The Standard Model and (some of) its extensions

R. Barbieri

GGI, Florence, January 9-27, 2017

IV. Anomalies in B-decays

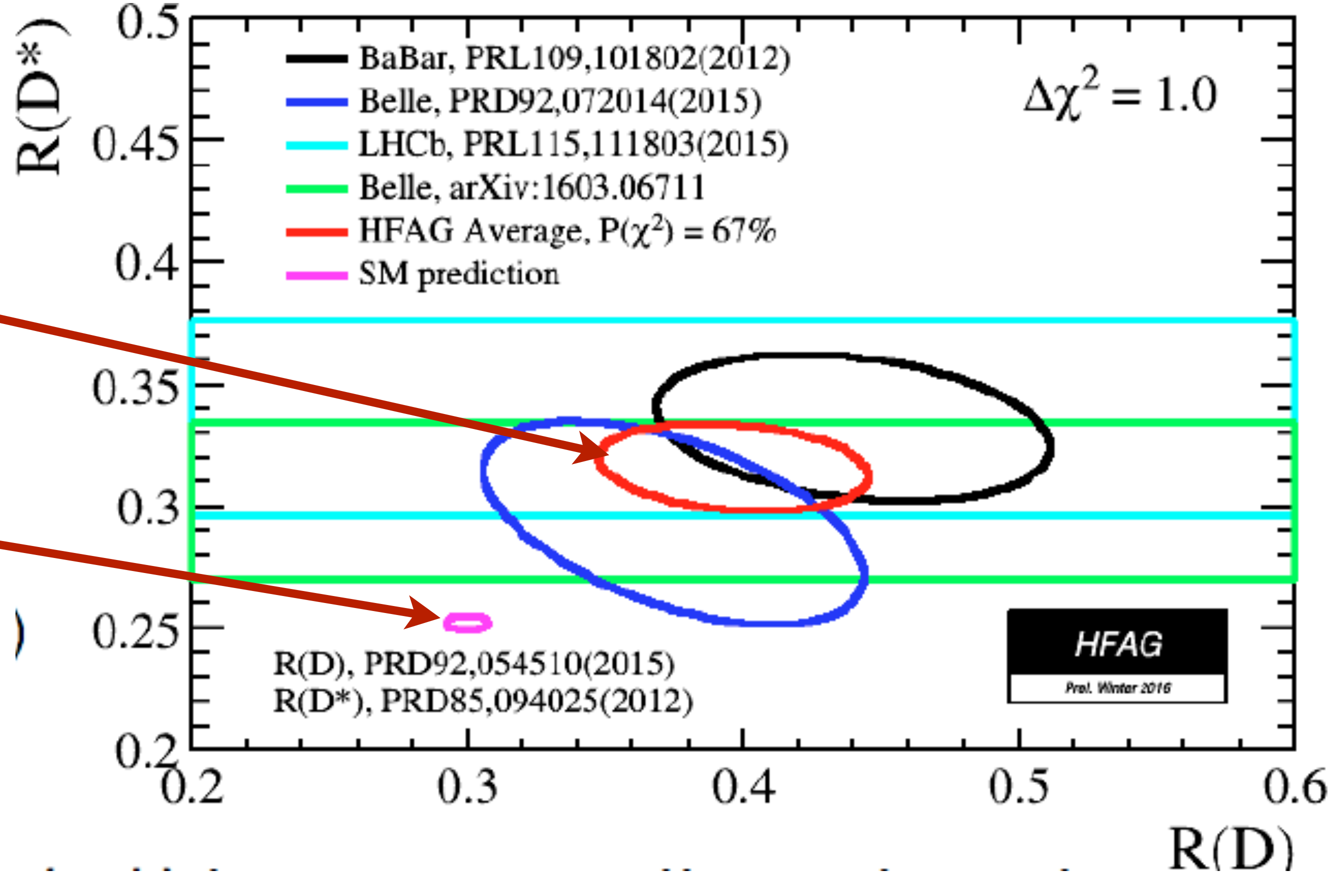
A deviation from the SM in flavour, finally?

$$R(D^*) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(\to D^{(*)}l\nu)} = 1.27 \pm 0.06$$

$$l = \mu, e$$

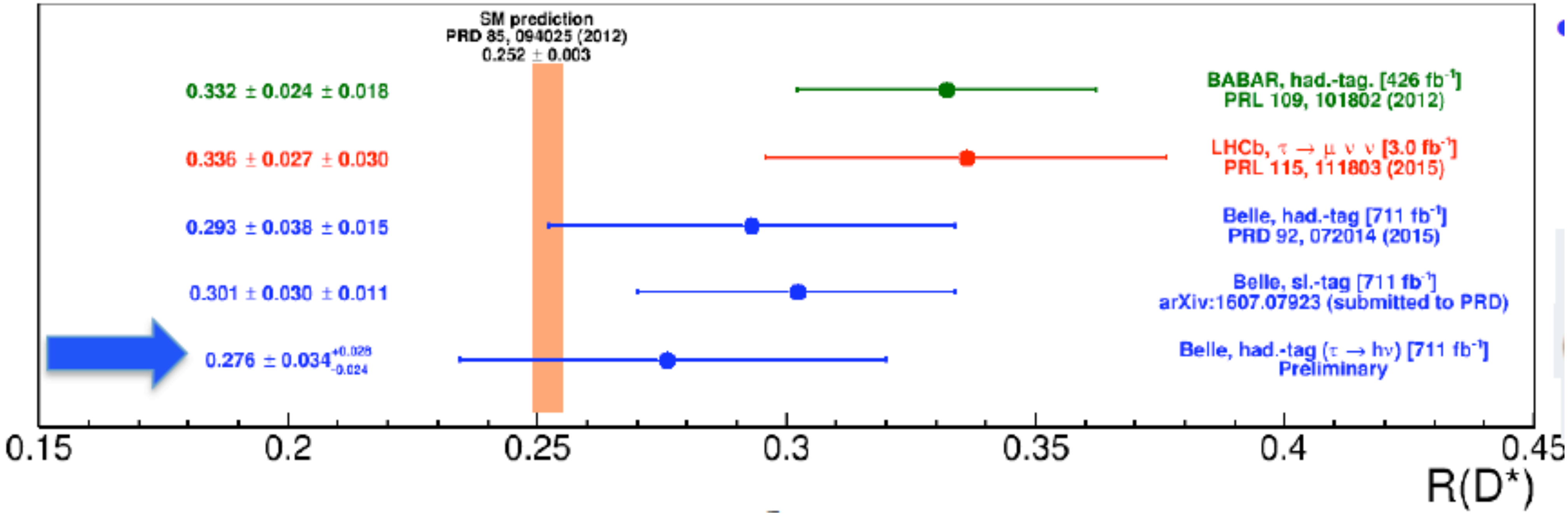
exp. average

SM prediction



A deviation from the SM in flavour, finally?

$$R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(\to D^* l \nu)}$$



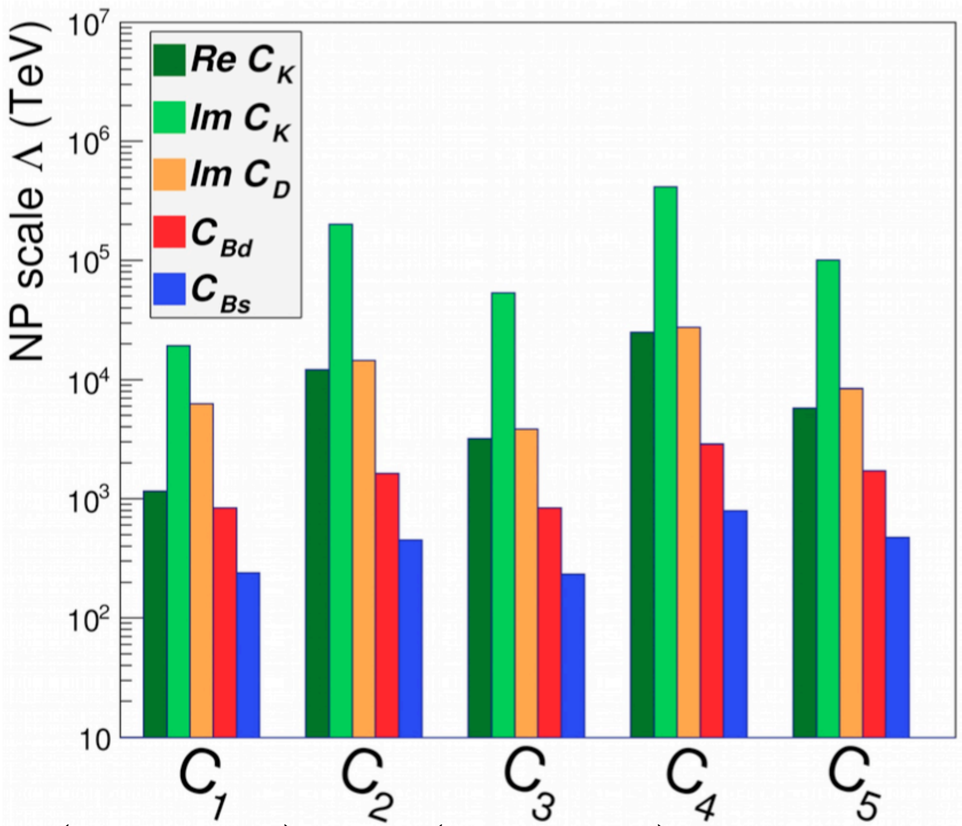
a 4σ deviation from the SM

from a collection of different (difficult) experiments

(no problem from the theory error)

Which direction to take?

1. High energy exploration



$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i^\alpha \frac{C_i^\alpha}{\Lambda_i^\alpha} (\bar{f} f \bar{f} f)_i^\alpha$$

$$\alpha = K(\Delta S = 2),\ D(\Delta C = 2),\ B_d(\Delta B = 1),\ B_s(\Delta B = 1)$$

i = 1,...,5 = different Lorentz structures

2. Indirect signals of new physics at the TeV scale

Minimal Flavour Violation in the quark sector

Phenomenological Definition:

In EFT the only relevant op.s correspond to the FCNC loops of the SM, weighted by a single scale Λ and by the standard CKM factors (up to $O(1)$ coeff.s)

Strong MFV $\quad U(3)_Q \times U(3)_u \times U(3)_d$

$$Y_u = (3, \bar{3}, 1) \to Y_u^D \qquad Y_d = (3, 1, \bar{3}) \to V Y_d^D$$

$$\Rightarrow \quad A(d_i \to d_j) = V_{tj} V_{ti}^* A_{SM}^{\Delta F=1} (1 + a_1 (\frac{4\pi M_W}{\Lambda})^2)$$

$$M_{ij} = (V_{tj} V_{ti}^*)^2 A_{SM}^{\Delta F=2} (1 + a_2 (\frac{4\pi M_W}{\Lambda})^2)$$

?

Chivukula, Georgi 1987
Hall, Randall 1990
D'Ambrosio et al 2002

Weak MFV

$$U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_{d3}$$

$$y_b = (1,1,1)_{-1} \quad \lambda_u = (2,\bar{2},1)_0 \quad \lambda_d = (2,1,\bar{2})_0 \quad \mathbf{V}_Q = (2,1,1)_0$$

1. gives a symmetry status to heavy and weakly mixed top
2. only broken by small spurions ($\lesssim 4 \cdot 10^{-2}$)

$$\Rightarrow \quad Y_u = \left(\begin{array}{c|c} \lambda_u & y_t x_t \mathbf{V} \\ \hline 0 & y_t \end{array}\right) \quad Y_d = \left(\begin{array}{c|c} \lambda_d & y_b x_b \mathbf{V} \\ \hline 0 & y_b \end{array}\right) \quad \mathbf{V} = \begin{pmatrix} 0 \\ \epsilon \end{pmatrix}$$

?

mimicked in the lepton sector by: $U(2)_L \times U(2)_e \times U(1)_{e3}$

$$y_\tau = (1,1)_{-1} \quad \lambda_e = (2,\bar{2})_0 \quad \mathbf{V_L} = (2,1)_0$$

(except for neutrinos, due to $N_R^T M N_R$)

B, Isidori, Jones-Perez, Lodone, Straub 2011
B, Buttazzo, Sala, Straub 2012

B-physics "anomalies"

1. $b \to c\tau\nu$

$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \to D^*\tau\nu)_{\rm exp}/\mathcal{B}(B \to D^*\tau\nu)_{\rm SM}}{\mathcal{B}(B \to D^*\ell\nu)_{\rm exp}/\mathcal{B}(B \to D^*\ell\nu)_{\rm SM}} = 1.28 \pm 0.08$$

$$R_{D}^{\tau/\ell} = \frac{\mathcal{B}(B \to D\tau\nu)_{\rm exp}/\mathcal{B}(B \to D\tau\nu)_{\rm SM}}{\mathcal{B}(B \to D\ell\nu)_{\rm exp}/\mathcal{B}(B \to D\ell\nu)_{\rm SM}} = 1.37 \pm 0.18\ ,$$

2. $b \to s l^+ l^-$

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

(could be related to the P_5' anomaly in the q^2distribution)

Both a $20 \div 30\%$ deviation from the SM

However tree (1) versus loop level (2)!

Question

Is there a flavour group $\mathcal{G}_F$ and a tree level exchange Φ such that:

1. With unbroken $\mathcal{G}_F$, Φ couples to the third generation of quarks and leptons only;

2. After small $\mathcal{G}_F$ breaking, the needed operators are generated

$$(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$

$(\bar{b}_L \gamma_\mu s_L)(\bar{\mu} \gamma_\mu \mu)$ at suppressed level

Answer

$\mathcal{G}_F = \mathcal{G}_F^q \times \mathcal{G}_F^l$ "minimally" broken

$$\mathcal{G}_F^q = U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_{d3}$$
$$\mathcal{G}_F^l = U(2)_L \times U(2)_e \times U(1)_{e3}$$

?

with mediators under $SU(3) \times SU(2) \times U(1)$:

1. $V_\mu = (3,1)_{2/3}$ Lorentz vector, $\mathcal{G}_F$ singlet
2. $\mathbf{V}_\mu = (3,3)_{2/3}$ Lorentz vector, $\mathcal{G}_F$ singlet
3. $\Phi = (3,3)_{-1/3}$ Lorentz scalar, $\mathcal{G}_F$ singlet

Couplings in the physical bases

$$\mathcal{L}_1 = g_U(\bar{u}_L\gamma^\mu F^U \nu_L + \bar{d}_L\gamma^\mu F^D e_L)U_\mu + \text{h.c}$$

and similar for $\mathcal{L}_{2,3}$

$$F^U = \begin{pmatrix} -V_{ub}(s_l\epsilon_l)[1-r_d] & -V_{ub}(c_l\epsilon_l)[1-r_d] & V_{ub}[1-r_d] \\ -V_{cb}(s_l\epsilon_l)[1-r_d] & -V_{cb}(c_l\epsilon_l)[1-r_d] & V_{cb}[1-r_d] \\ -V_{tb}(s_l\epsilon_l) & -V_{tb}(c_l\epsilon_l) & V_{tb} \end{pmatrix}$$

$$F^D = \begin{pmatrix} -V_{td}(s_l\epsilon_l)r_d & -V_{td}(c_l\epsilon_l)r_d & V_{td}r_d \\ -V_{ts}(s_l\epsilon_l)r_d & -V_{ts}(c_l\epsilon_l)r_d & V_{ts}r_d \\ -V_{tb}(s_l\epsilon_l) & -V_{tb}(c_l\epsilon_l) & V_{tb} \end{pmatrix}$$

in terms of $\quad r_d, \quad \epsilon_l, \theta_l$

$$\mathcal{L}_2 = \frac{g_{\vec{U}}}{\sqrt{2}}\Big[\frac{1}{\sqrt{2}}(\bar{u}_L\gamma^\mu F^U \nu_L - \bar{d}_L\gamma^\mu F^D e_L)U_\mu^{2/3} + (\bar{u}_L\gamma^\mu F^U e_L)U_\mu^{5/3} + (\bar{d}_L\gamma^\mu F^D \nu_L)U_\mu^{-1/3}\Big] + \text{h.c}$$

$$\mathcal{L}_3 = \frac{g_{\vec{S}}}{\sqrt{2}}\Big[\frac{1}{\sqrt{2}}(\bar{u}_L^c F^U e_L + \bar{d}_L^c F^D \nu_L)S^{1/3} + (\bar{u}_L^c F^U \nu_L)S^{-2/3} + (\bar{d}_L^c F^D e_L)S^{4/3}\Big] + \text{h.c}$$

Tree level effects

In terms of $$(R_U, R_{\vec{U}}, R_{\vec{S}}) \equiv \frac{4M_W^2}{g^2}(\frac{g_U^2}{M_U^2}, \frac{g_{\vec{U}}^2}{M_{\vec{U}}^2}, \frac{g_{\vec{S}}^2}{M_{\vec{S}}^2})$$

$b \longrightarrow c\tau\nu$

$$R_{D^{(*)}}^{\tau/l} \approx 1 + (R_U, -\frac{1}{4}R_{\vec{U}}, -\frac{1}{8}R_{\vec{S}})(1 - r_d)$$

$b \longrightarrow s\nu\bar{\nu}$

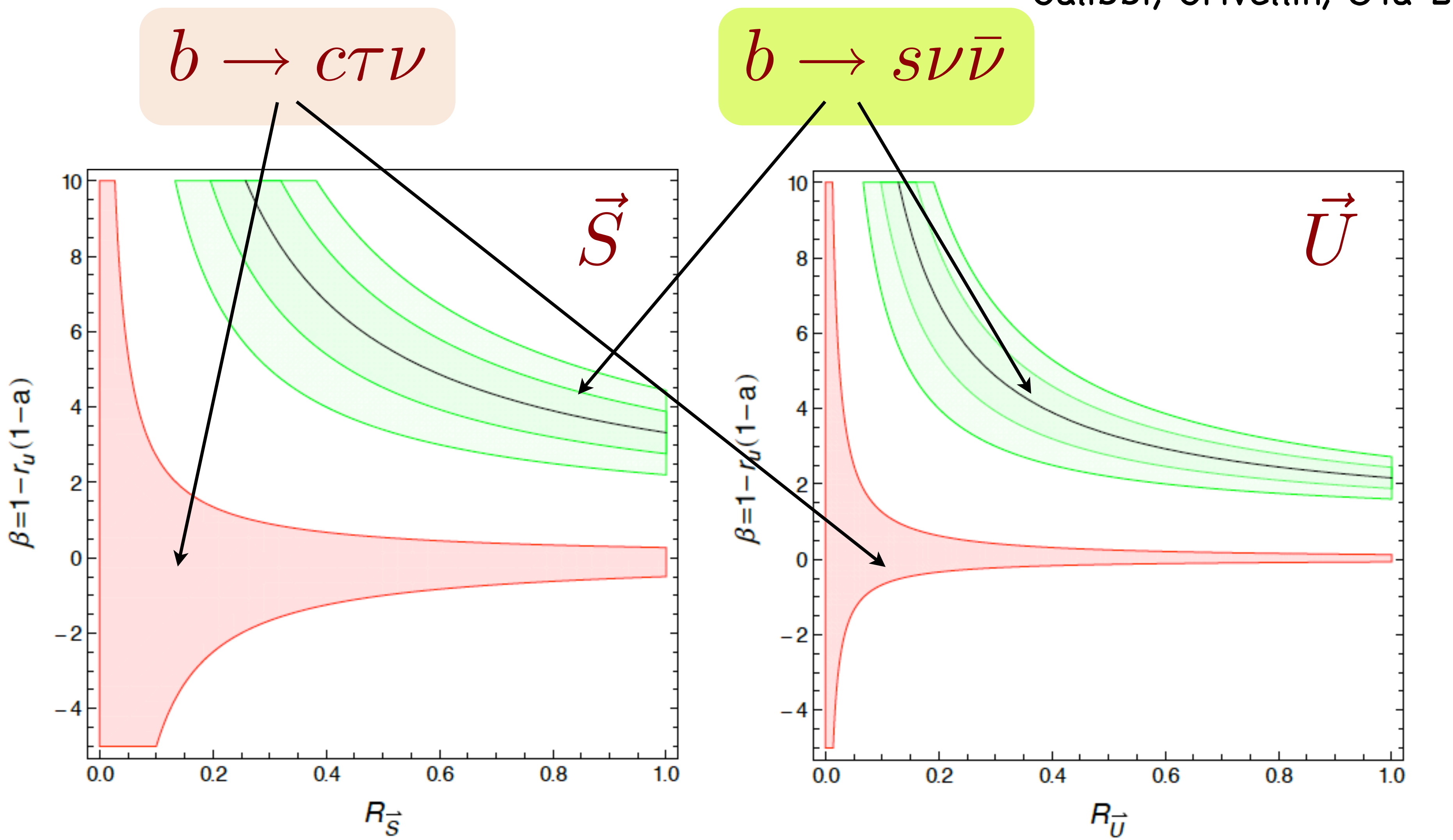
?

$$R_{K^{(*)}\nu} = \frac{\mathcal{B}(\bar{B} \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(\bar{B} \to K^{(*)}\nu\bar{\nu})_{SM}} \approx \frac{1}{3}\left(3 + 2\text{Re}(x) + |x|^2\right)$$

$$(x_U, x_{\vec{U}}, x_{\vec{S}}) = -\frac{\pi}{\alpha c_\nu^{SM}} r_d \left(0, -\frac{R_{\vec{U}}}{2}, \frac{R_{\vec{S}}}{8}\right)$$

B, Isidori, Pattori, Senia 2015

Calibbi, Crivellin, Ota 2015



⇒ Only U_μ survives tree level test (trivially)

but can one make sense of a vector lepto-quark?

Interpreting the lepto-quark as a ρ-like state in a composite Higgs picture

The global group $\mathcal{G}$ of a strong dynamics is broken down to a subgroup $\mathcal{H}$, producing a (pseudo)Goldstone boson H

In the "standard" picture:

$$\mathcal{G} = SU(3) \times SO(5) \times U(1)_X \xrightarrow{f} \mathcal{H} = SU(3) \times SO(4) \times U(1)_X$$

Extend it to:

$$\mathcal{G} = SU(4) \times SO(5) \times U(1)_X \xrightarrow{f} \mathcal{H} = SU(4) \times SO(4) \times U(1)_X$$

B, Murphy, Senia 2016

General structure of composite Higgs models

(a general insertion)

The global group $\mathcal{G}$ of a strong dynamics is broken down to a subgroup $\mathcal{H}$, producing a (pseudo)Goldstone boson H

common ingredients:

- composite vectors $\hat{V}_\mu$ in the adjoint of $\mathcal{H}$
- composite fermions F in full reps of $\mathcal{H}$
- elementary vectors V_μ in the adjoint of $SU_{321} \subset \mathcal{H}$
- elementary fermions f in the standard reps under $SU_{321} \subset \mathcal{H}$
- mass mixings $\bar{F} f$ and $\hat{V}^\mu V_\mu$ consistent with $SU_{321} \subset \mathcal{H}$

An explicit example ("2 site")

$$\mathcal{H} = U(1)_{T_{3R}} \times U(1)_X \qquad \mathcal{G}_{el} = U(1)_Y \qquad Y = T_{3R} + X$$

1. Double $\quad \mathcal{H} \;\Rightarrow\; U(1)^{el}_{T_{3R}} \times U(1)^{el}_X \times U(1)_{T_{3R}} \times U(1)_X$

2. Gauge $\quad \mathcal{G}^{gauge} = U(1)^{el}_Y \times U(1)_{T_{3R}} \times U(1)_X$

3. Introduce $\Sigma_T = (1/2, 0, -1/2, 0)$ and $\Sigma_X = (0, 1/2, 0, -1/2)$
   with $< \Sigma_T >= f_T$ and $< \Sigma_X >= f_X$

4. Under $\mathcal{G}^{gauge}$

   "elementary" fermions $\quad f = (1, 0, 0)$

   "composite" fermions $\quad F = (0, 1/2, 1/2)$

An explicit example ("2 site") ?

$$\mathcal{H} = U(1)_{T_{3R}} \times U(1)_X \qquad \mathcal{G}_{el} = U(1)_Y \qquad Y = T_{3R} + X$$

$$M_V^2 = \begin{pmatrix} \hat{g}^2(f_T^2 + f_X^2) & -\hat{g}\hat{g}_X f_X^2 & -\hat{g}\hat{g}_T f_T^2 \\ -\hat{g}\hat{g}_X f_X^2 & \hat{g}_X^2 f_X^2 & 0 \\ -\hat{g}\hat{g}_T f_T^2 & 0 & \hat{g}_T^2 f_T^2 \end{pmatrix}$$

$\Rightarrow T_{3R}^{el} + X^{el} + T_{3R} + X$ unbroken

$$B_\mu = \frac{1}{r}(\hat{g}_T\hat{g}_X V_\mu^{el} + \hat{g}\hat{g}_X W_{3\mu} + \hat{g}\hat{g}_T X_\mu) \qquad r = (\hat{g}_T^2\hat{g}_X^2 + \hat{g}^2\hat{g}_X^2 + \hat{g}^2\hat{g}_T^2)^{1/2}$$

"composite" $\hat{B}_{1\mu},\ \hat{B}_{2\mu}$ of mass $\approx \hat{g}_X^2 f_X^2,\ \hat{g}_T^2 f_T^2$

$$\mathcal{L}_\Psi = i\bar{f}\gamma^\mu(\partial_\mu - igB_\mu + \ldots)f + i\bar{F}\gamma^\mu(\partial_\mu - igB_\mu + \ldots)F$$

$$g = \frac{\hat{g}\hat{g}_X\hat{g}_T}{r}$$

Complete model: vectors

$$SU(3)\times SO(4)\times U(1)_X$$

$$Y = T^3_R + X$$

unbroken: $G^\alpha_\mu,\ W^i_{L\mu},\ B_\mu$

composite: $\hat{G}^\alpha_\mu,\ \hat{W}^i_{L\mu},\ \hat{W}^\pm_{R\mu},\ \hat{B}_{1\mu},\ \hat{B}_{2\mu}$

$$SU(4)\times SO(4)\times U(1)_X$$

$$\rho^A_\mu T^A = \begin{pmatrix} \frac{1}{2}\rho^a_\mu\lambda^a + \frac{1}{2\sqrt{6}}\rho^{15}_\mu \mathbf{1}_{3\times 3} & \frac{1}{\sqrt{2}}V_\mu \\ \frac{1}{\sqrt{2}}V^\dagger_\mu & -\frac{3}{2\sqrt{6}}\rho^{15}_\mu \end{pmatrix}$$

$$\sqrt{\frac{2}{3}}T^{15} = \frac{1}{2}(B-L)$$

$$Y = \sqrt{\frac{2}{3}}T^{15} + T^3_R + X$$

unbroken: $G^\alpha_\mu,\ W^i_{L\mu},\ B_\mu$

composite as above + $V^i_\mu + V^{i+}_\mu + \hat{B}_{3\mu}$

?

$$M_{\hat{G}} \approx M_{\hat{W}_L} \approx M_{\hat{B}_1} \equiv M_{\rho 1}$$

$$M_{\hat{W}^\pm_R} \approx M_{\hat{B}_2} \approx M_{\hat{B}_3} \equiv M_{\rho 2}$$

$$M_{\rho 1} \approx \frac{\hat{g}_\rho M_W}{g_2\sqrt{\xi}}$$

$$\xi = (\frac{v}{f})^2$$

Complete models: fermions

$$SU(3) \times SO(4) \times U(1)_X$$

$\mathcal{H} = (1,2,2)_0$

$Y = T_R^3 + X$

a possible choice for the composite fermions

$\mathcal{Q}_U = (3,2,2)_{2/3}$ $\qquad q_U = (3,1,1)_{2/3}$

$\mathcal{Q}_D = (3,2,2)_{-1/3}$ $\qquad q_D = (3,1,1)_{-1/3}$

$\mathcal{L} = (1,2,2)_{-1}$ $\qquad l = (1,1,1)_{-1}$

?

all vector-like. Under the SM gauge group:

$\mathcal{Q}_U = (3,2)_{7/6} + (3,2)_{1/6}$ $\qquad q_U = (3,1)_{2/3}$

$\mathcal{Q}_D = (3,2)_{1/6} + (3,2)_{-5/6}$ $\qquad q_D = (3,1)_{-1/3}$

$\mathcal{L} = (1,2)_{-1/2} + (1,2)_{-3/2}$ $\qquad l = (1,1)_{-1}$

Why not?

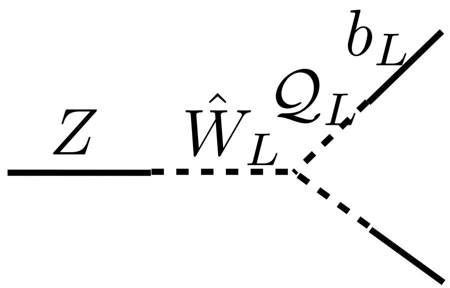
$$SU(3) \times SO(4) \times U(1)_X$$

$$\mathcal{H} = (1, 2, 2)_0$$

$$Y = T_R^3 + X$$

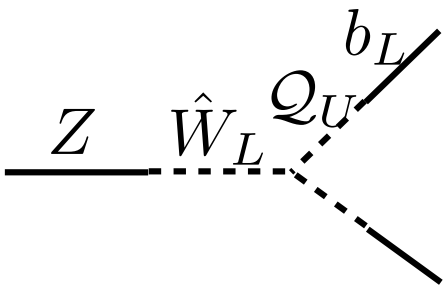
$$\mathcal{Q}_L = (3, 2, 1)_{1/6} \qquad \mathcal{Q}_R = (3, 1, 2)_{1/6}$$

$$\mathcal{L}_L = (1, 2, 1)_{-1/2} \qquad \mathcal{L}_R = (1, 1, 2)_{-1/2}$$



?

$$\mathcal{Q}_U = (3, 2, 2)_{2/3}$$



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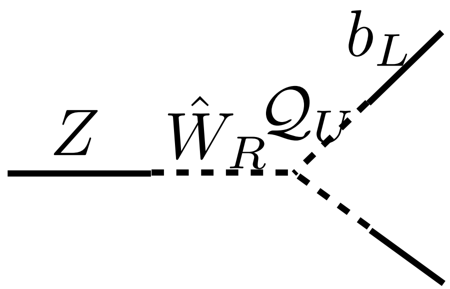


= 0

Complete models: fermions

$$SU(4)\times SO(4)\times U(1)_X$$

$$\mathcal{H}=(1,2,2)_0$$

$$Y=\sqrt{\frac{2}{3}}T^{15}+T^3_R+X$$

a possible choice for the composite fermions

$$\Psi_\pm=(4,2,2)_{\pm 1/2} \qquad \chi_\pm=(4,1,1)_{\pm 1/2}$$

?

all vector-like. Under the SM gauge group:

$$\Psi_+=(3,2)_{7/6}+(3,2)_{1/6}+(1,2)_{1/2}+(1,2)_{-1/2}$$

$$\Psi_-=(3,2)_{1/6}+(3,2)_{-5/6}+(1,2)_{-1/2}+(1,2)_{-3/2}$$

$$\chi_+=(3,1)_{2/3}+(1,1)_0$$

$$\chi_-=(3,1)_{-1/3}+(1,1)_{-1}$$

Tree level flavour violations

$$\mathcal{L}_{eff}^{b\to c\tau\nu} = r_u V_{cb}\Big(-\frac{g_2^2}{M_W^2}\Big)[\xi s_{Lu3}^2 s_{L\nu 3}^2]\Big(\frac{1}{2}+\frac{1}{2}f_{W*}\Big)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_{3L})$$

$$s_{Lu3}^2 s_{L\nu 3}^2 = (0.49 \div 0.77)\left(\frac{1.00}{r_u}\right)\left(\frac{0.10}{\xi}\right)$$

$$\xi = (\frac{v}{f})^2$$

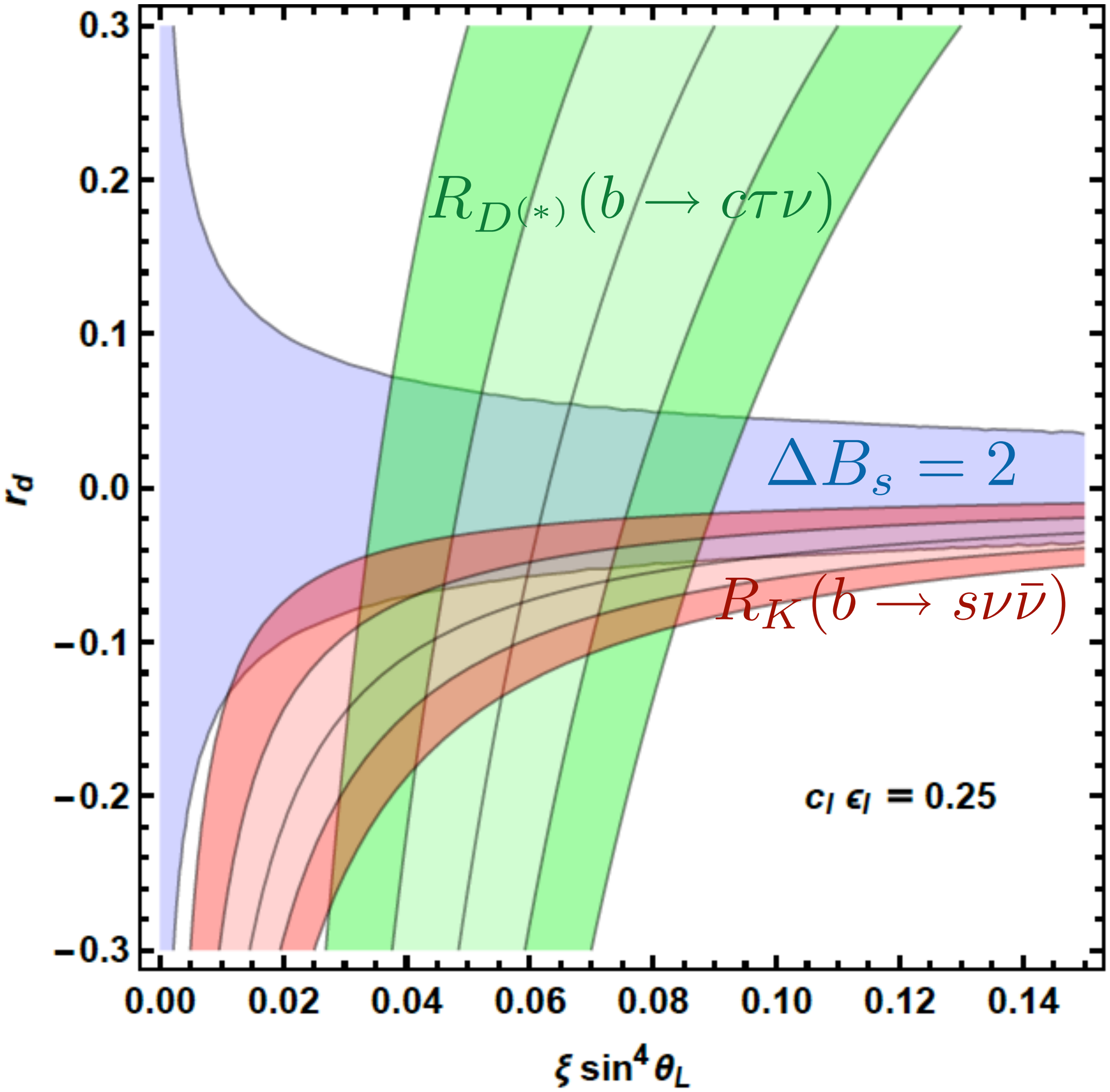
$$\mathcal{L}_{eff}^{b\to s\mu\mu} = r_d V_{ts}(c_l\epsilon_l)^2\Big(-\frac{g_2^2}{M_W^2}\Big)[\xi s_{Lu3}^2 s_{L\nu 3}^2]\times\Big(1+\frac{1}{4}f_{W*}-\frac{1}{12}\frac{3}{2}f_X\Big)(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$$

$$s_{Lu3}^2 s_{L\nu 3}^2 \approx -(0.65 \div 1.31)\Big(\frac{0.07}{c_l^2\epsilon_l^2}\Big)\Big(\frac{0.04}{r_d}\Big)\Big(\frac{0.10}{\xi}\Big)$$

$$\mathcal{L}_{eff}^{\Delta B_s=2} = r_d^2(V_{ts}V_{tb})^2\Big(-\frac{g_2^2}{M_W^2}\Big)[\xi s_{Lu3}^4]\times\Big(\frac{1}{2}+\frac{1}{3}f_{G^H}+\frac{1}{4}f_{W^*}+\frac{1}{36}\frac{3}{2}f_X\Big)(\bar{s}_L\gamma_\mu b_L)^2$$

$$r_d^2 s_{Lu3}^4\Big(\frac{\xi}{0.1}\Big) \lesssim 2\cdot 10^{-3}$$

Overall constraints



$$0.03 \lesssim \xi s_{Lu3}^2 s_{L\nu 3}^2 \lesssim 0.09$$

$$-0.08 \lesssim r_d \lesssim -0.02$$

$$s_{Lu3} = s_{L\nu 3} \equiv \sin\theta_L$$

LHC Phenomenology

1. Leptoquark pair production

2. Exotic Leptons

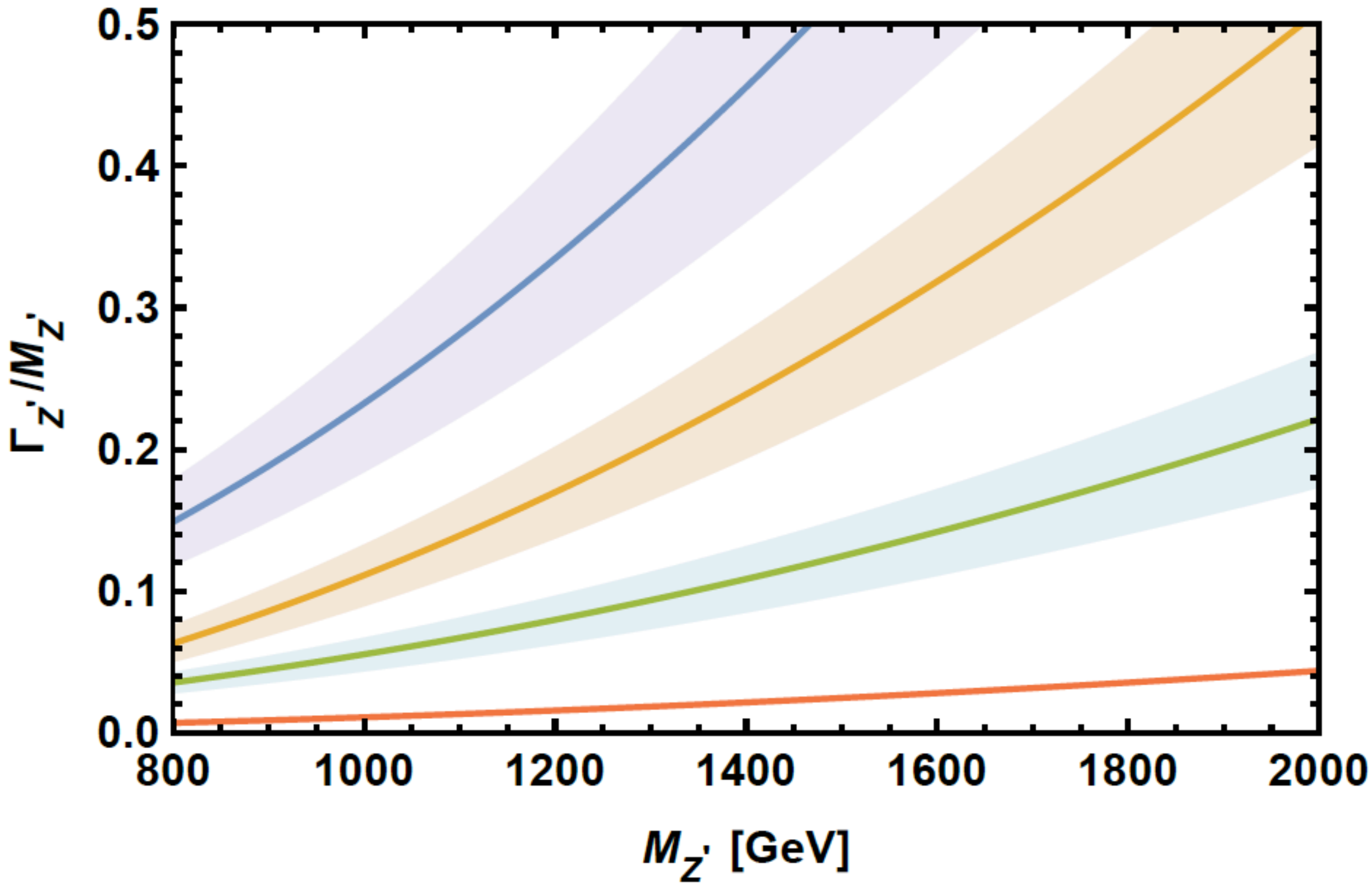
3. Resonances in $\tau^+\tau^-$

(concentrate on 3)

Resonances in $\tau^+\tau^-$

4 neutral Z′-type resonances

the signal crucially depends on Γ_{tot}/M



$s_{Lu3} = s_{L\nu 3}$

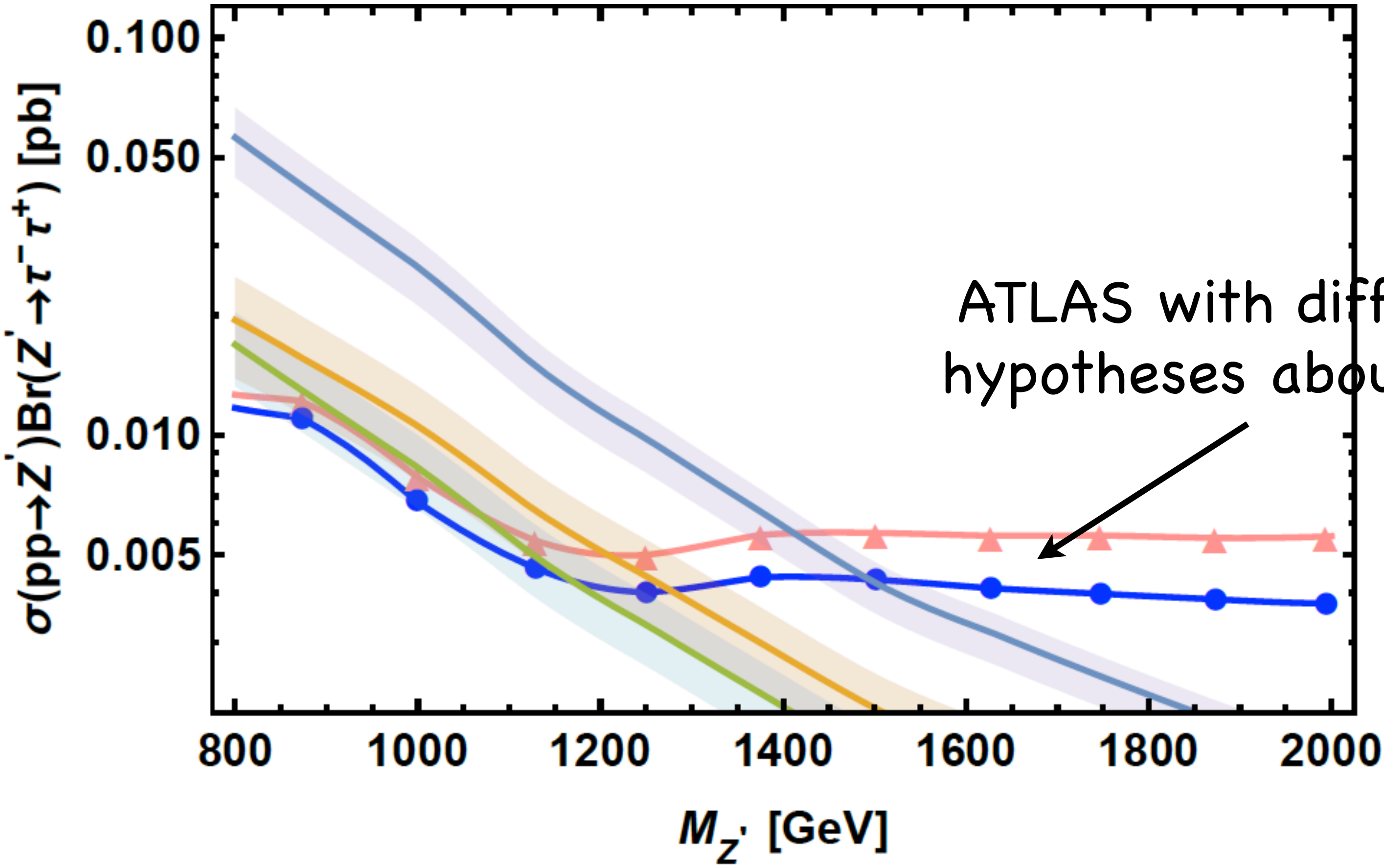
$\xi = 0.1$

bands reproduce $R_{D^{(*)}}$ at 1σ level

B, Murphy, Senia 2016

$$\sigma(pp \to Z' \to \tau^+\tau^-)$$

assuming dominance by 1 single Z′ + SM interference



ATLAS with different hypotheses about Γ_{tot}/M

$\xi = 0.1$

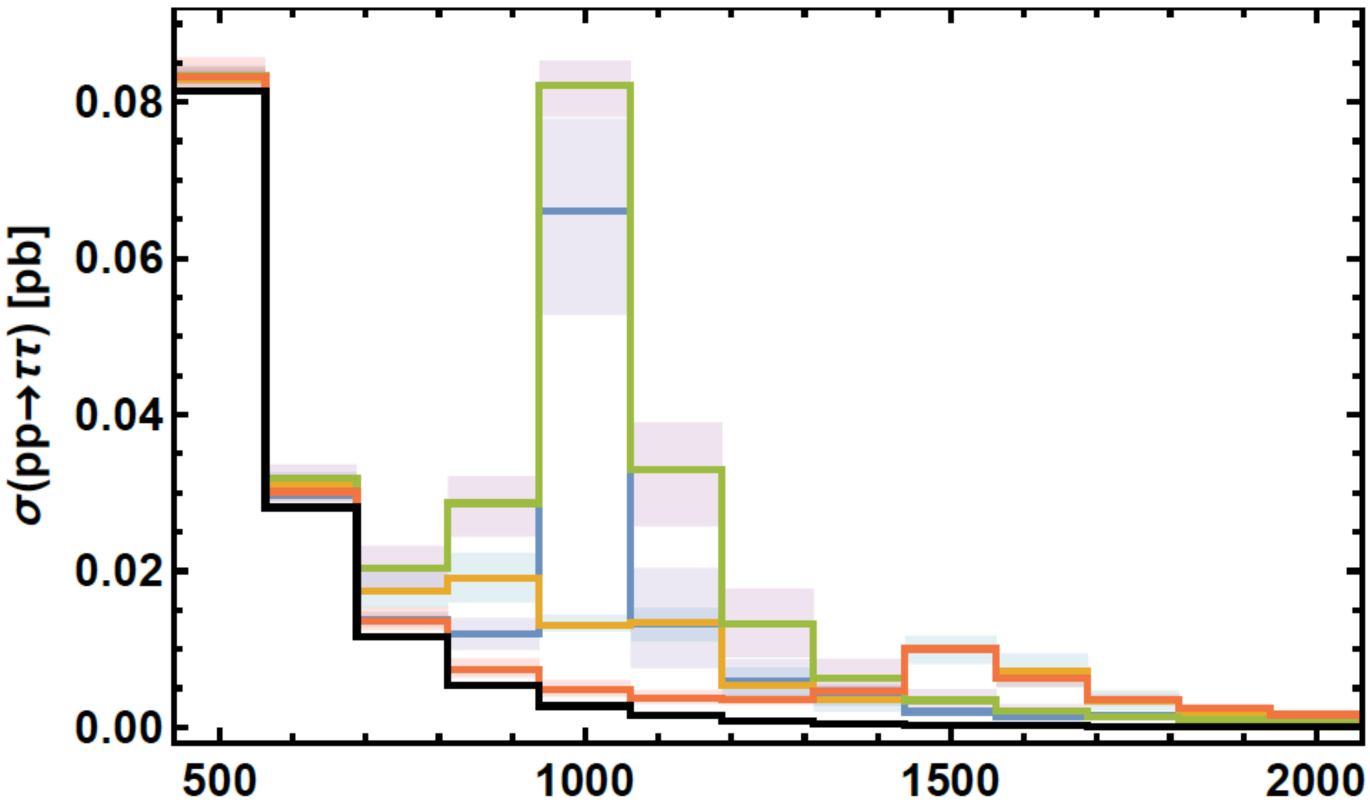
$M_{Z'} \gtrsim 1.1 \div 1.5\ TeV$

$M_{Z'} \sim g_\rho f/2 \qquad g_\rho \gtrsim 2.8 \div 3.8$

The actual $\sigma(pp \to \tau^+\tau^-)$

includes at amplitude level:

- 4 Z′ in the s-channel
- the leptoquark in the t-channel
- the SM contribution



$M_{\tau\tau}(GeV)$

$$M_{\rho 1}, M_{\rho 2} = (1.0, 1.5), (1.5, 1.0), (1.0, 1.0), (1.5, 1.5)\ TeV$$

Conclusion

Let us see if the anomalies
get reinforced or fade away

e.g. from the LHCb program

- not only R_K ($B \to K e^+ e^- / B \to K \mu^+ \mu^-$) but similar ratios with different hadronic systems (K^*, φ, Λ, etc.)
- not only $D^* \tau\nu$, but also $D\tau\nu$, $D_s \tau\nu$, $\Lambda_c \tau\nu$, etc.
  - also trying hadronic tau decays

If they are roses ...
take seriously the leptoquark and $U(2)^5$
and perhaps a composite picture

An “Extreme Flavour” experiment?

Vagnoni – SNS, 7-10 Dec 2014

- Currently planned experiments at the HL-LHC will only exploit a small fraction of the huge rate of heavy-flavoured hadrons produced
  - ATLAS/CMS: full LHC integrated luminosity of 3000 fb^{-1}, but limited efficiency due to lepton high p_T requirements
  - LHCb: high efficiency, also on charm events and hadronic final states, but limited in luminosity, 50 fb^{-1} vs 3000 fb^{-1}
- Would an experiment capable of exploiting the full HL-LHC luminosity for flavour physics be conceivable?
  - Aiming at collecting O(100) times the LHCb upgrade luminosity → 10^{14} b and 10^{15} c hadrons in acceptance at $L=10^{35}\ cm^{-2}s^{-1}$

Motivation: test CKM (FCNC loops) from ≃ 20% to ≲ 1%

A minimal list of key observables in QFV to be improved and not yet TH-error dominated

- γ from tree: $B \to DK$, etc (now better from loops)
- $|V_{ub}|, |V_{cb}|$
- $B \to \tau\nu, \mu\nu \ (+D^{(*)})$
- $B \to K^{(*)} \ l^+l^-, \nu\nu$ (in suitable observables?)
- $K_S, D, B_{s,d} \to l^+l^-$ ("Higgs penguins")
- $\phi^{\Delta}_{d,s}$ (CPV in $\Delta B_{d,s} = 2$)
- $K^+, K_L \to \pi\nu\nu$
- ΔA_{CP} in selected D modes