中山大學 物理学院
SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS

Muon：中微子物理

—precision measurement and new physics searches

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《缪子束加速和对撞机技术及其应用》论坛

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Sampsa Vihonen, Tse-Chun Wang, Yi-Bing Zhang

Ref: ***JHEP01(2021)124***, ***JHEP03(2021)019***, *arXiv: 2106.15800*

Snowmass Neutrino Frontier Workshop, Mar.16, 2022

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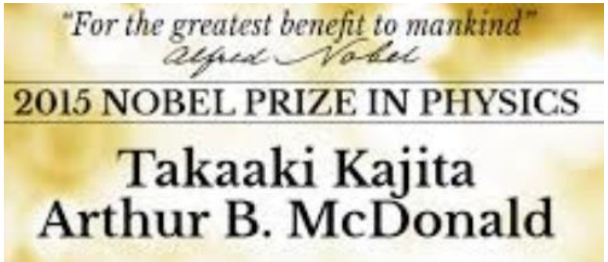
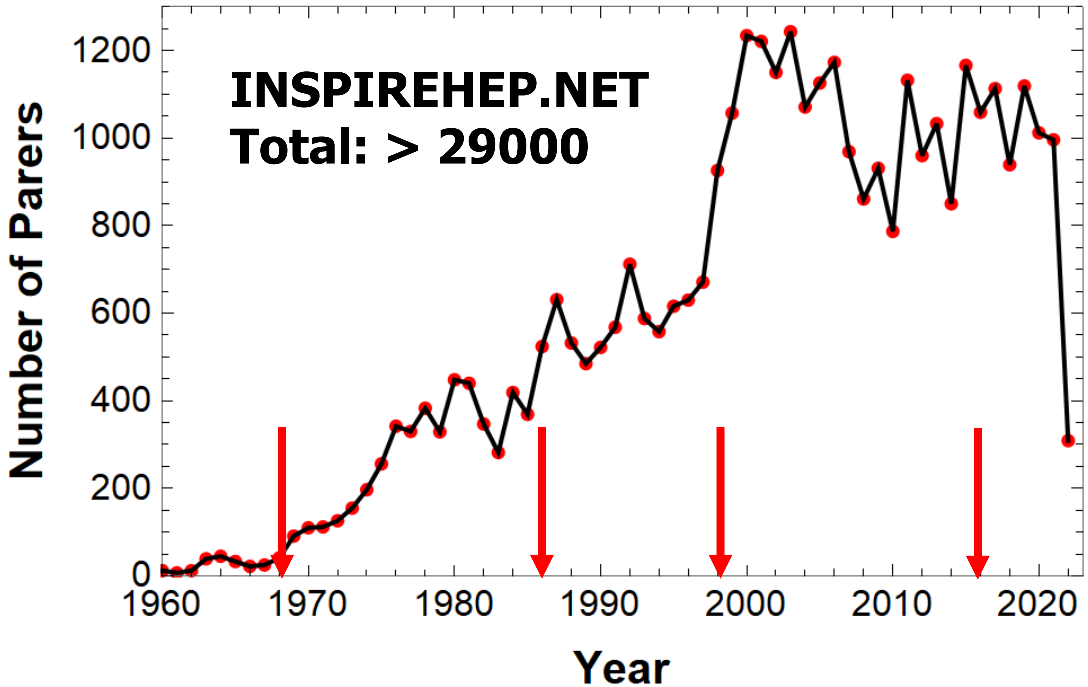
Neutrino physics is a hot topic



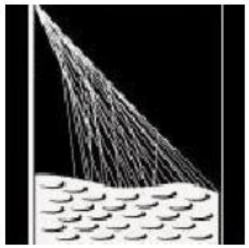
"For the discovery of neutrino oscillations, which shows that neutrinos have mass"



- **Proposed ν in 1933**
- **Discovery of ν in 1956**
- **Parity violation in 1957**
- **SM w.r.t ν in 1967**
- **NC of ν in 1973**
- **Detection of SN ν in 1987**
- **Evidence of ν osc. in 1998**

Three-generation neutrino oscillations

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

= () x (

) x ()

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} {\rm Re}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{i<j} {\rm Im}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin(\Delta_{ij})$$

$$U^\dagger U = 1$$

$$\frac{\Delta_{ij}}{2} = 1.27 \frac{m_i^2 - m_j^2}{{\rm eV}^2} \frac{L/E}{\rm Km/GeV}$$

- $\Delta m_{ij}^2 = m_i^2 - m_j^2$ The mass differences
- $U_{\alpha j}$ The mixing angles (and Dirac phases)
- E The neutrino energy
- L Distance ν source to detector

• For 3 ν framework , we have **6**+1 free parameters in neutrino oscillations:

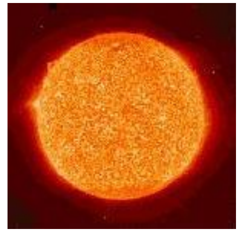
P (θ_{12}, θ_{13}, θ_{23}, δ, Δm_{21}^2, Δm_{31}^2) + ρ (in matter)

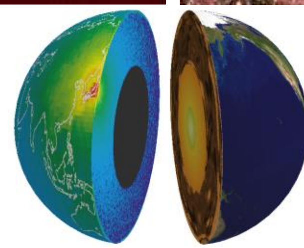
✓ ✓ ✓ ? ✓ ✓?

Where are neutrinos from?

Natural source

???





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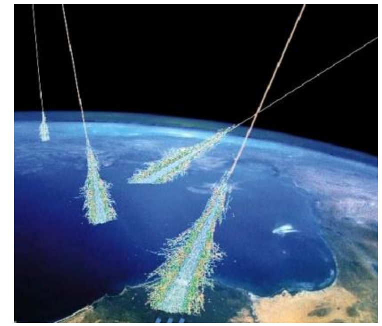

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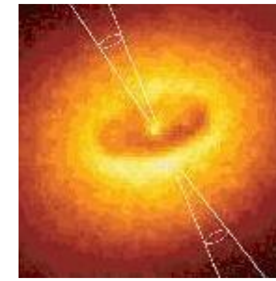


10^{-4}	10^{-3}	10^{3}	10^{4}	10^{5}	10^{6}	10^{7}	10^{8}	10^{9}	10^{10}	10^{11}	10^{12}	E [eV]
		keV			MeV			GeV			TeV	

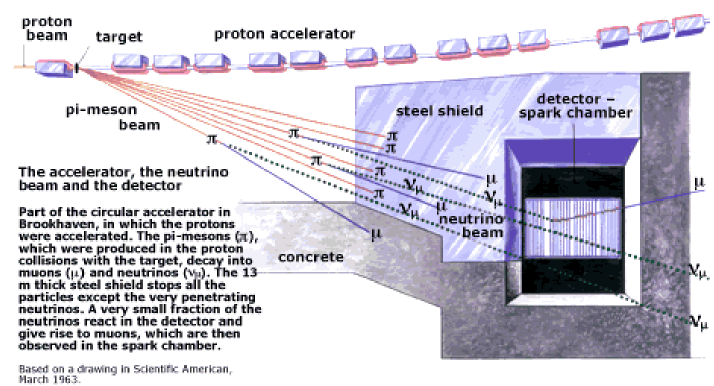
~Electron mass → MeV

~Proton mass → GeV

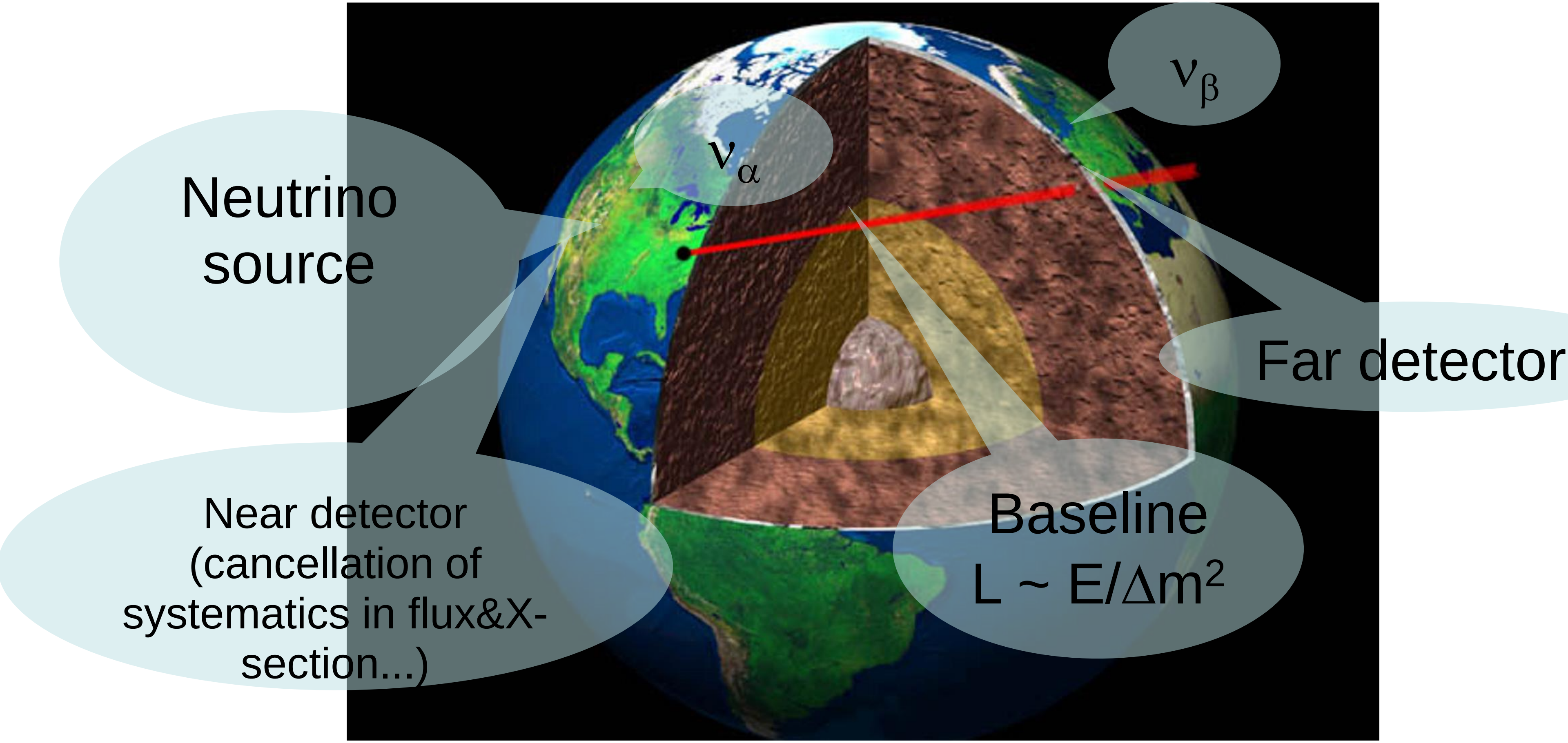
~LHC → TeV

Artificial source

??

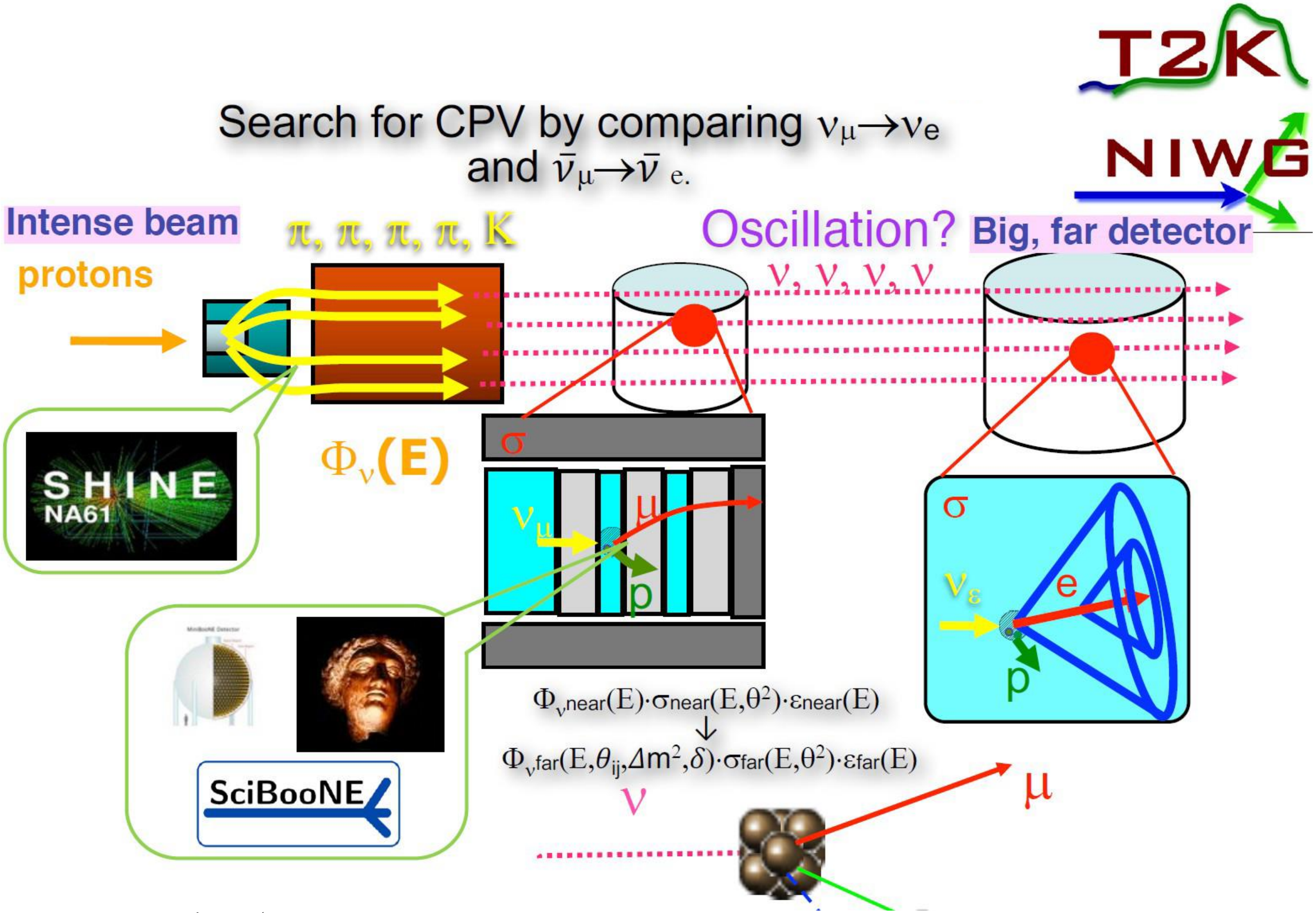


Working principles of neutrino oscillation experiments



- Get the neutrino source as clean as possible. Muon decay v.s pion decay beams.
- Deploy the best detector to reconstruct the oscillated neutrino spectra: Gd-WC, LAr TPC, scintillator detector with flavour&charge identifications…
- Data mining: precision measurement & discovery of new physics…

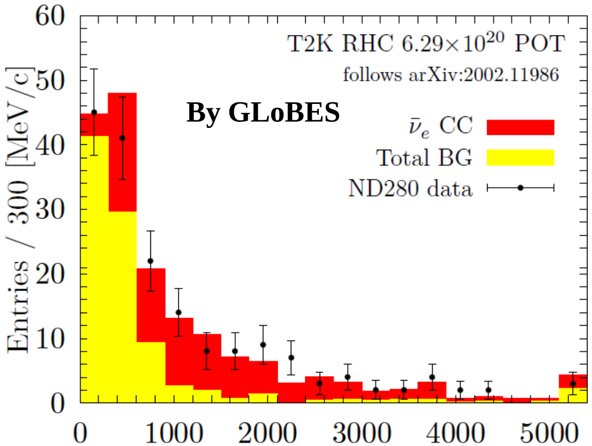
An example: T2K

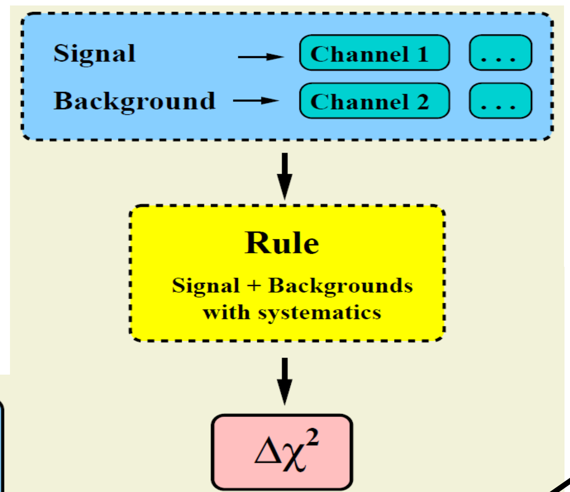


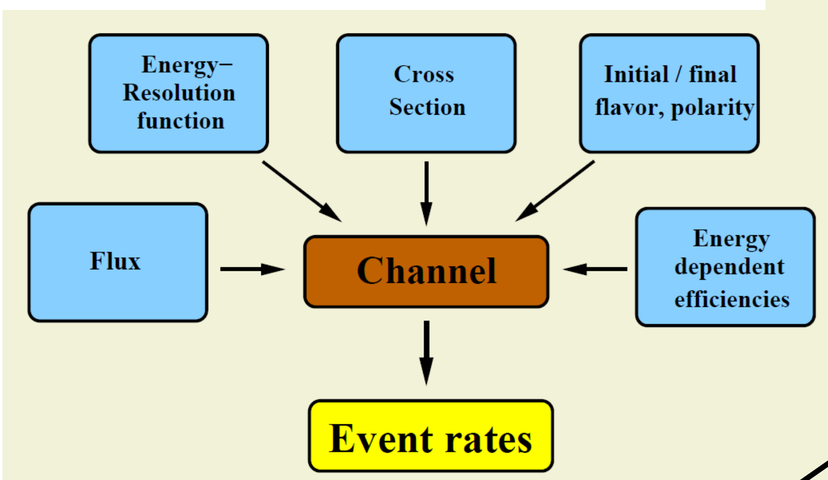
K. McFarland, Neutrino Interaction Uncertainties @ NNN2018

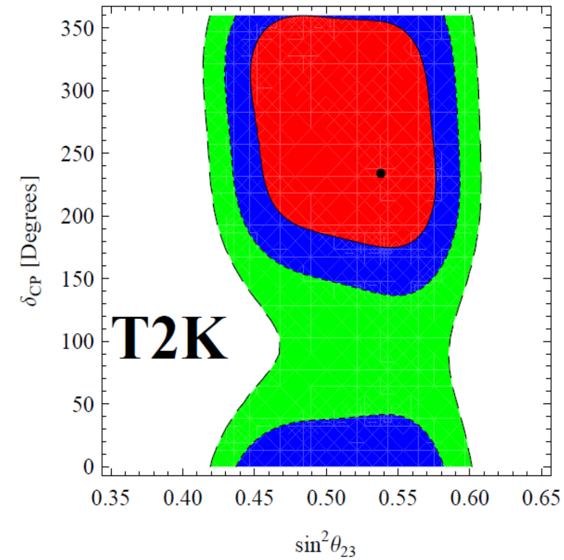
Simulations of neutrino oscillations w/o new physics

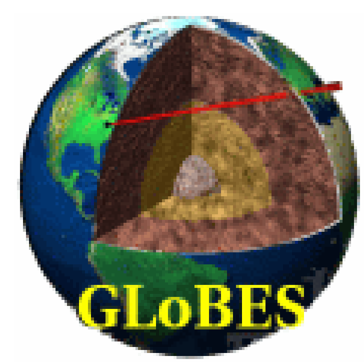
$$N = \text{time} \times \#\ \text{of targets} \times \text{efficiency} \times \int_{E_i}^{E_f} dE_\nu \frac{d\phi(E_\nu)}{dE_\nu}\sigma(E_\nu)$$



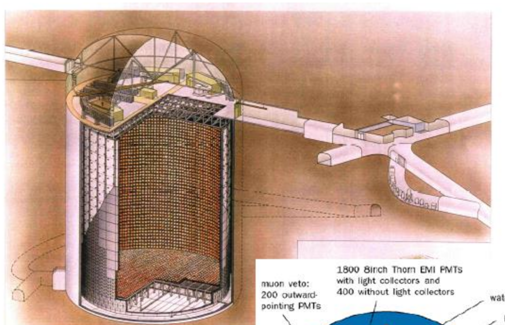


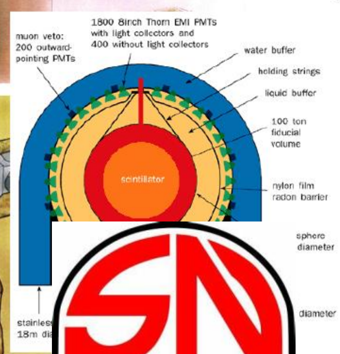


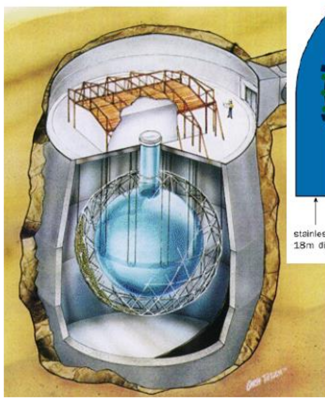


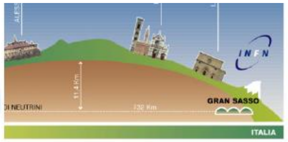


Lots of neutrino experiments to get a new horizon





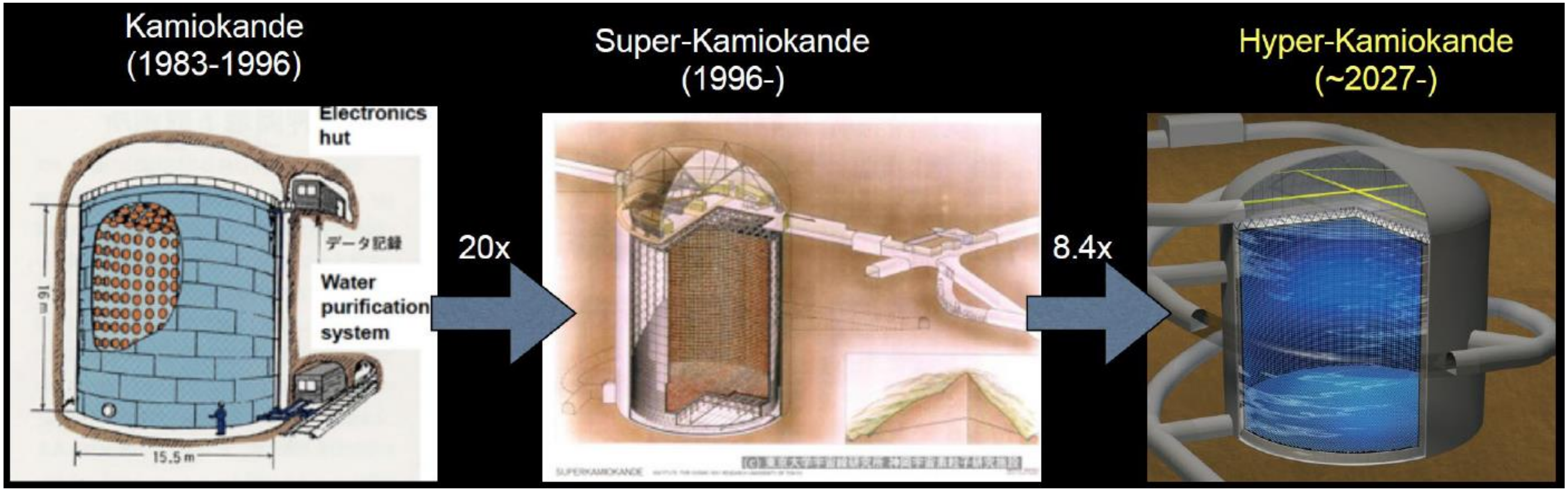




More are coming…

WC detectors: Kamiokande→SK→HyperK

- Bigger than bigger! PMT technology revolutionized!



3 kton WC 20% coverage with 20” PMT

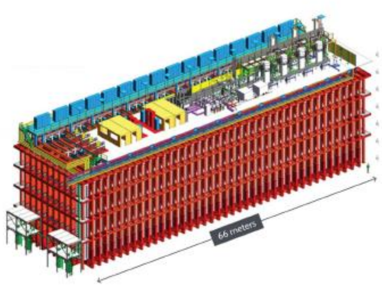
50 kton WC 40% coverage with 20” PMT

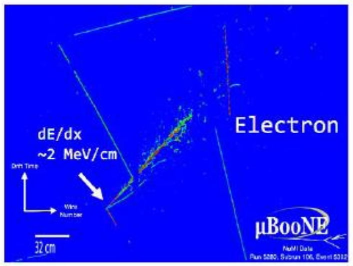
260 kton WC 40% coverage with 20”+HQE PMT

- **Construction started in 2020.**
- **Data taking from 2027.**
- **J-PARC neutrino beam will be upgraded from 0.7 to 1.3 MW**

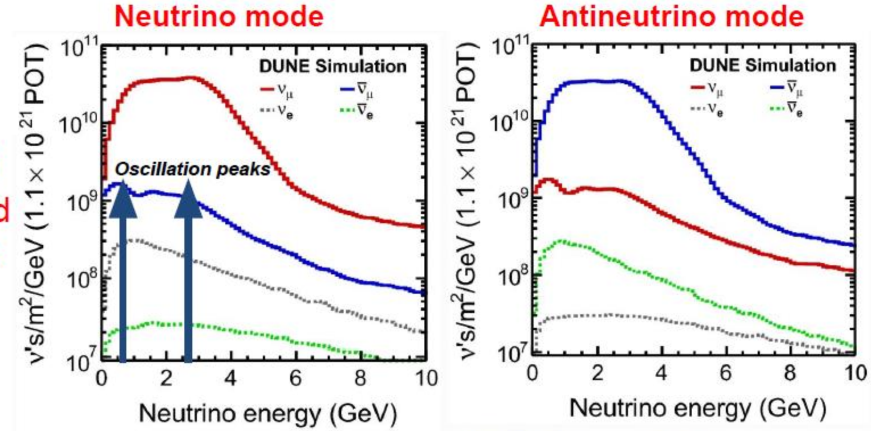
LAr TPC: DUNE

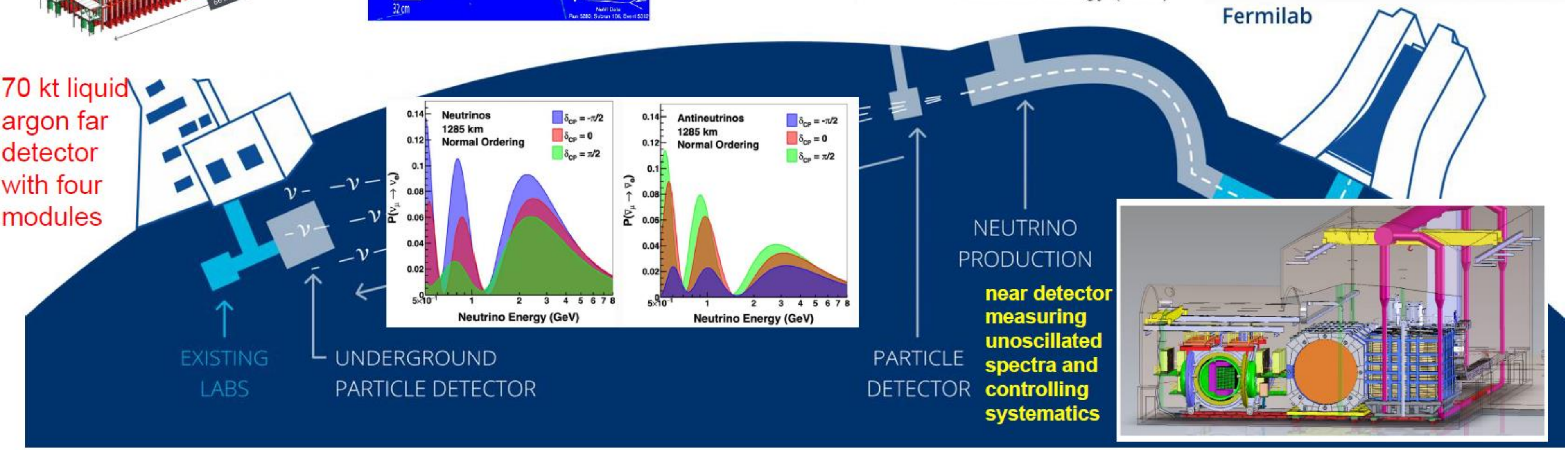
Courtesy: Guang Yang@NuFact2021





Broad band neutrino and antineutrino beam

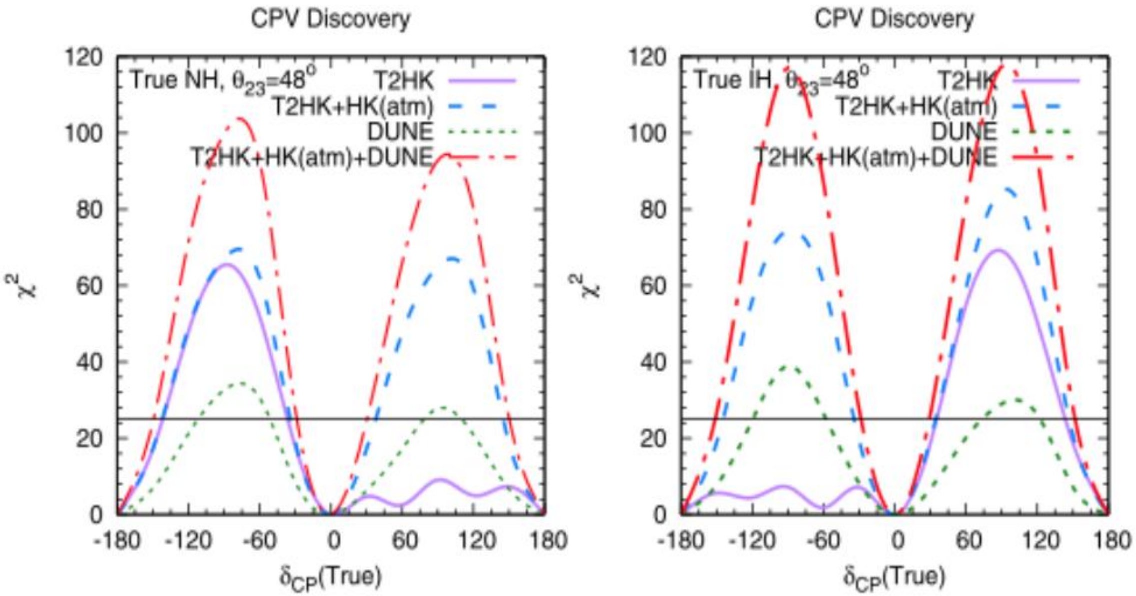


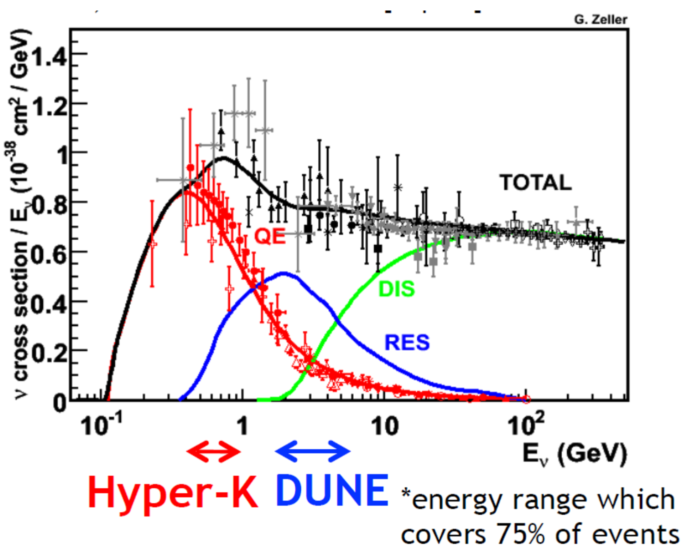


- **Built, operated and analyzed ProtoDUNE prototype at CERN**
- **Phase-I data taking expected in late 2020s. Phase-II likely in 2030s.**
- **FNAL neutrino beam will be upgraded from 1.2 to 2.4 MW in 2030s.**

Complementarity of T2HK and DUNE

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

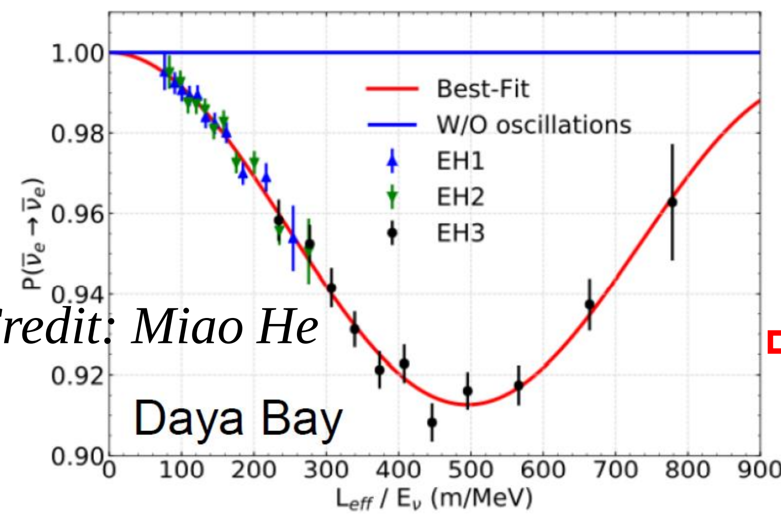




- **The next generation of accelerator-based oscillation experiments will require ~% uncertainties (on far detector event rate and shape predictions)**
- **Neutrino-nucleus interaction modeling is difficult at the GeV scale**
- **Existing models are unlikely to provide sufficient precision for future experiments**

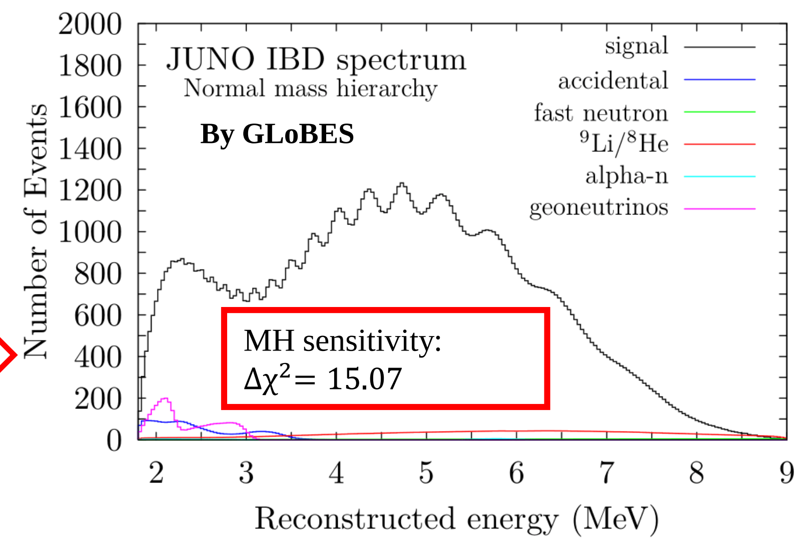
LSc: DYB (20 t*8) → JUNO (20 kt)

- Daya Bay neutrino experiment: mission completed!

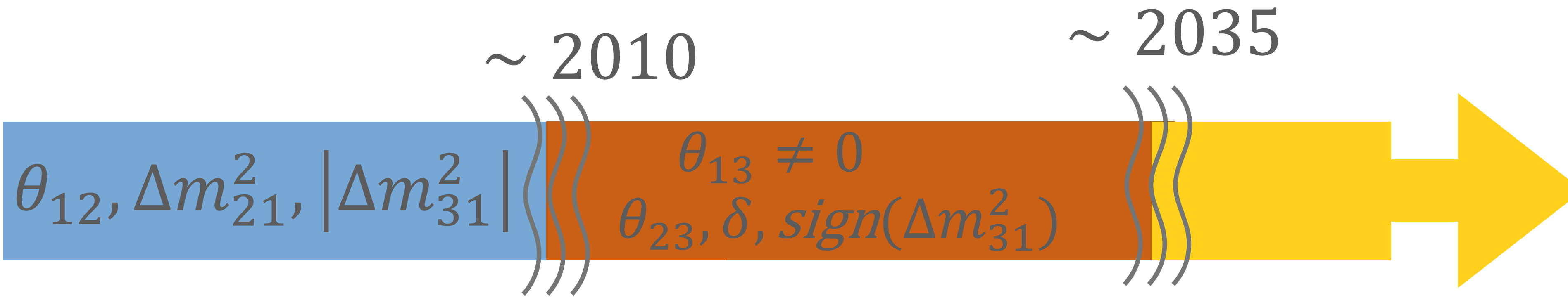


Credit: Miao He

MCP-PMT
20”+HQE



International efforts



solar e.g. SNO, etc…
atmosphere: SuperK, etc…
reactors: KamLAND, etc…

Reactor and superbeam experiments
DYB, Double Chooz, RENO…
MINOS, NOvA,T2K,
T2HK, DUNE…
JUNO…

Neutrino factory
e.g. NuSTORM
MOMENT…

It is important to upgrade the neutrino source:

1. decrease the statistical uncertainties, i.e. enhance the ν flux intensity;
2. decrease the systematic uncertainties from the source;
3. reduce backgrounds from the source…

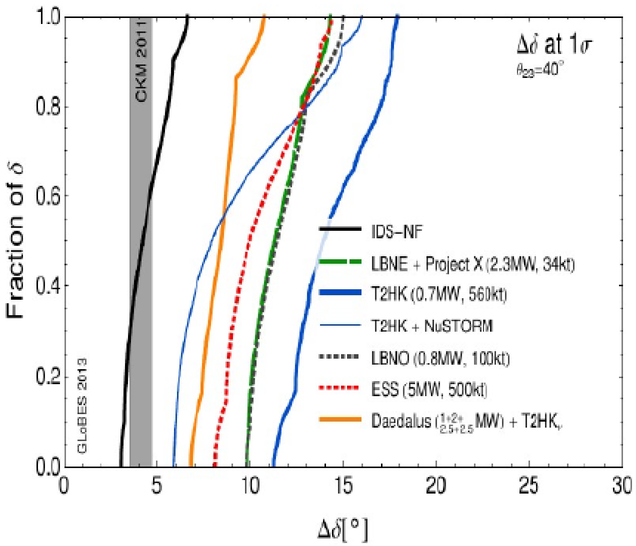
Dreaming machine——Neutrino Factory

- **Muon-decay neutrino beams with well-defined fluxes:**

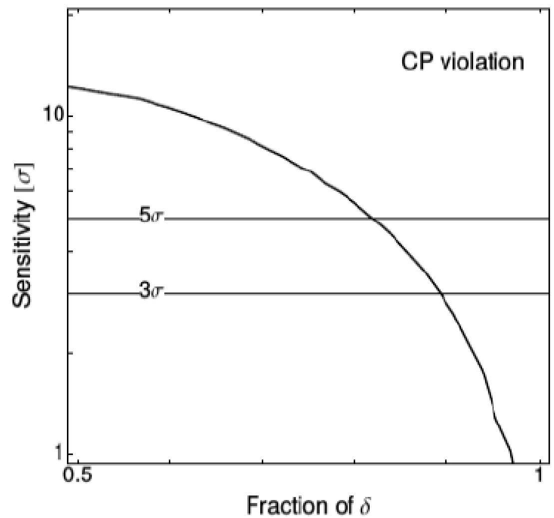
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

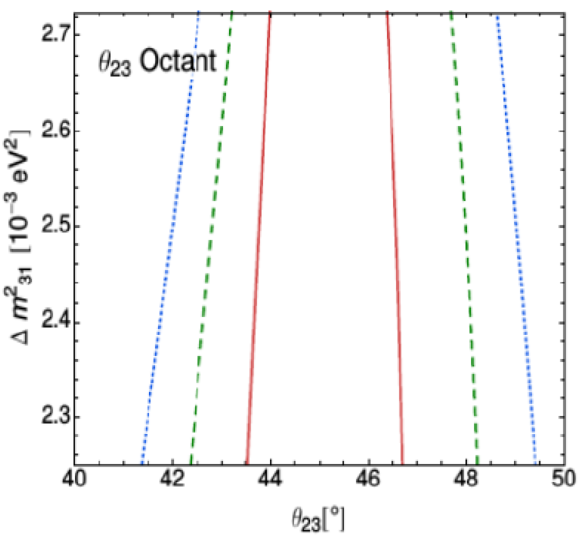
- **Dreaming machine to reach the sub-percent level sensitivity of neutrino mixing parameters.**



Global comparison



Discovery reach of CPV



Octant sensitivity

NuFACT2021: WG1 proposed questions

- **What is the neutrino mass ordering?**
- **Are there CP violations in the lepton sector?**
- **How much precision shall we reach to tell new physics?**
- What are the current and future systematic limitations on precision measurement and how to address them?
- Is the neutrino mixing matrix unitary?
- Are there non-standard neutrino interactions?
- Are there more than three-flavor neutrinos?
- How to deal with the reactor flux deficit?
- How consistent are results from NOvA and T2K?
- How to examine neutrino mass models based on flavor symmetries (A4, S4, Modular…)?
- What's next even after neutrino mass ordering and Dirac CP phase?
- …

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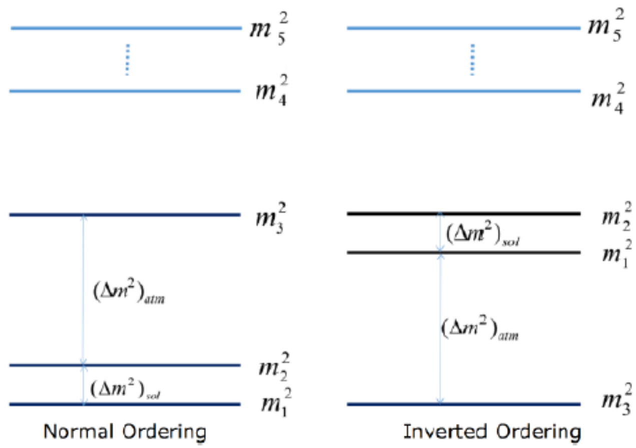
Non-unitary neutrino mixings (NU)

- Light sterile neutrino anomaly (eV scale)
- Heavy sterile neutrinos from see-saw model (GeV scale)
- Dark matter candidate (keV scale)
- IUV (indirect unitary violation) by heavy sterile neutrinos
- DUV (direct unitary violation) by light sterile neutrinos: oscillation with active ones



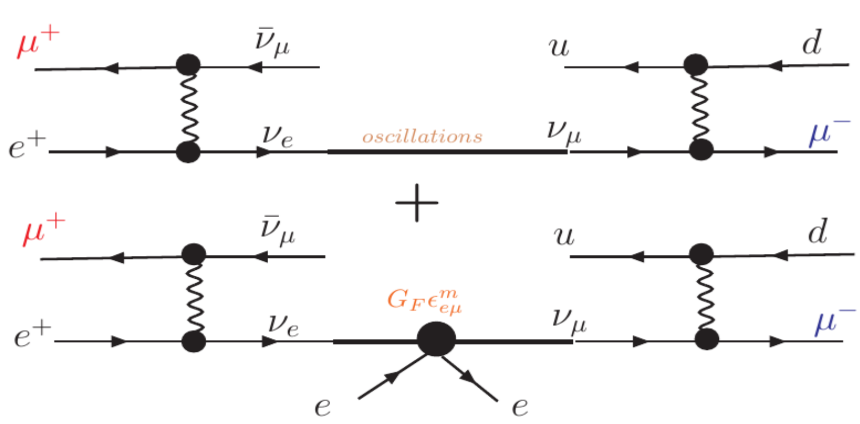
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1}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

- Simplifying the mixing matrix to deal with DUV and IUV, Phys. Lett., B718:1447-1453, 2013
- Pertubation study of oscillation probabilities for DUV and IUV, Phys. Rev., D93(3):033008

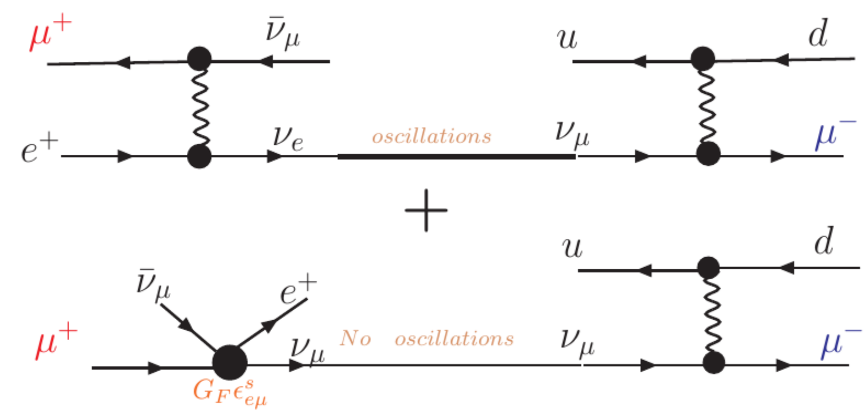
Non-Standard Interactions (NSIs)

- **New physics beyond SM: new particles, new couplings, new phenomenon...**

- Flavor violating interactions with neutrinos:
  $\nu_\alpha f \to \nu_\beta f, l_\alpha^- \to \nu_\beta e^- \bar{\nu}_e \cdots$
- 4-fermion vertices:
  $L_{\text{eff}} = 2\sqrt{2}\, G_F\, (\epsilon^{L/R})^{\alpha\gamma}_{\beta\delta}\, (\bar{\nu}^\beta \gamma^\rho P_L \nu_\alpha)\, (\bar{\ell}^\delta \gamma^\rho P_{L/R} \ell_\gamma)$



NSI happens to neutrino propagation in matter



NSI at neutrino productions

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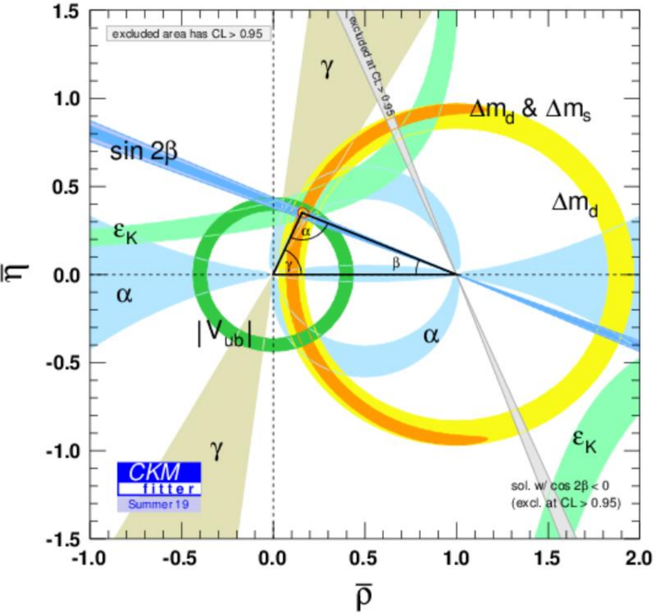
- Motivations
- Non-unitarity(NU) v.s non-standard interactions(NSIs)
- Global fits of mixing parameters without unitarity
- Constraints of NSIs based on SMEFT
- Future prospects
- Feasibility of a future accelerator neutrino experiment in China

What if there is non-unitary mixing?

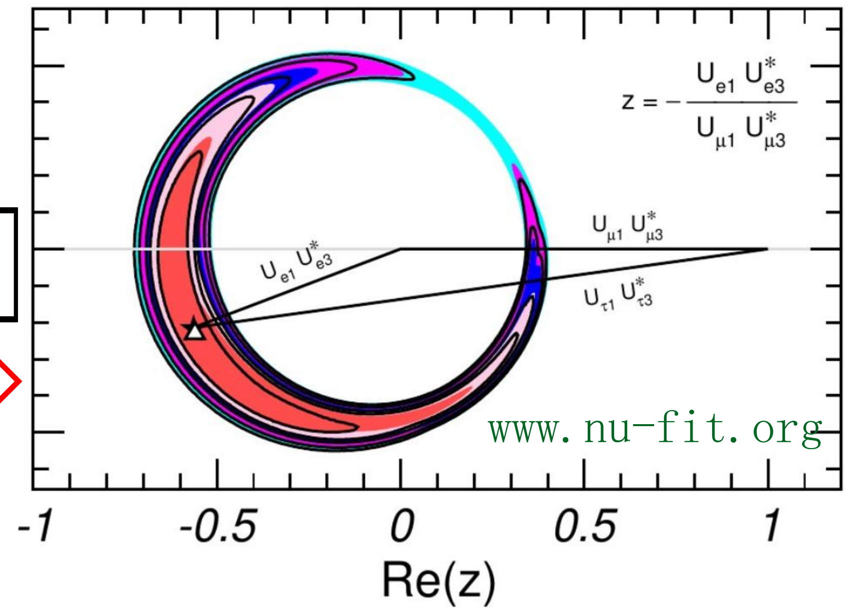
Quark mixing



No unitarity assumption here!

$$U^\dagger U \stackrel{?}{=} 1$$

Lepton mixing



$$U_{e1}U_{\mu 2}{}^* + U_{e2}U_{\mu 2}{}^* + U_{e3}U_{\mu 3}{}^* = 0$$

- Reduced constraints without the unitary assumption in the quark mixing.
- Let's keep the democratic way in quark and lepton mixing?

Simple mathematics w/o unitarity assumption

Unitarity

ROWS: $\alpha = (e, \mu, \tau)$ $\quad j = (1, 2, 3)$

COLUMNS:

$$UU^\dagger = 1$$

$$U^\dagger U = 1$$

$$\sum_j |U_{\alpha j}|^2 = 1 \quad \text{row normalizations}$$

$$\sum_\alpha |U_{\alpha j}|^2 = 1 \quad \text{column normalizations}$$

$$\sum_j U_{\alpha j} U^*_{\beta j} = 0 \quad \alpha \neq \beta \quad \text{row orthogonality}$$

$$\sum_\alpha U_{\alpha j} U^*_{\alpha k} = 0 \quad j \neq k \quad \text{column orthogonality}$$

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

Non-unitarity(NU)

18 real parameters in linear algebra

→ **-5** by rephrasing fields in physics

$$U^{\mathrm{NU}} = \begin{pmatrix} |U_{e1}|e^{i\phi_{e1}} & |U_{e2}|e^{i\phi_{e2}} & |U_{e3}| \\ |U_{\mu 1}|e^{i\phi_{\mu 1}} & |U_{\mu 2}|e^{i\phi_{\mu 2}} & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix}$$

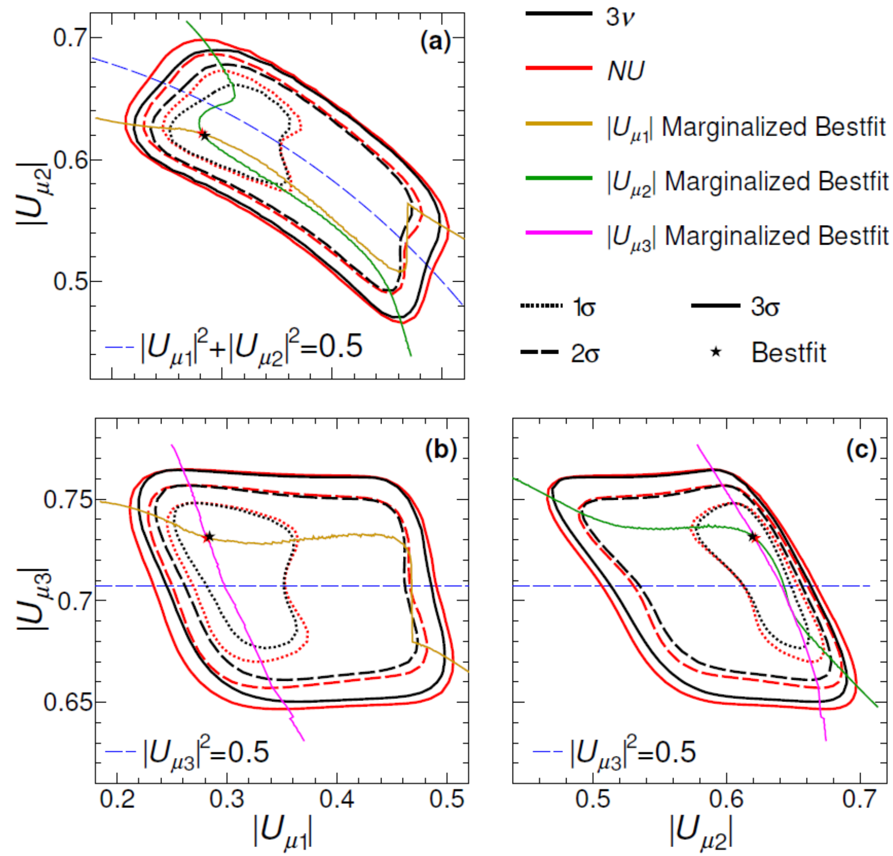
- Only 4 real parameters with unitarity.
- Now we have 13 real parameters after rephrasing fields for NU!

What if there is non-unitary mixing?

$$U^{NU} = \begin{pmatrix} |U_{e1}|e^{i\phi_{e1}} & |U_{e2}|e^{i\phi_{e2}} & |U_{e3}| \\ |U_{\mu1}|e^{i\phi_{\mu1}} & |U_{\mu2}|e^{i\phi_{\mu2}} & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{pmatrix}$$

$$P^{NU}_{\nu_\alpha\to\nu_\beta} = \left|\sum_{i=1} U^*_{\beta i}U_{\alpha i}\right|^2 - 4\sum_{i<j}\Re\left(U_{\alpha i}U_{\beta j}U^*_{\alpha j}U^*_{\beta i}\right)\sin^2\left(\frac{\Delta m^2_{ji}L}{4E_\nu}\right) \pm 2\sum_{i<j}\Im\left(U_{\alpha i}U_{\beta j}U^*_{\alpha j}U^*_{\beta i}\right)\sin\left(\frac{\Delta m^2_{ji}L}{2E_\nu}\right),$$

Type	Exps	Measurement
MBL Reactor	RENO, Daya Bay Double Chooz	$4\|U_{e3}\|^2(\|U_{e1}\|^2+\|U_{e2}\|^2)$
LBL Reactor	KamLAND	$4\|U_{e1}\|^2\|U_{e2}\|^2$
Solar	SNO	$\|U_{e2}\|^2$
LBL Accelerator ($\nu_\mu\to\nu_\mu$)	NOvA, T2K	$4\|U_{\mu3}\|^2(\|U_{\mu1}\|^2+\|U_{\mu2}\|^2)$
LBL Accelerator ($\nu_\mu\to\nu_e$)	NOvA, T2K	$4\Re[U_{e3}U^*_{\mu3}(U_{e1}U^*_{\mu1}+U_{e2}U^*_{\mu2})]$
LBL Accelerator ($\nu_\mu\to\nu_\tau$)	OPERA	$4\Re[U_{\tau3}U^*_{\mu3}(U_{\tau1}U^*_{\mu1}+U_{\tau2}U^*_{\mu2})]$



- Correlations between 3nu mixing matrix elements without unitarity assumption.
- Octant degeneracies get worse for NU.

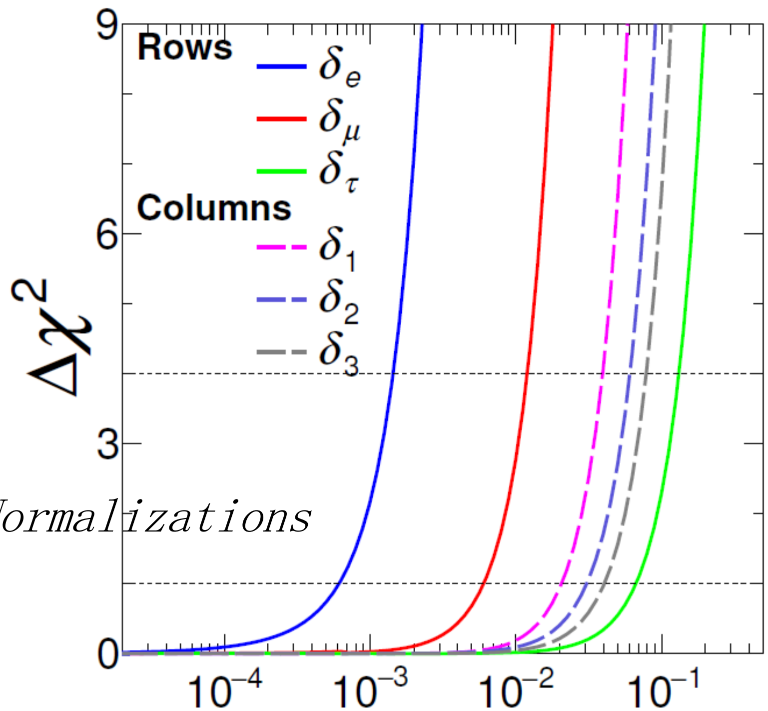
What if there is non-unitary mixing?

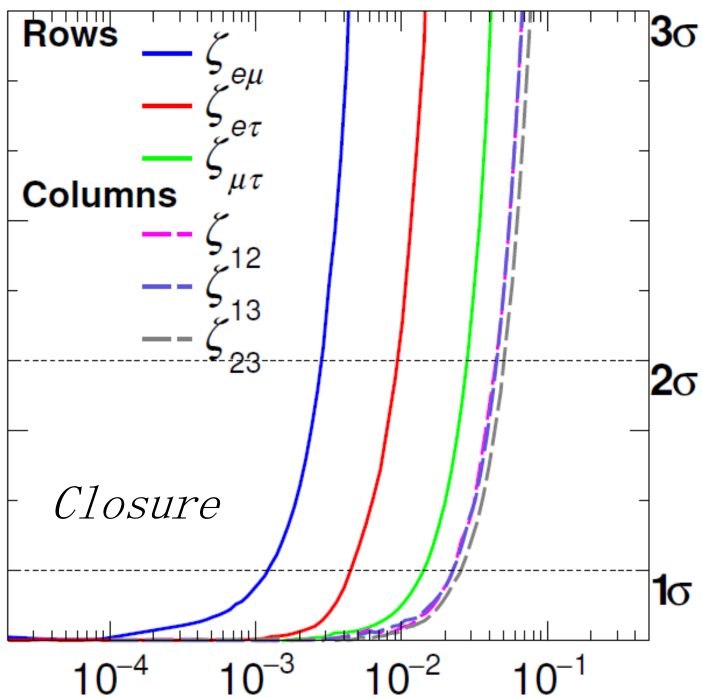
$$U^{\rm NU} = \begin{pmatrix} |U_{e1}|e^{i\phi_{e1}} & |U_{e2}|e^{i\phi_{e2}} & |U_{e3}| \\ |U_{\mu1}|e^{i\phi_{\mu1}} & |U_{\mu2}|e^{i\phi_{\mu2}} & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{pmatrix}$$

$$P^{\rm NU}_{\nu_\alpha\to\nu_\beta} = \left|\sum_{i=1} U^*_{\beta i}U_{\alpha i}\right|^2 - 4\sum_{i<j}\Re\left(U_{\alpha i}U_{\beta j}U^*_{\alpha j}U^*_{\beta i}\right)\sin^2\left(\frac{\Delta m^2_{ji}L}{4E_\nu}\right) \pm 2\sum_{i<j}\Im\left(U_{\alpha i}U_{\beta j}U^*_{\alpha j}U^*_{\beta i}\right)\sin\left(\frac{\Delta m^2_{ji}L}{2E_\nu}\right),$$

$\delta_\alpha = 1-|U_{\alpha1}|^2-|U_{\alpha2}|^2-|U_{\alpha3}|^2$ $\delta_i = 1-|U_{ei}|^2-|U_{\mu i}|^2-|U_{\tau i}|^2$

$\zeta_{\alpha\beta} = U_{\alpha1}U^*_{\beta1}+U_{\alpha2}U^*_{\beta2}+U_{\alpha3}U^*_{\beta3}$ $\zeta_{ij} = U_{ei}U^*_{ej}+U_{\mu i}U^*_{\mu j}+U_{\tau i}U^*_{\tau j}$





- Nice precision in the first and second row/column.
- Tau neutrino physics are to be improved for better constraints on 3rd row/column!

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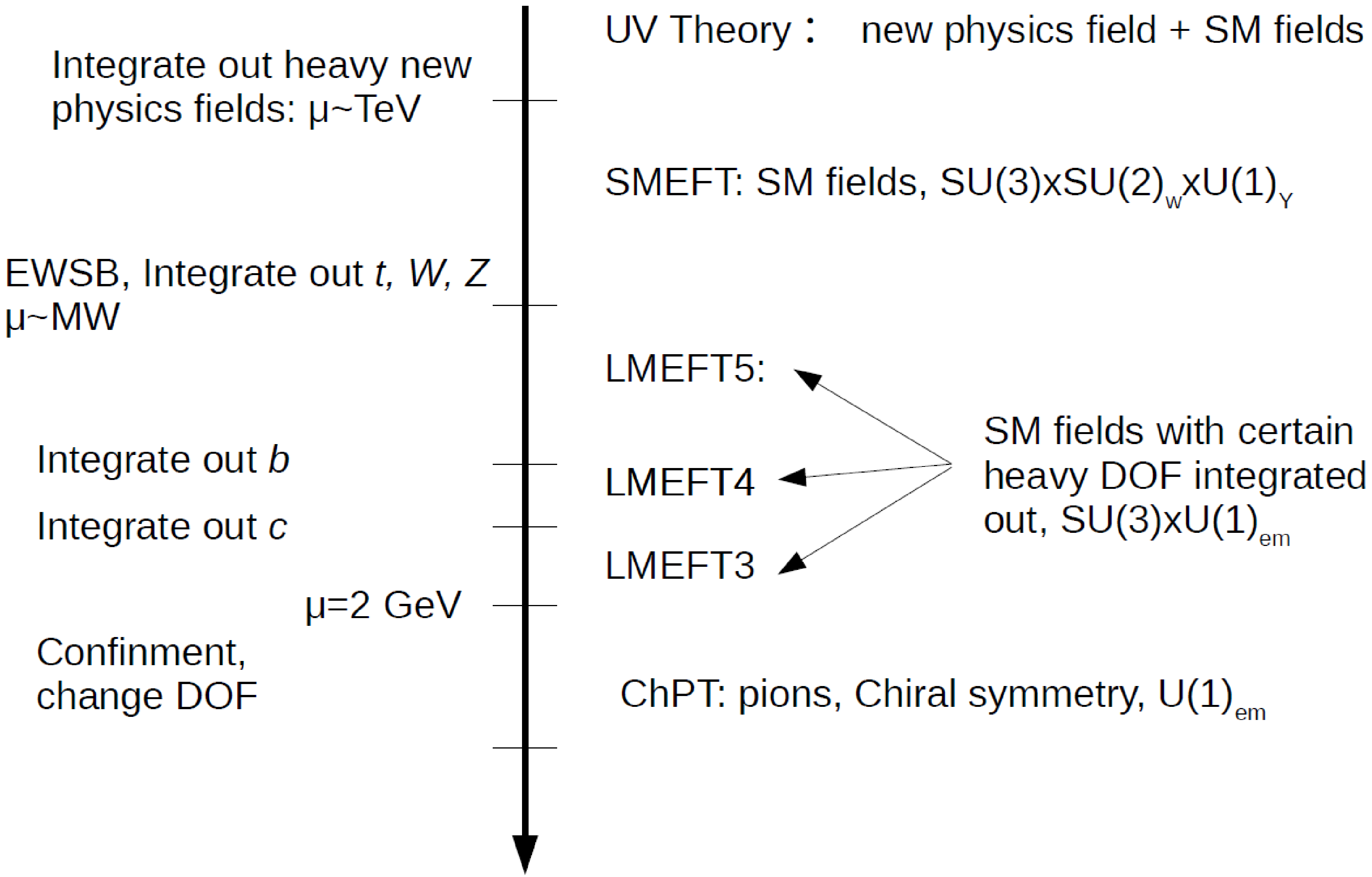
Working principle of effective field theory (EFT)



An example for demonstration

- Start from a UV theory

$$\Delta\mathcal{L} = (D_\mu H_2^\dagger)(D^\mu H_2) - M^2|H_2|^2 - Y\overline{L}_i H_{2i} e_R - Y^* \overline{e_R} H_{2i}^\dagger L_i$$

- Matching by covariant derivative expansion, EoM

$$(D^2 H_2^\dagger)_i + M^2 H_{2i}^\dagger = -Y\overline{L}_i e_R$$

$$(D_{ij}^2 + M^2\delta_{ij})H_{2j}^\dagger = -Y\overline{L}_i e_R$$

$$(D^2 H_2)_i + M^2 H_{2i} = -Y^*\overline{e_R} L_i$$

$$(D_{ij}^2 + M^2\delta_{ij})H_{2j} = -Y^*\overline{e_R} L_i$$

- Solve for classical solution

$$\begin{aligned} H_{c,2i} &= -(D_{ij}^2 + M^2\delta_{ij})^{-1} Y^* \overline{e_R} L_j \\ &= -\frac{1}{M^2}\left(1 + \frac{D^2}{M^2}\right)_{ij}^{-1} Y^* \overline{e_R} L_j \\ &= -\frac{1}{M^2} Y^* \overline{e_R} L_i + \mathcal{O}(\frac{1}{M^4}) \end{aligned}$$

$$H_{c,2i}^\dagger = -\frac{1}{M^2} Y \overline{L}_i e_R + \mathcal{O}(\frac{1}{M^4})$$

An example for demonstration

- Put the classical solution back to Lagrangian density

$$(D_\mu H^\dagger_{2,c})(D^\mu H_{2,c}) = -H^\dagger_{2,c} D^2 H_{2,c} \sim \mathcal{O}(\frac{1}{M^4})$$

$$-M^2|H_{2,c}|^2 = -\frac{|Y|^2}{M^2}\overline{L}_i e_R \overline{e_R} L_i$$

$$-Y\overline{L}_i H_{2i,c} e_R - Y^* \overline{e_R} H^\dagger_{2i,c} L_i = \frac{2|Y|^2}{M^2}\overline{L}_i e_R \overline{e_R} L_i$$

$$\mathcal{L}^{dim-6}_{eff} = \frac{|Y|^2}{M^2}\overline{L}_i e_R \overline{e_R} L_i$$

Not in Warsaw Basis

- Fierz transformation to Warsaw basis

$$\frac{|Y|^2}{M^2}\overline{L}_i e_R \overline{e_R} L_i = \frac{|Y|^2}{2M^2}(\overline{L}_i \gamma^\mu L_i)(\overline{e_R}\gamma^\mu e_R)$$

SMEFT at scale M

$$C_{le} = \frac{|Y|^2}{2M^2} \qquad Q_{le}$$

An example for demonstration

- Run down from scale M to electroweak scale v

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} C_i = \sum_j \gamma_{ij} C_j$$

- Probably generate non-zero Wilson coefficients other than C_{le}
- Matching at electroweak scale to LEFT

$$L_p = \begin{bmatrix} \nu_p \\ e_p \end{bmatrix}$$

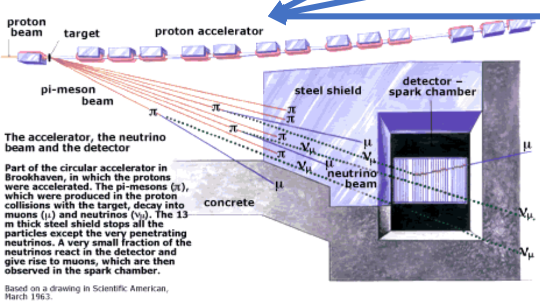
$$\begin{aligned} \frac{Y_{ps} Y_{tr}^{\dagger}}{2M^2} (\overline{L}_i^p \gamma^\mu L_i^r)(\overline{e_R^s} \gamma^\mu e_R^t) &= \frac{Y_{ps} Y_{tr}^{\dagger}}{2M^2} (\overline{\nu_L}^p \gamma^\mu \nu_L^r + \overline{e_L}^p \gamma^\mu e_L^r)(\overline{e_R^s} \gamma^\mu e_R^t) \\ &= \frac{Y_{ps} Y_{tr}^{\dagger}}{2M^2} [(\overline{\nu_L}^p \gamma^\mu \nu_L^r)(\overline{e_R^s} \gamma^\mu e_R^t) + (\overline{e_L}^p \gamma^\mu e_L^r)(\overline{e_R^s} \gamma^\mu e_R^t)] \end{aligned}$$

$\mathcal{O}_{\nu e}^{V,LR}$ $\mathcal{O}_{ee}^{V,LR}$

Matching between QM and QFT NSIs

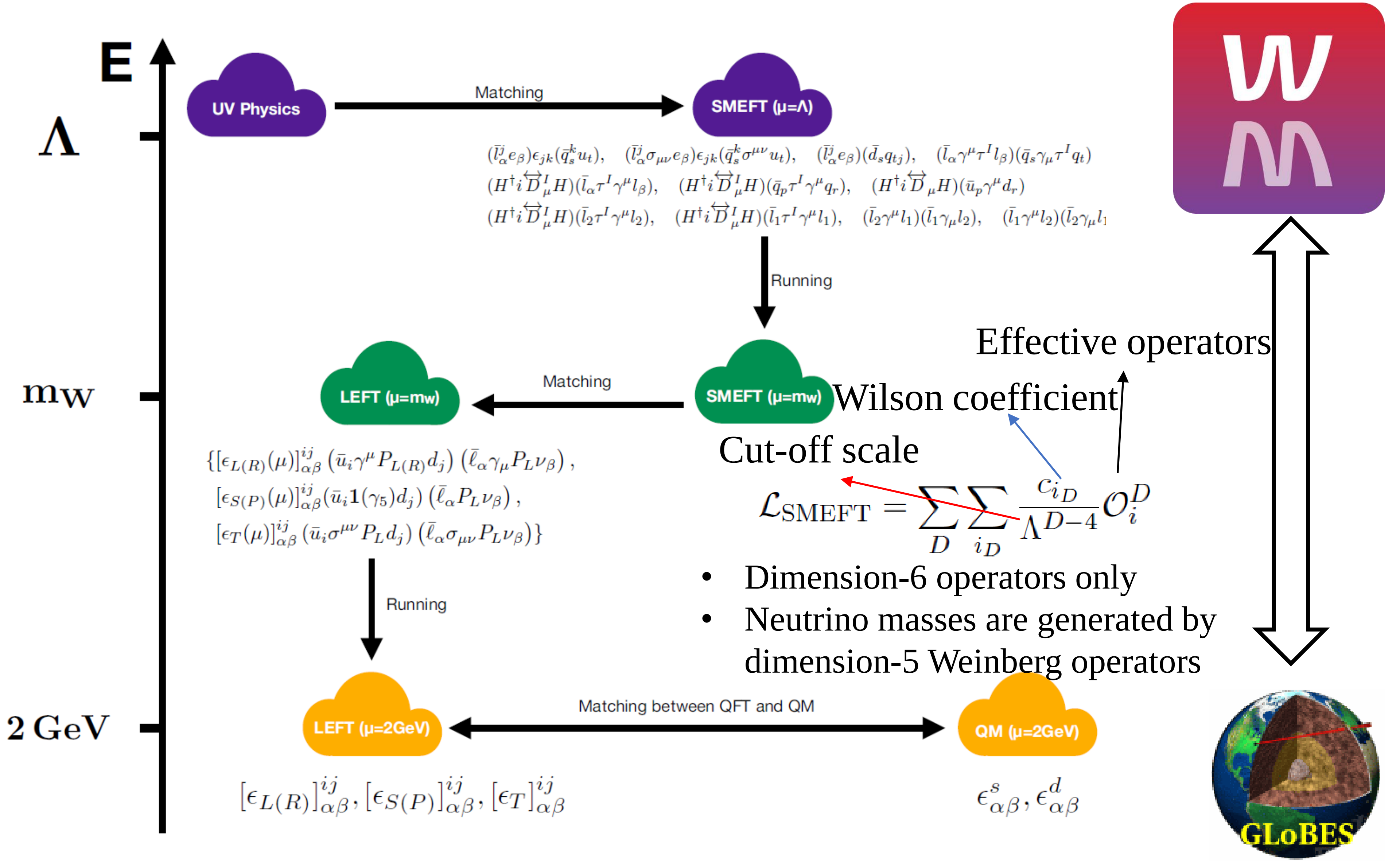
$$H=\frac{1}{2E_\nu}\left[U\begin{pmatrix}0&0&0\\0&\Delta m^2_{21}&0\\0&0&\Delta m^2_{31}\end{pmatrix}U^\dagger+A\begin{pmatrix}1+\varepsilon^m_{ee}&\epsilon^m_{e\mu}&\epsilon^m_{e\tau}\\\epsilon^{m*}_{e\mu}&\epsilon^m_{\mu\mu}&\epsilon^m_{\mu\tau}\\\epsilon^{m*}_{e\tau}&\epsilon^{m*}_{\mu\tau}&\epsilon^m_{\tau\tau}\end{pmatrix}\right]$$

QM NSIs	Relations to QFT NSIs
$\epsilon^s_{e\beta}$ (β decay)	$\left[\epsilon_L-\epsilon_R-\frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}\epsilon_T\right]^*_{e\beta}$
$\epsilon^d_{\beta e}$ (inverse β decay)	$\left[\epsilon_L+\frac{1-3g_A^2}{1+3g_A^2}\epsilon_R-\frac{m_e}{E_\nu-\Delta}\left(\frac{g_S}{1+3g_A^2}\epsilon_S-\frac{3g_Ag_T}{1+3g_A^2}\epsilon_T\right)\right]_{e\beta}$
$\epsilon^s_{\mu\beta}$ (pion decay)	$\left[\epsilon_L-\epsilon_R-\frac{m_\pi^2}{m_\mu(m_u+m_d)}\epsilon_P\right]^*_{\mu\beta}$
$\epsilon^s_{\mu\beta}$(muon decay)	$\left[g_{22}+\frac{3m_em_\mu(m_\mu-2E_\nu)}{16m_\mu E_\nu^2+6m_\mu(m_\mu^2+m_e^2)-4E_\nu(5m_\mu^2+m_e^2)}h_{21}\right]^*_{\mu\beta}$
$\epsilon^s_{e\beta}$ (muon decay)	$\left[g_{22}+\frac{m_e}{4(m_\mu-2E_{\bar\nu})}h_{21}\right]^*_{e\beta}$



- QM NSIs are fully independent without much info about the underlying theory.
- QFT NSIs allow their correlations.

EFT: connecting low-energy phenomenon to high-energy scale



$(\bar{l}^j_\alpha e_\beta)\epsilon_{jk}(\bar{q}^k_s u_t)$, $(\bar{l}^j_\alpha \sigma_{\mu\nu} e_\beta)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$, $(\bar{l}^j_\alpha e_\beta)(\bar{d}_s q_{tj})$, $(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(\bar{q}_s \gamma_\mu \tau^I q_t)$
$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_\alpha \tau^I \gamma^\mu l_\beta)$, $(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$, $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu d_r)$
$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_2 \tau^I \gamma^\mu l_2)$, $(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_1 \tau^I \gamma^\mu l_1)$, $(\bar{l}_2 \gamma^\mu l_1)(\bar{l}_1 \gamma_\mu l_2)$, $(\bar{l}_1 \gamma^\mu l_2)(\bar{l}_2 \gamma_\mu l_1)$

$\{[\epsilon_{L(R)}(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i\gamma^\mu P_{L(R)} d_j)\,(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta)\,,$
$[\epsilon_{S(P)}(\mu)]^{ij}_{\alpha\beta}(\bar{u}_i \mathbf{1}(\gamma_5) d_j)\,(\bar{\ell}_\alpha P_L \nu_\beta)\,,$
$[\epsilon_T(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i \sigma^{\mu\nu} P_L d_j)\,(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta)\}$

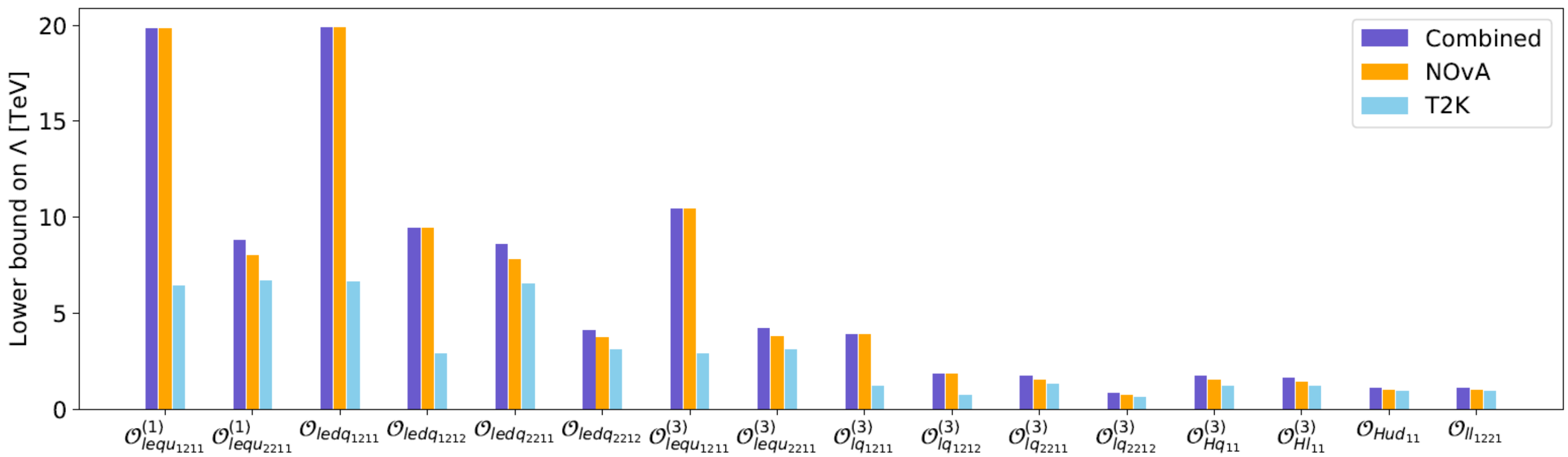
$[\epsilon_{L(R)}]^{ij}_{\alpha\beta}, [\epsilon_{S(P)}]^{ij}_{\alpha\beta}, [\epsilon_T]^{ij}_{\alpha\beta}$

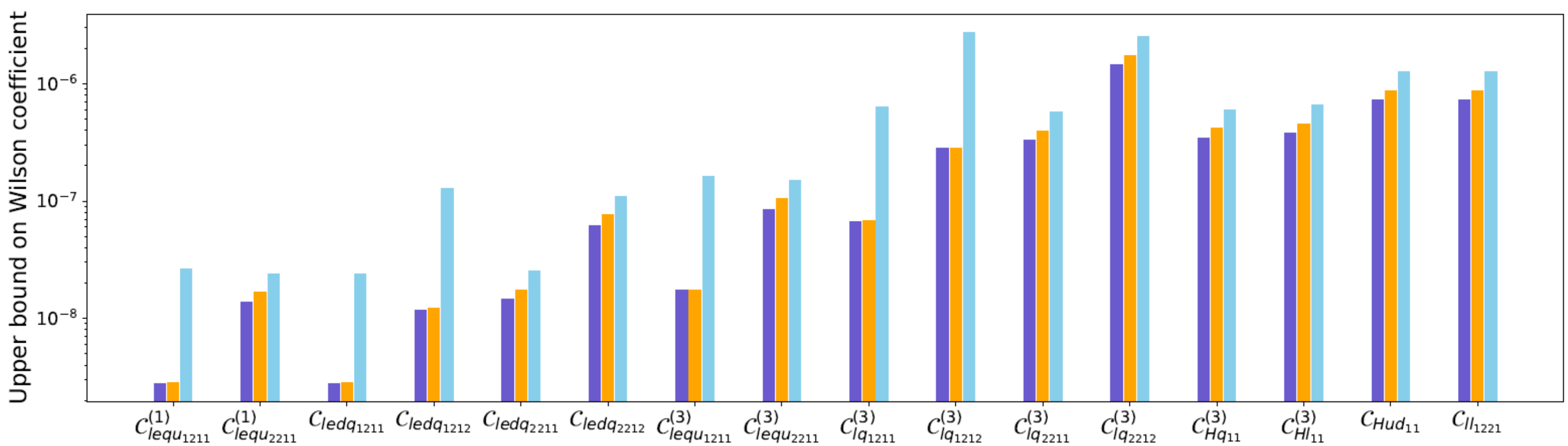
$\epsilon^s_{\alpha\beta}, \epsilon^d_{\alpha\beta}$

$$\mathcal{L}_{\text{SMEFT}} = \sum_D \sum_{i_D} \frac{c_{i_D}}{\Lambda^{D-4}} \mathcal{O}^D_i$$

- Dimension-6 operators only
- Neutrino masses are generated by dimension-5 Weinberg operators

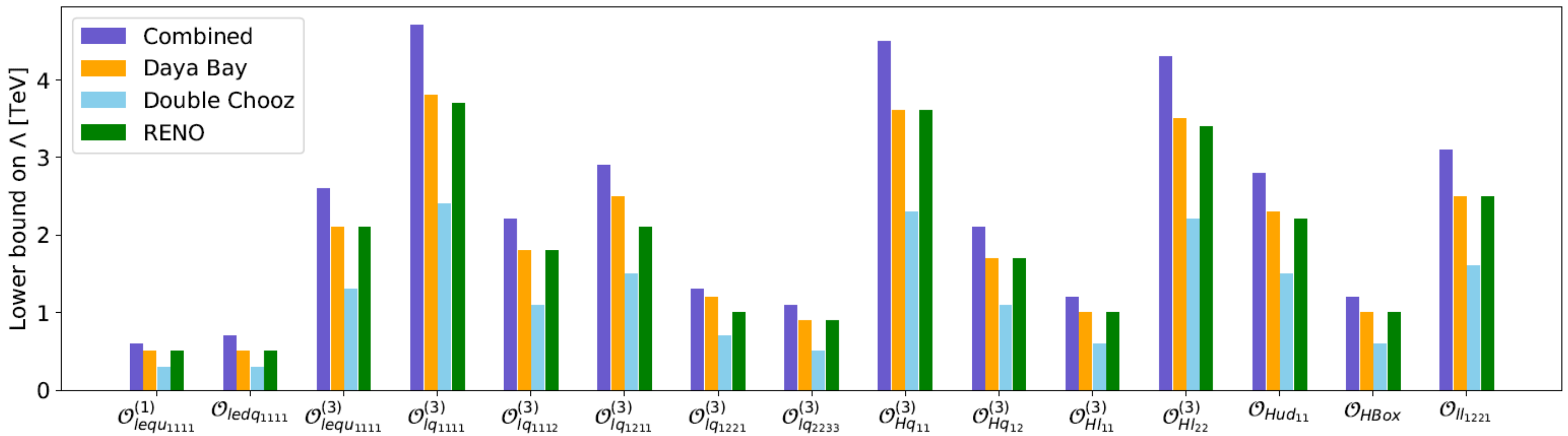
SMEFT-NSIs by T2K and NOvA

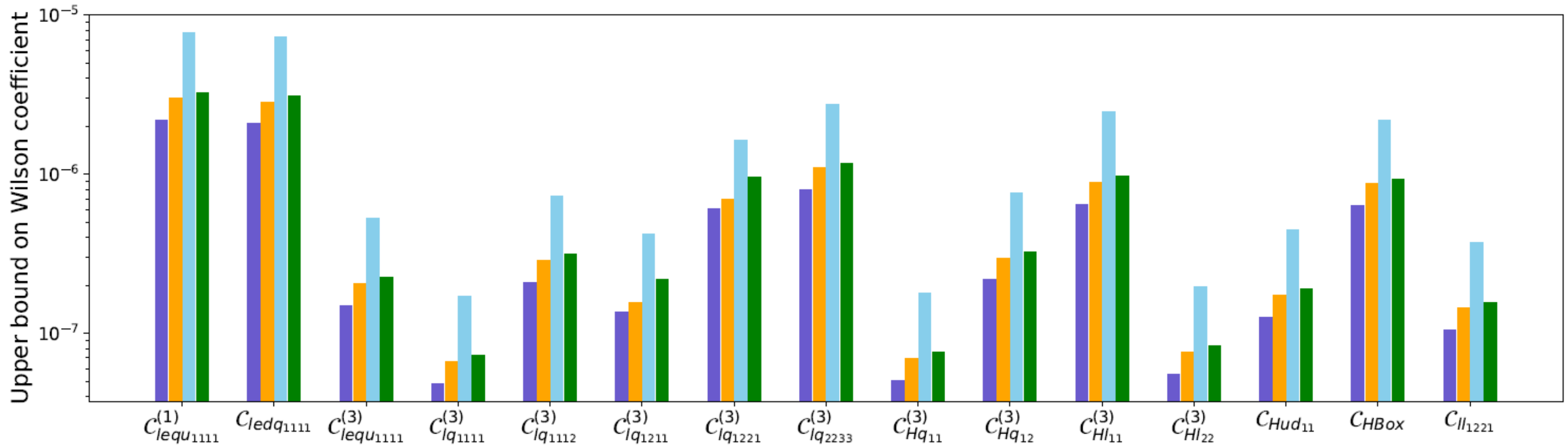




- T2K and NOvA are already sensitive to new physics around 20 TeV.
- Correlations among different dimension-6 operators play important roles.

SMEFT-NSIs by reactor neutrino experiments





- Reactor neutrino experiments are sensitive to new physics around 5 TeV.
- Complementarity between LBL and reactor expts due to different sets of operators

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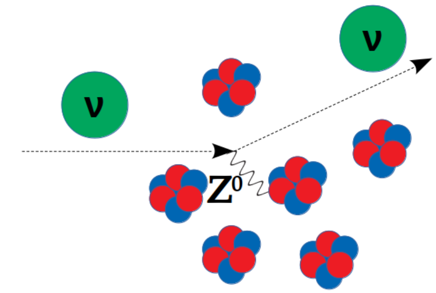

flavio

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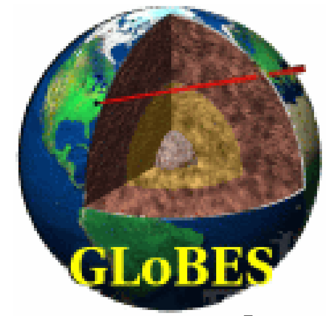
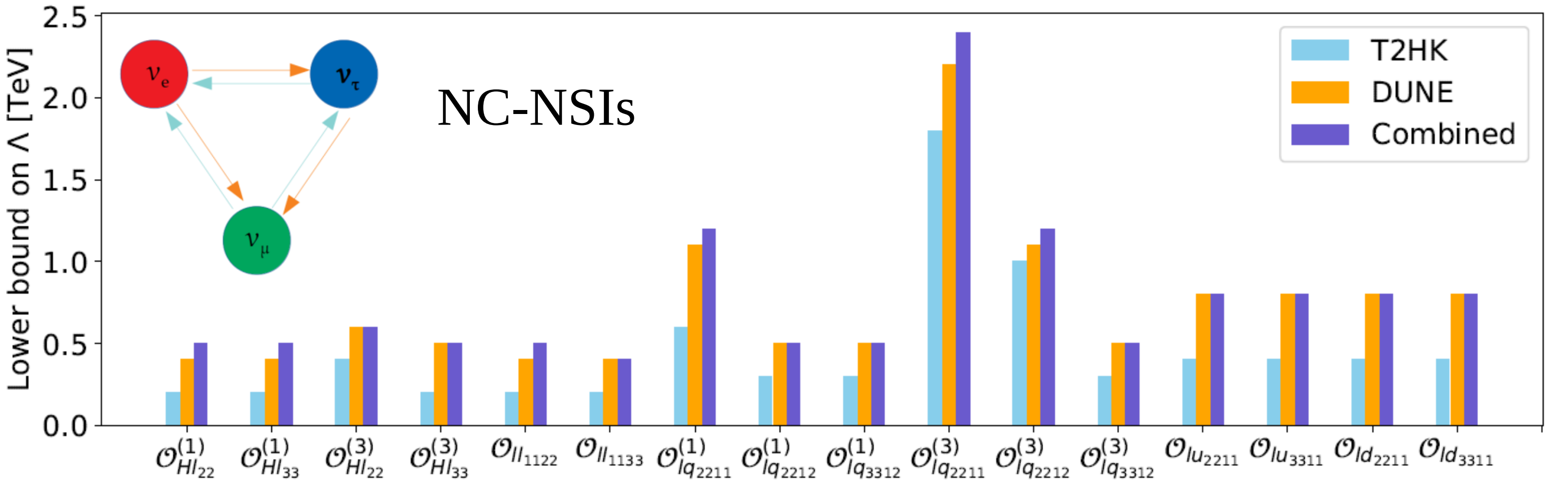


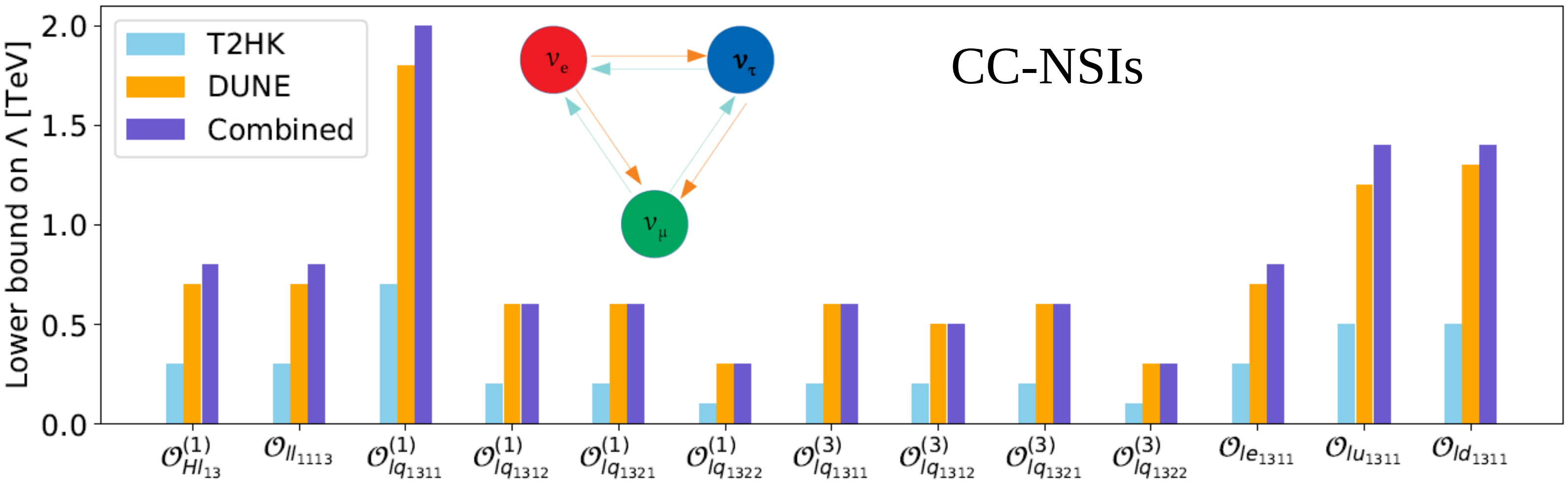
Quark mixing v.s neutrino mixing/scattering

$$\mathcal{O}^{\rm CKM}_{1,2,3,4} = \Gamma\left(K \to \mu\nu_\mu\right)/\Gamma\left(\pi \to \mu\nu_\mu\right),\ \mathrm{Br}(B \to X_c e\nu),\ \mathrm{Br}(B^+ \to \tau\nu),\ \Delta M_d/\Delta M_s.$$

Operator	$\mathcal{O}^{(1)}_{qq1313}$	$\mathcal{O}^{(1)}_{qq2323}$	$\mathcal{O}^{(3)}_{qq1313}$	$\mathcal{O}^{(3)}_{qq2323}$	$\mathcal{O}_{dd1313}$	$\mathcal{O}_{dd2323}$
Λ valid (TeV)	> 365	> 51	> 365	> 51	> 383	> 53
Operator	$\mathcal{O}^{(1)}_{qd1213}$	$\mathcal{O}^{(1)}_{qd1313}$	$\mathcal{O}^{(1)}_{qd2323}$	$\mathcal{O}^{(8)}_{qd1213}$	$\mathcal{O}^{(8)}_{qd1313}$	$\mathcal{O}^{(8)}_{dd2323}$
Λ valid (TeV)	> 23	> 1383	> 178	> 25	> 1466	> 188

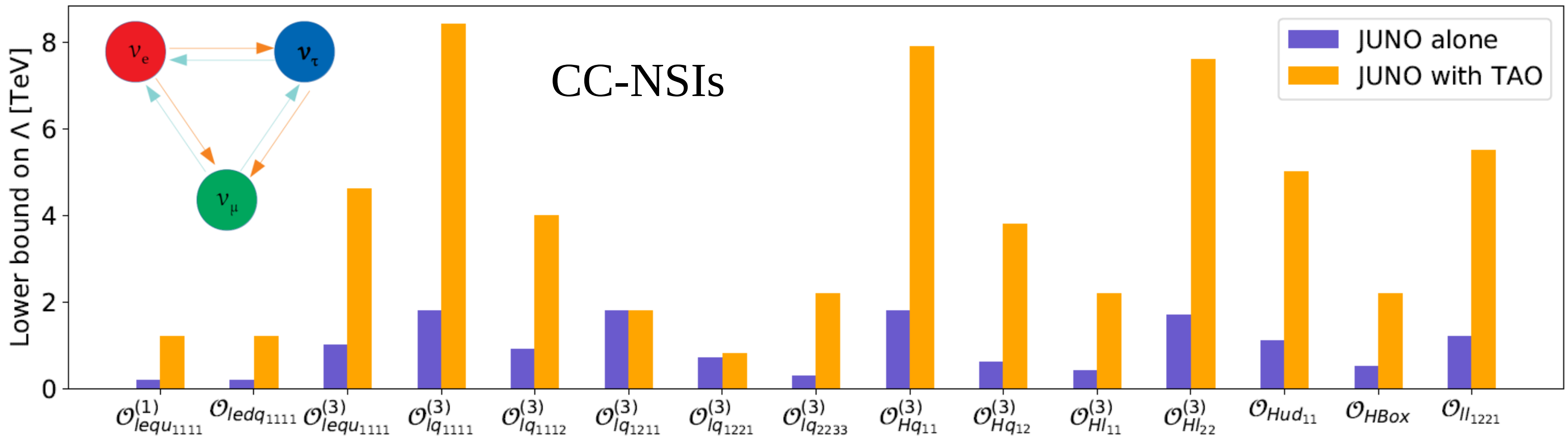
SMEFT-NSIs by T2HK and DUNE

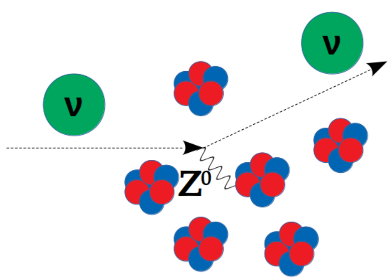


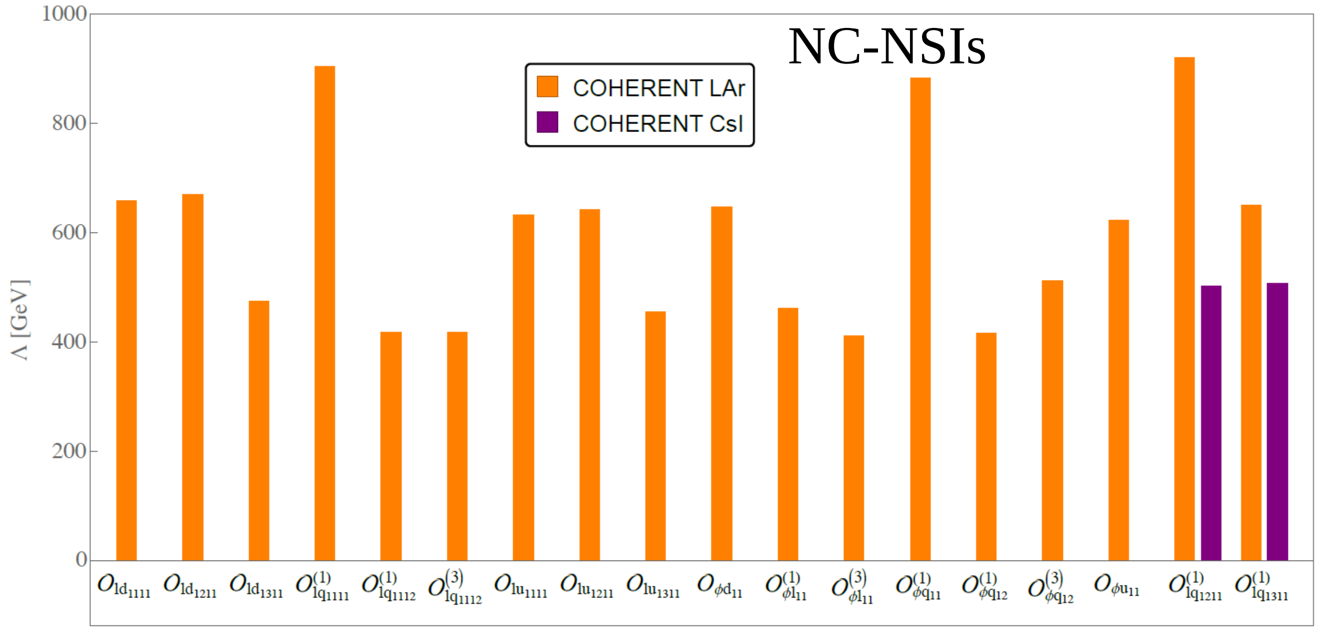


- Cover 1635 SMEFT operators in dimension-6. ND is important to constraint SMEFT-NSIs.
- DUNE has better sensitivity than T2HK due to the longer baseline.

SMEFT-NSIs by JUNO w/o TAO and COHERENT







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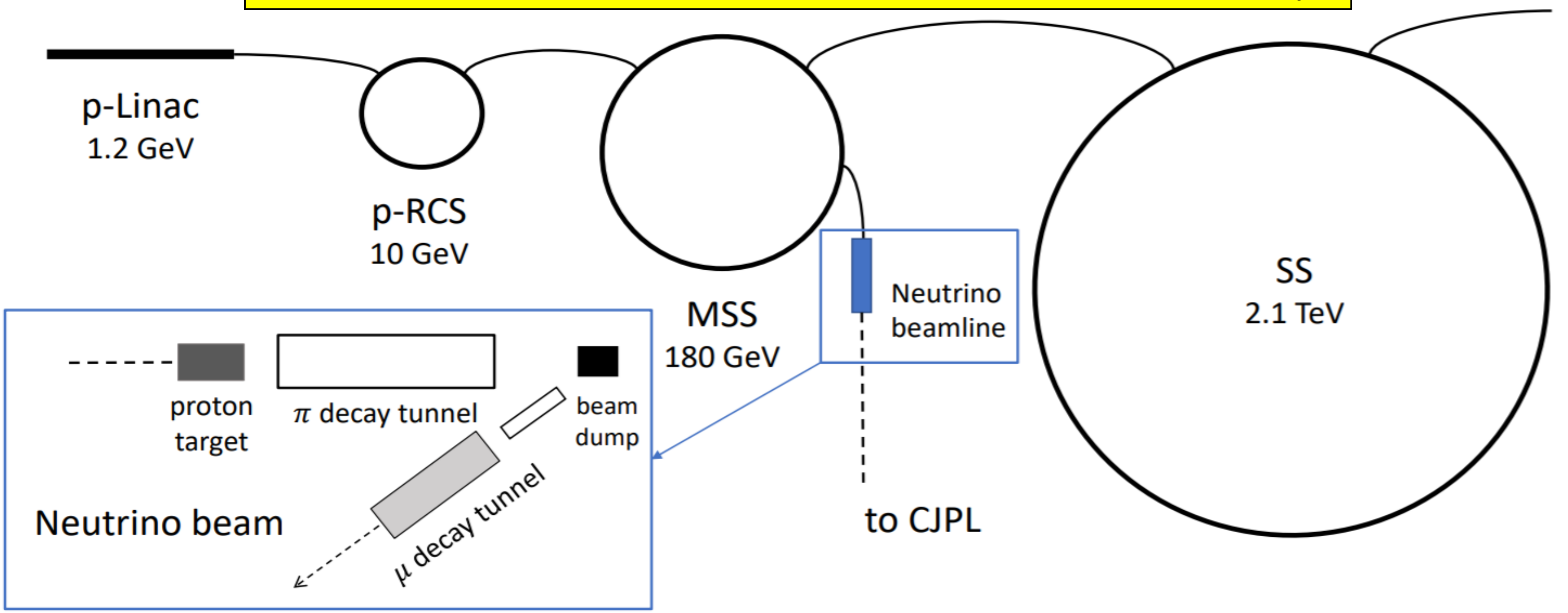
A future accelerator neutrino experiment in China?

arXiv:2108.11107

PROMPT:PRecisi**O**n **M**easurements and **P**hysics with ν_τ



- Not the end of story even after a discovery of CP violation in the lepton sector.
- Large uncertainties in the mixing matrix without direct measurement on ν_τ sector.
- New physics around the corner?
- Muon decay neutrino beam better than the conventional superbeam.
- Drive the accelerator muon beam in an unique way.

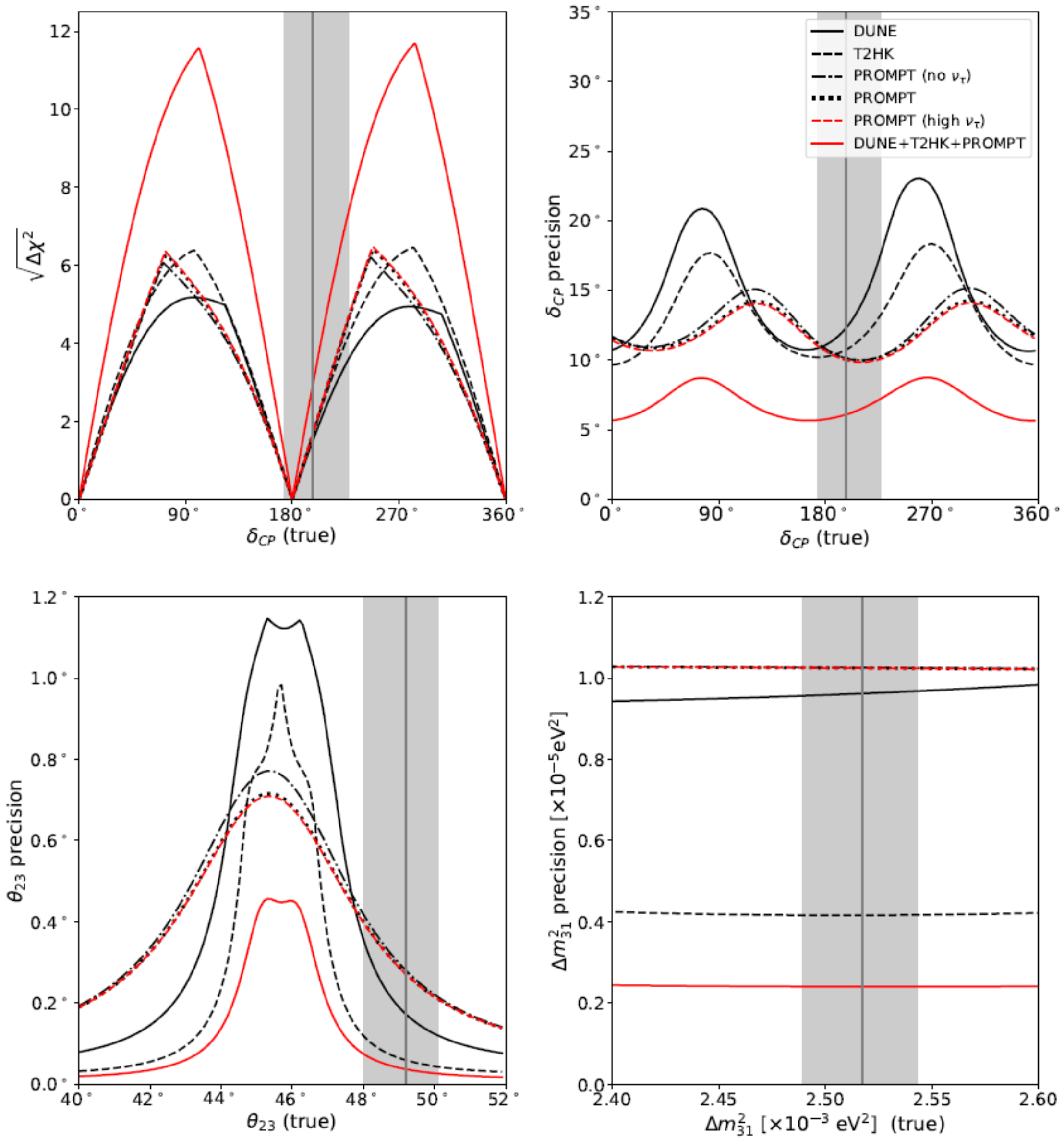
Site selections and baseline configurations

Accelerator facility	JUNO (22.12°, 112.51°)			CJPL (28.15°, 101.71°)		
	Baseline	1st maximum	2nd maximum	Baseline	1st maximum	2nd maximum
CAS-IMP (36.05°, 103.68°)	1759 km	3.6 GeV	1.2 GeV	894 km	1.8 GeV	600 MeV
CiADS (23.08°, 114.40°)	221 km	450 MeV	150 MeV	1389 km	2.8 GeV	940 MeV
CSNS (23.05°, 113.73°)	162 km	330 MeV	110 MeV	1329 km	2.7 GeV	900 MeV
Nanjing (32.05°, 118.78°)	1261 km	2.6 GeV	850 MeV	1693 km	3.4 GeV	1.1 GeV
SPPC (39.93°, 116.40°)	1871 km	3.8 GeV	1.3 GeV	1736 km	3.5 GeV	1.2 GeV

Parameter	Muon beam
Production method	muon decay-in-flight
Detection method	hybrid detector
Useful parent decays	2.5×10^{20} year^{-1}
Detector mass	50 kton
Detection threshold	1 GeV
Energy resolution	$15\%(15\%)/E_\nu$
Energy bins	45
Running time	5+5 years

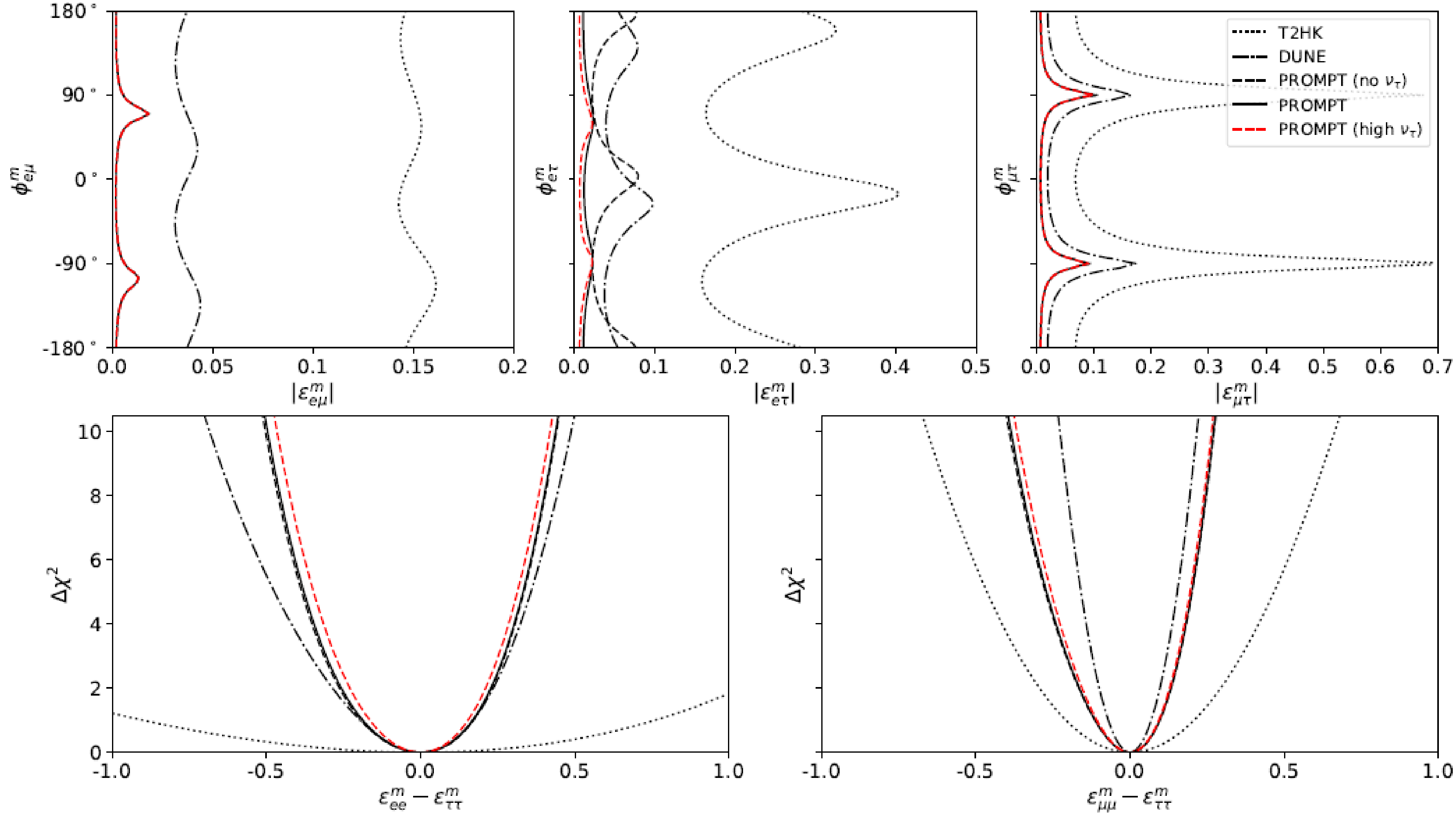
- Optimization of the neutrino beam and baseline length
- Muon beam energy: 25 GeV
- Baseline: ~1300 km
- Benchmark configurations: CiADS→CJPL

Precision measurement and tau-neutrino physics?



- The sensitivities obtained with the PROMPT setup very promising
- Pushing precision to sub-percent level and probe new physics

New physics searches



- In the e-μ sector, PROMPT has clear advantage over T2HK and DUNE setups.
- The tau neutrinos in PROMPT bears no significant effect on the sensitivities.

Summary

- Neutrino oscillation is the first direct evidence BSM.
- Discovery of CPV & determination of MH is around the corner. Neutrino will be used for new physics searches.
- New physics might be hidden in the uncertainties.
- Unitary mixing should not be taken by default, as tau neutrino-related part is yet to be improved.
- What else shall we prepare even after CPV discovery?
- A Chinese proposal will be unique of a great chance based on muon-decay neutrino beams, such as PROMPT…
- Let’s work together to discover new physics with neutrinos…

THANK YOU