Neutrinoless double beta decay in the LHC era

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Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics

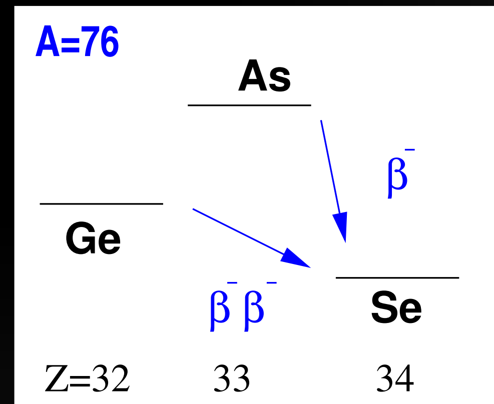
Outline

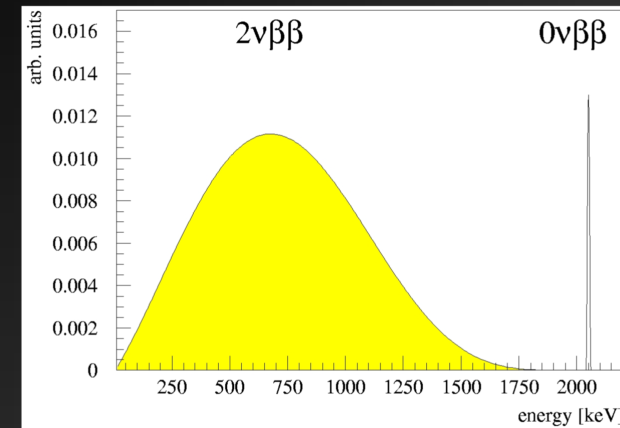
- What is double beta decay
- A general parametrization
- New physics contributions - How to discriminate the mechanisms?
- Half life ratios
- Double beta decay and the LHC
- Summary and conclusions

F. Deppisch, H. Päs, Phys. Rev. Lett. 98 (2007) 232501
B.C. Allanach, C.H. Kom, H. Päs, arXiv:0903.0347
B.C. Allanach, C.H. Kom, H. Päs, Phys. Rev. Lett. 103 (2009) 091801

What is neutrinoless double beta decay?

$$2n \rightarrow 2p + 2e^-$$





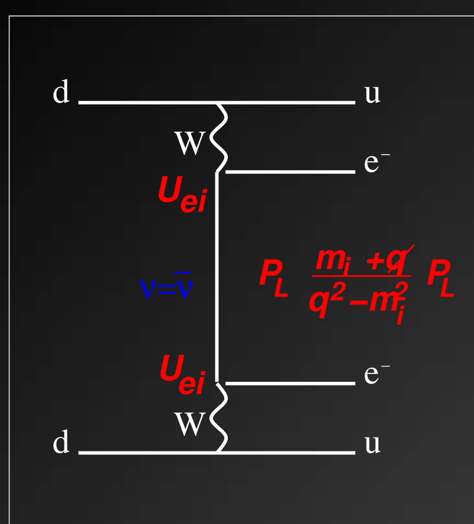
Mass mechanism:

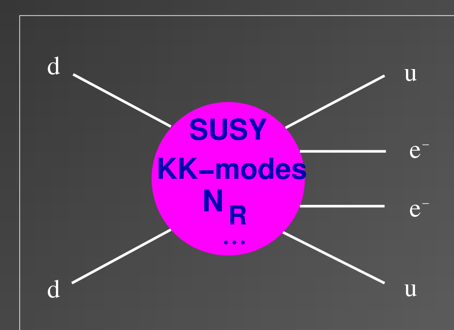
$$[T_{1/2}^{0\nu}]^{-1} \propto |\sum_i U_{ei}^2 m_i|^2$$

In general: Every operator

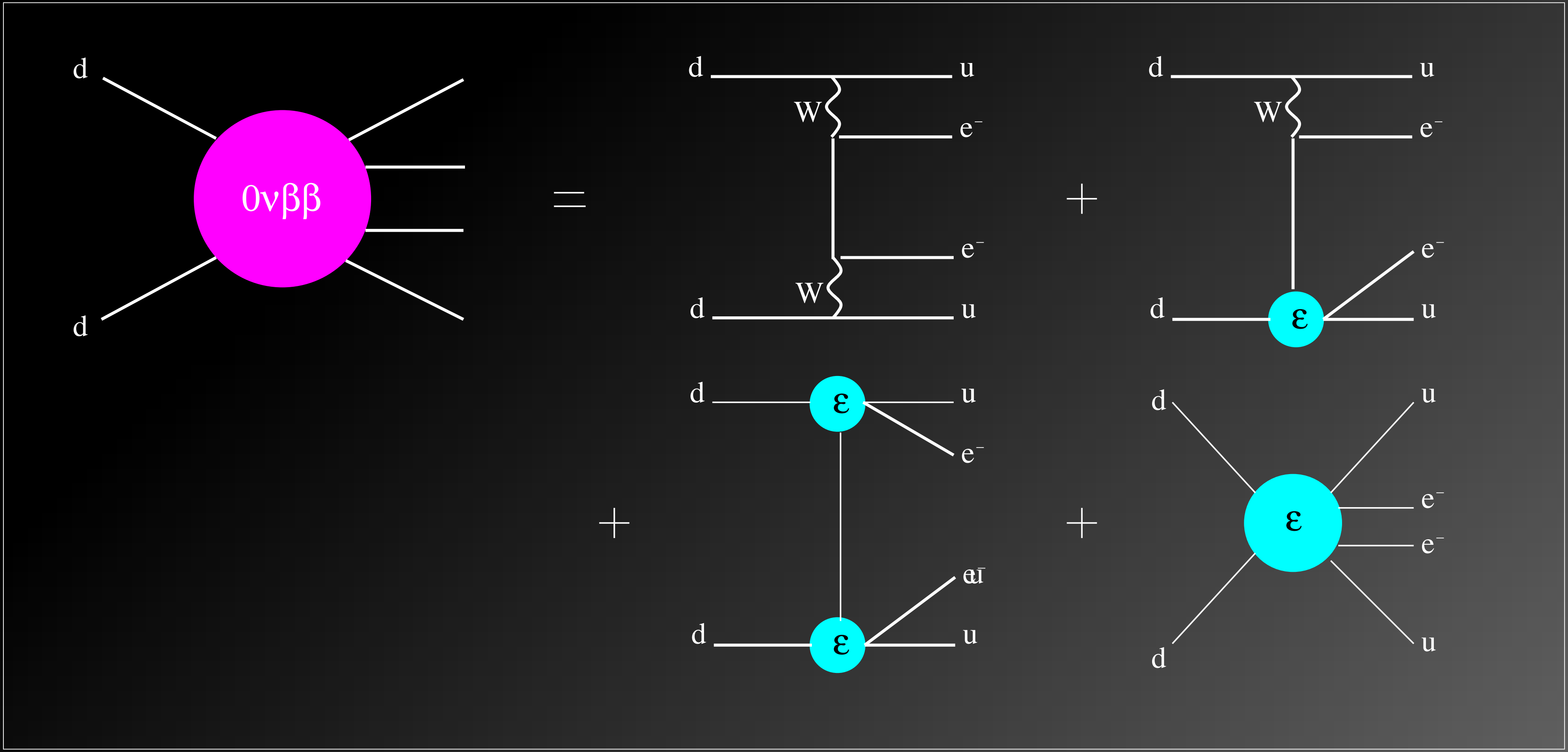
$$\overline{p}\,\overline{p}\,\overline{e}\,\overline{e}\,nn/M^5$$

will generate $0\nu\beta\beta$ decay





Expand in terms of vertices being point-like at the Fermi scale $p_F \sim 100$ MeV:



Päs, Hirsch, Klapdor-Kleingrothaus, Kovalenko 1999 & 2001

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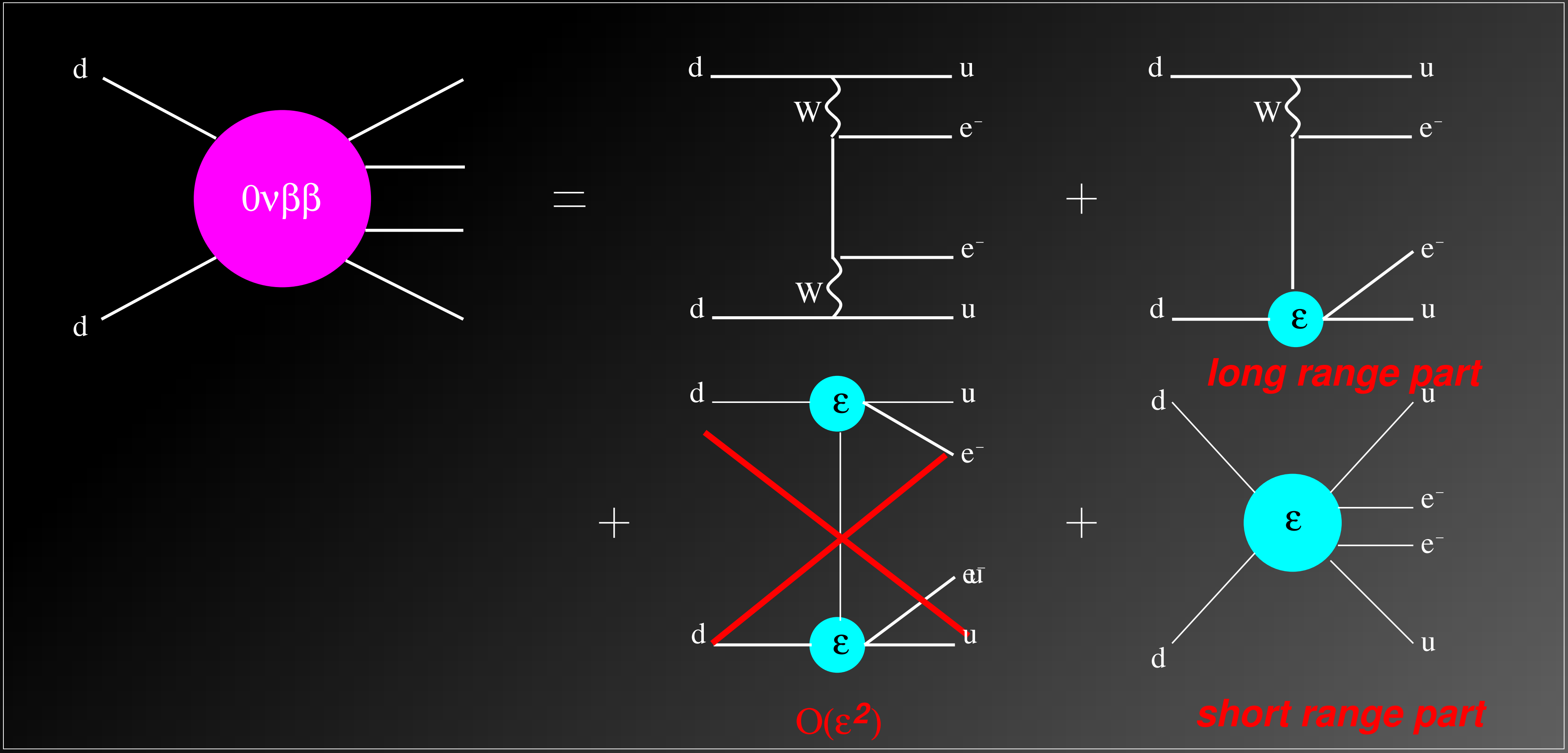


Päs, Hirsch, Klapdor-Kleingrothaus, Kovalenko 1999 & 2001

A general parametrization

Long range interaction

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left(j^{\mu}_{V-A} J_{V-A,\mu} + \sum \epsilon_{NP} j_{NP} J_{NP} \right)$$

with hadronic and leptonic Lorentz currents of defined chirality:

$J_{NP,V-A} = \bar{u}\mathcal{O}_J d$ and $j_{NP,V-A} = \bar{e}\mathcal{O}_j \nu$

($\mathcal{O}_{J,j}$: transition operator ϵ_{NP}: effective coupling strength)

Short range interaction

$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \sum \epsilon_{NP} J_{NP} J_{NP} j'_{NP}$$

with hadronic and leptonic currents of defined chirality:

$J_{NP} = \overline{u}\mathcal{O}_J d$ and $j'_{NP} = \overline{e}\mathcal{O}_j e^C$

$$[T^{NP}_{1/2}]^{-1} = {\epsilon_{NP}}^2 G^{NP} |\mathcal{M}^{NP}|^2$$

$\rightarrow$ calculate matrix elements for all Lorentz invariant combinations

Päs, Hirsch, Klapdor-Kleingrothaus, Kovalenko, 1999 & 2001

A major problem

Uncontroversial detection of $0\nu\beta\beta$ decay: uttermost importance!

- prove lepton number to be broken in Nature
- prove neutrinos to be Majorana particles Schechter and Valle, 1982

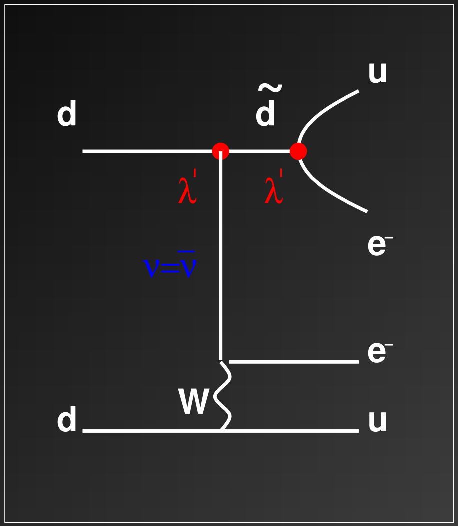
However: it will immediately generate another puzzle:

which mechanism that triggers the decay?

Without identification of the underlying mechanism:

- experimental evidence for $0\nu\beta\beta$ decay will only provide ambiguous information about the concrete physics underlying the decay!
- No information about m_ν can be obtained from a measurement of the neutrinoless double beta decay half life!

- integrating out a heavy d_k-squark
- $\not{R}_P$ couplings λ'_{11k} and λ'_{1k1}
- exchange of a light ν_i



$$\mathcal{L} \supset \frac{G_F U^*_{ei}}{4\sqrt{2}} \epsilon^{\rm SUSYacc} \Big[(\overline{\nu}_i(1+\gamma_5)e^c)\,(\overline{u}(1+\gamma_5)d) + \frac{1}{2}(\overline{\nu}_i\sigma^{\mu\nu}(1+\gamma_5)e^c)\,(\overline{u}\sigma^{\mu\nu}(1+\gamma_5)d) \Big]$$

New physics parameter:

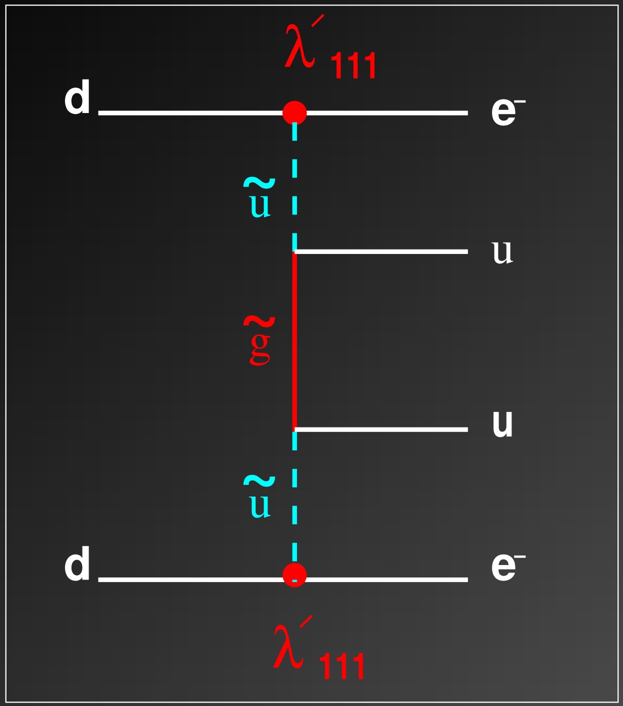
$$\epsilon^{\rm SUSYacc} = \sum_k \frac{\lambda'_{11k}\lambda'_{1k1}}{2\sqrt{2}G_F} \sin 2\theta_k \left(\frac{1}{m^2_{\tilde{d}_1}} - \frac{1}{m^2_{\tilde{d}_2}} \right)$$

θ_k: LR-mixing of $\tilde{d}_1$ and $\tilde{d}_2$

Babu, Mohapatra, 1995; Hirsch, Klapdor-Kleingrothaus, Kovalenko, Päs, 1996 & 1999

Gluino exchange mechanism in R-parity violating SUSY

- integrating out u- and d-squarks and a gluino



$$\mathcal{L} \supset \frac{G_F^2}{2} m_p^{-1} \epsilon^{\tilde{g}} \left((\overline{u}(1+\gamma_5)d)(\overline{u}(1+\gamma_5)d) - \frac{1}{4}(\overline{u}\sigma^{\mu\nu}(1+\gamma_5)d)(\overline{u}\sigma^{\mu\nu}(1+\gamma_5)d) \right. (\overline{e}(1+\gamma_5)e^c)$$

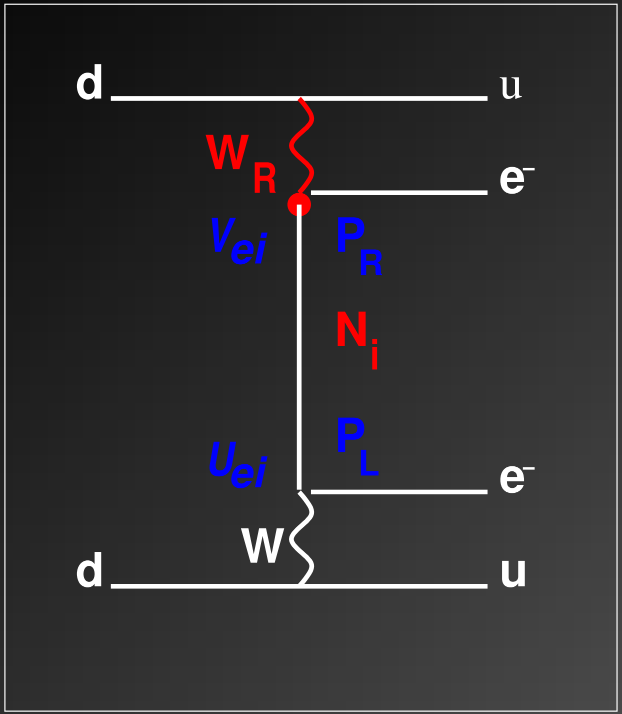
New physics parameter:

$$\epsilon^{\tilde{g}} = \frac{2\pi\alpha_s}{9} \frac{\lambda'^2_{111}}{G_F^2 m^4_{\tilde{d}_R}} \frac{m_p}{m_{\tilde{g}}} \left[1 + \left(\frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}} \right)^4 \right]$$

Mohapatra 1986; Vergados 1987; Hirsch, Klapdor-Kleingrothaus Kovalenko, 1996

Right-handed currents

- Integrating out right-handed W-bosons occurring in left-right symmetric models



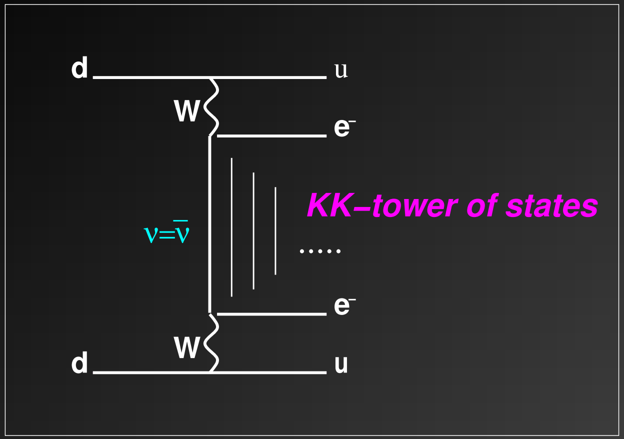
$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} (\overline{\nu}_i \gamma_\mu (1+\gamma_5) e^c) \left(\eta (\overline{u} \gamma^\mu (1-\gamma_5) d) + \lambda (\overline{u} \gamma^\mu (1+\gamma_5) d) \right)$$

where the new physics parameters are given by η and λ

Doi, Kotani, Nishiura, Takasugi, 1983

Kaluza-Klein neutrino exchange in extra-dimensional models

- sum over all KK-excitations with masses $m_{(n)}$



- weight with the mass dependent matrix element $\mathcal{M}^{m_\nu}(m_{(n)})$

$$\epsilon^{KK} = \frac{1}{\mathcal{M}^{m_\nu}} \sum_{-\infty}^{\infty} U_{en}^2 m_{(n)} \left(\mathcal{M}^{m_\nu}(m_{(n)}) - \mathcal{M}^{m_\nu}\right)$$

- ϵ^{KK} depends on NME $\mathcal{M}^{m_\nu}(m_{(n)}) \Leftrightarrow$ particle physics does not decouple from the nuclear physics.
- KK excitations vary from values much smaller than the nuclear Fermi momentum p_F to values much larger than p_F, while the $m_{(n)}$-dependence of $\mathcal{M}^{m_\nu}(m_{(n)})$ changes around p_F
- KK spectrum fixed by choosing brane shift parameter $a = 10\ \mathrm{GeV}^{-1}$ and the radius of the extra dimension $R = (1/300)$ eV^{-1}

Bhattacharyya, Klapdor-Kleingrothaus, Päs, Pilaftsis, 2003

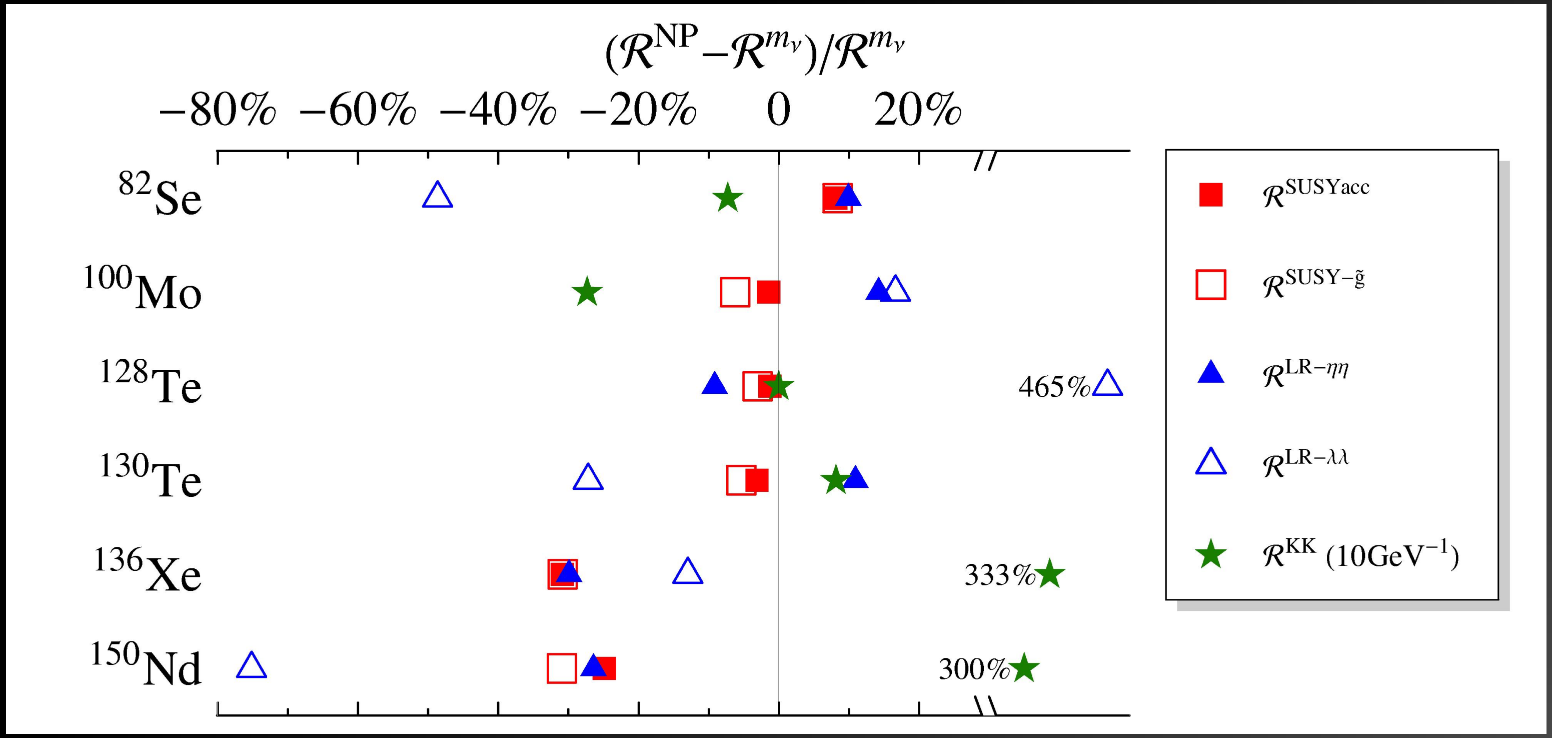
Half life ratios

- Concentrate on: different mechanisms result in different NMEs
- Problem: smaller NME for e.g. the mass mechanism as compared to any alternative new physics mechanism can be compensated by a larger value for the neutrino mass
- However: If one mechanism dominates $\rightarrow \langle m_\nu \rangle$ or ϵ_{NP} drops out in the ratio of experimentally determined half lives for two different emitter isotopes

$$\frac{T_{1/2}(^A X)}{T_{1/2}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}(^{76}\mathrm{Ge})|^2 G(^{76}\mathrm{Ge})}{|\mathcal{M}(^A X)|^2 G(^A X)}$$

- $\Rightarrow$ Half life ratios depend on the mechanism of double beta decay, but not on the new physics parameter!
- Compare with theoretical prediction for different mechanisms!
- Error in NME ratio can be reduced compared to theoretical error in one matrix element (cancellations of systematic effects)!

Results



F. Deppisch, H. Päs, Phys. Rev. Lett. 98 (2007) 232501

Matrix elements calculated in the QRPA approach of
A. Staudt, K. Muto and H. V. Klapdor- Kleingrothaus, Europhys. Lett. **13**, 31 (1990); M. Hirsch, K. Muto, T. Oda and H. V. Klapdor-Kleingrothaus, Z. Phys. A **347**, 151 (1994)
or taken from literature using the same code
See also: Gehmann, Elliott, 2007; Fogli, Lisi, Rotunno, 2009

Results

- $R\!\!\!/_P$ SUSY contributions:

similar and rather small deviations

Most effectively discriminated by comparing ^{82}Se and ^{136}Xe (60% variation)

- Left-right symmetric models:

strong deviations for $\lambda\lambda$ combination, comparing ^{128}Te and ^{150}Nd:

$$T^{LR}_{1/2}/T^{m_\nu}_{1/2}[^{128}\mathrm{Te}] \gtrsim 20\times \quad T^{LR}_{1/2}/T^{m_\nu}_{1/2}[^{150}\mathrm{Nd}]$$

small deviations for $\eta\eta$ combination comparison of ^{100}Mo and ^{136}Xe yields a variation of 70 %

- Extra-dimensional neutrino models with a large brane shift parameter:

large deviations for ^{136}Xe and ^{150}Nd:

$$T^{KK}_{1/2}/T^{m_\nu}_{1/2}[^{150}\mathrm{Nd}] \gtrsim 5\times \quad T^{KK}_{1/2}/T^{m_\nu}_{1/2}[^{100}\mathrm{Mo}]$$

Caution: strong deformation of ^{150}Nd is ignored in most QRPA calculations
$\longrightarrow$ Simkovic, Pacearescu, Faessler, 2004

Nuclear matrix element uncertainties

- Theoretical errors of NME calculation dominate experimental errors $\Rightarrow$ difficult to determine the confidence level with which either mechanism can be excluded to generate the observed double beta evidence!
- Assuming e.g. a statistical distribution of matrix element values $\Leftrightarrow$ relative variation of 60% in $\mathcal{R}^{NP}(^AX)$ w.r.t. $\mathcal{R}^{m_\nu}(^AX)$ is significant only if NMEs would be known with an accuracy of 15%! $\longrightarrow$ unrealistic!
- Estimates of uncertainties vary: factor 3-5 (spread of published values) to only 30% (uncertainties inherent in QRPA) Rodin, Faessler, Simkovic, Vogel, 2006

However:

- significance will increase if a whole set of measurements in different isotopes resembles the expected pattern
- systematical effects (like a too small g_{pp} in the pn-QRPA approach, a different g_A, higher-order terms, different model-space) will cancel out
- $\longrightarrow$ check results with alternative codes!
- $\longrightarrow$ include pion exchange which may be dominating in some of the models discussed! Faessler, Kovalenko, Simkovic 1998; ...and Gutsche 2007

Alternative ideas

Possibilities to disentangle at least some of the possible mechanisms:

- analysis of angular correlations between the emitted electrons
  Doi, Kotani, Nishiura and Takasugi, 1983; Ali, Borisov and Zhuridov, 2006 & 2007

  $\longrightarrow$ few experiments sensitive to electron tracks

- comparative study of $0\nu\beta\beta$ and $0\nu\beta^+$ with electron capture (EC) decay
  Hirsch, Muto, Oda, Klapdor-Kleingrothaus, 1994

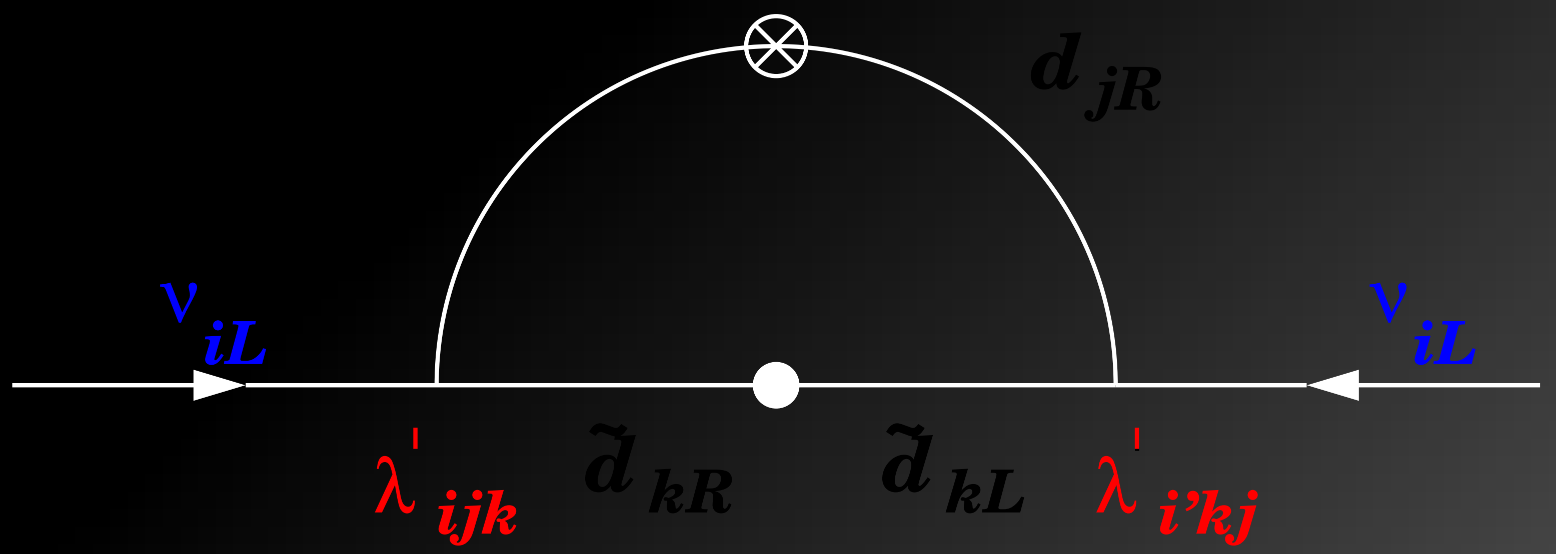
  $\longrightarrow$ small rates and experimental challenge to observe the produced X-rays or Auger electrons

- study of double beta decay to excited 0^+ states
  Simkovic, Nowak, Kaminski, Raduta, Faessler, 2001

  $\longrightarrow$ few experiments sensitive to transitions to excited states.

RPV vs. m_{ee} in mSUGRA

Couplings which generate direct RPV contributions also generate m_{ee}:



- $\lambda'_{112}\lambda'_{121}$: excluded by bounds from $K_0 - \bar{K}_0$ mixing
- $\lambda'_{113}\lambda'_{131}$: direct RPV and m_{ee} comparable
- ${\lambda'_{111}}^2$: direct RPV dominates

B.C. Allanach, C.H. Kom, H. Päs, arXiv:0903.0347

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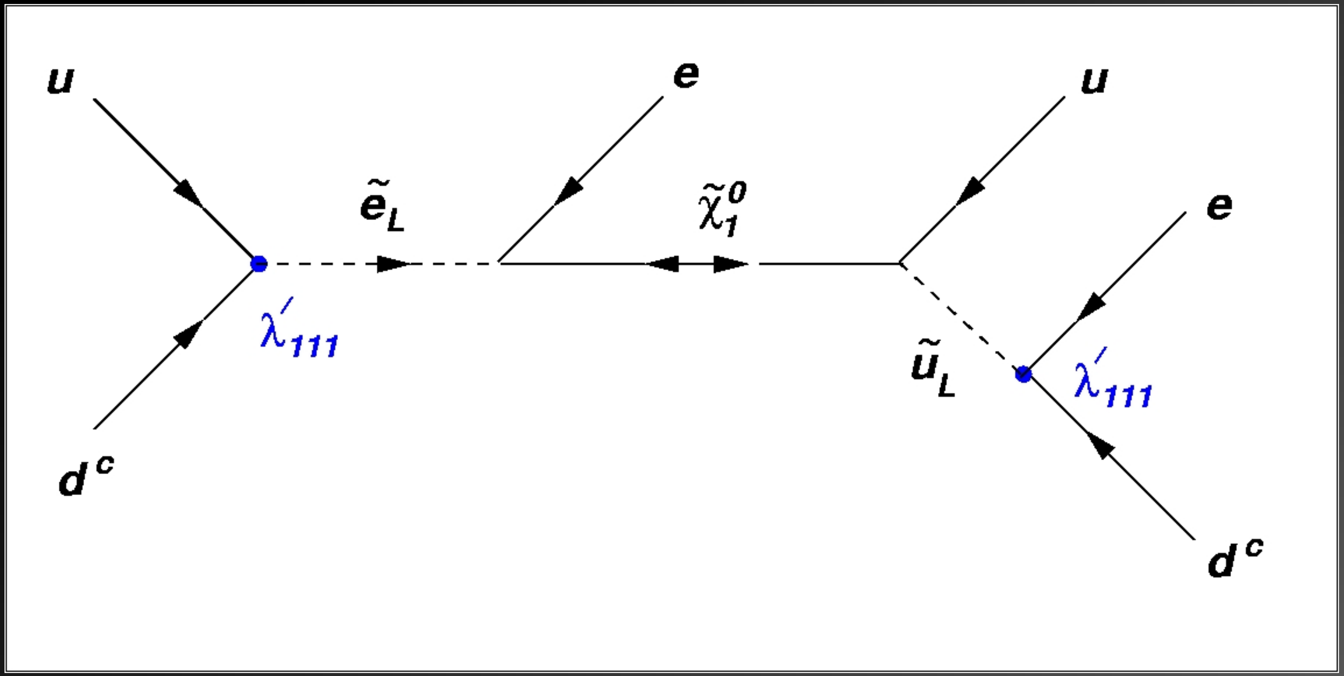
Complementary observables: LHC and B physics

- $\lambda'_{113}\lambda'_{131}$: if B meson mass difference entirely due to trilinear RPV $\Rightarrow$ $0\nu\beta\beta$ observable in next generation (100 kg) experiments (depending on NME!)
- ${\lambda'_{111}}^2$: LSD signal from single selectron production observable at the LHC $\rightarrow$ possibility of determination of λ'_{111}



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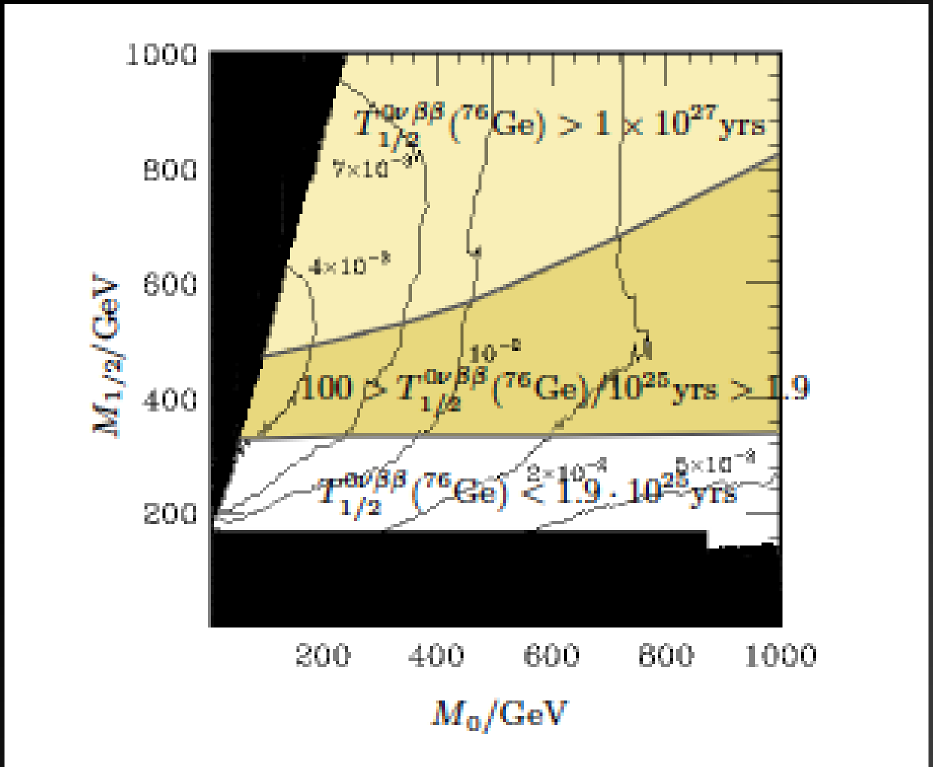
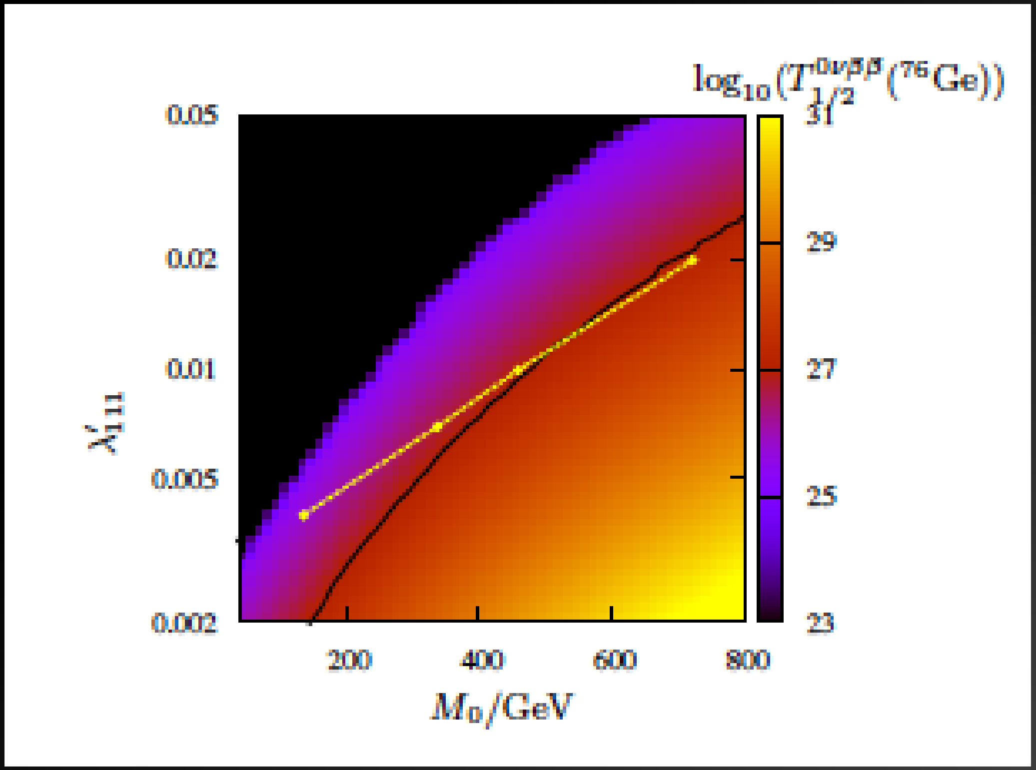
Neutrinoless double beta decay and the LHC



- white region: no single slepton production at LHC
- darker shaded region: 5 σ LHC discovery $\Rightarrow$ $0\nu\beta\beta$ decay in next generation experiments
- lighter shaded region: $0\nu\beta\beta$ $\Rightarrow$ more than 5 σ at LHC

(mSUGRA with $A_0 = 0$, $\tan\beta = 10$, $\mu = +1$, SOFTSUSY spectrum)

Neutrinoless double beta decay and the LHC



- above black line: $0\nu\beta\beta$ accessible
- above yellow line: LHC signal

(mSUGRA with $A_0 = 0$, $\tan\beta = 10$, $\mu = +1$, SOFTSUSY spectrum)

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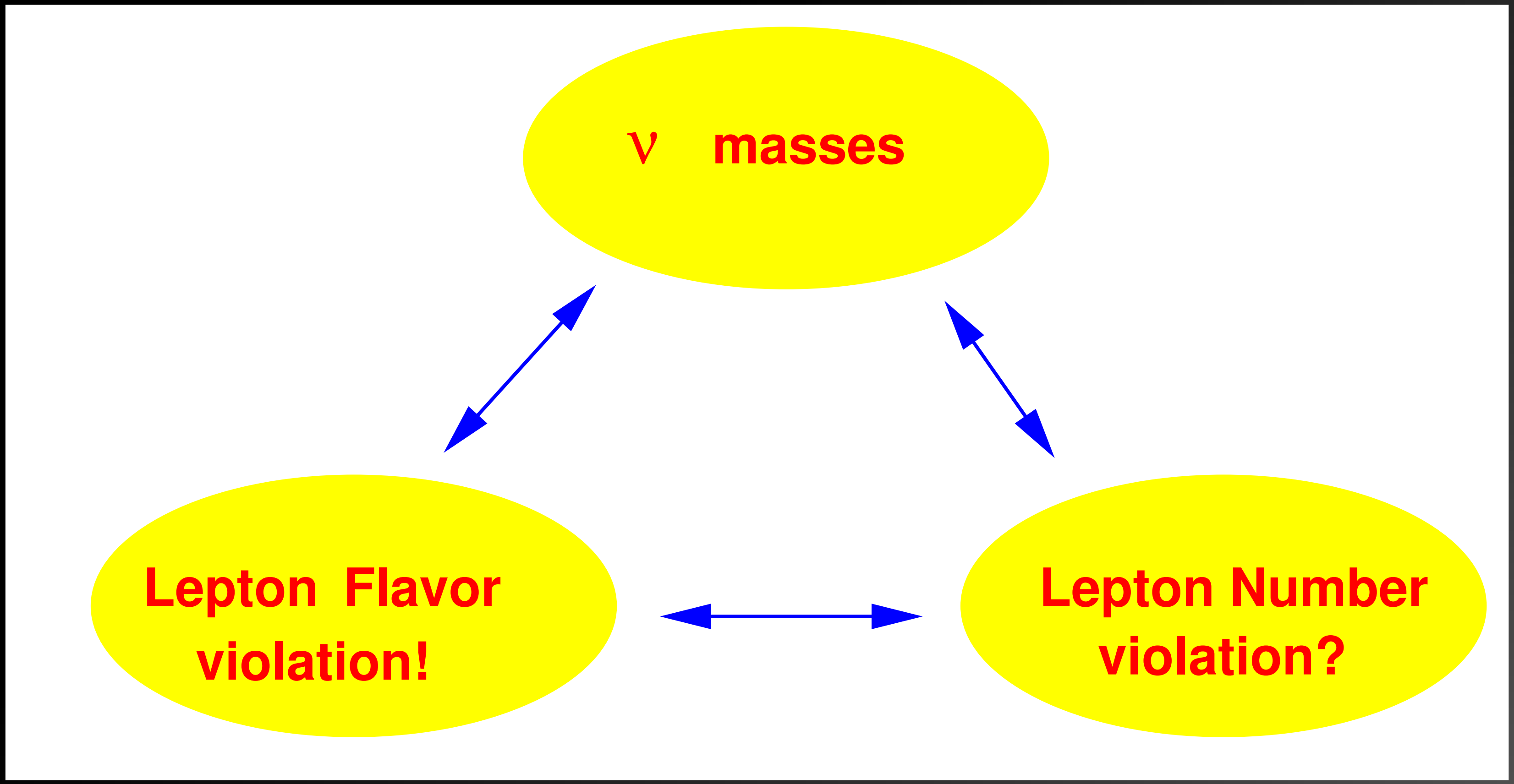
Outlook: Neutrino masses at the LHC



Outlook: Neutrino masses at the LHC

- Seesaw I + SUSY $\rightarrow$ LFV decays ($\tau \rightarrow \mu\gamma$), slepton mass splittings Deppisch, Päs, Redelbach, Rückl, Shimizu, 2003; Deppisch, Freitas, Porod, Zerwas, 2008
- Trinification ($SU(3)_C \times SU(3)_L \times SU(3)_R$) + SUSY $\Rightarrow$ Inverse Seesaw $\Rightarrow$ New physics at TeV scale! Cauet, Päs, Wiesenfeldt, work in progress
- S_3 flavor symmetry $\Rightarrow$ 3 Higgs doublets $\Rightarrow$ flavor violating and flavor specific Higgs decays at the LHC! Bhattacharyya, Leser, Päs, work in progress

Helmholtz Alliance Terascale Working group: Neutrino masses and Lepton Flavor violation at the LHC

Theory groups from Dortmund (Päs) and Würzburg (Porod) and Experimentalists from Dortmund, Würzburg (Gößling, Trefzger, ATLAS), Aachen (CMS)

Summary and conclusions

- There exist several alternatives to the mass mechanism for $0\nu\beta\beta$ decay
- different mechanisms of neutrinoless double beta decay would manifest themselves in half life ratios involving different isotopes
- Strong discriminators for at least some mechanisms (LR symmetry, KK excitations)
- Motivation for measurements in different isotopes!
- Motivation to seach for alternative observables
- $B\overline{B}$ mixing bound: $0\nu\beta\beta$ due to $\lambda'_{113}\lambda'_{131}$ RPV only in next generation experiments
- Single selectron production at the LHC: observation possible in large areas of the parameter space if $0\nu\beta\beta$ is due to ${\lambda'_{111}}^2$ RPV!
- Exploration of the TeV scala at LHC will be crucial for a variety of approaches to explain the generation of neutrino masses