Models for Top-philic Resonances

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Flavor and Top @ 100TeV Workshop
CFHEP, China, Mar 4-7 (2015)

Contents

- Top-philic Spin-0 Resonances (2HDM, sgluon)
- Top-philic Spin-1 Resonance (Chiral U(1)+Multi HDM by Ko, Omura, Yu)
- Top-philic DM models (singlet scalar DM, fermion DM)
- Phenomenology of Ko-Omura-Yu model

Talk today is not tuned to the 100TeV pp collider.
Plan to do so in the near future

Top-Philic Scalar

Simplest ansatz violates SU(2) gauge symmetry

$$\mathcal{L} = -S\left[y_{st}\overline{t_L}t_R + H.c.\right]$$

Introduce another Higgs doublet H_t with odd Z_t parity

$$\mathcal{L} = D_\mu H_t^\dagger D^\mu H_t - m_{Ht}^2\left|H_t\right|^2 - \lambda_{H_t}\left|H_t\right|^4 - \lambda_{HH_t}\left|H\right|^2\left|H_t\right|^2 + \lambda\left|H^\dagger H_t\right|^2$$
$$- \lambda\left[(H^\dagger H_t)^2 - H.c.\right] - \left[y'_{Ht}\overline{Q'_{3L}}\widetilde{H}_t t'_R + H.c.\right]\left(-m_{12}^2 H^\dagger H_t + H.c.????\right)$$

Models by Das, C.Kao (1996); Soni et al (2000),⋯

If we implement Z_t to $U(1)_t$, we end up with
Ko-Omura-Yu model (see later)

Top-Philic spin-1

Naive guess will be something like this:

$$\mathcal{L} = -g_t Z'_\mu \left[g_V \bar{t}\gamma^\mu t + g_A \bar{t}\gamma^\mu\gamma_5 t \right] = -g_t Z'_\mu \left[g_L \overline{t_L}\gamma^\mu t_L + g_R \overline{t_R}\gamma^\mu t_R \right]$$

If top couplings are chiral under new U(1)',
there is a problem with the top Yukawa coupling

One way out of this problem is to
introdue a new Higgs doublet coupled to Z'
Again, Ko-Omura-Yu model

So let me talk about Ko-Omura-Yu Model

Top FBA@Tevatron and Top CA@LHC in chiral U(1)' models with flavored Higgs fields

Is the Z' model for top FB asym excluded by the same sign top pair production ?

Is the Z' model for top FB asym excluded by the same sign top pair production ?

NO !

NOT YET !

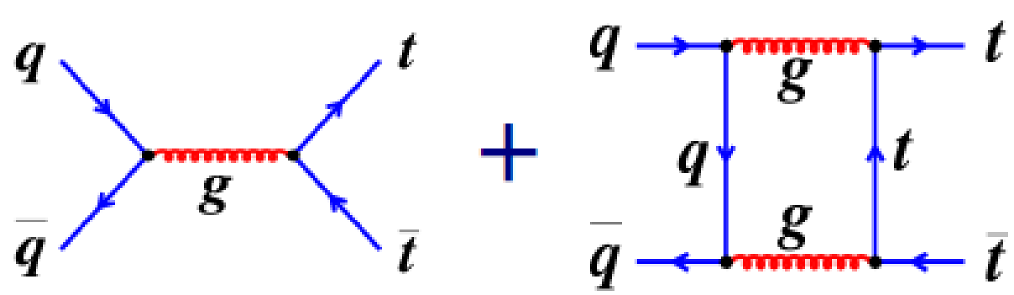
Contents

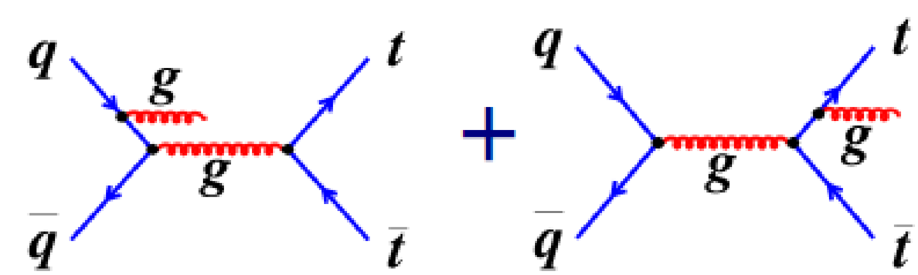
- SM Prediction vs. Data
- Z' model for Top FBA
- Flavor dependent U(1)' model
- Conclusion & General Remarks

Top Charge Asym in QCD (Muller@ICHEP2012)

NLO QCD: interference of higher order diagrams leads to asymmetry for $t\bar{t}$ produced through $q\bar{q}$ annihilation:

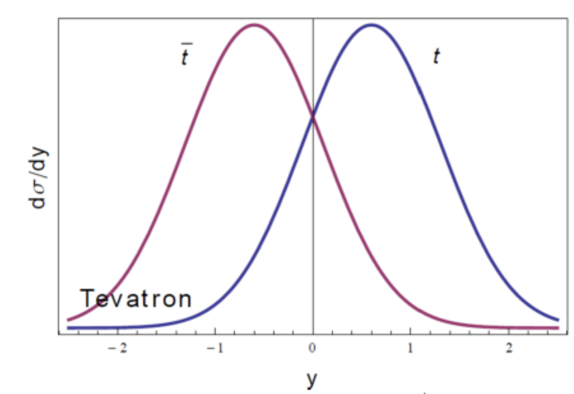
- Top quark is emitted preferentially in direction of the incoming quark
- Antitop quark opposite
- Production through new processes may lead to different asymmetries





- At Tevatron: define forward-backward asymmetry

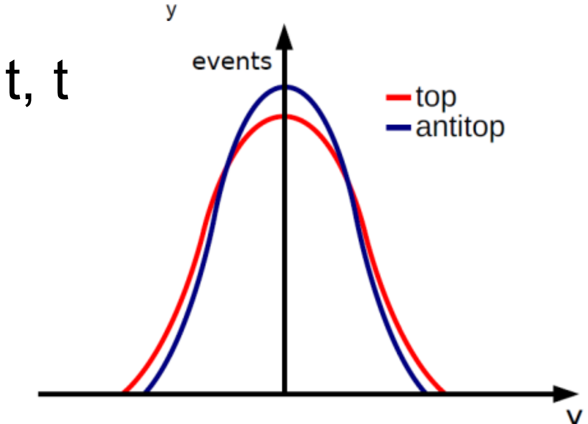
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



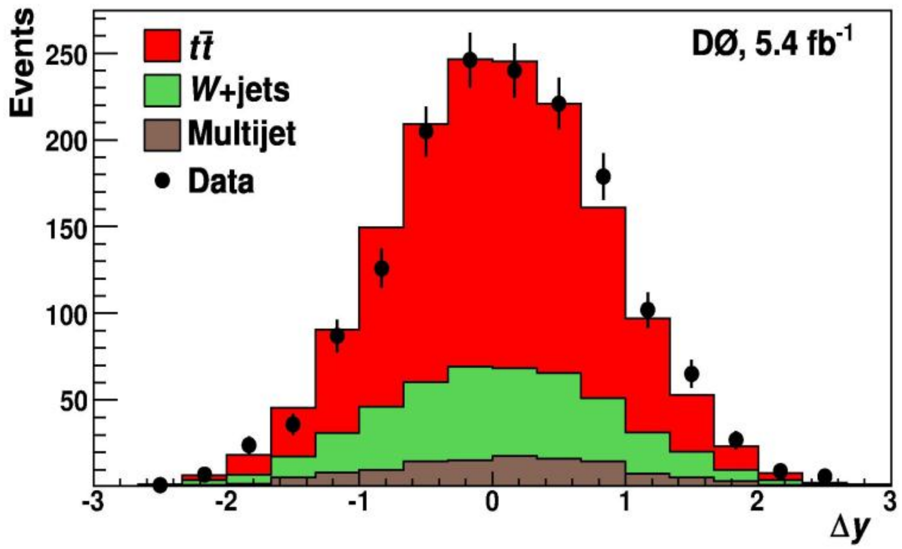
- At LHC: define asymmetry in the widths of rapidity distributions of t, t

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



ICHEP 2012 : Top FBA (Muller's talk)



Δy in the lepton-jets channel

Measured asymmetry on detector level after bkg subtraction:

A_{FB} det = 0.092 ± 0.037 (stat+syst)

MC@NLO: A_{FB} det = 0.024 ± 0.007

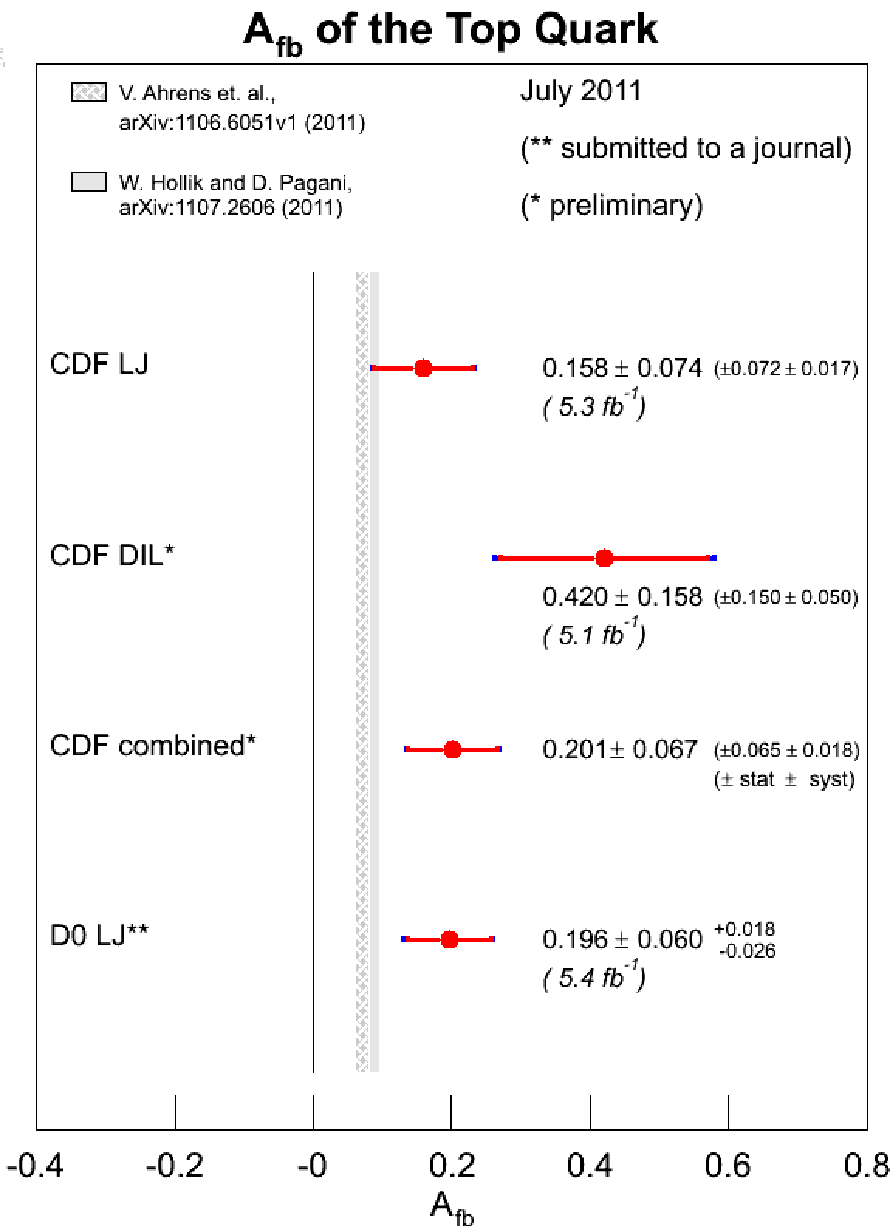
Measured asymmetry on parton level:

A_{FB} = 0.196 ± 0.065 (stat+syst)

D0 results in the di-lepton channel:

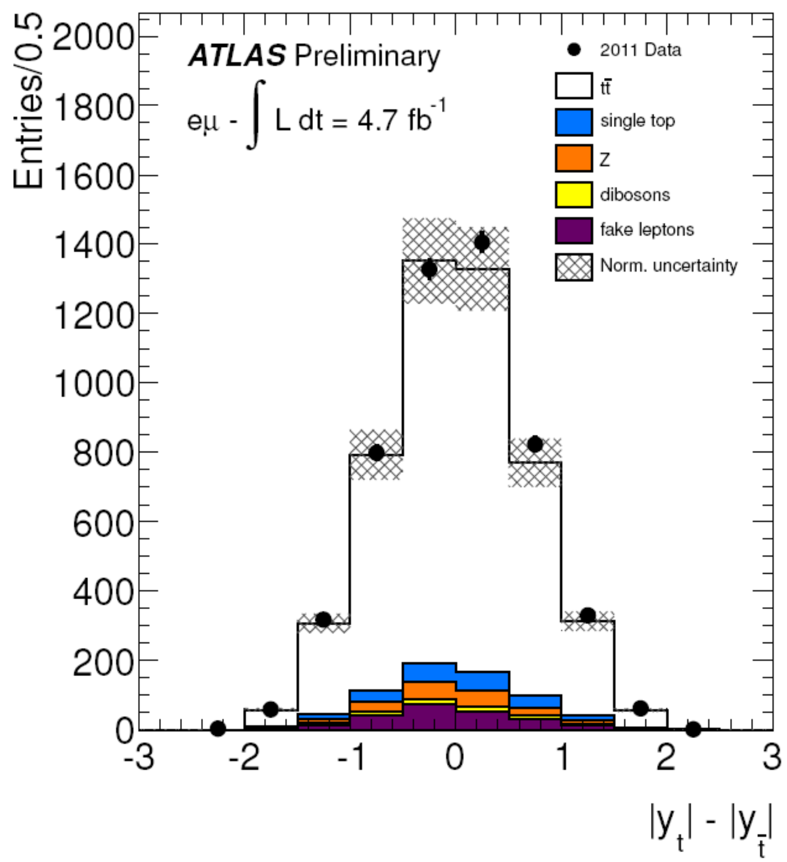
A_{FB} = 0.118 ± 0.032

Summary:

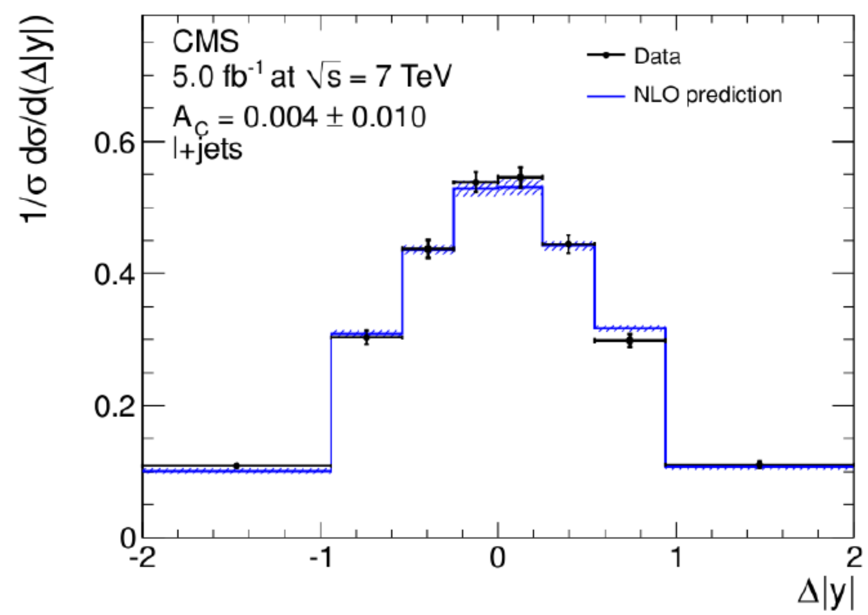


Both CDF and D0 see significant asymmetry in $t\bar{t}$ production in all channels with strong dependence on m_{tt}, in conflict with the SM

ICHEP 2012 : Top C Asym (Muller's talk)



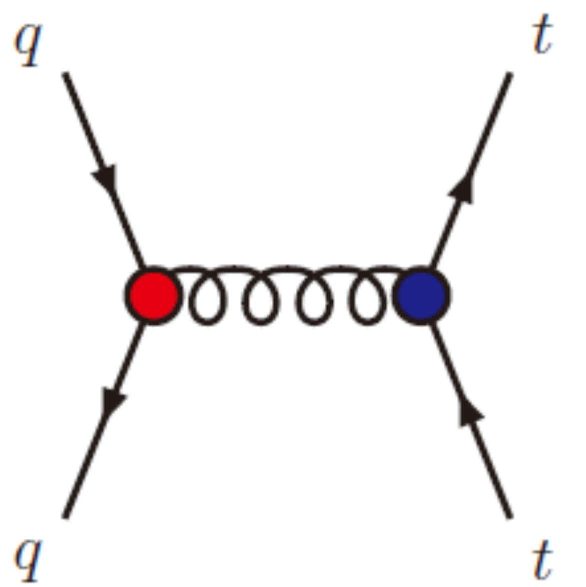
ATLAS-CONF-2012-057



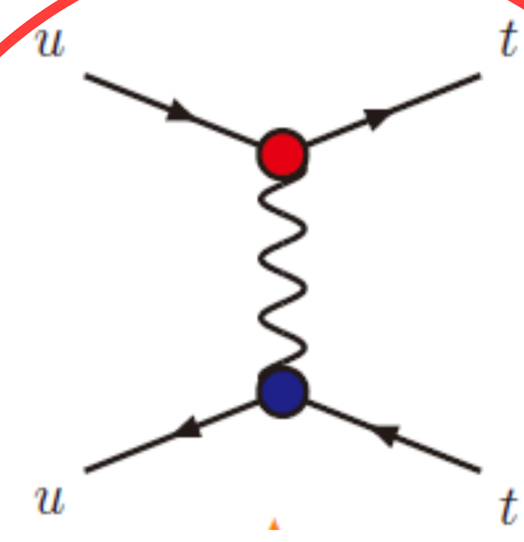
CMS PAPER TOP-11-030

- ATLAS: A_C = 0.029 +- 0.018 (stat.) +- 0.014 (syst.)
- CMS: Corrected: A_C = 0.004 +- 0.010 (stat.) +- 0.011 (syst.)
- Theory (Kühn, Rodrigo): A_C = 0.0115 +- 0.0006

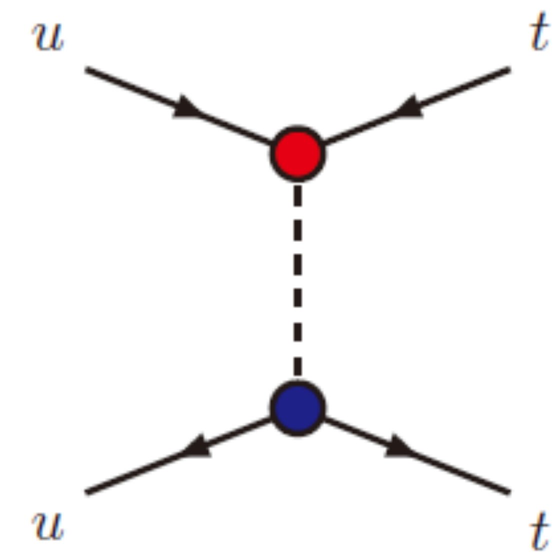
New physics models for top A_{FB}



s-channel: coloured resonance $\mathcal{G}_\mu$



t-channel: Z', W', ϕ



u-channel: exotic scalars

- flavor dependent.
- challenging to construct a realistic model.
  - anomaly free, renormalizable, and realistic Yukawa couplings.

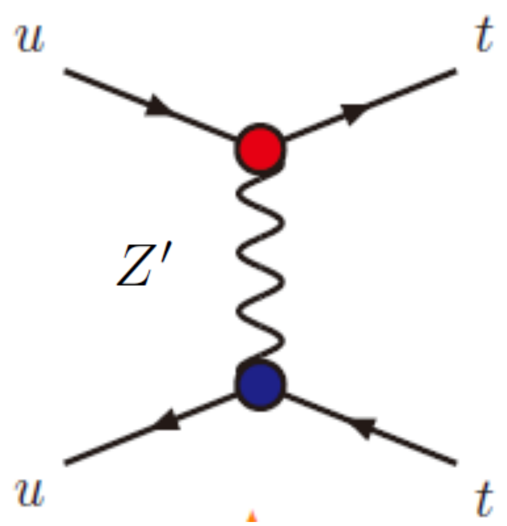
(new) heavy VB

4-fermion interaction

Ko et al (2009), (2010); Degrande et al (2010); etc.

Z′ model

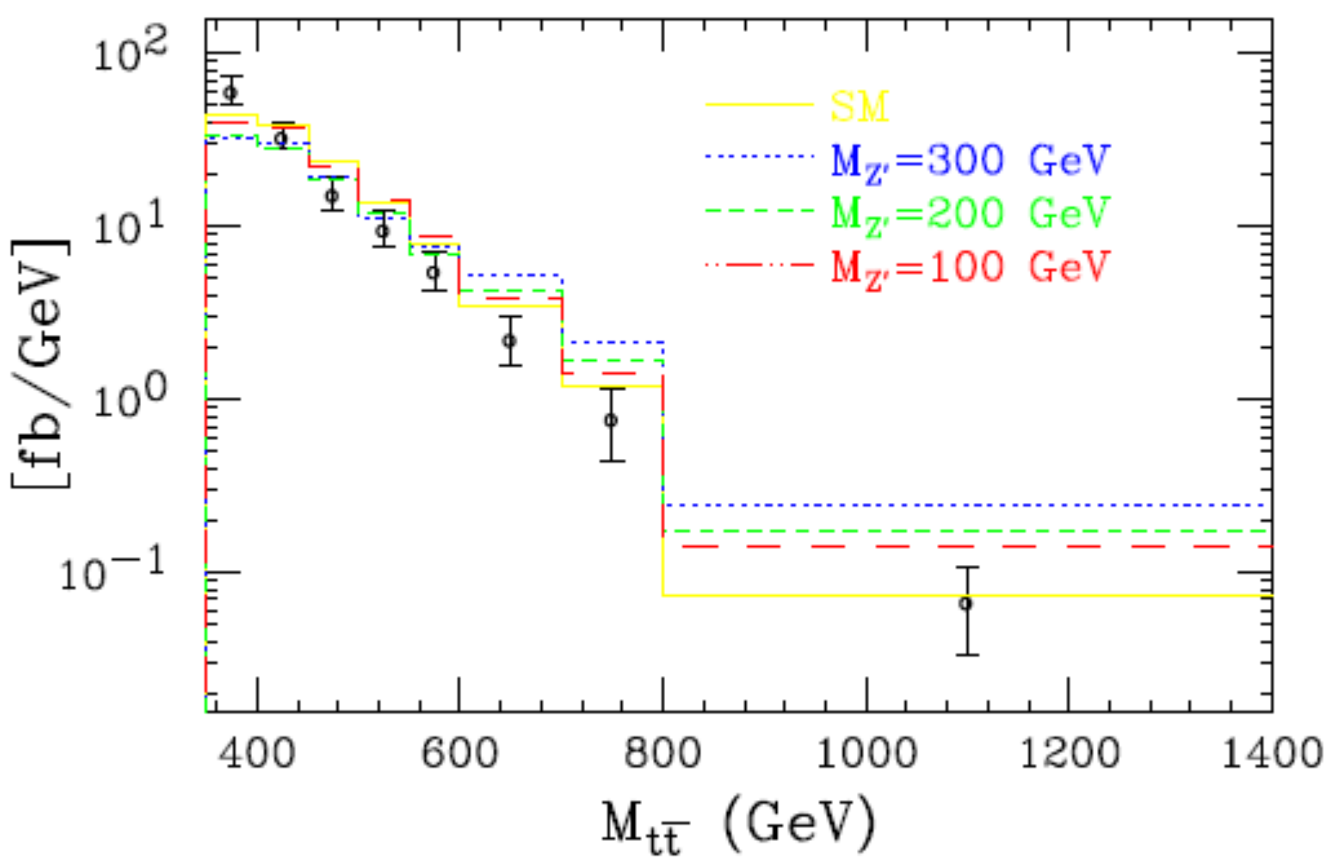
Jung, Murayama, Pierce, Wells, PRD81



- assume large flavor-offdiagonal coupling and small diagonal couplings.

$$\mathcal{L} \ni g_X Z'_\mu \bar{u}\gamma^\mu P_R t + h.c.$$

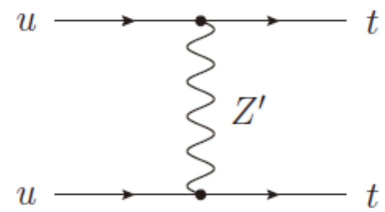
- In general, could have different couplings to the top and antitop quarks.



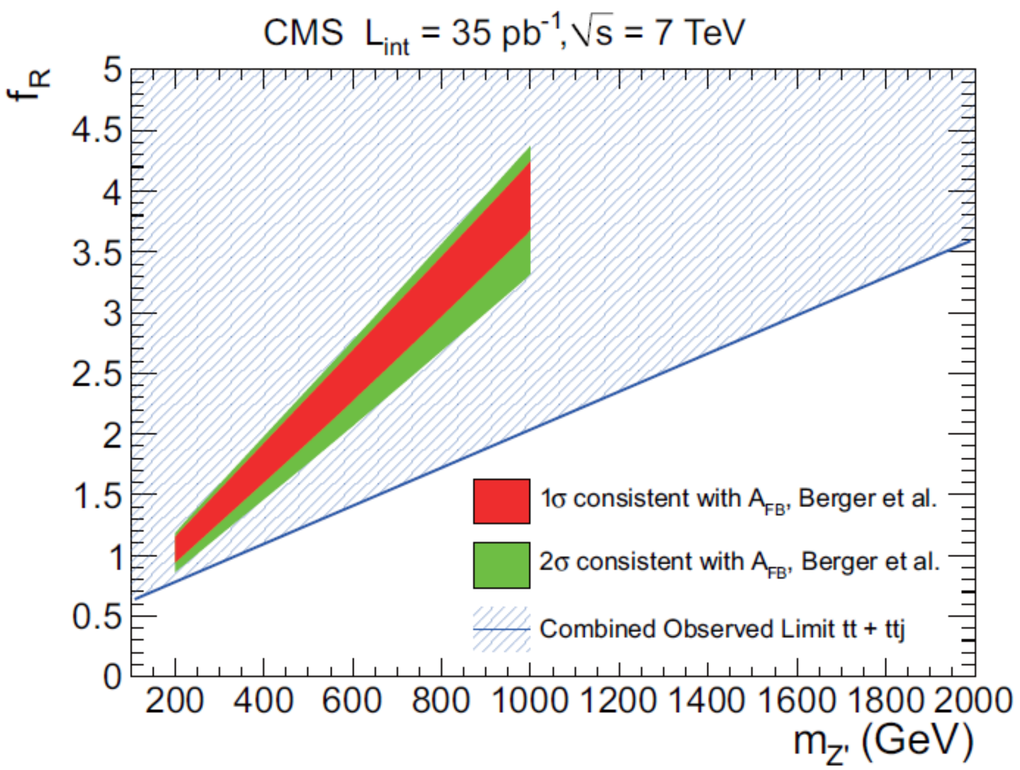
- light Z′ is favored from the M_{tt} distribution.

- severely constrained by the same sign top pair production.
  - the t-channel scalar exchange model has a similar constraint.

Same sign top pair production at LHC



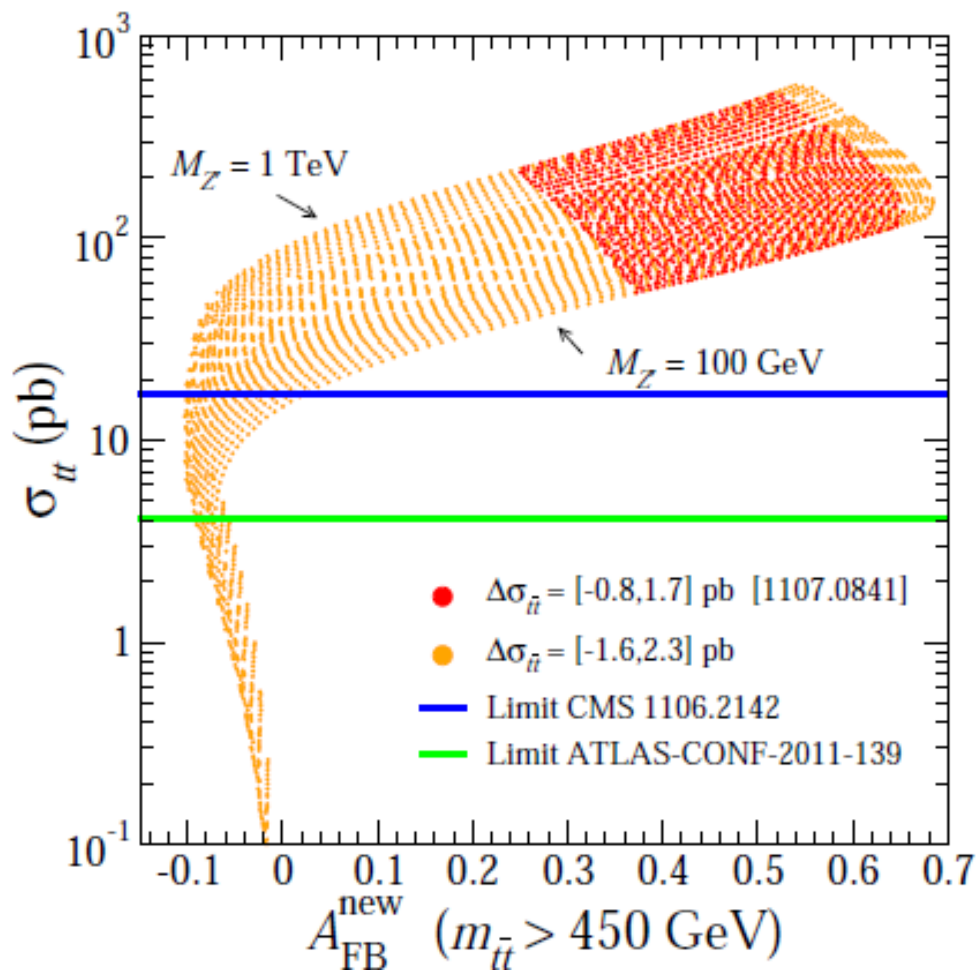
$$\mathcal{L} = g_W \bar{u}\gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + \text{h.c.},$$



CMS: σ(pp→tt(j))<17 pb at 95C.L.
ATLAS: σ(pp→tt(j))<4 pb at 95C.L.

CMS, JHEP1108; ATLAS-CONF-2011-169

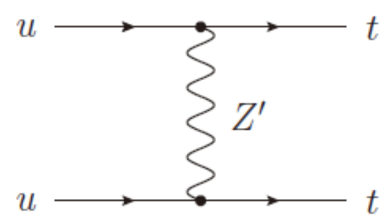
General exclusion plot



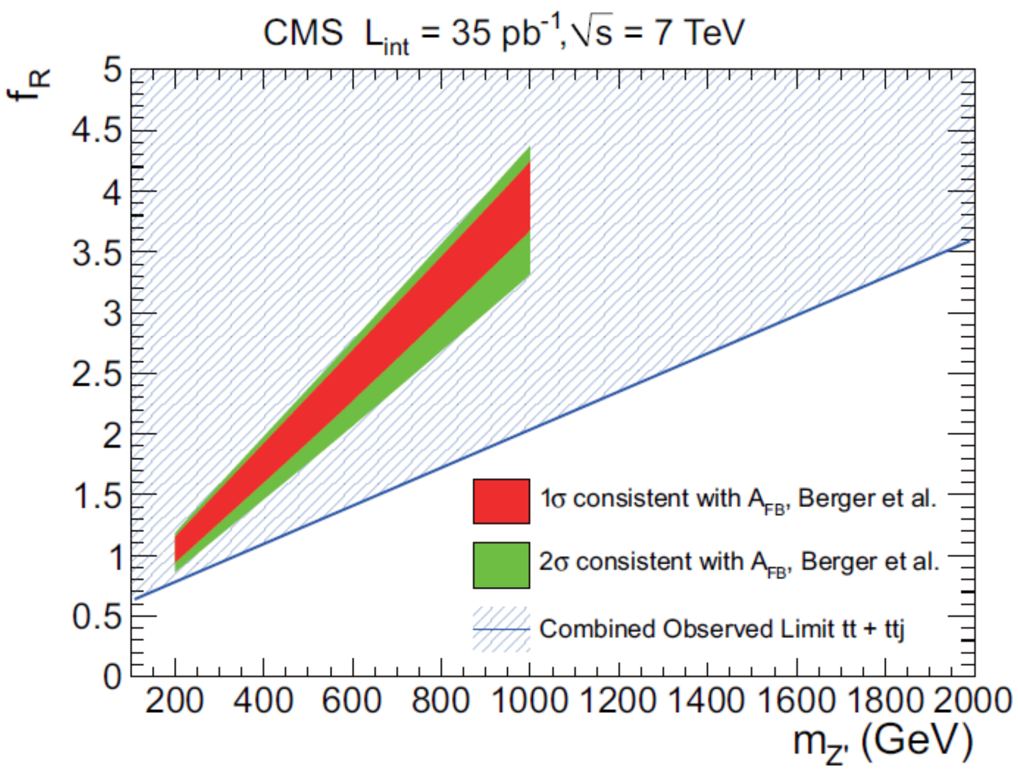
Aguilar-Saavedra, TOP2011

- the t-channel Z′ or scalar exchange models are excluded?

Same sign top pair production at LHC



$$\mathcal{L} = g_W \bar{u} \gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + \mathrm{h.c.},$$



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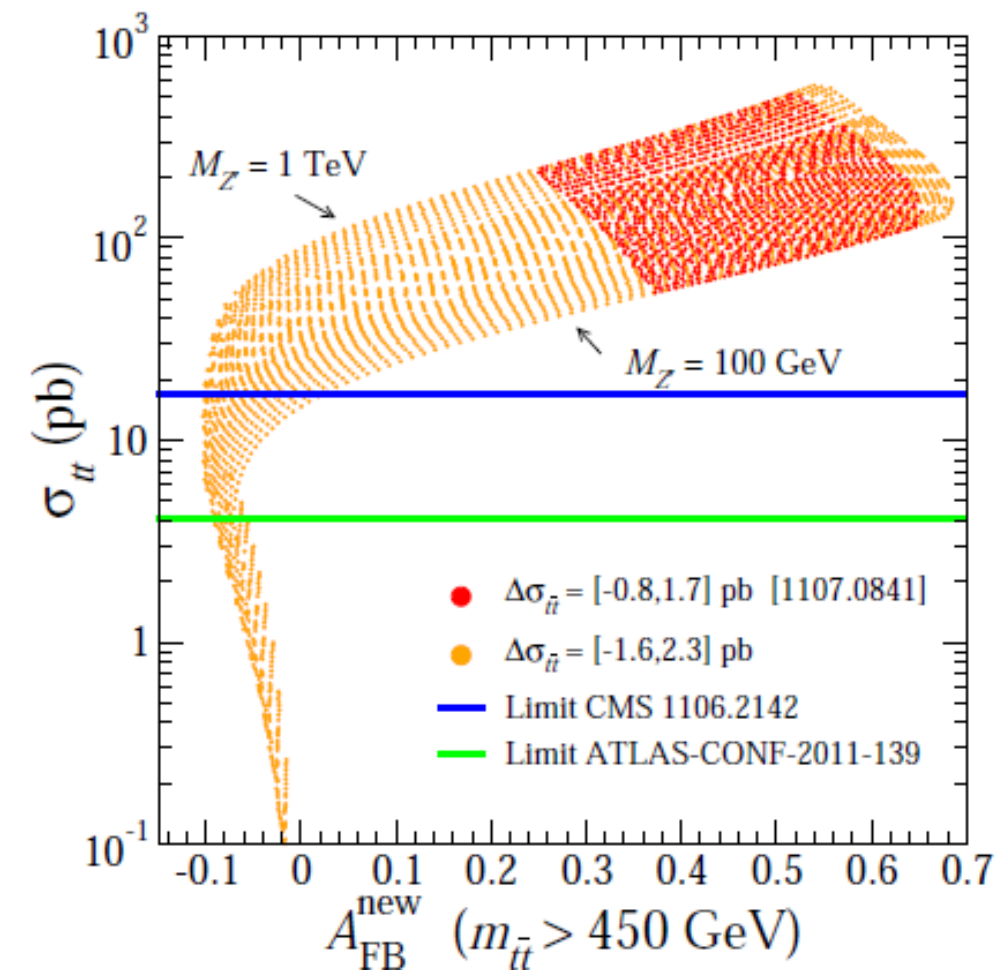


Aguilar-Saavedra, TOP2011

- the t-channel Z′ or scalar exchange models are excluded?
- the answer is NO.

However, the story is not so simple for models with vector bosons that have chiral couplings with the SM fermions !

Chiral U(1)' model (Ko, Omura, Yu)

(1) arXiv:1108.0350, PRD (2012)
(2) arXiv:1108.4005, JHEP 1201 (2012) 147
(3) arXiv:1205.0407, EPJC 73 (2013) 2269
(4) arXiv:1212.4607, JHEP 1303 (2013) 151

What is the problem of the original Z' model ?

- Z' couples to the RH up type quarks : leptophbic and chiral : ANOMALY ?
- No Yukawa couplings for up-type quarks : MASSLESS TOP QUARK ?
- Origin of Z' mass
- Origin of flavor changing couplings of Z'

What is the problem of the original Z' model ?

$$\mathcal{L}_Y = -Y^U_{ij}\overline{Q_{Li}}\tilde{H}U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

Not gauge invariant

Gauge invariant : OK!

No Yukawa's for up quarks !

How to cure this problem ?

Answer : Extend Higgs sector

$$\mathcal{L}_Y = -Y^U_{ij}\overline{Q_{Li}}\tilde{H}U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

Not gauge invariant

Gauge invariant : OK!

$$\mathcal{L}_Y = -Y^U_{ijk}\overline{Q_{Li}}\tilde{H}_k U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

$H_k : U(1)$ charged

Mandatory to extend Higgs sector!
Z' only model does not exist!

# of U(1)'-charged new Higgs doublets depend on U(1)' charge assigments to the RH up quarks

Flavor-dependent U(1)′ model

- Charge assignment : SM fermions

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
Q_1	3	2	$1/6$	q_L
Q_2	3	2	$1/6$	q_L
Q_3	3	2	$1/6$	q_L
$\overline{D_1}$	$\overline{3}$	1	$1/3$	$-q_L$
$\overline{D_2}$	$\overline{3}$	1	$1/3$	$-q_L$
$\overline{D_3}$	$\overline{3}$	1	$1/3$	$-q_L$
$\overline{U_1}$	$\overline{3}$	1	$-2/3$	u_1
$\overline{U_2}$	$\overline{3}$	1	$-2/3$	u_2
$\overline{U_3}$	$\overline{3}$	1	$-2/3$	u_3
H	1	2	$1/2$	0

LH quarks and RH down-type quarks have universal couplings.

Flavor-dependent

Higgs

Flavor-dependent U(1)′ model

- Charge assignment : Higgs fields

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H_1	1	2	1/2	$-q_L - u_1$
H_2	1	2	1/2	$-q_L - u_2$
H_3	1	2	1/2	$-q_L - u_3$
Φ	1	1	1	$-q_\Phi$

- introduce three Higgs doublets charged under U(1)′ in addition to the S M Higgs which is not charged under U(1)′.

$$\begin{aligned} V_y &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} \overline{D_j} Q_i i\tau_2 H^\dagger \\ &+ y^e_{ij} \overline{E_j} L_i i\tau_2 H^\dagger + y^n_{ij} H \overline{N_j} L_i. \end{aligned}$$

- The U(1)′ is spontaneously broken by U(1)′ charged complex scalar Φ.

Anomaly Cancellation : Sol. I

- Anomaly cancelation requires extra fermions I: SU(2) doublets

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q'	3	2	1/6	$-(q_1+q_2+q_3)$
D'_R	3	1	$-1/3$	$-(d_1+d_2+d_3)$
U'_R	3	1	2/3	$-(u_1+u_2+u_3)$
L'	1	2	$-1/2$	0
E'	1	1	-1	0
l_{L1}	1	2	$-1/2$	Q_L
l_{R1}	1	2	$-1/2$	Q_R
l_{L2}	1	2	$-1/2$	$-Q_L$
l_{R2}	1	2	$-1/2$	$-Q_R$

one extra generation

$SU(2)_L{}^2 \cdot U(1)'$

vector-like pairs

$U(1)'^2 \cdot U(1)$

a candidate for CDM

Anomaly Cancellation : Sol. II

- Anomaly cancelation requires extra fermions II: $SU(3)_c$ triplets

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
q_{L1}	3	1	$-1/3$	Q_L
q_{R1}	3	1	$-1/3$	Q_R
q_{L2}	3	1	$-1/3$	$-Q_L$
q_{R2}	3	1	$-1/3$	$-Q_R$

- introduce the singlet scalar X to the SM in order to allow the decay of th e extra colored particles.

$$V_m = \lambda_i X^\dagger \overline{D_{Ri}} q_{L1} + \lambda_i X \overline{D_{Ri}} q_{L2}$$

a candidate for CDM

Flavor-dependent U(1)′ model

- Gauge coupling in the mass base

- Z′ interacts only with the right-handed up-type quarks

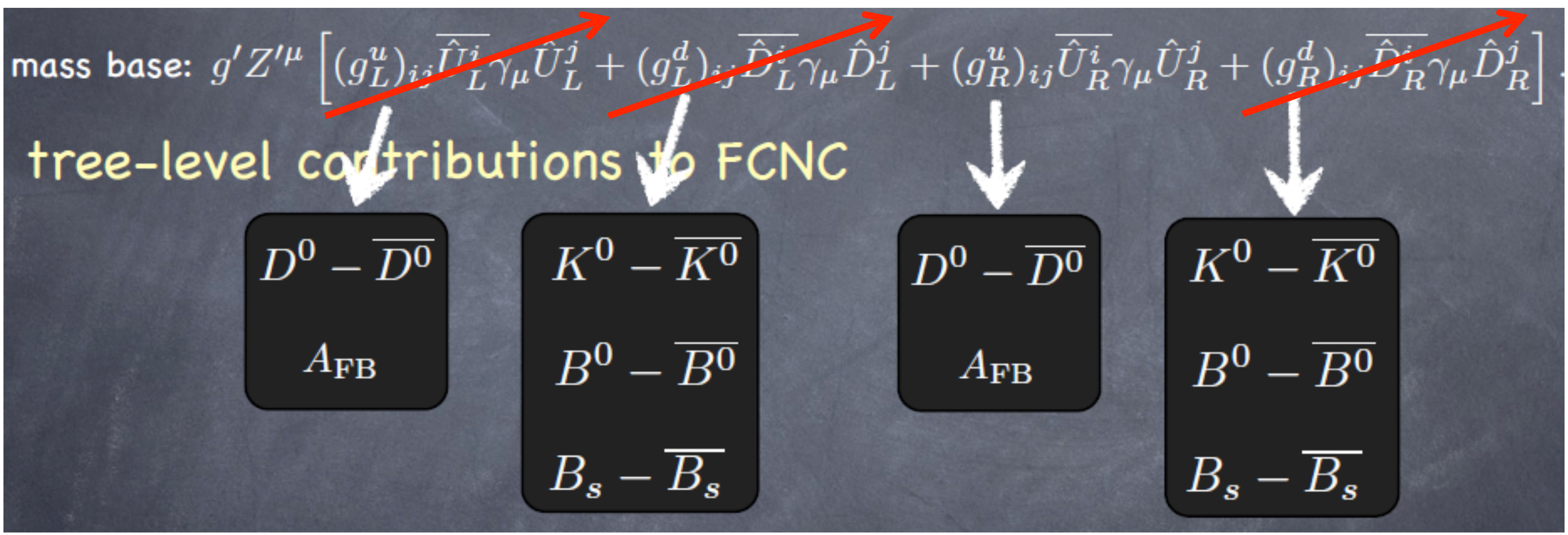
$$g' Z'^{\mu} \sum_{i,j=1,2,3} (g_R^u)_{ij} \overline{U_R}^i \gamma_\mu U_R^j$$

$$g' Z'^{\mu} \sum_{i=1,2,3} u_i \overline{U'_{Ri}} \gamma_\mu U'_{Ri}$$

- The 3 X 3 coupling matrix g_R^u is defined by

$$(g_R^u)_{ij} = (U_R^u)_{ik} u_k (U_R^u)^{\dagger}_{kj}$$

biunitary matrix diagonalizing the
up-type quark mass matrix



Flavor-dependent U(1)′ model

- 2 Higgs doublet model : $(u_1, u_2, u_3) = (0, 0, 1)$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H	1	2	1/2	0
H_3	1	2	1/2	1
Φ	1	1	1	q_Φ

$$\begin{aligned} V_y &= y^u_{i1}\overline{Q_i}\widetilde{H}U_{R1} + y^u_{i2}\overline{Q_i}\widetilde{H}U_{Rj} + y^u_{i3}\overline{Q_i}\widetilde{H_3}U_{Rj} \\ &\quad + y^d_{ij}\overline{Q_i}HD_{Rj} + y^e_{ij}\overline{L_i}H\overline{E_j} + y^n_{ij}\overline{L_i}\widetilde{H}N_j. \end{aligned}$$

$$V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}\hat{h}_0 + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}\hat{h}_0,$$

$$\left.\begin{aligned} Y^u_{ij} &= \frac{m^u_i \cos\alpha}{v\cos\beta}\delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta), \\ Y^d_{ij} &= \frac{m^d_i \cos\alpha}{v\cos\beta}\delta_{ij}, \end{aligned}\right\} \propto \text{the fermion mass}$$

Flavor-dependent U(1)′ model

- 3 Higgs doublet model: $(u_1, u_2, u_3) = (-q, 0, q)$

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
H_1	1	2	$1/2$	q
H_2	1	2	$1/2$	0
H_3	1	2	$1/2$	$-q$
Φ	1	1	0	-1

$$\begin{aligned} \mathcal{L}_{\mathrm{Y}} &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} H_2^\dagger \overline{D_j} Q_i + y^e_{ij} H_2^\dagger \overline{E_j} L_i + y^n_{ij} H_2 \overline{N_j} L_i . \end{aligned}$$

Flavor-dependent U(1)′ model

- Gauge coupling in the mass base

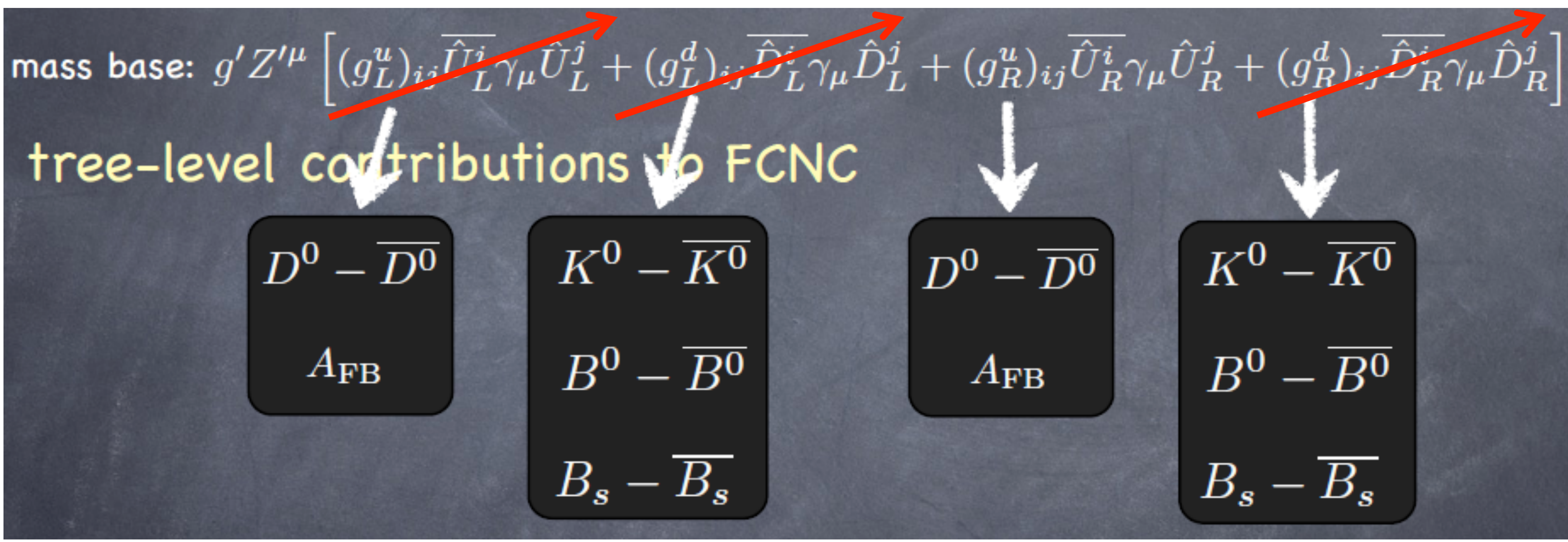
\- Z′ interacts only with the right-handed up-type quarks

$$g' Z'^{\mu} \sum_{i,j=1,2,3} (g_R^u)_{ij} \overline{U_R}^i \gamma_\mu U_R^j \longleftarrow g' Z'^{\mu} \sum_{i=1,2,3} u_i \overline{U'_{Ri}} \gamma_\mu U'_{Ri}$$

\- The 3 X 3 coupling matrix g_R^u is defined by

$$(g_R^u)_{ij} = (U_R^u)_{ik} u_k (U_R^u)^\dagger_{kj}$$

biunitary matrix diagonalizing the up-type quark mass matrix



Flavor-dependent U(1)′ model

- Yukawa coupling in the mass base (2HDM)

- lightest Higgs h:

$$V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}h + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}h + Y^e_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}h + h.c.,$$

$$Y^u_{ij} = \frac{m^u_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta)\cos\alpha_\Phi,$$

$$Y^d_{ij} = \frac{m^d_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij},$$

$$Y^e_{ij} = \frac{m^l_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij},$$

- lightest charged Higgs h^+:

$$V_{h^\pm} = -Y^{u-}_{ij}\overline{\hat{D}_{Li}}\hat{U}_{Rj}h^- + Y^{d+}_{ij}\overline{\hat{U}_{Li}}\hat{D}_{Rj}h^+ + h.c.,$$

$$Y^{u-}_{ij} = \sum_l (V_{\rm CKM})^*_{li}\left\{\frac{\sqrt{2}m^u_l \tan\beta}{v}\delta_{lj} - \frac{2\sqrt{2}m^u_l}{v\sin 2\beta}(g^u_R)_{lj}\right\},$$

$$Y^{d+}_{ij} = (V_{\rm CKM})_{ij}\frac{\sqrt{2}m^d_j \tan\beta}{v},$$

- lightest pseudoscalar Higgs a:

$$V_a = -iY^{au}_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}a + iY^{ad}_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}a + iY^{ae}_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}a + h.c.,$$

$$Y^{au}_{ij} = \frac{m^u_i \tan\beta}{v}\delta_{ij} - \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij},$$

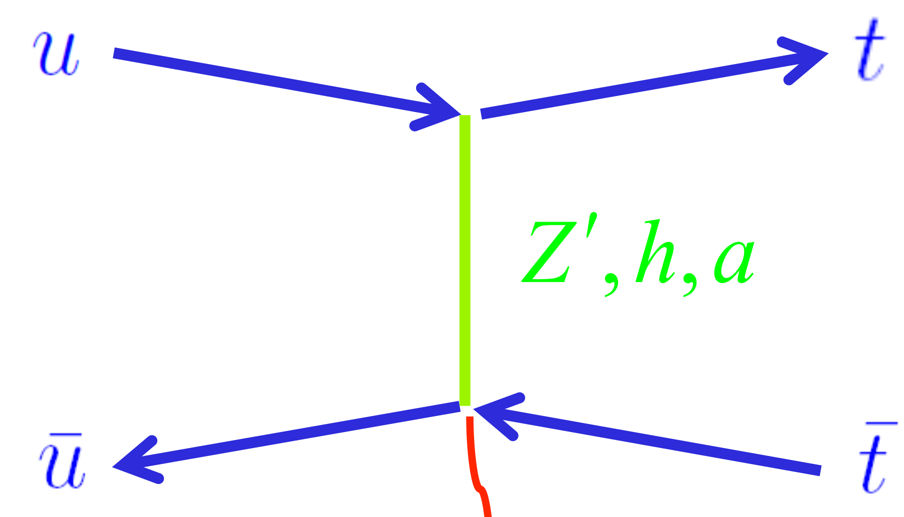
$$Y^{ad}_{ij} = \frac{m^d_i \tan\beta}{v}\delta_{ij},$$

$$Y^{ae}_{ij} = \frac{m^l_i \tan\beta}{v}\delta_{ij}.$$

Top-antitop pair production

1. Z′ dominant scenario

cf. Jung, Murayama, Pierce, Wells, PRD81(2010)♪



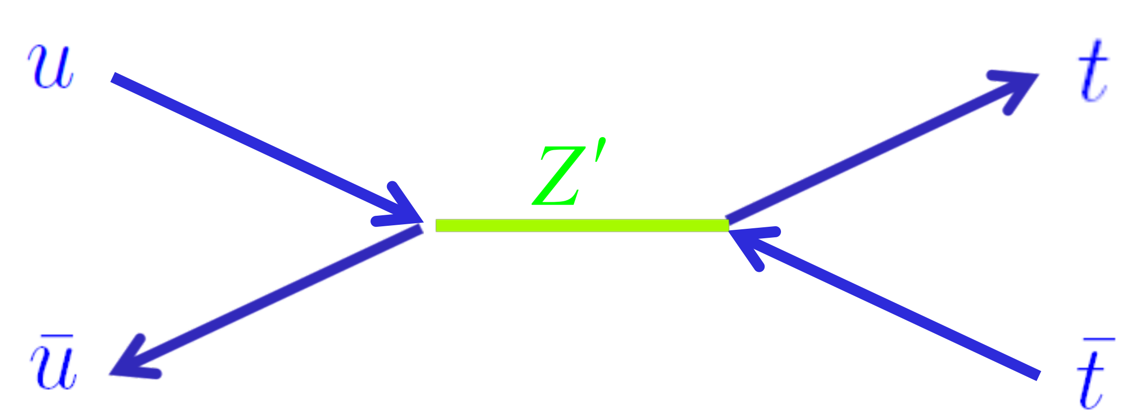
$$\alpha_X = \frac{(g' g^u_{Rut})^2}{4\pi}, Y_{tu}, Y^a_{tu}$$

2. Higgs dominant scenario

cf. Babu, Frank, Rai, PRL107(2011)♪

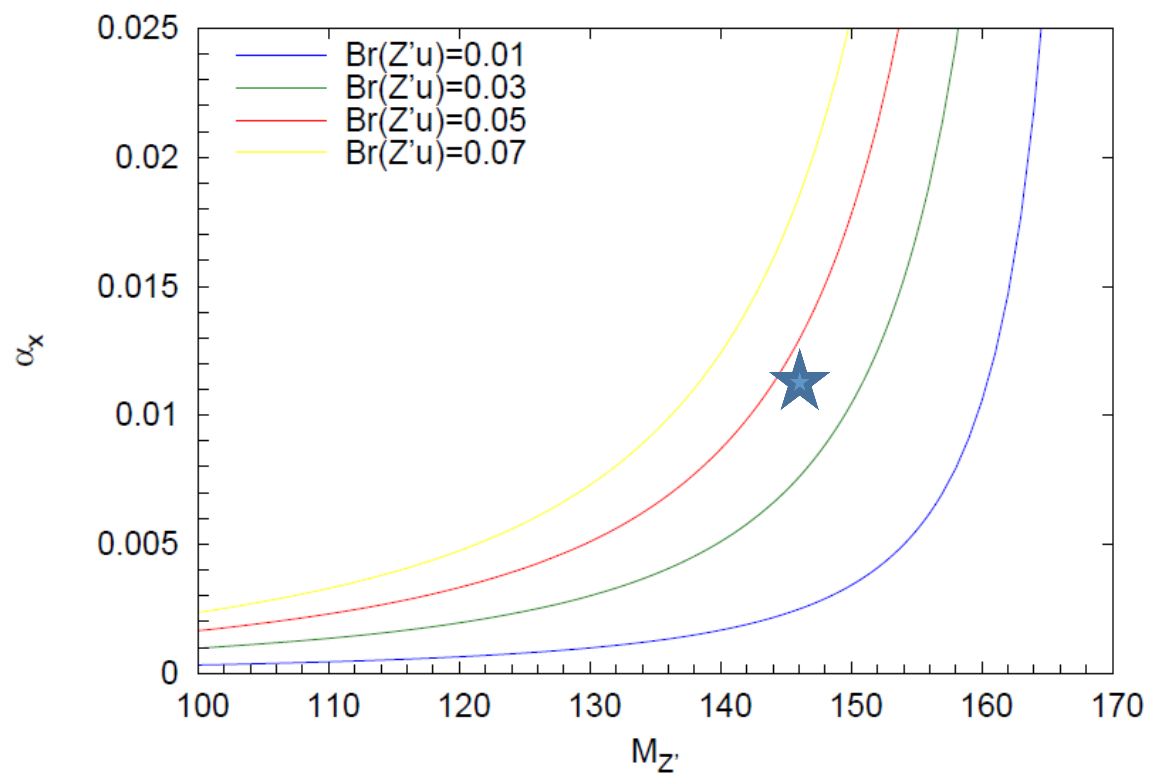
3. Mixed scenario

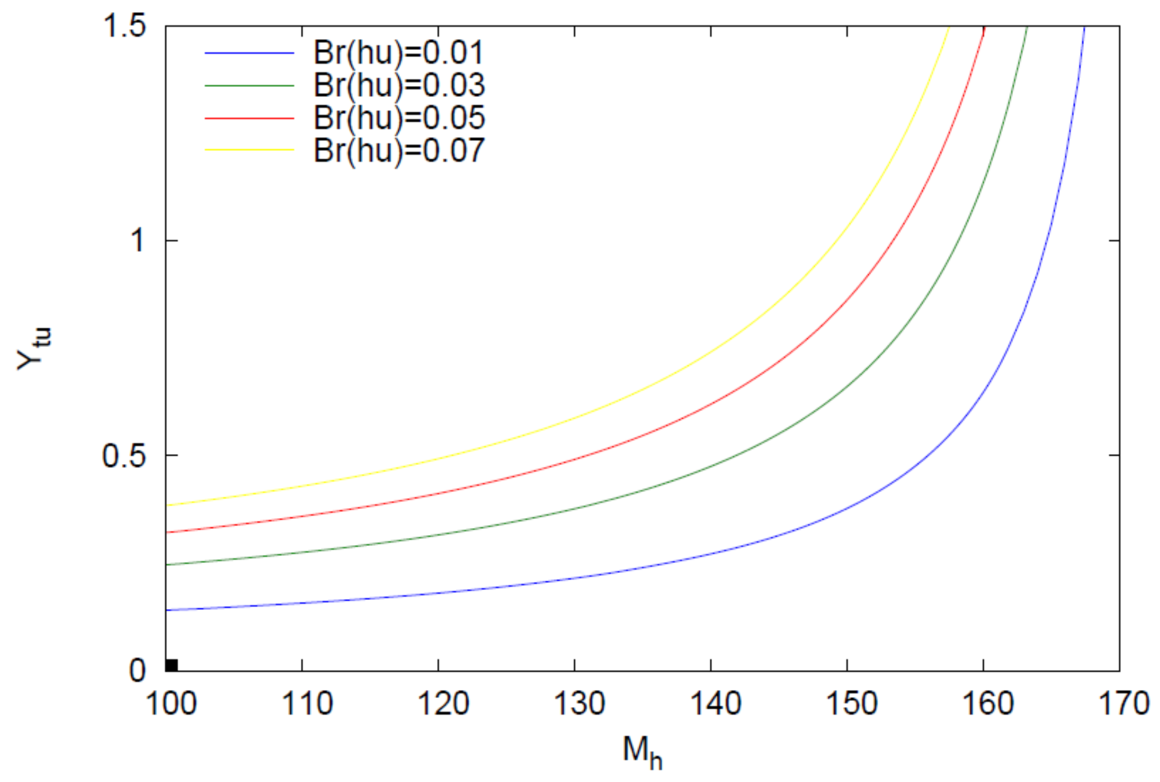
Destructive interference between Z' and h,a for the same sign pair production (Ko, Omura, Yu)



Top quark decay

- decay into W+b in SM : Br(t→Wb)~100%.
- If the top quark decays to $Z' + u$ or $h + u$, Br(t→Wb) might significantly be changed.

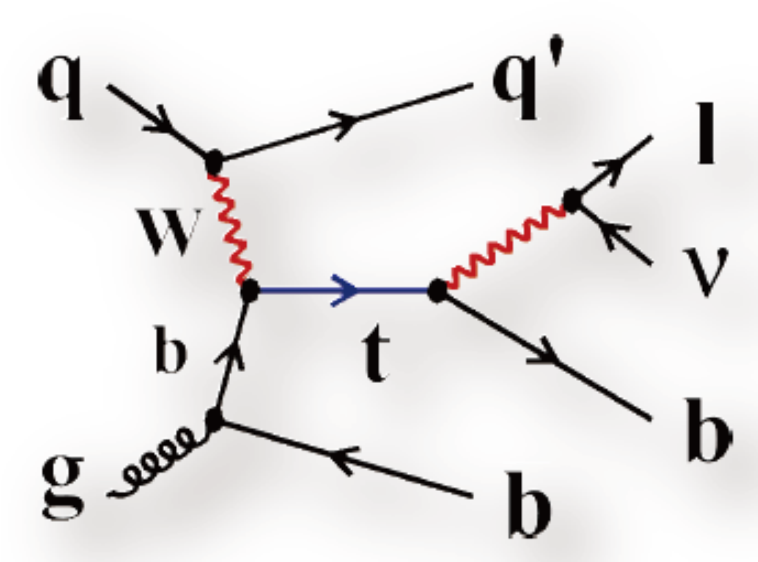




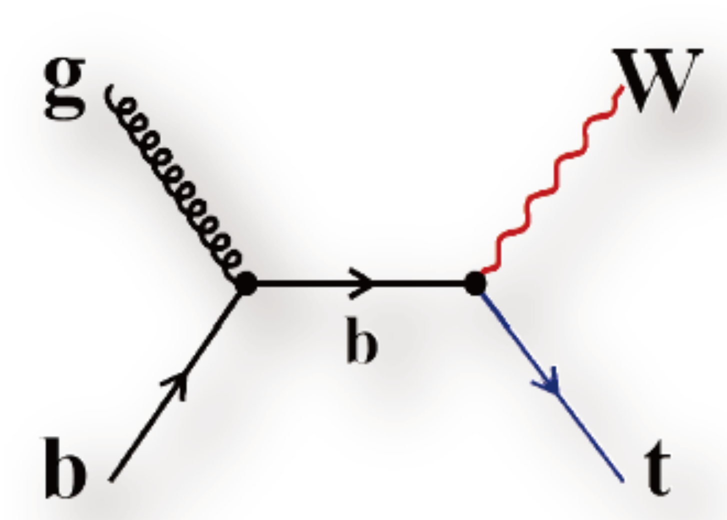
- requires Br(t →non-SM)<5% .
- choose either $m_{Z'} < m_t$ or $m_h < m_t$.

Single top quark production

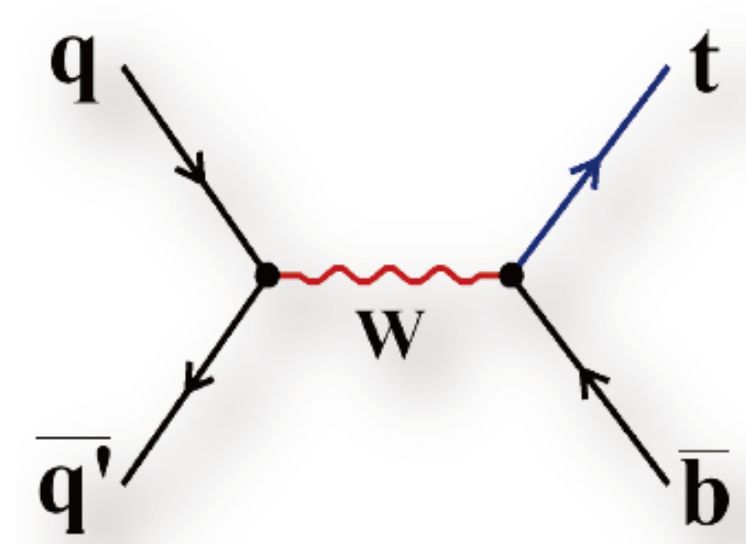
t channel



Wt channel



s channel



- D0 D0, 1105.2788

$$\sigma(p\bar{p} \to tbq) = 2.90 \pm 0.59 \text{ pb}$$

- CMS CMS, 1106.3052

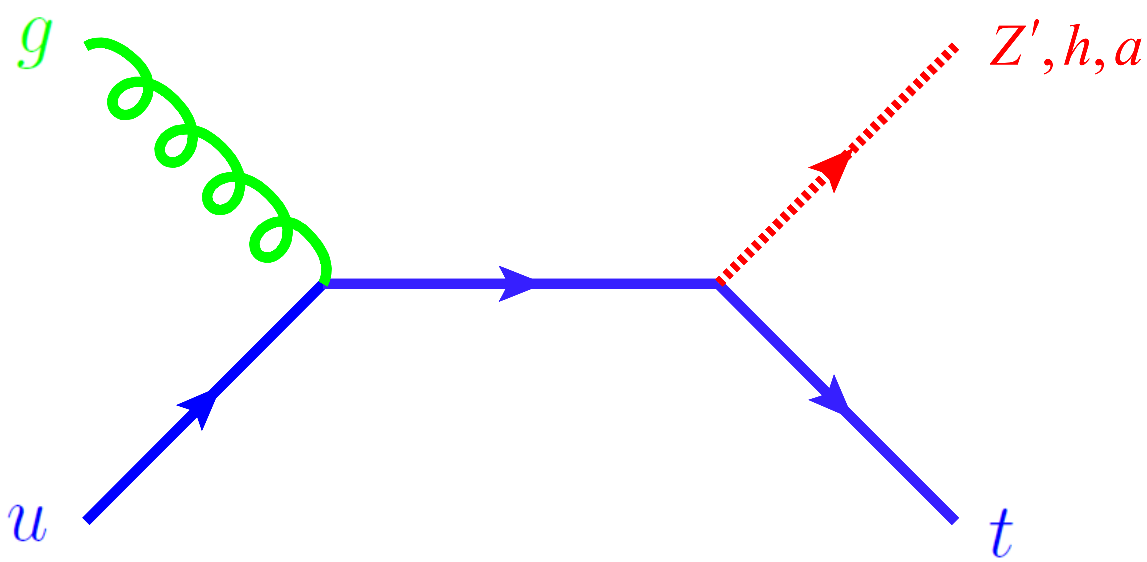
$$\sigma(pp \to tbq) = 83.6 \pm 29.8 \pm 3.3 \text{ pb}$$

In the SM,

$$\sigma(p\bar{p} \to tbq) = 2.26 \pm 0.12 \text{ pb}$$

$$\sigma(pp \to tbq) = 64.3^{+2.1+1.5}_{-0.7-1.7} \text{ pb}$$

Single top quark production



$\Rightarrow$ no b quark or W boson in the final state

- D0 D0, 1105.2788

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- CMS CMS, 1106.3052

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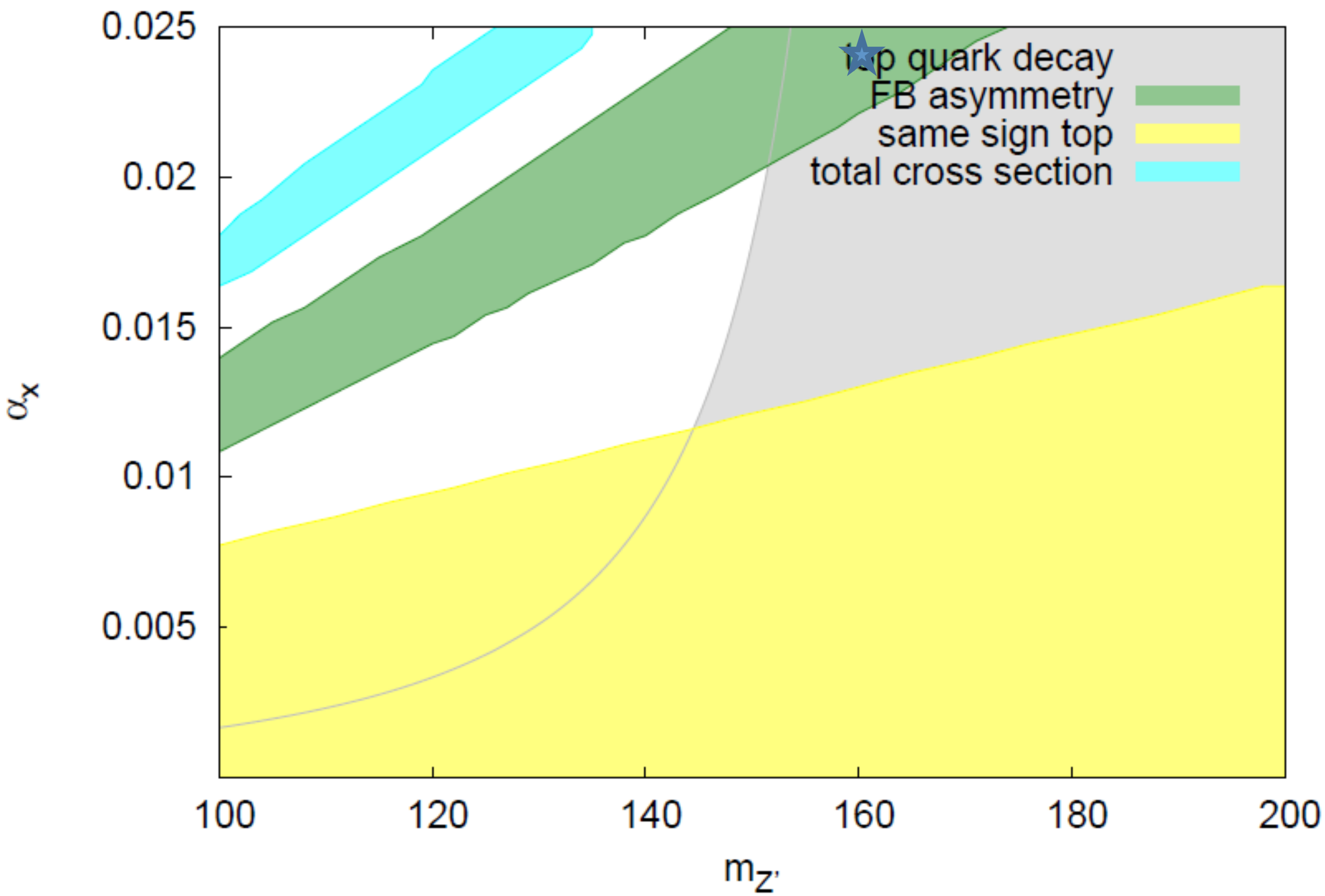
Favored region

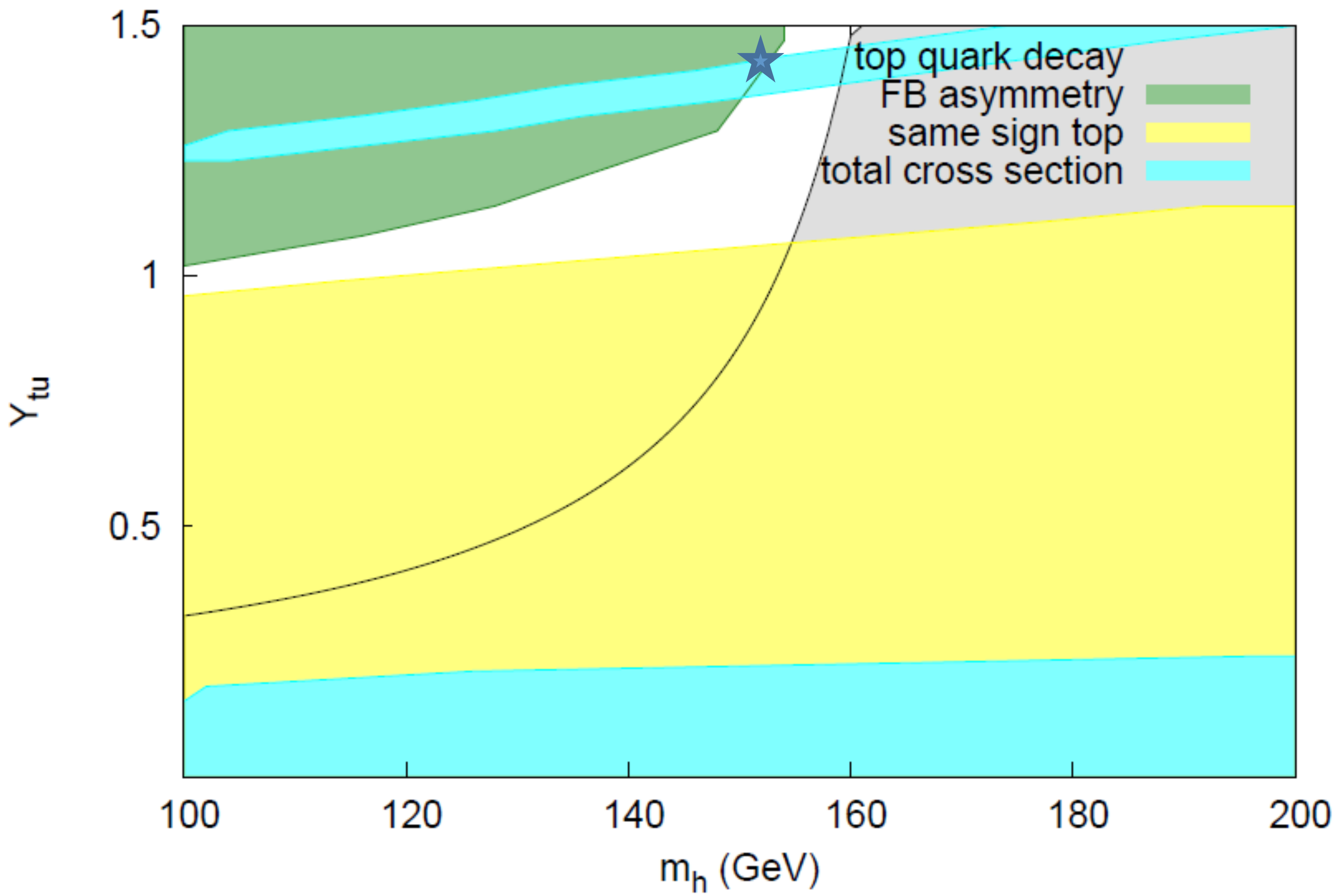
Z′ dominant case



★ = similar to Jung, Murayama, Pierce, Wells' model (PRD81)

Favored region

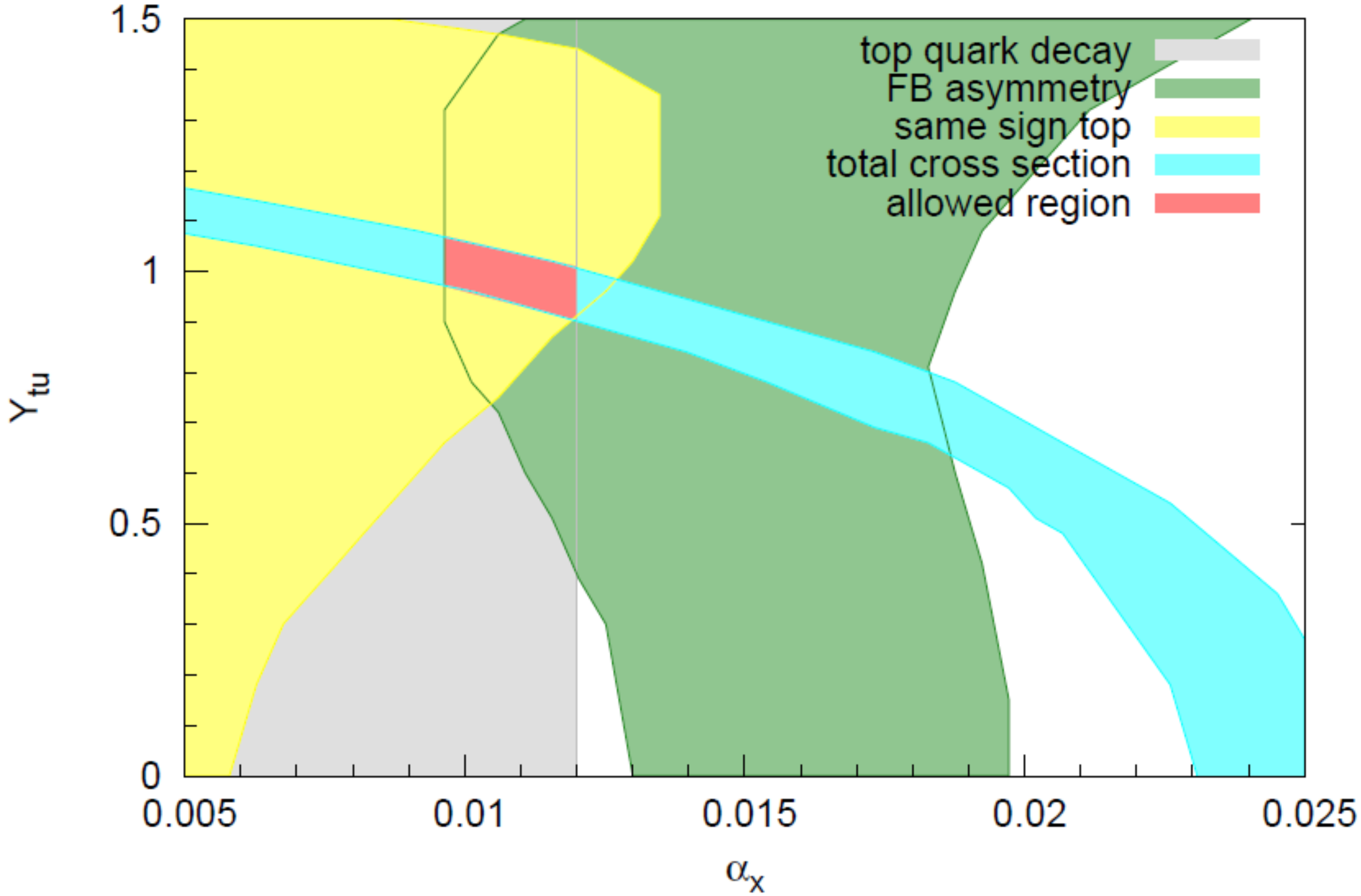
Scalar Higgs (h) dominant case



★ = similar to Babu, Frank, Rai's model (PRL107)

Favored region

Z′+h+a case



$m_{Z'} = 145$ GeV

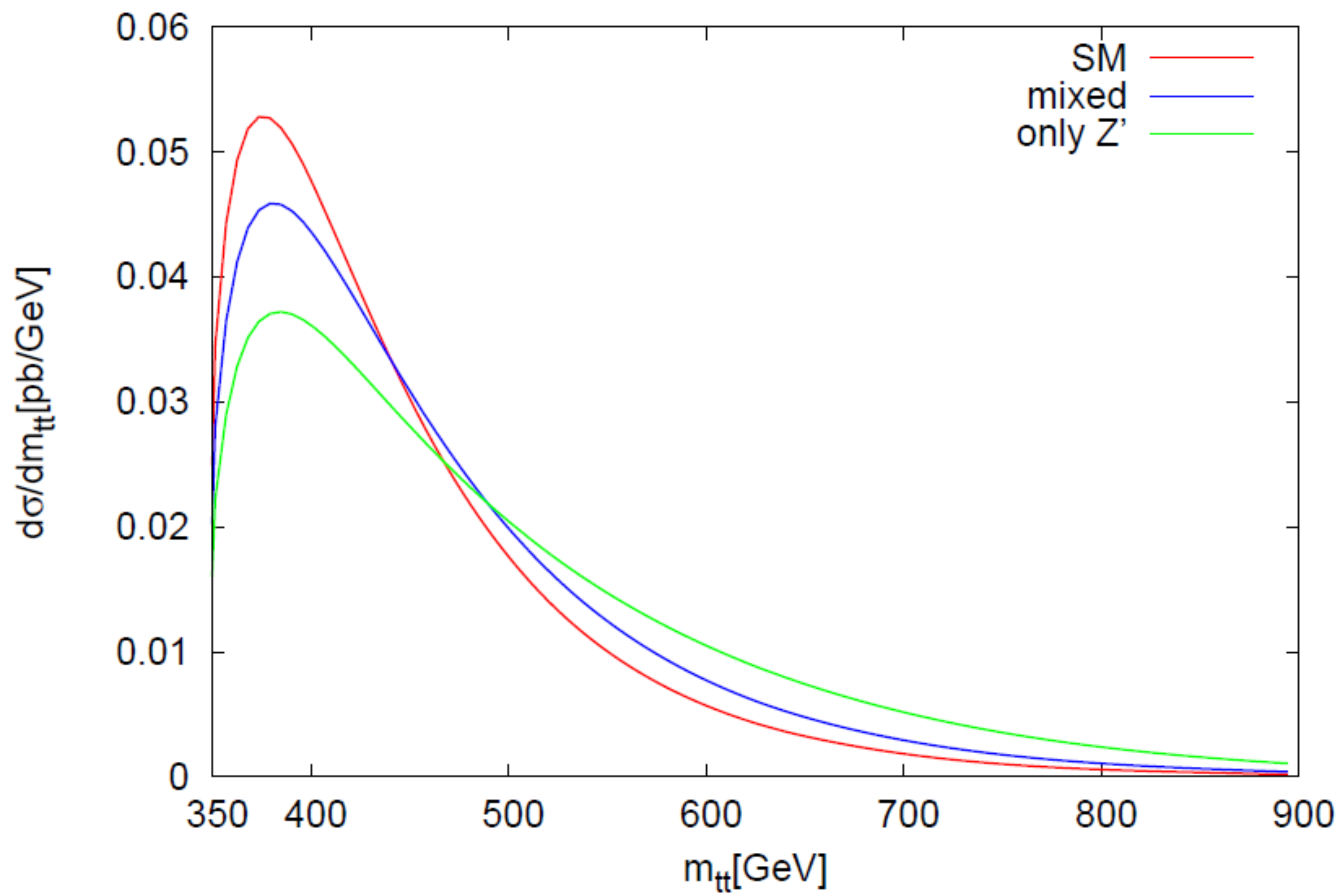
$m_h = 180$ GeV

$m_a = 300$ GeV

$Y^a_{tu} = 1.1$

- destructive interference between Z and Higgs bosons in the same signe top pair production.
- consistent with the CMS bound, but not with the ATLAS bound.

Invariant mass distribution



Only Z′ case

$m_{Z'} = 145$ GeV

$\alpha_x = 0.029$

mixed case

$m_{Z'} = 145$ GeV

$m_h = 180$ GeV

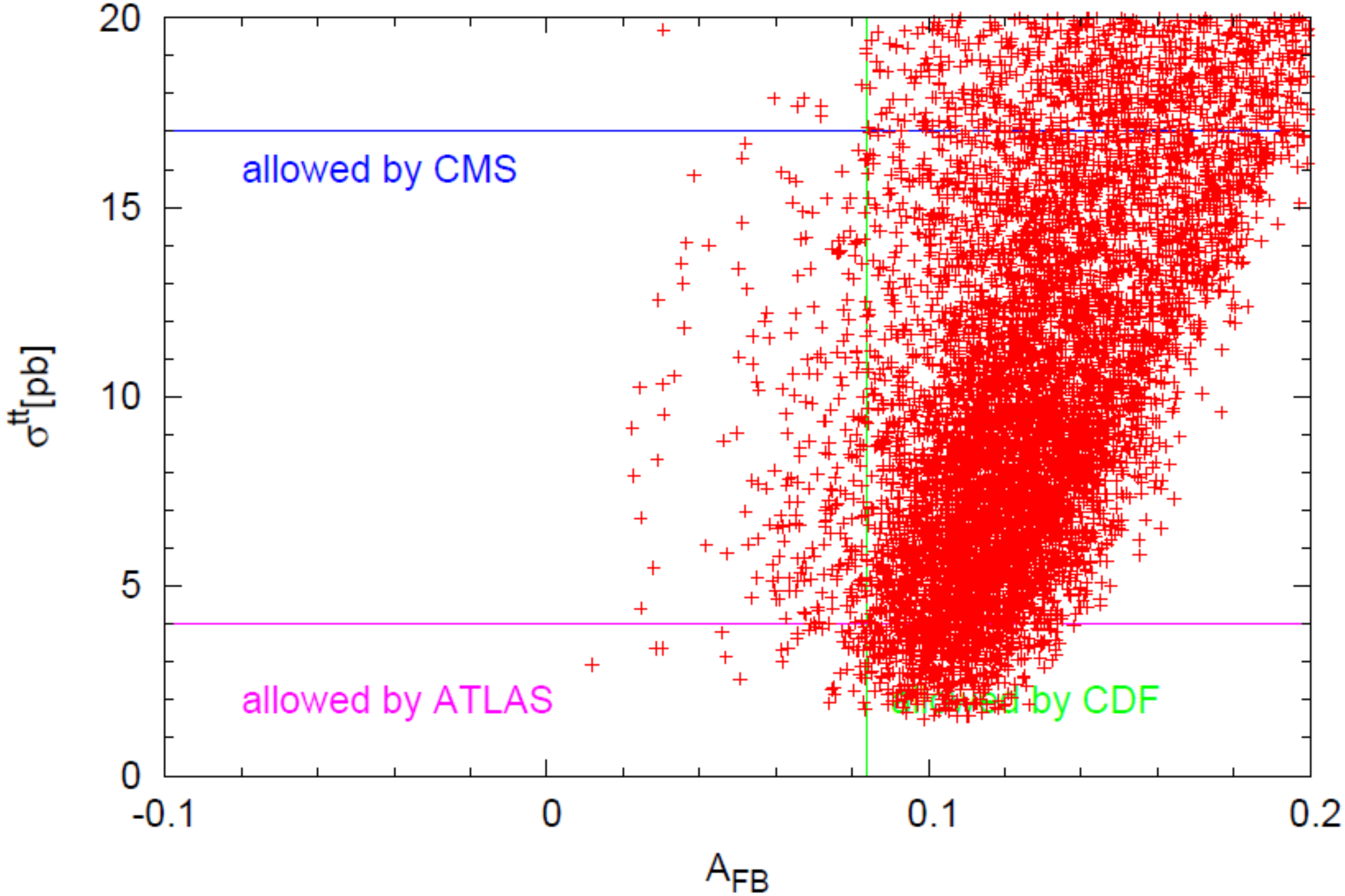
$m_a = 300$ GeV

$\alpha_x = 0.01$

$Y_{tu} = 1.0$

$Y_{tu}^a = 1.1$

A_{FB} versus σ_{tt}



$m_{Z'} = 145$ GeV

180 GeV$< m_h < 1$ TeV

180 GeV$< m_a < 1$ TeV

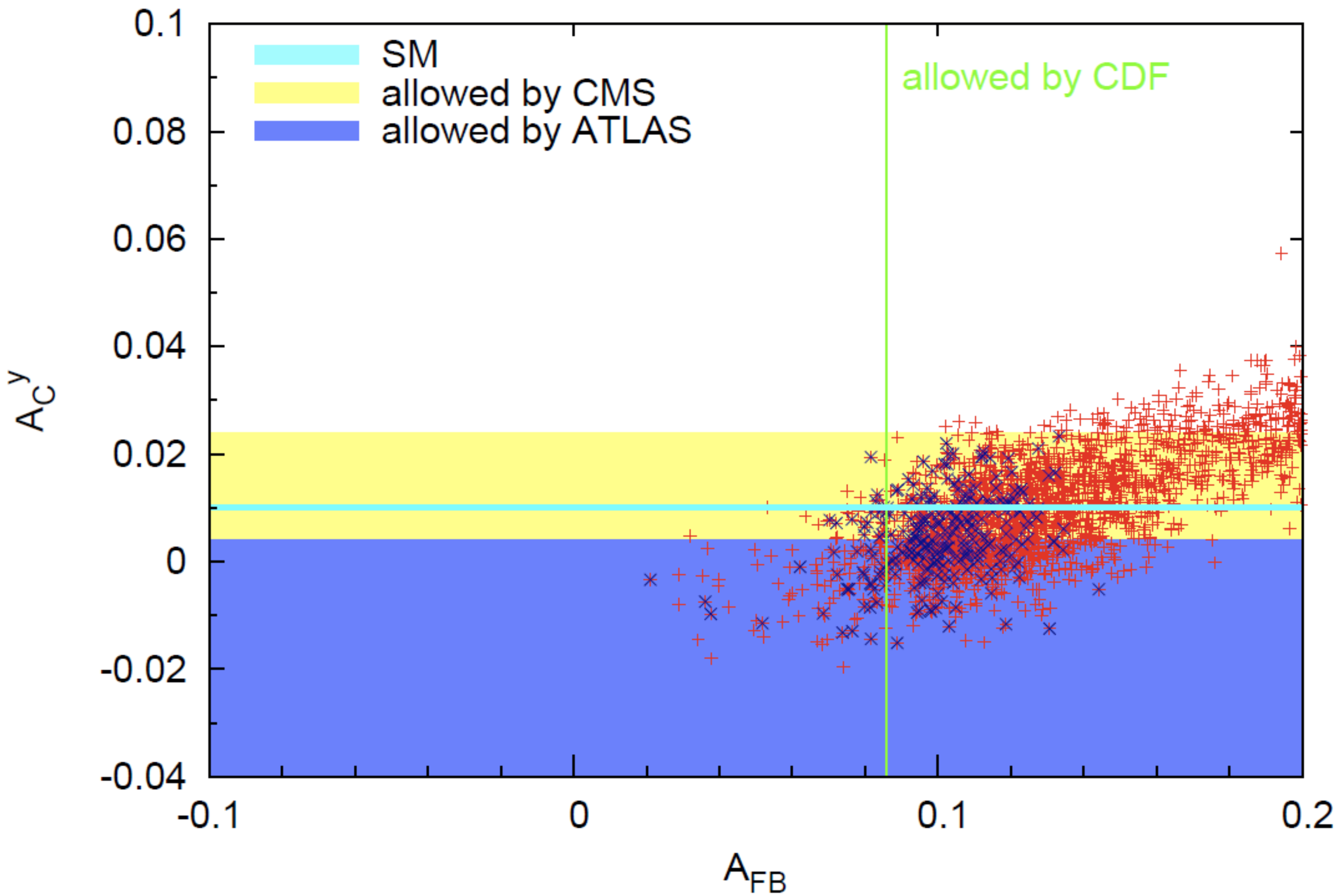
$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

$0.5 < Y_{tu}^{a} < 1.5$

Have a trouble with new CMS data < 0.39 pb

A_{FB} versus A_C^y



$\boxed{m_{Z'} = 145 \text{ GeV}}$

$180 \text{ GeV} < m_h < 1 \text{ TeV}$

$180 \text{ GeV} < m_a < 1 \text{ TeV}$

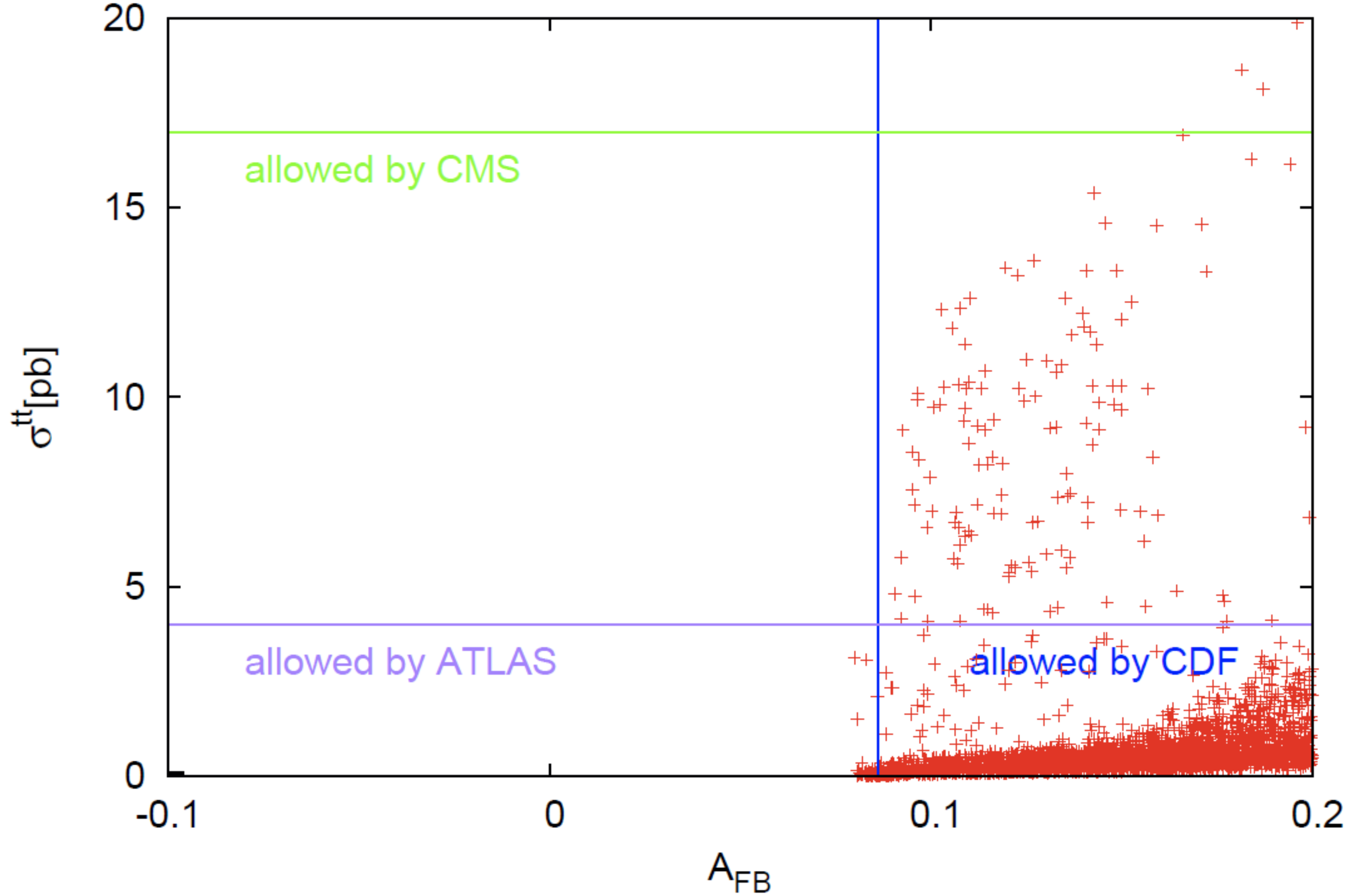
$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

$0.5 < Y_{tu}^a < 1.5$

Have a trouble with new CMS data < 0.39 pb

A_{FB} versus σ_{tt}



$\boxed{m_h = 126\ \text{GeV}}$

$180\ \text{GeV} < m_{Z'} < 1.5\ \text{TeV}$

$180\ \text{GeV} < m_a < 1\ \text{TeV}$

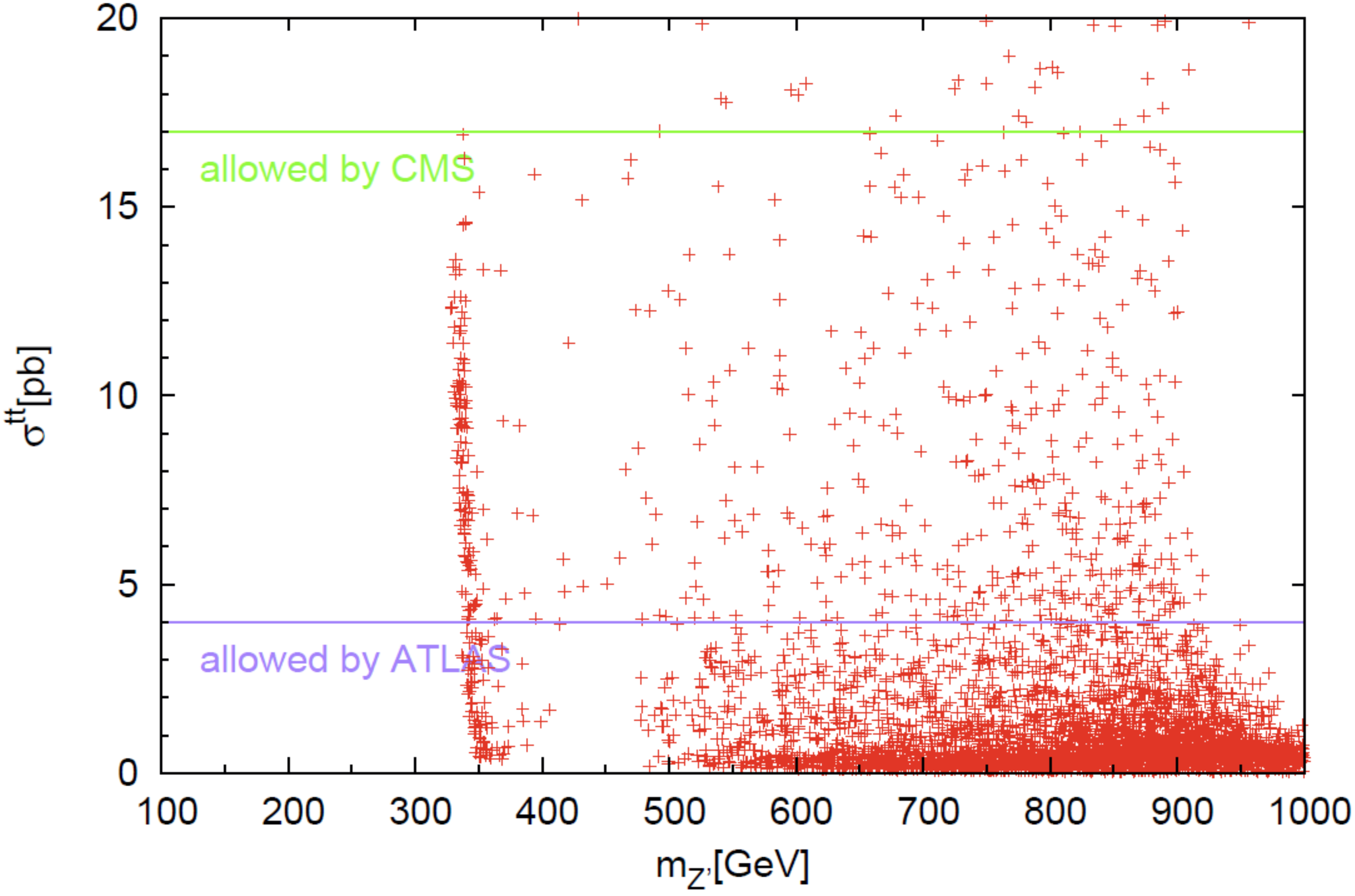
$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

$0.1 < Y_{tu}^{\ a} < 1.5$

Still OK with new CMS data < 0.39 pb

$m_{Z'}$ versus σ_{tt}



$\boxed{m_h = 126 \text{ GeV}}$

$180 \text{ GeV} < m_{Z'} < 1.5 \text{ TeV}$

$180 \text{ GeV} < m_a < 1 \text{ TeV}$

$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

$0.1 < Y_{tu}^{a} < 1.5$

Still OK with new CMS data < 0.39 pb

Conclusions

- We constructed realistic Z' models with additional Higgs doublets that are charged under U(1)' : Based on local gauge symmetry, renormalizable, anomaly free and realistic Yukawa
- New spin-one boson (Z') with chiral couplings to the SM fermion requires a new Higgs doublet that couples to the new Z'
- This is also true for axigluon, flavor SU(3)_R, W', etc.
- Our model can accommodate the top FB Asym @ Tevatron, the same sign top pair production, and the top CA@LHC

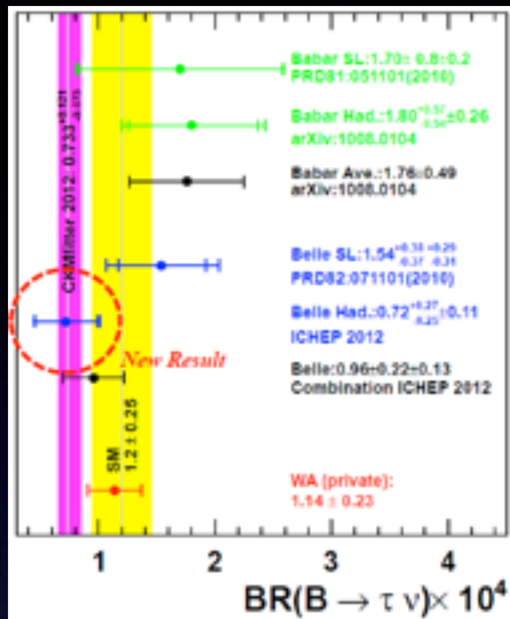
- Meaningless to say "The Z' model is excluded by the same sign top pair production."
- Important to consider a minimal consistent (renormalizable, realistic, anomaly free) in order to do phenomenology
- Flavor issues in B and charm systems were also studied (w/ Yuji Omura and C. Yu)
- Top longitudinal pol (which is zero in QCD because of Parity) could be another important tool for resolving the issue (Ko et al, Godbole et al, Degrande et al, etc)

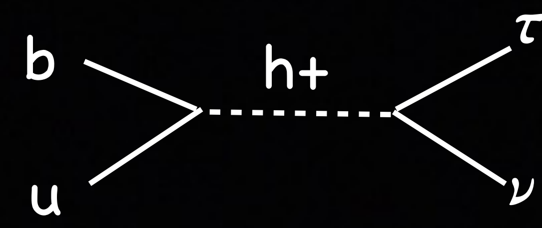
$B \to D^{(*)}\tau\nu$ and $B \to \tau\nu$ in chiral $U(1)'$ models with flavored multi Higgs doublets

Ko, Omura, Yu, arXiv:1212.4607, JHEP(2013)

(b,u) coupling

B→τν





the average

$$BR(B \to \tau\nu) = (1.67 \pm 0.3) \times 10^{-4}$$ HFAG, 1010.1589

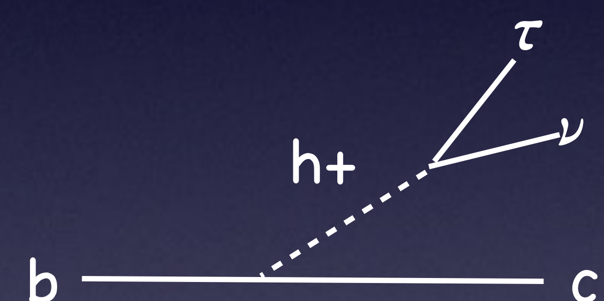
New Belle result

$$BR(B \to \tau\nu) = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$$ Belle, 1208.4678

(b,c) coupling

B→D(*)τν

$$R(D^{(*)}) = \frac{B(\overline{B} \to D^{(*)}\tau^- \overline{\nu}_\tau)}{B(\overline{B} \to D^{(*)} l^- \overline{\nu}_l)}$$



	$R(D)$	$R(D^*)$	
BaBar	0.440 ± 0.071	0.332 ± 0.029	BaBar, 1205.5442
	↕ 2.0σ	↕ 2.7σ	
SM	0.297 ± 0.017	0.252 ± 0.003	Fajfer, Kamenik, Nisandzic, Mescia
	$0.316 \pm 0.012 \pm 0.007$ (2+1 flavor lattice QCD, by Fermilab Lattice and MILC)		

combined 3.4σ

Question:

Is the enhancement of A_{FB} compatible with the (semi)leptonic B decays in our models?

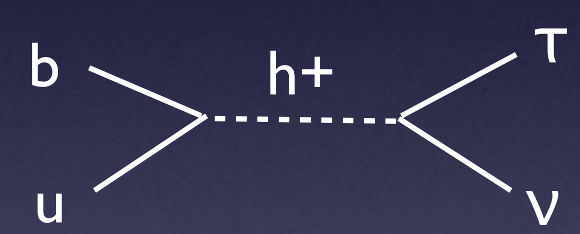
Our scenario for A_{FB} favors large new physics contribution

$m_a \sim 200\mathrm{GeV} \;\; |Y^{au}_{tu}| \sim 1.$ $\xrightarrow[Y^{u-}_{bu} \sim \sqrt{2}(V_{CKM})^*_{tb} Y^{au}_{tu}.]{}$ O(1) (b,u) and ~200 GeV charged Higgs

predict very large new physics contribution in B physics

can be compatible with

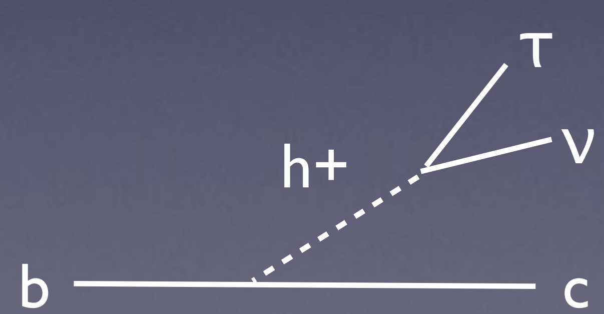
B→τν?



consistent with the SM.

requires small new physics contribution.

B→D(*)τν?



not consistent with the SM.

requires large new physics contribution.

Our scenario for AFB favors large new physics contribution

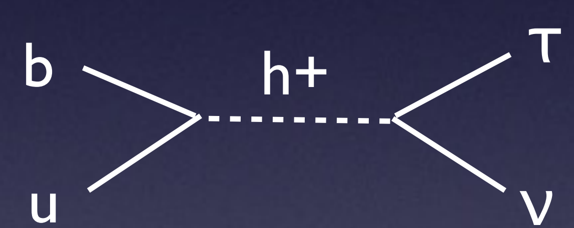
$m_a \sim 200\mathrm{GeV}$ $|Y^{au}_{tu}| \sim 1.$ $\longrightarrow$ O(1) (b,u) and ~200 GeV charged Higgs

$Y^{u-}_{bu} \sim \sqrt{2}(V_{CKM})^*_{tb} Y^{au}_{tu}.$

predict very large new physics contribution in B physics

can be compatible with

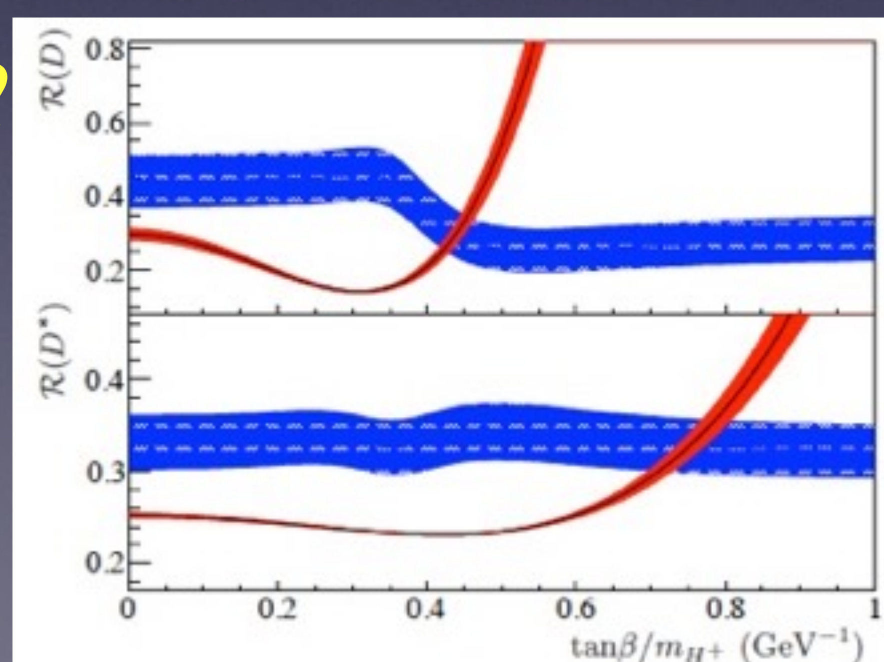
$B \to \tau\nu$?



consistent with the SM.

requires small new physics contribution.

$B \to D(*)\tau\nu$?



not consistent with the SM.

requires large new physics contribution.

Type-II 2HDM cannot explain.

BaBar, 1205.5442; Crivellin, Greub, Kokulu, 1206.2634; Fajfer, Kamenik, Nisandzic, Zupan, 1206.1872; M.Tanaka, R.Watanabe, 1212.1878

Flavor-dependent U(1)′ model

- Yukawa coupling in the mass base (2HDM)

- lightest Higgs h:

$$V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}h + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}h + Y^e_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}h + h.c.,$$

$$Y^u_{ij} = \frac{m^u_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta)\cos\alpha_\Phi,$$

$$Y^d_{ij} = \frac{m^d_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij},$$

$$Y^e_{ij} = \frac{m^l_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij},$$

- lightest charged Higgs h⁺:

$$V_{h^\pm} = -Y^{u-}_{ij}\overline{\hat{D}_{Li}}\hat{U}_{Rj}h^- + Y^{d+}_{ij}\overline{\hat{U}_{Li}}\hat{D}_{Rj}h^+ + h.c.,$$

$$Y^{u-}_{ij} = \sum_l (V_{\rm CKM})^*_{li}\left\{\frac{\sqrt{2}m^u_l\tan\beta}{v}\delta_{lj} - \frac{2\sqrt{2}m^u_l}{v\sin 2\beta}(g^u_R)_{lj}\right\},$$

$$Y^{d+}_{ij} = (V_{\rm CKM})_{ij}\frac{\sqrt{2}m^d_j\tan\beta}{v},$$

- lightest pseudoscalar Higgs a:

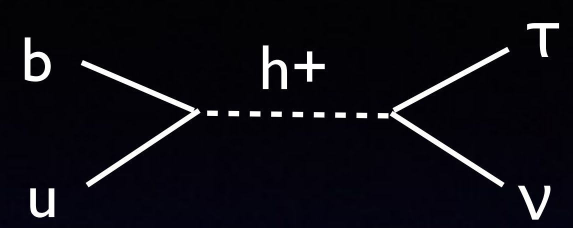
$$V_a = -iY^{au}_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}a + iY^{ad}_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}a + iY^{ae}_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}a + h.c.,$$

$$Y^{au}_{ij} = \frac{m^u_i\tan\beta}{v}\delta_{ij} - \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij},$$

$$Y^{ad}_{ij} = \frac{m^d_i\tan\beta}{v}\delta_{ij},$$

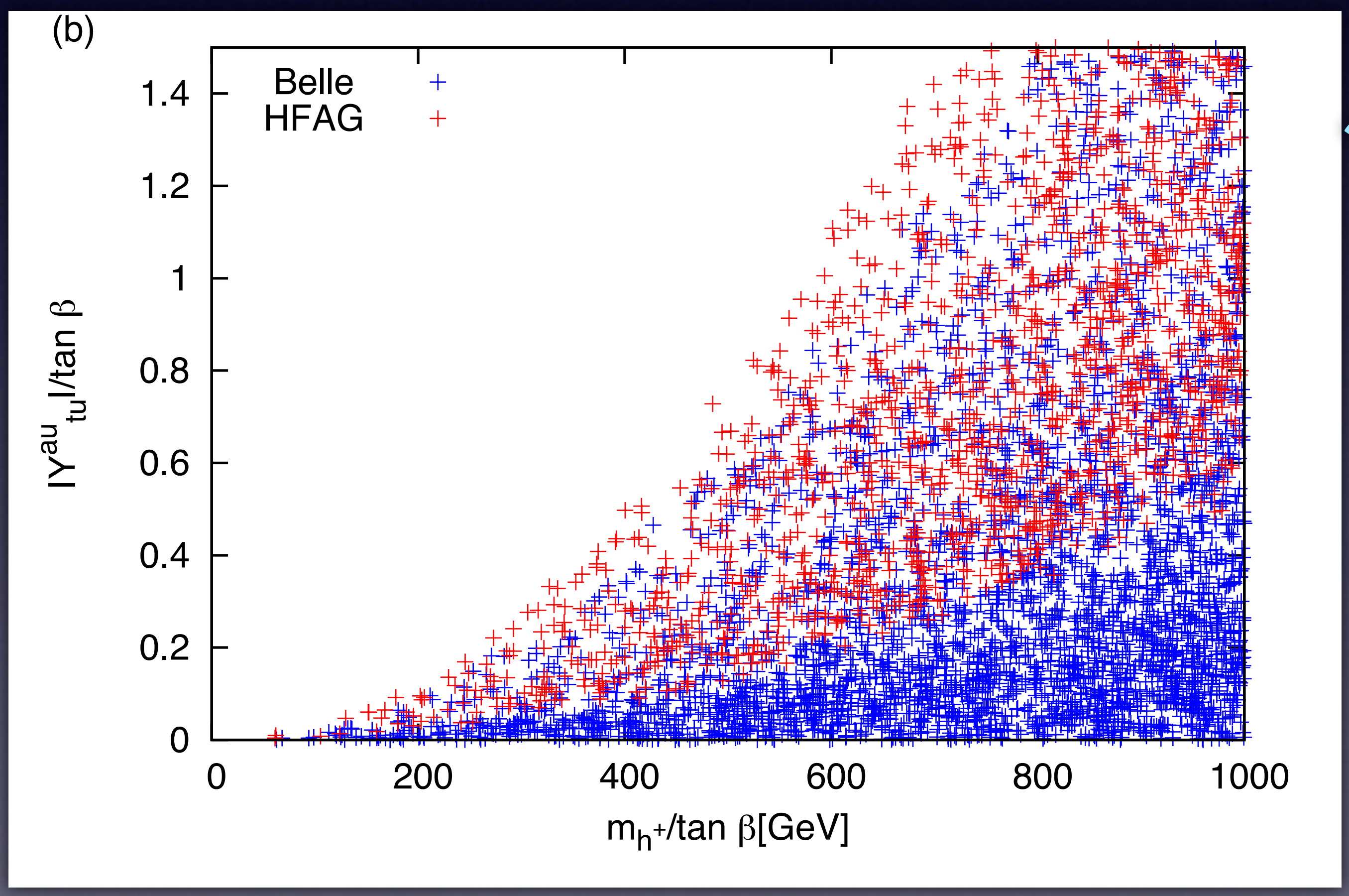
$$Y^{ae}_{ij} = \frac{m^l_i\tan\beta}{v}\delta_{ij}.$$

Constraint on B→τν decay in our 2HDM



$$-Y_{bu}^{-u} h^- \overline{b_L} u_R + Y_{ub}^{+d} h^+ \overline{u_L} b_R$$

In our 2HDM



coupling relation

$$Y_{bu}^{u-} \sim \sqrt{2}(V_{CKM})^*_{tb} Y_{tu}^{au}.$$

$$Y_{ub}^{d+} = \sqrt{2}(V_{CKM})_{ub} \frac{m_b \tan\beta}{v}$$

mass relation

$$m_{h+}^2 = m_a^2 - \widetilde{\lambda}_{12} \frac{v^2}{2}$$

where $V(H) = \cdots + \widetilde{\lambda}_{12}(H_1^\dagger H_2)(H_2^\dagger H_1).$

mass difference at most weak scale

$O(100) \lesssim m_{h+}/\tan\beta \longrightarrow$ can be $|Y_{tu}^{au}| \sim 1.$

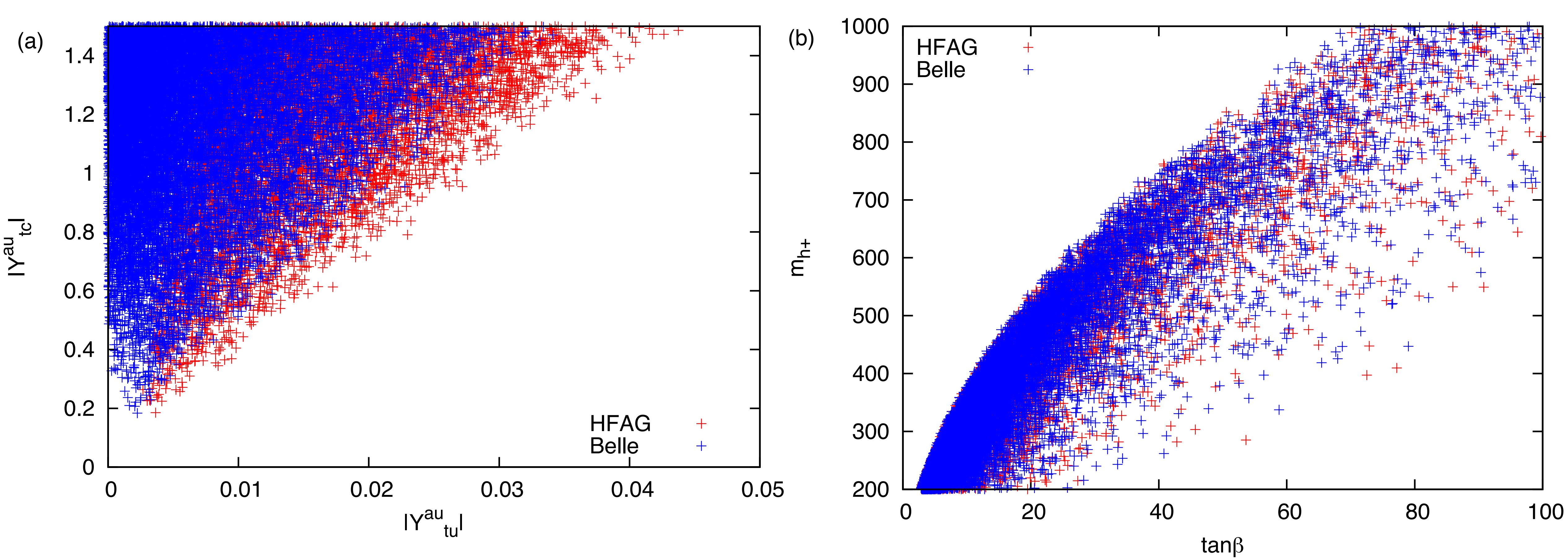
(pseudo scalar may be heavy.)

Constraints from B→D(*)τν and B→τν in 2HDM

parameter region within 1 σ of B->D(*)τν at BaBar and B->τν.

Ytc vs Ytu of pseudo scalar

mH+ vs tan β



The BaBar discrepancies require large charged Higgs contribution,

$$0.2 \lesssim |Y^{au}_{tc}|, \quad m_{h+}/\tan\beta \lesssim O(10).$$

→ B->τν requires small (t,u) coupling, $|Y^{au}_{tu}| \lesssim 0.03.$ cannot achieve enhancement AFB.

If the deviation is relaxed, (t,u) can be large.
(pseudo scalar should be heavy for B->τν in 2HDM.)

- To enhance A_{FB} and be consistent with the semi-leptonic and leptonic B decays, 3HDM is favored.

difference between 2HDM and 3HDM.

$$\begin{array}{ccc} U_R^1 & U_R^2 & U_R^3 \\ \hline 0 & 0 & q \end{array} \quad \Rightarrow \quad \begin{array}{ccc} U_R^1 & U_R^2 & U_R^3 \\ \hline -q & 0 & q \end{array}$$

2HDM

3HDM

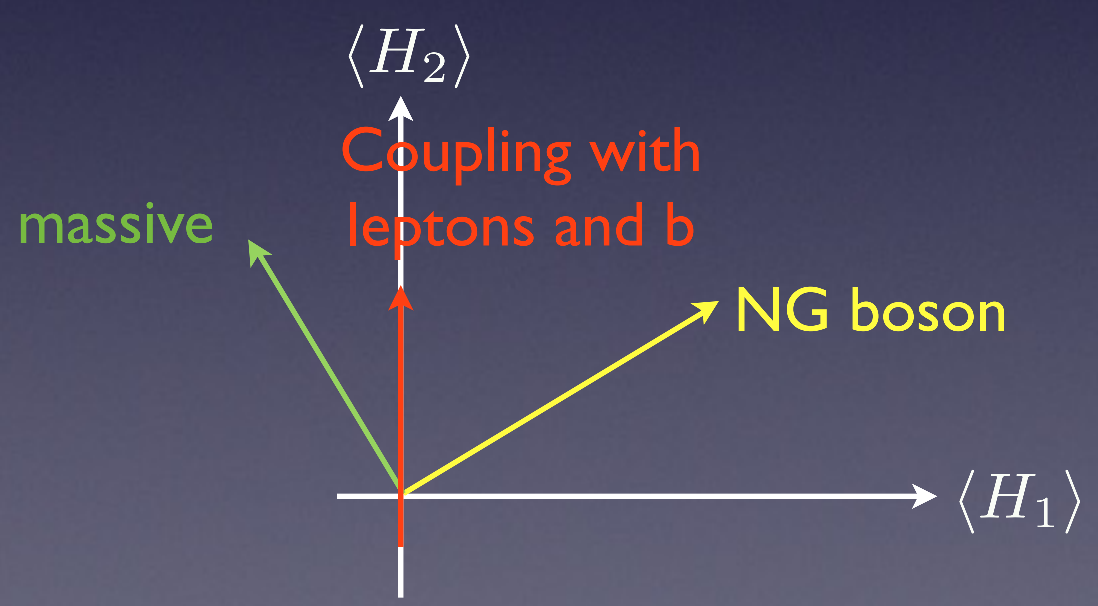
$$y^u_{i1}\overline{Q_{Li}}\widetilde{H_2}U_{R1} + y^u_{i2}\overline{Q_{Li}}\widetilde{H_2}U_{R2} + y^u_{i3}\overline{Q_{Li}}\widetilde{H_1}U_{R3}$$

$$y^d_{ij}\overline{Q_i}H_2 D_{Rj} + y^e_{ij}\overline{Q_i}H_2 E_{Rj}$$

$$y^u_{i1}\overline{Q_i}\widetilde{H_1}U_{R1} + y^u_{i2}\overline{Q_i}\widetilde{H_2}U_{R2} + y^u_{i3}\overline{Q_i}\widetilde{H_3}U_{R3}$$

$$y^d_{ij}\overline{Q_i}H_2 D_{Rj} + y^e_{ij}\overline{Q_i}H_2 E_{Rj}$$

pseudoscalar and charged Higgs directions in 2HDM



- To enhance AFB and be consistent with the semi-leptonic and leptonic B decays, 3HDM is favored.

difference between 2HDM and 3HDM.

$$\begin{array}{ccc} U_R^1 & U_R^2 & U_R^3 \\ \hline 0 & 0 & q \end{array} \quad \Rightarrow \quad \begin{array}{ccc} U_R^1 & U_R^2 & U_R^3 \\ \hline -q & 0 & q \end{array}$$

2HDM

$$y_{i1}^u \overline{Q_{Li}} \widetilde{H_2} U_{R1} + y_{i2}^u \overline{Q_{Li}} \widetilde{H_2} U_{R2} + y_{i3}^u \overline{Q_{Li}} \widetilde{H_1} U_{R3}$$

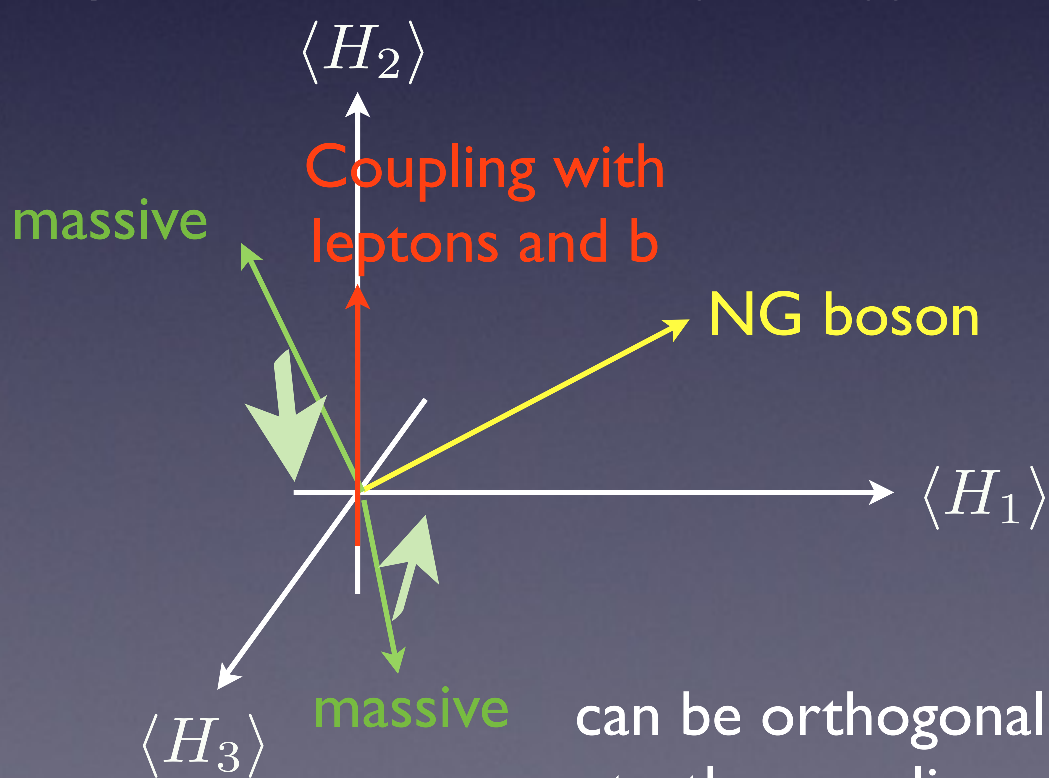
$$y_{ij}^d \overline{Q_i} H_2 D_{Rj} + y_{ij}^e \overline{Q_i} H_2 E_{Rj}$$

3HDM

$$y_{i1}^u \overline{Q_i} \widetilde{H_1} U_{R1} + y_{i2}^u \overline{Q_i} \widetilde{H_2} U_{R2} + y_{i3}^u \overline{Q_i} \widetilde{H_3} U_{R3}$$

$$y_{ij}^d \overline{Q_i} H_2 D_{Rj} + y_{ij}^e \overline{Q_i} H_2 E_{Rj}$$

pseudoscalars and charged Higgs directions in 3HDM



can be orthogonal to the coupling.

One of the charged Higgs (pseudoscalar) can decouple with leptons and do not contribute to (semi)leptonic B decay

→ The limit corresponds to the fine-tuning in Higgs potential

$$m_{12}^2 \tan\gamma = m_{23}^2 \cos\gamma \qquad \widetilde{\lambda}_{12} = \widetilde{\lambda}_{23}$$

where $\langle H_3 \rangle / \langle H_1 \rangle = \tan\gamma$ and

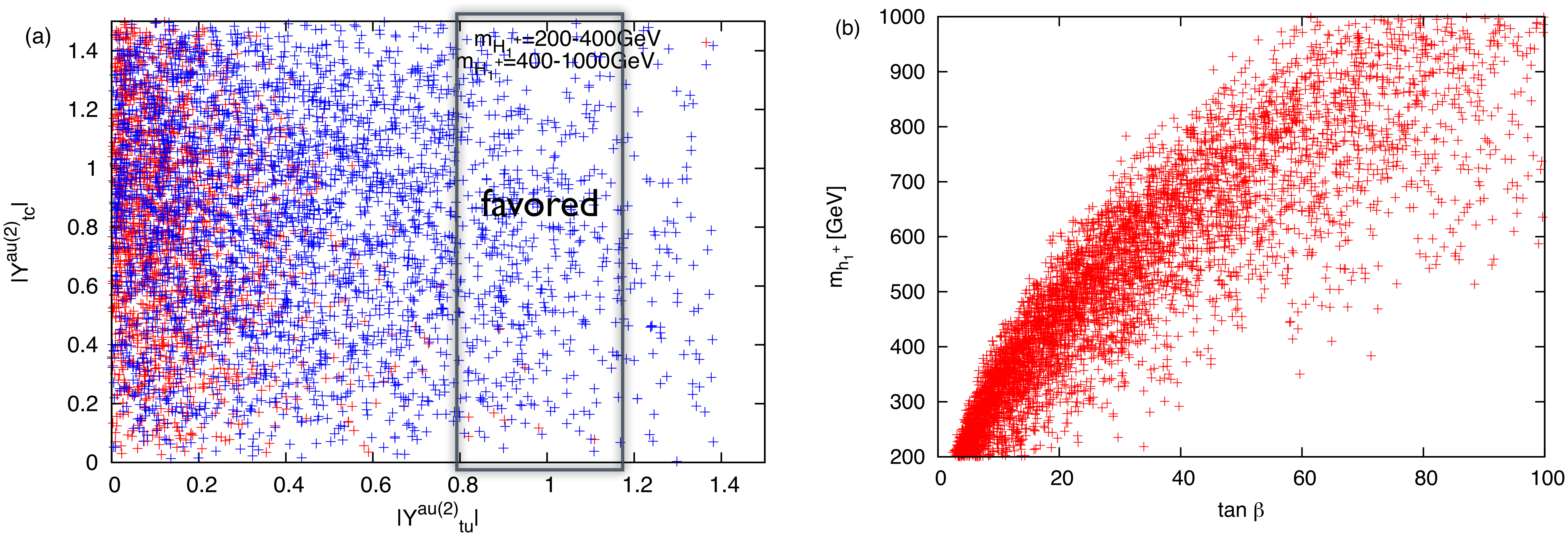
$$V(H) = \ldots m_{ij}^2 H_i^\dagger H_j + \widetilde{\lambda}_{ij} (H_i^\dagger H_j)(H_j^\dagger H_i).$$

- **Concrete analysis for other cases in 3HDM** P.Ko, Y.O, C.Yu, 1212.4607

parameter spaces are large, so we could expect some allowed region without the fine-tuning

but not so large, because of the bound from $D_0 - \overline{D_0}$ mixing.

ex) degenerate case $m_{h_1^+} = m_{h_2^+}$



$+ \; \ldots \; 200\text{GeV} \leq m_{h_1^+} \leq 400\text{GeV}$

$+ \; \ldots \; 400\text{GeV} \leq m_{h_1^+} \leq 1000\text{GeV}$

Other Constraints

The bound on $B \to X_s\gamma$ at leading order (LO) up to $O((100\ \text{GeV}/m_{h^+})^2)$ is given by

$$-0.20 \lesssim \left\{ -\left(46.26 + 46.83 \ln \left(\frac{100\ \text{GeV}}{m_{h^+}} \right) \right) Y_{tt}^{au} \tan\beta + 9.00 (Y_{tt}^{au})^2 \right\} \left(\frac{100\ \text{GeV}}{m_{h^+}} \right)^2 \lesssim 0.79, \tag{29}$$

where two relations $Y_{bt}^{-u} = \sqrt{2} V_{tb} Y_{tt}^{au}$ and $Y_{tb}^{+d} = \sqrt{2} V_{tb} Y_{bb}^{ad} = m_b \tan\beta / v$ are used [29]. If we assume $\tan\beta = 1$ and $m_{h^+} = 300$ GeV, then we obtain a constraint $-0.077 \lesssim Y_{tt}^{au} \lesssim 0.262$. Therefore we can expect that $(g_R^u)_{tt}$ can be $O(1)$ without conflict with the $B \to X_s\gamma$ constraint.

4. Summary

- I introduced 2HDM and 3HDM, where gauged U(1) controls the FCNC.
- There are tree-level FCNCs:especially (t,q) in neutral and (b,q) in charged Higgs are large because of top mass.
- Large (t,u) enhance AFB and can be consistent with LHC results according to destructive interference between CP-even scalar and CP-odd scalar. One good point is CP-even (-odd) mass ~200GeV and the Yukawa coupling ~1.
- We discussed whether the enhancement of AFB is compatible with the (semi)leptonic B decay at the BaBar and Belle experiments.
- AFB and B->D(*)τν requires large new physics effects, but B->τν requires the small effect. It is difficult to achieve all.
- Requirement of 2HDM to achieve B->D(*)τν at BaBar and B->τν:

$$|Y_{tu}^{au}| \lesssim 0.03. \quad 0.2 \lesssim |Y_{tc}^{au}|, \quad m_{h+}/\tan\beta \lesssim O(10).$$ →difficult to enhance AFB.

- In 3HDM, we can describe the scenario that one of charged Higgs decouples with the (semi)leptonic B decays. It is possible to achieve AFB, the BaBar discrepancies, and B->τν.

Thank you

General Remarks

- Model independent study or simplified models are useful only if the stuffs put away under the rug (such as gauge invariance, renormalizability, unitarity, anomaly cancellation, realistic Yukawa's, etc.) do not affect the physical observables we study

- Very often you don't know a priori if this assumption is true or not

- When some simple model can explain some phenomena, it is important to work out various UV completions and study the detailed phenomenology

- More examples in DM physics (papers by Baek, Ko, Park, etc.)