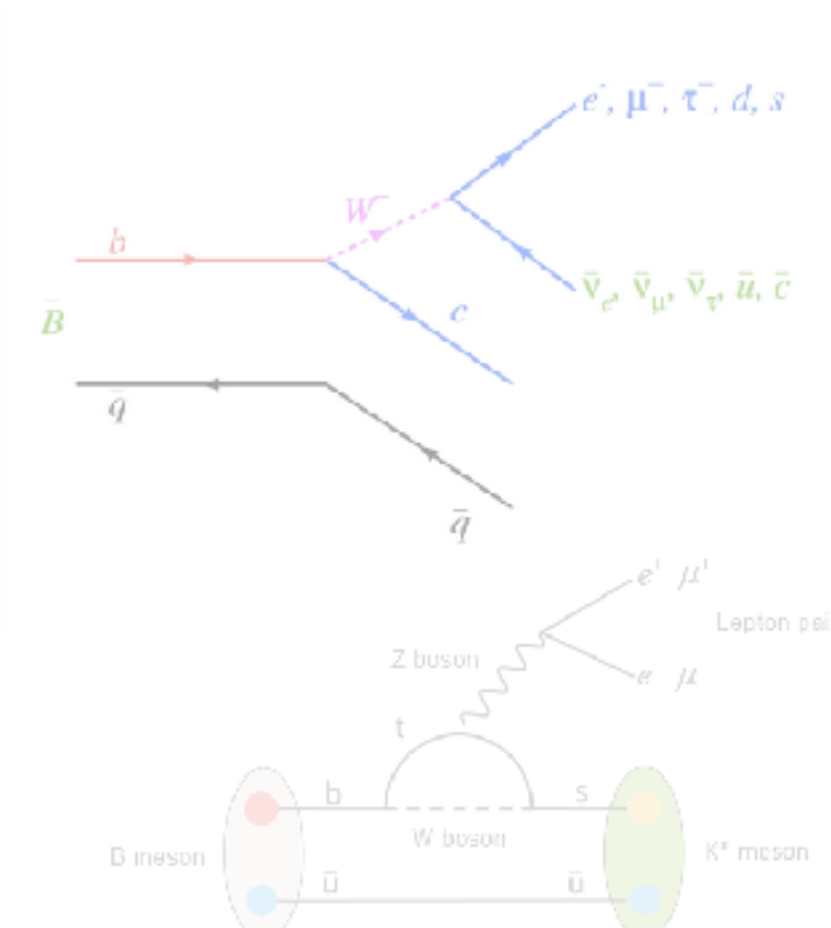
From B-physics anomalies to model building and direct searches



David Marzocca

INFN
Sezione di Trieste

Genova, 9/05/2018

Outline

- Introduction
- Recap: B-physics anomalies
- Combined EFT fit of the anomalies
- Simplified models & direct searches of the mediators
- UV example: a composite Higgs model with scalar LQ.
  - direct searches of other states

Introduction

The hierarchy problem of the EW scale suggests $\Lambda \lesssim \text{TeV}$

The strong bounds from flavour physics require instead $\Lambda \gg \text{TeV}^*$

* for arbitrary flavour structure

To have NP at the TeV scale, the common lore suggested that it should be almost flavour diagonal (MFV-like).

Many theorists believed the LHC era would give:

→ Abundance of new resonances at the LHC!!! 

Boring flavour physics… 

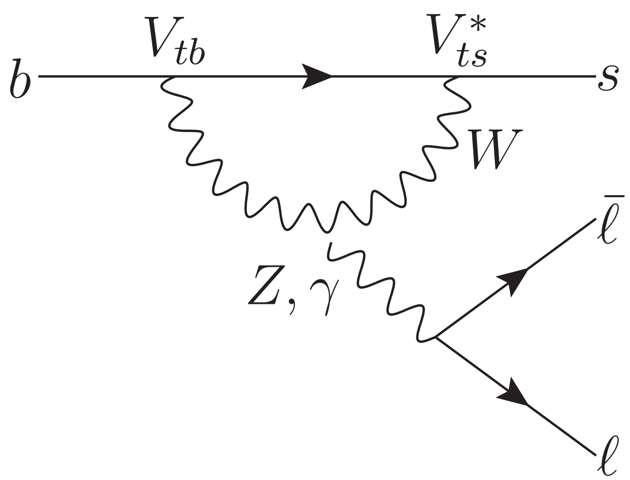
Instead we ended up with:

→ No direct signal of new particles… 

Exciting anomalies in flavour physics!!! 

Data

Neutral-current anomalies

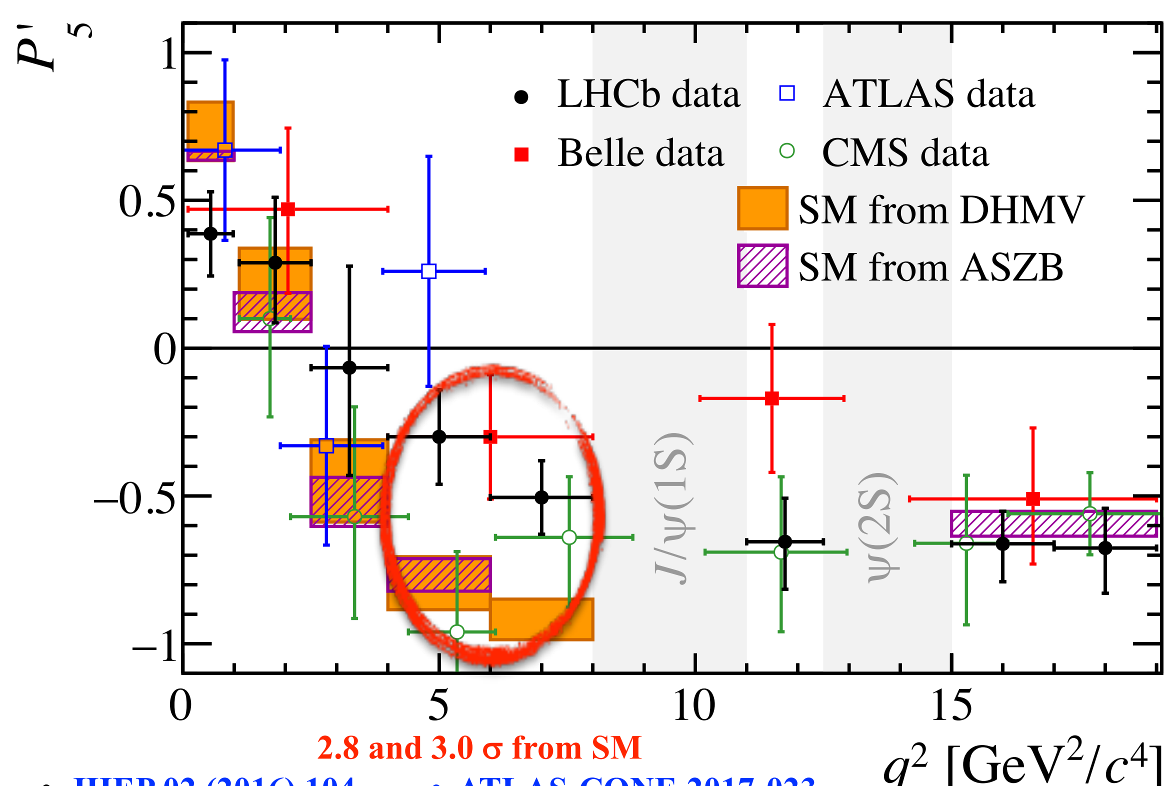


$b \to s\, \mu^+ \mu^-$ vs. $b \to s\, e^+ e^-$

The **LHCb** experiment measured:

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

Challenging SM prediction



2.8 and 3.0 σ from SM

- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

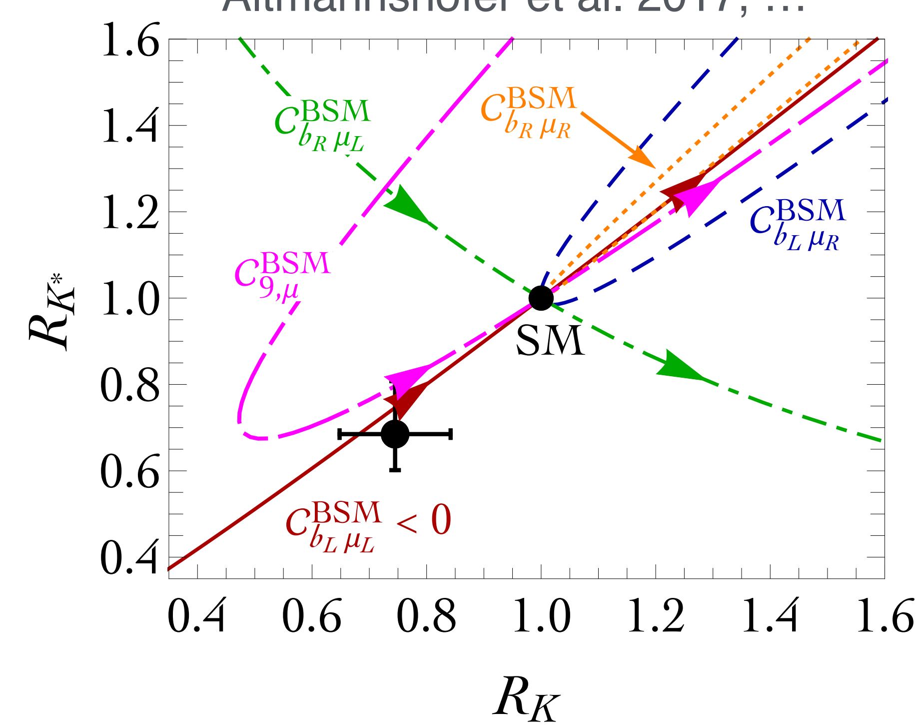
S. Bifani

Lepton Flavour Universality ratios

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

Clean SM prediction

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



Neutral-current anomalies

The SM contribution is aligned along the effective operator $(\bar{s}_L \gamma^\nu b_L)(\bar{\mu}_L \gamma_\nu \mu_L)$

→ all deviations are consistent

→ **4 - 6 σ** deviation in global fits

→ Best fit with NP in LH current

$$C_9^{\rm SM} \approx -C_{10}^{\rm SM} \approx 4.2$$

$$\Delta C_9^\mu = -\Delta C_{10}^\mu = -0.61 \pm 0.12$$

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

What is the scale of NP?

No suppression: $c_i = 1 \longrightarrow \Lambda \sim 31\ \mathrm{TeV}$

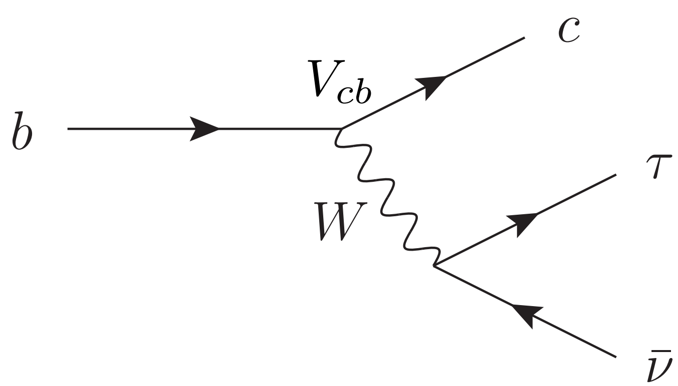
MFV or U(2): $c_i = V_{ts} \longrightarrow \Lambda \sim 6\ \mathrm{TeV}$

Loop + MFV: $c_i = V_{ts}/4\pi \longrightarrow \Lambda \sim 0.5\ \mathrm{TeV}$

Adding SM gauge invariance: New Physics in at least one of these operators

$$C_T\ (\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j)(\bar{L}_L^\alpha \gamma^\mu \sigma^a L_L^\beta) + C_S\ (\bar{Q}_L^i \gamma_\mu Q_L^j)(\bar{L}_L^\alpha \gamma^\mu L_L^\beta)$$

Charged-current anomalies



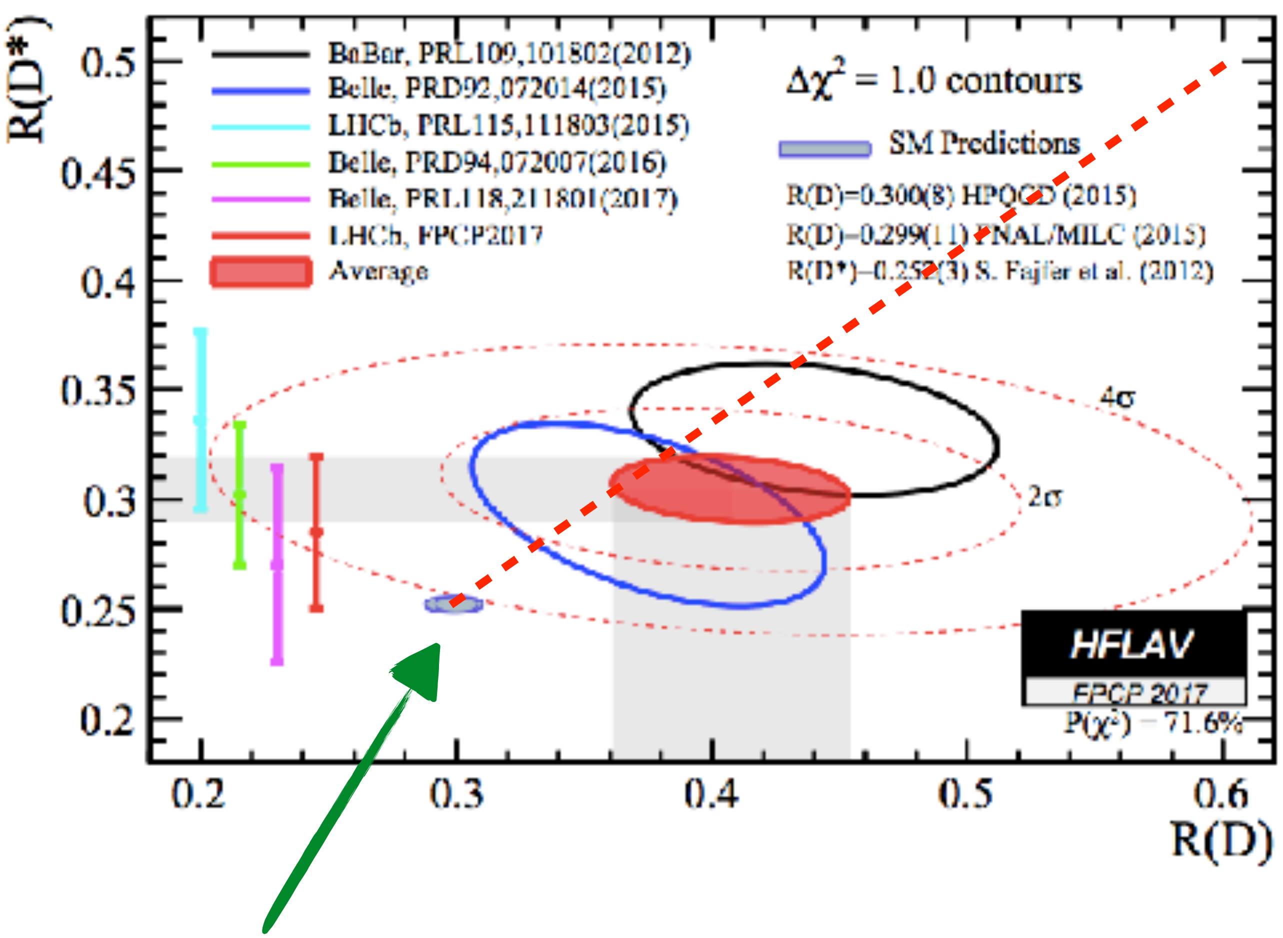
b to c transition in $\tau\nu$ final state.

Tree-level SM process with Vcb suppression.

LFU ratio to reduce QCD uncertainties

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

$$\ell = \mu, e$$



Robust SM prediction

All results since 2012 consistently above SM prediction

$$R_{D^{(*)}} \equiv R(D^{(*)})/R(D^{(*)})_{\rm SM} = 1.234 \pm 0.052$$

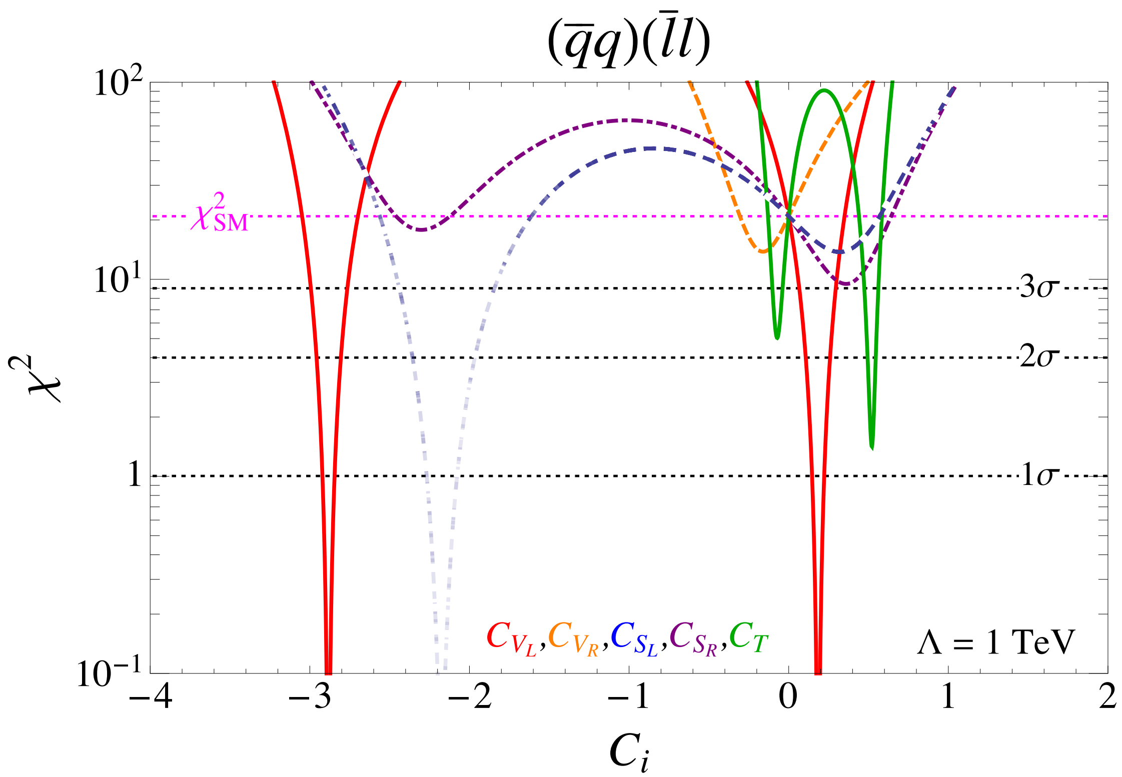
While μ/e universality tested at % level.

~ 20% enhancement from the SM

~ 4σ from the SM

Charged-current anomalies

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



The tree-level SM contribution is mediated by:

$$\mathcal{H}_{\rm SM} = \frac{4G_F}{\sqrt{2}} V_{cb} (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau) + h.c.$$

General BSM EFT fit

The V-A operator gives the best fit

Freytsis, Ligeti, Ruderman 2015

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

What is the scale of NP?

No suppression: $c_i = 1 \longrightarrow \Lambda \sim 3.7$ TeV

MFV or U(2): $c_i = V_{cb} \longrightarrow \Lambda \sim 0.7$ TeV

Loop + MFV: $c_i = V_{cb}/4\pi \longrightarrow \Lambda \sim 0.2$ TeV

Adding $SU(2)_L$ gauge invariance: New Physics in this operator

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

To summarise

Quark sector → New Physics in 3-2 transition (bs and bc)

Let me take $c_i \sim V_{cb}$

* very well motivated in concrete flavour setups: MFV, U(2), etc

Lepton sector →

Large effect in ττ → $\Lambda_{\tau\tau} \sim 0.7$ TeV

Smaller effect in μμ → $\Lambda_{\mu\mu} \sim 6$ TeV

Negligible effect in ee

Strongest effect in third generation fermions, smaller for second, negligible for first.

Very similar to SM fermion masses pattern!

Best SMEFT operators to fit the anomalies

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

CC & NC ← first term; second term → NC

Flavour Universality

Since fermions from different generations have same gauge quantum numbers, gauge interactions in the SM are *accidentally* flavour-universal.

$$\mathcal{L}_{\rm gauge} = i \sum_{j=1}^{3} \sum_{q,u,d,\ell,e} \bar{\psi}_j \not{D} \psi_j$$

Accidental global symmetry U(3)^5

The only other fermionic interactions in the SM (Yukawa interactions) completely break this symmetry and violate universality maximally!

$$\mathcal{L}_{\rm Yuk} = \bar{q}_L Y_u u_R H^* + \bar{d}_L Y_d d_R H + \bar{\ell}_L Y_e e_R H$$

Since $y_e \ll y_\mu \ll y_\tau \sim 10^{-2}$, in most high-energy SM processes Lepton-Flavour-Universality is a good approximate symmetry. Notably, this is absolutely not the case in Higgs physics.

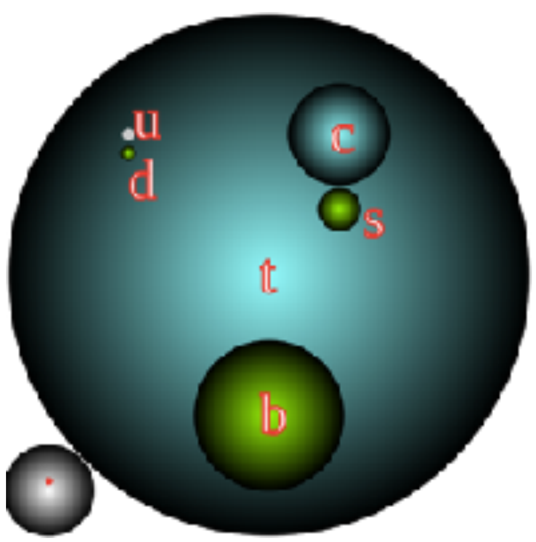
BSM interactions are expected to violate this.

New Physics in 3rd generation

In many motivated models:

New Physics ⟷ 3rd generation fermions

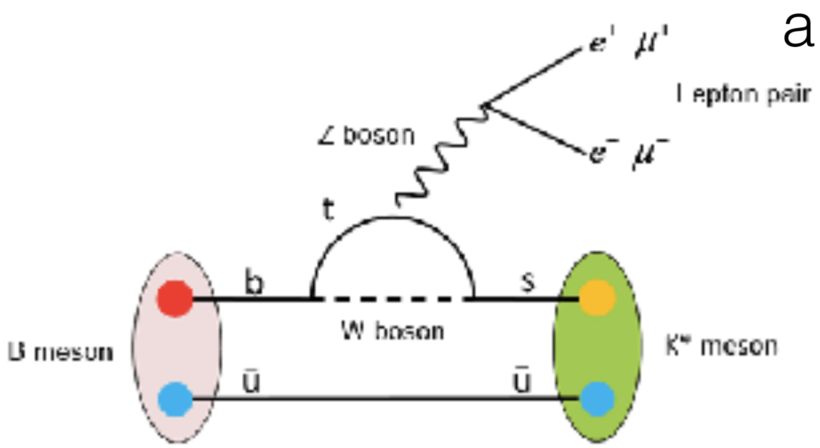
Top quark has biggest mass → biggest coupling to the Higgs. Maybe 3rd family is particularly related to EW scale dynamics.
e.g.: top partners.

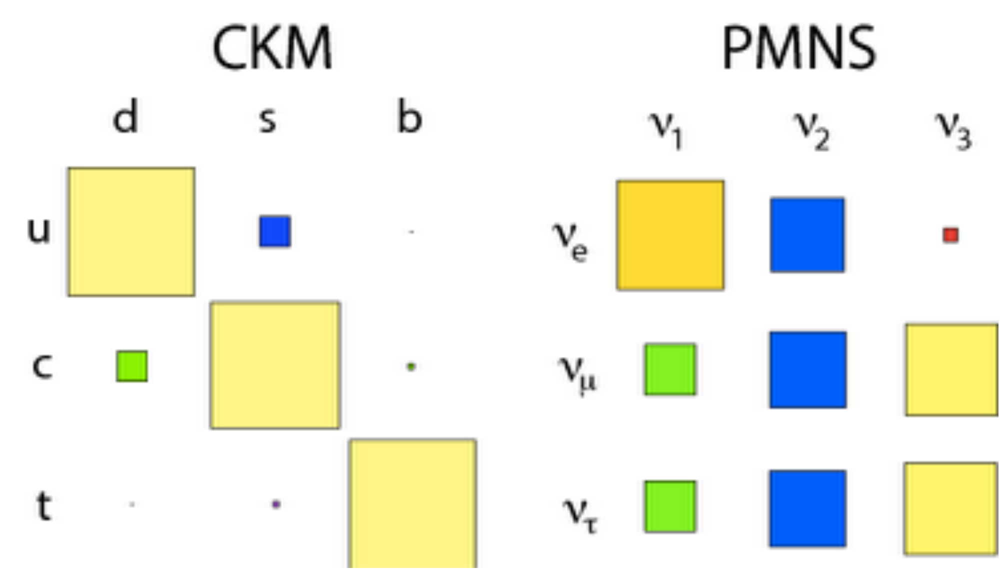


Rare B decays are very sensitive probes of such New Physics scenarios

↓

Suppressed in the SM
by loop factor, GIM,
and small mixing angles

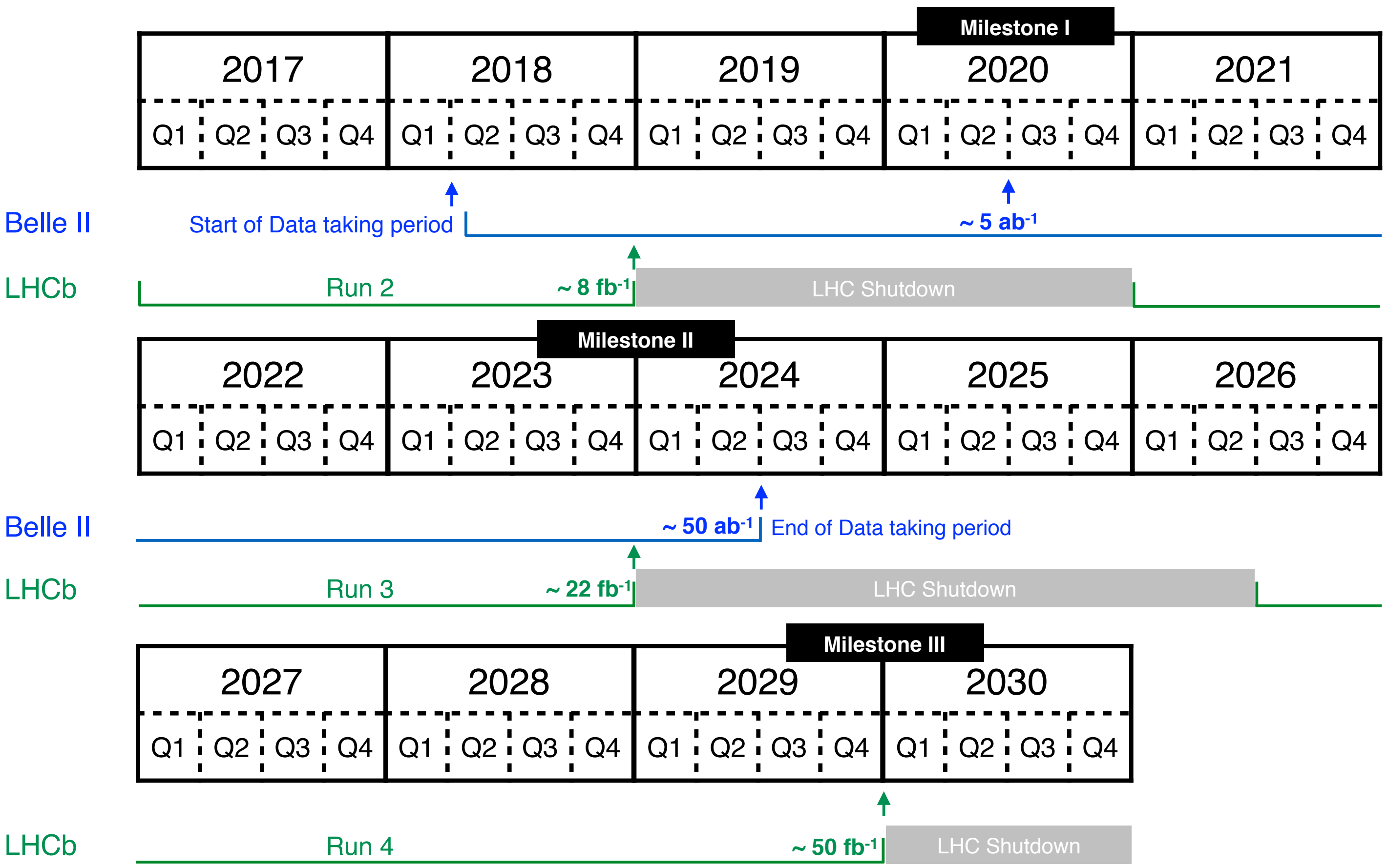




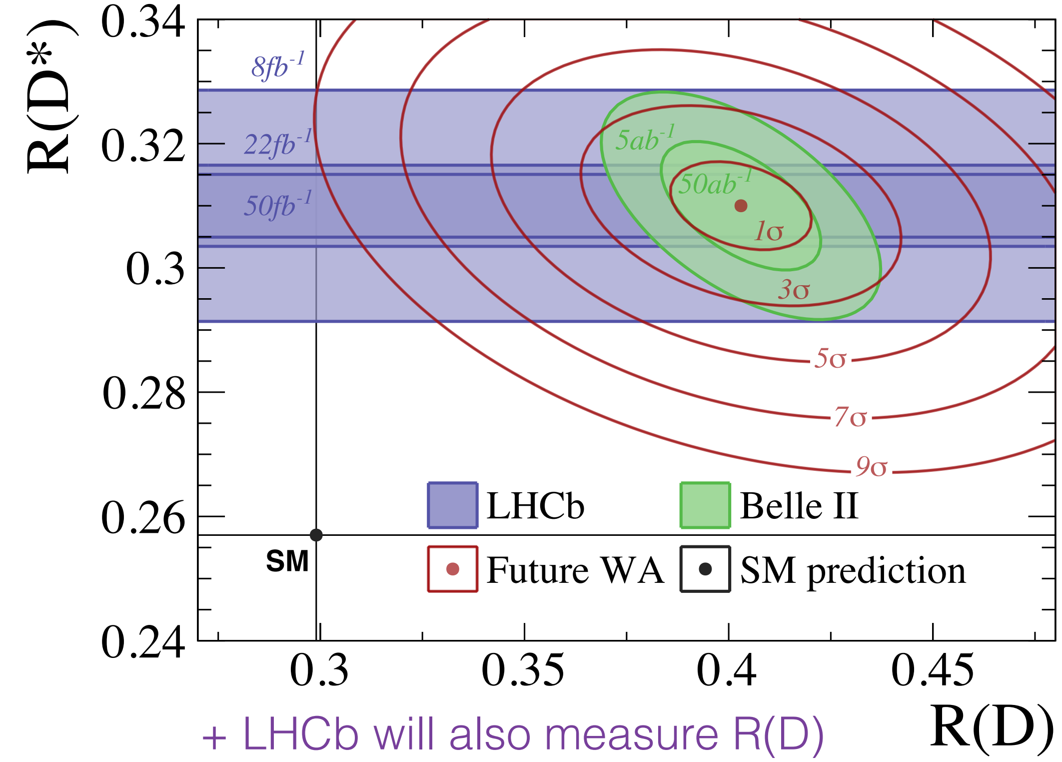
Future Prospects

Albrecht et al 1709.10308

Experimental Timeline



Charged-current



+ LHCb will also measure R(D)

+ very precise measurements on many other related observables.

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

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).

Let us assume these anomalies are due to New Physics.

Can we find at least one consistent solution?

SM EFT fit

Our EFT framework

$$Q_L^i = \begin{pmatrix} V_{ji}^* u_L^j \\ d_L^i \end{pmatrix}$$

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

- Large effect in 3rd gen.
- Smaller effects in light fermions.
- 3-2 mixing of O(CKM)

All this is automatic if the EFT enjoys an approximate

$U(2)_Q \times U(2)_L$

flavor symmetry minimally broken

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

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

Only 5 free parameters in the fit

C_T, C_S, $\lambda^q_{bs} \sim O(V_{ts})$, $\lambda^\ell_{\mu\mu} \sim O(\lambda^\ell_{\tau\mu})^2$, $\lambda^\ell_{\tau\mu}$

Challenge: to fit R(D$^{(*)}$)

The low-energy operator $(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau)$ receives two contributions:

$$R^{\tau\ell}_{D^{(*)}} \approx 1 + 2C_T \left(1 - \lambda^q_{sb} \frac{V^*_{tb}}{V^*_{ts}}\right) = 1.237 \pm 0.053$$

33 term:

$$-\frac{C_T}{v^2} (\bar{Q}^3_L \gamma_\mu \sigma^a Q^3_L)(\bar{L}^3_L \gamma^\mu \sigma^a L^3_L)$$

$$Q^3_L = (V^*_{tb} t_L + V^*_{cb} c_L + V^*_{ub} u_L,\ b_L)^T$$

32 term:

$$-\frac{C_T}{v^2} \lambda^q_{bs} (\bar{Q}^3_L \gamma_\mu \sigma^a Q^2_L)(\bar{L}^3_L \gamma^\mu \sigma^a L^3_L)$$

(we work in the down quark mass basis)

If the **32** term ($\lambda^q{}_{bs}$) is negligible, to fit the anomaly one needs $C_T \sim 0.12$

Assuming a tree-level mediator (required for having such a large effect):

$$C_T \sim g_X^2 \frac{v^2}{M_X^2} \longrightarrow M_X \sim 700\ \text{GeV} \quad (\text{for } g_X \sim 1)$$

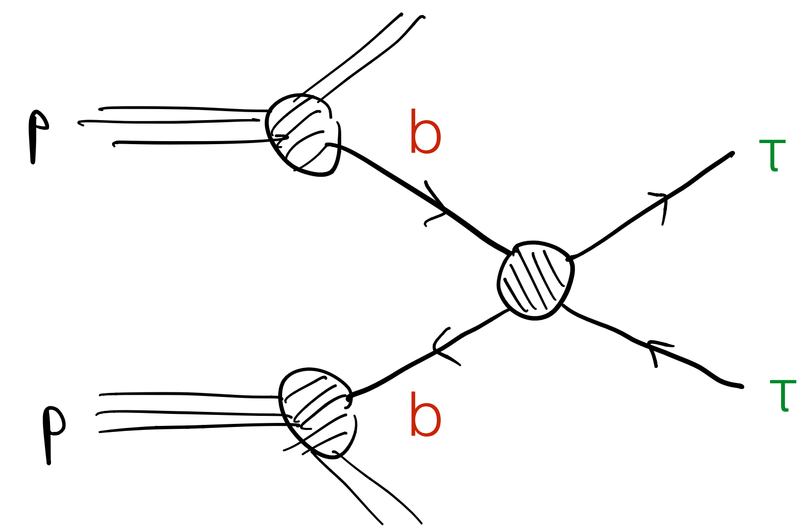
Challenge: to fit R(D$^{(*)}$)

$C_T \sim 0.12$

High-pT

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

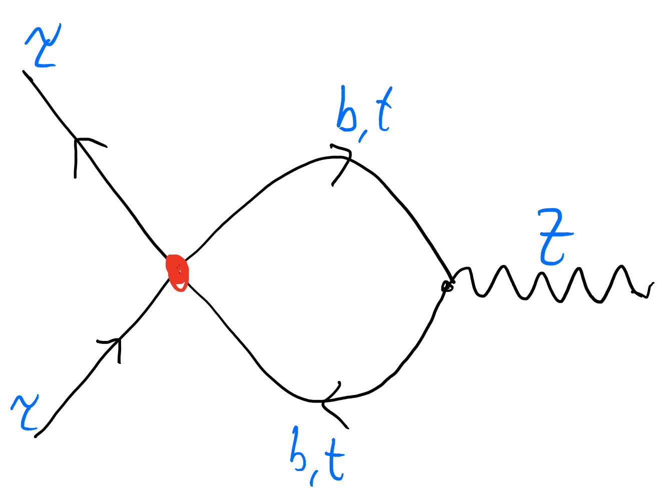
$M_X \sim 700$ GeV for $g_X \sim 1$.



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.

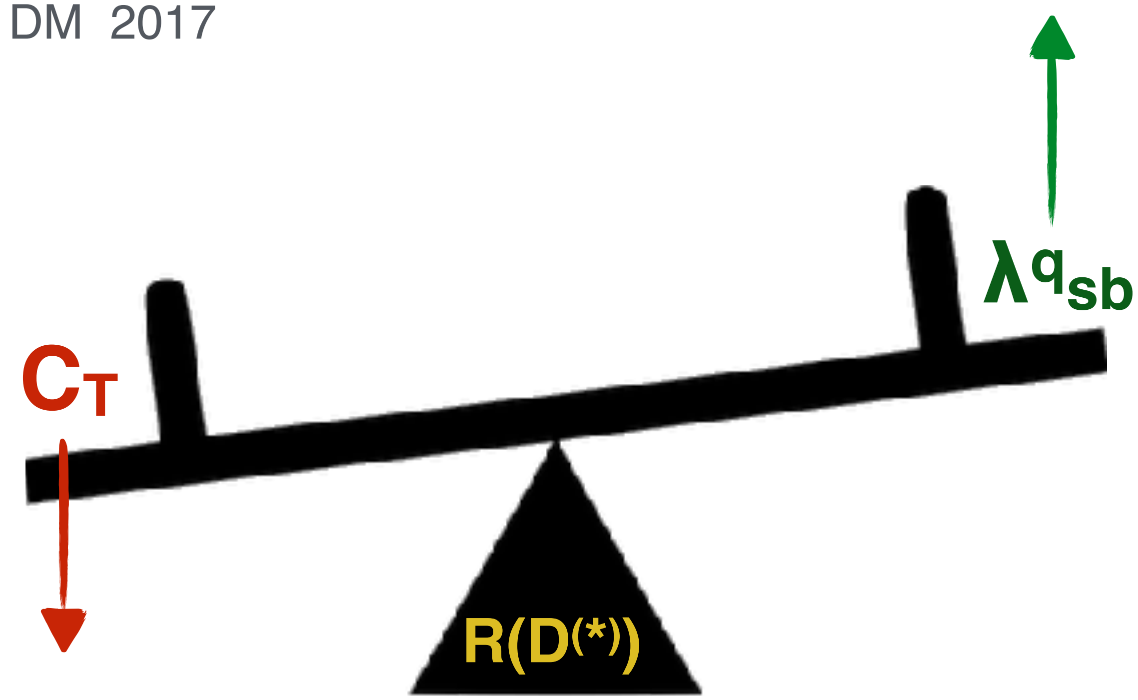
Ferruglio, Paradisi, Pattori 2016-2017

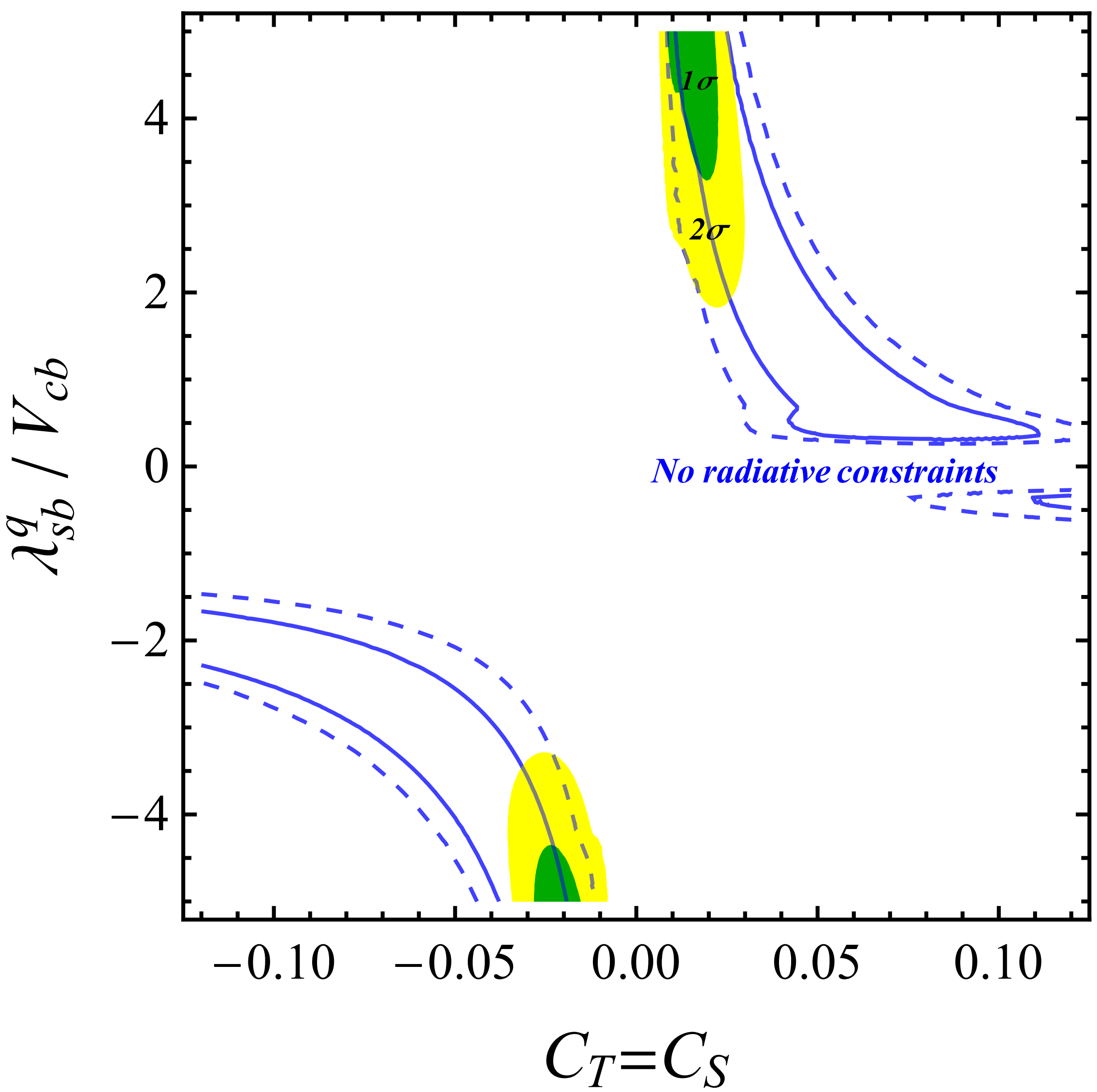
Solution: '*large mixing*'

Buttazzo, Greljo, Isidori, DM 2017

$$R^{\tau\ell}_{D^{(*)}} \approx 1 + 2C_T \left(1 - \lambda^q_{sb} \frac{V^*_{tb}}{V^*_{ts}}\right) = 1.237 \pm 0.053$$

Allow the **natural value** $\lambda^q_{sb} \sim$ (few) $\times$ $|V_{ts}|$.





With $\lambda^q_{sb} \approx 3\ |V_{ts}|$ C_T can be smaller by a factor of 4 → M_X larger by a factor of 2.

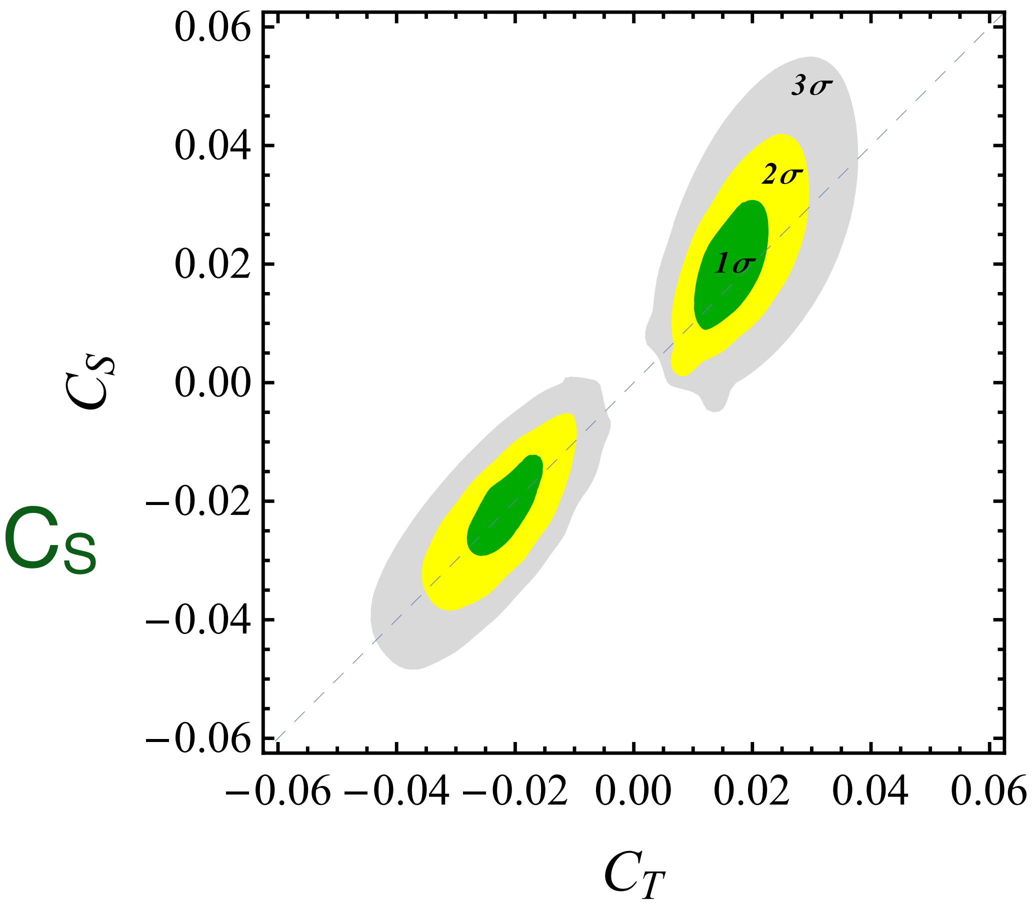
EWPT ($\propto C_{T,S}$) are crucial to select this region.

A posteriori, this also solves the direct searches problems: **allows heavier mediators**.

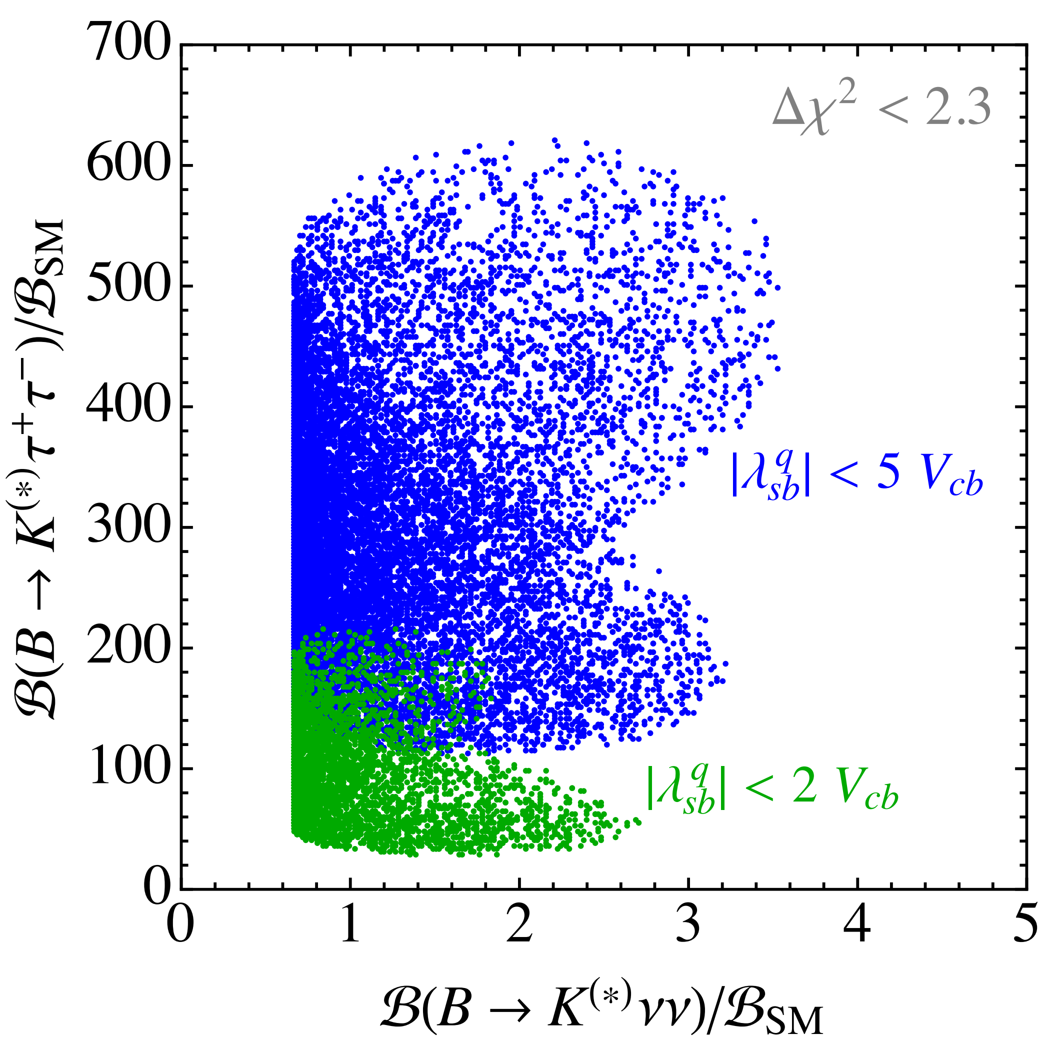
Other effects of large mixing

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

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 $B \to K^* \tau\tau$.

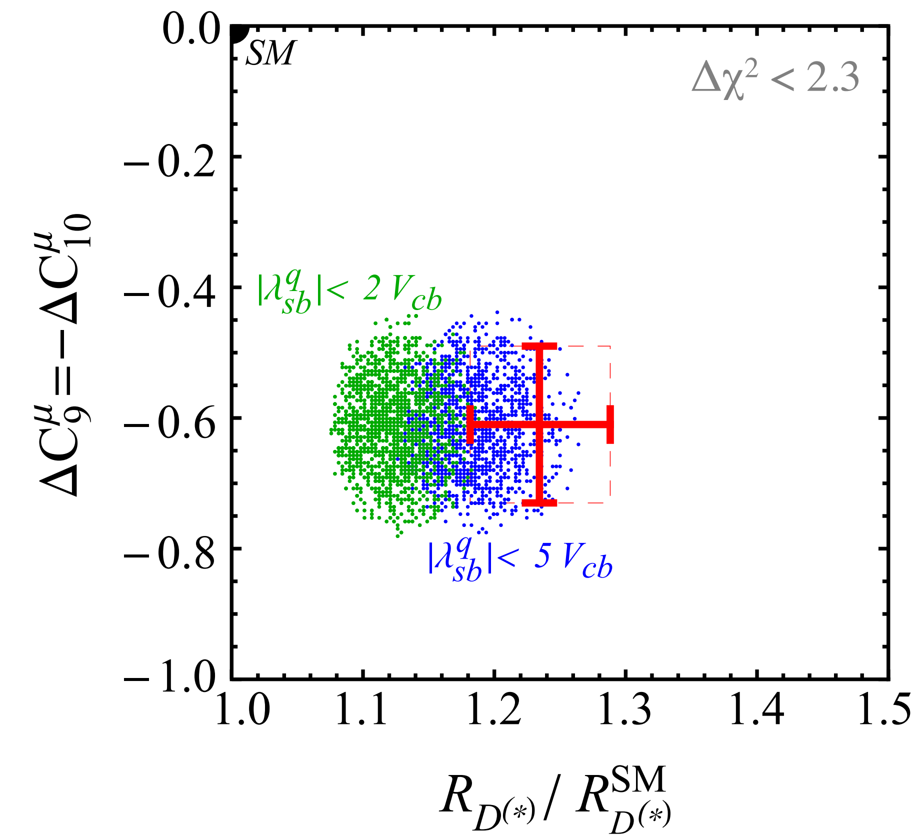
[See also Sebastien's talk from Tuesday]

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

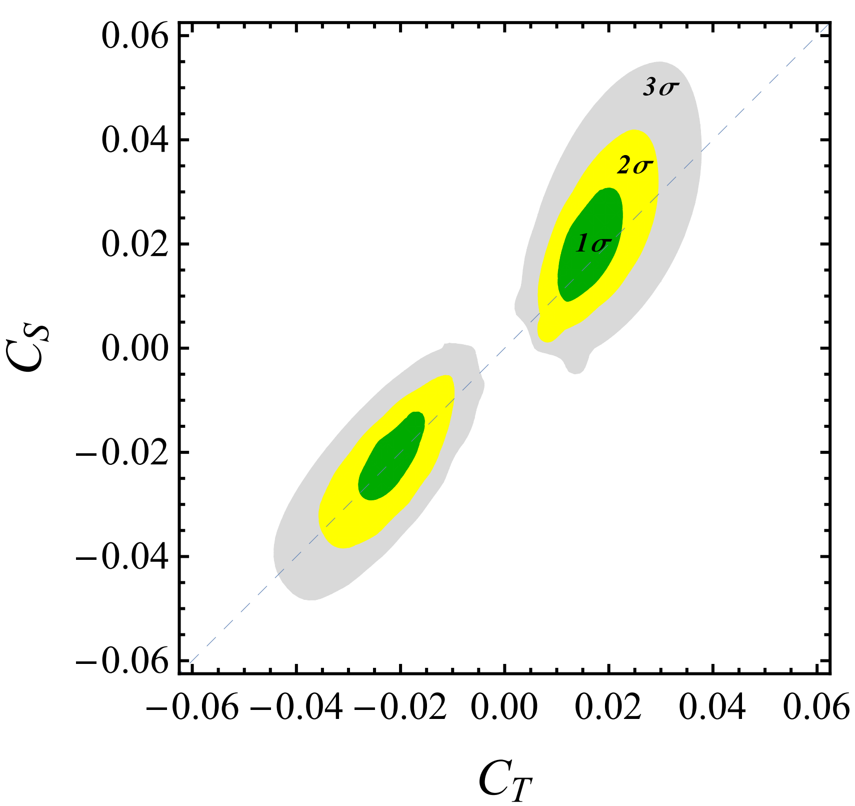
EFT Fit - Results

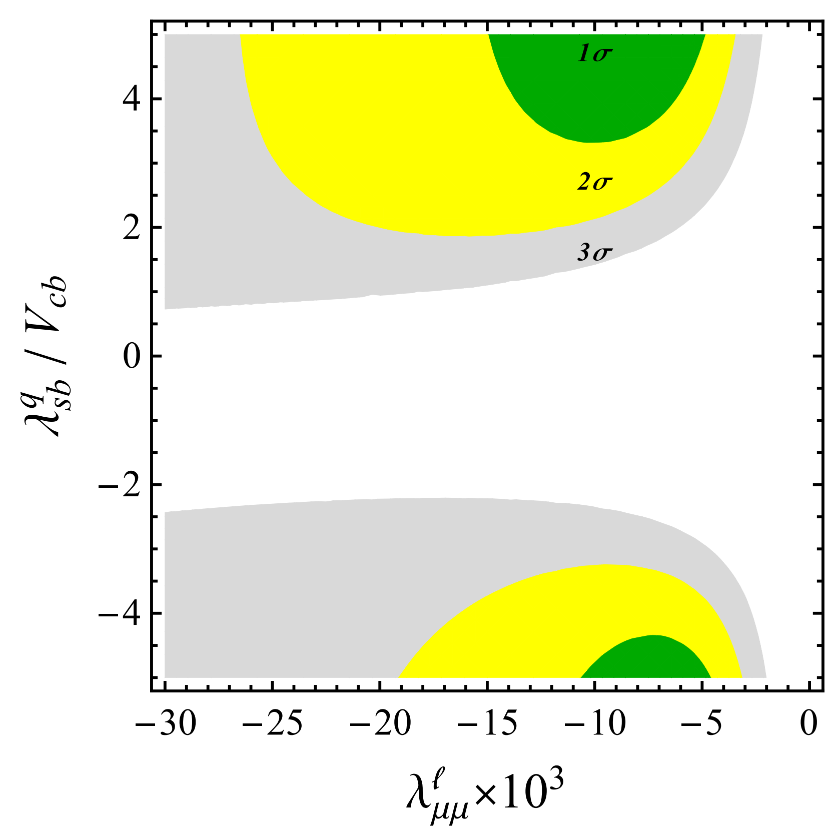
Buttazzo, Greljo, Isidori, DM 2017

Observable	Experimental bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	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]	$-\frac{\pi}{\alpha_{\rm em} V_{tb} V^*_{ts}} \lambda^\ell_{\mu\mu} \lambda^q_{sb} (C_T + C_S)$
$R^{\mu e}_{b\to c} - 1$	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	$1 + \frac{2}{3} \frac{\pi}{\alpha_{\rm em} V_{tb} V^*_{ts} C^{\rm SM}_\nu} (C_T - C_S) \lambda^q_{sb} (1 + \lambda^\ell_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033 C_T - 0.043 C_S$
$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033 C_T - 0.043 C_S$
$\lvert g^W_\tau / g^W_\ell \rvert$	1.00097 ± 0.00098	$1 - 0.084 C_T$
$\mathcal{B}(\tau \to 3\mu)$	$(0.0 \pm 0.6) \times 10^{-8}$	$2.5 \times 10^{-4} (C_S - C_T)^2 (\lambda^\ell_{\tau\mu})^2$



Very good fit





natural values of parameters

- small overall coefficient: higher NP scale
- no special alignment required
- R(K) can be easily fit by a suitable value of $\lambda_{\mu\mu} \sim 10^{-2}$
- $\lambda_{\tau\mu} \sim 0.1$ is OK for LFV bounds.

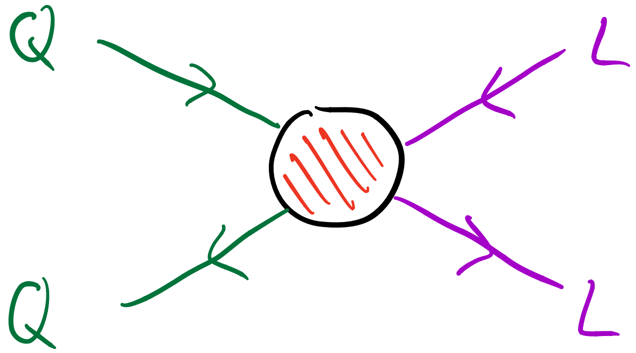
Simplified Models

Strong assumptions:

- both anomalies are due to the same mediator(s).
- LL operators give the leading contribution.

Tree-level mediators

Buttazzo, Greljo, Isidori, DM 2017



The size of R(D) anomaly suggests a tree-level mediator.

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

The Singlet and Triplet operators can be generated at the tree-level by:

Colorless vectors

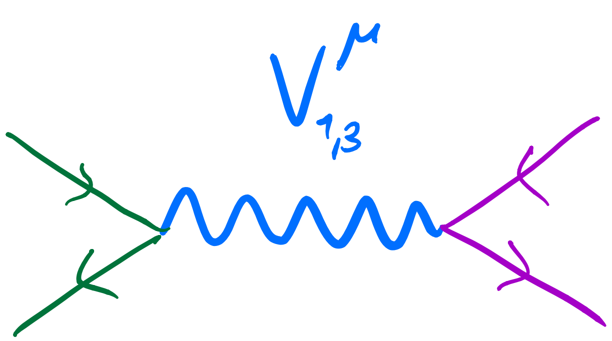
V_3 = W' = (**1**, **3**, 0),
V_1 = B' = (**1**, **1**, 0),

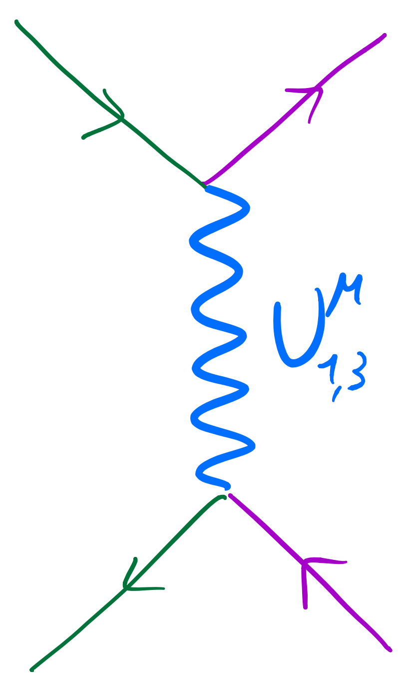
Vector Leptoquarks

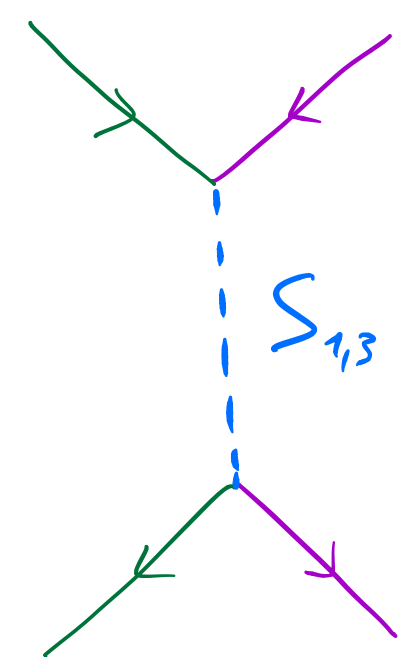
U_1 = (**3**, **1**, 2/3),
U_3 = (**3**, **3**, 2/3),

Scalar Leptoquarks

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



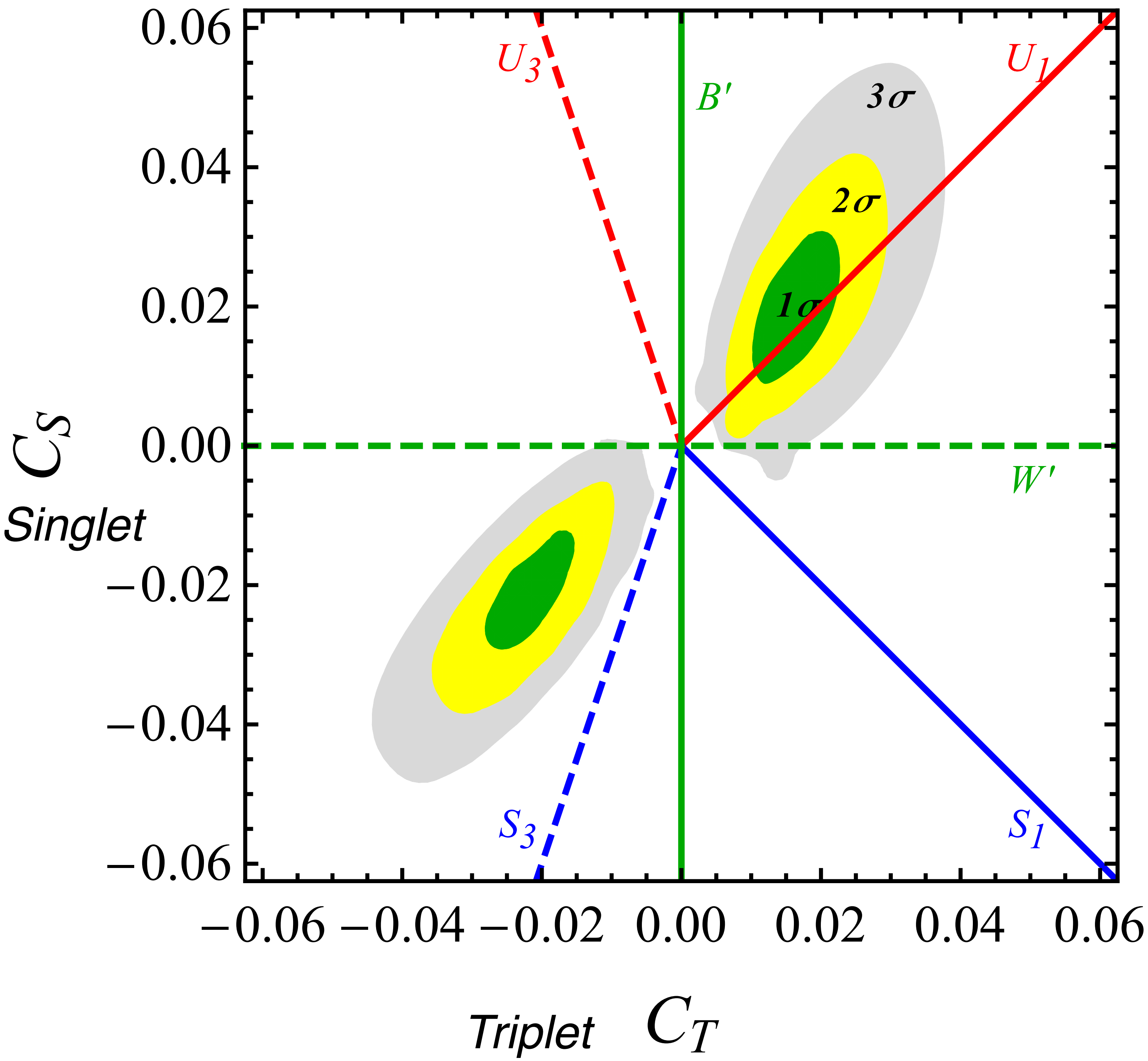




Tree-level mediators

Buttazzo, Greljo, Isidori, DM 2017

Each mediator generates a specific combination of the singlet and triplet operators:



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),

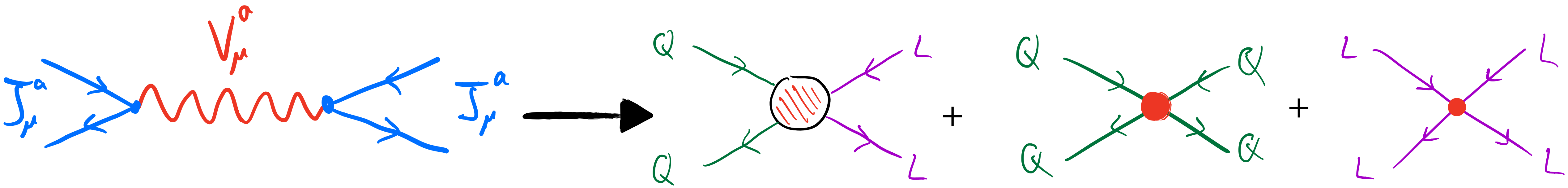
Notable:

The **U_1 can fit perfectly** the anomalies as a single mediator.

Combinations of mediators are also OK

Colorless Vectors

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



This generates also **4-Lepton and 4-Quark** operators.
Tree-level contribution to Bs mixing

C_T λ^q_{sb} Large-mixing, Small $C_{T,S}$

This corresponds to the fit shown previously.
Direct searches and EWPT are OK.

However

Bs mixing is too large by a factor ~ 500.
Requires a tuning of ~ 10^{-4} level with additional contributions (e.g. from RH currents)

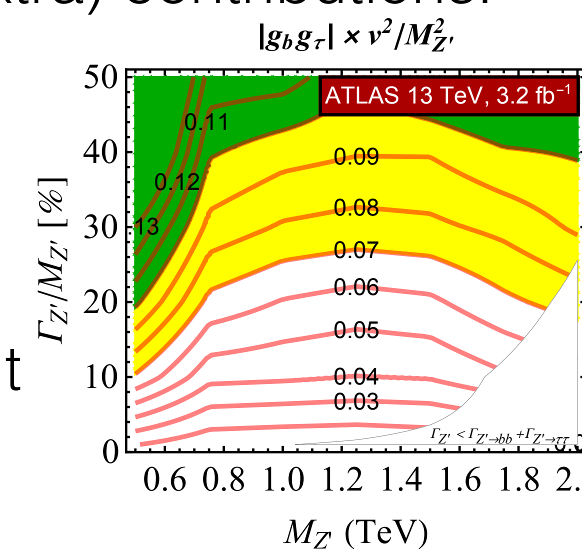
C_T λ^q_{sb} Small-mixing, Large $C_{T,S}$

Now Bs mixing can be OK.

RGE effects into EWPT are large, but can be tuned with additional (extra) contributions: 10% tuning

However

the Z' is excluded by direct searches, unless it has a very large width



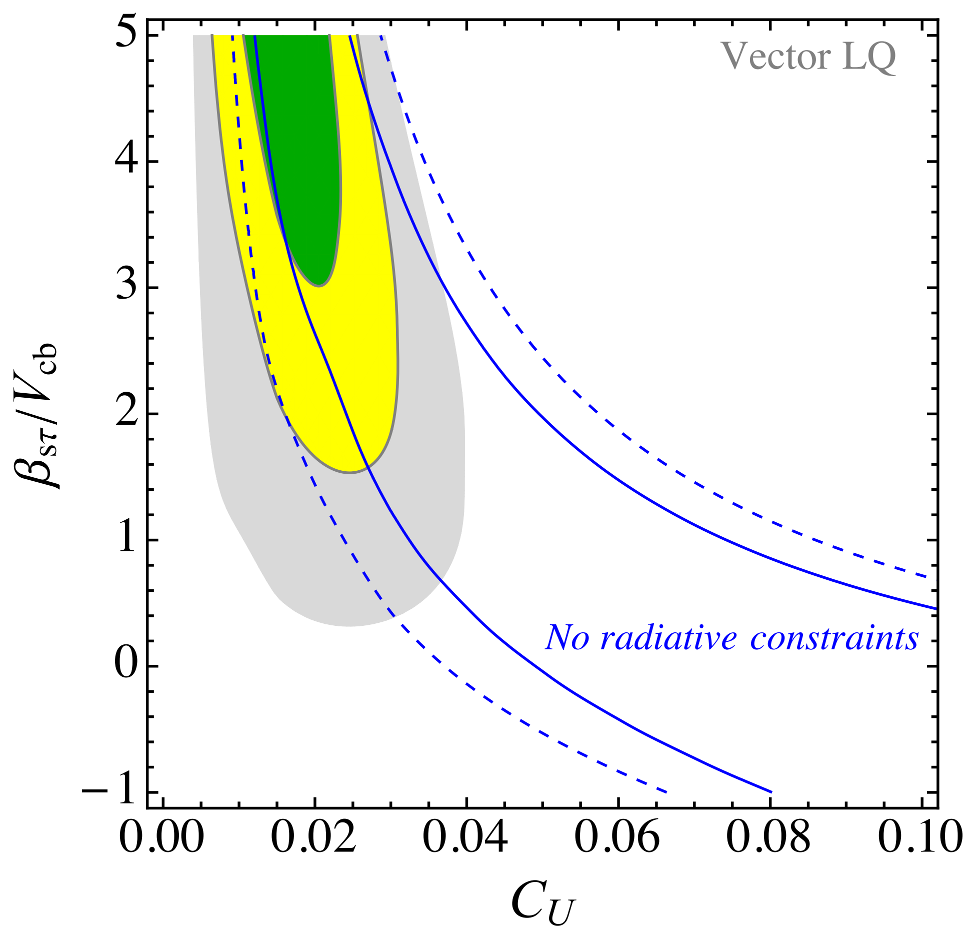
Vector Leptoquark

$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

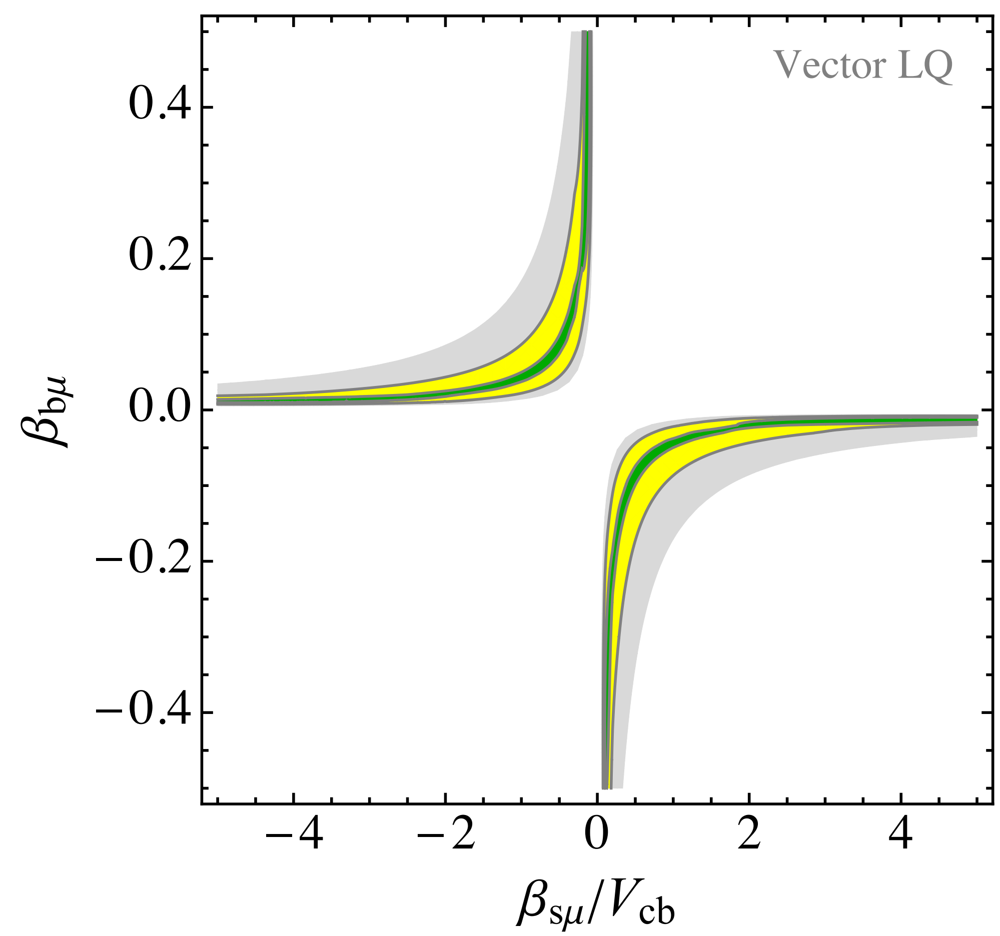
$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{1,\mu\nu}U^{1,\mu\nu} + M_U^2 U^\dagger_{1,\mu}U_1^\mu + g_U(J_U^\mu U_{1,\mu} + \text{h.c.})\,,$$

$$J_U^\mu \equiv \beta_{i\alpha}\;\bar{Q}_i\gamma^\mu L_\alpha\;.$$

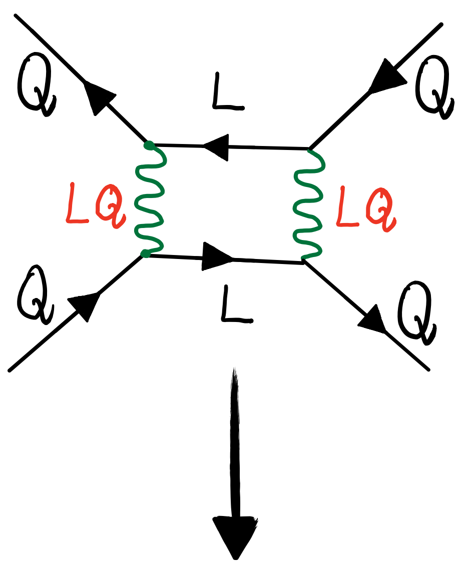
Requiring a single mediator, the vector LQ is the simplest solution.
It easily provides a good fit since dynamically $C_S = C_T$.



$$C_U = v^2|g_U|^2/(2M_U^2) > 0$$



B_s-mixing



Not calculable in the simplified model
Potentially dangerous.

Scalar Leptoquarks

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

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

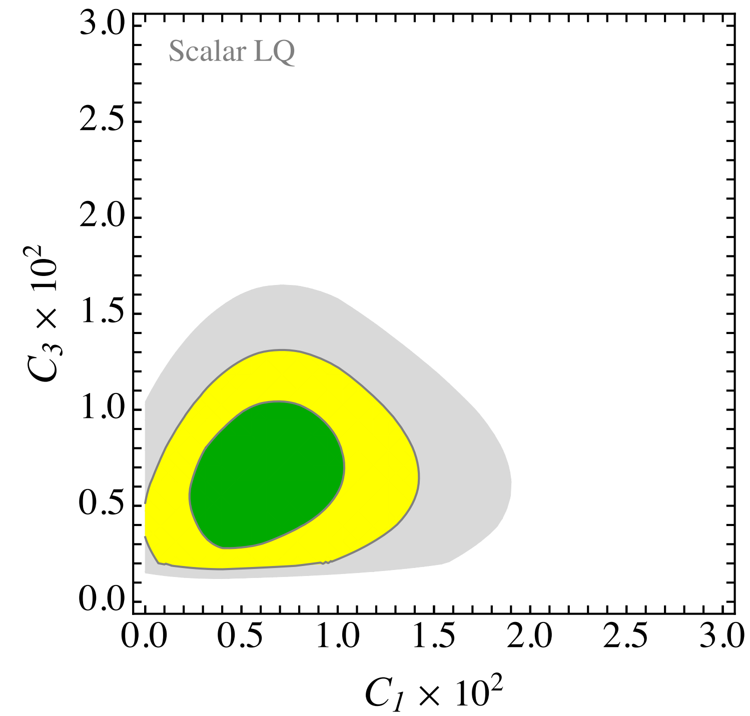
$$|\epsilon_{1,3}|^2 = C_{1,3} = v^2 |g_{1,3}|^2 / (4 M_{S_{1,3}}^2) > 0 \qquad C_S = -C_1 - 3C_3 \,, \qquad C_T = C_1 - C_3$$

EFT fit

$$R_{D^*}/R_{D^*}^{\text{SM}} \approx 1 + 2\left((|\epsilon_1|^2 - |\epsilon_3|^2) - (|\epsilon_1|^2 \beta_{1,s\tau} - |\epsilon_3|^2 \beta_{3,s\tau}) \frac{V_{tb}^*}{V_{ts}^*} \right)$$

$$\delta\mathcal{B}(B \to K^* \nu\nu) \propto \left(\frac{|\epsilon_1|^2 \beta_{1,s\tau} + |\epsilon_3|^2 \beta_{3,s\tau}}{0.01 |V_{ts}|} \right)$$

$$\delta g_{\tau_L} \approx 0.08 (|\epsilon_1|^2 + |\epsilon_3|^2) = (0.16 \pm 0.58) \times 10^{-3}$$



→ The flavor structure of the two LQ has to be misaligned: $\beta_{1,s\tau} \approx -\beta_{3,s\tau} \approx (\text{few}) \times |V_{ts}|$

→ Some residual tension at the ~1.5σ level between Zττ and R(D)

→ B_s-mixing is calculable and in tension with R(D):

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

Requires a tuning with extra contributions at the ~10% level.

Direct Searches

[D.M. 1803.10972]

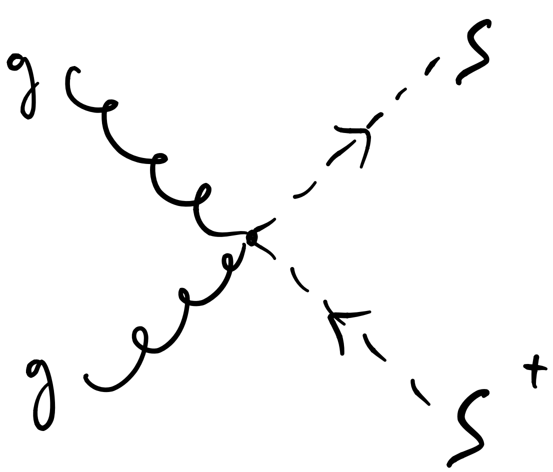
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$, $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

$s_{1,-\frac{1}{3}}$ $s_{3,-\frac{4}{3}}$, $s_{3,-\frac{1}{3}}$, $s_{3,\frac{2}{3}}$ ~ 3 of $SU(3)_c$

For LHC only the interactions with the third generation are relevant:

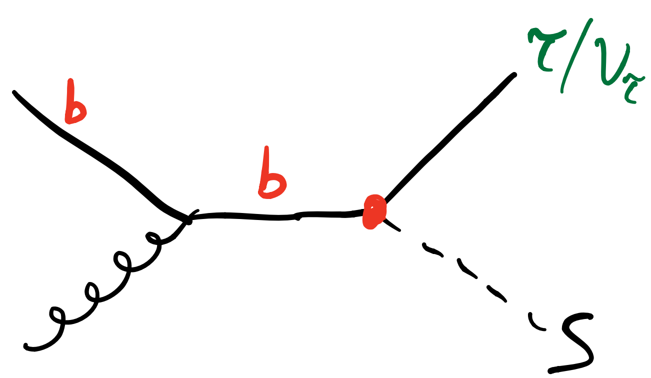
$$\mathcal{L}_{LQ} = g_1 s^\dagger_{1,-\frac{1}{3}} \left(\bar{t}^c_L \tau_L - \bar{b}^c_L \nu_\tau\right) + g_3 s^\dagger_{3,-\frac{1}{3}} \left(-\bar{t}^c_L \tau_L - \bar{b}^c_L \nu_\tau\right) + h.c.$$
$$+ \sqrt{2} g_3 \left(s^\dagger_{3,\frac{2}{3}} \bar{t}^c_L \nu_\tau - s^\dagger_{3,-\frac{4}{3}} \bar{b}^c_L \tau_L \right) + h.c. \ ,$$

QCD pair production



σ depends only on m_S

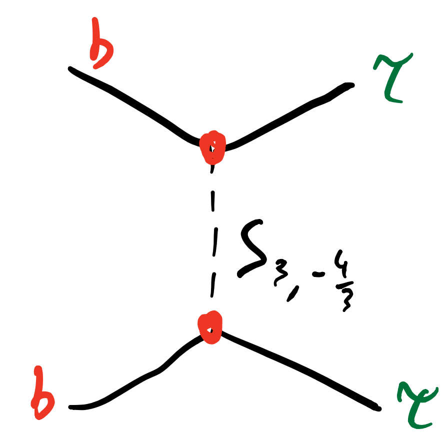
single production



$\sigma \propto |g_{1,3}|^2$

More sensitive at high masses

off-shell



For high masses:

$\sigma \propto (|g_{1,3}|^2 / m_S^2)^2 \propto (C_{1,3})^2$

Direct Searches

[D.M. 1803.10972]

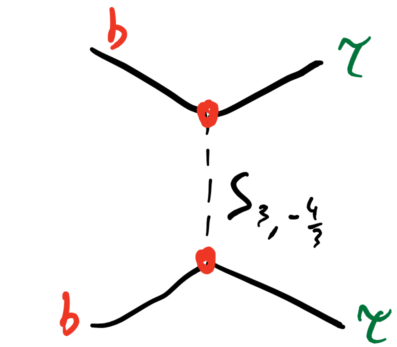
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$, $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

(All very similar for the vector LQ)

$$\mathcal{L}_{LQ} = g_1 s^\dagger_{1,-\frac{1}{3}} \left(\bar{t}^c_L \tau_L - \bar{b}^c_L \nu_\tau\right) + g_3 s^\dagger_{3,-\frac{1}{3}} \left(-\bar{t}^c_L \tau_L - \bar{b}^c_L \nu_\tau\right) + h.c.$$
$$+ \sqrt{2} g_3 \left(s^\dagger_{3,\frac{2}{3}} \bar{t}^c_L \nu_\tau - s^\dagger_{3,-\frac{4}{3}} \bar{b}^c_L \tau_L\right) + h.c. \,,$$

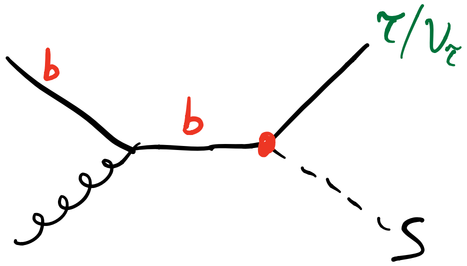
Limits and prospects from $\tau\tau$ final state (t-channel exchange of $S_{3,-4/3}$)

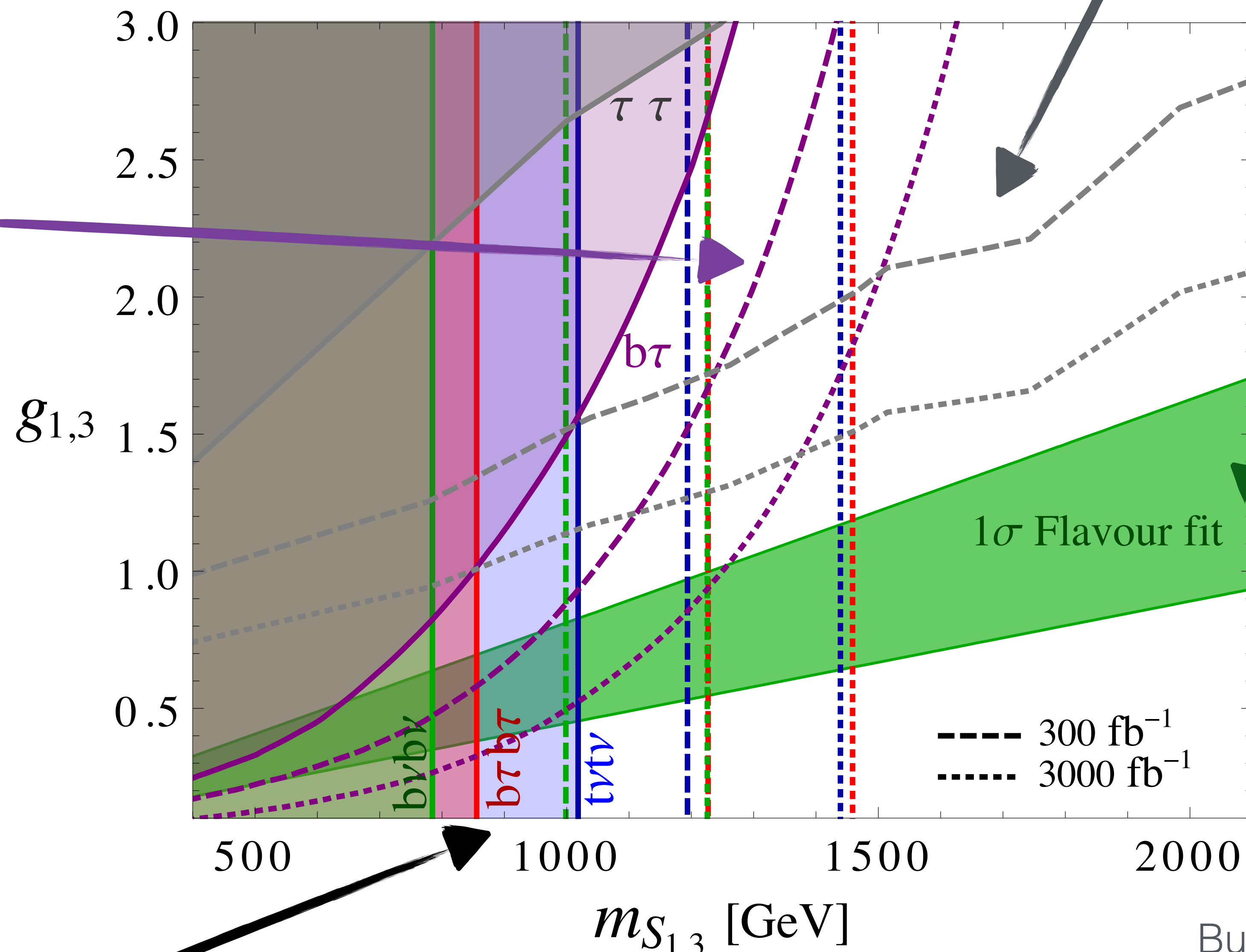
Faroughy et al. 1609.07138

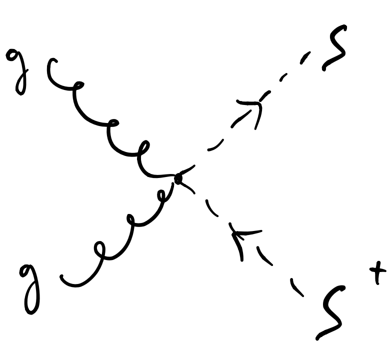


Limits and prospects from single-production of LQ in bτ final state (for $S_{3,-4/3}$)

CMS-PAS-EXO-17-029







Limits and prospects from LQ pair production.

CMS 1703.03995, CMS 1803.02864.
CMS-PAS-SUS-18-001

Region fitting B-anomalies (assuming B_s mixing is tuned)

Buttazzo et al. 1706.07808

Tree-level mediators for B anomalies

Colorless Vectors

Killed
either by B_s mixing
or direct searches.

Scalar Leptoquarks

B_s mixing still gives some tension with R(D)

Vector Leptoquark

UV completions

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

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; Dorsner et al 2017; Crivellin, Muller, Ota 2017; …
- Elementary LQ gauge boson [See Marzia's talk]
  Di Luzio, Greljo, Nardecchia 2017; Calibbi, Crivellin, Li 2017; Bordone, Cornella, Fuentes-Martin, Isidori 2017
- Elementary W', Z' gauge bosons
  Cline, Camalich 2017, Megias, Quiros, Salas, Panico [in 5D] 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

Vector LQ

$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

The U_1 LQ gives the best fit of the anomalies with smallest number of param.

The massive vector of Pati-Salam has same quantum numbers as U_1 LQ.

2 classes of UV completions

Gauge boson

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

Composite vector

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

Both also predict massive color-octed and massive Z', which couple to SM fermions.

It is crucial to avoid large tree-level FCNC effects and direct searches limits on these.

- All these constraint point to strong gauge couplings, at the limit of perturbativity.
- Doesn't address the EW hiearchy problem.

The theory is fully strongly coupled at that scale: no calculability

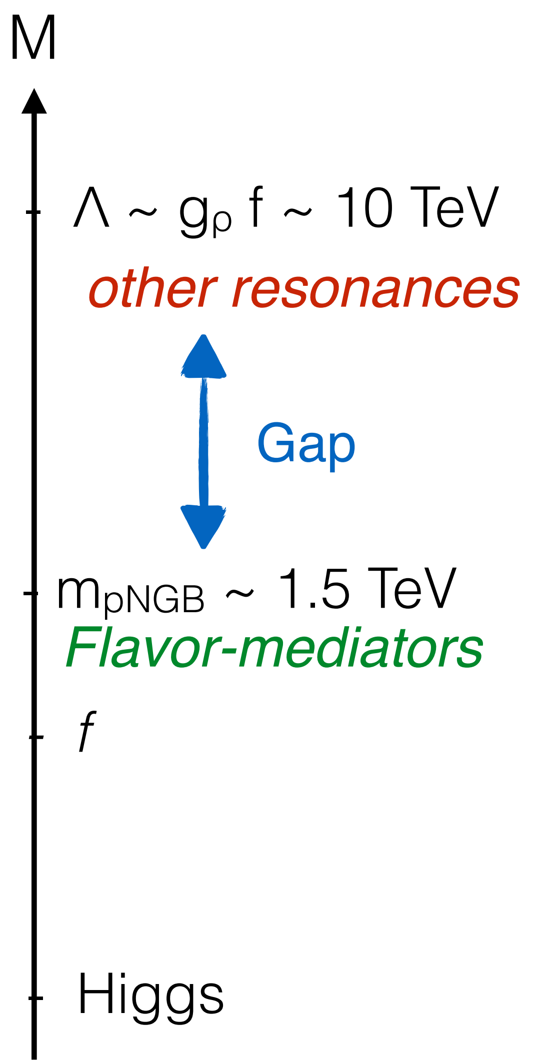
The issue is:

$$m_{VLQ} \sim \Lambda$$

No parametric splitting between LQ and other states

Composite Scalar LQ

One would like a mass splitting between the B anomalies mediator and other states: Z', heavy gluons, etc..



Scalar LQ as pseudo-Goldstone boson

A mass splitting in composite models is natural between the (pseudo) Goldstone bosons and the other resonances.

Like between pions and ρ mesons in QCD.

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

Requirements:

- Fundamental description of the strong-sector QCD-like
- Higgs boson and the two scalar LQ as Goldstones
- Custodial symmetry

Fermionic Composite Higgs

Buttazzo, Greljo, Isidori, D.M. 2017; D.M. 1803.10972

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

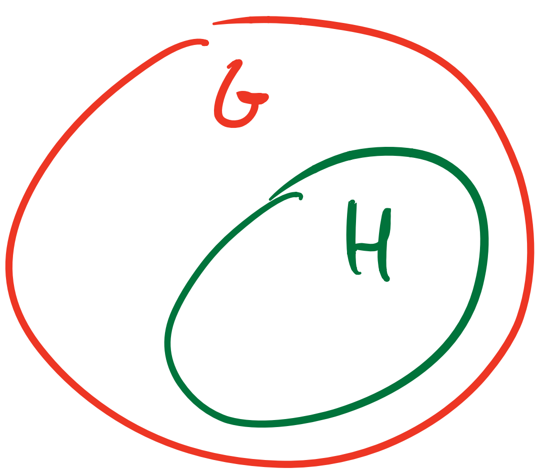
"HyperColor"

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	$\mathbf{N_{HC}}$	$\mathbf{3}$	$\mathbf{2}$	$Y_L - 1/3$

$\mathrm{SU}(N_{\mathrm{HC}})$ confines at $\Lambda_{\mathrm{HC}} \sim 10$ TeV

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

D.M. 1803.10972

$$G = SU(10)_L \times SU(10)_R \times U(1)_V \longrightarrow H = SU(10)_V \times U(1)_V$$

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

In terms of SM representations

Two Higgs doublets:	$H_{1,2} \sim (\mathbf{1},\mathbf{2})_{1/2}$
Singlet and Triplet LQ:	$S_1 \sim (\mathbf{3},\mathbf{1})_{-1/3} \;+\; S_1 \sim (\mathbf{3},\mathbf{3})_{-1/3}$
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.

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

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

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:

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

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

Good structure to fit the flavour anomalies!

Imposing conservation of B & L such that the proton is stable, automatically allows only the Higgses Yukawas and LQ couplings.

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:

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

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

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

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

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 $\tau \to \mu\gamma$.

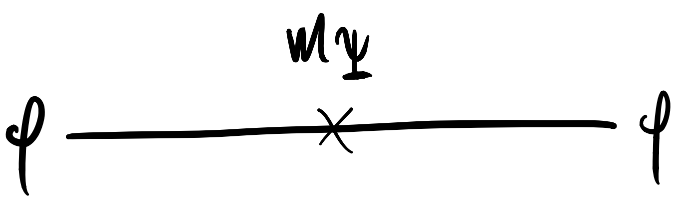
Requires $g_1^u \lesssim 10^{-2} g_1$

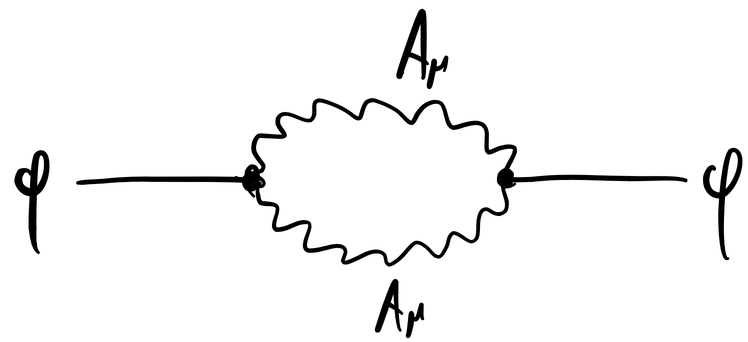
Introducing an extra approximate $U(1)_e$ symmetry for the RH leptons to protect the τ Yukawa would give:

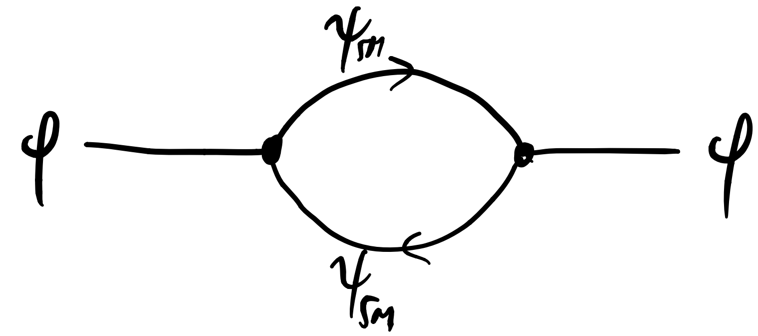
$$g_1^u/g_1 \sim y_\tau/y_t \sim 10^{-2}$$

Scalar Potential

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







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

$$V_{\mathcal{G}} = -\frac{3 f^2 \Lambda_{HC}^2}{16\pi^2} \sum_X c_X \mathrm{Tr}\left[\mathcal{G}_X^L U \mathcal{G}_X^R U^\dagger\right]$$

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

$$V_{\mathrm{LQ}} = -\frac{(c_1 g_1^2 + c_1^u g_1^{u2})\Lambda_{HC}^2}{8\pi^2}|S_1|^2 - \frac{c_3 g_3^2 \Lambda_{HC}^2}{8\pi^2}|S_3|^2$$

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

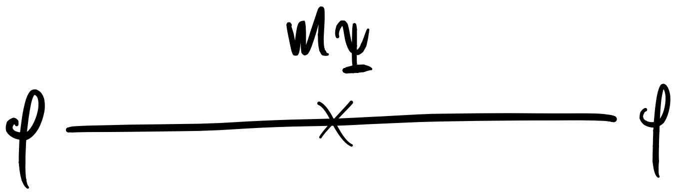
$$\Delta m^2_{S_1} \approx (0.17\Lambda_{HC})^2 \,, \quad \Delta m^2_{S_3} \approx (0.21\Lambda_{HC})^2 \,. \quad \Delta m^2_{\tilde{R}_2, T_2} \approx (0.19\Lambda_{HC})^2 \,.$$ ~ **3** of SU(3)c

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

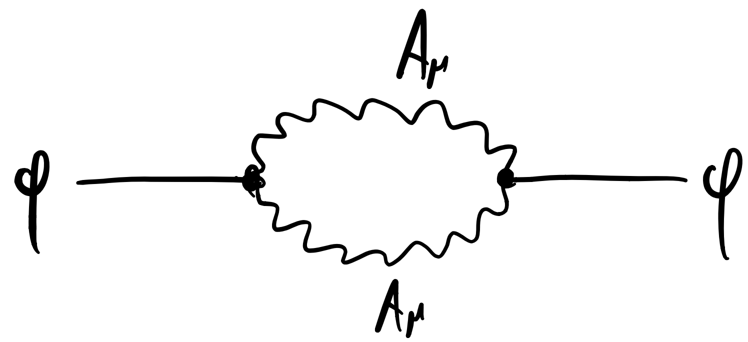
$$\Lambda_{HC} \gtrsim 10 \text{ TeV}$$

Scalar Potential

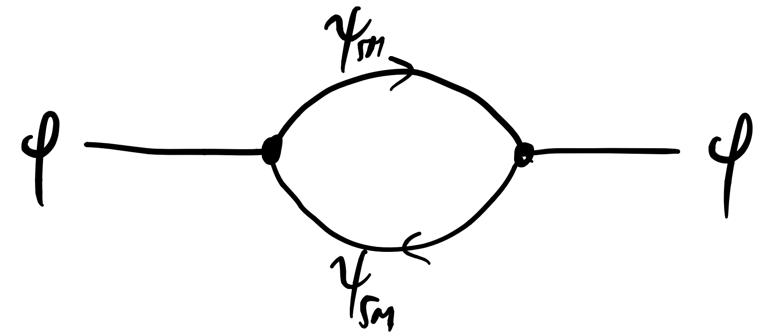
The pNGB potential arises at 1-loop from all the explicit breaking terms



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



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



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

$$V_{\mathrm{LQ}} = -\frac{(c_1 g_1^2 + c_1^u g_1^{u2})\Lambda^2_{HC}}{8\pi^2}|S_1|^2 - \frac{c_3 g_3^2 \Lambda^2_{HC}}{8\pi^2}|S_3|^2$$

Tuning to get EWSB as in usual Composite Higgs models:

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

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

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

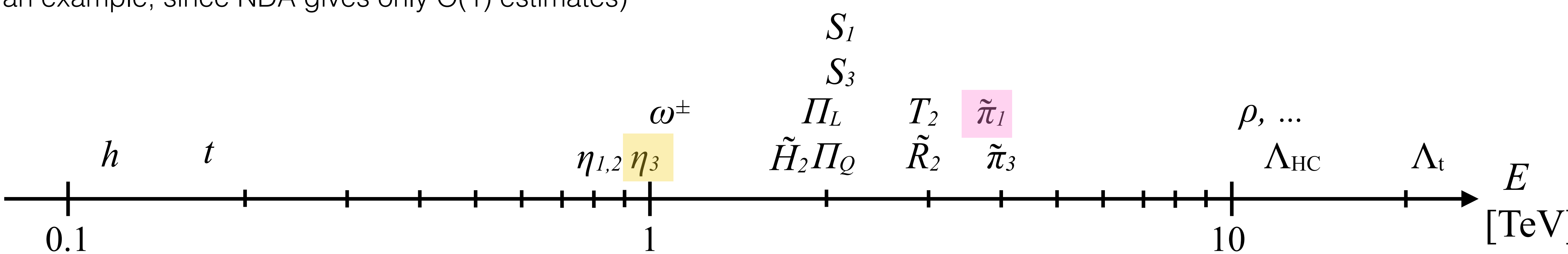
The deviations in Higgs couplings and the EWPT are similar to most Composite Higgs models.

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)



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

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

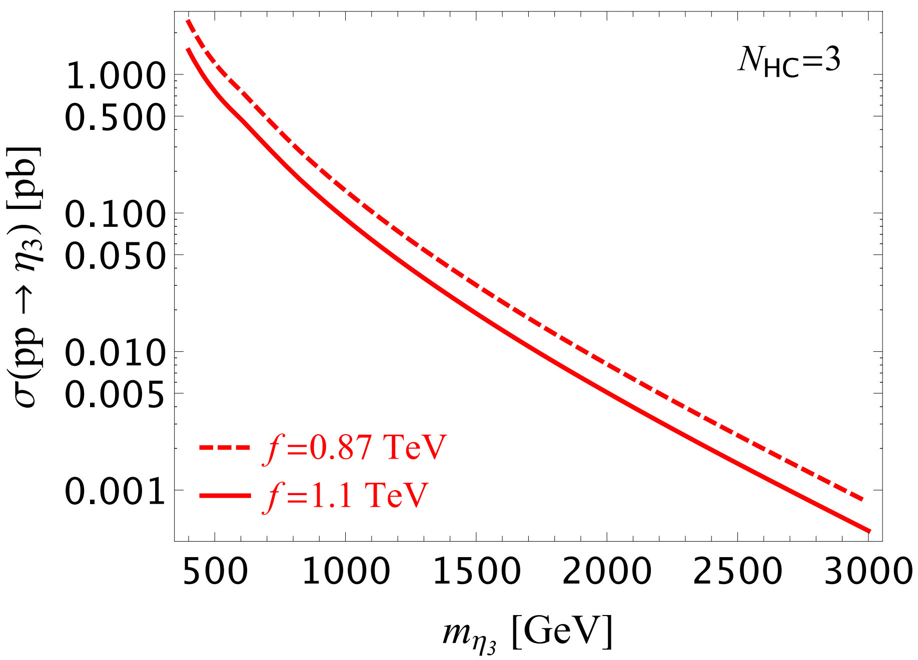
$A^{\phi\alpha}_{\beta\gamma}$	g_1^2	g_2^2	g_3^2	$g_1 g_2$	$g_1 g_3$	$g_2 g_3$
η_1	Y_L	0	0	0	0	0
η_2	$-\frac{1}{4\sqrt{2}}$	$\frac{1}{4\sqrt{2}}$	0	0	0	0
η_3	$\frac{1+48Y_L}{12\sqrt{30}}$	$-\frac{\sqrt{3}}{4\sqrt{10}}$	$-\frac{1}{\sqrt{30}}$	0	0	0
$\tilde{\pi}_1$	0	0	$d^{\alpha\beta\gamma}/(2\sqrt{2})$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

Can be produced in gg-fusion!

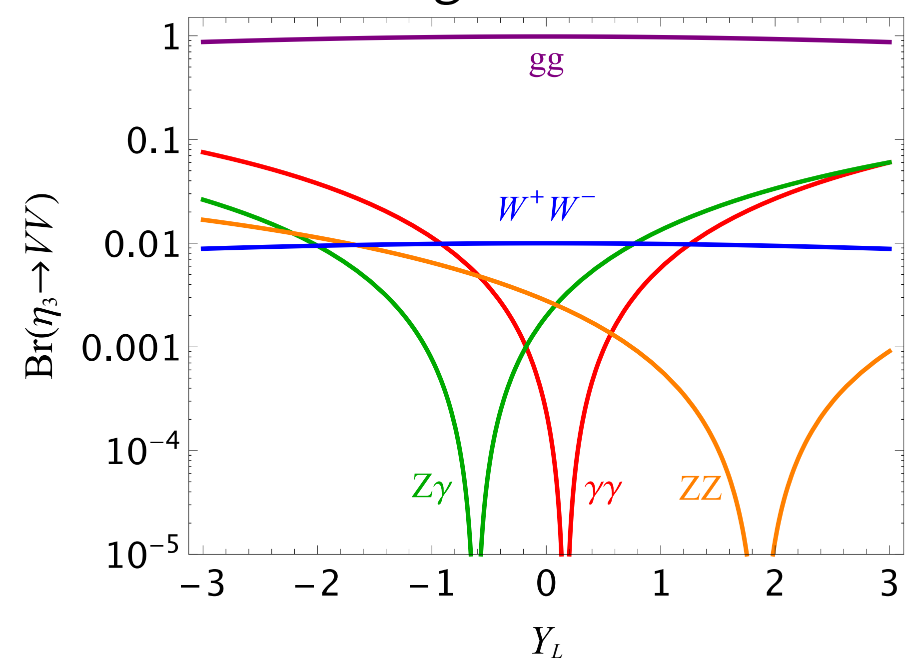
Singlet η3

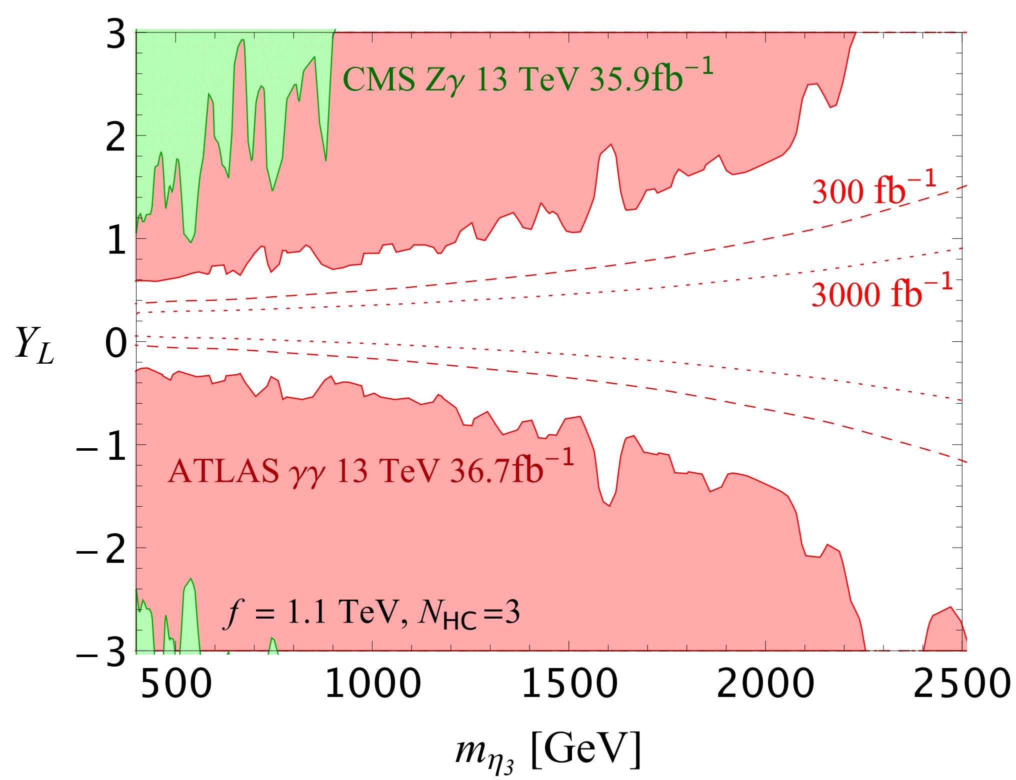
Couples to gluons and EW gauge bosons.
Possible signal in diphoton, ZZ,Zγ searches… reminds you of something?

Production xsec at LHC (13TeV)



Branching ratios

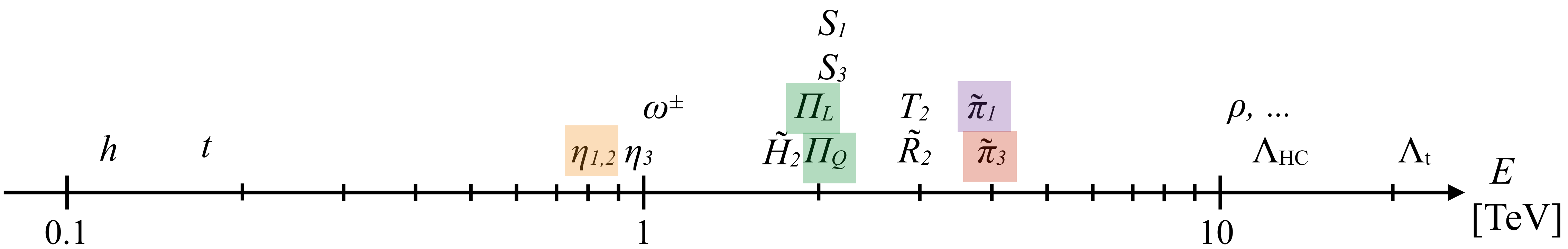




Excluded region from present searches and prospects from γγ

Already puts important limits on the model parameters!

Other pNGBs

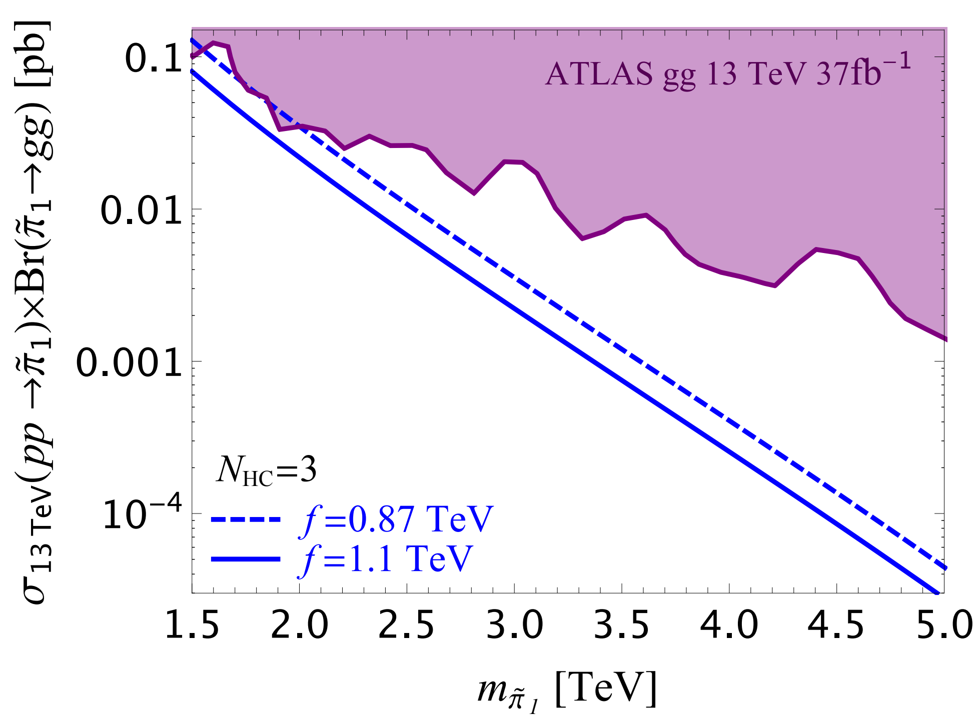


The other singlets $\eta_{1,2}$ and the triplets $\Pi_{L,Q}$ do not couple to gluons.

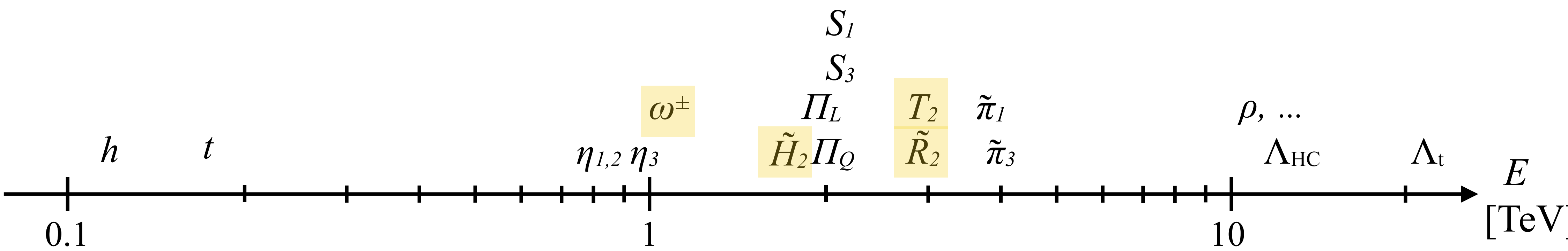
The SU(2)$_L$-triplet and color-octet $\tilde{\pi}_3$ only couples to gluon+EW gauge boson.

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

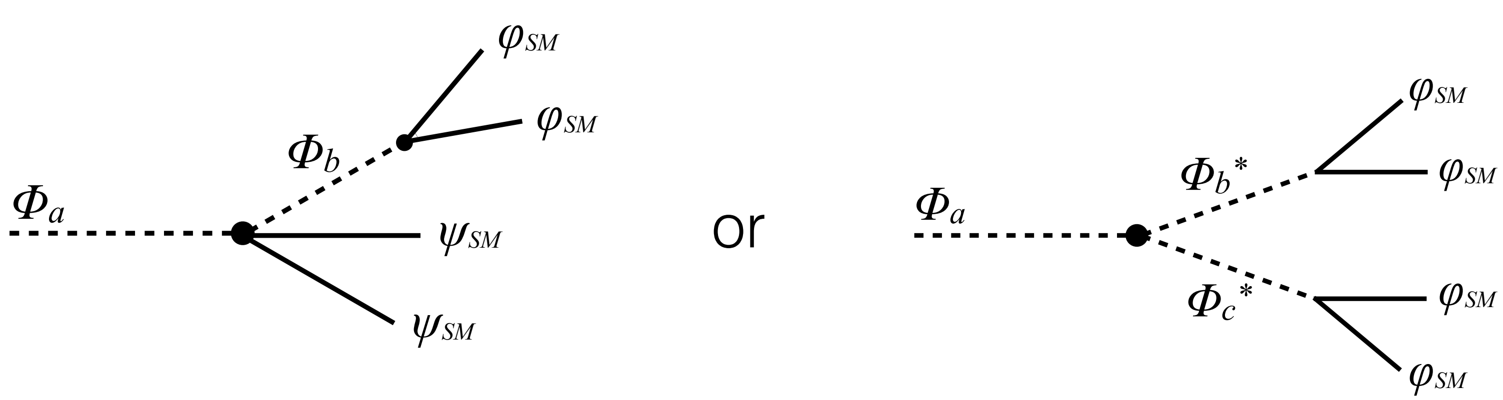
The color-octet $\tilde{\pi}_1$ can be searched in dijet but in this model it is too heavy for the LHC.



Other pNGBs



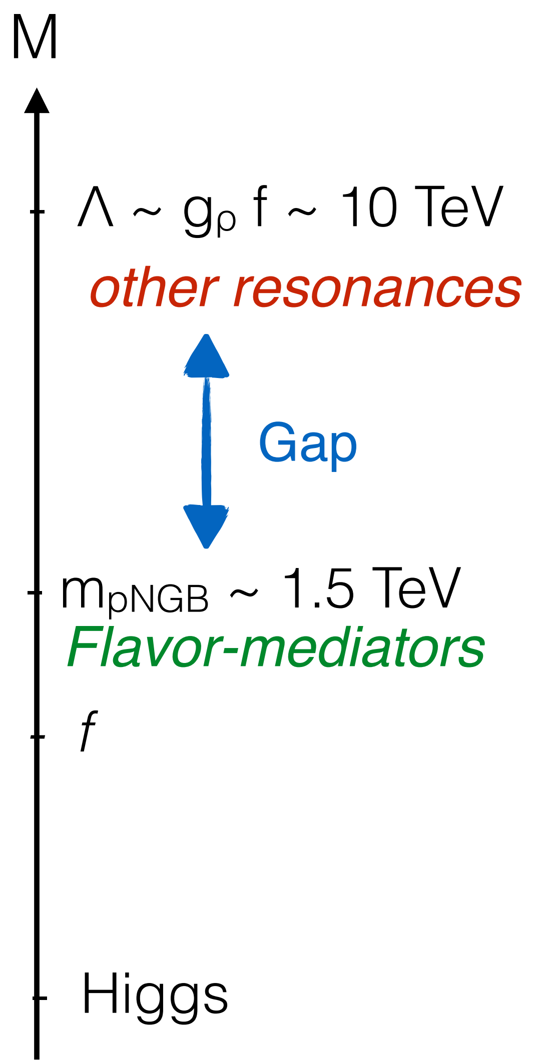
The other pNGBs can be pair-produced but do not decay directly to SM particles.
They can decay via higher-order terms such as:



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

Composite pNGB Scalar LQ



- natural separation of scales **$m_{pNGB} \ll M_{res}$**
  Unwanted effects from heavy Z' resonances automatically suppressed.
- EW Hierarchy problem is addressed
- Very rich collider phenomenology: leptoquarks and singlets!
- Non-minimal cosets (large number of states)
- Flavor structure put in by hand

UV models often point to interesting collider signatures not directly related to the anomalies: scalar singlets in this case.

Heavy Z', G' in vector LQ models.

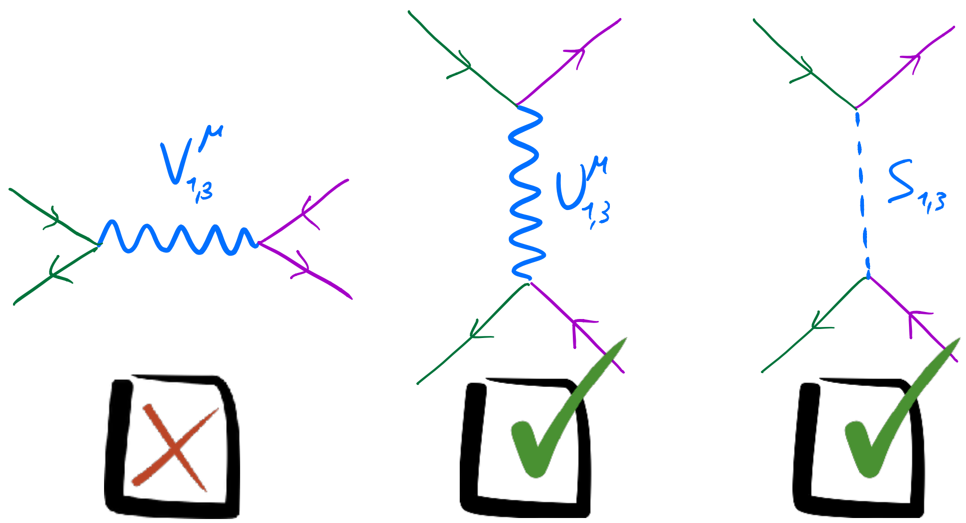
Summary

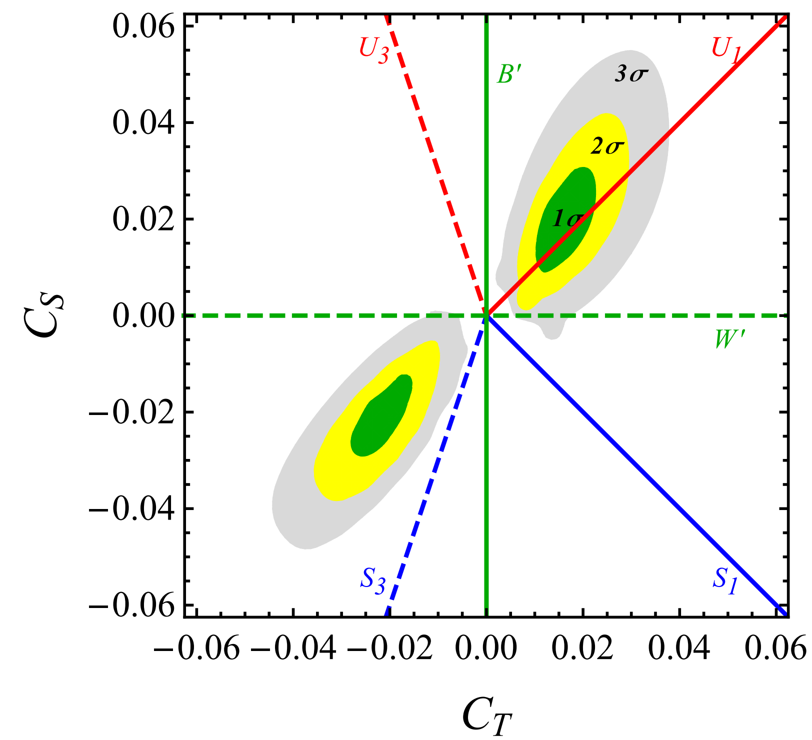
EFT fit

Including RGE effects

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

Tree-level mediators





First attempts on UV models for both vector and scalar LQ.

Scalar LQ can be naturally lighter than other mediators of flavour effects if they arise as pseudo-NGB of a strongly coupled sector.
Allows to address also the Higgs hierarchy problem.

Thank you!

Backup

U(2) flavour symmetry

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

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

$$\psi_i = (\underbrace{\psi_1 \;\; \psi_2}_{\mathbf{2}} \; \underbrace{\psi_3}_{\mathbf{1}})$$

One can assume this is
minimally broken by the spurions:

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

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:

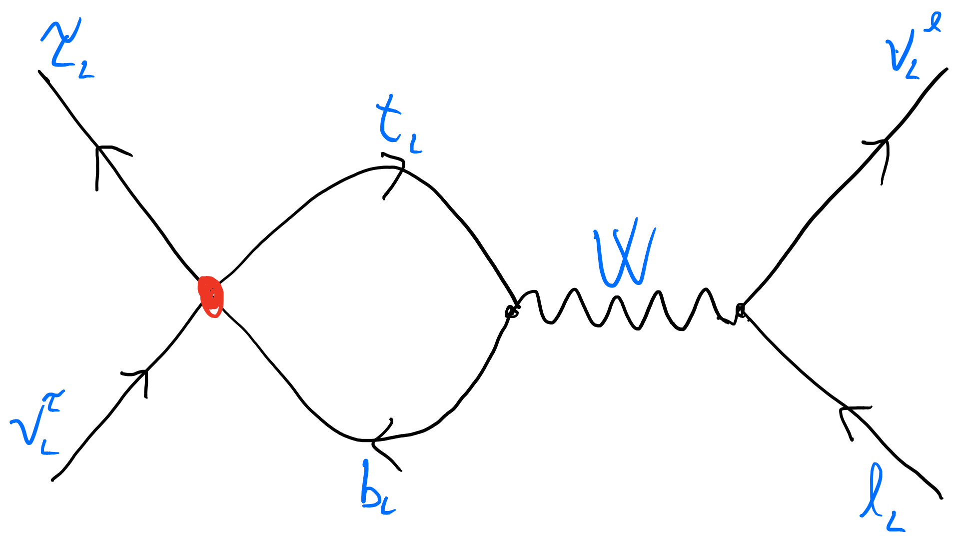
$$V_q = a_q \begin{pmatrix} V_{td}^* \\ V_{ts}^* \end{pmatrix} \qquad V_l \approx \begin{pmatrix} 0 \\ \lambda_{\tau\mu} \end{pmatrix}$$

CKM — unknowns

Problems from RG effects

Feruglio, Paradisi, Pattori [1606.00524]

Problems with LFU in τ decays at 1-loop



$$R_\tau^{\tau/\ell_{1,2}} = \frac{\mathcal{B}(\tau \to \ell_{2,1}\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\tau \to \ell_{2,1}\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm SM}}$$

$$R_\tau^{\tau/\mu} = 1.0022 \pm 0.0030$$
$$R_\tau^{\tau/e} = 1.0060 \pm 0.0030$$

$\Rightarrow$ $R_0 = 0{,}017 \pm 0{,}023$

our fit: $R_0 = 0{,}13 \pm 0{,}03$

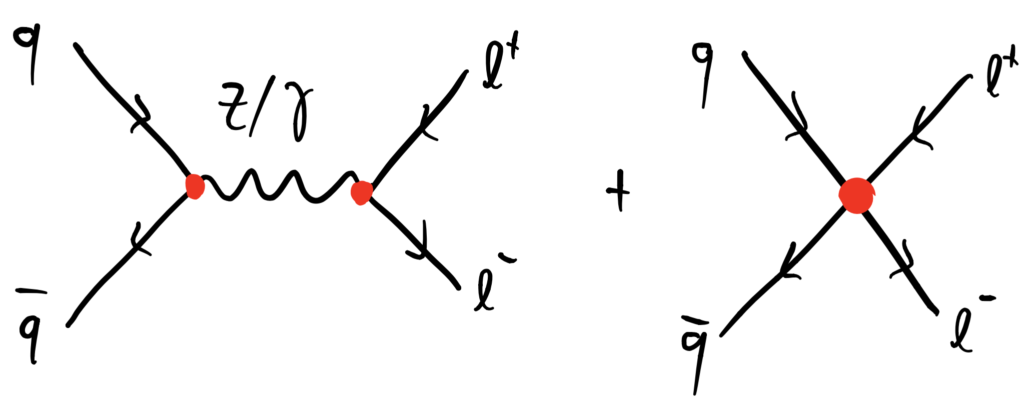
Need a ~ 20% tuning with some other contribution
(from 1-loop or direct from another dim-6 operator)

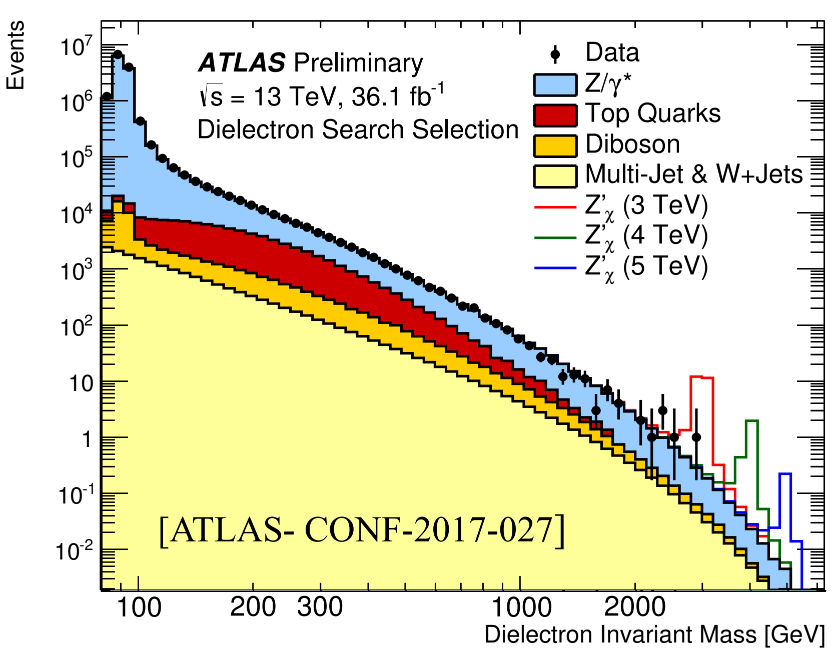
Di-muon tail & R(K$^{(*)}$)

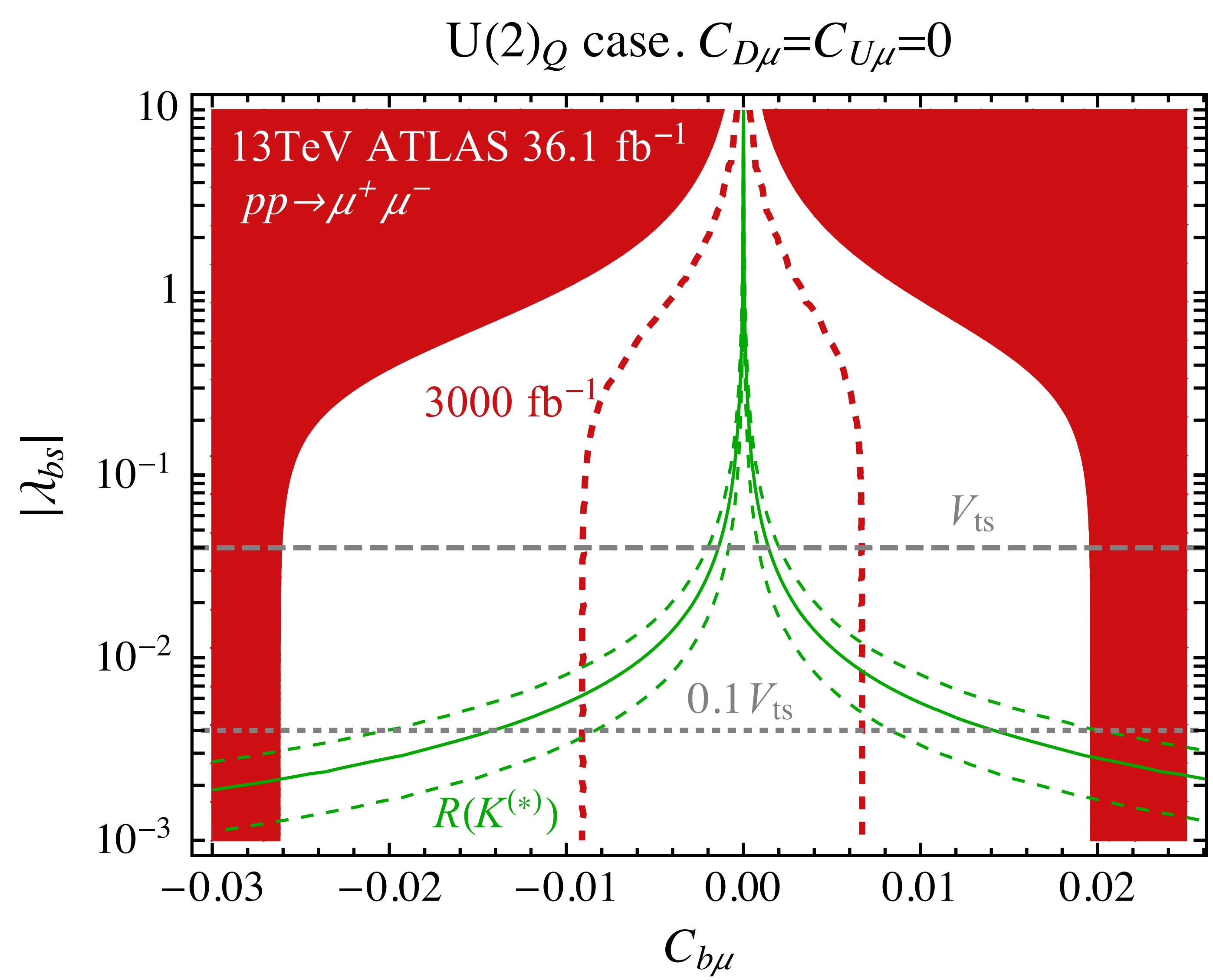
[Greljo, D.M. 1704.09015]

$$\frac{1}{\Lambda_{qq\mu}^2}\left[\lambda_{bs}^{q}(\bar{s}_L\gamma_\mu b_L) + (\bar{q}_L\gamma_\mu q_L)\right](\bar{\mu}_L\gamma^\mu\mu_L) \qquad \lambda_{bs}^{\mu} \ll 1$$

LHC might test this! $\quad \Lambda_{qq\mu} \ll \Lambda_{bs\mu}$







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

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

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

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

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

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

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

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:

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

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

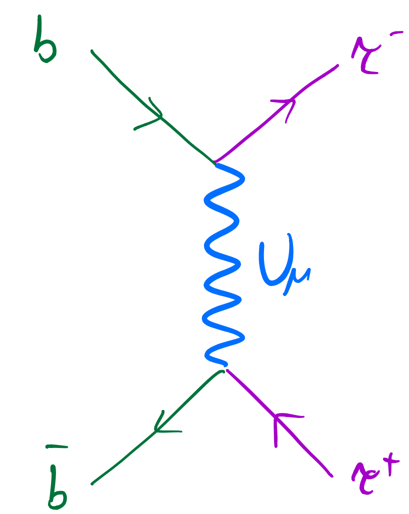
too small to fit the anomaly $(\delta a_\mu)_{exp} = (2.8 \pm 0.9) \times 10^{-9}$

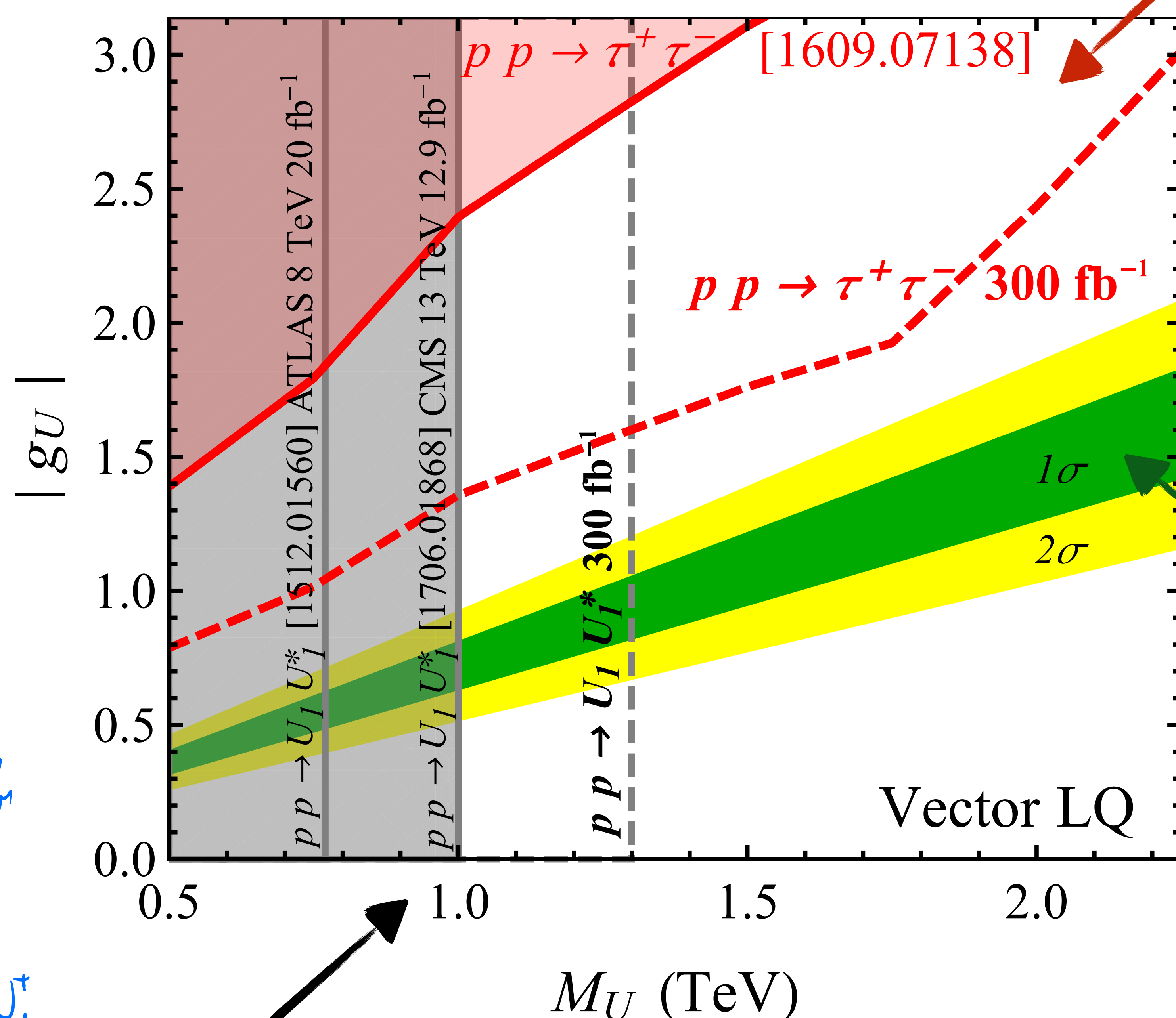
Direct Searches

Buttazzo, Greljo, Isidori, DM 2017

$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

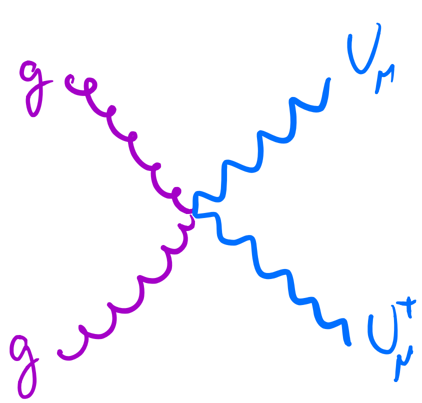
Limits and prospects from ττ final state (t-channel exchange)





Region fitting B-anomalies

$$C_U = v^2 |g_U|^2 / (2M_U^2) \approx 0.02$$



Limits and prospects from pair production of 3rd gen. LQ

Gauge Vector LQ

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

The U_1 LQ gives the best fit of the anomalies with smallest number of param.

The massive vector of Pati-Salam has same quantum numbers as U_1 LQ.

$SU(4)_{PS} \times U(1)' \to SU(3)_c \times U(1)_Y$ $\quad$ $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

But in PS $M_U \gtrsim 10^3$ TeV due to coupling with light generations.

Need to add extra (vectorlike) fermions or extra gauge bosons (or both) so that it mainly couples only to third generation.

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

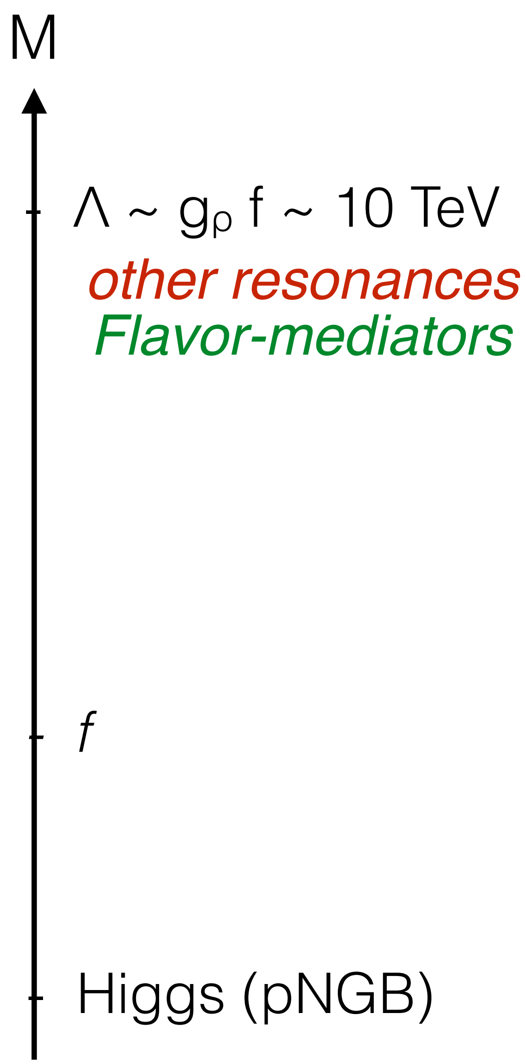
Di Luzio, Greljo, Nardecchia 2017

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	1	3	2	1/6
$u_R'^i$	1	3	1	2/3
$d_R'^i$	1	3	1	−1/3
$\ell_L'^i$	1	1	2	−1/2
$e_R'^i$	1	1	1	−1
Ψ_L^i	4	1	2	0
Ψ_R^i	4	1	2	0

There are also massive color-octed and massive Z'.
Crucial to avoid large FCNC effects and direct searches limits.
All these constraint point to strong gauge couplings, at the limit of perturbativity.

Doesn't address the EW hiearchy problem.

Composite Models



Vector LQ as Composite Resonance

The vector LQ can be considered as a composite resonance of a new strongly coupled sector, of which the Higgs arises as a pNGB.

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

$$m_{VLQ} \sim \Lambda$$

- The theory is fully strongly coupled at that scale: no calculability

- Many other vector resonances (Z’, G') are expected with similar mass and with same flavour-violating couplings: expect very strong bounds from tree-level contribution to Bs mixing.

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: $H_1 = \dfrac{i\tilde{H}_1 + \tilde{H}_2}{\sqrt{2}}$, $H_2 = \dfrac{-i\tilde{H}_1 + \tilde{H}_2}{\sqrt{2}}$

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:

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

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

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