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1951-23

Workshop on the original of P, CP and T Violation

2 - 5 July 2008

Impact of Non-Standard Interactions on Neutrino Physics

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Impact of Non-Standard Interactions on Neutrino Physics

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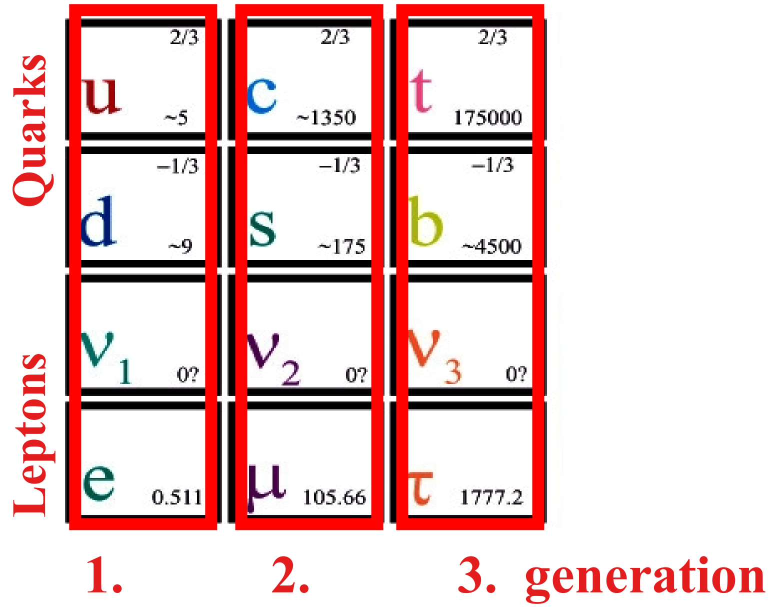
CPT@ICTP Workshop on the origin of P, CP and T violation

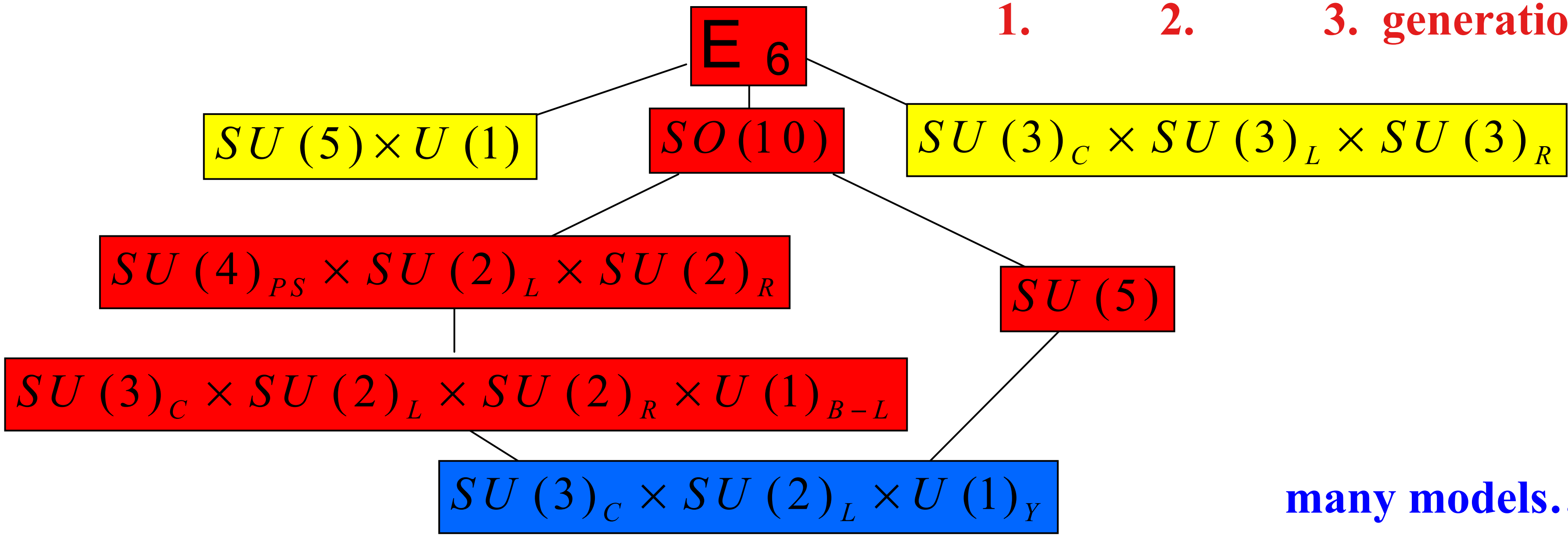
Trieste, July 2-5, 2008

The larger Picture: GUTs

Gauge unification suggests that some GUT / SUSY-GUT exists



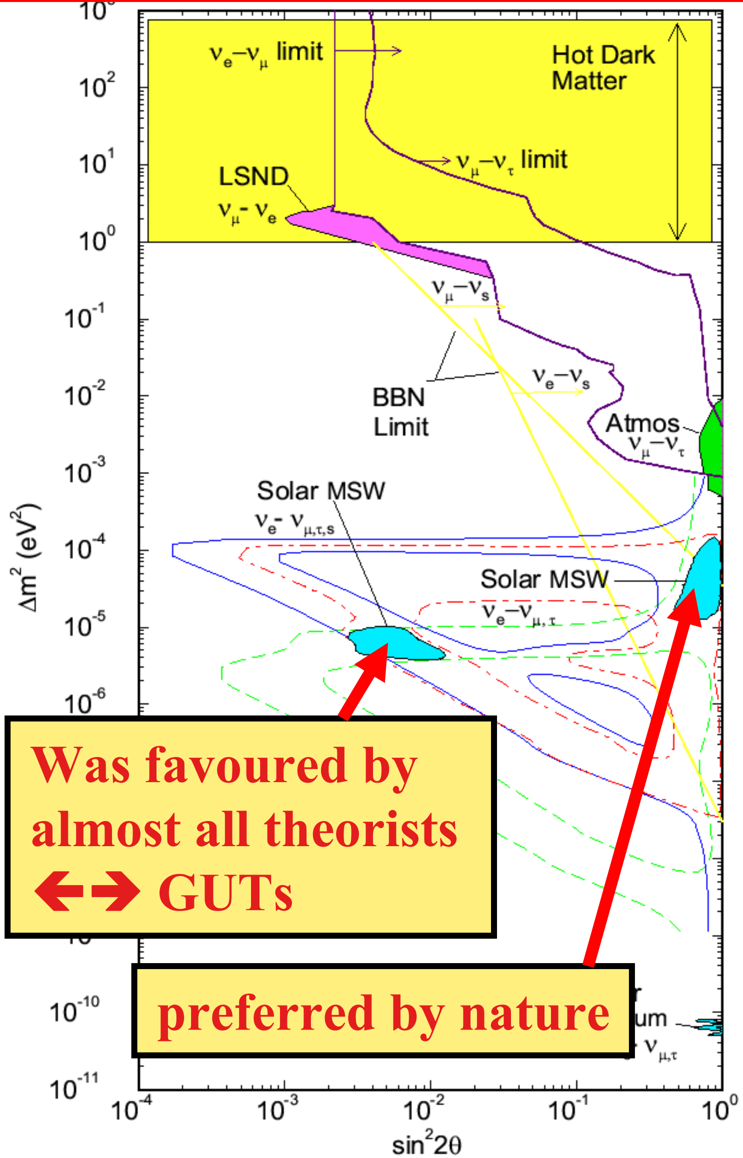
Features:
- gauge unification
- particle multiplets ←→ ν_R
- proton decay, …
- Yukawa couplings for GUT multiplets
  CKM → NMS connection?



many models…

Learning about Flavour from Neutrinos

History: Elimination of SMA



Mechanisms for large mixings:

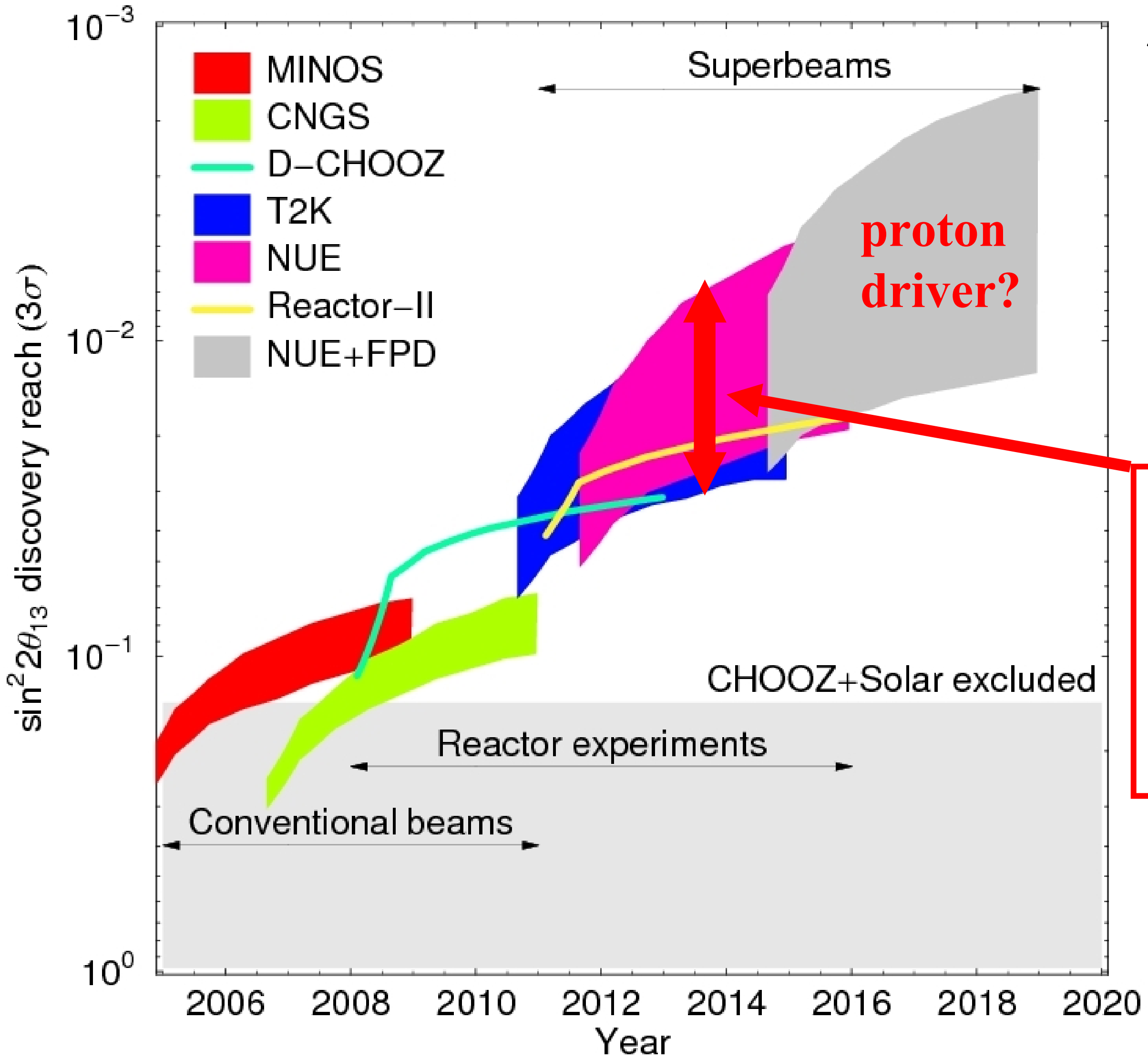
→ sequential dominance
→ type II see-saw
→ Dirac screening
→ …

→ generically 3 large/sizable mixings

Next: Smallness of θ_{13} and maximal θ_{23}

what if θ_{13} is very tiny?
or if θ_{23} is very close to maximal?
→ numerical coincidence?
→ special reasons (symmetry, …)
answered by coming experiments

θ_{13} Sensitivity Versus Time



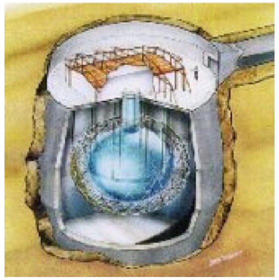
β-beams
neutrino factory

Range ←→
~unknown CP phase

combination with reactor
←→ synergies

precision!

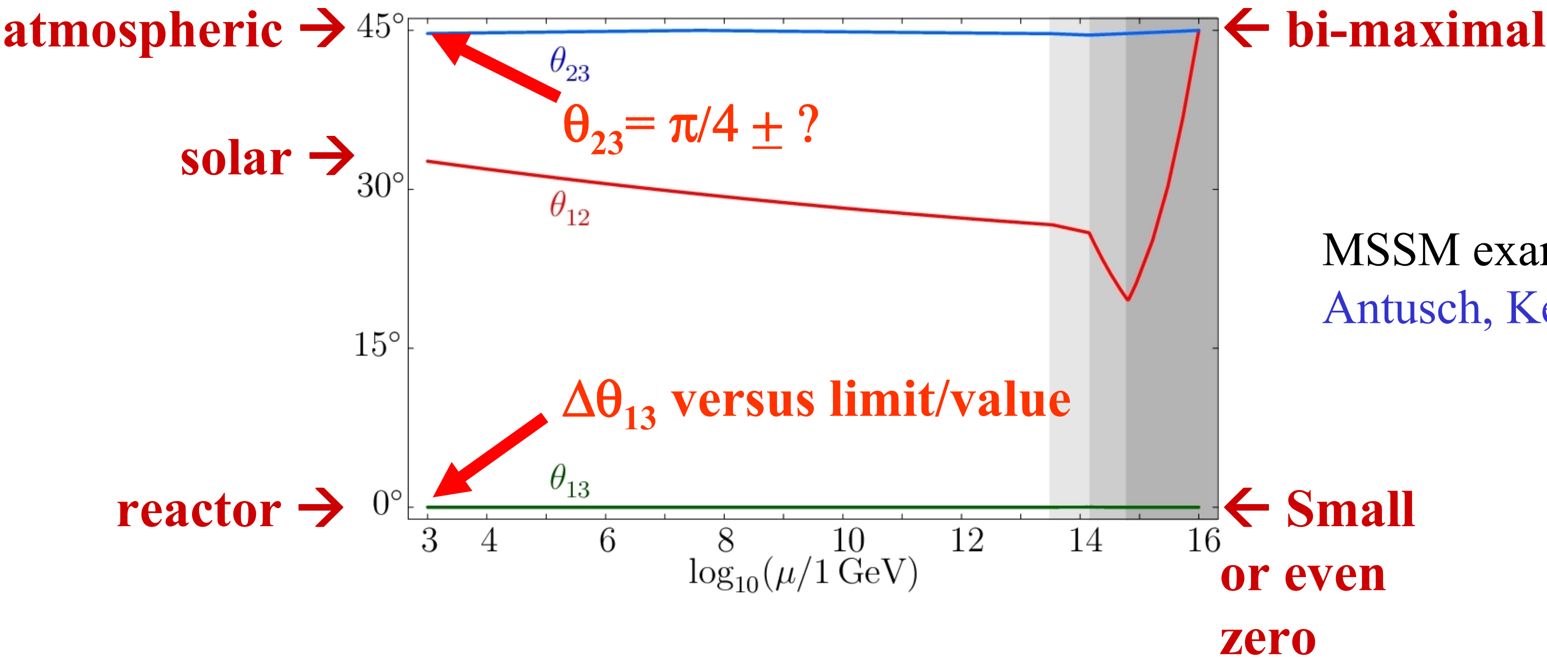
Renormalization Group Running



low energies:
- **small masses**
- **large mixings**

renormalization group running

high energies:
- **mass models**
- **flavour-symmetries**
- **GUT-models, ...**



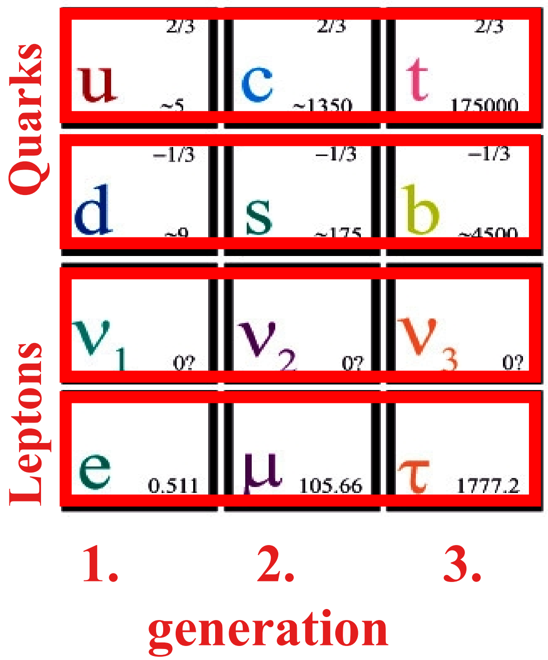
MSSM example:
Antusch, Kersten, ML , Ratz

Flavour Unification

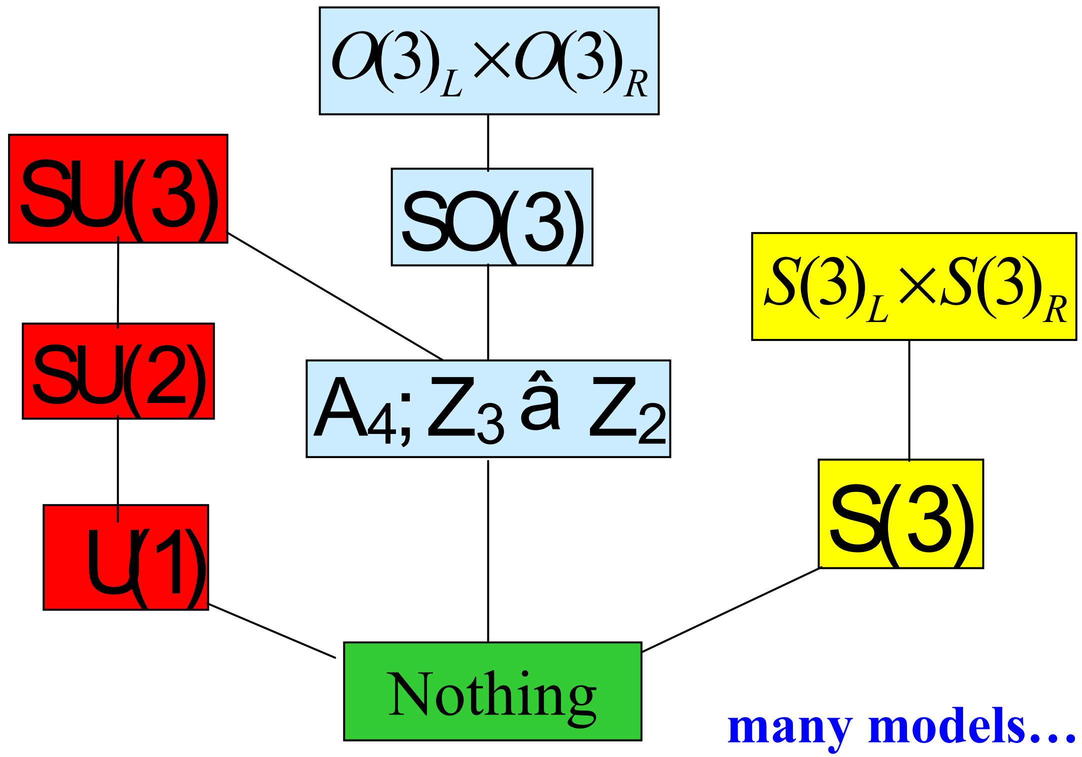
- so far **no understanding of flavour, 3 generations**
- apparant regularities in quark and lepton parameters

➔ flavour symmetries (finite number for limited rank)

➔ **symmetry** not texture zeros

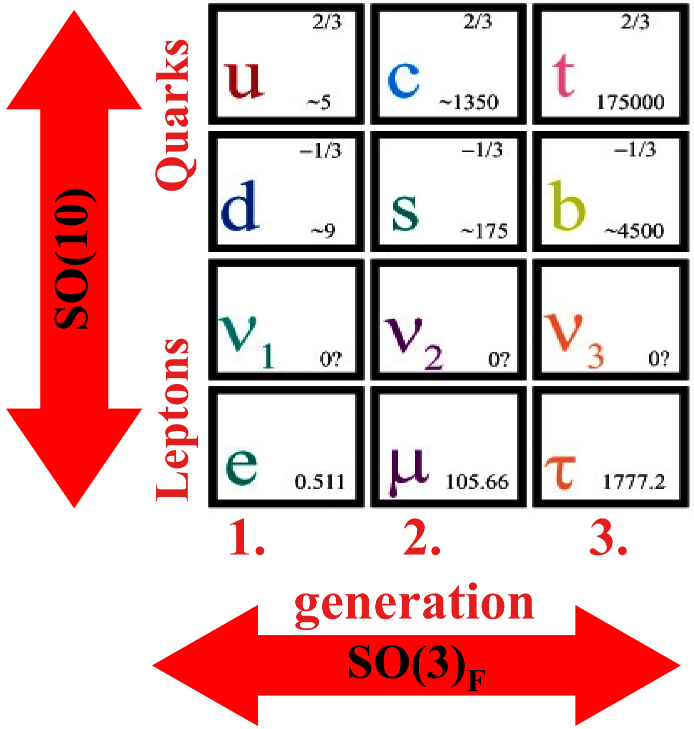


Examples:



many models…

GUT ⊗ Flavour Unification



➔ GUT group ⊗ flavour group

<u>example:</u> SO(10) ⊗ $SU(3)_F$

- SSB of $SU(3)_F$ between Λ_{GUT} and Λ_{Planck}
- all flavour Goldstone Bosons eaten
- discrete sub-groups survive ⇔SSB
  e.g. Z2, S3, D5, A4
  ➔ structures in flavour space
  ➔ compare with data

GUT ⊗ flavour is rather restricted

⇔ small quark mixings *AND* large leptonic mixings ; quantum numbers

➔ so far not many viable models, e.g.
Cai and Yu, Hagedorn, ML and Mohapatra, Chen and Mahantappa, King, Ross, …

➔ rather limited number of possibilities; phenomenological success non-trivial

➔ aim: <u>distinguish models further by future precision</u>

Could we be on the wrong track?

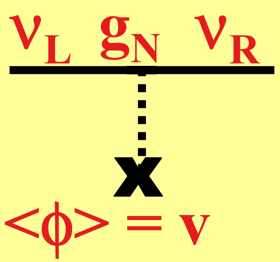
- **Top-down approach**
  - tries to solve problems, be complete, …
  - looks promising, aesthetical, predictions…
- **Bottom-up**
  - parametrize unknown physics

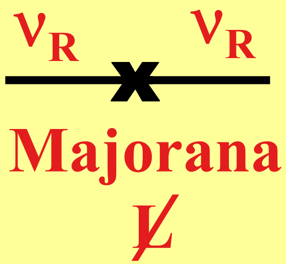
- **Options:**
  - is the low energy field content complete?
    → e.g. sterile ν's, …
  - are the underlying concepts correct?
    → d=4, …
  - QFT with known LE particle content: higher dimensional Operators from integrating out heavy unknown physics

Adding Neutrino Mass Terms

Renormalizable mass terms require new fields:

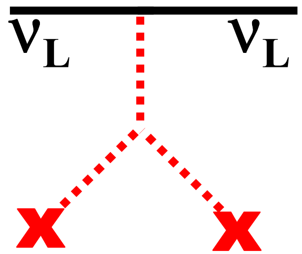
1) Simplest possibility: add 3 right handed neutrino fields





$$\rightarrow \quad \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

2) new Higgs triplets Δ_L



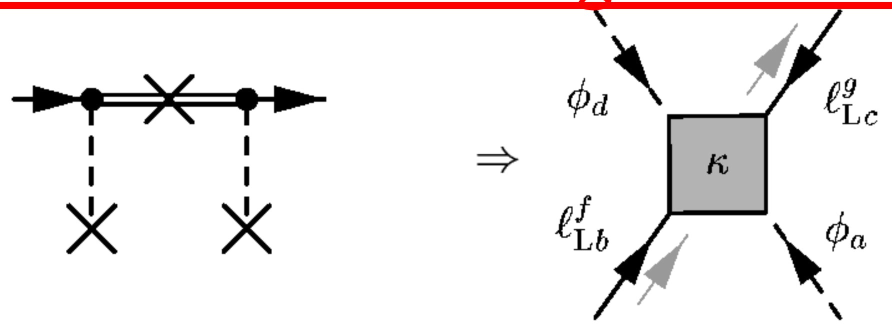
$\rightarrow$ **left-handed Majorana mass term:** $\rightarrow M_L \bar{L} L^c$

Other Neutrino Mass Operators

3) Both ν_R and new Higgs triplets Δ_L:

➔ see-saw type II $\quad m_\nu = M_L - m_D M_R^{-1} m_D^T$

4) No new fields: Higher dimensional operators: d=5, …



$\Leftrightarrow \quad \mathcal{L}_{mass} = \kappa \cdot \overline{\nu}_L^C \nu_L \Phi^T \Phi$

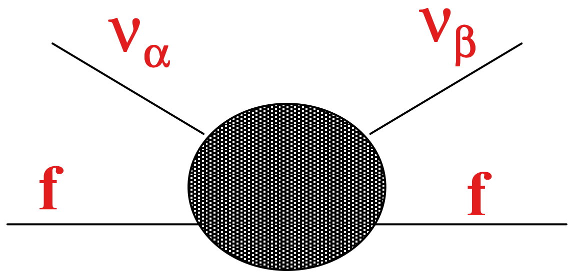
➔ $M_L \overline{L} L^c$

➔ other higher dimensional operators!?

NSI Operators

- **Good reasons for physics beyond the SM + ν's**
  ➔ **expect effects beyond 3 flavours in many models**
  ➔ **effective 4f operators = Non Standard Interactions=NSIs**
- **integrating out heavy physics**

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$



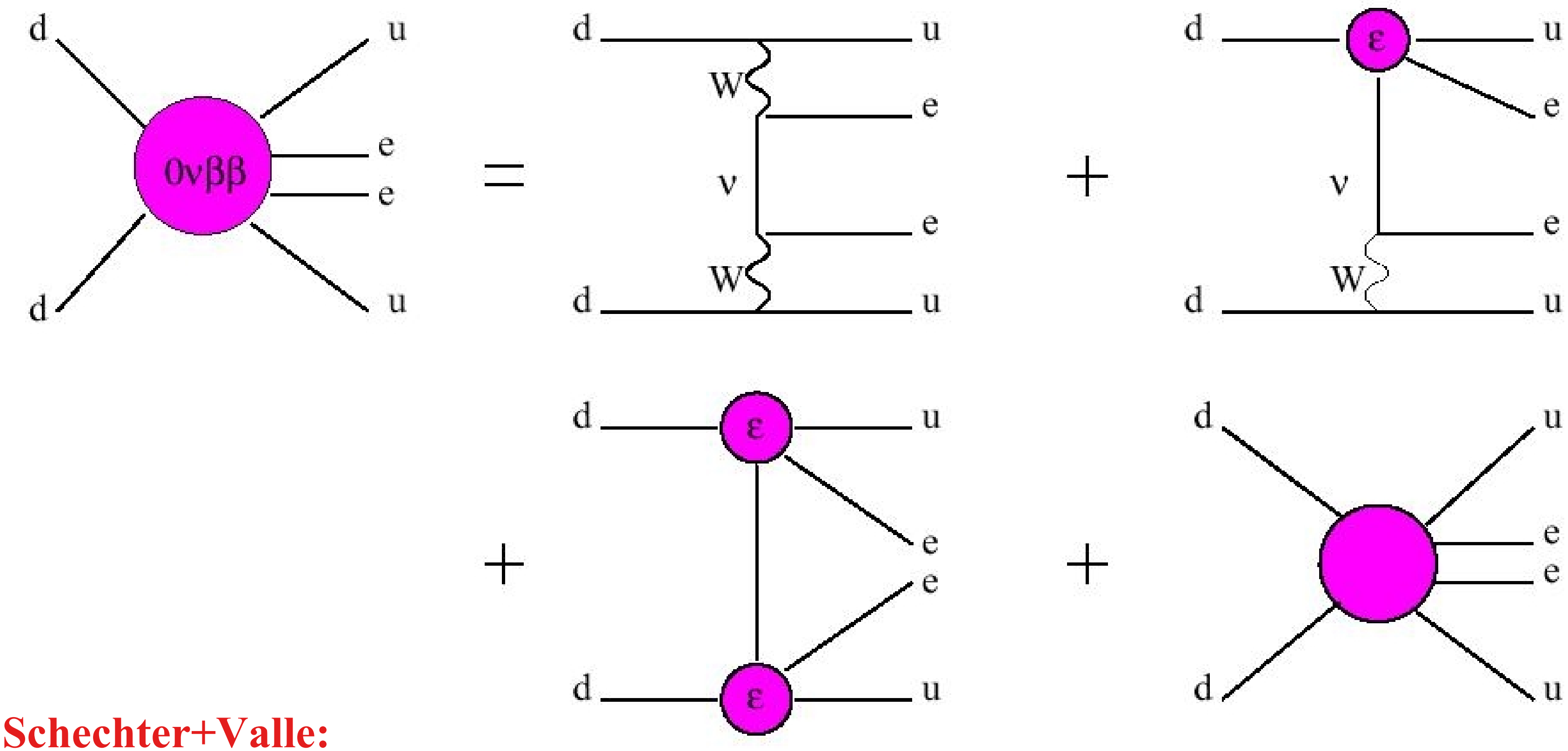
$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

Grossman, Bergmann+Grossman, Ota+Sato, Honda et al., Friedland+Lunardini, Blennlow+Ohlsson+Skrotzki, Huber+Valle, Huber+Schwetz+Valle, Campanelli+Romanino, Bueno et al., Kopp+ML+Ota, …

Contributions to 0νββ Decay

Alternative ways to generate neutrino-less double beta decay:

Majorana ν's, LR, RPV-SUSY, …➔ other $\not{L}$ operators ⟸⟹ NSI's



Schechter+Valle:

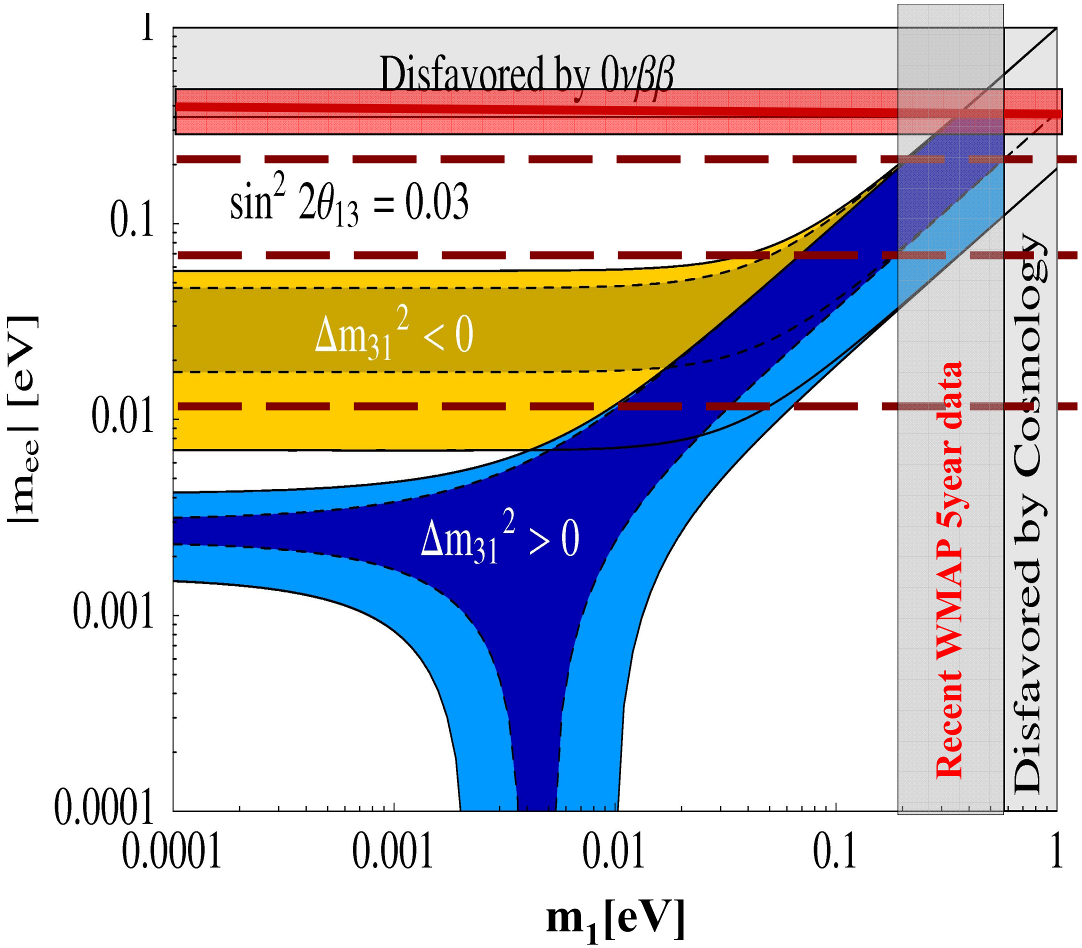
L violating operator ➔ radiative mass generation ➔ Majorana nature of ν's

However: This may only be a tiny correction to a much larger Dirac mass term

Claim of part of the original Heidelberg-Moscow experiment ⇔ cosmology ➔ ‚tension'

aims of new experiments:

- **test HM claim**
- **$(\Delta m_{31}^2)^{1/2} \simeq 0.05$eV $\pm$ errors**
  - **➔ reach 0.01eV**
  - **➔ CUORE**
  - **➔ GERDA phases I, II, (III)**



Comments:

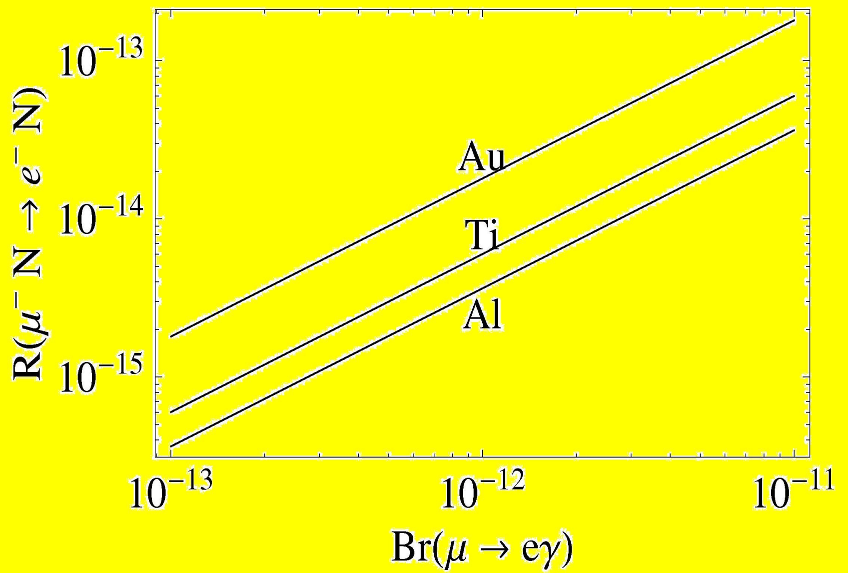
- **HM claim disputed, but what if right?**
- **reliability of cosmological results**
- **$0\nu\beta\beta$ signal from *some other* new BSM lepton number violating operator**

➔ very promising interplay of neutrino mass determinations, cosmology, LHC, LVF experiments and theory

Lepton Flavour Violation

- **Majorana neutrino mass terms**
- **…**
- **R-parity violating supersymmetry**
  Hall+Kosteleck+Rabi, Borzumati+Masiero, Hisano+Tobe, Casas+Ibarra, Antusch+Arganda+Herrero+Teixeira, Joaquim+Rossi, …

M=1TeV, best fit oscillation paramaters



Deppisch+Kosmas+Valle

➔LFV and leptonic CP violation can even exist for $m_\nu \to 0$

➔ e.g. modifications of correlations between $\mu^- \to e^- \gamma$ decay and nuclear $\mu^- \to e^-$ conversion
MEG: 10^{-13}
PRISM: 10^{-18}

➔interplay: ν's – LFV - LHC

NSIs & Oscillations

Future precision oscillation experiments:

- must include full 3 flavour oscillation probabilities
- matter effects
- define sensitivities on an event rate basis

  ➔ Simulations with GLoBES

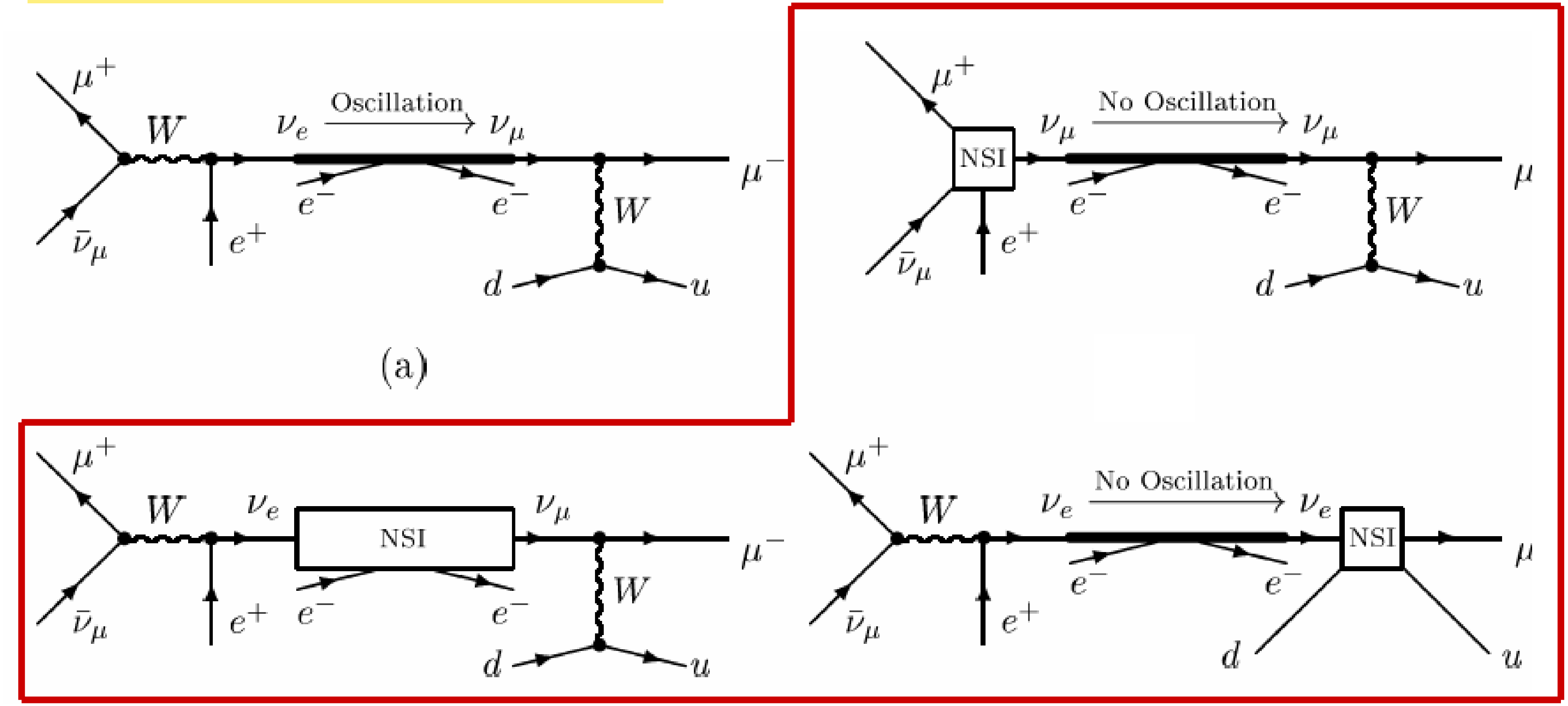
Source $\otimes$	Oscillation $\otimes$	Detector
- neutrino energy E	- oscillation channels	- effective mass, material
- flux and spectrum	- realistic baselines	- threshold, resolution
- flavour composition	- MSW matter profile	- particle ID (flavour, charge, event reconstruction, ...)
- contamination	- degeneracies	- backgrounds
- symmetric $\nu/\overline{\nu}$ operation	- correlations	- x-sections (at low E)

precision experiments might see new effects beyond oscillations ➔ NSIs!

NSIs interfere with Oscillations

the "golden" oscillation channel

NSI contributions to the "golden" channel



<u>note:</u> interference in oscillations ~ε ⇔ FCNC effects ~ε²

Physics Potential with NSIs included

Perform physics potential simulations

- full osciallation framework
- plus NSIs

➔4 possibilities for flavour transition:

- Oscillation
- NSI operator at source
- NSI operator at detector
- NSI effects in propagation

important: sensitivity limit comes from few events (small statistics)

➔ no capability to resolve characteristic L/E dependence of oscillation

➔ potential misinterpretation of NSI flavour transition effects

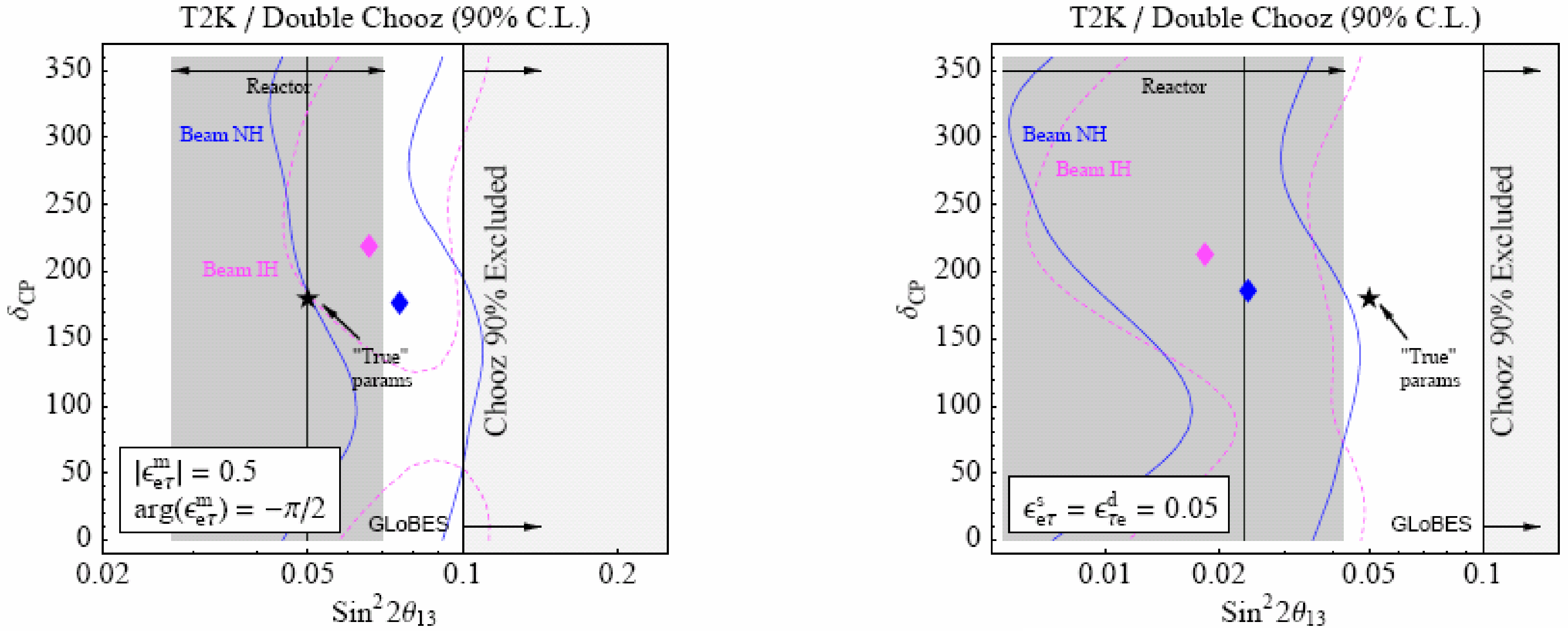
potential consequences:

- offsets in parameter determinations
- conflicting data

NSIs in Oscillation Experiments

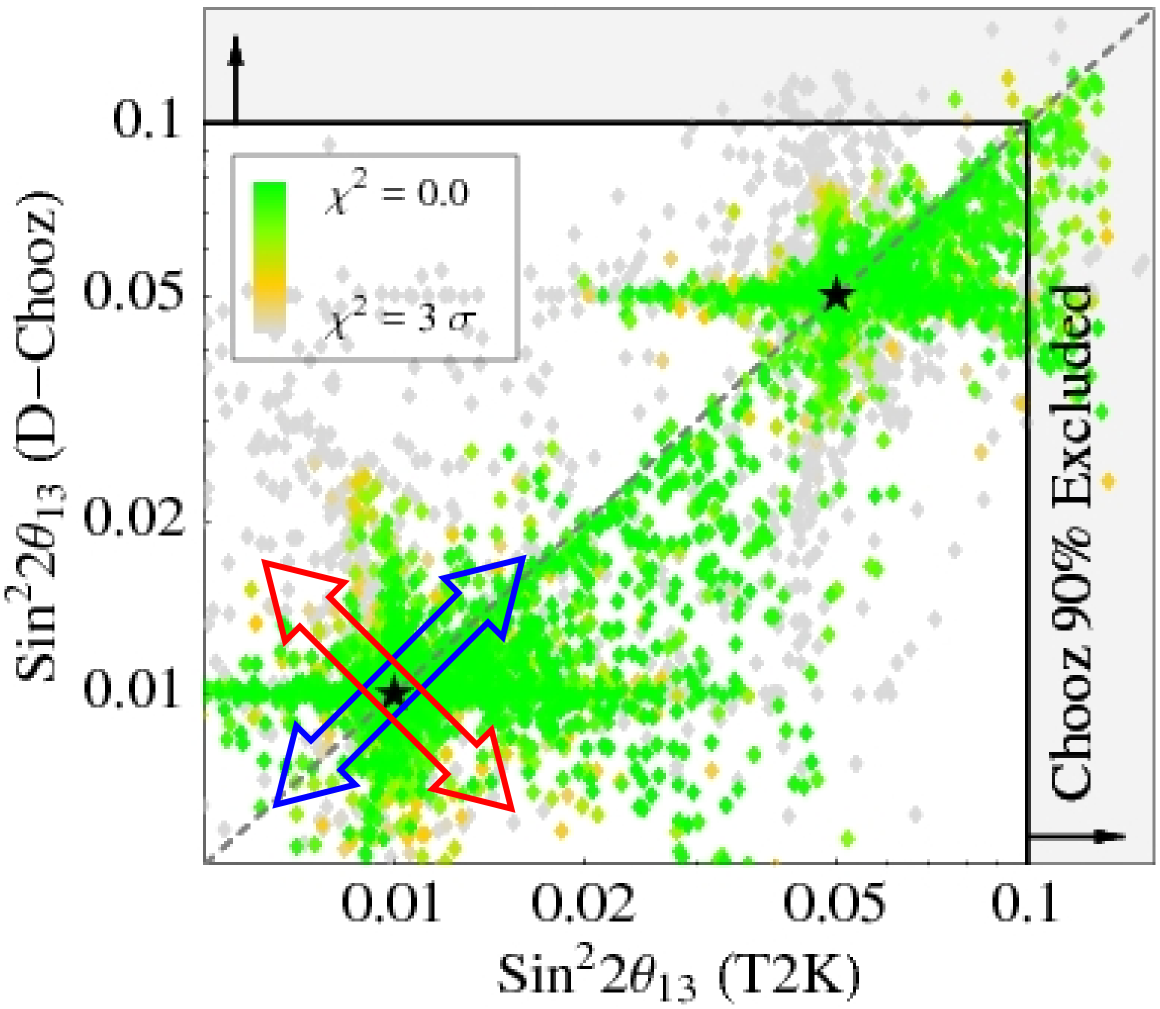
Possible consequences in oscillation experiments:

- Poor quality of standard oscillation fit ($\Rightarrow$ Detection of NSI possible)
- Offset: Wrong reconstruction of neutrino mixing parameters
- Mismatch between standard oscillation fits to different experiments



Kopp, ML, Ota

NSI: Offset and Mismatch in θ_{13}



redundant measurement of θ_{13}

Double Chooz + T2K

***=assumed 'true' values of θ_{13}**

scatter-plot:

- **ε values random**
- **below existing bounds**
- **random phases**

NSIs can lead to:

- **offset**
- **mismatch**

➔ **redundancy**

➔ **interesting potential**

Kopp, ML, Ota, Sato

Relevant NSI Operators

$$\boxed{\mathcal{L}_{\text{NSI}} = \mathcal{L}_{V\pm A} + \mathcal{L}_{S\pm P} + \mathcal{L}_{T}}$$

General Lorentz and flavour structure

$$\mathcal{L}_{V\pm A} =$$

$$\frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\epsilon}^{s,f,f',V\pm A}_{\alpha\beta} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma^5) \ell_\alpha\right] \left[\bar{f}' \gamma_\rho (1\pm\gamma^5) f\right]$$
$$+ \frac{G_F}{\sqrt{2}} \sum_{f} \tilde{\epsilon}^{m,f,V\pm A}_{\alpha\beta} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5) \nu_\beta\right] \left[\bar{f} \gamma_\rho (1\pm\gamma^5) f\right] +$$
h.c.

$$\mathcal{L}_{S\pm P} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\epsilon}^{s,f,f',S\pm P}_{\alpha\beta} \left[\bar{\nu}_\beta (1+\gamma^5) \ell_\alpha\right] \left[\bar{f}' (1\pm\gamma^5) f\right],$$
$$\mathcal{L}_{T} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\epsilon}^{s,f,f',T}_{\alpha\beta} \left[\bar{\nu}_\beta \sigma^{\rho\tau} \ell_\alpha\right] \left[\bar{f}' \sigma_{\rho\tau} f\right].$$

Reactor source and detector ($f = u,\ f' = d$)

	Source $\ell_\alpha = e$	Source $\ell_\alpha = \mu$	Source $\ell_\alpha = \tau$	Detector $\ell_\alpha = e$	Detector $\ell_\alpha = \mu$	Detector $\ell_\alpha = \tau$
$V - A$	✓	no μ production	no τ production	✓	no μ production	no τ production
$V + A$	✓	no μ production	no τ production	✓	no μ production	no τ production
$S - P$	strong constraints	no μ production	no τ production	strong constraints	no μ production	no τ production
$S + P$	strong constraints	no μ production	no τ production	strong constraints	no μ production	no τ production
T	strong constraints	no μ production	no τ production	strong constraints	no μ production	no τ production

Superbeam source and detector ($f = u,\ f' = d$)

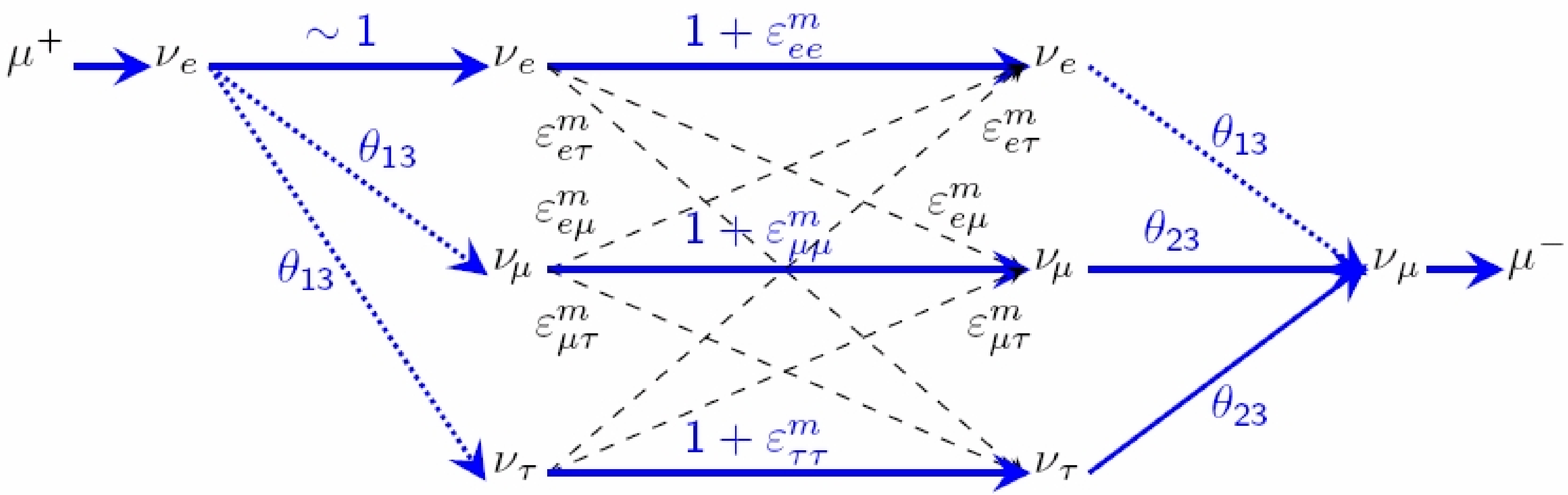
	Source $\ell_\alpha = e$	Source $\ell_\alpha = \mu$	Source $\ell_\alpha = \tau$	Detector $\ell_\alpha = e$	Detector $\ell_\alpha = \mu$	Detector $\ell_\alpha = \tau$
$V - A$	no e production	✓	no τ production	✓	✓	no τ detection
$V + A$	no e production	✓	no τ production	✓(mild supp.)	✓(mild supp.)	no τ detection
$S - P$	no e production	✓	no τ production	strong constraints	chiral supp.	no τ detection
$S + P$	no e production	✓	no τ production	strong constraints	chiral supp.	no τ detection
T	no e production	no P-odd part	no τ production	strong constraints	chiral supp.	no τ detection

Propagation ($f = e, u, d$)

$V - A$	✓
$V + A$	✓

Table I: Classification of the vertices from Eqs. (4) – (6) according to their impact on reactor and superbeam experiments. Terms marked with ✓ can give a sizeable contribution; for all other terms, the reason for their suppression is given (see text for details).

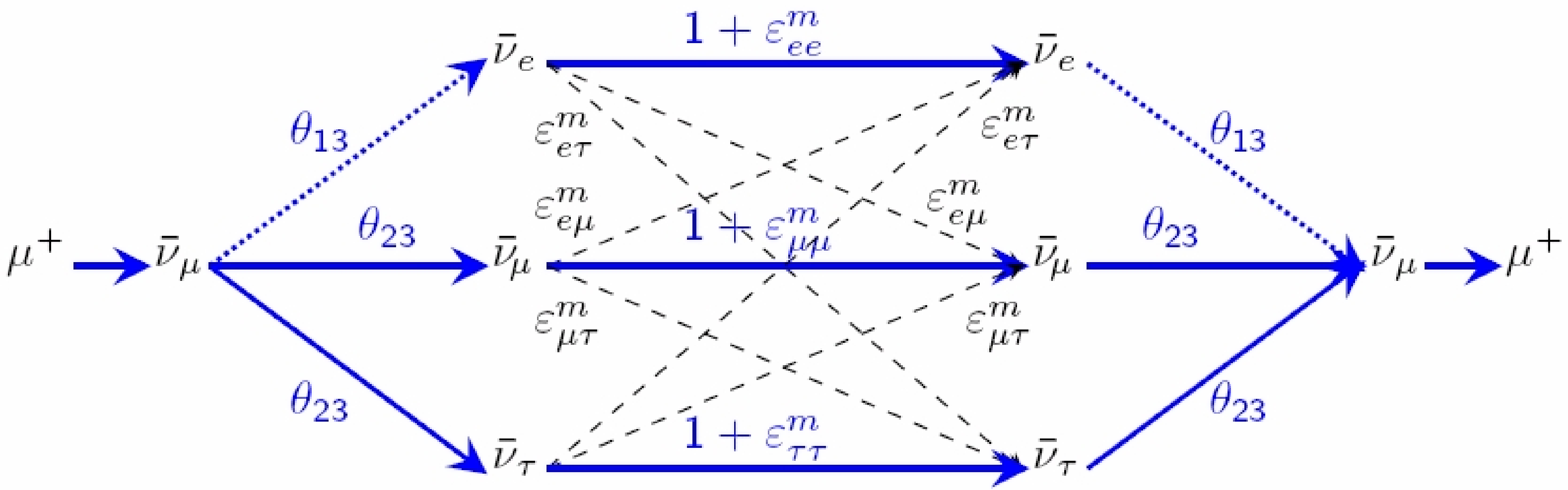
NSI in the NuFact appearance Channel



- Standard path (suppressed by θ_{13}): $\mu^+ \to \nu_e \xrightarrow{\theta_{13}} \nu_\mu \to \mu^-$
- Assume $\varepsilon \sim \theta_{13}$
- NSI paths with same level of suppression as standard path:

$$\mu^+ \to \nu_e \xrightarrow{\varepsilon^m_{e\mu}} \nu_\mu \to \mu^-$$
$$\mu^+ \to \nu_e \xrightarrow{\varepsilon^m_{e\tau}} \nu_\tau \xrightarrow{\theta_{23}} \nu_\mu \to \mu^-$$

NSI in the NuFact disappearance Channel



- Standard path (unsuppressed): $\mu^+ \to \bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+$
- Dominant NSI paths:

$$\mu^+ \to \bar{\nu}_\mu \xrightarrow{\varepsilon^m_{\mu\mu}} \bar{\nu}_\mu \to \mu^+$$
$$\mu^+ \to \bar{\nu}_\mu \xrightarrow{\theta_{23}} \bar{\nu}_\tau \xrightarrow{\varepsilon^m_{\tau\tau}} \bar{\nu}_\tau \xrightarrow{\theta_{23}} \bar{\nu}_\mu \to \mu^+$$
$$\mu^+ \to \bar{\nu}_\mu \xrightarrow{\varepsilon^m_{\mu\tau}} \bar{\nu}_\tau \xrightarrow{\theta_{23}} \bar{\nu}_\mu \to \mu^+$$

Modified Oscillation Probabilities

Standard Oscillations

$$P_{\nu_\alpha \to \nu_\beta} = \left|\langle \nu_\beta | e^{-iHL} | \nu_\alpha \rangle\right|^2$$

Oscillations with neutral current NSI

$$P_{\nu_\alpha^s \to \nu_\beta^d} = \left|\langle \nu_\beta | e^{-i(H+V_{\mathsf{NSI}})L} | \nu_\alpha \rangle\right|^2$$

$$V_{\mathsf{NSI}} = \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix}$$

Analytic Expression for $P_{e\mu}$ with $|\varepsilon_{e\tau}^{m}|$

$$
\begin{aligned}
P_{e\mu}^{\mathrm{NSI}} \simeq P_{e\mu}^{\mathrm{SO}} & - 2\,|\varepsilon_{e\tau}^{m}|\, \sin 2\theta_{13}\, \sin 2\theta_{23}\, s_{23}\, \sin(\delta_{\mathrm{CP}} + \phi_{e\tau}^{m})\, \mathcal{F}^{\mathrm{MB}}\, \mathcal{F}^{\mathrm{Res}}\, \sin\Delta \\
& - 2\,|\varepsilon_{e\tau}^{m}|\, \sin 2\theta_{13}\, \sin 2\theta_{23}\, s_{23}\, \cos(\delta_{\mathrm{CP}} + \phi_{e\tau}^{m})\, \mathcal{F}^{\mathrm{MB}}\, \mathcal{F}^{\mathrm{Res}}\, \cos\Delta \\
& + 4\,|\varepsilon_{e\tau}^{m}|\, \sin 2\theta_{13}\, c_{23}\, s_{23}^{2}\, \cos(\delta_{\mathrm{CP}} + \phi_{e\tau}^{m})\, \hat{A}\, (\mathcal{F}^{\mathrm{Res}})^{2} \\
& - 2\,|\varepsilon_{e\tau}^{m}|\, \alpha\, \sin 2\theta_{12}\, \sin 2\theta_{23}\, c_{23}\, \sin \phi_{e\tau}^{m}\, \mathcal{F}^{\mathrm{MB}}\, \mathcal{F}^{\mathrm{Res}}\, \sin\Delta \\
& + 2\,|\varepsilon_{e\tau}^{m}|\, \alpha\, \sin 2\theta_{12}\, \sin 2\theta_{23}\, c_{23}\, \cos \phi_{e\tau}^{m}\, \mathcal{F}^{\mathrm{MB}}\, \mathcal{F}^{\mathrm{Res}}\, \cos\Delta \\
& - 4\,|\varepsilon_{e\tau}^{m}|\, \alpha\, \sin 2\theta_{12}\, s_{23}\, c_{23}^{2}\, \cos \phi_{e\tau}^{m}\, \frac{1}{\hat{A}}\, (\mathcal{F}^{\mathrm{MB}})^{2} \\
& + 4\,|\varepsilon_{e\tau}^{m}|^{2}\, c_{23}^{2}\, s_{23}^{2}\, \hat{A}^{2}\, (\mathcal{F}^{\mathrm{Res}})^{2} \\
& - 2\,|\varepsilon_{e\tau}^{m}|^{2}\, \sin^{2} 2\theta_{23}\, \hat{A}\, \mathcal{F}^{\mathrm{MB}}\, \mathcal{F}^{\mathrm{Res}}\, \cos\Delta \\
& + 4\,|\varepsilon_{e\tau}^{m}|^{2}\, s_{23}^{2} c_{23}^{2}\, (\mathcal{F}^{\mathrm{MB}})^{2}\,.
\end{aligned}
$$

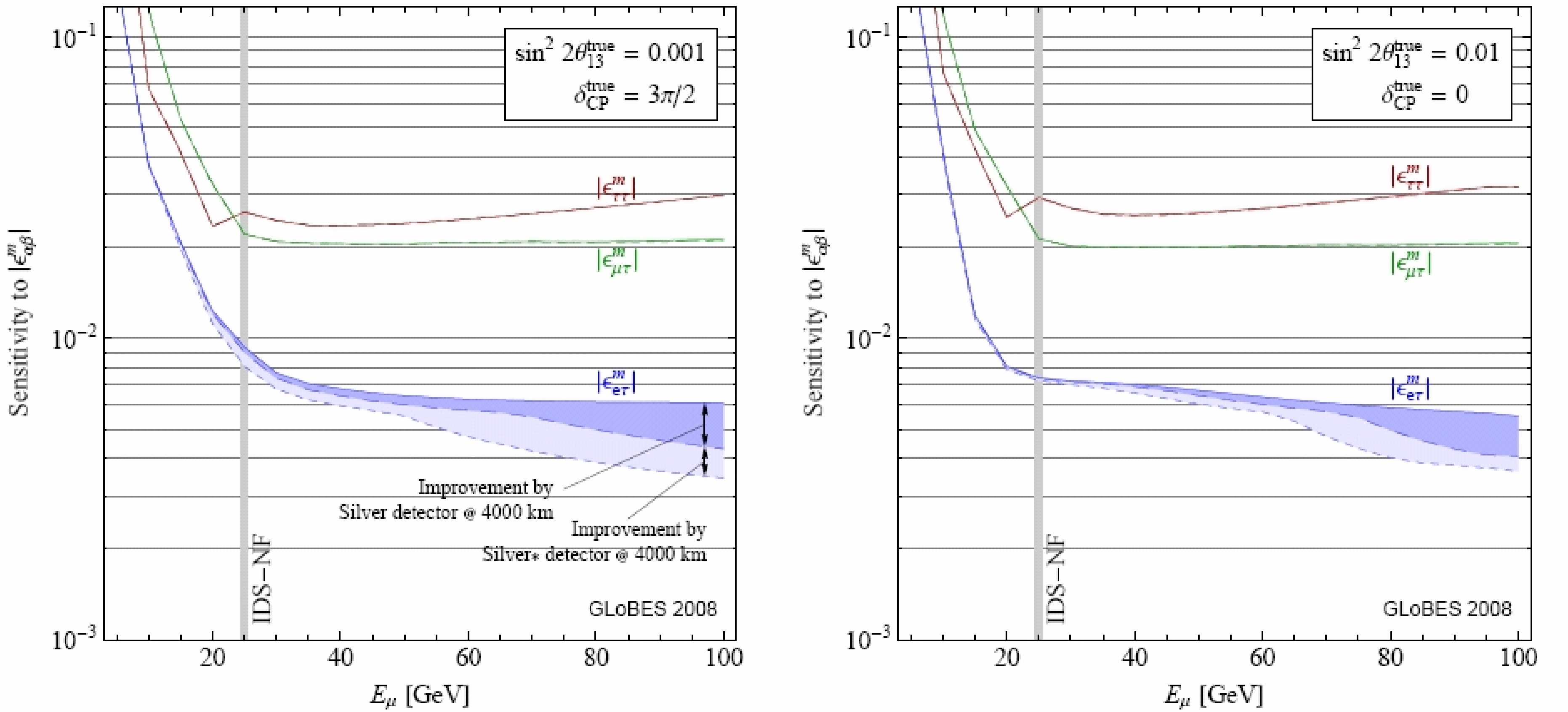
$\hat{A} \equiv \pm a_{\mathrm{CC}}/\Delta m_{31}^{2} = \pm 2\sqrt{2} E G_F N_e/\Delta m_{31}^{2}$, — Matter potential

$\Delta \equiv \Delta m_{31}^{2} L/4E$, — Vacuum oscillation phase

$\mathcal{F}^{\mathrm{Res}} \equiv \sin[(1-\hat{A})\Delta]/(1-\hat{A})$, — Maximal at matter resonance

$\mathcal{F}^{\mathrm{MB}} \equiv \sin(\hat{A}\Delta) = \sin\left(\pm \frac{G_F}{\sqrt{2}} N_e L\right)$. — Vanishes at magic baseline

Optimization of Muon Energy



Kopp, Ota, Winter

- $E_\mu = 25$ GeV is optimal.
  ($E_\mu > 25$ GeV $\rightarrow$ no significant improvement
  $E_\mu < 25$ GeV $\rightarrow$ sensitivity decreases dramatically)
- Silver channel only useful at $E_\mu \gg 25$ GeV.

Conclusions

- **Neutrino physics carries important flavour information**
  - large mixings ←→ small quark mixings
  - tiny θ_{13} and/or maximal θ_{23} could be hints for symmetries
- **Good reasons for unifications**
  - GUTs
  - horizontal flavour symmetries
  - GUT x flavour
- **Parametrize unknown new physics as NSIs**
  - effects in $0\nu\beta\beta$ decay
  - effects in LFV
  - interference terms in oscillations: limits or discovery potential

➔ **Interesting potential from interplay of neutrino physics, LHC and LFV**