Non-Standard Neutrino Interactions & Non-Unitarity

talk by *Stefan Antusch*

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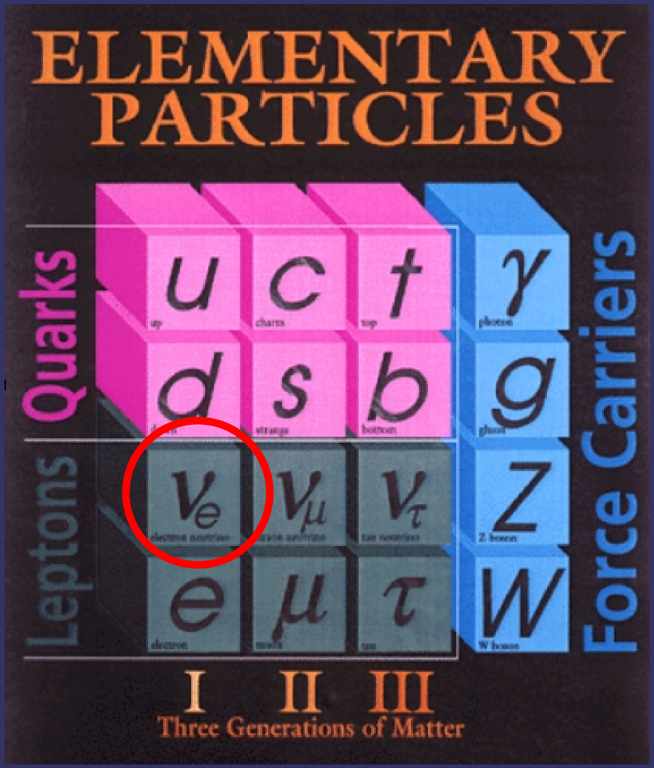
LAUNCH 09

Learning from Astroparticle, Underground, Neutrino Physics and Cosmology, Heidelberg
9 - 12 November 2009

MPIK Heidelberg, 9. - 12. November 2009

The Standard Model



- Symmetries of the SM:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{\langle H \rangle = v_{EW}} SU(3)_C \times U(1)_{em}$$

- Masses of particles by the Higgs mechanism

  - Higgs particle(s) not observed so far → search @ LHC

- With symmetries and field content of the SM:
  - neutrinos are massless
  - no mixing
  - couple only to Z and W

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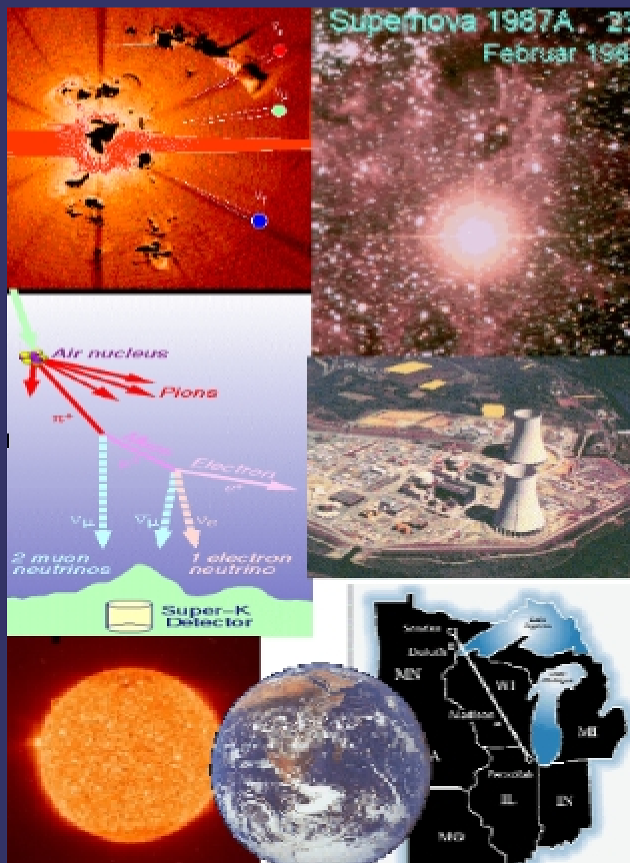
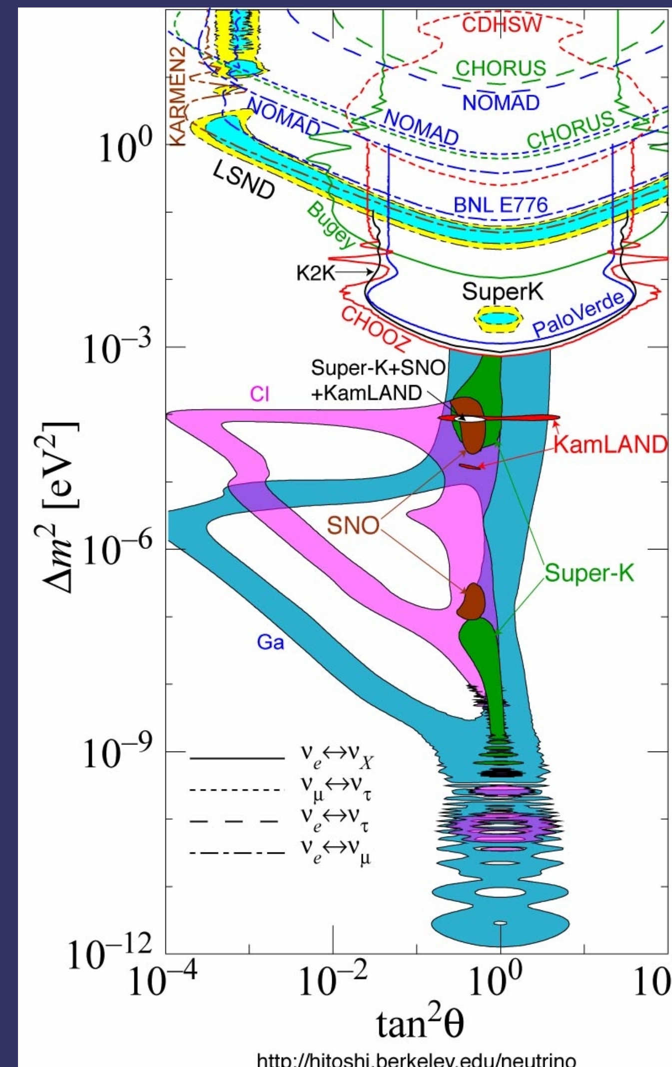
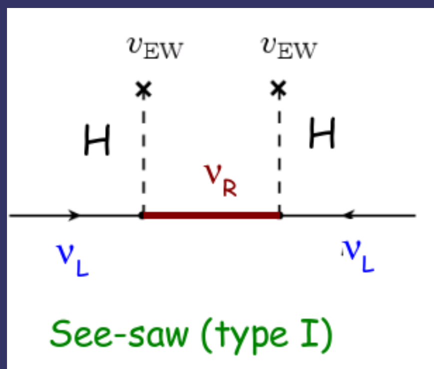
Evidence for neutrino masses



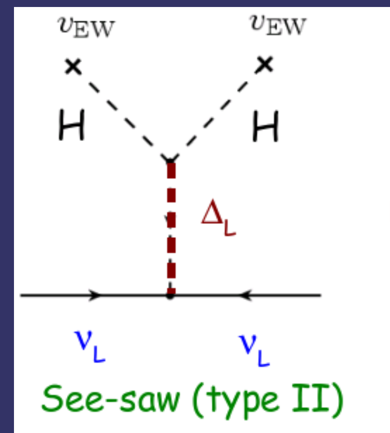


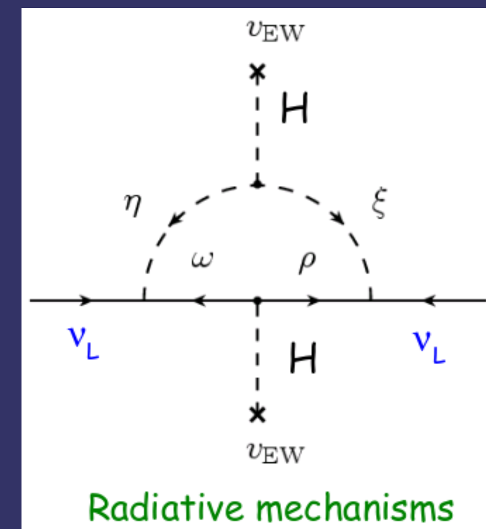
- Strong evidence for ν-oscillations:
  $\Rightarrow$ Neutrinos have mass
  $\rightarrow$ leptonic mixing matrix
  $\rightarrow$ new ν-interactions (mechanism of mass generation)

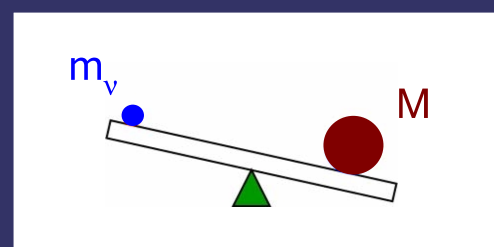
Origin of neutrino masses?



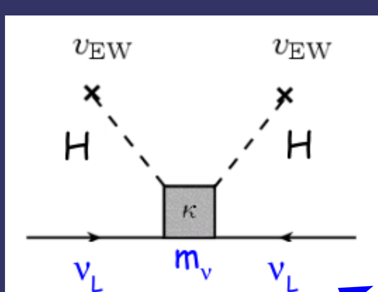
(or type III)







Seesaw mechanism



quite model independent:
unique dim. 5 Operator

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta}\, \left(\overline{L^c}_\alpha \tilde{\phi}^*\right) \left(\tilde{\phi}^\dagger\, L_\beta\right) + h.c.$$

P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, Magg, Wetterich, Ma, Foot, Lew, He, Joshi, ...

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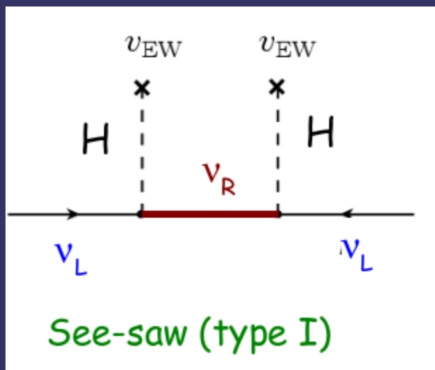
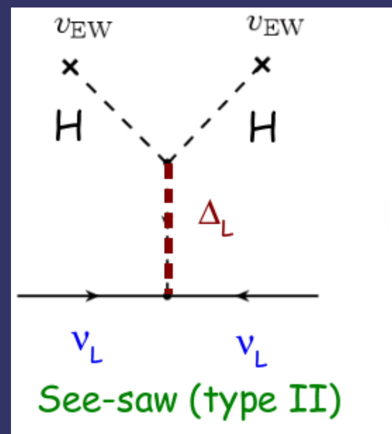
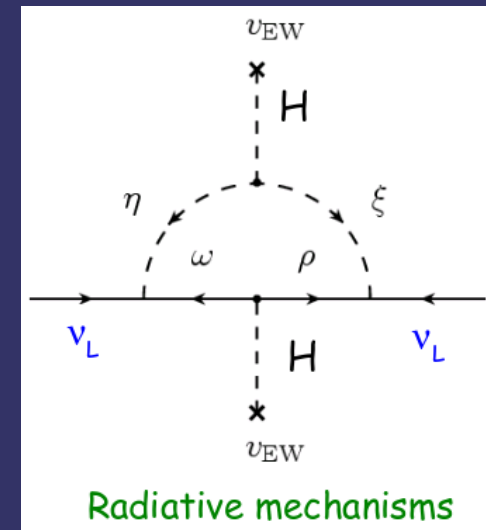
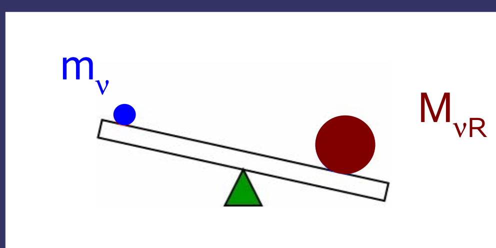
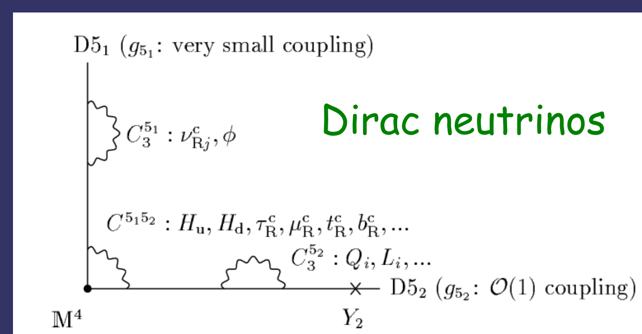
Origin of neutrino masses?

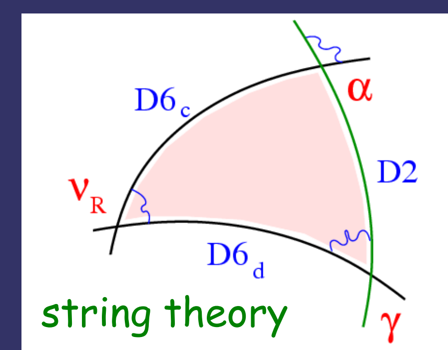


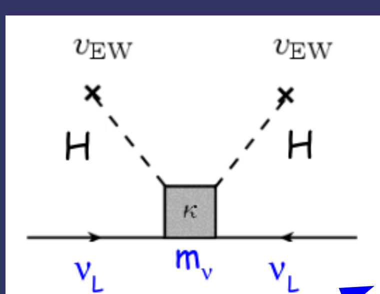






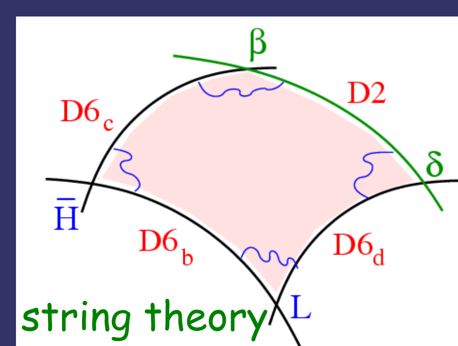






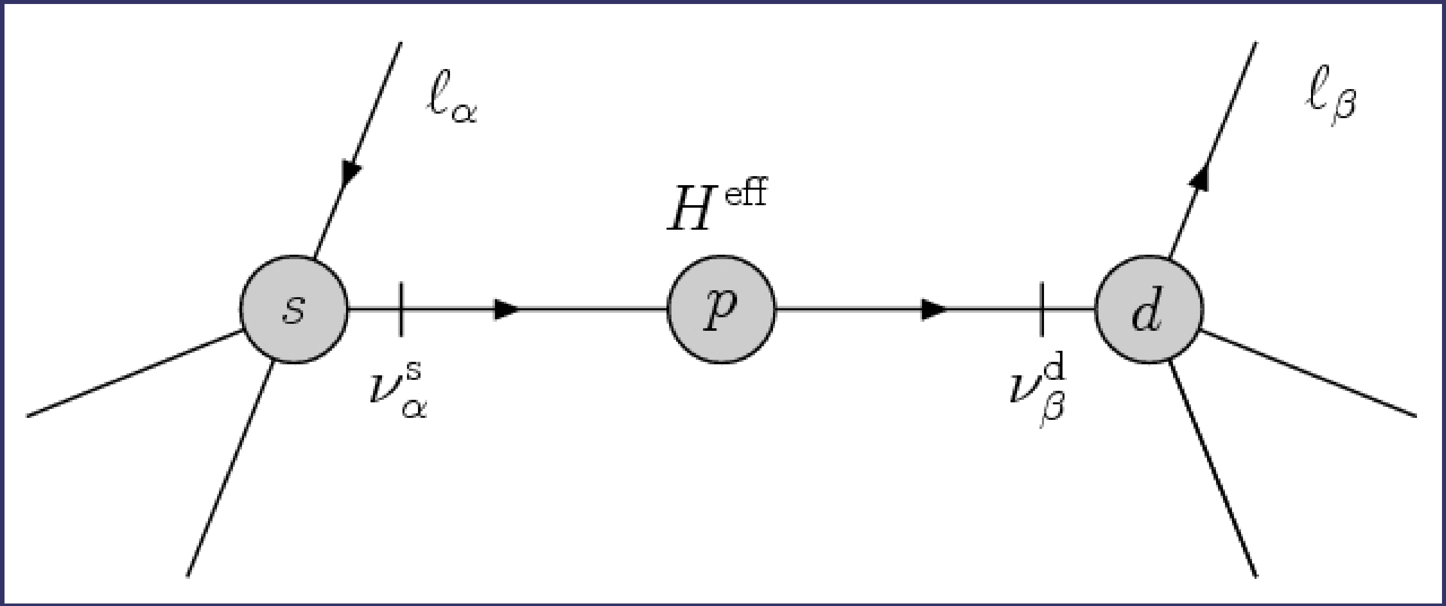
quite model independent:
unique dim. 5 Operator

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{L^c}_\alpha \tilde{\phi}^*\right) \left(\tilde{\phi}^\dagger L_\beta\right) + h.c.$$



Unknown:
- which mechanism?
- at which scale?

Typically: New ν-interactions will affect neutrino oscillations …

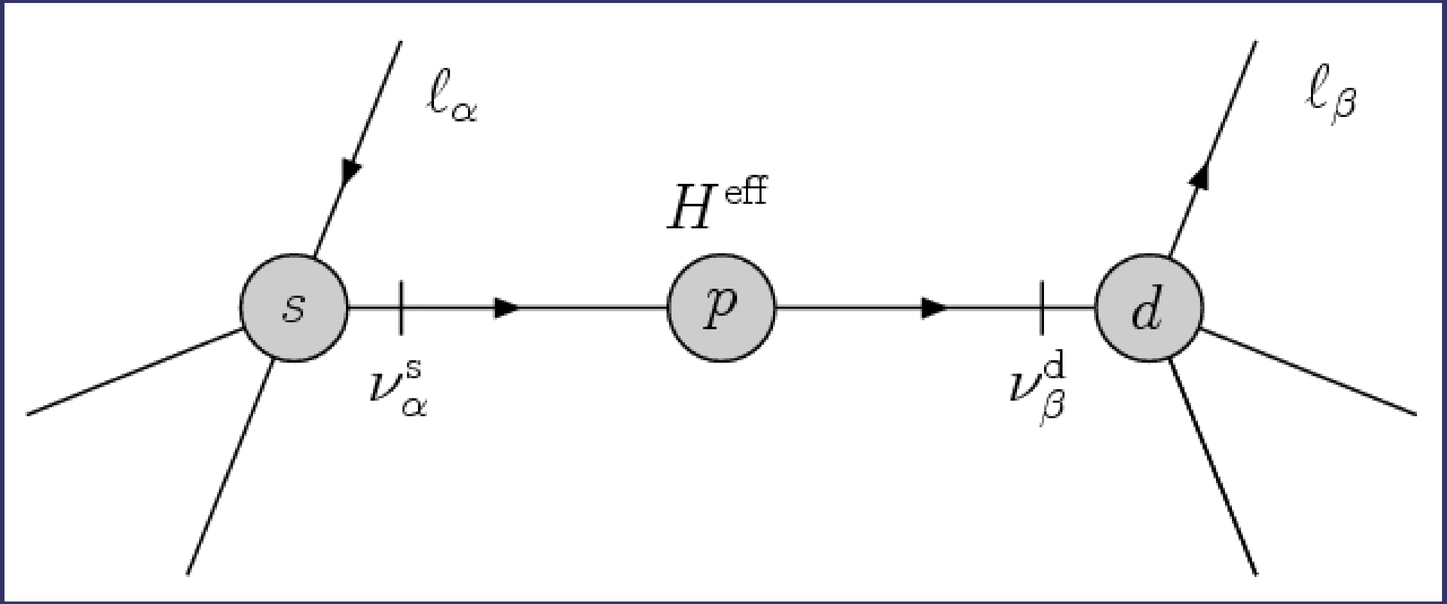


New interactions … at the source

… during propagation in matter

… at the detector

Typically: New ν-interactions will affect neutrino oscillations ...



New interactions ... at the source

... during propagation in matter

... at the detector

NSI parameterisation: $\mathcal{L}_{NSI} = 2\sqrt{2}G_F\, \epsilon^{f}_{\alpha\beta}\, (\overline{\nu}_{\alpha\mathrm{L}}\, \gamma^{\delta}\, \nu_{\beta\mathrm{L}})(\overline{f}_{\mathrm{L,R}}\, \gamma_\delta\, f_{\mathrm{L,R}})$

NSI: Non-Standard ν Interactions

$|\nu^s_\alpha> = (1 + \varepsilon^{*s})_{\alpha\beta}\, |\nu_\beta> = (1 + \varepsilon^{*s})_{\alpha\beta}\, U^*_{\beta i}|\nu_i>$

$|\nu^d_\beta> = (1 + \varepsilon^{*d})_{\beta\gamma}\, |\nu_\gamma> = (1 + \varepsilon^{*d})_{\beta\gamma}\, U^*_{\gamma j}|\nu_j>$

Y. Grossman ('95)

At present neutrino oscillation (and also @ non-oscillation) experiments: No clear signals of such new interactions yet ...

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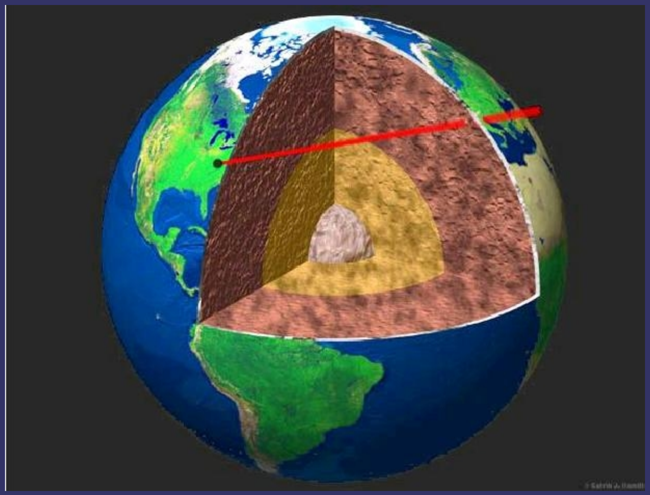
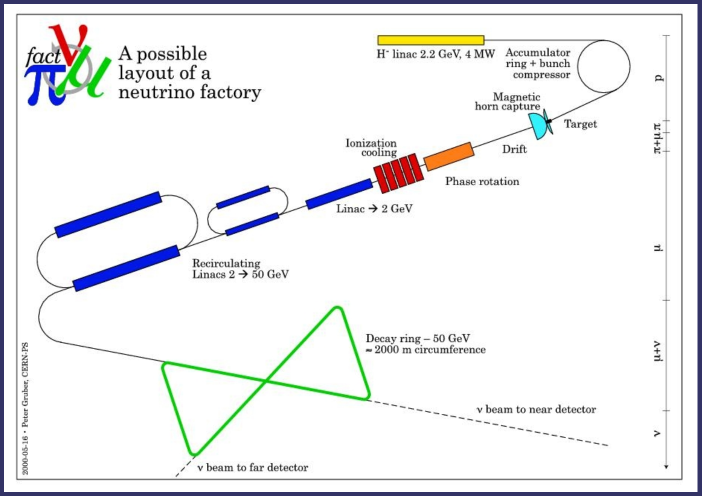
Future: Precision neutrino experiments

... aim mainly at measuring the remaining unknown parameters of the leptonic mixing matrix





International scoping study of a future
Neutrino Factory and super-beam facility
Physics working group

- In the presence of New Physics:
  - Confusion problem?
  - Discovery chance?

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Outline

- two generic examples for New Physics effects on neutrino oscillations
  - Non-unitarity of leptonic mixing matrix (and its relations to Non-Standard neutrino Interactions (NSIs))
  - NSIs during propagation through matter: How large can they be in explicit gauge invariant SM extensions?

... many other interesting NP effects: neutrino decays, decoherence, light sterile neutrinos, CPT and/or Lorentz-invariance violation, non-locality, ...
(but no time to discuss them in this talk)

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Non-Unitarity

of the Leptonic Mixing Matrix

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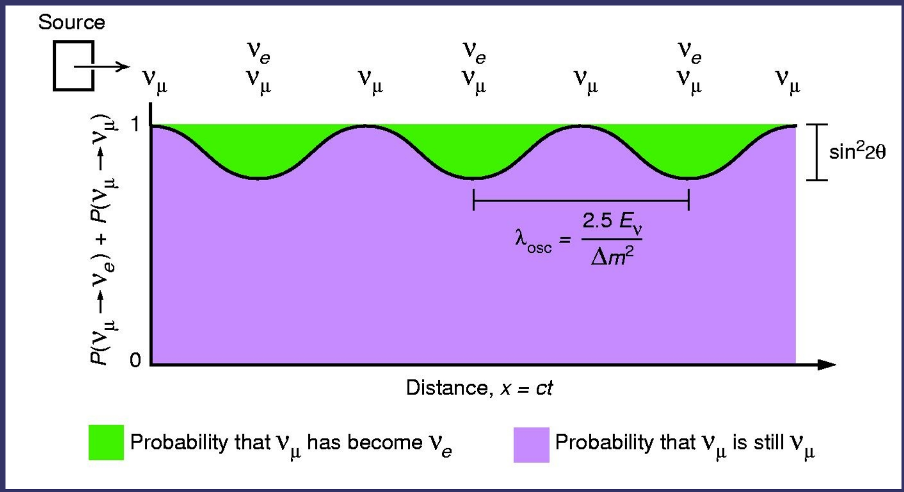
Neutrino Oscillations

- Flavour conversion $\nu_\alpha \rightarrow \nu_\beta$ when neutrinos travel from source $\rightarrow$ detector
  - Required:

    i) mixing between flavour & mass eigenstates
    ii) neutrino masses: $m_{\nu i}^2 - m_{\nu j}^2 \neq 0$
- In usual analyses of the neutrino data: Unitarity of the mixing matrix U (i.e. U U$^+$ = 1) is assumed!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Oscillation probability (U unitary):

$$P_{\alpha\beta} = 4 \sum_{i<j} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} sin^2 \Delta_{ij}$$

where $\Delta_{ij} = \frac{(m_i^2 - m_j^2) L}{4E}$

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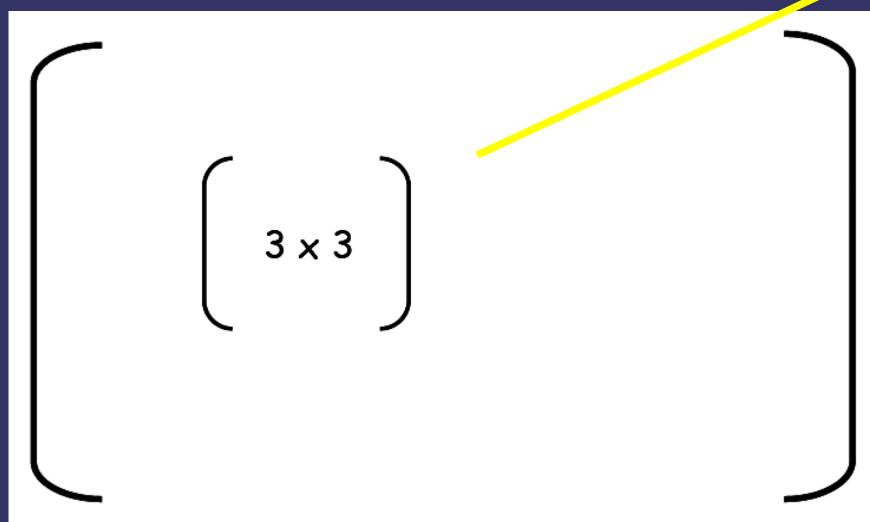
Origin of Non-Unitarity in Extensions of the SM

- Typical situation, intuitively:



(Effective) mixing matrix of light neutrinos is part of a larger unitary mixing matrix (mixing with additional heavy particles)

$\Rightarrow$ U_{MNS} non-unitary

Examples with possible large non-unitarity: 'inverse' seesaw or 'multiple' seesaw at TeV energies, SUSY with R-parity violation, large extra dimensions, ...

Origin of Non-Unitarity in Extensions of the SM

- Generic class of SM extensions which generate Non-Unitarity:
  SM + heavy singlet fermions N_i

  By 'heavy', I mean:
  - large mass compared to the energies of a ν-oscillation exp.

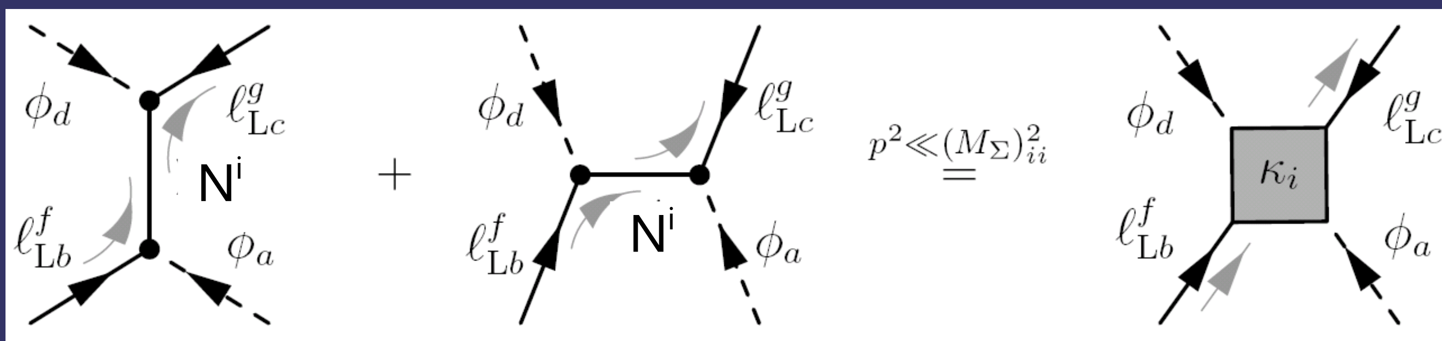
  'This is a 'minimal' realisation of Non-Unitarity, in the sense that:
  - only introduce new physics in neutrino sector
  - only 3 light neutrinos

- @ high energies: still many possible models ...
  @ low energies: physics contained in only two effective operators!

Origin of Non-Unitarity in Extensions of the SM

➲ Effective theory view point: integrate out SM gauge-singlet fields N^i:

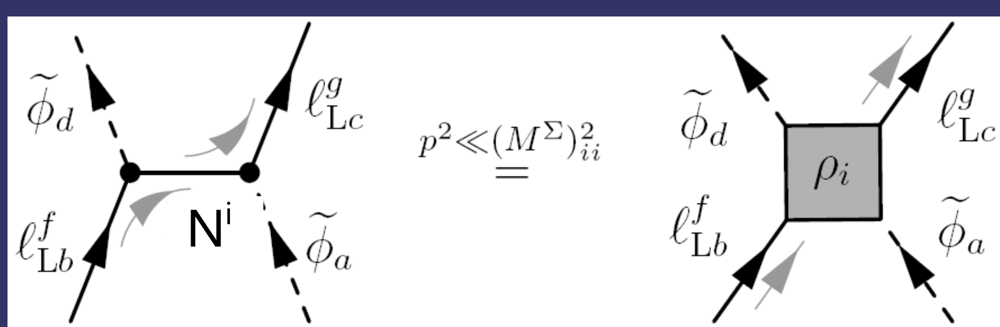
- dim. 5 operator: generates neutrino masses



Seesaw (type I)

violates L!

- dim. 6 operator: contributes to ν kinetic terms after EWSB; generates non-unitary leptonic mixing matrix after canonical normalisation



these are the lowest dimensional effective operators ... !

conserves L!

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Effective theory extension of SM: Minimal unitarity violation (MUV)

S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon (hep-ph/0607020)

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots$$

where

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{L^c}_\alpha \tilde{\phi}^*\right) \left(\tilde{\phi}^\dagger L_\beta\right) + h.c.$$

unique dim. 5 operator for neutrino masses violates L!

$$\delta\mathcal{L}^{d=6} = c^{d=6}_{\alpha\beta} \left(\overline{L}_\alpha \tilde{\phi}\right) i\partial\!\!\!/ \left(\tilde{\phi}^\dagger L_\beta\right)$$

unique dim. 6 operator leading to non-can. kinetic terms for neutrinos only

conserves L!

Consistent effective theory with non-unitary leptonic mixing
$\rightarrow$ can now be confronted with experiments ...

Minimal unitarity violation (MUV)

- After EWSB, dim=6 operator generates non-canonical kinetic terms (only for neutrinos!):

non-canonical neutrino kinetic terms

$$\begin{aligned}\mathcal{L}^{eff} &= \frac{1}{2}\left(i\,\bar{\nu}_\alpha\,\partial\!\!\!/\,(NN^\dagger)^{-1}_{\alpha\beta}\,\nu_\beta - \overline{\nu^c}_\alpha\,[(N^{-1})^t m N^{-1}]_{\alpha\beta}\,\nu_\beta + h.c.\right)\\ &- \frac{g}{2\sqrt{2}}\left(W^+_\mu\,\bar{l}_\alpha\,\gamma^\mu\,(1-\gamma_5)\,\nu_\alpha + h.c.\right)\\ &- \frac{g}{2\cos\theta_W}\left(Z_\mu\,\bar{\nu}_\alpha\,\gamma^\mu\,(1-\gamma_5)\,\nu_\alpha + h.c.\right) + \ldots\,,\end{aligned}$$

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Minimal unitarity violation (MUV)

- Canonically normalising the neutrino states and switching to the mass basis (by $\nu_\alpha = N_{\alpha i}\, \nu_i$) ...

kin. term — ν-mass term — charged current interaction — non-unitary matrix N

$$\mathcal{L}^{eff} = \frac{1}{2}\left(\bar{\nu}_i i \partial\!\!\!/ \nu_i - \overline{\nu^c}_i m_i \nu_i + h.c.\right) - \frac{g}{2\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma_\mu (1-\gamma_5) N_{\alpha i} \nu_i + h.c.\right)$$
$$- \frac{g}{2\cos\theta_W}\left(Z_\mu \bar{\nu}_i \gamma^\mu (1-\gamma_5) (N^\dagger N)_{ij} \nu_j + h.c.\right) + \dots$$

in addition: modification in neutral current interaction

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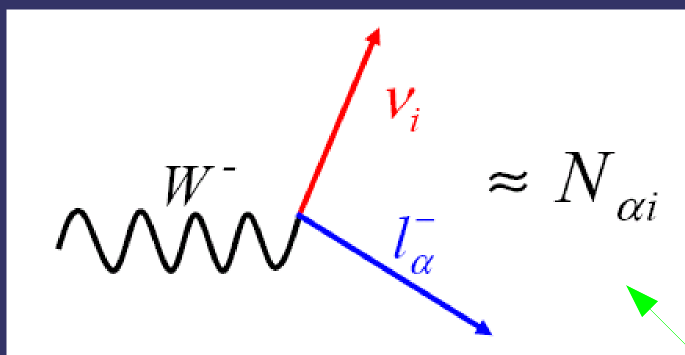
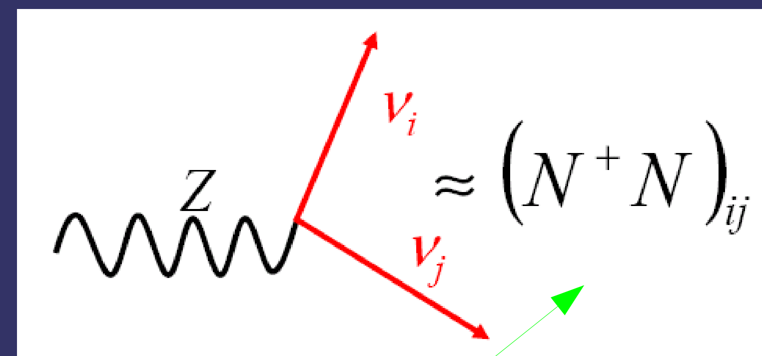
MUV and Non-Standard ν Interactions

- In the MUV scheme, weak interactions are modified:





Non-unitary leptonic matrix N

MUV and Non-Standard ν Interactions

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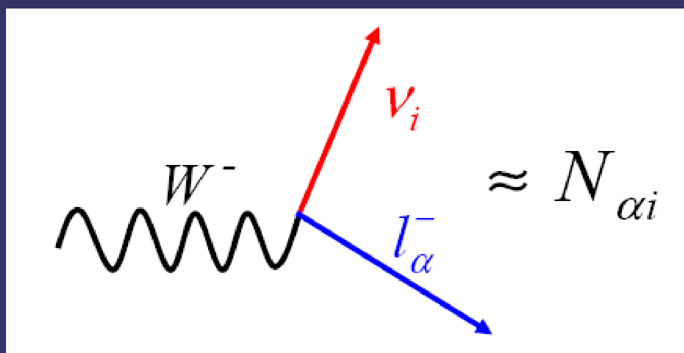

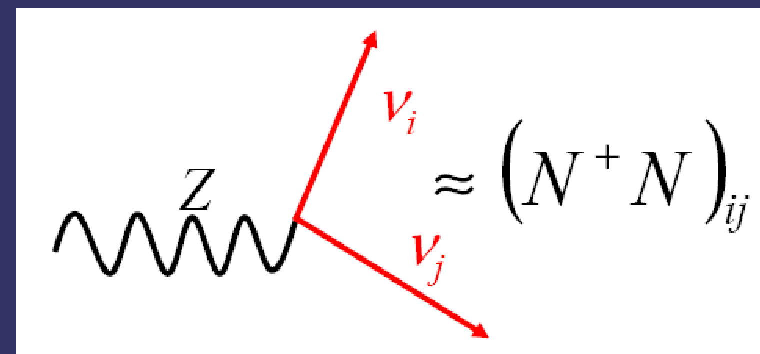

- Consequence: NSIs at the source/detector and in matter

NSI parameterisation: $$N \approx (1+\varepsilon)\cdot U$$

Hermitian x Unitary

e.g.:

$$\nu^s_\alpha> = N^*_{\beta i}|\nu_i> \approx (1 + \varepsilon^{*s})_{\alpha\beta}\, U^*_{\beta i}|\nu_i> = (1 + \varepsilon^{*s})_{\alpha\beta}\, |\nu_\beta>$$

Also: NSIs at detector and with matter related to N!

Rigorous treatment of ν-oscillations with non-unitary N:
S. A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)

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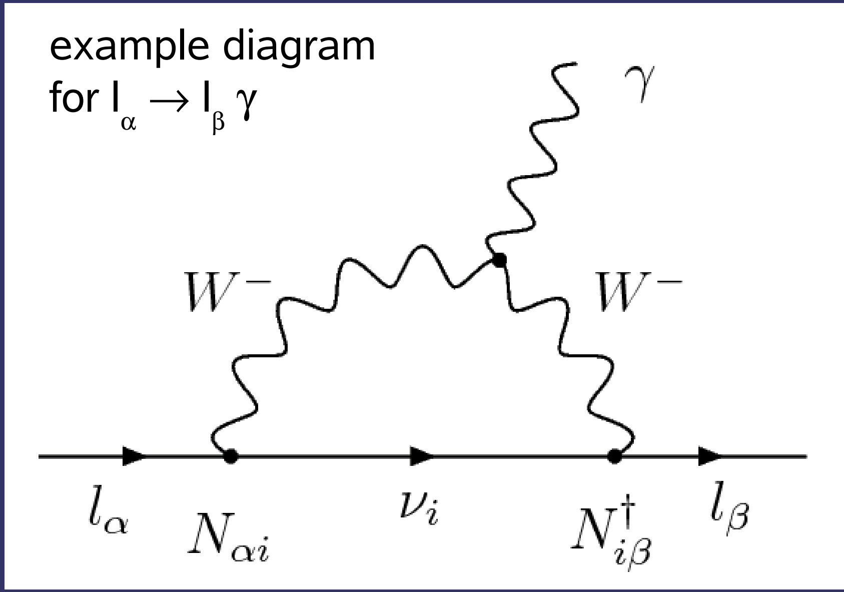
Minimal unitarity violation (MUV)

- Constraints on non-unitarity from:
  - W decays and invisible Z-decays
  - Universality tests
  - Rare decays of charged leptons, e.g.: $l_\alpha \to l_\beta \gamma$
  - ...



S. A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)

- Finally ... combined constraints (at 90% cl)

$$|(NN^\dagger)_{\alpha\beta} - \delta_{\alpha\beta}| = \frac{v^2}{2}|c^{d=6,kin}_{\alpha\beta}| < \begin{pmatrix} 4.0 \cdot 10^{-3} & 1.2 \cdot 10^{-4} & 3.2 \cdot 10^{-3} \\ 1.2 \cdot 10^{-4} & 1.6 \cdot 10^{-3} & 2.1 \cdot 10^{-3} \\ 3.2 \cdot 10^{-3} & 2.1 \cdot 10^{-3} & 5.3 \cdot 10^{-3} \end{pmatrix}$$

~ bounds on the NSIs @ source/detector and on NSIs with matter

S.A., Baumann, Fernandez-Martinez (0807.1003)

Minimal unitarity violation (MUV)

- Effects on neutrino oscillations in vacuum (schematically, 2 familiy example)

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) + 2\,\mathrm{Im}(\varepsilon_{\alpha\beta})\sin(2\theta)\sin\left(\frac{\Delta m^2 L}{2E}\right) + 4|\varepsilon_{\alpha\beta}|^2$$

SM

CP violating interference

Zero dist. effect

Remark: Near detector very important for testing non-unitarity (& new neutrino interactions in general). Desirable: τ-identification!

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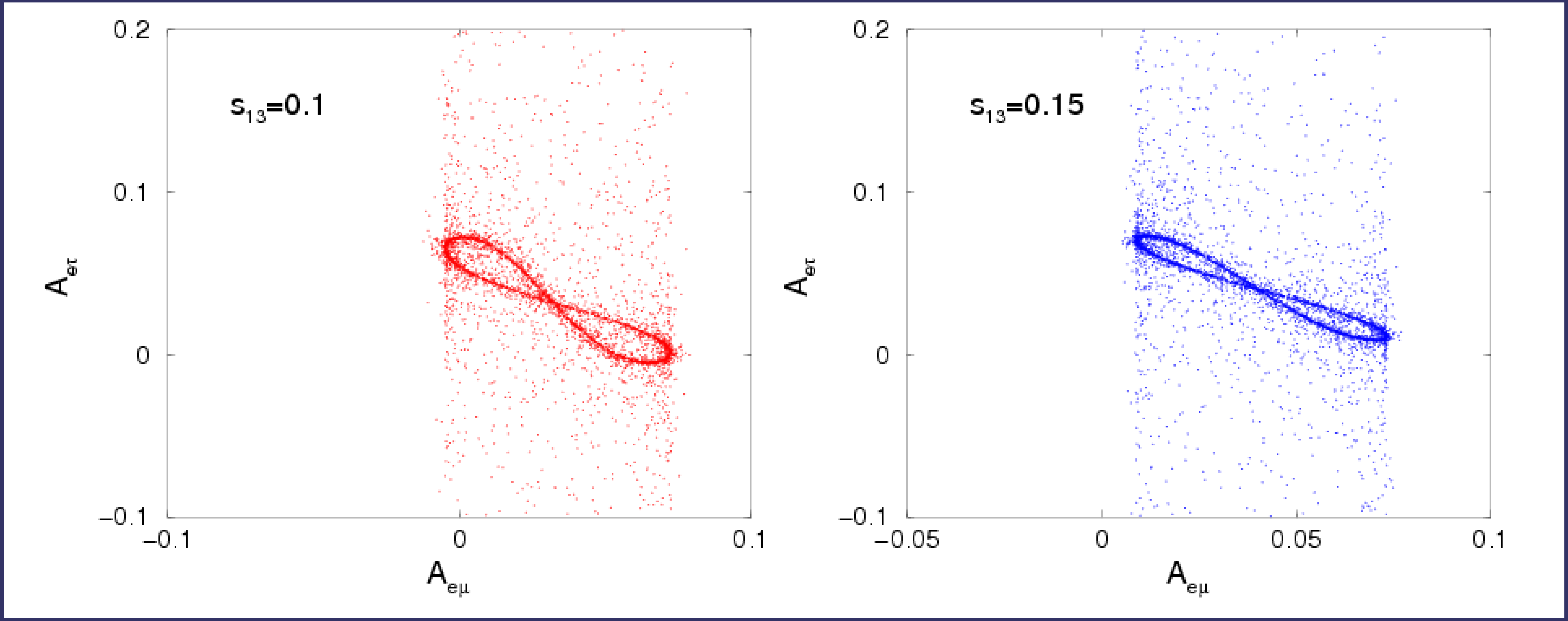
Which is the source of CP violation in ν-oscillations?

- Within MUV: deviations from the standard picture of CP violation (MUV parameters within present bounds)

G. Altarelli, D. Meloni (0809.1041)



See also: Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda ('07), Goswami, Ota ('08)

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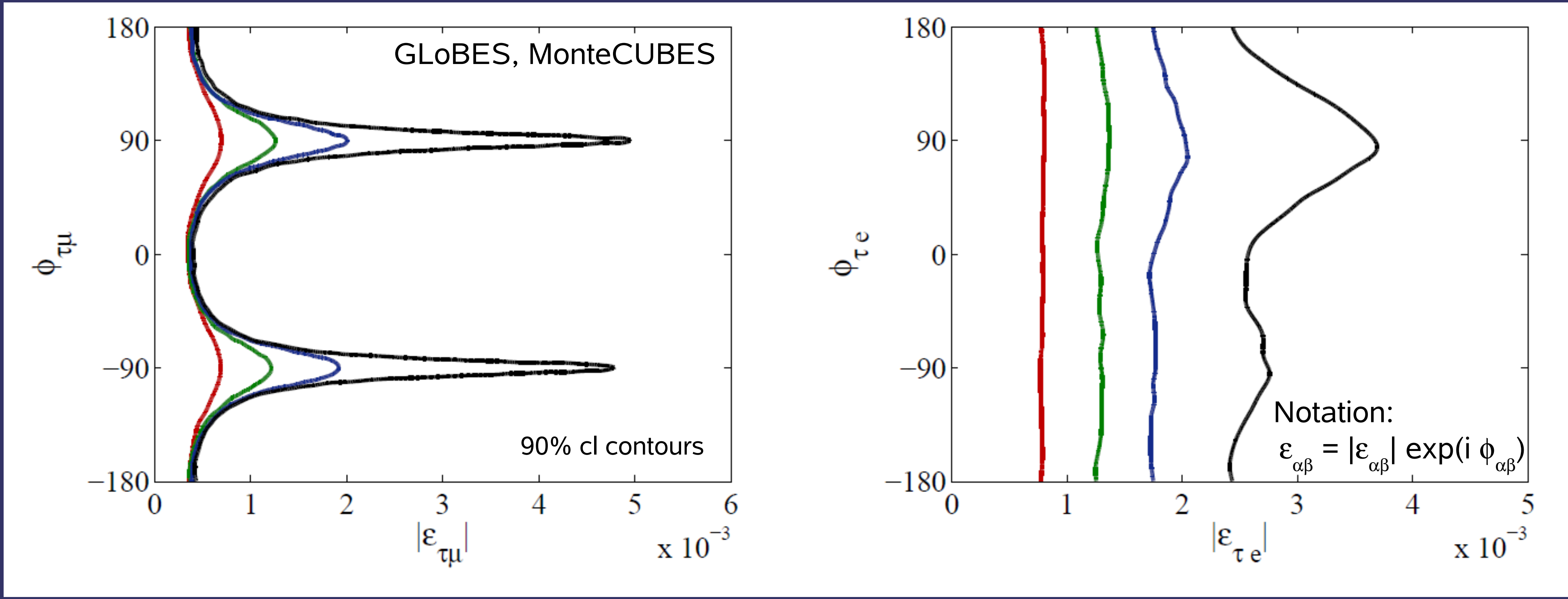
Non-unitarity at a Neutrino Factory

S. A., Blennow, Fernandez-Martinez, Lopez-Pavon ('09)



ν-Factory (IDS setup) + near Emulsion Cloud Chamber (ECC) τ-detector (10 kton, 1 kton, 100 tons, no)

- NF excellent sensitivity to probe non-unitarity
  - $\mathrm{Re}(\varepsilon_{\tau\mu}) \sim O(10^{-4})$ from matter effects in ν_μ-disapp., $|\varepsilon_{\tau\mu}| \sim O(10^{-3})$ from ND
  - $\varepsilon_{\tau e}$ up to $O(10^{-3})$, dominated by near detector (ND)
  - Far detector + ND combined: CP violation

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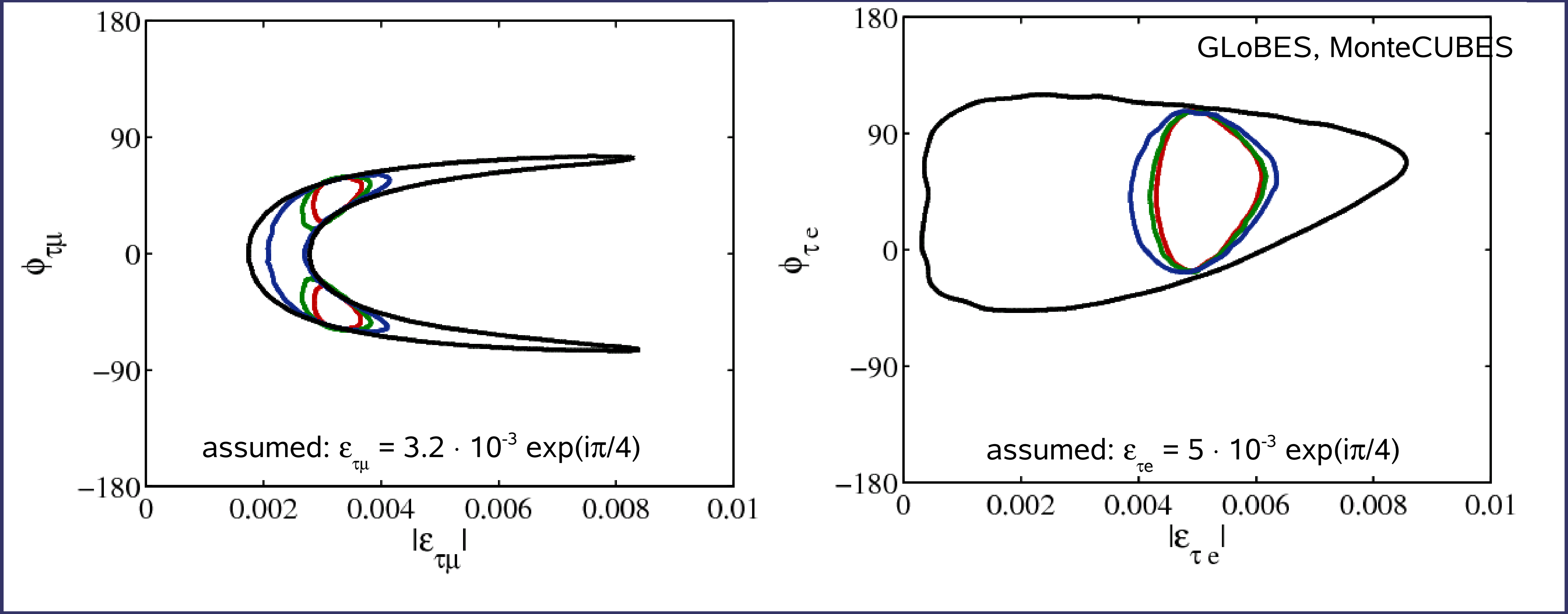
Measurement of non-unitarity?

S. A., Blennow, Fernandez-Martinez, Lopez-Pavon ('09)



ν-Factory (IDS setup) + near Emulsion Cloud Chamber (ECC) τ-detector (10 kton, 1 kton, 100 tons, no)

- NF could in fact really measure non-unitarity parameters and determine the source of CP violation! (No 'confusion problem'!)

Can there be large NSIs in matter?

$$\mathcal{L}_{NSI} = 2\sqrt{2} G_F \, \epsilon^{f}_{\alpha\beta} \, (\overline{\nu}_{\alpha \mathrm{L}} \, \gamma^{\delta} \, \nu_{\beta \mathrm{L}})(\overline{f}_{\mathrm{L,R}} \, \gamma_{\delta} \, f_{\mathrm{L,R}})$$

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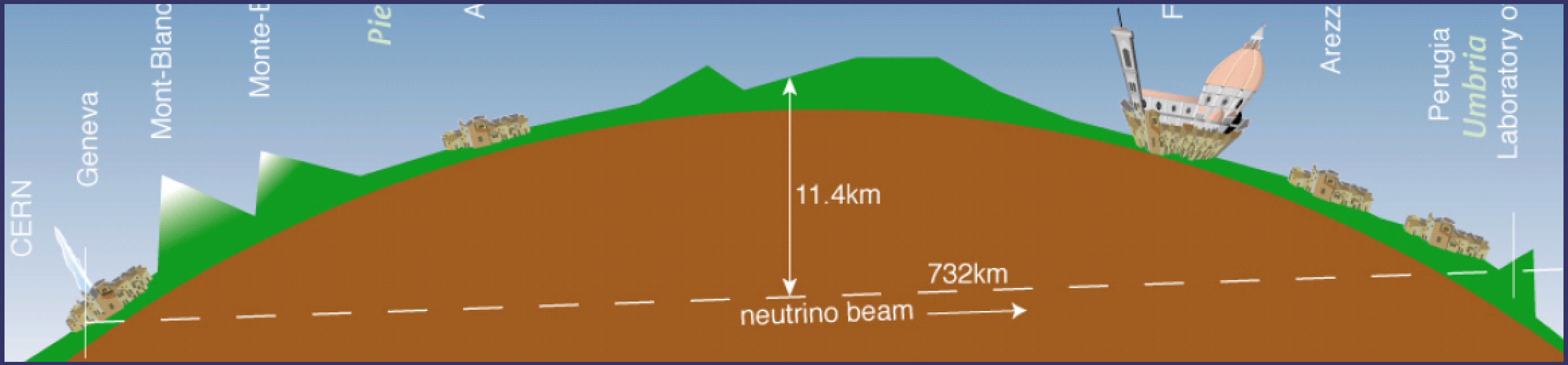
Non-Standard ν Interactions (NSIs)

... a parameterisation of BSM physics effects (local QFT, stable ν's, ...)



New physics effects on propagation through matter:

$$\mathcal{L}_{NSI} = 2\sqrt{2}G_F\, \epsilon^{f}_{\alpha\beta}\, (\overline{\nu}_{\alpha \mathrm{L}}\, \gamma^{\delta}\, \nu_{\beta \mathrm{L}})(\overline{f}_{\mathrm{L,R}}\, \gamma_{\delta}\, f_{\mathrm{L,R}})$$

Works on NSIs from many people: J. Barranco, Z. Berezhiani, S. Bergmann, M. Blennow, M. Campanelli, S. Davidson, A. Estaban Pretel, A. Friedland, A. M. Gago, M. C. Gonzalez Garcia, S. Goswami, Y. Grossman, A. Gusso, M. M. Guzzo, P. C. de Holanda, M. Honda, P. Huber, T. Kajita, N. Kitizawa, P. Ko, J. Kopp, M. Lindner, C. Lunardini, M. Maltoni, D. Meloni, H. Minakata, O. G. Miranda, C. A. Moura, S. Nakayama, E. Nardi, Y. Nir, H. Nunokawa, T. Ohlsson, N. Okamura, T. Ota, C. Pena Garay, N. C. Ribero, N. Rius, A. Romanino, A. Rossi, A. Santamaria, J. Sato, T. Schwetz, J. Skrotzki, H. Sugiyama, T. Takeuchi, F. Terranova, W. J. C. Teves, S. Uchinami, J. W. F. Valle, M. Westerberg, W. Winter, N. Yamashita, O. Yasuda, H. Zhang and R. Zukanovich Funchal (incomplete list: appologies!)

Large NSIs in matter? - Direct bounds

$$\mathcal{L}_{NSI} = 2\sqrt{2} G_F \, \epsilon^{f}_{\alpha\beta} \, (\overline{\nu}_{\alpha \mathrm{L}} \, \gamma^{\delta} \, \nu_{\beta \mathrm{L}})(\overline{f}_{\mathrm{L,R}} \, \gamma_{\delta} \, f_{\mathrm{L,R}})$$

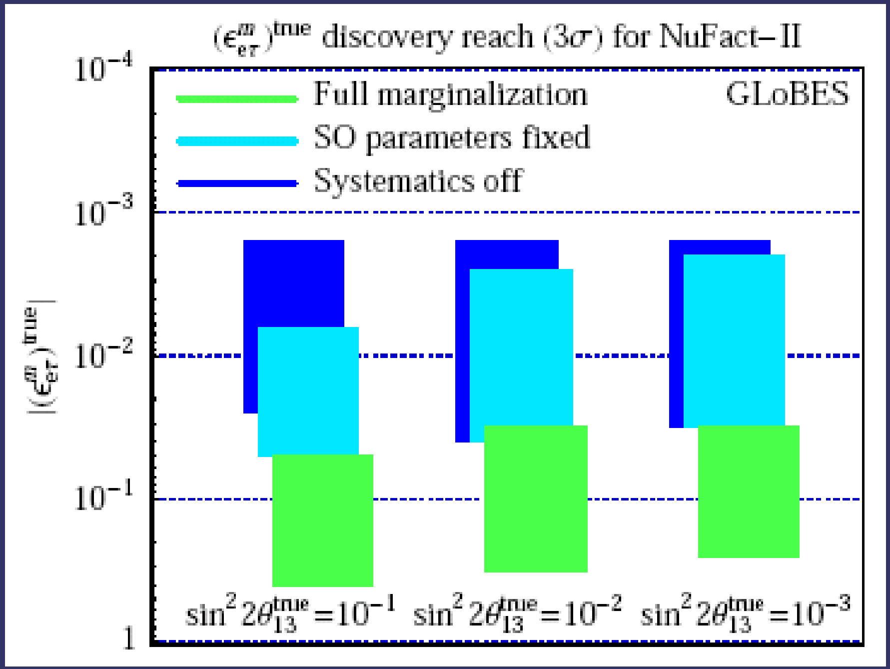
➲ 'Direkt 'bounds on NSIs with matter (example: with electrons)

$\lvert\varepsilon^{m}_{ee}\rvert < 0.7$	$\lvert\varepsilon^{m}_{e\mu}\rvert < 0.1$	$\lvert\varepsilon^{m}_{e\tau}\rvert < 0.5$
*	$\lvert\varepsilon^{m}_{\mu\mu}\rvert < 0.03$	$\lvert\varepsilon^{m}_{\mu\tau}\rvert < 0.1$
*	*	$\lvert\varepsilon^{m}_{\tau\tau}\rvert < 7$

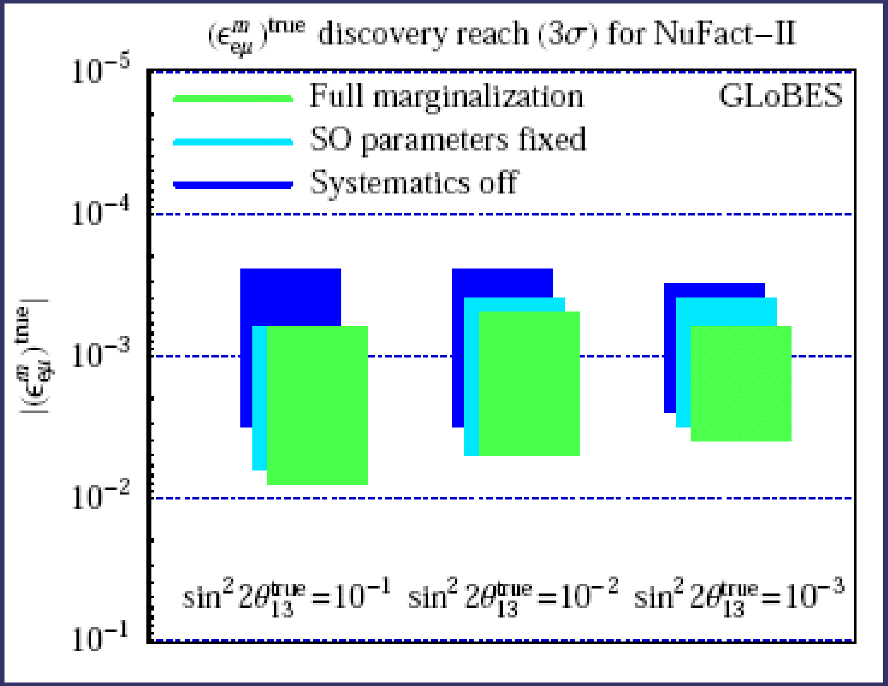
Davidson, Pena-Garay, Rius, Santamaria ('03,'09),
Barranco, Miranda, Moura, Valle ('05,'07)
Biggio, Blennow, Fernandez-Martinez ('09)

➲ Several 'direct' bounds very weak!

Sensitivities of Neutrino Factory to NSIs in matter



Plots from:
Kopp, Lindner, Ota ('07)



Early works::
Huber, Valle ('01),
Ota, Sato, Yamashita ('01),
Huber, Schwetz, Valle ('02), ...

➲ Sensitivities for $\varepsilon^m_{\alpha\beta}$ (NSIs) up to $O(10^{-2})$ ... $O(10^{-3})$

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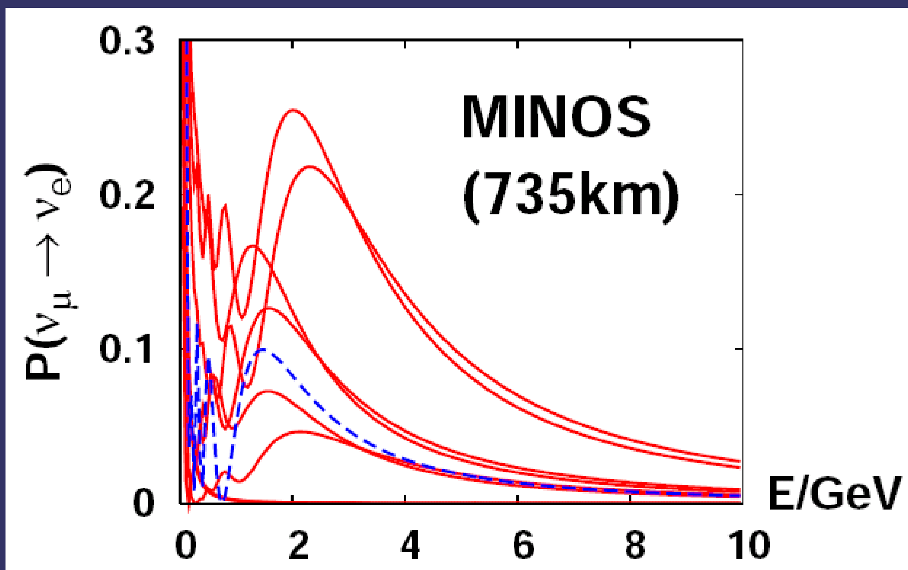
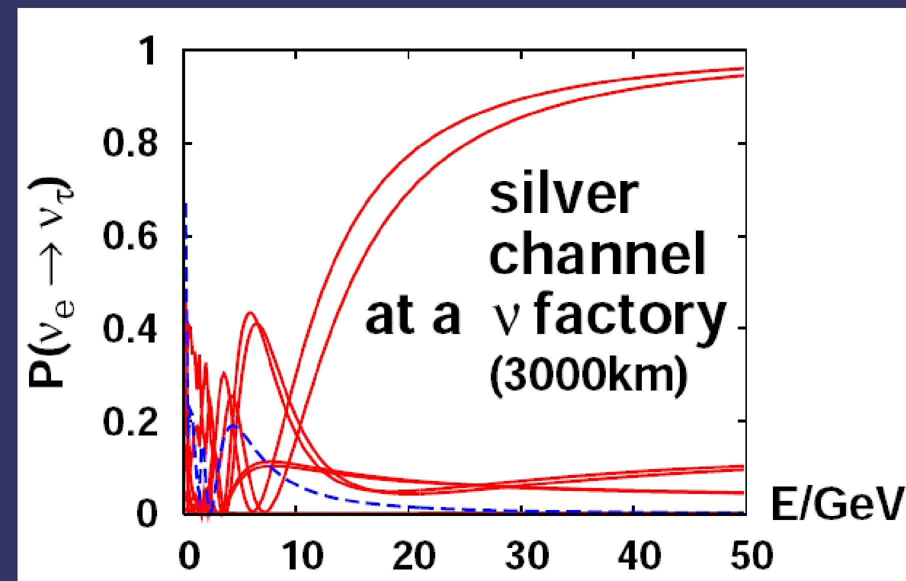
Large NSIs in matter? - Effects ...





$\varepsilon^m_{e\tau}$, ε^m_{ee} and $\varepsilon^m_{\tau\tau}$ = O(1)

Examples from:
Kitazawa, Sugiyama,Yasuda ('06)

- Large O(1) NSIs with matter would have dramatic effects!
- Can such large NSIs be realised in explicit models for BSM physics?

S.A., J. P. Baumann, E. Fernandez-Martinez (0807.1003)
M.B. Gavela, D. Hernandez, T. Ota, W. Winter (0809.3451)

Large NSIs in matter?

- To address this question we are looking for:
  - $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ – gauge invariant formulation of NSIs
  - Explicit SM extensions (not effective theories)

'Strategy' to generate large NSIs

- We search for gauge invariant extensions of the SM which lead to NSIs with matter and satisfy the following conditions:

  - no new 4cFI are generated at the same level (already quite constrained!)
  - NSIs with matter are generated at tree-level
  - Higgs mechanism is responsible for EWSB
  - no cancellations between diagrams with different messenger particles to avoid constraints

- Systematic scan over SM extensions ...

S.A., J. P. Baumann, E. Fernandez-Martinez (0807.1003)

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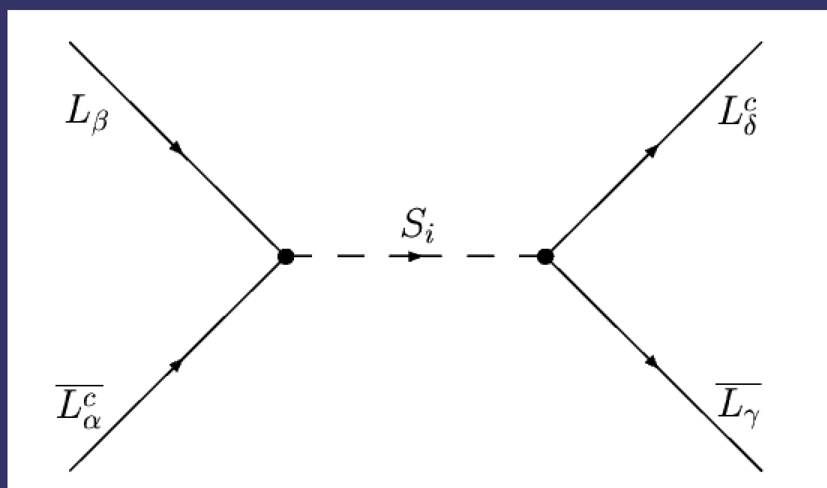
Large NSIs? - dim=6 operators

- At d=6 we found **two possibilities to satisfy our search criteria**:

Possibility 1: singly charged scalar fields → antisymmetric d=6 operator



$$\rightarrow \quad \mathcal{L}^{d=6,as}_{NSI} = c^{d=6,as}_{\alpha\beta\gamma\delta} (\overline{L^c}_\alpha \cdot L_\beta)(\bar{L}_\gamma \cdot L^c_\delta)$$

A. Bilenky, A. Santamaria ('93),
F. Cuypers, S. Davidson ('93)

Bounds:
(from rare decays,
μ and τ decays,
CKM unitarity, ...)

$$|\varepsilon^{m,e_L}_{\mu\mu}| < 8.2 \cdot 10^{-4}$$
$$|\varepsilon^{m,e_L}_{\tau\tau}| < 8.4 \cdot 10^{-3}$$
$$|\varepsilon^{m,e_L}_{\mu\tau}| < 1.9 \cdot 10^{-3}$$

Remark: Also NSIs at the source and/or detector!

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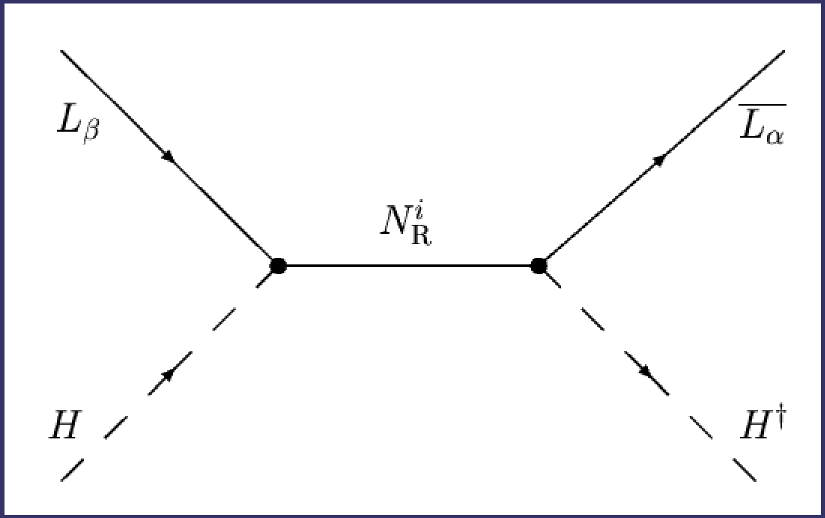
Large NSIs? - dim=6 operators

- **Possibility 2:** fermionic singlets $\rightarrow$ d=6 operator contribution to neutrino kinetic terms



$$\rightarrow \quad \mathcal{L}^{d=6}_{kin} = -c^{d=6,kin}_{\alpha\beta} (\bar{L}_\alpha \cdot H^\dagger)\, i\partial\!\!\!/ \,(H \cdot L_\beta)$$

after canonical normalisation:
non-unitary leptonic mixing matrix

... has already been discussed earlier in my talk

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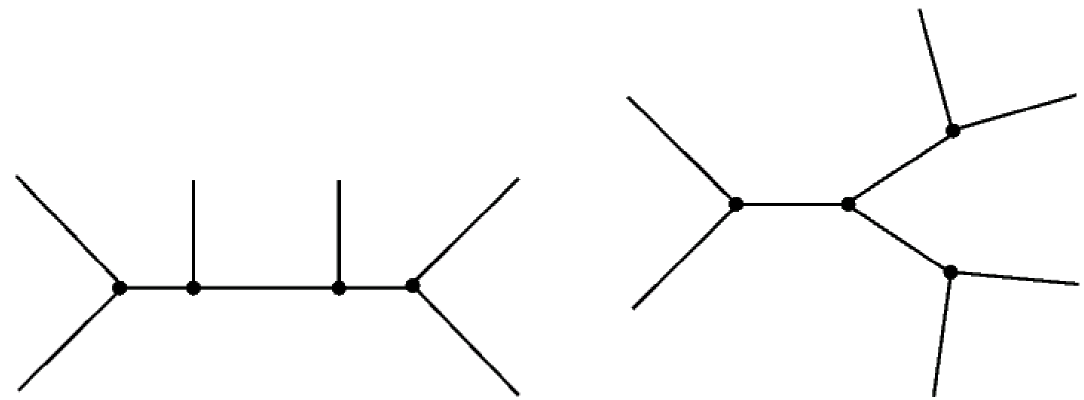
Large NSIs? - dim=8 operators

- At d=8, more possibilities to satisfy our rearch criteria because:
  - one can add two Higgs fields H to break the symmetry between ν_α and l_α (which helps to avoid 4cFIs)
  - Systematic treatment: Three topologies to generate gauge invariant d=8 operators with external fields $\bar{L}\ L\ \bar{f}\ f\ H\ H^*$ ...



(a) Topology 1 (b) Topology 2 (c) Topology 3

Large NSIs possible from d=8 operators?

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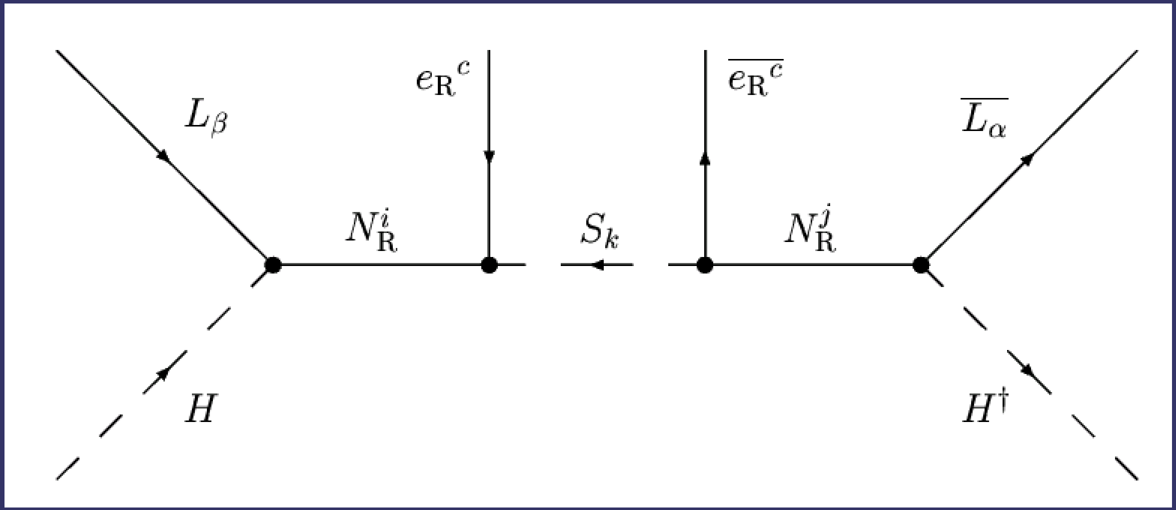
Large NSIs? - dim=8 operators

- At d=8 level we found **three classes of possibilities**:

  Class I: 2 x coupling of L and H to a fermionic singlet N

e.g.:



Remark: also for L or quarks as external fields f

$$\mathcal{L}_{NSI}^{d=8,I} = c_{\alpha\beta}^{d=8,f,I}\,(\overline{L_\alpha}\cdot H^\dagger)\, f^c\,\overline{f^c}\,(H\cdot L_\beta)$$

Note: At eff. operator level, this would allow for large NSIs with matter!

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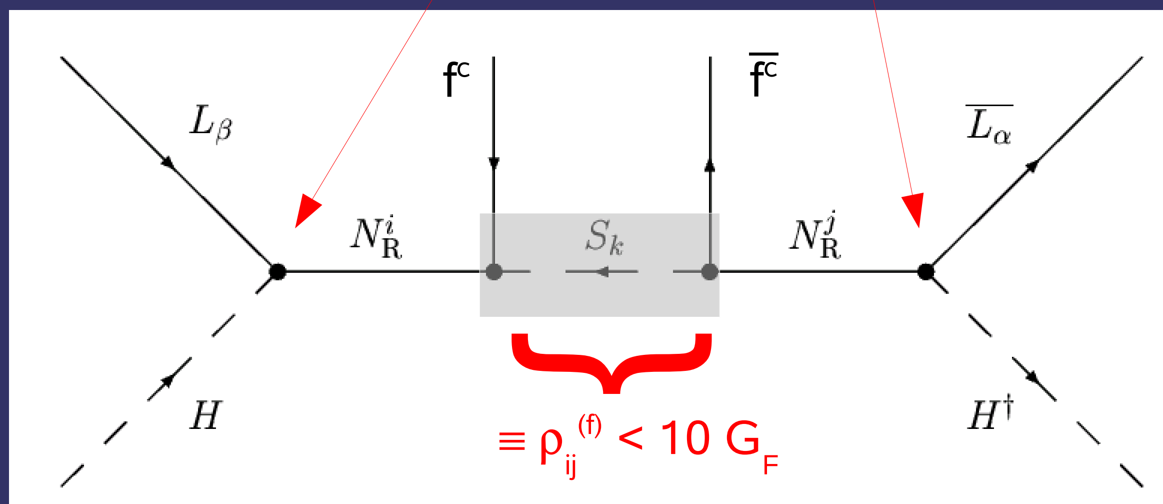
Large NSIs? - dim=8 operators

- Bounds from relation to d=6 operator which modifies neutrino kinetic terms

Bounds from d=6 (kin):

$$v|Y_{\alpha i}/M_i| < v\sqrt{|c^{d=6,kin}_{\alpha\alpha}|}$$



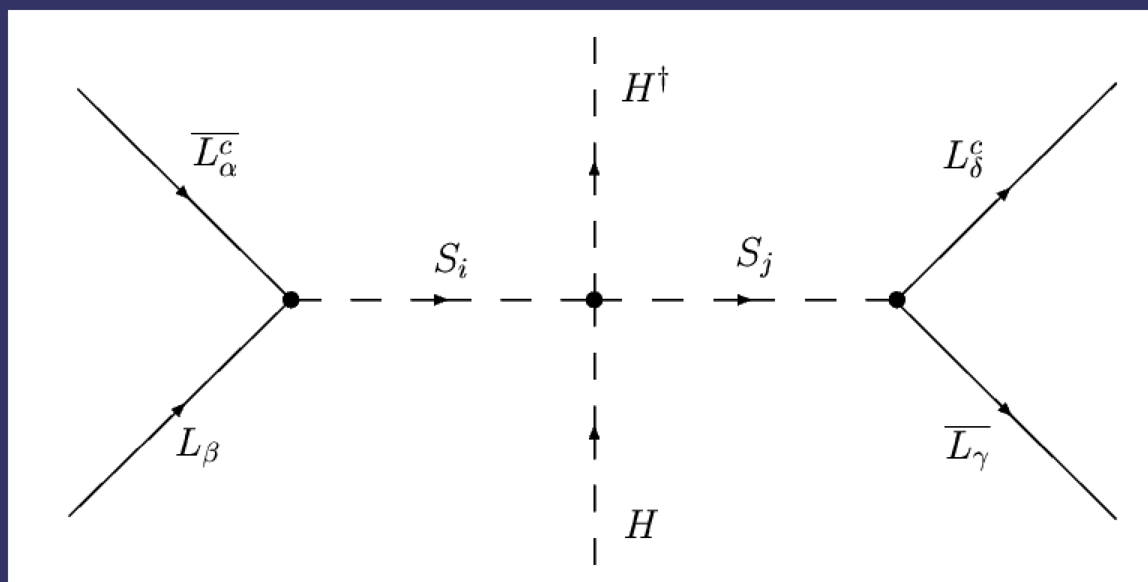
$$|\varepsilon^{m,f}_{\alpha\beta}| < \begin{pmatrix} 1.4\cdot 10^{-3} & 6.4\cdot 10^{-4} & 1.1\cdot 10^{-3} \\ 6.4\cdot 10^{-4} & 5.8\cdot 10^{-4} & 7.3\cdot 10^{-4} \\ 1.1\cdot 10^{-3} & 7.3\cdot 10^{-4} & 1.9\cdot 10^{-3} \end{pmatrix} \frac{\hat{\rho}^{(f)}}{G_F}$$

S.A., J. P. Baumann,
E. Fernandez-Martinez (0807.1003)

Large NSIs?

- **Class II:** 2 x antisymmetric coupling of $\bar{L}\, L$ to singly charged scalars S

e.g.:



$$\mathcal{L}^{d=8}_{NSI,II} = c^{d=8,f,II}_{\alpha\beta\gamma\delta} (\overline{L^c}_\alpha \cdot L_\beta)(\bar{L}_\gamma \cdot L^c_\delta)(H^\dagger H)$$

Remark: after EWSB

$$v^2/2\ \left(\overline{L}^c_\alpha i\sigma_2 L_\beta\right)\left(\overline{L}_\gamma i\sigma_2 L^c_\delta\right)$$

(same bounds as for anti-symmetric d=6 op.)

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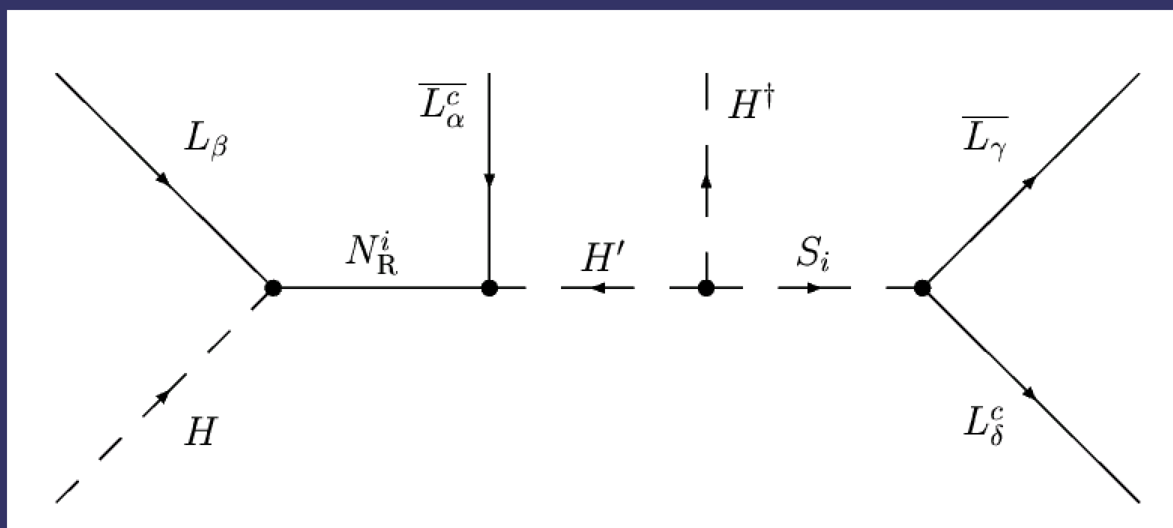
Large NSIs?

- **Class III:** mixed case: L and H to N and $\bar{L}$ L to singly charged scalars S



$$\mathcal{L}^{d=8}_{NSI,III} = c^{d=8,f,III}_{\alpha\beta\gamma\delta}(H^\dagger \bar{L}^c_\alpha)(L_\beta \cdot H)(\bar{L}_\gamma \cdot L^c_\delta)$$

Bounds from d=6 (kin):

$$v|Y_{\alpha i}/M_i| < v\sqrt{|c^{d=6,kin}_{\alpha\alpha}|}$$

and d=6 (anti-symm):

$$v|\lambda^i_{e\mu}/m_{S_i}| < 2.9 \cdot 10^{-2}$$

$$v|\lambda^i_{e\tau}/m_{S_i}| < 9.2 \cdot 10^{-2}$$

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Remark: only for leptons; bounds again $\varepsilon^m_{\alpha\beta} < 10^{-2}$

Remark: Operators of type I, II and III form a **basis** for d=8 operators which select neutrinos and avoid tree-level 4cFIs

Large NSIs? - Results

- In explicit SM extensions (and under the assumtions we have made)

  $\rightarrow$ NSIs with matter are much more constrained than in many phenomenological studies ($\varepsilon^{m}_{\alpha\beta} < 10^{-2}$)!

  $\rightarrow$ In addition to NSIs with matter, NSIs at the source and detector are generated as well.

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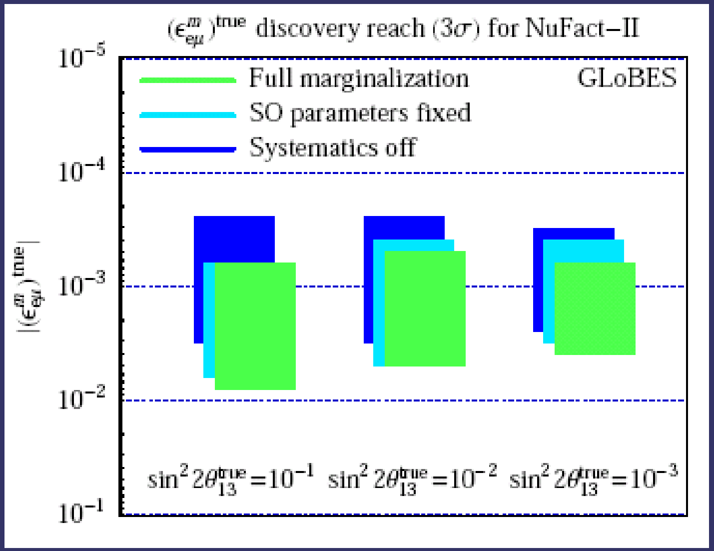
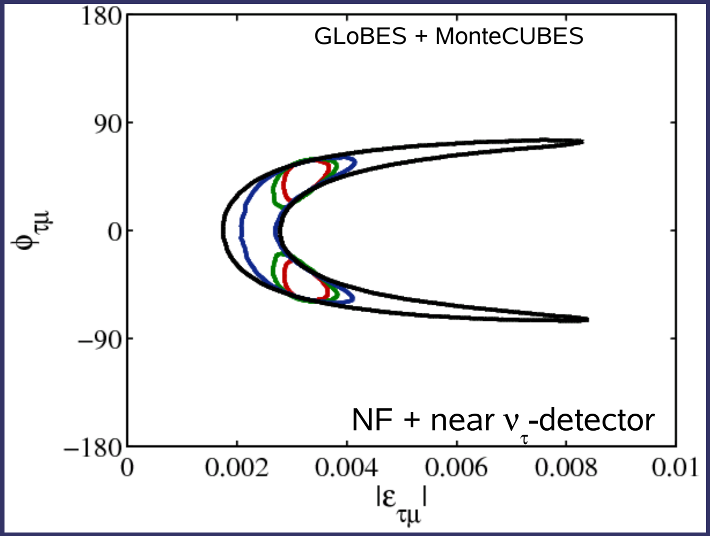
Summary and Conclusions

- Non-unitarity of leptonic mixing matrix: typical signal of 'new physics' in the lepton sector. In 'MUV': $(N N^{+} - 1)_{\alpha\beta} \sim \varepsilon^{s,d,m}_{\alpha\beta} < 10^{-2} \dots 10^{-3}$
- Non-standard neutrino interactions: parameterisation of new physics effects; in gauge invariant SM extensions $\Rightarrow \varepsilon^{m}_{\alpha\beta} < O(10^{-2})$, $\varepsilon^{m}_{\tau\tau} < 0.2$

... compared to expected sensitivities
of a possible future neutrino factory
of up to $\varepsilon_{\alpha\beta} \sim 10^{-2} \dots 10^{-3} \dots 10^{-4}$ (or better?)





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