Role of precision physics in constraining a BSM Higgs sector

Stefania Gori

Perimeter Institute for Theoretical Physics

„After the discovery: hunting for a non standard Higgs sector"

Benasque,

April 10th 2014

Outline

Overview talk aims

Getting to know the Higgs through „non-Higgs“ precision measurement

Electroweak precision measurements

Heavy flavor precision measurements

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Info about extended Higgs sectors (will focus on 2HDMs, Susy)

complementarity with direct searches
Some model dependence

potential to catch the unexpected

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Highlight the prospects for future experimental improvement

Electroweak precision data

Huge set of measurements of electroweak observables by SLC, LEP and Tevatron since the '90s

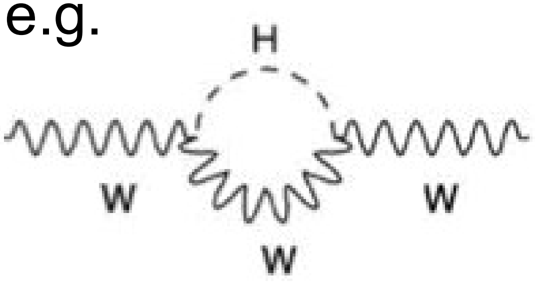
We had a prediction for the Higgs mass much before the Higgs discovery

EW precision data
M_W, $\sin^2(\theta)$, Γ_Z, ...

Theory
SM (Susy, composite models, ...)

M_h prediction

e.g.



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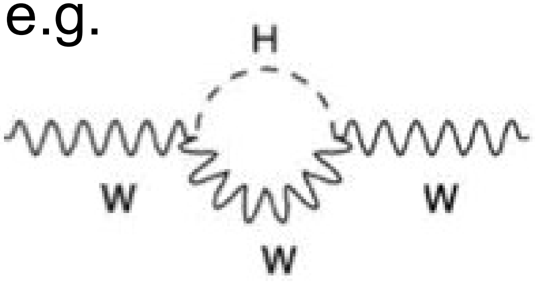
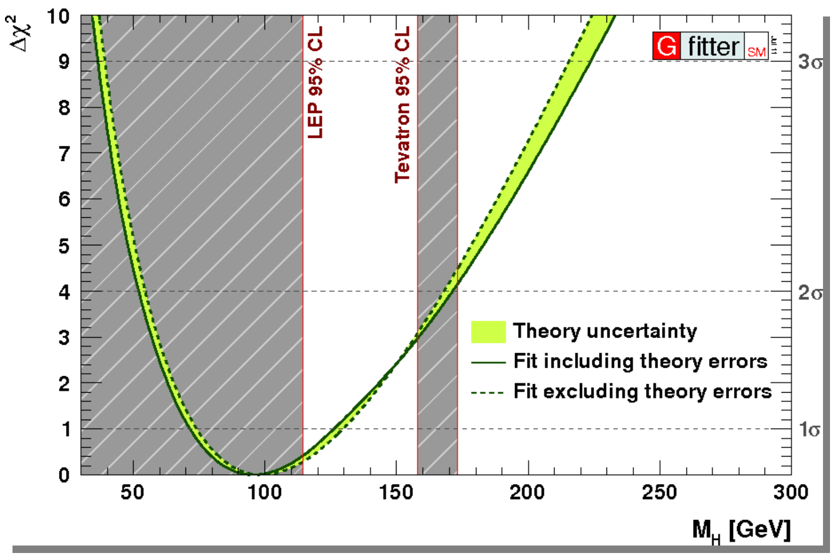
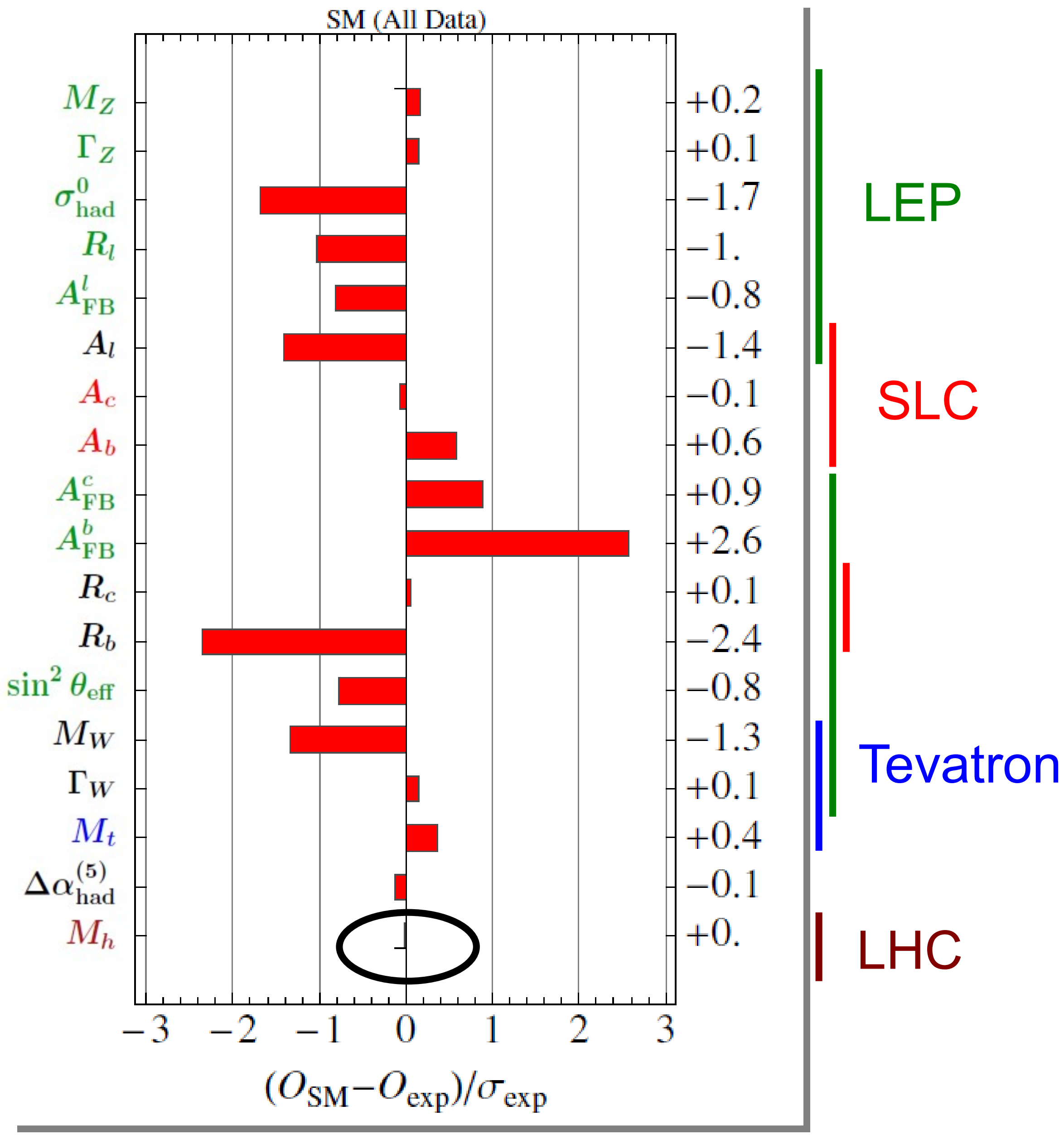


$$m_h = 91^{+30}_{-23}\,\mathrm{GeV}$$



as in 2011

Now we have the Higgs



p-value = 0.08

Batell, S.G., L.T.Wang, 1209.6382

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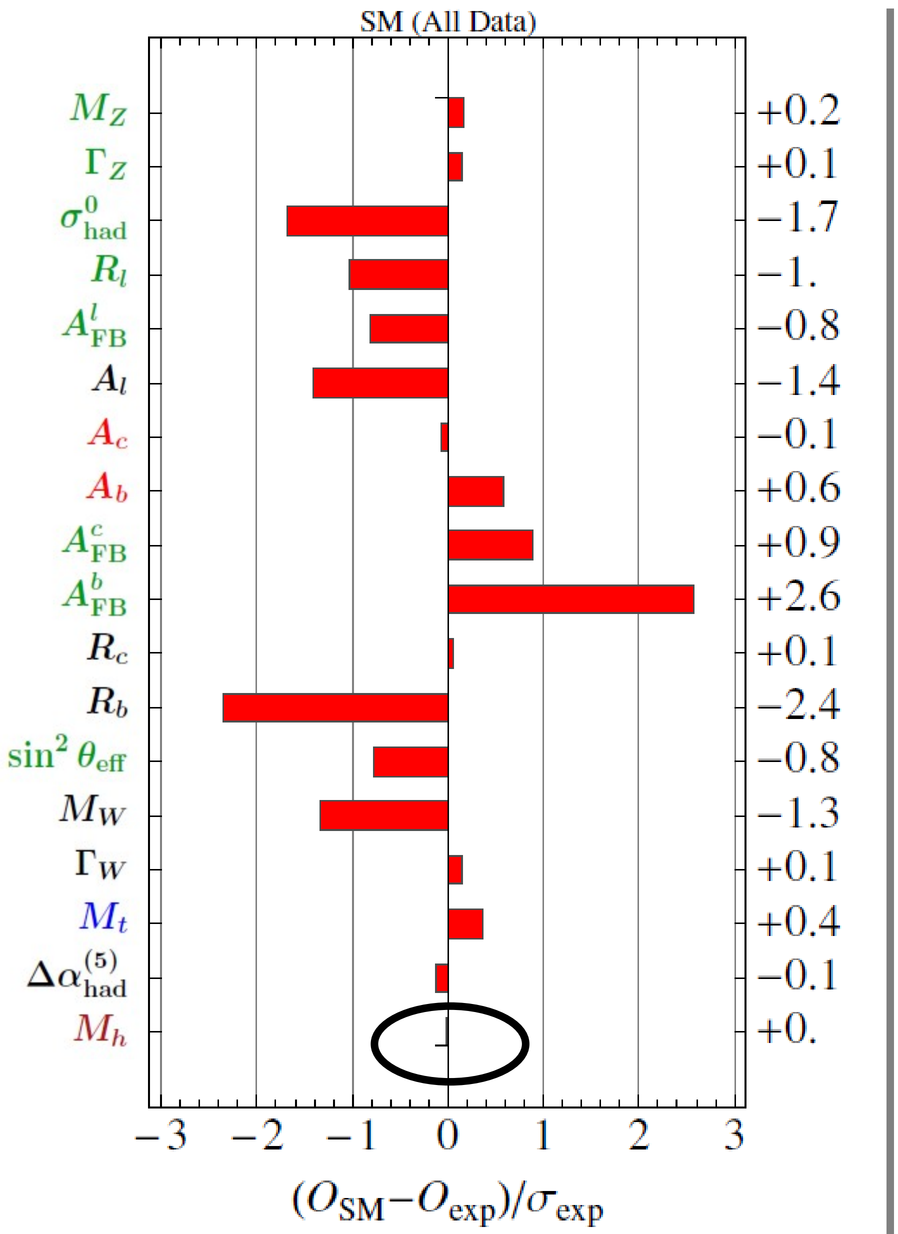


Batell, S.G., L.T.Wang, 1209.6382

Since then...

- New measurement of the top mass

  Tevatron with 8.7 fb^{-1}, 1305.3929

  M_t = 173.20 ± 0.87 GeV

  $M_t^{\rm fit}$ = 173.53 ± 0.82 GeV

  Combination with the LHC measurement:
  M_t = 173.34 ± 0.76 GeV (1403.4427)

  CMS new measurement:
  M_t = 172.22 ± 0.74 GeV (TOP-14-001)
  (instead of (173.18±0.94) GeV)

  New

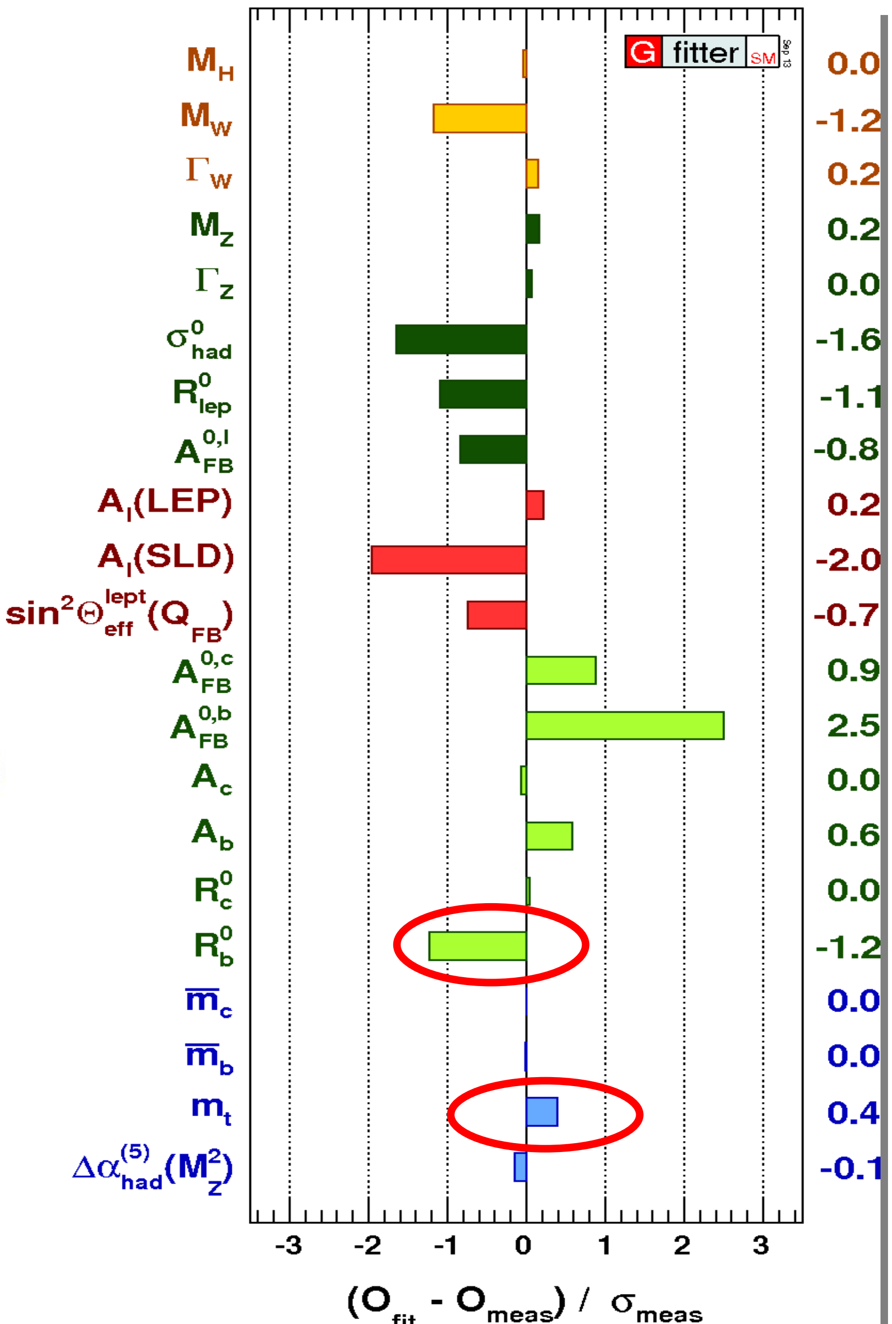
- Correction of the computation of the 2-loop ew corrections to R_b in the SM

  Freitas, Huang, Erratum 1205.0299

  $R_b^{\rm exp}$=0.21629±0.00066

  $R_b^{\rm SM}$=0.21548±0.00005 (instead of 0.21492)

Now we have the Higgs



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R_b^{exp}=0.21629±0.00066

R_b^{SM}=0.21548±0.00005 (instead of 0.21492)

p-value = 0.21

A^{b}_{FB} : a long standing anomaly

$$\boxed{e^+e^- \to \gamma, Z \to b\bar{b}}$$

A^{FB}_{b} would like the Higgs mass to be around 500 GeV

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\frac{\sigma_{LL} + \sigma_{RR} - \sigma_{LR} - \sigma_{RL}}{\sigma_{LL} + \sigma_{RR} + \sigma_{LR} + \sigma_{RL}}$$

$$\sigma_{LL} \equiv \sigma(e^+_L e^-_L \to b_L \bar{b}_L), \ldots$$

At Z-pole:

$$A_{FB} = \frac{3}{4}\frac{g^2_{Le} - g^2_{Re}}{g^2_{Le} + g^2_{Re}} \times \frac{g^2_{Lb} - g^2_{Rb}}{g^2_{Lb} + g^2_{Rb}}$$

$$\begin{aligned} A^{\text{exp}}_{FB} &= 0.0992 \pm 0.0016 \\ A^{\text{fit}}_{FB} &= 0.1032^{+0.0004}_{-0.0006} \end{aligned}$$

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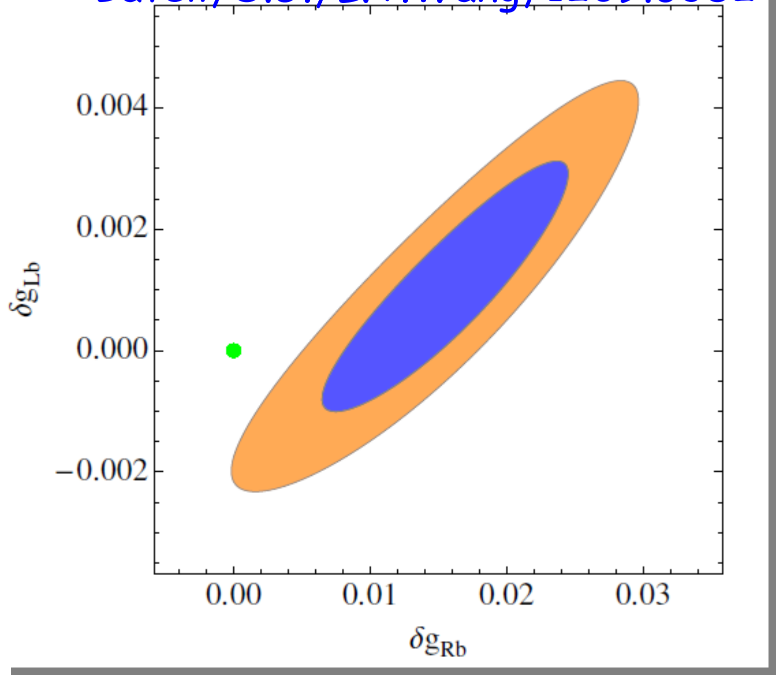

The deviation is mostly RH, and too large to be a loop effect

Beautiful mirrors

Choudhury, Tait, Wagner '01

Basic idea: Mix a new vector-like quark with the SM bottom quark

$$\begin{pmatrix} b'_L & B'_L \end{pmatrix} \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} b'_R \\ B'_R \end{pmatrix}$$

- The b quark of the Standard Model will be a superposition of b' and B'
- Shift in the Zbb coupling:

$$\boxed{\delta g_{Lb} = (t_{3L} + 1/2) s_L^2, \; \delta g_{Rb} = t_{3R} s_R^2}$$

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- The minimal model with $\Psi_{L,R} = (3, 2, -5/6)$ works rather well
- Even better fit in the custodial model with $\Psi_{L,R} = (3, 2, -5/6),\ (3, 1, -1/3)$

Batell, S.G., L.T.Wang, 1209.6382

Choudhury, Tait, Wagner '01

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- S

$$/2)s_L^2,\ \delta g_{Rb} = t_{3R} s_R^2$$

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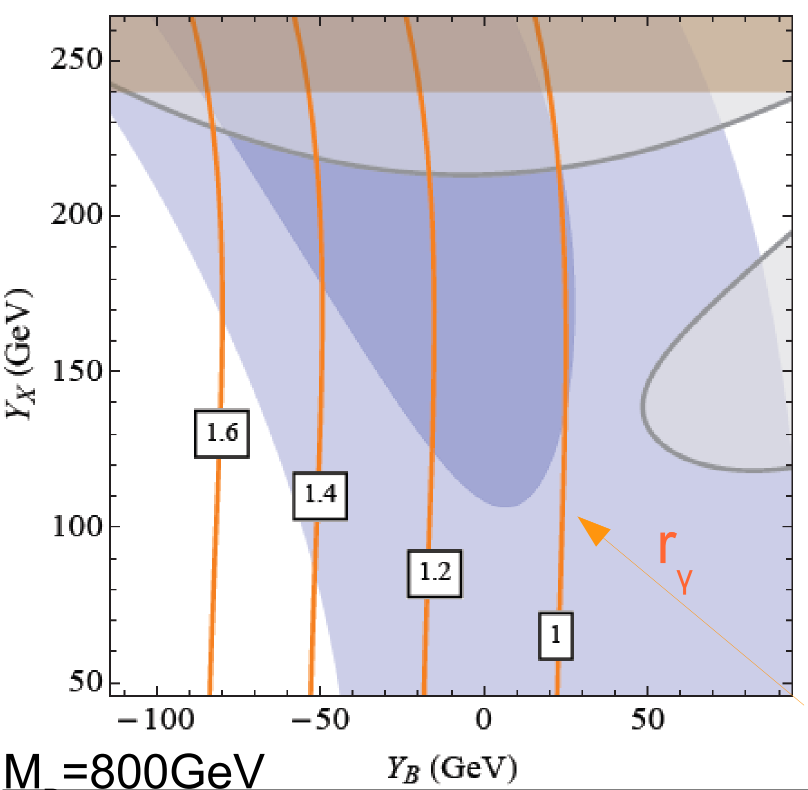
Batell, S.G., L.T.Wang, 1209.6382

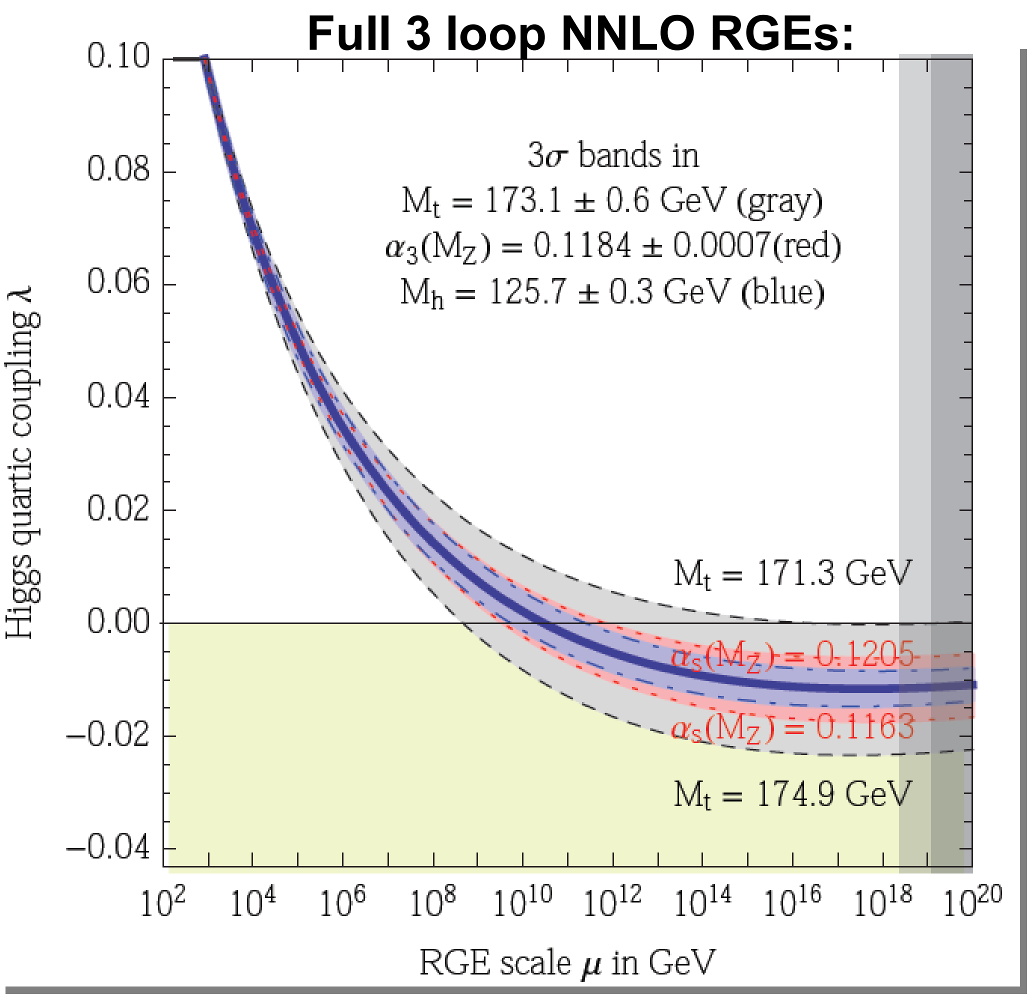


Effects in the Higgs pheno

What are the implications for the Higgs boson discovered by the LHC/ NP Higgs bosons ?

Vacuum stability

Buttazzo et.al. , 1307.3536



$$m_h\,(\mathrm{GeV}) > 129.1\ \mathrm{GeV} + 2.0\,(\mathrm{M_t} - 173.10\ \mathrm{GeV}) - 0.5\ \mathrm{GeV}\left(\frac{\alpha_s(\mathrm{M_Z}) - 0.1184}{0.0007}\right) \pm 0.3\ \mathrm{GeV}$$

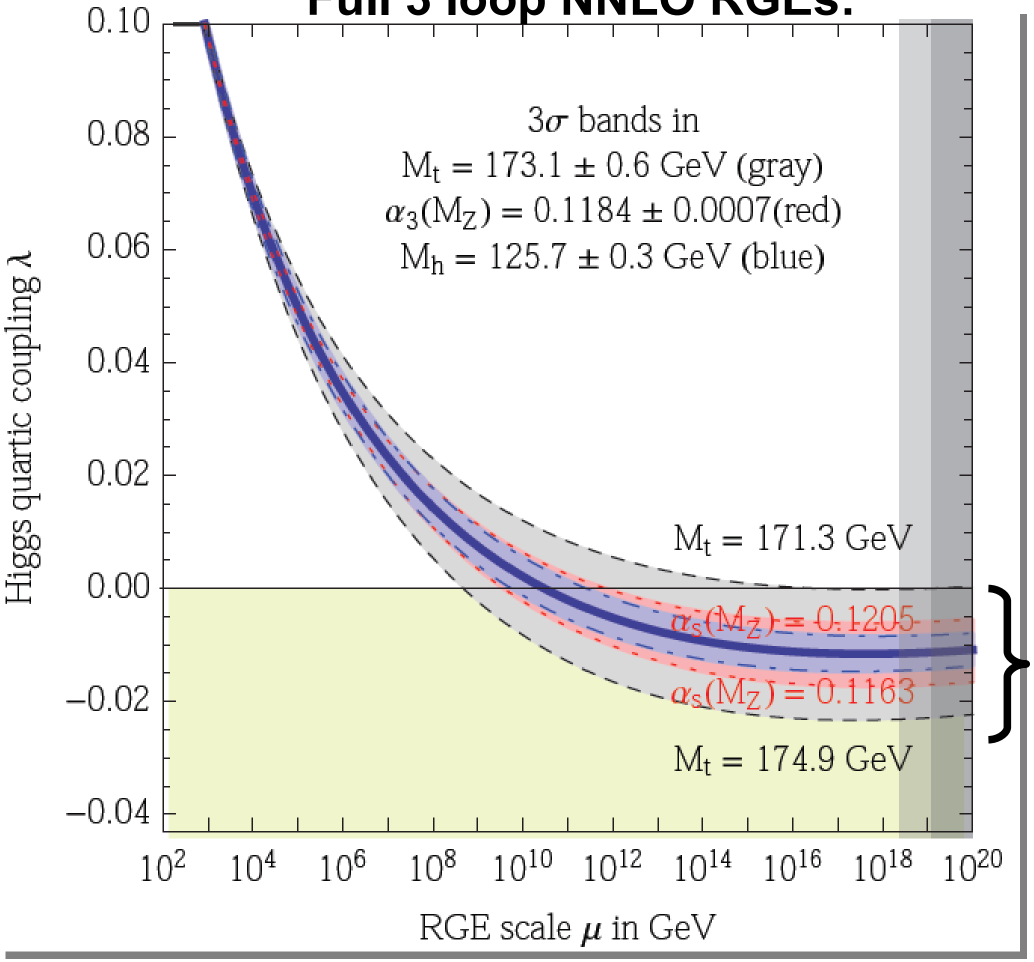
$$\Rightarrow \quad m_h > (129.1 \pm 1.5)\ \mathrm{GeV}$$ (stability condition)

Or viceversa in terms of the top mass: $m_t < (171.53 \pm 0.42)$ GeV

Vacuum stability

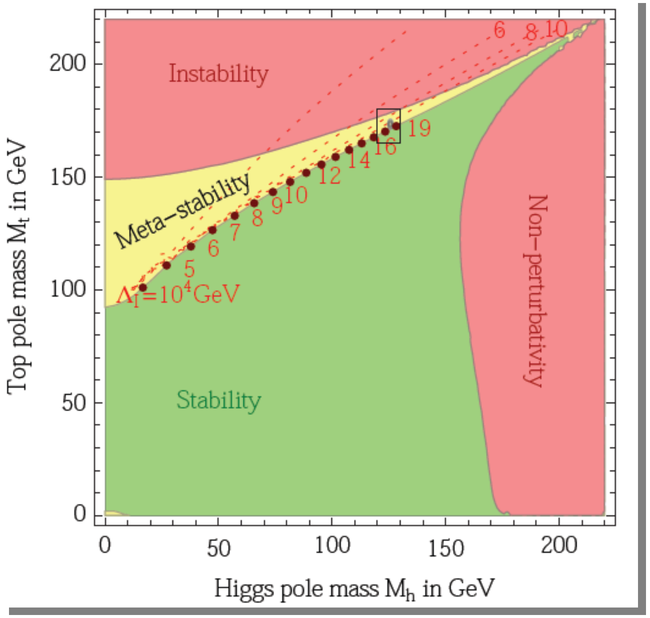
Buttazzo et.al. , 1307.3536

Full 3 loop NNLO RGEs:



Top mass uncertainty @ 3σ

We live in a metastable minimum at the 98.6% C.L. (~2.2σ)



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$$m_h > (129.1 \pm 1.5)\text{ GeV}$$ (stability condition)

Or viceversa in terms of the top mass: $m_t < (171.53 \pm 0.42)$ GeV

Higgs couplings and EWPTs

Huge experimental program in measuring the couplings of the Higgs boson to SM fermions and gauge bosons

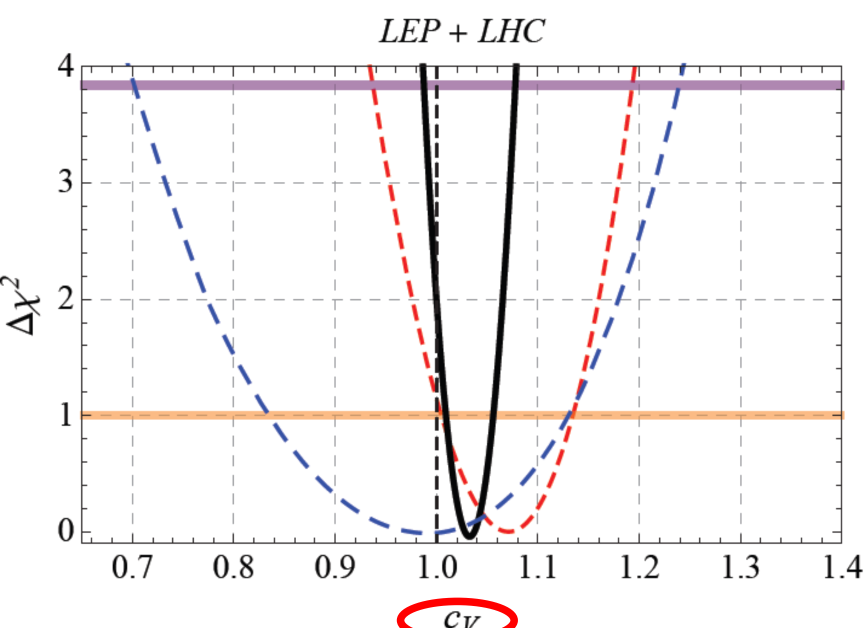
But what can EWPTs tell?

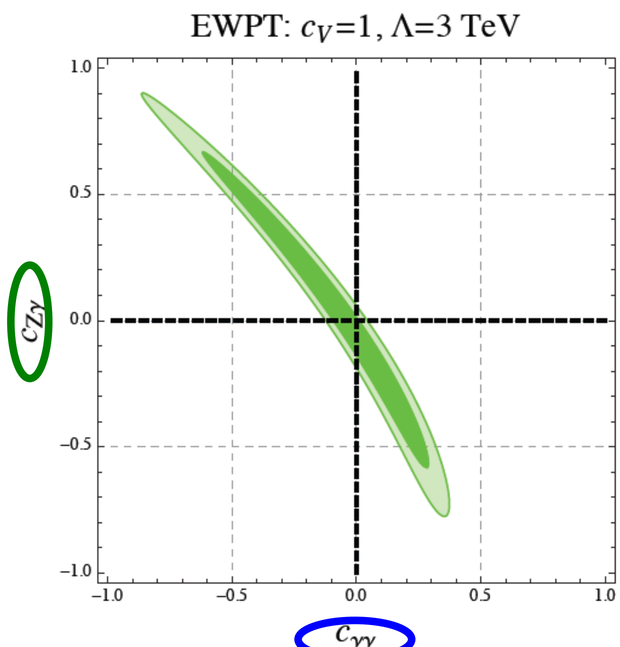
One can read the constraints in terms of the oblique parameters S, T, W, Y (≲ 0.1-0.2)

e.g.
$$\begin{cases} \alpha T \sim \frac{3g_y^2}{32\pi^2}\left(c_V^2 - 1\right)\log(\Lambda/m_Z) \\ \alpha W \sim \frac{g^2}{192\pi^2}\left(c_{\gamma\gamma} + \frac{g}{g_y}c_{\gamma Z}\right)^2 \log(\Lambda/m_Z) \end{cases}$$

$c_V,\ c_t,\ c_b,\ c_\tau,\ c_{gg},\ c_{\gamma\gamma},\ c_{Z\gamma}$

Falkowski et. al. 1303.1812





$C_V = 1.08 \pm 0.07$

$C_{\gamma\gamma} = 0.10 \pm 0.04$

More constrained by Higgs coupling meas.

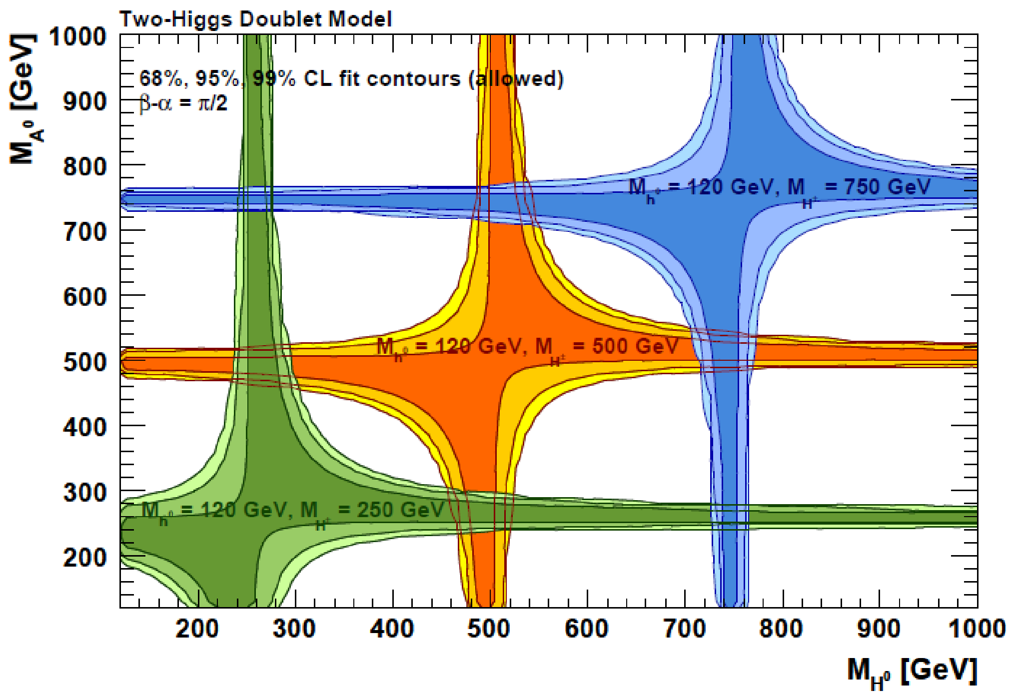
$C_{\gamma Z} = -0.04 \pm 0.06$

Comparably constrained by Higgs coupling meas.

Extended Higgs sectors and EWPTs

2HDMs:

splitting very much constrained:



Gfitter, 1107.0975

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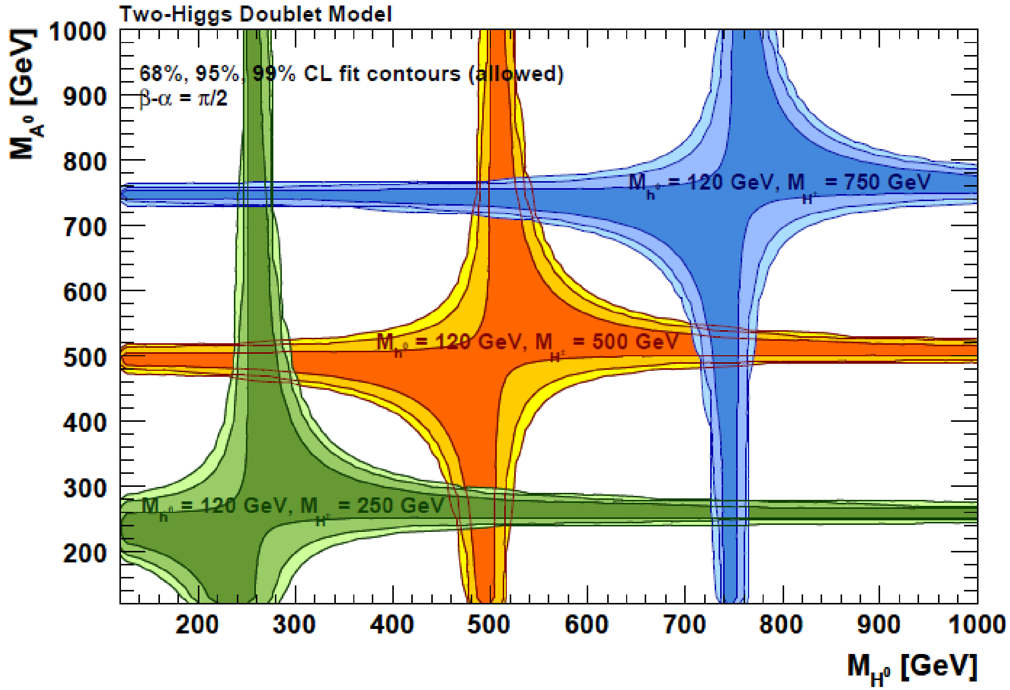
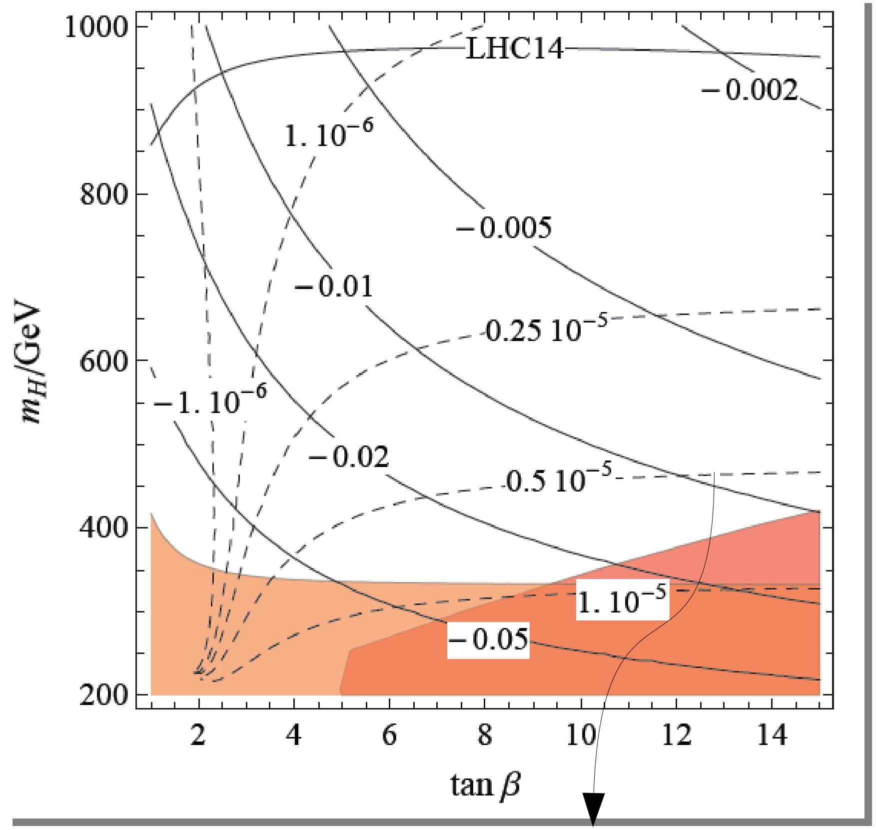


Gfitter, 1107.0975

A particular 2HDM: the MSSM



$\Delta\varepsilon_1$ (present bound ~ 5×10^{-4})

Barbieri, Tesi, 1311.7493

Flavor precision data

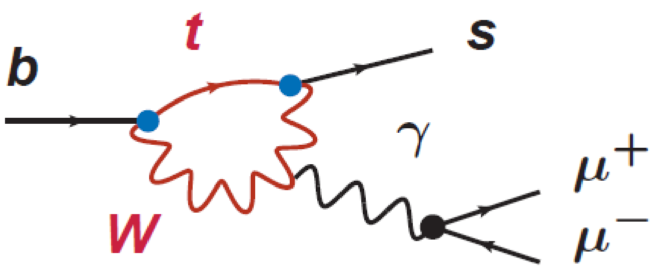
Why is it interesting?

In the SM

- Flavor changing neutral currents (FCNCs) arise only at the loop level.
- GIM mechanism suppresses these transitions even further.

⇒ Easy to get sizable NP effects in flavor transitions

Ex.



$$G \sim \frac{1}{16\pi^2}\frac{g^4}{m_W^2}\frac{m_t^2}{m_W^2}V_{tb}V_{ts}^*.$$

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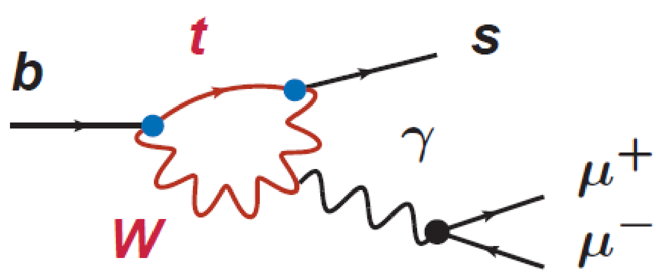
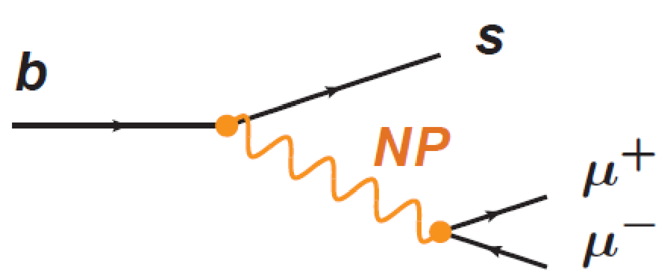


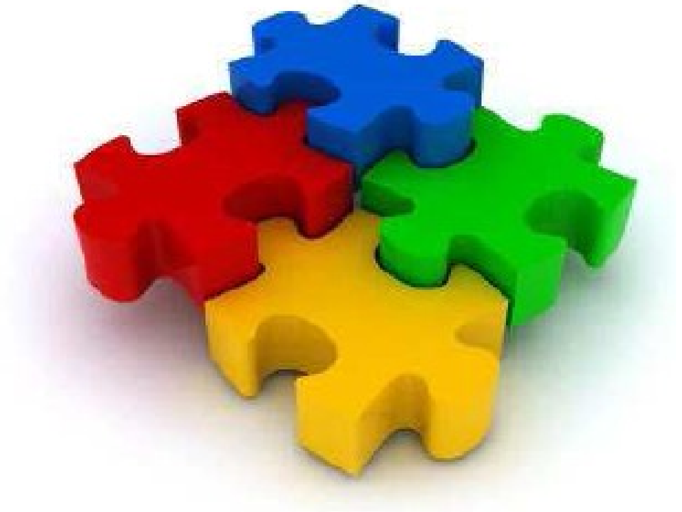


$$G \sim \frac{1}{16\pi^2}\frac{g^4}{m_W^2}\frac{m_t^2}{m_W^2}V_{tb}V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

Information on new physics
flavor couplings and mass scale

Huge experimental program: LHCb, Belle (II), Babar, Mu2e, ...

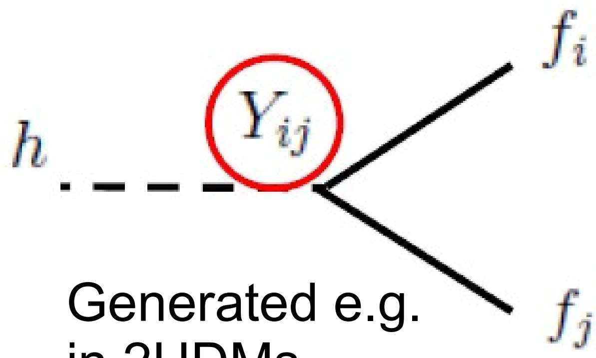
Flavor:
what can we learn on Higgs physics?



Higgs FCNCs

In the SM, Higgs flavor changing couplings are ~ 0

- Are sizable flavor violating Higgs couplings still allowed by flavor measurements?
- What can we see at the LHC? „unusual“ Higgs decays?



Generated e.g. in 2HDMs

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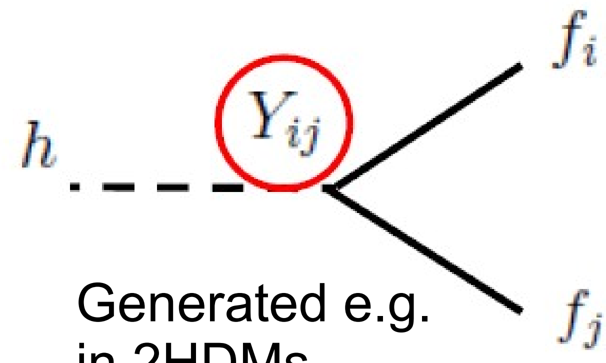


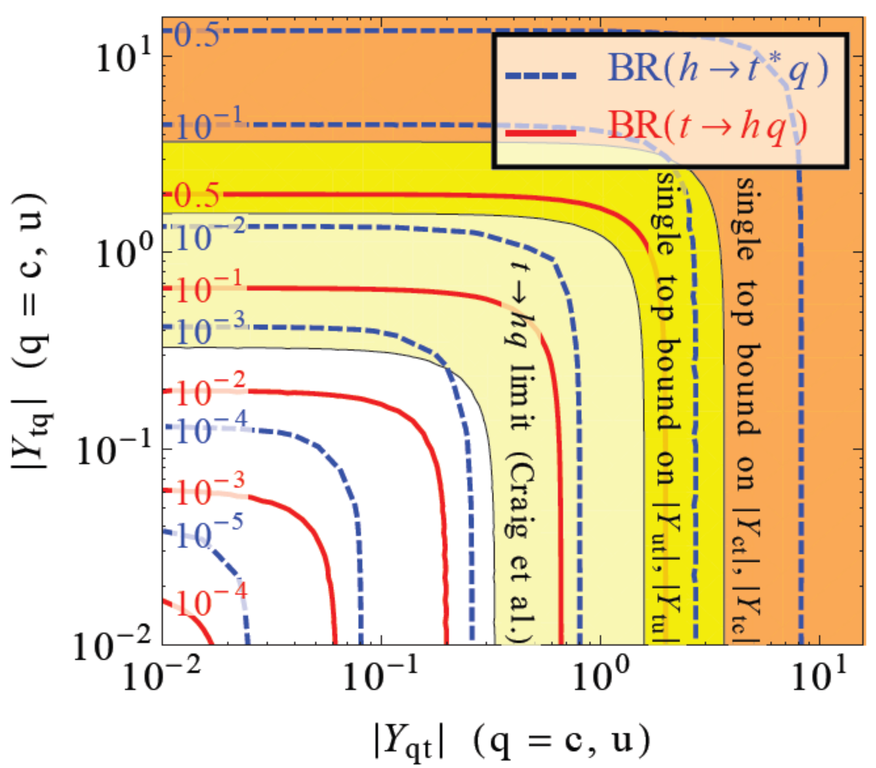
Generated e.g. in 2HDMs

In the quark sector

- Very strong constraints for transitions in the down sector and involving 1st and 2nd generations in the up sector

  e.g. Y_{sd}, $Y_{ds} \leq 10^{-12}$ (from Kaon mixing)

- Flavor transitions including the top are less constrained



Harnik, Kopp, Zupan, 1209.1397
(see also Davidson, Grenier, 1001.0434,
Goudelis et.al. 1111.1715,
Blankenburg, Ellis, Isidori, 1202.5704)

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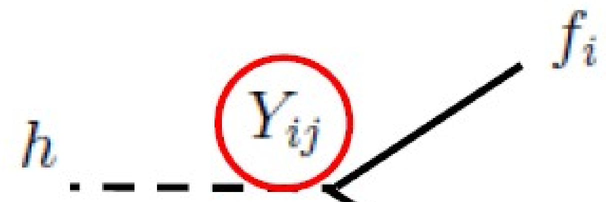


Generated e.g. in 2HDMs

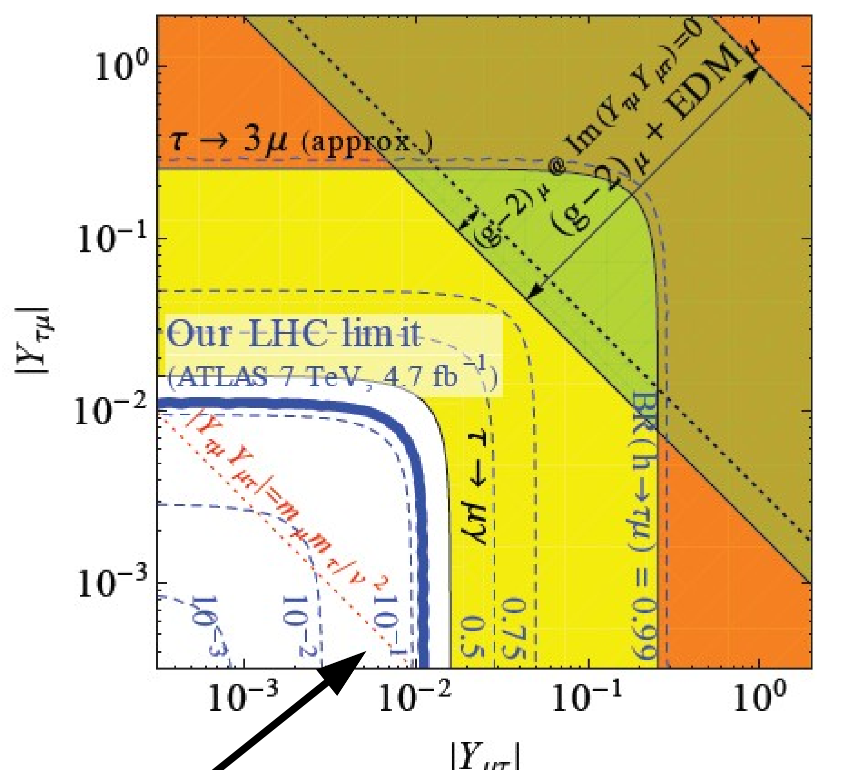
In the lepton sector

- Rather strong constraints for transitions involving 1st and 2nd generations

$$\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} \lesssim 3 \cdot 10^{-6}\, (3 \cdot 10^{-5})$$

(from μ→eγ, μ→3e)

- Transitions involving 3rd generation are weaker constrained



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(see also Davidson, Grenier, 1001.0434, Goudelis et.al. 1111.1715, Blankenburg, Ellis, Isidori, 1202.5704)

a spectacular signal can be expected in a dedicated search at the LHC

Constraints on extended Higgs sectors (tree)

What are the most constraining flavor observables?

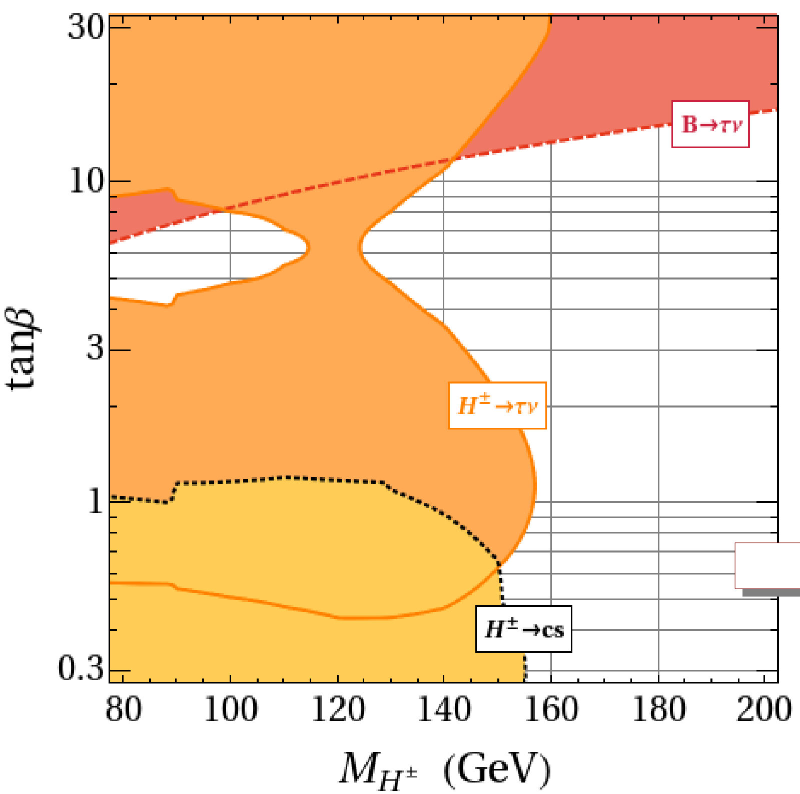
Belle/Babar measurement of the branching ratio of $B \to \tau\nu$

Last measurement: Belle 1208.4678: $(0.72^{+0.27}_{-0.25} \pm 0.11) \cdot 10^{-4}$

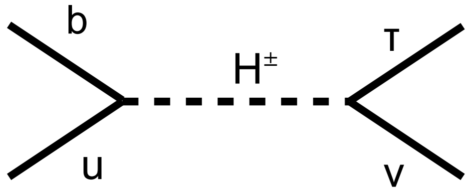
World average: PDG 2013: $(1.05 \pm 0.25) \cdot 10^{-4}$

SM prediction: $(1.11 \pm 0.27) \cdot 10^{-4}$

Expected precision
Belle II (50/ab): ± 5%



In type II 2HDMs light charged Higgs are strongly constrained



$$\frac{\mathrm{BR}}{\mathrm{BR_{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2} t_\beta^2\right)^2$$

LHC (and Tevatron) is looking for light charged Higgs:

$t \to bH^\pm,\ H^\pm \to \tau\nu$ ATLAS-CONF-2013-090 CMS-PAS-HIG-12-052

$t \to bH^\pm,\ H^\pm \to cs$ 1302.3694 (ATLAS)

Altmannshofer, SG, Kribs, 1210.2465

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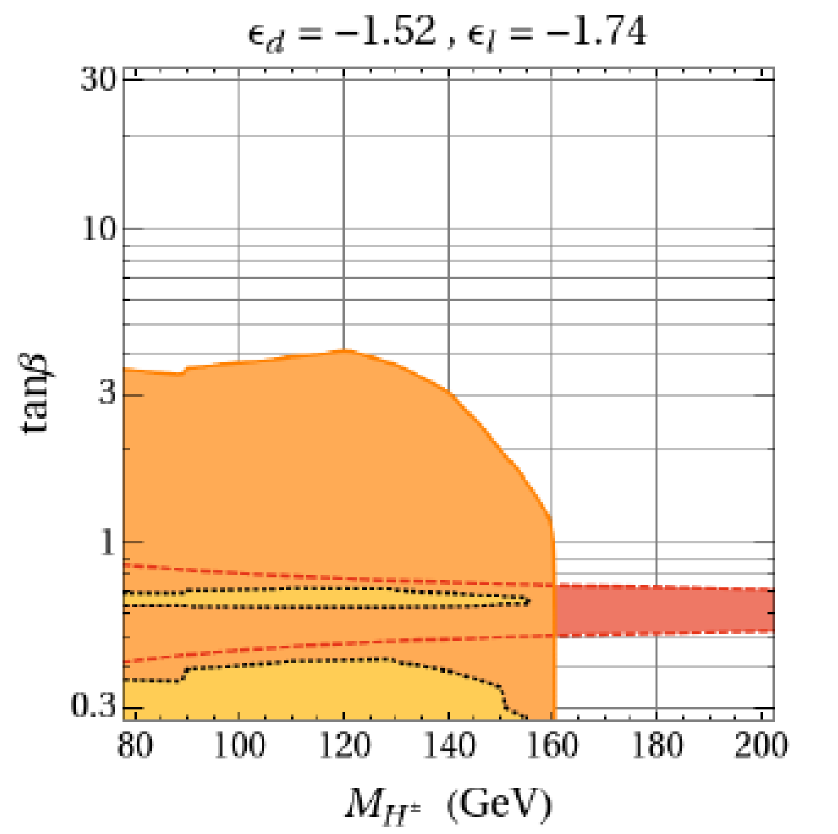


Important to keep an open mind...

In more general 2HDMs:

$$X_{d1}\bar{Q}_L D_R H_1 + X_{d2}\bar{Q}_L D_R H_2 + \text{h.c.} + \cdots$$

$$X_{d2} = \epsilon_d X_{d1}$$

$$\frac{\text{BR}}{\text{BR}_{\text{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2} \frac{t_\beta^2}{(1+\epsilon_d t_\beta)(1+\epsilon_\tau t_\beta)}\right)^2$$

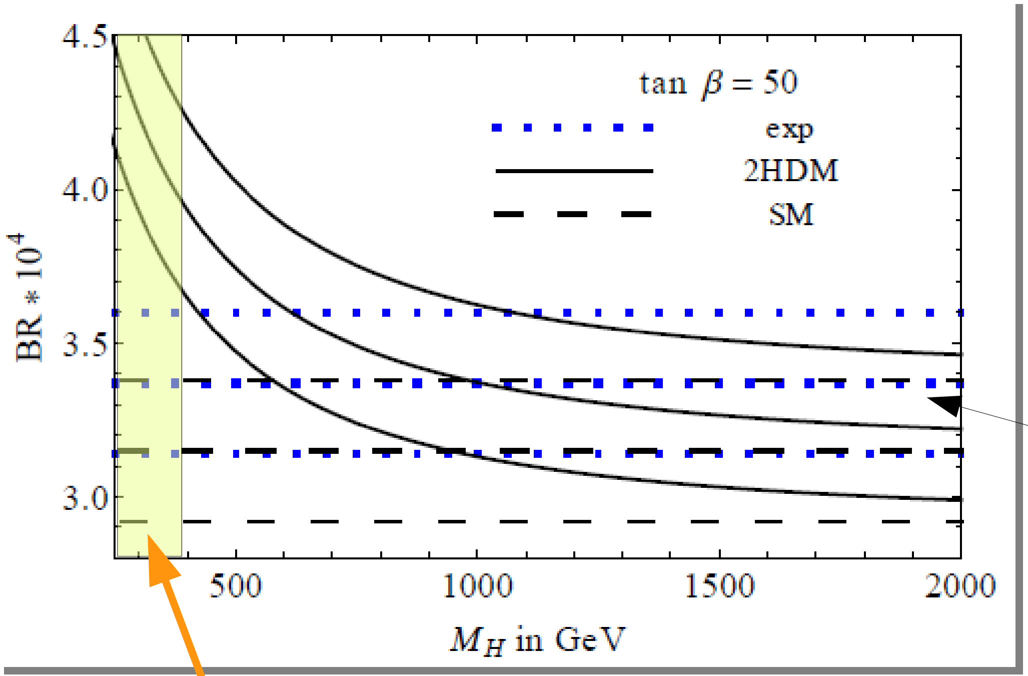
(see also Blankenburg, Isidori, 1107.1216)

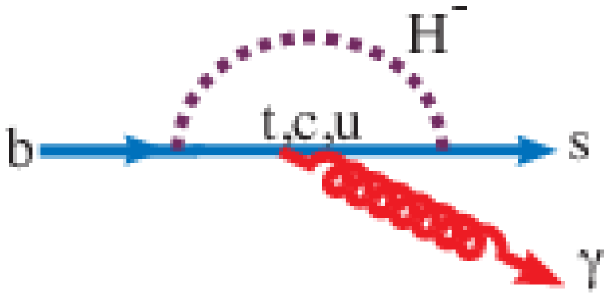
Altmannshofer, SG, Kribs, 1210.2465

Constraints on extended Higgs sectors (loop)

What are the most constraining flavor observables?

Belle/Babar measurement of the branching ratio of $b \to s\gamma$





Combination of CLEO, Belle and Babar

Hermann, Misiak, Steinhauser, 1208.2788

$m_{H^\pm} \gtrsim 380\,\mathrm{GeV}$ Fairly independent on the value of tanβ

Warning: model dependence!

Constraints on extended Higgs sectors (loop)

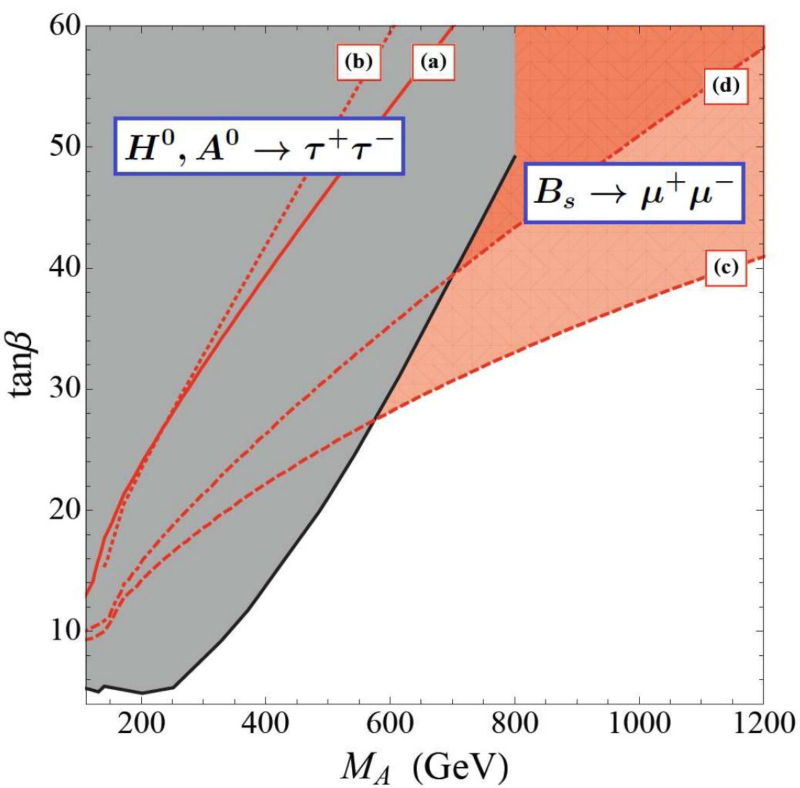
What are the most constraining flavor observables?

LHCb measurement of the branching ratio of $\boxed{B_s \to \mu\mu}$

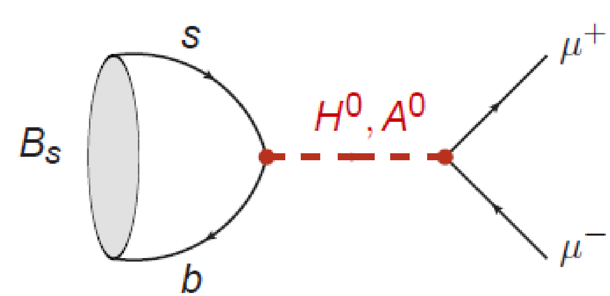
Combination LHCb, CMS measurements
LHCb-CONF-2013-012, CMS-PAS-BPH-13-007 $(2.9 \pm 0.7) \cdot 10^{-9}$

SM prediction: Bobeth et.al. 1311.0903 $(3.65 \pm 0.23) \cdot 10^{-9}$

Expected precision
LHCb (50/fb): ± 5%



Altmannshofer, Carena, Shah, Yu, 1211.1976



$$\text{MSSM} \propto \frac{\tan^3\beta}{M_A^2}$$

Conclusions

Higgs physics in our times

LHC direct measurements

<u>Higgs properties</u>
(mass, width, couplings, exotic decays and productions modes, ...)

<u>Search for new scalar degrees of freedom</u>

Indirect measurements

(LEP, SLC, Tevatron, LHCb, BelleII, ...)

<u>Electroweak precision observables</u>

<u>Flavor transitions</u>

Complementarity in the discovery of the unknown

Details on the vacuum stability computation

Buttazzo et.al. , 1307.3536

Renormalisation Group Equations

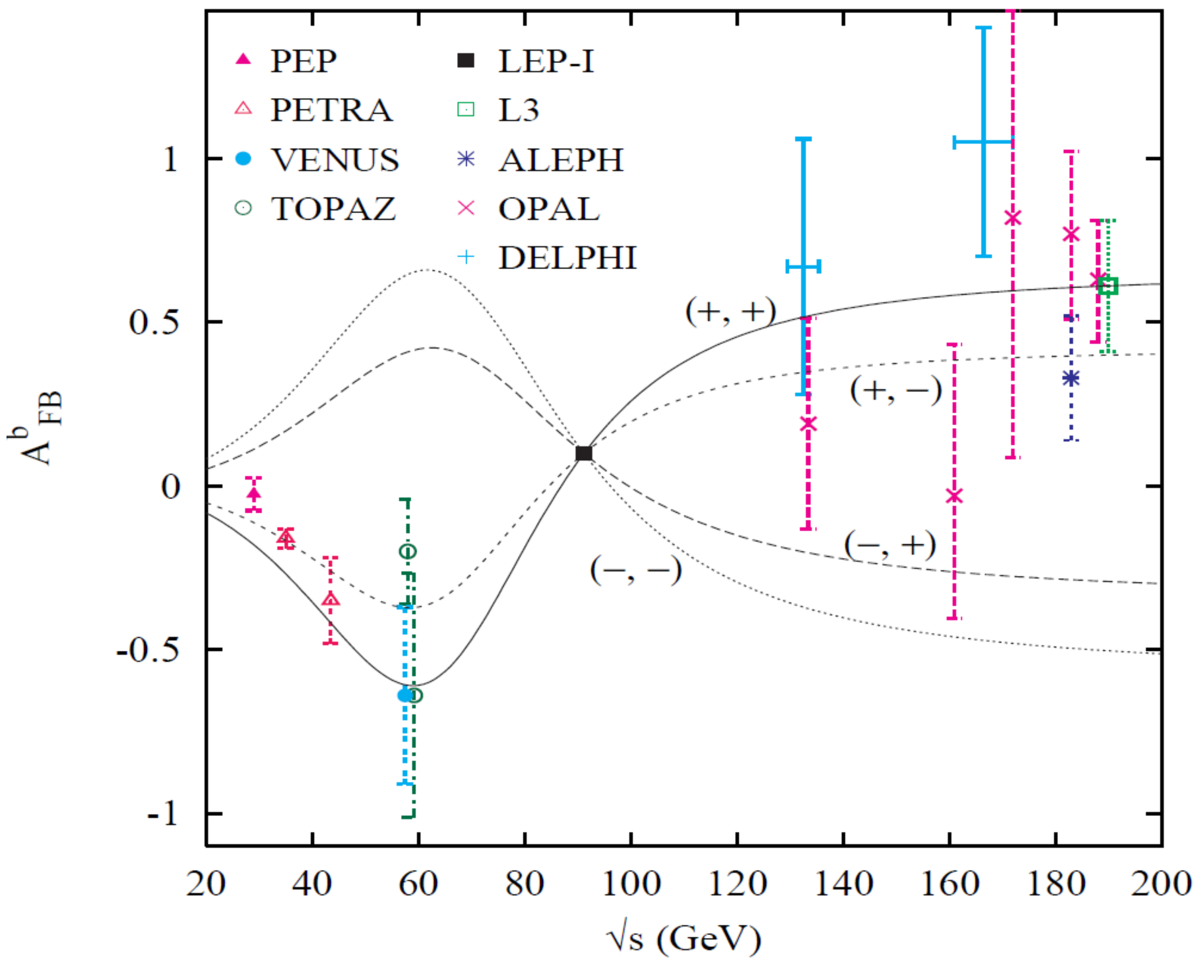
	LO 1 loop	NLO 2 loop	NNLO 3 loop	NNNLO 4 loop
g_3	full [53, 54]	$\mathcal{O}(\alpha_3^2)$ [55, 56] $\mathcal{O}(\alpha_3\alpha_{1,2})$ [61] full [63]	$\mathcal{O}(\alpha_3^3)$ [57, 58] $\mathcal{O}(\alpha_3^2\alpha_t)$ [62] full [64, 65]	$\mathcal{O}(\alpha_3^4)$ [59, 60]
$g_{1,2}$	full [53, 54]	full [63]	full [64, 65]	—
y_t	full [66]	$\mathcal{O}(\alpha_t^2, \alpha_3\alpha_t)$ [67] full [70]	full [68, 69]	—
λ, m^2	full [66]	full [71, 72]	full [73, 74]	—

Threshold corrections at the weak scale

	LO 0 loop	NLO 1 loop	NNLO 2 loop	NNNLO 3 loop
g_2	$2M_W/V$	full [75, 76]	full [This work]	—
g_Y	$2\sqrt{M_Z^2 - M_W^2}/V$	full [75, 76]	full [This work]	—
y_t	$\sqrt{2}M_t/V$	$\mathcal{O}(\alpha_3)$ [77] $\mathcal{O}(\alpha)$ [81]	$\mathcal{O}(\alpha_3^2, \alpha_3\alpha_{1,2})$ [34] full [This work]	$\mathcal{O}(\alpha_3^3)$ [78–80]
λ	$M_h^2/2V^2$	full [82]	for $g_{1,2} = 0$ [4] full [This work]	—
m^2	M_h^2	full [82]	full [This work]	—

Off-peak data

Choudhury, Tait, Wagner, 0109097



A little bit better fit for the „non-SM" like solution (+,-)

(updated values)

$$(g_L^{\rm fit}, g_R^{\rm fit}) \sim (\pm 0.997 g_L^{\rm SM}, \pm 1.22 g_R^{\rm SM})$$

Ingredients going into the fit

- Observables

$$m_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ R_\ell,\ R_c,\ R_b,$$
$$A^\ell_{FB},\ A_\ell,\ A_c,\ A_b,\ A^c_{FB},\ A^b_{FB},\ \sin^2\theta_{\rm eff},$$
$$m_W,\ \Gamma_W,\ m_t,\ \Delta\alpha^{(5)}_{\rm had},\ m_h.$$

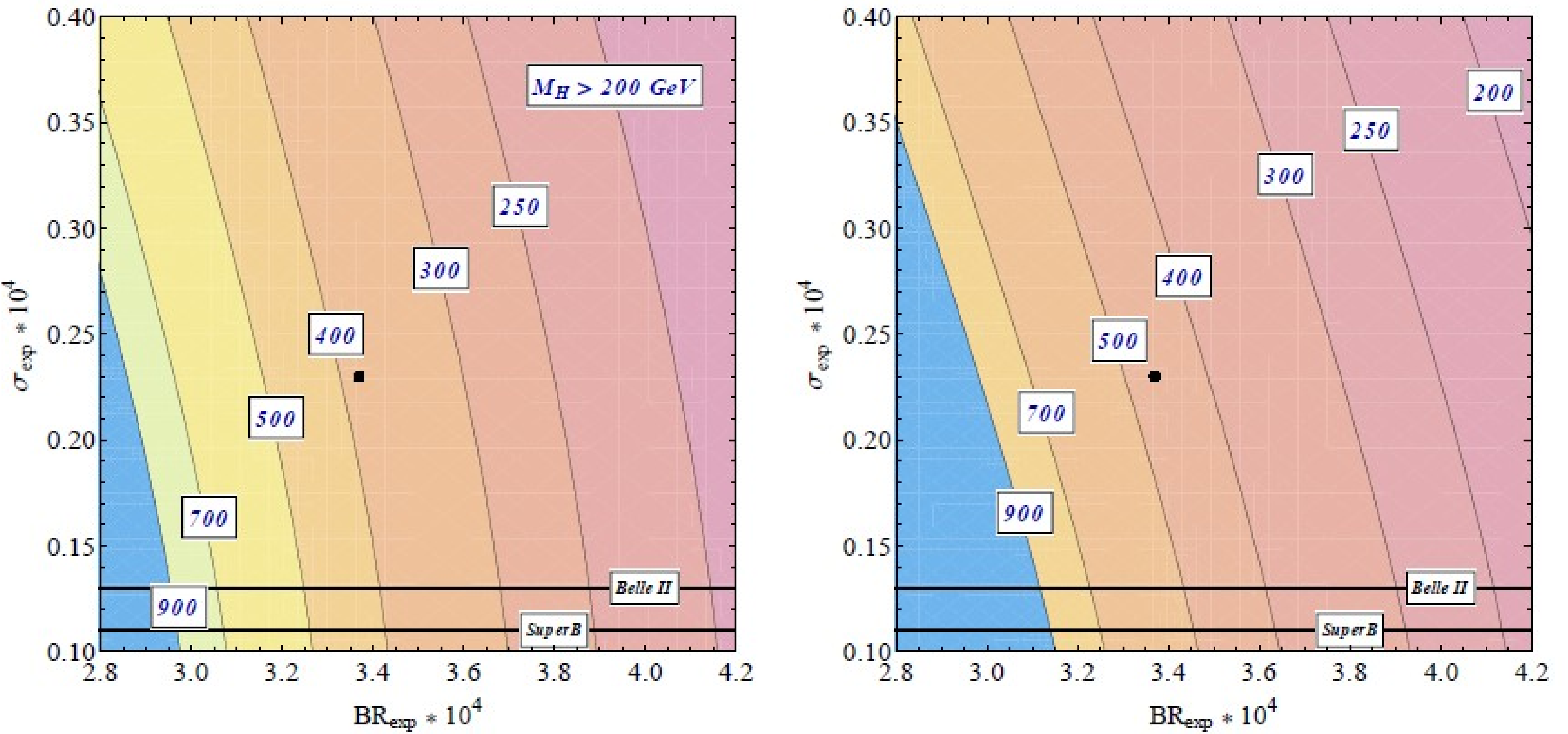
- Vary SM + NP parameters in fit

$$m_h, m_Z, m_t, \Delta\alpha^{(5)}_{\rm had}, \alpha_s$$
$$S, T, \delta g_{Lb}, \delta g_{Rb}$$

- Theory predictions taken from various numerical parameterizations in literature...

Parameter	Input value
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4
M_W [GeV]	80.385 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010
A_ℓ $^{(\star)}$	0.1499 ± 0.0018
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$
m_t [GeV]	173.18 ± 0.94
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\triangledown)}$	2757 ± 10
$\alpha_s(M_Z^2)$	–

Projections for b⟶sγ



From Hermann, Misiak, Steinhauser, 1208.2788

A custodial extension (1)

Batell, SG, Wang, '12

Field content:

$$\Psi_{L,R} = (B, X) \sim (3, 2, -5/6)$$
$$\hat{B}_{L,R} \sim (3, 1, -1/3)$$
$$\hat{X}_{L,R} \sim (3, 1, -4/3)$$

All fields can be embedded in representations of $SU(2)_L \times SU(2)_R \times U(1)_X$

$$\Psi_{L,R} = (B, X) \sim (2, 1)_{-5/6}$$
$$\hat{\Psi}_{L,R} = (\hat{B}, \hat{X}) \sim (1, 2)_{-5/6}$$

Such representations can find motivation in composite Higgs models

Agashe, Contino, Da Rold, Pomarol '06

A custodial extension (2)

- Most general Lagrangian

$$
\begin{aligned}
-\mathcal{L} \supset\ & M_1 \bar{\Psi}'_L \Psi'_R + M_2 \bar{\hat{B}}'_L \hat{B}'_R + M_3 \bar{\hat{X}}'_L \hat{X}'_R \\
+\ & y_1 \bar{Q}'_L H b'_R + y_2 \bar{Q}'_L H \hat{B}'_R \\
+\ & y_3 \bar{\Psi}'_L \tilde{H} b'_R + y_4 \bar{\Psi}'_L \tilde{H} \hat{B}'_R \\
+\ & y_5 \bar{\hat{B}}'_L \tilde{H}^\dagger \Psi'_R \\
+\ & y_6 \bar{\Psi}'_L H \hat{X}'_R \\
+\ & y_7 \bar{\hat{X}}'_L H^\dagger \Psi'_R + \text{h.c.}
\end{aligned}
$$

$$
\begin{pmatrix} Y_1 & 0 & Y_2 \\ Y_3 & M_1 & Y_4 \\ 0 & Y_5 & M_2 \end{pmatrix}_{\mathbf{B}}, \quad \begin{pmatrix} M_1 & Y_6 \\ Y_7 & M_3 \end{pmatrix}_{\mathbf{X}}
$$

- Custodial limit: $y_2=y_3=0$, $M_2=M_3$, $y_4=y_6$, $y_5=y_7$
- Direct searches for vector-like quarks tell us that M_i should be rather heavy (see later for details)
- We can integrate out the heavy fermions and expand in terms of Y_i/M_j

In particular $\delta g_{Lb} = \dfrac{Y_2{}^2}{2M_2^2}$, $\delta g_{Rb} = \dfrac{Y_3{}^2}{2M_1^2}$

They break the custodial symmetry **BUT** only small values are required

Extension of the minimal model

Batell, S.G., L.T.Wang, 1209.6382

One can further improve the EW fit by adding an SU(2) singlet quark $\hat{B}' \sim (3,1,-1/3)$ that mixes with the bottom of the SM

a shift δg_{Lb}~0.001 can arise

δg_{Lb}

$$\begin{array}{ccc} (2,1/6) & (2,-5/6) & (1,-1/3) \\ \end{array}$$

$$\begin{pmatrix} b'_L & B'_L & \hat{B}_L \end{pmatrix} \begin{pmatrix} Y_1 & 0 & Y_2 \\ Y_3 & M & Y_4 \\ 0 & Y_5 & M_2 \end{pmatrix} \begin{pmatrix} b'_R \\ B'_R \\ \hat{B}'_R \end{pmatrix} \begin{array}{c} (1,-1/3) \\ (2,-5/6) \\ (1,-1/3) \end{array}$$

δg_{Rb}

Higgs pheno

Large Y_4, Y_5 can alter Higgs rates, but also cause large <u>custodial symmetry breaking</u> (mixing between the singlet and the doublet of SU(2))

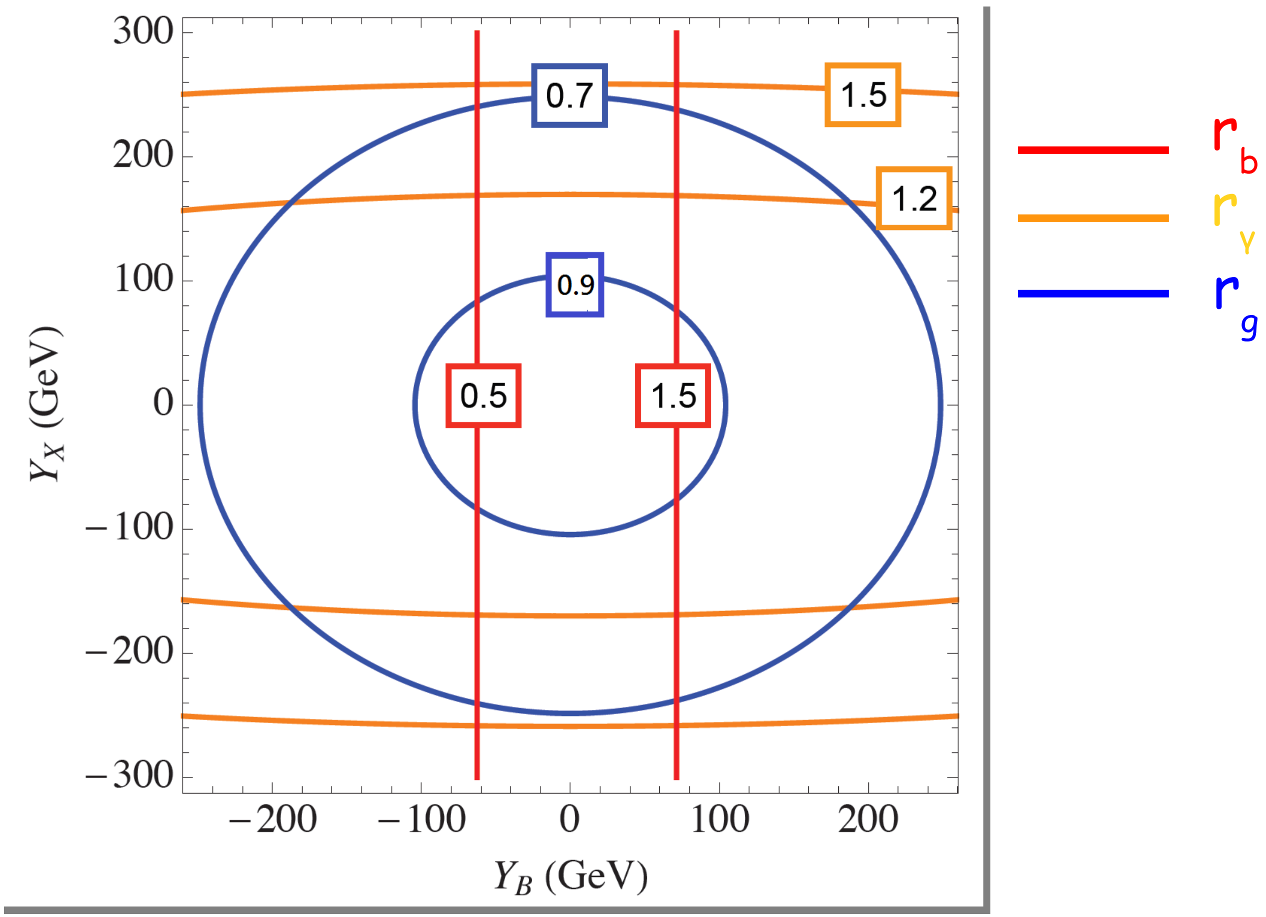
Problems with the T parameter!

NP effects in the Higgs pheno

The three effects mentioned before:

$$r_\gamma \sim \left|1 + 0.13\left(\frac{Y_4 Y_5}{M_1 M_2} + 16\frac{Y_6 Y_7}{M_1 M_3}\right)\right|^2 \qquad r_b \sim 1 + 8\sqrt{\delta g_{Lb}\delta g_{Rb}}\frac{Y_5}{m_b}$$

$$r_g \sim \left|1 - 2.1\left(\frac{Y_4 Y_5}{M_1 M_2} + \frac{Y_6 Y_7}{M_1 M_3}\right)\right|^2$$



Trading parameters

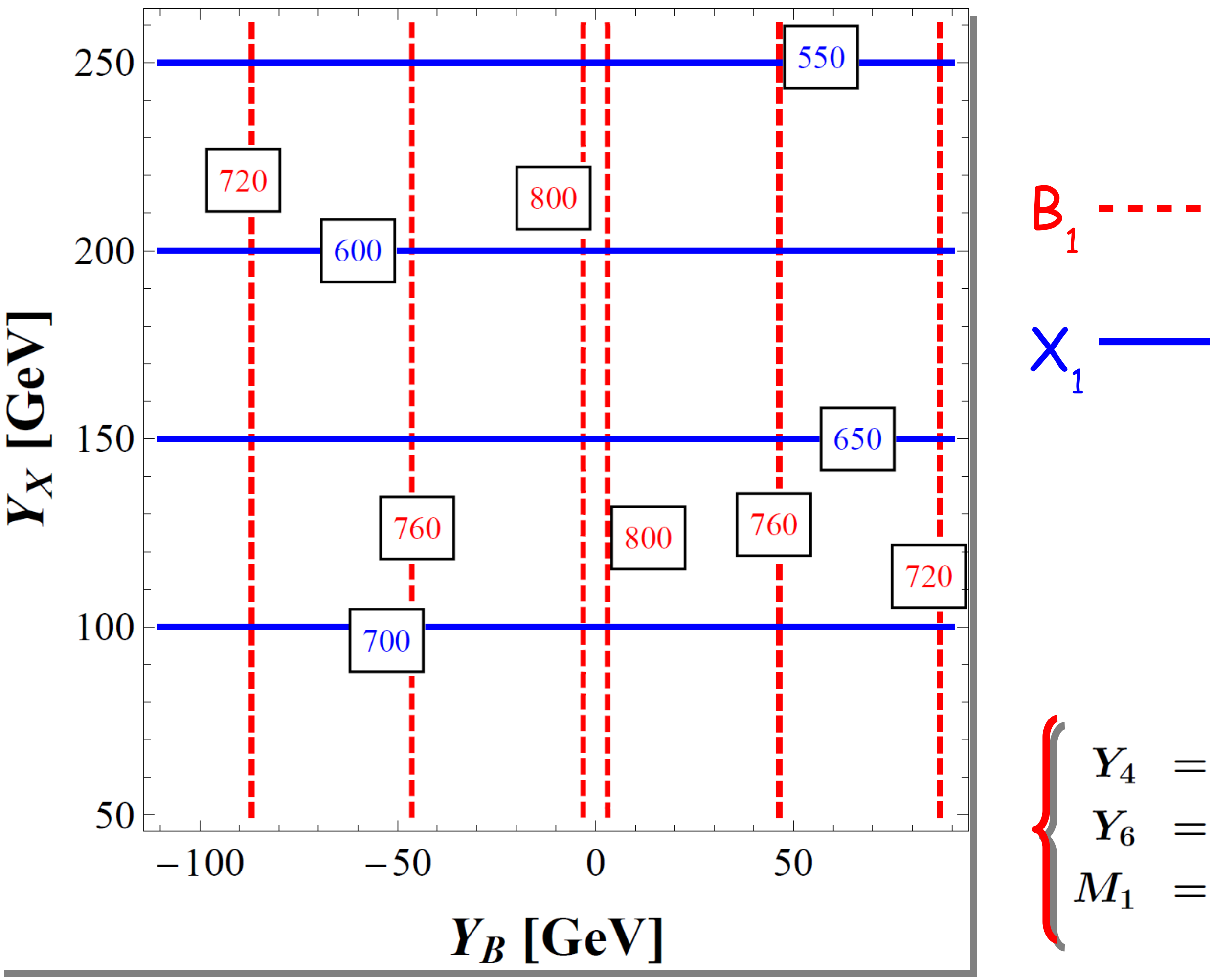
$$\begin{pmatrix} Y_1 & 0 & Y_2 \\ Y_3 & M_1 & Y_4 \\ 0 & Y_5 & M_2 \end{pmatrix}, \begin{pmatrix} M_1 & Y_6 \\ Y_7 & M_3 \end{pmatrix}$$

$$\begin{aligned} \delta g_{Lb} &\leftrightarrow Y_2 \\ \delta g_{Rb} &\leftrightarrow Y_3 \\ m_b &\leftrightarrow Y_1 \end{aligned}$$

$$\left\{\begin{aligned} Y_4 &= Y_5 = Y_B \\ Y_6 &= Y_7 = Y_X \\ M_1 &= M_2 = M_3 = 800\,\mathrm{GeV} \end{aligned}\right.$$

Pheno of vector-like quarks

Masses of the lightest B and X VL quark



X and B decays

- X → bW
- X → BW (kinematically not allowed)
- B → tW (suppressed)
- B → bZ
- B → bh

Comparable values

$$\begin{cases} Y_4 = Y_5 = Y_B \\ Y_6 = Y_7 = Y_X \\ M_1 = M_2 = M_3 = 800\,\mathrm{GeV} \end{cases}$$

VL quarks are mainly produced in pairs: $pp \to X\bar{X},\ B\bar{B}$