Model building in relation to recent flavour anomalies

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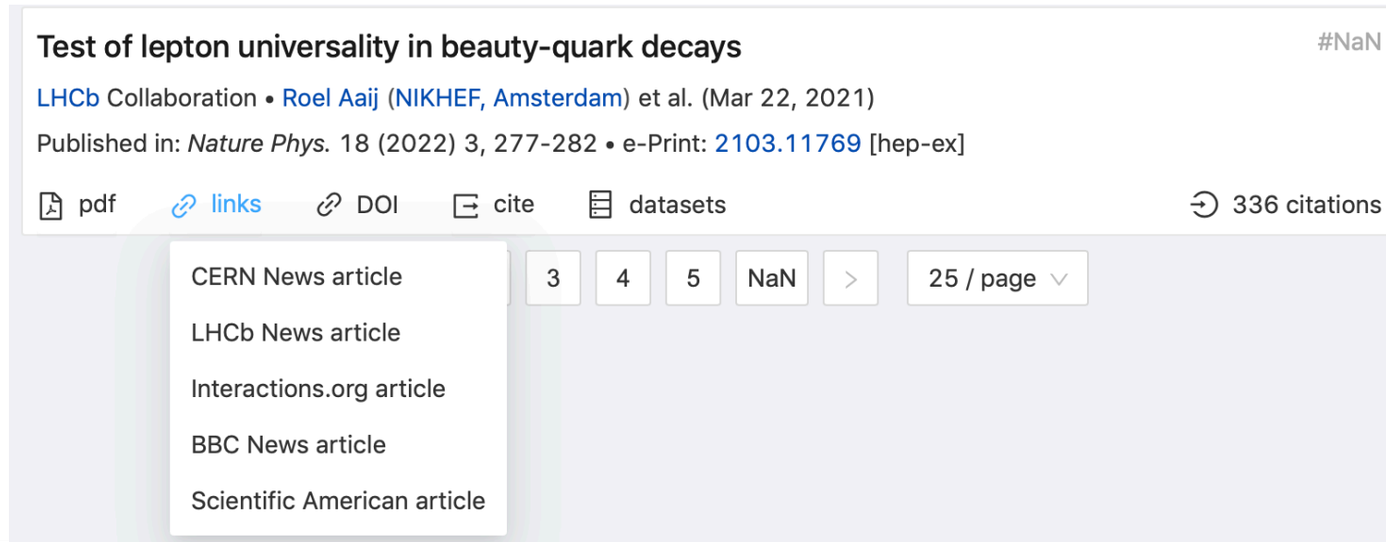
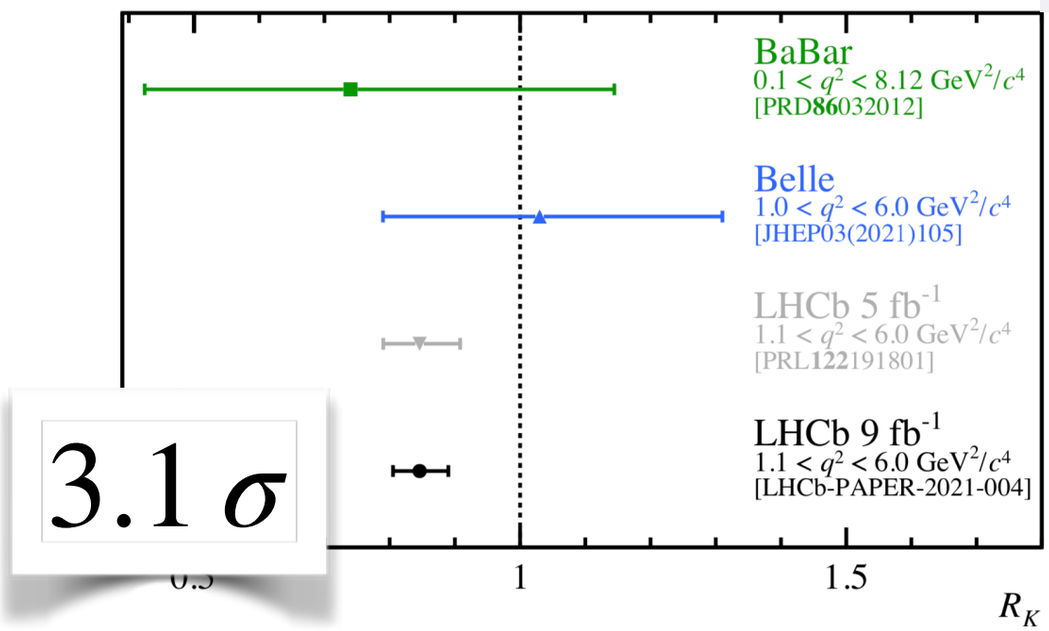
Flavour Anomalies





LHCb, 2103.11769

- R_K - *Evidence* for μ/e universality violation in $B \to K$

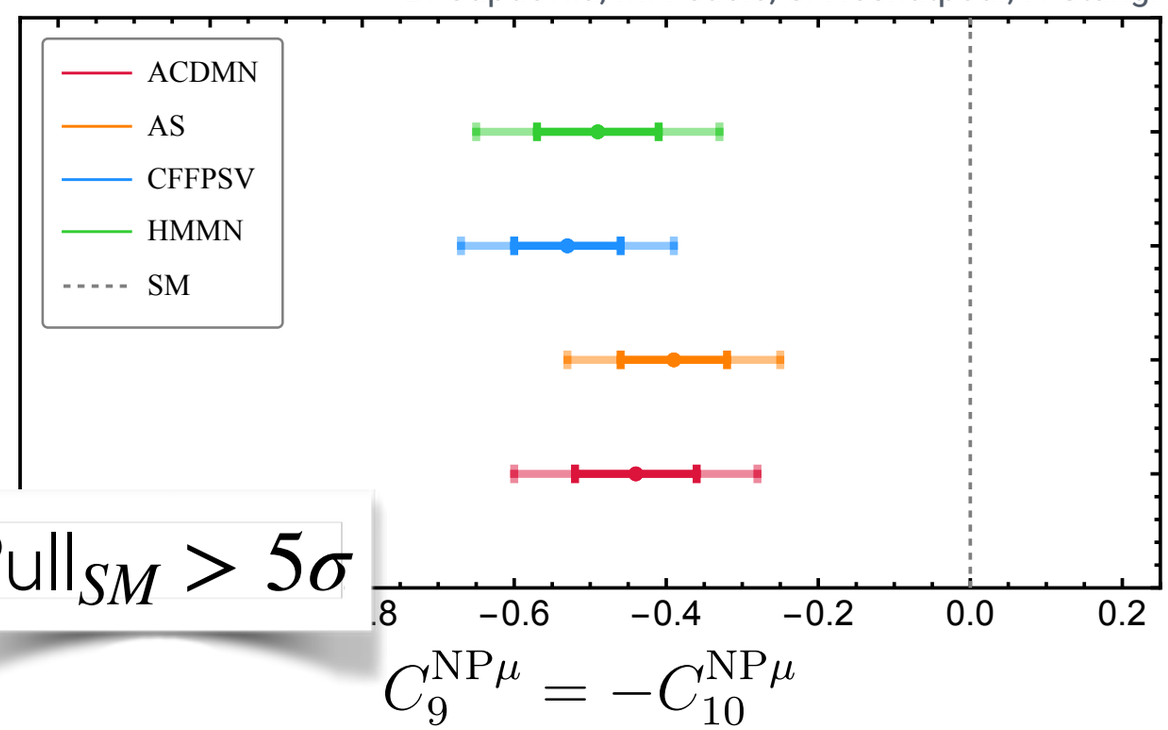
Flavour Anomalies

++ other anomalous observables with the underlying quark-level transition $b \to s\,\mu\mu$

Coherent EFT picture

See Planary III: Flavour Physics
See Flavour 2 & 3 parallel sessions

B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl



$\mathrm{Pull}_{SM} > 5\sigma$

*4.3σ conservative global significance including LEE, see 2104.05631

$$\mathscr{L}_{NP} \supset (40\ \mathrm{TeV})^{-2}\,(\bar{s}_L\gamma^\mu b_L)\,(\bar{\mu}_L\gamma_\mu\mu_L)$$

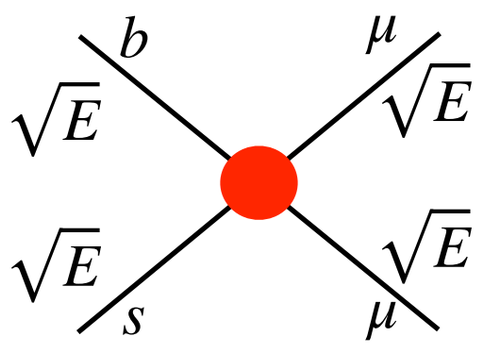
$\approx 10^{-4}\,G_F/2$

Bonus: $b \to c\tau\nu$, $(g-2)_\mu$

New mass scale?

- IF $b \to s\ell^+\ell^-$ anomalies are a genuine new physics effect
  $\Longrightarrow$ Major Revolution in HEP

4-fermion scattering at $E \gg v_{EW}$



$$\mathscr{A} \sim \frac{E^2}{(40\ \text{TeV})^2}$$

Observational evidence!

$$\Longrightarrow\ M_X \lesssim 100\,\text{TeV}$$

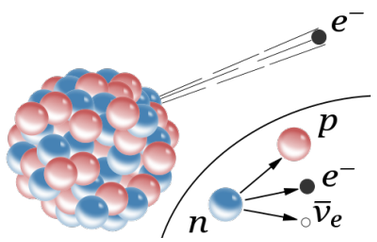
Violation of perturbative unitary

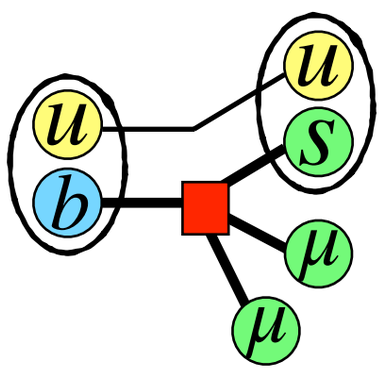
Di Luzio, Nardecchia; 1706.01868

- In many realistic models, the mediator is typically much lighter!
  $\Longrightarrow$ **opportunities for a discovery at the LHC**

- A bright long-term future for collider physics! [Backup]
  - Stronger than the EW naturalness!
  - Other observational evidence: *Neutrino oscillations, Dark Matter, Baryon asymmetry, Inflation, etc* could be a physics of a very high (or different) energy scale.

Mediators?

Phenomena	EFT	Mediator
	G_F $\Longrightarrow M_X \lesssim 1$ TeV	$W^\pm$

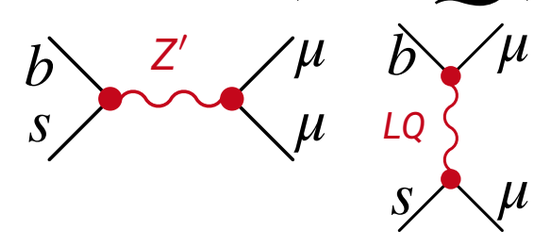


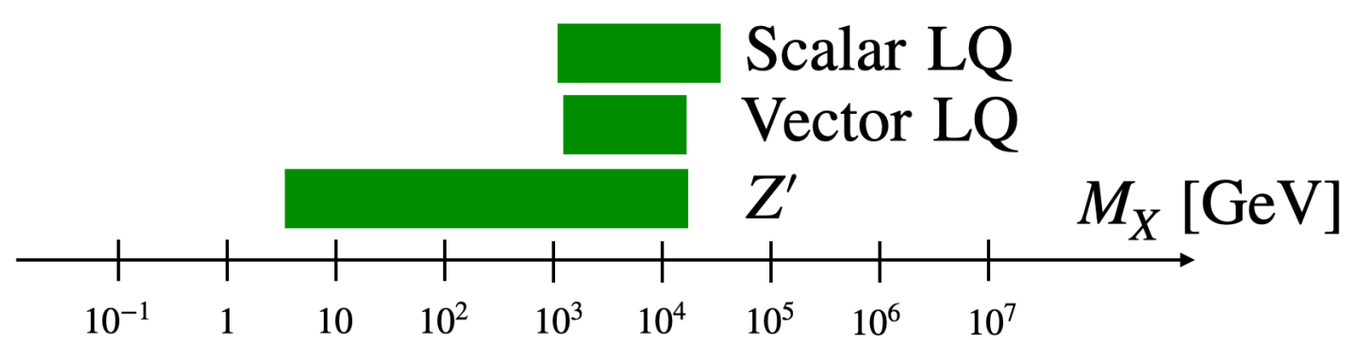
$\mathcal{O}(10^{-4})\, G_F$

$\Longrightarrow M_X \lesssim 100$ TeV

See also talk by M. Blanke

$Z', LQ, ?$



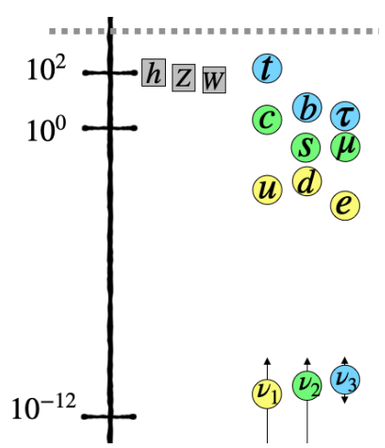


See the Flavour & BSM1/BSM2 Joint Session
See also talk by M. Son

Directions in model building

*some examples, not a review

Any connections with the big open questions?



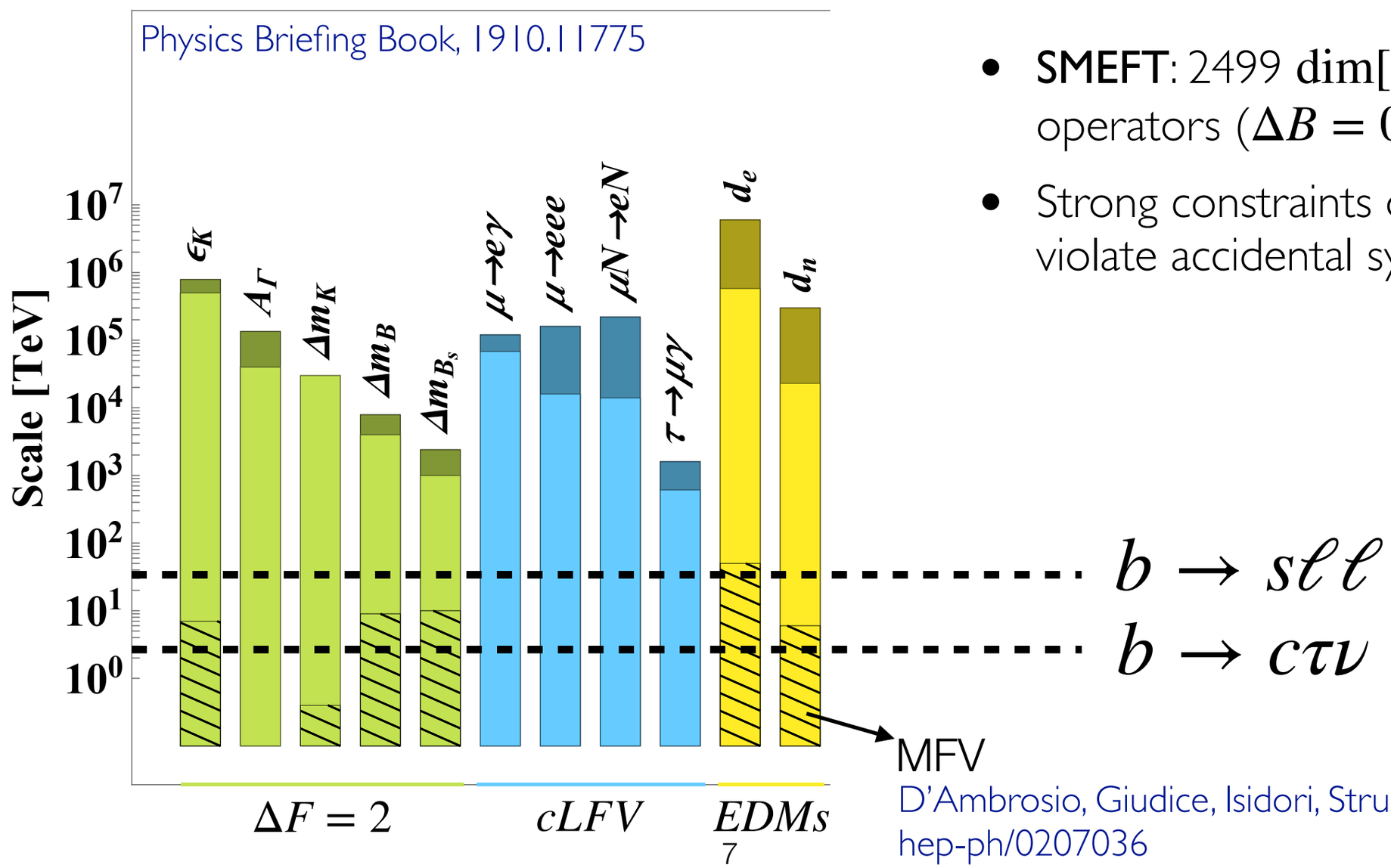
Flavour puzzle,
Higgs mass,
Charge quantisation,
…

See also talk by M. Blanke

Flavour Symmetries

- Exact and approximate accidental symmetries carefully revisited

  Consistency game
  Explain the anomalies while passing other constraints



- **SMEFT**: 2499 $\dim[\mathcal{O}] = 6$ operators ($\Delta B = 0$)
- Strong constraints on those which violate accidental symmetries

D'Ambrosio, Giudice, Isidori, Strumia; hep-ph/0207036

Flavour Symmetries

- MFV doesn't work well for B anomalies!
- Other flavour symmetries and their breaking patterns to be explored
- The winner in the quark sector: $U(2)^3$ Barbieri et at; 1105.2296 Buttazzo et al; 1706.07808

$$Y_{u,d} \sim \begin{pmatrix} \boxed{\Delta_{u,d}} & \boxed{V} \\ 0 \quad 0 & 1 \end{pmatrix}$$

$$\Delta \ll V \ll 1$$

$$V^\dagger \propto (V_{td}, V_{ts})$$

Flavour Symmetries

- MFV doesn't work well for B anomalies!
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  Buttazzo et al; 1706.07808

Charting the space of SMEFT with flavour symmetries

Faroughy, Isidori, Wilsch, Yamamoto; 2005.05366
AG, Thomsen, Palavric; 2203.09561

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector							
		MFV_L	$\mathrm{U}(3)_V$	$\mathrm{U}(2)^2 \times \mathrm{U}(1)^2$	$\mathrm{U}(2)^2$	$\mathrm{U}(2)_V$	$\mathrm{U}(1)^6$	$\mathrm{U}(1)^3$	No symm.
Quark sector	MFV_Q	47	54	65	71	80	87	111	339
	$\mathrm{U}(2)^2 \times \mathrm{U}(3)_d$	82	93	105	115	128	132	168	450
	$\mathrm{U}(2)^3 \times \mathrm{U}(1)_{b_R}$	96	107	121	128	144	150	186	480
	$\mathrm{U}(2)^3$	110	123	135	147	162	164	206	512
	No symm.	1273	1334	1347	1407	1470	1425	1611	2499

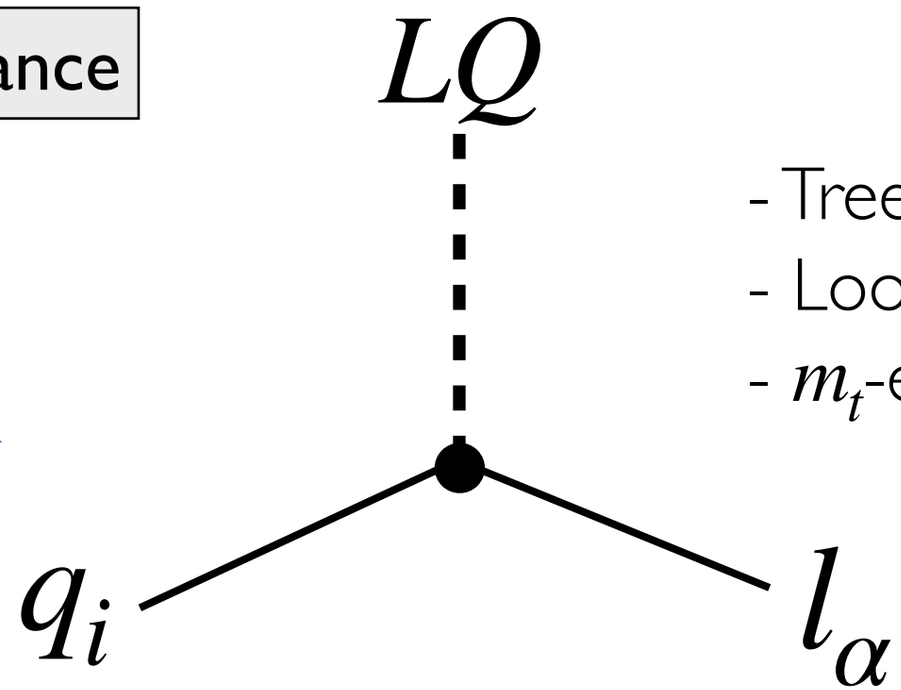
(*) Terms relevant for the high-p_T physics: Top, Higgs & electroweak
See talks by Juan Rojo and Tevong You. See also the Top 2 parallel session

The LHC EFT WG: the flavour structure compatible with B anomalies?

TeV-scale Leptoquarks

The leptoquark renaissance

[Phys.Rept. 641 (2016) 1-68]
Doršner, Fajfer, AG, Kamenik, Košnik



- Tree-level $2q2\ell$,
- Loop-suppressed $4q$ and 4ℓ,
- m_t-enhanced $(g-2)_\mu$.

Flavour symmetries + Leptoquarks

$U(2)_q \times U(2)_\ell$

$\mathscr{L} \supset q_3 \ell_3 S$

$U(2)_q \times U(1)_\mu$

$\mathscr{L} \supset q_3 \ell_2 S$

(Small breaking gives $b \to s\mu\mu$)

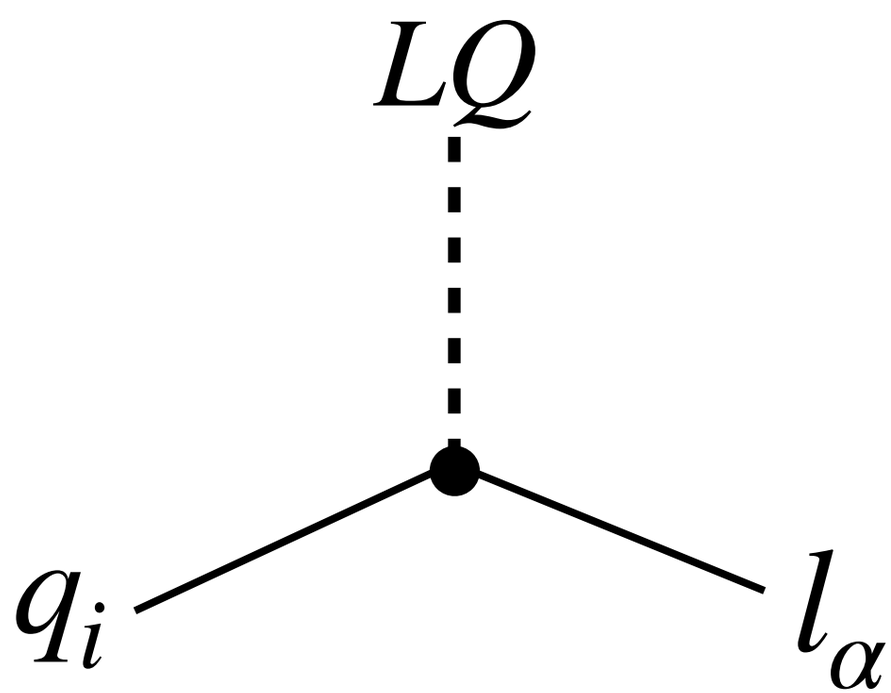
$+b \to c\tau\nu$

Buttazzo et al; 1706.07808

$+(g-2)_\mu$

AG, Stangl, Thomsen; 2103.13991

TeV-*scale Leptoquarks*



Two thriving model-building directions:

Quark-Lepton Unification

- Variations of the original Pati-Salam idea

  $SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$

  e.g. Di Luzio, AG, Nardecchia; 1708.08450
  AG, Stefanek; 1802.04274

The Composite Higgs

- If Higgs was a π, LQ would be a K, …

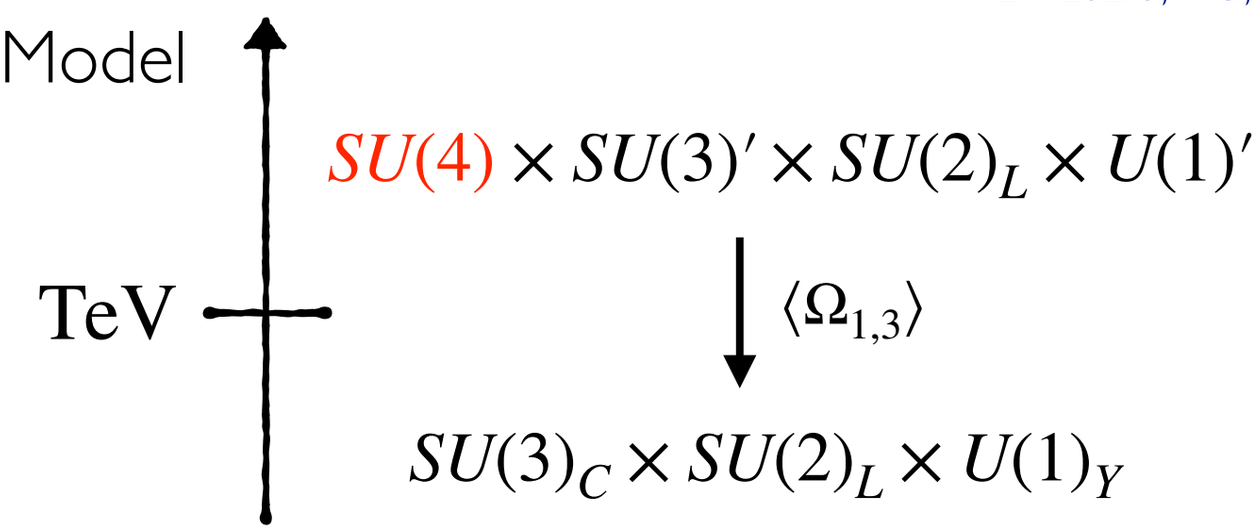
  e.g. Marzocca; 1803.10972
  Gripaios, Nardecchia, Renner; 1412.1791

Fuentes-Martin, Stangl; 2004.11376

The 4321 model

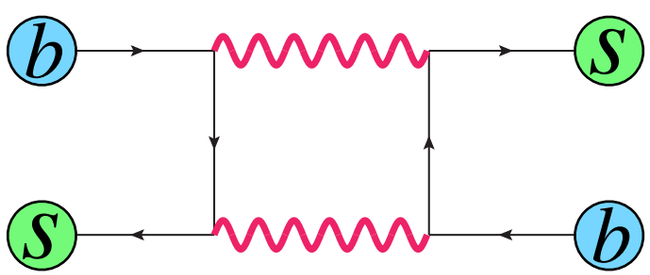
- New gauge extension of the Standard Model

Di Luzio, AG, Nardecchia; 1708.08450

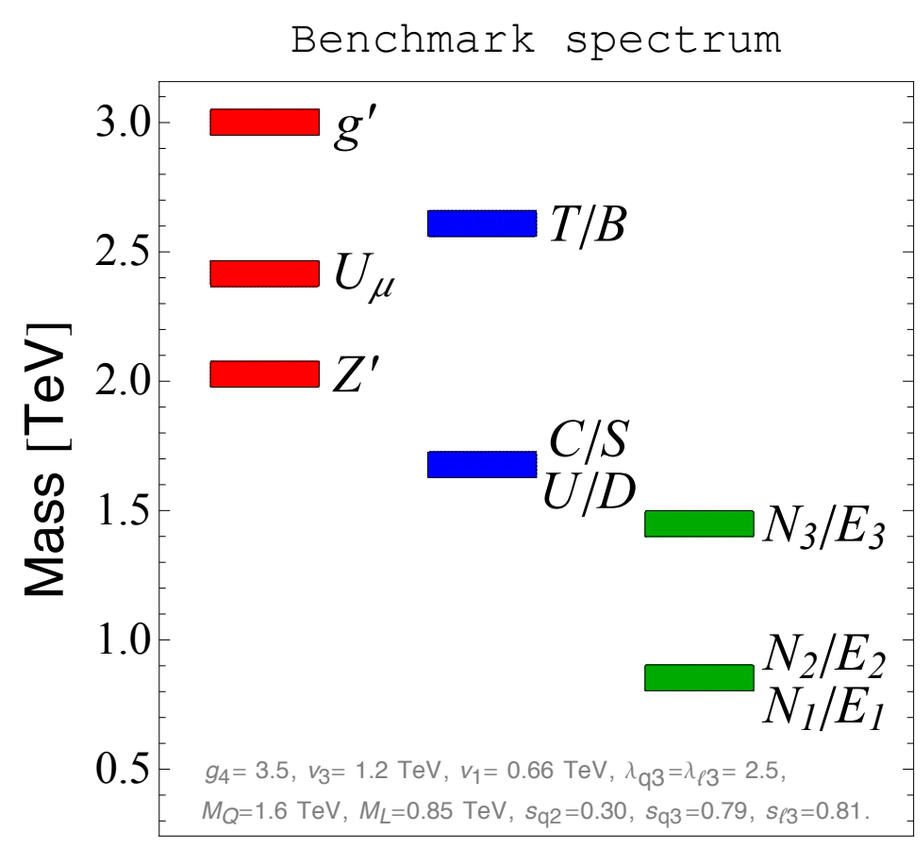


- Comprehensive investigation:

Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner; 1708.08450



$$C_{bs}^{LL} \sim \Delta R^2_{D^{(*)}} \, M_L^2$$



The lightest new states are vector-like leptons!

The 4321 model

- New gauge extension of the Standard Model

Di Luzio, AG, Nardecchia; 1708.08450

TeV

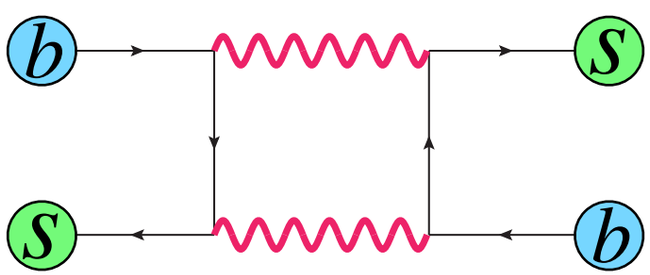
$$SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

$$\Big\downarrow \langle \Omega_{1,2} \rangle$$

$$SU(3)_C \times SU(2)_L$$

- Comprehensive investigation:

Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner; 1708.08450



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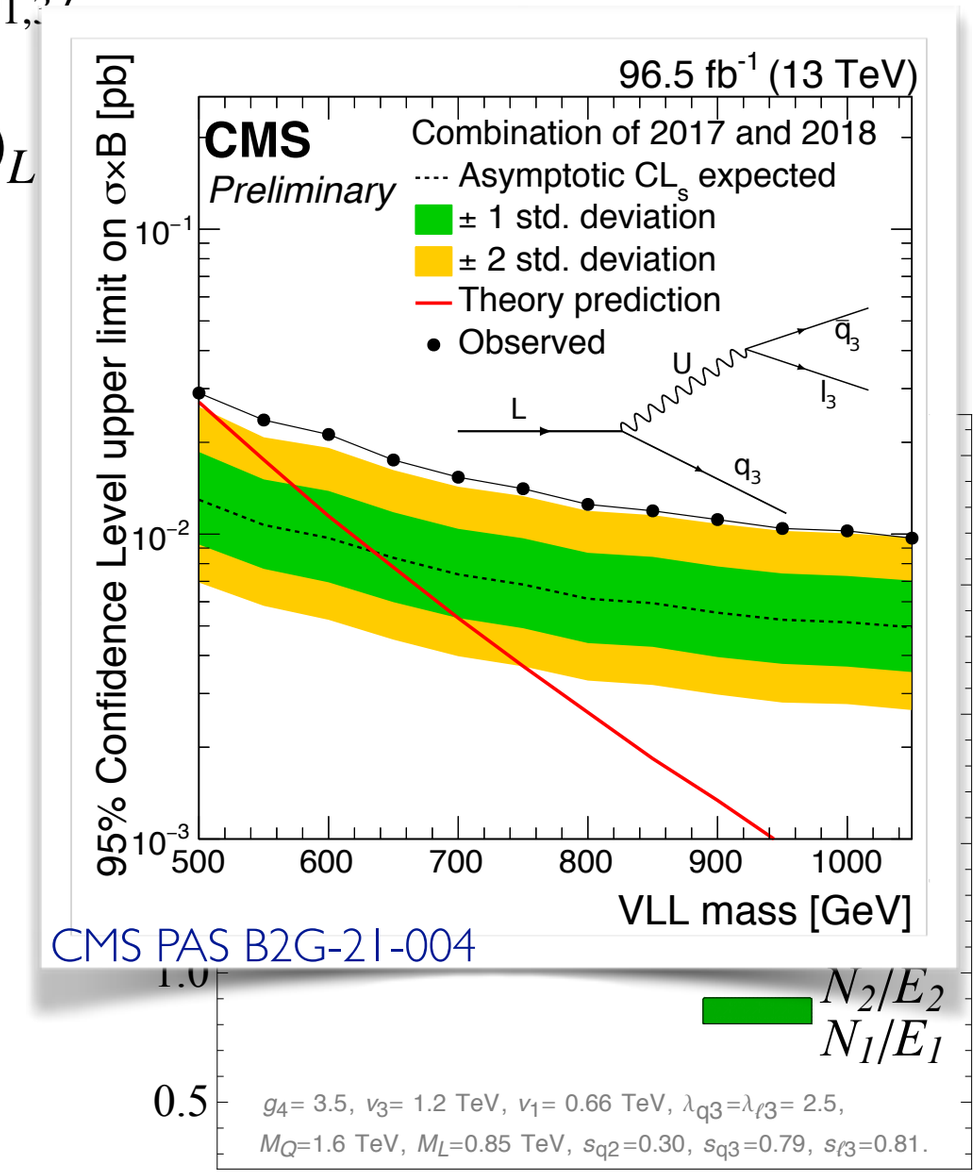
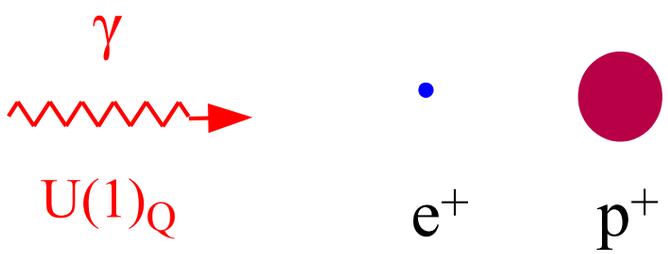


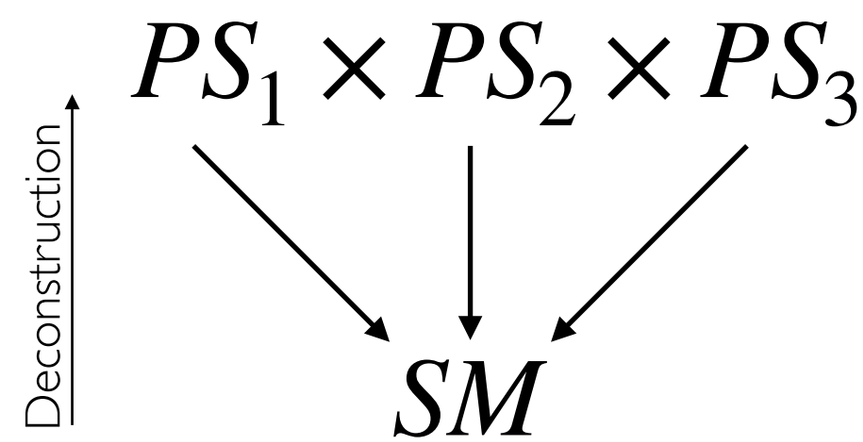
CMS PAS B2G-21-004

Non-universal gauge interactions

Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368



Far apart at short distances!



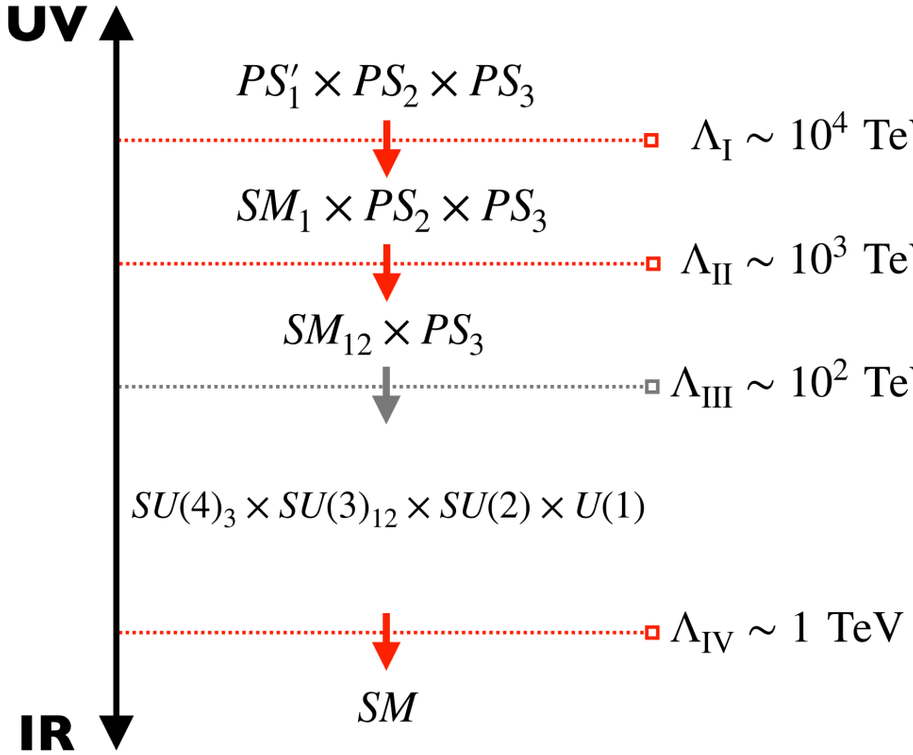
Universality of gauge interactions:
Only **a low-energy property**?

Flavour hierarchies

Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368

Multi-scale flavour

- Series of hierarchical SSBs
  $\Longrightarrow$ Flavour hierarchies



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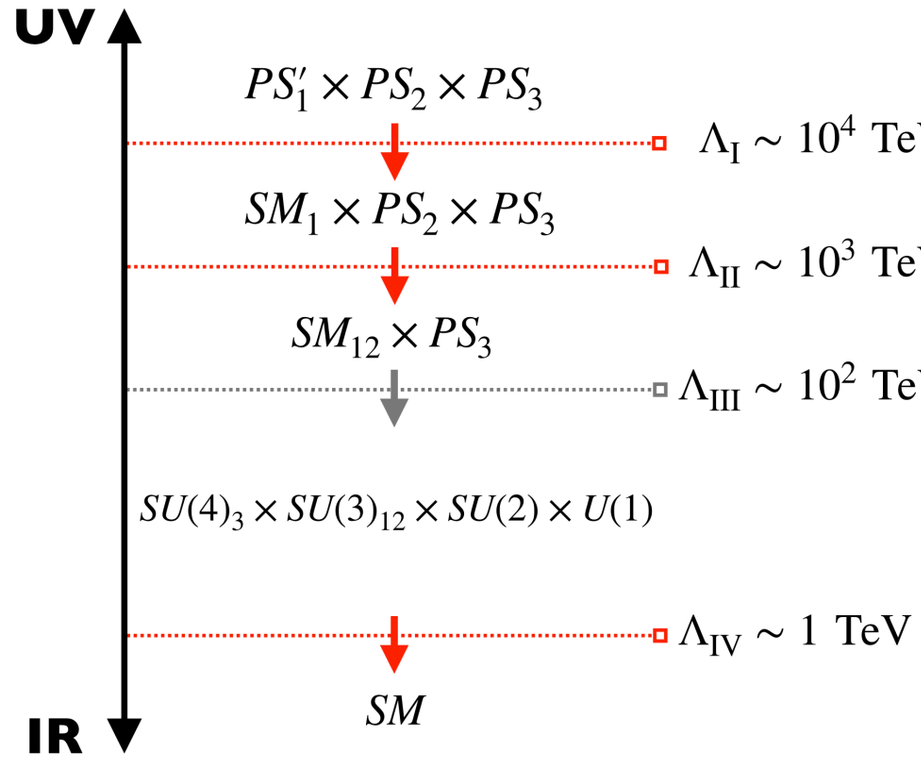
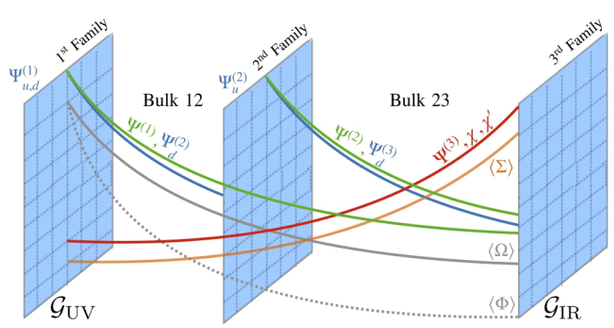


Flavour as a topological defect

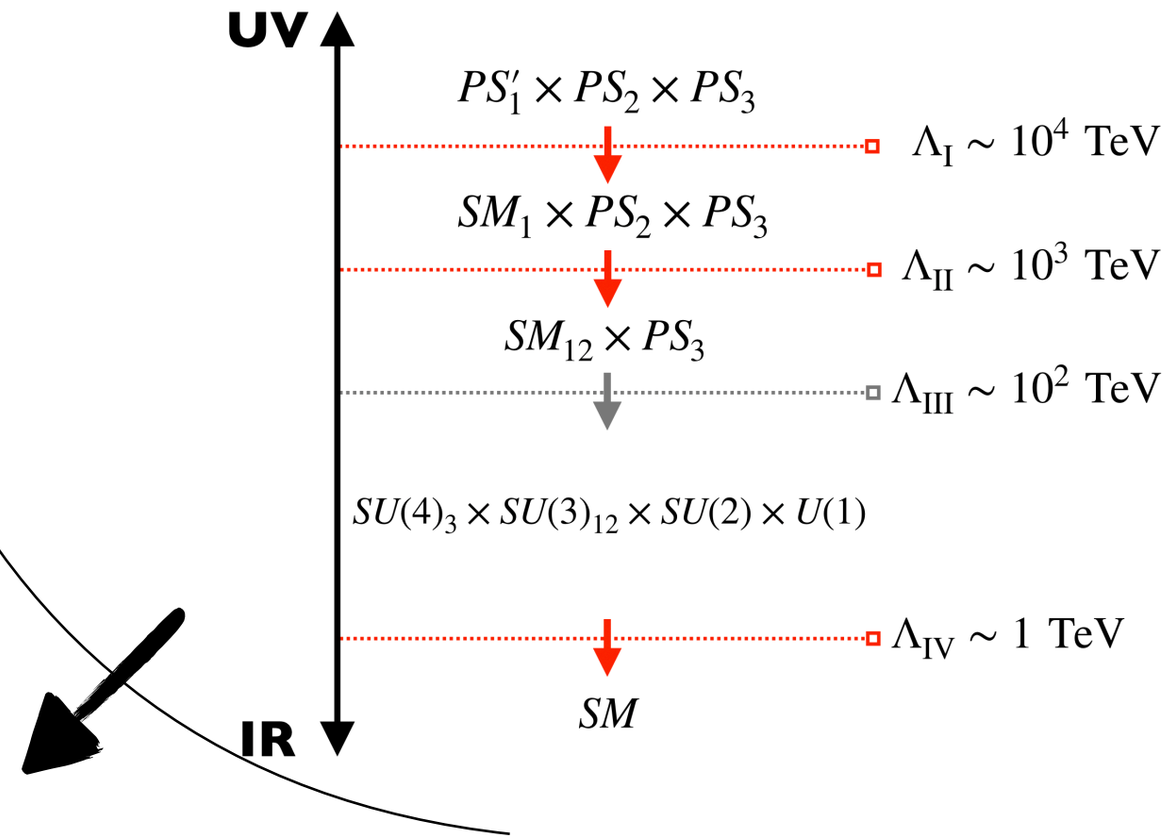
- 5D warped compactification
  $\Longrightarrow$ Flavour + Higgs



Fuentes-Martin et al; 2203.01952

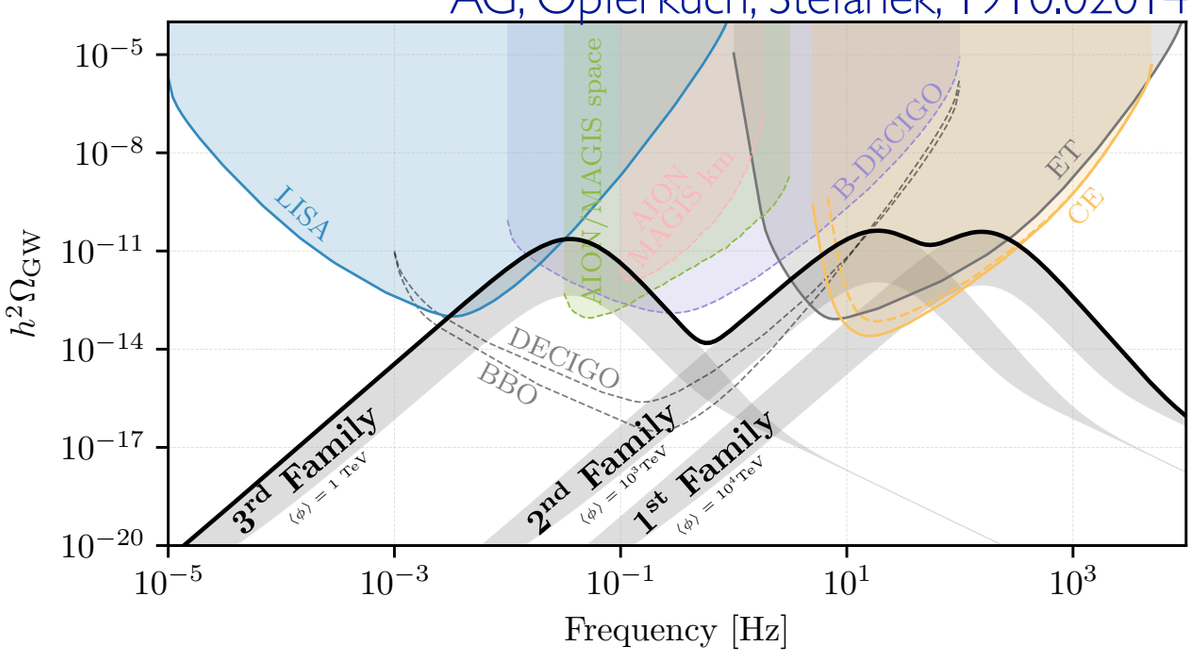
Cosmological implications

Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368



- <u>Novel connections</u>
  GW astronomy & Flavour physics

AG, Opferkuch, Stefanek; 1910.02014



Stochastic gravitational wave radiation with the characteristic **three-peaked** signature.

$$\begin{array}{ccccc} \sqrt{m_t m_b} & : & \sqrt{m_s m_c} & : & \sqrt{m_u m_d} \\ 1 & : & 10^{-2} & : & 10^{-4} \\ f_{\rm LISA}^{-1} & : & \dots & : & f_{\rm ET}^{-1}\,. \end{array}$$

(Partial) Unification

$$\begin{tikzcd} & G \arrow[dr] & \\ SU(3)\times SU(2)\times U(1) \arrow[ur] \arrow[rr] & & SU(48) \end{tikzcd}$$

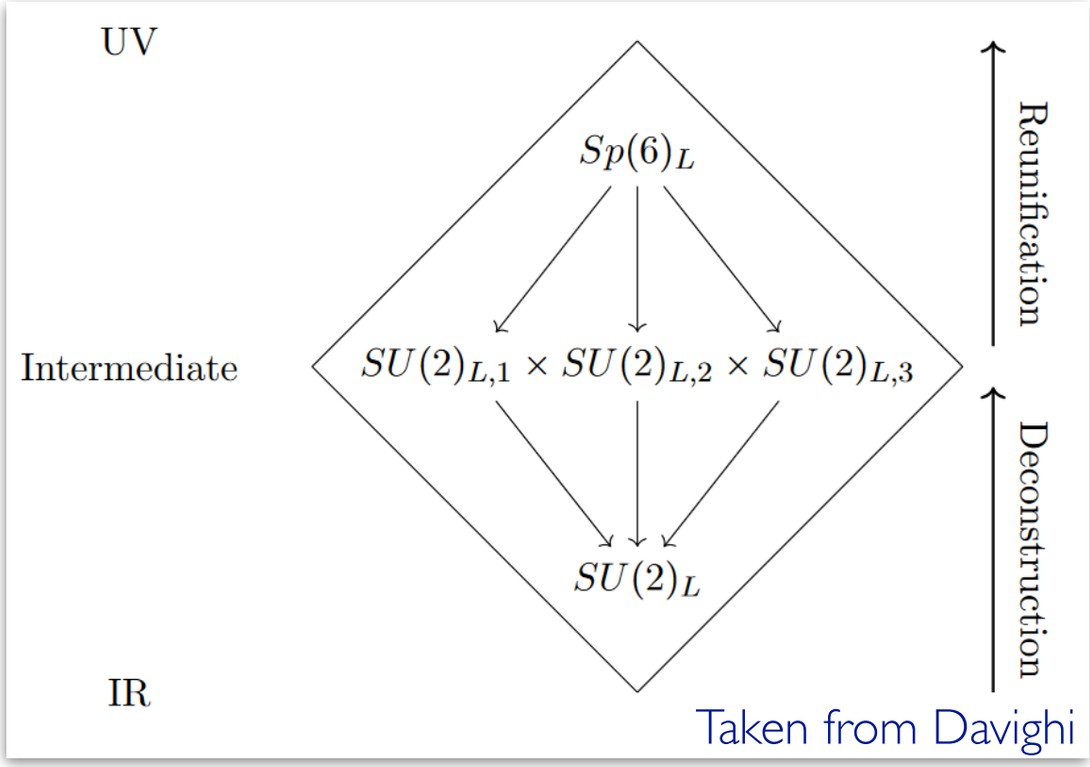
Assumption:
SM + $3\nu_R$ Weyl fermions
$48 = 16 \times 3$

Allanach, Gripaios, Tooby-Smith; 2104.14555

- Classification of anomaly-free semisimple algebras containing the SM
- Novel 'GUTs' beyond the universal PS, $SU(5)$ or $SO(10)$
- An example is $G = PS_1 \times PS_2 \times PS_3$ Bordone et al; 1712.01368

Gauge-Flavour unification

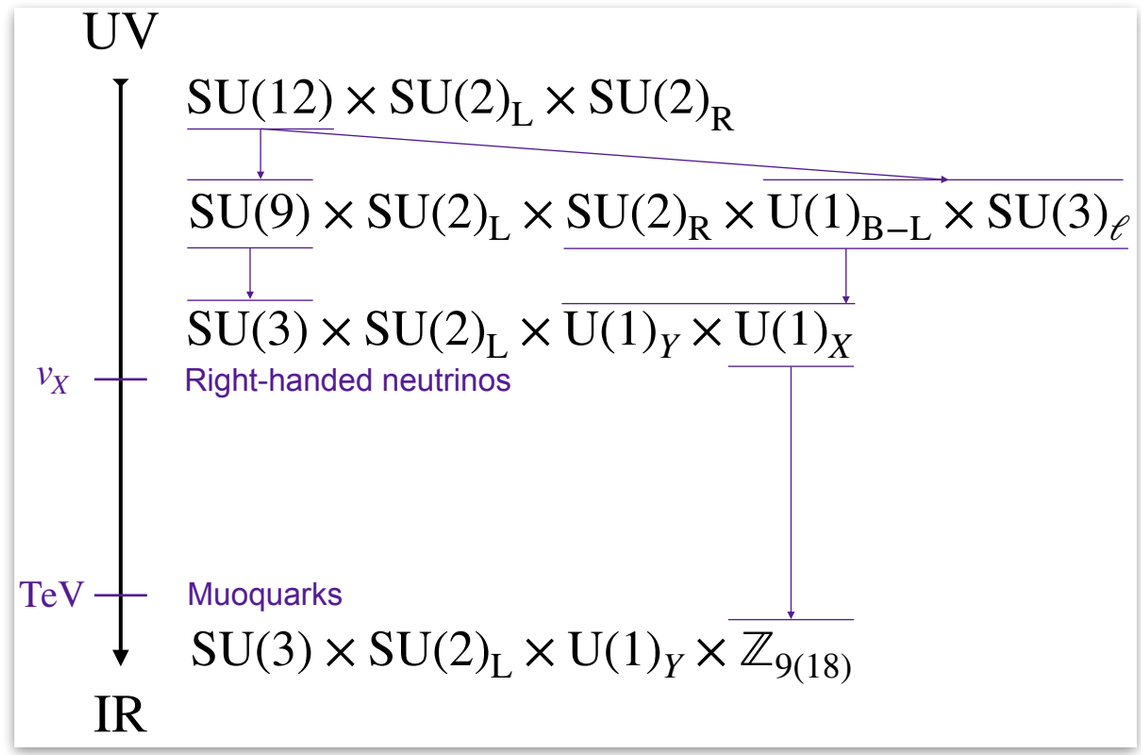
$$G = SU(4) \times Sp(6) \times Sp(6)$$



Electroweak flavour unification

Davighi, Tooby-Smith; 2201.07245

$$G = SU(12) \times SU(2) \times SU(2)$$



Color flavour unification

Davighi, AG, Thomsen; 2202.05275

Fresh ideas to be carefully explored irrespective of B anomalies!

Summary

- Flavour anomalies triggered flourishing model building directions:
  - *Flavour Symmetries*
  - *TeV-scale Leptoquarks*
  - *Non-universal gauge extensions*
  - *Multi-scale flavour*
  - *Quark-lepton unification*
  - *Gauge-flavour unification*
- Valuable results even if the anomalies go away
- If the anomalies 'stay' $\Longrightarrow$
  a major boost for the existing and future collider physics program

Backup

Non-universal gauged $U(1)$

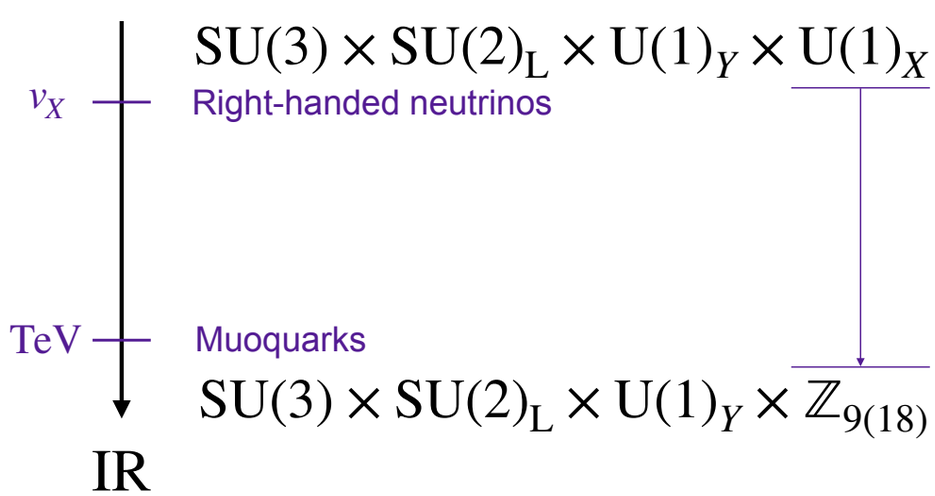
Lepton non-universal $U(1)$

- The prime example: $U(1)_{L_\mu - L_\tau}$ Altmannshofer et all, 1403.1269, 1406.2332
- Classification of anomaly-free $U(1)$ extensions Allanach, Davighi, Melville; 1812.04602
- Selection rules for leptoquarks and deriving accidental $U(1)^3$ AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Lepton non-universal

Davighi, AG, Thomsen; 2202.05275

$$X = 3m(B-L) - n\,(2L_\mu - L_e - L_\tau)$$



$$(m,\,n) = \big(3a+r,\,9b+3r\big), \quad \text{for} \quad r\in\{1,\,2\},$$
$$(a,\,b)\in\mathbb{Z}^2, \text{ and } \gcd\big(3a+r,\,b-a\big)=1\,.$$

Novel mechanism

Exact proton stability!

(to all orders in the SMEFT)

$$\Delta B = 0 \pmod 3$$

✗ p decay, $n \leftrightarrow \bar{n}$

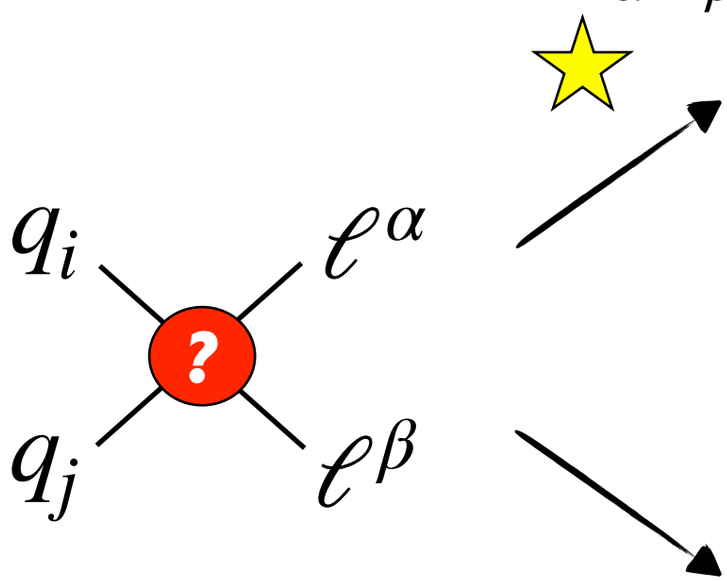
✓ sphaleron

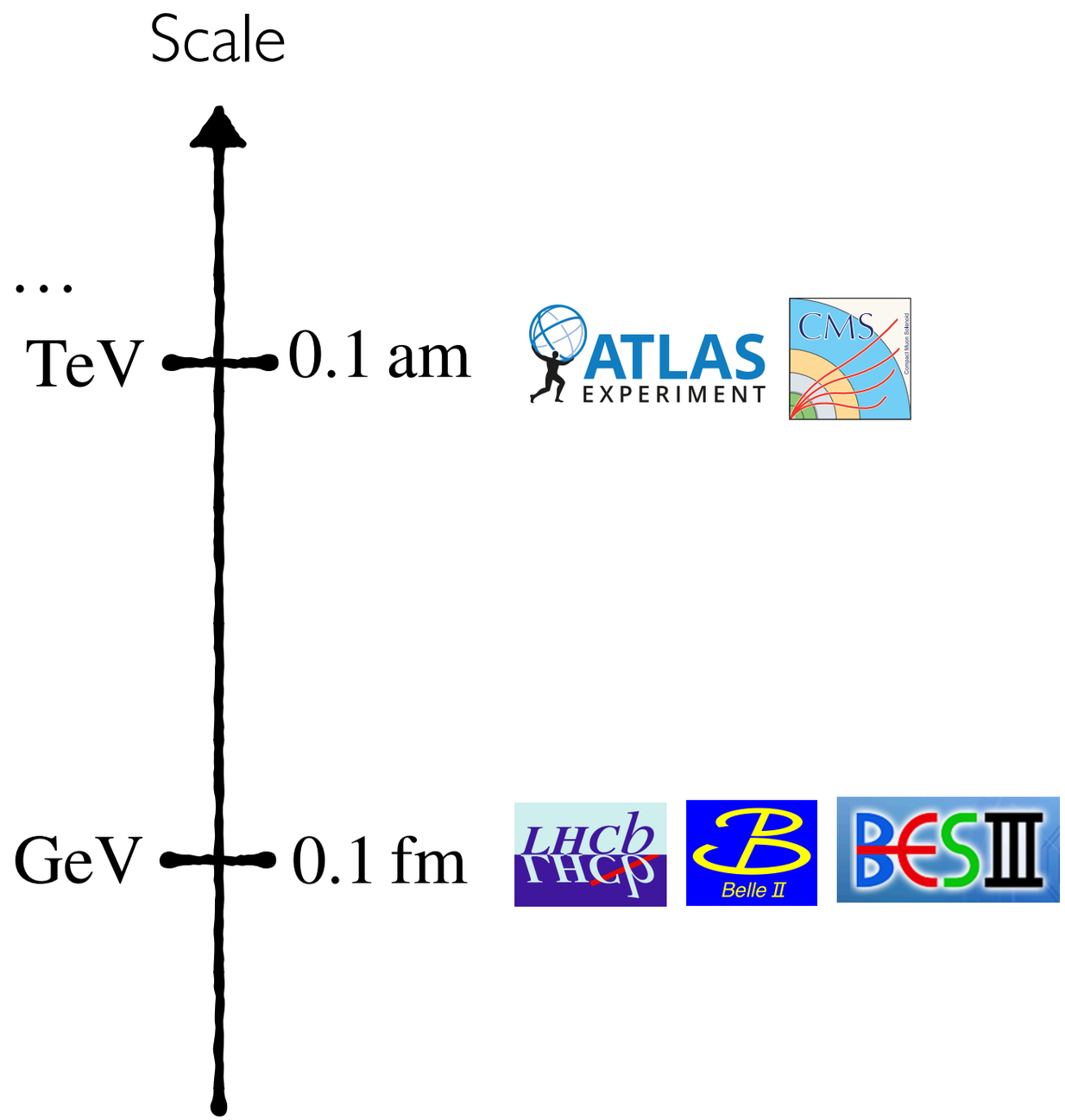
Similar mechanisms shortly after:
Koren; 2204.01741,
Wang, Wan, You; 2204.08393

Flavour Physics in High-p_T Tails

for flavor-sensitive interactions

$$pp \to \ell^+_\alpha \ell^-_\beta (j), \ \ldots$$





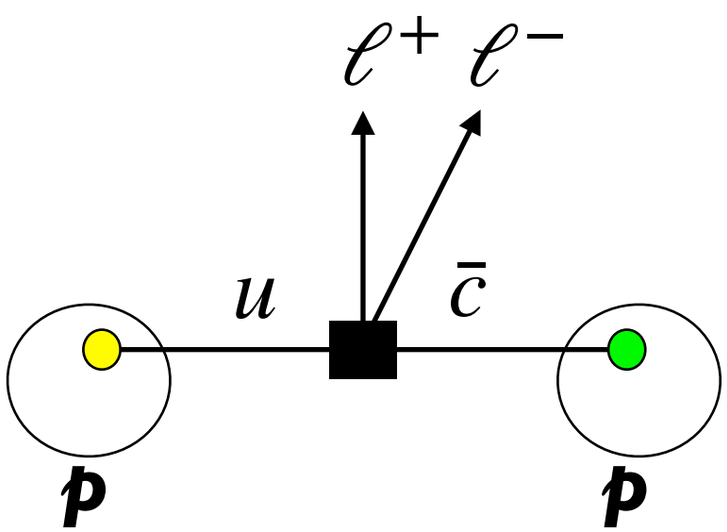
A wealth of information for flavour physics, **complementary** to hadron decays.

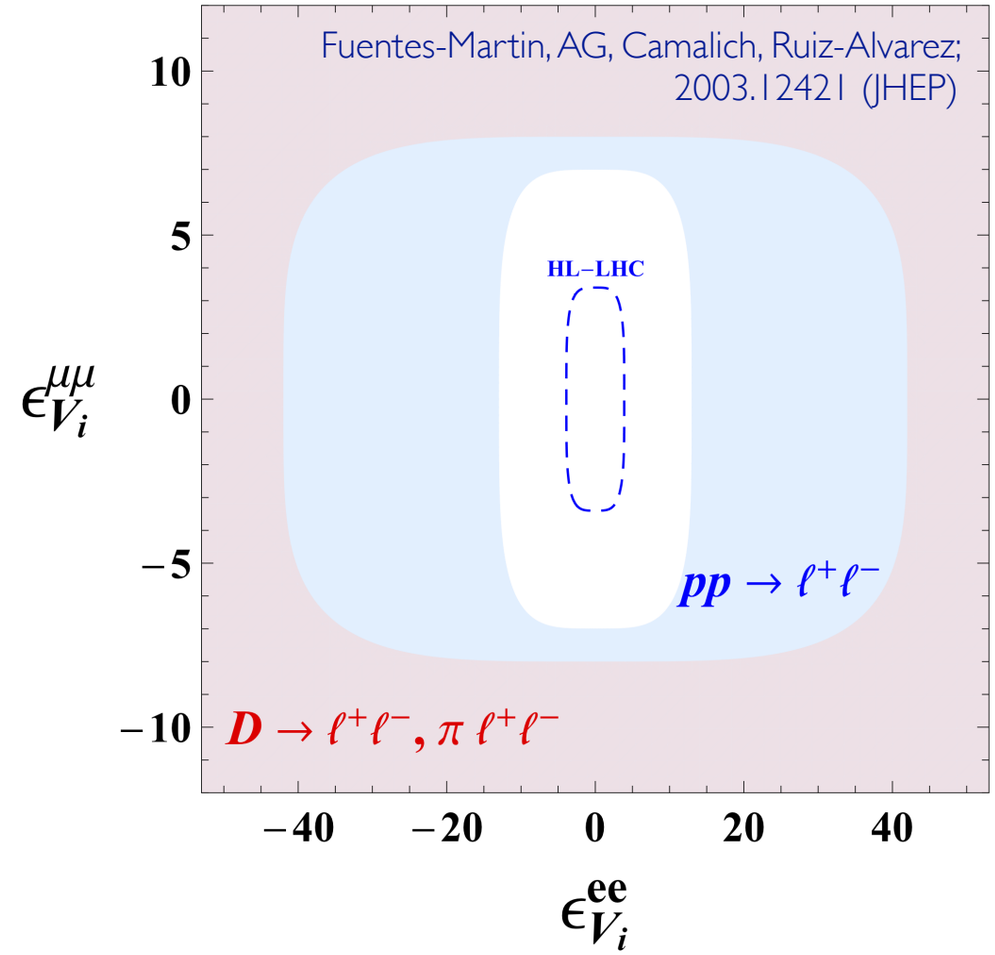
Flavour Physics in High-p_T Tails

Example: Rare $c \to u\ell^+\ell^-$ decays

- Tiny SM rates: $BR(D^0 \to \mu^+\mu^-) \sim \mathcal{O}(10^{-13})$
  short-distance contribution negligible (efficient GIM suppression), long-distance dominated
- Already strong experimental upper limits: $BR(D^0 \to \mu^+\mu^-) \lesssim 6 \times 10^{-9}$ LHCb, 1305.5059
- **Null test of the SM** sensitive to New Physics

$$\mathscr{L}_{NP} \approx \frac{\epsilon_V^{\ell\ell}}{15\,\text{TeV}} (\bar{u}_R \gamma^\mu c_R)(\bar{\ell}_R \gamma^\mu \ell_R)$$





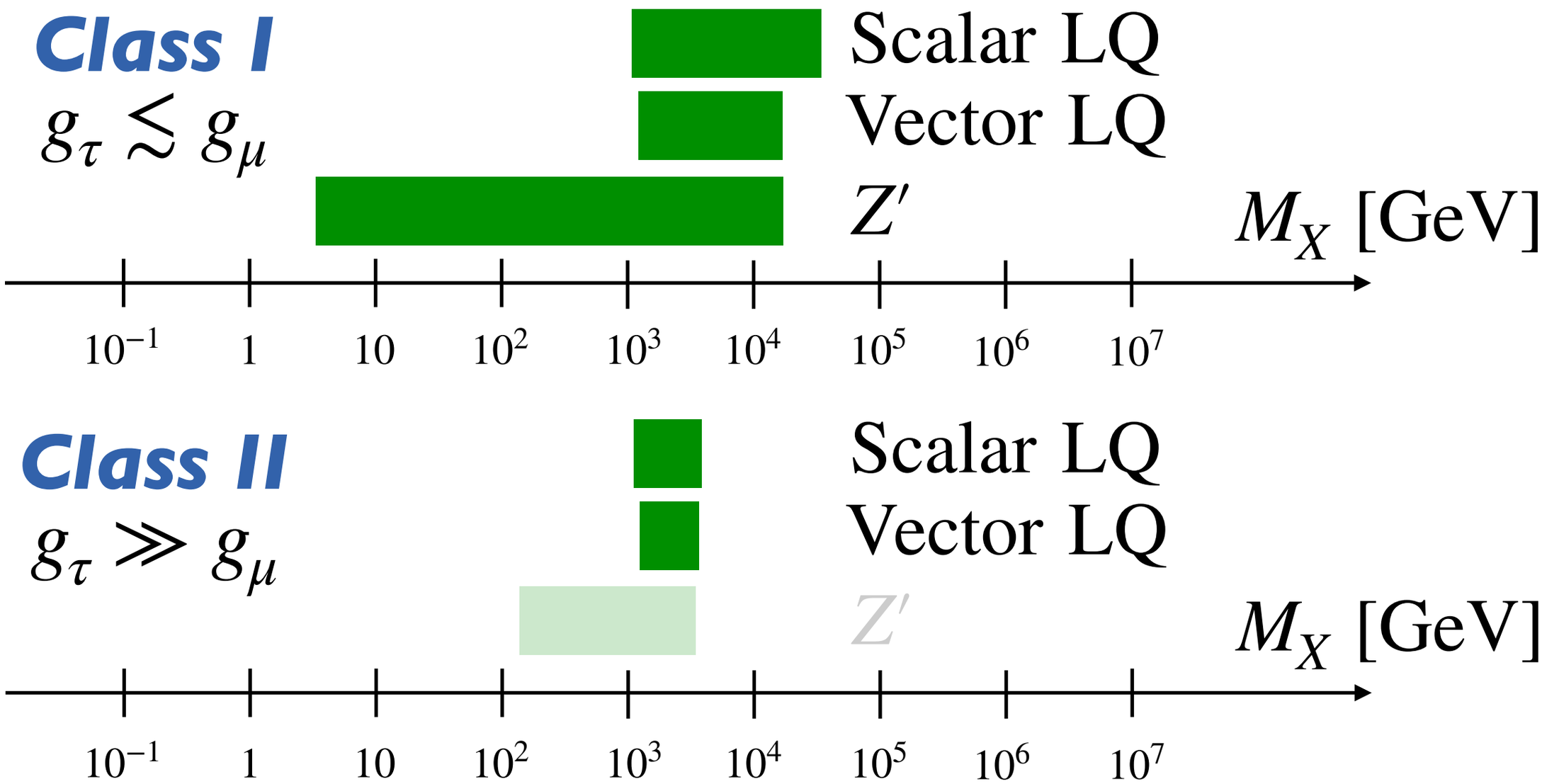
Systematic exploration needed!

Low-p_T roadmap

1. $b \to s\ell\ell$: Only μ? LH or vectorial? Universal contribution?
2. $b \to c\tau\nu$: Yes or No?
   If yes, $\Lambda \lesssim 10$ TeV, $U(2)_\ell$ preferred, $g_\tau \gg g_\mu$. Eg $LQ \to \tau b$.
3. $(g-2)_\mu$: Yes or No? Leptonic $U(1)^3$.
4. $b \to s\nu\nu$ & $b \to s\tau\tau$:
   $SU(2)_L$ prediction. If large $\gg 10\,\%$, $U(2)_\ell$ again.
5. $b \to d\ell\ell(\nu\nu)$: Test $U(2)_q$, also in $s \to d\nu\nu$
6. LFV in b decays: Leptonic flavour, e.g. $U(2)_\ell$ vs $U(1)^3$
7. cLFV ($e_i \to e_j$), τ LFU, $\Delta F = 2$, EDMs, EWPO: Z and W pole physics, …

The high-p_T targets

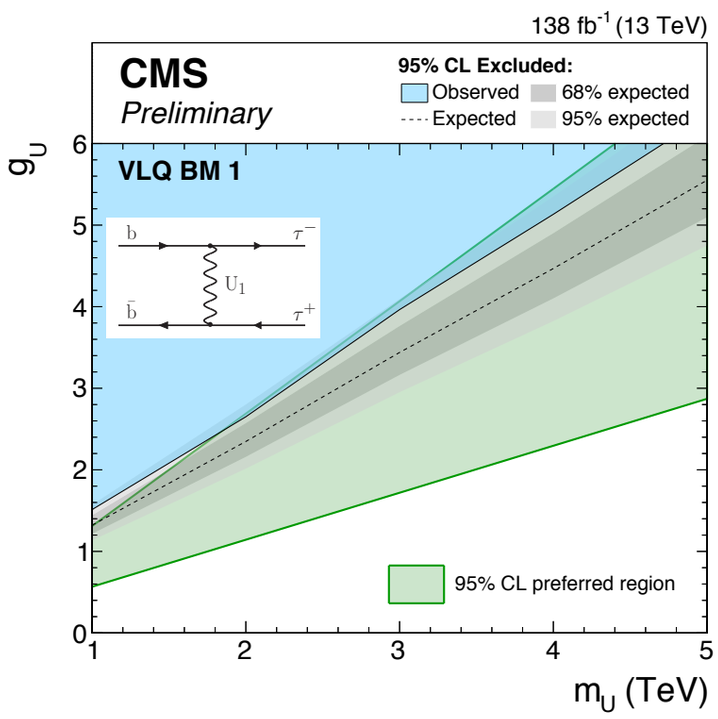
- $b \to s\ell\ell$: Tree-level



- Loop-level mediators $\gtrsim$ 0.1 TeV and $\lesssim$ few TeV

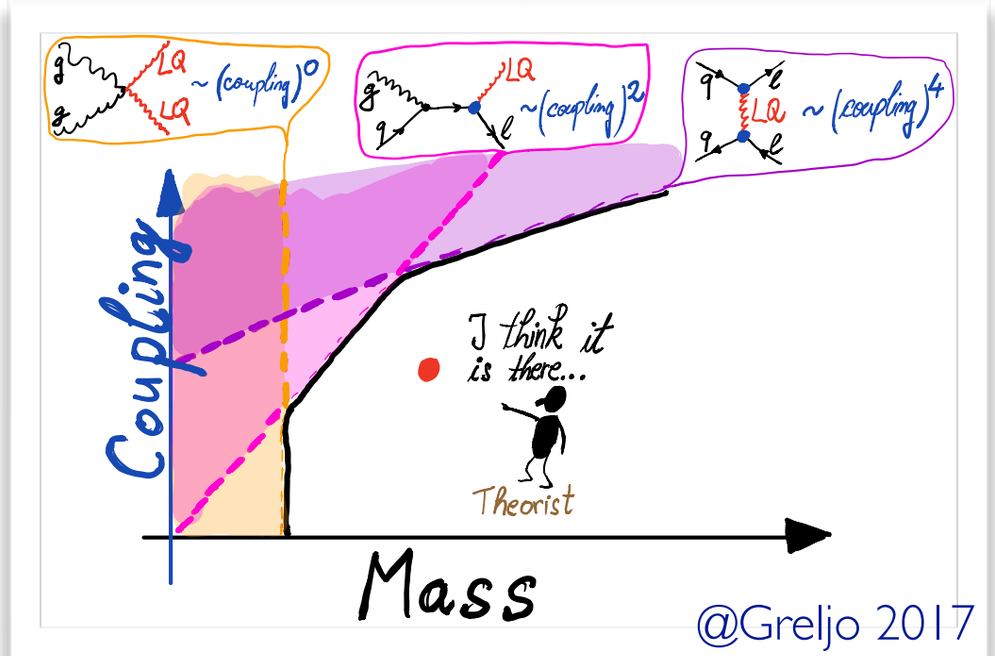
High-p_T LHC

- Resonances and tails in:
  - $\tau\tau(b)$, Faroughy, AG, Kamenik; 1609.07138
  - $\tau\nu(b)$, AG, Camalich, Ruiz-Alvarez; 1811.07920
    Marzocca, Min, Son; 2008.07541
  - $\mu\mu(b)$, AG, Marzocca; 1704.09015
    Afik et al; 1805.11402, 1912.00425
  - …



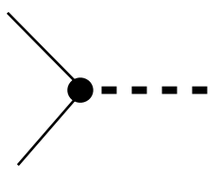
CMS PAS HIG-21-001

- Leptoquark searches



<u>Novel mechanism</u>
Resonant LQ production

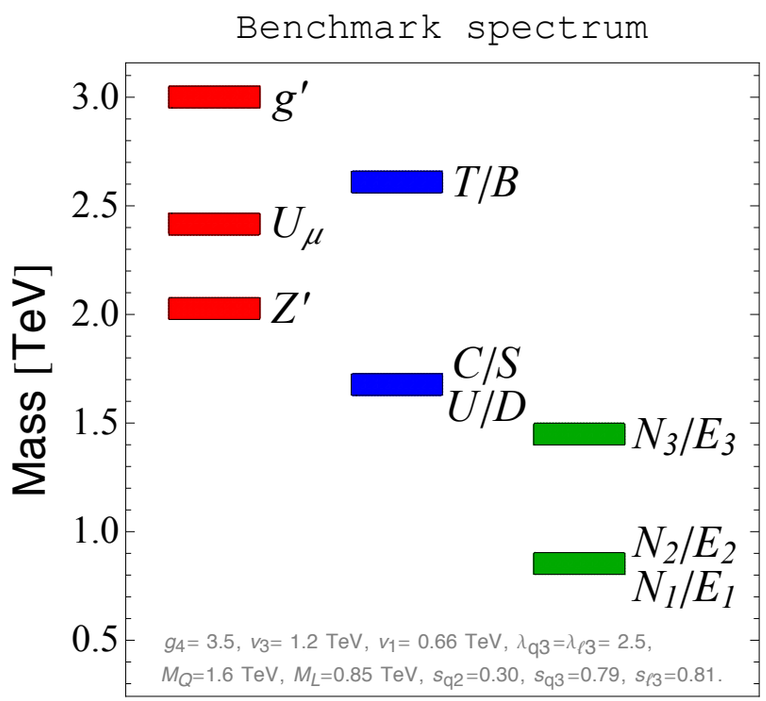
$pp \to \Phi$



Buonocore, Haisch, Nason,
Tramontano, Zanderighi; 2005.06475
Haisch,Polesello; 2012.11474
AG, Selimovic; 2012.02092

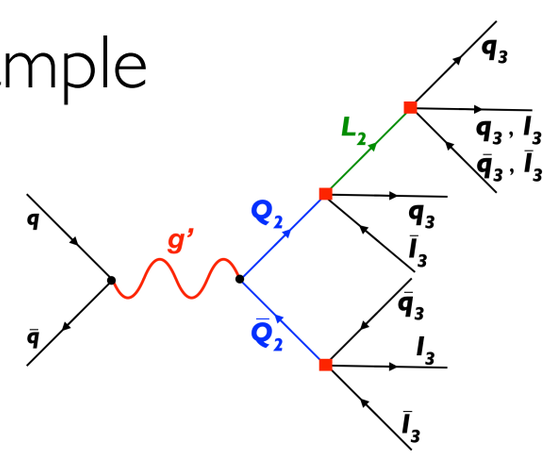
High-p_T LHC

- Explicit models:
  The 4321 model

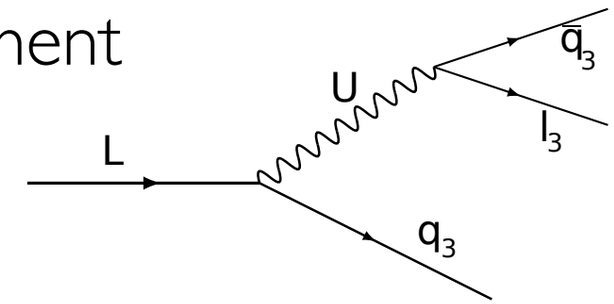


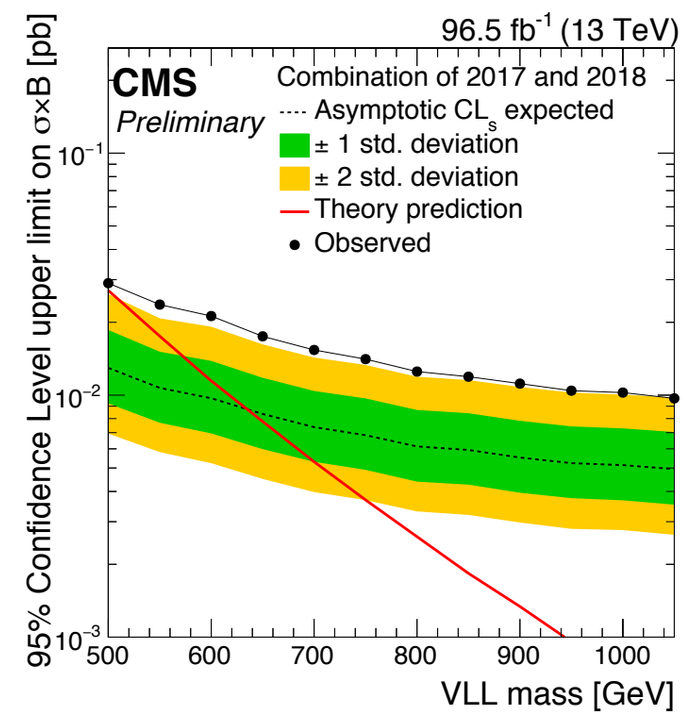
Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner; 1708.08450

- Example



- Experiment



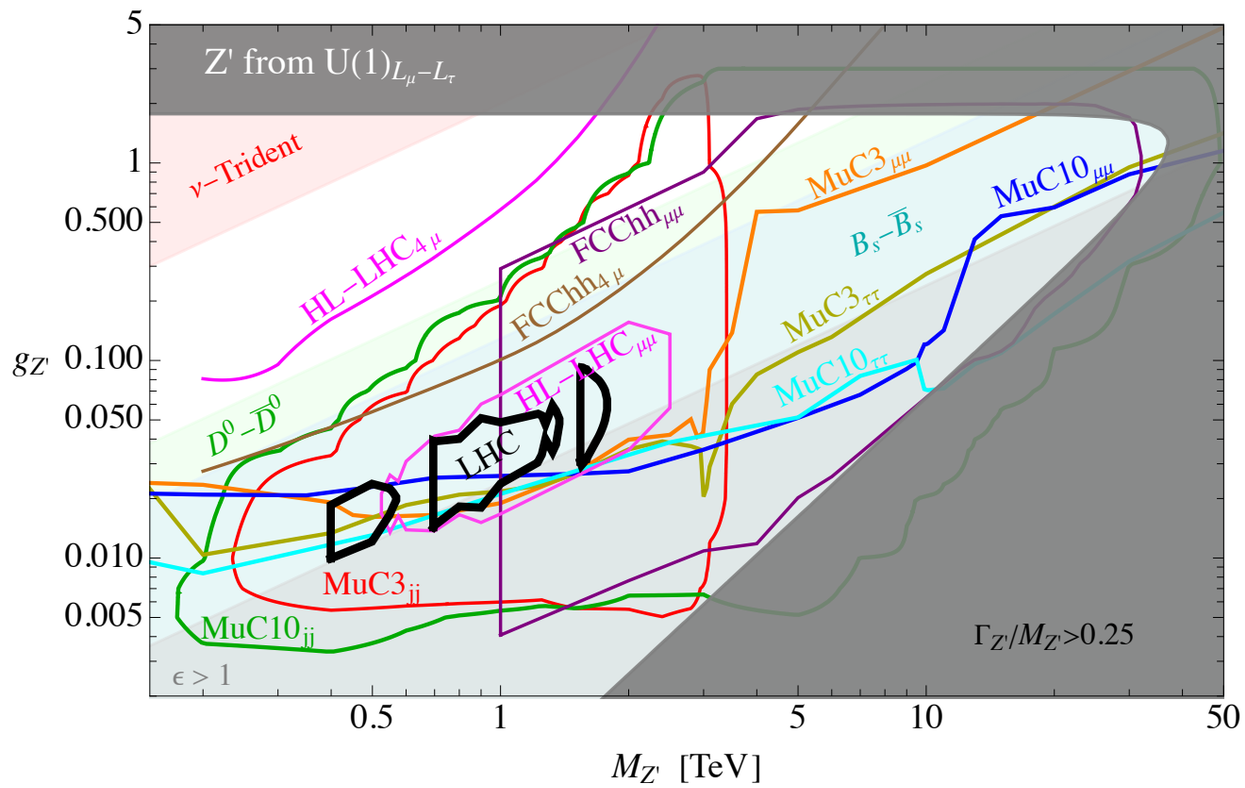


CMS PAS B2G-21-004

The CMS quote:
"The observed excess is consistent with the presence of VLLs in the context of the 4321 model, and the excess of events over the background-only hypothesis corresponds to a significance of 2.8σ."

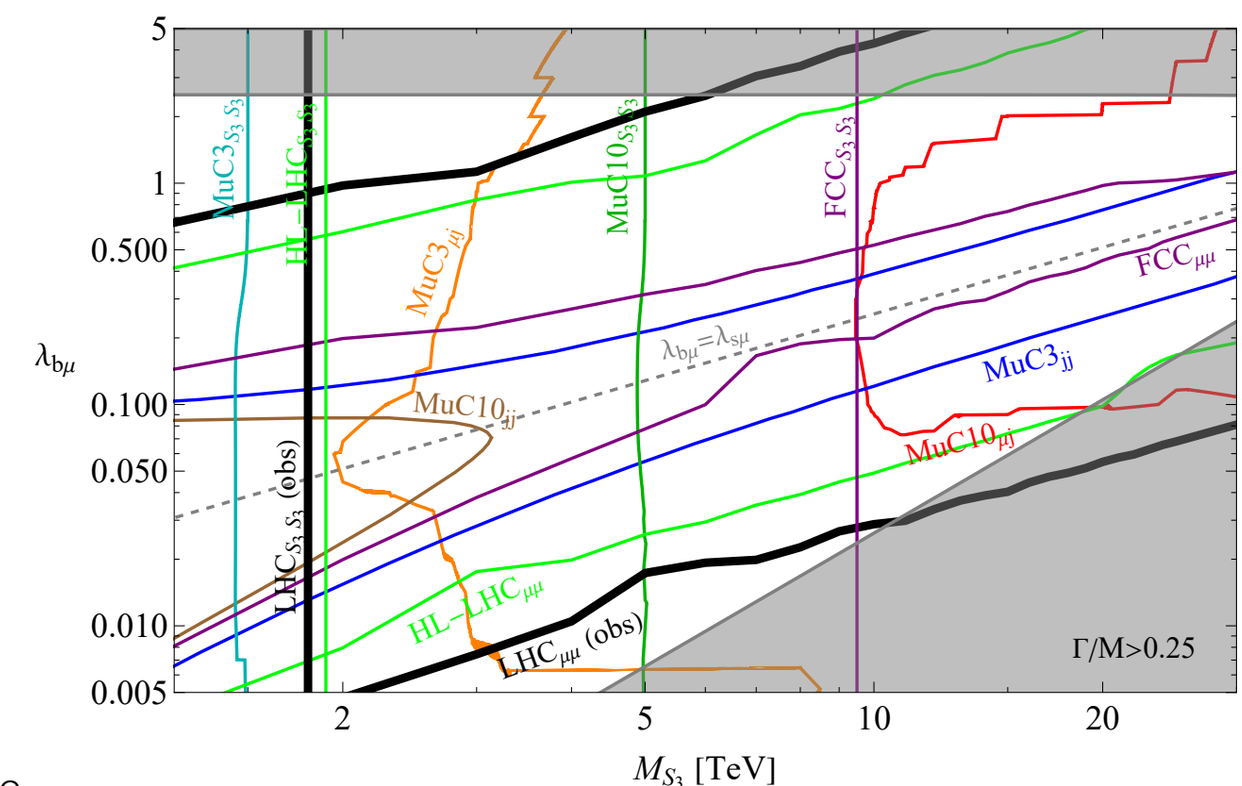
FCC-hh versus MuC

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; w.i.p



< Minimalistic Z' model

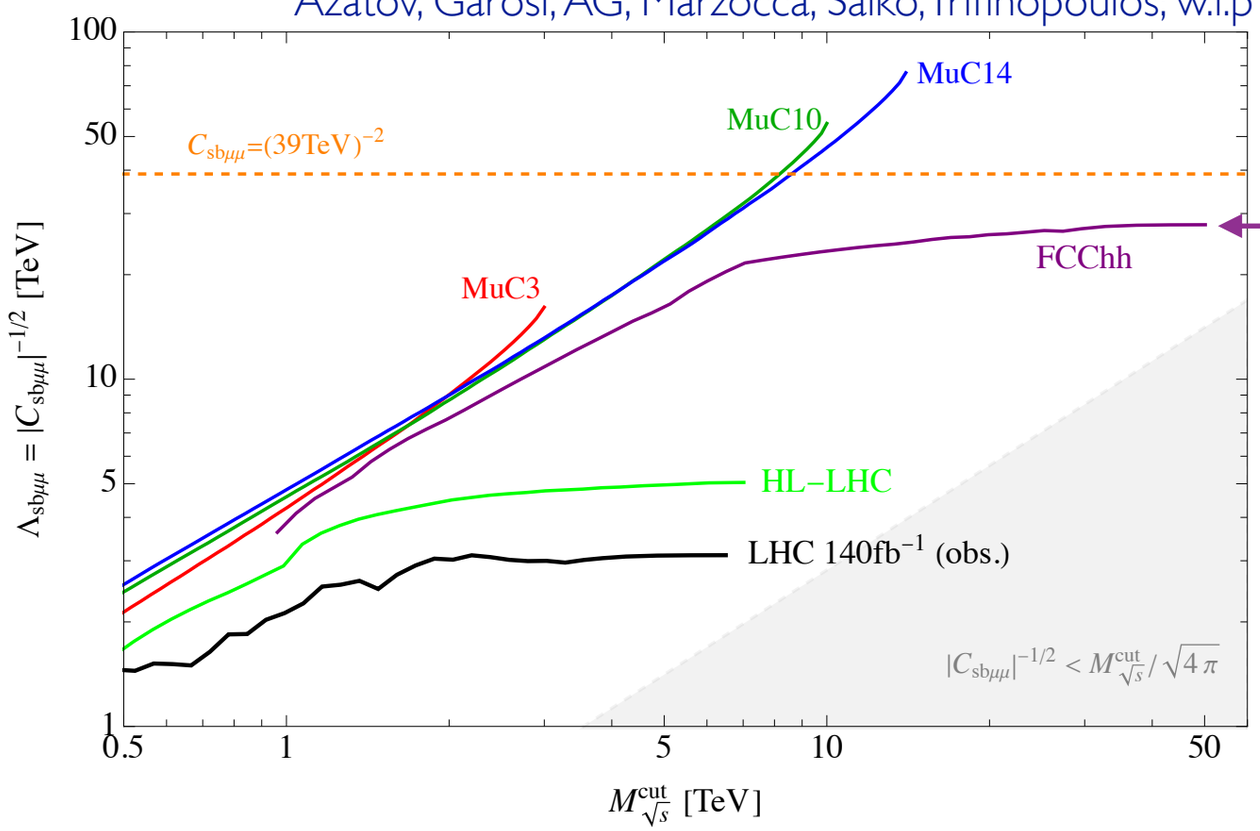
Minimalistic LQ model >



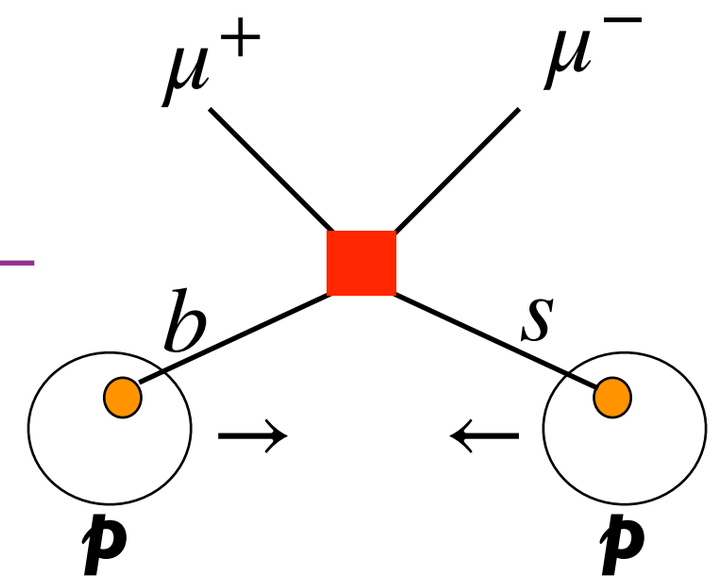
FCC-hh versus MuC

Minimalistic EFT >

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; w.i.p

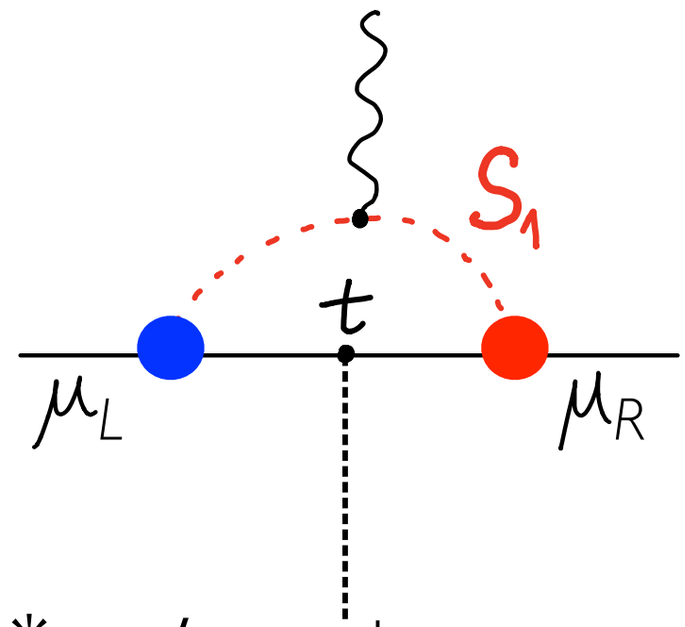


High-mass tails



AG, Marzocca; 1704.09015

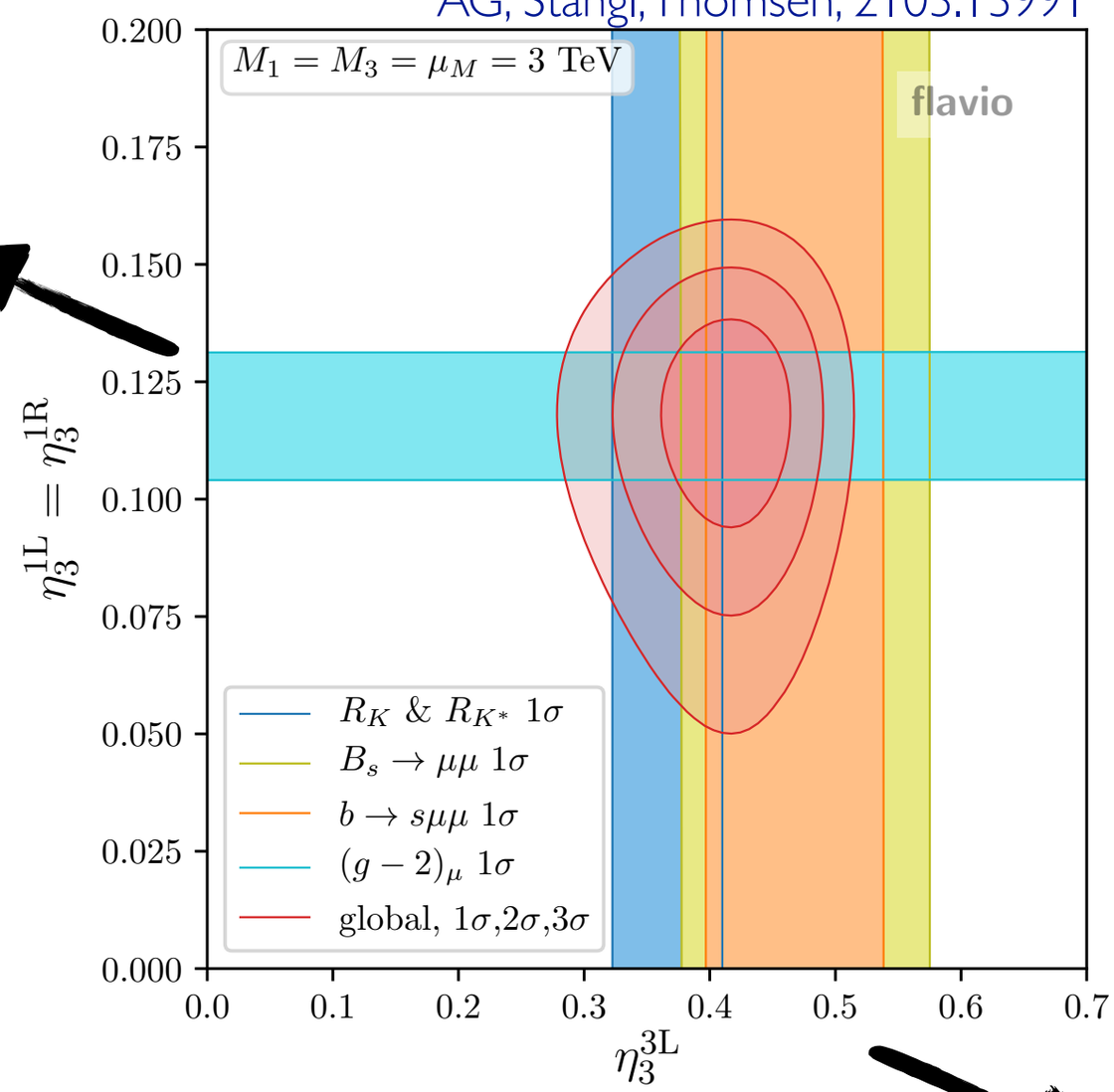
LQ model example



* m_t/m_μ enhancement

Queiroz, Shepherd; 1403.2309,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Coluccio Leskow, Crivellin, D'Ambrosio, Müller; 1612.06858
Dorsner, Fajfer, Sumensari; 1910.03877
Gherardi, Marzocca, Venturini; 2008.09548
+ many more

AG, Stangl, Thomsen, 2103.13991



$$\eta_i^{3L} = (V_{td},\, V_{ts},\, 1)\, \eta_3^{3L}$$

* V-A structure

Hiller, Schmaltz, 1408.1627,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Buttazzo, AG, Isidori, Marzocca; 1706.07808,
Gherardi, Marzocca, Venturini; 2008.09548
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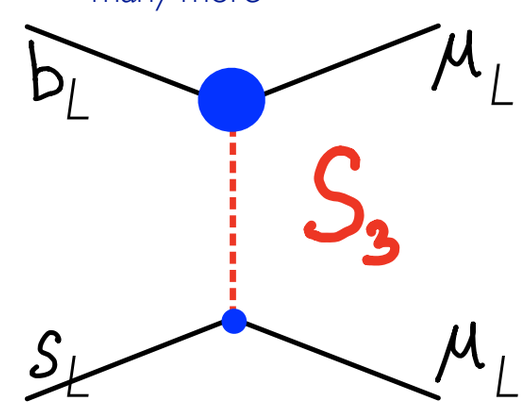

- One-loop matching to SMEFT from 2003.12525
- 399 observables in **smelli** 1810.07698
- EW and flavor opservables, LFV, LFU, magnetic moments, neutral meson mixing, semileptonic and rare B, D, K decays, etc.

A $U(1)$ story

- Lepton non-universal gauge extensions:

Davighi, AG, Thomsen; 2202.05275
AG, Stangl, Thomsen; 2103.13991 (PLB)

  - Chiral fermions: SM + $3\nu_R$

  - A class of chiral anomaly-free $U(1)_X$ gauge extensions:

$$X = 3m(B-L) - n\left(2L_\mu - L_e - L_\tau\right) , \quad \gcd(m,n) = 1$$

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Gauge symmetry selection rules:

✔ $q\mu S$

✘ $qqS^\dagger, qeS, q\tau S$

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- Proton decay & cLFV no

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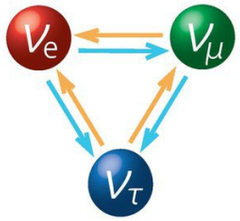
  - ***LFV is observed in nature***! The PMNS is full of $\mathcal{O}(1)$ elements.



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  - The correct neutrino masses and mixings dictate the $U(1)_X$ breaking!
  - A *dense* Majorana mass matrix needs two SM-singlet scalar fields with charges $6m - 2n$ and $6m + n$ to get a VEV ($n_i n_j \phi$)

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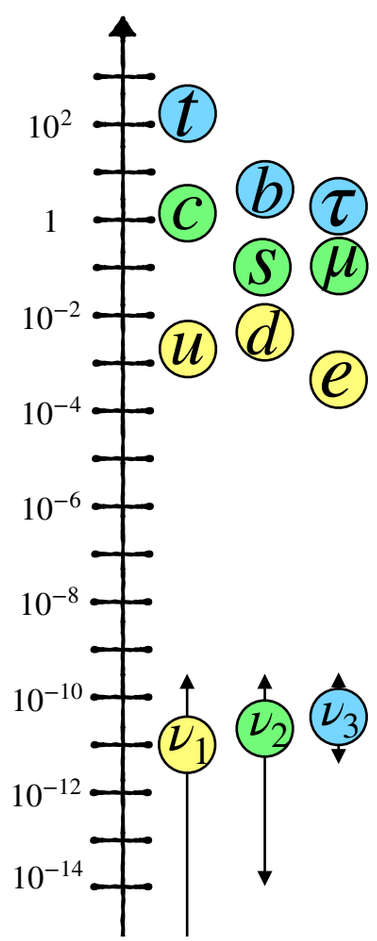

Type-I seesaw mechanism

The mass gap is explained if

$\langle \phi_{e\tau} \rangle, \langle \phi_\mu \rangle \gg \langle H \rangle$

Standard thermal leptogenesis > 10^9 GeV

A $U(1)$ story

Davighi, AG, Thomsen; 2202.05275

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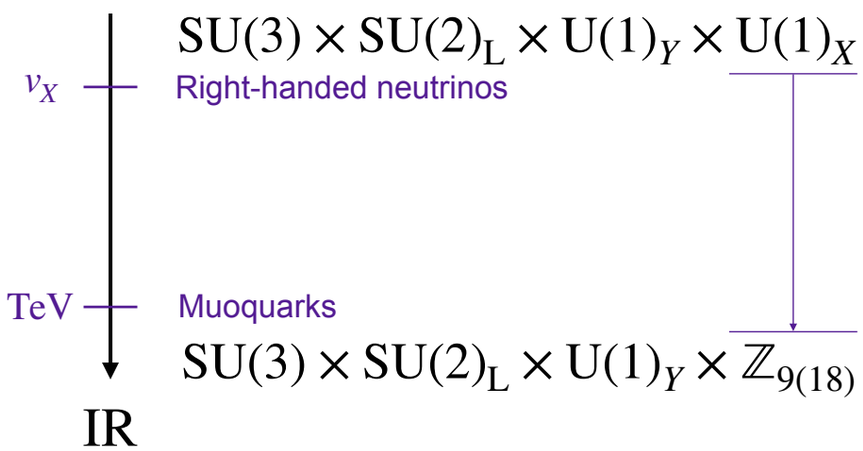

- Residual unbroken discrete subgroup $\Gamma \subset U(1)_X$ remarkably forbids proton decay to all orders in the EFT.

$$(m,\, n) = \big(3a + r,\, 9b + 3r\big), \quad \text{for} \quad r \in \{1,\, 2\},$$
$$(a,\, b) \in \mathbb{Z}^2, \text{ and } \gcd\big(3a + r,\, b - a\big) = 1\,.$$

- Approximate $U(1)_\ell^3$ in S interactions

A $U(1)$ story

- Lepton non-universal gauge extensions:

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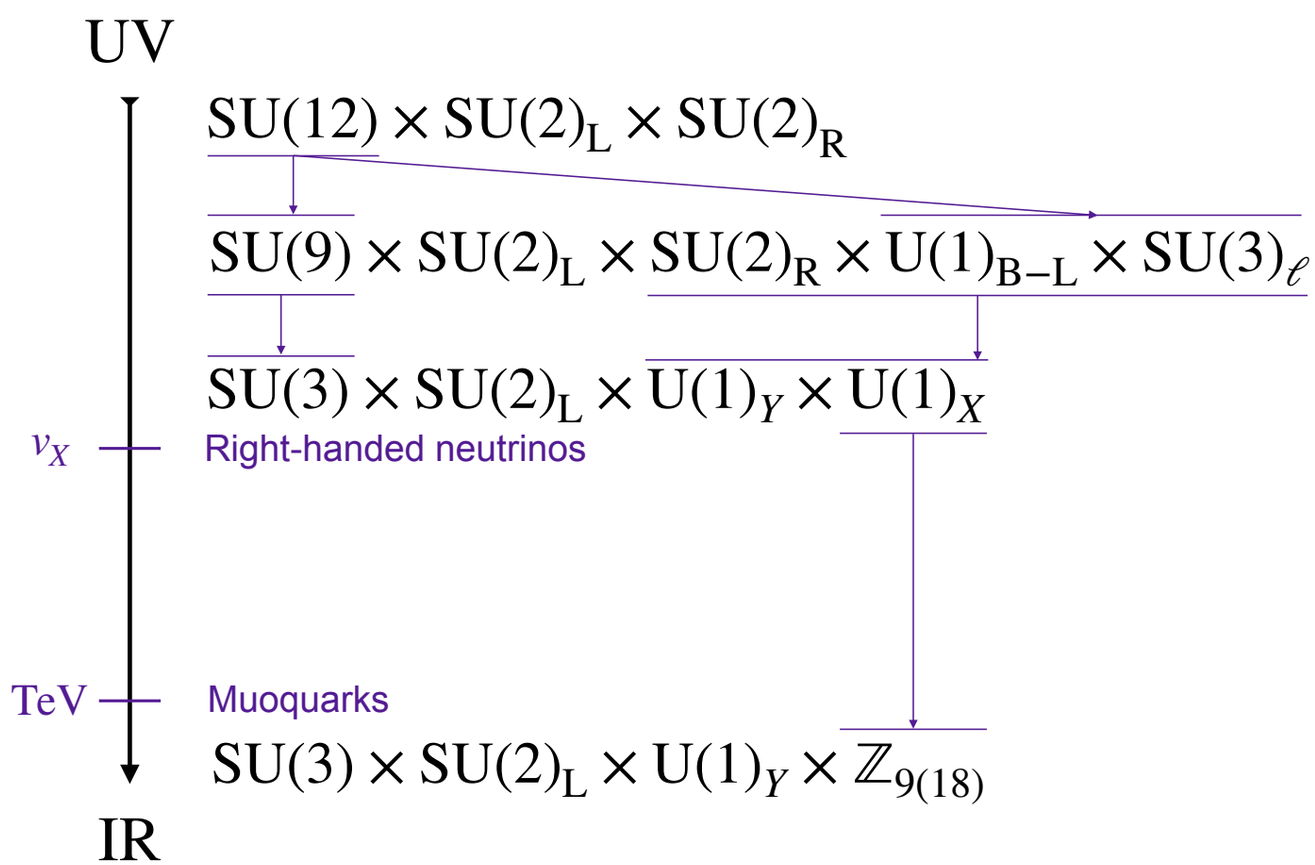

Gauge-flavour unification