The top FB asymmetry and Charge asymmetry in Chiral U(1) flavor models

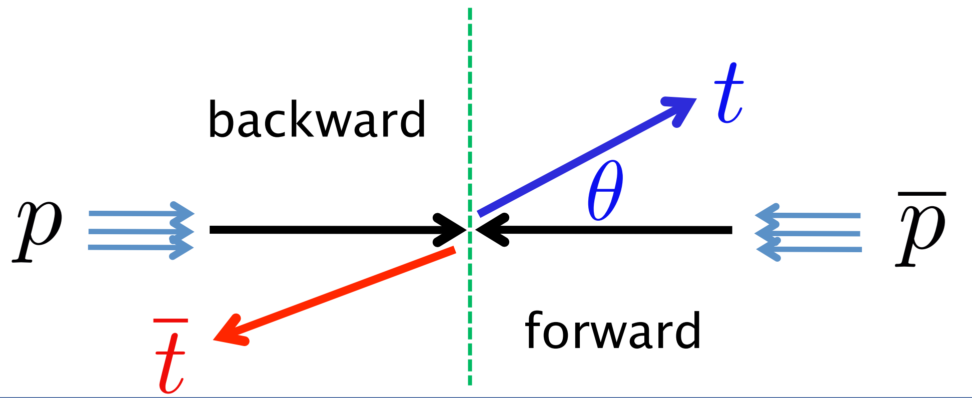
Yuji Omura (KIAS, Korea)

Based on arXiv:1108.0350, 1108.4005, 1205.0407
with P. Ko and Chaehyun Yu (KIAS)

1. Introduction

Motivation

Top forward asymmetry(A_{FB}) at Tevatron



$$A_{FB} = \frac{N(t;\cos\theta > 0) - N(t;\cos\theta < 0)}{N(t;\cos\theta > 0) + N(t;\cos\theta < 0)}$$

$$A^t_{\rm FB} = \begin{cases} 0.158 \pm 0.074 & (\text{CDF, lepton+jets channel}) \\ 0.42 \pm 0.158 & (\text{CDF, dilepton channel}) \\ 0.19 \pm 0.065 & (\text{D0, lepton+jets channel}) \end{cases}$$

$$A^t_{\rm FB} = 0.162 \pm 0.047 \ @\ 8.7 fb^{-1} \ (\text{CDF, lepton + jets})$$

SM prediction

$$A^t_{\rm FB} = 0.072^{+0.011}_{-0.007} \ (\text{NLO + NNLL})$$

Ahrens, Ferroglia, Neubert, Peciak, Yang, PRD84 (2011).

$$A^t_{\rm FB} = 0.087 \pm 0.010 \ (\text{NLO + EW correction})$$

Hollik, Pagani, PRD84(2011); Kuhn, Rodrigo, JHEP1201.

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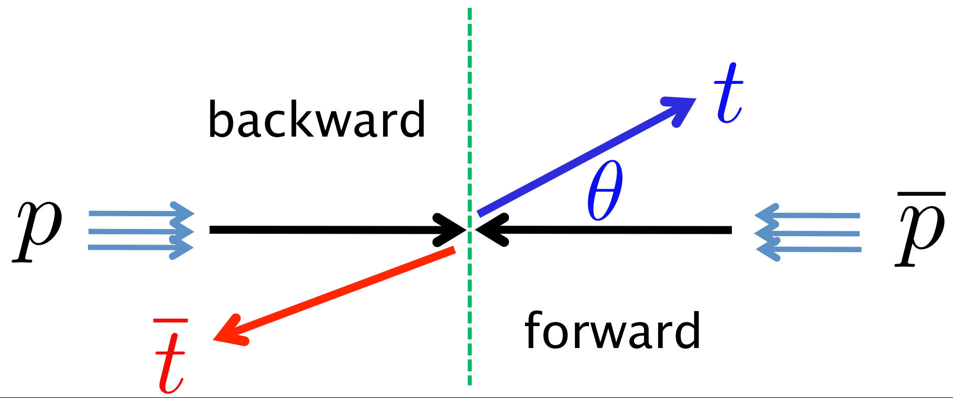

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SM prediction ↕ **New particle?**

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Candidates for A_{FB}

- colored spin-1 (axigluon, Kaluza-Klein gluon, etc.) exchange in the s-channel
- color triplet or sextet in the u-channel
- light Z' exchange or W' in the t-channel
- color-singlet scalar exchange in the t-channel

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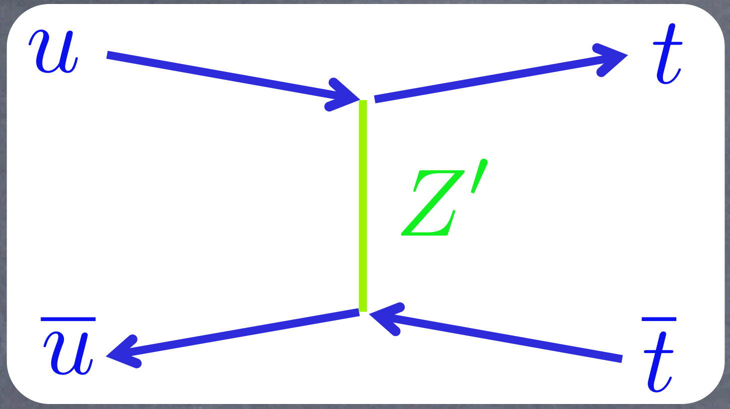
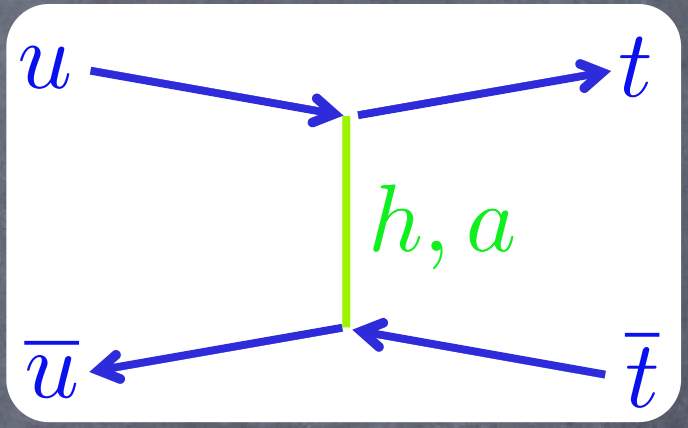
Our models

Our models

- Flavor-dependent U(1) charge assignment for the t-channel



- Extra Higgs doublets required for realistic fermion mass matrices



- Gauge + Yukawa relax the experimental bound from the same sign top

- Anomaly free, adding extra chiral fermion

→CDM candidates

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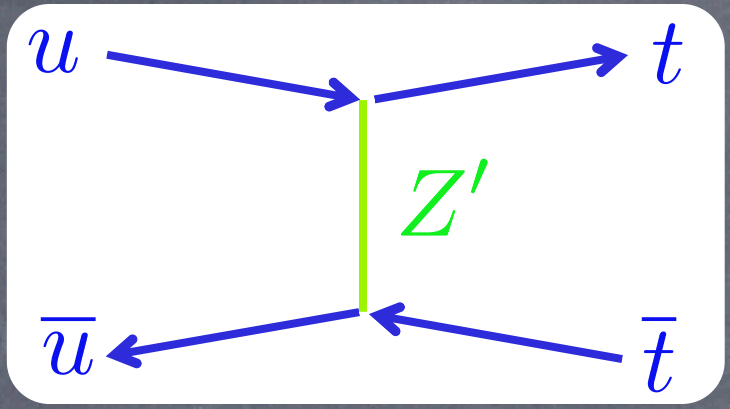

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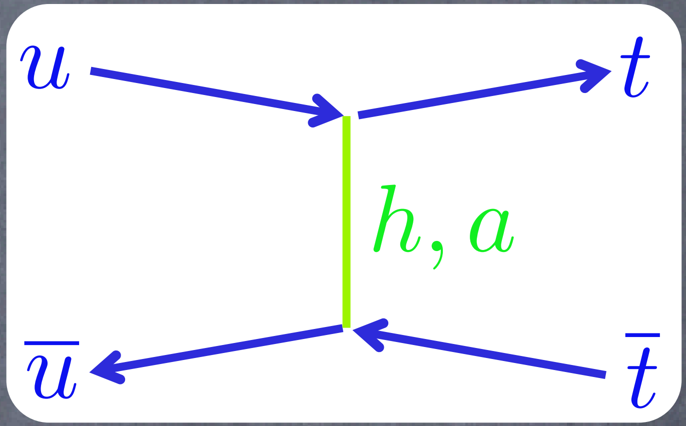


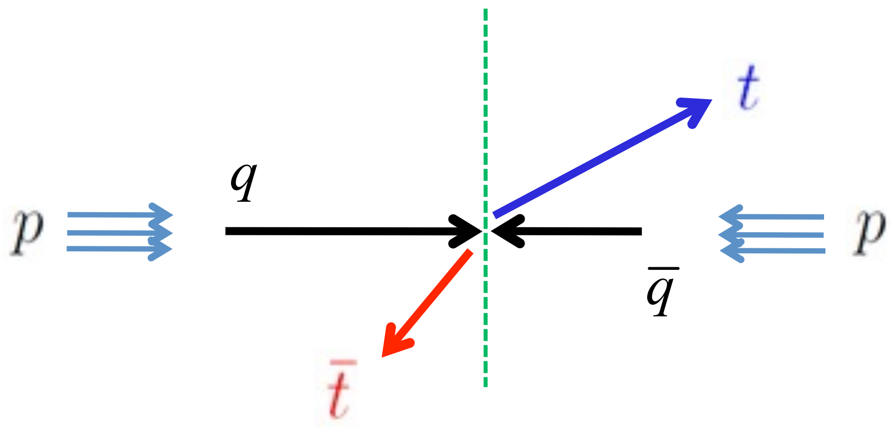
- Gauge + Yukawa relax the experimental bound from the same sign top

- Anomaly free, adding extra chiral fermion

  → CDM candidates

<u>Charge asymmetry at LHC!</u>

Charge asymmetry (A_C) at LHC



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

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

$$A_C^y = \begin{cases} -0.018 \pm 0.028 \pm 0.023 & \text{(ATLAS)} \\ 0.004 \pm 0.010 \pm 0.012 & \text{(CMS)} \end{cases}$$

ATLAS, 1203.4211

CMS-PAS-TOP-11-030

SM prediction

$$A_C^y = 0.01 \ \text{(NLO)}$$

Antunano, Kuhn, Rodrigo, 0709.1652

Contents

- Introduction
- Our U(1) flavor models
- Phenomenology
  - Top forward-backward asymmetry (AFB)
  - Charge asymmetry at LHC
- Other topics
- Summary

2. Chiral U(1) flavor models

- construct explicit models for A_{FB}
- SM gauge symmetries × U(1)′ models
- U(1)′ charges are flavor-dependent and assigned to only quarks, which can avoid LEP bound, Drell-Yang, etc.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_i	3	2	1/6	q_{Li}
D_{Ri}	3	1	$-1/3$	d_i
U_{Ri}	3	1	2/3	u_i
L_i	1	2	$-1/2$	0
E_{Ri}	1	1	-1	0

gauge couplings in the mass base

Interaction base: $$g' Z'_\mu \Big[\ q_i \overline{U^i_L}\gamma^\mu U^i_L + q_i \overline{D^i_L}\gamma^\mu D^i_L + u_i \overline{U^i_R}\gamma^\mu U^i_R + d_i \overline{D^i_R}\gamma^\mu D^i_R \Big]$$

mass base: $$g' Z'^\mu \Big[(g^u_L)_{ij}\overline{\hat{U}^i_L}\gamma_\mu \hat{U}^j_L + (g^d_L)_{ij}\overline{\hat{D}^i_L}\gamma_\mu \hat{D}^j_L + (g^u_R)_{ij}\overline{\hat{U}^i_R}\gamma_\mu \hat{U}^j_R + (g^d_R)_{ij}\overline{\hat{D}^i_R}\gamma_\mu \hat{D}^j_R\Big] .$$

tree-level contributions to FCNC

gauge couplings in the mass base

Interaction base: $$g' Z'_\mu \left[q_i \overline{U^i_L} \gamma^\mu U^i_L + q_i \overline{D^i_L} \gamma^\mu D^i_L + u_i \overline{U^i_R} \gamma^\mu U^i_R + d_i \overline{D^i_R} \gamma^\mu D^i_R \right]$$

mass base: $$g' Z'^\mu \left[(g^u_L)_{ij} \overline{\hat{U}^i_L} \gamma_\mu \hat{U}^j_L + (g^d_L)_{ij} \overline{\hat{D}^i_L} \gamma_\mu \hat{D}^j_L + (g^u_R)_{ij} \overline{\hat{U}^i_R} \gamma_\mu \hat{U}^j_R + (g^d_R)_{ij} \overline{\hat{D}^i_R} \gamma_\mu \hat{D}^j_R \right].$$

tree-level contributions to FCNC

(g^u_L)	(g^d_L)	(g^u_R)	(g^d_R)
$D^0 - \overline{D^0}$	$K^0 - \overline{K^0}$	$D^0 - \overline{D^0}$	$K^0 - \overline{K^0}$
$A_{\rm FB}$	$B^0 - \overline{B^0}$	$A_{\rm FB}$	$B^0 - \overline{B^0}$
	$B_s - \overline{B_s}$		$B_s - \overline{B_s}$

CKM matrix requires sizable mixing
(1,2) element ~0.22*(qL1-qL2)

ex) $K_0 - \overline{K_0}$ mixing

$$10^{-6} \gtrsim |g'_{12}|^2 \left(\frac{1TeV}{M_{Z'}} \right)^2$$

By Blum, Grossman, Nir, Perez

gauge couplings in the mass base

Interaction base: $$g' Z'_\mu \left[q_i \overline{U^i_L} \gamma^\mu U^i_L + q_i \overline{D^i_L} \gamma^\mu D^i_L + u_i \overline{U^i_R} \gamma^\mu U^i_R + d_i \overline{D^i_R} \gamma^\mu D^i_R \right]$$

mass base: $$g' Z'^\mu \left[(g^u_L)_{ij} \overline{\hat{U}^i_L} \gamma_\mu \hat{U}^j_L + (g^d_L)_{ij} \overline{\hat{D}^i_L} \gamma_\mu \hat{D}^j_L + (g^u_R)_{ij} \overline{\hat{U}^i_R} \gamma_\mu \hat{U}^j_R + (g^d_R)_{ij} \overline{\hat{D}^i_R} \gamma_\mu \hat{D}^j_R \right].$$

tree-level contributions to FCNC

$(g^u_L)_{ij}$	$(g^d_L)_{ij}$	$(g^u_R)_{ij}$	$(g^d_R)_{ij}$
$D^0 - \overline{D^0}$	$K^0 - \overline{K^0}$	$D^0 - \overline{D^0}$	$K^0 - \overline{K^0}$
$A_{\rm FB}$	$B^0 - \overline{B^0}$	$A_{\rm FB}$	$B^0 - \overline{B^0}$
	$B_s - \overline{B_s}$		$B_s - \overline{B_s}$

CKM matrix requires sizable mixing
(1,2) element ~0.22*(qL1-qL2)

To avoid the strong constraints from FCNC,
only right-handed up-type quarks are charged.

Examples

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_i	3	2	1/6	0
D_{Ri}	3	1	$-1/3$	0
U_{Ri}	3	1	2/3	u_i

- We can consider many cases.
- (u1,u2,u3)=(0,0,1) (2HDM)
- (u1,u2,u3)=(-1,0,1) (3HDM)
- Right-handed mixing of up quarks must be controlled,

$\hat{D}^i_R = (R^u)_{ij} D^j_R$ $(g^u_R)_{ij} = (R_u)_{ik} u_k (R_u)^\dagger_{kj}$

small (u,c) for D0
large (u,t) for A_{FB}

depend on Yukawa

Yukawa Couplings

- Flavor-dependent chiral U(1) requires extension of Higgs sector for realistic mass matrices and renormalizability.

$$y^u_{ij}\overline{Q_i}\widetilde{H}U_{Rj}$$

U(1)' charge: $0 \ 0 \ u_j$ → U(1)' symmetry forbids the Yukawa couplings

- Add extra Higgs charged under U(1)'.

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- Add extra Higgs charged under U(1)'.
  - (u1,u2,u3)=(0,0,1) → 2 Higgs (2HDM)

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

U(1)' charge: $0\ 0\ 0$ $0\ 0\ 0$ $0\ -1\ 1$

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U(1)' charge: $0\ 0\ 0$ $0\ 0\ 0$ $0\ -1\ 1$

  - (u1,u2,u3)=(-1,0,1) → 3 Higgs (3HDM)

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

U(1)' charge: $0\ 1\ -1$ $0\ 0\ 0$ $0\ -1\ 1$

Yukawa couplings in the mass base

- (u1,u2,u3)=(0,0,1) → 2 Higgs (2HDM)

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

3 neutral scalar
+
1 pseudo-scalar
+
1 charged Higgs pair

$$Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}h - Y^{u-}_{ij}\overline{\hat{D}_{Li}}\hat{U}_{Rj}h^- - iY^{au}_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}a$$

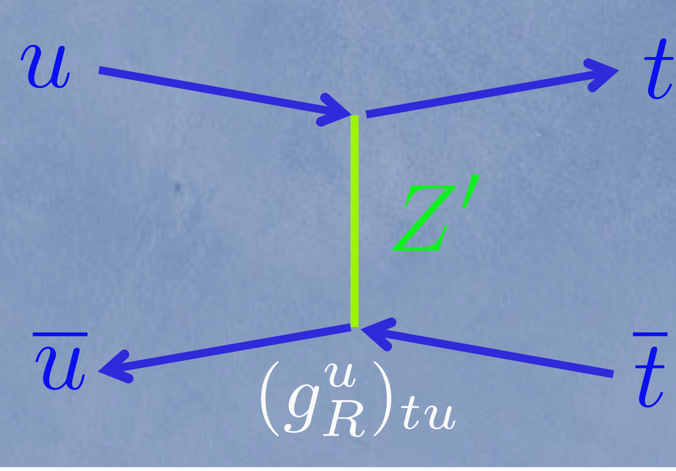
$$Y^u_{ij}: \quad \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta)\cos\alpha_\Phi$$

$$Y^{u-}_{ij}: \quad -\frac{2\sqrt{2}m^u_l}{v\sin 2\beta}(g^u_R)_{lj}$$

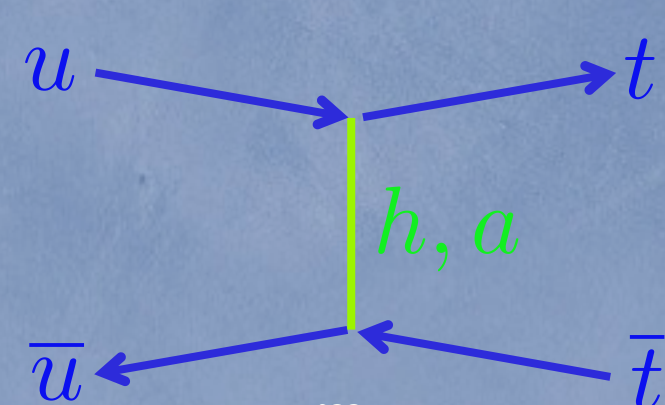
$$Y^{au}_{ij}: \quad -\frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}$$

large (t,u) are possible in the both gauge and Yukawa

$$g'Z'^\mu(g^u_R)_{tu}\overline{t_R}\gamma_\mu u_R$$



$$Y_{tu}h\overline{t_L}u_R$$



$$Y_{tu} \sim \frac{m_t}{v}(g^u_R)_{tu}$$

Yukawa couplings in the mass base

- (u1,u2,u3)=(-1,0,1) → 3 Higgs (3HDM)

4 neutral scalar
+
2 pseudo-scalar
+
2 charged Higgs pair

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

$$Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}h - Y^{u-}_{ij}\overline{\hat{D}_{Li}}\hat{U}_{Rj}h^- - iY^{au}_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}a$$

assumption (gauge coupling)

$$g^u_R = \begin{pmatrix} -\cos 2\theta & 0 & -e^{i(\delta_1-\delta_3)}\sin 2\theta \\ 0 & 0 & 0 \\ -e^{-i(\delta_1-\delta_3)}\sin 2\theta & 0 & \cos 2\theta \end{pmatrix},$$

Large

$$(Y^u_{ij}) = \begin{pmatrix} \frac{m_u}{v}\left(\frac{O^h_{11}\cos^2\theta}{\cos\beta_1\cos\beta_2} + \frac{O^h_{31}\sin^2\theta}{\sin\beta_2}\right) & 0 & \frac{m_u e^{i(\delta_1-\delta_3)}}{2v}\left(\frac{O^h_{11}\sin 2\theta}{\cos\beta_1\cos\beta_2} - \frac{O^h_{31}\sin 2\theta}{\sin\beta_2}\right) \\ 0 & \frac{m_c}{v}\frac{O^h_{21}}{\sin\beta_1\cos\beta_2} & 0 \\ \frac{m_t e^{-i(\delta_1-\delta_3)}}{2v}\left(\frac{O^h_{11}\sin 2\theta}{\cos\beta_1\cos\beta_2} - \frac{O^h_{31}\sin 2\theta}{\sin\beta_2}\right) & 0 & \frac{m_t}{v}\left(\frac{O^h_{11}\sin^2\theta}{\cos\beta_1\cos\beta_2} + \frac{O^h_{31}\cos^2\theta}{\sin\beta_2}\right) \end{pmatrix}$$

Large

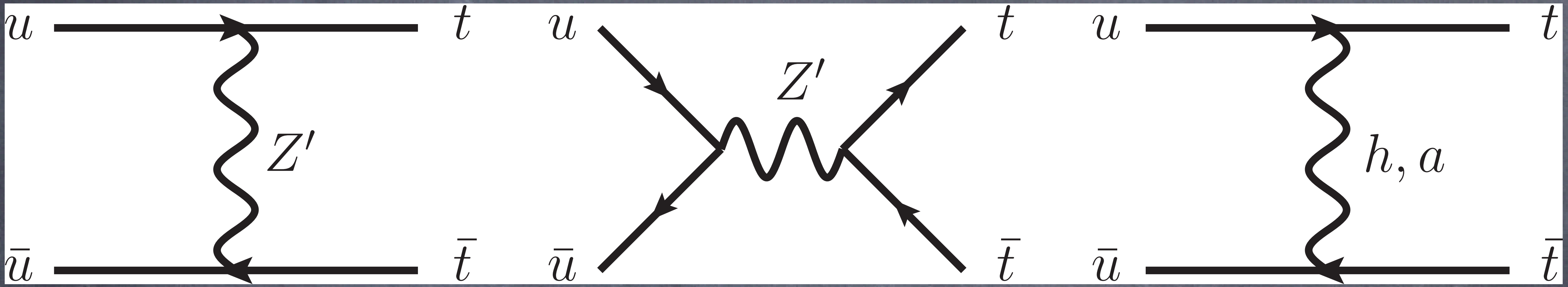
$$\left(\frac{(V_{\rm CKM})_{il}Y^{u-}_{lj}}{\sqrt{2}}\right) = (Y^{au}_{ij}) = \begin{pmatrix} \frac{m_u\tan\beta_2}{v}\left(\cos^2\theta - \frac{\sin^2\theta}{\tan^2\beta_2}\right) & 0 & \frac{m_u\sin 2\theta e^{i(\delta_1-\delta_3)}}{v\sin 2\beta_2} \\ 0 & \frac{m_c\tan\beta_2}{v} & 0 \\ \frac{m_t\sin 2\theta e^{-i(\delta_1-\delta_3)}}{v\sin 2\beta_2} & 0 & \frac{m_t\tan\beta_2}{v}\left(\sin^2\theta - \frac{\cos^2\theta}{\tan^2\beta_2}\right) \end{pmatrix}$$

3. Phenomenology

- A_{FB} in our models:
  - Z'
  - neutral and pseudo scalar
- related constraints from collider:
  - $t\bar{t}$ cross section
  - same-sign top
  - dijet search
  - top decay

$t\bar{t}$ in our models

Z′ exchanging + neutral (pseudo) scalar



mass matrix for up sector

$$\overline{U_{Li}} M^u_{ij} U_{Rj}$$

$$||$$

$$\overline{\hat{U}_{Ln}} \underline{L_{ni} M^u_{ij} R^\dagger_{jk}} \hat{U}_{Rk}$$

$$||$$

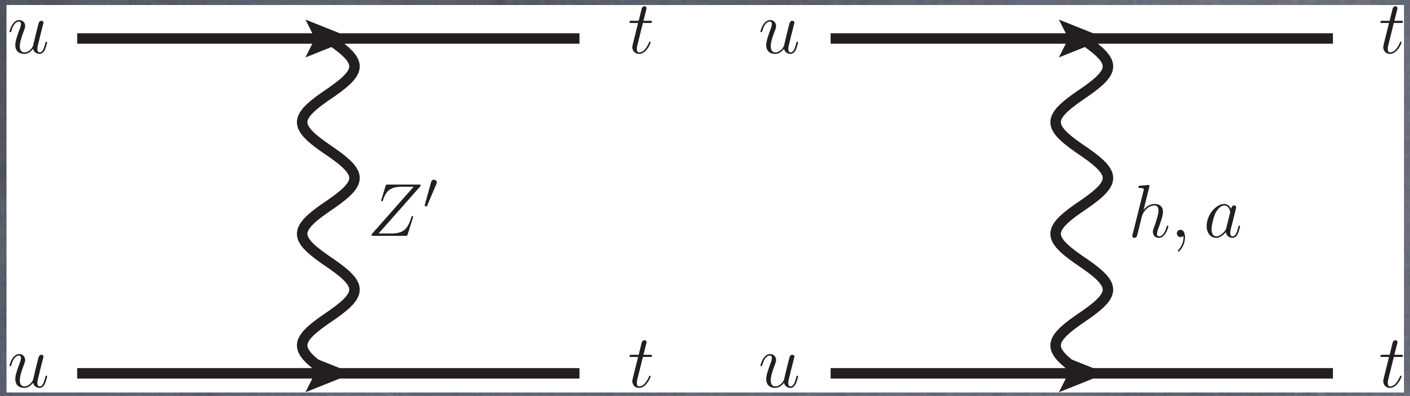
$$m^u_k \delta_{nk}$$

assumption
large (1,3) mixing

Large (t,u) elements in Z′ and (pseudo) scalar.

Small element (d,t) in charged Higgs.

- In our models, same-sign top signal is also predicted



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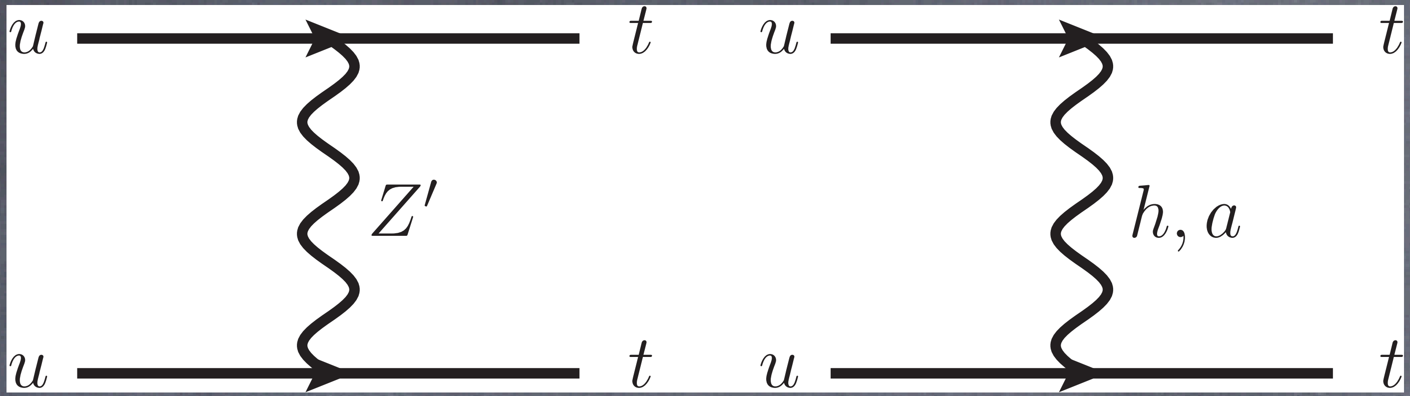
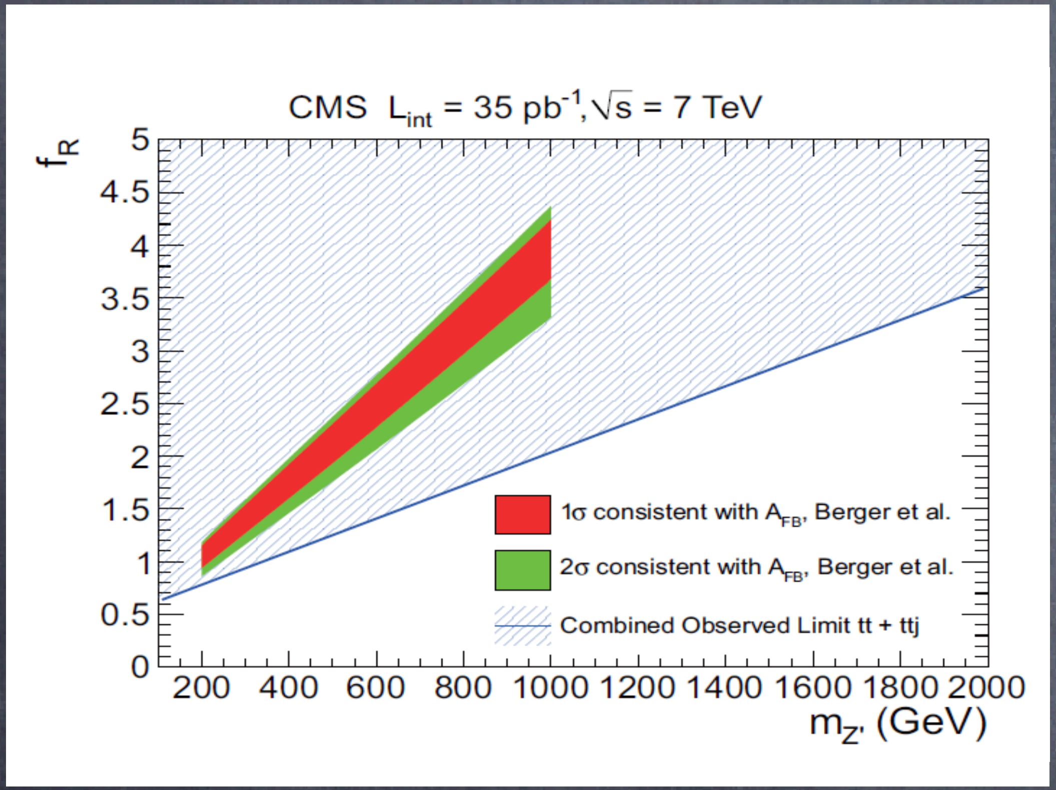
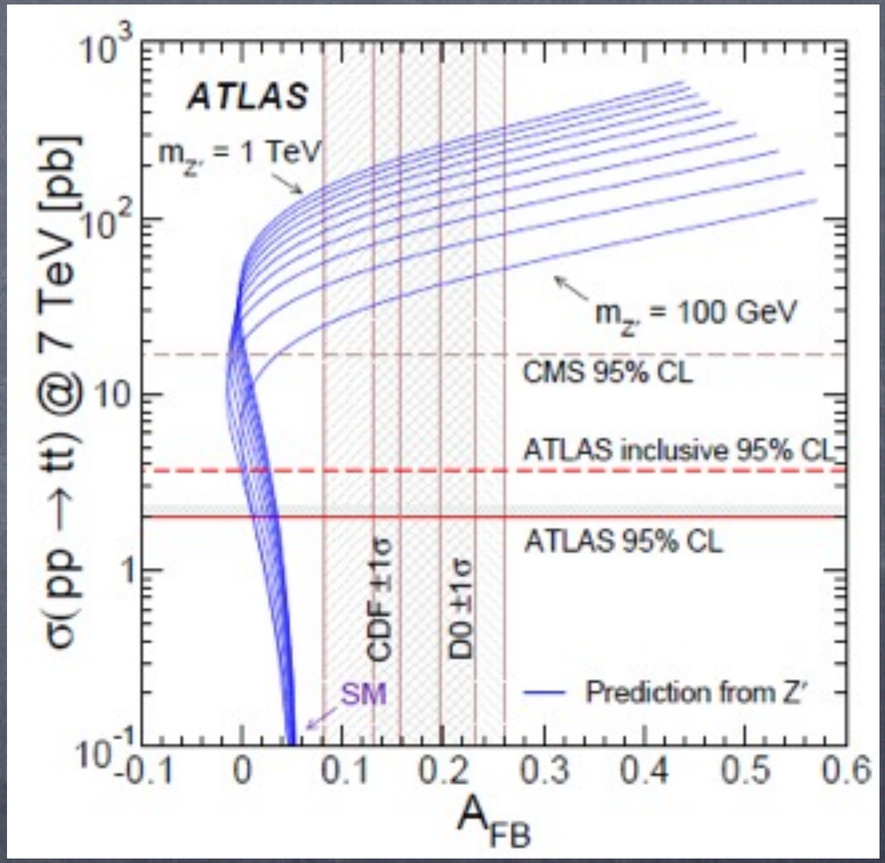


- same-sign top @CMS





The upper bound on the same-sign top

$$\sigma(tt) < 17pb$$

CMS, 1106.2142

$\sigma(tt) < 4pb$ inclusive

$\sigma(tt) < 2pb$ optimized for Z'

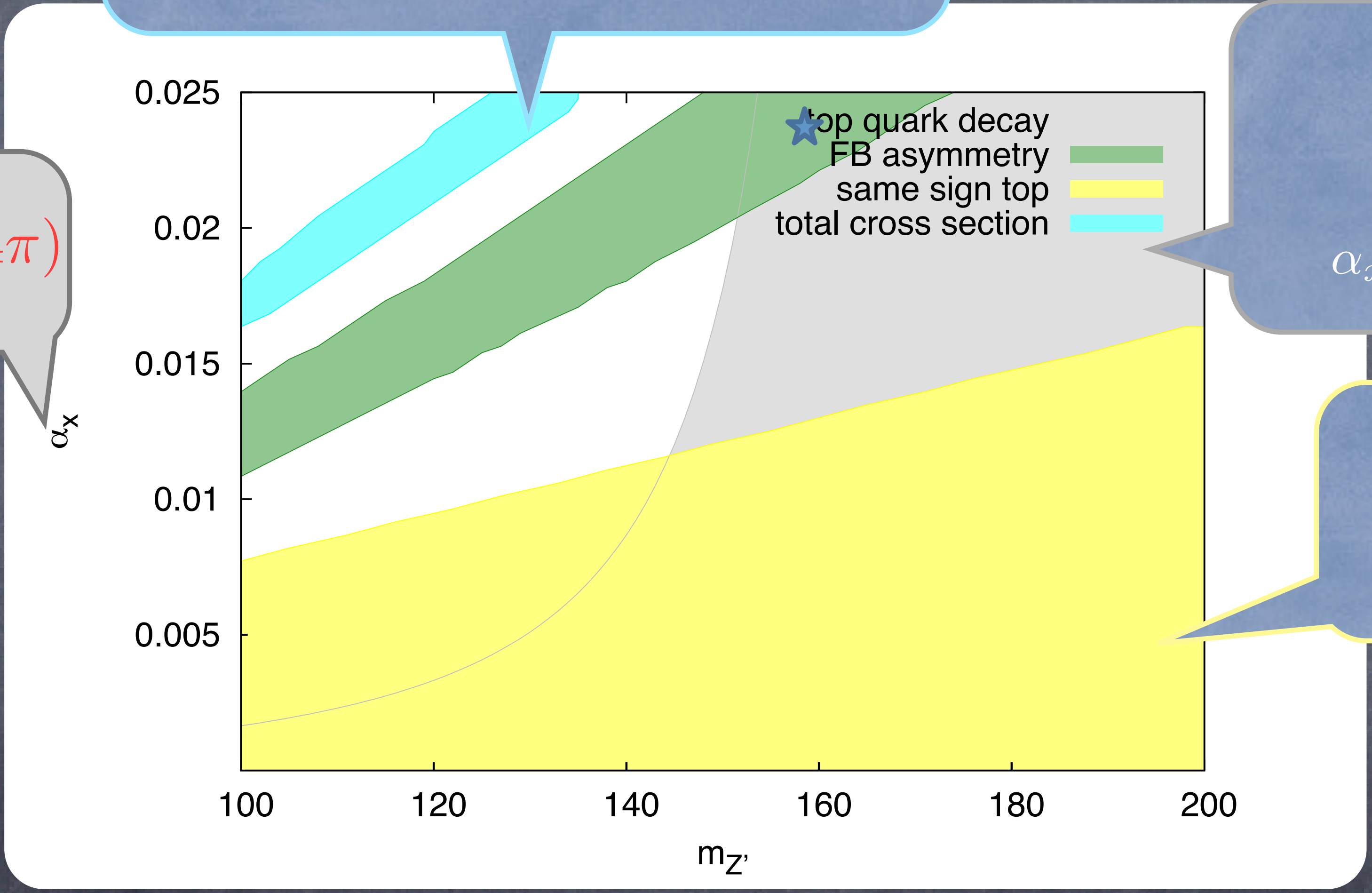
ATLAS, 1202.5520

Only Z′ contribution

- Z′ dominant case ((t,u) gauge coupling vs Z′ mass)

$\sigma(t\bar{t}) = (7.5 \pm 0.48)pb$

$\alpha_x \equiv (g'(g_R^u)_{tu})^2/(4\pi)$



top decay

Br(t →Z′u)<5%

$\alpha_x \lesssim 0.012(M_{Z'} = 145GeV)$

same sign top

$\sigma(tt) < 17pb$

Z′ is light to evade dijet search

★ = Jung, Murayama, Pierce, Wells' model PRD81,015004 (2010)

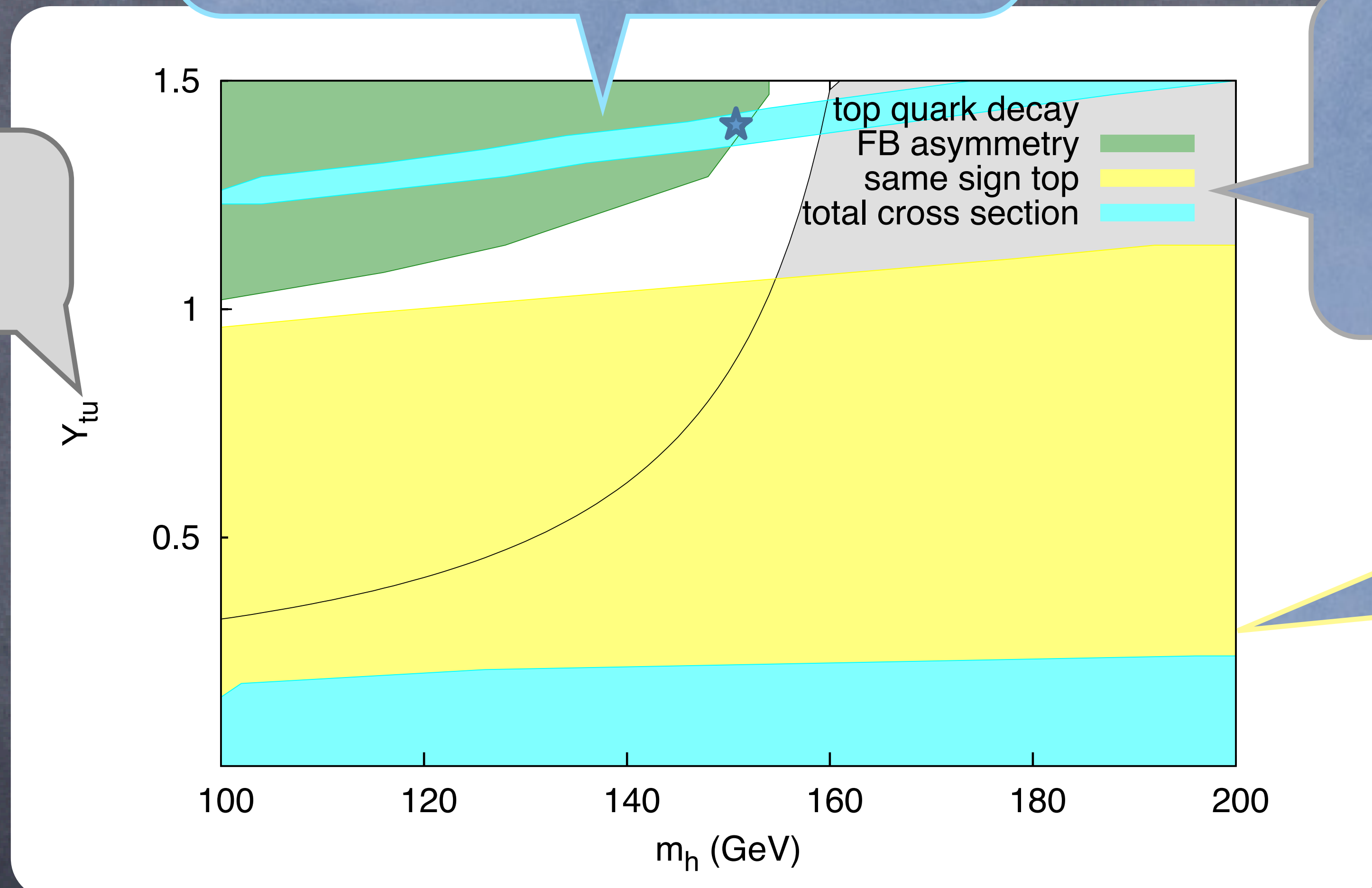
Only Z′ is excluded by the same-sign top!

Only scalar contribution

- lightest scalar (h) dominant case ((t,u) Yukawa vs h mass)

$\sigma(t\bar{t}) = (7.5 \pm 0.48)pb$

(t,u) element of Yukawa



top decay

Br(t →Z′u)<5%

$Y_{tu} \lesssim 0.5(M_h = 125GeV)$

same sign top

$\sigma(tt) < 17pb$

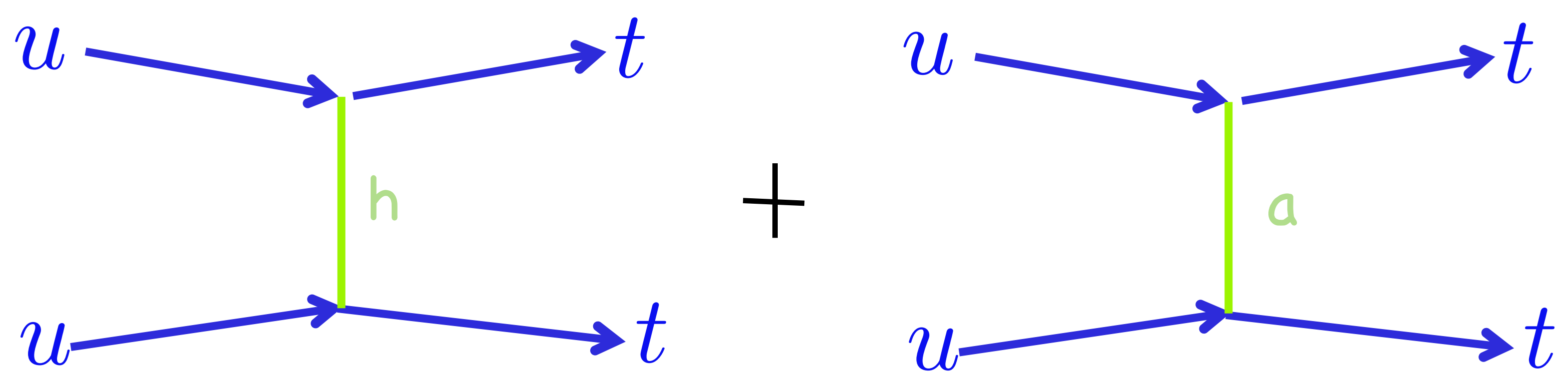
★= Babu, Frank, Rai's model 1104.4782

Only scalar is excluded by the same-sign top!

Scalar + Pseudo scalar

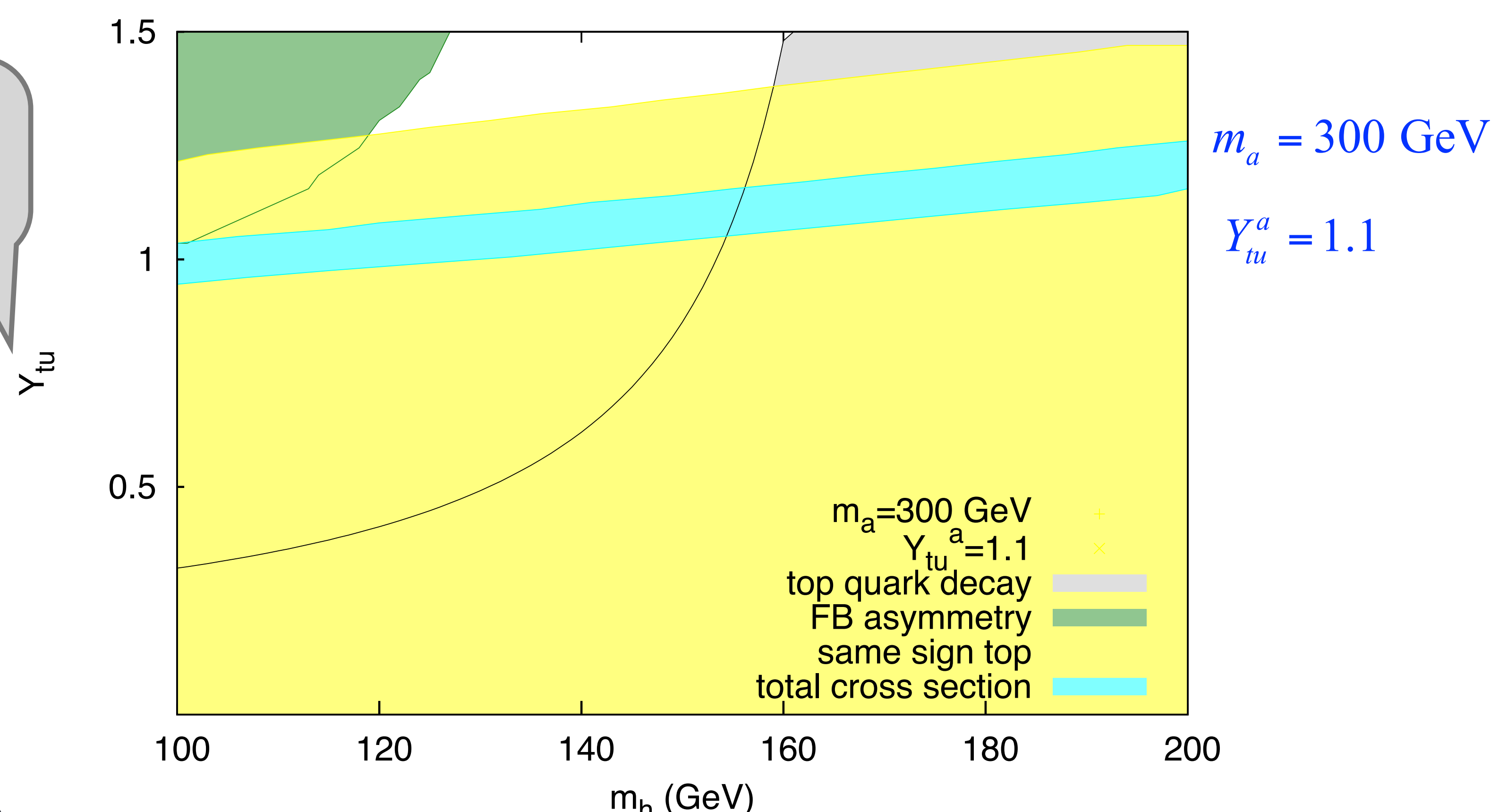
- lightest scalar (h) and pseudo-scalar (a) dominant

The same-sign top could be relaxed by the Interference



$$\text{If} \sim Y_{tu}\overline{t_L}(h+ia)u_R,$$
$$\sigma(uu \to tt) \to 0$$

(t,u) element of Yukawa

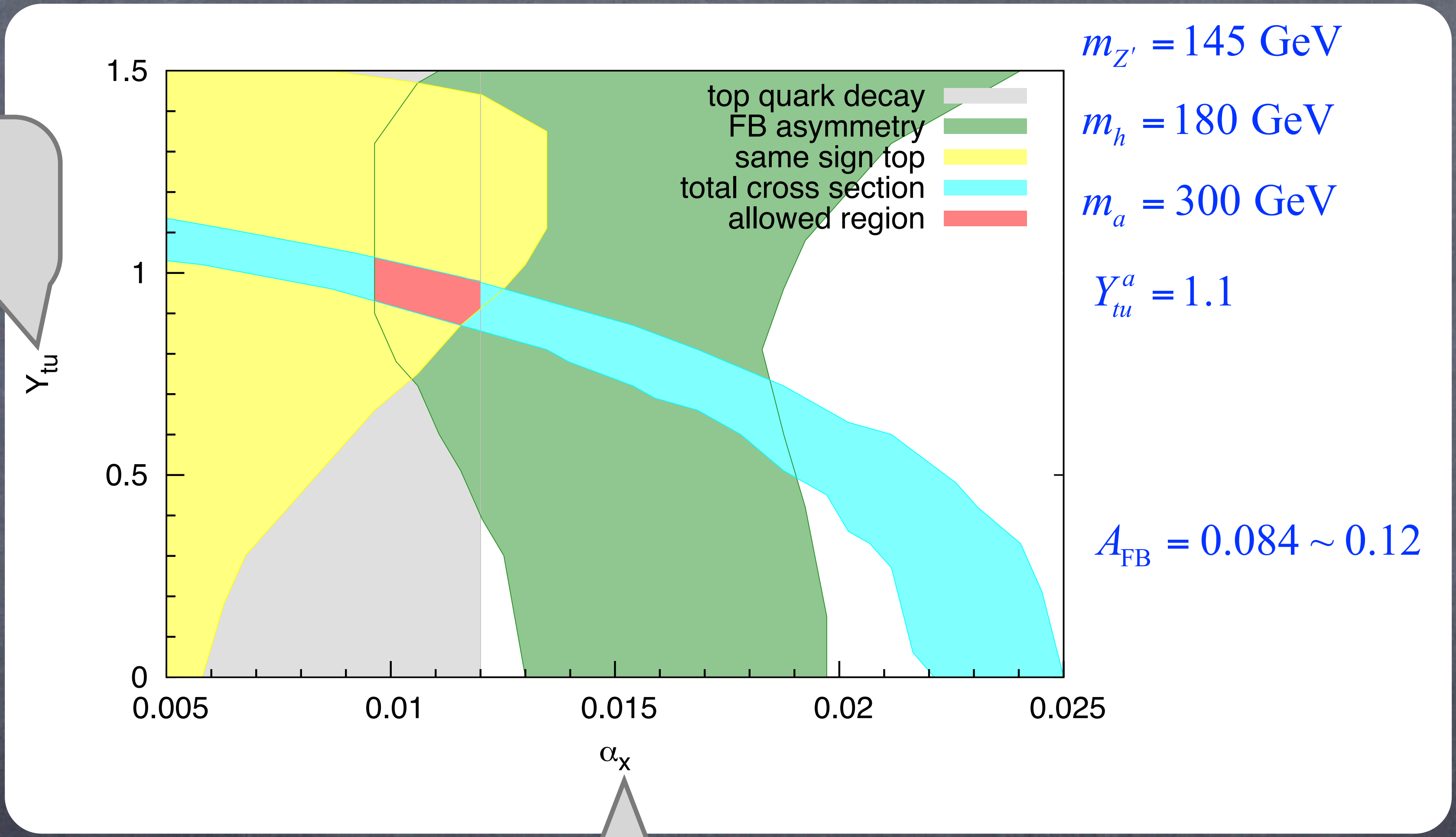


Z′+Scalars result

- Z′+h+a case ((t,u)of gauge vs (t,u) of Yukawa) @mz′=145GeV

The red region is allowed!

(t,u) element of Yukawa



$\alpha_x \equiv (g'(g^u_R)_{tu})^2/(4\pi)$

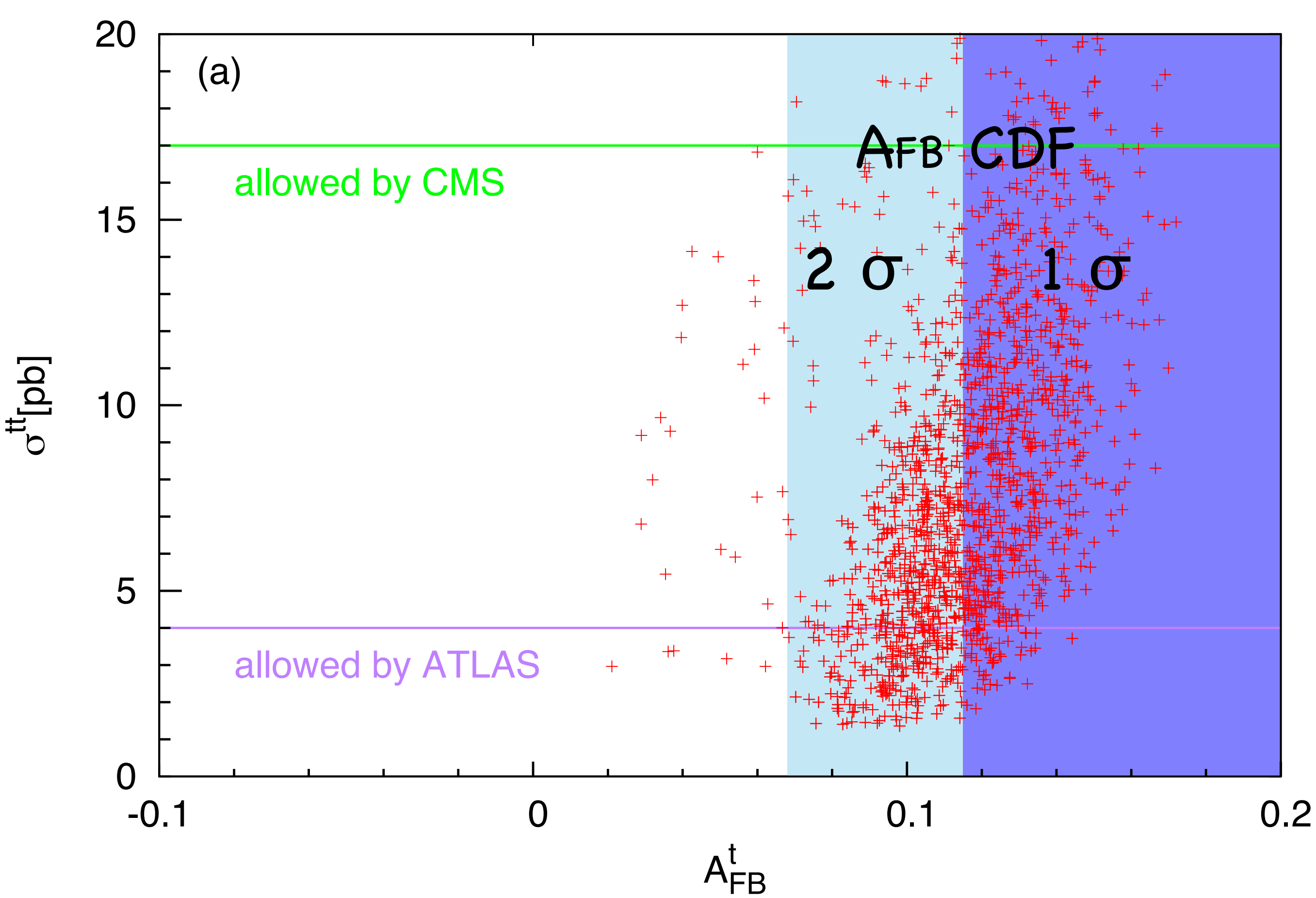
allowed region

$$(Y_{tu},\ \alpha_x) \sim (1,\ 0.01)$$ @mz′=145GeV

Z′+Scalars result

- Z′+h+a case ((t,u)of gauge vs (t,u) of Yukawa) @mz′=145GeV

Possible to evade the ATLAS bound, σ_{tt} < 2 pb.



$m_{Z'} = 145$ GeV

$180GeV \leq m_h, m_a \leq 1TeV$

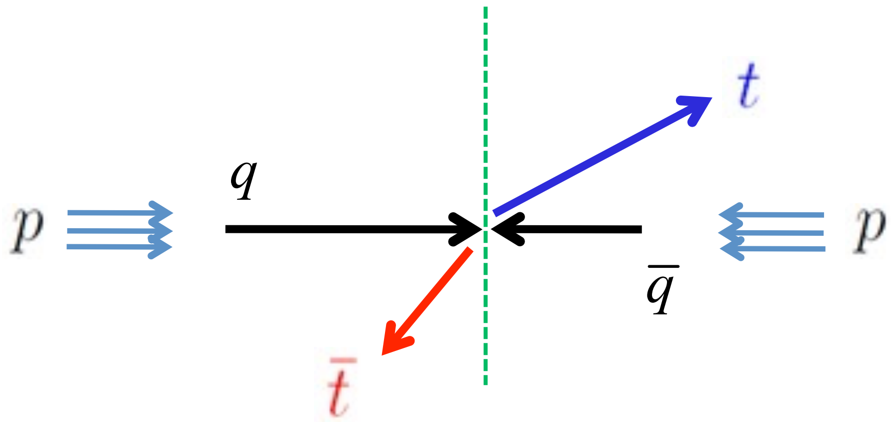
$0.005 \leq \alpha_x \leq 0.012$

$0.5 \leq Y_{tu}, Y^a_{tu} \leq 1.5$

Branching ratio of h could be reduced by the decay to dark matters

Charge asymmetry

- Charge asymmetry at LHC



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

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

$$A_C^y = \begin{cases} -0.018 \pm 0.028 \pm 0.023 & \text{(ATLAS)} \\ 0.004 \pm 0.010 \pm 0.012 & \text{(CMS)} \end{cases}$$

SM prediction

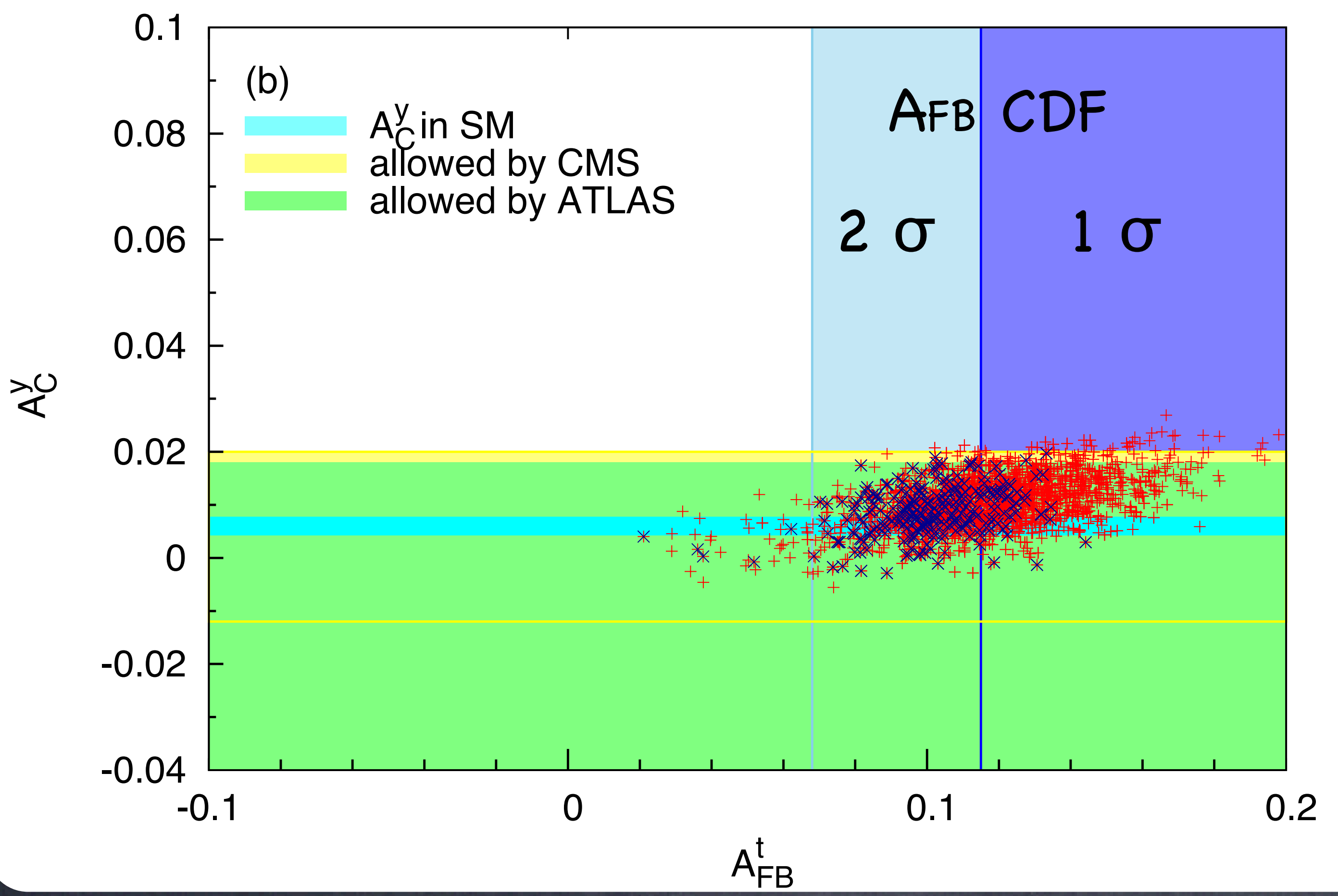
$$A_C^y = 0.01 \text{ (NLO)}$$

Antunano, Kuhn, Rodrigo, 0709.1652

AFB vs Charge asymmetry

- Z′+h+a case ((t,u)of gauge vs (t,u) of Yukawa) @mz′=145GeV

Ac can be also consistent.



$m_{Z'} = 145$ GeV

$180GeV \leq m_h, m_a \leq 1TeV$

$0.005 \leq \alpha_x \leq 0.012$

$0.5 \leq Y_{tu}, Y^a_{tu} \leq 1.5$

$* = \sigma_{tt} < 4pb$

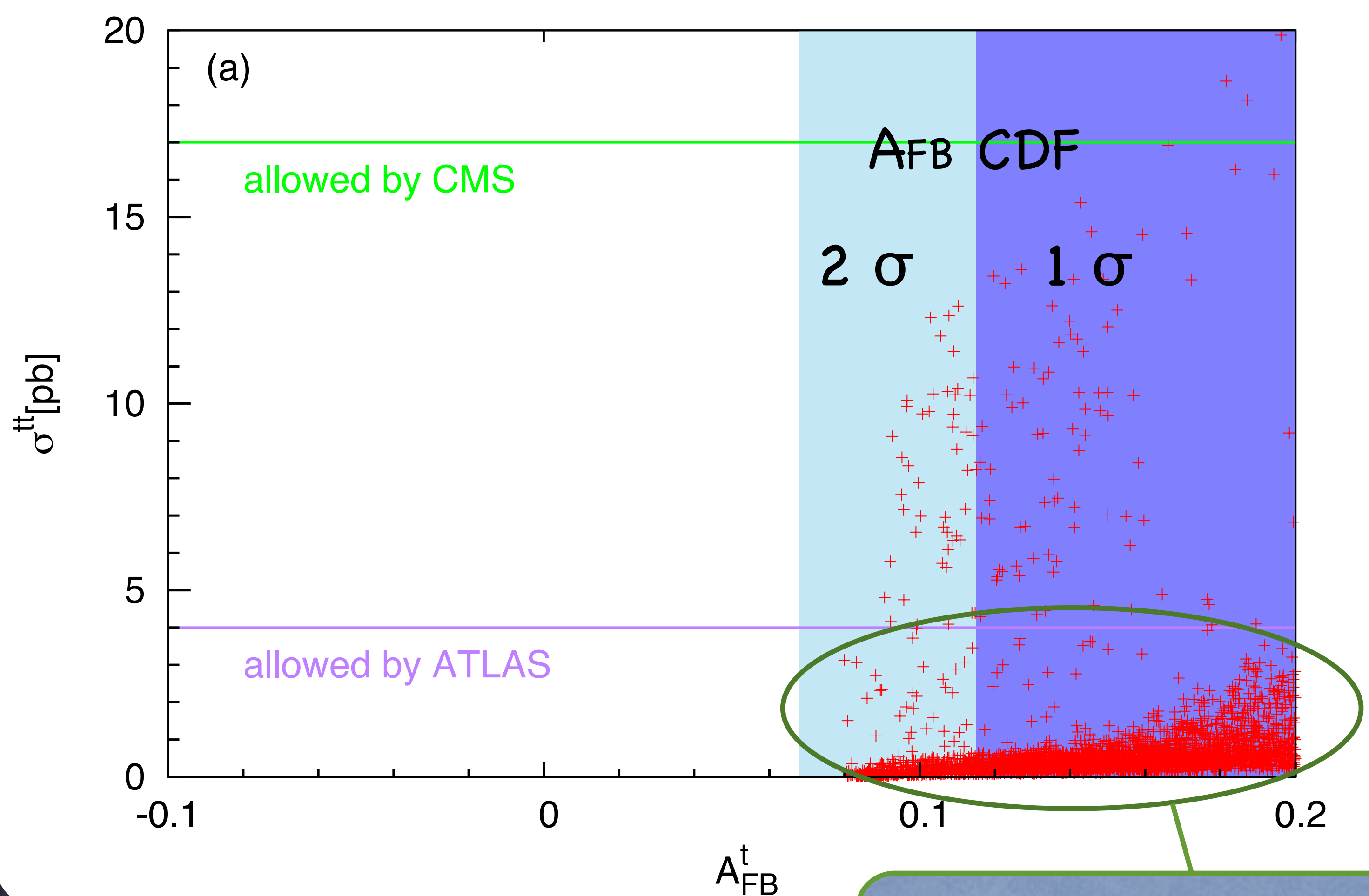
$* = \sigma_{t\bar{t}}$ within 1σ

AFB vs Charge asymmetry

How about ~125GeV Higgs ?

Top can decay to Higgs. Y_{tu} should be small!

$m_h = 125GeV$



$$180GeV \le m_a \le 1TeV$$
$$180GeV \le m_{Z'} \le 1.5TeV$$
$$0.005 \le \alpha_x \le 0.025$$
$$0.1 \le Y^a_{tu} \le 1.5$$
$$0.1 \le Y_{tu} \le 0.5$$

$* = \sigma_{t\bar{t}}$ within 1σ

Z' too heavy

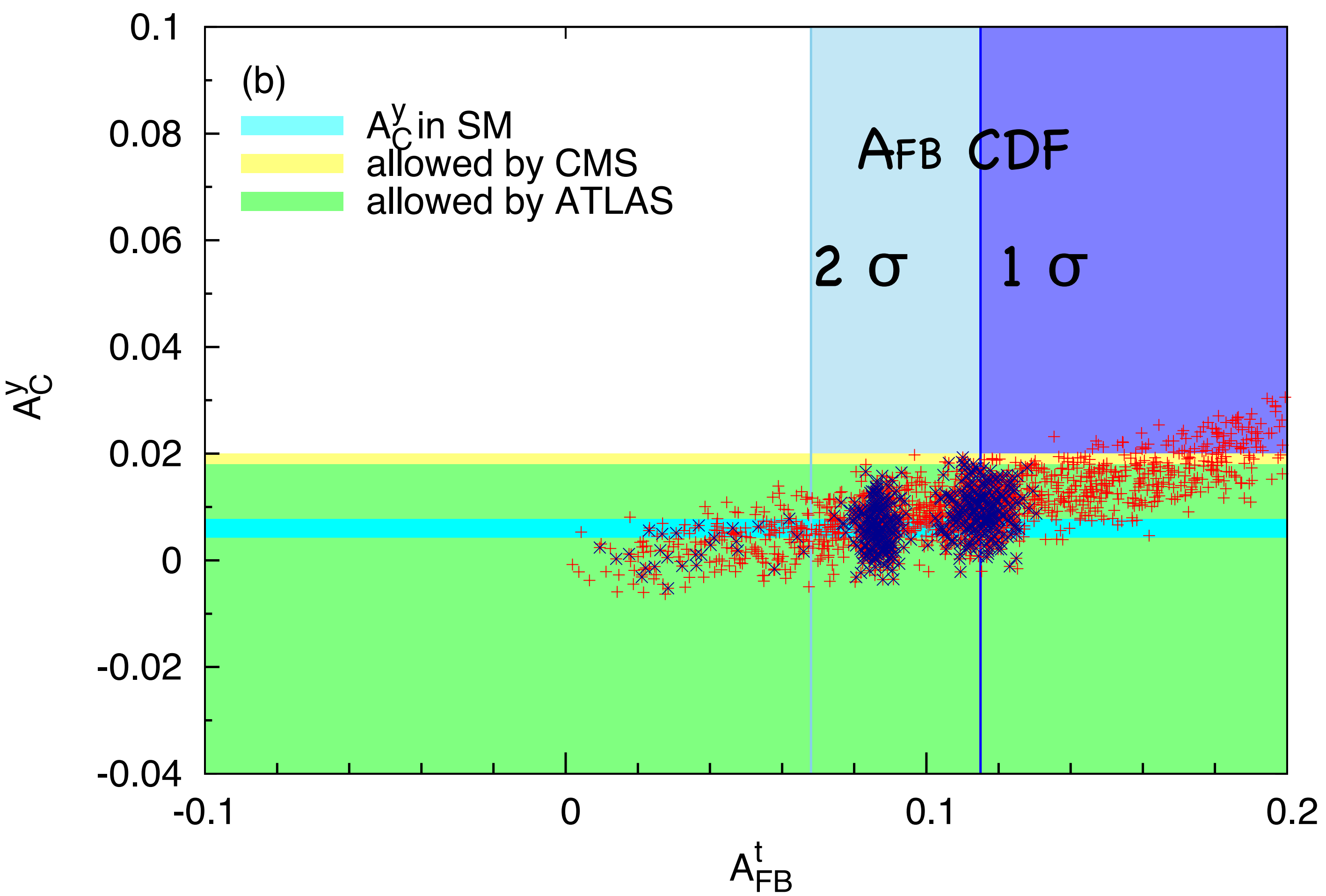
dijet bound excludes

AFB vs Charge asymmetry

How about ~125GeV Higgs ?

Heavier Higgs contribution should be sizable

$m_h = 125GeV$



$160GeV \leq m_H, m_a \leq 1TeV$

$160GeV \leq m_{Z'} \leq 300GeV$

$0 \leq \alpha_x \leq 0.025$

$0 \leq Y_{tu} \leq 0.5$

$0 \leq Y_{tu}^H, Y_{tu}^a \leq 1.5$

$* = \sigma_{tt} < 4pb$

$* = \sigma_{t\bar{t}}$ within 1σ

4. Other topics

4. Other topics

- $m_{t\bar{t}}$ ditribution

Jung, Murayama, Pierce, Wells, PRD81

light Z′ is favored

- EWPT

Cheng-Wei Chiang, Yi-Fan Lin, and Jusak Tandean, 1108.3969
P.Ko, Y. Omura and C. Yu,1204.4588

The tree-level mixing between Z and Z′ change the ρ,

$$\rho_0 \sim 1 + \boxed{\{h_1(\cos\beta)^2 + h_2(\sin\beta)^2\}^2 \frac{g'^2}{g_Z^2} \frac{m_{\hat{Z}}^2}{m_{\hat{Z}'}^2 - m_{\hat{Z}}^2}} \lesssim O(10^{-3})$$

Works in progress

- Single top $gu \to tZ' \to tu\bar{u}, u\bar{u} \to Z' \to t\bar{u}$
- Higgs bound $h \to DM\ DM$
- Charged Higgs $Y_{bu}^{\pm} \sim Y_{tu}^{a}$ cause problems in B decay

  contribute to $B \to D^{(*)}\tau\nu, B \to \tau\nu$

BABAR, 1205.5442,PRD81; Belle 1006.4201.

5. Summary and Comments

- Construct complete U(1)′ models where RH up-type quarks are charged.
- Require extra Higgs charged under U(1)′ for realistic mass matrices and renormalizability.
- Possible to evade strong bounds from top physics, according to interference among Z′, h, and a.
- Charge asymmetry at LHC was discussed and could be consistent with the LHC results.
- ~125 GeV Higgs is constrained by top decay.
  It seems to be difficult to enhance the A_{FB}.
- require chiral fermions for anomaly free →CDM

5. Summary and Comments

- How about theoretical motivations?

- Our flavor symmetry may be used to explain SM Yukawa textures, such as Froggatt-Nielsen. But we have to consider very specific textures

  ((t,u) element is large) to avoid FCNC bounds and realize large A_{FB}. It may not be easily compatible with the solution of the hierarchy ......

- Other issues

- against the Higgs bound from LHC

- constraints on charged Higgs

- extra matters

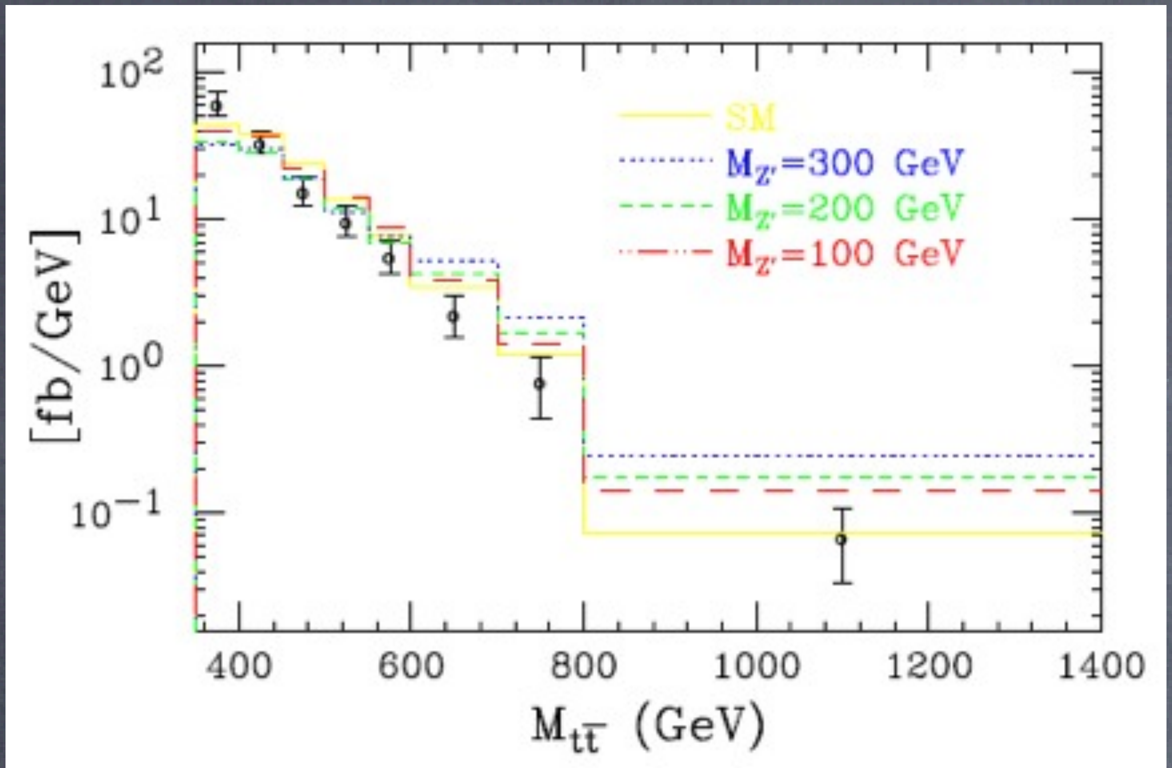
- How can test our model?

Thank you

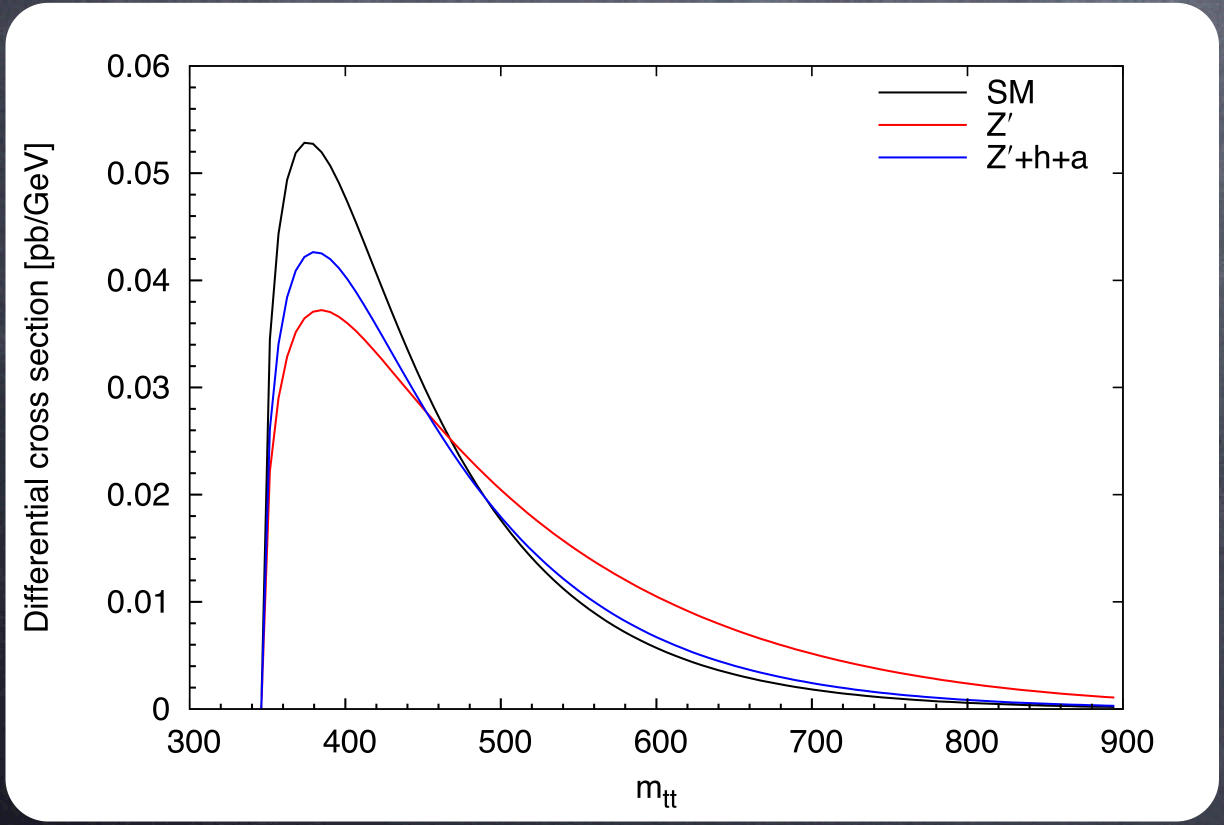
Back up

$m_{t\bar{t}}$ distribution

Jung, Murayama, Pierce, Wells, PRD81



lighter Z′ is favored



the destructive interference could improve

EWPT

Cheng-Wei Chiang, Yi-Fan Lin, and Jusak Tandean, 1108.3969
P.Ko, Y. Omura and C. Yu,1204.4588

Higgs interact with Z′

$$D^\mu H_i = D^\mu_{\rm SM} H_i - i g' h_i \hat{Z}'^\mu H_i$$

$(\hat{Z}, \hat{Z}_H)$ mass base (2HDM)

SM

$$M^2 = \begin{pmatrix} g_Z^2(v_1^2+v_2^2) & -g_Z g'(h_1 v_1^2 + h_2 v_2^2) \\ -g_Z g'(h_1 v_1^2 + h_2 v_2^2) & g'^2(h_1^2 v_1^2 + h_2^2 v_2^2 + h_\phi^2 v_\phi^2) \end{pmatrix}$$

$$g_Z = \sqrt{g_1^2 + g_2^2}/2$$

Z and Z′ mix at tree level.

EWPT

Cheng-Wei Chiang, Yi-Fan Lin, and Jusak Tandean, 1108.3969
P.Ko, Y. Omura and C. Yu,1204.4588

$$\rho_0^{\rm SM} = \frac{m_W^2}{c_W^2 m_{\hat{Z}}^2} = 1$$

In 2HDM, the tree-level mixing between Z and Z′ change the ρ,

$$\rho_0 \sim 1 + \{h_1(\cos\beta)^2 + h_2(\sin\beta)^2\}^2 \frac{g'^2}{g_Z^2} \frac{m_{\hat{Z}}^2}{m_{\hat{Z}'}^2 - m_{\hat{Z}}^2}$$

Compared with experimental data, $\rho = 1.008^{+0.0017}_{-0.0007}$

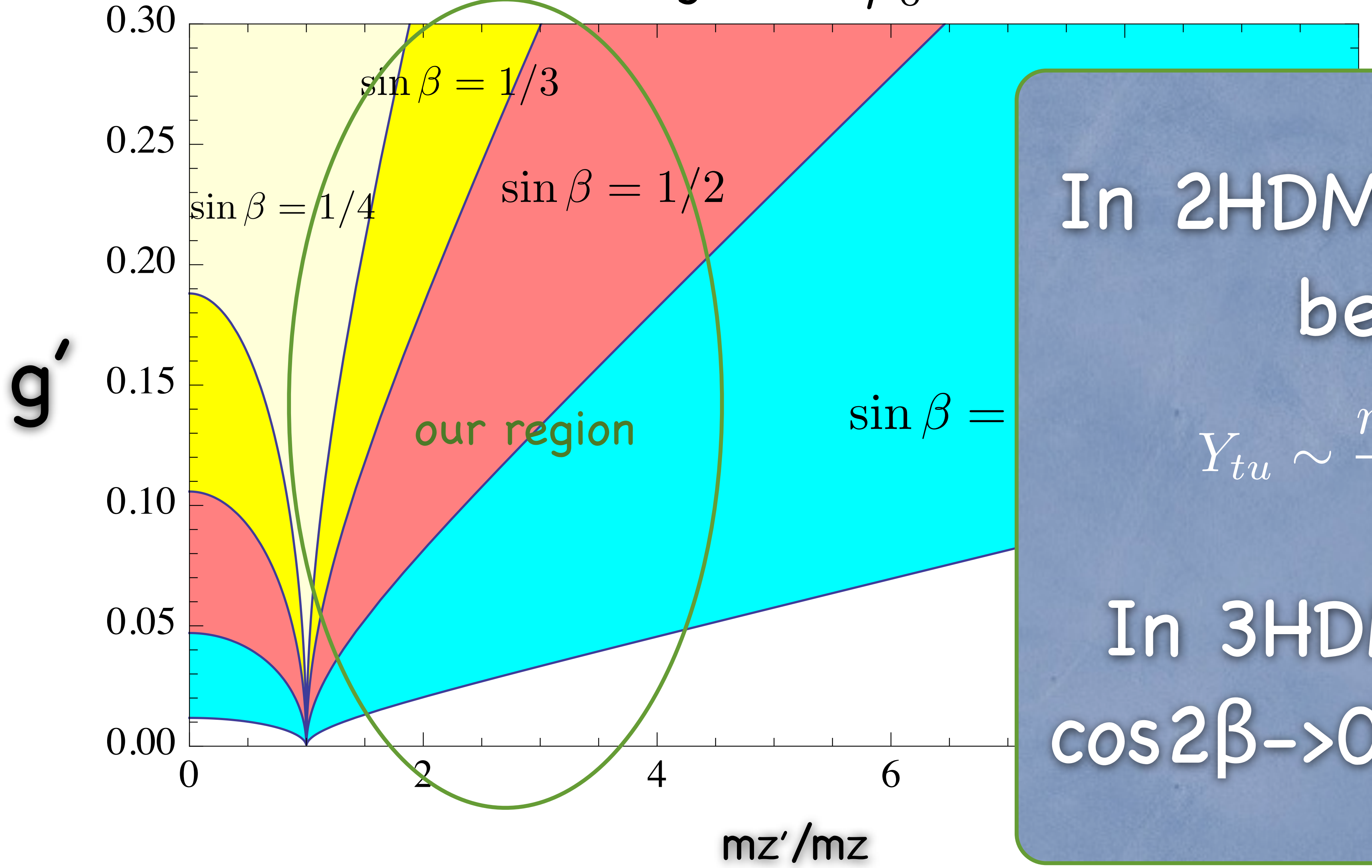
$$\{h_1(\cos\beta)^2 + h_2(\sin\beta)^2\}^2 \frac{g'^2}{g_Z^2} \frac{m_{\hat{Z}}^2}{m_{\hat{Z}'}^2 - m_{\hat{Z}}^2} \lesssim O(10^{-3})$$

The bound on the tree-level mixing (h1,h2)=(0,1)

$$(\sin\beta)^4 \frac{g'^2}{g_Z^2} \frac{m_{\hat{Z}}^2}{m_{\hat{Z}'}^2 - m_{\hat{Z}}^2} \lesssim O(10^{-3})$$

$$m_{\hat{Z}'}^2 = |\sin\beta|^2 g'^2 v^2 + h_\Phi^2 g'^2 v_\Phi^2$$

each colored region is $\delta\rho_0 > 0.001$.



In 2HDM, sinβ should be small,

$$Y_{tu} \sim \frac{m_t}{v} \frac{\sin(\alpha-\beta)}{\sin\beta\cos\beta}$$

In 3HDM, the limit, cos2β->0,suppress δρ.

anomaly

- Leptophobic U(1) symmetry is usually anomalous
- We have to add extra chiral fields: extra generation (for U(1)' sum=0), two SM vector-like pairs (for $U(1)_Y U(1)'^2$)

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
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

This set gives

$$U(1)' = SU(3)^2 U(1)' = U(1)_Y^2 U(1)' = 0$$

but

$$U(1)_Y U(1)'^2 \neq 0$$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
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	$-1/2$	$-Q_R$

or

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
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	$-1/3$	$-Q_R$

Cold Dark Matter Candidates

SU(2) doublet case

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
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	$-1/2$	$-Q_R$

$$l_{Li} = (n_{Li}, l^-_{Li})$$

2 neutral + 2 charged pairs

U(1)' forbids the mixing with SM fileds

stable charged and neutral

radiative correction make charged heavier and neutral becomes CDM

or

SU(3) triplet case

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
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	$-1/3$	$-Q_R$

U(1)' forbids the mixing with SM fileds

stable colored particles

adding U(1)' charged scalar, X

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

X is CDM

The other experimental bounds

- Single top production

D0 D0, 1105.2788

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

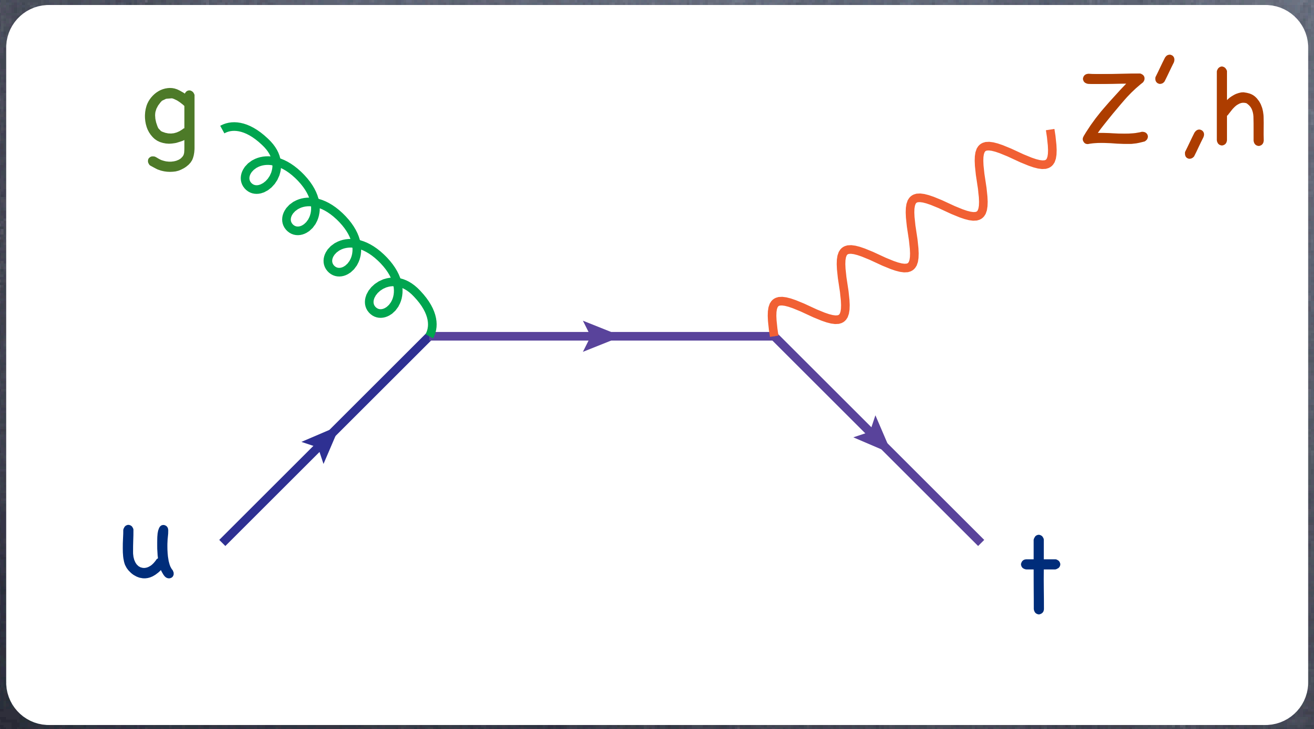
CMS CMS, 1106.3052

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

In the SM,

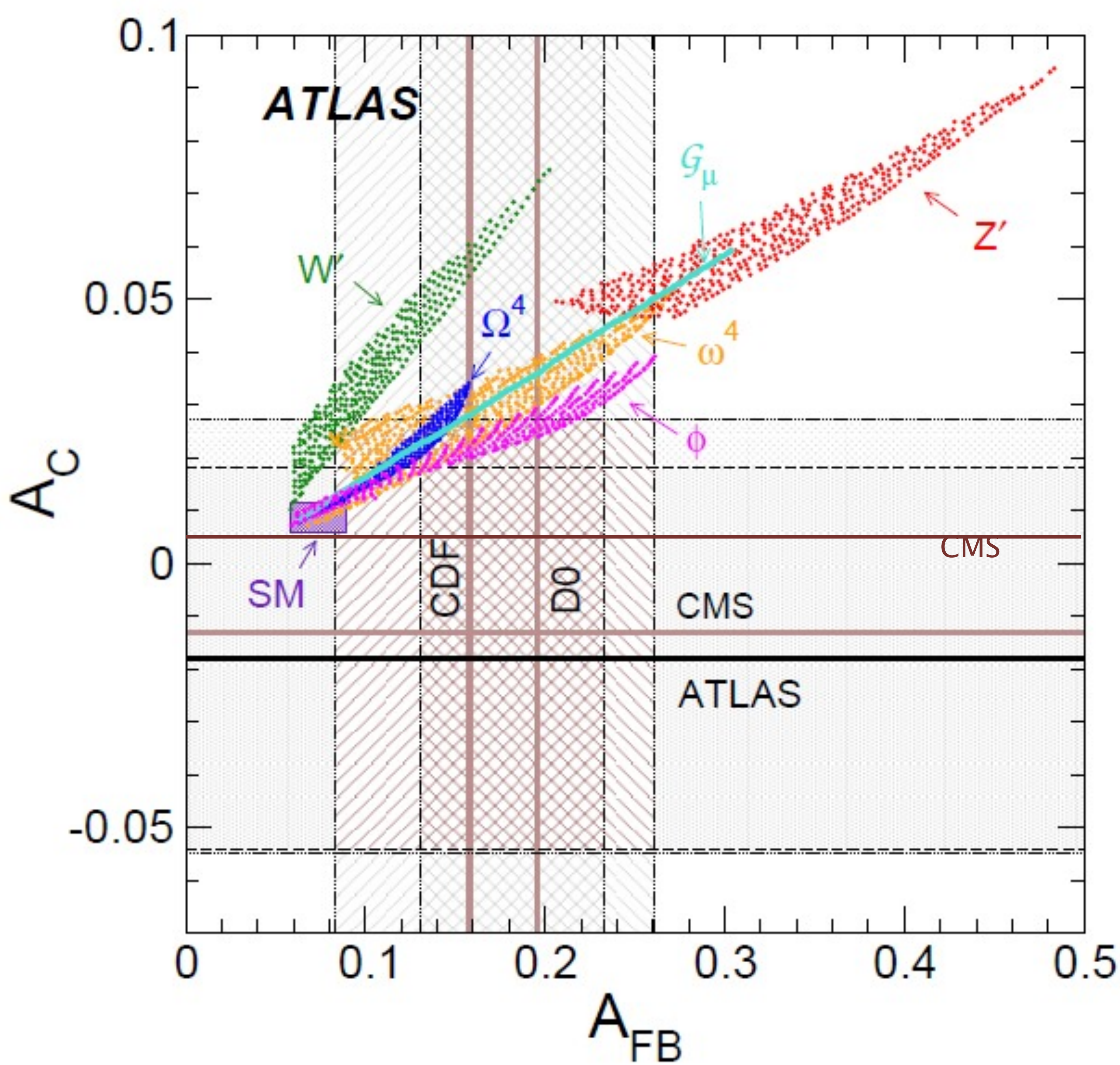
$$\sigma(p\bar{p} \to tbq)_{SM} = 2.26 \pm 0.12 pb$$

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



We do not have b in the final state

A_{FB} and A_C



ATLAS, 1203.4211

A_{FB} with SM NLO contribution

- In the SM,

$$A_{\rm FB}^{\rm SM} = \frac{\sigma_{\rm LO,F} + \sigma_{\rm NLO,F} - \sigma_{\rm LO,B} - \sigma_{\rm NLO,B}}{\sigma_{\rm LO} + \sigma_{\rm NLO}} = \frac{\Delta\sigma_{\rm LO} + \Delta\sigma_{\rm NLO}}{\sigma_{\rm LO} + \sigma_{\rm NLO}} \sim 8.7\%.$$

- In our calculation,

$$A_{\rm FB}^{\rm New} = \frac{K(\Delta\sigma_{\rm LO} + \Delta\sigma_{\rm NEW})}{K(\sigma_{\rm LO} + \sigma_{\rm NEW})} = \frac{\Delta\sigma_{\rm LO} + \Delta\sigma_{\rm NEW}}{\sigma_{\rm LO} + \sigma_{\rm NEW}} \sim 12\%.$$

- Combining both contributions of NLO and New physics,

$$A_{\rm FB} = A_{\rm FB}^{\rm SM} + A_{\rm FB}^{\rm New} / K \sim 18\%.$$