Physics beyond the SM in the light of the LHC experiments

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Some introductory remarks

One specific subject and proposal

The SM Lagrangian
(since 1973 in its full content)

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}\,\not{D}\psi \qquad (\sim 1975\text{-}2000)$$

$$+|D_\mu h|^2 - V(h) \qquad (\sim 1990\text{-}2012\text{-now})$$

$$+\psi_i\lambda_{ij}\psi_j h + h.c. \qquad (\sim 2000\text{- now})$$

In () the approximate dates of the experimental confirmation of the various lines (at different levels)

The synthetic nature of PP exhibited

All of Particle Physics in 1 page

1. Symmetry group $L \times \mathcal{G}$

L = Lorentz (space-time)

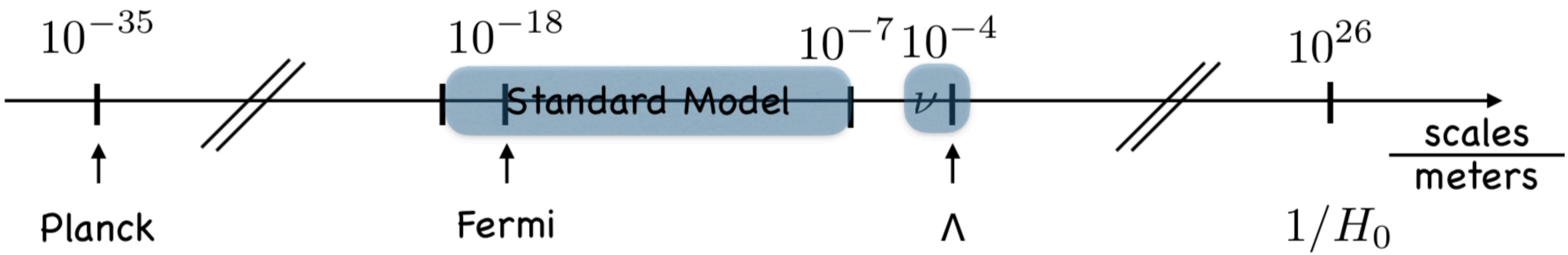
$\mathcal{G} = SU(3) \times SU(2) \times U(1)$ (local)

2. Particle content (rep.s of $L \times \mathcal{G}$)

	h	Q	L	u	d	e
Lorentz	0	$1/2_L$	$1/2_L$	$1/2_R$	$1/2_R$	$1/2_R$
$SU(3)$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$
$SU(2)$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)$	$-1/2$	$1/6$	$-1/2$	$2/3$	$-1/3$	-1

3. All "operators" (products of $\Phi, \partial_\mu \Phi$) in $\mathcal{L}$ of dimension ≤ 4

The Standard Model or not the SM?



Question:

1: Give the SM for granted and "look elsewhere"

or ?

2: Keep testing the SM to learn how to complete it

Answer:

the "or" is the problem

reasons of poor understanding and reasons of incompleteness

Problems of (questions for) the SM

0. Which rationale for matter quantum numbers?

$$|Q_p + Q_e| < 10^{-21} e$$

1. Phenomena unaccounted for

neutrino masses
Dark matter
matter-antimatter asymmetry
inflation?

2. Why $\theta \lesssim 10^{-10}$? $\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$

Axions

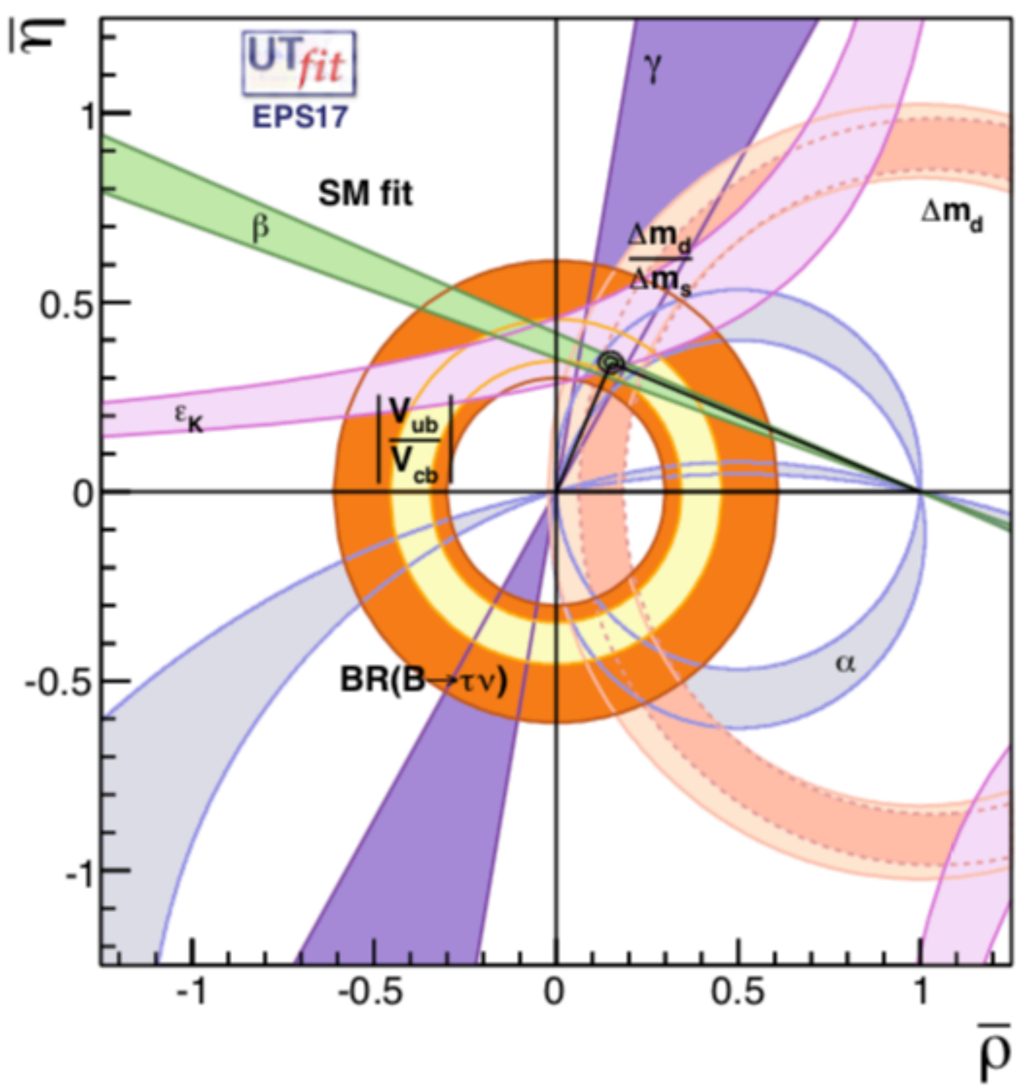
3. $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ only?

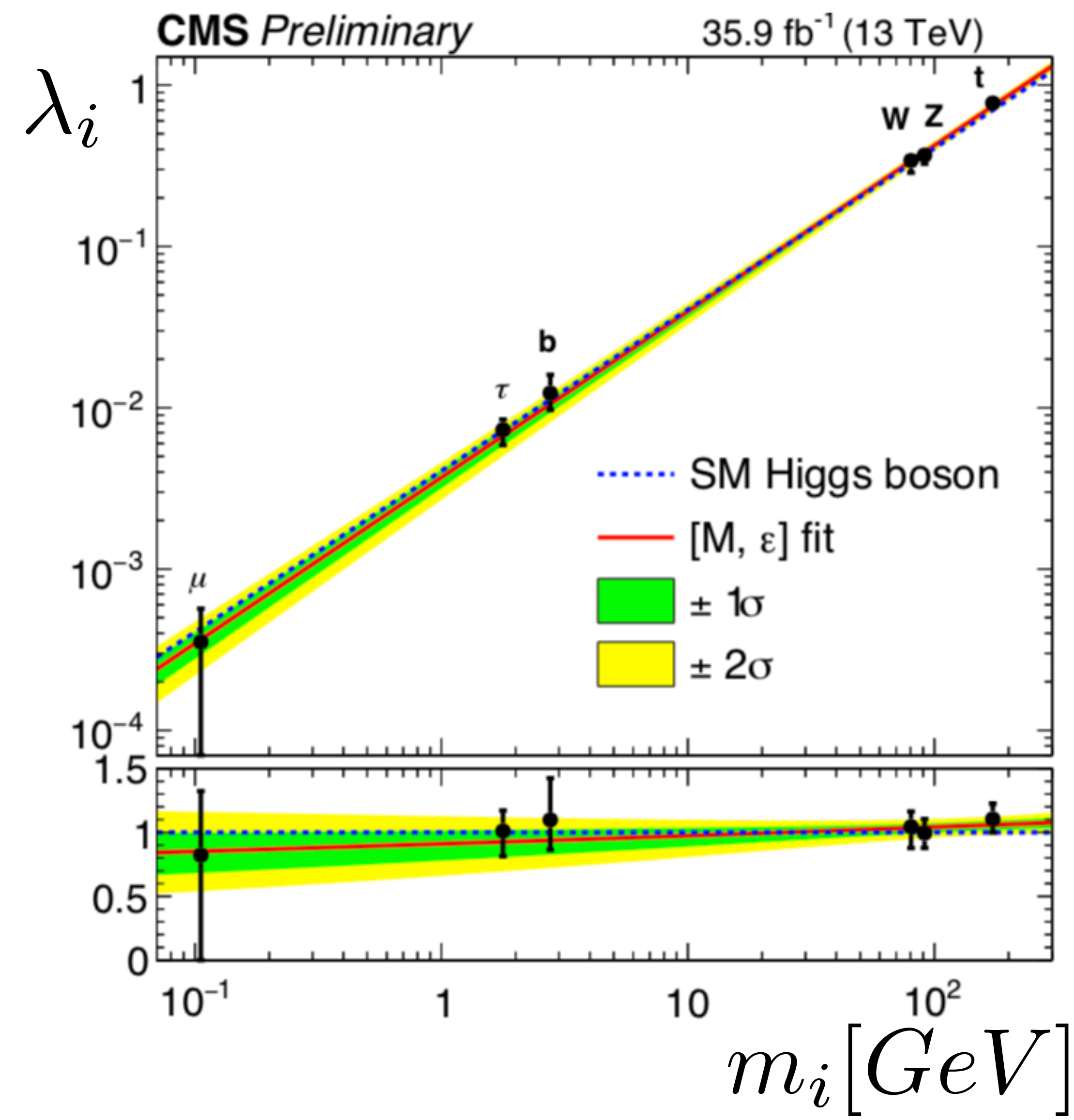
neutrino masses
Gravity
Are the protons forever?

4. Lack of calculability (a euphemism)

$\Rightarrow$ the hierarchy problem
the flavour paradox $\Leftarrow$

The flavour paradox $\lambda_{ij}\Psi_i\Psi_j$



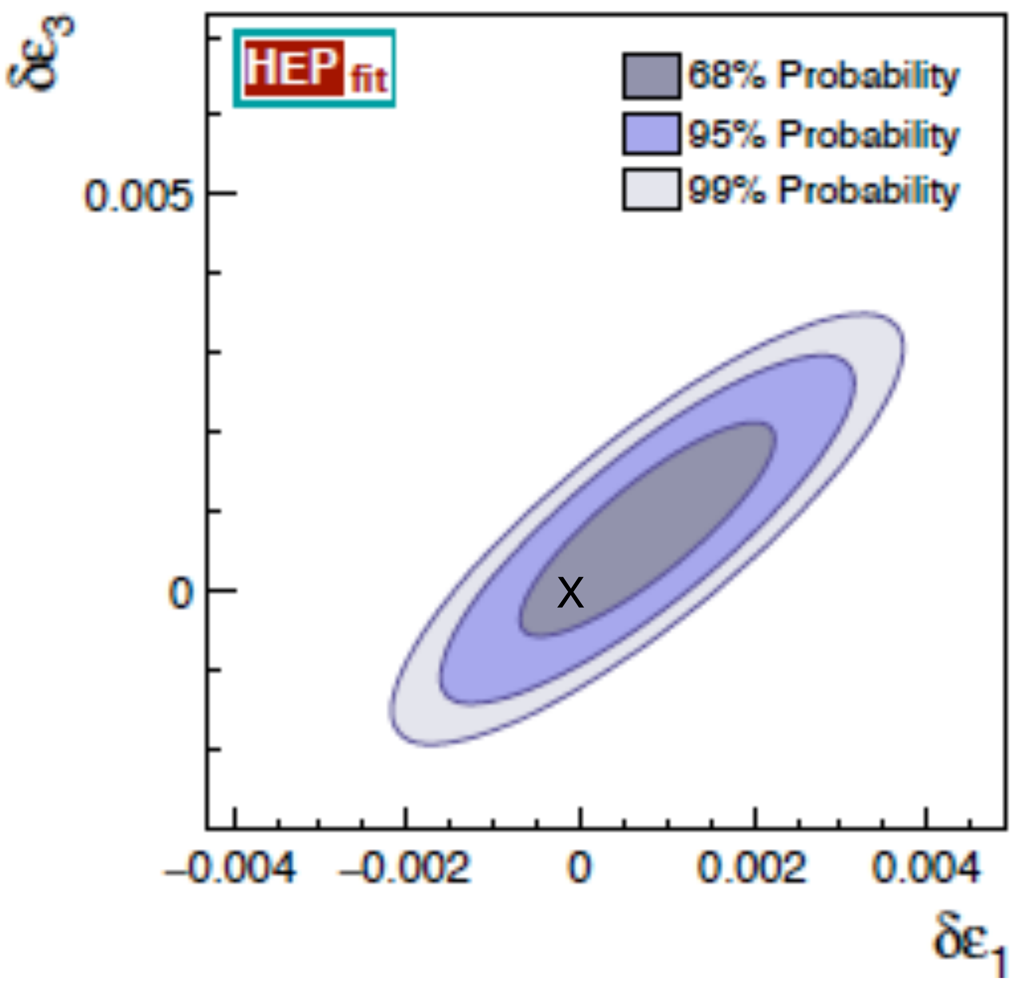


As opposed to the hard time in trying to explain the spectrum and the mixing of quarks and leptons

Not easy to improve without observing deviations from the SM

A significant comparison

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

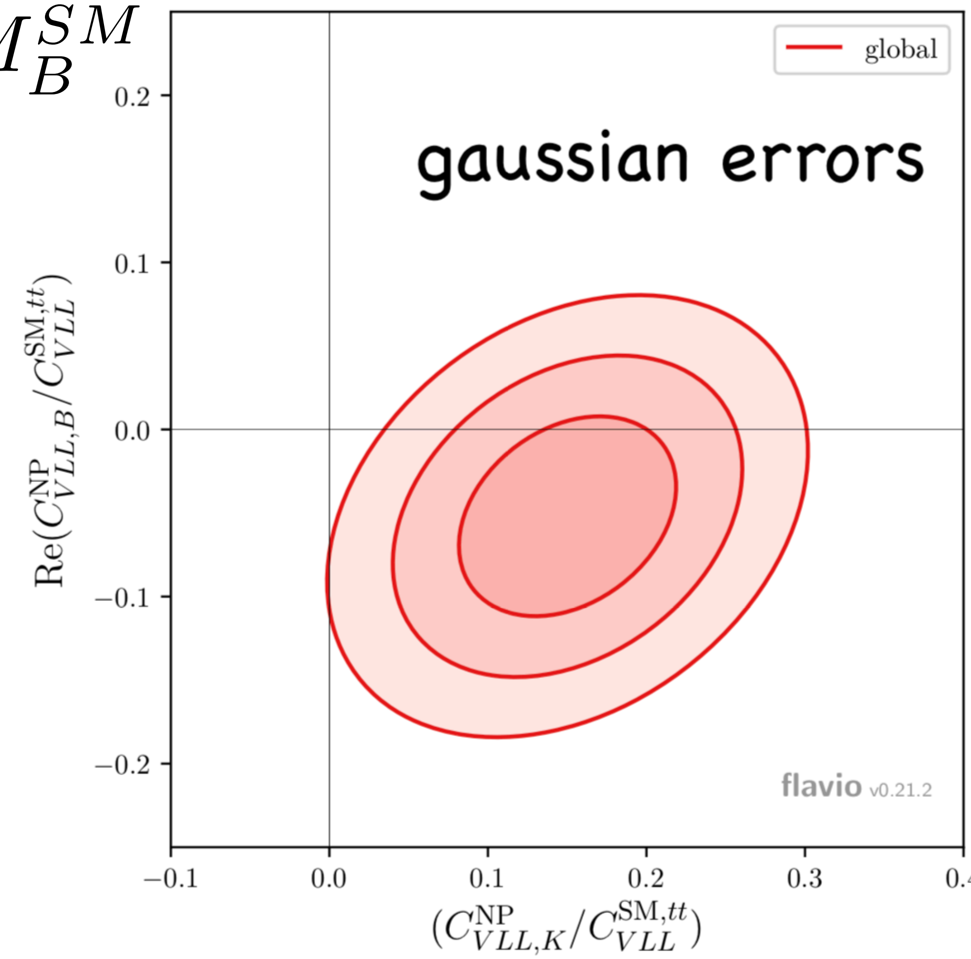


measures EW loops
at about 20% level

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

Straub 2016

$$\frac{\Delta M_B}{\Delta M_B^{SM}}$$



$$\frac{\epsilon_K}{\epsilon_K^{SM}}$$

measures FCNC loops
at about 20% level

An “aggressive” flavour program
could go to 2% level

An "Extreme Flavour" experiment?

Vagnoni – SNS, 7-10 Dec 2014

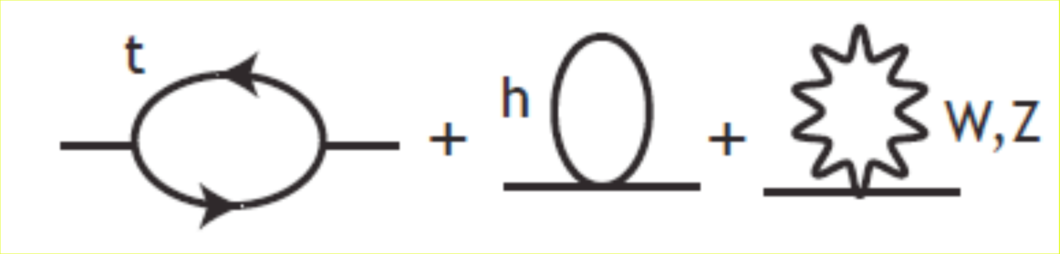
- Currently planned experiments at the HL-LHC will only exploit a small fraction of the huge rate of heavy-flavoured hadrons produced
  - ATLAS/CMS: full LHC integrated luminosity of 3000 fb^{-1}, but limited efficiency due to lepton high p_T requirements
  - LHCb: high efficiency, also on charm events 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 $\simeq$ 20% to $\lesssim$ 1%

The hierarchy problem, once again

Can we compute the Higgs mass/vev in terms of some fundamental dynamics?

NOT in the SM

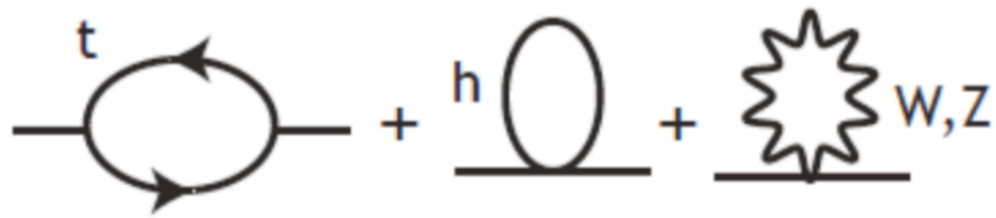


$$\delta m_h^2 \propto \Lambda^2$$

We have seen $\log \Lambda$ divergences everywhere: running of gauge couplings, scaling violations, anomalies

Power law divergences prevent us from calculating or even estimating the Fermi scale nor the cosmological constant

The standard reaction



$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_t^2 - \frac{9g^2}{32\pi^2}\Lambda_g^2 - \frac{3g'^2}{32\pi^2}\Lambda_{g'}^2 + \dots$$

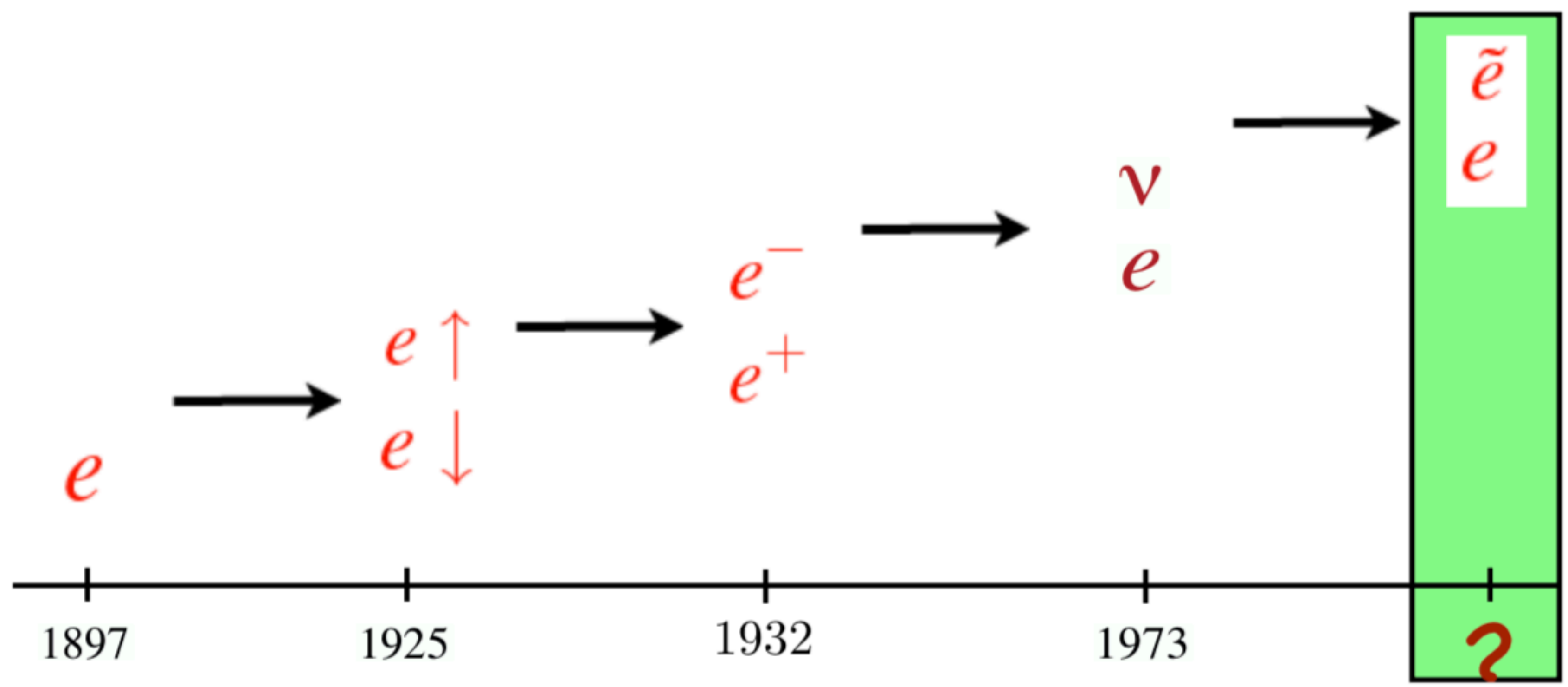
$$\Lambda_t \lesssim 0.4\sqrt{\Delta}\ TeV \qquad \Lambda_g \lesssim 1.1\sqrt{\Delta}\ TeV \qquad \Lambda_{g'} \lesssim 3.7\sqrt{\Delta}\ TeV$$

$1/\Delta$ = amount of tuning

$\Rightarrow$ Look for a top "partner" (coloured, S=0 or 1/2) with a mass not far from 1 TeV

aesthetically and theoretically
SUSY as the best option

(among others)



$$< h > \approx m_{\tilde{e}} \approx m_{SUSY\ particles}$$

But this is a quantitative relation only
if one bars accidental cancellations

Not a problem for SUSY but for knowing if true in nature

Where are the superpartners?

$$\delta m^2_{H_u} \approx -\frac{3y_t^2}{8\pi^2}(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} + A_t^2)\log M/m_{\tilde{t}}$$

Define an "inverse fine-tuning" measure

$$\Delta = \frac{\delta m_h^2}{m_h^2}, \quad Max_{a_i}\frac{dm_h^2/m_h^2}{da_i/a_i}, \ldots$$

G. Ross (sept 2016)

Is low energy SUSY alive ?

$\Delta^{CMSSM} > 350$ ✗

$\Delta^{(C)MSSM} > 40\ (200)^{SUSY\ DM}$

$\Delta^{CGMSSM} > 60$ ✗

$\Delta^{(C)GNMMS} > 20$ ✔8TEV 13TEV?

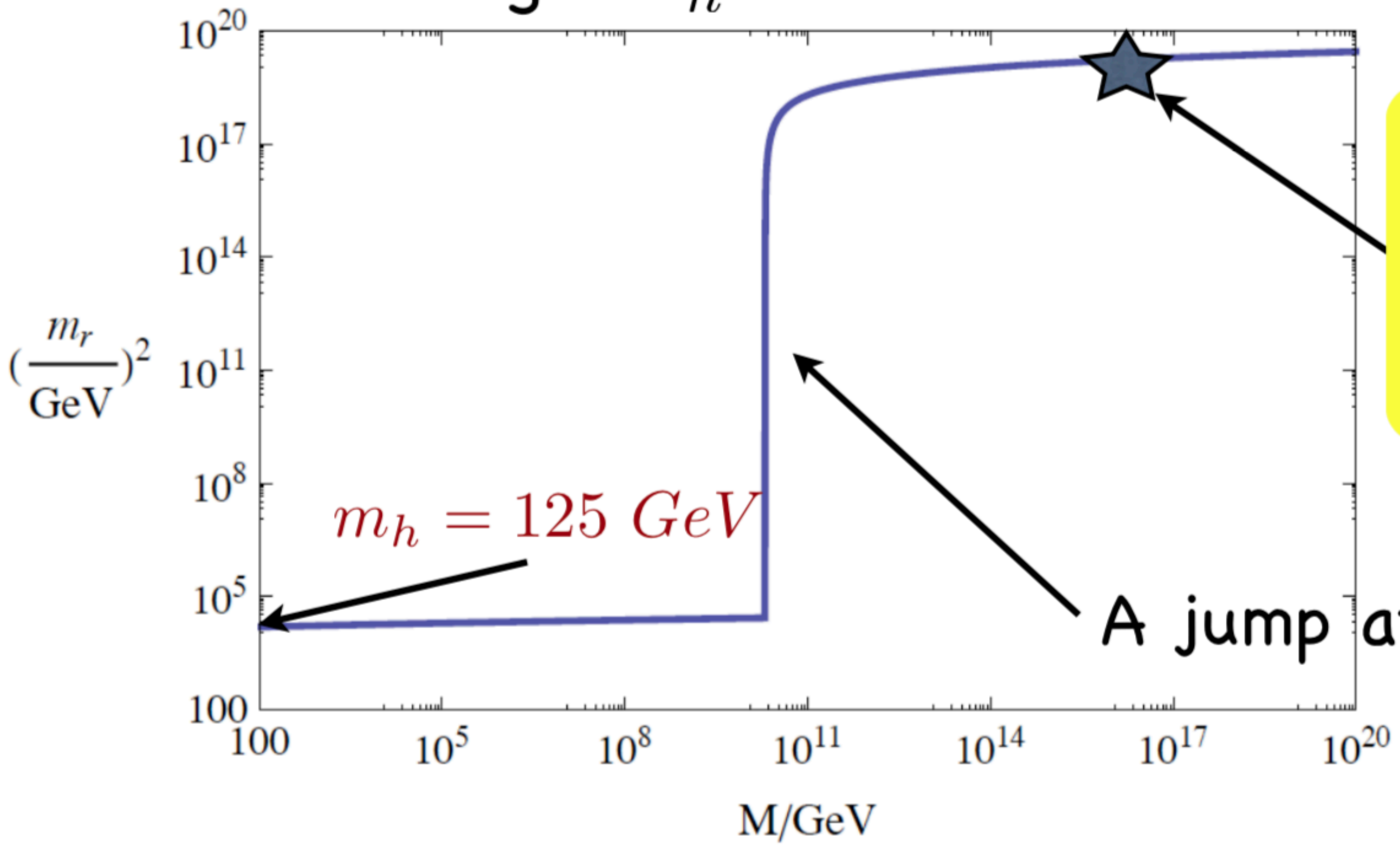
$\Delta^{(C)MSSM+\mu'} > 20\ (40)^{SUSY\ DM}$

The judgement suspended. Reasons of concern

Λ^2-divergences as a signal of the problem

The running m_h^2 versus the scale M

"fine tuning"



m_h depends on a very precise initial condition of order $O(m_h^2/m_H^2)$ at some short distance

A jump at M_H of size $\dfrac{(\lambda_H M_H)^2}{16\pi^2}$

Pending questions to avoid a "low energy" explanation of the hierarchy:

- gravity?
- Non-asymptotically free couplings?
- No higher physical scale?

Can we lack a clever IR-UV connection?

The possible reactions to the blank in the LHC searches (so far)

HP = Hierarchy Problem

1. The solution(s) of the HP “screened” in some way at the LHC

2. The solution(s) of the HP “weakly” fine tuned

3. $< h > \to v = 175\ GeV$ from a suitable cosmological evolution

4. The multiverse explains the HP (as the Λ-problem)

5. A clever IR-UV connection missing?

Specific proposal to be discussed in the following:

1 $\Rightarrow$ Minimal Mirror Twin Higgs

2 $\Rightarrow$ The flavour puzzle and the B-decay anomalies

B-decay anomalies (exp. versus SM)

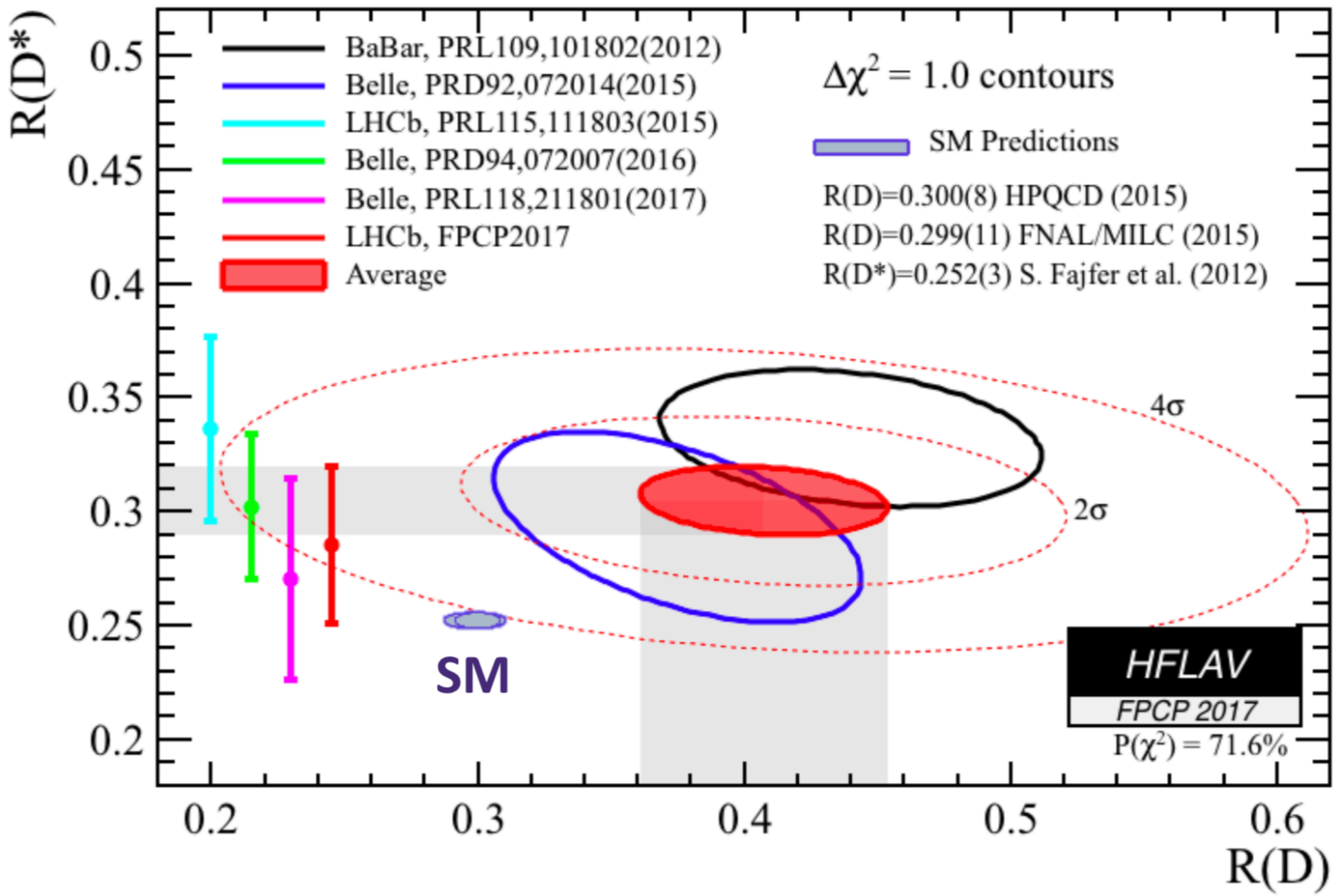
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}l\nu, l = \mu, e)}$$

exp	R_D	R_{D^*}
$BaBar$ [9]	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
$Belle(2015)$ [10]	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
$Belle(2016)$ [11]	$-$	$0.302 \pm 0.030 \pm 0.011$
$Belle(2016, full)$ [12]	$-$	$0.270 \pm 0.035 \pm 0.011$
$LHCb(2015)$ [13]	$-$	$0.336 \pm 0.027 \pm 0.030$
$LHCb(2017)$ [14]	$-$	$0.286 \pm 0.019 \pm 0.033$
$Average$ [5]	$0.407 \pm 0.039 \pm 0.024$	$0.304 \pm 0.013 \pm 0.007$
$SM\ prediction$	0.299 ± 0.003 [15]	0.257 ± 0.005 [16]

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

	R_K	$R_{K^*}^{low}$	$R_{K^*}^{high}$
$LHCb$ [17, 18]	$0.745^{+0.090}_{-0.074} \pm 0.036$	$0.66^{+0.11}_{-0.07} \pm 0.03$	$0.69^{+0.11}_{-0.07} \pm 0.05$
$SM\ prediction$ [19]	1.00 ± 0.01	0.91 ± 0.03	1.00 ± 0.01

4.1σ deviation from the SM in $B \to D^{(*)} l\bar{l}$



CARDINI:

In $B \to K^{(*)} l\bar{l}$ a 4σ deviation from the SM AS WELL

general caveats

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

Difficult and/or statistically limited experiments

Lepton Flavour Violation never seen before
in charged leptons $BR(K_L \to \mu e) < 4.7 \cdot 10^{-12}$

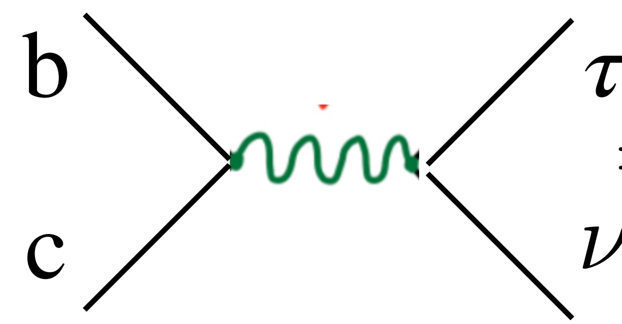
No "mediator" seen in LHC searches

In case one wants to see them correlated:
$b \to c\ l\nu$ tree level, $b \to s\ ll$ loop level

The need of a "mediator"

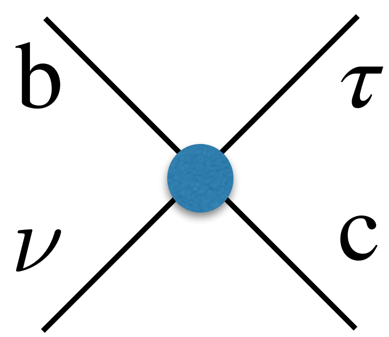
$\frac{R_{D^{(*)}}}{R^{SM}_{D^{(*)}}} = 1.237 \pm 0.053$ is a deviation from the SM at about 20% level in $b \to c\tau\nu$

Need to interfere with



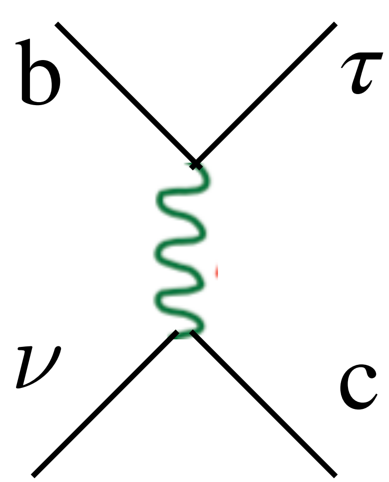
$$= \frac{g^2 V_{cb}}{m_W^2}$$

From



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

From



need $\frac{g}{m} \approx \frac{2}{TeV}\left(\frac{V_{cb}}{\mathcal{V}_{cb}\mathcal{V}_{\tau\nu}}\right)^{1/2}$

The role of flavour symmetries

For vanishing Yukawa's $\mathcal{G}^{SM}_{global} = U(3)^5$ (the basis for MFV)

With Yukawa's switched on, $\mathcal{G}^{SM}_{global} \approx U(2)^5$, under which $q_3,\ l_3$ are singlets and $(q_1, q_2),\ (l_1, l_2)$ doublets, is an approximate observed symmetry (masses and angles)

$\Rightarrow$ Third generation special

If anomalies are due to a leptoquark exchange: $\Rightarrow$

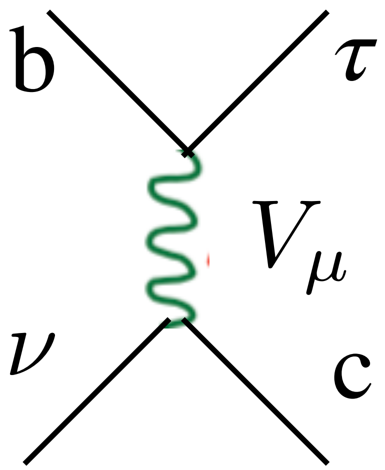
1. $V^a_\mu(\bar{q}^a_3 \gamma_\mu l_3)$ only allowed by exact $U(2)^n$

2. After (small) $U(2)^n$-breaking, mixing gives

   $b \to c\ \tau\nu$ (once suppressed)

   $b \to s\ \mu\mu$ (3 times suppressed)

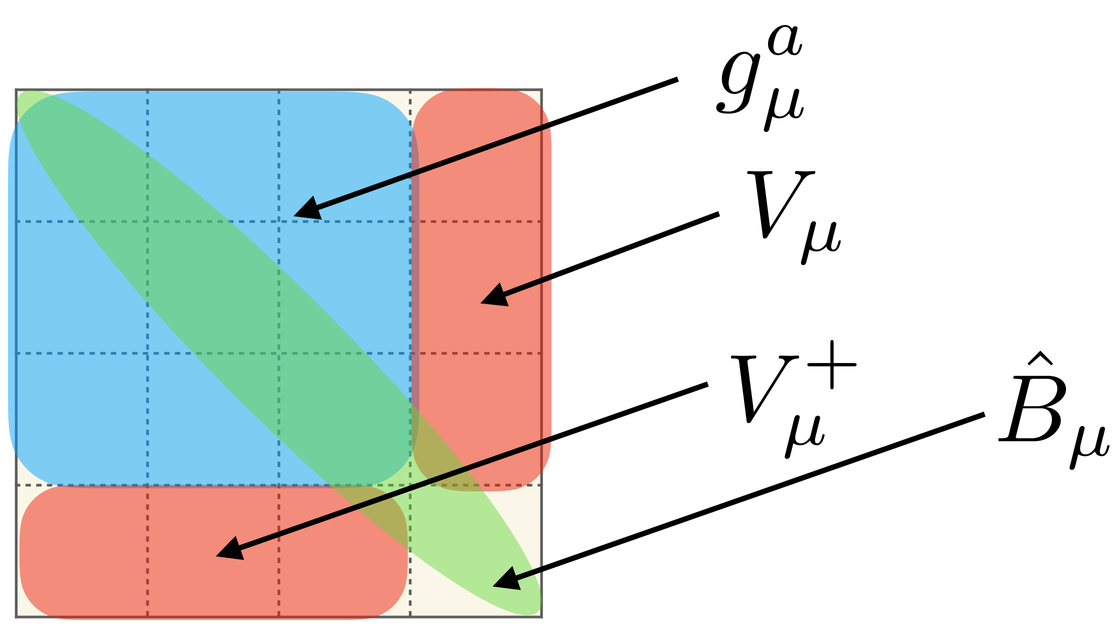
Can one make sense of a vector leptoquark?



$V_\mu = (3,1)_{2/3}$

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

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



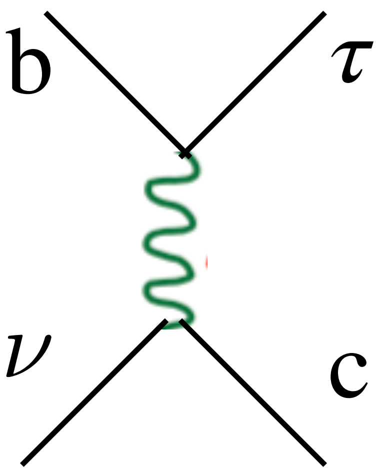
coupled to B-L

B, Isidori, Pattori, Senia 2015

B, Murphy, Senia 2016

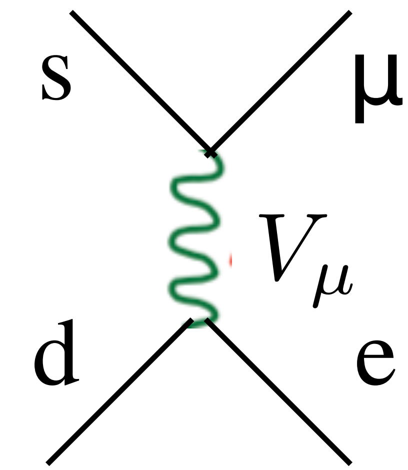
B, Tesi 2017

Back to $K_L \to \mu e$



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

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



(s^a, μ) and (d^a, e) cannot live in the same SU(4) quartet

Way out:

Consider heavy $(Q^a, L)_{Dirac}$ with $V_\mu^a(\bar{Q}_L^a \gamma_\mu L_L)$
and mix them appropriately with standard q_L, l_L

(not trivial if SU(4) is a standard gauge group)

The largish coupling and the new heavy fermions suggest:

$$\mathcal{G}_{global} = SU(4) \times SU(2)_L \times SU(2)_R \times U(1)_X$$

is a global symmetry of a new strong dynamics,
inside which only the standard $SU(3) \times SU(2)_L \times \times U(1)_Y$
is gauged and which gives rise to the Higgs as a PGB

Does such a strong dynamics exists? Assume it does

➡ Both the heavy vectors and the heavy fermions are composite states

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

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

Particles and (relevant) parameters

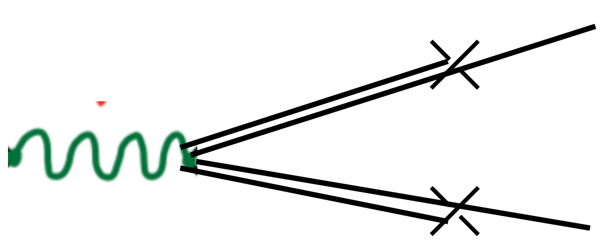
➡ heavy vectors:

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

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

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

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



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

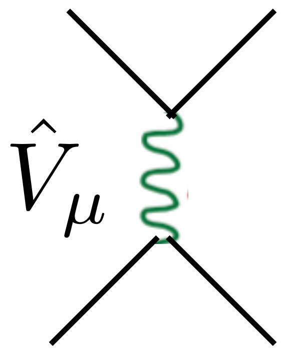
$$D_{Li} \Rightarrow s_{qi} D_{ij} d_{Lj} \quad L_{Li} \Rightarrow s_{li} E_{ij} l_{Lj}$$

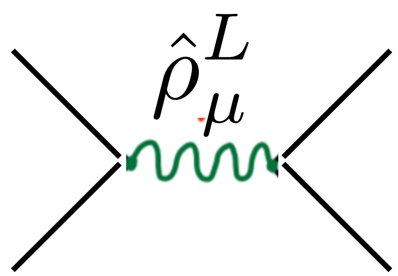
with $\quad UU^+ = DD^+ = EE^+ = \mathbf{1} \qquad V_{CKM} = UD^+$

$s_3 >> s_2, s_1$ because of $U(2)^n$

Observed anomalies

$b \to c l \nu$

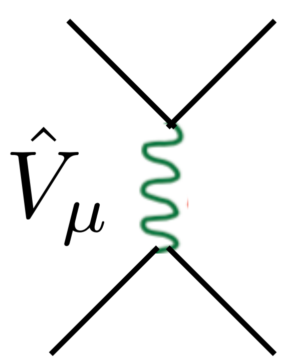




$$\frac{R_{D^{(*)}}}{R^{SM}_{D^{(*)}}} = 1.237 \pm 0.053$$

$$\left(\frac{\hat{g}_G^2}{m_G^2} + \frac{\hat{g}_\rho^2}{m_\rho^2}\right) s_{l3}^2 s_{q3}^2 \approx 5/TeV^2$$

$b \to s \mu \mu$



$$\frac{R_{K^{(*)}}}{R^{SM}_{K^{(*)}}} = 0.70 \pm 0.10$$

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

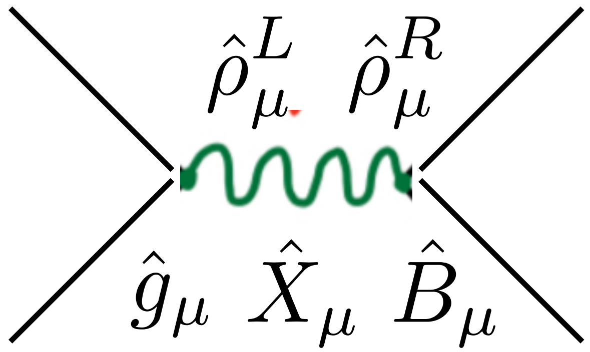
Low energy observables

$$\frac{s_{q2}s_{l2}}{s_{q3}s_{l3}}\frac{E_{\mu3}}{V_{ts}} \sim 5\cdot 10^{-3}$$

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

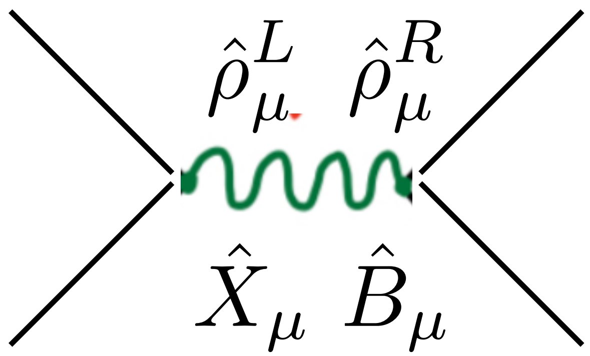
BR($B \to D^*\tau\nu$)/BR$_{SM}$ = BR($B \to D\tau\nu$)/BR$_{SM}$ = BR($\Lambda_b \to \Lambda_c\tau\nu$)/BR$_{SM}$
= BR($B \to \pi\,\tau\nu$)/BR$_{SM}$ = BR($\Lambda_b \to p\,\tau\nu$)/BR$_{SM}$ = BR($B_u \to \tau\nu$)/BR$_{SM}$

$\Delta C = 2$



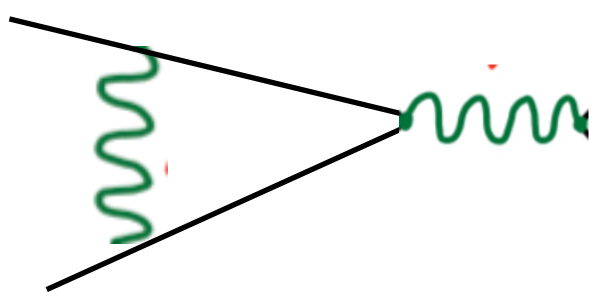
$$\frac{s_{q2}^2}{s_{q3}s_{l3}} \lesssim 10^{-3}$$

$\tau \to 3\mu$



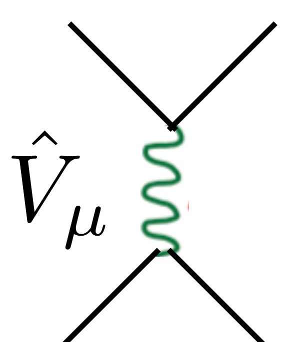
$$E_{\mu3}\left(\frac{s_{l2}^2}{s_{l3}^2} + |E_{\mu3}|^2\right) \lesssim 3\cdot 10^{-3}$$

$\tau \to \mu\gamma$



$$\left(A_G + \left(\frac{s_{l3}}{s_{q3}}\right)^2 A_\rho\right)E_{\mu3} \lesssim 0.1$$

$B^+ \to K^+\mu^+\tau^-$



$$\frac{s_{q2}s_{l2}}{s_{q3}s_{l3}} \lesssim 10^{-2}$$

$\Delta B = 2$

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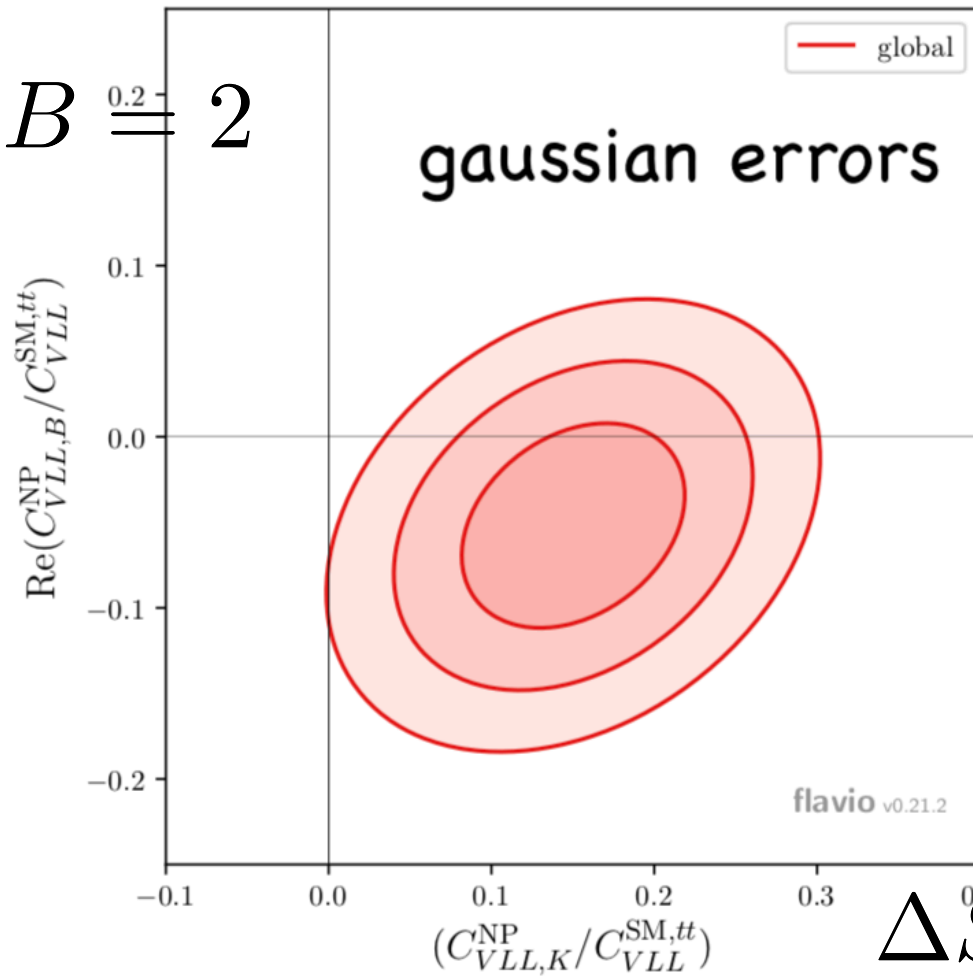
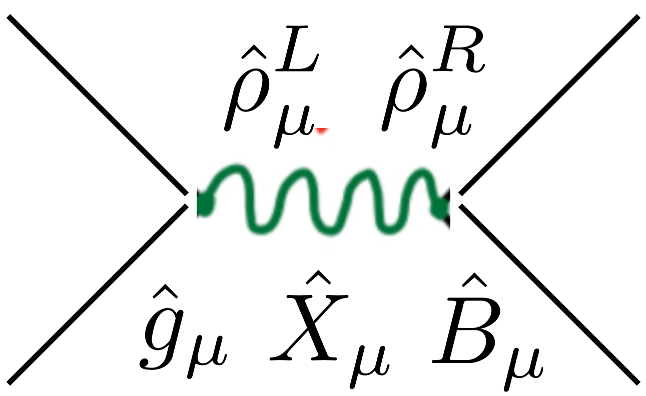


Current status

Straub 2017

$\Delta S = 2$



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

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

Summary on low energy observables

Can accommodate anomalies and low energy obs.s with $U(2)^n$ breaking parameters

$$\frac{s_{q2}}{s_{q3}} \approx \frac{s_{l2}}{s_{l3}} \approx 5 \cdot 10^{-2} \quad E_{3\mu} \approx 10^{-1} \quad D_{s3} \lesssim 4 \cdot 10^{-3}$$

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

effects in $\Delta B = 2,\ K \to \pi\nu\nu,\ K \to \mu e,\ \mu \to e\gamma$ possible but not constrained by $R_D,\ R_K$

Direct searches of the heavy vectors

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

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

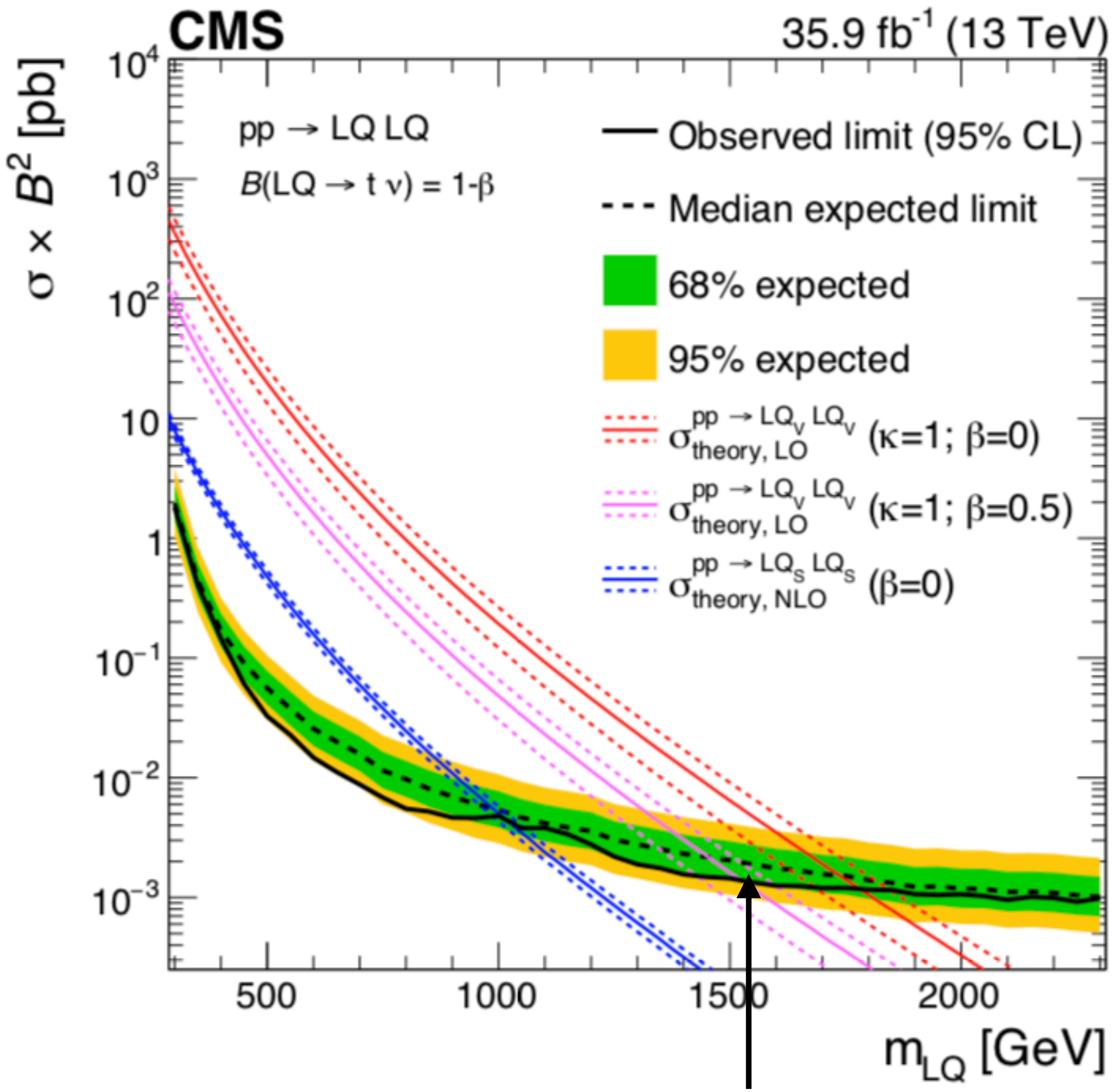
$\hat{V}_\mu$ exchanged in the t-channel: $b\bar{b} \to \tau\bar{\tau}$

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

All other vectors but $\hat{\rho}^{R\pm}_\mu$: $\hat{G}^\alpha_\mu, \hat{B}_\mu, \hat{\rho}^{La}_\mu, \hat{\rho}^{R3}_\mu, \hat{X}_\mu$
couple to the light fermions by $F - f$ mixing (mostly f_3)
and, flavour universally, by vector mixing

$$\hat{G}^a_\mu = \frac{g_G \mathcal{G}^a_\mu - g_3 G^a_\mu}{\sqrt{g_G^2 + g_3^2}} \quad \Rightarrow \quad \begin{array}{c} \dfrac{\Gamma_{\hat{G}\to t\bar{t}}}{m_G} \approx \dfrac{\Gamma_{\hat{G}\to b\bar{b}}}{m_G} \approx \dfrac{\hat{g}_G^2 s_{q3}^4}{48\pi} \\[2ex] \dfrac{\Gamma_{\hat{G}\to u\bar{u}}}{m_G} \approx \dfrac{\Gamma_{\hat{G}\to d\bar{d}}}{m_G} \approx \dfrac{g_3^4}{24\pi g_G^2} \end{array}$$

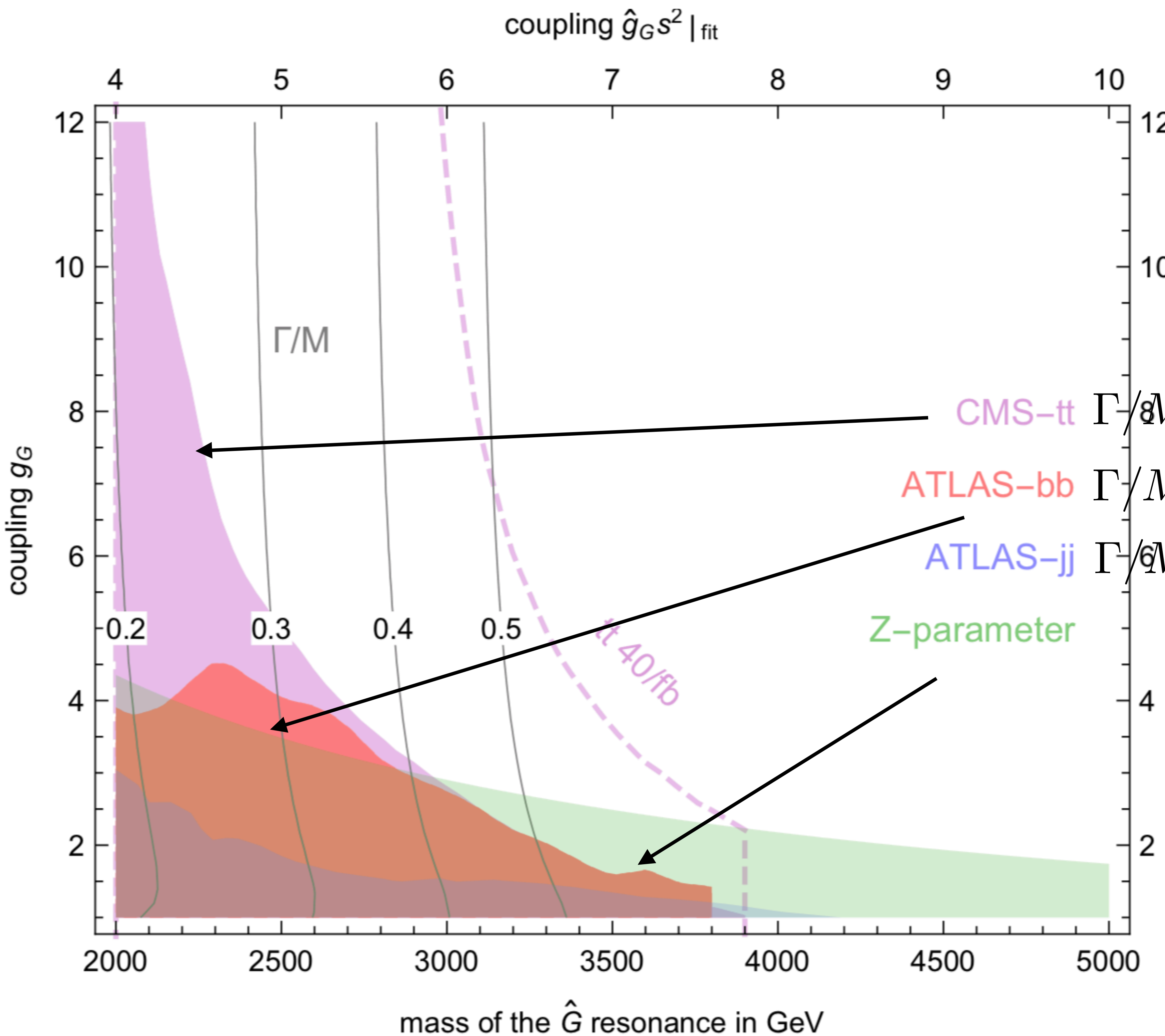
$$gg \to \hat{V}_\mu^+ \hat{V}_\mu^- \to (t\bar{\nu}_\tau)(\bar{t}\nu_\tau)$$



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

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

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



$\Gamma/M < 30\%$

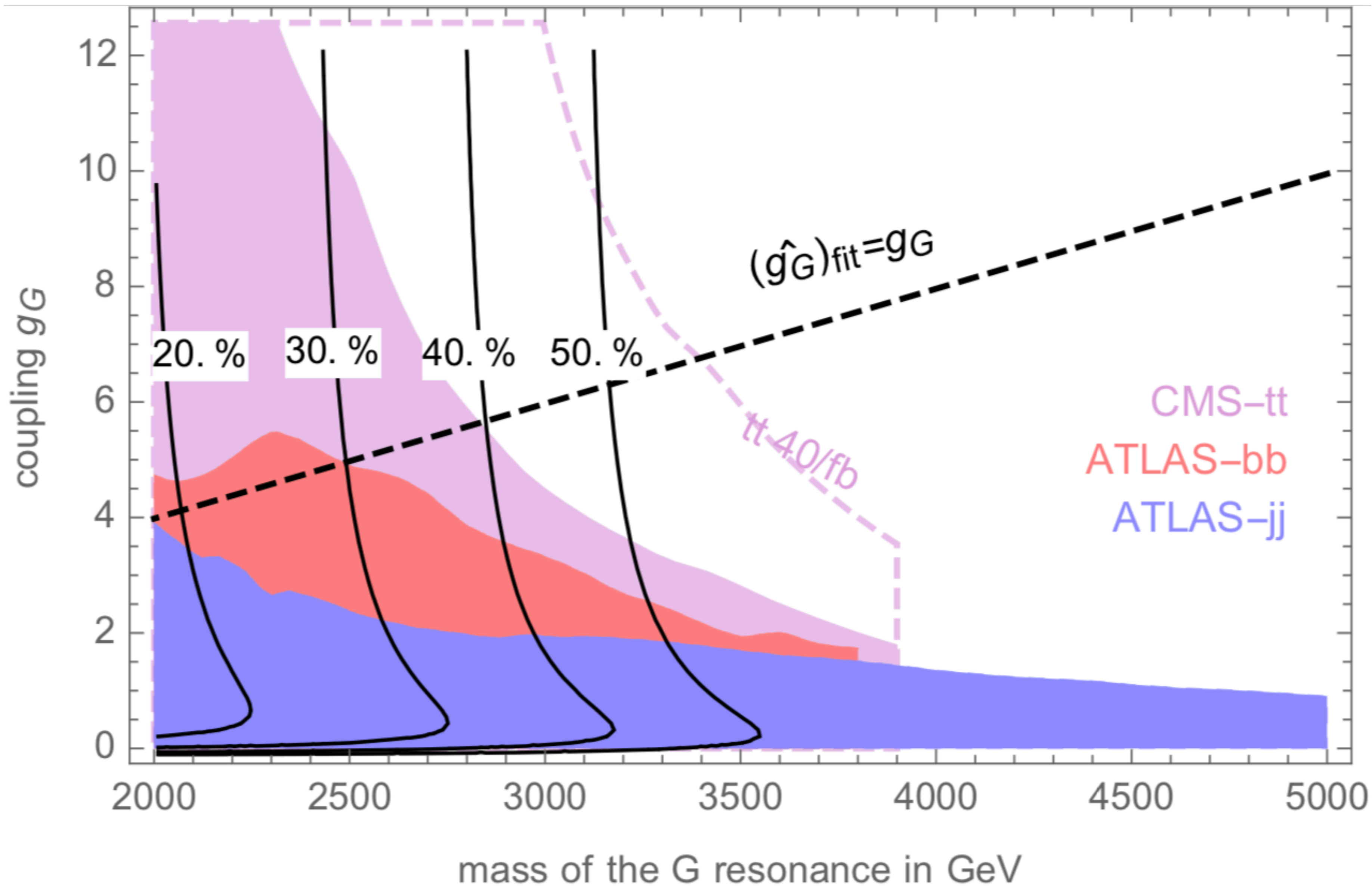
$\Gamma/M < 15\%$

$\Gamma/M < 15\%$

$$m_{\hat{G}} > 2 \div 2.5\ TeV$$

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

Using as benchmark $\hat{g}_G = 4\frac{m_G}{2\ TeV}$



Bounds from σB at $\Gamma_G/m_G = 30\%$

Summary

Anomalies in B-decays motivated by $U(2)^n$

To be seen in LFV, yes! (provided $\delta g^{(3)}_{Z,W}$ accounted for)

No lack of expected signals:

Low energy: $b \to c\tau\nu$ universally deviating from the SM

Low energy: $\Delta C = 2, \tau \to 3\mu, \tau \to \mu\gamma$ at current limits

Direct searches: $gg \to \hat{V}^+_\mu \hat{V}^-_\mu \quad gb \to \hat{V}_\mu \tau \quad \hat{V}_\mu \to t\nu, b\tau$

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

If confirmed by experiments to come,

Pati-Salam SU(4) as an emerging candidate