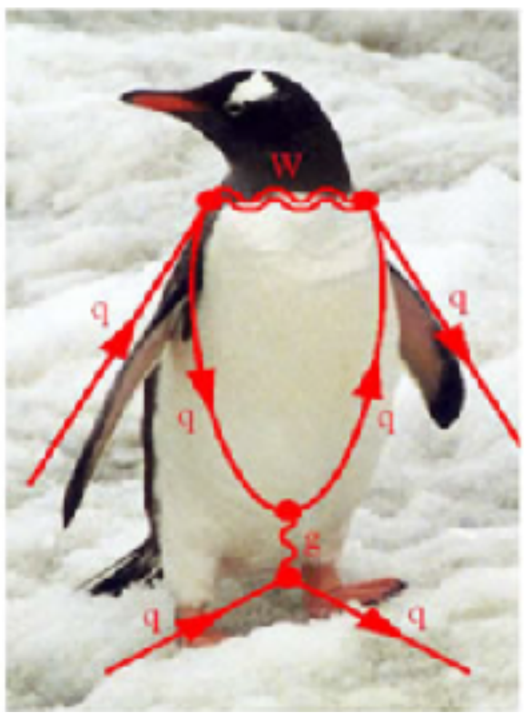
B-meson anomalies & Higgs physics in flavored U(1)' model



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L. Bian, S.-M. Choi, Y.-J. Kang, HML, Phys. Rev. D96 (2017) 075038;
L. Bian, HML, C.B. Park, arXiv:1711.08930

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High 1 resort, January 7-13, 2018

Outline

- Motivation
- Minimal flavored U(1)’
- Flavor violation from extra Higgs
- Higgs production at LHC
- Conclusions

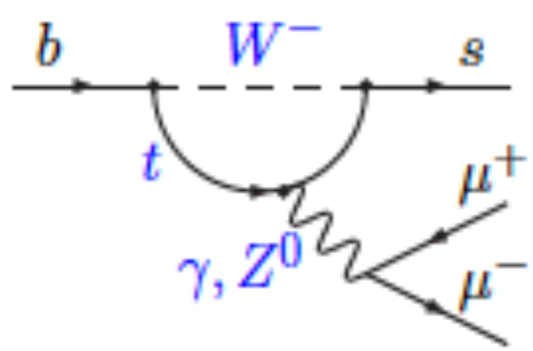
FCNC in SM

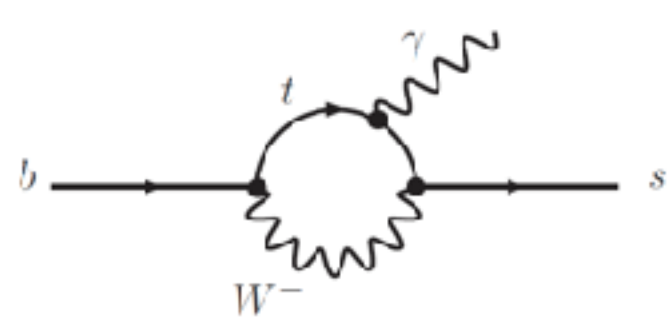
- "Charged currents" induce flavor violating processes at tree level, while FCNCs are induced at loop level.

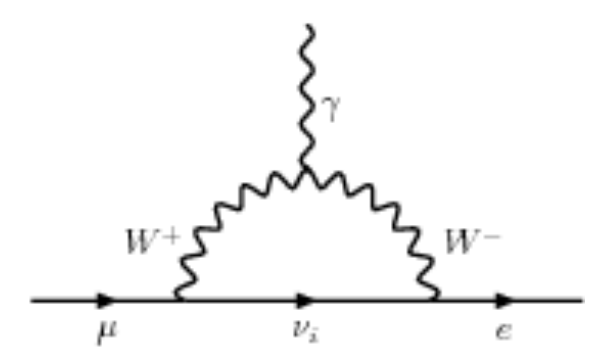
$$\frac{-g}{\sqrt{2}}(u_L,\, c_L,\, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + {\rm h.c.}, \qquad V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

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

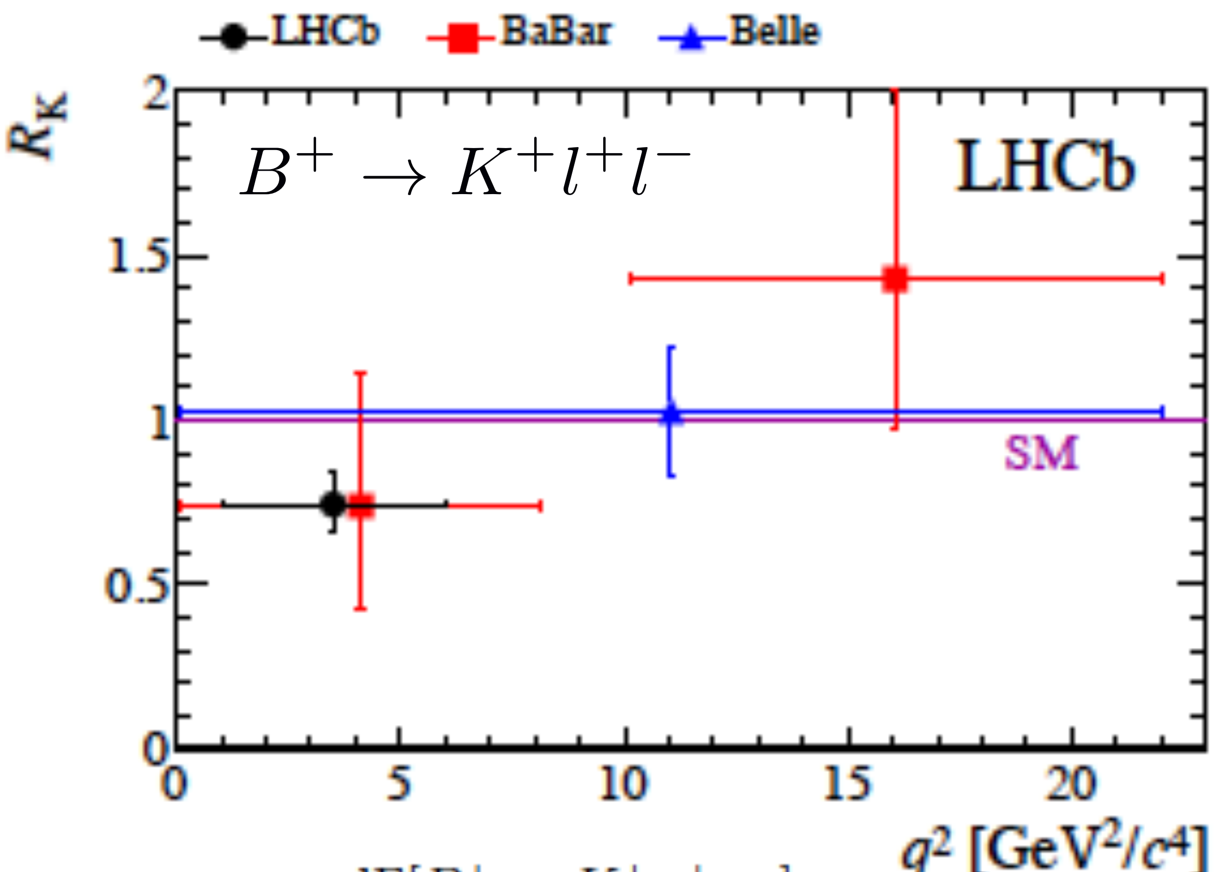
- "FCNC processes" are sensitive probes to a violation of lepton flavors & universal interactions, due to new physics.

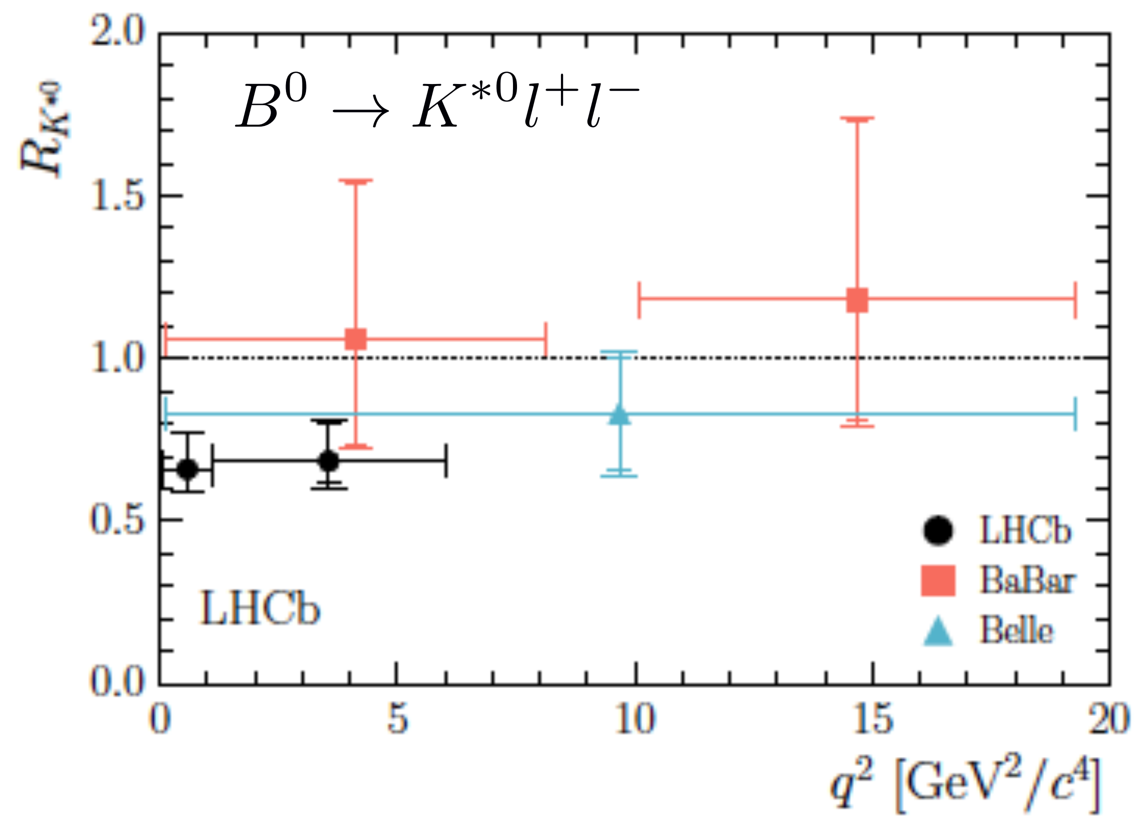






B-anomalies at LHCb





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

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

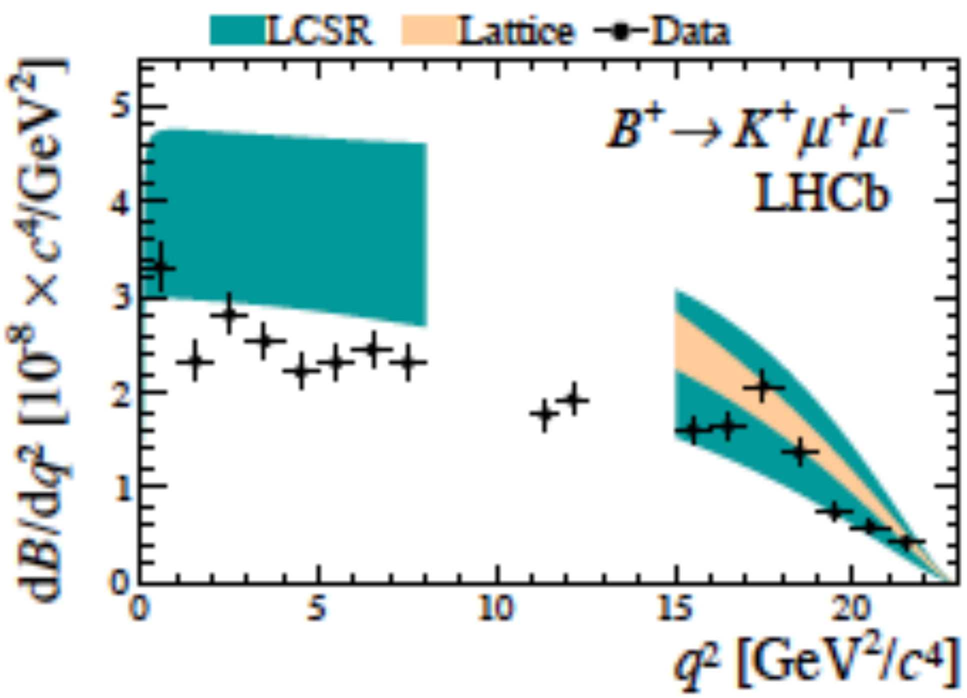
$$1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2$$

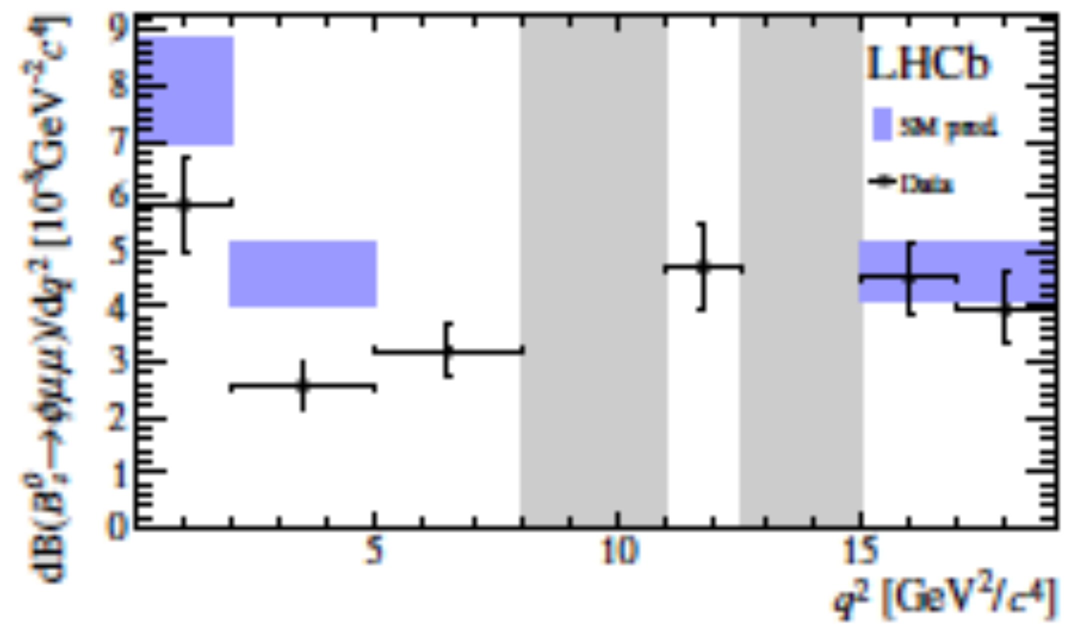
LHCb Preliminary	**low-q^2**	**central-q^2**
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

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

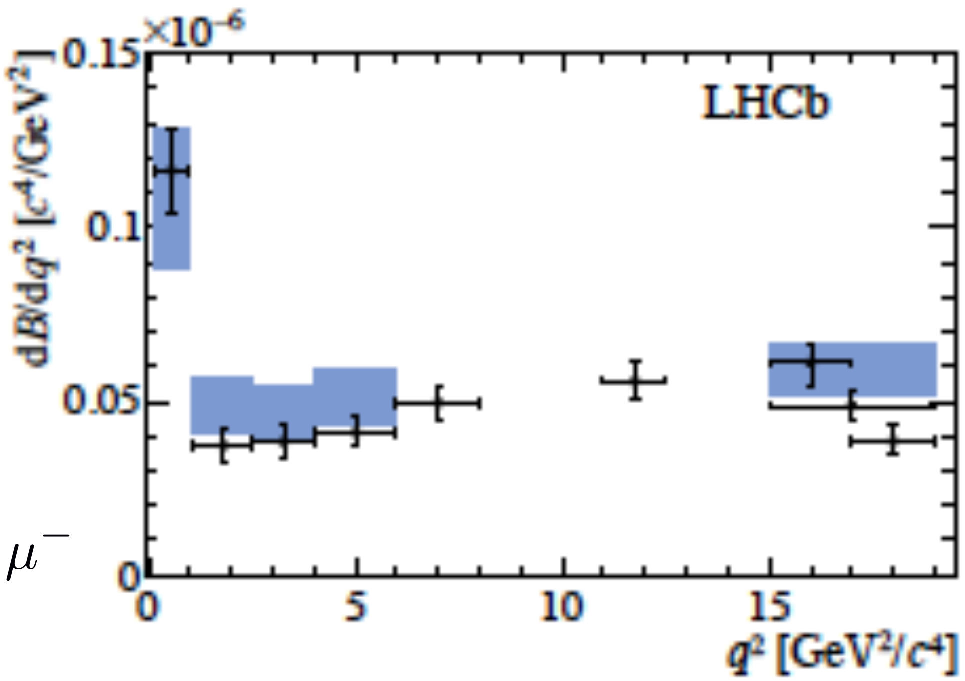
lepton flavor non-universality?

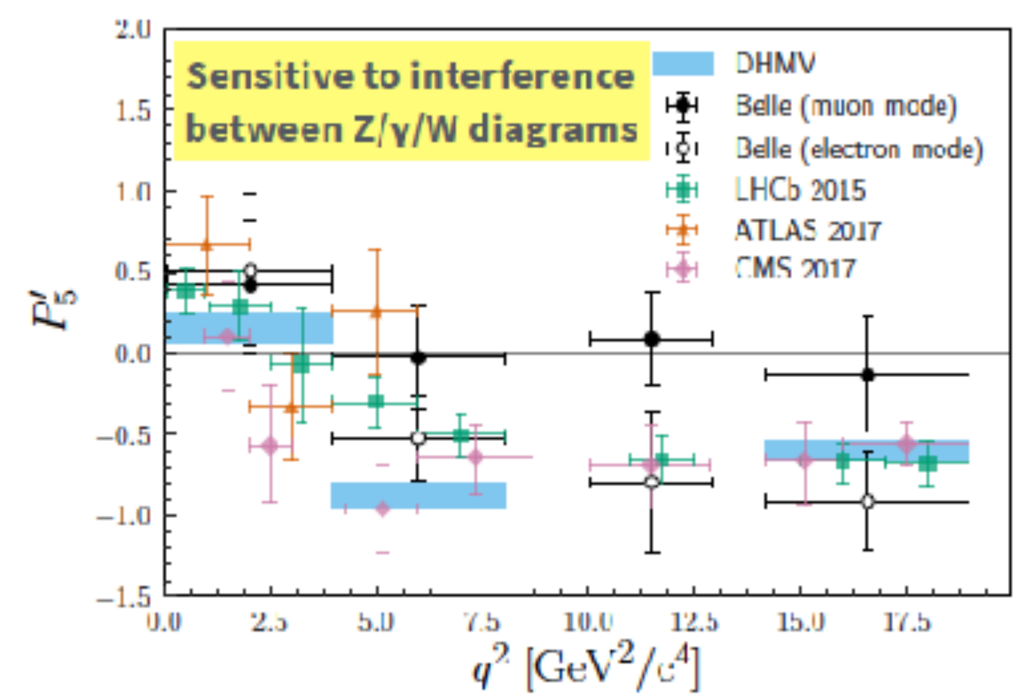
Distributions of B-decays





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

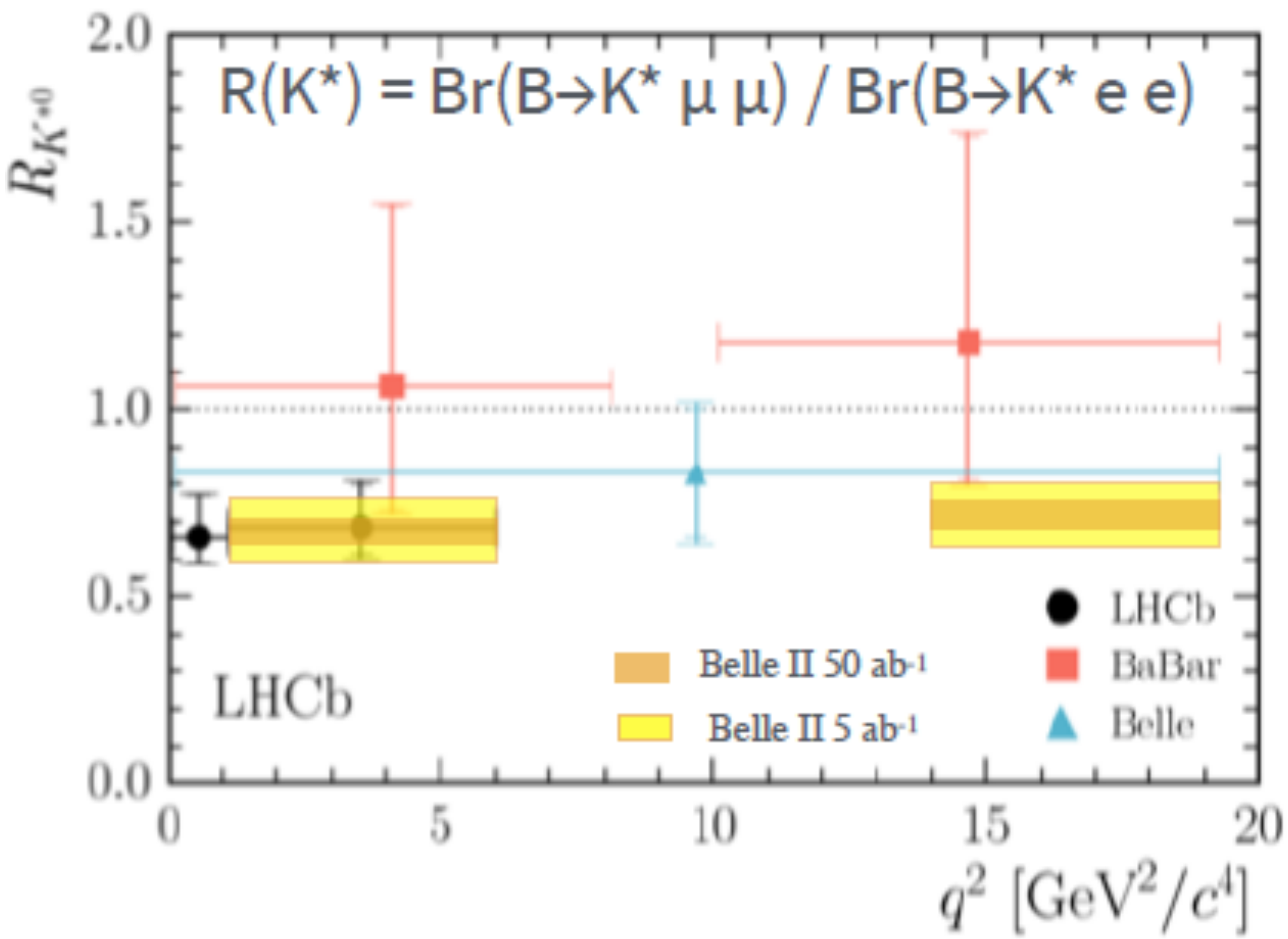


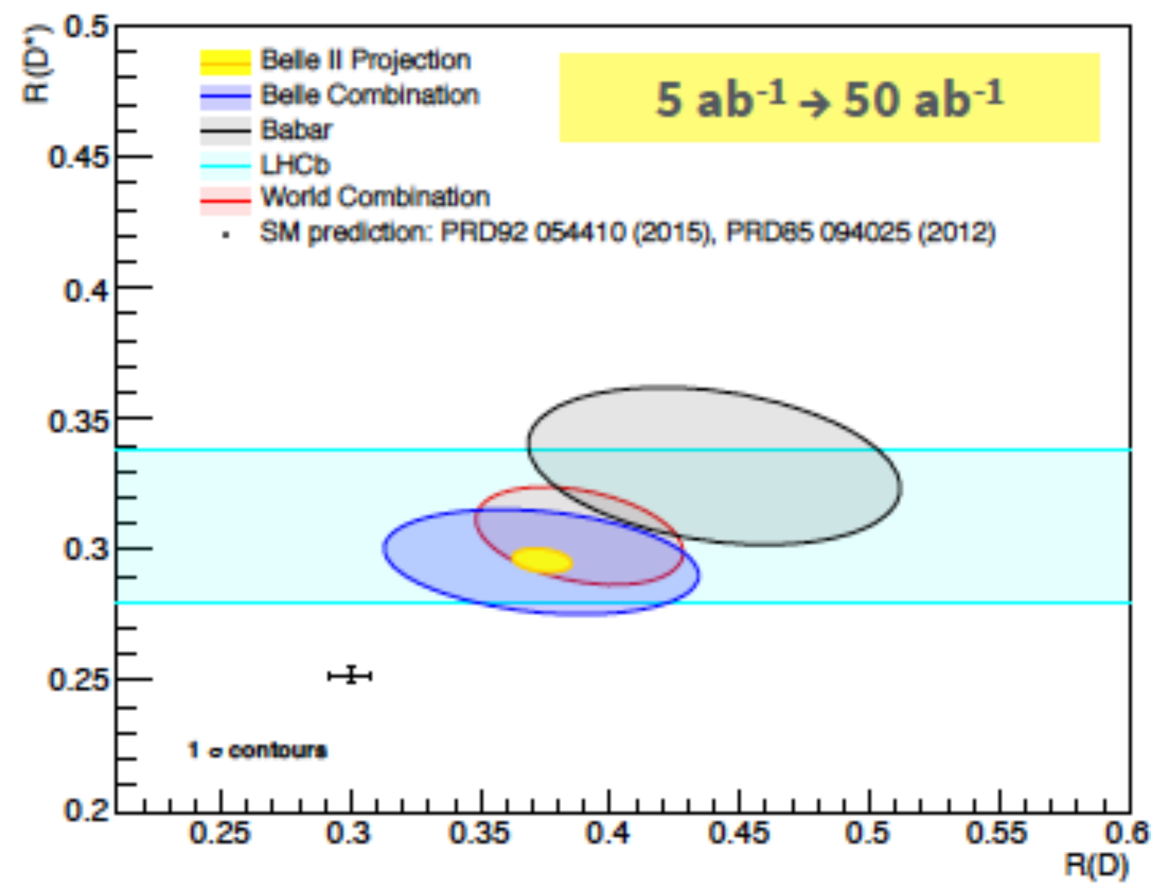


- Differential branching fractions & angular distribution are consistently lower than the SM values.

Belle II for B-anomalies

[Philip Urquijo, SUSY 2017 Plenary]



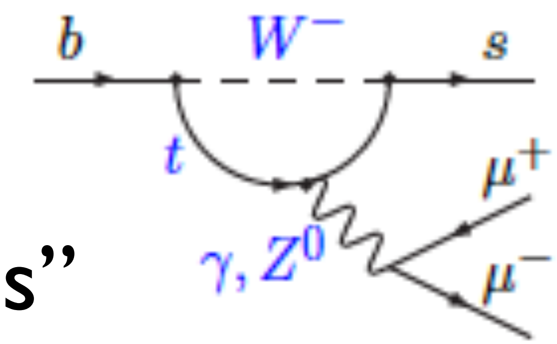


- Belle II can test LFUV in B-meson decays to few % with data of 5 ab^{-1}.

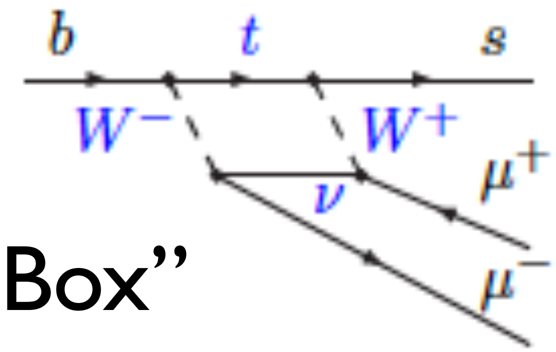
EFT for B-decays

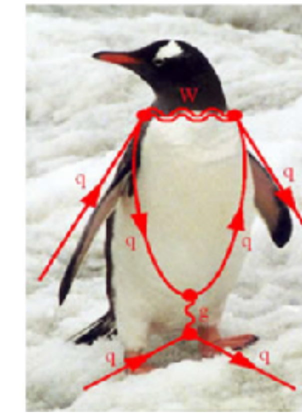
SM:

"Penguins"



"Box"





Effective Hamiltonian for b→sl⁺l⁻ :

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell) + \text{h.c.}$$

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \;\; O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

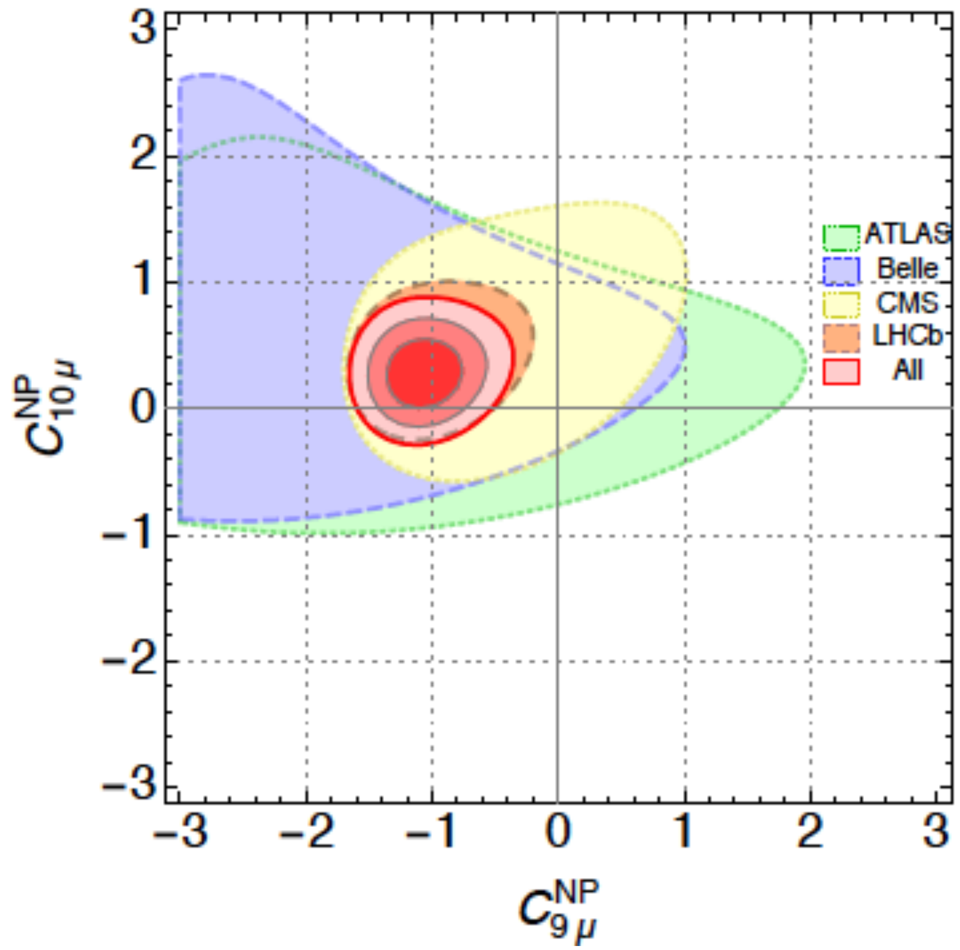
$$O_9'^\ell = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell), \;\; O_{10}'^\ell = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

New physics contributions encoded in Wilson coefficients:

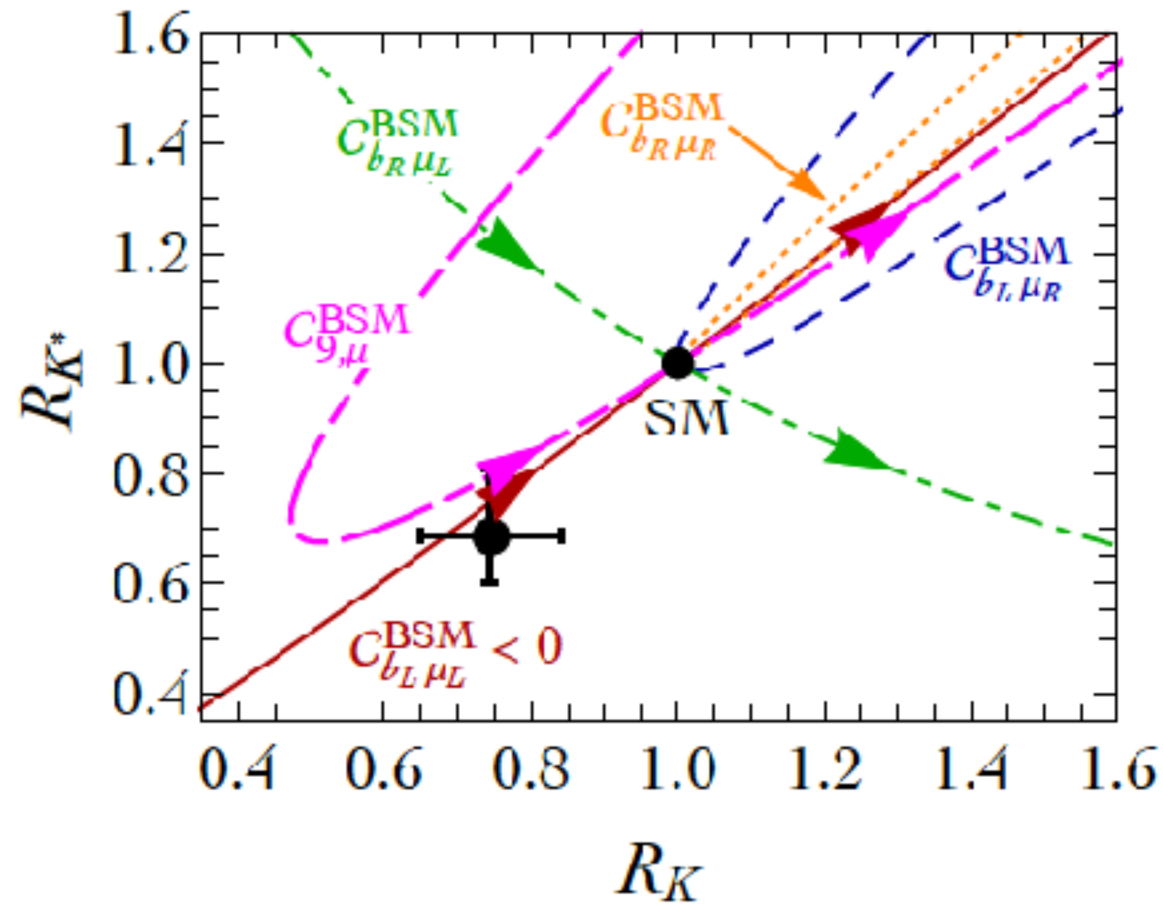
$$C_i^\ell = C_i^{\ell,\rm SM} + C_i^{\ell,\rm NP}$$

Global fits

[Capdevila et al, 2017]



[D'Amico et al, 2017]



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

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

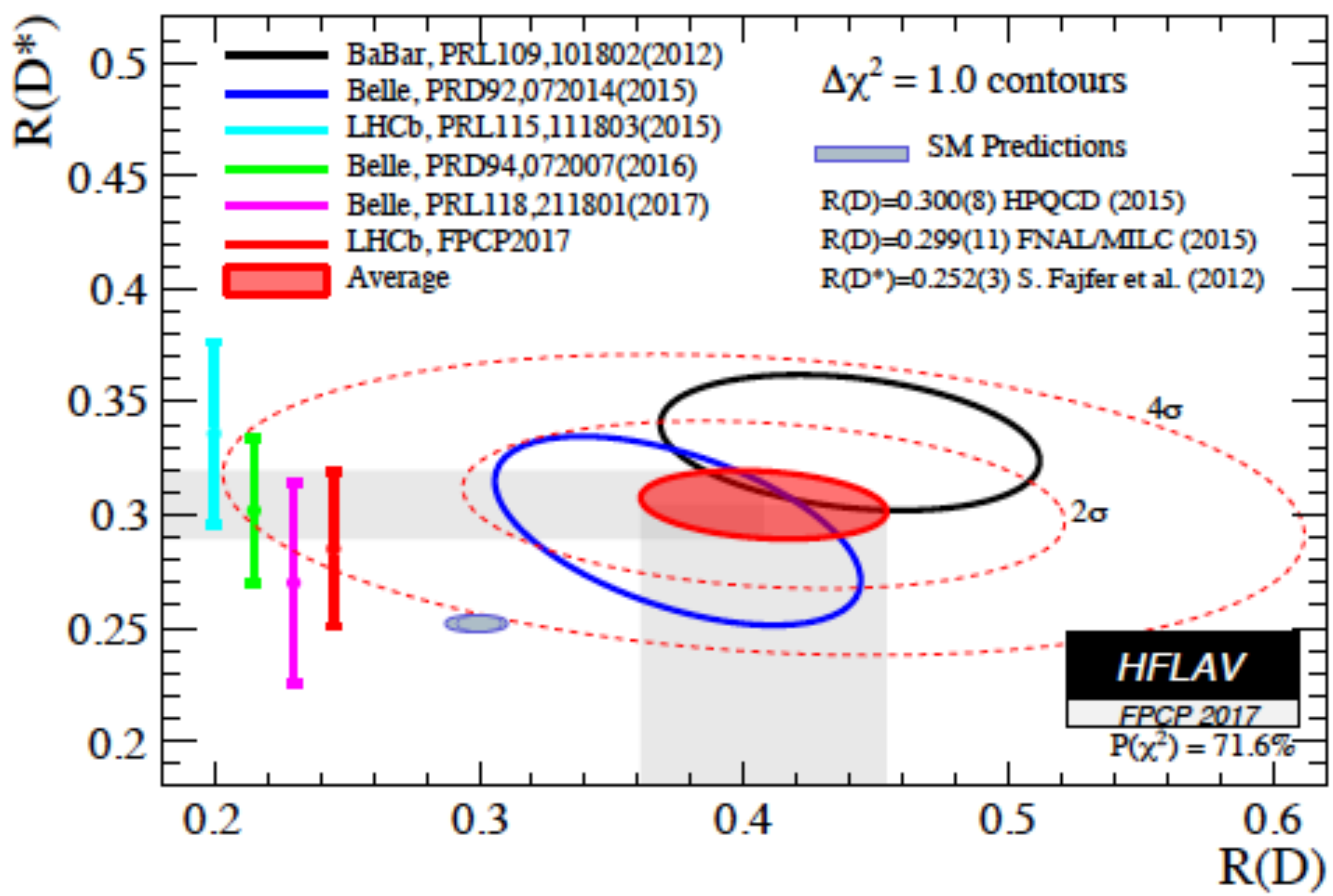
~ 5σ from SM !

QCD? ~ 4σ or less

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

More violation of LFU?

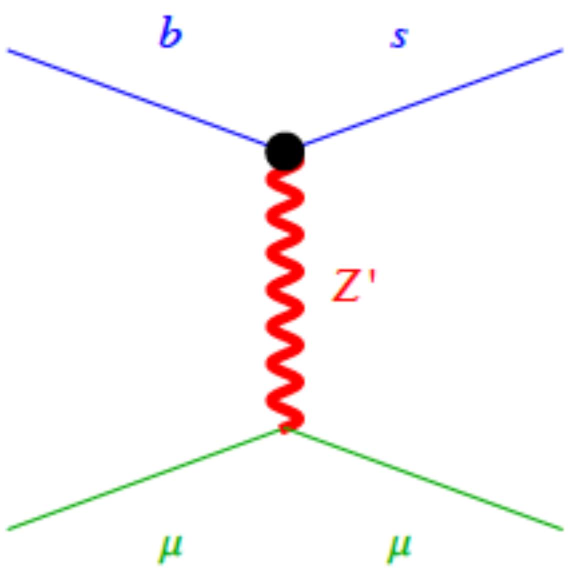
$B \rightarrow D^{(*)}\tau\nu$



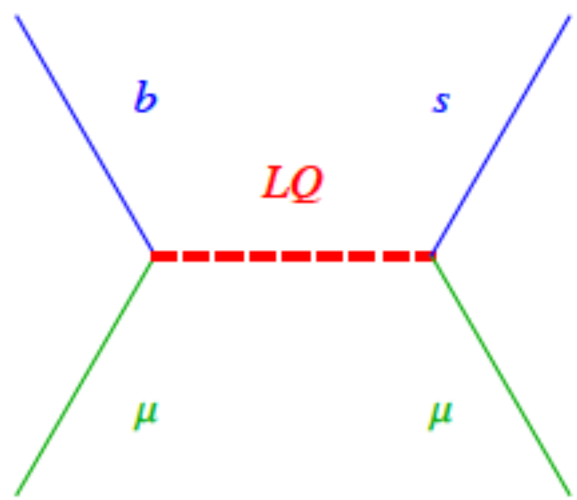
- 4σ anomalies in $B \rightarrow D^{(*)}\tau\nu$ decays from BaBar, Belle and LHCb.

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

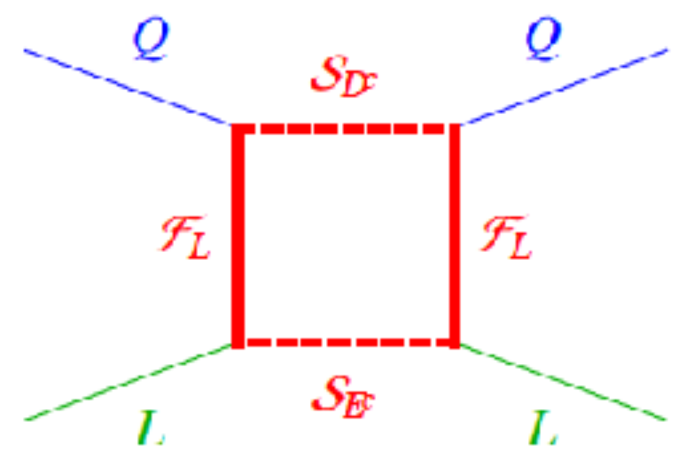
New physics for B-meson anomalies:



Flavor-violating U(1)’



Leptoquarks



New scalars/fermions in loops

“this work”

[Review: D’Amico et al, 1704.05438]

Minimal flavored U(1)’

Flavored U(1)'

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

$U(1)_{L_e-L_\mu}$, $U(1)_{L_\mu-L_\tau}$ and $U(1)_{L_\tau-L_e}$ ➡ flavor non-universal

Anomaly-free U(1)' with 3 right-handed neutrinos: $U(1)_{B-L}$

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

with one right-handed neutrino per each generation

Flavored U(1)' for B-meson anomalies

➡ $\boxed{Q' \equiv y(L_\mu - L_\tau) + x(B_3 - L_3)}$

[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

ν_{1R} : neutral

RH2

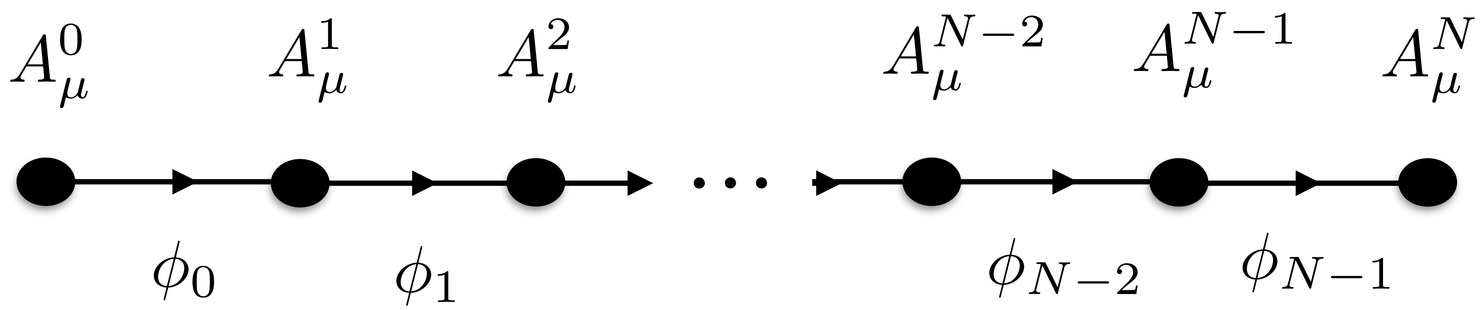
RH3

Scalar sector

B3-L3 from clockwork

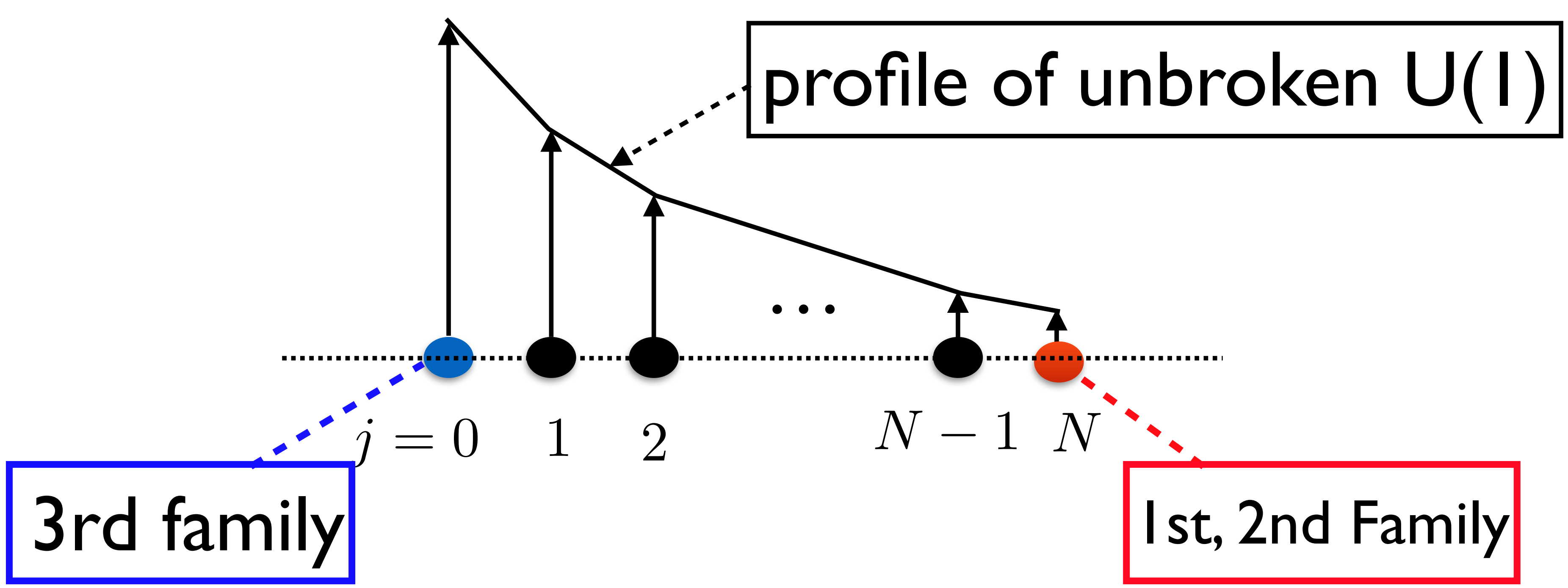
- [U(1)$_{B\text{-}L}$]$^{N+1}$ clockwork with third family localized at different sites from first two families.

[Giudice, McCollough, 2016; HML, 2017]



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

$\langle\phi_i\rangle = \frac{1}{\sqrt{2}} f$ $+U(1)_{L_\mu-L_\tau}$: LFUV

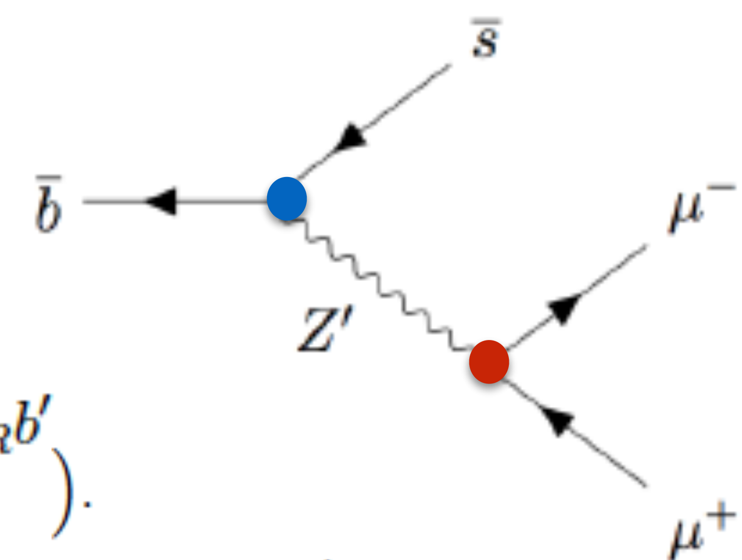


B-meson anomalies

Z' interactions in interaction basis:

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

Flavor violation in physical basis:



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

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

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

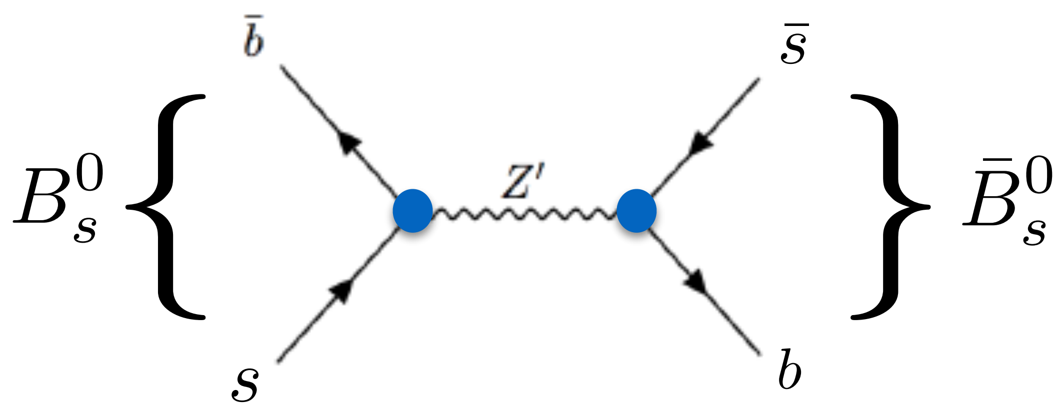
$$\Delta\mathcal{H}_{\text{eff},\bar{b}\to\bar{s}\mu^+\mu^-} = -\frac{4G_F}{\sqrt{2}} \boxed{V^*_{ts}V_{tb}} \frac{\alpha_{em}}{4\pi} C_9^{\mu,\text{NP}} \mathcal{O}_9^\mu, \qquad \boxed{C_9^{\mu,\text{NP}} = -\frac{8xy\pi^2 \alpha_{Z'}}{3\alpha_{\text{em}}} \left(\frac{v}{m_{Z'}}\right)^2}$$

Bottom-quark transition induced by CKM mixings.

Bounds on quark couplings

Quark couplings: $x g_{Z'}$

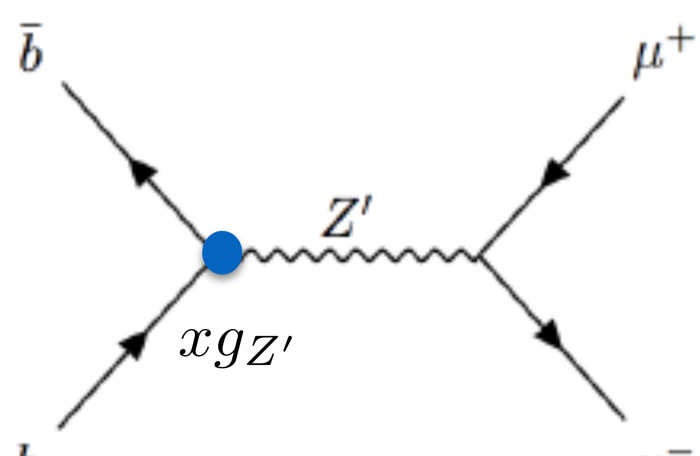
- Meson mixing and decays: $C_{VLL}^{\rm NP} \lesssim 0.15(0.30) \times C_{VLL}^{\rm SM} \simeq 0.74(1.48)$



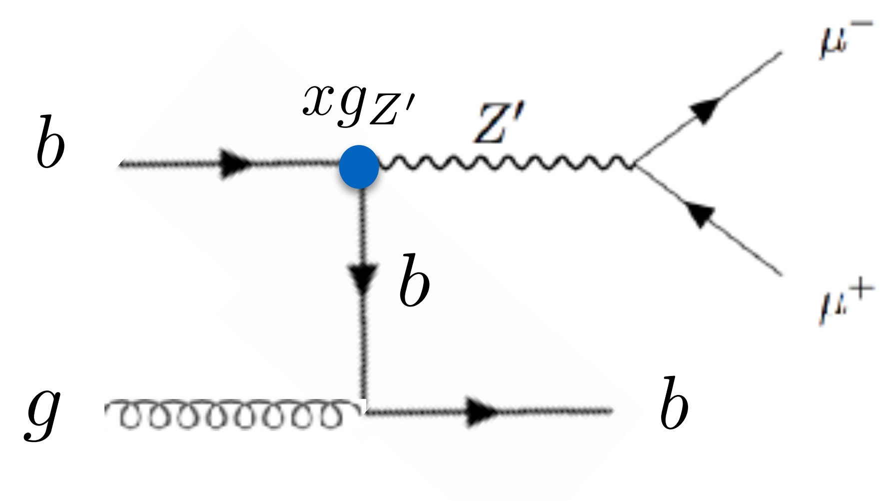
$$\Delta\mathcal{H}_{\text{eff},B_s^0-\bar{B}_s^0} = \frac{G_F^2 m_W^2}{16\pi^2} (V_{ts}^* V_{tb})^2 \, C_{VLL}^{\rm NP} \, (\bar{s}\gamma^\mu P_L b)(\bar{s}\gamma_\mu P_L b)$$

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

- LHC dimuon searches: MadGraph5_aMC@NLO + NN23LO1 PDF



$b\bar{b}$ fusion



etc

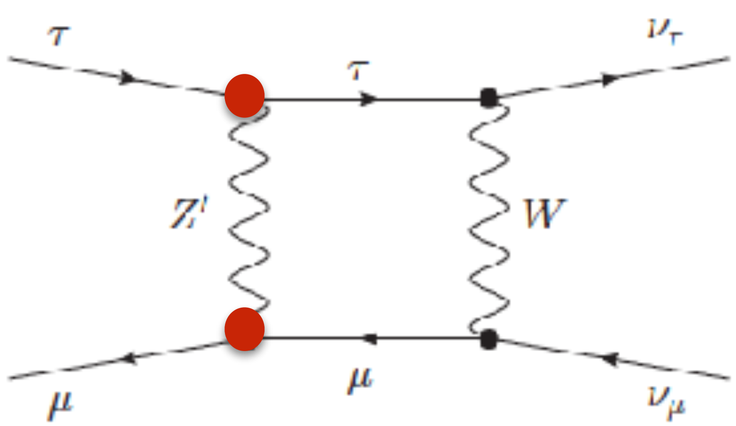
$pp \to Z'j$, and $pp \to Z'jj$.

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

Bounds on lepton couplings

Lepton couplings: $yg_{Z'}$

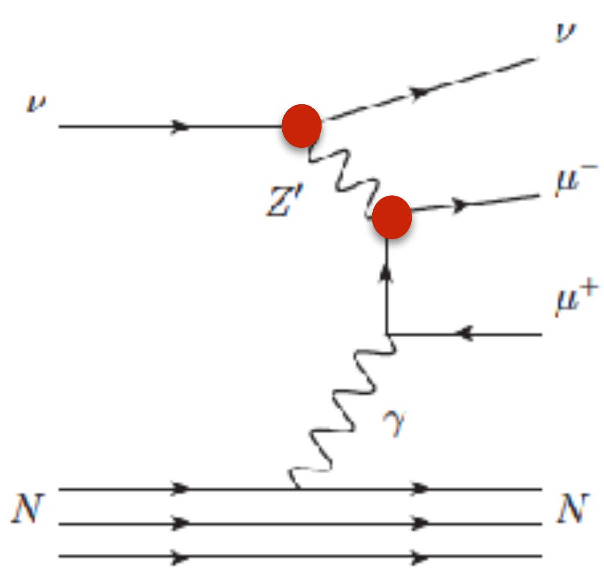
- Tau decays



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

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

- Neutrino trident production

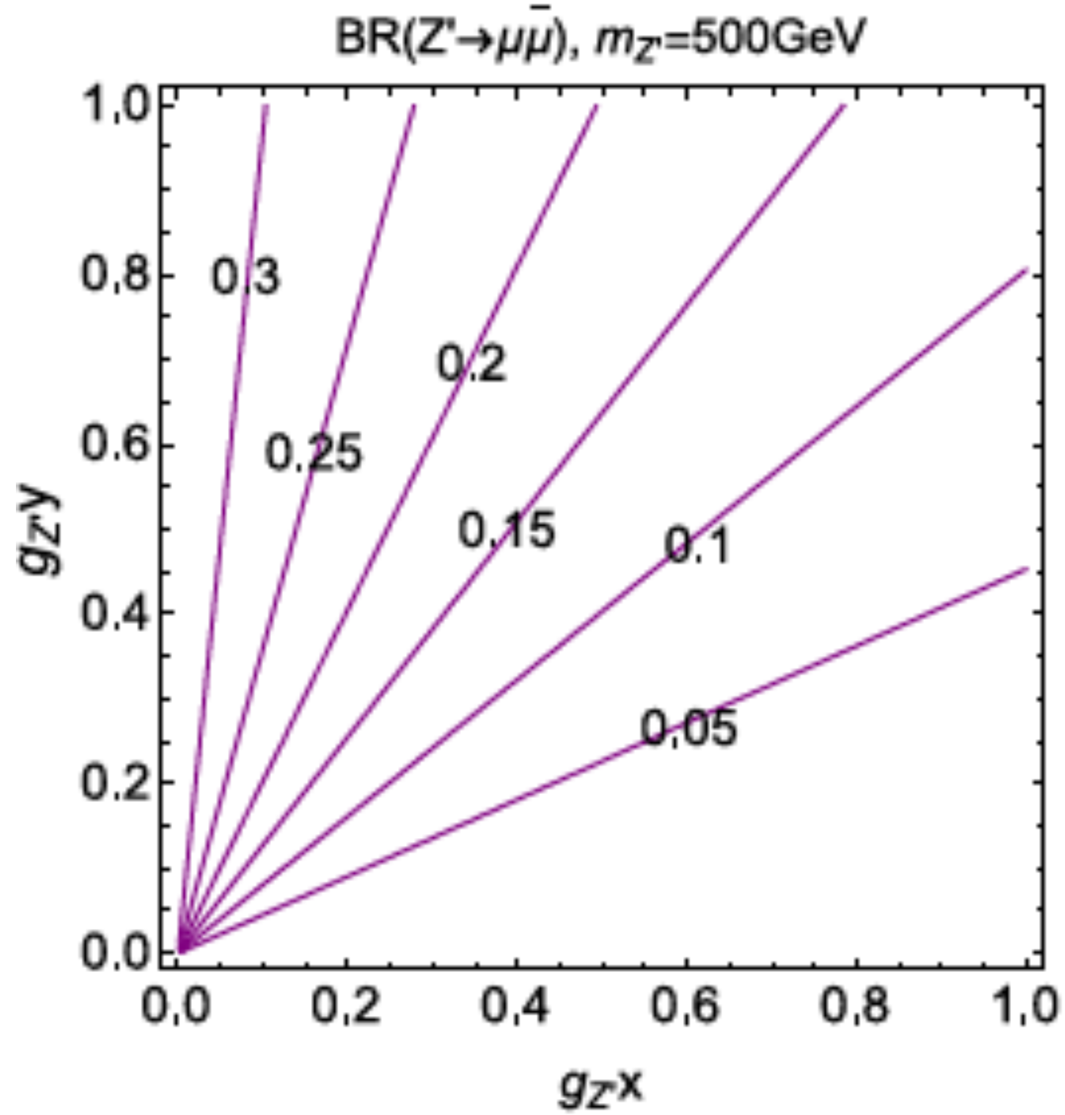


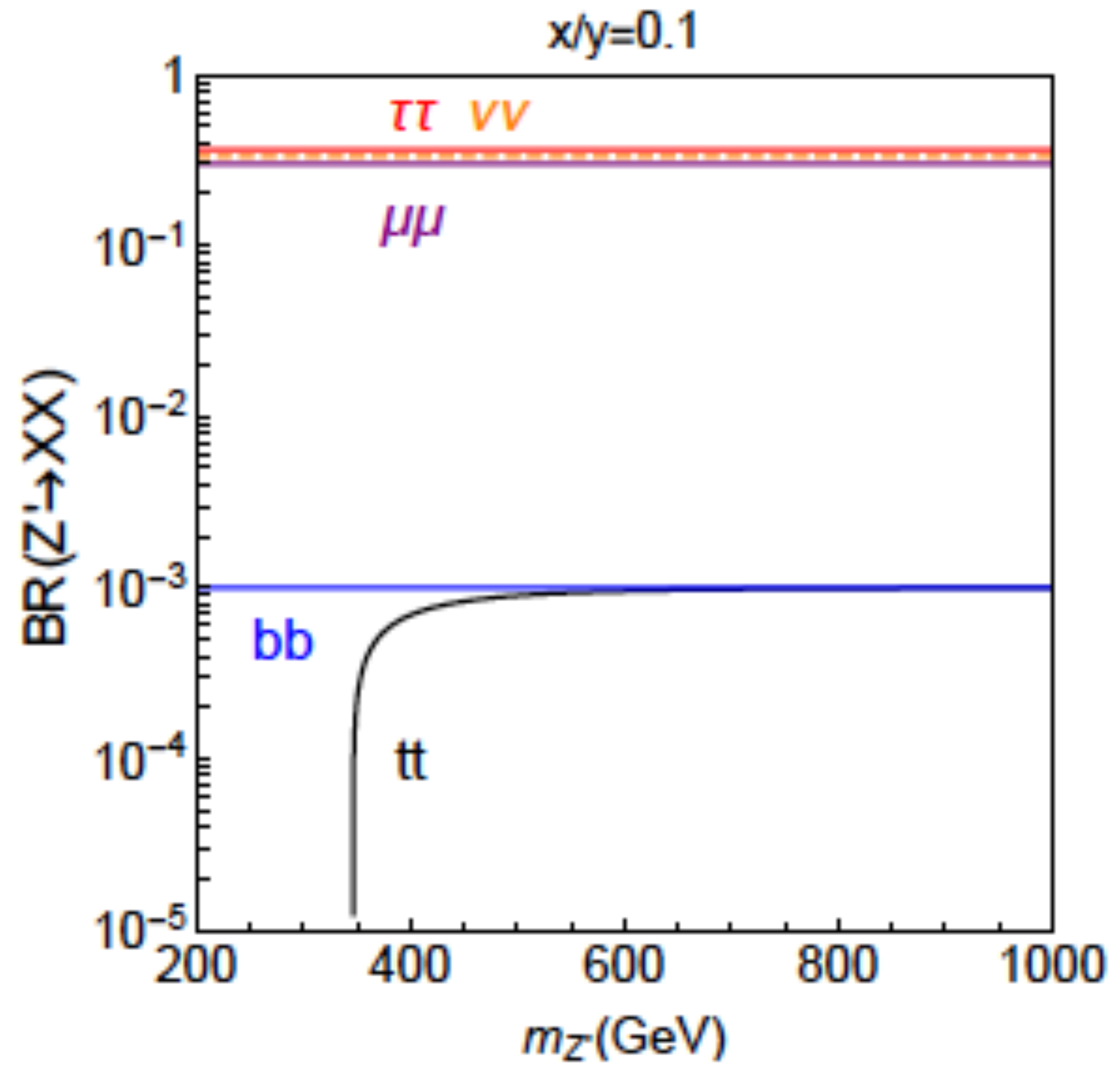
$$\frac{\sigma}{\sigma_{\mathrm{SM}}} \simeq \frac{1 + (1 + 4s_W^2 + 2y^2g_{Z'}^2v^2/m_{Z'}^2)^2}{1 + (1 + 4s_W^2)^2}$$

$$< 1.45(2\sigma)$$

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

Z' Decay BR





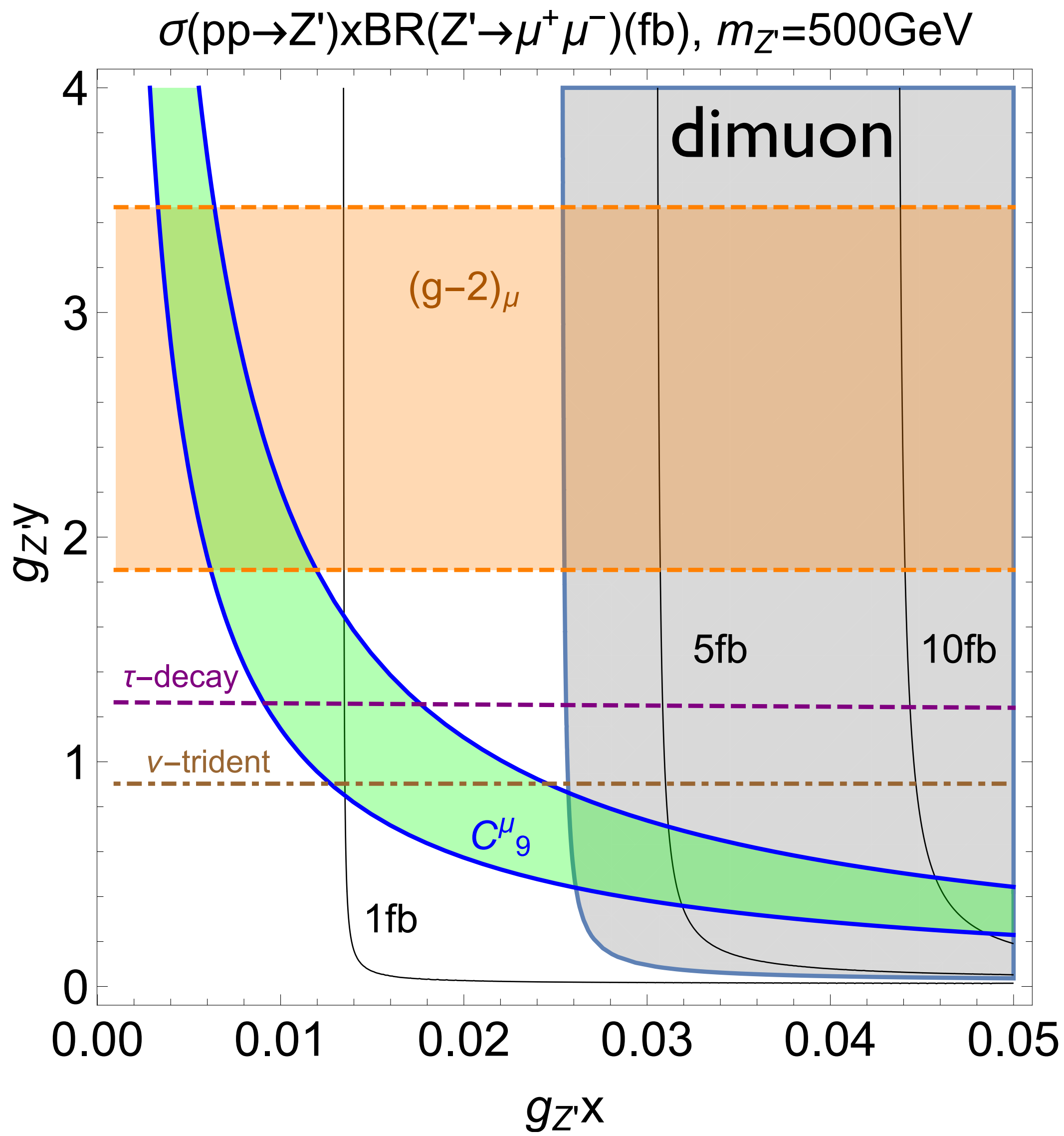
$$\mathrm{BR}(t\bar{t}, b\bar{b}) \,:\, \mathrm{BR}(\mu\bar{\mu}) \,:\, \mathrm{BR}(\tau\bar{\tau}) \,:\, \mathrm{BR}(\nu_\mu\bar{\nu}_\mu + \nu_\tau\bar{\nu}_\tau) = 2x^2 \,:\, 6y^2 \,:\, 6(x+y)^2 \,:\, 3(y^2 + (x+y)^2).$$

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

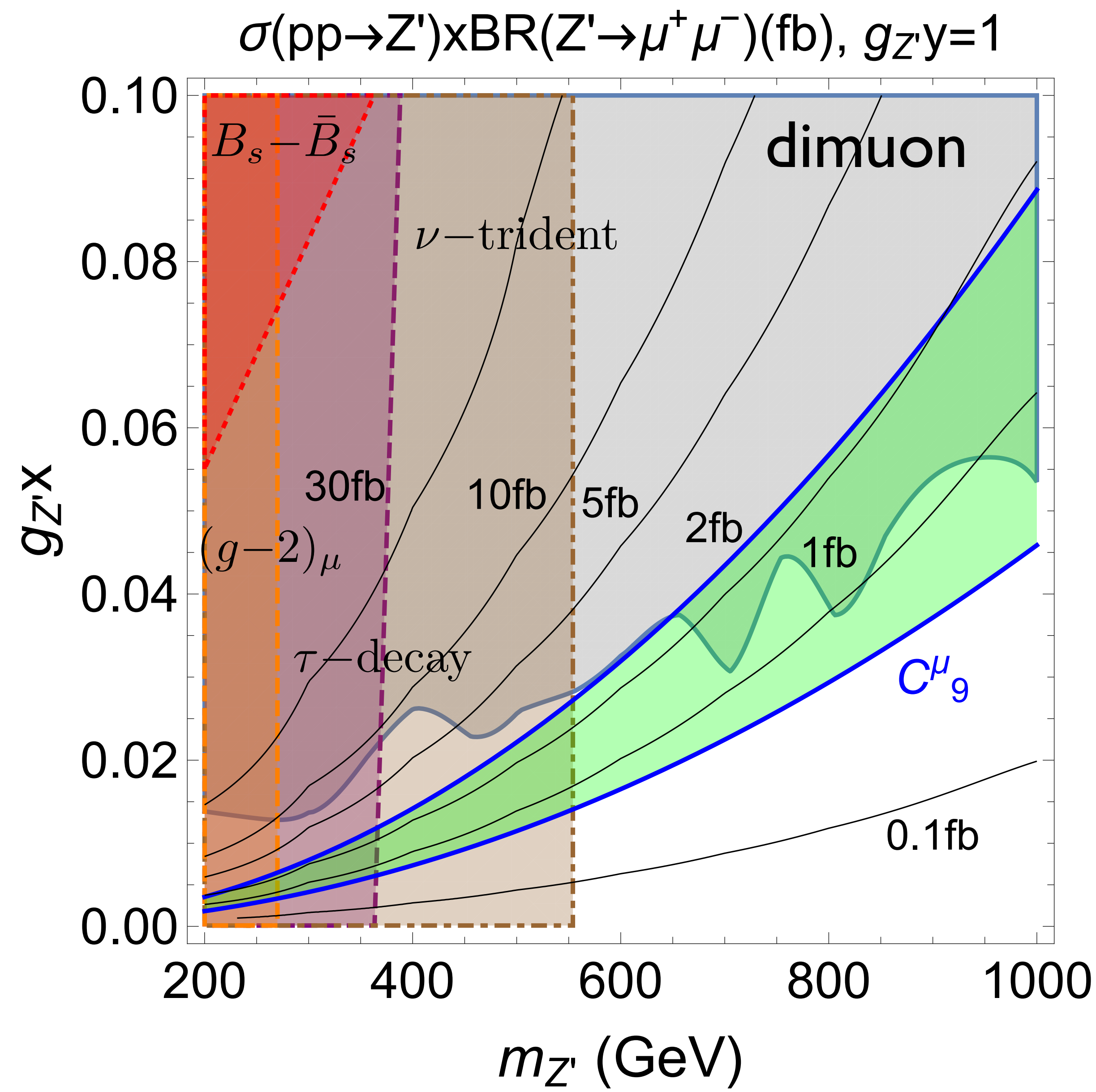
"$(L_\mu - L_\tau) -$ like"

Bounds on Z' mass

Lepton couplings



Quark couplings



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

Flavor violation from extra Higgs

Quark mixing

Two Higgs doublets H1 , H2 needed for quark mixing:

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

Flavor-Violating couplings fixed only by $\tan\beta$:

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

down-type:
$$y^d_{11} = \frac{\sqrt{2}m_d}{v\cos\beta}V_{ud}, \quad y^d_{12} = \frac{\sqrt{2}m_s}{v\cos\beta}V_{us},$$
$$y^d_{21} = \frac{\sqrt{2}m_d}{v\cos\beta}V_{cd}, \quad y^d_{22} = \frac{\sqrt{2}m_s}{v\cos\beta}V_{cs}, \quad y^d_{33} = \frac{\sqrt{2}m_b}{v\cos\beta}V_{tb}.$$
$$h^d_{13} = \frac{\sqrt{2}m_b}{v\sin\beta}V_{ub}, \quad h^d_{23} = \frac{\sqrt{2}m_b}{v\sin\beta}V_{cb}, \qquad h^d_{13} \ll h^d_{23}.$$

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

up-type:
$$|y^u_{11}|^2 + |y^u_{12}|^2 = \frac{2m_u^2}{v^2\cos^2\beta},$$
$$|y^u_{21}|^2 + |y^u_{22}|^2 = \frac{2m_c^2}{v^2\cos^2\beta},$$
$$|y^u_{33}|^2 + \tan^2\beta(|h^u_{31}|^2 + |h^u_{32}|^2) = \frac{2m_t^2}{v^2\cos^2\beta},$$
$$y^u_{11}(y^u_{21})^* + y^u_{12}(y^u_{22})^* = 0,$$
$$y^u_{21}(h^u_{31})^* + y^u_{22}(h^u_{32})^* = 0,$$
$$y^u_{11}(h^u_{31})^* + y^u_{12}(h^u_{32})^* = 0.$$

Quark Yukawa couplings

Neutral Higgs bosons: b-quark flavor violating

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

$$-\mathcal{L}_Y^{h/H/A} = \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta}\bar{b}_R\left(\tilde{h}_{13}^{d*}d_L+\tilde{h}_{23}^{d*}s_L\right)h + \frac{\lambda_b^h}{\sqrt{2}}\bar{b}_R b_L h + \frac{\lambda_t^h}{\sqrt{2}}\bar{t}_R t_L h$$
$$+\frac{\sin(\alpha-\beta)}{\sqrt{2}\cos\beta}\bar{b}_R\left(\tilde{h}_{13}^{d*}d_L+\tilde{h}_{23}^{d*}s_L\right)H + \frac{\lambda_b^H}{\sqrt{2}}\bar{b}_R b_L H + \frac{\lambda_t^H}{\sqrt{2}}\bar{t}_R t_L H$$
$$-\frac{i}{\sqrt{2}\cos\beta}\bar{b}_R\left(\tilde{h}_{13}^{d*}d_L+\tilde{h}_{23}^{d*}s_L\right)A + \frac{i\lambda_b^A}{\sqrt{2}}\bar{b}_R b_L A - \frac{i\lambda_t^A}{\sqrt{2}}\bar{t}_R t_L A + \text{h.c.}$$

"no flavor violation in top"

SM Higgs if

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

2HDM-I like

$$\lambda_b^h = -\frac{\sqrt{2}m_b\sin\alpha}{v\cos\beta} + \frac{\tilde{h}_{33}^d\cos(\alpha-\beta)}{\cos\beta},$$
$$\lambda_t^h = -\frac{\sqrt{2}m_t\sin\alpha}{v\cos\beta} + \frac{\tilde{h}_{33}^u\cos(\alpha-\beta)}{\cos\beta},$$
$$\lambda_b^H = \frac{\sqrt{2}m_b\cos\alpha}{v\cos\beta} + \frac{\tilde{h}_{33}^d\sin(\alpha-\beta)}{\cos\beta},$$
$$\lambda_t^H = \frac{\sqrt{2}m_t\cos\alpha}{v\cos\beta} + \frac{\tilde{h}_{33}^u\sin(\alpha-\beta)}{\cos\beta},$$
$$\lambda_b^A = \frac{\sqrt{2}m_b\tan\beta}{v} - \frac{\tilde{h}_{33}^d}{\cos\beta},$$
$$\lambda_t^A = \frac{\sqrt{2}m_t\tan\beta}{v} - \frac{\tilde{h}_{33}^u}{\cos\beta}.$$

"H-t-t reduced"

$$\tilde{h}_{33}^u = \frac{\sqrt{2}m_t}{v\sin\beta}\left(1-\frac{v^2\cos^2\beta}{2m_t^2}|y_{33}^u|^2\right),$$
$$\tilde{h}_{13}^d = 1.80\times10^{-2}\left(\frac{m_b}{v\sin\beta}\right),$$
$$\tilde{h}_{23}^d = 5.77\times10^{-2}\left(\frac{m_b}{v\sin\beta}\right),$$
$$\tilde{h}_{33}^d = 2.41\times10^{-3}\left(\frac{m_b}{v\sin\beta}\right).$$

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"

$$\lambda_{t_L}^{H^-} = \frac{\sqrt{2} m_b \tan\beta}{v} V_{tb}^* - \frac{(V_{\rm CKM}\tilde{h}^d)_{33}^*}{\cos\beta},$$

$$\lambda_{t_R}^{H^-} = -\left(\frac{\sqrt{2} m_t \tan\beta}{v} - \frac{\tilde{h}_{33}^u}{\cos\beta}\right) V_{tb}^*,$$

$$\lambda_{c_L}^{H^-} = \frac{\sqrt{2} m_b \tan\beta}{v} V_{cb}^* - \frac{(V_{\rm CKM}\tilde{h}^d)_{23}^*}{\cos\beta},$$

$$\lambda_{c_R}^{H^-} = -\frac{\sqrt{2} m_c \tan\beta}{v} V_{cb}^*,$$

$$\lambda_{u_L}^{H^-} = \frac{\sqrt{2} m_b \tan\beta}{v} V_{ub}^* - \frac{(V_{\rm CKM}\tilde{h}^d)_{13}^*}{\cos\beta}$$

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

Lepton mixing

SM lepton matrices "diagonal"

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

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

"2HDM-I like"

Three singlet scalars $\Phi_{1,2,3}$ for RH neutrino masses

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

correct neutrino masses and mixings
from RH neutrino masses

[Fritzsch et al, 2011]

Extra Higgs bosons

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

Scalar potential with two Higgs doublets H_1 , H_2 and singlet S

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

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

SSB of electroweak and U(1)'

(Extra singlet VEVs determine Z' mass)

Extra scalars mix with SM Higgs and themselves.

CP-even:

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

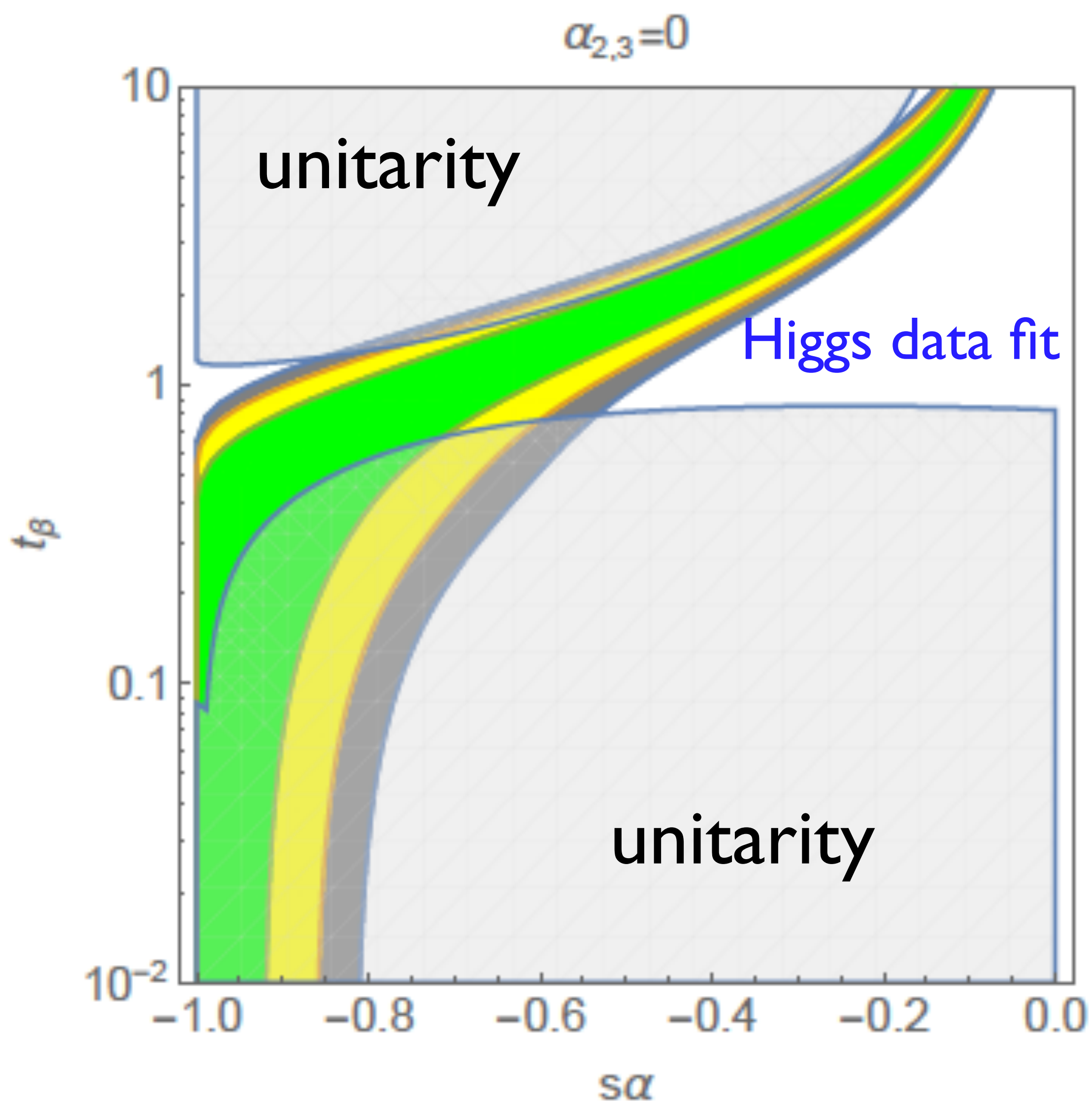
CP-odd:

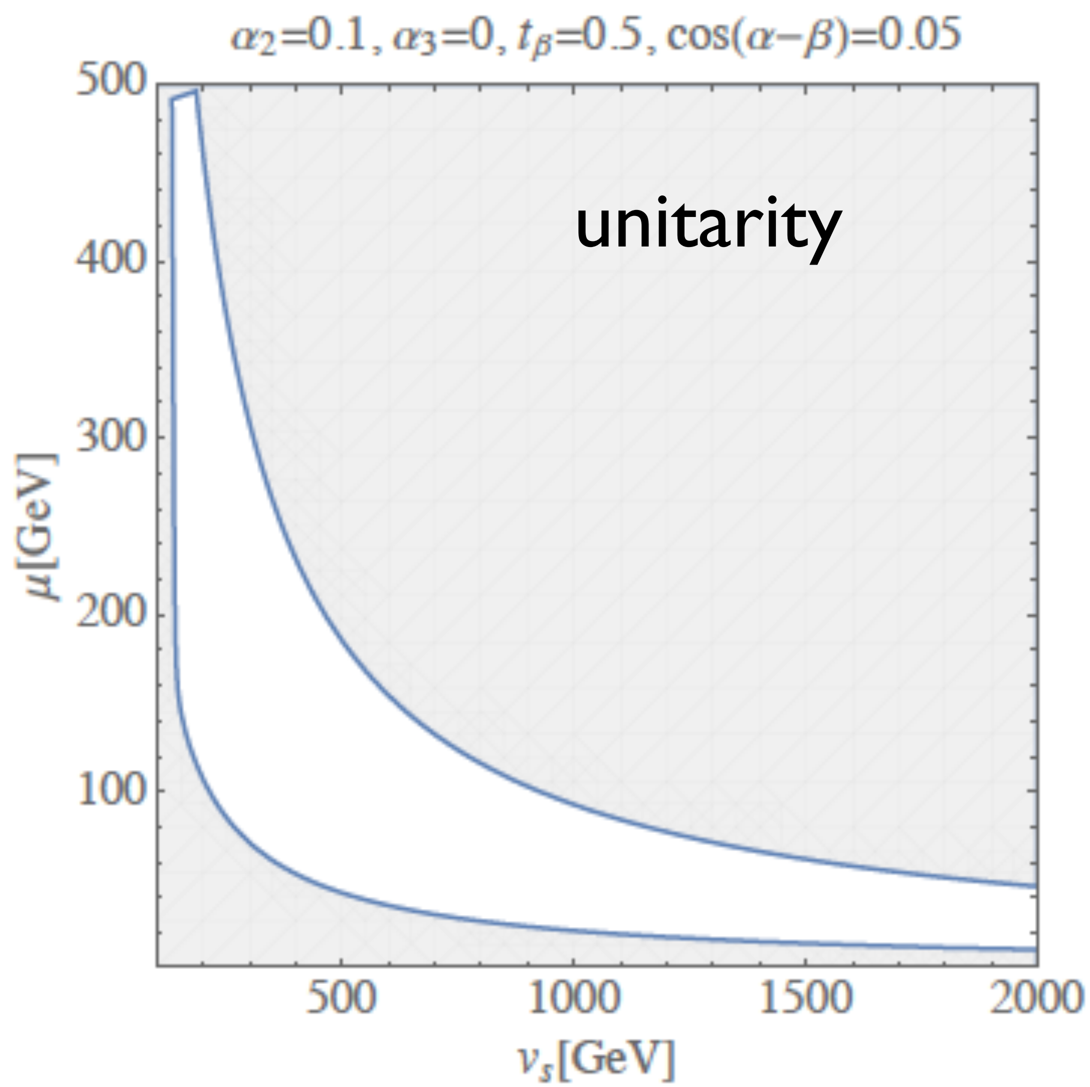
$$m_A^2 = \frac{\mu \sin\beta\cos\beta}{\sqrt{2} v_s}\left(v^2 + \frac{v_s^2}{\sin^2\beta\cos^2\beta}\right)$$

Charged Higgs:

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

Higgs data and unitarity



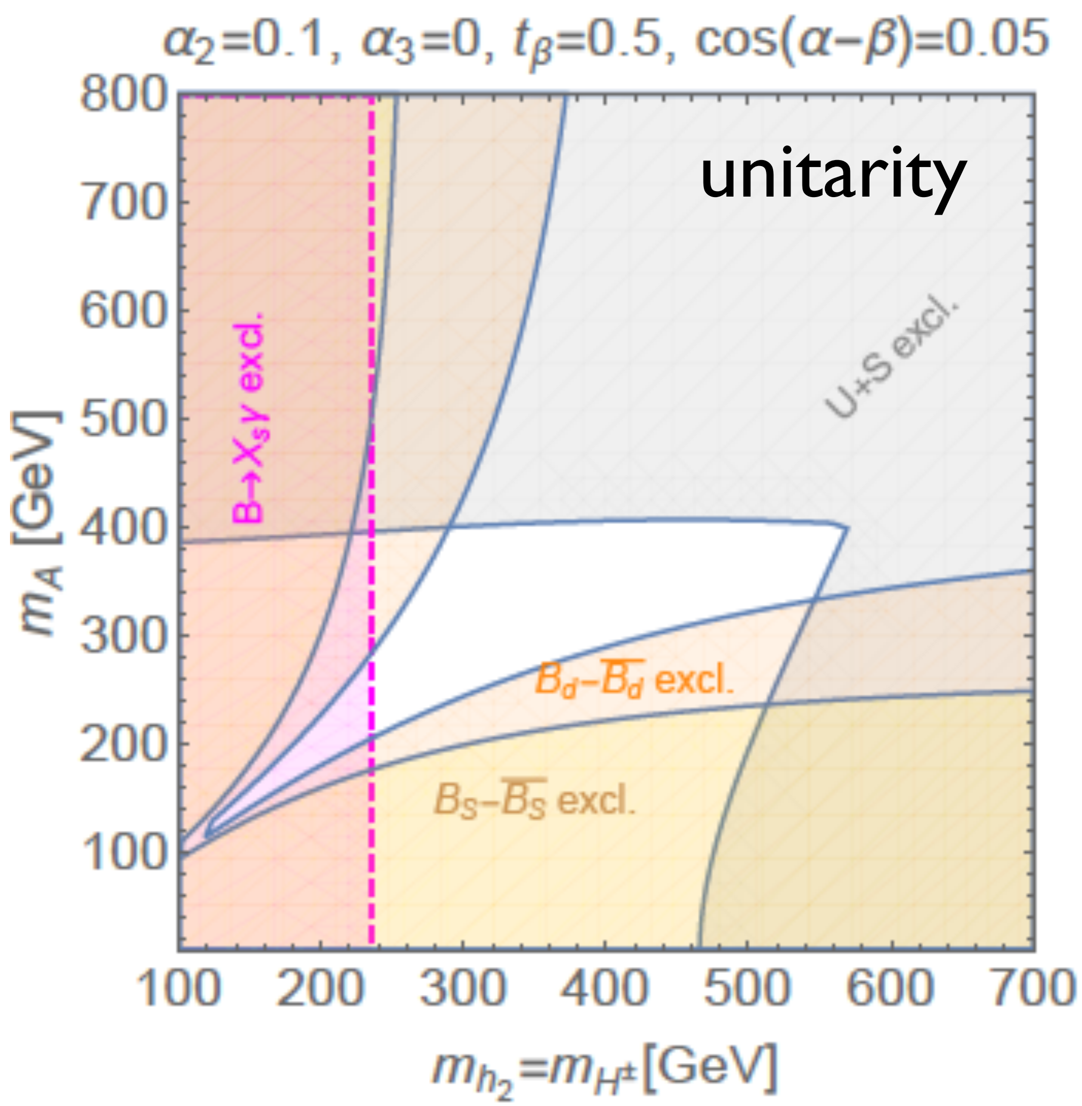


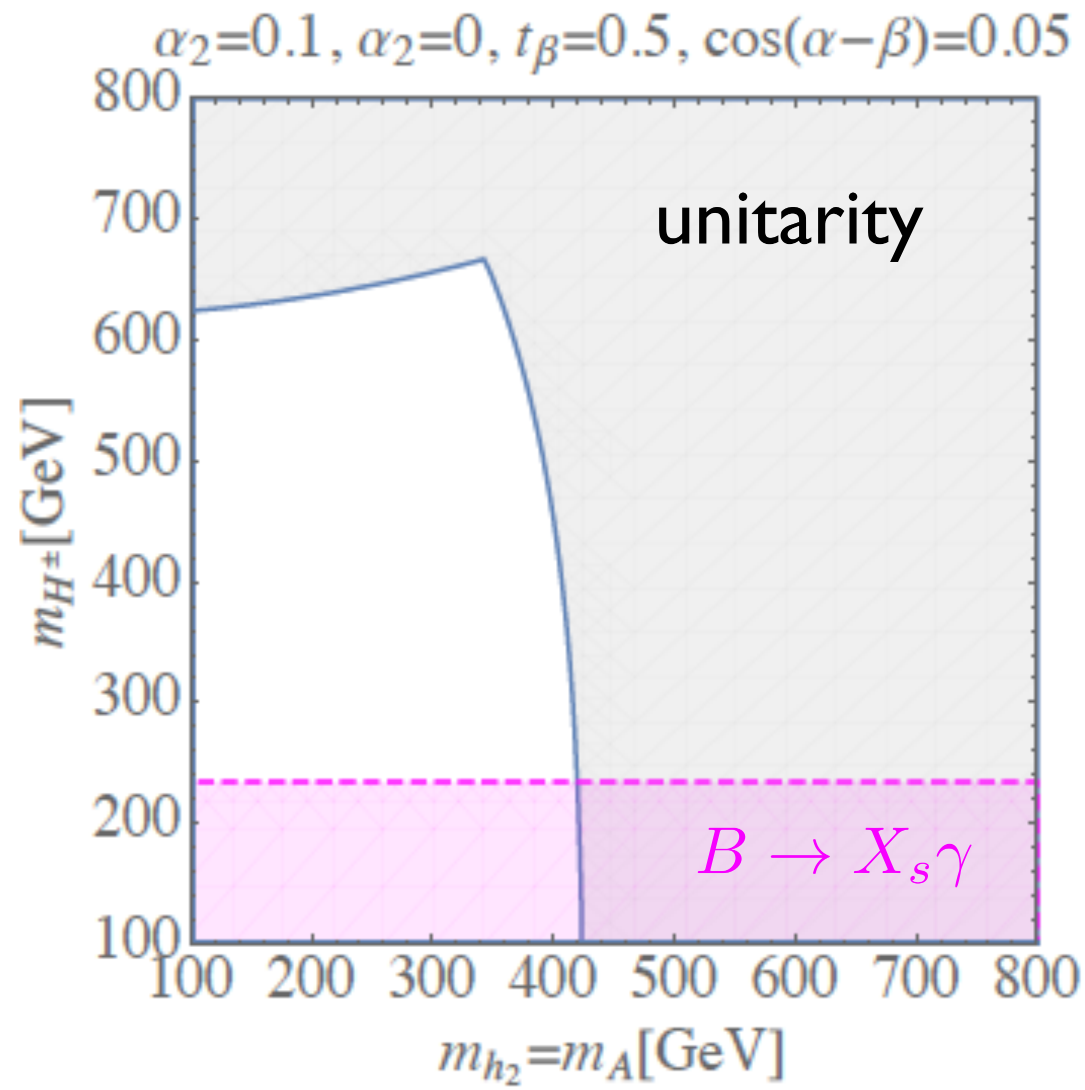
Lower bounds on tanβ from Higgs mixing & unitarity.

Upper bounds 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





$$\left.\begin{array}{l} B_s \to \mu^+\mu^- \\ \\ B_s\text{–}\bar{B}_s \text{ mixing} \end{array}\right\}$$ Bounds on neutral Higgs masses:

$$m_H \sim m_A$$

cf. EW data

$B \to X_s\gamma$ Bounds on charged Higgs mass

Anomalies in $R_{D^{(*)}}$ are not accommodated in our model.

Higgs production at LHC

Neutral Higgs production

Gluon fusion

$gg \to H$

b-quark fusion

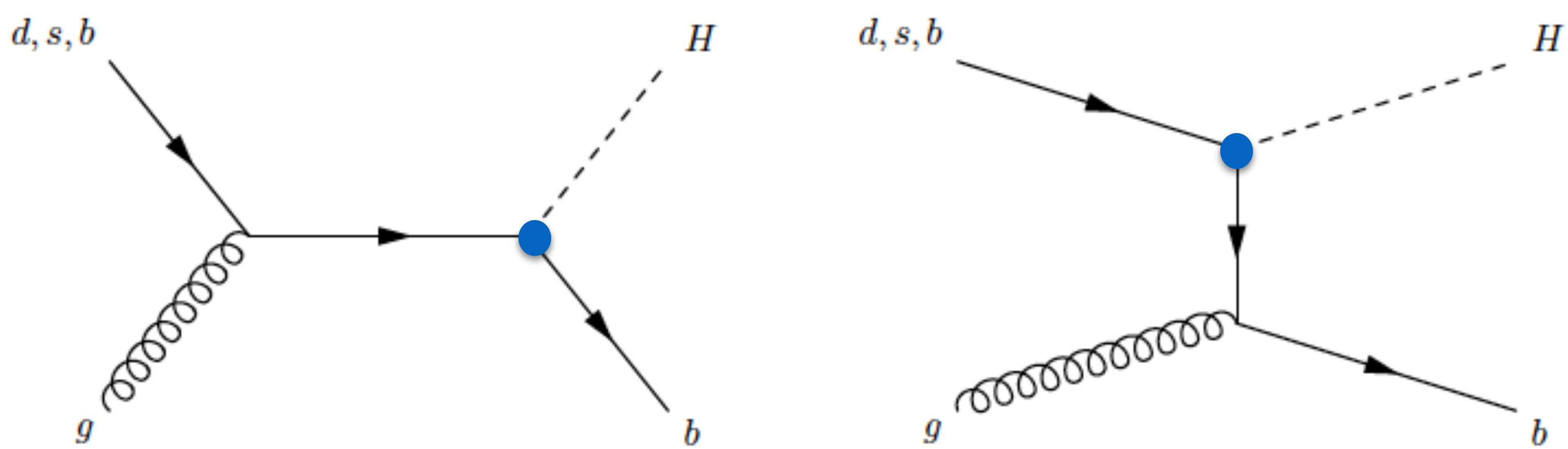
$b\bar{b} \to H$

→ Standard channels for single Higgs production

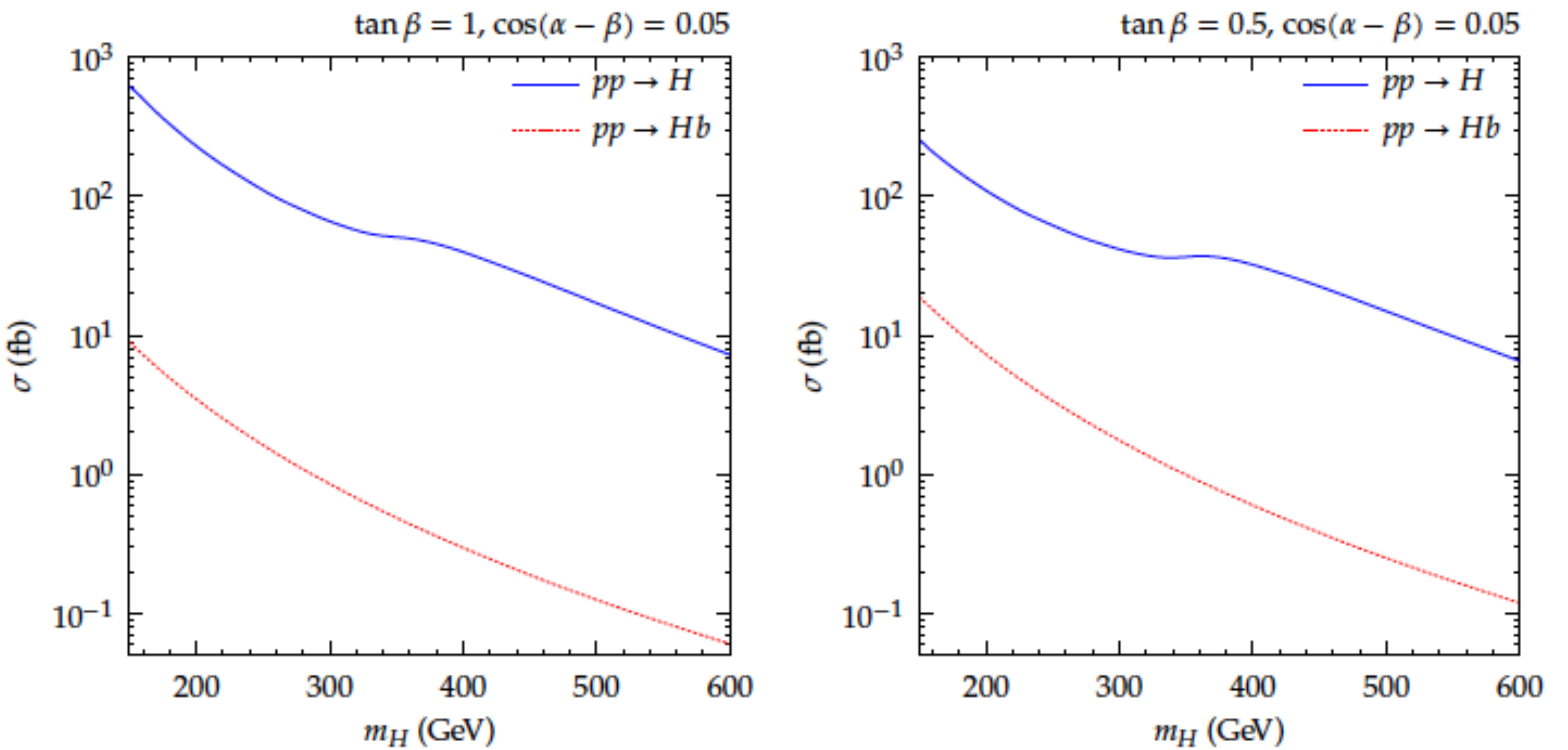
b-quark associated production

[Altmanshofer et al, 2016;
L. Bian, HML, C.B. Park, 2017]

→ New d,s-fusion contributions



Neutral Higgs production

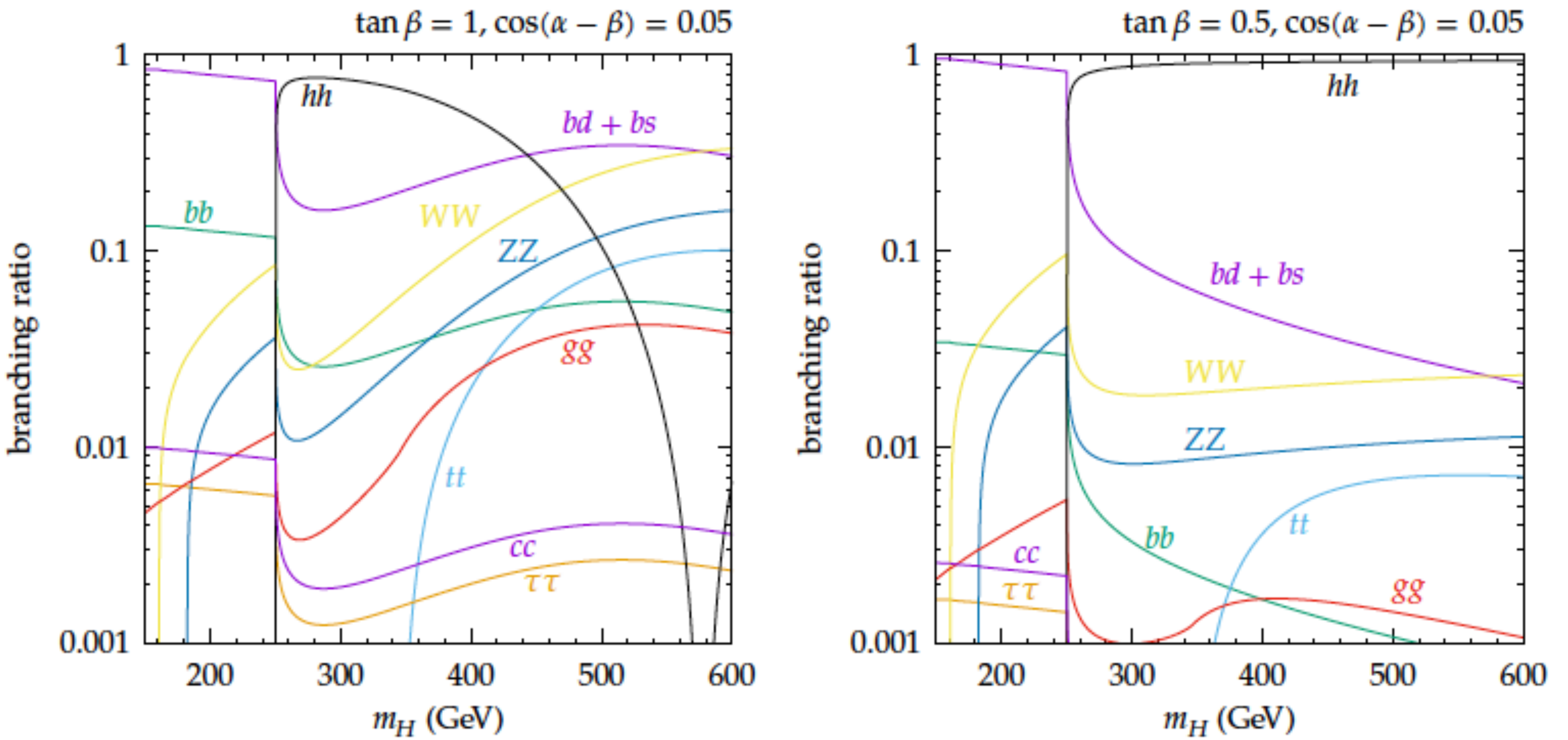


e.g. $m_H = 200$ GeV, $\tan\beta = 1\ (0.5)$, $\Rightarrow$ $\sigma_{pp\to H} \simeq 225.2\ (110.5)$ fb,

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

$(\sigma_{b\bar{d}_i\to H} + \sigma_{d_i\bar{b}\to H})/\sigma_{gg\to H} = 0.62\%\ (1.6\%)$

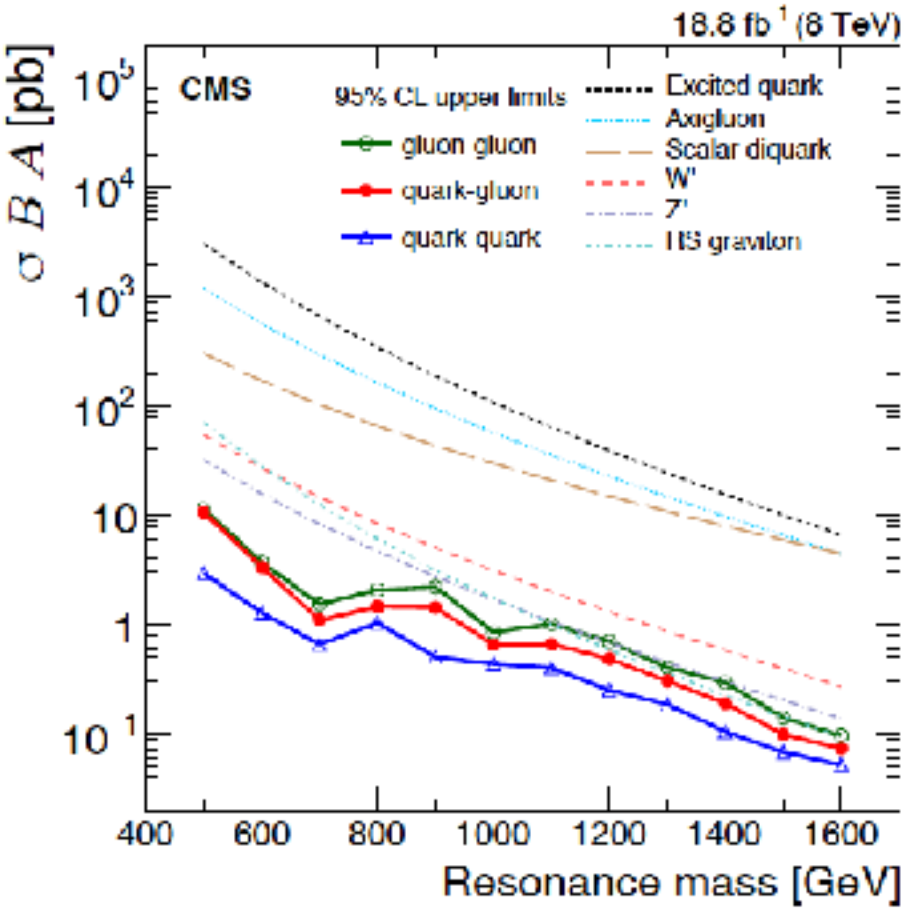
Neutral Higgs decays

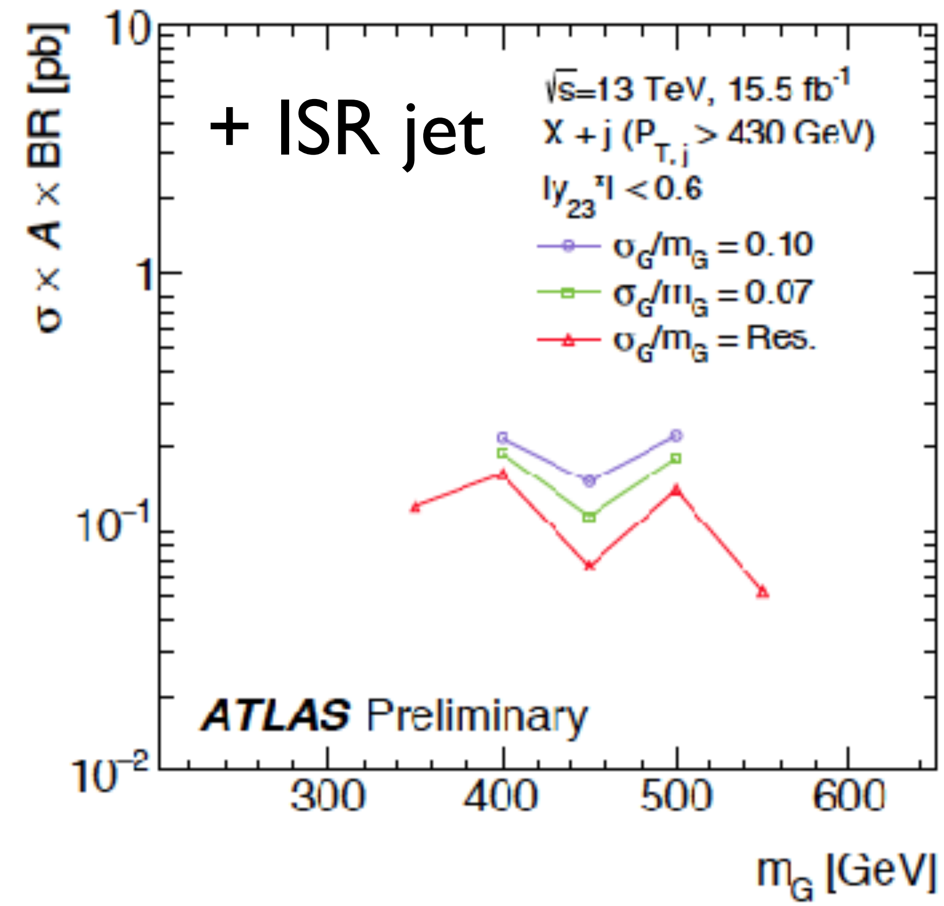


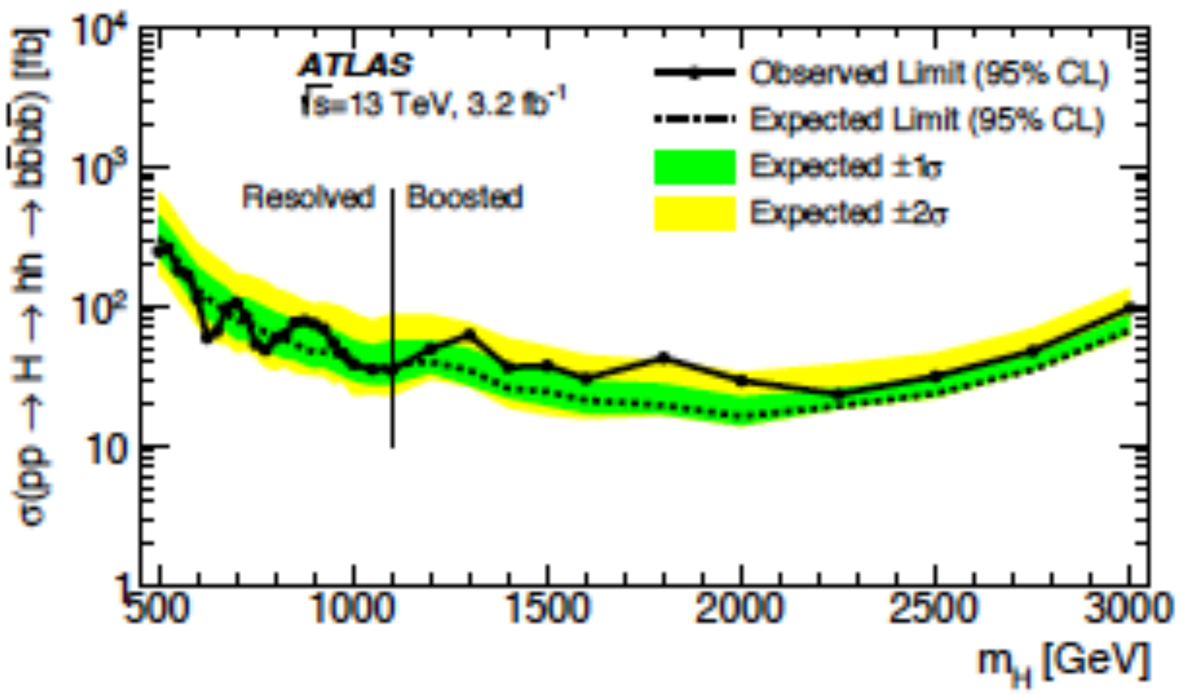
$m_H \lesssim 2m_h$: $bd + bs$ dominant → dijet (b-jet) bounds

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

LHC limits







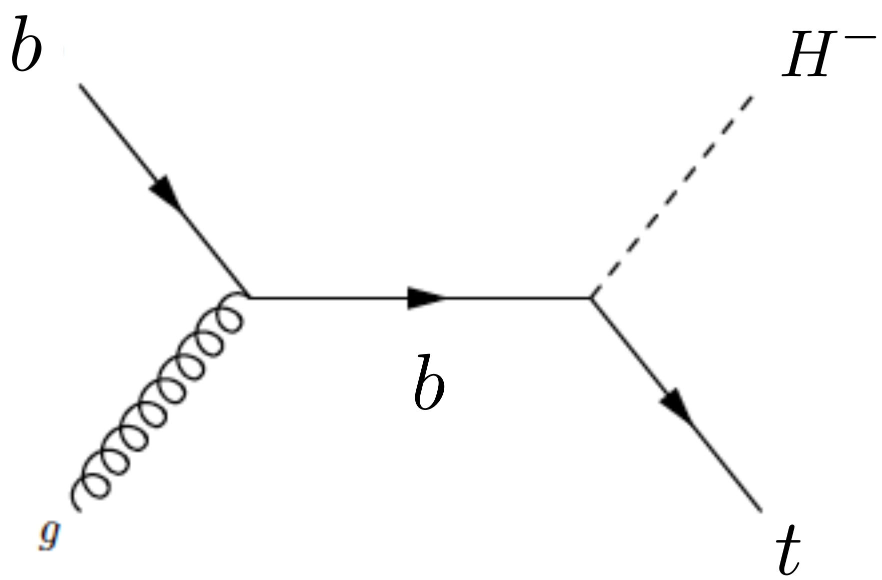
(c) Spin-0 narrow-width *H* boson

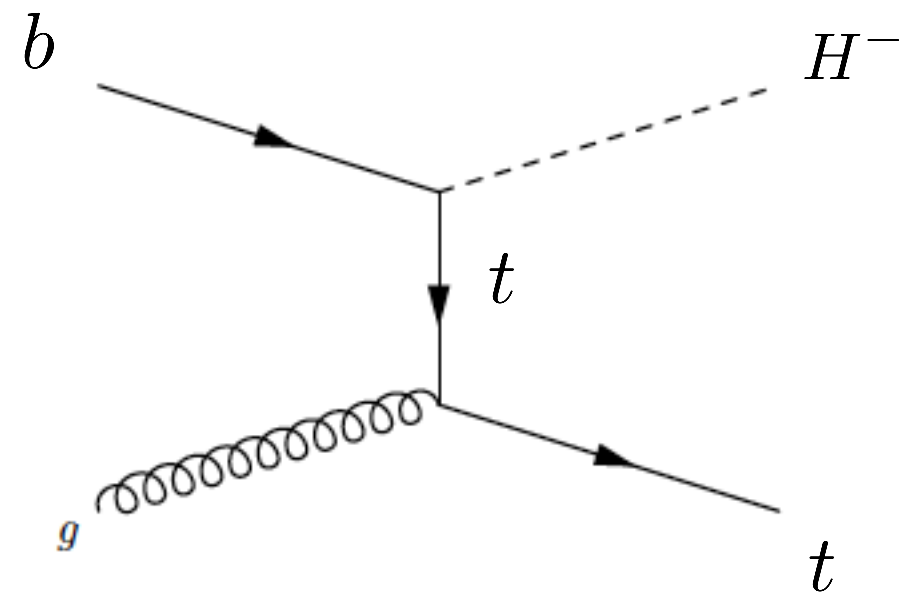
g-fusion dominant:
ISR photon limit does not apply.

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

Charged Higgs production

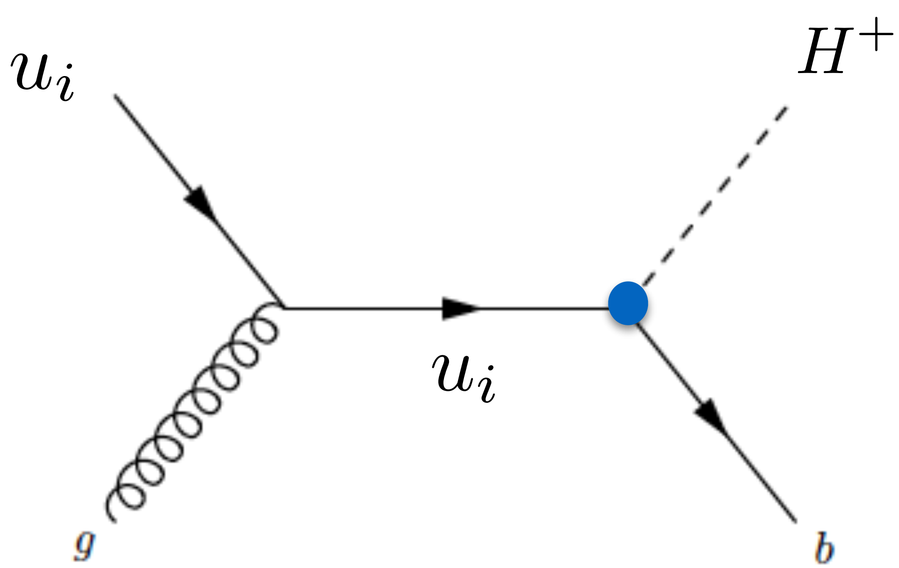
$bg \to tH^-$: Standard channels for charged Higgs

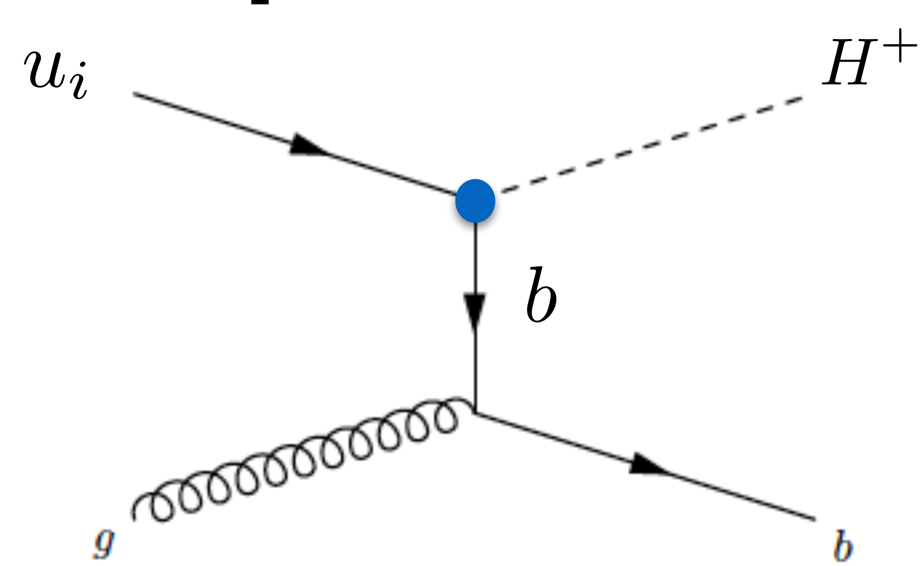




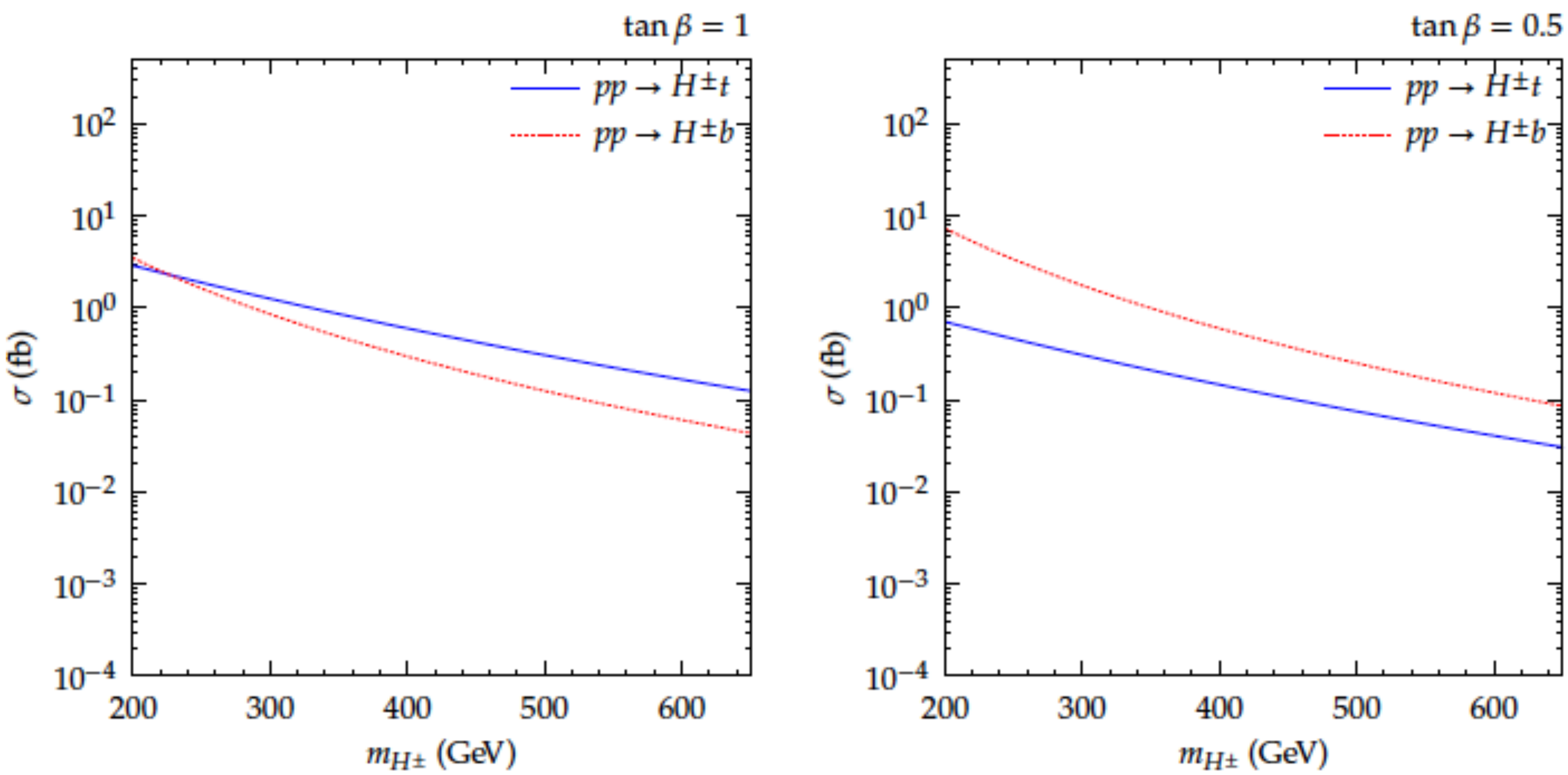
$u_i g \to bH^+$, $u_i = u,\, c.$: New u,c-fusion contributions

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



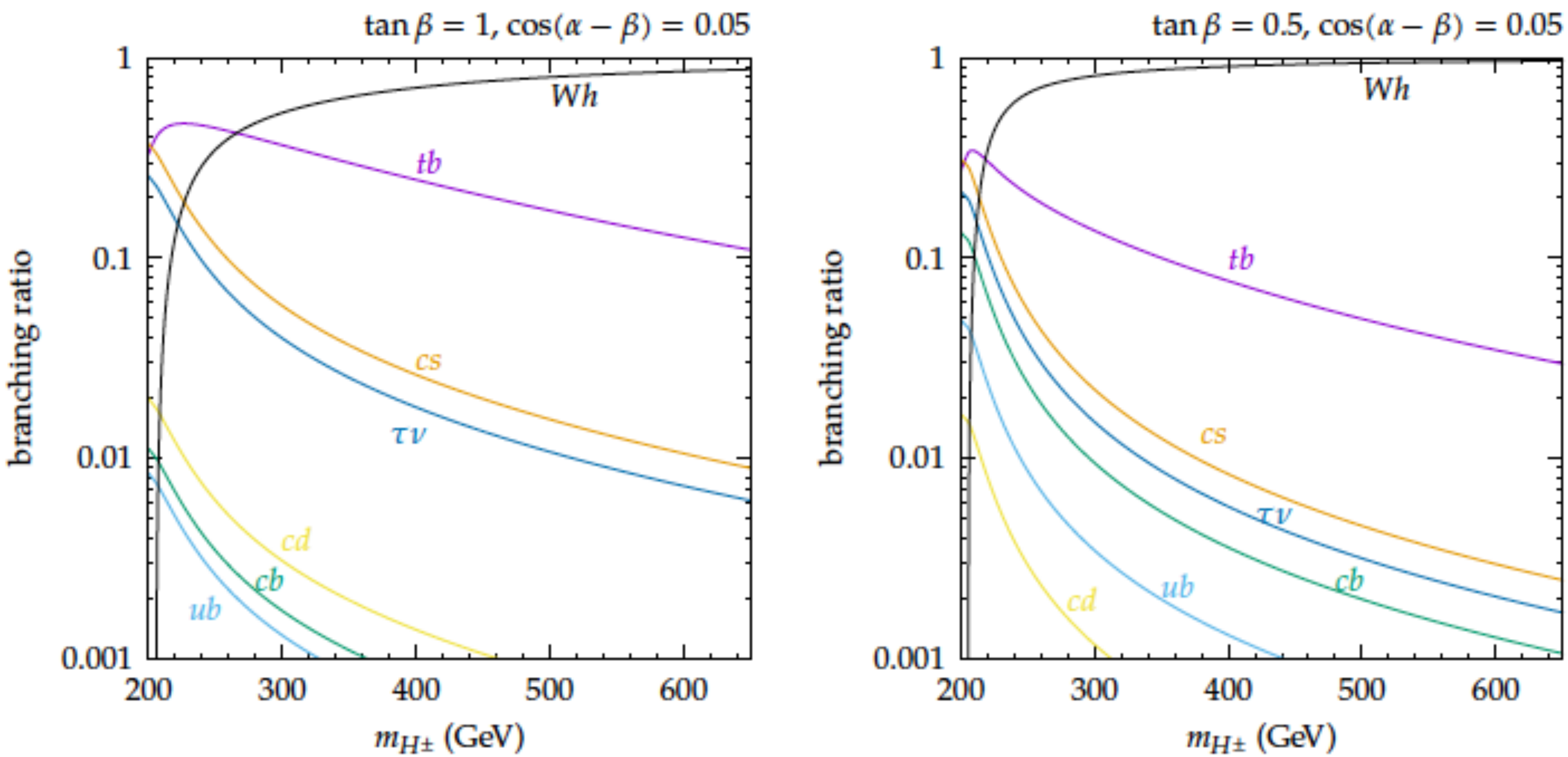


Charged Higgs production



Flavor-violating production is comparable to standard one and it can be dominant for small $\tan\beta$.

Charged Higgs decays



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

"smoking gun signal"

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

no constraints from LHC yet!

Conclusions

- B-meson anomalies can be explained due to anomaly-free U(1)' interactions with heavy flavors.
- Z'-couplings in our model are constrained by meson mixing/decays & LHC dimuon searches as well as tau decays and neutrino trident production.
- Flavor violating couplings to bottom quark and modified Yukawa coupling to top-quark lead to new production and decay channels for heavy Higgs bosons have at LHC.
- Smoking-gun signatures for LHC are dijet (w/ b-jet) and hh for neutral heavy Higgs and b+Wh for charged Higgs.