μ–e Conversion for Models with Doubly Charged Scalars

Tanja Geib

with Stephen F. King, Alexander Merle, Jose Miguel No and Luca Panizzi
arXiv:1510.xxxxx

Max Planck Institute for Physics

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Introduction: Why Loop Level Neutrino Masses??

Why are radiative models so interesting?

- naturally small neutrino mass
- possibility to introduce new particles (e.g. DM candidate, further Higgs doublets or doubly charged scalars)
- neutrinos massive $\rightarrow$ LFV/LNV couplings exist $\rightarrow$ rich phenomenology:
  - $\mu \rightarrow e\,\gamma$ (LFV)
  - $\mu \rightarrow 3\,e$ (LFV)
  - neutrinoless double beta decay (LNV)

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Testability: complementary between neutrino and LHC physics

- low energy precision physics: indirect detection of e. g. charged scalars due to contribution to LFV/LNV processes
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Effective theory of a doubly charged scalar singlet

based on King, Merle, Panizzi arXiv:1406.4137

Minimal extension of SM:

- only **one** extra particle: S^{++}
  $\rightarrow$ lightest of possible new particles (UV completion e.g. Cocktail model)
  $\rightarrow$ reduction of input parameters
- tree-level coupling to SM (to charged right-handed leptons)
  $\rightarrow$ **LNV and LFV!**
- effective Dim-7 operator (necessary to generate neutrino mass)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - V(H, S)$$

$$+ (D_\mu S)^\dagger (D^\mu S) + \boxed{f_{ab}\, \overline{(\ell_{Ra})^c} \ell_{Rb}\, S^{++}} + \mathrm{h.c.} - \boxed{\frac{g^2 v^4 \xi}{4 \Lambda^3} S^{++} W^-_\mu W^{-\mu}} + \mathrm{h.c.}$$

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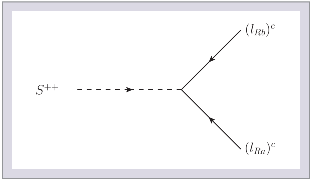

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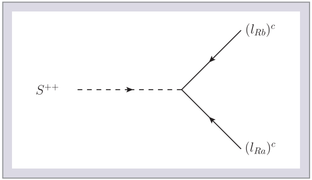
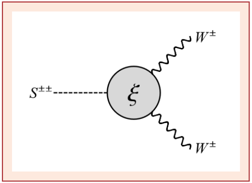




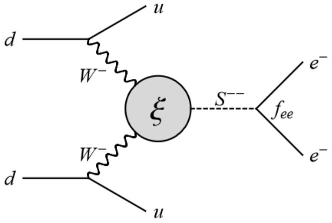
Testing the Model

based on King, Merle, Panizzi arXiv:1406.4137

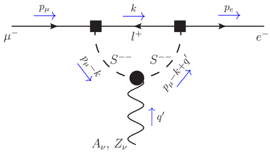
Selection of interesting processes: **low energy physics**

- neutrinoless double beta decay:

$$\boxed{\frac{\xi\, f_{ee}}{M_S^2\, \Lambda^3} < \frac{4.0 \cdot 10^{-3}}{\mathrm{TeV}^5}}$$



- $\mu^- \to e^- \gamma$:



$$\boxed{\left| f_{ee}^*\, f_{e\mu} + f_{e\mu}^*\, f_{\mu\mu} + f_{e\tau}^*\, f_{\mu\tau} \right| < 3.2 \cdot 10^{-4}\, M_S^2 [\mathrm{TeV}]}$$

Testing the Model

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benchmark points:

$\boxed{f_{ab} \text{ such that bounds fulfilled + suitable light neutrino mass matrix reproduced}}$

- 'red': $f_{ee} \simeq 0$ and $f_{e\tau} \simeq 0$
- 'purple': $f_{ee} \simeq 0$ and $f_{e\mu} \simeq \frac{f^*_{\mu\tau}}{f^*_{\mu\mu}} f_{e\tau}$
- 'blue': $f_{e\mu} \simeq \frac{f^*_{\mu\tau}}{f^*_{\mu\mu}} f_{e\tau}$

$\downarrow$

complementary check with **high energy experiments**:
compute cross sections for e.g.

- $S^{\pm\pm} \rightarrow W^{\pm\pm}$
- $S^{\pm\pm} \rightarrow l_a^{\pm\pm}\, l_b^{\pm\pm}$
- ...

$\rightarrow$ some of the benchmark points already excluded by LHC data (7 TeV run)

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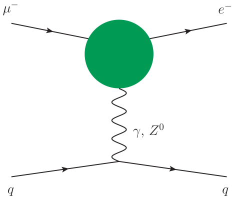
μ–e Conversion

within **muonic atom**:
bound μ^- captured by nucleus
and re-emitted as e^-



→ **coherent** μ–e conversion: same initial and final state of the nucleus

past: SINDRUM II for ^{48}Ti (1993), ^{208}Pb (1995), ^{197}Au (2006)

future: DeeMee for ^{28}Si, COMET and Mu2e (first results $\sim$ 2020) for ^{27}Al, PRISM/PRIME for ^{48}Ti

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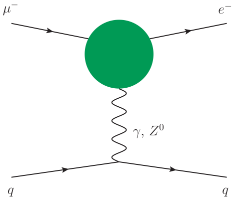

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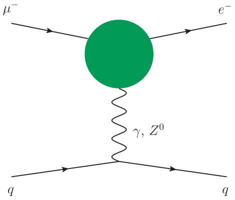

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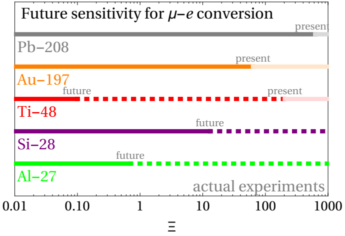

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μ–e Conversion

- Write **branching ratio** as product of nuclear and particle part

$$\boxed{\mathrm{BR}(\mu^- N \to e^- N) = \frac{8\alpha^5 m_\mu Z_{\mathrm{eff}}^4 Z F_p^2}{\Gamma_{\mathrm{capt}}} \, \Xi^2}$$

see e.g. Kuno & Okada, 1999

$\to$ factorisation works perfectly for **photonic** (long-range) contributions
$\to$ Ξ has to be modified for **non-photonic** contributions to be a function of nuclear characteristics

- μ–e conversion realised at one-loop level $\to$ determine **form factors** (particle physics part) $\to$ dominant contributions from:

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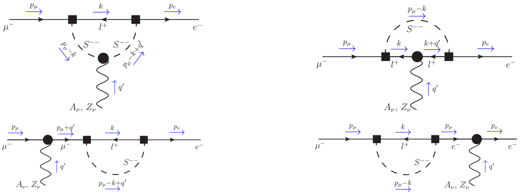

μ–e Conversion: Photonic Contributions

Most general photonic **matrix element**

$$i\mathcal{M} = i\,e\,A_\nu(q')\,\overline{u_e}(p_e)\left[\left(\gamma^\nu - \frac{\not{q}'\,q'^\nu}{q'^2}\right)F_1(q'^2) + \frac{i\,\sigma^{\nu\rho}\,q'_\rho}{m_\mu}\,F_2(q'^2) + 2\frac{q'^\nu}{m_\mu}\,F_3(q'^2)\right.$$
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with $q' = p_e - p_\mu$.

Branching ratio factorises → **particle physics** absorbed into

$$\boxed{\Xi^2 = \left|-F_1(-m_\mu^2) + F_2(-m_\mu^2)\right|^2 + \left|G_1(-m_\mu^2) + G_2(-m_\mu^2)\right|^2}$$

→ determine form factors with the help of Mathematica package *Package*-X (Patel, arXiv:1503.01469)
→ simplify result for $M_S \gg m_a$ (for $a = e, \mu, \tau$)
→ leading order: $\Xi \propto 1/M_S^2$

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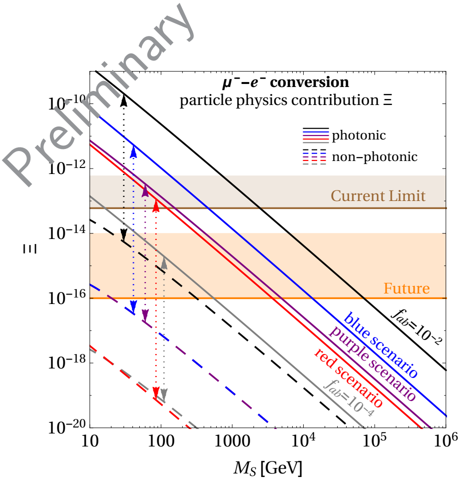
Results: Observations



→ non-photonic: widths of the bands so small → appear as lines

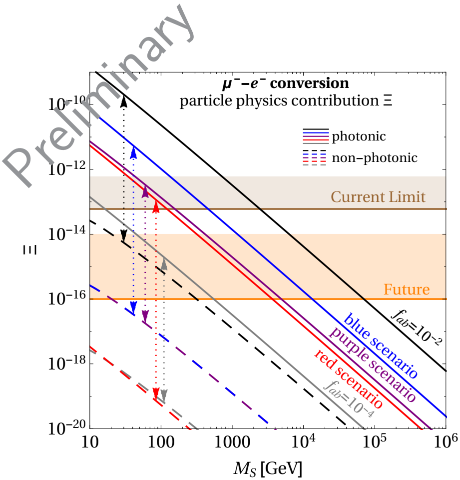
→ non-photonic (DASHED) contributions **negligibly small**

⇓

→ approximate process by its purely photonic (SOLID) contribution

→ **factorisation**: dependence on isotope only in width of limit

Results: Photonic Contributions



For $\mu^- \to e^- \gamma$:
strongest bound for red, weakest for blue points

$$\mathcal{A} \propto \left| f^*_{ee}\, f_{e\mu} + f^*_{e\mu}\, f_{\mu\mu} + f^*_{e\tau}\, f_{\tau\mu} \right| \cdot C$$

→ some amount of cancellation

For $\mu^- - e^-$ conversion:
!! other way around !!

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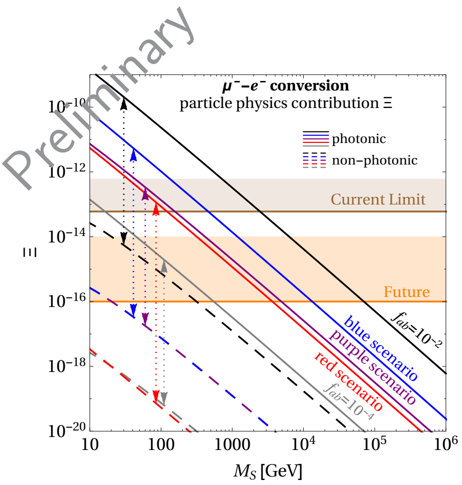

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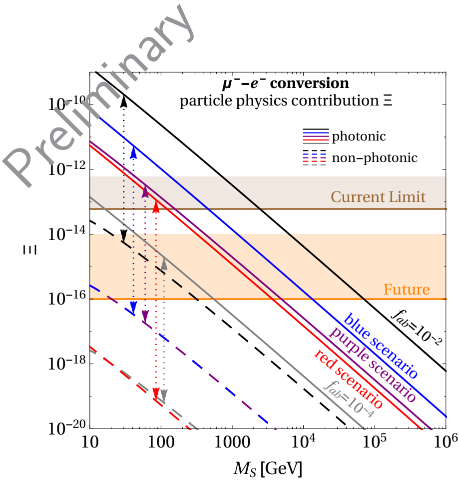

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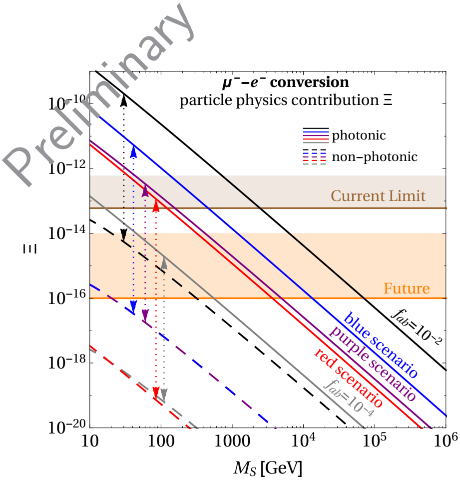
Results: Bounds on Scalar Mass

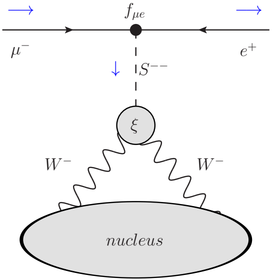


For the **scalar mass**, we can extract lower bounds along the lines of:

	current limit in GeV	future limit in GeV
black	$M_S > 2450$	$M_S > 70370$
grey	$M_S > 16$	$M_S > 550$
red	$M_S > 120$	$M_S > 3660$
blue	$M_S > 460$	$M_S > 13270$
purple	$M_S > 160$	$M_S > 4880$

Summary and Outlook

- **complementarity**: rich phenomenology of loop models $\rightarrow$ high- and low-energy processes $\rightarrow$ μ^-–e^- conversion important part of study
- work in progress: $\boldsymbol{\mu^-}$–$\boldsymbol{e^+}$ **conversion**
  $\rightarrow$ LNV process
  $\rightarrow$ same experimental setup
  $\rightarrow$ access not only to M_S but to a combination of M_S and ξ

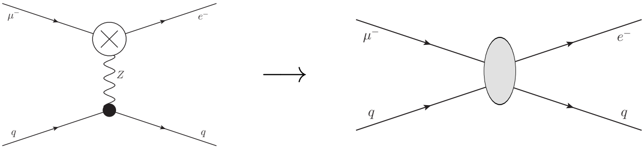


Thank you for your attention!!

Any questions?

μ–e Conversion: Non-Photonic Contributions

'**Integrating out**' the Z-boson:



The relevant **effective** Lagrangian for the coherent μ–e conversion is

$$\mathcal{L}_{\text{short-range}} = -\frac{G_F}{\sqrt{2}} \underbrace{\frac{2(1+k_q)\sin^2\vartheta_W\cos\vartheta_W}{g} A_R(q'^2)}_{g_{RV(q)}} \overline{e_R}\,\gamma_\nu\,\mu_R\,\overline{q}\,\gamma^\nu\, q$$

which leads to

$$\boxed{\Xi^2_{\text{non-photonic}}\left[Z,\,N\right] = \frac{m_\mu^4 \sin^4\vartheta_W\cos^2\vartheta_W}{128\,\pi\,\alpha\,Z^2\,M_W^4}\left|(3N-Z)A_R(-m_\mu^2))\right|^2 .}$$

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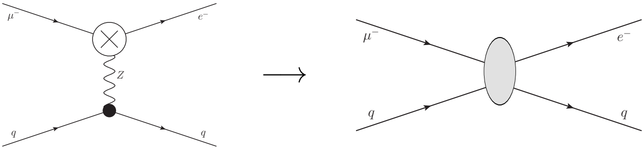

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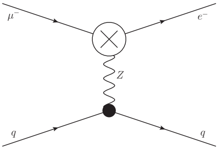

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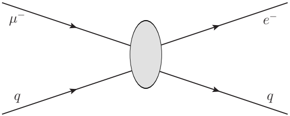

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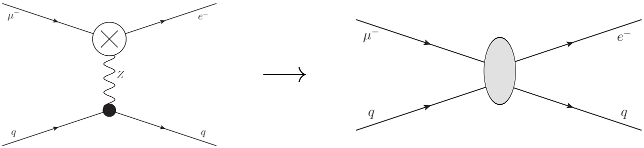

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'Average Scenario' Couplings

	red	purple	blue
f_{ee}	10^{-16}	10^{-15}	10^{-1}
$f_{e\mu}$	10^{-2}	10^{-3}	10^{-4}
$f_{e\tau}$	10^{-19}	10^{-2}	10^{-2}
$f_{\mu\mu}$	10^{-4}	10^{-3}	10^{-3}
$f_{\mu\tau}$	10^{-5}	10^{-4}	10^{-4}
$f_{ee}\, f_{e\mu}$	10^{-18}	10^{-18}	$\mathbf{10^{-5}}$
$f_{e\mu}\, f_{\mu\mu}$	$\mathbf{10^{-6}}$	$\mathbf{10^{-6}}$	10^{-7}
$f_{e\tau}\, f_{\mu\tau}$	10^{-24}	$\mathbf{10^{-6}}$	10^{-6}

Table: First part: 'average scenario' couplings for the benchmark points as extracted from Tab. 7 in *King, Merle, Panizzi: arXiv:1406.4137*. Second part: combination of couplings that enter the μ–e conversion amplitude. The bold values indicate the dominant photonic contribution.

Non-Photonic Bands

- The amplitude that enters the non-photonic Ξ takes the form

$$\mathcal{A} \propto \left| f_{ee}^* \, f_{e\mu} \, D(m_e) + f_{e\mu}^* \, f_{\mu\mu} \, D(m_\mu) + f_{e\tau}^* \, f_{\tau\mu} \, D(m_\tau) \right| .$$

- The function $D(m_a)$ strongly varies with m_a.
  $\rightarrow$ **dominant term** stems from the tau propagating within the loop, i.e. $\boldsymbol{D(m_\tau)}$
  $\rightarrow$ exeeds the muon and electron contribution by three to four orders of magnitude
- blue/purple scenario: neither $f_{ee}^* f_{e\mu}$ nor $f_{e\mu}^* f_{\mu\mu}$ bypasses this difference
  $+$ **identic** $\boldsymbol{f_{e\tau}^* f_{\tau\mu}}$ in both scenarios
  $\rightarrow$ indistinguishable curves
- red/grey scenario:
  dominant contributions: $f_{e\mu}^* \, f_{\mu\mu} \, D(m_\mu) \sim f_{e\tau}^* \, f_{\tau\mu} \, D(m_\tau)$
  $\rightarrow$ same order of magnitude, i.e. **comparable values** of non-photonic contribution