Theory confronting LFU data

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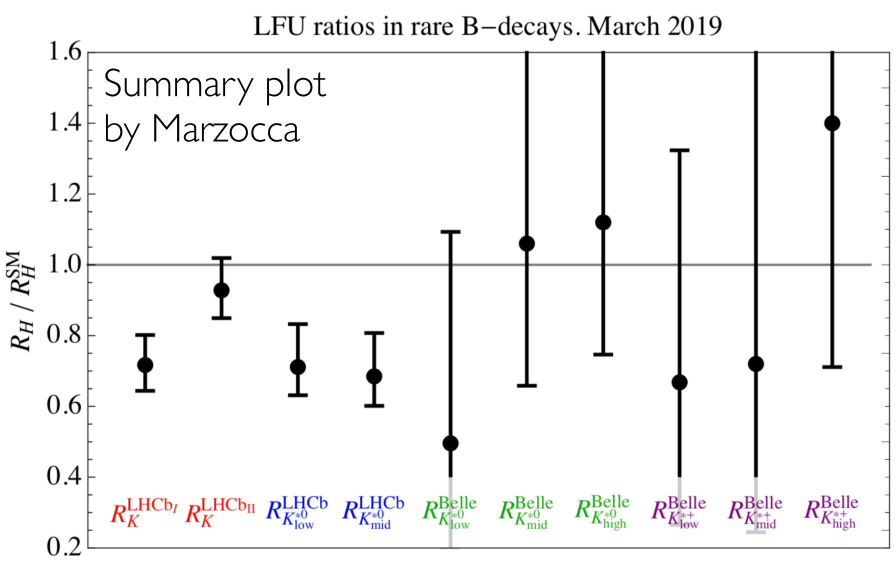
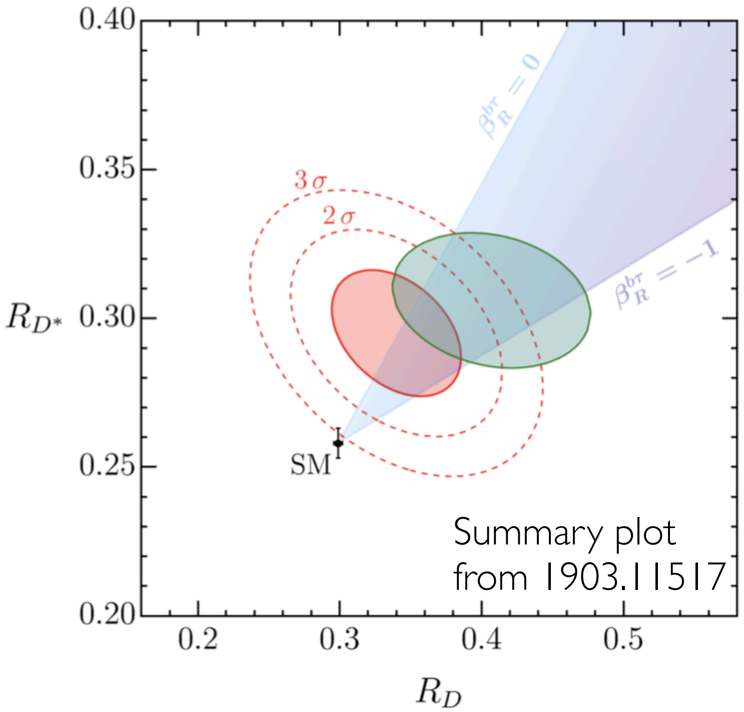
Motivation

Tests of LFU in B-meson decays

LHCb



BaBar, Belle, LHCb



NP in $b \to s\mu\mu$?

NP in $b \to c\tau\nu$?

Premise

- B-anomalies hint physics beyond the SM(*)
  (*) compelling, yet inconclusive
- A call for a bottom-up model building adventure

A bottom-up approach

IR consistency checks

- ***Q0***: Is there a consistent explanation of anomalies within the SM EFT while respecting all experimental constraints?
  [The SM EFT is a motivated framework that encompasses specific short-distance models at low-energies.]
- If yes, ***Q1***: what generates the required higher-dimensional operators? What is an emerging set of new heavy mediators? Can they pass the new consistency checks, e.g. direct searches at the LHC?
- If yes, ***Q2***: is there a working prototypical model that is fully-calculable and can be extrapolated to high energies?

A bottom-up approach

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UV insights and connections

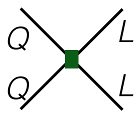
- ***Q3***: If such construction exists, how does it fit in the "UV picture"? Could it be linked to open problems of the SM such are the hierarchy, the flavour puzzle, etc.
- ***Q4***: What connections with other sectors follow from this? Where should we look further?

New Fermi interactions

SM EFT + U(2) flavour symmetry

- The analysis of SU(2) gauge invariant dimension-6 operators.
- Large number of flavour parameters in the SM EFT. Flavour symmetries and breaking patterns serve as the organising principle [2005.05366].
- Coherent picture of NP [1706.07808]

1) Semi-leptonic four-fermion operators involving left-handed fermions



$$\mathscr{L} \supset \frac{c^{(3)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l) + \frac{c^{(1)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_k\gamma^\mu L_l)$$

2) $U(2)_q \times U(2)_l$ flavour symmetry with minimal breaking spurions

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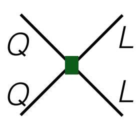
1) Semi-leptonic four-fermion operators involving left-handed fermions



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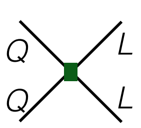
2) $U(2)_q$ x $U(2)_l$ flavour symmetry with minimal breaking spurions

- Triplet versus singlet operator: new dynamics gives $b \to c\tau\nu$, $b \to s\mu\mu$ but not $b \to s\nu\nu$
- The role of U(2):
  - Accommodates for the right ratio of CC and NC anomalies
  - Protects against LFU tests in kaons and light lepton flavours
- Drell-Yan constraints important [1609.07138, 1811.07920]. Suppression of flavour-blind int. [1704.09015].
- Radiatively induced effects important [1606.00524, 1807.02068]
- NP in right-handed currents could be useful [1909.02519]

Simplified models

New heavy mediators

Colour singlet	Colour triplet
	Scalar LQ:
	$S_1 \sim (\bar{3}, 1, 1/3)$
Vectors:	$S_3 \sim (\bar{3}, 3, 1/3)$
$W'_\mu \sim (1, 3, 0)$	Vector LQ:
$B'_\mu \sim (1, 1, 0)$	$U_1^\mu \sim (3, 1, 2/3)$
	$U_3^\mu \sim (3, 3, 2/3)$



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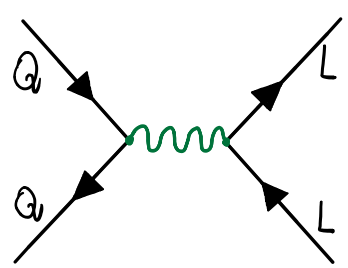

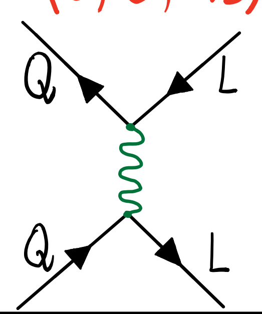

(SU(3), SU(2), U(1))

Simplified models

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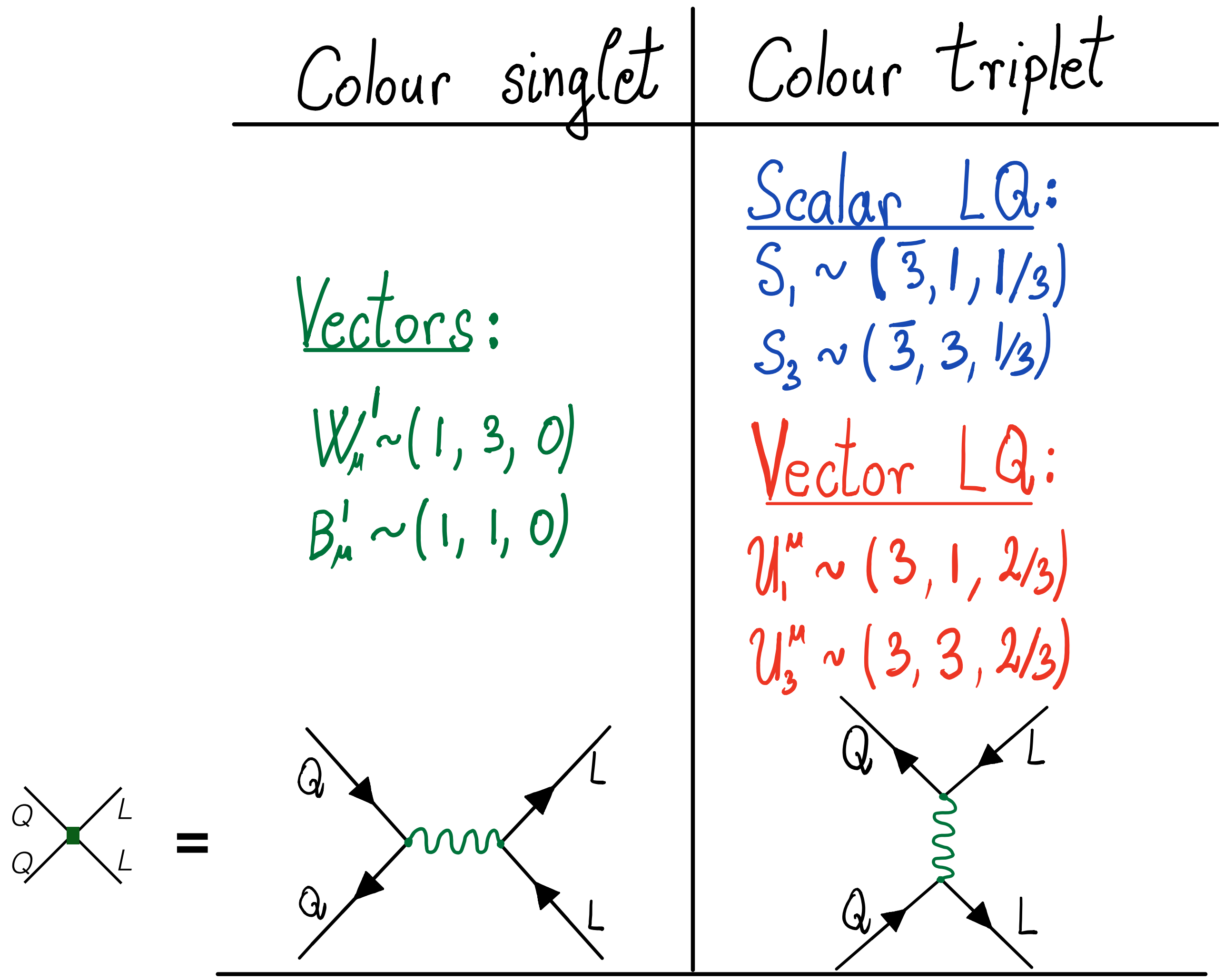
1706.07808



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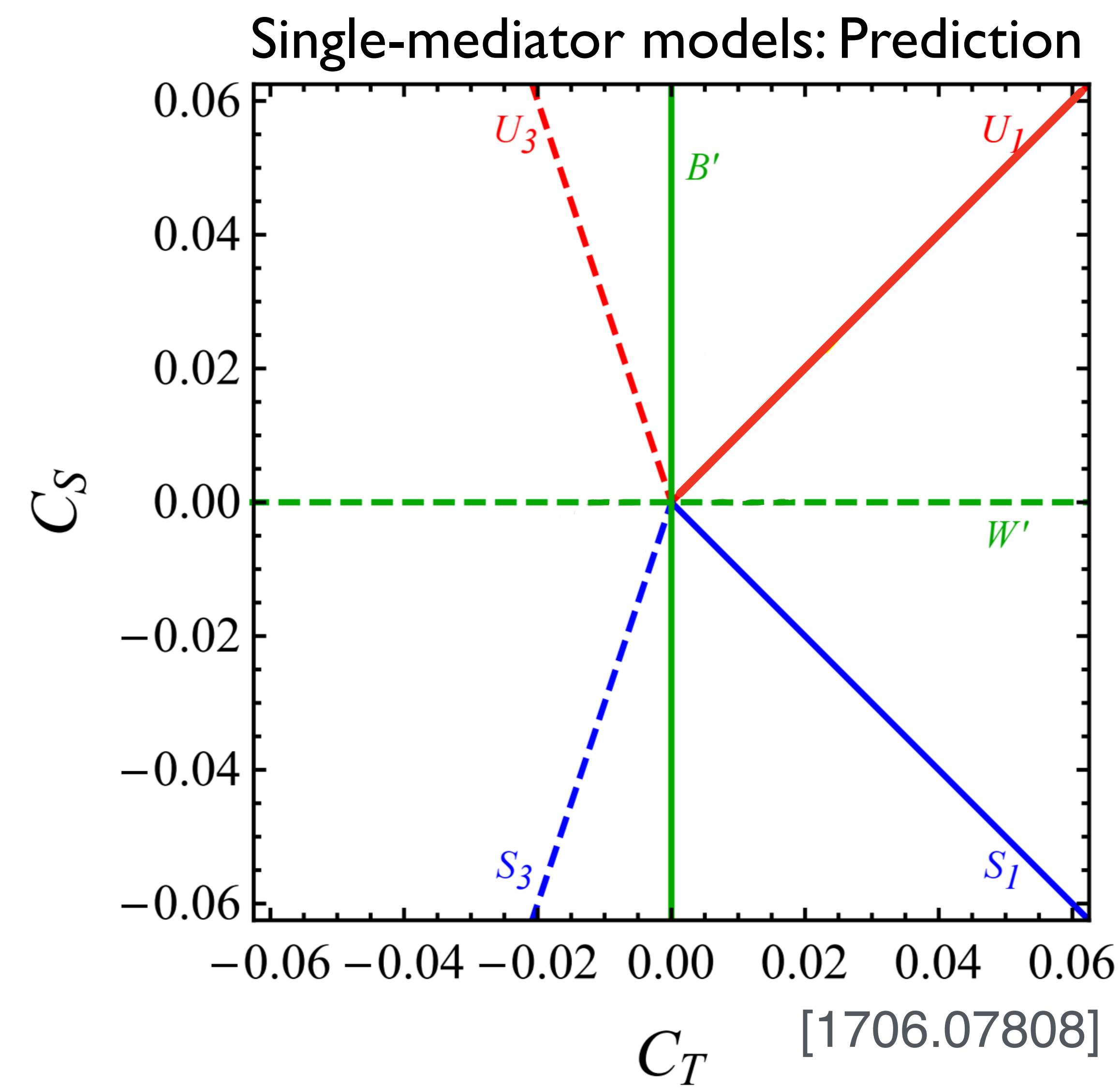

$$\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

Simplified models

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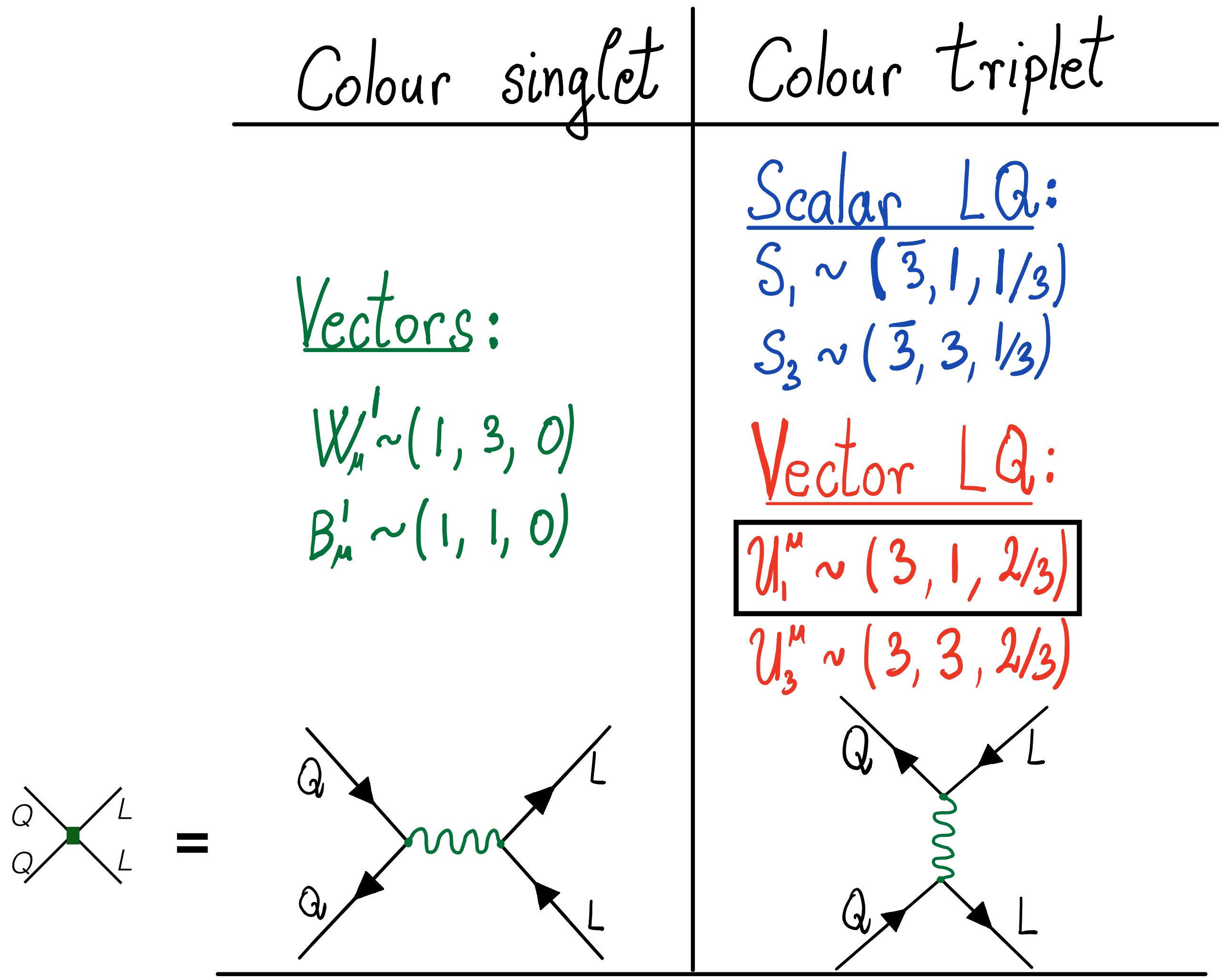

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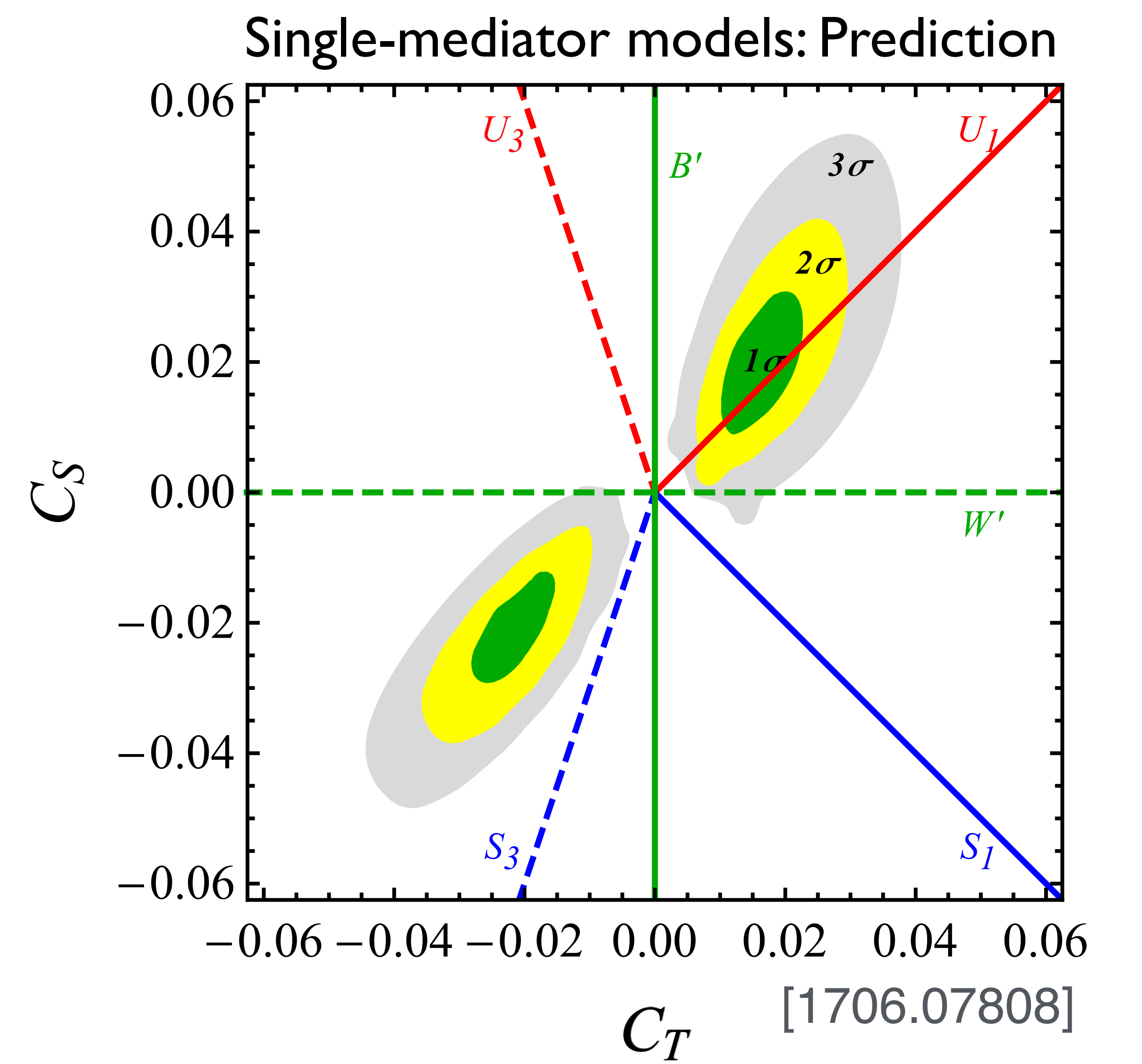

$$\left[C_T\ (\bar{Q}^i_L \gamma_\mu \sigma^a Q^j_L)(\bar{L}^\alpha_L \gamma^\mu \sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L \gamma_\mu Q^j_L)(\bar{L}^\alpha_L \gamma^\mu L^\beta_L)\right]$$

- Vector LQ singlet is the most successful single mediator. M ~ TeV, $g_{33} \sim 1$.

Successful simplified models with multiple mediators exist, e.g. S1 + S3.

The prototype

Vector LQ singlet option

- Massive vector crave an UV completion.
- This is **the Pati-Salam leptoquark**!
- Quark-lepton unification $\mathbf{4} = \mathbf{3}_q + \mathbf{1}_l$ resolves the charge quantisation puzzle.
- Low-scale Pati-Salam model possible (no proton decay). However, the original Pati-Salam leptoquark mass $\gtrsim$ PeV by FCNC, eg. K_L > mu e.
- How to achieve a successful TeV-scale quark-lepton unification?

"4321 models"

1706.05033, 1708.08450, 1712.01368, 1802.04274, 1805.09328, 1808.00942, 1903.11517, 1910.13474, 2004.11376, …

The prototype: 4321

4321 gauge sector

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

SSB: $\langle \Omega_3 \rangle, \langle \Omega_1 \rangle$

15 broken generators

$$G_{\text{SM}} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

$\longrightarrow$ **Z'** $(1, 1, 0)$

$\longrightarrow$ **G'** $(8, 1, 0)$

$\longrightarrow$ $(3, 1, 2/3)$ ***Leptoquark***

The prototype: 4321

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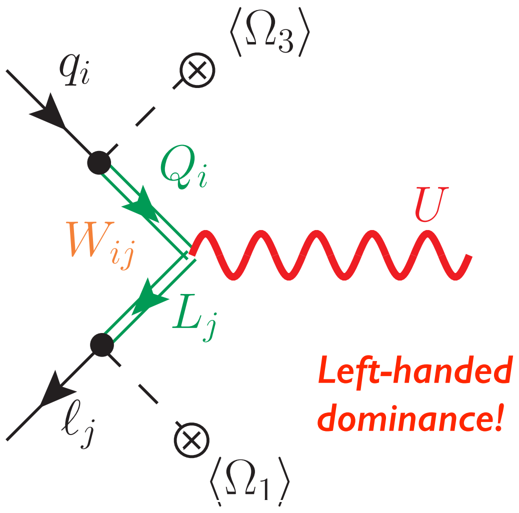
→ **Z'** $(1,1,0)$

→ **G'** $(8,1,0)$

→ $(3,1,2/3)$ **Leptoquark**

4321 fermionic content

- ***Class I***: All three generations of SM fermions charged under 321.
- ***Class II***: The third SM generation charged under 421.
- Mixing with the vector-like fermion doublets.



The prototype: 4321

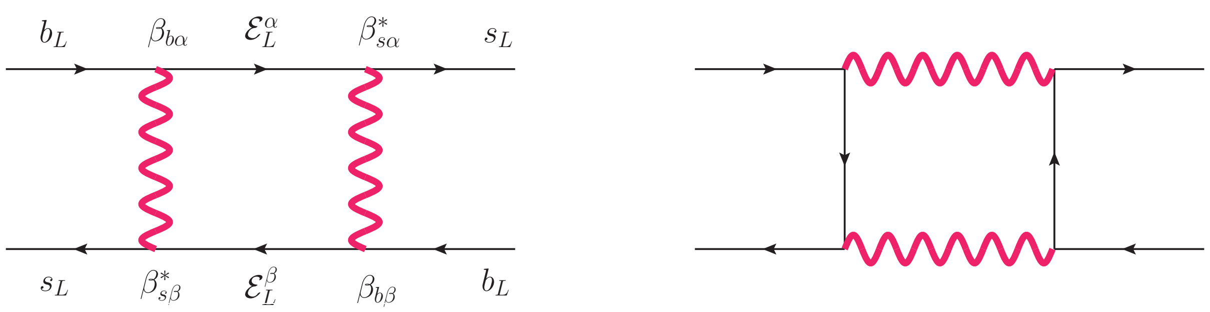
4321 model

Contents

1808.00942

Calculable, so calculate!

eg.



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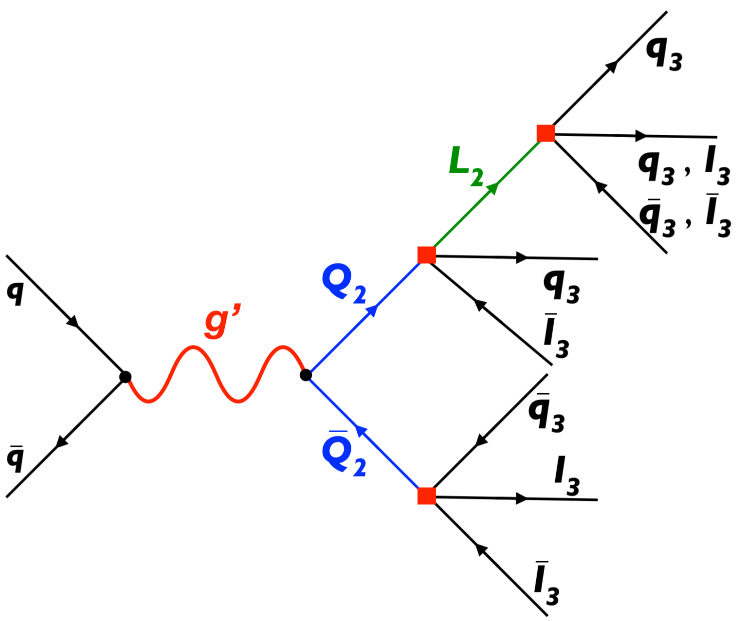
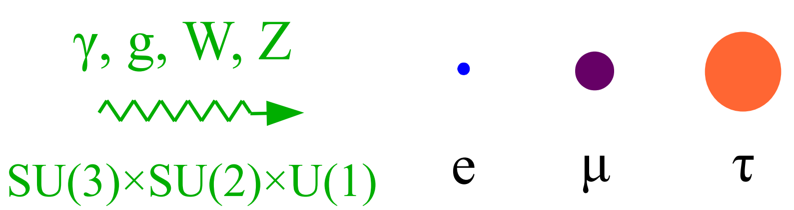


- Exhaustive phenomenological studies show there is a prototype model with rich signatures at low- and high-p_T.

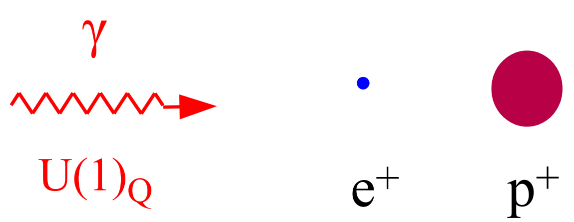
The flavour puzzle & PS³

Flavour deconstruction

LFU: at long distances the only difference is the mass



but remember



Far apart at short distances!

[Taken from Isidori]

The flavour puzzle & PS³

Flavour deconstruction

1712.01368

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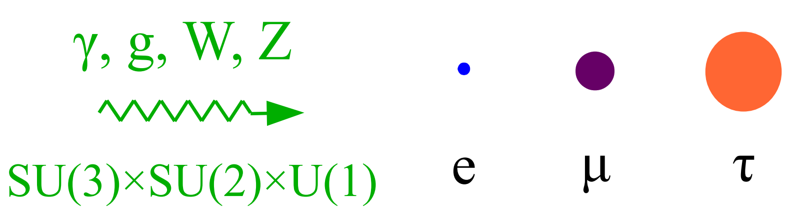

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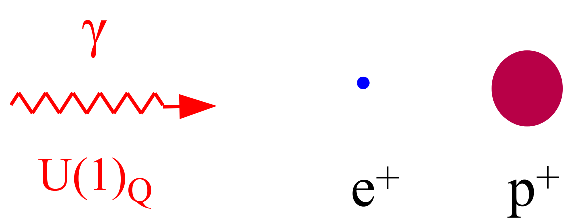

Far apart at short distances!

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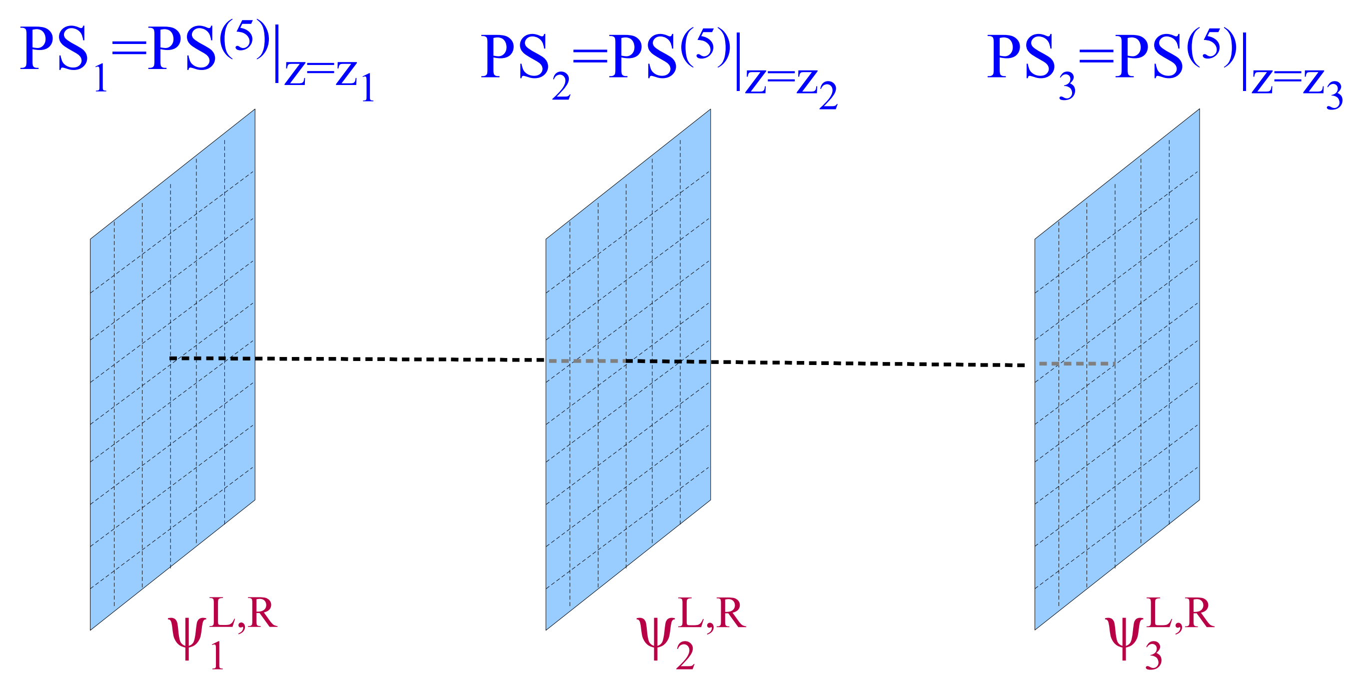
▶ *The PS³ model*

$[\,PS\,]^3 = [\,SU(4)\times SU(2)_L\times SU(2)_R\,]^3$



- 4D formulation:
  - One PS gauge group per family.
  - Hierarchical SSBs down to the 4321 at the TeV scale.
- Natural realisation in extra dimensions

Connections: Neutrino physics

- The options for the neutrino masses consistent with this picture are drastically narrowed.

$$(\psi_R^u)^T = \left(u_R'^3 \;\; \nu_R'^3\right) \;\; \rightarrow \;\; \begin{aligned} m_t' &= \frac{v_{\rm EW}}{\sqrt{2}}\left(y_H^u \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^u \sin\beta\right) \\ m_{\nu_\tau}' &= \frac{v_{\rm EW}}{\sqrt{2}}\left(y_H^u \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^u \sin\beta\right) \end{aligned}$$

- Disastrous prediction! Needs a fix.

Inverse seesaw mechanism 1802.04274

Introduce a singlet

$$\mathcal{L}_S = -\Omega_1^T\, \overline{S_R^c}\, \lambda_R \psi_R^u - \overline{S_R^c}\, M_R\, \nu_R' - \frac{1}{2}\overline{S_R^c}\, \mu_S\, S_R + \text{h.c.}$$

$$\frac{\text{meV}}{v_{\rm EW}} \sim 10^{-14}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & \widetilde{M}_R^T \\ 0 & \widetilde{M}_R & \mu_S \end{pmatrix}$$

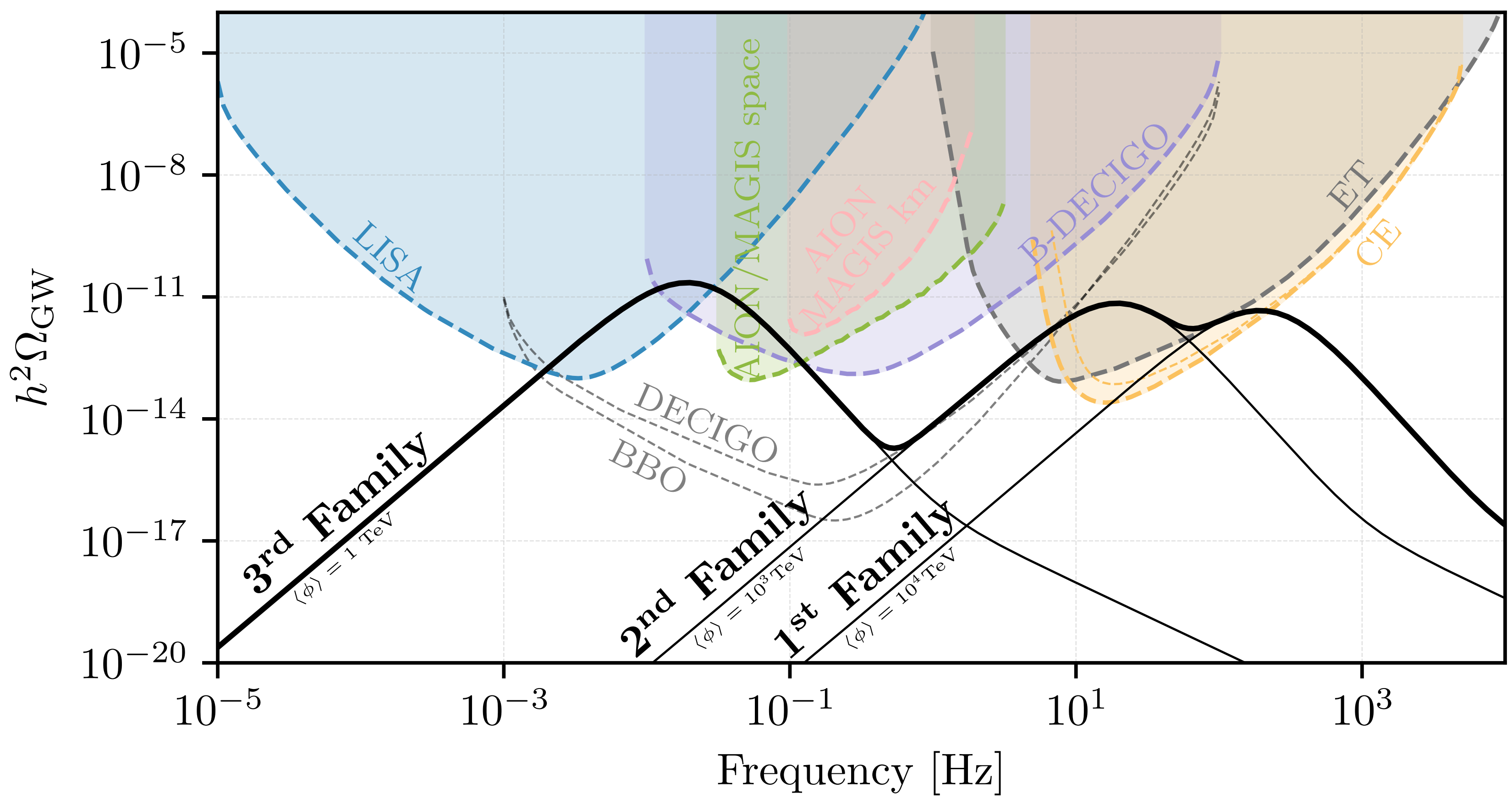
$$M_{\rm light} \approx M_\nu^D \widetilde{M}_R^{-1} \mu_S\, (\widetilde{M}_R^T)^{-1} (M_\nu^D)^T$$

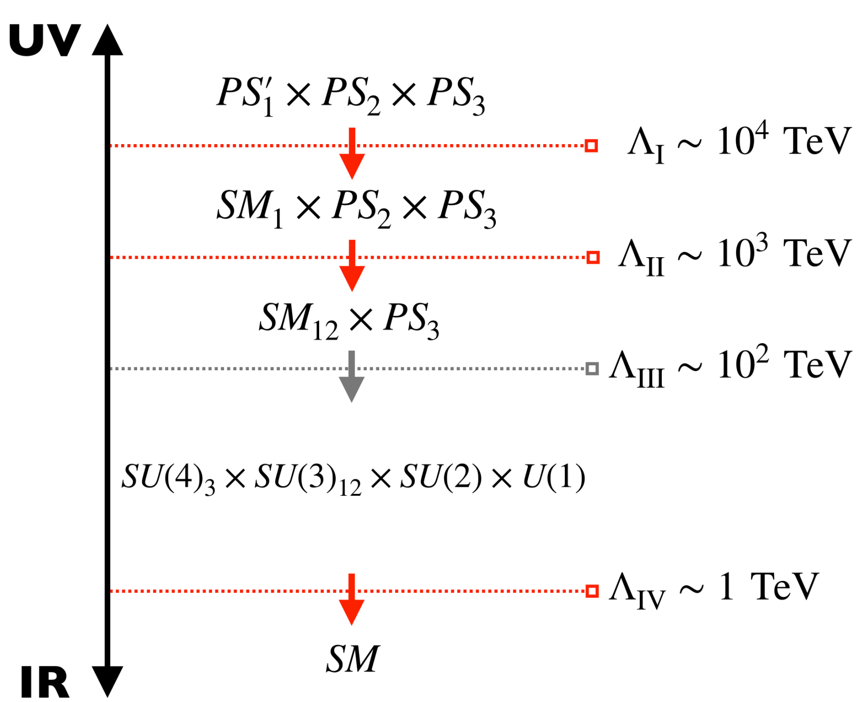
Lepton number breaking spurion

- Connection:
  B-anomalies and the PMNS non-unitarity

Connections: Cosmology & GW

The Triglav signature 1910.02014





- Hierarchical strongly first order phase transitions in the early Universe
- **Footprint**: Stochastic gravitational wave radiation with the characteristic three-peaked signature (the Triglav signature).

Conclusions[(1)]

- *B*-anomalies showed the power of data to sparkle new ideas.

  - **New directions in model building**

  - **New connections / Spectacular signatures**

(1) Working models exist, however, the final judge is the experiment.