Top Quark Forward-Backward Asymmetry 2011 Update

Konkuk University WCU/National Tsing Hua University

KC, Wai-Yee Keung, Tzu-Chiang Yuan (0908.2589, PLB)
KC, Tzu-Chiang Yuan (1101.1445, PRD)

Yonsei – May 4, 2011

Outline

- Experimental measurements
- $d - t - W'$ model
- Other constraints
- Implications at the Tevatron and LHC
- A few other explanations

CDF Experimental Data

Reported in 3.2 fb^{-1} (CDF-note-9724, 1.9 fb^{-1} in 0806.2473)

- The forward-backward asymmetry in the $p\bar{p}$ frame:

$$A_{fb}^{p\bar{p}} \equiv \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)} = 0.19 \pm 0.065\ (\text{stat}) \pm 0.024\ (\text{syst})\ ,$$

- Here one of the t or $\bar{t}$ decays hadronically (for momentum reconstruction with angle θ) while the other decays semileptonically (for identification of the charge lepton). Since $t \to \ell^+$ while $\bar{t} \to \ell^-$, they used $(-1.Q_\ell)$ to give equivalent top momentum direction:

$$-Q_\ell \cdot \cos\theta$$

So the

$$A_{fb} \equiv \frac{N(-Q_\ell \cdot \cos\theta > 0) - N(-Q_\ell \cdot \cos\theta < 0)}{N(-Q_\ell \cdot \cos\theta > 0) + N(-Q_\ell \cdot \cos\theta < 0)}$$

- The production angle $\theta_{t\bar{t}}$ in the $t\bar{t}$ rest frame is related to the rapidity difference of the t and $\bar{t}$ in the $p\bar{p}$ frame by

$$y_t - y_{\bar{t}} = 2 \,\mathrm{arctanh}\, \left(\sqrt{1 - \frac{4m_t^2}{\hat{s}}} \, \cos\theta_{t\bar{t}} \right)$$

where $\hat{s}$ is the square of the center-of-mass energy of the $t\bar{t}$ pair.

- Since the sign$(y_t - y_{\bar{t}})$ =sign$(\cos\theta_{t\bar{t}})$,

$$A_{fb}^{t\bar{t}} = \frac{N_t(y_t - y_{\bar{t}} > 0) - N_t(y_t - y_{\bar{t}} < 0)}{N_t(y_t - y_{\bar{t}} > 0) + N_t(y_t - y_{\bar{t}} < 0)} \,.$$

- The current measurement: the rapidity y_{had} of the hadronic decaying top (or antitop) and the charge of the lepton from the semi-leptonic decay of the antitop (or top):

$$A_{fb}^{p\bar{p}} = \frac{N(-Q_\ell \cdot y_{had} > 0) - N(-Q_\ell y_{had} < 0)}{N(-Q_\ell \cdot y_{had} > 0) + N(-Q_\ell y_{had} < 0)}$$

- The measurement in the $p\bar{p}$ laboratory frame is correspondingly smaller, because of the Lorentz boost along the beam axis.

DØData

DØNote 6062

- Use 4.3 fb^{-1} data, and lepton+jets channel of the $t\bar{t}$, they found

$$A_{fb} = 8 \pm 4\ (\mathrm{stat})\ \pm 1\ (\mathrm{syst})\ \%$$

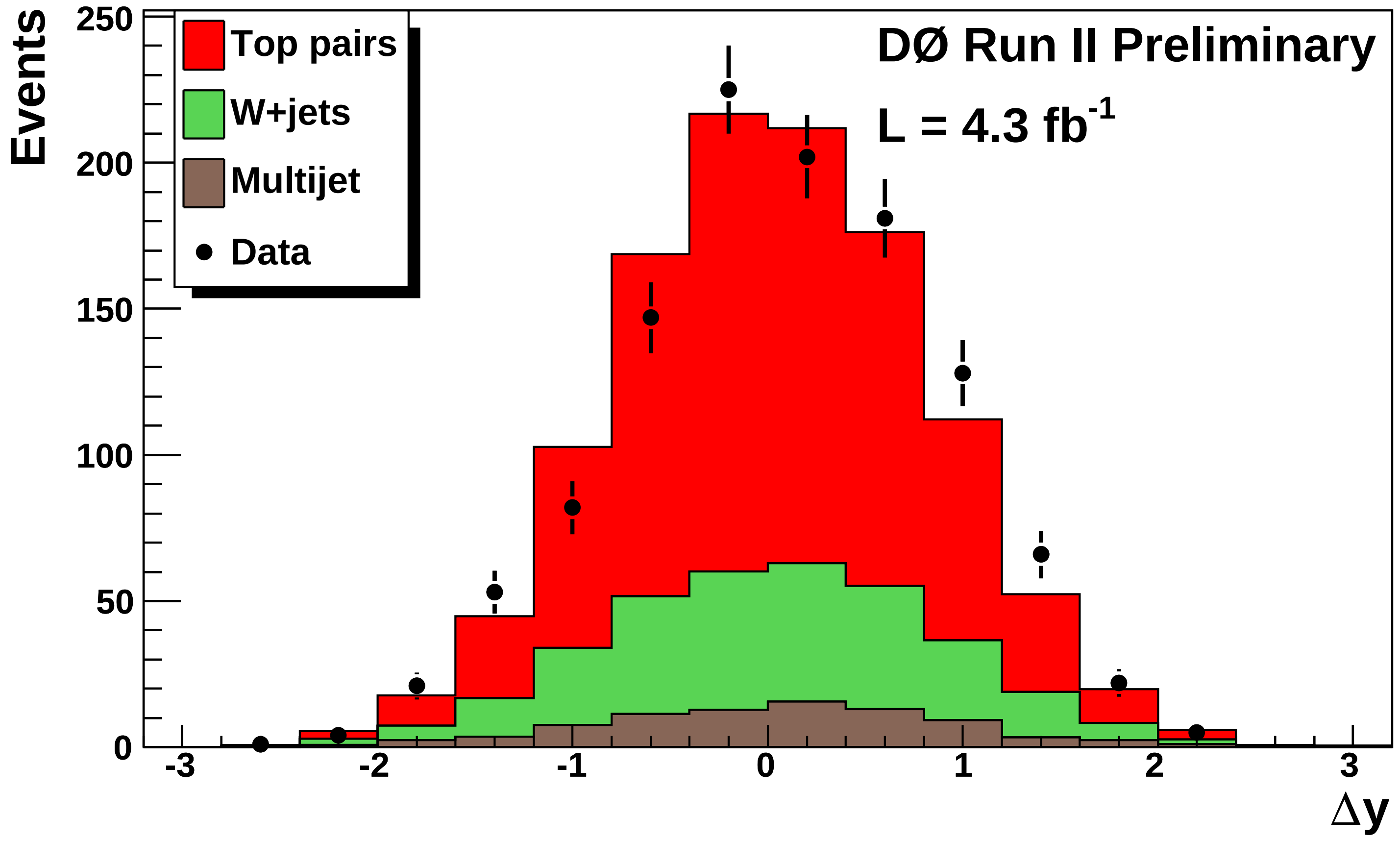
- This is to be compared with the MC@NLO-based prediction

$$A_{fb}^{pred} = 1^{+2}_{-1}\ (\mathrm{syst})\ \%$$

- They used the rapidity difference $\Delta y = y_t - y_{\bar{t}}$ to measure the asymmetry in the $t\bar{t}$ frame:

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

- No corrections back to the parton-level asymmetry.


Events
250
200
150
100
50
0
-3
-2
-1
0
1
2
3
Δy
Top pairs
W+jets
Multijet
Data
DØ Run II Preliminary
L = 4.3 fb-1

Reported in 5.3 fb^{-1} (CDF-note-10224)

- The forward-backward asymmetry

$$A_{fb}^{p\bar{p}} = 0.150 \pm 0.050 \pm 0.024$$

$$A_{fb}^{t\bar{t}} = 0.158 \pm 0.072 \pm 0.017$$

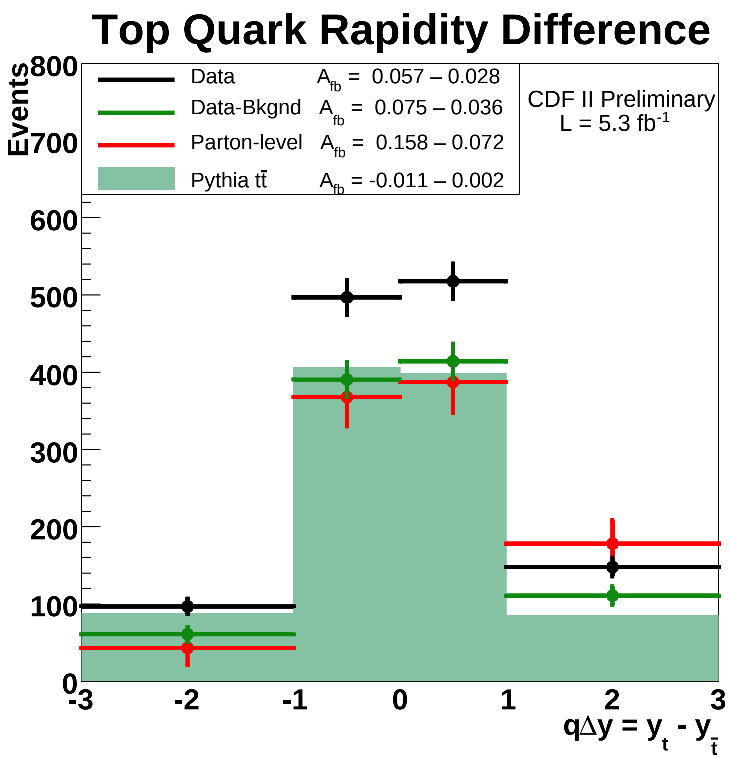
in comparison to 0.038 ± 0.006 and 0.058 ± 0.009, respectively, in the NLO QCD.

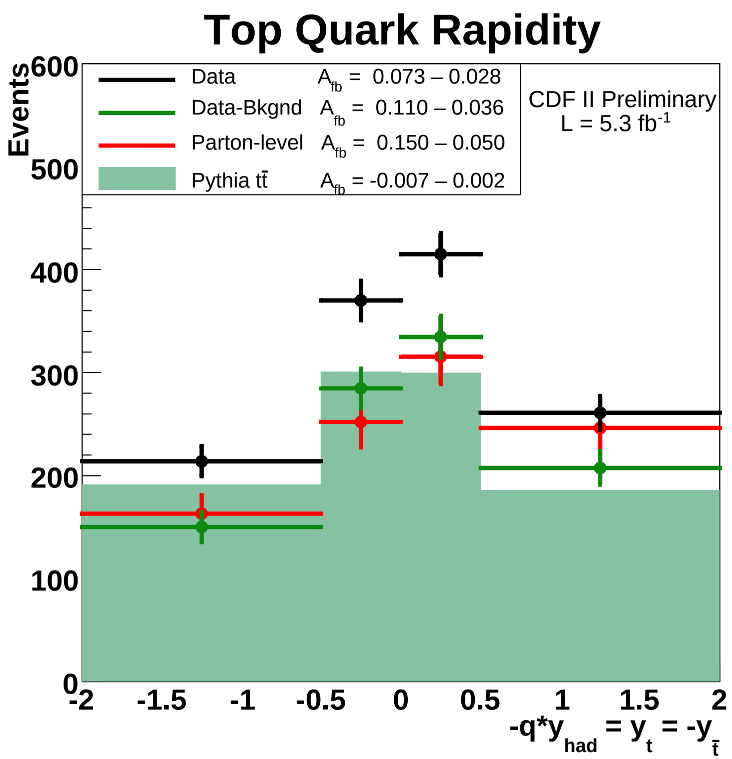
- Additional measurement in small and large $\Delta y_t = y_t - y_{\bar{t}}$

$$A_{fb}(|\Delta y_t| < 1.0) = 0.026 \pm 0.104 \pm 0.055$$

$$A_{fb}(|\Delta y_t| > 1.0) = 0.611 \pm 0.210 \pm 0.141$$

- Again, one of the t and $\bar{t}$ decays hadronically while the other one semileptonically.


Top Quark Rapidity Difference
Events
Data A_fb = 0.057 – 0.028
Data-Bkgnd A_fb = 0.075 – 0.036
Parton-level A_fb = 0.158 – 0.072
Pythia tt̄ A_fb = -0.011 – 0.002
CDF II Preliminary
L = 5.3 fb-1
qΔy = y_t - y_t̄


Top Quark Rapidity
Events
Data A_fb = 0.073 – 0.028
Data-Bkgnd A_fb = 0.110 – 0.036
Parton-level A_fb = 0.150 – 0.050
Pythia tt̄ A_fb = -0.007 – 0.002
CDF II Preliminary
L = 5.3 fb-1
-q*y_had = y_t = -y_t̄

Reported in 5.3 fb^{-1} (1101.0034)

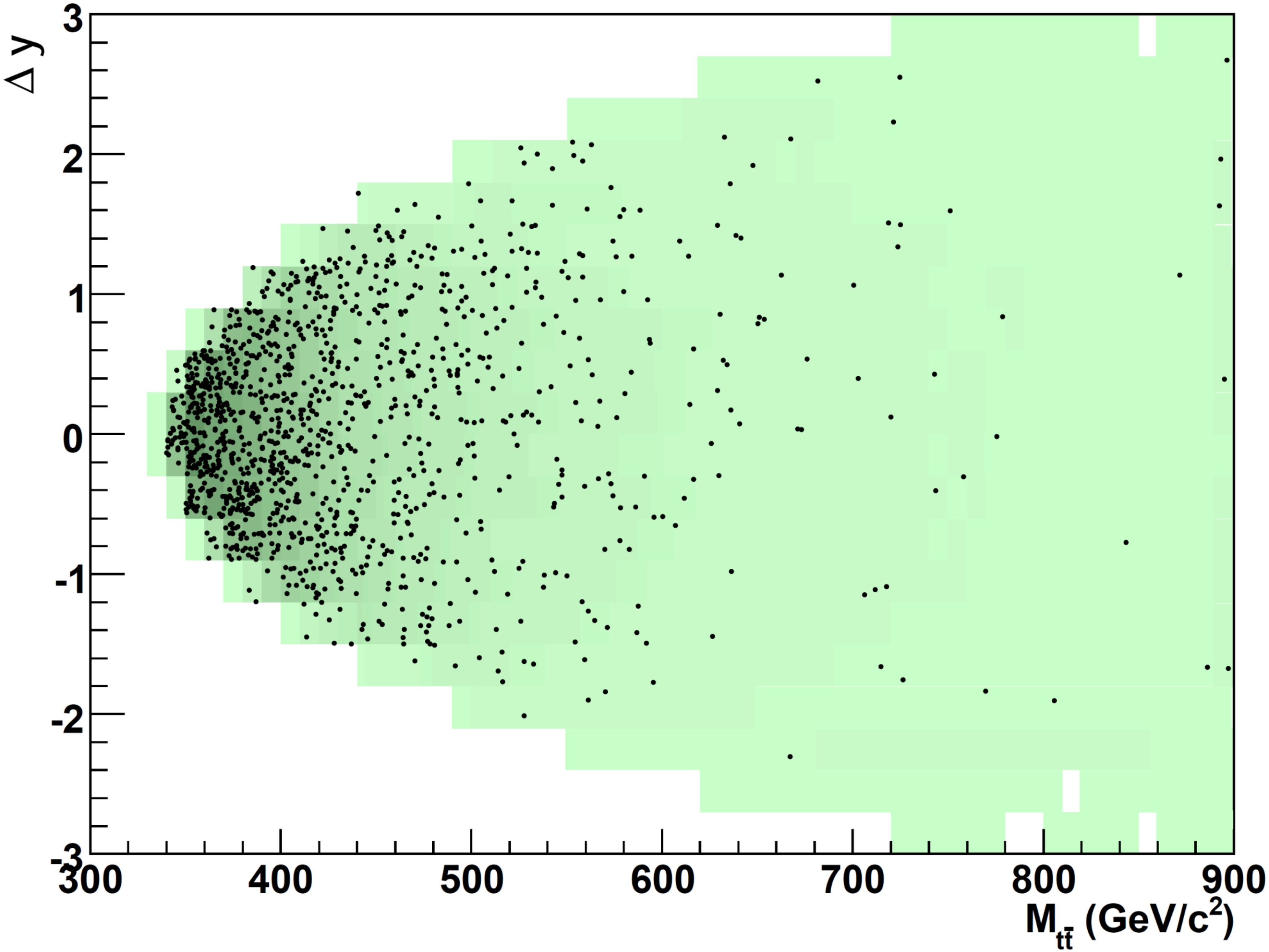
- The forward-backward asymmetry levels off a little

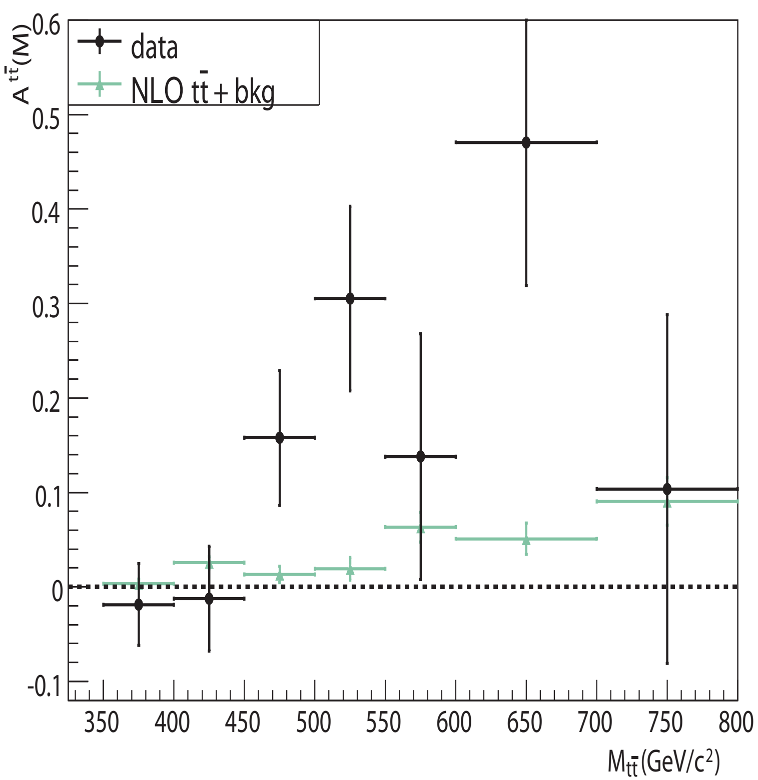
$$A^{t\bar{t}} = 0.158 \pm 0.074 \quad (< 2\sigma)$$

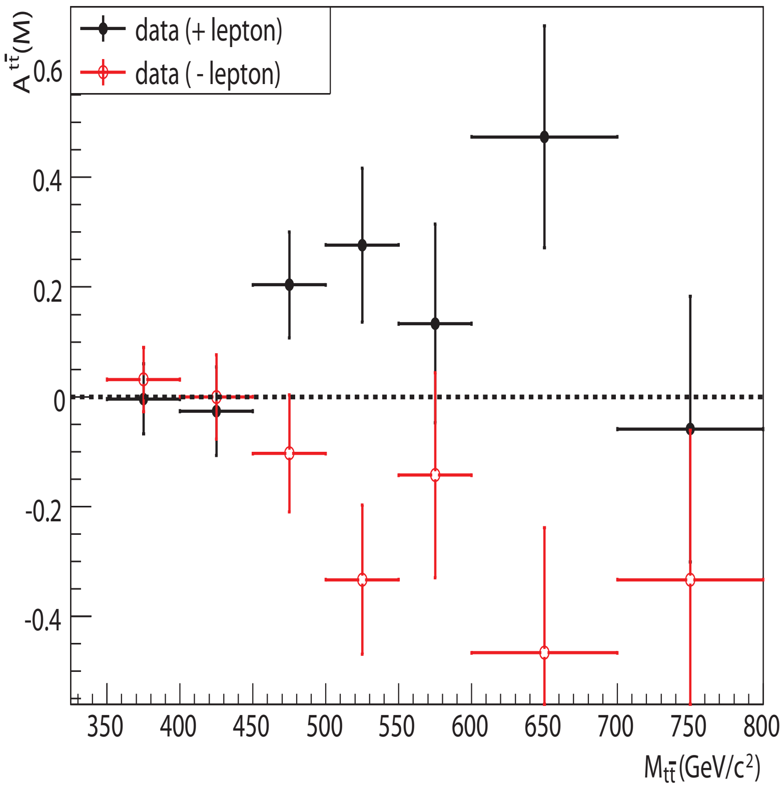
compared to $A^{t\bar{t}}_{\rm SM} = 0.058 \pm 0.009$.

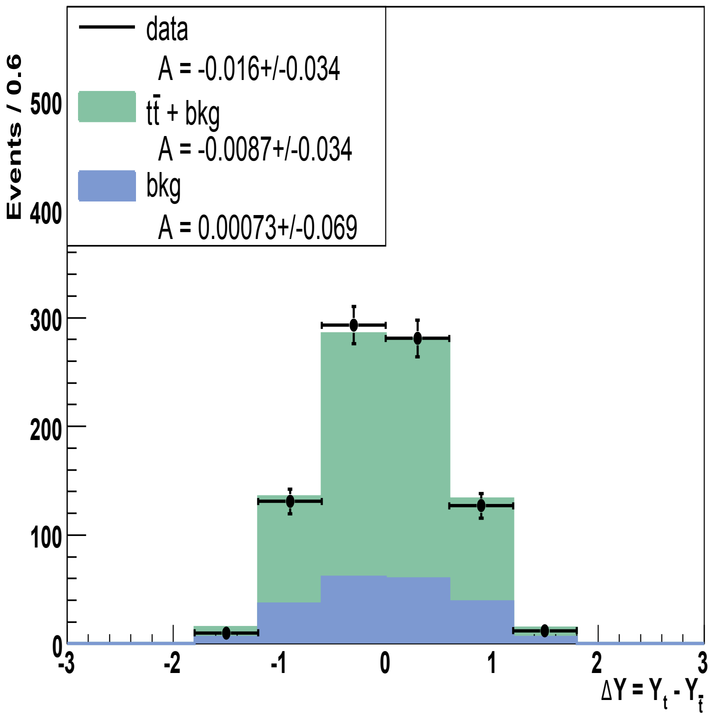
- New distributions of $A^{t\bar{t}}$ versus Δy and $M_{t\bar{t}}$ are surprising.

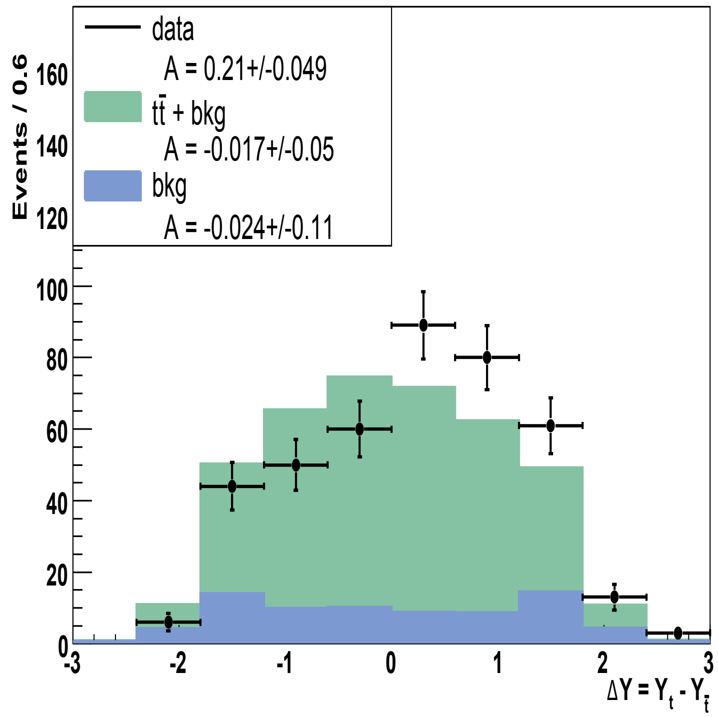
	$A^{t\bar{t}}$	$A^{t\bar{t}}$		$A^{t\bar{t}}$	
		$\lvert\Delta y\rvert < 1$	$\lvert\Delta y\rvert > 1$	$M_{t\bar{t}} < 450$	> 450 GeV
Data	0.158 ± 0.074	0.026 ± 0.118	0.611 ± 0.256	-0.116 ± 0.153	0.475 ± 0.112
MCFM	0.058 ± 0.009	0.039 ± 0.006	0.123 ± 0.018	0.04 ± 0.006	0.088 ± 0.0013
N.P.	0.100 ± 0.074	–	0.488 ± 0.257	–	0.387 ± 0.112


Δ y
3
2
1
0
-1
-2
-3
300
400
500
600
700
800
900
$M_{t\bar{t}}$ (GeV/c^2)


data
NLO tt̄ + bkg
$A^{t\bar{t}}(M)$
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
350 400 450 500 550 600 650 700 750 800
$M_{t\bar{t}}(GeV/c^2)$


data (+ lepton)
data (- lepton)
$A^{t\bar{t}}(M)$
0.6
0.4
0.2
0
-0.2
-0.4
350 400 450 500 550 600 650 700 750 800
$M_{t\bar{t}}(GeV/c^2)$





Left: low mass $M_{t\bar{t}}$ region

Right: high mass $M_{t\bar{t}}$ region

Interpretations

- Whether or not in parton-level there are more top quarks than antitop quarks in the forward direction (defined by the p direction).
- The NLO QCD correction gives

$$A_{fb}^{t\bar{t}} = 0.058 \pm 0.009$$

- Need to find ways to make the top to go more forward than backward while at the same time not to increase the total $t\bar{t}$ cross section or change the invariant mass $m(t\bar{t})$ spectrum.
- A new t-channel exchange. This is perhaps the easiest to increase the forward production. An unknown particle that couples to the top quark and a (u, d, s, or c) quark. Examples are: W', Z', RPV squarks.

- An unknown particle that couple to the top quark and light quarks with uneven left- and right-handed couplings. The couplings have to tuned. This diagram then interferes with the SM gluon diagram. Examples are axigluons.

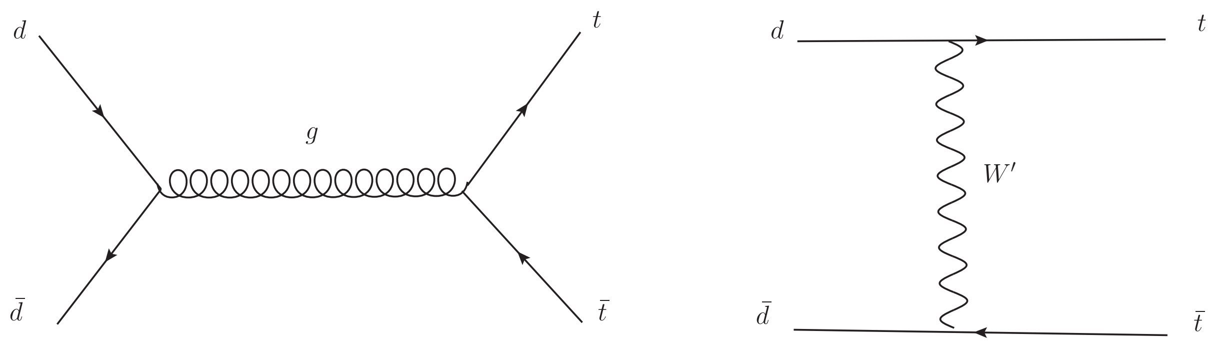
W'

- Suppose the interaction vertex for the W' boson with the down and top quarks is

$$\mathcal{L} = -g' \, W'^{+}_{\mu} \, \bar{t}\gamma^{\mu} \left(g_L P_L + g_R P_R \right) d \; + \; \text{h.c.} \;\; ,$$

- W' couples to t and s is equally good, but needs a larger coupling, because of smaller parton luminosity.

- Two Feynman diagrams for the process $d\bar{d} \to t\bar{t}$.

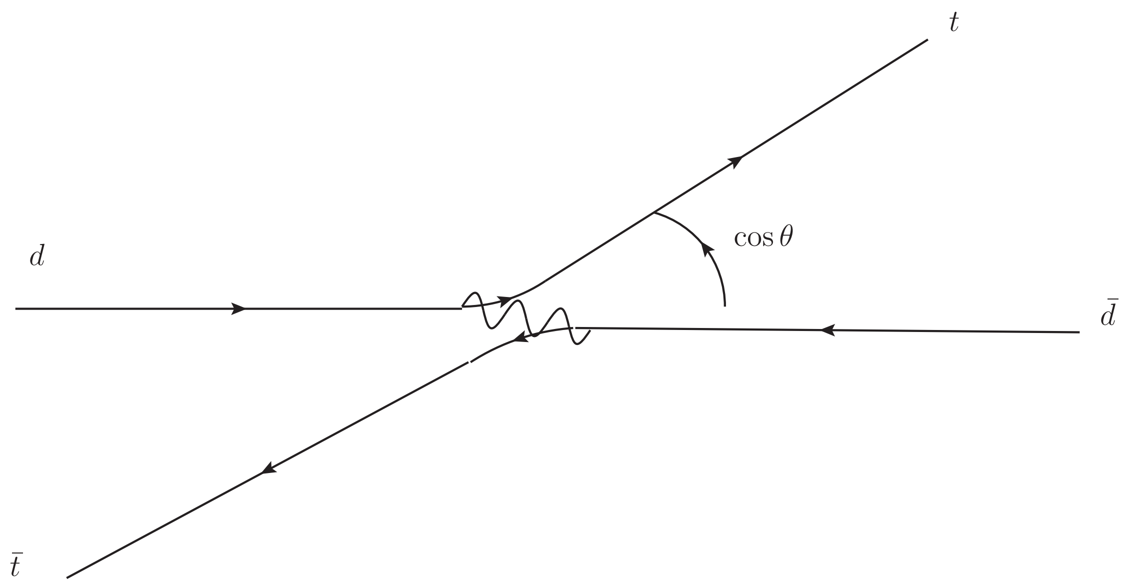


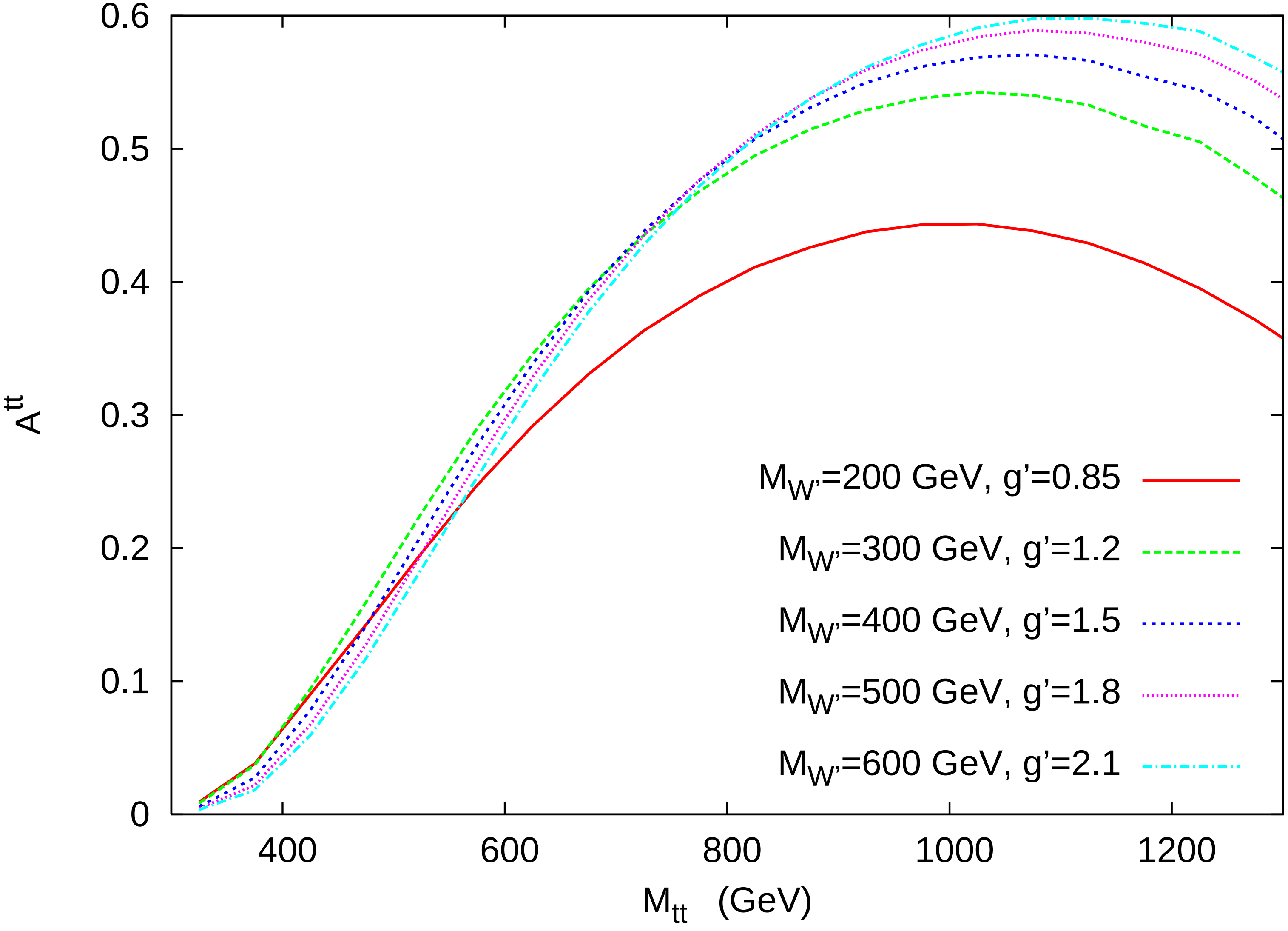
- The interference term in the amplitude squared

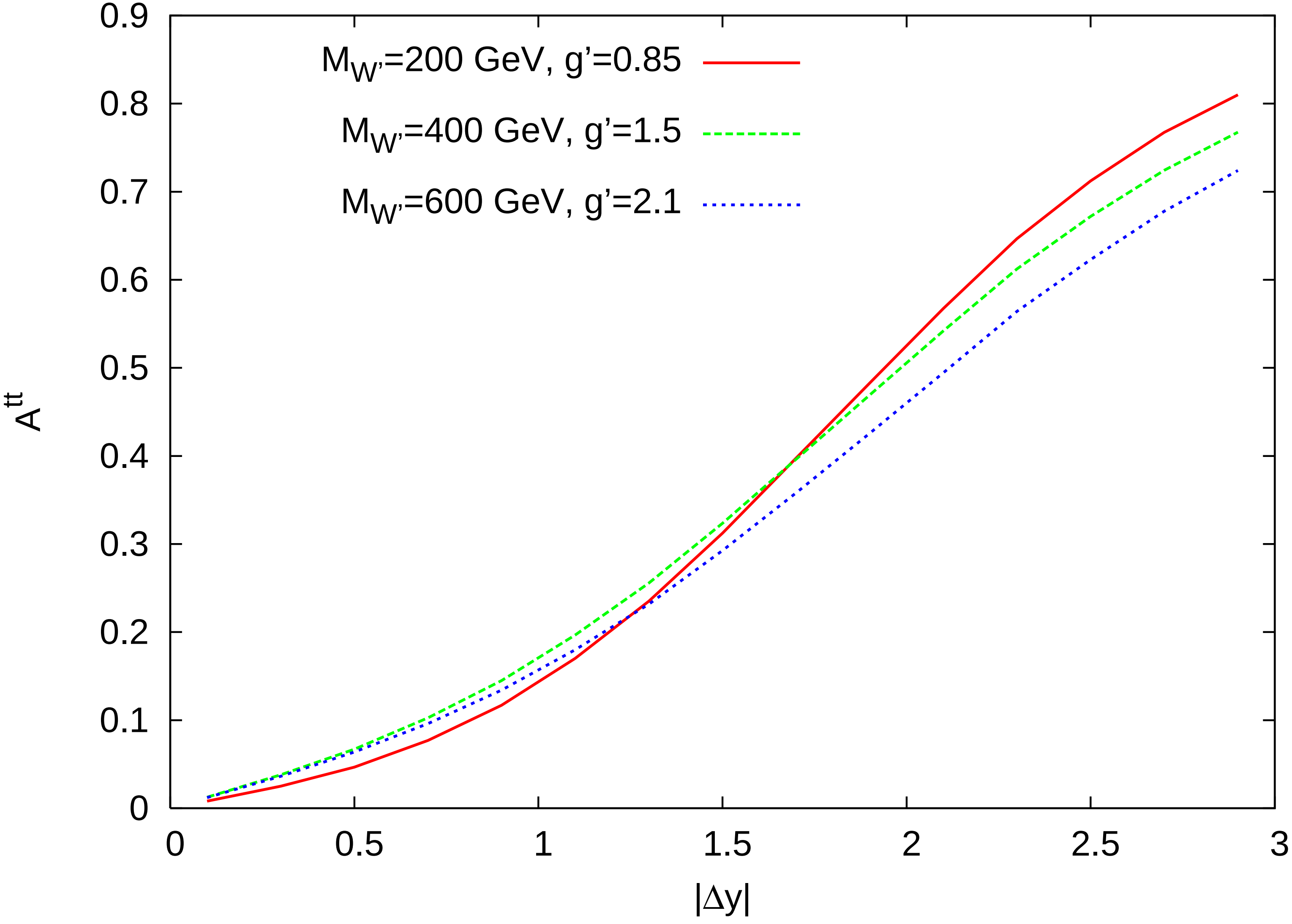
$$\sum |\mathcal{M}|^2 = \cdots + \frac{16 g'^2 g_s^2}{\hat{s}\, t_{W'}} (g_L^2 + g_R^2) \left[2u_t^2 + 2\hat{s} m_t^2 + \frac{m_t^2}{m_{W'}^2} (t_t^2 + \hat{s} m_t^2) \right]$$

where $t_{W'} = -\frac{1}{2}\hat{s}(1 - \beta \cos\theta) + m_t^2 - m_{W'}^2$.

- The factor $t_{W'}$ explains why the top quark is produced in the forward direction.




0.6
0.5
0.4
0.3
0.2
0.1
0
A^{tt}
400
600
800
1000
1200
M_{tt} (GeV)
$M_{W'}$=200 GeV, g'=0.85
$M_{W'}$=300 GeV, g'=1.2
$M_{W'}$=400 GeV, g'=1.5
$M_{W'}$=500 GeV, g'=1.8
$M_{W'}$=600 GeV, g'=2.1



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
A^{tt}
$M_{W'}$=200 GeV, g'=0.85
$M_{W'}$=400 GeV, g'=1.5
$M_{W'}$=600 GeV, g'=2.1
0
0.5
1
1.5
2
2.5
3
|Δy|

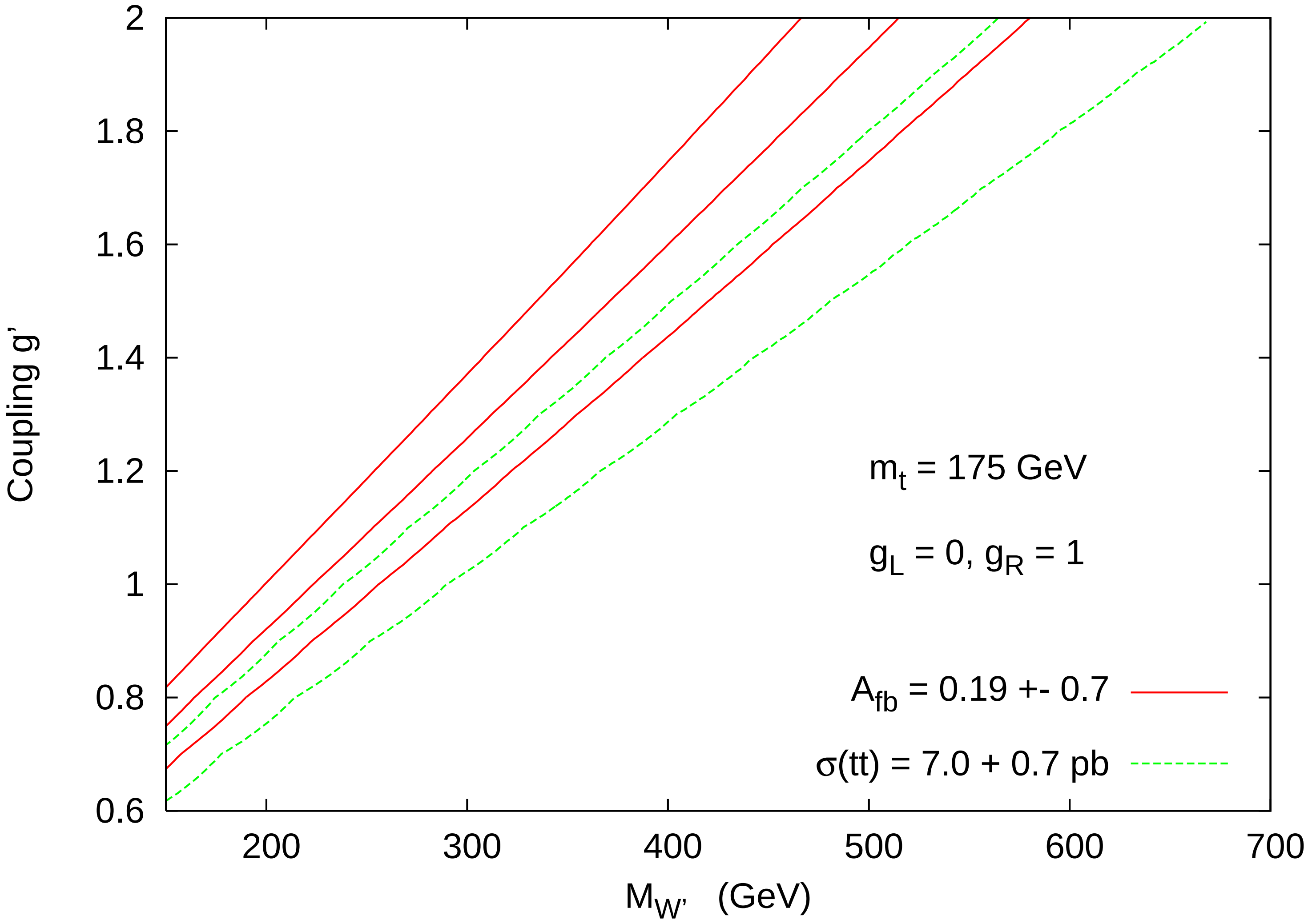
$M_{W'}$ (GeV)	g'	$\sigma_{t\bar{t}}$ (pb)	$A^{t\bar{t}}$	$A^{t\bar{t}}$ $\lvert\Delta y\rvert < 1$	$A^{t\bar{t}}$ $\lvert\Delta y\rvert > 1$	$A^{t\bar{t}}$ $M_{t\bar{t}} < 450$	$A^{t\bar{t}}$ $M_{t\bar{t}} > 450$ GeV
200	0.85	7.99	0.129	0.044	0.321	0.061	0.217
300	1.2	8.28	0.151	0.065	0.348	0.062	0.257
400	1.5	8.24	0.140	0.063	0.324	0.050	0.247
500	1.8	8.21	0.132	0.060	0.305	0.042	0.237
600	2.1	8.19	0.125	0.058	0.290	0.036	0.229
Data		7.70 ± 0.52	0.158 ± 0.074	0.026 ± 0.118	0.611 ± 0.256	-0.116 ± 0.153	0.475 ± 0.112
MCFM		$7.45^{+0.72}_{-0.63}$	0.058 ± 0.009	0.039 ± 0.006	0.123 ± 0.018	0.04 ± 0.006	0.088 ± 0.0013
N. P.		–	0.100 ± 0.074	–	0.488 ± 0.257	–	0.387 ± 0.112

Constraints: $t\bar{t}$ Cross Section and $m(t\bar{t})$

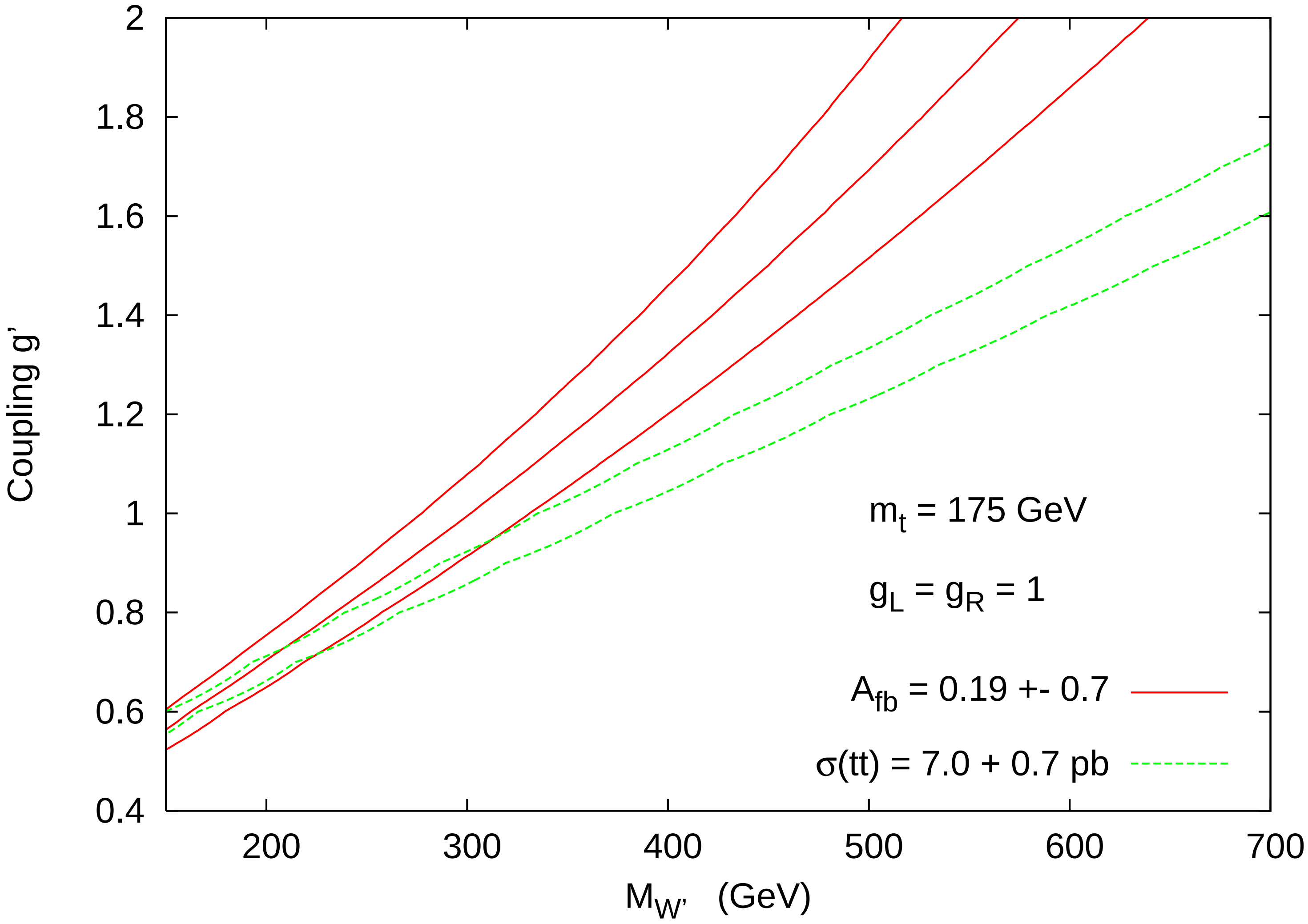
- The $t\bar{t}$ cross section is well measured at the Tevatron

$$\sigma^{\rm exp}(t\bar{t}) = 7.7 \pm 0.52 \text{ pb}$$

- Additional t channel W' diagram can increase the total cross section. It becomes a constraint.
- Another constraint is the invariant mass distribution. The W' diagram also modifies the $m(t\bar{t})$ spectrum.
- Therefore, we will attempt to use the W' contribution to explain the A_{fb} while maintaining the constraints from $\sigma(t\bar{t})$ and $m(t\bar{t})$

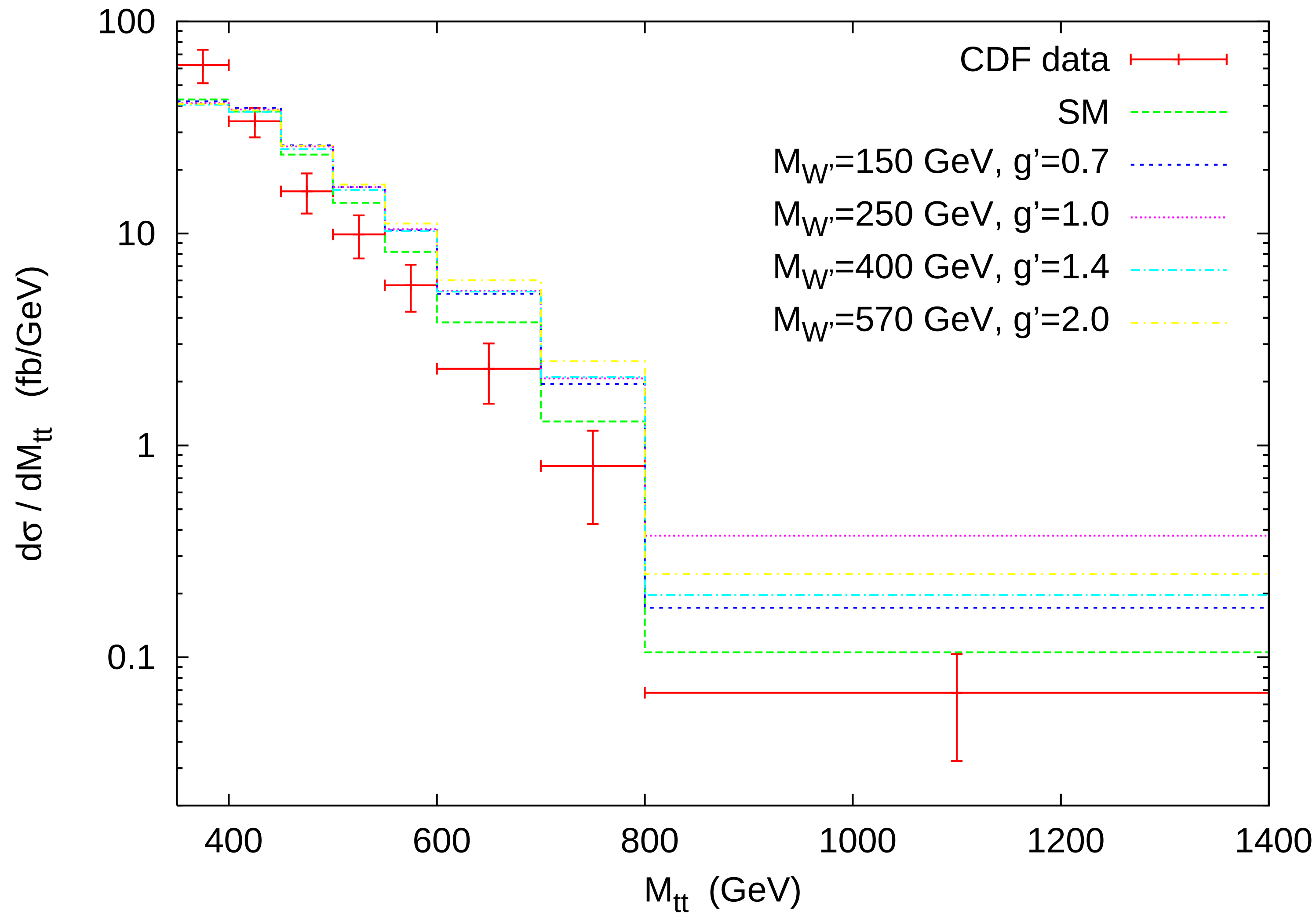


Chiral coupling for W'-d-t: $g_R = 1$, $g_L = 0$



Chiral coupling for W'-d-t: $g_R = g_L = 1$

Invariant mass spectrum



Discussion

- The contours tell us that the heavier the W' the larger the g' needed to produce the same effect.
- For the case $g_L = g_R = 1$, $m_{W'} = 200$ GeV and $g' = 0.6$, and $m_{W'} = 300$ GeV and $g' = 0.8$ to produce the same effect. But there is no solution that satisfies both A_{fb} and $\sigma(t\bar{t})$ for $m_{W'} > 350$ GeV.
- For the case $g_L = 0,\ g_R = 1$, $m_{W'} = 200$ GeV and $g' = 0.8$, and $m_{W'} = 300$ GeV and $g' = 1.1$ to produce the same effect. There are solutions that satisfies both A_{fb} and $\sigma(t\bar{t})$ for $m_{W'} > 200$ GeV upto 600 GeV.

Implications at the Tevatron/LHC

- Since the W' is relatively light, $200 - 600$ GeV here, it can be directly produced at the Tevatron and the LHC.

$$gd \to tW'^-, \qquad g\bar{d} \to \bar{t}W'^+$$

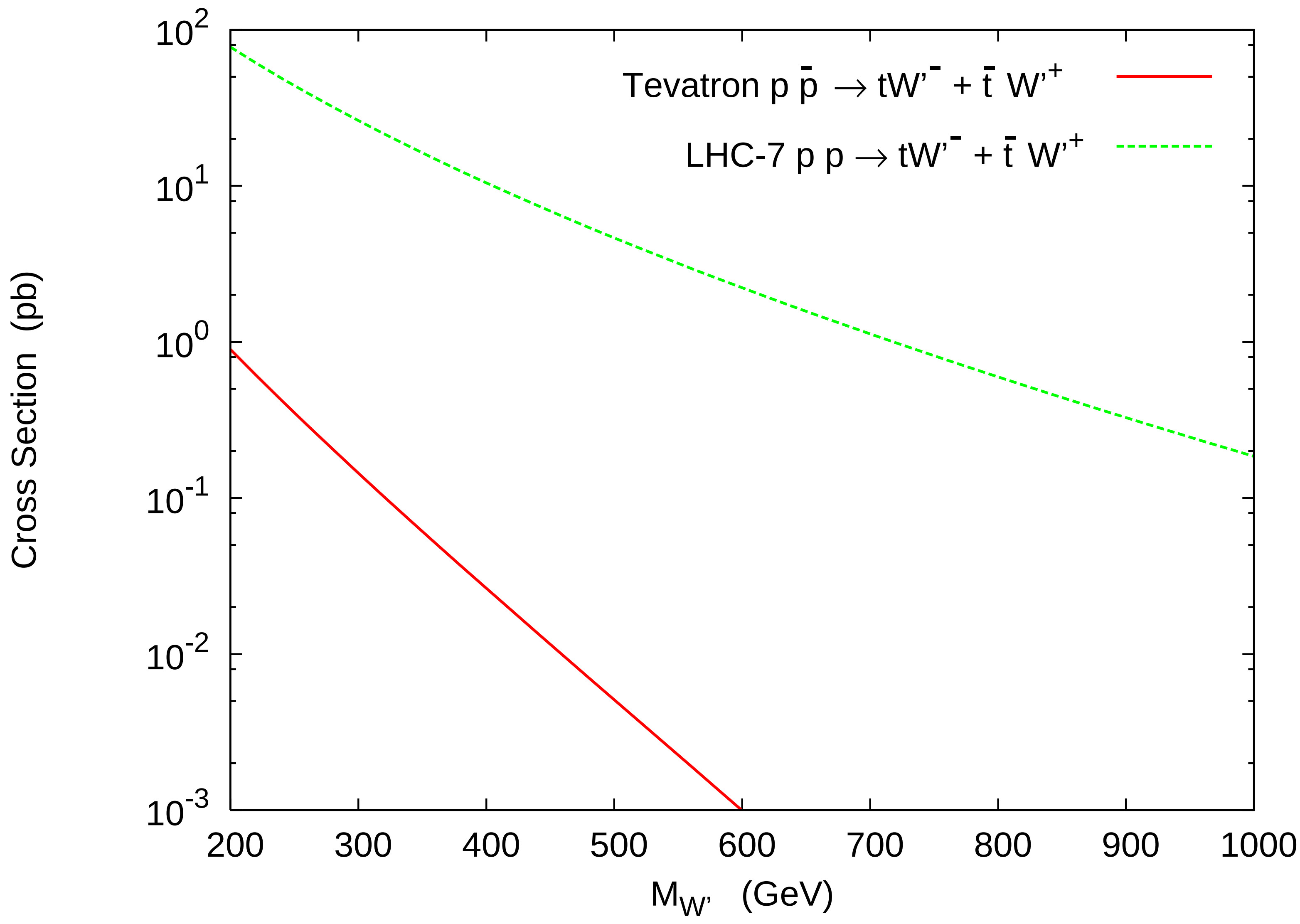
- The W' decays 100% back into $t\bar{d}$ or $\bar{t}d$. So we reconstruct the invariant mass of one of the top and the jet, it will be right at the W' mass.

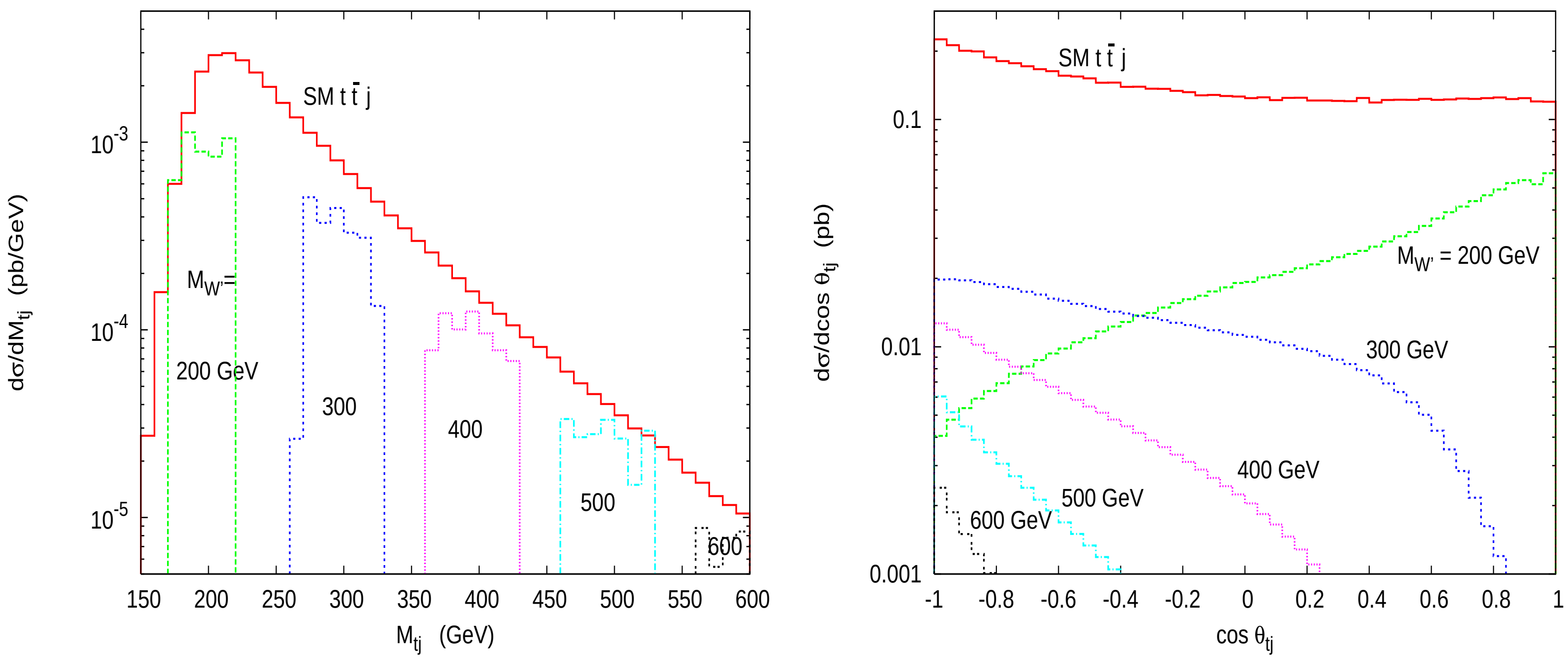
- In the final state, we require to see one hadronic top and one semileptonic top, plus 1 jet. Kinematic cuts for Tevatron (LHC):

$$p_{T_\ell} > 15\ (20)\,\mathrm{GeV}\,, \quad |\eta_\ell| < 2\ (2.5)$$

$$p_{T_j} > 15\ (20)\,\mathrm{GeV}\,, \quad |\eta_j| < 2\ (2.5)$$

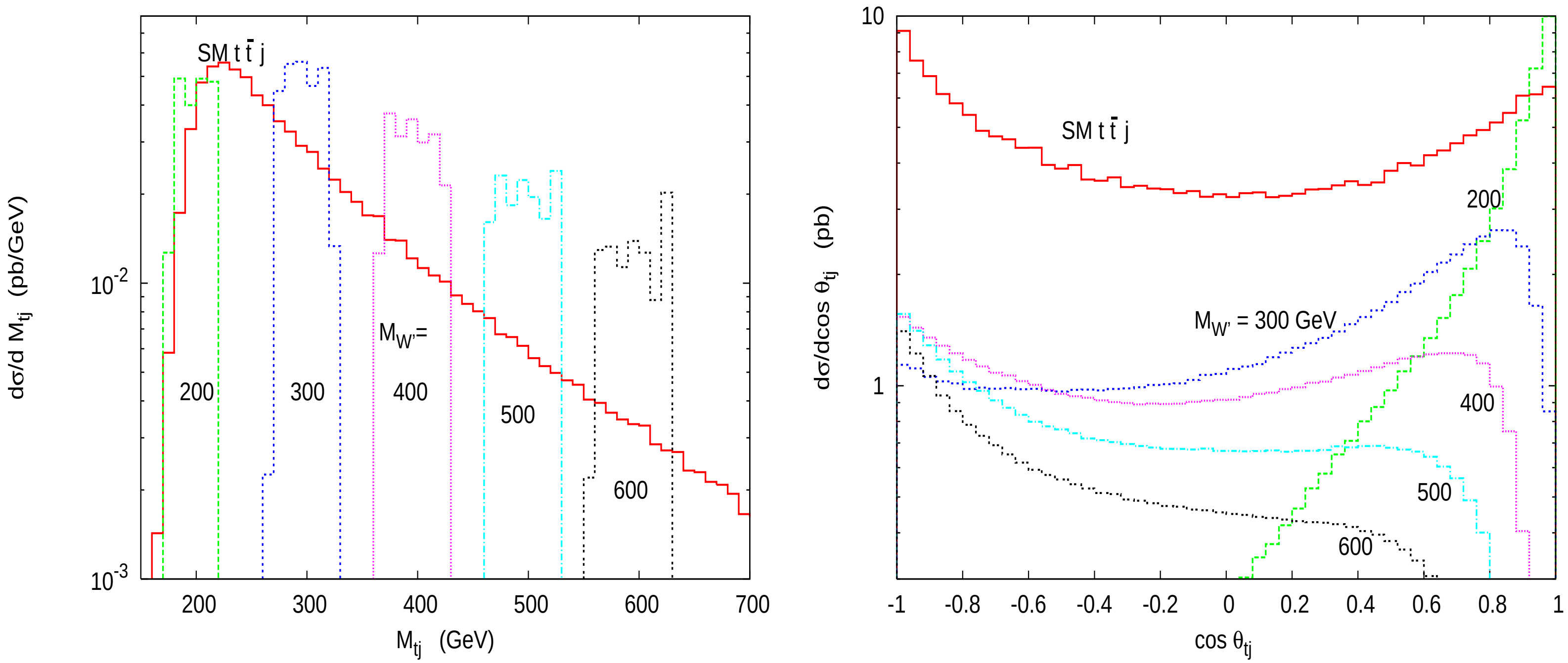
- We look at the invariant mass M_{tj} and opening angle between the top and the jet $\cos\theta_{tj}$.


Tevatron p p̄ → tW'⁻ + t̄ W'⁺
LHC-7 p p → tW'⁻ + t̄ W'⁺
Cross Section (pb)
10^2
10^1
10^0
10^-1
10^-2
10^-3
200
300
400
500
600
700
800
900
1000
M_W' (GeV)



SM t t̄ j
$M_{W'}$=
200 GeV
300
400
500
600
10^{-3}
10^{-4}
10^{-5}
150
200
250
300
350
400
450
500
550
600
$d\sigma/dM_{tj}$ (pb/GeV)
M_{tj} (GeV)
SM t t̄ j
$M_{W'}$ = 200 GeV
300 GeV
400 GeV
500 GeV
600 GeV
0.1
0.01
0.001
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
$d\sigma/d\cos\theta_{tj}$ (pb)
$\cos\theta_{tj}$

Tevatron



SM t t̄ j
200
300
$M_{W'}$=
400
500
600
10⁻²
10⁻³
dσ/d M_{tj} (pb/GeV)
200
300
400
500
600
700
M_{tj} (GeV)
10
1
dσ/dcos θ_{tj} (pb)
SM t t̄ j
200
$M_{W'}$ = 300 GeV
400
500
600
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos θ_{tj}

LHC

Tevatron Signal & Background (10 fb^{-1})

$M_{W'}$ (GeV)	g'	Signal events S	Bkgd events B	S/B	$S/\sqrt{B}$
200	0.85	285	640	0.44	11
300	1.2	210	460	0.46	9.8
400	1.5	67	130	0.52	5.9
500	1.8	19	40	0.48	3.0
600	2.1	5	14	0.36	1.3

LHC Signal & Background (100 pb^{-1} and 1000 pb^{-1})

$M_{W'}$ (GeV)	g'	Signal events S	Bkgd events B	S/B	$S/\sqrt{B}$
200	0.85	180 (1800)	130 (1300)	1.4	16 (50)
300	1.2	270 (2700)	170 (1700)	1.6	21 (65)
400	1.5	200 (2000)	98 (980)	2.0	20 (64)
500	1.8	140 (1400)	60 (600)	2.3	18 (57)
600	2.1	96 (960)	39 (390)	2.4	15 (49)

A flavor-changing Z'

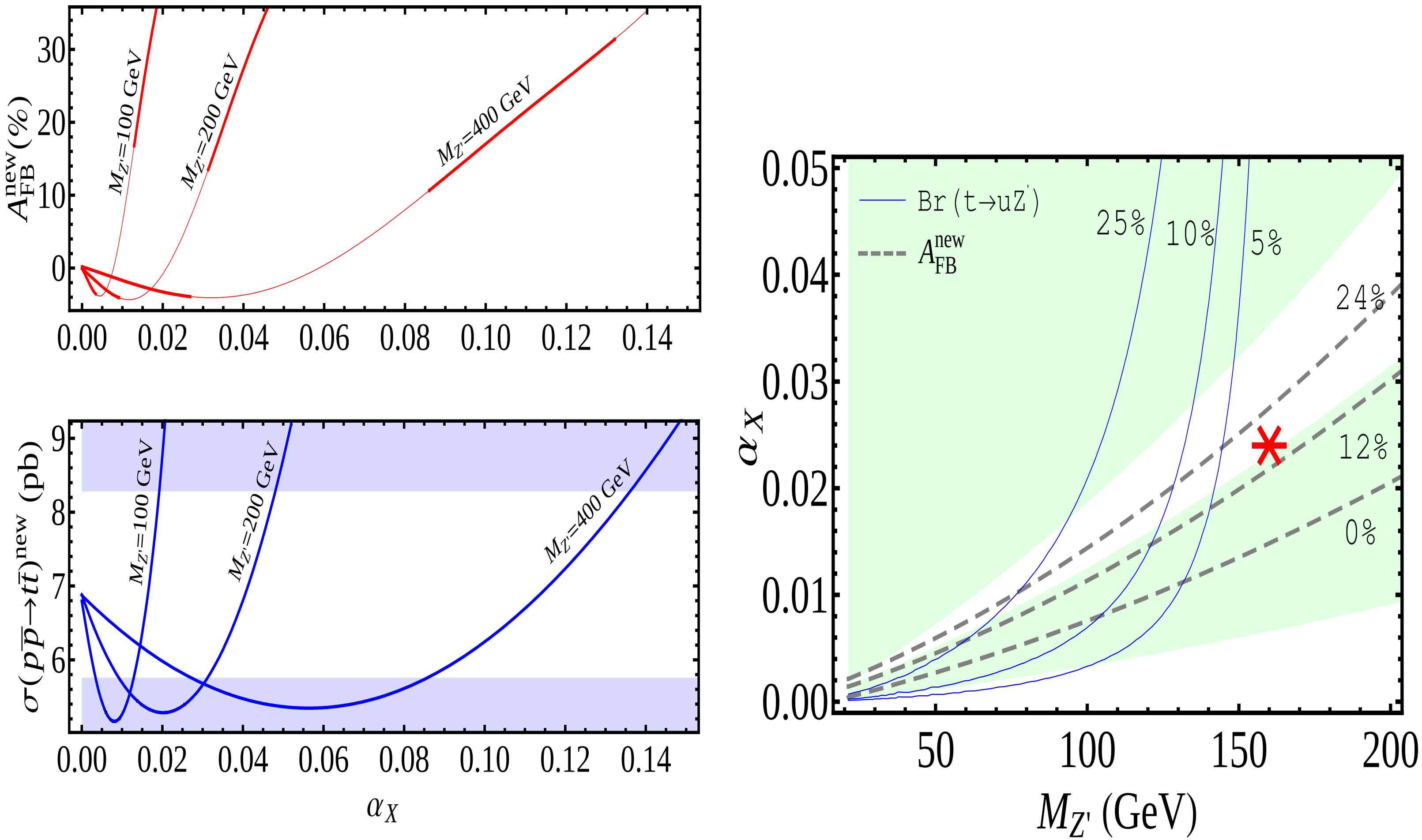
Jung, Murayama, Pierce, Wells

The model is a new Z' with an abelian $U(1)$ symmetry and flavor off-diagonal couplings

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

The best point to describe all the data, including $t\bar{t}$ cross section and A_{FB} is

$$\alpha_X = \frac{g_X^2}{4\pi} = 2.4 \times 10^{-2}, \qquad M_{Z'} \approx 160 GeV$$



A_{FB}^{new} (%)
$M_{Z'}$=100 GeV
$M_{Z'}$=200 GeV
$M_{Z'}$=400 GeV
$\sigma(p\bar{p}\to t\bar{t})^{new}$ (pb)
α_X
Br(t→uZ')
A_{FB}^{new}
25%
10%
5%
24%
12%
0%
α_X
$M_{Z'}$ (GeV)

Axigluon

Frampton, Shu, Wang

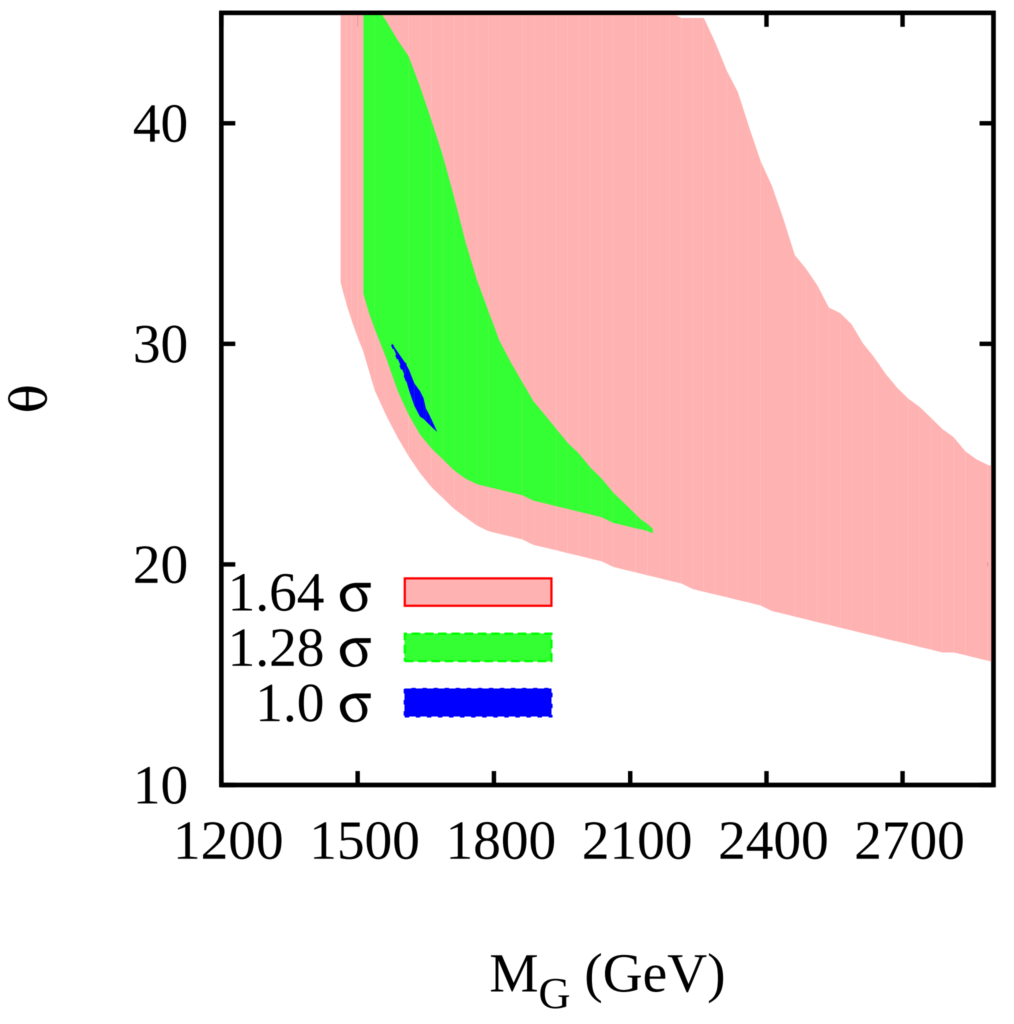
It is a color-octet massive object that couples the top quark and light quarks in s channel with specific chiral couplings:

$$g_V^q = g_V^t = -\frac{g\cos 2\theta}{2}, \qquad -g_A^q = g_A^t = \frac{g}{2}$$

The combination

$$g_A^q g_A^t < 0\ , \qquad g_V^q g_V^t > 0$$

with $g_V < g_A$ is needed to fit the data.



θ
40
30
20
10
1200 1500 1800 2100 2400 2700
1.64 σ
1.28 σ
1.0 σ
M_G (GeV)

An model independent Analysis

Jung, Ko, Lee, Nam

They considered color-singlet and color-octet exchanges

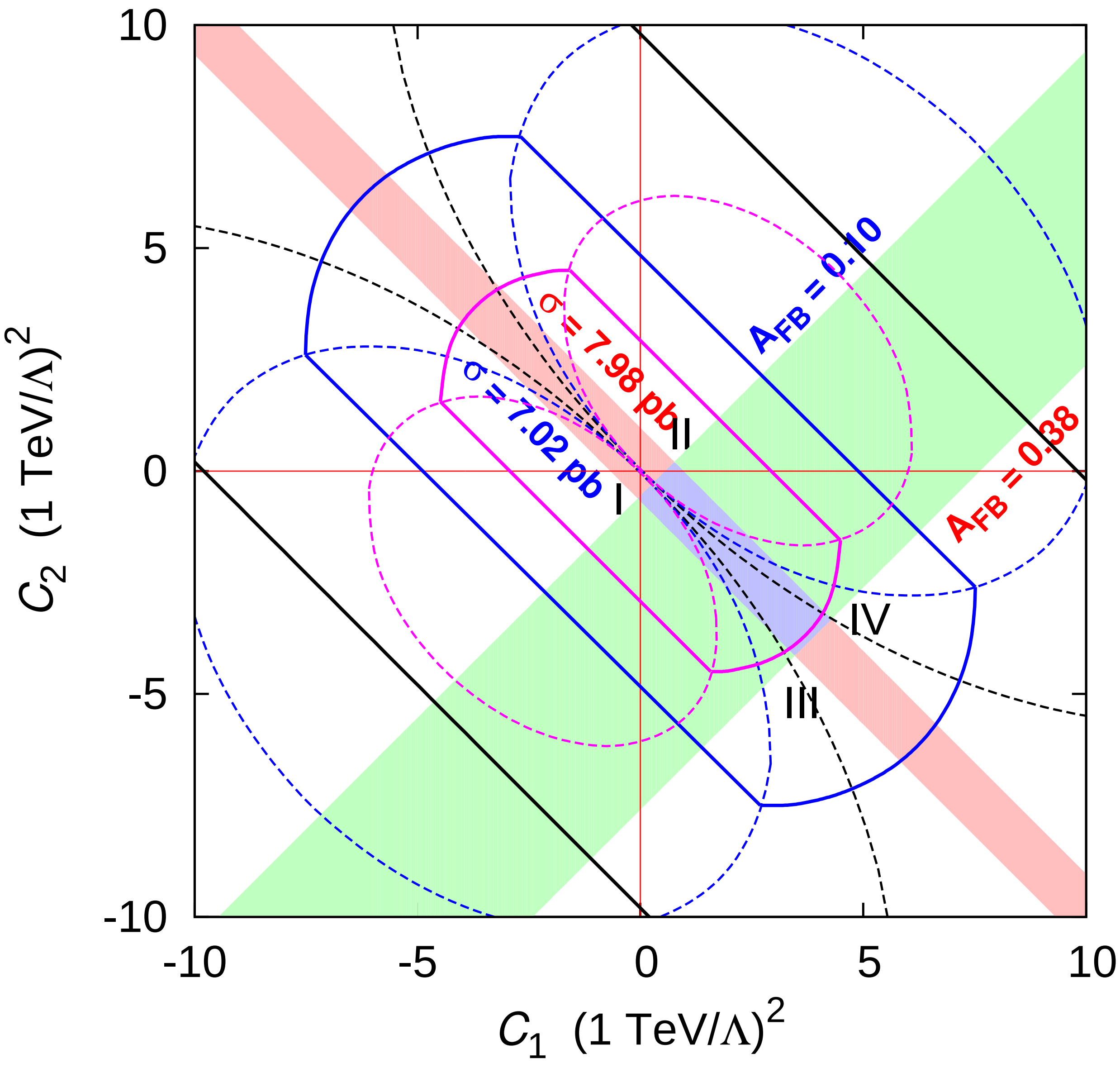
$$L = \frac{g_s^2}{\Lambda^2} \sum_{\alpha\beta=L,R} \left[C_{1q}^{\alpha\beta} (\bar{q}_\alpha \gamma^\mu q_\alpha)(\bar{t}_\beta \gamma_\mu q_\beta) + C_{8q}^{\alpha\beta} (\bar{q}_\alpha T^a \gamma^\mu q_\alpha)(\bar{t}_\beta T^a \gamma_\mu q_\beta) \right]$$

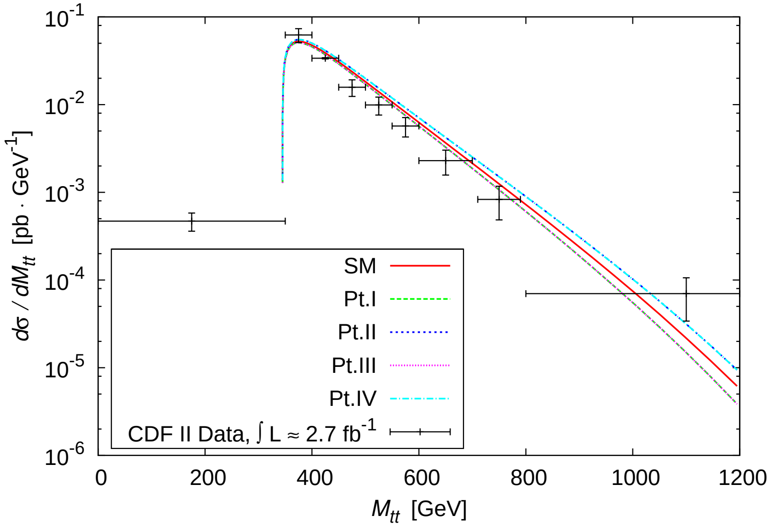
They also define the spin-correlation,

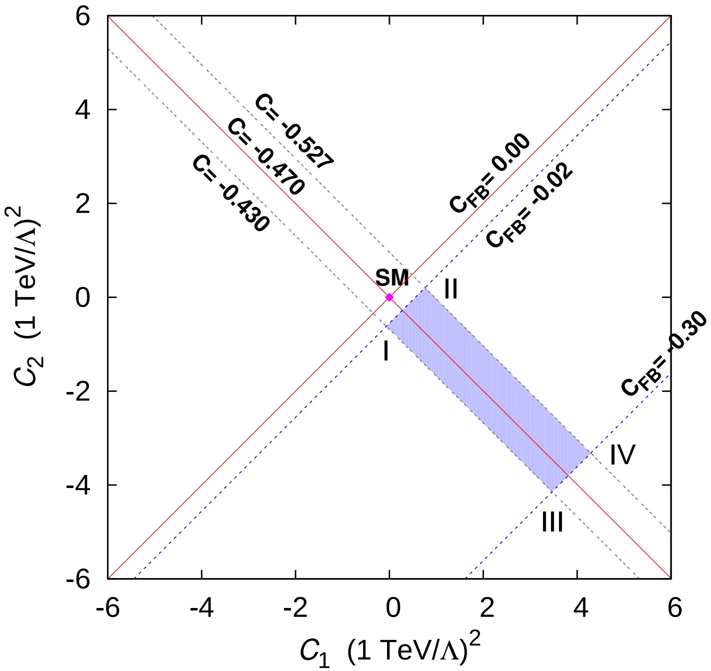
$$C = \frac{\sigma(t_L \bar{t}_L + t_R \bar{t}_R) - \sigma(t_L \bar{t}_R + t_R \bar{t}_L)}{\sigma(t_L \bar{t}_L + t_R \bar{t}_R) + \sigma(t_L \bar{t}_R + t_R \bar{t}_L)}$$

The FB asymmetry is defined by

$$C_{FB} \equiv C(\cos\theta \geq 0) - C(\cos\theta < 0)$$


10
5
0
-5
-10
-10
-5
0
5
10
C_2 (1 TeV/Λ)^2
C_1 (1 TeV/Λ)^2
σ = 7.98 pb
σ = 7.02 pb
A_{FB} = 0.10
A_{FB} = 0.38
I
II
III
IV


SM
Pt.I
Pt.II
Pt.III
Pt.IV
CDF II Data, ∫ L ≈ 2.7 fb-1
dσ / dMtt [pb · GeV-1]
Mtt [GeV]


C= -0.527
C= -0.470
C= -0.430
CFB= 0.00
CFB= -0.02
CFB= -0.30
SM
I
II
III
IV
C2 (1 TeV/Λ)2
C1 (1 TeV/Λ)2

Conclusions

- The top quark FB asymmetry cannot be explained by the NLO QCD calculation. New physics is needed.
- A flavor-changing particle exchanged in t-channel can explain the increase in forward production of the top quark, and production in large $M_{t\bar{t}}$ region.
- We have used a W' coupling to the d and t as an example. It explains the FB asymmetry in the large Δy and large $M_{t\bar{t}}$ region.
- The total $t\bar{t}$ cross section and $m(t\bar{t})$ provide strong constraints on the size of the new interaction.
- Such a W' can be directly produced at the Tevaton and LHC. Tevatron can observe up to 400 GeV with 10 fb^{-1} while the LHC can observe all the way.