Close-out: the Legacy of Flavour Anomalies

"… remarks on what the anomalies might mean for the longer term future of the field"

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FNSNF Swiss National Science Foundation
Eccellenza, Project-186866

28.04.2022, Beyond the Flavour Anomalies III

Flavour anomalies?

$b \to s\ell\ell$ $b \to c\tau\nu$ $(g-2)_\mu$

$b \to c u d_i$

See talk by Ferlewicz & Gubernari & Lenz

Flavour anomalies?

$b \to s\ell\ell$ $b \to c\tau\nu$ $(g-2)_\mu$

I) An experimental glitch

red her•ring

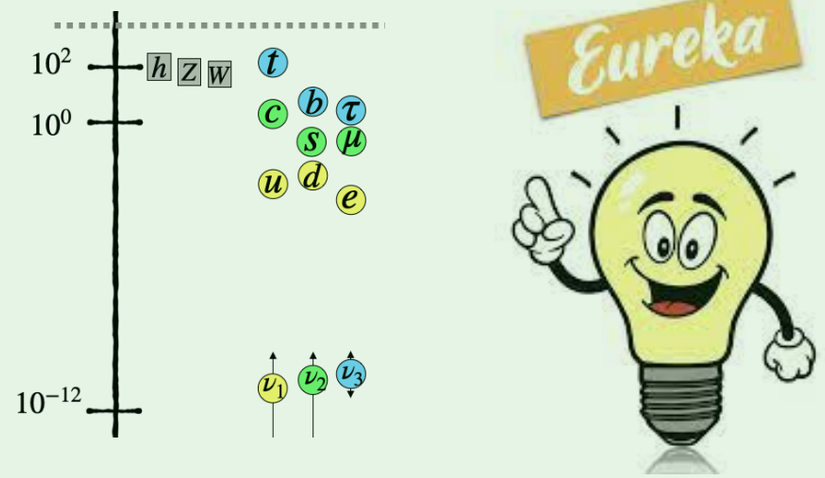
noun

1 a dried smoked herring, which is turned red by the smoke.

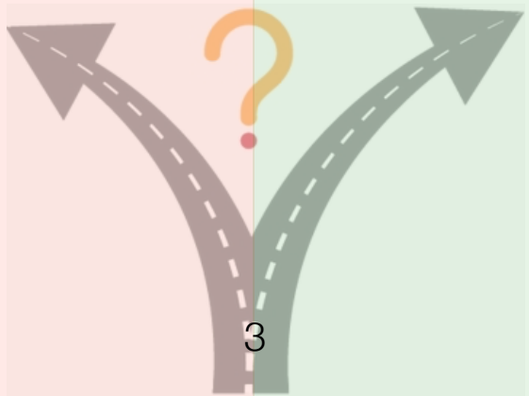
2 something, esp. a clue, that is or is intended to be misleading or distracting : *the book is fast-paced, exciting, and full of red herrings.* [ORIGIN: so named from the practice of using the scent of red herring in training hounds.]

II) A clue to address the known open questions?

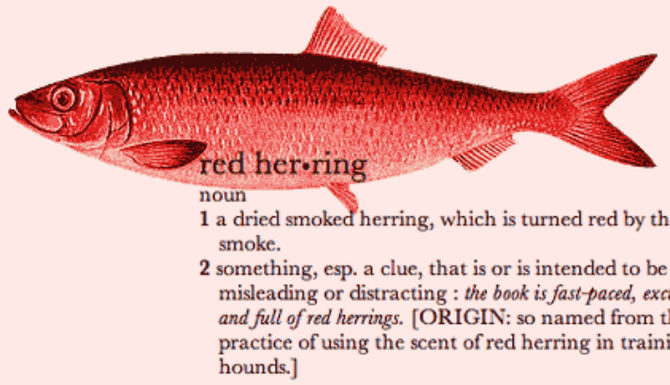
Flavour puzzle, Higgs mass, Charge quantisation, …



III) A discovery of a next big puzzle?



Scenario I

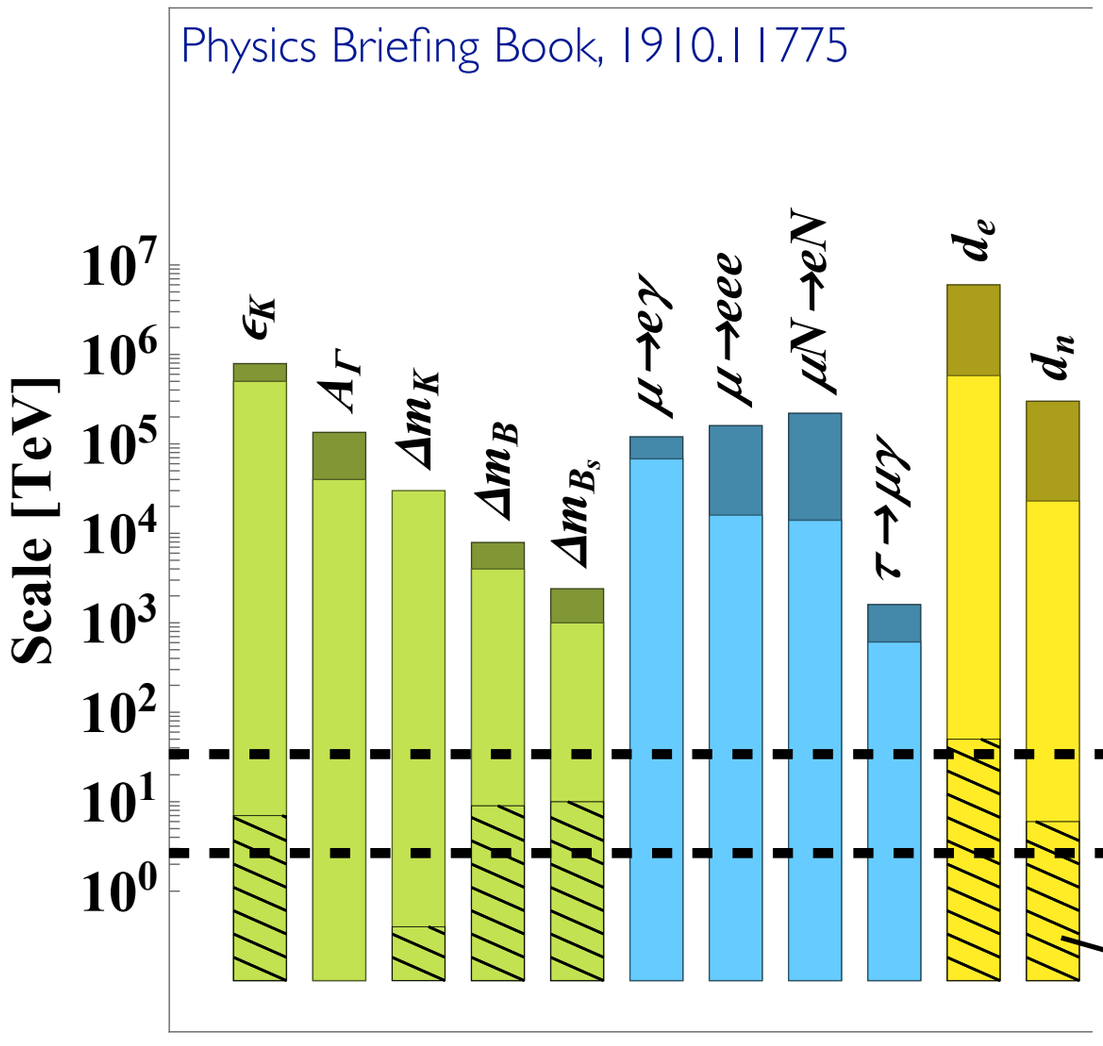


(*) Very personal and selective.
Not a review!
Apologies for missing citations.

1) *Flavour Symmetries in the IR*

- The exact and approximate accidental symmetries carefully revisited

  Consistency game
  Explain the anomalies while passing other tests of accidental symmetries



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

See talk by Renner & Craik

1) *Flavour Symmetries in the IR*

- MFV doesn't work well for B anomalies!
- Other flavour symmetries and their breaking patterns to be explored
- The winner in the quark sector: $U(2)^3$!
- Several options in the leptonic sector…

- $U(2)^3$ suggested before the anomalies — Talk by Isidori, Talk by Marzocca

1) *Flavour Symmetries in the IR*

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Charting the space of SMEFT with flavour symmetries

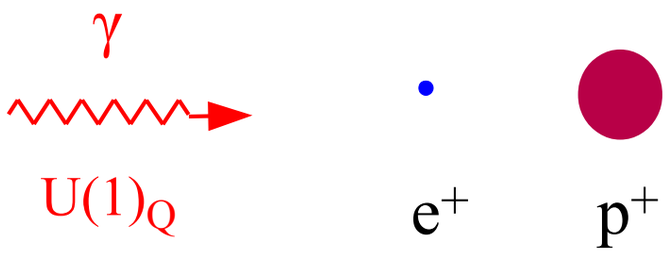
Faroughy, Isidori, Wilsch, Yamamoto; 2005.05366
AG, Thomsen, Palavric; 2203.09561

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

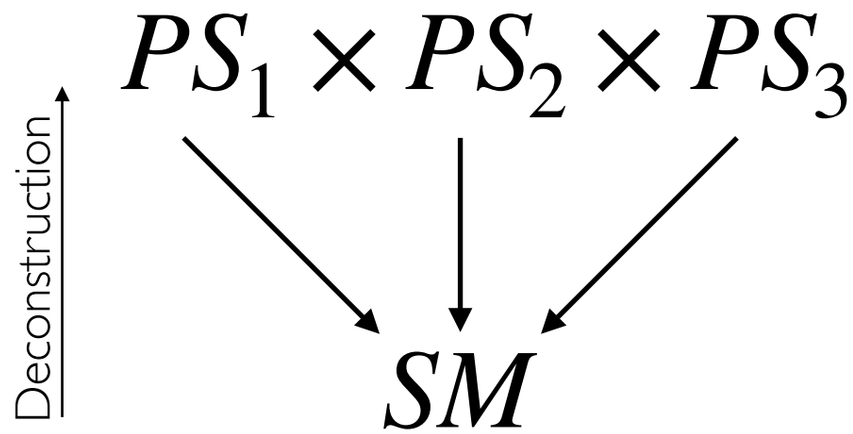
(*) Terms relevant for the high-p_T physics: Top, Higgs & electroweak
Impact: **The LHC EFT WG** asked for the flavour structure compatible with B anomalies

2) ***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**?

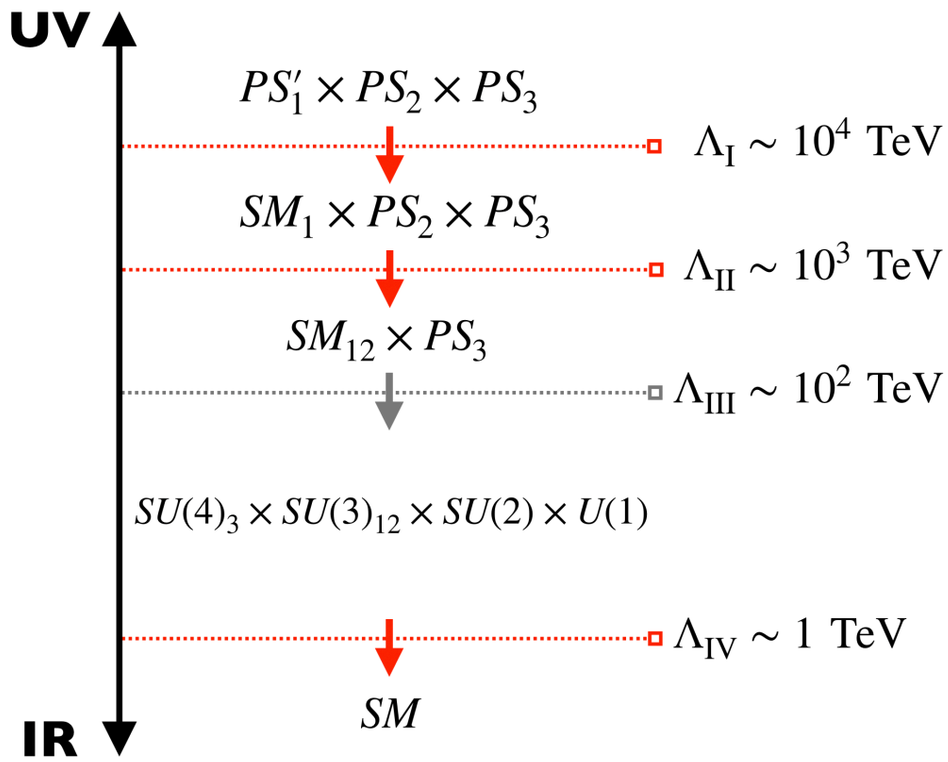
See talk by Isidori

2) ***Non-universal gauge interactions***

Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368

Multi-scale flavour

- Series of hierarchical SSBs
  $\Longrightarrow$ Flavour hierarchies



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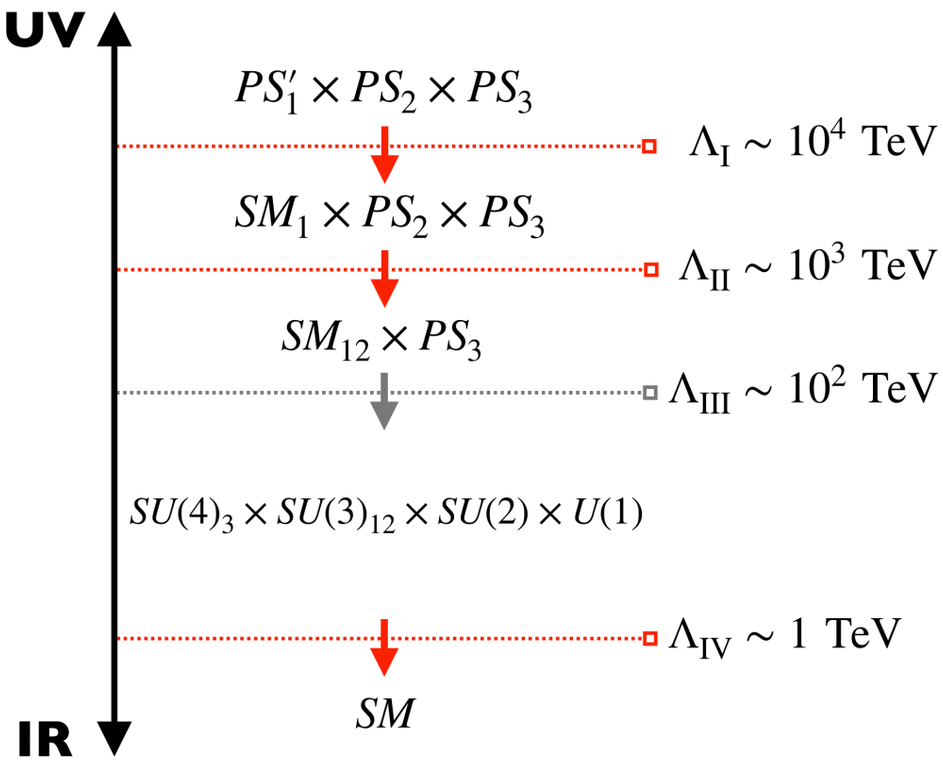
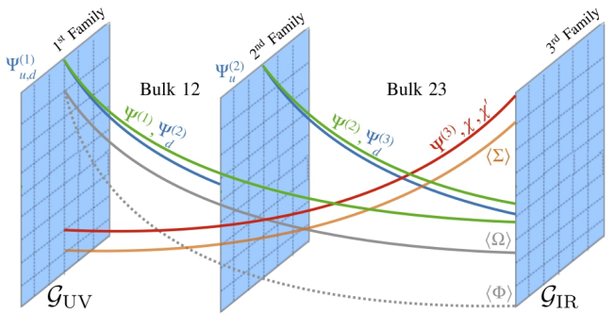


Flavour as a topological defect

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



Fuentes-Martin et al; 2203.01952

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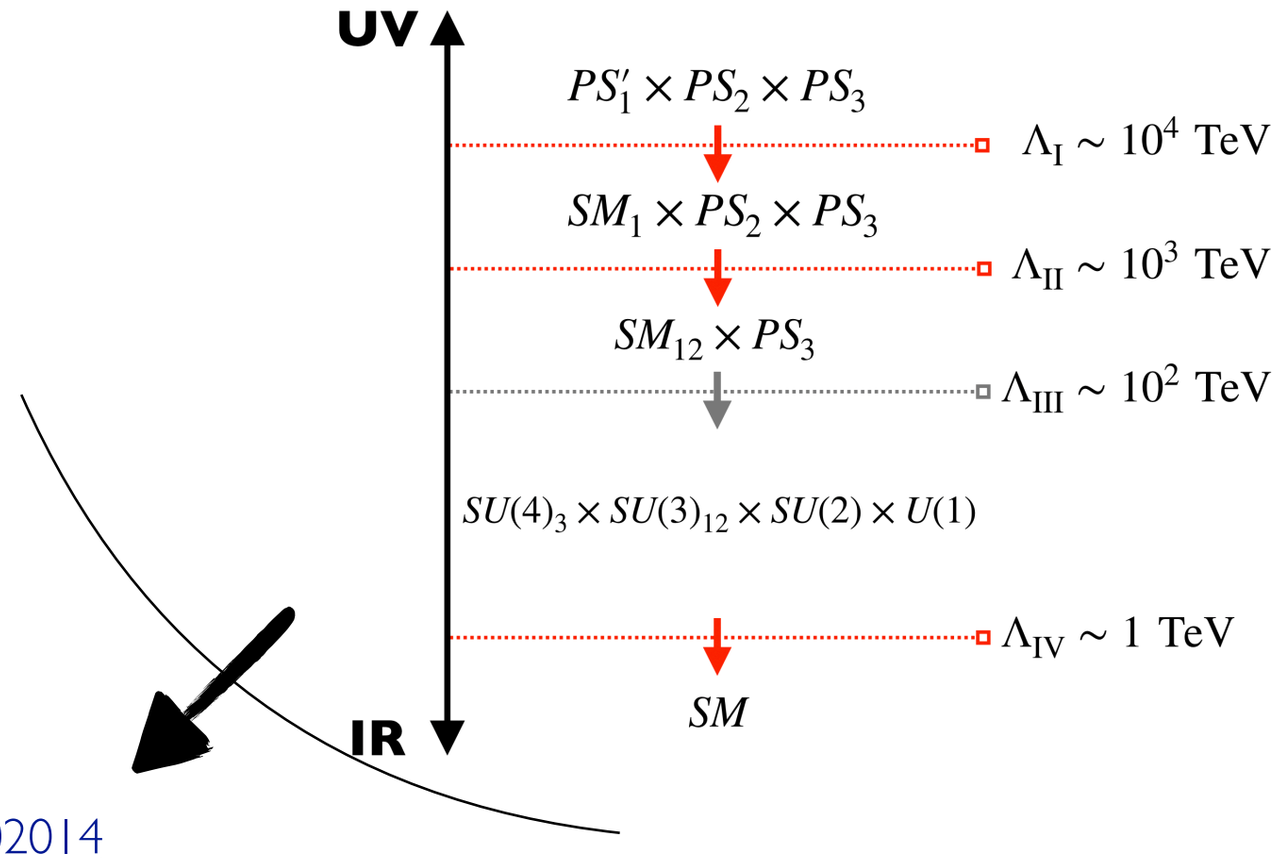
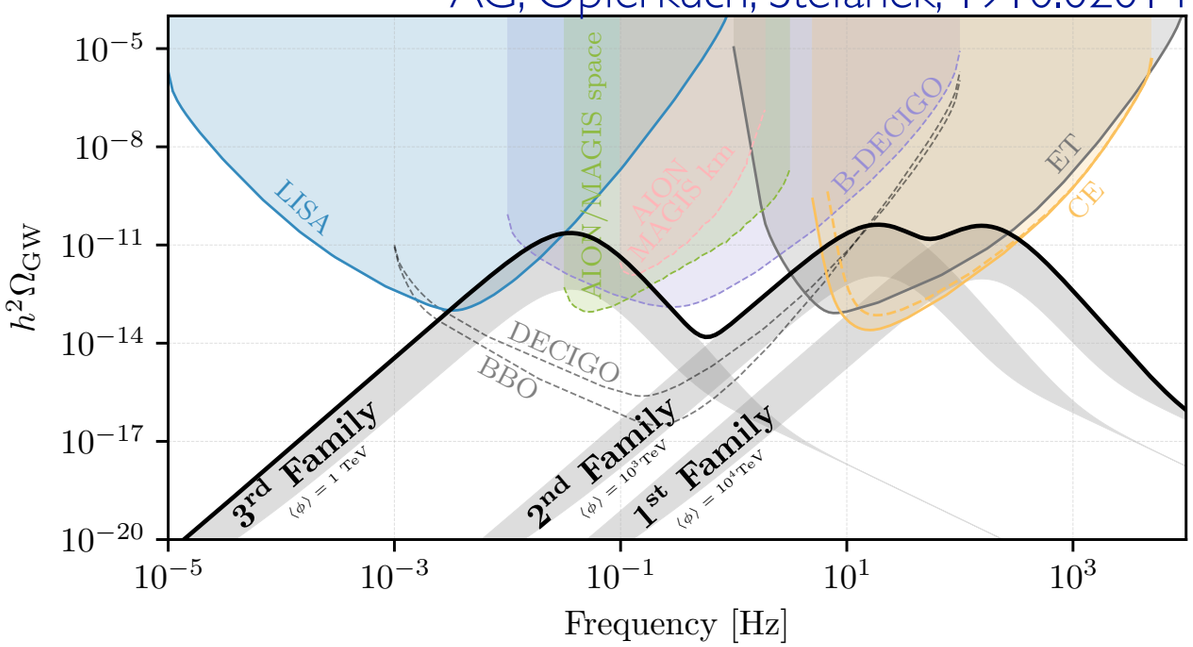


- Novel connections
  GW astronomy & Flavour physics

AG, Opferkuch, Stefanek; 1910.02014

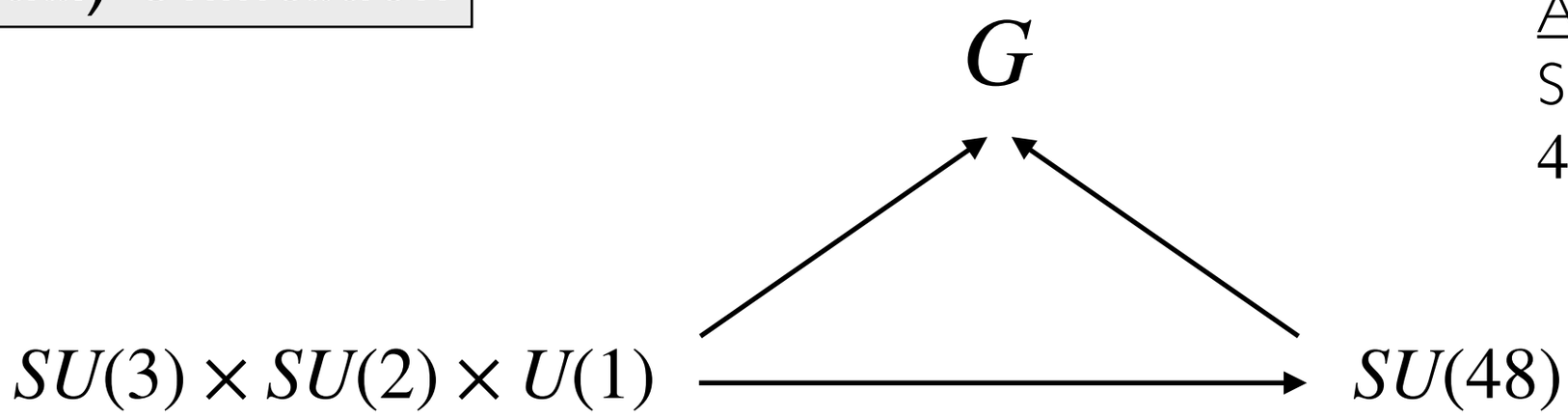


Stochastic gravitational wave radiation with the characteristic **three-peaked** signature.

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

2) ***Non-universal gauge interactions***

(Partial) Unification



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

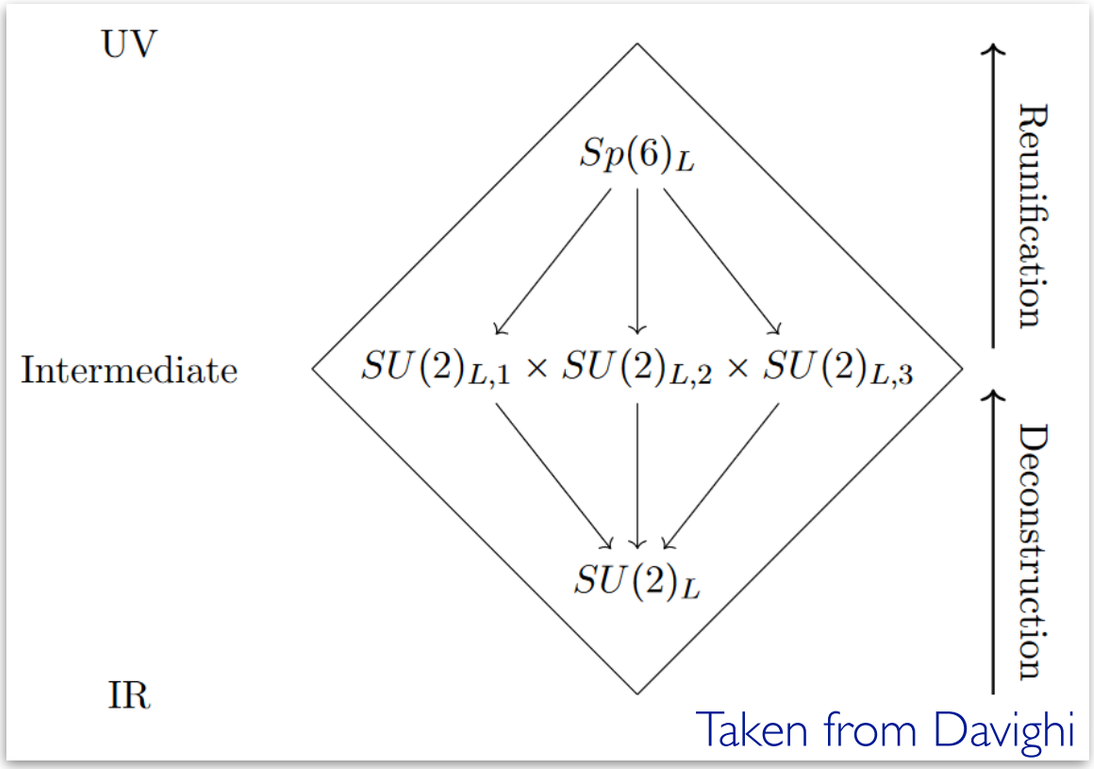
Allanach, Gripaios, Tooby-Smith; 2104.14555

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

2) *Non-universal gauge interactions*

(Partial) Unification

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

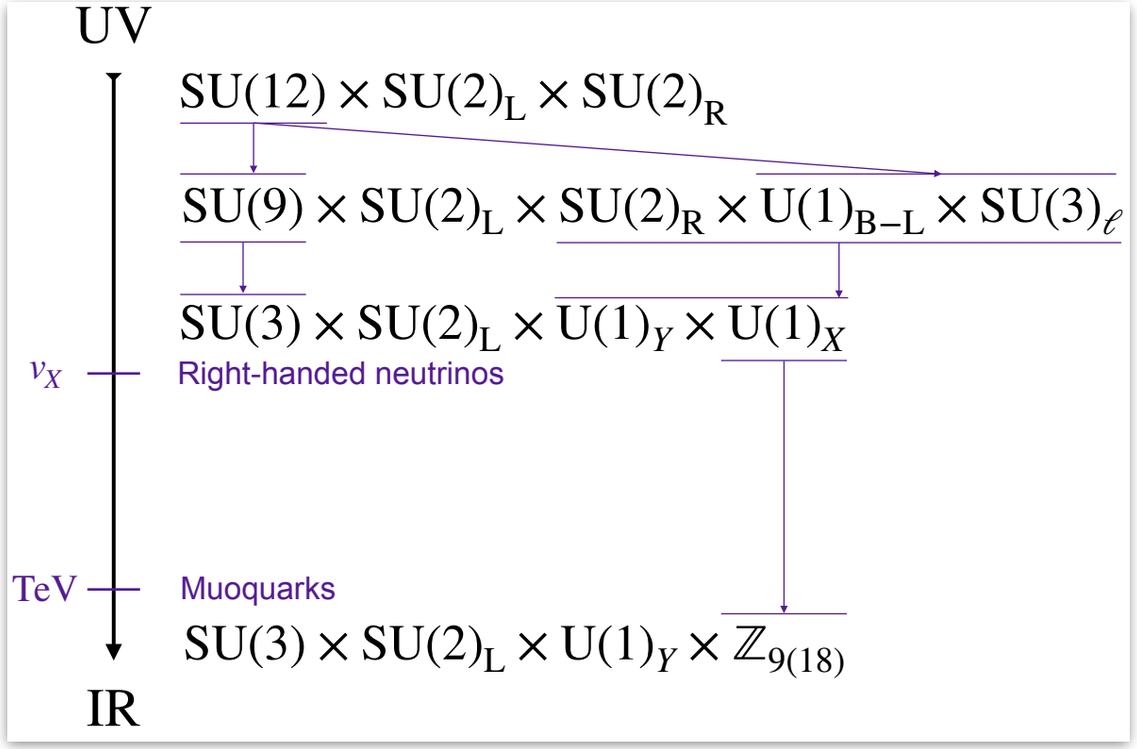


Taken from Davighi

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!

2) ***Non-universal gauge interactions***

Lepton non-universal $U(1)$ See talk by Zupan

- 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

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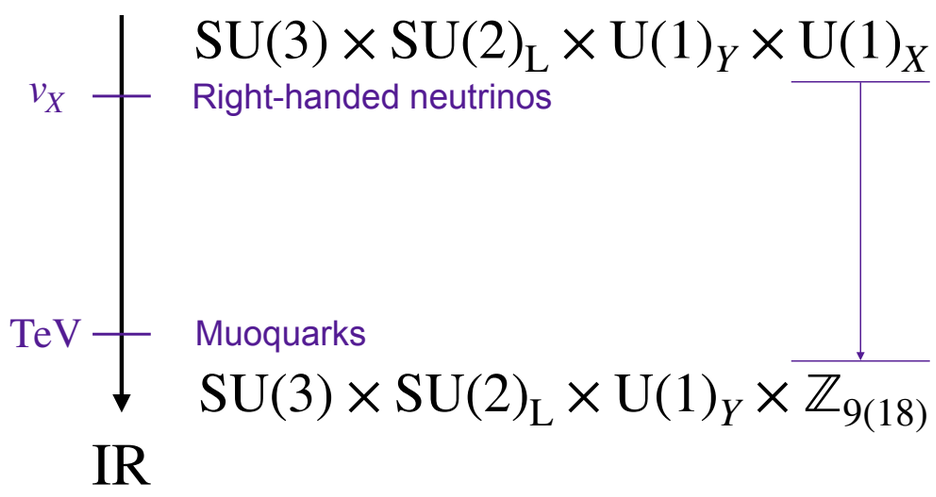
Lepton non-universal

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

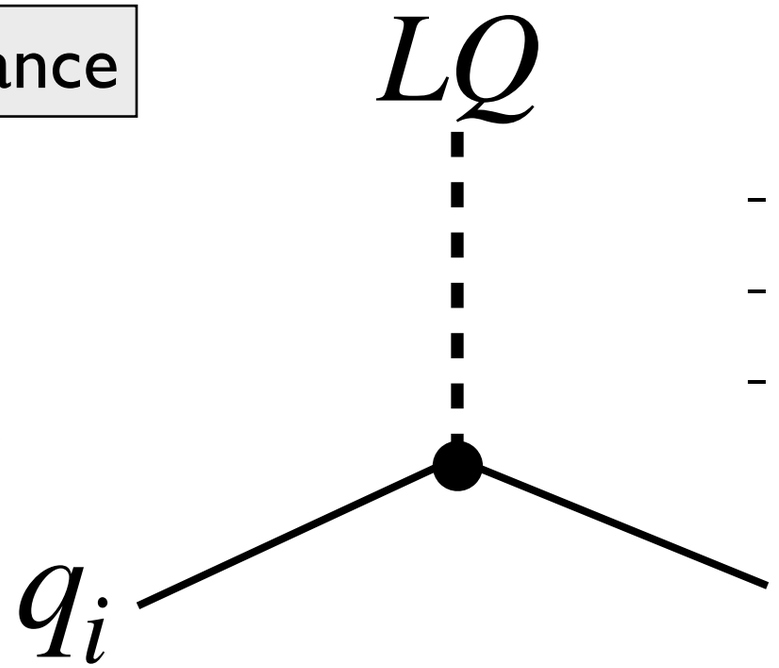
Similar mechanisms shortly after: Koren; 2204.01741, Wang, Wan, You; 2204.08393

3) **TeV-scale Leptoquarks**

The leptoquark renaissance

See talk by Becirevic & Marzocca

[Phys.Rept. 641 (2016) 1-68]
Doršner, Fajfer, AG, Kamenik, Košnik
is by now outdated!



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

3) TeV-scale Leptoquarks

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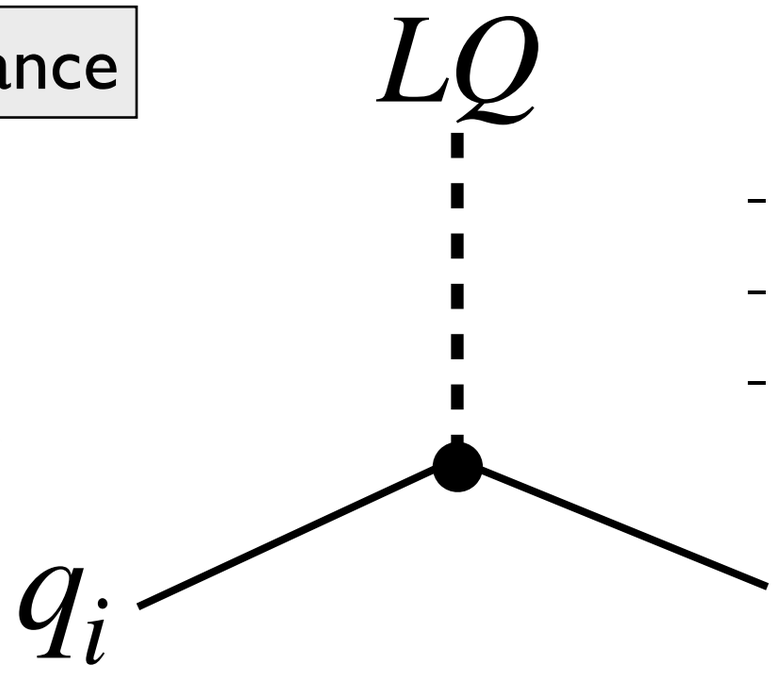

- Tree-level $2q2\ell$,
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Two flourishing model-building directions at the TeV-scale

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

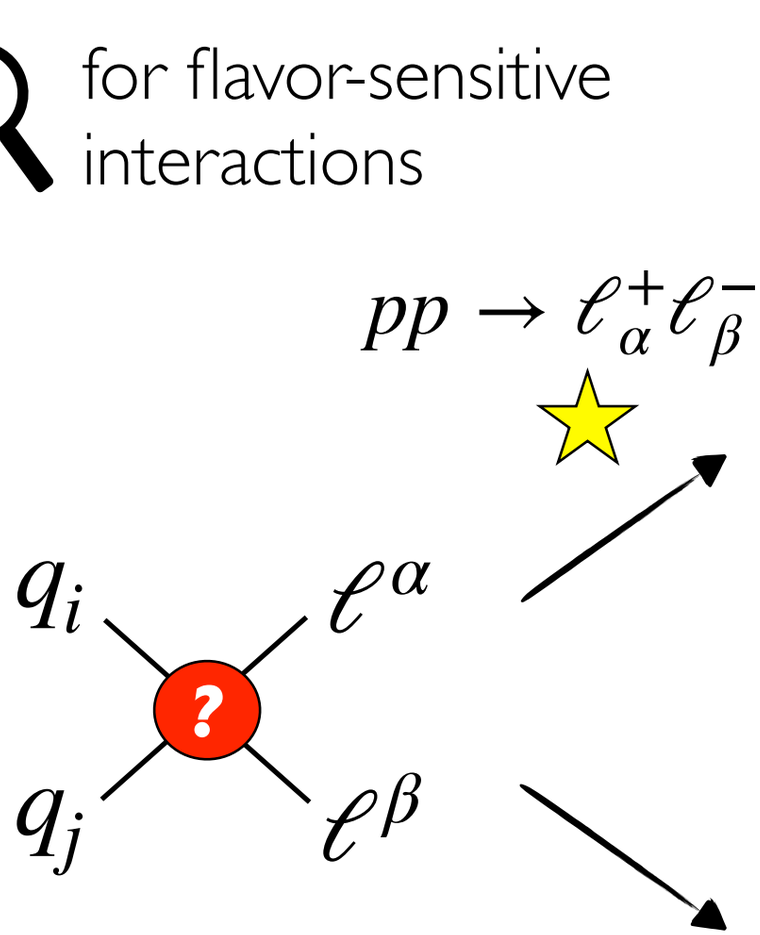
- If Higgs was a π, LQ would be a K, …

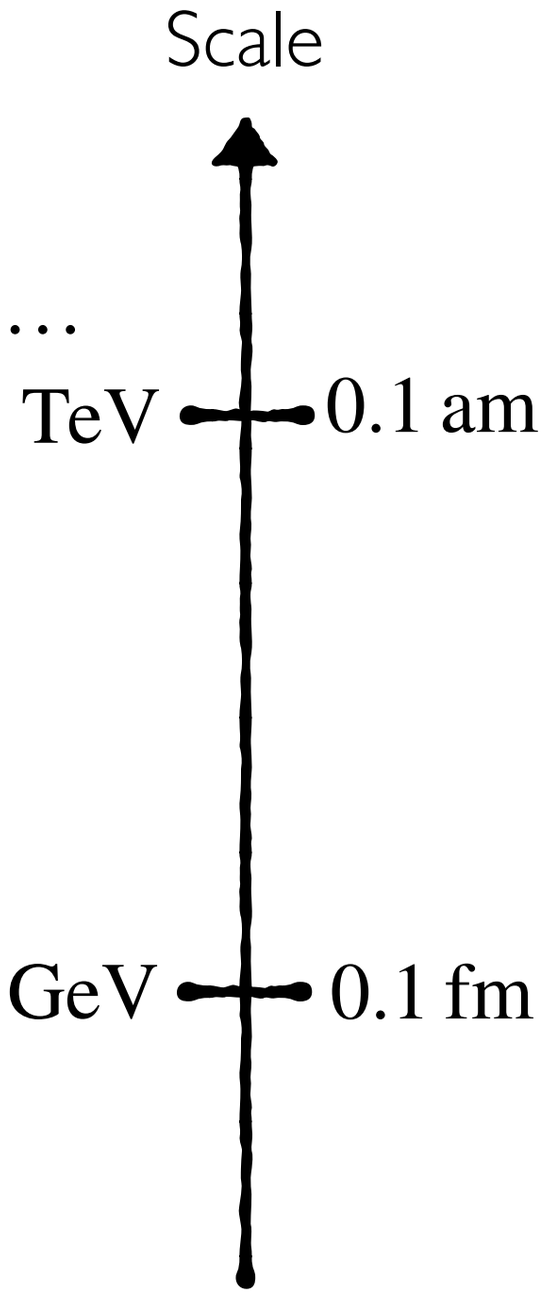
e.g. Marzocca; 1803.10972
Gripaios, Nardecchia, Renner; 1412.1791

Fuentes-Martin, Stangl; 2004.11376

4) ***Flavour Physics in High-p_T Tails***

for flavor-sensitive interactions





See talk by Becirevic

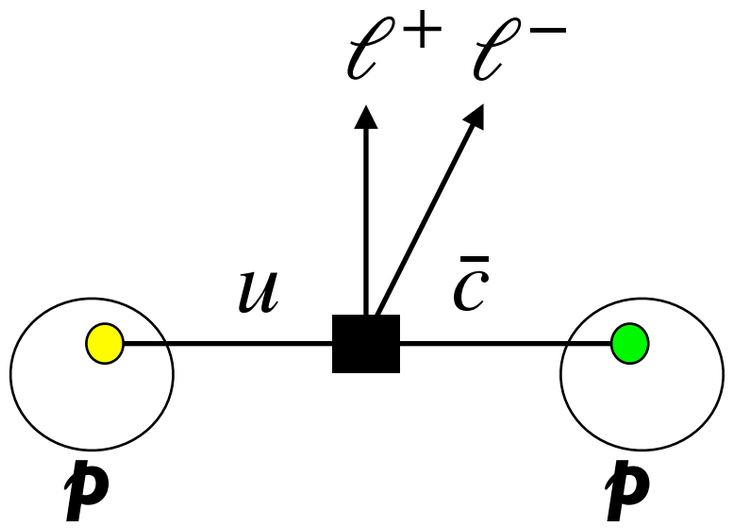
A wealth of information for flavour physics, **complementary** to hadron decays.

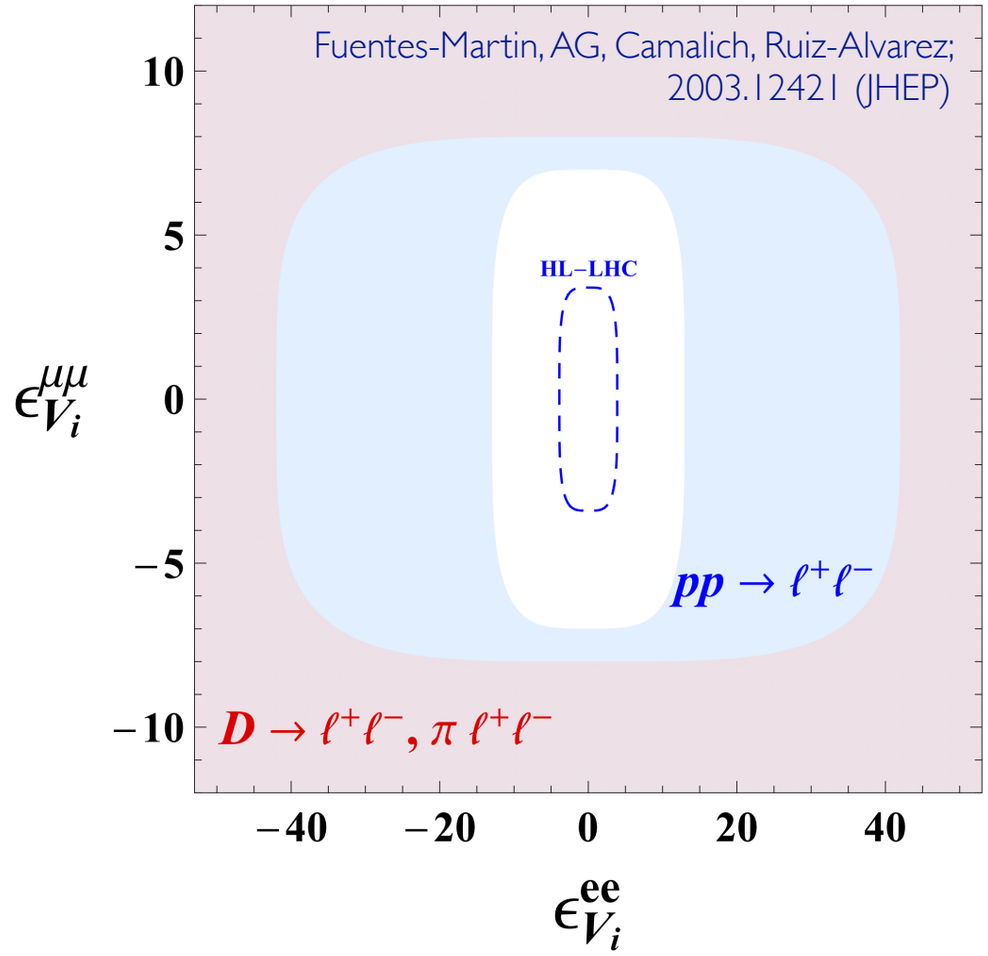
4) *Flavour Physics in High-p_T Tails*

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

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





Systematic exploration needed!

Scenario II

(*) Very personal and selective.
Not a review!
Apologies for missing citations.

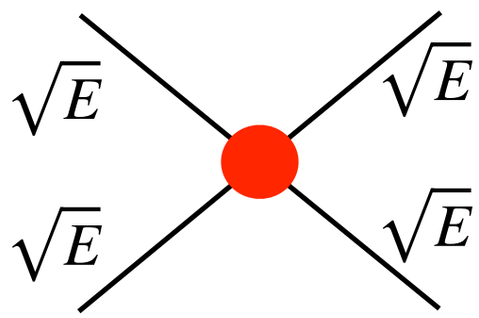
New mass scale?

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

$$\mathscr{L} \supset \frac{1}{(40\ \text{TeV})^2}\,(\bar{s}_L\gamma^\mu b_L)\,(\bar{\mu}_L\gamma_\mu\mu_L)$$

See talk by Capdevila et al
See talk by Descotes Genon

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



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

$\Longrightarrow$ Violation of perturbative unitary $\lesssim 100\,\text{TeV}$
Di Luzio, Nardecchia; 1706.01868

Observational evidence!
Stronger than the EW naturalness!
Neutrino oscillations, Dark Matter, Baryon asymmetry, Inflation, etc could be a physics of a very high (or different) energy scale

- A bright long-term future for collider physics!

Low-p_T roadmap

1. $b \to s\ell\ell$: Only μ? LH or vectorial? Universal contribution? Matias, Nabeebaccus, Reboud, Schune, Coutinho, Hadavizadeh, Inguglia, Amhis, Owen, Serra

2. $b \to c\tau\nu$: Yes or No? Pardinas and Jung; Mathad and Smith; Bernlocher
   If yes, $\Lambda \lesssim 10\,\text{TeV}$, $U(2)_\ell$ preferred, $g_\tau \gg g_\mu$. Eg $LQ \to \tau b$.

3. $(g-2)_\mu$: Yes or No? Leptonic $U(1)^3$. Chislett and Hagelstein

4. $b \to s\nu\nu$ & $b \to s\tau\tau$: Tilquin and Mohan
   $SU(2)_L$ prediction. If large $\gg 10\,\%$, $U(2)_\ell$ again.

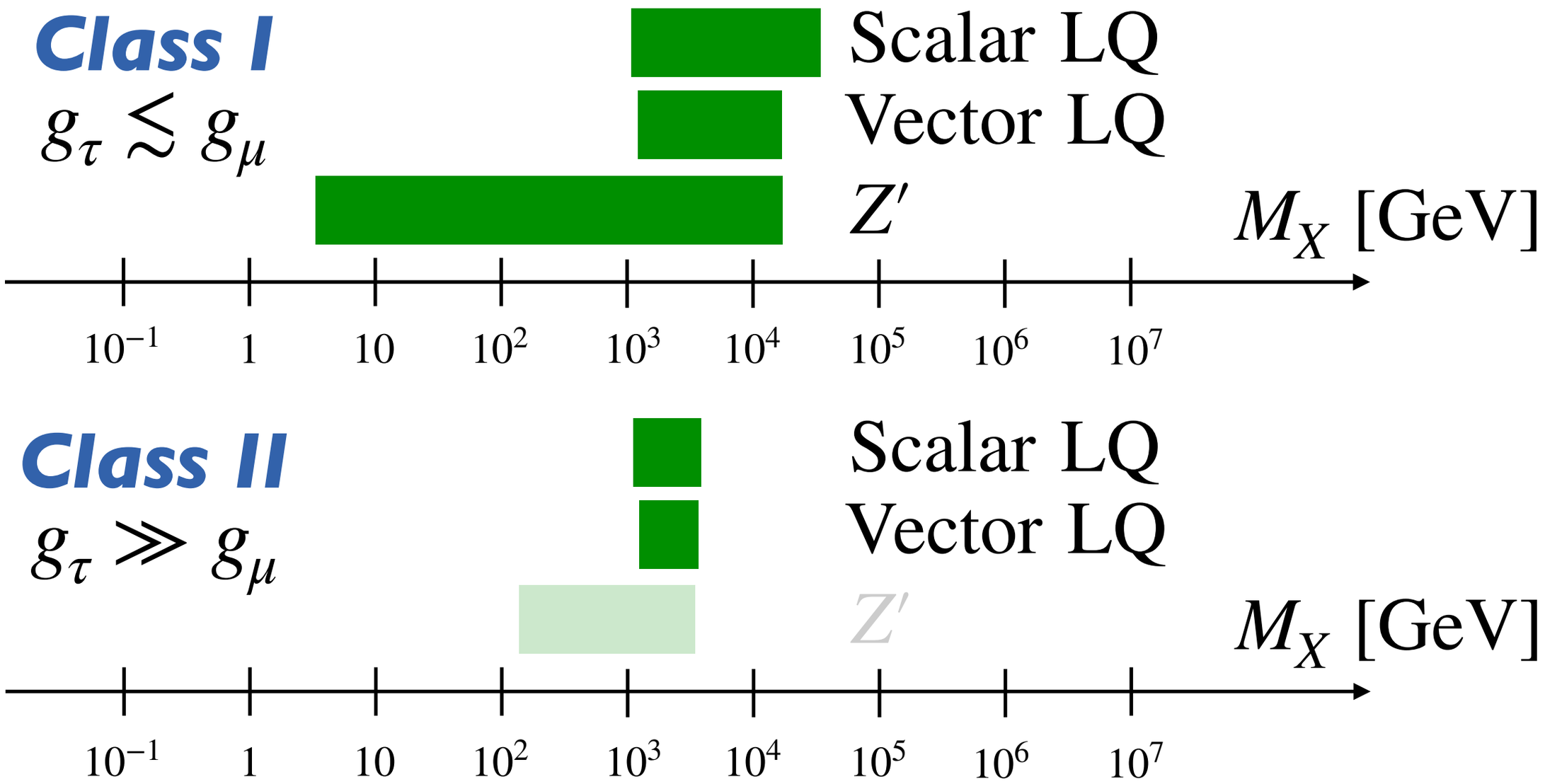
5. $b \to d\ell\ell(\nu\nu)$: Test $U(2)_q$, also in $s \to d\nu\nu$ Altmannshofer and McCann

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

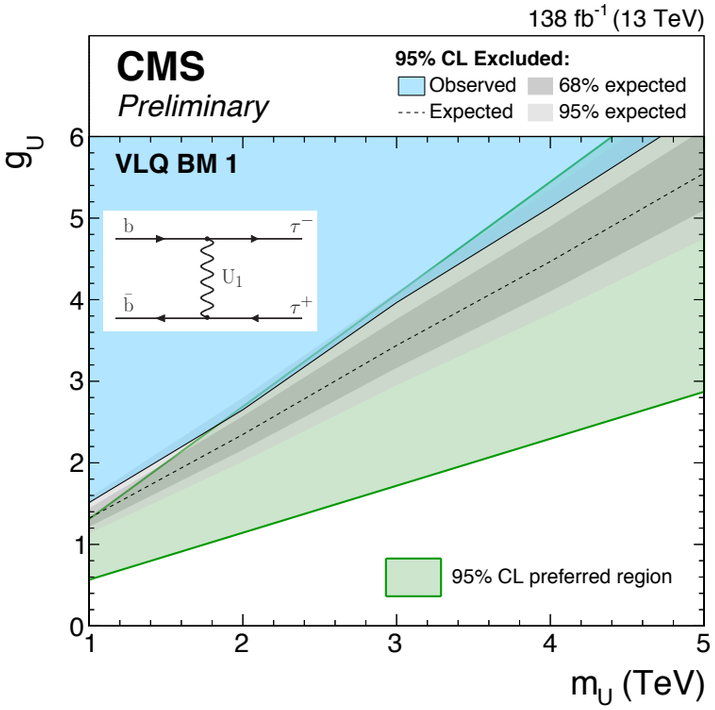
- $b \to s\ell\ell$: Tree-level



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

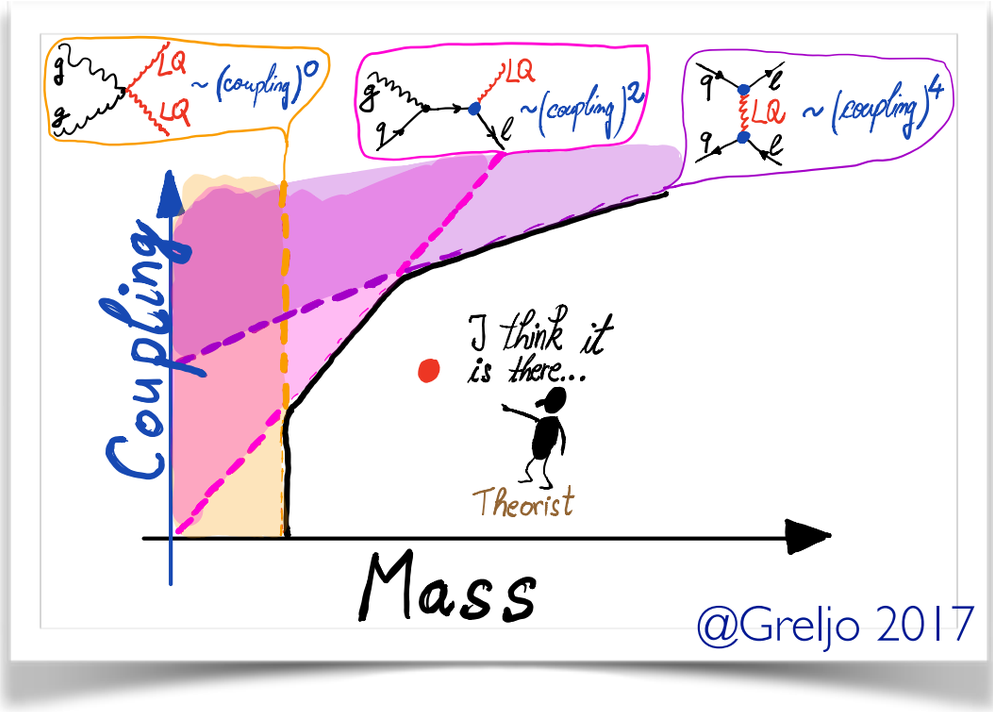
High-p_T LHC

- 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
  - …



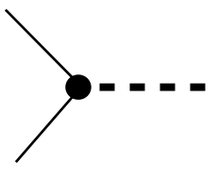
CMS PAS HIG-21-001

- Leptoquark searches



Novel mechanism
Resonant LQ production

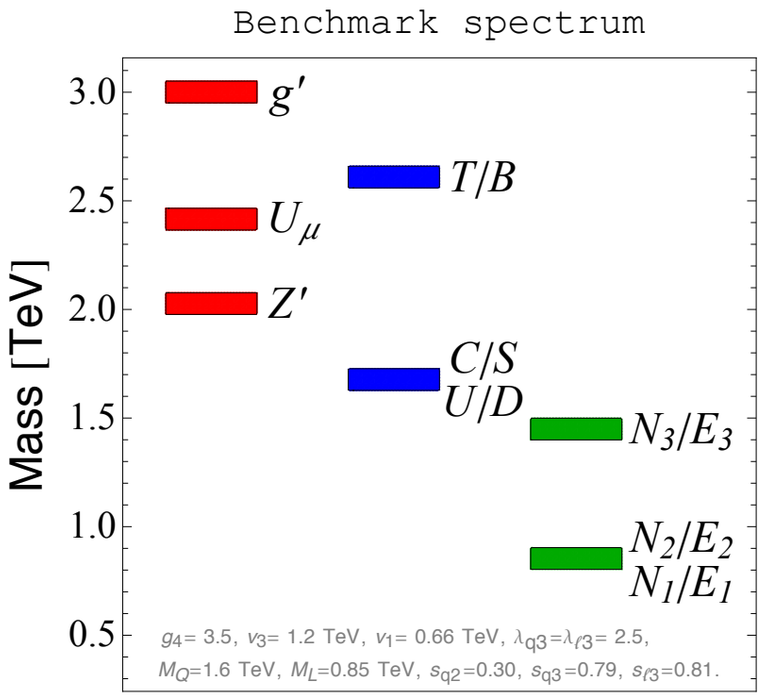
$pp \to \Phi$



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

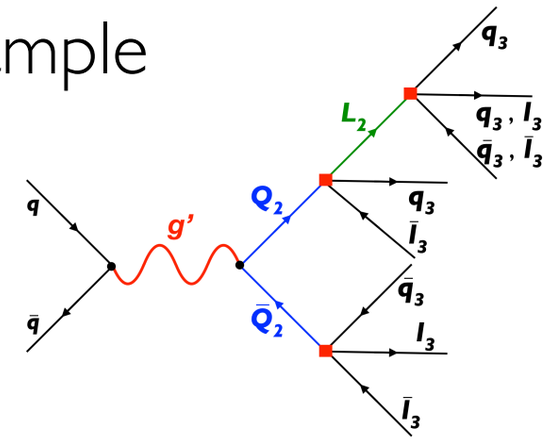
High-p_T LHC

- Explicit models:
  The 4321 model

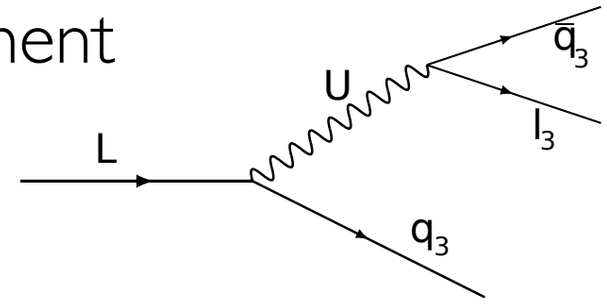


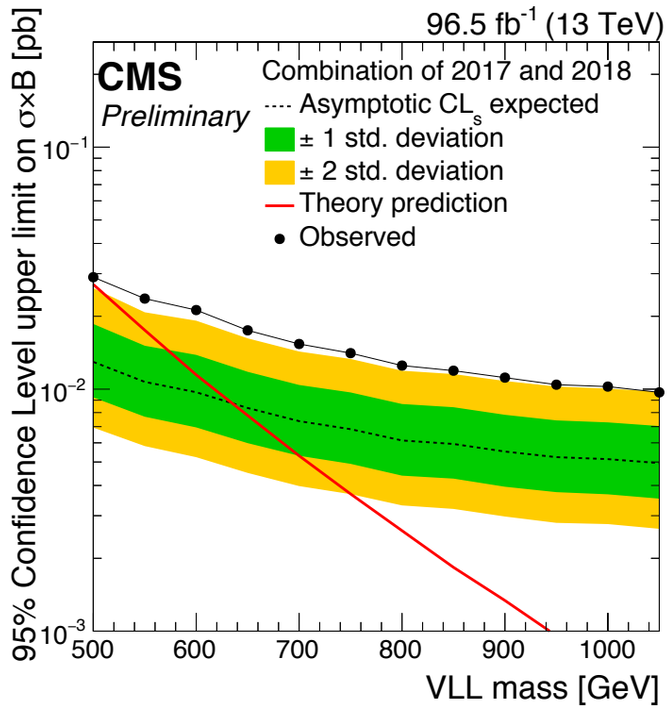
Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner; 1708.08450

- Example



- Experiment





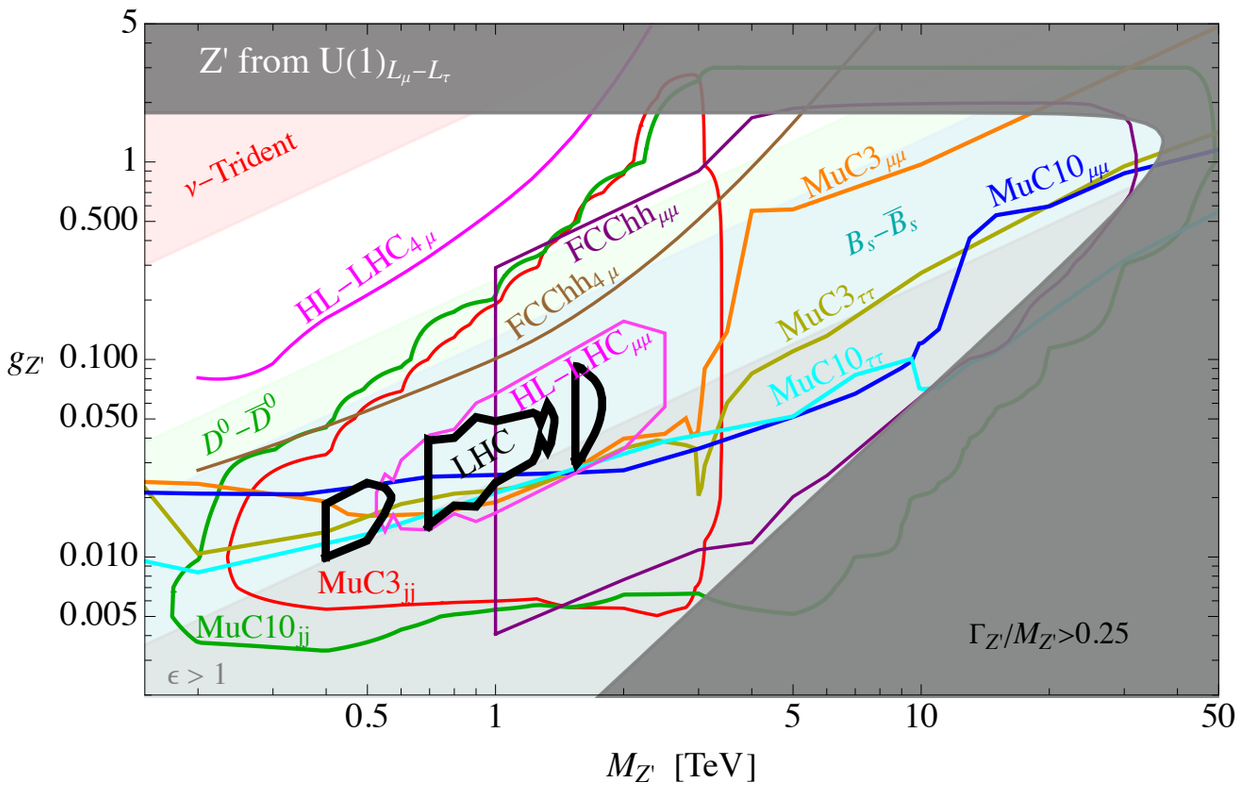
CMS PAS B2G-21-004

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."

Long-term future

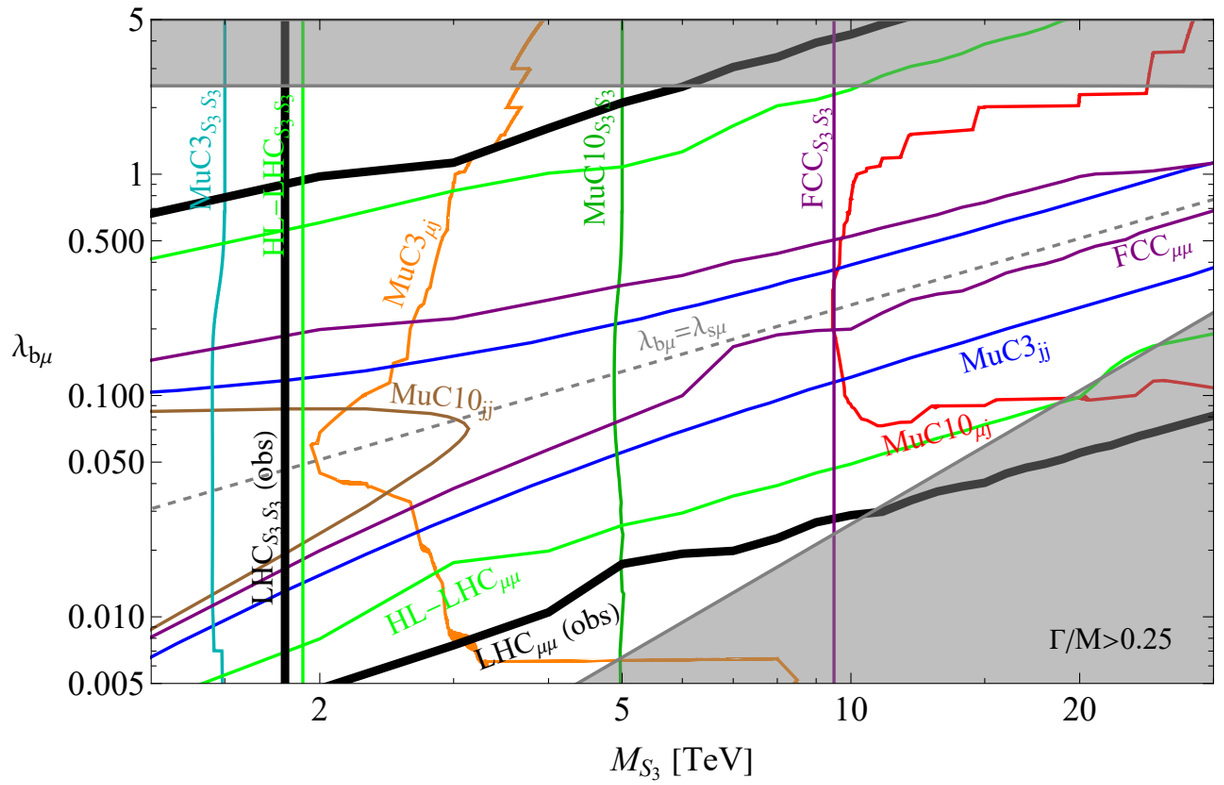
FCC-hh versus MuC

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



< Minimalistic Z' model

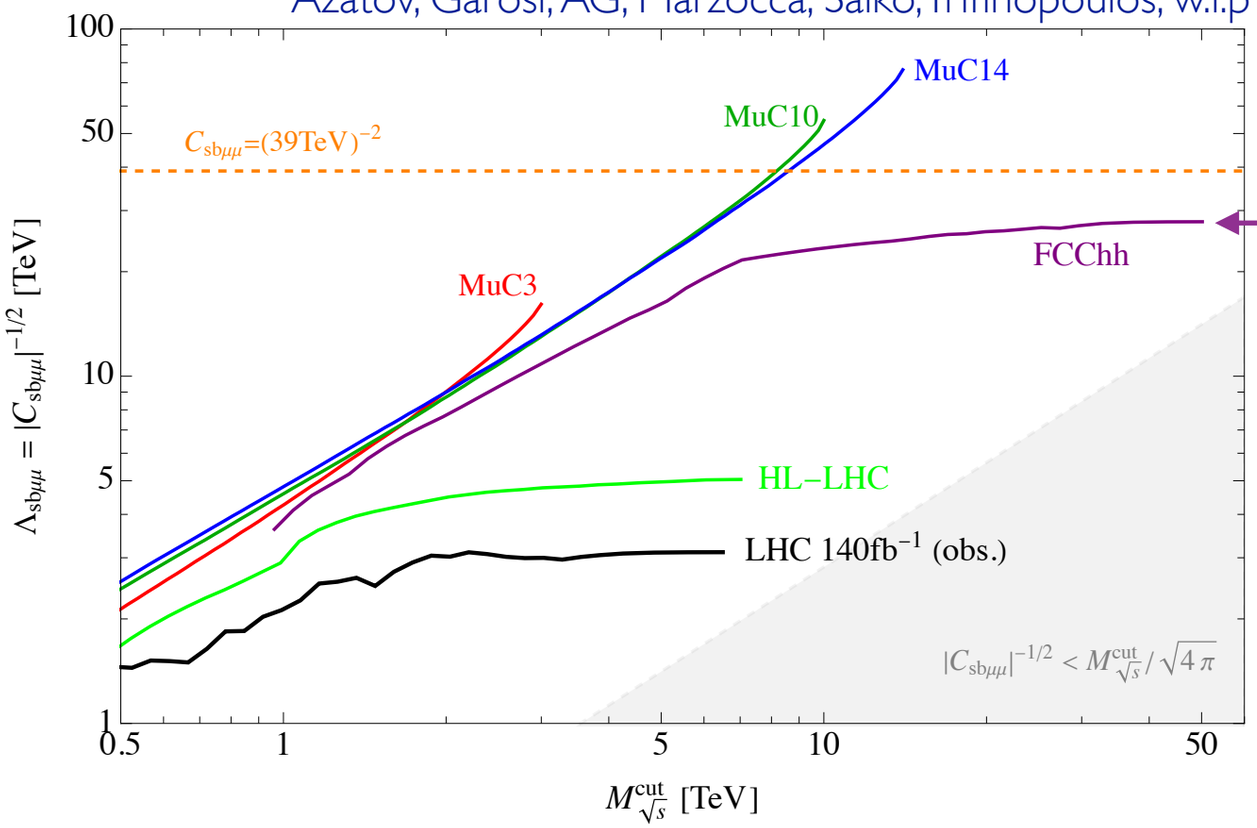
Minimalistic LQ model >



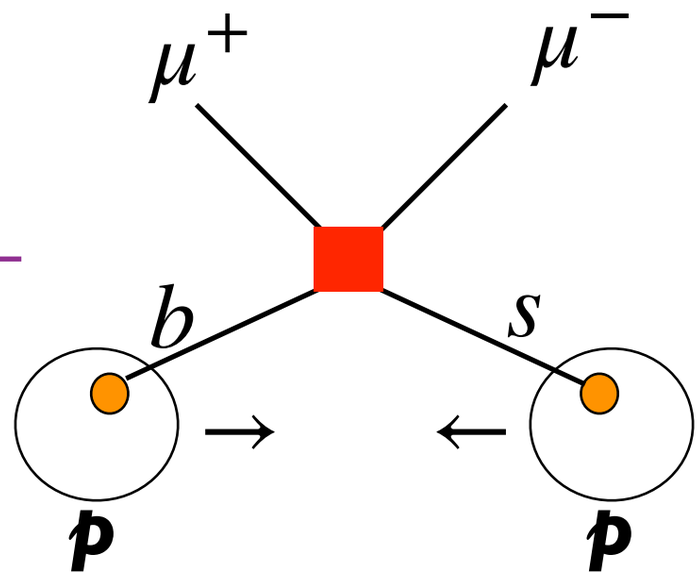
FCC-hh versus MuC

Minimalistic EFT >

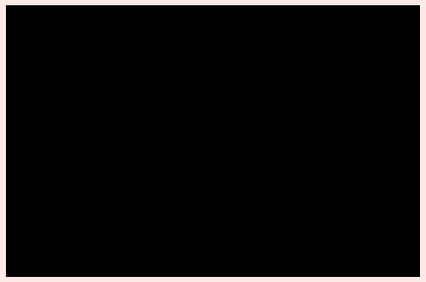
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; w.i.p



High-mass tails



AG, Marzocca; 1704.09015



Obituary I:

Died tragically due to overlooked systematics. Contributed to the development of new consistency tests at low- and high-p_T, revisited the flavour structure of the SMEFT, and ignited novel model-building ideas about non-universal gauge extensions, multi-scale flavour, accidental symmetries, etc.

Obituary II:

A noble death only to give birth to a new physics beyond the Standard Model close to the electroweak scale. In their short lifetime, they manage to shake the world of particle physics. Their death marks the beginning of a new era. They secured the well-being of collider physics in the century to come.