Overview of cLFV in the muon sector

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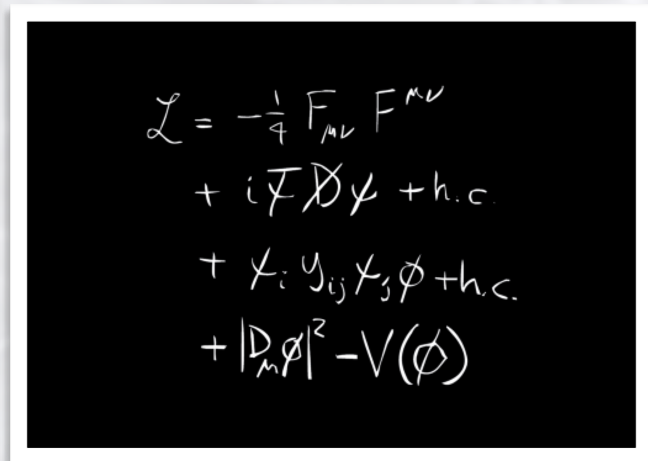
@Snowbird

Flavour and CP violation: SM

Flavour in the **Standard Model:** interactions (and transitions) between **fermion families**



Gauge interactions are **flavour universal**

Yukawas Y^u_{ij}, Y^d_{ij} and Y^ℓ_{ij} encode all **flavour dynamics**

(Masses, mixings and **CP violation**)

SM quark sector:

6 massive states

flavour violated in charged current interactions $V^{ij}_{\mathrm{CKM}} W^\pm \bar{q}_i q_j$

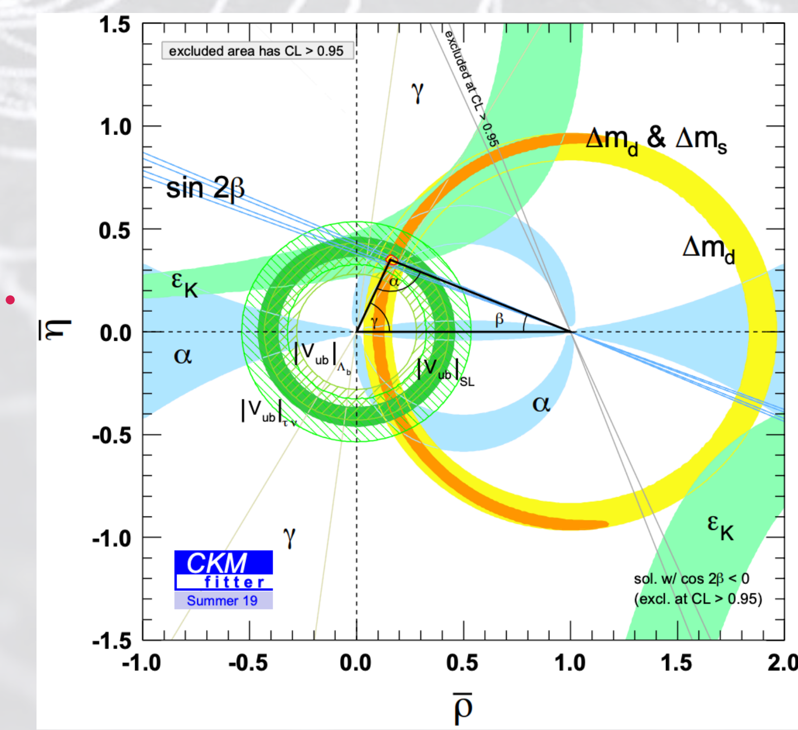
total **baryon number** is conserved in **SM** interactions

CP violation: δ_{CKM} and θ_{QCD}

(not enough to explain BAU from baryogenesis)

CKM paradigm extensively probed:

Meson oscillations & decays, β decays, CP violation…



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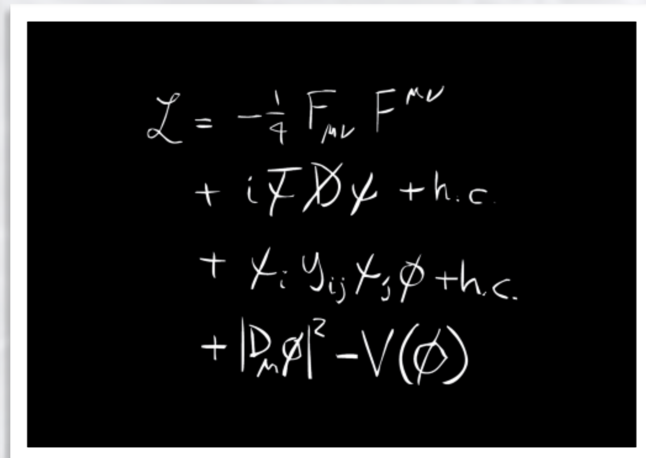

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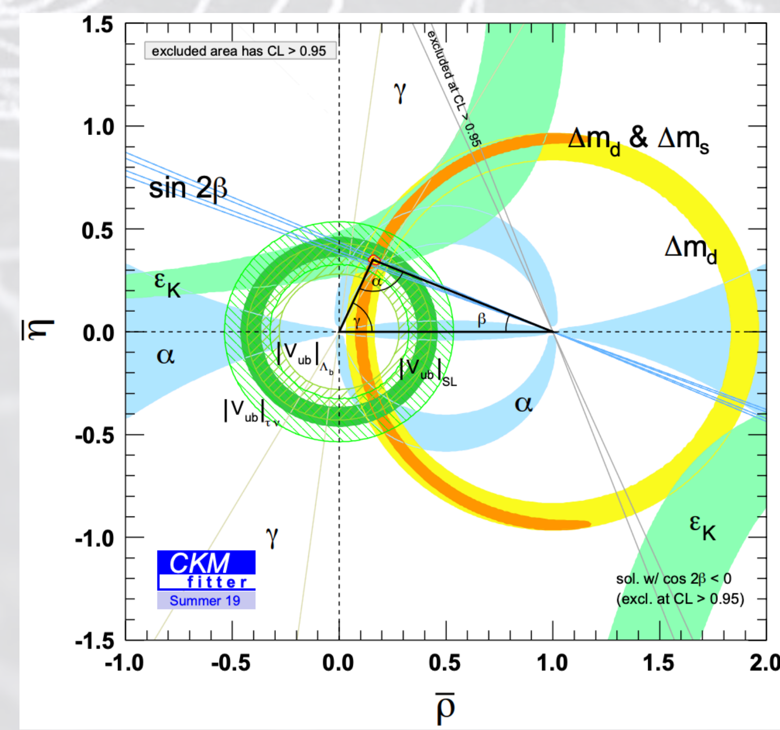

SM lepton sector: neutrinos are strictly massless

- **Conservation of** (total) **lepton number** and **lepton flavour**
- **Lepton flavour universality** only broken by **Yukawas**
- No intrinsic **CPV sources** — (tiny) lepton **EDMs** @ 4-loop

Lepton flavour and CP violation beyond SM

Strong arguments in f(l)avour of **New Physics!**

Observations unaccounted for in SM: ν-oscillations, **Dark matter,**

baryon asymmetry of the Universe (also some theoretical caveats…)

How to unveil the NP model at work?

⇒Test SM symmetries with flavour observables:

(c)LFV, lepton flavour universality violation, …

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ν-oscillations 1st laboratory *evidence* of New Physics!

- New mechanism of mass generation? **Majorana fields?**
- New sources of **CP violation?**

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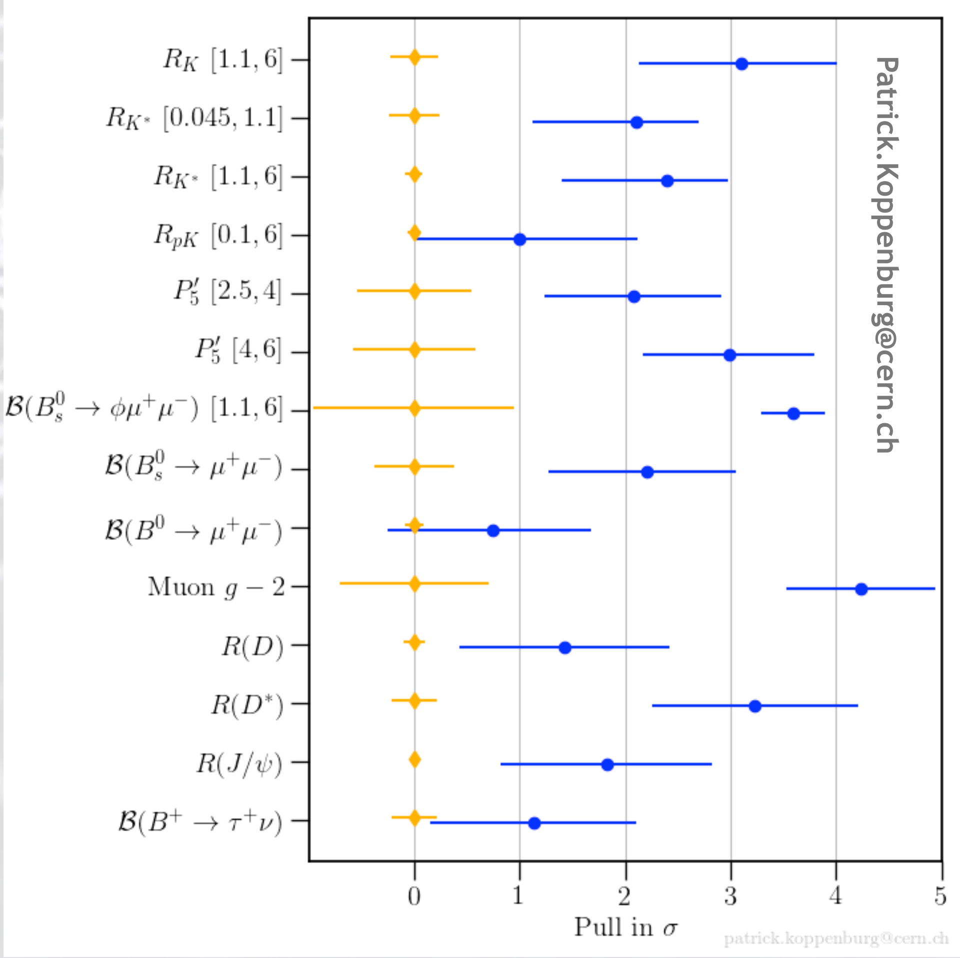
Currently many tensions with SM related to **charged leptons**

- $(g-2)_{\mu,e}$, **B-meson anomalies, …**



Muons are uniquely versatile and sensitive probes of NP!

- **Abundantly available, many different observables**
- **Unprecedented future experimental prospects**

(See talks by Angela Papa & Kevin Lynch, and maaaaany WG4 contributions)

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Lepton flavour probes of New Physics

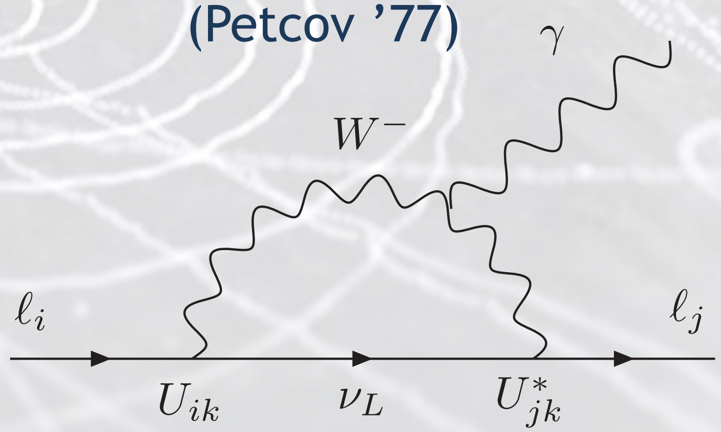
Neutrinos oscillate ⇒ **neutral lepton flavour violated, neutrinos are massive,**
new sources of **CPV?**

Extend SM to accommodate $\nu_\alpha \leftrightsquigarrow \nu_\beta$: ad-hoc 3 ν_R ⇒ Dirac masses, "**SM$_{m_\nu}$**", U_{PMNS}

In **SM$_{m_\nu}$**: **flavour-universal** lepton couplings, lepton number conserved

cLFV possible … but not observable! $\text{BR}(\mu \to e\gamma) \propto |\sum U^*_{\mu i} U_{ei} m^2_{\nu_i}/m^2_W| \simeq 10^{-54}$
(Petcov '77)

EDMs still tiny… (2-loop from δ_{CP}, $|d_\ell| \sim 10^{-35} e\text{cm}$)



⇒ any **cLFV signal** would imply **non-minimal New Physics!**
(Not necessarily related to m_ν generation)

Lepton flavours offer a plethora of observables and **probes of New Physics**

⇒**Negative search results:** allow to place **tight bounds** on **New Physics**

Outline

- Muons: a gateway for New Physics
- (Dis)entangling cLFV sources
- The probing power of Muons
- Conclusions

Muons: a gateway for New Physics

Muons: a long history

Muon (aka **mu-meson** or **mesotron**) discovered in cosmic rays in 1937

Early searches and limits on $\mu(e^*) \to e\gamma$ decay (Hincks, Pontecorvo 1947)

$\Rightarrow$ hypothesis of ν_μ , second lepton family

Since then: μ one of the best understood **SM** particles:

Mass $m_\mu = 105.6583755 \pm 0.0000023$ MeV , **Lifetime** $\tau_\mu = 2.1969811 \pm 0.0000022\ \mu s$

Magnetic moment: $(g-2)/2 = (11659206.1 \pm 4.1) \times 10^{-10}$ **(BNL + FNAL)**

Electric dipole moment: $|d_\mu| \lesssim 1.8 \times 10^{-19} e\mathrm{cm}$ **(BNL)**

For future prospects see WG4 talks

Michel decay: $\mathrm{BR}(\mu^- \to e^- \bar{\nu}_e \nu_\mu) \approx 100\,\%$ (determination of G_F)

Rare SM decays: $\mathrm{BR}(\mu^- \to e^- \bar{\nu}_e \nu_\mu \gamma) = (6.0 \pm 0.5) \times 10^{-8}$

$\mathrm{BR}(\mu^- \to e^- \bar{\nu}_e \nu_\mu e^+ e^-) = (3.4 \pm 0.4) \times 10^{-5}$

Bound states: **Muonium** $(\mu^+ e^-) \rightsquigarrow$ **QED and gravity tests**

Muonic atoms: search for P violation

Anomalous magnetic moments

Magnetic moment: particle's tendency to align with a **magnetic field**

$$\overrightarrow{\mu_\ell} = g_\ell \frac{e}{2\,m_\ell}\vec{s}$$

$g_\ell \rightsquigarrow$ gyromagnetic ratio (**Landé factor**)
Dirac's prediction: $g_e = 2$

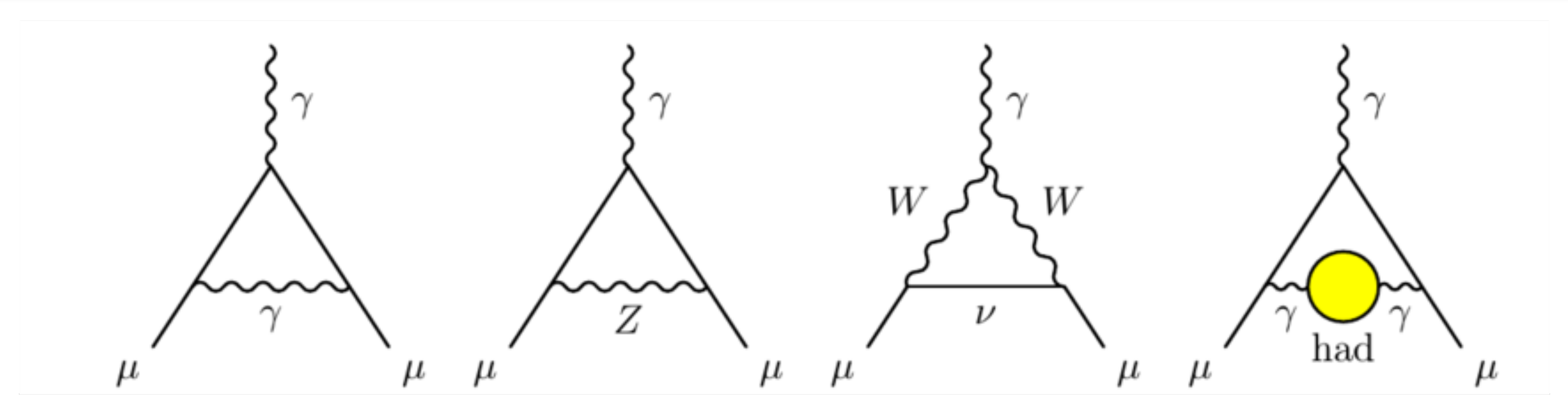
SM electromagnetic current: $\mathcal{J}_\mu = \bar{\ell}(p')\left[\gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_\ell}F_2(q^2) + \gamma_5\frac{i\sigma_{\mu\nu}q^\nu}{2m_\ell}F_3(q^2) + \gamma_5(q^2\gamma_\mu - \not{q}q_\mu)F_4(q^2)\right]\ell(p)$

@ tree-level: $F_1(0) = 1;\ F_{2,3,4}(0) = 0 \ \Rightarrow\ g_\ell = 2\left(F_1(0) + F_2(0)\right) = 2$

@ higher orders: quantum corrections to $F_2(0)$ ⇒ anomalous magnetic moment

$$\Delta a_\ell = \frac{g_\ell - 2}{2} = F_2(0)$$

Higher-order (SM) corrections from **QED, EW** ($W^\pm, Z$ and Higgs) and **QCD**



Muon anomalous magnetic moment circa 2022

- Anomalous magnetic moment of the muon: from theory to experiment and back

$$a_\mu^{\text{SM}} = \frac{1}{2}\left(g_\mu - 2\right) = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{had}}$$

in conflict with BNL & FNAL? Or not?

see WG4 talks for future exp prospects

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = ?$$

Full QED $\mathcal{O}(\alpha^5)$ - 12672 diagrams!

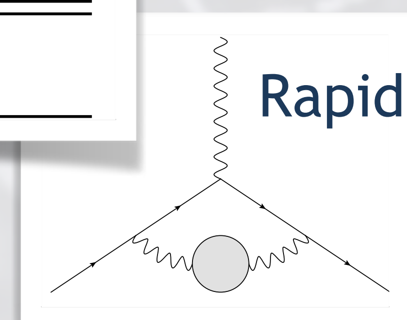
EW completed at **2-loop** (3-loop negligible)

	$10^{11} \cdot a_\mu$	$10^{11} \cdot \Delta a_\mu$
QED total	116 584 718.931	0.104
EW	153.6	1.0
HVP	6 845	40
HLbL	92	18
SM total	116 591 810	43

Hadronic: smaller than QED, but dominate theoretical uncertainties!

HVP - evaluated from *dispersion relations* & *data-driven* input from $e^+e^- \to$ hadrons

(a_μ "White paper" HVP result)

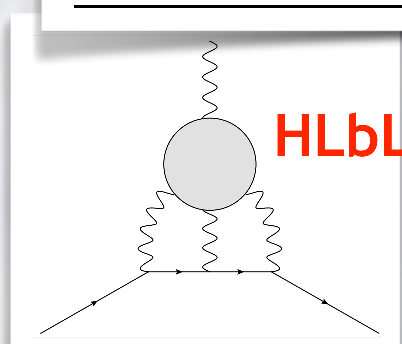


Rapid *LQCD progress!*

BMW 2021: $10^{11} \,.\, a_\mu^{\text{LQCD}} = 7\,075\,(55)$

$\Rightarrow 2.1\sigma$ **tension !**

2022: confirmation by Mainz & ETMC



HLbL - recent progress, from hadronic models to dispersive framework, 1st LQCD results!

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Muon anomalous magnetic moment circa 2022

▷ Anomalous magnetic moment of the muon: from theory to experiment and back

$$a_\mu^{\text{SM}} = \frac{1}{2}\left(g_\mu - 2\right) = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{had}}$$ in conflict with BNL & FNAL? Or not?

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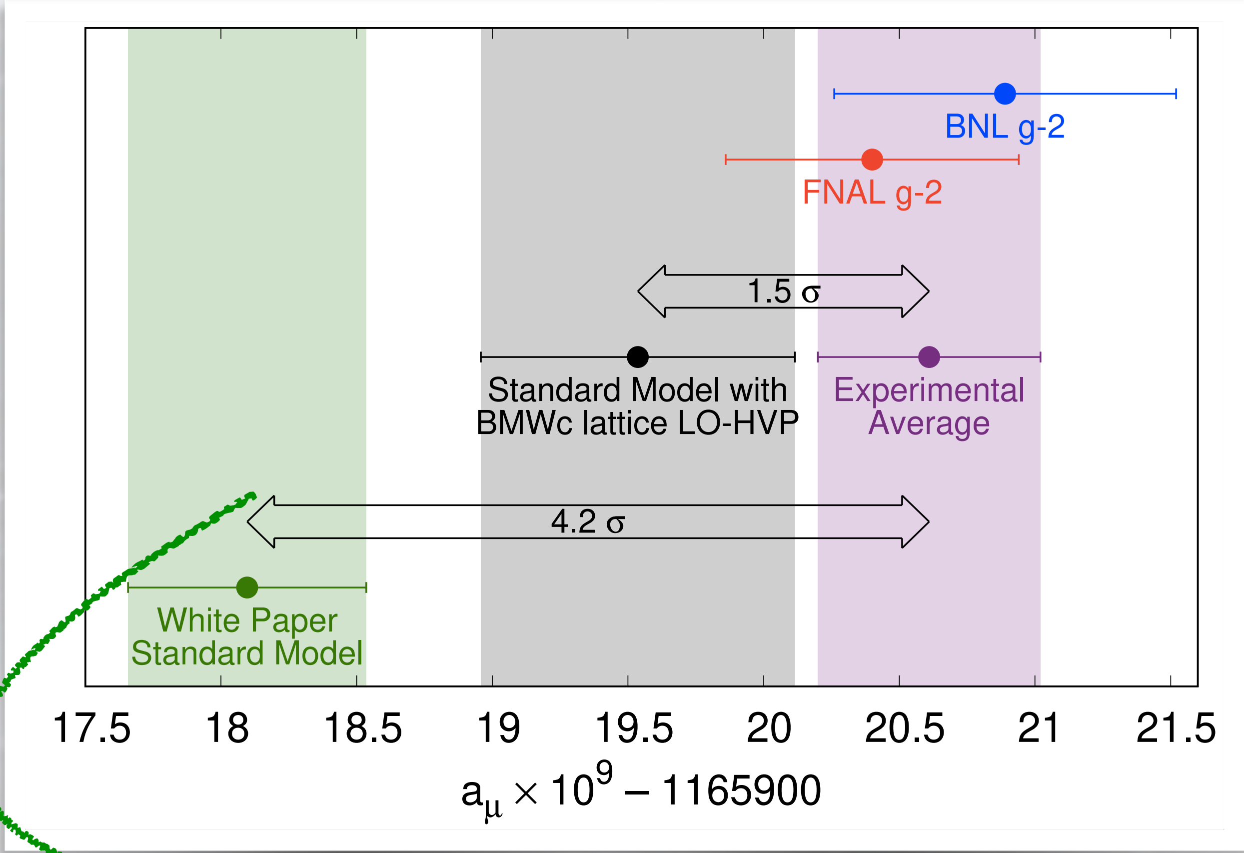


Recent **LQCD** results seem to ***confirm*** BMWc

Mainz [2206.06582], ETMC [2206.15084]

$\Rightarrow$ New tensions with $e^+e^- \to$ hadrons scattering

New Physics needed elsewhere?

see e.g. Darmé et al. [2112.09139], Di Luzio et al. [2112.08312]

MUonE experiment to conclusively measure **HVP!**

see talks by Javad Komijani and Lorenzo Capriotti

New Physics needed for $g-2$? or not?

$$\mathscr{H}_{\text{eff}}^{\text{NP}} \sim \frac{C^6_{a_\mu}}{\Lambda^2_{\text{NP}}}\left(\bar{\Psi}_\mu \sigma_{\alpha\beta} \Psi_\mu\right) F^{\alpha\beta} H$$

If $\Delta a_\mu \sim \mathcal{O}(\text{few}\,\sigma) \approx 2 \times a_\mu^{\text{SM, weak}}$

$$\Rightarrow \Delta a_\mu \approx \frac{C^6_{a_\mu}}{\Lambda^2_{\text{NP}}}(m_\mu v)$$

Loop-induced, **chirality-flipping**,

Typically $\Lambda_{\text{NP}} \sim \text{few} \times 100$ GeV

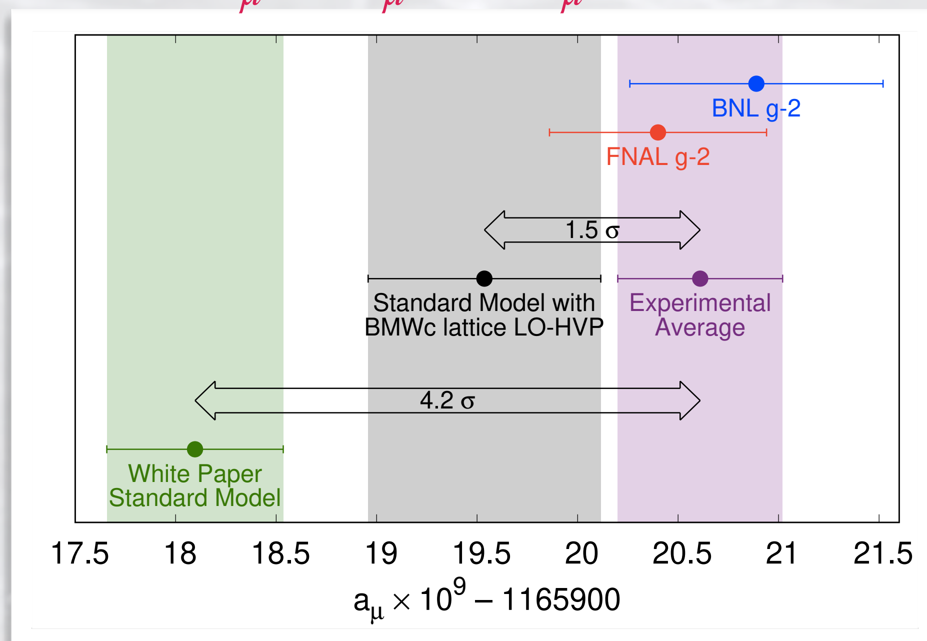
$\Rightarrow$ Huge impact for **flavour pheno!**

For recent "model survey" see e.g. Athron et al. [2104.03691]

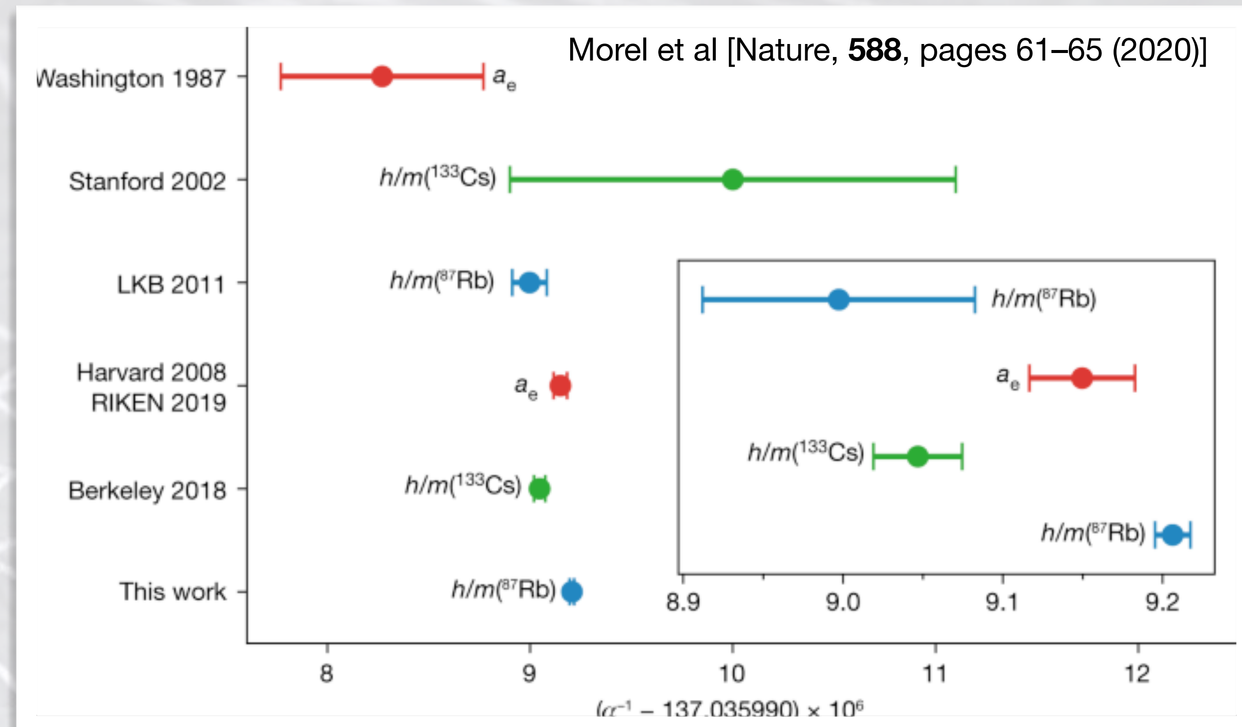
Anomalous magnetic moments: muon and electrons

Anomalous magnetic moment of the muon

$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = ?$



New Physics: badly needed? or not?



Recent experimental progress on α_e & a_e:

(2018) $\Delta a_e^{\text{Cs}} = -0.88(36) \times 10^{-12} \sim \mathbf{-2.3\sigma}$

(2020) $\Delta a_e^{\text{Rb}} = +0.48(30) \times 10^{-12} \sim \mathbf{+1.7\sigma}$

Difference of $\mathbf{5.4\sigma}$ in determination of α_e ???

Lepton universality (**MFV**) suggests:

$\Delta a_e / \Delta a_\mu \simeq m_e^2 / m_\mu^2 = +2.4 \times 10^{-5}$

But $\Delta a_e^{\text{Cs}} / \Delta a_\mu = -3.3 \times 10^{-4}$!

⇒Hint of violation of **lepton universality?**

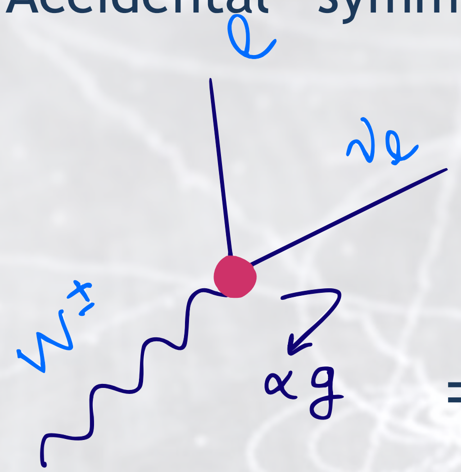
Explaining both Δa_e^{Cs} & Δa_μ in simple **BSM is very hard…**

… but possible! e.g. scalar **leptoquarks, axions,** light Z' , etc.

Lepton flavour universality

Accidental "symmetry" in the SM: couplings of electroweak gauge bosons are "blind" to lepton flavour

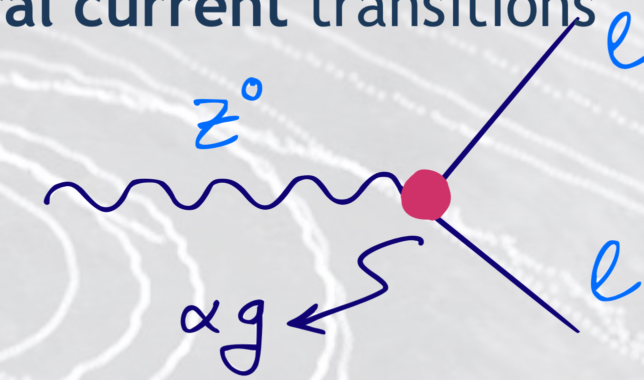
$\Rightarrow$Lepton Flavour Universality (LFU)



Violation of LFU also signals the presence of NP!

Construct observables sensitive to LFUV:

$\Rightarrow$Compare **flavour-dependent** rates of **charged** and **neutral current** transitions



e.g. ratios of **EW gauge boson decays:**

$$R_Z^{\alpha\beta}, R_W^{\alpha\beta} = \frac{\Gamma(Z \to \ell_\alpha^+ \ell_\alpha^-)}{\Gamma(Z \to \ell_\beta^+ \ell_\beta^-)}, \frac{\Gamma(W \to \ell_\alpha \nu)}{\Gamma(W \to \ell_\beta \nu)}$$, in **SM:** $R_Z^{\alpha\beta}, R_W^{\alpha\beta} \simeq 1$

$R_Z^{\mu e} = 1.0001 \pm 0.0024$ (LEP)

$R_Z^{\tau\mu} = 1.0010 \pm 0.0026$ (LEP)

$R_Z^{\tau e} = 1.0020 \pm 0.0032$ (LEP)

$R_W^{\mu e} = 0.996 \pm 0.008$ (ATLAS)

$R_W^{\tau\mu} = 1.070 \pm 0.026$ (LEP)

$R_W^{\tau e} = 1.063 \pm 0.027$ (LEP)

$R_W^{\tau e} = 0.992 \pm 0.013$ (ATLAS)

$\Rightarrow$Place **strong bounds** on **New Physics:** e.g. neutrino mass models modifying W-vertex ...

Lepton flavour universality: leptonic meson decays

Accidental “symmetry” in the SM: couplings of electroweak gauge bosons are “blind” to lepton flavour

⇒Lepton Flavour Universality (LFU)

Violation of LFU also signals the presence of NP!

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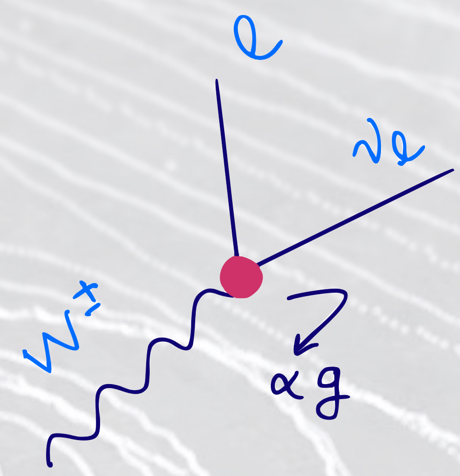


Kaon sector: $R_K^\ell = \dfrac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)} \propto \dfrac{m_e^2}{m_\mu^2}$

$R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$ [Cirigliano et al. ’07]

$R_K^{\text{exp}} = (2.488 \pm 0.009) \times 10^{-5}$ [NA62]

Pion sector: $R_{e/\mu}^\pi = \dfrac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$

⇒New Physics contributions can be at most $\mathcal{O}(10^{-3})$!!!

$R_\pi^{\text{SM}} = (1.2354 \pm 0.0002) \times 10^{-4}$

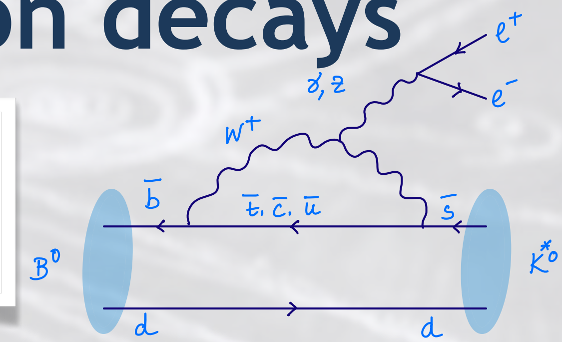
$R_\pi^{\text{exp}} = (1.2327 \pm 0.0023) \times 10^{-4}$ [PiENu]

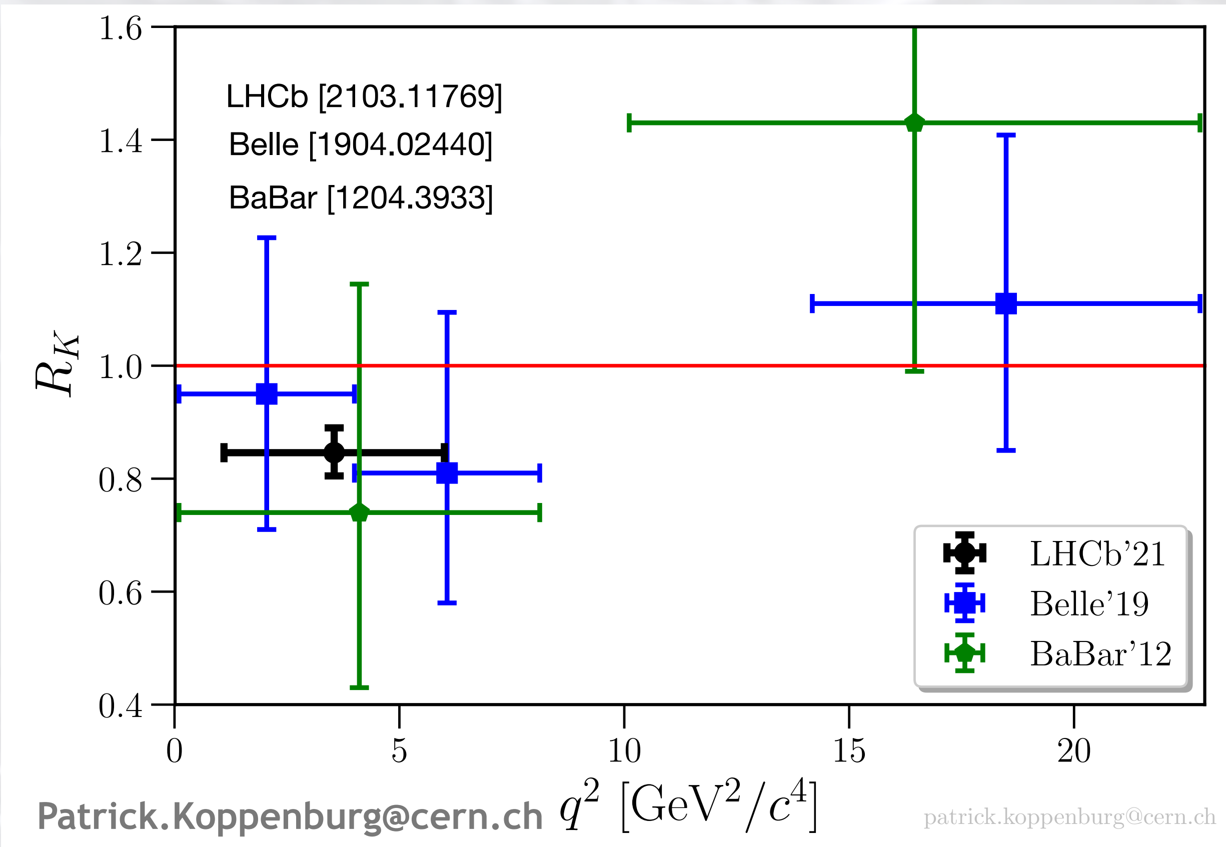
(Similar observables for τ decays…)

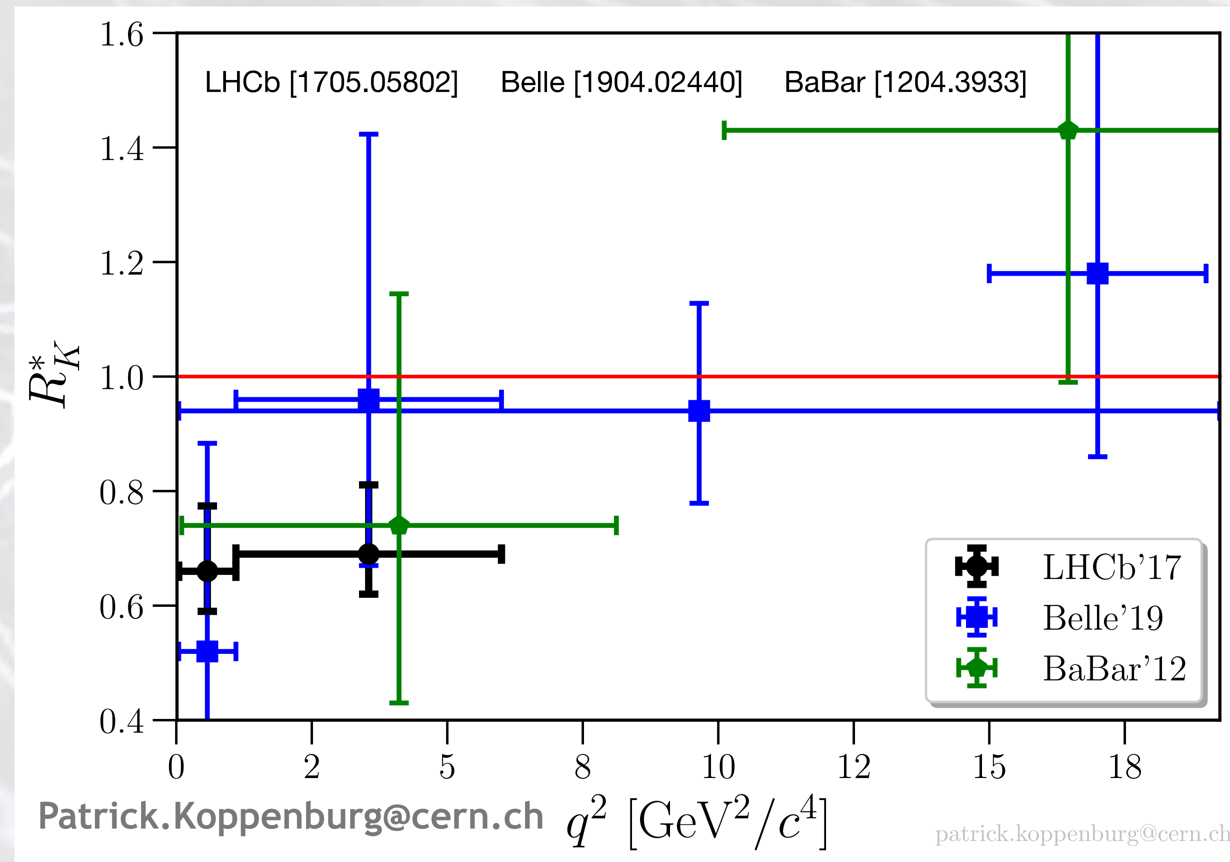
Lepton flavour universality: semi-leptonic meson decays

Violation of **LFU** signals the presence of **NP!**

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$$







Theoretically clean: **hadronic uncertainties** (mostly) cancel in ratios

SM: $R_K = R_{K*} \simeq 1$

Exp: $R_K^{[1.1,6]} = 0.846^{+0.044}_{-0.041}$ **[LHCb]**

Exp: $R_{K*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$ **[LHCb]**

$\Rightarrow 2 - 3\sigma$ **smaller than SM!** Hint on **LFUV New Physics** coupled to **muons?**

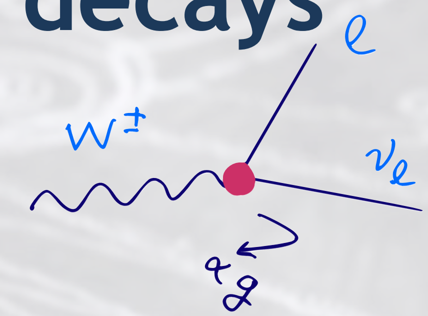
(Many other observables in $b \to s\ell\ell$ also in tension with SM)

See ATLAS, Belle II and LHCb talks in WG4!

Lepton flavour universality: semi-leptonic meson decays

Violation of **LFU** signals the presence of **NP!**

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

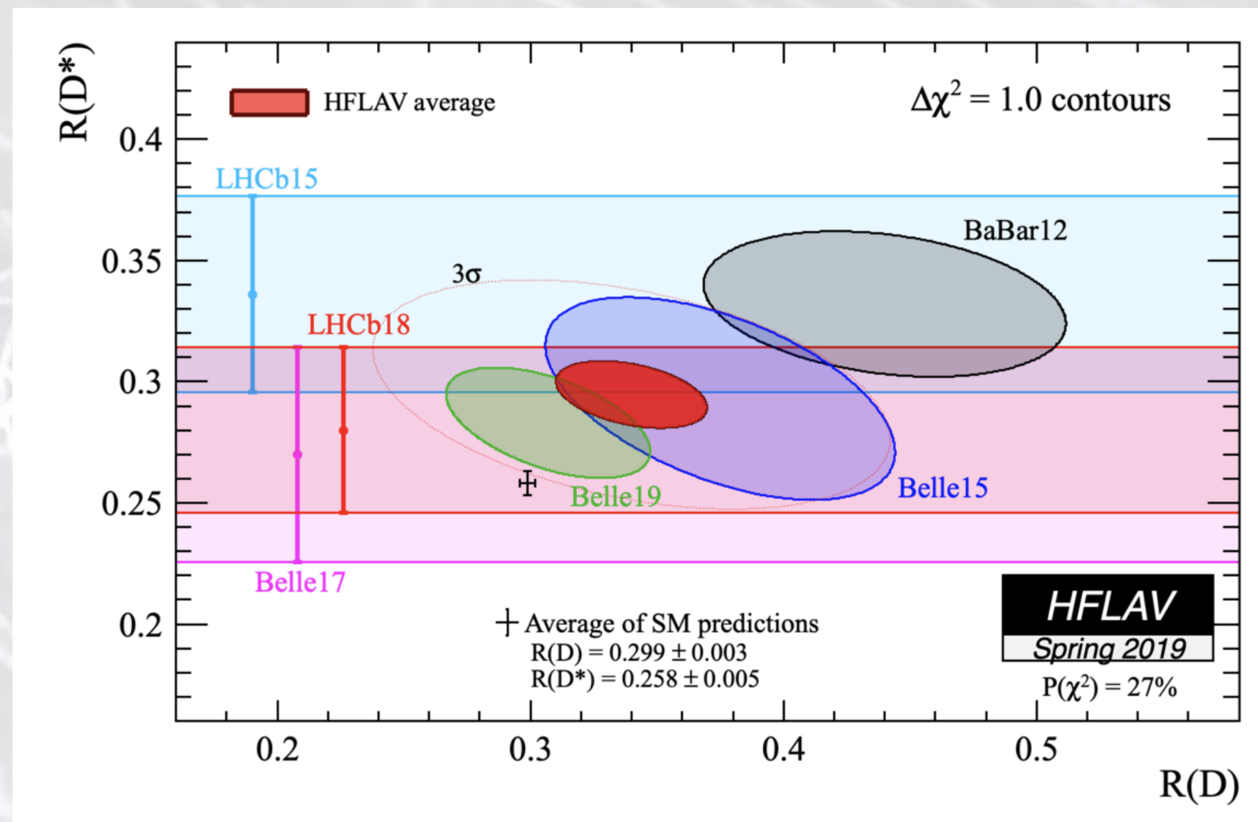


Theoretically clean: **hadronic uncertainties** (mostly) cancel in ratios

SM: $R_D \simeq 0.299 \pm 0.003\,,\; R_{D^*} \simeq 0.258 \pm 0.005$

Exp: $R_D = 0.340 \pm 0.027 \pm 0.013$

$R_{D^*} = 0.295 \pm 0.011 \pm 0.008$



$\Rightarrow$ **combined:** $\sim 3\sigma$ ***larger*** **than SM!**

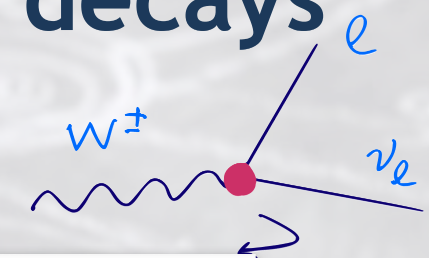
Hint on **LFUV New Physics** coupled to **tau leptons?**

See ATLAS, Belle II and LHCb talks in WG4!

Lepton flavour universality: semi-leptonic meson decays

Violation of **LFU** also signals the presence of **NP!**

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



The

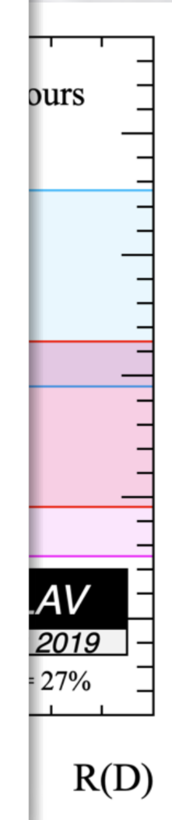
SM: R_D

Exp: R

R

S. Glashow '14: "[...] any departure from **lepton universality** is necessarily associated with the **violation of lepton flavour conservation**. *No known symmetry principle can protect the one in the absence of the other*"

[1411.0565]



⇒ combined: $\sim 3\sigma$ *larger* than SM!

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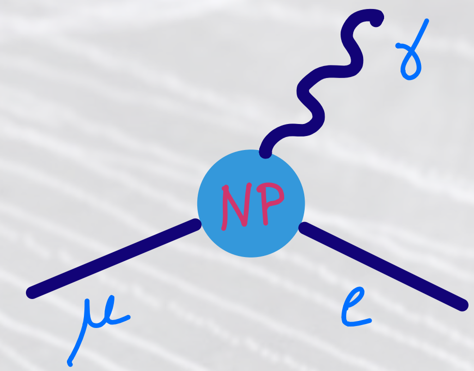
cLFV decays

Any **cLFV** signal necessarily implies the presence of **New Physics!**



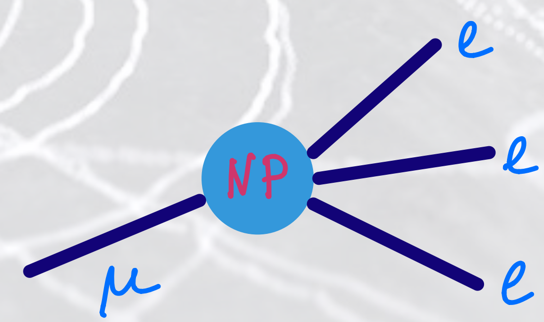
cLFV decay $\mu^+ \to e^+\gamma$:

Clean event signature: **back-to-back** $e^+\gamma$, with $E_\gamma = E_{e^+} \simeq m_\mu/2$

Current bound: $\mathrm{BR}(\mu \to e\gamma) \lesssim 4.2 \times 10^{-13}$ (MEG)

Future **prospects:** $\mathrm{BR}(\mu \to e\gamma) \lesssim 6 \times 10^{-14}$ (MEG II)

(see also WG4 talk by Dylan Palo)



cLFV decay $\mu^+ \to e^+e^-e^+$:

Event signature: **3 electrons in coincidence,** with $\sum p_e = (m_\mu, \vec{0})^T$

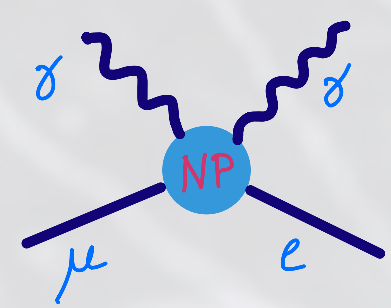
Current bound: $\mathrm{BR}(\mu \to eee) \lesssim 1 \times 10^{-12}$ (Sindrum)

Future **prospects:** $\mathrm{BR}(\mu \to eee) \lesssim 10^{-15(16)}$ (Mu3e)

(see also WG4 talk by Ann-Kathrin Perrevoort)

More cLFV decays:

$\mu^+ \to e^+\gamma\gamma$, $\mu^+ \to e^+X(\to \gamma\gamma, e^+e^-)$, $\mu \to ea$ **(ALPs), ...**

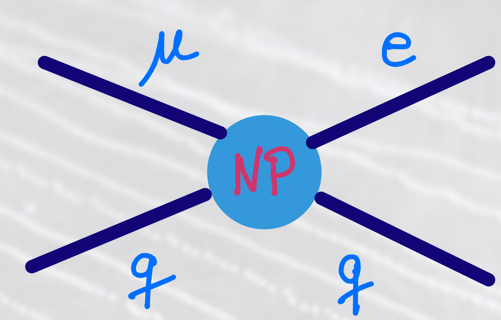


Muonic bound states & muonic atoms

Any **cLFV** signal necessarily implies the presence of **New Physics!**

- **cLFV $\mu^- \to e^-$ conversion: $\mu^- + (A,Z) \to e^- + (A,Z)^{(*)}$** (coherent conversion dominant)

  Event signature: single **mono-energetic** e^-, with $E_e \simeq \mathcal{O}(100\,\mathrm{MeV})$

  Current bound: $\mathrm{CR}(\mu \to e, \mathrm{Au}) \lesssim 7 \times 10^{-13}$ (Sindrum II)

  Future **prospects:** $\mathrm{CR}(\mu \to e, \mathrm{Al}) \lesssim \mathcal{O}(10^{-17} - 10^{-18})$ **(Mu2e, COMET)**

  See many talks in WG4! **(also DeeMe)**

- **Coulomb enhanced $\mu^- e^- \to e^- e^-$ decay: $\Gamma \propto \sigma_{\mu e \to ee} v_{\mathrm{rel}} [(Z-1)\alpha_e m_e]^3$**

  Clean event signature: **back-to-back e^- pair,** with $E_e \simeq m_\mu/2$ Koike et al. [1003.1578]

  Experimental status: **NEW observable!** (to be studied at COMET phase I ?)

  Large Z enhancement, very complementary to $\mu \to eee$ & $\mu \to e\gamma$ Uesaka et al. [1508.05747]

- **cLFV & LNV $\mu^- - e^+$ conversion: $\mu^- + (A,Z) \to e^+ + (A, Z-2)^*$**

  Complicated event signature, NMEs poorly known… **but: strong correlation with $0\nu 2\beta$!**

- **Muonium: $\mathrm{Mu}(\mu^+ e^-) \to \overline{\mathrm{Mu}}(\mu^- e^+)$ oscillation, $\mathrm{Mu}(\mu^+ e^-) \to e^+ e^-$ decay**

  $P(\mathrm{Mu} \to \overline{\mathrm{Mu}}) \lesssim 8 \times 10^{-11}$ (Willmann et al. '99)

cLFV observables across all sectors and energies

Any **cLFV** signal necessarily implies the presence of **New Physics!**

- **"Purely" leptonic cLFV observables:** $\ell_\beta \to \ell_\alpha \gamma, \ell_\beta \to \ell_\alpha \ell_\gamma \ell_{\gamma'}$
  Most stringent exp. bounds: $\text{BR}(\mu \to e\gamma) \lesssim 4.2 \times 10^{-13}$, $\text{BR}(\mu \to eee) \lesssim 10^{-12}$

- **Muonic atoms:** many **"nuclear-assisted"** cLFV observables
  e.g. neutrinoless $\mu - e$ conversion $(\mu^- N \to e^- N)$: $\text{CR}(\mu - e, \text{Au}) \lesssim 7 \times 10^{-13}$

- **Semi-leptonic cLFV τ decays:** $\tau \to P\ell', \tau \to V\ell'$; $\text{BR}(\tau \to \phi\mu) \lesssim 8.4 \times 10^{-8}$

- **(Semi-) leptonic cLFV meson decays:** $M \to \ell_\alpha^\pm \ell_\beta^\mp, M \to M' \ell_\alpha^\pm \ell_\beta^\mp$;
  $\text{BR}(K_L \to \mu^\pm e^\mp) \lesssim 4.7 \times 10^{-12}$, $\text{BR}(B_{(s)} \to \ell_\alpha^\pm \ell_\beta^\mp) \lesssim \mathcal{O}(10^{-5})$

- **cLFV @ higher energies:** $Z \to \ell_\alpha^\pm \ell_\beta^\mp, H \to \ell_\alpha^\pm \ell_\beta^\mp$, high-p_T di-lepton tails $pp \to \ell_\alpha^\pm \ell_\beta^\mp$,
  $\text{BR}(Z \to \ell_\alpha^\pm \ell_\beta^\mp) \lesssim \mathcal{O}(10^{-6})$

cLFV observables across all sectors and energies

Any **cLFV** sign

▷ "Purely

Mos

$e) \lesssim 10^{-12}$

▷ Muonic

e.g. ne

10^{-13}

▷ Semi-le

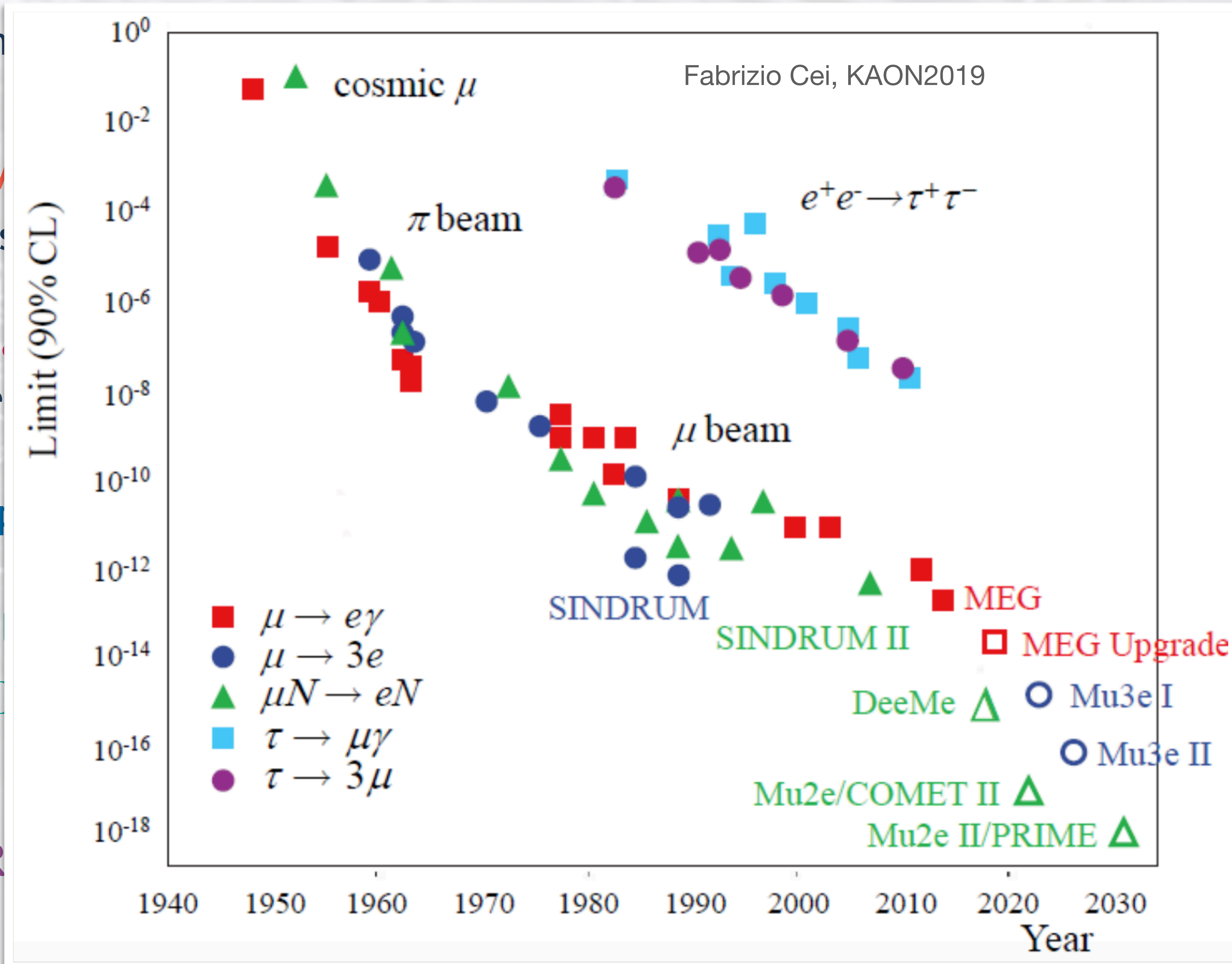
0^{-8}

▷ (Semi-)

▷ cLFV @

$p \to \ell^{\pm}_{\alpha}\ell^{\mp}_{\beta}$,

BR



(Dis)entangling cLFV sources

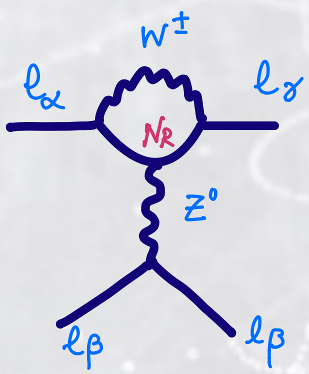
cLFV signals — correlations matter

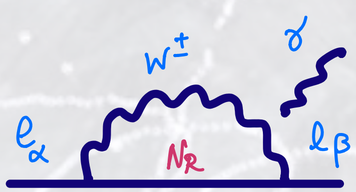
Synergy of **cLFV observables very important:** probe different operators/topologies

$\mathrm{BR}(\mu \to e\gamma), \mathrm{BR}(\mu \to eee), \mathrm{CR}(\mu - e, \mathrm{N})$ **correlated** by **common topologies:**

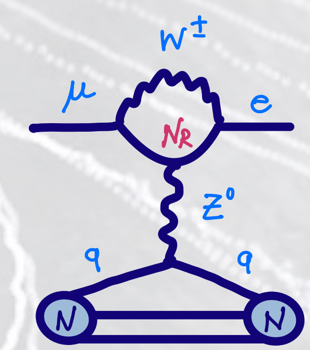
γ **dipoles & anapoles**, Z **penguins**, **tree-level contributions,…** $\Rightarrow$**4-fermion operators**

Model-dependent: certain **topologies dominate, tree-level cont. might be present**





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



Calibbi et al. [1709.00294]

$\Rightarrow$ study correlations/ratios of cLFV observables, **might find peculiar cLFV patterns**

$\Rightarrow$ **provide complementary information to direct searches**

In **EFT:** **RGE** leads to **operator mixing, need to consider as many observables** as possible

to constrain $\mathscr{L}^{\mathrm{eff}} = \mathscr{L}^{\mathrm{SM}} + \frac{\mathscr{C}^5\,\mathscr{O}^5}{\Lambda_{\mathrm{LNV}}}(m_\nu) + \frac{\mathscr{C}^6\,\mathscr{O}^6}{\Lambda^2_{\mathrm{cLFV}}}(\ell_i \leftrightarrow \ell_j) + \ldots + \frac{\mathscr{C}^9\,\mathscr{O}^9}{\Lambda'^5_{\mathrm{LNV}}}(0\nu 2\beta) + \ldots$

See S. Davidson NuFact 2021

Neutrino mass generation

Mechanisms of m_ν generation: account for **oscillation data**

and ideally address **SM issues** — **BAU** (leptogenesis), **DM** candidates, ...

Many well motivated possibilities, featuring distinct **NP states** (singlets, triplets)

Realised at **very different scales** $\Lambda_{EW} \rightsquigarrow \Lambda_{GUT}$

$\Rightarrow$ Expect *very* different **phenomenological impact**

See also talk by Julian Heeck tomorrow

Compare "vanilla" **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")

$\Rightarrow$ **low-scale seesaws** (and variants): **non-decoupled states, modified lepton currents!**

$\Rightarrow$ rich phenomenology at **colliders, high intensities** and **low energies**

testability!!

(Also expect tight constraints)

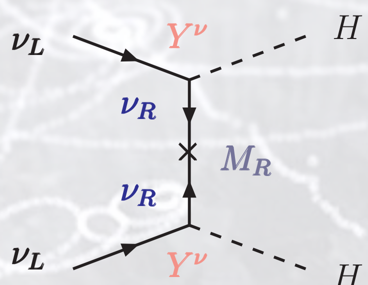
Disentangle seesaw mass models — more correlations

- **Models of m_ν** (and leptonic LFV) predict/accommodate **extensive ranges for cLFV...**

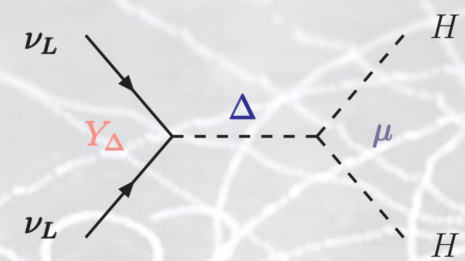
  In the absence of direct NP discovery - **correlations** might allow to disentangle models and provide important **complementary information** to direct searches!

- **Seesaw realisations:** distinctive signatures for numerous **cLFV observables**

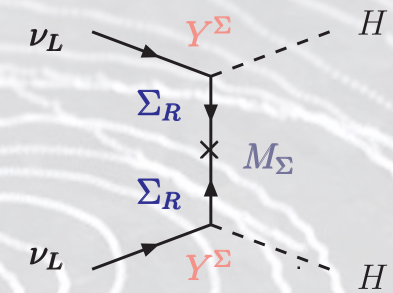
  ratios of observables to **identify seesaw mediators** & constrain their **masses!**



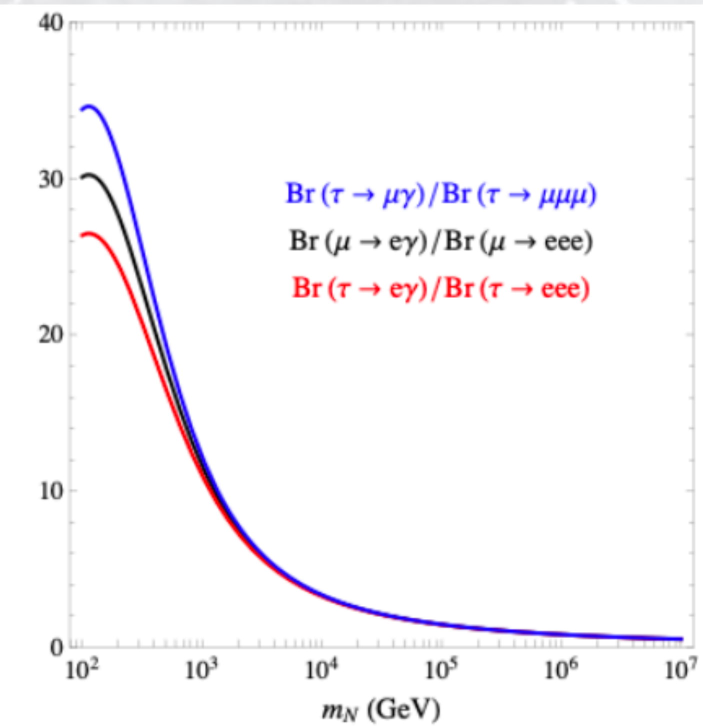
Type I (fermion singlet)



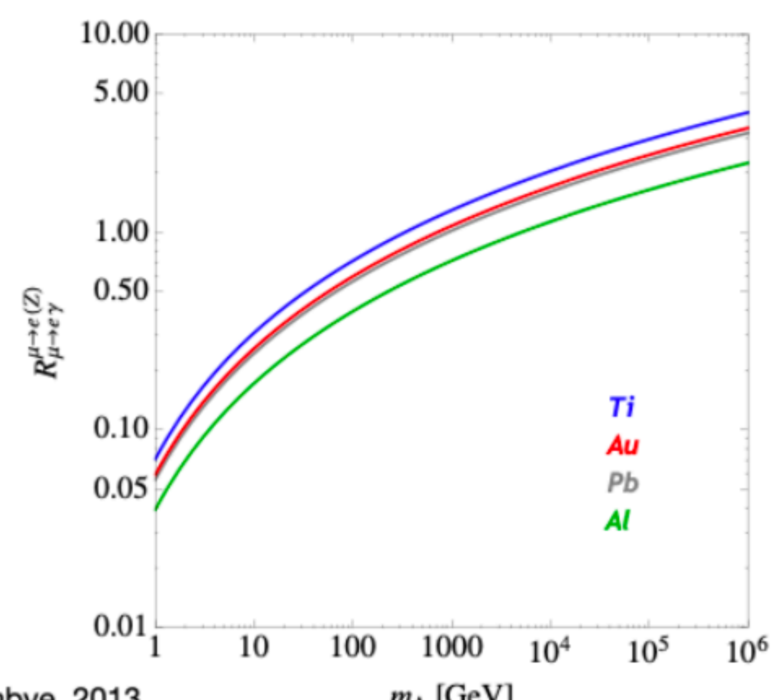
Type II (scalar triplet)



Type III (fermion triplet)



Hambye, 2013



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

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

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

A "3+2" neutrino toy model

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

- **Ad-hoc** (low-energy) **constructions: SM** extended via n_S **Majorana massive** states

No assumption on **mechanism of mass generation**

Well-defined interactions in physical basis

Phenomenological low-energy limit of complete constructions (type I seesaw, ISS, ...)

Hypotheses: 3 active neutrinos + 2 sterile states $n_L = (\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_s^c, \nu_{s'}^c)^T$

interaction basis ⇝ **physical** basis $|n_L\rangle = \mathcal{U}_{5\times5} |\nu_i\rangle$

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

3 × 3 sub-block, **non-unitary!**

Active-sterile mixing $\mathrm{U}_{\alpha i}$

3 × 5 rectangular matrix

$$\mathcal{U}_{5\times5} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & U_{\mu5} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & U_{\tau5} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} \end{pmatrix}$$

$$\mathcal{U} = R_{45} R_{35} R_{25} R_{15} R_{34} R_{24} R_{14} R_{23} R_{13} R_{12} \times \mathrm{diag}(1, e^{i\varphi_2}, e^{i\varphi_3}, e^{i\varphi_4}, e^{i\varphi_5})$$

Would-be **PMNS** no longer unitary, leptonic W and Z vertices modified

- **Physical parameters: 5** masses [3 light (mostly active) & **2 heavier (mostly sterile) states**]

10 mixing angles, **10 CPV phases** (6 **Dirac** δ_{ij}, 4 **Majorana** φ_i)

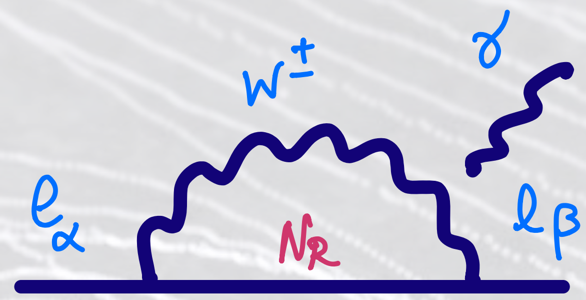
The impact of CP violating phases

cLFV processes mediated by HNL at loop-level

Consider "3+2" toy model (addition of 2 heavy sterile states; leptonic mixing $\mathcal{U}_{5\times5}$, CPV phases)

- **Radiative decays:** $\mathrm{BR}(\mu \to e\gamma) \propto |G_\gamma^{\mu e}|^2$

$$G_\gamma^{\mu e} = \sum_{i=4,5} \mathcal{U}_{ei}\mathcal{U}^*_{\mu i} G_\gamma\left(\frac{m_{N_i}^2}{m_W^2}\right)$$



Assume (for *simplicity & illustrative purposes*): $m_4 \approx m_5$ and $\sin\theta_{\alpha 4} \approx \sin\theta_{\alpha 5} \ll 1$

$$|G_\gamma^{\mu e}|^2 \approx 4\,\sin^2\theta_{e4}\,\sin^2\theta_{\mu 4}\,\cos^2\left(\frac{\delta_{14}+\delta_{25}-\delta_{15}-\delta_{24}}{2}\right) G_\gamma\left(\frac{m_{N_i}^2}{m_W^2}\right)$$

$\Rightarrow$ **Radiative decays: rate** depends **only on Dirac phases**; full cancellation for $\Sigma\delta = \pi$

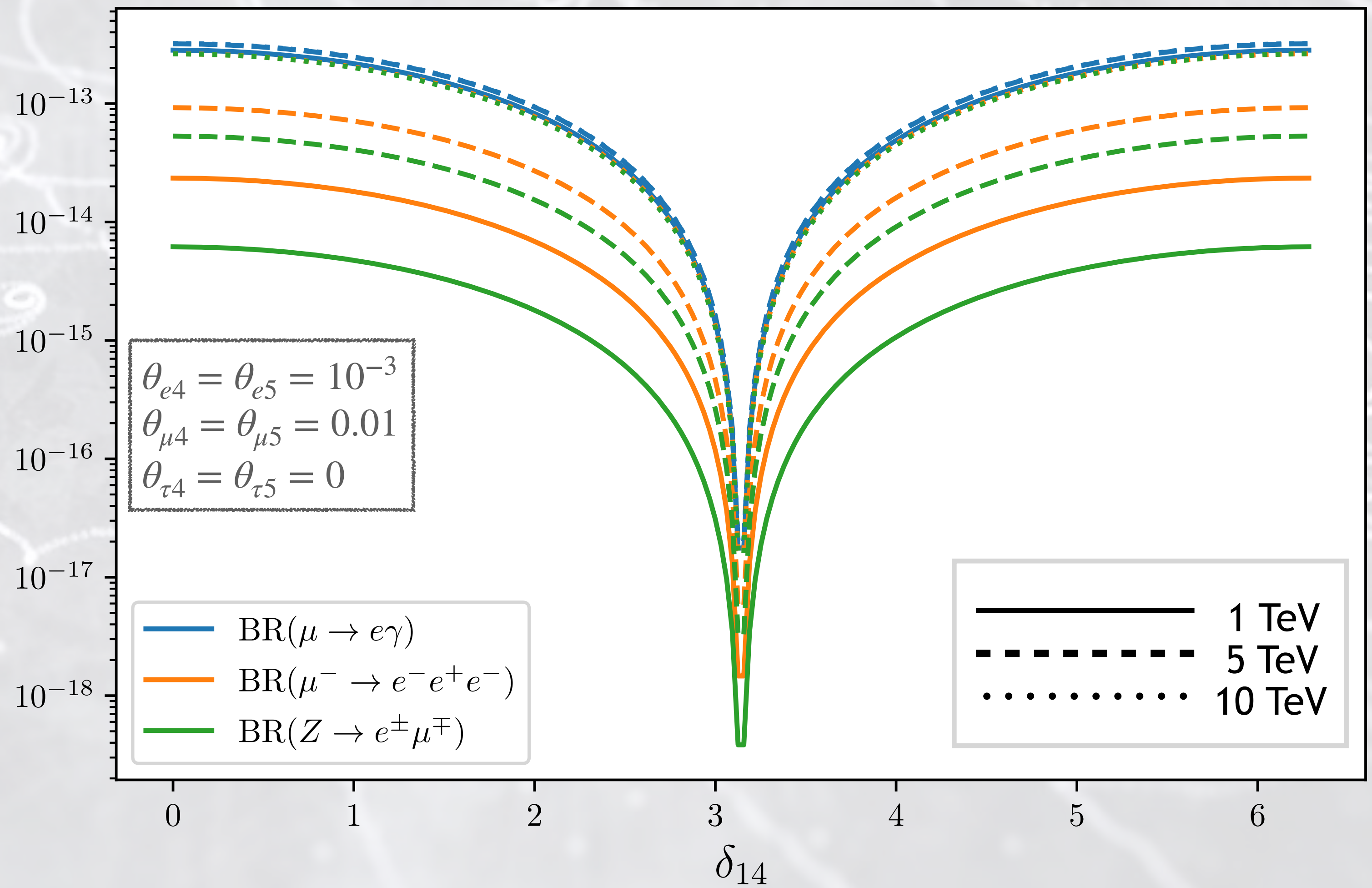
(Other form factors - more involved expressions, depend also on Majorana phases $\varphi_{4,5}$)

The impact of CP violating phases: Dirac

cLFV processes mediated by HNL at loop-level

Consider **"3+2" toy model** (addition of **2 heavy sterile** states; leptonic mixing $\mathscr{U}_{5\times5}$, **CPV** phases)

Abada, **JK,** Teixeira [2107.06313]



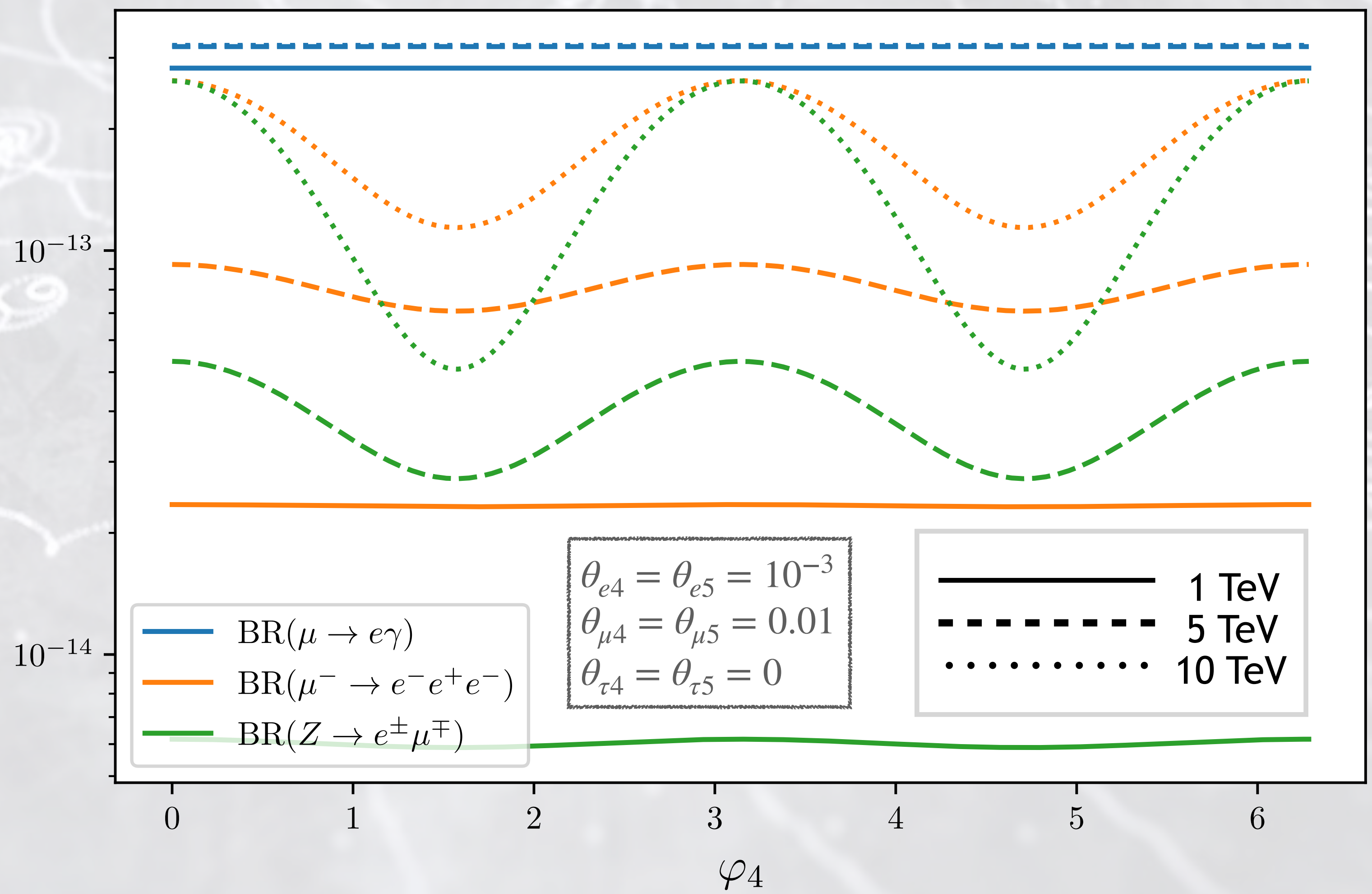
⇒ Full cancellation of the rates for $\delta_{14} = \pi$, similar results for other (Dirac) phases

The impact of CP violating phases: Majorana

cLFV processes mediated by HNL at loop-level

Consider "3+2" toy model (addition of 2 heavy sterile states; leptonic mixing $\mathcal{U}_{5\times5}$, CPV phases)

Abada, **JK,** Teixeira [2107.06313]



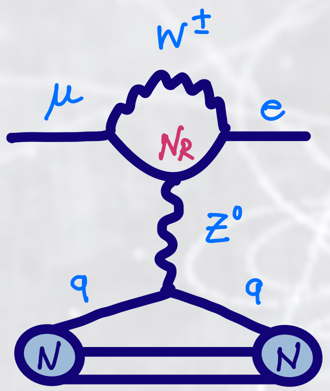
⇒Milder dependence, γ-penguin independent of Majorana phases

The impact of CP violating phases — no more correlations

cLFV signatures: ratios of **observables** to **identify mediators** & constrain their **masses!**

But - CP violating phases do matter! *And impact naïve expectations…*

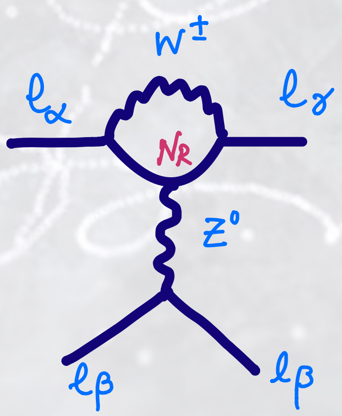
Consider "3+2" toy model (addition of **2 heavy sterile** states; leptonic mixing $\mathcal{U}_{5\times5}$, **CPV** phases)



Observables dominated by **common topology: Z-penguins**

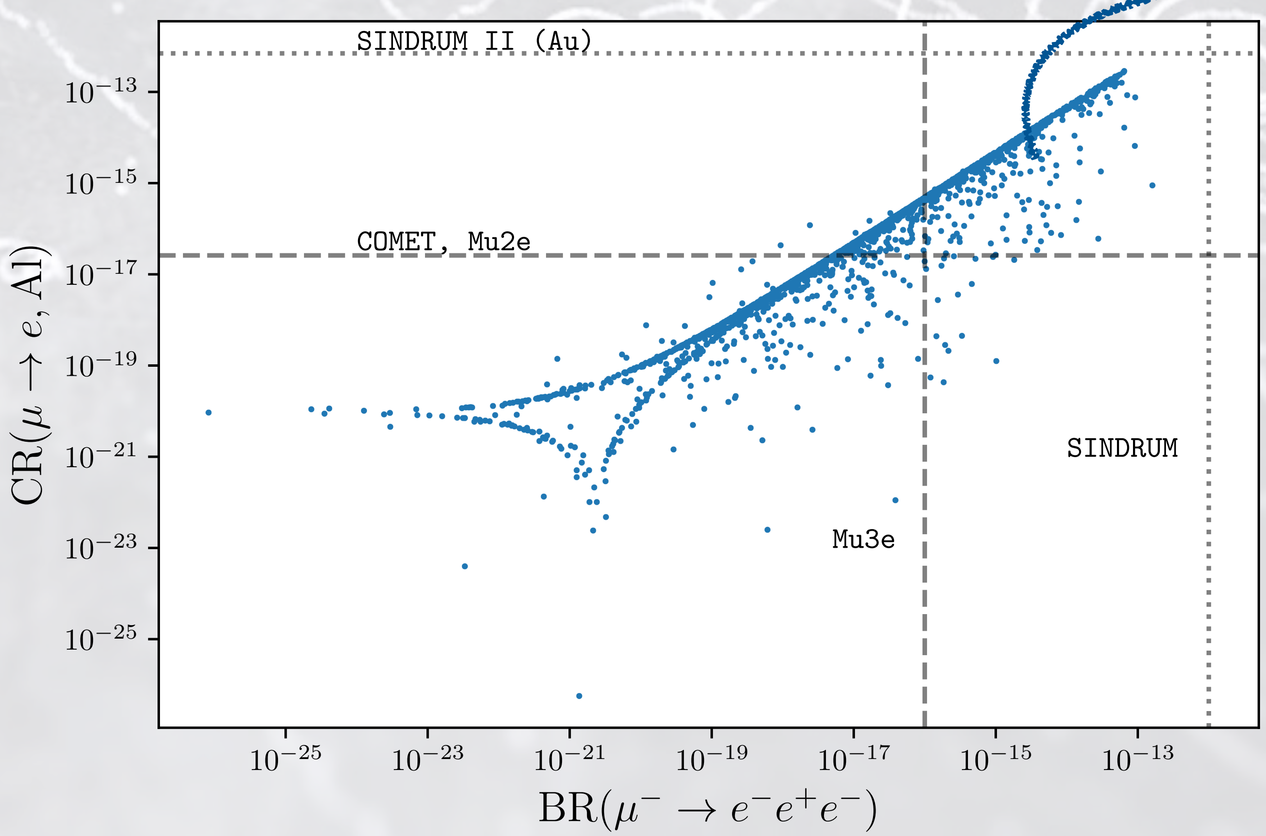
$\mu - e$ **conversion in nuclei**

3-body muon decays ($\mu \to 3e$)



$m_4 = m_5 = 1$ TeV

- CP conserving



Abada, **JK**, Teixeira [2107.06313]

Strong correlation
(CP conserving)

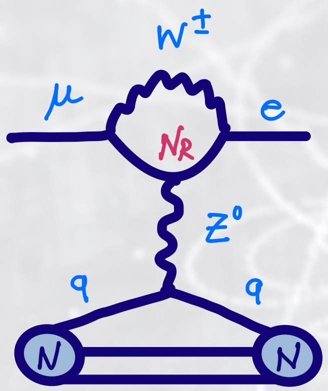
Observation *of* $\mu \to 3e$
$\Rightarrow$ *observation of*
$\mu - e$ **conversion**

The impact of CP violating phases — no more correlations

cLFV signatures: ratios of observables to **identify mediators** & constrain their **masses!**

But - CP violating phases do matter! *And impact naïve expectations...*

Consider "3+2" toy model (addition of **2 heavy sterile** states; leptonic mixing $\mathcal{U}_{5\times5}$, **CPV** phases)



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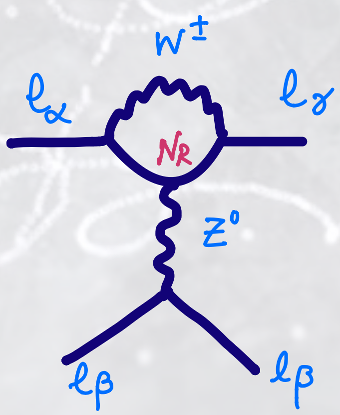
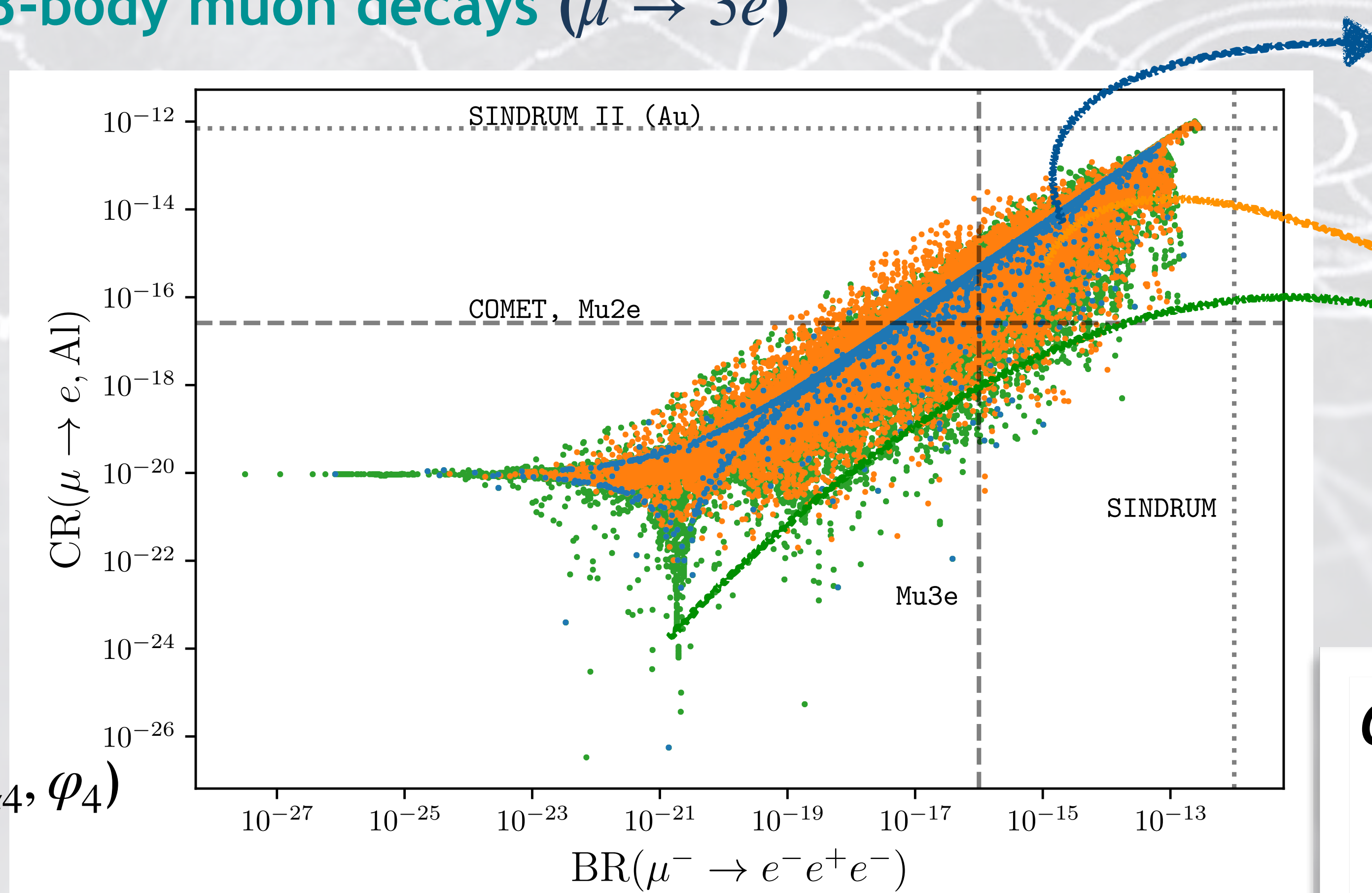


$m_4 = m_5 = 1$ TeV

- CP conserving
- CPV phases (random $\delta_{\alpha 4}, \varphi_4$)
- CPV phases (grid $n\pi/4$)



Abada, **JK**, Teixeira [2107.06313]

Strong correlation (CP conserving)

Loss of correlation! (CP violating)

Observation of $\mu \to 3e$ $\not\Rightarrow$ *observation* of $\mu - e$ **conversion**

The impact of CP violating phases — no more correlations

cLFV signatures: ratios of observables to **identify mediators** & constrain their **masses!**

But - CP violating phases do matter! *And impact naïve expectations...*

Some *illustrative* **benchmark points** - CP conserving (P_i) and CPV variants (P'_i)

	BR($\mu \to e\gamma$)	BR($\mu \to 3e$)	CR($\mu - e$, Al)	BR($\tau \to 3\mu$)	BR($Z \to \mu\tau$)
P_1	3×10^{-16} ∘	1×10^{-15} ✓	9×10^{-15} ✓	2×10^{-13} ∘	3×10^{-12} ∘
P'_1	1×10^{-13} ✓	2×10^{-14} ✓	1×10^{-16} ✓	1×10^{-10} ✓	2×10^{-9} ✓
P_2	2×10^{-23} ∘	2×10^{-20} ∘	2×10^{-19} ∘	1×10^{-10} ✓	3×10^{-9} ✓
P'_2	6×10^{-14} ✓	4×10^{-14} ✓	9×10^{-14} ✓	8×10^{-11} ✓	1×10^{-9} ✓
P_3	2×10^{-11} ✗	3×10^{-10} ✗	3×10^{-9} ✗	2×10^{-8} ✓	8×10^{-7} ✓
P'_3	8×10^{-15} ∘	1×10^{-14} ✓	6×10^{-14} ✓	2×10^{-9} ✓	1×10^{-8} ✓

Abada, **JK**, Teixeira [2107.06313]

P_3: only cLFV τ decays **in allowed region;** cLFV μ transitions already experimentally disfavoured

Regime of large mixing angles excluded?

P'_3: ***all*** considered **cLFV transitions currently allowed,** $\mu \to e\gamma$ **beyond sensitivity!**

(Non)-observation of cLFV observable(s) $\Rightarrow$ *not* necessarily ***disfavour*** **HNL extension!**

CP-asymmetries

Correlations **broken**, large mixing angles still possible, how do we "tag" the presence of **CPV**?

Benchmark points (with different mixing)
P_1 (CP-conserving), P_2 (CP-violating)
lead to identical **cLFV predictions!**

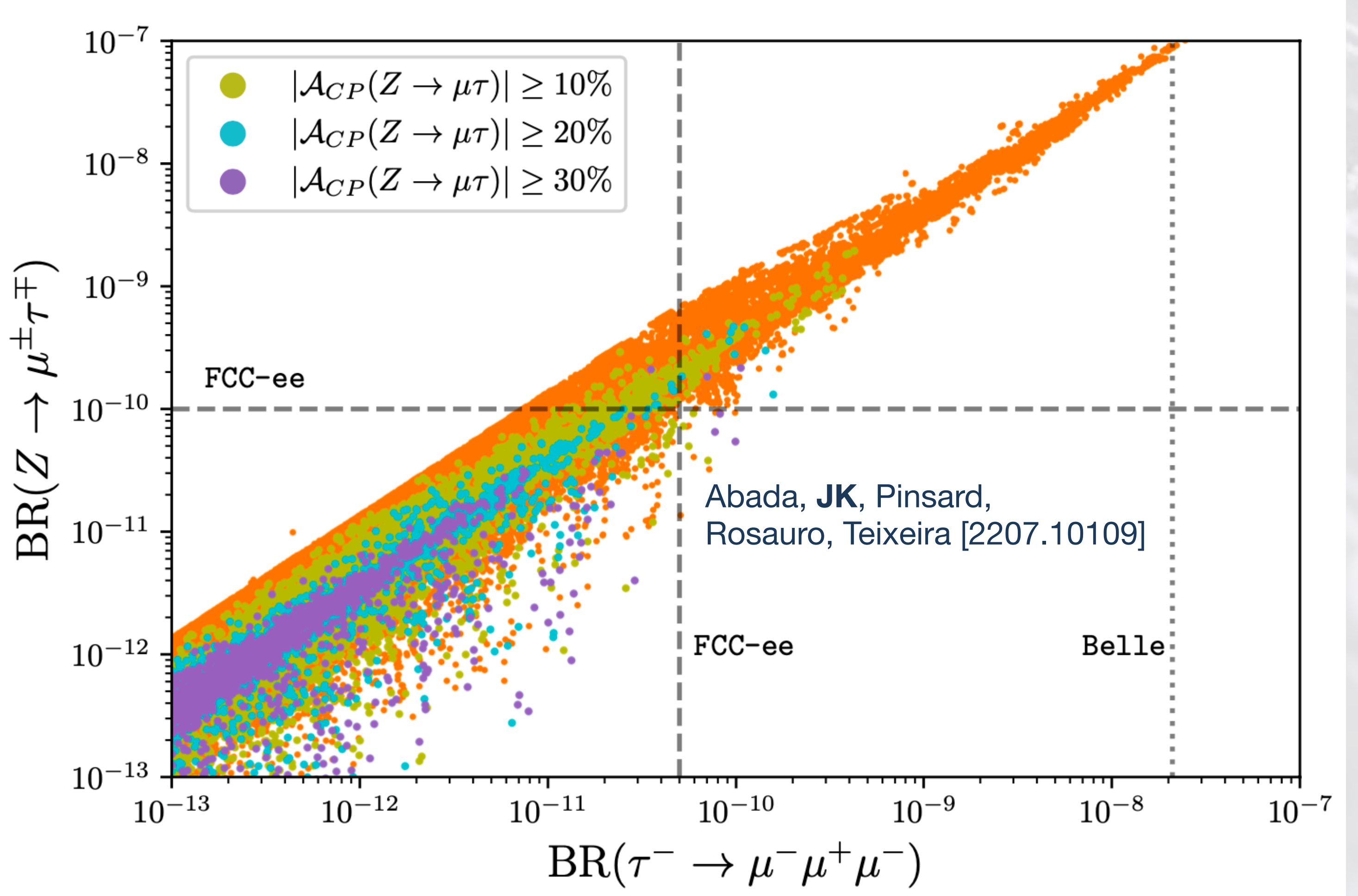
Observable	$\mu \to eee$	$\mu - e$ (Al)	$\tau \to \mu\mu\mu$	$Z \to \mu\tau$
$P_{1,2}$ prediction	2×10^{-15}	5×10^{-14}	1×10^{-10}	2×10^{-10}

Abada, **JK**, Pinsard, Rosauro, Teixeira [2207.10109]

Consider **CP-asymmetries:** $\mathscr{A}_{CP}(Z \to \ell_\alpha \ell_\beta) = \dfrac{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) - \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) + \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}$

$\Rightarrow P_2$: $\mathscr{A}_{CP}(Z \to \mu\tau) \simeq 30\,\%$!

Measuring **CP-asymmetries, i.e.** searching
for $Z \to \ell_\alpha^+ \ell_\beta^-$ and $Z \to \ell_\alpha^- \ell_\beta^+$ independently
might allow to constrain **CPV phases**
and can help to identify the **source of cLFV!**



CP (T)-asymmetries have also been considered in **angular distributions** of $\mu \to eee$ (see Bolton & Petcov [2204.03468])

CP-asymmetries

Correlations **broken**, large mixing angles still possible, how do we "tag" the presence of CPV?

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lead to identical cLFV predictions!

Observable	$\mu \to eee$	$\mu - e$ (Al)	$\tau \to \mu\mu\mu$	$Z \to \mu\tau$
$P_{1,2}$ prediction	2×10^{-15}	5×10^{-14}	1×10^{-10}	2×10^{-10}

...bada, **JK**, Pinsard, ...osauro, Teixeira [2207.10109]

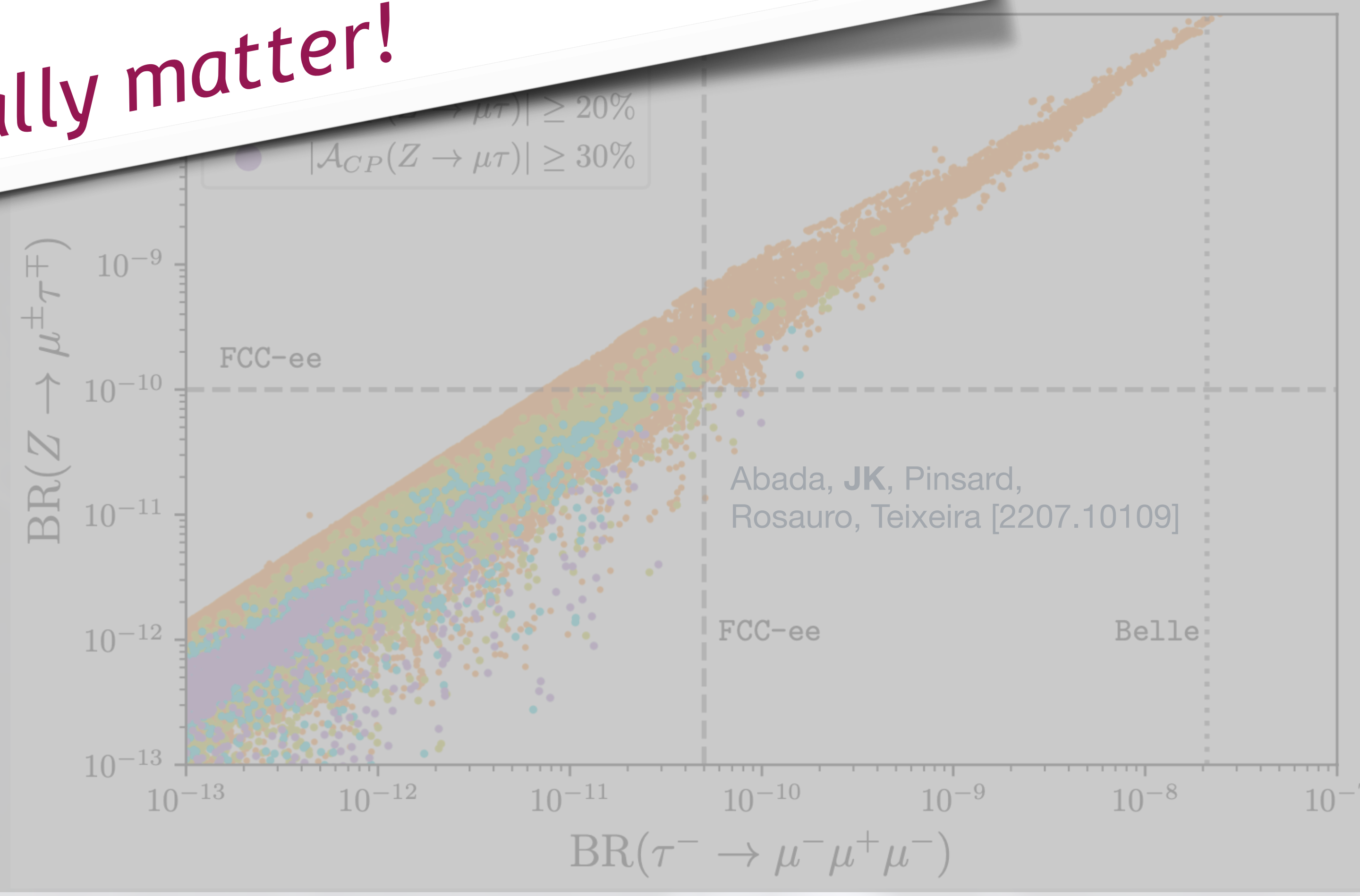
Consider CP-asymmetries: $\mathcal{A}_{CP}(Z \to \ell \ell)$ ... $\Gamma(Z \to \ell$ ...

$\Rightarrow P_2$: $\mathcal{A}$ ...

"You cannot spell flaVour without CP Violation"

Phases do really matter!

Measuring CP-... ...ing
for $Z \to \ell_\alpha^+ \ell_\beta^-$ ... $Z \to \ell_\alpha^- \ell_\beta^+$ independently
might allow to constrain CPV phases
and can help to identify the source of cLFV!



CP (T)-asymmetries also been considered in angular distribution of $\mu \to eee$
(see Bolton & Petcov [2204.03468])

The probing power of muons

The probing power of flavour violation

Paving the way to the **SM:** from prediction of charm to the existence of **3 families!**

$\Rightarrow$ **Indirect probes** of much higher scales: e.g. **top mass** in $K^0 - \bar{K}^0$ oscillations

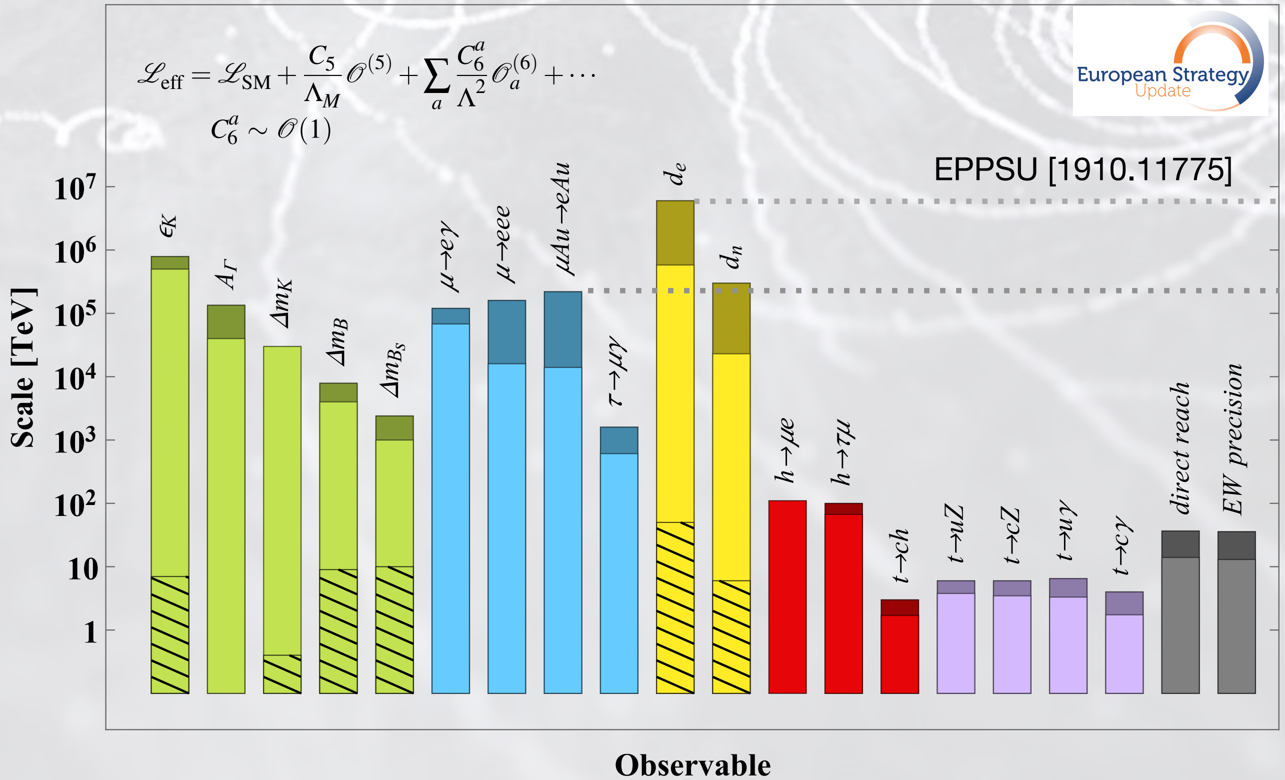
SM interpreted as a **low-energy limit** of a (complete, yet unknown) **NP model**

$\Rightarrow$ Study **various classes** of well-motivated **models**

$\Rightarrow$ **Model-independent**, **effective approach (EFT)**

$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} \mathscr{C}^n(g, Y, \ldots)\, \mathscr{O}^n(\ell, q, H, \gamma, \ldots)$$

Cast **current data** in terms of $\mathscr{C}^6_{ij}$ and Λ_{NP} : $\mathscr{C}^6_{ij} \approx 1 \Rightarrow$ **bounds on** Λ_{NP}

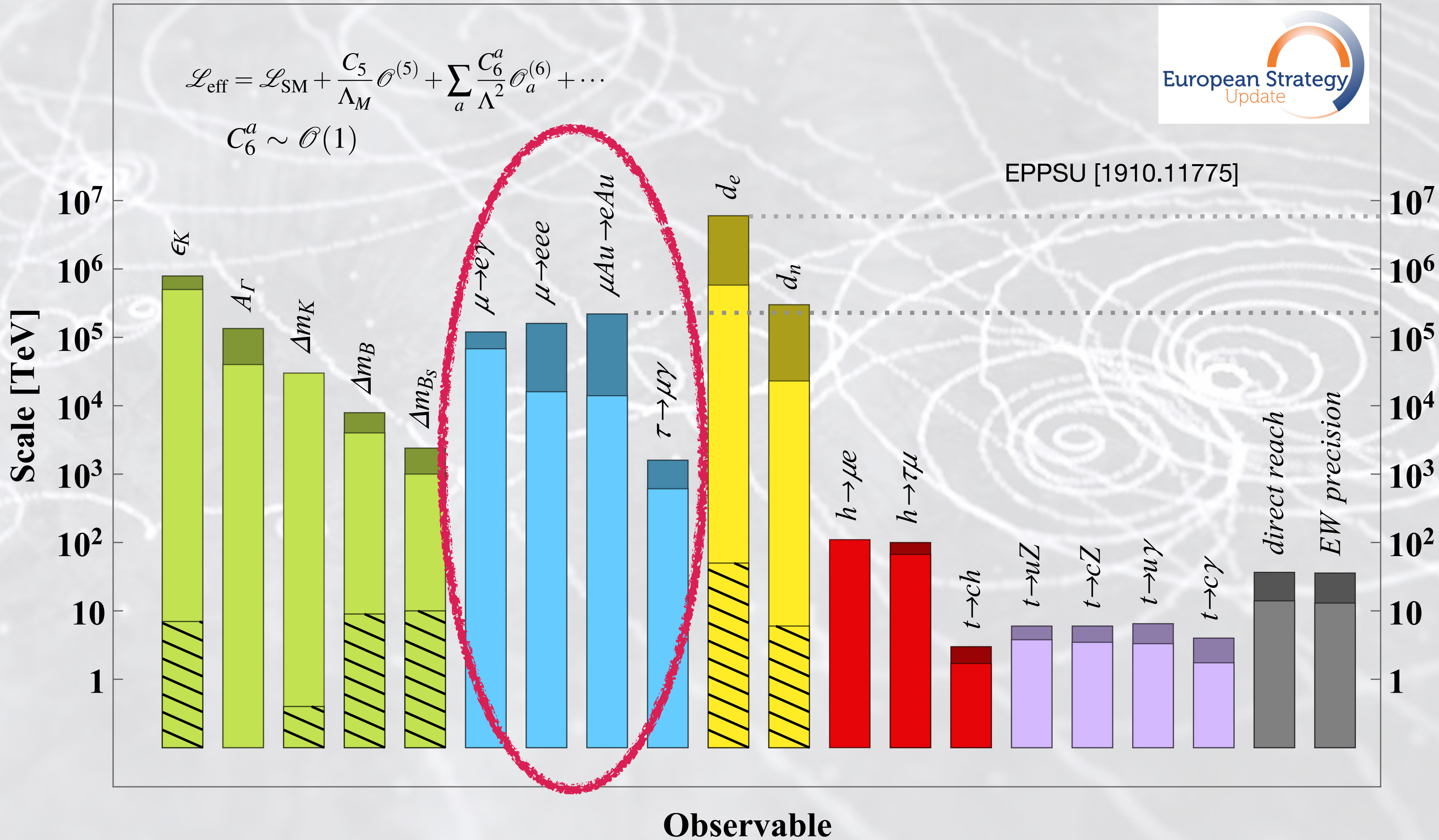


The probing power of flavour violation

SM interpreted as a low-energy limit of a (complete, yet unknown) NP model

⇒ Study **various classes** of well-motivated **models**

⇒ **Model-independent, effective approach (EFT)**



Probe scales **much higher** than direct collider reach!

⇒possibly **indirect NP signals** long before (direct) discovery LHC...

Low-scale type I seesaw

Extend **SM** with 3 "heavy" **RH** **Majorana neutrinos:** $\mathrm{MeV} \lesssim m_{N_i} \lesssim 1 - 100\ \mathrm{TeV}$

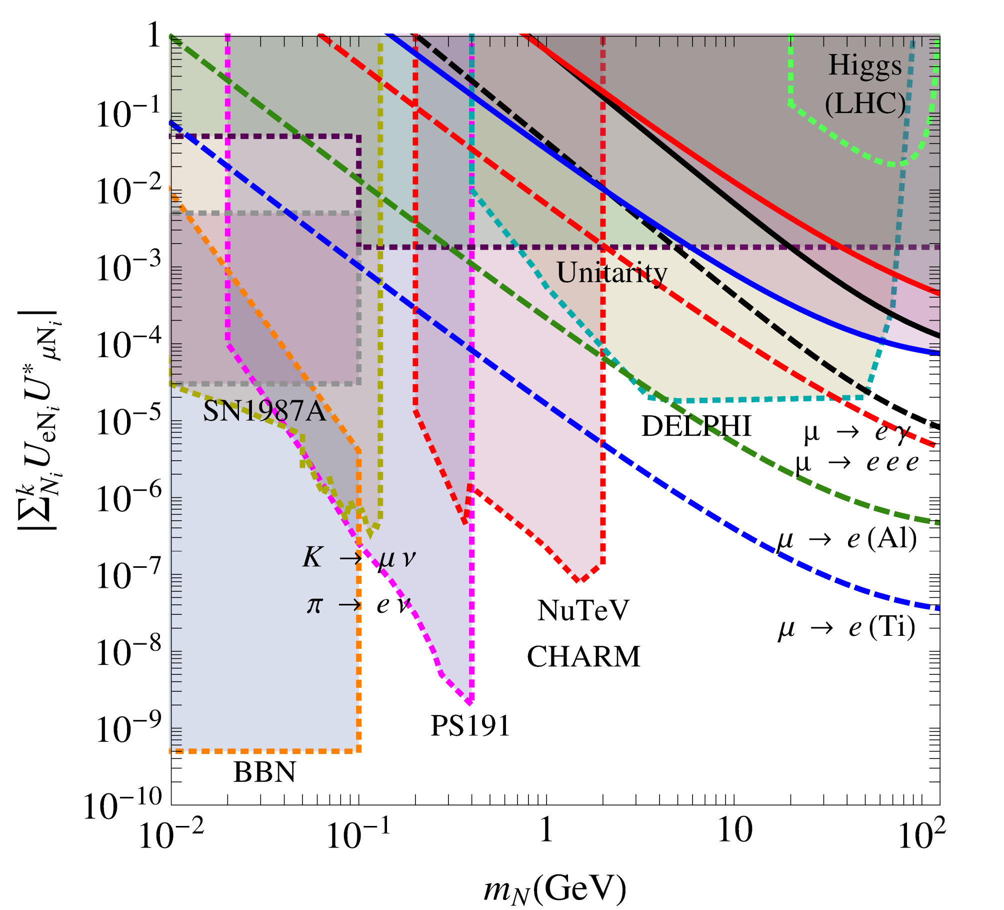
Spectrum & mixings:

$$m_\nu \simeq -v^2 Y_\nu^T M_N^{-1} Y_\nu \ , \quad \mathcal{U}^T \mathcal{M}_\nu^{6\times 6} \mathcal{U} = \mathrm{diag}(m_i)$$

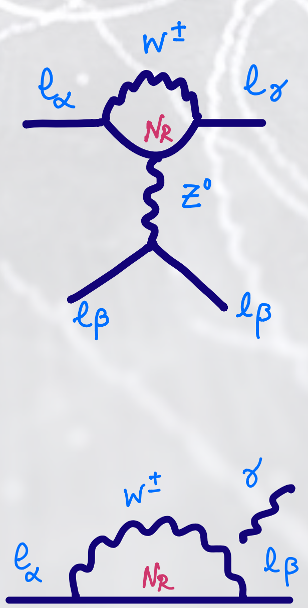
$$\mathcal{U} = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \ , \quad U_{\nu\nu} \simeq (1-\eta)\, U_{\mathrm{PMNS}}$$

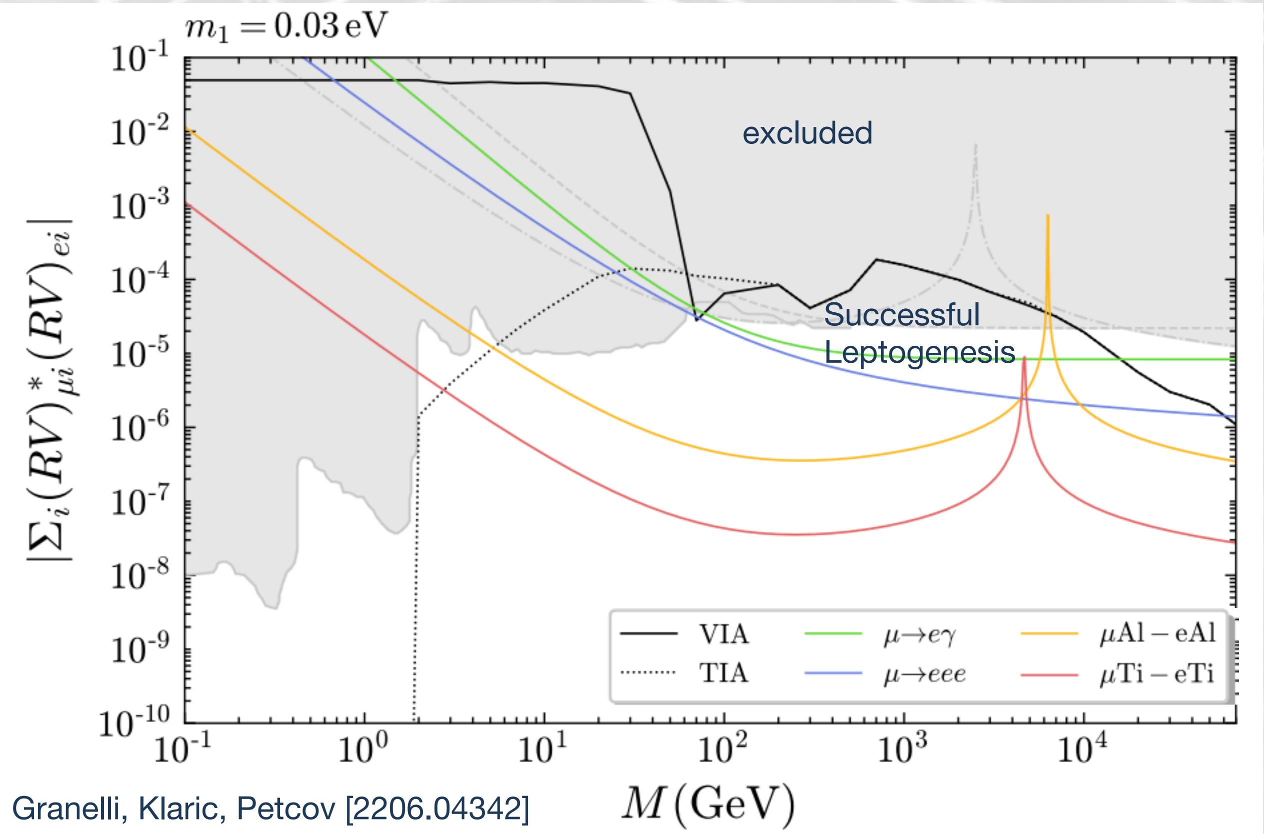
Heavy states do not decouple ⇒ neutral and charged leptonic currents **modified**

Rich phenomenology at **high intensities and at colliders**



Alonso, Dehn, Gavela, Hambye [1209.2679]





Granelli, Klaric, Petcov [2206.04342]

Scotogenic models — connection to dark matter

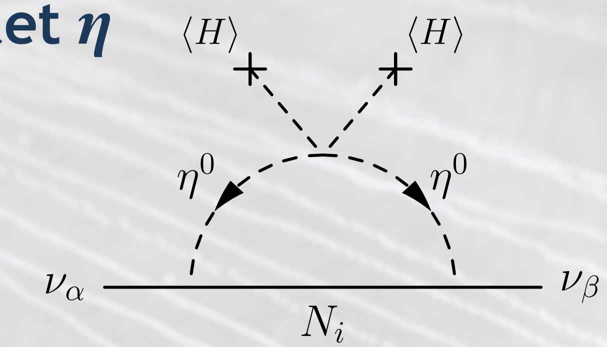
- **Scotogenic models:** a link between **neutrino mass** generation and **dark matter!**

  minimal realisations: extend SM by **(inert) scalar doublet η**

  and **RH neutrinos N_R**

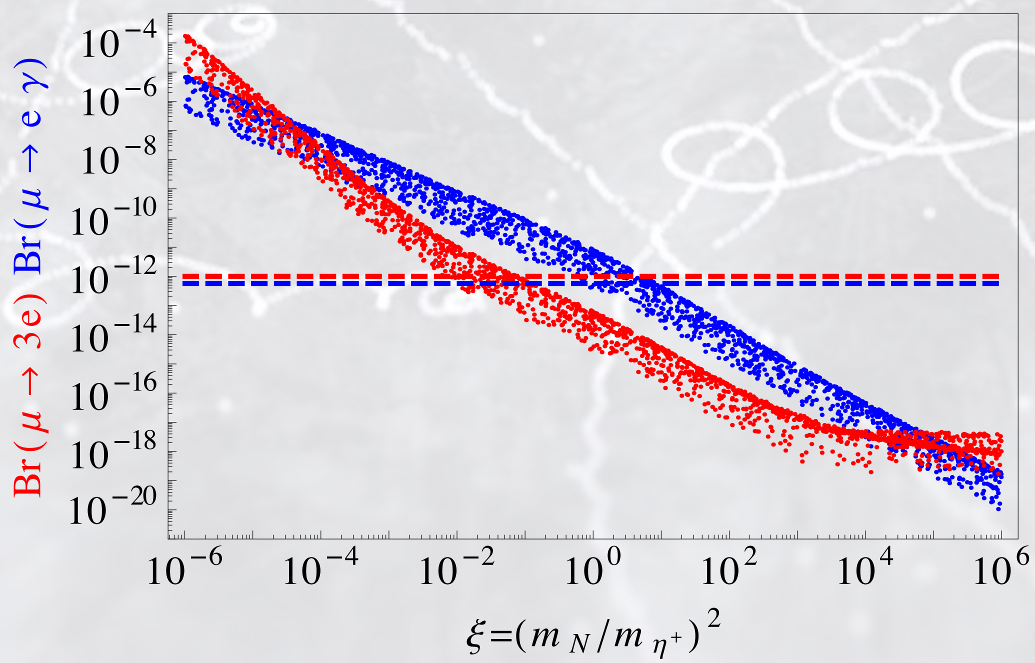
  Additional Z_2 symmetry: **neutrino masses** @ 1-loop

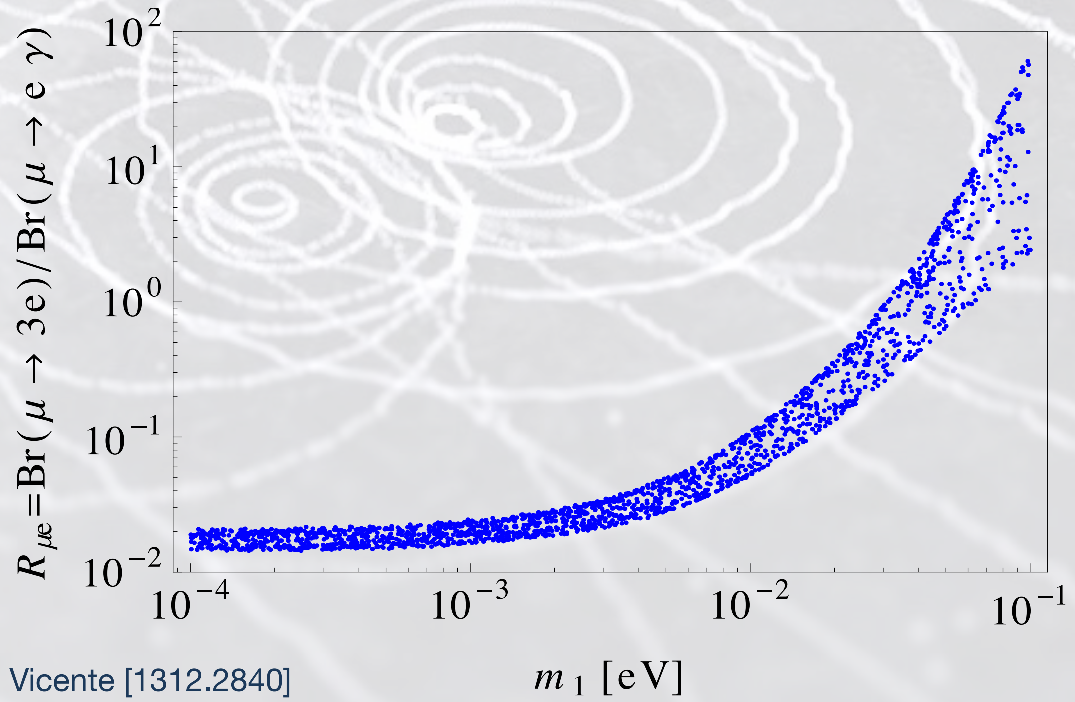
  dark matter candidate (**η** or **N_R**)



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

- **cLFV observables:** hints on the **nature of the DM candidate** and absolute ν **mass scale**





Toma and Vicente [1312.2840]

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

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

Leptoquarks — flavour anomalies and muon cLFV

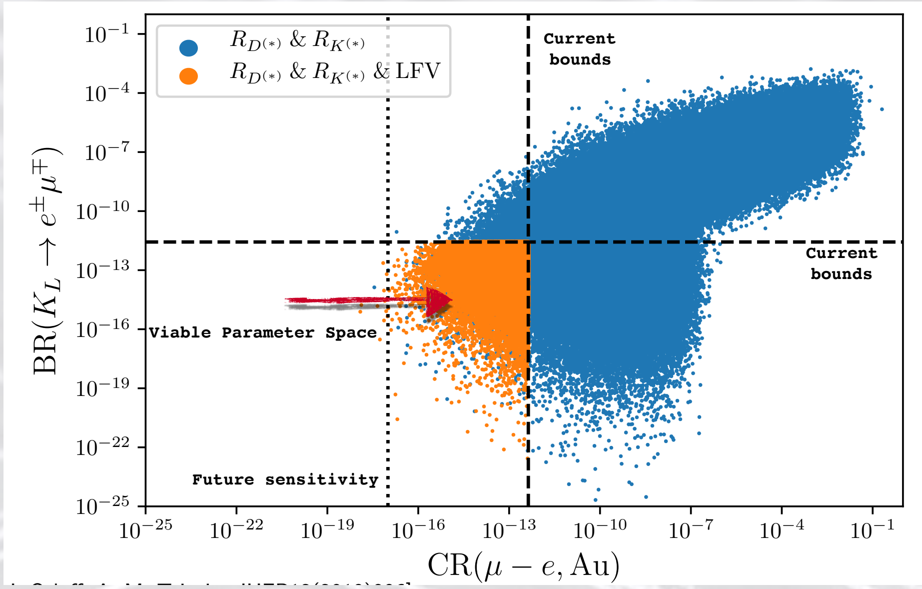
- **Minimal SM extension** via **single vector LQ (V_1^μ)** explain both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ at tree-level

  Strongly constraining observables:

  $K_L \to e\mu$ and $\mu - e$ conversion in nuclei

  $\Rightarrow$ viable regimes within **sensitivity** of **Mu2e** and **COMET**

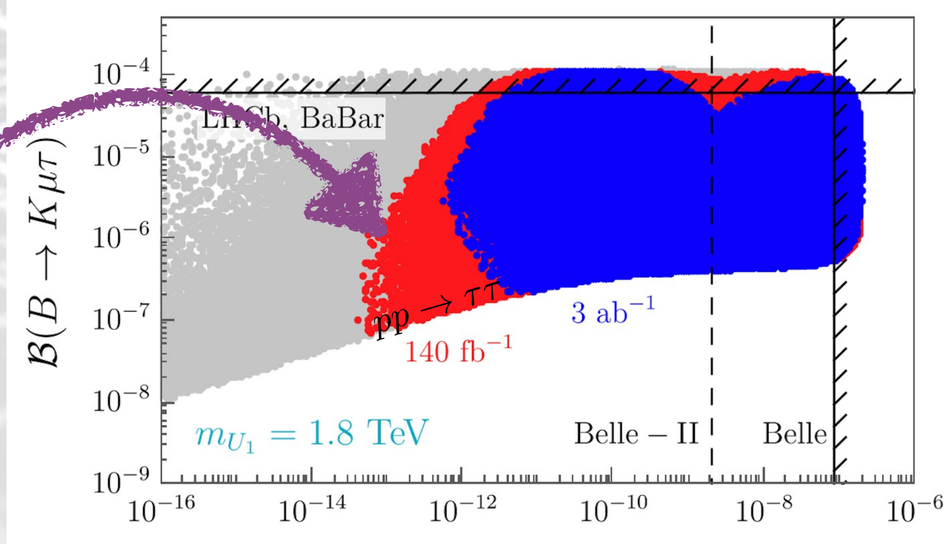
  ("Natural" Pati-Salam scales pushed to $\gtrsim 100$ TeV)



Hati, **JK,** Orloff, Teixeira [1907.05511]

- **Flavour** + high$_{p_T}$ **di-lepton tails:**

  predict lower bounds on $B \to K\mu\tau$ & $\tau \to \phi\mu$ (close to current limit)



Angelescu et al [2103.12504]

- **Minimal SM extensions via 1 or 2 scalar LQs:** explain both Δa_μ & Δa_e , $\mu \to e\gamma$ **crucial** to identify viable scenarios!!!

  Doršner et al. [2006.11624]

Muon cLFV without cLFV @ muon colliders

Light(ish) Z' with only off-diagonal lepton couplings to accommodate Δa_μ

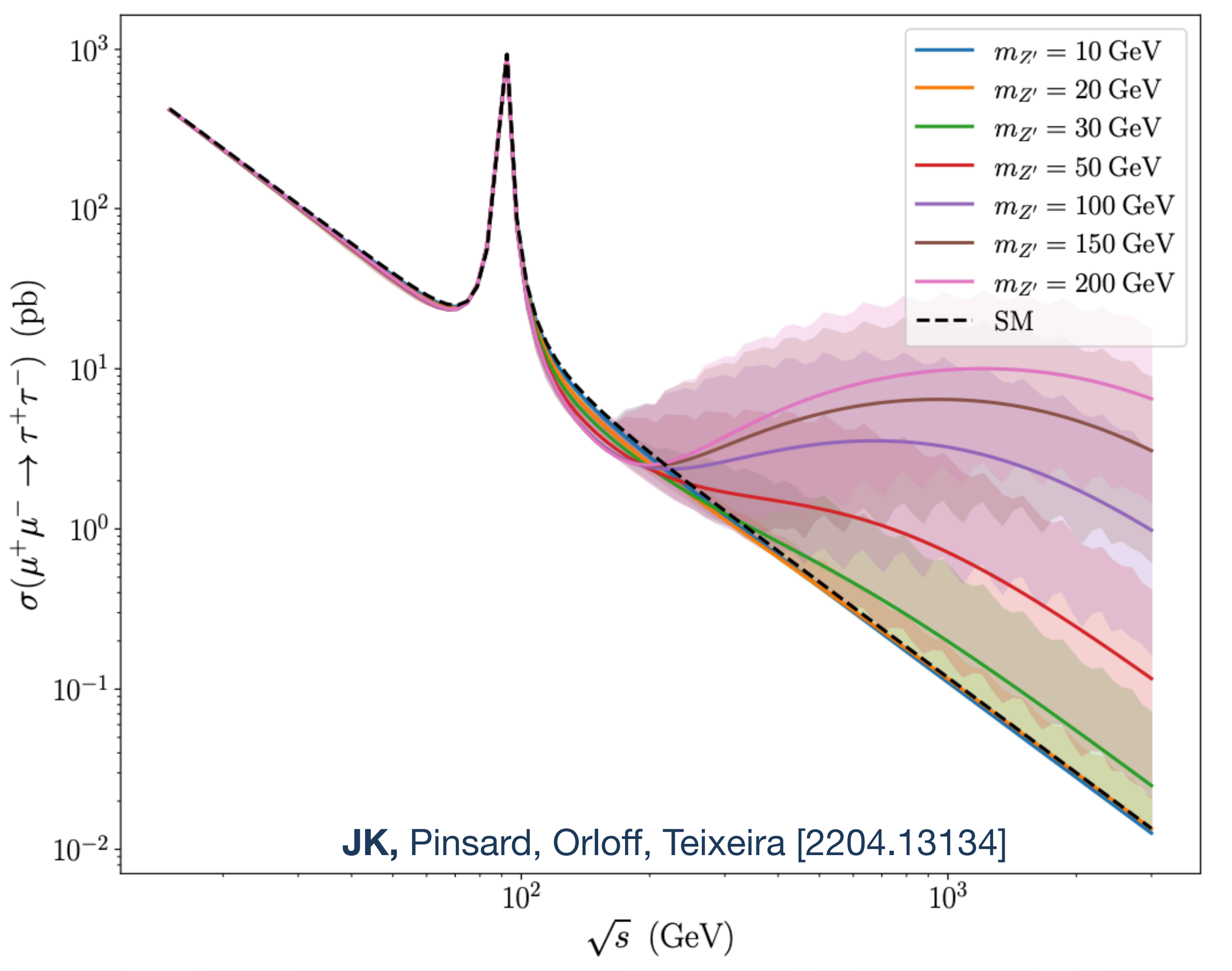
$\mu \to e\gamma$ and $\mathrm{Mu} - \overline{\mathrm{Mu}}$ conversion strongly constrain $e\mu$ & $e\tau$ couplings

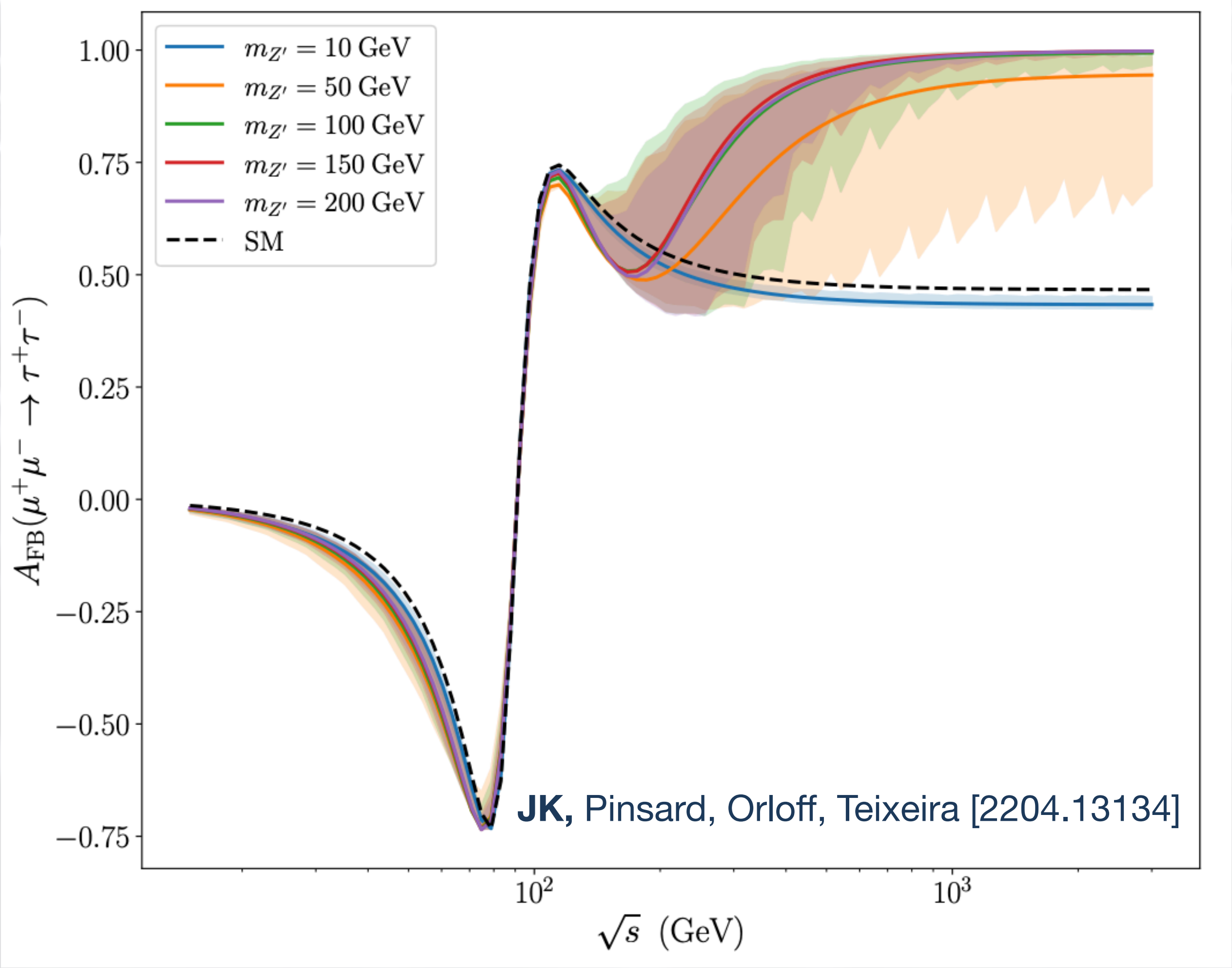
$\mu\tau$ **couplings can be sizeable** $\mathcal{O}(10^{-3} - 10^{-2})$

$\Rightarrow$ new t-channel in $\mu^+\mu^- \to \tau^+\tau^-$ **scattering**

Interference with huge impact on σ and A_{FB}!

"Indirect" muon cLFV





Concluding remarks

Muons rock!

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Currently intriguing hints of New Physics related to muon-flavoured observables

- $(g-2)_\mu$ (and $(g-2)_e$???) puzzles, rapid EXP and TH progress
- B-meson decay anomalies (& $(g-2)_{\mu,e}$) might signify the breakdown of lepton universality!
- LFUV necessarily implies cLFV! $\Rightarrow$ if confirmed, we should expect signals

Concluding remarks

Muons rock!

Currently intriguing hints of New Physics related to muon-flavoured observables

- $(g-2)_\mu$ (and $(g-2)_e$???) puzzles, rapid EXP and TH progress
- B-meson decay anomalies (& $(g-2)_{\mu,e}$) might signify the breakdown of lepton universality!
- LFUV necessarily implies cLFV! $\Rightarrow$ if confirmed, we can be **cautiously** optimistic

Muon (cLFV) observables crucial to probe countless models,

many of them related to mechanisms of m_ν generation...

But: need to consider correlations and effects of CPV

to disentangle sources of cLFV

Very exciting future ahead, leave no flavoured stone unturned :)