Flavour physics and neutrinos

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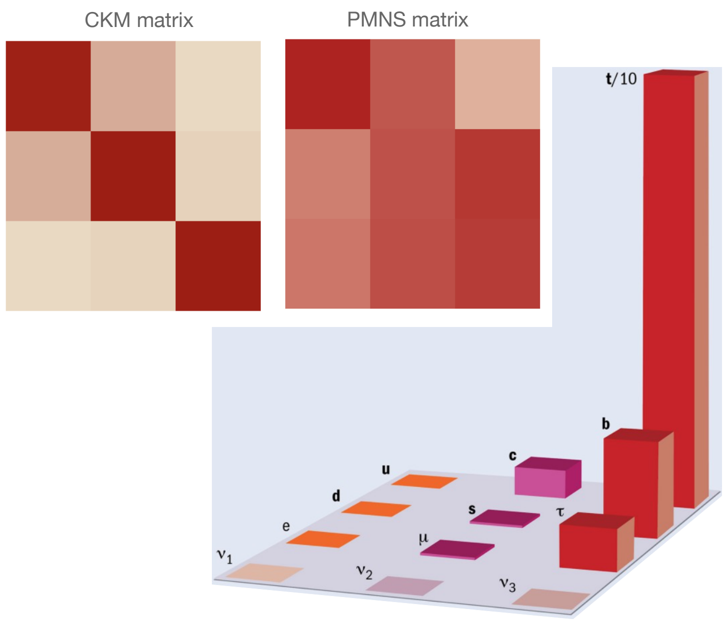
Flavour and CP violation beyond the SM

Strong arguments in favour of New Physics!

A number of theoretical caveats... and observations unaccounted for in the SM:
baryon asymmetry of the Universe, viable dark matter candidate, neutrino oscillations



- **Neutrino oscillations**: 1st laboratory evidence of NP
  - ⇒ massive neutrinos and leptonic mixings $U^{\alpha i}_{\text{PMNS}}$
  - ⇒ New (Majorana) fields? New sources of CP violation?
    $\Delta L \neq 0$ and leptogenesis... (?)

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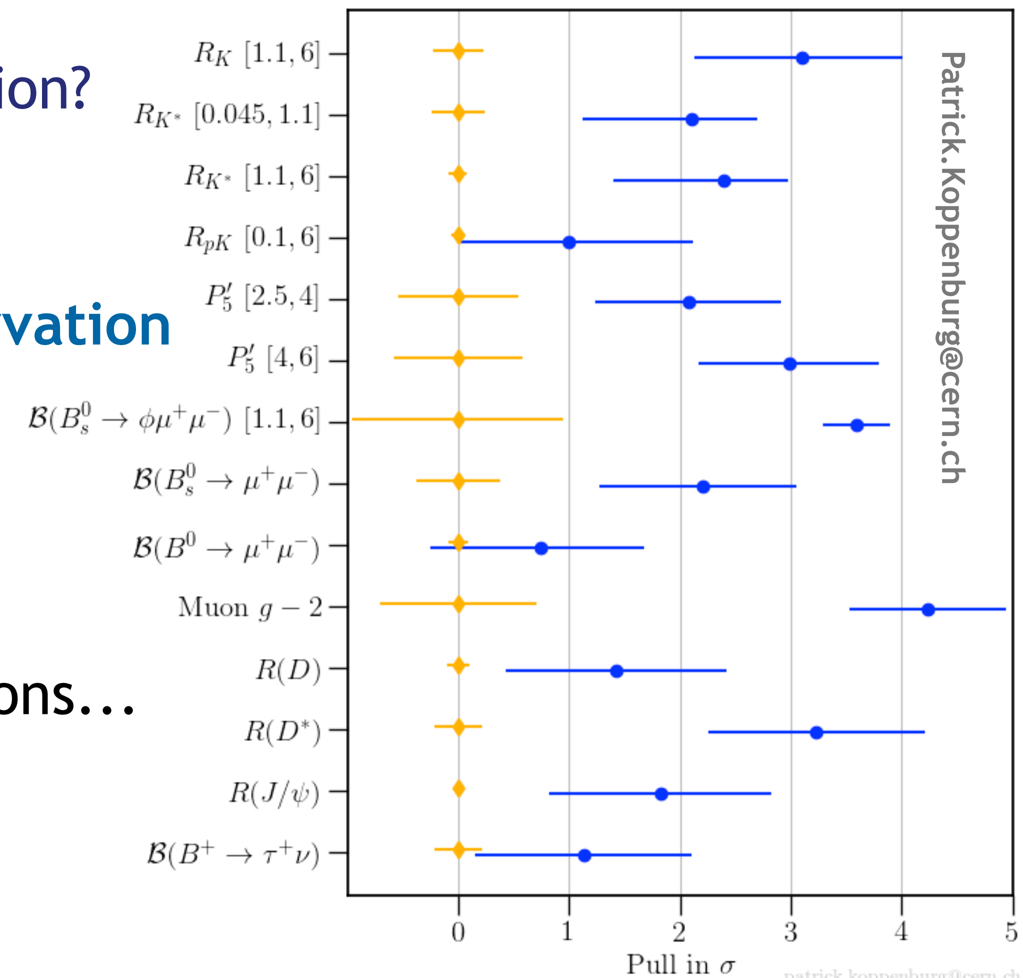
- **Numerous** (significant!) **tensions** between **SM and observation**
  B-meson "anomalies", Cabibbo-angle "anomaly",
  $(g-2)_\ell$, anomalies in atomic decays, ...
  - ⇒ mostly around 2σ (*or above!*)
  - ⇒ and many in close relation with charged leptons...



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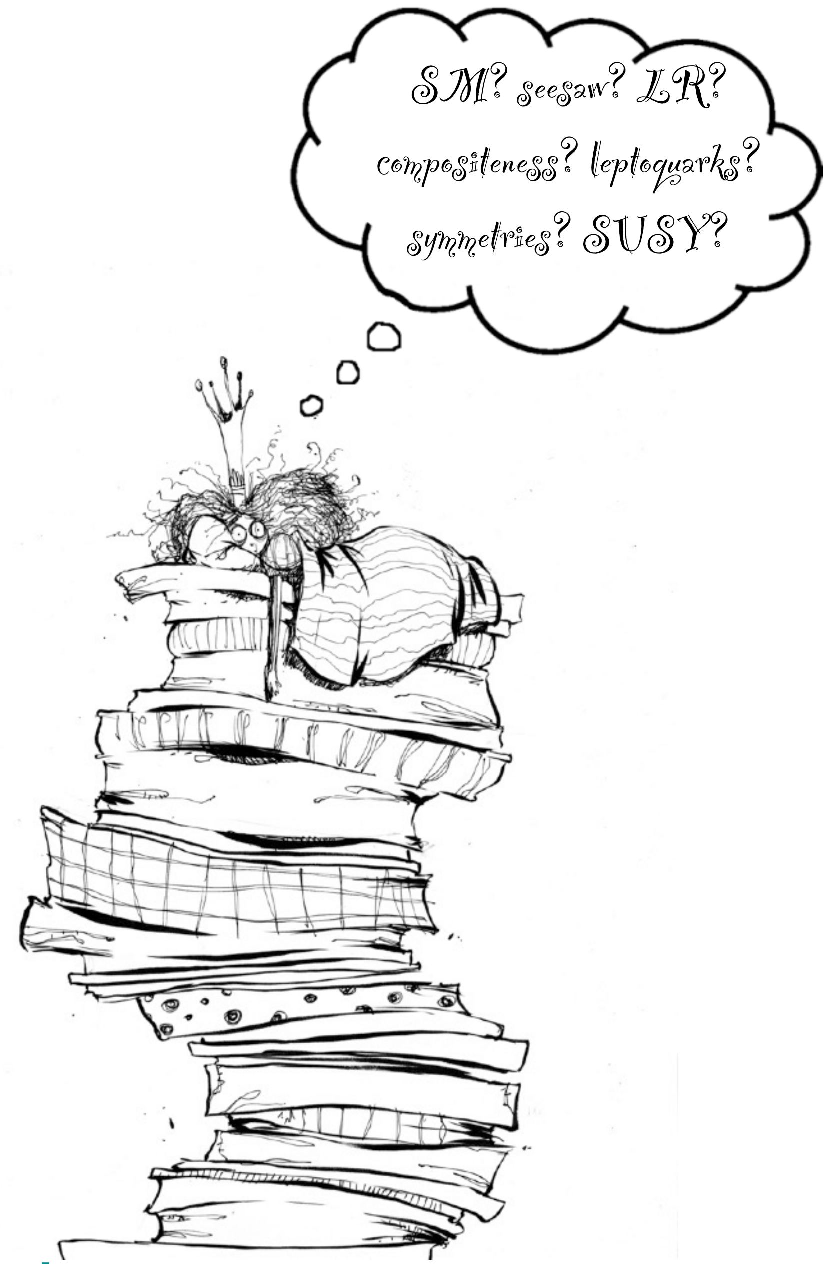

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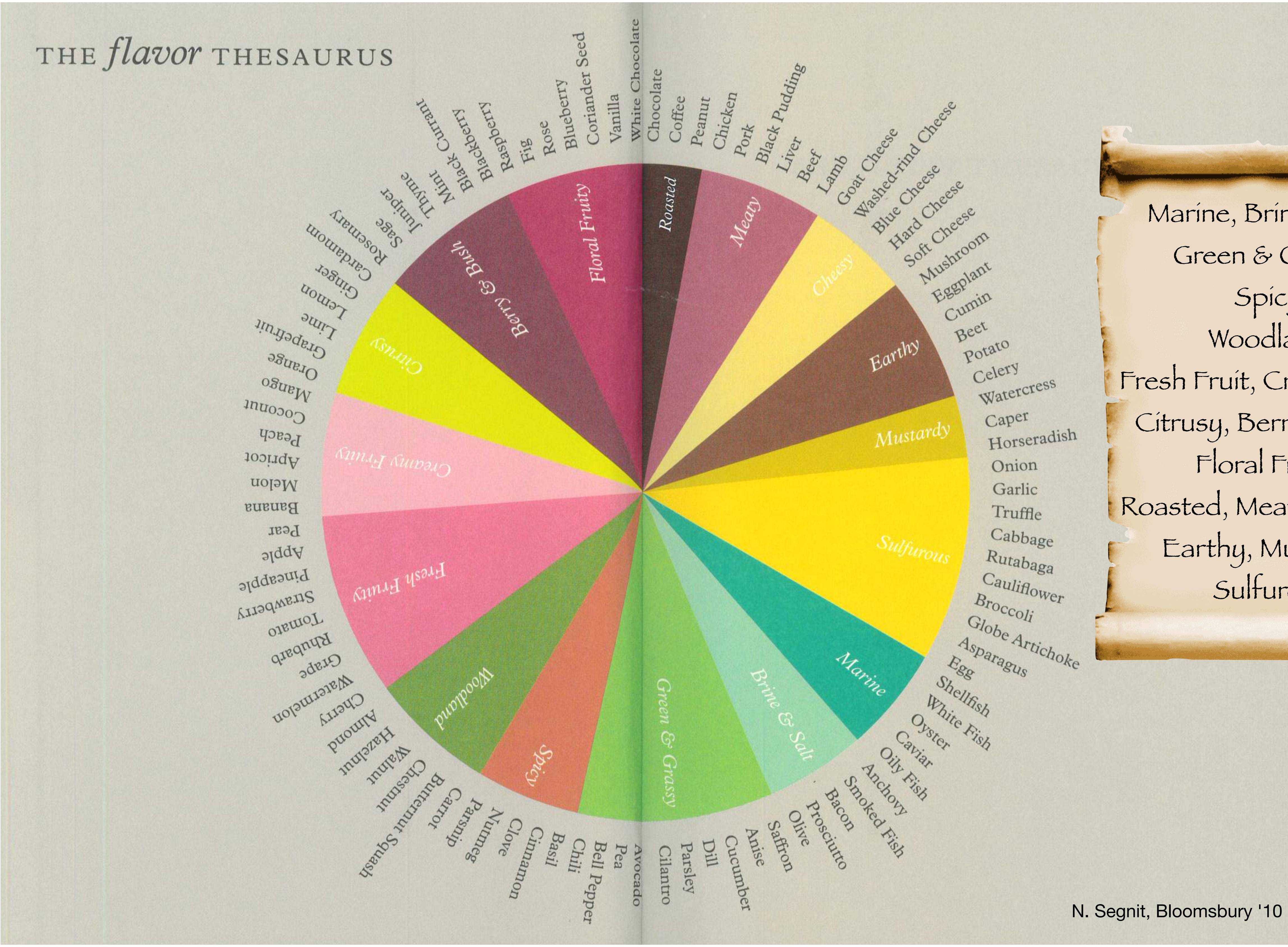
Many **hints** and a clear **necessity** of **New Physics...**
Which NP model? Realised at which **scale** Λ_{NP}?
$\Rightarrow$ **Unique opportunities to search for NP in the lepton sector**
exploring connections to **mechanism of ν mass generation!**

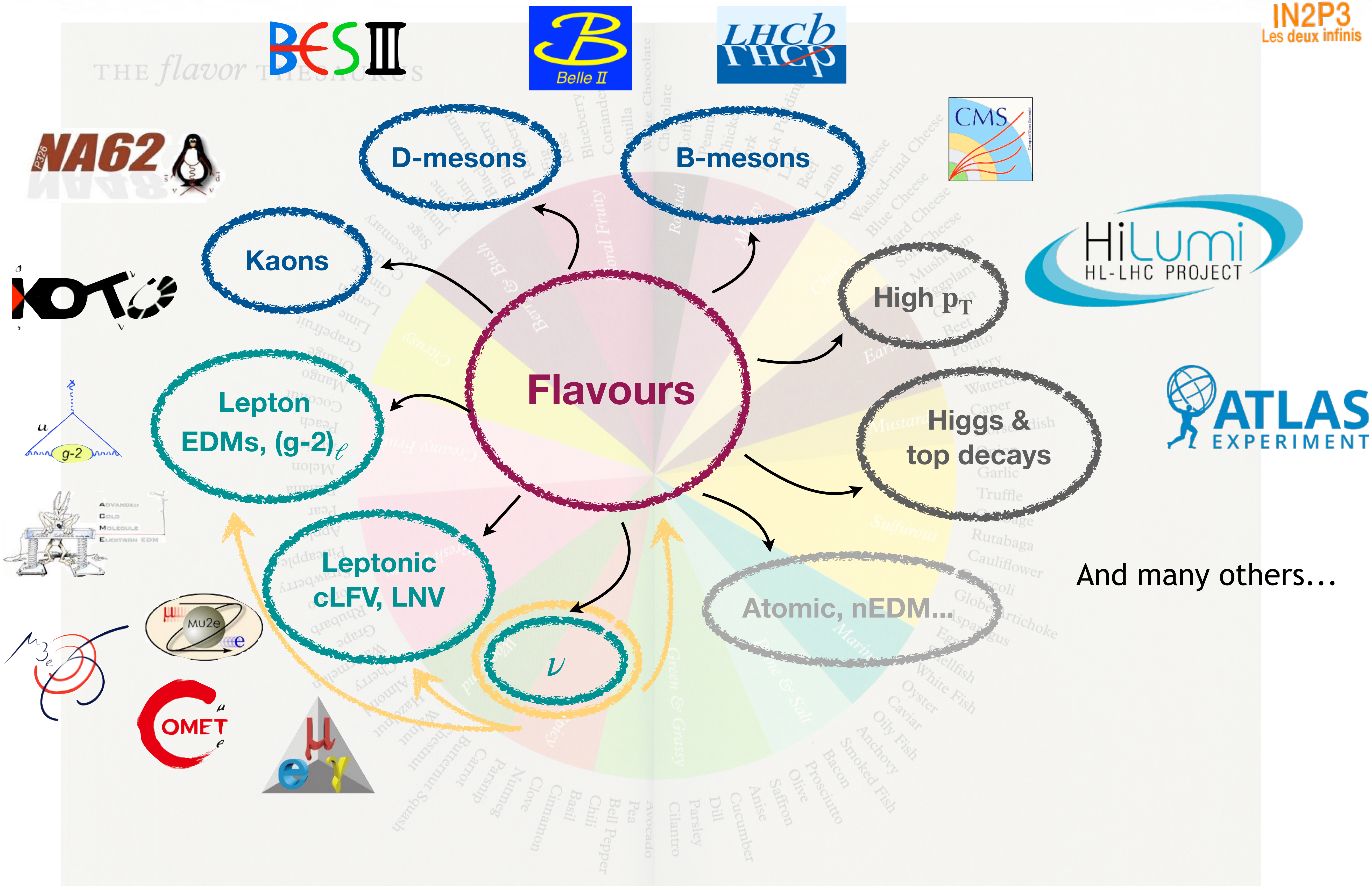
Flavour: across sectors and energies!



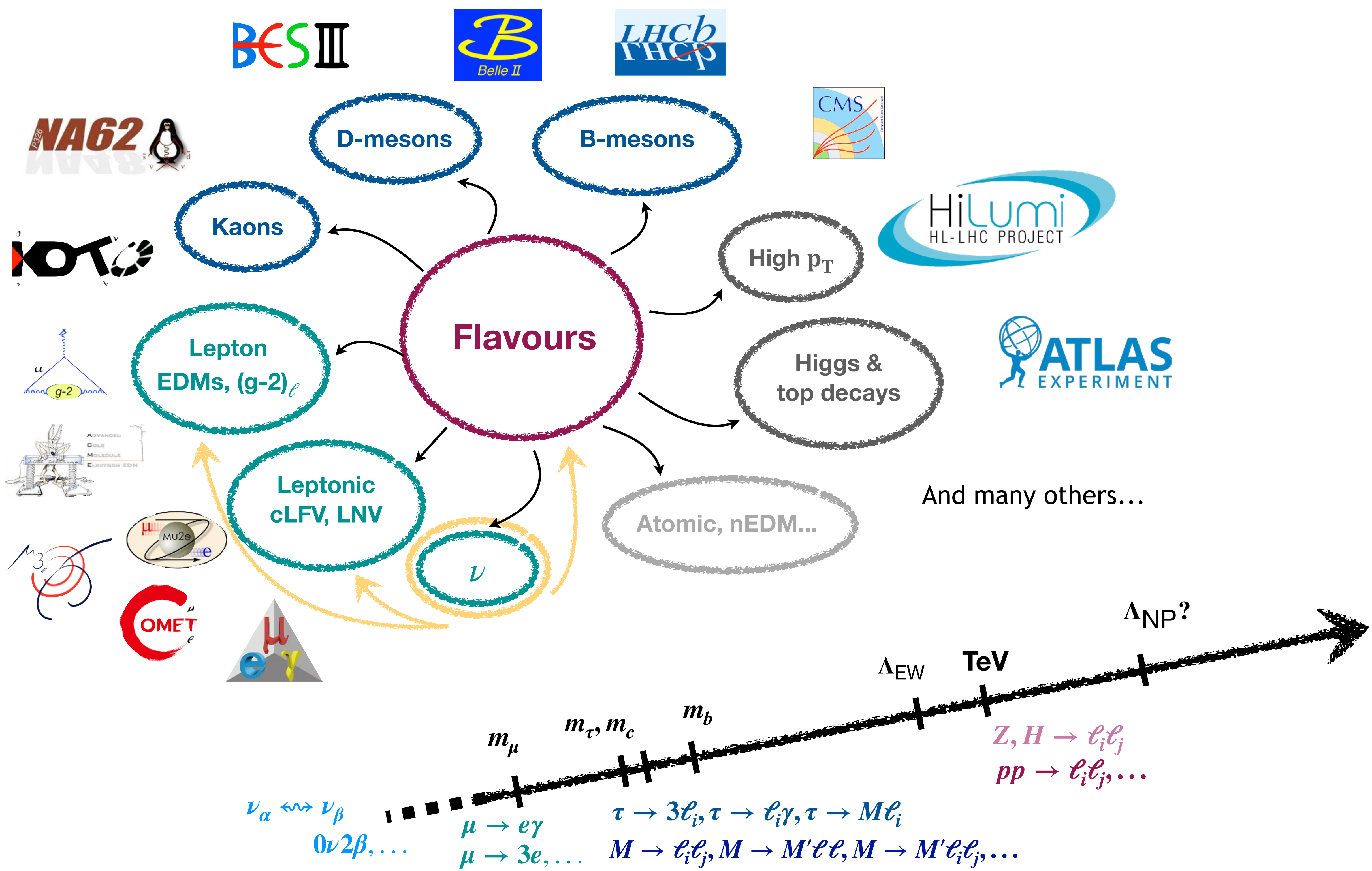
N. Segnit, Bloomsbury '10

Marine, Brine & Salt,
Green & Grassy,
Spicy,
Woodland,
Fresh Fruit, Creamy Fruit,
Citrusy, Berry & Bush,
Floral Fruity,
Roasted, Meaty, Cheesy,
Earthy, Mustardy,
Sulfurous

Flavour: across sectors and energies!



Flavour: across sectors and energies!



Outline

- Overview of flavour observables; the probing power of flavour
- Brief overview of BSM lepton flavour observables
  - Charged lepton flavour violation (cLFV)
  - Lepton flavour universality violation
  - Anomalous magnetic moments
- Models of neutrino mass generation & implications for flavoured observables
  - Seesaw mechanism and variants
- Addressing SM caveats and flavour anomalies: m_ν, DM and lepton flavours
  - Beyond minimal mechanisms of neutrino mass generation
  - Lepton-related "anomalies"
  - Further examples
- Overview and discussion

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Very vast field, huge developments in recent years (data & theoretical ideas) ...
Excellent presentations in the past sessions!
Here - only a tiny view... subject to time constraints and personal "flavour-bias" 🙂

The probing power of flavour

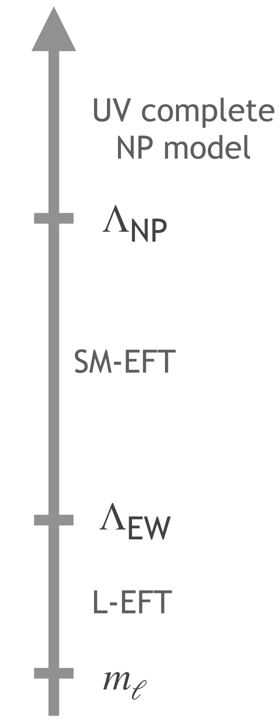
The probing power of flavour

New Physics is required! So far, **no discovery** of "exotic" **resonance at the LHC...**

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)**



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

(unknown) **NP scale** — **effective** coefficients — effective **operators**

$\mathscr{O}^5 \rightsquigarrow$ Weinberg operator (m_ν)
$\mathscr{O}^6 \rightsquigarrow$ flavoured contributions
(among many others!)

Parametrise NP effects on observables suppressed/forbidden in SM

observables suggesting deviations from SM

$$\mathscr{A} \sim \mathscr{A}\left(\frac{\mathscr{C}^6}{\Lambda^2_{\text{NP}}}\right) + \ldots \qquad \mathscr{A} \sim \mathscr{A}^{\text{SM}} + \mathscr{A}\left(\frac{\mathscr{C}^6}{\Lambda^2_{\text{NP}}}\right) + \ldots$$

$\Rightarrow$ master SM prediction!

Cast current data (limits, ...) in terms of $\mathscr{C}^6_{ij}$ and Λ^2_{NP} : minimal assumptions

$\mathscr{C}^6_{ij} \ll 1$ (additional flavour problem...)

✔ $\mathscr{C}^6_{ij} \approx 1$ ($\Rightarrow \Lambda_{\text{NP}} \gg$ TeV)

The probing power of flavour

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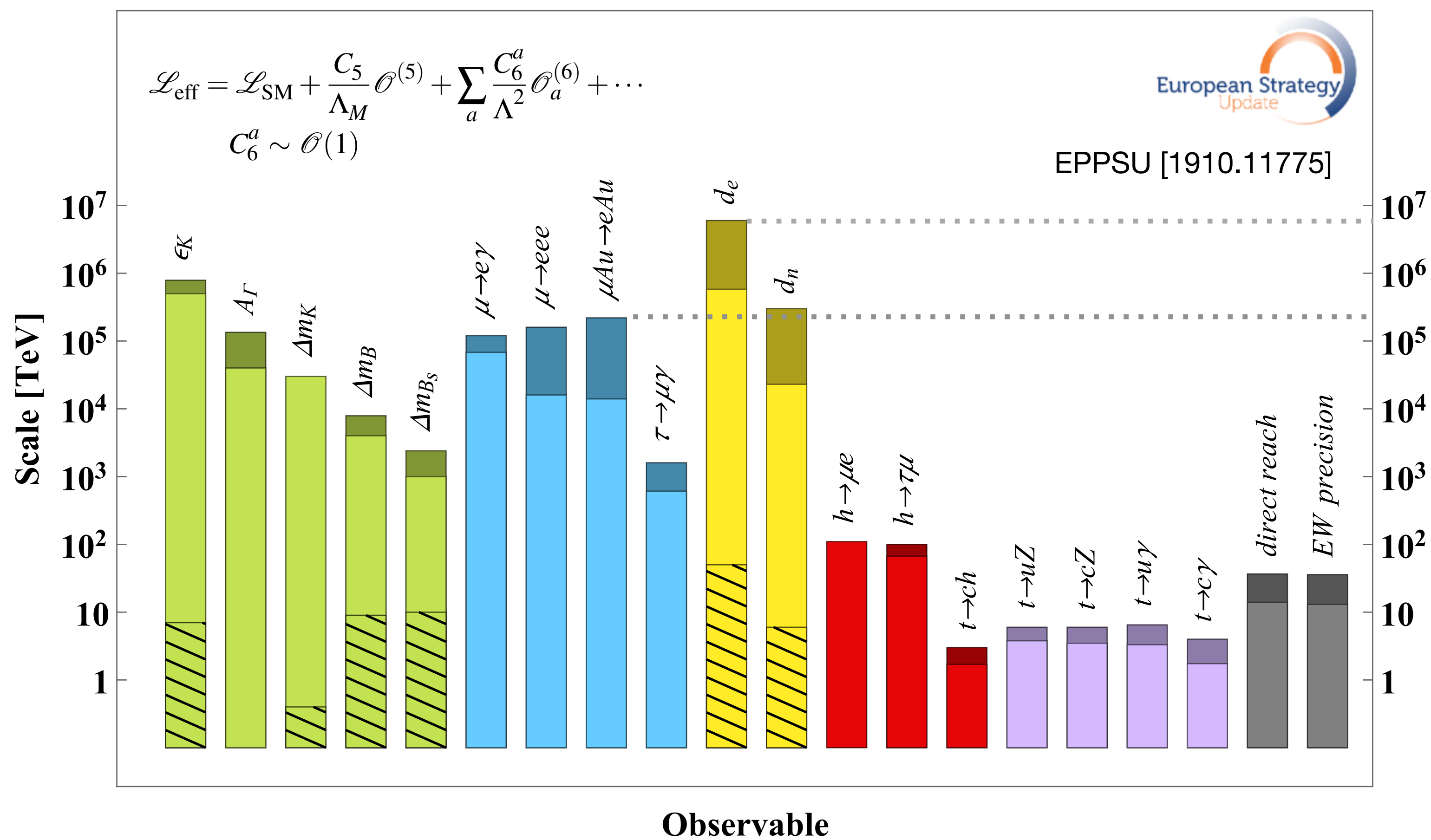
Cast **current data** in terms of $\mathscr{C}^6_{ij}$ and Λ_{NP} : $\mathscr{C}^6_{ij} \approx 1 \Rightarrow$ **bounds on** Λ_{NP}



Flavour observables:
probes sensitive to NP **scales**

$\Lambda_{\text{NP}} \sim \mathscr{O}(10^5 \text{ TeV})$

well beyond collider's reach!

Flavour(s) and CP violation in the lepton sector

See talks by:

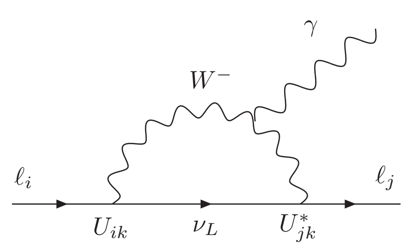
S.Davidson, R.Shrock, J.Miller, S.DiFalco, L.Calibbi and D. Guadagnoli, August 21st (I)
M.Incagli, Th.Blum, C.A.Manzari, S. Heinemeyer, R.Dermisek and J.Kawamura, August 21st (II)
L.ValeSilva, J.Matias, A.Tulupov and R.Mandal, August 21st (III)

Lepton flavours: from ν oscillations...

SM lepton sector: (strictly) **massless neutrinos**
conservation of total lepton number and lepton flavours
lepton flavour universality preserved (only broken by Yukawas)
tiny leptonic **EDMs** (4-loop... $d_e^{\text{CKM}} \leq 10^{-38} e$ cm)

Extend the SM to accommodate $\nu_\alpha \leftrightsquigarrow \nu_\beta$: assume most **minimal extension** $\textbf{SM}_{m_\nu}$
[SM_{m_ν}= "ad-hoc" m_ν (Dirac), U_{PMNS}]

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



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

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

▷ cLFV, LNV, EDMs, ...: observation of SM-forbidden leptonic modes and/or tensions with data
$\Rightarrow$ Discovery of New Physics! (Possibly before direct signal @ LHC!)

Lepton flavours: from ν oscillations...

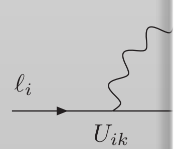
SM lep

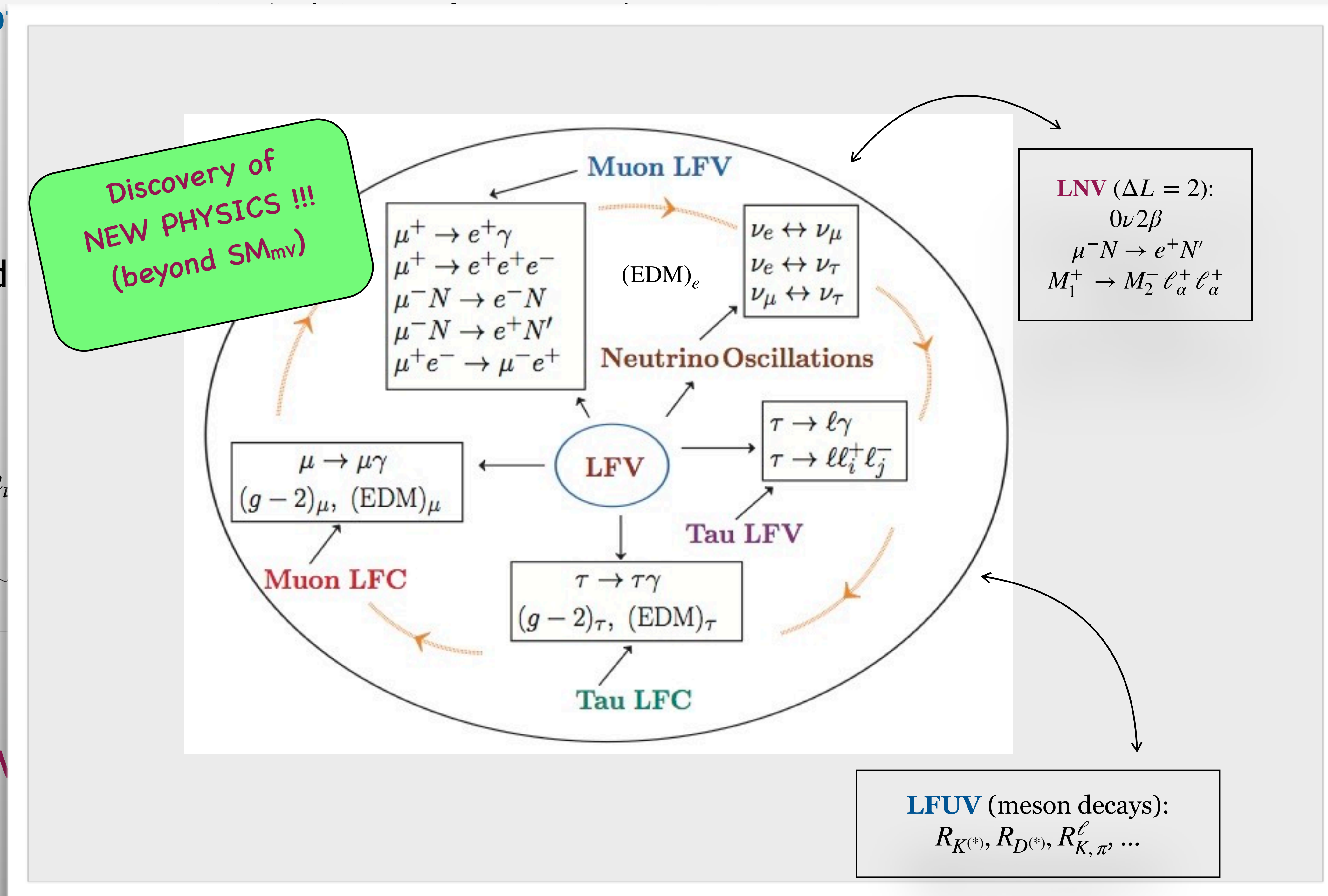
Extend

ac), U_{PMNS}]

In SM$_{m_\nu}$

m δ_{CP})



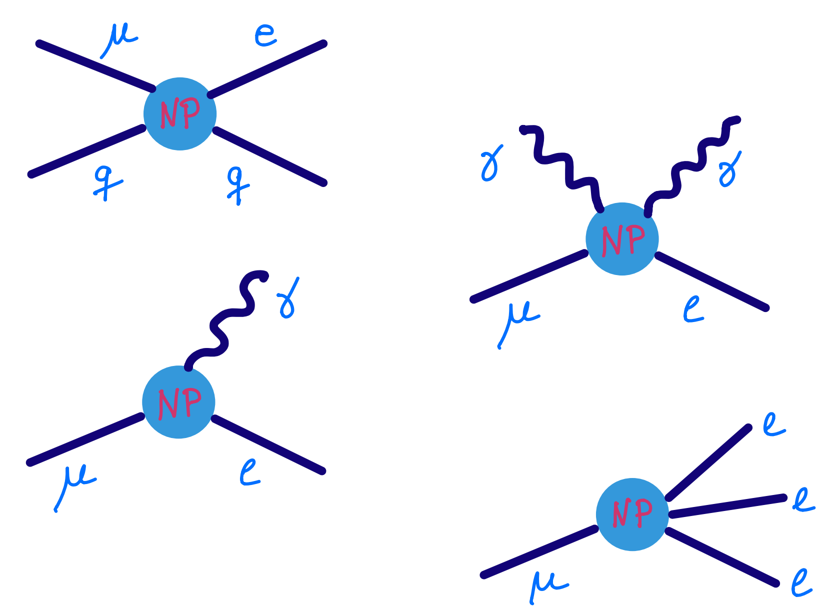


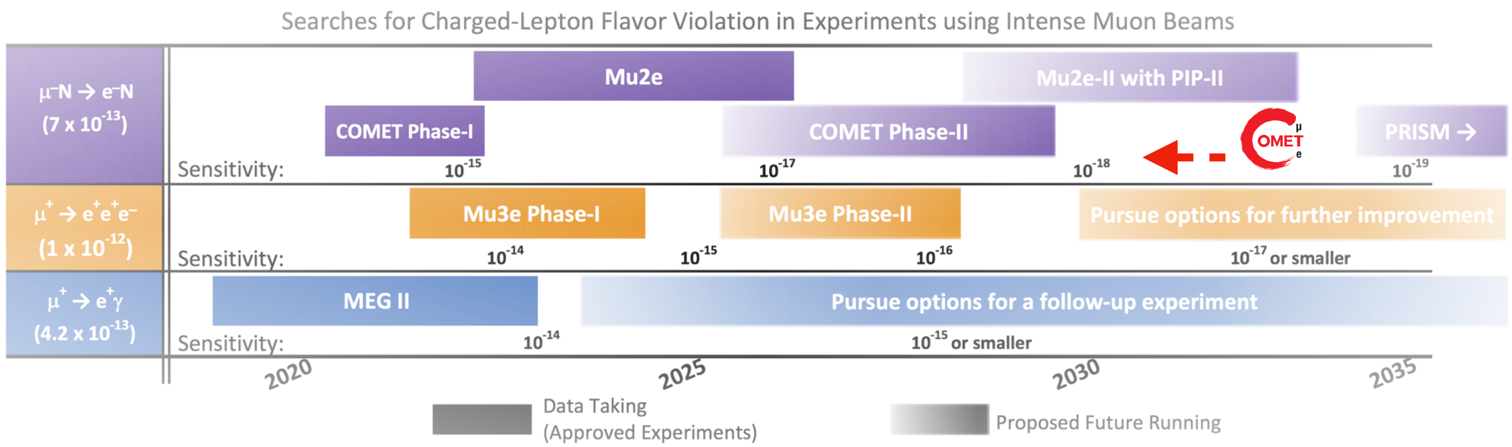
▶ cLFV ... with data

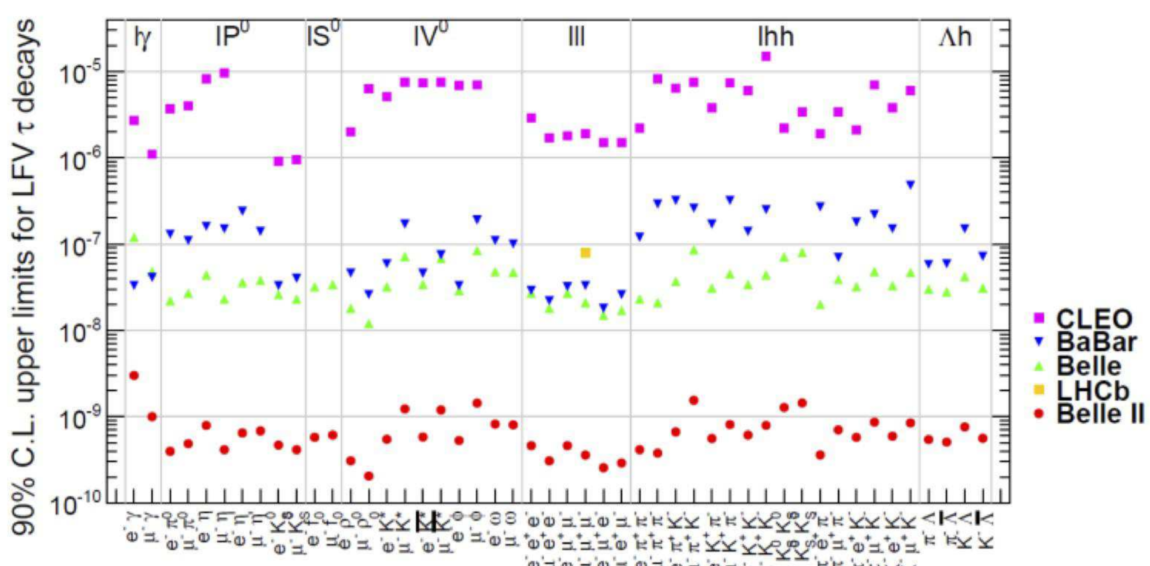
Searches for cLFV: where do we stand?

- **Comprehensive searches** - pure lepton modes, semileptonic τ and meson decays, gauge and Higgs boson decays... **Amazing future prospects!**

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]







From Belle II physics book arXiv:1808.10567

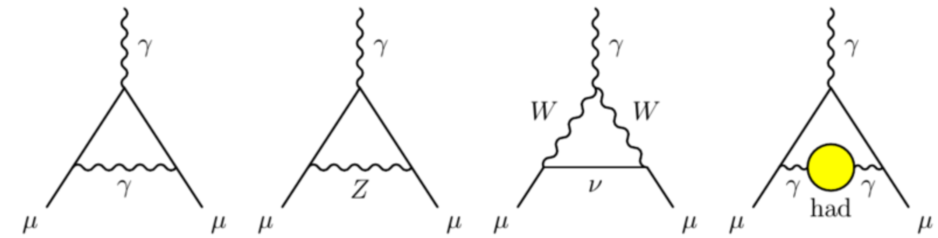
cLFV decay	Bound (90% C.L.)
$\mathrm{BR}(Z \to e\mu)$	7.5×10^{-7}
$\mathrm{BR}(Z \to e\tau)$	9.8×10^{-6}
$\mathrm{BR}(Z \to \mu\tau)$	1.2×10^{-5}
$\mathrm{BR}(H \to e\mu)$	6.1×10^{-5}
$\mathrm{BR}(H \to e\tau)$	4.7×10^{-3}
$\mathrm{BR}(H \to \mu\tau)$	2.5×10^{-3}

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

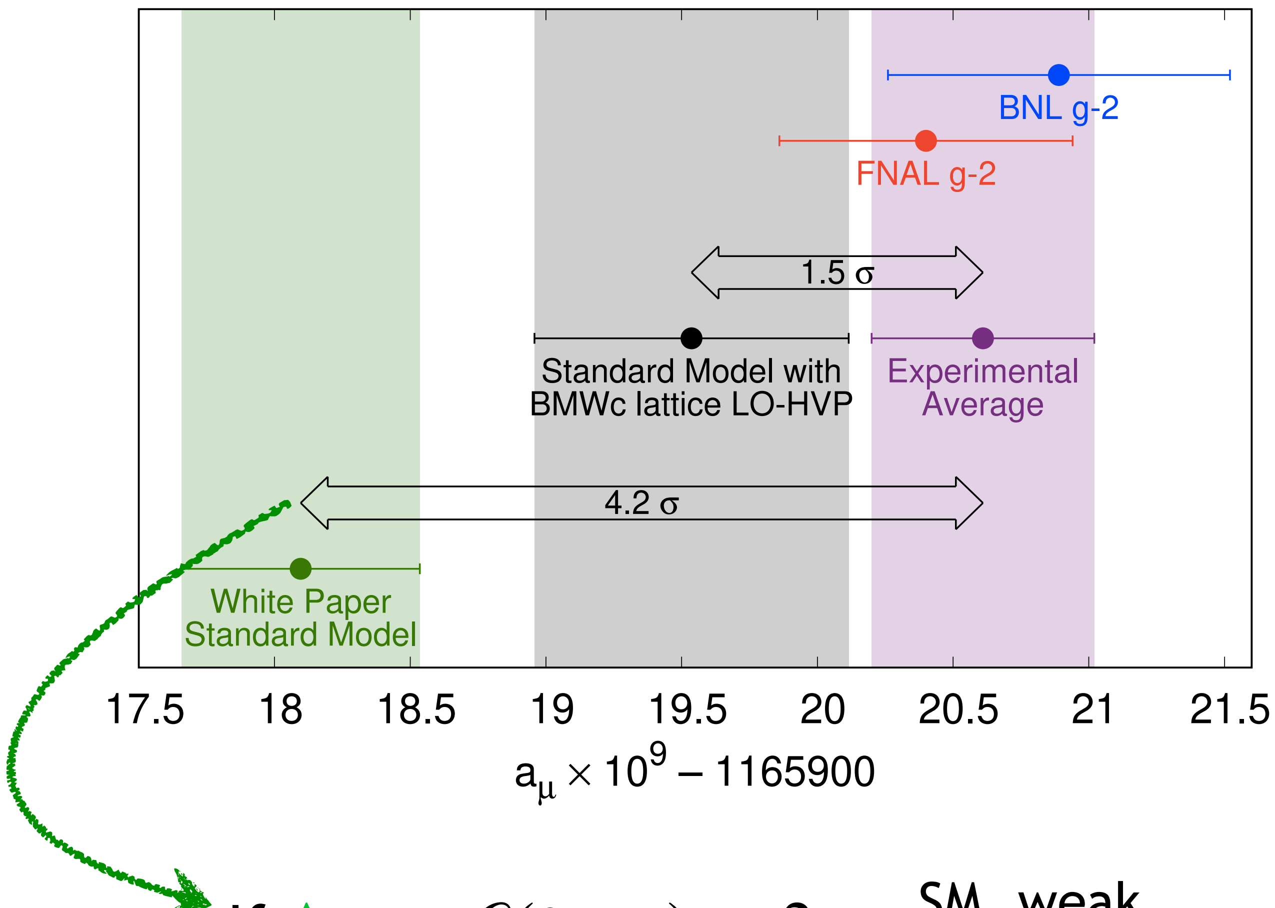
Anomalous magnetic moments: muons and electrons

- Anomalous **magnetic moment of the muon @ 2021:**

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



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



Long-awaited result for a **long-standing tension** between **theory and observation**

a_μ^{the}	=	11659181.0 ± 4.3	WP
a_μ^{the}	=	11659195.4 ± 5.5	Lattice QCD [BMW]
a_μ^{exp}	=	11659209.1 ± 6.3	BNL
a_μ^{exp}	=	11659204.0 ± 5.4	FNAL
a_μ^{exp}	=	11659206.1 ± 4.1	World average

F. Jegerlehner, 2021

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

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

New Physics: badly **needed? or not?**

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

Loop-induced, **chirality-flipping**,
(MFV) **flavour** conserving, ... !

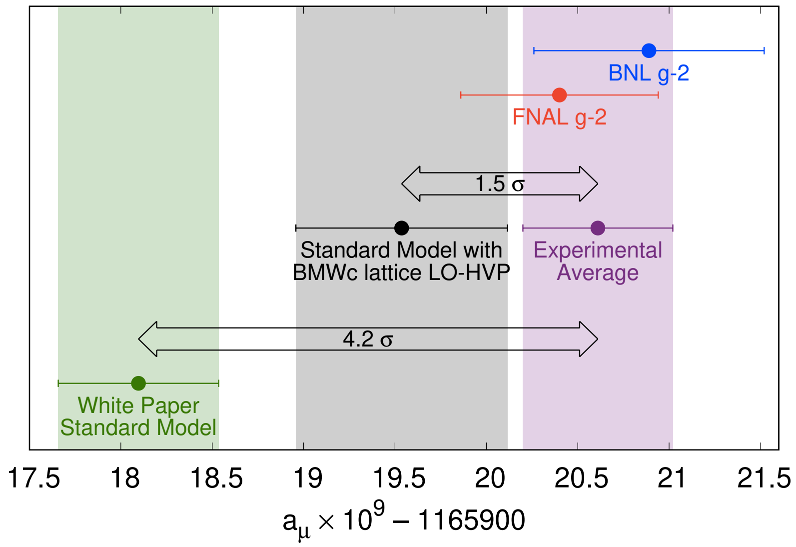
Typically $\Lambda_{\text{NP}} \sim$ few $\times$ 100 GeV

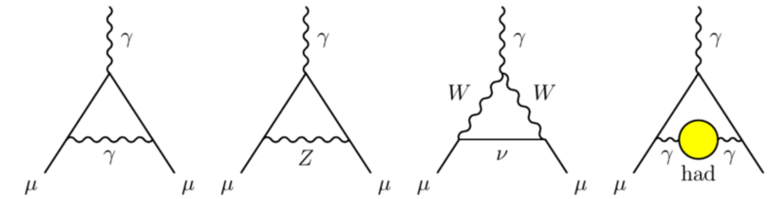
(For recent "taxonomy", see Athron et al, [2104.03691])

Anomalous magnetic moments: muons and electrons

- **Anomalous magnetic moment of the muon @ 2021:**

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



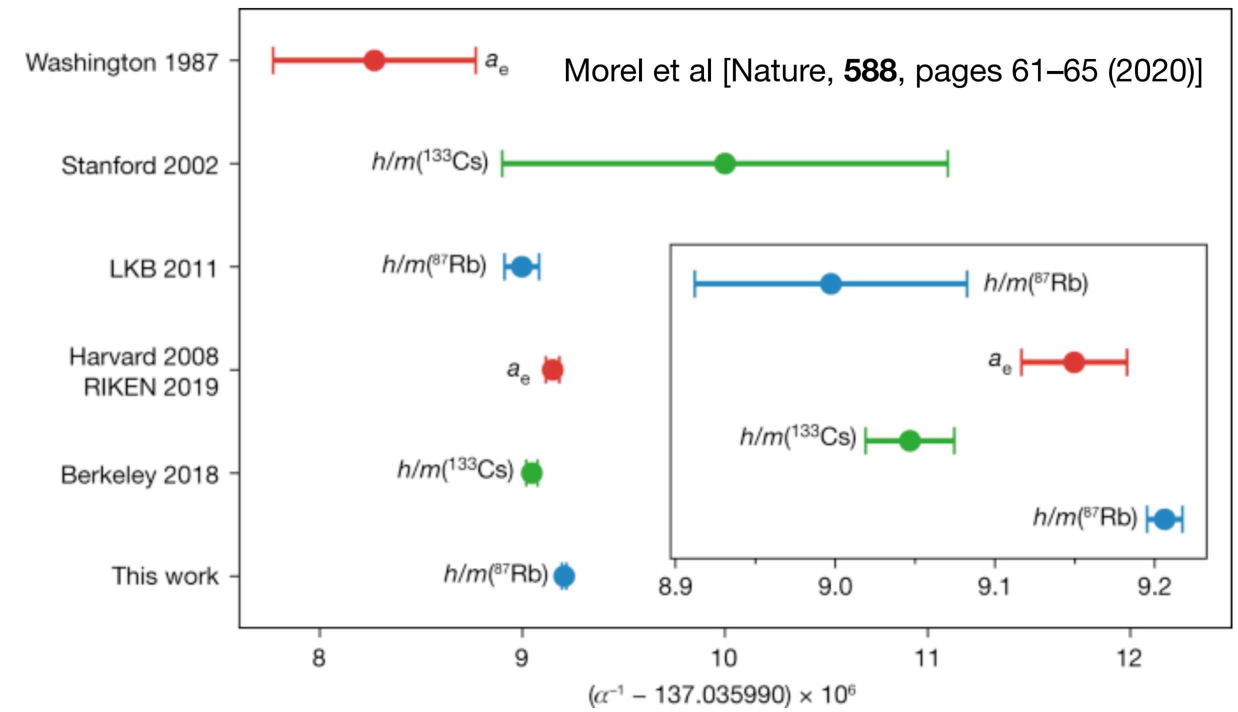


New Physics: badly needed? or not?

- **Anomalous magnetic moment of the electron**

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

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



Difference of 5.4σ in **determination of** α ?!
(SM input parameter!)

- **Two anomalies in** Δa_μ **and** Δa_e^{Cs} **?**

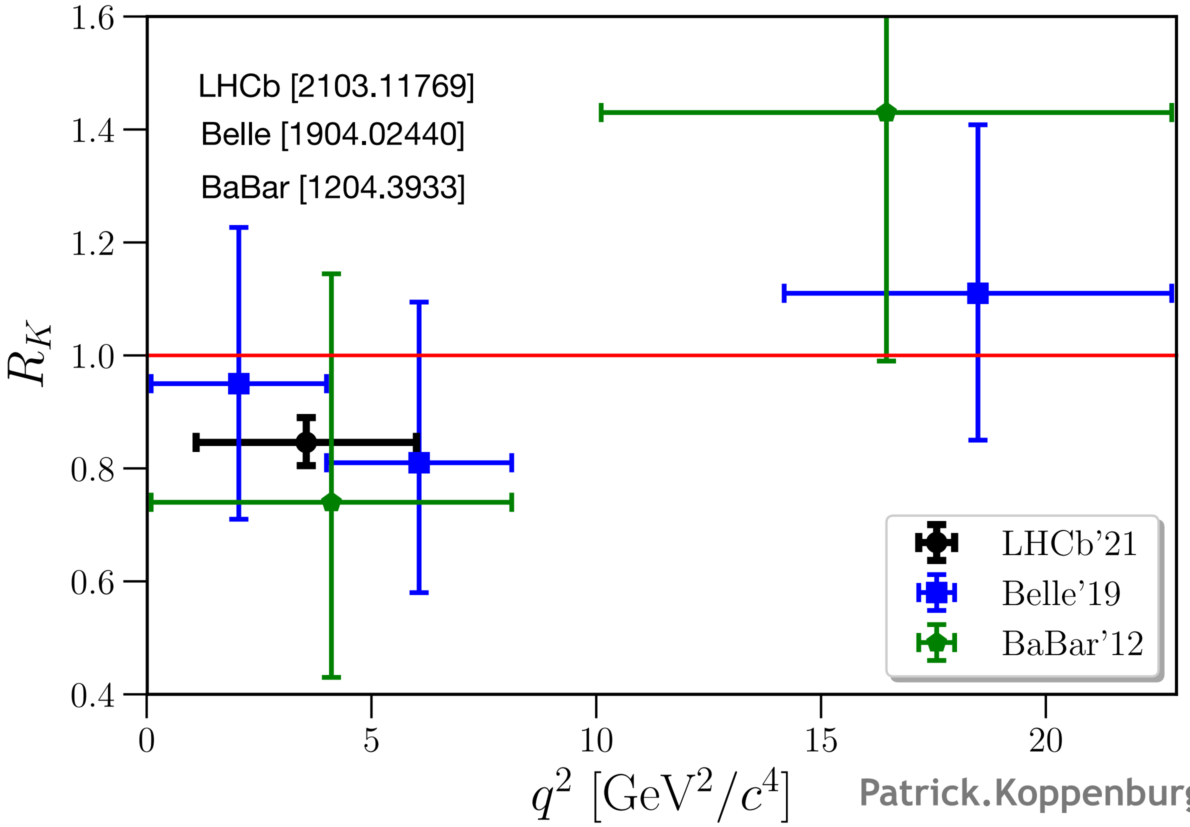
Possible hint of **lepton flavour universality violation?**

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

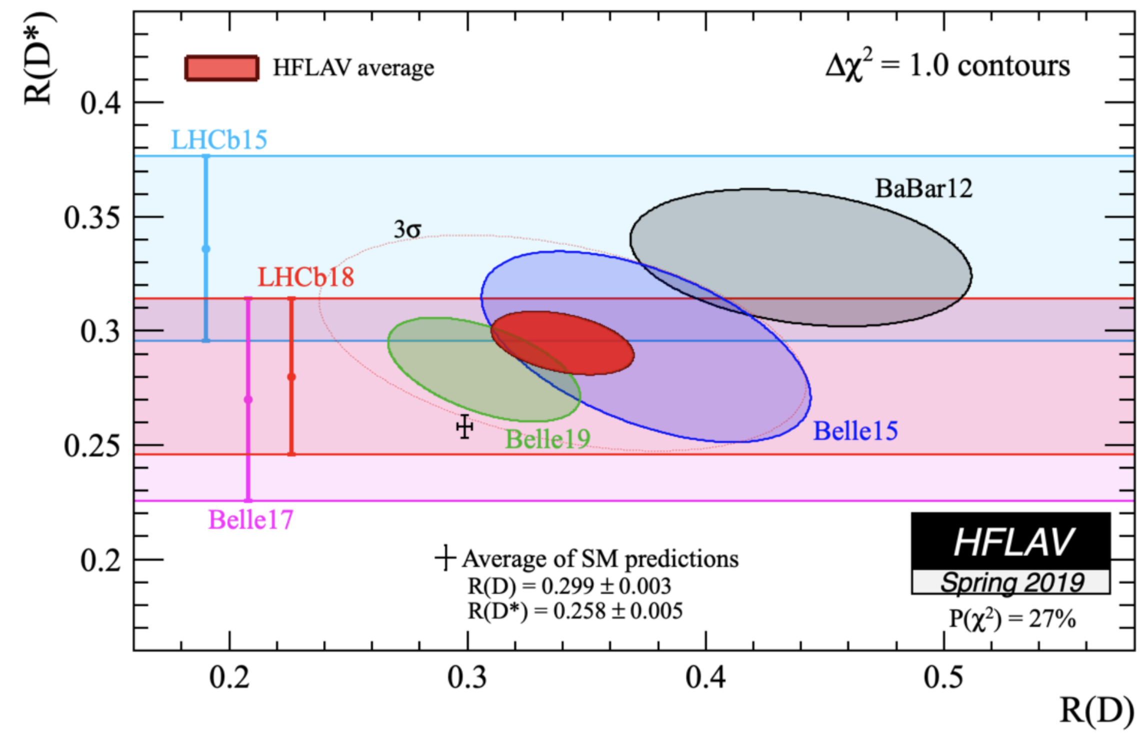
but $\Delta a_e^{\text{Cs}} / \Delta a_\mu \sim -3.3 \times 10^{-4}$...

B-meson observables: "anomalies" & more

- **Rare B decays** as probes of SM paradigm of flavour:
  conflicting **tensions with SM predictions!** or **hints for New Physics?**



Patrick.Koppenburg@cern.ch



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

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

Exp: $R_K^{[1,6]} = 0.845^{+0.60+0.16}_{-0.054-0.014}$

$R_{K^{(*)}}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$; $R_{K^{(*)}}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$

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

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

Exp: $R_D = 0.340 \pm 0.027 \pm 0.013$;
$R_{D^*} = 0.295 \pm 0.011 \pm 0.008$

New Physics: models of neutrino mass generation

See J.Valle's talk, August 19th

Neutrino masses and NP realisations

- **Mechanisms of neutrino mass** generation: should account for **oscillation data,** and ideally address **SM issues** - **BAU** (via leptogenesis), **DM** candidates,...

Numerous well-motivated possibilities, calling upon distinct NP states (singlets, triplets) **realised at very different scales** - $\Lambda_{EW} \to \Lambda_{GUT}$

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")

Low-scale seesaw realisations (and variants): non-decoupled states, modified lepton currents!
rich phenomenology @ low-energies, high-intensities and colliders

testability!!

Low-scale models of m_ν generation: type I seesaw

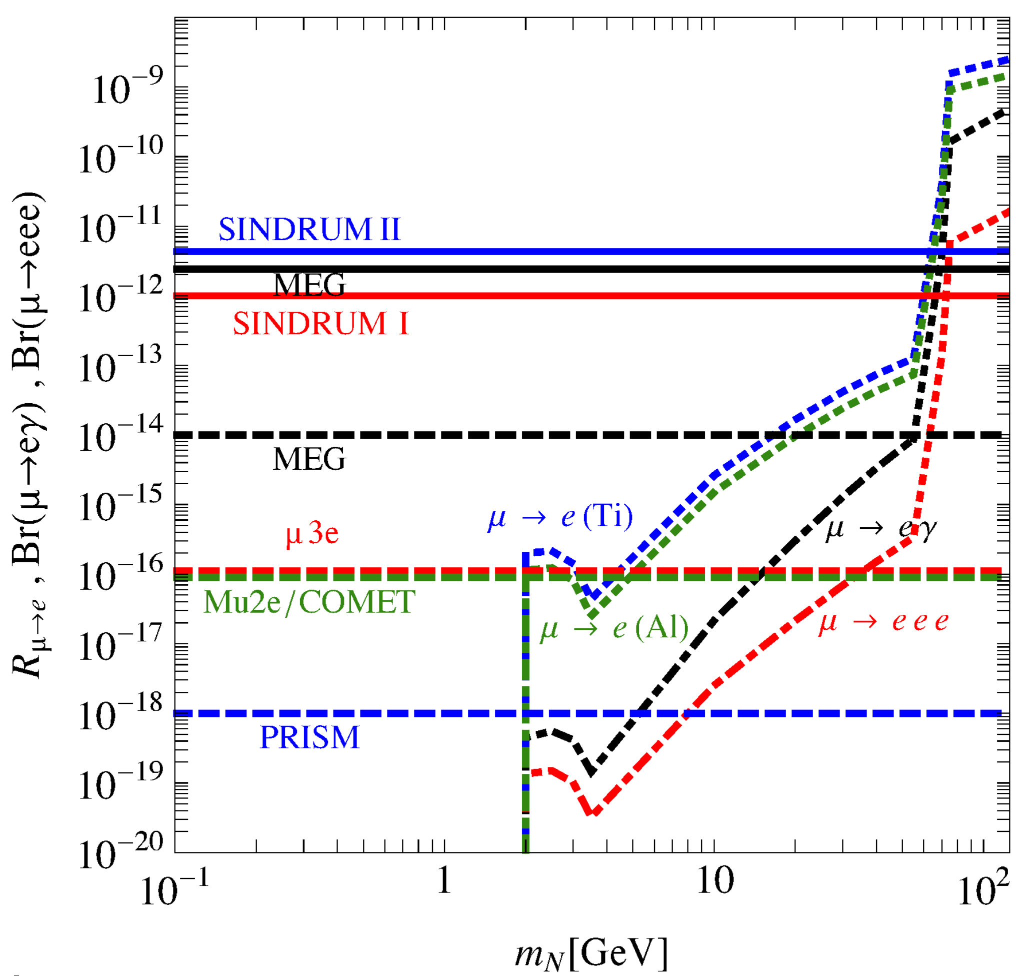
Addition of **3 "heavy" Majorana RH neutrinos** to the SM: **MeV $\lesssim m_{N_i} \lesssim 10^{\text{few}}$ TeV**

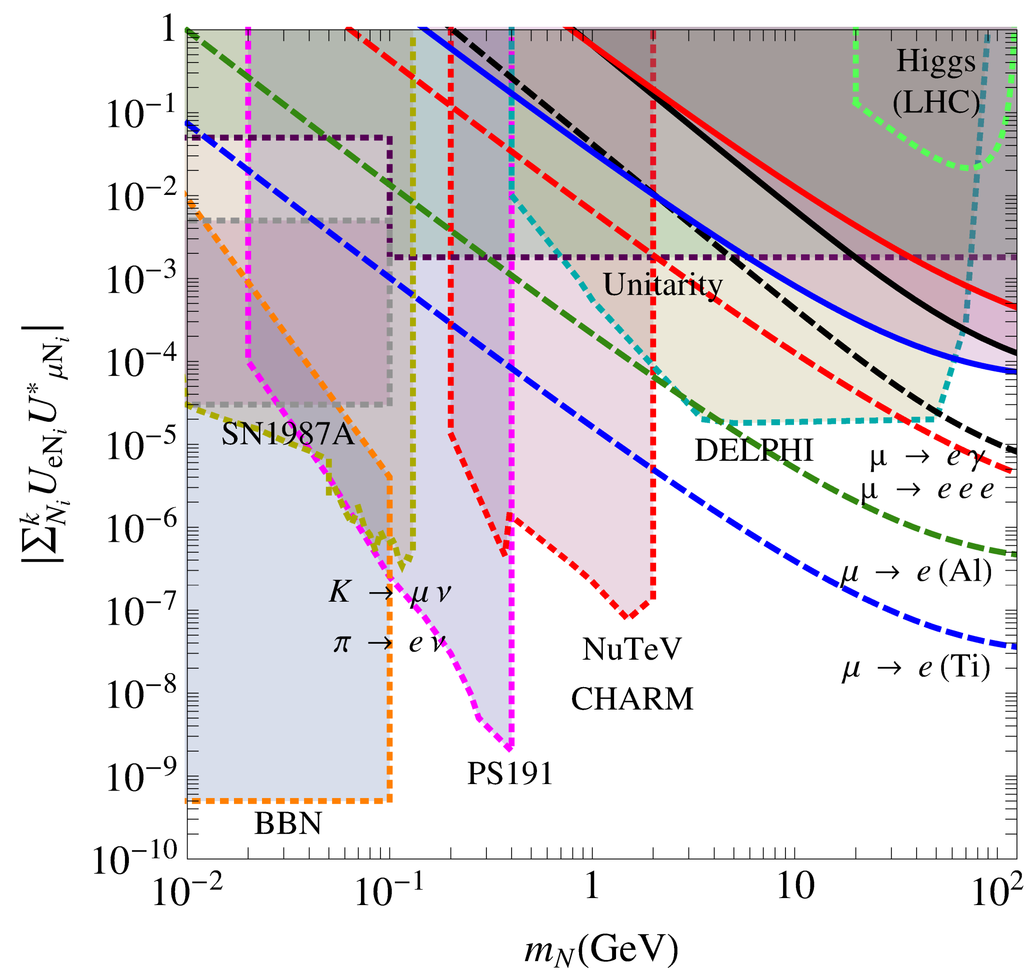
Spectrum & mixings: $m_\nu \approx -v^2 Y_\nu^T M_N^{-1} Y_\nu \qquad U^T \mathcal{M}_\nu^{6\times 6} U = \text{diag}(m_i)$

$$U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \qquad U_{\nu\nu} \approx (1-\varepsilon)\, U_{\text{PMNS}}$$

Heavy states do not decouple $\Rightarrow$ modified neutral and charged leptonic currents

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





Alonso et al [1209.2679]

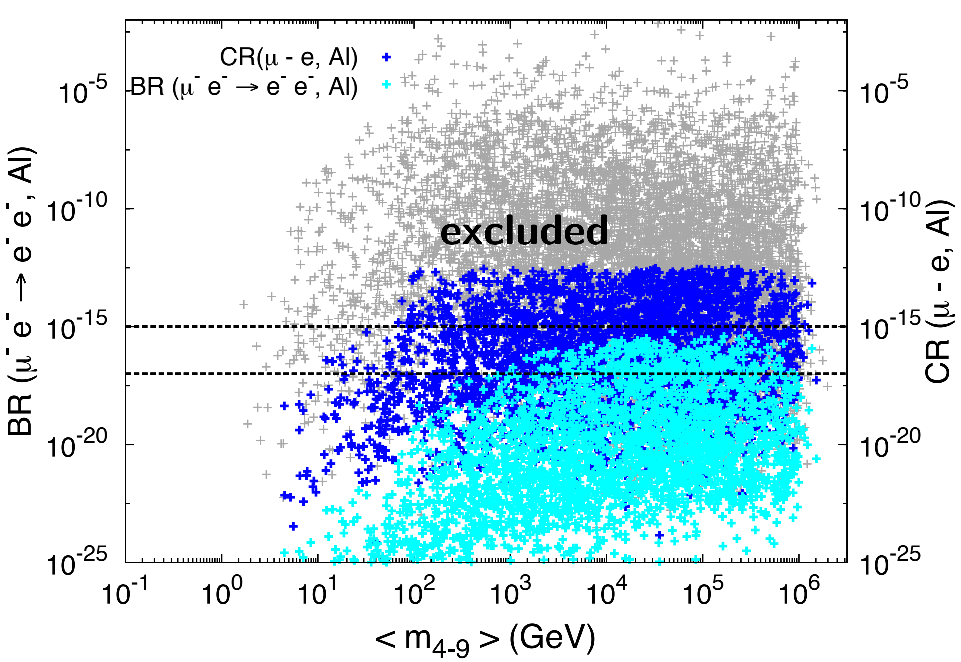
Low-scale models of m_ν generation: Inverse Seesaw

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

$$\mathcal{M}^{9\times9}_{\text{ISS}} = \begin{pmatrix} 0 & Y_\nu v & 0 \\ Y_\nu^T v & 0 & M_R \\ 0 & M_R & \mu_X \end{pmatrix} \Rightarrow \begin{cases} \textbf{3 light } \boldsymbol{\nu} : m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2} \mu_X \\ \textbf{3 pseudo-Dirac pairs} : m_{N^\pm} \approx M_R \pm \mu_X \end{cases}$$

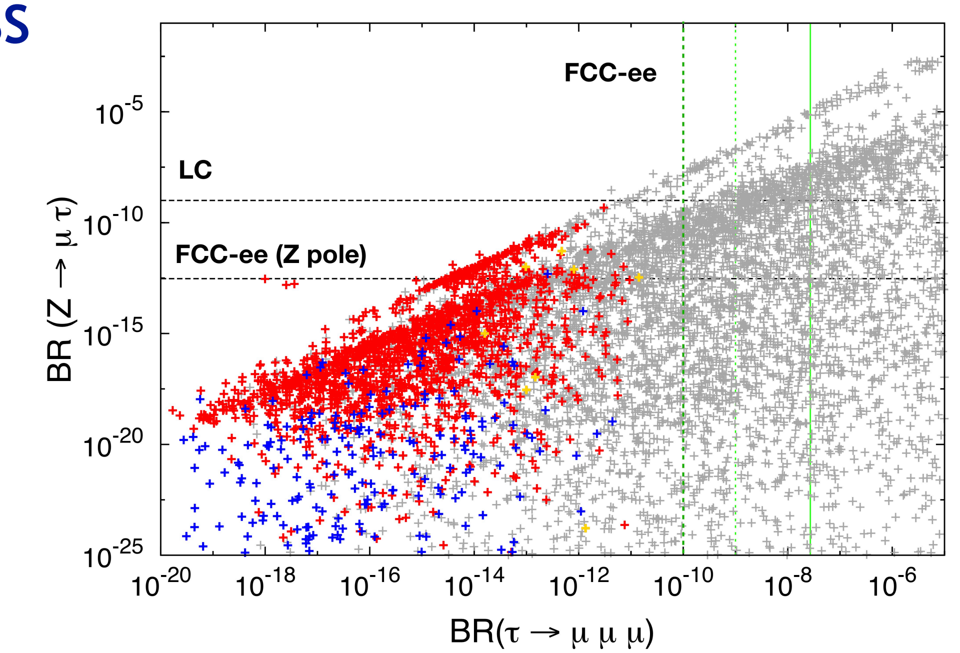
Abundant "flavour" signals: cLFV at high-intensities and at colliders!

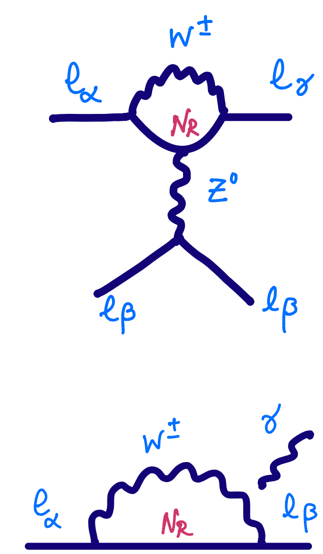
Abada, De Romeri, AMT [1510.06657]



(3,3) ISS

Abada, De Romeri, Monteil, Orloff, AMT [1412.6322]





Sizeable values for cLFV muon observables - well within future experimental sensitivity!

cLFV $Z \to \mu\tau$ within FCC-ee reach! Allows probing $\mu - \tau$ cLFV beyond Belle II reach...

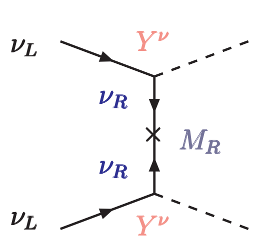
Peculiar patterns: disentangling seesaws

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

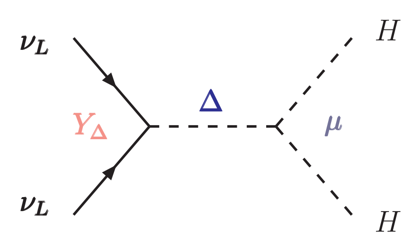
  In the absence of direct NP discovery - **correlations** might allow to disentangle models and provide important complementary information to direct searches!

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

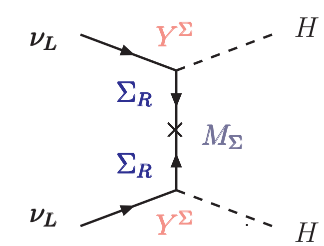
  ratios of observables to **identify seesaw mediators** & constrain their **masses!**



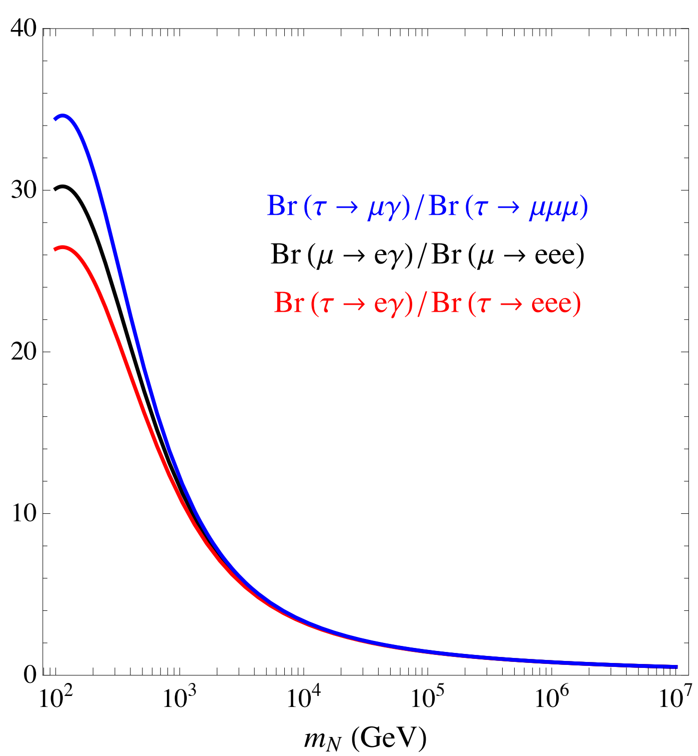
Type I (fermion singlet)



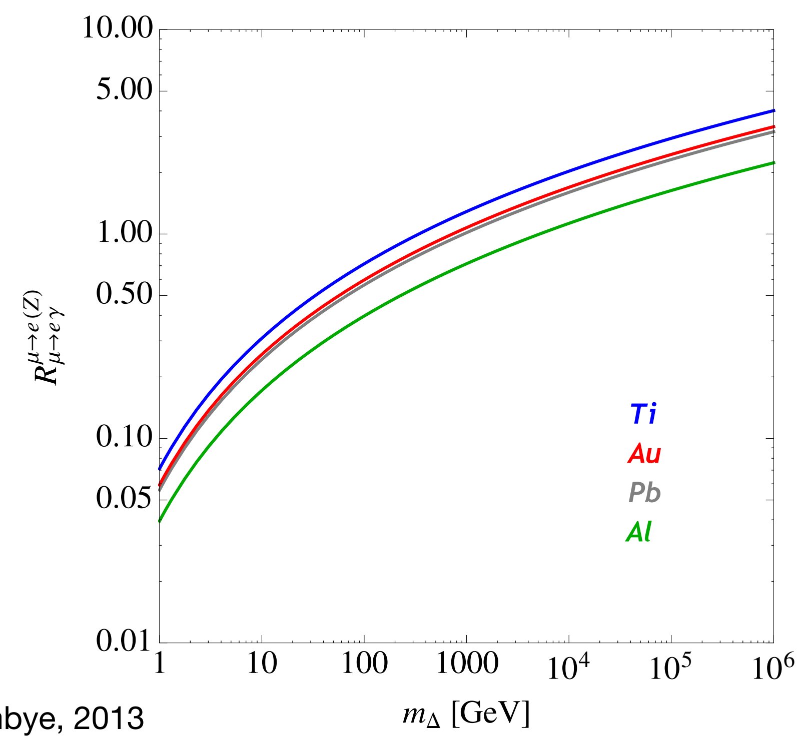
Type II (scalar triplet)



Type III (fermion triplet)



Hambye, 2013



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

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

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

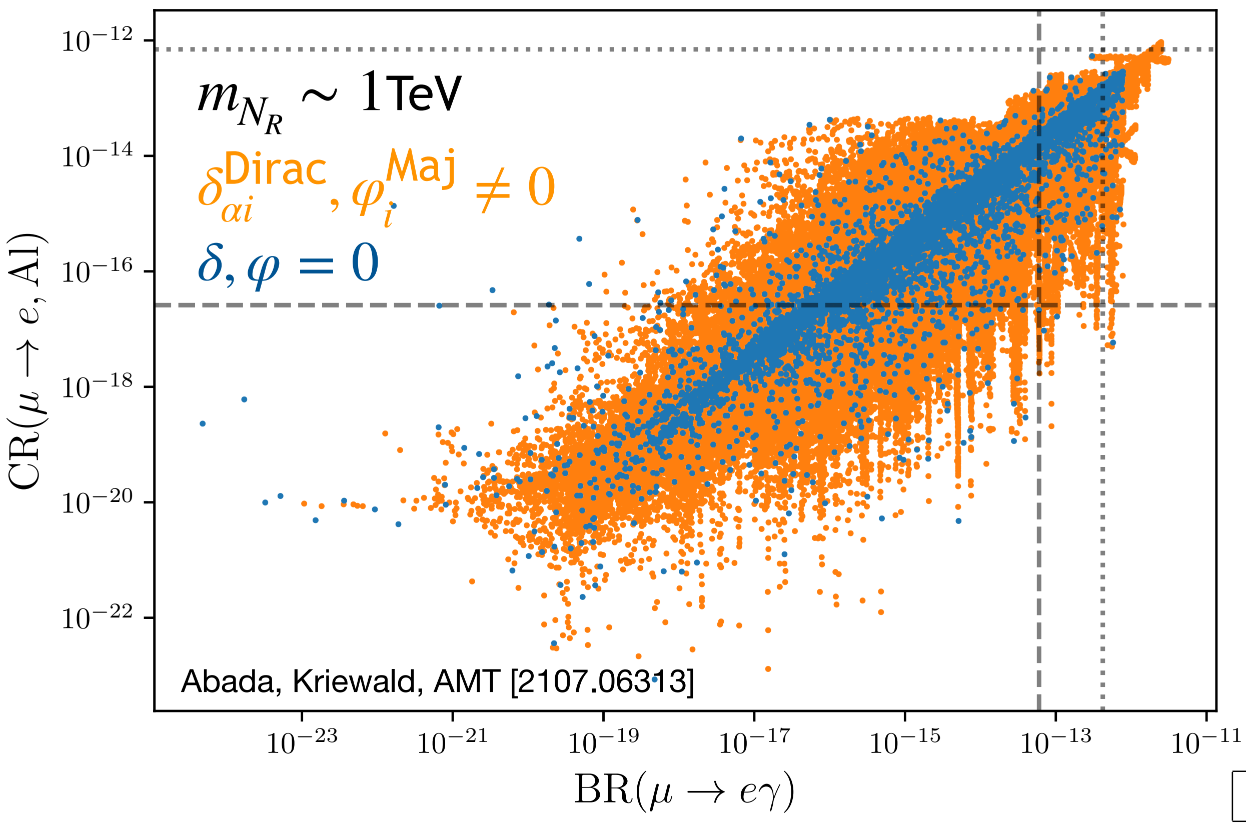
The role of CP phases and cLFV

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

But - CP violating phases do matter!

CP phases (Dirac and/or Majorana) generically present in most **models of ν masses...**

And impact naïve expectations...



Minimal "3+2 N_R" toy model

SM extension via **"heavy" RH neutrinos**

Additional active-sterile mixings,

Dirac and Majorana phases $\delta_{\alpha i}^{\text{Dirac}}, \varphi_i^{\text{Maj}}$

$\Rightarrow$ significant **loss of correlation between observables**

$\Rightarrow$ impact for (future) **data interpretation**

	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} ✓

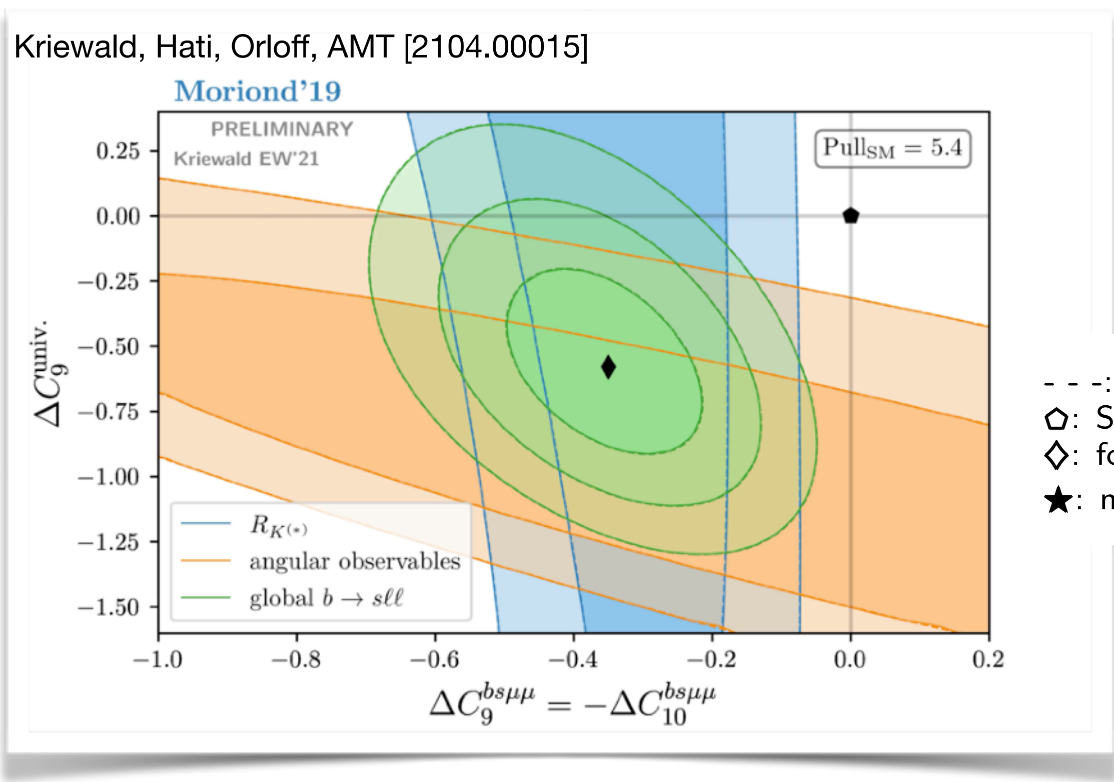
large mixings not excluded if CPV!

SM caveats & flavoured anomalies: m_ν, dark matter and lepton flavours

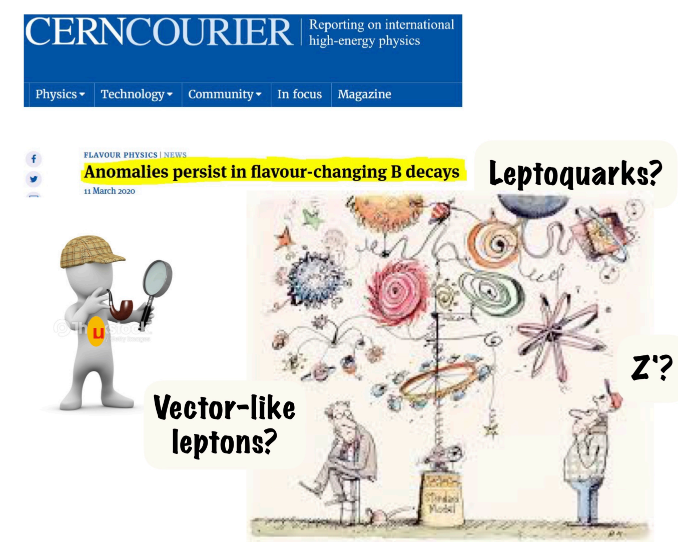
Exotic states for new NP hints and m_ν

- **Flavoured hints, DM** & massive neutrinos: pointing the way to the BSM realisation ?!

Well-motivated constructions aiming at explaining neutrino masses and lepton mixings,
offering dark matter candidates,
accounting for Δa_μ (and Δa_e^{Cs}),
and for B-meson decay LFUV "anomalies"...



- - -: old data
⬠: SM
◇: former best fit
★: new B.F.



- **However - a word of caution...**

Generic flavoured BSM addressing $R_{K^{(*)}}$ and $R_{D^{(*)}}$ might lead to **sizeable cLFV**
(some constructions suggesting ***lower bounds*** on LFV BRs)

$\Rightarrow$ cLFV might allow **testing BSM LFUV hypotheses** (LQs, ...) in absence of direct discovery

Stability of dark matter candidate may preclude realisation of standard (tree-level) seesaws
$\Rightarrow$ exciting new approaches: **generation at higher order, ...**

Beyond "standard" seesaw realisations

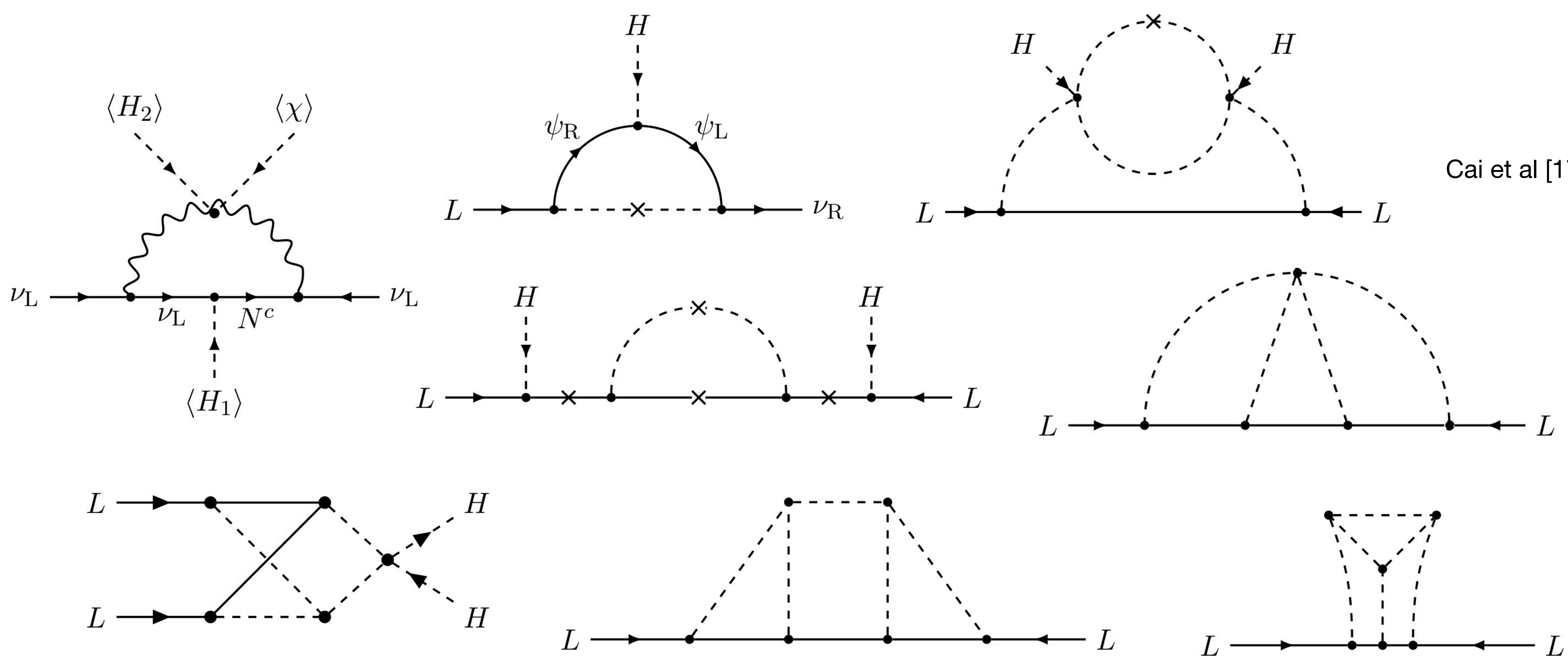
Seesaw (and its variants) remains one of the most appealing mechanisms for m_ν **generation**

Several **other** interesting and theoretically **well-motivated possibilities exist:**

Tree-level realisations 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!**



Cai et al [1706.08524]

(For cLFV implications see
Cepedello et al [2005.00015];
for a comprehensive review,
Cepedello [2105.01896])

And **further variants** - depending on the **NP framework**...

⇒ **Here, some examples** in association with **SM observational problems and tensions!**

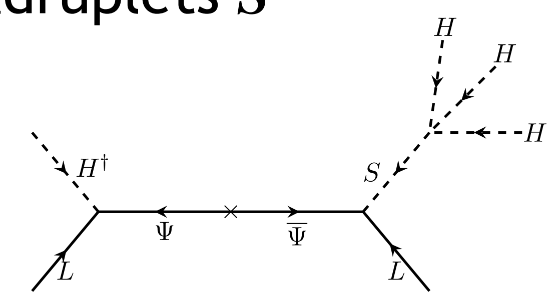
Higher-order m_ν and anomalous magnetic moments

CNRS IN2P3 Les deux infinis

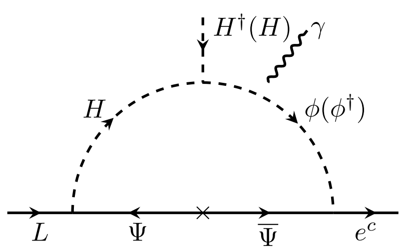
- **BNT-like models:** extend SM by vector-like fermions $(\Psi, \bar{\Psi})$ and scalar quadruplets S

Babu et al [0905.2710]

neutrino mass generation $\Rightarrow$ **dimension 7 operator**



BNTϕ - variants adding extra complex scalar triplet ϕ



Explain **neutrino masses** and **account** for **both** Δa_μ and Δa_e^{Cs} !

Arbelaez et al [2007.11007]

Neutrino masses: $\mathcal{M}^0 = \begin{pmatrix} 0 & m_{Y_\Psi} & m^T_{Y_{\overline{\Psi}}} \\ m^T_{Y_\Psi} & 0 & M_\Psi \\ m_{Y_{\overline{\Psi}}} & M^T_\Psi & 0 \end{pmatrix}$

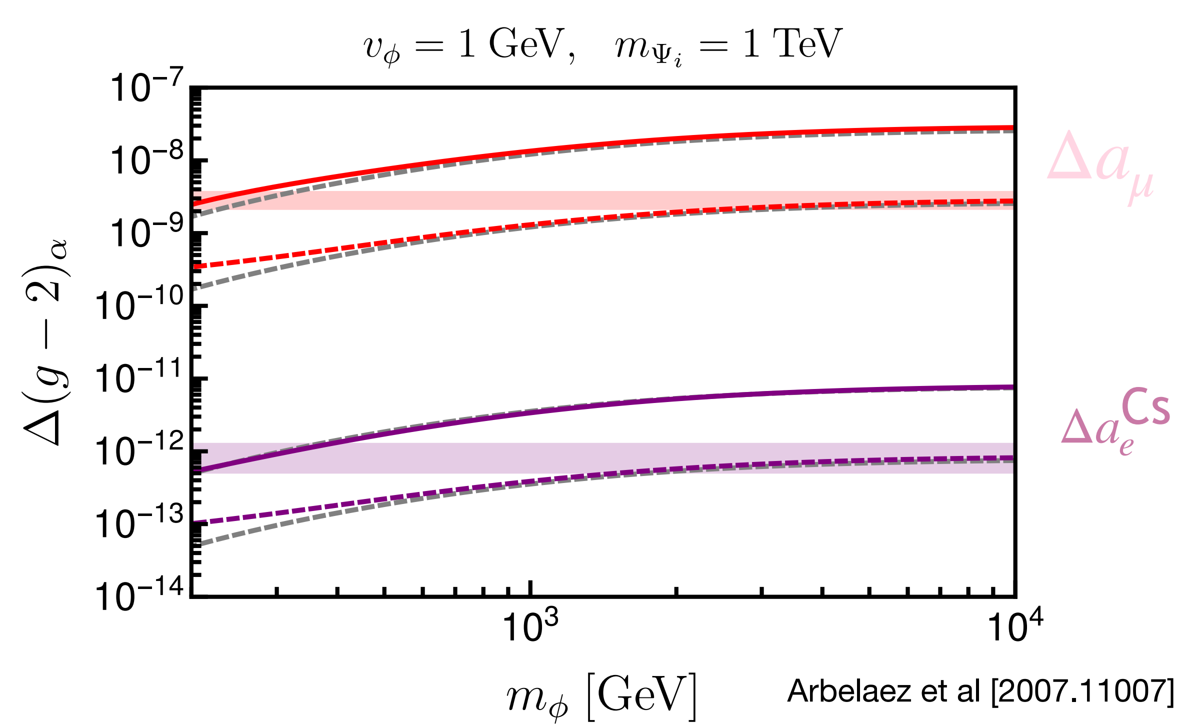
$$M_\nu = m_{Y_\Psi} \left(M_\Psi^{-1}\right)^T m_{Y_{\overline{\Psi}}} + m^T_{Y_{\overline{\Psi}}} M_\Psi^{-1} m^T_{Y_\Psi}$$

$$m_{Y_\Psi} = Y_\Psi v_H/\sqrt{2} \qquad m_{Y_{\overline{\Psi}}} = Y_{\overline{\Psi}} v_S/\sqrt{2}$$

(and radiative contributions...)

- **Saturate** Δa_μ and Δa_e^{Cs} while complying with oscillation data and current **cLFV bounds** on $\mu \to e\gamma$ and $\tau \to \mu\gamma$ decays !

  Heavy **VL-states** within **LHC reach**



Arbelaez et al [2007.11007]

Scotogenic models: neutrinos, DM and cLFV

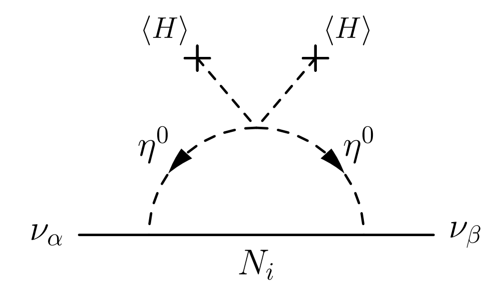
- **Scotogenic models:** a link between **neutrino mass** generation and **dark matter!**

[Ma, 2006] minimal realisations: extend SM by **(inert) scalar doublet η**

and **RH neutrinos N_R**

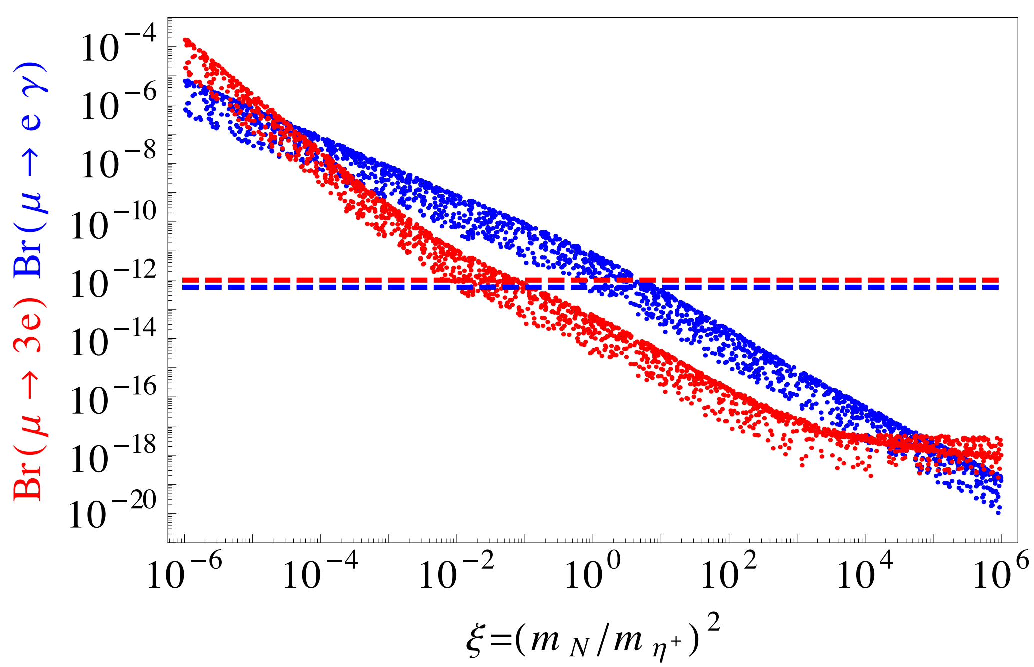
Additional Z_2 symmetry: **neutrino masses @ 1-loop**

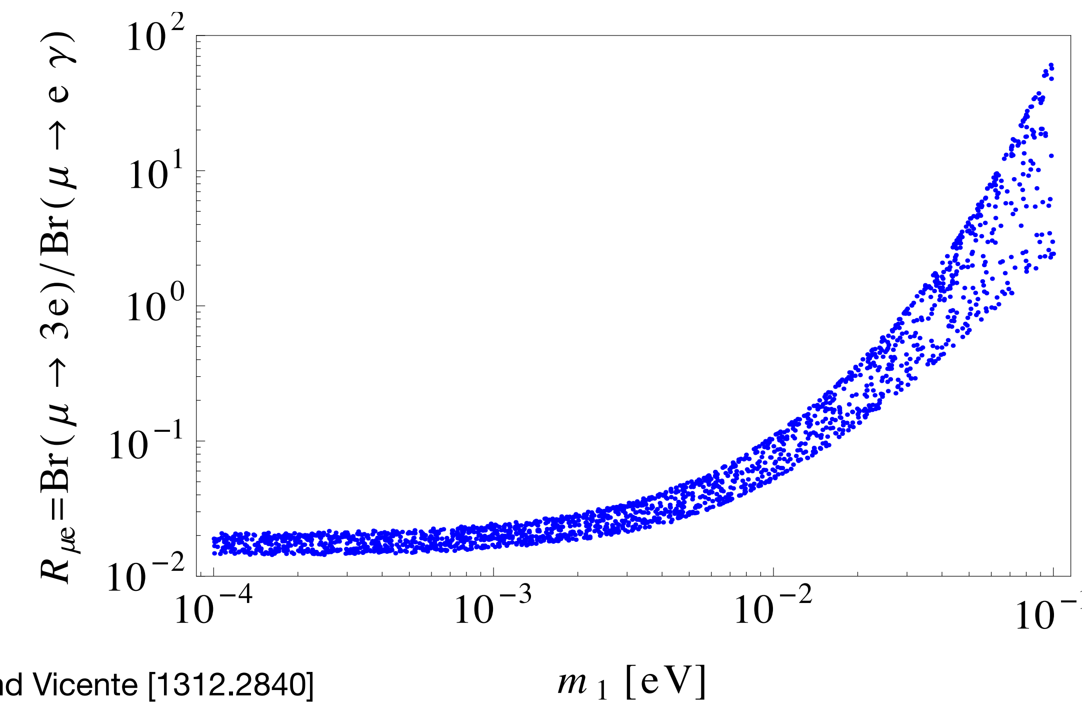
dark matter candidate (η or N_R)



(*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]

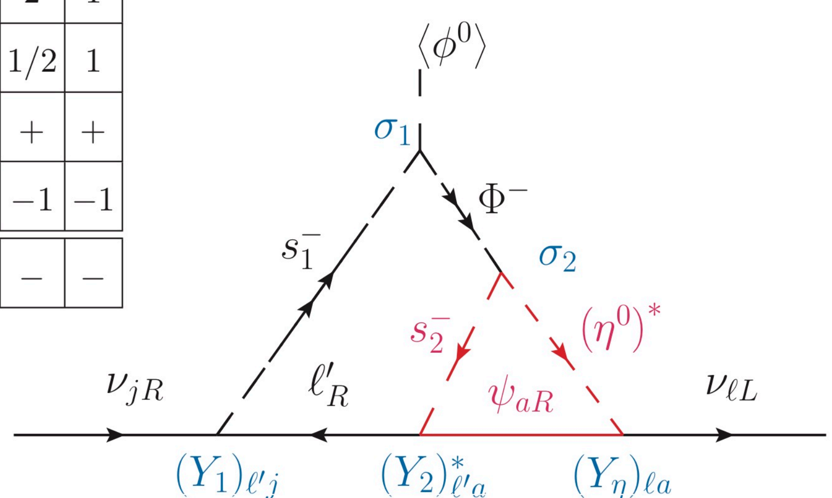
Current (muon) cLFV bounds favour $m_N \geq m_\eta$; $\eta \rightsquigarrow$ **DM candidate!**

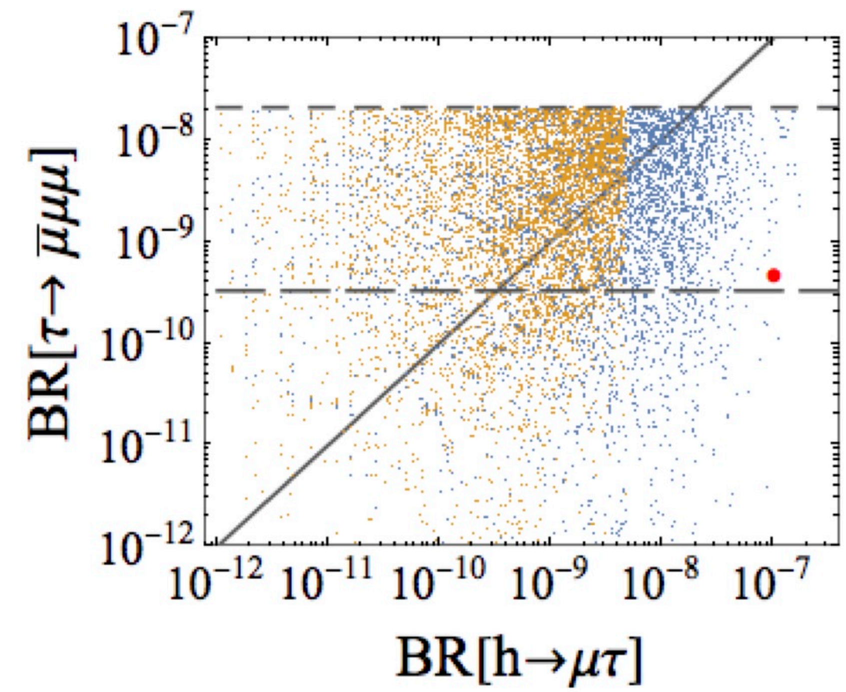
Determination of $R_{\mu e}$ = BR($\mu \to 3e$)/BR($\mu \to e\gamma$) $\Rightarrow$ hints on lightest neutrino mass m_{ν_1}

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 (but **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
$SU(2)_L$	1	1	2	1	2	1
$U(1)_Y$	0	0	3/2	1	1/2	1
Z_2'	$-$	$+$	$(+)$	$-$	$+$	$+$
L	1	0	-2	-2	-1	-1
Z_2	$+$	$-$	$+$	$+$	$-$	$-$





Enomoto et al [1904.07039]

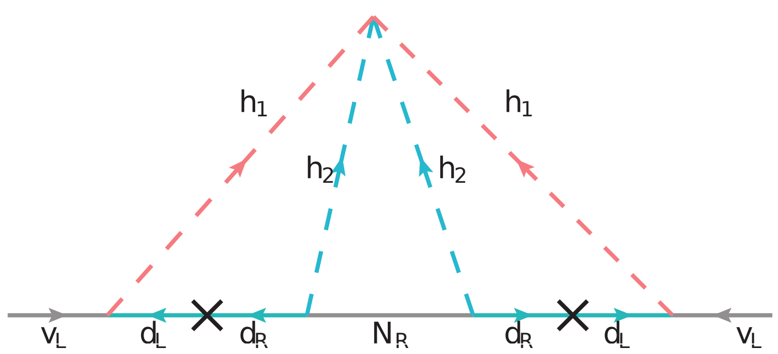
Scenarios comply with ν **data** (masses, mixings) for both NO and IO,
viable DM candidate (correct relic density) in **agreement with experimental bounds**

cLFV rates for Higgs decays **much larger** than those of pure leptonic cLFV modes
(important DM-mediated contributions to decays)

B-meson anomalies, m_ν, dark matter... and cLFV

- SM extended via **scalar leptoquarks** ($h_{1,2}$) and **lepton triplets** (Σ_R)

  Gauge group reinforced via $Z_2^{\rm DM}$ ⇒ **SU(3) x SU(2) x U(1) x $Z_2^{\rm DM}$**



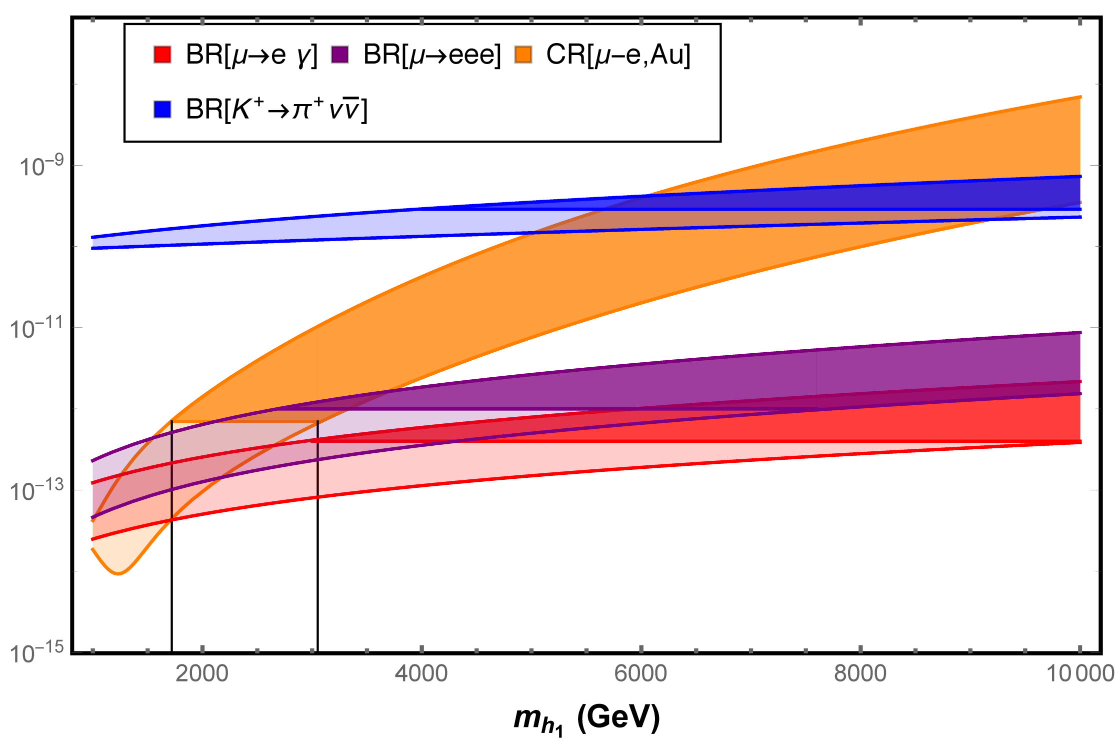
Hati, Kumar, Orloff, AMT [1806.10146]

⇒ Radiatively induced m_ν (3-loop, "KNT")

⇒ **Non-trivial structure** in leptoquark Yukawa couplings y

account for $R_{K^{(*)}}$ **anomalies**

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



Oscillation data (with **perturbative** couplings!)

viable **DM candidate** ⇝ Σ_R^0

Explain $R_{K^{(*)}}$ **anomalies** (but not $R_{D^{(*)}}$, nor Δa_μ)

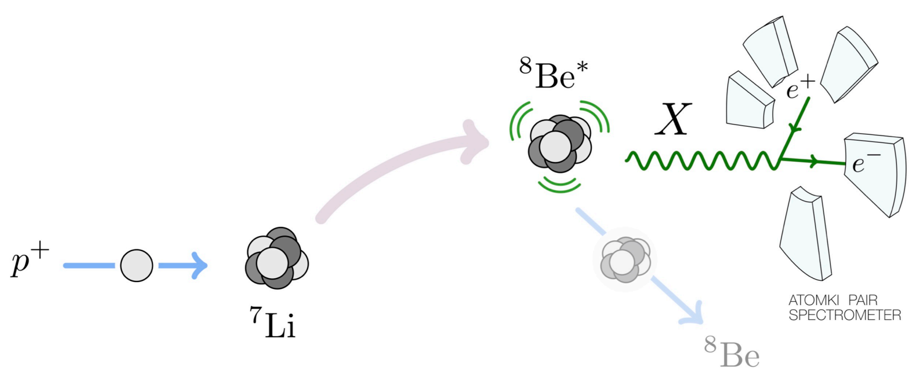
Leptoquarks and triplets within LHC reach

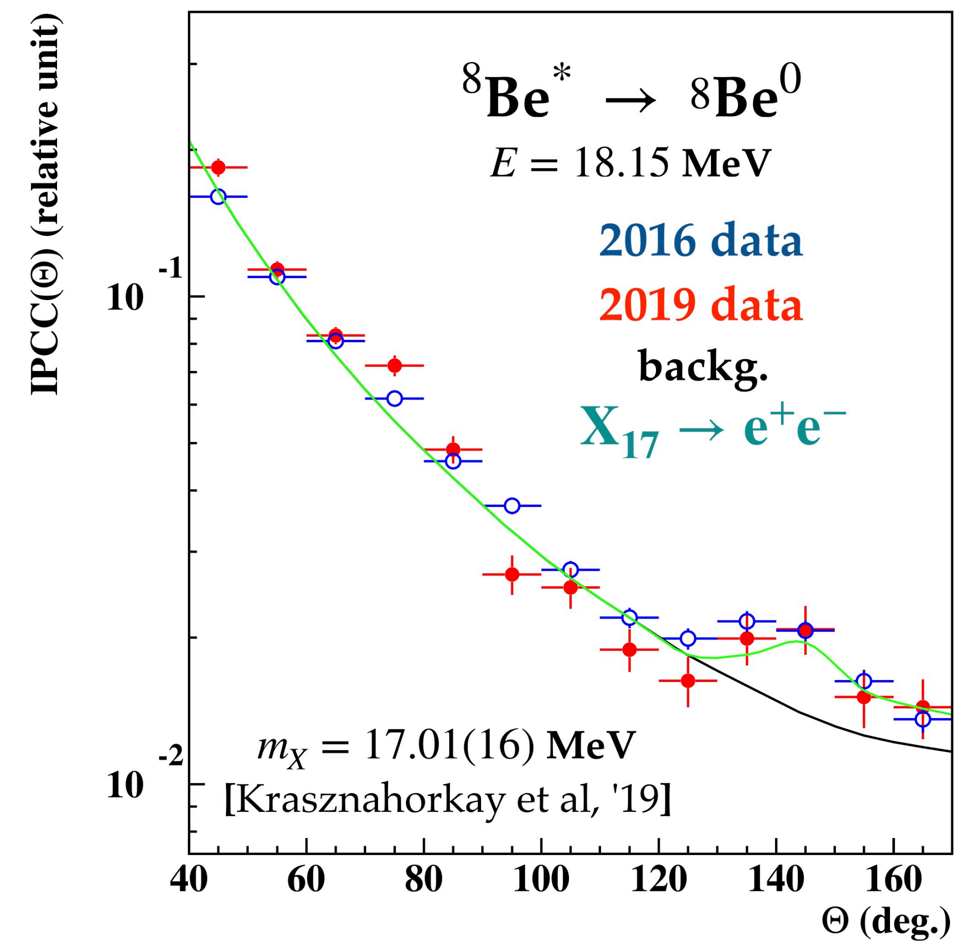
Strong constraints from **cLFV and kaon decays:**

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

Unflavoured atomic anomalies, m_ν and $(g-2)_\ell$

"Anomalies" in atomic decays: ^8Be and ^4He ⇒ further hints of NP? Flavoured or not?





Angular correlation of ^8Be e^+e^- internal pair creation

$$^8Be^*(j^\pi = 1^+, T=0) \to {}^8Be^0(j^\pi = 0^+, T=0) \quad @\ 5\sigma - 6\sigma$$

Similar deviations in ^4He e^+e^- angular correlation

$$^4He(0^- \to 0^+, E = 21.01\text{ MeV}) \quad @\ 7.2\sigma$$

⇒ Production and decay of (hypothetical) light vector boson $\quad m_X \sim 17$ MeV, $\Gamma_X \sim \mathcal{O}(10^{-5})$ eV

Feng et al [2006.01151]

⇒ If such a state exists, could it ease further SM "tensions"?

Unflavoured atomic anomalies, m_ν and $(g-2)_\ell$

A simultaneous explanation to Δa_μ and Δa_e^{Cs} and to ^8Be **atomic decay "anomaly"?**

⇒ Could a **light Z' boson framework** explain these and **account for neutrino masses?**

Minimal framework: **SU(3) x SU(2) x U(1) x U(1)$_{B-L}$** $\rightsquigarrow Z'$

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

⇒ m_ν from **mixings** with N_R and L^0 (dynamical seesaw)

diagonalisation of $\begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{v_X}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{v_X}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{v_X}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix}$ $\rightsquigarrow \boldsymbol{m_\nu} \simeq -\frac{y_\nu^2 v^2}{m_M}$ with **dynamical** $\boldsymbol{m_M} = v_X y_M$

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

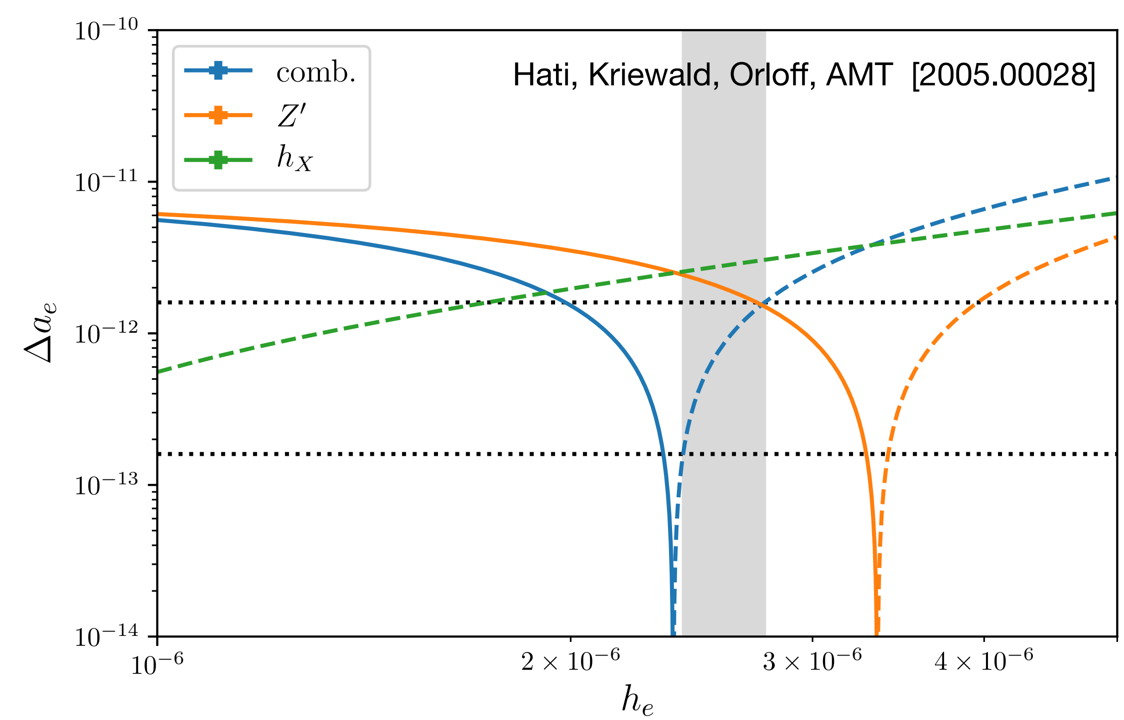
(regime subject to extensive experimental constraints!)

Cancellation of NP contributions: **saturate** Δa_μ and Δa_e^{Cs}

Constrained parameter space! ^8Be and $\Delta a_\mu \Rightarrow \Delta a_e$!

(More challenging with Δa_e^{Rb}...)

Minimal "prototype model" $\rightsquigarrow$ incorporated into protophobic U(1) SM extensions



The flavour puzzle: the role of symmetries

See talks by J.Valle, August 19th
P.Fileviez Perez, L.Merlo, S.Pokorsky, August 20th

Flavour symmetries & more

- **Hints of an organising principle:** reduce **arbitrariness** of flavour sources (Y^f_{ij}, LQ couplings...)

  $\Rightarrow$ **increase** prediction power (and **testability!**)

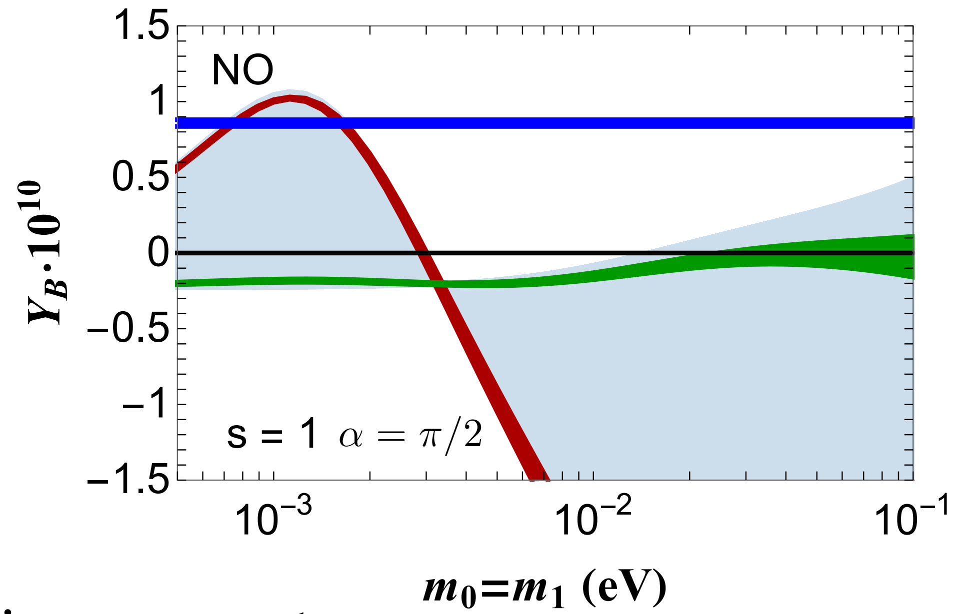
  Discrete and continuous (flavour) **symmetries**, extensions of the SM gauge group, ..., **GUTs**

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

  Patterns for **lepton mixings** and **CPV phases**

  $\Rightarrow$ predictions for m_{ee} $(0\nu2\beta)$

  $\Rightarrow$ interplay of **low-energy CP phases** and **BAU**



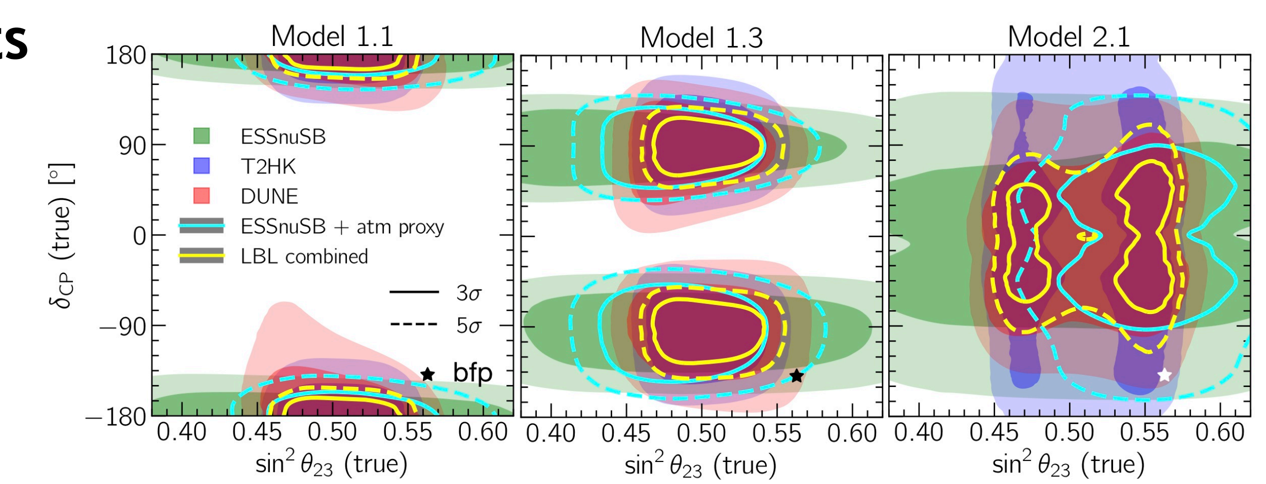
Hagedorn and Molinaro [1602.04206]

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

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

Model	Case [Ref.]	Group	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	δ_{CP}	$\chi^2_{\min}$
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
⋮						

Blennow et al [2005.12277]



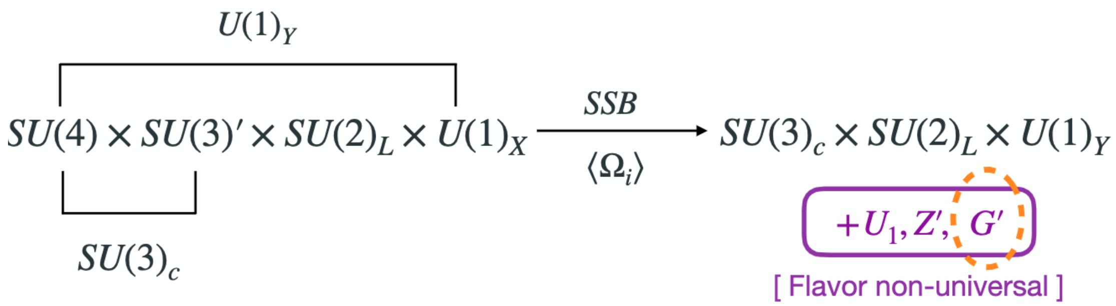
- **Restrictive Abelian groups:** U_1, Z_N and **Dirac ν (realised in 2HDM)**

  $\Rightarrow$ **Impact for tests** of **LFUV in $\tau \to \ell\nu\bar{\nu}$** decays and **cLFV rare decays...**

Correia et al [1909.00833]

Towards "complete" flavoured constructions

- From **Pati-Salam** $SU(4) \times SU(2)_L \times SU(2)_R$ to ***"4321"*** to ***"flavoured 4321" models***



See, e.g.,
di Luzio et al [1808.00942]
Bordone et al [1805.09328, 1903.11517]
Greljo and Stefanek [1802.04272], ...

Field	$SU(4)_3$	$SU(3)_{1+2}$	$SU(2)_L$	$U(1)_{Y'}$
q_L^i	**1**	**3**	**2**	$1/6$
u_R^i	**1**	**3**	**1**	$2/3$
d_R^i	**1**	**3**	**1**	$-1/3$
ℓ_L^i	**1**	**1**	**2**	$-1/2$
e_R^i	**1**	**1**	**1**	-1
ψ_L^3	**4**	**1**	**2**	0
$\psi_{R_{u,d}}^3$	**4**	**1**	**1**	$\pm 1/2$
χ_L^i	**4**	**1**	**2**	0
χ_R^i	**4**	**1**	**2**	0
$H_{1,15}$	**1, 15**	**1**	**2**	$1/2$
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$
Ω_{15}	**15**	**1**	**1**	0

Flavoured 4321: low-energy limit of PS^3

flavour dependent embedding

$\Rightarrow$ coloron G' coupled mostly to 3rd generation

$\Rightarrow$ **TeV scale U_1 (LH & RH couplings) and Z'; ν masses**

Cornella et al [2103.16558]

- **Neutrino masses** in **flavour non-universal Pati-Salam extra-dimensional 3-site model**

$\Rightarrow$ unification of all families of quark and leptons

$\Rightarrow$ natural description of SM Yukawa couplings

$\Rightarrow$ account for B-meson decay anomalies

Natural implementation of neutrino masses via
Inverse Seesaw (additional singlet fermions $S_L^{(i)}$)

Fuentes-Martin et al [2012.10492]

One of the most successful attempts at
UV completion!

Exciting prospects for
model building and
quark-lepton unification

Concluding remarks

New Physics and "flavoured" 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**

New Physics is there! Attempt at **identifying the underlying model** capable of accounting for *all* **SM problems** and **"tensions" with observation!**

(Possibly deeply related with ν**-mass generation**, or at least **encompassing a mechanism!**)

Explore different paths, and **profit from amazing experimental prospects in the near future!**

New Physics and "flavoured" lepton observables

IN2P3
Les deux infinis

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Explore different paths, and **profit from amazing** experimental prospects **in the near future!**

"Leave no (flavoured) stone unturned" -
leave no single grain of sand **unobserved,**
or flavour unte(a)sted! 😀

Thank you !