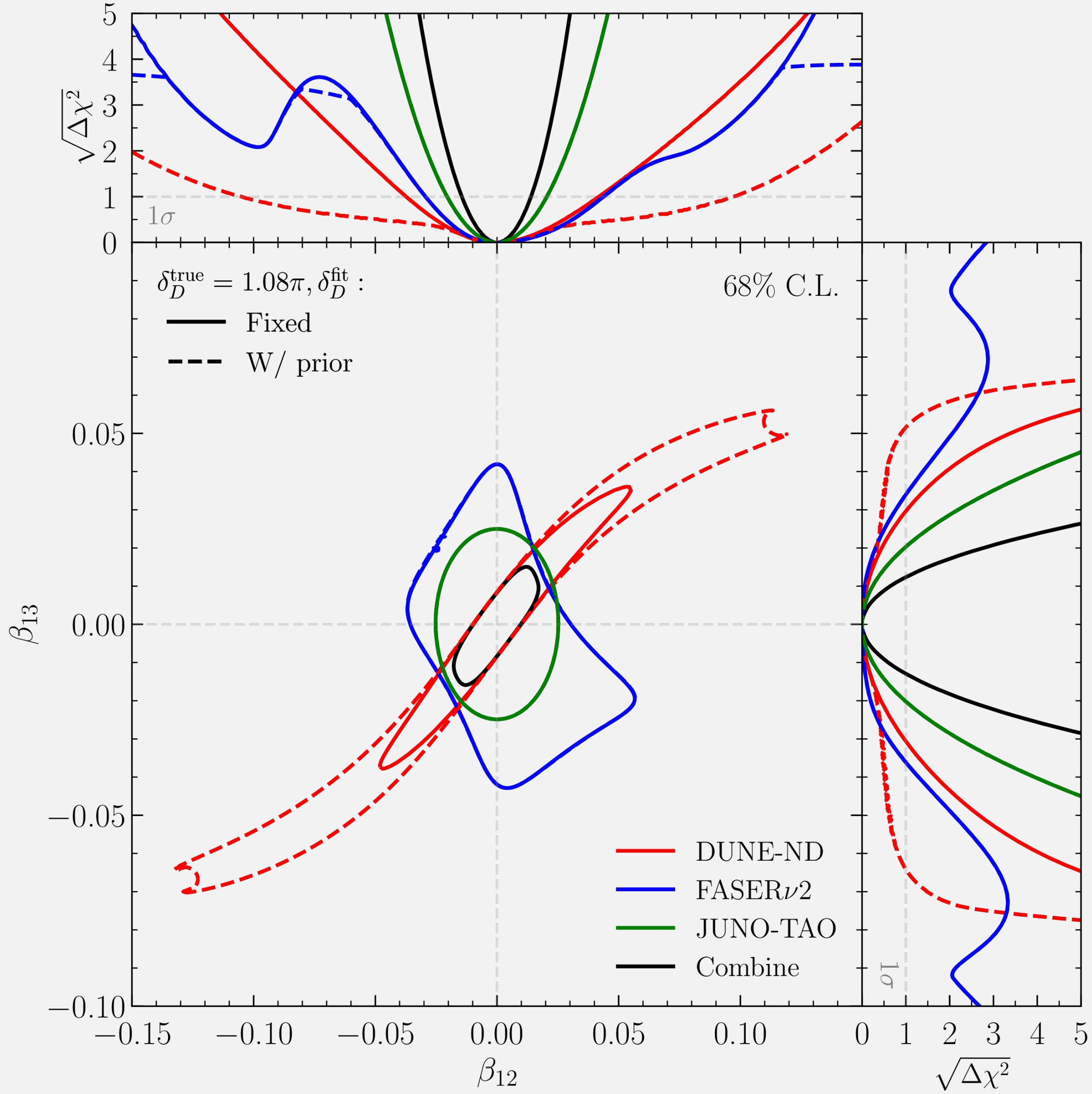
Pheno Results: Effect at Multiple Exps

$\beta_{12} - \beta_{13}$ space



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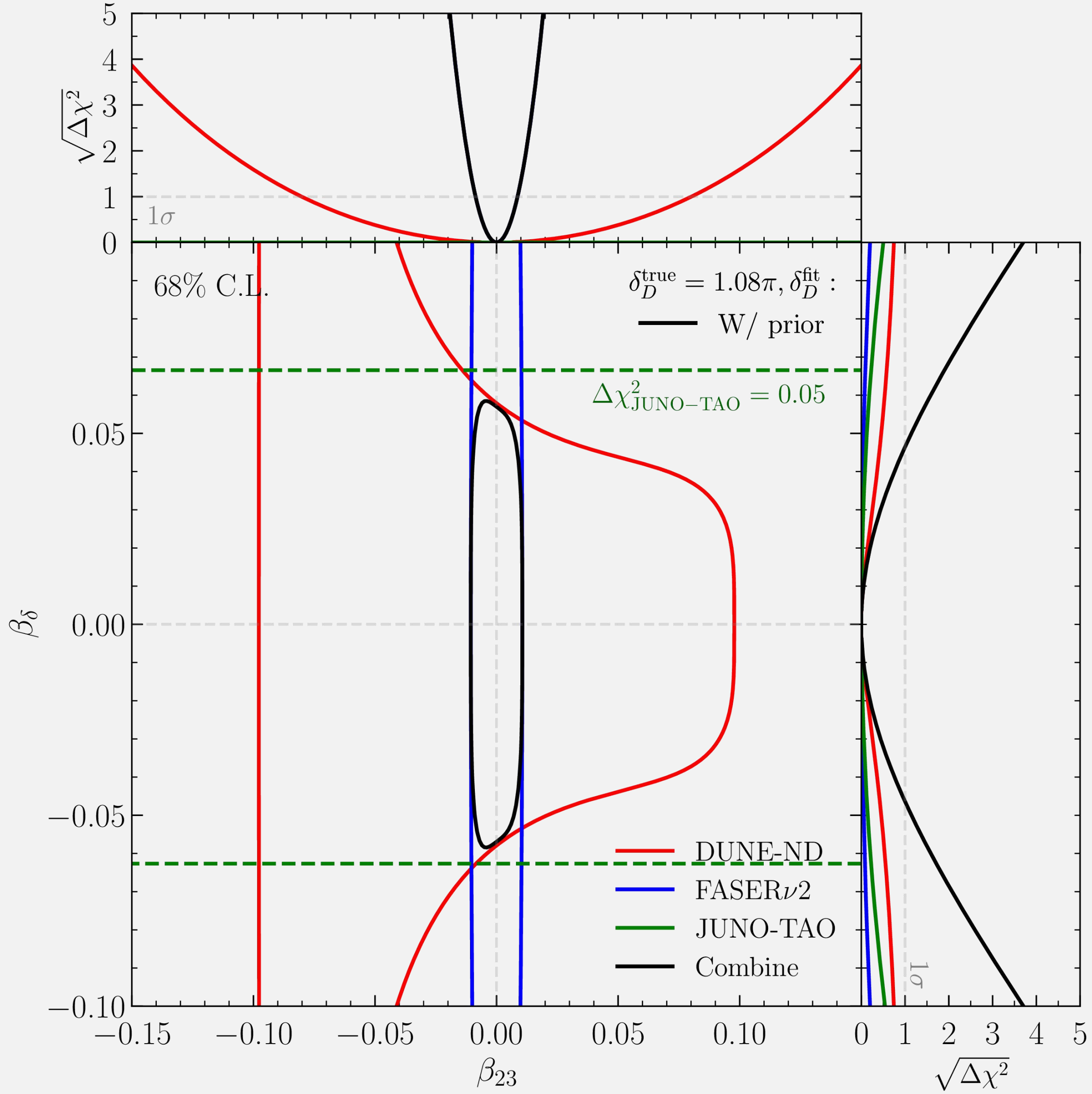
arXiv: 2606.26720

Pheno Results: Effect at Multiple Exps

$\beta_{23} - \beta_{\delta}$ space



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Thank you for your attention!

Summary

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- BSM induced RG running effect can modify neutrino oscillation
- It can affect experimental sensitivities to neutrino mixing parameters
- It’s desirable to combine experimental data at different energy scales

Back up

Back up

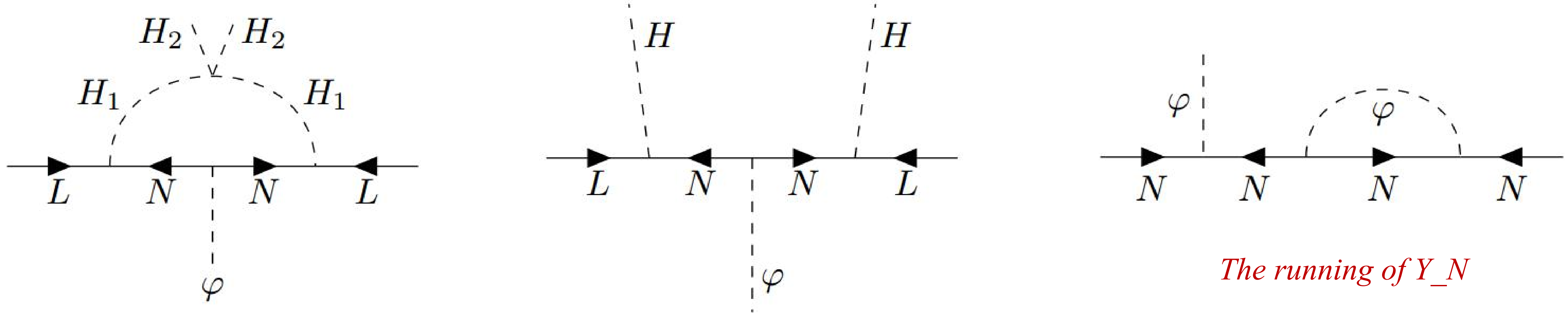


FIG. 2: *Left*: Feynman diagram associated to the generation of neutrino masses in a scotogenic-like neutrino mass model in which $\mathcal{M} \propto Y_N$ (Model 1). *Middle*: Feynman diagram associated to the generation of neutrino masses in an inverse seesaw model in which $\mathcal{M} \propto Y_N^{-1}$ (Model 2). *Right:* Representative Feynman diagram responsible for the running of Y_N in both Model 1 and Model 2. See text for details.

$$-\mathcal{L}_\nu^{(1)} = \overline{L} Y_\nu \tilde{H}_1 N_R + \varphi \overline{N_R^c} Y_N N_R + \text{h.c.},$$

$$-\mathcal{L}_\nu^{(2)} = \overline{L} Y_\nu \tilde{H} N_R + \varphi \overline{N_R^c} Y_N N_R + \text{h.c.},$$

$$M_\nu \simeq \frac{v_\varphi}{16\sqrt{2}\pi^2} Y_\nu Y_N Y_\nu^T \ln \frac{M_H^2}{M_A^2}.$$

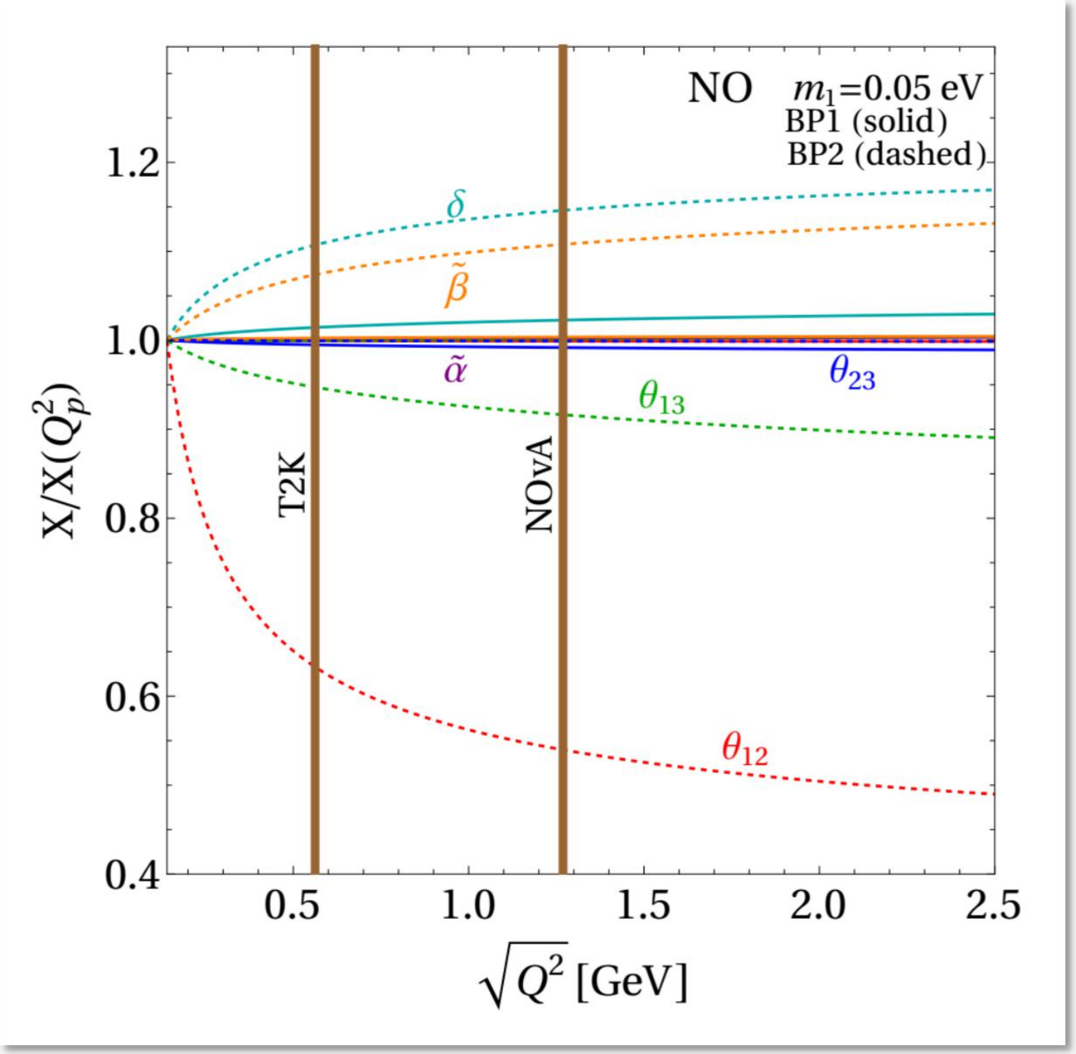
$$M_\nu = \frac{\sqrt{2} v^2}{4 v_\varphi} Y_\nu (Y_N)^{-1} Y_\nu^T .$$

K. S. Babu et al,
arXiv: 2108.11961

$$16\pi^2 \beta(Y_N) \equiv 16\pi^2 \frac{dY_N}{d\ln|Q|} = 4Y_N \left[Y_N^2 + \frac{1}{2}\mathrm{Tr}(Y_N^2) \right].$$

Casas-Ibarra parametrization

$$Y_\nu = \frac{1}{\sqrt{C}} Y_N^{-x/2} R \,\mathrm{diag}\,(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})\, U(Q_p^2)\,,$$



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zero-distance limit

$$1/E_\nu \ll L \ll 2E_\nu/\Delta m_{ij}^2$$

$$i\frac{\partial}{\partial\tau_i}|\nu_i(\tau_i)> = m_i|\nu_i(\tau_i)> \quad .$$

$$|\nu_i(\tau_i)> = e^{-im_i\tau_i}|\nu_i(0)> \quad .$$

$$m_i\tau_i = E_i t - p_i L \quad .$$

$$p_i = \sqrt{E^2 - m_i^2} \cong E - \frac{m_i^2}{2E} \quad .$$

$$m_i\tau_i \cong E(t-L) + \frac{m_i^2}{2E}L \quad .$$

$$\nu_i \equiv \nu_i(Q^2 = m_{\nu_i}^2)$$

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energy reconstruction:

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

momentum transfer reconstruction:

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