The Standard Model and (some of) its extensions

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Zuoz, August 14-20, 2016

I. The SM and its status, as of 2016

II. Problems of (questions for) the SM

III. Mirror Twin Higgs World

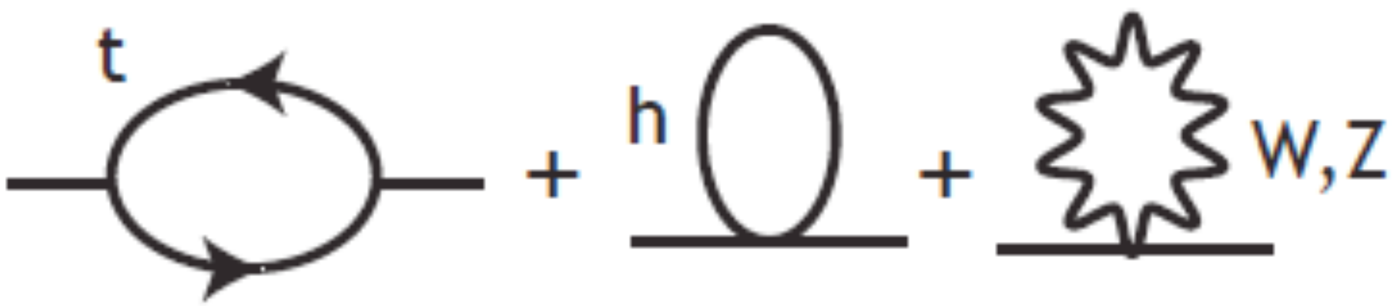
IV. Anomalies in B-decays

V. Axion searches by way of their coupling to the spin

The Mirror Twin Higgs World

The hierarchy problem, once again

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



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

$1/\Delta$ = amount of tuning

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

The Mirror World

Lee, Yang 1956

Kobzarev, Okun, Pomeranchuk 1966

Berezhiani 2006 and ref.s therein

Can one restore parity?

Introduce:

$$SU_{321} : (A^a_\mu, H, f_L, f_R) \qquad SU'_{321} : (A^{a\prime}_\mu, H', f'_L, f'_R)$$

and require that $\mathcal{L}_{SM} + \mathcal{L}'_{SM}$ be invariant under

$$(\vec{x}, t) \rightarrow (-\vec{x}, t)$$

$$f_L \leftrightarrow \gamma_0 (f'_L)^c, \quad f_R \leftrightarrow \gamma_0 (f'_R)^c \qquad [f_L \leftrightarrow \gamma_0 f_R]$$

$$H \leftrightarrow H', \quad A^a_\mu \leftrightarrow A^{a\prime}_{\tilde{\mu}}$$

Need:

$$m_H = m_{H'}, \quad \lambda = \lambda', \quad g_{3,2,1} = g'_{3,2,1}, \quad Y = Y'^*$$

The Twin Higgs

Chacko, Goh, Harnik 2005

Consider the most general

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}'_{SM} + \sigma |H|^2 |H'|^2 + \epsilon B_{\mu\nu} B'_{\mu\nu}$$

$$\Rightarrow \quad V(H, H') = m^2(|H|^2 + |H'|^2) + \lambda(|H|^4 + |H'|^4) + \sigma |H|^2 |H'|^2$$

The mass term is $SO(8)$-symmetric

What if the quartic were also $SO(8)$-symmetric? $\sigma = 2\lambda$

$$\Rightarrow \quad V(H, H') \to V(\mathcal{H}), \quad |\mathcal{H}|^2 = |H|^2 + |H'|^2$$

$$V(H) : SO(4) \to SO(3) \ at \ v^2 = \frac{m^2}{2\lambda} \Rightarrow 3 \ PGBs, \ SU(2) \times U(1) \to U(1)_{em}$$

$$V(\mathcal{H}) : SO(8) \to SO(7) \ at \ v'^2 = \frac{m^2}{2\lambda} \Rightarrow 7 \ PGBs, \ SU(2)' \times U(1)' \to U(1)'_{em}$$

+ $SU(2) \times U(1)$ unbroken and 1 massless Higgs doublet

(remember that $SO(8) \supset SO(4) \times SO(4)'$)

The Mirror Twin Higgs World

The mirror world with a maximally symmetric Higgs system

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}'_{gauge} + \mathcal{L}_Y + \mathcal{L}'_Y + V(H, H')$$

$$V(H, H') = V_{SO(8)-inv} + V_{Z_2-inv} + V_{Z_2-broken}$$

$$V_{Z_2-inv} = \delta\lambda(|H|^4 + |H'|^4) \qquad V_{Z_2-broken} = \delta m^2 |H|^2$$

Minimizing the potential for $\delta\lambda << \lambda,\ \delta m^2 << m^2$

$$v'^2 =< H' >^2 = -\frac{m^2}{2\lambda} \qquad v^2 =< H >^2 = \frac{v'^2}{2}(1 - \frac{\delta m^2}{2\delta\lambda v'^2})$$

$$m^2_{\tilde{h}'} = 4\lambda v'^2 \qquad m^2_{\tilde{h}} = 8\delta\lambda v^2$$

$$\tilde{h}' = s_\theta h + c_\theta h' \qquad \tilde{h} = c_\theta h - s_\theta h'$$

$$\tan\theta = \frac{v}{v'}$$

what does one gain?

Fine tuning in the MTHW

$$v'^2 = < H' >^2 = -\frac{m^2}{2\lambda} \qquad v^2 = < H >^2 = \frac{v'^2}{2}(1 - \frac{\delta m^2}{2\delta\lambda v'^2})$$

need to fine tune v' (or $m_{h'}$) and v/v'

$$\Delta_{m_h^{TH}} = \Delta_{m'_h}\Delta_{v/v'}$$ (if both Δ's > 1)

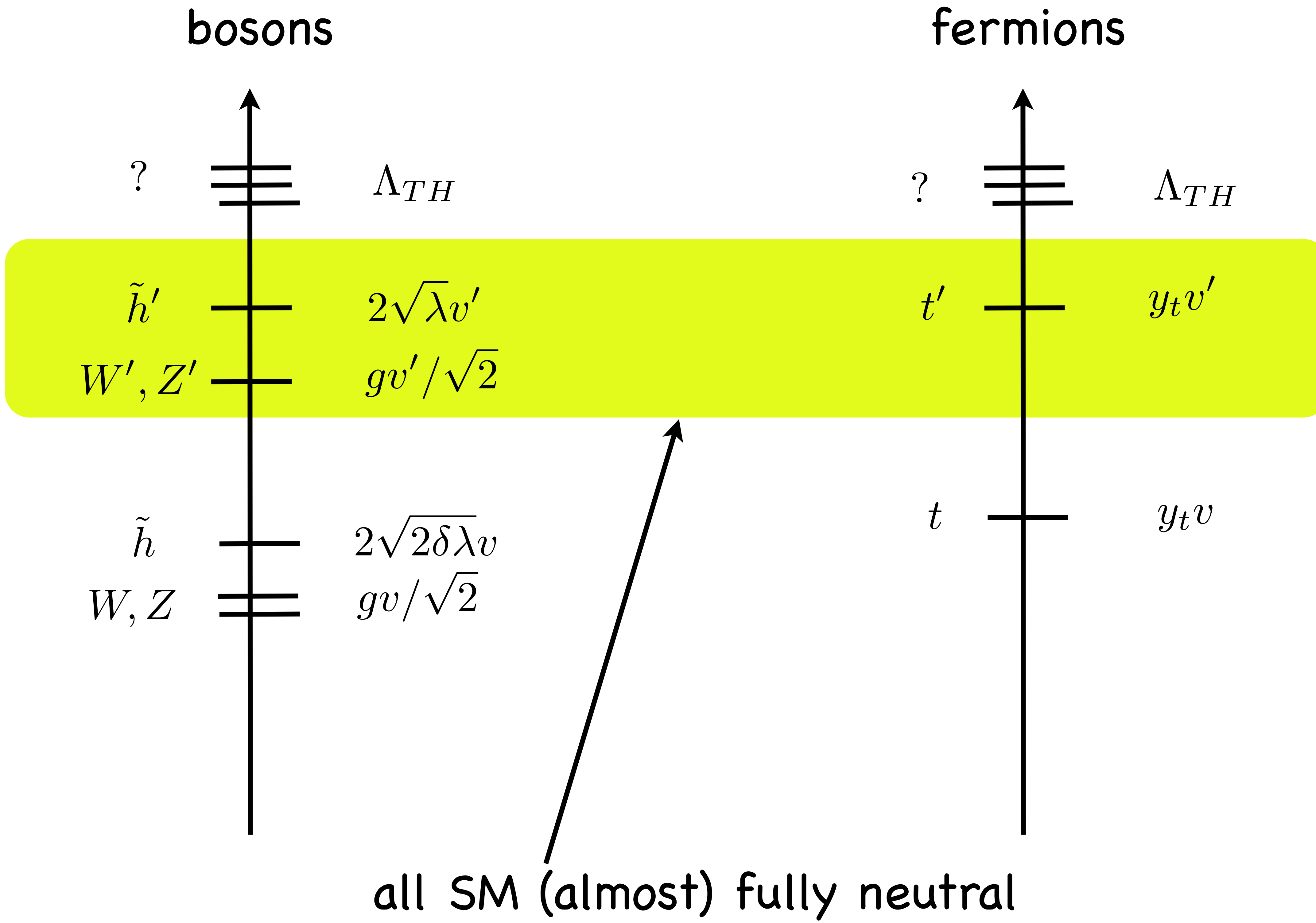
$$\Delta_{m_{h'}} = \frac{3}{4\pi^2}\frac{y_t^2\Lambda_{TH}^2}{m_{h'}^2} \qquad \Delta_{v/v'} = \frac{d\log v^2}{d\log\delta m^2} \approx \frac{1}{2}\frac{v'^2}{v^2}$$

how does one compare it with the SM?

$$\Delta_{m_h^{SM}} = \frac{3}{4\pi^2}\frac{y_t^2\Lambda_{SM}^2}{(m_h^{SM})^2} \qquad \frac{\Delta_{m_h^{TH}}}{\Delta_{m_h^{SM}}} = \frac{1}{2}\frac{\lambda_{SM}}{\lambda_{TH}}\frac{\Lambda_{TH}^2}{\Lambda_{SM}^2}$$

A considerable gain for $\lambda_{TH} \gtrsim 1 >> \lambda_{SM} \approx 0.1$

The MTHW spectrum

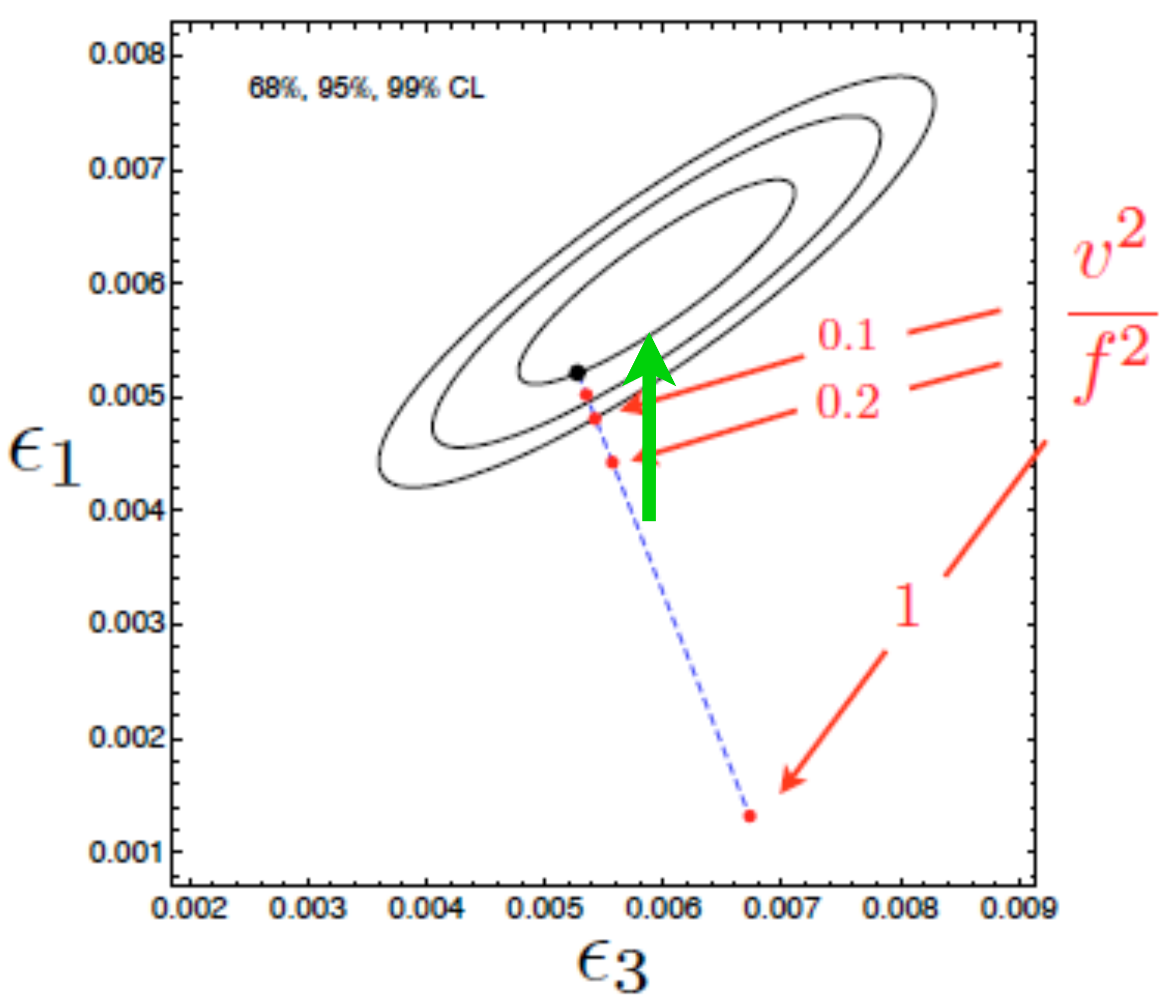


What do we know of v'?

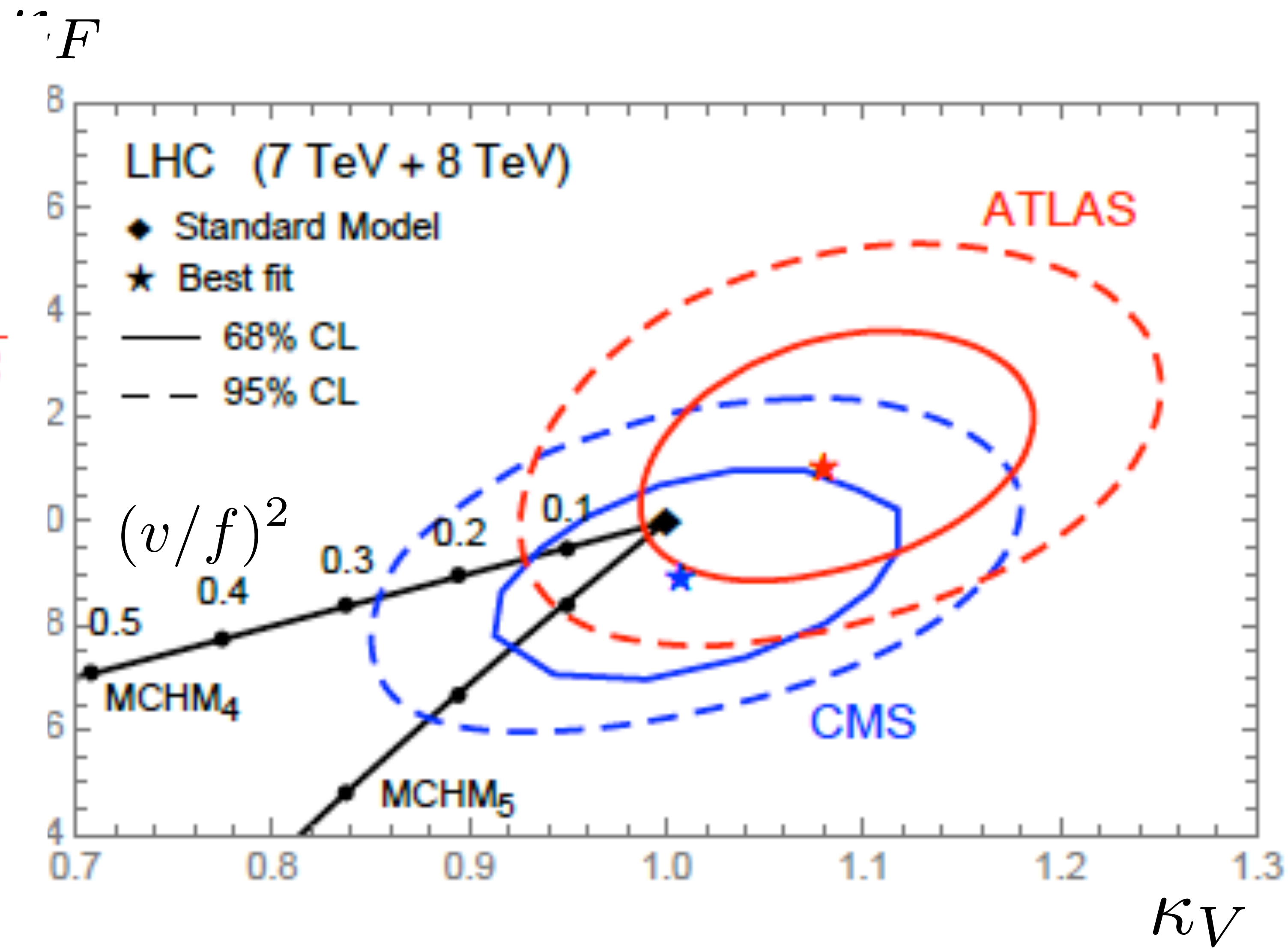
(here called f for historical reasons)

B, Hall, Gregoire 2005

$$\tilde{h} = c_\theta h - s_\theta h' \qquad \tan\theta = \frac{v}{v'}$$



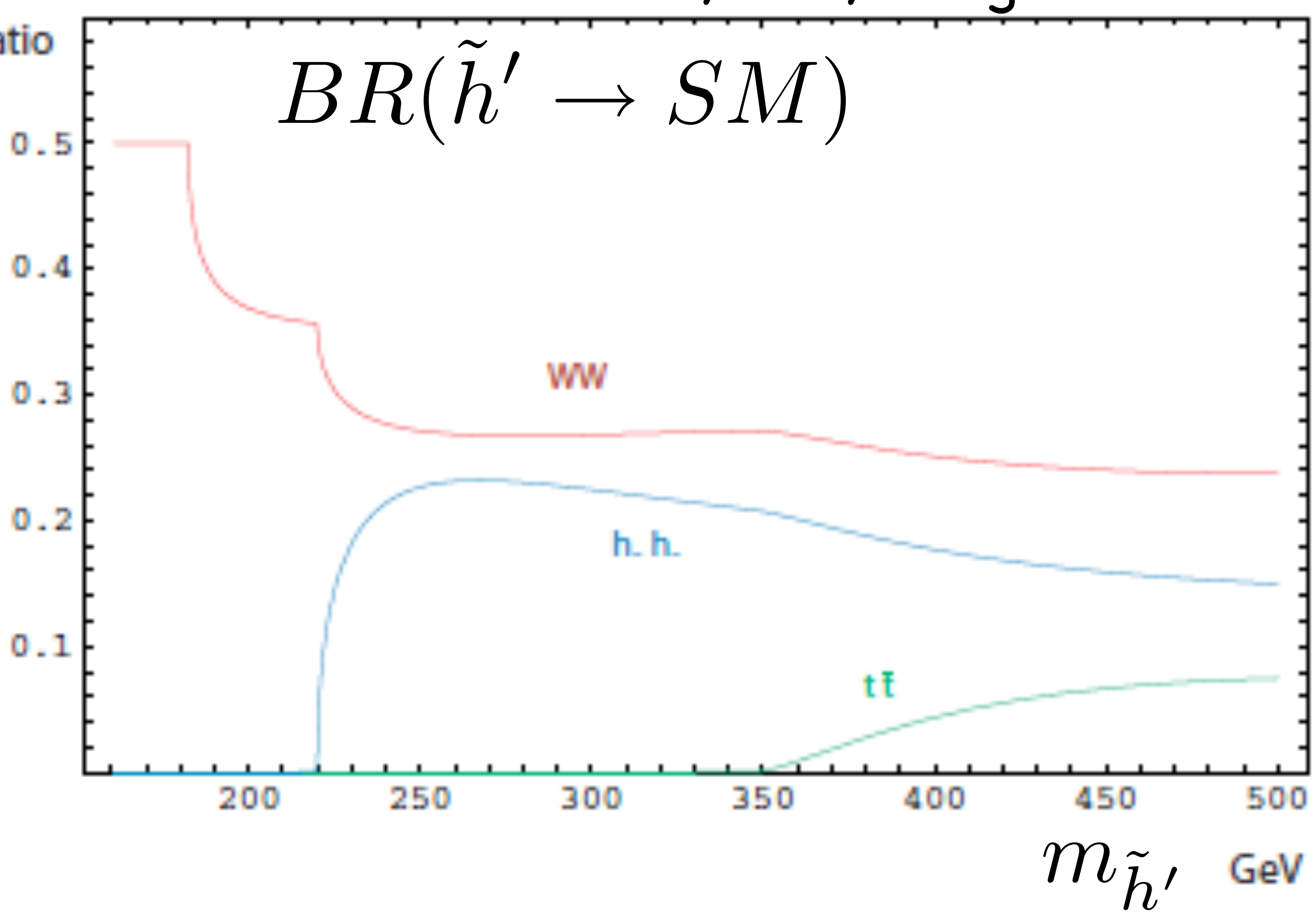
EWPT



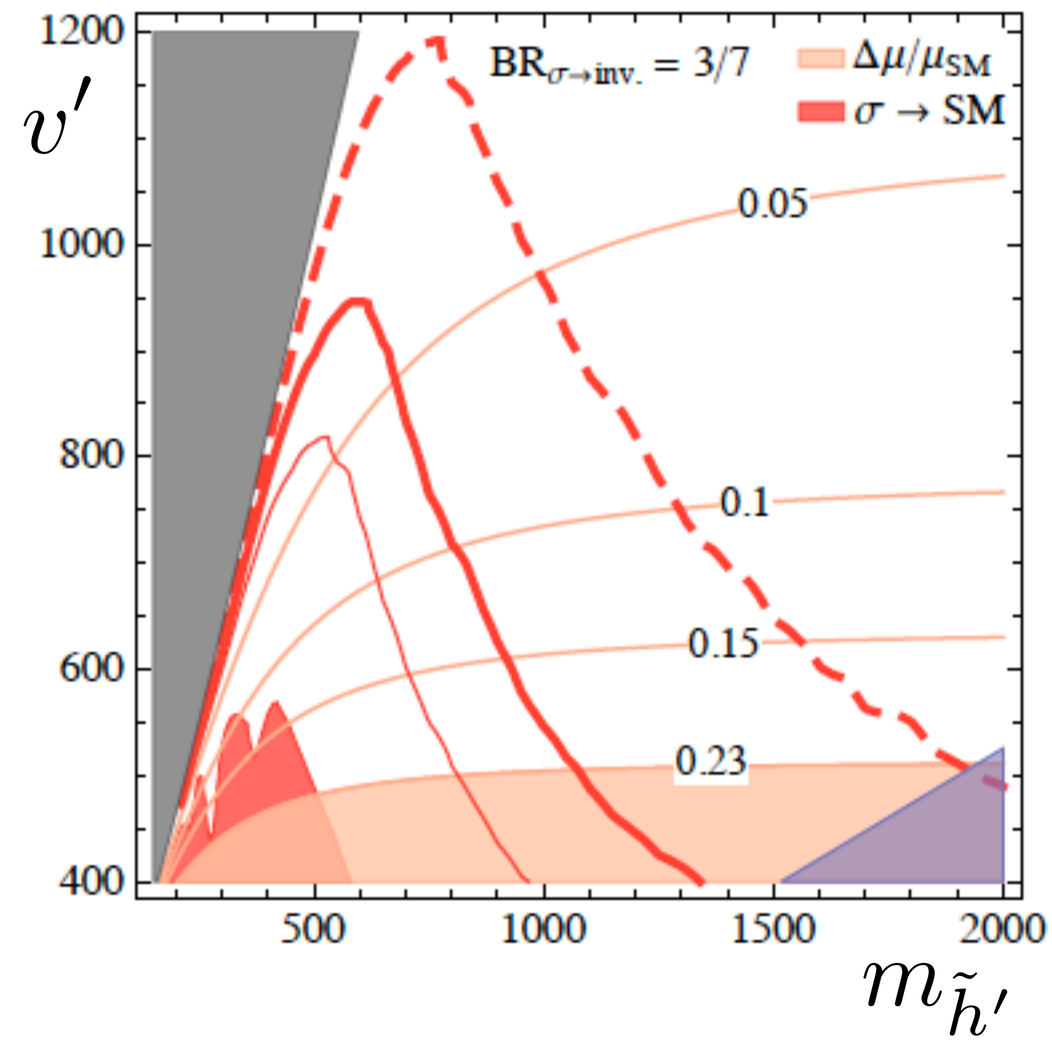
Higgs precision

$\tilde{h}'$ production and decays

B, Hall, Gregoire 2005



Buttazzo, Sala, Tesi 2015



$$\sigma(pp \to \tilde{h}') \approx (\frac{v}{v'})^2 \sigma(pp \to h_{SM}(m = m_{h'}))$$ via a top loop

Neglecting phase space, relative to $\Gamma(\tilde{h}' \to ZZ)$

f	WW	hh	$W'W'$	$Z'Z'$
$\Gamma(\tilde{h}' \to f)$	2	1	2	1

Open problems(/signals?)

1. Where does the breaking of Z_2-parity come from?

$$V_{Z_2-broken} = \delta m^2 |H|^2$$

2. Dark/mirror Radiation

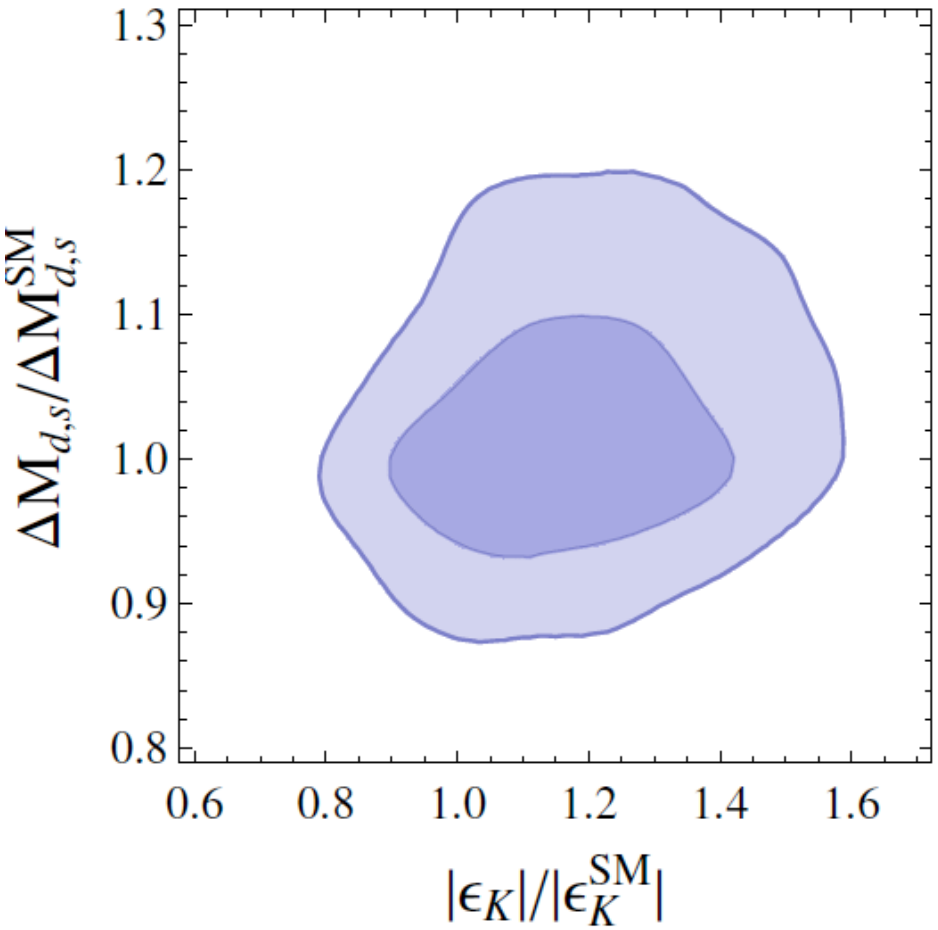
$$\gamma', \nu' \qquad \Rightarrow \Delta N_{eff}$$

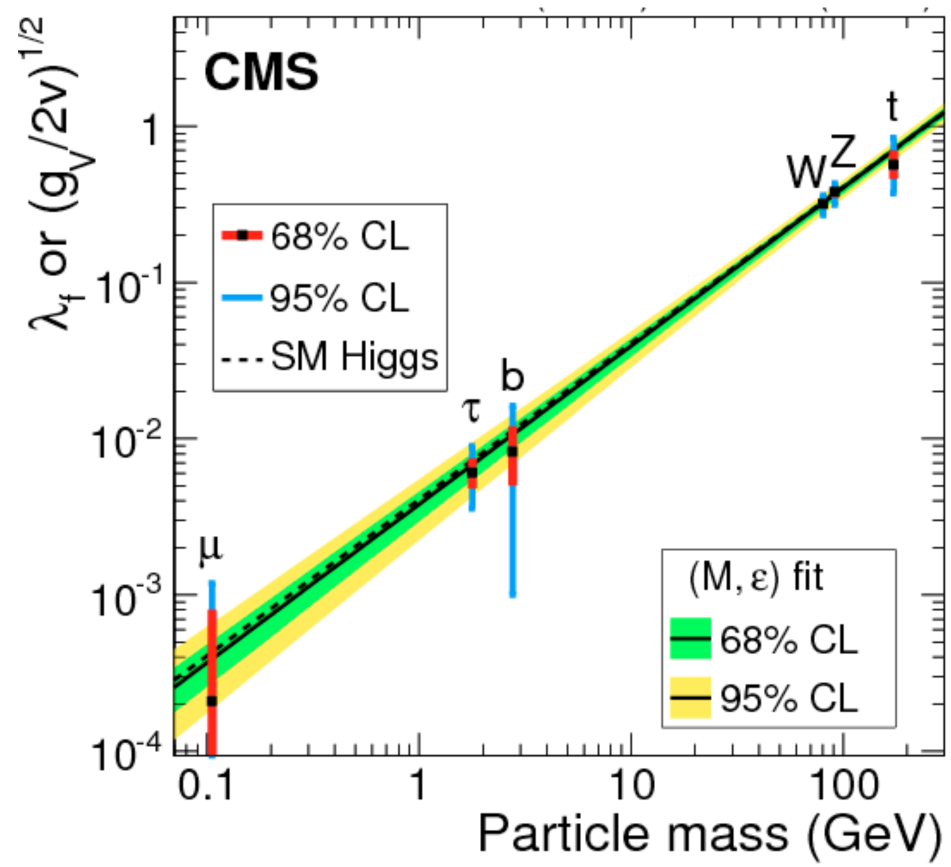
3. Dark/mirror Matter

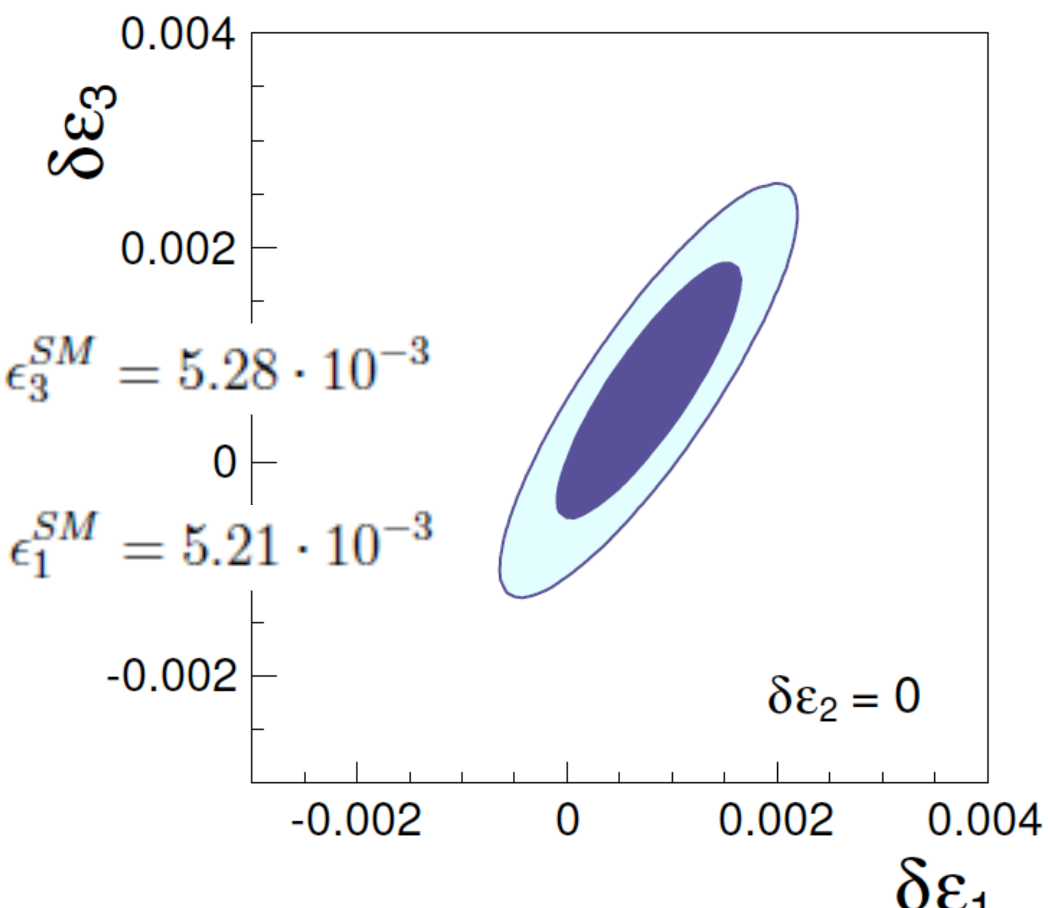
B′, L′, Q′ conserved

Anomalies in B-decays

Back to the beginning





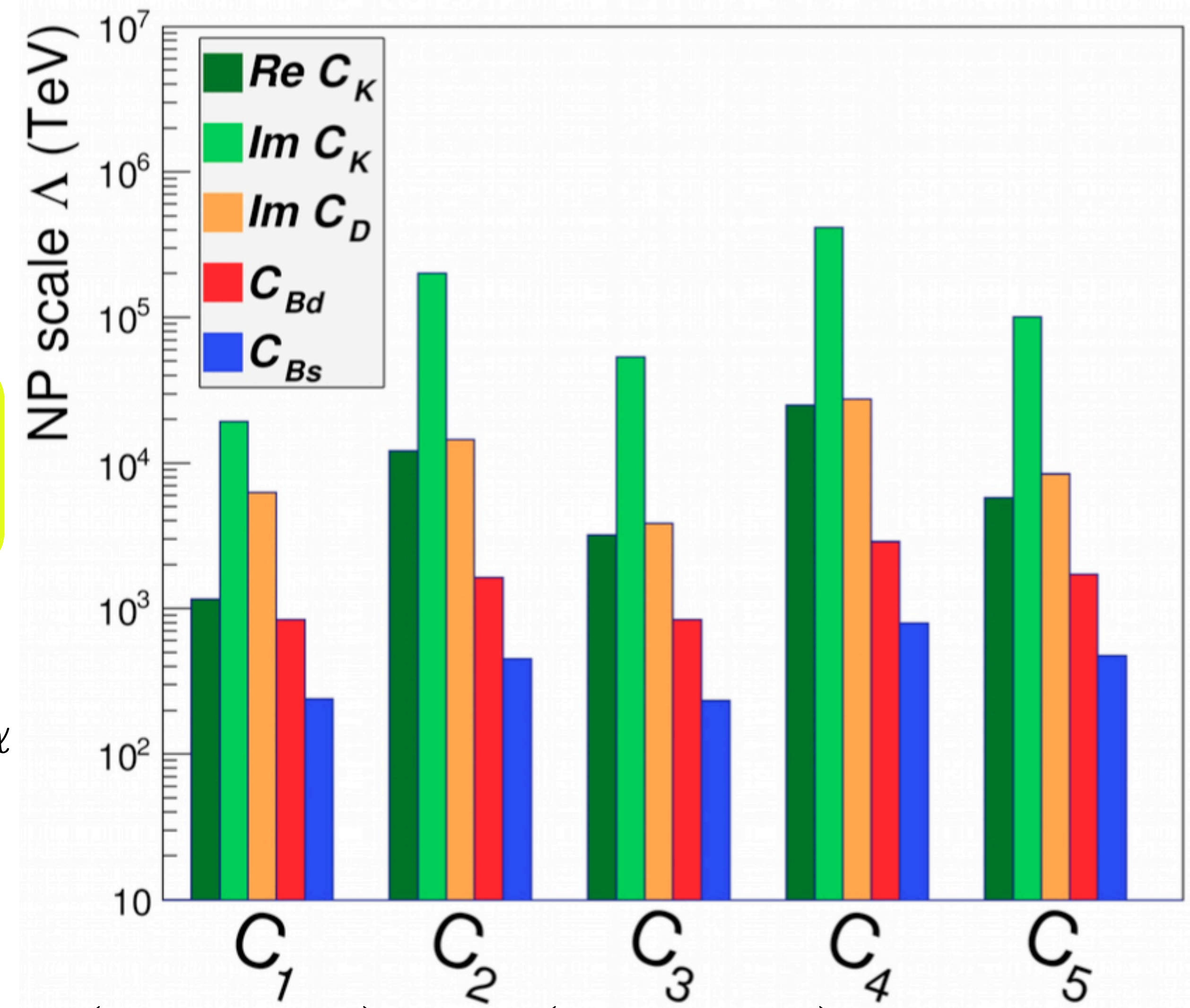


To make progress, new flavour signals badly needed

A suitable flavour program can reduce errors on CKM tests from about 20% (now, similar to $\delta\epsilon_i/\epsilon_i^{SM}$) to ≲ 1%

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

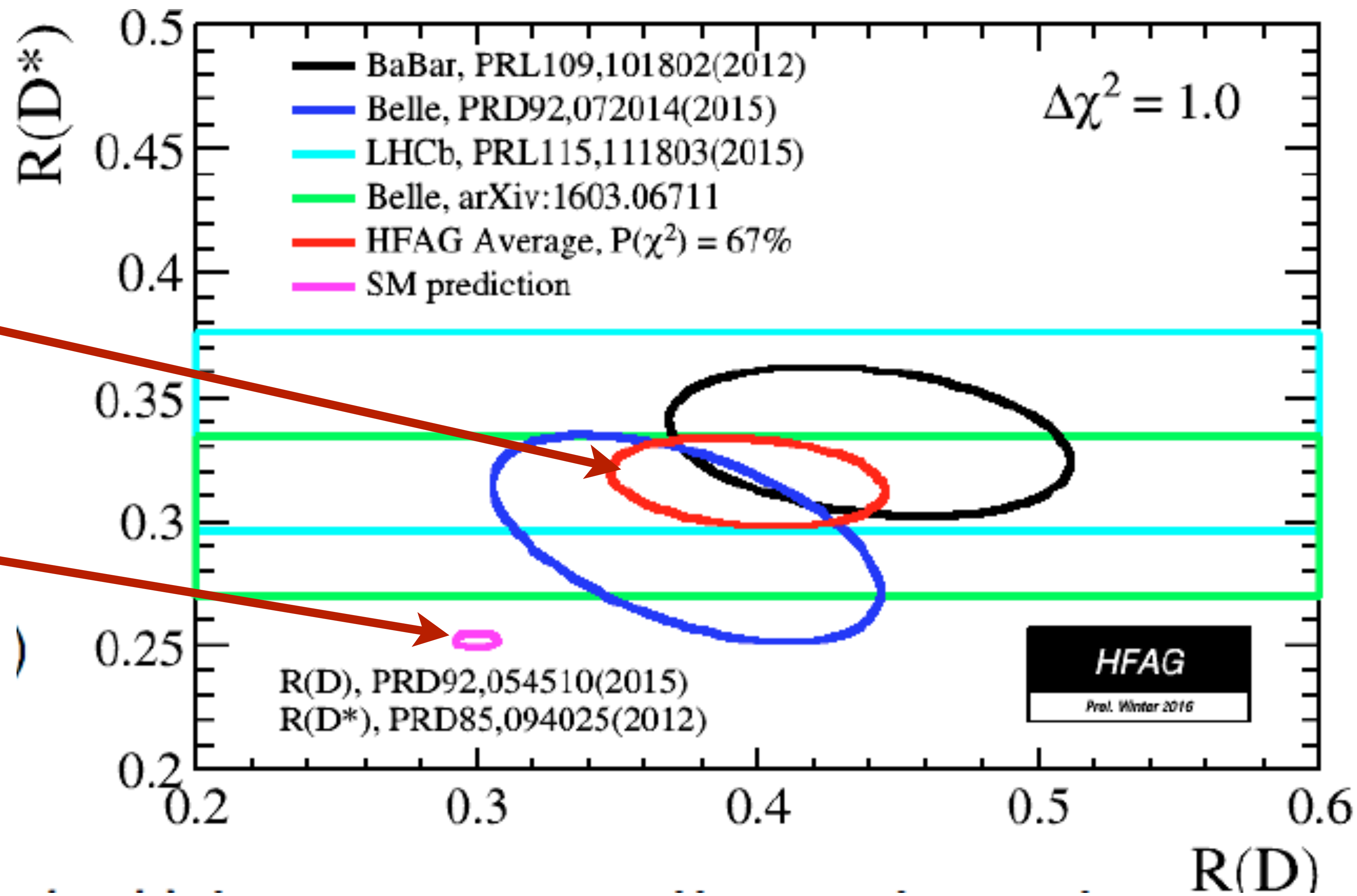
2. Indirect signals of new physics at the TeV scale

A deviation from the SM in flavour, finally?

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

exp. average

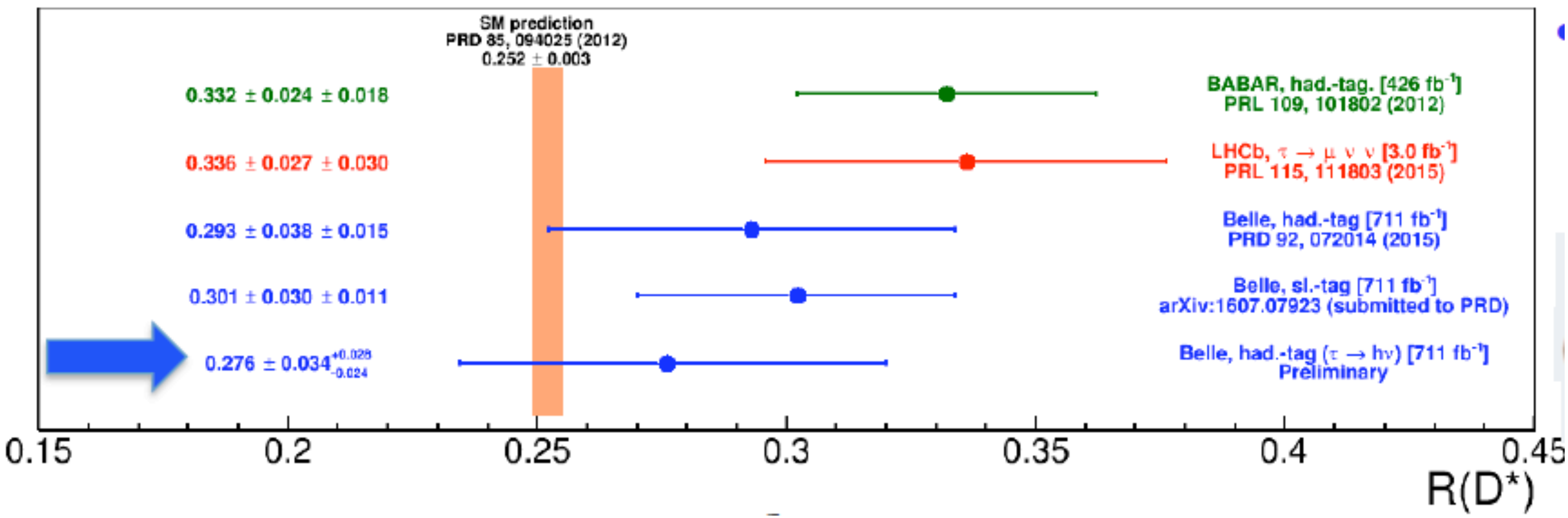
SM prediction



A deviation from the SM in flavour, finally?

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

Vagnoni 2016



a 4σ deviation from the SM

from a collection of different experiments

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^2 distribution)

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

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

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

$$U(3)_Q \times U(3)_u \times U(3)_d$$

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

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

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

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. allows observables deviations from the SM by nearby BSM

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

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

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:

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

(unique, if I were a mathematician)

Couplings in the physical bases

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

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

$$F^U = \begin{pmatrix} V_{ub}(s_l\epsilon_l)A_u & V_{ub}(c_l\epsilon_l)A_u & V_{ub}(1-a)r_u \\ V_{cb}(s_l\epsilon_l)A_u & V_{cb}(c_l\epsilon_l)A_u & V_{cb}(1-a)r_u \\ V_{tb}(s_l\epsilon_l)(b-1) & V_{tb}(c_l\epsilon_l)(b-1) & V_{tb} \end{pmatrix}$$

$$F^D = \begin{pmatrix} V_{td}(s_l\epsilon_l)A_d & V_{td}(c_l\epsilon_l)A_d & V_{td}[1-(1-a)r_u] \\ V_{ts}(s_l\epsilon_l)A_d & V_{ts}(c_l\epsilon_l)A_d & V_{ts}[1-(1-a)r_u] \\ V_{tb}(s_l\epsilon_l)(b-1) & V_{tb}(c_l\epsilon_l)(b-1) & V_{tb} \end{pmatrix}$$

in terms of ϵ_l, θ_l and 4 O(1) coefficients

Tree level effects

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

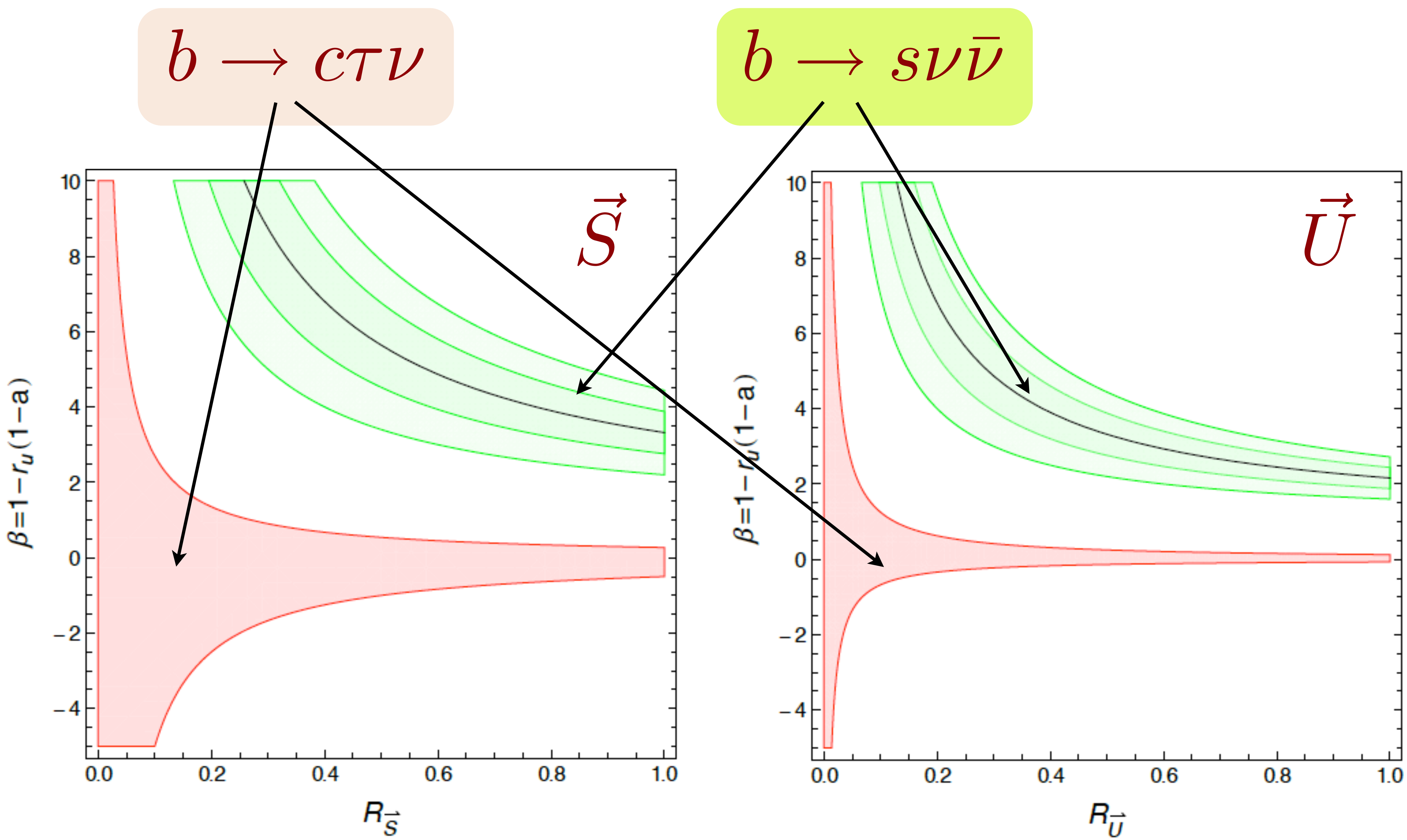
$b \longrightarrow c\tau\nu$

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

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

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

$$(x_U, x_{\vec{U}}, x_{\vec{S}}) = -\frac{\pi}{\alpha c_\nu^{SM}}[1 - r_u(1-a)]\left(0, -\frac{R_{\vec{U}}}{2}, \frac{R_{\vec{S}}}{8}\right)$$



$\Rightarrow$ Only U_μ survives tree level test (trivially)

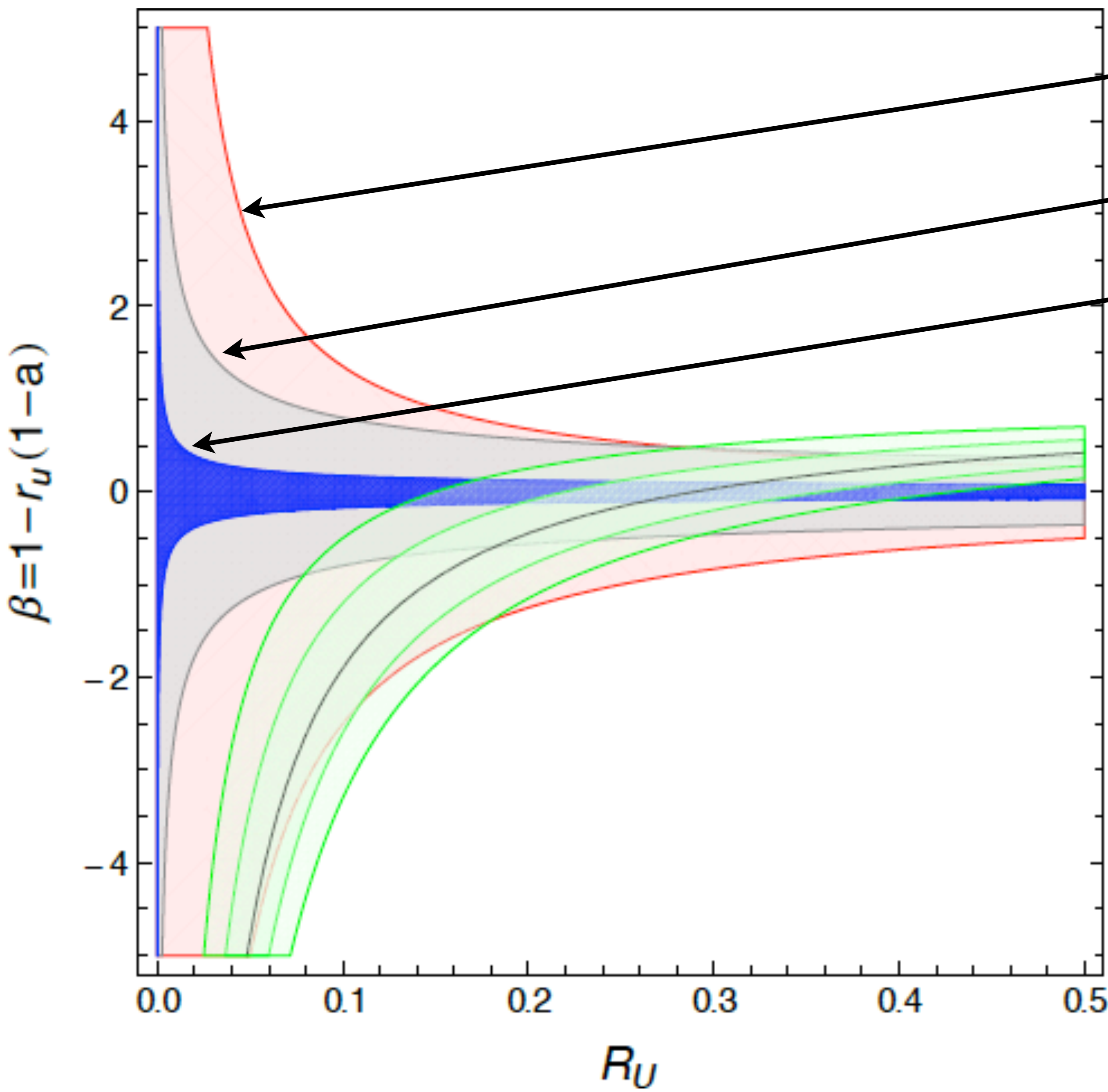
B, Isidori, Pattori, Senia 2015

Consistency with data (and expected signals) 1

EWPT: No S,T,U $\Rightarrow$ mild bound on k_Y

$Z \to \tau\bar{\tau}(b\bar{b}) \Rightarrow \quad k_Y \lesssim 3 \cdot 10^{-2} g_U^2/gg'$

$b \to c\tau\nu$ and correlated processes



$B \to K\nu\bar{\nu}$

$K \to \pi\nu\bar{\nu}$ (all loop effects)

$b\bar{s} \to \bar{b}s$

$R^{\tau/l}_{D^{(*)}}(b \to c\tau\nu)$

$\Downarrow$

$$R_U = 4g_U^2 M_W^2/g^2 M_U^2 \approx 0.2 \div 0.3$$

$B \to K\tau\bar{\tau} \quad R_K^{\tau/\mu} \approx 1 \div 10$

B, Isidori, Pattori, Senia 2015

The phenomenological model passes the tests but cries out for a UV completion

A sketch

A strong sector with a global $SU(4) \times SO(5)$

$\Rightarrow$ Composite vectors in adjoint of $SU(4) \times SO(4)$

in $SU(4)$: $G_\mu + X_\mu + U_\mu + U_\mu^+$

Composite fermions in

$$\Psi = (4,2,2)_{1/2} \oplus (4,2,2)_{-1/2} \oplus (4,1,1)_{1/2} \oplus (4,1,1)_{1/2}$$

If $M_{V_i} \approx g^* f$ then

$g_U \lesssim g^*$ $\quad$ $R_U \lesssim (v/f)^2$

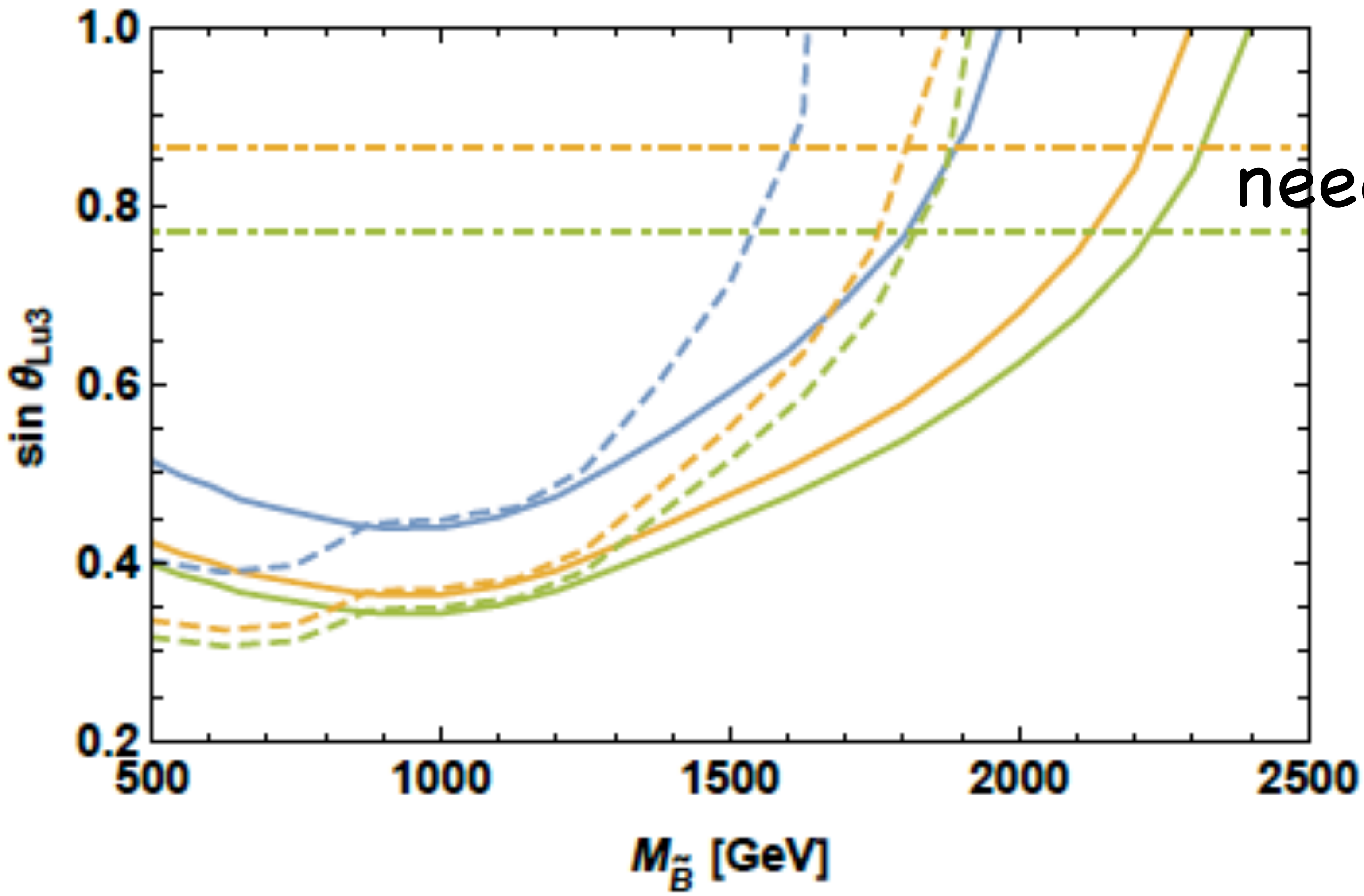
B, Murphy, Senia, to appear

Phenomenology

1. Leptoquark pair production
2. Exotic Leptons
3. Resonances in $\tau^+\tau^-$

Since $Y = \sqrt{\frac{2}{3}}T_4^{15} + T_R^3 + X$

expect 3 neutral composite vectors



needed for $b \to c\tau\nu$

B, Murphy, Senia, to appear

Conclusion

Let us see if the anomalies
get reinforced or fade away

e.g. from the LHCb program

- not only R_K ($B \to Ke^+e^-/B \to K\mu^+\mu^-$) 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 $\simeq$ 20% to $\lesssim$ 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