Flavour physics and Neutrinos

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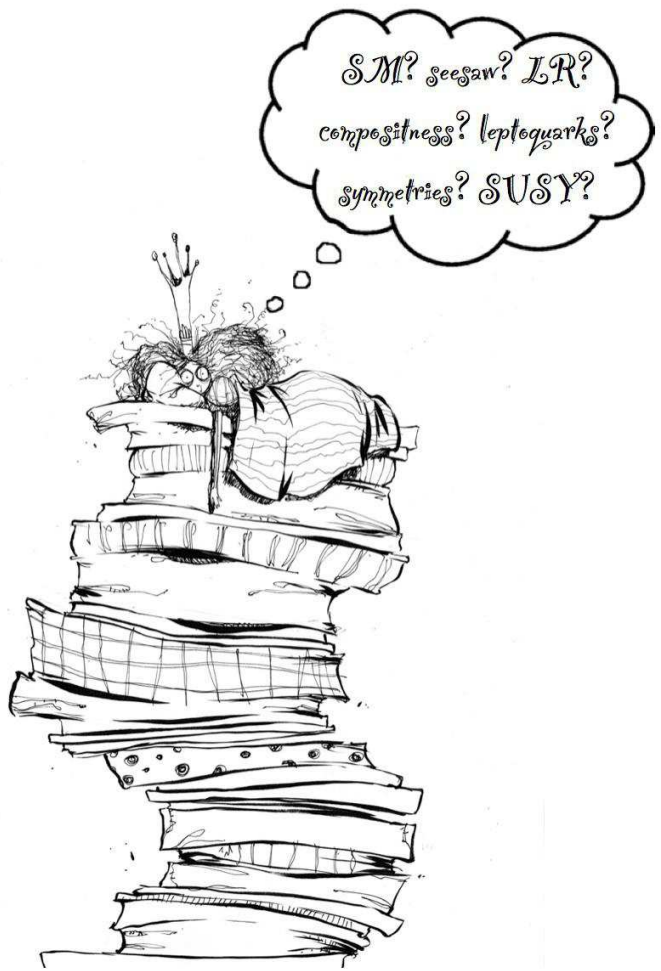
Beyond the Standard Model: New Physics

▶ **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?!

$\Rightarrow \Delta L \neq 0$ and **leptogenesis...** [$\rightsquigarrow$ G. Arcadi's talk..]

▶ **Charged leptons** "host" several lingering **tensions with SM...**

$(g-2)_\ell$, **B-meson anomalies** $(R_{K^{(*)}}, R_{D^{(*)}})$, ...

▸ **Unique opportunities to search for NP**

Survey subset of "flavoured" lepton observables,

explore connections with ν-mass generation mechanism

Summary

- **Brief overview of BSM lepton flavour observables**

  Charged lepton flavour violation (cLFV)

  Lepton flavour universality violation (LFUV)

- **Models of neutrino mass generation and implications for flavoured observables**

  Seesaw mechanism and variants

  Extended frameworks

- **Addressing SM caveats and flavour anomalies: m_ν and lepton flavours**

  Beyond minimal mechanisms of neutrino mass generation

  Lepton anomalies (LFUV and magnetic moments) & dark matter

  Further examples

- **Overview & discussion**

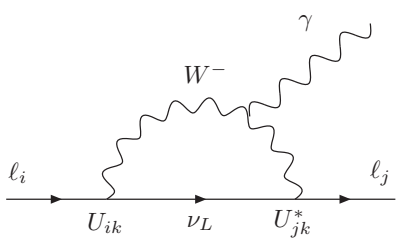
- **“Flavoured” leptonic observables: probes of New Physics**

Leptonic observables: signs of New Physics

- In the **Standard Model:** (strictly) **massless neutrinos**
  conservation of total lepton number & lepton flavours
  lepton flavour universality preserved (only broken by Yukawas)
  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}]

- In the SM_{m_ν}: **(total) Lepton number conserved, flavour-universal lepton couplings**



cLFV possible... but **not observable!!** **BR**$(\mu \to e\gamma) \sim 10^{-54}$

EDMs still beyond observation (contributions from δ_{CP} @ 2-loop...)

- **Observation of SM-"forbidden" modes and/or tensions with data**

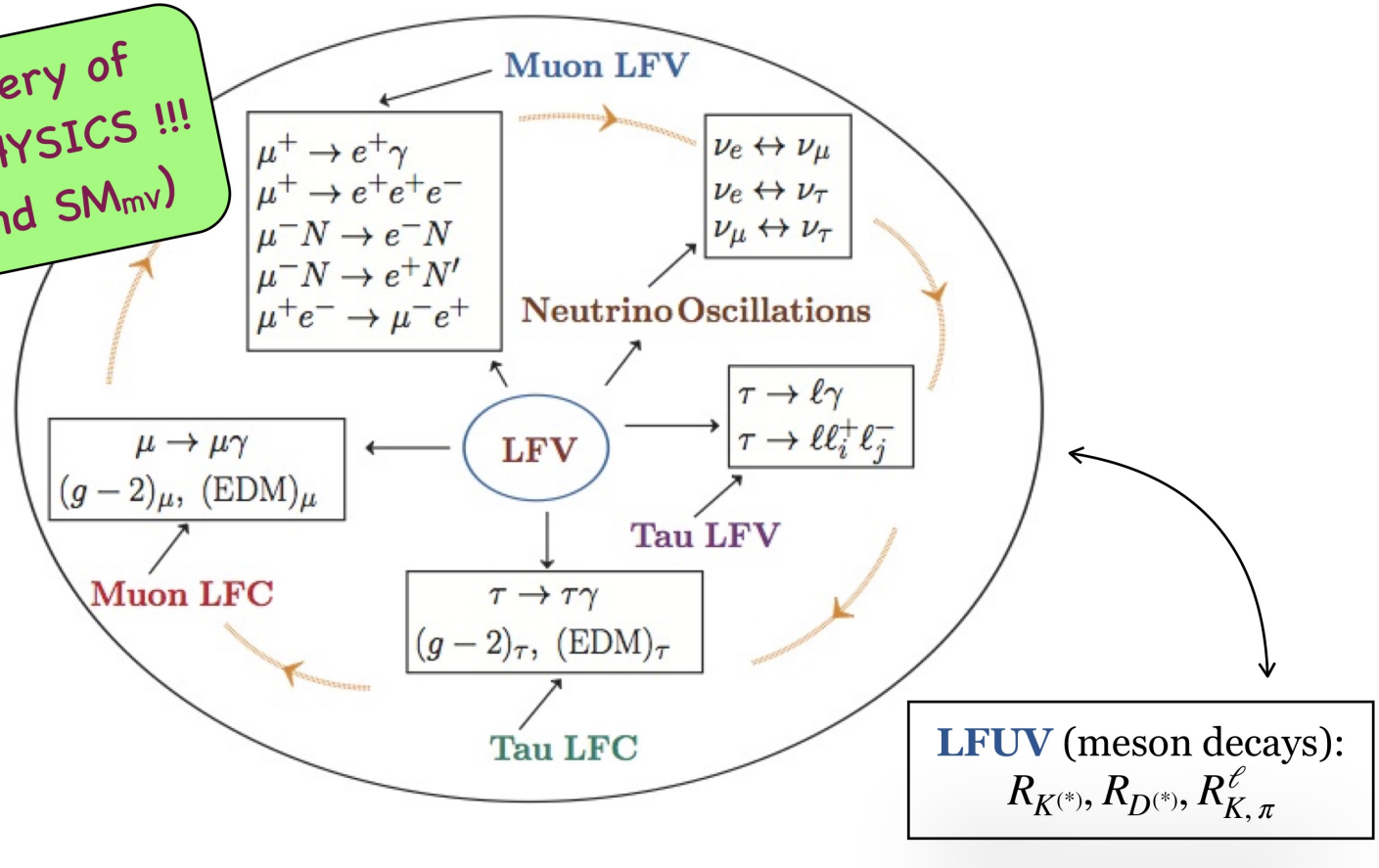
  $\Rightarrow$ **discovery of New Physics! Possibly before LHC!**

Leptonic observables: signs of New Physics

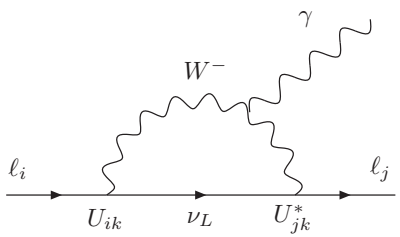
- In the **Standard Model:** (strictly) **massless neutrinos**

Discovery of NEW PHYSICS !!! (beyond SM$_{m\nu}$)

- **Extend the SM**



- In the **SM$_{m_\nu}$**:



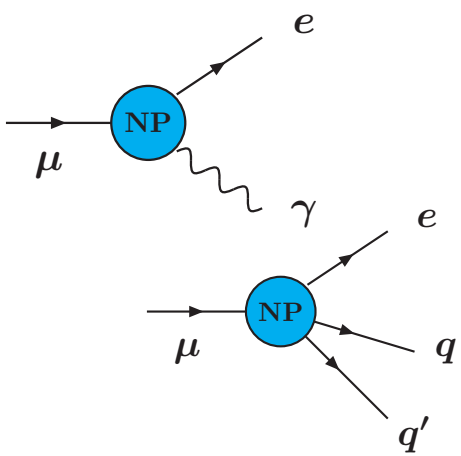
- **Observation of SM-"forbidden" modes and/or tensions with data**

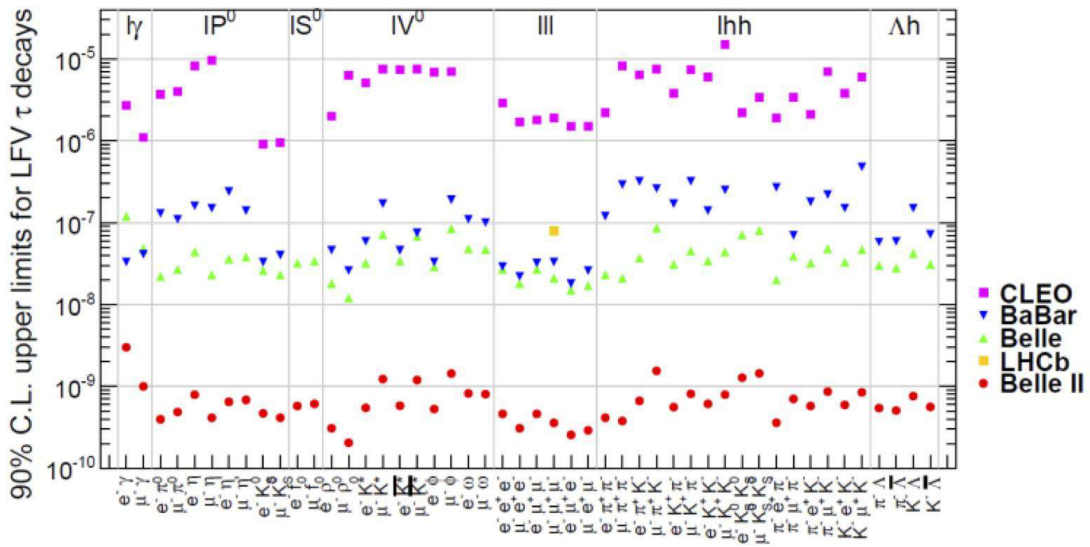
$\Rightarrow$ **discovery of New Physics! Possibly before LHC!**

Searches for cLFV: where do we stand?

- **Comprehensive searches** - from pure lepton modes, to semileptonic tau and meson decays, gauge boson decays, Higgs decays...

cLFV μ decay	Bound (90% C.L.)	Future prospects
$\mathrm{BR}(\mu \to e\gamma)$	4.2×10^{-13}	4×10^{-14} [MEG II]
$\mathrm{BR}(\mu \to 3e)$	1.0×10^{-12}	10^{-15} [Mu3e]
$\mathrm{CR}(\mu - e,\mathrm{N})$	7×10^{-13} (Au)	$\sim 10^{-17}$ (Al) [Mu2e/COMET]
$\mathrm{BR}(\mu^- e^- \to e^- e^-)$	—	10^{-17} (Al) [COMET ?]





From Belle II physics book
arXiv:1808.10567

cLFV decay	Bound (90% C.L.)
$\mathrm{BR}(Z \to e\mu)$	7.5×10^{-7}
$\mathrm{BR}(Z \to e\tau)$	9.8×10^{-6}
$\mathrm{BR}(Z \to \mu\tau)$	1.2×10^{-5}
$\mathrm{BR}(H \to e\mu)$	6.1×10^{-5}
$\mathrm{BR}(H \to e\tau)$	4.7×10^{-3}
$\mathrm{BR}(H \to \mu\tau)$	2.5×10^{-3}

Further competitive bounds in meson decays! $\mathrm{BR}(K \to e\mu) < 4.7 \times 10^{-12}$

Anomalous magnetic moment: muons and electrons

- **Muon a_μ:** longstanding tension between **theory and experiment!**
  - **Experimental measurement** [E821@BNL, '06]: $a_\mu^{\text{exp}} = 11\,659\,209.1(5.4)(3.3) \times 10^{-10}$
  - **SM prediction:** contributions from QED, EW, HVP, HLbL, ...

$$a_\mu^{\text{SM}} = \tfrac{1}{2}\,(g_\mu - 2) = 116591810(43) \times 10^{-11} \quad \text{[MG-2TI, 2006.04822]}$$

$$\Rightarrow \Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 279(76) \times 10^{-11}$$

"Muon $g-2$ Theory Initiative" $\Rightarrow \Delta a_\mu \leftrightsquigarrow 3.7\sigma$

- **Electron a_e:** surprising **"recent" developments!** A new **th vs. exp** tension?

$$a_e^{\text{exp}} = 1\,159\,652\,180.73(28) \times 10^{-12} \quad \text{[Gabrielse et al, '08]}$$

Improvement on SM computation & new determination of α_e (Cs atoms) [Ayoma et al, '18]

$$a_e^{\text{SM}} = 1\,159\,652\,181.61(23) \times 10^{-12} \quad \Rightarrow \Delta a_e = -0.88(36) \times 10^{-12} \quad (2.5\sigma)$$

- **Two anomalies** in a_e and a_μ? Possible hint of **lepton flavour universality violation?**

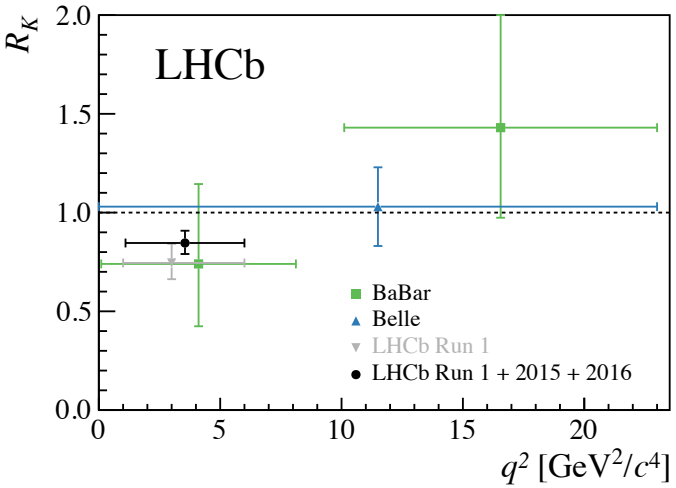
"Lepton universality" (MFV) naïvely suggests $\Delta a_e / \Delta a_\mu \approx m_e^2/m_\mu^2 \sim +2.4 \times 10^{-5}$

but $\Delta a_e^{\text{exp}} / \Delta a_\mu^{\text{exp}} \sim -3.3 \times 10^{-4}$

Lepton flavour non-universality: B-meson decays

★ **In the SM, universal charged lepton couplings** $\rightsquigarrow$ $g_e = g_\mu = g_\tau = g$

▶ **B-meson decay "anomalies"** (neutral current): $R_{K^{(*)}} = \dfrac{\mathrm{BR}(B \to K^{(*)}\, \mu^+ \mu^-)}{\mathrm{BR}(B \to K^{(*)}\, e^+ e^-)}$



$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$ $\quad R_{K[1.1,6]}^{\mathrm{LHCb}} = 0.846 \pm^{0.060}_{0.054} \pm^{0.016}_{0.014}$

$R_{K^*[0.045,1.1]}^{\mathrm{SM}} \sim 0.93$ $\quad R_{K^*[0.045,1.1]}^{\mathrm{LHCb}} = 0.66^{+0.11}_{-0.07} \pm 0.03$

$R_{K^*[0.045,1.1]}^{\mathrm{Belle}} = 0.52^{+0.36}_{-0.26} \pm 0.05$

$R_{K^*[1.1,6]}^{\mathrm{SM}} \sim 0.99$ $\quad R_{K^*[1.1,6]}^{\mathrm{LHCb}} = 0.69^{+0.11}_{-0.07} \pm 0.05$

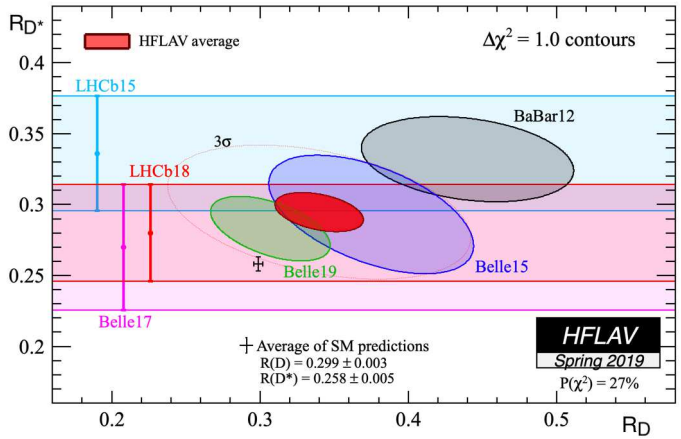
$R_{K^*[1.1,6]}^{\mathrm{Belle}} = 0.96^{+0.45}_{-0.29} \pm 0.11$

▶ **And also for τ vs light leptons** (charged current):

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\, \tau^- \bar{\nu})}{\mathrm{BR}(B \to D^{(*)}\, \ell^- \bar{\nu})}$$

$R_D^{\mathrm{SM}} = 0.299 \pm 0.003$ $\quad R_D^{\mathrm{exp}} = 0.340 \pm 0.027 \pm 0.013$

$R_{D^{(*)}}^{\mathrm{SM}} = 0.295 \pm 0.011 \pm 0.008$ $\quad R_{D^{(*)}}^{\mathrm{exp}} = 0.258 \pm 0.005$



- **New Physics: neutrino mass generation models (seesaw and larger embeddings)**

Neutrino masses and NP realisations

- What do we **know about the mechanism** of **neutrino mass generation?**

  ⇒ Should account for **ν oscillation data!**

  ⇒ **Address SM problems** (e.g. BAU from leptogenesis); not worsen TH caveats!

- **Numerous (appealing) mechanims of ν mass generation**

  Calling upon **distinct new states (singlets, triplets, ...)**, realised at **very different scales!**

- **Quick comparison** [SM + RH ν]: "standard" high-scale type I seesaw vs low-scale seesaw

High scale: $\mathcal{O}(10^{10-15}$ **GeV)**	**Low scale:** $\mathcal{O}$**(MeV - TeV)**
Theoretically **"natural"** $Y^\nu \sim 1$	Finetuning of Y^ν (or approximate LN conservation)
"Vanilla" leptogenesis	Leptogenesis possible (resonant, ...)
Decoupled new states	New states **within experimental reach!**
	Collider, high-intensities ("leptonic observables")

- **Testability:** in general comparatively light new states, non-negligible couplings!

  Explore signatures regarding **"leptonic observables"**

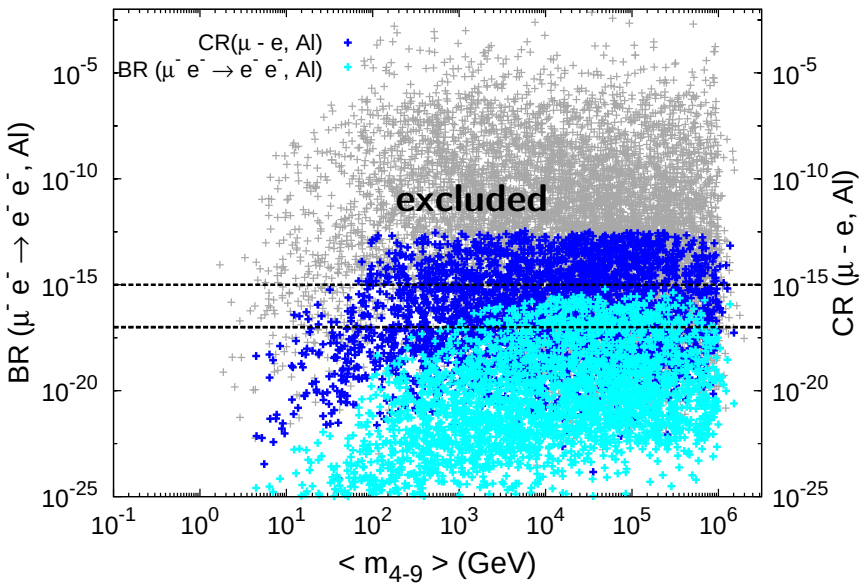
Low scale models of mass generation: Inverse Seesaw (ISS)

- Addition of **3 "heavy" RH** neutrinos and **3 extra "sterile" fermions X** to the SM

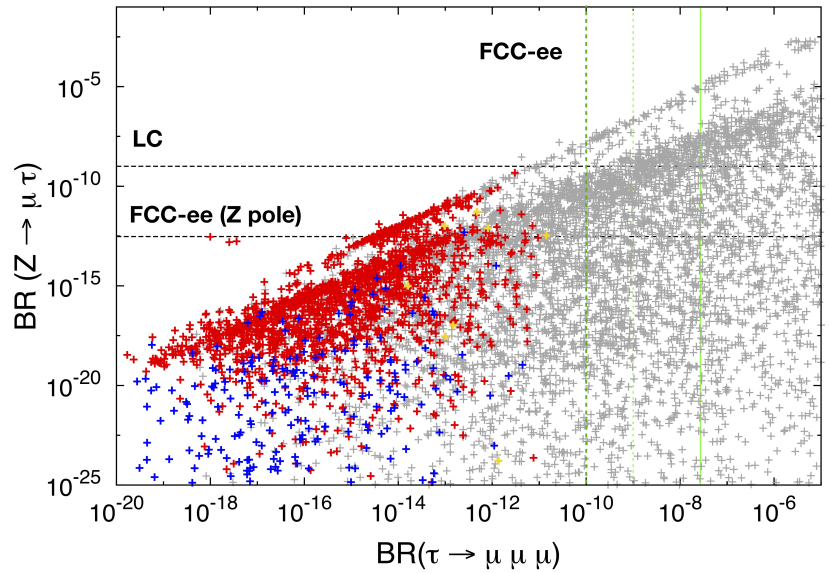
$$\mathcal{M}_{\rm ISS}^{9\times 9} = \begin{pmatrix} 0 & Y_\nu v & 0 \\ Y_\nu^T v & 0 & M_R \\ 0 & M_R & \mu_X \end{pmatrix} \Rightarrow \begin{cases} \textbf{3 light } \nu : m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2}\mu_X \\ \textbf{3 pseudo-Dirac pairs} : m_{N^\pm} \approx M_R \pm \mu_X \end{cases}$$

- **Abundant "flavour" signals! At high-intensities and at colliders...**

(3,3) ISS realisation [Abada, De Romeri and AMT, '16]



[Abada, De Romeri, Monteil, Orloff, AMT, '15]



- **Sizeable values for the cLFV muon observables! Within experimental reach!**
- $Z \to \mu\tau$ **within FCC-ee reach!** Probe $\mu - \tau$ **cLFV** beyond **Belle II reach...**

Peculiar flavour patters: disentangling seesaws (?)

⇒ Seesaw realisations: **distinctive signatures** for numerous (cLFV) **observables:**

singlet fermions N (type I), **triplet scalars Δ** (type II) or **fermions Σ (type III)**

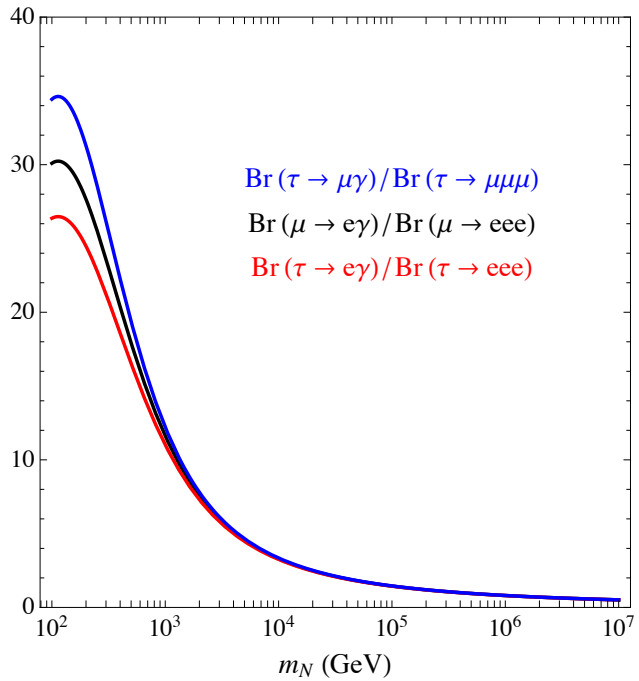
Type I: cLFV transitions at **loop level** (radiative, 3-body, conversion in Nuclei)

Type II: $\ell_i \to \ell_j \gamma$ & $\mu - e$, N at loop level; 3-body decays $\boldsymbol{\ell_i \to 3\ell_j}$ at **tree level!**

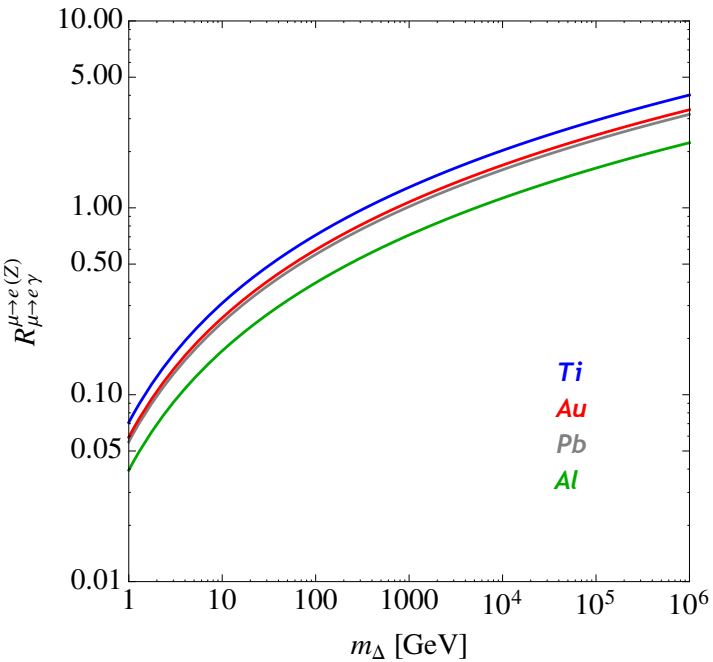
Type III: 3-body decays and coherent conversion at tree-level! $\ell_i \to \ell_j \gamma$ @ loop...

▶ Use **ratios of observables to constrain and identify mediators!**

Type I



Type II



Type III

$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{BR}(\mu\to 3e)} = 1.3\times 10^{-3}$$

$$\frac{\mathrm{BR}(\tau\to \mu\gamma)}{\mathrm{BR}(\tau\to 3\mu)} = 1.3\times 10^{-3}$$

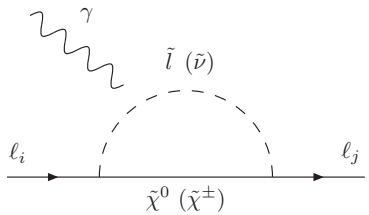
$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{CR}(e-\mu,\mathrm{Ti})} = 3.1\times 10^{-4}$$

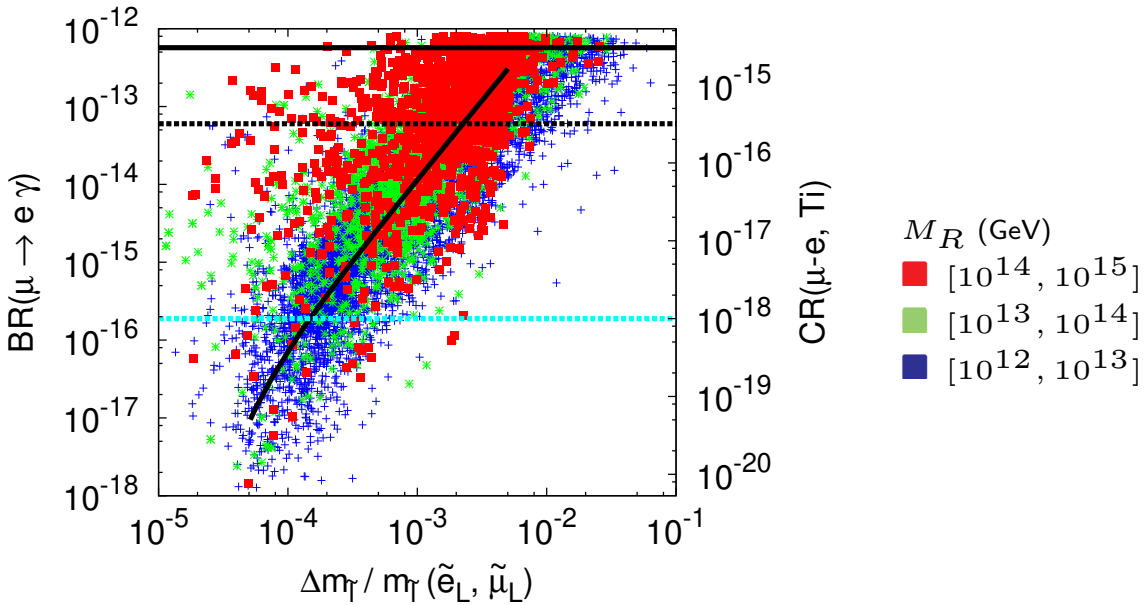
[Hambye, 2013]

High-scale supersymmetric seesaws

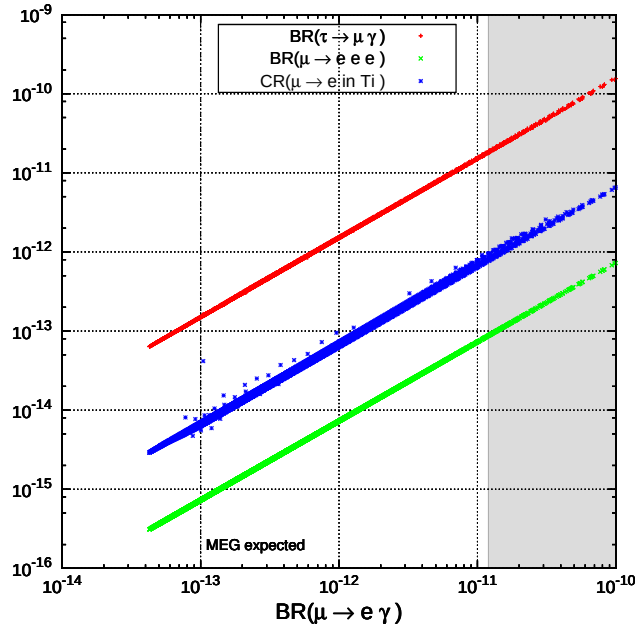
- **Large Y^ν: sizable contributions to cLFV observables**

  cLFV $\leftrightsquigarrow$ exchange of *virtual* **SUSY particles** $\quad \Lambda_{\text{cLFV}} \ll \Lambda_{\text{seesaw}}^{m_\nu}$





[*Type I SUSY seesaw*, Figueiredo and AMT, '13]



[*SO(10) type II SUSY seesaw*, Calibbi et al, '09]

- **Y^ν unique source of LFV: synergy of high- and low-energy cLFV observables**
- **Grand Unified Theories: reduce arbitrariness of Y^f $\Rightarrow$ increase predictivity!**
- **(Non)-observation of "correlated" observables $\Rightarrow$ test SUSY seesaw hypothesis !**

- **SM caveats and flavour anomalies: m_ν, dark matter and lepton flavours**

Exotic matter, different approaches to m_ν, light bosons...

★ **B-decay anomalies:** intensive study of **numerous LFUV SM extensions...**

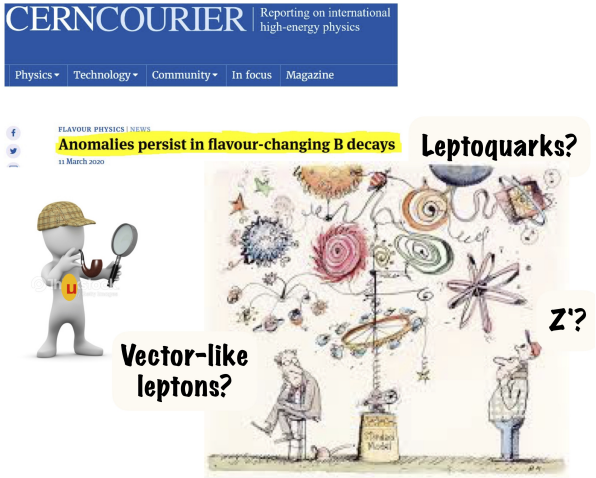
Significant deviation from SM suggests **New Physics** effects at **tree-level!**

▶ **Many appealing candidates:** **Leptoquarks (LQ),**

Vector-like fermions (VLF), Z', **...**

⇒ **New states** with potential to address **SM problems**

(dark matter, m_ν**)** and other **tensions** (Δa_ℓ)



★ **However - a word of caution...**

▶ **Generic (flavour) models** addressing $R_{K^{(*)},D^{(*)}}$ might lead to **sizeable cLFV**

⇒ **Test** LQ (or VLF) hypothesis via **cLFV** in the absence of **direct discovery!**

▶ **Stability of DM candidate** may preclude **realisation of "standard" seesaws...**

⇒ exciting (different) approaches - higher order, etc...

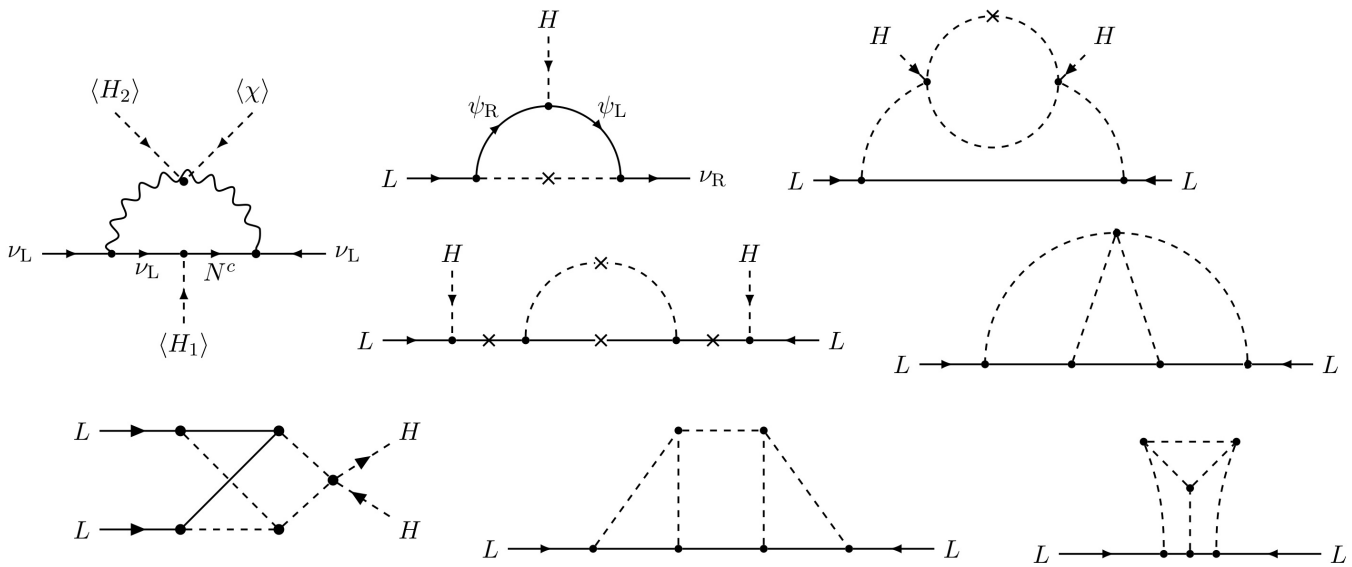
Beyond "standard" seesaw realisations

- **Seesaw** (and its variants) remains one of the most **appealing mechanisms for m_ν**
- But several **other** interesting and theoretically **well-motivated possibilities exist:**

  Tree-level realisation via **higher-dimension** operators, **dynamical "seesaws"...**

  Higher order realisations (Dirac or Majorana): from first **Zee model,** to **R$_p$V SUSY, ...**

  to **3-loops and more!**



[*From recent review by* Cai et al., 1706.08524]

[*For cLFV implications, see* Cepedello et al., 2005.00015]

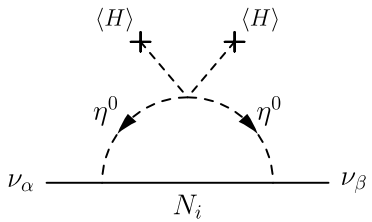
- Depending on the **NP framework, further variants ...**
- **Here, some examples - in association with SM observational problems and tensions!**

Scotogenic models: neutrinos, dark matter and cLFV

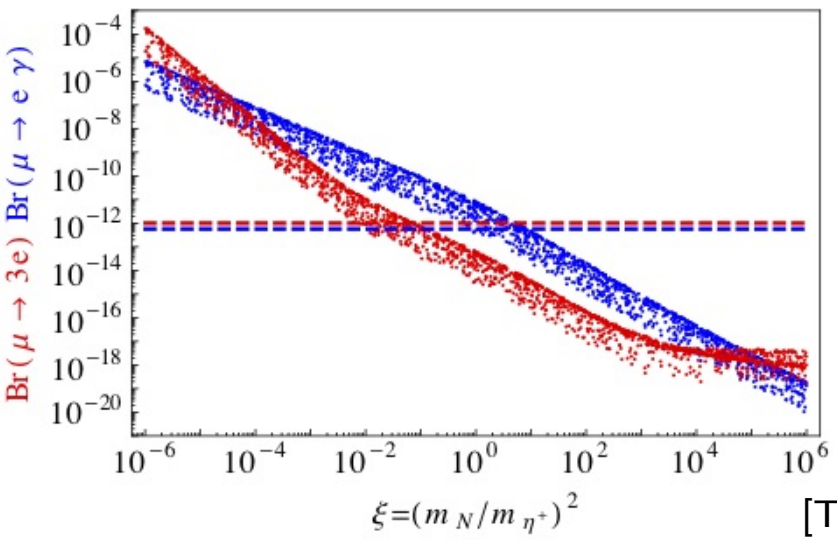
- **SM extended by (inert) scalar doublet η and RH neutrinos N** [Ma, '06]

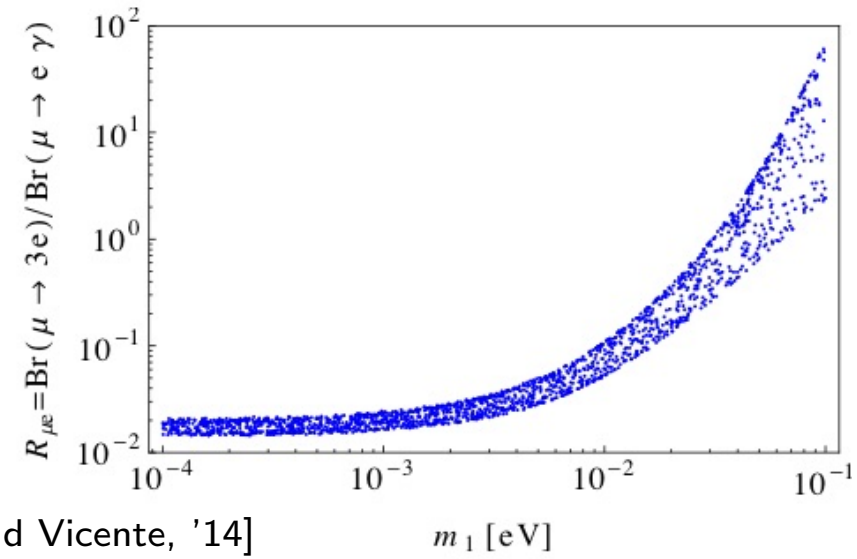
  Additional Z_2 symmetry: **neutrino masses @ 1 loop**

  dark matter candidate (N or η)



- **cLFV observables: nature of DM candidate** & absolute **neutrino mass** scale





[Toma and Vicente, '14]

- **Current (muon) cLFV bounds favour $m_N \geq m_\eta$;** $\eta \rightsquigarrow$ **DM candidate!**

  Determination of $R_{\mu e} = \frac{\mathrm{BR}(\mu \to 3e)}{\mathrm{BR}(\mu \to e\gamma)}$ $\Rightarrow$ **hints on lightest neutrino mass m_{ν_1}**

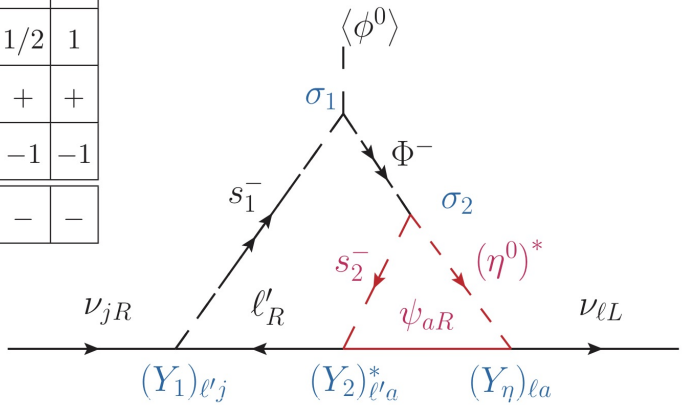
[*Review on phenomenology of generalised scotogenic models:* Hagedorn et al, 1804.04117]

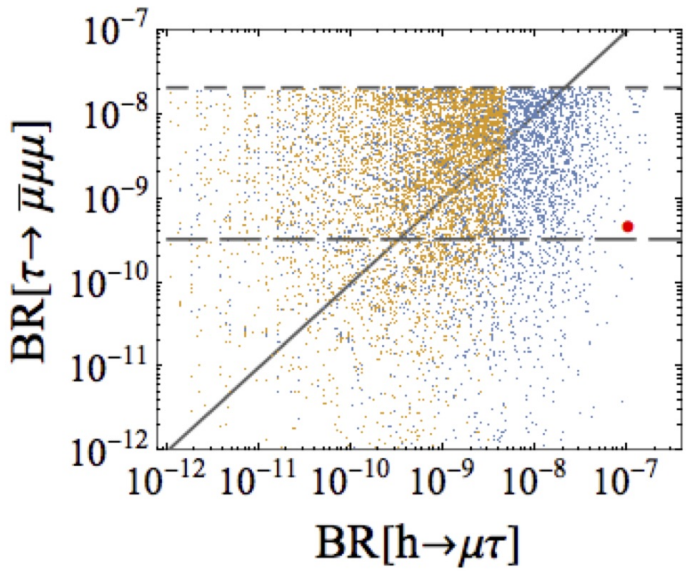
Neutrino masses @ 2-loop: DM and cLFV

- **Lepton number conservation:** **Dirac m_ν** at **2-loop** level through **DM candidate**

  Additional **Z_2' symmetry:** **stabilises** DM candidate & **forbids tree-level Y^ν_{ij}**

	ν_{iR}	ψ_{aR}	Φ	s_1^+	η	s_2^+
Spin J	1/2	1/2	0	0	0	0
$\mathrm{SU(2)_L}$	1	1	2	1	2	1
$\mathrm{U(1)_Y}$	0	0	3/2	1	1/2	1
Z_2'	$-$	$+$	$(+)$	$-$	$+$	$+$
L	1	0	-2	-2	-1	-1
Z_2	$+$	$-$	$+$	$+$	$-$	$-$





[Enomoto et al., '19]

- Scenarios comply with **ν data** (masses, mixings) for both NO and IO,

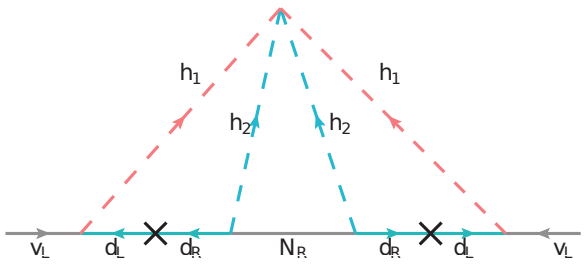
  viable DM candidate (correct relic density), in agreement with **experimental bounds**

- **cLFV rates for Higgs decays** **much larger than pure leptonic cLFV modes**

  (important DM-mediated contributions to decays)

B-meson anomalies, neutrinos, dark matter (and cLFV!)

- **SM + scalar leptoquarks ($h_{1,2}$) + lepton triplets Σ_R; SU(3)×SU(2)×U(1)×Z_2^{DM}**



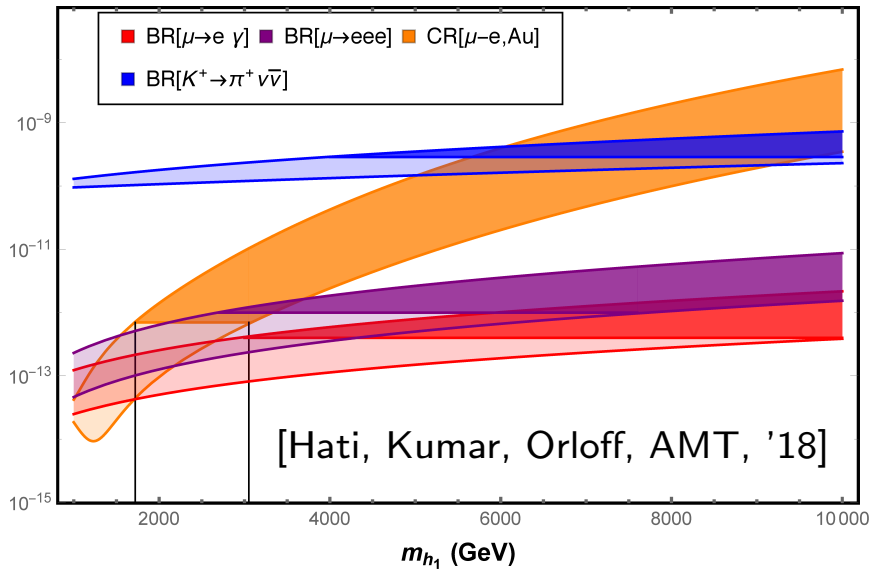
- Radiatively induced m_ν (3-loop)
- **Non-trival structure** in leptoquark Yukawa couplings y

  ⇒ **account for $R_K^{(*)}$ anomalies!**

$$y \sim \begin{pmatrix} \epsilon^4 & \epsilon^5 & \epsilon^2 \\ \epsilon^3 & \epsilon^3 & \epsilon^4 \\ \epsilon^4 & \epsilon & \epsilon \end{pmatrix}$$

- **Huge impact / constraints from cLFV and meson decays**:

  CR($\mu - e$,N), $K \to \pi\nu\bar{\nu}$ the most **stringent**



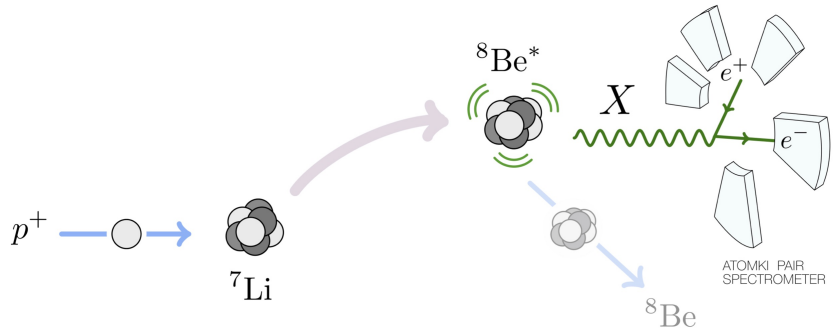
- **Oscillation data** (**perturbative** couplings)

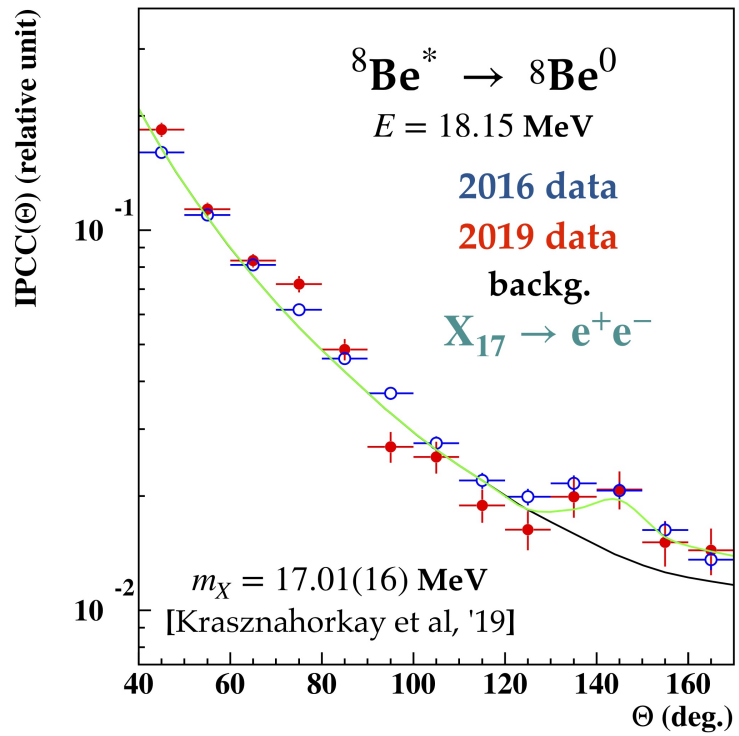
  viable DM candidate ⟷ Σ^0
- **Explain $R_{K^{(*)}}$ anomalies** [no $R_{D^{(*)}}$, $(g-2)_\mu$]
- **Leptoquarks and triplets: within LHC reach!**

Anomalies in "nuclear" transitions: ^{8}Be and ^{4}He

★ ^{8}Be: **anomaly** in **angular correlation** of e^+e^- **internal pair creation @ $5\sigma - 6\sigma$**

$$^8\mathrm{Be}^* \ (j^\pi = 1^+, T = 0) \ \rightarrow \ ^8\mathrm{Be}^0 \ (j^\pi = 0^+, T = 0)\,, \qquad E \ = \ 18.15 \text{ MeV}$$





★ Similar **anomaly** in e^+e^- angular correlation of ^{4}He ($0^- \rightarrow 0^+$, 21.01 MeV decay) @ 7.2σ

- **Both anomalies** can be interpreted as *production and decay of hypothetical* **light vector boson $m_X \sim 17$ MeV,** $\Gamma_X/\Gamma_\gamma \sim \mathcal{O}(10^{-5})$ [Feng et al., '20]

  (regime subject to very strong experimental constraints...)

- **If such a state exists, could it ease/solve other SM tensions?**

"Nuclear" ^{8}Be* $\to^8$ Be^0 anomalies and LFUV $(g-2)_\ell$

- Could a **light Z' boson** ($m_{Z'} \sim 17$ MeV) framework *simultaneously* explain **ν masses,** the **nuclear decay anomalies** *and* the **LFUV** tensions in **$(g-2)_{e,\mu}$?**
- **Minimal framework:** SU(3)×SU(2)×U(1)×U(1)$_{B-L}$

  Additional **RH** neutrinos, heavy **vector-like leptons** and new **scalar h_X**

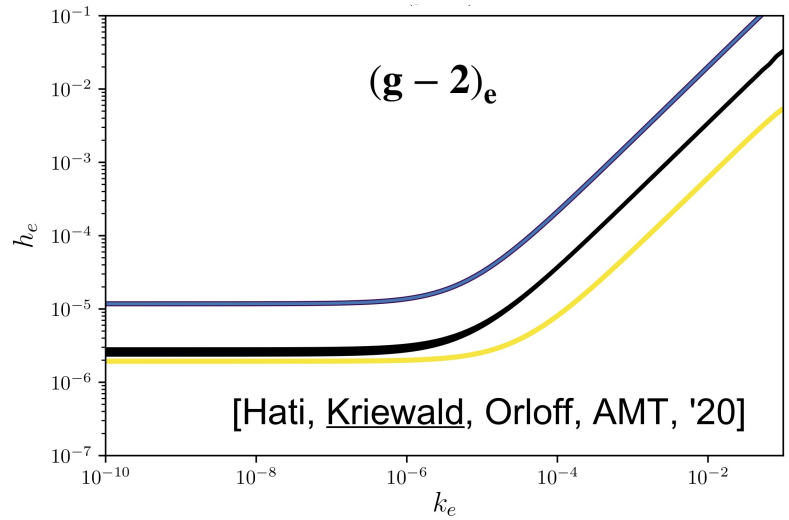
  $\Rightarrow$ **ν masses** from mixings with N_R, L^0: diagonalisation of $\begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{v_X}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{v_X}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{v_X}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix}$

  $\rightsquigarrow m_\nu \simeq -\frac{y_\nu^2 v^2}{m_M}$, with $m_M = v_X\, y_M$

  $\Rightarrow$ new neutral currents (h_X and Z'); **suppressed $Z'\nu\nu$ couplings** (mixings with L^0)

- **Extensive experimental constraints!**
  - **Searches for Z', Caesium atomic PV, ...**
  - **$\nu - e$ scattering: TEXONO and CHARM-II**

  $Z'\nu\nu_{|\text{vector}} \to 0$; new $Z'\nu\nu_{|\text{axial}}$ $(\nu_{e,\mu})$



- **Cancellations between NP contributions** allow to **saturate both observed $(g-2)_{e,\mu}$**
- **Constrained parameter space:** experimental bounds, **^{8}Be & Δa_μ $\Rightarrow$ "predict" Δa_e**

Theories of flavour and the lepton sector

Extensive examples of complete constructions aiming at a **"theory of (lepton) flavours"**

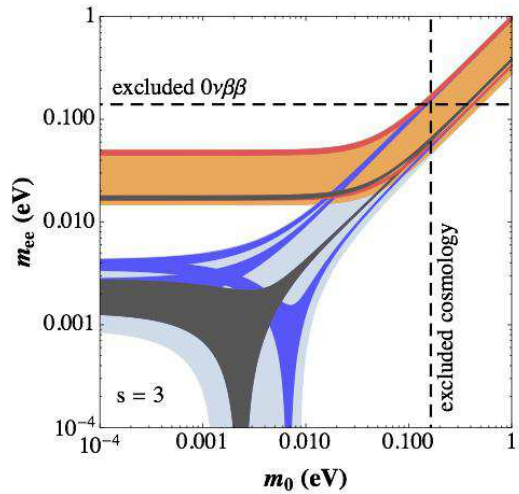
- **Discrete Flavour symmetries:** $G_f \sim \Delta(3n^2)$ type

$\Rightarrow$ **lepton mixings & CP phases** (low and high-energies)

Strong predictions for $0\nu2\beta$ **decay** m_{ee}

Interplay of low-energy **CP phases and BAU**

[Hagedorn and Molinaro, '16]

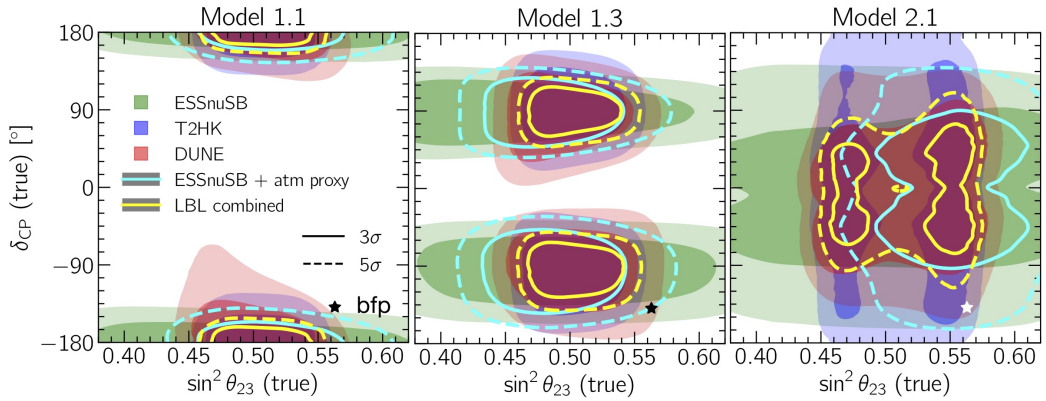


- **Discrete Flavour symmetries:** $A_{4,5}$, S_4 type $\Rightarrow$ **leptonic mixing parameters**

$\Rightarrow$ **Impact for future** ν **oscillation experiments**

[Blennow et al, '20]

Model	Case [Ref.]	Group	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	δ_{CP}	χ^2_{min}
1.1	VII-b [18]	$A_5 \rtimes CP$	0.331	0.523	180°	5.37
1.3	IV [17]	$S_4 \rtimes CP$	0.318	1/2	±90°	7.28
⋮						
2.1	A1 [21]	A_5	—	0.554	$f_1(\theta_{12})$	0.151
⋮						



- **Restrictive Abelian groups:** U_1, Z_N and **Dirac** ν **in 2HDM**

$\Rightarrow$ **Impact for tests of LFU in** $\tau \to \ell\nu\bar{\nu}$ **decays and cLFV rare decays...** [Correia et al, '19]

▶ Concluding remarks

New Physics and lepton observables

- **Confirmed observations** and several **"tensions"** suggest the need to go **beyond the SM**

  In the **lepton sector**, **ν-masses** provided the 1st laboratory **evidence of NP**

  Many experimental **"tensions"** nested in **lepton-related observables**

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

  New Physics can **be manifest via cLFV, LNV, ...** even **before any direct discovery!**

  (Synergy of) lepton observables can provide **information on the underlying NP model**

- **"Leptonic" observables (cLFV, LFUV, LNV, CPV, "anomalies", ...)**

  might be induced by NP at the origin of ν masses... or not!

- **New Physics is there!** Attempt to **identify the underlying model**

  capable of **accounting for** *all* **SM problems and tensions with observation!**

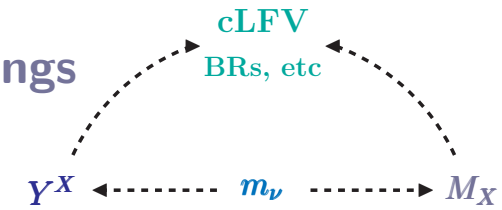
  Explore different paths, and profit from an experimentally exciting near-future!

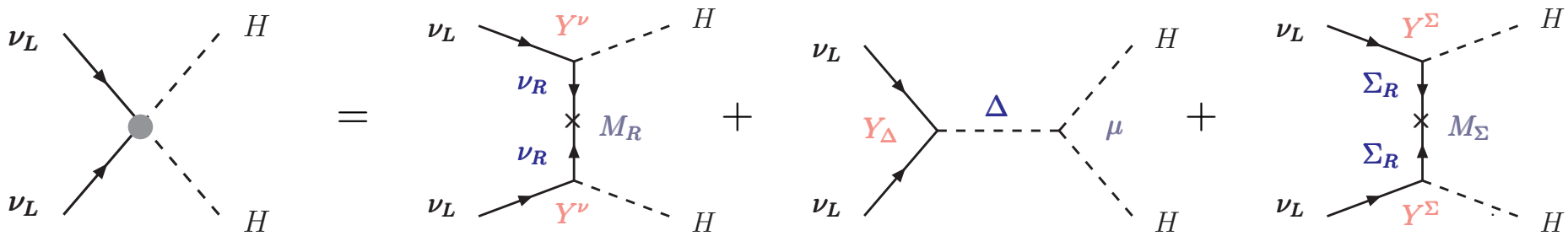
"Leave no flavoured stone unturned !"

▶ Backup

The seesaw mechanism

★ **Seesaw mechanism:** explain **small ν masses** with **"natural" couplings** via **new dynamics** at **"heavy" scale**





$\frac{1}{\Lambda} L\,L\,H\,H$	ν_R (fermion singlet)	Δ (scalar triplet)	Σ_R (fermion triplet)
"Seesaw mechanism"	**Type I**	**Type II**	**Type III**

- **Observables:** depend on **powers of Y^ν** $\rightsquigarrow$ large rates $\Rightarrow$ sizable Y^ν

  and on the **mass of** the (virtual) **NP propagators**

- **Fermionic seesaws:** $Y^\nu \sim \mathcal{O}(1) \Rightarrow M_{\text{new}} \approx 10^{13-15}$ **GeV!**

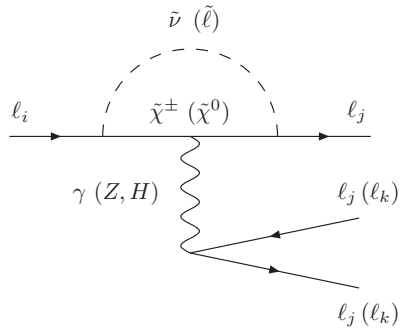
  Suppression of rates due to the **large mass of the mediators!**

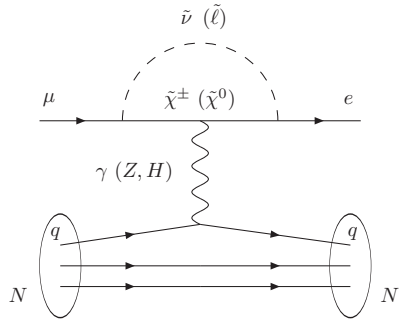
- **Low scale seesaws:** **rich phenomenology at high-intensities!** (and also at LHC)

Correlation of observables in NP models: peculiar patterns

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu\to eee)}{\mathrm{BR}(\mu\to e\gamma)}$	$\frac{\mathrm{CR}(\mu N\to eN)}{\mathrm{BR}(\mu\to e\gamma)}$
Type-I seesaw	Loop*	Loop*	$3\times10^{-3}-0.3$	0.1−10
Type-II seesaw	Tree	Loop	$(0.1-3)\times10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
MSSM+Seesaw I	Loop	Loop	$\approx 6\times10^{-3}$	$10^{-3}-10^{-2}$
LFV Higgs	Loop†	Loop* †	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05-0.5$	$2-20$

[*Adapted from* Calibbi et al, 1709.00294]





- Most **models predict/accommodate** extensive **ranges for observables**

  (no new physics yet discovered, only bounds on new scale!)

- **Correlations** might allow to **disentagle models of cLFV** in the absence of **NP discovery** ... and provide complementary information to **direct searches!**

Impact of heavy states: "toy model" (SM + ν_s)

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

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

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

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

- **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:**

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

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

- **Extensive phenomenolical impact: high intensities & colliders!**

Sterile neutrinos and cLFV: high-intensity & colliders

- **Radiative decays: $\mu \to e\gamma$**

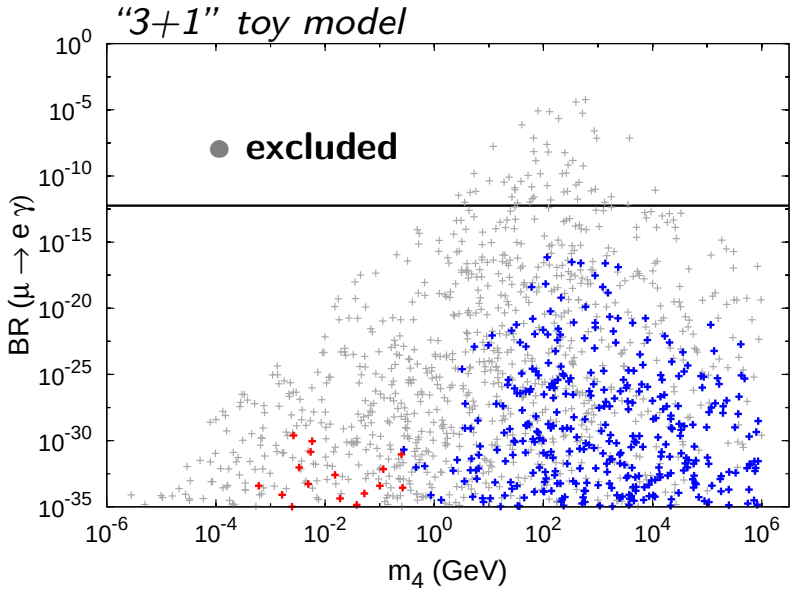
  For $m_4 \gtrsim 10$ GeV sizable ν_s contributions

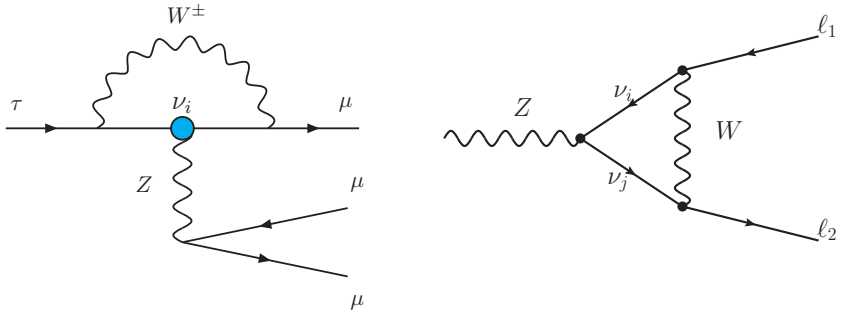
  .. but precluded by other cLFV observables

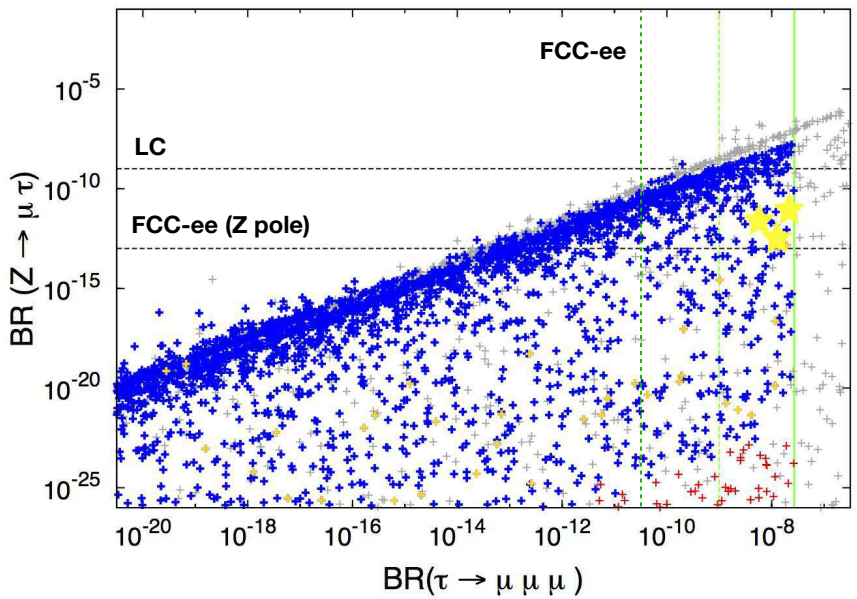
- **Three-body decays and $\mu - e$ conversion**

  well within experimental reach!

  For sterile states above EW scale, strongly dominated by Z **penguin** contributions







- Strong correlation between $Z \to \mu\tau$ and $\tau \to 3\mu$
- **FCC-ee: probe $\mu - \tau$ cLFV** beyond **Belle II reach**

[Abada, De Romeri, Orloff, Monteil, AMT '15]

“Nuclear” ^{8}Be* $\to^8$ Be^0 anomalies and LFUV $(g-2)_\ell$ (I)

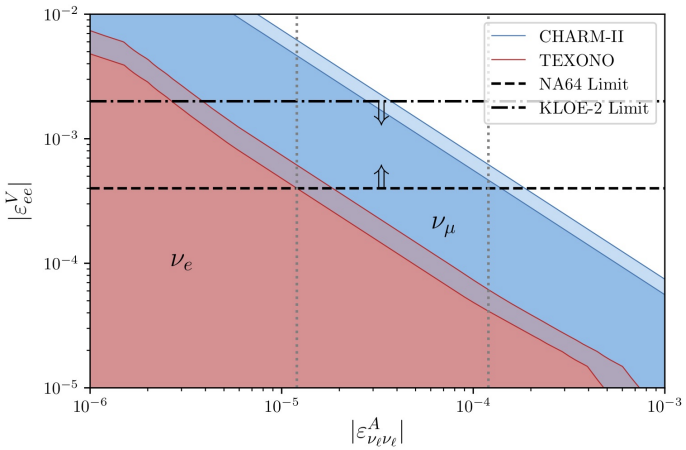


Figure 3: New χ^2-fit of the $\bar{\nu}_e\, e$ scattering data of TEXONO (red) and the $\bar{\nu}_\mu\, e$ scattering data of CHARM-II (blue), displaying the 1- and 2-σ allowed regions around the best fit point (respectively darker and lighter colours). The lower bound of NA64 (dashed line) and the upper bound by KLOE-2 (dash-dotted line) are also shown, with the arrows identifying the viable allowed regions. The obtained upper limits on the axial coupling to neutrinos, cf. Eq (73), are marked by dotted lines: the TEXONO data mostly constrains the couplings to electron neutrinos while the CHARM-II data is responsible for the constraints on the couplings to muon neutrinos.

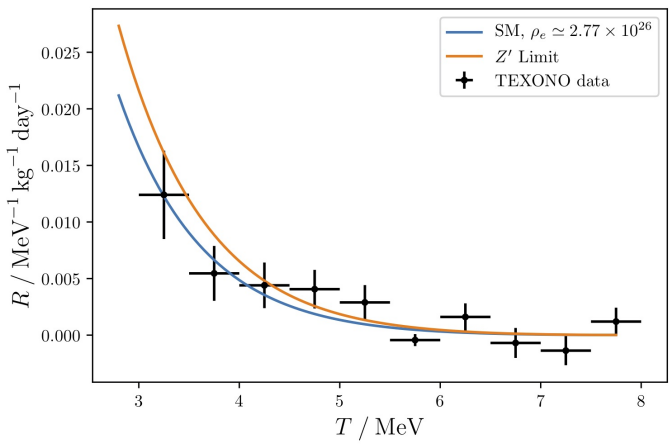
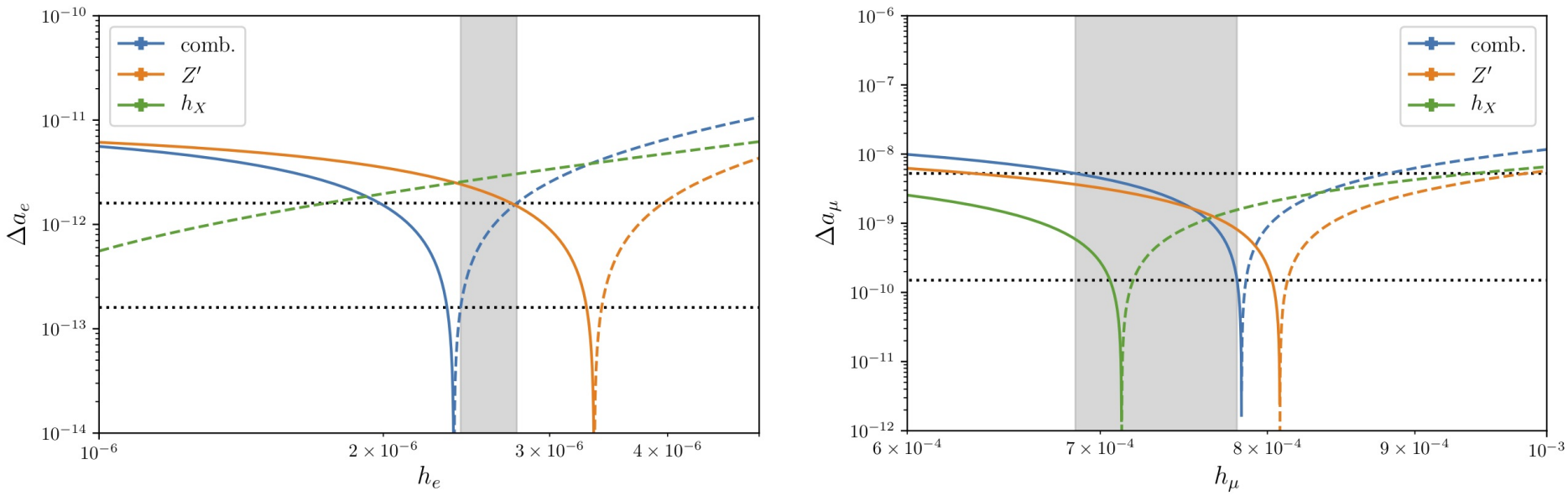


Figure 6: Data of the TEXONO experiment (neutrino rate R in units of MeV^{-1} kg^{-1} day^{-1} function of the binned recoil energy T) [119], to which we superimpose our SM and Z' predict respectively corresponding to blue and orange lines.

[Hati, Kriewald, Orloff, AMT, ’20]

"Nuclear" ^{8}Be* $\to^8$ Be^0 anomalies and LFUV $(g-2)_\ell$ (II)



[Hati, Kriewald, Orloff, AMT, '20]

- **Cancellations between NP contributions** allow to

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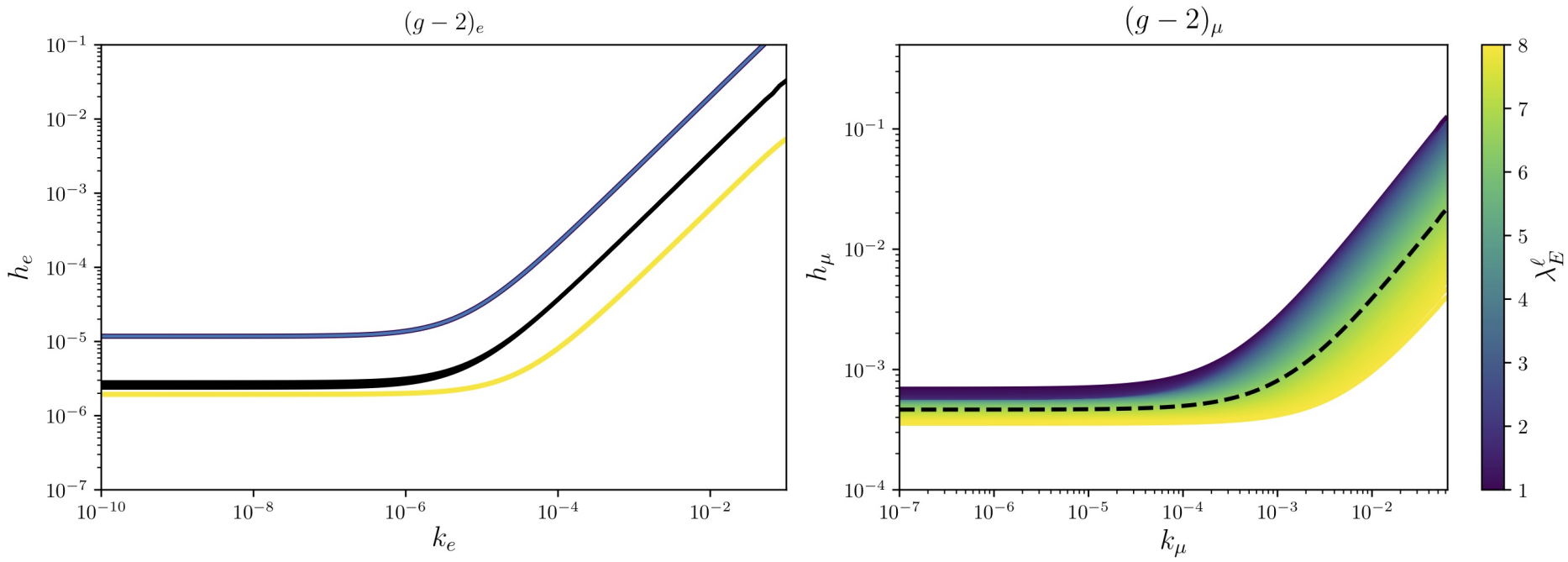

[Hati, Kriewald, Orloff, AMT, '20]

- **Constrained parameter space:** experimental bounds, ^{8}Be & Δa_μ $\Rightarrow$ **"predict"** Δa_e