Purely flavor-changing Z' bosons and where they might hide

Based on work in collaboration with Joerg Jaeckel [JHEP **1705** (2017) 010]

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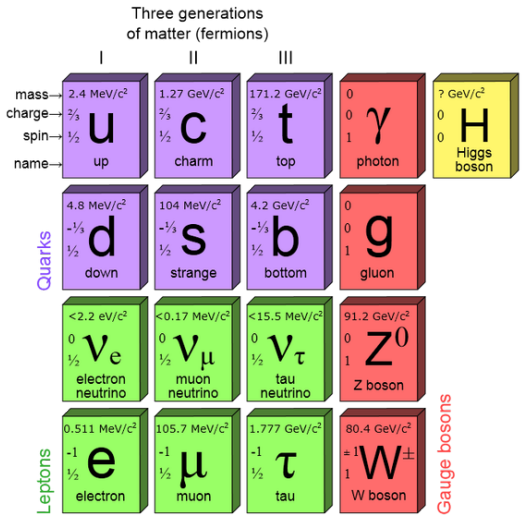
A flavorful Z' model

What is the origin of flavor?

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

- Horizontal/gauged flavor group G_H?
- Breaking leads to massive gauge bosons (possibly mediating FCNCs)
- Simplest approach: extra U(1)
- Explore limits of standard tests & probe corners of parameter space



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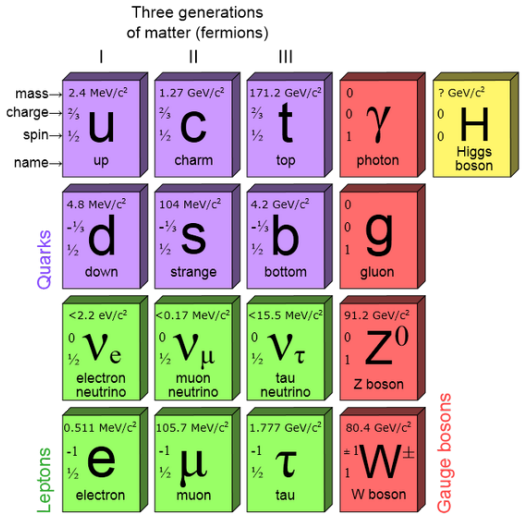

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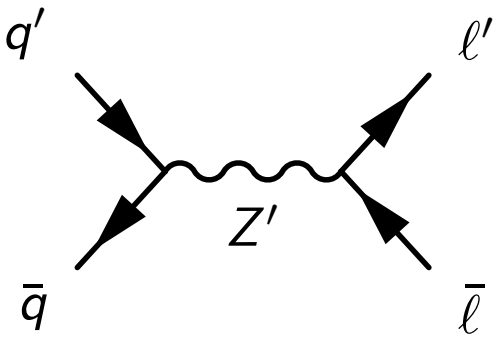
Phenomenological Model

$$\begin{aligned}\mathcal{L}_{Z'} = \quad & \bar{q}\,\gamma^\mu\,[g^L_{qq'}\,P_L + g^R_{qq'}\,P_R]\,q'\,Z'_\mu \\ & + \bar{\ell}\,\gamma^\mu\,[g^L_{\ell\ell'}\,P_L + g^R_{\ell\ell'}\,P_R]\,\ell'\,Z'_\mu + h.c.\end{aligned}$$

The collider point of view

Explore potential of multipurpose experiments in flavor physics.
$\rightarrow$ reinterpret $e\mu, e\tau, \mu\tau$ s-channel peak search [ATLAS, arXiv:1503.04430]



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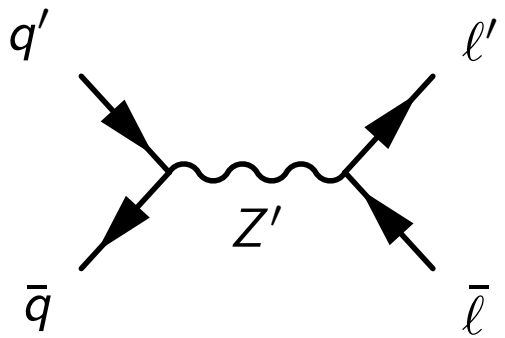
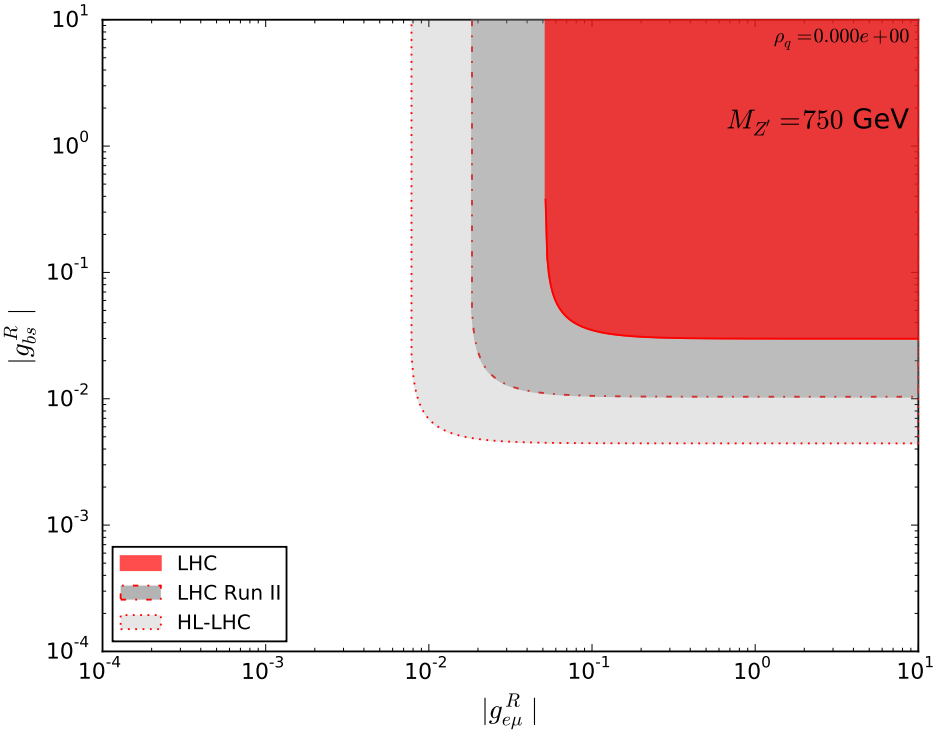


Strategy

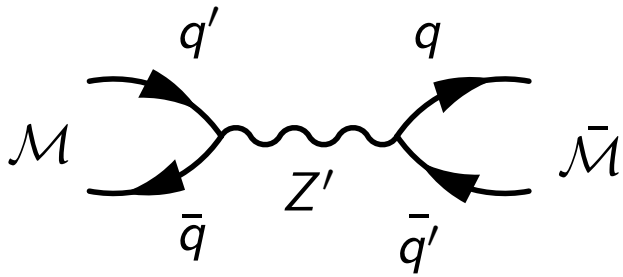
1. Simulate partonic cross section σ_{LO}
2. Include K-factor and detector effects $A \times \epsilon$
3. Recast ATLAS limit from approximate scaling:

$$\sigma \approx \frac{1}{3} \frac{s}{M_{Z'}^4} \frac{g_{qq'}^2 \, g_{\ell\ell'}^2}{3\, g_{qq'}^2 + g_{\ell\ell'}^2}$$



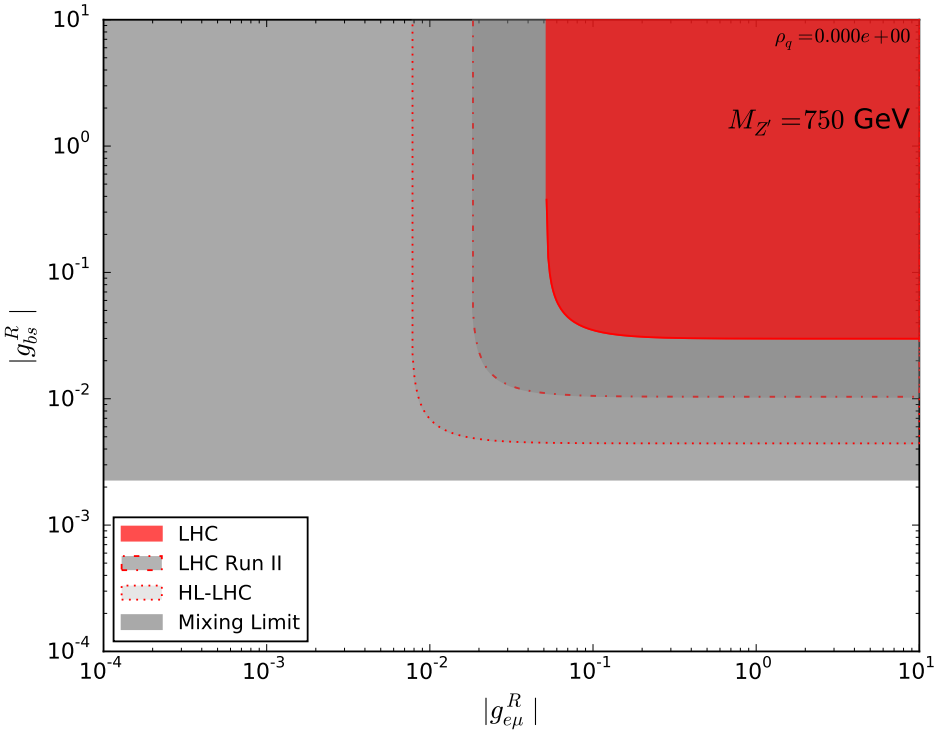
Meson mixing

- Usually strong constraints arise from mass splitting of neutral meson $\mathcal{M}$ and its conjugate state $\bar{\mathcal{M}}$
- Treat Z' contribution in an EFT framework [Buras, Girrbach, arXiv:1201.1302]



$$\Delta M \propto \frac{\left(g^R_{qq'}\right)^2}{M^2_{Z'}} \left[\mathcal{C}^{\mathrm{LL}}\left(1+\rho_q^2\right)+\mathcal{C}^{\mathrm{LR}}\,\rho_q\right]$$

with $\rho_q = g^L_{qq'}/g^R_{qq'}$



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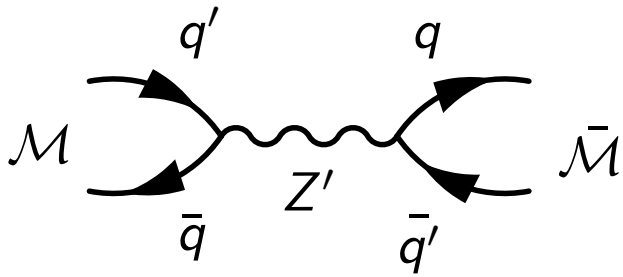

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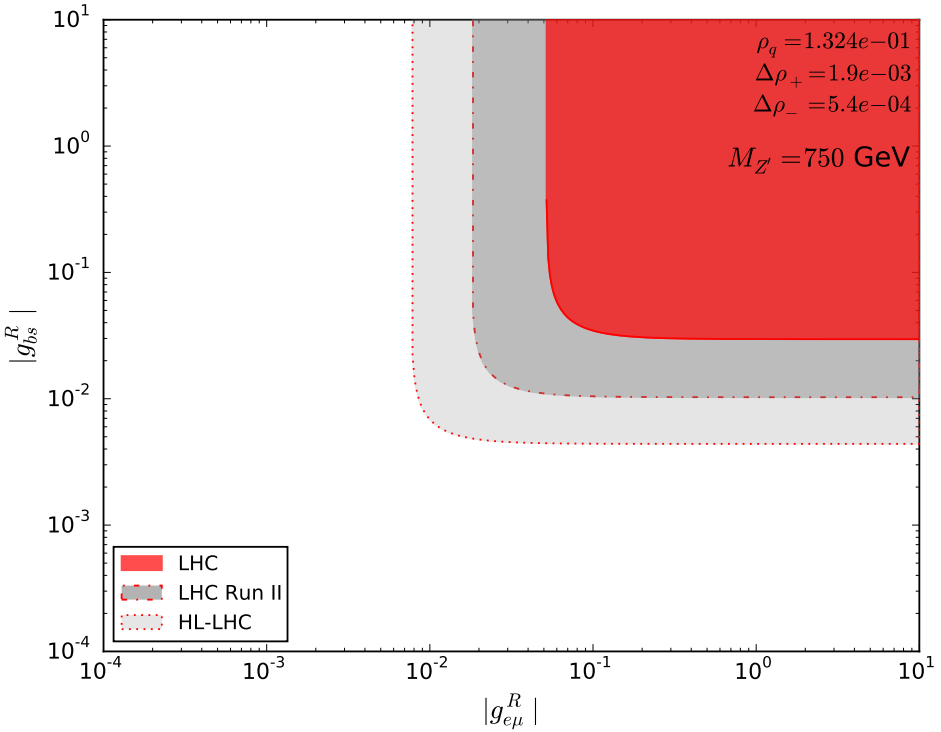
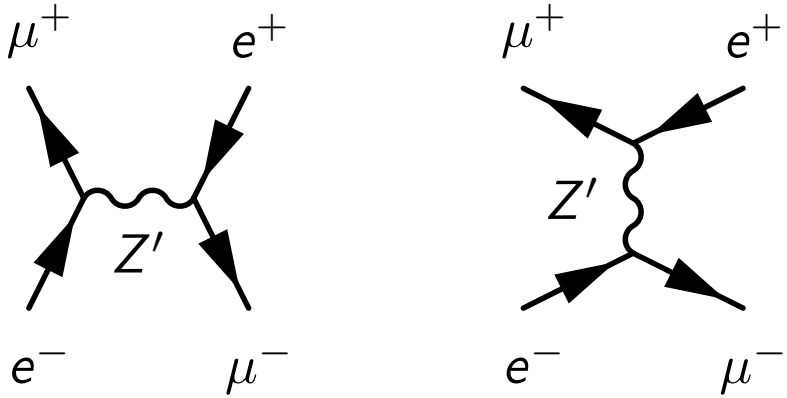
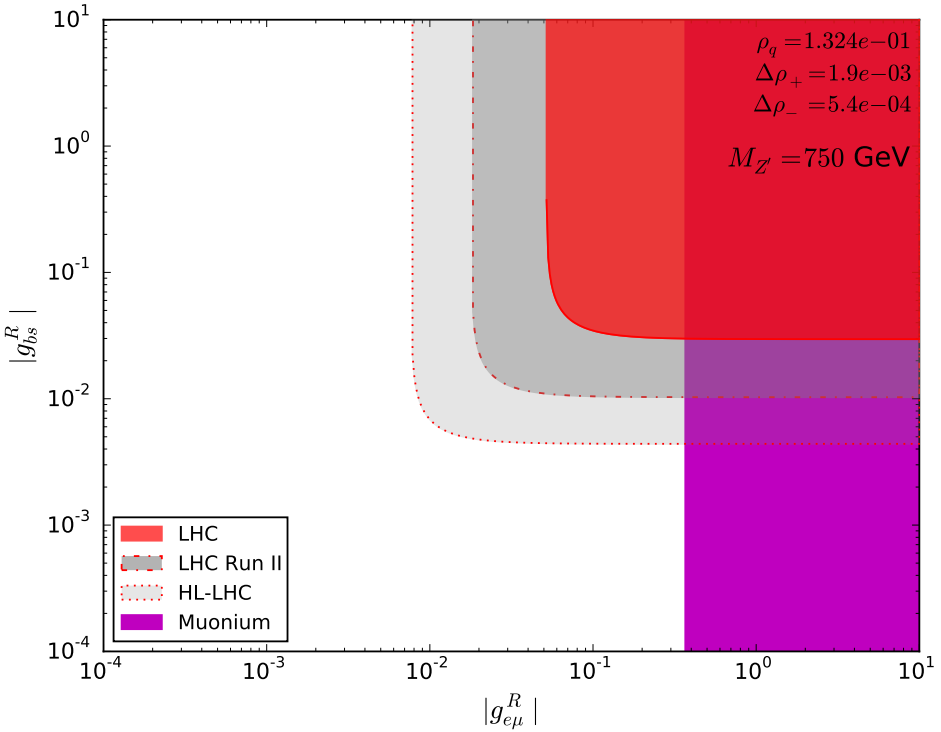


Muonium oscillation

- Muonium is hydrogen-like $e^-\mu^+$ bound state
- In presence of FCNCs can oscillate into conjugate bound state consisting of $e^+\mu^-$
- MACS experiment at PSI has searched for muonium oscillations [Willmann, hep-ex/9807011]





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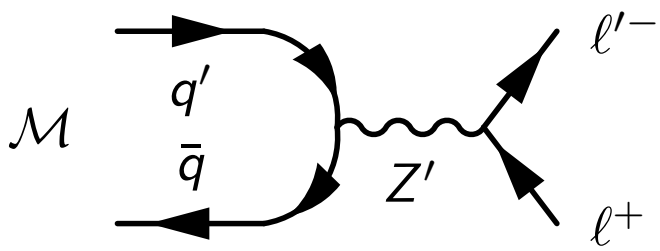
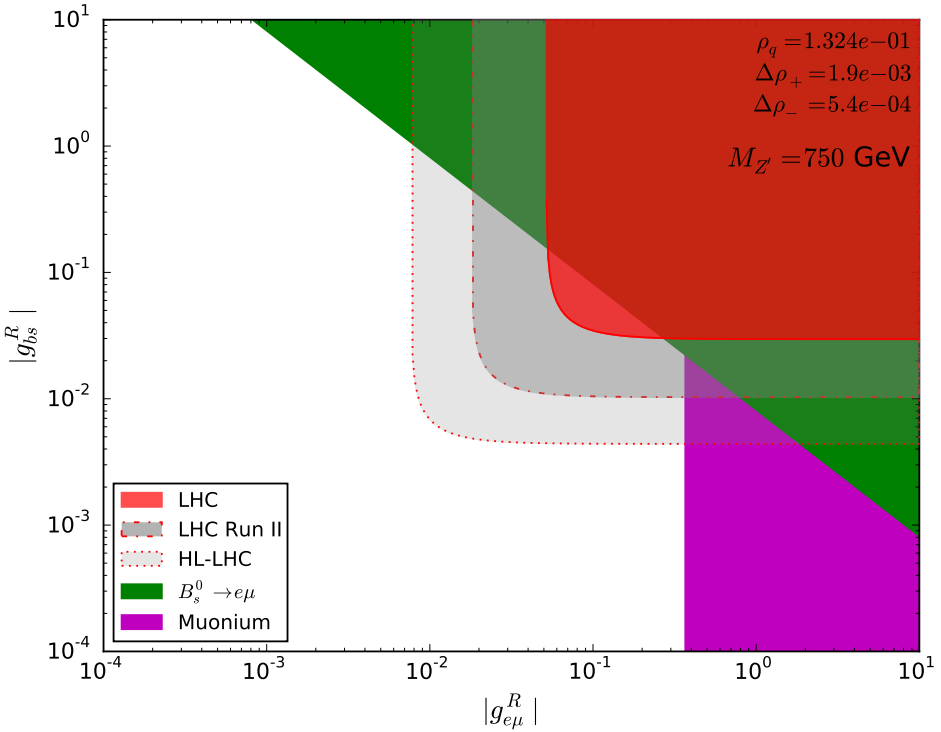


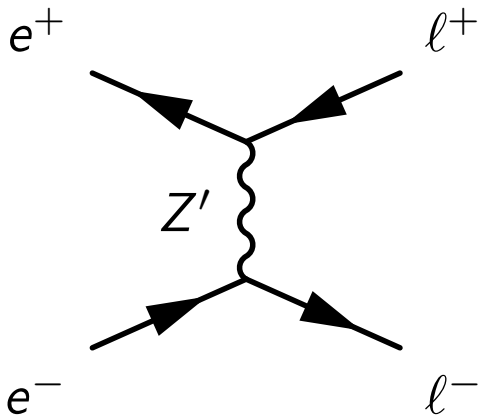
Leptonic meson decays

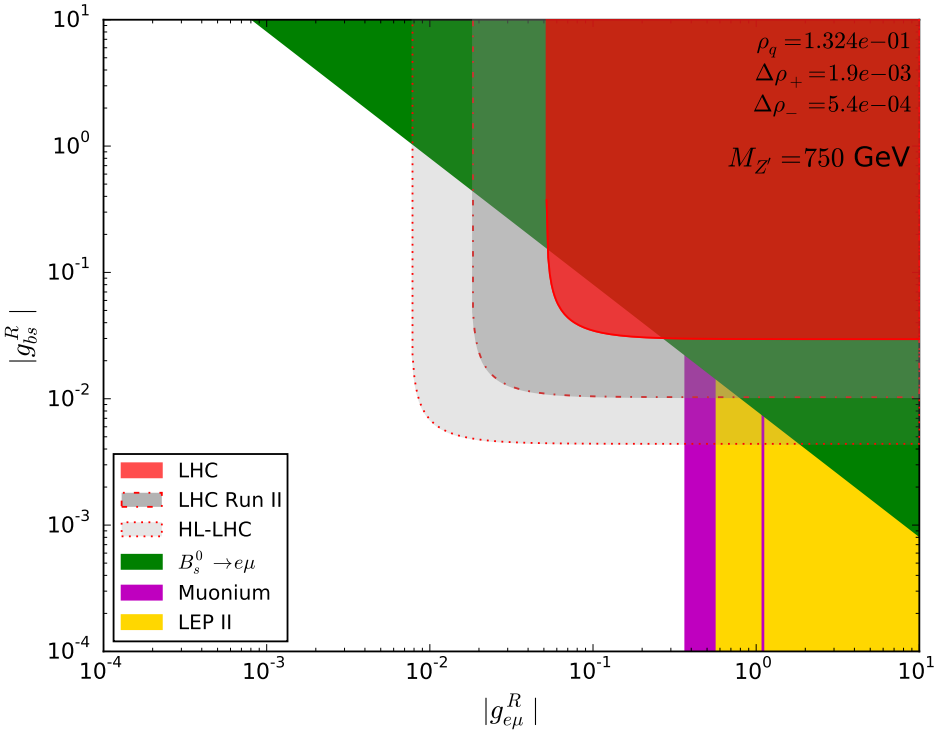
- Tree-level decay of flavored mesons via $\bar{q}q' \to Z' \to \bar{\ell}\ell'$
- Get contribution to BR($\mathcal{M} \to \bar{\ell}\ell'$)
  [Golowich, arXiv:0903.2830]



Further Constraints

- Dijet limits from $pp \to jj$
- LEP limits from (t-channel) process $e^+e^- \to \ell^+\ell^-$





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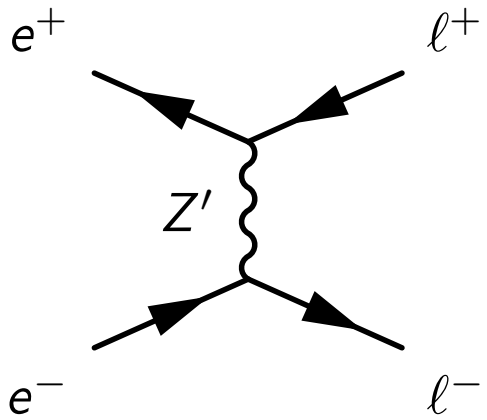
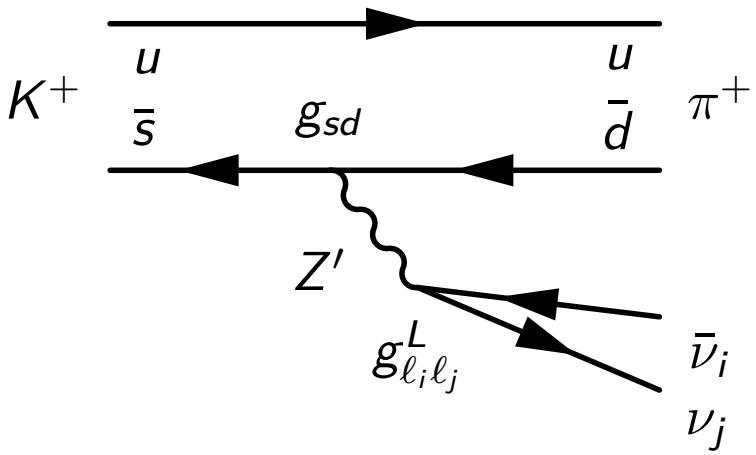
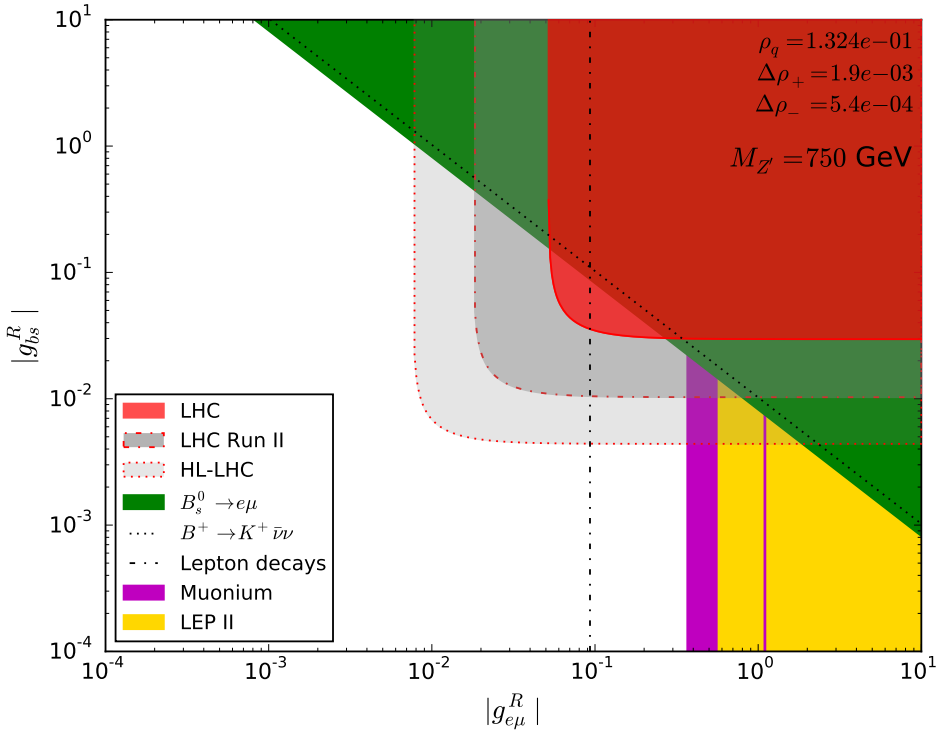


For LH lepton couplings (dashed)

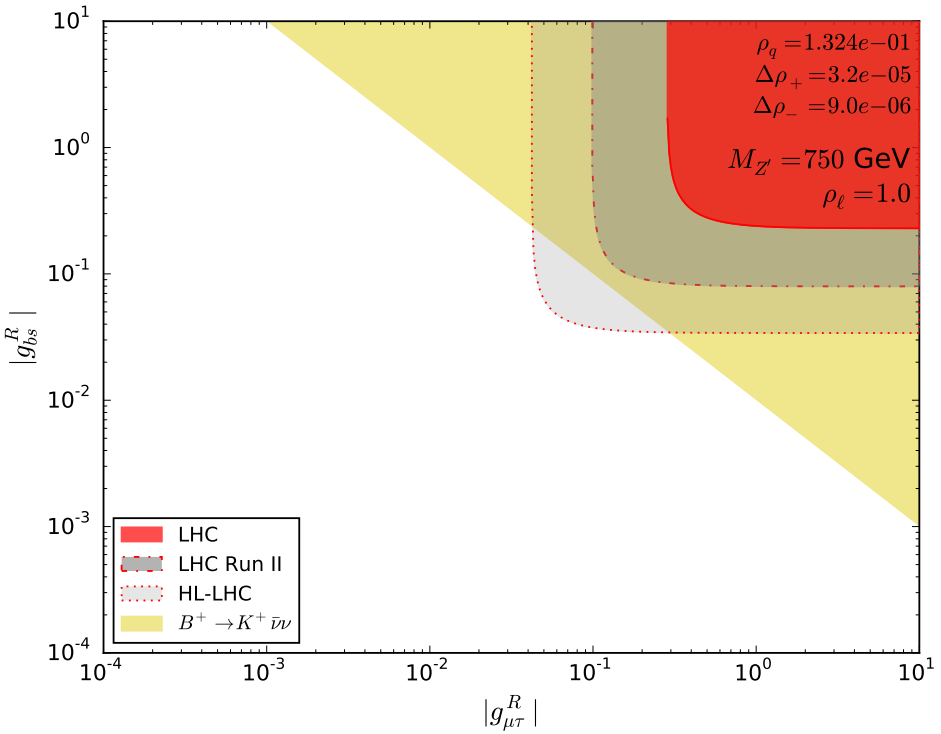
- Lepton decay $\ell \to \ell' \, \bar{\nu} \, \nu'$
- Semi-leptonic meson decay $\mathcal{M} \to \mathcal{M}' \; \nu \, \bar{\nu}'$





Leptonic τ decay

Consider $\mu\tau$ sector:



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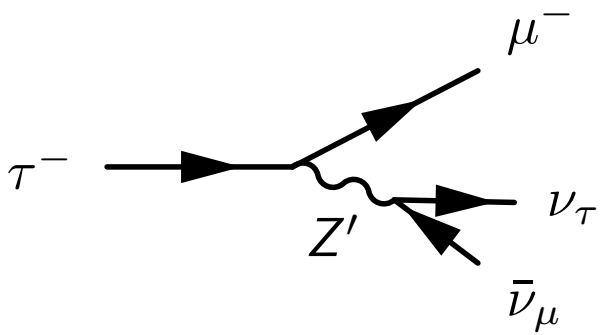
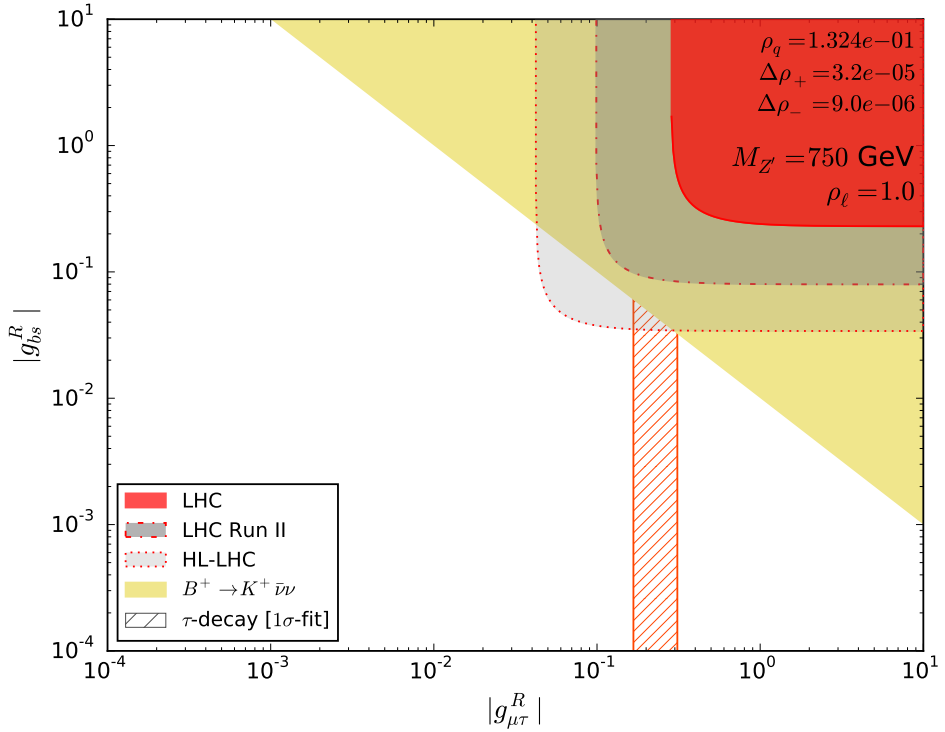
- Measured decay rate of $\tau \to \mu\bar{\nu}\nu$ shows $\sim 2.4\,\sigma$ deviation from SM

$$\frac{\Gamma_{\tau\to\mu\bar{\nu}\nu}}{\Gamma^{\mathrm{SM}}_{\tau\to\mu\bar{\nu}\nu}} - 1 = (0.69 \pm 0.29)\%$$





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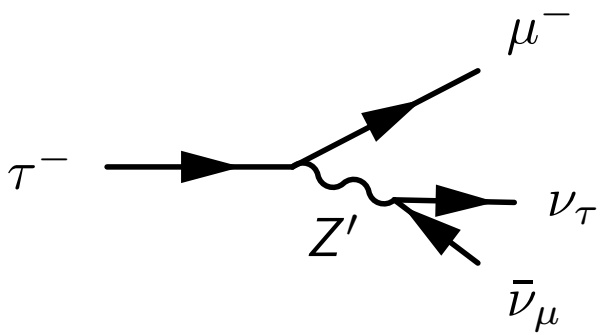
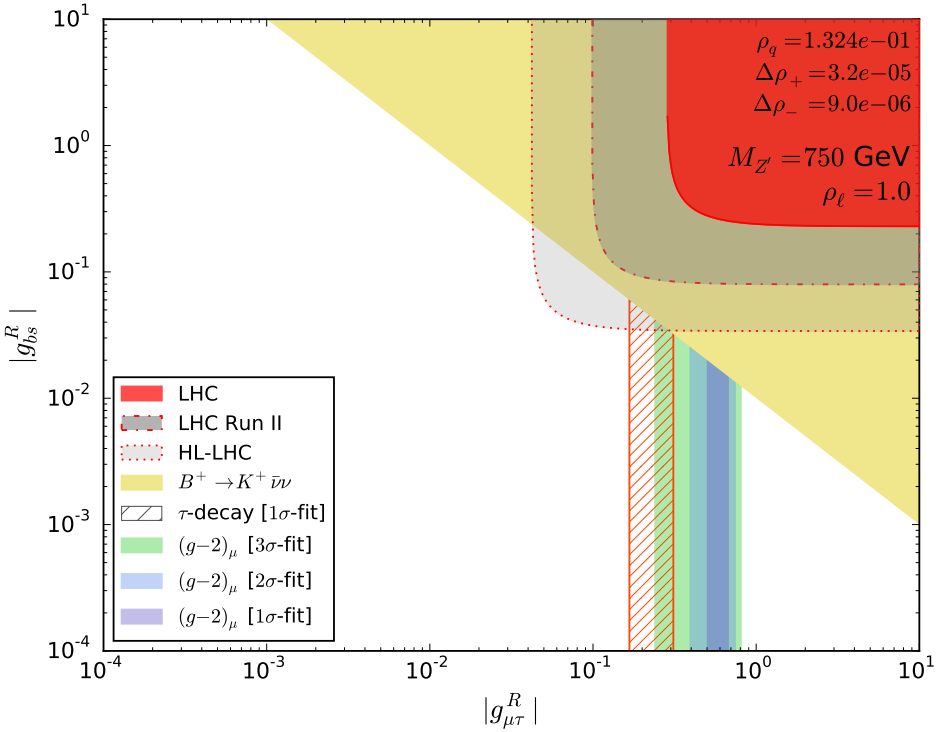


Muon magnetic moment

- Observed anomalous magnetic moment of muon exhibits $\sim 3.6\,\sigma$ excess

$$\Delta a_\mu = (2.87 \pm 0.80) \times 10^{-9}$$



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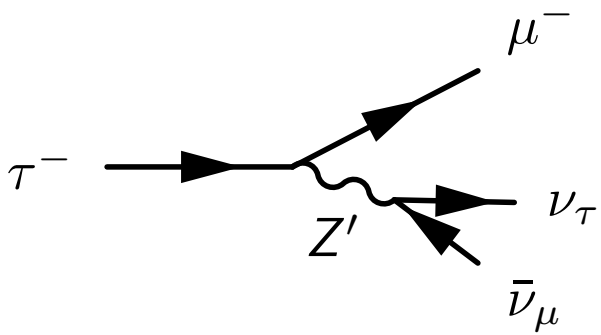

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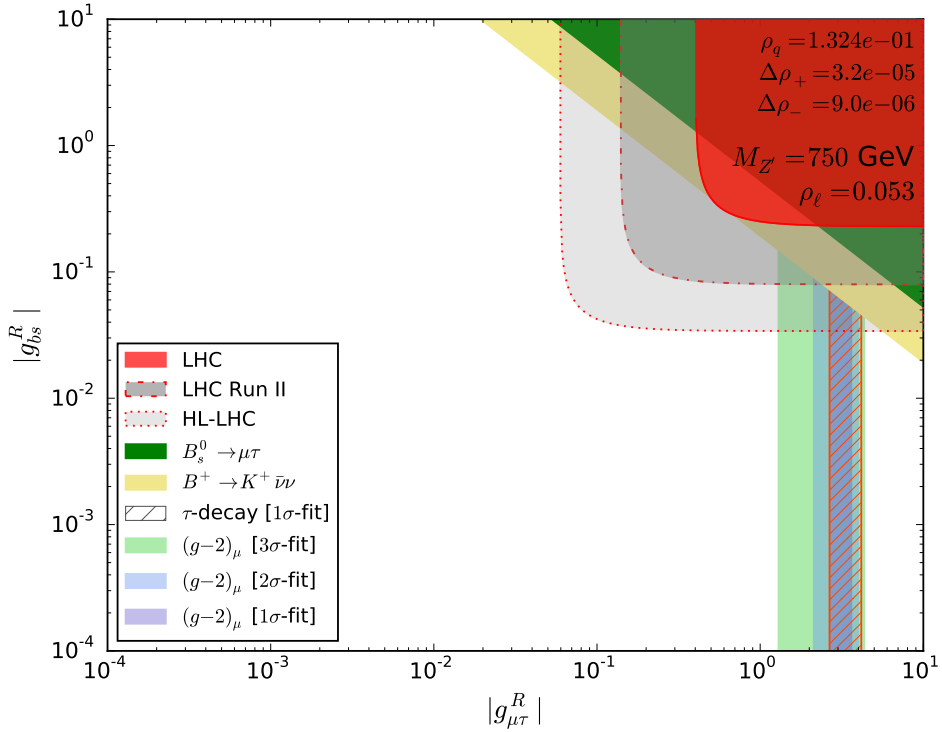
- **Simultaneous explanation with Z' for $g^L_{\mu\tau}/g^R_{\mu\tau} \approx 0.05$**



New exotic τ decay

Consider $\mu\tau$ sector:

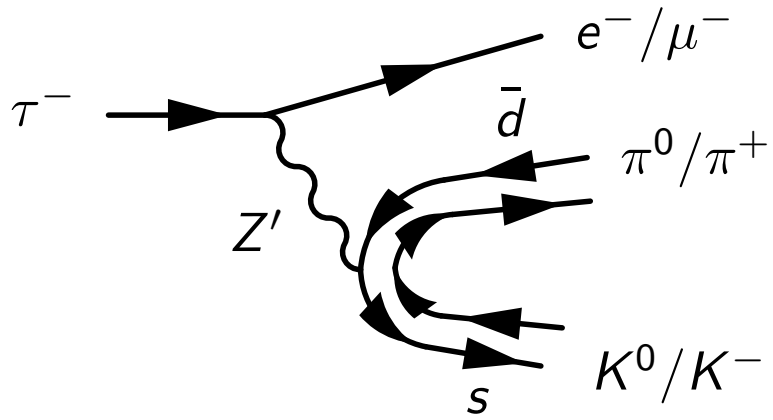
- New exotic τ decay

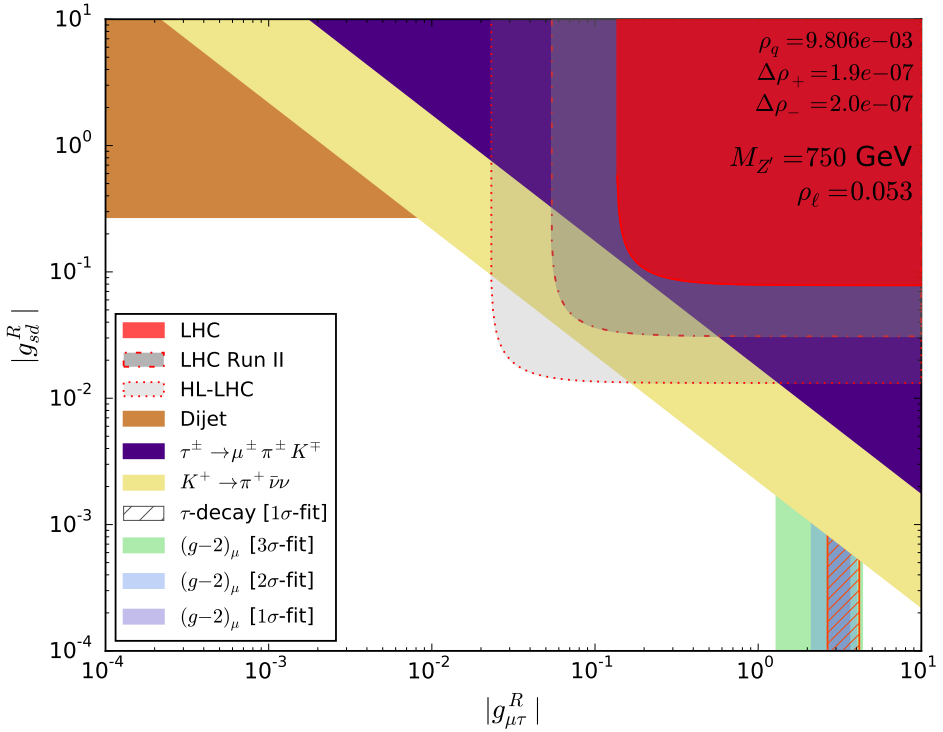
$$\tau^{\pm} \to \ell^{\pm} (\pi^0 K^0 / \pi^{\pm} K^{\mp})$$

- Has been searched for at BaBar and Belle
- Current limit $\Gamma_{\tau \to \mu \pi^+ K^-} < 16 \times 10^{-8}$
- Belle-II aims at $\mathcal{O}(10^{-9})$ sensitivity in τ branching fraction!

$$\Gamma_{\tau \to K^- \pi^+ \mu} \approx 3.4 \times 10^{-9}$$

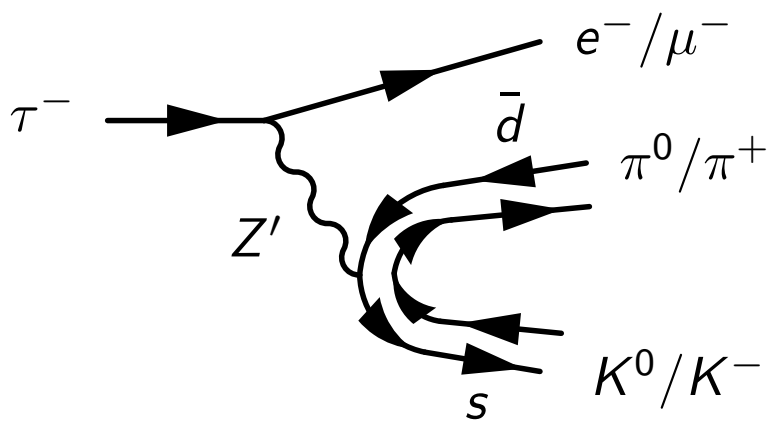
$(m = 750 \text{ GeV}, g_{sd} = 6 \cdot 10^{-4}, g_{\mu\tau} = 4)$





Conclusion

- Investigated models with one flavor-changing coupling in quark and lepton sector
- Large parameter scan for $qq' \in \{sd, bd, bs, cu\}$ and $\ell\ell' \in \{e\mu, e\tau, \mu\tau\}$
- For $g^L_{\mu\tau}/g^R_{\mu\tau} \approx 0.05$ simultaneous explanation of a_μ and τ decay anomaly
- New exotic signature:



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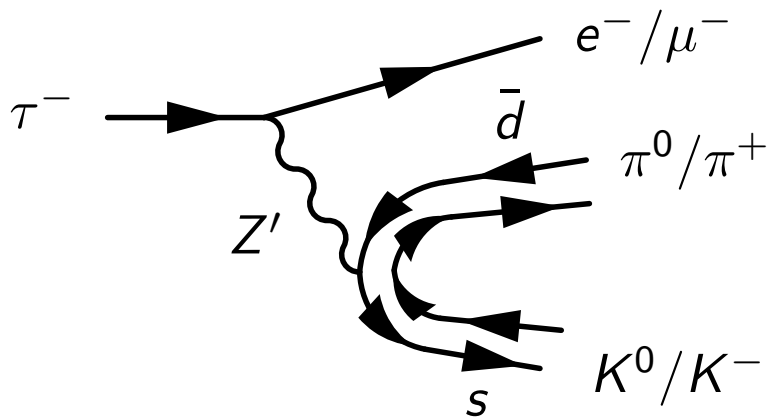

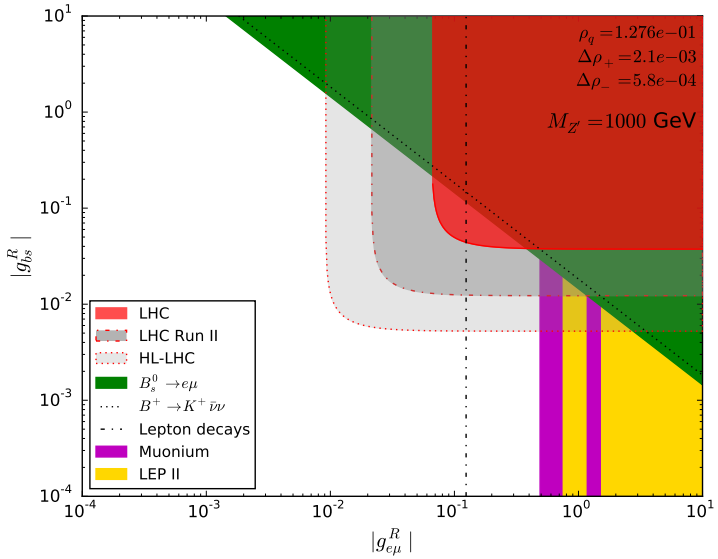
$\rho_q = 1.276e{-}01$
$\Delta\rho_+ = 2.1e{-}03$
$\Delta\rho_- = 5.8e{-}04$
$M_{Z'} = 1000$ GeV
LHC
LHC Run II
HL-LHC
$B_s^0 \to e\mu$
$B^+ \to K^+ \bar{\nu}\nu$
Lepton decays
Muonium
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$|g^R_{bs}|$
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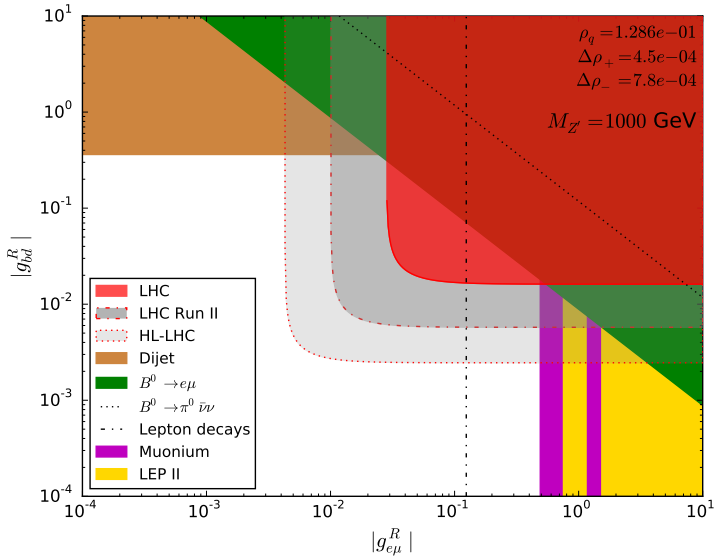
$\rho_q = 1.286e{-}01$
$\Delta\rho_+ = 4.5e{-}04$
$\Delta\rho_- = 7.8e{-}04$
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LHC
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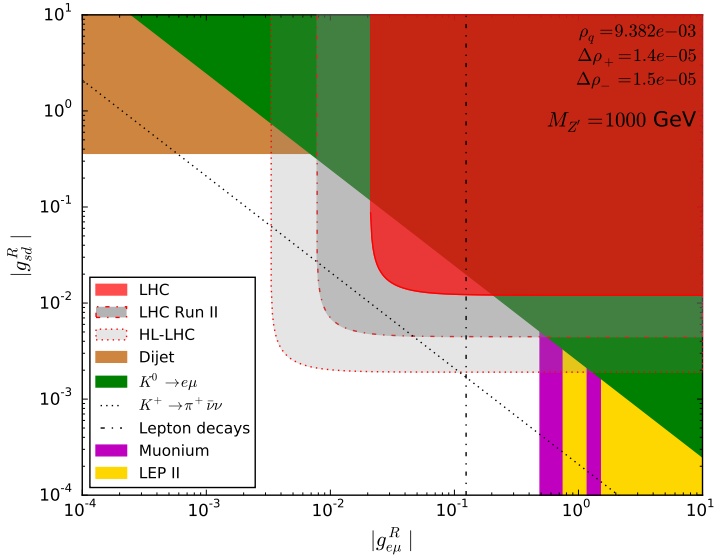
$\rho_q = 9.382e{-}03$
$\Delta\rho_+ = 1.4e{-}05$
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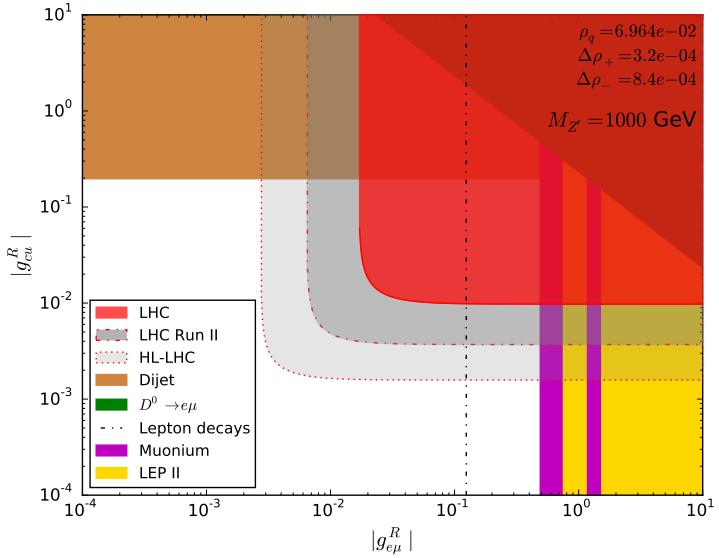
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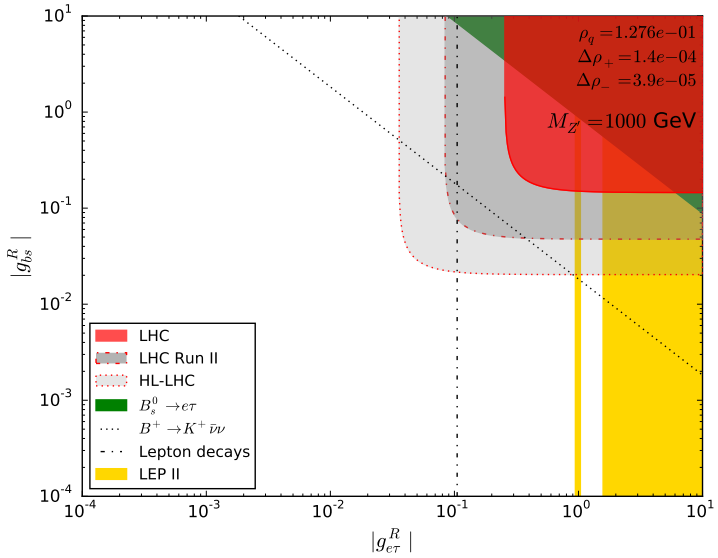
$|g^R_{e\mu}|$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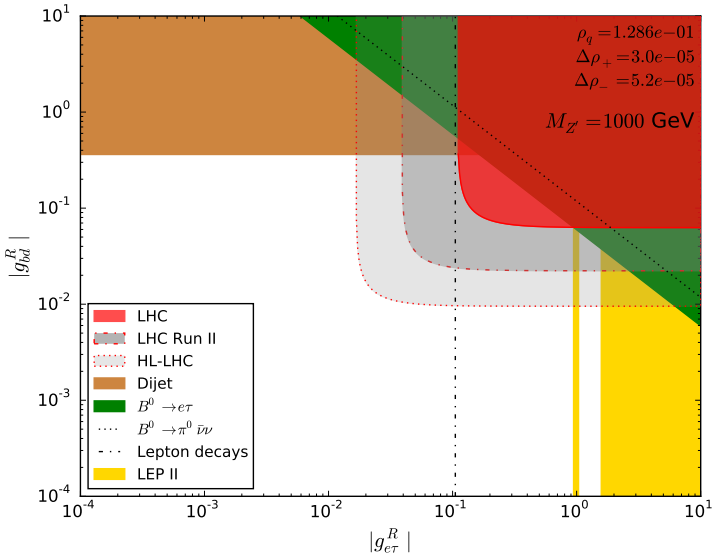
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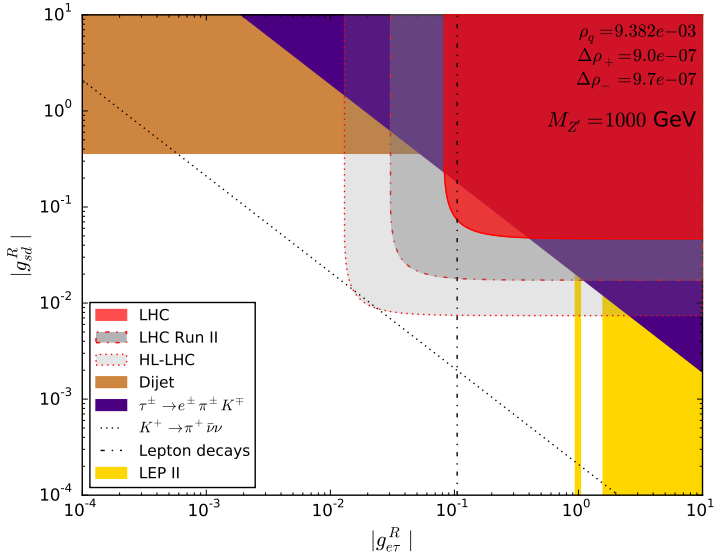
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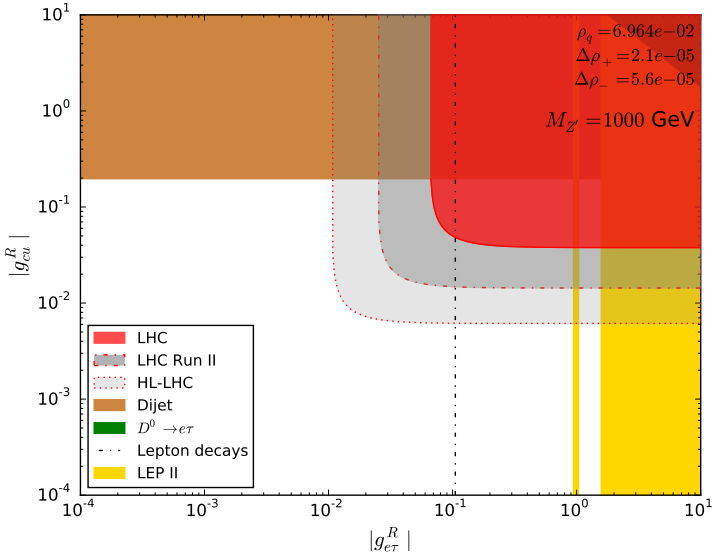
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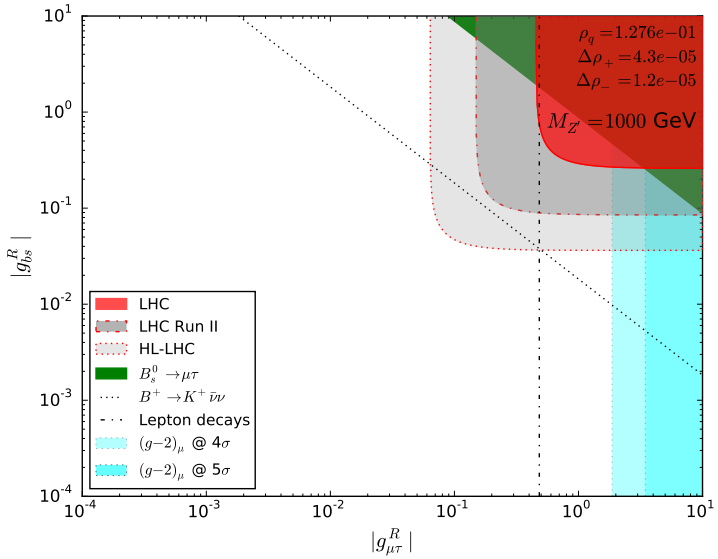
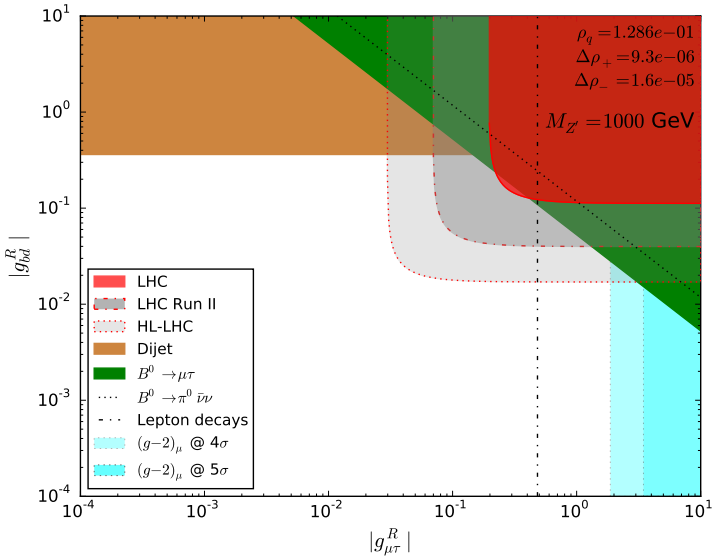
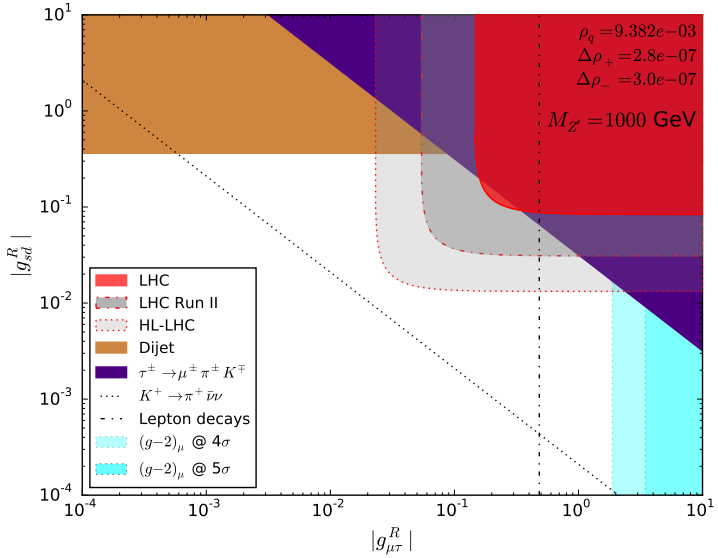
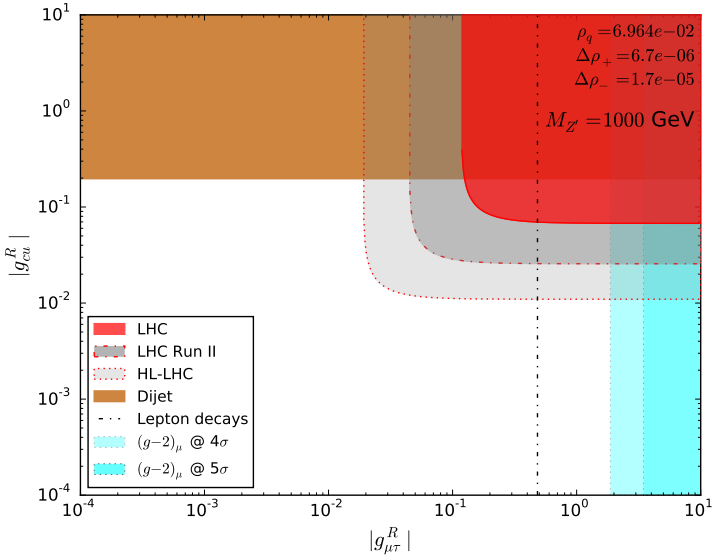

$\rho_q = 1.276e{-}01$
$\Delta\rho_+ = 4.3e{-}05$
$\Delta\rho_- = 1.2e{-}05$
$M_{Z'} = 1000$ GeV
LHC
LHC Run II
HL-LHC
$B_s^0 \to \mu\tau$
$B^+ \to K^+ \bar{\nu}\nu$
Lepton decays
$(g-2)_\mu$ @ 4σ
$(g-2)_\mu$ @ 5σ
$|g^R_{bs}|$
$|g^R_{\mu\tau}|$

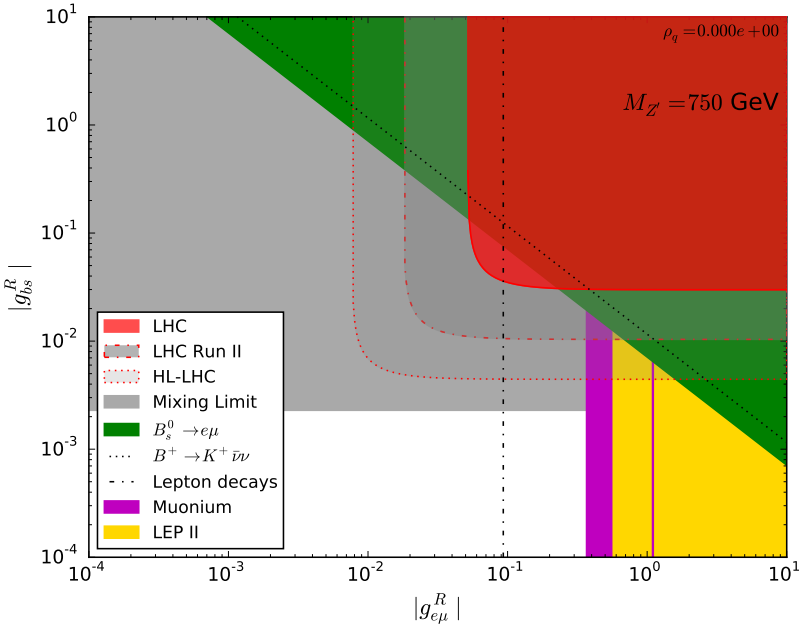

$\rho_q = 1.286e{-}01$
$\Delta\rho_+ = 9.3e{-}06$
$\Delta\rho_- = 1.6e{-}05$
$M_{Z'} = 1000$ GeV
LHC
LHC Run II
HL-LHC
Dijet
$B^0 \to \mu\tau$
$B^0 \to \pi^0 \bar{\nu}\nu$
Lepton decays
$(g-2)_\mu$ @ 4σ
$(g-2)_\mu$ @ 5σ
$|g^R_{bd}|$
$|g^R_{\mu\tau}|$

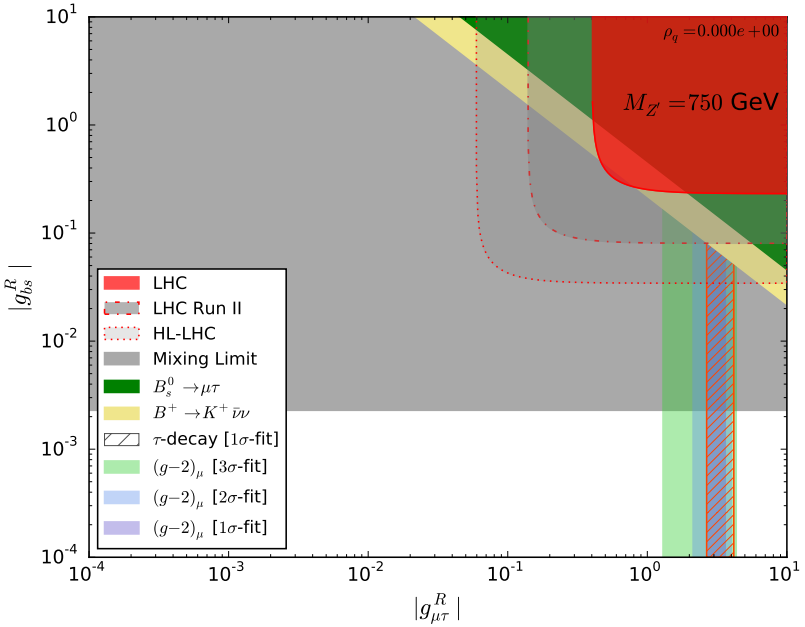

$\rho_q = 9.382e{-}03$
$\Delta\rho_+ = 2.8e{-}07$
$\Delta\rho_- = 3.0e{-}07$
$M_{Z'} = 1000$ GeV
LHC
LHC Run II
HL-LHC
Dijet
$\tau^\pm \to \mu^\pm \pi^\pm K^\mp$
$K^+ \to \pi^+ \bar{\nu}\nu$
Lepton decays
$(g-2)_\mu$ @ 4σ
$(g-2)_\mu$ @ 5σ
$|g^R_{sd}|$
$|g^R_{\mu\tau}|$


$\rho_q = 6.964e{-}02$
$\Delta\rho_+ = 6.7e{-}06$
$\Delta\rho_- = 1.7e{-}05$
$M_{Z'} = 1000$ GeV
LHC
LHC Run II
HL-LHC
Dijet
Lepton decays
$(g-2)_\mu$ @ 4σ
$(g-2)_\mu$ @ 5σ
$|g^R_{cu}|$
$|g^R_{\mu\tau}|$

No cancellation

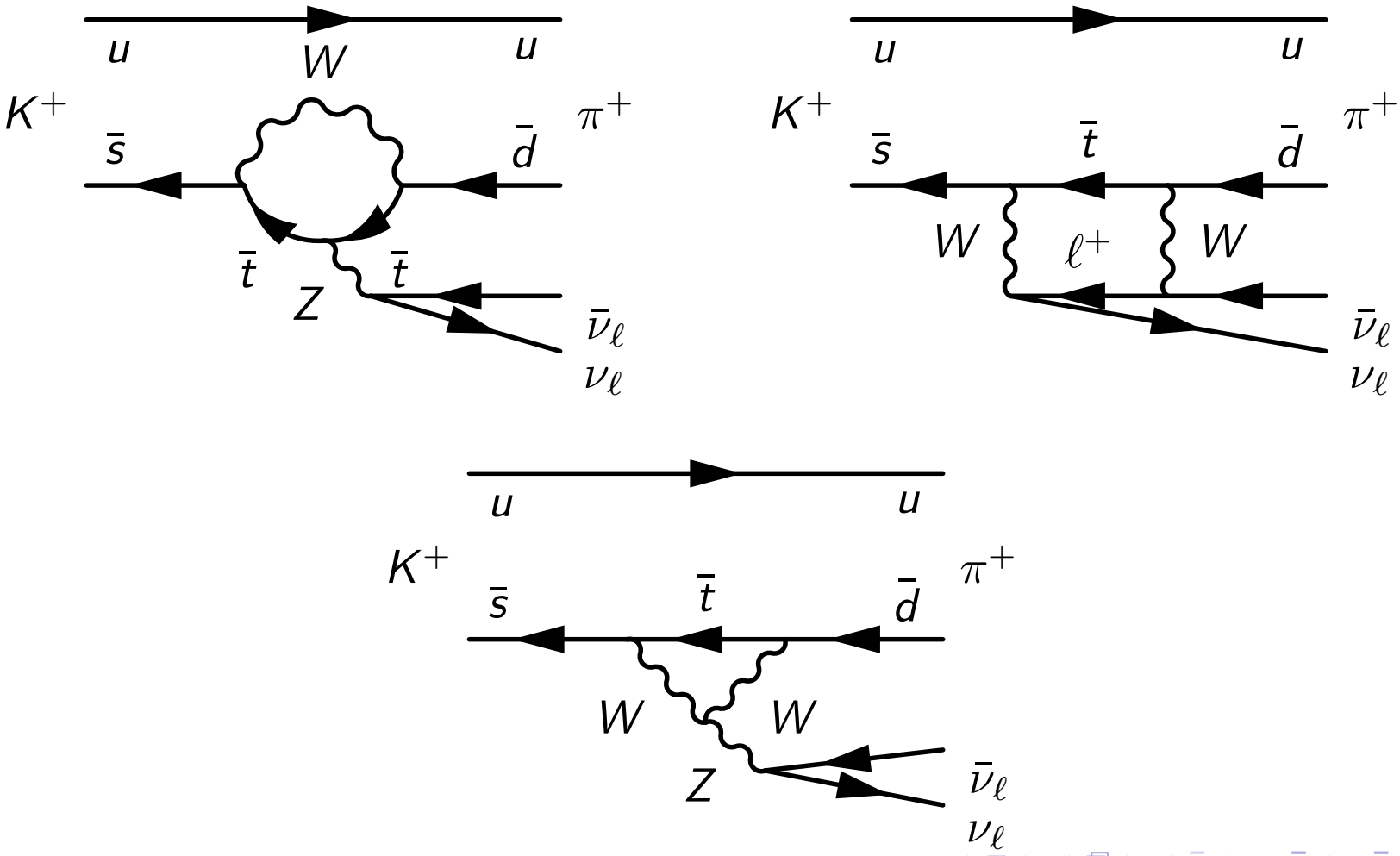
Without tuning the quark couplings the parameter space looks much more constrained!





Meson decay with neutrinos - SM

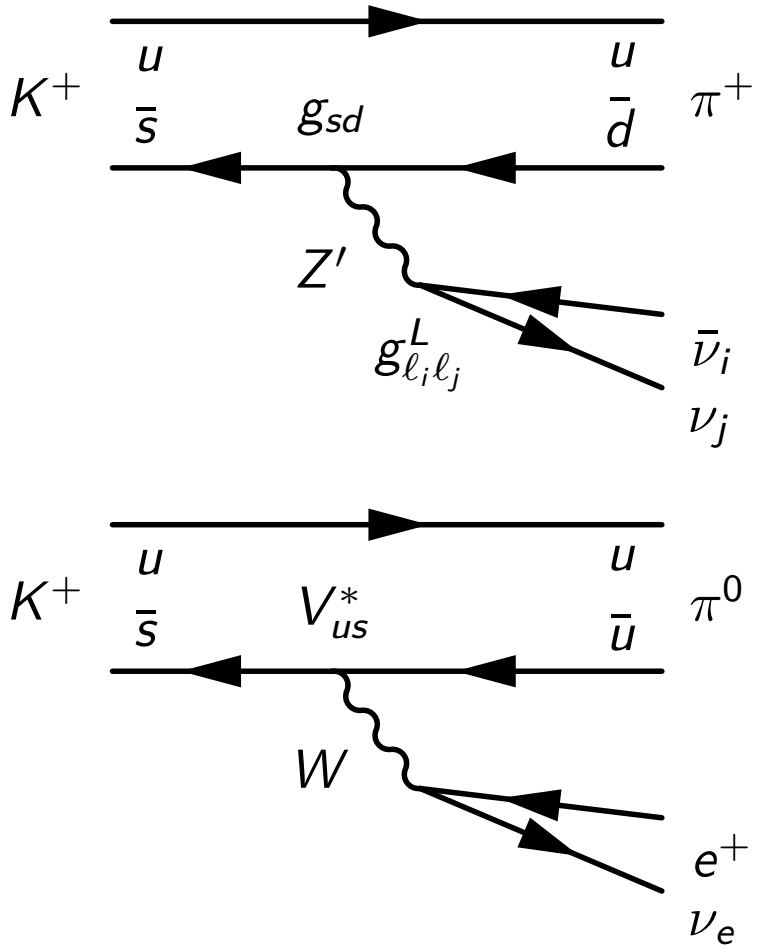
Example $K \to \pi \bar{\nu} \nu$



Meson decay with neutrinos - Z'

Example $K \to \pi \bar{\nu} \nu$

- SM decay loop suppressed
- Z' induces tree-level decay $\Rightarrow$ strong effect and thus sensitive channel
- Only present if Z' couples to LH leptons (assuming only SM neutrinos)
- Extract hadronic matrix element from related SM process (using isospin symmetry)



Anomalous magnetic moment

- Observed anomalous magnetic momenta discrepancies ($\Delta a = a^{\rm exp} - a^{\rm SM}$)

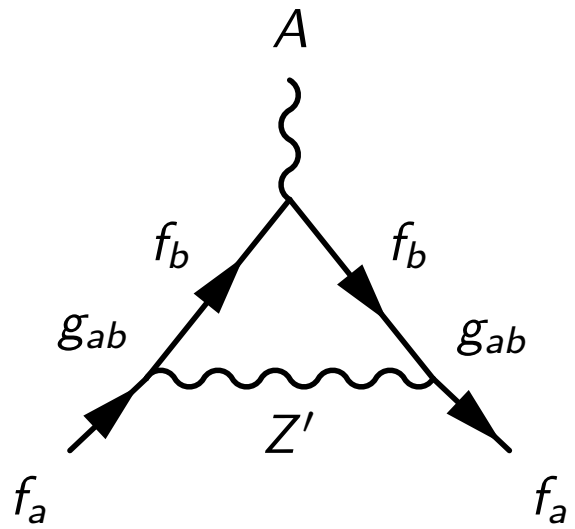
$$\Delta a_\mu = (2.87 \pm 0.80) \times 10^{-9}$$
$$\Delta a_e = (-1.05 \pm 0.81) \times 10^{-12}$$

- Approximate contribution

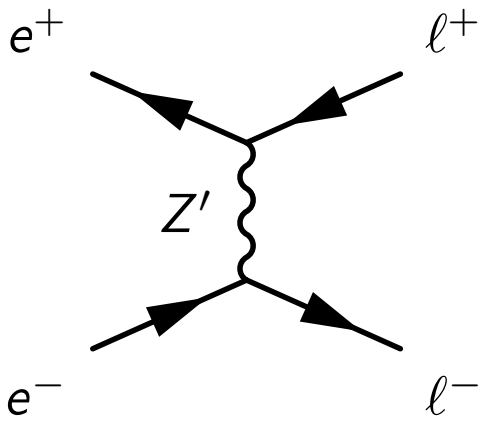
$$a_{f_a} \approx \frac{(g^R_{ab})^2}{4\,\pi^2 M^2_{Z'}}\, m_a \left[m_b\, \rho_\ell - \frac{m_a}{3}\,(1+\rho^2_\ell) \right]$$

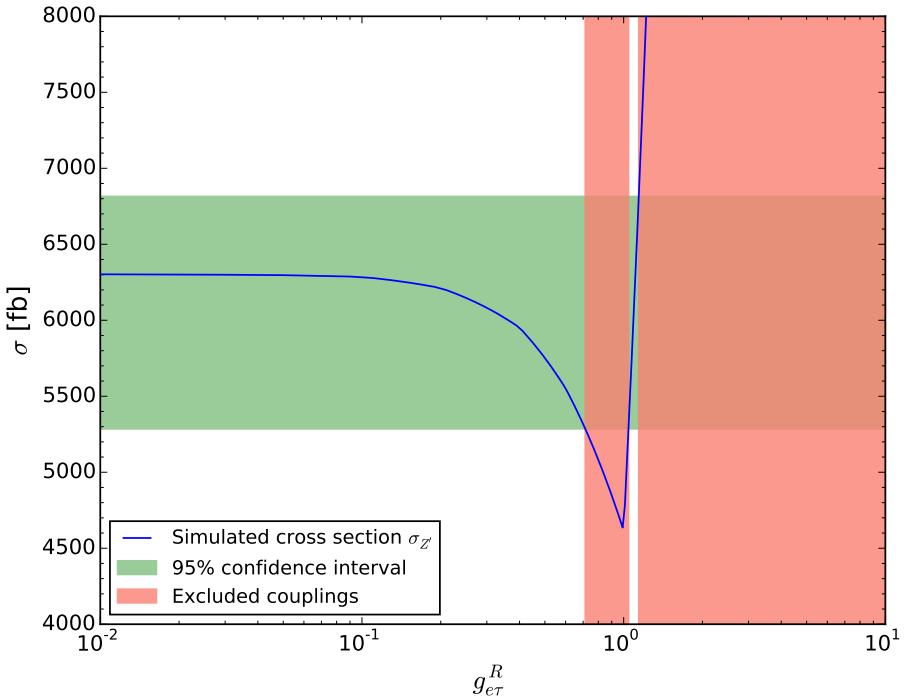
- Contribution to $(g-2)_e$ suppressed by light mass

$$\frac{m_e^2}{m_\mu^2} \approx \frac{1}{(200)^2} \sim \mathcal{O}(10^{-5})$$



LEP





- Simulate cross section σ_{LEP}
- Construct limit from two-sided hypothesis test @ 95% CL

Measuring $\tau \to \ell K \pi$

- Current limits for neutrinoless LFV τ decays [Belle, arxiv:0908.3156]

$$\Gamma_{\tau \to \ell\ h^{\pm}\ h'^{\mp}} \lesssim (5 - 16) \times 10^{-8}$$

- For 50 ab^{-1} of data SuperKEKB aims at a branching fraction sensitivity of 1×10^{-9} [Aushev et al., arxiv:1002.5012]