Top A_{FB} and charge asymmetry in chiral U(1) models

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with P. Ko and Yuji Omura (KIAS)

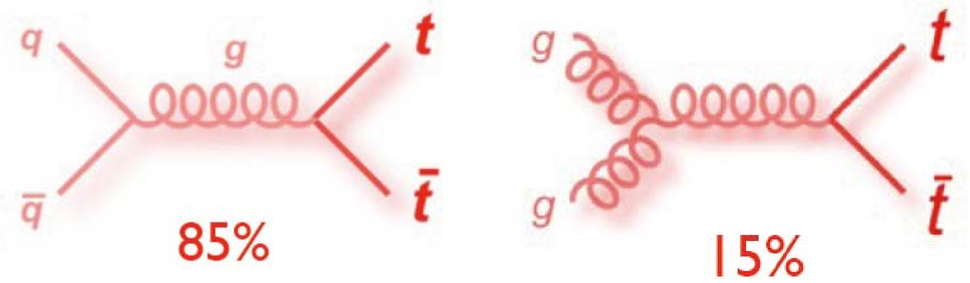
Top physics and electroweak symmetry breaking in the LHC era,
The Shilla Seoul, Korea, Feb. 24-29, 2012

Contents

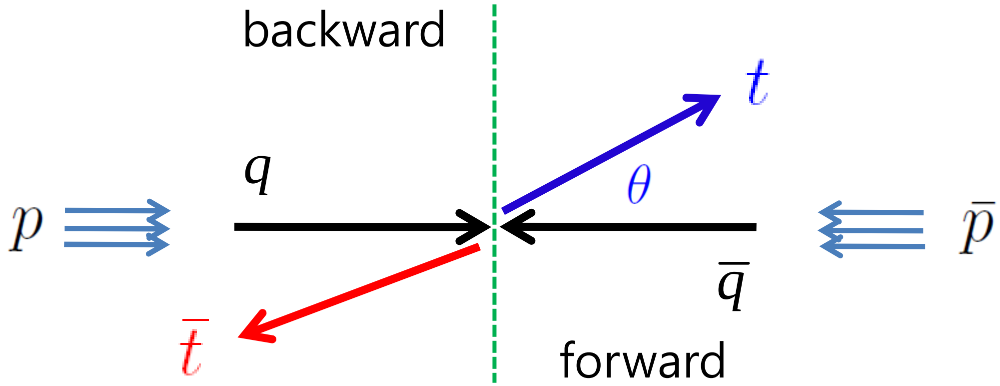
- Top A_{FB} and A_C in experiments
- recent progress of Top A_{FB} in the SM
- Z′ model
- chiral U(1)′ models with flavored Higgs doublets
- Conclusions

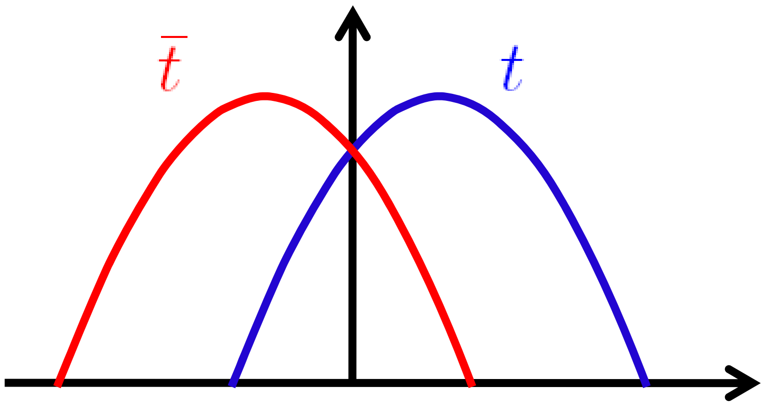
Top A_{FB} at the Tevatron

- Tevatron



- A_{FB} is generated by the difference between top and anti-top distributions.





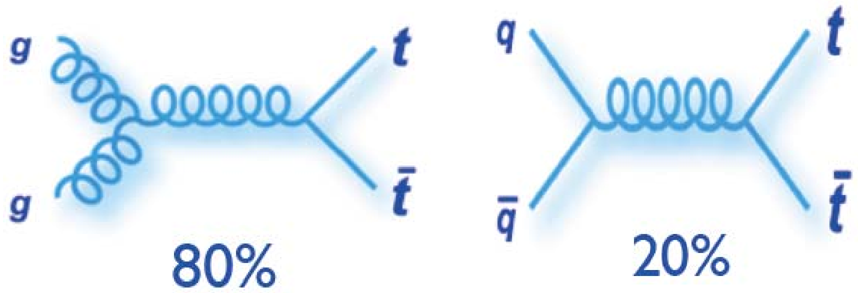
- QCD Coulomb interaction

- an incident quark repels the top quark, while it attracts the anti-top quark.

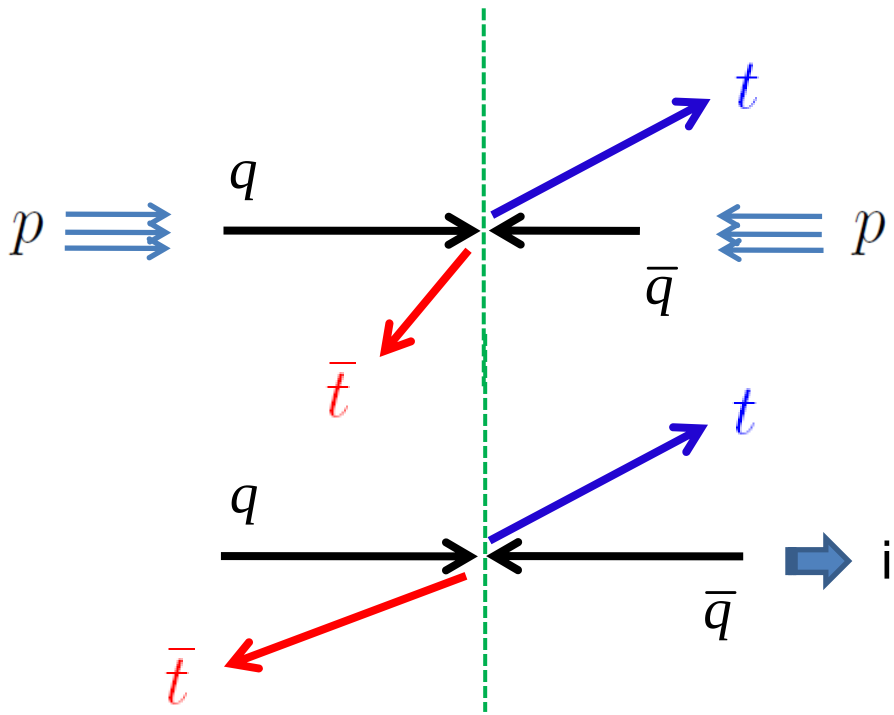
- an incident anti-quark repels the anti-top quark, while it attracts the top quark.

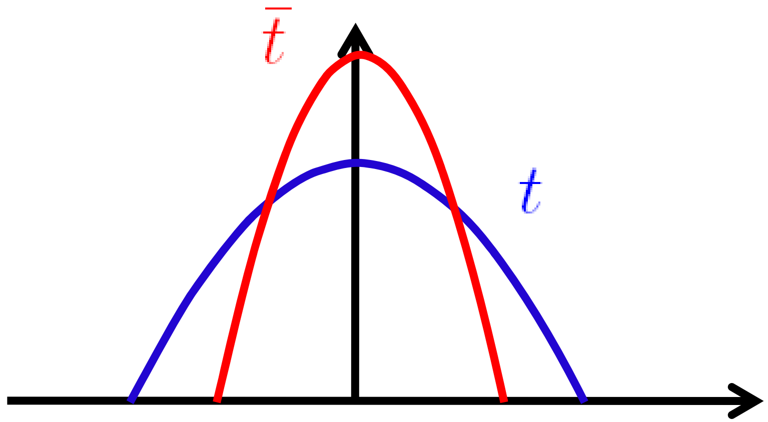
Top charge asymmetry at LHC

- LHC



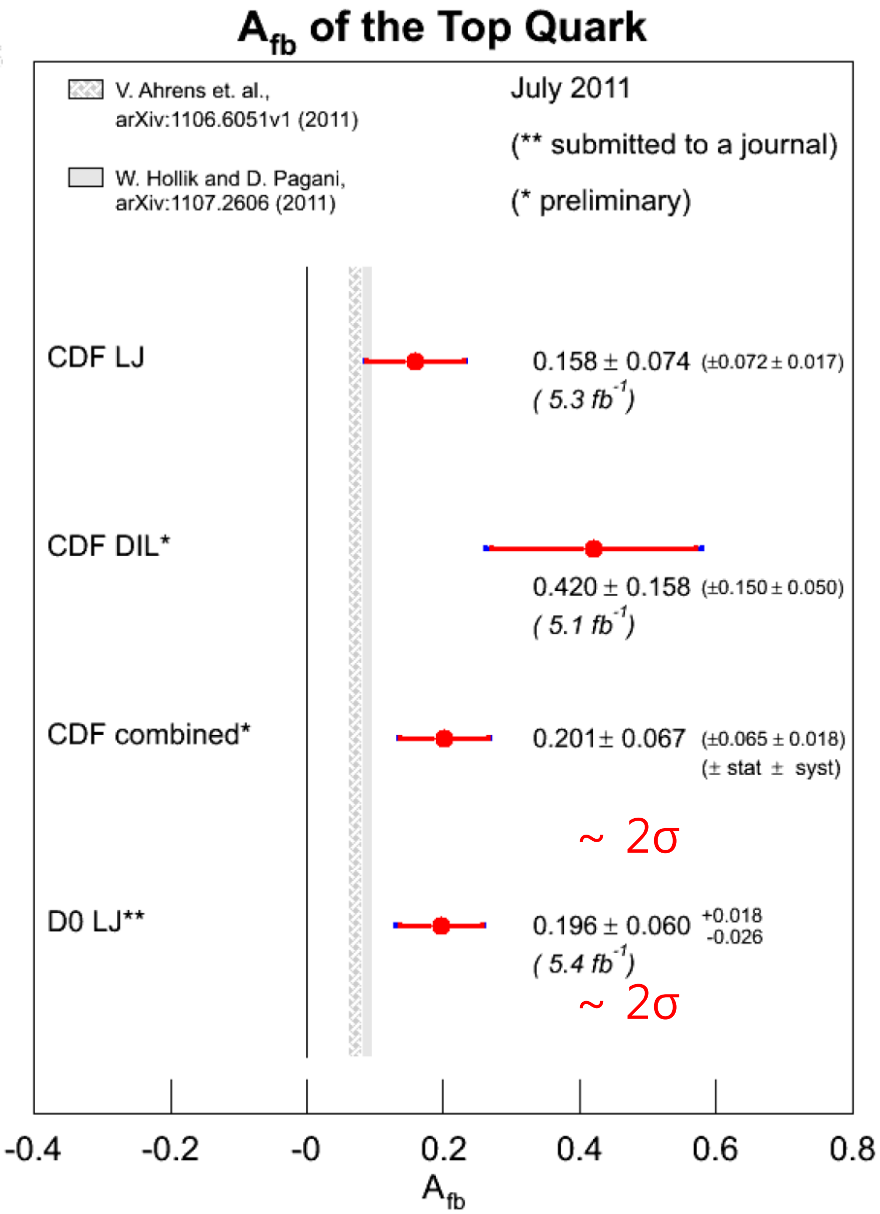
- Charge asymmetry is generated by the shape difference in distributions.

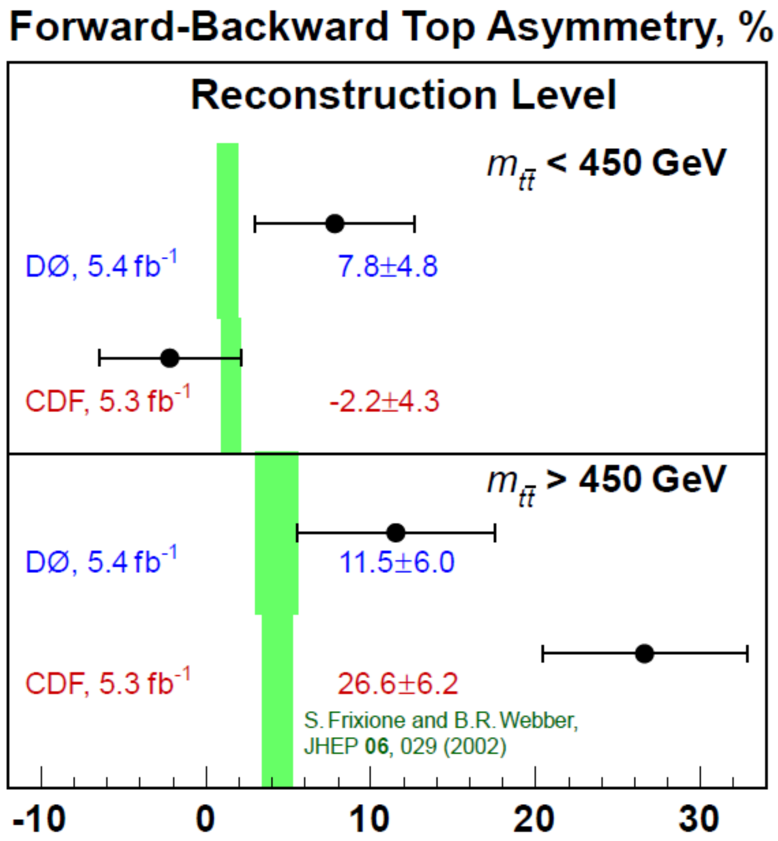




in the parton rest frame

Summary of Top A_{FB} at the Tevatron





No conclusive evidence for the dependence of top A_{FB} on the ttbar invariant mass.

Top charge asymmetry at LHC

ATLAS-CONF-2011-106

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

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

L_{int}=0.7 fb^{-1}

$$A_C^y = -0.024 \pm 0.016(stat.) \pm 0.023(syst.)$$

CMS 1112.5100

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

$$\Delta|\eta| = |\eta_t| - |\eta_{\bar{t}}|$$

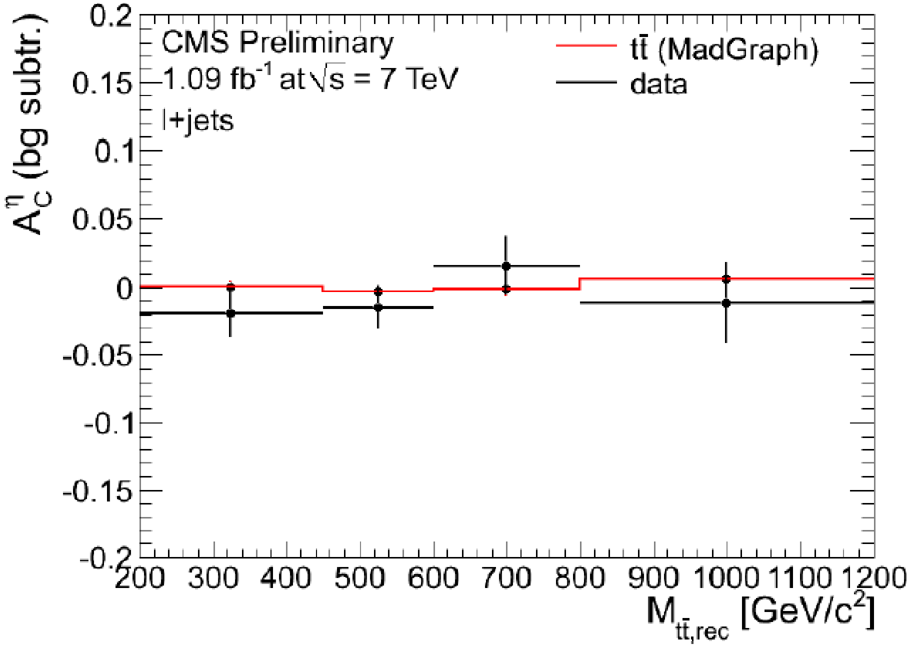
$$A_C^\eta = -0.016 \pm 0.030(stat.)^{+0.010}_{-0.019}(syst.)$$

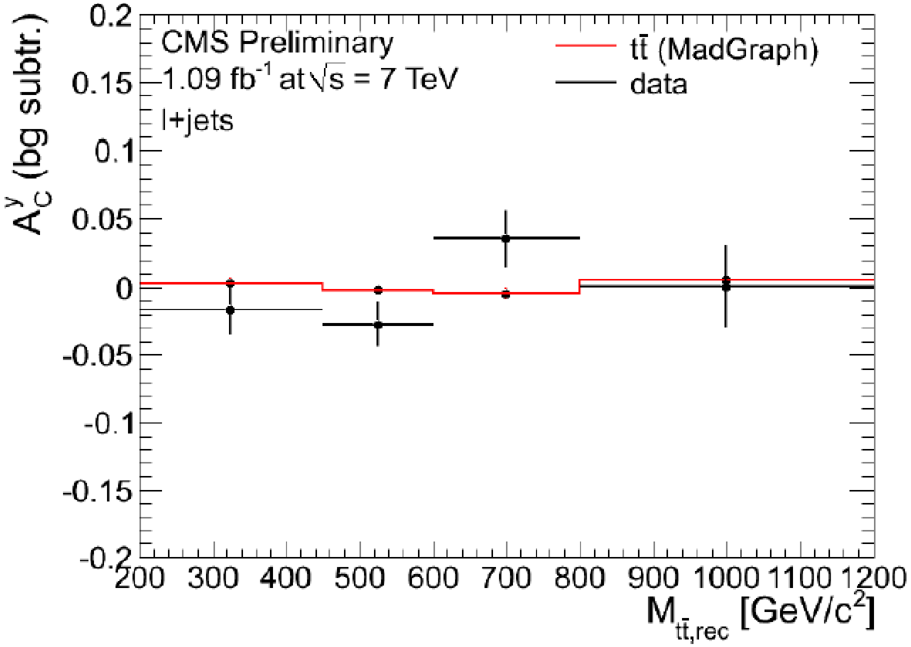
L_{int}=1.1 fb^{-1}

$$A_C^y = -0.013 \pm 0.026(stat.)^{+0.026}_{-0.021}(syst.)$$

SM prediction: $A_C \approx 0.01$ (G. Rodrigo)

Top charge asymmetry at LHC





- No tendency in $m_{t\bar{t}}$ distribution.

L_{int}=1.1 fb^{-1}

History of A_{FB} in the SM

• A_{FB} in the b, t quark production in QCD : Halzen, Hoyer, Kim, PLB195 (1987).

• detailed QCD calculation at NLO : Kuhn, Rodrigo, PRL81 (1998).

- 4~5% at the Tevatron.

• update the previous analysis: Kuhn, Rodrigo, PRD77 (2008).

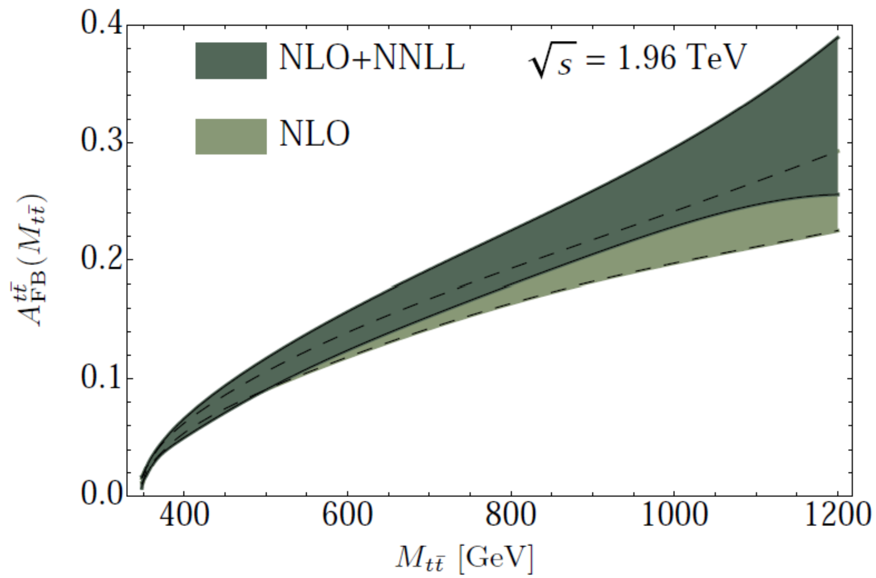
- $5.1 \pm 0.6\%$ at the Tevatron.

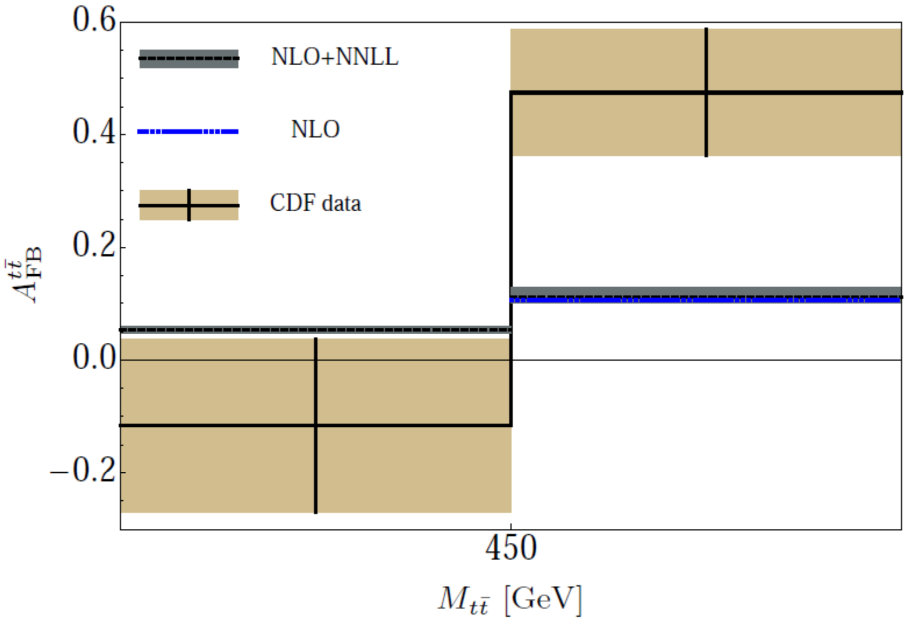
• NLO+NNLL accuracy: Ahrens, Ferroglia, Neubert, Peciak, Yang, PRD84 (2011).

• EW contributions at NLO: Hollik, Pagani, PRD84(2011); Kuhn, Rodrigo, JHEP1201.

SM prediction at NLO+NNLL

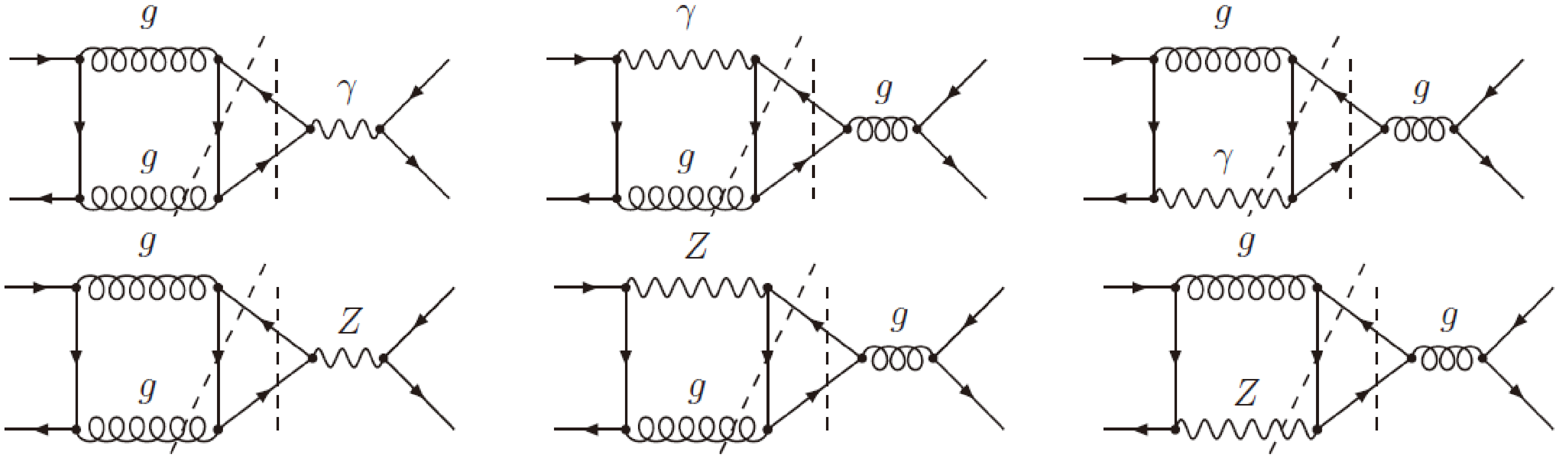
Ahrens,Ferroglia,Neubert,Pecjak,Yang,PRD84





(In units of %)	$A_{FB}^{t\bar{t}}$	$A_{FB}^{t\bar{t}}(M_{t\bar{t}} < 450\text{ GeV})$	$A_{FB}^{t\bar{t}}(M_{t\bar{t}} > 450\text{ GeV})$
NLO	$7.14^{+0.67}_{-0.54}$	$5.3^{+0.4}_{-0.4}$	$10.4^{+1.0}_{-0.6}$
NLO+NNLL	$7.16^{+1.05}_{-0.68}$	$5.2^{+0.8}_{-0.6}$	$10.8^{+1.7}_{-0.9}$
CDF lep+jets	15.8 ± 7.5	-11.6 ± 15.3	47.5 ± 11.2

EW contributions in the SM



- reanalyze electromagnetic as well as weak corrections. Kühn, Rodrigo, JHEP1201

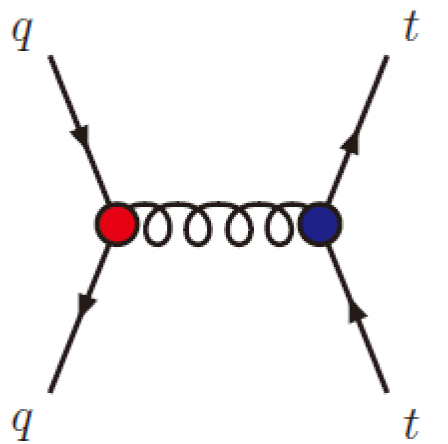
  - enhancement of A_{FB} by about a factor 1.1.

- restrict the $t\bar{t}$ system to a transverse momentum < 20 GeV.

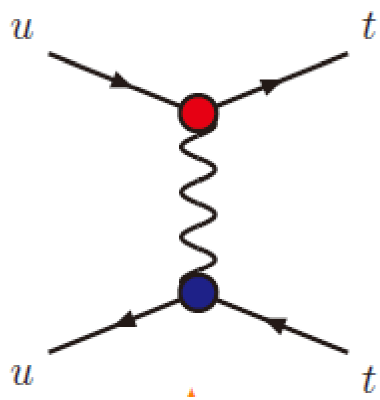
  - enhancement of A_{FB} by factors between 1.3 and 1.5.

(In units of %)	$A_{\rm FB}^{t\bar{t}}$	$A_{\rm FB}^{t\bar{t}}(M_{t\bar{t}} < 450\ \rm GeV)$	$A_{\rm FB}^{t\bar{t}}(M_{t\bar{t}} > 450\ \rm GeV)$
SM(NLO+EW)	8.7 ± 1.0	6.2 ± 0.4	12.8 ± 1.1
MCFM(NLO)	5.8 ± 0.9	4.0 ± 0.6	8.8 ± 1.3
CDF lep+jets	15.8 ± 7.5	-11.6 ± 15.3	47.5 ± 11.2

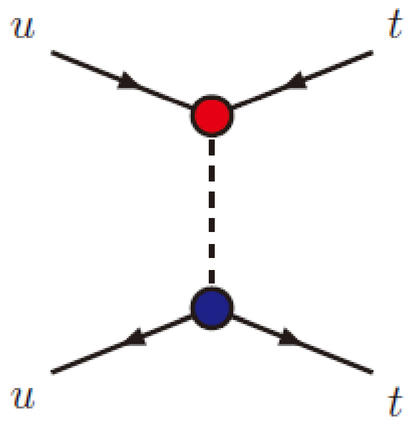
New physics models for top A_{FB}



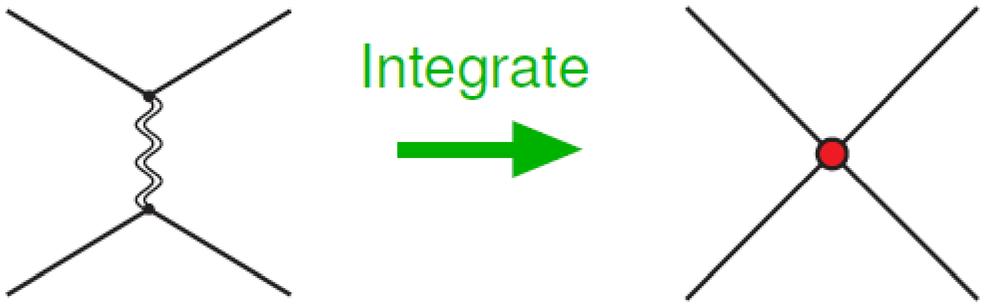
s-channel: coloured resonance $\mathcal{G}_\mu$



t-channel: Z', W', ϕ



u-channel: exotic scalars

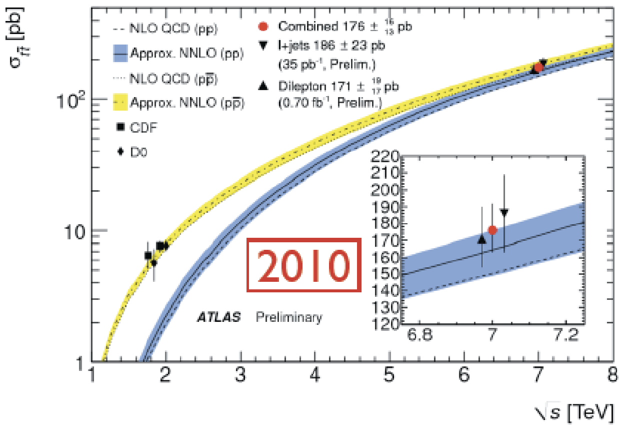


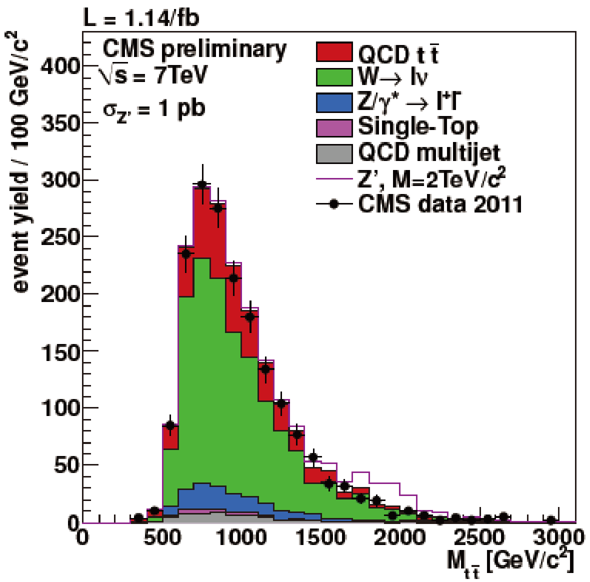
(new) heavy VB

4-fermion interaction

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

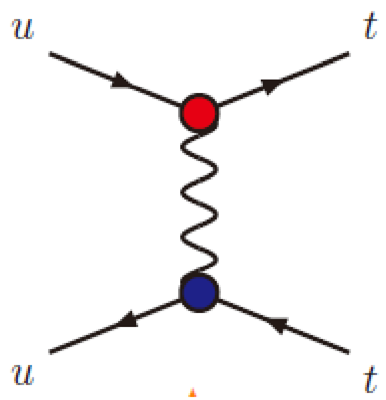
General remarks on new models





- σ_{th} in new physics models must be close to σ_{exp}.
- $\delta\sigma_{\text{int}} \approx -\delta\sigma_{\text{quad. in new physics}}$
- required to produce a large A_{FB}.
- no evidence for a resonant state between 350 GeV and 1.5 TeV (model-dependent).
- the exotic decay of the top quark must be suppressed.

Models with t-channel exchange



• Z′, W′, or scalar exchanges with large flavor changing neutral currents.

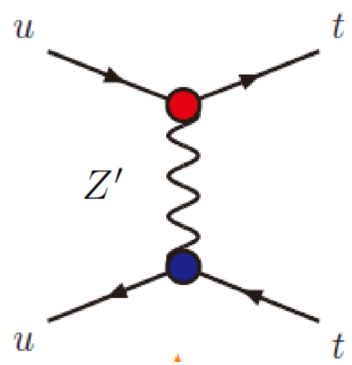
• could not be constrained by dijet production and top resonance searches.

• usually assume that only one off-diagonal coupling to the top quark is relevant.

- can be realized in a complete model?

Z′ model

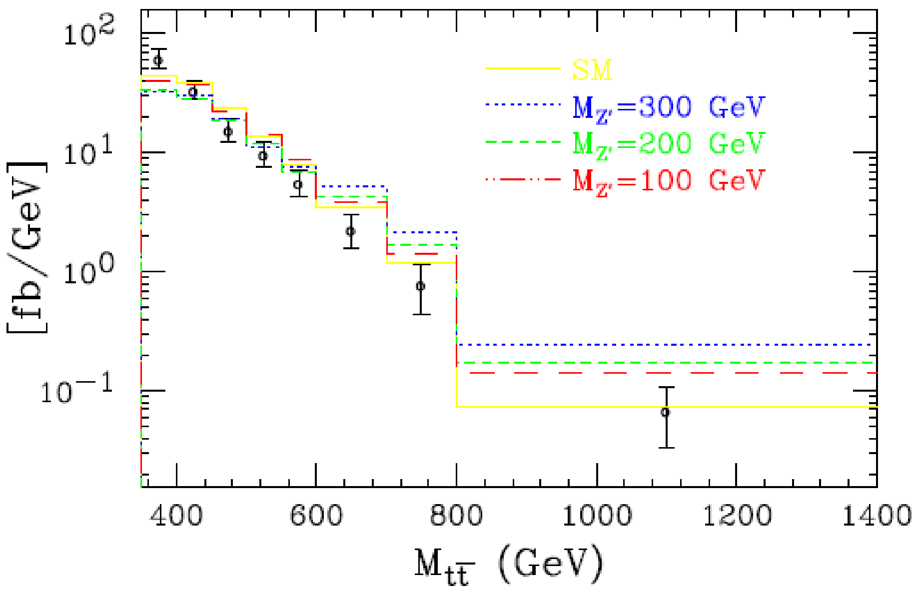
Jung, Murayama, Pierce, Wells, PRD81



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

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

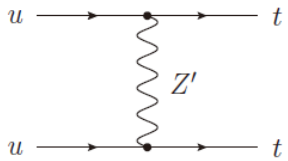
- In general, could have different couplings to the top and antitop quarks.



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

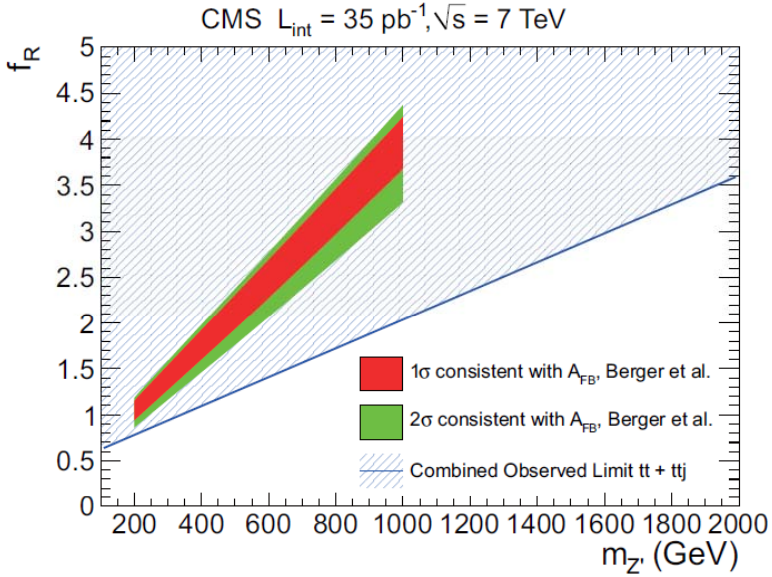
- severely constrained by the same sign top pair production.
  - the t-channel scalar exchange model has a similar constraint.

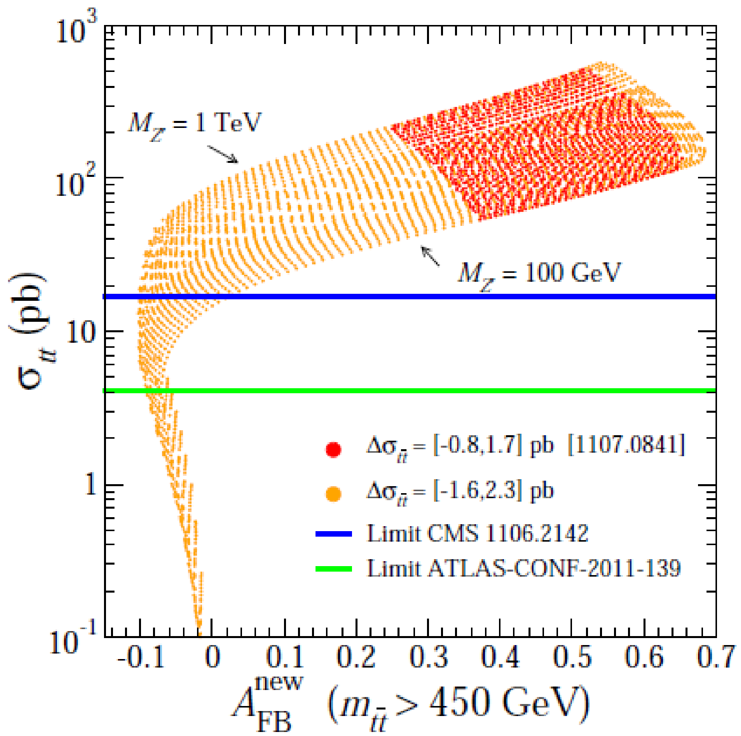
Same sign top pair production at LHC



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

General exclusion plot





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

Aguilar-Saavedra, TOP2011

- the t-channel Z′ or scalar exchange models are excluded? – No.

Flavor-dependent U(1)′ model

• many studies for a relatively light Z′ gauge boson with mass ~ 150 GeV.

• the Z′ is associated with some U(1)′ gauge symmetry.

• better be leptophobic to avoid the LEP II and Drell-Yan bounds.

• approximately lighter than 200 GeV from the dijet production in the UA2, Tevatron, LHC experiments and has flavor-dependent couplings.

• difficult to assign flavor-dependent charges to down-type quarks due to the strong constraints from FCNC experiments → assign U(1)′ charges only to right-handed up-type quarks.

• Yukawa interactions : additional Higgs fields are inevitable.

• a flavor-dependent leptophobic U(1)′ : anomalous.
  - introduce additional fermions to cancel the gauge anomalies.

• Both Z′ and Higgs fields affect the top A_{FB} and charge asymmetry.

Why need additional Higgs?

• If there is no Higgs fields charged under U(1)′, the top quark would be massless.

• U(1)′ charged Higgs fields generate the Z′ boson mass.

• similar to the $W_L W_L$ scattering in the intermediate vector boson model.

- restores unitarity with U(1)′ charged Higgs fields.

• also true in the W′, axigluon, and any other models if a new spin-1 particle has a chiral U(1)′ charge.

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

Left-handed quarks and right-handed 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 H uncharged 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.

Flavor-dependent U(1)′ model

- 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

Flavor-dependent U(1)′ model

• 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 the 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

- 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

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

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

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

$\propto$ 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

$$\begin{aligned}\mathcal{L}_{\rm Y} &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} H^\dagger_2 \overline{D_j} Q_i + y^e_{ij} H^\dagger_2 \overline{E_j} L_i + y^n_{ij} H_2 \overline{N_j} L_i .\end{aligned}$$

Flavor-dependent U(1)′ model

- Gauge coupling in the mass base

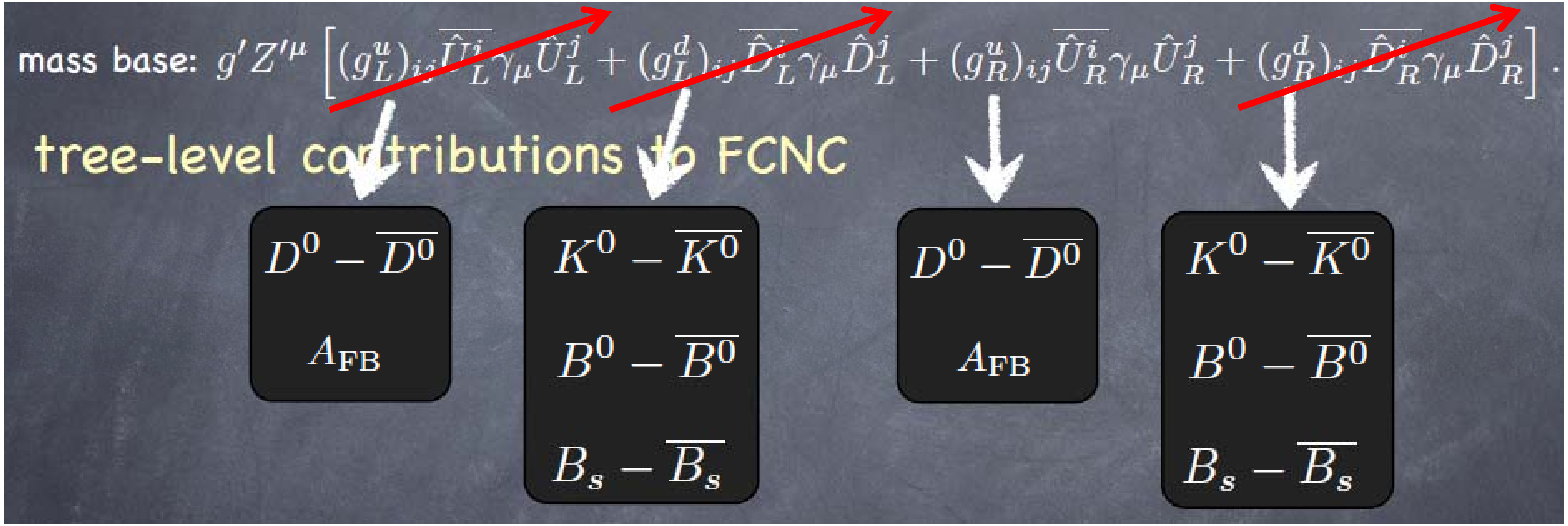
- Z′ interacts only with the right-handed up-type quarks

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

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

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

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

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

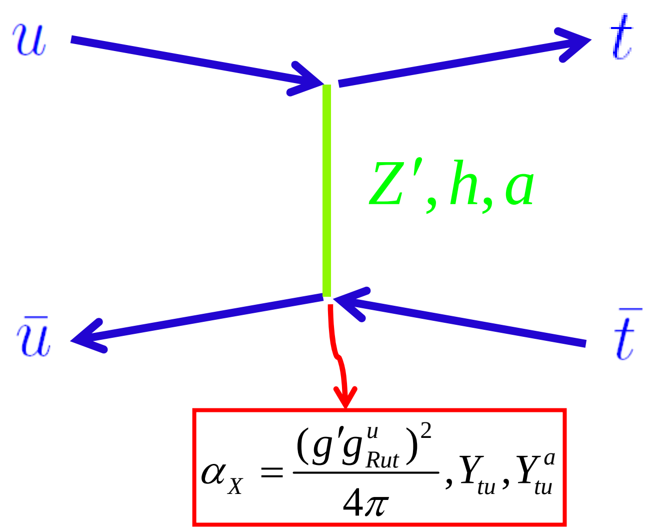
Top-antitop pair production

1. Z′ dominant scenario

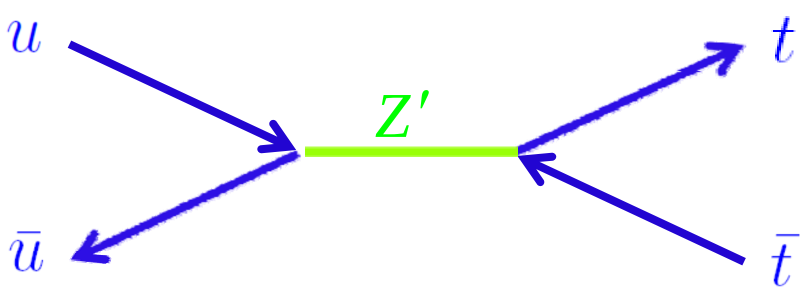
cf. Jung, Murayama, Pierce, Wells, PRD81(2010)

2. Higgs dominant scenario

cf. Babu, Frank, Rai, PRL107(2011)



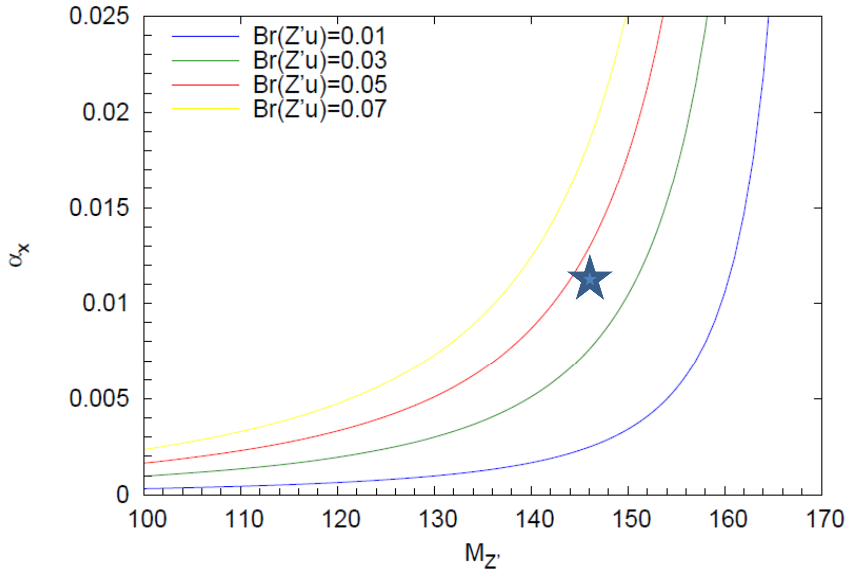
3. Mixed scenario

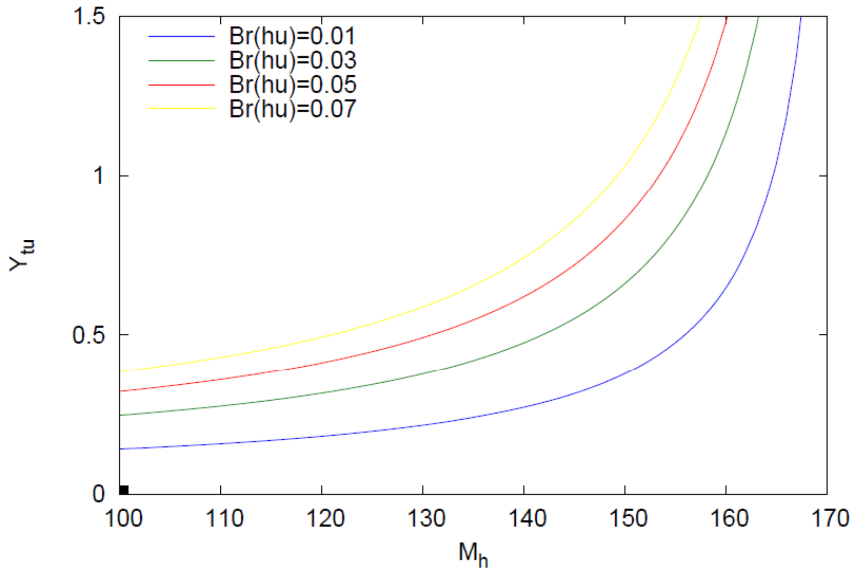


Top quark decay

- 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.

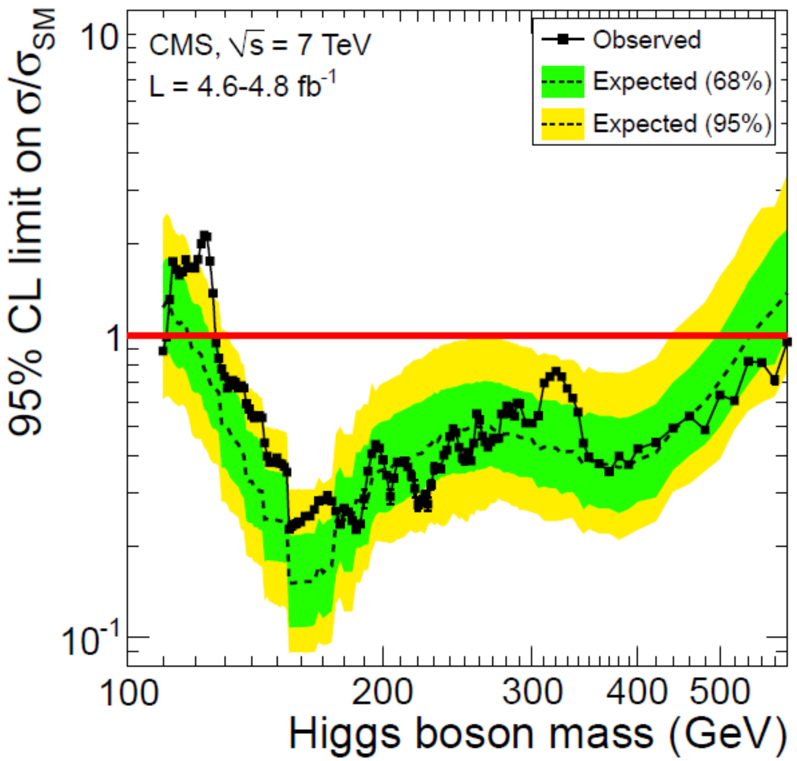




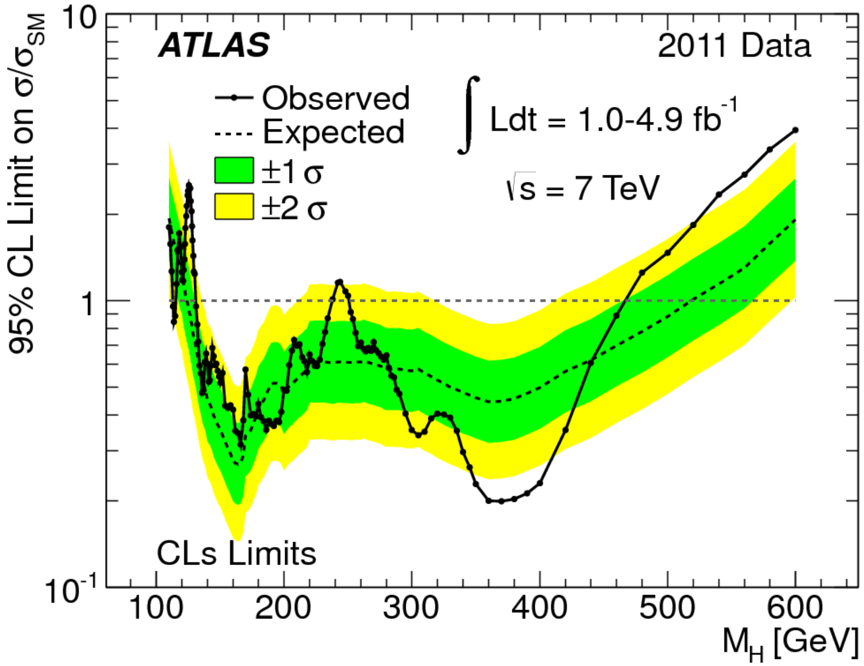
- assume Br(t →non-SM)<5% .

- choose either $m_{Z'} < m_t$ or $m_h < m_t$.

Higgs search at LHC



CMS, 1202.1488



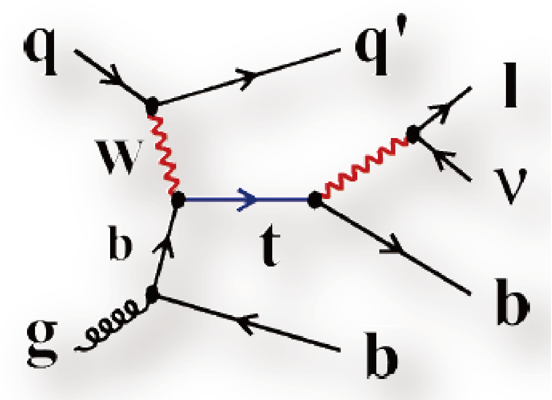
ATLAS, 1202.1408

- $m_h > m_t$: conflict with Higgs mass bounds at CMS and ATLAS?
- The bounds are weaker because new decay channels are open.

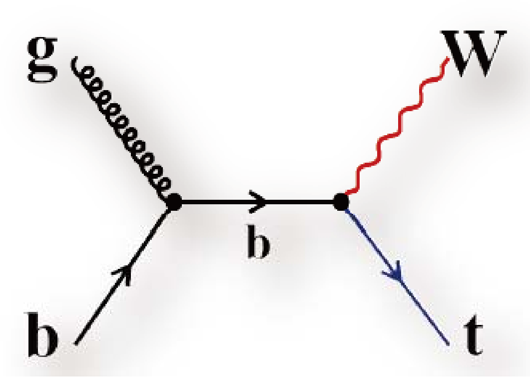
$$h \to t\bar{u}, h \to \text{dark matters}$$

Single top quark production

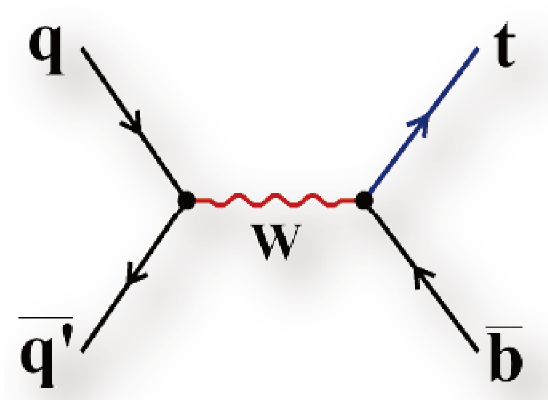
t channel



Wt channel



s channel



- D0 D0, 1105.2788

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

In the SM,

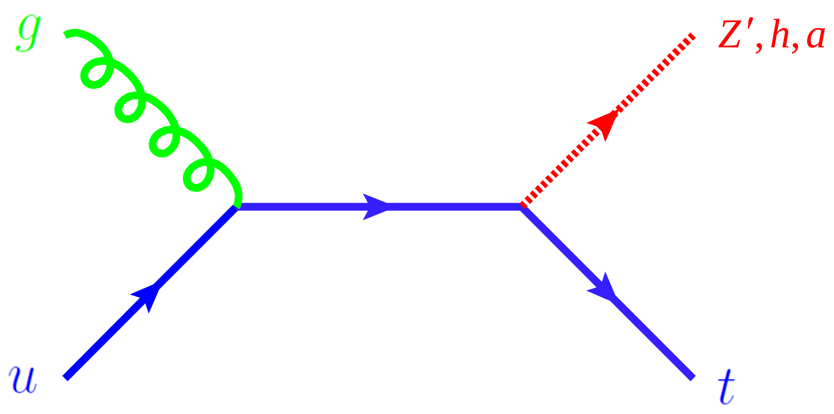
$$\sigma(p\bar{p} \to tbq) = 2.26 \pm 0.12 \text{ pb}$$

- CMS CMS, 1106.3052

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

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

Single top quark production



⇒ no b quark or W boson in the final state

- D0 D0, 1105.2788

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

- CMS CMS, 1106.3052

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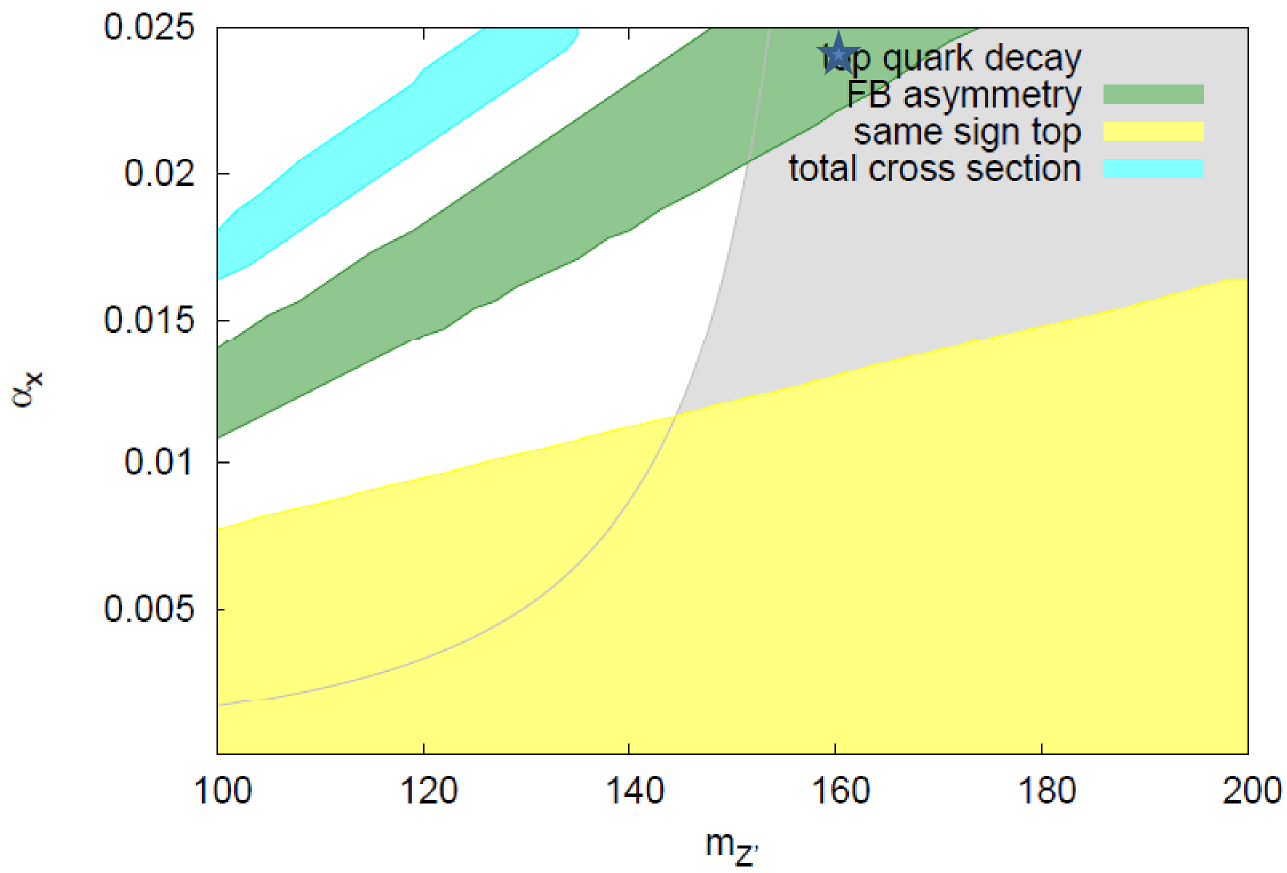
Favored region

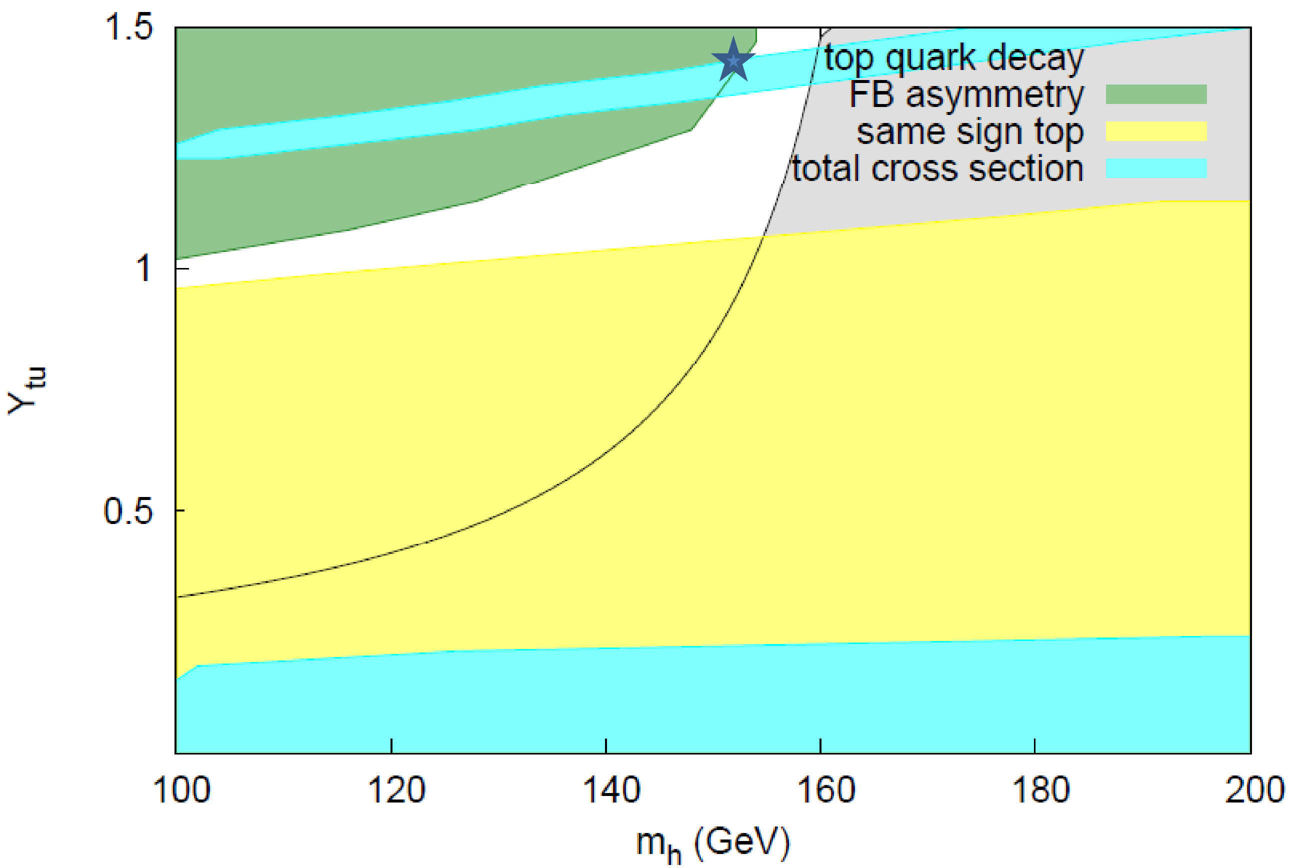
Z' dominant case



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

Favored region

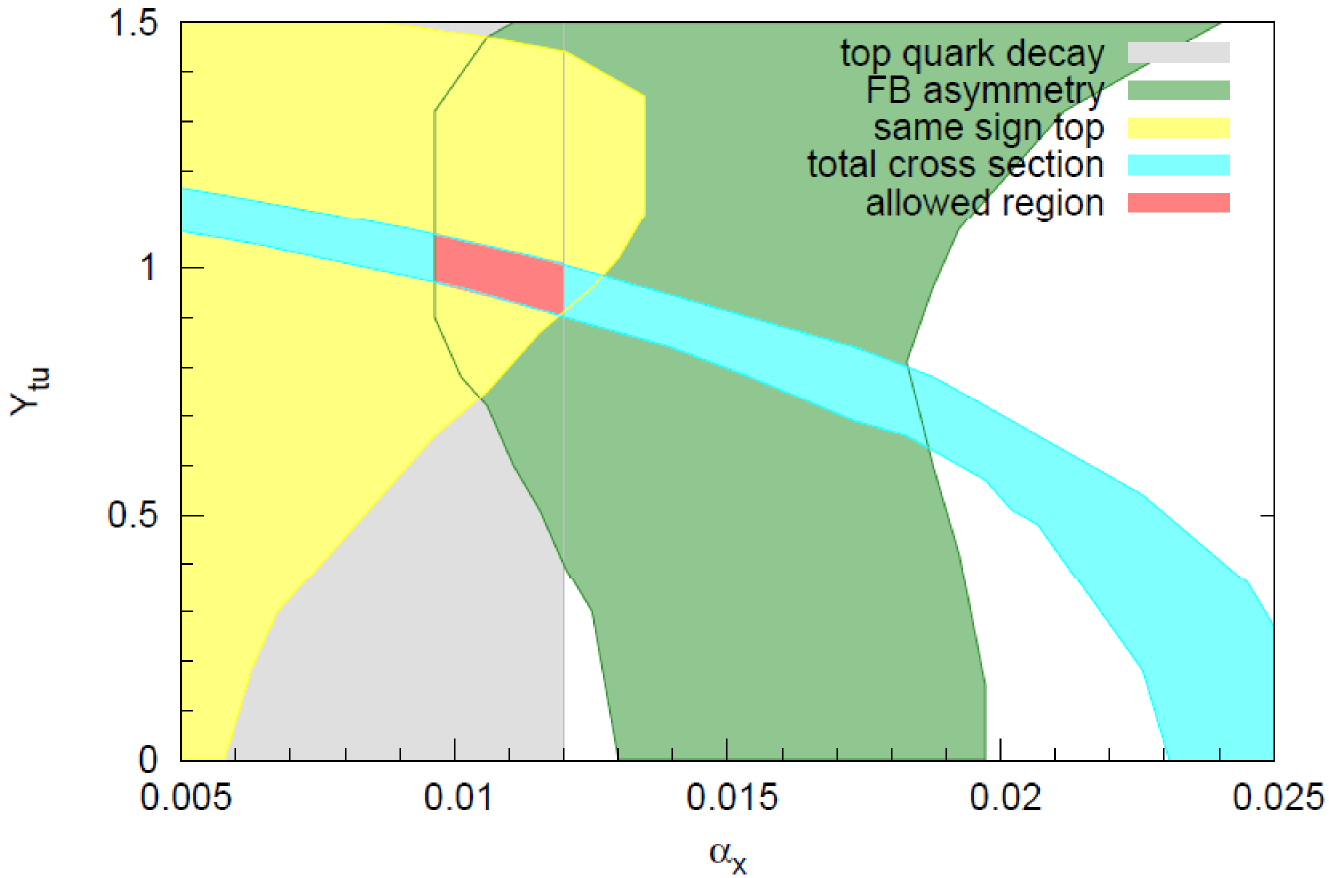
Scalar Higgs (h) dominant case



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

Favored region

Z′+h+a case



$m_{Z'} = 145$ GeV

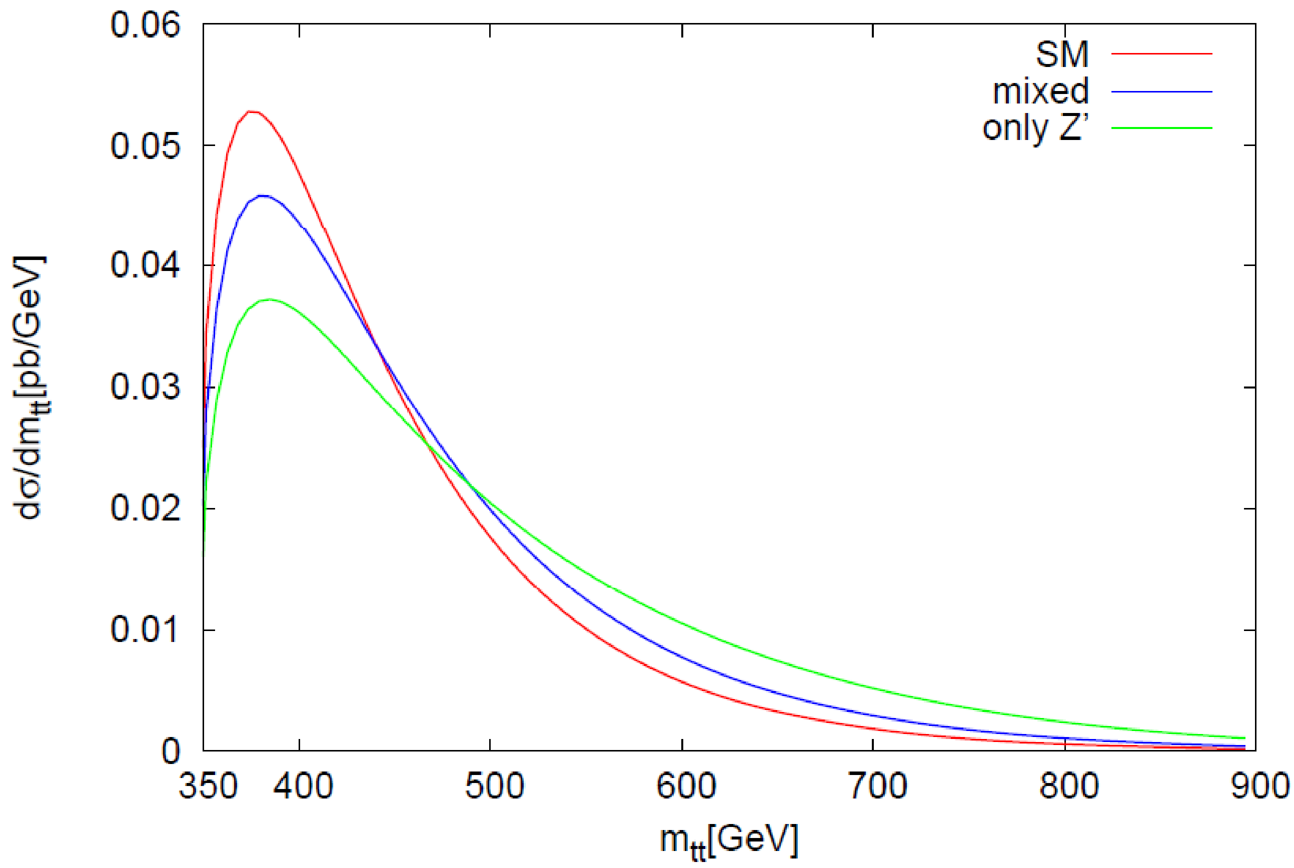
$m_h = 180$ GeV

$m_a = 300$ 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

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

$\alpha_x = 0.029$

mixed case

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

$m_h = 180 \text{ GeV}$

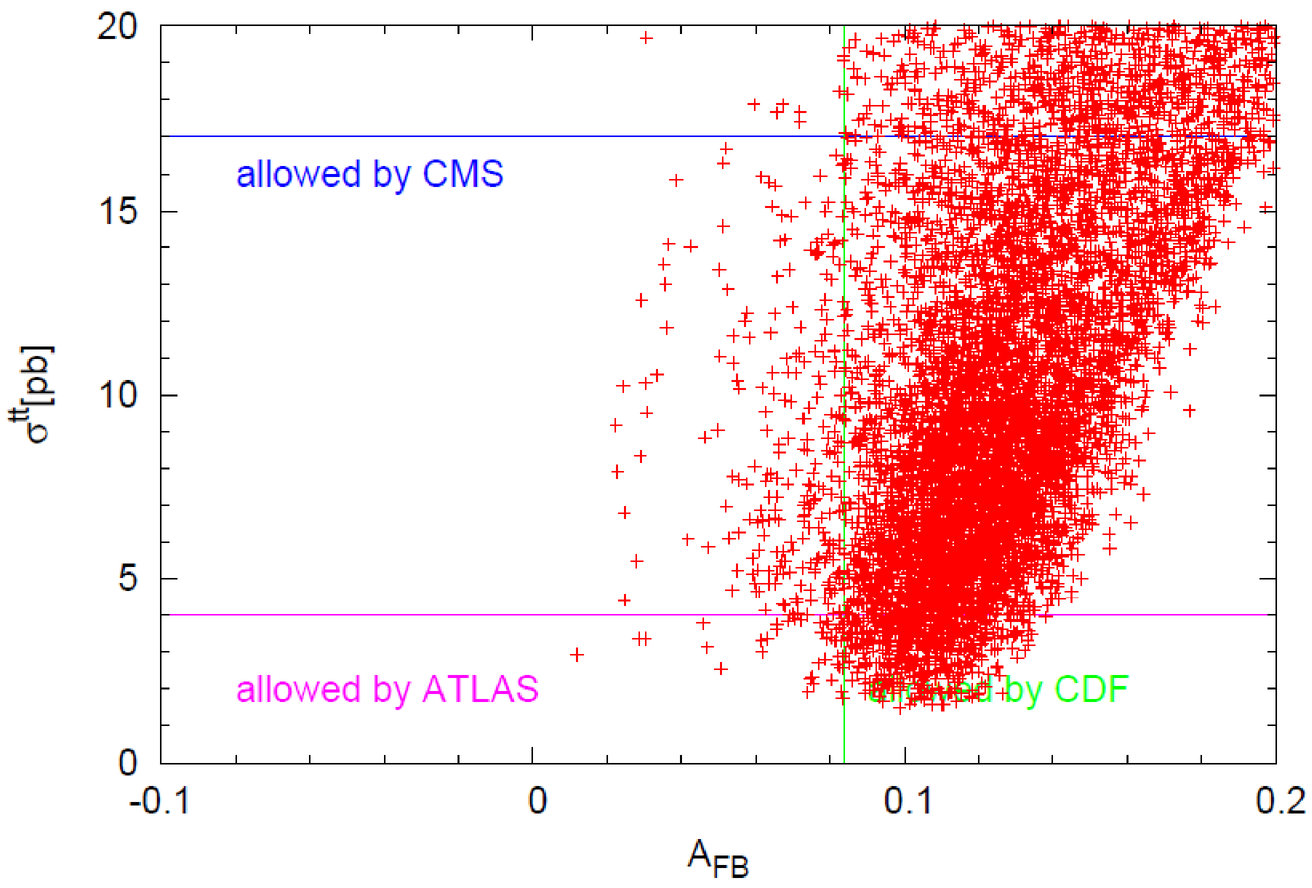
$m_a = 300 \text{ GeV}$

$\alpha_x = 0.01$

$Y_{tu} = 1.0$

$Y_{tu}^a = 1.1$

A_{FB} versus σ_{tt}



$m_{Z'} = 145$ GeV

180 GeV$< m_h < 1$ TeV

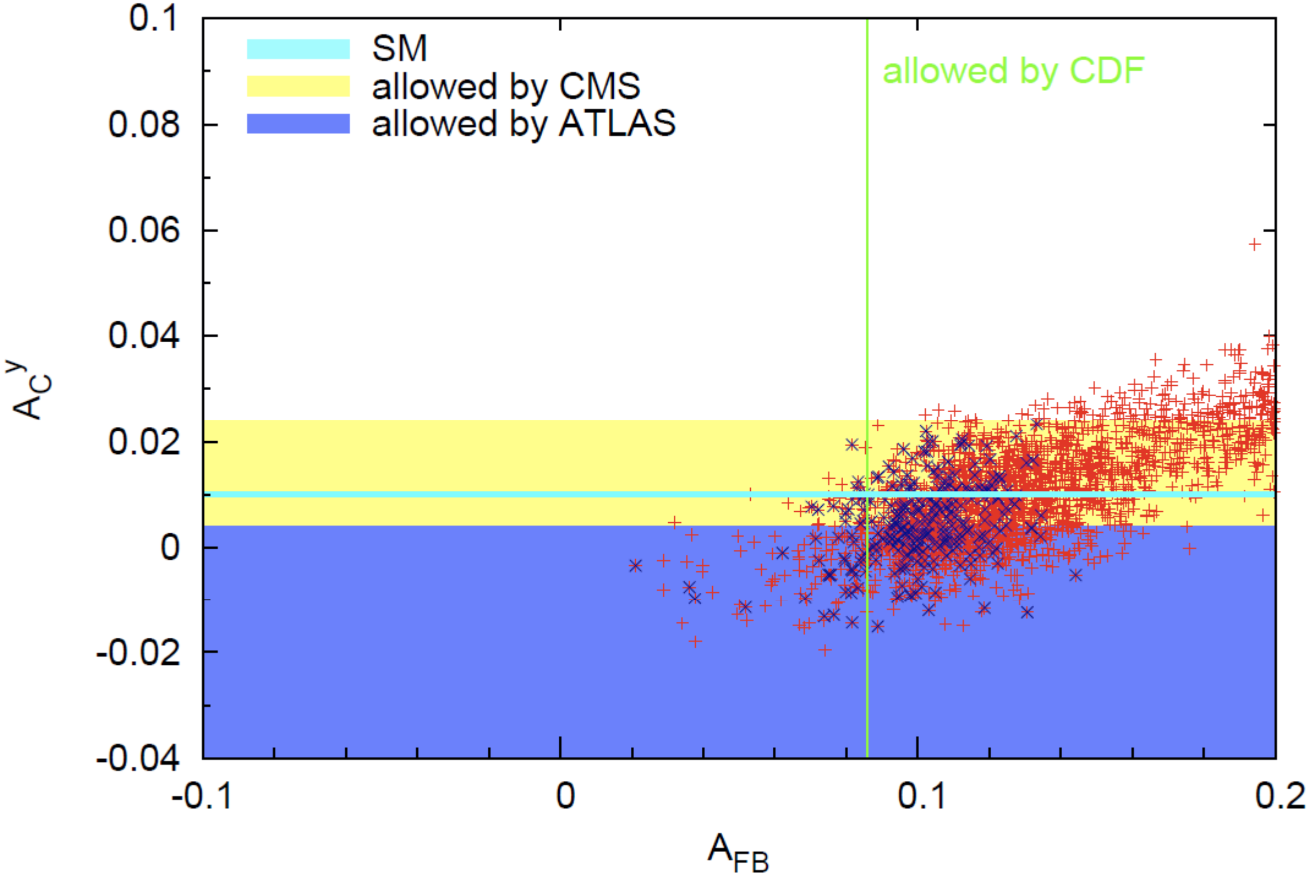
180 GeV$< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

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

A_{FB} versus A_C^y



$m_{Z'} = 145$ GeV

180 GeV$< m_h < 1$ TeV

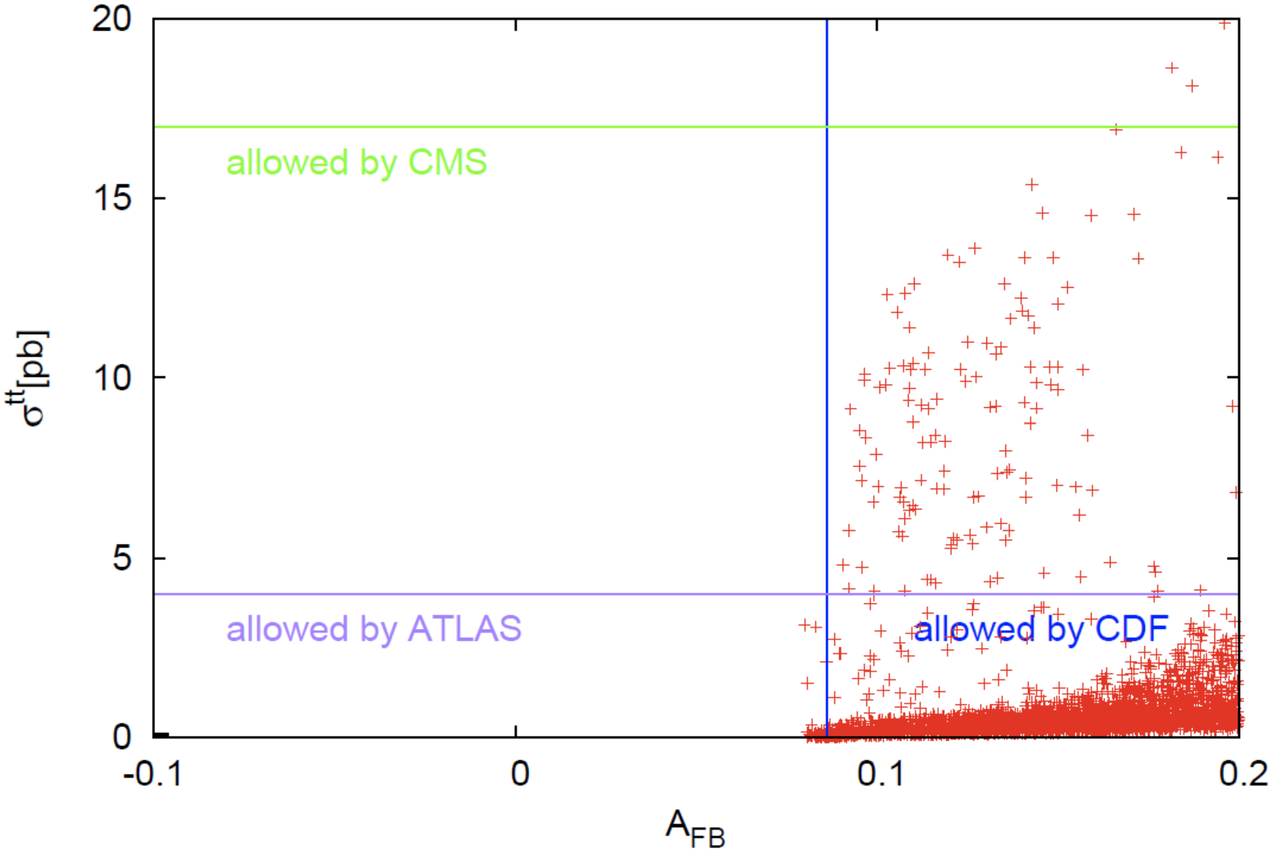
180 GeV$< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

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

A_{FB} versus σ_{tt}



$m_h = 126$ GeV

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

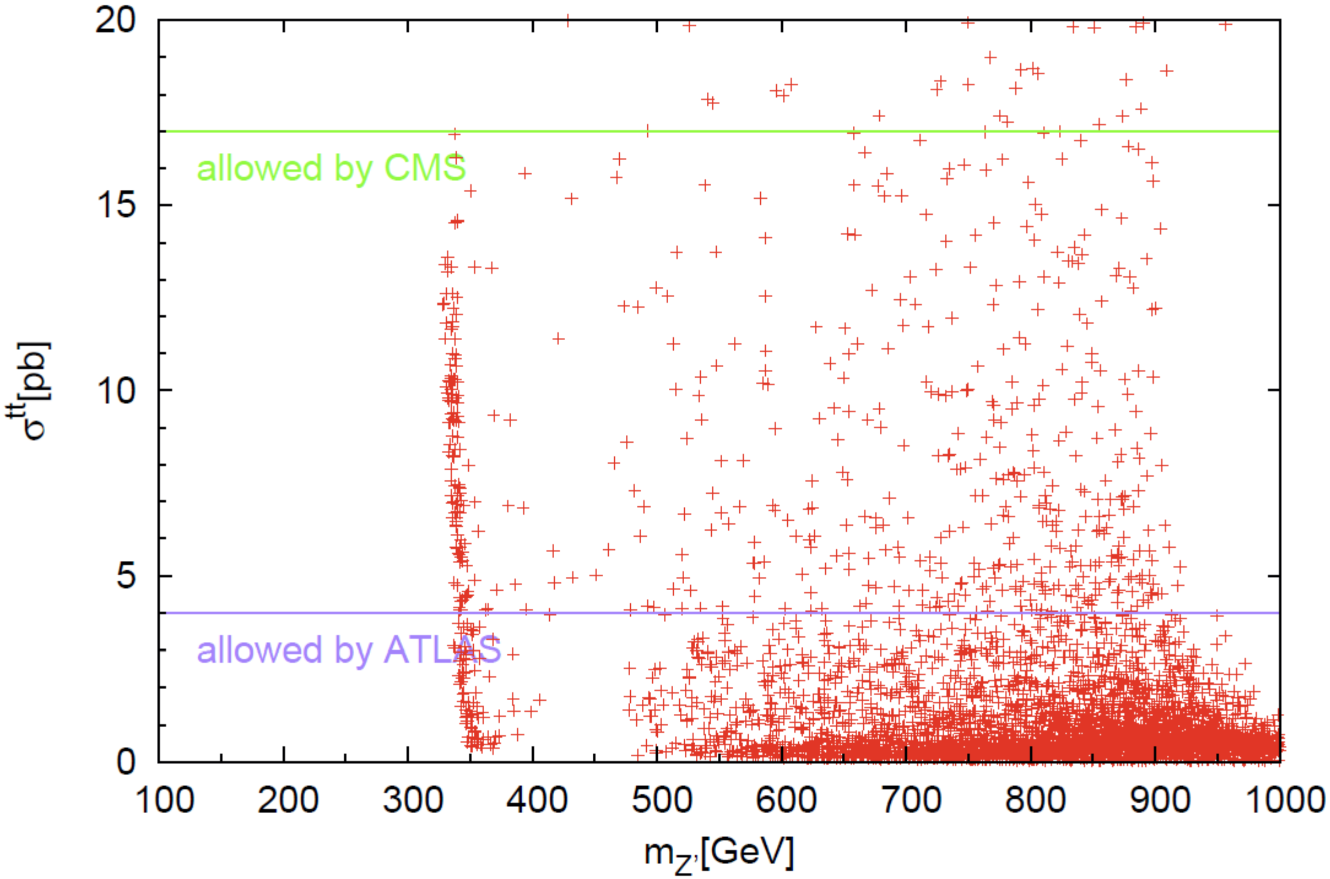
180 GeV $< m_a <$ 1 TeV

$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

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

$m_{Z'}$ versus σ_{tt}



$m_h = 126$ GeV

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

180 GeV$< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

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

Conclusions

• Top A_{FB} is the only signal for new physics in the top sector.

• It has motivated brilliant ideas of new physics, but many of them are rather phenomenological.

• constructed a compete U(1)′ model where only the right-handed up-type quarks in the standard model are charged.

• requires extra Higgs doublets charged under U(1)′ for a realistic model.

• requires extra chiral fermions for anomaly cancellation → CDM.

• Destructive interferences between Z', h, and a reduce the rate for the same sign top pair production.

Conclusions

• Simple models as well as our chiral U(1)′ models would be constrained by the measurements for the charge asymmetry , same sign top pair production, the m_{tt} distribution at the LHC, polarization of the top quark, and etc.

• The light Higgs boson could be compatible with our model if its coupling to the top and up quarks is well suppressed. In this case, the second lightest Higgs boson could be assumed to be responsible for the t-channel diagram.

Thank you for your attention!