# A composite model for flavor and diphoton anomalies





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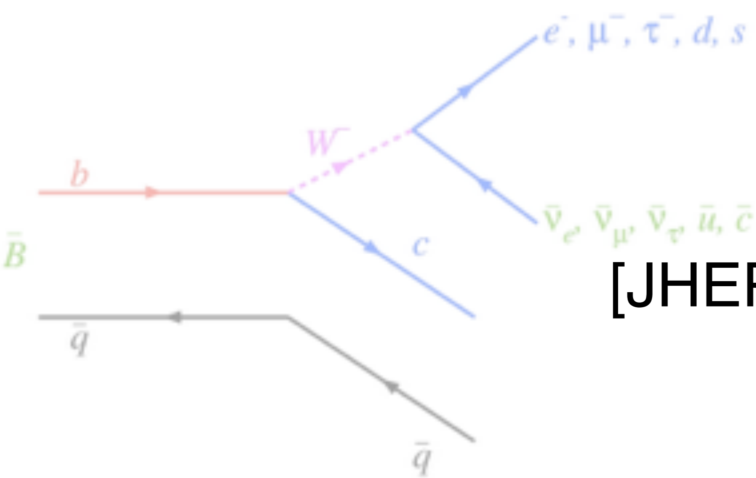







[JHEP 1507 (2015) 142, 1506.01705] & [1604.03940]


In collaboration with

D. Buttazzo, A. Greljo, G. Isidori

Holography, conformal field theories, and lattice

*Edinburgh, 30/06/2016*

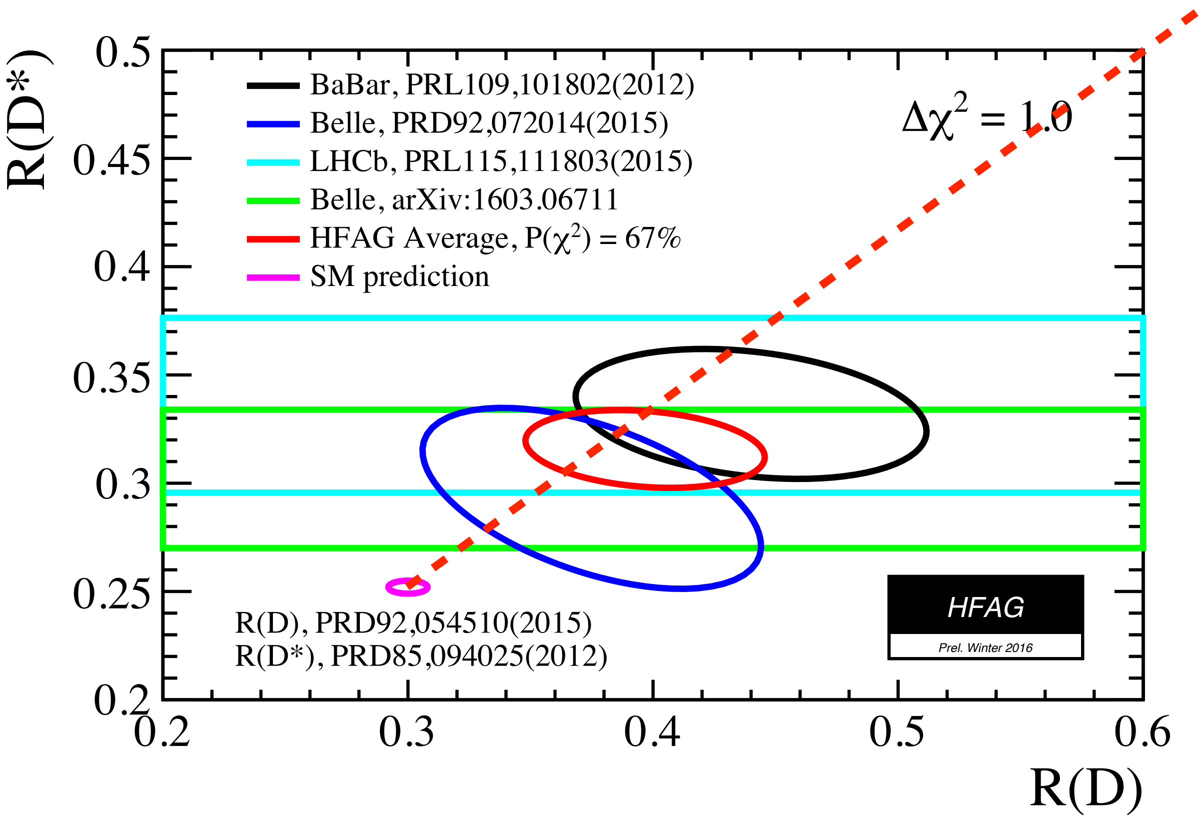
# Outline

- Introduction: experimental anomalies in semileptonic B decays and diphoton excess
- Simple New Physics interpretations for each anomaly
- Putting together a coherent framework: **vectorlike confinement**
- Low-energy flavour fit.
- Constraints from direct searches at the LHC and predictions
- Conclusions

# Experimental Results

# LFU violation in charged current

Combination from HFAG fit.



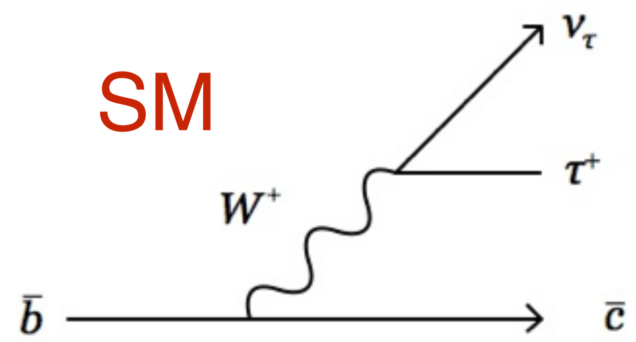

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)},$$

$$\ell = \mu, e$$

**+13%** of the tree-level SM contribution, assuming NP interferes.

**4.4σ**

SM




- Good agreement between 4 (very) different measurements.
- Clean SM prediction: most uncertainties cancel in the ratio
- 13% enhancement of tree-level $b_L \to c_L\, \tau_L\, \nu$ amplitude

$$R_0 = \frac{1}{2}\left(\frac{R^{\tau/\ell}(D^{(*)})}{R^{\tau/\ell}_{\rm SM}(D^{(*)})} - 1\right) \simeq 0.13 + 0.03$$

# LFU violation in neutral current

$b_L \longrightarrow s_L \, \mu_L \, \mu_L$

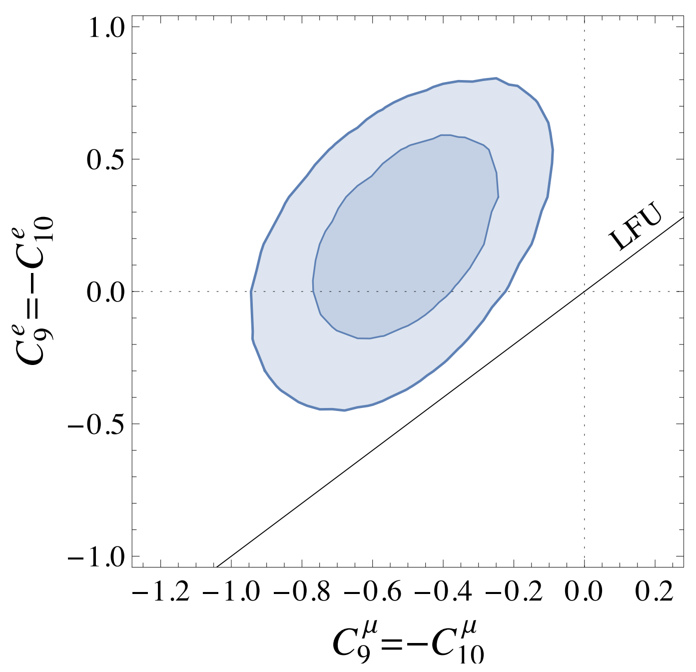
- **~ 2.6σ** deviation in decays to muons w.r.t. electrons [LHCb 1406.6482]

$$R_K^{\mu/e} = \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{\rm exp}}{\mathcal{B}(B \to Ke^+e^-)_{\rm exp}}\bigg|_{q^2\in[1,6]{\rm GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

**Theoretically very clean! ~ 1% error.**

- **3-4σ** anomaly is also present in the $P_5'$ observable in differential distributions in $B \longrightarrow K^* \mu^+\mu^-$. <u>However</u>: **sizable QCD uncertainties**.

[Altmannshofer and Straub 1411.3161]

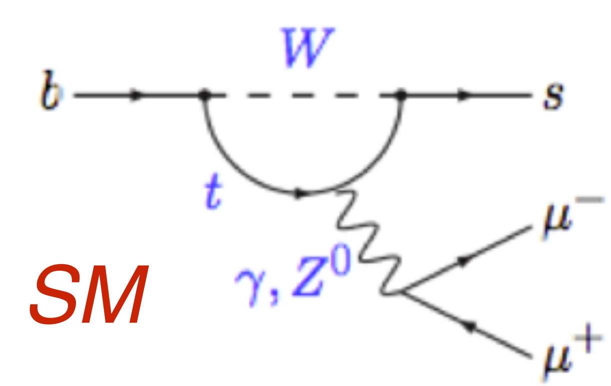



**Global fit** assuming left-handed interaction:

$$C_9^{{\rm NP},e} = -C_{10}^{{\rm NP},e} = 0$$
$$C_9^{{\rm NP},\mu} = -C_{10}^{{\rm NP},\mu} = (-0.14 \pm 0.04)\; C_9^{{\rm SM},\mu}$$

**-14%** of SM (1-loop).

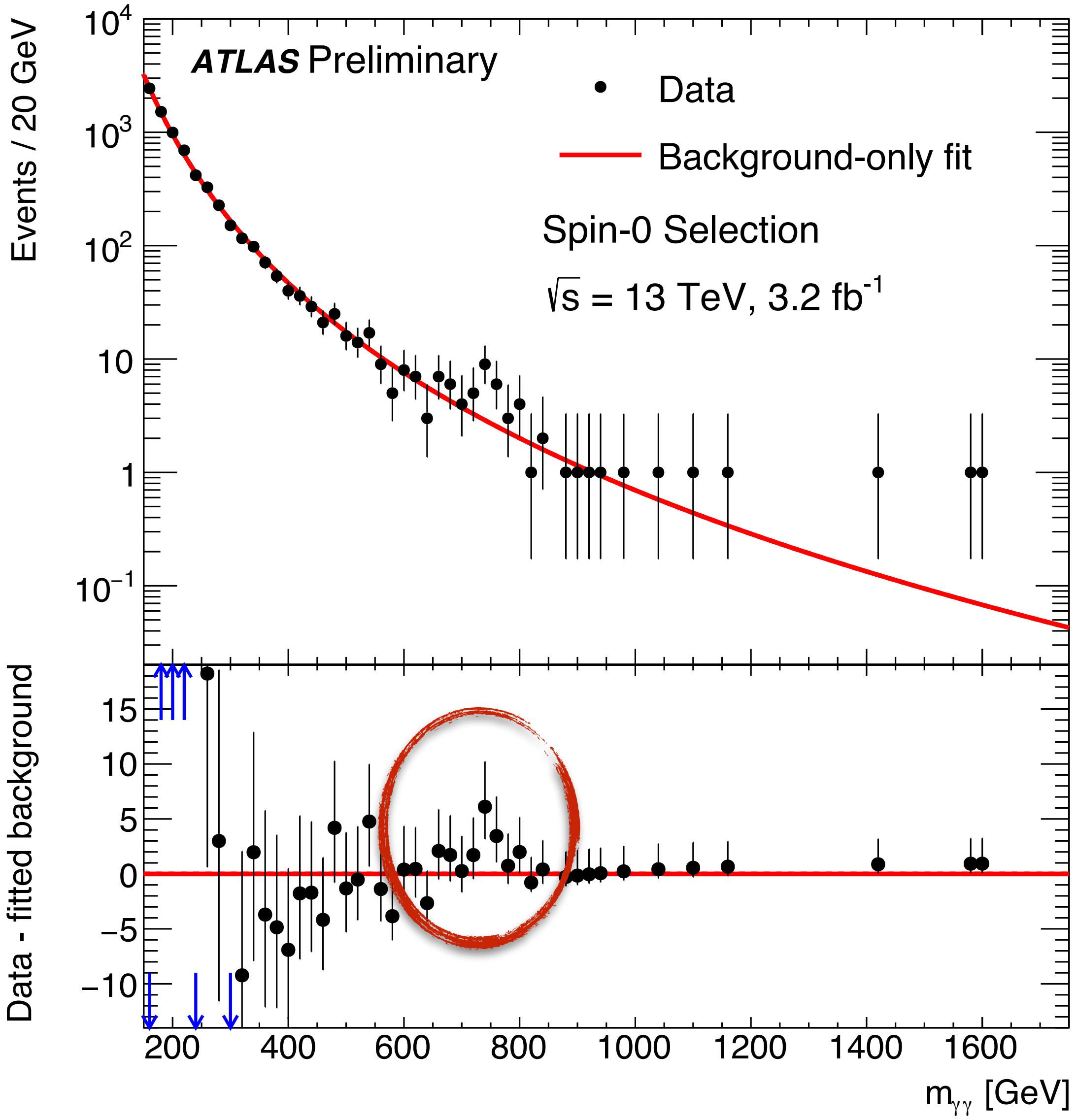
**~3.9σ** deviation, consistent with New Physics only in muons.



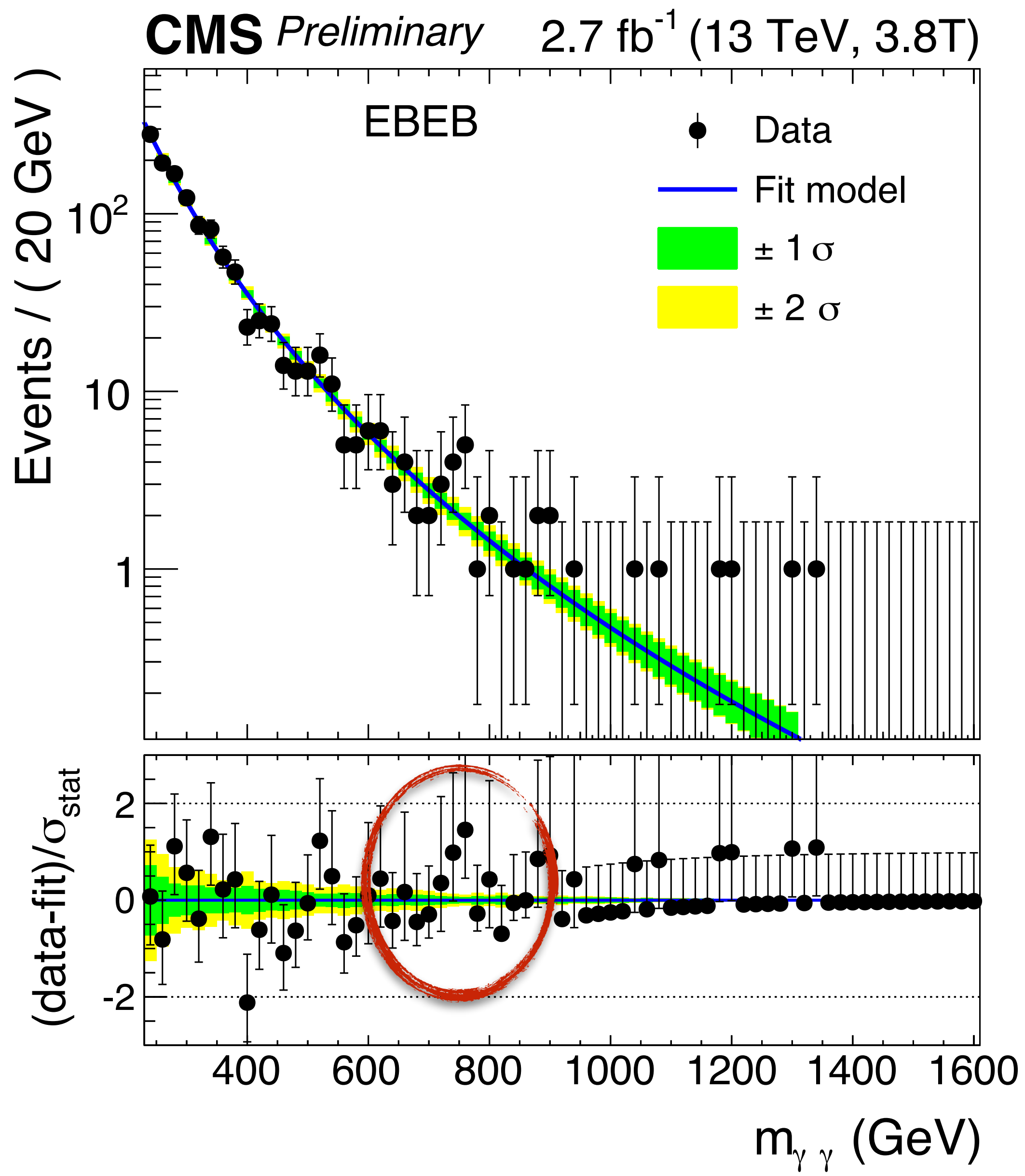

See also:
[Altmannshofer, Straub 1411.3161, 1503.06199; Crevellin, Pokorski 1407.1320; Hiller, Schmaltz 1408.1627; Alonso, Grinstein, Camalich 1407.7044, 1505.05164; Gosh, Nardecchia, Renner 1408.4097; Glashow, Guadagnoli, Lane 1411.0565; Crevellin D'Ambrosio, Heeck 1503.03477]

# Diphoton excess @ 750GeV

ATLAS-CONF-2016-018




CMS PAS EXO-16-018

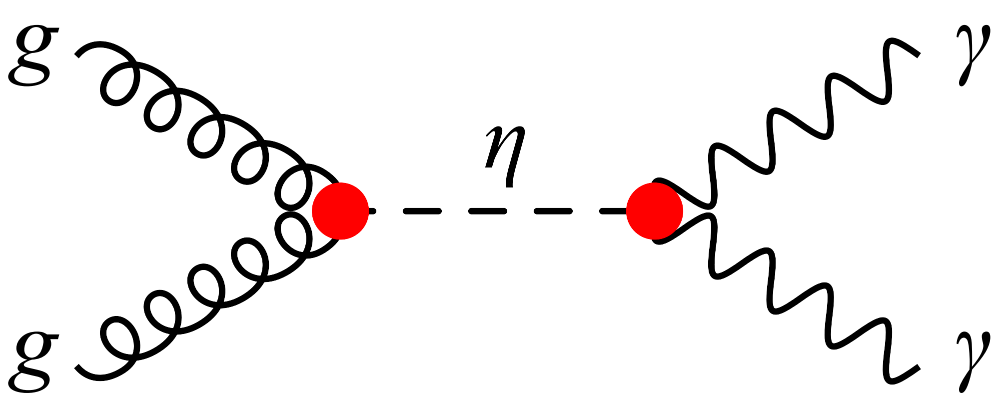



+ ~ 2σ excesses also in Run-1 in both experiments at the same mass.

# Diphoton excess @ 750GeV

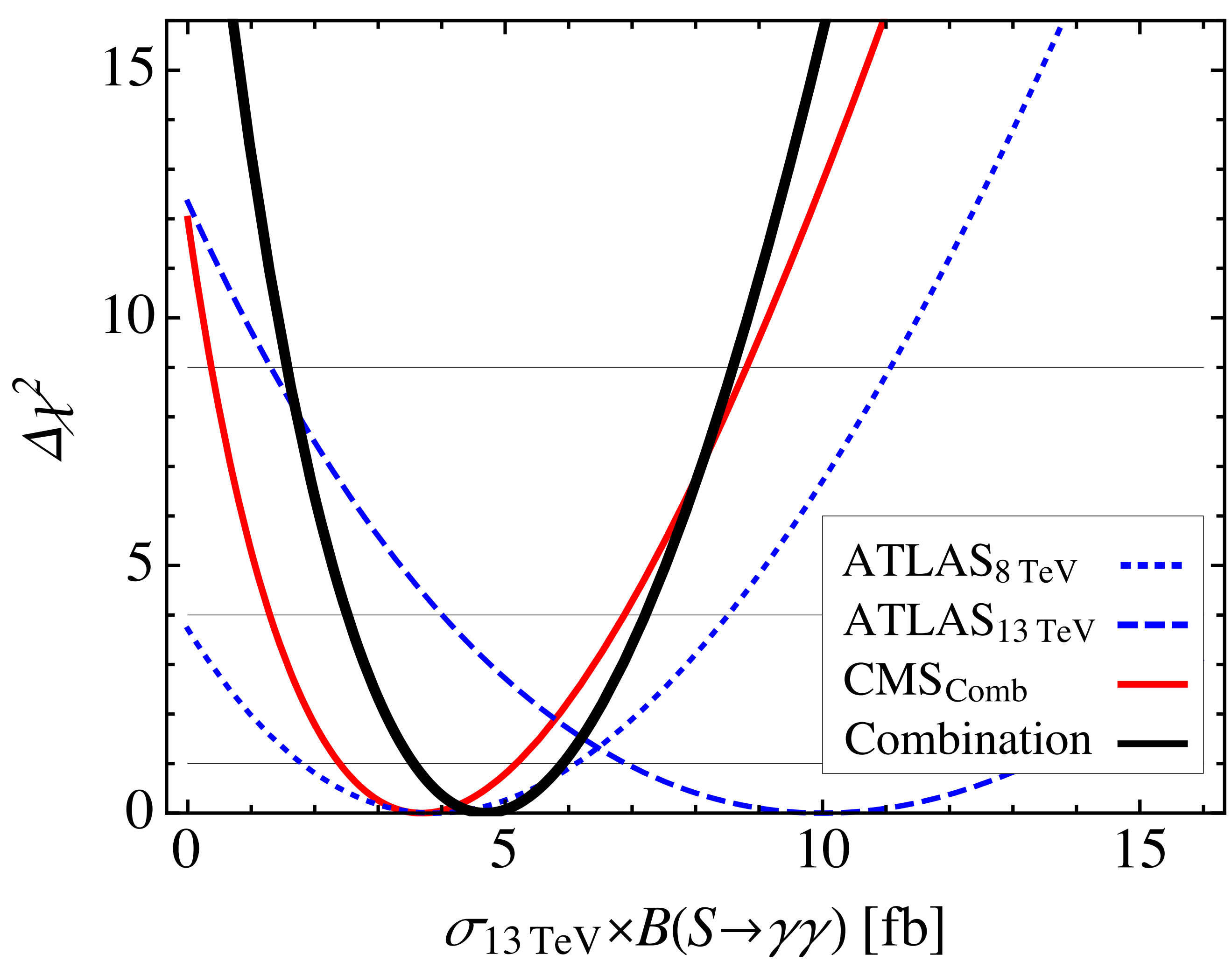
By Moriond 2016:
ATLAS: ~3.6σ
CMS: ~3.4σ

Interpretation as a spin-0 particle produced in gluon-fusion and decaying to two photons.




## Our combination

Buttazzo, Greljo, D. M. *Eur. Phys. J.* [1512.04929]
Buttazzo, Greljo, Isidori, D. M. [1604.03940]




$$\sigma_{13\ \mathrm{TeV}}(pp \to \eta) \times \mathcal{B}(\eta \to \gamma\gamma) = 4.7^{+1.2}_{-1.1}\ \mathrm{fb}$$

These anomalies could all be

**<u>statistical flukes</u>** or unknown uncertainties…

but..


For the patient ones: sit and wait, data will tell.

# SU(2)$_L$ Structure

**Charged current** contribution

$b \to c\, \tau\, \nu$

$V_{cb}$ & 3rd gen. lepton.

need $R_0 \sim$ 13% of SM tree-level

$$SM \sim -\frac{4G_F}{\sqrt{2}} V_{cb} (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau)$$

$$\Delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}} R_0 V_{cb} (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L^\tau)$$

**Neutral current** contribution

$b \to s\, \mu\, \mu$

FCNC & 2nd gen. lepton.

need -14% of SM loop

$$\Delta\mathcal{L} = -\frac{2G_F}{\sqrt{2}} R_0 \lambda^q_{bs} \lambda^\ell_{\mu\mu} (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}_L \gamma^\mu \mu_L)$$

$$\lambda^q_{bs} \lambda^\ell_{\mu\mu} \ll 1$$

Write both in a SU(2)$_L$ invariant way:

$$\Delta\mathcal{L} = \frac{8G_F}{\sqrt{2}} R_0 \lambda^q_{ij} \lambda^\ell_{kl} (\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

# Flavour Structure

$$\Delta\mathcal{L} = \frac{8G_F}{\sqrt{2}} R_0 \lambda^q_{ij} \lambda^\ell_{kl} (\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

$$\lambda^q \simeq \begin{pmatrix} \sim 0 & \sim 0 & \sim 0 \\ \sim 0 & \lambda_{ss} \ll \lambda_{bs} & \lambda_{bs} \ll 1 \\ \sim 0 & \lambda^*_{bs} \ll 1 & 1 \end{pmatrix} \qquad \lambda^\ell \simeq \begin{pmatrix} \sim 0 & \sim 0 & \sim 0 \\ \sim 0 & \lambda_{\mu\mu} \ll \lambda_{\tau\mu} & \lambda_{\tau\mu} \ll 1 \\ \sim 0 & \lambda^*_{\tau\mu} \ll 1 & 1 \end{pmatrix}$$

Barbieri, Isidori, Jones-Perez, Lodone, Straub 1105.2296

Pattern fits in **U(2) flavour symmetry**

$$\lambda^q \simeq \begin{pmatrix} |\epsilon|^2 V^*_{3\alpha} V_{3\beta} & \epsilon^* V^*_{3\alpha} \\ \epsilon V_{3\beta} & 1 \end{pmatrix} \qquad |\lambda^q_{bs}| \sim |V_{ts}|$$

in the mass-basis of charged-leptons
and down-type quarks

# Flavour Dynamics

$R_0 \sim 0.13$ → Better think of a **tree-level mediator**!

- If same structure as SM: constructing interference.
- Couplings of scalar mediators suppressed by light fermion masses.

$$\Delta\mathcal{L} = \frac{8G_F}{\sqrt{2}} R_0 \lambda^q_{ij} \lambda^\ell_{kl} (\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

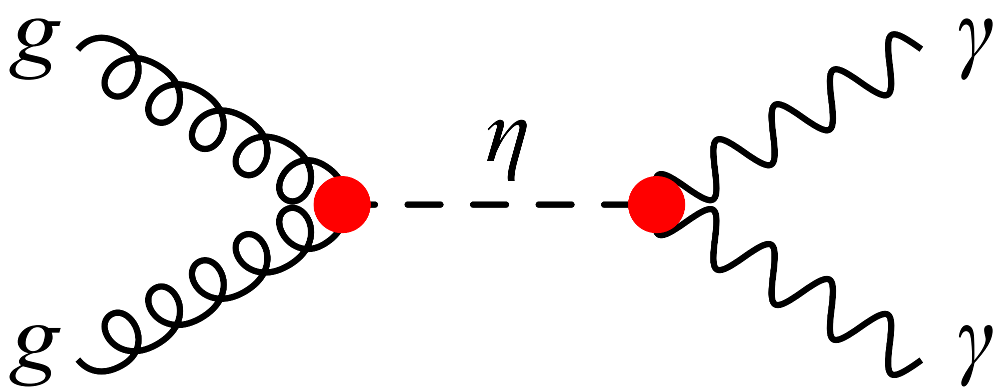
Preferred interpretations: Spin-1 states:

- **Vector triplet (1,3,**0) — Greljo, Isidori, DM 1506.01705

- Leptoquark triplet (**3**,**3**,2/3)
- Leptoquark singlet (**3**,**1**,2/3)

Barbieri, Isidori, Pattori, Senia 1512.01560

# Diphoton



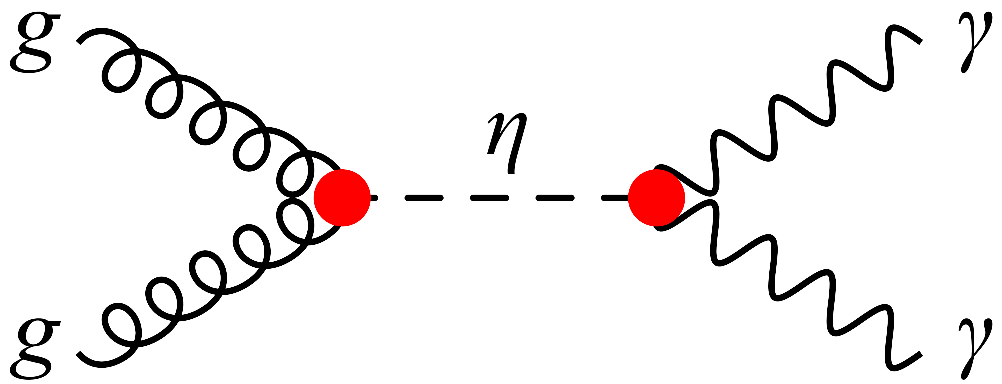

$$\sigma_{13\ \mathrm{TeV}}(pp \to \eta) \times \mathcal{B}(\eta \to \gamma\gamma) = 4.7^{+1.2}_{-1.1}\ \mathrm{fb}$$

**MANY** possible explanations, some basic common features:

- Use vectorlike quarks (& leptons) to enhance $\eta gg$ & $\eta\gamma\gamma$ couplings,
- If it is a pNGB, then these couplings could arise via the axial anomaly (as $\pi^0 \to \gamma\gamma$),
- Having other tree-level decays (large width) is challenging:

  need even stronger couplings,
- Most explanations in this setup are strongly coupled (at a nearby scale).

# Diphoton




$$\sigma_{13\ \text{TeV}}(pp \to \eta) \times \mathcal{B}(\eta \to \gamma\gamma) = 4.7^{+1.2}_{-1.1}\ \text{fb}$$

Possible interpretation:

$\eta$ is a pNGB of a new strongly-coupled sector at the TeV scale, coupled to photons and gluons via the axial anomaly.

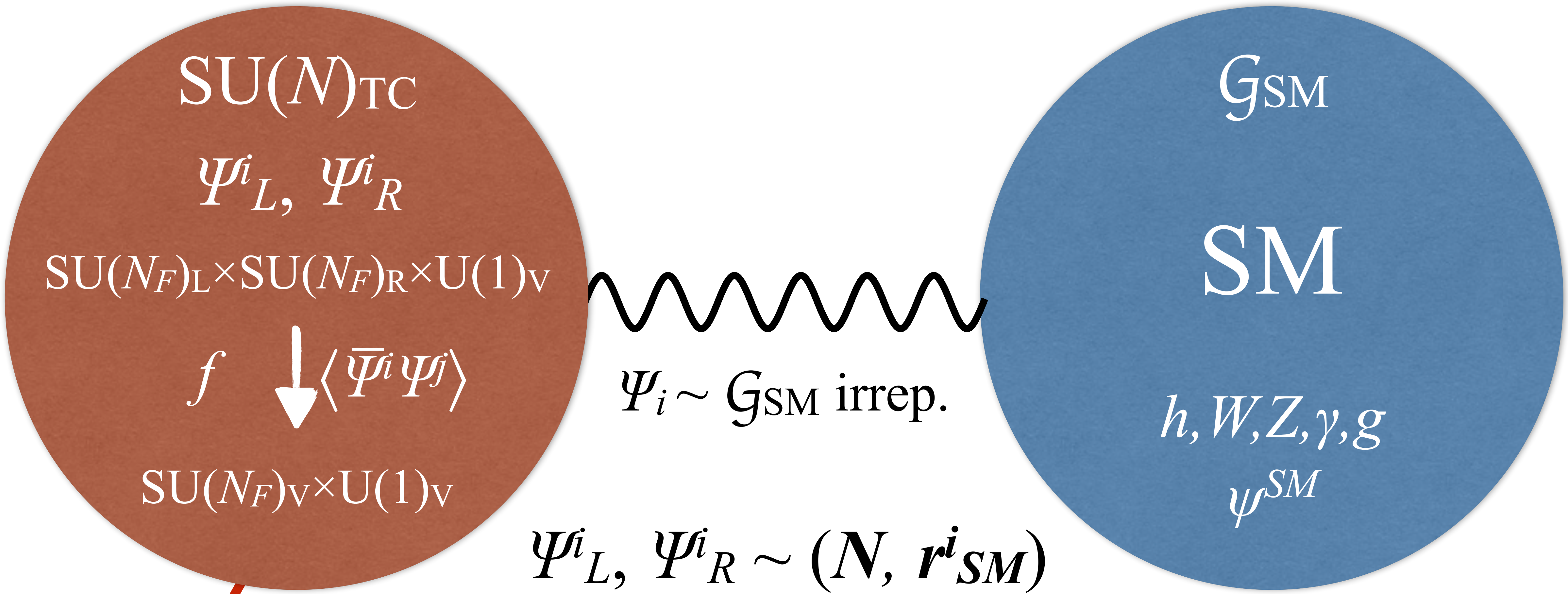
First day! → [Franceschini et al. 1512.04933; Harigaya, Nomura 1512.04850+1602.01092+1603.05774; Nakai et al. 1512.04924]

[Bian et al. 1512.05759; Braig et al. 1512.07733; Bai et al. 1512.05779; Kamenik, Redi 1603.07719]

See in particular [Redi, Strumia, Tesi, Vigniani 1602.07297]

# Vectorlike Confinement

Kilic, Okui, Sundrum 0906.0577, 1001.4526




$\Psi^i{}_L,\ \Psi^i{}_R \sim (\boldsymbol{N},\ \boldsymbol{r}^i{}_{SM})$

**$N_F^2$ - 1 pNGB**

$\eta,\ \pi^\pm,\ \pi^0,\ \ldots$

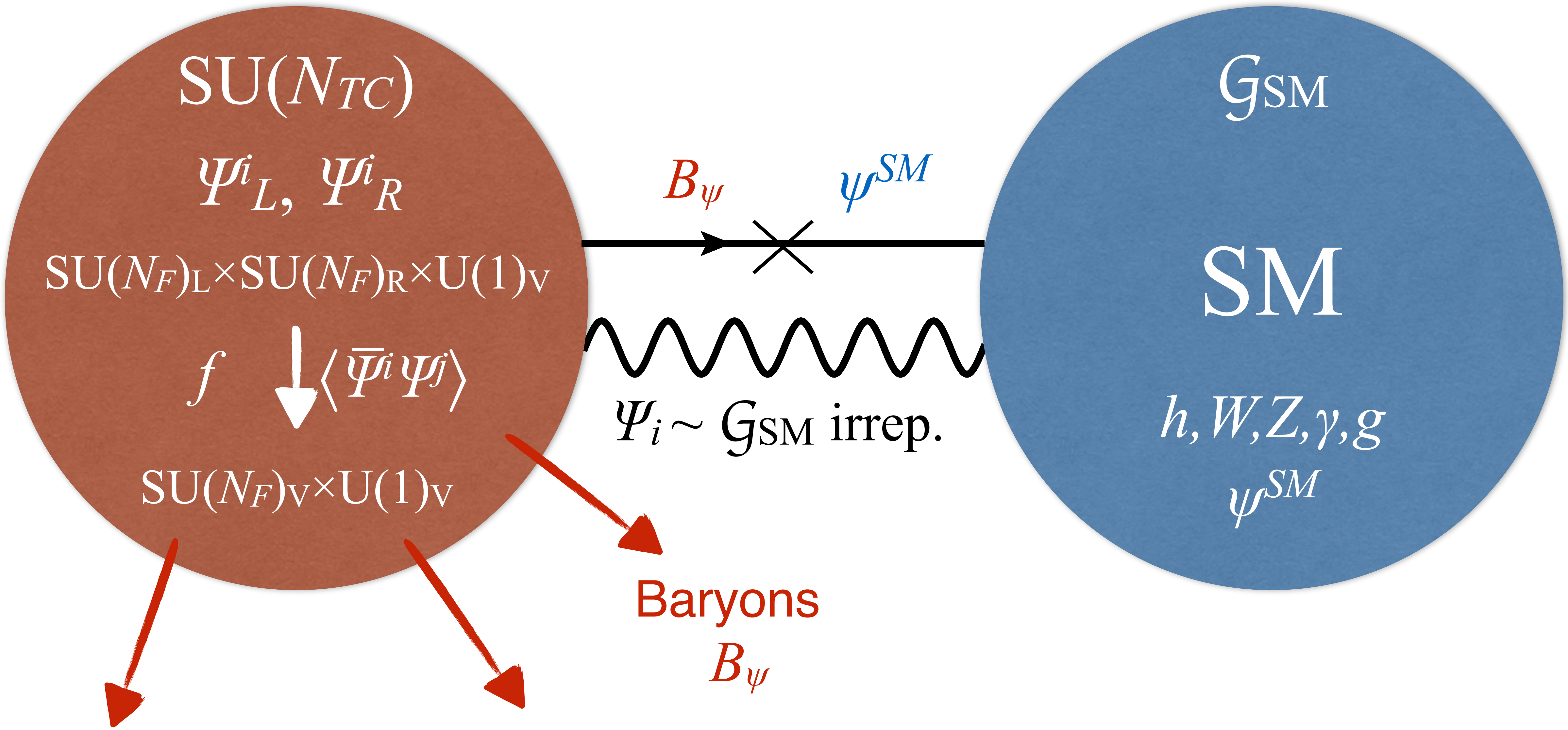
$gg \longrightarrow \eta \longrightarrow \gamma\gamma$

Via axial anomaly

Like $\pi^0 \longrightarrow \gamma\gamma$

# Our setup for combining both anomalies

# Flavorful Vectorlike Confinement




**pNGB**

$\eta,\ \pi^\pm,\ \pi^0,\ \ldots$

$gg \to \boldsymbol{\eta} \to \gamma\gamma$

**Vector Mesons**

$\rho^a{}_\mu = (\mathbf{1},\mathbf{3},0)$
$U_\mu = (\mathbf{3},\mathbf{1},2/3)$
$U^a{}_\mu = (\mathbf{3},\mathbf{3},2/3)$
$\ldots$

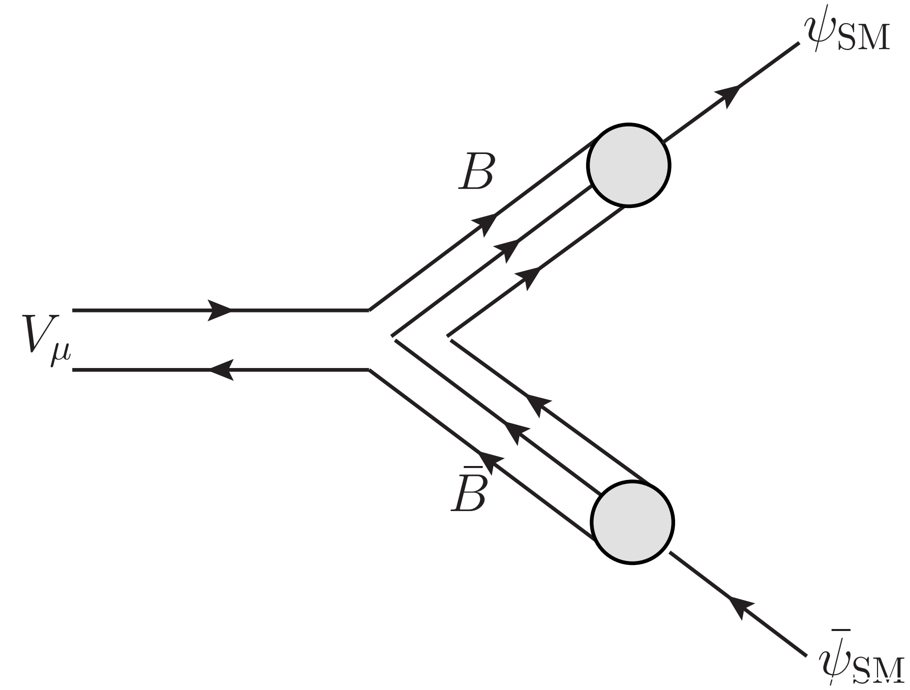
→ **Flavor physics mediators**

e.g. through baryon-SM mixing

# Partial compositeness

## Baryon - rho coupling

$$\mathcal{L}_{\rho BB} = g_\rho a^\rho_\psi \bar{B}_\psi \gamma^\mu \tau^a B_\psi \ \rho^a_\mu$$




## + Baryon - SM fermion mixing

$$B_q \to \kappa_q \chi^q_i q^i_L \ , \ B_\ell \to \kappa_\ell \chi^\ell_i \ell^i_L$$

$$\chi^{q(\ell)} = \begin{pmatrix} \varepsilon_1^{q(\ell)} \\ \varepsilon_2^{q(\ell)} \\ 1 \end{pmatrix}$$

SU(2)-doublet spurions

SU(2)-singlet

**This generates the necessary flavor phenomenology to describe the anomalies**

$$\lambda^\ell_{\mu\mu} = (\lambda^\ell_{\tau\mu})^2 \qquad \lambda^q_{ss} = (\lambda^q_{bs})^2$$

The mixing could arise from a flavour theory at a scale

$$\Lambda_F \gtrsim \Lambda_{\rm TC}$$

$$\mathcal{L}^{\rm eff} \sim \frac{1}{\Lambda_F^2} \Psi\Psi\Psi \, \chi_\psi \psi^{\rm SM}$$

Possible UV completion with a scalar [D. Kaplan '91], if large anomalous dimension then high scale $\Lambda_F \gg \Lambda_{UV}$ is viable.

# Minimal model - SU(5$_F$)

We require baryons with same SM quantum numbers of $q_L$ & $\ell_L$.

The **minimal** set of TC-fermions is

$$N_{TC} = 3 \qquad Q = (N_{TC}, 3, 1, Y_Q) \qquad L = (N_{TC}, 1, 2, Y_L)$$

Requiring baryons: two possible hypercharge assignments

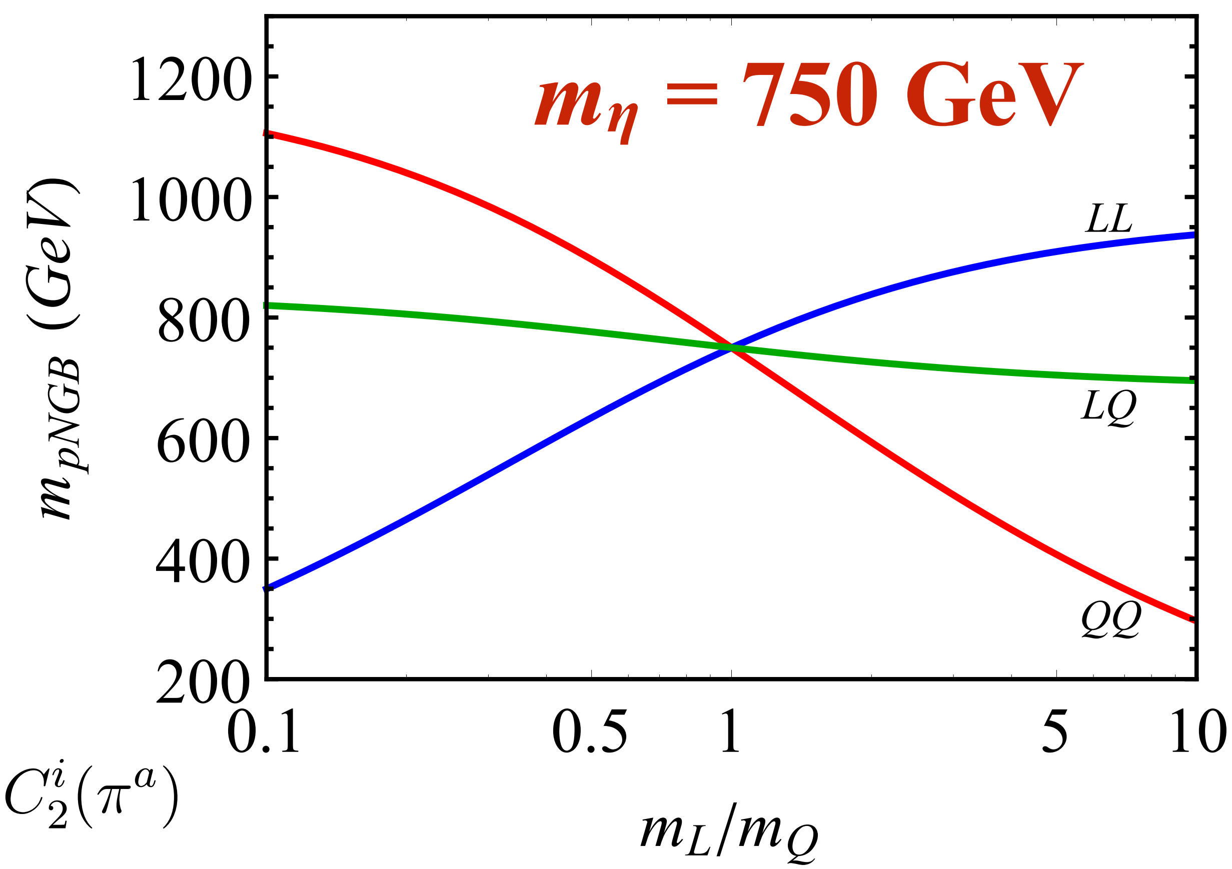
| | $(Y_Q, Y_L)$ |
|---|---|
| A: | $(-\frac{1}{6}, \frac{1}{6})$ |
| B: | $(0, -\frac{1}{6})$ |

mesons:

| Flavor structure | $\mathcal{G}_{SM}$ irrep | pNGB Mass |
|---|---|---|
| $(\bar{Q}Q)$ | $(\mathbf{8}, \mathbf{1}, 0)$ | $m^2_{(\bar{Q}Q)} = 2B_0 m_Q$ |
| $(\bar{L}Q)$ + h.c. | $(\mathbf{3}, \mathbf{2}, \Delta Y)$ + h.c. | $m^2_{(\bar{L}Q)} = B_0(m_L + m_Q)$ |
| $(\bar{L}L)$ | $(\mathbf{1}, \mathbf{3}, 0)$ | $m^2_{(\bar{L}L)} = 2B_0 m_L$ |
| $3(\bar{L}L) - 2(\bar{Q}Q)$ | $(\mathbf{1}, \mathbf{1}, 0)$ $= \eta$ | $m^2_\eta = \frac{2}{5}B_0(3m_L + 2m_Q)$ |

- From QCD: $B_0 \sim 20f$,
- TC quark mass ~ 100 GeV

**Model I: pNGB spectrum**




pNGB mass from SM gauge: $$\Delta m^2_{\pi^a} \sim \frac{3\Lambda^2}{16\pi^2}\sum_i g_i^2 C_2^i(\pi^a)$$

# Extended model - SU($8_F$)

$N_{TC} = 3$

$Q = (N_{TC}, 3, 2, Y_Q)$
$L = (N_{TC}, 1, 2, Y_L)$

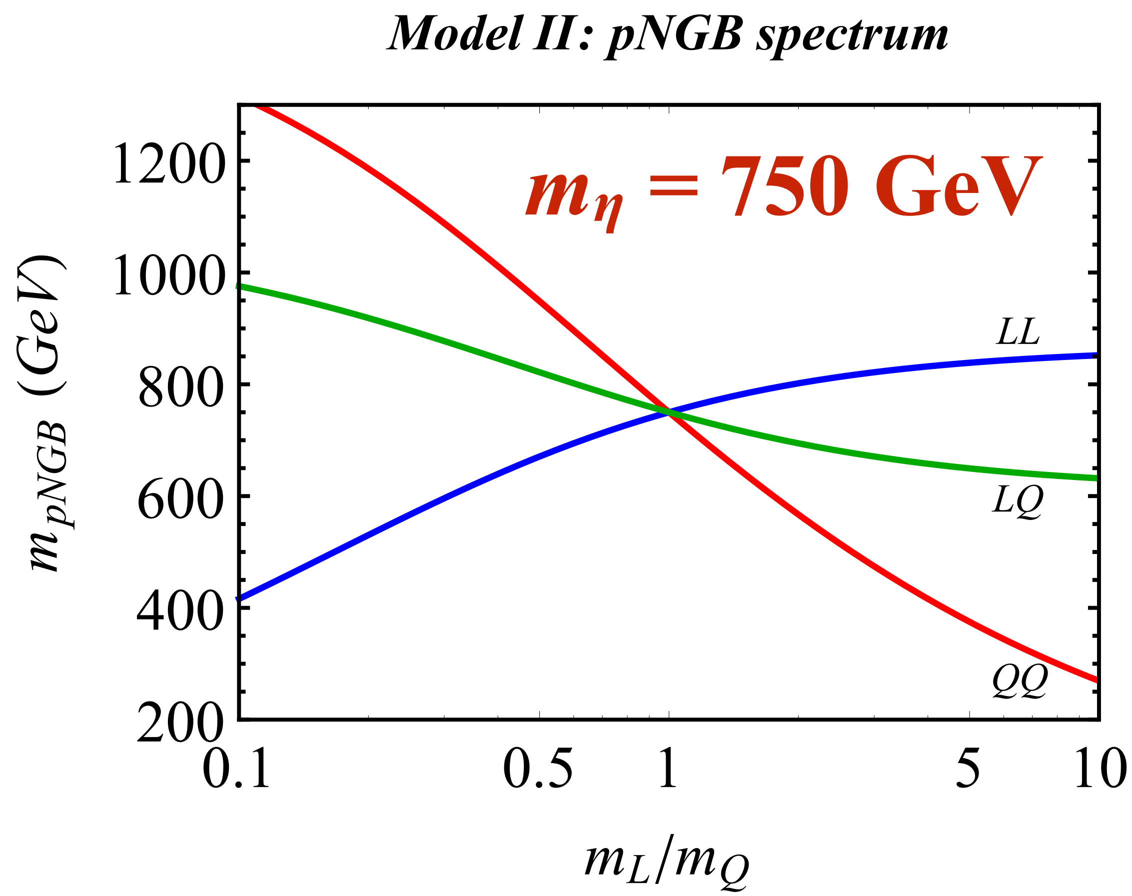
two hypercharge assignments

| | A | B |
|---|---|---|
| $Y_Q$ | $1/6$ | $1/2$ |
| $Y_L$ | $-1/2$ | $-1/6$ |

pNGB:

| Flavor structure | $\mathcal{G}_{SM}$ irrep | pNGB Mass |
|---|---|---|
| $(\bar{Q}Q)$ | $(\mathbf{8},\mathbf{3},0),\ (\mathbf{8},\mathbf{1},0),\ (\mathbf{1},\mathbf{3},0)$ | $m^2_{(\bar{Q}Q)} = 2B_0 m_Q$ |
| $(\bar{L}Q)$ + h.c. | $(\mathbf{3},\mathbf{1},\Delta Y),\ (\mathbf{3},\mathbf{3},\Delta Y)$ + h.c. | $m^2_{(\bar{L}Q)} = B_0(m_L + m_Q)$ |
| $(\bar{L}L)$ | $(\mathbf{1},\mathbf{3},0)$ | $m^2_{(\bar{L}L)} = 2B_0 m_L$ |
| $3(\bar{L}L) - (\bar{Q}Q)$ | $(\mathbf{1},\mathbf{1},0)$ $= \eta$ | $m^2_\eta = \frac{1}{2}B_0(3m_L + m_Q)$ |

- TC quark mass ~ 100 GeV



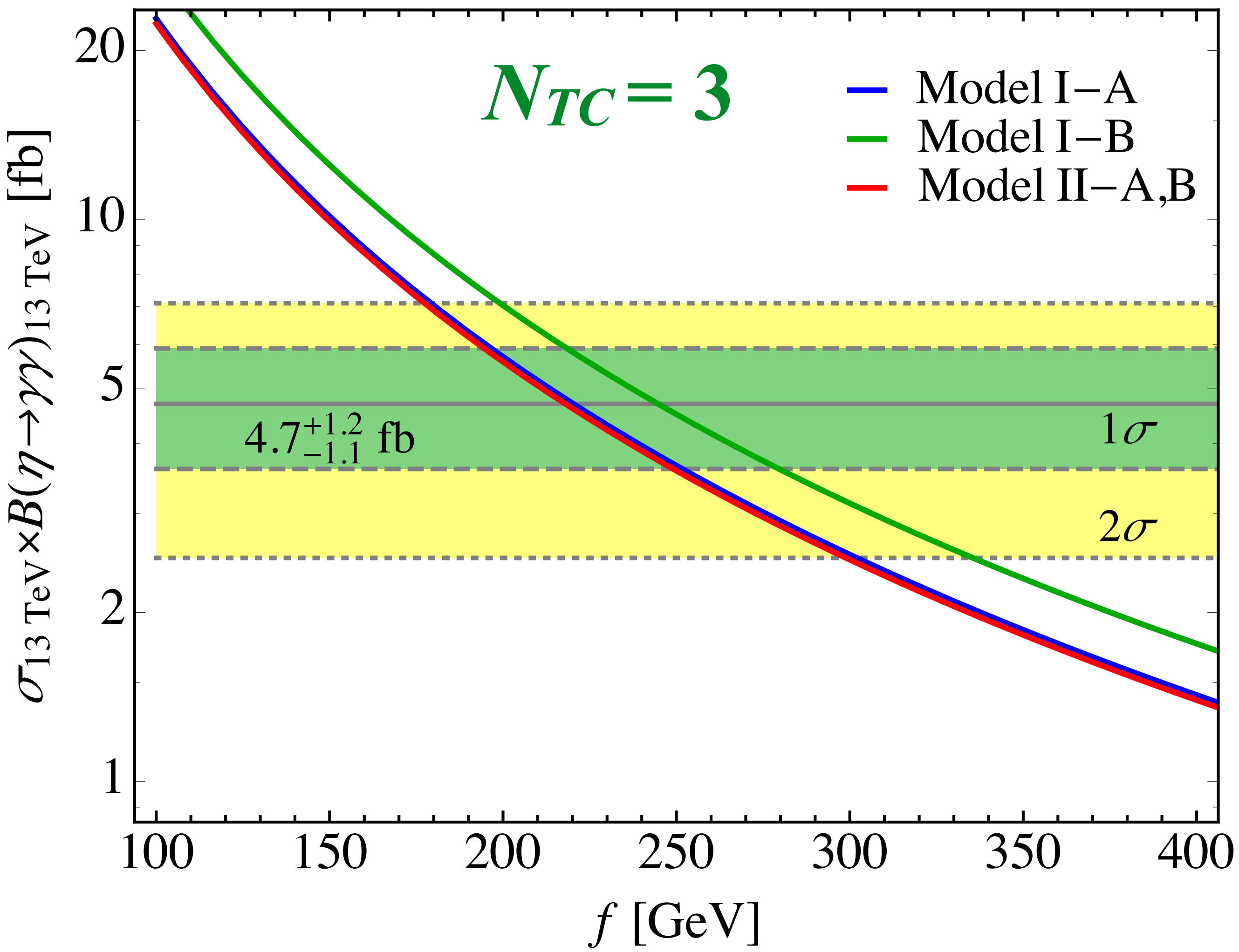
# pNGB dynamics

$$\mathcal{L}^{\chi PT} = \frac{f^2}{4}\left\{\mathrm{Tr}\left[(D_\mu U)^\dagger (D^\mu U)\right] + 2B_0(\mathrm{Tr}[\mathcal{M}U] + \mathrm{Tr}[\mathcal{M}^\dagger U^\dagger])\right\}$$

Coupling of the pNGB via the anomaly: $\mathcal{L}^{\mathrm{WZW}} \supset -\frac{g_b g_c}{16\pi^2}\frac{\pi^a}{f} A^{\pi^a}_{V^b V^c} F^b_{\mu\nu}\widetilde{F}^{c\mu\nu}$

$$A^{\pi^a}_{V^b V^c} = 2N_{TC}\mathrm{Tr}\left[t^a t^b t^c\right]$$

$$\mathcal{L}^{\mathrm{WZW}} \supset -\frac{\eta}{16\pi^2 f}\left(g'^2 A^\eta_{BB} B_{\mu\nu}\widetilde{B}^{\mu\nu} + g^2 A^\eta_{WW} W^i_{\mu\nu}\widetilde{W}^{i\mu\nu} + g_s^2 A^\eta_{GG} G^A_{\mu\nu}\widetilde{G}^{A\mu\nu}\right)$$




Given the model, diphoton cross section fixes *f*

***f* ~ 230 GeV**

# Other diboson channels

Given the diphoton cross section of ~5fb (@13TeV),
one can predict the rate in other diboson channels in each model

$$R_{VV} \equiv \frac{\Gamma(\eta \to VV)}{\Gamma(\eta \to \gamma\gamma)} = \frac{\sigma(pp \to \eta \to VV)}{\sigma(pp \to \eta \to \gamma\gamma)}$$

→ ~ 5fb

LHC bounds: $R_{Z\gamma} \lesssim 5.6$ , $R_{ZZ} \lesssim 11$ , $R_{WW} \lesssim 36$

E.g. from Buttazzo, Greljo, D. M. [1512.04929]

Predictions:

SU(5) Model I

| | $(Y_Q, Y_L)$ | $R_{Z\gamma}$ | $R_{ZZ}$ | $R_{WW}$ |
|---|---|---|---|---|
| A: | $(-\frac{1}{6}, \frac{1}{6})$ | 6.7 | 11 | 37 |
| B: | $(0, -\frac{1}{6})$ | 5.0 | 9.1 | 34 |

→ Already near the bounds. Measurable in the near future!

SU(8) Model II

| | $(Y_Q, Y_L)$ | $R_{Z\gamma}$ | $R_{ZZ}$ | $R_{WW}$ |
|---|---|---|---|---|
| A: | $(\frac{1}{2}, -\frac{1}{6})$ | 0.6 | 0.09 | 0 |
| B: | $(\frac{1}{6}, -\frac{1}{2})$ | | | |

# Vector Mesons

$$|V_{ij}\rangle = |(\bar{\psi}_i \psi_j)_{J=1}\rangle$$

- In the minimal model
  - (***LL***) $\rho_\mu = (\mathbf{1},\mathbf{3},0)$ , $\omega_\mu = (\mathbf{1},\mathbf{1},0)$
  - (***LQ***) Leptoquark doublet $D_\mu = (\mathbf{3},\mathbf{2},\Delta Y)$
  - (***QQ***) $\varphi_\mu = (\mathbf{1},\mathbf{1},0)$ , $V^A{}_\mu = (\mathbf{8},\mathbf{1},0)$
- Extra/different states in the extended model:
  - (***QQ***) Extra triplets: $\rho'_\mu = (\mathbf{1},\mathbf{3},0)$ , $V^{A,a}{}_\mu = (\mathbf{8},\mathbf{3},0)$
  - (***LQ***) Leptoquark singlet $U_\mu = (\mathbf{3},\mathbf{1},\Delta Y)$ and triplet $U^a{}_\mu = (\mathbf{3},\mathbf{3},\Delta Y)$

Their mass is $$m^2_{V_{ij}} = c_0^2 (4\pi f)^2 + c_1^2 B_0 (m_{\bar{\psi}_i} + m_{\psi_j})$$

**From the diphoton anomaly:**

$$\boldsymbol{f \sim 230\ \text{GeV} \;\rightarrow\; m_V \sim 1.5 \div 2\ \text{TeV}}$$

# Baryons

We are interested in the baryons with quantum numbers of SM fermions

In the minimal model:

$$|\bar{B}_\ell(B_\ell)\rangle_{(\mathbf{1},\mathbf{2},\pm 1/2)} \propto |LLL\rangle$$
$$|\bar{B}_q\rangle_{(\bar{\mathbf{3}},\mathbf{2},-1/6)} \propto |QQL\rangle$$

in model I-B also:

$$|B_d\rangle_{(\mathbf{3},\mathbf{1},-1/3)} \propto |QLL\rangle \quad \sim d_R$$

In the extended model:

$$\text{A:} \quad |B_\ell\rangle_{(\mathbf{1},\mathbf{2},-1/2)} \propto |LLL\rangle \quad \text{and} \quad |B_q\rangle_{(\mathbf{3},\mathbf{2},1/6)} \propto |QLL\rangle\,,$$
$$\text{B:} \quad |\bar{B}_\ell\rangle_{(\mathbf{1},\mathbf{2},1/2)} \propto |QQQ\rangle \quad \text{and} \quad |\bar{B}_q\rangle_{(\bar{\mathbf{3}},\mathbf{2},-1/6)} \propto |QQL\rangle\,.$$

# Baryons' group theory

$N_{TC} = 3$ $\quad\Psi$ $Q = (N_{TC}, \mathbf{3}, \mathbf{1}, Y_Q)$ $\quad$ **SU($5_F$)**

$L = (N_{TC}, \mathbf{1}, \mathbf{2}, Y_L)$

$|\Psi\Psi\Psi\rangle$ The wave function should be antisymmetric.

SU($N_{TC}$) → antisymmetric

(flavor) x (spin) = SU(5)$_F$ x SU(2)$_s$ ⊂ SU(10) → symmetric

Baryons are in

10 x 10 x 10 = $120_A$ + $220_S$ + 2 x 330 of SU(10).

$220_S$ = (40,2) + (35,4) of SU(5)$_F$ x SU(2)$_s$

40 = (1,2) + (3,1) + (3,2) + (3,3) + (6,2) + (8,1) of SU(3)$_c$ x SU(2)$_L$

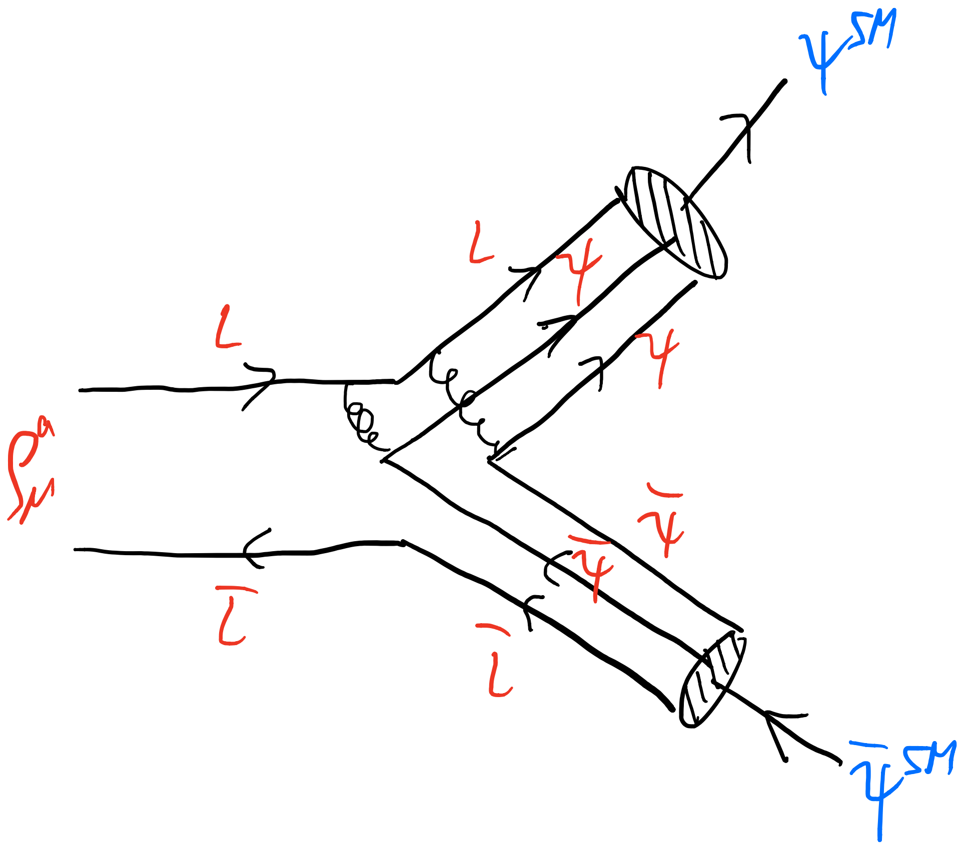
$\ell_L$ $\quad$ $q_L$

$|LLL\rangle$ $\quad$ $|QQL\rangle$

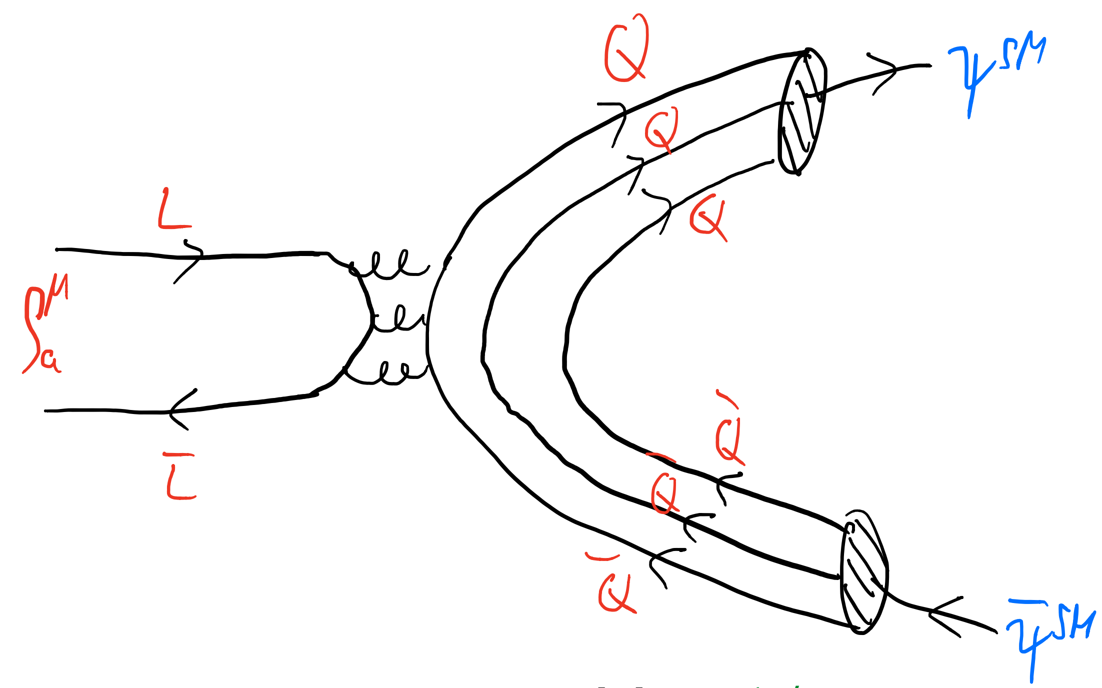
# Meson-Baryon coupling: OZI rule

Estimate the size of the various couplings

$$\mathcal{L}_{\rho BB} = g_\rho a^\rho_\psi \bar{B}_\psi \gamma^\mu \tau^a B_\psi \, \rho^a_\mu$$




$\gg$




suppressed by $1/N_{TC}$

$a^\rho{}_B \sim O(1)$

$a^\rho{}_B \ll 1$

# Low-energy constraints

# Low-energy Lagrangian

Let's focus on the

$\rho_\mu = (\mathbf{1},\mathbf{3},0)$

For $E \ll m_\rho$ the effective Lagrangian can be written in terms of a single $\mathrm{SU(2)_L}$ current $J^a_\mu$ :

$$J^a_\mu = g_q \lambda^q_{ij} \left( \bar{q}^i_L \gamma_\mu \tau^a q^j_L \right) + g_\ell \lambda^\ell_{ij} \left( \bar{\ell}^i_L \gamma_\mu \tau^a \ell^j_L \right)$$

$$\tau^a = \sigma^a/2$$

$$\Delta \mathcal{L}^{(T)}_{4f} = -\frac{1}{2 m_V^2} J^a_\mu J^a_\mu$$

→ Correlate $qqqq$, $qq\ell\ell$ and $\ell\ell\ell\ell$ processes

The flavor structure is

$$\lambda^q_{bs} \ll \lambda^q_{bb} = 1 \qquad \lambda^q_{ss} = (\lambda^q_{bs})^2 \qquad |\lambda^q_{bs}| \sim |V_{ts}|$$

$$\lambda^\ell_{\tau\mu} \ll \lambda^\ell_{\tau\tau} = 1 \qquad \lambda^\ell_{\mu\mu} = (\lambda^\ell_{\tau\mu})^2$$

# Flavor Fit $\rho + \omega$ contribution

$$\epsilon_{\ell,q} \equiv \frac{g_{\ell,q}\, m_W}{g\, m_V} \approx g_{\ell,q} \frac{122\,\text{GeV}}{m_V} \quad + \quad \lambda^{\ell}_{\tau\mu}, \quad \lambda^{q}_{bs}$$

4 parameters

$$R_0 \equiv \frac{g_\ell g_q}{g^2} \frac{m_W^2}{m_V^2} = \epsilon_\ell \epsilon_q \quad + \quad \frac{g_q}{g_\ell} = \frac{\epsilon_q}{\epsilon_\ell}$$

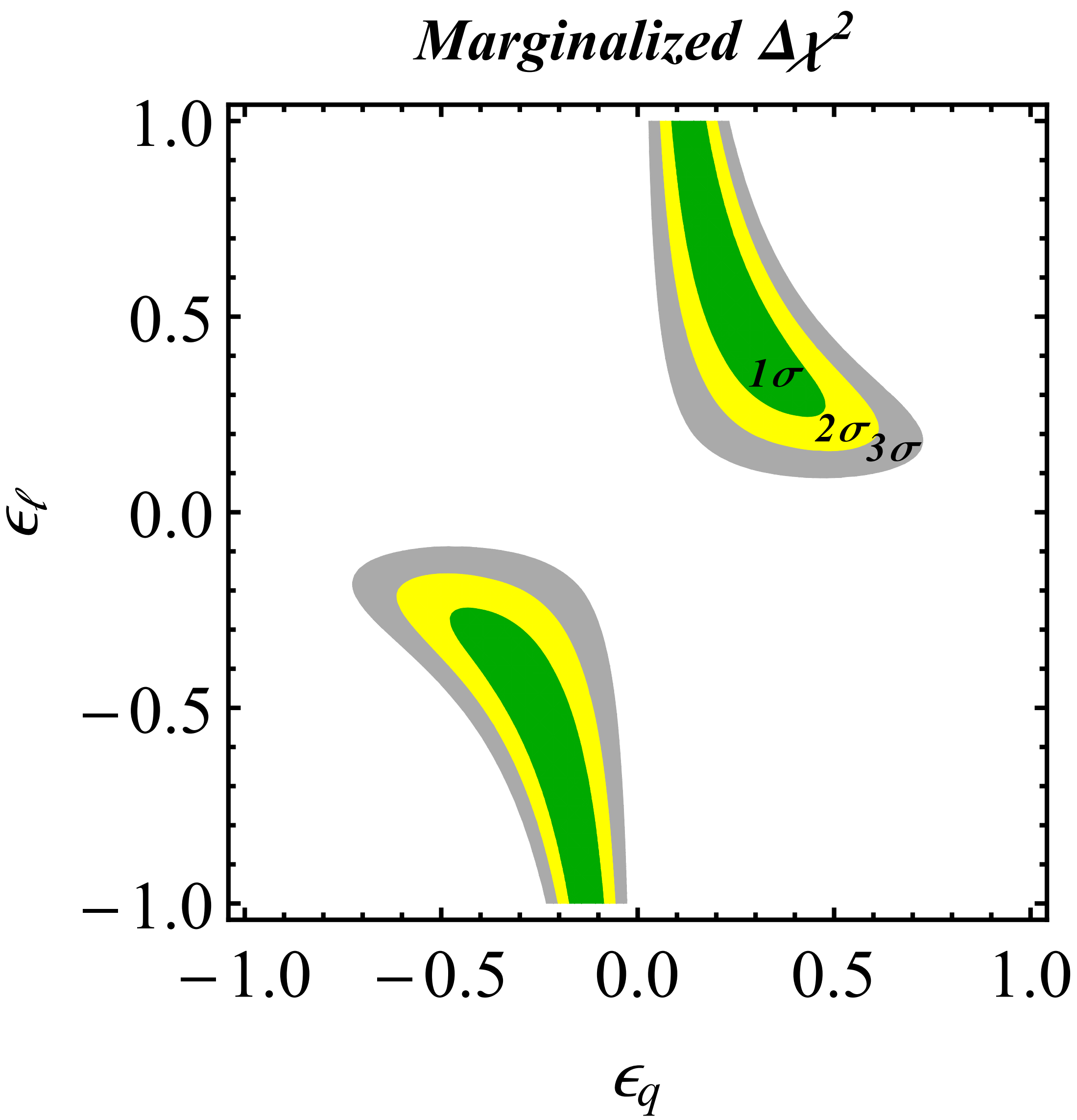
Greljo, Isidori, DM [1506.01705]
Buttazzo, Greljo, Isidori DM [1604.03940]

Input data:

| | Obs. $\mathcal{O}_i$ | Prediction $\mathcal{O}_i(x_\alpha)$ | Experimental value |
|---|---|---|---|
| 1) b→c τ ν | $R_0$ | $\epsilon_\ell \epsilon_q$ | $0.13 \pm 0.03$ |
| 2) b→s μ μ | $\Delta C_9^\mu$ | $-(\pi/\alpha_{\rm em})\, \lambda^\ell_{\mu\mu} (\epsilon_\ell \epsilon_q + \epsilon^0_\ell \epsilon^0_q)\, \lambda^q_{bs} / \lvert V^*_{tb} V_{ts} \rvert$ | $-0.58 \pm 0.16$ |
| 3) $B_s$ mix | $\Delta R^{\Delta F=2}_{B_s}$ | $\left(\epsilon_q^2 + (\epsilon_q^0)^2\right) \lvert \lambda^q_{bs} \rvert^2 \left( \lvert V^*_{tb} V_{ts} \rvert^2 R^{\rm loop}_{\rm SM} \right)^{-1}$ | $-0.10 \pm 0.07$ |
| 4) b→ c$\nu\mu(e)$ | $\Delta R^{\mu e}_{b \to c}$ | $2 \epsilon_\ell \epsilon_q \lambda^\ell_{\mu\mu}$ | $0.00 \pm 0.01$ |
| 5) τ → $\nu\nu\mu(e)$ | $R_{\tau \to \mu/e}$ | $\left\lvert 1 + \epsilon_\ell^2 \lambda^\ell_{\mu\mu} + \frac{1}{2}\left((\epsilon^0_\ell)^2 - \epsilon_\ell^2\right) \lvert \lambda^\ell_{\tau\mu} \rvert^2 \right\rvert^2 + \left\lvert \frac{1}{2}\left(\epsilon_\ell^2 + (\epsilon^0_\ell)^2\right) \lambda^\ell_{\tau\mu} \right\rvert^2$ | $1.0040 \pm 0.0032$ |
| 6) τ → 3$\mu$ | $\Lambda^{-2}_{\tau\mu}$ | $(G_F/\sqrt{2})\left(\epsilon_\ell^2 + (\epsilon^0_\ell)^2\right) \lambda^\ell_{\mu\mu} \lambda^\ell_{\tau\mu}$ | $(0.0 \pm 4.1) \times 10^{-9}$ GeV$^{-2}$ |
| 7) $D$ mix | $\Lambda^{-2}_{uc}$ | $(G_F/\sqrt{2})\left(\epsilon_q^2 + (\epsilon^0_q)^2\right) \lvert V_{ub} V^*_{cb} \rvert^2$ | $(0.0 \pm 5.6) \times 10^{-14}$ GeV$^{-2}$ |
| 8) b→s ν ν | $R_{K^{(*)}\nu}$ | $\left[ 2 + \left\lvert 1 + (\pi/\alpha_{\rm em})(\epsilon_\ell \epsilon_q - \epsilon^0_\ell \epsilon^0_q) \lambda^q_{bs} / (\lvert V^*_{tb} V_{ts} \rvert C^{\rm SM}_\nu) \right\rvert^2 \right] /3$ | $0.0 \pm 2.6$ |

# Low-energy Fit

$\rho + \omega$ contribution $\qquad \epsilon_{q,\ell} = \epsilon^{0}_{q,\ell}$




$\varepsilon_{\ell,q} \sim 0.4$ driven mainly by $R_0$

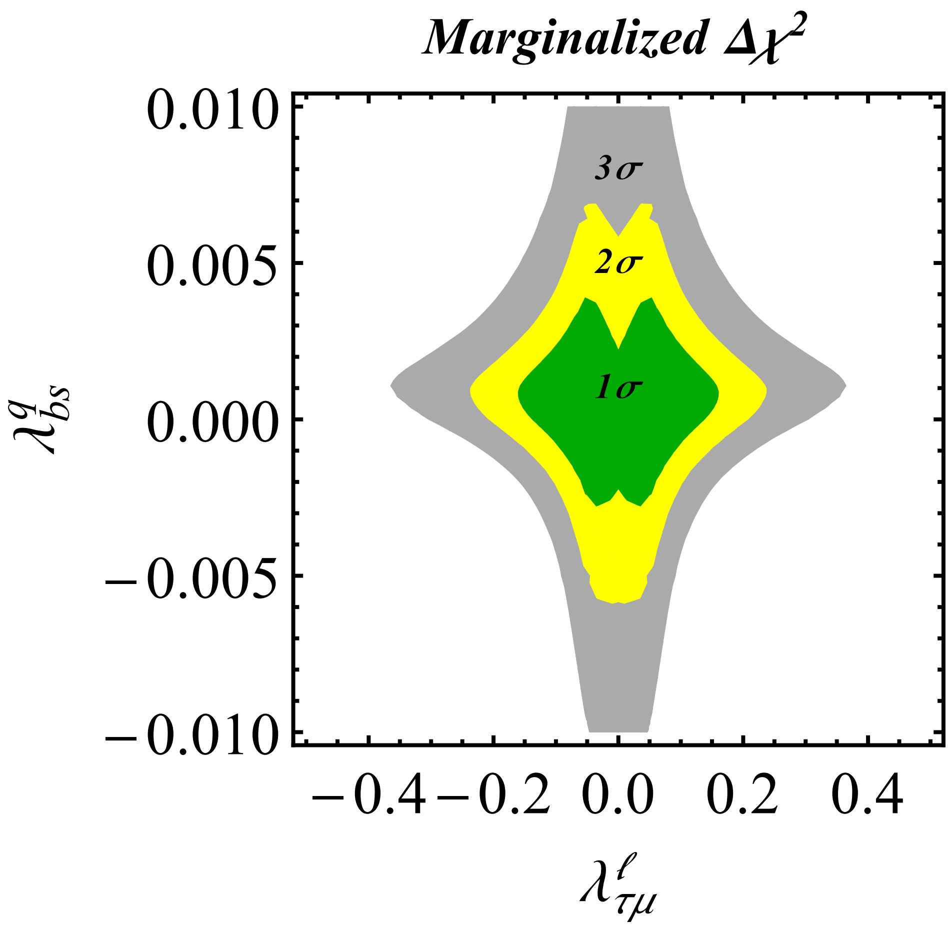
$$\epsilon^{(0)}_{\ell,q} \equiv \frac{g^{(0)}_{\ell,q}\, m_W}{g\, m_\rho} \approx g^{(0)}_{\ell,q} \frac{122 \;\; \text{GeV}}{m_\rho}$$

From diphoton:

$f \sim 230$ **GeV** $\rightarrow$ $m_V \sim 2$ **TeV**

**Strong coupling** $g_\ell \sim 6$

# Low-energy Fit

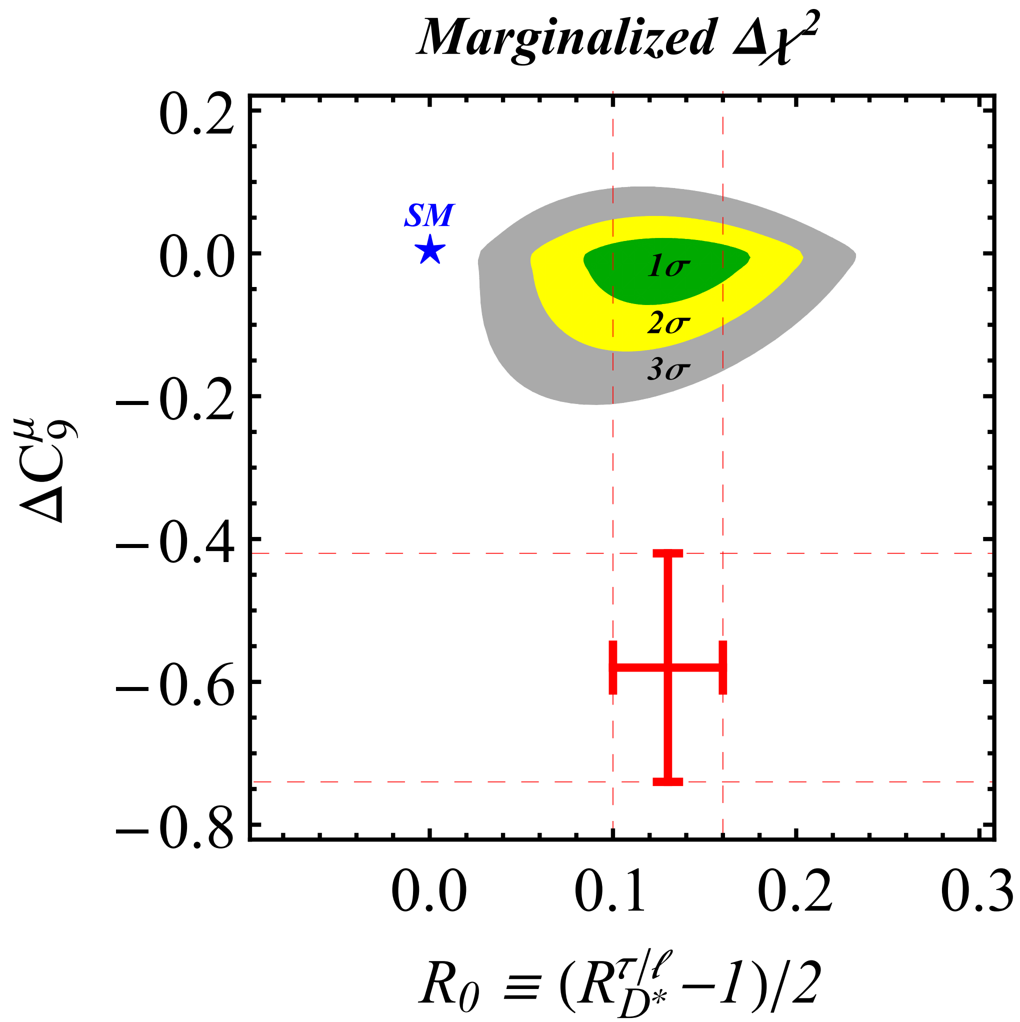



$\rho + \omega$ contribution $\epsilon_{q,\ell} = \epsilon^0_{q,\ell}$

$\lambda^q_{bs} \sim 10^{-3}$

While SU(2) symmetry predicts

$|\lambda^q_{bs}| \sim |V_{ts}| \sim 4 \times 10^{-2}$




Some residual tension in $b \to s\, \mu\, \mu$ remains.

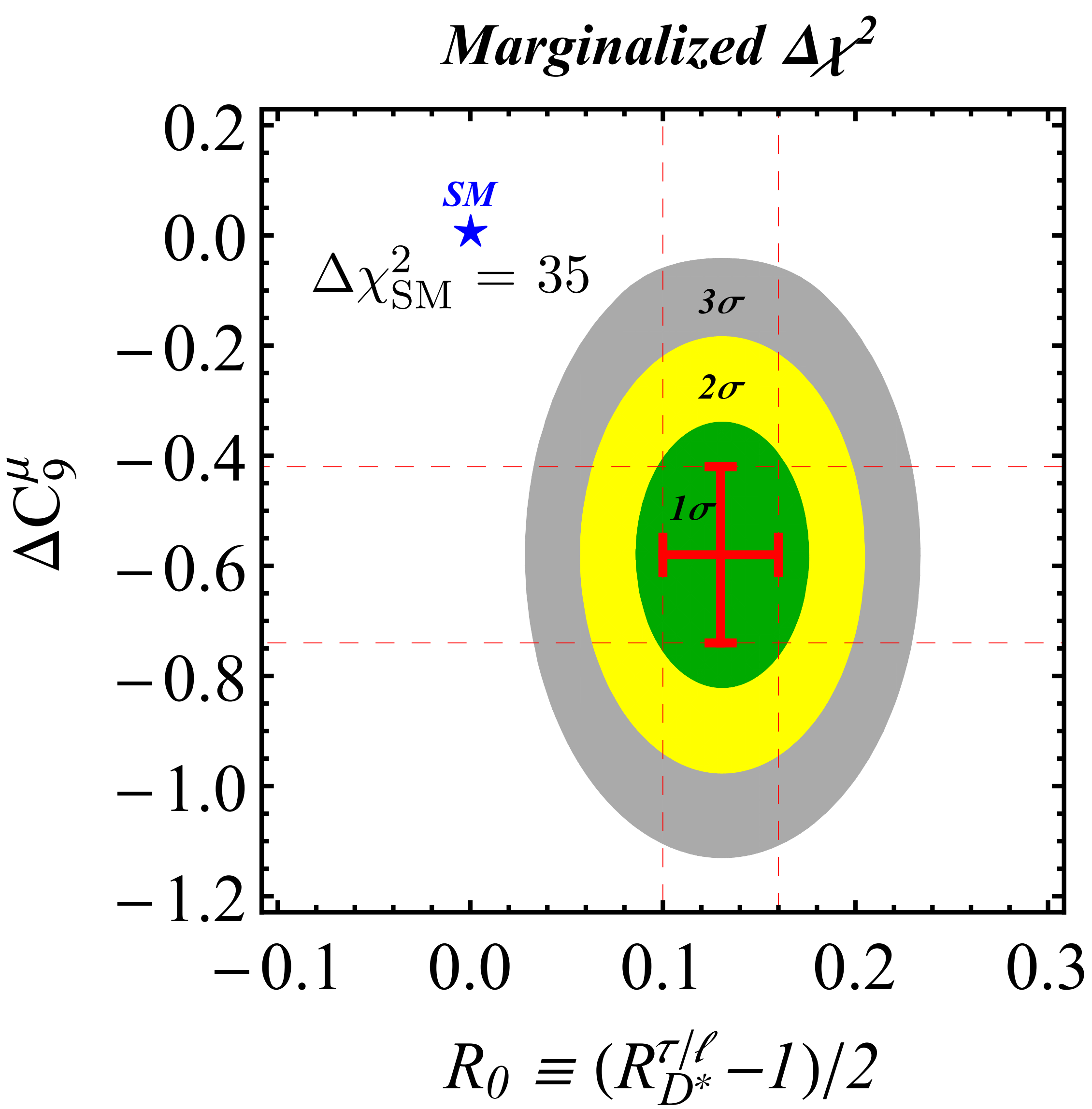
This is due to the bounds from $B_s$ mixing, LFU/V in $\tau$ decays, and the relation $\lambda^\ell_{\mu\mu} = (\lambda^\ell_{\tau\mu})^2$

# Low-energy Fit with the vector-octets

$\rho + \omega + V^A$ contribution

$\epsilon_I \equiv \epsilon_q = \epsilon_\ell$

$\epsilon_O$

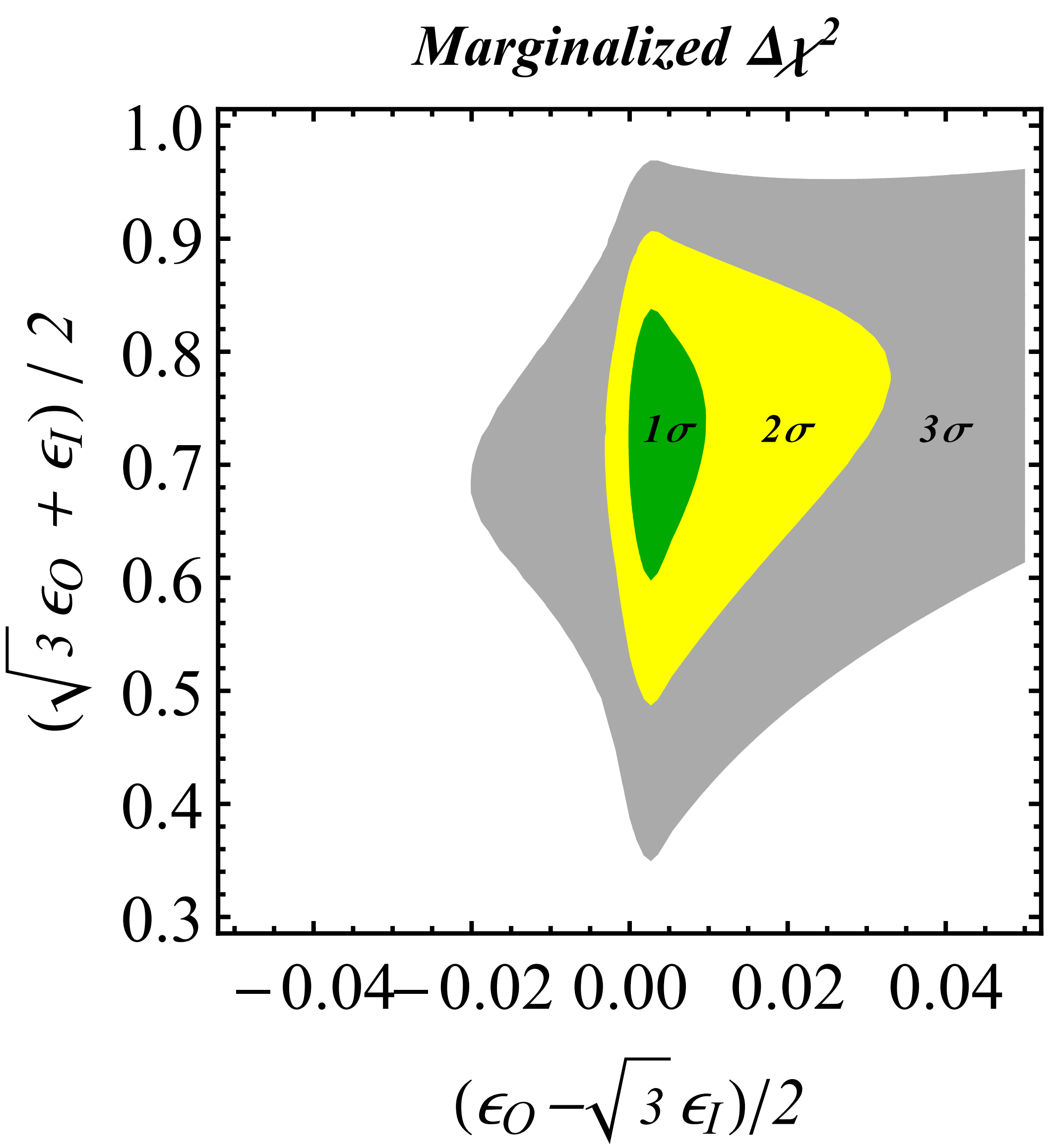



Perfect fit of $\Delta C_9$ possible.

& $|\lambda^q_{bs}| \sim |V_{ts}| \sim 4 \times 10^{-2}$

is OK

The price is a tuning of the couplings of the vectors (non-perturbative param.):



# Flavor Predictions of the Model

*Charged Current.* $R_D^{\tau/\ell} = R_{D*}^{\tau/\ell}$ $R_D^{\mu/e} \lesssim 10\% R_D^{\tau/\ell}$

*FCNC*

In B → Kμμ $\Delta C_9^\mu = -\Delta C_{10}^\mu$ → Central value should decrease.

In b → s τ̄τ | NP | ~ | SM | → Big enhancement or strong suppression

$B_s \leftrightarrow \bar{B}_s$ If anomaly in B → Kμμ persists, expected O(10%) deviation.

If $SU(2)_Q$ symmetry → $\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \left.\frac{\Delta M_{B_s}}{\Delta M_{B_d}}\right|_{SM}$

$D \leftrightarrow \bar{D}$ Bound almost saturated. NP (CP phase) behind the corner.

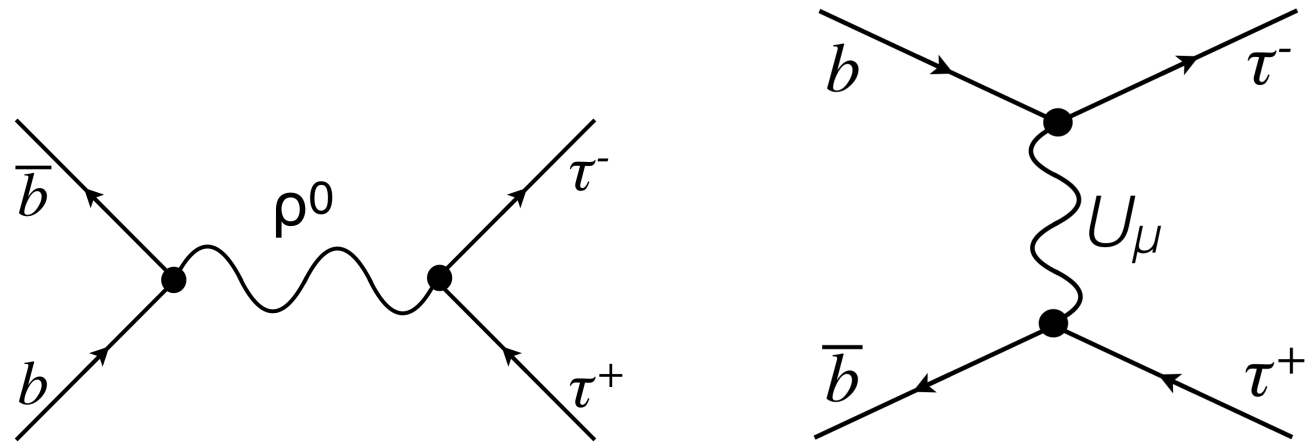
*τ decays* $\tau \to 3\mu$ & $\frac{BR(\tau \to \mu\nu\bar{\nu})}{BR(\tau \to e\nu\bar{\nu})}$ Just below the bound.

# High-energy searches

# Flavor anomalies → $\tau\tau$ and $bb$ signals

Large deviations in $B \to D^{(*)}\tau\nu$ strongly suggests tree-level mediators

strongly coupled to 3rd-gen. fermions




**Expect signal in $\tau\tau$ (or $bb$) channel at LHC,**

**from $bb$-fusion production.**

# Vector meson Mass & Width

**From the diphoton anomaly:**

$f \sim 230$ **GeV** $\longrightarrow$ $m_V \sim 2$ **TeV**

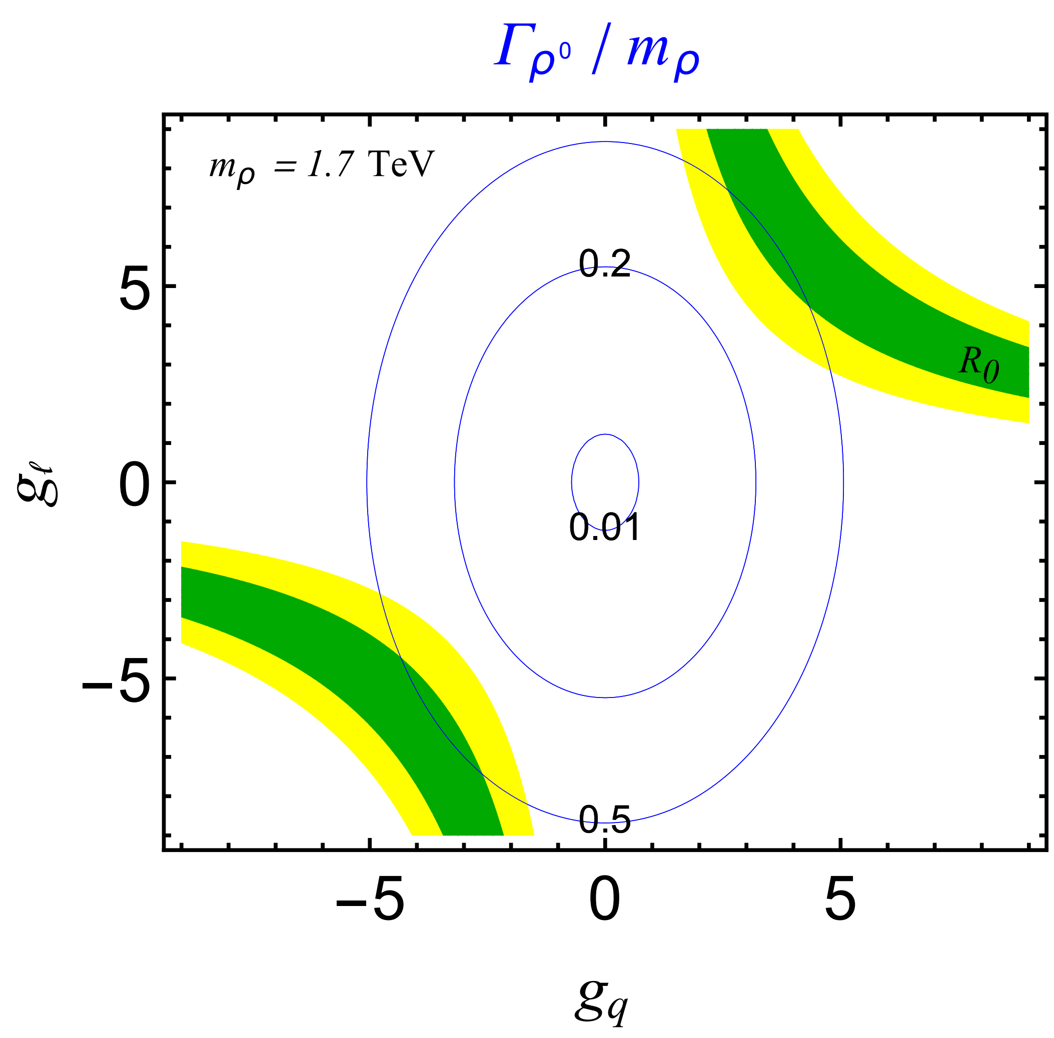
**From Flavor Fit: Very Large Width**

Triplet:

$$\frac{\Gamma_{V^\pm}}{m_{V^\pm}} \approx \frac{\Gamma_{V^0}}{m_{V^0}} \approx \frac{1}{48\pi}(g_\ell^2 + 3 g_q^2)$$

$$R_0 \equiv \frac{g_\ell g_q}{g^2} \frac{m_W^2}{m_V^2} \simeq 0.13$$

Decay into pNGB is subleading.



# Vector Triplet / Singlet

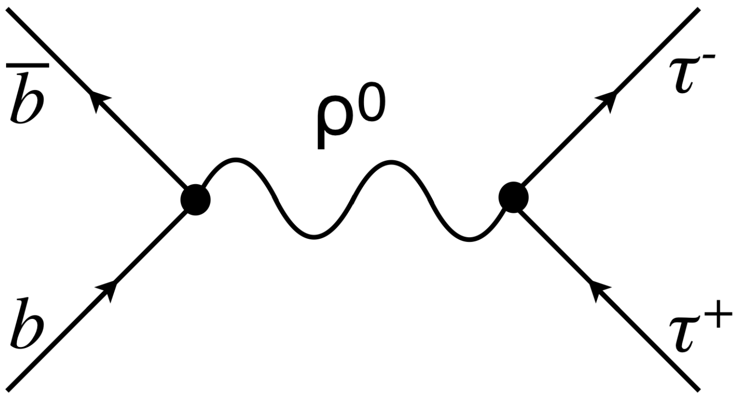
## Decay channels

- **Neutral vector:**
  - $\tau\ \tau$
  - $b\ b$
  - $\nu_\tau\ \nu_\tau$
  - $t\ t$
- **Charged vector:**
  - $\tau\ \nu$
  - $t\ b$
  - $V_{cb}\ c\ b$

$$\frac{\Gamma_{V^\pm}}{m_{V^\pm}} \approx \frac{\Gamma_{V^0}}{m_{V^0}} \approx \frac{1}{48\pi}(g_\ell^2 + 3g_q^2)$$

## Production

Single production ( $\boldsymbol{bb \to \rho^0}$, $bc \to \rho^\pm$)



# Vector Triplet / Singlet

- Usually, in such models the leading decay channel of vector mesons is in pNGB:

$$\Gamma(\rho \to \pi\pi) = \frac{g_{\rho\pi\pi}^2}{192\pi} m_\rho \left(1 - \frac{4m_\pi^2}{m_\rho^2}\right) \qquad g_{\rho\pi\pi} \lesssim 4\pi$$

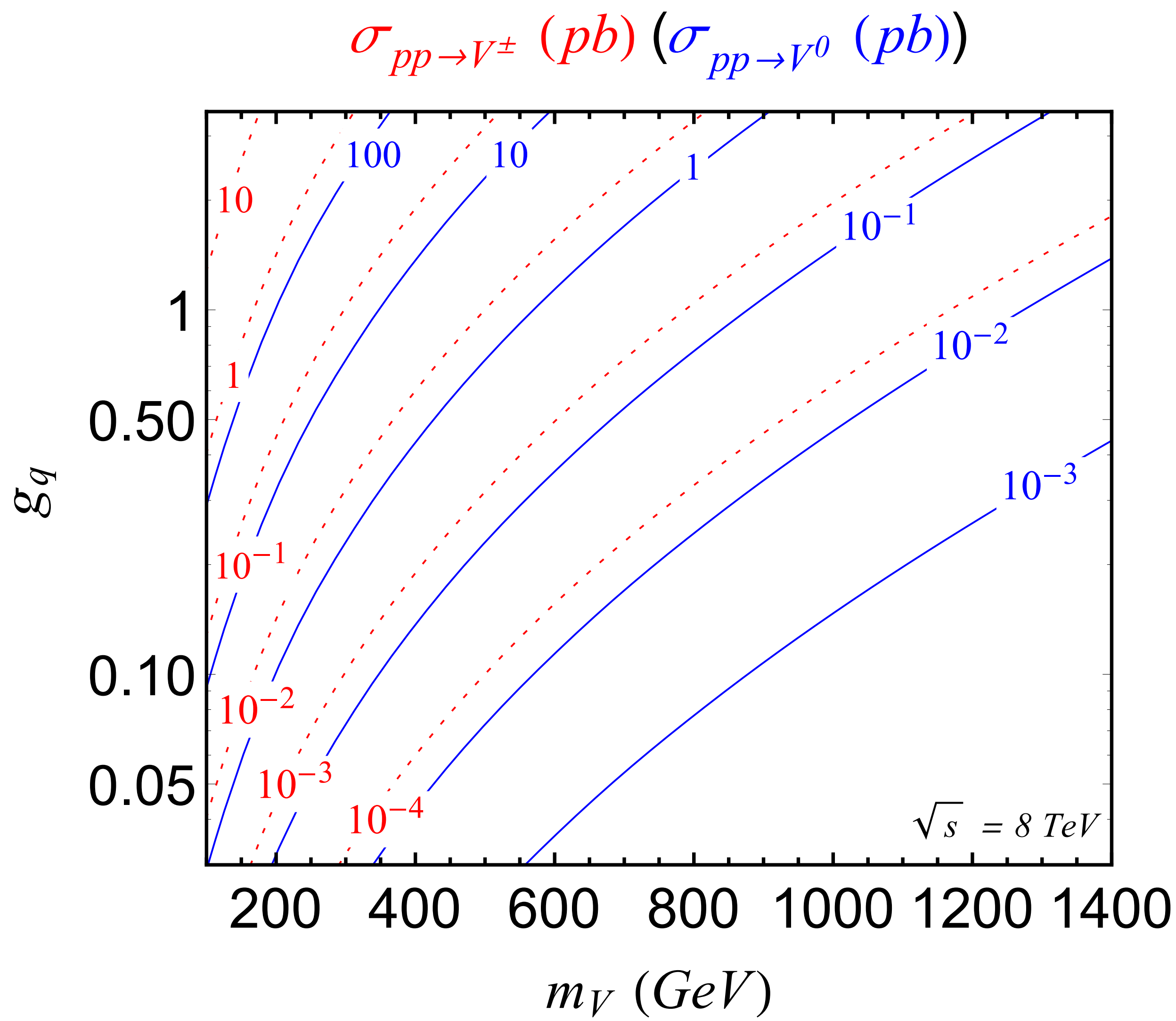
In our case, due to large coupling with 3rd generation fermion, this is subleading, or at most of the same order, w.r.t. the fermionic ones.

- In vectorlike confinement models, vector mesons mix with the corresponding SM gauge boson: $\theta_{mix} \sim g/g_\rho$ .

Production via Drell-Yan through the mixing is negligible.

$$R_{b\bar{b}/u\bar{u}} \approx \frac{g_q^2}{(g^2/g_\rho)^2} \frac{\mathcal{L}_{b\bar{b}}}{\mathcal{L}_{u\bar{u}}} \sim 7 \quad @1.7\text{TeV}$$

# Production




Greljo, Isidori, DM 1506.01705

$V_{cb} \sim 0.04$

$V_{cb}\, c\, \bar{b} \to \rho^+$

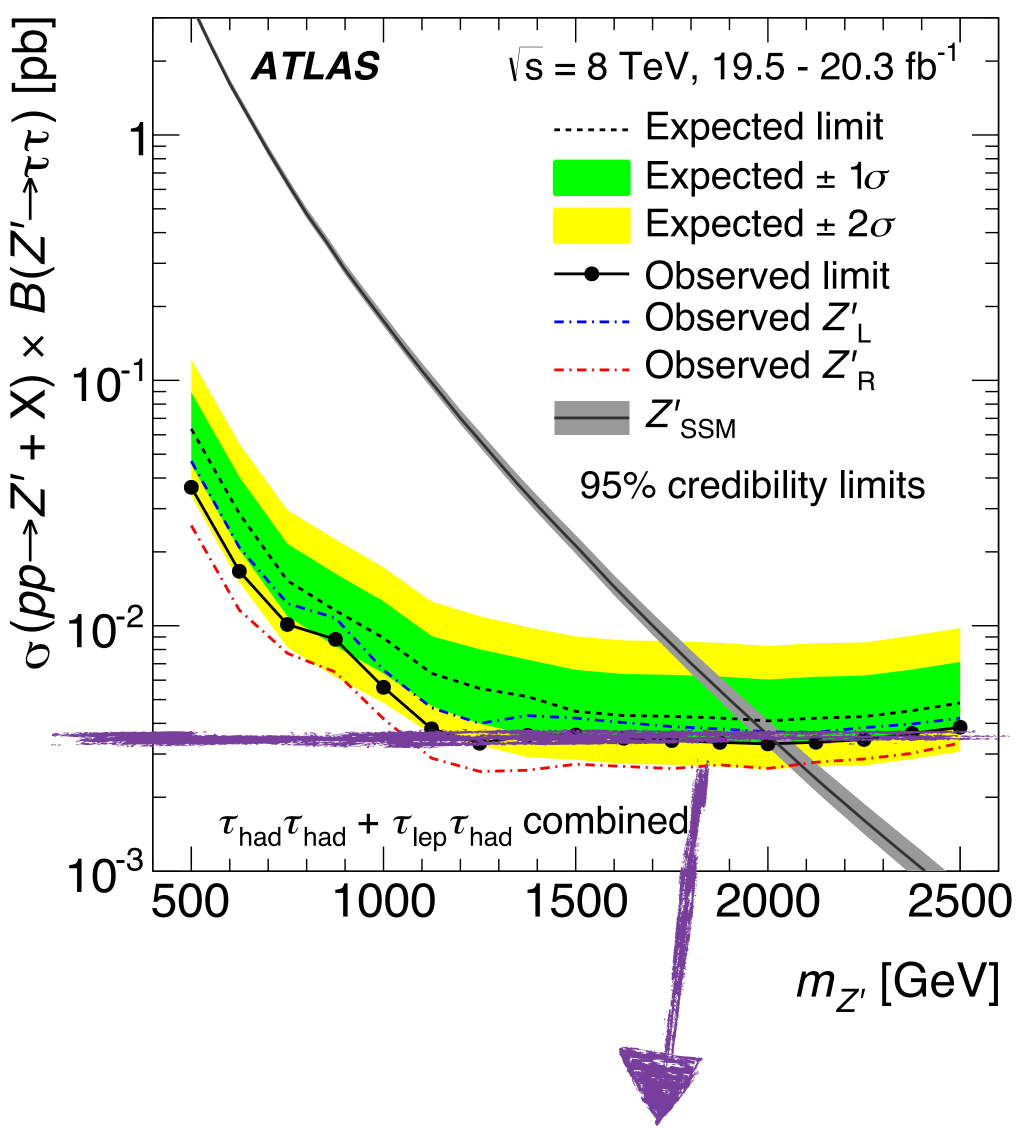
Production of the charged vector is suppressed by $V_{cb}$.

$b\, \bar{b} \to \rho^0$

Neutral vectors are the relevant ones.

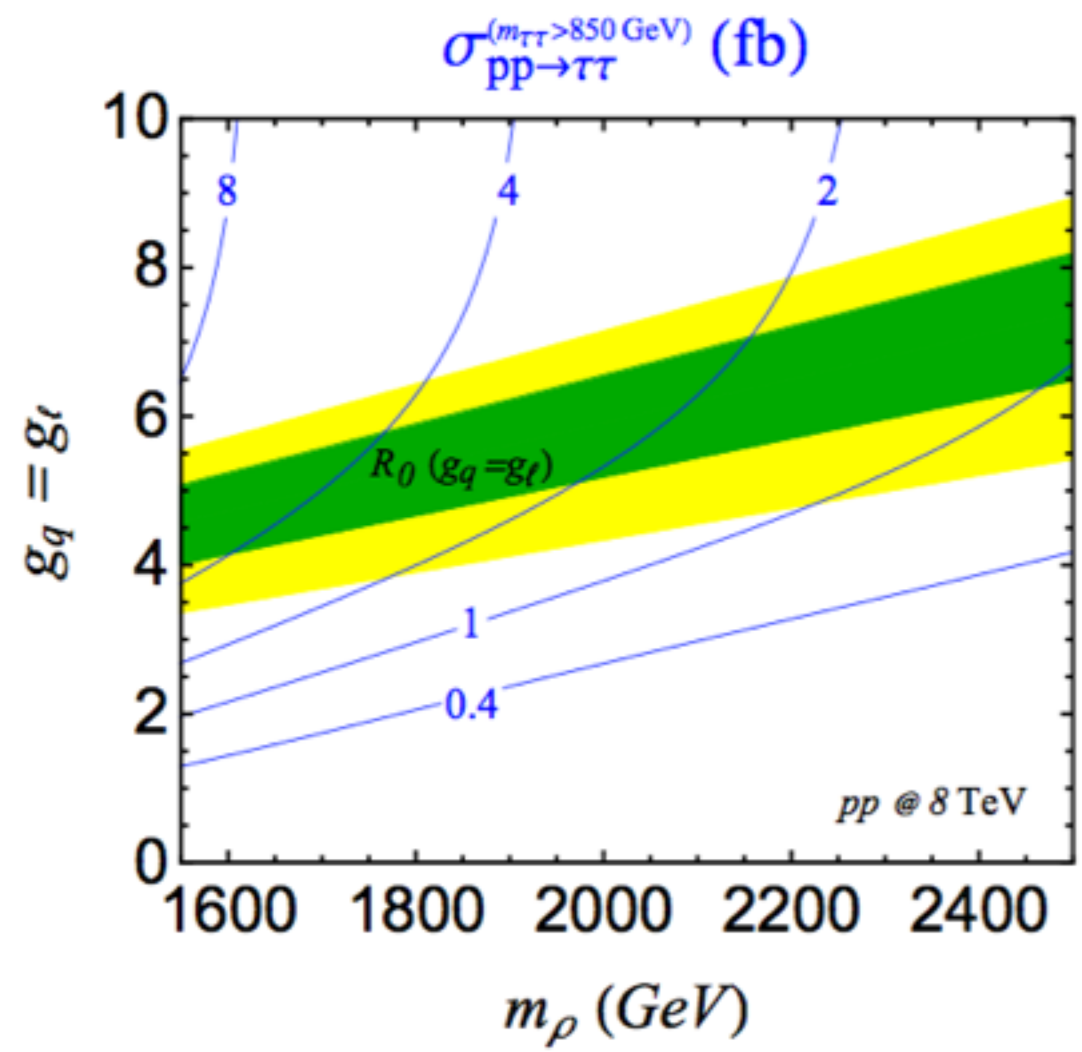
# Experimental bound

ATLAS 1502.07177




$$\sigma(pp \to Z' + X) \times \mathcal{B}(Z' \to \tau^+\tau^-) \lesssim 4\ (7)\ \text{fb}$$

for a narrow (moderate) resonance
in 1.5-2.0 TeV

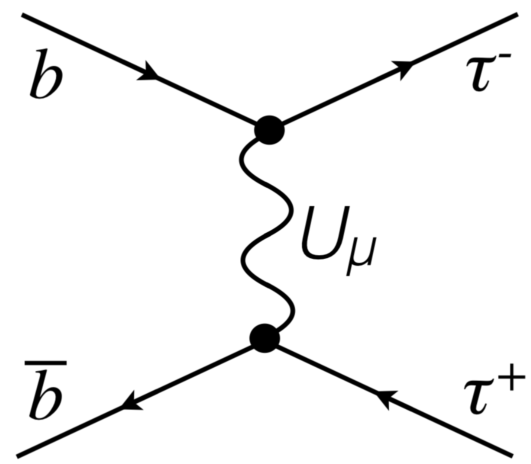



**Expected to show up soon at LHC**

A detailed recast is necessary to extract precise bounds.

[work in progress by Kamenik, Greljo et al.]

# Vector Leptoquark




For $m_U \gg m_{\tau\tau}/2$ angular distr. is similar to s-channel exchange

$R_0 = 0.13$
$m_U = 1.7$ TeV → $\sigma(pp \to \tau^+\tau^-) \sim 10$ fb for $m_{\tau\tau} \geq 850$ GeV

**Expected to show up soon at LHC**

# Phenomenology of the other pNGBs

$\pi^a = (\mathbf{1},\mathbf{3},0)$

Lightest pNGB: $m_\pi \sim 400$ - $800$ GeV

Production $q\bar{q} \to W^{\pm *} \to \pi^\pm \pi^0$ or $q\bar{q} \to Z^*/\gamma^* \to \pi^+\pi^-$

Decay $\pi^0 \to tt, \;\; \pi^+ \to t\bar{b}$

**Challenging to look for at the LHC**

Also:

$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{N_{TC}^2 \alpha^2 Y_L^2}{16\pi^3} \frac{m_{\pi^0}^3}{f^2}$$

$\tilde{\pi}^{A(a)} = (\mathbf{8},\mathbf{1},0) + (\mathbf{8},\mathbf{3},0)$

Heaviest pNGB: $m_{\tilde{\pi}} \sim 1$ - $1.5$ TeV

Production $g\, g \to \tilde{\pi}^A, \quad g\, g \to \tilde{\pi}^A\, \tilde{\pi}^A$

Decay $\tilde{\pi}^A \to tt,\, gg,\, g\gamma$

[Bai, Barger, Berger 1604.07835]

Already very strong bound: signal should be expected soon.

Leptoquarks $m \sim 1$ TeV

Model I: $D = (\mathbf{3},\mathbf{2},\Delta Y) + \text{h.c.}$ → stable in minimal model.

Model II: $S,\, T^a = (\mathbf{3},\mathbf{1},3/2) + (\mathbf{3},\mathbf{3},3/2) + \text{h.c.}$

They are both pair produced, present bounds ~ 700GeV.

# Conclusions

- Interesting anomalies are present both
in low-energy flavour observables & in high-pT searches.

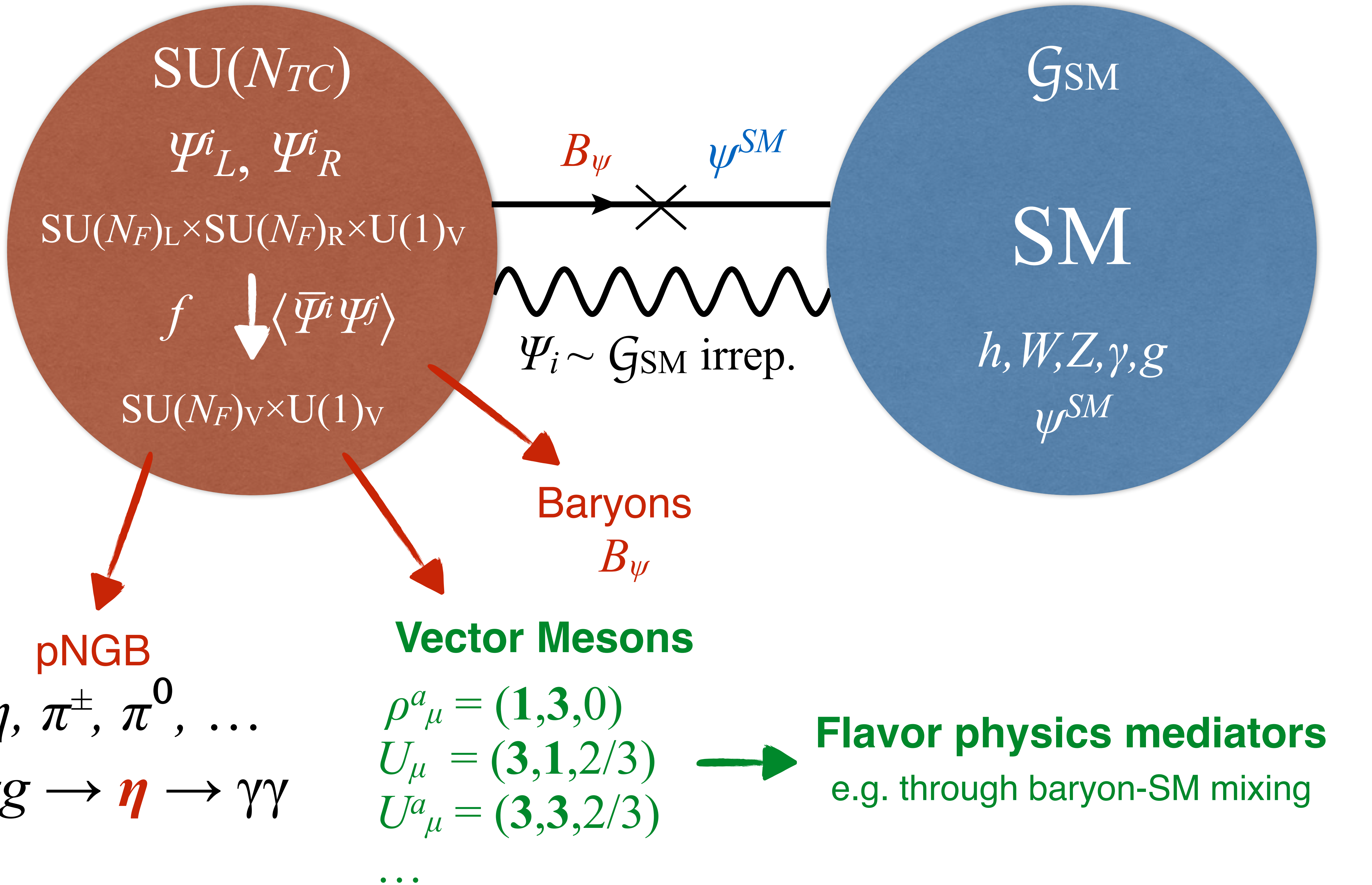
- **Vectorlike confinement** could offer a setup to explain both:
a pNGB for the observed diphoton excess &
vector mesons as mediators of flavour anomalies.

- Many testable predictions can be derived:
new resonances and flavour signatures: **a new spectroscopy**!

- Does this have anything to do with reality?
Soon we will know more.

**Exciting times ahead!**

# Thank you!


SU($N_{TC}$)
$\Psi^i{}_L$, $\Psi^i{}_R$
SU($N_F$)L×SU($N_F$)R×U(1)V
$f$ $\langle \bar{\Psi}^i \Psi^j \rangle$
SU($N_F$)V×U(1)V
$B_\psi$
$\psi^{SM}$
$\Psi_i \sim \mathcal{G}_{SM}$ irrep.
$\mathcal{G}_{SM}$
SM
$h, W, Z, \gamma, g$
$\psi^{SM}$
Baryons
$B_\psi$
pNGB
$\eta,\ \pi^{\pm},\ \pi^0,\ \ldots$
$gg \to \eta \to \gamma\gamma$
Vector Mesons
$\rho^a{}_\mu = (\mathbf{1},\mathbf{3},0)$
$U_\mu = (\mathbf{3},\mathbf{1},2/3)$
$U^a{}_\mu = (\mathbf{3},\mathbf{3},2/3)$
$\ldots$
Flavor physics mediators
e.g. through baryon-SM mixing

# Backup

# UV completion for partial compositeness

[D. Kaplan '91]

$N_{TC} = 3$

$Q = (N_{TC}, \mathbf{3}, \mathbf{1}, 1/6)$
$L = (N_{TC}, \mathbf{1}, \mathbf{2}, -1/2)$

Add two scalars charged under $SU(N_{TC}) \times G_{SM}$

$$\phi \equiv (\bar{\mathbf{3}}, 1, 1)_{1/3} \;,\;\; \chi \equiv (\bar{\mathbf{3}}, \bar{\mathbf{3}}, 1)_{-1/3}$$

Mass: $m_{\varphi,\chi} \gtrsim \Lambda_{TC}$

Yukawa interaction:

$$\mathcal{L} \supset y_\phi \bar{\ell}_L^C L_L \phi + z_\phi \bar{L}_L^C L_L \phi^* + y_\chi \bar{q}_L^C L_L \chi + z_\chi \bar{Q}_L^C Q_L \chi^* + \text{h.c.}$$

Below their mass:

$$\mathcal{L}_{eff} \supset -\frac{y_\phi z_\phi}{m_\phi^2} \; \bar{\ell}_L^C L_L \bar{L}_L^C L_L - \frac{y_\chi z_\chi}{m_\chi^2} \; \bar{q}_L^C L_L \bar{Q}_L^C Q_L$$

# $\rho$ - SM fermion coupling - 2

Another possibility without invoking baryons:

Assume that at the flavor scale $\Lambda_F \gtrsim \Lambda_{\rm TC}$,
a 4-fermion operator is generated

$$\frac{c_f^{ij}}{\Lambda_F^2}(\bar{\psi}_{\rm TC}\gamma_\mu\psi_{\rm TC})(\bar{f}^i_{\rm SM}\gamma_\mu f^j_{\rm SM})$$

$\Lambda^2{}_{\rm TC}\,\rho_\mu$

This framework is more general (less predictive) than the baryon-mixing one.
Also, the doublets can be contracted to form a singlet: coupling not suppressed.
For these reasons we focus on the baryon-mixing case.

# Heavy Vector Triplet

These 4-fermion operators can naturally be generated by integrating out a heavy Vector Boson, triplet of $SU(2)_L$:

[Pappadopulo, Thamm, Torre, Wulzer 1402.4431]

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]a} + \frac{m_V^2}{2} V^a_\mu V^{\mu a} + \boxed{g_H} V^a_\mu (H^\dagger T^a i \overleftrightarrow{D}_\mu H) + V^a_\mu J^a_\mu$$

$$J^a_\mu = g_q \lambda^q_{ij} \left( \bar{Q}^i_L \gamma_\mu T^a Q^j_L \right) + g_\ell \lambda^\ell_{ij} \left( \bar{L}^i_L \gamma_\mu T^a L^j_L \right)$$

Coupling to the Higgs current

The dimension-6 operators obtained by integrating it out are:

$$\mathcal{L}^{d=6}_{\rm eff} = \boxed{-\frac{1}{2 m_V^2} J^a_\mu J^a_\mu} - \boxed{\frac{g_H^2}{2 m_V^2} (H^\dagger T^a i \overleftrightarrow{D}_\mu H)(H^\dagger T^a i \overleftrightarrow{D}_\mu H)} - \boxed{\frac{g_H}{m_V^2} (H^\dagger T^a i \overleftrightarrow{D}_\mu H) J^a_\mu}$$

4-fermion op. $\quad$ $Z$, $W$ masses, $hVV$ couplings $\quad$ $Zff$ and $Zhff$ couplings

# EW-scale effects: Z-pole

$$-\frac{g_H}{m_V^2}(H^\dagger T^a i \overleftrightarrow{D}_\mu H) J^a_\mu$$

Deviation in Z couplings to $b\bar{b}$ and $\tau\bar{\tau}$.

Bounds from Flavorful fit of LEP-I

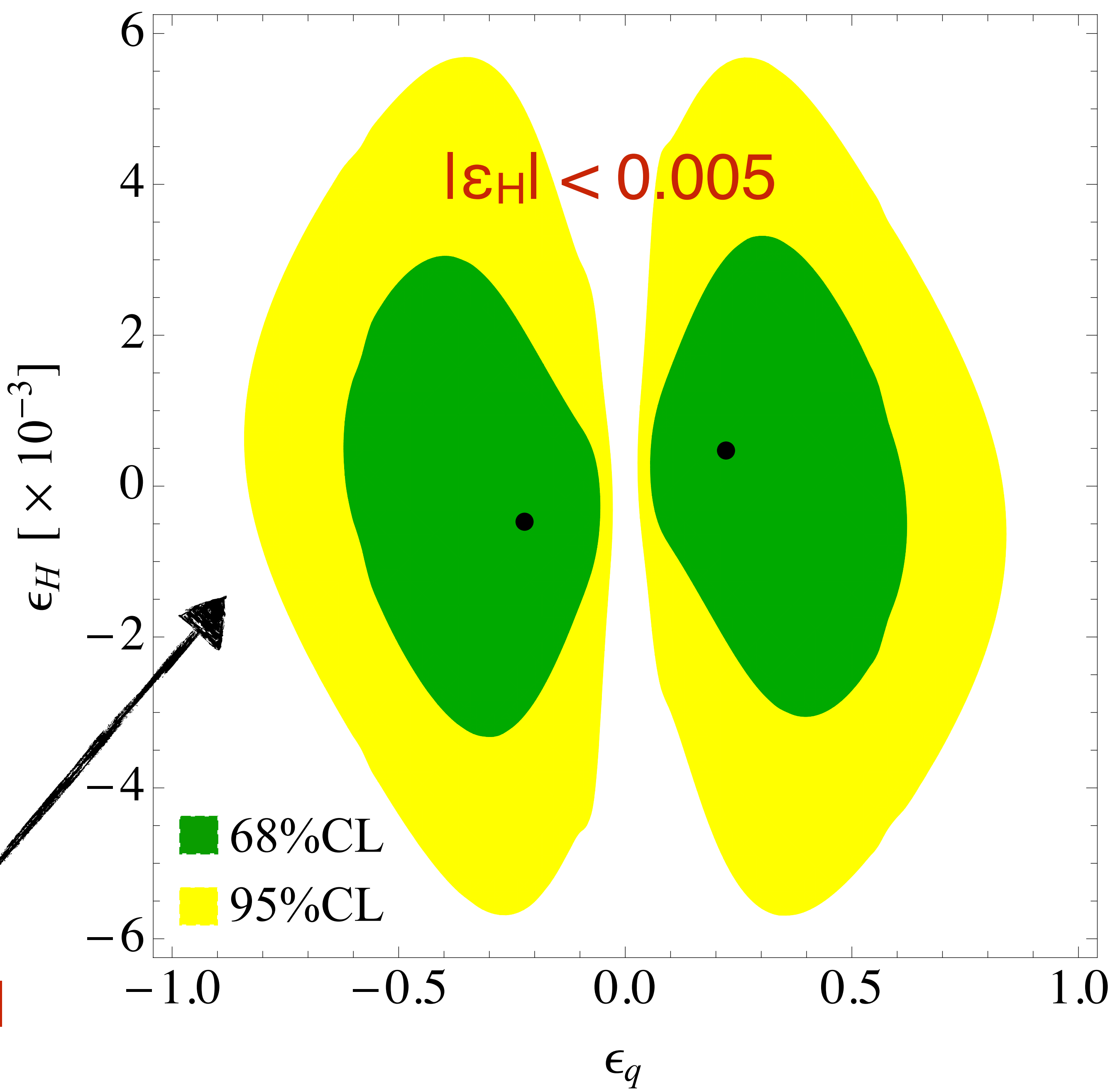
[Non-Universal fit by Efrati, Falkowski, Soreq 1503.07872]

$$\epsilon_\ell\, \epsilon_H \equiv \frac{g_\ell g_H m_W^2}{g^2 m_V^2} = (4.3 \pm 8.7) \times 10^{-4}$$

$$\epsilon_q\, \epsilon_H \equiv \frac{g_q g_H m_W^2}{g^2 m_V^2} = (-0.8 \pm 1.4) \times 10^{-3}$$

Greljo, Isidori, DM [1506.01705]

Flavor + LEP-I



# EW-scale effects: Higgs

$$-\frac{g_H^2}{2m_V^2}(H^\dagger T^a i \overleftrightarrow{D}_\mu H)(H^\dagger T^a i \overleftrightarrow{D}_\mu H)$$

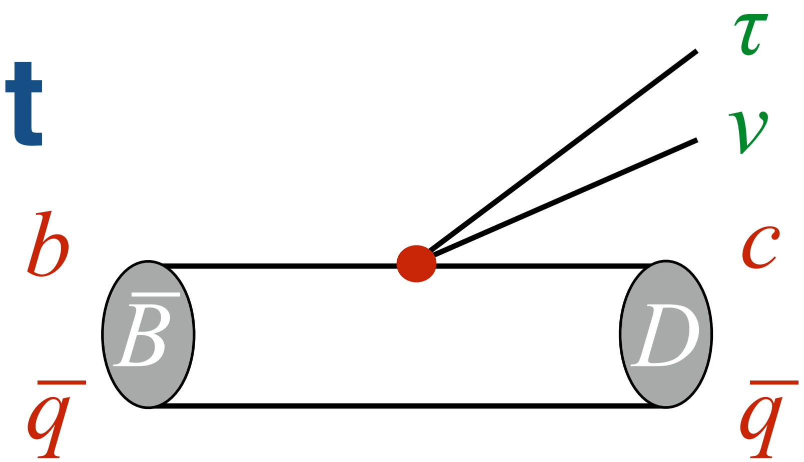
=

$$-\frac{g_H^2 v^2}{4m_V^2}\left(m_W^2 W_\mu^+ W_\mu^- + \frac{m_Z^2}{2} Z_\mu Z_\mu\right)\left(1+\frac{h}{v}\right)^4$$

Unphysical W and Z mass shift, deviations in Higgs couplings ~ $\varepsilon_H$.

Irrelevant given the constraint on $\varepsilon_H$ from LEP-I. $|\varepsilon_H| < 0.005$

# Charged Current




$$\Delta\mathcal{L} = -\frac{g_q g_\ell}{2m_V^2} V_{cb} (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L^\tau)$$

Same structure as the SM: overall rescaling.

$$\frac{\mathcal{A}(b \to c\, \ell^i \bar{\nu}^i)_{\rm SM+NP}}{\mathcal{A}(b \to c\, \ell^i \bar{\nu}^i)_{\rm SM}} = 1 + R_0 \lambda^\ell_{ii}$$

$$R_0 \equiv \frac{g_\ell g_q}{g^2} \frac{m_W^2}{m_V^2}$$

For $B \longrightarrow D^{(*)}\, \tau\, \nu$ :

$$R_D^{\tau/\ell} = R_{D*}^{\tau/\ell} \simeq 1 + 2R_0 \quad \longrightarrow \quad R_0 = 0.14 \pm 0.04$$

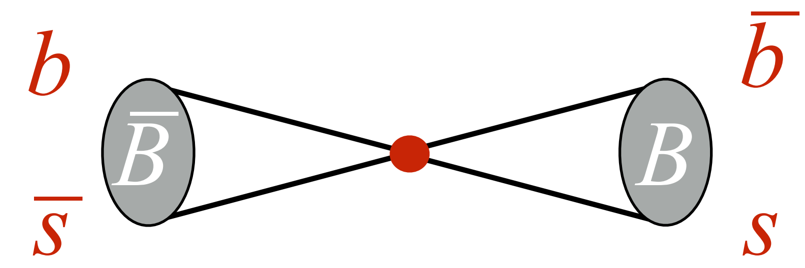
For decays to μ we have:

deviations ≲ 2%

$$\frac{\Gamma(b \to c(u)\mu\nu)}{\Gamma(b \to c(u)e\nu)} \simeq 1 + 2R_0 \lambda^\ell_{\mu\mu} \quad \longrightarrow \quad |\lambda^\ell_{\mu\mu}| \lesssim 0.07 \left(\frac{0.15}{R_0}\right)$$

# $\Delta B = 2$ processes: $B \leftrightarrow \bar{B}$ mixing

$$\Delta\mathcal{L} = -\frac{g_q^2}{8m_V^2}(\lambda_{bs})^2(\bar{b}_L\gamma_\mu s_L)^2$$




Contributes to $\bar{B}^0 \leftrightarrow B^0$ mixing. No deviations observed here.

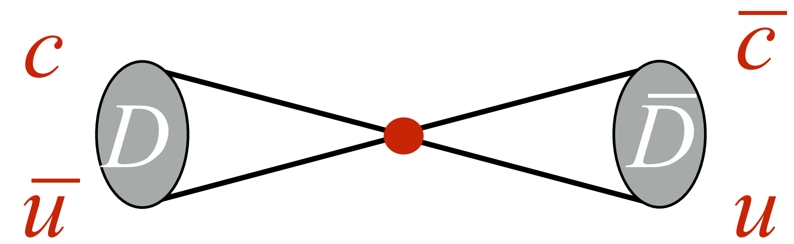
$$R_{B_q}^{\Delta F=2} = \frac{\mathcal{A}(B_q \to \bar{B}_q)_{\rm SM+NP}}{\mathcal{A}(B_q \to \bar{B}_q)_{\rm SM}} = 1 + R_0 \frac{g_q}{g_\ell}\frac{(\lambda_{bq}^q)^2}{(V_{tb}^* V_{tq})^2} \times (R_{\rm SM}^{\rm loop})^{-1}$$

$R_0$ is fixed → bound on $\lambda_{bq}$ and $g_q/g_\ell$.

$$|\lambda_{bs}^q| < |\lambda_{bs}^q|_{\rm max} = 0.093\,|V_{ts}| \left|\frac{g_\ell}{g_q}\right|^{1/2} \left(\frac{0.15}{R_0}\right)^{1/2}$$

# $\Delta C = 2$ processes: $D \leftrightarrow \bar{D}$ mixing

$$\Delta\mathcal{L} = -\frac{g_q^2}{8m_V^2}(V_{ub}V_{cb}^*)^2(\bar{u}_L\gamma_\mu c_L)^2$$




CKM-induced from $\lambda_{bb} = 1$.

Contributes to $\bar{D}^0 \leftrightarrow D^0$ mixing. No deviations observed here.

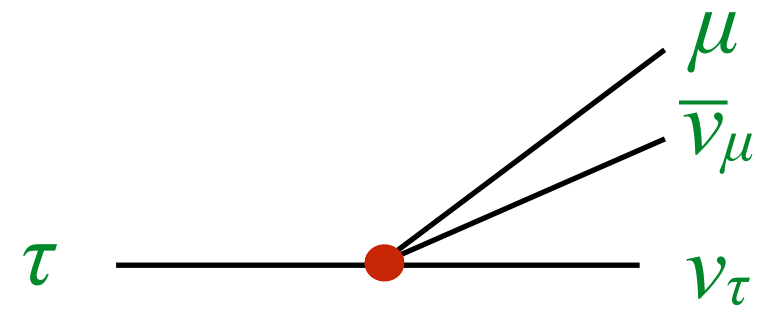
The scale probed is:

$$\Lambda_{uc} = 6.9 \times 10^3 \text{ TeV} \times \left|\frac{g_\ell}{g_q}\right|^{1/2} \left(\frac{0.15}{R_0}\right)^{1/2} > 3 \times 10^3 \text{ TeV}$$

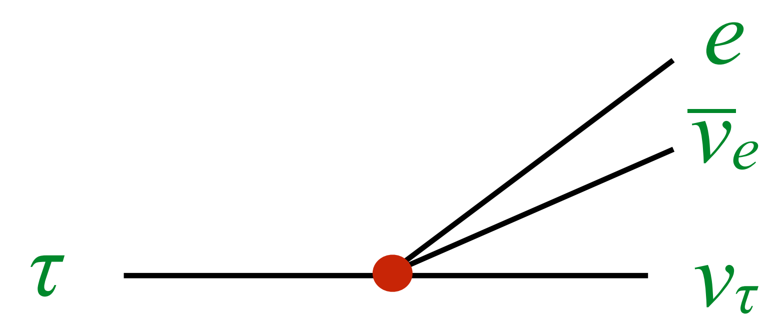
[Isidori 1302.0661]

$R_0$ is ~ fixed $\longrightarrow$ $\left|\frac{g_q}{g_\ell}\right| \lesssim 5.4$

# LFU in $\tau$ decays




vs.




$\lambda^\ell_{ee} \ll \lambda^\ell_{\mu\mu}$

SM + $\Delta\mathcal{L} = -\frac{g_\ell^2}{2m_V^2}\lambda^\ell_{\mu\mu}(\bar{\tau}_L\gamma_\mu\mu_L)(\bar{\nu}_\tau\gamma^\mu\nu_\mu)$

SM only

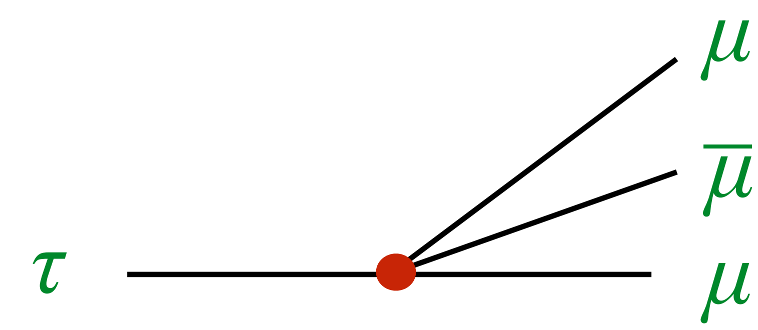
Tau decays well measured (permil), no deviation from LFU observed:

[Stugu hep-ex/9811048]

$$\lambda^\ell_{\mu\mu} = (0.013 \pm 0.011) \times \frac{g_q}{g_\ell}\left(\frac{0.15}{R_0}\right)$$

# LFV: $\tau \to 3\mu$

$$\Delta\mathcal{L} = -\frac{g_\ell^2}{4m_V^2}\lambda^\ell_{\tau\mu}\lambda^\ell_{\mu\mu}(\bar{\tau}_L\gamma_\mu\mu_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$




Experimental bound: $\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$

$$|\lambda^\ell_{\mu\mu}\lambda^\ell_{\tau\mu}| < 0.005\left|\frac{g_q}{g_\ell}\right|\left(\frac{0.15}{R_0}\right)$$

Given that

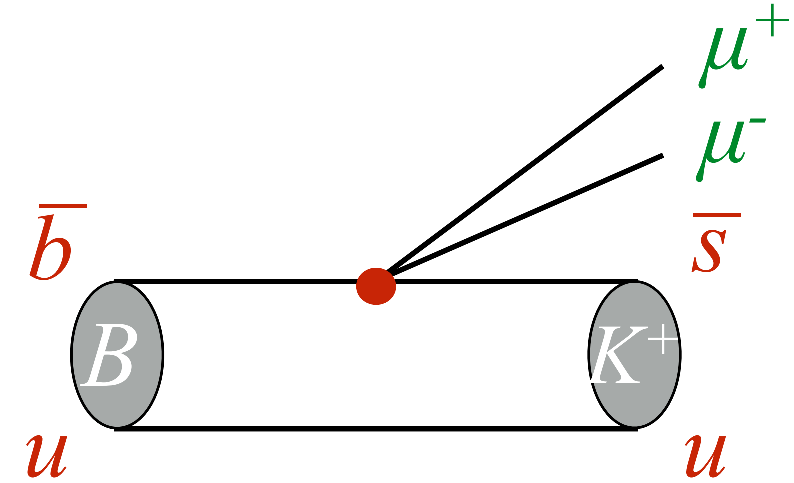
$$|\lambda^\ell_{\mu\mu}| \lesssim 0.07\left(\frac{0.15}{R_0}\right)$$

from b→c(u)μν

$$|\lambda^\ell_{\tau\mu}| \lesssim 0.15$$

# Neutral Current

The experimental measurement




$$R_K^{\mu/e} = \left. \frac{\mathcal{B}(B \to K \mu^+ \mu^-)_{\rm exp}}{\mathcal{B}(B \to K e^+ e^-)_{\rm exp}} \right|_{q^2 \in [1,6] {\rm GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

and all other $b \to s\bar{\mu}\mu$ transitions get a contribution from:

$$\Delta \mathcal{L}^{(V)}_{b \to s \ell^+ \ell^-} = - \frac{2 G_F}{\sqrt{2}} R_0 \lambda^q_{bs} \left( \bar{b}_L \gamma_\mu s_L \right) \left( \bar{\tau}_L \gamma_\mu \tau_L + \lambda^\ell_{\mu\mu} \bar{\mu}_L \gamma_\mu \mu_L + \cancel{\lambda^\ell_{ee}} \bar{e}_L \gamma_\mu e_L \right)$$

From Global analysis $\xrightarrow{\Delta C_9^\mu = -\Delta C_{10}^\mu}$

$$\lambda^q_{bs} \lambda^\ell_{\mu\mu} = (3.4 \pm 1.1) \times 10^{-4} \times \left( \frac{0.15}{R_0} \right)$$

[Altmannshofer, Straub 1411.3161, 1503.06199]

Combining with the bound from $B \leftrightarrow \bar{B}$:

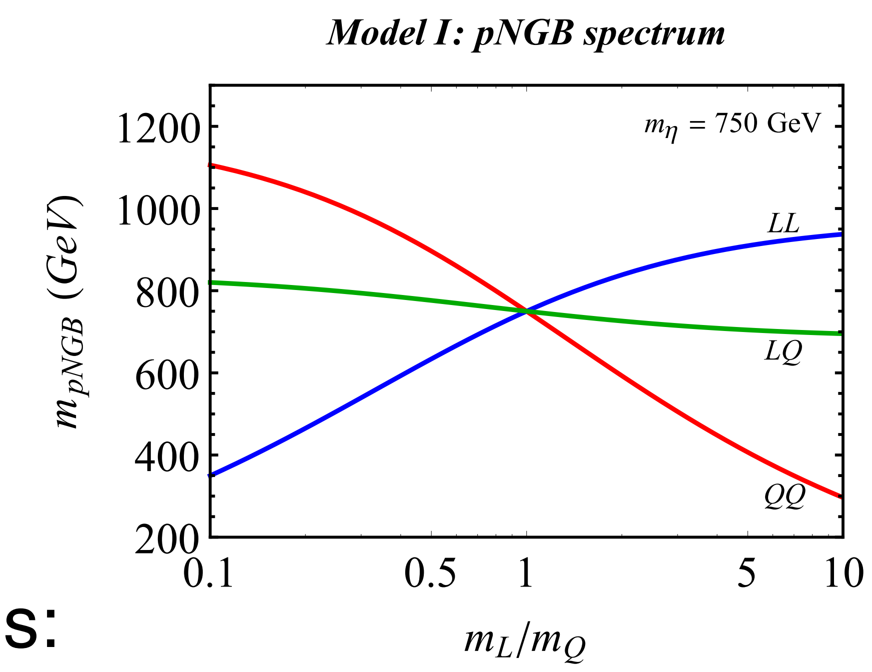
$$\frac{\lambda^q_{bs}}{|\lambda^q_{bs}|_{\rm max}} \left( \frac{R_0}{0.15} \right)^{1/2} \left| \frac{g_\ell}{g_q} \right|^{1/2} \lambda^\ell_{\mu\mu} = (0.09 \pm 0.03)$$

From LFU in $\tau$ decays:

$$\lambda^\ell_{\mu\mu} = (0.013 \pm 0.011) \times \frac{g_q}{g_\ell} \left( \frac{0.15}{R_0} \right)$$

Some tension to saturate the excess in $B \to K \mu\mu$.

# pNGB - $\pi^a$




$\pi^a = (\mathbf{1},\mathbf{3},0)$

For $m_L < m_Q$ it is the lightest pNGB.
$m_\pi \sim$ 400 - 800 GeV

Couples to 3rd gen. fermions via mixing with baryons:

$$\Delta\mathcal{L} = i\frac{g_{\pi BB}\kappa_q^2 m_t}{m_B}\left(\pi^0\bar{t}\gamma^5 t + \frac{1}{\sqrt{2}}\pi^+\bar{t}_L\gamma^5 b_R + \frac{1}{\sqrt{2}}\pi^-\bar{b}\gamma^5 t\right) \qquad g_{\pi BB} \sim g_\rho$$

Leading decay modes: $\pi^0 \longrightarrow tt,\ \ \pi^+ \longrightarrow t\bar{b}$

Also:
$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{N_{TC}^2\alpha^2 Y_L^2}{16\pi^3}\frac{m_{\pi^0}^3}{f^2}$$

Pair-production via Drell-Yan:

$$q\bar{q} \to W^{\pm *} \to \pi^\pm\pi^0 \ \text{or}\ q\bar{q} \to Z^*/\gamma^* \to \pi^+\pi^-$$

**Challenging to look for at the LHC**

# pNGB - $\tilde{\pi}^{A(a)}$

$$\tilde{\pi}^{A(a)} = (\mathbf{8},\mathbf{1},0) + (\mathbf{8},\mathbf{3},0)$$

These are the heaviest pNGB. $m_{\tilde{\pi}} \sim 1$ - $1.5$ TeV

As before, they couple to 3rd gen. fermions via mixing with baryons.

Single-production at LHC in gluon-fusion via the anomalous coupling, pair-production in gluon-fusion with strong coupling.

See e.g. [Craig, Draper, Kilic, Thomas 1512.07733], [Redi, Strumia, Tesi, Vigniani 1602.07297]

Decays to $gg$ or $g\gamma$ are the most relevant ones if no fermionic decay is open.

[Bai, Barger, Berger 1604.07835]

In our setup: Decay to $t\bar{t}$ could be dominant, or comparable to $gg$.

**expect a signal in this channel soon**.

# pNGB - Leptoquarks

Model I: $D = (\mathbf{3},\mathbf{2},\Delta Y) + \text{h.c.}$ $\Delta Y = Y_Q - Y_L = -\frac{1}{3}\ (\frac{1}{6})$

$m_D \sim 0.8 - 1$ TeV

B = 1/6, L = -1/2 → No decay to SM fermions.

Pair-production at the LHC.

After hadronization, if lightest state neutral → possible DM candidate
if charged → problems with cosmology → need to extend the model.

Model II: $S,\ T^a = (\mathbf{3},\mathbf{1},3/2) + (\mathbf{3},\mathbf{3},3/2) + \text{h.c.}$ $m_{S,T} \sim 1 - 1.5$ TeV

They couple to 3rd gen. fermions via mixing with baryons.

Pair-production in gluon-fusion.

LHC bounds on 3rd gen. leptoquarks:

$$m_{\rm LQ} \lesssim 700 \div 750\ \text{GeV}$$