Non-unitarity & Non-standard Interactions (NSIs)

- Part 1: Non-unitarity (theory) – S. A.
- Part 2: Non-unitarity (bounds) – Mattias Blennow
- Part 3: NSIs (theory) – Enrique Fernandez-Martinez
- Part 4: NSIs (bounds) – Toshihiko Ota

Minsis workshop, UA Madrid, '09

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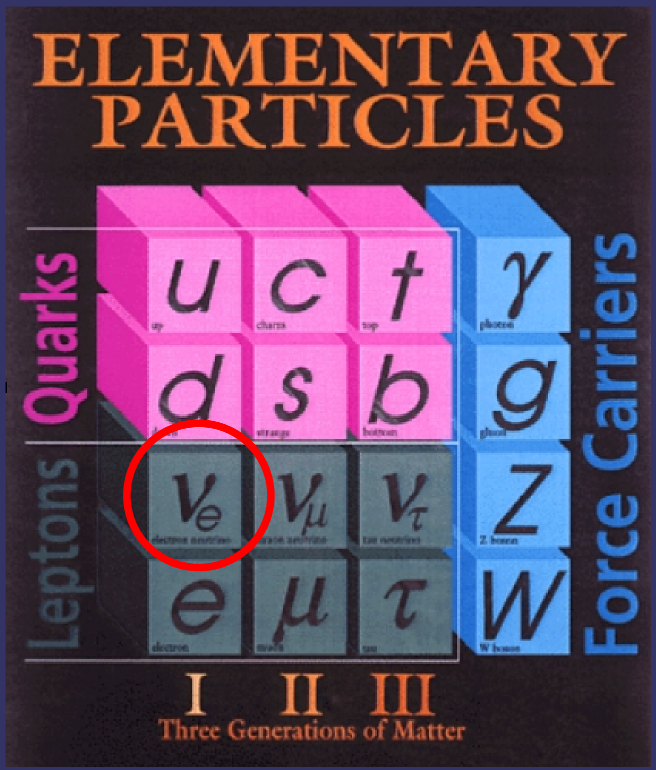
MPI für Physik (Munich)

Overview

- Origin of Non-Unitarity; minimal scheme (MUV)
- Recent study: Non-unitarity of U_{PMNS} and leptogenesis?

Neutrinos in 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 elementary particles via the Higgs mechanism (exception: neutrinos remain massless)

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

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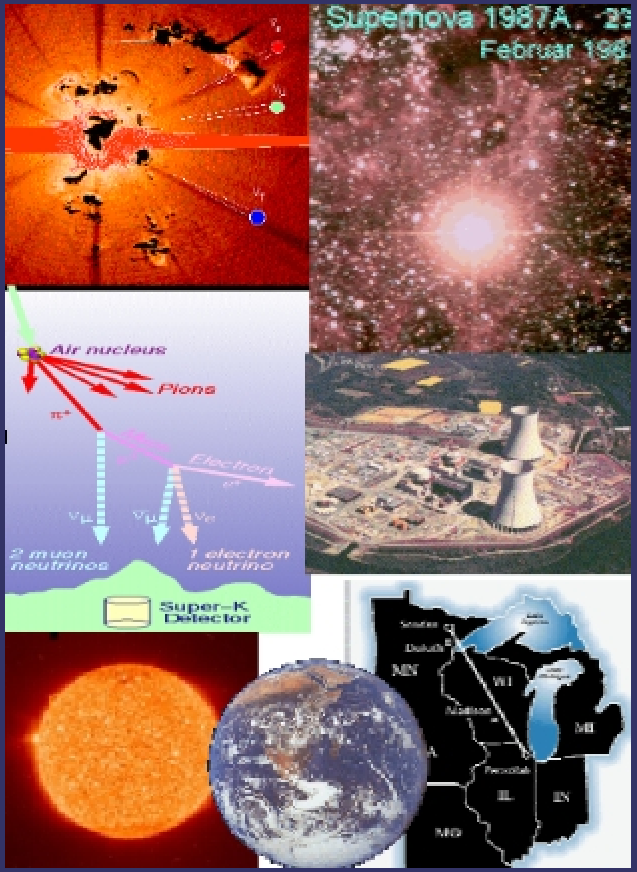
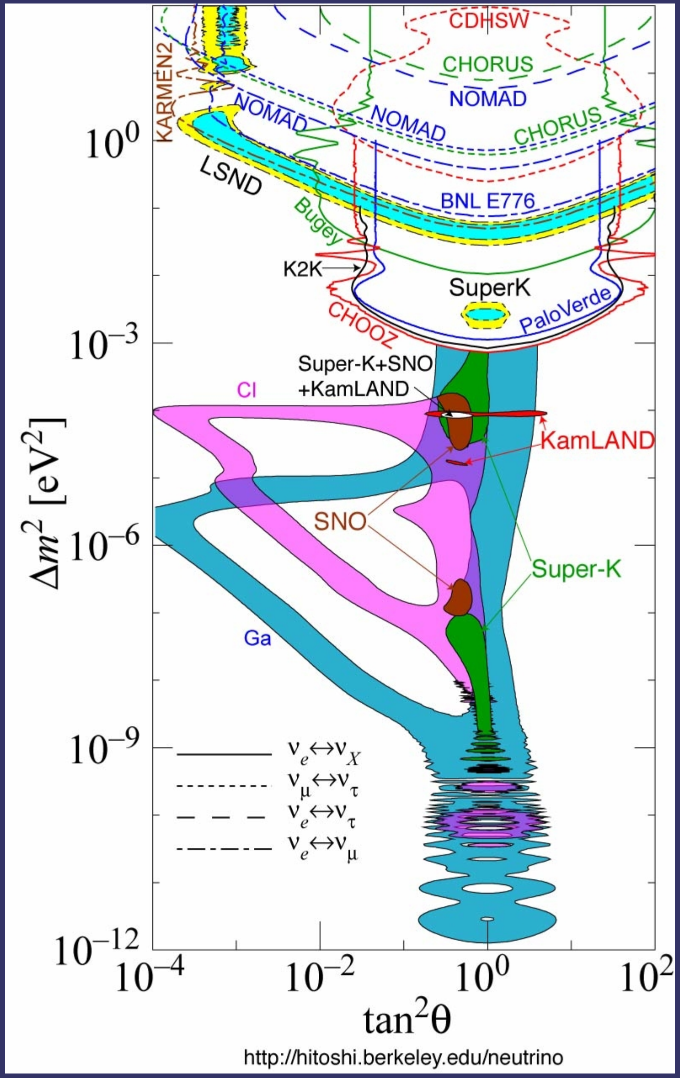
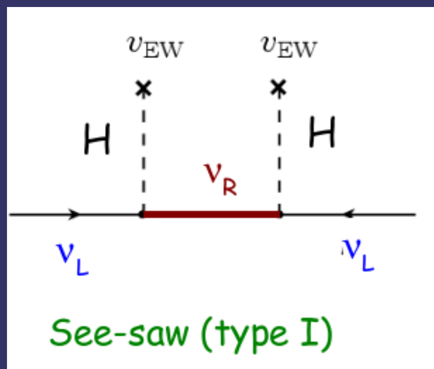
However: Evidence for ν masses!



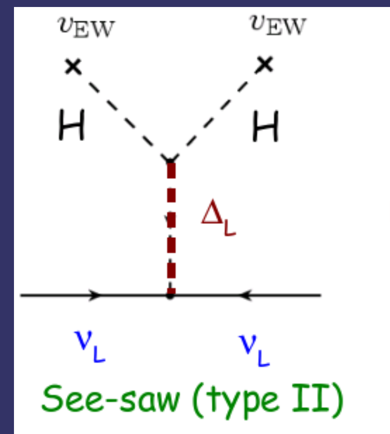


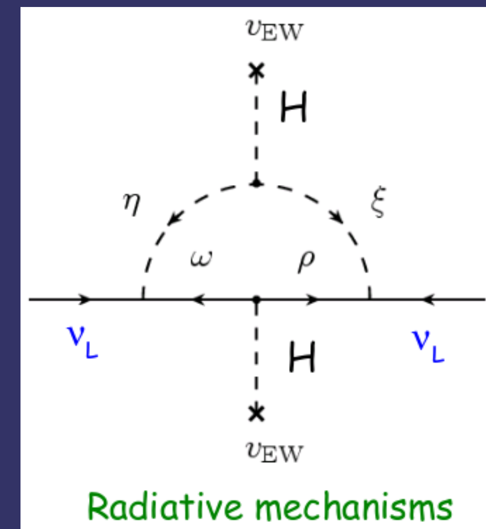
- Strong evidence for ν-oscillations:
  $\Rightarrow$ Neutrinos have mass
  $\rightarrow$ leptonic mixing matrix
  $\rightarrow$ new ν-interactions (mechanism of mass generation)

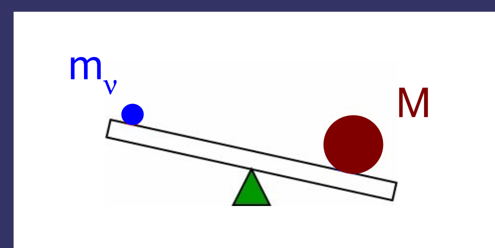
Origin of neutrino masses?



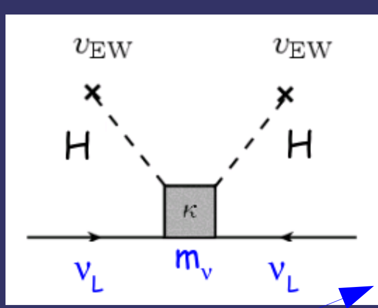
(or type III)







Smallness of m_ν: Seesaw mechanism?



quite model independent:
unique dim. 5 Operator

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

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

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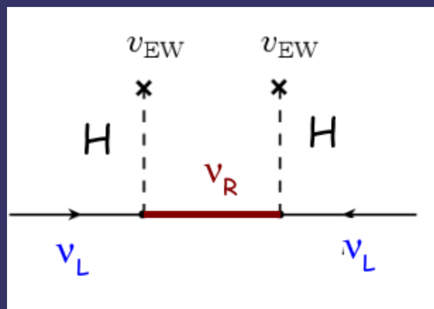
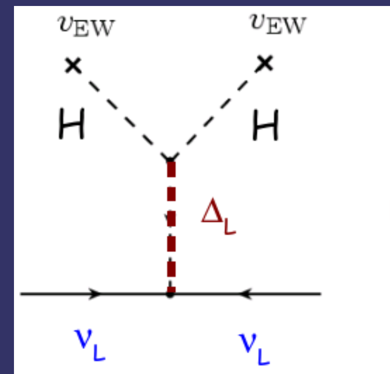
Origin of neutrino masses?

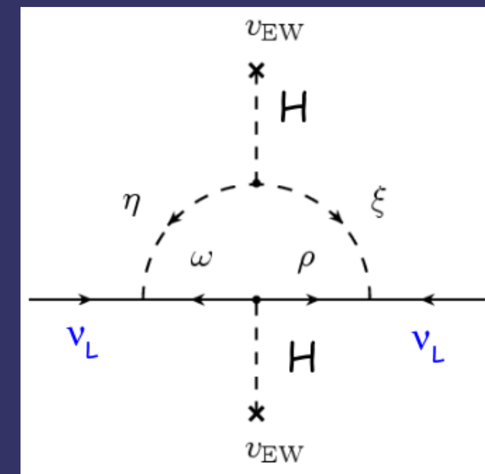


See-saw (type I)

(or type III)



See-saw (type II)



Radiative mechanisms

Smallness of m_ν:

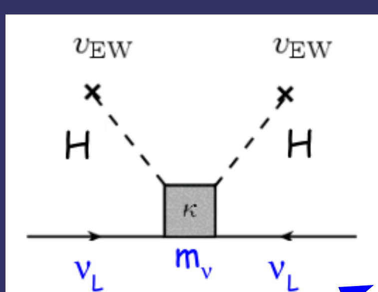
... or because lepton number symmetry is violated only by small amount?

Example: so-called 'Inverse seesaw'

$$M_\nu = \begin{pmatrix} 0 & D_N^T & 0 \\ D_N & 0 & X_N^T \\ 0 & X_N & \mu \end{pmatrix}$$

small

Mohapatra, Valle ('86)



quite model independent: unique dim. 5 Operator

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

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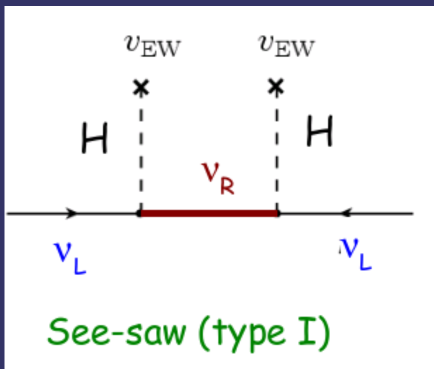
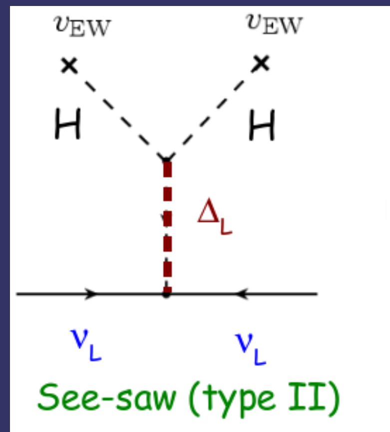
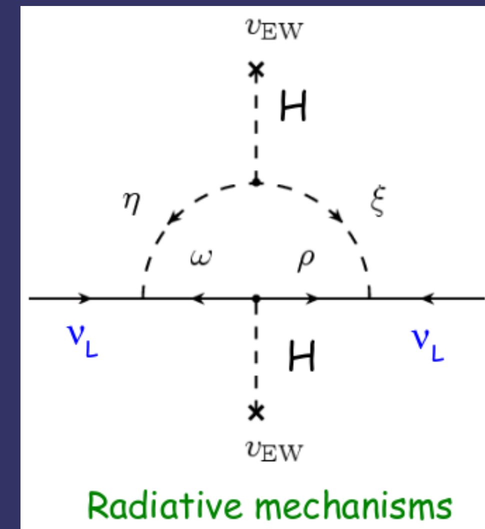
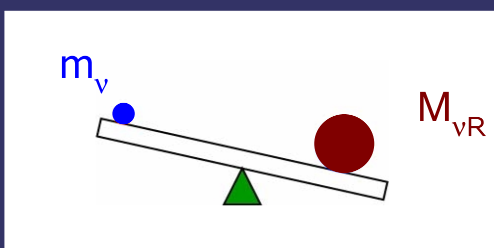
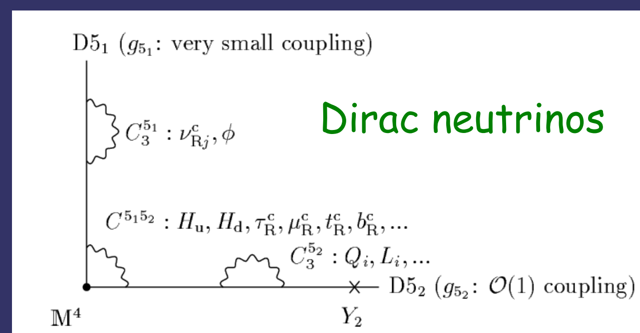
Origin of neutrino masses?

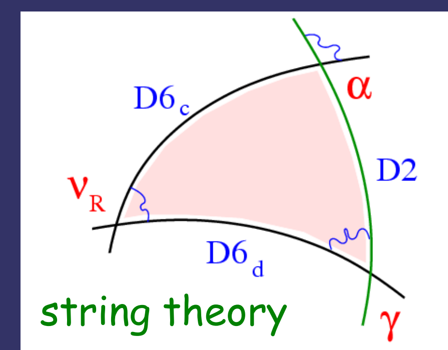


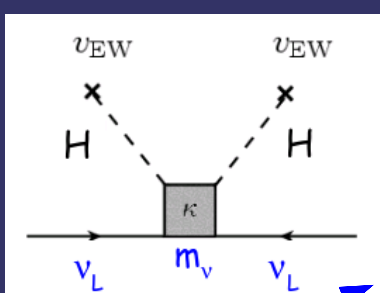












quite model independent:
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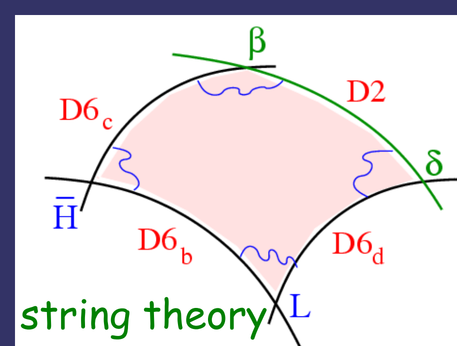
$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta}\, \left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) + h.c.$$



Unknown:
- **which mechanism?**
- **at which scale?**
- **which new interactions (effects beyond m_ν)?**

Status: Neutrino masses & mixing

- Known:
  - (At least) two of the light neutrinos are massive
  - Large mixing

- Unknown:
  - Which mechanism generates the neutrino masses? Dirac or Majorana?
  - At which scale?
  - Which additional interactions are generated (effects beyond ν-masses)

→ chance to distinguish ν-mass mechanisms

Since new interactions in the lepton sector are required (to generate ν-masses):

Is the (effective low energy) leptonic mixing matrix unitary?

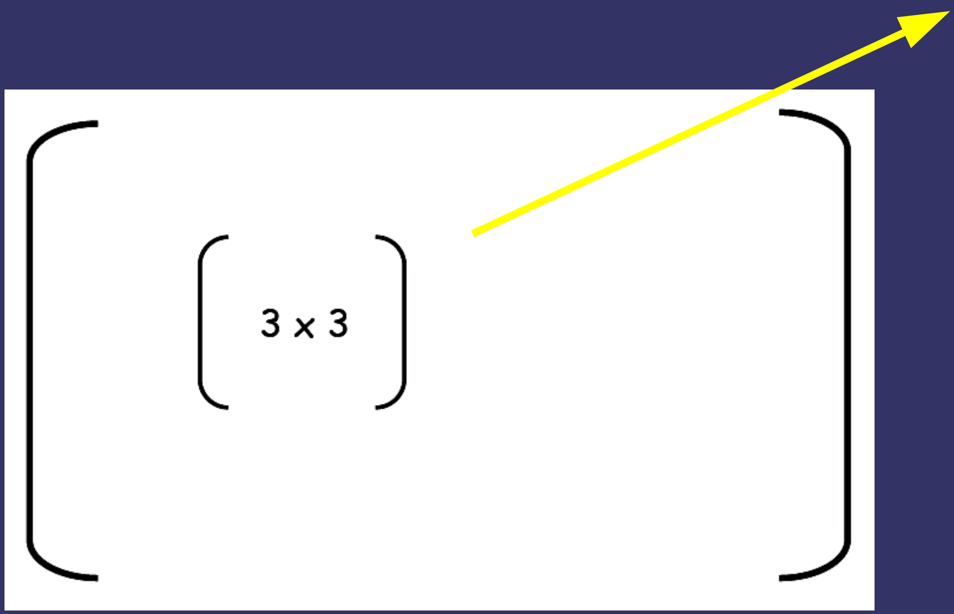
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$U\,U^+ = 1$?

Non-unitarity (theory)

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_{PMNS} non-unitary

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

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MPI für Physik (Munich)

Non-unitary leptonic mixing

- Lagrangian in the mass basis ...

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

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

modification in neutral current interaction:
will be justified later ...

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... now we change to the flavour basis

- Field transformation: $\nu_\alpha = N_{\alpha i}\, \nu_i$

non-canonical kin. terms

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

Non-unitary leptonic mixing $\leftrightarrow$ Non-canonical kinetic term

Non-unitary leptonic mixing

Gauge invariant non-canonical kinetic term in the SM: e.g.

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

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

conserves L!

Effects after EW symmetry breaking (in mass basis):

non-unitary matrix N

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

in addition: modification in neutral current interaction

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

Non-unitary leptonic mixing

- Which neutrino mass mechanisms (or other SM extensions) lead to non-unitary leptonic mixing?

Non-unitarity and *neutrino masses* from heavy fermionic singlets

- Consider the SM + 'heavy' singlet fermions F^i as effective field theory:
  - 'heavy' = large mass compared to the energies of the experiment
  - effective theory: below the masses of the singlet fermions

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Non-unitarity and neutrino masses from heavy fermionic singlets

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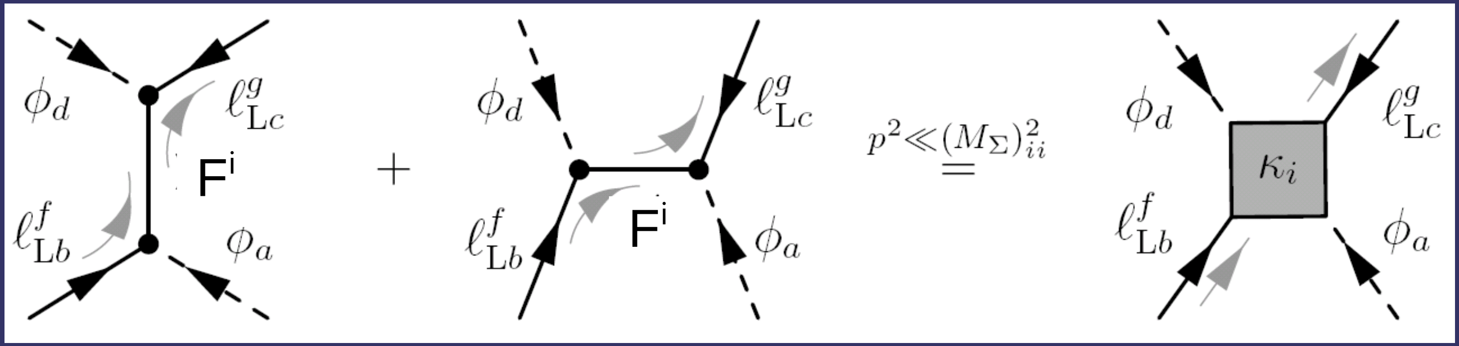
  - effective theory: below the masses of the singlet fermions

- At dimension 5 operator level:



violates L!

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Non-unitarity and neutrino masses from heavy fermionic singlets

- Consider the SM + 'heavy' singlet fermions F^i as effective field theory:
  - 'heavy' = large mass compared to the energies of the experiment
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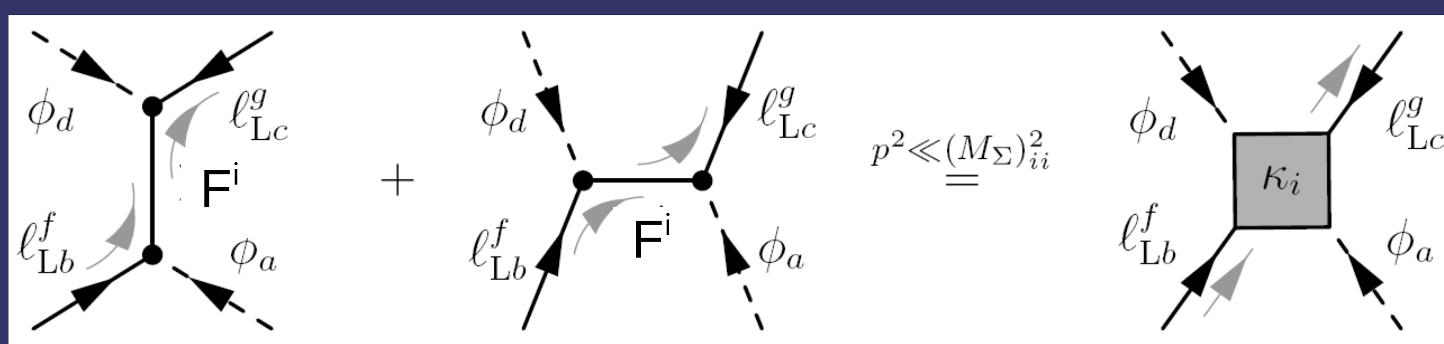
Weinberg ('79)

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

- At dimension 5 operator level:



violates L!

After EW symmetry breaking: $m_\nu \equiv -\frac{v^2}{2}\, c^{d=5}$

Seesaw (type I)

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Non-unitarity and neutrino masses from heavy fermionic singlets

- Consider the SM + 'heavy' singlet fermions F^i as effective field theory:
  - 'heavy' = large mass compared to the energies of the experiment
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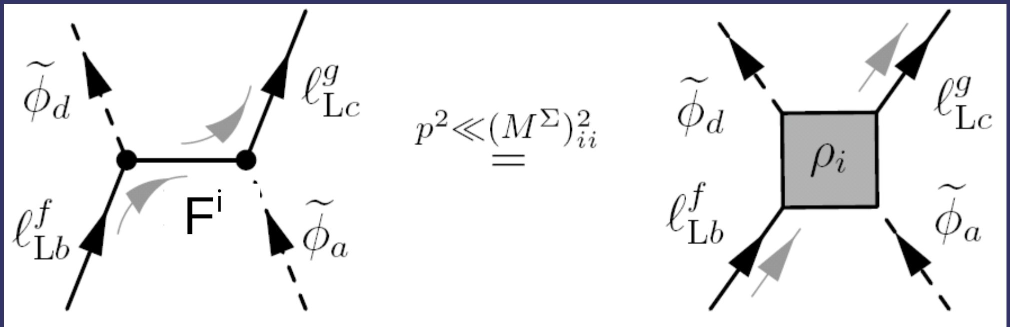
- At dimension 6 operator level:



conserves L!

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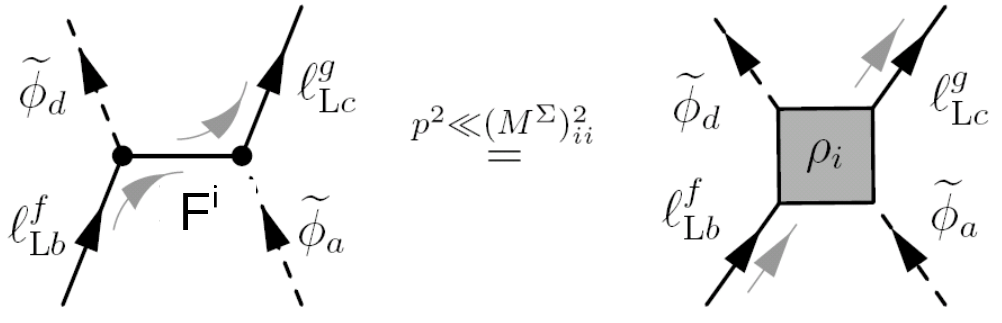
Non-unitarity and neutrino masses from heavy fermionic singlets

- Consider the SM + 'heavy' singlet fermions F^i as effective field theory:
  - 'heavy' = large mass compared to the energies of the experiment
  - effective theory: below the masses of the singlet fermions

- At dimension 6 operator level:

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



conserves L!

De Gouvea, Giudice, Strumia, Tobe ('01)
Broncano, Gavela Jenkins ('02)

After EW symmetry breaking: Non-unitarity

$$|NN^\dagger - 1|_{\alpha\beta} = \frac{v^2}{2}\,|c^{d=6}|_{\alpha\beta}$$

via non-canonical kin. terms for neutrinos!

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

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

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

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

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!

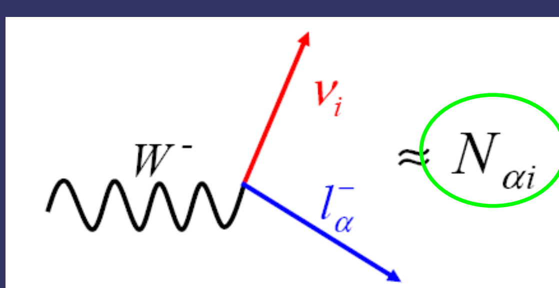
$$\delta\mathcal{L}^{d=6} = c^{d=6}_{\alpha\beta} \left(\overline{L}_\alpha \tilde{\phi}\right) i\partial\!\!\!/ \left(\tilde{\phi}^\dagger L_\beta\right)$$

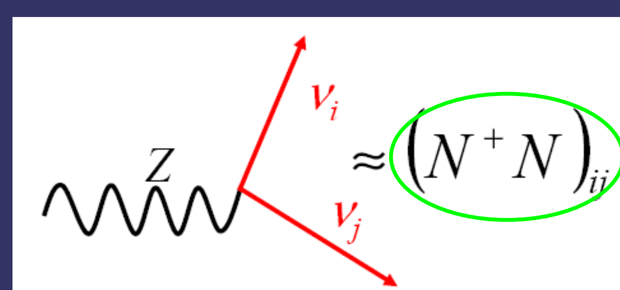
unique dim. 6 operator leading to non-can. kinetic terms for neutrinos only

conserves L!

Minimal unitarity violation:

All non-standard effects governed by (non-unitary) leptonic mixing matrix N





Consistent framework: Can now be confronted with experiment ...

→ talk by M. Blennow

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Non-Unitarity and Leptogenesis

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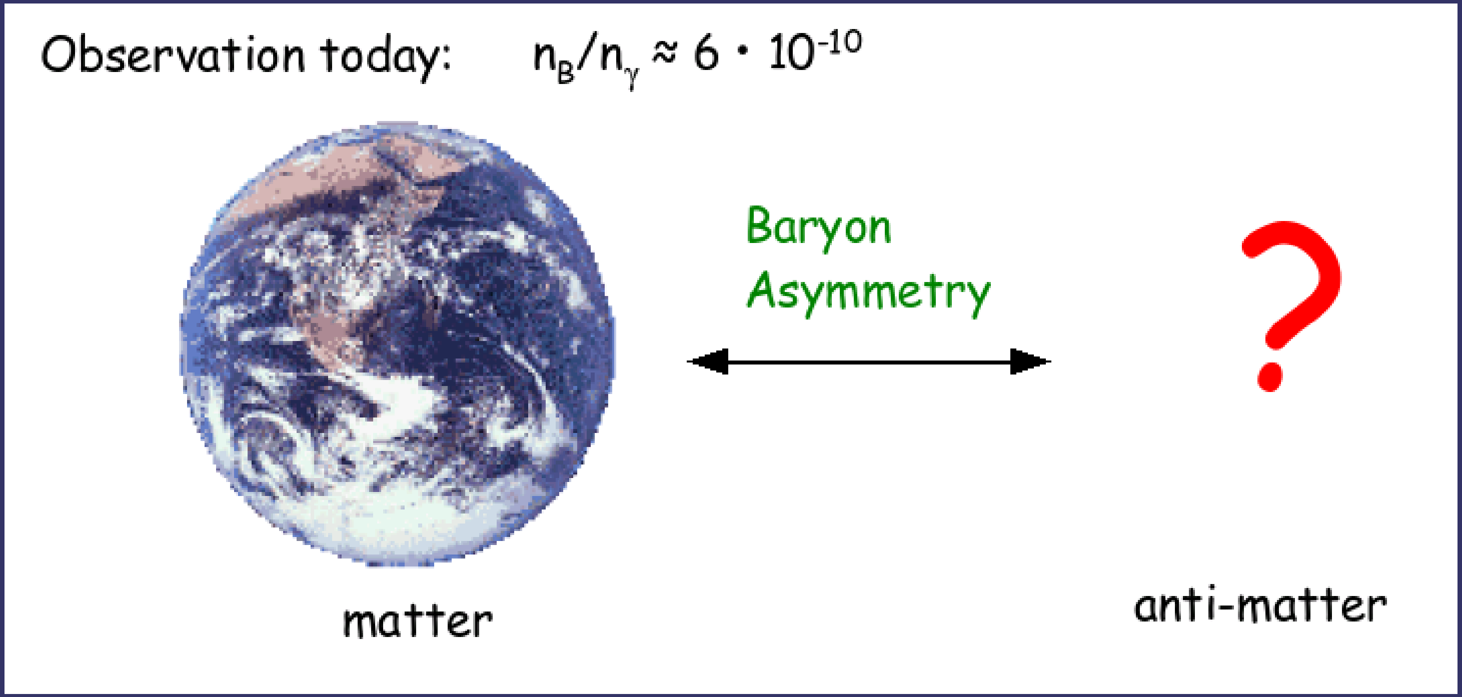
Non-Unitarity and Leptogenesis

- How does non-unitarity U_{PMNS} affect leptogenesis?
- *As we will see:* In 'low scale seesaw models' non-unitarity can lead to a strong enhancement of the decay asymmetries for leptogenesis!
- Can the non-unitarity of U_{PMNS} drive (testable) low scale leptogenesis?

Motivation: The baryon asymmetry of the universe



- How was the observed baryon asymmety of the universe (BAU) generated?

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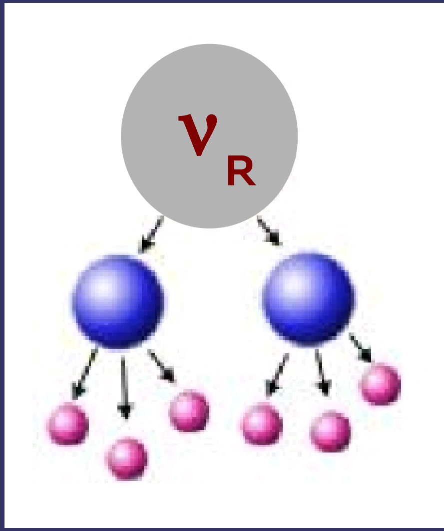
Leptogenesis: The mechanism

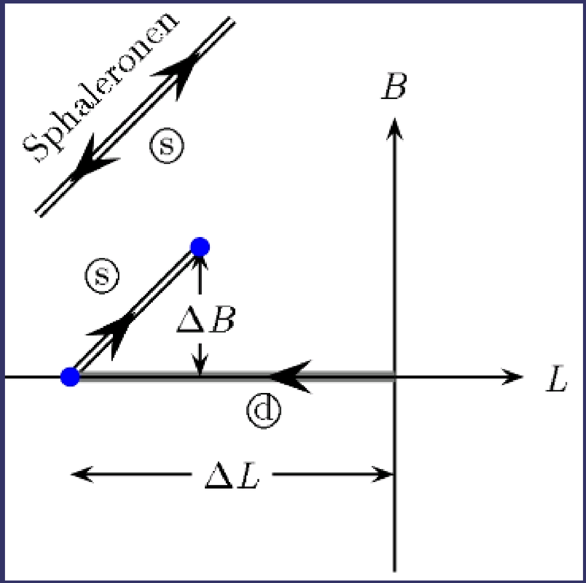
- Out-of-equilibrium decay of heavy fermionic singlets (RH neutrinos) in the early universe
  $\Rightarrow$ lepton asymmetries ΔL_α

Fukugita, Yanagida ('86)



- Sphaleron processes (conserve B – L but violate B and L) within SM (MSSM) partly convert lepton asymmetries into baryon asymmetry ΔB

Kuzmin, Rubakov, Shaposhnikov ('85)



SM + 'heavy' singlet fermions can explain neutrino masses <u>and</u> the baryon asymmetry!

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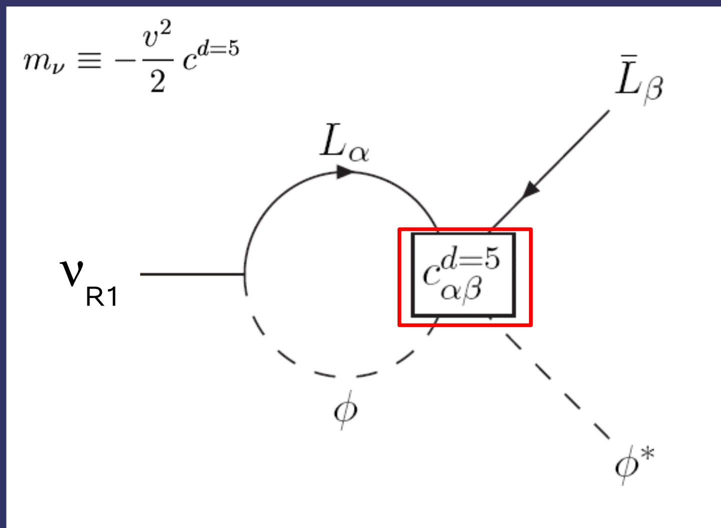
How much baryon asymmetry is produced?

$$\text{BAU} \propto \sum_\alpha \eta_\alpha \, \varepsilon_{1,\alpha}$$

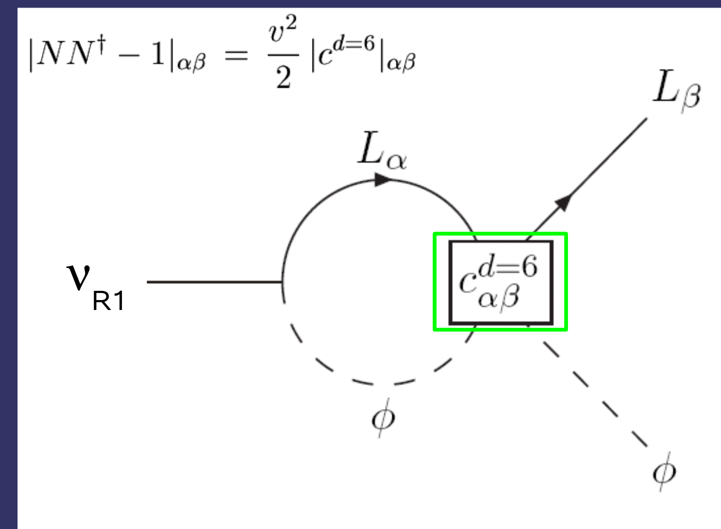
η_α: efficiency factors (from Boltzmann eqs., can be O(1))

$\varepsilon_{1,\alpha}$: decay asymmetries (ν_R^1 into L_α + H); interference of tree-level decay with loop-diagrams; assumed here: ν_R^1 dominates leptogenesis

Decay Asymmetries and Non-Unitarity (in effective theory)



related to neutrino masses!



related to non-unitarity!

$$\varepsilon_{1,\alpha} \simeq \frac{1}{8\pi (YY^\dagger)_{11}} \sum_\beta \left\{ \mathrm{Im}\left[-\frac{3M'}{2} Y^*_{1\alpha}\, c^{d=5}_{\alpha\beta}\, Y^\dagger_{\beta 1} + M'^2\, Y_{1\alpha}\, c^{d=6}_{\alpha\beta}\, Y^\dagger_{\beta 1} \right] \right\}$$

assumed: ν_{R1} dominates; $M' = M_{\nu R1} << M_{\nu R2}, M_{\nu R3}$

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

Explicit example: minimal scenario

'Lepton number' symmetry allowed (leading order)

Lepton numbers
L_f: 1, N_1: 0, N_2: +1, N_3:-1

$$Y_N = \begin{pmatrix} 0 & 0 & 0 \\ y_e & y_\mu & y_\tau \\ 0 & 0 & 0 \end{pmatrix} \quad , \quad M^N = \begin{pmatrix} M' & 0 & 0 \\ 0 & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

Non-unitarity!

$$c^{d=6}_{\alpha\beta} = \frac{y^*_\alpha y_\beta}{M^2}$$

unsuppressed by symmetry

'Lepton number' breaking terms (L breaking small)

$$Y_N = \begin{pmatrix} \mu'_e & \mu'_\mu & \mu'_\tau \\ y_e & y_\mu & y_\tau \\ \mu_e & \mu_\mu & \mu_\tau \end{pmatrix} \quad , \quad M^N = \begin{pmatrix} M' & \mu'_4 & \mu'_5 \\ \mu'_4 & \mu_4 & M \\ \mu'_5 & M & \mu_5 \end{pmatrix}$$

$$c_{\alpha\beta}^{d=5} \leftrightarrow m_\nu$$

suppressed by symmetry

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Explicit example: minimal scenario

'Lepton number' symmetry allowed (leading order)

$$Y_N = \begin{pmatrix} 0 & 0 & 0 \\ y_e & y_\mu & y_\tau \\ 0 & 0 & 0 \end{pmatrix}, \quad M^N = \begin{pmatrix} M' & 0 & 0 \\ 0 & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

Non-unitarity!

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$$c_{\alpha\beta}^{d=5} \leftrightarrow m_\nu$$

suppressed by symmetry

$$\varepsilon_{1,\alpha} \simeq \frac{1}{8\pi (YY^\dagger)_{11}} \sum_\beta \left\{ \mathrm{Im} \left[-\frac{3M'}{2} Y^*_{1\alpha} c^{d=5}_{\alpha\beta} Y^\dagger_{\beta 1} + M'^2 Y_{1\alpha} c^{d=6}_{\alpha\beta} Y^\dagger_{\beta 1} \right] \right\}$$

The d=6 contribution (→ non-unitarity) dominates flavoured decay asymmetries $\varepsilon_{1,\alpha}$! This is generic in 'low scale seesaw' with approximate lepton number!

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

Non-unitarity driven (testable) low scale leptogenesis?

... operating, e.g.,at TeV energies?

- Promising: Decay asymmetries can be strongly enhanced!
- Note: Flavour effects (different efficiencies for different flavours are crucial, since sum over $\varepsilon_{1,\alpha}$ from d=6 operator vanished exactly)

$$\text{BAU} \propto \sum_\alpha \eta_\alpha \, \varepsilon_{1,\alpha}$$

different factors for different lepton flavours

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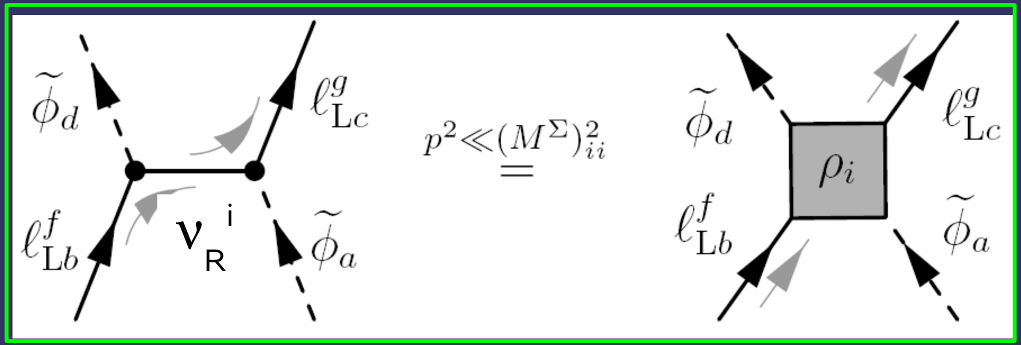
However, non-unitarity has another important effect ...

- The d=6 operator for non-unitarity can also mediate flavour equillibration in the thermal bath!

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

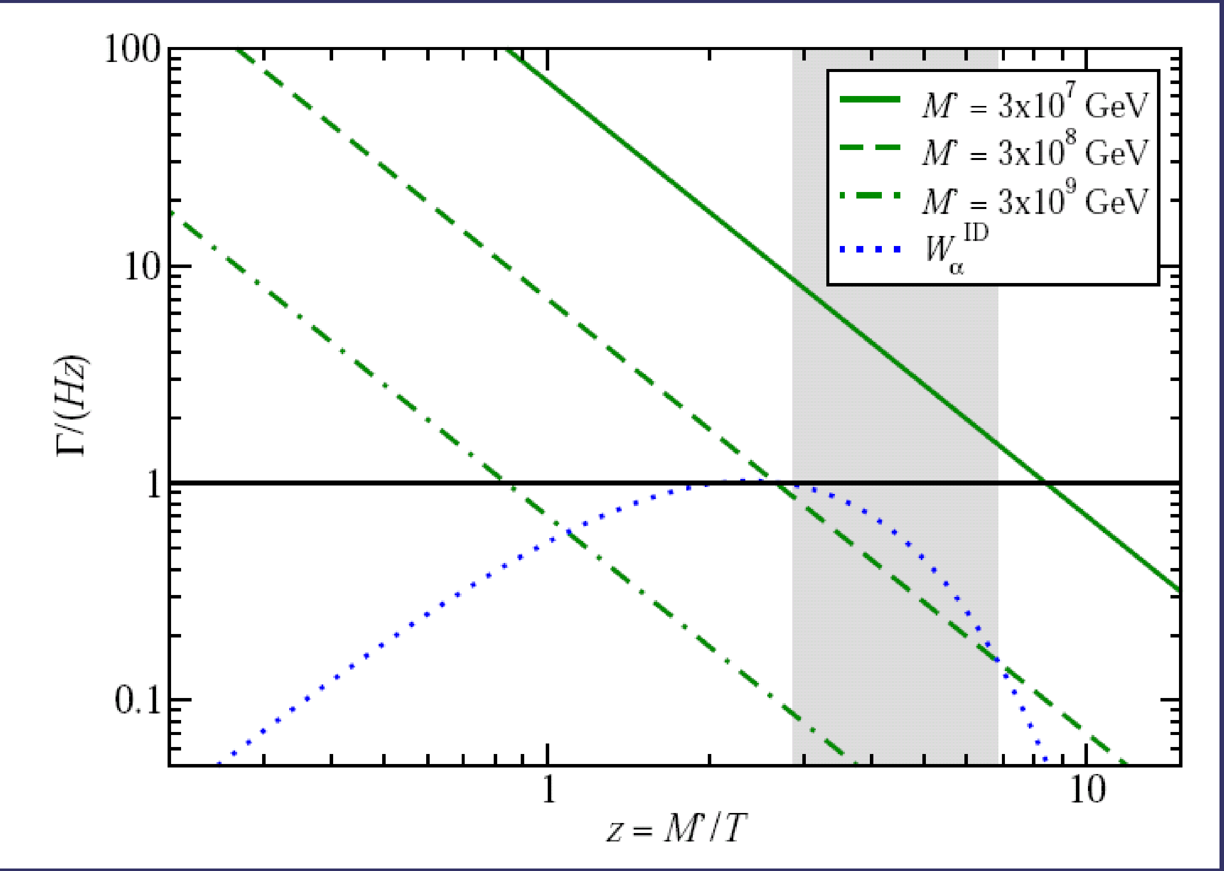


- If flavour equilibrating processes dominate over the flavour-dependent washout processes, then the d=6 operator can **not** sucessfully drive leptogenesis!

For other sources of flavour equillibration, see also:
Sierra, Losada, Nardi ('09)

In a minimal realisation of non-unitarity driven leptogenesis ...

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



- ... we find that TeV scale leptogenesis with observable non-unitarity is not possible (but, nevertheless, leptogenesis bound relaxed to M' > 10^8 GeV)

Brief Summary and Conclusions

➲ Non-unitarity

- Typical signal of new phyiscs in the lepton sector
- Minimal Unitarity Violation (MUV): Consistent minimal scheme

➲ Leptogenesis and Non-unitarity

- Non-unitarity effects (d=6 operator) can strongly enhance the flavoured decay asymmetries for leptogenesis. Enhancement generic in low scale seesaw models with approximately conserved 'lepton number' symmetry!
- Additional effect: Same d=6 operator can mediate flavour equillibrating processes in the thermal bath
- Open question: Is there a well motivated model which realises low scale (testable) 'non-unitarity driven leptogenesis'?

Next: Part 2 - Bounds on non-unitarity, by M. Blennow

Stefan Antusch
MPI für Physik (Munich)