Perspectives in Flavour Physics

Admir Greljo

UNIVERSITÄT BERN

FNSNF Swiss National Science Foundation
Eccellenza, Project-186866

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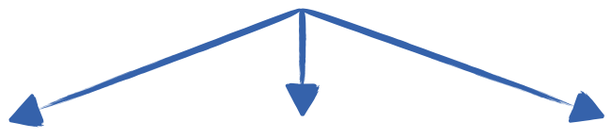
Flavour



	1st	2nd	3rd	
Quarks	u	c	t	$+\frac{2}{3}$
	d	s	b	$-\frac{1}{3}$
Leptons	e	μ	τ	-1
	ν_e	ν_μ	ν_τ	0

?

Mysterious property of matter!

The Standard Model

Basic notions:

1. "A" quantum field theory

2. Symmetries

$$\text{Poincaré} + SU(3)_C \times SU(2)_L \times U(1)_Y$$

3. Field Content

$$H \quad + \quad q_i, \ell_i, u_i, d_i, e_i$$

Flavour $i = 1,2,3$ Complexity!

The Standard Model

Lagrangian:

Parameter

Cutoff scale

Local operator
- a monomial in fields and derivatives

$$\mathscr{L}(x) = \sum c_{\mathcal{O}} \, \Lambda_{\mathcal{O}}^{4-\dim \mathcal{O}} \, \mathcal{O}(x)$$

$$\text{Physical effects} \sim \left(\frac{E}{\Lambda_{\mathcal{O}}} \right)^{\dim \mathcal{O} - 4}$$

The SM
$\dim \mathcal{O} \leq 4$ →

parameters:

- Gauge and Higgs sector: ***5***
- Yukawa sector: ***13*** (3 for a single gen.)

The SMEFT
$\dim \mathcal{O} > 4$ →

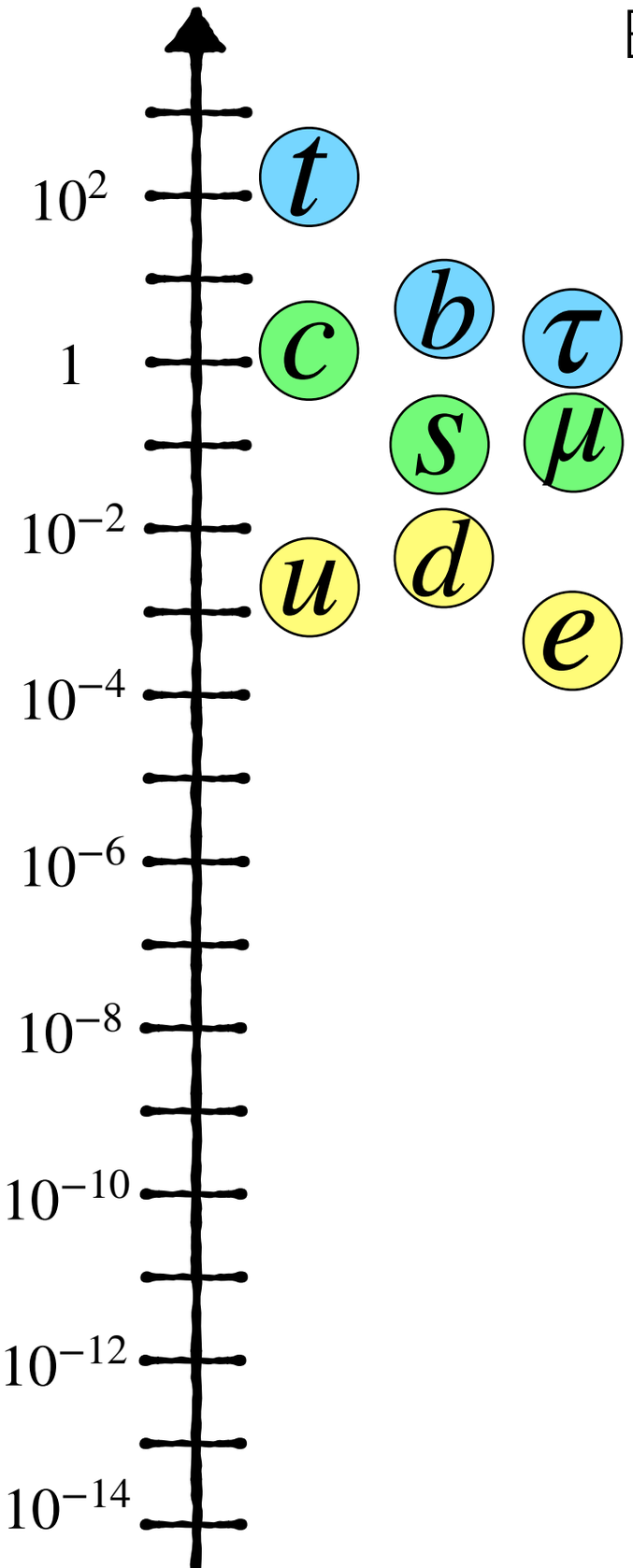
Truncation at $\dim \mathcal{O} \leq N$ where $N > 4$

$\Longrightarrow$ *proliferation of parameters*

$\dim[\mathcal{O}] = 6$ $(\Delta B = 0)$: ***2499*** (59 for a single gen.)

Flavour Puzzle

Empirical



The Weak Force Mixing:

$$V_{\rm CKM} \sim \begin{pmatrix} \blacksquare & \blacksquare & \\ \blacksquare & \blacksquare & \\ & & \blacksquare \end{pmatrix}$$

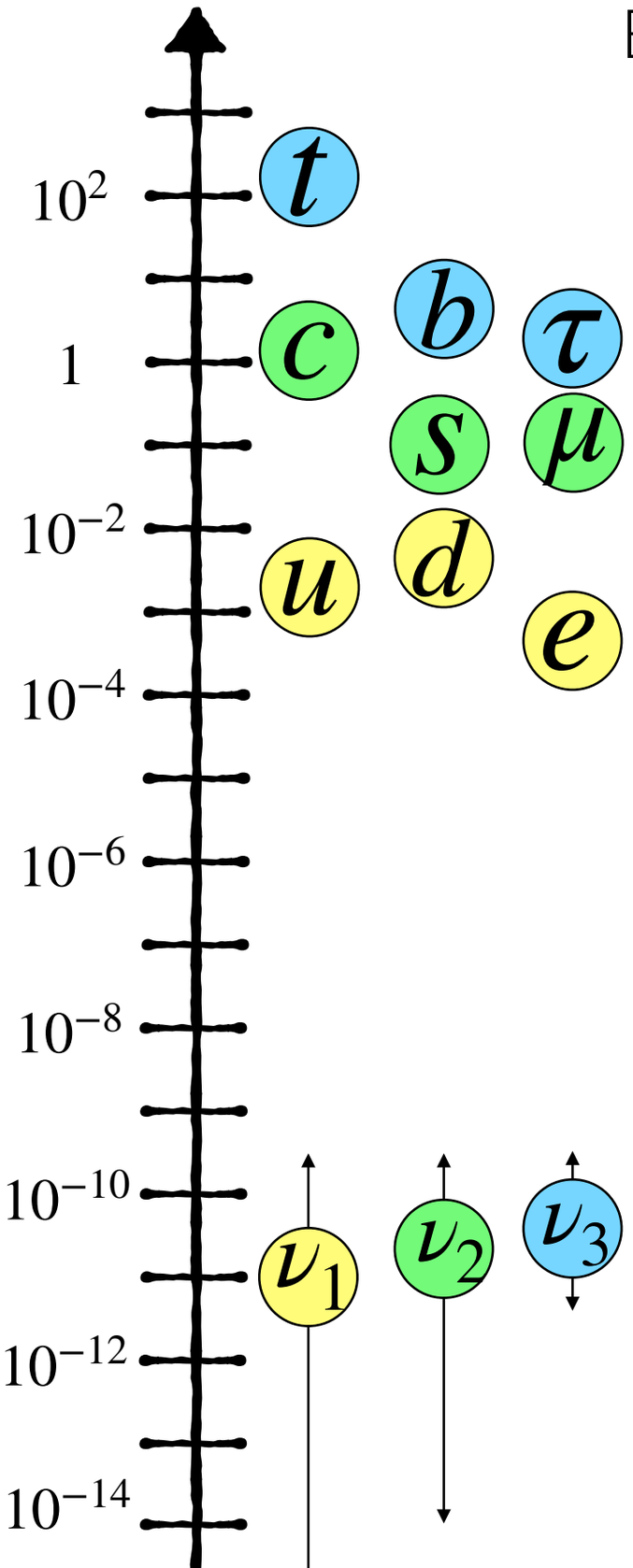
$$-\mathcal{L}_{\rm SM} \supset \bar{q}_i Y_u^{ij} u_j \tilde{H} + \bar{q}_i Y_d^{ij} d_j H + \bar{\ell}_i Y_e^{ij} e_j H$$

$$\Im \det[Y_d Y_d^\dagger, Y_u Y_u^\dagger] \approx \mathcal{O}(10^{-22})$$

*sample uniformly in [0,1] interval $\approx \mathcal{O}(1)$

Flavour Puzzle

Empirical



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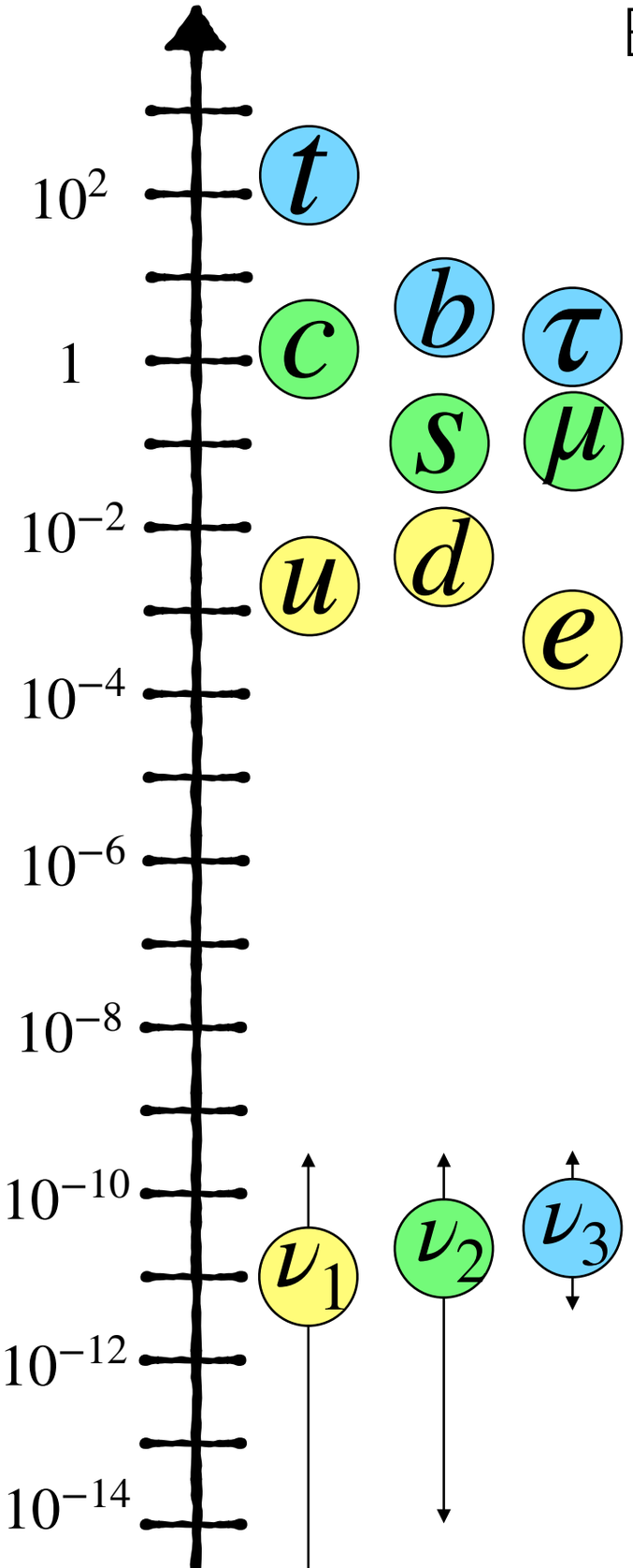
$$-\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda_\nu} \ell_i Y_\nu^{ij} \ell_j H H$$

$$V_{\rm PMNS} \sim \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}$$

Flavour Puzzle

Empirical



?

Pattern

The Weak Force Mixing:

$$V_{\text{CKM}} \sim \begin{pmatrix} \blacksquare & \blacksquare & \\ \blacksquare & \blacksquare & \\ & & \blacksquare \end{pmatrix}$$

Analogy:
The periodic table of elements

$$V_{\text{PMNS}} \sim \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}$$

Flavour Model Building

- Explain (fully or partially) the peculiar flavour patterns

Warped compactification

hep-ph/9905221, hep-ph/9903417, hep-ph/0003129, hep-ph/9912408, hep-ph/0408134, 0903.2415, 1004.2037, 1509.02539, 2203.01952, …

(Gauged) flavour symmetries

hep-ph/9512388, hep-ph/9507462, 1009.2049, 1105.2296, 1505.03862, 1609.05902, 1611.02703, 1807.03285, 1805.07341, 2201.07245, …

Partial compositeness

hep-ph/030625, 0804.1954, 1404.7137, 1506.01961, 1506.00623, 1607.01659, 1908.09312, 1911.05454, …

…

Froggatt-Nielsen

Froggatt:1978nt, hep-ph/9212278, hep-ph/9310320, 1909.05336, 1907.10063, 2009.05587, 2002.04623, 2010.03297, …

Multi-scale flavour

1603.06609, 1712.01368, 2011.01946, 2203.01952…

Clockwork flavour

1610.07962, 1711.05393, 1807.09792, 2106.09869, …

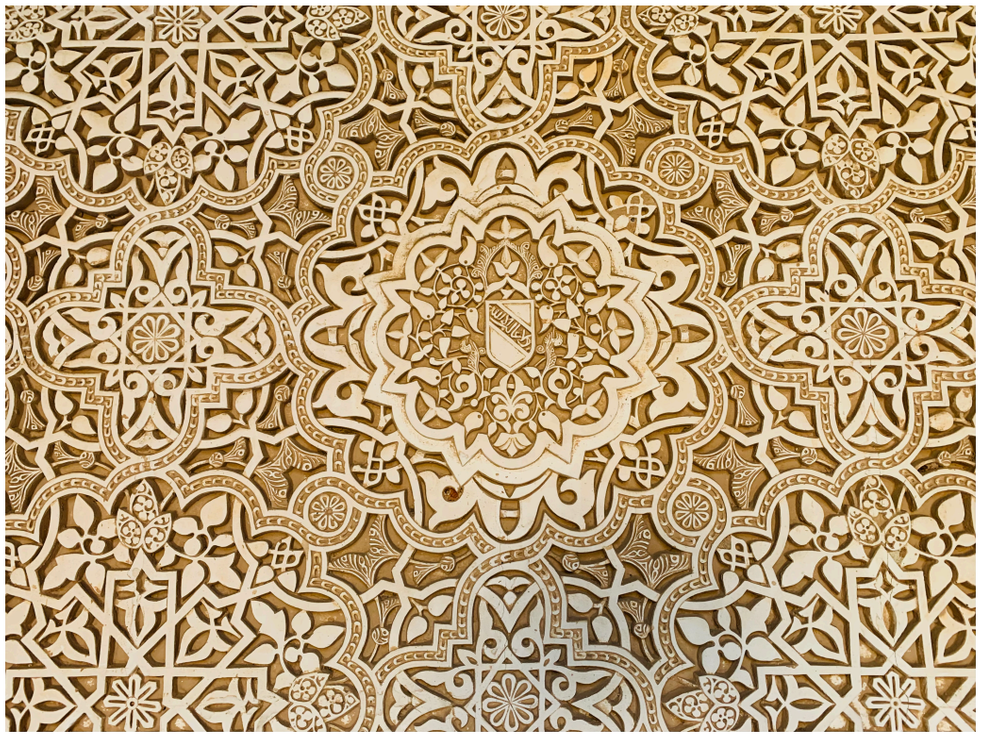
Radiative masses

Weinberg:1972ws, hep-ph/9601262, 1409.2522, 2001.06582, 2012.10458, …

An example later in the talk…

Patterns <> Symmetries

- Flavour patterns observed in the Yukawa sector
  $\Longrightarrow$ *Approximate flavour symmetries in the SM*



Alhambra of **Granada**

1 Important to understand the SM phenomenology:

- *isospin, SU(3), heavy-quark symmetries, GIM, …*

2 Stringent tests of the SM
— a window to new physics.

Theoretical predictions of weak decay amplitudes

Effective Field Theory

Factorisation

$$\langle \mathscr{H}_{eff} \rangle \propto \langle Q(\mu) \rangle \, C(\mu)$$

long-distance contributions $E < \mu$ ↙ ↘ *short-distance contributions* $E > \mu$

Hadronic matrix elements

2205.15373, 2205.13952, 2204.09091, 2108.05589, 1904.08731, 1902.09553, 1908.09398, 1912.09335, 1908.07011, 2002.00020, 2006.07287, 2101.12028, 2105.09330, 2106.12168, 2112.07685, 2206.11281, …

Lattice QCD, http://flag.unibe.ch/2021/

Heavy quark effective theory,

Heavy quark expansion,

QCD factorisation,

SCET,

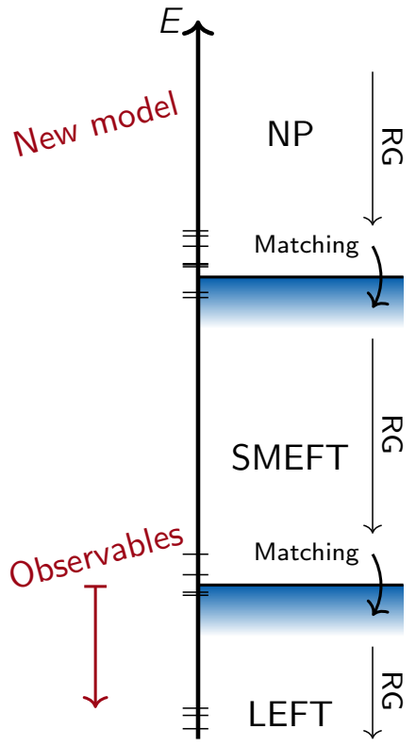
ChPT,

QCD sum rules,

Light-cone sum rules,

…

Wilson coefficients

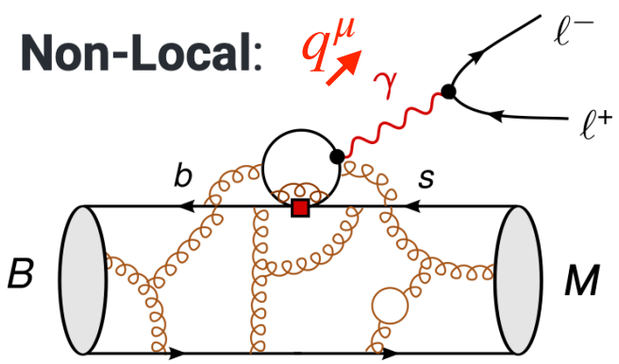


1308.2627, 1310.4838, 1312.2014, 1709.04486, 1711.05270, 1711.10391, 1710.06445, 1804.05033, 1908.05295, 2010.16341, 2012.08506, 2012.07851, …

Example: $b \to s\ell^+\ell^-$

- Fast progress at the LHC
- Better SM predictions for $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\,\mu^+\mu^-$ needed!

The bottleneck



$$\int dx^4 e^{iq\cdot x} \langle M|T\{j^\mu_{\rm em}(x), O_i(0)\}|B\rangle$$

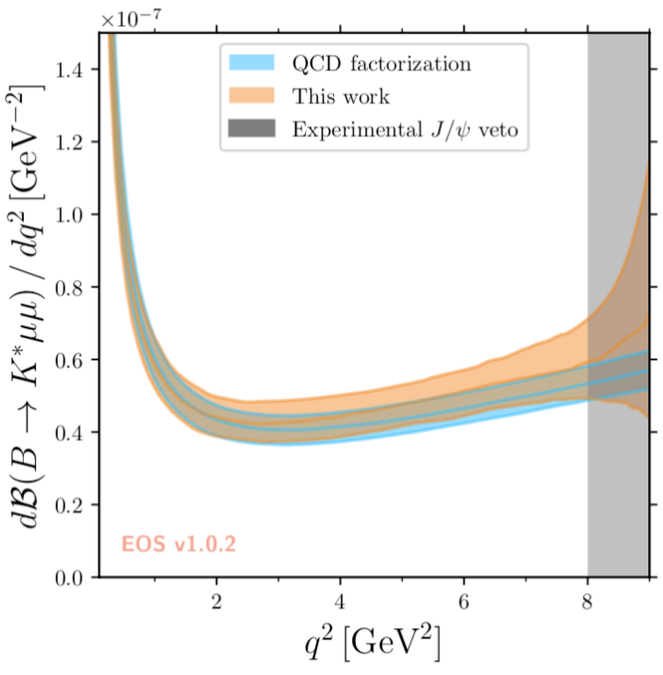
The standard method

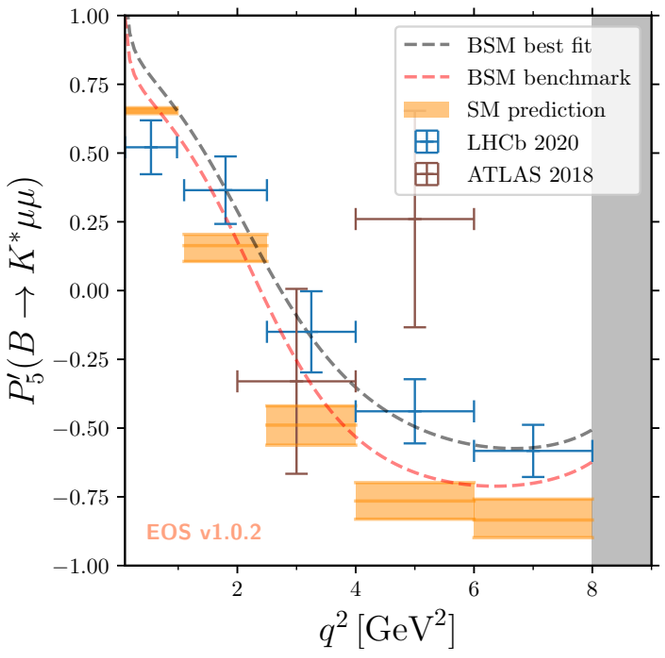
- QCD factorisation
- A perturbative calculation of the charm loop contribution
- Uncontrollable systematic uncertainties?

Recent developments

Gubernari, Reboud, van Dyk, Virto; 2206.03797

- z-expansion exploiting the analytic structure
- Residues from $B \to M\,J/\psi$ data
- LCOPE calculations for negative q^2
- The dispersive (unitarity) bounds crucial to close the fit





The tension remains!

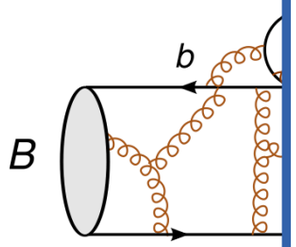
Example: $b \to s\ell^+\ell^-$

- Fast progres
- Better SM p

The bottl

yk, Virto; 2206.03797

Non-Local:



$$\int dx^4 e^{iq\cdot x} \langle M|T\{$$

The standard m

- QCD factor
- A perturbat
  the charm lo
- Uncontrolla
  uncertaintie

fit

★ Make use of the approximate flavour symmetries to construct clean observables

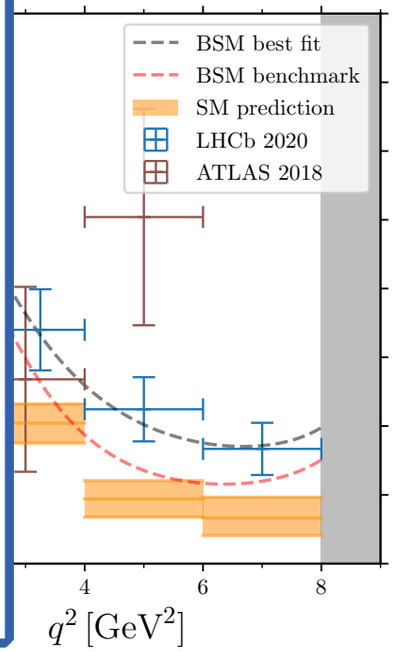
Example: Lepton Flavour Universality

$$R_K = \frac{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

Hiller, Kruger
hep-ph/0310219

$$R_K = 1 + \mathcal{O}\left(10^{-2}\right)$$

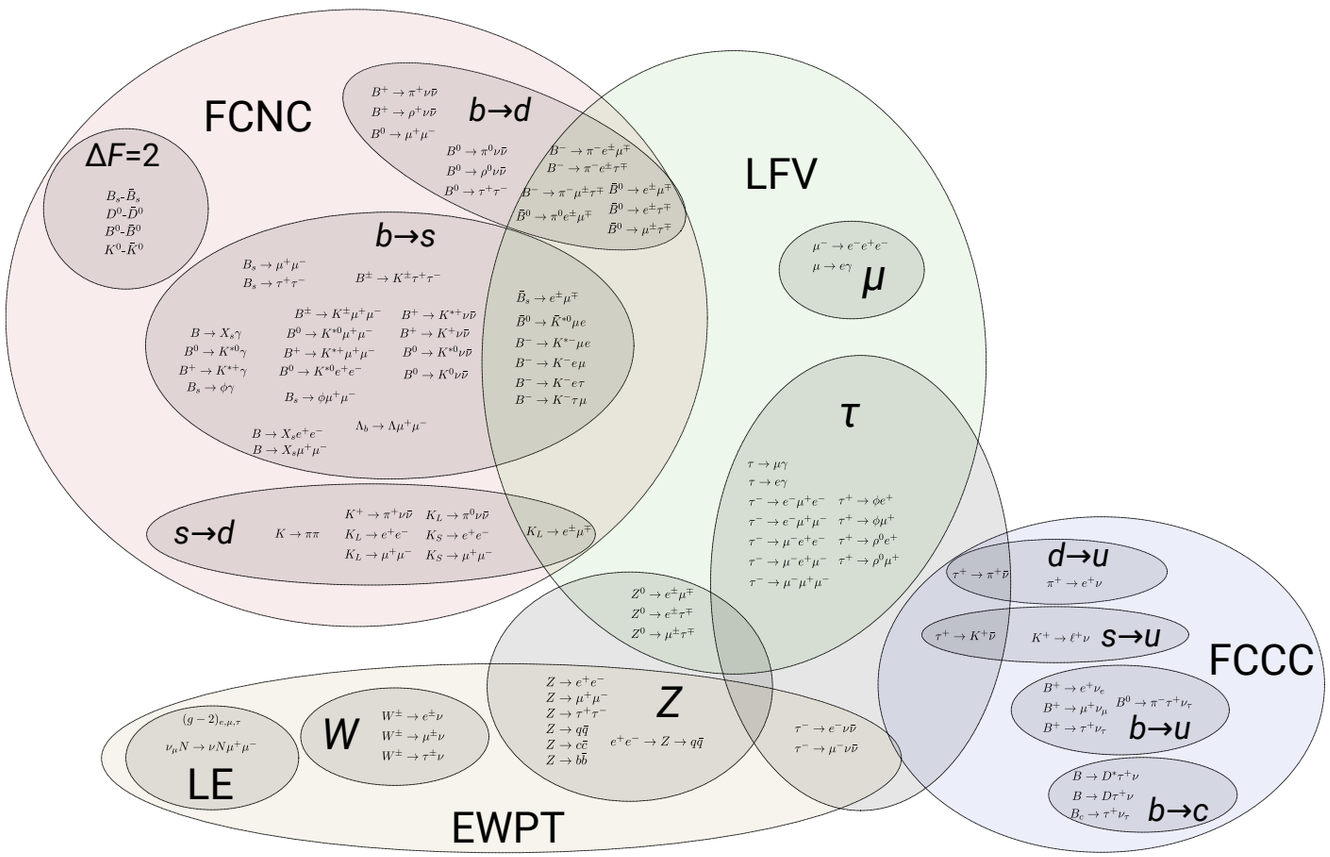
Bordone, Isidori, Pattori; 1605.07633
Isidori, Nabeebaccus, Zwicky; 2009.00929
Isidori, Lancerini, Nabeebaccus, Zwicky; 2205.08635



The tension remains!

Towards a global SMEFT likelihood

- **SMEFT** - the low-energy limit of a generic microscopic new physics
- Correlated deviations expected — **global approach** needed

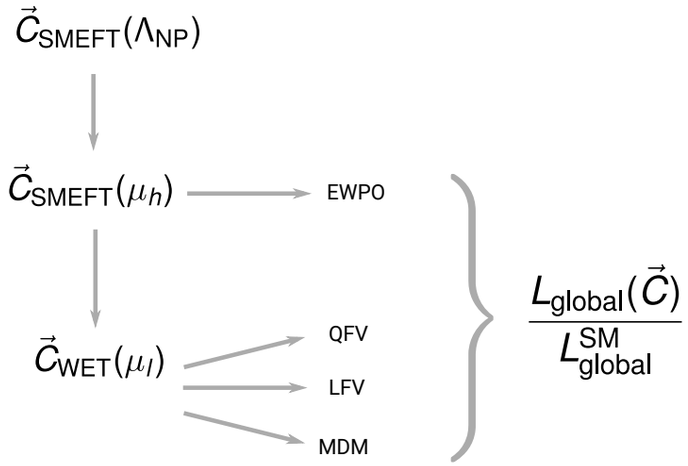


smelli Aebischer, Kumar, Stangl, Straub, 1810.07698

wilson Aebischer, Kumar, Straub, 1804.05033

flavio Straub, 1810.08132

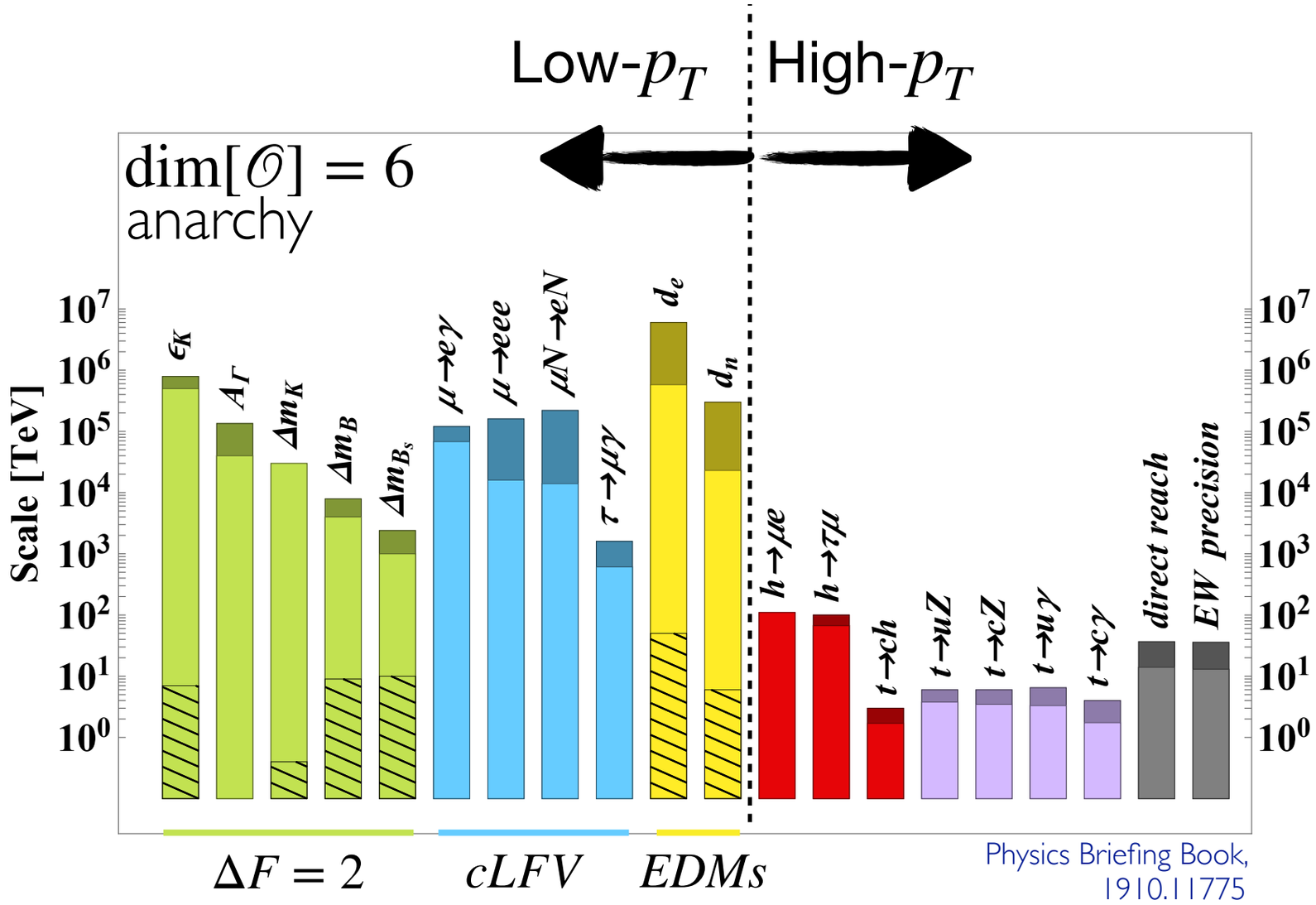
$$L(\vec{C}) \approx \prod_i L^i_{\text{exp}}(\vec{O}_{\text{th}}(\vec{C}, \vec{\theta}_0)) \times \tilde{L}_{\text{exp}}(\vec{O}_{\text{th}}(\vec{C}, \vec{\theta}_0))$$



See also:
https://hepfit.roma1.infn.it Blas et al, 1910.14012
https://eos.github.io van Dyk et al, 2111.15428
…

The importance of flavour data!

- SMEFT at $\dim[\mathcal{O}] = 6$ - new sources of flavour violation
- Strong constraints from flavour experiments



Physics Briefing Book, 1910.11775

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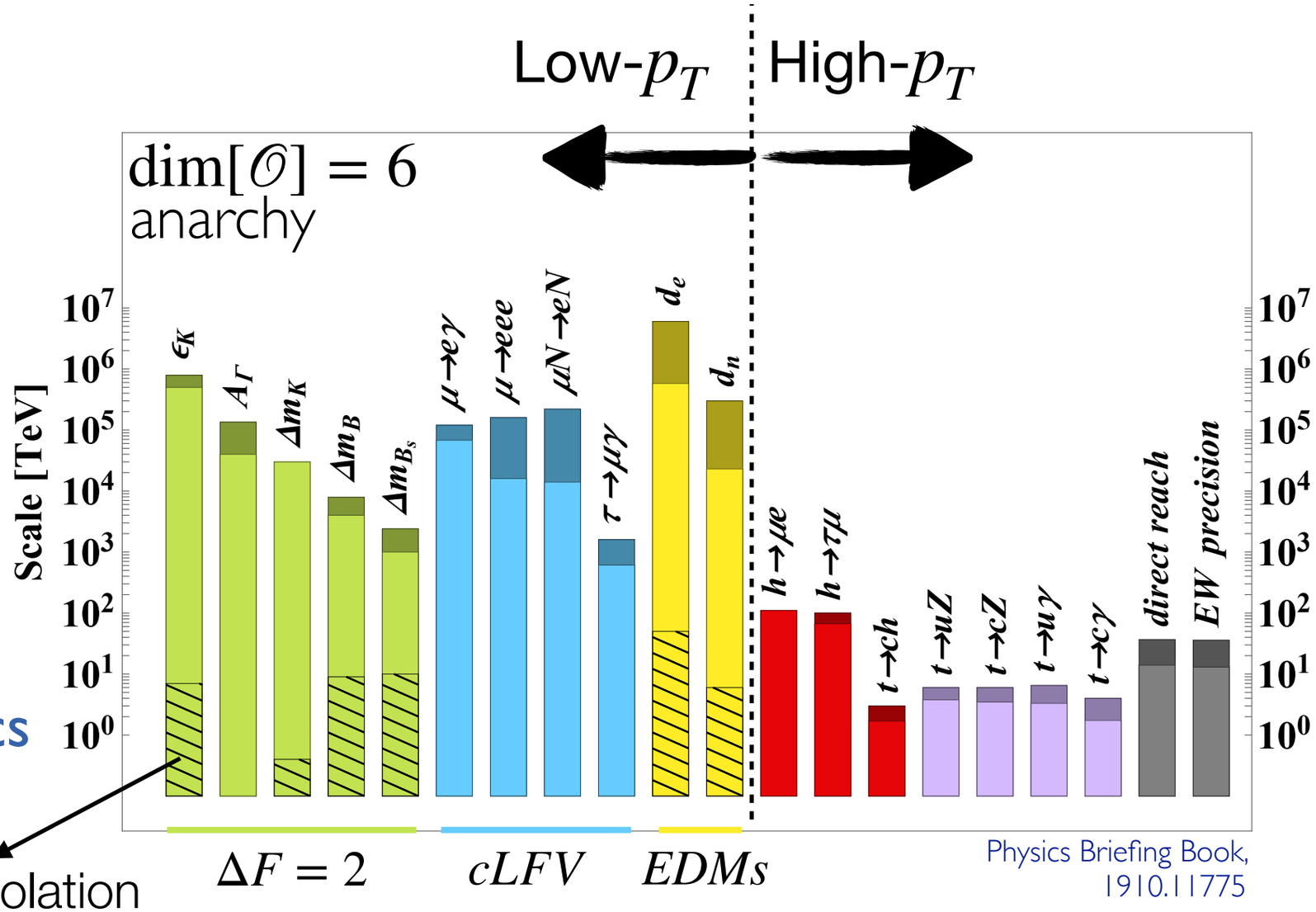


Physics Briefing Book, 1910.11775

The new physics flavour puzzle?

Minimal Flavour Violation

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

SMEFT flavour

Charting the space of SMEFT with flavour symmetries

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector							
		MFV_L	$\mathrm{U}(3)_V$	$\mathrm{U}(2)^2 \times \mathrm{U}(1)$	$\mathrm{U}(2)^2$	$\mathrm{U}(2)_V$	$\mathrm{U}(1)^6$	$\mathrm{U}(1)^3$	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
	$\mathrm{U}(2)^3 \times \mathrm{U}(1)_{b_\mathrm{R}}$	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

AG, Thomsen, Palavric; 2203.09561
Faroughy et al; 2005.05366

- Systematically moving away from the MFV towards anarchy: $U(3) \supset U(2) \supset U(1)$
- Non-trivial interplay of Top/Higgs/EW with flavour physics

*see also the LHC EFT WG

Interplay with high-p_T

Example:

$$\mathscr{L}_{NP}^{\Delta C=1} \approx \frac{\epsilon_V^{\ell\ell}}{(15\,\text{TeV})^2}\,(\bar{u}_R\gamma^\mu c_R)(\bar{\ell}_R\gamma^\mu \ell_R)$$

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

Theory:

$BR(D^0 \to \mu^+\mu^-)_{SM} \sim \mathcal{O}(10^{-13})$

- Efficient GIM suppression
- Long-distance dominated

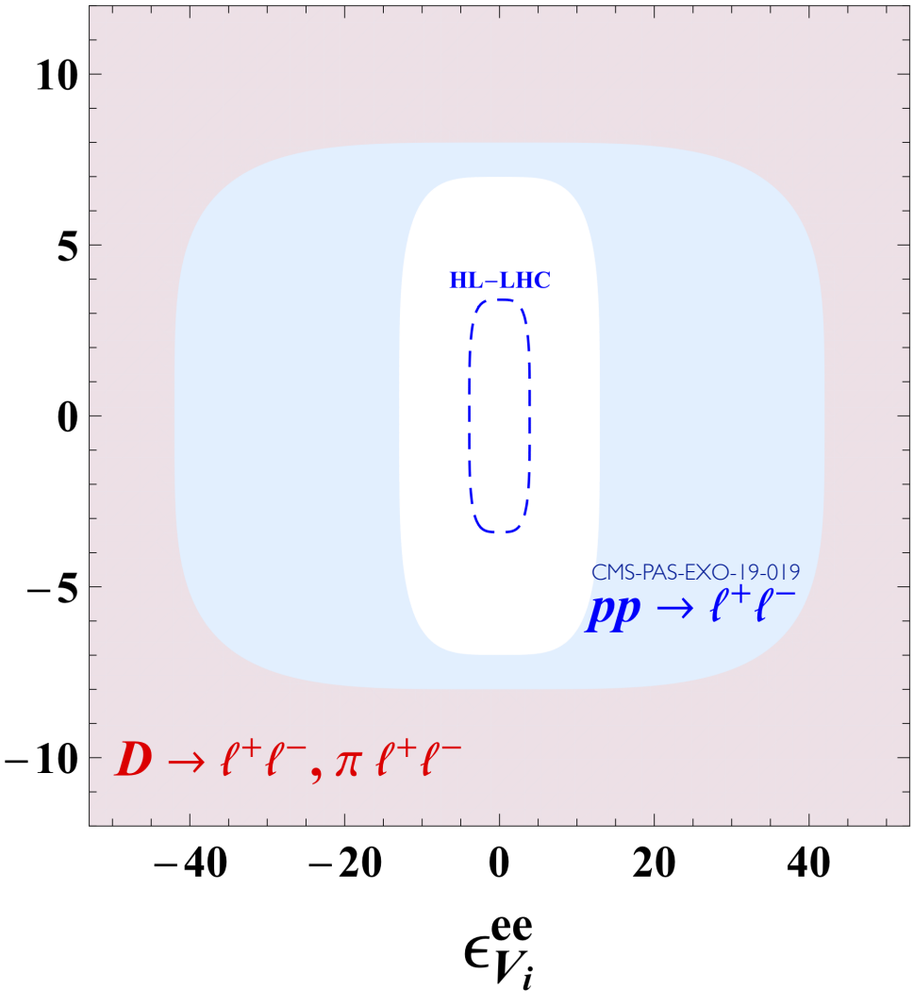
Experiment:

$BR(D^0 \to \mu^+\mu^-) \lesssim 6 \times 10^{-9}$

LHCb, 1305.5059

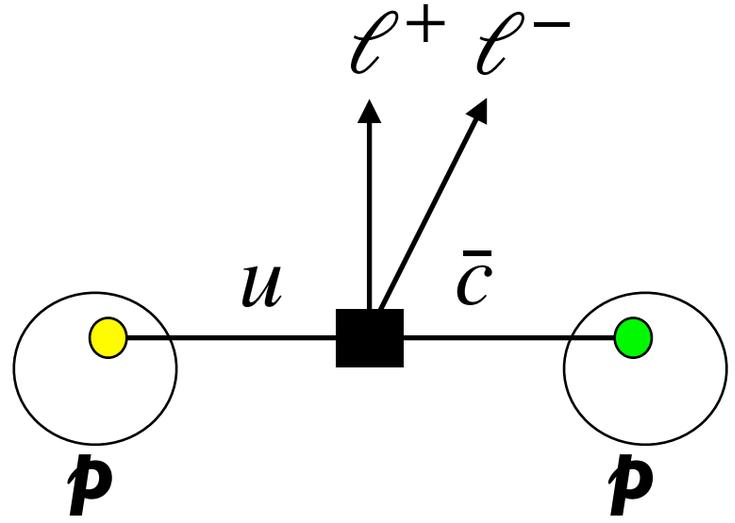
Null test of the SM sensitive to NP

Fuentes-Martin, AG, Camalich, Ruiz-Alvarez; 2003.12421



Drell-Yan $cu \to \ell^+\ell^-$

- Energy enhancement
- PDF suppression



Systematic exploration of the low-p_T / high-p_T interplay

1609.07138, 1704.09015, 1811.07920, 1805.11402, 1912.00425, 2002.05684, 2008.07541, 2104.02723, 2111.04748, …

See parallel session talks by:
F. Jaffredo & L. Allwicher

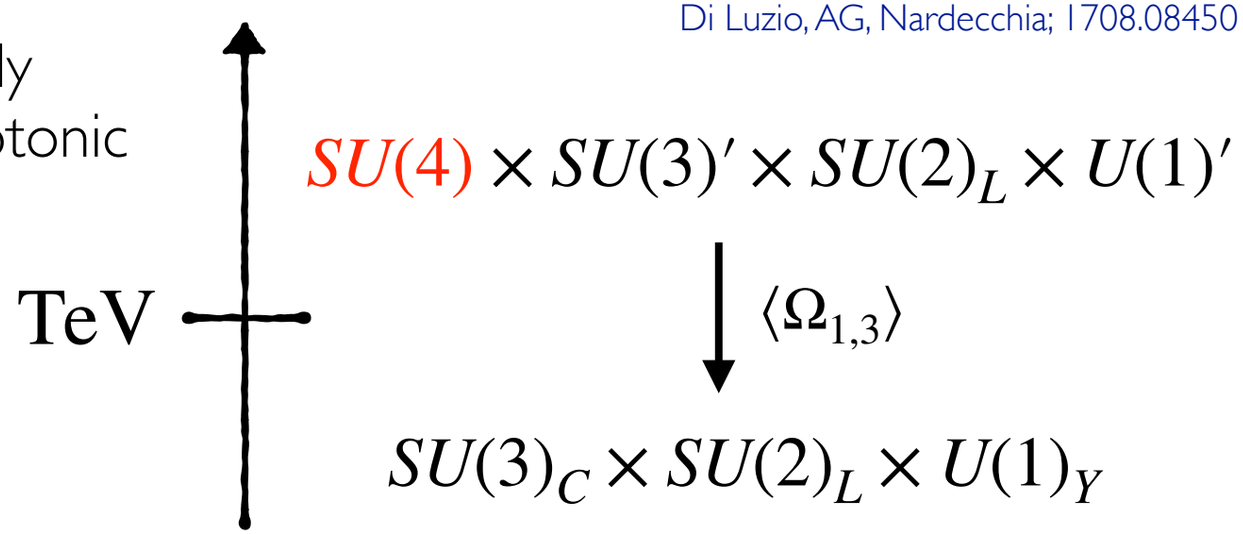
Flavour Anomalies' inspired model building

*Selective, not a review

4321

- A model example addressing coherently anomalies in semileptonic B meson decays

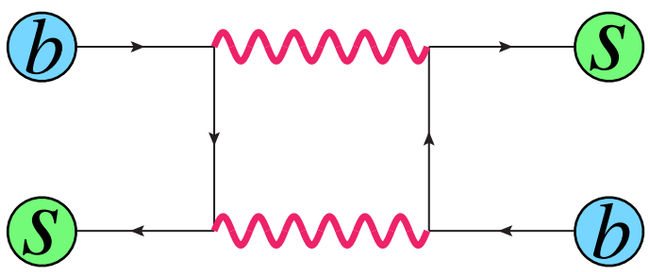
Di Luzio, AG, Nardecchia; 1708.08450



1708.08450, 1712.01368, 1802.04274, 1805.09328, 1808.00942, 1903.11517, 1910.13474, 2004.11376, 2006.16250, 2009.11296, 2207.00018, ...

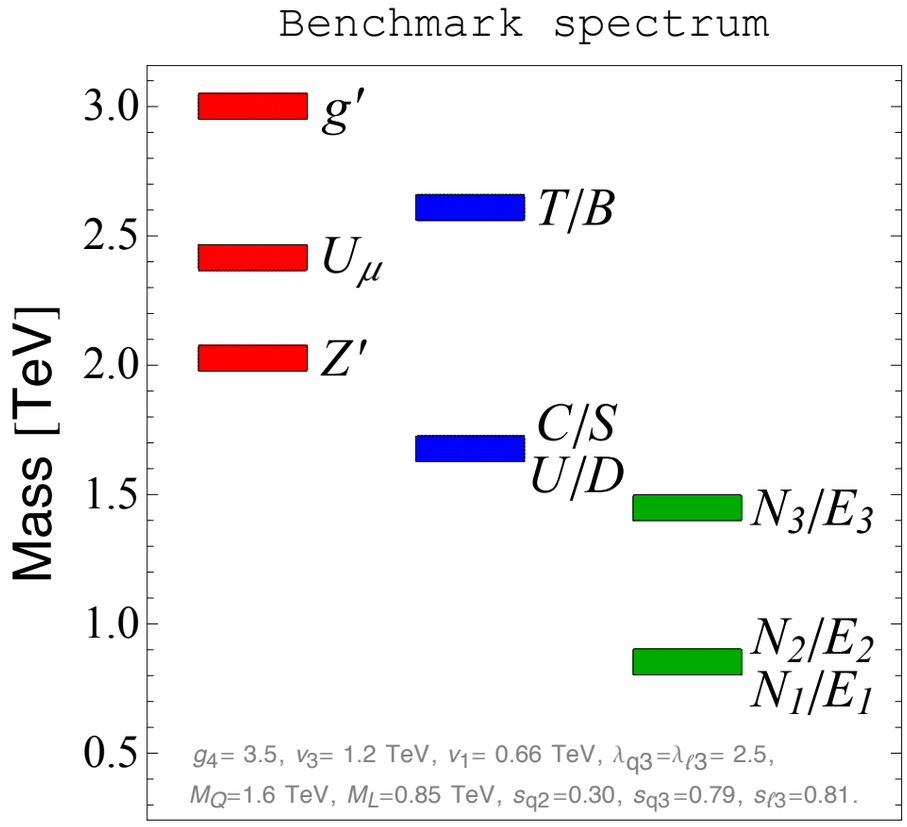
- Comprehensive investigation:

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



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

The lightest new states are vector-like leptons!



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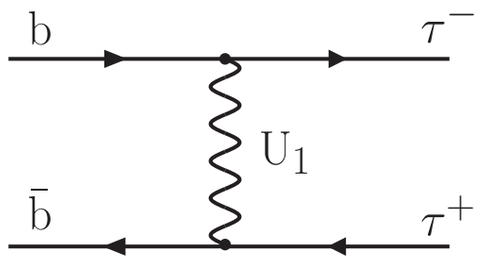
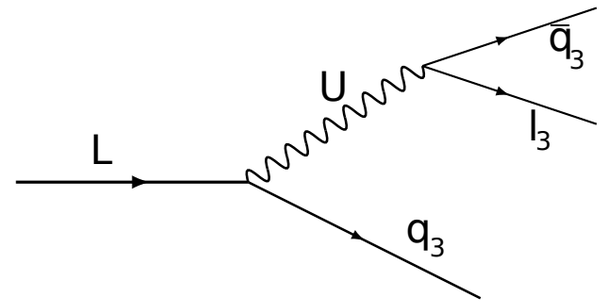
Exciting predictions for direct searches!

Faroughy, AG, Kamenik; 1609.07138



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



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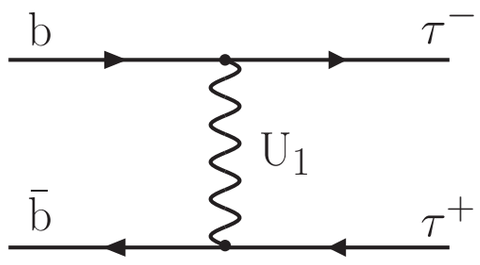
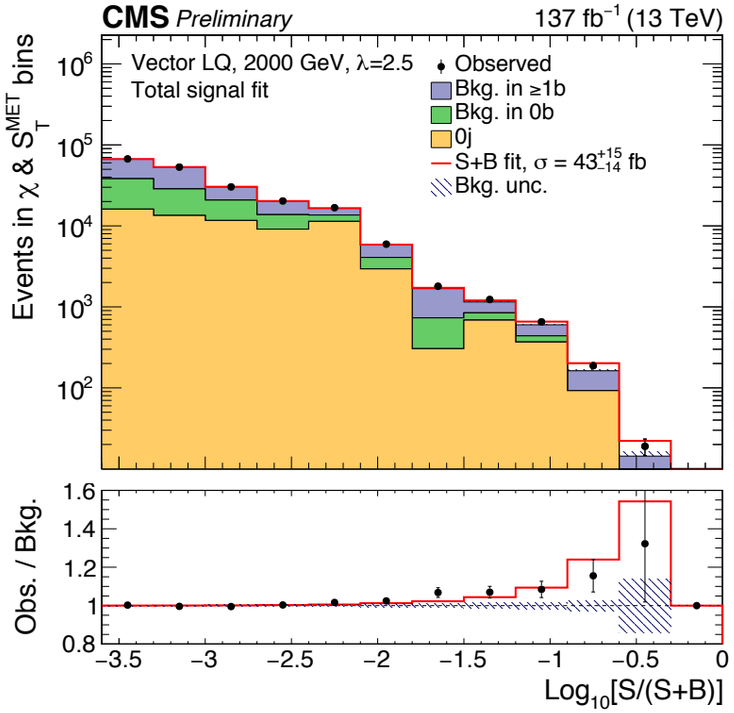




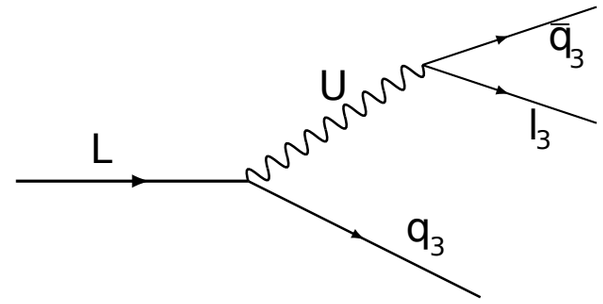
3.4σ

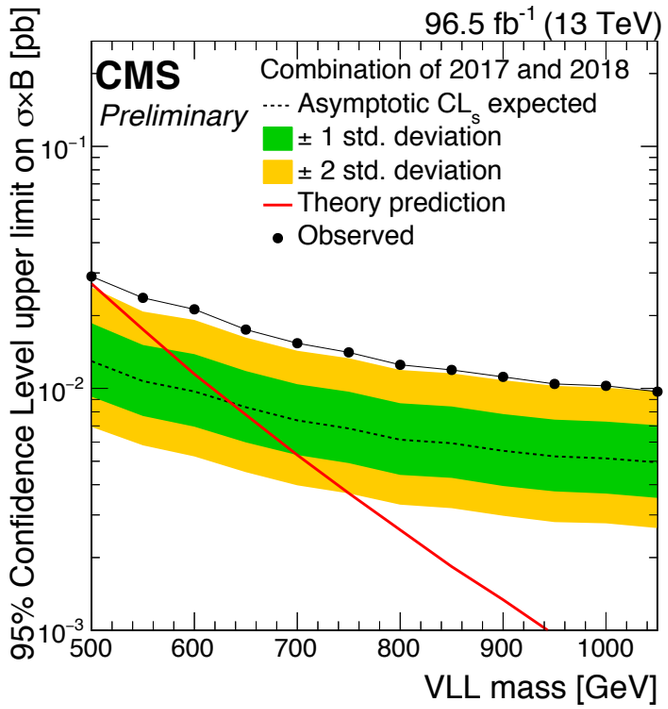
CMS PAS EXO-19-016

ICHEP 2022

Talk by Olena Karacheban

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





2.8σ

CMS PAS B2G-21-004

Moriond 2022

Maybe nothing, but remember

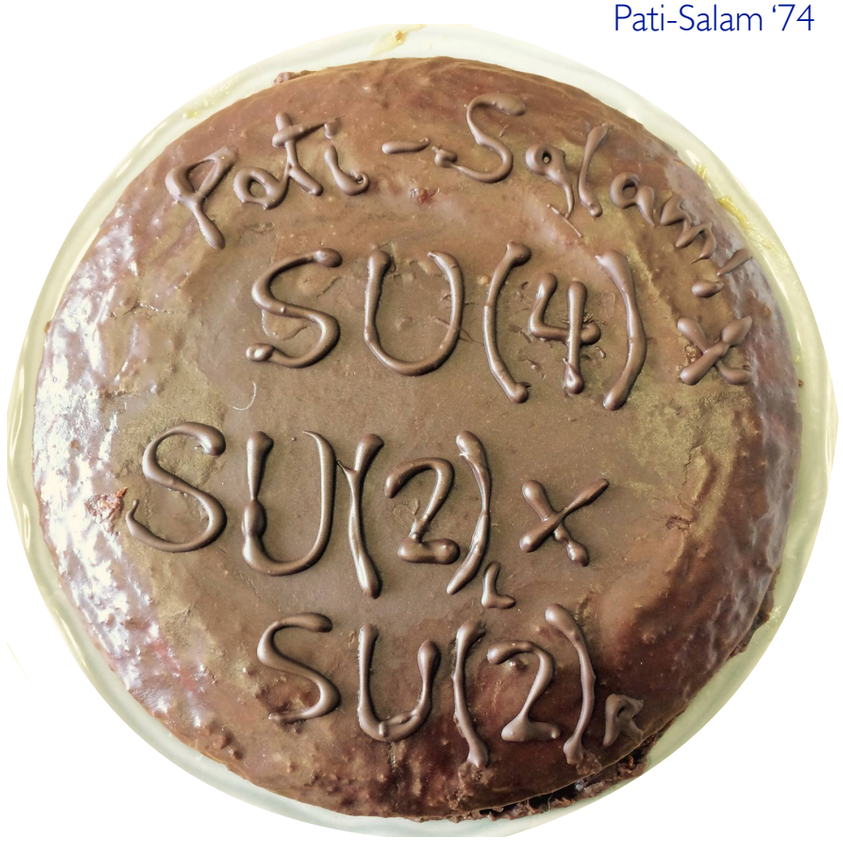
History

- <u>Charm quark</u>
  - Postulated to explain $\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu)$ (GIM '70)
  - Mass estimated from Δm_K (GL '74)
  - Direct discovery (SLAC/BNL '74)

- <u>Third-generation quarks</u>
  - Postulated to explain $\epsilon_K \neq 0$ (KM '73)
  - Top quark mass estimated from Δm_B ('86)
  - Direct discovery: b (FNAL '77), t (FNAL '95)

Flavour physics:
a trailblazer for direct searches!

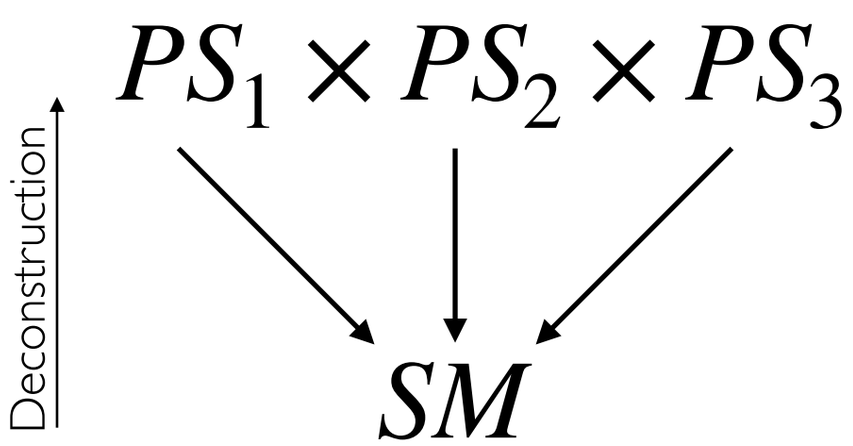
Links: Charge quantisation



Leptoquark: a messenger of an underlying quark-lepton unification

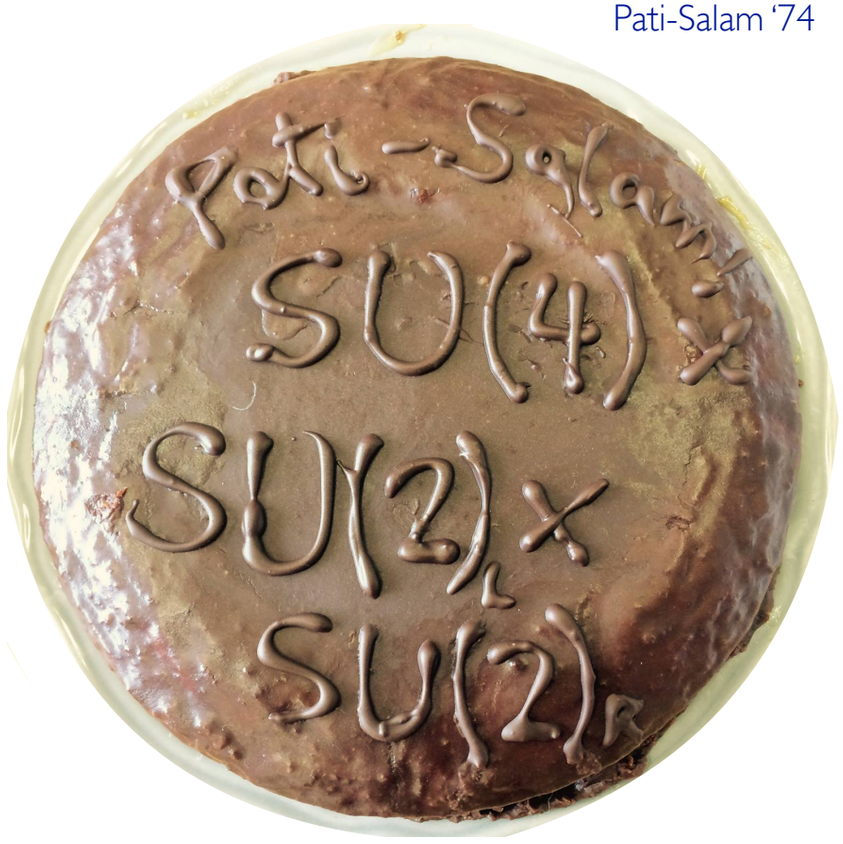
Links: Charge quantisation

Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368



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

Pati-Salam '74



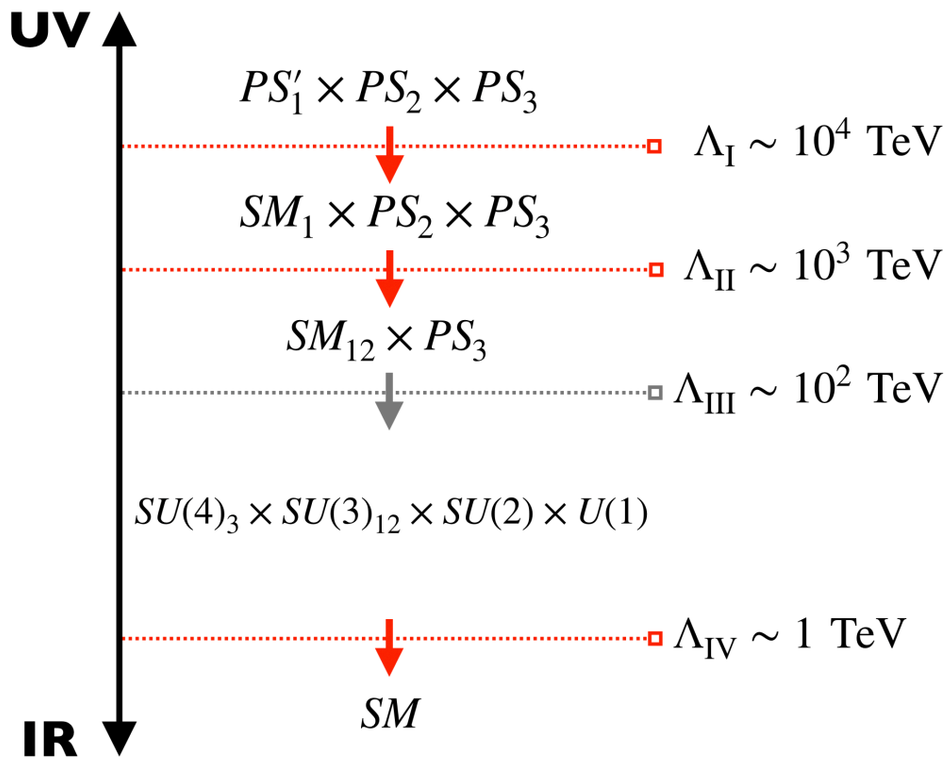
Leptoquark: a messenger of an underlying quark-lepton unification

Links: Hierarchies

Multi-scale flavour

- Series of hierarchical SSBs
  $\Longrightarrow$ Flavour hierarchies

Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368

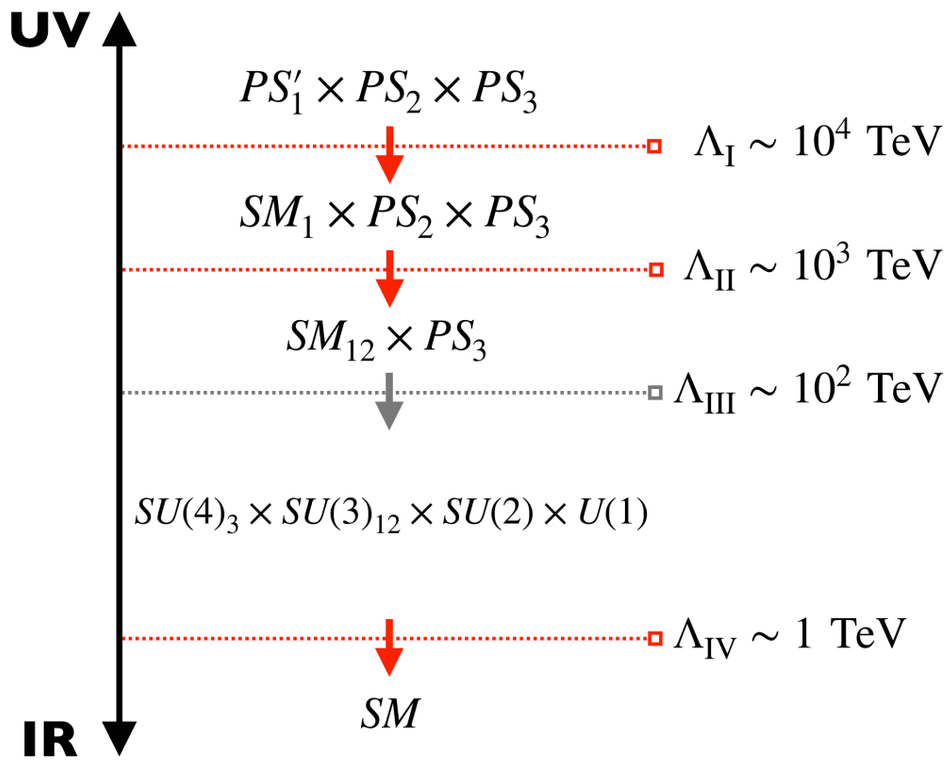


Links: Hierarchies

Multi-scale flavour

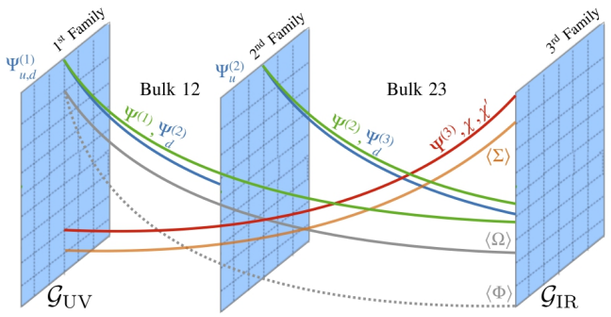
- Series of hierarchical SSBs
  $\Longrightarrow$ Flavour hierarchies

Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368



Flavour as a topological defect

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

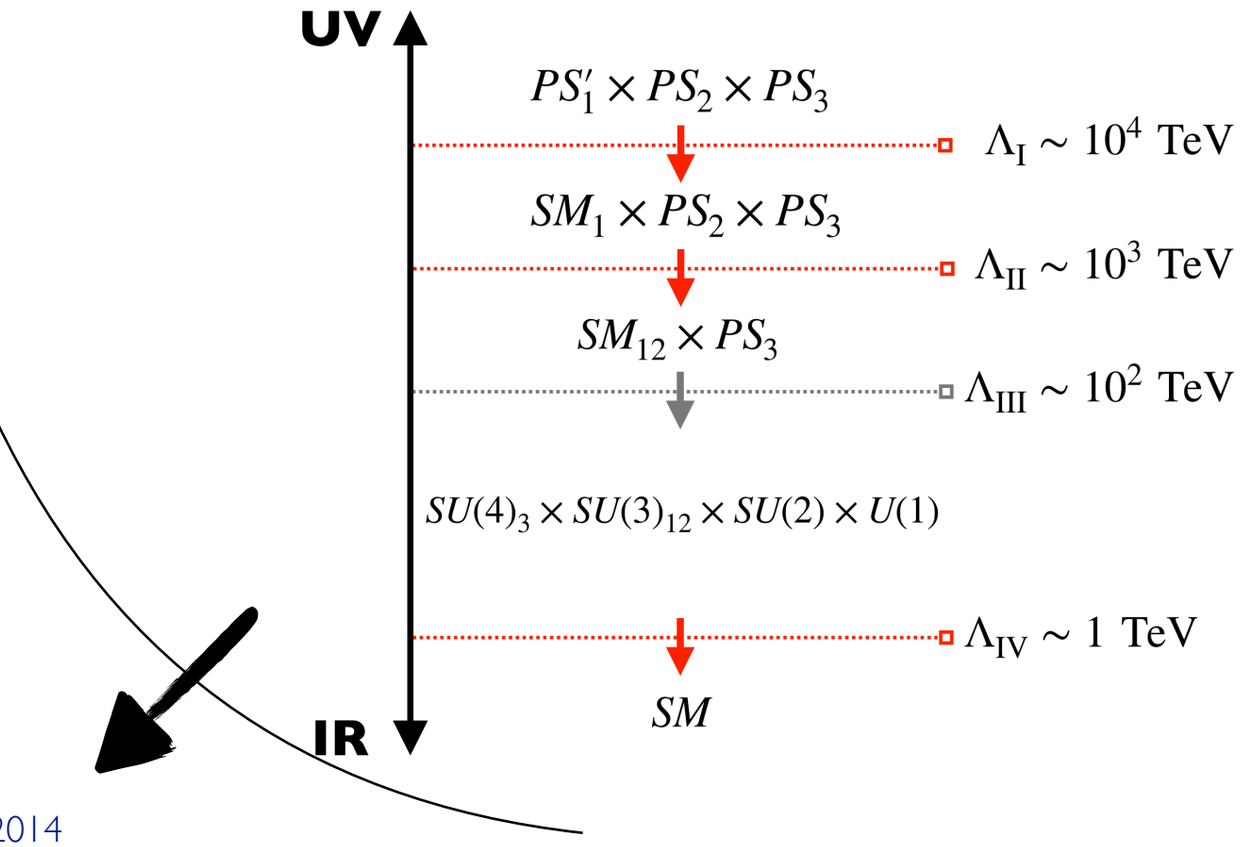


Fuentes-Martin et al; 2203.01952

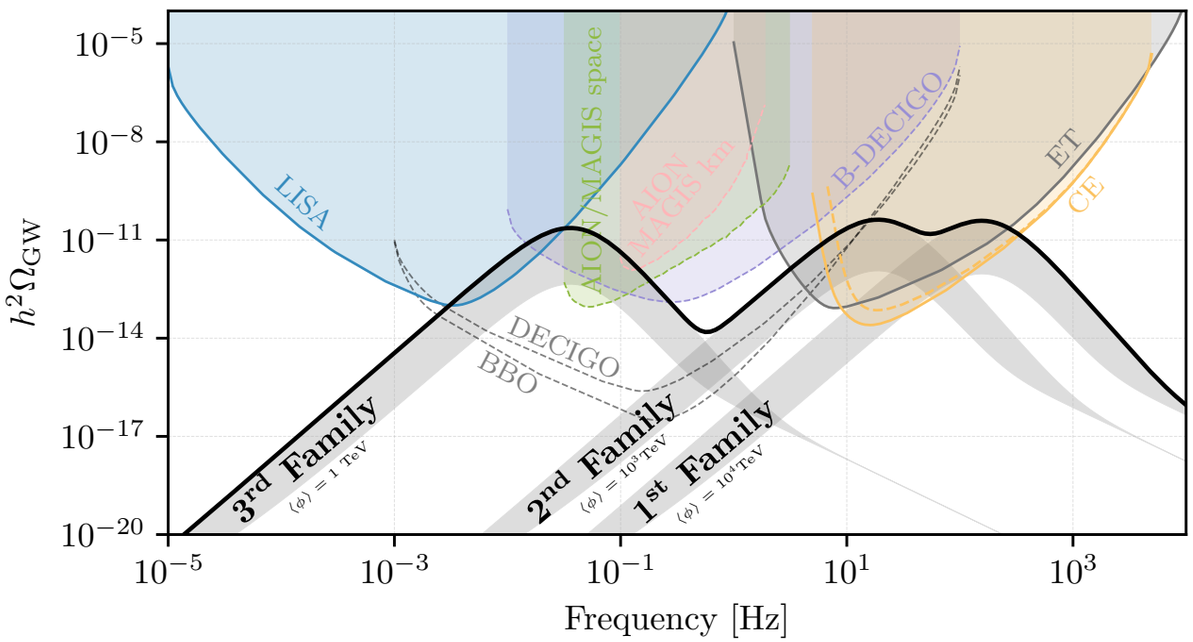
Links: Cosmology

- Novel connections
  GW astronomy & Flavour physics

Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368



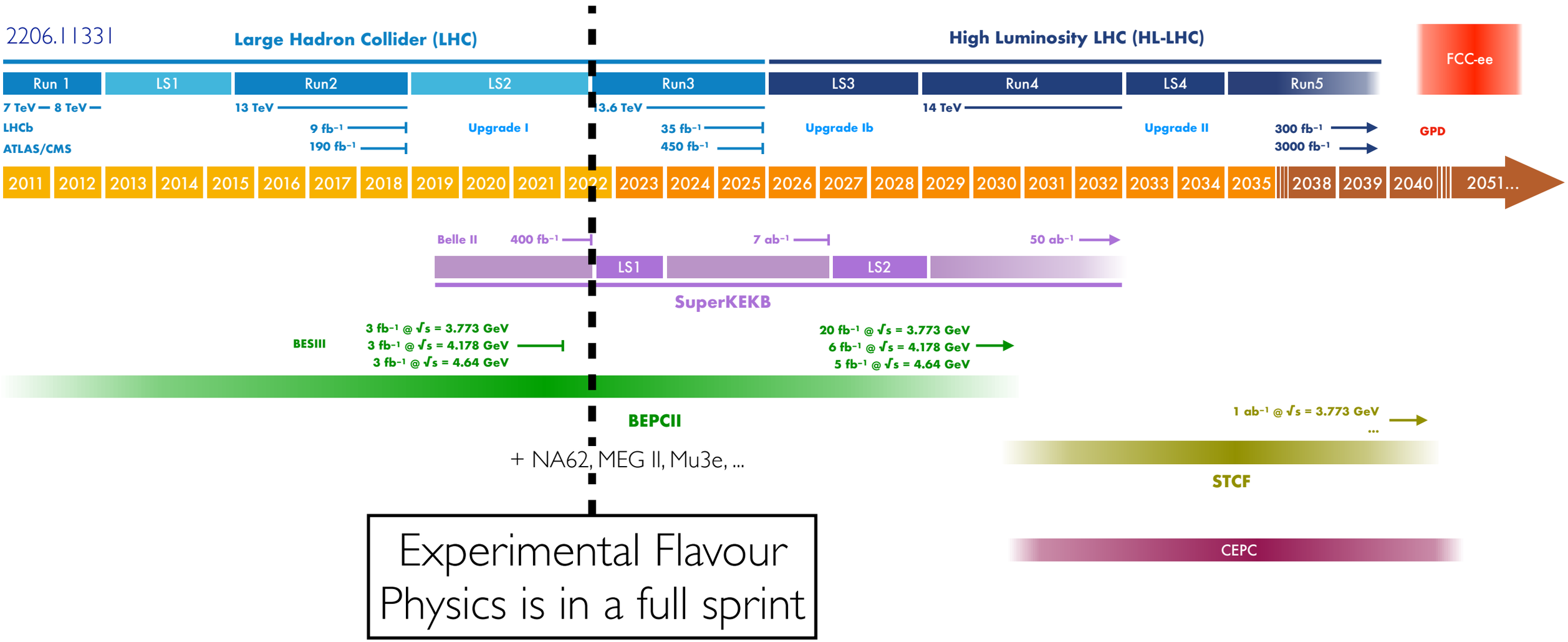
AG, Opferkuch, Stefanek; 1910.02014



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

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

Outlook



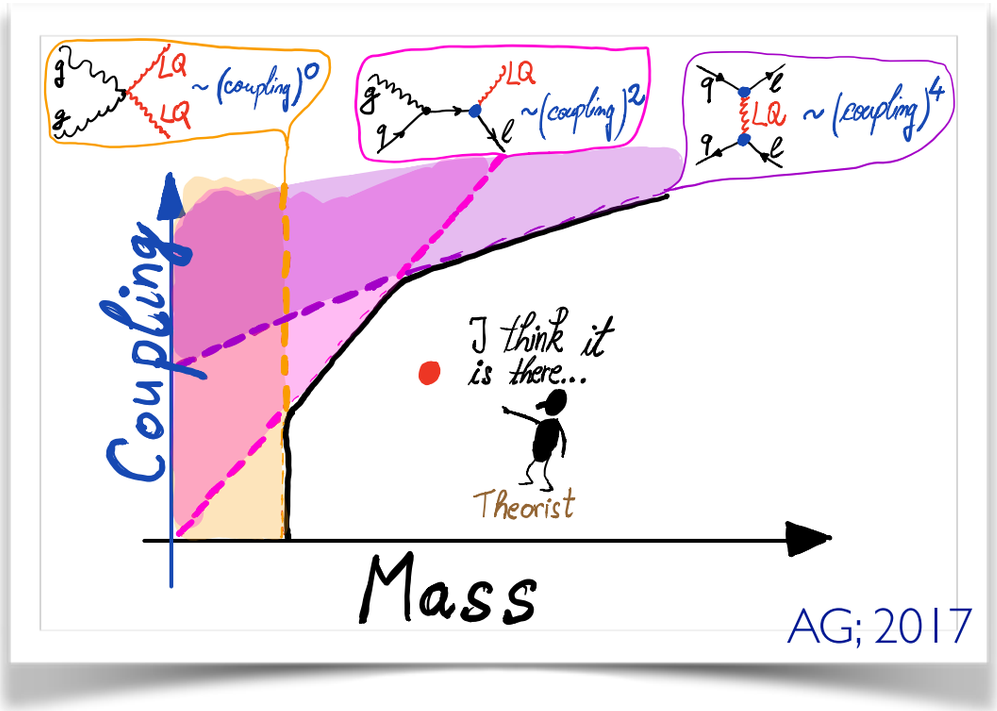
- Theoretical Flavour Physics
  - Precision calculations of flavour observables in and beyond the SM
    - to match the (foreseen) experimental precision
  - Flavour model building
    - to explain the SM and the new physics flavour puzzle, …

July 11th

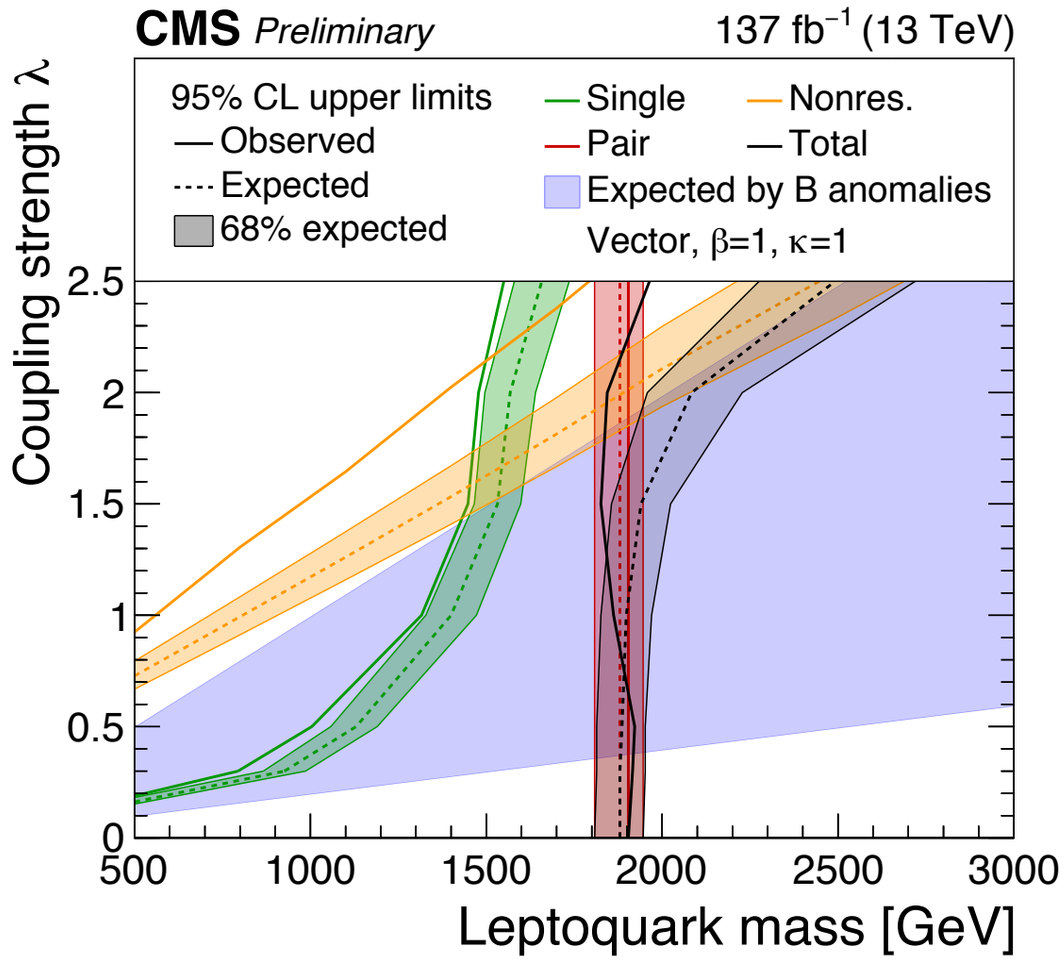
https://srebrenicamemorial.org/en

Backup

Leptoquark searches



AG; 2017



CMS PAS EXO-19-016

The Standard Model

- Flavour symmetry $G^f = U(3)_q \times U(3)_\ell \times U(3)_u \times U(3)_d \times U(3)_e$ *Fermionic kinetic terms

- The Yukawa sector breaks $G^f \to U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ *Exact (classical) accidental symmetry of the SM

- G^f equivalency classes, $Y^u \sim U_q Y^u U_u^\dagger$, etc. $\Longrightarrow$ $54 \to 13$ physical parameters

*By G^f and SVD theorem

$$-\mathscr{L}_{\rm Yuk} = \bar{q} V^\dagger \hat{Y}^u \tilde{H} u + \bar{q} \hat{Y}^d H d + \bar{\ell} \hat{Y}^e H e$$

13 parameters

- *6* quark and *3* charged lepton masses
- The CKM: *3* angles + *1* CPV phase

$$V_{ij} \to e^{i(\theta_u^i - \theta_d^j)} V_{ij}$$

The 4321 model

Field content

	Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
Fermions	q'^i_L	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
	u'^i_R	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
	d'^i_R	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
	ℓ'^i_L	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
	e'^i_R	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
	Ψ^i_L	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	Ψ^i_R	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
Scalars	H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
	Ω_1	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
	Ω_3	$\overline{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
	Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0

i=1,2,3

The 4321 model

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

$$\downarrow \quad \text{SSB: } \langle \Omega_3 \rangle > \langle \Omega_1 \rangle \gg \langle \Omega_{15} \rangle \gg \langle H \rangle$$

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

Embedding:

$$SU(3)_4 \times U(1)_4 \subset SU(4)$$

$$SU(3)_c = (SU(3)_4 \times SU(3)')_{\rm diag}$$
$$U(1)_Y = (U(1)_4 \times U(1)')_{\rm diag}$$

Scalars:

$$\Omega_1 = \left(\overline{4}, 1, 1, -1/2\right)$$
$$\Omega_3 = \left(\overline{4}, 3, 1, 1/6\right)$$

$$\langle \Omega_3 \rangle = \begin{pmatrix} \frac{v_3}{\sqrt{2}} & 0 & 0 \\ 0 & \frac{v_3}{\sqrt{2}} & 0 \\ 0 & 0 & \frac{v_3}{\sqrt{2}} \\ 0 & 0 & 0 \end{pmatrix}, \quad \langle \Omega_1 \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}$$

Gauge couplings:

$$g_s = \frac{g_4 g_3}{\sqrt{g_4^2 + g_3^2}} \qquad g_Y = \frac{g_4 g_1}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}}$$

The 4321 model

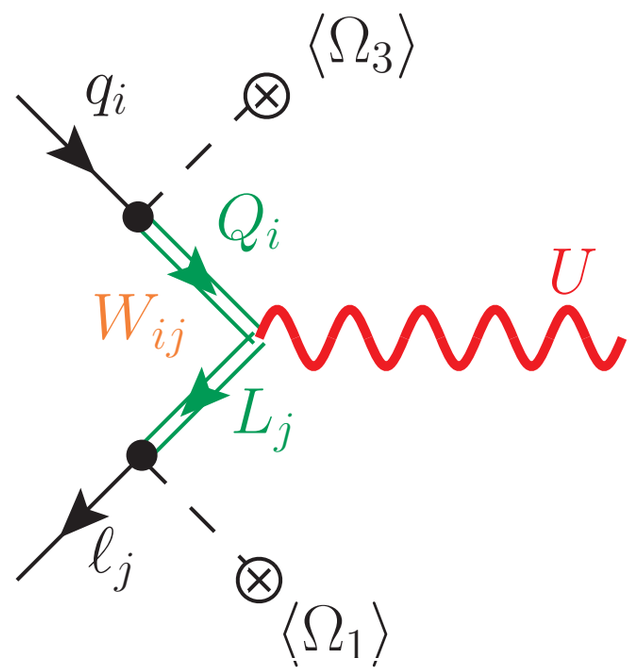
A vector-like fermion rep. $(4, 1, \mathbf{2}, 0)$

$$\Psi_{L,R} = (Q'_{L,R}, L'_{L,R})^T$$

$$-\overline{q}'_L \, \lambda_q \, \Omega_3^T \Psi_R - \overline{\ell}'_L \, \lambda_\ell \, \Omega_1^T \Psi_R$$

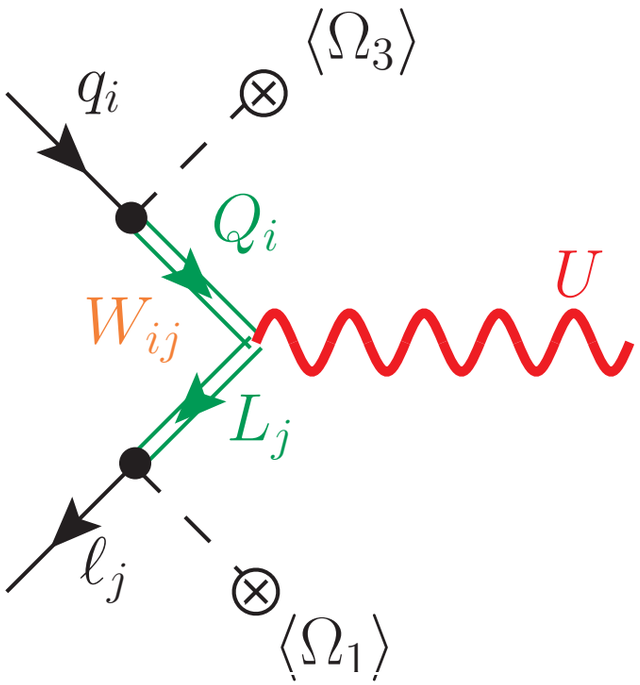
- $\langle \Omega_3 \rangle$ mixes the would-be SM state q'_L with $Q'_L \subset \Psi_L$
- $\langle \Omega_1 \rangle$ mixes the would-be SM state ℓ'_L with $L'_L \subset \Psi_L$.

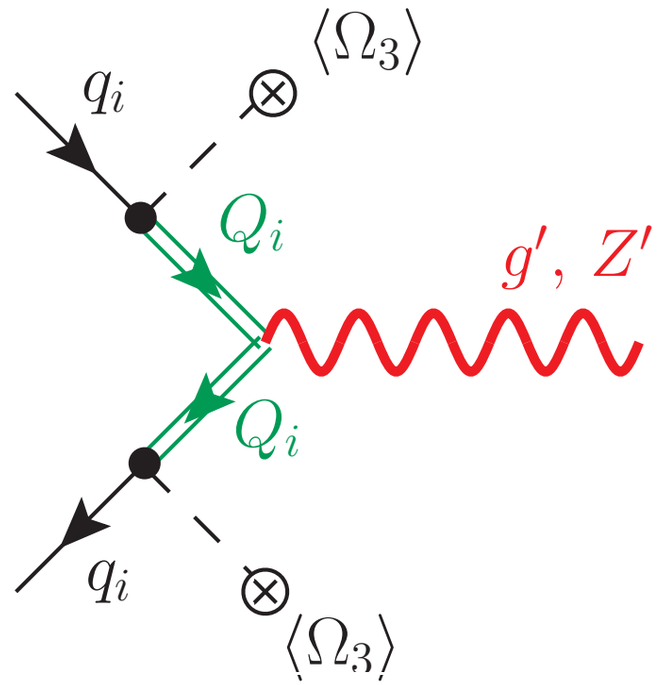
SM fermion doublets mix with the vector-like partners

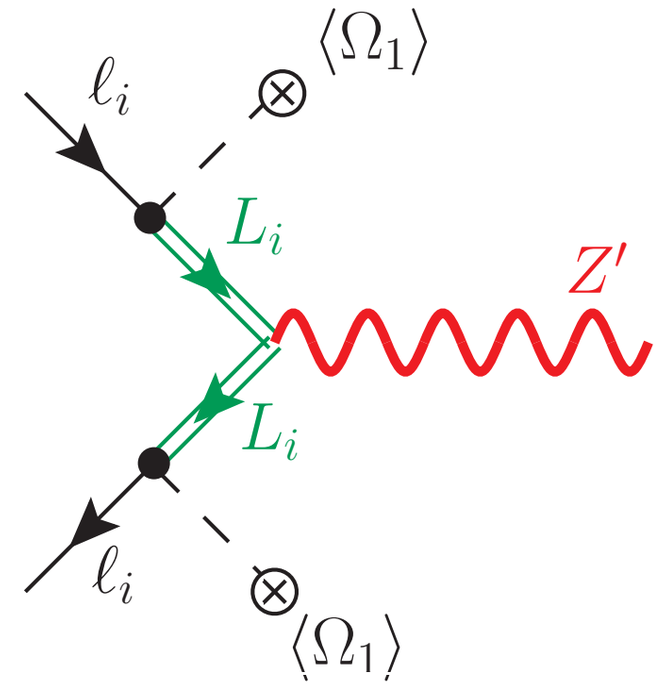


Left-handed dominance!

The 4321 model







- Large flavour violation mediated by the LQ only

The 4321 model

$\mathcal{G}_{321}$	$\mathcal{G}_{4321}$
θ_C	θ_{LQ}
V	W
W_μ	U_μ
$q_L = \begin{pmatrix} u_L \\ V d_L \end{pmatrix}$	$\Psi_L = \begin{pmatrix} Q_L \\ W L_L \end{pmatrix}$
Y_u, Y_d	λ_q, λ_ℓ
$SU(2)_L$	$SU(4)$
$U(1)_u \times U(1)_c \times U(1)_t$	$U(2)_{q'+\Psi} \times U(1)_{q'_3+\Psi_3}$
$U(1)_d \times U(1)_s \times U(1)_b$	$U(1)_{\ell'_1+\tilde{\Psi}_1} \times U(1)_{\ell'_2+\tilde{\Psi}_2} \times U(1)_{\ell'_3+\tilde{\Psi}_3}$
$U(1)_B$	$U(1)_{q'_1+\ell'_1+\Psi_1} \times U(1)_{q'+\ell'+\Psi}$
$u \to d$ tree level	$Q \to L$ tree level
$u_i \to u_j$ loop level	$Q_i \to Q_j$ loop level
$d_i \to d_j$ loop level	$L_i \to L_j$ loop level

Table 2. Analogies between the SM and the 4321 model.