



# Top Quark Physics at the LHC

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## Brief History

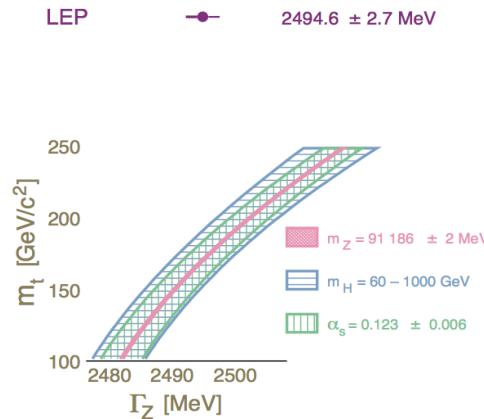
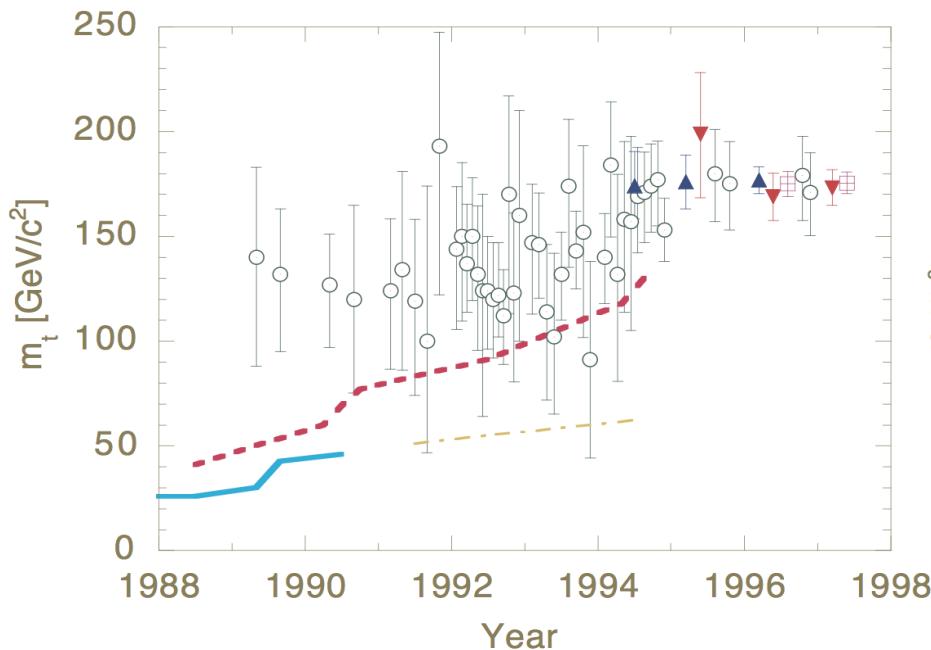
1973, Kobayashi and Masukawa, propose a 3x3 unitary matrix to incorporate CP phase, which is now called CKM matrix

→ existence of 3<sup>rd</sup> generation quarks

1977, **b** quark was discovered at Fermilab

SPS at CERN set the lower bound  $m_{top} > 77 \text{ GeV}$

1995 CDF&D0 jointly reported the discovery of top quark at Fermilab,  
 $m_{top} = 176 \text{ & } 180 \text{ GeV}$  → complete 3-generation structure quark sector

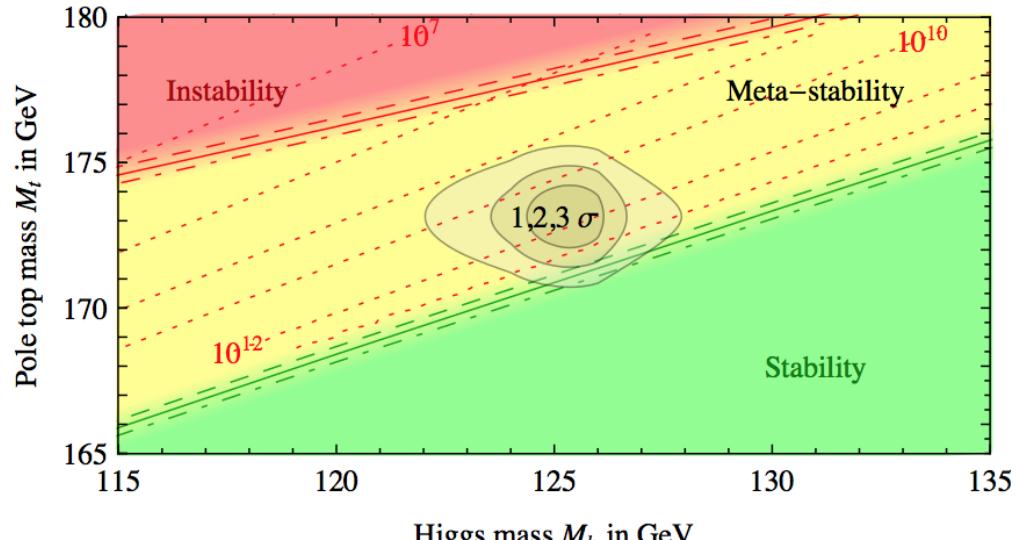
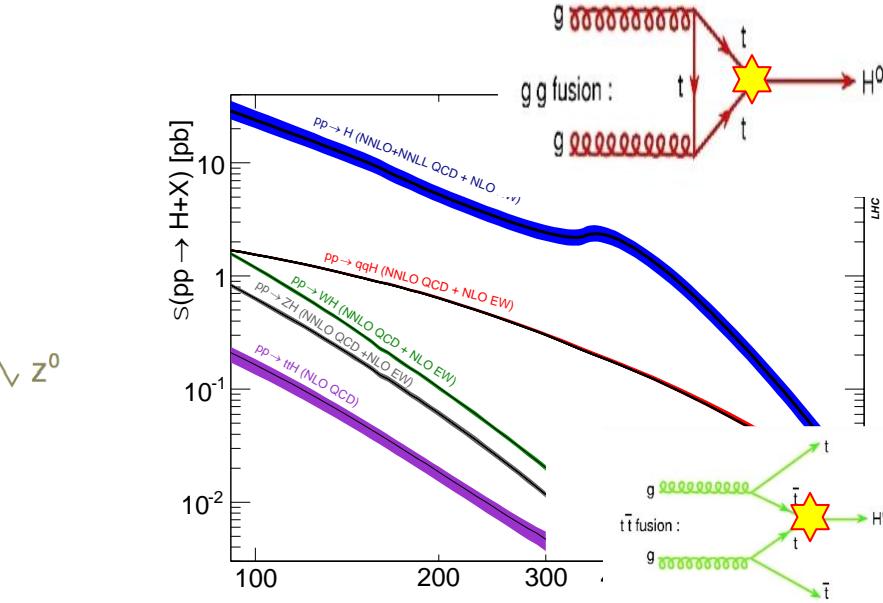
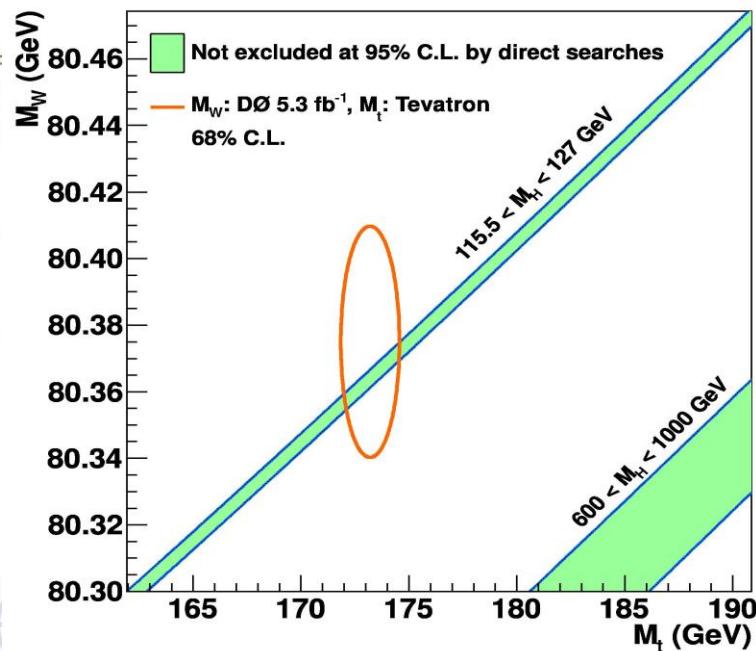


# Top Matters



$$M_W^2 = M_Z^2(1 - \sin^2 \theta_W)(1 + \Delta\rho),$$

$$\Delta\rho = 3G_F m_t^2 / 8\pi^2 \sqrt{2} + \dots$$



CRC (NTNU)

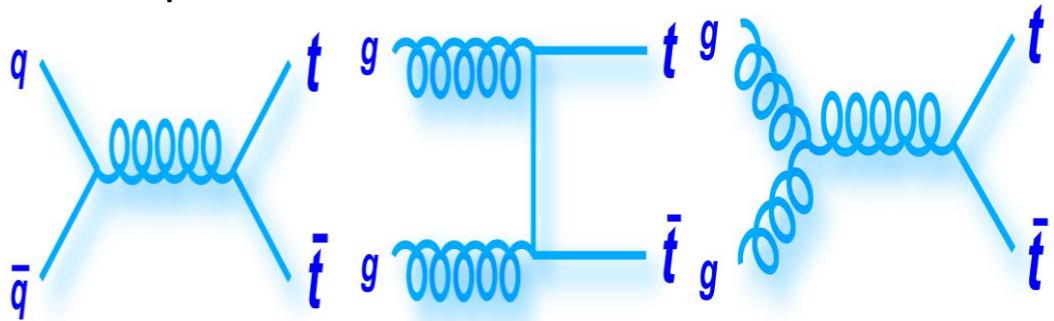
Ian Low's talk

Higgs mass  $M_h$  in GeV

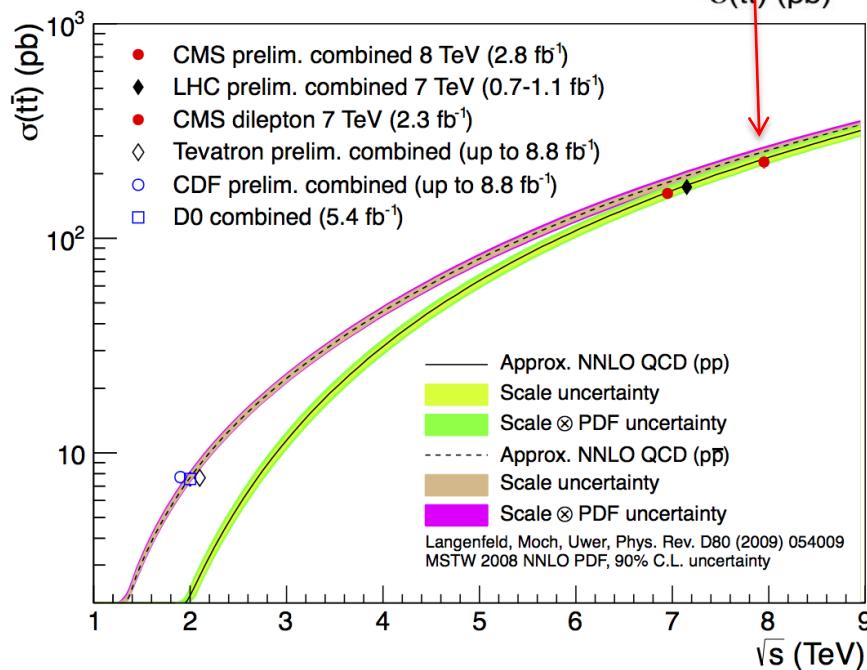
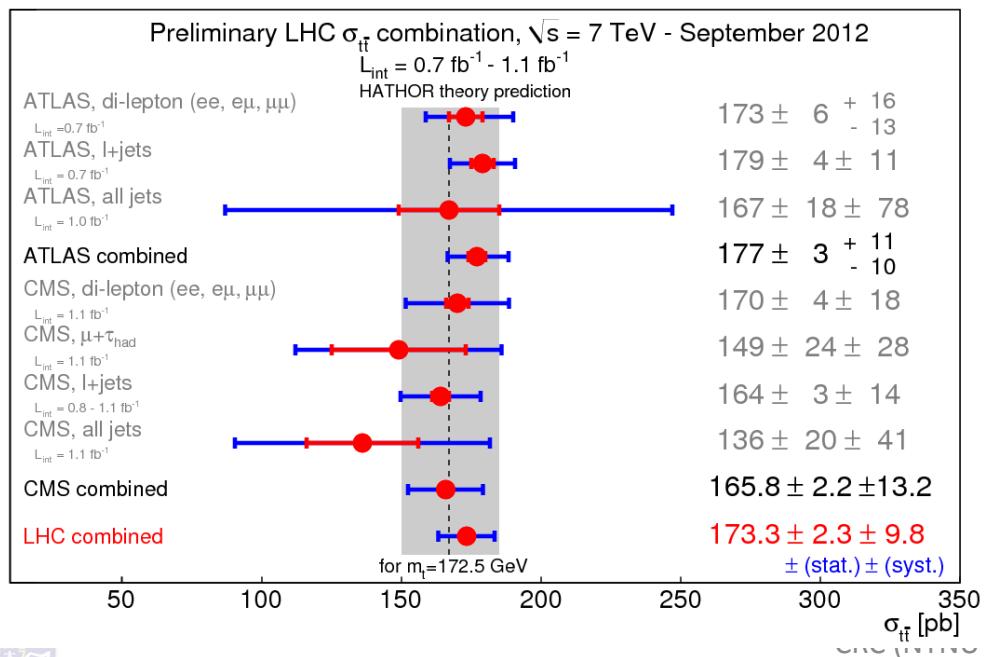
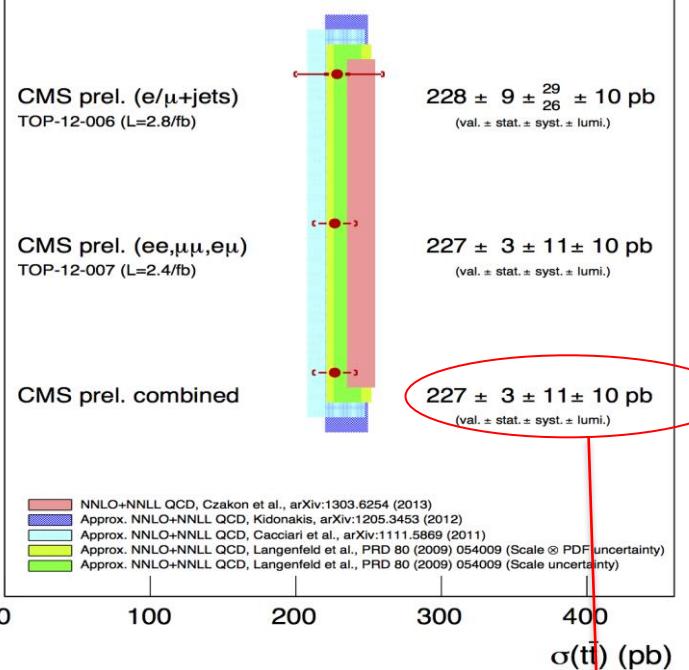
Degrandi et al. 1205.6497

# t Pair Production

t tbar pair

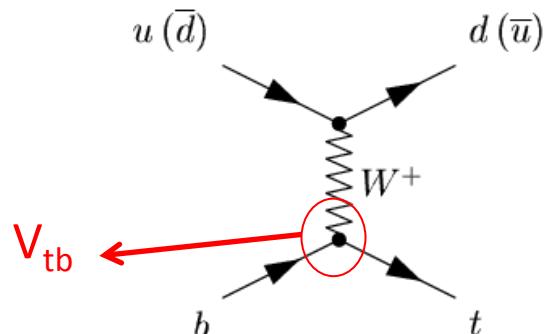


CMS Preliminary,  $\sqrt{s} = 8$  TeV

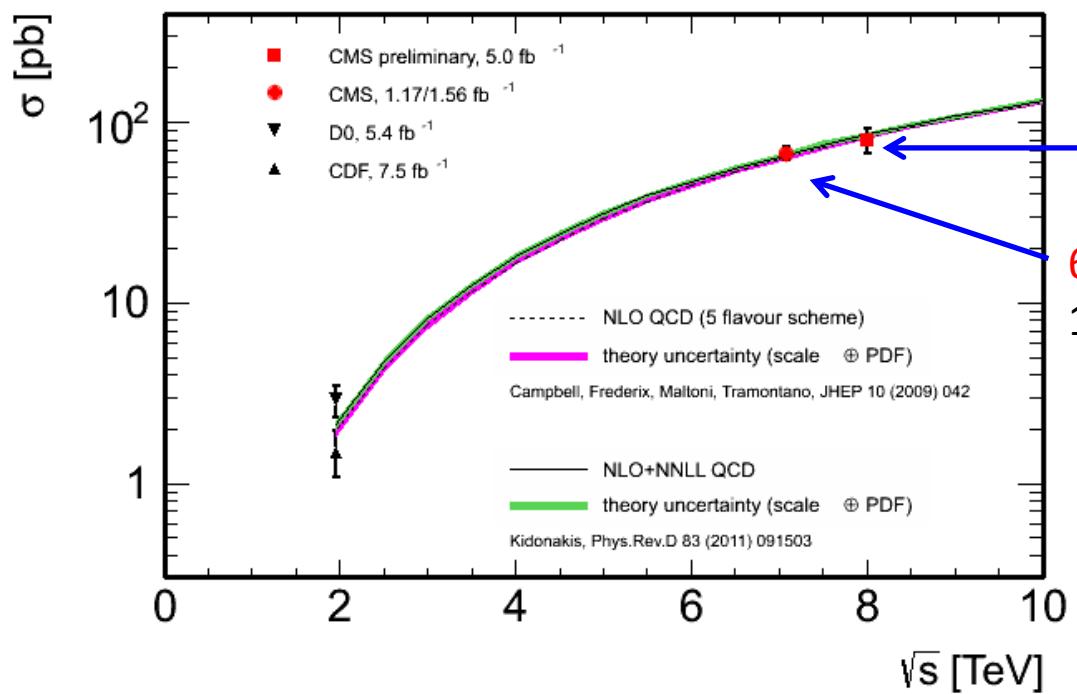
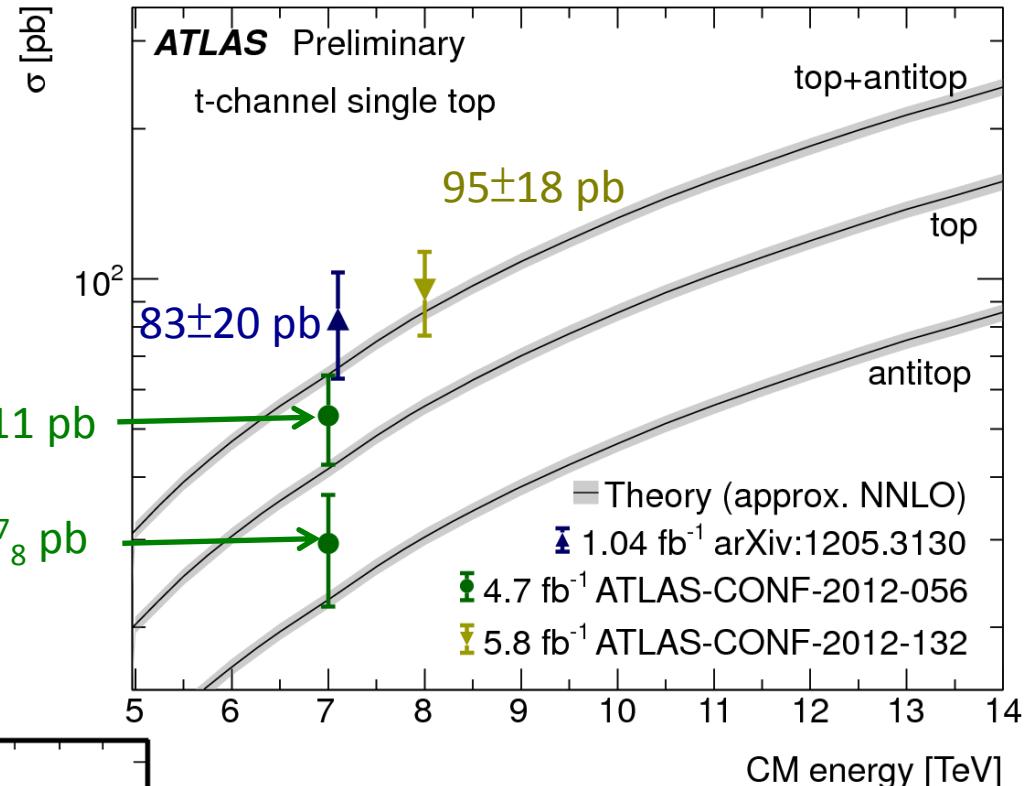


# Single t Production

single-top, t-channel



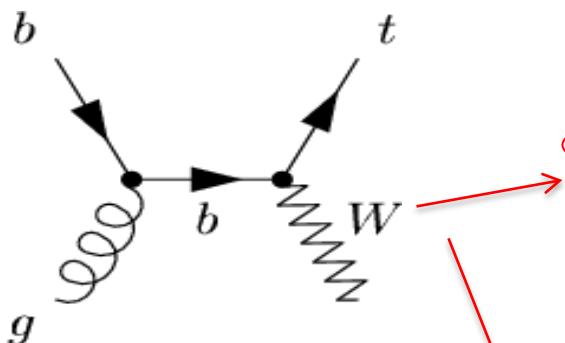
$$\propto |V_{tb}|^2$$



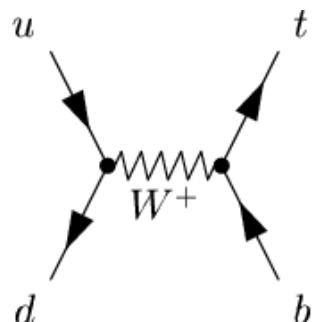
$|V_{tb}| > 0.8$  with 95 C.L.

# Single t Production

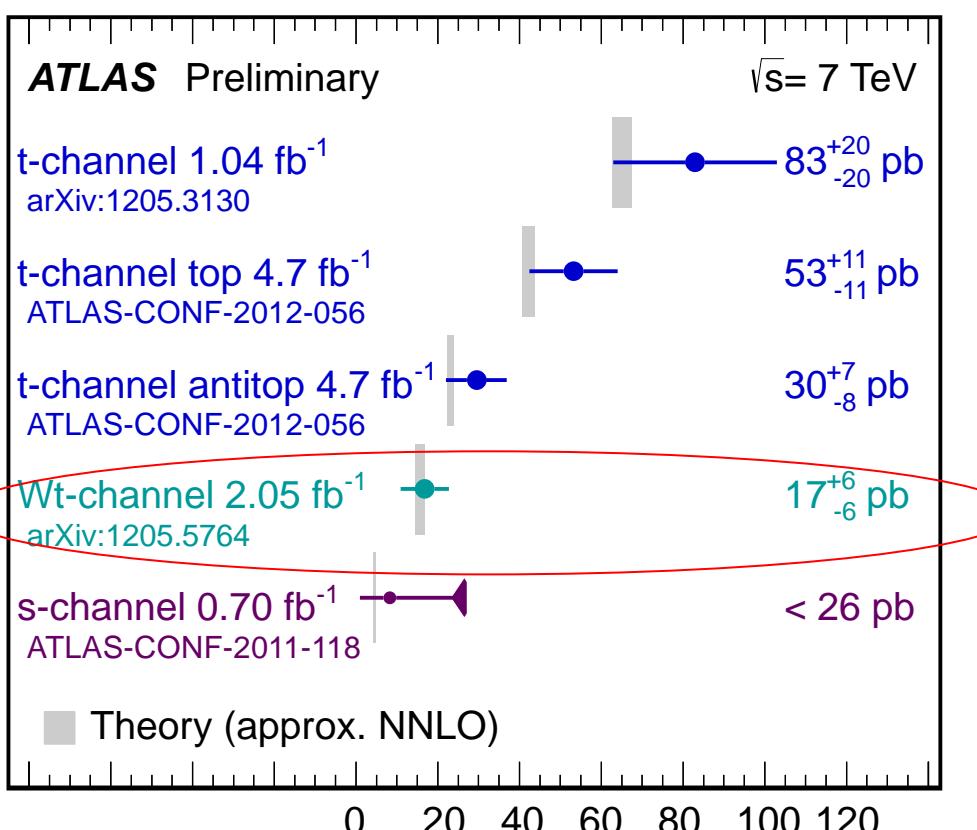
single-top, W t association



single-top s-channel



NOT found yet.



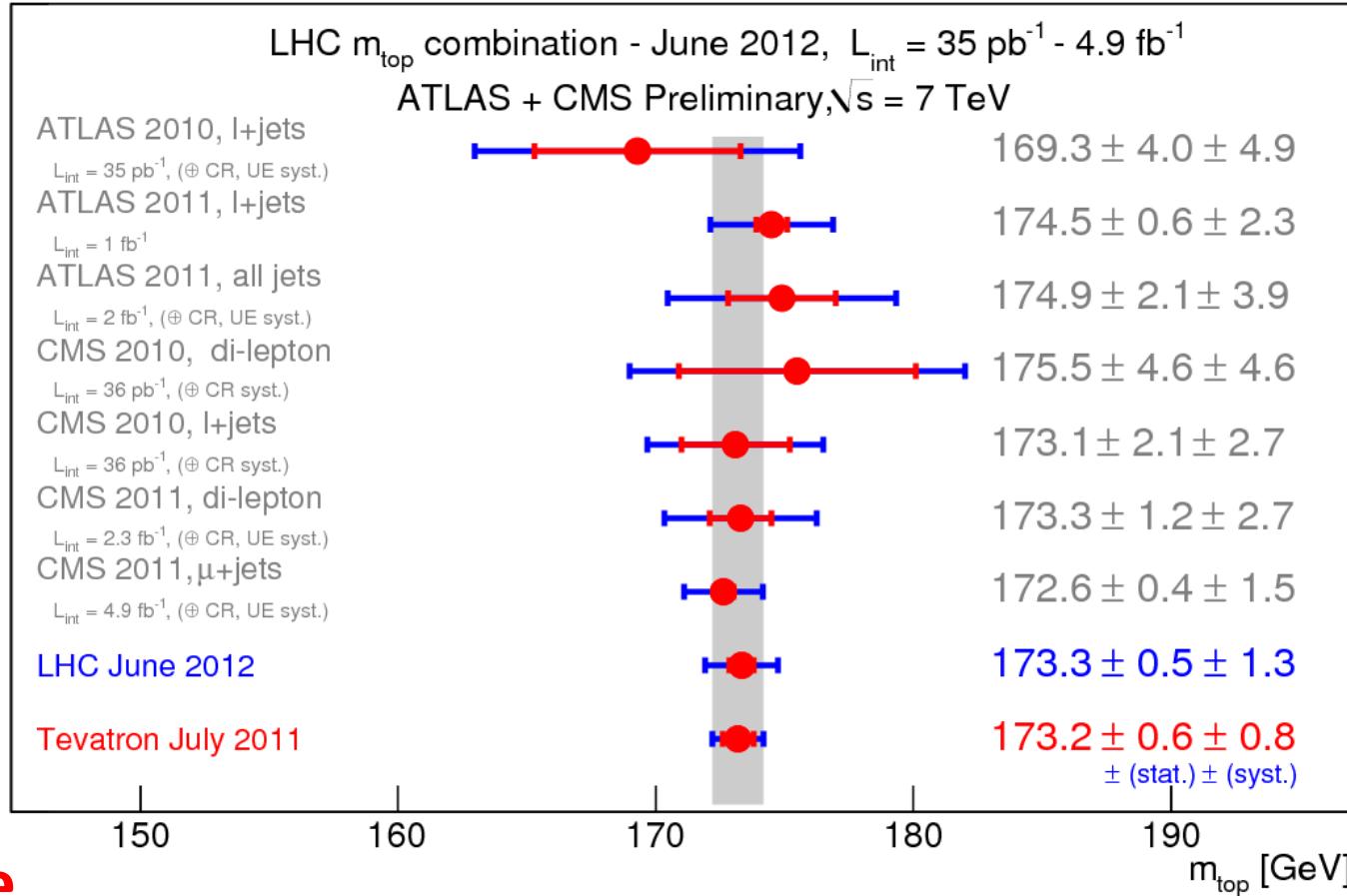
single top cross section [pb]

CMS: 7 TeV (4.9 fb $^{-1}$ ),  $16^{+5}_{-4}$  pb  
1209.3489

8 TeV (12.2 fb $^{-1}$ ),  $23.4^{+5.5}_{-5.4}$  pb  
TOP-12-040



# Mass & Charge



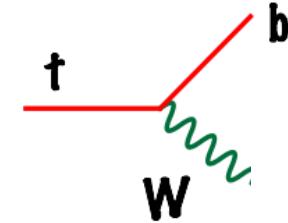
charge

ATLAS, 7 TeV,  $2.05 \text{ fb}^{-1}$  :  $0.64 \pm 0.02 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$ , prefers SM (2/3),  
 exclude exotic case  $-4/3$  by  $> 8 \sigma$

# Decay

dominant mode:  $t \rightarrow W b$        $|V_{tb}| \gg |V_{ts}|, |V_{td}|$

$$\Gamma_t^B(t \rightarrow bW) = \frac{G_F}{8\pi\sqrt{2}} m_t^3 |V_{tb}|^2 \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_t^2}\right)$$



$m_t$	$\Gamma_t^{(0)}$	$\delta_f^b$	$\delta_f^W$	$\delta_{EW}$	$\delta_{QCD}^{(1)}$	$\delta_{QCD}^{(2)}$	(%)
172.5	1.4806	-0.26	-1.49	1.68	-8.58	-2.09	
173.5	1.5109	-0.26	-1.49	1.69	-8.58	-2.09	
174.5	1.5415	-0.25	-1.48	1.69	-8.58	-2.09	

Gao, Li and Zhu, PRL 110 (2013) 041001

other decay modes:

$$B(t \rightarrow bW^+) = 0.998, \quad B(t \rightarrow sW^+) \simeq 1.9 \times 10^{-3}, \quad B(t \rightarrow dW^+) \simeq 10^{-4}$$

FCNC:     $t \rightarrow X^0 q$ , where  $X^0 = g, \gamma, Z, H$  and  $q = c, u$ ,     $\text{Br} \sim \mathcal{O}(10^{-13})$

Diaz-Cruz et al. PRD 41(1990); Eilam et al. PRD 44(1991); Yue et al. PRD 64(2001)

CMS(7 TeV, 5 fb<sup>-1</sup>):  $BR(t \rightarrow Zq) < 0.21\%$

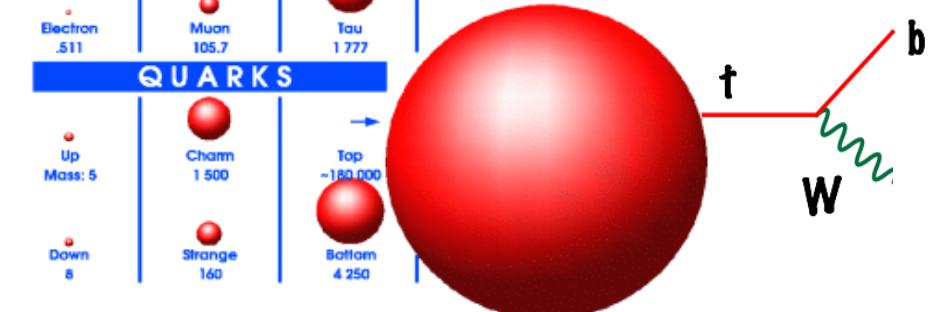
# Basic Review

- The heaviest particle found

~173 GeV

- ~100% decay into W, b

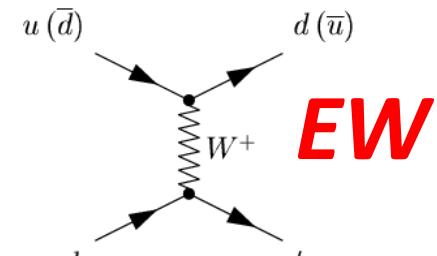
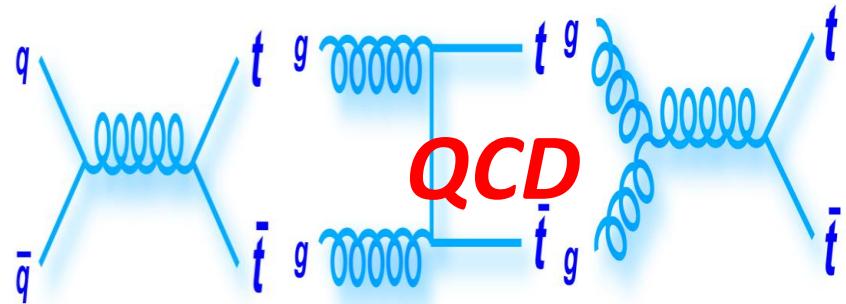
LEPTONS		
Electron Neutrino Mass = 0	Muon Neutrino = 0	Tau Neutrino = 0
Electron .511	Muon 105.7	Tau 1777
QUARKS		
Up Mass: 5	Charm 1 500	Top ~180 000
Down 5	Strange 160	Bottom 4 250



- mainly produced as t tbar pair

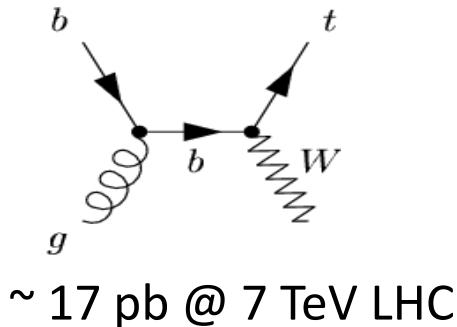
~ 173 pb @ 7 TeV LHC

~ 227 pb @ 8 TeV LHC

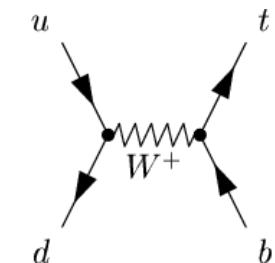


~ 80 pb @ 7 TeV LHC

~ 95 pb @ 8 TeV LHC

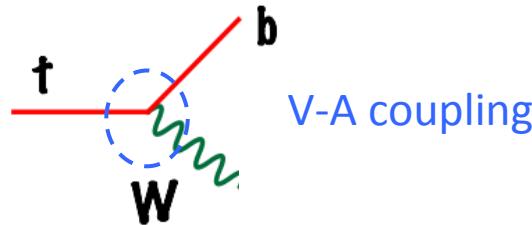


~ 17 pb @ 7 TeV LHC



not found yet  
< ~26 pb @ 7 TeV LHC

## More About Decay



$$\Gamma_{th} \simeq 1.5 \text{ GeV}$$

top decays quickly before hadronization ( $\sim 10^{-25}$  sec) → bare quark!!  
**Spin information is kept!!**

### W-boson helicity

In SM, the V-A coupling structure allow W-boson with  $\lambda=0$  and  $\lambda=+1$ , while  $\lambda=-1$  is suppressed

$$b \quad \begin{array}{c} \longleftarrow \\ \Rightarrow \end{array} \quad t \quad \begin{array}{c} \bullet \\ \longrightarrow \end{array} \quad W^+(\lambda=0) \quad F_0 = \frac{\Gamma_0}{\Gamma} = \frac{m_t^2}{m_t^2 + 2m_W^2} \sim 0.7$$

$$b \quad \begin{array}{c} \longleftarrow \\ \Rightarrow \end{array} \quad t \quad \begin{array}{c} \bullet \\ \longleftarrow \quad \longleftarrow \end{array} \quad W^+(\lambda=-1) \quad F_+ = \frac{\Gamma_+}{\Gamma} = \frac{2m_W^2}{m_t^2 + 2m_W^2} \sim 0.3$$

$$b \quad \begin{array}{c} \longleftarrow \\ \Rightarrow \end{array} \quad t \quad \begin{array}{c} \bullet \\ \longrightarrow \quad \Rightarrow \end{array} \quad W^+(\lambda=+1) \quad F_- = \frac{\Gamma_-}{\Gamma} \rightarrow 0 \quad \text{in } m_b = 0 \text{ limit}$$

NNLO:  $(F_0, F_-, F_+) = (0.687, 0.311, 0.0017)$

Czarnzej, Korner, Piclum, 1005.2625

# More About Decay

## W-boson helicity

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{3}{8} (1 + \cos \theta^*)^2 F_+ + \frac{3}{8} (1 - \cos \theta^*)^2 F_- + \frac{3}{4} (1 - \cos^2 \theta^*) F_0$$

$\theta^*$ :  $p_L$  at W-rest &  $p_W$  at t-rest

$\sin^2 \theta$

$(1 - \cos \theta)^2$

$(1 + \cos \theta)^2$

$$\frac{dN}{d \cos \theta^*}$$

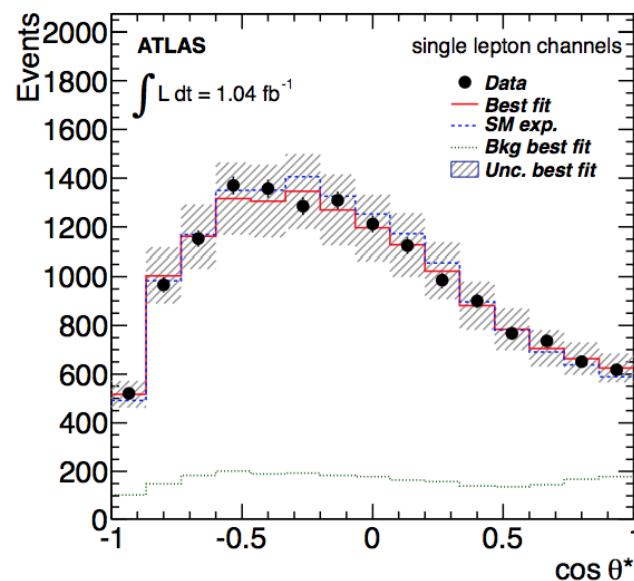
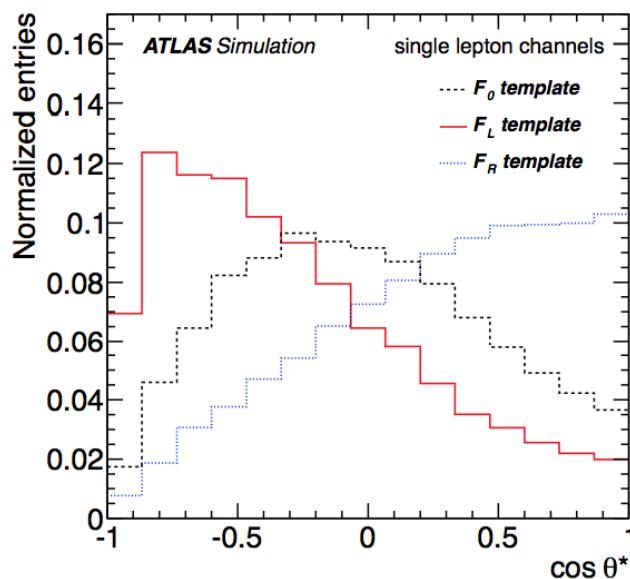
SM

Long

+

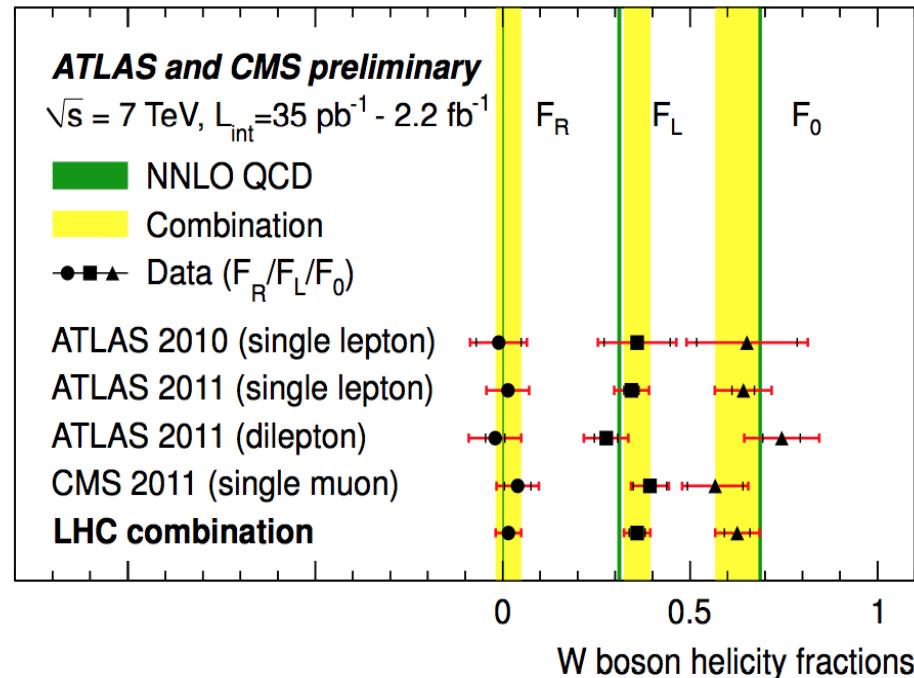
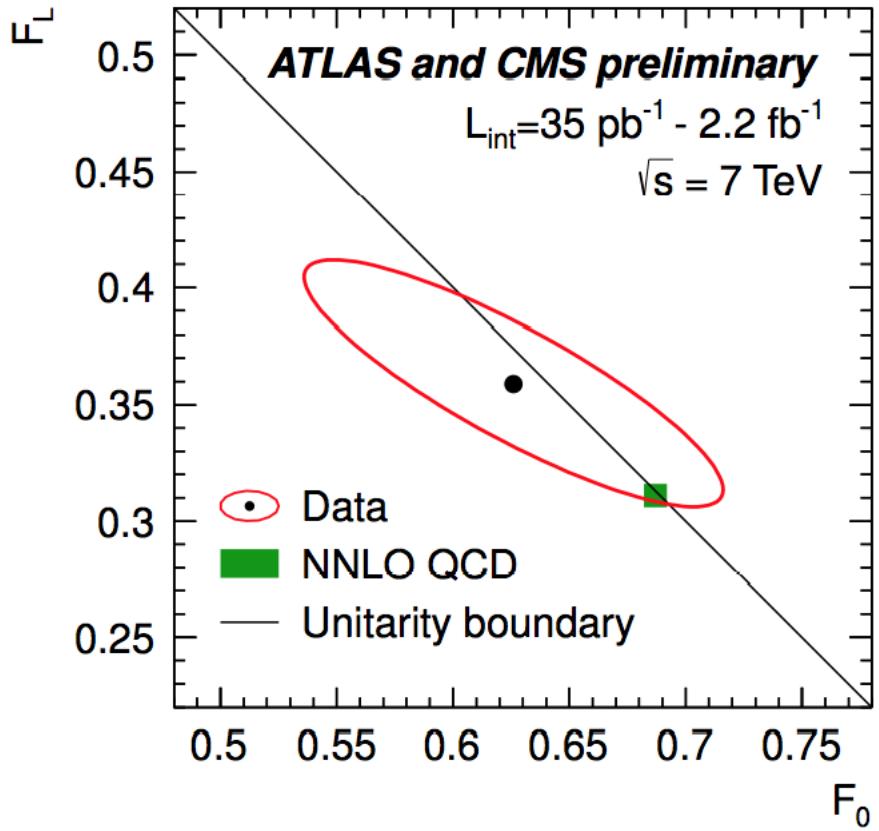
-

- left-handed
- longitudinal
- right-handed
- sum (SM)



# More About Decay

## W-boson helicity



$$F_0 = 0.626 \pm 0.034(\text{stat.}) \pm 0.048(\text{syst.})$$

$$F_- = 0.359 \pm 0.021(\text{stat.}) \pm 0.028(\text{syst.})$$

↓ sum = 1

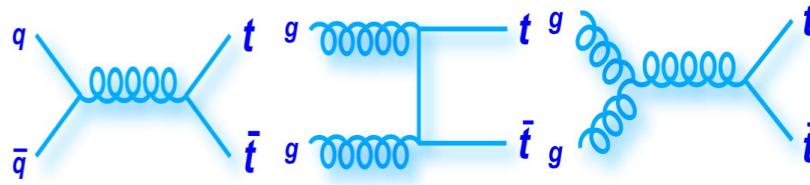
$$F_+ = 0.015 \pm 0.034$$

consistent with SM

$$(F_0, F_-, F_+) = (0.687, 0.311, 0.0017)$$

(NTNU)

# Spin Correlation



general expression of helicity amplitude

Mahlon and Sparke

$$\sum_{\uparrow\downarrow, \downarrow\uparrow} |\mathcal{M}(q\bar{q} \rightarrow t\bar{t})|^2 = \frac{16g^4}{(2q \cdot \bar{q})^2} \left[ (2q \cdot t_1)(2\bar{q} \cdot \bar{t}_2) + (2q \cdot \bar{t}_1)(2\bar{q} \cdot t_2) + \frac{1}{m_t^2} \text{Tr}(q t_1 t_2 \bar{q} \bar{t}_2 \bar{t}_1) \right] + (q \leftrightarrow \bar{q})$$

$$\sum_{\uparrow\downarrow, \downarrow\uparrow} |\mathcal{M}(q\bar{q} \rightarrow t\bar{t})|^2 = \frac{16g^4}{(2q \cdot \bar{q})^2} \left[ (2q \cdot t_1)(2\bar{q} \cdot \bar{t}_1) + (2q \cdot \bar{t}_2)(2\bar{q} \cdot t_2) + \frac{1}{m_t^2} \text{Tr}(q t_1 t_2 \bar{q} \bar{t}_1 \bar{t}_2) \right] + (q \leftrightarrow \bar{q})$$

$$\begin{aligned} \sum_{\uparrow\downarrow, \downarrow\uparrow} |\mathcal{M}(gg \rightarrow t\bar{t})|^2 &= \frac{4}{3} g^4 \left\{ \frac{4}{(t \cdot g_1)^2} - \frac{1}{(t \cdot g_1)(t \cdot g_2)} + \frac{4}{(t \cdot g_2)^2} \right\} \left\{ m_t^2 [(2t_1 \cdot \bar{t}_1) + (2t_2 \cdot \bar{t}_2)] \right. \\ &\quad \left. - \frac{\text{Tr}(g_1 t g_2 \bar{t})}{(2g_1 \cdot g_2)^2} [(2g_1 \cdot t_1)(2g_2 \cdot \bar{t}_2) + (2g_1 \cdot \bar{t}_1)(2g_2 \cdot t_2) + \frac{1}{m_t^2} \text{Tr}(g_1 t_1 t_2 g_2 \bar{t}_2 \bar{t}_1)] \right\} + (g_1 \leftrightarrow g_2) \end{aligned}$$

$$\begin{aligned} \sum_{\uparrow\downarrow, \downarrow\uparrow} |\mathcal{M}(gg \rightarrow t\bar{t})|^2 &= \frac{4}{3} g^4 \left\{ \frac{4}{(t \cdot g_1)^2} - \frac{1}{(t \cdot g_1)(t \cdot g_2)} + \frac{4}{(t \cdot g_2)^2} \right\} \left\{ m_t^2 [(2t_1 \cdot \bar{t}_2) + (2\bar{t}_1 \cdot t_2)] \right. \\ &\quad \left. - \frac{\text{Tr}(g_1 t g_2 \bar{t})}{(2g_1 \cdot g_2)^2} [(2g_1 \cdot t_1)(2g_2 \cdot \bar{t}_1) + (2g_1 \cdot \bar{t}_2)(2g_2 \cdot t_2) + \frac{1}{m_t^2} \text{Tr}(g_1 t_1 t_2 g_2 \bar{t}_1 \bar{t}_2)] \right\} + (g_1 \leftrightarrow g_2) \end{aligned}$$

$t = t_1 + t_2$     $\bar{t} = \bar{t}_1 + \bar{t}_2$     $t_1(\bar{t}_1)$  defines the spin axis for (anti)top

# Spin Correlation

suppressed for both small  $\beta$  and large  $\beta$

beam basis

$$\sum_{\uparrow\downarrow, \downarrow\uparrow} |\mathcal{M}(q\bar{q} \rightarrow t\bar{t})|^2 = 8g^4 \frac{\beta^2(1 - \beta^2)\sin^2 \theta^*}{(1 - \beta \cos \theta^*)^2}$$

$$\sum_{\uparrow\downarrow, \uparrow\uparrow} |\mathcal{M}(q\bar{q} \rightarrow t\bar{t})|^2 = 8g^4 \left[ 1 + \frac{(1 - \beta \cos \theta^* - \beta^2 \sin^2 \theta^*)^2}{(1 - \beta \cos \theta^*)^2} \right]$$

$$\sum_{\uparrow\downarrow, \downarrow\downarrow} |\mathcal{M}(gg \rightarrow t\bar{t})|^2 = \frac{16}{3}g^4 \mathcal{Y}(\beta, \cos \theta^*) \times (1 - \beta^2) \left[ 1 + \beta^2 \cos^2 \theta^* + 2\beta^3 \sin^2 \theta^* \frac{(\beta - \cos \theta^*)}{(1 - \beta \cos \theta^*)^2} \right]$$

$$\sum_{\uparrow\downarrow, \uparrow\uparrow} |\mathcal{M}(gg \rightarrow t\bar{t})|^2 = \frac{16}{3}g^4 \mathcal{Y}(\beta, \cos \theta^*) \times \beta^2 \sin^2 \theta^* \left[ 1 + \frac{(1 - \beta^2)^2 + (1 - \beta \cos \theta^* - \beta^2 \sin^2 \theta^*)^2}{(1 - \beta \cos \theta^*)^2} \right]$$

suppressed for small  $\beta$

helicity basis

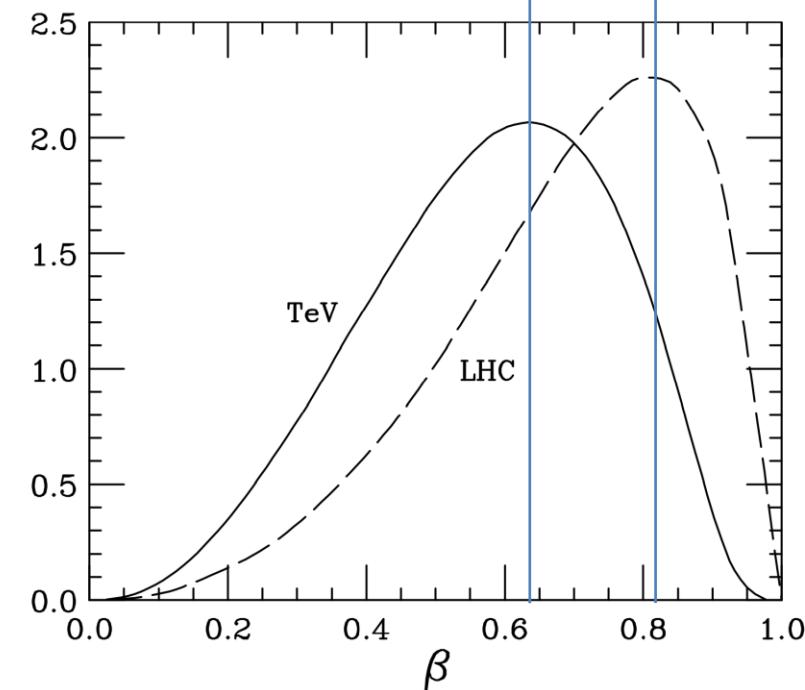
$$\sum_{LL, RR} |\mathcal{M}(q\bar{q} \rightarrow t\bar{t})|^2 = 8g^4 (1 - \beta^2) \sin^2 \theta^*$$

$$\sum_{LR, RL} |\mathcal{M}(q\bar{q} \rightarrow t\bar{t})|^2 = 8g^4 (1 + \cos^2 \theta^*)$$

$$\sum_{LL, RR} |\mathcal{M}(gg \rightarrow t\bar{t})|^2 = \frac{16}{3}g^4 \mathcal{Y}(\beta, \cos \theta^*) (1 - \beta^2) (1 + \beta^2 + \beta^2 \sin^4 \theta^*)$$

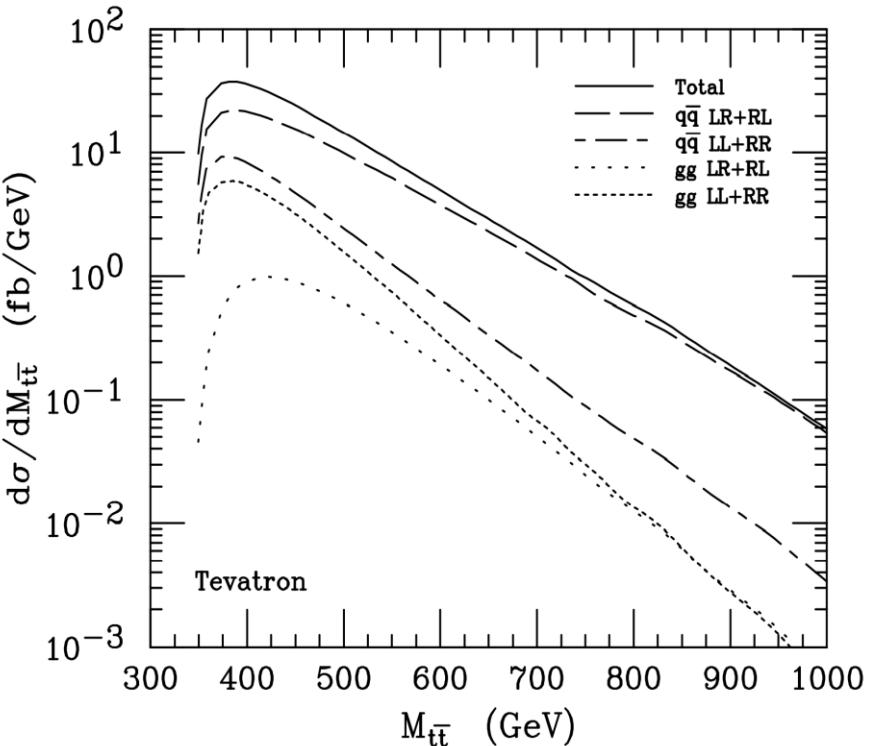
$$\sum_{LR, RL} |\mathcal{M}(gg \rightarrow t\bar{t})|^2 = \frac{16}{3}g^4 \mathcal{Y}(\beta, \cos \theta^*) \beta^2 \sin^2 \theta^* (1 + \cos^2 \theta^*)$$

suppressed for large  $\beta$

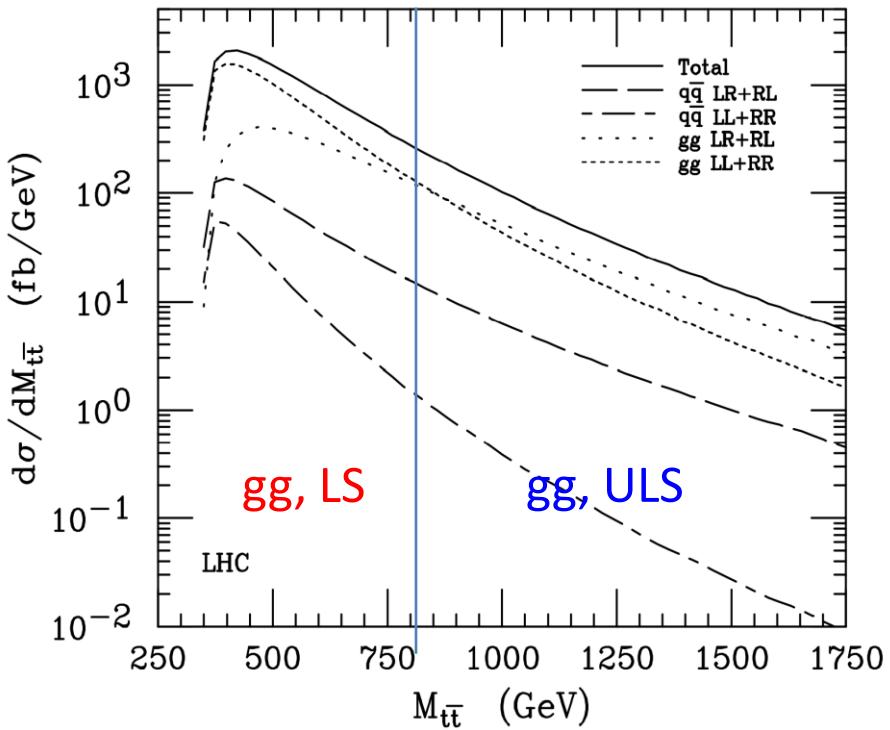


# Spin Correlation

helicity basis



unlike-spin event dominates at the Tevatron



LHC: like-spin event dominates @ low energy region; unlike-spin event dominates high energy region

overall, like-spin wins



# Spin Correlation

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

$A < 0$  @ Tevatron,  
 $A > 0$  @ LHC

$A$  is sensitive to

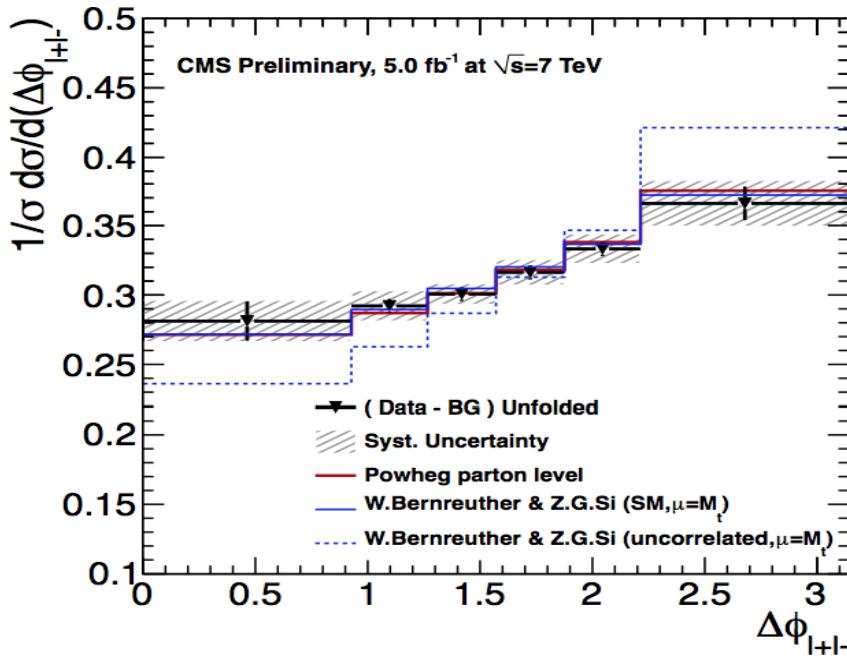
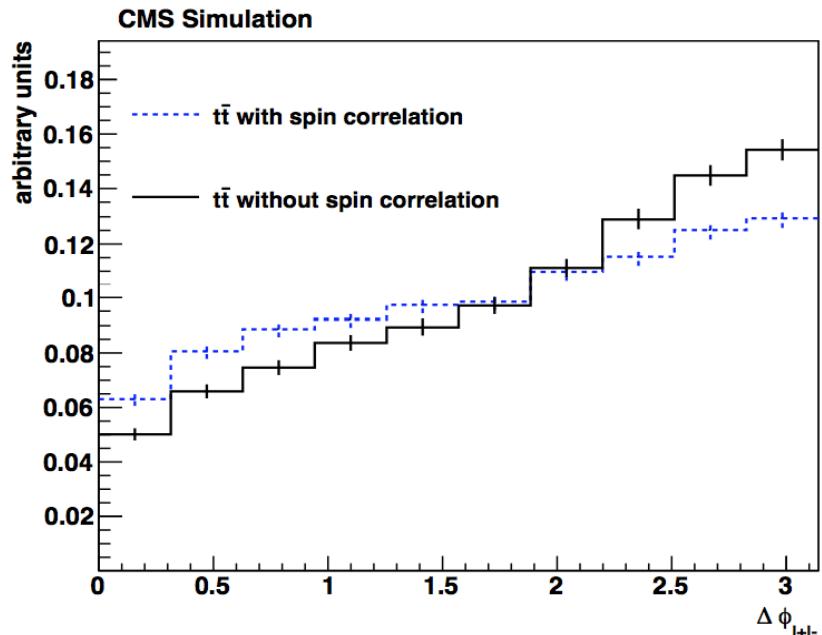
$$\Delta\phi_{l+l-} = |\phi_{l+} - \phi_{l-}|$$

fitting  $\Delta\phi$  to determine  $A$

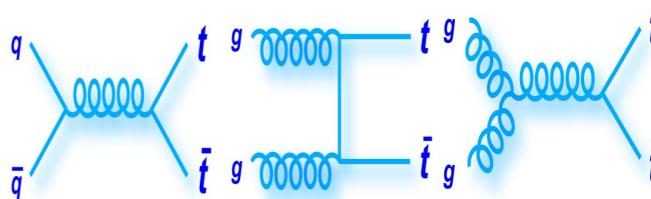
$$A_{hel.}^{SM} = 0.31$$

$$A_{hel.}^{meas.} = 0.24 \pm 0.02(\text{stat.}) \pm 0.08(\text{syst.})$$

consistent!



# $t\bar{t}$ F-B Asymm



Forward-Backward Asymmetry  $\equiv$

(event # w/ t in forward – event # w/ t in backward)

ALL

@ Tevatron

$$\text{Lab frame } A_{fb}^{pp\bar{p}} = \frac{N(\cos\theta_t > 0) - N(\cos\theta_t < 0)}{N(\cos\theta_t > 0) + N(\cos\theta_t < 0)}$$

$$\text{c.m. frame } A_{fb}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N_t(\Delta y < 0)}$$

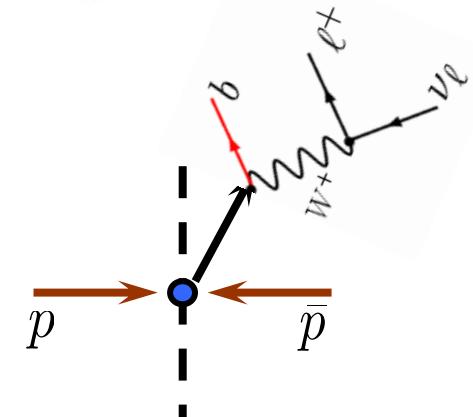
$$\Delta y = y_t - y_{\bar{t}} = 2 \cdot \tanh^{-1} \left( \frac{\cos(\theta_{t\bar{t}})}{\sqrt{1 + \frac{4m_t^2}{\hat{s}-4m_t^2}}} \right)$$

Lepton Asymmetry

$$A_{FB}^l = \frac{N_F^l - N_B^l}{N_F^l + N_B^l}, \quad \begin{array}{ll} N_F^l : qy_l > 0 \\ N_B^l : qy_l < 0 \end{array}$$

SM: 0 at tree level, but induced in NLO  $A^{t\bar{t}} \sim 0.058$  (MCFM)

$$A_{FB}^l \sim 0.021 \quad (\text{MC@NLO})$$



## A<sub>fb</sub> of the Top Quark

# Data

## CDF

$$A_{FB}^{t\bar{t}} = 0.24 \pm 0.13 \text{ (stat)} \pm 0.04 \text{ (syst)} \quad 1.9 \text{ fb}^{-1}$$

$$A_{FB}^{t\bar{t}} = 0.158 \pm 0.074 \text{ (stat & syst)} \quad 5.3 \text{ fb}^{-1}$$

$$A_{FB}^{t\bar{t}} = 0.162 \pm 0.047 \text{ (stat & syst)} \quad 8.7 \text{ fb}^{-1}$$

$$A_{FB}^{t\bar{t}} = 0.164 \pm 0.047 \text{ (stat & syst)} \quad 9.4 \text{ fb}^{-1}$$

$$A_{FB}^l = (9.4 \pm 2.4^{+2.2}_{-1.7})\% \quad 9.4 \text{ fb}^{-1}$$

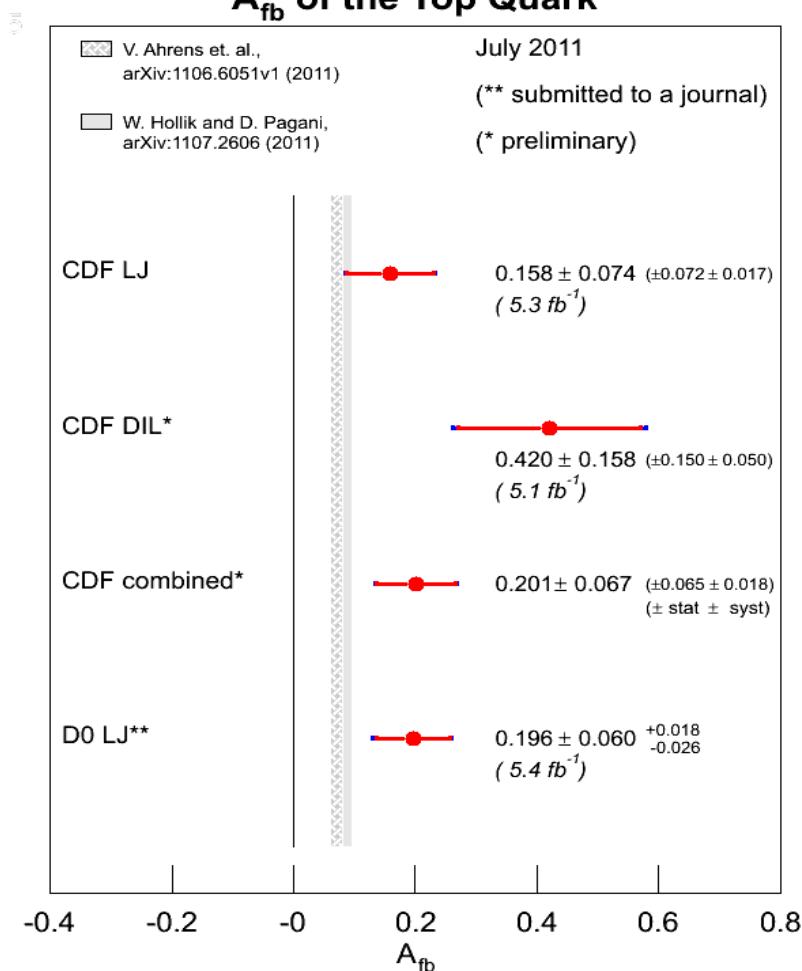
## D0

$$A_{FB}^{t\bar{t}} = 0.12 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)} \quad 0.9 \text{ fb}^{-1}$$

$$A_{FB}^{t\bar{t}} = 0.196 \pm 0.065 \text{ (stat & syst)} \quad 5.4 \text{ fb}^{-1}$$

$$A_{FB}^l = (15.2 \pm 4.0)\% \quad 5.4 \text{ fb}^{-1}$$

$$A_{FB}^l = (4.7 \pm 2.3^{+1.1}_{-1.4})\% \quad 9.7 \text{ fb}^{-1}$$

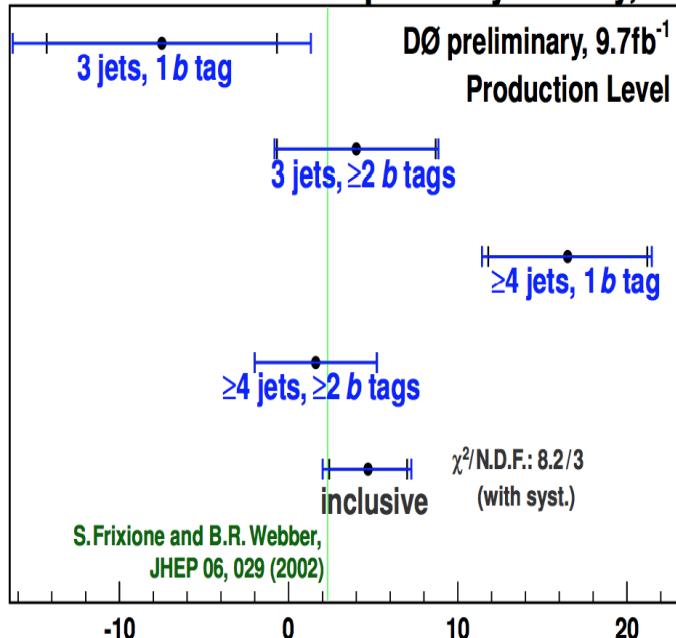


NOTE, SM:  $A^{t\bar{t}} \sim 0.058$  (MCFM)

# Data

D0,  $9.7 \text{ fb}^{-1}$  data set, new  $A_{FB}^l = (4.7 \pm 2.3^{+1.1}_{-1.4})\%$   
 however, for the same event category of previous measurement, lepton asymmm is still high!

## Forward-Backward Lepton Asymmetry, %



Channel	$A_{FB}^l (\%)$	MC@NLO
$l + 3 \text{ jets}, 1 \text{ } b \text{ tag}$	$-7.5 \pm 6.8 \text{ (stat.)} \pm 5.6 \text{ (syst.)}$	
$l + 3 \text{ jets}, \geq 2 \text{ } b \text{ tags}$	$4.0 \pm 4.7 \text{ (stat.)}^{+1.2}_{-1.1} \text{ (syst.)}$	
$l + \geq 4 \text{ jets}, 1 \text{ } b \text{ tag}$	$16.5 \pm 4.7 \text{ (stat.)}^{+1.6}_{-1.9} \text{ (syst.)}$	2.3
$l + \geq 4 \text{ jets}, \geq 2 \text{ } b \text{ tags}$	$1.6 \pm 3.6 \text{ (stat.)}^{+0.4}_{-0.2} \text{ (syst.)}$	
Total	$4.7 \pm 2.3 \text{ (stat.)}^{+1.1}_{-1.4} \text{ (syst.)}$	

previous event selection

add new data sets

combined  $(1.5 \pm 2.8)\%$

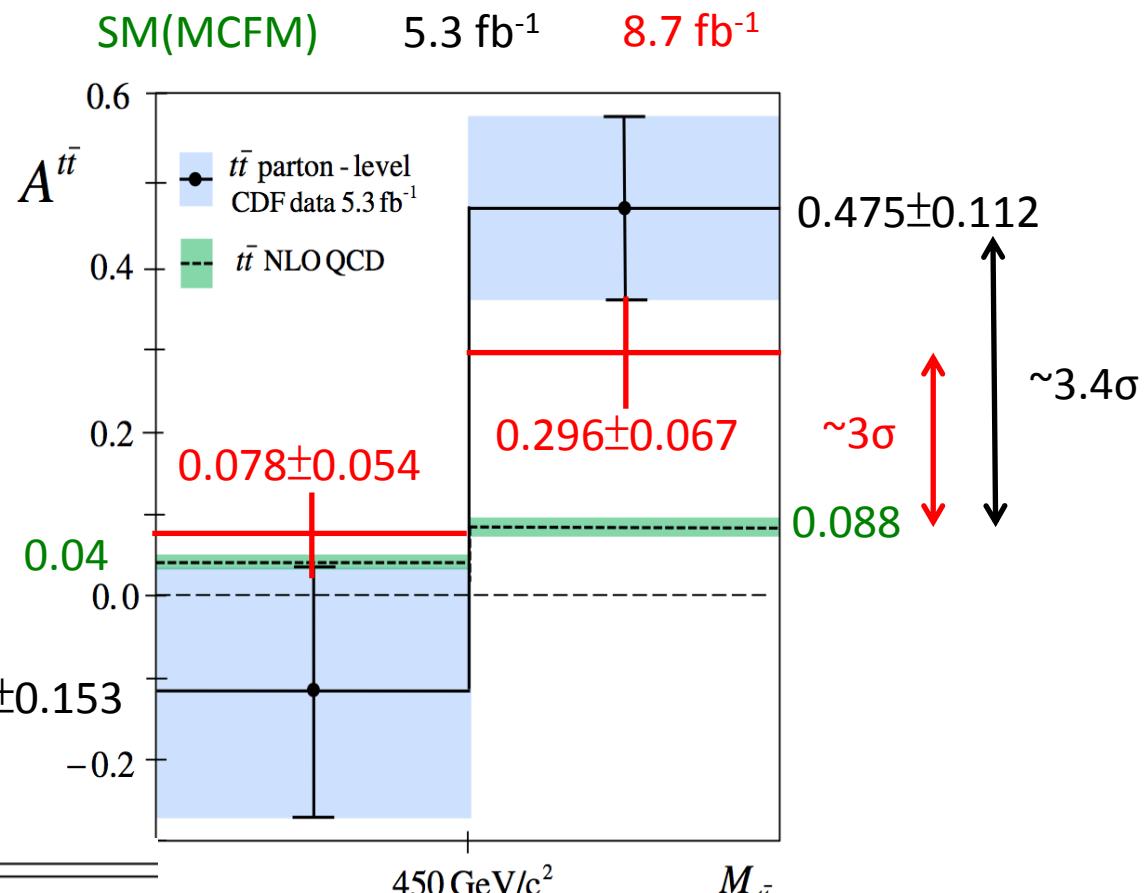
# Data

CDF:

energy-dependent  $A_{FB}$

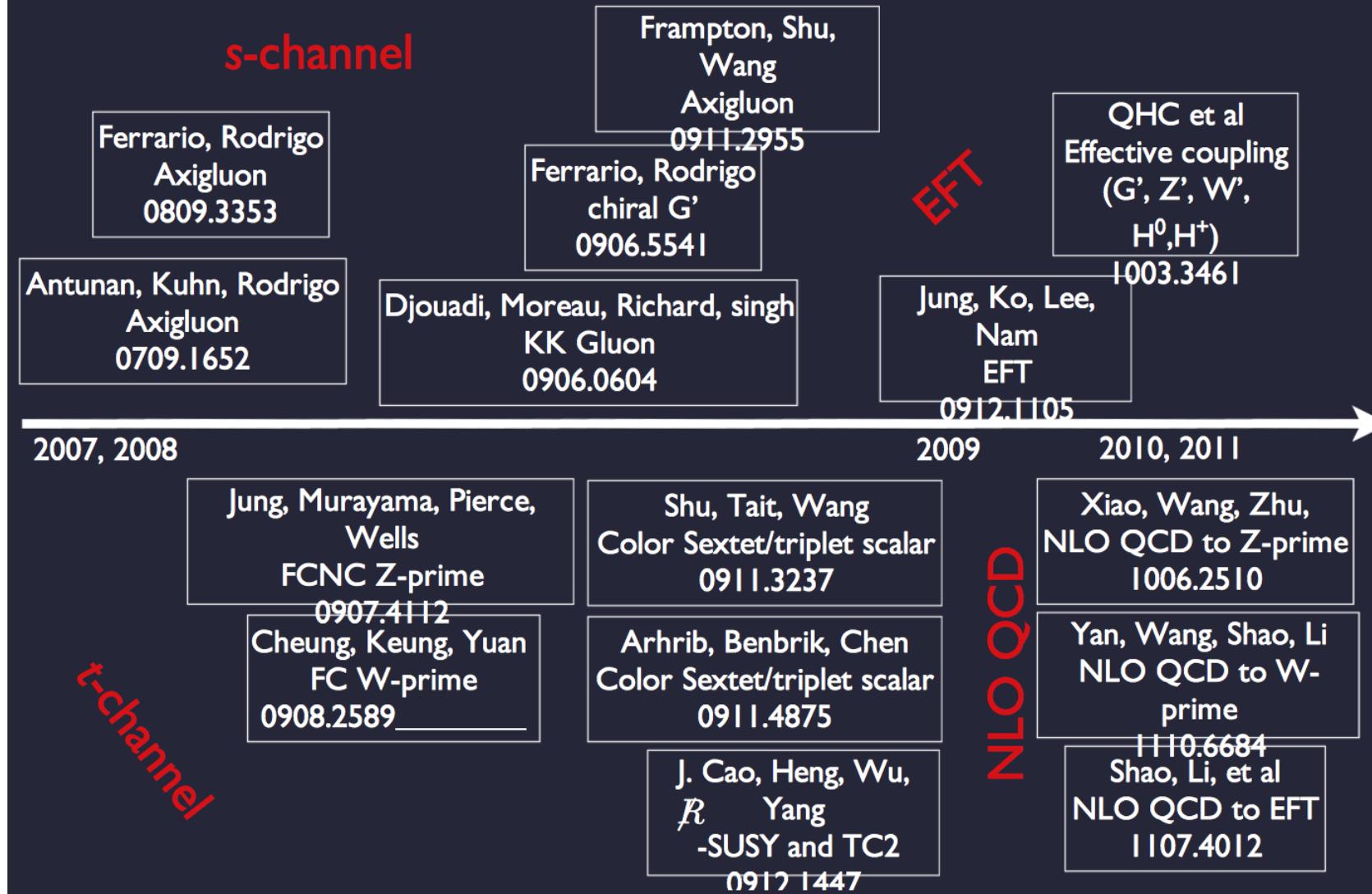
$\approx$  SM @  $M_{t\bar{t}} < 450$  GeV  
 $> 3 \sigma$  @  $M_{t\bar{t}} > 450$  GeV

$9.4 \text{ fb}^{-1}$



Parton level		Data		
$M_{t\bar{t}}$ ( $\text{GeV}/c^2$ )	$A_{FB}$	$\pm$ stat	$\pm$ syst	
< 450	$0.084 \pm 0.046 \pm 0.030$			
$\geq 450$	$0.295 \pm 0.058 \pm 0.033$			

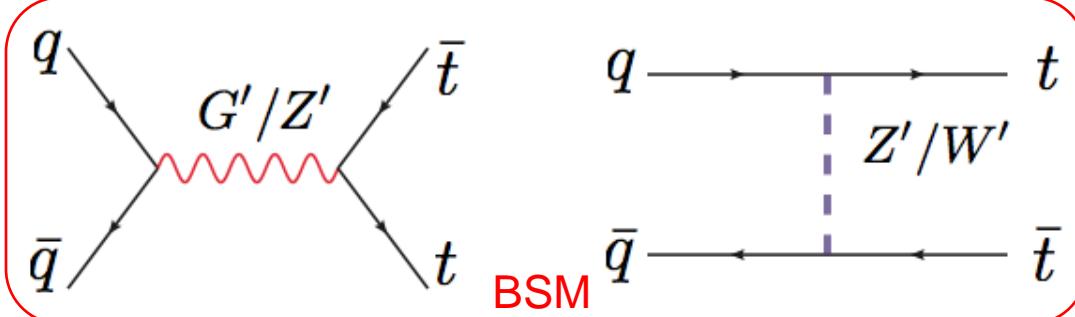
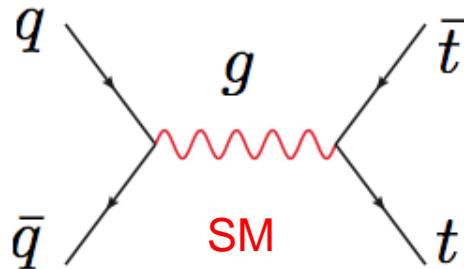
# Timeline of $A_{FB}^t$ and NP models



Steal from Q.-H. Cao's talk slide

# New Physics

NP models may be divided into two classes



s-channel: extra octet vector gluon (**axigluon**, ....?)

- “small” couplings to the first two generations: dijet constraints at 7 TeV.
- large couplings to third generation: to generate large  $A_{FB}$ .
- heavy resonances: ttbar invariant mass spectrum constraints.
- broad width: to interfere with the SM amplitude.

t-channel: flavor changing interaction

- color singlet: **Z'-u-t**, **W'+-d-t**
- color sextet or triplet

[Jung,Murayama,Pierce,Wells, arXiv:0907.4112]

[Cheung,Keung,Yuan, arXiv:0908.2589]

[Shu,Tait,Wang, arXiv:0911.3237]

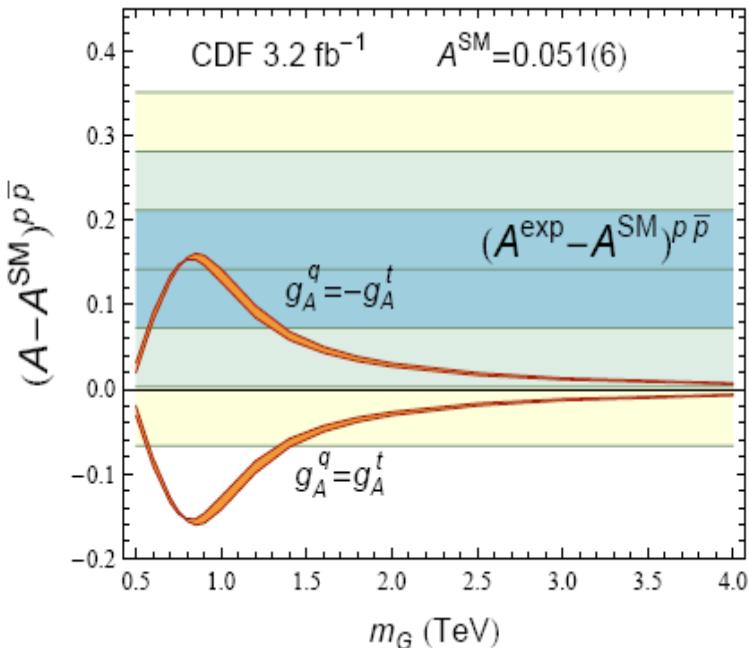


# New Physics

## possible explanations (s-ch)

Color-octet resonances  $L = g_S T^a \bar{q}_i \gamma^\mu (g_V^{qi} + g_A^{qi} \gamma_5) G_\mu q_i$

- But this asymmetry is negative because it is proportional to  $(s-m_G^2) g_A^q g_A^t$



[Ferrario, Rodrigo, arXiv:0906.5541]

$$\begin{aligned} \frac{d\sigma^{q\bar{q} \rightarrow t\bar{t}}}{d\cos\hat{\theta}} &= \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \left\{ 1 + c^2 + 4m^2 \right. \\ &+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[ g_V^q g_V^t (1 + c^2 + 4m^2) \right. \\ &\left. \left. + 2g_A^q g_A^t c \right] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[ ((g_V^q)^2 + (g_A^q)^2) \right. \right. \\ &\times \left. ((g_V^t)^2 (1 + c^2 + 4m^2) + (g_A^t)^2 (1 + c^2 - 4m^2)) \right. \\ &\left. \left. + 8g_V^q g_A^q g_V^t g_A^t c \right] \right\}, \end{aligned} \quad (1)$$

- It is still possible to generate a positive asymmetry if  $\text{sign}(g_A^q) = -\text{sign}(g_A^t)$

[Frampton, Shu, Wang, arXiv:0911.2955]

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

$$\frac{d\sigma}{d \cos \theta} = \mathcal{A}_{SM} + \mathcal{A}_{INT} + \mathcal{A}_{NPS}$$

$$\mathcal{A}_{SM} = \frac{2g_s^4}{9} (2 - \beta^2 + \beta^2 \cos^2 \theta)$$

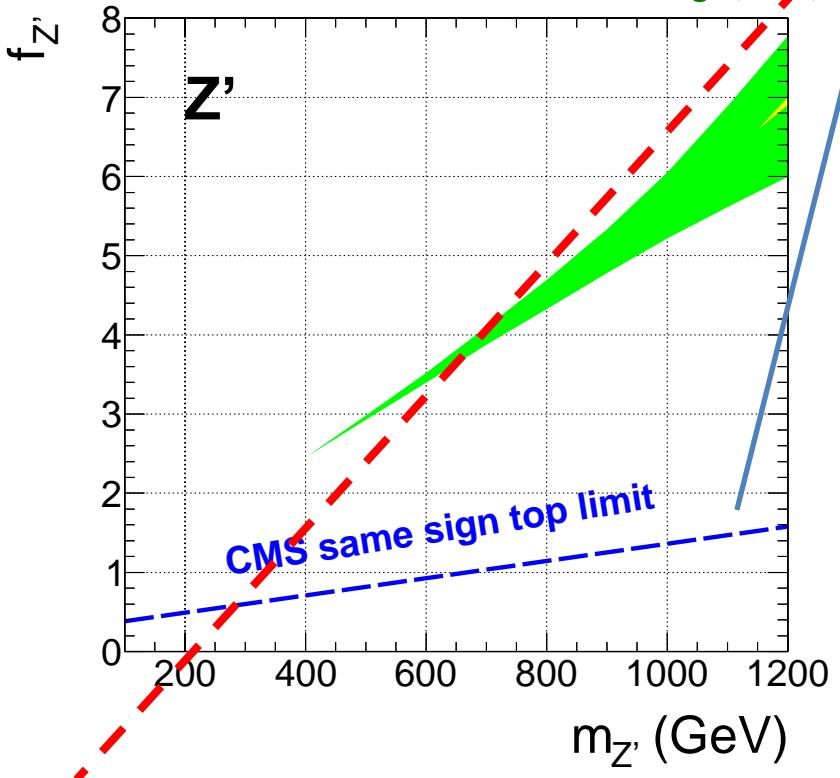
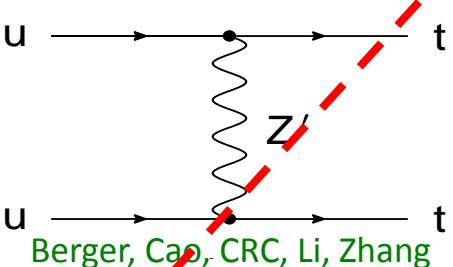
$$\mathcal{A}_{INT} = \frac{\beta g_s^2 g_w^2}{72\pi \hat{s}} \frac{f_R^2}{\hat{s}(\hat{t} - m_{Z'}^2)} \left[ 2(\hat{u} - m_t^2)^2 + 2\hat{s}m_t^2 + \frac{m_t^2}{m_{Z'}^2} ((\hat{t} - m_t^2)^2 + \hat{s}m_t^2) \right]$$

$$\mathcal{A}_{NPS} = \frac{\beta g_w^4}{128\pi \hat{s}} \frac{f_R^4}{(\hat{t} - m_{Z'}^2)^2} \left[ 4(\hat{u} - m_t^2)^2 + \frac{m_t^4}{m_{Z'}^4} (4\hat{s}m_{Z'}^2 + (\hat{t} - m_{Z'}^2)^2) \right]$$

- ❑ INT contribution is negative.
- ❑ NPS contribution is positive.
- ❑ Left-handed coupling is highly constrained by  $\bar{B}_d - \bar{B}_d$  mixing, set  $f_L = 0$ .
- ❑ For heavy  $Z'$ , one needs a large  $f_R$  such that NPS contribution dominates over INT contribution to produce positive  $A_{FB}$ .



# Fitting Tevatron

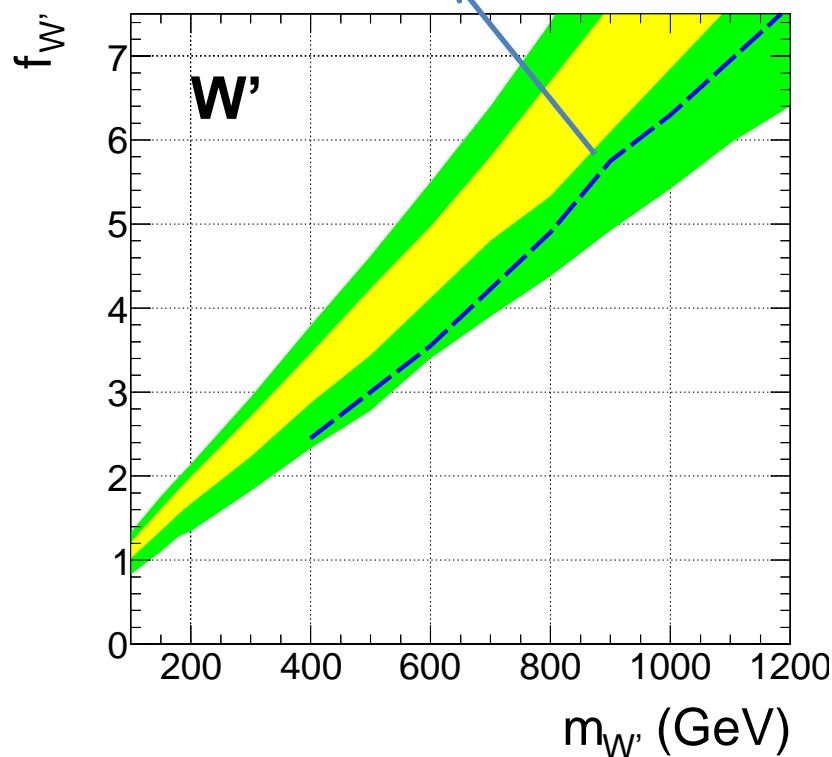
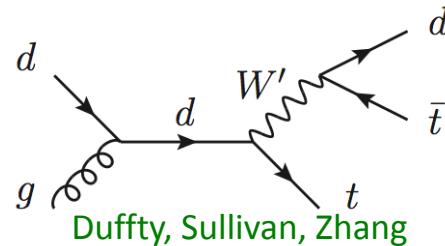


only a tiny parameter space fits  $1\sigma$

w/  $m_{Z'} > 1100$  GeV

no parameter space can fit w/  $m_{Z'} < 400$  GeV

produces too many  $t\bar{t}$  events



fits data well

in tension with  $t\bar{t} + \text{jets}$

Berger, Cao, CRC, Zhang, PRD 88, 014003



# Fitting Tevatron

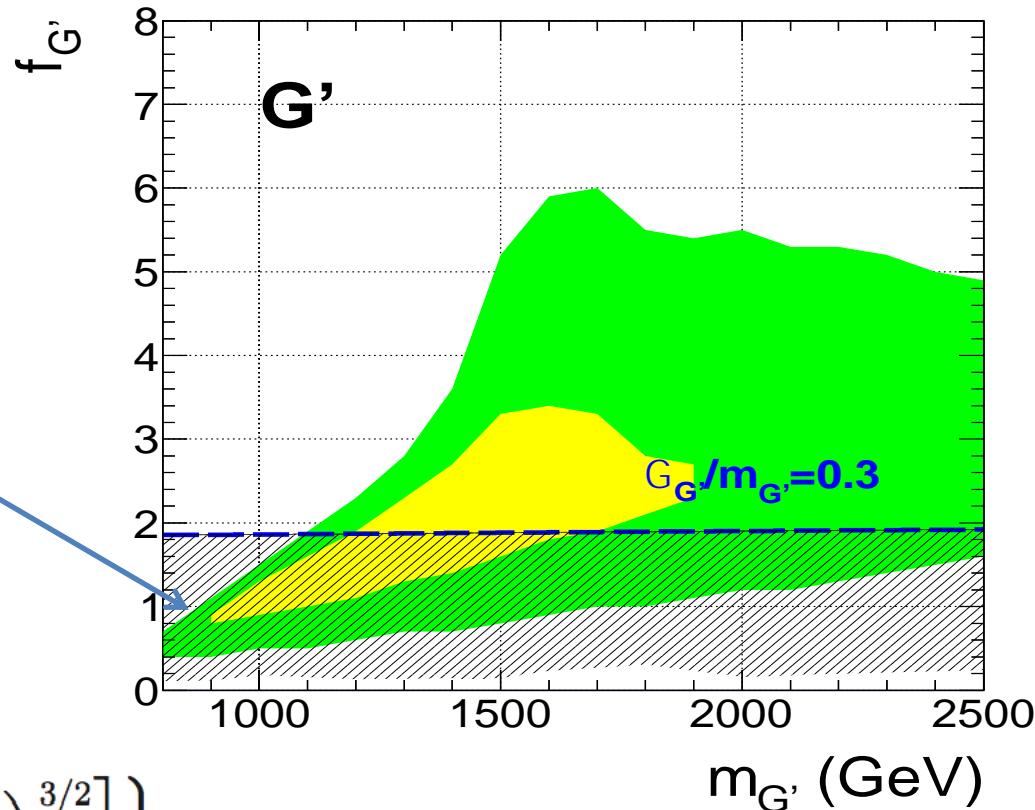
for simplicity  $g_\ell = g_h = f_{G'}$

large parameter space fits data well  
 $w/ m_{G'} > 1000 \text{ GeV}$

constrained by dijet search

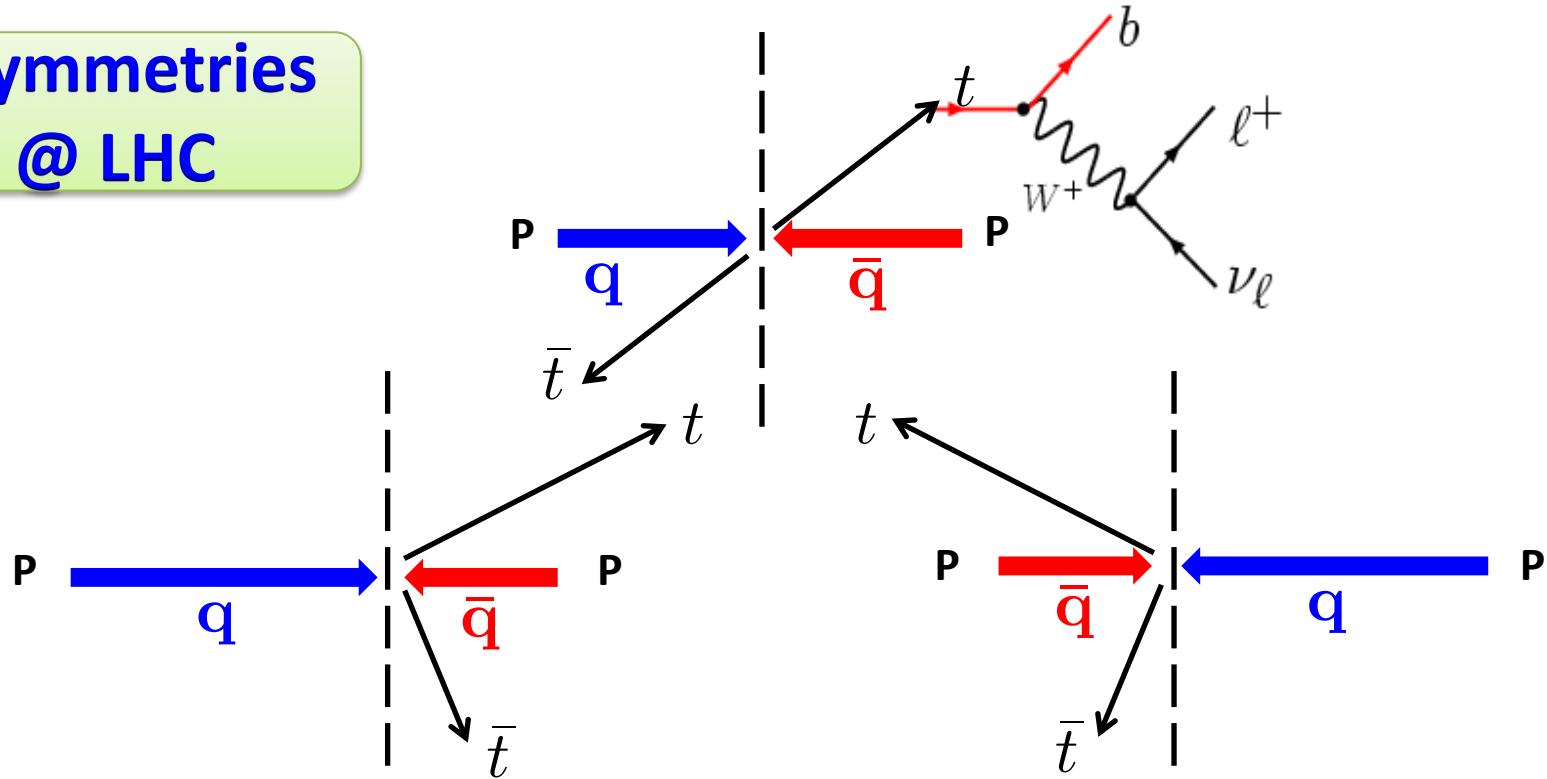
Note that,  $f_{G'} \uparrow, \Gamma_{G'} \uparrow,$   
 broaden the peak, search strategy  
 for narrow width fails.

$$\Gamma_{G'} = \frac{\alpha_S m_{G'}}{6} \left\{ 4g_l^2 + g_h^2 \left[ 1 + \left( 1 - \frac{4m_t^2}{m_{G'}^2} \right)^{3/2} \right] \right\}$$



Berger, Cao, CRC, Zhang, PRD 88, 014003

# Asymmetries @ LHC



if there is a top quark forward-backward asymmetry, top quarks are produced more closed to beam line

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \quad \Delta|y| = |y_t| - |\bar{y}_{t\bar{t}}|$$

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

# Extrapolation

how large the asymmetry should we expect?

$$A_C \approx \frac{\sigma(q\bar{q} \rightarrow t\bar{t})}{\sigma(gg \rightarrow t\bar{t}) + \sigma(q\bar{q} \rightarrow t\bar{t})} \times A_{FB}^t(q\bar{q} \rightarrow t\bar{t}) \times \tilde{\epsilon}.$$

$$A_{FB}^t(q\bar{q} \rightarrow t\bar{t}) \approx A_{FB}^t / 88\%$$

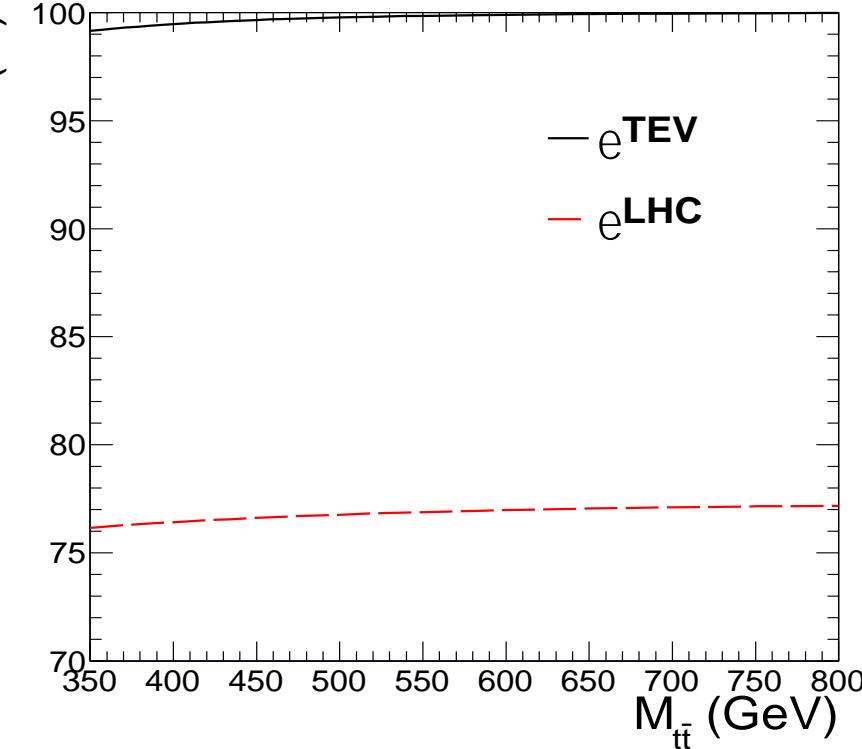
$$\tilde{\epsilon} = \frac{2\epsilon^{LHC} - 1}{2\epsilon^{TEV} - 1}$$

$$\epsilon^{TEV} = \frac{\sigma(q\bar{q} \rightarrow t\bar{t})_{q/P, \bar{q}/\bar{P}}}{\sigma(q\bar{q} \rightarrow t\bar{t})_{\text{total}}}$$

$$\epsilon^{LHC} = \frac{\sigma(q\bar{q} \rightarrow t\bar{t})_{q > \bar{q}}}{\sigma(q\bar{q} \rightarrow t\bar{t})_{\text{total}}}$$

$\approx 54\%$

$$A_C \simeq 0.17 \times (A_{FB}^t / 88\%) \times 54\% \simeq 0.1 A_{FB}^t \xrightarrow{A_{FB}^t \sim 0.2} \simeq 0.02$$



## Data

ATLAS

$$A_C^{t\bar{t}} = 0.057 \pm 0.024 \text{ (stat.)} \pm 0.015 \text{ (syst.)} \text{ dilepton, } 4.7 \text{ fb}^{-1}$$

$$A_C = -0.019 \pm 0.028 \text{ (stat.)} \pm 0.024 \text{ (syst.) JL, } 1.09 \text{ fb}^{-1}$$

Combined

$$A_C^{t\bar{t}} = 0.029 \pm 0.018 \text{ (stat.)} \pm 0.014 \text{ (syst.)}$$

$$A_C^{\ell\ell} = 0.023 \pm 0.012 \text{ (stat.)} \pm 0.008 \text{ (syst.) dilepton, } 4.7 \text{ fb}^{-1}$$

CMS

$$A_C^y = -0.013 \pm 0.028 \text{ (stat.)} {}^{+0.029}_{-0.031} \text{ (syst.) JL, } 1.09 \text{ fb}^{-1}$$

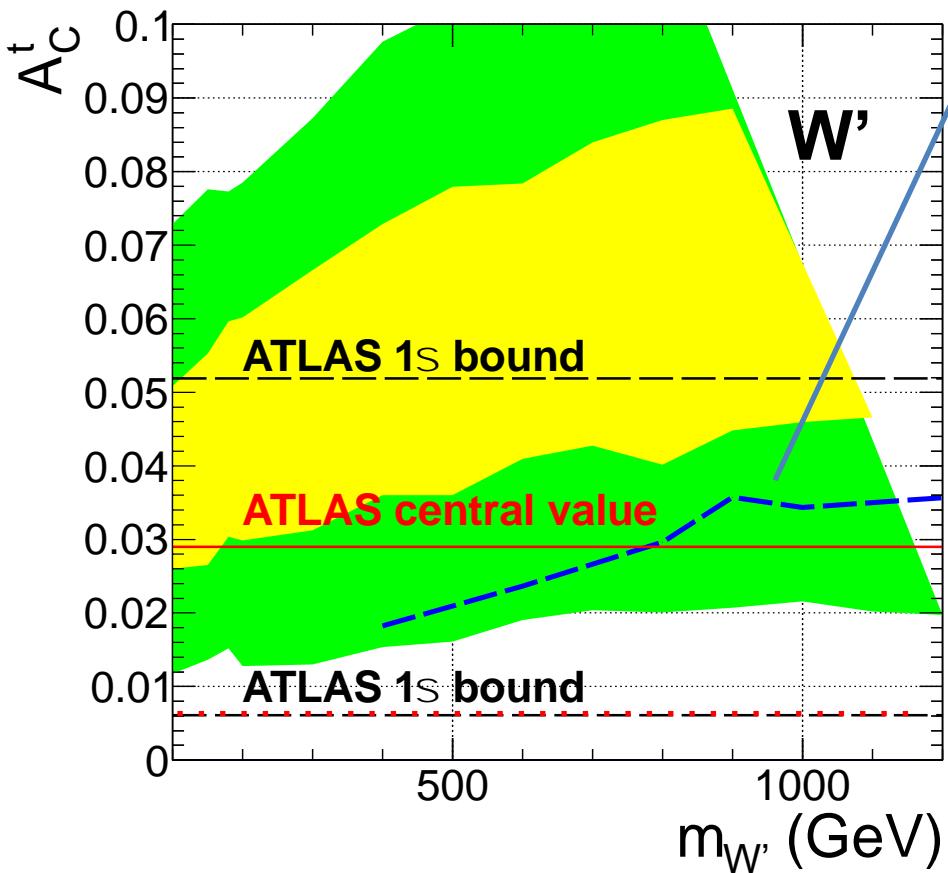
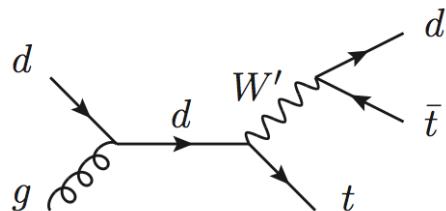
$$A_C = 0.004 \pm 0.010 \text{ (stat.)} \pm 0.012 \text{ (syst.) JL, } 4.7 \text{ fb}^{-1}$$

SM (MC@NLO)  $A_C^{\ell\ell} = 0.004 \pm 0.001$  and  $A_C^{t\bar{t}} = 0.006 \pm 0.002$

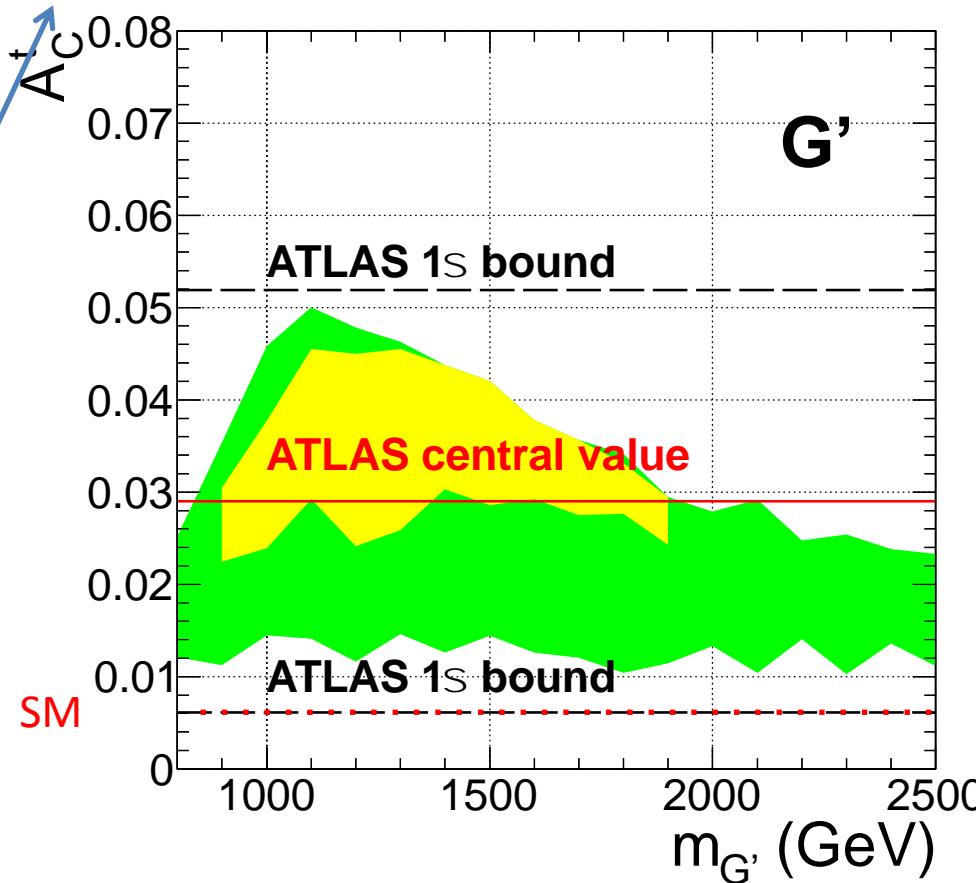
SM (QCD EW NLO; norm to LO)  $A_C^t = 0.0115$

**NOTE, we expect  $A_C \simeq 0.02$  (or  $0.1 A_{FB}^t$ )**

# Comparison w/ ATLAS

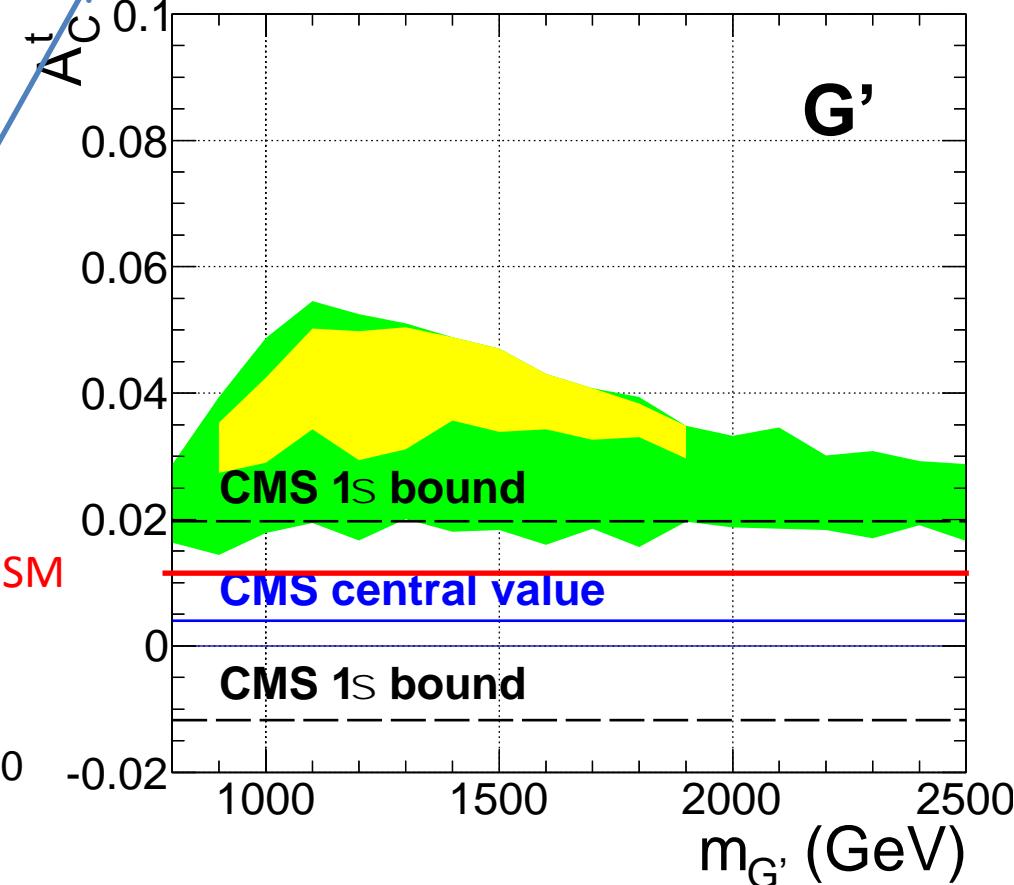
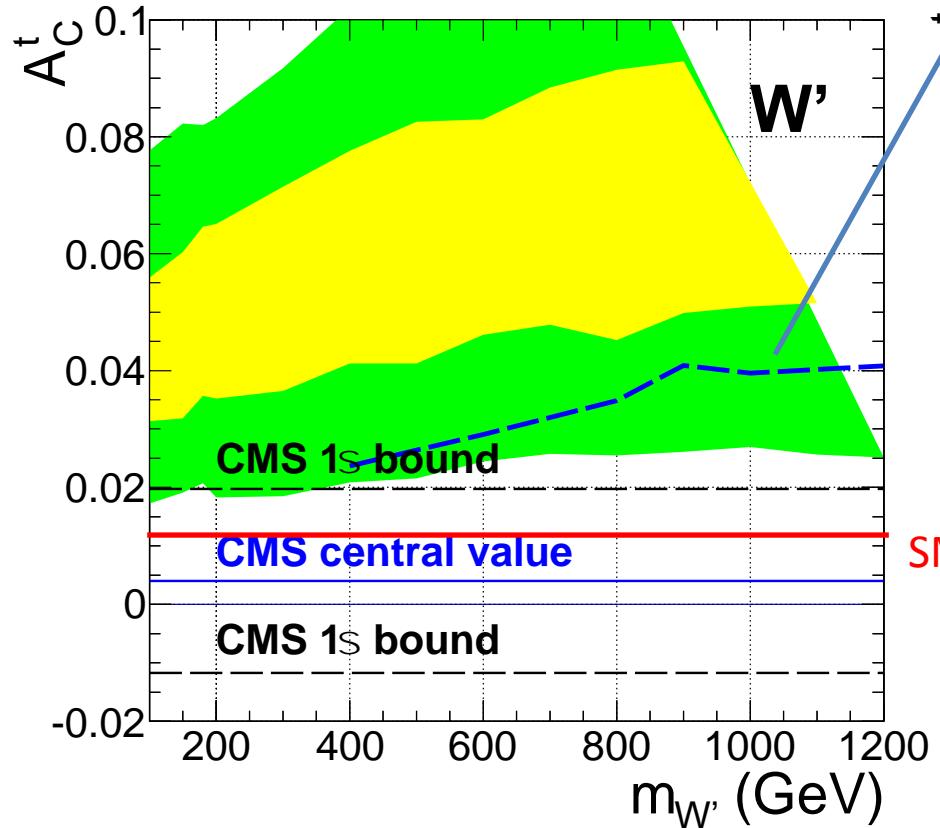
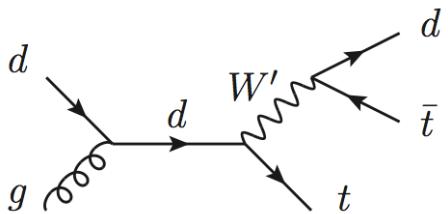


use  $A_C^t = 0.006$  for SM



consistent with ATLAS data

# Comparison w/ CMS



use  $A_C^t = 0.0115$  for SM

most of cases  $> 1\sigma$   
in tension with ttbar + jets data

# Asymmetry A<sup>I</sup>

**SM:**  $A_{FB}^t = 0.051 \pm 0.001$

$A_{FB}^\ell = 0.021 \pm 0.001$

$$\frac{A_{FB}^\ell}{A_{FB}^t} \sim 40\%$$

**D0:**  $A_{FB}^t = 0.196 \pm 0.065$

$A_{FB}^\ell = 0.152 \pm 0.040$

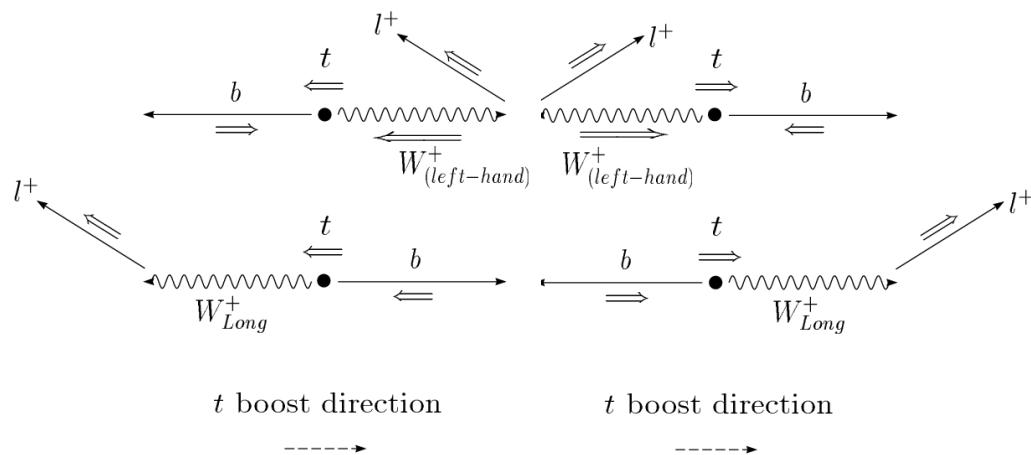
$\sim 3\sigma$

$$\frac{A_{FB}^\ell}{A_{FB}^t} \sim 75\%$$

❖ correlation between these two asymmetries?

→ kinematics, in the point of view of top quark polarization

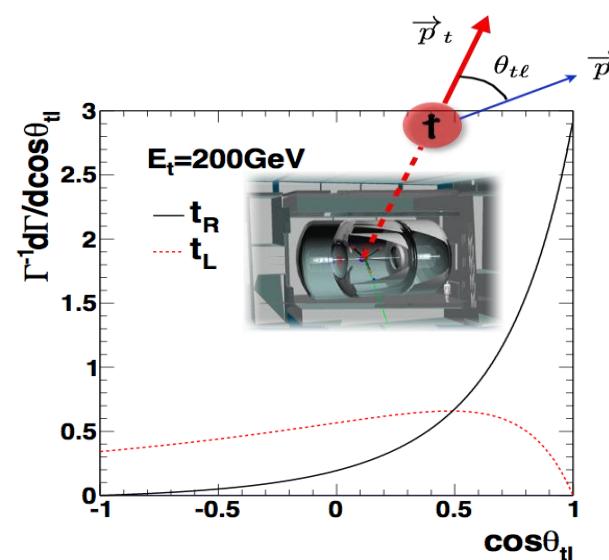
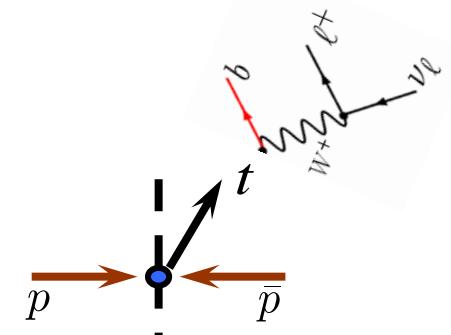
(a) left-handed top



charged lepton from right- (left-) handed top decay prefers to move along (against) the direction of top boost direction

$$(1 \pm \cos \theta)/2$$

CRC (NTNU)



# Correlation

■  $A_{FB}^\ell = n_\ell^F - n_\ell^B = \sum_{\substack{\lambda=+,- \\ y_t > 0}} \int [2R_F^\lambda(\beta, y_t) - 1] \frac{1}{\sigma} \left[ \frac{d^2\sigma|_{\lambda_t=\lambda}}{d\beta dy_t} \Big|_{y_t} - \frac{d^2\sigma|_{\lambda_t=\lambda}}{d\beta dy_t} \Big|_{-y_t} \right] d\beta \wedge dy_t$

if  $R_F \sim \text{constant}$   $A_{FB}^\ell \simeq \rho_L(2R_F^L - 1)A_{FB}^{t_L} + \rho_R(2R_F^R - 1)A_{FB}^{t_R}$

threshold region

$\rho_L \sim 1, \rho_R \sim 0, R_F \sim 0.5$  if  $t_L$  dominates

→  $A_{FB}^\ell \simeq 0$

$\rho_L \sim 0, \rho_R \sim 1, R_F \sim 1$  if  $t_R$  dominates

→  $A_{FB}^\ell \simeq A_{FB}^{t_R}$

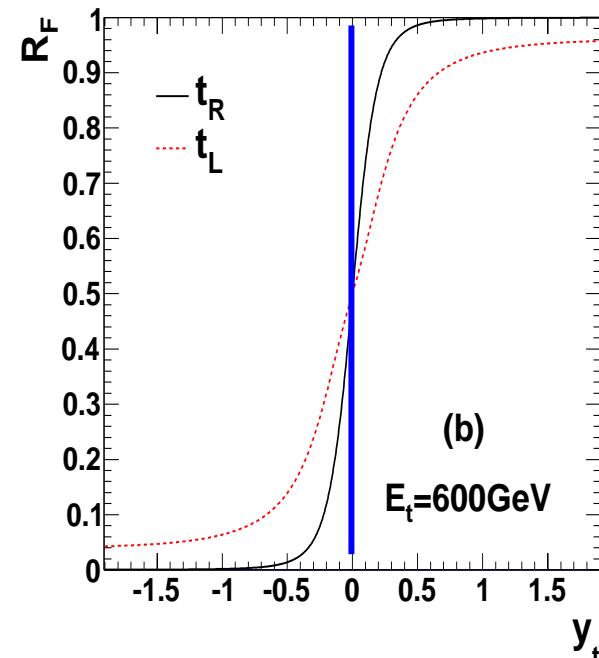
for large energy  $t$  (boosted region),  $R_F^R \sim R_F^L \sim 1$

either  $t_R$  or  $t_L$  dominates

→  $A_{FB}^\ell \simeq A_{FB}^{t_R}$

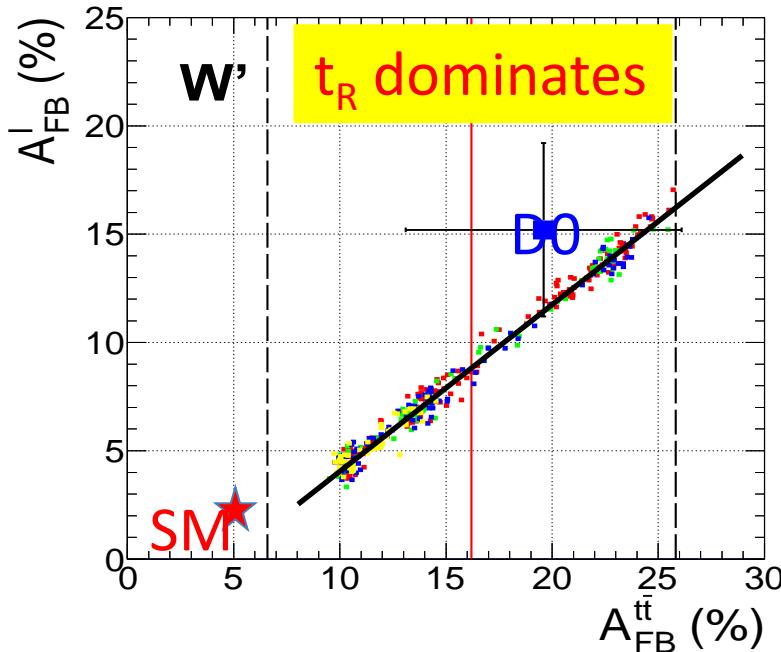
if unpolarized,  $\rho_L = \rho_R = 0.5$

→  $A_{FB}^\ell \simeq 0.5A_{FB}^{t_R}$



# NP– W' & G'

Tevatron

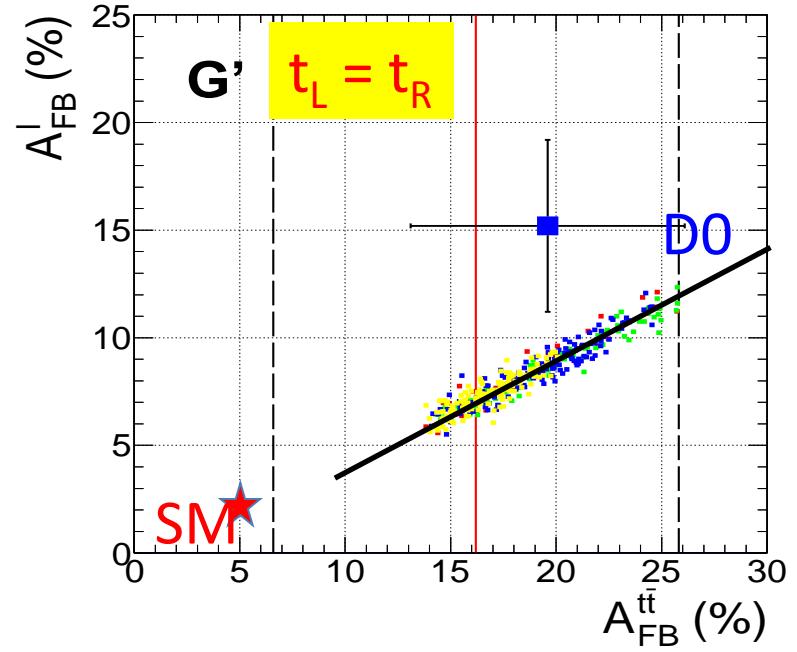


$$A_{FB}^l = 0.77 \times A_{FB}^t - 3.6\%$$

$$A_{FB}^l / A_{FB}^t \simeq 0.77$$

$D0 \approx 0.75$  ( $5.4 \text{ fb}^{-1}$ ),  $0.24 *$   
prefers more right-handed tops

recall:  $SM \approx 0.4$



$$A_{FB}^l = 0.5 \times A_{FB}^t - 1\%$$

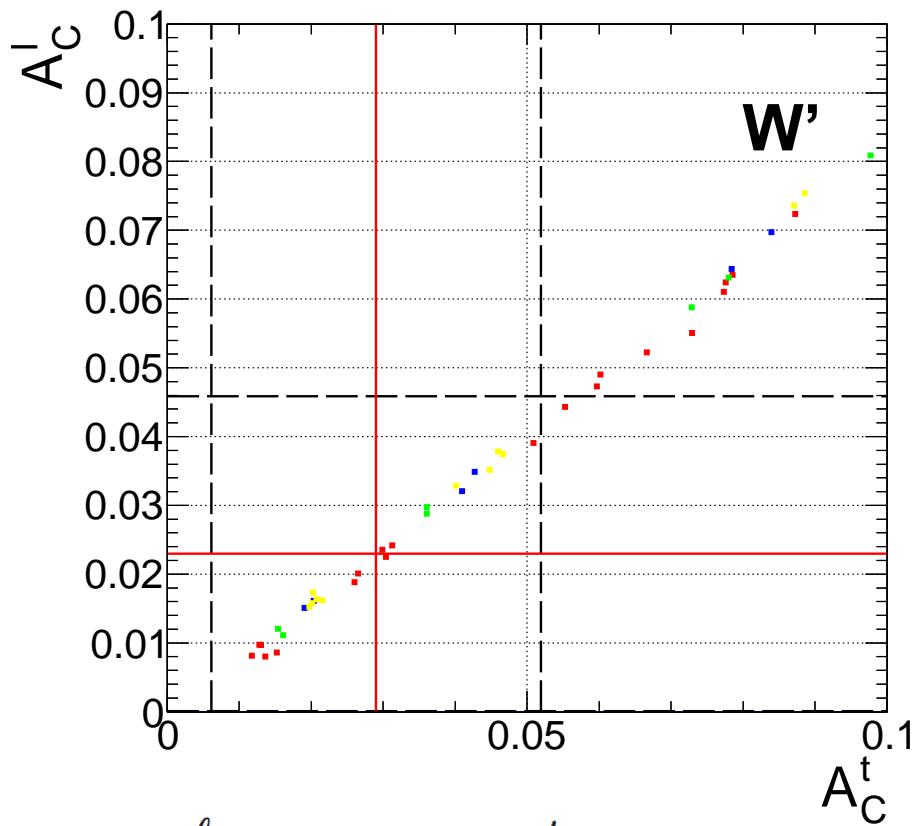
$$A_{FB}^l / A_{FB}^t \simeq 0.5$$

$CDF \approx 0.57$  ( $9.4 \text{ fb}^{-1}$ )  
prefers boosted tops

Berger, Cao, CRC, Zhang, PRD 88, 014003

# NP– W' & G'

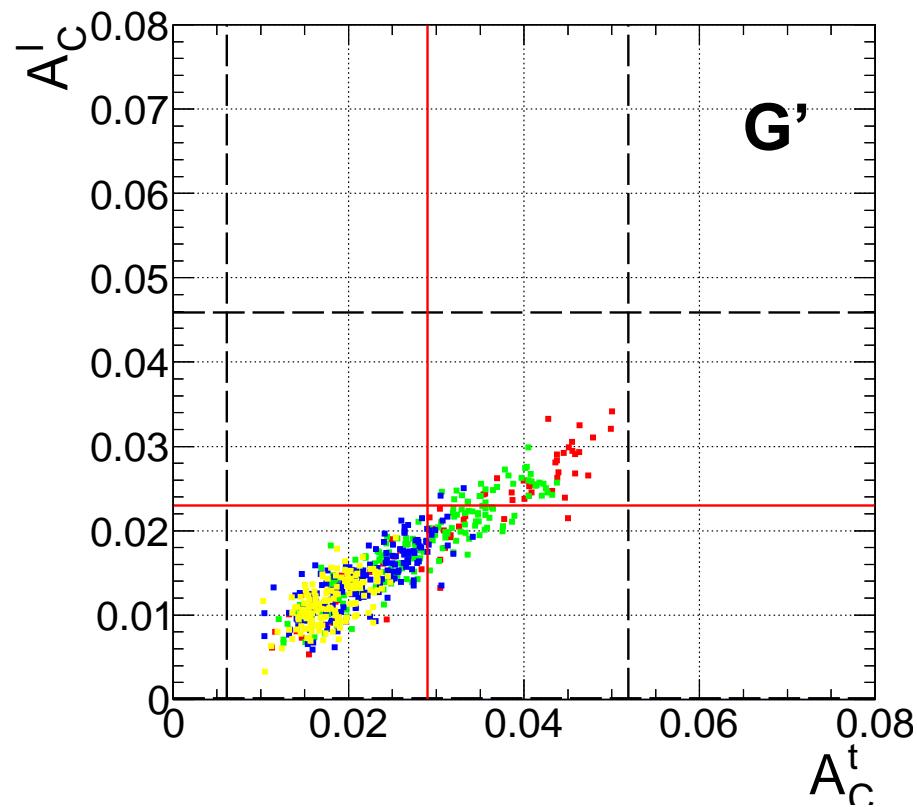
ATLAS



$$A_C^\ell = 0.85 \times A_C^t - 0.002$$

Both W' and G' reproduce ATLAS data

\*\* SM central value  $A_C^\ell/A_C^t \simeq 0.67$



$$A_C^\ell = 0.61 \times A_C^t + 0.0008$$

Berger, Cao, CRC, Zhang, PRD 88, 014003



# Anomalous Wtb

Kane, Landisky, Yuan, PRD 45, 124;  
del Aguila, Aguilar-Saavedra, PRD  
67,014009

$$\begin{aligned}\mathcal{L}_{tbW} = & \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t \\ & - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t + h.c.,\end{aligned}$$

In SM,  $f_1^L = V_{tb} \approx 1$   $f_1^R = f_2^L = f_2^R = 0$

decay width  $\Gamma_t = \Gamma_0 + \Gamma_- + \Gamma_+ = \frac{g^2 m_t}{64\pi} \frac{(a_t^2 - 1)^2}{a_t^4} (a_t^2 L_0^2 + 2T_m^2 + 2T_p^2)$ ,

$$L_0^2 \equiv 1 + x_0 = \left( f_1^L + \frac{f_2^R}{a_t} \right)^2 + \left( f_1^R + \frac{f_2^L}{a_t} \right)^2, \quad \text{function of f's}$$

$$T_m^2 \equiv 1 + x_m = (f_1^L + a_t f_2^R)^2,$$

$$T_p^2 \equiv x_p = (f_1^R + a_t f_2^L)^2, \quad a_t \equiv \frac{m_t}{m_W}.$$

t-ch xsection  $\sigma(ub \rightarrow dt) = \frac{g^4}{64\pi s} (I_0 L_0^2 + I_m T_m^2 + I_p T_p^2 - I_i x_i + I_5 x_5)$

s-ch xsection  $\sigma(u\bar{d} \rightarrow t\bar{b}) = \frac{g^4}{128\pi s} \frac{(s - m_t^2)^2}{(s - m_t^2)^2 + m_w^2 \Gamma_w^2} \times (T_m^2 + T_p^2 - I_s),$

CRC, Larios, Yuan, 0503040

# Anomalous Wtb

$$f_0 = \frac{a_t^2(1+x_0)}{a_t^2(1+x_0) + 2(1+x_m+x_p)}, \quad f_- = \frac{2(1+x_m)}{a_t^2(1+x_0) + 2(1+x_m+x_p)},$$

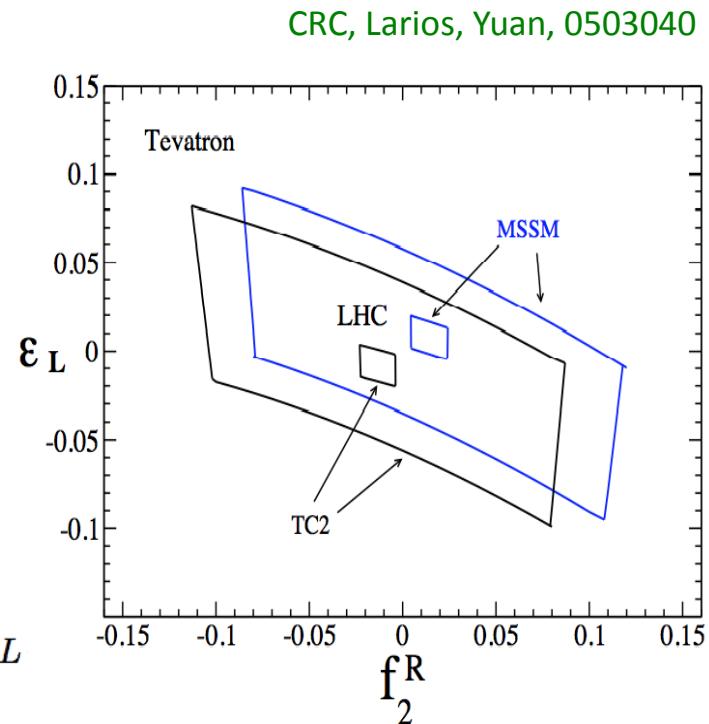
$$\Delta\sigma_t = a_0x_0 + a_mx_m + a_px_p + a_5x_5, \quad \Delta\sigma_s = b_0x_0 + b_mx_m + b_px_p + b_5x_5,$$

where  $x_0 = (f_1^L + f_2^R/a_t)^2 + (f_1^R + f_2^L/a_t)^2 - 1$ ,  $x_m = (f_1^L + a_tf_2^R)^2 - 1$ ,  
 $x_p = (f_1^R + a_tf_2^L)^2$ ,  $x_5 = a_t^2(f_2^{L2} + f_2^{R2})$ , with  $a_t = m_t/M_W$ .

<i>t</i> -channel:	$a_0$	$a_m$	$a_p$	$a_5$
Tevatron	0.896	-0.069	-0.153	0.292
LHC ( <i>t</i> )	165.2	-19.1	-34.2	71.7
LHC ( $\bar{t}$ )	105.8	-20.9	-12.5	44.5
<i>s</i> -channel:	$b_0$	$b_m$	$b_p$	$b_5$
Tevatron	-0.081	0.352	0.352	0.230
LHC ( <i>t</i> )	-1.41	5.67	5.67	6.34
LHC ( $\bar{t}$ )	-0.836	3.43	3.43	3.38

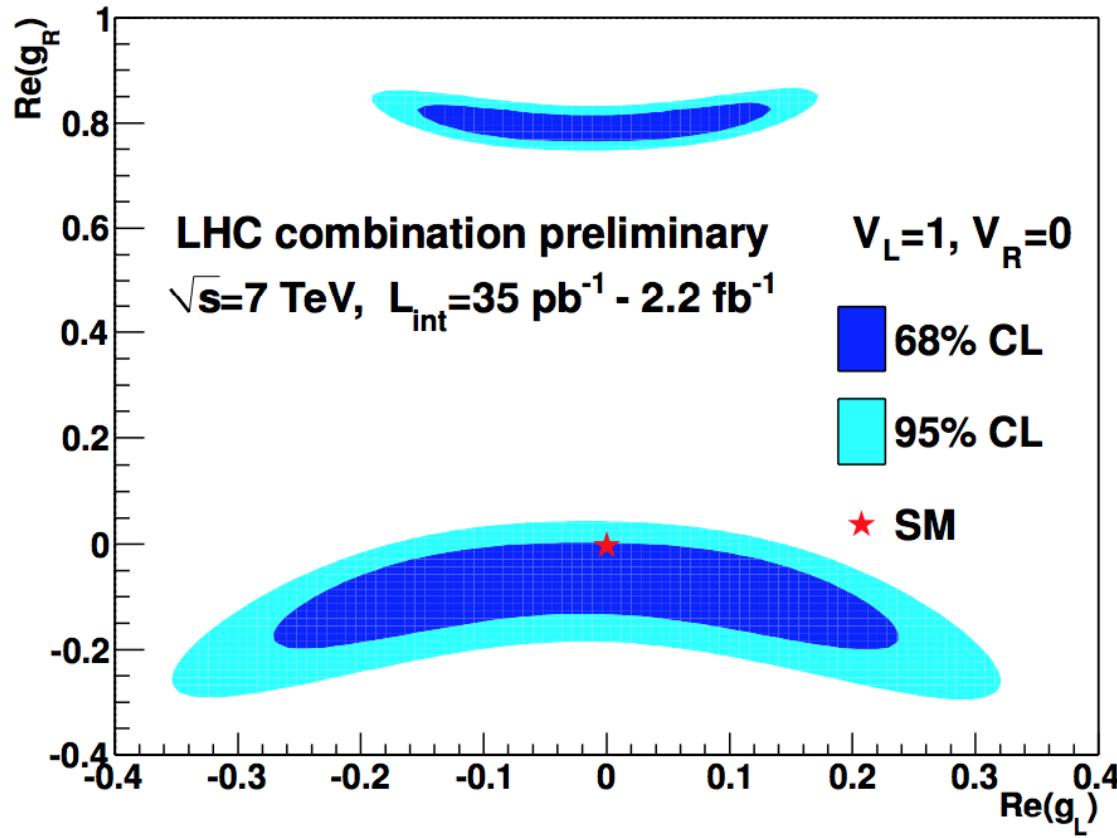
assume:  $f_0$  and  $\sigma_t$  can be measured to 10% at Tevatron, 1% and 2% at the LHC

$$f_1^L \equiv 1 + \epsilon_L$$

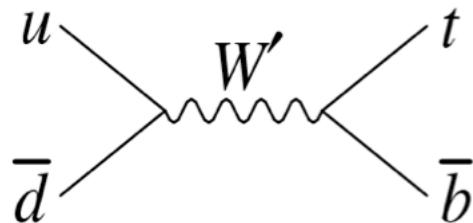


# Anomalous Wtb

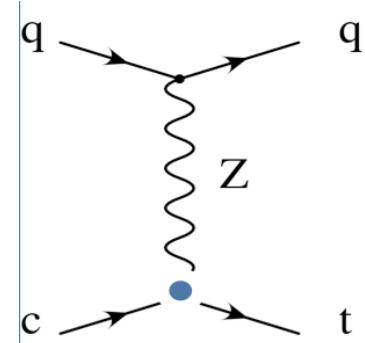
$$\begin{aligned}\mathcal{L}_{tbW} = & \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t \\ & - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t + h.c.,\end{aligned}$$



# Beyond SM

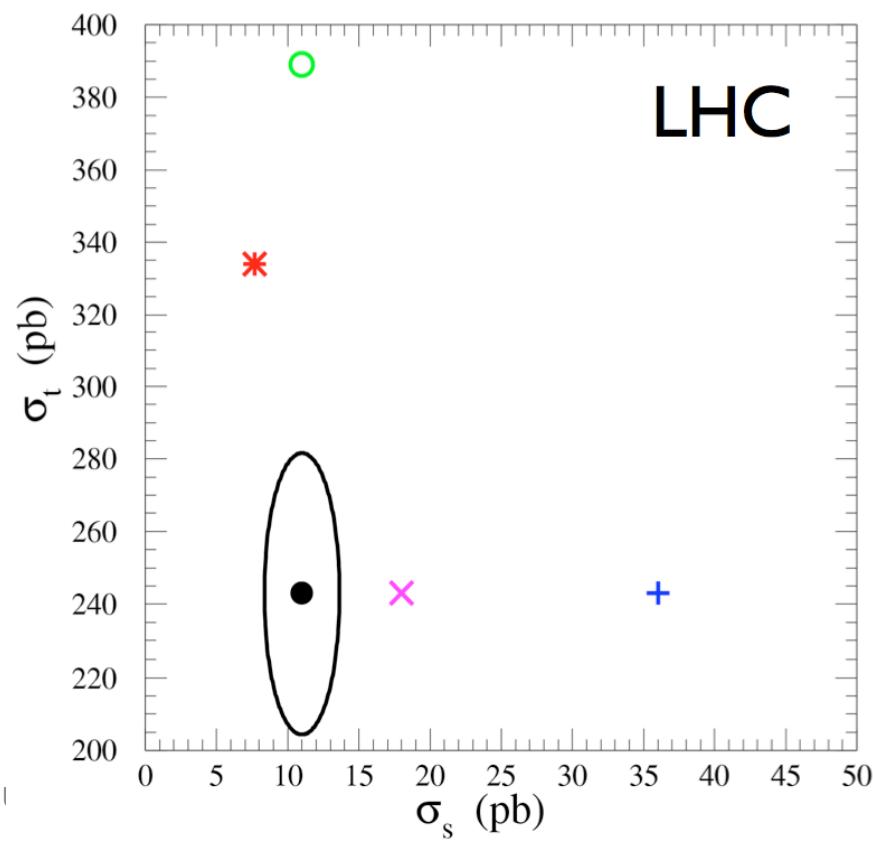
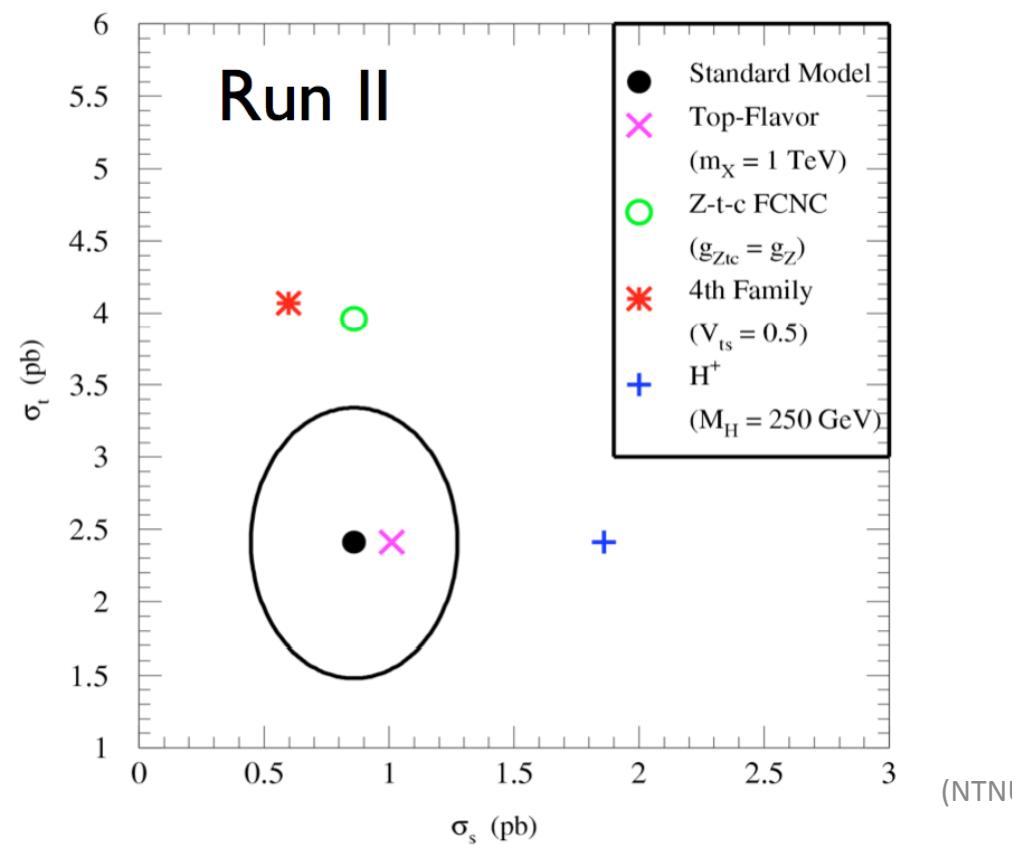


s-channel  $\rightarrow$  sensitive to new resonance



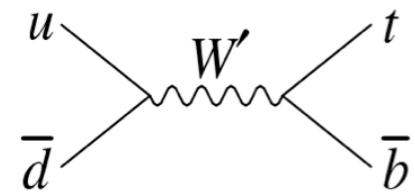
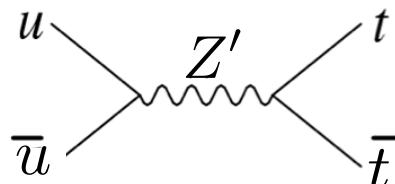
t-channel  $\rightarrow$  sensitive to FCNC

Tait, Yuan, PRD63, 014018

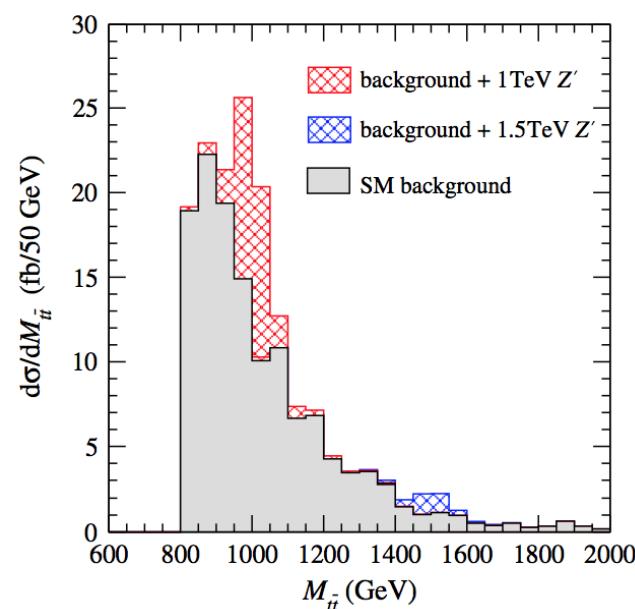
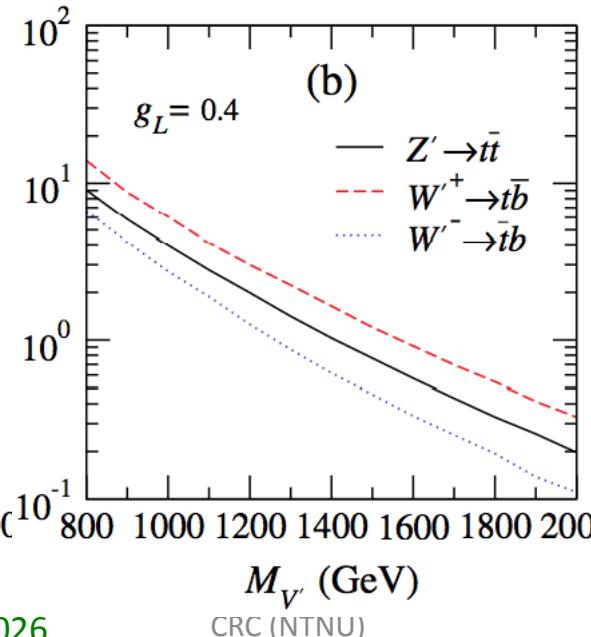
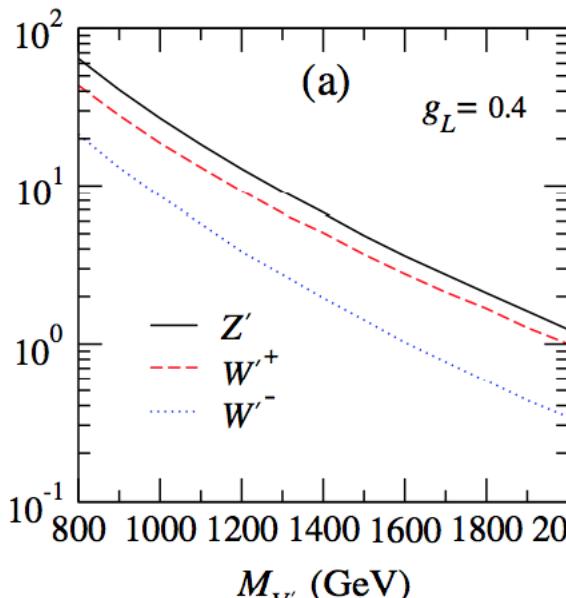


# Heavy V'

$$\mathcal{L} = \bar{q}\gamma^\mu(g_L^{Z'}P_L + g_R^{Z'}P_R)qZ'_\mu + \bar{q}\gamma^\mu(g_L^{W'}P_L + g_R^{W'}P_R)q'W'^\mu + \text{h.c.}$$



	$W'tb$	$Z't\bar{t}$
SSM	$\frac{g_2}{\sqrt{2}} \bar{b} \gamma_\mu P_L t W'^\mu$	$\frac{g_2}{6 c_w} \bar{t} \gamma_\mu ((-3 + 4 s_w^2) P_L + 4 s_w^2 P_R) t Z'^\mu$
LRM	$\frac{g_2}{\sqrt{2}} \bar{b} \gamma_\mu P_R t W'^\mu$	$\frac{g_2 t_w}{6} \bar{t} \gamma_\mu (\frac{1}{\alpha_{LR}} P_L + (\frac{1}{\alpha_{LR}} - 3 \alpha_{LR}) P_R) t Z'^\mu$
Top-Flavor	$\frac{g_2 \sin \tilde{\phi}}{\sqrt{2}} \bar{b} \gamma_\mu P_L t W'^\mu$	$\frac{g_2 \sin \tilde{\phi}}{\sqrt{2}} \bar{t} \gamma_\mu P_L t Z'^\mu$

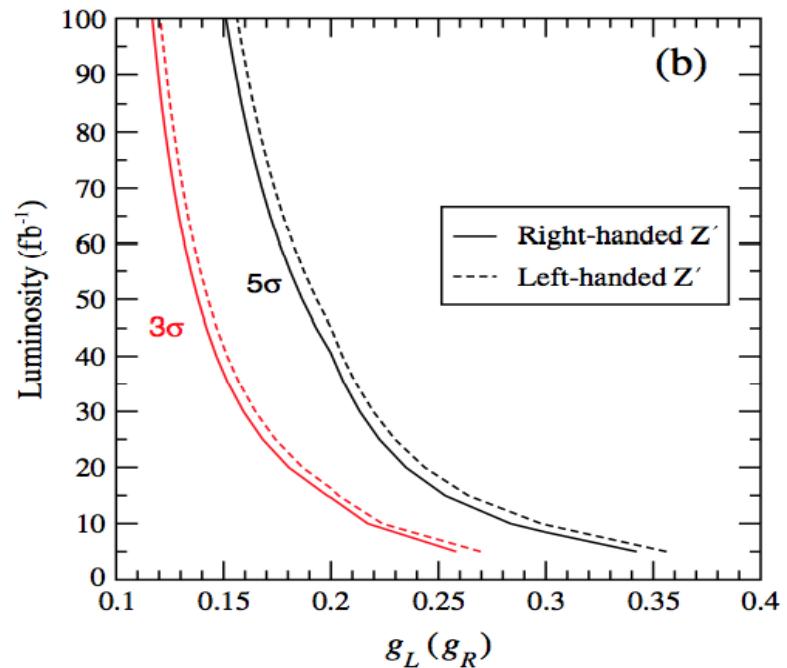
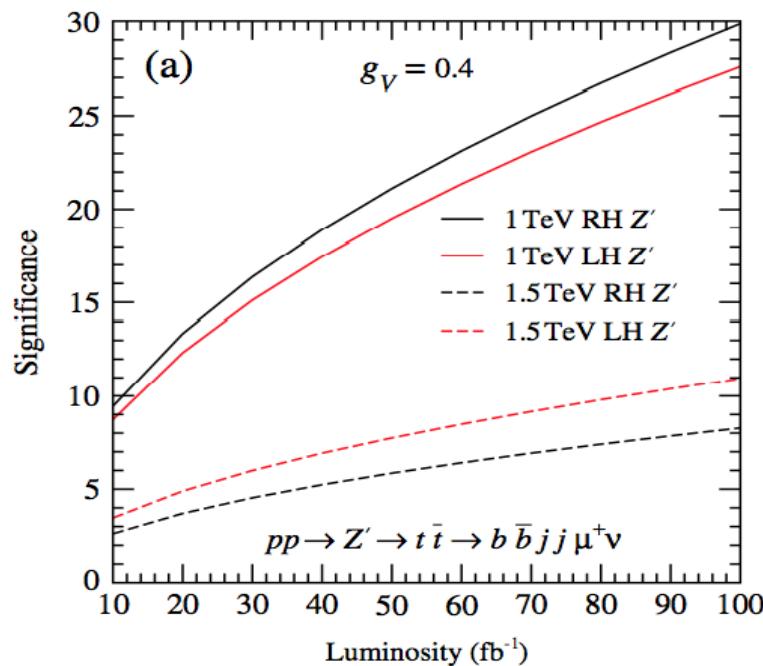


# Discovery

$$p_T(\ell, j) > 20 \text{ GeV}, \quad |\eta(\ell, j)| < 2.5,$$

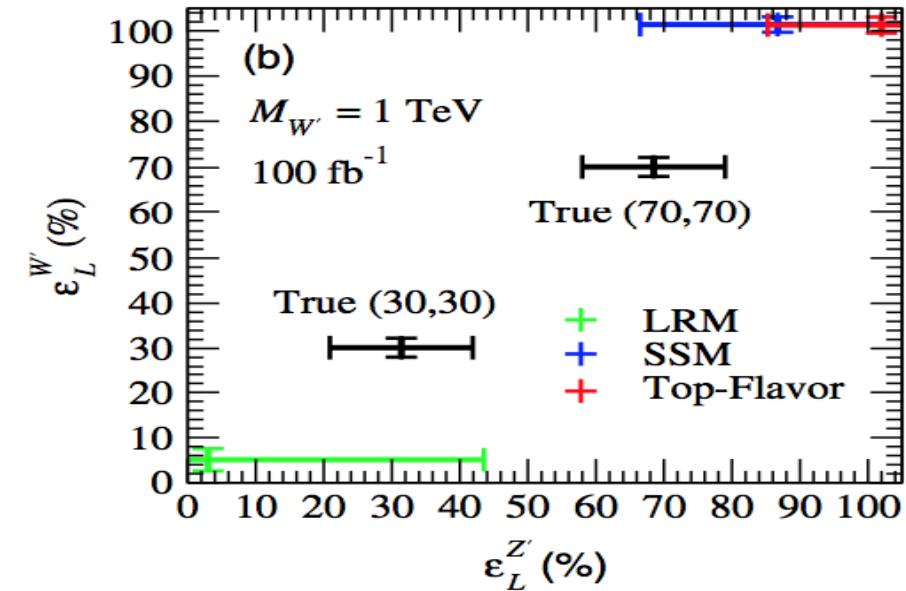
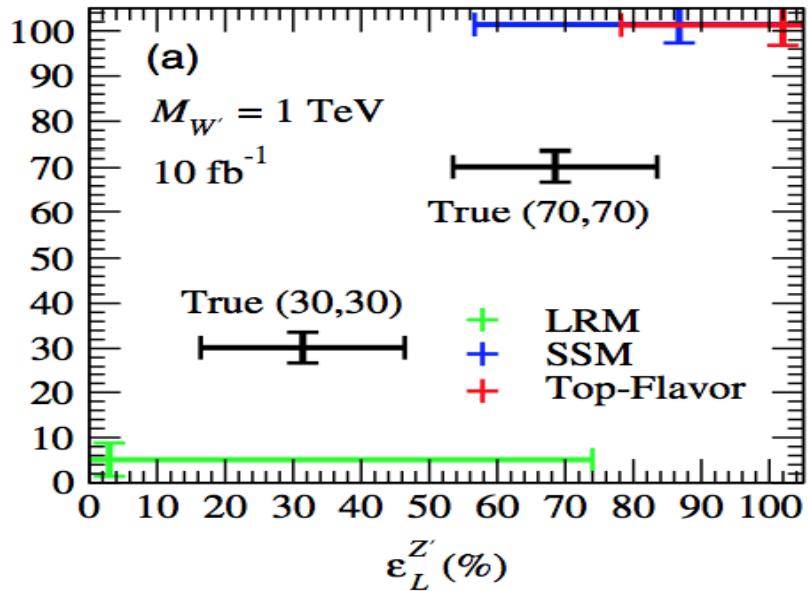
$$\Delta R_{jj,j\ell} > 0.4, \quad E_T > 30 \text{ GeV},$$

$$H_T > 500 \text{ GeV}, \quad M_T > 800 \text{ GeV}, \quad |m_{t\bar{t}} - m_{Z'}| \leq 150(200) \text{ GeV}, \quad \text{for } 1(1.5) \text{ TeV } Z'.$$



very promising to **discover** Z', in other words, easy to **exclude**!

# Discriminate Models



$$\epsilon_L \equiv \frac{\sigma(t_L)}{\sigma(t_L) + \sigma(t_R)} \approx \frac{g_L^2}{g_L^2 + g_R^2}.$$

$$O(y) = \epsilon_L F_L(y) + \epsilon_R F_R(y),$$

$$\chi^2 = \sum_{i=1}^N \left[ \frac{O(y_i) - \epsilon_L F_L(y_i) - \epsilon_R F_R(y_i)}{\sigma_i} \right]^2,$$

$Z'$	Theory $\epsilon_L$ (%)	Measured $\epsilon_L$ (%)
LRM	2.0	$3.0 \pm 70.9$
SSM	83.6	$86.7 \pm 30.1$
top-flavor	100.0	$101.9 \pm 23.8$

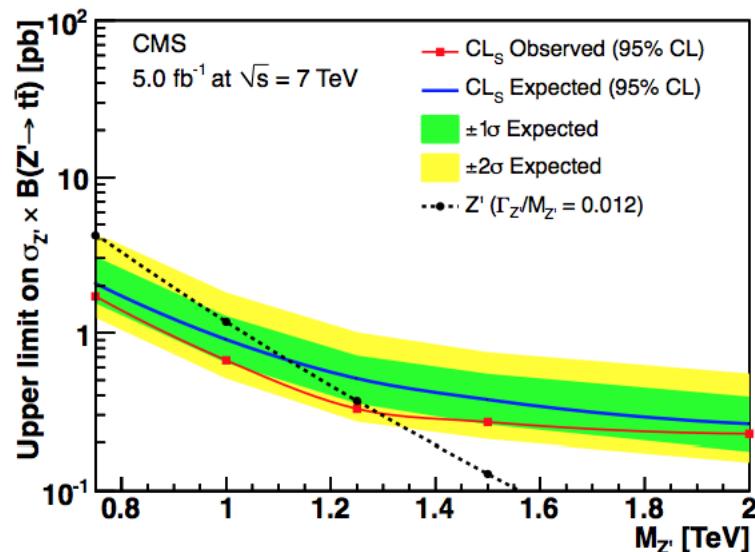
$W'$	Theory $\epsilon_L$ (%)	Measured $\epsilon_L$ (%)
LRM	0.0	$5.1 \pm 3.7$
SSM	100.0	$101.4 \pm 4.1$
top-flavor	100.0	$101.3 \pm 4.5$



# Z'->tt @ LHC

narrow width

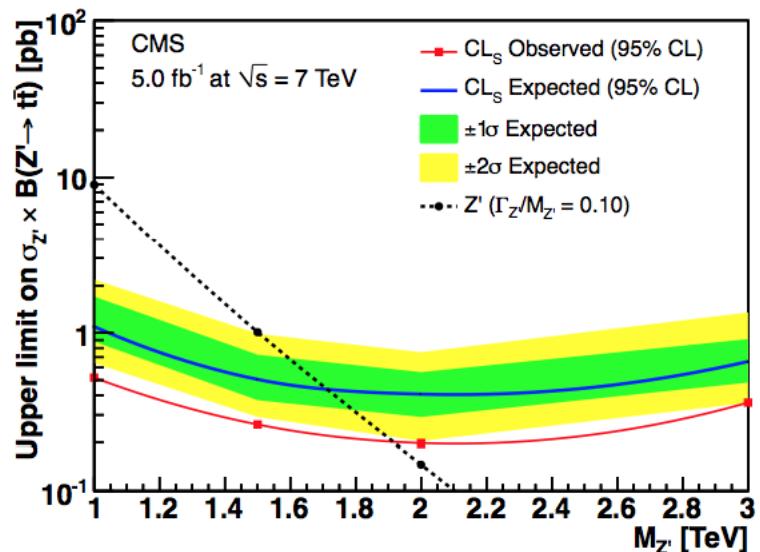
$$\Gamma/M = 0.012$$



exclude  $M_{Z'} < 1.3$  TeV @ 95% C.L.

wide width

$$\Gamma/M = 0.1$$



exclude  $M_{Z'} < 1.9$  TeV @ 95% C.L.

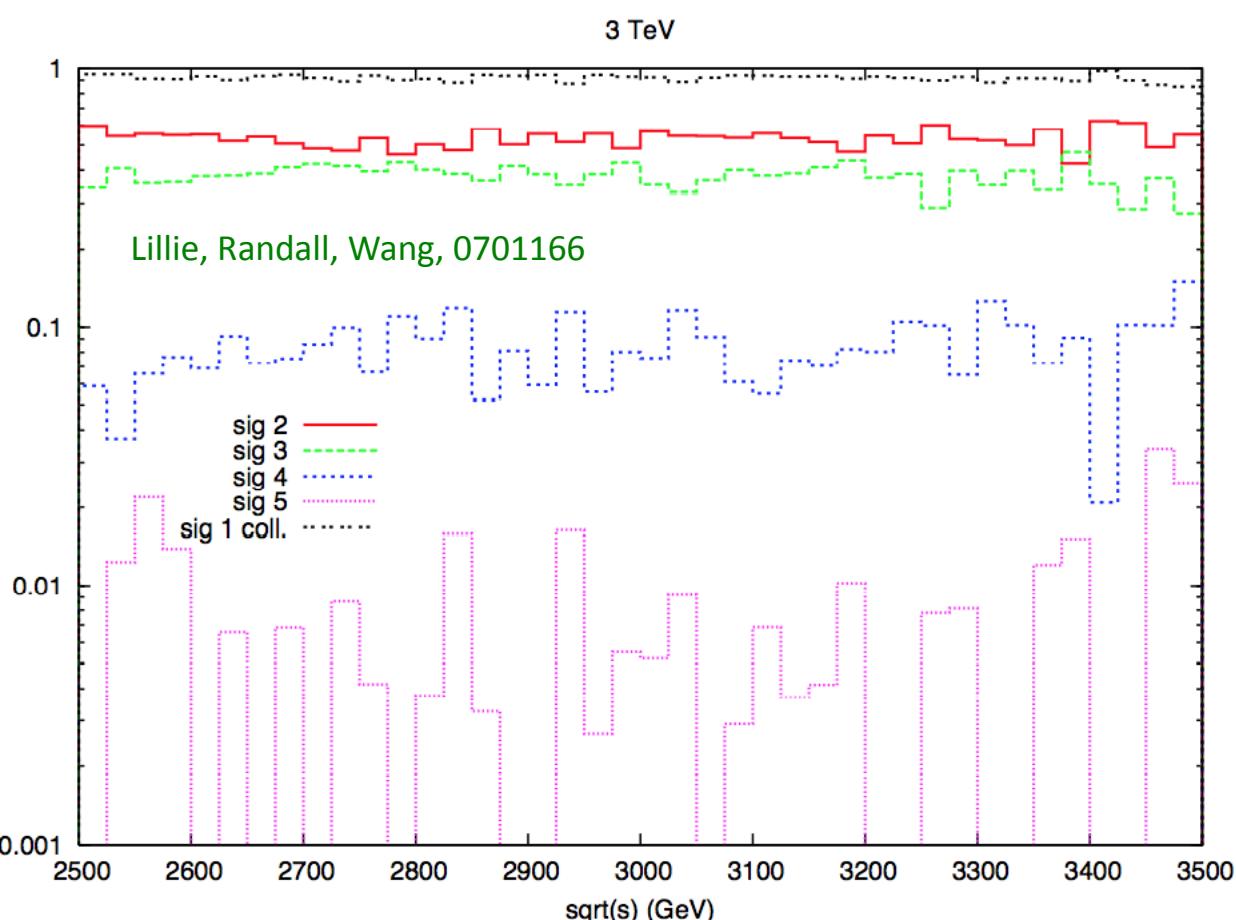


## Boosted top

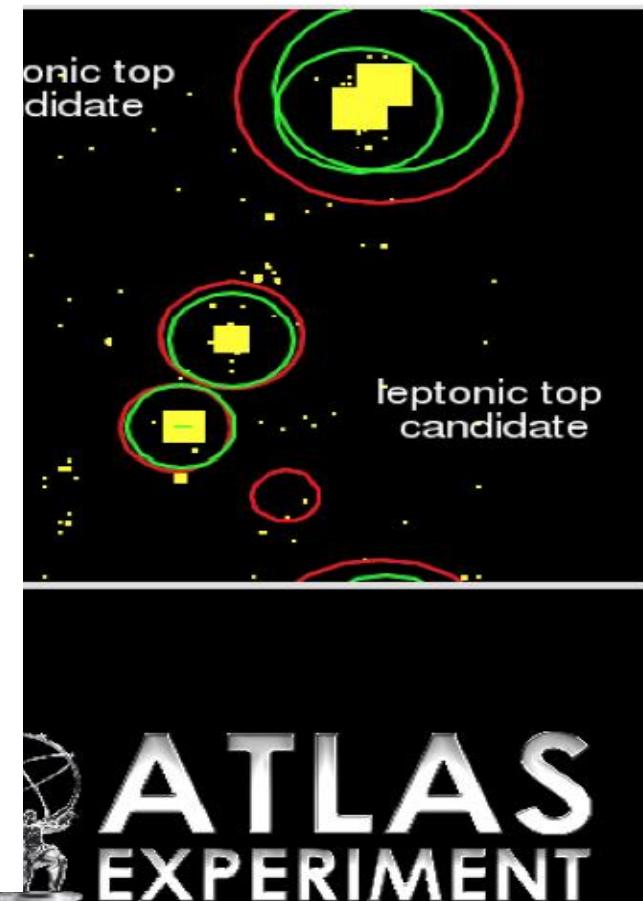
top quarks from heavy resonance decay are expected to be energetic!

decay products in top decay will be moving very close to each other!

top decay products look like “a single jet”, instead of three well-separated jets.



2.5 TeV  $\rightarrow$  t tbar



# Top tagging

jet substructure

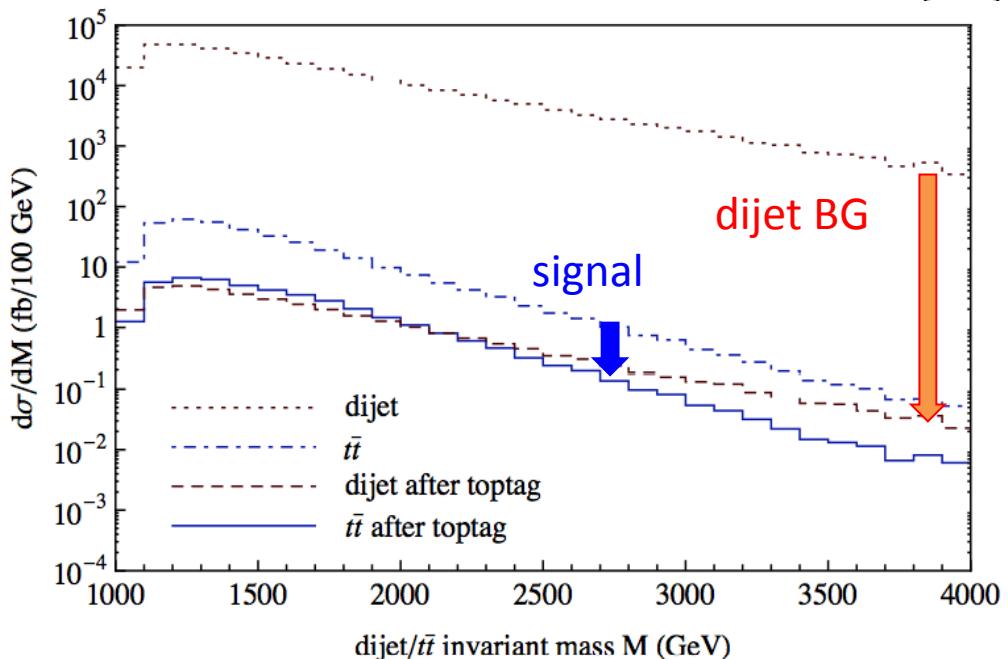
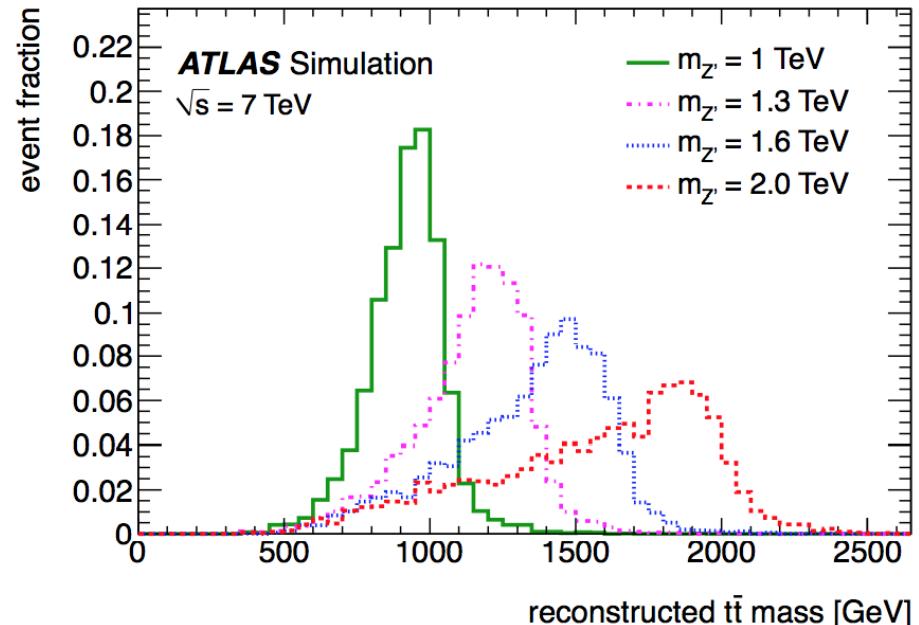
Seymour, Z. Phys. C62, 127; Butterworth et al. 0201098;  
Butterworth et al., 0802.2470

start with larger “R” to have a “fat” jet

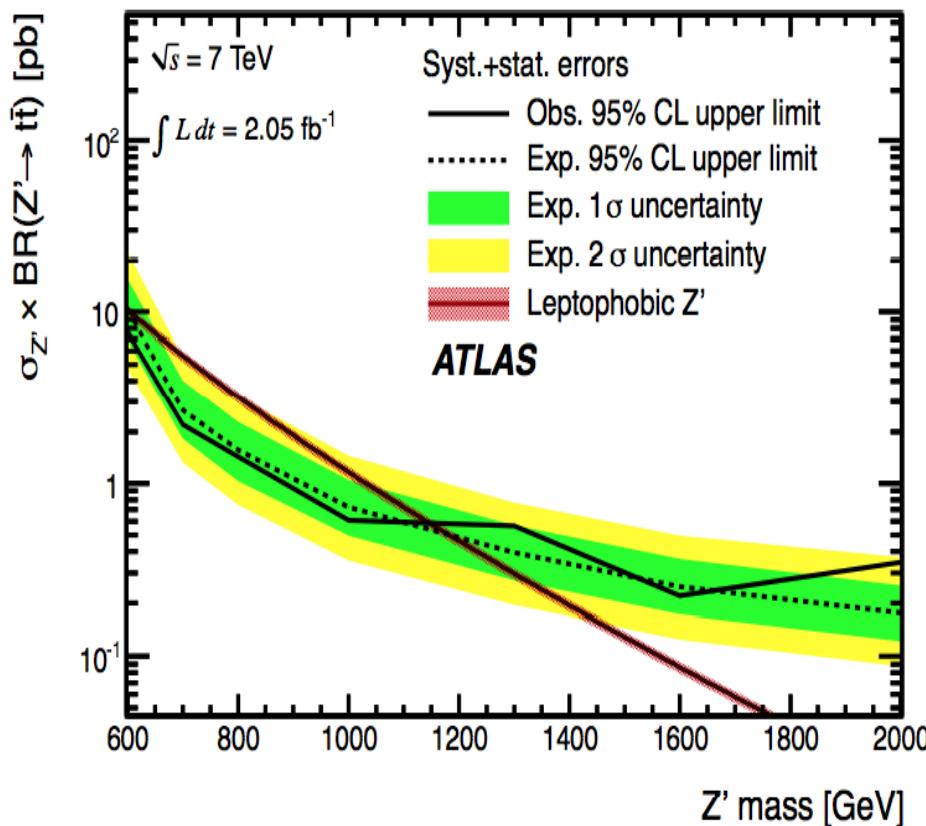
decluster the fat jet with some  
conditions to see whether the fat jet  
contains substructures that match the  
top decay

Kaplan et al. 0806.0848

	$p_T$ (GeV)	subjets	$m_t$	$m_W$	$\theta_h$
$\epsilon_t$	500-600	0.56	0.43	0.38	0.32
	1000-1100	0.66	0.52	0.44	0.39
	1500-1600	0.40	0.33	0.28	0.25
$\epsilon_g$	500-600	0.135	0.045	0.027	0.015
	1000-1100	0.146	0.054	0.032	0.018
	1500-1600	0.083	0.038	0.025	0.015
$\epsilon_q$	500-600	0.053	0.018	0.011	0.005
	1000-1100	0.063	0.023	0.013	0.006
	1500-1600	0.032	0.015	0.010	0.006



## Boosted top



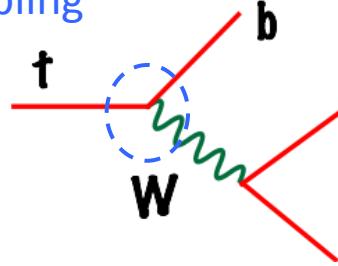
$600 \text{ GeV} < M_{Z'} < 1.15 \text{ TeV}$  is excluded @ 95 C.L.

## Summary

- top quark physics is important both for test of SM and search for NP.
- top quark is the only one quark that we can study the properties of the bare quark.
- LHC is a top factory, precision measurements in top quark physics is expected.
- anomalous  $t\bar{t}$  asymmetries was found at the Tevatron.  
:  $\gtrsim 2\sigma$  inclusive measurement;  $\sim 3\sigma$  differential measurement.
- w/ large errors, CMS and ATLAS agree on top quark FBA even though central values are not closed.

# Polarization

V-A coupling



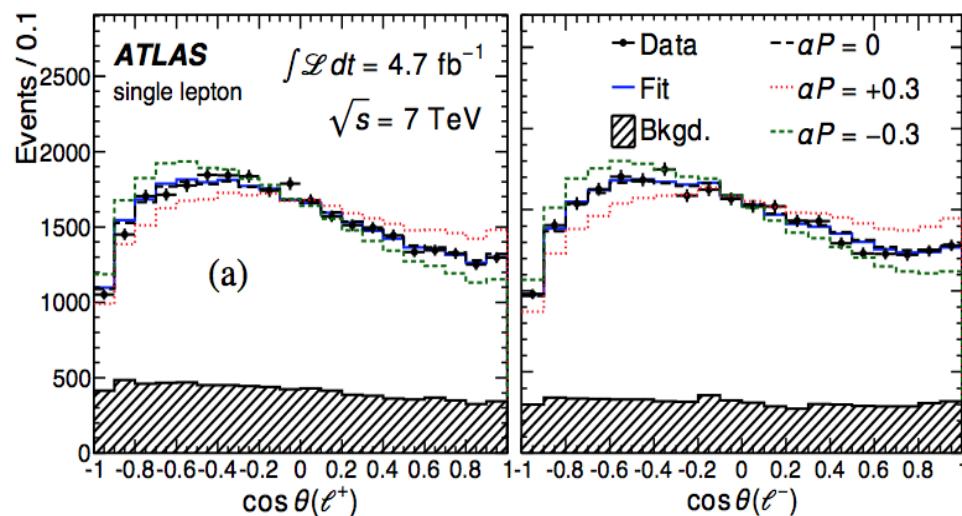
$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta} = \frac{1}{2} (1 + \alpha P \cos \theta)$$

spin analyzer

	$\ell^+$	$d$	$u$	$b$	$j_<$	$T$	$j_>$
LO:	1	1	-0.32	-0.39	0.51	-0.32	0.2
NLO:	0.999	0.97	-0.31	-0.37	0.47	-0.31	

Mahlon, Parke, 9512264;  
Brandenburg, Si, Uwer, 0205023

t quarks are mainly produced by QCD  $\rightarrow$  unpolarized.



$$\alpha_\ell P_{\text{CPC}} = -0.035 \pm 0.014(\text{stat}) \pm 0.037(\text{syst}) \text{ and } \alpha_\ell P_{\text{CPV}} = 0.020 \pm 0.016(\text{stat})^{+0.013}_{-0.017}(\text{syst}).$$



consistent with 0 polarization in SM



# backup

Czakon, Fiedler, 1303.6254

Collider	$\sigma_{\text{tot}}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) -0.200(2.8%)	+0.169(2.4%) -0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) -5.8(3.4%)	+4.7(2.7%) -4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) -8.4(3.4%)	+6.2(2.5%) -6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) -33.9(3.6%)	+16.2(1.7%) -17.8(1.9%)

TABLE I: Our best NNLO+NNLL theoretical predictions for various colliders and c.m. energies.

Collider	$\sigma_{\text{tot}}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	+0.259(3.7%) -0.374(5.3%)	+0.169(2.4%) -0.121(1.7%)
LHC 7 TeV	167.0	+6.7(4.0%) -10.7(6.4%)	+4.6(2.8%) -4.7(2.8%)
LHC 8 TeV	239.1	+9.2(3.9%) -14.8(6.2%)	+6.1(2.5%) -6.2(2.6%)
LHC 14 TeV	933.0	+31.8(3.4%) -51.0(5.5%)	+16.1(1.7%) -17.6(1.9%)

TABLE II: Pure NNLO theoretical predictions for various colliders and c.m. energies.