Flavor phenomena in the lepton sector

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Plan

* Sources of lepton flavour violation (LFV) and CP violation (CPV)
* Low energy manifestations in supersymmetric models
* Large neutrino angles and colliders

The SM flavor sector
(at the ren. pert. level)

* No lepton or baryon number violation
* No individual lepton number or CP violation in the lepton sector

$$\begin{cases} e_i^{c\prime} = U_{ij}^{e^c} e_j^c \\ L_j' = U_{ij}^{e} L_j \end{cases} \qquad \to \lambda_{ij}^E e_i^c L_j H^\dagger = \lambda_{e_i} e_i^{c\prime} L_i' H^\dagger$$

* All flavor and CP violating effects (neglecting ϑ_{QCD})
  - reside in the quark charged current
  - are encoded in the unitary 3x3 CKM matrix V

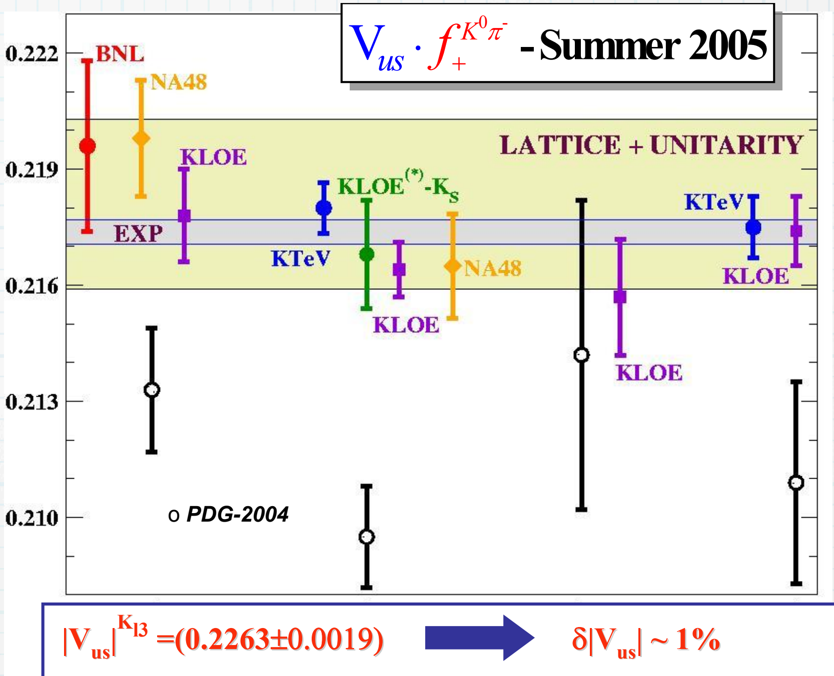
Is that so?

* Unitarity of V (I)

$$\sum_{i \text{ or } a} |V_{ai}|^2 = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

0.9739(3) + 0.2263(19) + small = 0.9997(10)



$|V_{us}|^{K_{l3}}$ =(0.2263±0.0019) → $\delta|V_{us}| \sim 1\%$

(dominated by the $f_+(0)$ theoretical uncertainty)

[Mescia]

$$|V_{ud} f^{ud}(0)| \text{ from } N \to N' e\nu \quad (\delta f^{ud}(0) = \mathcal{O}(0.1\%))$$

$$|V_{us} f^{us}(0)| \text{ from } K \to \pi e\nu \quad (\delta f^{us}(0) = \mathcal{O}(1\%))$$

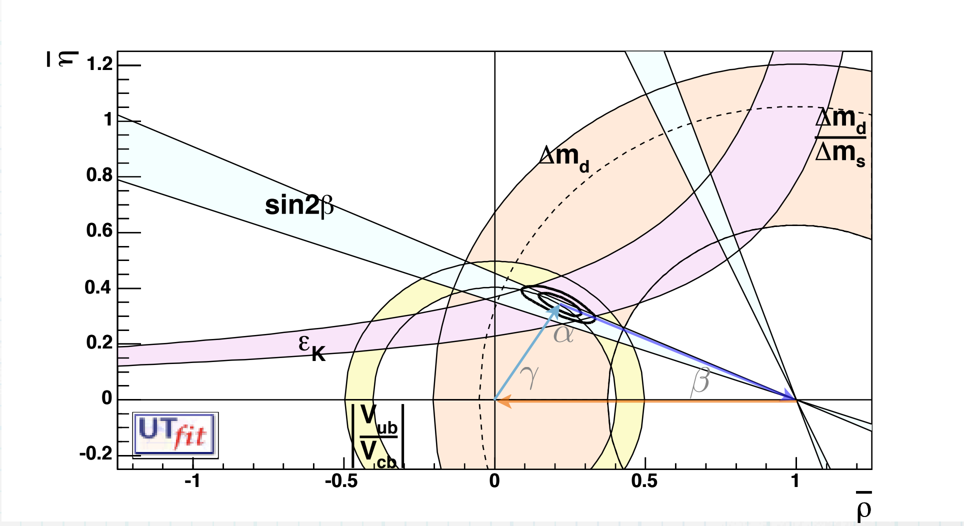
$$|V_{ub}| \text{ from } b \to u l \bar{\nu} \quad (\text{subdominant})$$

Is that so?

* Unitarity of V (II)

$$\sum_i V_{ai} V_{bi}^* = 1 \quad (a \neq b)$$

$$\sum_a V_{ai} V_{aj}^* = 1 \quad (i \neq j)$$



$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

A triangle in the complex plane
(when properly normalized, it has vertex in (ρ,η)

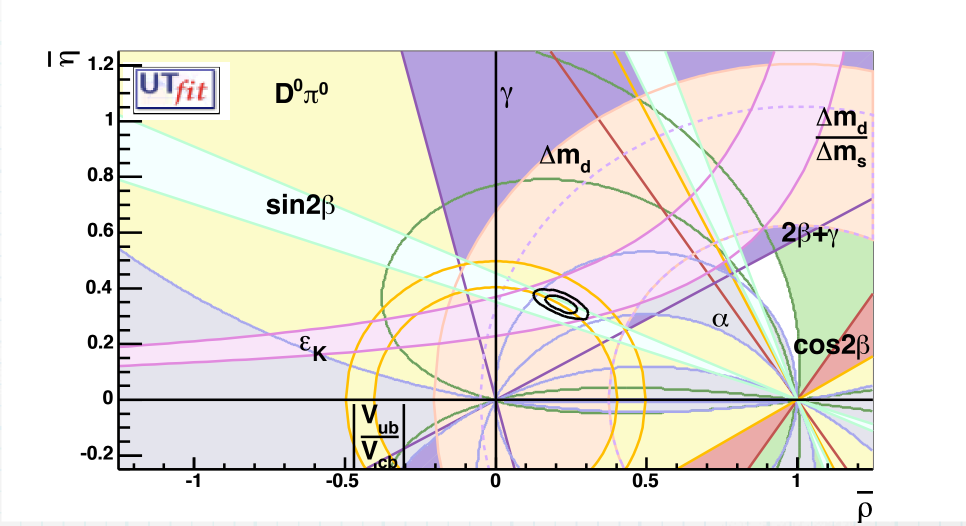
$$-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} - \frac{V_{cd} V_{cb}^*}{V_{cd} V_{cb}^*} - \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} = 0$$

Is that so?

* Unitarity of V (II)

$$\sum_i V_{ai} V^*_{bi} = 1 \quad (a \neq b)$$

$$\sum_a V_{ai} V^*_{aj} = 1 \quad (i \neq j)$$



$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

A triangle in the complex plane
(when properly normalized, it has vertex in (ρ,η)

$$-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} - \frac{V_{cd}V^*_{cb}}{V_{cd}V^*_{cb}} - \frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}} = 0$$

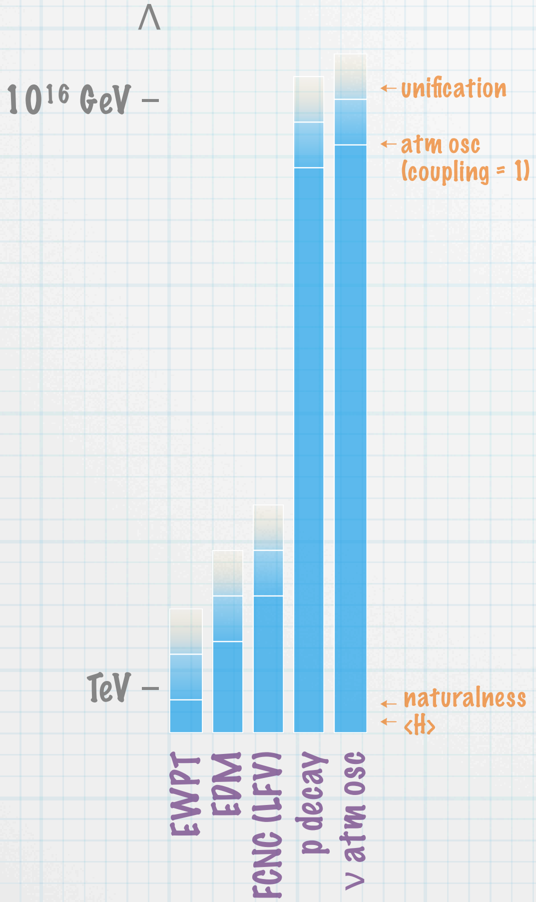
Is that so?

* $BR(\mu \to e\gamma) < 1.2 \times 10^{-11}$ ✓

* $d_e < 1.6 \times 10^{-27}$ e cm ~ $10^{-11}\ \mu_B$ ✓

* $\nu_{ei} \leftrightarrow \nu_{ej}$ $(i \neq j)$ ✗

Large scale indirect probes

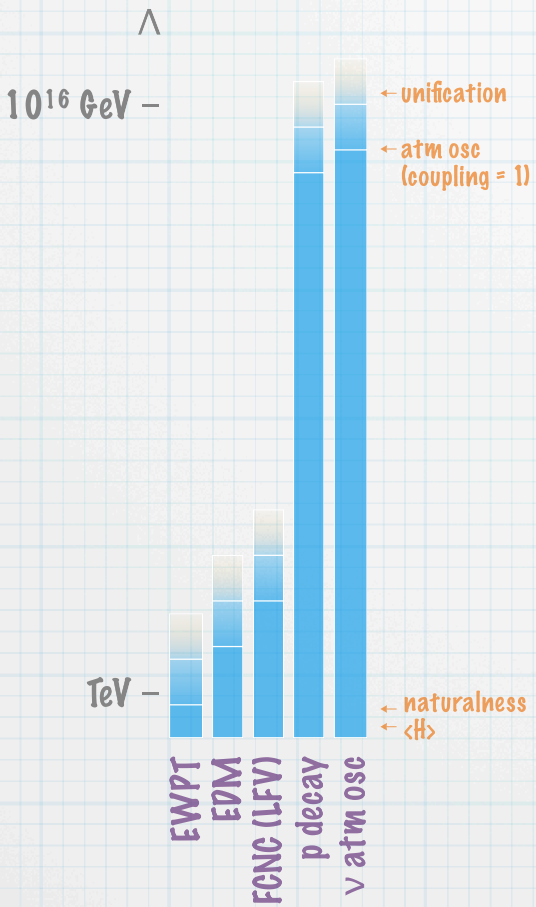


* Neutrino physics (as proton decay) is sensitive to much higher scales than the flavour physics of charged fermions

* and strongly suggests the existence of a source of lepton flavour violation (LFV) from lepton number violation at $\Lambda \approx 10^{15}$ GeV

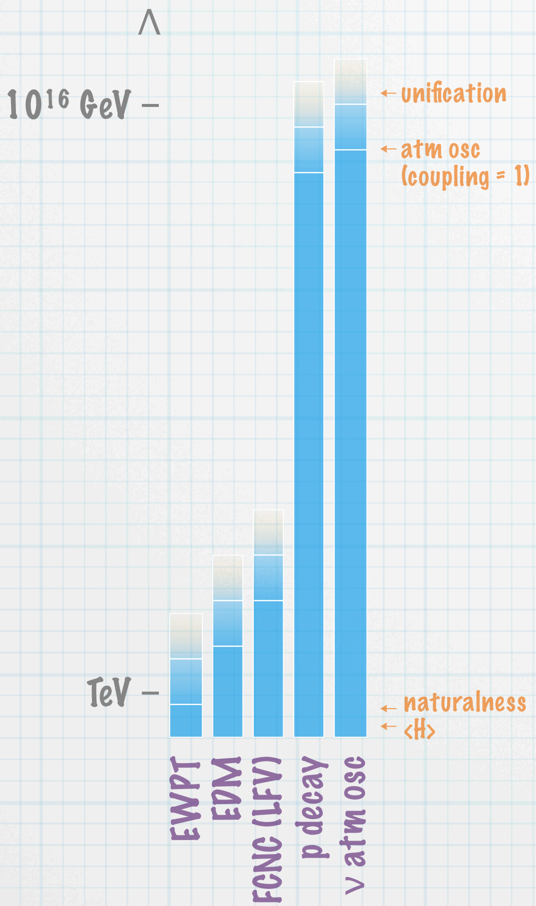
* in addition to the source of LFV suggested by GUT

Supersymmetry



Source of LFV – effects suppressed by $(1/\Lambda_{LFV})^n$

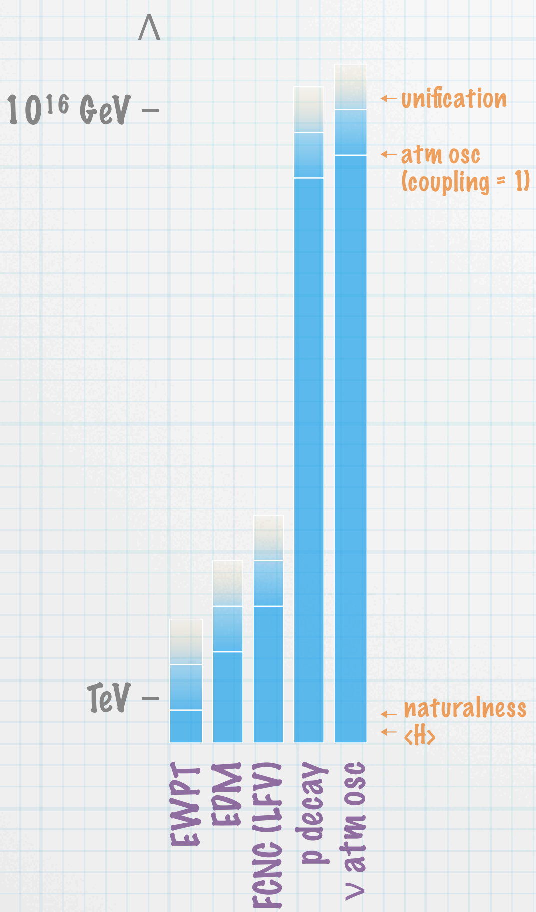
Supersymmetry



Source of LFV – effects suppressed by $(1/\Lambda_{LFV})^n$

$\tilde{m}$: SUSY

Supersymmetry



M0: $m_0^2 \tilde{L}_i^\dagger \tilde{L}_i^\dagger + m_0^2 \tilde{e}_i^{c\dagger} \tilde{e}_i^c + \ldots$ (flavour and CP blind)

Source of LFV – effects suppressed by $(1/\Lambda_{LFV})^n$

$\tilde{m}$: SUSY

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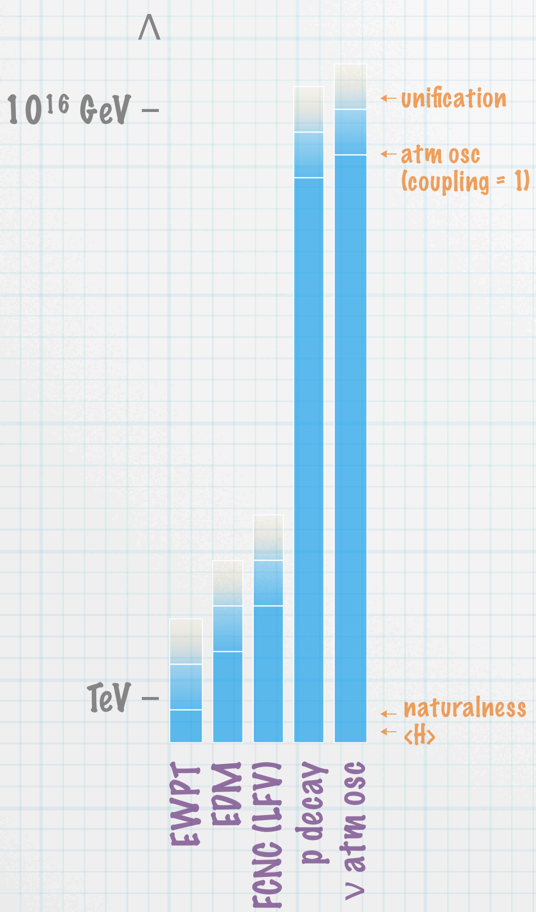
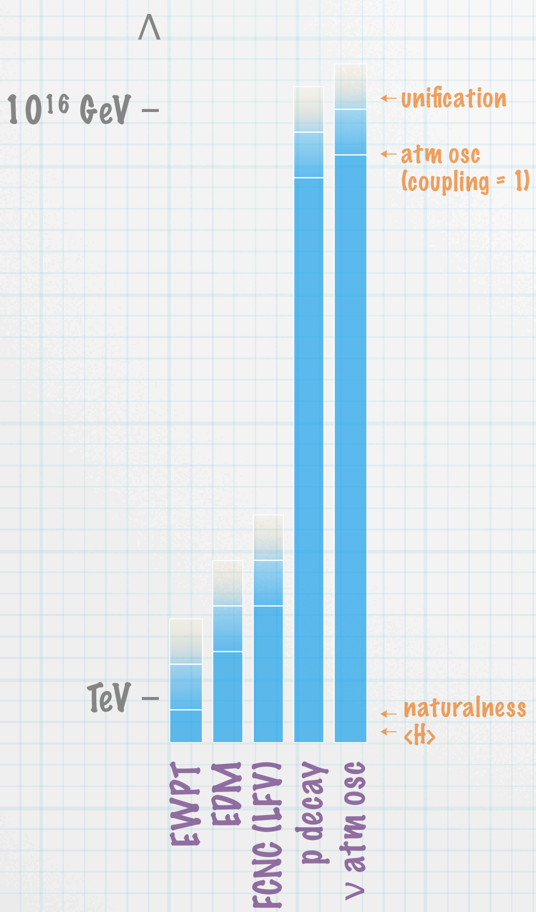


M0: $m_0^2 \tilde{L}_i^\dagger \tilde{L}_i^\dagger + m_0^2 \tilde{e}_i^{c\dagger} \tilde{e}_i^c + \dots$ (flavour and CP blind)

Source of LFV – effects suppressed by $(1/\Lambda_{LFV})^n$

m̃: SUSY $(m_L^2)_{ij} \tilde{L}_i^\dagger \tilde{L}_j^\dagger + (m_{e^c}^2)_{ij} \tilde{e}_i^{c\dagger} \tilde{e}_j^c + \dots$

Supersymmetry



M₀: $m_0^2 \tilde{L}_i^\dagger \tilde{L}_i^\dagger + m_0^2 \tilde{e}_i^{c\dagger} \tilde{e}_i^c + \ldots$ (flavour and CP blind)

Source of LFV – effects suppressed by $(1/\Lambda_{LFV})^n$

$\tilde{m}$: SUSY $(m_L^2)_{ij} \tilde{L}_i^\dagger \tilde{L}_j^\dagger + (m_{e^c}^2)_{ij} \tilde{e}_i^{c\dagger} \tilde{e}_j^c + \ldots$

$$\frac{1}{\Lambda_{\mathrm{LFV}}} \longrightarrow \frac{1}{\tilde{m}_{\mathrm{SUSY}}}$$

Neutrino physics and LFV

Physical parameters in the lepton sector

$$-\mathcal{L} \supset \frac{m_{\nu_i}}{2}\nu_i\nu_i + m_{e_i}e_i^c e_i + \frac{g}{\sqrt{2}}U_{ij}\bar{e}_i\hat{W}\nu_j + \text{h.c.}$$

$$m_e,\ m_\mu,\ m_\tau,\ m_{\nu_1},\ m_{\nu_2},\ m_{\nu_3},\ \theta_{23},\ \theta_{12},\ \theta_{13},\ \delta,\ \alpha,\ \beta$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}s^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}s^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

$$0 \le \theta_{23}, \theta_{12}, \theta_{13} \le \frac{\pi}{2}, \quad 0 \le \delta < 2\pi, \quad 0 \le \alpha, \beta < 2\pi$$

Accessible to oscillations

Not accessible to oscillations

Charged sector

$$\Delta m^2_{12}$$

$$|\Delta m^2_{23}|$$

$$\mathrm{sign}(\Delta m^2_{23})$$

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$$m_{\mathrm{lightest}}$$

$$\alpha$$

$$\beta$$

$$m_{e,\mu,\tau}$$

Charged sector

$m_{e,\mu,\tau}$

Well known

Accessible to oscillations

Δm^2_{12}

$|\Delta m^2_{23}|$

$\text{sign}(\Delta m^2_{23})$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

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Accessible
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$$\text{sign}(\Delta m^2_{23})$$

$$\beta$$

Well known

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

Known

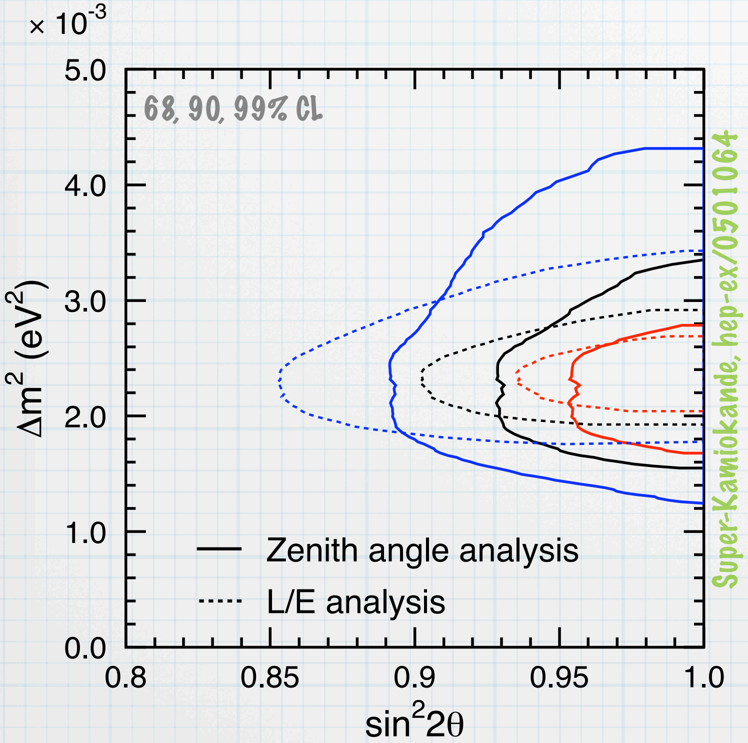
Bounds

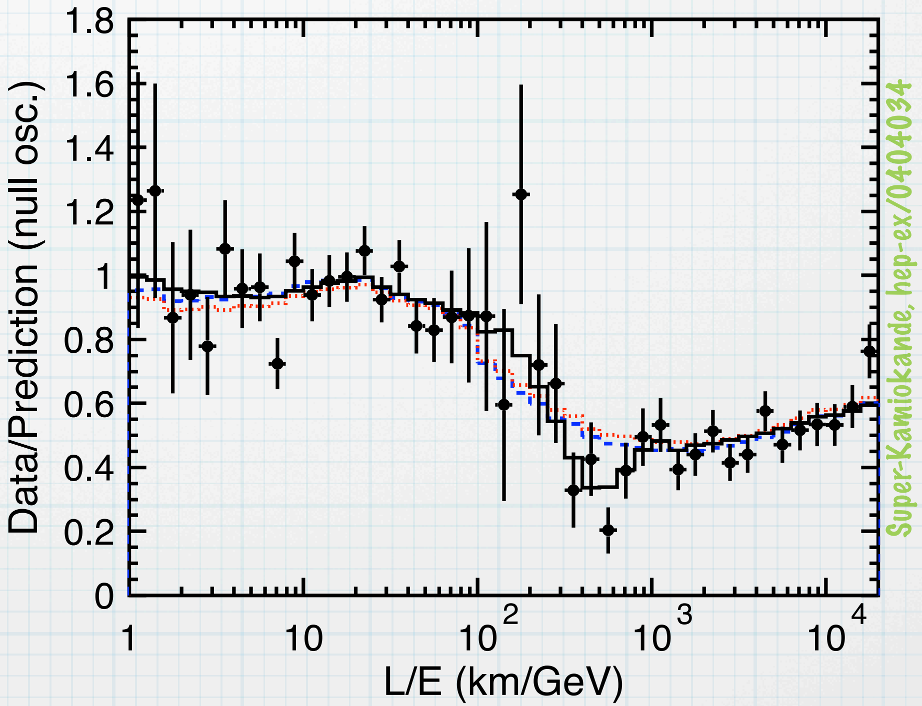
Experimental constraints (oscillations)

$\Delta m^2_{23} \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2 \quad \theta_{23} \sim 45°$ (ATM, K2K)

$\Delta m^2_{12} \sim 0.8 \times 10^{-4}\,\mathrm{eV}^2 \quad \theta_{12} \sim 30°–35°$ (SUN,KamLAND)

$\theta_{13} < 10°$ (CHOOZ, Palo Verde + ATM)





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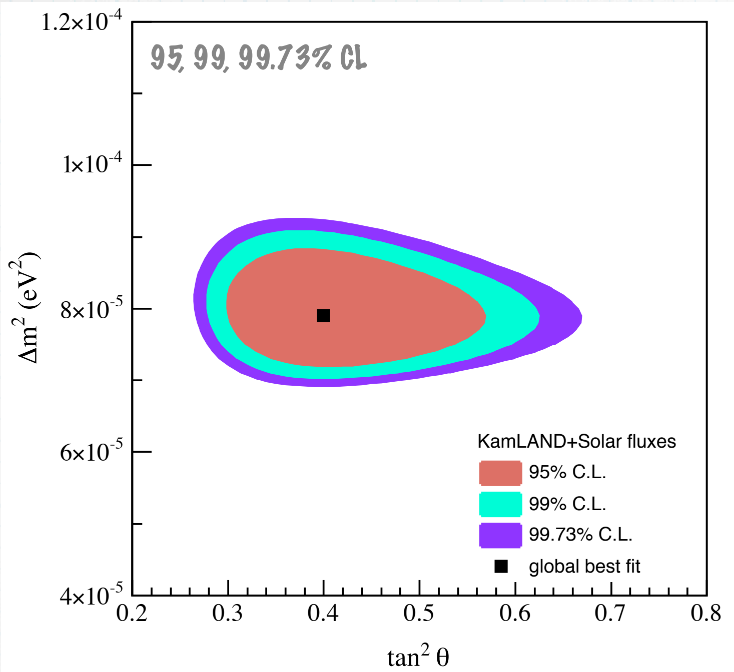
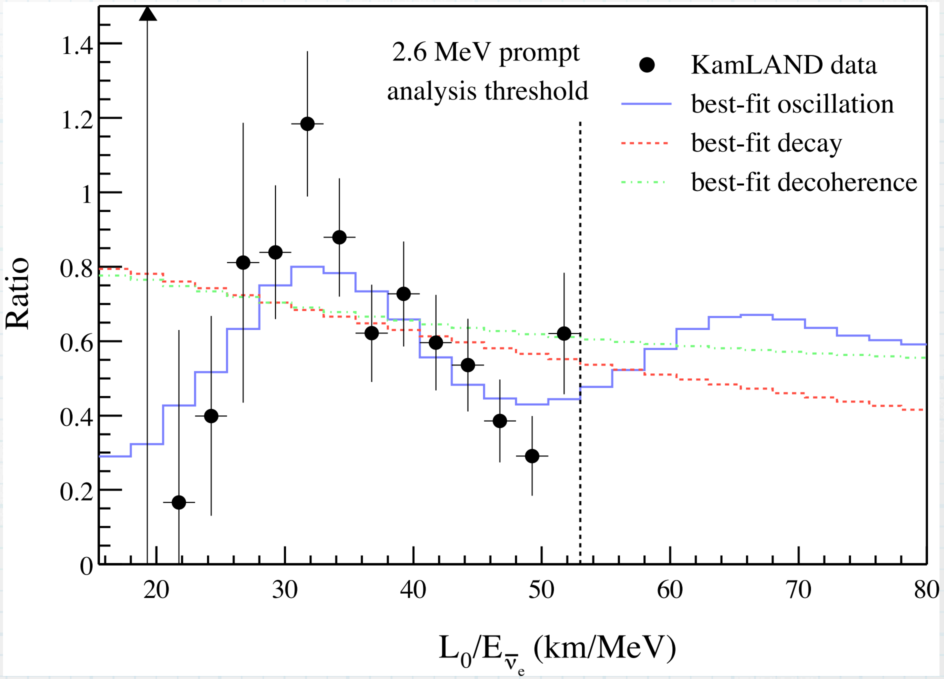


LamLAND, hep-ex/0406035



LamLAND, hep-ex/0406035

Experimental constraints (oscillations)

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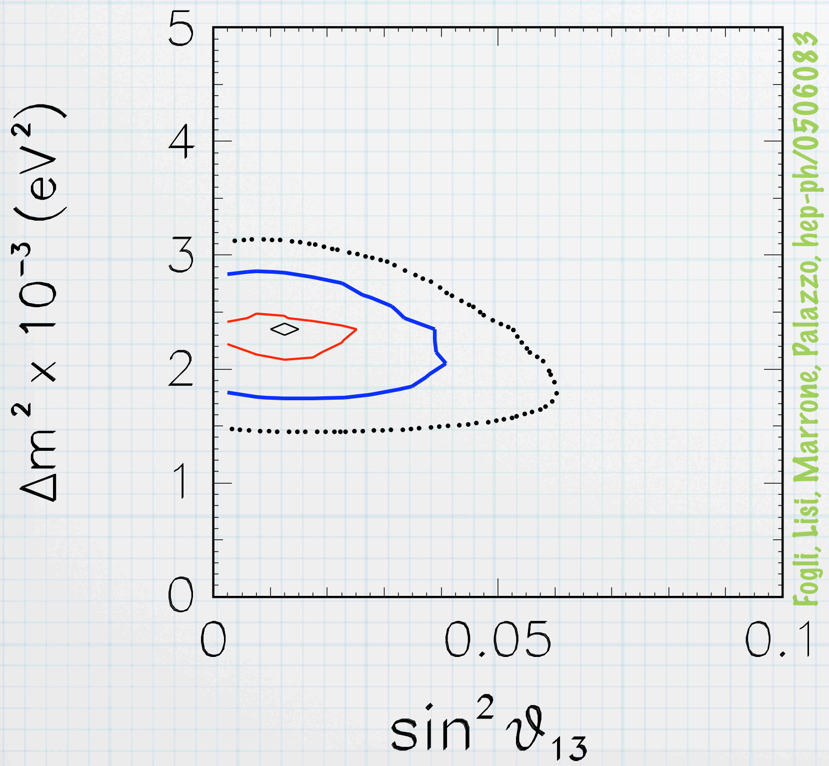

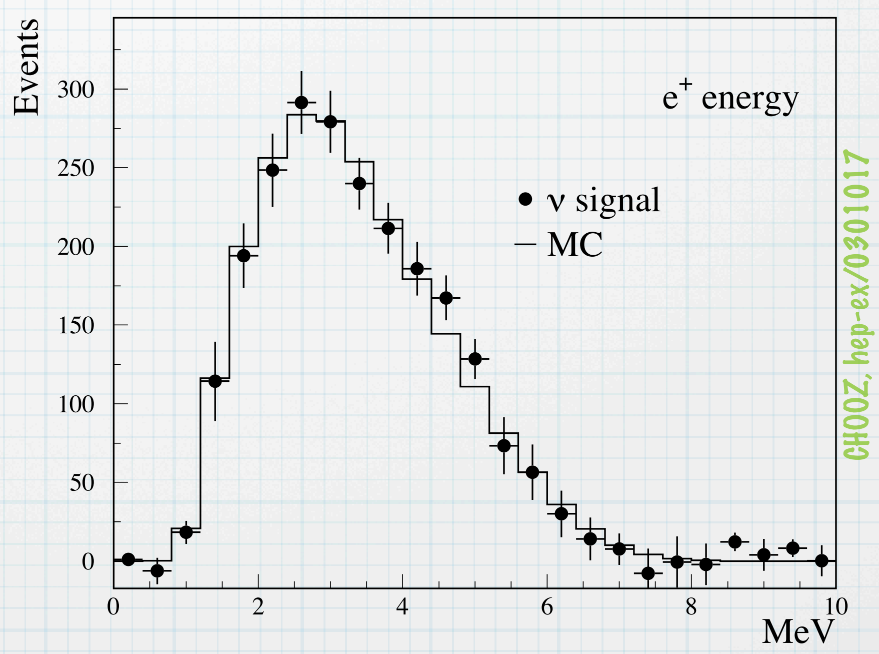

Experimental constraints

$$\Delta m^2_{\rm ATM} \sim 2.5 \times 10^{-3}\,{\rm eV}^2 \quad \theta_{23} \sim 45^\circ$$ (ATM, K2K)

$$\Delta m^2_{\rm SUN} \sim 0.8 \times 10^{-4}\,{\rm eV}^2 \quad \theta_{12} \sim 30^\circ\text{–}35^\circ$$ (SUN,KamLAND)

$$\theta_{13} < 10^\circ$$ (CHOOZ, Palo Verde + ATM)

$$|m_{ee}| = |U^2_{ei} m_{\nu_i}| < \mathcal{O}(1) \times 0.4\,{\rm eV}$$ (Heidelberg-Moscow)

$$(m^\dagger m)_{ee} = |U_{ei}|^2 m^2_{\nu_i} < (2.2\,{\rm eV})^2$$ (Mainz, Troitsk)

$$\sum_i m_{\nu_i} < 0.6\,{\rm eV} \;\; ({\rm priors})$$ (Cosmology)

Experimental constraints

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$$\sum_i m_{\nu_i} < 0.6\,{\rm eV} \;\; ({\rm priors})$$ (Cosmology)

Guidelines for theory:

$$m_{\nu_i} \ll 174\,{\rm GeV}$$

$$\theta_{23} \sim 45^\circ (= 45^\circ ?)$$

$$\theta_{12} \sim 30^\circ\text{–}35^\circ \neq 45^\circ \;\; (> 5\sigma)$$

$$\theta_{13} < 10^\circ$$

$$|\Delta m^2_{12} / \Delta m^2_{23}| \approx 0.035 \ll 1$$

Origin of neutrino masses

$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM}^{\rm ren} + \frac{h_{ij}}{\Lambda}(HL_i)(HL_j) + \ldots$$

$$m_\nu = hv \times \frac{v}{\Lambda}$$

$$\Lambda \sim 0.5 \times 10^{15}\,\text{GeV}\,h \left(\frac{0.05\,\text{eV}}{m_\nu}\right)$$

* $M_{GUT} \approx 2 \times 10^{16}$ GeV
* $\Lambda_L \sim 10^{15}$ GeV, $\Lambda_B > 4 \times 10^{15}$ GeV
* (no or small L, B violation at TeV scale)

Right-handed neutrinos

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{matrix} u^c \\ d^c \end{matrix} \quad \begin{pmatrix} \nu \\ e \end{pmatrix} \quad \begin{matrix} \nu^c \\ e^c \end{matrix}$$

$SU(3)_C \times SU(2)_W \times U(1)_Y$

$$\lambda \nu_c L H \to m_\nu = \lambda_\nu v$$

(like the other fermions)

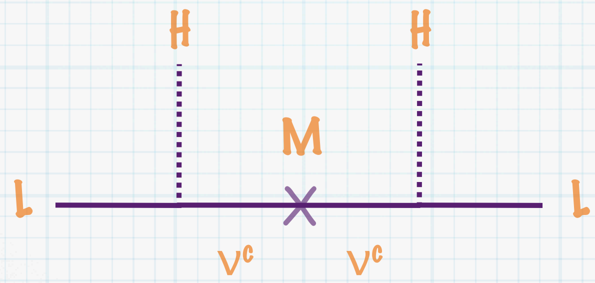
ν_c is a SM singlet and can therefore be heavy

$$\mathcal{L}_{\mathrm{HE}} \supset -\frac{M}{2} \nu^c \nu^c$$

(unlike the other fermions)

See-saw

Integrate out ν^c:



$$\frac{h}{\Lambda}(HL)(HL)$$

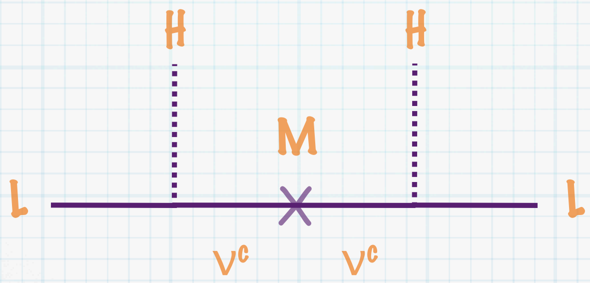
$$\frac{h}{\Lambda} \to -\lambda^T \frac{1}{M} \lambda$$

$$m_\nu = -m_{\rm D}^T \frac{1}{M} m_{\rm D}$$

Majorana

See-saw

Integrate out ν^c:



$$\frac{h}{\Lambda}(HL)(HL)$$

$$\frac{h}{\Lambda} \to -\lambda^T \frac{1}{M} \lambda$$

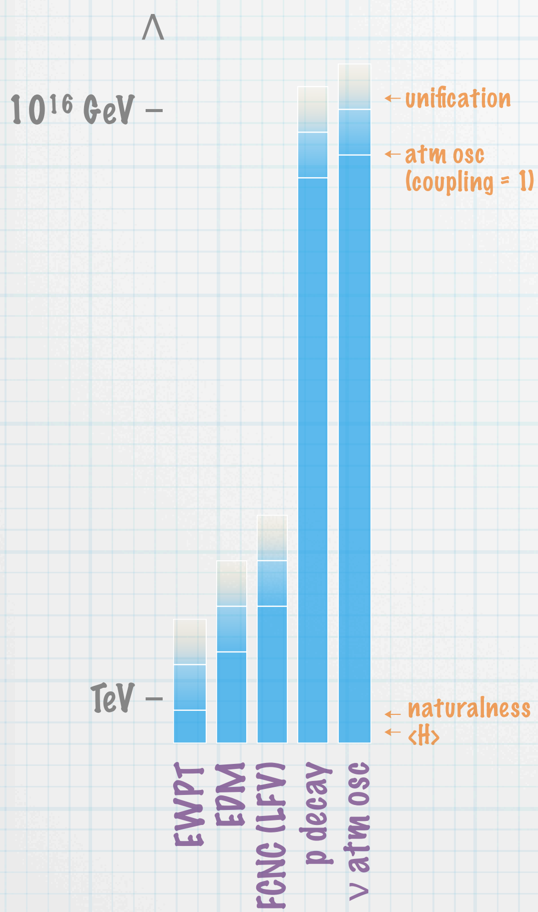
$$m_\nu = -m_D^T \frac{1}{M} m_D$$

Majorana

More options: additional fermion singlets, fermion or scalar triplets, type II see-saw

See-saw induced LFV

Borzumati Masiero 86
Hisano Moroi Tobe Yamaguchi Yanagida 95



M0: $m_L^2 = m_0^2 \mathbf{1}$

Source of LFV: $\lambda^E_{ij} e^c_i L_j H_d + \lambda^N_{ij} \nu^c_i L_j H_u + \frac{M_{ij}}{2} \nu^c_i \nu^c_j$

m̃: $\delta^L_{e_i e_j} \equiv \frac{(m_L^2)_{e_i e_j}}{m^2_{\tilde{e}}} \sim -\frac{3}{(4\pi)^2} \left(\lambda_N^\dagger \log \frac{M_0^2}{M M^\dagger} \lambda_N \right)_{e_i e_j}$

$$\mathrm{BR}(e_i \to e_j \gamma) \sim \frac{\alpha^3}{G_F^2} \frac{|\delta^L_{ij}|^2}{m^4_{\tilde{l}}} \tan^2\beta$$

Model dependence

Ellis Gomez Leontaris Lola Nanopoulos 99
Lavignac Masina Savoy 01
Casas Ibarra 01
Masiero Vempati Vives 02
Petcov Shindou Takanishi 05

* **Overall size of neutrino Yukawa couplings**

$$\begin{matrix} \lambda_N \to k\,\lambda_N \\ M \to k^2 M \end{matrix} \;\Rightarrow\; \begin{matrix} m_\nu \to m_\nu \\ \mathrm{BR}(e_i \to e_j\gamma) \to k^4 \log k\, \mathrm{BR}(e_i \to e_j\gamma) \end{matrix}$$

* **Unknown flavour structure**

$v_d\lambda_E,\ v_u\lambda_N,\ M$ — 21 physical parameters

$m_e\, m_\mu\, m_\tau,\ m_{\nu_1}\, m_{\nu_2}\, m_{\nu_3},\ U$ — 12 known or measurable parameters

9 unknowns = 3 masses + 3 angles + 3 phases

e.g. $v_u\lambda_N = v_u\lambda_N^{\text{diag}} V_N$ or M^{diag},

$R = 1/\sqrt{M^{\text{diag}}}\, v_u\lambda_N\, U^\dagger/\sqrt{M^{\text{diag}}}$

↰ Casas Ibarra 01

The overall size of λ_N and Pati-Salam (SO(10))

* G_{PS} = SU(2)$_L$ x SU(2)$_R$ x SU(4)$_c$ SU(4)$_c$ $\supset$ SU(3)$_c$ x U(1)$_{B-L}$

* 3rd family:

$$F_{L,R} = \begin{pmatrix} \nu_\tau & t_1 & t_2 & t_3 \\ \tau & b_1 & b_2 & b_3 \end{pmatrix}_{L,R}$$

$$\lambda_1 \bar{F}_R F_L H_1 + \lambda_{15} \bar{F}_R F_L H_{15} \rightarrow \begin{cases} \lambda_{\nu_3} = a\lambda_1 + 3b\lambda_{15} \\ \lambda_t = a\lambda_1 - b\lambda_{15} \end{cases} \qquad (H_{15} \propto B - L)$$

$$\lambda_{\nu_3} \sim \lambda_t$$

* Lighter families: may involve NR operators

The flavour structure and the origin of $\vartheta_{\rm ATM}$

* The large atmospheric neutrino angle can originate from m_ν or m_E

$$m_\nu = U_\nu^T m_\nu^{\rm diag} U_\nu \qquad\qquad U = U_\nu U_e^\dagger$$
$$m_E = U_{e^c}^T m_E^{\rm diag} U_e$$

* In the see-saw context, from

$$\lambda_E \quad \text{or} \quad \lambda_N^T \frac{1}{M} \lambda_N$$

* Ultimately, from the Yukawa matrices (presumably λ_E) or the see-saw mechanism

* The large atmospheric angle originates from (misaligned) Yukawas:

$$\delta^L_{\mu\tau} \sim -\frac{3}{(4\pi)^2}\left(\lambda_N^\dagger \log\frac{M_0^2}{MM^\dagger}\lambda_N\right)_{\mu\tau} \sim -\lambda^2_{\nu_3}\sin 2\theta_{\rm ATM}\frac{3}{2(4\pi)^2}\left(\log\frac{M_0^2}{MM^\dagger}\right)_{33}$$

→ B-physics

Harnik Larson Murayama 02

* The large atmospheric angle originates from the see-saw

$$\delta^L_{\mu\tau} \sim -\frac{3}{(4\pi)^2}\left(\lambda_N^\dagger \log\frac{M_0^2}{MM^\dagger}\lambda_N\right)_{\mu\tau} \sim -\lambda^2_{\nu_3}\sin 2\theta_{\rm CKM}\frac{3}{2(4\pi)^2}\left(\log\frac{M_0^2}{MM^\dagger}\right)_{33}$$

* LFV processes probe the origin of neutrino angles

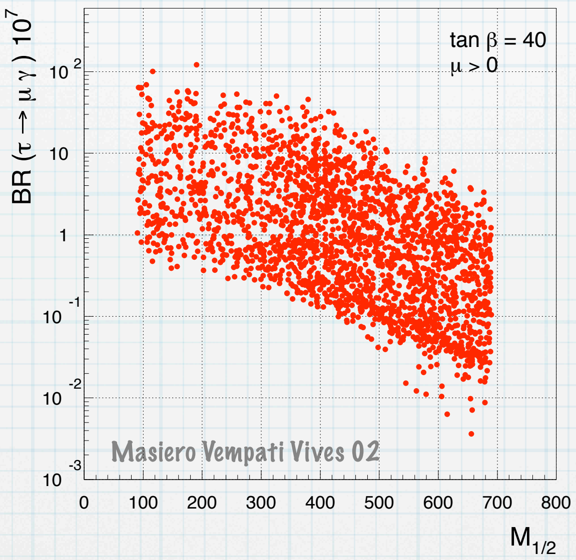
SO(10) inspired example

* Assume $\lambda_U = \lambda_N$ and λ_N, M_N can be simultaneously diagonalized (ϑ_{ATM} from λ's)

* Then $$\delta^L_{\mu\tau} = -\lambda_t^2 \sin 2\theta_{\rm ATM} \frac{3}{(4\pi)^2} \log \frac{M_0}{M_3}, \qquad M_3 = \frac{m_t^2}{2m_{\nu_1}}$$

$BR(\tau \to \mu\gamma) < 3 \times 10^{-7}$ →

Future: $BR(\tau \to \mu\gamma) < 10^{-8}$



90 GeV < m_0 < 900 GeV
90 GeV < $M_{1/2}$ < 700 GeV
$A_0 = a\, m_0$ $-3 < a < 3$
$m_{\nu 1} = 10^{-3}$ eV $\tan\beta = 40$

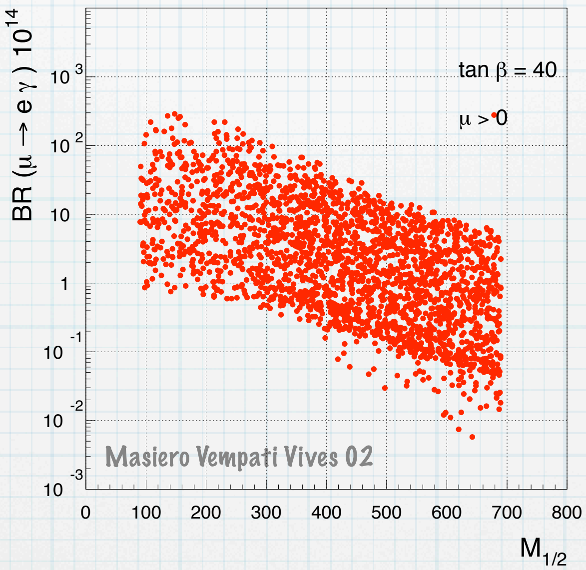
* $BR(\mu \to e\gamma)$ can also be predicted (in terms of U_{e3}) and turns out to be large (all angles from Yukawas?)

* Assume $\lambda_U = \lambda_N$ and $\lambda_E = \lambda_D = (\lambda_D)^T$ (ϑ_{ATM} from see-saw)

* Then $\delta^L_{\mu\tau} = -\lambda_t^2 V_{ts}^* V_{tb} \frac{6}{(4\pi)^2} \log \frac{M_0}{M_3}, \qquad M_3 = \frac{m_t^2}{2 m_{\nu_1}}$

BR($\mu \to e\gamma$) < 1.2 x 10^{-11} →

Future: BR($\mu \to e\gamma$) < $10^{-(13\text{-}14)}$



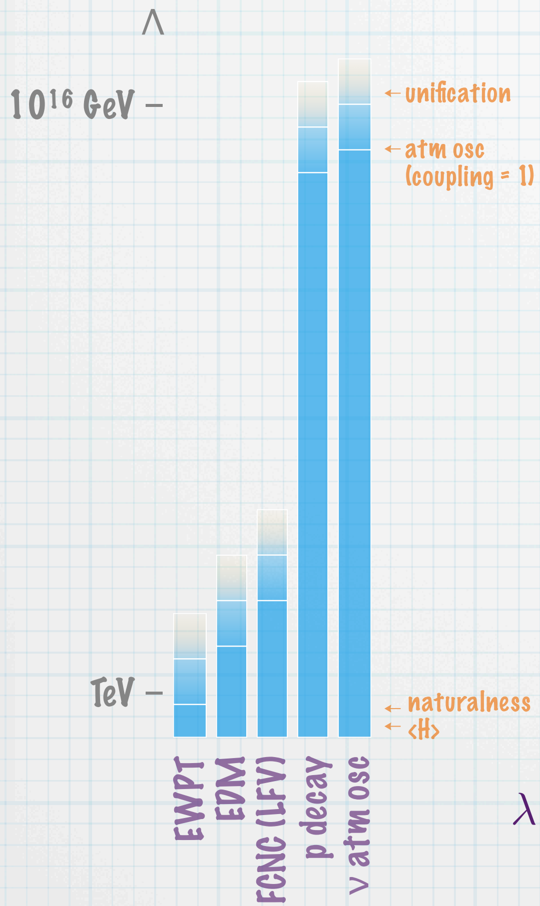
90 GeV < m_0 < 900 GeV
90 GeV < $M_{1/2}$ < 700 GeV
A_0 = a m_0 -3 < a < 3
$m_{\nu 1}$ = 10^{-3} eV tanβ = 10

* BR($\tau \to \mu\gamma$) can also be predicted and turns out to be interesting only for large tanβ

GUT and LFV

SU(5) induced LFV

Barbieri Hall 94



M0: $m^2_{e^c} = m^2_0 \mathbf{1}$

Source of LFV: $\lambda^U_{ij} u^c_i e^c_j H_3$

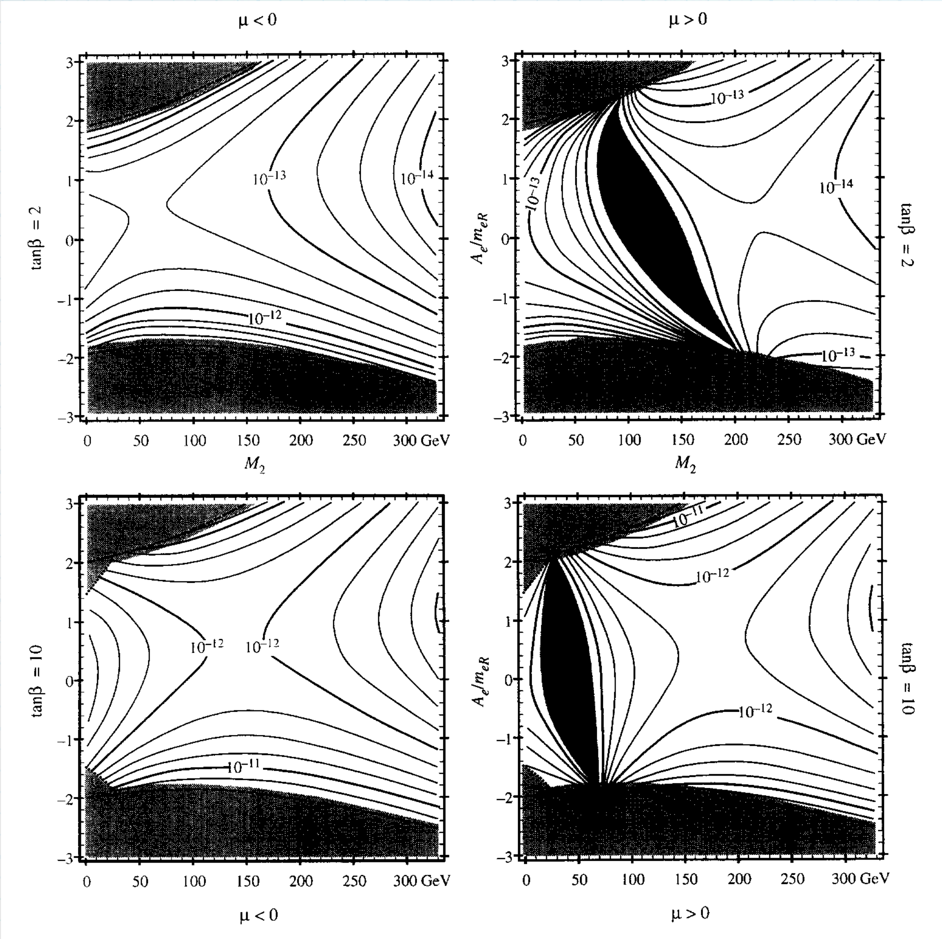
SU(5): $e^c + u^c + Q = 10 \Rightarrow \quad \lambda^U_{ij} u^c_i Q_j H_U \Rightarrow \lambda^U_{ij} u^c_i e^c_j H_3$

m̃: $\delta^e_{e^c_i e^c_j} \equiv \frac{(m^2_{e^c})_{e^c_i e^c_j}}{m^2_{\tilde{e}^c}} \sim -\frac{9}{(4\pi)^2} (\lambda_U^\dagger \lambda_U)_{e^c_i e^c_j} \log \frac{M_0^2}{M^2_{\mathrm{GUT}}}$

$$\lambda_U = \lambda_U^{\mathrm{diag}} \qquad \lambda_D = U_d^T \lambda_D^{\mathrm{diag}} V^\dagger_{\mathrm{CKM}} \qquad \lambda_E = \lambda_D^T = V^*_{\mathrm{CKM}} \lambda_E^{\mathrm{diag}} U_d^T$$

$$(\lambda_U^\dagger \lambda_U)_{e^c_i e^c_j} = V^*_{ti} V_{tj} \lambda_t^2$$

$\mathrm{BR}(\mu \to e\gamma)$ Future: $\mathrm{BR}(\mu \to e\gamma) < 10^{-(13\text{-}14)}$



$\tilde{m}_e$ = 300 GeV

Barbieri Hall Strumia 95

* $$\lambda_D = \begin{pmatrix} 0 & \epsilon_1' & 0 \\ \epsilon_2' & \epsilon & x \\ 0 & y & 1 \end{pmatrix}$$

$$\lambda_E = \begin{pmatrix} 0 & \epsilon_2' & 0 \\ \epsilon_1' & -3\epsilon & y \\ 0 & x & 1 \end{pmatrix}$$

Georgi Jarlskog

$$\mathrm{BR}(\mu \to e\gamma) \to \frac{1}{9}\,\mathrm{BR}(\mu \to e\gamma)$$

* SO(10): $(m_\tau/m_\mu)^2$ enhancement of $\mathrm{BR}(\mu \to e\gamma)$
* $\mathrm{BR}(\tau \to \mu\gamma)$ suppressed compared to the SU(5) case by V_{ts}

Lepton EDMs

* From see-saw: significantly below the present experimental limit

Ellis Hisano Lola Raidal 01
Masina 03
Farzan Peskin 04

$$d_e \sim 10^{-29} e\,\mathrm{cm}\, \lambda_\nu^4 \log \frac{M_3^2}{M_1^2} \left(\frac{200\,\mathrm{GeV}}{\tilde{m}}\right)^2 \qquad \tan\beta \lesssim 10$$

$$d_e \sim 10^{-29} e\,\mathrm{cm}\, \lambda_\nu^4 \left(\frac{\tan\beta}{10}\right)^3 \log \frac{M_3^2}{M_1^2} \left(\frac{200\,\mathrm{GeV}}{\tilde{m}}\right)^2 \frac{(\log M_0^2/M_N^2)^2}{200} \qquad \tan\beta \gtrsim 10$$

$$\text{“}\lambda_\nu^4\text{”} = \lambda_{\nu_3}^3 \lambda_{\nu_2} \times \mathrm{Im(mixings)}$$

($SU(3)_L$ x $SU(3)_e$ x $SU(3)_\nu$ transformation properties:

$$d_{e_i} \propto \lambda_{e_i} \mathrm{Im}[\lambda_N^\dagger f(MM^\dagger)\,\lambda_N \lambda_N^\dagger g(MM^\dagger)\lambda_N]_{e_i e_i}$$)

* In unified models: prediction close to the present experimental limit (SO(10) allows to avoid $d_{ei} \propto m_{ei}$)

($SU(3)_{16}$ transformation properties: $d_{e_i} \propto \mathrm{Im}[\lambda_U \lambda_D^\dagger \lambda_U \lambda_U^\dagger \lambda_U]_{e_i e_i}$)

$$\frac{d_e}{10^{-27} e\,\mathrm{cm}} = \sin\phi \left(\frac{\mathrm{BR}(\mu\to e\gamma)}{10^{-12}}\right)^{1/2}$$

Future: d_e/(e cm) $\to 10^{-29} \to 10^{-31}$, muon EDM

LFV and colliders

Arkani-Hamed Cheng Feng Hall 96
Hisano Nojiri Shimizu Tanaka 98
Hinchliffe Paige 00
Carvalho Ellis Gomez Lola Romao 05
Bartl Hidaka Hohenwarter-Sodek
Kernreiter Majerotto Porod 05

Mixing angles and limits on mass insertions

* The $e_i \to e_j \gamma$ rates are controlled by the size of the mass insertions
  - e.g. for "left-handed" sleptons

$$\delta^L_{e_i e_j} \equiv \frac{(m^2_L)_{e_i e_j}}{m^2_{\tilde{e}}} \qquad \begin{cases} |\delta^L_{e\mu}| < 3 \times 10^{-4} \\ |\delta^L_{\mu\tau}| < 0.09 \\ |\delta^L_{e\tau}| < 0.09 \end{cases}$$

(m_0 = 400 GeV)

Hisano Nomura 98
Masina Savoy 02
Ciuchini Masiero Silvestrini
Vempati Vives 03

* $\delta_{ij} \ll 1$ ($i \neq j$) ⇔ small mixing or GIM cancellation

e.g. neglecting 1-[23] mixing: $\delta^L_{\mu\tau} = \sin 2\tilde{\theta}_L \, \dfrac{m^2_{\tilde{\mu}} - m^2_{\tilde{\tau}}}{2\tilde{m}^2}$ ($\tilde{\theta}_L$ = mixing $[\mu\tau]_L$- $[\tilde{\mu}\tilde{\tau}]_L$)

- $$\frac{m^2_{\tilde{\mu}} - m^2_{\tilde{\tau}}}{2\tilde{m}^2} = \mathcal{O}(1), \text{ small } \tilde{\theta}: \qquad \begin{cases} \tilde{\tau} \to \tau \text{ (mainly)} \\ \tilde{\mu} \to \mu \text{ (mainly)} \end{cases}$$
- $$\sin 2\tilde{\theta} = \mathcal{O}(1), \text{ small } \frac{m^2_{\tilde{\mu}} - m^2_{\tilde{\tau}}}{2\tilde{m}^2}: \qquad \begin{cases} \tilde{\tau} \to \tau + \mu \\ \tilde{\mu} \to \mu + \tau \end{cases}$$

* If $\tilde{\vartheta}$ is large

  - example: see-saw induced LFV + large mixings in Yukawas

$$(m_L^2)_{e_i e_j} \sim m_0^2\, \delta_{ij} - \frac{1}{(4\pi)^2} (\lambda_N^\dagger \log \frac{M_0^2}{M M^\dagger} \lambda_N)_{e_i e_j} m_0^2$$

(the lepton-slepton mixings is determined by)

then $P(\chi_2 \to (\tilde{e}_i e_j)_L \to \mu^\pm \tau^\mp \chi_1) \sim P(\chi_2 \to (\tilde{e}_i e_j)_L \to \mu^\pm \mu^\mp \chi_1)$, independently of $\Delta m^2_{\tilde{\mu}\tilde{\tau}}$, provided that

  - the process is allowed
  - $\frac{\Delta m^2_{\tilde{\mu}\tilde{\tau}}}{2\tilde{m}^2} \gtrsim \frac{\Gamma_{\tilde{\mu},\tilde{\tau}}}{\tilde{m}}$ Arkani-Hamed Cheng Feng Hall 96

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Origin of flavour

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Origin of flavour ⇒

$$\begin{cases} \lambda_E \\ m_L^2 \end{cases}$$

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Origin of flavour

$$\begin{cases} \lambda_E = U_{e^c}^T \lambda_E^{\text{diag}} U_L, \quad \text{with } U_L \ni \theta_{\text{ATM}} \\ m_L^2 = \text{ whatever (with } \tilde{\mu},\, \tilde{\tau} \text{ degenerate enough)} \end{cases}$$

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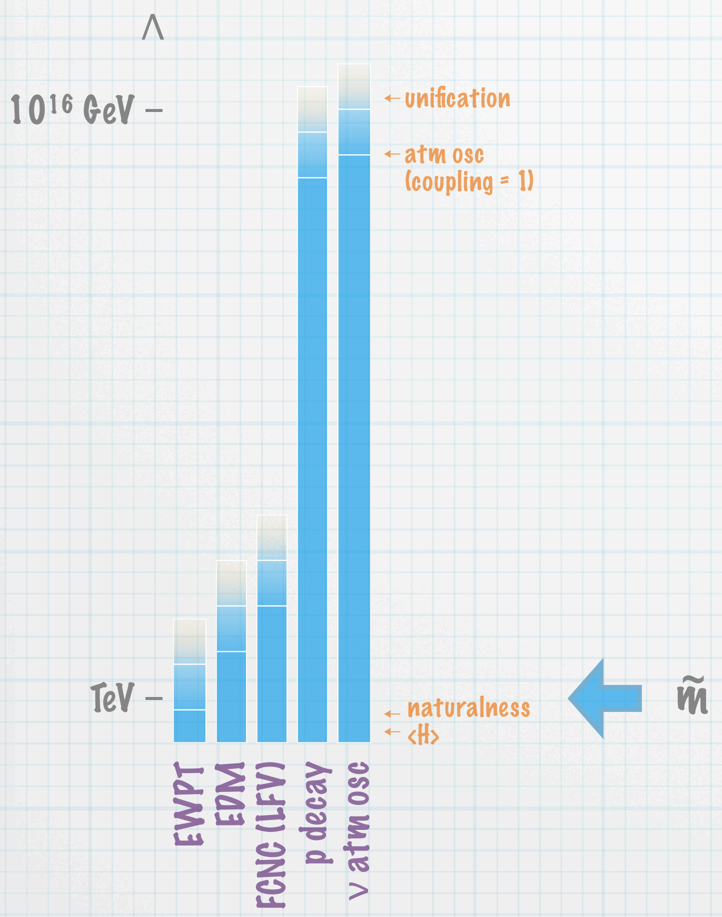
⇓

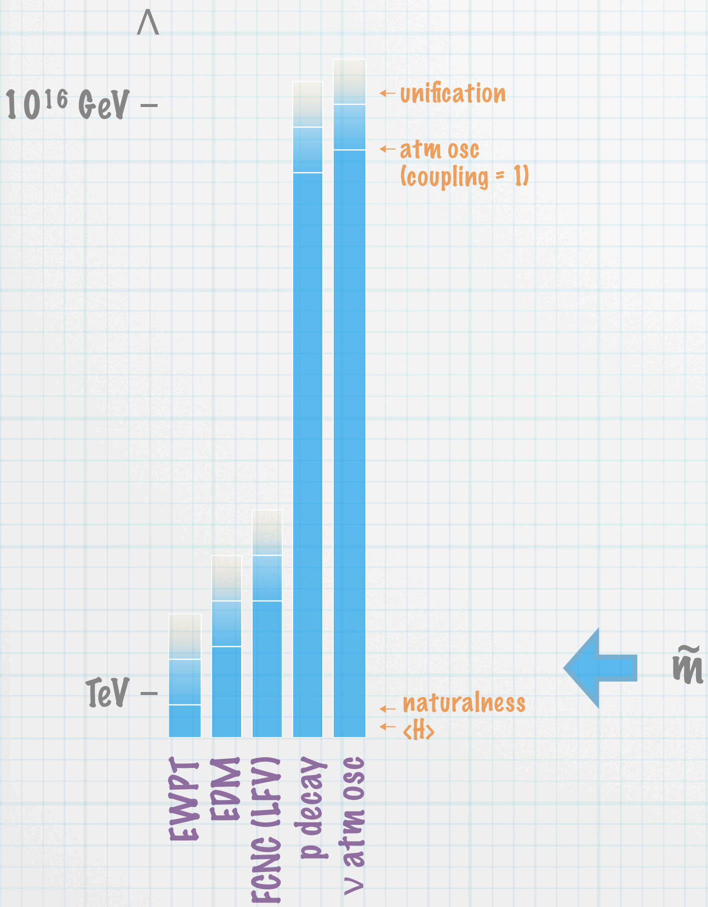
$$m_L^2 \to U_L^\dagger m_L^2 U_L \ni \theta_{ATM}$$

* Measuring lepton-slepton mixing at colliders would provide a crucial handle on the origin of flavour

Dependence of LFV and CPV effects on slepton masses

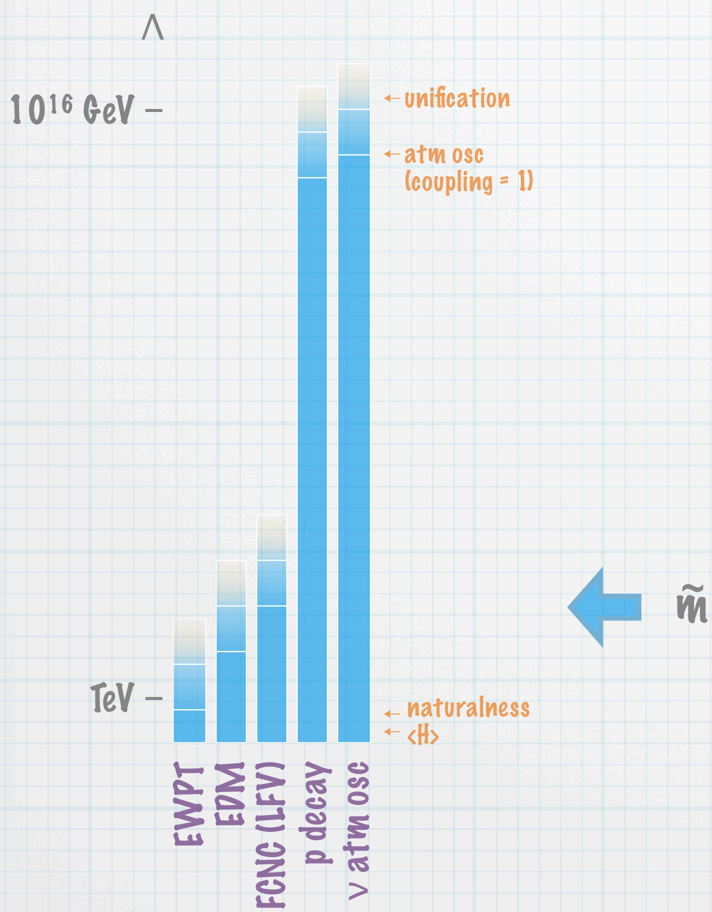


Dependence of LFV and CPV effects on slepton masses



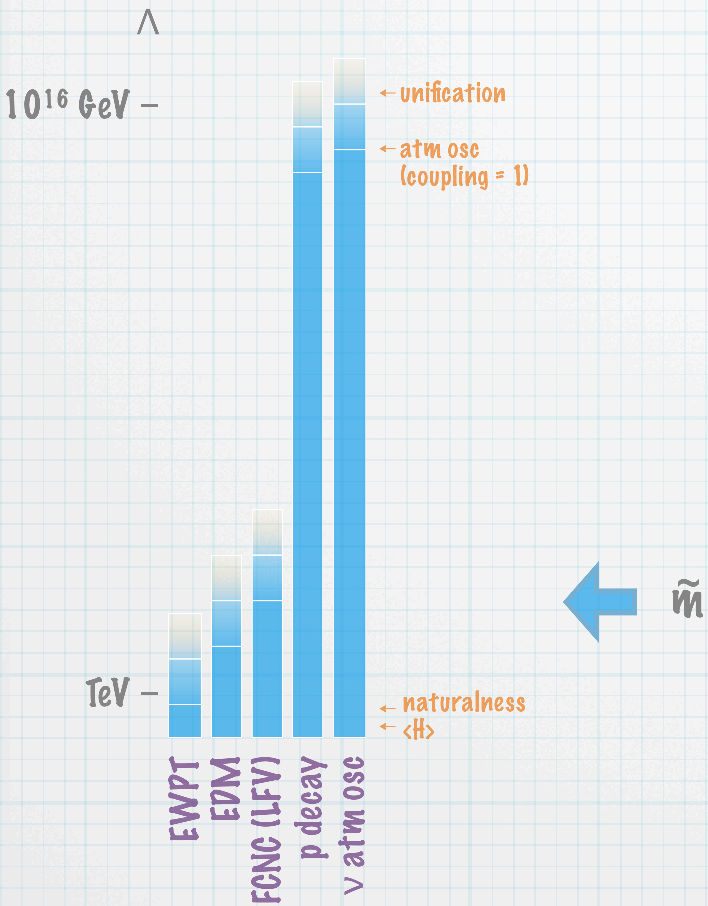
* Minimal effects get quickly negligible for heavier slepton masses

Dependence of LFV and CPV effects on slepton masses

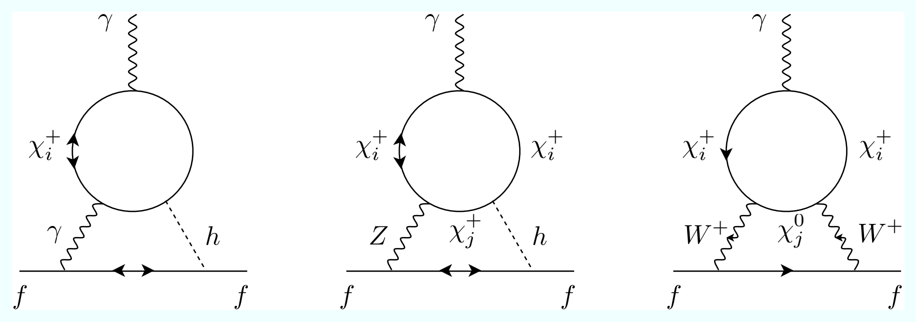


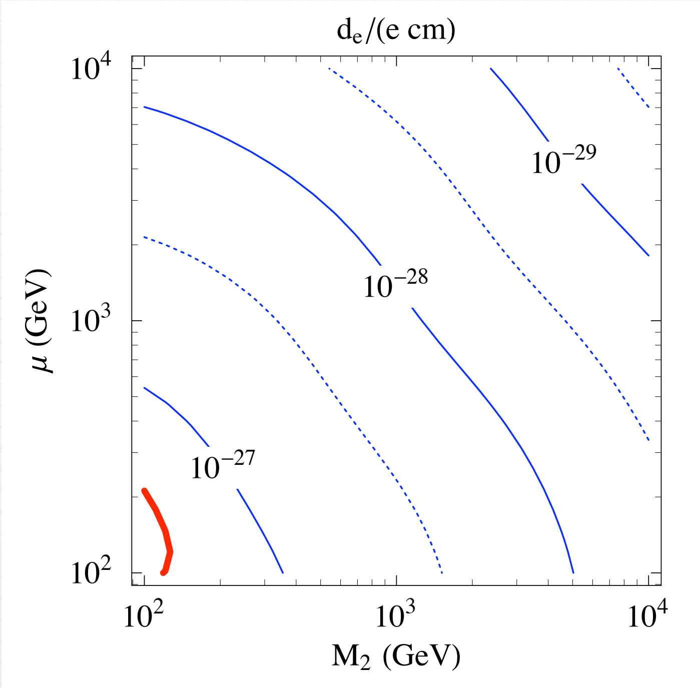
* Minimal effects get quickly negligible for heavier slepton masses
* The effects of generic soft terms become unobservable above 100 TeV

Dependence of LFV and CPV effects on slepton masses



* Minimal effects get quickly negligible for heavier slepton masses
* The effects of generic soft terms become unobservable above 100 TeV
* except the EDMs (provided that the charginos are light enough to account for dark matter)





$\tan\beta = 1$

$\sin\phi = 1$

Future: $d_e/(e\ cm) \rightarrow 10^{-29} \rightarrow 10^{-31}$

Giudice R 05

Conclusions

1. Leptons provide so far the only clear evidence of flavour structure beyond the SM

2. The new flavour structure is characterized by large mixings

3. Lepton radiative decays and EDMs provide important constraints on possible manifestation of LFV and CPV. Signals could be around the corner.

4. 1+2: in a supersymmetric scenario the slepton sector would be especially suited to study flavour changing phenomena and could provide unique information on the origin of flavour structure