Baryon number violation in tau decays

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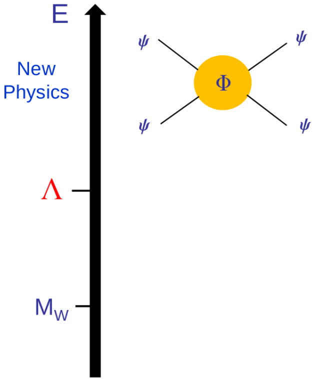
General framework



ψ ≡ SM fields
Φ ≡ NF heavier fields

$$\mathcal{L}_{\rm NP}\left[\psi, \Phi\right]$$

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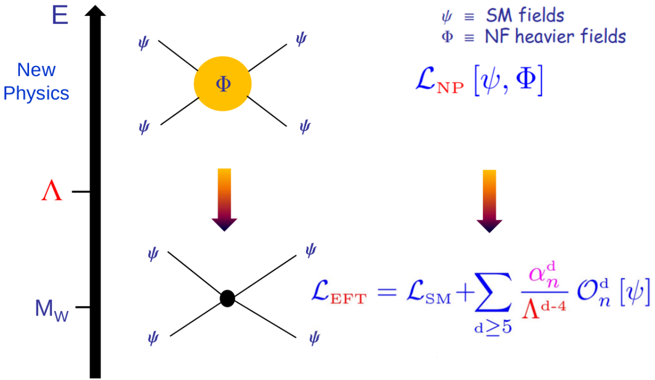

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$$\mathcal{L}_{\mathrm{NP}}\left[\psi,\Phi\right]$$

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\mathrm{d}\geq 5} \frac{\alpha_n^{\mathrm{d}}}{\Lambda^{\mathrm{d\text{-}4}}}\,\mathcal{O}_n^{\mathrm{d}}\left[\psi\right]$$

[Buchmüller, Wyler, 1986], [B. Grzadkowski et al., 2010]

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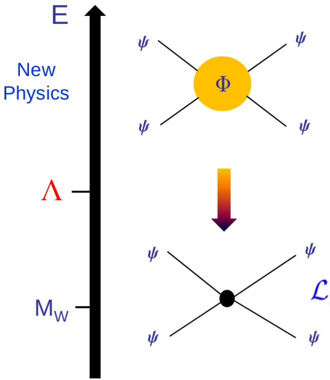

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$$\downarrow$$

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Baryon number violation?

Baryon number (B)

Lepton number (L)

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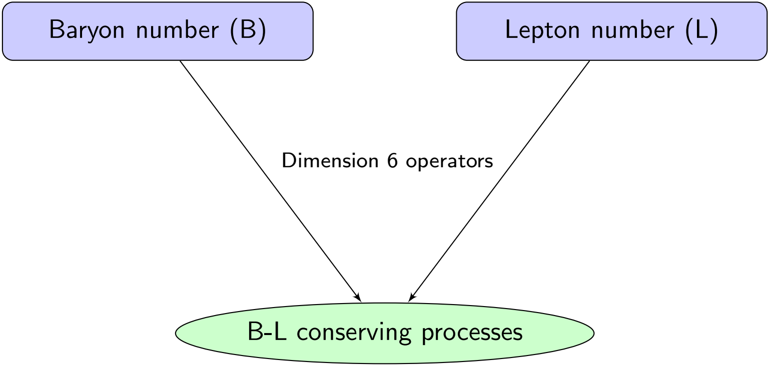

Baryon number (B)

Lepton number (L)

Dimension 6 operators

B-L conserving processes

Why baryon number violation?

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   [G. 't Hooft, 1976]

   ⇒ The measurement of BNV would have the track of new physics.
3. Some BSM theories such as Grand Unified theories put quarks and leptons in the same multiplets which in general leads to B-violating processes which much larger probability.

BNV decays

$$\tau^+ \to p\mu^+\mu^-$$

[LHCb Collaboration, 2013]

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$$\tau^+ \to \Lambda\pi^+$$

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A framework to deal with hadrons

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$$u\left(\phi\right) = e^{\frac{i}{\sqrt{2}f}\phi}, \quad \phi = \frac{1}{\sqrt{2}}\sum_{i=1}^{8}\lambda_i\phi_i = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}$$

[Gasser and Leutwyler, 1984]

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$$\text{Symmetry: } G \equiv SU(3)_L \otimes SU(3)_R \xrightarrow{SSB} SU(3)_{L+R}$$

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$$V_{\mu\nu} = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega_8}{\sqrt{6}} + \frac{\omega_1}{\sqrt{3}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega_8}{\sqrt{6}} + \frac{\omega_1}{\sqrt{3}} & K^{*0} \\ K^{*-} & \overline{K}^{*0} & -\frac{2\omega_8}{\sqrt{6}} + \frac{\omega_1}{\sqrt{3}} \end{pmatrix}_{\mu\nu}$$

[G. Ecker et al., 1989]

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$$\text{Matter content: } \begin{cases} \text{Mesons octect} & \chi\text{PT} \\ \text{Resonances} & \text{R}\chi\text{T} \\ \text{Baryons} & \end{cases}$$

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

[A. Krause, 1990]

BNV effective operators

$\Delta S = 0$

$$
\begin{aligned}
\mathcal{O}_{RL} &= \epsilon_{\alpha\beta\gamma}\overline{(d_{R\alpha})^C}u_{R\beta}\overline{(u_{L\gamma})^C}\tau_L \\
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\end{aligned}
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    - finding operators in terms of mesonic and baryonic fields with the same transformation rules.

Effective Field Theories
Baryon number violation?
Why baryon number violation?
BNV decays
A framework to deal with hadrons
Results
Take home message

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Analogue to the $\Delta S = 1$ Weak Chiral Lagrangian!

Hadronizing the operators II

Hadronized operators

$$
\begin{aligned}
\mathcal{O}^h_{RL} &= \alpha\overline{(\tau_L)^C}\langle Pu^\dagger B_L u^\dagger\rangle & \tilde{\mathcal{O}}^h_{RL} &= \alpha\overline{(\tau_L)^C}\langle \tilde{P}u^\dagger B_L u^\dagger\rangle \\
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\end{aligned}
$$

Strong coefficients

$$
\begin{aligned}
\langle 0 \mid \mathcal{O}_{RL} \mid p\rangle &= \alpha P_L u_p & \langle 0 \mid \mathcal{O}_{LR} \mid p\rangle &= -\alpha P_R u_p \\
\langle 0 \mid \mathcal{O}_{LL} \mid p\rangle &= \beta P_L u_p & \langle 0 \mid \mathcal{O}_{RR} \mid p\rangle &= -\beta P_R u_p
\end{aligned}
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$$\mathcal{O}^h_{LR} = -\alpha\overline{(\tau_R)^C}\langle P u B_R u\rangle \qquad \tilde{\mathcal{O}}^h_{LR} = -\alpha\overline{(\tau_R)^C}\langle \tilde{P} u B_R u\rangle$$

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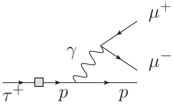
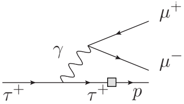
[Weinberg, 1979]

$\tau^+ \to p\mu^+\mu^-$


μ^+
γ
μ^-
τ^+
p
p


μ^+
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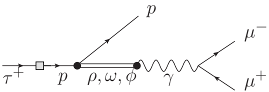
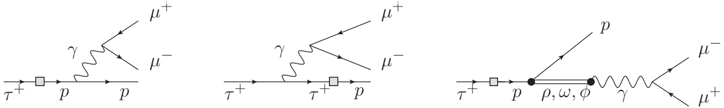

p
μ^-
τ^+
p
ρ, ω, ϕ
γ
μ^+

$\tau^+ \to p\mu^+\mu^-$



$$\Gamma_{\tau^+\to p\mu^+\mu^-} = \frac{1}{\Lambda^4}\Big[2.23\times 10^{-9}\ \mathrm{GeV}^5\left(|C_{RL}|^2+|C_{LR}|^2\right)$$
$$+2.66\times 10^{-9}\ \mathrm{GeV}^5\ Re\left\{C_{RL}C_{LR}^*\right\}\Big]$$

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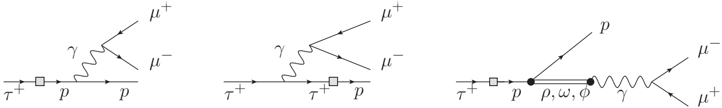

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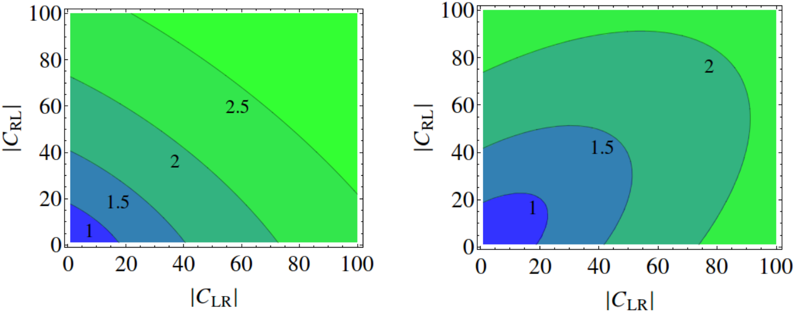
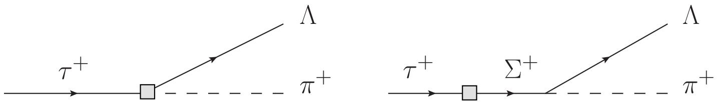
$$\mathcal{B}\left(\tau^+\to p\mu^+\mu^-\right) < 3.3\times 10^{-7} \overset{\text{Naturalness}}{\Longrightarrow} \begin{cases}\Lambda_+ \geq 0.3\ \mathrm{TeV}\\ \Lambda_- \geq 0.2\ \mathrm{TeV}\end{cases}$$

[LHCb Collaboration, 2013]

$\tau^+ \to p\mu^+\mu^-$. Contour plots



$\tau^+ \to \Lambda\pi^+$



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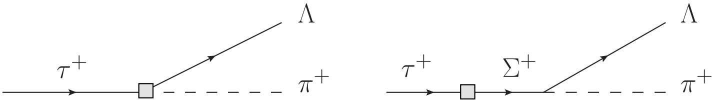

$$\Gamma\left(\tau^+ \to \Lambda\pi^+\right) = \frac{1}{\Lambda^4}\left[4.41 \times 10^{-3}\ \mathrm{GeV}^5 \left(\left|\tilde{C}_{LR}\right|^2 + \left|\tilde{C}_{RL}\right|^2\right)\right.$$
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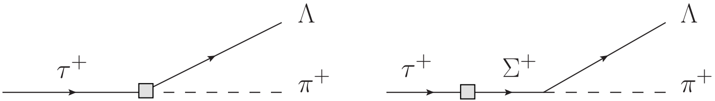

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$$\left. -0.57 \times 10^{-3}\ \mathrm{GeV}^5\, Re\left\{\tilde{C}_{LR}\tilde{C}^*_{RL}\right\}\right]$$

$$\mathcal{B}\left(\tau^+ \to \Lambda\pi^+\right) < 1.4 \times 10^{-7} \overset{\text{Naturalness}}{\Longrightarrow} \Lambda \geq 13\ \mathrm{TeV}$$

[Belle Collaboration, 2006]

Take home message

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1. Direct searches of BNV tau decays do not constrain them too much. But from proton decay analysis one can obtain way heavier constraints [W. Hou et al., 2005]
   ⇒ It is unlikely that BNV tau decays will be measured in future experiments.
2. A more exhaustive analysis of BNV channels involving dimension six operators can be used to disentangle the operators (Work in progress).

Backup slides

Standard Model effective operators

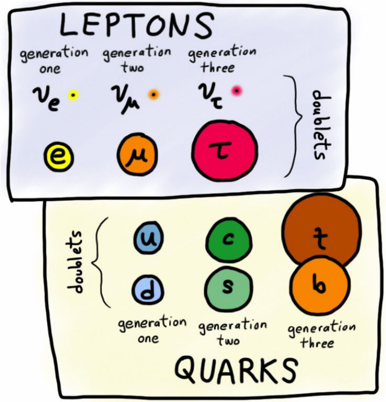
Lepton Flavor Violating (LFV) operators

$$
\begin{aligned}
\mathcal{O}_{eW} &= \left(\bar{l}_p \sigma^{\mu\nu} e_r\right) \tau^I \varphi W^I_{\mu\nu} & \mathcal{O}_{eB} &= \left(\bar{l}_p \sigma^{\mu\nu} e_r\right) \varphi B_{\mu\nu} \\
\mathcal{O}_{e\varphi} &= \left(\varphi^\dagger \varphi\right)\left(\bar{l}_p e_r \varphi\right) & \mathcal{O}^{(1)}_{\varphi l} &= \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{l}_p \gamma^\mu l_r\right) \\
\mathcal{O}^{(3)}_{\varphi l} &= \left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{l}_p \tau^I \gamma^\mu l_r\right) & \mathcal{O}_{ll} &= \left(\bar{l}_p \gamma_\mu l_r\right)\left(\bar{l}_s \gamma^\mu l_t\right) \\
\mathcal{O}_{ee} &= \left(\bar{e}_p \gamma_\mu e_r\right)\left(\bar{e}_s \gamma^\mu e_t\right) & \mathcal{O}_{le} &= \left(\bar{l}_p \gamma_\mu l_r\right)\left(\bar{e}_s \gamma^\mu e_t\right)
\end{aligned}
$$

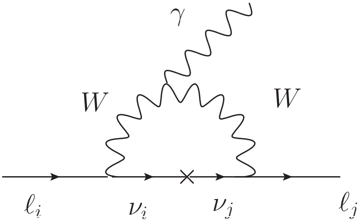
Baryon Number Violating (BNV) operators

$$
\begin{aligned}
\mathcal{O}_{RL} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}\overline{(d_{R\alpha})^C} u_{R\beta}\overline{(q_{iL\gamma})^C} l_{jL} \\
\mathcal{O}_{LR} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}\overline{(q_{L\alpha})^C} q_{L\beta}\overline{(u_{R\gamma})^C} e_R \\
\mathcal{O}_{LL} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}\epsilon_{kl}\overline{(q_{iL\alpha})^C} q_{jL\beta}\overline{(q_{kL\gamma})^C} l_{lL} \\
\mathcal{O}_{RR} &= \epsilon_{\alpha\beta\gamma}\overline{(d_{R\alpha})^C} u_{R\beta}\overline{(u_{R\gamma})^C} e_R
\end{aligned}
$$

Flavor violation?



Why flavor violation?

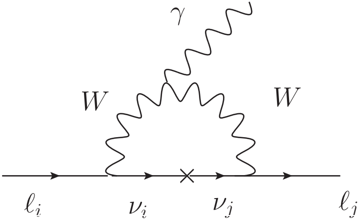


$$\mathcal{B}\left(\ell_i \to \ell_j\gamma\right) \sim \mathcal{O}\left(10^{-40}\right)$$

$$i \neq j$$

[Cheng, Li, 1980]

Why flavor violation?



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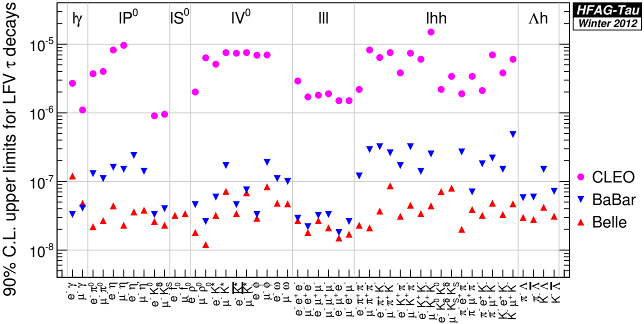
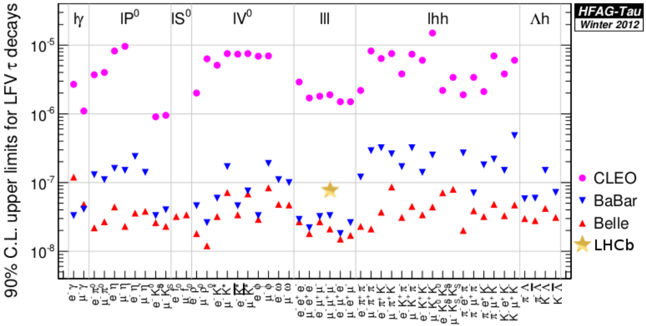
LFV can be used to constrain new physics models!

Experimental bounds



[HFAG-Tau Report, Early 2012]

Experimental bounds



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[LHCb Collaboration, 2013]

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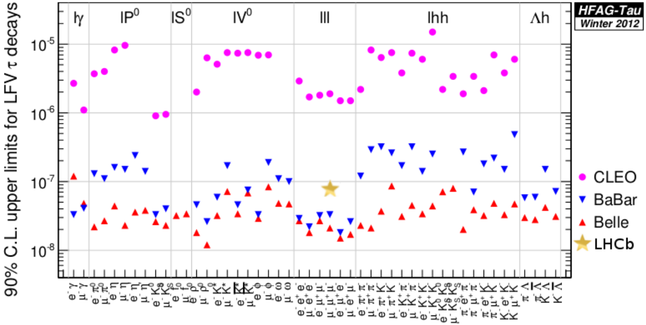

$$\ell_i \to \ell_j \gamma$$

$$\ell_i \to \ell_j \ell_k^+ \ell_k^-$$

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[LHCb Collaboration, 2013]

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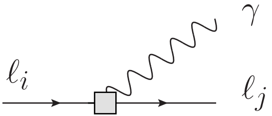
2. LFV vertices between the electron and the muon are strongly suppressed.
3. LFV vertices involving the tau can be well accommodated in a BSM theory at energies around 10 TeV.
4. If ever measured, comparison between the different flavor violating channels allows us to exclude theories.

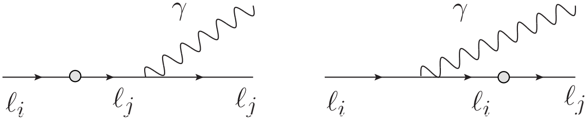
$\ell_i \to \ell_j\gamma$



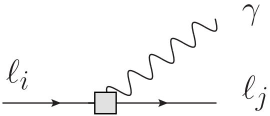
Contributing operators

$$\mathcal{O}_{e\gamma} = \frac{v}{\sqrt{2}} \left(\bar{l}_p \sigma^{\mu\nu} e_r\right) F_{\mu\nu}$$

$$\mathcal{O}_{ev^3} = \frac{v^3}{2\sqrt{2}} \left(\bar{l}_p e_r\right)$$



$\ell_i \to \ell_j\gamma$



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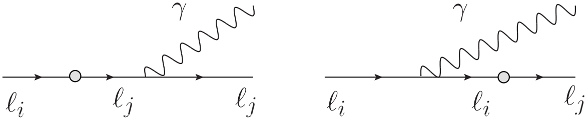

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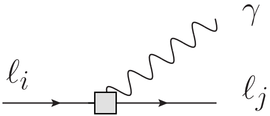

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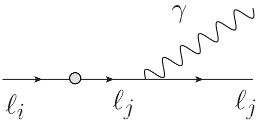

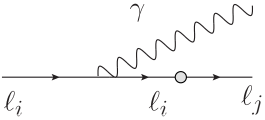

$$\Gamma\left(\ell_i \to \ell_j\gamma\right) = \frac{v^2}{8\pi m_{\ell_i}^3 \Lambda^4} \left(m_{\ell_i}^2 - m_{\ell_j}^2\right)^3 \left(\left|\alpha_L\right|^2 + \left|\alpha_R\right|^2\right)$$

$\ell_i \to \ell_j \ell_k^+ \ell_k^-$

Contributing operators

$$\mathcal{O}_{e\gamma} = \frac{v}{\sqrt{2}} \left(\bar{l}_p \sigma^{\mu\nu} e_r\right) F_{\mu\nu} \qquad \mathcal{O}_{lH} = i \frac{v}{\sqrt{2}} \partial_\mu H \left(\bar{l}_p \gamma^\mu l_r\right)$$

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Contributing operators

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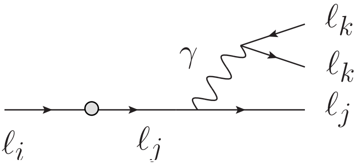
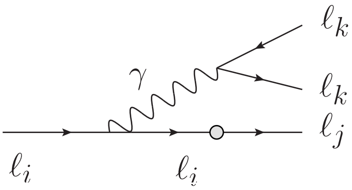
\end{aligned}
$$





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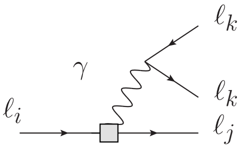
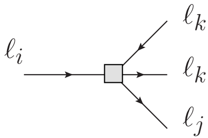


$$\mathcal{O}\left(\frac{ev}{m_{\ell_i}}\right)$$



$$\mathcal{O}(1)$$

A stone in the road

1. If the BSM theory is a general gauge theory consisting of scalars, fermions and vectors, photon exchange operators are loop generated.

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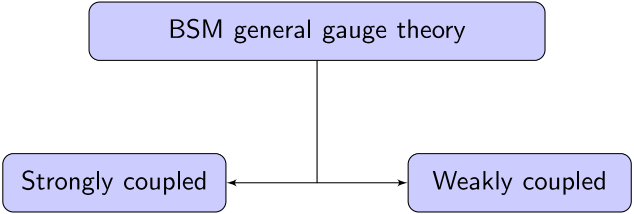
3. We need to clearly establish the conditions where photon contribution dominates.

Clarifying the framework

BSM general gauge theory

Clarifying the framework

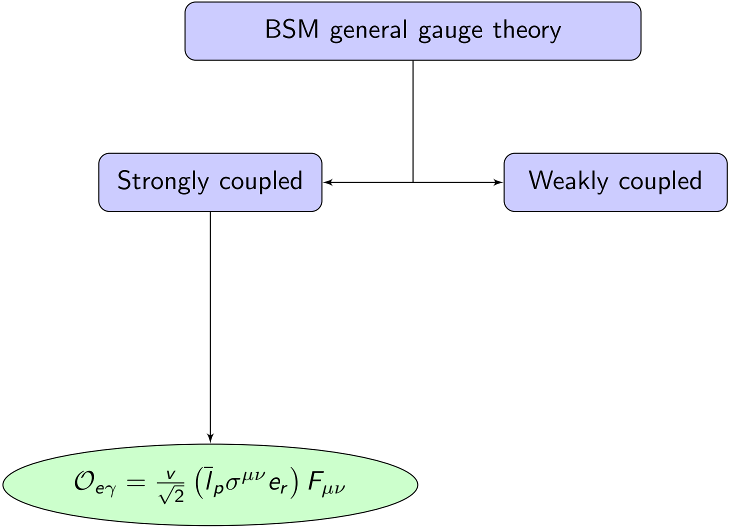


BSM general gauge theory

Strongly coupled

Weakly coupled

Clarifying the framework



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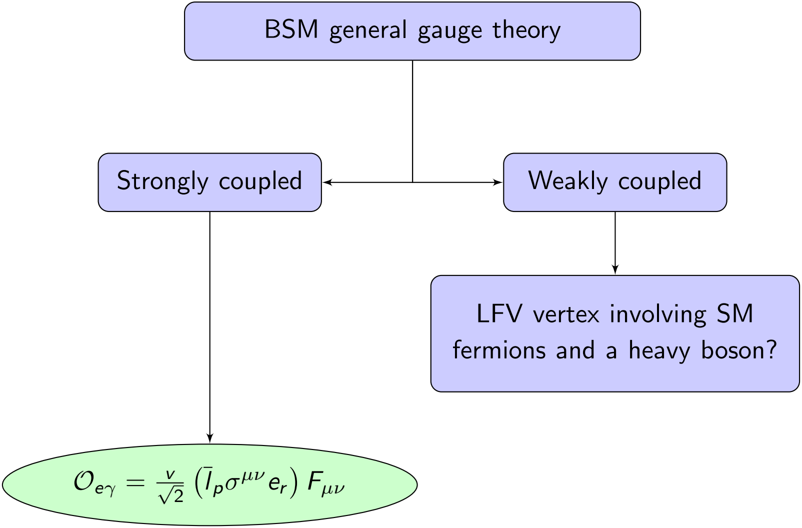

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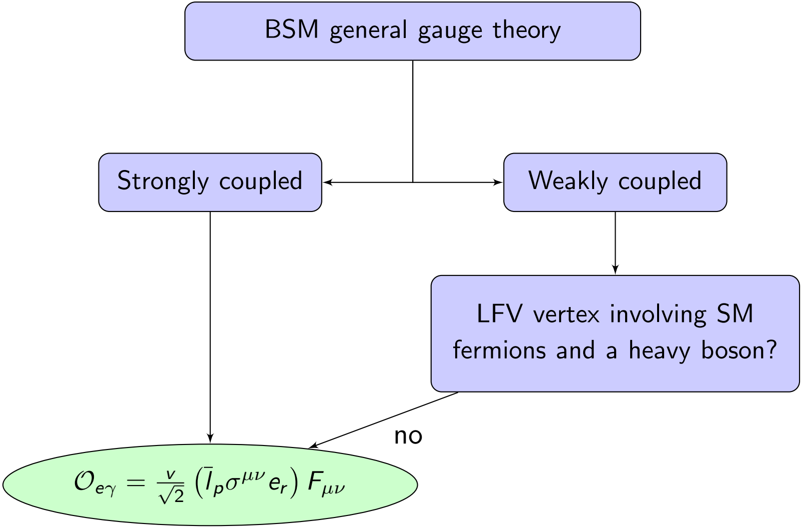

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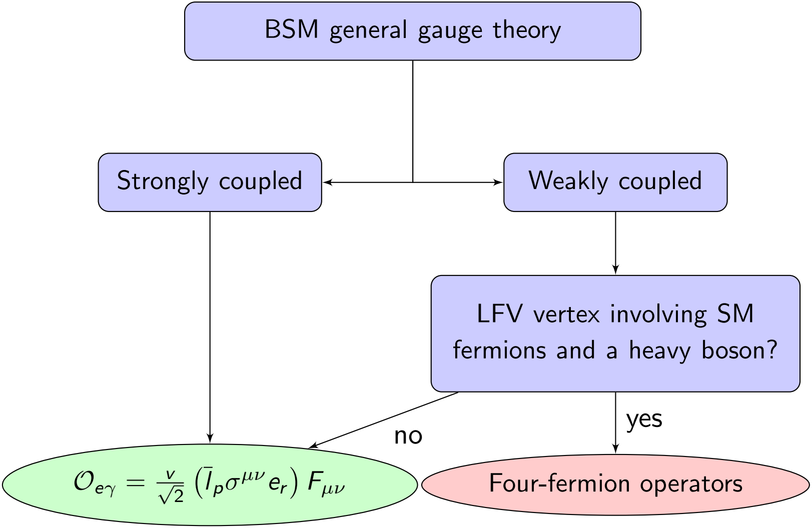

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no

yes

$\mathcal{O}_{e\gamma} = \frac{v}{\sqrt{2}} \left(\bar{l}_p \sigma^{\mu\nu} e_r \right) F_{\mu\nu}$

Four-fermion operators

Results

$$\Gamma\left(\ell_i^{\pm} \to \ell_j^{\pm} \ell_k^{+} \ell_k^{-}\right) = \frac{1}{\Lambda^4}\left[A\left(|\alpha_L|^2 + |\alpha_R|^2\right) + B\, Re\left\{\alpha_R \alpha_L^*\right\}\right]$$

Results

Standard Model effective operators

Charged lepton flavor violation

$\ell_i \to \ell_j \gamma$

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Results in the LFV sector

LFV in SUSY theories with R-parity

Pontencially tree-level is not tree-level

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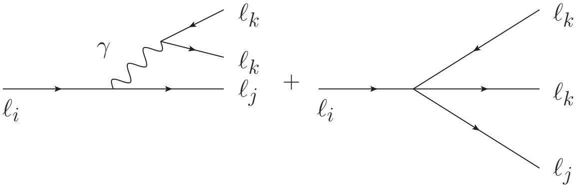
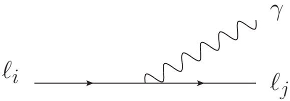
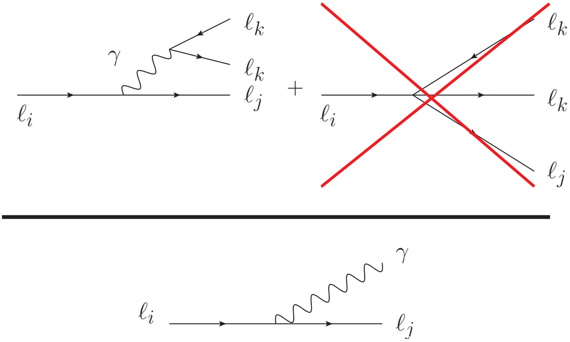
Coefficient	A	B
$\tau^\pm \to \mu^\pm \mu^+ \mu^-$	30.64	-2.51
$\tau^\pm \to \mu^\pm e^+ e^-$	137.84	-1.79
$\tau^\pm \to e^\pm \mu^+ \mu^-$	28.05	-8.67×10^{-3}
$\tau^\pm \to e^\pm e^+ e^-$	142.08	-1.13×10^{-2}
$\mu^\pm \to e^\pm e^+ e^-$	1.74×10^{-2}	-3.99×10^{-5}

Phenomenological branching fractions





Phenomenological branching fractions



$= \mathcal{O}(\alpha)$

Standard Model effective operators

Charged lepton flavor violation

$\ell_i \to \ell_j \gamma$

$\ell_i \to \ell_j \ell_k^+ \ell_k^-$

Results in the LFV sector

LFV in SUSY theories with R-parity

Pontencially tree-level is not tree-level

Phenomenological branching fractions

$$\frac{\mathcal{B}\left(\tau^\pm \to \mu^\pm e^+ e^-\right)}{\mathcal{B}(\tau^\pm \to \mu^\pm \gamma)} \simeq \frac{1}{82} \qquad \frac{\mathcal{B}\left(\tau^\pm \to \mu^\pm \mu^+ \mu^-\right)}{\mathcal{B}(\tau^\pm \to \mu^\pm \gamma)} \simeq \frac{1}{370}$$

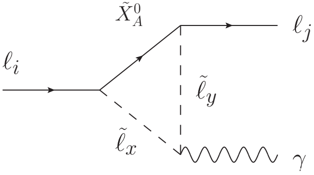
$$\frac{\mathcal{B}\left(\tau^\pm \to e^\pm \mu^+ \mu^-\right)}{\mathcal{B}(\tau^\pm \to e^\pm \gamma)} \simeq \frac{1}{481} \qquad \frac{\mathcal{B}\left(\tau^\pm \to e^\pm e^+ e^-\right)}{\mathcal{B}(\tau^\pm \to e^\pm \gamma)} \simeq \frac{1}{95}$$

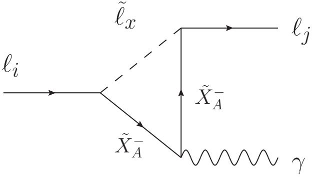
$$\frac{\mathcal{B}\left(\mu^\pm \to e^\pm e^+ e^-\right)}{\mathcal{B}(\mu^\pm \to e^\pm \gamma)} \simeq \frac{1}{163}$$

Bounds to new physics

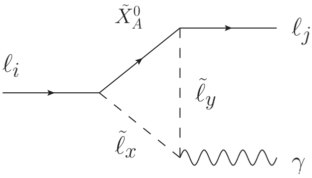
Process	Experimental branching ratio	Bound to new physics scale (TeV) Weakly coupled	Strongly coupled
$\tau^\pm \to \mu^\pm \gamma$	4.4×10^{-8} (BaBar)	$\Lambda \geq 57$	$\Lambda \geq 722$
	4.5×10^{-8} (Belle)		
$\tau^\pm \to e^\pm \gamma$	3.3×10^{-8} (BaBar)	$\Lambda \geq 62$	$\Lambda \geq 775$
	1.2×10^{-7} (Belle)		
$\mu^\pm \to e^\pm \gamma$	5.7×10^{-13} (MEG)	$\Lambda \geq 6039$	$\Lambda \geq 75892$
$\tau^\pm \to \mu^\pm \mu^+ \mu^-$	2.1×10^{-8} (Belle)	$\Lambda \geq 15$	$\Lambda \geq 190$
	3.3×10^{-8} (BaBar)		
$\tau^\pm \to \mu^\pm e^+ e^-$	1.8×10^{-8} (Belle)	$\Lambda \geq 23$	$\Lambda \geq 289$
	2.2×10^{-8} (BaBar)		
$\tau^\pm \to e^\pm \mu^+ \mu^-$	2.7×10^{-8} (Belle)	$\Lambda \geq 14$	$\Lambda \geq 174$
	3.2×10^{-8} (BaBar)		
$\tau^\pm \to e^\pm e^+ e^-$	2.7×10^{-8} (Belle)	$\Lambda \geq 21$	$\Lambda \geq 261$
	2.9×10^{-8} (BaBar)		
$\mu^\pm \to e^\pm e^+ e^-$	1.0×10^{-12} (SINDRUM)	$\Lambda \geq 1469$	$\Lambda \geq 18461$

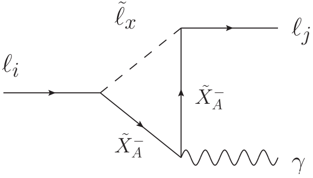
LFV in SUSY theories with R-parity

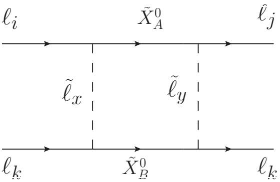


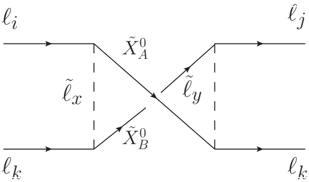


LFV in SUSY theories with R-parity

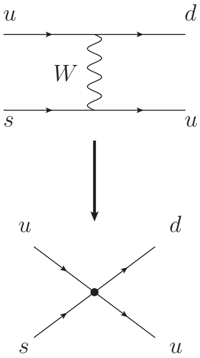




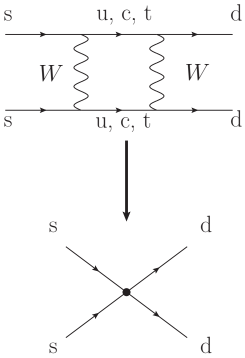




Pontencially tree-level is not tree-level



$\overline{u}\gamma^\mu P_L d \overline{s}\gamma_\mu P_L u$



GIM suppressed

$\overline{s}\gamma^\mu P_L d \overline{s}\gamma_\mu P_L d$

[E. Jenkins et al., 2013]