A Composite Model for the B anomalies

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INFN Trieste

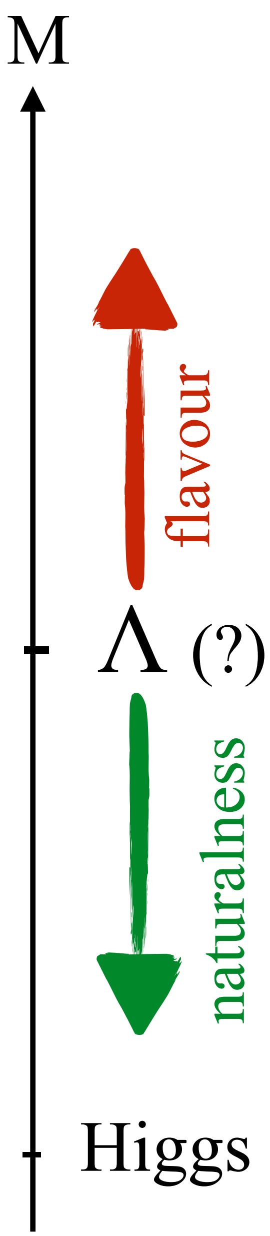
IPPP Durham, 22/11/2018

Outline

- Introduction
- Recap: B-physics anomalies
- Combined EFT fit of the anomalies
- Simplified models & direct searches of the mediators
- UV construction:
  - pNGB scalar leptoquarks → composite Higgs

Introduction

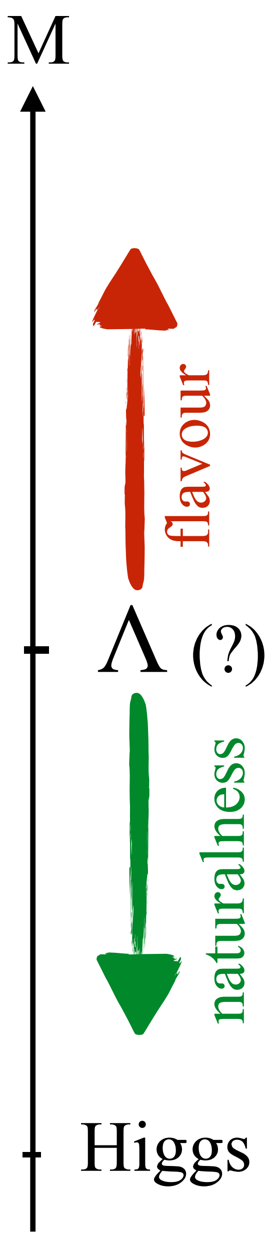
The hierarchy problem of the EW scale suggests a new physics scale $\Lambda \lesssim \mathrm{TeV}$.
Most of model-building effort has been focussed on solutions of this problem:
SUSY, compositeness, extra dimensions, twin Higgs, NNaturalness, relaxion, etc…



The strong bounds from flavour physics require instead $\Lambda \gg \mathrm{TeV}^{*}$:
flavour was a "problem" to be avoided → postponed to high scales.

* for arbitrary flavour structure

Introduction



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Predictions for the LHC era:

→ Abundance of new (s)particles at the LHC!!!

Flavour-blind New Physics (maybe something in FCNC, LFV) …

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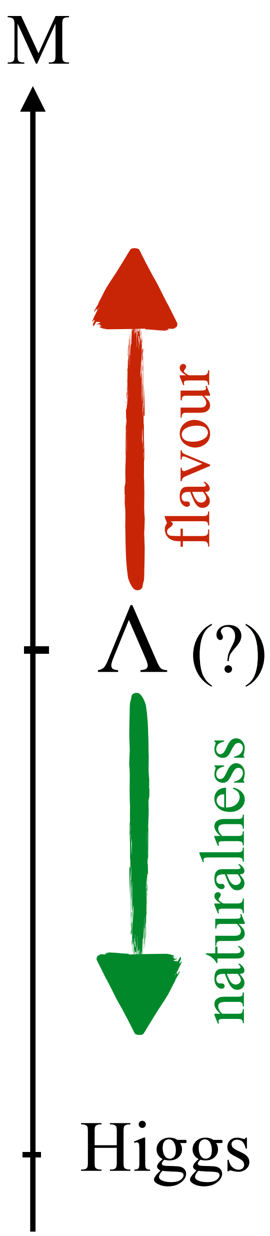

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Predictions for the LHC era:

→ Abundance of new (s)particles at the LHC!!!

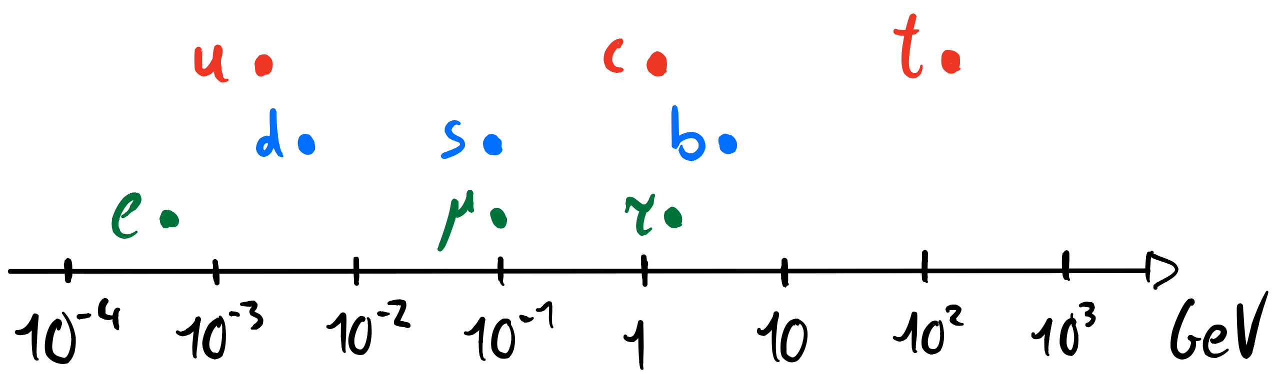
Flavour-blind New Physics (maybe something in FCNC, LFV) …

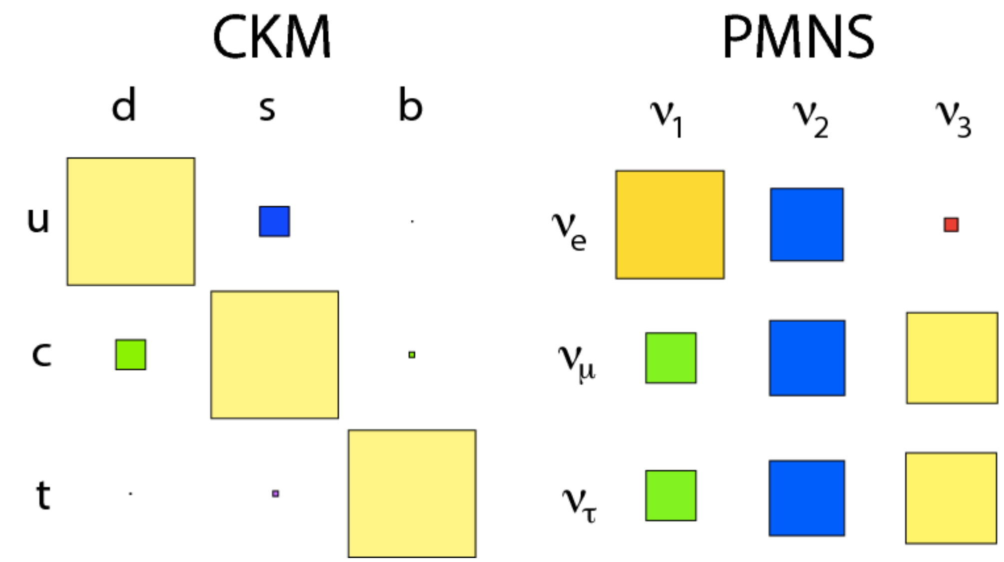
Instead we ended up with:

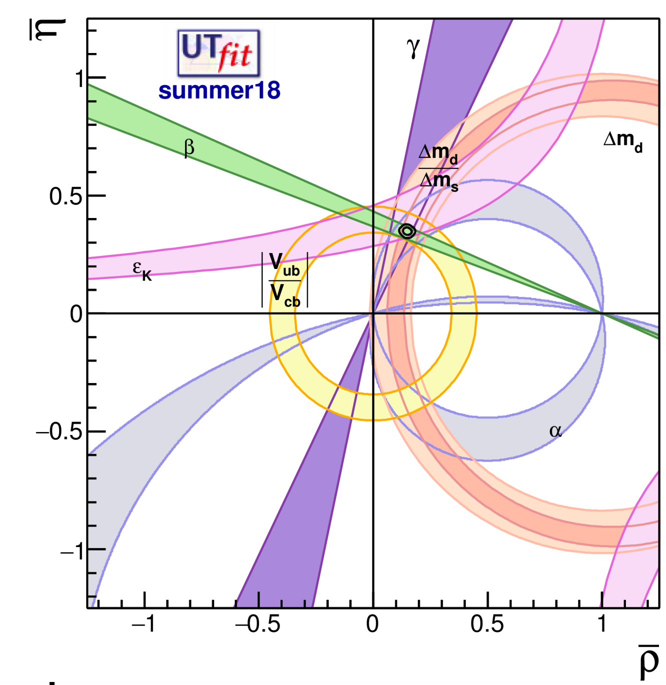
→ No direct signal of new particles…

Exciting anomalies in flavour physics!!!

The Flavour "puzzle"







$$Y_u \sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix}$$

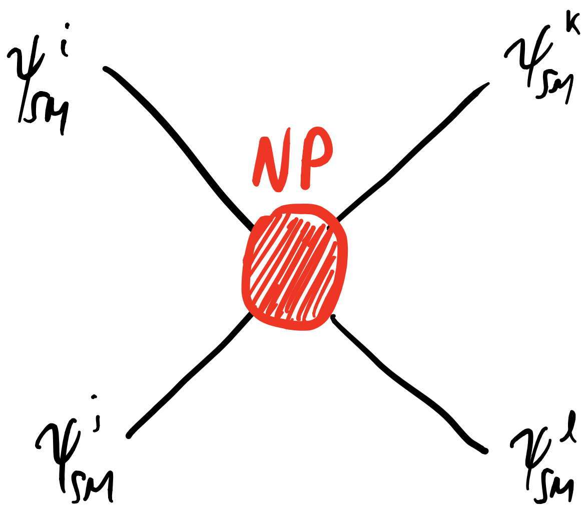
$$Y_d \sim \mathrm{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right)$$

$$Y_e \sim \mathrm{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right)$$

This peculiar pattern does not seem accidental

What is the origin of the SM Yukawas?

The Flavour “Problem"

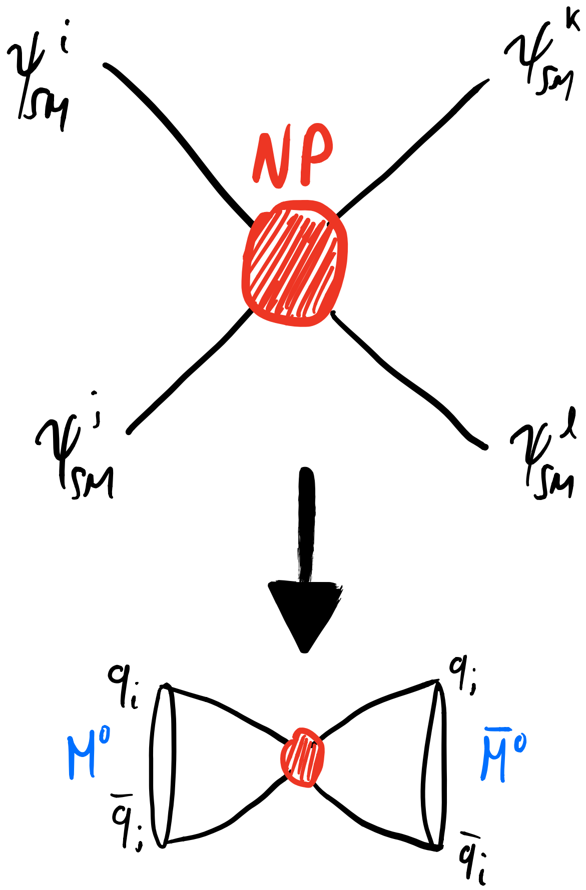


$$\frac{c}{\Lambda^2}(\bar{\psi}_i \psi_j)(\bar{\psi}_k \psi_l)$$

For the hierarchy problem

$$\Lambda \lesssim \text{TeV}$$

The Flavour “Problem"



Meson — anti-Meson mixing

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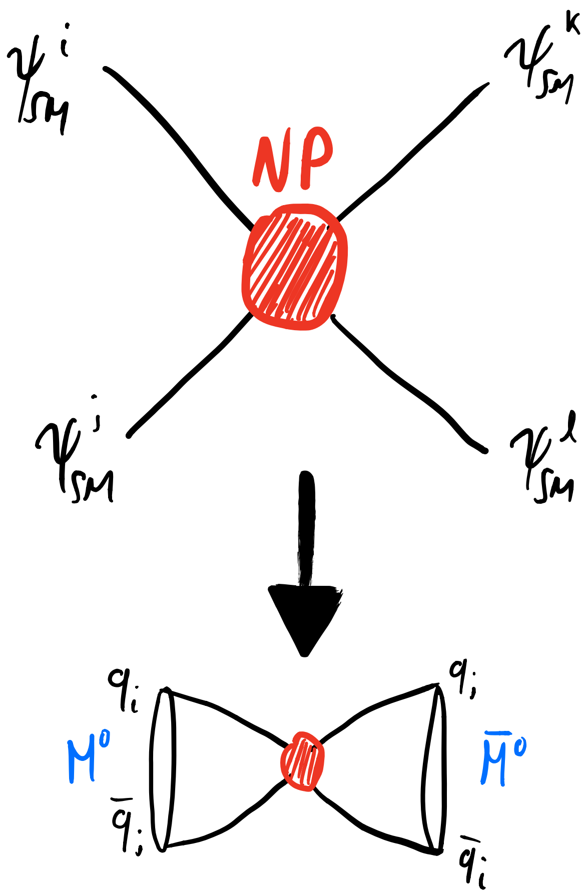

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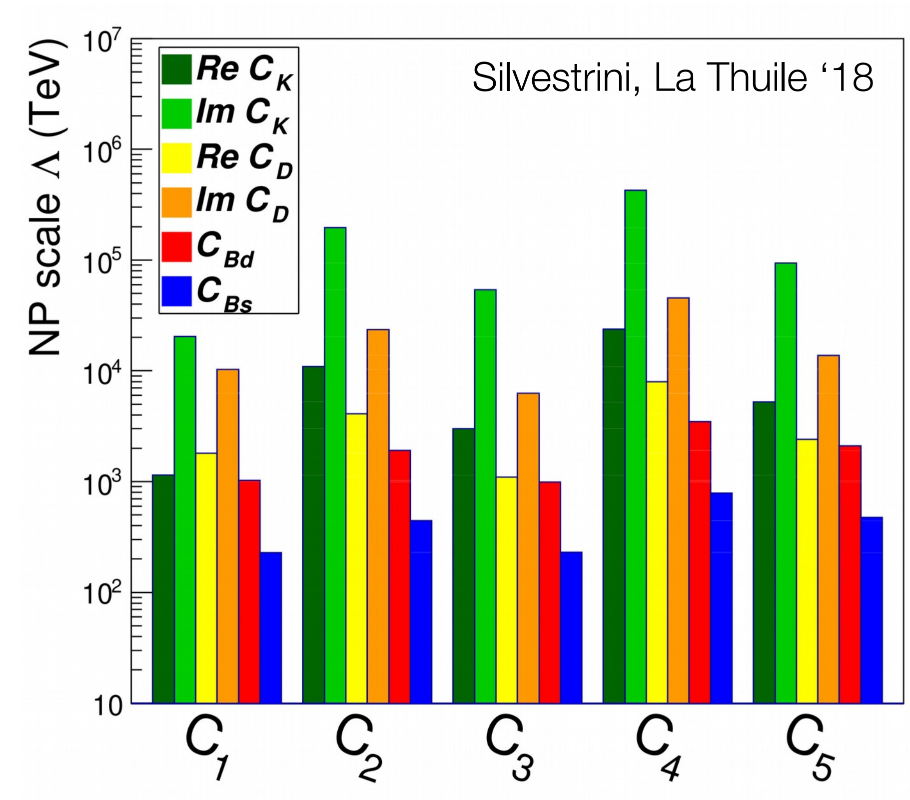

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For generic NP flavour-violation (c=1) $\Lambda \gtrsim 10^5$ TeV

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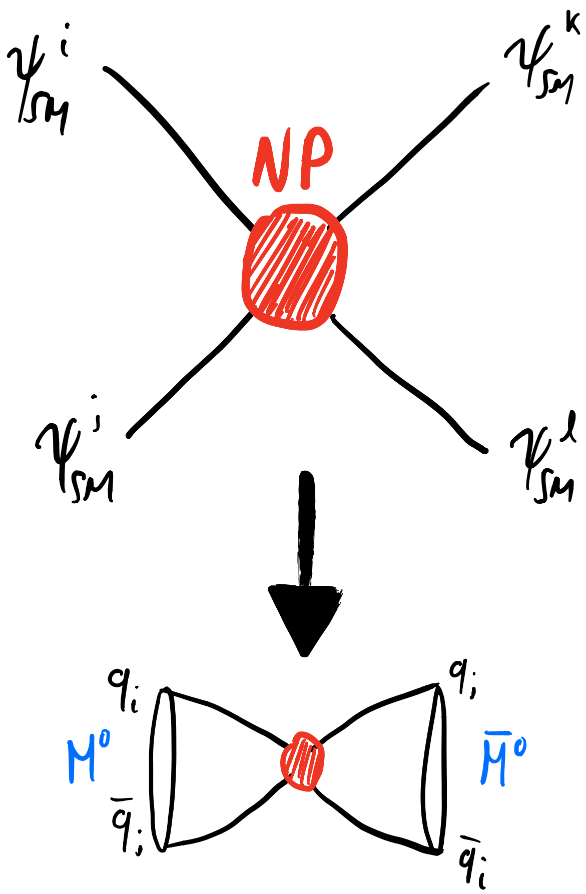

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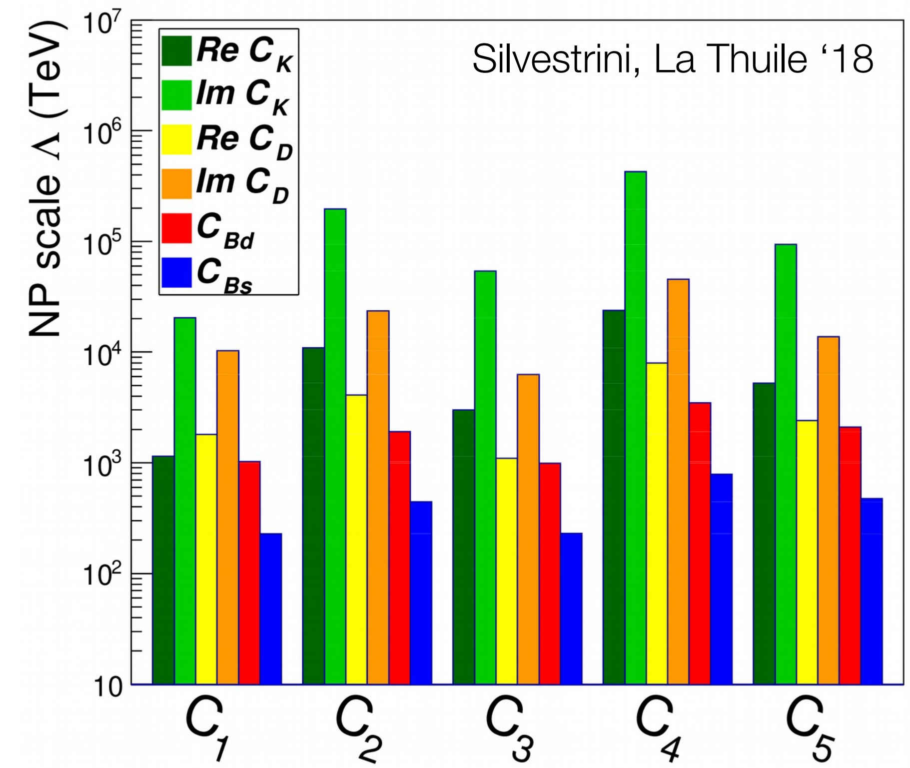
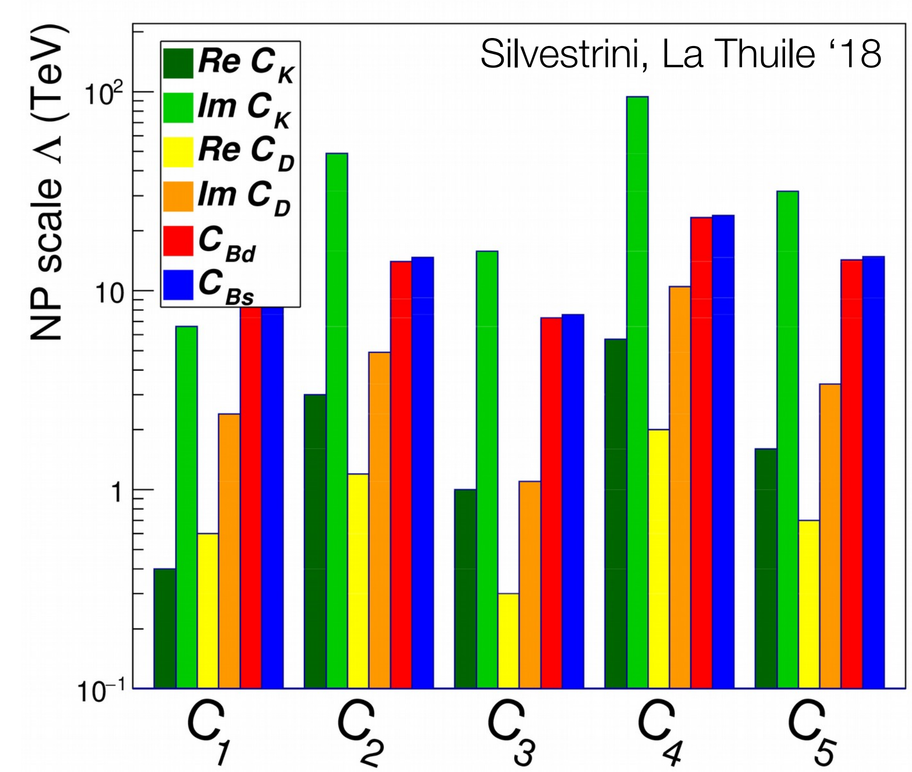




For generic NP flavour-violation (c=1) $\Lambda \gtrsim 10^5$ TeV

For MFV-like (c ~ CKM) NP $\Lambda \gtrsim 10^2$ TeV

For U(2)-like (3rd gen c ~ CKM) NP $\Lambda \gtrsim 10$ TeV

For U(2)-like and loop-generated $\Lambda \gtrsim 1$ TeV

Beyond Flavour-Universality

To reconcile a low NP scale in flavour physics with present bounds its flavour structure should have some protection.

Structures like U(2) flavour symmetry or partial compositeness are very motivated

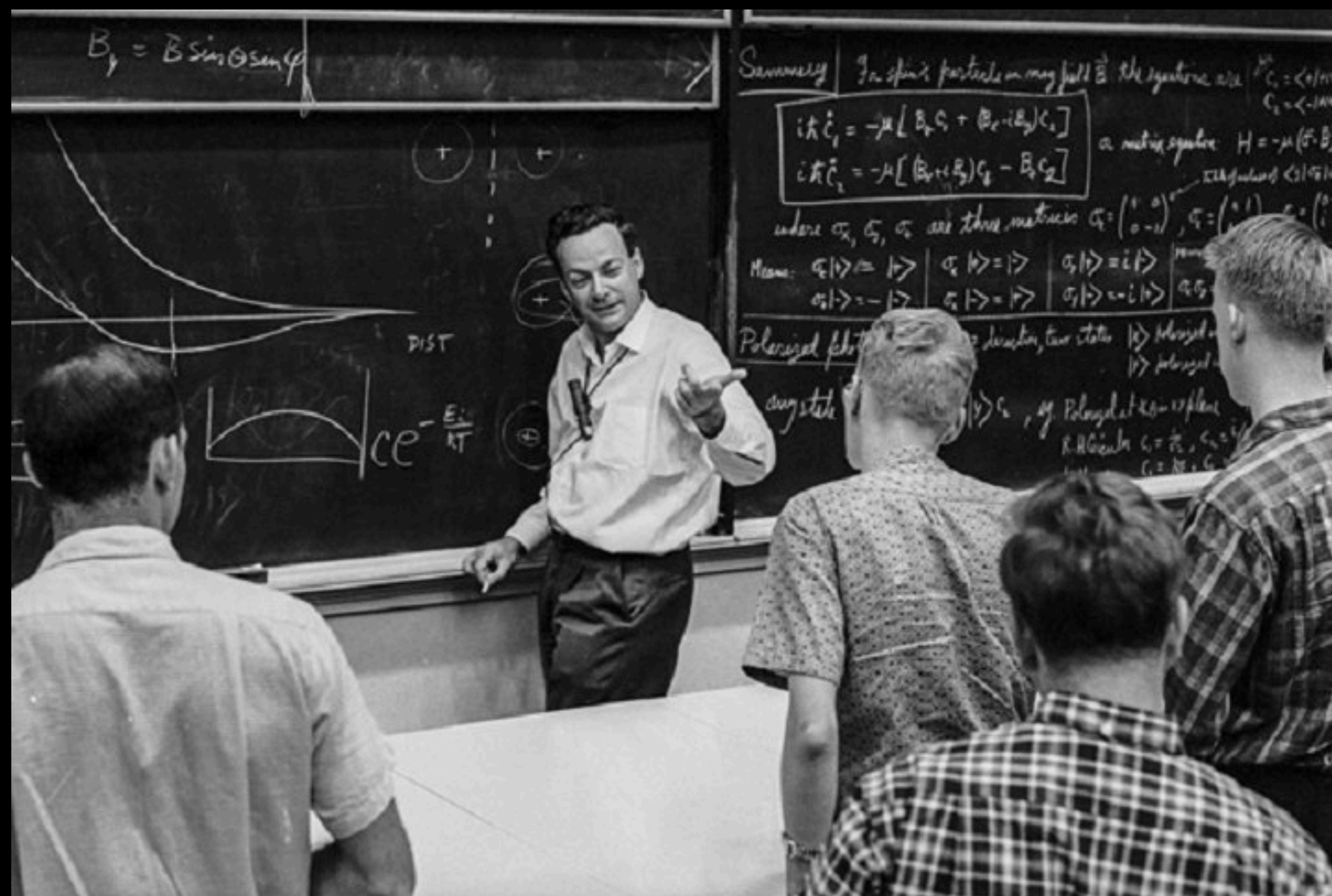
Violation of flavour-universality!

↓

Expect largest coupling to 3rd generation

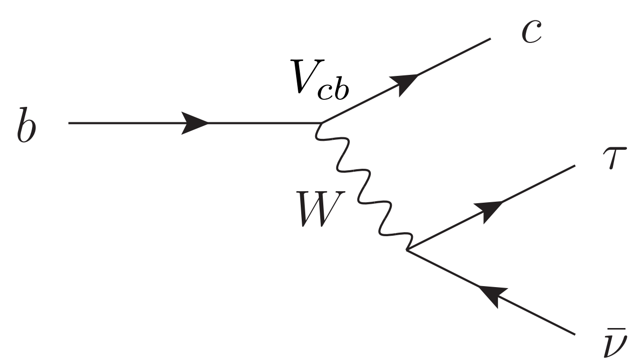
NP scale $\Lambda_{3rd} \ll \Lambda_{2nd} \ll \Lambda_{1st}$

Data



It doesn't matter how beautiful your theory is,
it doesn't matter how smart you are.
If it doesn't agree with experiment, it's wrong.

Charged-current anomalies

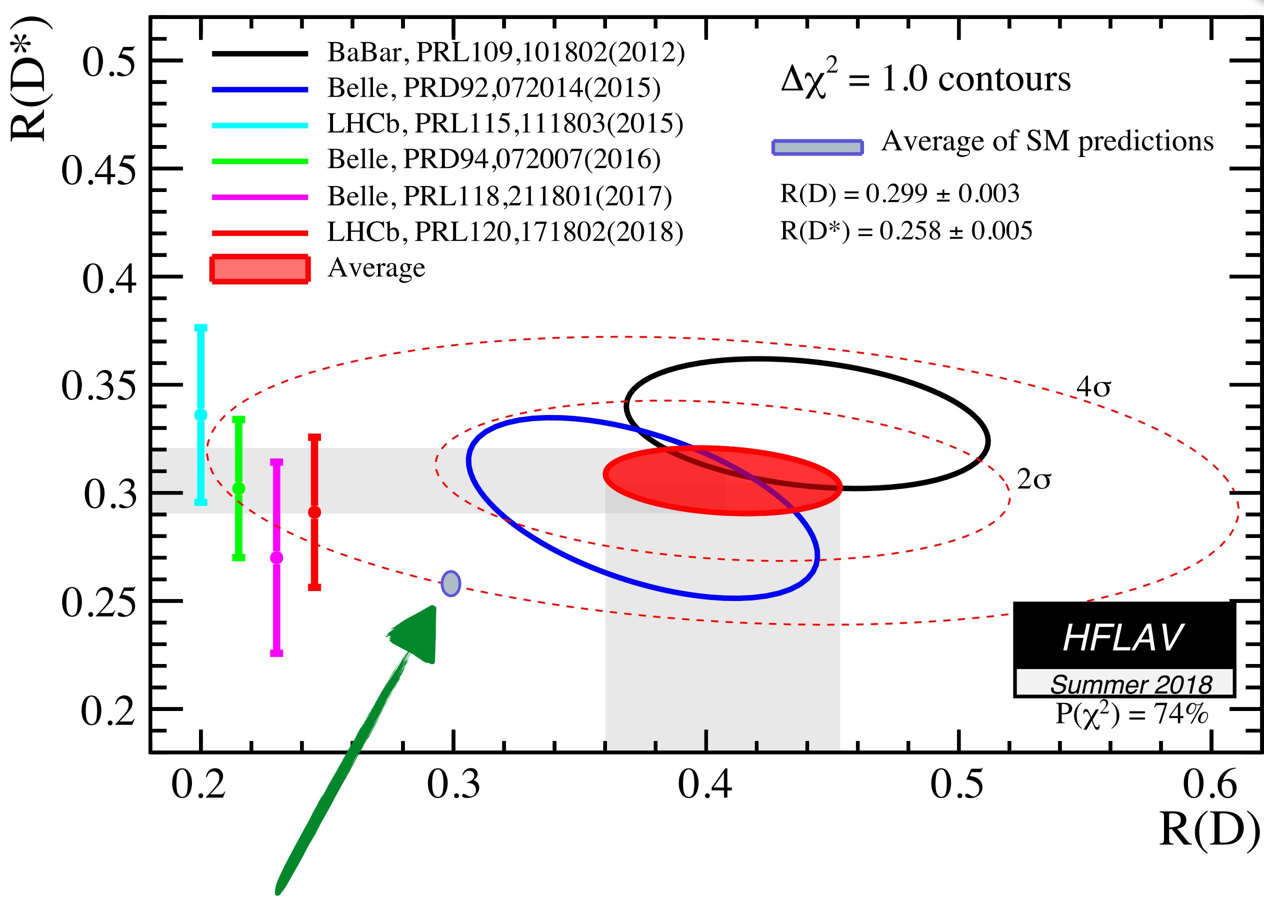


Tree-level SM process with V_{cb} suppression.

$b \to c\,\tau\,\nu$ vs. $b \to c\,\ell\,\nu$

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)},$$

$$\ell = \mu, e$$



Robust SM prediction

All results since 2012 consistently above SM prediction

$$R_{D^{(*)}} \equiv R(D^{(*)})/R(D^{(*)})_{\rm SM} = 1.218 \pm 0.052$$

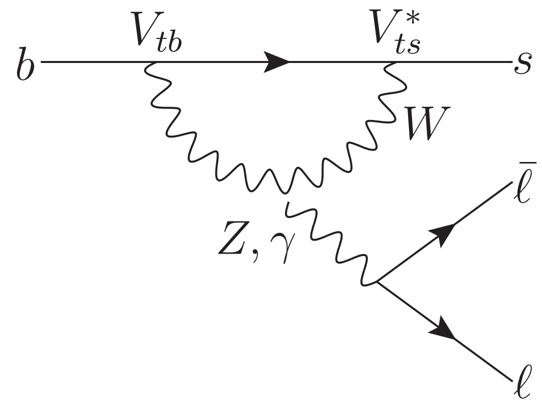
~ 20% enhancement from the SM

~ 4σ from the SM

While μ/e universality tested at O(1%) level.

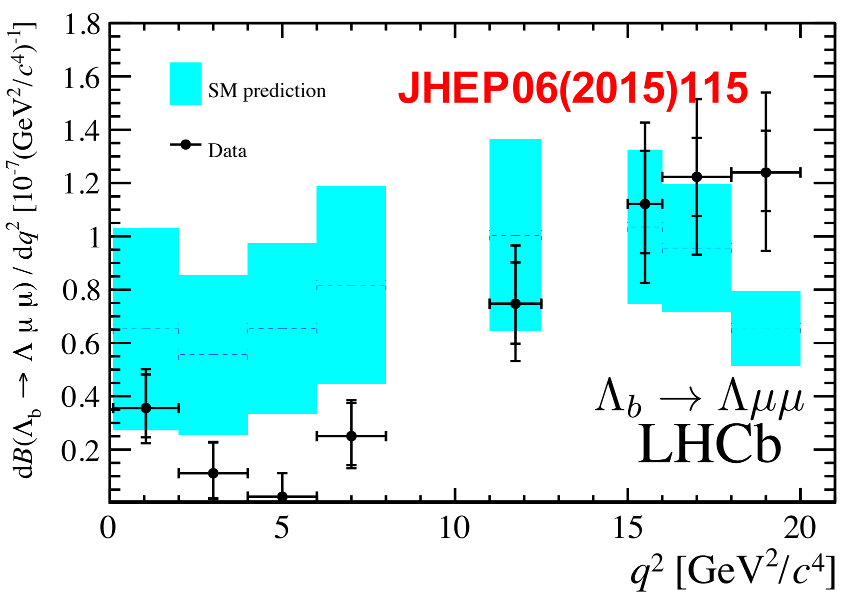
Straub, Jung, et al. 2018

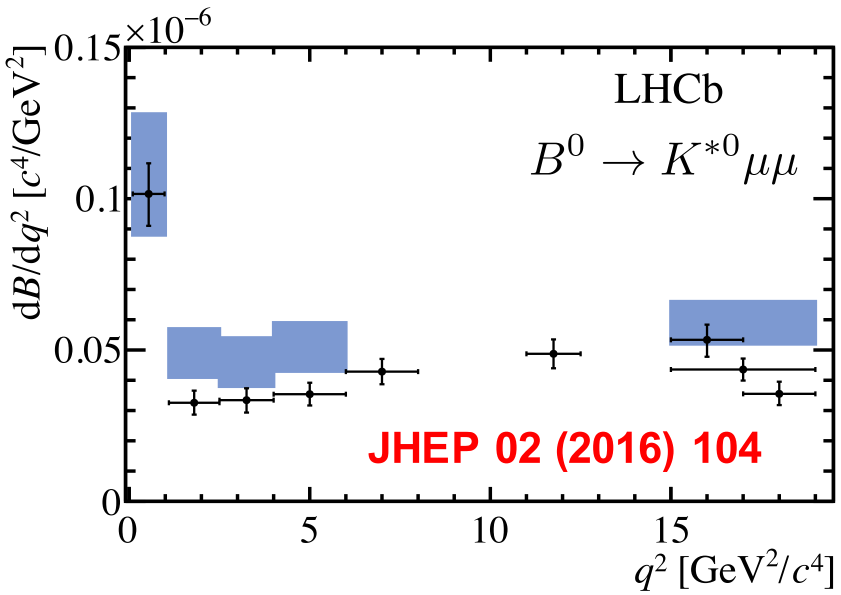
Neutral-current anomalies (1)

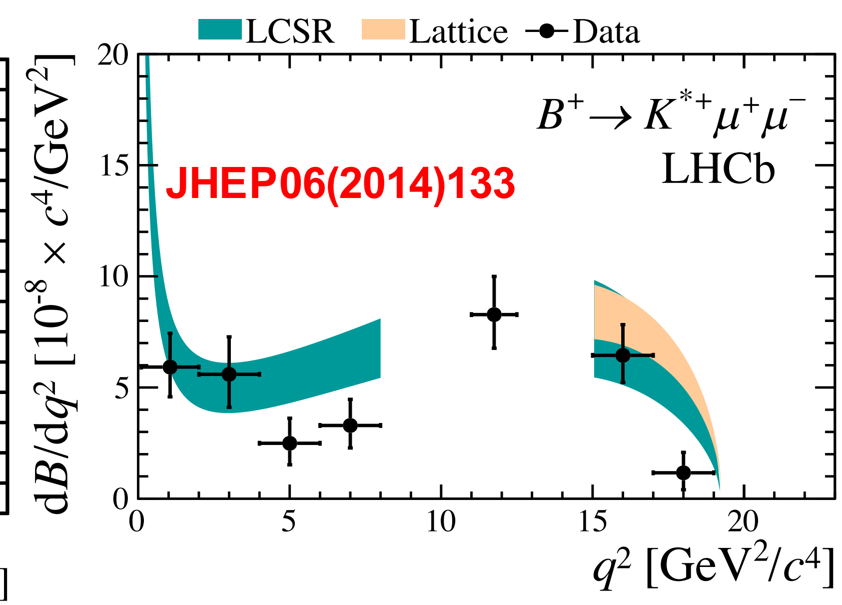


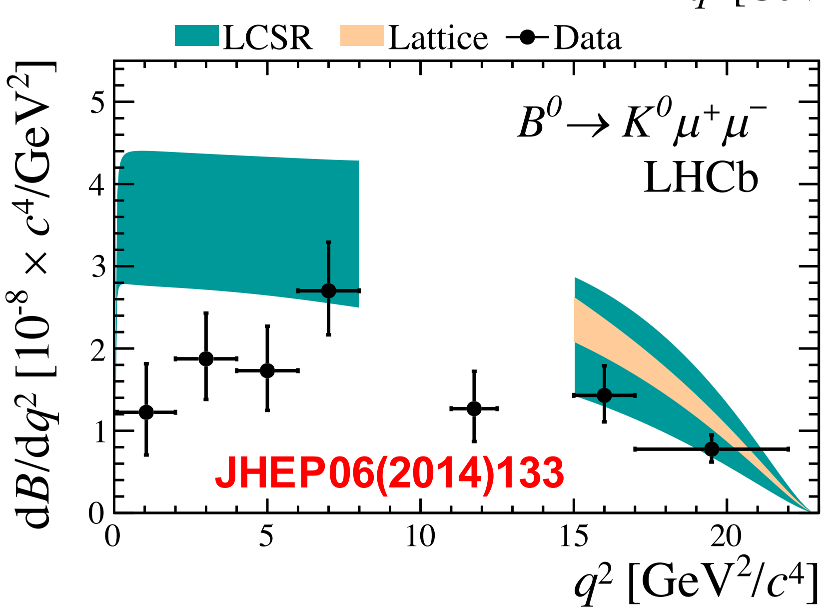
$b \to s\, \mu^+ \mu^-$

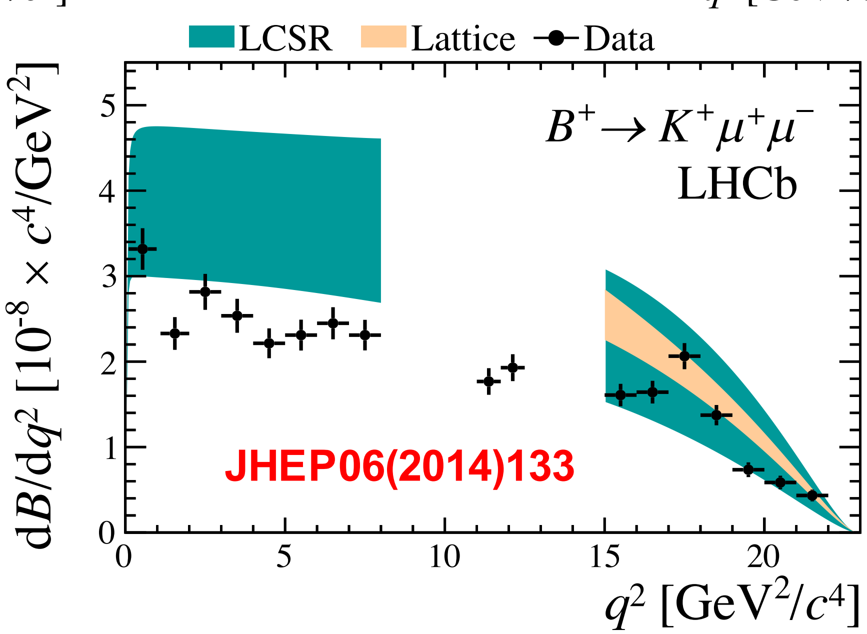
Differential branching fractions in $q_{\mu\mu}^2$.

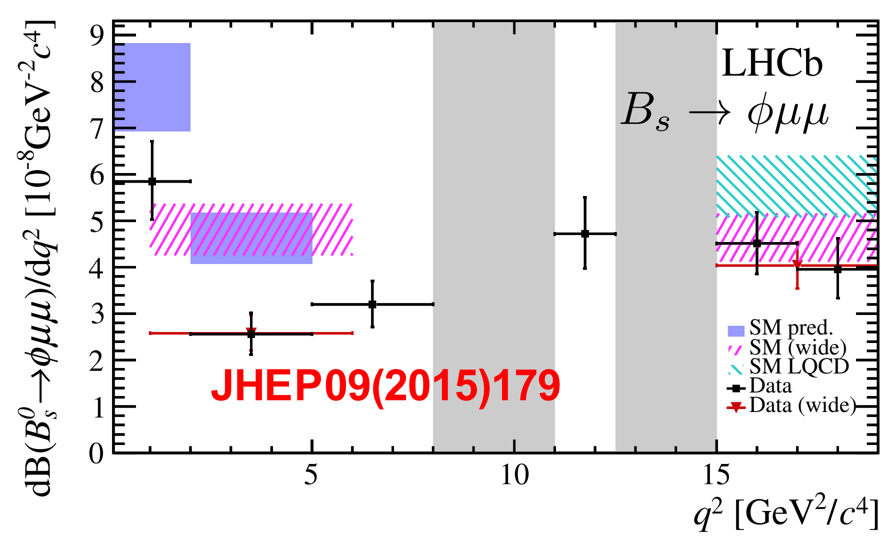






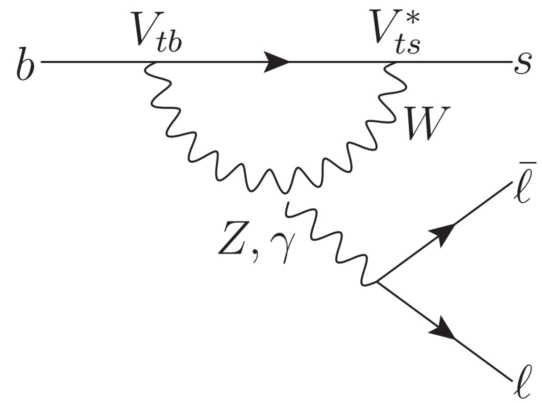






All are below the SM prediction

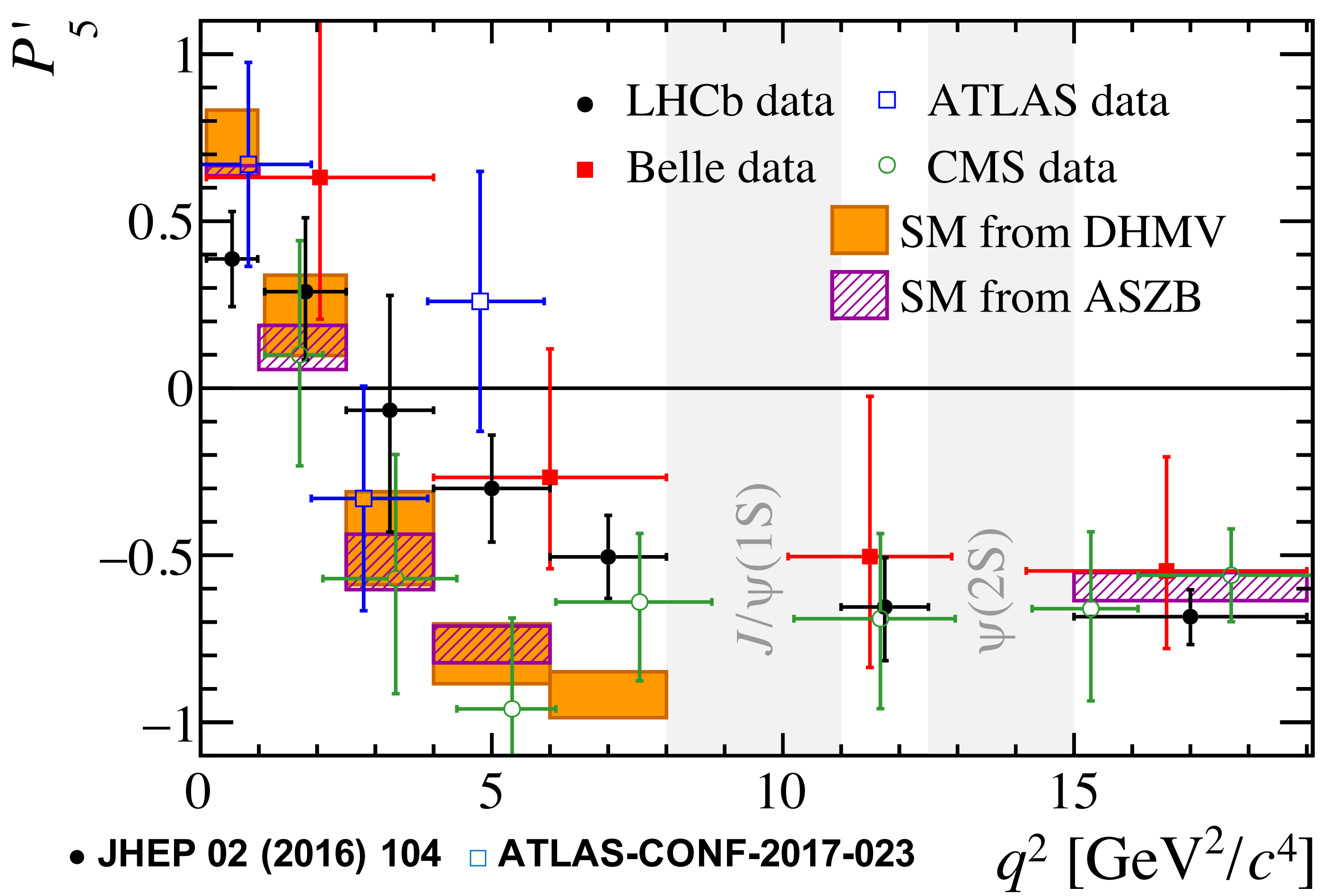
Neutral-current anomalies (2)



$b \to s\, \mu^+ \mu^-$

in $B \to K^*(\to K\pi)\, \mu^+ \mu^-$

Angular coefficient P'_5 as function of q^2.



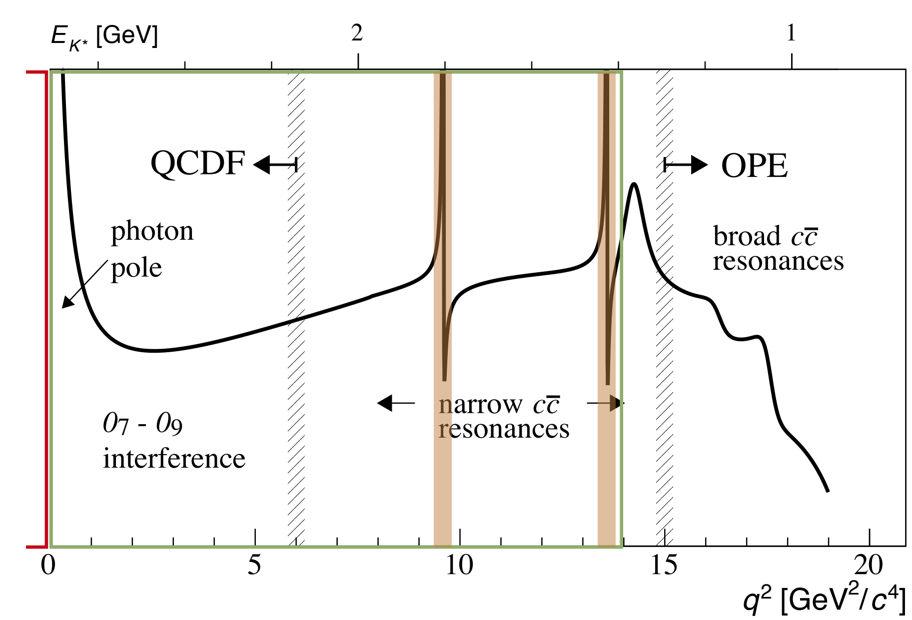
• **JHEP 02 (2016) 104** □ **ATLAS-CONF-2017-023**
■ **PRL 118 (2017)** ○ **CMS-PAS-BPH-15-008**

~4-5 σ

SM prediction is challenging

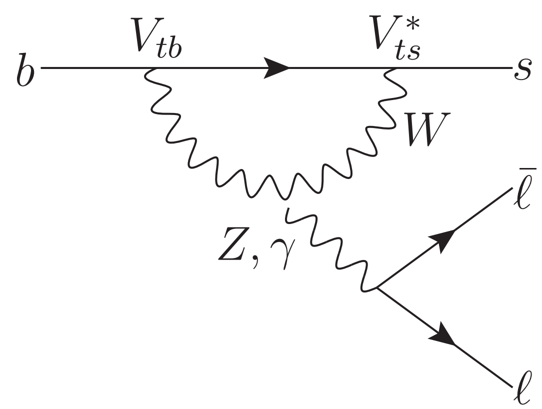
due to possibly large non-perturbative "long distance" effects (in $c\bar{c}$ loops)

First attempts to extract these from data confirm a large significance of the deviation.



Bobeth et al. 1707.07305

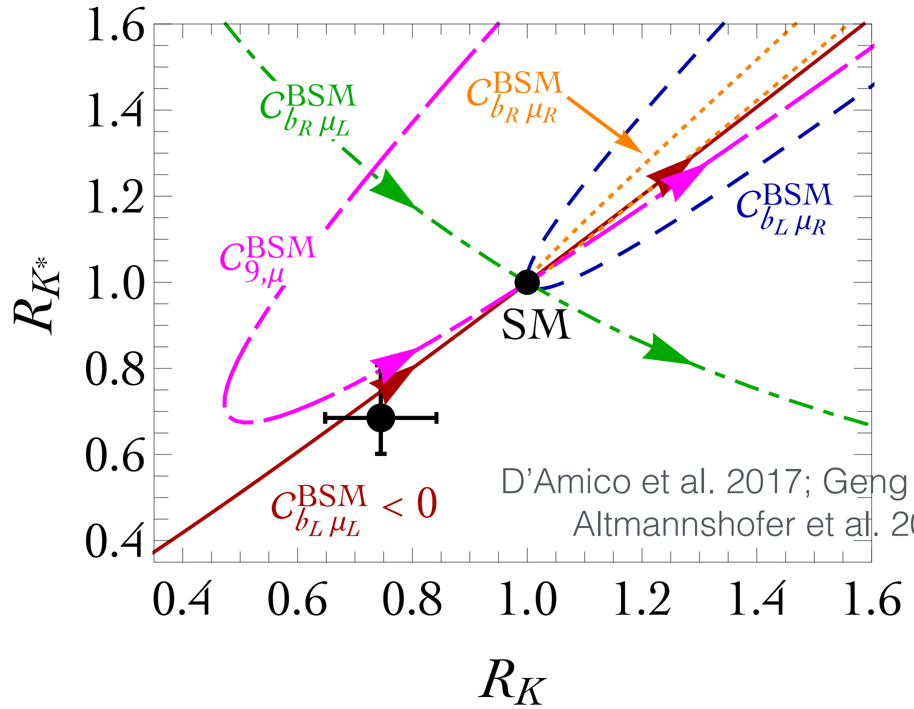
Neutral-current anomalies (3)



$b \to s\, \mu^+ \mu^-$* vs. *$b \to s\, e^+ e^-$

Lepton Flavour Universality ratios

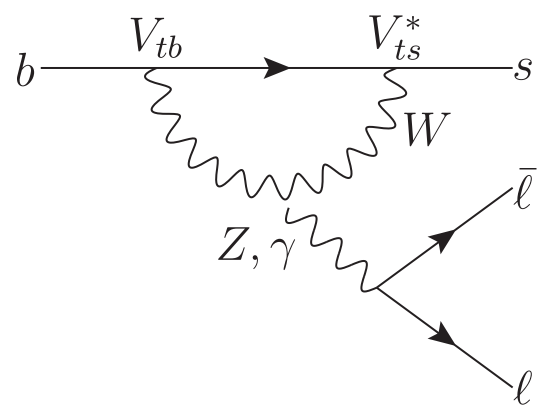
$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$



D'Amico et al. 2017; Geng et al. 2017, Altmannshofer et al. 2017, …

Clean SM prediction

Neutral-current anomalies (3)



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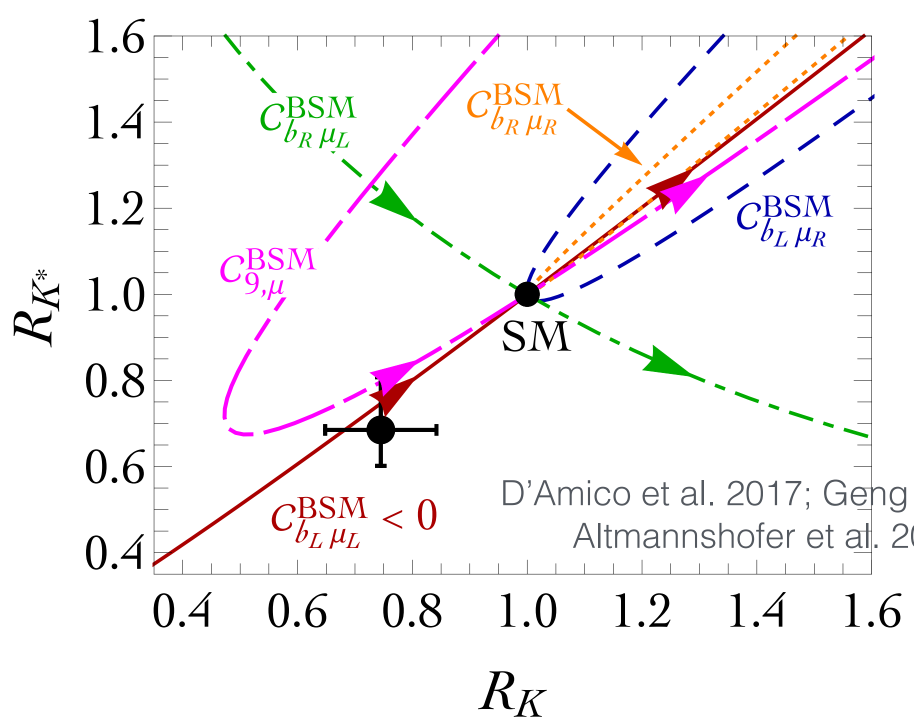


D'Amico et al. 2017; Geng et al. 2017, Altmannshofer et al. 2017, …

Clean SM prediction

Perfectly compatible with the observed deviations in

- Differential distributions in $B \to K^* \mu^+ \mu^-$
- Branching ratios of $b \to s\, \mu^+ \mu^-$ transitions

4 - 5 σ deviation in global fits

~ 20% below the **small** SM amplitude

When R(K$^{(*)}$) is included, all fitting groups agree.

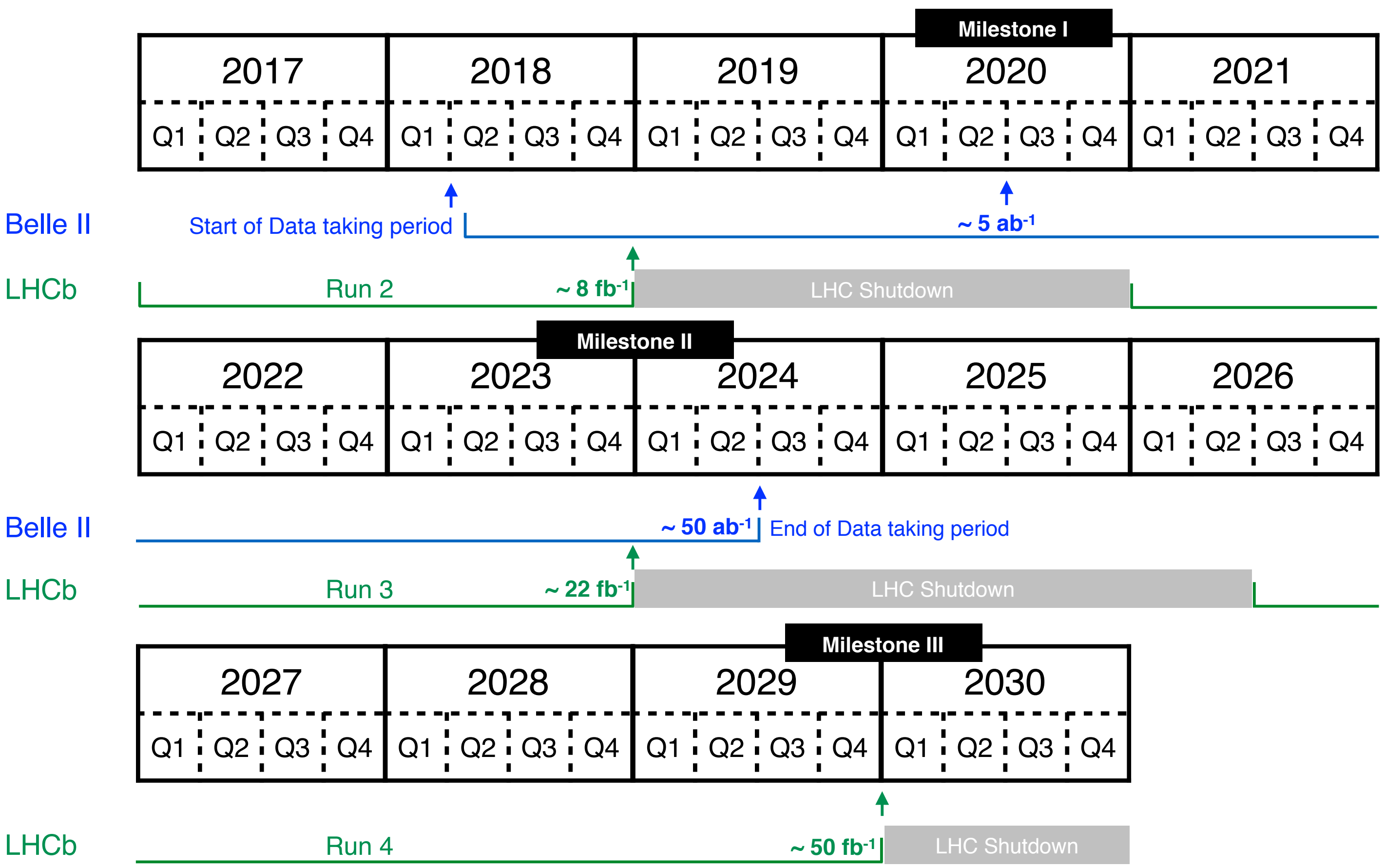
who	C_9^μ shift	C_{10}^μ shift	pull	details
AS+	−1.15	+0.28	"very high"	$b \to s\mu\mu$ + LFU
CJ+	−1.15	+0.28	4.17σ	no $B_s \to \phi\mu\mu$
DGMV+	−1.01	+0.29	5.7σ	
HM+	−1.08	+0.08	5.48σ	
Rome	−1.16	+0.26	$3 \ldots 4\sigma$	from PDD C_9–C_{10} fit

from Van Dyke's talk at CKM 2018

Future Prospects

Albrecht et al 1709.10308

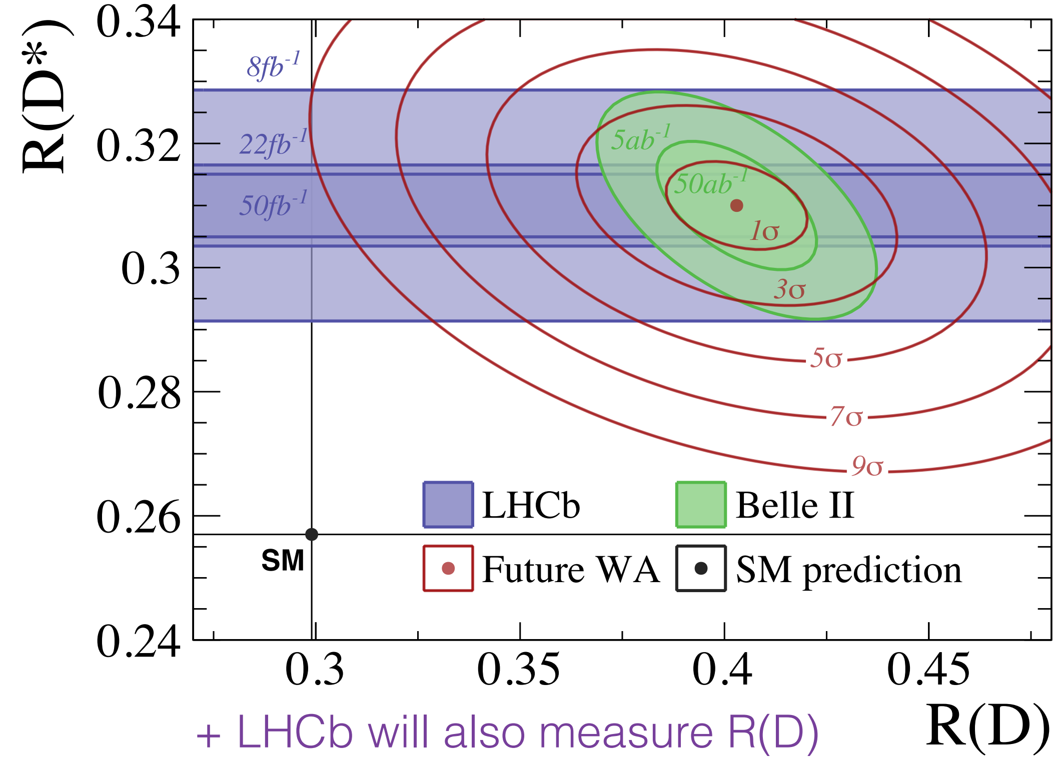
Experimental Timeline



+ very precise measurements on many other related observables.

In just a few years we will know if these are genuine NP signals or not.

Charged-current



+ LHCb will also measure R(D)

Neutral-current

Assuming present central value, LHCb will measure R(K) and R(K*)
at >5σ by Milestone I (2020),
~15σ at Milestone III (2030).

Also Belle-II will reach 7-8σ by Milestone II (2025).

Who ordered THAT??

New Physics effects in rare decays was expected,
NOT in tree-level decays…

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NOT in tree-level decays…

History shows that often discoveries come
as unexpected surprises

Michelson Morley (1887):	→	Einstein's Special Relativity
Black-body, photoelectric effect (end 1800s - 1920s)	→	QM. Einstein: "God doesn't play dice"
Universe expansion (1929):	→	The Universe was thought as static [Einstein 1917]
Muon discovery (1936):	→	Rabi: "Who ordered that?"
Galaxy rotation curves (1933):	→	Dark Matter
Accelerated expansion of the Universe (1998)	→	Dark Energy
Beyond the SM physics (?)	→	???

THE SKEPTICS' GUIDE

Difficult to rely only on statistical fluctuations, given the **large significance**.

To avoid new physics in any of these observables one needs:

- an unknown experimental systematic entering in R(D) and R(D*),
- an unknown experimental systematic in R(K) and R(K*),
- non-perturbative QCD effects to explain the deviations in P_5' and Br,
- the size of QCD and systematic effects should exactly coincide.

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- the size of QCD and systematic effects should exactly coincide.

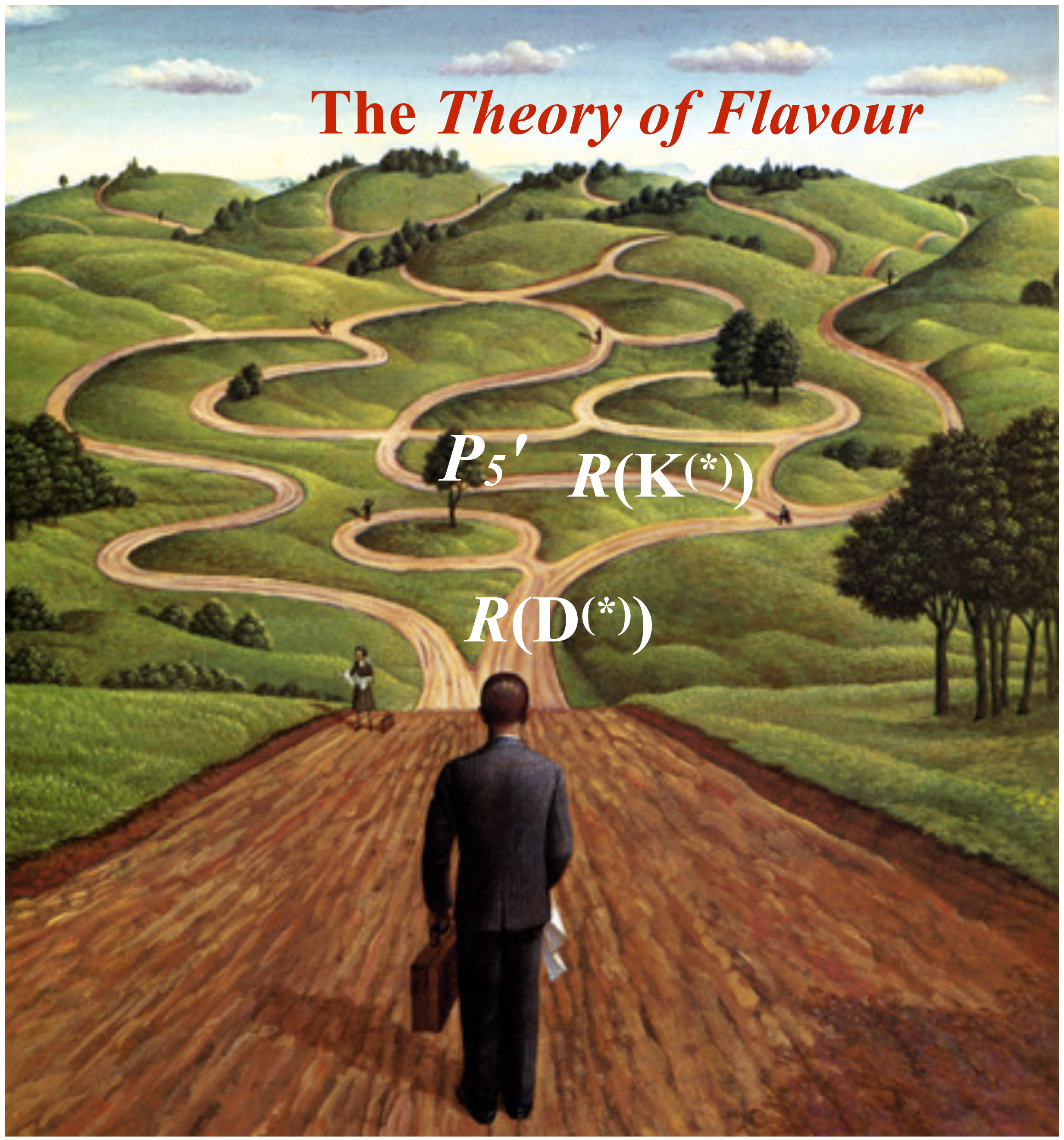
Or wait patiently for a couple of years…

More data will help in solving these issues, for example measuring a differential LFU ratio in $R(P_5')(q^2)$, measuring LFU ratios in charged-currents in other systems ($\Lambda_b \to \Lambda_c\ \tau\ (\mu)\ \nu$, ecc..), angular observables in $B \to D^{(*)}\tau\nu$…

… but what if it's genuine?

A physicist's job is to explain experimental results with some model,
keeping into account all present constraints,
and derive predictions for other observables which can test it.

Bottom-up approach to model building



UV completions

↑

Simplified Models

↑

EFT

↑

Data

Best BSM low-energy interpretation

Neutral-current

$$\boldsymbol{b \to s\, \mu^+ \mu^-}$$

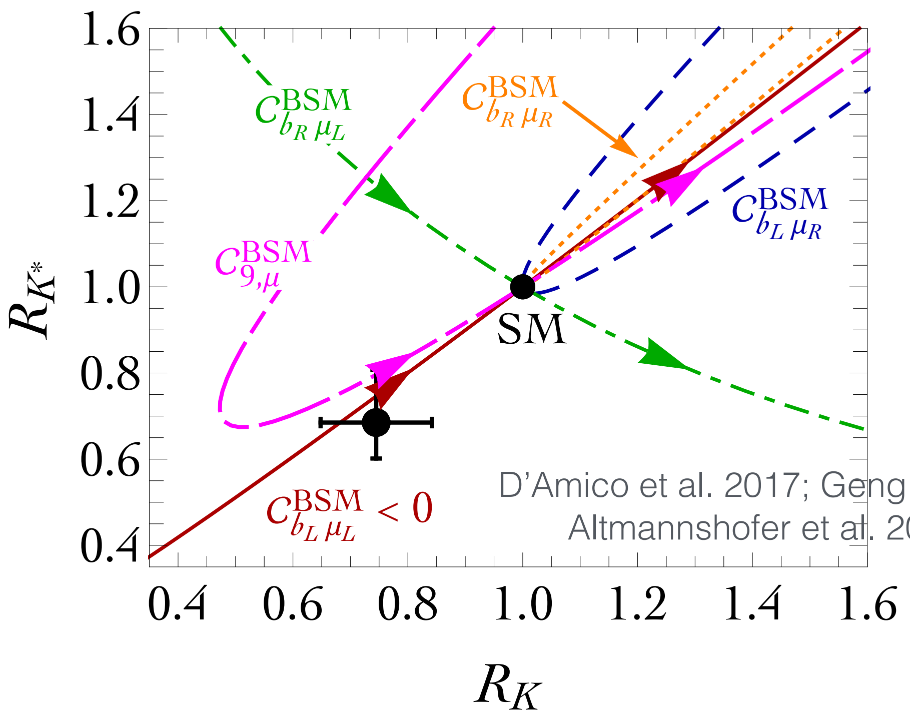
$$\mathcal{L} \supset \frac{c_i}{\Lambda^2}(\bar{s}_L \gamma^\alpha b_L)(\bar{\mu}_L \gamma_\alpha \mu_L) + h.c.$$

where

$c_i = 1 \quad \longrightarrow \quad \Lambda \sim 32$ TeV

$c_i = \mathrm{V_{ts}} \quad \longrightarrow \quad \Lambda \sim$ **6 TeV**

… and so on



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… and so on

Charged-current $b \longrightarrow c\, \tau + (\text{missing E})$

Freytsis et al. 2015, Angelescu et al. 1808.08179

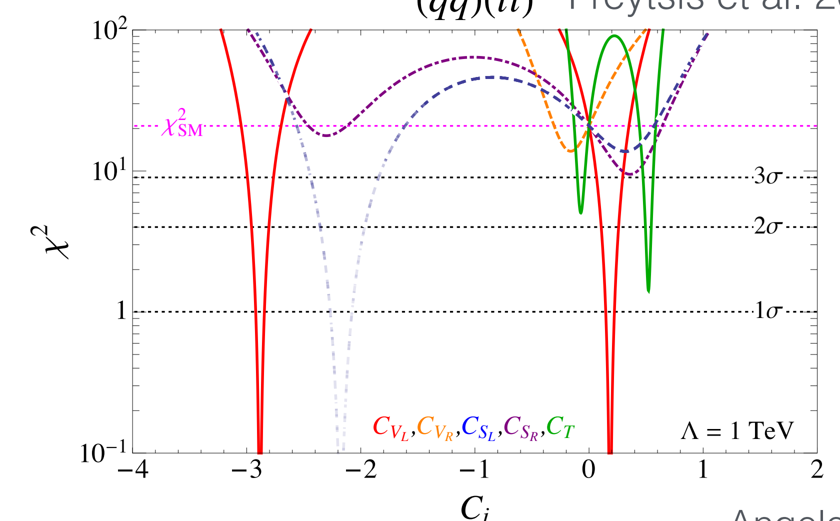
1) LH currents

$$\mathcal{L}_{\text{BSM}} = \frac{2c}{\Lambda^2}(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau) + h.c.$$

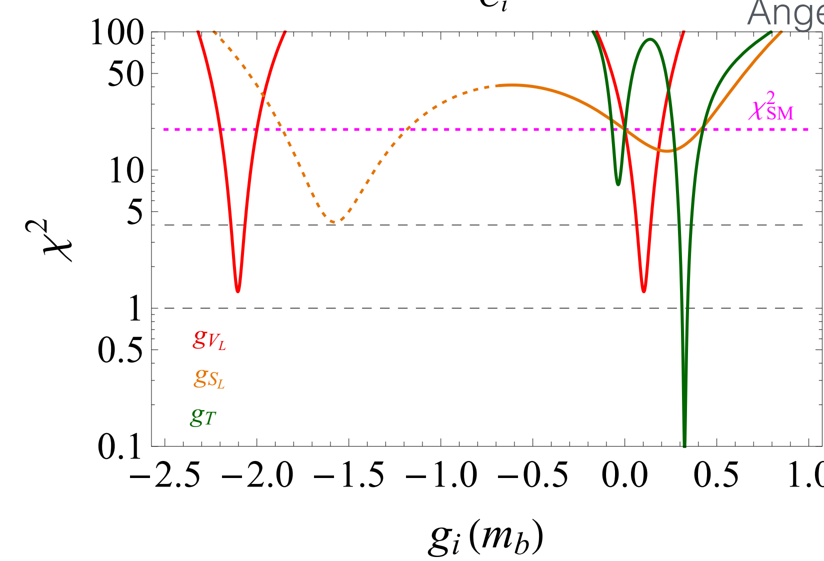
if $c_i = 1 \longrightarrow \Lambda \sim 3.7\ \text{TeV}$

$c_i = \text{V}_{\text{cb}} \longrightarrow \Lambda \sim \mathbf{0.7\ TeV}$

$(\bar{q}q)(\bar{l}l)$ Freytsis et al. 2015



Angelescu, Becirevic, et al. 1808.08179



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Charged-current

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if $c_i = 1 \quad \rightarrow \quad \Lambda \sim 3.7$ TeV

$c_i = V_{cb} \quad \rightarrow \quad \Lambda \sim$ **0.7 TeV**

2) Tensor + Scalar solution

A good fit can also be obtained with this setup:

$$\mathcal{L}_{\rm eff} = -2\sqrt{2}G_F V_{ud}\Big[\, g_{S_L}(\mu)\,(\overline{u}_R d_L)(\overline{\ell}_R\nu_L) + g_T(\mu)\,(\overline{u}_R\sigma_{\mu\nu}d_L)(\overline{\ell}_R\sigma^{\mu\nu}\nu_L)\Big]$$

$$g_{S_L} = 4\, g_T$$

Angelescu, Becirevic, et al. 1808.08179

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… and so on

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Freytsis et al. 2015, Angelescu et al. 1808.08179

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Angelescu, Becirevic, et al. 1808.08179

3) RH currents & New RH sterile neutrino

mass below ~ 100 MeV

$$\mathcal{L}^{b\to c\tau\nu}_{BSM} = \frac{c_{R_D}}{\Lambda^2}\,(\bar{c}_R \gamma_\mu b_R)\,(\bar{\tau}_R \gamma^\mu N_R) + h.c.$$

if $c_i = 1 \quad \to \quad \Lambda \sim 1.3$ TeV

Asadi et al. 1804.04135, Greljo et al. 1804.04642,
Robinson et al. 1807.04753
Azatov, Barducci, Gosh, D.M., Ubaldi 1807.10745

Why a combined explanation?

R(K^(*)) → $\sim \frac{g_\mu V_{ts}}{\Lambda^2}(\bar{b}_L \gamma_\alpha s_L)(\bar{\mu}_L \gamma^\alpha \mu_L)$

$\Lambda/\sqrt{g_\mu} \sim$ **6 TeV**

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SM gauge invariance $SU(2)_L$

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

Usually UV physics generates both.

A Z' model can generate only the singlet, but such a solution is already in strong tension with B_s-mixing (tree-level).

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$\sim \frac{g_\mu V_{cb}}{\Lambda^2} (\bar{b}_L \gamma_\alpha c_L)(\bar{\nu}^\mu_L \gamma^\alpha \mu_L)$ Charged-current in muons

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U(2)^q

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Charged-current in muons

Generalising lepton flavour

$$\sim \frac{g_\tau V_{cb}}{\Lambda^2}(\bar{b}_L\gamma_\alpha c_L)(\bar{\nu}^\tau_L\gamma^\alpha\tau_L)$$

Why a combined explanation?

R(K$^{(*)}$) → $\sim \frac{g_\mu V_{ts}}{\Lambda^2}(\bar{b}_L\gamma_\alpha s_L)(\bar{\mu}_L\gamma^\alpha \mu_L)$

$\Lambda/\sqrt{g_\mu} \sim$ **6 TeV**

U(2)^q

SM gauge invariance SU(2)$_L$

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

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Charged-current in muons

Generalising lepton flavour

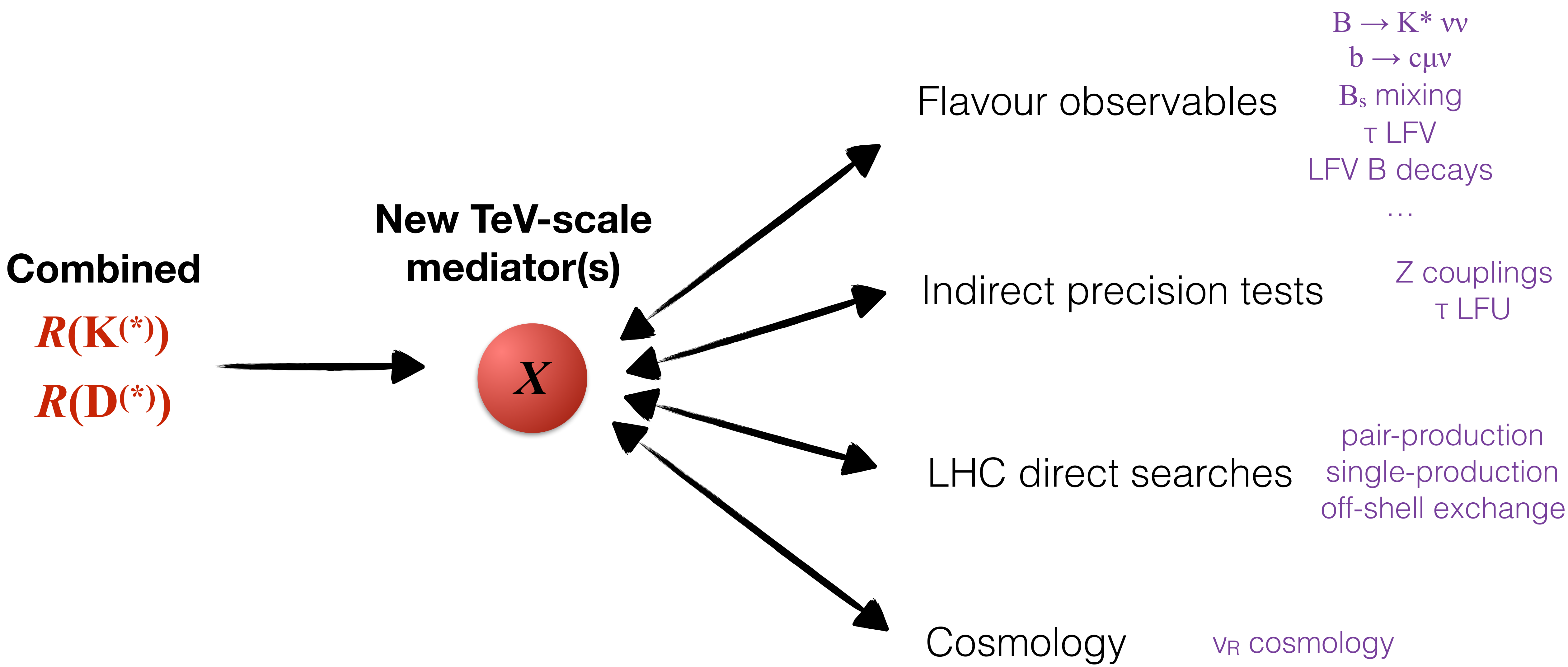
R(D$^{(*)}$) ← $\sim \frac{g_\tau V_{cb}}{\Lambda^2}(\bar{b}_L\gamma_\alpha c_L)(\bar{\nu}^\tau_L\gamma^\alpha \tau_L)$

$\Lambda/\sqrt{g_\tau} \sim$ **0.7 TeV**

$g_\mu \sim 10^{-2}\, g_\tau$ e.g. U(2)$^\ell$

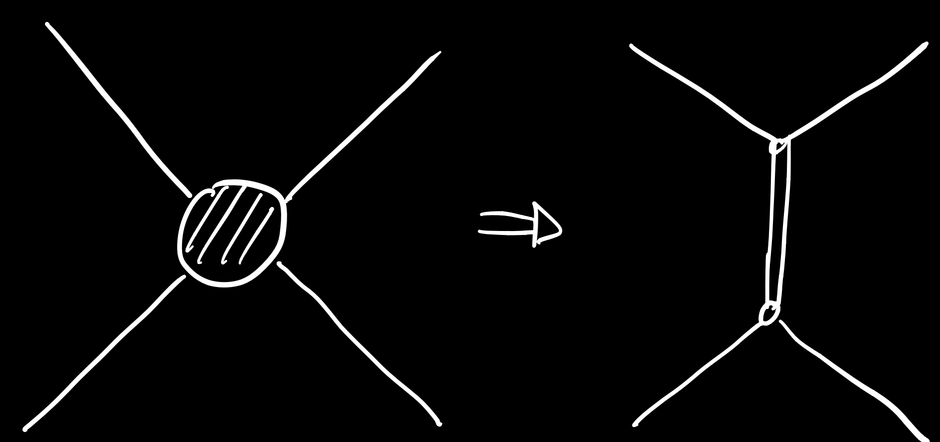
The LH solutions is natural for a combined explanation.

Is there a successful candidate?



A realistic New Physics interpretation must be compatible with all present limits from both low-energy and high-energy observables.
Crucial to consider both at the same time.

SM EFT
&
Simplified Models



Combined Fit of B anomalies (LH)

Buttazzo, Greljo, Isidori, DM 1706.07808

Adding SM SU(2)$_L$ gauge invariance:

$$\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

triplet operator *singlet operator*

	Observable	Experimental bound	Linearised expression
Anomalies	$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
	$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
Flavour	$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$
	$B_{K^{(*)}\nu\bar{\nu}}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}C^{\rm SM}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
Z couplings	$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T - 0.043C_S$
	$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T - 0.043C_S$
τ LFU	$\lvert g^W_\tau/g^W_\ell\rvert$	1.00097 ± 0.00098	$1 - 0.084C_T$
τ LFV	$\mathcal{B}(\tau\to 3\mu)$	$(0.0 \pm 0.6)\times 10^{-8}$	$2.5\times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\tau\mu})^2$

Combined Fit of B anomalies (LH)

Buttazzo, Greljo, Isidori, DM 1706.07808

Adding SM $SU(2)_L$ gauge invariance:

$$\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

triplet operator *singlet operator*

Flavour Structure:

$$\lambda^q \sim \begin{pmatrix} 0 & 0 & \lambda_{bs}\frac{V_{ub}}{V_{cd}} \\ 0 & \lambda_{ss} & \lambda_{bs} \\ \lambda_{bs}\frac{V_{ub}}{V_{cd}} & \lambda_{bs} & 1 \end{pmatrix} \qquad \lambda_{bs} \sim O(V_{ts}) \quad \lambda_{ss} \sim O(\lambda_{bs}^2)$$

$$\lambda^\ell \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{\mu\mu} & \lambda_{\tau\mu} \\ 0 & \lambda_{\tau\mu} & 1 \end{pmatrix} \qquad \lambda_{\mu\mu} \sim O(\lambda_{\tau\mu}^2)$$

Very good fit!

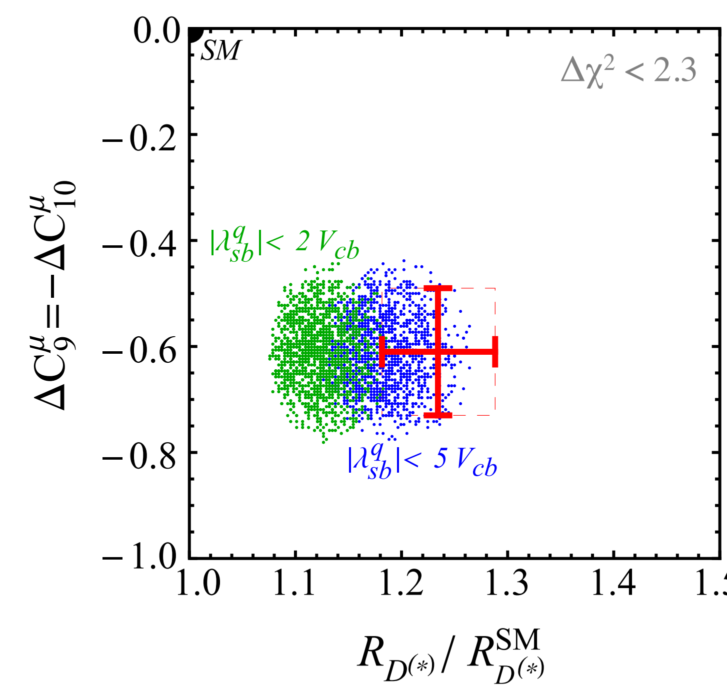
These values are compatible with a minimally-broken **$SU(2)_q \times SU(2)_\ell$** flavour symmetry

$C_T \sim C_S \sim 0.02$

$\lambda^q_{bs} \gtrsim 3 V_{ts}$

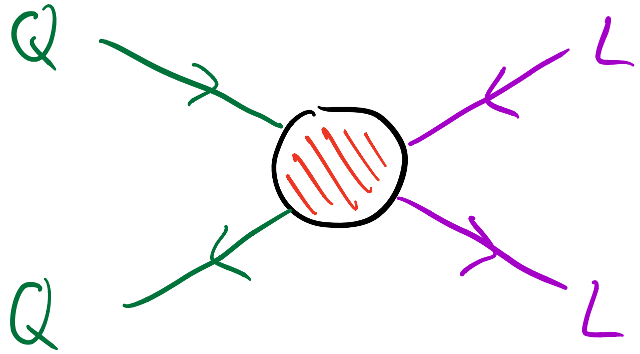
$\lambda^\ell_{\mu\mu} \sim 10^{-2}$

$\lambda^\ell_{\tau\mu} \sim 10^{-1}$



Small $C_{T,S}$ to evade EWPT,
Large b-s coupling to fit $R(D^{(*)})$,
$C_T \sim C_S$ to evade $R_{\nu\nu}$.

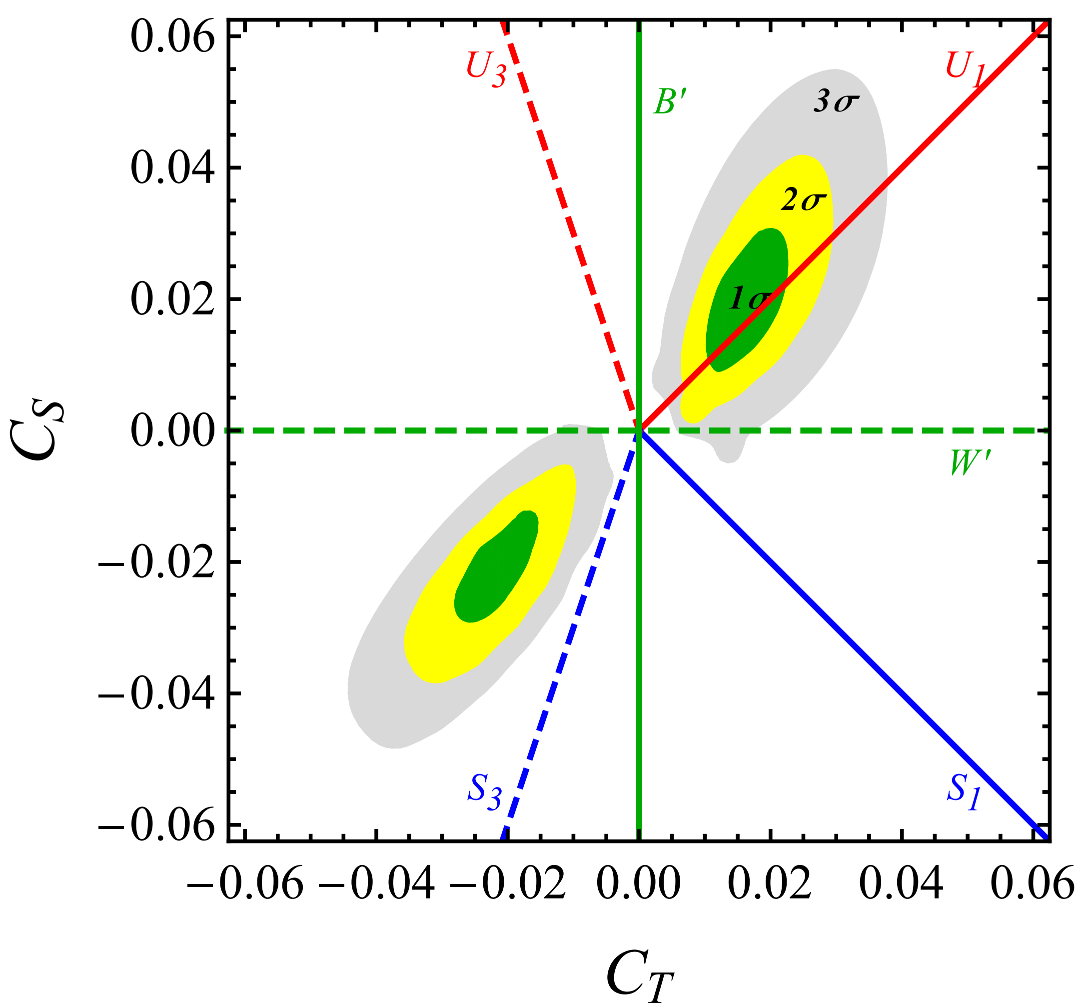
Simplified Models



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

Let us assume the operators are generated at the tree-level by some TeV-scale mediator.

$$C_T \sim g_X^2 \frac{v^2}{M_X^2} \xrightarrow{C_T \sim 0.02} \boxed{M_X \sim 1.7\ \text{TeV}\ \ (\text{for } g_X \sim 1)}$$



Colorless vectors

~~W' = (**1**, **3**, 0),~~
~~B' = (**1**, **1**, 0),~~

Vector Leptoquarks

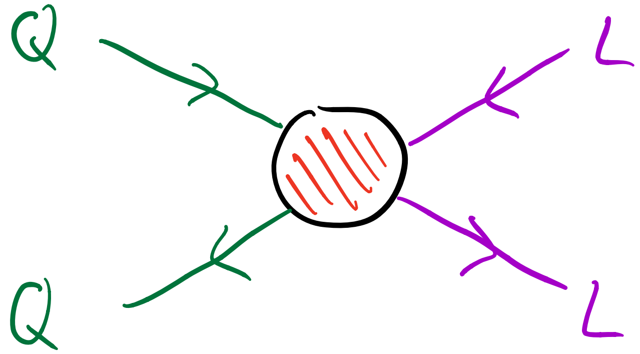
U_1 = (**3**, **1**, 2/3),
~~U_3 = (**3**, **3**, 2/3),~~

Scalar Leptoquarks

S_1 = (**$\bar{3}$**, **1**, 1/3),
S_3 = (**$\bar{3}$**, **3**, 1/3),

Buttazzo, Greljo, Isidori, D.M. 1706.07808

Simplified Models



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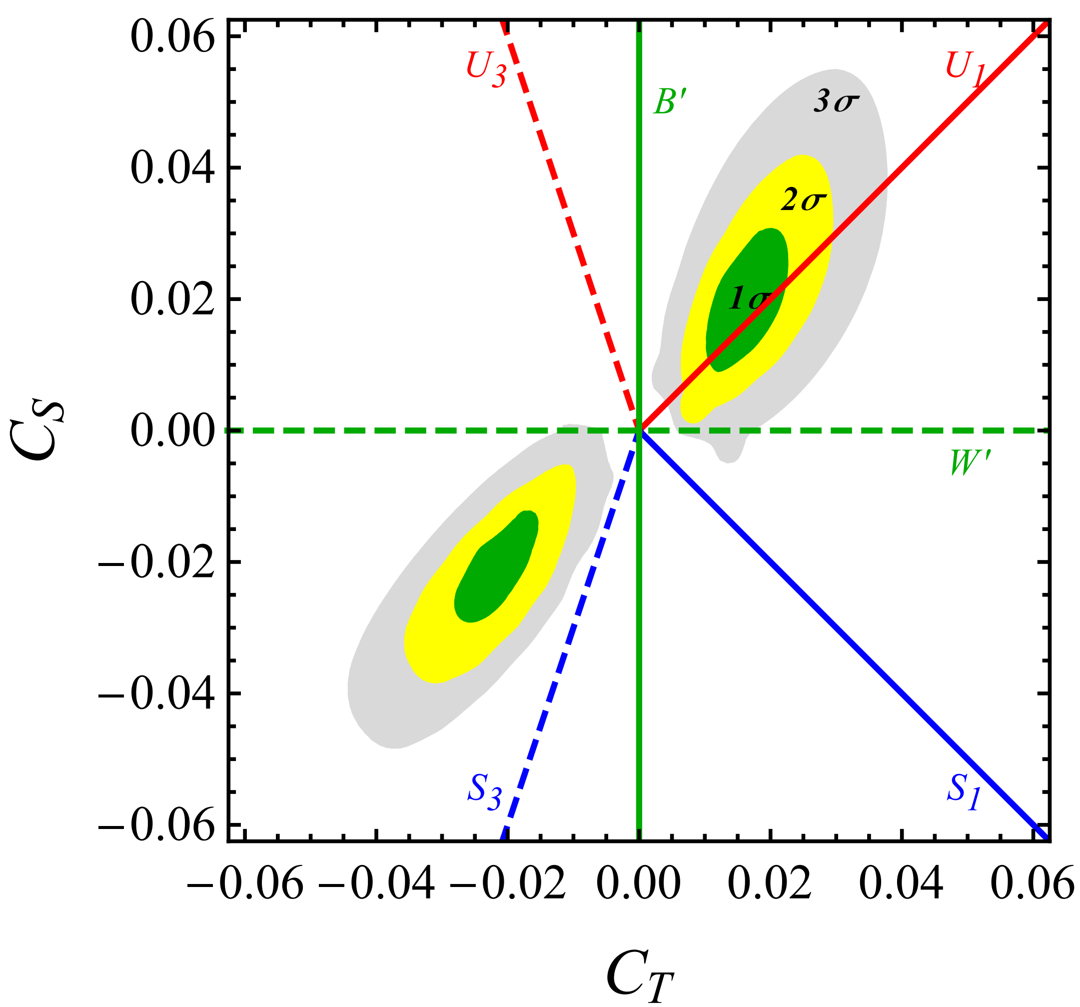
$M_X \sim$ 1.7 TeV (for $g_X \sim 1$)



Buttazzo, Greljo, Isidori, D.M. 1706.07808

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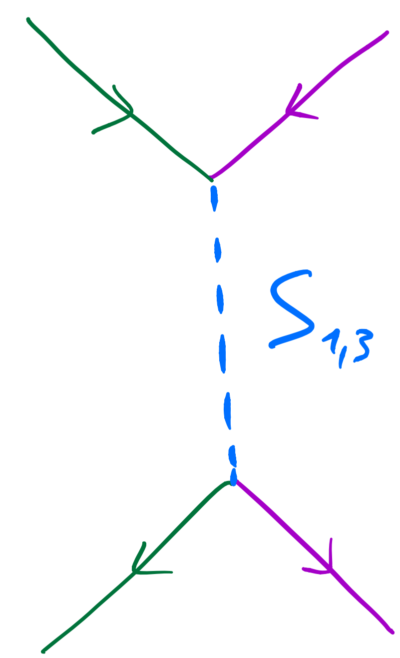

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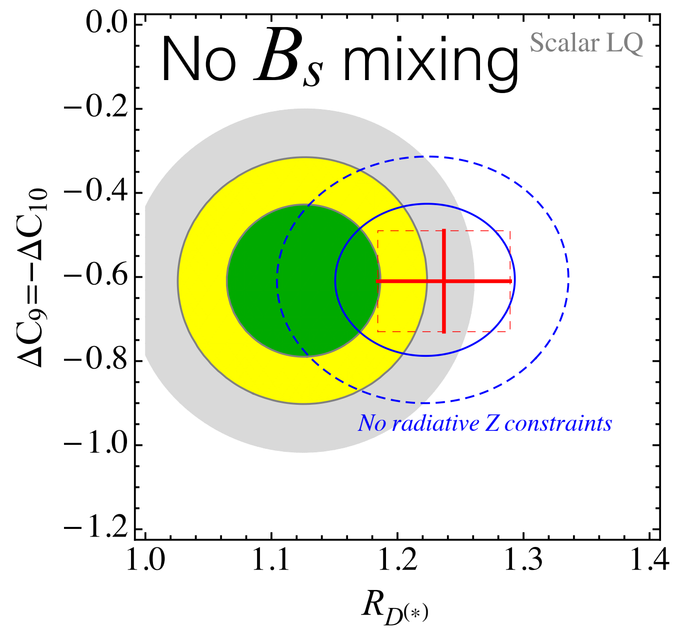
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

$$\mathcal{L} \supset g_1 \beta_{1\,i\alpha} (\bar{Q}_L^{c\,i} \epsilon L_L^\alpha) S_1 + g_3 \beta_{3\,i\alpha} (\bar{Q}_L^{c\,i} \epsilon \sigma^a L_L^\alpha) S_3^a + \text{h.c.}$$

The desired operator structure is reproduced, but:

→ Some residual tension at the ~1.5σ level remains between $Z\tau\tau$ and $R(D^{(*)})$



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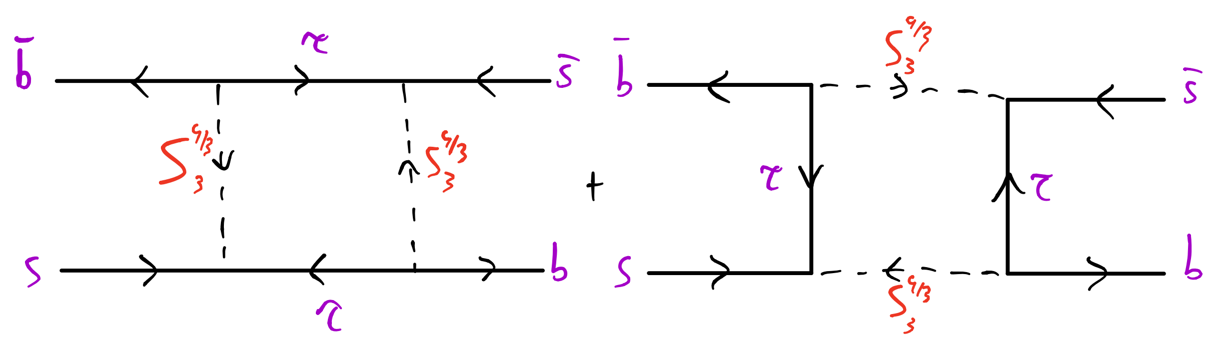
The desired operator structure is reproduced, but:

→ Some residual tension at the ~1.5σ level remains between $Z\tau\tau$ and $R(D^{(*)})$

→ B_s-mixing is calculable but in tension with $R(D^{(*)})$:

D.M. 1803.10972

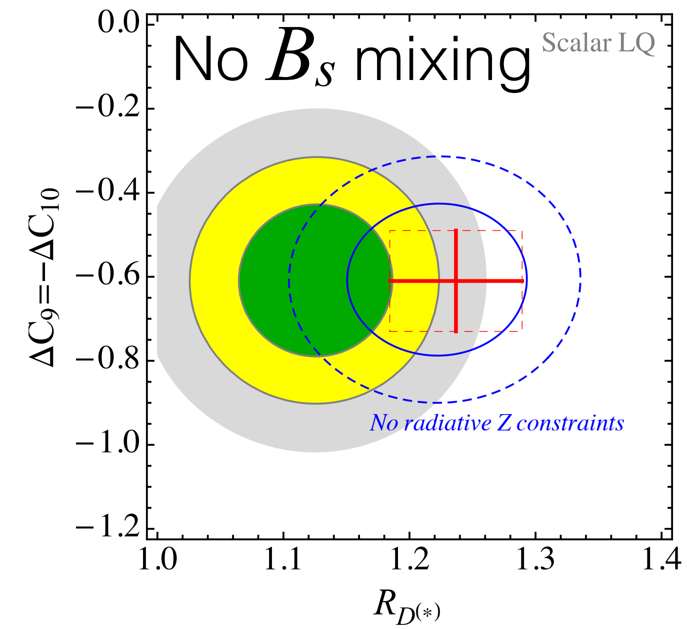
e.g.

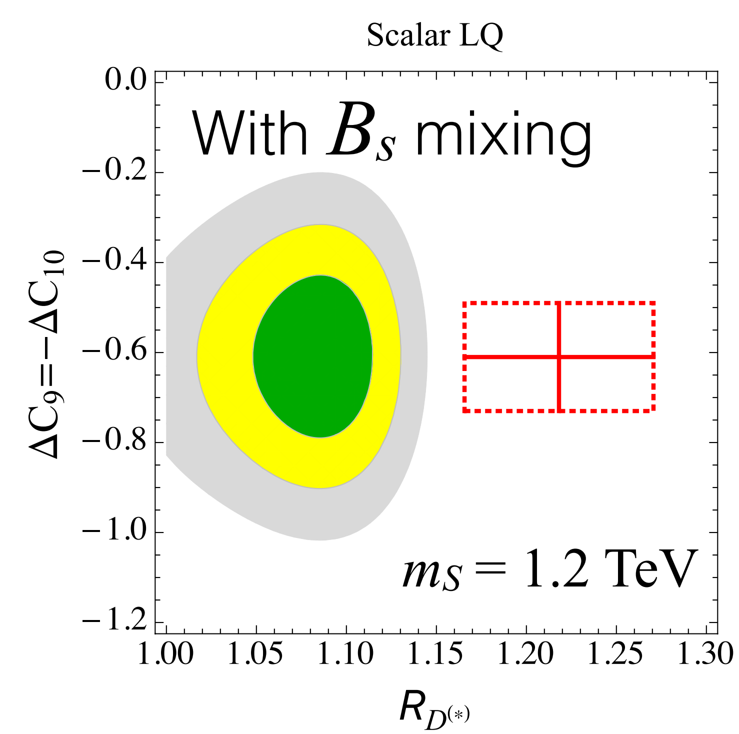


$$\frac{(\Delta M_{B_s})^{S_1+S_3}}{(\Delta M_{B_s})^{\rm SM}} \approx 0.74 \left(\frac{m_{S_{1,3}}}{1\ \text{TeV}}\right)^2 \left(\frac{R_{D^{(*)}}/R_{D^{(*)}}^{\rm SM} - 1}{0.23}\right)^2 \lesssim 10\%$$

At face values, allows only $\Delta R_D \sim 10\%$ instead of ~23%.

To completely fit the anomaly requires a tuning with some extra contributions at the ~10% level.





Scalar Leptoquarks

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

$$-g_1 \beta_{1,i\alpha} (\bar{q}_L^{c\,i} \epsilon l_L^\alpha) S_1 - g_1^u (\beta_1^u)^T_{\alpha i} (\bar{e}_R^{c\,\alpha} u_R^i) S_1 - g_3 \beta_{3,i\alpha} (\bar{q}_L^{c\,i} \epsilon \sigma^A l_L^\alpha) S_3^A + \text{h.c.}$$

All these tensions can be completely removed simply by allowing a coupling of S_1 to RH currents: $S_1 \, c_R \, \tau_R$.

This generates a further contribution to $R(D^{(*)})$ via scalar + tensor operators, uncorrelated with electroweak precision tests or B_s-mixing.

$$\mathcal{O}_{V_L}^\tau = (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau)\,, \quad \mathcal{O}_T^\tau = (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_\tau)\,, \quad \mathcal{O}_{S_L}^\tau = (\bar{c}_R b_L)(\bar{\tau}_R \nu_\tau)$$

$S_1 + S_3$ S_1 $c_{SL} = -4\, c_T$ S_1

D.M. in progress

Scalar Leptoquarks

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

$$-g_1\beta_{1,i\alpha}(\bar{q}_L^{c\,i}\epsilon l_L^\alpha)S_1 - g_1^u(\beta_1^u)^T_{\alpha i}(\bar{e}_R^{c\,\alpha}u_R^i)S_1 - g_3\beta_{3,i\alpha}(\bar{q}_L^{c\,i}\epsilon\sigma^A l_L^\alpha)S_3^A + \text{h.c.}$$

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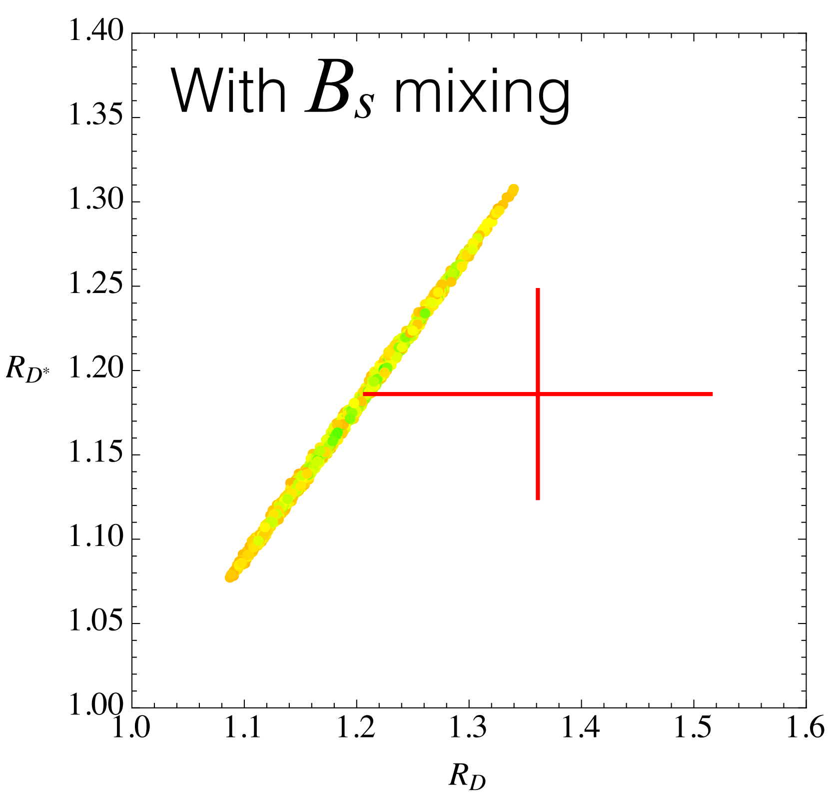
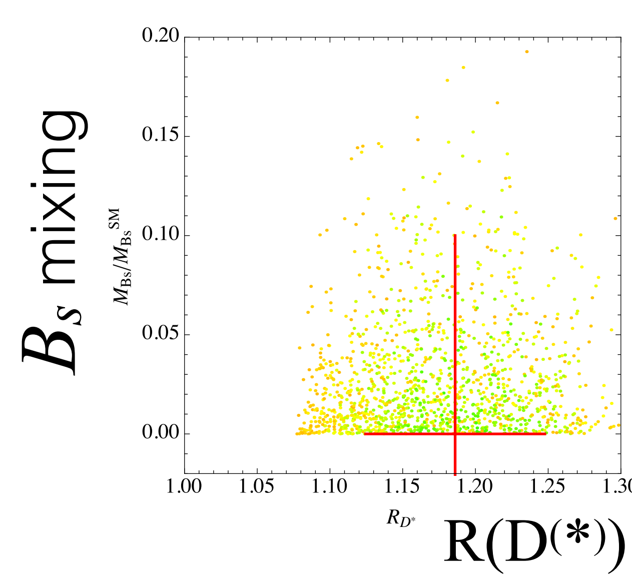
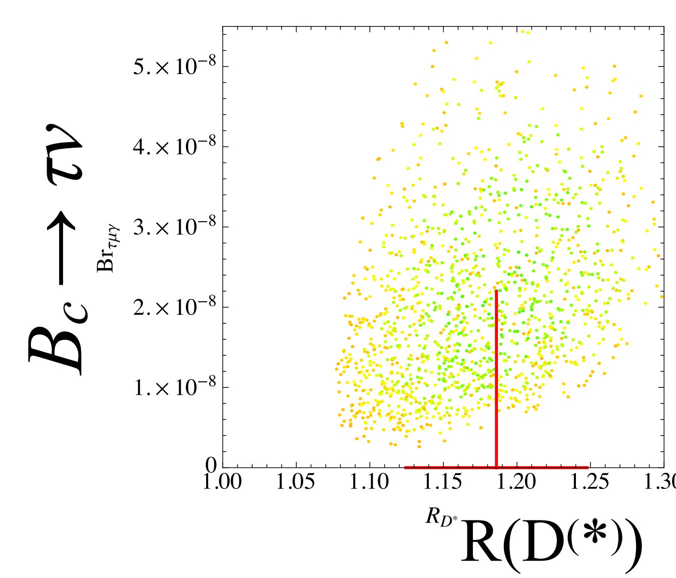
$S_1 + S_3$ $\qquad$ S_1 $\quad$ $c_{SL} = -4\, c_T$ $\quad$ S_1



The fit to $R(D^{(*)})$ is now greatly improved, being able to reproduce with no problem the best-fit value of $R(D) = R(D^*)$ D.M. in progress





Direct Searches

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
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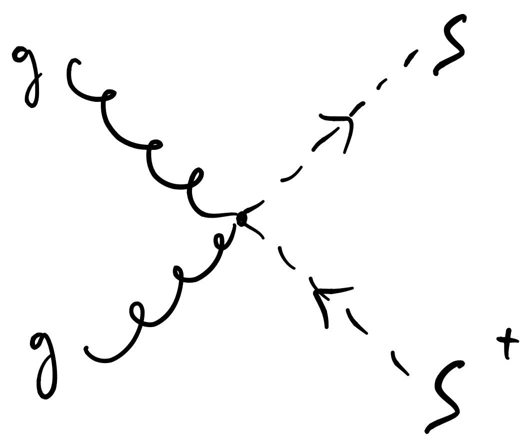
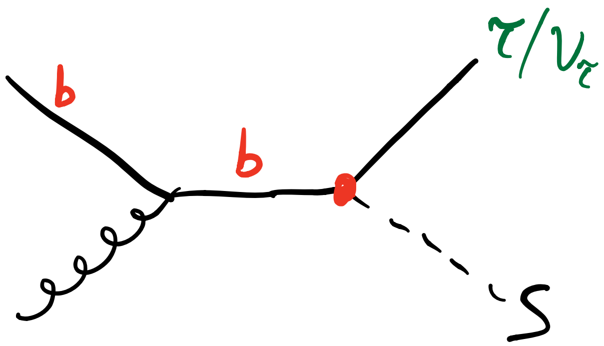
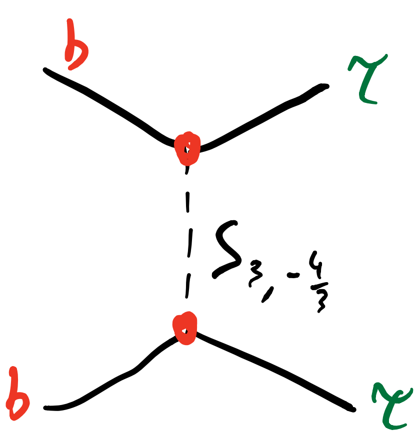
QCD pair production

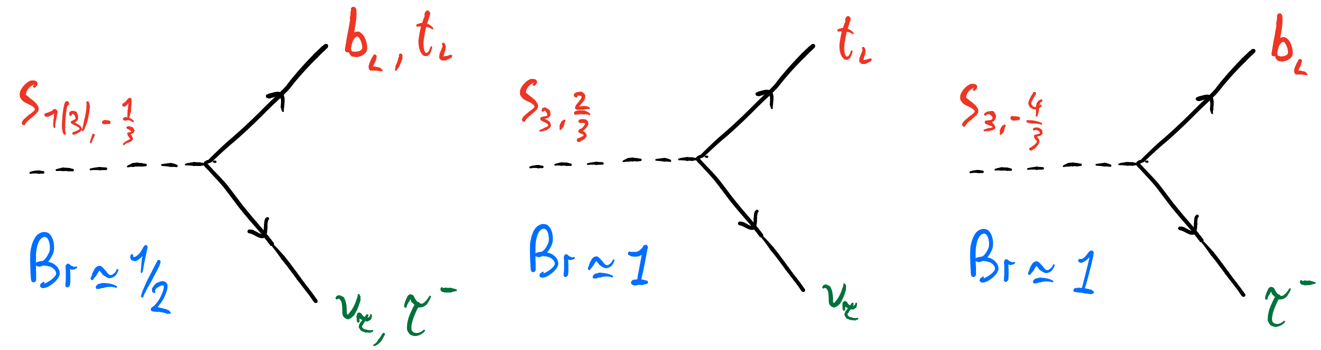


single production

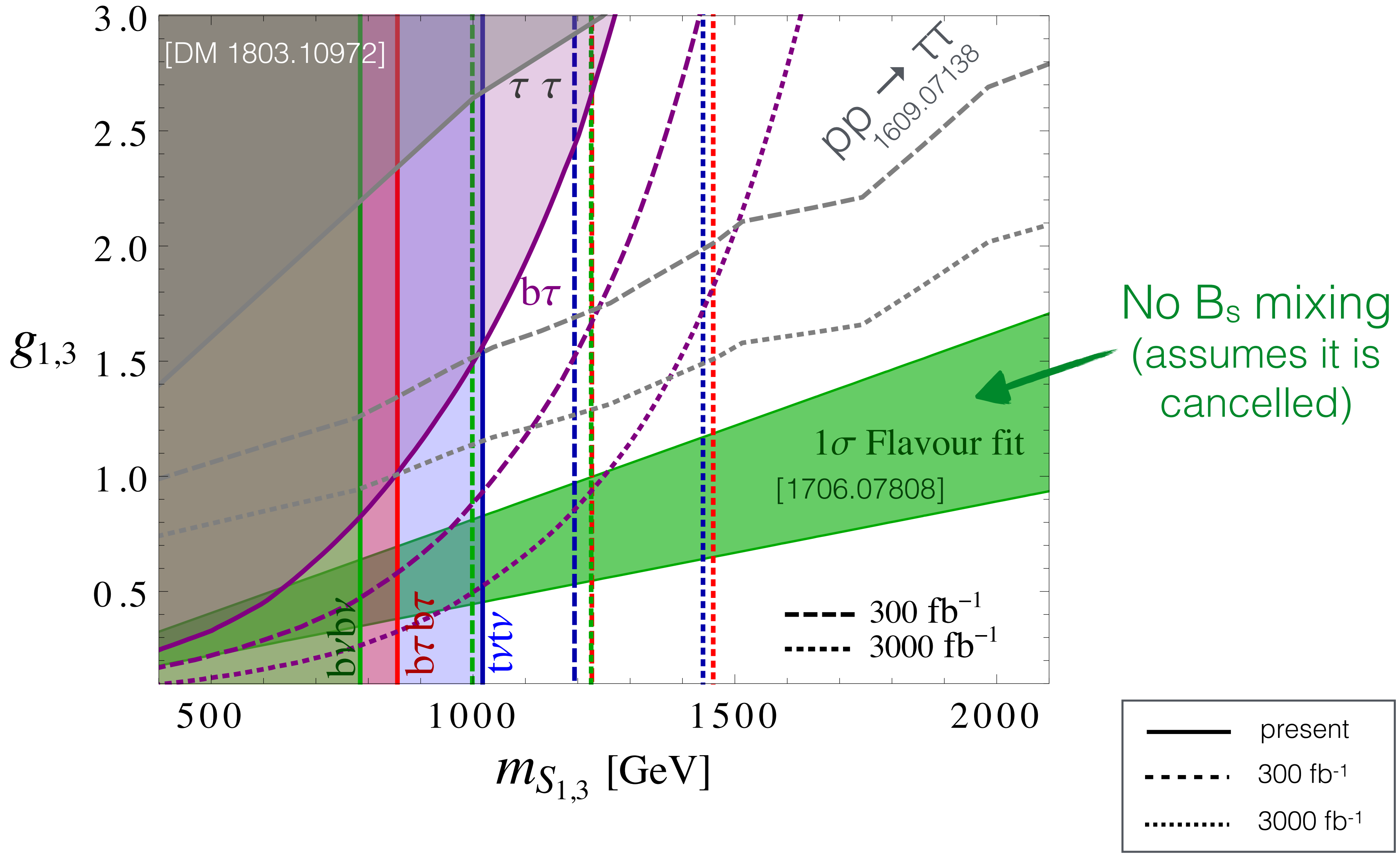


off-shell

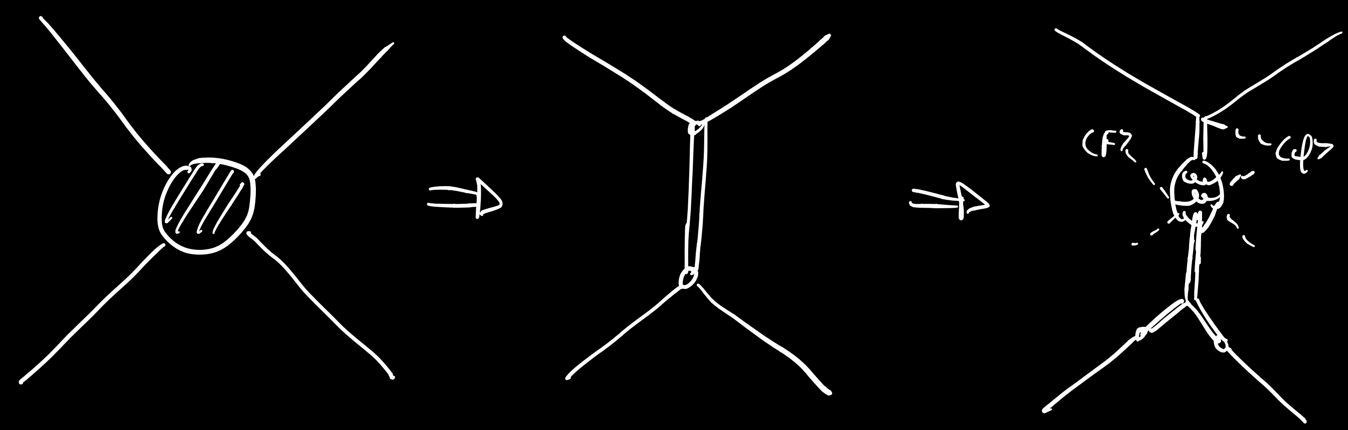




tools: Dorsner, Greljo 1801.07641



UV-completion



Extrapolating from B-anomalies

The starting point is given by the two observed deviations and the collection set of low- and high-energy constraints

$b \longrightarrow s\, \mu^{+} \mu^{-}$

$b \longrightarrow c\, \tau\, \nu$

↓

Preferred mediators (simplified models)

Extrapolating from B-anomalies

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Preferred mediators (simplified models)

↓

UV completion

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$b \longrightarrow s\, \mu^+ \mu^-$

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↓

Preferred mediators (simplified models)

↓

UV completion

In the absence of other experimental hints (high-p_T), one needs other criteria to build a UV model: connection to other problems of the SM

Hierarchy | **Flavour** | **Unification** | **Dark Matter** | **Renorm.**

(of course, not a SM problem, just a requirement for UV)

Connection with the Higgs

M_{LQ} ~ TeV & **$M_{BSM\text{-}Higgs\ hierarchy\ problem}$ ~ TeV**

Is it an accident or is there a connection?

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Two broad possibilities to build a “Natural” model

Elementary:
SUSY

These mediators do not arise in the MSSM.
Need much more complicated setups.

Compositeness:
Composite Higgs

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Compositeness:
Composite Higgs

- Scalar LQ as Goldstone bosons

  Gripaios, Nardecchia, Renner 2014; Buttazzo, Greljo, Isidori, D.M. 2017; D.M. 2018

- Composite Vector LQ

  Barbieri, Isidori, Pattori, Senia 2015; Barbieri, Murphy, Senia 2016; Buttazzo, Greljo, Isidori, D.M. 2017; Barbieri, Tesi 2017

- Composite W', Z' resonances

  Buttazzo, Greljo, Isidori, D.M. 2016, Megias, Quiros, Salas, Panico [in 5D] 2017

Connection with the Higgs

M_{LQ} ~ TeV & **$M_{\text{BSM-Higgs hierarchy problem}}$ ~ TeV**

Is it an accident or is there a connection?

Two broad possibilities to build a “Natural” model

Elementary:
SUSY

These mediators do not arise in the MSSM.
Need much more complicated setups.

If we forget about naturalness:

- Elementary scalar LQ

  Becirevic et al 2016,2018; Dorsner et al 2017; Crivellin, Muller, Ota 2017; …

- Elementary LQ gauge boson

  Di Luzio, Greljo, Nardecchia 2017; Calibbi, Crivellin, Li 2017; Bordone, Cornella, Fuentes-Martin, Isidori 2017

- Elementary W’, Z’ gauge bosons

  Cline, Camalich 2017

Compositeness:
Composite Higgs

- Scalar LQ as Goldstone bosons

  Gripaios, Nardecchia, Renner 2014; Buttazzo, Greljo, Isidori, D.M. 2017; D.M. 2018

- Composite Vector LQ

  Barbieri, Isidori, Pattori, Senia 2015; Barbieri, Murphy, Senia 2016; Buttazzo, Greljo, Isidori, D.M. 2017; Barbieri, Tesi 2017

- Composite W’, Z’ resonances

  Buttazzo, Greljo, Isidori, D.M. 2016, Megias, Quiros, Salas, Panico [in 5D] 2017

Scalar LQ as pseudo-Goldstones

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1)

M_{LQ} ~ TeV & **$M_{\text{BSM-Higgs hierarchy problem}}$ ~ TeV**

Is it an accident or is there a connection?

In Composite Higgs models (Higgs as pseudo-Goldstone) coloured resonances are also expected since $SU(3)_c$ is (at least) a global symmetry.

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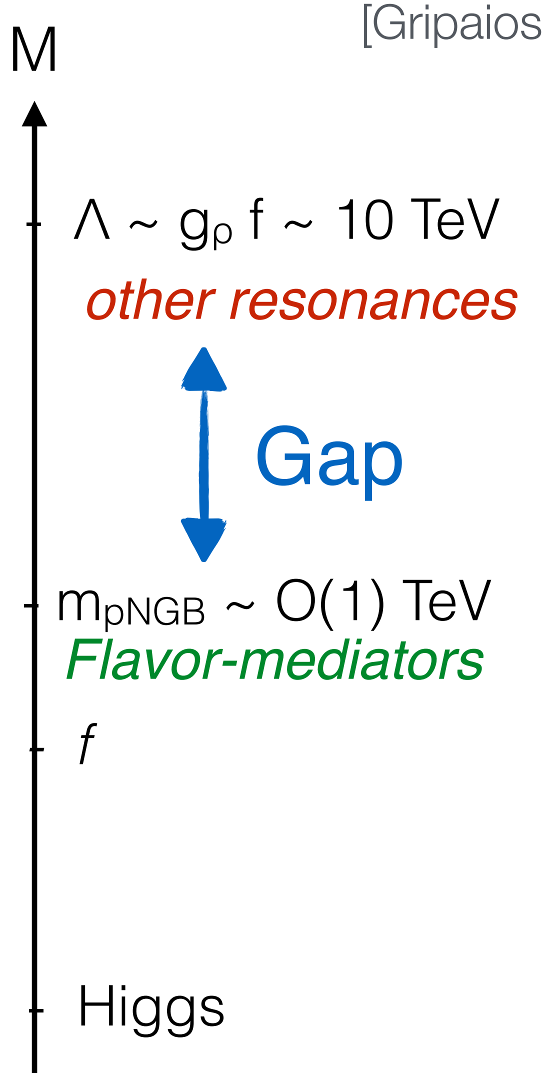

2) If the strong sector undergoes a spontaneous symmetry breaking, composite scalar pseudo-Goldstone bosons are expected to be the lightest states.

$$m_{SLQ} \ll \Lambda$$

vs. vector LQ, where

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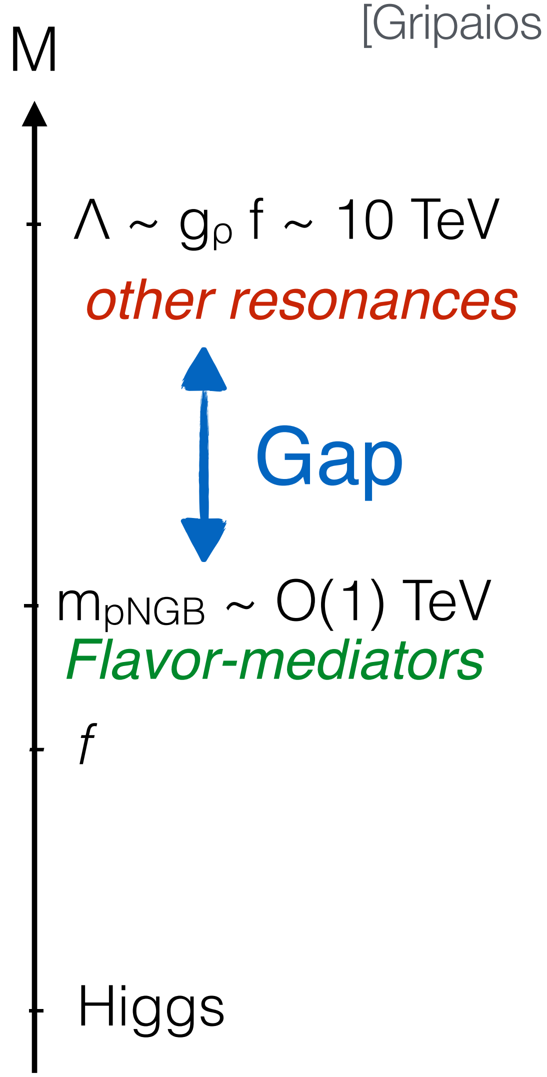

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3) Scalar LQ could be pseudo-Goldstone partners of the Higgs!

→ **Connection with SM flavour!**

Scalar LQ as pseudo-Goldstones in a Composite Higgs Model

D.M. 1803.10972

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Requirements for this model-building attempt:

- Fundamental description of the strong-sector: *vectorlike confinement*
- S_1, S_3, Higgs $\in$ pseudo-Goldstones of the same dynamics
- Custodial symmetry to protect the EW T-parameter
- Look for the “minimal" solution (in N_F of the strong sector)

Fundamental Composite Higgs

Buttazzo, Greljo, Isidori, D.M. 1706.07808; D.M. 1803.10972

Gauge group: $\mathrm{SU}(N_{HC}) \times \mathrm{SU}(3)_c \times \mathrm{SU}(2)_w \times \mathrm{U}(1)_Y$

"HyperColor"

Extra HC Dirac fermions:

	$\mathrm{SU}(N_{HC})$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_w$	$\mathrm{U}(1)_Y$
Ψ_L	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{2}$	Y_L
Ψ_N	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L + 1/2$
Ψ_E	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L - 1/2$
Ψ_Q	$\mathbf{N_{HC}}$	$\mathbf{3}$	$\mathbf{2}$	$Y_L - 1/3$

For similar constructions see:
Shmaltz et al 1006.1356,
Vecchi 1506.00623,
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GUT: can add a complete 'copy' of the SM generations.

QCD-like!!

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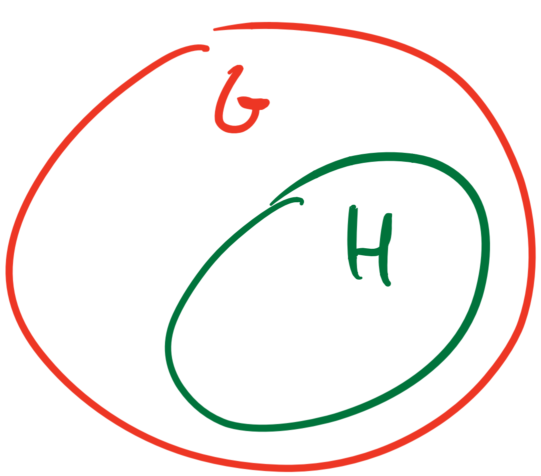
In absence of SM gauging, the strong sector has a global chiral symmetry



$$G = \mathrm{SU}(10)_L \times \mathrm{SU}(10)_R \times \mathrm{U}(1)_V$$

$$\langle \bar{\Psi}_i \Psi_j \rangle = -B_0 f^2 \delta_{ij} \qquad f \sim 1\,\mathrm{TeV}$$

$$H = \mathrm{SU}(10)_V \times \mathrm{U}(1)_V$$

Goldstone Bosons

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Like QCD pions, the pNGB are composite states of HC-fermion bilinears: $\bar{\Psi}\Psi$

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In terms of SM representations

Two Higgs doublets: $H_{1,2} \sim (\mathbf{1},\mathbf{2})_{1/2}$

Singlet and Triplet LQ: $S_1 \sim (\mathbf{3},\mathbf{1})_{-1/3} \;+\; S_3 \sim (\mathbf{3},\mathbf{3})_{-1/3}$

Three singlets: $\eta_{1,2,3} \sim (\mathbf{1},\mathbf{1})_0$

Other electroweak states: $\omega \sim (\mathbf{1},\mathbf{1})_1 \;+\; \Pi_{L,Q} \sim (\mathbf{1},\mathbf{3})_0$

Other coloured states: $R_2 \sim (\mathbf{3},\mathbf{2})_{1/6} \;+\; T_2 \sim (\mathbf{3},\mathbf{2})_{-5/6}$

$\tilde{\pi}_1 \sim (\mathbf{8},\mathbf{1})_0 \;+\; \tilde{\pi}_3 \sim (\mathbf{8},\mathbf{3})_0$

For energies $E \ll \Lambda_{HC}$ the theory is described by a weakly coupled effective chiral Lagrangian.
Structure driven by the symmetries and spurions.

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H and LQ are close partners!!

$$H_1 \sim i\sigma^2 (\bar{\Psi}_L \Psi_N)$$
$$H_2 \sim (\bar{\Psi}_E \Psi_L)$$
$$S_1 \sim (\bar{\Psi}_Q \Psi_L)$$
$$S_3 \sim (\bar{\Psi}_Q \sigma^a \Psi_L)$$

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Yukawas & LQ couplings

Coupling with SM fermions from 4-Fermi operators

$$\mathcal{L}_{4-\mathrm{Fermi}} \sim \frac{c_{\psi\Psi}}{\Lambda_t^2}\bar{\psi}_{\mathrm{SM}}\psi_{\mathrm{SM}}\bar{\Psi}\Psi \quad \xrightarrow{E \lesssim \Lambda_{HC}} \quad \sim y_{\psi\phi}\,\bar{\psi}_{\mathrm{SM}}\psi_{\mathrm{SM}}\,\phi + \ldots$$

$\Lambda_t \gtrsim \Lambda_{HC}$

SM Yukawas + LQ couplings arise from the same UV dynamics

A new sector responsible for these operators is necessary (as Extended Technicolor)

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Scalar operators allowed by gauge-invariance

Higgses Yukawas

$$\left(\bar{q}_L u_R + \bar{d}_R q_L + \bar{e}_R l_L\right)\left(\bar{\Psi}_N \Psi_L\right)$$
$$\left(\bar{q}_L u_R + \bar{d}_R q_L + \bar{e}_R l_L\right)\left(\bar{\Psi}_L \Psi_E\right)$$

S_1 and S_3 couplings

$$\left(\bar{q}_L^c l_L + \bar{e}_R^c u_R\right)\left(\bar{\Psi}_Q \Psi_L\right)$$
$$\left(\bar{q}_L^c \sigma^a l_L\right)\left(\bar{\Psi}_Q \sigma^a \Psi_L\right)$$

S_1 coupling to diquark

$$\left(\bar{q}_L^c q_L + \bar{u}_R^c d_R\right)\left(\bar{\Psi}_L \Psi_Q\right)$$

ω coupling to dilepton

$$\left(\bar{l}_L^c l_L\right)\left(\bar{\Psi}_E \Psi_N\right)$$

$\tilde{R}_2$ coupling

$$\left(\bar{d}_R l_L\right)\left(\bar{\Psi}_E \Psi_Q\right)$$

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S_1 and S_3 couplings

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~~S_1 coupling to diquark $\left(\bar{q}_L^c q_L + \bar{u}_R^c d_R\right)\left(\bar{\Psi}_L \Psi_Q\right)$~~

~~ω coupling to dilepton $\left(\bar{l}_L^c l_L\right)\left(\bar{\Psi}_E \Psi_N\right)$~~

~~$\tilde{R}_2$ coupling $\left(\bar{d}_R l_L\right)\left(\bar{\Psi}_E \Psi_Q\right)$~~

Assuming conservation of this symmetry $F_+ = 3B + L$ so that Yukawas and LQ coupl. allowed all other couplings are forbidden. $F_+(\Psi_L) = F_+(\Psi_N) = F_+(\Psi_E) = F_L\,, \qquad F_+(\Psi_Q) = F_L + 2$

Flavour Structure

$$\mathcal{L}_{\text{4-Fermi}} \supset \frac{c_{\psi\psi}}{\Lambda_t^2}\bar{\psi}_{\text{SM}}\psi_{\text{SM}}\bar{\psi}_{\text{SM}}\psi_{\text{SM}}$$ → Dangerous since $\Lambda_t \sim$ (tens) TeV

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An approximate **SU(2)⁵** flavor symmetry protects from unwanted flavor violation

$$G_F = \mathrm{SU}(2)_q \times \mathrm{SU}(2)_u \times \mathrm{SU}(2)_d \times \mathrm{SU}(2)_l \times \mathrm{SU}(2)_e$$

minimally broken by these spurions:

$$\Delta Y_u = (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1}, \mathbf{1}, \mathbf{1}) \ , \quad \Delta Y_d = (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}}, \mathbf{1}, \mathbf{1}) \ , \quad \Delta Y_e = (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2}, \bar{\mathbf{2}})$$

$$V_q = (\mathbf{2}, \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1}) \ , \qquad V_l = (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2}, \mathbf{1})$$

Flavour Structure

$\mathcal{L}_{\text{4-Fermi}} \supset \frac{c_{\psi\psi}}{\Lambda_t^2} \bar{\psi}_{\text{SM}} \psi_{\text{SM}} \bar{\psi}_{\text{SM}} \psi_{\text{SM}}$ → Dangerous since $\Lambda_t \sim$ (tens) TeV

An approximate **SU(2)^5** flavor symmetry protects from unwanted flavor violation

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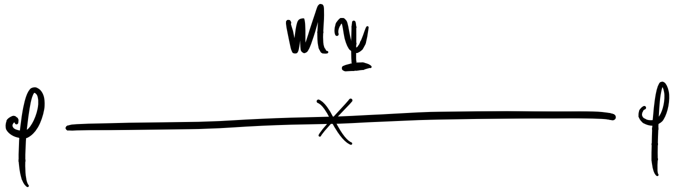
$$y_u \sim y_t \begin{pmatrix} \Delta Y_u & V_q \\ 0 & 1 \end{pmatrix}, \quad y_d \sim y_b \begin{pmatrix} \Delta Y_d & V_q \\ 0 & 1 \end{pmatrix}, \quad y_e \sim y_\tau \begin{pmatrix} \Delta Y_e & V_l \\ 0 & 1 \end{pmatrix} \qquad V_q = a_q \begin{pmatrix} V_{td}^* \\ V_{ts}^* \end{pmatrix}$$

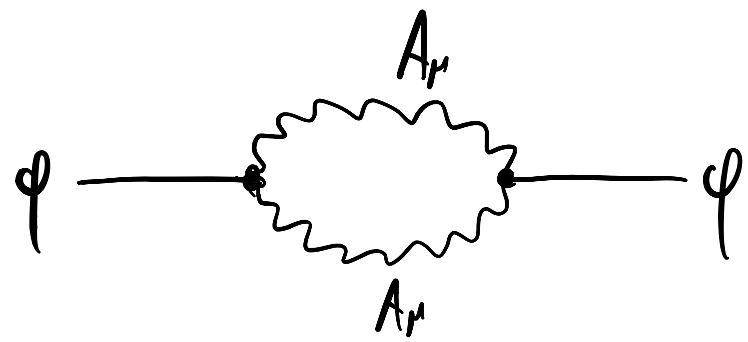
$$\beta_{1,3} \sim \begin{pmatrix} V_q^* V_l^\dagger & V_q^* \\ V_l^\dagger & 1 \end{pmatrix}, \quad \beta_1^u \sim \begin{pmatrix} 0 & (V_q^\dagger \Delta Y_u)^T \\ V_l^\dagger \Delta Y_e & 1 \end{pmatrix}$$

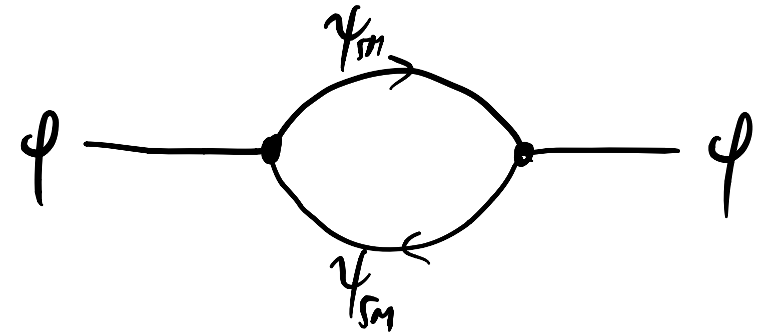
Good structure to fit the flavour anomalies, related to the SM Yukawas!

Scalar Potential: NDA + symmetry

The pNGB potential arises at 1-loop from all the explicit breaking terms







NDA + spurion analysis

$$m^2_{(\bar{\Psi}_i \Psi_j)} = B_0 (m_i + m_j)$$

$$V_{\mathcal{G}} = -\frac{3 f^2 \Lambda^2_{HC}}{16\pi^2} \sum_X c_X \mathrm{Tr}\left[\mathcal{G}^L_X U \mathcal{G}^R_X U^\dagger\right]$$

$$V_t = -\frac{c_t y_t^2 N_c \Lambda^2_{HC}}{16\pi^2} |H_1 - H_2|^2$$

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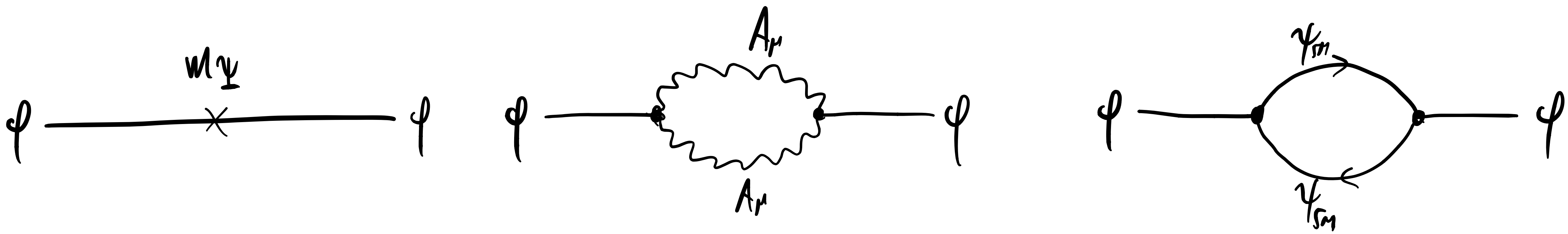

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The gauge contribution is positive and is larger for colored states.
EW charges give subleading corrections.

$$\Delta m^2_\omega \approx (0.05 \Lambda_{HC})^2 \,, \quad \Delta m^2_{H_{1,2}} \approx (0.08 \Lambda_{HC})^2 \,, \quad \Delta m^2_{\Pi_{L,Q}} \approx (0.13 \Lambda_{HC})^2 \,,$$ ~ **1** of SU(3)c

$$\Delta m^2_{S_1} \approx (0.17 \Lambda_{HC})^2 \,, \quad \Delta m^2_{S_3} \approx (0.21 \Lambda_{HC})^2 \,. \quad \Delta m^2_{\tilde{R}_2, T_2} \approx (0.19 \Lambda_{HC})^2 \,.$$ ~ **3** of SU(3)c

$$\Delta m^2_{\tilde{\pi}_1} \approx (0.26 \Lambda_{HC})^2 \,, \quad \Delta m^2_{\tilde{\pi}_3} \approx (0.28 \Lambda_{HC})^2 \,,$$ ~ **8** of SU(3)c

$\Lambda_{HC} \sim 4\pi f \gtrsim 10$ TeV

Scalar Potential

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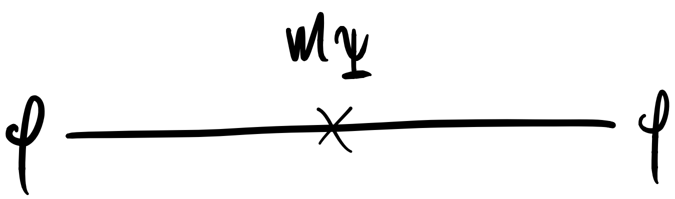

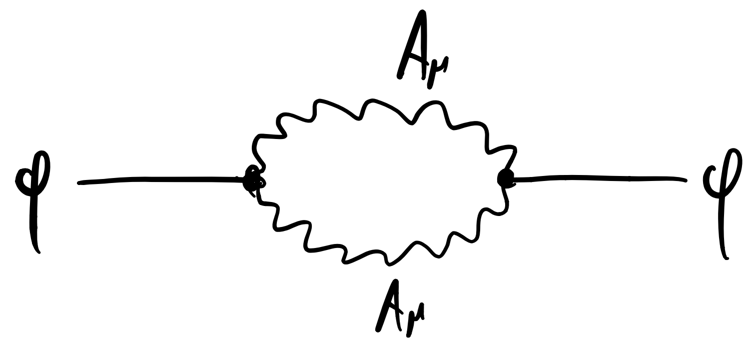

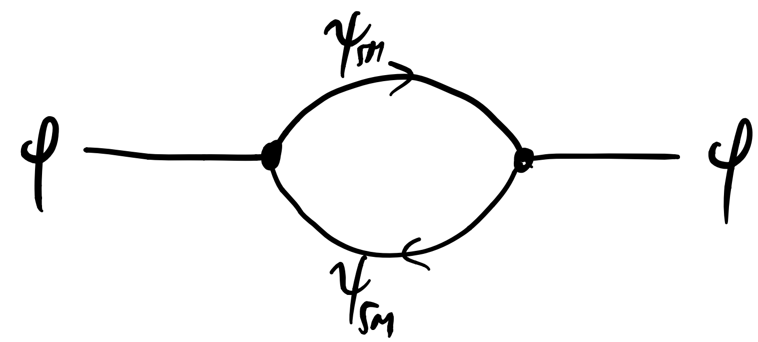

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Tuning to get EWSB as in usual Composite Higgs models:

$$m^2_{H_{1,2}} \approx 2B_0(m_L + m_E) + \Delta m^2_{\mathrm{gauge}} + \Delta m^2_{\mathrm{Yuk}} < 0 \qquad \xi \equiv \frac{v^2}{f^2} = 2\sin^2\frac{v_h}{\sqrt{2}f} \lesssim 10\%$$

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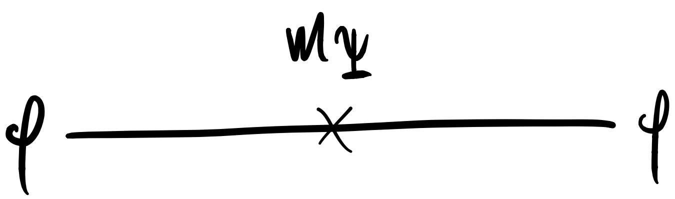

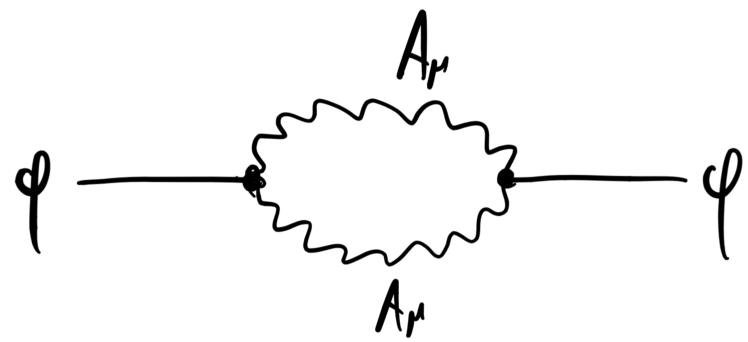

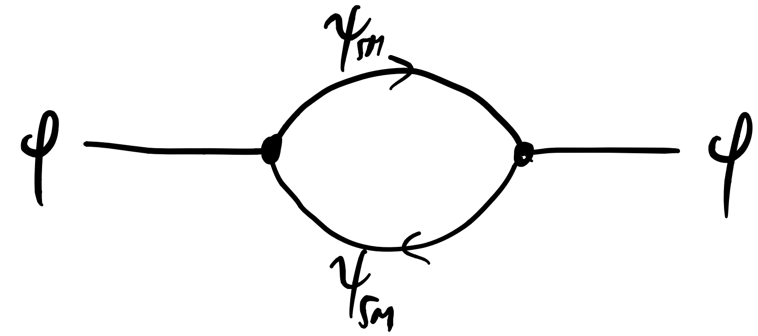

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From the structure of the potential and the expressions for the various terms I get

$$m_h^2 = (C_t - C_g) f^2 \xi \sim N_c c_t m_t^2 - 3 c_w m_W^2$$

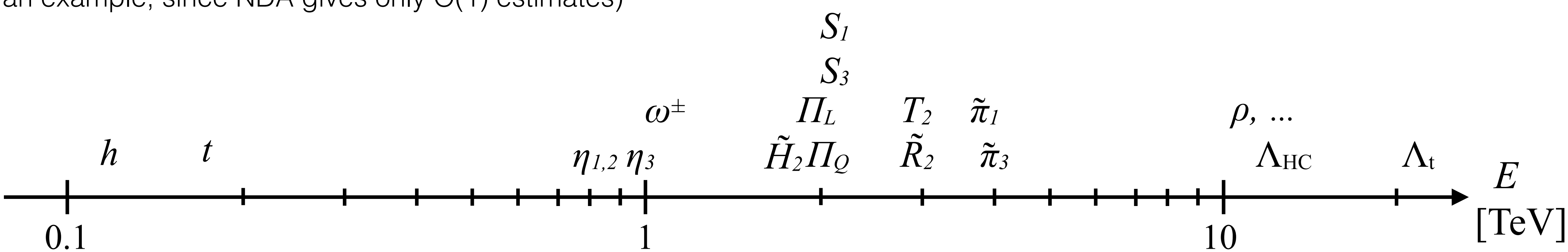
The deviations in Higgs couplings and the EWPT are similar to most Composite Higgs models.

Spectrum

valence	irrep.	valence	irrep.
$H_1 \sim i\sigma^2(\bar{\Psi}_L\Psi_N)$	$(\mathbf{1},\mathbf{2})_{1/2}$	$H_2 \sim (\bar{\Psi}_E\Psi_L)$	$(\mathbf{1},\mathbf{2})_{1/2}$
$S_1 \sim (\bar{\Psi}_Q\Psi_L)$	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$S_3 \sim (\bar{\Psi}_Q\sigma^a\Psi_L)$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$
$\omega^\pm \sim (\bar{\Psi}_N\Psi_E)$	$(\mathbf{1},\mathbf{1})_{-1}$	$\Pi_L \sim (\bar{\Psi}_L\sigma^a\Psi_L)$	$(\mathbf{1},\mathbf{3})_0$
$\tilde{R}_2 \sim (\bar{\Psi}_E\Psi_Q)$	$(\mathbf{3},\mathbf{2})_{1/6}$	$T_2 \sim (\bar{\Psi}_Q\Psi_N)$	$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$
$\tilde{\pi}_1 \sim (\bar{\Psi}_Q T^A\Psi_Q)$	$(\mathbf{8},\mathbf{1})_0$	$\tilde{\pi}_3 \sim (\bar{\Psi}_Q T^A\sigma^a\Psi_Q)$	$(\mathbf{8},\mathbf{3})_0$
$\Pi_Q \sim (\bar{\Psi}_Q\sigma^a\Psi_Q)$	$(\mathbf{1},\mathbf{3})_0$	$\eta_i \sim 3\times c_i^a(\bar{\Psi}_a\Psi_a)$	$(\mathbf{1},\mathbf{1})_0$

Using the structure of the potential from the explicit breaking terms and the NDA estimates I get

(just an example, since NDA gives only O(1) estimates)



valence	irrep.	valence	irrep.
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$\tilde{R}_2 \sim (\bar{\Psi}_E \Psi_Q)$	$(\mathbf{3},\mathbf{2})_{1/6}$	$T_2 \sim (\bar{\Psi}_Q \Psi_N)$	$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$
$\tilde{\pi}_1 \sim (\bar{\Psi}_Q T^A \Psi_Q)$	$(\mathbf{8},\mathbf{1})_0$	$\tilde{\pi}_3 \sim (\bar{\Psi}_Q T^A \sigma^a \Psi_Q)$	$(\mathbf{8},\mathbf{3})_0$
$\Pi_Q \sim (\bar{\Psi}_Q \sigma^a \Psi_Q)$	$(\mathbf{1},\mathbf{3})_0$	$\eta_i \sim 3 \times c_i^a(\bar{\Psi}_a \Psi_a)$	$(\mathbf{1},\mathbf{1})_0$

Spectrum

Using the structure of the potential from the explicit breaking terms and the NDA estimates I get

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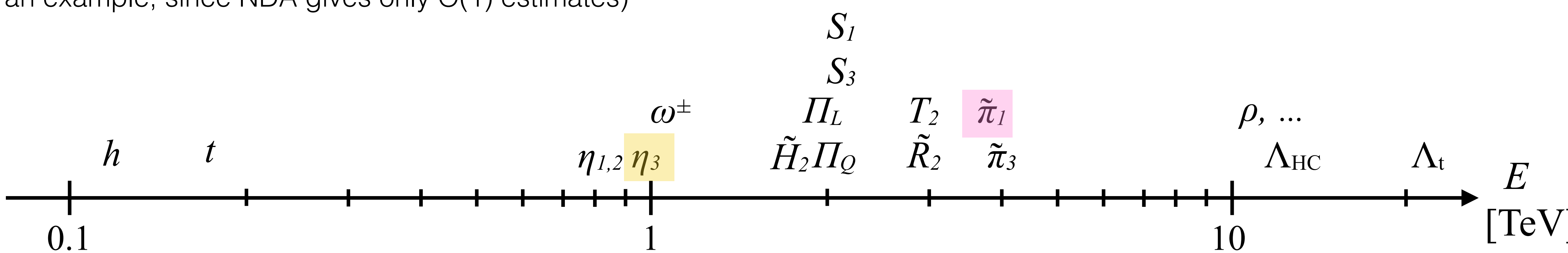

The lightest pNGBs are the singlets. Some pNGB have anomalous couplings to gauge bosons:

$$\mathcal{L}_{\rm WZW} \supset -\frac{g_\beta g_\gamma}{16\pi^2}\frac{\phi^\alpha}{f} 2 N_{HC} A^{\phi^\alpha}_{\beta\gamma} F^\beta_{\mu\nu} \widetilde{F}^{\gamma\mu\nu}$$

Can be produced in gg-fusion!

$A^{\phi^\alpha}_{\beta\gamma}$	g_1^2	g_2^2	g_3^2	$g_1 g_2$	$g_1 g_3$	$g_2 g_3$
η_1	Y_L	0	0	0	0	0
η_2	$-\frac{1}{4\sqrt{2}}$	$\frac{1}{4\sqrt{2}}$	0	0	0	0
η_3	$\frac{1+48Y_L}{12\sqrt{30}}$	$-\frac{\sqrt{3}}{4\sqrt{10}}$	$-\frac{1}{\sqrt{30}}$	0	0	0
$\tilde{\pi}_1$	0	0	$d^{\alpha\beta\gamma}/(2\sqrt{2})$	0	$\frac{1}{\sqrt{2}}\left(Y_L - \frac{1}{3}\right)$	0
$\tilde{\pi}_3$	0	0	0	0	0	$\frac{1}{2\sqrt{2}}$
Π_L	0	0	0	$\frac{Y_L}{2}$	0	0
Π_Q	0	0	0	$\frac{\sqrt{3}}{2}\left(Y_L - \frac{1}{3}\right)$	0	0

valence	irrep.	valence	irrep.
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$\omega^\pm \sim (\bar\Psi_N \Psi_E)$	$(\mathbf{1},\mathbf{1})_{-1}$	$\Pi_L \sim (\bar\Psi_L \sigma^a \Psi_L)$	$(\mathbf{1},\mathbf{3})_0$
$\tilde R_2 \sim (\bar\Psi_E \Psi_Q)$	$(\mathbf{3},\mathbf{2})_{1/6}$	$T_2 \sim (\bar\Psi_Q \Psi_N)$	$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$
$\tilde\pi_1 \sim (\bar\Psi_Q T^A \Psi_Q)$	$(\mathbf{8},\mathbf{1})_0$	$\tilde\pi_3 \sim (\bar\Psi_Q T^A \sigma^a \Psi_Q)$	$(\mathbf{8},\mathbf{3})_0$
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Spectrum

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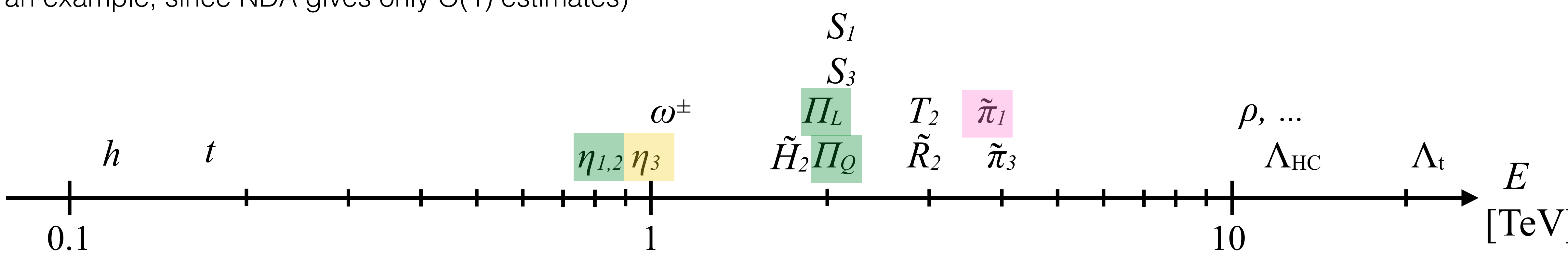
(just an example, since NDA gives only O(1) estimates)



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η_3	$\frac{1+48Y_L}{12\sqrt{30}}$	$-\frac{\sqrt3}{4\sqrt{10}}$	$-\frac{1}{\sqrt{30}}$	0	0	0
$\tilde\pi_1$	0	0	$d^{\alpha\beta\gamma}/(2\sqrt2)$	0	$\frac{1}{\sqrt2}\left(Y_L - \frac13\right)$	0
$\tilde\pi_3$	0	0	0	0	0	$\frac{1}{2\sqrt2}$
Π_L	0	0	0	$\frac{Y_L}{2}$	0	0
Π_Q	0	0	0	$\frac{\sqrt3}{2}\left(Y_L - \frac13\right)$	0	0

The other singlets $\eta_{1,2}$ and the triplets $\Pi_{L,Q}$ do not couple to gluons.

The $SU(2)_L$-triplet and color-octet $\tilde\pi_3$ only couples to gluon+EW gauge boson.

→ Too small production XS at the LHC and heavy mass.

Spectrum

valence	irrep.	valence	irrep.
$H_1 \sim i\sigma^2(\bar{\Psi}_L \Psi_N)$	$(\mathbf{1},\mathbf{2})_{1/2}$	$H_2 \sim (\bar{\Psi}_E \Psi_L)$	$(\mathbf{1},\mathbf{2})_{1/2}$
$S_1 \sim (\bar{\Psi}_Q \Psi_L)$	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$S_3 \sim (\bar{\Psi}_Q \sigma^a \Psi_L)$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$
$\omega^\pm \sim (\bar{\Psi}_N \Psi_E)$	$(\mathbf{1},\mathbf{1})_{-1}$	$\Pi_L \sim (\bar{\Psi}_L \sigma^a \Psi_L)$	$(\mathbf{1},\mathbf{3})_0$
$\tilde{R}_2 \sim (\bar{\Psi}_E \Psi_Q)$	$(\mathbf{3},\mathbf{2})_{1/6}$	$T_2 \sim (\bar{\Psi}_Q \Psi_N)$	$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$
$\tilde{\pi}_1 \sim (\bar{\Psi}_Q T^A \Psi_Q)$	$(\mathbf{8},\mathbf{1})_0$	$\tilde{\pi}_3 \sim (\bar{\Psi}_Q T^A \sigma^a \Psi_Q)$	$(\mathbf{8},\mathbf{3})_0$
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Using the structure of the potential from the explicit breaking terms and the NDA estimates I get

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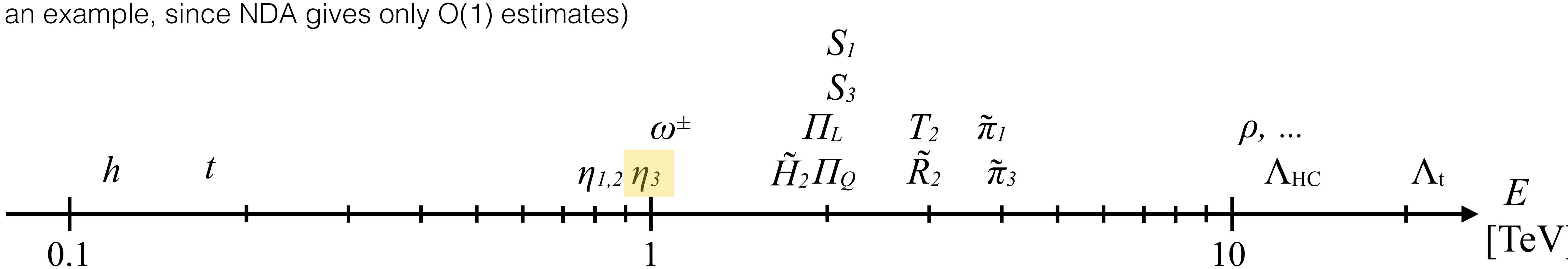
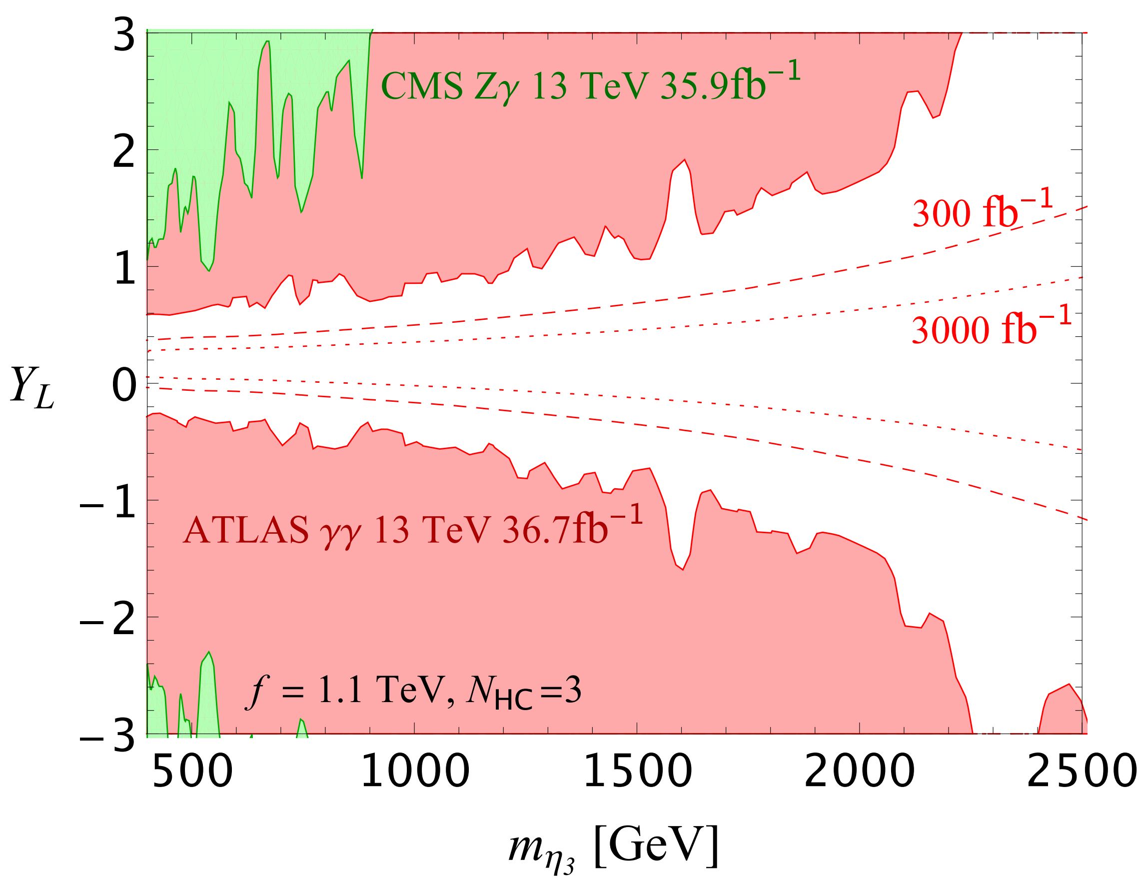
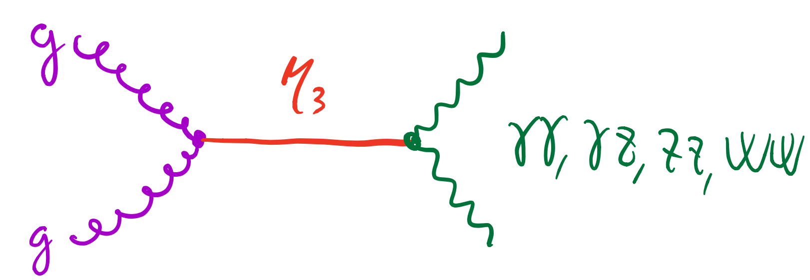




η_3 Couples to gluons and EW gauge bosons.
Possible signal in diphoton, ZZ,Zγ searches.



Excluded region from present searches and prospects from γγ

Spectrum

valence	irrep.	valence	irrep.
$H_1 \sim i\sigma^2(\bar{\Psi}_L\Psi_N)$	$(\mathbf{1},\mathbf{2})_{1/2}$	$H_2 \sim (\bar{\Psi}_E\Psi_L)$	$(\mathbf{1},\mathbf{2})_{1/2}$
$S_1 \sim (\bar{\Psi}_Q\Psi_L)$	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$S_3 \sim (\bar{\Psi}_Q\sigma^a\Psi_L)$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$
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$\tilde{\pi}_1 \sim (\bar{\Psi}_Q T^A\Psi_Q)$	$(\mathbf{8},\mathbf{1})_0$	$\tilde{\pi}_3 \sim (\bar{\Psi}_Q T^A\sigma^a\Psi_Q)$	$(\mathbf{8},\mathbf{3})_0$
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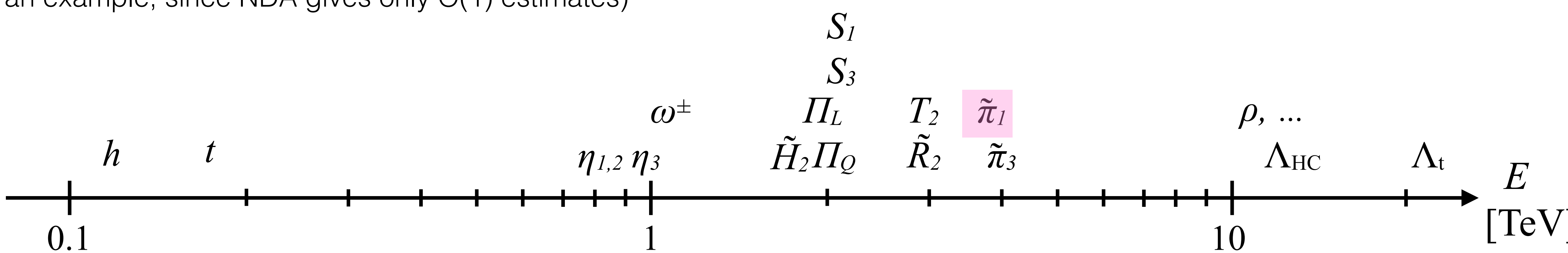

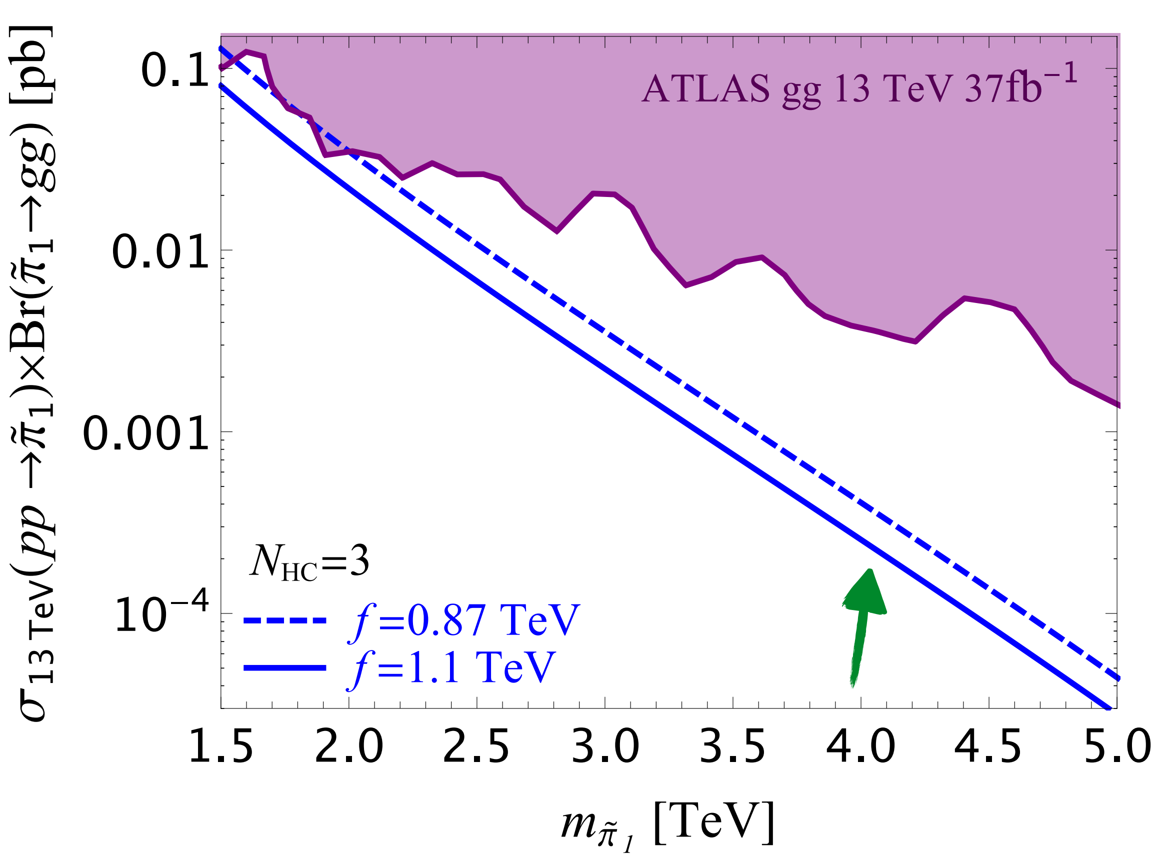

The color-octet $\tilde{\pi}_1$ can be searched in dijet but in this model it is too heavy for the LHC.

Spectrum

valence	irrep.	valence	irrep.
$H_1 \sim i\sigma^2(\bar{\Psi}_L\Psi_N)$	$(\mathbf{1},\mathbf{2})_{1/2}$	$H_2 \sim (\bar{\Psi}_E\Psi_L)$	$(\mathbf{1},\mathbf{2})_{1/2}$
$S_1 \sim (\bar{\Psi}_Q\Psi_L)$	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$S_3 \sim (\bar{\Psi}_Q\sigma^a\Psi_L)$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$
$\omega^\pm \sim (\bar{\Psi}_N\Psi_E)$	$(\mathbf{1},\mathbf{1})_{-1}$	$\Pi_L \sim (\bar{\Psi}_L\sigma^a\Psi_L)$	$(\mathbf{1},\mathbf{3})_0$
$\tilde{R}_2 \sim (\bar{\Psi}_E\Psi_Q)$	$(\mathbf{3},\mathbf{2})_{1/6}$	$T_2 \sim (\bar{\Psi}_Q\Psi_N)$	$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$
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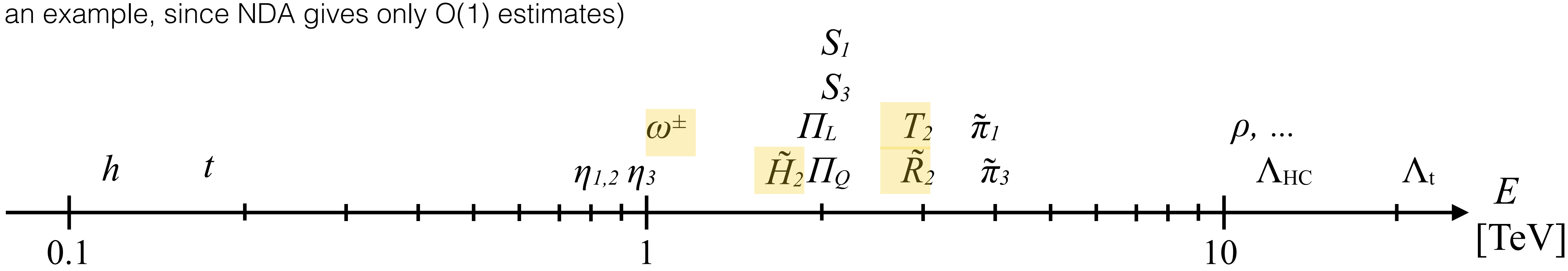
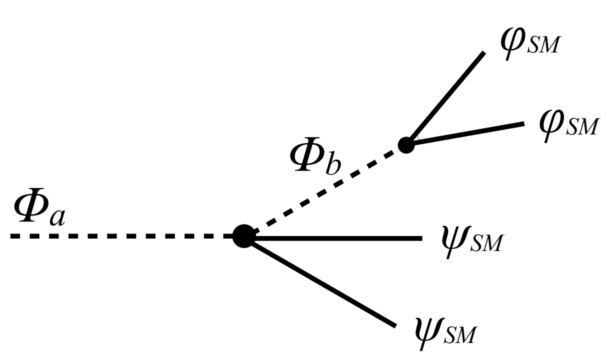
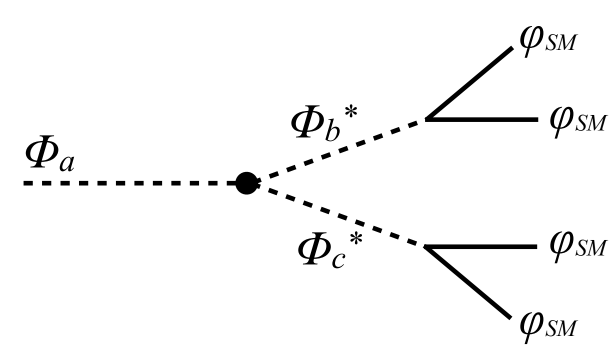


The other pNGBs can be pair-produced but do not decay directly to SM particles.
They can decay via higher-order terms such as:



or



None of them is expected to be observable at the LHC (too heavy or only EW couplings).

The other resonances have masses at the $\Lambda \sim 4\pi f > 10$ TeV scale

Summary - bottom-up

B-physics anomalies are the most compelling experimental hints for New Physics at the TeV scale.
Experimental measurements in the next few years by LHCb, Belle-II, CMS, and ATLAS will settle the question of their nature (new physics or systematics).

Combined solutions of both sets of anomalies — in charged AND neutral current — can be obtained.

The favourite mediators are scalar or vector leptoquarks, which offer a rich program for direct searches at the LHC and future colliders.

Summary - UV picture

Scalar leptoquarks can arise as composite resonances in composite models.
If they are pseudo-Goldstones, they are naturally lighter than other resonances:

$$m_{SLQ} \ll \Lambda$$

If embedded in composite Higgs models, also the Hierarchy problem is addressed.

The flavour structure of LQ and Higgs couplings are closely related, however a complete UV theory of flavour in composite models is still missing.

Even with such a rich spectrum (99 NGB d.o.f.), searches at LHC are challenging due to heavy masses and/or only EW charges.

Thank you!

Backup

Challenge: to fit R(D$^{(*)}$) For small λ^q_{bs}

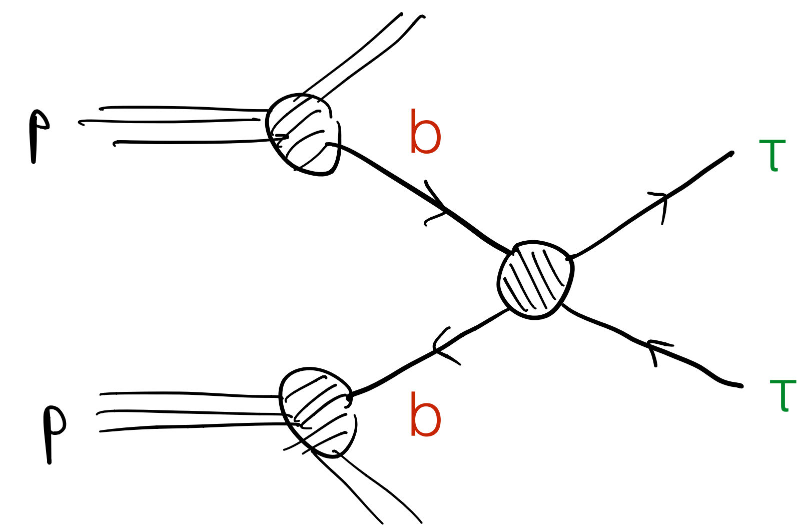
High-pT

With a tree-level mediator $C_T \sim g_X^2 \frac{v^2}{M_X^2}$

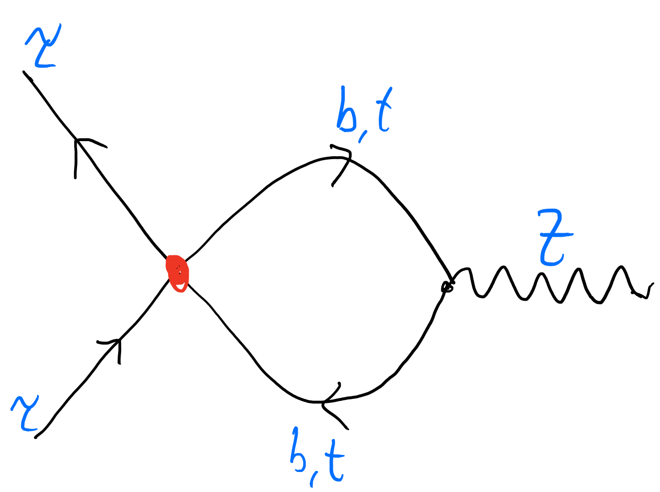
M_X ~ 700 GeV for g_X ~1.

Problems with direct searches at LHC in bb→ττ for all mediators.

Greljo, Isidori, DM 2015; Faroughy, Greljo, Kamenik 2016



RGE effects and EWPT



$$\sim \frac{3y_t^2}{16\pi^2} \log \frac{M_X^2}{m_t^2} \frac{C_T}{v^2} (H^\dagger \sigma^a i \overleftrightarrow{D}_\mu H)(\bar{L}_L^3 \gamma^\mu \sigma^a L_L^3)$$

Problems in well measured (per-mille) Zττ couplings at LEP-1 and LFU in τ decays.

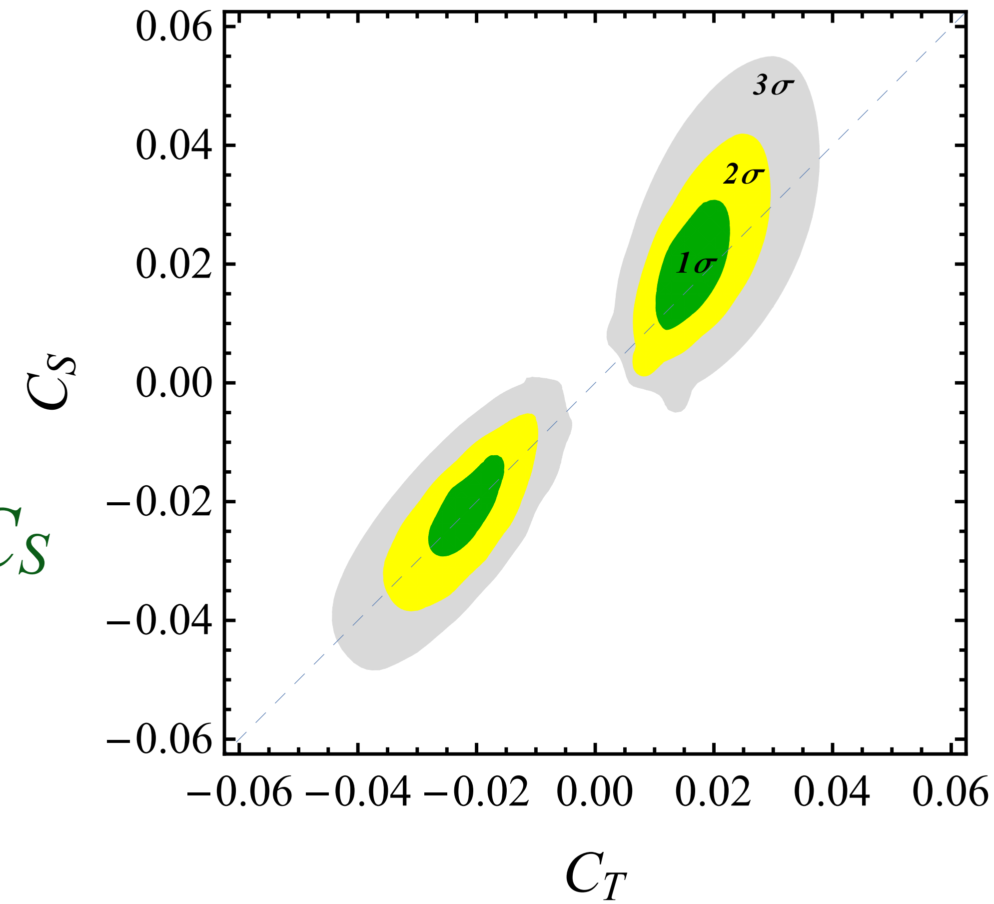
Ferruglio, Paradisi, Pattori 2016-2017

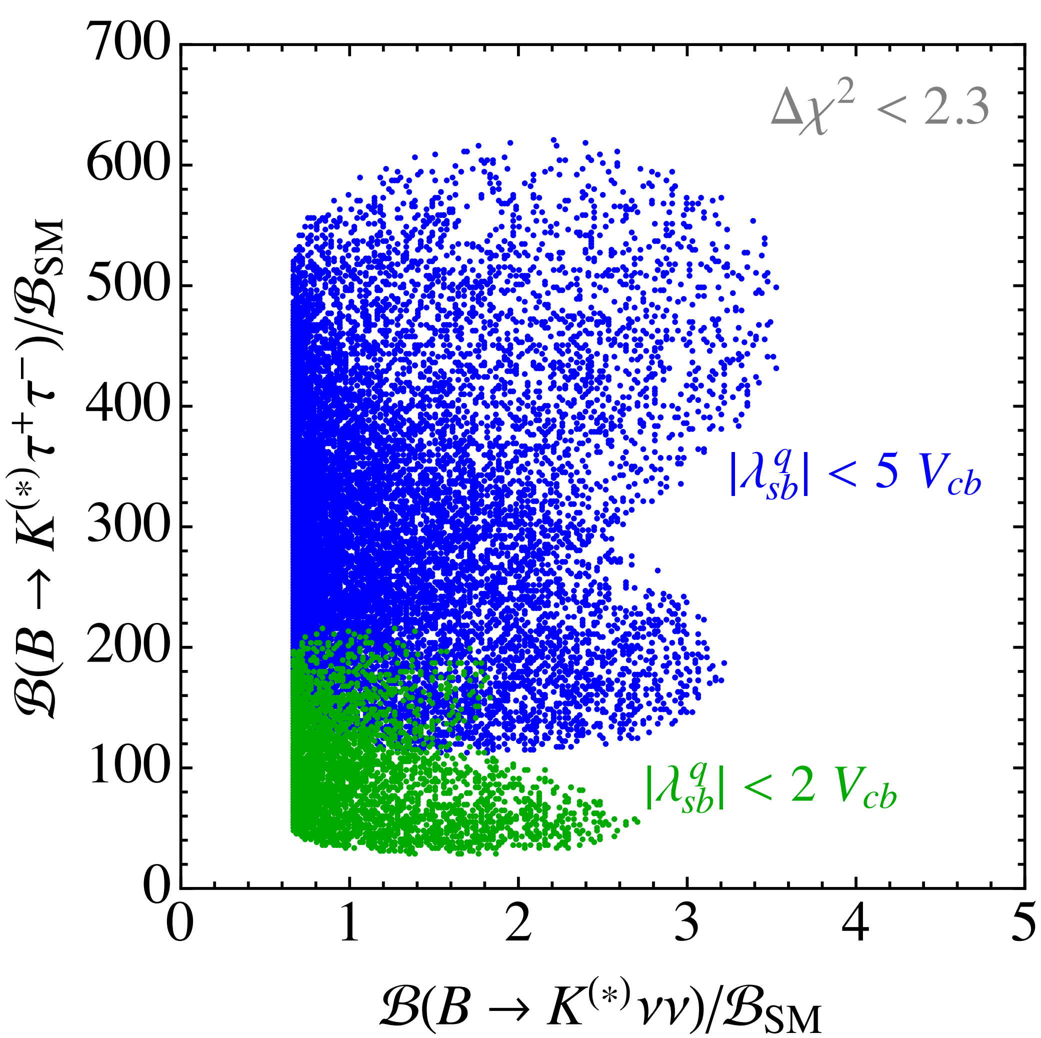
Challenge: to fit R(D$^{(*)}$) For large λ^q_{bs}

$$(C_T - C_S)\lambda_{bs}(\bar{b}_L\gamma_\mu s_L)(\bar{\nu}_\tau\gamma^\mu\nu_\tau)$$

This can generate too large corrections O(1) to $B \to K^* \nu\nu$

Requires the singlet operator with $C_T \sim C_S$





$$(C_T + C_S)\lambda_{bs}(\bar{b}_L\gamma_\mu s_L)(\bar{\tau}_L\gamma^\mu\tau_L)$$

Huge corrections O(>10^2) in $B \to K^* \tau\tau$.

Also, depending on the UV model, there might be **problems with B_s mixing** (see later).

U(2) flavour symmetry

Keeping only the third-generation Yukawa couplings, the SM enjoys an approximate
SU(2)^5 flavor symmetry

$$G_F = \mathrm{SU}(2)_q \times \mathrm{SU}(2)_u \times \mathrm{SU}(2)_d \times \mathrm{SU}(2)_l \times \mathrm{SU}(2)_e$$

$$\psi_i = (\overbrace{\psi_1 \;\; \psi_2}^{\mathbf{2}} \; \overbrace{\psi_3}^{\mathbf{1}})$$

One can assume this is minimally broken by the spurions:

$$\Delta Y_u = (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1}, \mathbf{1}, \mathbf{1})\,, \quad \Delta Y_d = (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}}, \mathbf{1}, \mathbf{1})\,, \quad \Delta Y_e = (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2}, \bar{\mathbf{2}})$$

$$V_q = (\mathbf{2}, \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})\,, \qquad V_l = (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2}, \mathbf{1})$$

The Yukawa matrices get this structure:

$$y_u \sim y_t \begin{pmatrix} \Delta Y_u & V_q \\ 0 & 1 \end{pmatrix}\,, \quad y_d \sim y_b \begin{pmatrix} \Delta Y_d & V_q \\ 0 & 1 \end{pmatrix}\,, \quad y_e \sim y_\tau \begin{pmatrix} \Delta Y_e & V_l \\ 0 & 1 \end{pmatrix}$$

The doublet spurions regulate the mixing of the third generation with the lighter ones:

$$V_q = a_q \begin{pmatrix} V_{td}^* \\ V_{ts}^* \end{pmatrix} \qquad V_l \approx \begin{pmatrix} 0 \\ \lambda_{\tau\mu} \end{pmatrix}$$

CKM   unknowns

Higgs Yukawas

UV effective Lagrangian:

$$\mathcal{L}_F \supset \frac{1}{\Lambda_t^2}\left(\bar{u}_R c_{1,u}^\dagger q_L + \bar{q}_L c_{1,d} d_R\, \epsilon + \bar{l}_L c_{1,e} e_R\, \epsilon\right)(\bar{\Psi}_L \gamma_5 \Psi_N) + \\ + \frac{1}{\Lambda_t^2}\left(\bar{u}_R c_{2,u}^\dagger q_L \epsilon + \bar{q}_L c_{2,d} d_R + \bar{l}_L c_{2,e} e_R\right)(\bar{\Psi}_E \gamma_5 \Psi_L) + h.c.$$

At low energy:

$$\mathcal{L}_{\text{Yuk}}^{\text{eff}} = \frac{f}{2}\left(\bar{u}_R \tilde{y}_{1,u}^\dagger q_L^\beta \epsilon^{\beta\alpha} + \bar{q}_L^\alpha \tilde{y}_{1,d} d_R + \bar{l}_L^\alpha \tilde{y}_{1,e} e_R\right) \text{Tr}[\Delta_{H_1}^\alpha (U - U^\dagger)] + \\ + \frac{f}{2}\left(\bar{u}_R \tilde{y}_{2,u}^\dagger q_L^\beta \epsilon^{\beta\alpha} + \bar{q}_L^\alpha \tilde{y}_{2,d} d_R + \bar{l}_L^\alpha \tilde{y}_{2,e} e_R\right) \text{Tr}[\Delta_{H_2}^\alpha (U - U^\dagger)] + h.c.$$

The spurion gives the Higgses as leading terms: $\text{Tr}[\Delta_{H_{1,2}}^\alpha (U - U^\dagger)] = i\frac{2\sqrt{2}}{f} H_{1,2}^\alpha + \mathcal{O}(\phi^2/f^2)$

Fermion masses: $m_f = f \sin\theta(\tilde{y}_{1,f} - \tilde{y}_{2,f}) = \frac{v}{\sqrt{2}}(\tilde{y}_{1,f} - \tilde{y}_{2,f}) \equiv \frac{v}{\sqrt{2}} y_f$

The Yukawa matrices of the two Higgses need to be identical to avoid flavour-violating couplings and custodial symmetry-breaking effects

LQ couplings

UV effective Lagrangian:

$$\mathcal{L}_F \supset \frac{1}{\Lambda_t^2}\left[\left(\bar{q}_L^c c_{1,ql}\epsilon l_L + \bar{e}_R^c c_{1,eu} u_R\right)\left(\bar{\Psi}_Q \gamma_5 \Psi_L\right) + \left(\bar{q}_L^c c_{3,ql}\epsilon\sigma^A l_L\right)\left(\bar{\Psi}_Q \gamma_5 \sigma^A \Psi_L\right)\right] + h.c.$$

$$\bar{\Psi}_{i,L}\Psi_{j,R} \to -B_0 f^2 U(\phi)_{ji}\ , \qquad \bar{\Psi}_{i,R}\Psi_{j,L} \to -B_0 f^2 U^\dagger(\phi)_{ji}$$

At low energy it becomes:

spurions

$$\mathcal{L}_{\rm LQ}^{\rm eff} = i\frac{f}{4}\left(g_1 \bar{q}_L^{c,a}\beta_1 \epsilon l_L + g_1^u \bar{e}_R^c \beta_1^u u_R^a\right) {\rm Tr}[\Delta_{S_1}^a (U - U^\dagger)] + h.c.$$
$$+ i\frac{f}{4}\left(g_3 \bar{q}_L^{c,a}\beta_3 \epsilon\sigma^A l_L\right) {\rm Tr}[\Delta_{S_3}^{A,a}(U - U^\dagger)] + h.c. =$$
$$= -g_1\beta_{1,i\alpha}(\bar{q}_L^{c\,i}\epsilon l_L^\alpha)S_1 - g_1^u(\beta_1^u)^T_{\alpha i}(\bar{e}_R^{c\,\alpha} u_R^i)S_1 - g_3\beta_{3,i\alpha}(\bar{q}_L^{c\,i}\epsilon\sigma^A l_L^\alpha)S_3^A + h.c. + \mathcal{O}(\phi^2)$$

Flavour structure: $\beta_{1,3} \sim \begin{pmatrix} V_q^* V_l^\dagger & V_q^* \\ V_l^\dagger & 1 \end{pmatrix}$ $\quad \beta_1^u \sim \begin{pmatrix} 0 & (V_q^\dagger \Delta Y_u)^T \\ V_l^\dagger \Delta Y_e & 1 \end{pmatrix}$

LQ couplings

UV effective Lagrangian:

$$\mathcal{L}_F \supset \frac{1}{\Lambda_t^2}\left[\left(\bar{q}_L^c c_{1,ql}\epsilon l_L + \bar{e}_R^c c_{1,eu} u_R\right)\left(\bar{\Psi}_Q \gamma_5 \Psi_L\right) + \left(\bar{q}_L^c c_{3,ql}\epsilon\sigma^A l_L\right)\left(\bar{\Psi}_Q\gamma_5\sigma^A\Psi_L\right)\right] + h.c.$$

$$\bar{\Psi}_{i,L}\Psi_{j,R} \to -B_0 f^2 U(\phi)_{ji}\ , \qquad \bar{\Psi}_{i,R}\Psi_{j,L} \to -B_0 f^2 U^\dagger(\phi)_{ji}$$

At low energy it becomes:

spurions

$$\mathcal{L}_{\rm LQ}^{\rm eff} = i\frac{f}{4}\left(g_1 \bar{q}_L^{c,a}\beta_1\epsilon l_L + g_1^u \bar{e}_R^c \beta_1^u u_R^a\right) {\rm Tr}[\Delta_{S_1}^a (U-U^\dagger)] + h.c.$$
$$+ i\frac{f}{4}\left(g_3 \bar{q}_L^{c,a}\beta_3\epsilon\sigma^A l_L\right) {\rm Tr}[\Delta_{S_3}^{A,a}(U-U^\dagger)] + h.c. =$$
$$= -g_1\beta_{1,i\alpha}(\bar{q}_L^{c\,i}\epsilon l_L^\alpha)S_1 - g_1^u(\beta_1^u)^T_{\alpha i}(\bar{e}_R^{c\,\alpha}u_R^i)S_1 - g_3\beta_{3,i\alpha}(\bar{q}_L^{c\,i}\epsilon\sigma^A l_L^\alpha)S_3^A + h.c. + \mathcal{O}(\phi^2)$$

Flavour structure: $\beta_{1,3} \sim \begin{pmatrix} V_q^* V_l^\dagger & V_q^* \\ V_l^\dagger & 1 \end{pmatrix}$ $\quad \beta_1^u \sim \begin{pmatrix} 0 & (V_q^\dagger \Delta Y_u)^T \\ V_l^\dagger \Delta Y_e & 1 \end{pmatrix}$

The coupling of S_1 to RH fermions induces an m_t-enhanced contribution to $\tau \to \mu\gamma$.

Requires $g_1^u \lesssim 10^{-2} g_1$

Introducing an extra approximate $U(1)_e$ symmetry for the RH leptons to protect the τ Yukawa would give:

$$g_1^u / g_1 \sim y_\tau / y_t \sim 10^{-2}$$

$\tau \to \mu\gamma$ & $(g-2)_\mu$

The S1 LQ in general couples to both LH and RH fermions:

$$\mathcal{L}_{S_1} \supset \bar{t}^c \left[g_1 \beta_{1,b\alpha} P_L + g_1^u \beta^u_{1,t\alpha} P_R \right] \ell^\alpha S_1 + h.c.$$

This induces an mt-enhanced contribution to $\tau \to \mu\gamma$ and $(g-2)_\mu$

$$\mathcal{B}(\tau \to \mu\gamma) \approx (7.0 \times 10^{-2}) \frac{|\epsilon_1|^2}{0.01} |\epsilon_1^u|^2 \left(\frac{|\beta_{1,b\mu}|^2}{0.1^2} + \frac{|\beta^u_{1,t\mu}|^2}{0.1^2} \right) < 4.4 \times 10^{-8}$$

$$|\epsilon_1^u|^2 \lesssim 10^{-6}$$

$$\epsilon_1^u = \frac{g_1^u v}{2 m_{S_1}}$$

Requires $g_1^u \lesssim 10^{-2} g_1$

Introducing an extra approximate $U(1)_e$ symmetry for the RH leptons to protect the τ Yukawa would give:

$$g_1^u / g_1 \sim y_\tau / y_t \sim 10^{-2}$$

$$\delta a_\mu \approx (7.9 \times 10^{-11}) \times \frac{\epsilon_1^u}{10^{-3}} \frac{\epsilon_1}{0.1} \frac{\beta_{1,b\mu}}{0.1} \frac{\beta^u_{1,t\mu}}{0.1}$$

too small to fit the anomaly

$$(\delta a_\mu)_{exp} = (2.8 \pm 0.9) \times 10^{-9}$$

B and L conservation

I assign a combination of B and L, F+ = 3B + L, to the HC fermions such that the Higgs Yukawas and LQ couplings are allowed:

$$(\bar{q}_L u_R + \bar{d}_R q_L + \bar{e}_R l_L)(\bar{\Psi}_N \Psi_L) \; , \qquad (\bar{q}_L u_R + \bar{d}_R q_L + \bar{e}_R l_L)(\bar{\Psi}_L \Psi_E)$$

$$(\bar{q}^c_L l_L + \bar{e}^c_R u_R)(\bar{\Psi}_Q \Psi_L) \; , \qquad (\bar{q}^c_L \sigma^a l_L)(\bar{\Psi}_Q \sigma^a \Psi_L) \; ,$$

↓

$$F_+(\Psi_L) = F_+(\Psi_N) = F_+(\Psi_E) = F_L \; , \qquad F_+(\Psi_Q) = F_L + 2$$

↓

These operators are then automatically forbidden

$$(\bar{q}^c_L q_L + \bar{u}^c_R d_R)(\bar{\Psi}_L \Psi_Q) \; , \qquad (\bar{d}_R l_L)(\bar{\Psi}_E \Psi_Q) \; , \qquad (\bar{l}^c_L l_L)(\bar{\Psi}_E \Psi_N)$$

EWSB and Higgs mass

Better to change basis in the two Higgs doublets: $H_1 = \frac{i\tilde{H}_1 + \tilde{H}_2}{\sqrt{2}}$, $H_2 = \frac{-i\tilde{H}_1 + \tilde{H}_2}{\sqrt{2}}$

so that only one Higgs takes a vev

$$\tilde{H}_1 = \left(G^+, \frac{v_h + h + iG^0}{\sqrt{2}}\right)^T , \qquad \tilde{H}_2 = \left(H^+, \frac{h_2 + iA_0}{\sqrt{2}}\right)^T$$

'eaten NGB' and light Higgs couples linearly to fermions and SM gauge bosons

Heavy Higgs
no linear couplings to SM

Effective potential for the light Higgs vev:

$$V(\theta) = -C_m f^4 \cos\theta - C_g f^4 \cos 2\theta - 2C_t f^4 \sin^2\theta \qquad \theta = v_h/\sqrt{2}f$$

$$C_m = \frac{2B_0}{f^2}(m_E + m_L) , \quad C_g = \frac{3\Lambda_{HC}^2}{16\pi^2 f^2}\left(\frac{3}{4}c_w g_w^2 + \frac{1}{4}c_Y g_Y^2\right) , \quad C_t = \frac{N_c y_t^2 c_t \Lambda_{HC}^2}{16\pi^2 f^2}$$

$$\frac{v^2}{f^2} \equiv \xi = 2\sin^2\theta_{\min} = 2 - \frac{C_m^2}{8\,(C_t - C_g)^2} \qquad m_h^2 = (C_t - C_g) f^2 \xi \sim N_c c_t m_t^2 - 3c_w m_W^2$$