Teaching through research: remembering Raul Gatto

“Beyond the Standard Model”

R. Barbieri

GGI, Florence, Sept 28, 2018

SINGULAR BINDING DEPENDENCE IN THE HADRONIC WIDTHS OF 1^{++} AND 1^{+-} HEAVY QUARK ANTIQUARK BOUND STATES

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Received 10 February 1976

The annihilation rates into hadrons of P-wave heavy quark-antiquark bound states are calculated within SU(3) colour gauge theory (in particular for the charm scheme). An interesting feature we find is a logarithmic divergence for small binding for the states 1^{++} and 1^{+-}. Implications for the asymptotic freedom approach to the decay rates of the new particles are discussed. An attempt to use quantitatively the obtained results for all the *C*-even P-waves gives $\Gamma_{\mathrm{ann}}(0^{++}) : \Gamma_{\mathrm{ann}}(2^{++}) : \Gamma_{\mathrm{ann}}(1^{++}) \approx 15 : 4 : 1$.

Experimentally, mostly from E760, E835:

$$\Gamma(\chi_{c0}) = 10.5 \pm 0.6 \qquad \Gamma(\chi_{c2}) = 1.93 \pm 0.11 \qquad \Gamma(\chi_{c1}) = 0.84 \pm 0.04 \qquad MeV$$

$$\Gamma(0^{++}) : \Gamma(2^{++}) : \Gamma(1^{++}) = 12 : 2.4 : 1$$

WEAK SELF-MASSES, CABIBBO ANGLE, AND BROKEN $SU_2 \times SU_2$

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Received 16 September 1968

if: $\mathbf{y}^{u,d}$ $\quad |y_{12}| = |y_{21}|, \quad y_{11}, y_{13}, y_{31} << y_{12}$

$$|V_{us}| = \left|\sqrt{\frac{m_d}{m_s}} - e^{i\varphi}\sqrt{\frac{m_u}{m_c}}\right|$$

BSM question: A curious accident or a deep relation?

QUARK MASS MATRIX AND DISCRETE SYMMETRIES IN THE SU(2) ⊗ U(1) MODEL ☆

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Received 27 February 1978

(no discrete symmetry can explain the relation above)

Extending GST

Fritzsch
Weinberg
...
Hall, Rasin 1993

If $\quad \left|\dfrac{m^{U,D}}{m^{U,D}_{33}}\right| = \begin{pmatrix} \ll \epsilon'^2/\epsilon & \epsilon' & \ll \epsilon' \\ \epsilon' & \epsilon & \mathcal{O}(\epsilon) \\ \ll \epsilon' & \mathcal{O}(\epsilon) & 1 \end{pmatrix}$ with arbitrary phases

$$|V_{us}| = \left|\sqrt{\frac{m_d}{m_s}} - e^{i\varphi}\sqrt{\frac{m_u}{m_c}}\right|$$

$$\left|\frac{V_{ub}}{V_{cb}}\right| = \sqrt{\frac{m_u}{m_c}} \qquad \left|\frac{V_{ub}}{V_{cb}}\right| = (8.0 \pm 0.6)10^{-2} \qquad \sqrt{\frac{m_u}{m_c}} = (4.5 \pm 0.5)10^{-2}$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = \sqrt{\frac{m_d}{m_s}} \qquad \left|\frac{V_{td}}{V_{ts}}\right| = 0.25 \pm 0.02 \qquad \sqrt{\frac{m_d}{m_s}} = 0.22 \pm 0.01$$

Remarkable, although not quite perfect

Ziegler et al, 2014-2017

With $\mathbf{y}^u$ as above and $\mathbf{y}^d \to \mathbf{y}^d U^{23}(s^{Rd}_{23})$

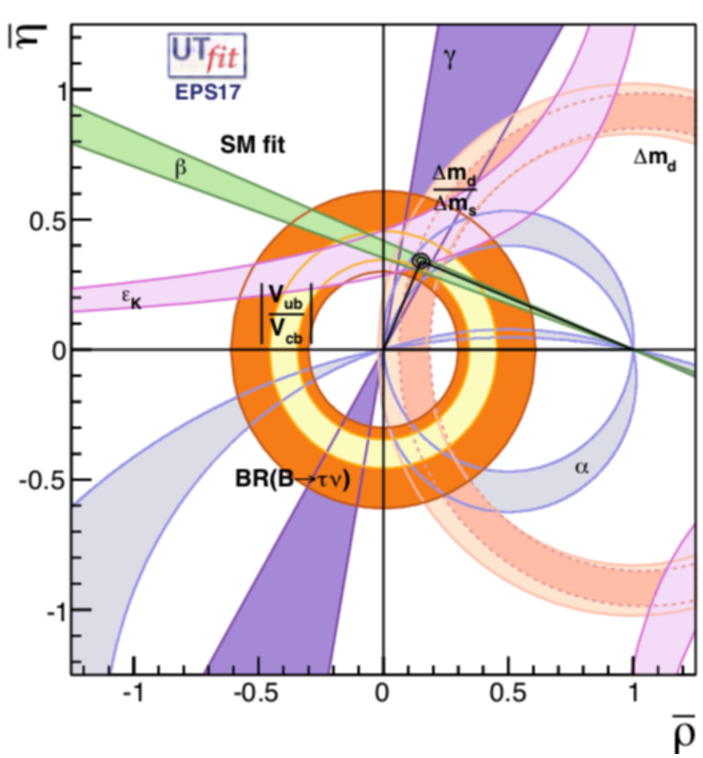
$$|V_{us}| = |\sqrt{\frac{m_d}{m_s}}\sqrt{c^{Rd}_{23}} - e^{i(\phi_1-\phi_2)}\sqrt{\frac{m_u}{m_c}}|$$

$$|V_{ub}| = |\sqrt{\frac{m_u}{m_c}}|V_{cb}| - e^{i\phi_1}\sqrt{c^{Rd}_{23}}\frac{s^{Rd}_{23}}{c^{Rd}_{23}}\frac{m_s}{m_b}|$$

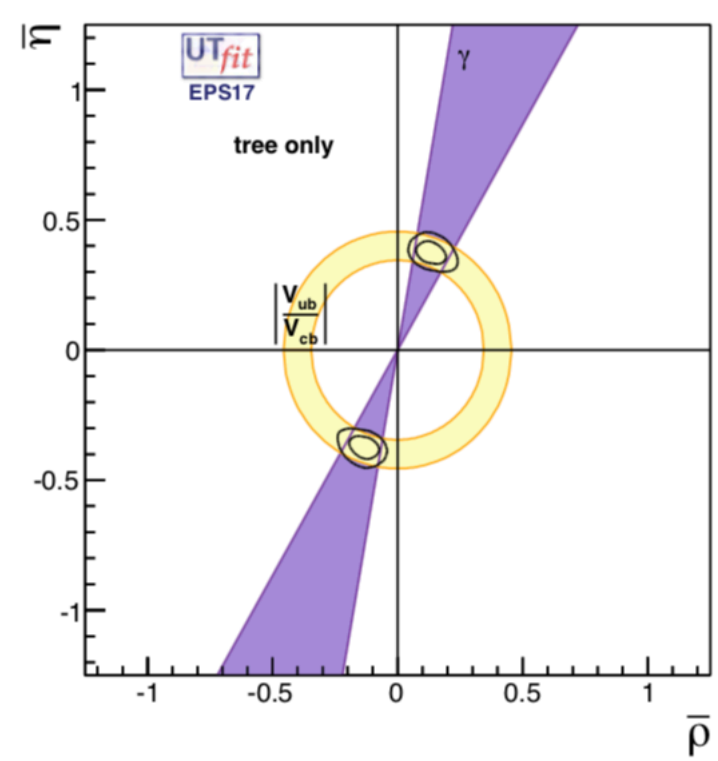
$$|V_{td}| = \sqrt{\frac{m_d}{m_s}}||V_{cb}| - e^{i\phi_2}\frac{s^{Rd}_{23}}{c^{Rd}_{23}}\frac{m_s}{m_b}|$$

can get a perfect fit with:

$$s^{Rd}_{23} = 0.6 \pm 0.06$$



$$s^{Rd}_{23} \geq 0.3 \pm 0.01$$



$\mathbf{y}^{u,d}$ as above, where from? U(2)

Pomarol, Tommasini 1995
B, Dvali, Hall 1995
B, Hall, Romanino 1997
...
Ziegler et al, 2014-2017

Organise the standard fermions
in $SU(4) \times SU(2) \times U(1)$ multiplets

$$p_i = \begin{pmatrix} q \\ l \end{pmatrix}_i \qquad p_i^u = \begin{pmatrix} u \\ \nu^c \end{pmatrix}_i \qquad p_i^d = \begin{pmatrix} d \\ e \end{pmatrix}_i \qquad i = (a, 3), \quad a = (1, 2)$$

Under a flavour $SU(2)_f \times U(1)_f$ group:

	p_a	p_a^u	p_a^d	p_3	p_3^u	p_3^d	ϕ	χ
$SU(2)_f$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_f$	1	1	1	0	0	1	-1	-1

with ϕ and χ scalar "flavons"

$\mathbf{y}^{u,d}$ as above, where from? U(2)

Take most general $\mathcal{L}_Y$ invariant under $SU(2)_f \times U(1)_f$

$$\mathcal{L}_Y = \lambda^u_{33} q_3 u_3 H + \frac{\lambda^u_{12}}{\Lambda^2}\chi^2 \epsilon_{ab} q_a u_b H + \frac{\lambda^u_{11}}{\Lambda^6}\chi^4 (\phi^*_a q_a)(\phi^*_b u_b) H + \dots$$

Without loss of generality $<\phi>= \begin{pmatrix} \epsilon_\phi \Lambda \\ 0 \end{pmatrix}$ $<\chi>= \epsilon_\chi \Lambda$

$$Y_u \approx \begin{pmatrix} \lambda^u_{11}\varepsilon_\phi^2\varepsilon_\chi^4 & \lambda^u_{12}\varepsilon_\chi^2 & \lambda^u_{13}\varepsilon_\phi\varepsilon_\chi^2 \\ -\lambda^u_{12}\varepsilon_\chi^2 & \lambda^u_{22}\varepsilon_\phi^2 & \lambda^u_{23}\varepsilon_\phi \\ \lambda^u_{31}\varepsilon_\phi\varepsilon_\chi^2 & \lambda^u_{32}\varepsilon_\phi & \lambda^u_{33} \end{pmatrix}, \qquad Y_d \approx \begin{pmatrix} \lambda^d_{11}\varepsilon_\phi^2\varepsilon_\chi^4 & \lambda^d_{12}\varepsilon_\chi^2 & \lambda^d_{13}\varepsilon_\phi\varepsilon_\chi^3 \\ -\lambda^d_{12}\varepsilon_\chi^2 & \lambda^d_{22}\varepsilon_\phi^2 & \lambda^d_{23}\varepsilon_\phi\varepsilon_\chi \\ \lambda^d_{31}\varepsilon_\phi\varepsilon_\chi^2 & \lambda^d_{32}\varepsilon_\phi & \lambda^d_{33}\varepsilon_\chi \end{pmatrix}$$

A perfect fit of u,d,e masses and CKM angles with

$\epsilon_\phi \approx 0.02, \quad \epsilon_\chi \approx 0.01$ and $\lambda^{u,d,e}_{ij} = O(1)$

Plausible? **Yes**

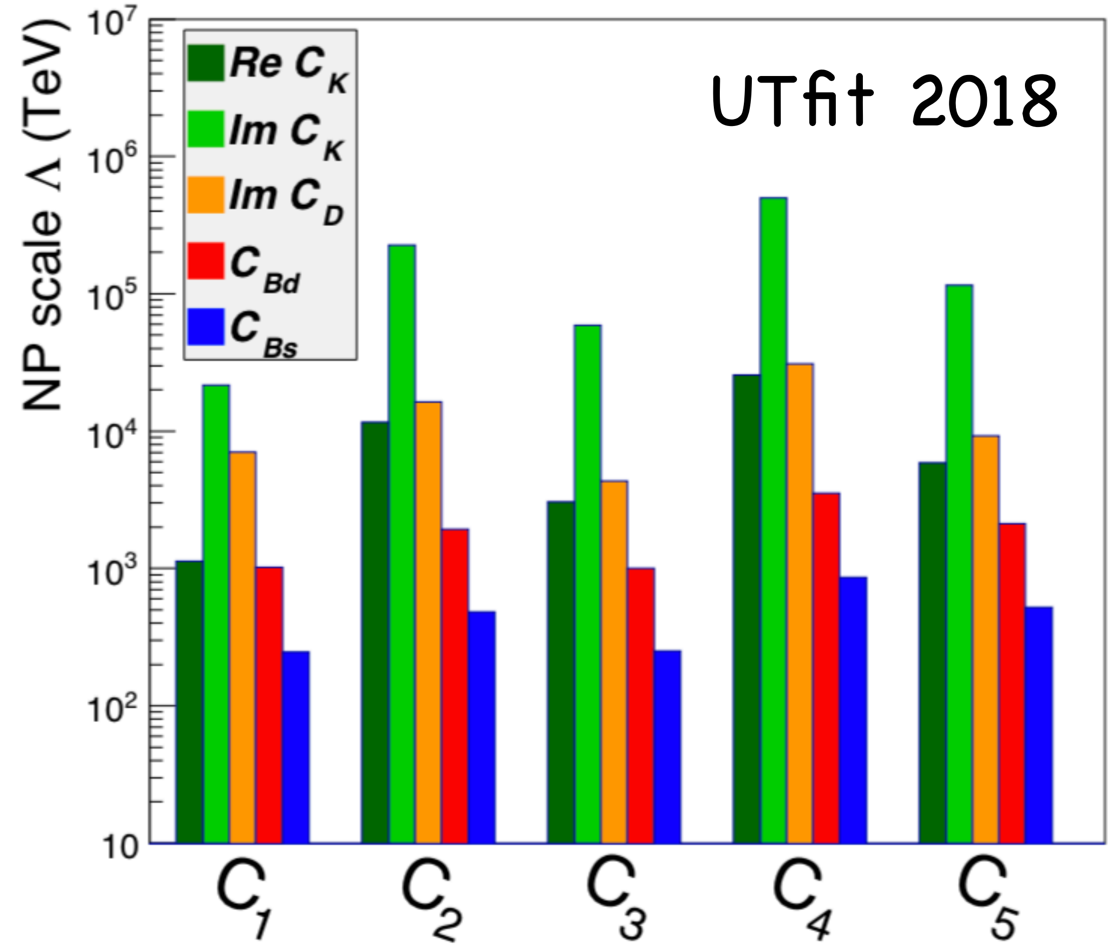
Compelling? Need some other key observation

Which attitude towards flavour in BSM?

1. Flavour physics confined to high energy
   (the prevailing lore)

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

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



2. New physics at the TeV scale hidden by the approximate $U(2)$ $(U(2)^n)$ symmetry

(the attitude I advocate since a while)

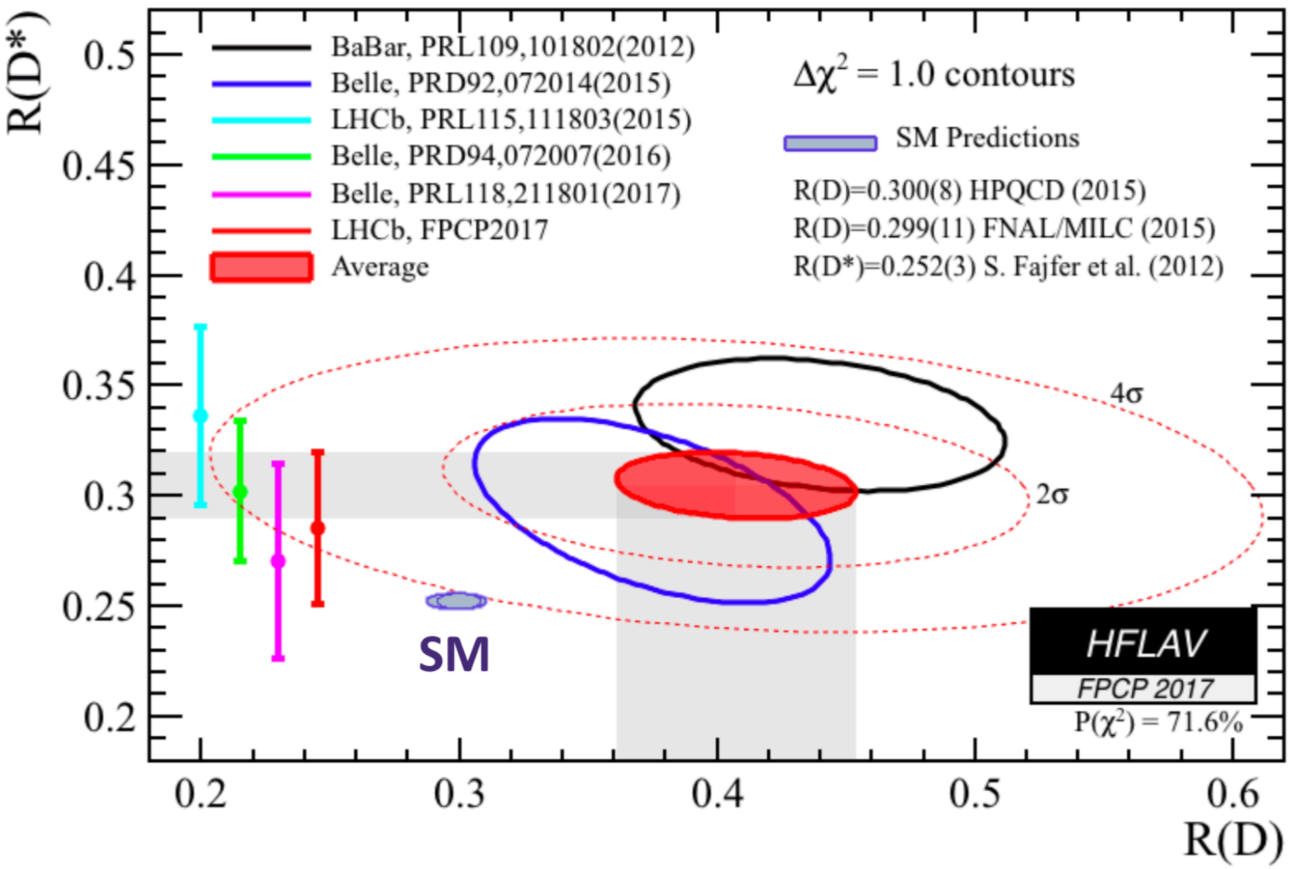
If so, a special role played by the third generation

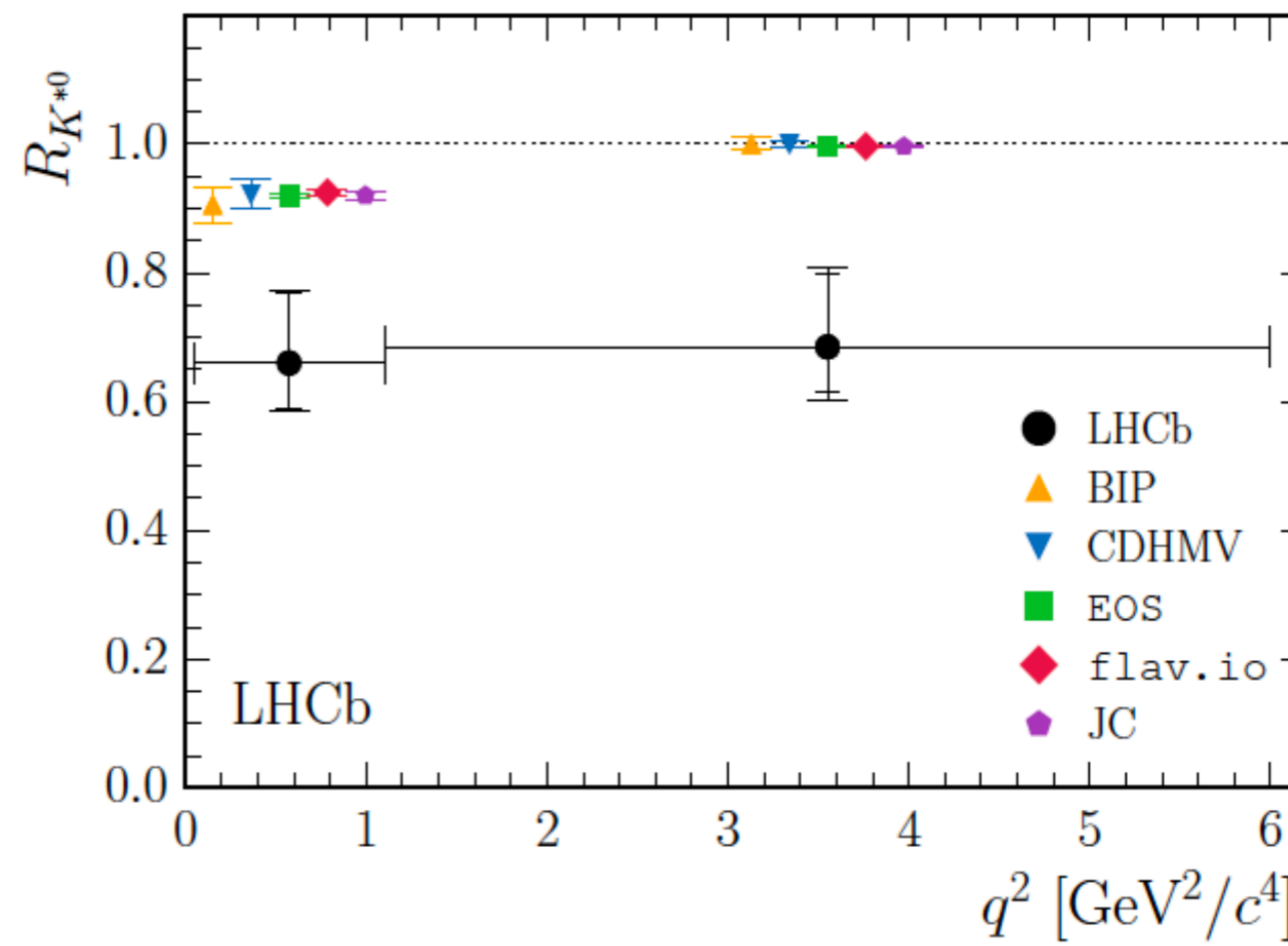
B, Isidori, Jones-Perez, Lodone, Straub 2011

B-decay anomalies (exp. versus SM)

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}l\nu, l = \mu, e)}$$

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$





About 20-30% deviations from the SM in

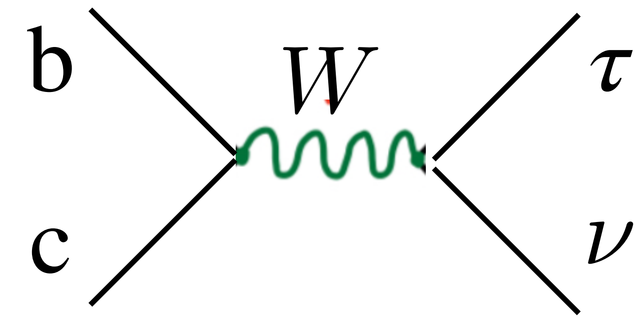
tree level $b \to cl\nu$ loop level $b \to sll$

at near 4σ level

Concentrate first on $\frac{R_{D^{(*)}}}{R^{SM}_{D^{(*)}}} = 1.237 \pm 0.053$

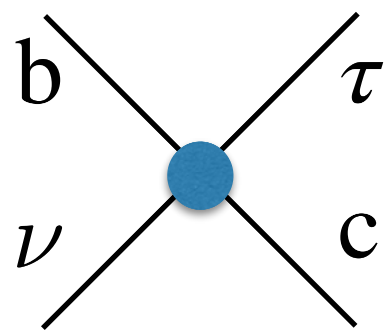
harder to explain consistently with everything else we know

Need to interfere with



$$= \frac{g^2 V_{cb}}{2 m_W^2}$$

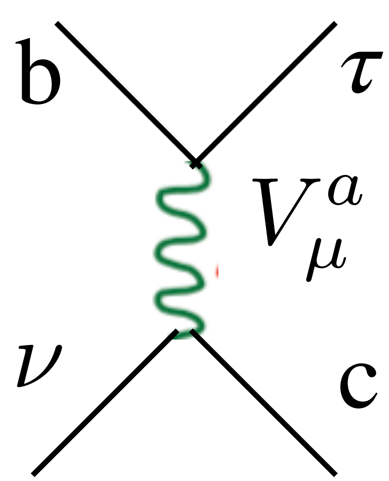
From



need $\Lambda \approx 500\ GeV (\frac{\mathcal{V}_{cb}\mathcal{V}_{\tau\nu}}{V_{cb}})^{1/2}$

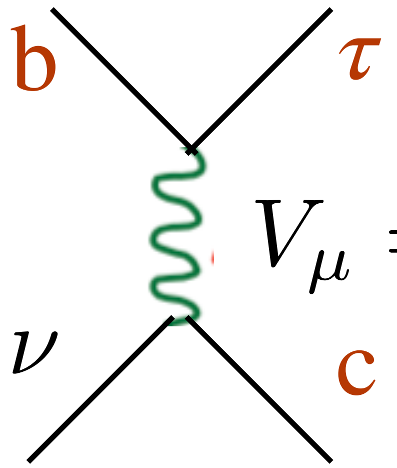
➡ A suitable mediator required
Phenomenologically emerging: $V_\mu = (3,1)_{2/3}$

From



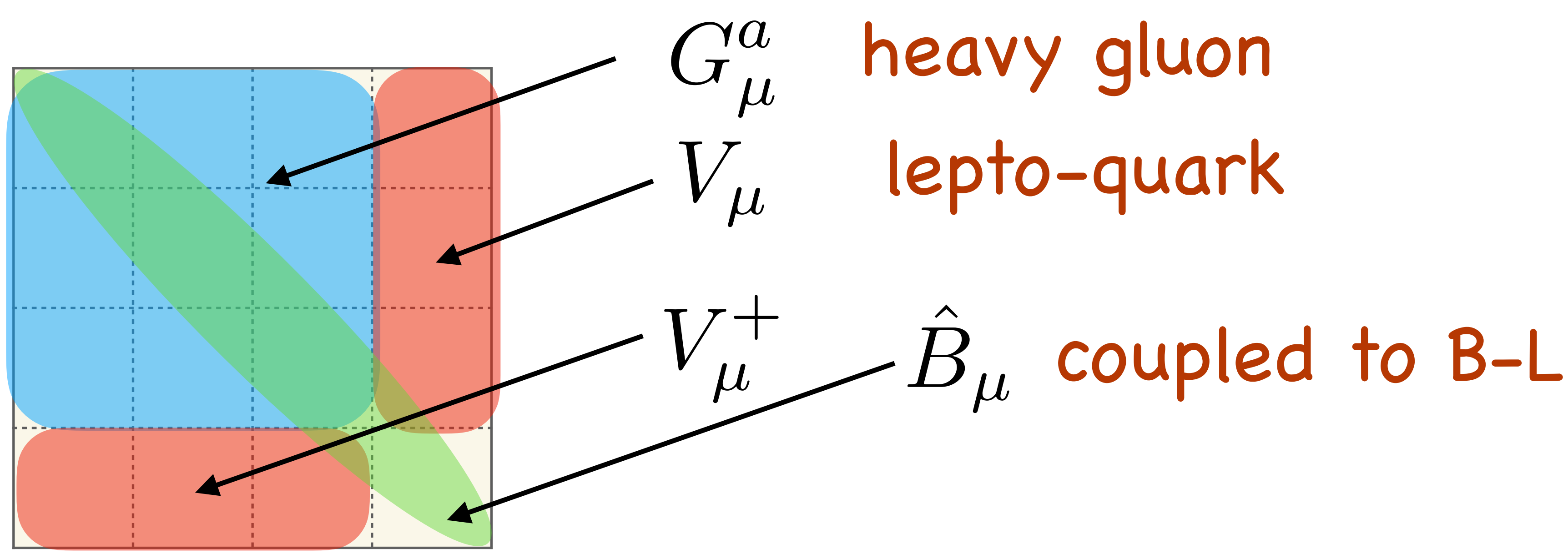
need $\frac{g_V}{m_V} \approx \frac{2}{TeV} (\frac{V_{cb}}{\mathcal{V}_{cb}\mathcal{V}_{\tau\nu}})^{1/2}$

Can one make sense of a vector leptoquark?



$$V_\mu = (3,1)_{2/3} \qquad V_\mu^a(\bar{q}_L^a \gamma_\mu l_L) = V_\mu^a(\bar{u}_L^a \gamma_\mu \nu_L + \bar{d}_L^a \gamma_\mu e_L)$$

Pati-Salam SU(4): L as a fourth colour

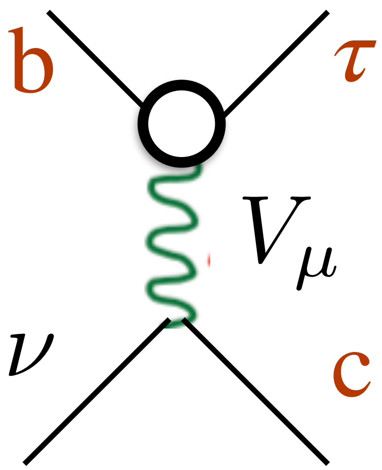


B, Isidori, Pattori, Senia 2015
B, Murphy, Senia 2016
Diaz, Schamaltz, Zhong 2017
Calibbi, Crivellin, Li 2017

Di Luzio, Greljo, Nardecchia 2017
Cline 2017
Bordone, Cornella, Fuentes, Isidori 2107
B, Tesi 2017
...

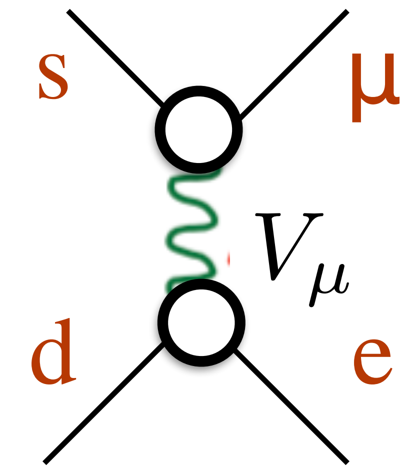
Since we are talking of Lepton Flavour Violation

What about $K_L \to \mu e$? $BR(K_L \to \mu e) < 4.7 \cdot 10^{-12}$



$$V_\mu^a(\bar{q}_L^a \gamma_\mu l_L) = V_\mu^a(\bar{u}_L^a \gamma_\mu \nu_L + \bar{d}_L^a \gamma_\mu e_L)$$

➡



$\Rightarrow$ SU(4) cannot be a "trivial" extension of colour-SU(3)

1. SU(4) as a global symmetry of a new strong interaction
2. $SU(4) \times SU(3) \times SU(2) \times U(1)$ fully gauged
3. $SU(4)_i$ with i = generation index
4. ...

In all cases need heavy $(Q^a, L)_{Dirac}$ quartets under SU(4)

In case 1 (Q^a, L) composites, like V_μ^a itself, with $V_\mu^a(\bar{Q}^a \gamma_\mu L)$
(as suggested by the largish g_V coupling)

Back to U(2)

a reminder [under discussion with R. Ziegler]

Organise the standard fermions
in $SU(4) \times SU(2) \times U(1)$ multiplets

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	p_a	p_a^u	p_a^d	p_3	p_3^u	p_3^d	ϕ	χ
$SU(2)_f$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_f$	1	1	1	0	0	1	-1	-1

with ϕ and χ scalar "flavons"

We have to integrate in the picture the heavy F, quartets of SU(4)

$$P_i = \begin{pmatrix} Q \\ L \end{pmatrix}_i \qquad P_i^u = \begin{pmatrix} U \\ N \end{pmatrix}_i \qquad P_i^d = \begin{pmatrix} D \\ E \end{pmatrix}_i \qquad i = (a, 3), \quad a = (1, 2)$$

Under a flavour $SU(2)_F \times U(1)_F$ group:

	P_a	P_a^u	P_a^d	P_3	P_3^u	P_3^d	Σ
$SU(2)_F$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$
$U(1)_F$	1	1	0	0	0	1	-1

$$< \Sigma >= \begin{pmatrix} \epsilon_\Sigma \Lambda \\ 0 \end{pmatrix}$$

$$\epsilon_\Sigma = O(1)$$

Take most general $\mathcal{L}_m = \bar{F} M F + \bar{F} \lambda_F \Omega f + \bar{f} \lambda f h$

respecting $U(2)_f \times U(2)_F$

Note that, in the unbroken $U(2)_f \times U(2)_F$ limit

$$V_\mu^a (\bar{Q}_i^a \gamma_\mu L_i) \Rightarrow V_\mu^a (\bar{q}_{L3}^a \gamma_\mu l_{L3})$$

Key effective operators

(all L-fields) | Need

$$\frac{1}{2}\frac{g_V^2}{m_V^2}\beta_{\tau b}\beta_{c\nu_\tau}(\bar{\tau}\gamma_\mu b)(\bar{c}\gamma_\mu \nu)$$ (V_μ -exchange) $$\frac{1}{2}\frac{g_V^2}{m_V^2}\beta_{\tau b}\beta_{c\nu_\tau} \approx \frac{0.1}{TeV^2}$$

$$\frac{1}{2}\frac{g_V^2}{m_V^2}\beta_{\mu b}\beta_{s\mu}(\bar{\mu}\gamma_\mu b)(\bar{s}\gamma_\mu \mu)$$ (V_μ -exchange) $$\frac{1}{2}\frac{g_V^2}{m_V^2}\beta_{\mu b}\beta_{s\mu} \approx \frac{5\cdot 10^{-4}}{TeV^2}$$

After $U(2)_f \times U(2)_F$ breaking $<\phi>=\epsilon$

$$\beta_{\tau b} = s_{l3}V_{33}s_{q3} = O(1) \qquad \beta_{c\nu_\tau} = U_{c3}s_{q3}V_{33}s_{l3} + s_{q2}V_{23}s_{l3} = O(\epsilon)$$

$$\beta_{\mu b} = E_{\mu 3}s_{l3}V_{33}s_{q3} + s_{l2}V_{23}s_{q3} = O(\epsilon) \qquad \beta_{s\mu} = s_{q2}V_{22}s_{l2} + s_{q2}V_{23}s_{l3}E^*_{\mu 3} = O(\epsilon^2)$$

Data OK with order 1 parameters and

$$\frac{g_V}{m_V} \sim \frac{g_G}{m_G} \sim \frac{2}{TeV}, \qquad \epsilon \sim 5\cdot 10^{-2}$$

(ideally: a fit of masses, CKM and anomalies in terms of $\epsilon_\phi, \epsilon_\chi, \frac{g_V}{m_V}; \lambda' s$)

Phenomenological consequences

1. Plenty of flavour signals at the border of observability

$\Delta B = 2, \Delta C = 2, \tau \to 3\mu, \tau \to \mu\gamma$ at current limits

2. Direct searches of the heavy vectors

Leptoquarks $\hat{V}_\mu$ pair produced: $gg \to \hat{V}_\mu^+ \hat{V}_\mu^-$

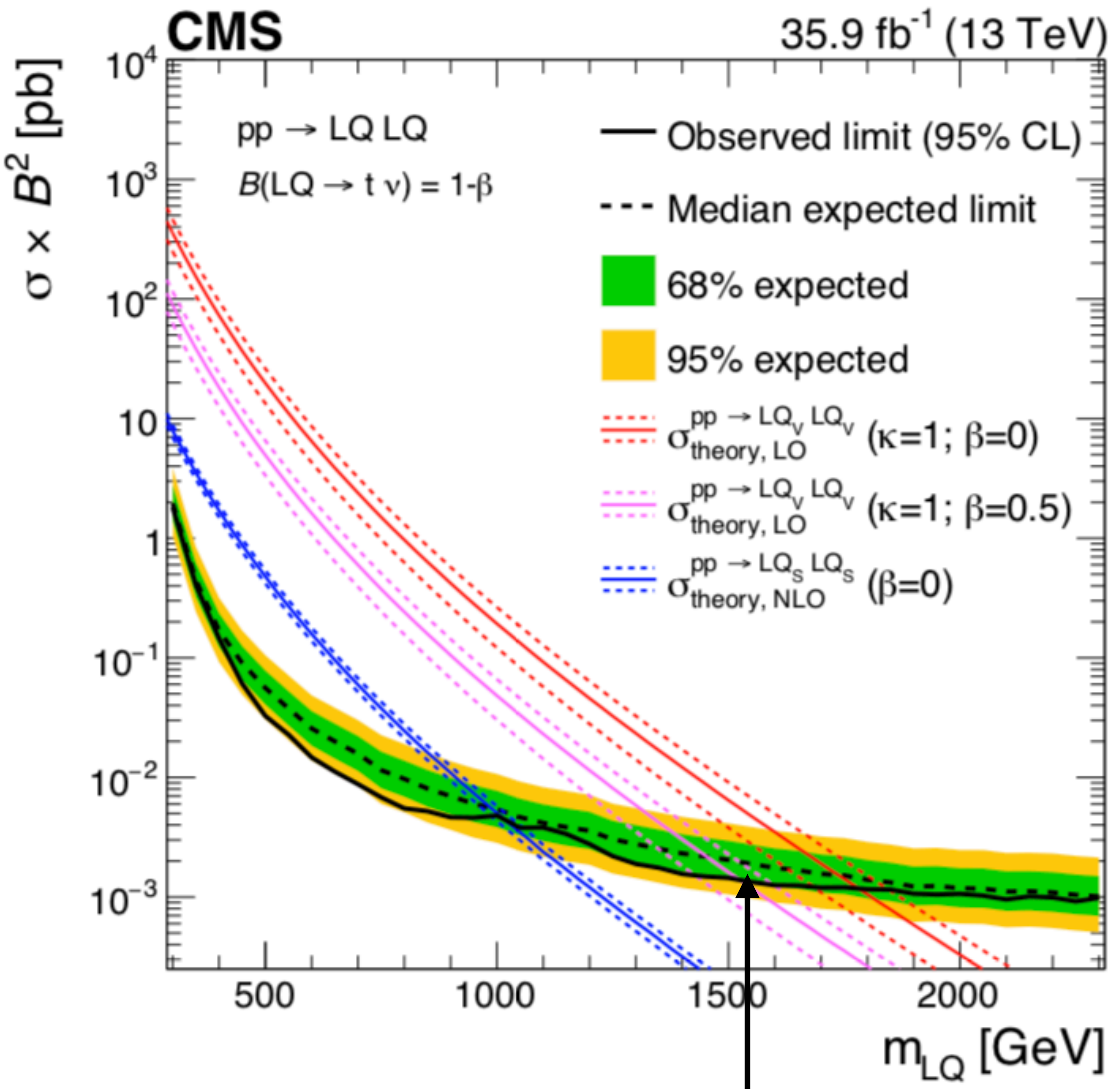
$\hat{V}_\mu \to t\nu, b\tau$

$\hat{V}_\mu$ exchanged in the t-channel: $b\bar{b} \to \tau\bar{\tau}$

Single $\hat{V}_\mu$ production $gb \to \hat{V}_\mu \tau$

The other SU(4) vectors G_μ, B_μ
couple to the light fermions by $F - f$ mixing (mostly f_3)
and, flavour universally, by vector mixing

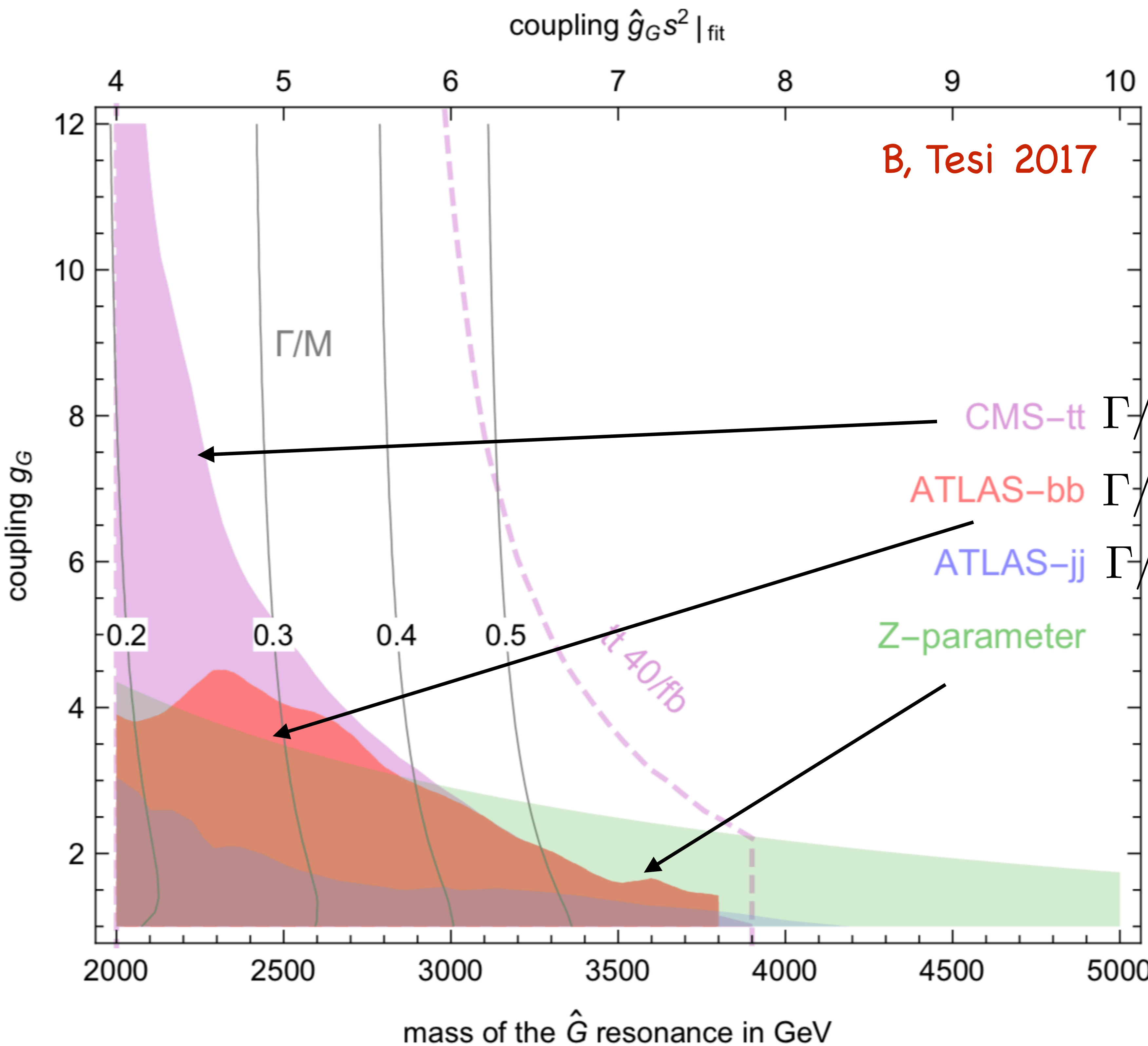
$$gg \to \hat{V}_\mu^+ \hat{V}_\mu^- \to (t\bar{\nu}_\tau)(\bar{t}\nu_\tau)$$



$$m_{\hat{V}} > 1.5\ TeV$$

$$u\bar{u}, d\bar{d}, b\bar{b} \to \hat{G} \to t\bar{t}, b\bar{b}, jj$$

$$\hat{g}_G s_{q3} s_{l3} = 2\frac{m_G}{TeV}$$



$\Gamma/M < 30\%$

$\Gamma/M < 15\%$

$\Gamma/M < 15\%$

$$m_{\hat{G}} \gtrsim 2.5\ TeV$$

(a dedicated analysis most welcome)

Conclusions

1. How far from the TeV is the new physics that is being searched for?

(and needed, in my view, to turn the SM into a "complete" theory)

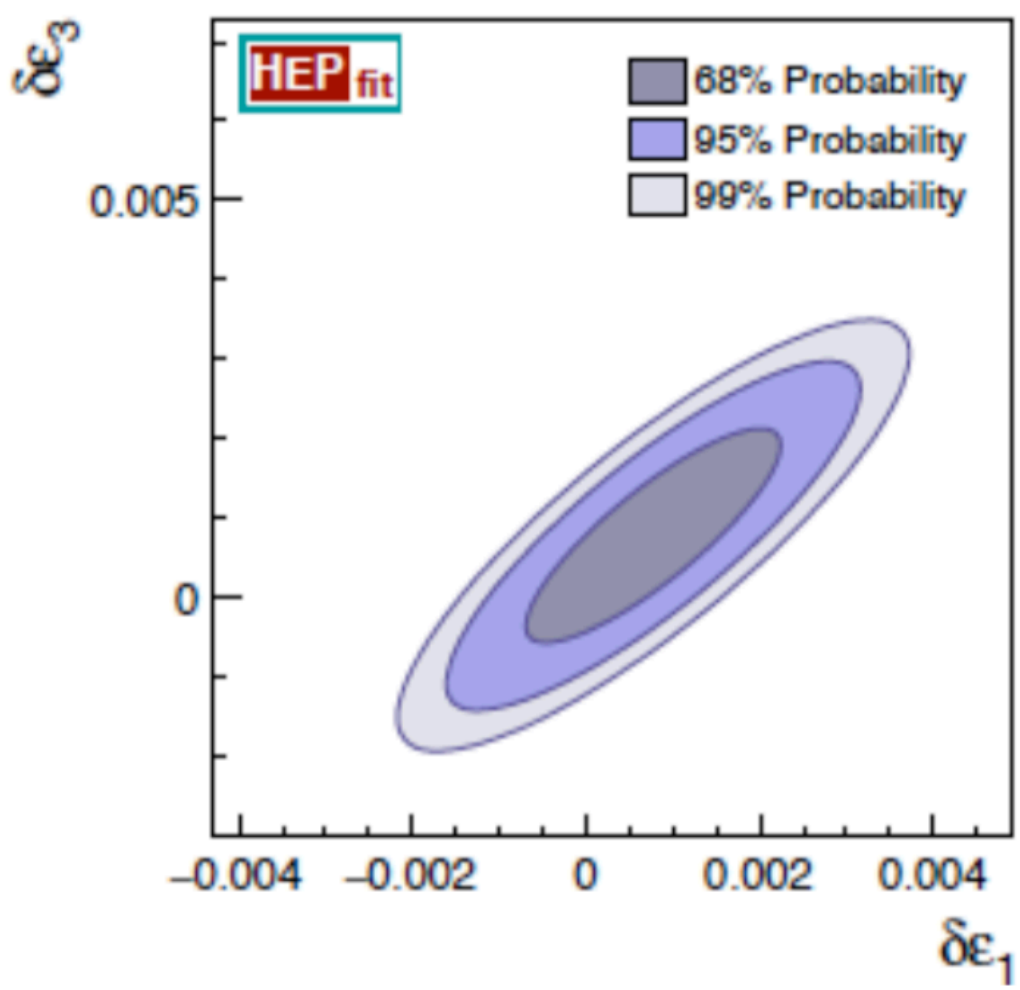
2. What is the true meaning of the GST relation?

A curious accident or a deep relation?

The B-anomalies, if confirmed by further data, could be a first signal to relate the two questions

A significant comparison

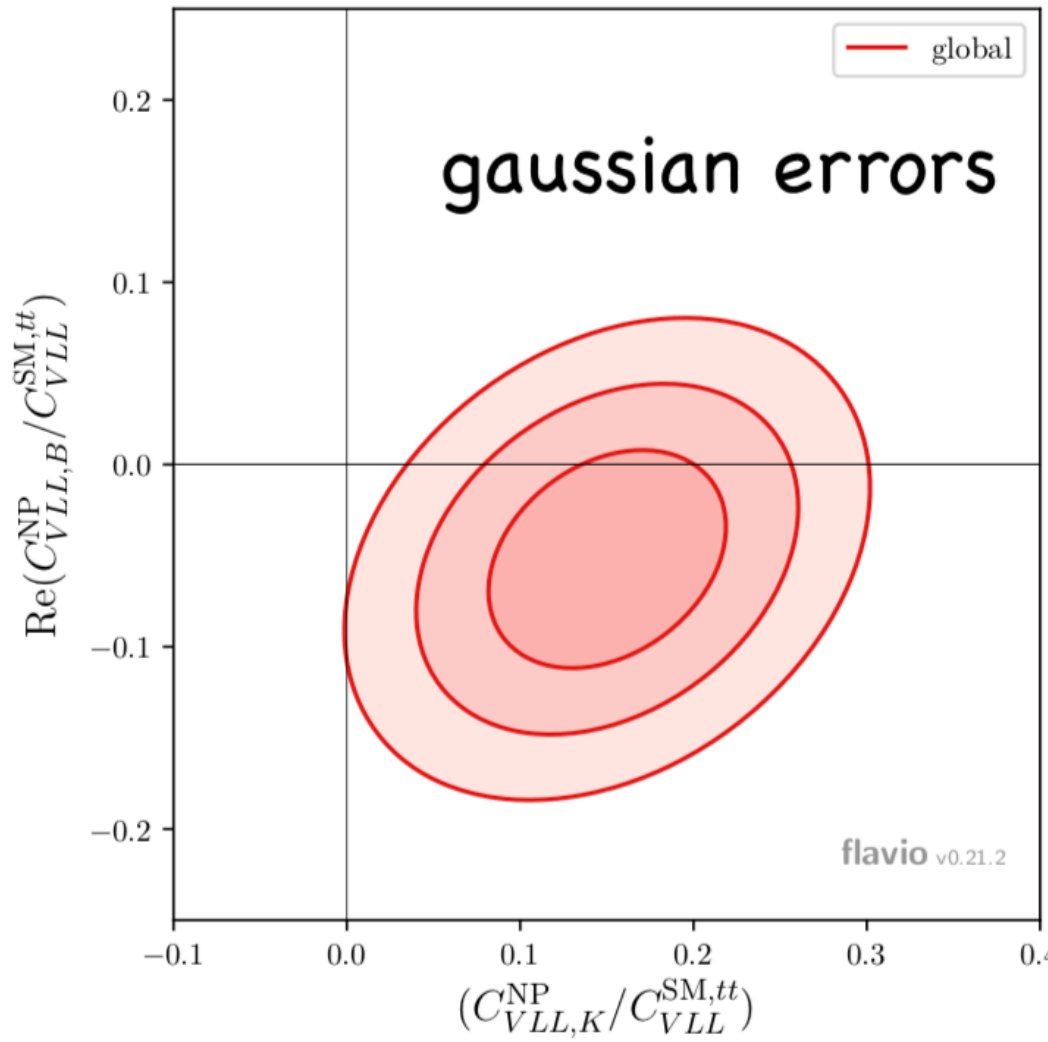
$\epsilon_1^{SM} = 5.21 \cdot 10^{-3}$, $\epsilon_3^{SM} = 5.28 \cdot 10^{-3}$



measures EW loops
at about 20% level

A future facility (FCCee, ...)
could go to 2% level

Straub 2016



measures FCNC loops
at about 20% level

An "aggressive" flavour program
could go to 2% level

➡ Lagrangian $\mathcal{L} = \mathcal{L}_{ele} + \mathcal{L}_{comp} + \mathcal{L}_{mix}$

$\mathcal{L}_{ele}$ = SM $\mathcal{L}$ without Higgs

$$G_{ele}^{flavour} = U(3)^5$$

$\mathcal{L}_{comp}$ = most general $\mathcal{L}$ invariant under $\mathcal{G}/\mathcal{H}$ up to p^2-terms and no coupling of negative dim

$$G_{comp}^{flavour} = U(3)_\Psi \times U(3)_\chi$$

$\mathcal{L}_{mix}$ = most general fermion bilinear

$$(q_L, l_L, u_R, d_R, e_R)\ (U, U^+)\ (\Psi_\pm, \chi_\pm) \qquad U = e^{iH/f}$$

(formally) invariant under $\mathcal{G}/\mathcal{H}$

$$G_{mix}^{flavour} \approx U(2)_\Psi \times U(2)_\chi \times U(2)^5$$

Relevant parameters

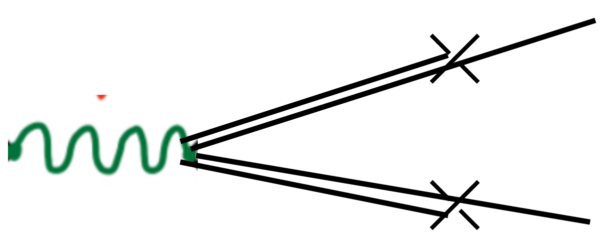
➡ heavy vectors:

$$\hat{V}^a_\mu, \hat{G}^\alpha_\mu, \hat{B}_\mu \qquad (g_G, \hat{g}_G, m_G) \qquad SU(4)$$

$$\hat{\rho}^i_{\mu L}, \hat{\rho}^3_{\mu R}, \qquad (g_\rho, \hat{g}_\rho, m_\rho) \qquad SU(2) \times SU(2)$$

$$\hat{X}_\mu \qquad (g_X, \hat{g}_X, m_X) \qquad U(1)_X$$

➡ relevant heavy fermions: Q_L, L_L (why?)
mixed with the light fermions by s_q, s_l so that



$$Q_L = (U_L, D_L) \qquad U_{Li} \Rightarrow s_{qi} U_{ij} u_{Lj}$$

$$D_{Li} \Rightarrow s_{qi} D_{ij} d_{Lj} \quad L_{Li} \Rightarrow s_{li} E_{ij} l_{Lj}$$

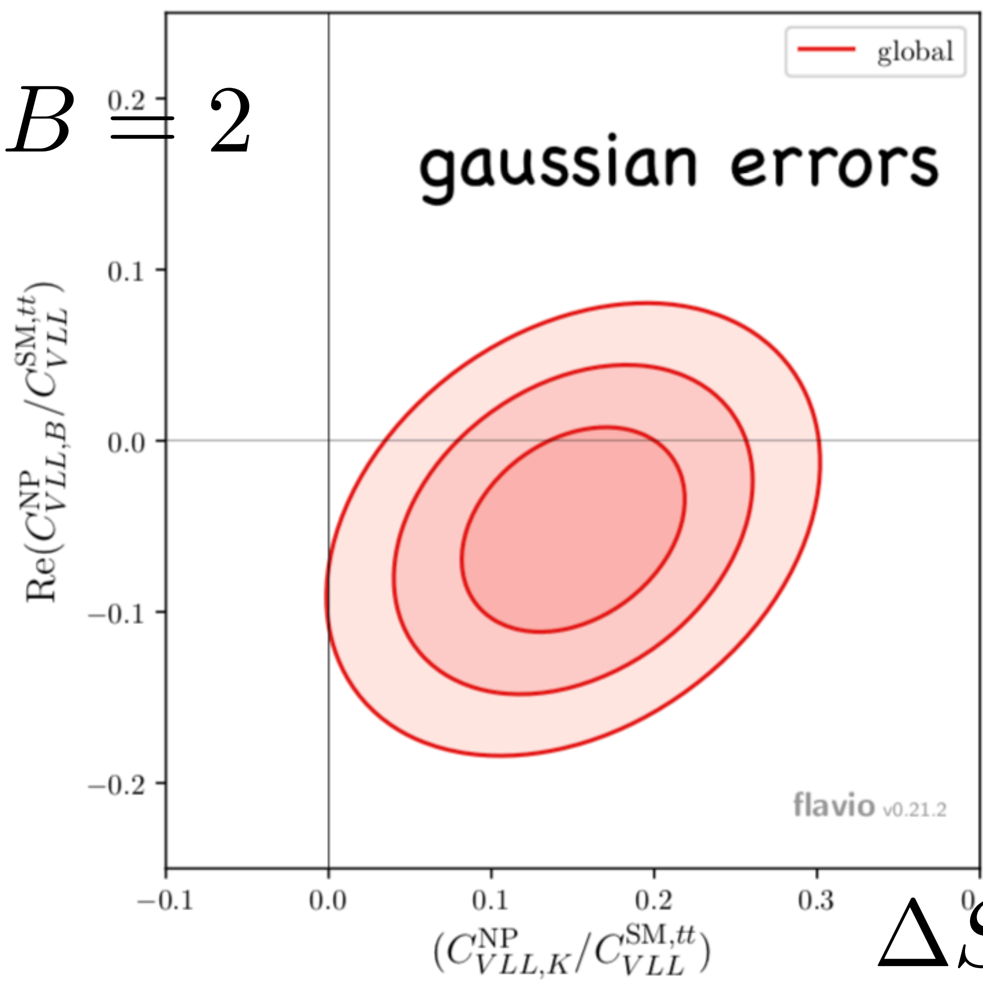
with $\quad UU^+ = DD^+ = EE^+ = \mathbf{1} \qquad V_{CKM} = UD^+$

$s_3 >> s_2, s_1$ and $(U, D, E)_{32,31} << 1$ because of $U(2)^n$

$$\Delta B = 2$$

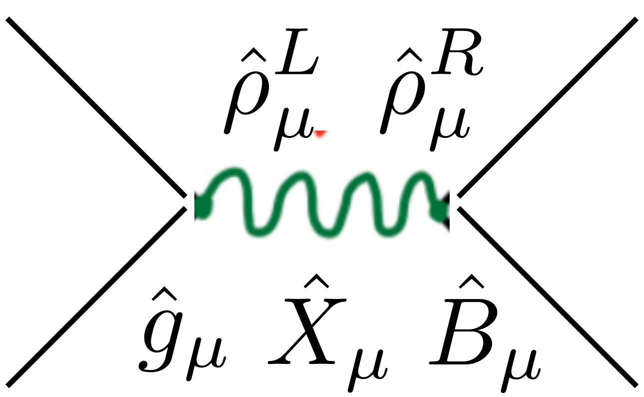
Current status

$\Delta B = 2$



Straub 2017

$\Delta S = 2$



$$\frac{s_{q3}}{s_{l3}} D_{s3} \lesssim 2 \cdot 10^{-3}$$

(against $V_{ts} \approx U_{t2} + D_{s3} = 4 \cdot 10^{-2}$)

$\Delta B = 2$

$$\frac{3}{16}\frac{g_G^2}{m_G^2}\beta_{sb}\beta_{bs}(\bar{s}\gamma_\mu b)(\bar{b}\gamma_\mu s)$$ (G_μ-exchange) $$\frac{3}{16}\frac{g_G^2}{m_G^2}\beta_{sb}\beta_{bs} \lesssim \frac{2\cdot 10^{-5}}{TeV^2}$$

After $U(2)_f \times U(2)_F$ breaking $< \phi >= \epsilon$

$$\beta_{sb} = D_{s3}s_{q3}^2 = \beta_{bs}^* = O(\epsilon)$$

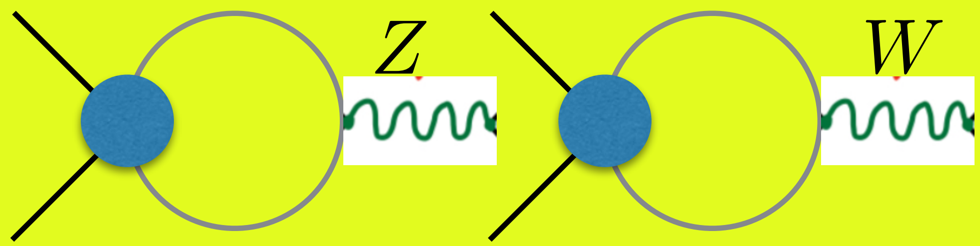
Fit of data OK with order 1 parameters

$$\frac{g_V}{m_V} \sim \frac{g_G}{m_G} \sim \frac{2}{TeV}, \qquad \epsilon \sim 5\cdot 10^{-2}$$

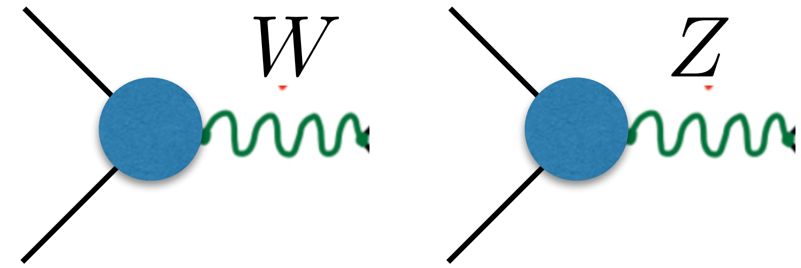
Need $D_{s3} \lesssim 0.1\ \epsilon$

$$\tau \to \mu\nu\nu, \quad Z \to \tau\tau, \quad Z \to \nu_\tau\nu_\tau, \quad Z \to b\bar{b}$$

all "normal" within 10^{-3}



Loops



Tree level

name	structure	coefficient
$\mathcal{O}^1_{Hl}$	$iH^\dagger \overleftrightarrow{D}_\mu H(\bar{l}_{L3}\gamma^\mu l_{L3})$	C_{1l}
$\mathcal{O}^3_{Hl}$	$iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H(\bar{l}_{L3}\gamma^\mu \sigma^a l_{L3})$	C_{3l}
$\mathcal{O}^1_{Hq}$	$iH^\dagger \overleftrightarrow{D}_\mu H(\bar{q}_{L3}\gamma^\mu q_{L3})$	C_{1q}
$\mathcal{O}^3_{Hq}$	$iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H(\bar{q}_{L3}\gamma^\mu \sigma^a q_{L3})$	C_{3q}
$\mathcal{O}^1_{ql}$	$(\bar{q}_{L3}\gamma^\mu q_{L3})(\bar{l}_{L3}\gamma^\mu l_{L3})$	$-C_1$
$\mathcal{O}^3_{ql}$	$(\bar{q}_{L3}\gamma^\mu \sigma^a q_{L3})(\bar{l}_{L3}\gamma^\mu \sigma^a l_{L3})$	$-C_3$
$\mathcal{O}_{ll}$	$(\bar{l}_{L3}\gamma^\mu l_{L3})^2$	C_{ll}
$\mathcal{O}^1_{qq}$	$(\bar{q}_{L3}\gamma^\mu q_{L3})^2$	C_{1qq}
$\mathcal{O}^3_{qq}$	$(\bar{q}_{L3}\gamma^\mu \sigma^a q_{L3})^2$	C_{3qq}

Tree level
(if present)

Sources of loops
(there by necessity)

$$\tau \to \mu\nu\nu, \quad Z \to \tau\tau, \quad Z \to \nu_\tau\nu_\tau, \quad Z \to b\bar{b}$$

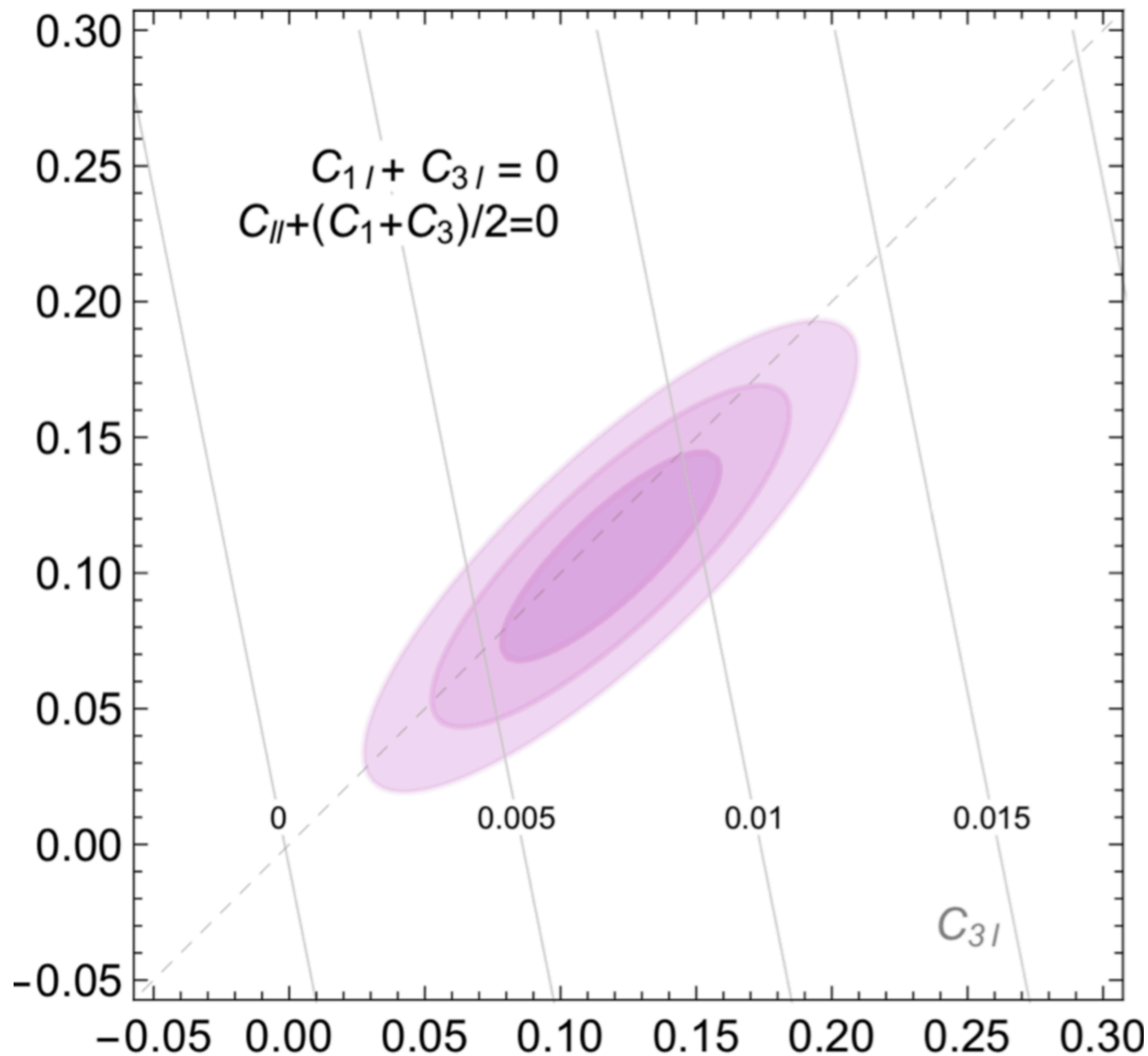
A fit of these couplings and of $R_{D^{(*)}}$ in terms of

C_1, C_3, C_{1l}

$R_{D^{(*)}} = 1.237$

at central value

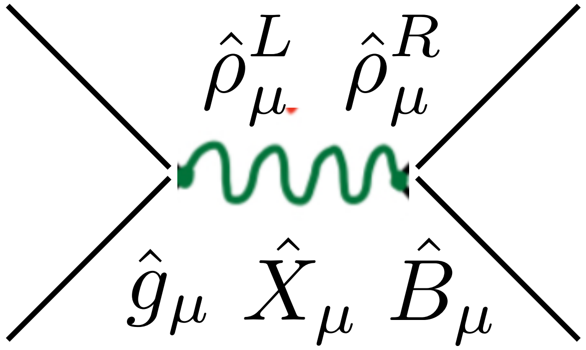
C_1



C_3

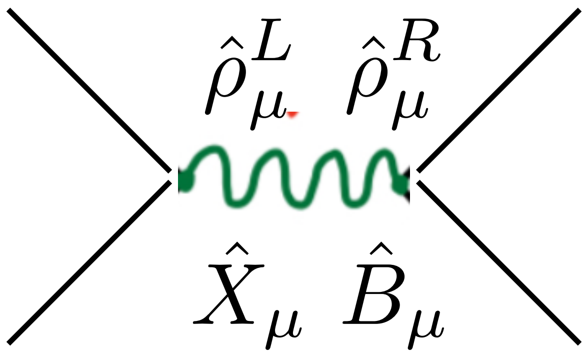
Low energy observables

$\Delta C = 2$



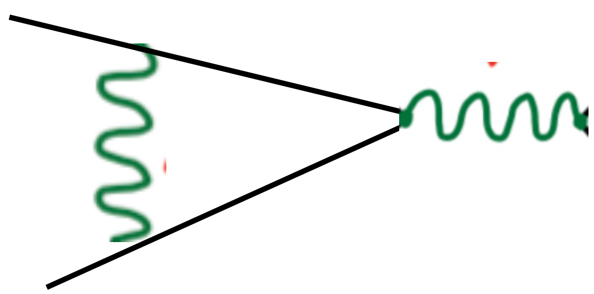
$$\frac{s_{q2}^2}{s_{q3}s_{l3}} V_{cd}^* \lesssim 2 \cdot 10^{-4}$$

$\tau \to 3\mu$



$$E_{\mu 3}\left(\frac{s_{l2}^2}{s_{l3}^2} + |E_{\mu 3}|^2\right) \lesssim 3 \cdot 10^{-3}$$

$\tau \to \mu\gamma$



$$\left(A_G + \left(\frac{s_{l3}}{s_{q3}}\right)^2 A_\rho\right) E_{\mu 3} \lesssim 0.1$$

$$\frac{s_{q2}s_{l2}}{s_{q3}s_{l3}} \frac{E_{\mu 3}}{V_{ts}} \sim 5 \cdot 10^{-3}$$ from $b \to s\mu\mu$

Direct searches of the heavy vectors

Leptoquarks $\hat{V}_\mu$ are pair produced:

$$gg \to \hat{V}_\mu^+ \hat{V}_\mu^-$$
$$\hat{V}_\mu \to t\nu, b\tau$$

All other vectors but $\hat{\rho}_\mu^{R\pm}$: $\hat{G}_\mu^\alpha, \hat{B}_\mu, \hat{\rho}_\mu^{La}, \hat{\rho}_\mu^{R3}, \hat{X}_\mu$

couple to the light fermions by $F - f$ mixing (mostly f_3)

controlled by $\hat{g}_G s_{q3}^2$, and, flavour universally,

by vector mixing, controlled by g_3^2/g_G

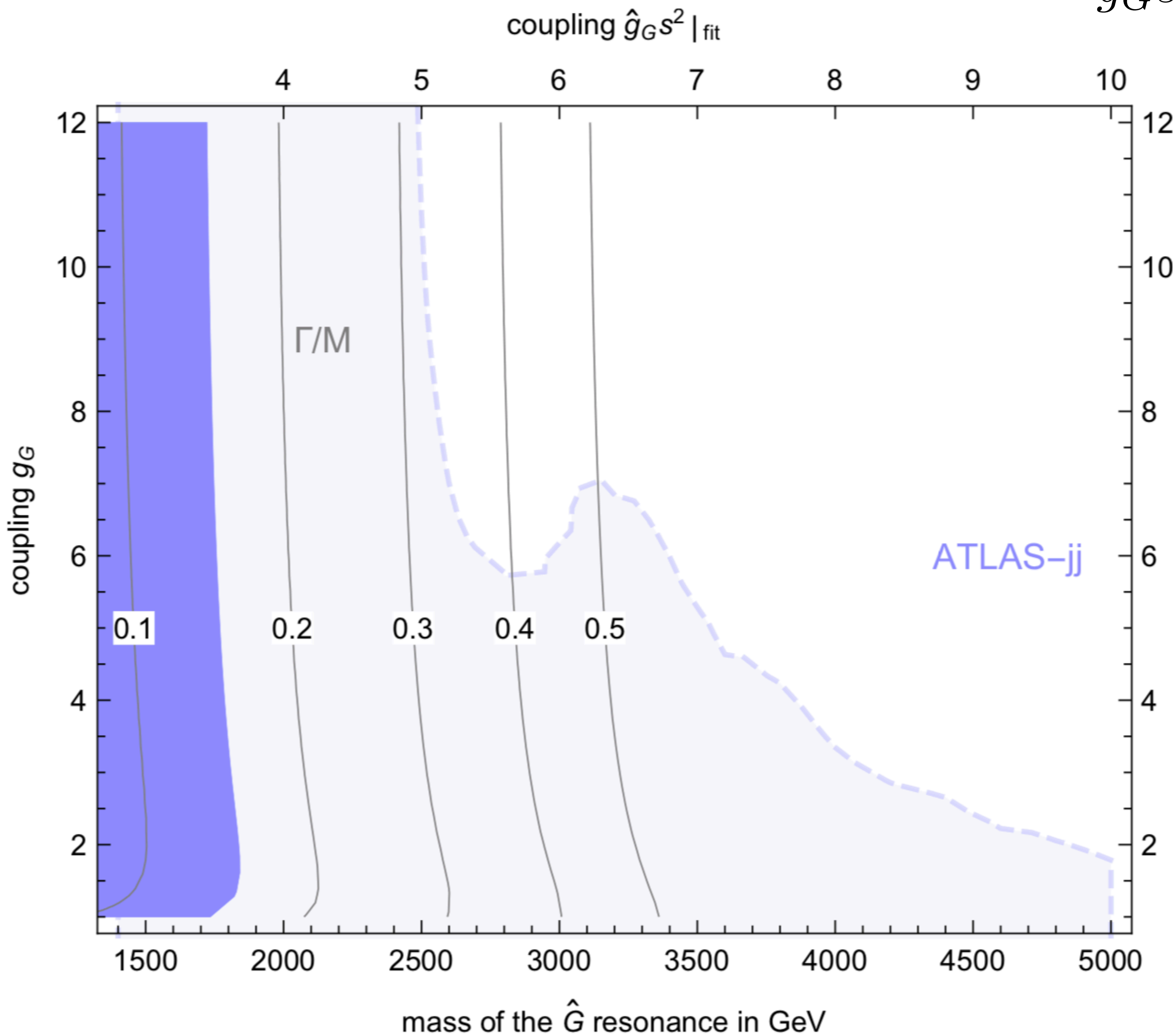
$$\hat{G}_\mu^a = \frac{g_G \mathcal{G}_\mu^a - g_3 G_\mu^a}{\sqrt{g_G^2 + g_3^2}} \quad \Rightarrow \quad \begin{aligned} \frac{\Gamma_{\hat{G}\to t\bar{t}}}{m_G} &\approx \frac{\Gamma_{\hat{G}\to b\bar{b}}}{m_G} \approx \frac{\hat{g}_G^2 s_{q3}^4}{48\pi} \\ \frac{\Gamma_{\hat{G}\to u\bar{u}}}{m_G} &\approx \frac{\Gamma_{\hat{G}\to d\bar{d}}}{m_G} \approx \frac{g_3^4}{24\pi g_G^2} \end{aligned}$$

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
- Lepton Flavour Violation in a variety of channels

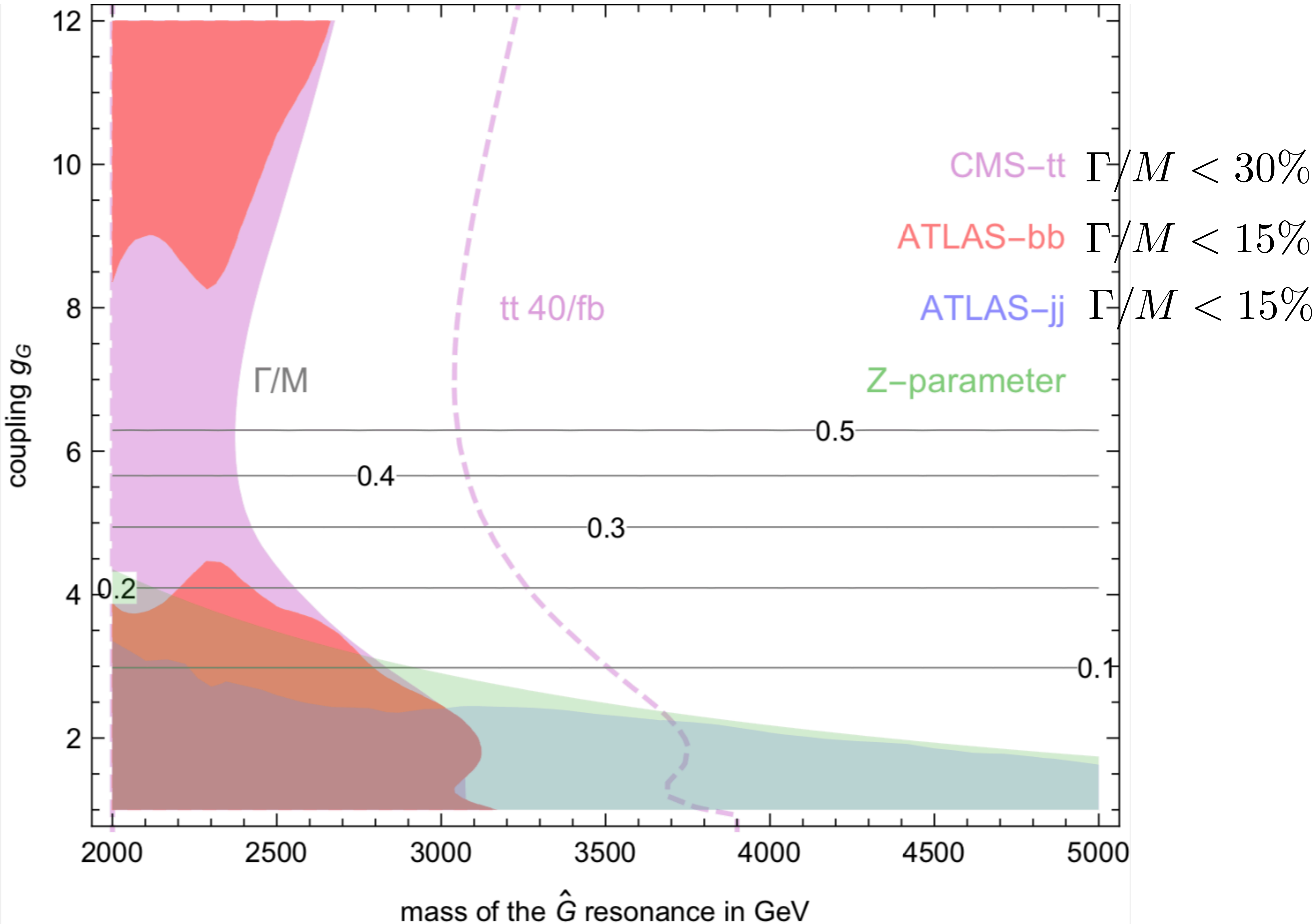
$$u\bar{u}, d\bar{d}, b\bar{b} \to \hat{G} \to jj(including\ b\bar{b})$$

$$\hat{g}_G s_{q3} s_{l3} = 2\frac{m_G}{TeV}$$



$$\Gamma/M < 15\%$$

$$g_G = \hat{g}_G$$


CMS−tt $\Gamma/M < 30\%$
ATLAS−bb $\Gamma/M < 15\%$
ATLAS−jj $\Gamma/M < 15\%$
Z−parameter
tt 40/fb
Γ/M
0.5
0.4
0.3
0.2
0.1
coupling g_G
mass of the $\hat{G}$ resonance in GeV
2000
2500
3000
3500
4000
4500
5000
2
4
6
8
10
12

The model in detail

➡ Symmetries (vertical)

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

(How important is the choice of $\mathcal{G}$?)

➡ Particle content (other than the SM ones)

Vectors G^a_μ in the adjoint of $\mathcal{H}$

Dirac fermions transforming under $\mathcal{H}$ as

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

all in 3 generations