B-meson anomalies and Higgs physics

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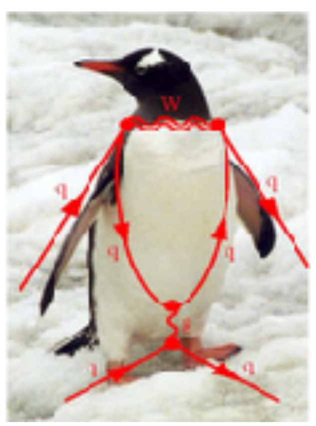
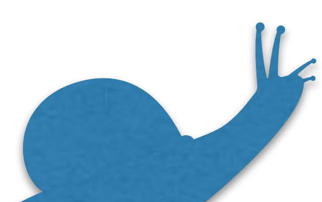


L. Bian, S.-M. Choi, Y.-J. Kang, HML, Phys. Rev. D96 (2017) 075038;
L. Bian, HML, C.B. Park, EPJ C78, 306 (2018)



APCTP FRP meeting on Charged Higgs
Konkuk Univ, Sep 1, 2018

Outline

- Introduction
- Minimal flavored U(1)’
- Z’-2HDM
- Higgs production at LHC
- Conclusions

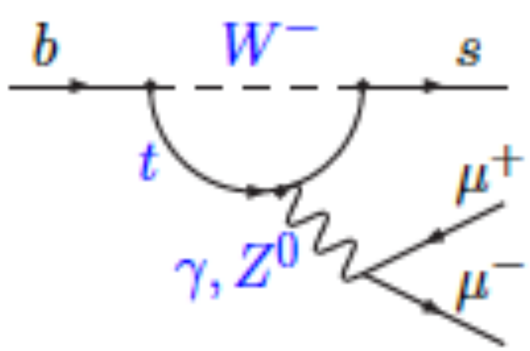
FCNC in SM

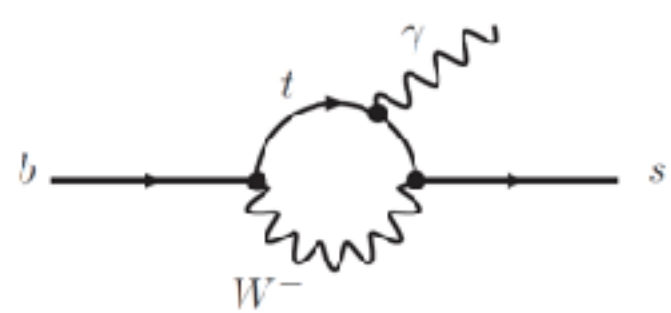
- "Charged currents" induce flavor violating processes at tree level, while FCNCs are induced at loop level.

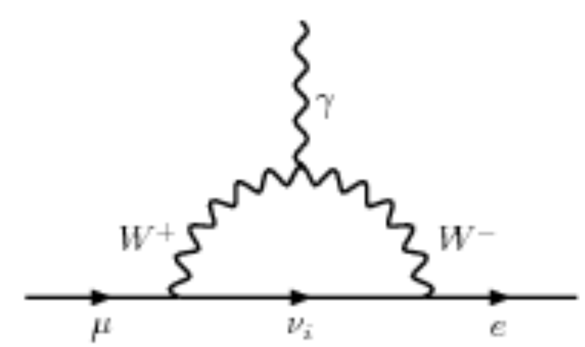
$$\frac{-g}{\sqrt{2}}(u_L, c_L, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}, \qquad V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

$$V_{\rm CKM} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

- "FCNC processes" are sensitive probes to a violation of lepton flavors & universal interactions, due to new physics.







Extended Higgs sector

- Higgs sector is extended in models with supersymmetry, flavor symmetries, new gauge symmetries, etc, but we need to have CP/ flavor violations under control.

$$\mathcal{L}_Y = -\lambda_{ijk} H_i \bar{\psi}_{Lj} \psi_{Rk} + \mathrm{h.c.} \quad \xrightarrow[M_{jk} \neq \lambda_{ijk}]{} \quad \text{CP/ flavor violations?}$$

- Singlet extensions are always possible, coupled indirectly through Higgs portal: No FCNC but Higgs productions/ decays are modified.

$$\mathcal{L}_S = -\lambda_{HS_i} S_i^2 |H|^2$$

- In two Higgs doublet models, discrete symmetries such as Z_2 are imposed for no tree-level FCNC.

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

[Banco et al, 1106.0034]

Addendum to 2HDM

[Banco et al, 1106.0034]

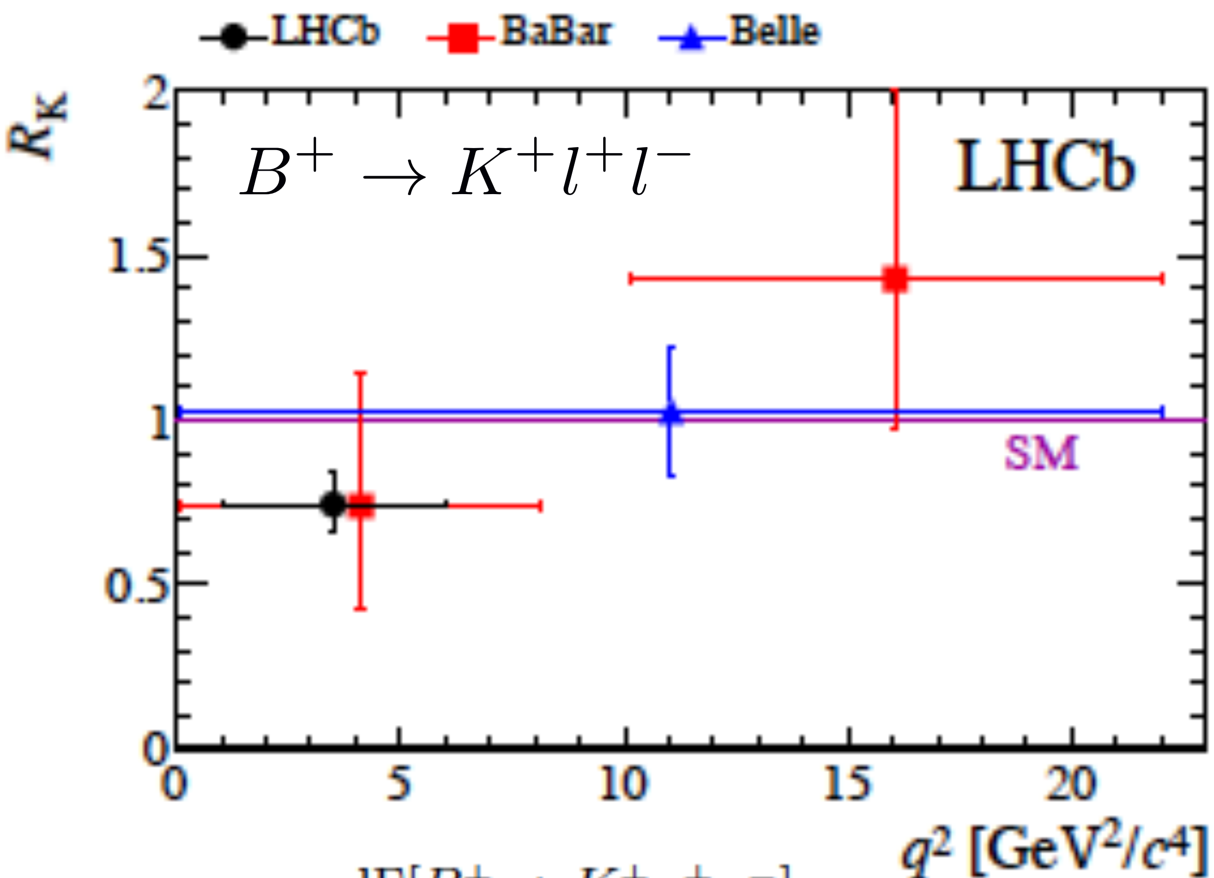
	Type I	Type II	Lepton-specific	Flipped	Z'-2HDM
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta + \Delta_u\delta_{33}$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta + \Delta_d\delta_{i3}$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\tan\beta - \Delta_u\delta_{33}$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$	$-\tan\beta + \Delta_d\delta_{i3}$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$	$-\tan\beta$

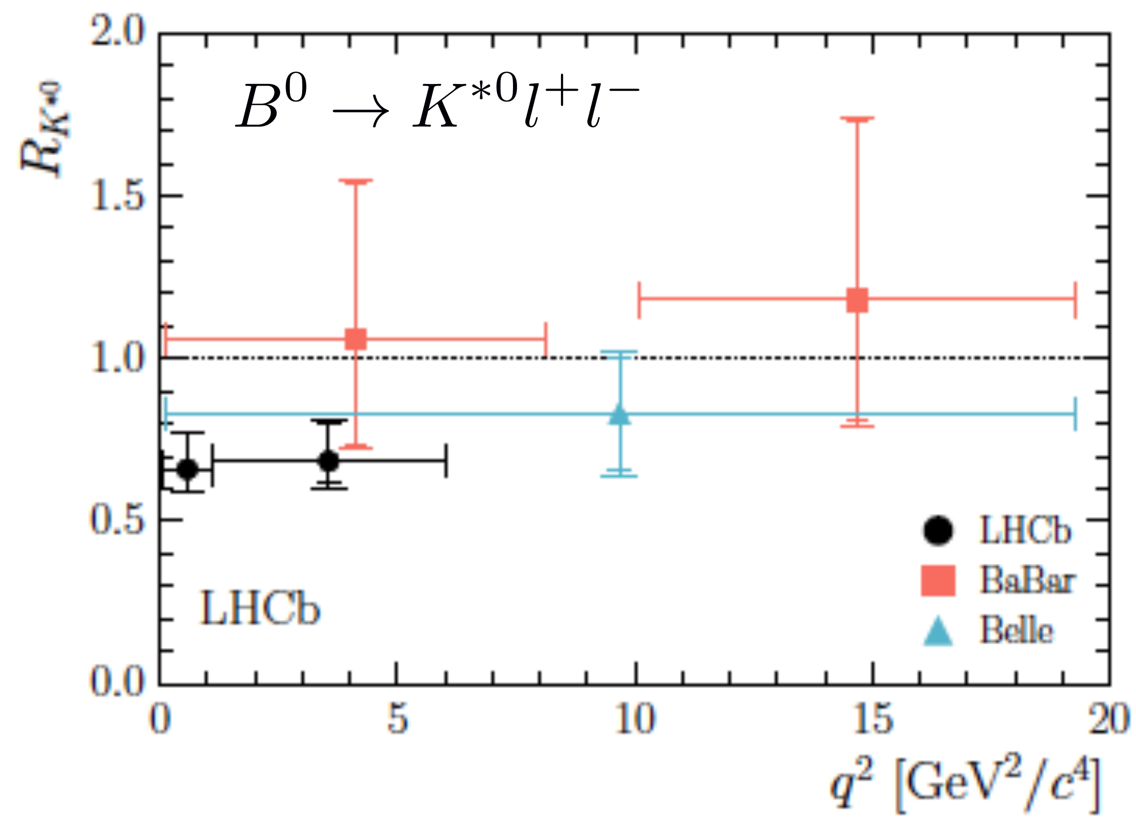
$$\mathcal{L}^{\text{2HDM}}_{\text{Yukawa}} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - i\xi_A^f \overline{f}\gamma_5 f A\right)$$
$$-\left\{\frac{\sqrt{2}V_{ud}}{v}\,\overline{u}\left(m_u\xi_A^u \mathrm{P}_L + m_d\xi_A^d \mathrm{P}_R\right) dH^+ + \frac{\sqrt{2}m_\ell\xi_A^\ell}{v}\,\overline{\nu_L}\ell_R H^+ + \text{H.c.}\right\}$$

$$\Phi_1 \leftrightarrow \Phi_2$$
$$(\beta \to \beta - \frac{\pi}{2},\quad \alpha \to \alpha + \frac{\pi}{2})$$

2HDM-Type I like, except the 3rd generation quark couplings for heavy Higgs:
flavor-conserving top, flavor-violating bottom.

B-anomalies at LHCb





$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst}).$$

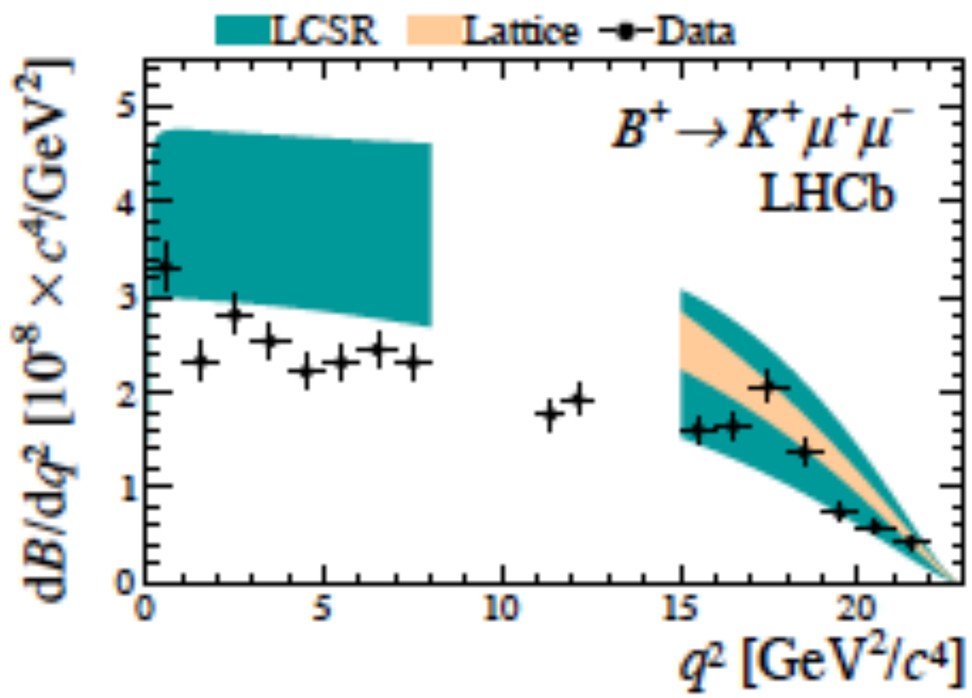
$$1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2$$

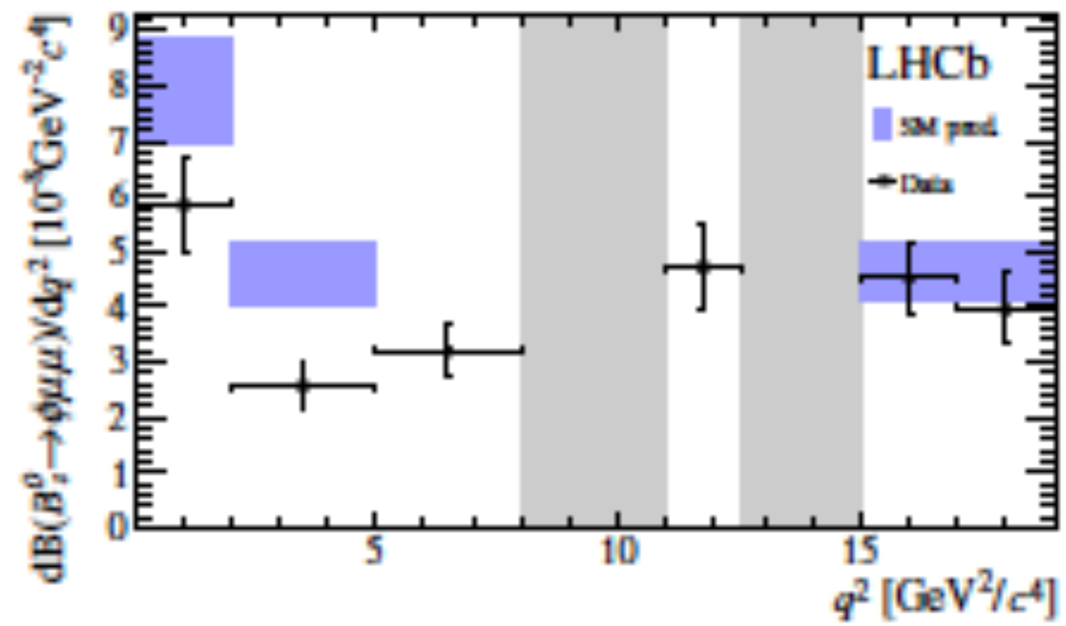
LHCb Preliminary	**low-q^2**	**central-q^2**
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\,0.110}_{-\,0.070} \pm 0.024$	$0.685\ ^{+\,0.113}_{-\,0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

- R_K: 2.6σ deviation; R_{K^*}: 2.2-2.4σ deviation and 2.4-2.5σ deviation.

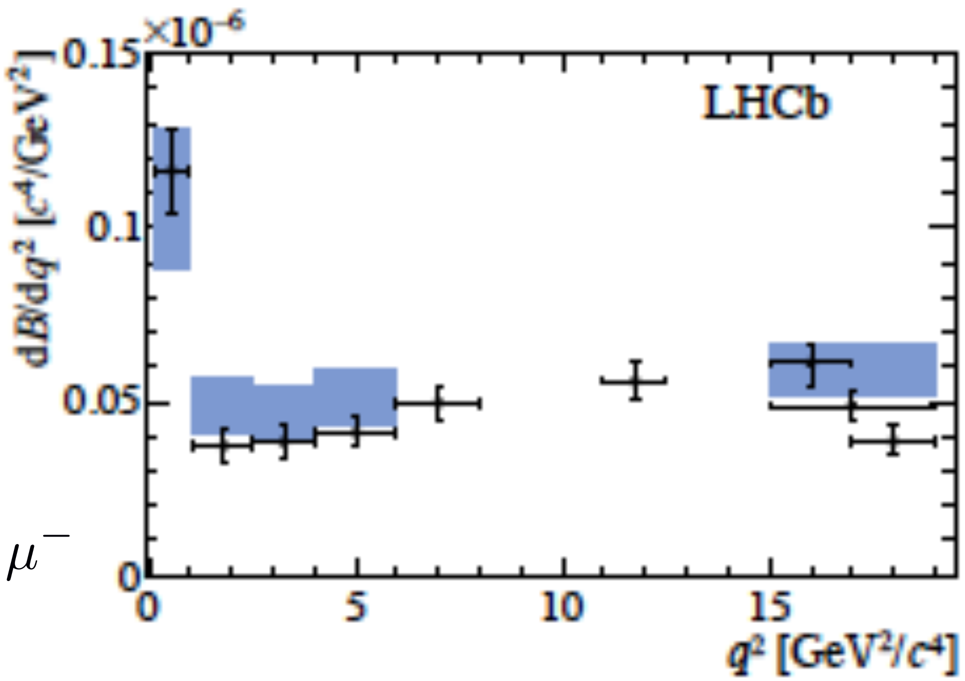
lepton flavor non-universality?

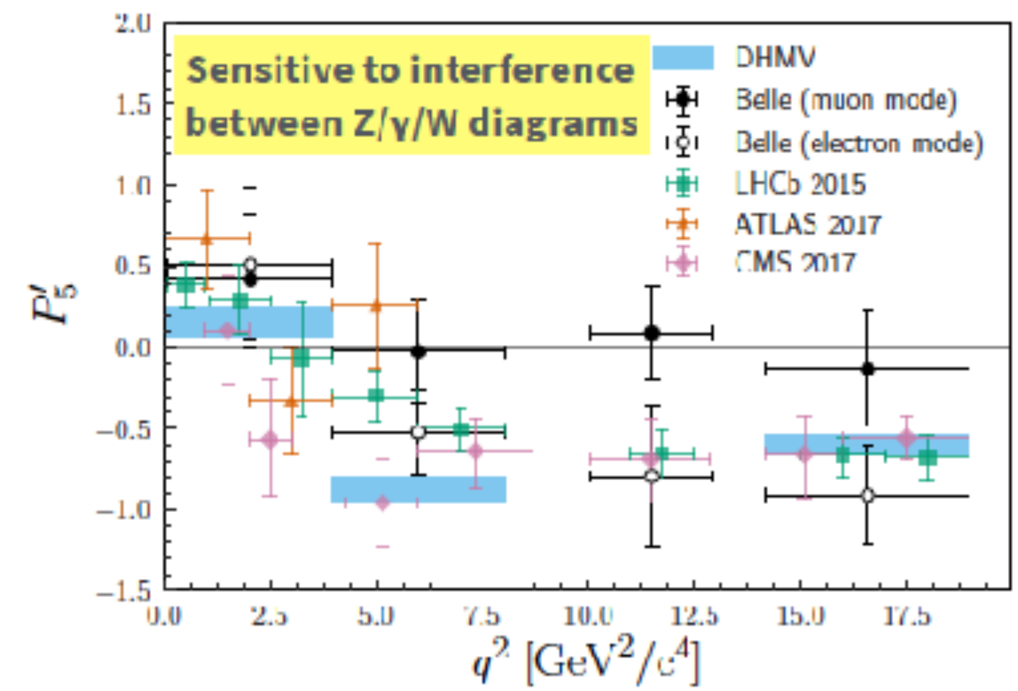
Muonic B-decays





$B^0 \to K^{0*}\mu^+\mu^-$

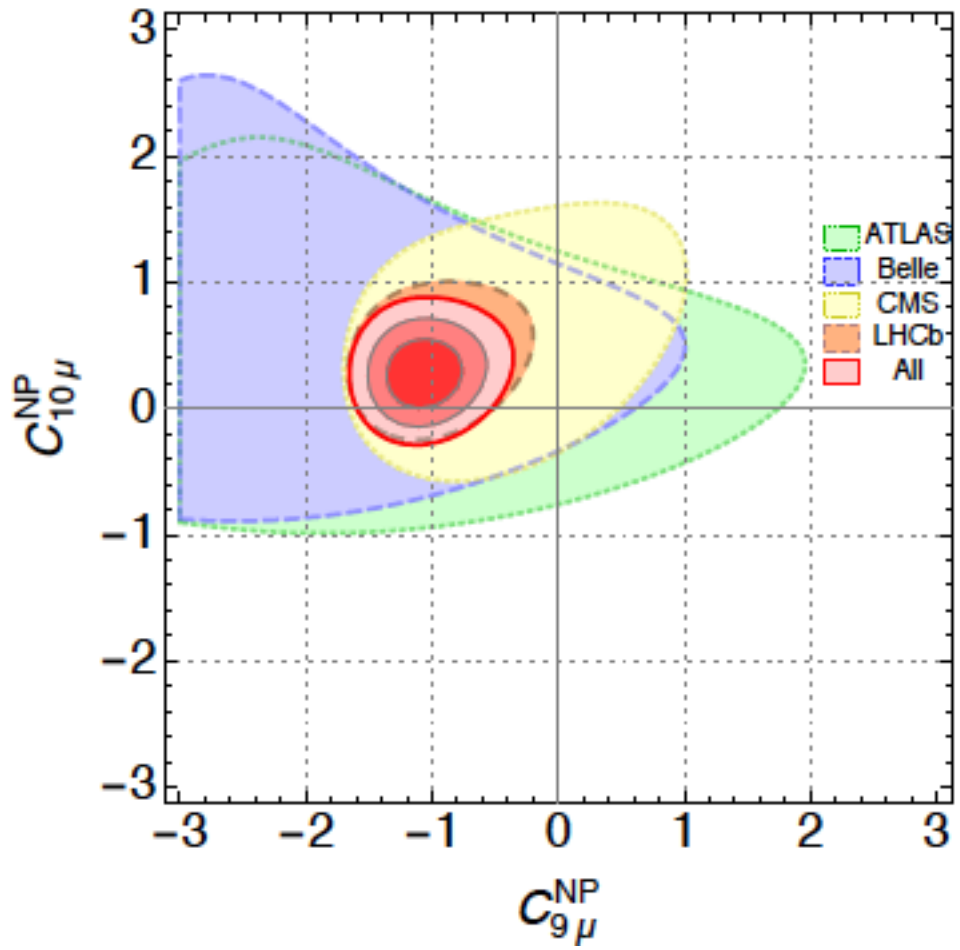




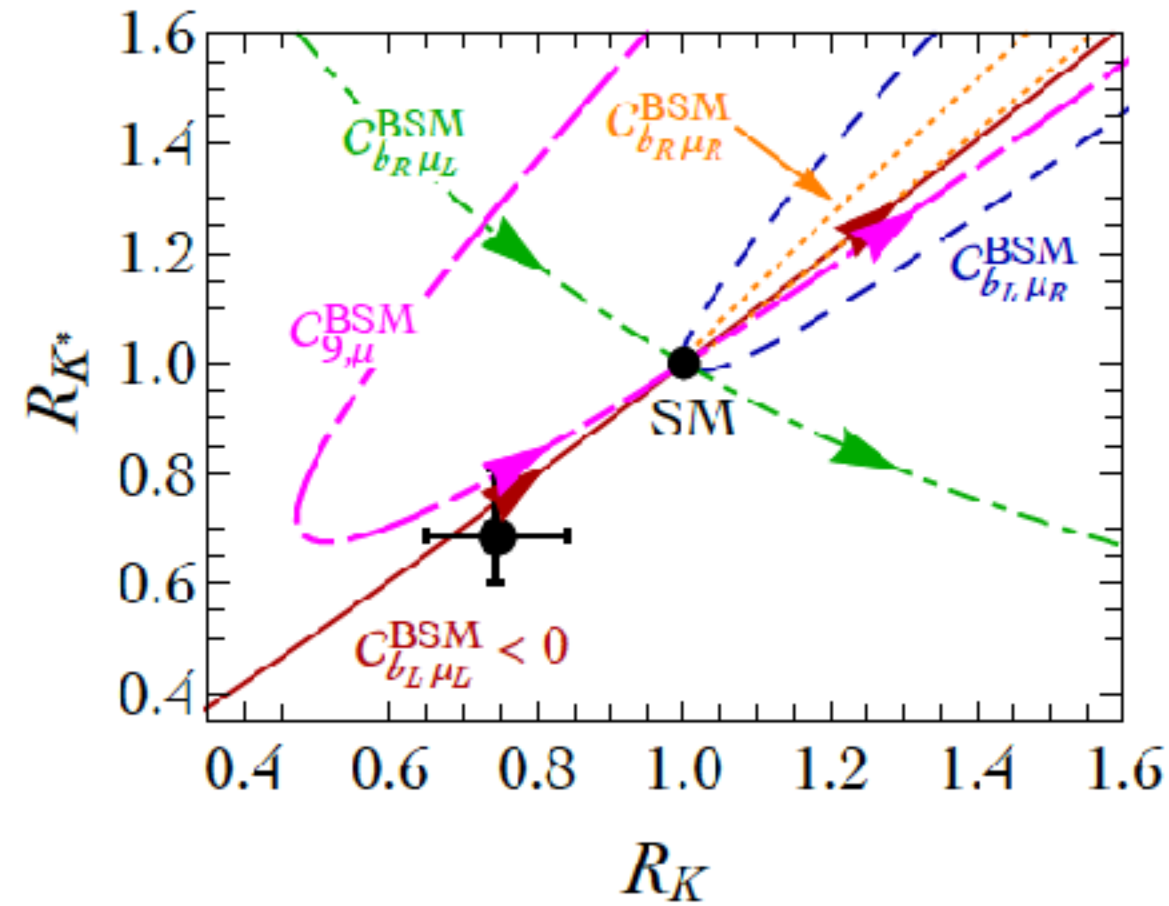
- Differential branching fractions & angular distribution are consistently lower than the SM values in muon channels.

Global fits

[Capdevila et al, 2017]



[D'Amico et al, 2017]



1D Hyp.	Best fit	1 σ	2 σ	Pull$_{SM}$	p-value
$\mathcal{C}_{9\mu}^{NP}$	-1.10	$[-1.27, -0.92]$	$[-1.43, -0.74]$	5.7σ	72 %
$\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$	-0.61	$[-0.73, -0.48]$	$[-0.87, -0.36]$	5.2σ	61 %

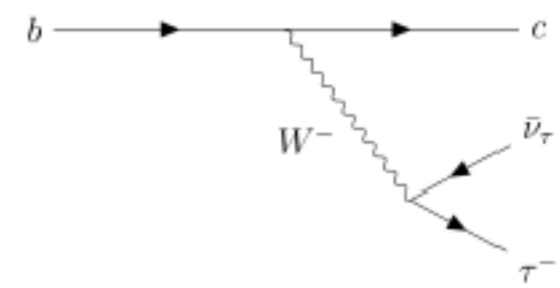
2D Hyp.	Best fit	Pull$_{SM}$	p-value
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{10\mu}^{NP})$	(-1.17,0.15)	5.5σ	74 %

$\boxed{\sim 5\sigma \text{ from SM !}}$

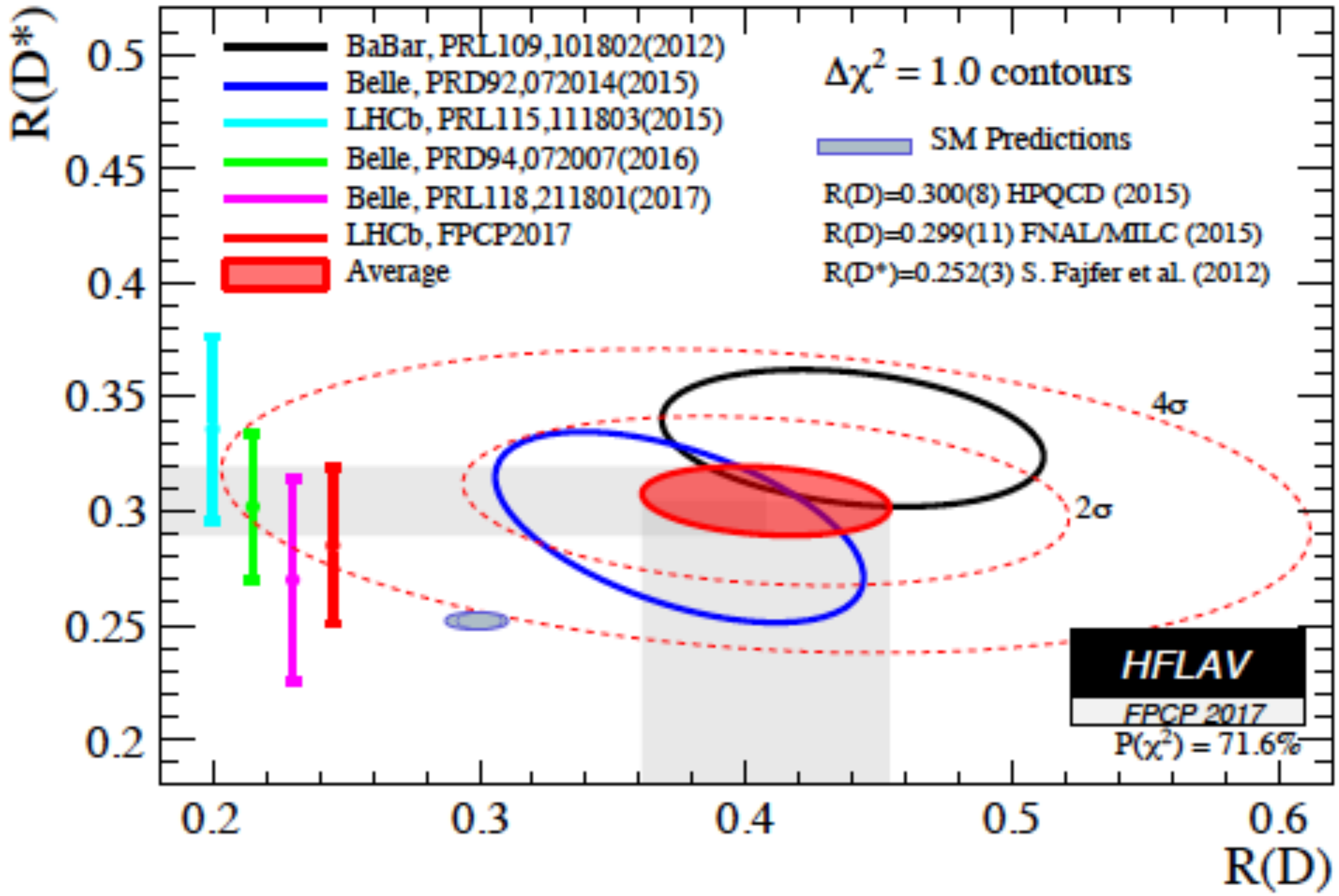
QCD? ~ 4σ or less

[Ciuchini et al, 1512.07157;
Hurth et al, 1705.06274]

B→D$^{(*)}\tau\nu$



R_{D^*} $\mathcal{B}(B \to D^*\tau\nu)/\mathcal{B}(B \to D^*l\nu)$



$$R_D^{SM} = 0.299 \pm 0.011,$$
$$R_{D^*}^{SM} = 0.260 \pm 0.010.$$

$l - e, \mu$ for BaBar and Belle

$l - \mu$ for LHCb

$R_D - \mathcal{B}(B \to D\tau\nu)/\mathcal{B}(B \to Dl\nu)$

Belle: Hadronic tag, leptonic τ Semileptonic tag, leptonic τ Hadronic tag, hadronic τ

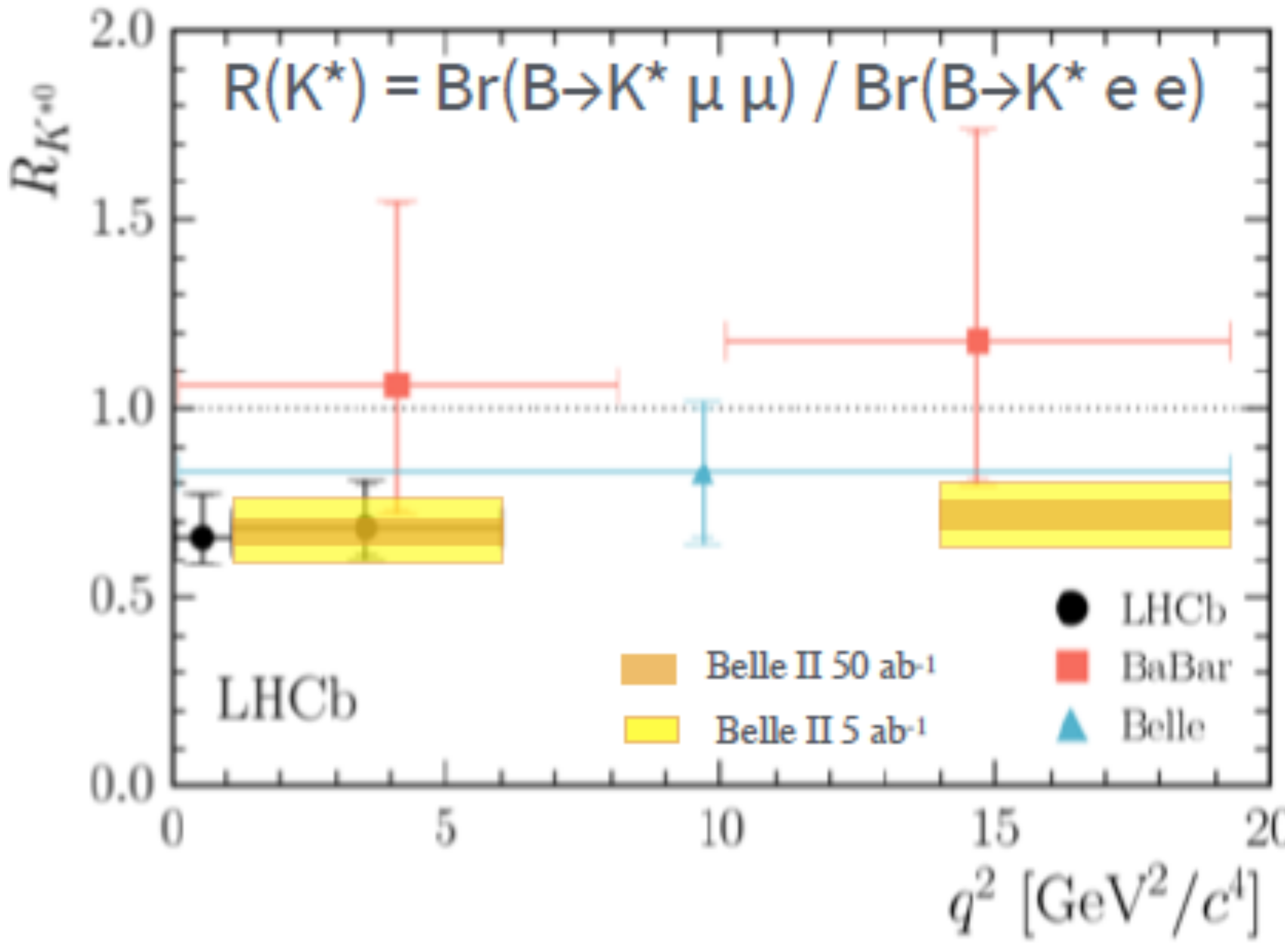
BaBar: Hadronic tag, leptonic τ LHCb: leptonic τ hadronic τ

- ~4σ anomalies in B→D$^{(*)}\tau\nu$.

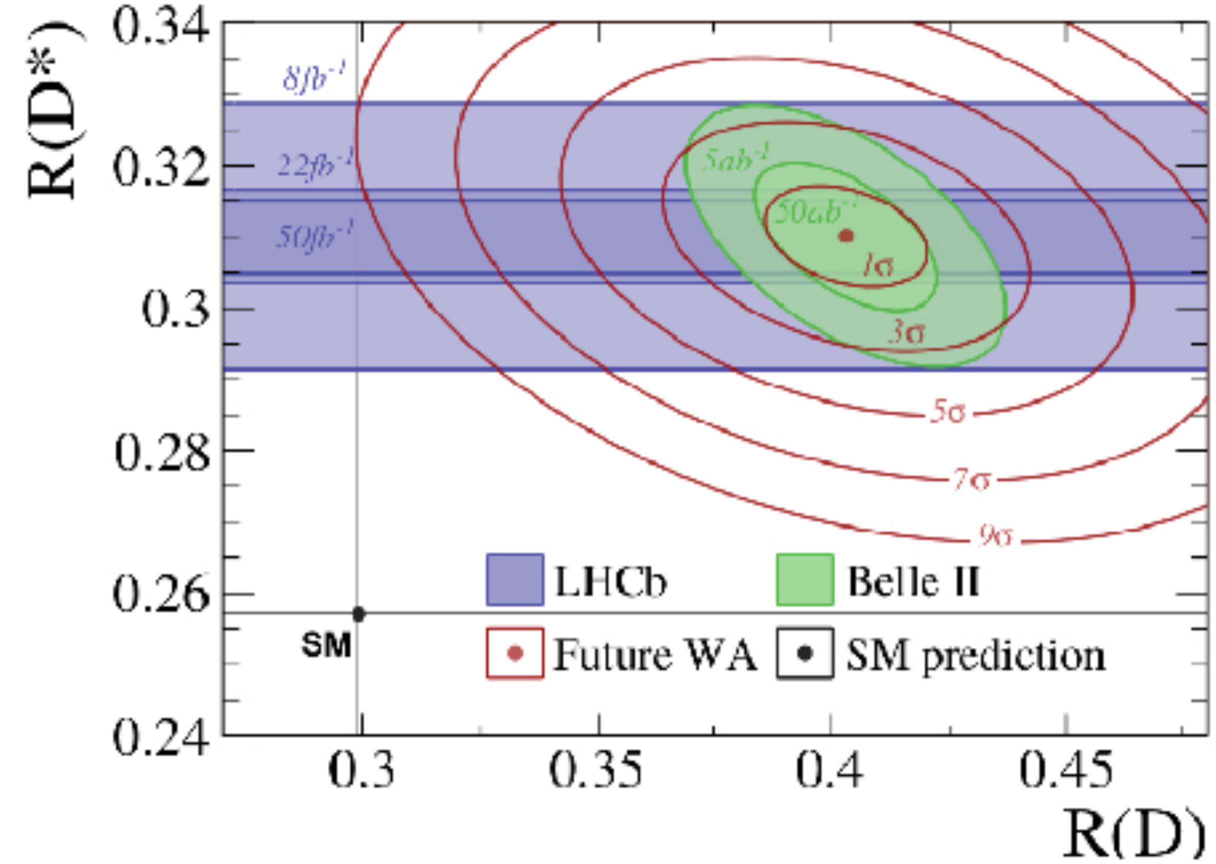
$$R_D^{exp} = 0.403 \pm 0.040 \pm 0.024,$$
$$R_{D^*}^{exp} = 0.310 \pm 0.015 \pm 0.008.$$

increased tau coupling?

Belle II for B-anomalies



[Philip Urquijo, SUSY 2017 Plenary]



[Albrecht et al, 1709.10308]

- Starting in early 2019, Belle II can test LFUV in B-meson decays to few % accuracy with data of 5 ab^{-1}.

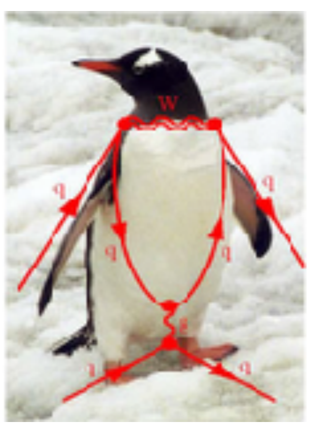
EFT for B-decays

Effective Hamiltonian for b→$s\mu\mu$:

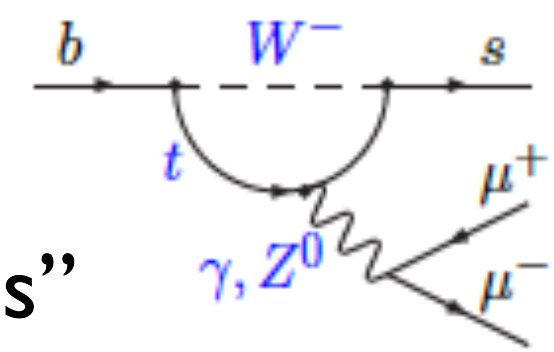
$$\mathcal{H}_{\text{eff},\bar{b}\to\bar{s}\mu^+\mu^-} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha_{em}}{4\pi} \left(C_9^\mu \mathcal{O}_9^\mu + C_{10}^\mu \mathcal{O}_{10}^\mu + C_9'^\mu \mathcal{O}_9'^\mu + C_{10}'^\mu \mathcal{O}_{10}'^\mu\right) + \text{h.c.}$$

$$\mathcal{O}_9^\mu \equiv (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \mu),\ \mathcal{O}_{10}^\mu \equiv (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \gamma^5 \mu),$$

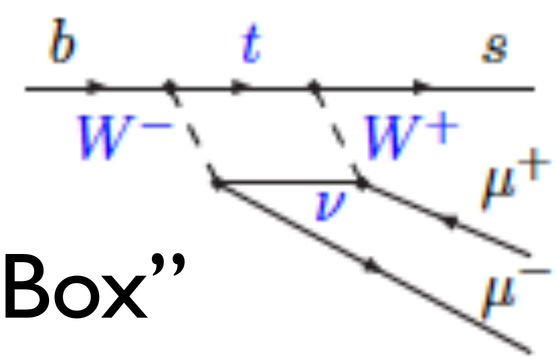
$$\mathcal{O}_9'^\mu \equiv (\bar{s}\gamma^\mu P_R b)(\bar{\mu}\gamma_\mu \mu),\ \mathcal{O}_{10}'^\mu \equiv (\bar{s}\gamma^\mu P_R b)(\bar{\mu}\gamma_\mu \gamma^5 \mu)$$



"Penguins"



"Box"



$$C_9^{\mu,\text{SM}}(m_b) = -C_{10}^{\mu,\text{SM}}(m_b) = 4.27, \quad C_9'^{\mu,\text{SM}}(m_b) \approx -C_{10}'^{\mu,\text{SM}}(m_b) \approx 0.$$

Effective Hamiltonian for b→cτν:

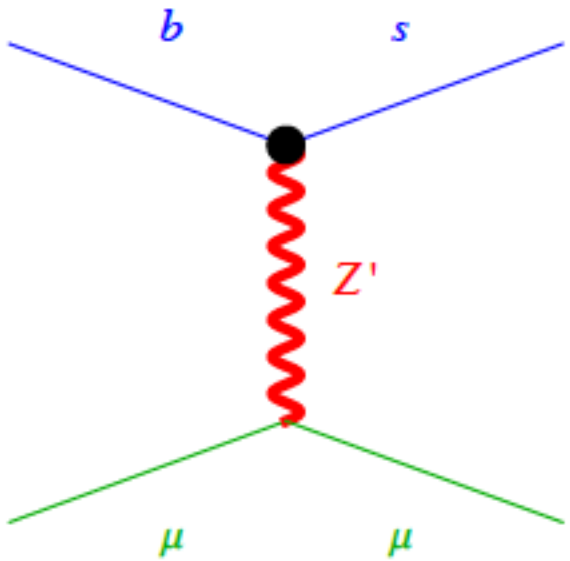
$$\mathcal{H}_{\text{eff}} - \frac{4G_F V_{cb}}{\sqrt{2}} (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + \text{h.c.}$$

"Tree"

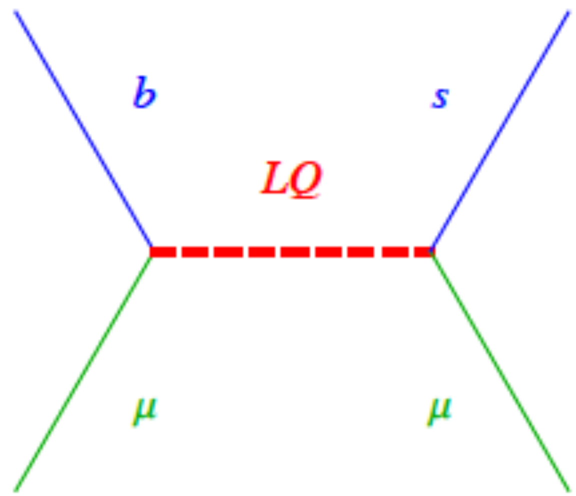
New physics for B-anomalies

New physics for $R_{K^{(*)}}$ anomalies:

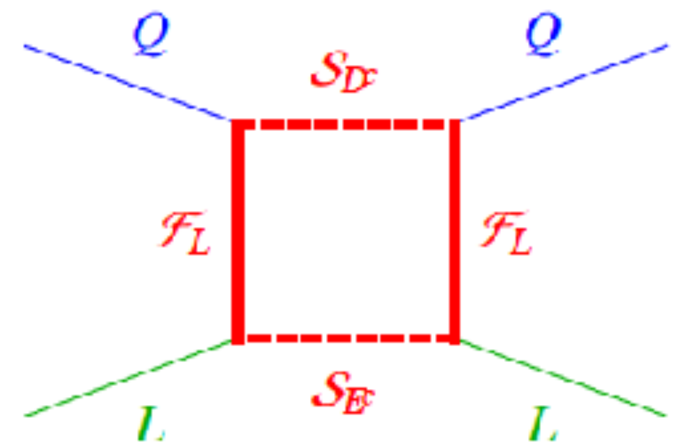
[D'Amico et al, 1704.05438; Choi, Kang, HML, Ro, 2018]



Flavor-violating U(1)'



Leptoquarks



Colored particles in loops

Best fits: $C_9^{\mu,\mathrm{NP}} = -1.10^{+0.18}_{-0.17}\,,$ or $C_9^{\mu,\mathrm{NP}} = -C_{10}^{\mu,\mathrm{NP}} = -0.61^{+0.13}_{-0.12}\,.$

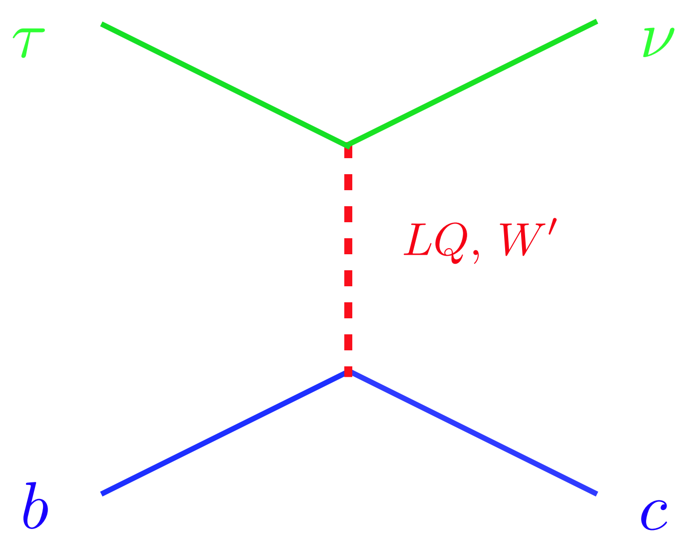
$$\mathcal{L}_{\mathrm{eff}} = \frac{1}{\Lambda^2_{\mathrm{NP}}}(\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \mu), \qquad \Lambda_{\mathrm{NP}} \simeq 30\,\mathrm{TeV}.$$

Bounds from other meson decays/mixing & LHC

3rd generation specific!

New physics for B-anomalies

New physics for $R_{D^{(*)}}$ anomalies: [Choi, Kang, HML, Ro, 2018]



Leptoquarks, W', charged Higgs

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda_{\rm NP}^2}\,(\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau),$$

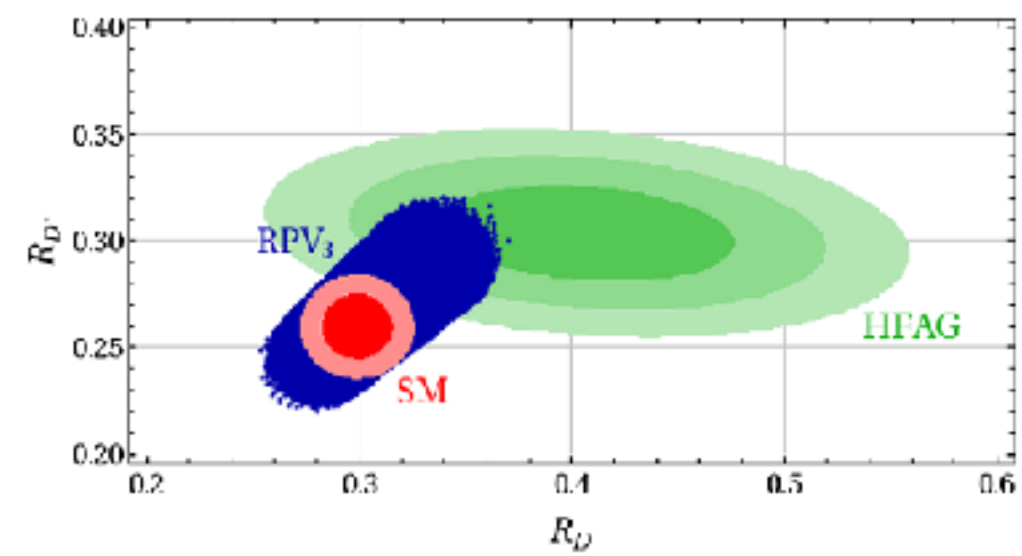
$$\Lambda_{\rm NP} \simeq 3.5\,{\rm TeV}.$$

e.g. sbottom in MSSM with RPV

$$W_{\rm RPV} = \lambda'_{333} L_3 Q_3 D_3^c$$

$$\mathcal{L}_{\rm RPV} = -\lambda'_{333}\nu_{\tau L} b_L \tilde{b}_R^* - \lambda'_{333}\tau_L t_L \tilde{b}_R^* + {\rm h.c.},$$

$$t_L \to V_{tb} t_L + \boxed{V_{cb} b_L} + V_{ub} d_L,$$



[Altmannshoefer et al, 2017]

LHC direct searches:

$$\tilde{b} \to t\tau, \quad m_{\tilde{b}_R} \gtrsim 680\,{\rm GeV}.$$

$$\tilde{b} \to b\nu_\tau, \quad m_{\tilde{b}_R} \gtrsim 1.22\,{\rm TeV}.$$

in a tension with perturbative unification.

Minimal flavored U(1)’

Flavored U(1)'

- Anomaly-free U(1)' with 3 right-handed neutrinos:

→ flavor-dependent $U(1)_{B_i-L_i}, \quad i=1,2,3$

with one right-handed neutrino per each generation

- Anomaly-free U(1)' with SM fermions only:

$U(1)_{L_e-L_\mu}, U(1)_{L_\mu-L_\tau}, U(1)_{L_\tau-L_e}$ → LFU violation

Flavored U(1)' for B-meson anomalies

$U(1)_{B_3-L_3} \times U(1)_{L_\mu-L_\tau}$ → $U(1)_{x(B_3-L_3)+y(L_\mu-L_\tau)}$

[L. Bian, S.-M. Choi, Y.-J. Kang, HML, 2017]

U(1)' charges

	q_{3L}	u_{3R}	d_{3R}	l_{2L}	e_{2R}	ν_{2R}	l_{3L}	e_{3R}	ν_{3R}	S	H_1	H_2	Φ_1	Φ_2	Φ_3
Q'	$\frac{1}{3}x$	$\frac{1}{3}x$	$\frac{1}{3}x$	y	y	y	$-x-y$	$-x-y$	$-x-y$	$-\frac{1}{3}x$	0	$\frac{1}{3}x$	$-y$	$x+y$	x

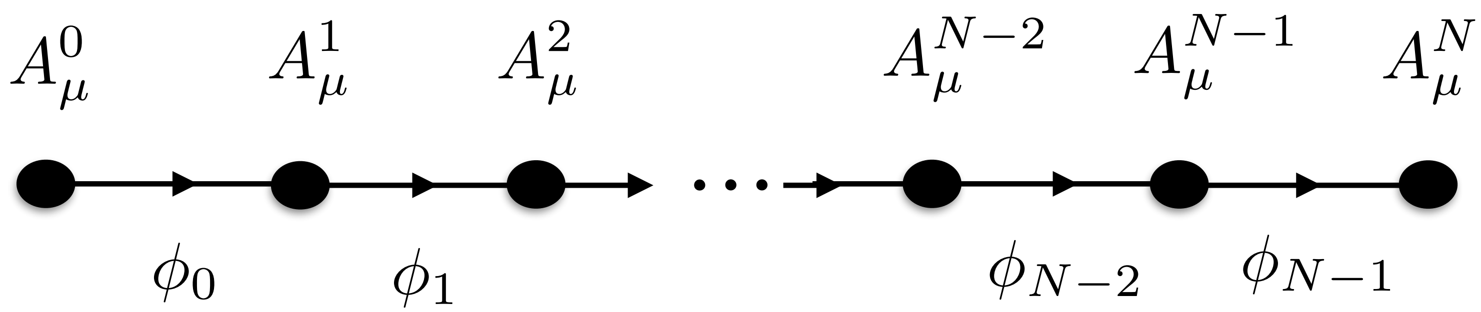
RH2 RH3 Scalar sector

ν_{1R} : neutral

U(1)' from clockwork

- $[U(1)_{B-L}]^{N+1}$ clockwork with third family localized at different sites from first two families.

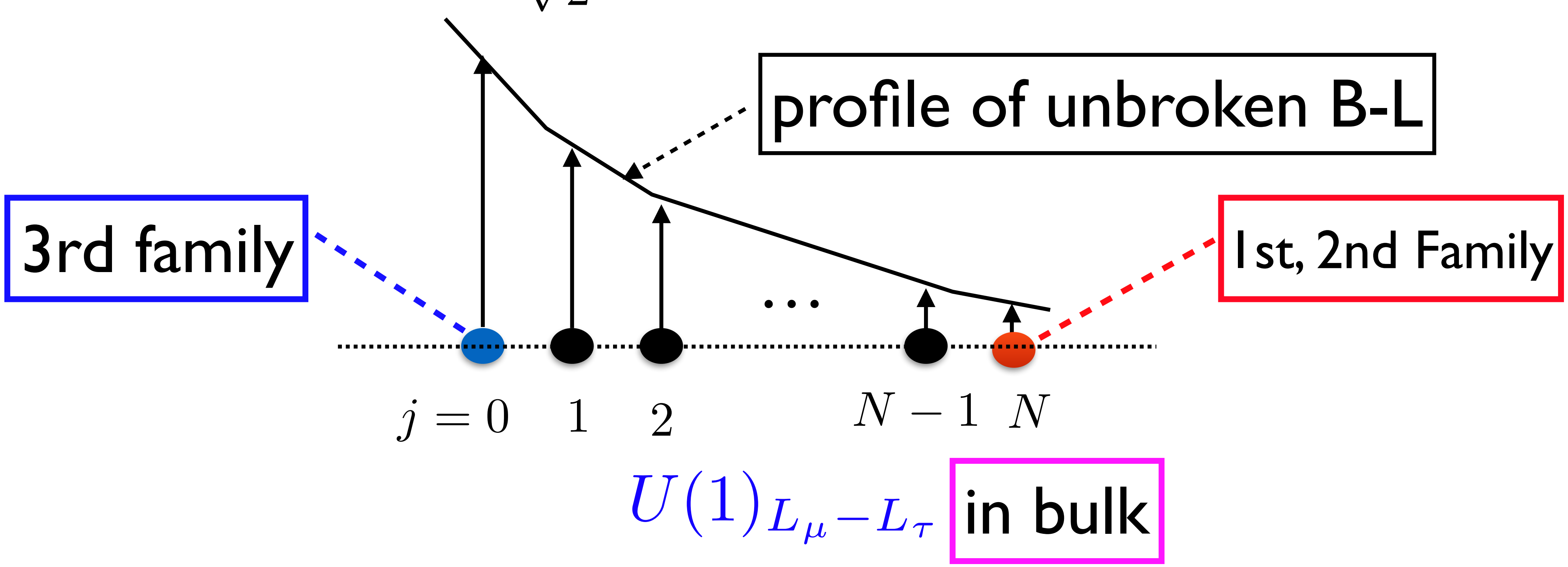
[Giudice, McCollough, 2016; HML, 2017]



$[U(1)_{B-L}]^{N+1} \Rightarrow U(1)_{B_3-L_3}$: unbroken U(1)

$+U(1)_{L_\mu-L_\tau}$: LFUV in bulk

$$\langle\phi_i\rangle = \frac{1}{\sqrt{2}} f$$



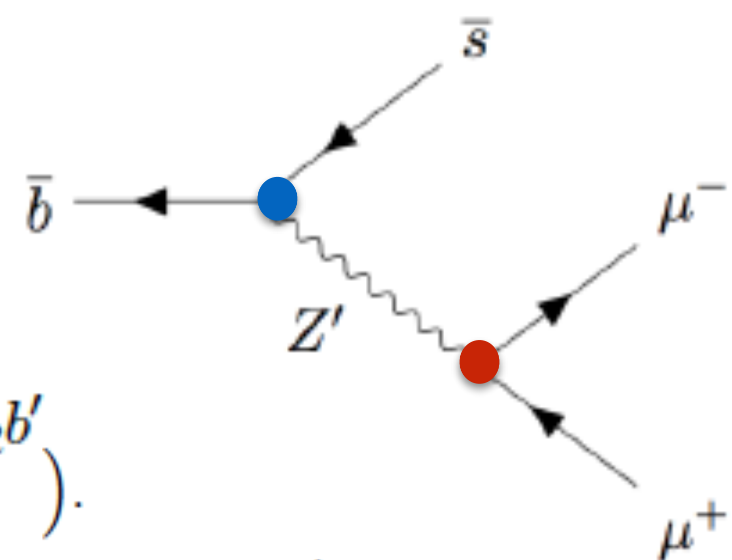
EFT from flavored Z'

- Z' interactions in interaction basis:

$$\mathcal{L}_{Z'} = g_{Z'} Z'_\mu \Big(\frac{1}{3} x \, \bar{t}\gamma^\mu t + \boxed{\frac{1}{3} x \, \bar{b}\gamma^\mu b} + \boxed{y \bar{\mu}\gamma^\mu \mu} + y \, \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu - (x+y) \, \bar{\tau}\gamma^\mu \tau$$
$$- (x+y) \, \bar{\nu}_\tau \gamma^\mu P_L \nu_\tau + y \, \bar{\nu}_{2R}\gamma^\mu P_R \nu_{2R} - (x+y) \, \bar{\nu}_{3R}\gamma^\mu P_R \nu_{3R} \Big).$$

- CKM from down-type quarks:

$$U_L = 1 \text{ and } D_L = V_{\rm CKM}$$



$$\Rightarrow \quad g_{Z'} Z'_\mu \Big(\frac{1}{3} x \, \bar{t}'\gamma^\mu t' + \boxed{\frac{1}{3} x \, \bar{d}'_i \gamma^\mu \Gamma^{dL}_{ij} P_L d'_j} + \frac{1}{3} x \, \bar{b}'\gamma^\mu P_R b' \Big).$$

$$\Gamma^{dL} \equiv V^\dagger_{\rm CKM} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} V_{\rm CKM} = \begin{pmatrix} |V_{td}|^2 & V^*_{td} V_{ts} & V^*_{td} V_{tb} \\ V^*_{ts} V_{td} & |V_{ts}|^2 & V^*_{ts} V_{tb} \\ V^*_{tb} V_{td} & \boxed{V^*_{tb} V_{ts}} & |V_{tb}|^2 \end{pmatrix}.$$

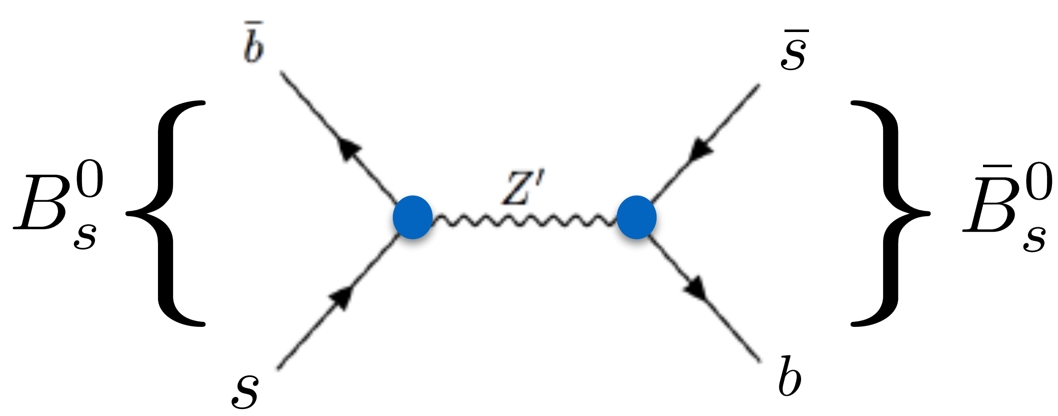
$$\Delta \mathcal{H}_{{\rm eff}, \bar{b}\to\bar{s}\mu^+\mu^-} = -\frac{4G_F}{\sqrt{2}} \boxed{V^*_{ts} V_{tb}} \frac{\alpha_{em}}{4\pi} C_9^{\mu,{\rm NP}} \mathcal{O}_9^\mu , \qquad \boxed{C_9^{\mu,{\rm NP}} = -\frac{8xy\pi^2 \alpha_{Z'}}{3\alpha_{\rm em}} \left(\frac{v}{m_{Z'}}\right)^2}$$

CKM mixing is the only source for bottom-quark transition.

Bounds on quark couplings

Quark couplings: $x g_{Z'}$

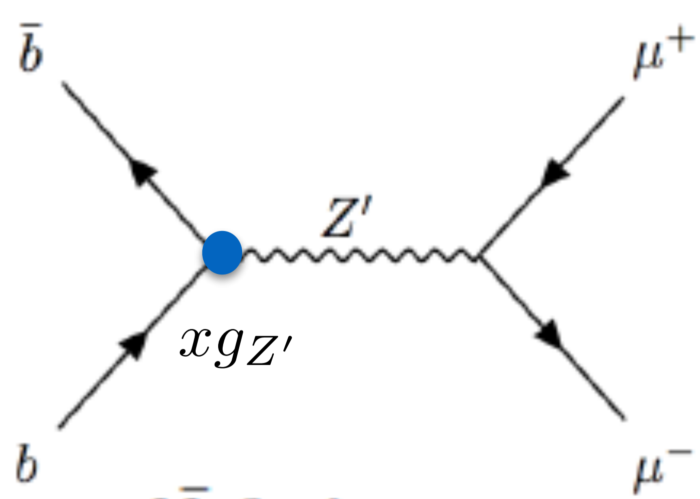
- Meson mixing and decays: $C_{VLL}^{\rm NP} \lesssim 0.15(0.30) \times C_{VLL}^{\rm SM} \simeq 0.74(1.48)$



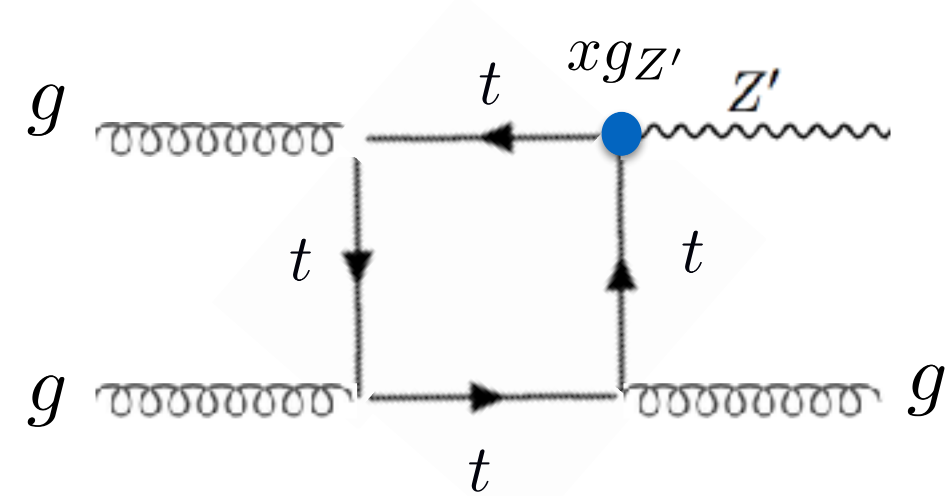
$$\Delta\mathcal{H}_{{\rm eff},B_s^0-\bar{B}_s^0} = \frac{G_F^2 m_W^2}{16\pi^2}(V_{ts}^* V_{tb})^2\, C_{VLL}^{\rm NP}\, (\bar{s}\gamma^\mu P_L b)(\bar{s}\gamma_\mu P_L b)$$

$$\begin{aligned} C_{VLL}^{\rm NP} &= \frac{16\pi^2 x^2}{9}\,\frac{g_{Z'}^2 v^4}{m_{Z'}^2 m_W^2} \\ &= 0.25\left(\frac{x}{0.04}\right)^2\left(\frac{g_{Z'}}{2}\right)^2\left(\frac{500\,{\rm GeV}}{m_{Z'}}\right)^2. \end{aligned}$$

- LHC dimuon searches: MadGraph5_aMC@NLO + NN23LO1 PDF



$b\bar{b}$ fusion



etc

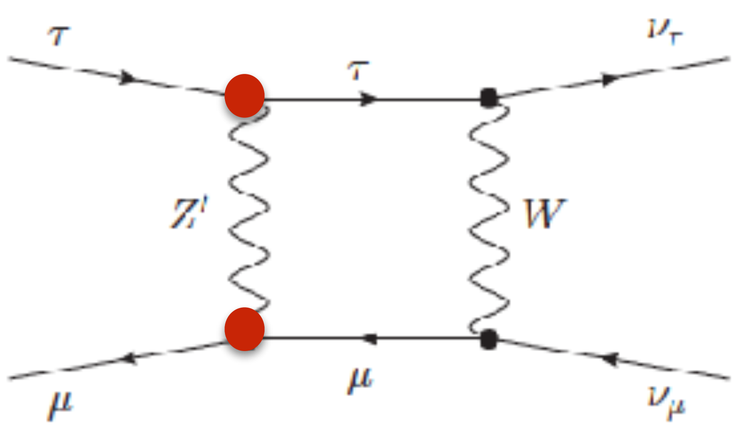
~dominant

$\tau\bar{\tau},\ \nu\bar{\nu}$: additional signatures of the model.

Bounds on lepton couplings

Lepton couplings: $yg_{Z'}$

- Tau decays

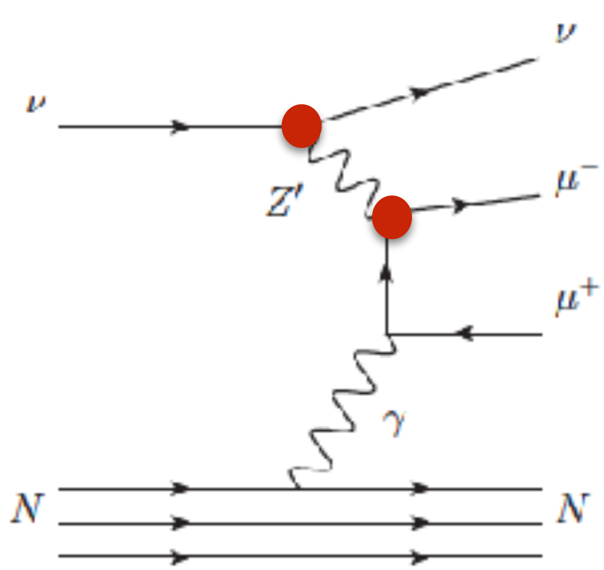


$$\frac{\mathrm{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}{\mathrm{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)_{\mathrm{SM}}} = 1 + \Delta$$

$$\Delta = \frac{3y(x+y)g_{Z'}^2}{4\pi^2}\frac{\log(m_W^2/m_{Z'}^2)}{1 - m_{Z'}^2/m_W^2} < 1.8 \times 10^{-2}$$

$$(2\sigma)$$

- Neutrino trident production

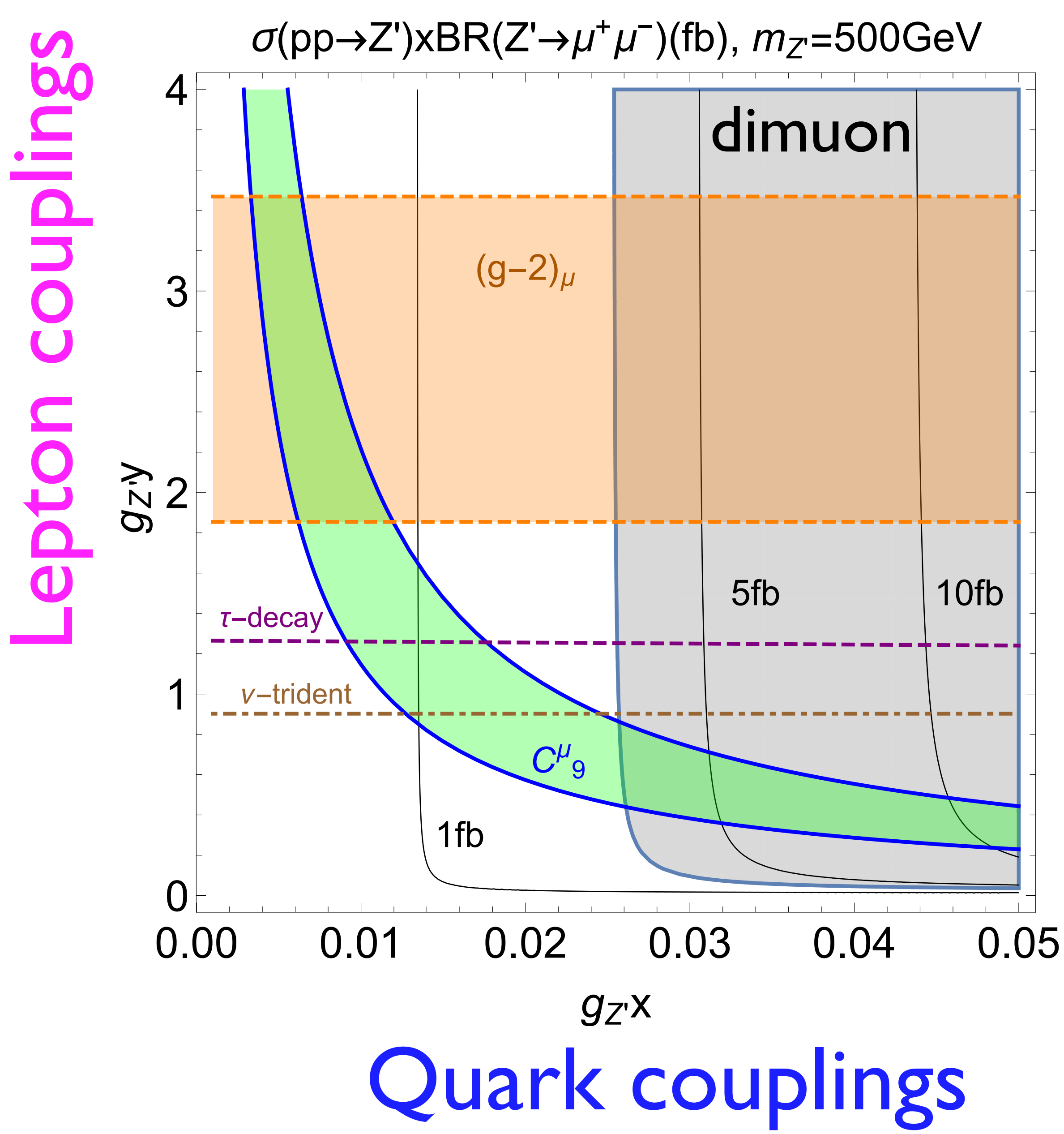


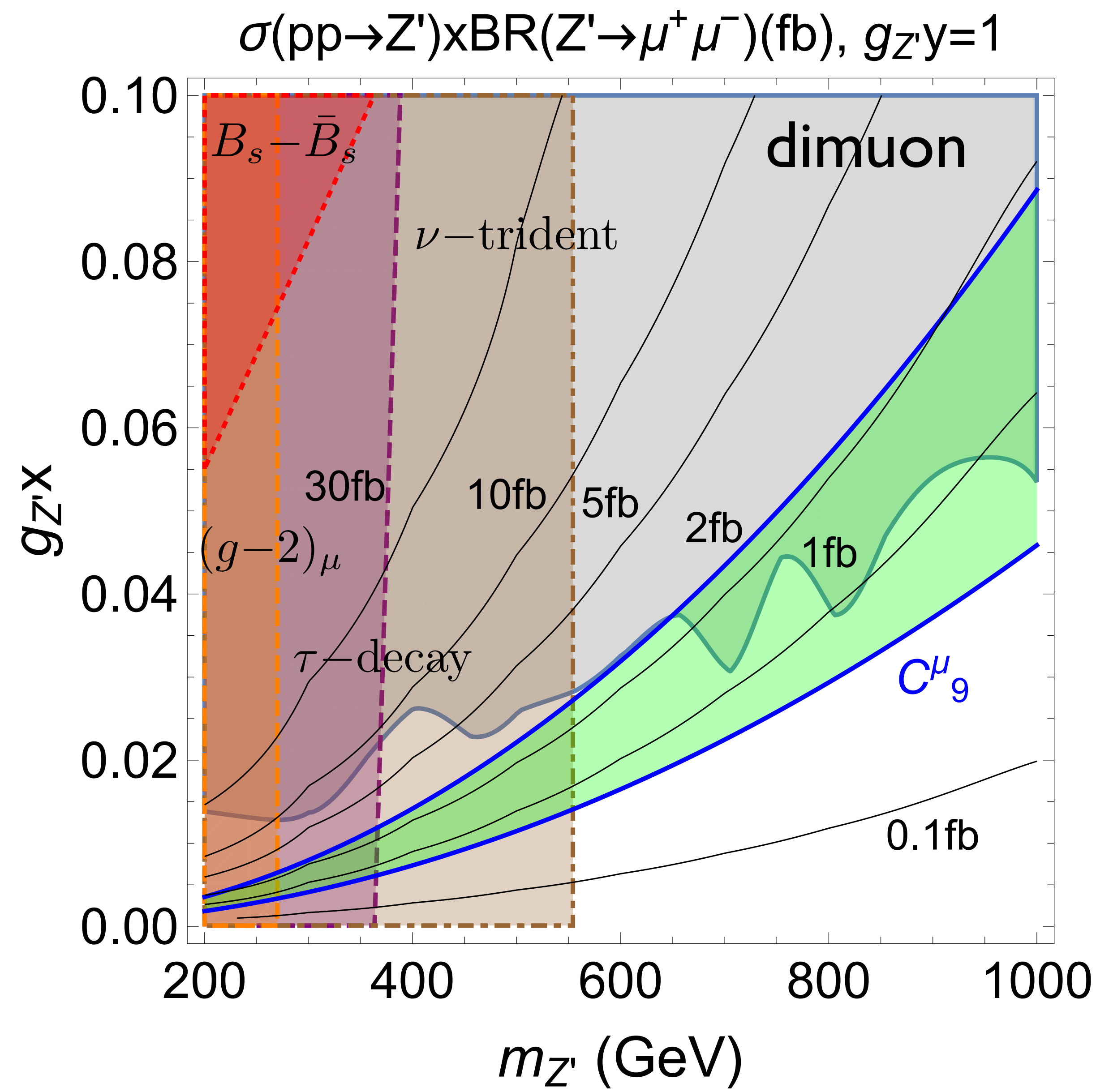
$$\frac{\sigma}{\sigma_{\mathrm{SM}}} \simeq \frac{1 + (1 + 4s_W^2 + 2y^2g_{Z'}^2v^2/m_{Z'}^2)^2}{1 + (1 + 4s_W^2)^2}$$

$$< 1.45(2\sigma)$$

$$\frac{m_{Z'}}{yg_{Z'}} > 554\,\mathrm{GeV}.$$

Bounds on Z' mass





- LHC dimuon constrains B charges much smaller than L charges; tau decay/neutrino trident searches are complementary.

Z’-2HDM

Extra Higgs bosons

[L. Bian, HML, C.B. Park, 2017]

Two Higgs doublets H_1 , H_2 for quark mixing + singlet S:

$$
\begin{aligned}
V(H_1, H_2, S) \;=\;& \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 - (\mu S H_1^\dagger H_2 + \text{h.c.}) \\
&+\lambda_1|H_1|^4 + \lambda_2|H_2|^4 + 2\lambda_3|H_1|^2|H_2|^2 + 2\lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1) \\
&+2|S|^2(\kappa_1|H_1|^2 + \kappa_2|H_2|^2) + m_S^2|S|^2 + \lambda_S|S|^4.
\end{aligned}
$$

$$v_{1,2} = \sqrt{2}\langle H_{1,2}\rangle; \quad v_s = \sqrt{2}\langle S\rangle$$

SSB of electroweak and U(1)'

(Extra singlet VEVs determine Z' mass)

Extra scalars mix with SM Higgs and themselves.

CP-even:

$$
M_S = \begin{pmatrix}
2\lambda_1 v_1^2 + \frac{\mu v_2 v_s}{\sqrt{2} v_1} & 2v_1v_2(\lambda_3+\lambda_4) - \frac{\mu v_s}{\sqrt{2}} & 2\kappa_1 v_1 v_s - \frac{\mu v_2}{\sqrt{2}} \\
2v_1v_2(\lambda_3+\lambda_4) - \frac{\mu v_s}{\sqrt{2}} & 2\lambda_2 v_2^2 + \frac{\mu v_1 v_s}{\sqrt{2} v_2} & 2\kappa_2 v_2 v_s - \frac{\mu v_1}{\sqrt{2}} \\
2\kappa_1 v_1 v_s - \frac{\mu v_2}{\sqrt{2}} & 2\kappa_2 v_2 v_s - \frac{\mu v_1}{\sqrt{2}} & 2\lambda_S v_s^2 + \frac{\mu v_1 v_2}{\sqrt{2} v_s}
\end{pmatrix}
$$

CP-odd:

$$m_A^2 = \frac{\mu \sin\beta\cos\beta}{\sqrt{2} v_s}\left(v^2 + \frac{v_s^2}{\sin^2\beta\cos^2\beta}\right)$$

Charged Higgs:

$$m_{H^+}^2 = m_A^2 - \left(\frac{\mu\sin\beta\cos\beta}{\sqrt{2}v_s} + \lambda_4\right)v^2.$$

Quark mixing

Quark mass matrices: 3rd generation mixings due to H_2.

$$M_u = \begin{pmatrix} y^u_{11}\langle H_1\rangle & y^u_{12}\langle H_1\rangle & 0 \\ y^u_{21}\langle H_1\rangle & y^u_{22}\langle H_1\rangle & 0 \\ h^u_{31}\langle H_2\rangle & h^u_{32}\langle H_2\rangle & y^u_{33}\langle H_1\rangle \end{pmatrix}, \quad M_d = \begin{pmatrix} y^d_{11}\langle \tilde{H}_1\rangle & y^d_{12}\langle \tilde{H}_1\rangle & h^d_{13}\langle \tilde{H}_2\rangle \\ y^d_{21}\langle \tilde{H}_1\rangle & y^d_{22}\langle \tilde{H}_1\rangle & h^d_{23}\langle \tilde{H}_2\rangle \\ 0 & 0 & y^d_{33}\langle \tilde{H}_1\rangle \end{pmatrix}$$

- CKM mixings constrain flavor-violating couplings up to $\tan\beta$.

$$h^d_{13} = \frac{\sqrt{2}m_b}{v\sin\beta}V_{ub}, \quad h^d_{23} = \frac{\sqrt{2}m_b}{v\sin\beta}V_{cb}. \qquad h^d_{13} \ll h^d_{23}.$$

$$|y^u_{33}|^2 + \tan^2\beta(|h^u_{31}|^2 + |h^u_{32}|^2) = \frac{2m_t^2}{v^2\cos^2\beta}, \qquad \begin{aligned} y^u_{21}(h^u_{31})^* + y^u_{22}(h^u_{32})^* &= 0, \\ y^u_{11}(h^u_{31})^* + y^u_{12}(h^u_{32})^* &= 0. \end{aligned}$$

physical new couplings

$$\tilde{h}^d \equiv D_L^\dagger h^d D_R$$

$$\tilde{h}^u \equiv U_L^\dagger h^u U_R$$

$$\boxed{\begin{aligned} \tilde{h}^u_{33} &= \frac{\sqrt{2}m_t}{v\sin\beta}\left(1 - \frac{v^2\cos^2\beta}{2m_t^2}|y^u_{33}|^2\right), \\ \tilde{h}^d_{13} &= 1.80\times10^{-2}\left(\frac{m_b}{v\sin\beta}\right), \\ \tilde{h}^d_{23} &= 5.77\times10^{-2}\left(\frac{m_b}{v\sin\beta}\right), \\ \tilde{h}^d_{33} &= 2.41\times10^{-3}\left(\frac{m_b}{v\sin\beta}\right). \end{aligned}}$$

flavor-violation

Lepton mixing

SM lepton matrices are “diagonal”

$$M_l = \begin{pmatrix} y^l_{11}\langle\tilde{H}_1\rangle & 0 & 0 \\ 0 & y^l_{22}\langle\tilde{H}_1\rangle & 0 \\ 0 & 0 & y^l_{33}\langle\tilde{H}_1\rangle \end{pmatrix}, \quad M_D = \begin{pmatrix} y^\nu_{11}\langle H_1\rangle & 0 & 0 \\ 0 & y^\nu_{22}\langle H_1\rangle & 0 \\ 0 & 0 & y^\nu_{33}\langle H_1\rangle \end{pmatrix},$$

$$\Rightarrow \quad -\mathcal{L}^\ell_Y = -\frac{m_{e_j}\sin\alpha}{v\cos\beta}\,\bar{e}_j\,e_j\,h + \frac{m_{e_j}\cos\alpha}{v\cos\beta}\,\bar{e}_j\,e_j\,H + \frac{i m_{e_j}\tan\beta}{v}\,\bar{e}_j\gamma^5 e_j\,A^0 + \frac{\sqrt{2}m_{e_j}\tan\beta}{v}\left(\bar{\nu}_j\,P_R\,e_j\,H^+ + \mathrm{h.c.}\right)$$

“2HDM-I like”

RH neutrinos mix from three singlet scalars $\Phi_{1,2,3}$

$$M_R = \begin{pmatrix} M_{11} & z^{(1)}_{12}\langle\Phi_1\rangle & z^{(2)}_{13}\langle\Phi_2\rangle \\ z^{(1)}_{21}\langle\Phi_1\rangle & 0 & z^{(3)}_{23}\langle\Phi_3\rangle \\ z^{(2)}_{31}\langle\Phi_2\rangle & z^{(3)}_{32}\langle\Phi_3\rangle & 0 \end{pmatrix}.$$

$\Rightarrow$ Correct neutrino masses and mixings arise from RH neutrino masses

[Fritzsch et al, 2011]

Addendum to 2HDM

[Banco et al, 1106.0034]

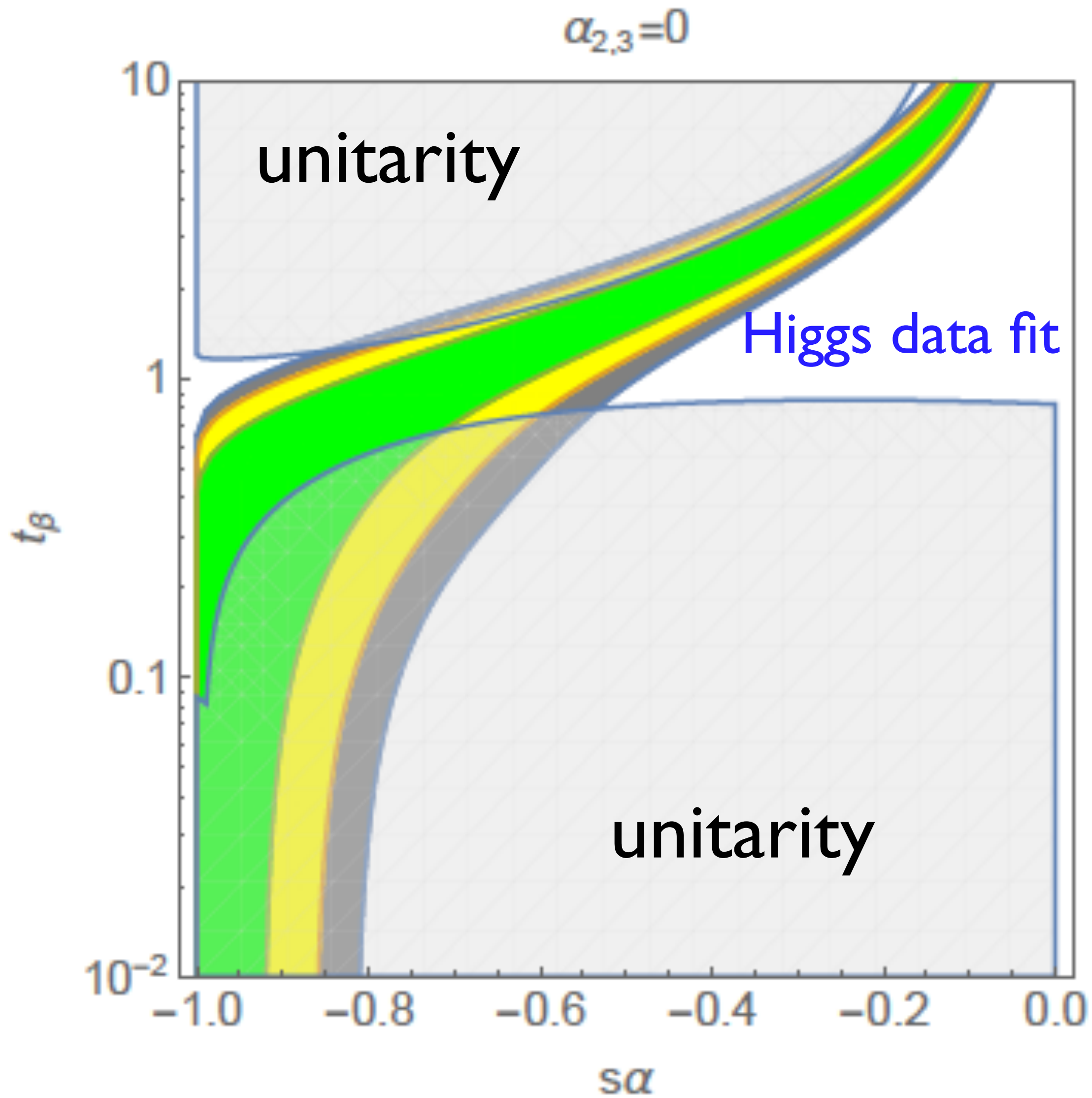
	Type I	Type II	Lepton-specific	Flipped	Z'-2HDM
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta + \Delta_u\delta_{33}$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta + \Delta_d\delta_{i3}$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\tan\beta - \Delta_u\delta_{33}$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$	$-\tan\beta + \Delta_d\delta_{i3}$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$	$-\tan\beta$

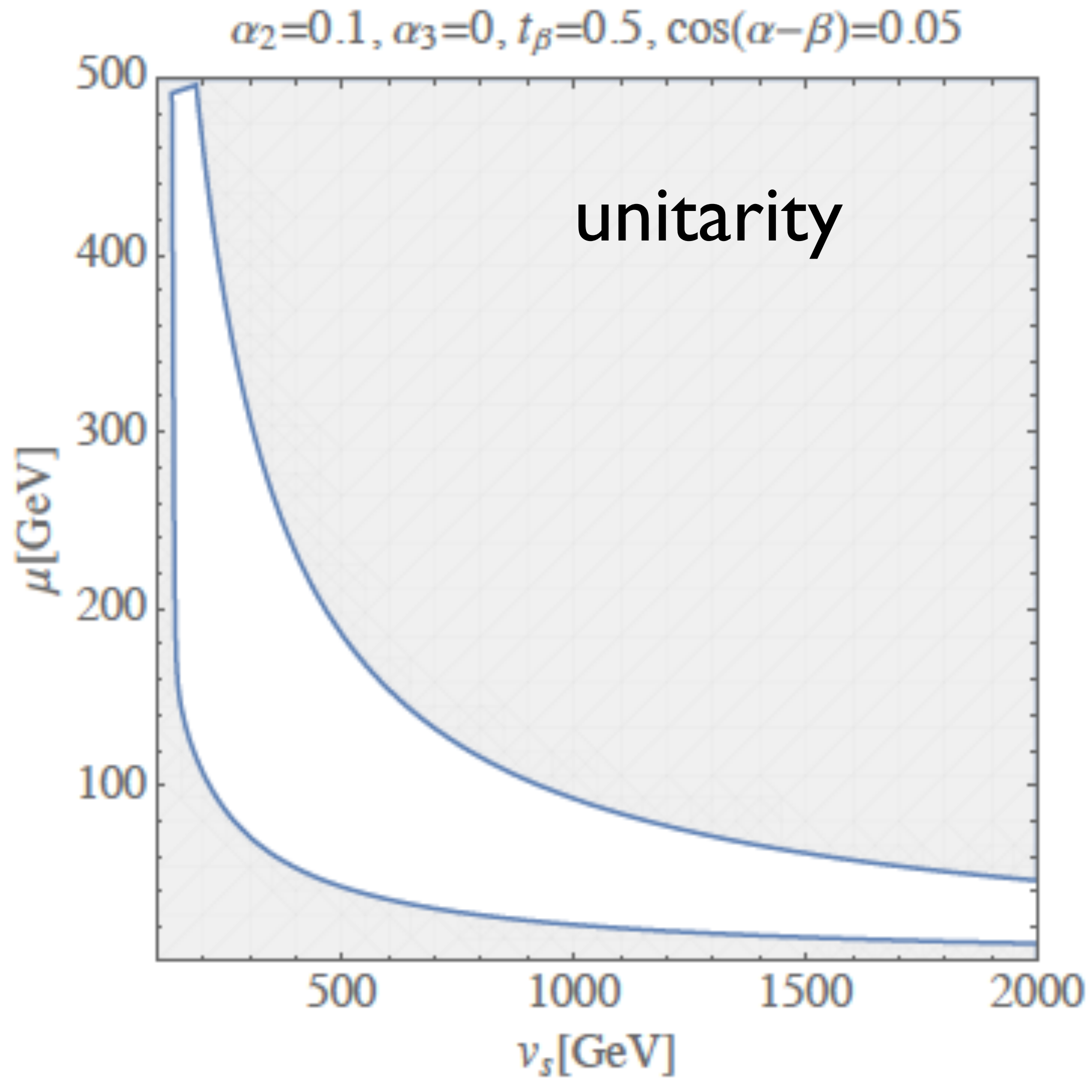
$$\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - i\xi_A^f \overline{f}\gamma_5 f A\right) - \left\{\frac{\sqrt{2}V_{ud}}{v}\overline{u}\left(m_u\xi_A^u \mathrm{P}_L + m_d\xi_A^d \mathrm{P}_R\right) d H^+ + \frac{\sqrt{2}m_\ell\xi_A^\ell}{v}\overline{\nu_L}\ell_R H^+ + \text{H.c.}\right\}$$

$$\Phi_1 \leftrightarrow \Phi_2$$
$$(\beta \to \beta - \frac{\pi}{2},\quad \alpha \to \alpha + \frac{\pi}{2})$$

2HDM-Type I like, except the 3rd generation quark couplings for heavy Higgs: flavor-conserving top, flavor-violating bottom.

Higgs data and unitarity



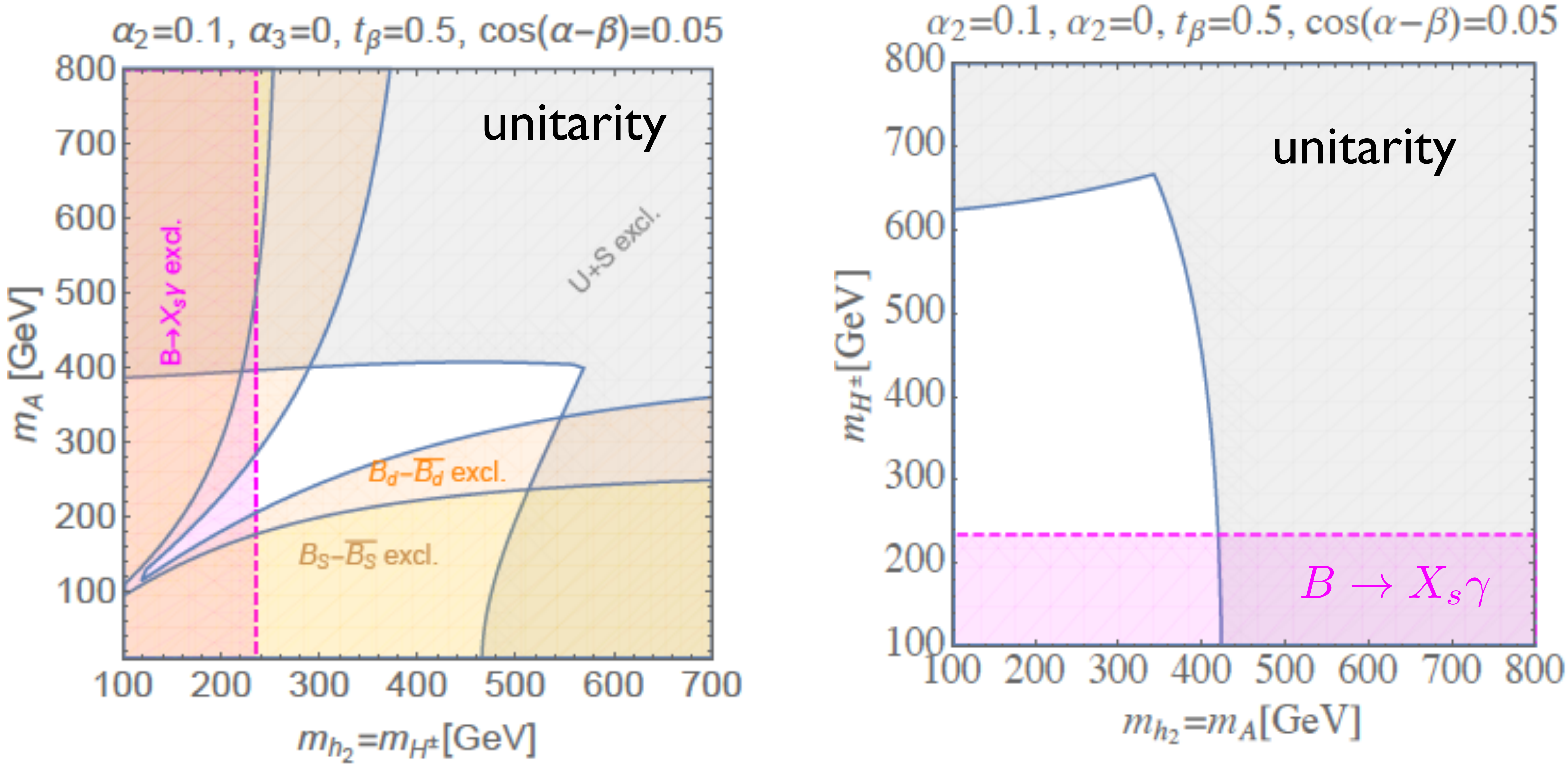


Lower and upper bounds on tanβ from unitarity/perturbatity.

There is also an upper bound on tanβ from EW data:

$$\Delta\rho \simeq 10^{-4}\left(\frac{x}{0.05}\right)^2 g_{Z'}^2 \sin^4\beta \left(\frac{400\,\mathrm{GeV}}{m_{Z'}}\right)^2$$

B-physics bounds



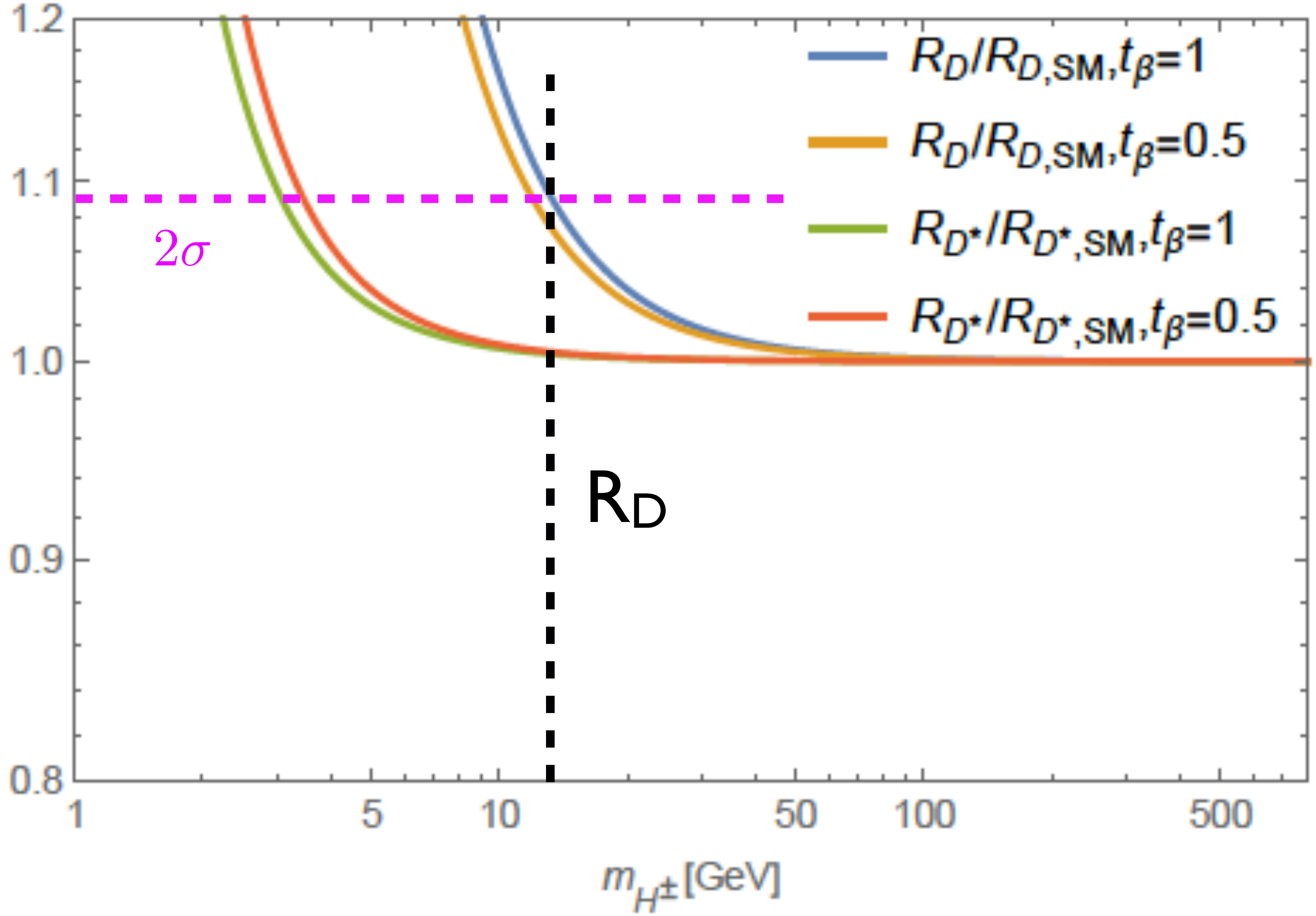
$B_s \to \mu^+\mu^-$

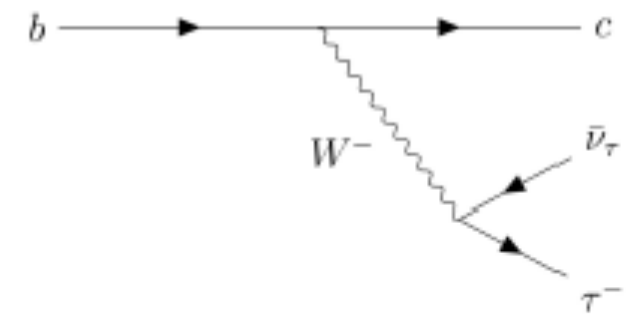
B_s–$\bar{B}_s$ mixing

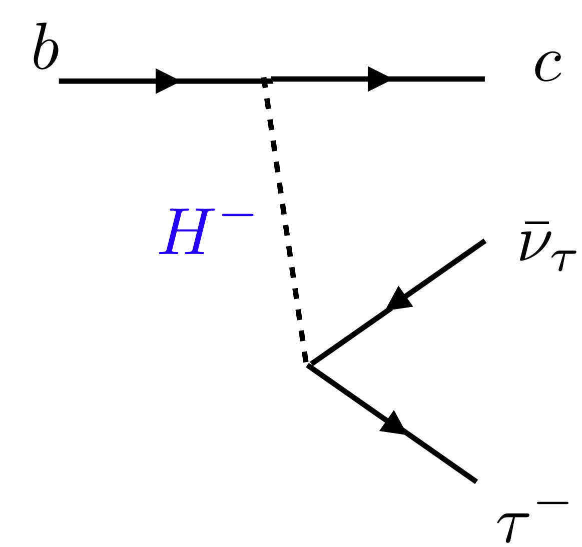
} Bounds on neutral Higgs masses: $m_H \sim m_A$ for EWPT data.

B→X$_s\gamma$ Lower bounds on charged Higgs mass

Anomalies in $R_{D^{(*)}}$







BaBar, Belle, LHCb: $\frac{R_D}{R_D^{\mathrm{SM}}} = \frac{R_{D^*}}{R_{D^*}^{\mathrm{SM}}} = 1.21 \pm 0.06$

Charged Higgs mass is bounded by $B \to X_s \gamma$ so cannot explain $R_{D^{(*)}}$ anomalies in our model.

Higgs production at LHC

Neutral Higgs production

[L. Bian, HML, C.B. Park, 2017]

Standard channels for single Higgs production

Gluon fusion

$gg \to H$

b-quark fusion

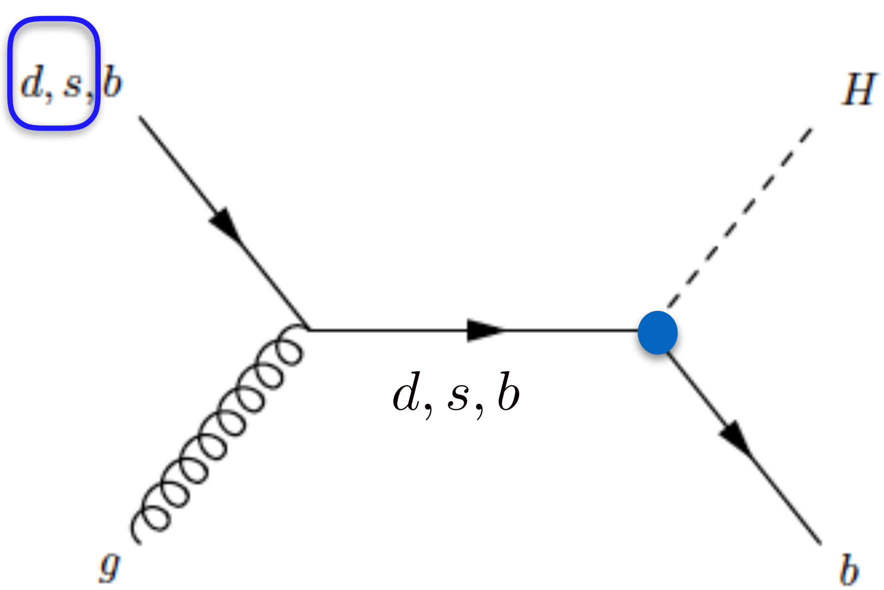
$b\bar{b} \to H$

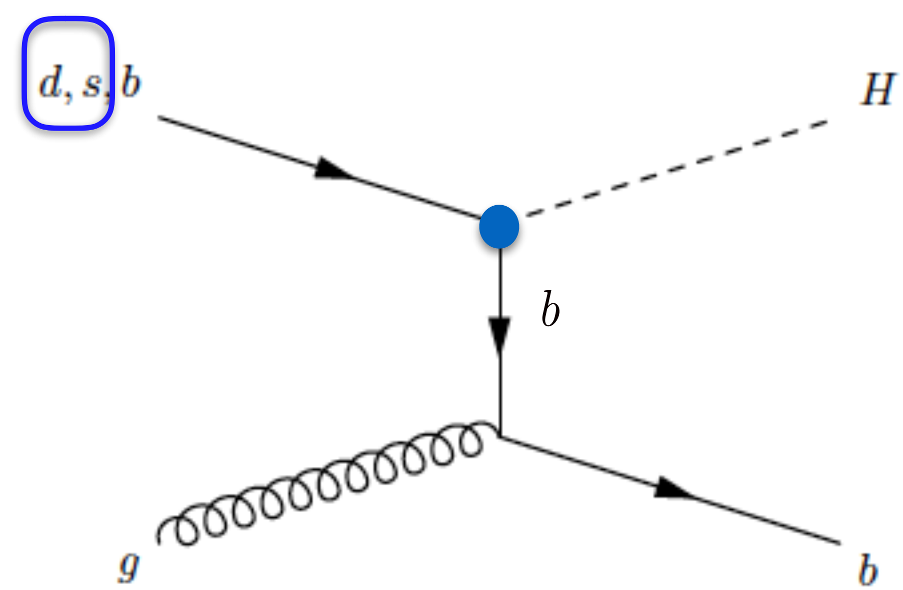
$\boxed{d_i g \to bH}$: b-quark associated production

+ flavor-violation (d_i=d,s)

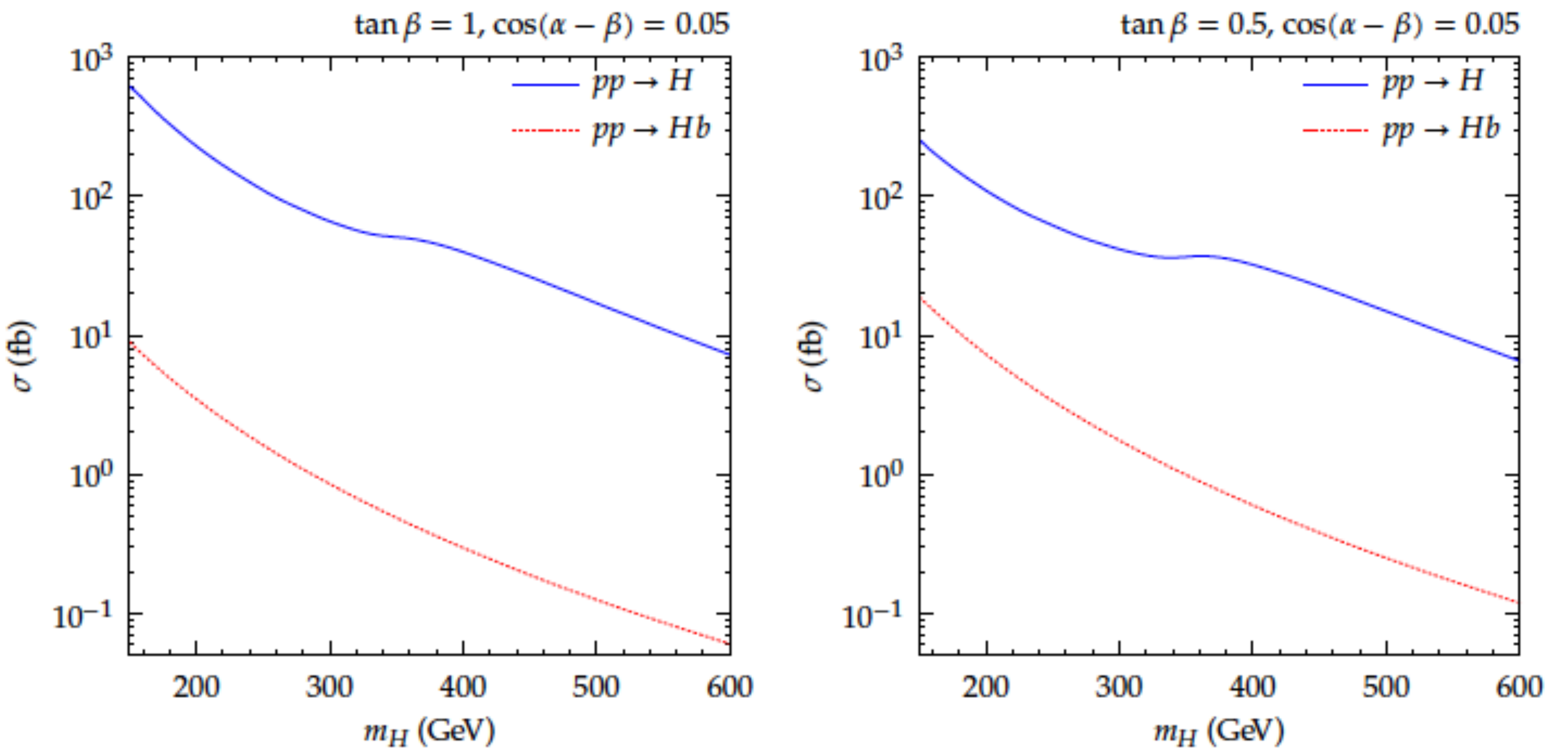
cf. Altmanshofer et al, 2016.

Light quarks (d,s)-fusion contributions





Neutral Higgs production

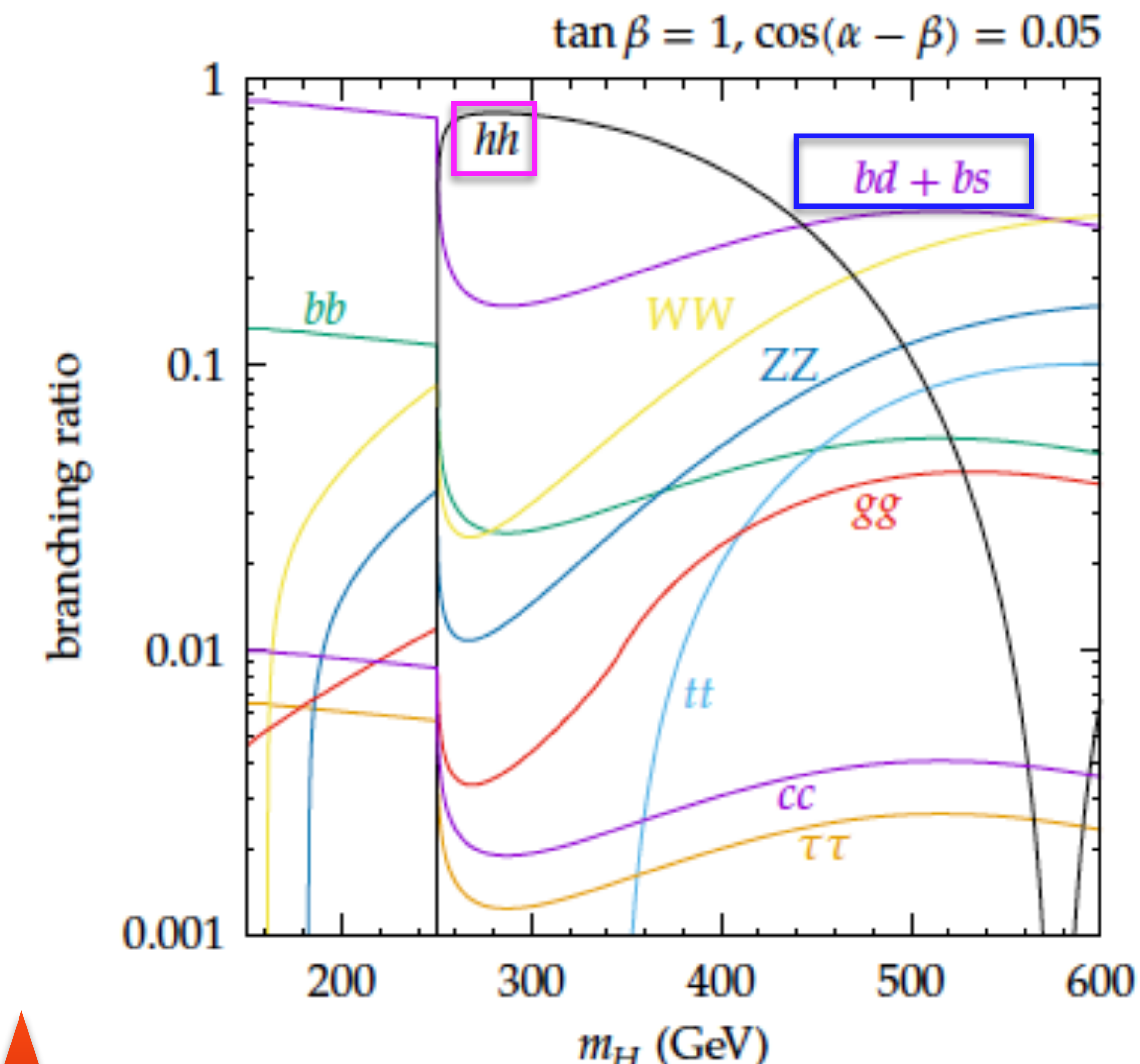


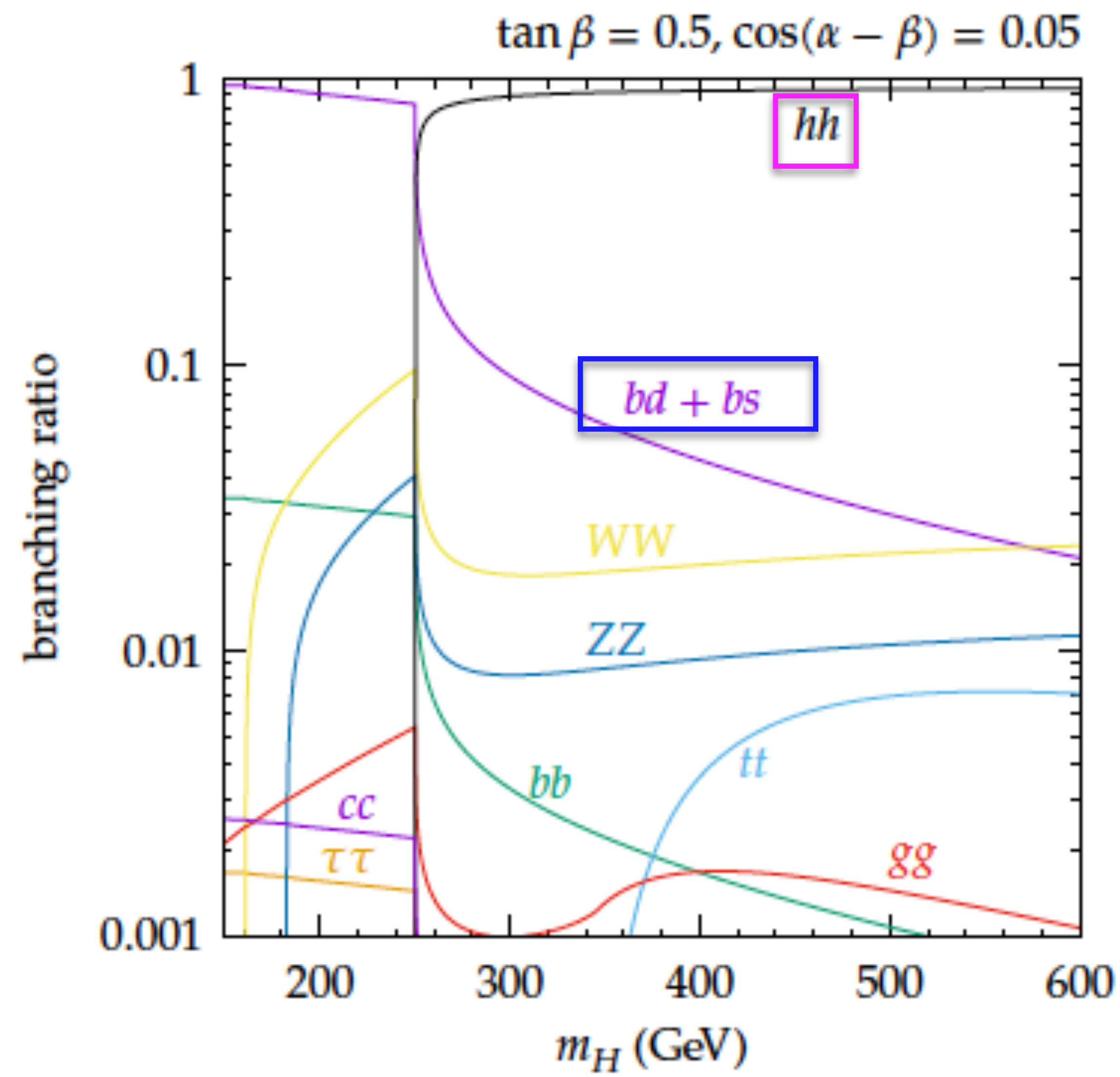
e.g. $m_H = 200$ GeV, $\tan\beta = 1\ (0.5)$, ➡ $\sigma_{pp\to H} \simeq 225.2\ (110.5)$ fb,

$\sigma_{b\bar{b}\to H}/\sigma_{gg\to H} = 0.39$ "g-fusion dominant"

$(\sigma_{bd_i\to H} + \sigma_{d_i\bar{b}\to H})/\sigma_{gg\to H} = 0.62\%\ (1.6\%)$ light-quark channels small

Neutral Higgs decays





New!

$m_H \lesssim 2m_h$: $bd + bs$ dominant → dijet (b-jet) bounds

$m_H \gtrsim 2m_h$: hh dominant → Resonant di-Higgs production

hh vs bd(s)

$$\Gamma(H \to hh) = \frac{g_{Hhh}^2 v^2}{32\pi m_H}\left(1 - \frac{4m_h^2}{m_H^2}\right)^{1/2}$$

$$\alpha = \beta - \pi/2$$

"alignment limit"

Light Higgs

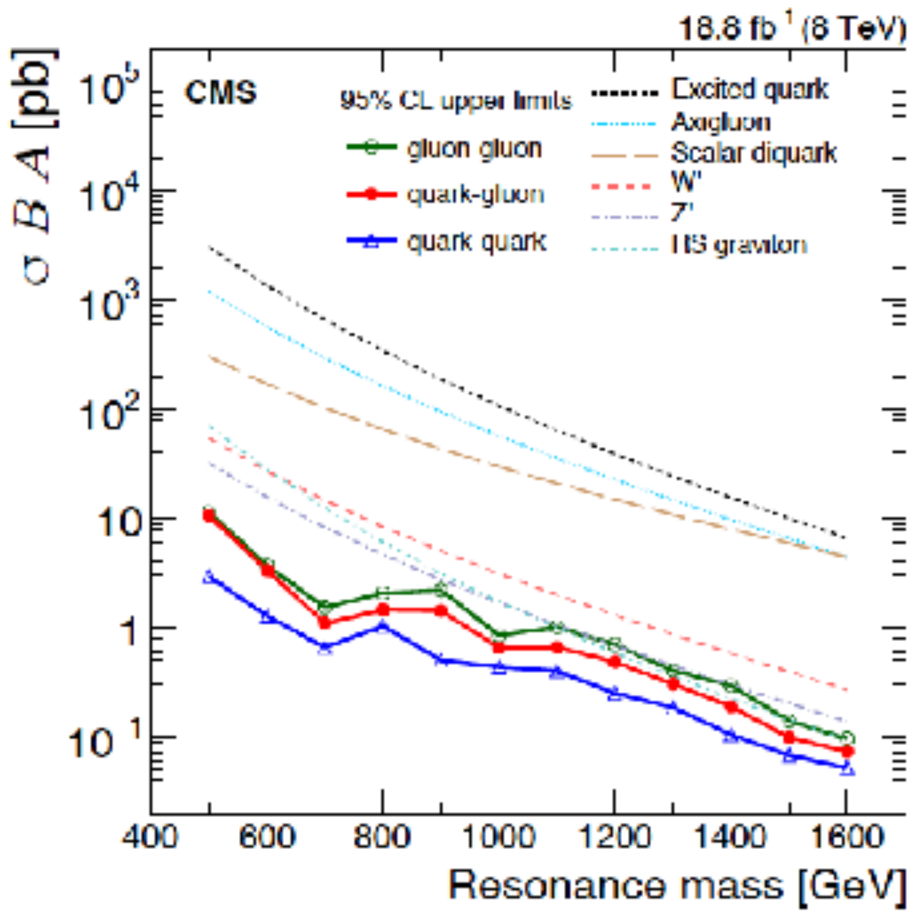
$$\begin{aligned} g_{Hhh} = &\, 3(\lambda_1 \sin\alpha\cos\beta + \lambda_2 \cos\alpha \sin\beta)\sin(2\alpha) \\ &+ (\lambda_3 + \lambda_4)\left[3\cos(\alpha+\beta)\cos(2\alpha) - \cos(\alpha - \beta)\right]. \end{aligned}$$

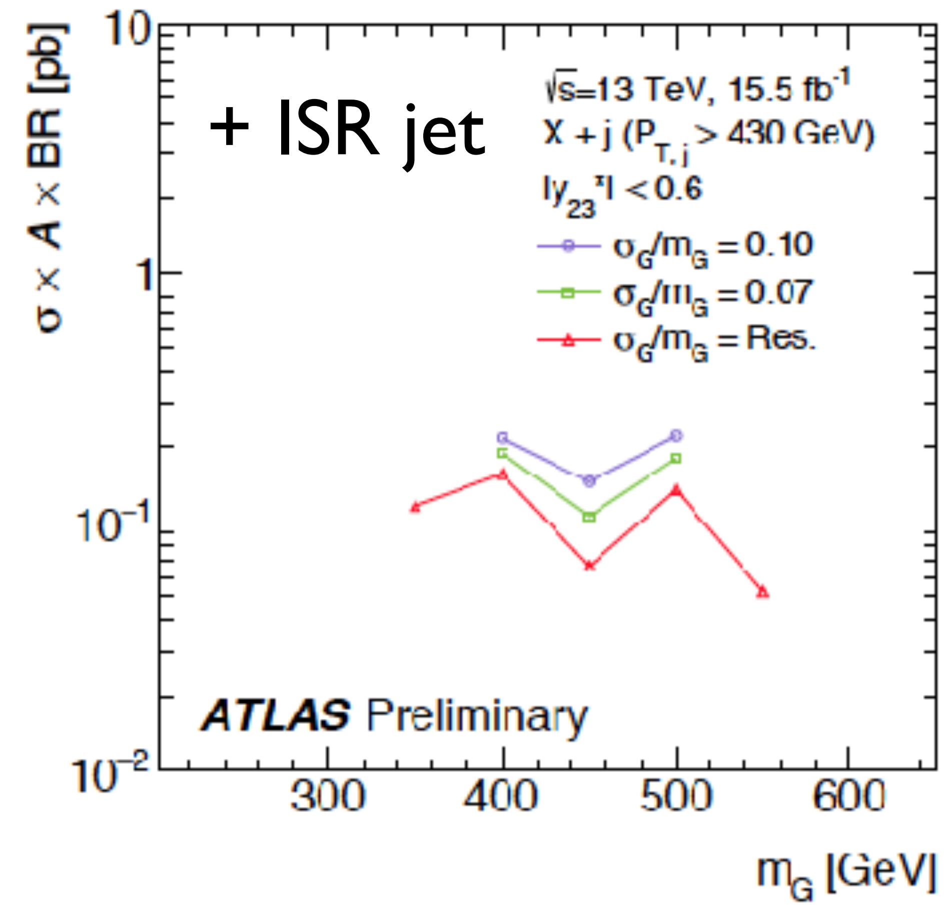
$$\Gamma(H \to b\bar{d}_i) = \Gamma(H \to d_i \bar{b}) = \frac{3|\tilde{h}_{i3}^d|^2 \sin^2(\alpha-\beta)}{32\pi\cos^2\beta} m_H \left(1 - \frac{m_b^2}{m_H^2}\right)^2$$

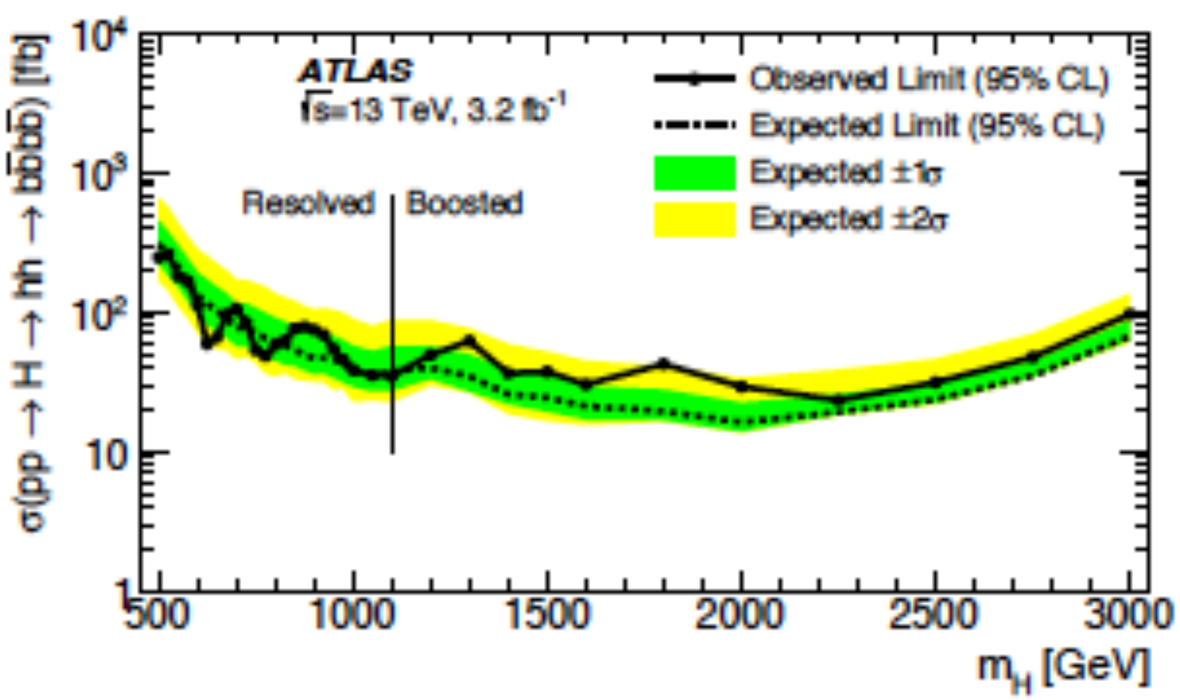
Heavy Higgs

$$\begin{aligned} \tilde{h}_{13}^d &= 1.80 \times 10^{-2}\left(\frac{m_b}{v\sin\beta}\right), \\ \tilde{h}_{23}^d &= 5.77 \times 10^{-2}\left(\frac{m_b}{v\sin\beta}\right), \\ \tilde{h}_{33}^d &= 2.41 \times 10^{-3}\left(\frac{m_b}{v\sin\beta}\right). \end{aligned}$$

LHC resonances







(c) Spin-0 narrow-width *H* boson

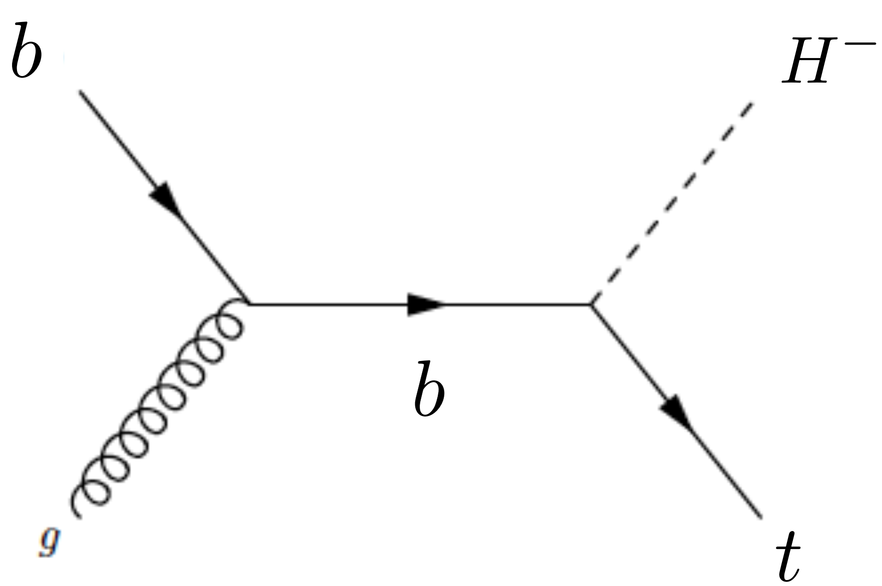
If gluon-fusion dominant,
dijet+ISR photon does not apply.

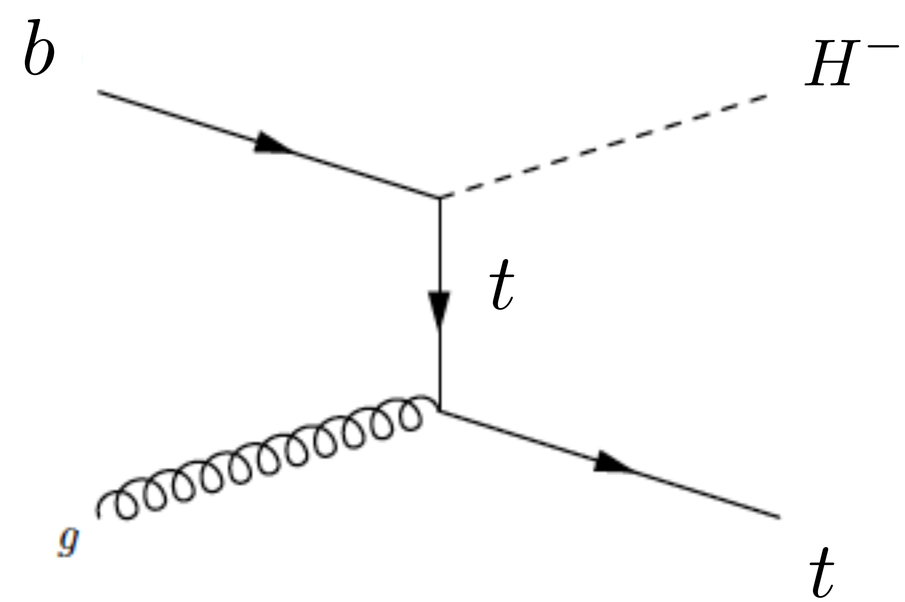
Heavy Higgs searches
do not have enough
sensitivity for our model yet.

Charged Higgs production

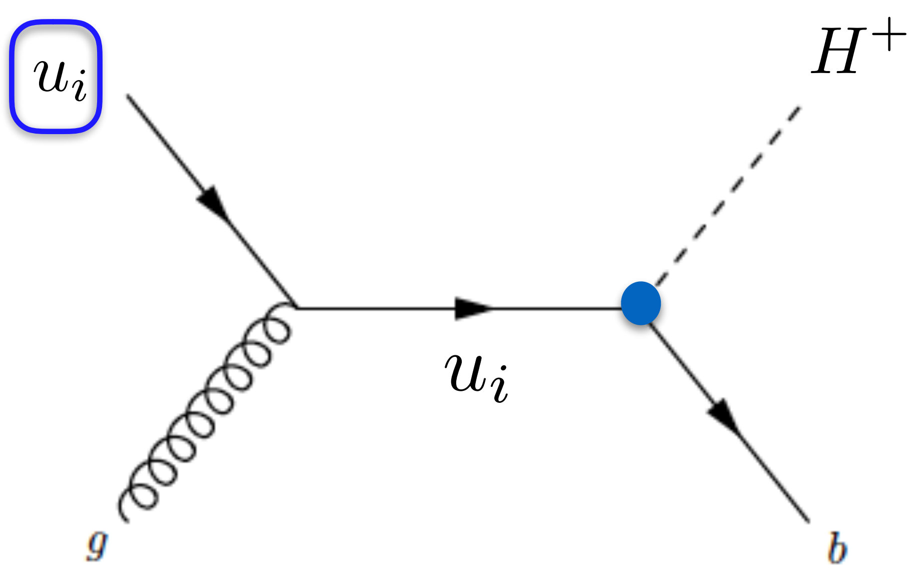
[L. Bian, HML, C.B. Park, 2017]

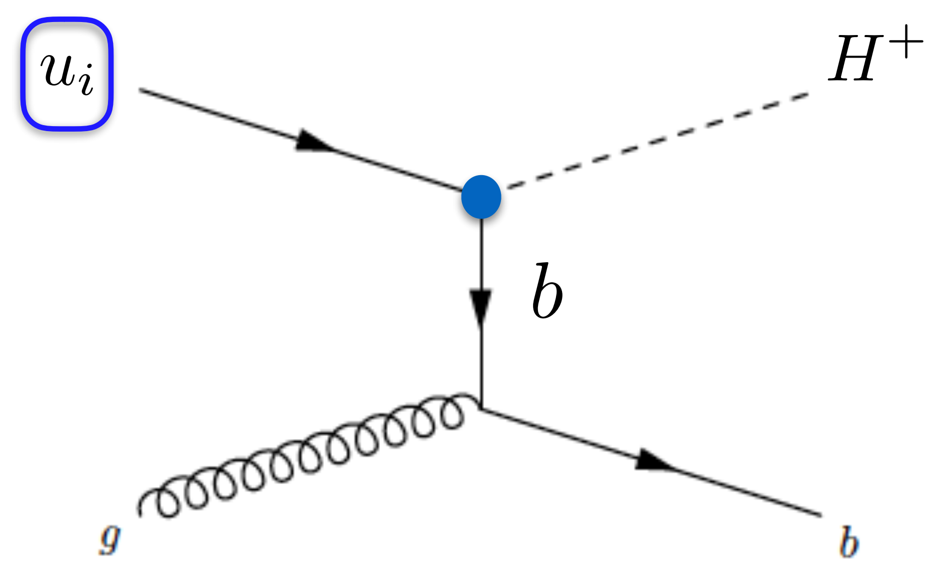
$ba \to tH^-$: Standard channels for charged Higgs



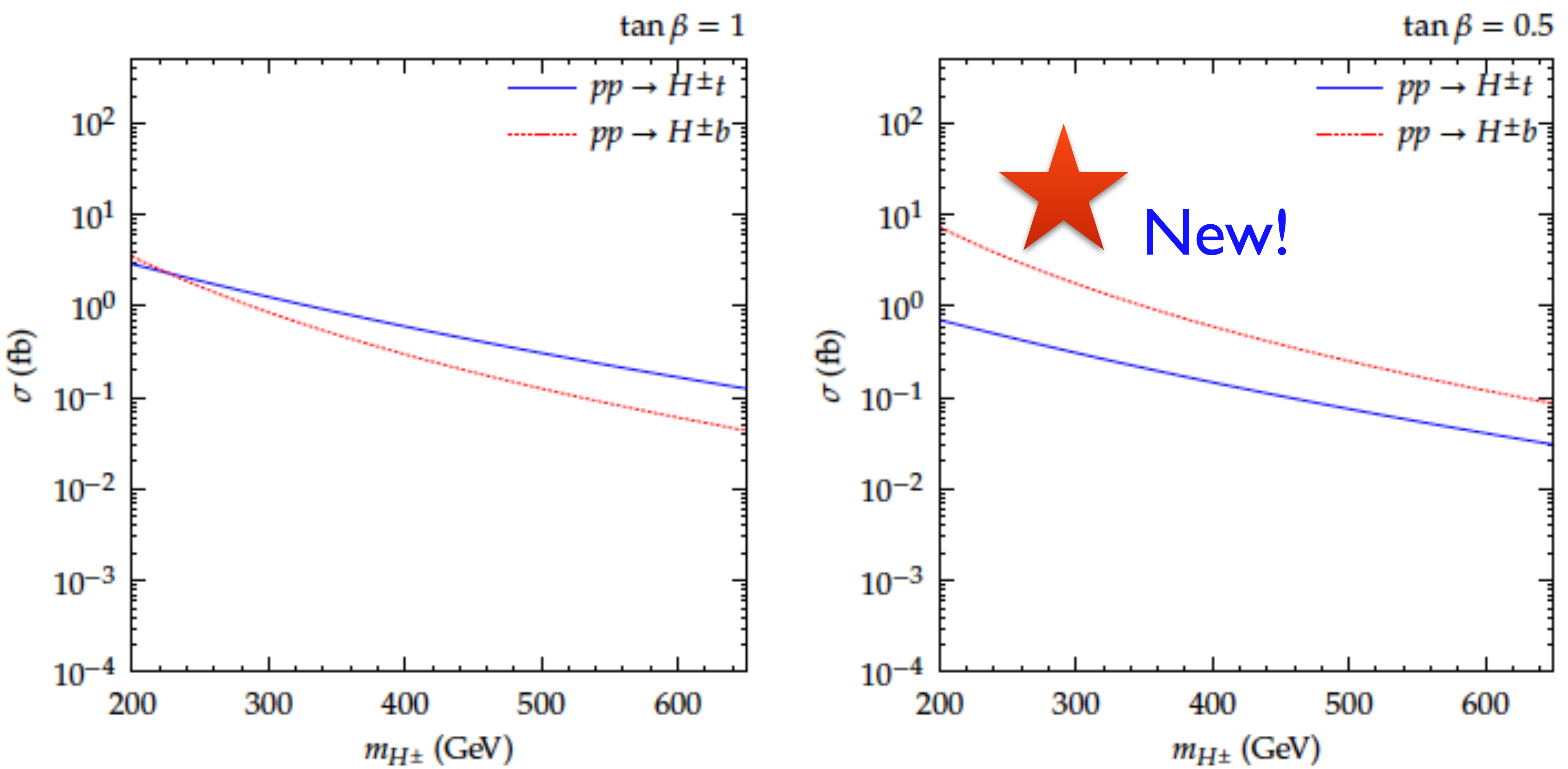


$\boxed{u_i g \to bH^+,}$ $u_i = u,\ c.$: light quarks(u,c)-fusion contributions



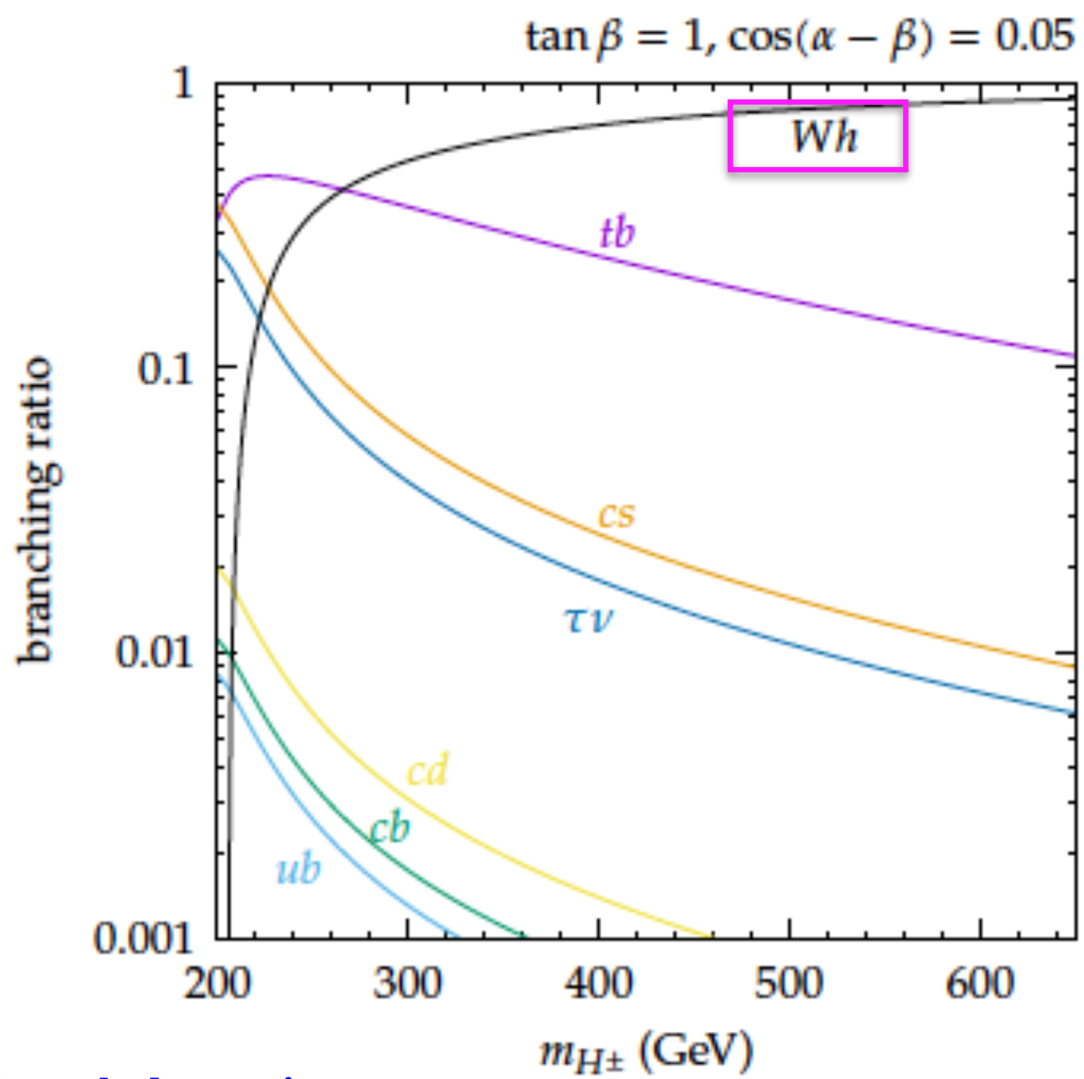


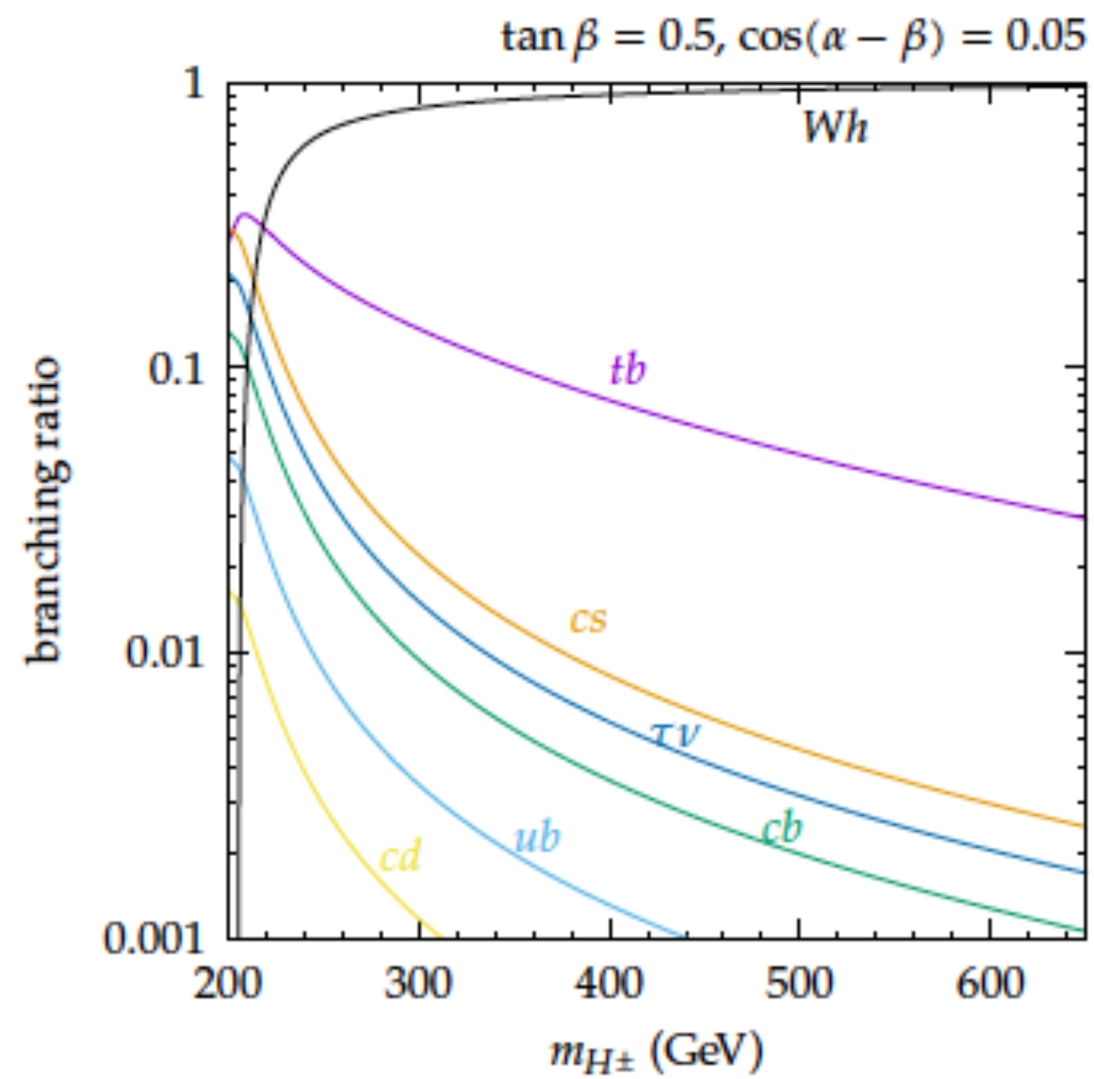
Charged Higgs production



Flavor-violating production can be dominant for small $\tan\beta$.

Charged Higgs decays





New!

$m_{H^\pm} \gtrsim m_W + m_h \sim 225\,\mathrm{GeV}$: $pp \to H^\pm b \to \boxed{W^\pm h + b}$

$m_{H^\pm} \lesssim 225\,\mathrm{GeV}$: tb dominant

"3b's: smoking gun signal"

No constraints from LHC yet!

tb vs Wh

$$\Gamma(H^+ \to t\bar{b}) = \Gamma(H^- \to b\bar{t})$$
$$= \frac{3}{16\pi} m_{H^\pm} \left[\left(1 - \frac{(m_t+m_b)^2}{m_{H^\pm}^2}\right)\left(1 - \frac{(m_t-m_b)^2}{m_{H^\pm}^2}\right)\right]^{1/2}$$
$$\times \left[\left(|\lambda_{t_L}^{H^-}|^2 + |\lambda_{t_R}^{H^-}|^2\right)\left(1 - \frac{m_t^2+m_b^2}{m_{H^\pm}^2}\right) - 2\left(\lambda_{t_L}^{H^-}(\lambda_{t_R}^{H^-})^* + \lambda_{t_R}^{H^-}(\lambda_{t_L}^{H^-})^*\right)\frac{m_t m_b}{m_{H^\pm}^2}\right].$$

"Suppressed, cancelled"

$$\Gamma(H^+ \to W^+ h) = \Gamma(H^- \to W^- h)$$
$$= \frac{g^2 \cos^2(\alpha-\beta) m_{H^\pm}^3}{64\pi m_W^2}\left[\left(1 - \frac{m_W^2}{m_{H^\pm}^2} - \frac{m_h^2}{m_{H^\pm}^2}\right)^2 - \frac{4 m_W^2 m_h^2}{m_{H^\pm}^4}\right]^{3/2}.$$

"Longitudinal enhancement"

$$\lambda_{t_L}^{H^-} = \frac{\sqrt{2} m_b \tan\beta}{v} V_{tb}^* - \frac{(V_{\mathrm{CKM}}\tilde{h}^d)_{33}^*}{\cos\beta},$$
$$\lambda_{t_R}^{H^-} = -\left(\frac{\sqrt{2} m_t \tan\beta}{v} - \frac{\tilde{h}_{33}^u}{\cos\beta}\right) V_{tb}^*, \xrightarrow[y_{33}^u = y_t^{\mathrm{SM}} = \sqrt{2} m_t/v]{} \lambda_{t_R}^{H^-} = 0.$$

$$\tilde{h}_{33}^u = \frac{\sqrt{2} m_t}{v \sin\beta}\left(1 - \frac{v^2\cos^2\beta}{2m_t^2}|y_{33}^u|^2\right)$$

$$V_{\mathrm{CKM}}\tilde{h}^d = \begin{pmatrix} 0 & 0 & V_{ud}\tilde{h}_{13}^d + V_{us}\tilde{h}_{23}^d + V_{ub}\tilde{h}_{33}^d \\ 0 & 0 & V_{cd}\tilde{h}_{13}^d + V_{cs}\tilde{h}_{23}^d + V_{cb}\tilde{h}_{33}^d \\ 0 & 0 & V_{td}\tilde{h}_{13}^d + V_{ts}\tilde{h}_{23}^d + V_{tb}\tilde{h}_{33}^d \end{pmatrix}$$

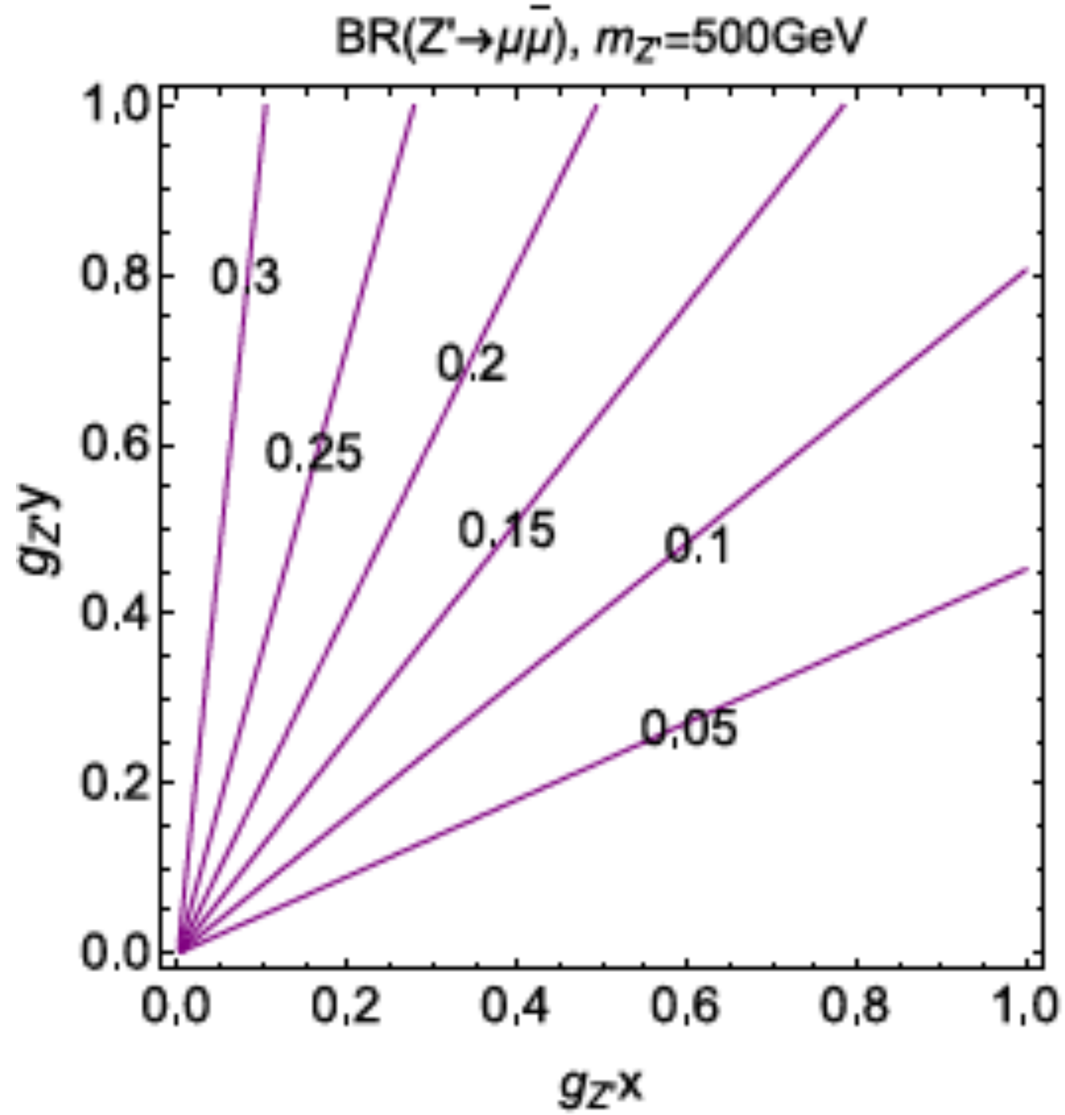
$$\tilde{h}_{13}^d = 1.80 \times 10^{-2}\left(\frac{m_b}{v\sin\beta}\right),$$
$$\tilde{h}_{23}^d = 5.77 \times 10^{-2}\left(\frac{m_b}{v\sin\beta}\right),$$
$$\tilde{h}_{33}^d = 2.41 \times 10^{-3}\left(\frac{m_b}{v\sin\beta}\right).$$

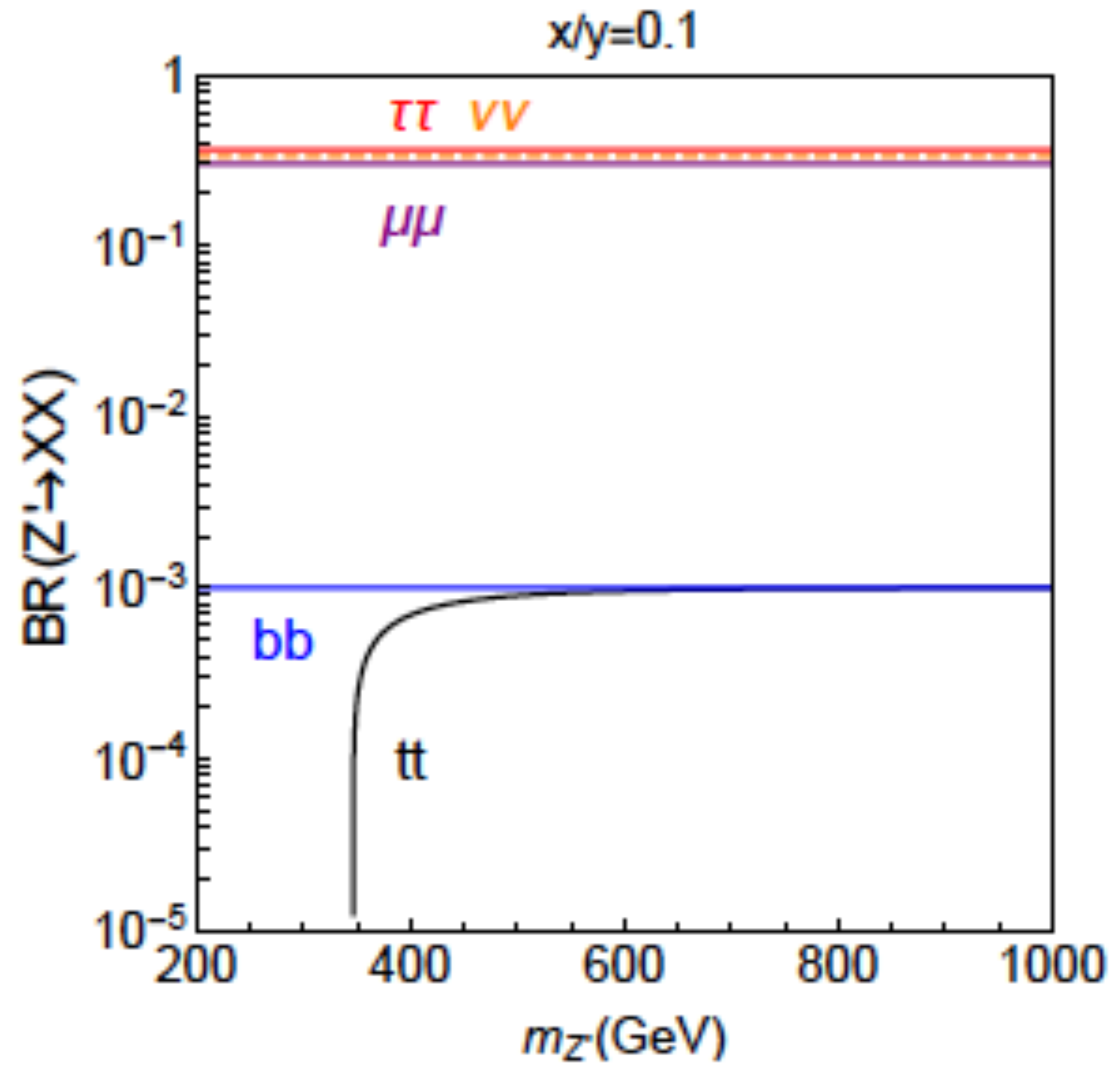
Conclusions

- B-meson anomalies can be explained due to anomaly-free U(1)’ interactions with heavy flavors.
- Meson mixing/decays & LHC dimuons as well as tau decays and neutrino trident production are complementary to constrain the flavored Z’ models.
- Flavor violating couplings in Z’-2HDM lead to smoking-gun signatures for LHC: dijet (w/ b-jet) or hh for neutral heavy Higgs and b+Wh for charged Higgs.
- Both B-anomalies hint at new flavor violations in both neutral and charged currents.

Backup

Z' Decay BR





$$\mathrm{BR}(t\bar{t}, b\bar{b}) \,:\, \mathrm{BR}(\mu\bar{\mu}) \,:\, \mathrm{BR}(\tau\bar{\tau}) \,:\, \mathrm{BR}(\nu_\mu\bar{\nu}_\mu + \nu_\tau\bar{\nu}_\tau) = 2x^2 \,:\, 6y^2 \,:\, 6(x+y)^2 \,:\, 3(y^2 + (x+y)^2).$$

$$x \ll y, \quad \mathrm{BR}(\mu\bar{\mu}, \tau\bar{\tau}) \,:\, \mathrm{BR}(\nu_\mu\bar{\nu}_\mu + \nu_\tau\bar{\nu}_\tau) \sim 1 \,:\, 1$$

"$(L_\mu - L_\tau) -$ like"

Quark mixing

Flavor-violating couplings depend only on tanβ :

$$U_L = 1, \text{ so } V_{\text{CKM}} = D_L. \quad \Rightarrow \quad M_d \approx V_{\text{CKM}} M_d^D$$

$\boxed{\text{down-type:}}$

$$y_{11}^d = \frac{\sqrt{2}m_d}{v\cos\beta}V_{ud}, \quad y_{12}^d = \frac{\sqrt{2}m_s}{v\cos\beta}V_{us},$$

$$y_{21}^d = \frac{\sqrt{2}m_d}{v\cos\beta}V_{cd}, \quad y_{22}^d = \frac{\sqrt{2}m_s}{v\cos\beta}V_{cs}, \quad y_{33}^d = \frac{\sqrt{2}m_b}{v\cos\beta}V_{tb}.$$

$$\boxed{h_{13}^d = \frac{\sqrt{2}m_b}{v\sin\beta}V_{ub}, \quad h_{23}^d = \frac{\sqrt{2}m_b}{v\sin\beta}V_{cb},} \qquad h_{13}^d \ll h_{23}^d.$$

$U_R^\dagger = (M_u^D)^{-1}M_u,$ unitarity condition.

$\boxed{\text{up-type:}}$

$$|y_{11}^u|^2 + |y_{12}^u|^2 = \frac{2m_u^2}{v^2\cos^2\beta},$$

$$|y_{21}^u|^2 + |y_{22}^u|^2 = \frac{2m_c^2}{v^2\cos^2\beta},$$

$$|y_{33}^u|^2 + \tan^2\beta(|h_{31}^u|^2 + |h_{32}^u|^2) = \frac{2m_t^2}{v^2\cos^2\beta},$$

"free"

$$y_{11}^u(y_{21}^u)^* + y_{12}^u(y_{22}^u)^* = 0,$$

$$y_{21}^u(h_{31}^u)^* + y_{22}^u(h_{32}^u)^* = 0,$$

$$y_{11}^u(h_{31}^u)^* + y_{12}^u(h_{32}^u)^* = 0.$$

Quark Yukawa couplings

Neutral Higgs bosons: "b-quark flavor violating"

[Crivellin et al, 2015;
L. Bian, HML, C.B. Park, 2017]

$$
\begin{aligned}
-\mathcal{L}_Y^{h/H/A} = & \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta}\bar{b}_R\left(\tilde{h}^{d*}_{13}d_L+\tilde{h}^{d*}_{23}s_L\right)h+\frac{\lambda^h_b}{\sqrt{2}}\bar{b}_R b_L h+\frac{\lambda^h_t}{\sqrt{2}}\bar{t}_R t_L h \\
& +\frac{\sin(\alpha-\beta)}{\sqrt{2}\cos\beta}\bar{b}_R\left(\tilde{h}^{d*}_{13}d_L+\tilde{h}^{d*}_{23}s_L\right)H+\frac{\lambda^H_b}{\sqrt{2}}\bar{b}_R b_L H+\frac{\lambda^H_t}{\sqrt{2}}\bar{t}_R t_L H \\
& -\frac{i}{\sqrt{2}\cos\beta}\bar{b}_R\left(\tilde{h}^{d*}_{13}d_L+\tilde{h}^{d*}_{23}s_L\right)A+\frac{i\lambda^A_b}{\sqrt{2}}\bar{b}_R b_L A-\frac{i\lambda^A_t}{\sqrt{2}}\bar{t}_R t_L A+\text{h.c.}
\end{aligned}
$$

SM Higgs if

$\alpha=\beta-\pi/2$

2HDM-I like

$$
\begin{aligned}
\lambda^h_b &= -\frac{\sqrt{2}m_b\sin\alpha}{v\cos\beta}+\frac{\tilde{h}^d_{33}\cos(\alpha-\beta)}{\cos\beta}, \\
\lambda^h_t &= -\frac{\sqrt{2}m_t\sin\alpha}{v\cos\beta}+\frac{\tilde{h}^u_{33}\cos(\alpha-\beta)}{\cos\beta}, \\
\lambda^H_b &= \frac{\sqrt{2}m_b\cos\alpha}{v\cos\beta}+\frac{\tilde{h}^d_{33}\sin(\alpha-\beta)}{\cos\beta}, \\
\lambda^H_t &= \frac{\sqrt{2}m_t\cos\alpha}{v\cos\beta}+\frac{\tilde{h}^u_{33}\sin(\alpha-\beta)}{\cos\beta}, \\
\lambda^A_b &= \frac{\sqrt{2}m_b\tan\beta}{v}-\frac{\tilde{h}^d_{33}}{\cos\beta}, \\
\lambda^A_t &= \frac{\sqrt{2}m_t\tan\beta}{v}-\frac{\tilde{h}^u_{33}}{\cos\beta}.
\end{aligned}
$$

"no flavor violation in top but reduced H-t-t"

$$
\begin{aligned}
\tilde{h}^u_{33} &= \frac{\sqrt{2}m_t}{v\sin\beta}\left(1-\frac{v^2\cos^2\beta}{2m_t^2}|y^u_{33}|^2\right), \\
\tilde{h}^d_{13} &= 1.80\times10^{-2}\left(\frac{m_b}{v\sin\beta}\right), \\
\tilde{h}^d_{23} &= 5.77\times10^{-2}\left(\frac{m_b}{v\sin\beta}\right), \\
\tilde{h}^d_{33} &= 2.41\times10^{-3}\left(\frac{m_b}{v\sin\beta}\right).
\end{aligned}
$$

Quark Yukawa couplings

Charged Higgs boson: b-quark flavor violating

$$-\mathcal{L}_Y^{H^-} = \bar{b}(\lambda_{t_L}^{H^-} P_L + \lambda_{t_R}^{H^-} P_R) t H^- + \bar{b}(\lambda_{c_L}^{H^-} P_L + \lambda_{c_R}^{H^-} P_R) c H^- + \lambda_{u_L}^{H^-} \bar{b} P_L u H^- + \text{h.c.}$$

2HDM-I like

"H-t-b reduced"

$$\begin{aligned}
\lambda_{t_L}^{H^-} &= \frac{\sqrt{2} m_b \tan\beta}{v} V_{tb}^* - \frac{(V_{\rm CKM} \tilde{h}^d)_{33}^*}{\cos\beta}, \\
\lambda_{t_R}^{H^-} &= -\left(\frac{\sqrt{2} m_t \tan\beta}{v} - \frac{\tilde{h}_{33}^u}{\cos\beta} \right) V_{tb}^*, \\
\lambda_{c_L}^{H^-} &= \frac{\sqrt{2} m_b \tan\beta}{v} V_{cb}^* - \frac{(V_{\rm CKM} \tilde{h}^d)_{23}^*}{\cos\beta}, \\
\lambda_{c_R}^{H^-} &= -\frac{\sqrt{2} m_c \tan\beta}{v} V_{cb}^*, \\
\lambda_{u_L}^{H^-} &= \frac{\sqrt{2} m_b \tan\beta}{v} V_{ub}^* - \frac{(V_{\rm CKM} \tilde{h}^d)_{13}^*}{\cos\beta}
\end{aligned}$$

$$V_{\rm CKM} \tilde{h}^d = \begin{pmatrix} 0 & 0 & V_{ud} \tilde{h}_{13}^d + V_{us} \tilde{h}_{23}^d + V_{ub} \tilde{h}_{33}^d \\ 0 & 0 & V_{cd} \tilde{h}_{13}^d + V_{cs} \tilde{h}_{23}^d + V_{cb} \tilde{h}_{33}^d \\ 0 & 0 & V_{td} \tilde{h}_{13}^d + V_{ts} \tilde{h}_{23}^d + V_{tb} \tilde{h}_{33}^d \end{pmatrix}.$$