University of Zurich[UZH]

A possible "coherent" explanation of X(750) and flavor anomalies

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- Introduction
- On the flavor anomalies
- On the "X(750)" anomaly
- A possible coherent explanation
- Where to look for, for further signals
- Conclusions

Introduction (Where do we stand in the search for NP?)

The 1st run of the LHC has tested the validity of the SM in an un-explored range of energies, finding no significant deviations. The key results of the 1st LHC run can be summarized as follows:

- The Higgs boson (= last missing ingredient of the SM) has been found
- The Higgs boson is "light" ($m_h \sim 125$ GeV → not the heaviest SM particle)
- There is a "mass-gap" above the SM spectrum (i.e. no unambiguous sign of NP up to ~ 1 TeV)

▶ *Introduction* (Where do we stand in the search for NP?)

The 1st run of the LHC has tested the validity of the SM in an un-explored range of energies, finding no significant deviations. The key results of the 1st LHC run can be summarized as follows:

- The Higgs boson has been found
- The Higgs boson is "light" ($m_h \sim 125$ GeV)
- There is a "mass-gap" above the SM spectrum

This is perfectly consistent with the (pre-LHC) indications coming from indirect NP searches (EWPO + flavor → light Higgs + mass gap above SM spectrum).

But all the problems of the SM (hierarchy problem, flavor pattern, dark-matter, U(1) charges,…) are still unsolved → the motivation for NP are still there (*somehow even stronger than before*)

The key questions are (*as in the "pre LHC era"*):

- How large is the "mass gap"?
- Can we expect a non-minimal flavor pattern?

Introduction (Where do we stand in the search for NP?)

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- Can we expect a non-minimal flavor pattern?

Some "too pessimistic" conclusions (*big desert, anthropic principle,...*) have been put forward in the last 2-3 years given

- the absences of direct NP signals
- the SM is potentially stable up to very high energies with m_h=125 GeV

Introduction (Where do we stand in the search for NP?)

The key questions are:

- How large is the "mass gap"?
- Can we expect a non-minimal flavor pattern?

The 2 questions may well be connected !!

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- the absences of direct NP signals
- the SM is potentially stable up to very high energies with m_h=125 GeV

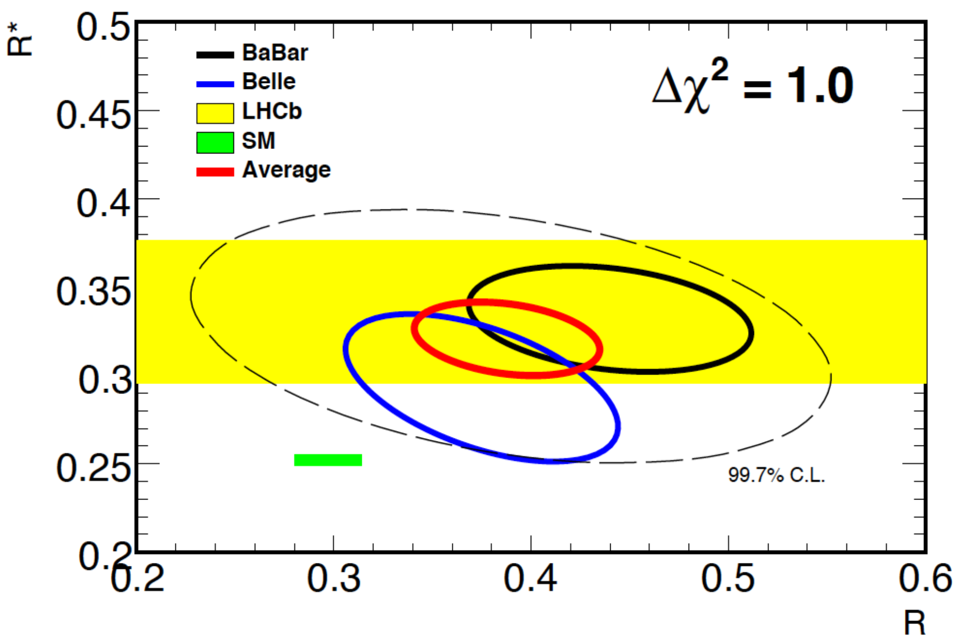
However, looking more closely to data:

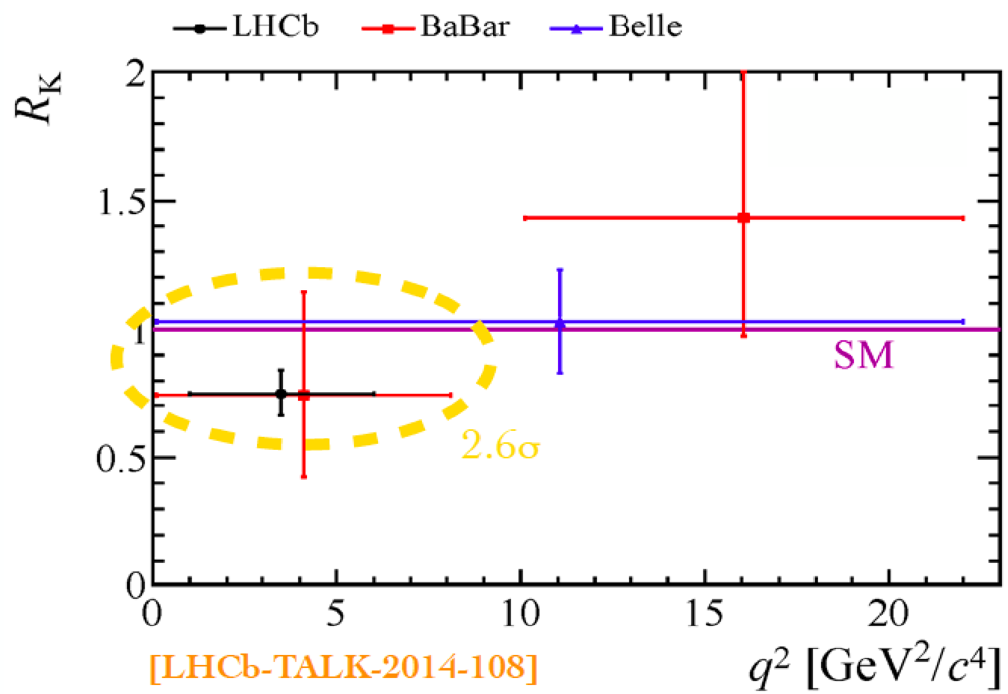
- Direct bounds on NP exceed ~ 1 TeV only for new states colored and/or strongly coupled to 1st & 2nd generation of quarks
- Similarly, the tight indirect bounds from flavor physics always involve transitions with 1st & 2nd generation of quarks & leptons

↓

NP models with (relatively) light NP and where 3rd generation of quarks & leptons have a special role are (still) very well-motivated
The interplay of flavor-physics and high-pT physics extremely important

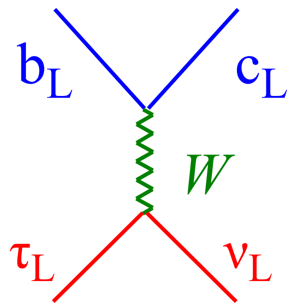
On the flavor anomalies

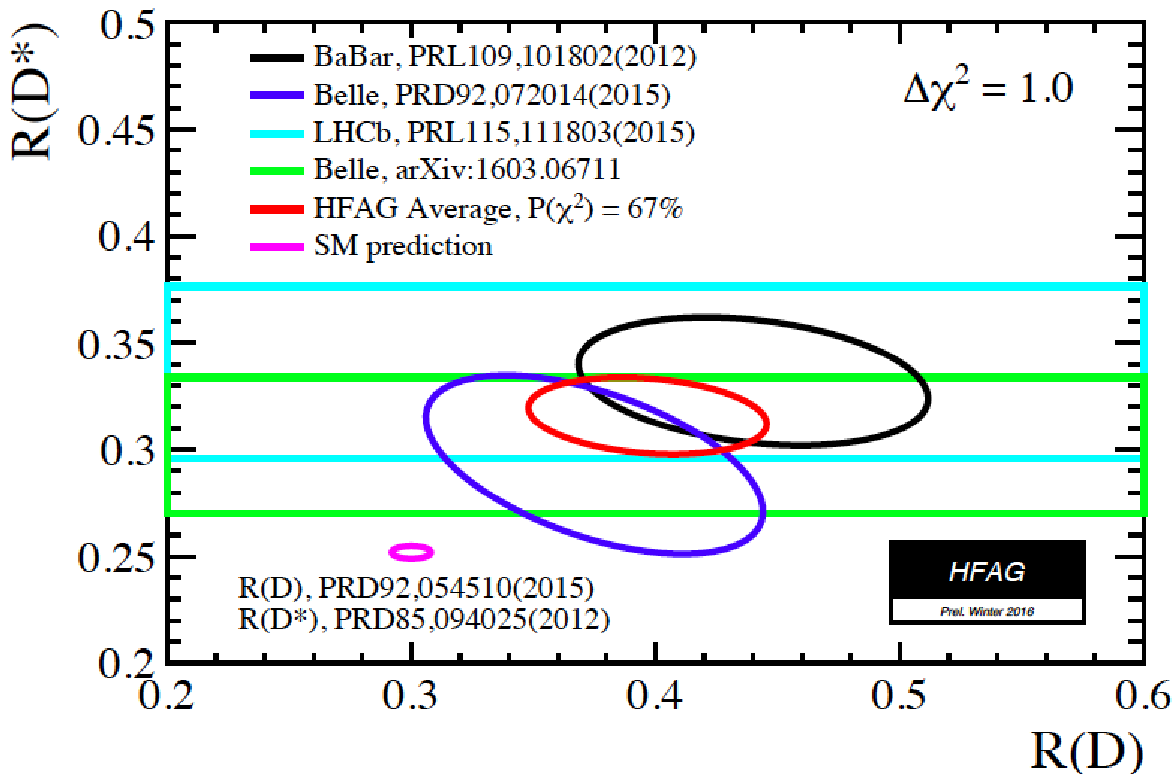




The observed violations of LFU [I. $b \to c$ (charg. curr.): τ vs. light leptons (μ, e)]

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$





- SM prediction quite solid: f.f. error cancel (*to a good extent*) in the ratio
- Consistent exp. results by 3 (very) different experiments

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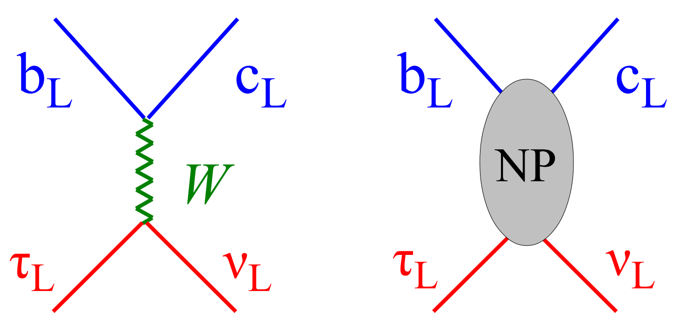
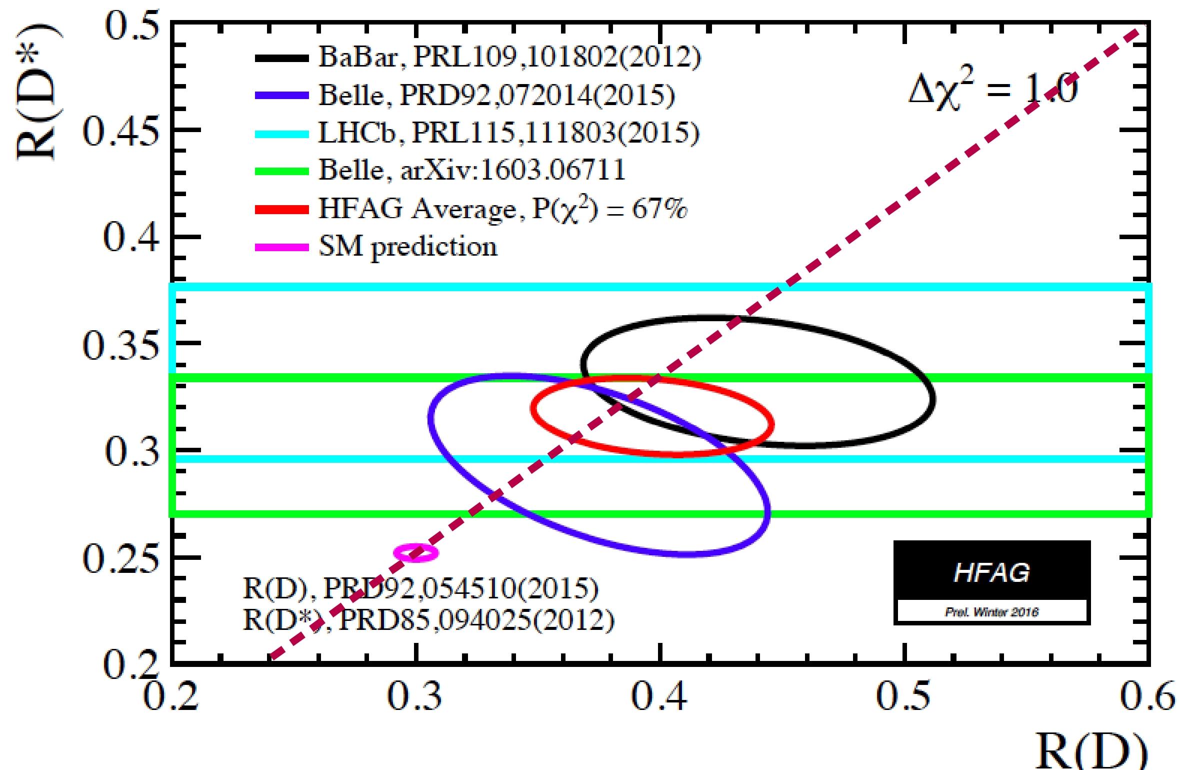




- SM prediction quite solid: f.f. error cancel (*to a good extent*) in the ratio
- Consistent exp. results by 3 (very) different experiments
  - The two channels are well consistent with a universal enhancement (~15%) of the SM $b_L \to c_L\, \tau_L\, \nu_L$ amplitude (*RH or scalar amplitudes disfavored*)
  - In this case the combined significance of a deviation from the SM raises to 4.4σ

$$\frac{R^{\tau/\ell}(D)}{R^{\tau/\ell}_{\rm SM}(D)} = \frac{R^{\tau/\ell}(D^*)}{R^{\tau/\ell}_{\rm SM}(D^*)}$$

The observed violations of LFU [II. $b \to s$ (neutral curr.): μ vs. e)]

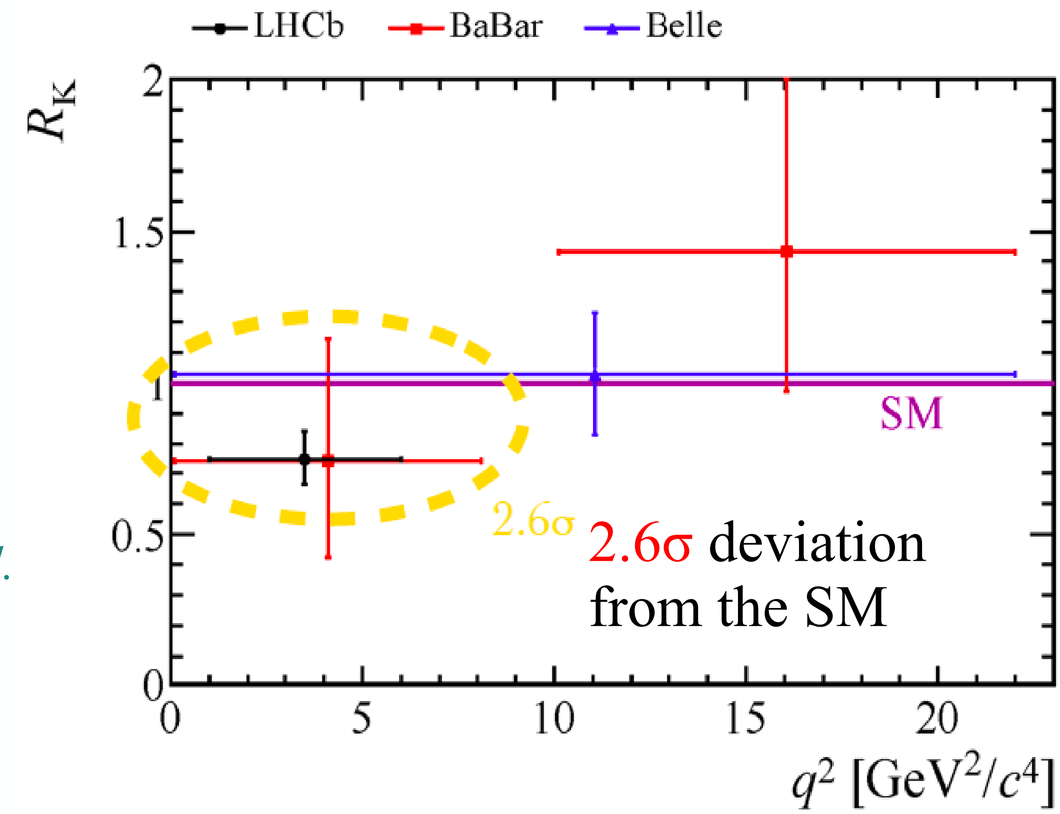
$$R_K = \frac{\int d\Gamma(B^+ \to K^+ \mu\mu)}{\int d\Gamma(B^+ \to K^+ ee)}$$

[1-6] GeV^2

- Negligible th. error → clean test of LFU (in neutral currents)

$$R_K = 1 \pm O(1\%)$$

Bordone *et al.* to appear this week



- The statistical significance of RK alone is small, but it increases a lot taking into account also the P5' anomaly and considering NP models that affects only (mainly) $b \to s\mu\mu$ [*and not* $b \to see$]

→ perfect consistency of the 2 anomalies under this (motivated) hypothesis

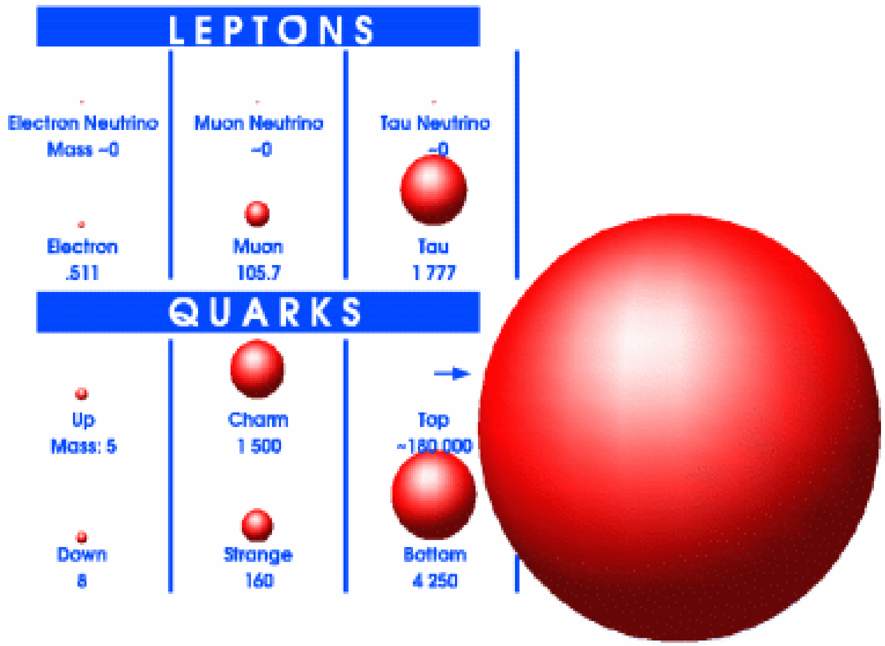
General considerations about the breaking of LFU

These recent results have stimulated a significant amount of theoretical activity.

The most interesting (ans somehow surprising...) aspect is the possible breaking of LFU, both in charged currents ($b \to c\tau\nu$ vs. $b \to c\mu\nu$) and in neutral currents ($b \to s\mu\mu$ vs. $b \to see$)

A few general messages:

- LFU is not a fundamental symmetry of the SM Lagrangian (*accidental symmetry in the gauge sector, broken by Yukawas*)
- LFU tests at the Z peak are not too stringent (→ gauge sector)
- Most stringent tests of LFU involve only 1st-2nd gen. quarks & leptons



→ Natural to conceive NP models where LFU is violated more in processes with 3rd gen. quarks (↔ hierarchy in Yukawa coupl.)

General considerations about the breaking of LFU

These recent results have stimulated a significant amount of theoretical activity:

S. Fajfer, J. F. Kamenik, I. Nisandzic and J. Zupan, Phys. Rev. Lett. **109** (2012) 161801 [arXiv:1206.1872].

S. Descotes-Genon, J. Matias and J. Virto, Phys. Rev. D **88** (2013) 074002 [arXiv:1307.5683].

W. Altmannshofer and D. M. Straub, Eur. Phys. J. C **73** (2013) 2646 [arXiv:1308.1501].

A. Datta, M. Duraisamy and D. Ghosh, Phys. Rev. D **89** (2014) 7, 071501 [arXiv:1310.1937].

G. Hiller and M. Schmaltz, Phys. Rev. D **90** (2014) 054014 [arXiv:1408.1627]; JHEP **1502** (2015) 055

A. Crivellin and S. Pokorski, Phys. Rev. Lett. **114** (2015) 1, 011802 [arXiv:1407.1320].

S. L. Glashow, D. Guadagnoli and K. Lane, Phys. Rev. Lett. **114** (2015) 091801 [arXiv:1411.0565].

+ many others...

...but till a few months ago most attempts were focused only on one set of anomalies (either charged or neutral currents)

What I will discuss next are some general considerations in trying to describe both these effects within simplified (rather general) dynamical models that are an important “prelude” for a combination of these anomalies with high-pT physics

EFT-type considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- RR and scalar currents disfavored → LL current-current operators
- Necessity of at least one $SU(2)_L$-triplet effective operator (*as in the Fermi theory*):

$$\frac{g_q g_\ell}{\Lambda^2}\lambda^q_{ij}\lambda^\ell_{kl}(\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15

- Large coupling (competing with SM tree-level) in bc (=$33_{\rm CKM}$) → $l_3\, \nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\, l_2$

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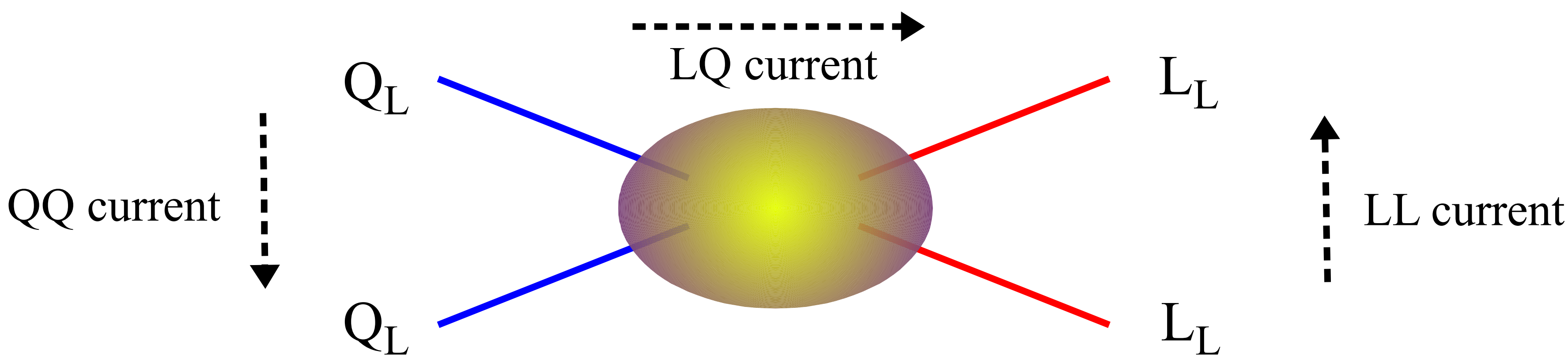


- Two natural classes of mediators, giving rise to different correlations among quark×lepton, (evidence) and quark×quark + lepton×lepton (bounds)

A simplified dynamical model (I)

Greljo, GI, Marzocca '15

Main assumptions:

- We assume the effective triplet operator is the result of integrating-out a heavy triplet of vector bosons (W', Z') coupled to a single current:

$$J_\mu^a = g_q \boxed{\lambda_{ij}^q} \left(\bar{Q}_L^i \gamma_\mu T^a Q_L^j\right) + g_\ell \boxed{\lambda_{ij}^\ell} \left(\bar{L}_L^i \gamma_\mu T^a L_L^j\right) \longrightarrow \frac{1}{2m_V^2} J_\mu^a J_\mu^a$$

- Non-Universal flavor structure of the currents → mainly 3rd generations

→ Coupling to 3rd generations not suppressed

→ Coupling to light generations controlled by small $U(2)_q \times U(2)_l$ breaking terms related to sub-leading terms in the Yukawa couplings (*link to models explaining CKM hierarchy*)

A simplified dynamical model (I)

A brief detour: $U(2)^n$ flavor symmetries

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

- 3rd generations fermions are singlets
- 1st and 2nd generation fermions are doublets

- Efficient protection of FCNCs (~MFV like)
- The exact symmetry limit is good starting point for the SM spectrum ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$) → small breakings terms needed

$$Y_u = y_t \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \rightarrow \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix}$$

unbroken symmetry $|V| \sim 0.04 \quad |\Delta| \sim 0.006$

Possible "natural solution" of models with "dynamical Yukawas"

Alonso, Gavela, G.I., Maiani '13

Coming back to the heavy-triplet model, the flavor symmetry implies:

$$\lambda_{bd} << \lambda_{bs} << \lambda_{bb} = 1 \qquad \lambda_{ss} \sim \lambda_{bs}^2 \sim |V_{ts}|^2$$

A simplified dynamical model (I)

Five free parameters:

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

Several constraints:

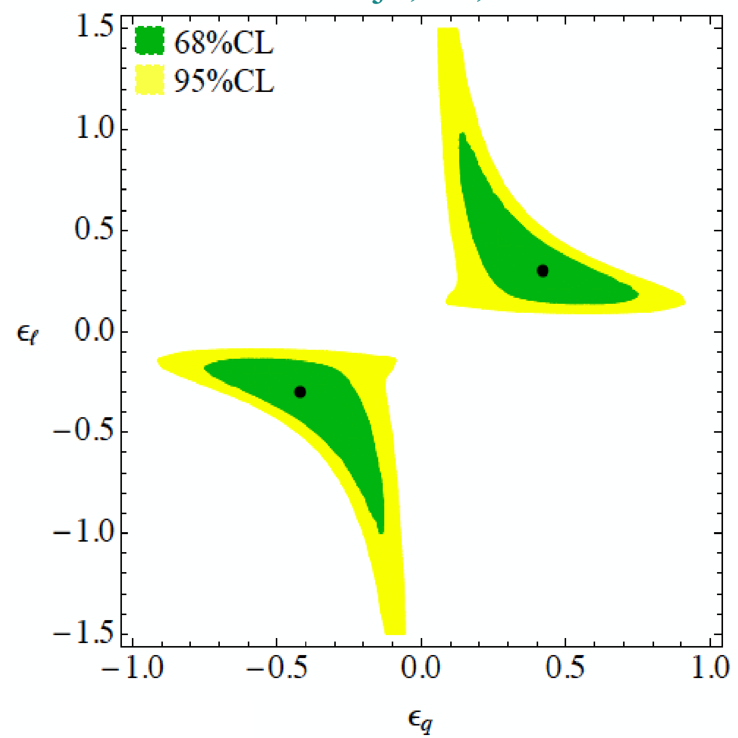
- $R(D^*)$ & $R(D)$
- R_K & P_5'

- $B(B \to K\nu\nu)$
- ΔM_{Bs}, ΔM_{Bd}
- CPV(D-D̲)
- $\Gamma(B \to X\mu\nu)/\Gamma(B \to Xe\nu)$
- $\tau \to 3\mu$
- $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\tau \to e\nu\nu)$

Overall good fit of low-energy data

(*non-trivial given tight constraints from ΔF=2 & LFV*)

Greljo, GI, Marzocca '15



Best fit point: $\epsilon_\ell \approx 0.37$, $\epsilon_q \approx 0.38$

$p(\text{SM}) = 0.002$

Heavy vector mass: 200 GeV (weak coupl.) ⟷ 2 TeV (strong coup.)

A simplified dynamical model (II)

Barbieri, GI, Pattori, Senia '15

Main assumptions:

- We assume the effective triplet operator is the result of integrating-out Lepto-Quark (LQ) fields
- Non-Universal flavor structure of the current, based again on approximate $U(2)_q \times U(2)_l$ flavor symmetry
- Both Vector and Scalar LQ tried → Vector LQ produce a very good fit to data (*essentially as good as in model I*)

↓

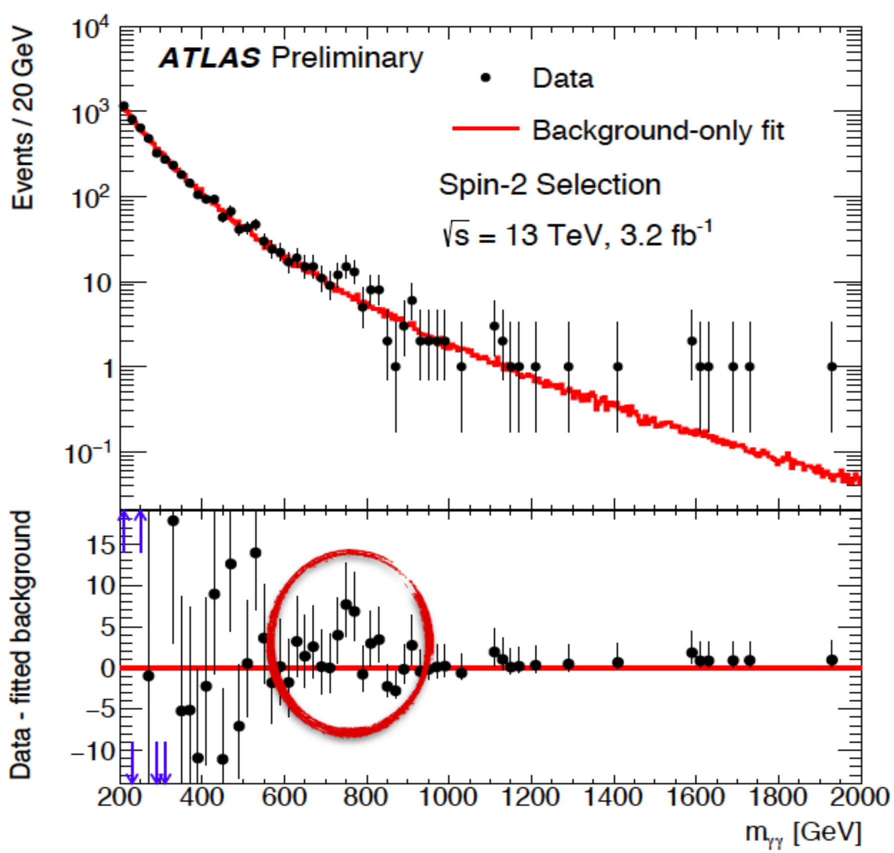
Vector LQ mass: 200 GeV (weak coupl.) ⟷ 2 TeV (strong coup.)

Common features of the 2 models:

- Vector mediators, strongly-interacting (*to avoid direct bounds*)
- Coupling to LH quarks & leptons controlled by $U(2)^2$ flavor symmetry

On the X(750) anomaly

ATLAS-CONF-2016-018



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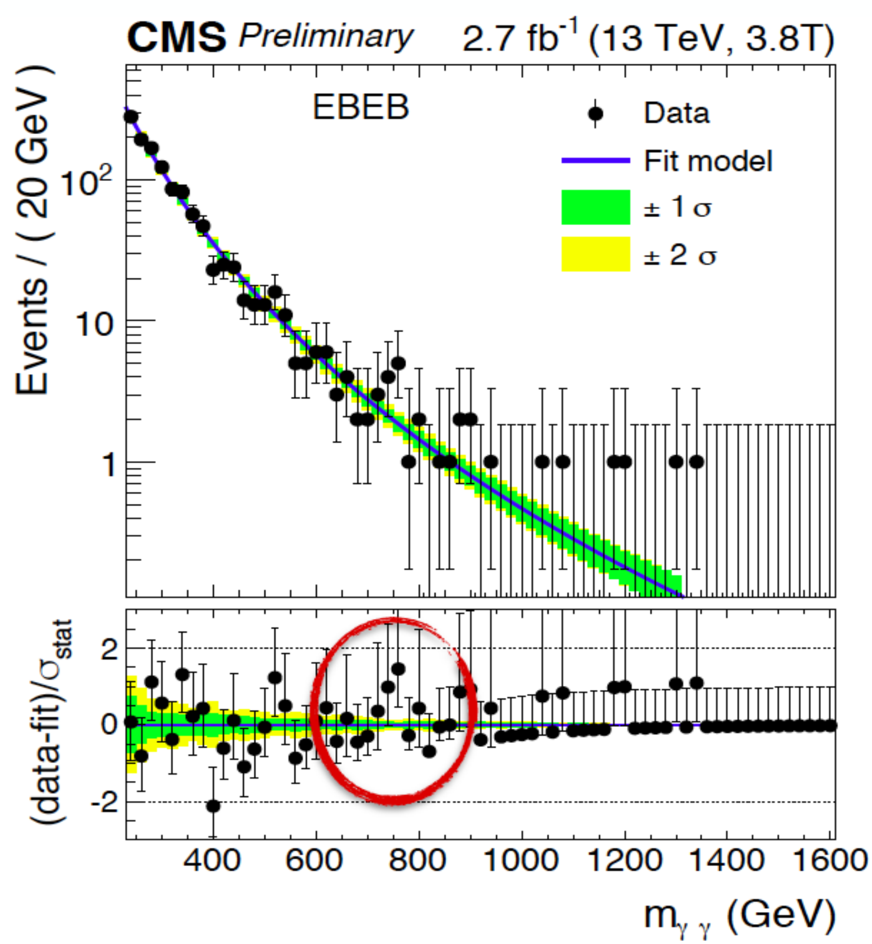


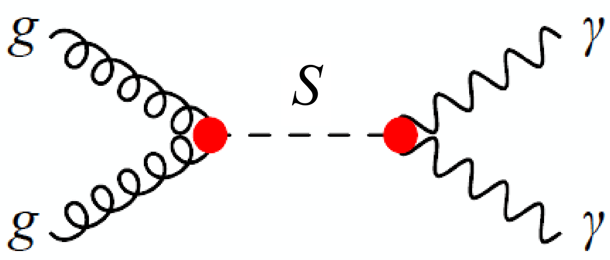
▶ *General considerations on the "X(750)"*

The simplest (and most natural/popular) interpretation is a scalar resonance (*S*) produced (mainly) via gluon fusion and decaying (*at least in…*) two photons

$$\mathcal{L}^{\rm eff} = c_{gg}\frac{\alpha_s}{12\pi m_S} S G^a_{\mu\nu}G^{a,\mu\nu} + c_{\gamma\gamma}\frac{\alpha}{4\pi m_S} S F_{\mu\nu}F^{\mu\nu}$$

Buttazzo, Greljo, Marzocca, '15
(& many others)

$$\sigma_{pp\to S}(8\,\text{TeV}) = c_{gg}^2 \times (12\pm 1)\,\text{fb},$$
$$\sigma_{pp\to S}(13\,\text{TeV}) = c_{gg}^2 \times (55\pm 6)\,\text{fb}.$$



The large 13TeV/8TeV ratio in $\sigma(gg \to \eta)$
Explains why no anomalies @ 8 TeV

$$\mu_{pp\to S\to\gamma\gamma} = \sigma_{pp\to S} \times \mathcal{B}_{S\to\gamma\gamma} \approx (4.7\pm 1)\ \text{fb}$$

data

General considerations on the "X(750)"

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$$\frac{\alpha}{4\pi m_S} S\left(c_W W^i_{\mu\nu} W^{i,\mu\nu} + c_B B_{\mu\nu} B^{\mu\nu}\right)$$

There are 2 gauge-invariant operators at d=5 that controls 4 accessible final states: γγ, Zγ, ZZ, WW → we should see comparable signals (σ×B) in all of them (at most one eff. coupling can be tuned to 0)

Right now OK (other channels less constraining than γγ), but this will be a key test for the near future

$$\frac{\mu_{Z\gamma}}{\mu_{\gamma\gamma}} = \frac{2(1-R_{WB})^2\tan^2\theta_W}{(1+R_{WB}\tan^2\theta_W)^2}$$

$$\frac{\mu_{ZZ}}{\mu_{\gamma\gamma}} = \frac{(\tan^2\theta_W + R_{WB})^2}{(1+R_{WB}\tan^2\theta_W)^2}$$

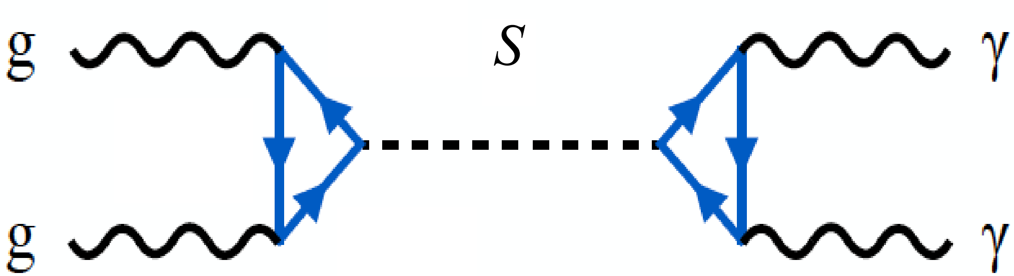
$$\frac{\mu_{WW}}{\mu_{\gamma\gamma}} = \frac{2R^2_{WB}}{(\cos^2\theta_W + R_{WB}\sin^2\theta_W)^2}$$

$$(R_{WB} = c_W/c_B)$$

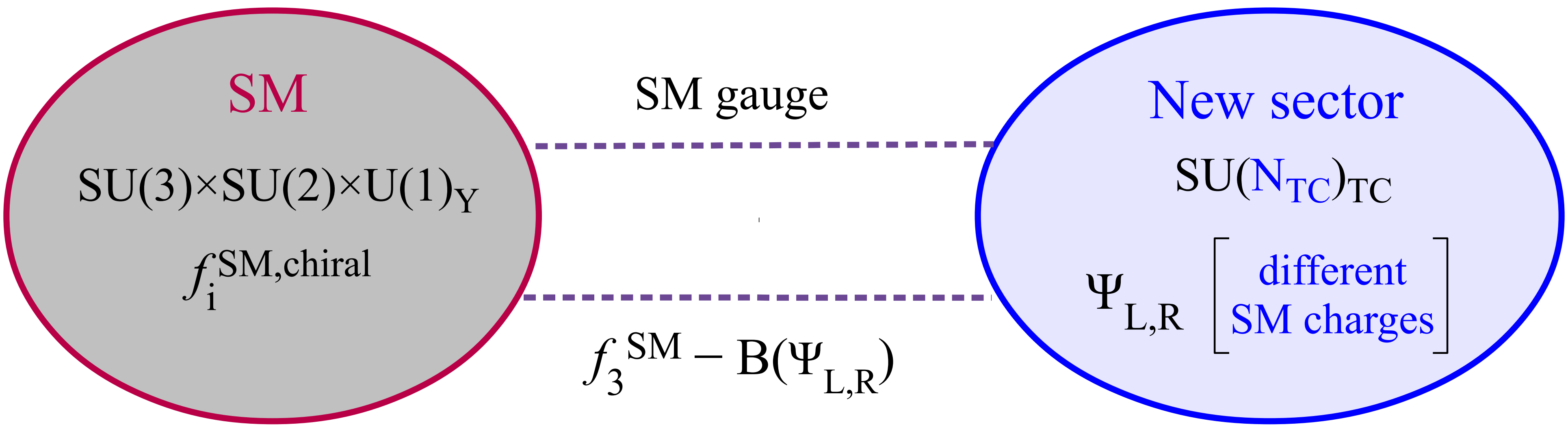
General considerations on the "X(750)"

There are many possible dynamical explanations for origin, mass, and couplings of this hypothetical state, but most of them share some common features:

- Need additional vector-like fermions to enhance c_{gg} and $c_{\gamma\gamma}$
- If S is a pNGB, these couplings arise naturally via the anomaly (as in $\pi^0 \to \gamma\gamma$)
- A large width (i.e. some leading "tree-level" decays) is very challenging
- Virtually all proposed explanations points to near-by new strong dynamics



A possible coherent explanation



Buttazzo, Greljo, GI, Marzocca, '16

▸ *A possible "coherent" explanation*

SM

$SU(3)\times SU(2)\times U(1)_Y$

$f_i^{\mathrm{SM,chiral}}$

New sector

$SU(N_{TC})_{TC}$

$\Psi_{L,R}$ [different SM charges]

$SU(N_F)_L\times SU(N_F)_R\times U(1)_V$

↓

$SU(N_F)_{L+R}\times U(1)_V$

Global "flavor symmetry"
Spontaneously broken as in QCD at a scale $\Lambda_{TC}\sim$ TeV

The basic construction is based on the idea of "*Vector-like confinement*"

Kilic, Okhui, Sudrum,'09

- Very similar to the old idea of technicolor
- Key difference is that the SSB of the new sector preserves the SM gauge symmetry, that is broken in a 2nd step by an appropriate Higgs field

A possible "coherent" explanation

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Lowest-lying spectrum of resonances:

pseudo-GB
π, η, ...

Heavy vectors
ρ, ω, φ, ...

A possible "coherent" explanation

SM

$SU(3)\times SU(2)\times U(1)_Y$

$f_i^{\rm SM, chiral}$

SM gauge

New sector

$SU(N_{TC})_{TC}$

$\Psi_{L,R}$ [different SM charges]

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Lowest-lying spectrum of resonances:

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Heavy vectors
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$pp \to \eta(750) \to \gamma\gamma$
[wide literature]

[Λ_{TC} & m_{TC} fixed
$\to M_V \sim$ 1.5-2.5 TeV]

▸ *A possible "coherent" explanation* [Buttazo, Greljo, GI, Marzocca, '16]

SM

$SU(3)\times SU(2)\times U(1)_Y$

$f_i^{\rm SM,chiral}$

SM gauge

$f_3^{\rm SM} - B(\Psi_{L,R})$

New sector

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$\Psi_{L,R}$ [different SM charges]

$SU(N_F)_L\times SU(N_F)_R\times U(1)_V$

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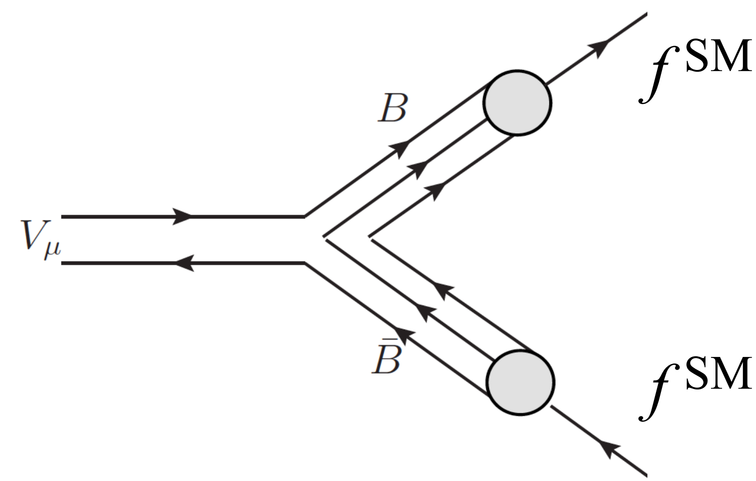
$SU(N_F)_{L+R}\times U(1)_V$

Lowest-lying spectrum of resonances:

pseudo-GB	Heavy vectors
π, η, ...	ρ, ω, φ, ...
pp → η(750) → γγ [wide literature]	4f ops. that solve flavor anomalies



▶ A closer look to the model

I. The mixing between heavy-vectors and SM fermions:

A) rho-baryon coupling:

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

Expected and predicted, up to O(1) factors, by TC dynamics

B) baryon-SM mixing:

$$B_q \to \kappa_q \chi_i^q q_L^i \;,\;\; B_\ell \to \kappa_\ell \chi_i^\ell \ell_L^i$$

Extra ingredient attributed to (unspecified) flavor dynamics → flavor structure predicted by U(2)xU(2) flavor symmetry

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

SU(2)-doublet spurions ($\varepsilon_1^{q(\ell)}$, $\varepsilon_2^{q(\ell)}$)

SU(2)-singlet (1)

A key requirement is to have TC baryons with quantum numbers of SM LH fermions

↓

More complicated mixing structures are possible, but this simple construction turns out to be very predictive and successful in "curing" the flavor anomalies

▶ *A closer look to the model*

II. Possible explicit constructions:

A) Minimal model: $SU(5_F)$

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

Two possible hyper-charge assignments:

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

The mesons:

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

A closer look to the model

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The mesons:

Flavor structure	$\mathcal{G}_{SM}$ irrep
$(\bar{Q}Q)$	$(\mathbf{8}, \mathbf{1}, 0)$
$(\bar{L}Q)$ + h.c.	$(\mathbf{3}, \mathbf{2}, \Delta Y)$
$(\bar{L}L)$	$(\mathbf{1}, \mathbf{3}, 0)$
$3(\bar{L}L) - 2(\bar{Q}Q)$	$(\mathbf{1}, \mathbf{1}, 0)$

$(\bar{Q}Q)$ → color octet — Can improve the flavor fit with contribution to $\Delta B=2$

$(\bar{L}Q)$ + h.c. → "harmless"

$(\bar{L}L)$ → ρ

$3(\bar{L}L) - 2(\bar{Q}Q)$ → ω, φ

(ρ; ω, φ): states needed in model I for flavor anomalies

A closer look to the model

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Two possible hyper-charge assignments:

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

B) Extended model: $SU(8_F)$

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

Two possible hyper-charge assignments:

Y_Q	$1/6$	$1/2$
Y_L	$-1/2$	$-1/6$

Flavor structure	$\mathcal{G}_{\rm SM}$ 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.	$m^2_{(\bar{L}Q)} = B_0(m_L + m_Q)$
$(\bar{L}L)$	$(\mathbf{1},\mathbf{3},0)$	$m^2_{(\bar{L}L)} = 2B_0 m_L$
$3(\bar{L}L) - (\bar{Q}Q)$	$(\mathbf{1},\mathbf{1},0) = \eta$	$m^2_\eta = \frac{1}{2}B_0(3m_L + m_Q)$

→ states needed in model II for flavor anomalies

A closer look to the model

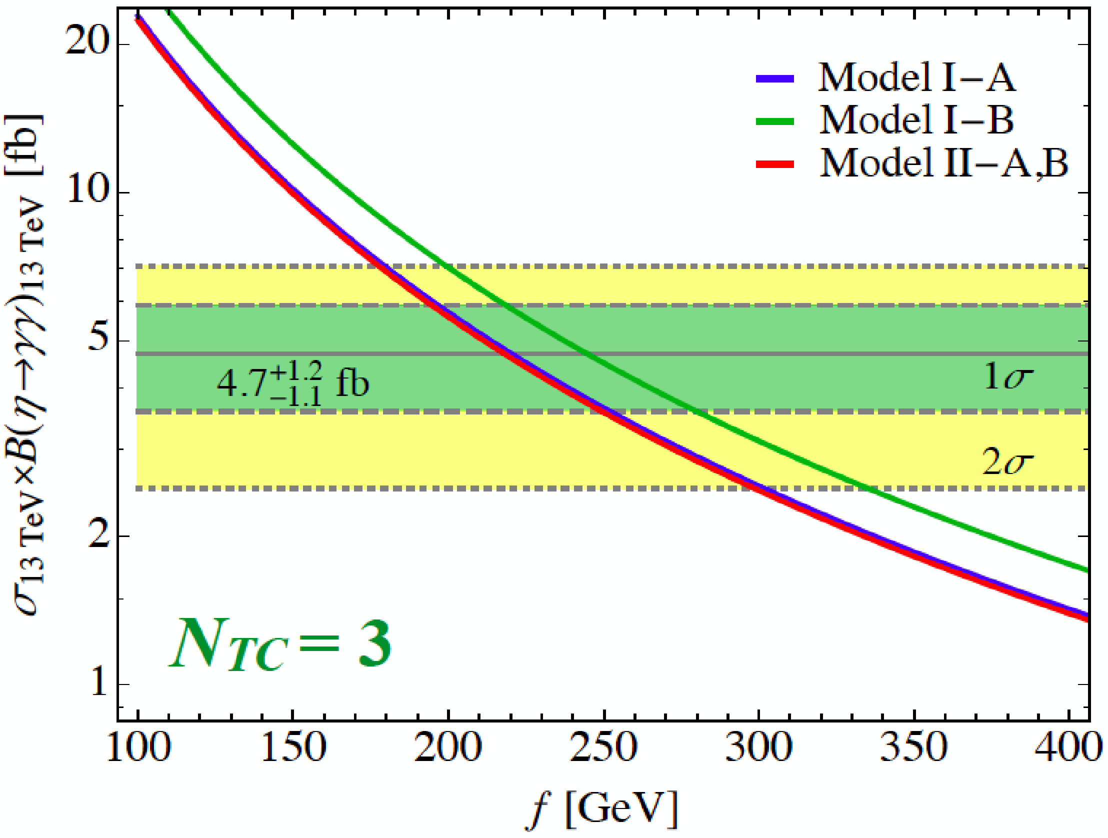
II. Possible explicit constructions:

A) Minimal model: $SU(5_F)$

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

B) Extended model: $SU(8_F)$

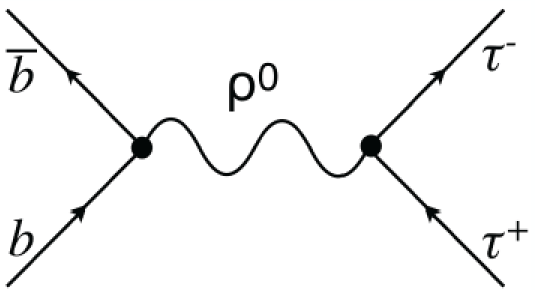
$$Q = (N_{TC}, \mathbf{3}, \mathbf{2}, Y_Q)$$
$$L = (N_{TC}, \mathbf{1}, \mathbf{2}, Y_L)$$

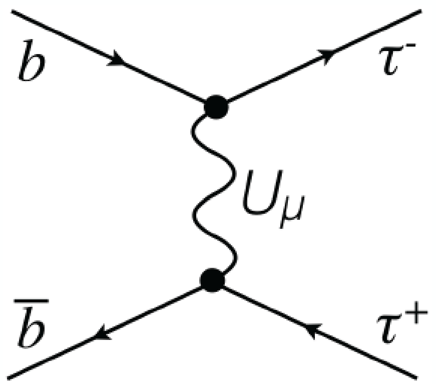


$f \sim$ 200-250 GeV

$M_V \sim$ 1.5-2.0 TeV ($m_{TC} \sim$ 100 GeV)

Where to look for, for further signals





Other di-boson channels from the X(750)

For a given choice of hyper-charge assignment we can completely determine the rates for production and decay of the X(750) in any SM di-boson pair:

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

→ ~ 5fb

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

Buttazzo, Greljo, Marzocca, '15

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:	$(\frac{1}{6}, -\frac{1}{2})$			

Other low-energy signatures from the vector mesons

The effective Lagrangian
$$\mathscr{L}_{\rm eff} = -\frac{1}{2m_V^2} J_\mu^a J_\mu^a$$

give rise to a rich low-energy phenomenology:

- $b \to c(u)\, l\nu$

$BR(B\to D^*\tau\nu)/BR_{SM} = BR(B\to D\tau\nu)/BR_{SM} = BR(\Lambda_b \to \Lambda_c\tau\nu)/BR_{SM}$

$= \ldots = BR(B_u \to \tau\nu)/BR_{SM}$

$R^{\mu/e}(X) \sim 10\%\, R^{\tau/\mu}(X)$

- universal 20-30% enhancement of C.C. semi-leptonic decays into tau leptons

- 1-2 % (universal) breaking of universality between muons & electrons (in leading CC modes)

Other low-energy signatures from the vector mesons

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- $b \to s\, \mu\mu$ — $\Delta C_9^\mu = -\Delta C_{10}^\mu$, but overall size of the anom. should decrease
- $b \to s\, \tau\tau$ — $|NP| \sim |SM| \longrightarrow$ large enhanc. (up to 10×SM !) or strong suppr.
- $b \to s\, \nu\nu$ — $\sim \pm 50\%$ deviation from SM in the rate

N.B: the deviations should be seen <u>universally</u> in all the hadronic modes: $B \to K^*\tau\tau$, $B \to K\tau\tau$, $\Lambda_b \to \Lambda\tau\tau$,...

Other low-energy signatures from the vector mesons

The effective Lagrangian
$$\mathscr{L}_{\rm eff} = -\frac{1}{2m_V^2} J_\mu^a J_\mu^a$$

give rise to a rich low-energy phenomenology:

- $b \to c(u)\, l\nu$ — $BR(B \to D^*\tau\nu)/BR_{SM} = BR(B \to D\tau\nu)/BR_{SM} = BR(\Lambda_b \to \Lambda_c\tau\nu)/BR_{SM}$ $= \ldots = BR(B_u \to \tau\nu)/BR_{SM}$ $\qquad R^{\mu/e}(X) \sim 10\%\ R^{\tau/\mu}(X)$

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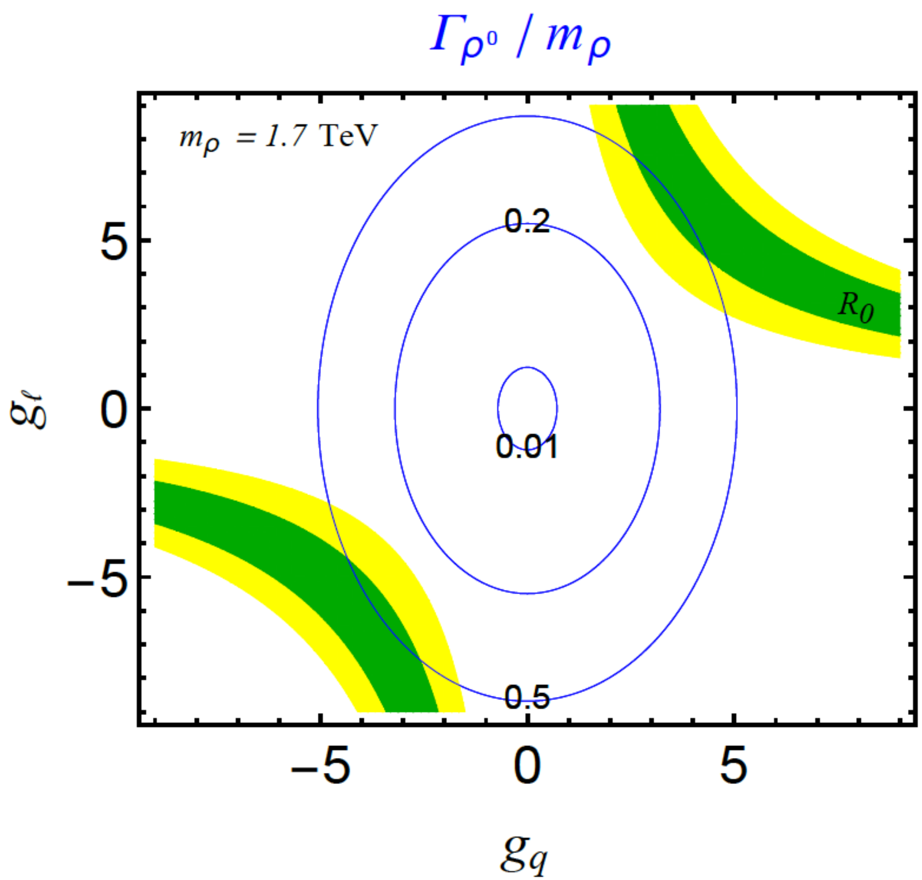
- Meson mixing — $\sim 10\%$ deviations from SM both in ΔM_{Bs} & ΔM_{Bd}
- τ decays — $\tau \to 3\mu$ not far from present exp. Bound ($BR \sim 10^{-9}$)

▶ *High-pT signatures of the vector (and pNGB) mesons*

The phenomenology is rich, non-trivial, with various options

Some general features:

- Vector mesons are expected to have large widths and to decay predominantly in pNGB (difficult signatures)

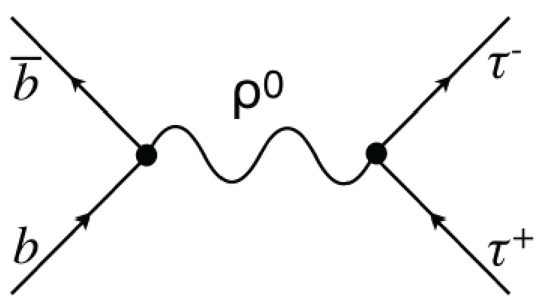


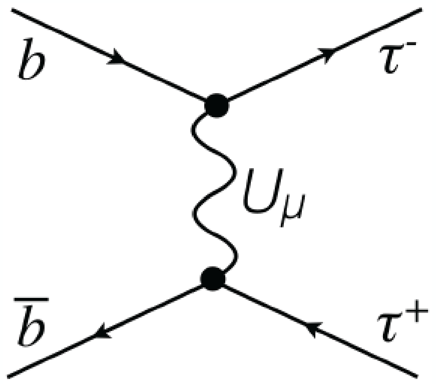
▸ *High-pT signatures of the vector (and pNGB) mesons*

The phenomenology is rich, non-trivial, with various options

Some general features:

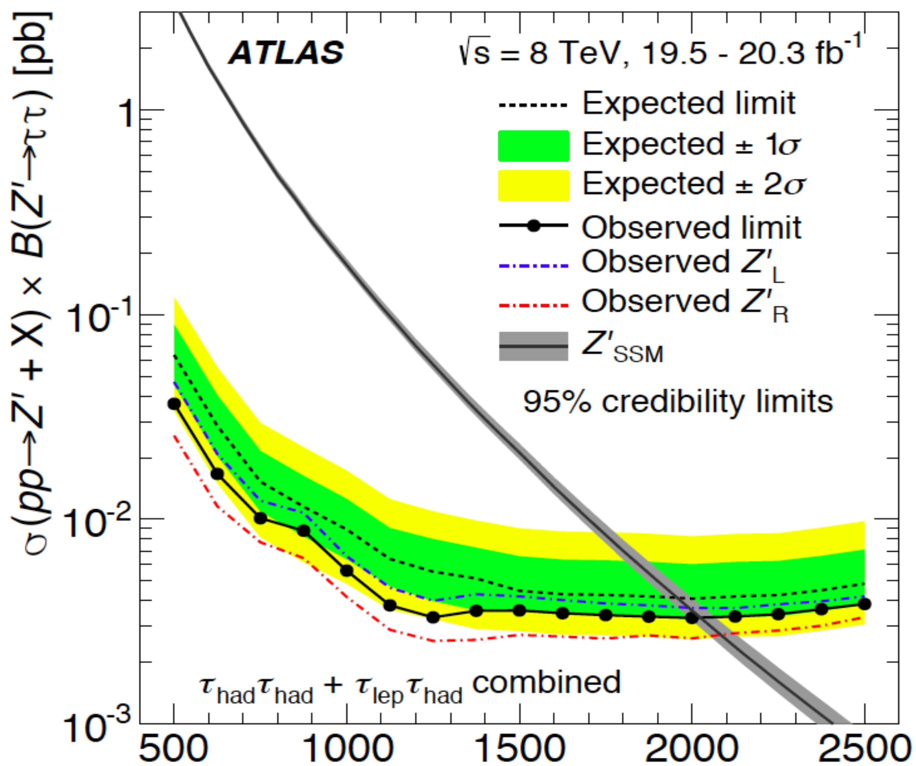
- Vector mesons are expected to have large widths and to decay predominantly in pNGB (difficult signatures)
- The mixing of the heavy vectors with SM gauge bosons (hence light SM fermions) is very suppressed → dominant coupling to SM via 3rd generation
- Almost model-independent expectation of sizable (broad) excess in $pp \to \tau\tau$ & $pp \to bb$, tt that should be accessible in run-II

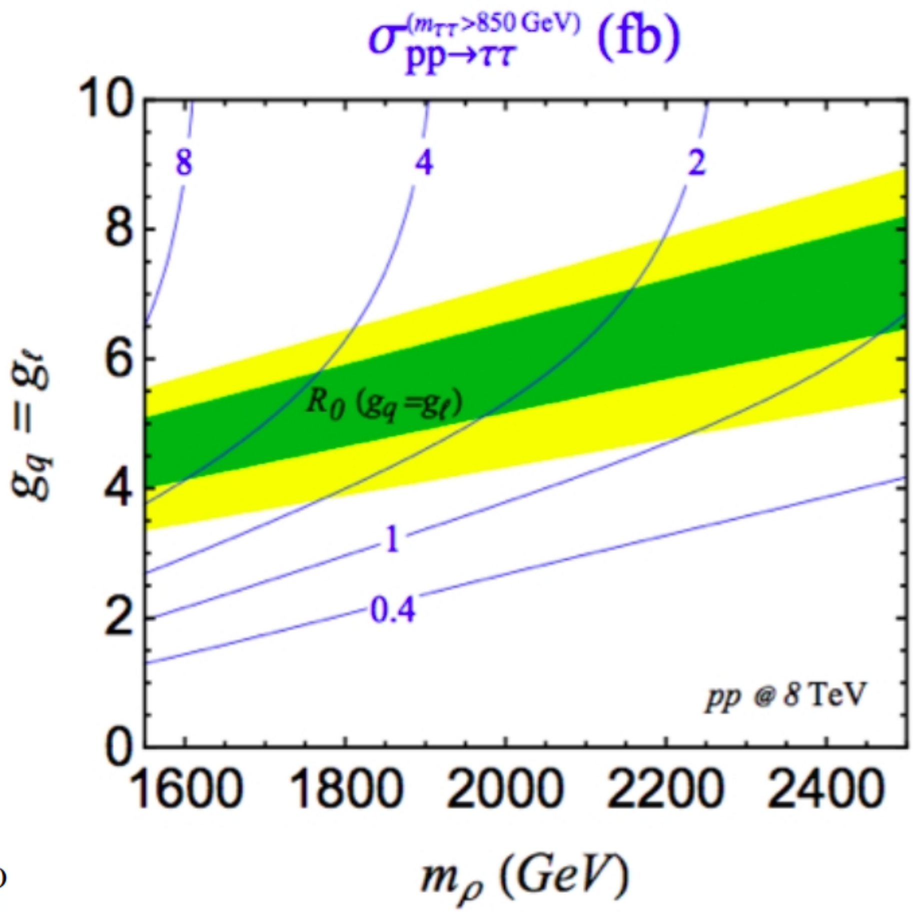




▸ High-pT signatures of the vector (and pNGB) mesons

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

A detailed recast would be necessary to extract precise bounds

Conclusions

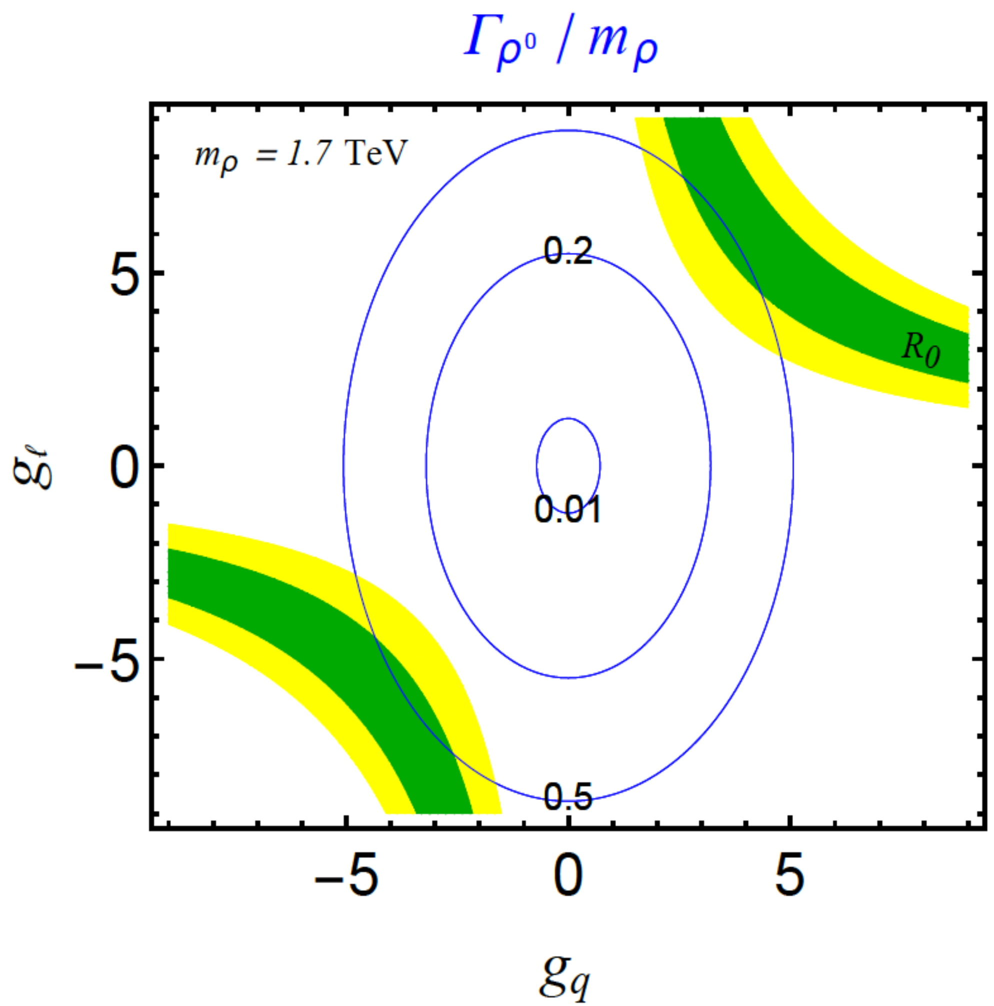
- We entered in a very special era in particle physics: the SM is a successful theory that has no intrinsic energy limitations.

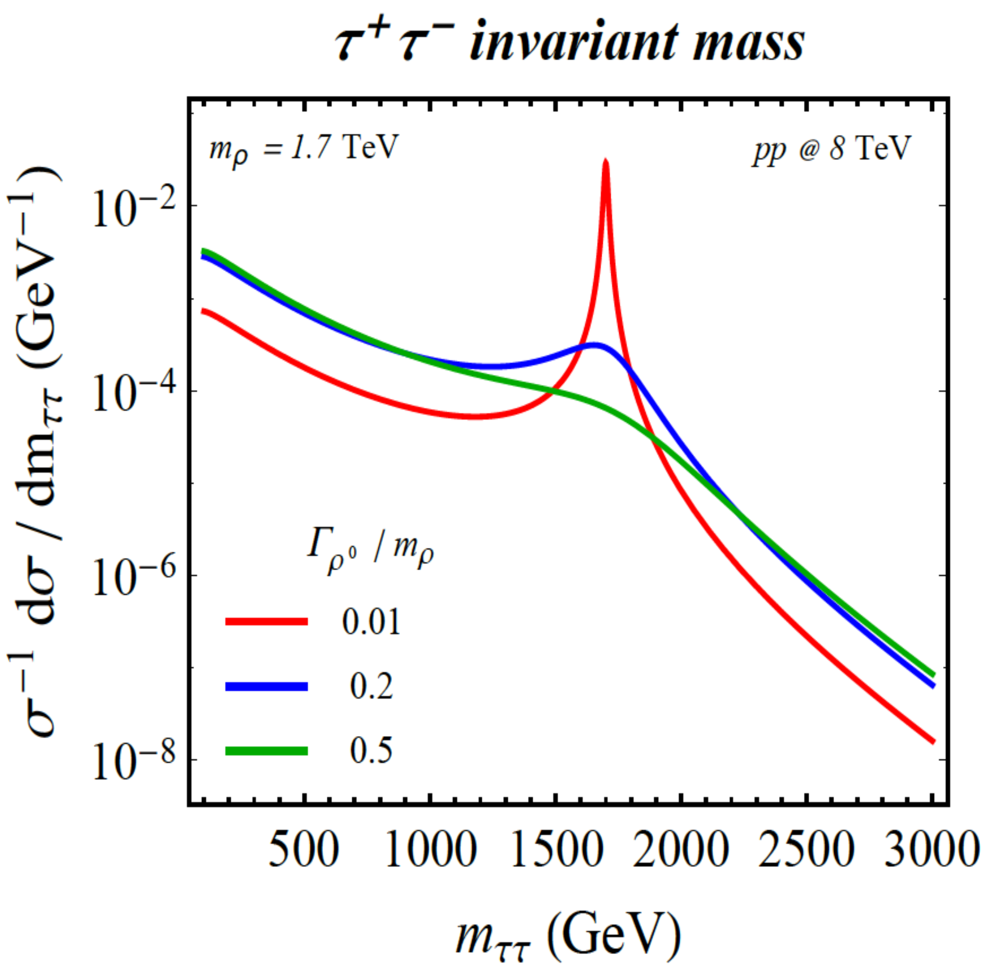
- Motivations for NP still there (*including the puzzling structure of quark and lepton masses matrices, or the origin of flavor...*) → We must search for NP with an "open-mind" perspective, given the lack of a clear preferred direction in "model space".

- Recent data show interesting hints of deviations from the SM, both in the flavor sector and at high Pt → Vector-like confinement offer an interesting framework to address both anomalies

- If this is the correct explanation and, especially, if these anomalies persist... we maybe facing the beginning of a new rich spectroscopy...

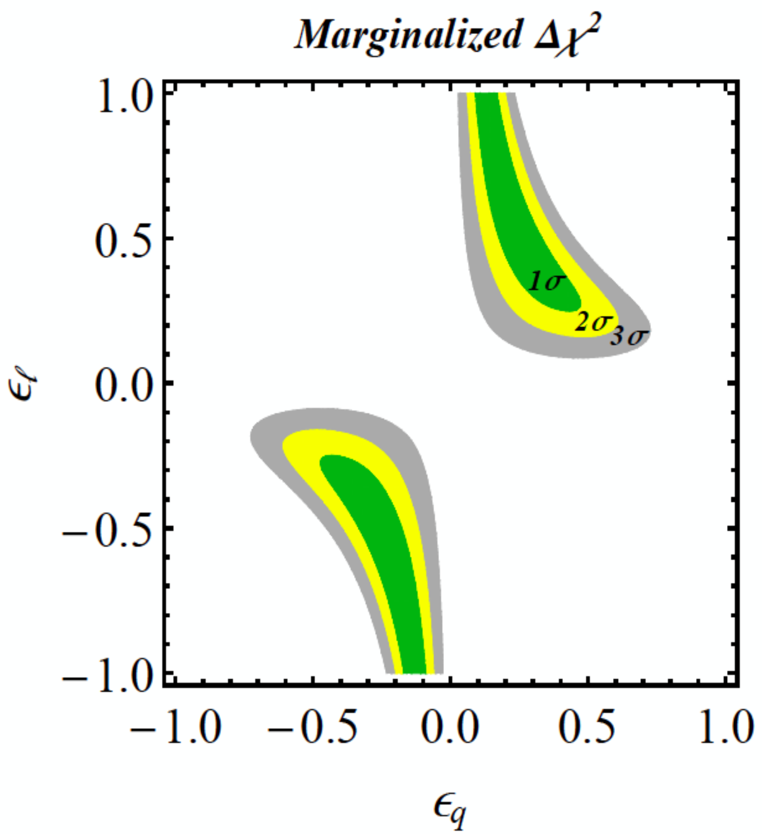

Backup

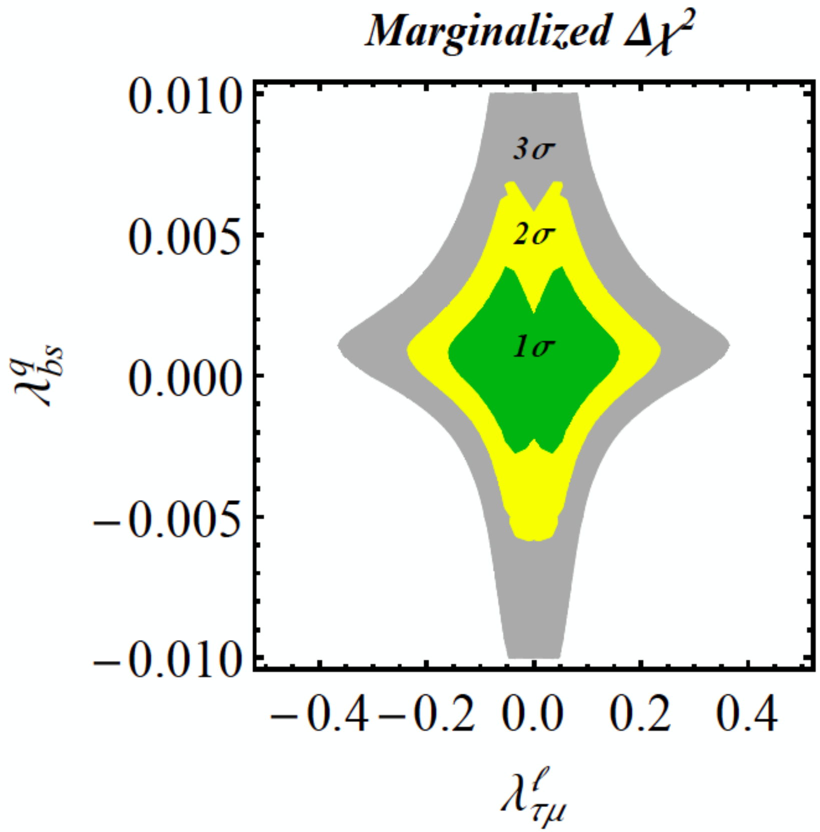

Γ_{ρ^0} / m_ρ
m_ρ = 1.7 TeV
0.2
0.01
0.5
R_0
g_ℓ
g_q
5
0
−5


$\tau^+\tau^-$ invariant mass
m_ρ = 1.7 TeV
pp @ 8 TeV
$\sigma^{-1}\, d\sigma / dm_{\tau\tau}$ (GeV^{-1})
10^{-2}
10^{-4}
10^{-6}
10^{-8}
Γ_{ρ^0} / m_ρ
0.01
0.2
0.5
500 1000 1500 2000 2500 3000
$m_{\tau\tau}$ (GeV)

Low-energy Fit

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





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

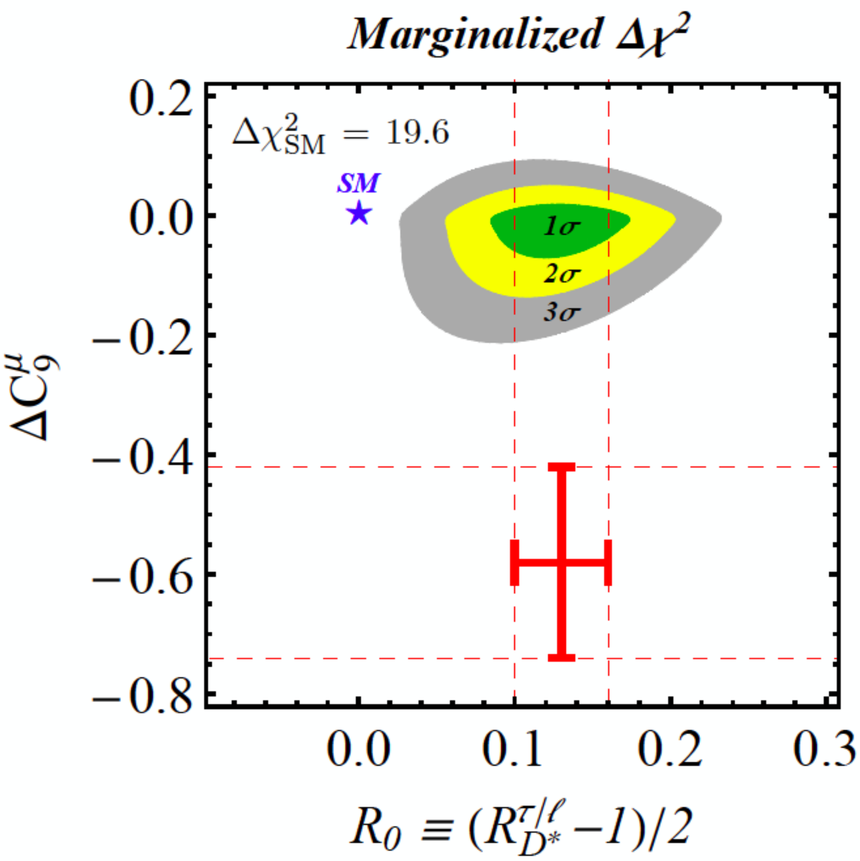
Strong coupling for heavy resonances

While one would expect

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

Low-energy Fit

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



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

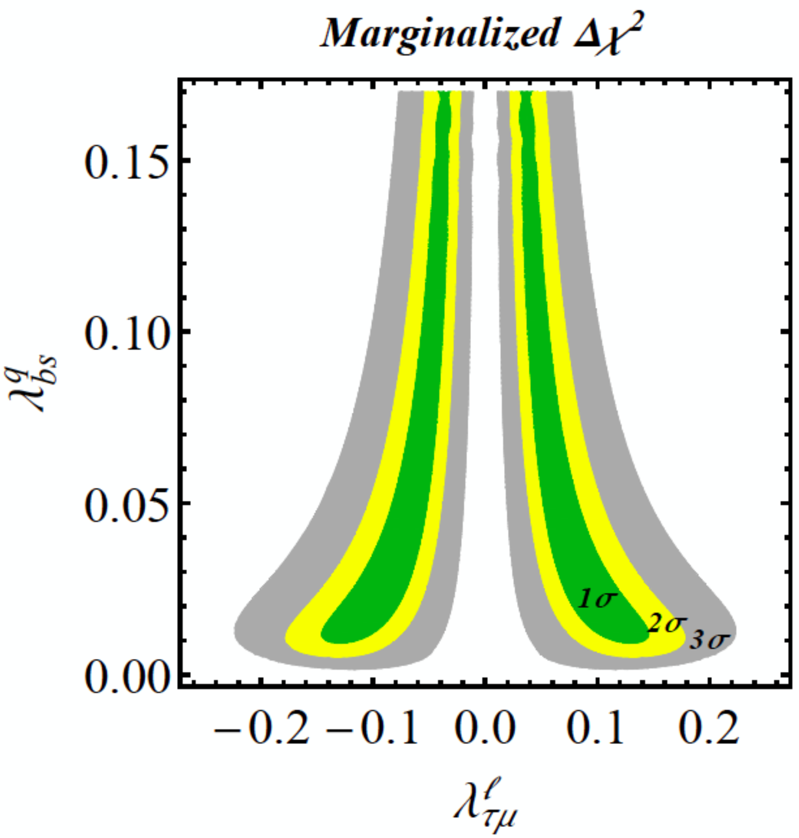
This is due to the bounds from B_s mixing, LFU/V in τ decays, and the assumption $\lambda^\ell_{\mu\mu} = (\lambda^\ell_{\tau\mu})^2$

Low-energy Fit with the vector-octets

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

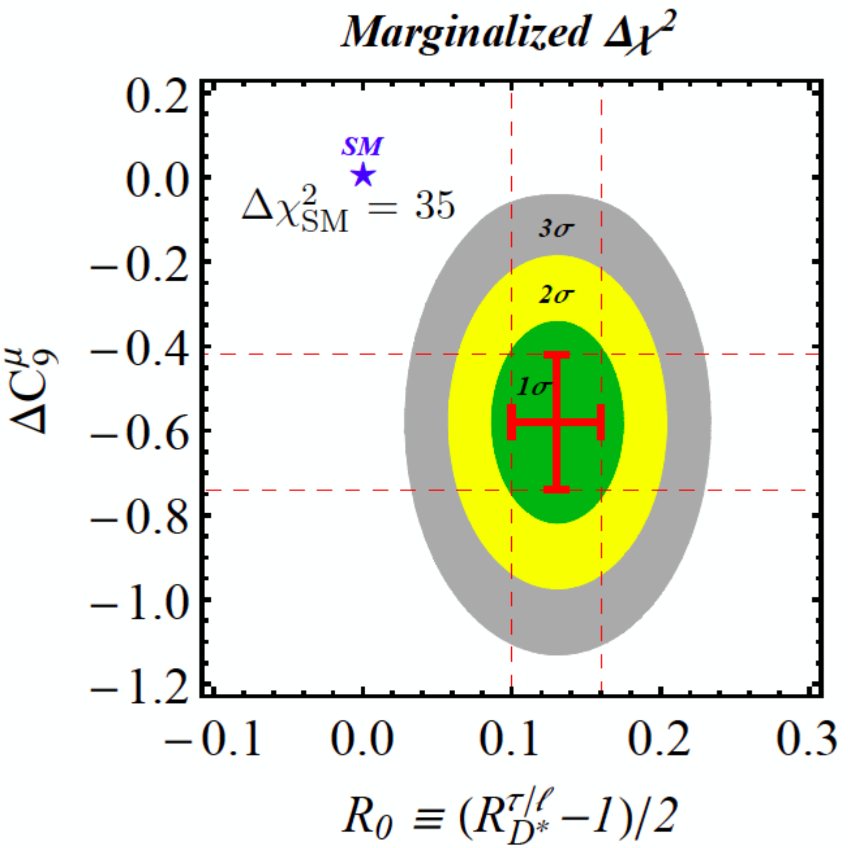
$\epsilon_I \equiv \epsilon_q = \epsilon_\ell$

ϵ_O



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

OK



Perfect fit of ΔC_9 possible.