LNV and cLFV probes of heavy Majorana fermions

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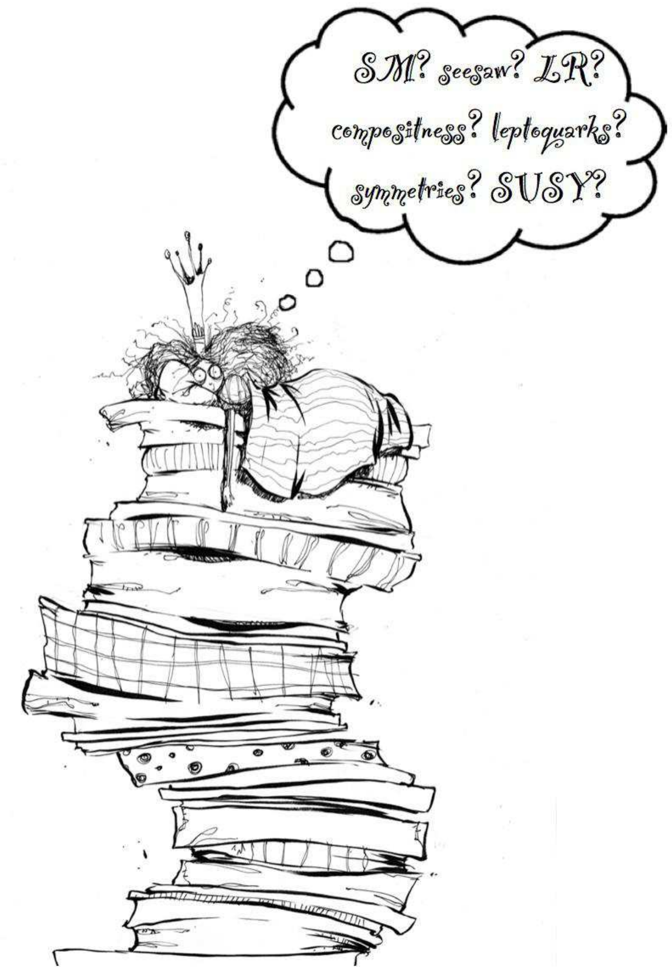
Beyond the Standard Model: New Physics

- **Strong arguments in favour of New Physics!**

  Observations unaccounted for in the **Standard Model: neutrino oscillations, baryon asymmetry of the Universe, viable dark matter candidate**

  And a number of theoretical caveats...

  How to unveil the NP model at work?



- **Neutrino oscillations: 1st laboratory evidence of NP**

  New mechanism of mass generation? New **Majorana** fields?!

  $\Rightarrow \Delta L \neq 0$ with implications for **leptogenesis...**

- SM extensions via " heavy" **sterile fermions**

  Theoretically well-motivated! **Rich phenomenology!**

- **How to unveil presence of (Majorana) sterile states?**

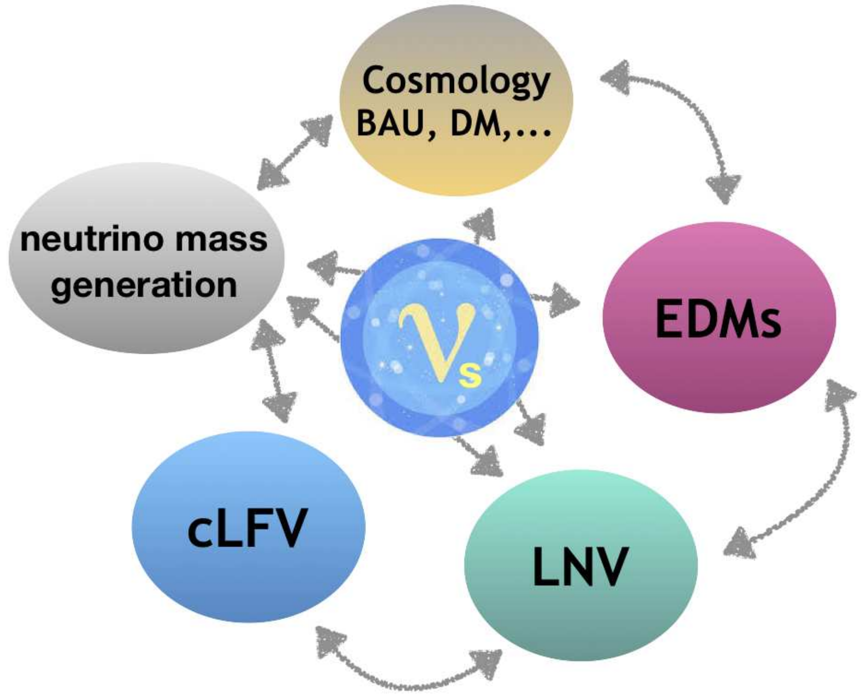
  Numerous observables to be explored!

  Forbidden or highly suppressed in the SM...

SM extended by sterile neutrinos: signs of New Physics?

- **Majorana sterile fermions:** an appealing **hypothesis**

  NP candidate motivated by numerous theoretical and observational arguments



- Potentially a very **"visible" NP portal:** **extensive imprints,**

  from **colliders to low-energies,** from **flavour dedicated experiments to CPV searches...**

  ⇒ **experimental signatures** within **reach of current and future sensitivities!**

  ⇒ **focus on contributions to** lepton number violation processes

Why Lepton Number Violation?

- Why not? **"Lepton number"** is only an accidental symmetry of the SM...
- Neutrino oscillations: **evidence of NP!** $\Rightarrow$ **Majorana fermions,** and $\Delta L = 2$ **transitions**
- $\Delta L = 2$ processes at the **"crossroads" of many BSM constructions**

  New theoretical ideas, with massive implications

  $\Rightarrow$ **addressing the BAU via leptogenesis!**

  Many processes to study, at very **distinct energy scales**
- **Impressive** experimental prospects **(in the near future...)**

  and exciting new theoretical ideas & models!

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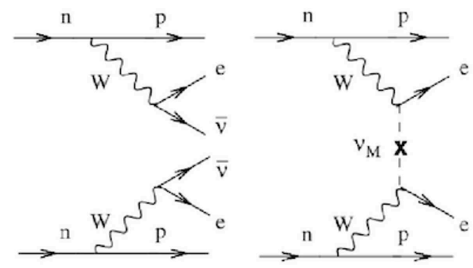
Experimental prospects:
Schönert
Zsigmond, O'Donnell
Wonsak, Sorel

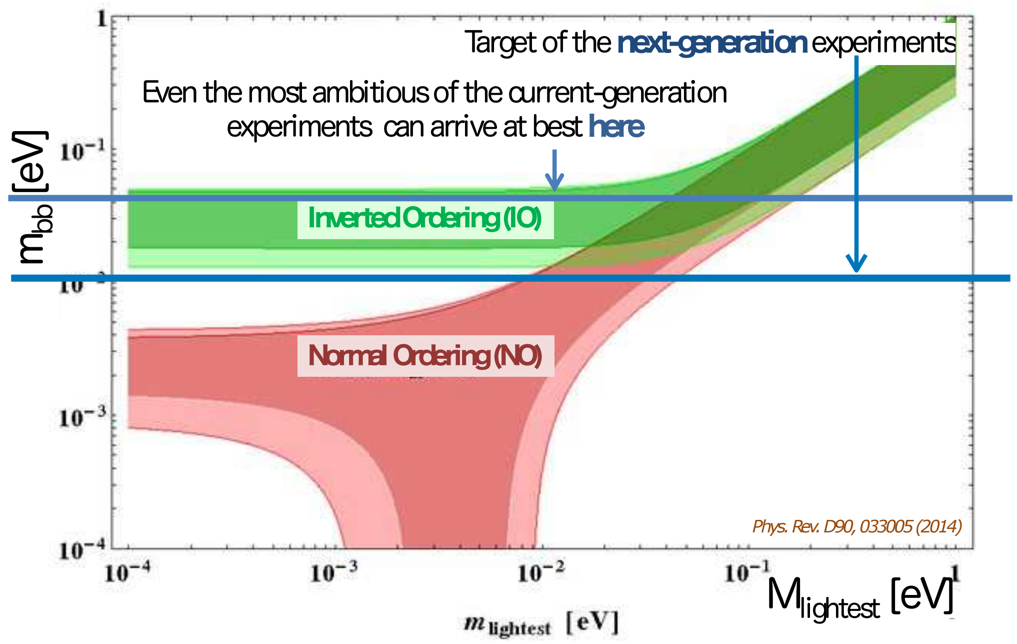
Theory overview & new ideas:
Dekens, Herrero
Fonseca

LNV ($\Delta L = 2$) observables: neutrinoless double beta decays

★ **LNV** suggests the presence of **Majorana states**; opens the door for leptogenesis...

▶ **Neutrinoless double beta decays:** $(A, Z) \to (A, Z+2) + 2e^-$





[adapted from Giuliani, EPPSU'19]

source=detector		NOW	MID-TERM	LONG-TERM
Scalability – Fluid embedded source	Xe-based TPC	EXO-200 NEXT-10	NEXT-100 PandaX-III	nEXO NEXT-2.0 PandaX-III 1t
	Liquid scintillator as a matrix	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
High DE and e – Crystal embedded source	Germanium diodes	GERDA-II MJD	LEGEND 200	LEGEND 1000
	Bolometers	AMoRE pilot, I CUORE CUPID-0, CUPID-Mo	AMoRE II	CUPID

These experiments aim to explore deeply or fully the IO region and to cover a substantial part of the NO region
$T_{1/2} > 10^{27} - 10^{28}$ y – $m_{bb} <$ 20 meV

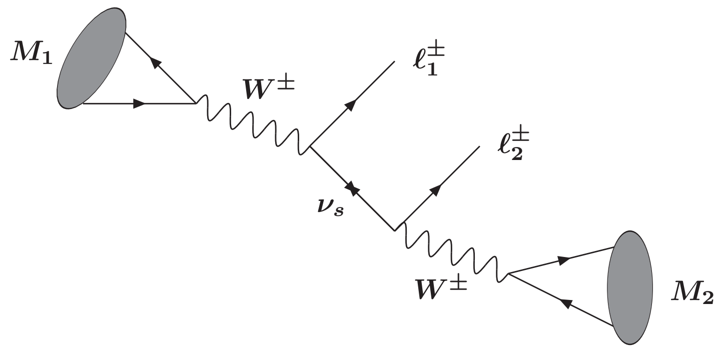
▶ **Current status:** $m_{\beta\beta} < (61 - 165)$ meV

[Kamland-Zen, '16]

LNV ($\Delta L = 2$) in semileptonic tau and meson decays

- **A (small) subset of semileptonic tau and meson LNV bounds**

LNV decay	Current Bound	
	$\ell = e,\ \ell' = e$	$\ell = \mu,\ \ell' = \mu$
$K^- \to \ell^- \ell'^- \pi^+$	6.4×10^{-10}	1.1×10^{-9}
$D^- \to \ell^- \ell'^- \pi^+$	1.1×10^{-6}	2.2×10^{-8}
$D^- \to \ell^- \ell'^- K^+$	9.0×10^{-7}	1.0×10^{-5}
$B^- \to \ell^- \ell'^- \pi^+$	2.3×10^{-8}	4.0×10^{-9}
$B^- \to \ell^- \ell'^- K^+$	3.0×10^{-8}	4.1×10^{-8}
$B^- \to \ell^- \ell'^- \rho^+$	1.7×10^{-7}	4.2×10^{-7}
$B^- \to \ell^- \ell'^- D^+$	2.6×10^{-6}	6.9×10^{-7}



◄ ▼ **Experimental status: BaBar, Belle**

LNV decay	Current Bound	
	$\ell = e$	$\ell = \mu$
$\tau^- \to \ell^+ \pi^- \pi^-$	2.0×10^{-8}	3.9×10^{-8}
$\tau^- \to \ell^+ \pi^- K^-$	3.2×10^{-8}	4.8×10^{-8}
$\tau^- \to \ell^+ K^- K^-$	3.3×10^{-8}	4.7×10^{-8}

- Also **LNV in 4-body meson decays**
  and **in (cLFV) $\mu^- \to e^+$ conversion...**

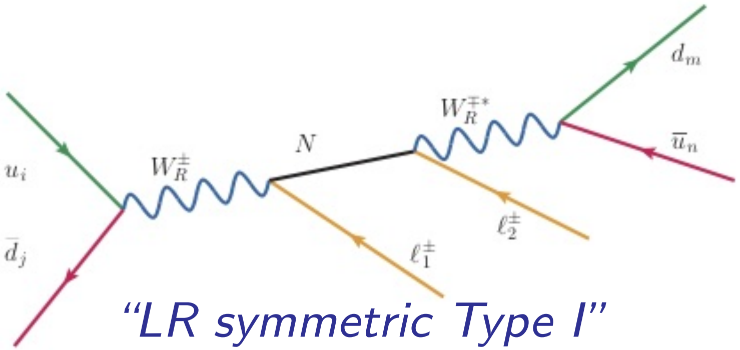
- **Future prospects: LHCb (Upgrade I & II), Belle II (upgrade),**
  TauFV, Super Charm-Tau factory... NA62, KOTO, KLEVER, ...

LNV at higher energies: $\Delta L = 2$ collider searches

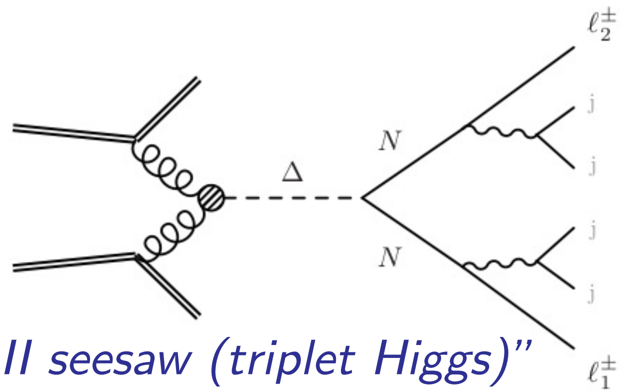
★ Many **NP models** predict **"heavy" Majorana** mediators, produced **on-shell at colliders**

- ▶ **Production and decay modes** (LNV final states & signatures) ⇝ **model dependent**

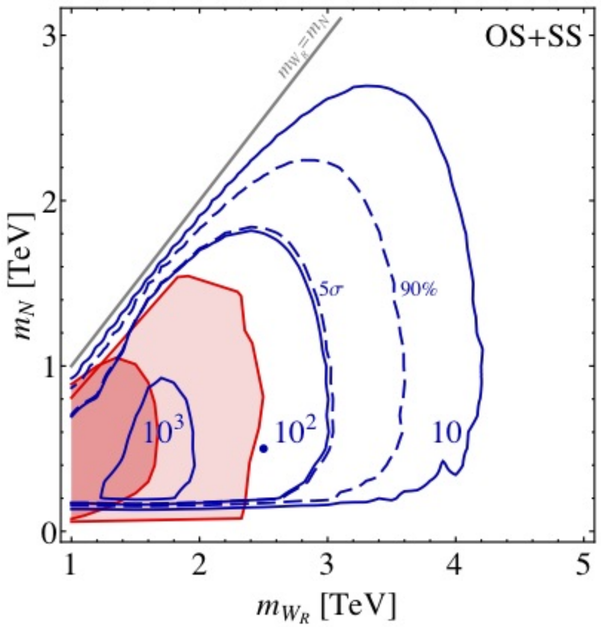
E.g.: **"observable" LNV $\ell^\pm \ell^\pm + n$ jets** from N_R, $W_R^\pm$, Z_R, H, $\Delta^{\pm\pm}$, $\Sigma^{\pm\pm}$, ...

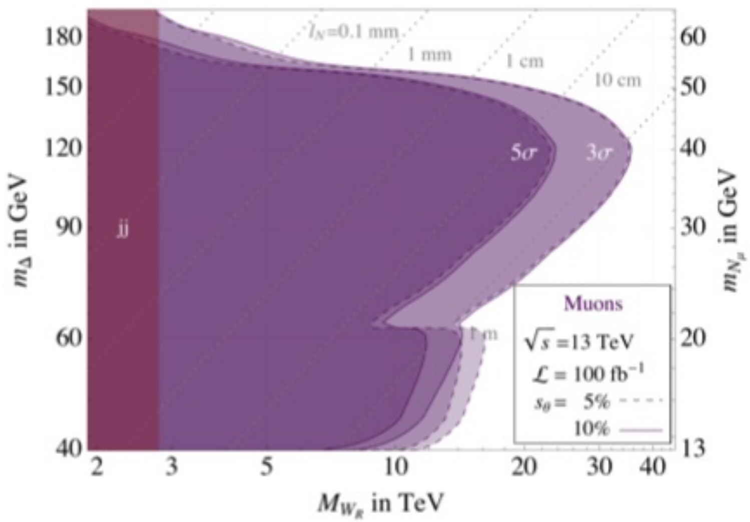


"LR symmetric Type I"



"Type II seesaw (triplet Higgs)"





(For a review: [Cai et al, 1711.02180])

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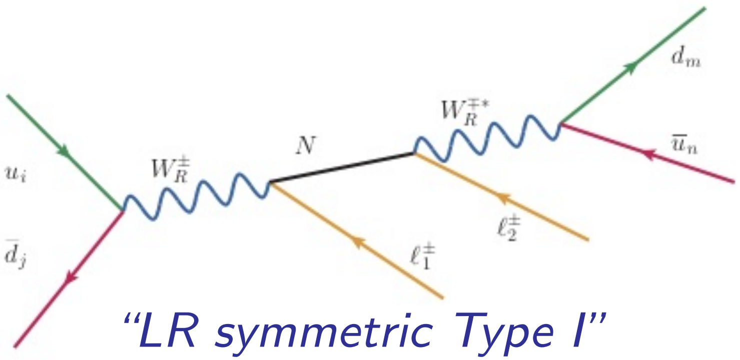

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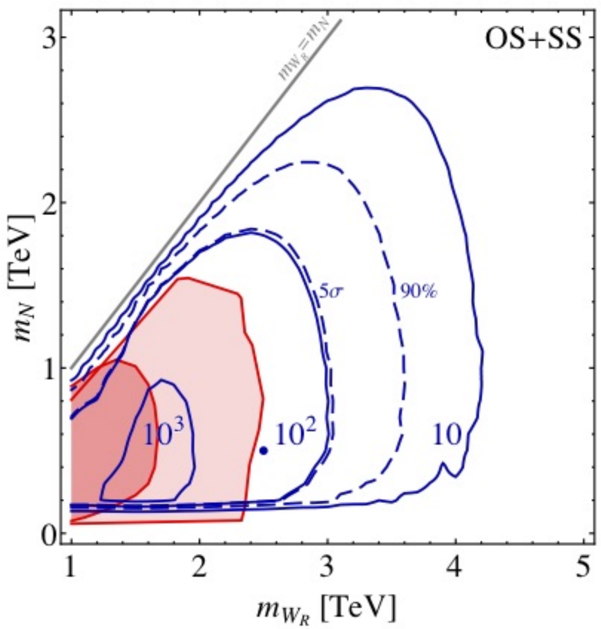

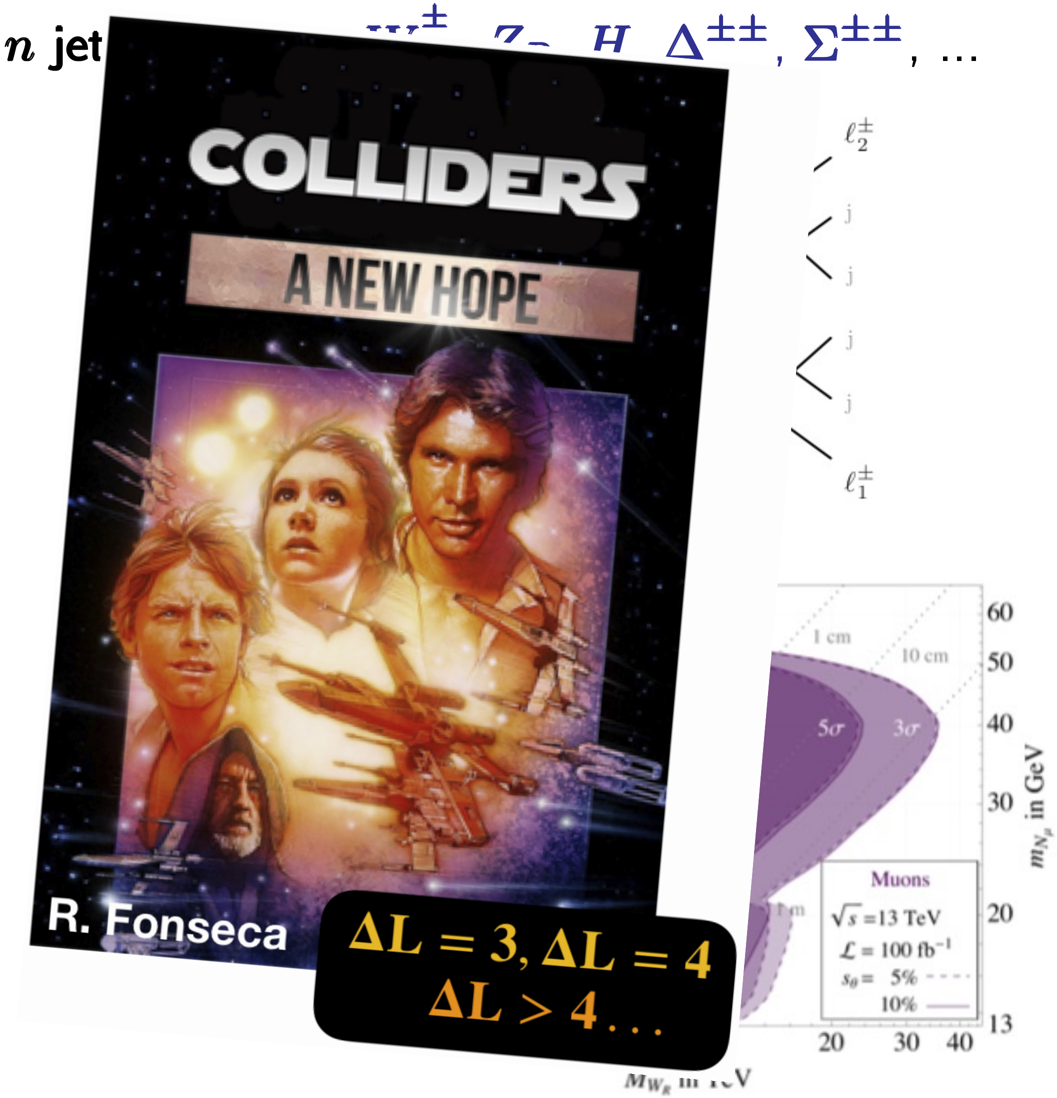

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Brief summary

- **Sterile fermion extensions of the SM**

  Motivation & minimal theoretical constructions

  Experimental searches

- **LNV and new physics models with sterile fermions**

  LNV observables - from $0\nu2\beta$ to semileptonic decays

  Semileptonic meson and τ decays: effective Majorana masses

- **Interference effects in LNV and cLFV semileptonic meson decays**

  The role of CP phases & impact for experimental prospects

- **Further LNV (and cLFV) impact of sterile fermions**

- **Overview & discussion**

Many dedicated talks on the "LNV & LFV" session!

- **Sterile fermion extensions of the SM**

Sterile fermions: beyond the 3-neutrino paradigm

- **Sterile fermions:** singlets under $SU(3)_c \times SU(2)_L \times U(1)_Y$

  Interactions with SM fields: through **mixings** with **active neutrinos** (via Higgs)

  No bound on the **number** of sterile states, **no limit** on their **mass scale(s)**

  Present in several **theoretical models** accounting for $\boldsymbol{\nu}$ **masses and mixings**

- **Interest & phenomenological implications** - strongly dependent on their **mass!**

  eV scale $\leftrightarrow$ extra neutrinos suggested by short baseline ν oscillation anomalies

  (oscillation results not explained within 3 flavour oscillation)

  keV scale $\leftrightarrow$ warm dark matter candidates; explain pulsar velocities (kicks)

  (extensive bounds to be complied with...)

  MeV - TeV scale $\leftrightarrow$ experimental testability! (and BAU, DM, m_ν generation...)

  (direct and indirect effects, both at the high-intensity and high-energy frontiers)

  Beyond 10^9 GeV $\leftrightarrow$ theoretical appeal: "standard" seesaw, BAU, GUTs

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  No bound on the **number** of sterile states, **no limit** on their **mass scale(s)**

  Present in several **theoretical models** accounting for ν **masses and mixings**

- Sterile fermions **integral part of (low scale) mechanisms of ν mass generation**

  $\rightsquigarrow$ **Right-handed neutrinos** (low scale seesaws: type I, νMSM, ...)

  $$\mathcal{L}_{\text{type I}} = -Y^{\ell}\,\bar{L}_L\,H\,e_R - Y^{\nu}\,\overline{\nu_R}\,\tilde{H}\,\nu_L - \tfrac{1}{2}\,\overline{\nu_R}\,M_N\,\nu_R^c \qquad \Rightarrow m_\nu \sim \frac{v^2\,Y_\nu^2}{M_N}$$

  $\rightsquigarrow$ **Other neutral fermions** (ν_R + extra sterile states in Inverse Seesaw, ...)

  $$\mathcal{L}_{\text{ISS}} = -Y^{\nu}\,\overline{\nu_R}\,\tilde{H}\,L - M_R\,\overline{\nu_R}\,X - \tfrac{1}{2}\mu_X\,\bar{X}^c\,X + \tfrac{1}{2}\mu_R\,\overline{\nu_R}\,\nu_R^c \qquad \Rightarrow m_\nu \sim \frac{v^2\,Y_\nu^2}{M_R}\,\frac{\mu_X}{M_R}$$

- **Simplified "toy models" for phenomenological analyses:** SM + ν_s

  "ad-hoc" construction (no specific assumption on mechanism of mass generation)

"Toy model" for phenomenological analyses: SM + ν_s

- **Assumptions:** 3 active neutrinos + 1 sterile state $\quad n_L = (\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_s^c)^T$

  interaction basis ⇝ physical basis $\quad n_L = U_{4\times4}\,\nu_i$

  $U^T_{4\times4}\,M\,U_{4\times4} = \text{diag}(m_{\nu_1}, ..., m_{\nu_4})$ "**Majorana** mass": $\mathcal{L}_{\text{toy}} \sim n_L^T C M n_L$

- **Active-sterile mixing $\mathbf{U}_{\alpha i}$:**

  rectangular matrix ← $\mathbf{U} = U|_{3\times4}$

- **Left-handed lepton mixing $\tilde{U}_{\text{PMNS}}$:**

  3×3 sub-block, non-unitary!

$$U_{4\times4} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- **Physical parameters: 4 masses [3 light (mostly active) + 1 heavier (mostly sterile)** states]

  6 mixing angles [θ_{12}, θ_{23}, θ_{13}, & θ_{i4}] and **6 phases** [(3 Dirac and 3 Majorana)]

- **Modified charged ($W^\pm$) and neutral (Z^0) current interactions:**

$$\mathcal{L}_{W^\pm} \sim -\frac{g_w}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3+n_S} \mathbf{U}_{\alpha i}\, \bar{\ell}_\alpha\, \gamma^\mu\, P_L\, \nu_i$$

$$\mathcal{L}_{Z^0} \sim -\frac{g_w}{2\cos\theta_w} Z_\mu \sum_{i,j=1}^{3+n_S} \bar{\nu}_i\, \gamma^\mu \left[P_L\, (\mathbf{U}^\dagger\mathbf{U})_{ij} - P_R\, (\mathbf{U}^\dagger\mathbf{U})^*_{ij} \right] \nu_j$$

Sterile fermions: experimental prospects

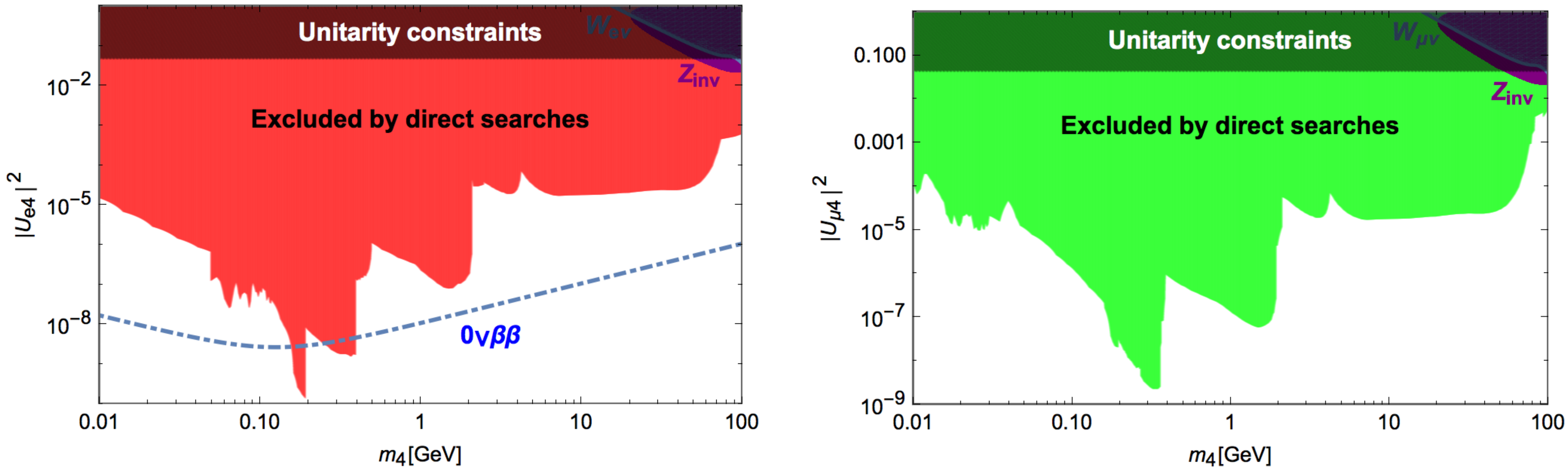
- **Phenomenological impact: modified $W^\pm$ charged currents** and **Z^0, H neutral currents**

  If sufficiently light, sterile νs can be **produced as final states**

- **Contributions to many processes and observables** [low and high energies]

  Electroweak precision tests, cLFV, $0\nu2\beta$ decays, rare meson decays (cLFV, LNV, LFUV), collider searches, beam dump experiments, cosmology...

- **Current data already allowing to constrain ν_s parameter space:** $[m_4, |U_{\alpha 4}U_{\beta 4}|]$



[Abada, De Romeri, Lucente, Toma, AMT '18]

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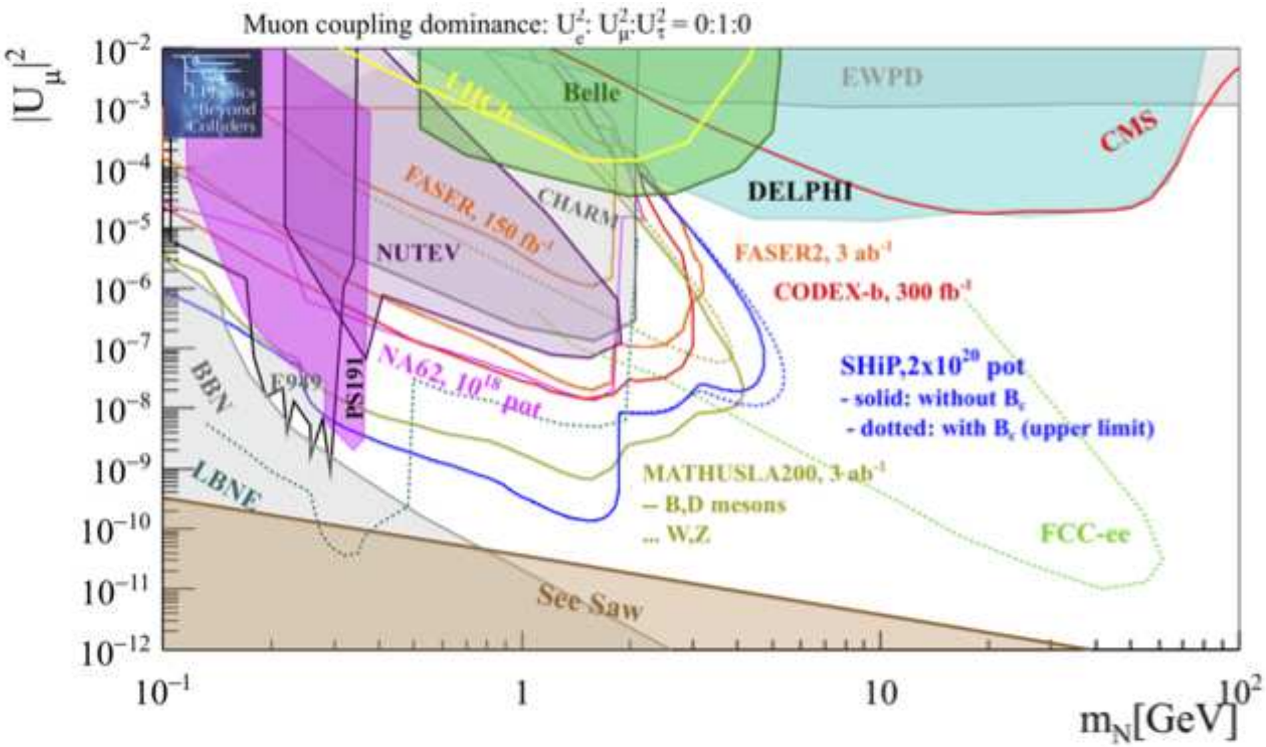
  Electroweak precision tests, cLFV, $0\nu2\beta$ decays, rare meson decays (cLFV, LNV, LFUV), collider searches, beam dump experiments, cosmology...

- **Excellent prospects for future experiments, covering impressive regions in $[m_N, |U_{\alpha N}|^2]$**



- **LNV and New Physics models with sterile fermions: from $0\nu2\beta$ to semileptonic decays**

Sterile neutrinos: impact for LNV observables

- If sterile neutrinos are Majorana fermions, expect contributions to LNV processes
  - **Neutrinoless double beta decays ($0\nu 2\beta$)**

$$m_{ee} \simeq \sum_{i=1}^{4} U_{ei}^2\, p^2 \frac{m_i}{p^2 - m_i^2} \simeq \left(\sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i}\right) + p^2\, U_{e4}^2\, \frac{m_4}{p^2 - m_4^2}$$

  - ν_s can strongly impact **predictions for $|m_{ee}|$**

    $\Rightarrow$ **augmented ranges** for effective mass

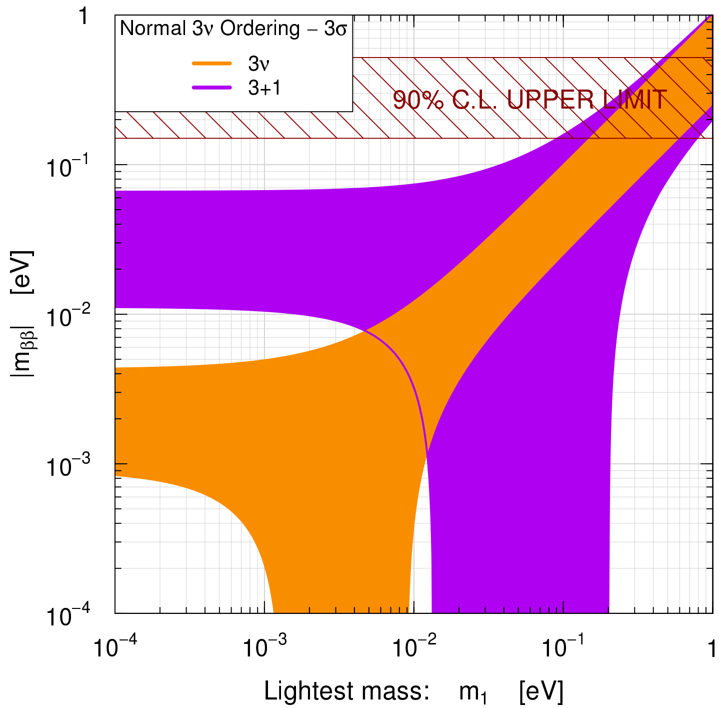
    for both cases of light neutrino spectra

    (IO and NO)

  - **Observation** of **$0\nu 2\beta$ signal** in future experiments

    does not imply Inverted Ordering for light νs

    [Abada, De Romeri and AMT, '14; ...; Giunti et al, '15 ←]



- **LNV and sterile fermions: semileptonic decays**

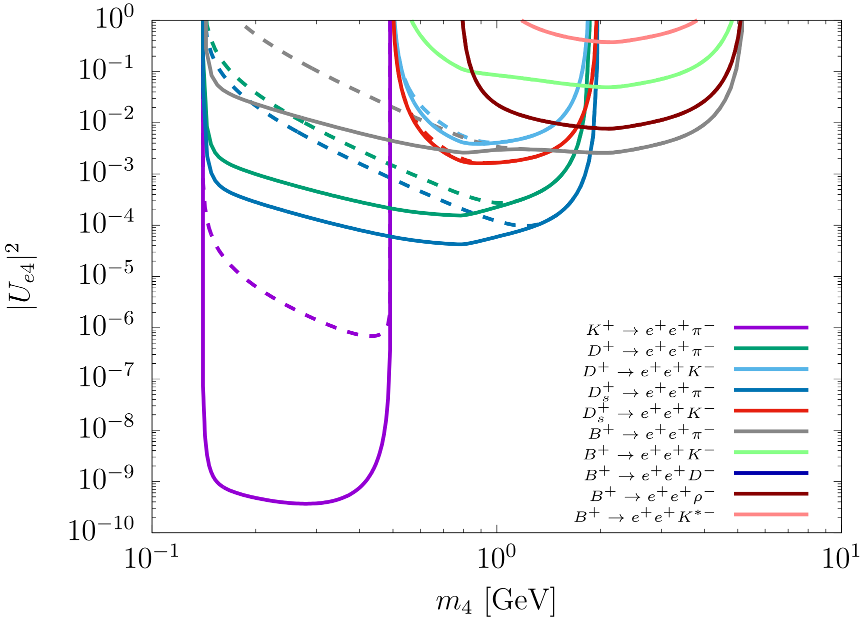
What can we learn from experiment?

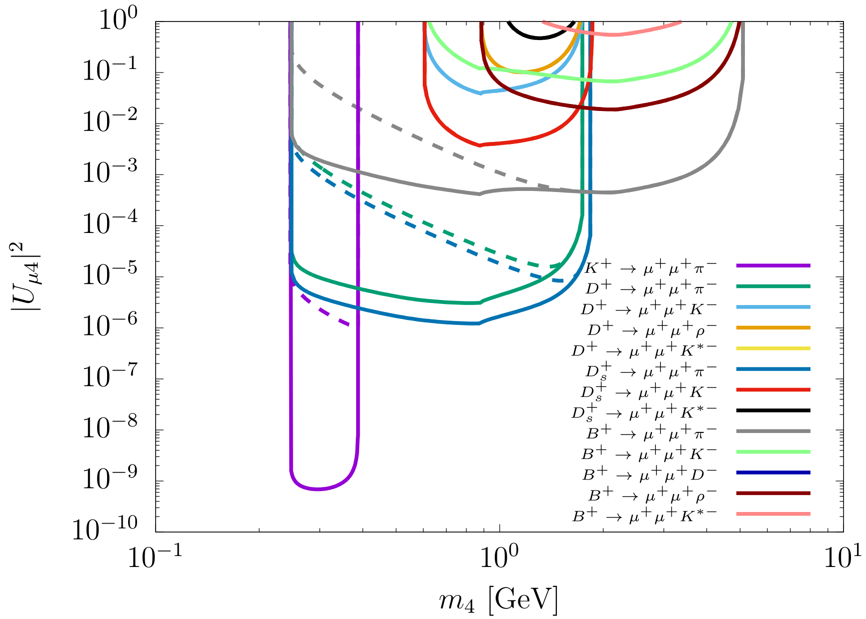
How should data be interpreted in view of

their (hypothetical) presence?

Sterile neutrinos: impact for LNV meson and tau decays

- **On-shell ν_s:** **"resonant-enhancement"** of $M_1 \to M_2 \ell_\alpha^\pm \ell_\beta^\pm$ and $\tau^\pm \to M_1 M_2 \ell^\mp$ decays
- **Bounds** from BaBar, Belle, LHCb; **near future** - LHCb, Belle II, BES-III, NA62...
- Full update of **LNV constraints** on ν_s ($[0.1\ \text{GeV}, 10\ \text{GeV}]$) [1712.03984; see also Atre at al, '09]





- **Prospects for observation:**
  - $\Rightarrow$ ν_s must **decay inside the detector** (sufficiently short-lived)
  - $\Rightarrow$ **Sizeable $\#_{\text{events}}$: BRs $\sim \mathcal{O}(10^{-8,-10})$**

  } **Non-negligible mixings!**

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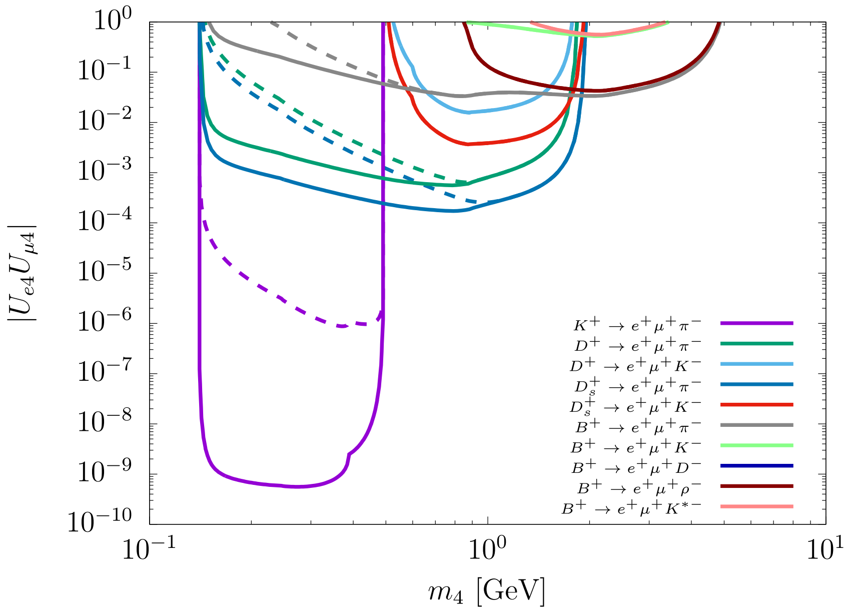
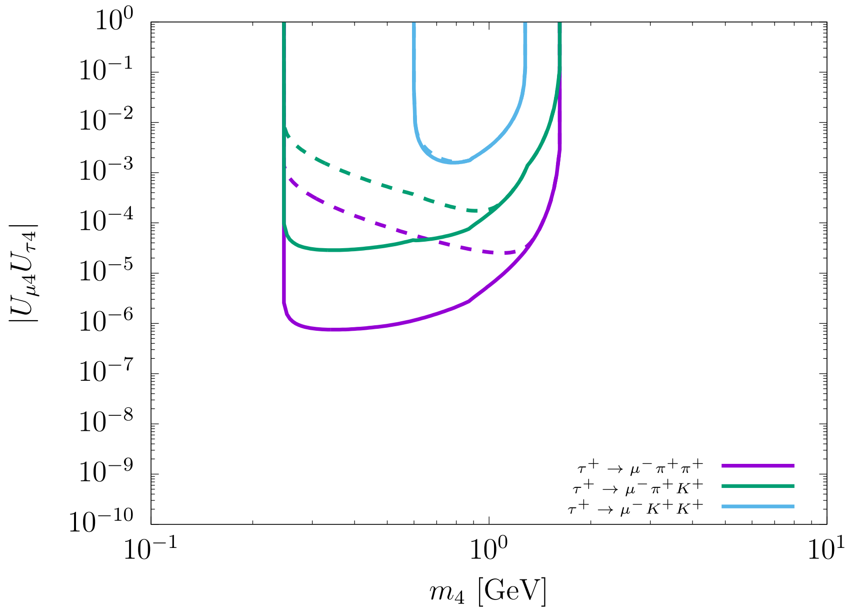


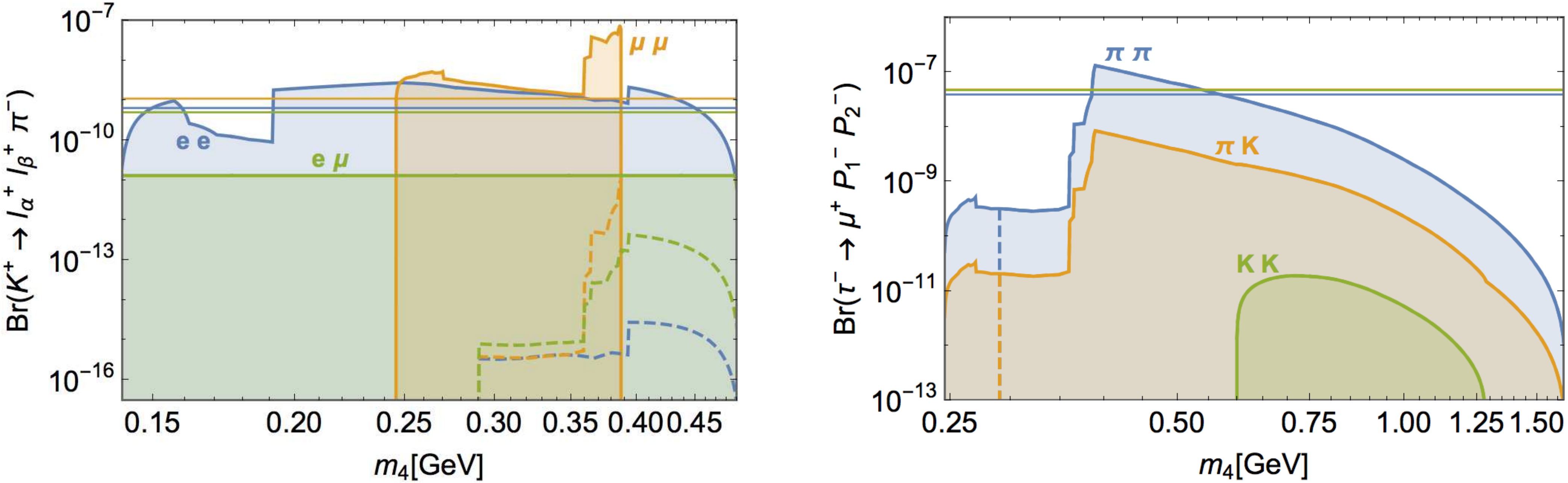


- **Evaluation of constraints from available semileptonic decays**

  $\Rightarrow$ bounds on distinct **active-sterile mixings** $|U_{\alpha4}U_{\beta4}|$ for corresponding ν_4 **mass regime**

Sterile neutrinos: impact for LNV meson and tau decays

- **LNV meson and tau decays via ν_s: prospects for discovery**



[Abada, De Romeri, Lucente, Toma, AMT '18]

- BRs of **several LNV meson and tau decays** close to **current sensitivities**

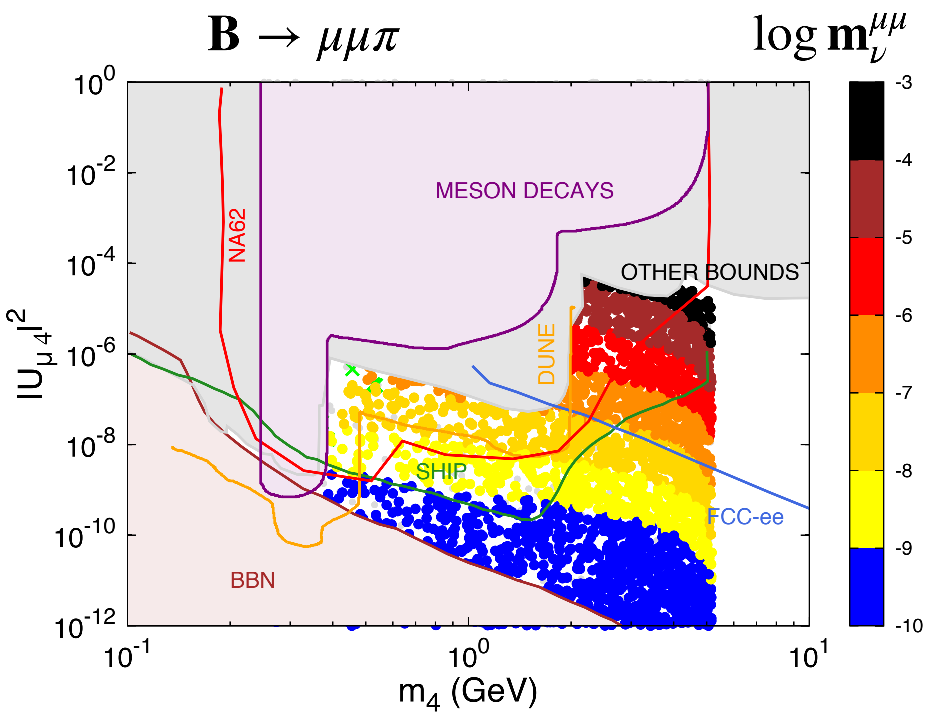
  ⇒ Certain **τ and K LNV decay modes** already in **conflict with experimental data!**

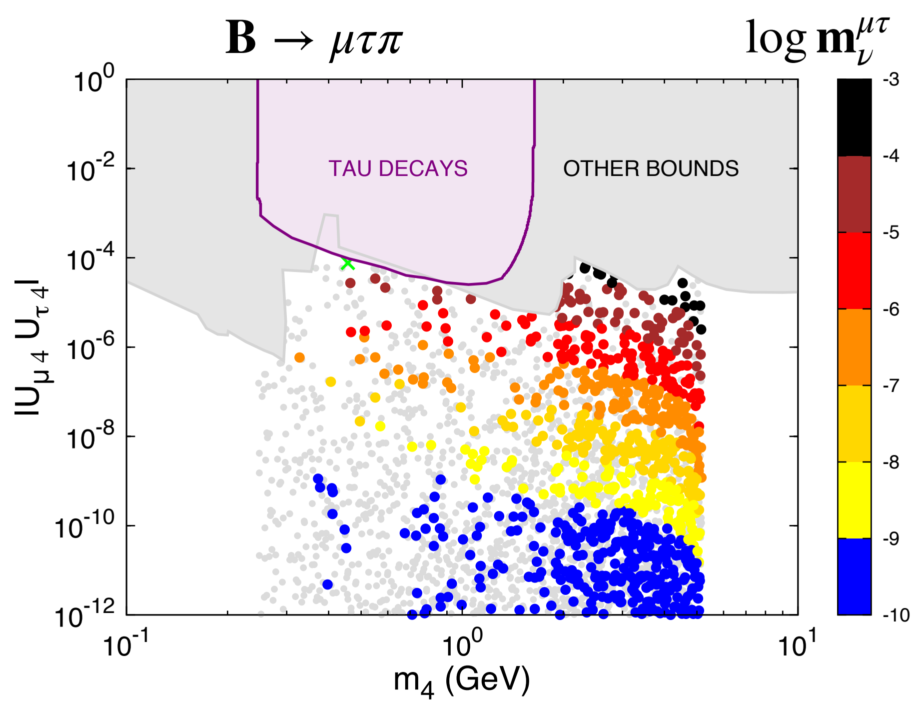
Sterile neutrinos: impact for LNV meson and tau decays

- **LNV meson and tau decays** offer possibility to **infer information** on $m_\nu^{\ell_\alpha \ell_\beta}$

$$m_\nu^{\ell_\alpha \ell_\beta} = \left| \sum_{i=1}^{4} \frac{U_{\alpha i}\, m_i\, U_{\beta i}}{1 - m_i^2/p_{12}^2 + i\, m_i \Gamma_i / p_{12}^2} \right|$$

- m_ν^{ee} best constraints from $0\nu 2\beta$
- **New bounds** on all $m_\nu^{\ell_\alpha \ell_\beta}$ entries - $\lesssim \mathcal{O}(10^{-3}\text{GeV})$ $[m_\nu^{\tau\tau} \lesssim \mathcal{O}(10^{-2}\text{GeV})]$





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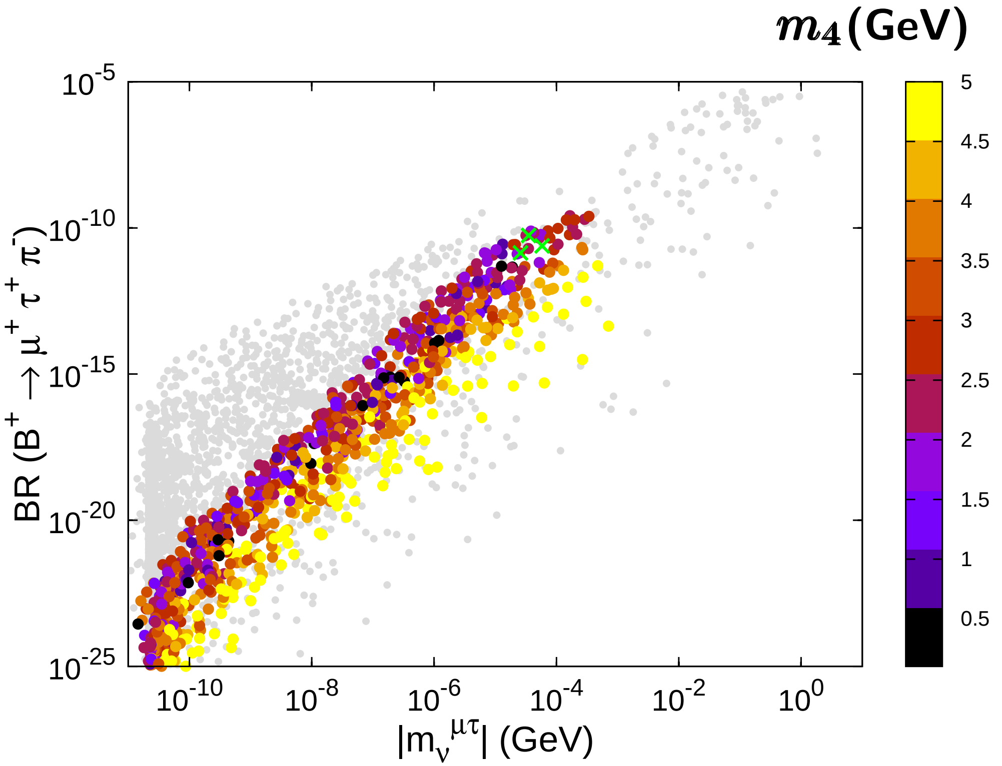
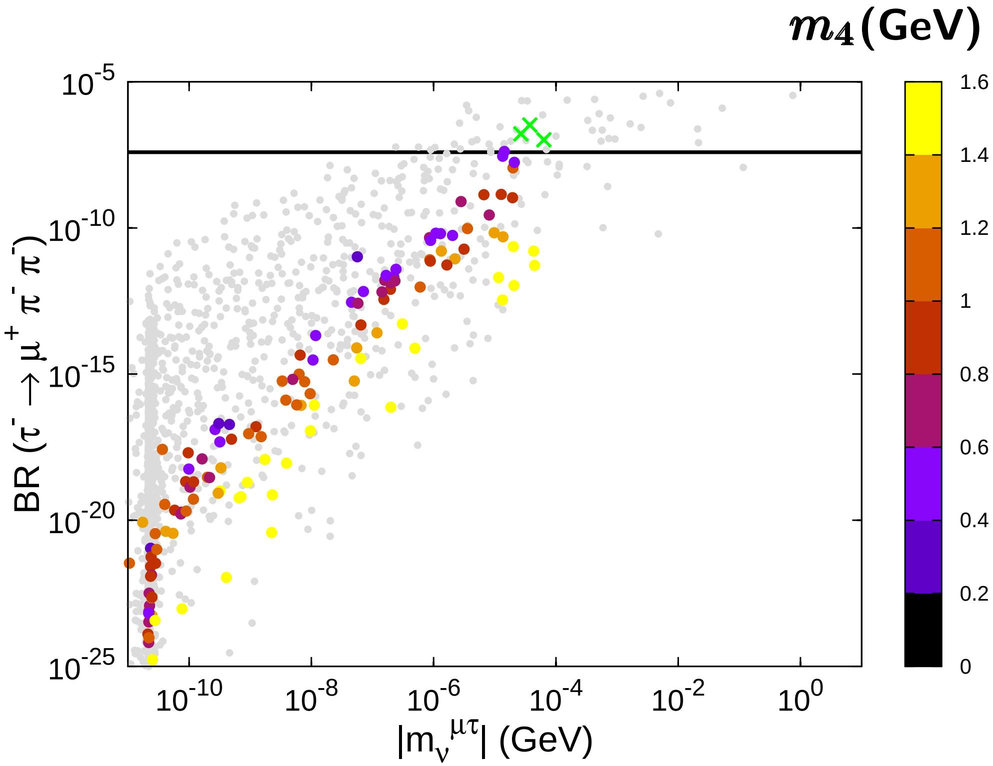




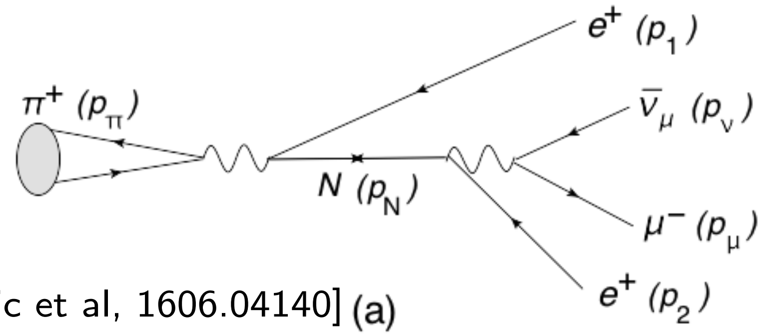
[Abada, De Romeri, Lucente, Toma, AMT '18]

Sterile neutrinos: impact for LNV meson 4-body decays

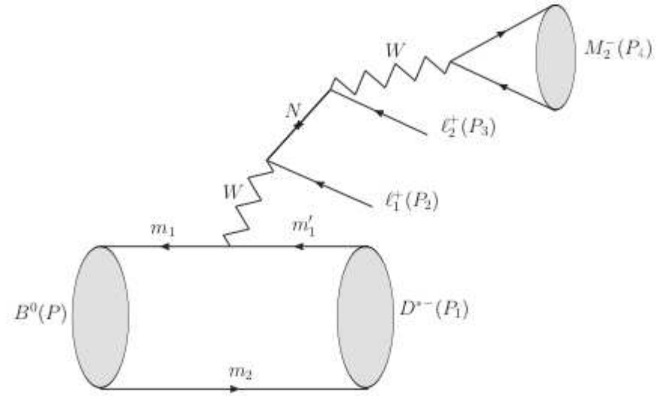
- **Additional LNV meson observables - 4 body decays** $M_1 \to M_2\, \ell^\pm_\alpha\, \ell^\pm_\beta\, M_3$

Typically, **heavier meson** decays (e.g. $B^0 \to D^{*-}\mu^+\mu^+K^-$)

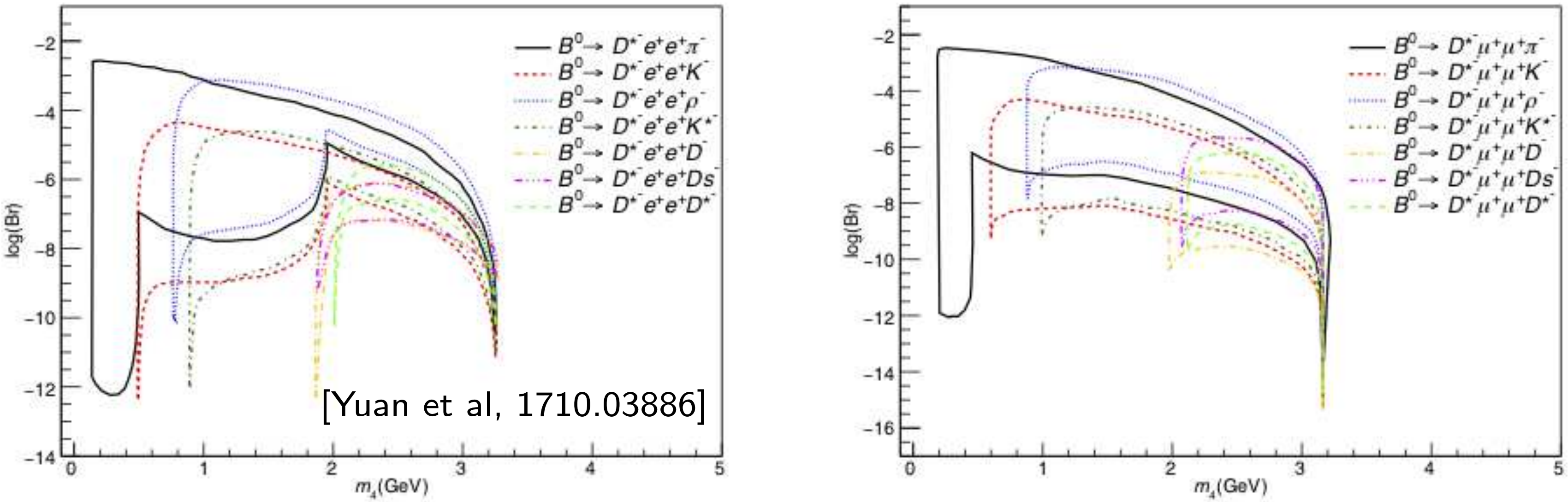
Also: **lighter mesons to 4 leptons** (e.g. $\pi^+ \to e^+\bar{\nu}_\mu\mu^- e^+$)



[Cvetic et al, 1606.04140] (a)



- **Estimation of sterile neutrino contributions**



[Yuan et al, 1710.03886]

- **LNV and sterile fermions: interference effects in semileptonic decays**

What can we learn from experiment?

How should data be interpreted in view of

their (hypothetical) presence?

Sterile neutrinos: impact for LNV decays

- **LNV (& cLFV) meson and tau decays** in SM extended by **Majorana** states

  ⇒ **resonant enhancement** of BRs from **on-shell ν_s exchange**

  ⇒ several **LNV decay modes** close to (or even in conflict with) **experimental data**

- In the presence of a **single sterile state:**

  ⇒ **identical widths for LNV and LNC processes** (same-sign and opposite-sign dileptons)

$$\Gamma^{\text{LNV}}(M \to M' \ell_\alpha^\pm \ell_\beta^\pm) = \Gamma^{\text{LNC}}(M \to M' \ell_\alpha^\pm \ell_\beta^\mp)$$

  ⇒ LNV decays not sensitive to Majorana CP phases

- What if **LNV and cLFV decays** are mediated via **several** (on-shell) **Majorana ν_s ?**

  ⇒ Expect **constructive** & **destructive** (coherent) **interference effects**

  in both LNV and LNC decays!

In particular, $R_{\ell_\alpha \ell_\beta} \equiv \dfrac{\Gamma^{\text{LNV}}_{M \to M' \ell_\alpha^\pm \ell_\beta^\pm}}{\Gamma^{\text{LNC}}_{M \to M' \ell_\alpha^\pm \ell_\beta^\mp}} \neq 1$ (for $\alpha \neq \beta$)

Interference effects in semileptonic cLFV & LNV decays

- **Assume** "3+2" toy model: 3 active neutrinos + 2 sterile states
- Enlarged mixing matrix, $\boldsymbol{U_{5\times5}}$: $\boldsymbol{U_{\alpha i} = e^{-i\phi_{\alpha i}}|U_{\alpha i}|}$, $\alpha = e, \mu, \tau$, and $i = 4, 5$

  Introduce "relative phase", $\boldsymbol{\psi_\alpha = \phi_{\alpha 5} - \phi_{\alpha 4}}$ (combination of Dirac and Majorana phases)

$$\left|\mathcal{A}^{\text{LNV}}_{M\to M'\ell^\pm_\alpha \ell^\pm_\beta}\right|^2 \propto |U_{\alpha 4}|^2 |U_{\beta 4}|^2 |f(M)|^2 \left|1 + \kappa\, e^{\mp i(\psi_\alpha + \psi_\beta)}\right|^2$$

$$\left|\mathcal{A}^{\text{LNC}}_{M\to M'\ell^\pm_\alpha \ell^\mp_\beta}\right|^2 \propto |U_{\alpha 4}|^2 |U_{\beta 4}|^2 |g(M)|^2 \left|1 + \kappa'\, e^{\mp i(\psi_\alpha - \psi_\beta)}\right|^2$$

- **Sizeable interference effects:** (i) important overlap between heavy ν_s contributions

  (ii) similar strength of ν_s contributions

$$\Rightarrow \boldsymbol{\Delta M \ll M} \text{ and } \boldsymbol{\Delta M < \Gamma_N}, \quad |\boldsymbol{\kappa}| \simeq |\boldsymbol{\kappa'}| = \frac{|U_{\alpha 5} U^*_{\beta 5}|}{|U_{\alpha 4} U^*_{\beta 4}|}\left(1 + \mathcal{O}\left(\frac{\Delta M}{\Gamma_N}\right)\right)$$

(maximal effects for $|\kappa| \sim |\kappa'| \approx 1$)

- $R_{\ell_\alpha \ell_\beta} \rightsquigarrow \dfrac{\cos^2\left[\frac{1}{2}(\psi_\alpha + \psi_\beta)\right]}{\cos^2\left[\frac{1}{2}(\psi_\alpha - \psi_\beta)\right]}$

  $\psi_\alpha + \psi_\beta \leftrightsquigarrow$ "LNV" (Majorana and Dirac phases)

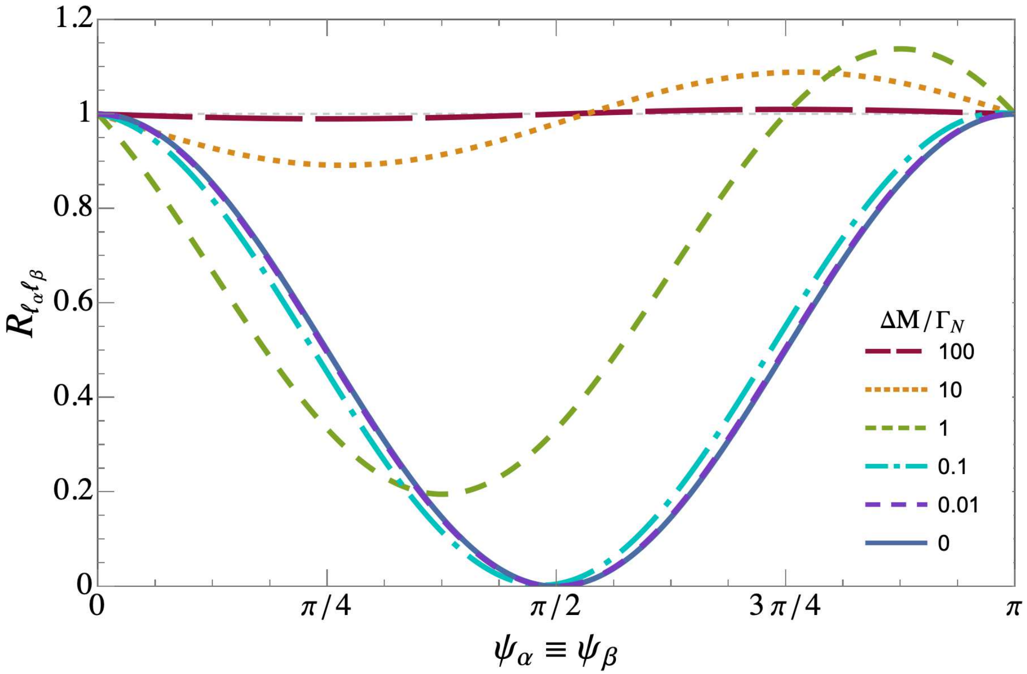
  $\psi_\alpha - \psi_\beta \leftrightsquigarrow$ "LNC" (Dirac phases for cLFV $\alpha \neq \beta$)

Interference effects: illustrative example

▶ Ratio of **LNV** to **LNC** BRs (different flavour final states): $R_{\ell_\alpha \ell_\beta} \equiv \frac{\Gamma^{\text{LNV}}_{M\to M'\ell^\pm_\alpha \ell^\pm_\beta}}{\Gamma^{\text{LNC}}_{M\to M'\ell^\pm_\alpha \ell^\mp_\beta}}$

for distinct regimes of $\Delta M < \Gamma_N$

[Abada, Hati, Marcano, AMT, 1904.05367]



$K \to \pi e \mu$:

$M \sim 350$ MeV and $|U_{\ell 4}| \approx |U_{\ell 5}| = 10^{-5}$

$\psi_\alpha = \phi_{\alpha 5} - \phi_{\alpha 4}$, $U_{\alpha i} = |U_{\alpha i}|\, e^{-i\phi_{\alpha i}}$

(combination of Dirac and Majorana phases)

▶ $\psi_\alpha = \psi_\beta$: interference effects only in LNV

▶ $\alpha \neq \beta$, $R_{\ell_\alpha \ell_\beta} \neq 1 \Rightarrow$ **constructive** & **destructive interference;** important cancellations!

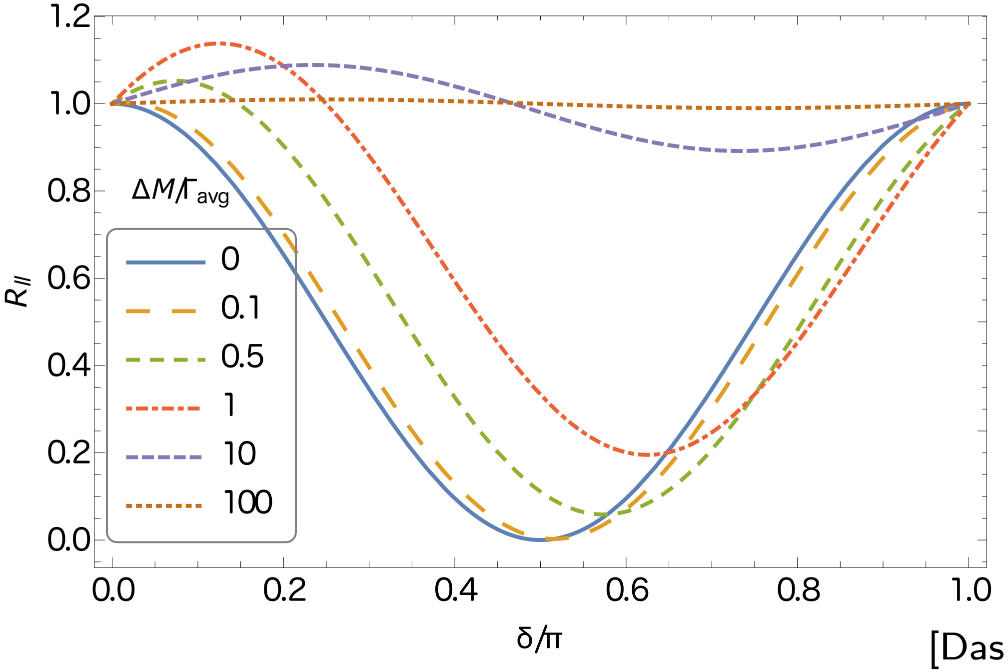
▶ In agreement with collider studies [Gluza et al '15, Das et al '17]

Interference effects: same-sign vs opposite-sign dileptons @LHC

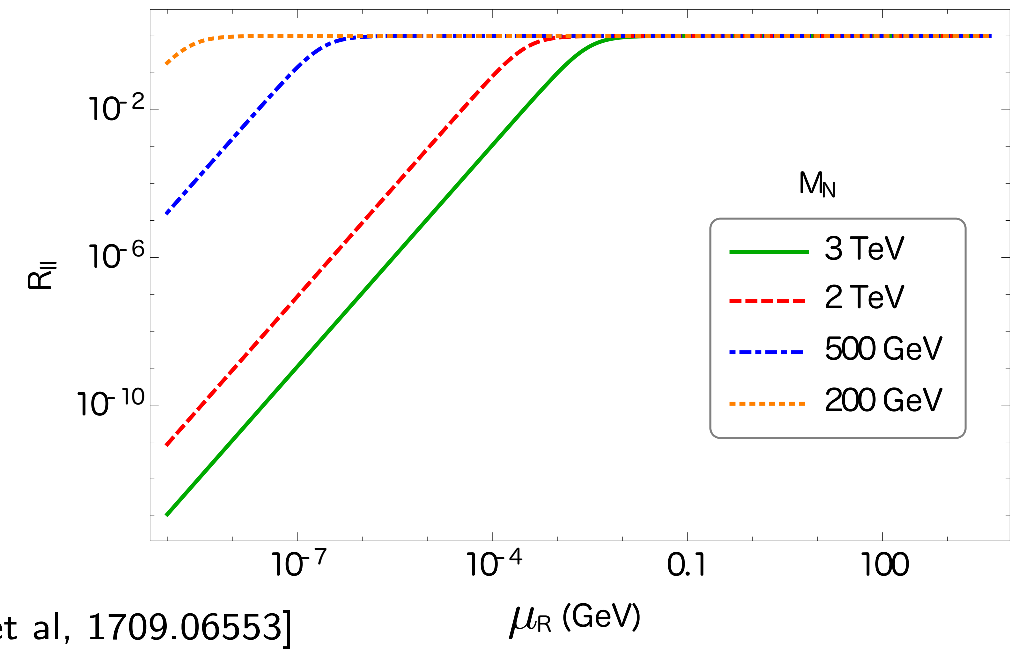
- At **colliders**, compare **number of SS** vs. **number of OS dileptons:** $R_{\ell_\alpha \ell_\beta} \equiv \frac{N^{SS}_{\ell_\alpha \ell_\beta}}{N^{OS}_{\ell_\alpha \ell_\beta}}$
- **TeV scale seesaw realisations**, embedded in generic **Left-Right symmetric models**

Sterile states from W_R decays: $W_R^\pm \to N_R \ell^\pm$

Type I seesaw



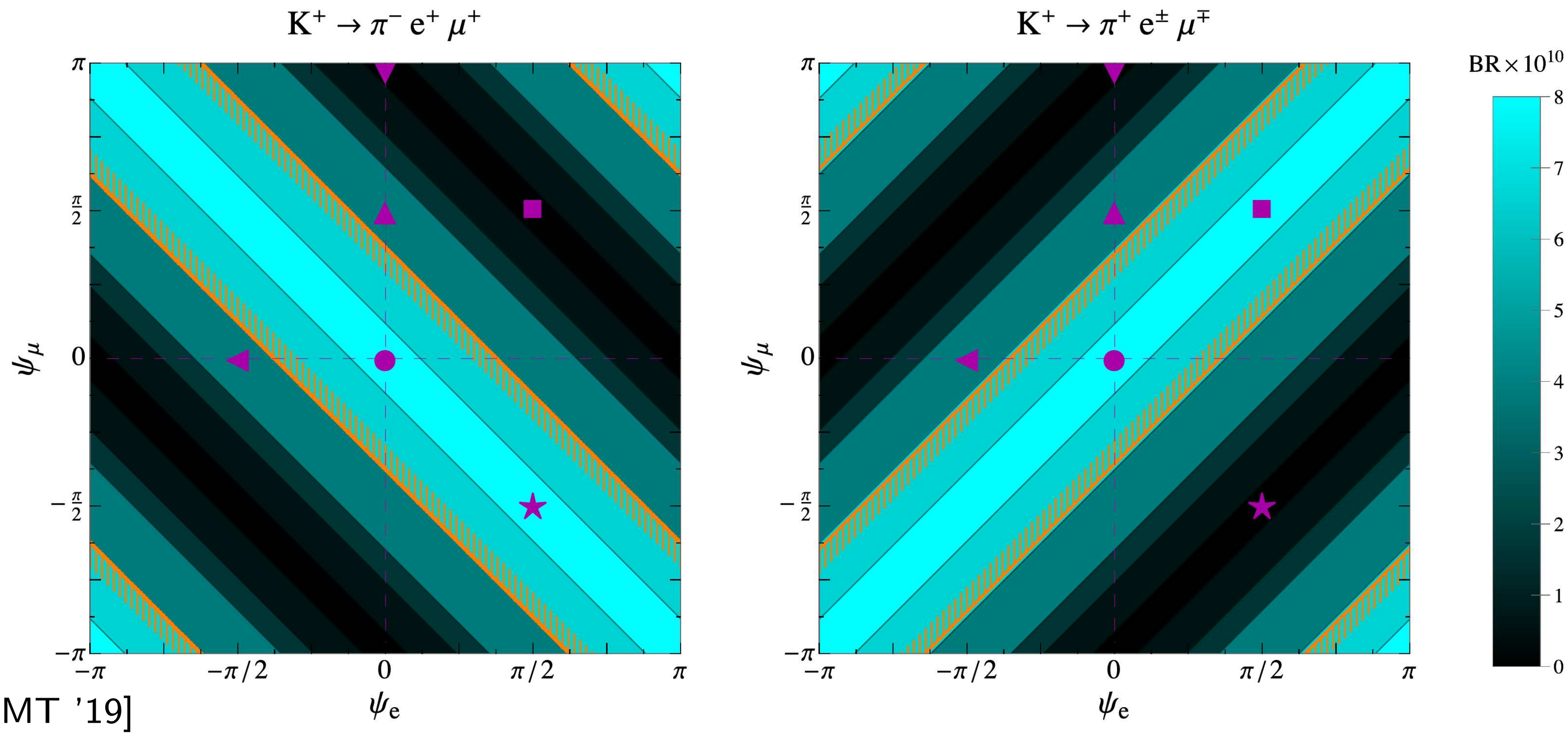
Inverse seesaw



[Das et al, 1709.06553]

- High degree of **degeneracy** for N_{Ri}... (determined by the size of Yukawa couplings)
- **Type I:** $R_{\ell\ell}$ determined by **CP phases**; **ISS:** $R_{\ell\ell}$ governed by **LNV parameter** μ_R

Interference effects in cLFV & LNV Kaon decays



- ● $\psi_\alpha = 0$
- ■ $\psi_e = \psi_\mu = \pi/2$
- ★ $\psi_e = -\psi_\mu = \pi/2$
- ▲ $\psi_e = 0,\ \psi_\mu = \pi/2$
- ▼ $\psi_e = 0,\ \psi_\mu = 0$
- ◀ $\psi_e = \pi/2,\ \psi_\mu = 0$
- exp. bounds

[Abada, Hati, Marcano, AMT '19]

- $\psi_e = \psi_\mu$: from **LNV** BRs in **conflict with data** [●] to BR($K^+ \to \pi^- e^+ \mu^+$)≈ 0 [■]

  $\psi_e = -\psi_\mu$: from **LNC/LFV** BRs in **conflict with data** [●] to BR($K^+ \to \pi^- e^\pm \mu^\mp$)≈ 0 [★]

- Understanding experimental searches (and learning about nature of mediators)

  ⇒ **thorough analyses** of $R_{e\mu}$ - take into account **all 4 (non-SM) decay modes!**

  $K^+ \to \pi^- e^+ \mu^+$, $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^- \mu^+ \mu^+$ and $K^+ \to \pi^+ e^\pm \mu^\mp$

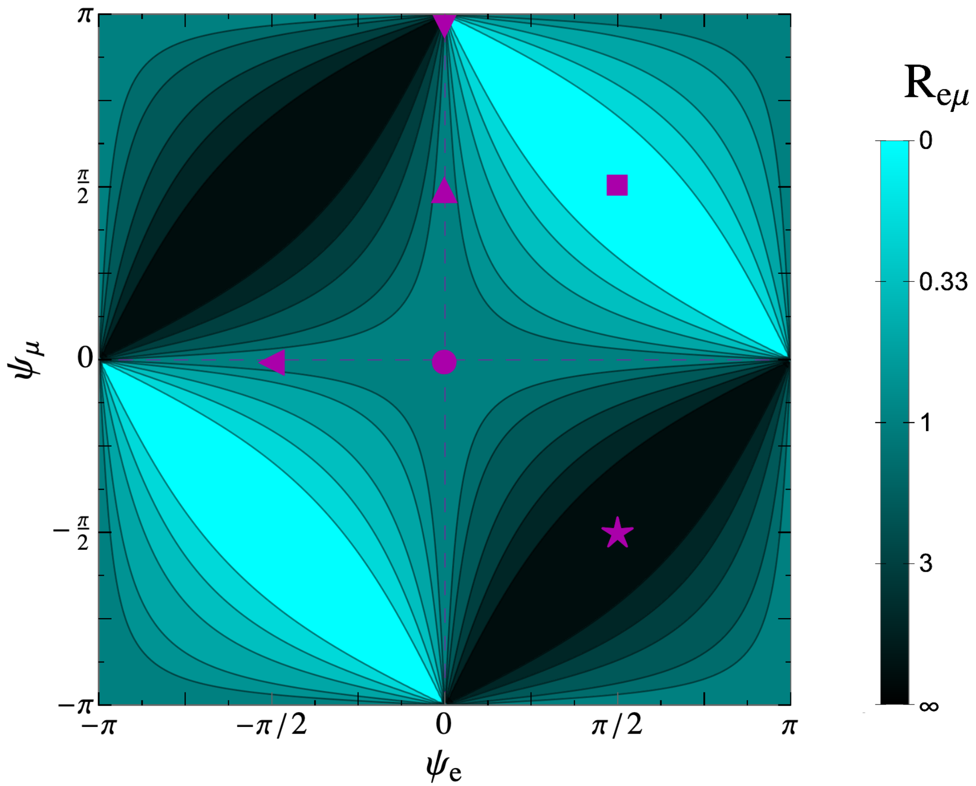
Interference effects in cLFV & LNV Kaon decays

- **Hints on sterile Majorana states: $\#_{\nu_s}$ and CP phases**

$$R_{\ell_\alpha \ell_\beta} \equiv \frac{\Gamma^{\text{LNV}}_{M \to M' \ell^\pm_\alpha \ell^\pm_\beta}}{\Gamma^{\text{LNC}}_{M \to M' \ell^\pm_\alpha \ell^\mp_\beta}}$$

Illustrative ("extreme") cases in Kaon decays: $R_{e\mu} = 0$, ∞ and 1

[Abada, Hati, Marcano, AMT '19]



- $R_{e\mu} = 0$ [■]: $\text{BR}(K^+ \to \pi^- e^+ \mu^+) \approx 0$

No LNV modes observed, possibly LNC

$$K^+ \to \pi^+ e^\pm \mu^\mp$$

⇒ mediated by a **Dirac neutrino...** *OR*

⇒ mediated by **2 interfering Majorana states**

maximal destructive interference in LNV mode

(*E.g. low-scale seesaws with approximate lepton number conservation)*

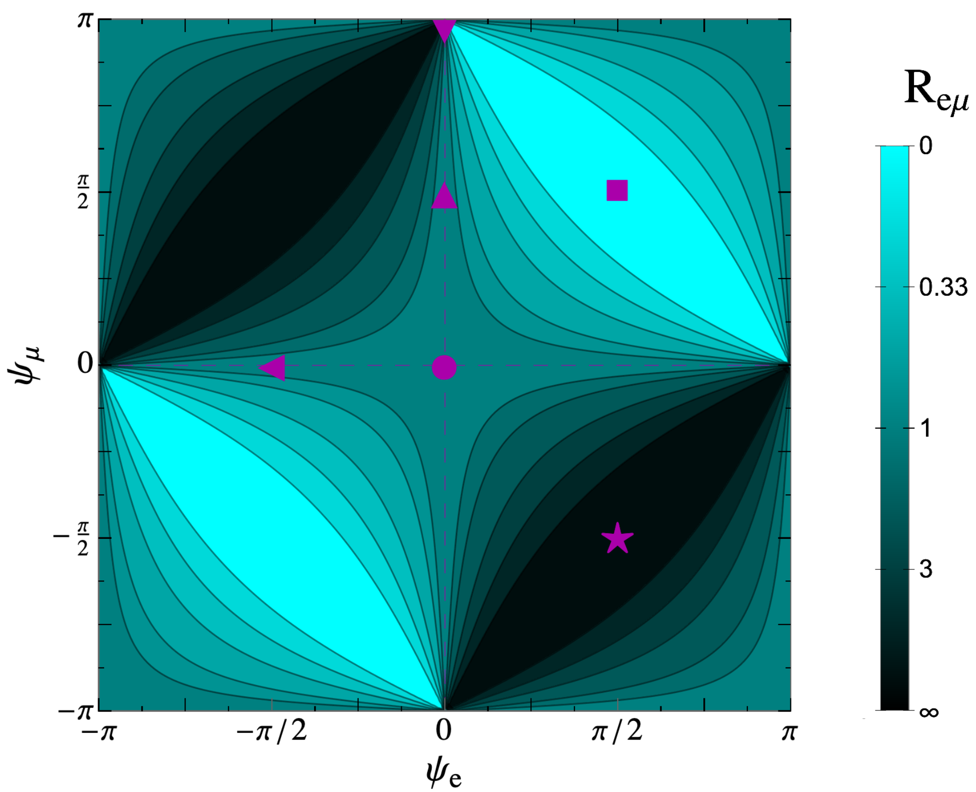
Interference effects in cLFV & LNV Kaon decays

▶ **Hints on sterile Majorana states:** $\#_{\nu_s}$ **and CP phases**

$$R_{\ell_\alpha \ell_\beta} \equiv \frac{\Gamma^{\rm LNV}_{M \to M' \ell^\pm_\alpha \ell^\pm_\beta}}{\Gamma^{\rm LNC}_{M \to M' \ell^\pm_\alpha \ell^\mp_\beta}}$$

Illustrative ("extreme") cases in Kaon decays: $R_{e\mu} = 0$, ∞ and 1

[Abada, Hati, Marcano, AMT '19]



▶ $R_{e\mu} \ggg 1$ [★]: $\text{BR}(K^+ \to \pi^+ e^\pm \mu^\mp) \approx 0$

Observation of LNV modes ($\alpha \neq \beta$)

⇒ **incompatible with Dirac** states...

⇒ possibly **mediated by 2 Majorana states:**

(maximal) **constructive** interference for

$$K^+ \to \pi^- e^+ \mu^+$$

(maximal) **destructive** interference in LNC mode

and same-flavour LNV modes

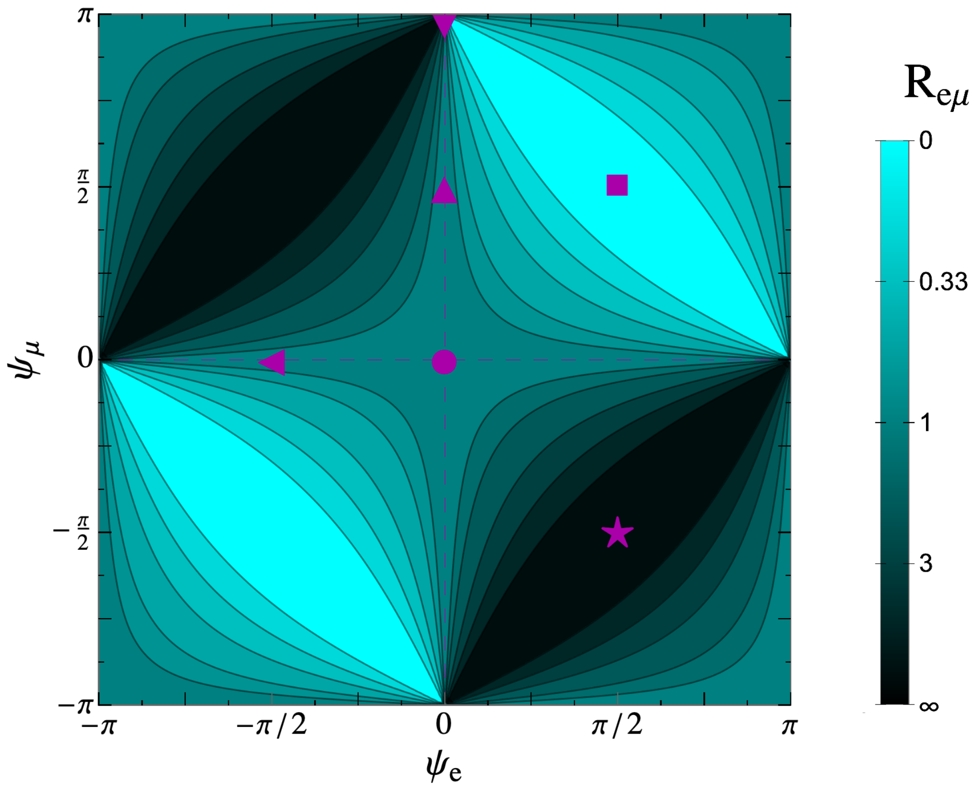
$$K^+ \to \pi^- e^+ e^+,\ K^+ \to \pi^- \mu^+ \mu^+$$

Interference effects in cLFV & LNV Kaon decays

▶ **Hints on sterile Majorana states:** $\#_{\nu_s}$ **and CP phases** $R_{\ell_\alpha \ell_\beta} \equiv \frac{\Gamma^{\text{LNV}}_{M \to M' \ell^\pm_\alpha \ell^\pm_\beta}}{\Gamma^{\text{LNC}}_{M \to M' \ell^\pm_\alpha \ell^\mp_\beta}}$

Illustrative ("extreme") cases in Kaon decays: $R_{e\mu} = 0$, ∞ and 1

[Abada, Hati, Marcano, AMT '19]



▶ $R_{e\mu} \approx 1$ [●]:

$\text{BR}(K^+ \to \pi^- e^+ \mu^+) \sim \text{BR}(K^+ \to \pi^+ e^\pm \mu^\mp)$

Possible observation of *all* LNV & cLFV modes

⇒ **LNV incompatible with Dirac state!**

⇒ **Cannot disentangle** between:

2 Majorana states

(constructive interferences)

OR **1 Majorana** state ("larger" $|U_{\alpha 4}|$)

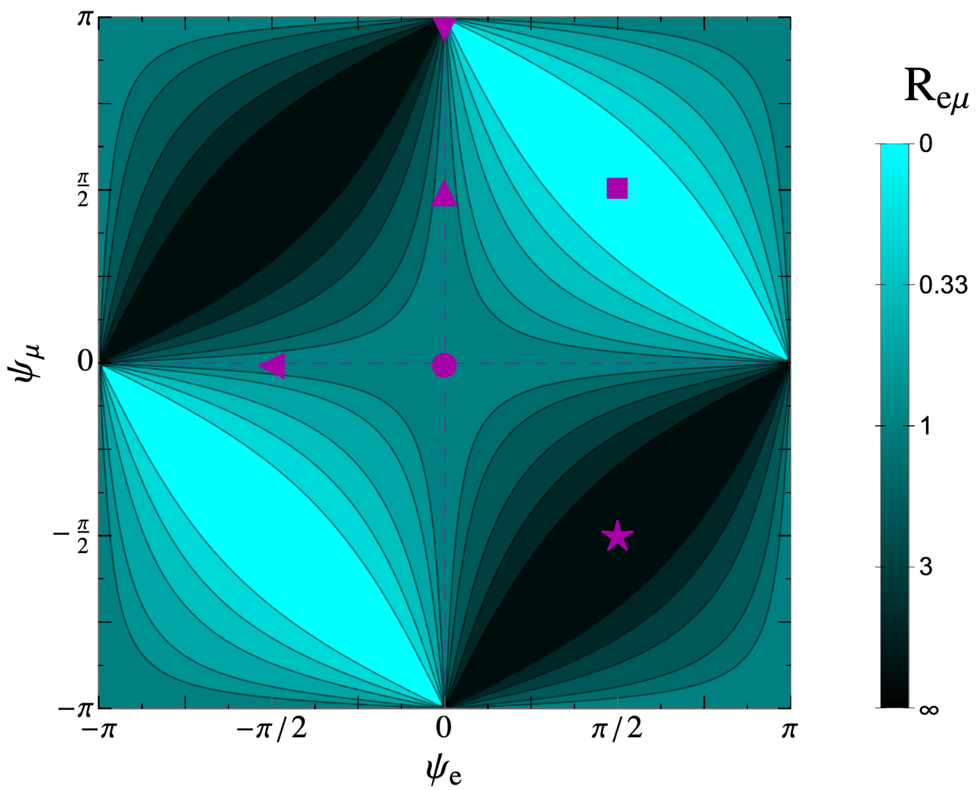
Interference effects in cLFV & LNV Kaon decays

▶ **Hints on sterile Majorana states: $\#_{\nu_s}$ and CP phases**

$$R_{\ell_\alpha \ell_\beta} \equiv \frac{\Gamma^{\rm LNV}_{M\to M' \ell^\pm_\alpha \ell^\pm_\beta}}{\Gamma^{\rm LNC}_{M\to M' \ell^\pm_\alpha \ell^\mp_\beta}}$$

Illustrative ("extreme") cases in Kaon decays: $R_{e\mu} = 0$, ∞ and 1

[Abada, Hati, Marcano, AMT '19]



▶ $R_{e\mu} \approx 1$ [▲, ◀]:

Partial cancellation in distinct-flavour modes

BR($K^+ \to \pi^- e^+ \mu^+$)∼ BR($K^+ \to \pi^+ e^\pm \mu^\mp$)

⇒ Study same-flavour LNV modes

Substantiate **2 ν_s hypothesis** and

hint on **CP phases ψ_e and ψ_μ**

E.g. [◀] observable $R_{e\mu} \approx 1$

potentially observable $K^+ \to \pi^- \mu^+ \mu^+$

(maximal) destructive interference $K^+ \to \pi^- e^+ e^+$

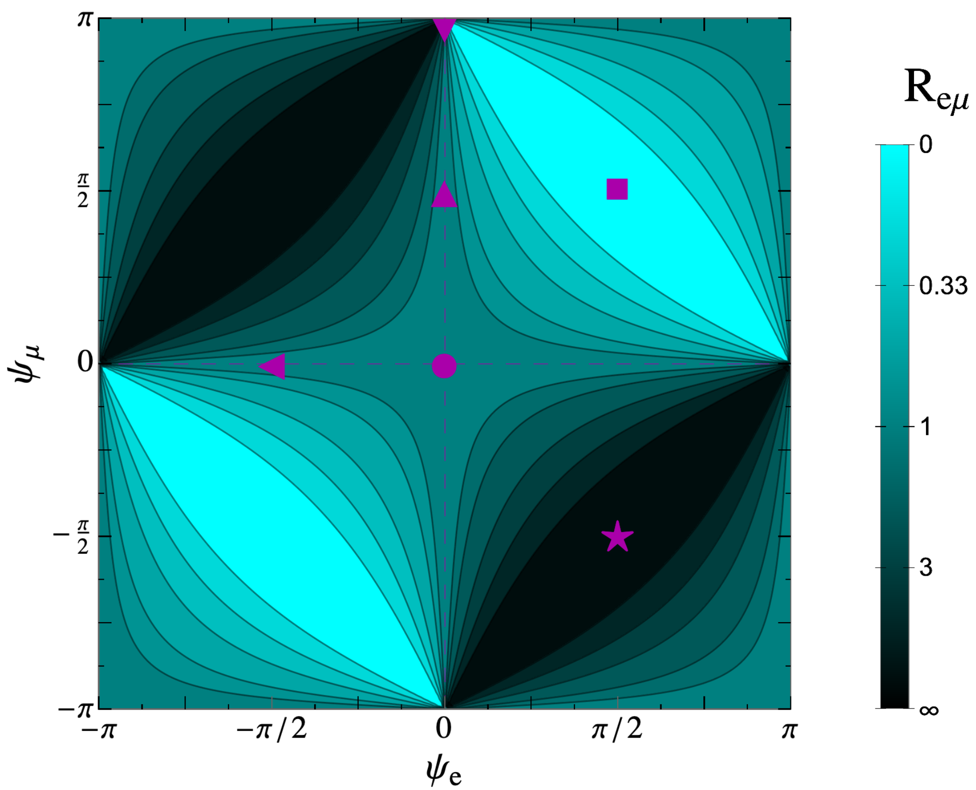
Interference effects in cLFV & LNV Kaon decays

$$R_{\ell_\alpha \ell_\beta} \equiv \frac{\Gamma^{\mathrm{LNV}}_{M \to M' \ell^\pm_\alpha \ell^\pm_\beta}}{\Gamma^{\mathrm{LNC}}_{M \to M' \ell^\pm_\alpha \ell^\mp_\beta}}$$

- **Hints on sterile Majorana states: $\#_{\nu_s}$ and CP phases**

  Illustrative ("extreme") cases in Kaon decays: $R_{e\mu} = 0, \infty$ and 1

[Abada, Hati, Marcano, AMT '19]



- If **neither mode observed** [▼]

  $K^+ \to \pi^- e^+ \mu^+$ and $K^+ \to \pi^+ e^\pm \mu^\mp$

  (maximal destructive interference)

  $\Rightarrow$ Crucial role of same-flavour LNV modes:

  potentially **observable** $K^+ \to \pi^- \mu^+ \mu^+$

  and $K^+ \to \pi^- e^+ e^+$

Interference effects in cLFV & LNV meson decays

- **Generic analysis,** applicable to *all* semileptonic LNV meson decays

- **Interpretation** of **LNV searches** under **hypothesis of SM + Majorana ν_s:**

  $\Rightarrow$ allow for **multiple sterile states**, and possible **interference effects**

  ($\Delta M \ll \Delta\Gamma$, non-vanishing Dirac & Majorana CP phases)

- **Experimental searches [NA62]: negative LNV/LNC results**

  do not necessarily imply increasingly stringent bounds on $|U_{\alpha 4}|$!

- **Observation** of **LNC** *only*: **Majorana nature not ruled out!**

- Other observables sensitive to the **Majorana nature of sterile neutrinos...**

  CP asymmetries in LNV decays: $\mathcal{A}_{CP}^{\alpha\beta} \equiv \frac{\Gamma(M^- \to M'^+ \ell_\alpha^- \ell_\beta^-) - \Gamma(M^+ \to M'^- \ell_\alpha^+ \ell_\beta^+)}{\Gamma(M^- \to M'^+ \ell_\alpha^- \ell_\beta^-) + \Gamma(M^+ \to M'^- \ell_\alpha^+ \ell_\beta^+)}$

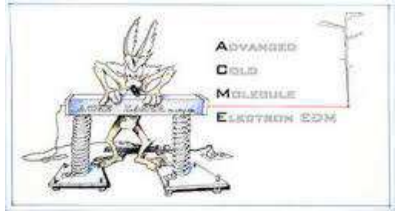
  $\Rightarrow$ In certain regimes, $\mathcal{A}_{CP}^{\alpha\beta} \approx 1$ [Cvetic et al, '14 & '15]

- **And in other (unexpected) sectors...**

- **Leptonic EDMs, sterile neutrinos and cLFV**

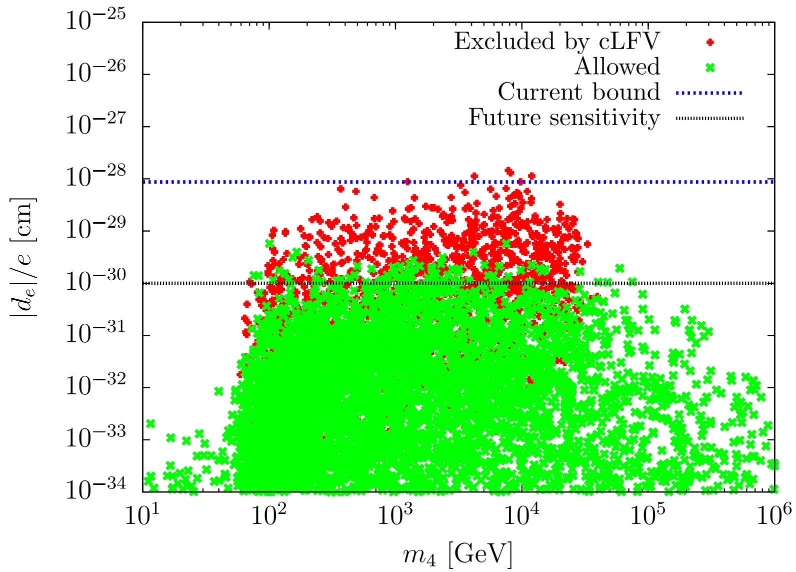
Sterile neutrinos: impact for leptonic EDMs

- **Electron EDM:** increasingly **stronger bounds** from **paramagnetic atoms** (e.g. Tl, Cs) and **molecules** (HfF^+, ThO, ...)



- **New ACME result '18:** $|d_e|/e \lesssim 1.1 \times 10^{-29}$cm

  mid-term increase of **10-20 in sensitivity** (developments of the ACME technique)



- **Majorana (and Dirac) phases** $\Rightarrow$ **lepton EDMs**
- **Non-vanishing** contributions: at least **two sterile** ν
- $|d_e|/e \geq 10^{-30}$ **cm** for $m_{\nu_{4,5}} \sim$ **[100 GeV, 100 TeV]**

[Abada and Toma, '15]

- **Independent of active-sterile mixings Majorana contribution** is dominant!
- **EDM observation:** suggest new sources of CPV$\Rightarrow$ **Majorana νs?** $\rightsquigarrow$ **Leptogenesis??**

Sterile neutrinos: ... and for cLFV

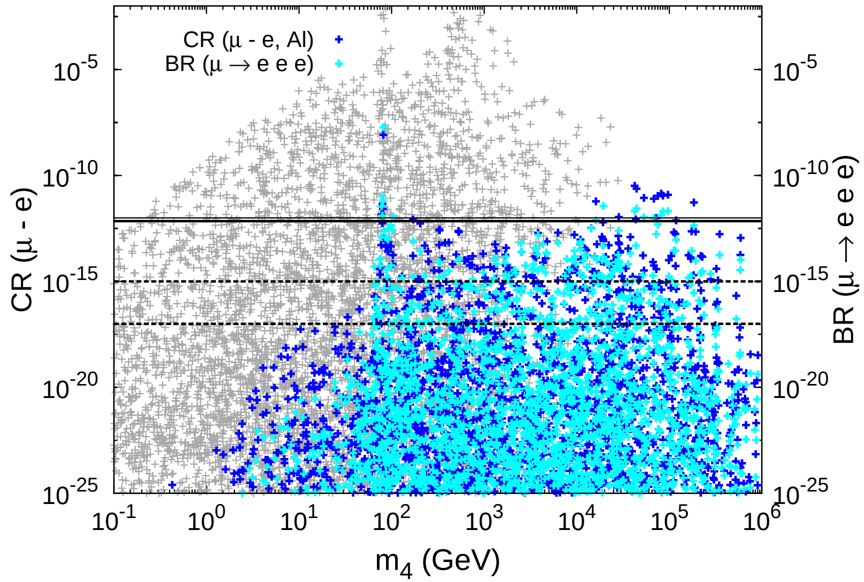
- **Hints on Majorana nature from (flavour conserving) EDMs ⇝ sizeable contributions**

  States too heavy for "on-shell" production in meson decays...

- **Expect important impact for cLFV observables (high-intensity)!**

  [experimental review by L. Galli]

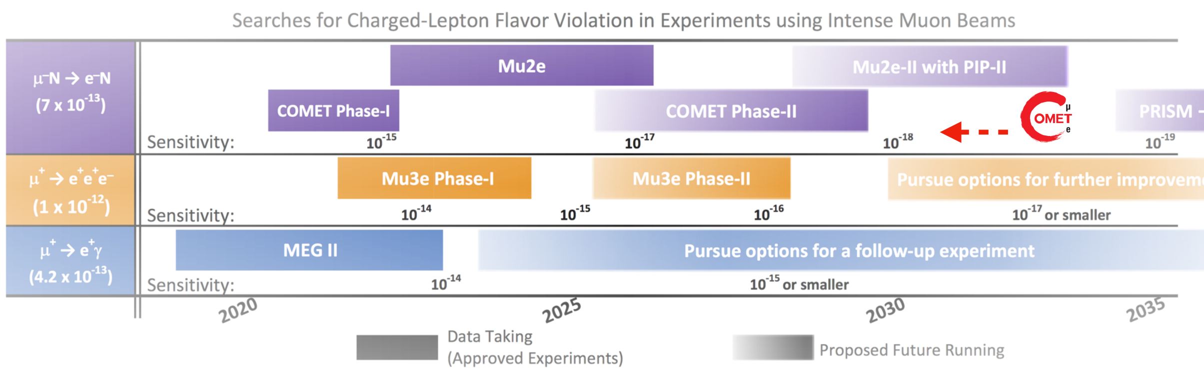
- Example: **three-body decays $\ell_i \to 3\ell_j$ (■) and conversion in Nuclei $\mu - e$ (■)**



[Abada, De Romeri and AMT, '16]

- For **sterile states above EW scale,** sizeable contributions, well **within experimental reach**

  Mu3e, COMET, Mu2e, ...



- **Concluding remarks**

New Physics and lepton observables

- **Confirmed observations** suggest the need to go **beyond the SM**

  Other than **ν-masses**, many experimental **"tensions"** nested in **lepton-related observables**

- **Lepton physics** might offer valuable hints in **constructing and probing NP models**

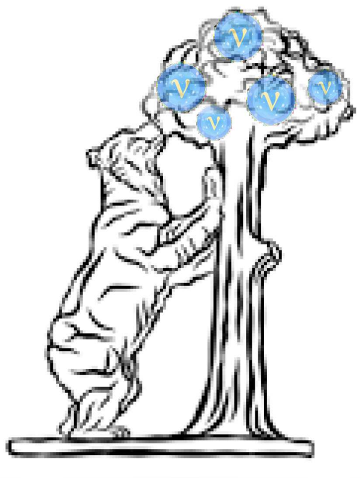
- **Lepton number violation:** signal **Majorana states**, hints on nature of neutrinos,

  necessary ingredient to a leptogenesis explanation of the BAU...

- **Majorana sterile neutrinos** - **appealing (minimal) SM extension**

  Depending on the **regime**, important contributions to "leptonic" NP observables

  Hypothesis that can motivate a **"re-interpretation"** of experimental data:



light ν spectrum ordering from $\mathbf{0\nu2\beta}$,

constraints on **active-sterile mixings** from **meson decays**

Dirac vs Majorana nature from non-observation of **LNV modes**

New Physics and lepton observables

▶ **Confirmed observations** suggest the need to go **beyond the SM**

Other than **ν-masses**, many experimental **"tensions"** nested in **lepton-related observables**

▶ **Lepton physics** might offer valuable hints in **constructing and probing NP models**

▶ **Lepton number violation:** signal **Majorana states**, hints on nature of neutrinos,

necessary ingredient to a leptogenesis explanation of the BAU...

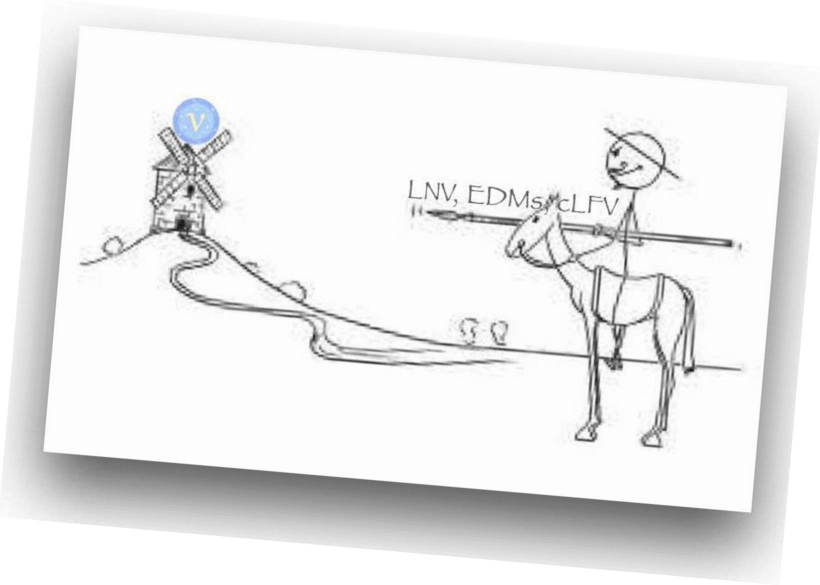
▶ **Majorana sterile neutrinos** - **appealing (minimal) SM extension**

Depending on the **regime**, important contributions to "leptonic" NP observables

▶ **Exciting near-future @ "experimental" front!**

Active searches (and analyses)

to unveil **New (leptonic) Physics**



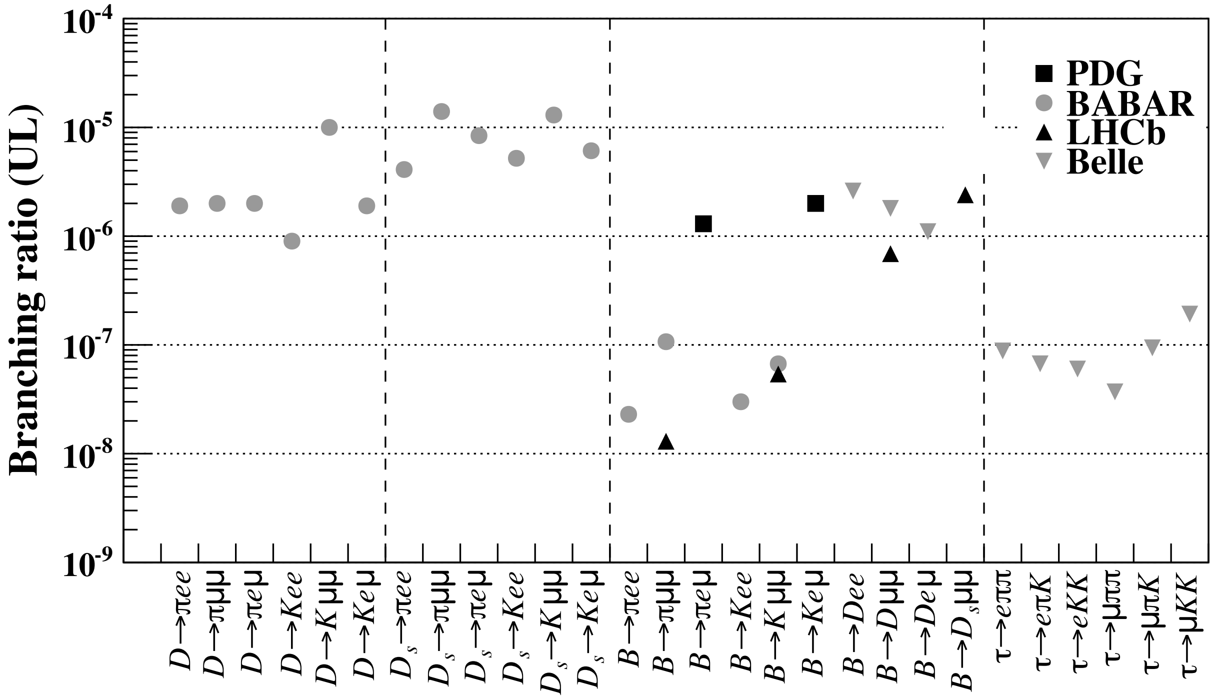
Backup

LNV in semileptonic decays: current bounds

LNV decay	Current bound		
	$\ell_\alpha = e,\ \ell_\beta = e$	$\ell_\alpha = e,\ \ell_\beta = \mu$	$\ell_\alpha = \mu,\ \ell_\beta = \mu$
$K^- \to \ell_\alpha^- \ell_\beta{}^- \pi^+$	6.4×10^{-10}	5.0×10^{-10}	1.1×10^{-9}
$D^- \to \ell_\alpha^- \ell_\beta{}^- \pi^+$	1.1×10^{-6}	2.0×10^{-6}	2.2×10^{-8}
$D^- \to \ell_\alpha^- \ell_\beta{}^- K^+$	9.0×10^{-7}	1.9×10^{-6}	1.0×10^{-5}
$D^- \to \ell_\alpha^- \ell_\beta{}^- \rho^+$	———	———	5.6×10^{-4}
$D^- \to \ell_\alpha^- \ell_\beta{}^- K^{*+}$	———	———	8.5×10^{-4}
$D_s^- \to \ell_\alpha^- \ell_\beta{}^- \pi^+$	4.1×10^{-6}	8.4×10^{-6}	1.2×10^{-7}
$D_s^- \to \ell_\alpha^- \ell_\beta{}^- K^+$	5.2×10^{-6}	6.1×10^{-6}	1.3×10^{-5}
$D_s^- \to \ell_\alpha^- \ell_\beta{}^- K^{*+}$	———	———	1.4×10^{-3}
$B^- \to \ell_\alpha^- \ell_\beta{}^- \pi^+$	2.3×10^{-8}	1.5×10^{-7}	4.0×10^{-9}
$B^- \to \ell_\alpha^- \ell_\beta{}^- K^+$	3.0×10^{-8}	1.6×10^{-7}	4.1×10^{-8}
$B^- \to \ell_\alpha^- \ell_\beta{}^- \rho^+$	1.7×10^{-7}	4.7×10^{-7}	4.2×10^{-7}
$B^- \to \ell_\alpha^- \ell_\beta{}^- D^+$	2.6×10^{-6}	1.8×10^{-6}	6.9×10^{-7}
$B^- \to \ell_\alpha^- \ell_\beta{}^- D^{*+}$	———	———	2.4×10^{-6}
$B^- \to \ell_\alpha^- \ell_\beta{}^- D_s^+$	———	———	5.8×10^{-7}
$B^- \to \ell_\alpha^- \ell_\beta{}^- K^{*+}$	4.0×10^{-7}	3.0×10^{-7}	5.9×10^{-7}
LNV matrix m_ν	m_ν^{ee}	$m_\nu^{e\mu}$	$m_\nu^{\mu\mu}$

LNV in semileptonic decays: current bounds

cLFV decay	Current bound		
	$\ell_\alpha = e,\ \ell_\beta = \mu$	$\ell_\alpha = e,\ \ell_\beta = \tau$	$\ell_\alpha = \mu,\ \ell_\beta = \tau$
$K^+ \to \ell_\alpha^\pm \ell_\beta{}^\mp \pi^+$	5.2×10^{-10} (1.3×10^{-11})	—	—
$D^+ \to \ell_\alpha^\pm \ell_\beta{}^\mp \pi^+$	$2.9(3.6) \times 10^{-6}$	—	—
$D^+ \to \ell_\alpha^\pm \ell_\beta{}^\mp K^+$	$1.2(2.8) \times 10^{-6}$	—	—
$D_s^+ \to \ell_\alpha^\pm \ell_\beta{}^\mp \pi^+$	$1.2(2.0) \times 10^{-5}$	—	—
$D_s^+ \to \ell_\alpha^\pm \ell_\beta{}^\mp K^+$	$14(9.7) \times 10^{-6}$	—	—
$B^+ \to \ell_\alpha^\pm \ell_\beta{}^\mp \pi^+$	0.17×10^{-6}	75×10^{-6}	72×10^{-6}
$B^+ \to \ell_\alpha^\pm \ell_\beta{}^\mp K^+$	91×10^{-6}	30×10^{-6}	48×10^{-6}
$B^+ \to \ell^\pm \ell_\beta{}^\mp K^{*+}$	1.4×10^{-6}		
$B^0 \to \ell_\alpha^\pm \ell_\beta{}^\mp \pi^0$	0.14×10^{-6}		
$B^0 \to \ell_\alpha^\pm \ell_\beta{}^\mp K^0$	0.27×10^{-6}		
$B^0 \to \ell_\alpha^\pm \ell_\beta{}^\mp K^{*0}$	0.53×10^{-6}		

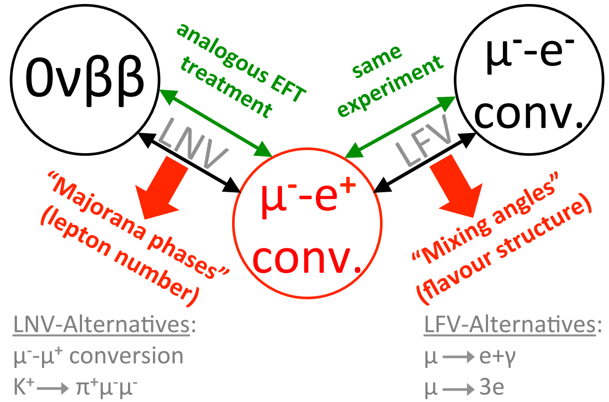


LNV in "muonic" atoms: $\mu^- - e^+$ conversion

- **LNV ($\Delta L = 2$) $\mu^- - e^+$ conversion:** $\mu^- + (A, Z) \to e^+ + (A, Z-2)^*$

  $\mu^- - e^-$: coherent, single nucleon, nuclear ground state

  $\mu^- - e^+$: 2 nucleons ($\Delta Q = 2$), possibly **excited final states**



- **Event signature:** single positron - but *complex* E-spectrum

$$E^{\text{N}^*}_{\mu^- e^+} = m_\mu - E_B(A, Z) - E_R(A, Z) - \Delta_{Z-2^{(*)}}$$

$$E^{\text{Al,GDR}}_{\mu^- e^+} \approx \mathcal{O}(83.9 \text{ MeV}) \quad [< \text{GDR}_{\text{Al}} >\sim 21.1 \text{ MeV } (6.7 \text{ MeV})]$$

[Geib et al, '16]

- **Experimental status - present bounds:**

Collaboration	year	Process	Bound
PSI/SINDRUM	1998	μ^-+Ti→ e^++Ca*	3.6×10^{-11}
PSI/SINDRUM	1998	μ^-+Ti→ e^++Ca	1.7×10^{-12}

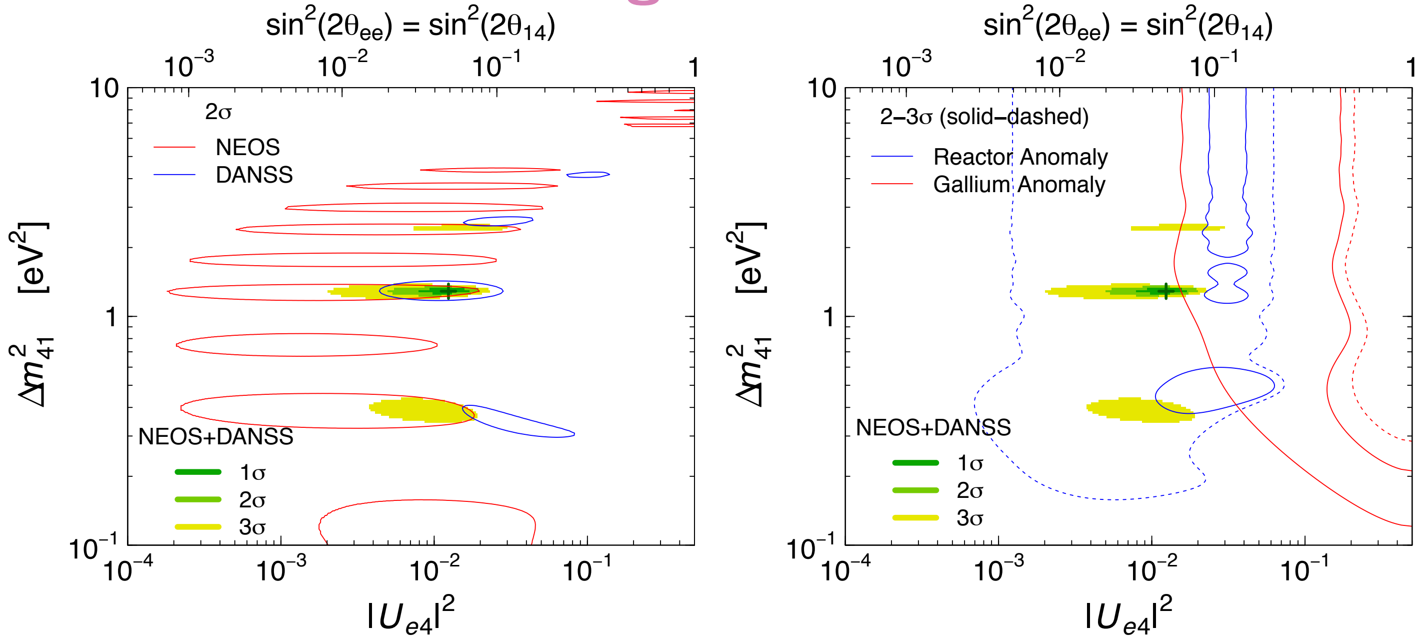
- **Experimental status - future prospects:**

  Recent studies: **best sensitivity** associated with Calcium, Sulphur and Titanium **targets**

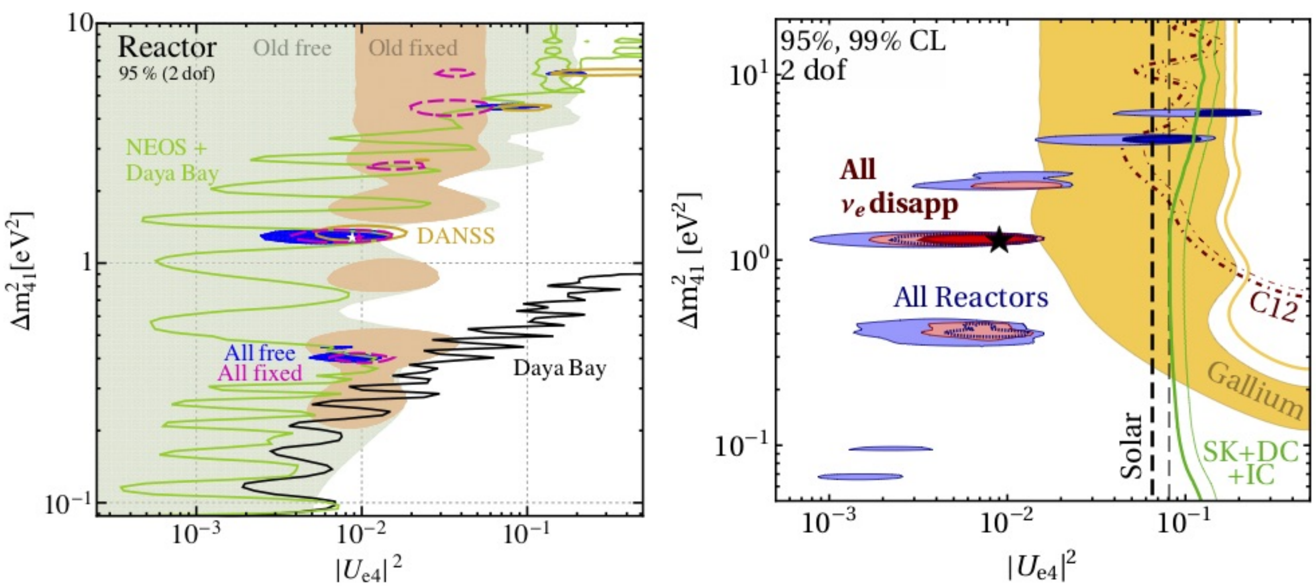
  CR($\mu^- - e^+$) < $\mathcal{O}$(few × 10^{-15}) for ^{48}Ti (both LNC and LNV searches) [Yeo et al, '17]

  For Aluminium targets improvement of current sensitivity maybe very hard (even factor 10)...

Light sterile neutrinos



[Gariazzo et al, '18]



(a)

(b)

[Dentler et al, '18]

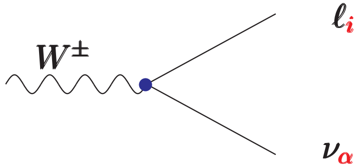
Minimal models of m_ν: signs of New Physics?

- In the **Standard Model:** (strictly) **massless neutrinos**
  conservation of total lepton number & lepton flavours
  tiny leptonic EDMs (at 4-loop level.. $d_e^{\text{CKM}} \leq 10^{-38} e$ cm)

- **Extend the SM** to accommodate $\nu_\alpha \leftrightsquigarrow \nu_\beta$

  Assume **most minimal** extension SM_{m_ν}

  [SM_{m_ν} = "ad-hoc" m_ν (Dirac), U_{PMNS}]



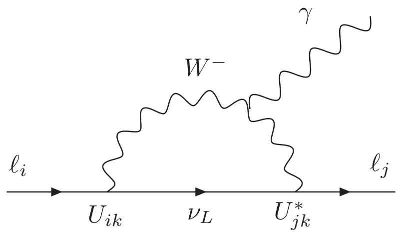
$\bullet \propto U_{\alpha i}^{\text{PMNS}}$

$m_\nu \neq 0$

$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$

- In the SM_{m_ν}: **(total) Lepton number conserved;** what about lepton flavours? And CP?

- SM_{m_ν} - **cLFV possible??**



$$\text{BR}(\mu \to e\gamma) \propto \left| \sum U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \sim 10^{-54}$$

[Petcov, '77]

Possible - **yes...** but **not observable!!**

- SM_{m_ν} - **observable EDMs?** Contributions from δ_{CP} (2-loop)... still $d_e^{\text{lep}} \leq 10^{-35} e$ cm