Lessons from the bygone anomalies: From Data to Models to Theories

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The Joint International Workshop on SM and Beyond 2024 &
The 3rd Gordon Godfrey Workshop on Astroparticle Physics
UNSW, Sydney, Dec 9-13 (2024)

Two Ways to Interprete the Data

EFT & Simplified Models vs.
(The Simplest) UV Completions

Many Bygone Anomalies

- Large FCNC ~ FCCC Weak Interactions before GIM
- Muon g-2, ATOMKI, MiniBooNE, ….
- CDF Wjj, Top FBA, 750 GeV diphoton,
- DM related ones: 511 keV γ ray excess, PAMELA e^+ excess, Galactic Center γ ray excess, XENON1T, ….

Reappraisal of SM

Current Status of SM

- Only Higgs (~SM) and Nothing Else so far at the LHC
- Yukawa & Higgs self couplings to be measured and tested
- Nature is described by Quantum Local Gauge Theories
- Unitarity and gauge invariance played key roles in development of the SM

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Exp's
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

Accidental Sym’s of SM

- Renormalizable parts of the SM Lagrangian conserve baryon #, lepton # : broken only by dim-6 and dim-5 op’s $\longrightarrow$“longevity of proton” and “lightness of neutrinos” becoming Natural Consequences of the SM (with conserved color in QCD)

- QCD and QED at low energy conserve P and C, and flavors

- In retrospect, it is strange that P and C are good symmetries of QCD and QED at low energy, since the LH and the RH fermions in the SM are independent objects

- What is the correct question ? “P and C to be conserved or not ?” Or “LR sym or not ?”

How to do Model Building

- Specify local gauge sym, matter contents and their representations w/o any global sym
- Write down all the operators upto dim-4
- Check anomaly cancellation
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- You may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

Usual Approaches

- Introduce a minimal set of particles to explain anomalies
- Very often symmetry issues (SM gauge symmetry or new gauge/global symmetry) are ignored
- Very often nonrenormalizable operators are used, ignoring unitarity issues $\longrightarrow$ can produce incorrect results, especially for DM productions at high energy colliders
- Unitarity and Gauge invariance: most important

Motivations for BSM

Pheno'cal Motivations

- Neutrino masses and mixings
- Baryogenesis
- Inflation (inflaton)
- Nonbaryonic DM
- Origin of EWSB and Cosmological Const ?

Leptogenesis

Starobinsky & Higgs Inflations

?

Many candidates

Can we attack these problems ?

Theoretical Motivations

- Fine tuning problem of Higgs mass parameter : SUSY, RS, ADD, etc.
- Critical comments in the Les Houches Lecture by Aneesh Manohar (arXiv:1804.05863)
- Standard arguments :
  - Electron self-energy in classical E&M vs. QED
  - Δm_K without/with charm quark
  - $\Delta m^2 = m_{\pi^\pm}^2 - m_{\pi^0}^2$ without/with ρ mesons
  - These arguments are simply wrong !

My Personal Viewpoints

- Traditionally Fine Tuning or Naturalness problem was the driving force for many BSM, and predicted many signatures @ LHC
- No signatures @ LHC means that the traditional motivation is not that well motivated
- Mathematical and Theoretical Consistency : more important for BSM model buildings
- Unitarity is one of the Holy Grails in EFT approach

Anomaly Free : before/after GIM

Before GIM

- Weinberg Model for u,d,s :
  $(u_L, d_L \cos\theta_c + s_L \sin\theta_c)^T$, $u_R, d_R, s_R,$

- Predicts FCNC ~ FCCC :
  $\Gamma(K^+ \to \mu^+\nu_\mu) \sim \Gamma(K^0 \to \mu^+\mu^-)$, in contradiction to the exp data. What is going on ?

- Where is another combination,
  $(-d_L \sin\theta_c + s_L \cos\theta_c)$?

GIM (1970)

- GIM proposed to introduce the 4th quark, “charm”, as the SU(2) partner of the 2nd combination
- FCNC=0 @ tree level, and induced at loops
- $m_c \sim 1.5$ GeV explains Δm_K (Gaillard, Lee, Rossner, 1974), and confirmed by discovery of J/ψ in 1974 !
- In retrospect, large FCNC is a wrong prediction of anomalous gauge theory for 3 quark flavors, which is not a healthy theory

Extra spin-1 requires extensions of the Higgs sector : Top FBA as an example

Contents

- EFT approach for Top FBA
- Phenomenological top FCNC from extra Z' with chiral interaction + Local gauge invariance : Multi-Higgs doublet models with chiral U(1)' : Ko-Omura-Yu Model
- Details of top FCNC, B decays and related issues
- EFT : Reappraisal and Caution

- In the usual EFT approach, one imposes only the SM gauge invariance (full or unbroken)
- If there are new spin-1 particle around, then one has to impose a new gauge symmetry on EFT operators
- Within EFT, some observables cannot be described without introducing additional sets of effective operators
- If we consider renormalizable and unitary models with local gauge invariance, one can study many different observables, although the results are model-dependent
- This approach is discussed in this talk in the context of top forward-backward asymmetry

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

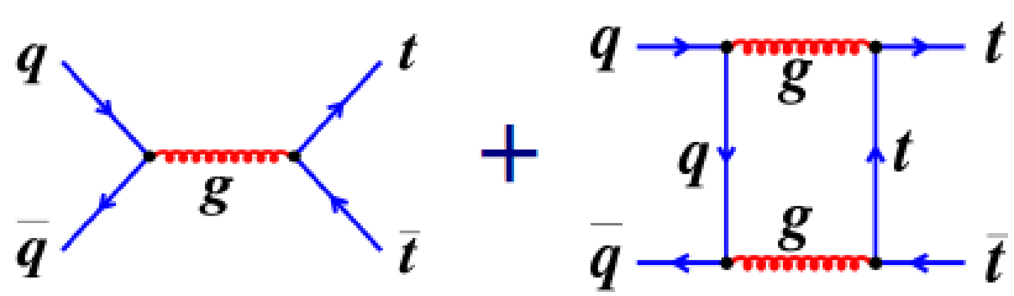
Contents

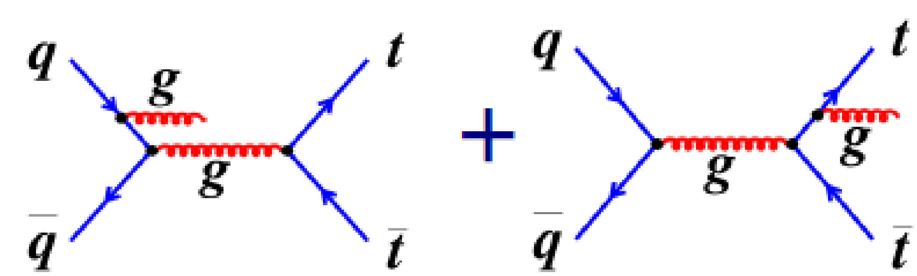
- SM Prediction vs. Data
- Z' model for Top FBA
- Flavor dependent U(1)' model
- Conclusion & General Remarks

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:

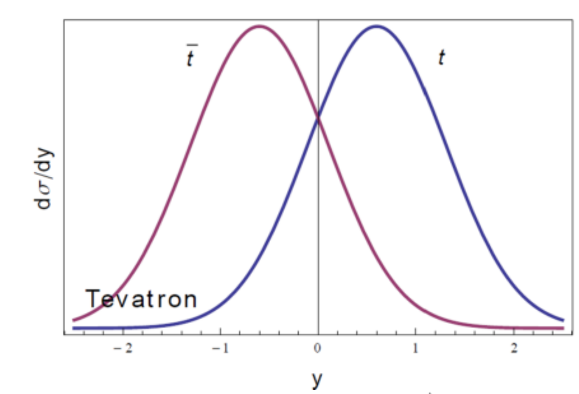
- Top quark is emitted preferentially in direction of the incoming quark
- Antitop quark opposite
- Production through new processes may lead to different asymmetries





- At Tevatron: define forward-backward asymmetry

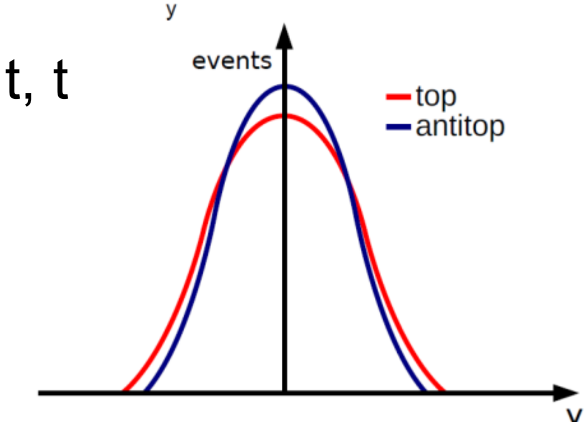
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



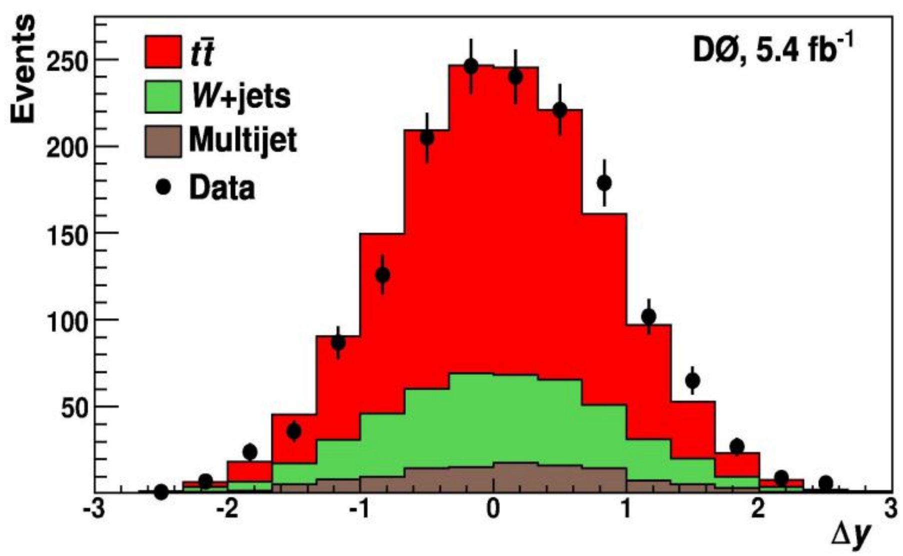
- At LHC: define asymmetry in the widths of rapidity distributions of t, $\bar{t}$

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

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



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

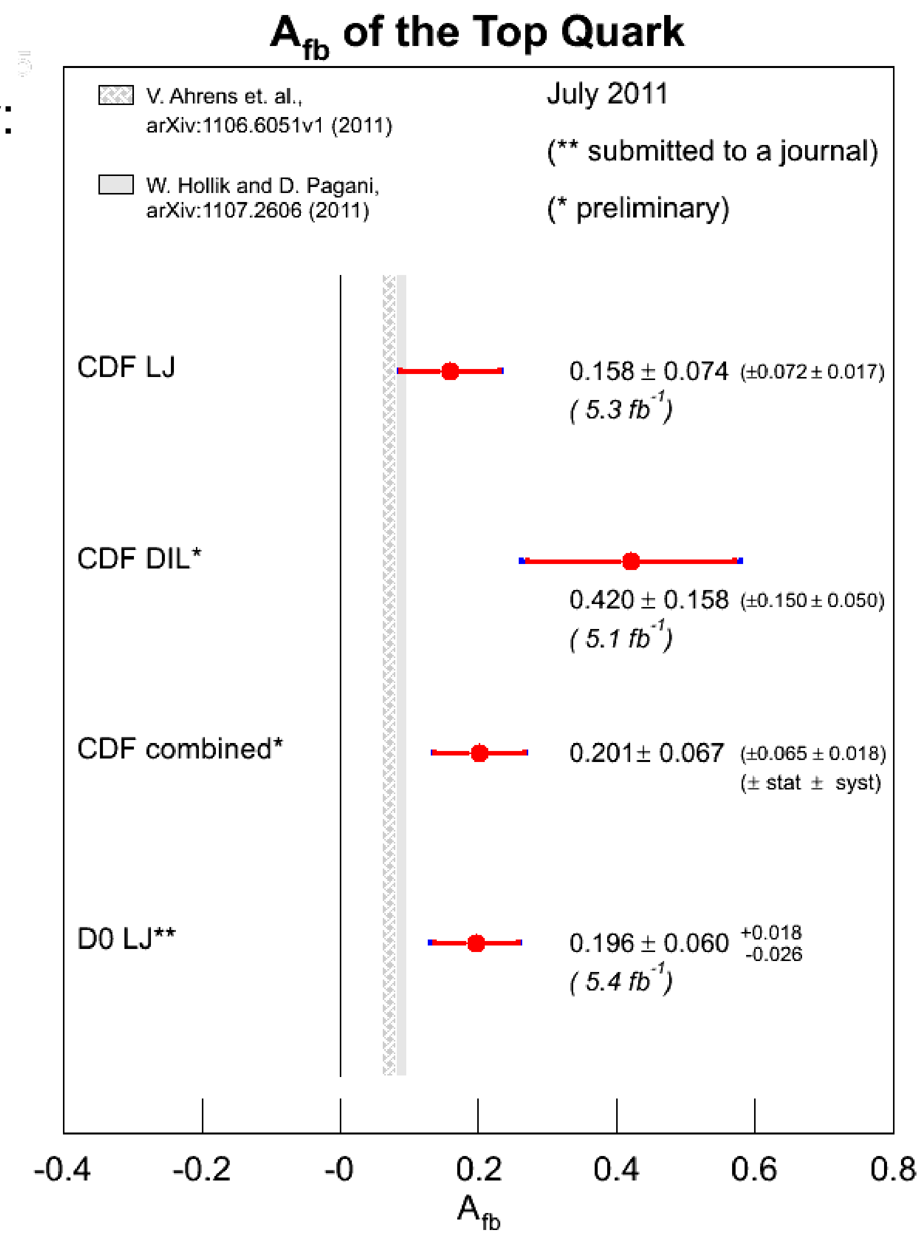
Measured asymmetry on parton level:

A_{FB} = 0.196 ± 0.065 (stat+syst)

D0 results in the di-lepton channel:

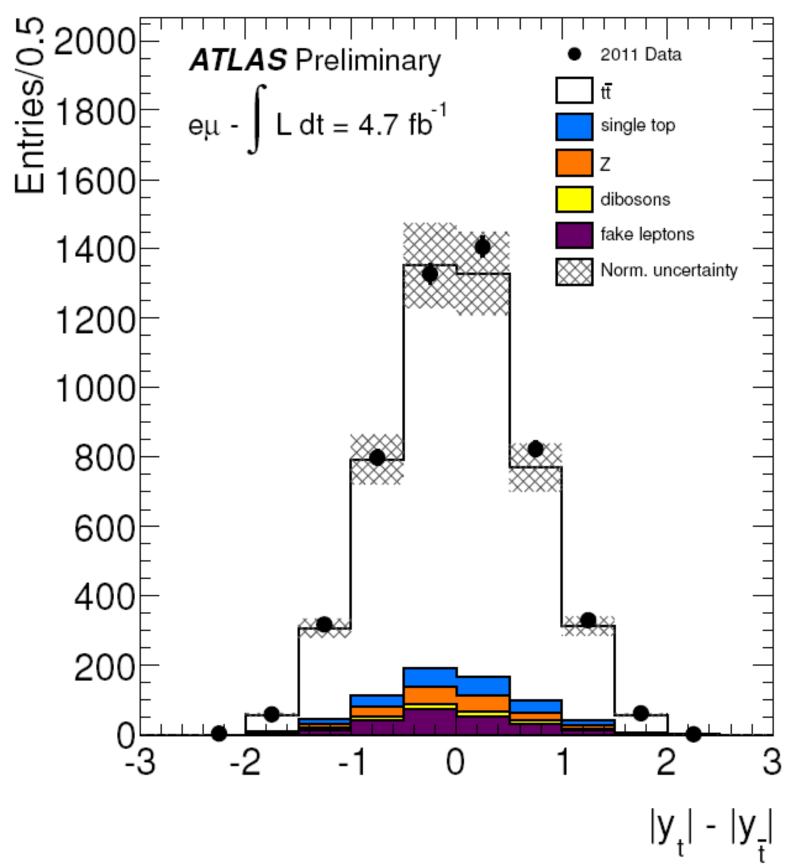
A_{FB} = 0.118 ± 0.032

Summary:

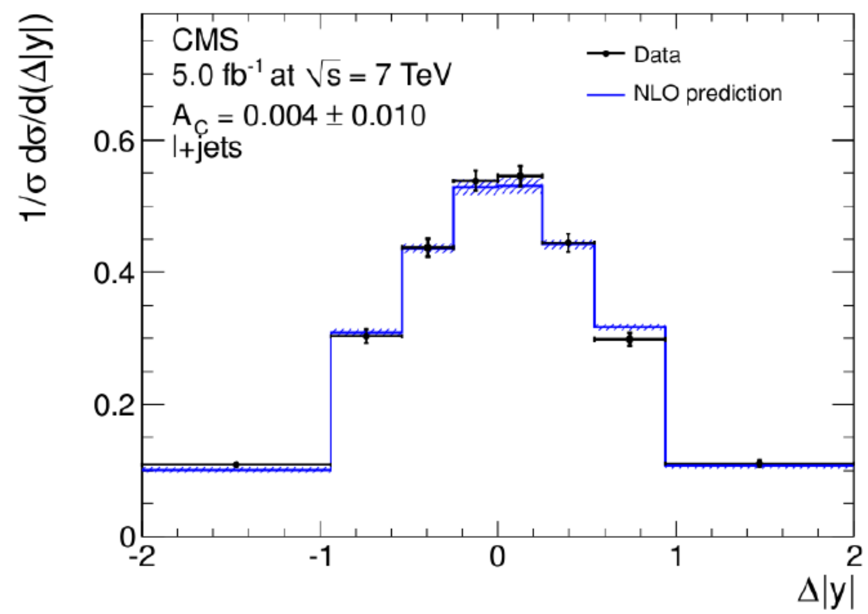


Both CDF and D0 see significant asymmetry in $t\bar{t}$ production in all channels with strong dependence on m_{tt}, in conflict with the SM

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



ATLAS-CONF-2012-057

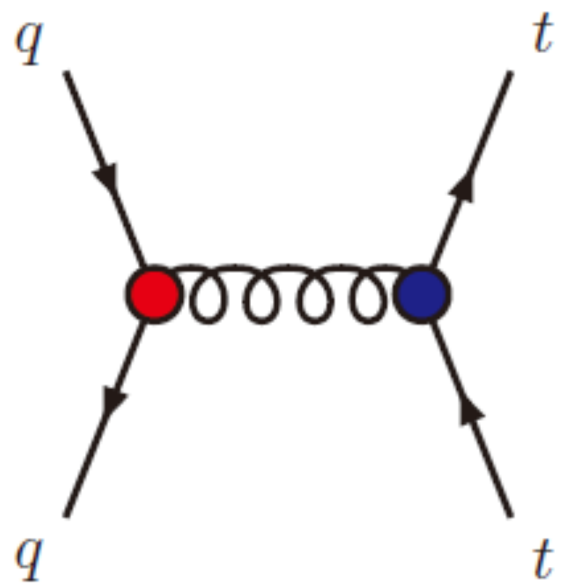


CMS PAPER TOP-11-030

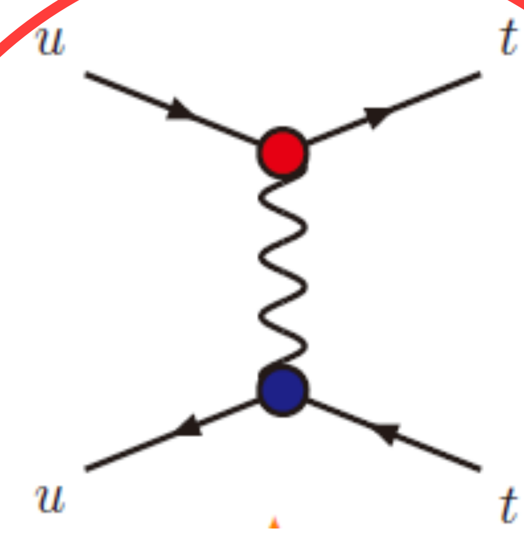
- ATLAS: A_C = 0.029 +- 0.018 (stat.) +- 0.014 (syst.)
- CMS: Corrected: A_C = 0.004 +- 0.010 (stat.) +- 0.011 (syst.)

- Theory (Kühn, Rodrigo): A_C = 0.0115 +- 0.0006

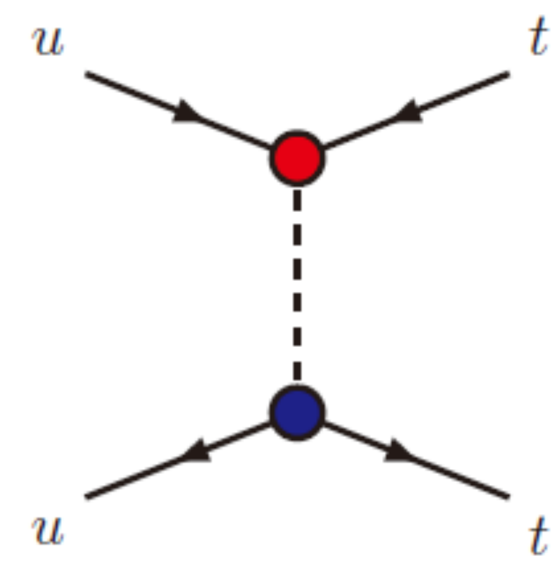
New physics models for top A_{FB}



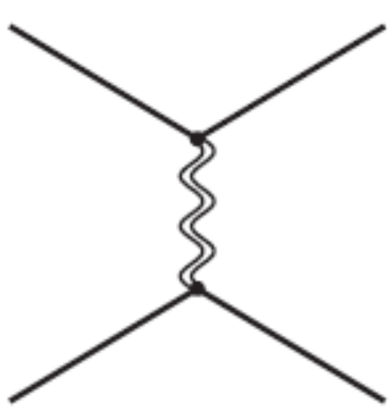
s-channel: coloured resonance $\mathcal{G}_\mu$



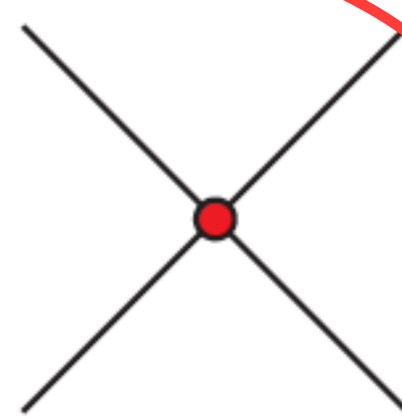
t-channel: Z', W', ϕ



u-channel: exotic scalars



(new) heavy VB



4-fermion interaction

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

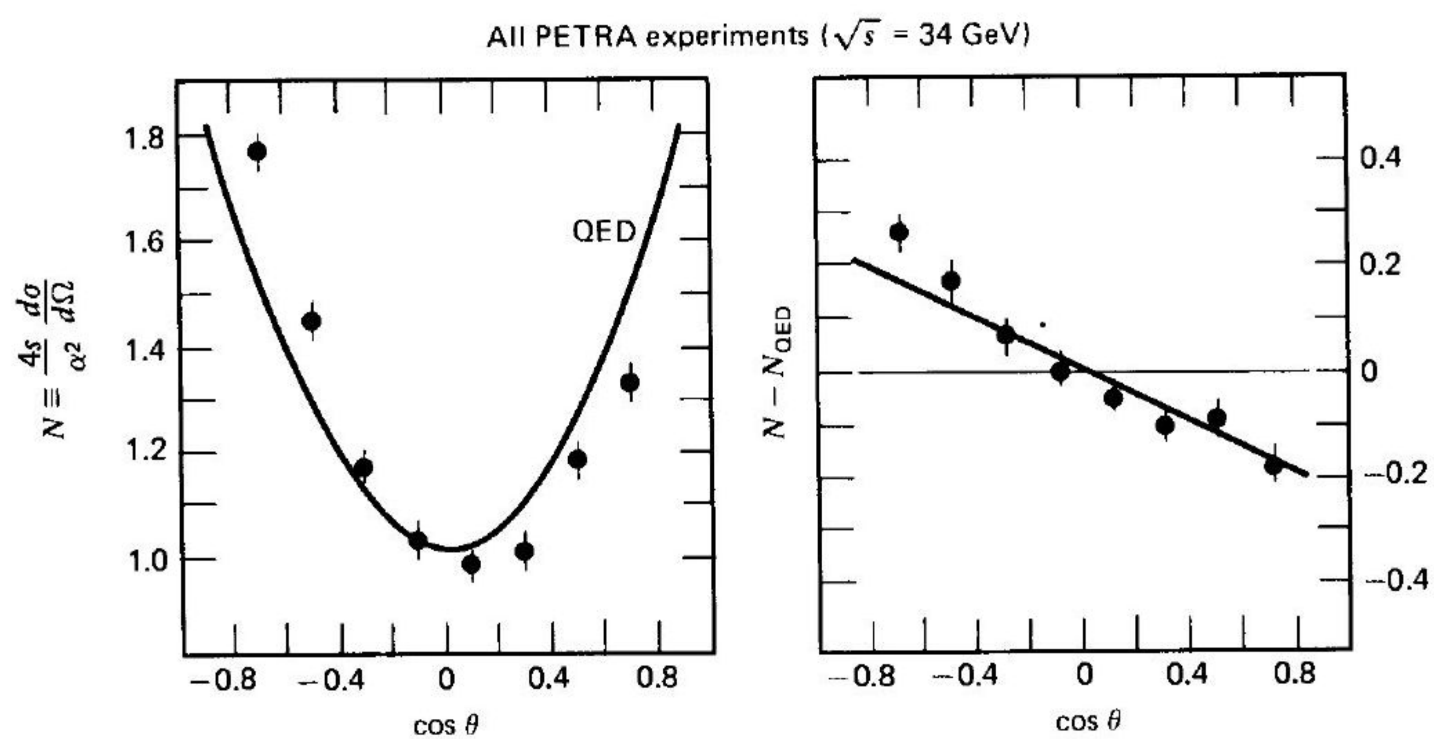
- flavor dependent.
- challenging to construct a realistic model.
  - anomaly free, renormalizable, and realistic Yukawa couplings.

EFT Approaches

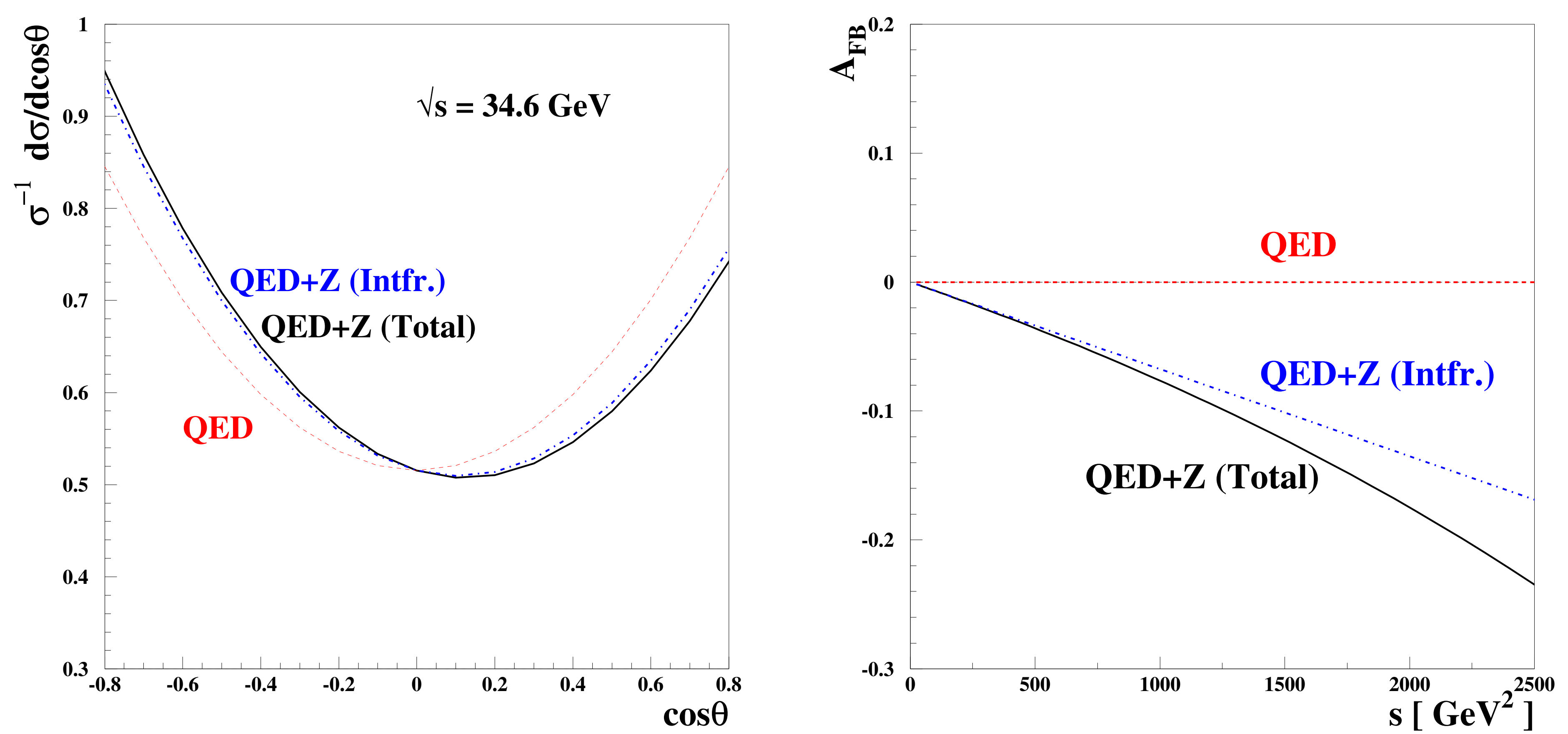
Based on arXiv:0912.1105 (PLB)
arXiv:1011.5976 (PLB)
arXiv:1104.4443 (PRD)
with Dong Won Jung, Jae Sik Lee
(and Su Hyun Nam)

Wisdom from EW Physics

- The first evidence of asymmetry was found in angular distribution of muons from e^+e^- collisions at PETRA in the 80's ($\sqrt{s} \sim 30$ GeV , well below the Z^0 pole)



- Source of A_{FB} is a term linear in $\cos\theta$ from interference between γ or Z vector coupling and the axial vector Z coupling.



- Since $\sqrt{s} \ll M_Z$, good approx. to assume 4 fermion interactions by integrating out Z boson
- $A_{\rm FB} \simeq -\frac{3G_F}{\sqrt{2}} \frac{s}{4\pi\alpha}(g_L - g_R)^2 \equiv kG_F s$
- $k \simeq -7$ from EFT, whereas $k = -5.78$ from the full expression

Dim-6 Effective Op's

- $t\bar{t}$ production at the Tevatron dominated by $q\bar{q}$ channel
- Enough to consider dimension-6 four-quark operators assuming new physics scale is high enough:

$$\mathcal{L}_6 = \frac{g_s^2}{\Lambda^2} \sum_{A,B} \left[C_{1q}^{AB} (\bar{q}_A \gamma_\mu q_A)(\bar{t}_B \gamma^\mu t_B) + C_{8q}^{AB} (\bar{q}_A T^a \gamma_\mu q_A)(\bar{t}_B T^a \gamma^\mu t_B) \right]$$

where

$$T^a = \lambda^a/2, \quad \{A, B\} = \{L, R\}, \quad L, R \equiv (1 \mp \gamma_5)/2 \quad (q = u, d, s, c, b)$$

- Other d=6 operators are all reducible to the above operators after Fierzing (Hill and Parke 1994)
- We ignore flavor changing dim-6 operators such as $\overline{d_R}\gamma^\mu s_R \overline{t_R}\gamma_\mu t_R$, since those contributions to the $t\bar{t}$ production cross section will be of a order $1/\Lambda^4$

(Helicity Amp)^2

- The squared helicity amplitude is given by

$$\overline{|\mathcal{M}(t_L\bar{t}_L + t_R\bar{t}_R)|^2} = \frac{4\,g_s^4}{9\,\hat{s}} m_t^2 \left[2 + \frac{\hat{s}}{\Lambda^2}(C_1 + C_2)\right] s_{\hat{\theta}}^2$$

$$\overline{|\mathcal{M} t_L\bar{t}_R + t_R\bar{t}_L)|^2} = \frac{2\,g_s^4}{9} \Big[\left(1 + \frac{\hat{s}}{2\Lambda^2}(C_1 + C_2)\right)(1 + c_{\hat{\theta}}^2) + \hat{\beta}_t \left(\frac{\hat{s}}{\Lambda^2}(C_1 - C_2)\right) c_{\hat{\theta}} \Big]$$

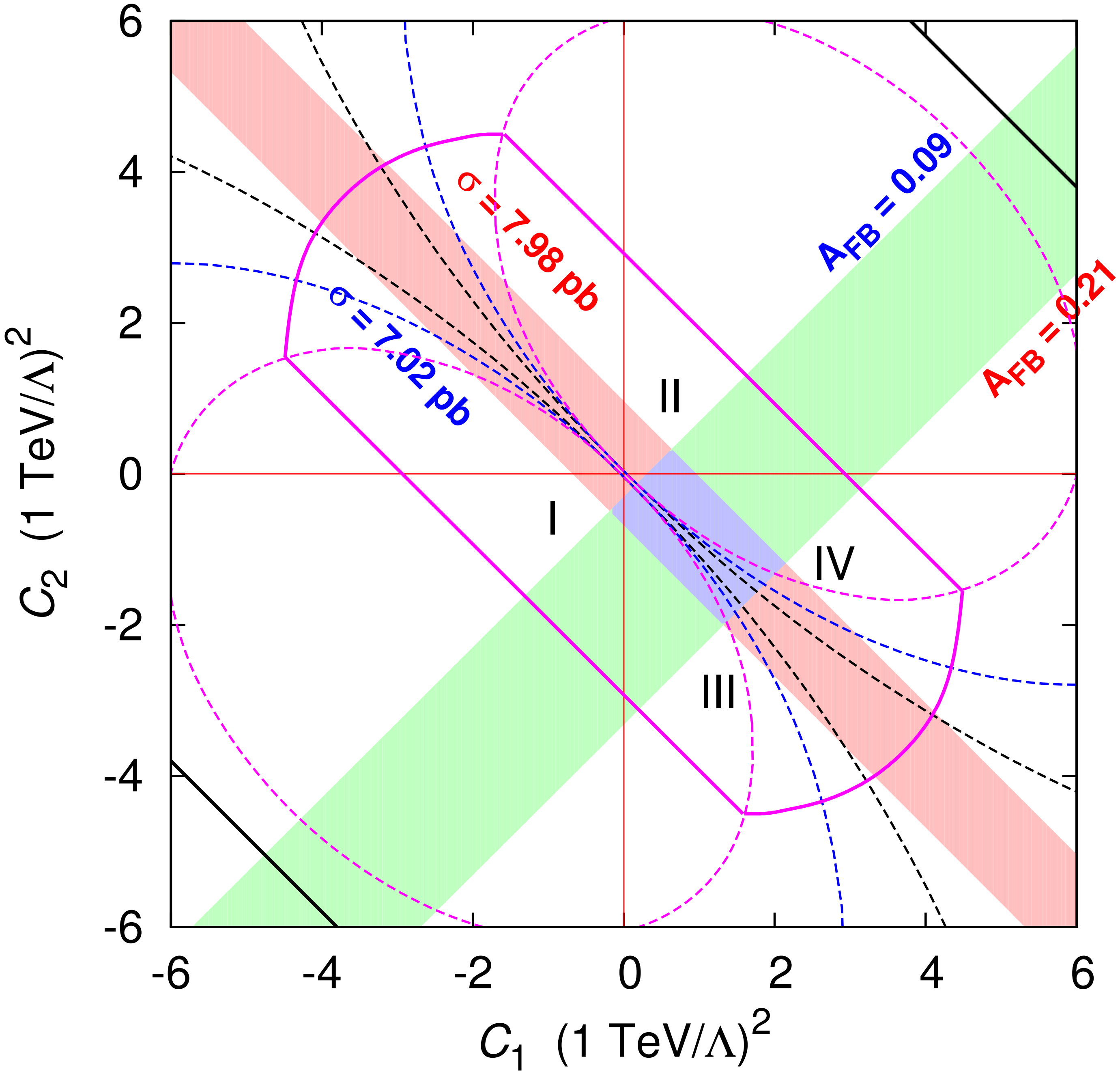
where

$$C_1 \equiv C_{8q}^{LL} + C_{8q}^{RR}, \quad C_2 \equiv C_{8q}^{LR} + C_{8q}^{RL}$$

$$\hat{\beta}_t^2 = 1 - 4m_t^2/\hat{s}, \quad s_{\hat{\theta}} \equiv \sin\hat{\theta}, \quad c_{\hat{\theta}} \equiv \cos\hat{\theta}$$

- The term linear in $\cos\hat{\theta}$ could generate the foreward-backward asymmetry which is propotional to $\Delta C \equiv C_1 - C_2$.

Favored Region



AFB as functions of M(tt)

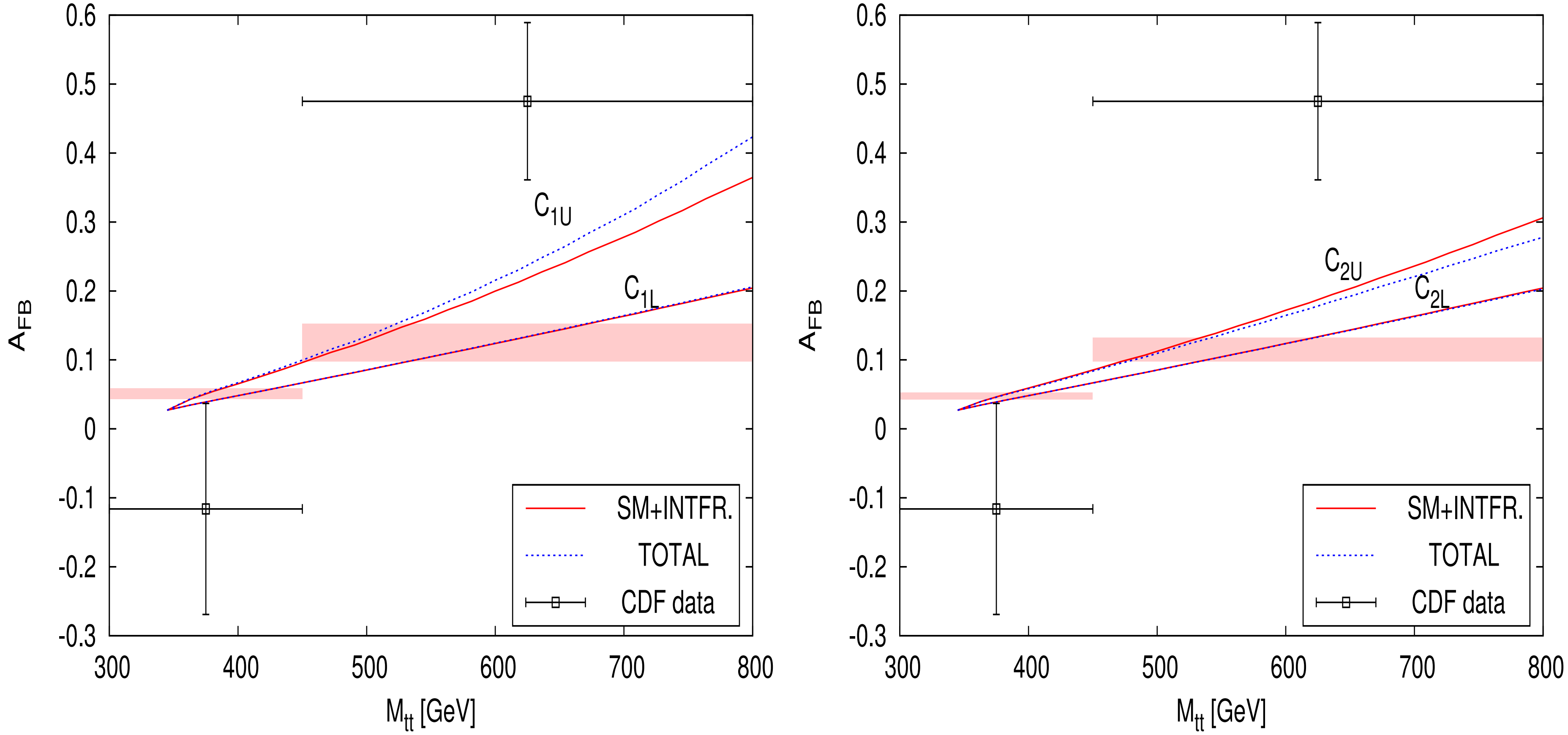


Figure: *Top FB asymmetry as functions of $M_{t\bar{t}}$. In the left frames we are taking C_1 in the range between $C_{1L} = 0.15$ and $C_{1U} = 0.97$ with $C_2 = 0$. In the right frames, we vary C_2 in the range between $C_{2L} = -0.15$ and $C_{2U} = -0.67$ with $C_1 = 0$.*

Spin-1 Resonances

- One can consider the following interactions of quarks with spin-1 flavor-conserving (changing) color-singlet $V_1(\tilde{V}_1)$ and color-octet $V_8^a(\tilde{V}_8^a)$ vectors ($A = L, R$) relevant to A_{FB}^t:

$$\mathcal{L}_V = g_s V_1^\mu \sum_A \left[g_{1q}^A (\bar{q}_A \gamma_\mu q_A) + g_{1t}^A (\bar{t}_A \gamma_\mu t_A) \right]$$
$$+ g_s V_8^{a\mu} \sum_A \left[g_{8q}^A (\bar{q}_A \gamma_\mu T^a q_A) + g_{8t}^A (\bar{t}_A \gamma_\mu T^a t_A) \right]$$
$$+ g_s [\tilde{V}_1^\mu \sum_A \tilde{g}_{1q}^A (\bar{t}_A \gamma_\mu q_A) + \tilde{V}_8^{a\mu} \sum_A \tilde{g}_{8q}^A (\bar{t}_A \gamma_\mu T^a q_A) + \text{h.c.}]$$

Spin-0 resonance

- Following interactions of quarks with spin-0 flavor-changing color-singlet $\tilde{S}_1$ and color-octet $\tilde{S}_8^a$ scalars could also contribute to A_{FB}^t:

$$\mathcal{L}_{\tilde{S}} = g_s \big[\tilde{S}_1 \sum_A \tilde{\eta}_{1q}^A (\bar{t} A q) + \tilde{S}_8^a \sum_A \tilde{\eta}_{8q}^A (\bar{t} A T^a q) + \mathrm{h.c.} \big]$$

- One can also consider color-triplet S_k^γ and color-sextet scalars $S_{ij}^{\alpha\beta}$ with minimal flavor violating interactions with the SM quarks (Arnold, Pospelov, Trott, Wise):

$$\mathcal{L}_S = g_s \Big[\frac{\eta_3}{2} \epsilon_{\alpha\beta\gamma} \epsilon^{ijk} u_{iR}^\alpha u_{jR}^\beta S_k^\gamma + \eta_6 u_{iR}^\alpha u_{jR}^\beta S_{ij}^{\alpha\beta} + h.c. \Big]$$

Wilson Coefficients

- After integrating out the heavy vectors and scalars, we obtain the Wilson coefficients as follows:

$$
\begin{aligned}
\frac{C_{8q}^{LL}}{\Lambda^2} &= -\frac{1}{m_V^2} g_{8q}^L g_{8t}^L - \frac{1}{m_{\tilde{V}}^2}\left[2|\tilde{g}_{1q}^L|^2 - \frac{1}{N_c}|\tilde{g}_{8q}^L|^2\right] \\
\frac{C_{8q}^{RR}}{\Lambda^2} &= -\frac{1}{m_V^2} g_{8q}^R g_{8t}^R - \frac{1}{m_{\tilde{V}}^2}\left[2|\tilde{g}_{1q}^R|^2 - \frac{1}{N_c}|\tilde{g}_{8q}^R|^2\right] - \frac{|\eta_3|^2}{m_{S_3}^2} + \frac{2|\eta_6|^2}{m_{S_6}^2} \\
\frac{C_{8q}^{LR}}{\Lambda^2} &= -\frac{1}{m_V^2} g_{8q}^L g_{8t}^R - \frac{1}{m_{\tilde{S}}^2}\left[|\tilde{\eta}_{1q}^L|^2 - \frac{1}{2N_c}|\tilde{\eta}_{8q}^L|^2\right] \\
\frac{C_{8q}^{RL}}{\Lambda^2} &= -\frac{1}{m_V^2} g_{8q}^R g_{8t}^L - \frac{1}{m_{\tilde{S}}^2}\left[|\tilde{\eta}_{1q}^R|^2 - \frac{1}{2N_c}|\tilde{\eta}_{8q}^R|^2\right]
\end{aligned}
$$

Scoreboard

New particle	couplings	C_1	C_2	1 σ favor
V_8 (spin-1 FC octet)	$g^{L,R}_{8q,8t}$	indefinite	indefinite	$\surd$
$\tilde{V}_1$ (spin-1 FV singlet)	$\tilde{g}^{L,R}_{1q}$	$-$	0	$\times$
$\tilde{V}_8$ (spin-1 FV octet)	$\tilde{g}^{L,R}_{8q}$	$+$	0	$\surd$
$\tilde{S}_1$ (spin-0 FV singlet)	$\tilde{\eta}^{L,R}_{1q}$	0	$-$	$\surd$
$\tilde{S}_8$ (spin-0 FV octet)	$\tilde{\eta}^{L,R}_{8q}$	0	$+$	$\times$
S^{α}_3 (spin-0 FV triplet)	η_3	$-$	0	$\times$
$S^{\alpha\beta}_6$ (spin-0 FV sextet)	η_6	$+$	0	$\surd$

Constraints

- 1-σ favored values of the couplings Updated data:

$$\tilde{V}_8 \;:\; \frac{1}{N_c}\left(\frac{1\,\mathrm{TeV}}{m_{\tilde{V}}}\right)^2 \left(|\tilde{g}^L_{8q}|^2 + |\tilde{g}^R_{8q}|^2\right) \simeq 0.76(0.64)\,,$$

$$\tilde{S}_1 \;:\; \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{S}}}\right)^2 \left(|\tilde{\eta}^L_{1q}|^2 + |\tilde{\eta}^R_{1q}|^2\right) \simeq 0.62(0.49)\,,$$

$$S^{\alpha\beta}_{13} \;:\; 2\left(\frac{1\,\mathrm{TeV}}{m_{S_6}}\right)^2 |\eta_6|^2 \simeq 0.76(0.64)$$

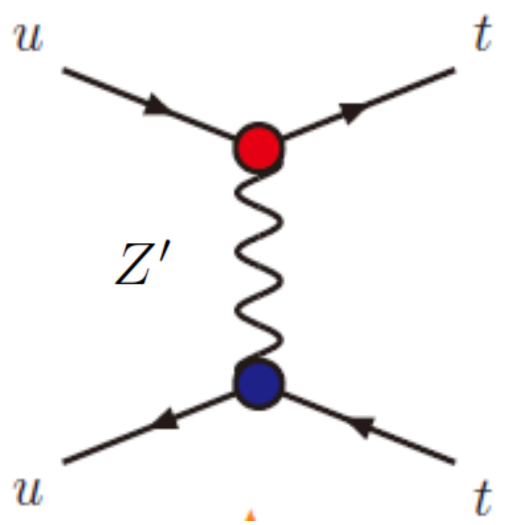
These could be discovered and tested at the LHC, by measuring the mass and the couplings

RG running effect studied in arXiv:1406.4570
w/ S.Jung, YWYoon,C.Yu (2014)

Beyond EFT : Simplified (Pheno) Model

Z′ model

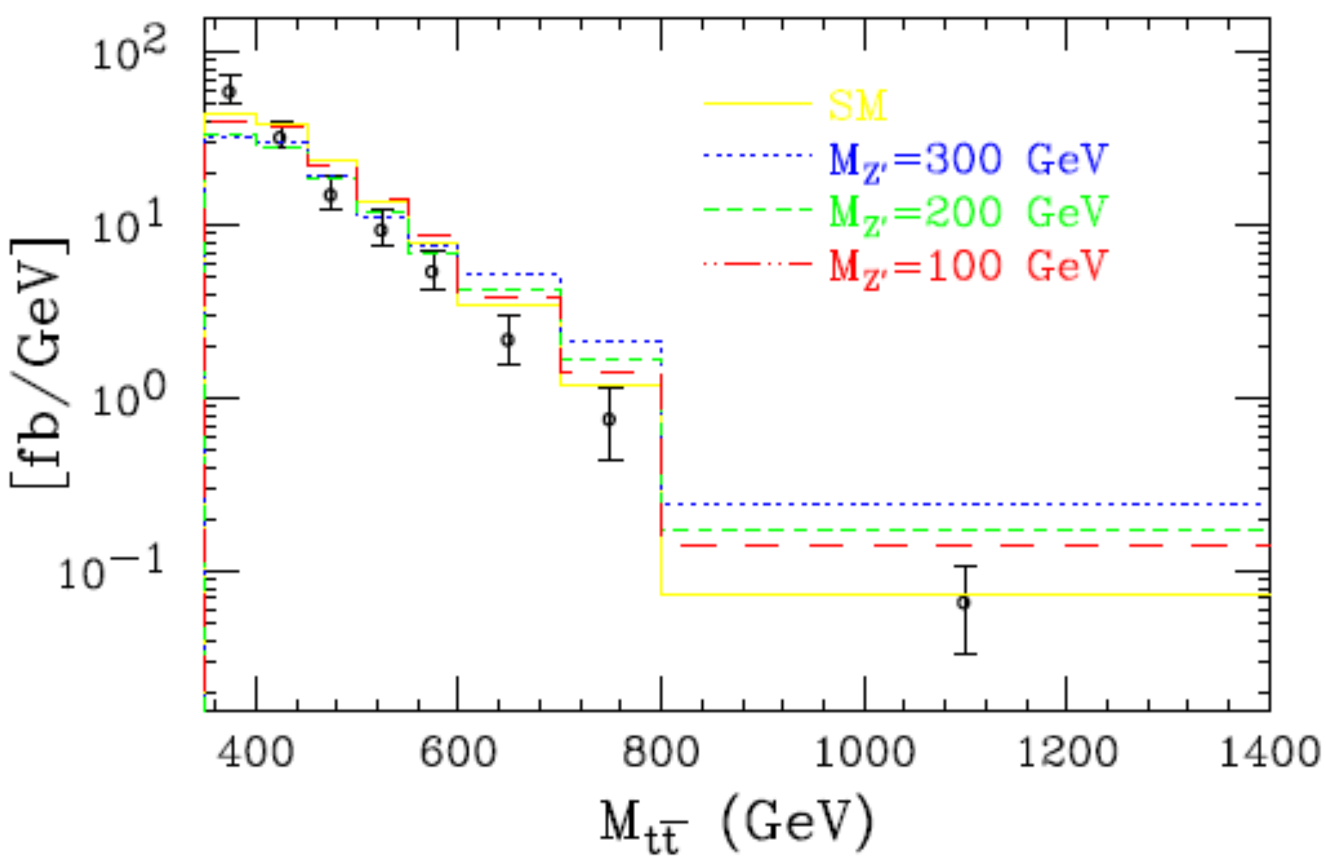
Jung, Murayama, Pierce, Wells, PRD81♪



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

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

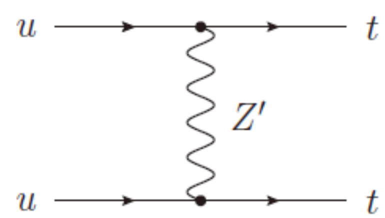
- In general, could have different couplings to the top and antitop quarks.



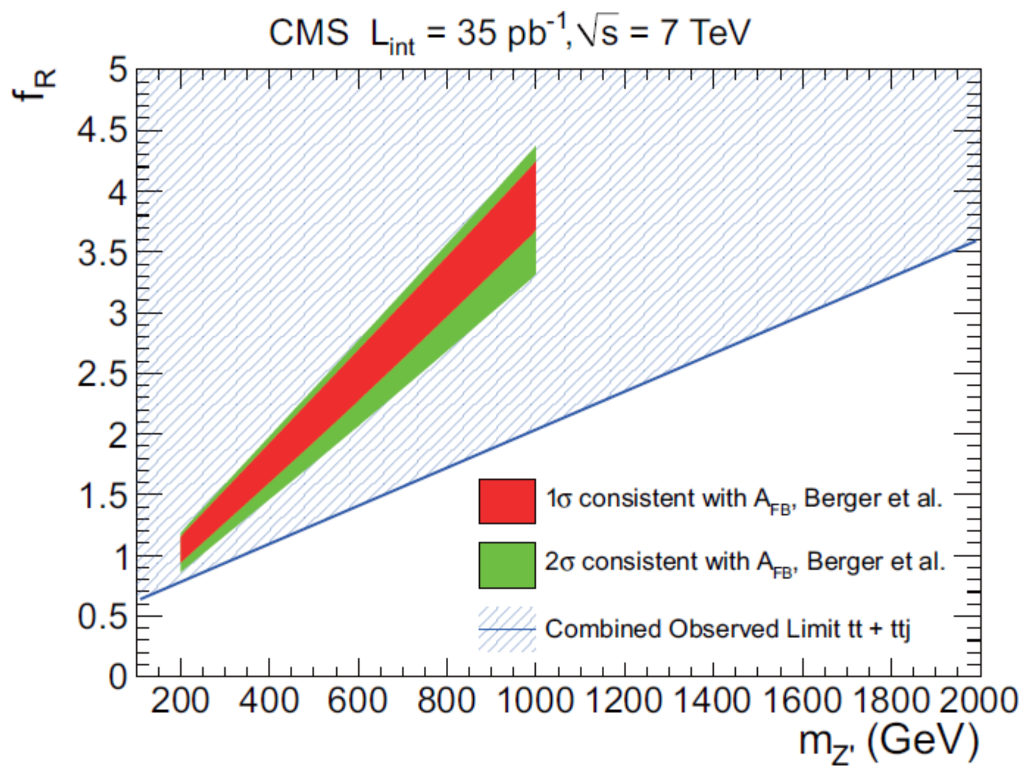
- light Z′ is favored from the M_{tt} distribution.

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

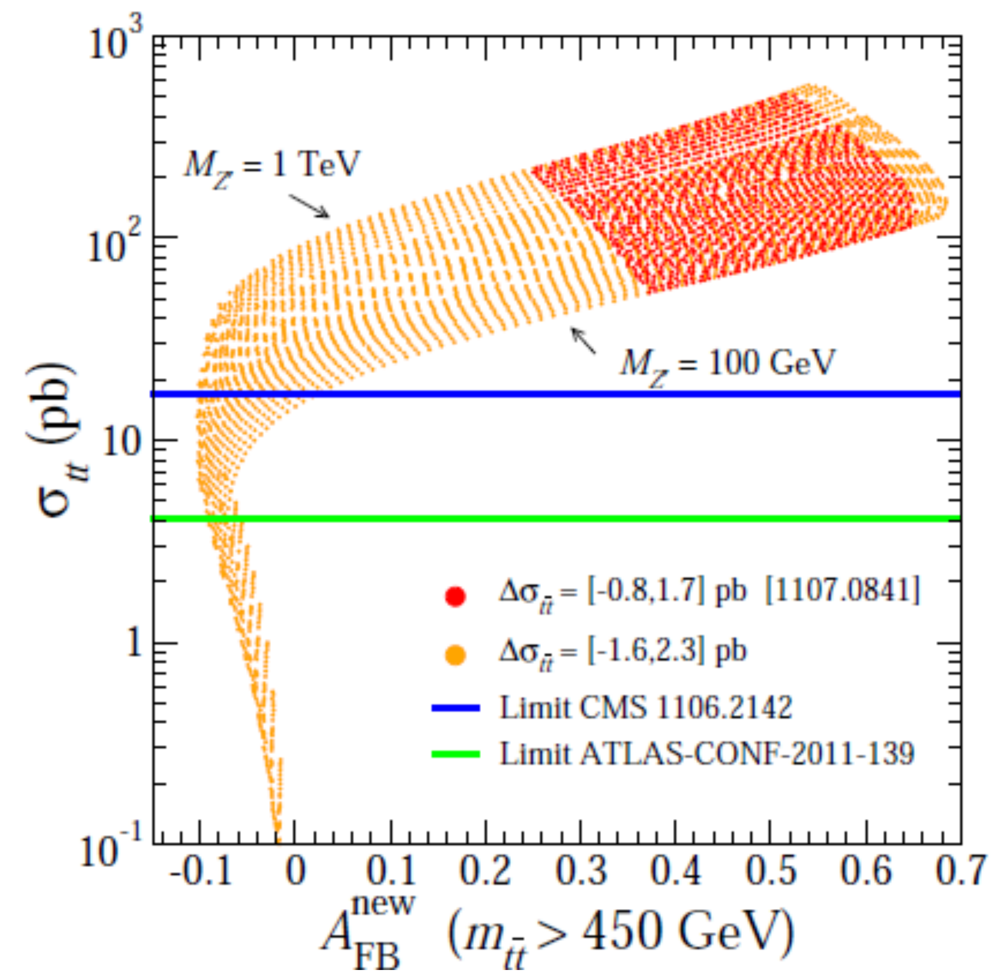
Same sign top pair production at LHC



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



General exclusion plot



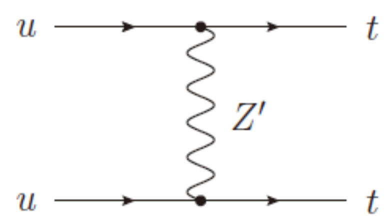
CMS: σ(pp→tt(j))<17 pb at 95C.L.
ATLAS: σ(pp→tt(j))<4 pb at 95C.L.

CMS, JHEP1108; ATLAS-CONF-2011-169♪

Aguilar-Saavedra, TOP2011♪

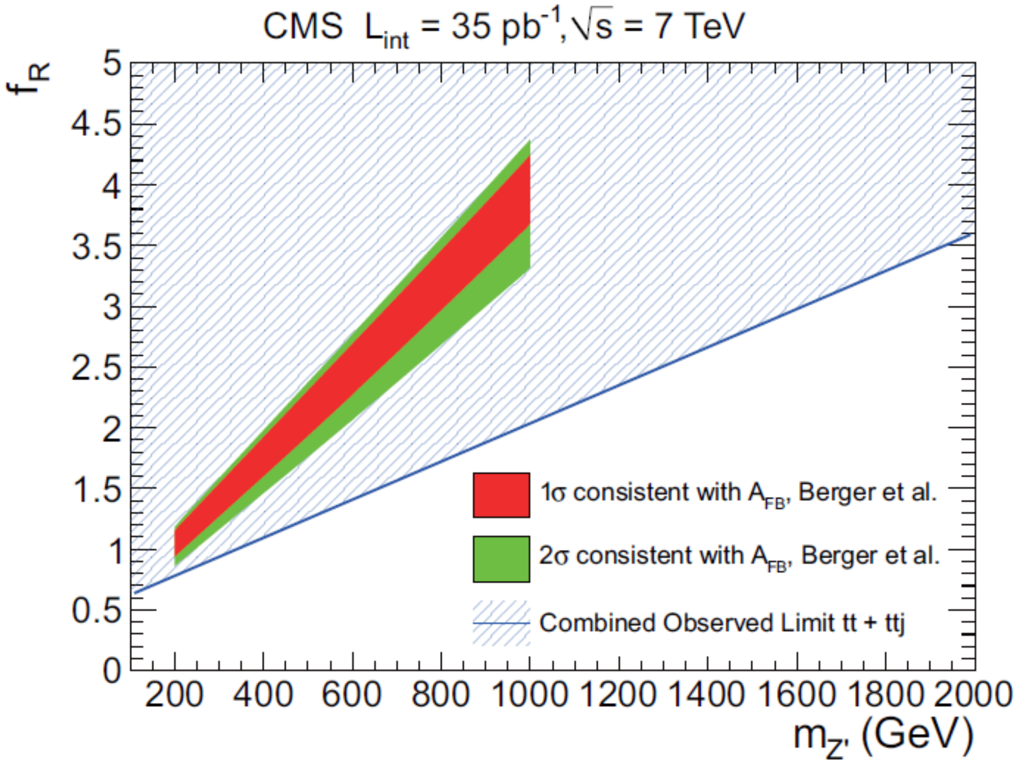
- the t-channel Z′ or scalar exchange models are excluded?

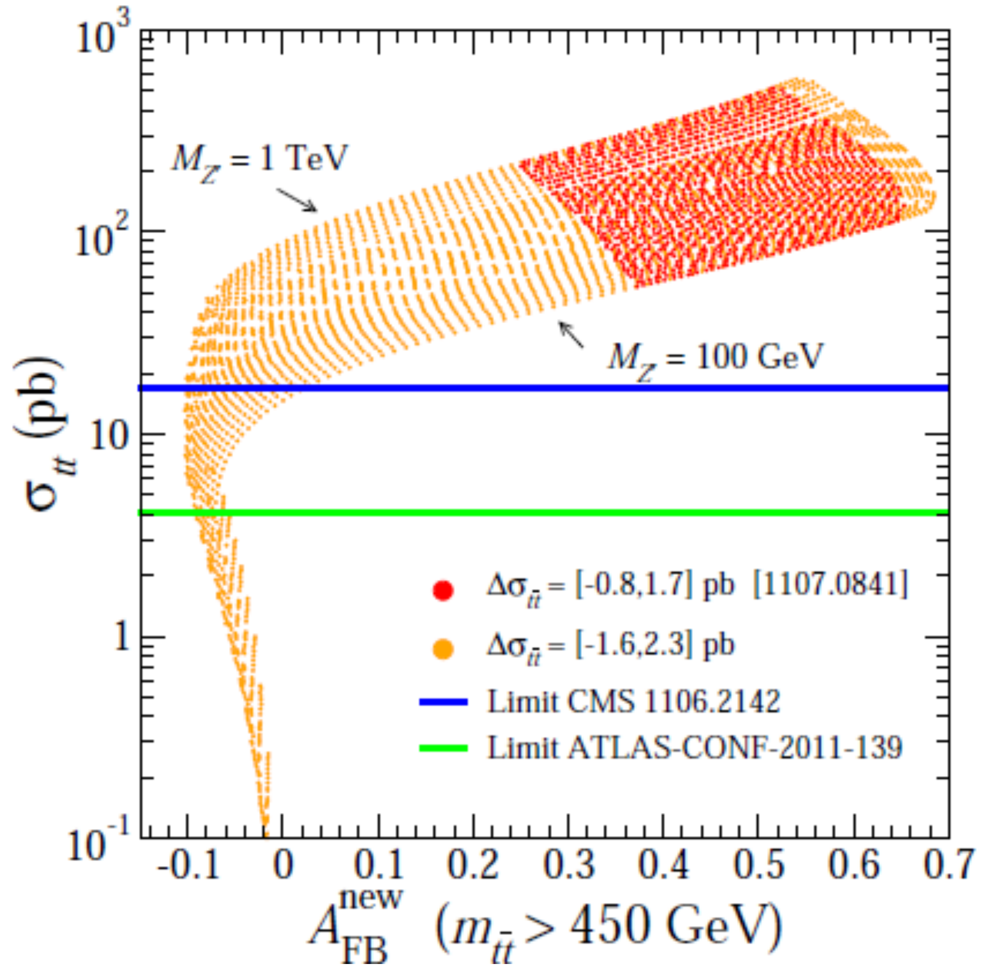
Same sign top pair production at LHC



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

General exclusion plot





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Aguilar-Saavedra, TOP2011

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

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 !

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 : leptophobic 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 ?

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

Not gauge invariant

Gauge invariant : OK!

No Yukawa's for up-type quarks:

MASSLESS TOP QUARK !

How to cure this problem ?

This problem is independent of top FCNC

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

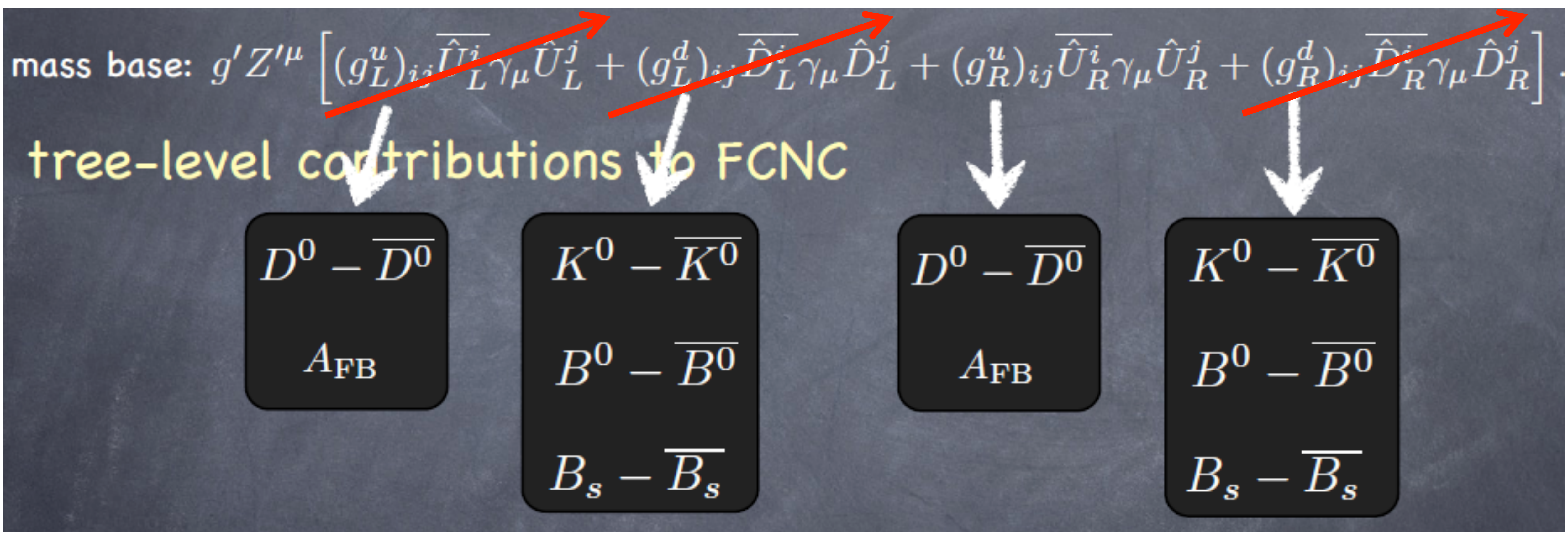
- Z′ interacts only with the right-handed up-type quarks

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

- 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

- 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

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

Flavor-dependent U(1)′ model

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

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

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

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

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

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

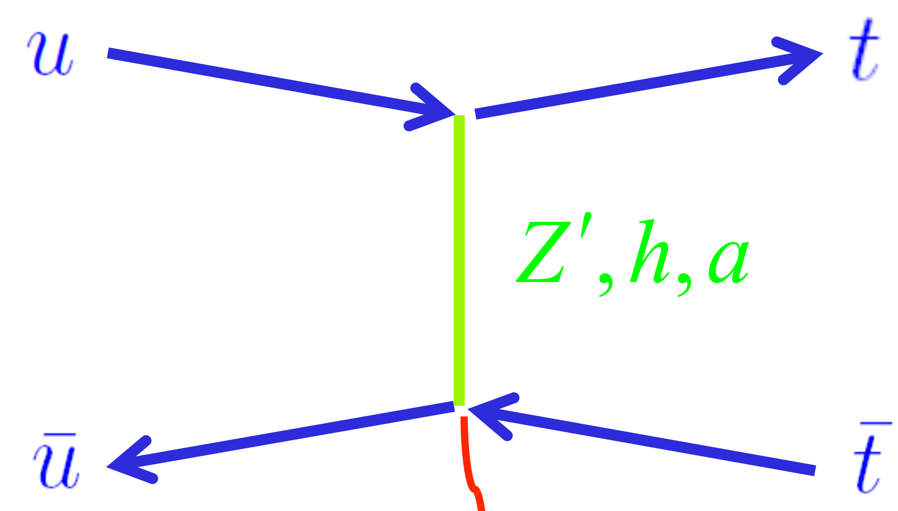
$$Y^{ad}_{ij} = \frac{m^d_i\tan\beta}{v}\delta_{ij},$$

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

Top-antitop pair production

1. Z′ dominant scenario

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



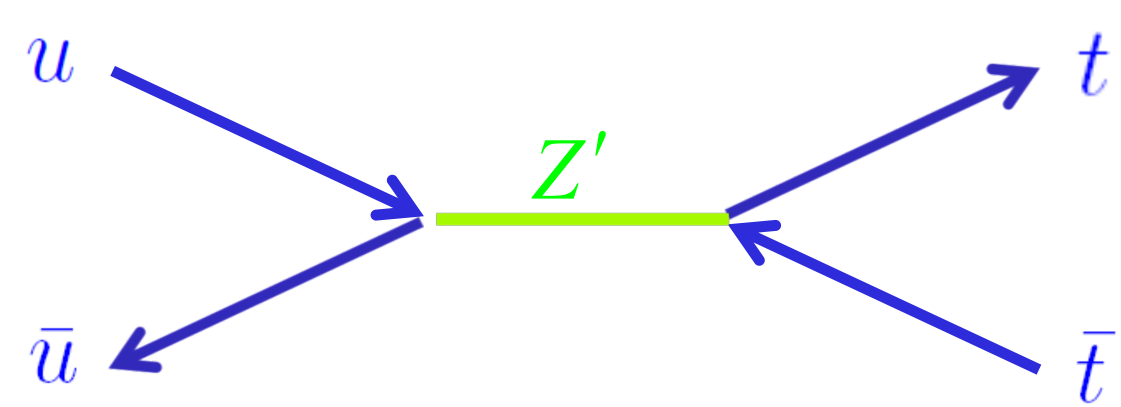
2. Higgs dominant scenario

cf. Babu, Frank, Rai, PRL107(2011)♪

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

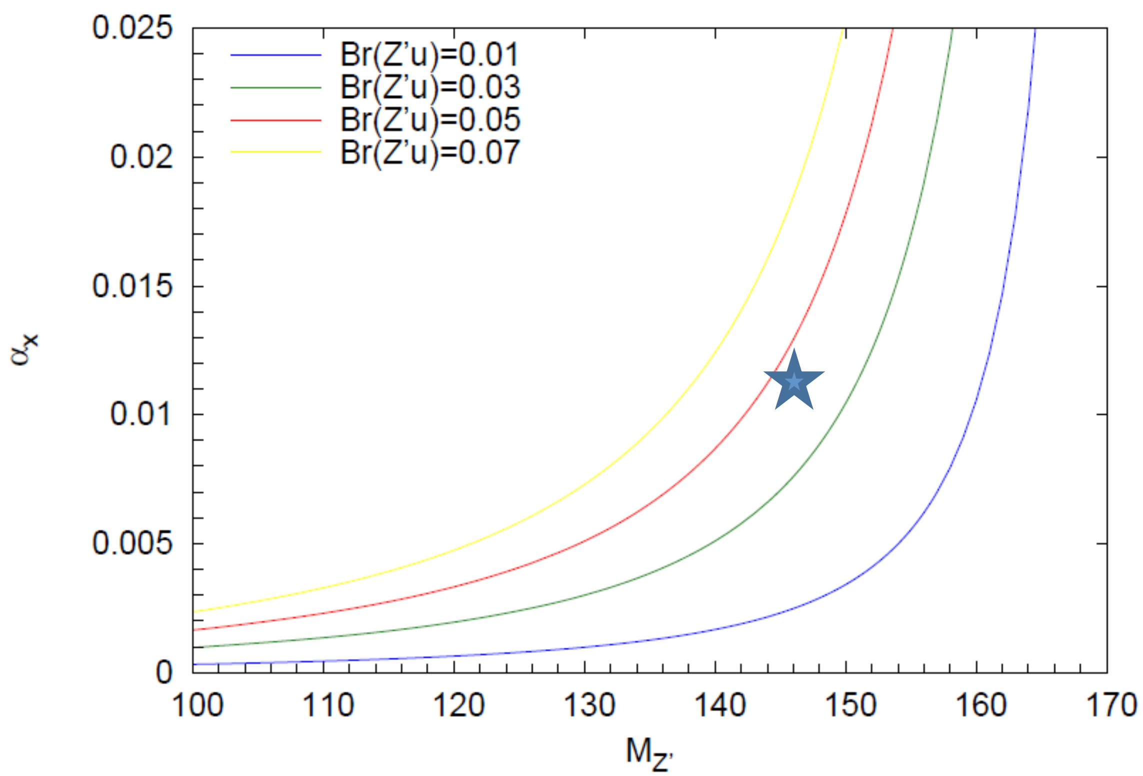
3. Mixed scenario

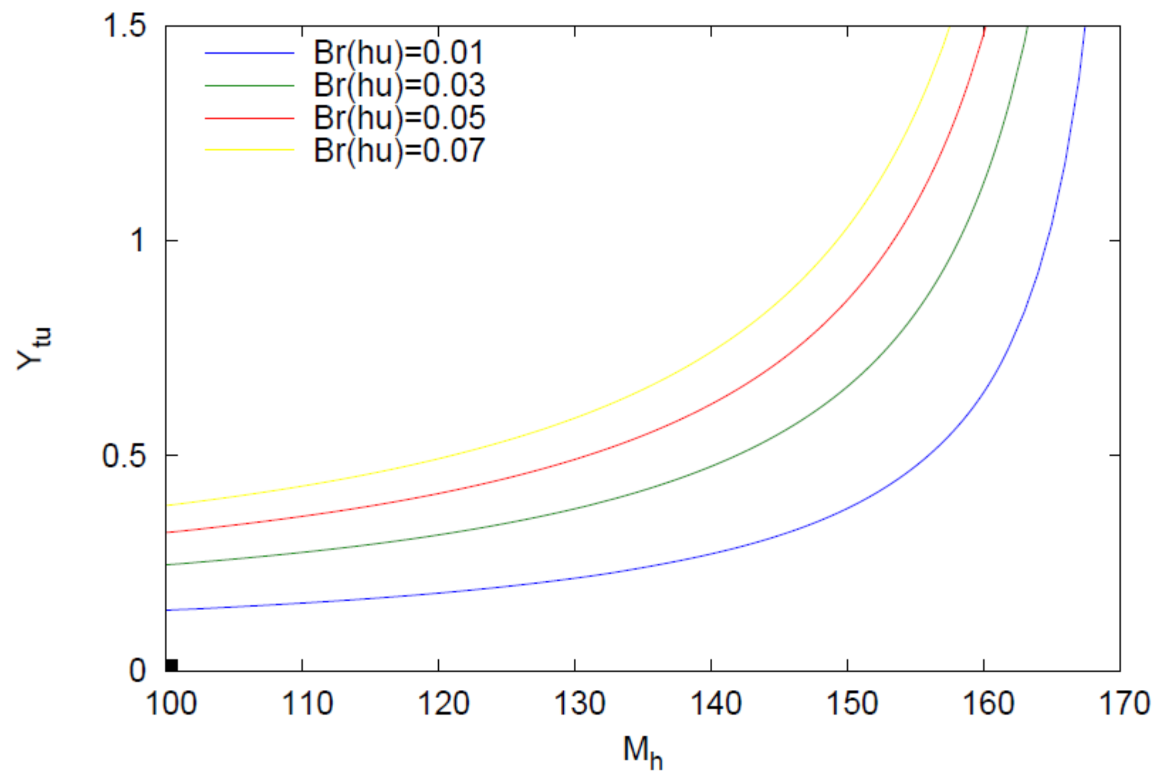
Destructive interference between Z’ and h,a for the same sign pair production (Ko, Omura, Yu)



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.

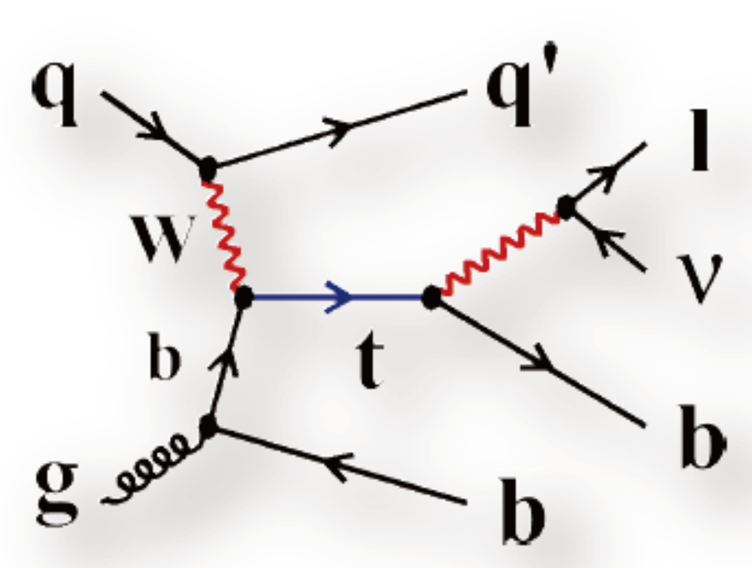




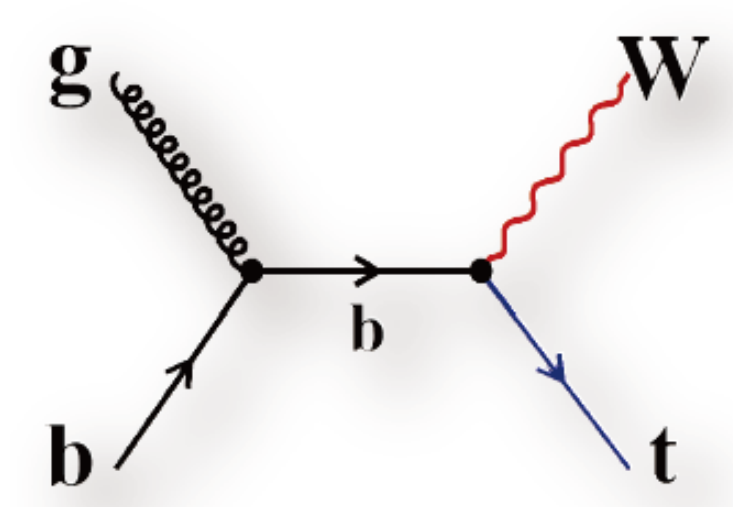
- requires Br(t →non-SM)<5% .
- choose either $m_{Z'} < m_t$ or $m_h < m_t$.

Single top quark production

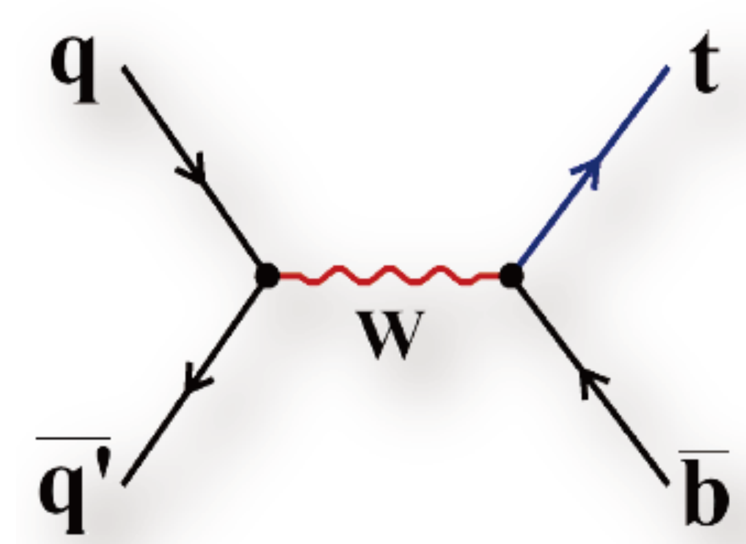
t channel



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

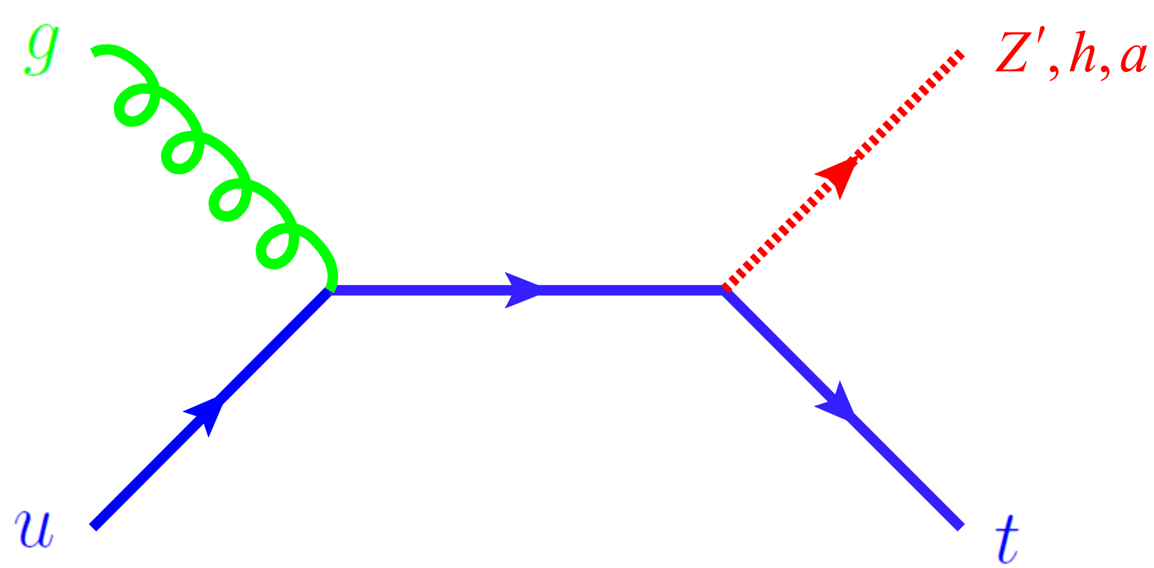
$$\sigma(pp \to tbq) = 83.6 \pm 29.8 \pm 3.3 \text{ pb}$$

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

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

- CMS CMS, 1106.3052

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

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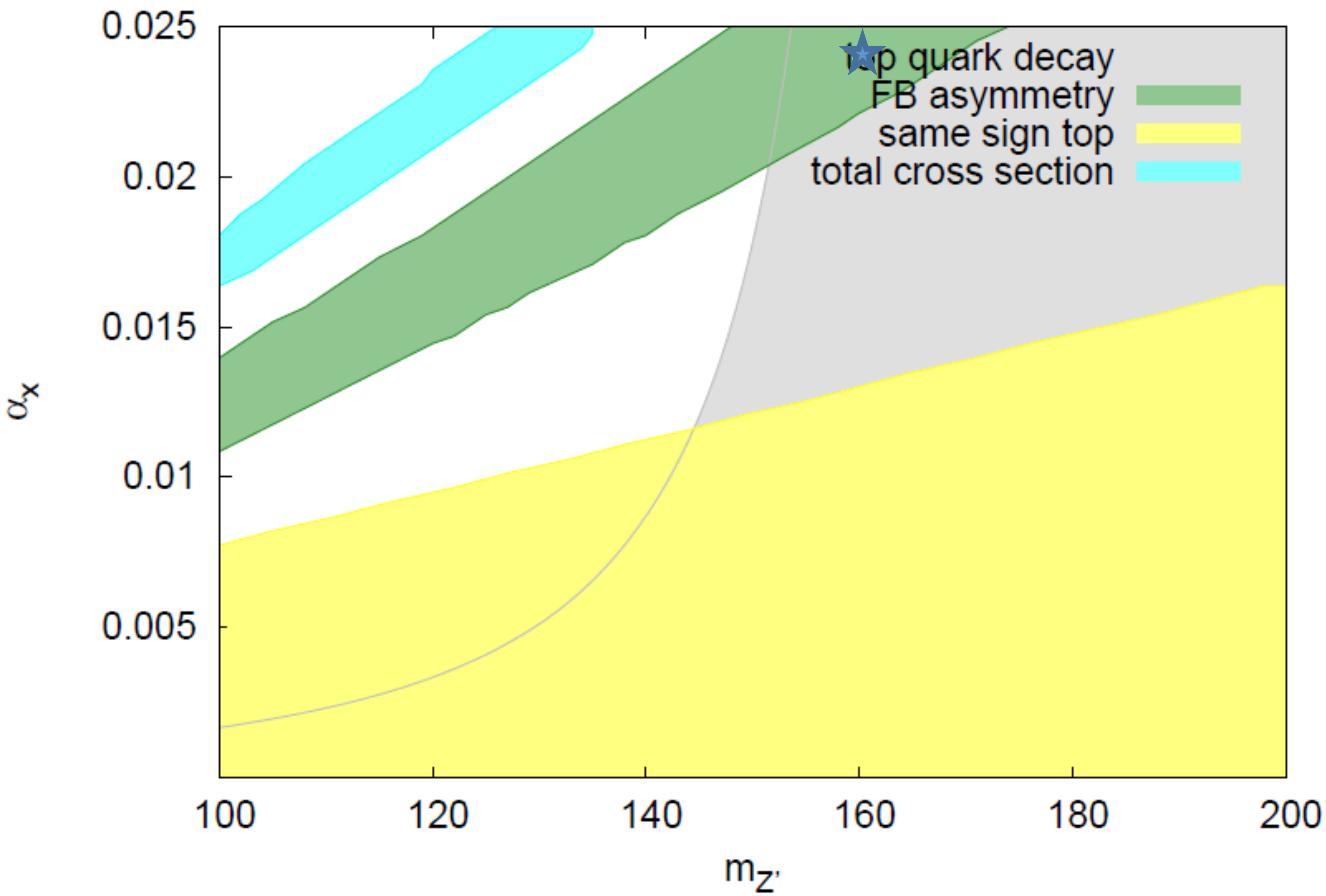
Favored region

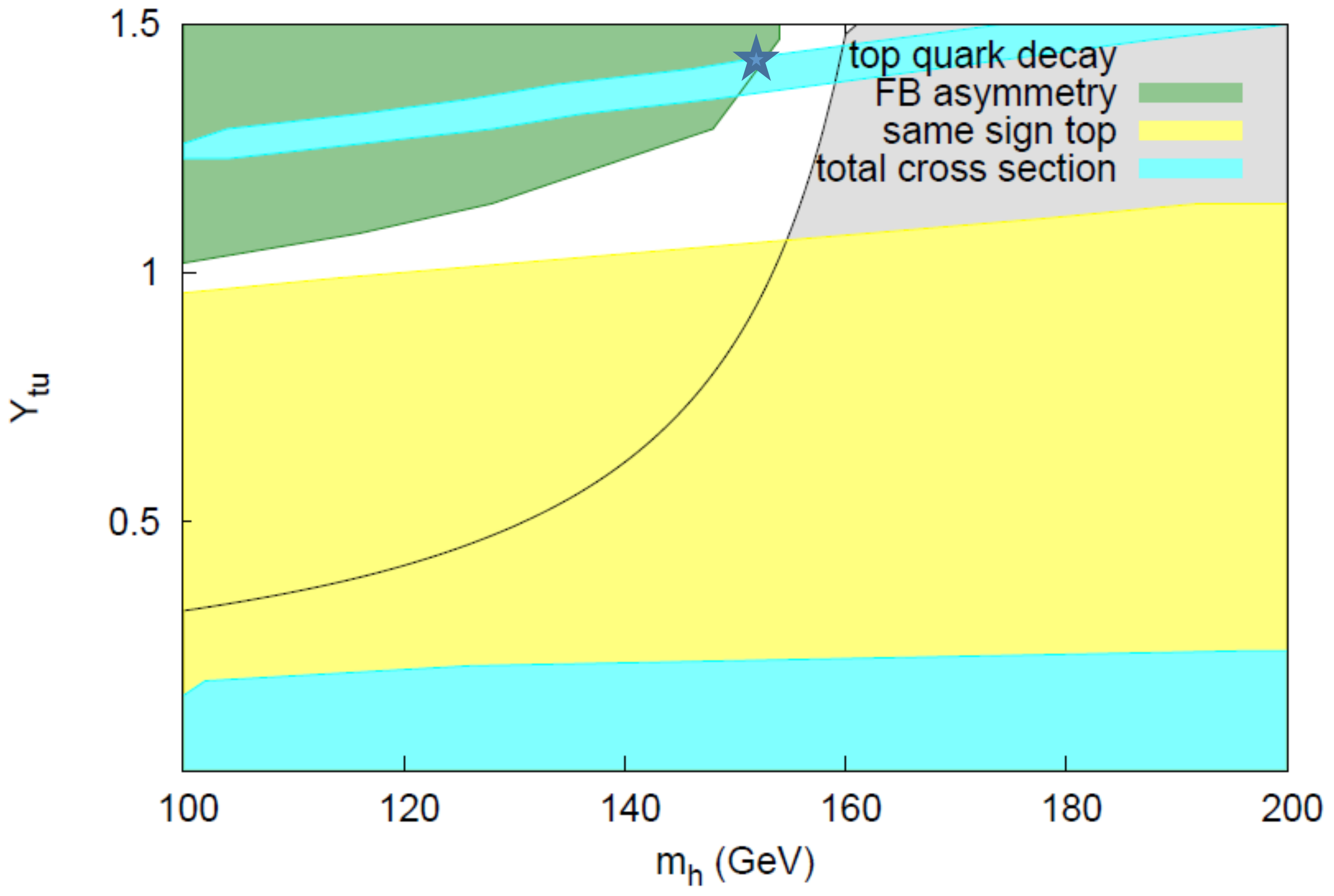
Z′ dominant case



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

Favored region

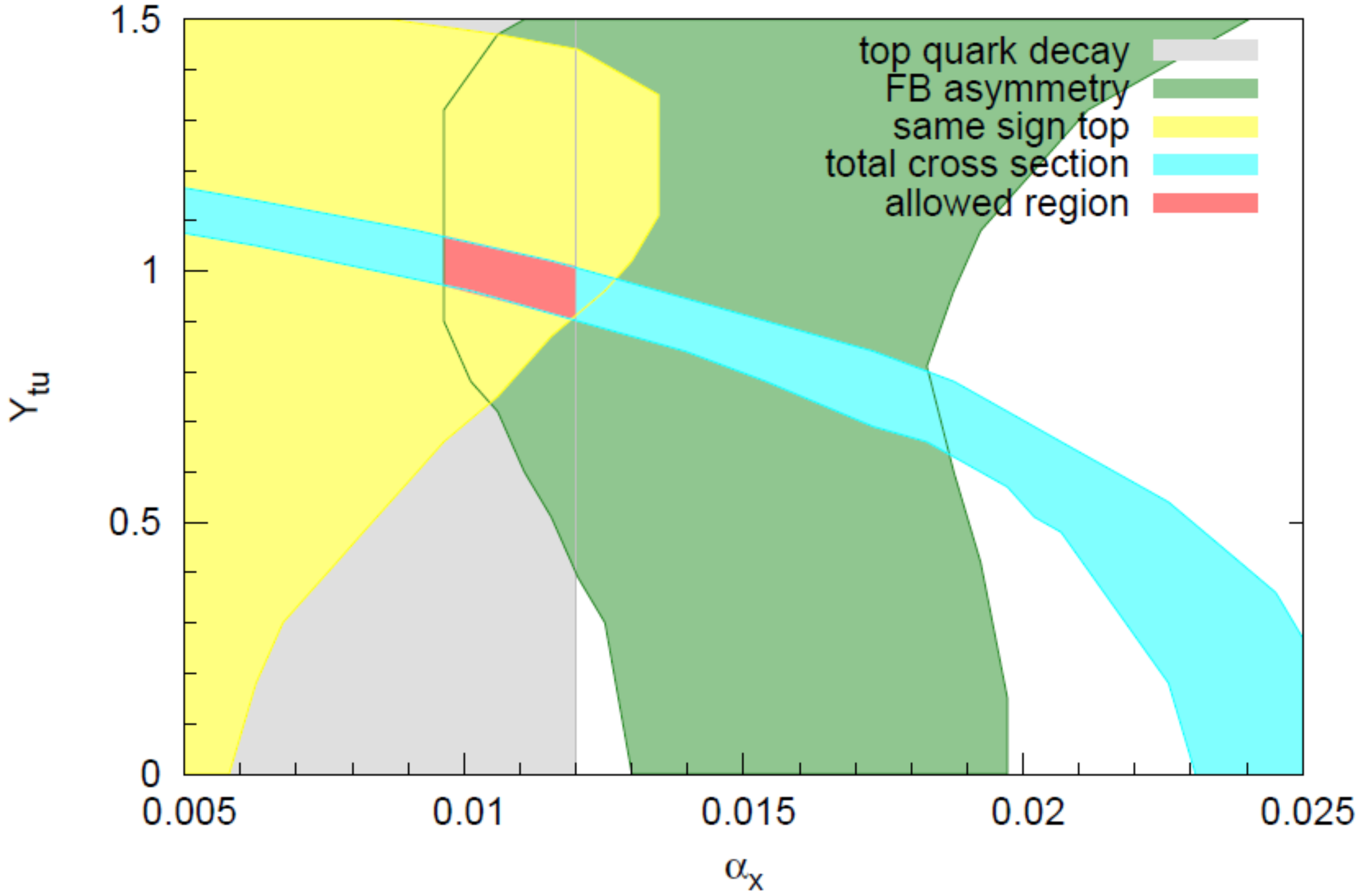
Scalar Higgs (h) dominant case



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

Favored region

Z′+h+a case



$m_{Z'} = 145$ GeV

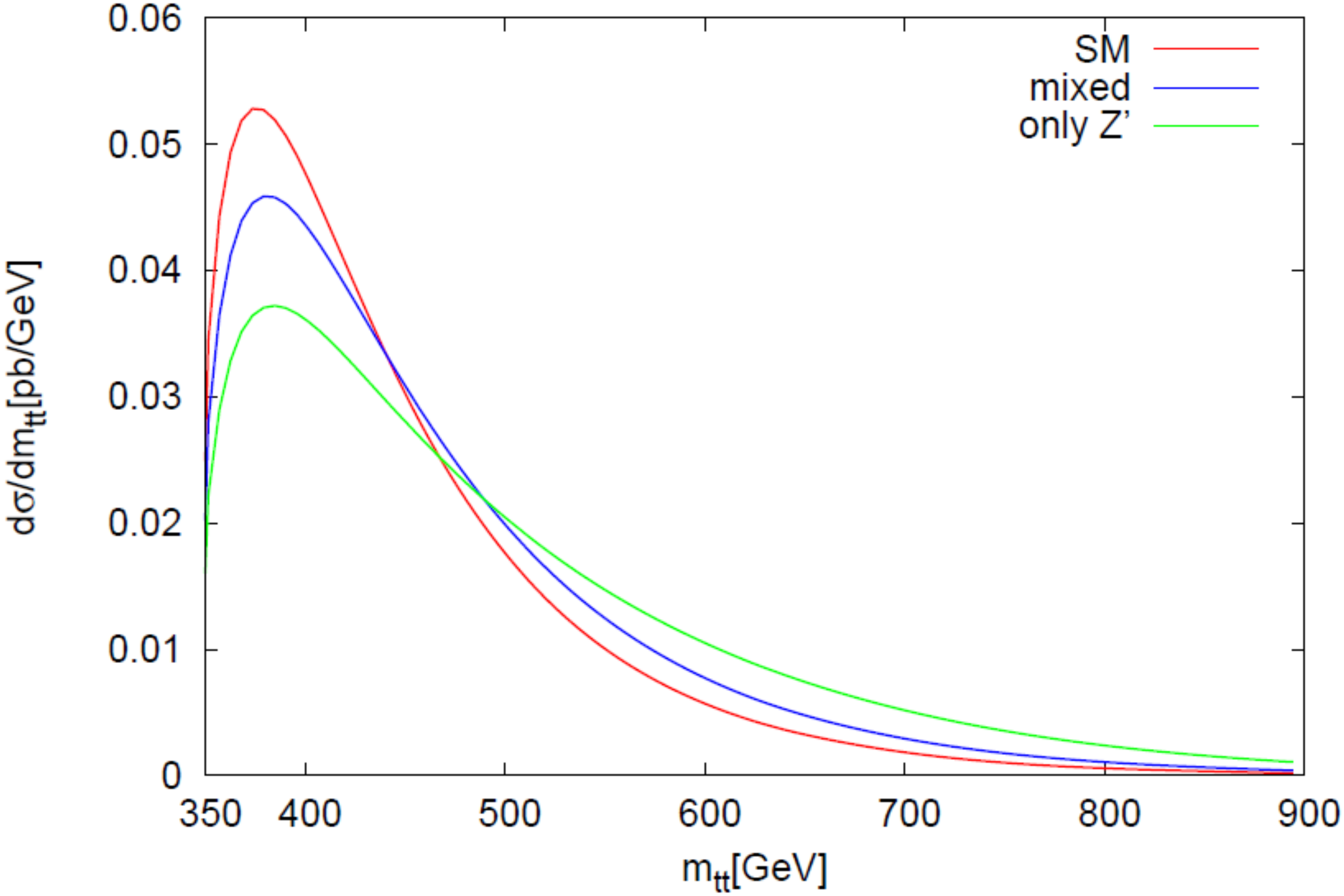
$m_h = 180$ GeV

$m_a = 300$ 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

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

$m_h = 180\ \text{GeV}$

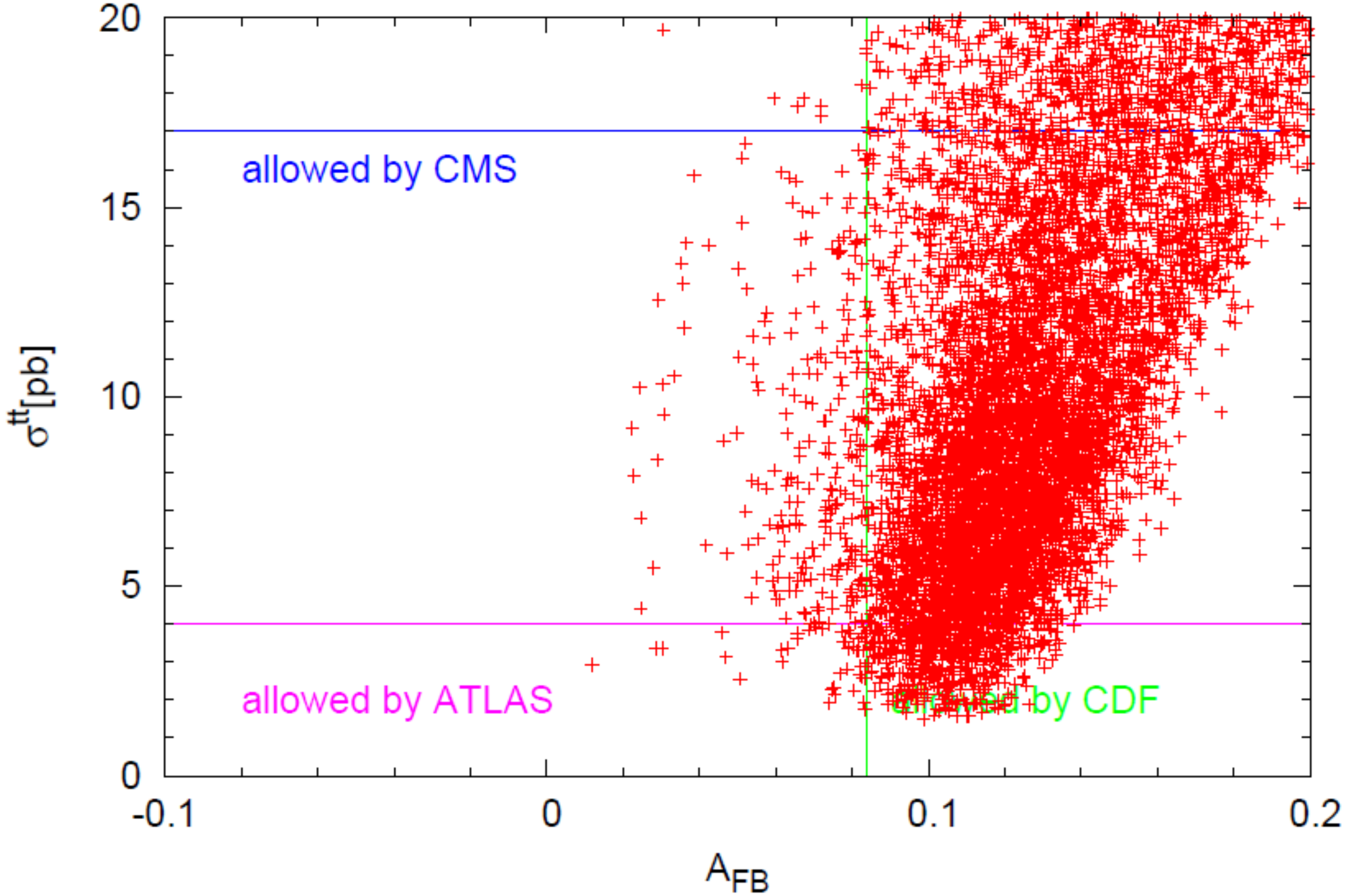
$m_a = 300\ \text{GeV}$

$\alpha_x = 0.01$

$Y_{tu} = 1.0$

$Y_{tu}^a = 1.1$

A_{FB} versus σ_{tt}



$m_{Z'} = 145$ GeV

180 GeV$< m_h < 1$ TeV

180 GeV$< m_a < 1$ TeV

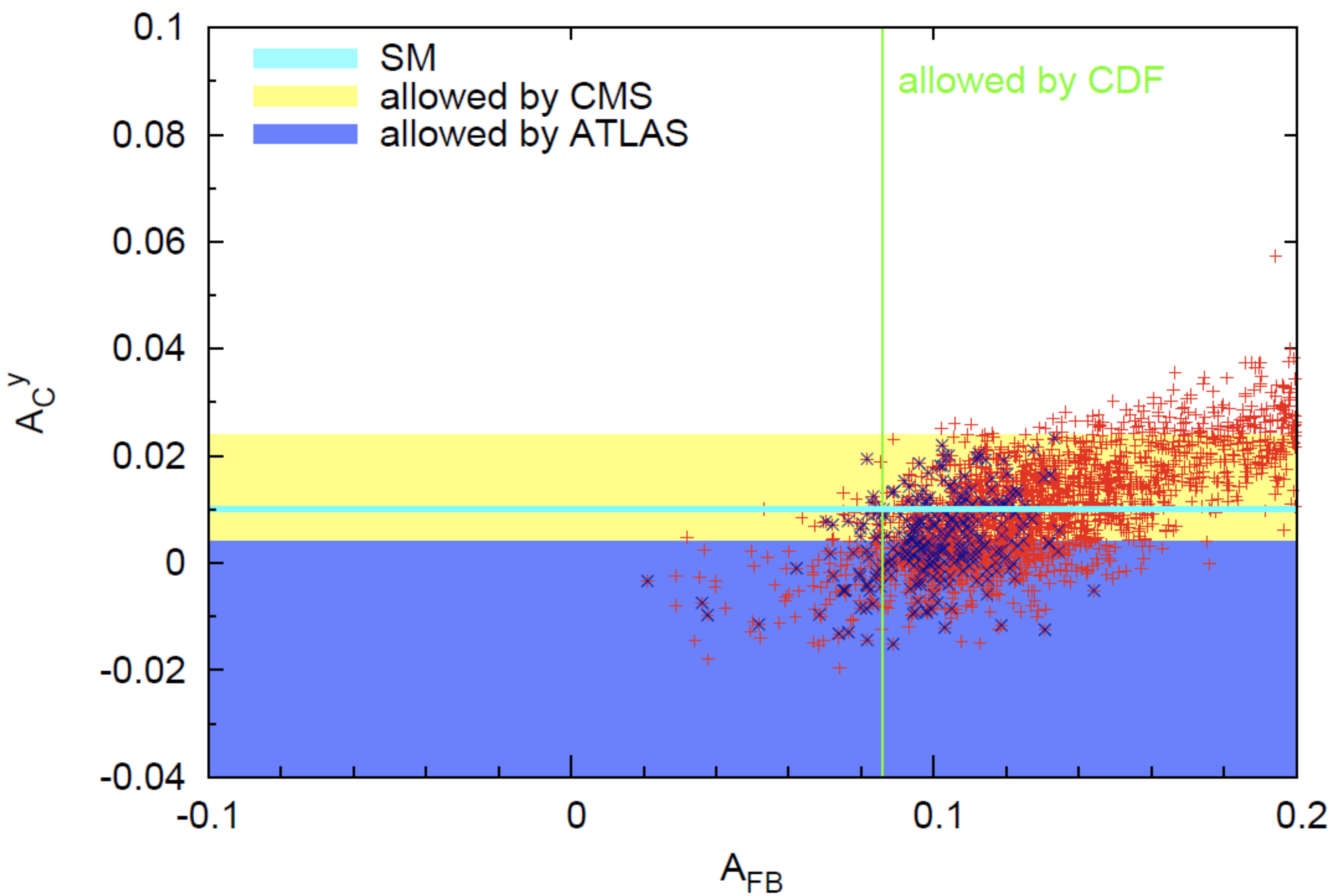
$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

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

Have a trouble with new CMS data < 0.39 pb

A_{FB} versus A_C^y



$m_{Z'} = 145$ GeV

180 GeV $< m_h < 1$ TeV

180 GeV $< m_a < 1$ TeV

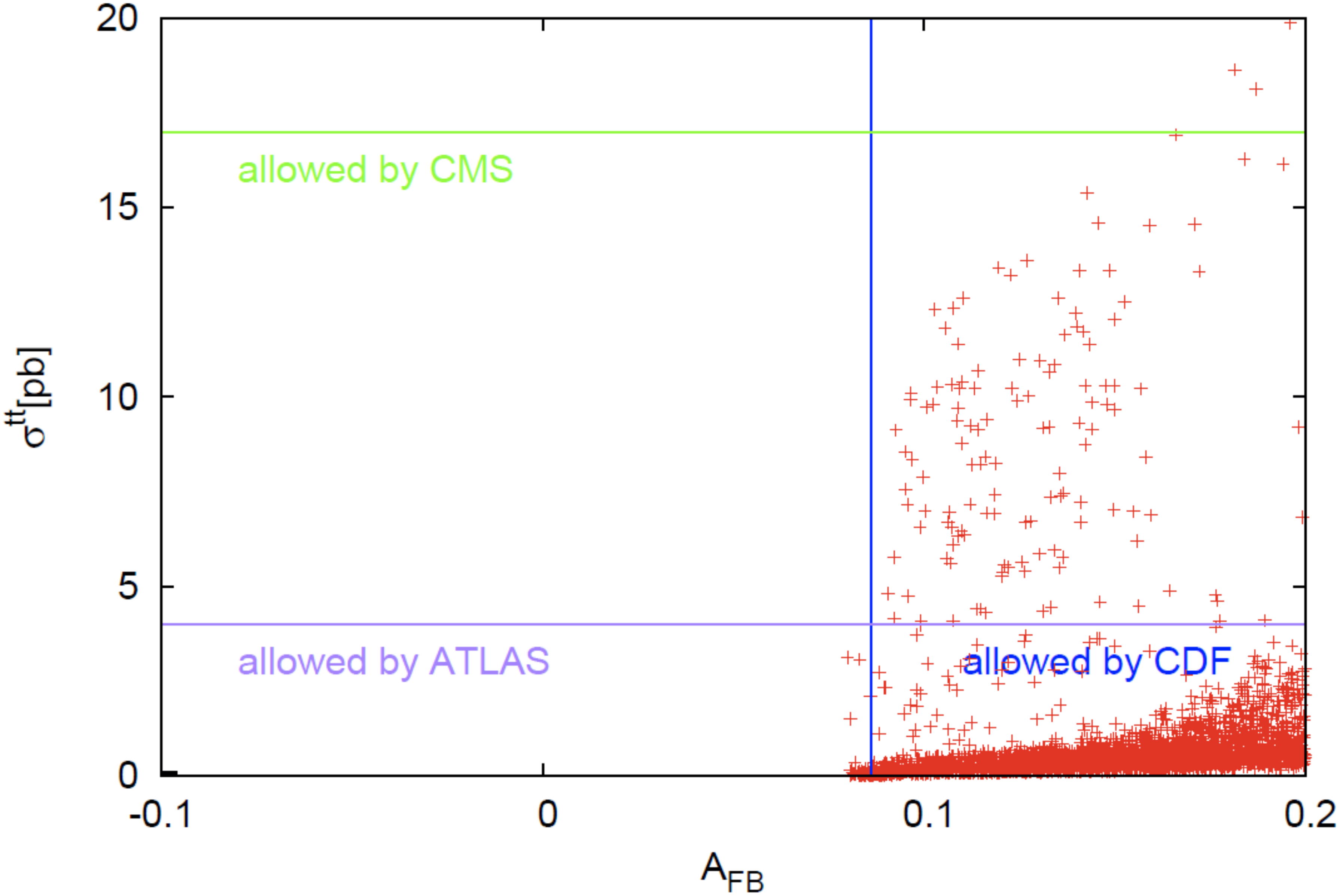
$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

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

Have a trouble with new CMS data < 0.39 pb

A_{FB} versus σ_{tt}



$m_h = 126$ GeV

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

180 GeV $< m_a < 1$ TeV

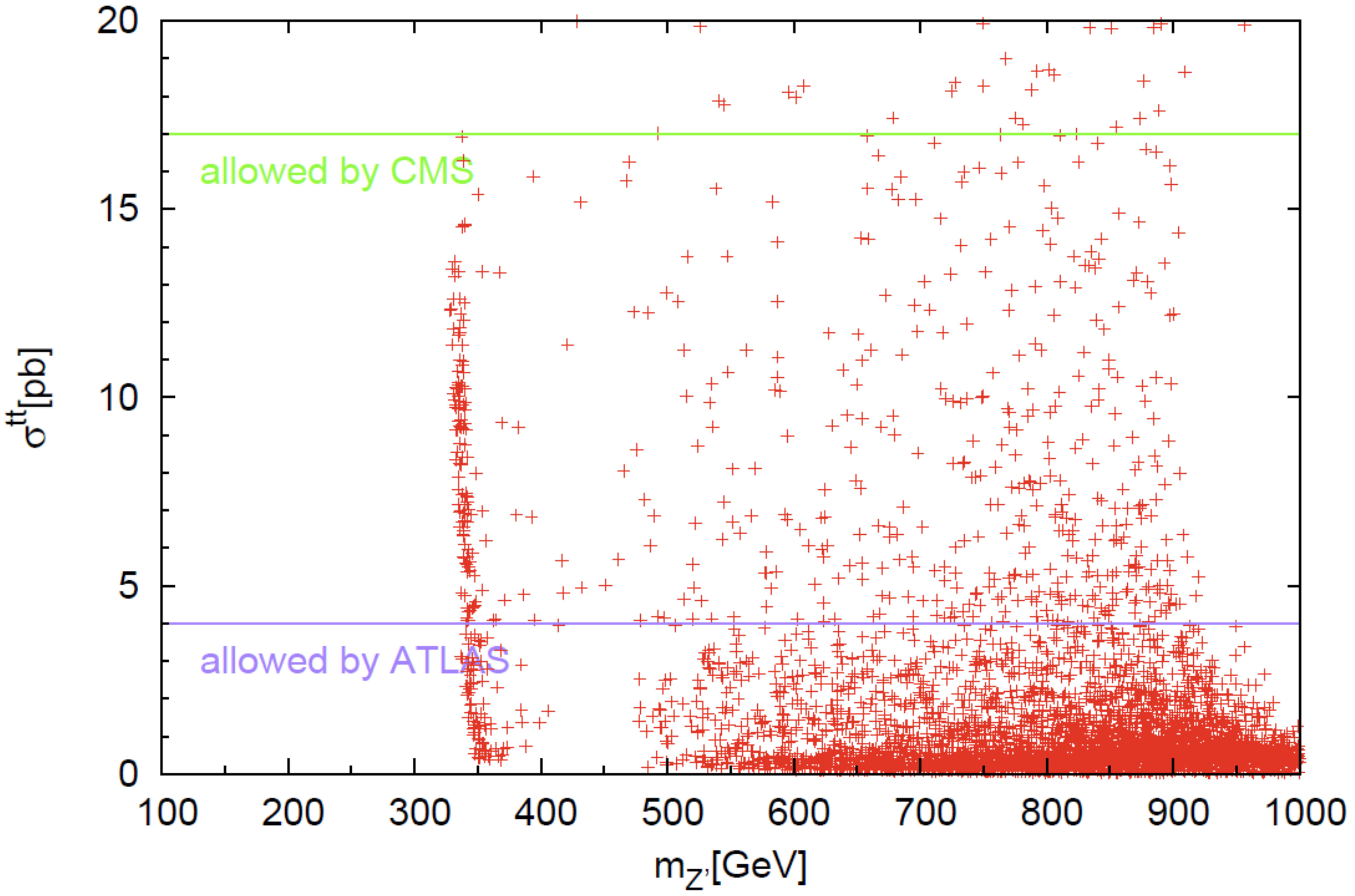
$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

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

Still OK with new CMS data < 0.39 pb

$m_{Z'}$ versus σ_{tt}



$m_h = 126$ GeV

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

180 GeV$< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

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

Still OK with new CMS data < 0.39 pb

Summary for top FBA

- 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)

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:

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

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

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

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

Comparison with other similar works

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

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

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 discussed in this talk

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
introduce a new Higgs doublet coupled to Z'
Again, Ko-Omura-Yu model

So let me talk about Ko-Omura-Yu Model

Conclusion

- In this talk, I showed that theory predictions based on simplified toy model and the simplest UV completions can be vastly different
- Simplified models often used for data analysis are arbitrary truncations of underlying theories, and not even well defined EFT
- They are useful 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

Conclusion-Con’d

- 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 which could not be covered here, lacking time

Lesson from $\pi \to \mu\nu_\mu$

- The simplest guess for the EFT is not correct:

  $\mathscr{L}_{\rm eff} \sim \pi\bar{\mu}\nu_\mu$ (dim-4) (X)

- The correct guess is $\mathscr{L}_{\rm eff} \sim \partial_\mu \pi \bar{\mu}\gamma^\mu \nu$ (dim-5:OK)

- In the SM, the correct answer is dim-6 involving quarks, $\sim \bar{u}_L \gamma_\mu d_L \mu_L \gamma^\mu \nu_L$

- We may have been doing something similar for DM physics too