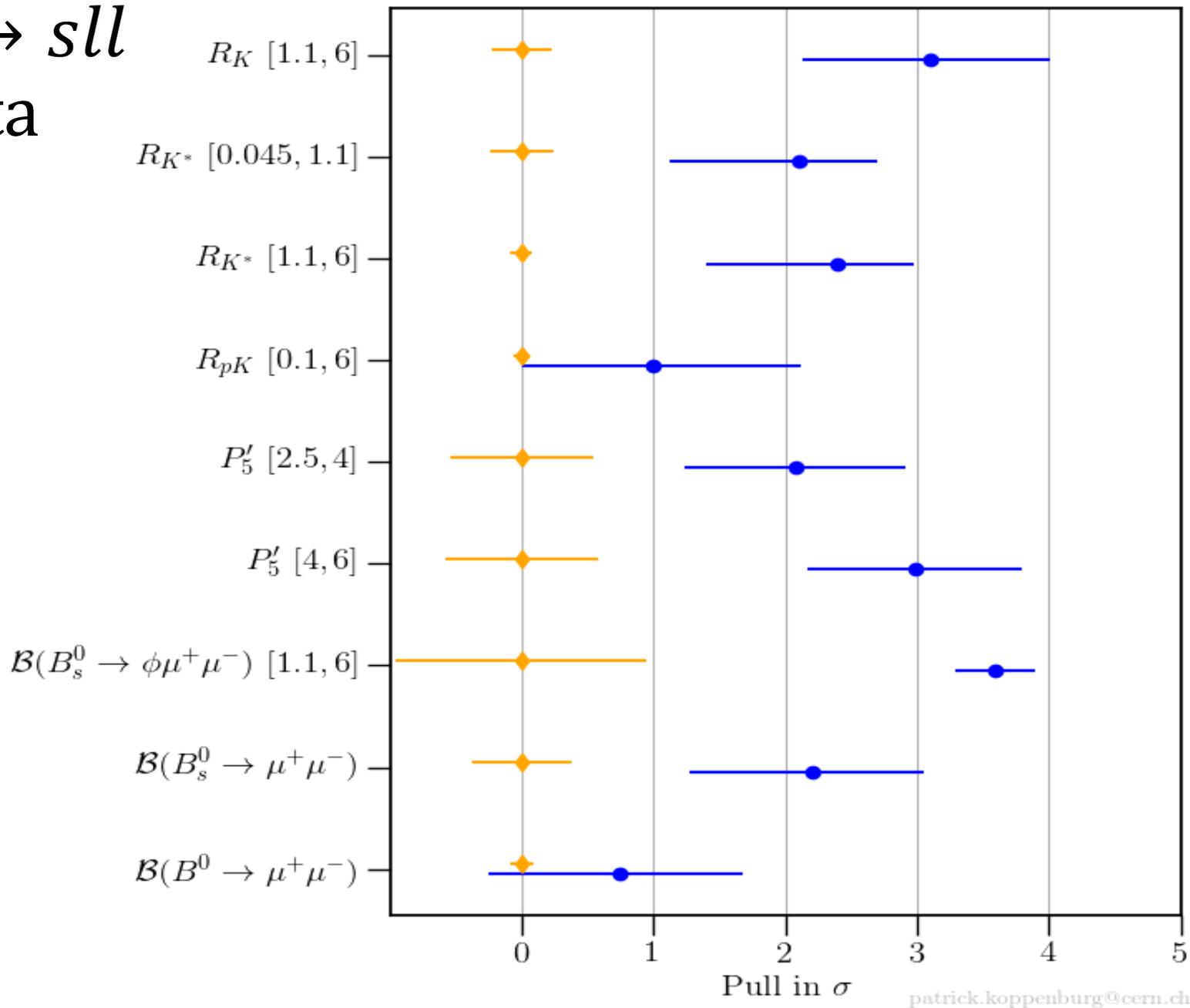


New physics in $b \rightarrow sll$ transitions

Joe Davighi, DAMTP/UZH

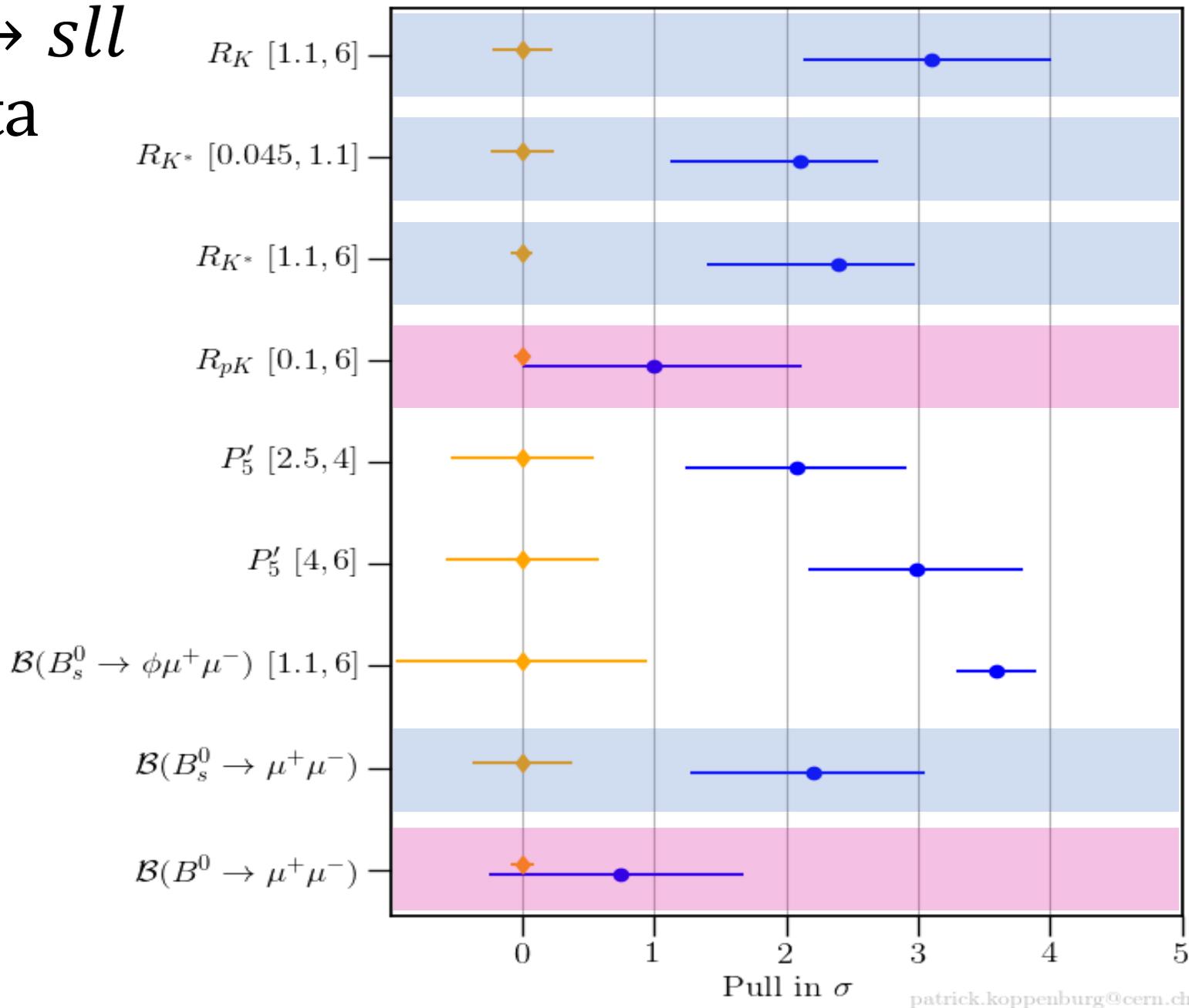
Anomalies and Precision in the Belle II era @ Vienna, September 2021

$b \rightarrow sll$
data



P. Koppenburg
(Twitter, July 29th 2021)

$b \rightarrow sll$ data



Theoretically cleanest
observables (that show
anomalies)

Clean, agree with SM

For the other observables,
hadronic effects *could* be
unexpectedly big
(as Mitesh & Nazila discussed)

P. Koppenburg
(Twitter, July 29th 2021)

The “clean” observables alone provide strong evidence for NP

(see Nazila’s talk)

E.g. $\sqrt{\Delta\chi^2} = 4.6\sigma$ for $\Delta C_L \neq 0$ vs. SM

$$(\overline{s_L}\gamma_\rho b_L)(\overline{\mu_L}\gamma^\rho \mu_L)$$

Hurth, Mahmoudi, Martínez Santos, Neshatpour, 2104.10058

Similar results obtained in

Altmannshofer, Stangl, 2103.13370

Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert 2103.16558

Geng, Grinstein, Jäger, Li, Camalich, Shi, 2103.12738

Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet, 2104.08921

Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, 2103.12504

...

See also Lancierini, Isidori, Owen, Serra, 2104.05631

Including all observables, significance is greater still

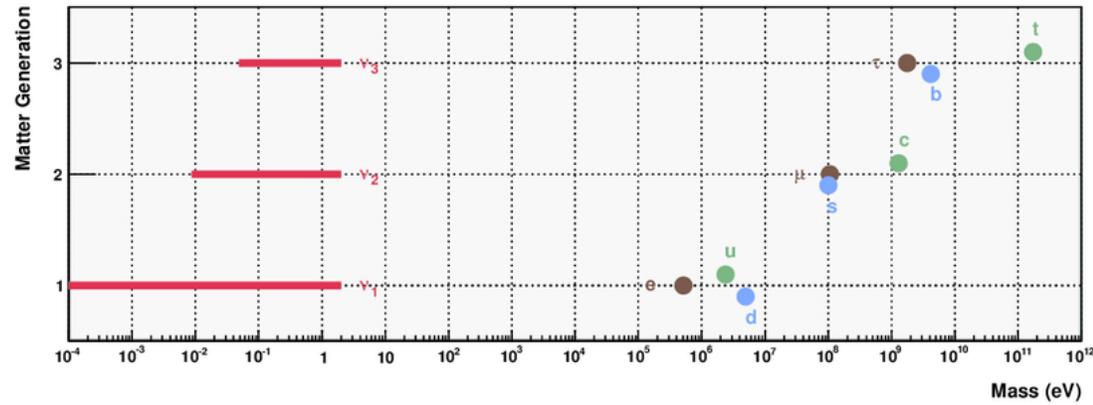
Let's suppose these $b \rightarrow sll$ anomalies persist, and will be confirmed by Belle II ;)

What might they be telling us about NP?

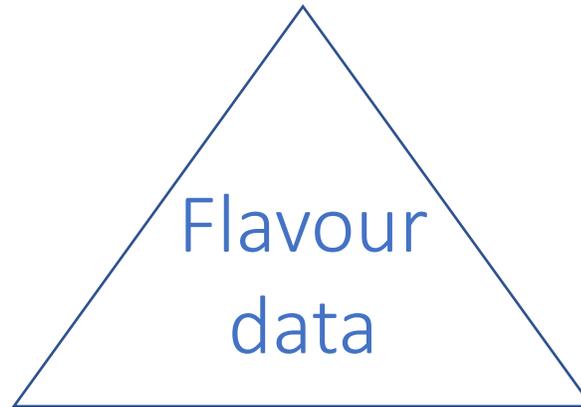
Let's take a broader view of flavour data:

1. Hierarchies:

Fermion masses and mixing angles



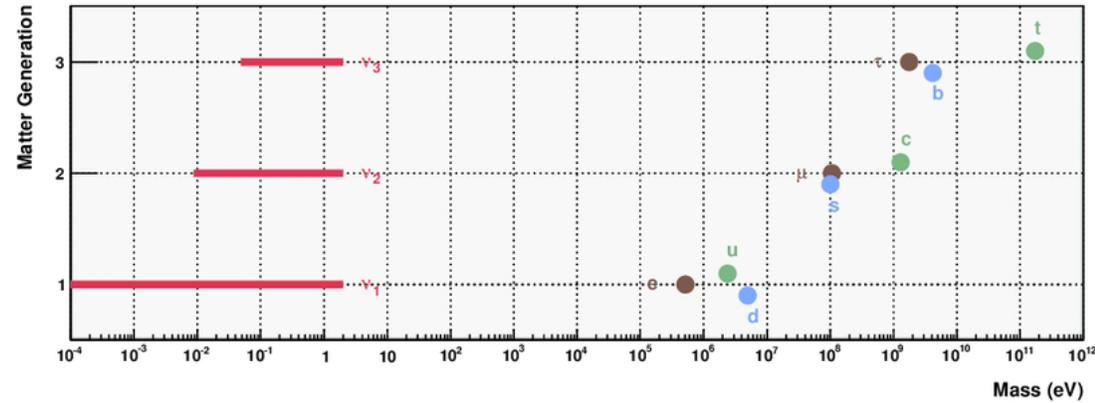
From 1109.5515



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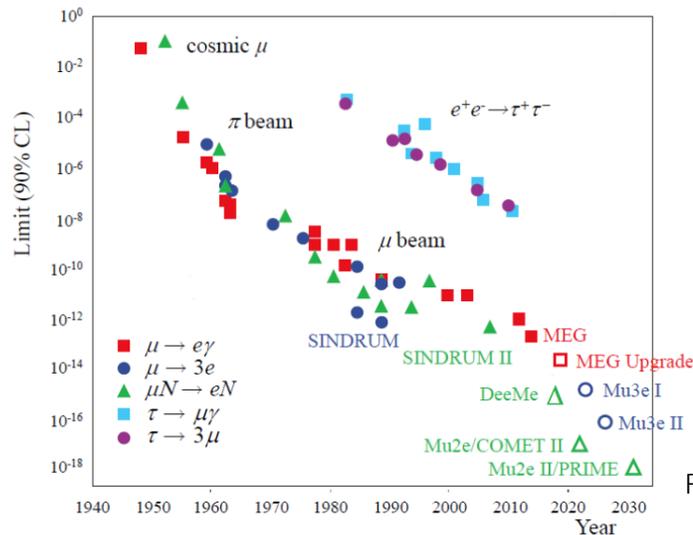
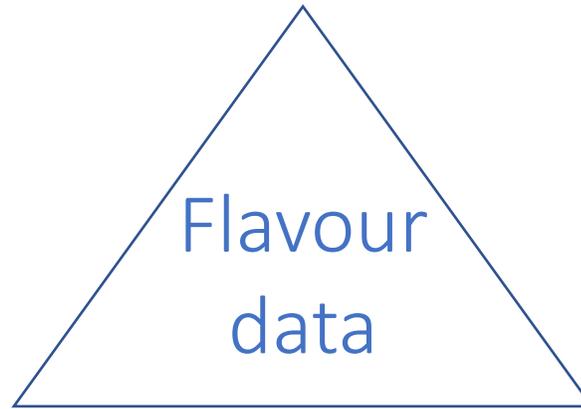
Fermion masses and mixing angles



From 1109.5515

2. Accidents:

No lepton flavour violation;
No baryon number violation



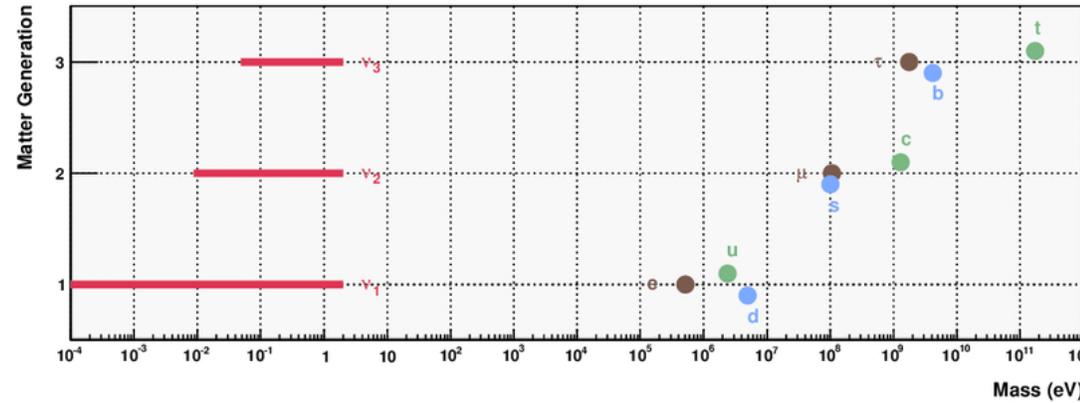
F. Cei @ KAON2019

Joe Davighi, DAMTP/UZH

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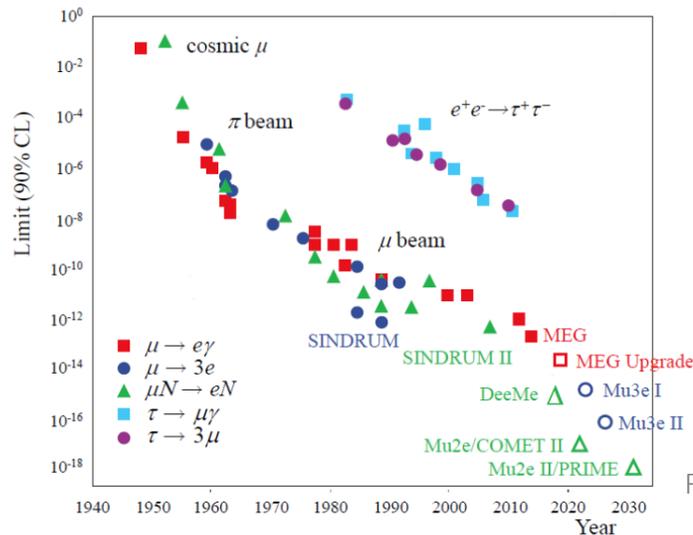
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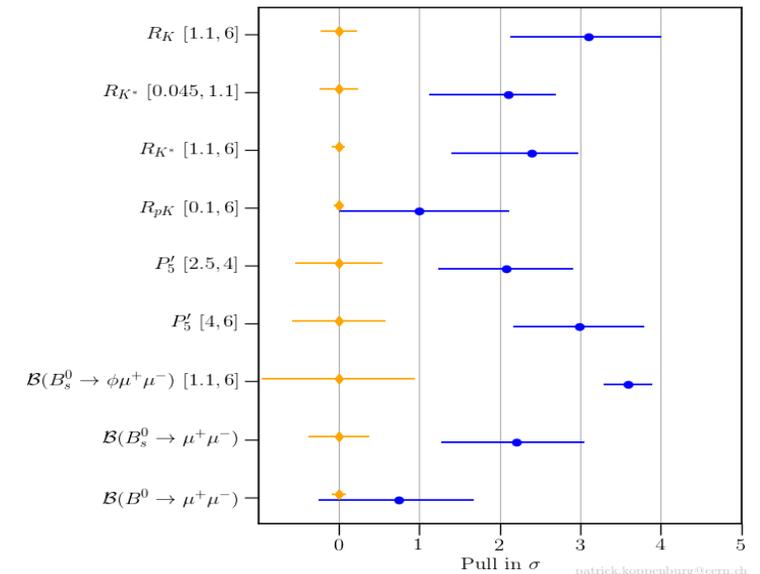
F. Cei @ KAON2019

Joe Davighi, DAMTP/UZH

Flavour data

3. Anomalies:

$b \rightarrow sll + \text{others}$

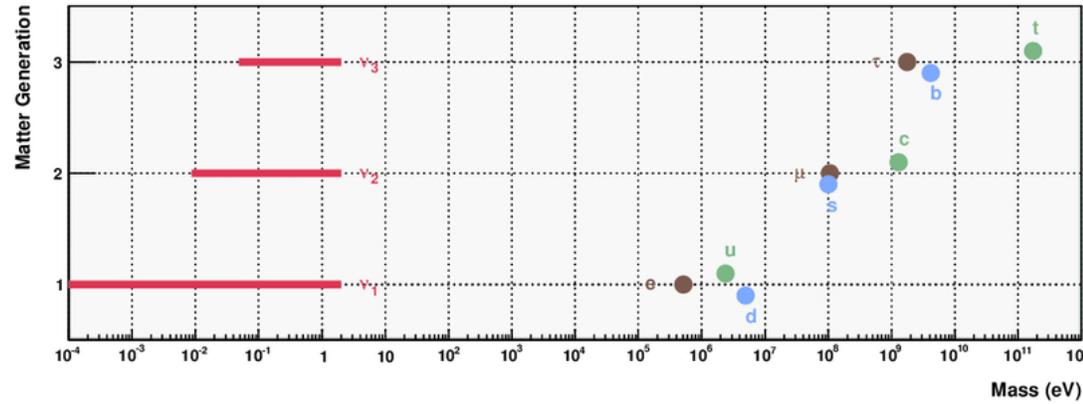


patrick.koppenburg@cern.ch

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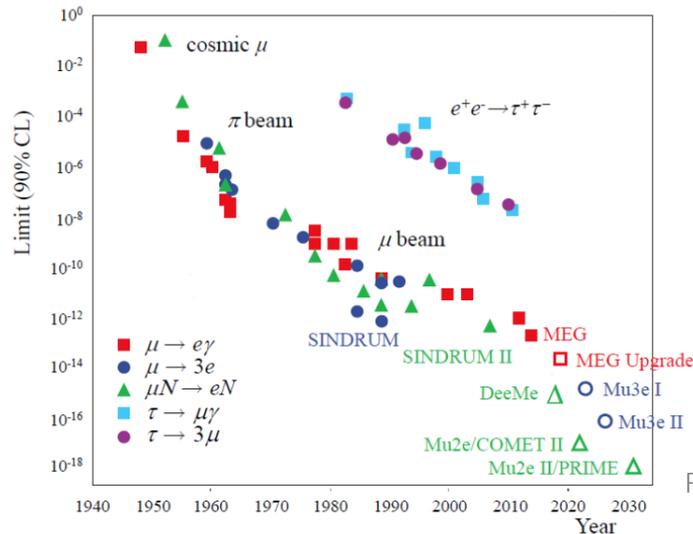
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From 1109.5515

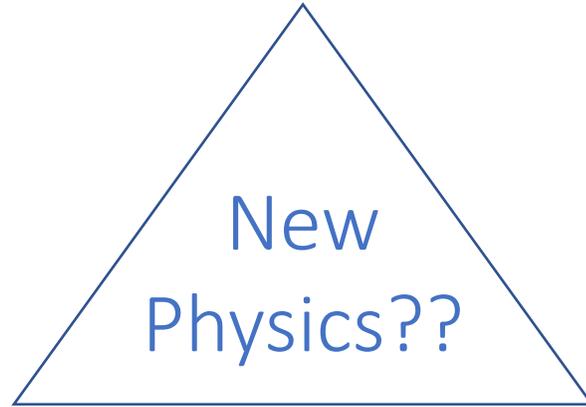
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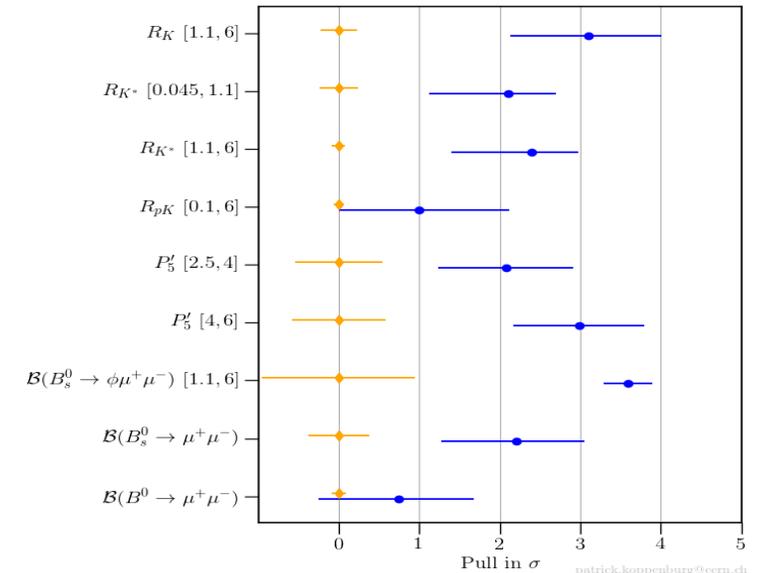
F. Cei @ KAON2019

Joe Davighi, DAMTP/UZH



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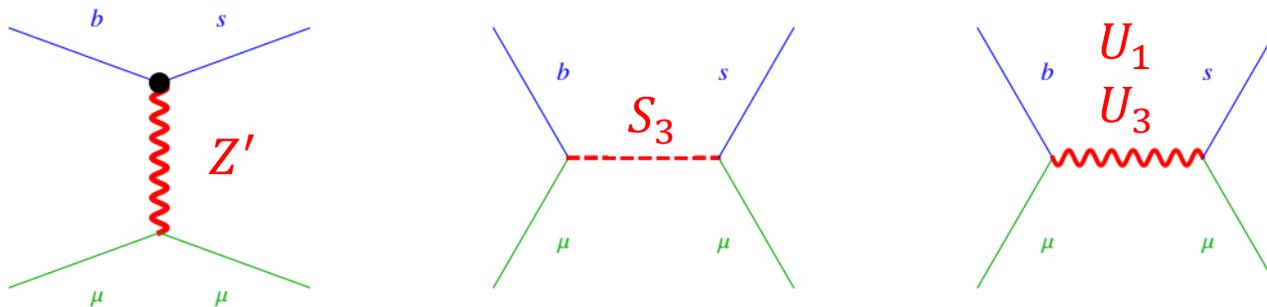
$b \rightarrow sll + \text{others}$



patrick.koppenburg@cern.ch

General lessons for NP models

1. Hierarchies \Rightarrow suggest (approximate) global symmetries $H \subset U(3)^5$ e.g. $U(2)^5$
2. Accidents \Rightarrow need $U(1)^4 := U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_B$ global symmetries; as exact as possible
3. Anomalies \Rightarrow new particles. If tree-level, mass/g $\sim 3 \text{ TeV}/0.1$:

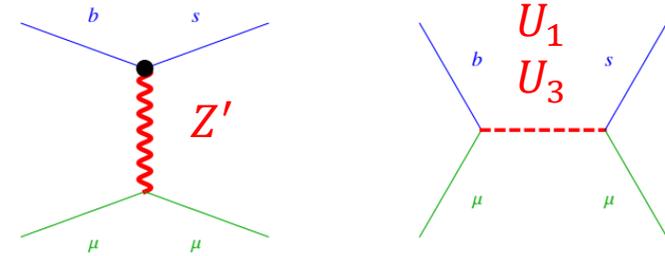


Linking hierarchies + accidents + anomalies

- Can efficiently connect the $b \rightarrow sll$ NP particles with hierarchies + accidents by introducing a [new gauge symmetry](#) (NP particles = heavy gauge bosons), designed to simultaneously modify the (approximate) global symmetry structure at low energies

Linking hierarchies + accidents + anomalies

- Can efficiently connect the $b \rightarrow sll$ NP particles with hierarchies + accidents by introducing a **new gauge symmetry** (NP particles = heavy gauge bosons), designed to simultaneously modify the (approximate) global symmetry structure at low energies
 - Ignoring CC anomalies ($R_{D^{(*)}}$), only need a neutral Z' gauge boson; a **gauged $U(1)_X$** will do! **[this talk]**
 - To also explain CC anomalies, want **VLQs** e.g. $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$ arising from **non-abelian symmetries**, such as **Pati-Salam** or related groups. Example: $PS^3 \rightarrow SM$ gives $U(2)^5$ global symmetry [not in this talk – sorry!]

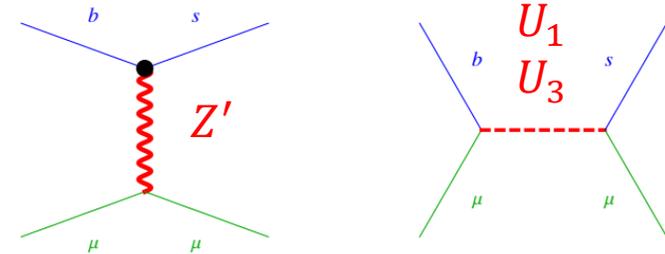


Linking hierarchies + accidents + anomalies

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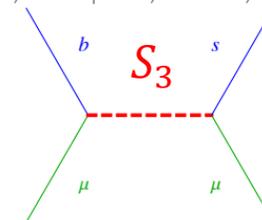
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- On the other hand, **SLQs** don't shed light on hierarchies/accidents unless we add extra structure, e.g.
 - Partial compositeness – also explains lightness of new scalar
 - Charge the SLQ under a new gauge symmetry** **[this talk]**

Gripaios, 0910.1789; Gripaios, Renner, Nardecchia, 1412.1791



Let's look at some Z' and SLQ examples which offer joint explanations of hierarchies and/or accidents

The Z' option: anomaly-free $U(1)_X$ [Part I]

Q: How big a global symmetry do we want $U(1)_X$ to preserve?

Extreme case: full $U(3)_{q,u,d}^3$ quark symmetry

If no BSM fermions, only anomaly-free options are $X = L_i - L_j$

- E.g. $X = L_\mu - L_\tau$ + extra heavy quark for $b \rightarrow s$ mixing; can explain $b \rightarrow sll$ data with renormalizable model
- Lepton Yukawa precisely diagonal \therefore exact $U(1)^4$ accidental symmetries (even though we have LFUV)

If SM + 3 singlets, can gauge any $X = \sum_{i=1}^3 a_i L_i - (a_e + a_\mu + a_\tau)B/3$

BUT: these $U(3)_{q,u,d}^3$ models cannot explain any hierarchies;

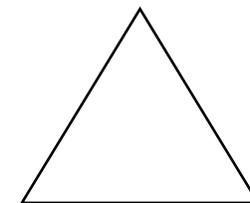
All Yukawas allowed at renormalizable level by construction!

He, Joshe, Lew, Volkas, 1991

Altmannshofer, Gori, Pospelov, Yavin, 1403.1269
Altmannshofer, Gori, Pospelov, Yavin, 1406.2332
Crivellin, D'Ambrosio, Heeck, 1501.00993
Altmannshofer, Yavin, 1508.07009
Crivellin, Fuentes-Martín, Greljo, Isidori, 1601.02703

Slavioni, Strumia, Villadoro, Zwirner, 0911.1450,
Altmannshofer, JD, Nardecchia, 1909.02021

1. Hierarchies



2. Accidents

3. Anomalies

The Z' option: anomaly-free $U(1)_X$ [Part II]

Q: *How big* a global symmetry do we want $U(1)_X$ to preserve?

Smaller $U(2)_{q,u,d}^3 \subset U(3)_{q,u,d}^3$ symmetry \Rightarrow start to explain hierarchies

Pomarol, Tommassini, hep-ph/9507462
Barbieri, Dvali, Hall, hep-ph/9512388
Barbieri, Isidori, Jones-Perez, Lodone, Straub, 1105.2296
Blankenburg, Isidori, Jones-Perez 1204.0688
Barbieri, Buttazzo, Sala, Straub, 1203.4218

Examples:

$X = Y_3$ and deformations, $X = L_\mu - L_\tau - a(B_1 + B_2 - 2B_3)$, gauging $U(1)_X \subset U(2)$

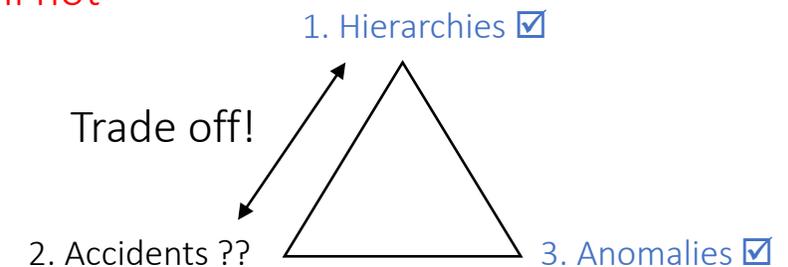
- Can explain hierarchies with 3rd family in quark Yukawas, w/o contravening flavour data
- Remaining 1st-2nd hierarchies then explained by controlled $U(2)_{q,u,d}^3$ breaking

Allanach, JD, 1809.01158
Allanach, JD, 1905.10327
Crivellin, D'Ambrosio, Heeck, 1503.03477
Calibbi, Crivellin, Kirk, Manzari, Montull, 1910.00014
Falkowski, Nardecchia, Ziegler, 1509.01249

BUT:

- Now we *need* higher-dim operators with low suppression scale, to explain light Yukawas. Even if $U(1)^4$ are accidental symmetries of renormalizable lagrangian, $U(1)^4$ will not persist to “infinite order” in the EFT

\rightarrow Key Q: can we preserve the high quality accidental symmetries that ban LFV, while explaining light Yukawas?



The Z' option: anomalous $U(1)_X$

JD, 2105.06918.

Gauge $X = Y_3 + \frac{a}{6}(L_\mu - L_\tau)$, $a > 9$ (ish).

Anomaly cancellation at TeV scale via pair of *charged fermions* $\sim [1,30]$ TeV

Hierarchies:

$\Lambda \in [70, 210]$ TeV

$$Y_u = y_t \begin{pmatrix} \frac{\Delta_u^{ab}\Phi}{\Lambda^2} & \frac{V_q^a}{\Lambda} \\ 0 & 1 \end{pmatrix} + \text{dim } 9$$

$$Y_d = y_b \begin{pmatrix} \frac{\Delta_d^{ab}\Phi}{\Lambda^2} & \frac{V_q^a}{\Lambda} \\ 0 & 1 \end{pmatrix} + \text{dim } 7$$

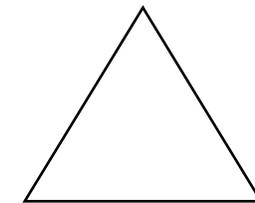
Accidents:

$$Y_e = \begin{pmatrix} c_e \frac{\epsilon_\Phi^3}{\Lambda^3} & 0 & 0 \\ 0 & c_\mu \frac{\epsilon_\Phi^3}{\Lambda^3} & 0 \\ 0 & 0 & y_\tau \end{pmatrix} + \text{dim } > 10$$

Field	Chirality	G_{SM}	$6 \times U(1)_X$
ψ_1	L	$(\mathbf{1}, \mathbf{1}, y/6)$	$3y + \frac{3a}{2y} + \frac{1}{2}$
ψ_2	L	$(\mathbf{1}, \mathbf{1}, y/6)$	$3y - \frac{3a}{2y} - \frac{1}{2}$
χ_1	R	$(\mathbf{1}, \mathbf{1}, y/6)$	$3y + \frac{3a}{2y} - \frac{1}{2}$
χ_2	R	$(\mathbf{1}, \mathbf{1}, y/6)$	$3y - \frac{3a}{2y} + \frac{1}{2}$

1. Hierarchies

2. Accidents



3. Anomalies
(see backup)

$\mu \rightarrow e\gamma$, due to dim > 12 operators. Need

$$\frac{\Lambda}{\sqrt{\tilde{c}}} \epsilon_\Phi^{-\frac{a-3}{2}} \gtrsim 58\,000 \text{ TeV} \quad (\text{Satisfied for order-1 WCs})$$

$l_j \rightarrow 3l_i$, due to dim > 15 operators.

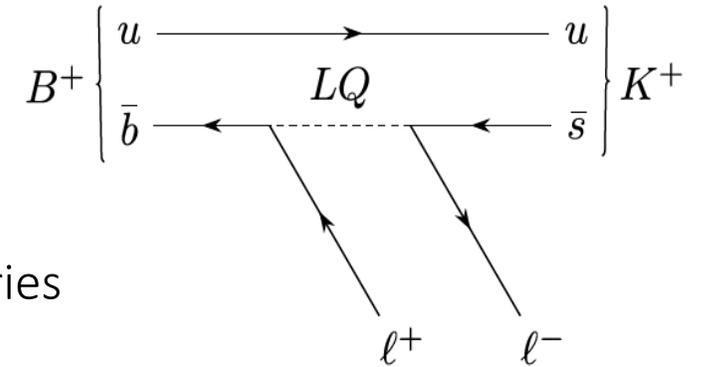
$$\Delta BR(\mu \rightarrow 3e) \sim \frac{m_\mu^5}{768\pi^3\Gamma_\mu} \frac{1}{\Lambda^4} \epsilon^{2a} \lesssim 10^{-29} \quad \text{etc tiny!!}$$

The SLQ option

Explain $b \rightarrow sll$ via $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, \frac{1}{3})$; desirable coupling $Q_3 S_3 L_2 \Rightarrow b \rightarrow sll$

But would also expect similar size couplings

- $Q_i S_3 Q_j \Rightarrow$ B violation ($i = j = 1$) ...
- $Q_i S_3 L_{1,3} \Rightarrow$ LFV... expect gross violation of SM accidental symmetries

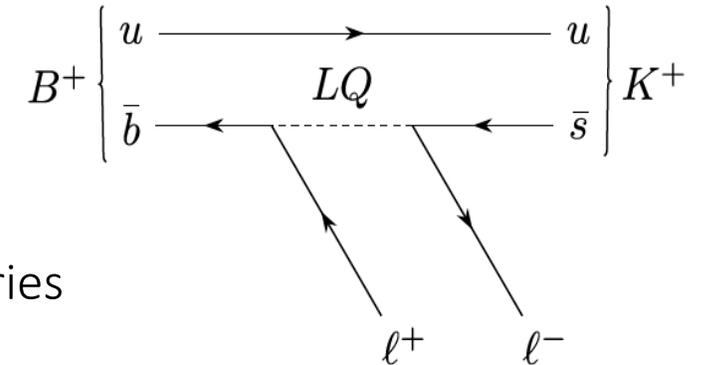


The SLQ option: from Leptoquarks to Muoquarks

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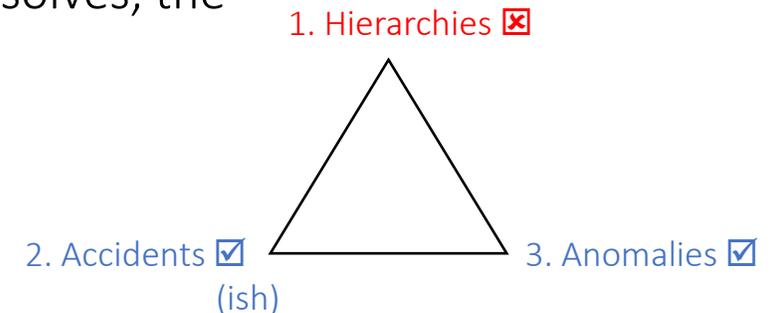
Resolution: charge S_3 under a *lepton-flavoured, anomaly-free* $U(1)_X$ gauge symmetry

Example 1: $X = L_\mu - L_\tau$, assign S_3 a charge $X = -1$.

- $Q_3 S_3 L_i$ is $U(1)_X$ -invariant only for $i = 2$; hence “muoquark”; suppressed LFV
- Diquark operators at **dim-5**, if the model is to minimally explain neutrino masses. For order-1 WCs, still requires $\Lambda > M_{\text{Pl}}$; so this only ameliorates, rather than solves, the proton decay problem.

JD, Kirk, Nardecchia
2007.15016

Hambye, Heeck
1712.04871

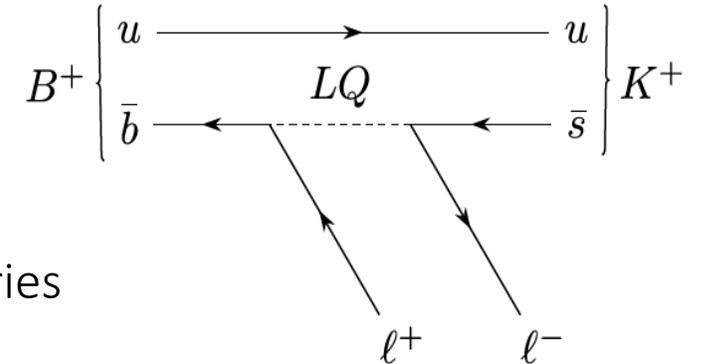


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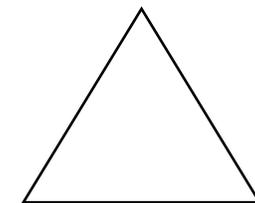
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- Diquark operators at **dim-5**, if the model is to minimally explain neutrino masses. For order-1 WCs, still requires Λ transplanckian; so this only ameliorates, rather than solves, the proton decay problem.
- But with more complicated neutrino mass mechanism (more scalars), can push back diquark ops to **dim-6**; good enough B number protection

JD, Kirk, Nardecchia
2007.15016

Hambye and Heeck
1712.04871

1. Hierarchies



2. Accidents

3. Anomalies

Finally, there are also other intriguing anomalies. Principally:

- $(g - 2)_\mu$

See Dominik Stoeckinger's talk

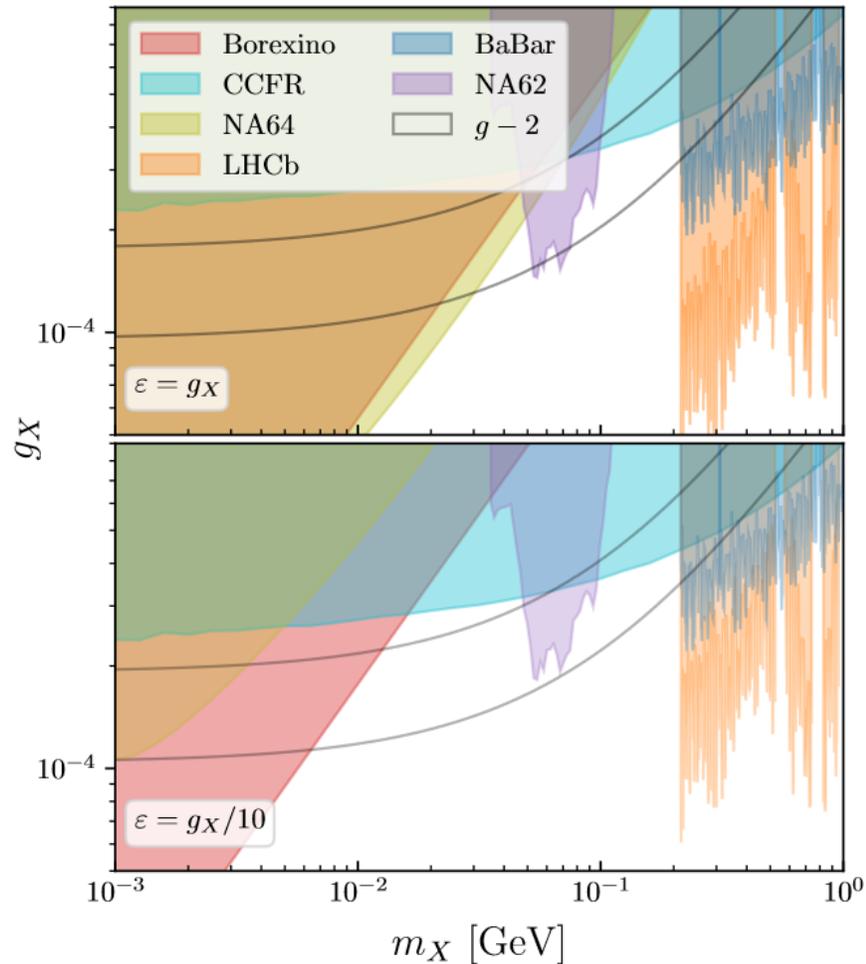
- $b \rightarrow c\tau\nu$ e.g. $R_{D^{(*)}}$

See Monika Blanke's talk

Charged SLQs are good candidates for explaining these leptonic anomalies, while preserving accidental symmetries

In the $X = L_\mu - L_\tau$ charged muoquark above,

the light Z' can explain $(g - 2)_\mu$,¹ no further ingredients needed



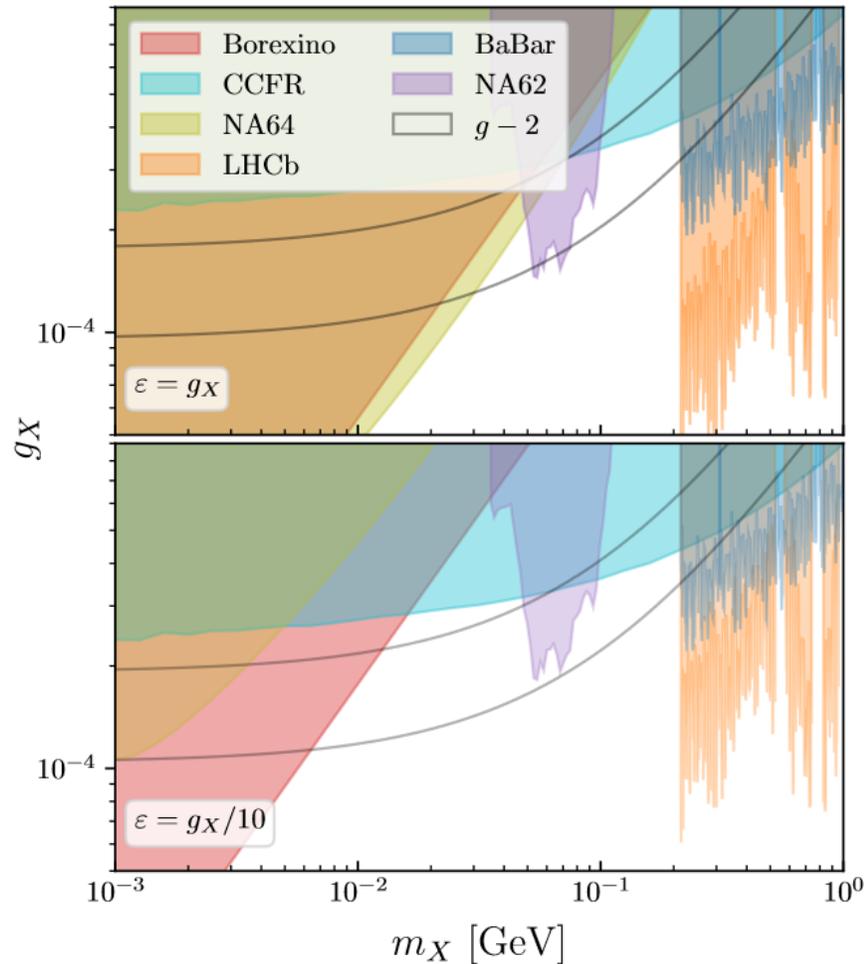
Greljo, Stangl, Eller Thomsen, 2103.13991

¹n.b. not possible to explain $b \rightarrow sll$ and $(g - 2)_\mu$ anomalies with a single Z' , largely due to neutrino trident constraint

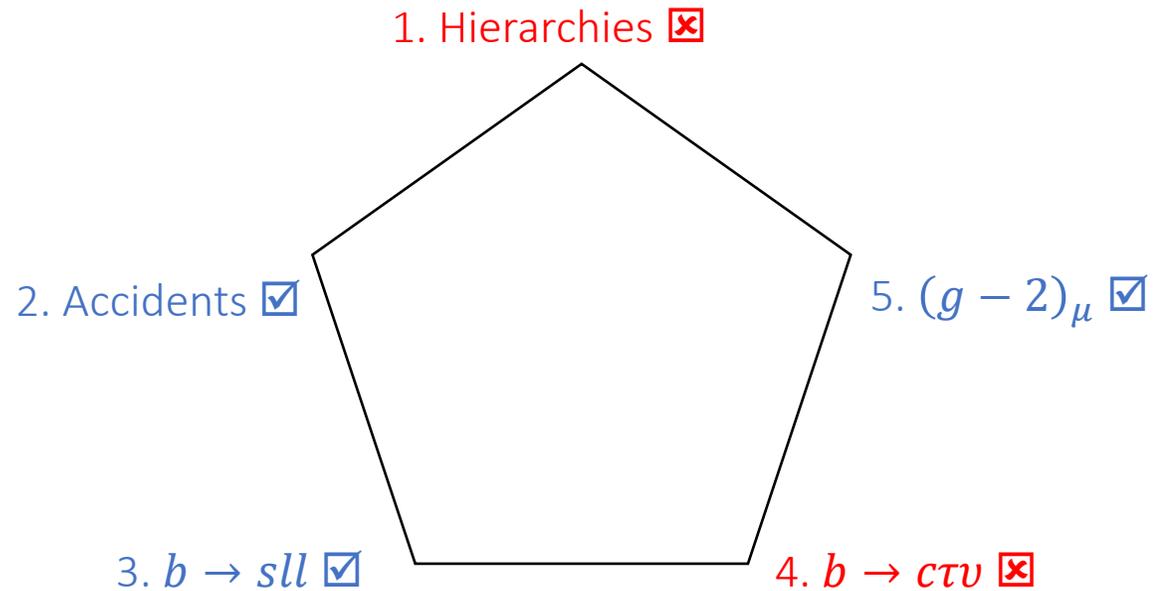
Eller-Thomsen, Greljo, Stangl, Soreq, Zupan 2107.07518
 See also Altmannshofer, Gori, Pospelov, Yavin 1406.2332, Sala, Straub 1704.06188,
 Altmannshofer, Gori, Martin-Albo, Sousa, Wallbank, 1902.06765

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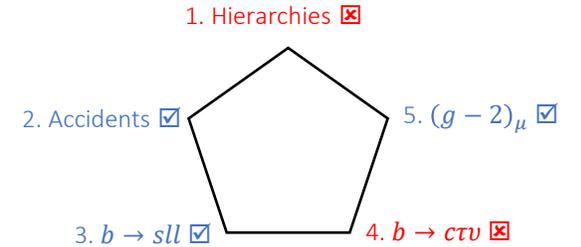
Altmannshofer, Gori, Martin-Albo, Sousa, Wallbank, 1902.06765

More Muoquarks

Example 2: $X = B - 3L_\mu$, $+ S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$ ($X = 8/3$) $+ S_3$ ($X = 8/3$)

- Diquark operators dim-6; good enough B number protection
- S_1 explains $(g - 2)_\mu$; S_3 explains $b \rightarrow sll$

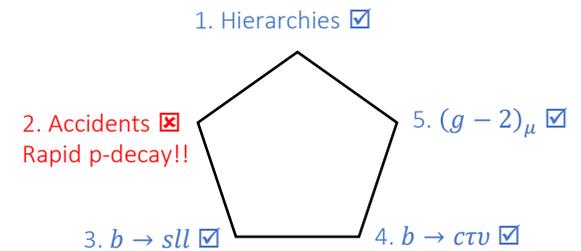
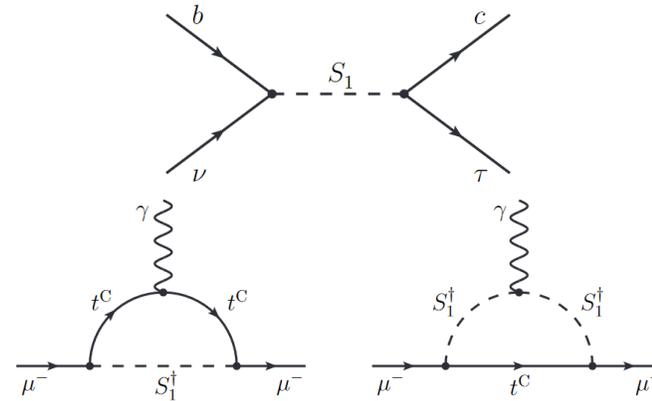
Greljo, Stangl, Eller Thomsen, 2103.13991



Example 3: $X = B_3 - \frac{2}{3}L_\mu - \frac{1}{3}L_\tau$, $+ S_1$ ($X = 1/3$)

- Fermion mass hierarchies
- $b \rightarrow sll$ (heavy Z'), $(g - 2)_\mu$ and $b \rightarrow c\tau\nu$ (S_1).
- BUT: B -violation at renormalizable level!

Wang, 2108.01279



A systematic analysis of (many) more such $U(1)_X$ -charged LQ models reveals many via models, including chiral ones:

- $(X_{L_1}, X_{L_2}, X_{L_3}) = (0, 7, -7)$, $(X_{E_1}, X_{E_2}, X_{E_3}) = (-3, 8, -5)$, $X_{\text{quark}} = 0$
- $(X_{L_1}, X_{L_2}, X_{L_3}) = (-3, 8, 4)$, $(X_{E_1}, X_{E_2}, X_{E_3}) = (-2, 9, 2)$, $X_{\text{quark}} = -1$
- ...

Eller-Thomsen, Greljo, Stangl, Soreq, Zupan, 2107.07518

Summary

- $b \rightarrow sll$ anomalies are sticking around, for now – we await Belle II!
- Tempting to tie in $b \rightarrow sll$ anomalies with a symmetry-based mechanism for fermion masses and/or SM accidental symmetries
- Focussed on two classes of example:
 - Anomaly-free and anomalous $U(1)_X$ models
 - Scalar “muoquarks” [can also explain $(g - 2)_\mu$ and $b \rightarrow c\tau\nu$ anomalies]
- In both cases, the new gauge symmetry modifies the global symmetry structure of the lagrangian, to explain hierarchies and/or accidents

Summary of stuff I left out

Did *not* discuss:

- Vector leptoquarks! Natural combined explanations for NC and CC B-anomalies; arise e.g. in multi-site Pati-Salam theories that explain fermion mass hierarchies
- Loop models, feebly-interacting particles, SUSY models, many more...

Also did not discuss other hints of flavoured NP:

- Cabibbo anomaly See Matthew Kirk's talk
- Non-resonant lepton pairs at high p_T CMS, 2103.02708. See Claudio Manzari's talk
- 400 GeV resonance in $t\bar{t}$ CMS, 2008.07860
- ...

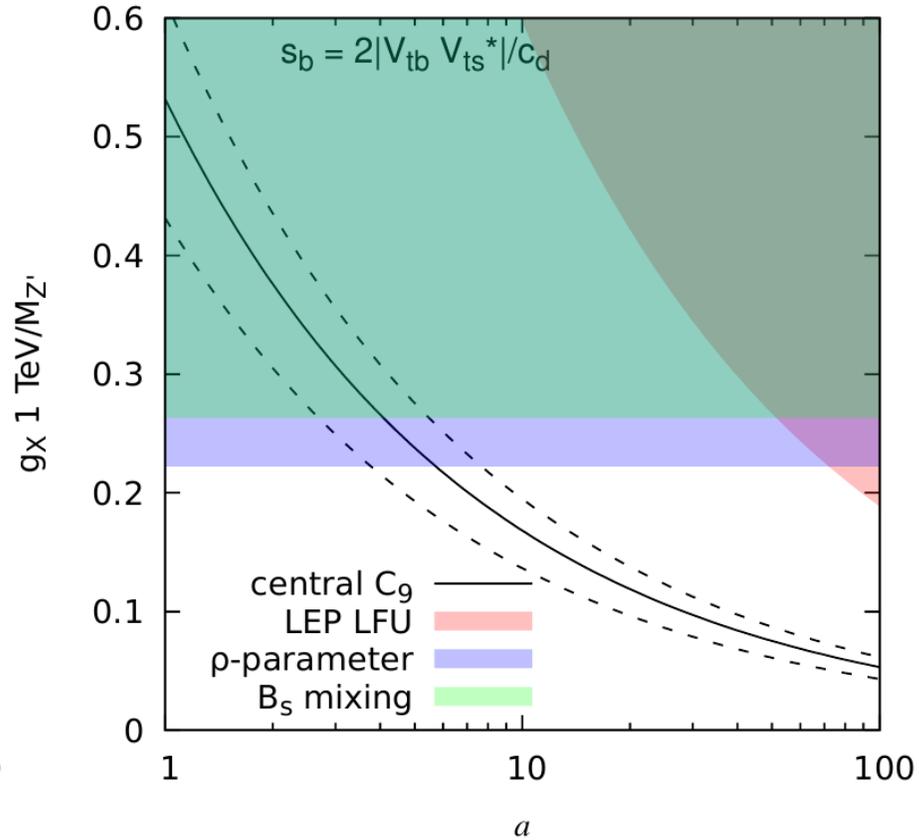
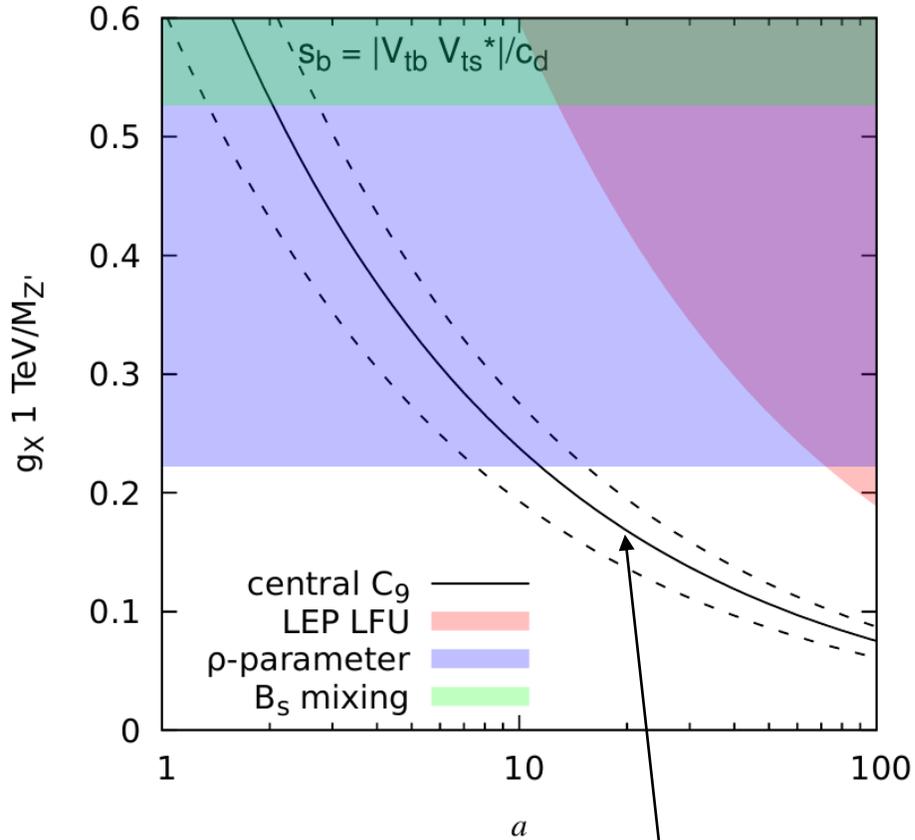
If persistent, some of these anomalies might *also* be explained by flavoured NP that might simultaneously shed light on accidents + hierarchies.

Backup slides

Fit to $b \rightarrow sll$ in anomalous Z' model

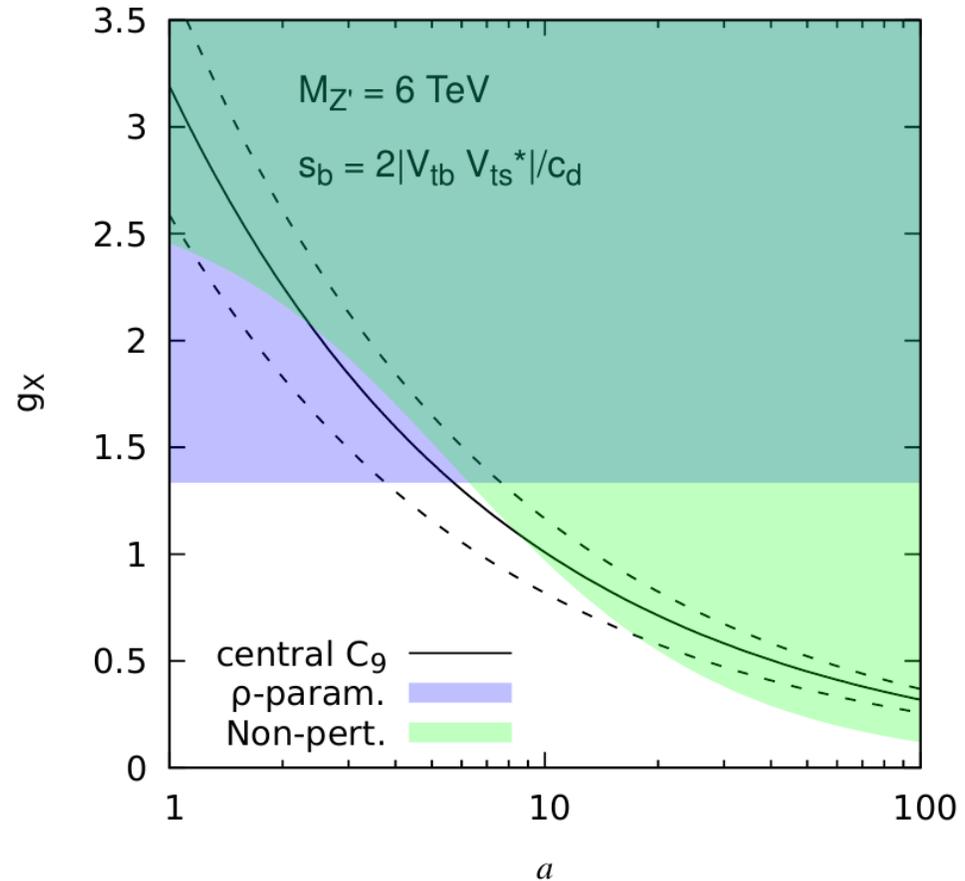
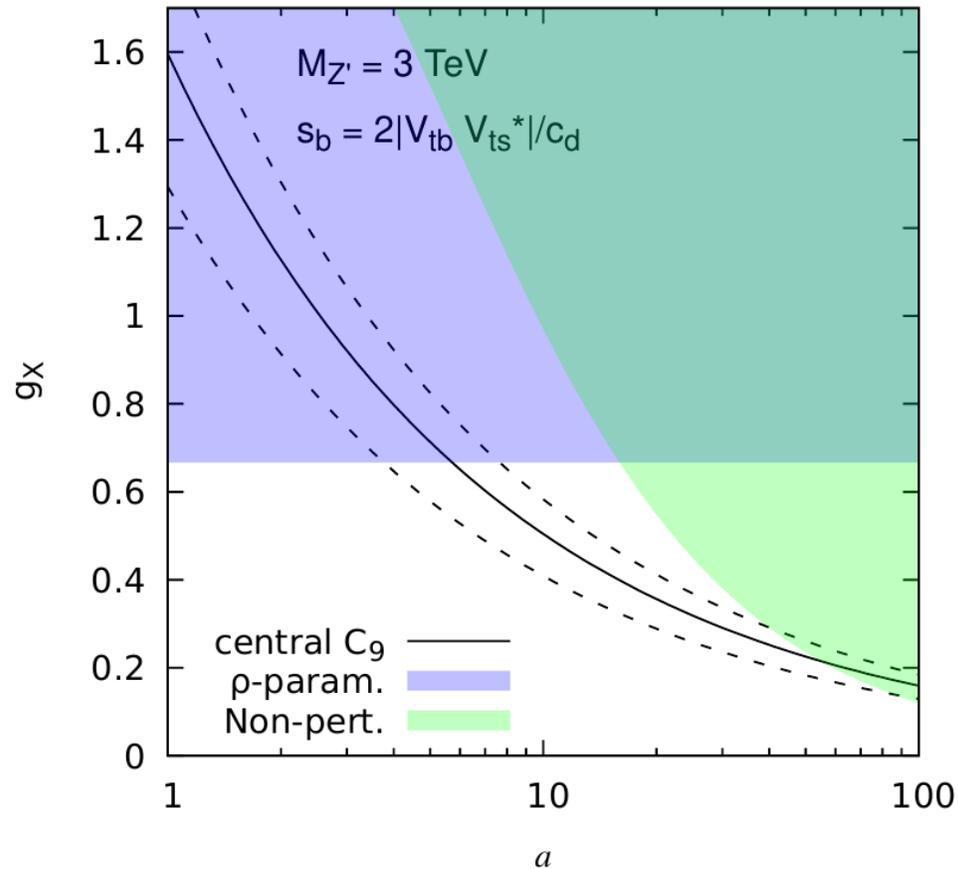
$$X = Y_3 + \frac{a}{6} (L_\mu - L_\tau)$$

The Z' is the new particle explaining the $b \rightarrow sll$ anomalies via a vector-like muon current $\Delta C_9^{bs\mu\mu} = ag_X^2 \frac{c_d s_b}{V_{tb} V_{ts}^*} \frac{1.45 \text{ TeV}^2}{M_{Z'}^2}$



$\Delta C_9 = -0.82_{-0.14}^{+0.14}$ [Altmannshofer & Stangl, 2103.13370]

Can put an upper bound on a from **perturbativity** of Z' couplings $X = Y_3 + \frac{a}{6}(L_\mu - L_\tau)$



$M_X = 3$ TeV should be safe from direct searches; **can access $6 < a < 50$** or so.

$M_X < 6$ TeV or so from combined constraints + perturbativity