

# Top Quark Forward-Backward Asymmetry 2011 Update

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Cross Strait – April 1, 2011

## Outline

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

## CDF Experimental Data

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Reported in  $3.2 \text{ fb}^{-1}$  (CDF-note-9724,  $1.9 \text{ fb}^{-1}$  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  $\theta$ ) while the other decays semileptonically (for identification of the charge lepton).

- 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

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

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

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

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

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

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

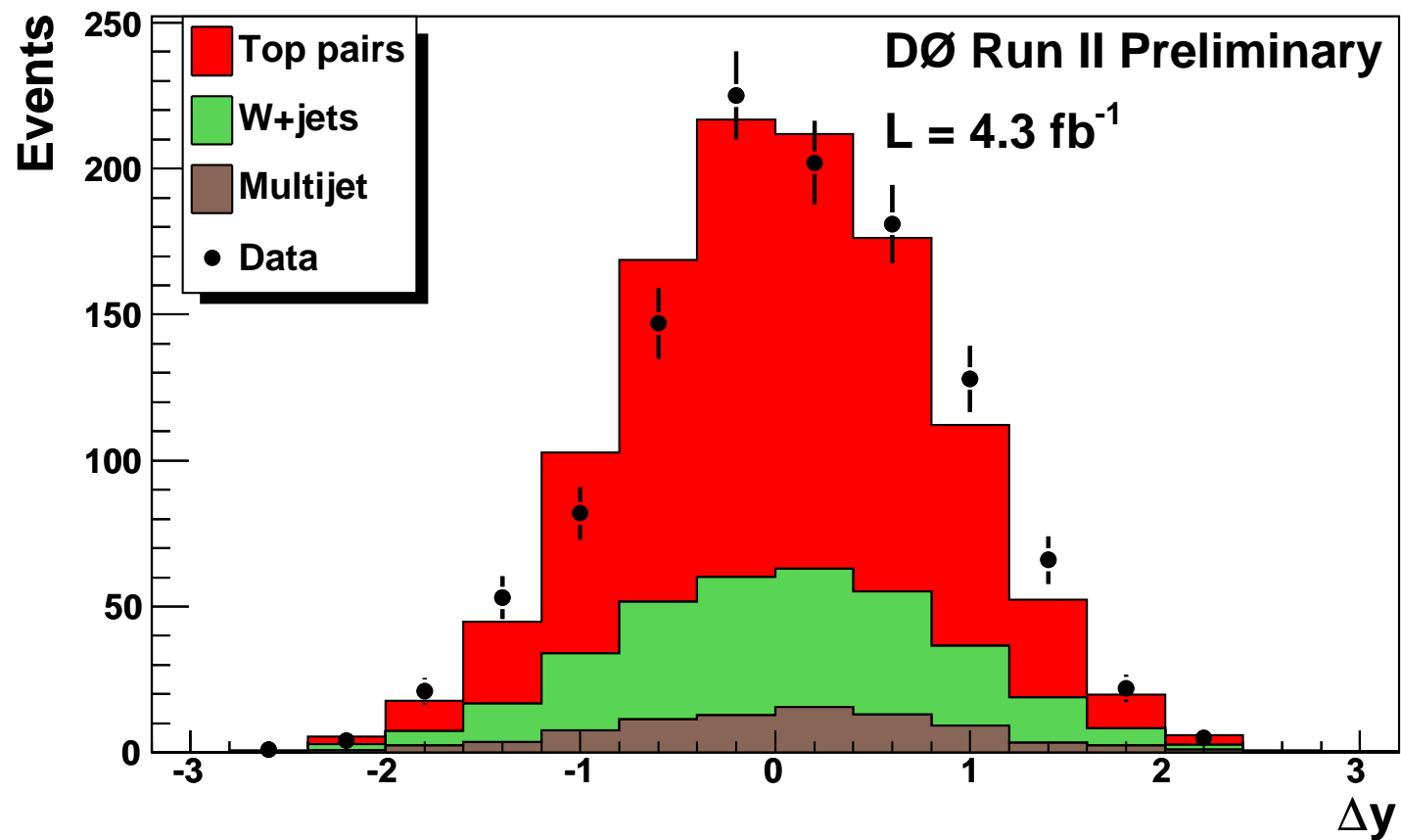
- This is to be compared with the MC@NLO-based prediction

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

- 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.



Reported in 5.3 fb<sup>-1</sup> (CDF-note-10224)

- The forward-backward asymmetry

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

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

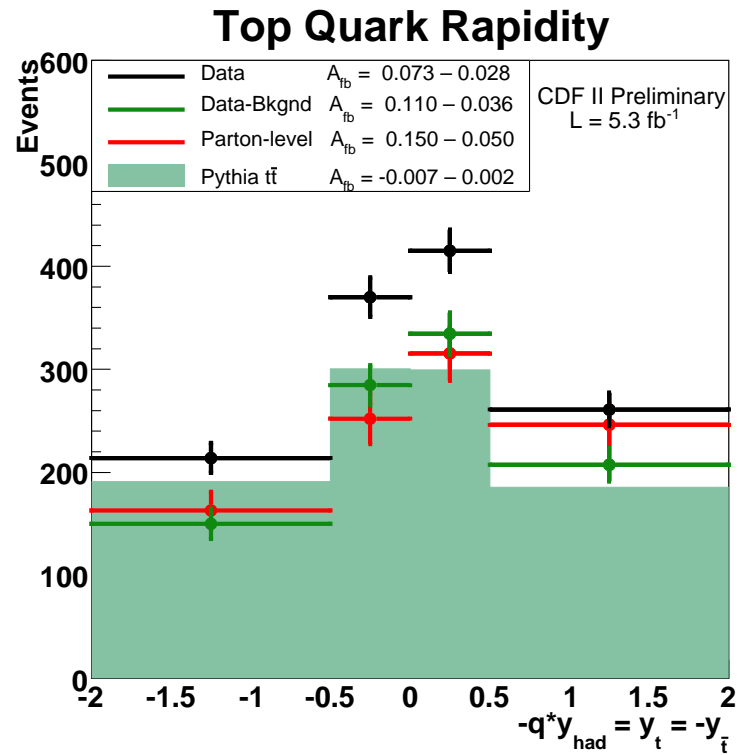
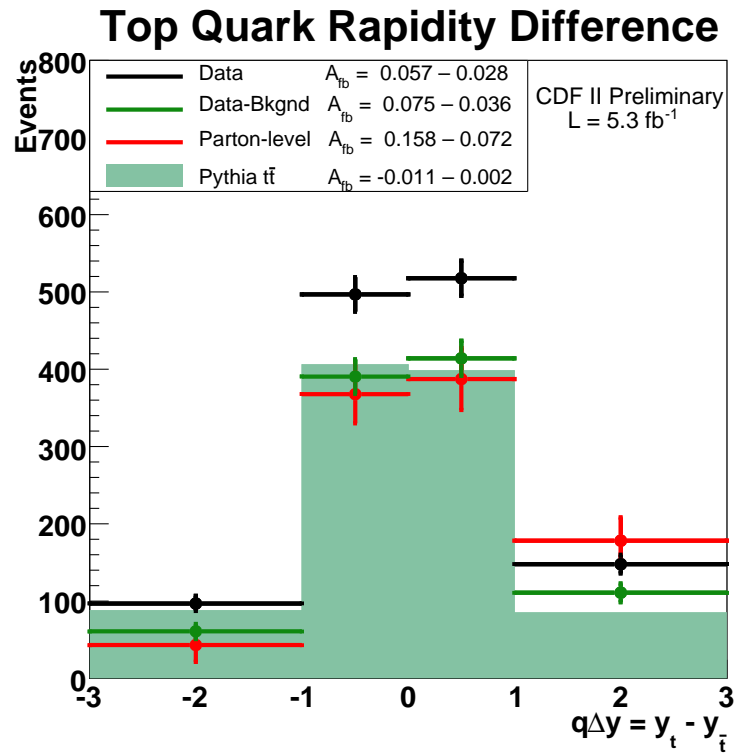
in comparison to  $0.038 \pm 0.006$  and  $0.058 \pm 0.009$ , respectively, in the NLO QCD.

- 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.





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

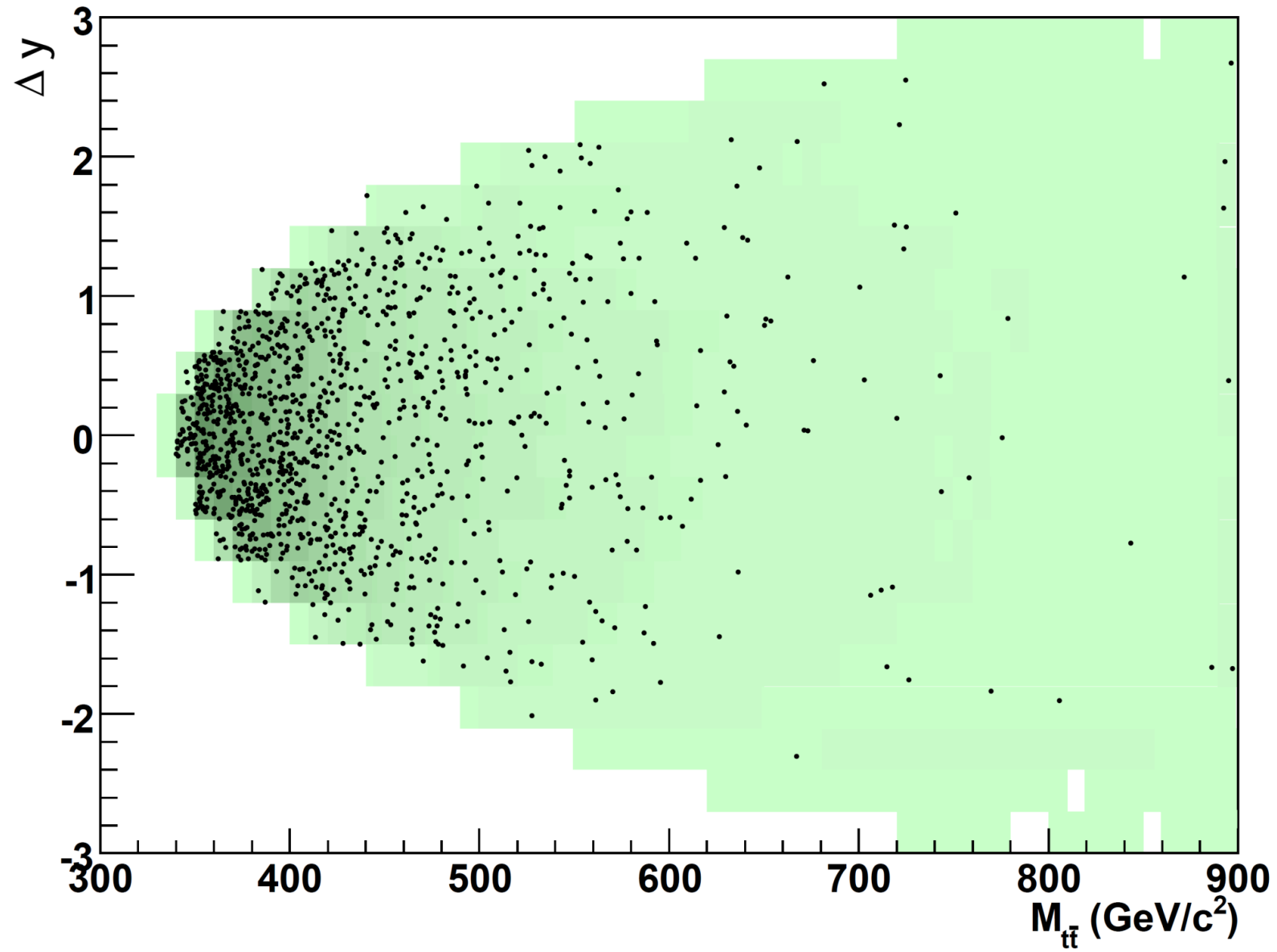
- The forward-backward asymmetry levels off a little

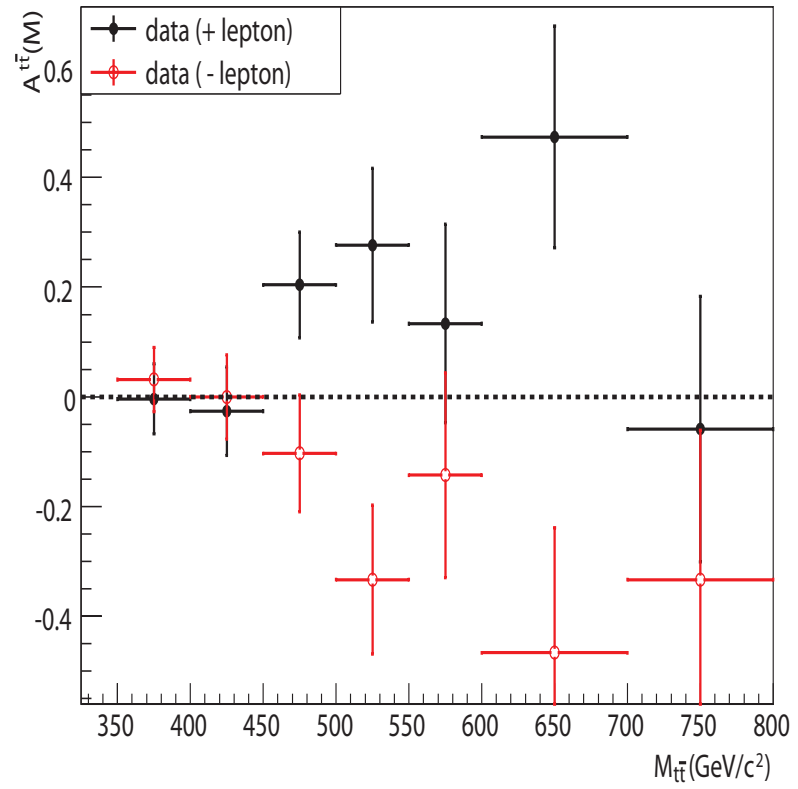
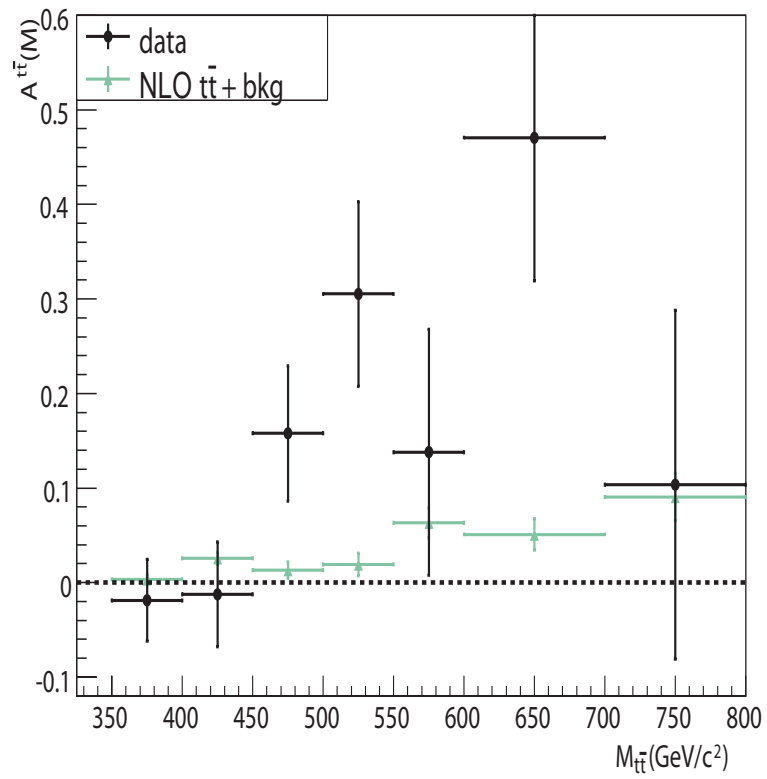
$$A^{t\bar{t}} = 0.158 \pm 0.074 \quad (< 2\sigma)$$

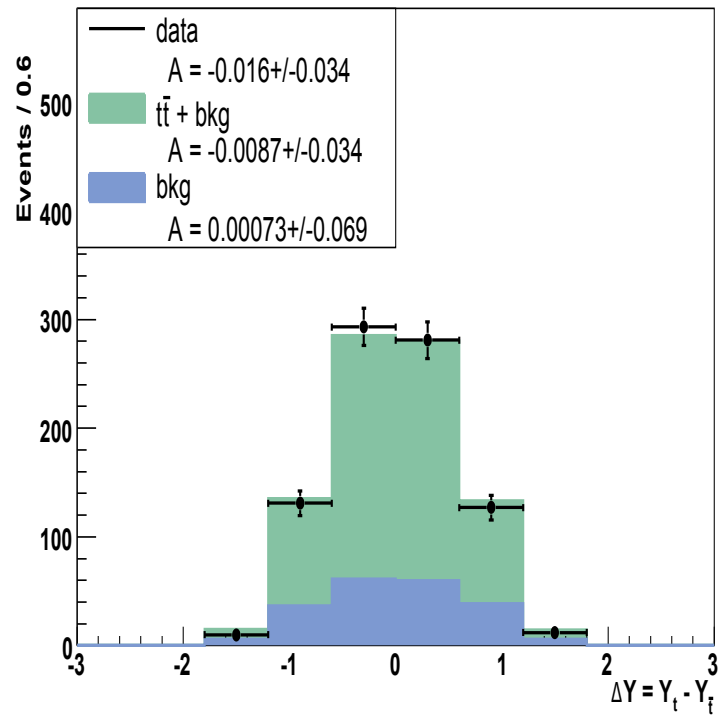
compared to  $A_{\text{SM}}^{t\bar{t}} = 0.058 \pm 0.009$ .

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

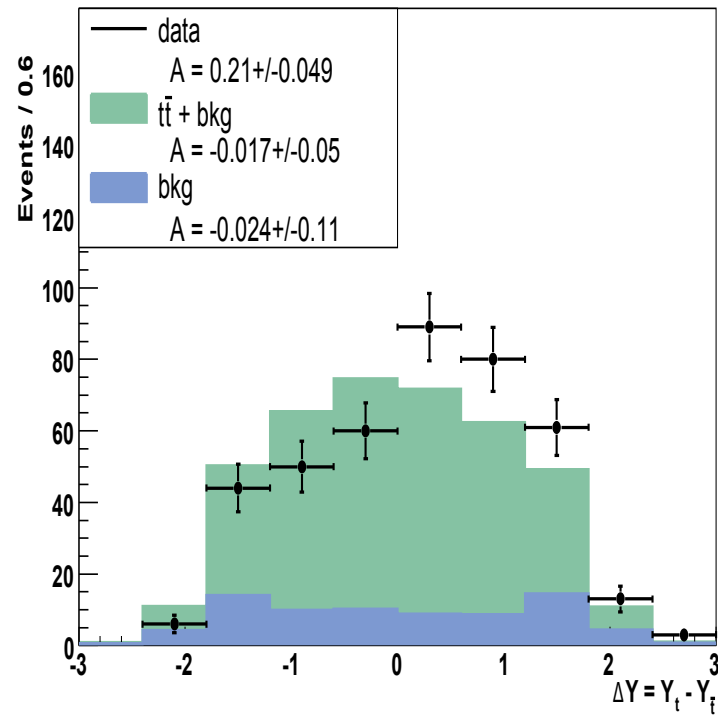
	$A^{t\bar{t}}$	$A^{t\bar{t}}$		$A^{t\bar{t}}$	
		$ \Delta y  < 1$	$ \Delta y  > 1$	$M_{t\bar{t}} < 450$	$> 450 \text{ GeV}$
Data	$0.158 \pm 0.074$	$0.026 \pm 0.118$	$0.611 \pm 0.256$	$-0.116 \pm 0.153$	$0.475 \pm 0.112$
MCFM	$0.058 \pm 0.009$	$0.039 \pm 0.006$	$0.123 \pm 0.018$	$0.04 \pm 0.006$	$0.088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







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



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

## Interpretations

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- 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 ( $u, d, s, \text{ or } c$ ) quark. Examples are:  $W', Z', \text{ RPV squarks}$ .

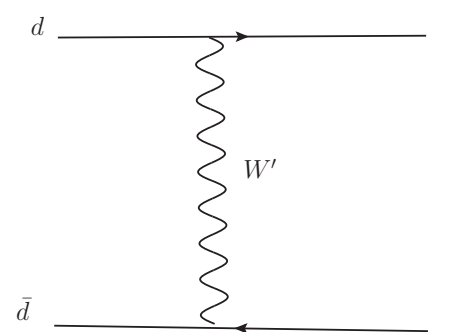
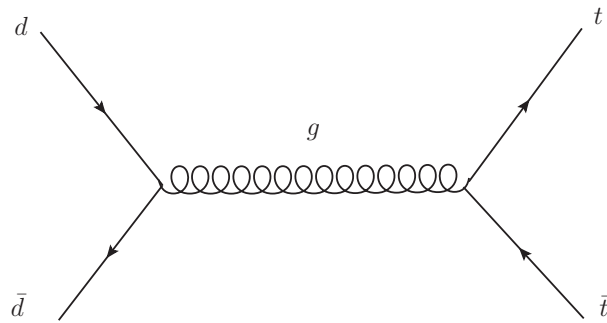
- An unknown particle that couple to the top quark and light quarks with uneven left- and right-handed couplings. The couplings have to be tuned. This diagram then interferes with the SM gluon diagram. Examples are **axigluons**.

$$W'$$

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

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

- $W'$  couples to  $t$  and  $s$  is equally good, but needs a larger coupling, because of smaller parton luminosity.
- Two Feynman diagrams for the process  $d\bar{d} \rightarrow t\bar{t}$ .

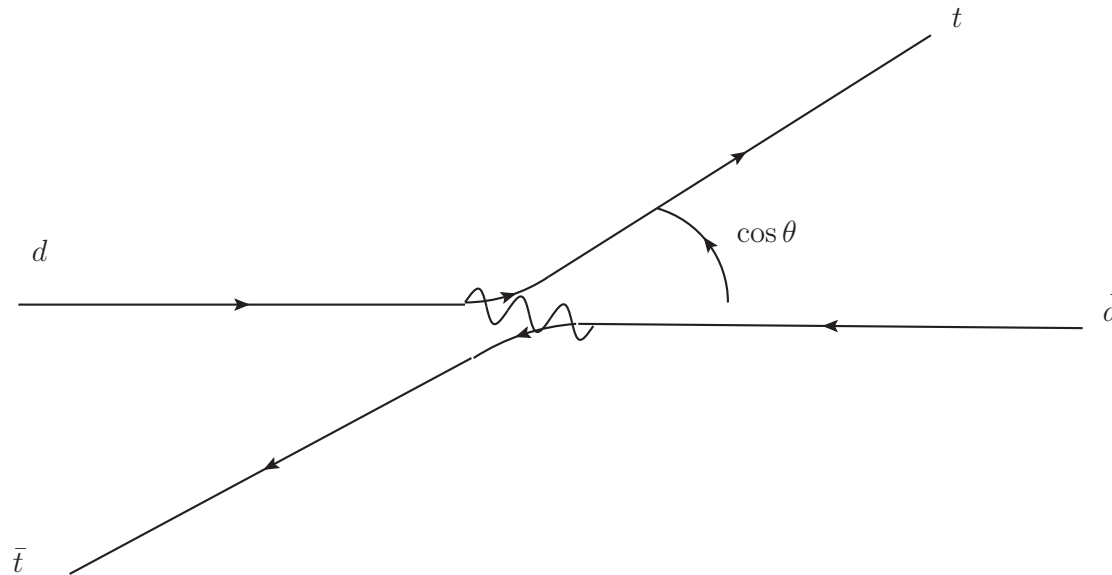


- The interference term in the amplitude squared

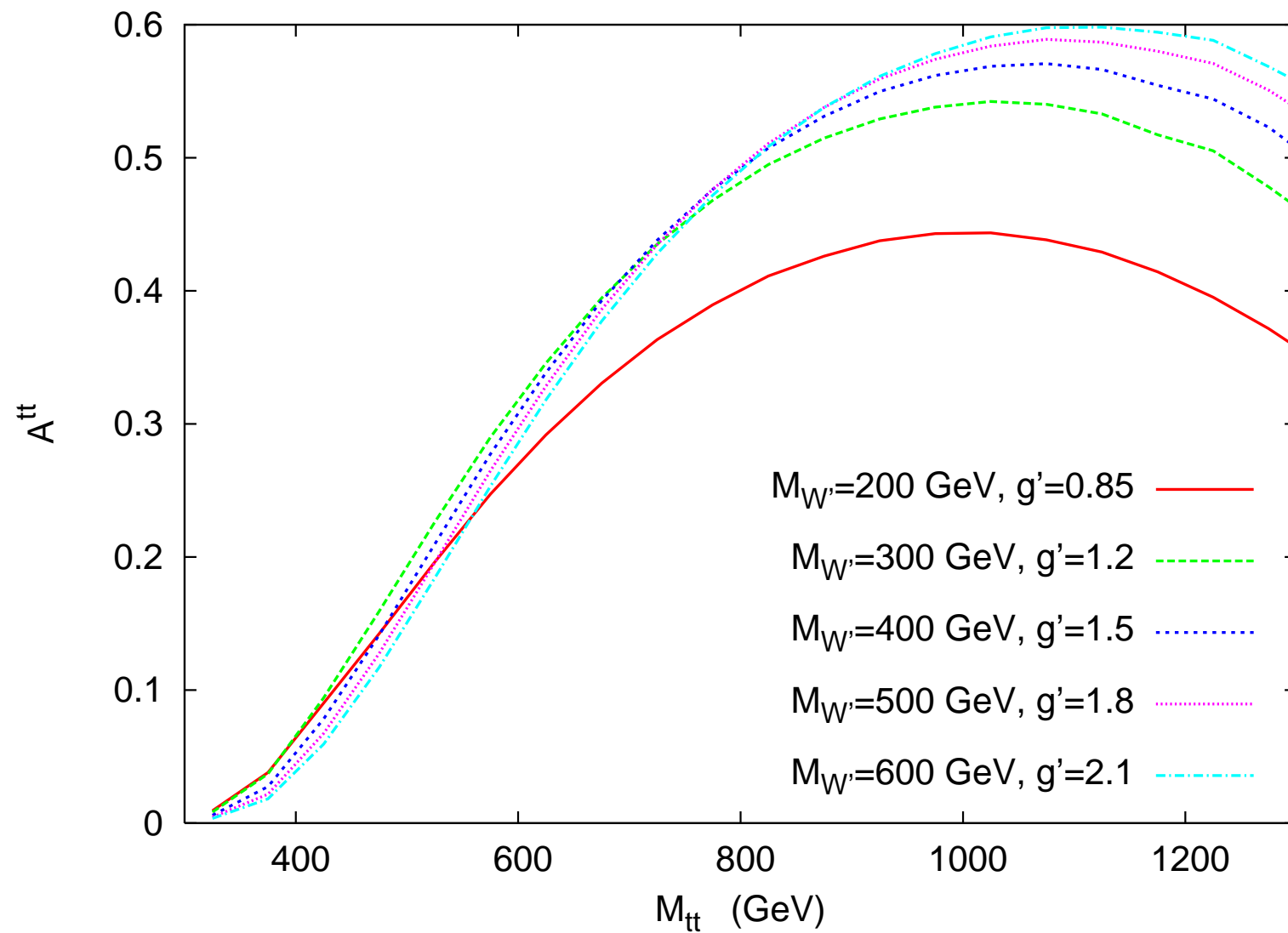
$$\sum |\mathcal{M}|^2 = \dots + \frac{16g'^2 g_s^2}{\hat{s} t_{W'}} (g_L^2 + g_R^2) \left[ 2u_t^2 + 2\hat{s}m_t^2 + \frac{m_t^2}{m_{W'}^2} (t_t^2 + \hat{s}m_t^2) \right]$$

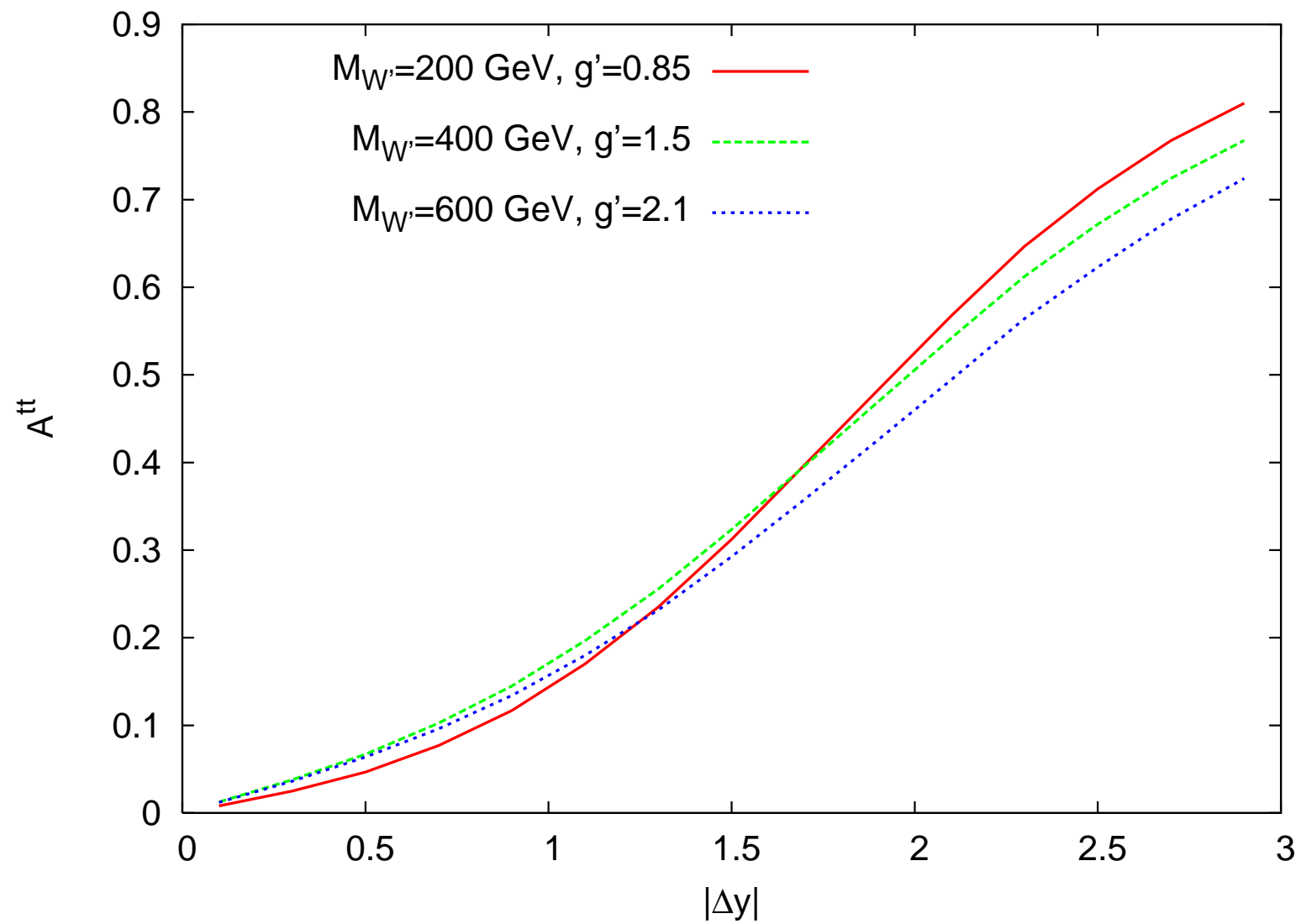
where  $t_{W'} = -\frac{1}{2}\hat{s}(1 - \beta \cos \theta) + m_t^2 - m_{W'}^2$ .

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









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

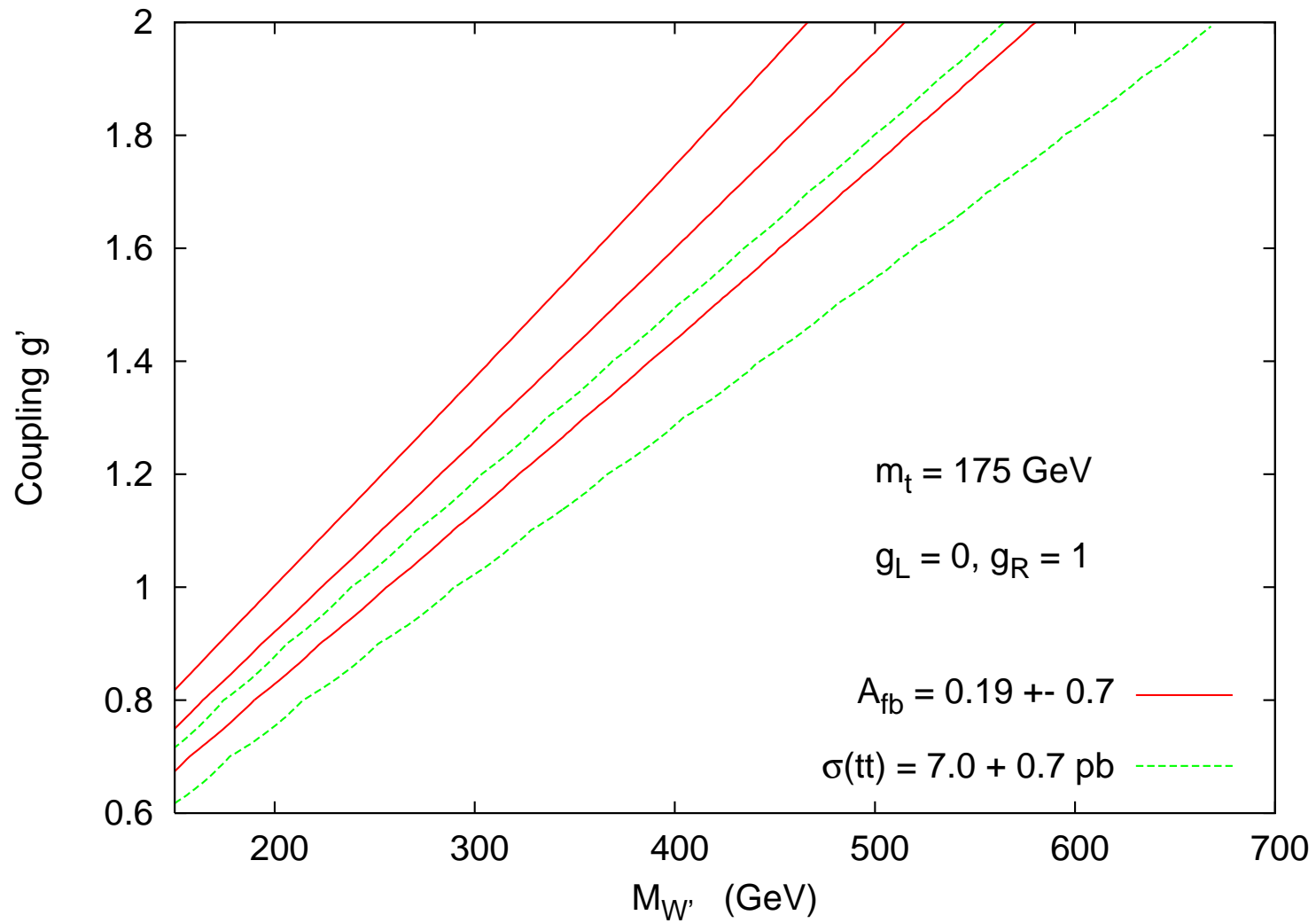
## Constraints: $t\bar{t}$ Cross Section and $m(t\bar{t})$

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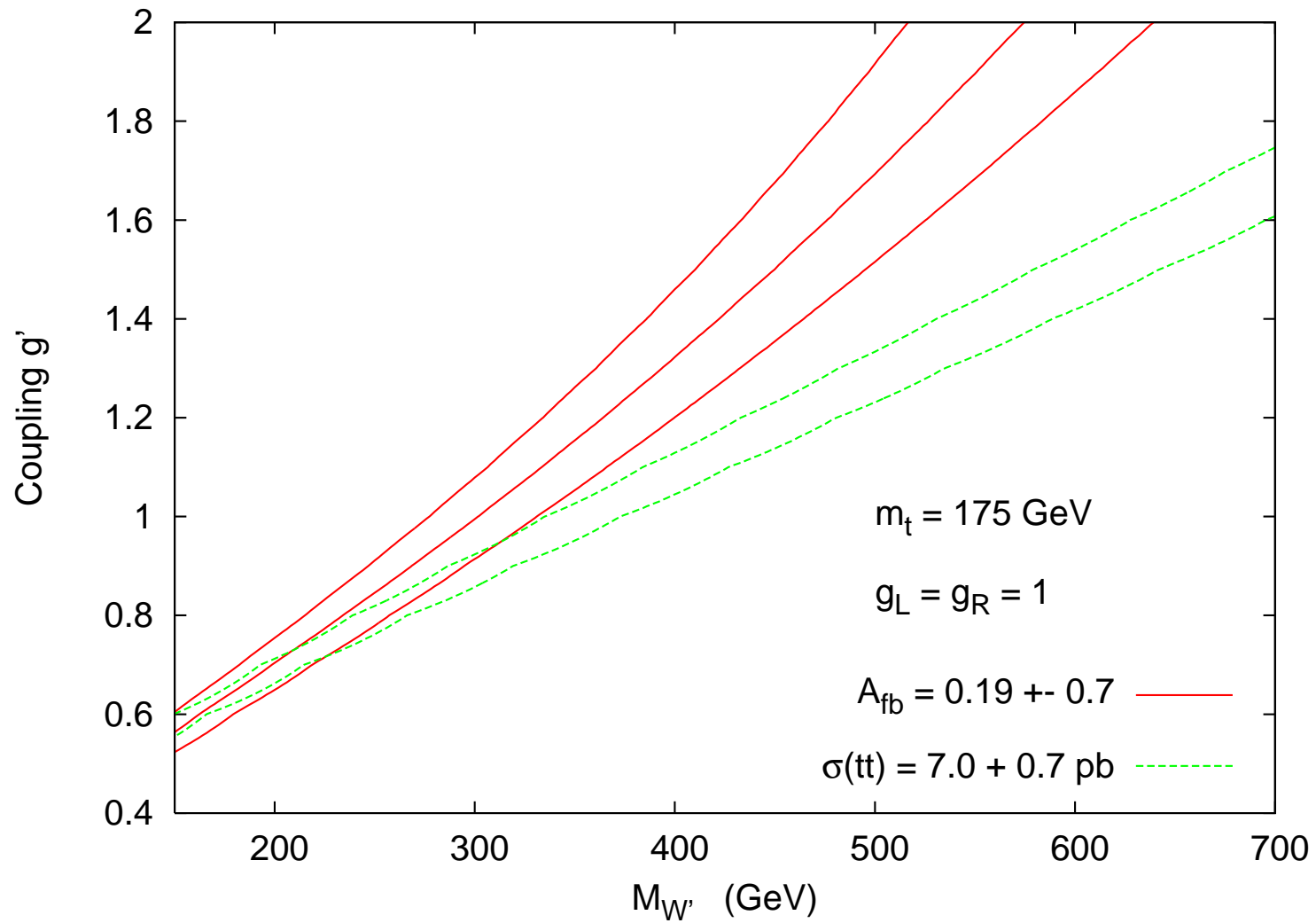
- The  $t\bar{t}$  cross section is well measured at the Tevatron

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

- 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  $m(t\bar{t})$

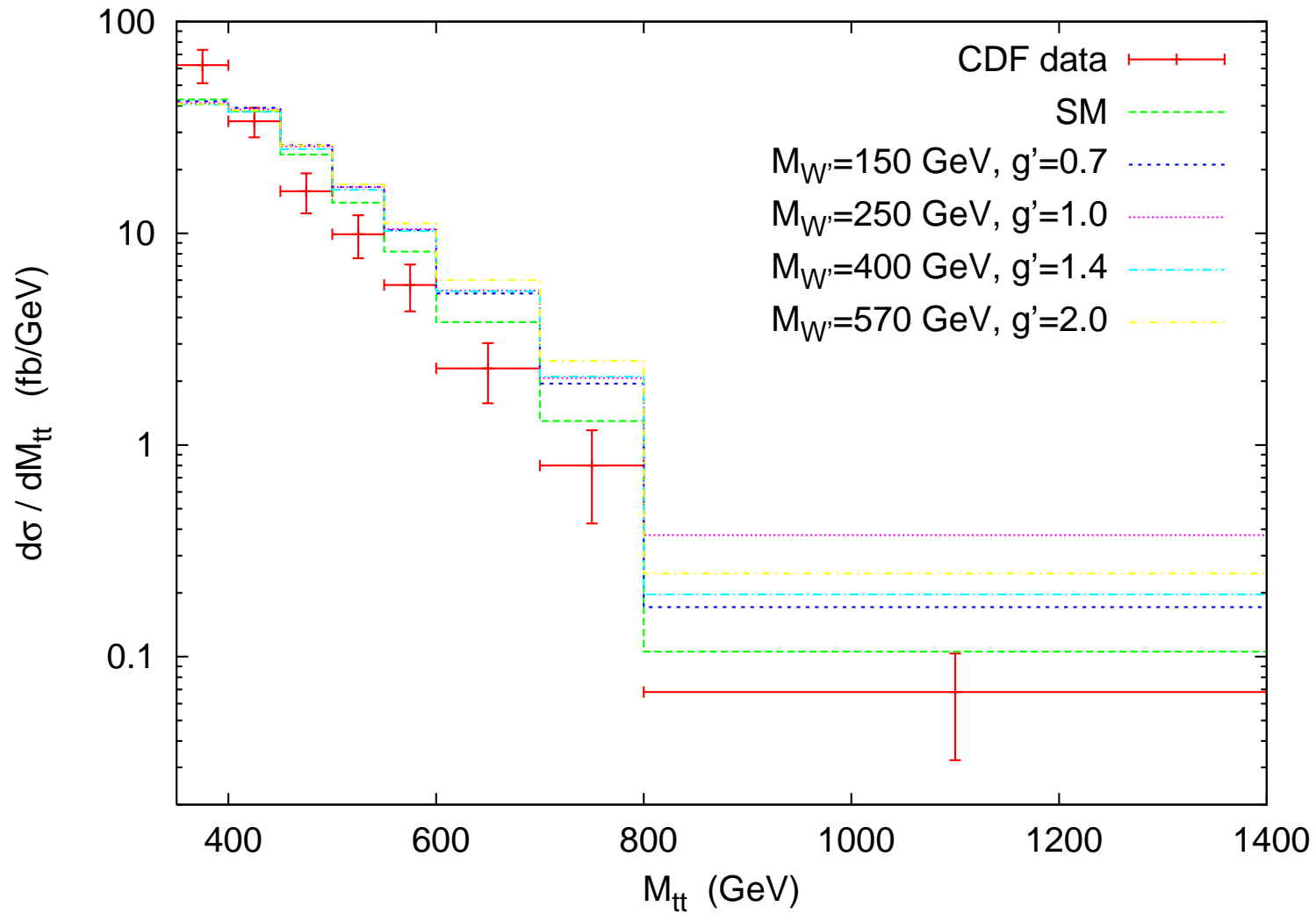


Chiral coupling for  $W'-d-t$ :  $g_R = 1, g_L = 0$



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

# Invariant mass spectrum



## Discussion

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- 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  $\sigma(tt)$  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  $\sigma(tt)$  for  $m_{W'} > 200$  GeV upto 600 GeV.



## Implications at the Tevatron/LHC

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

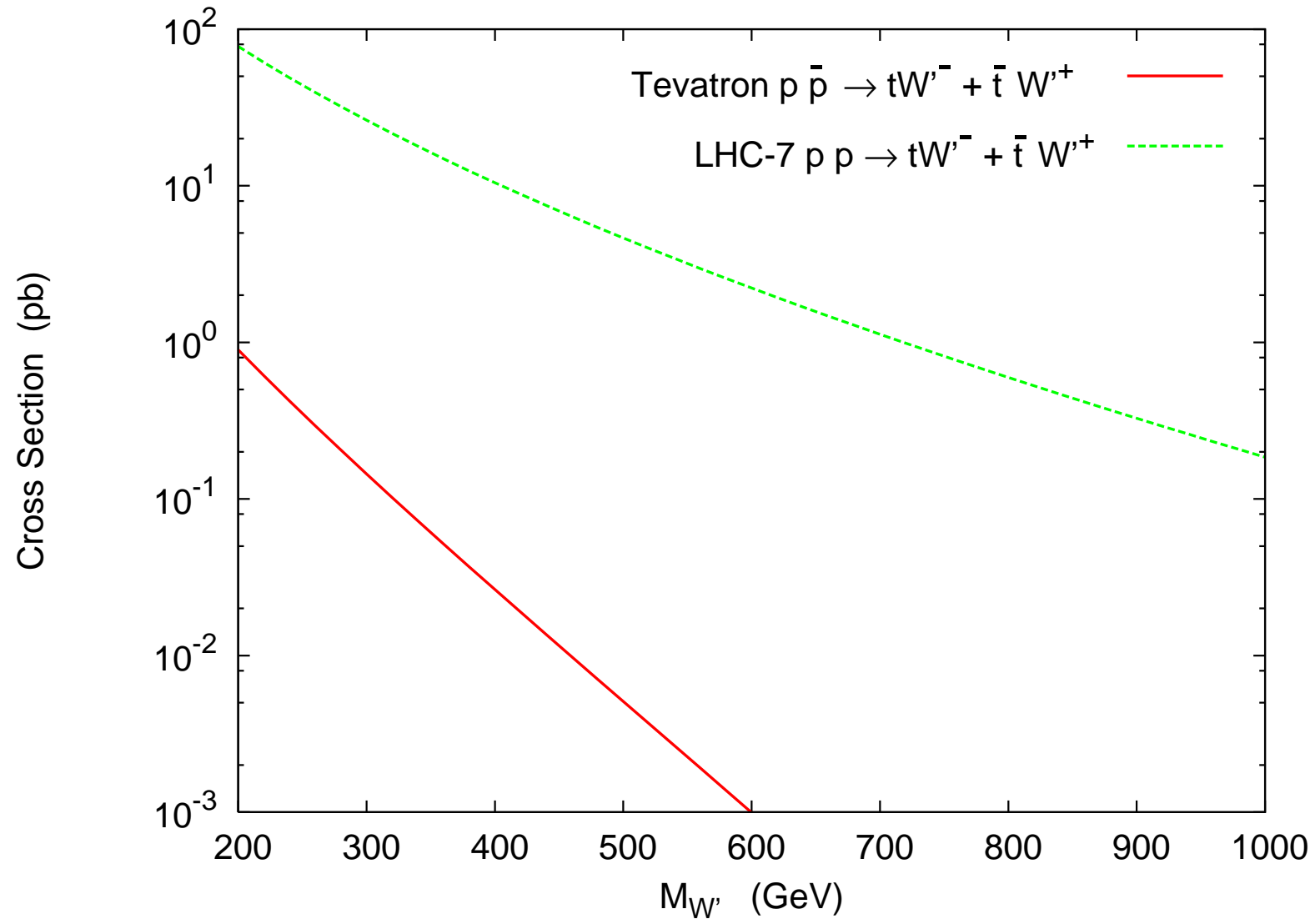
$$gd \rightarrow tW'^-, \quad g\bar{d} \rightarrow \bar{t}W'^+$$

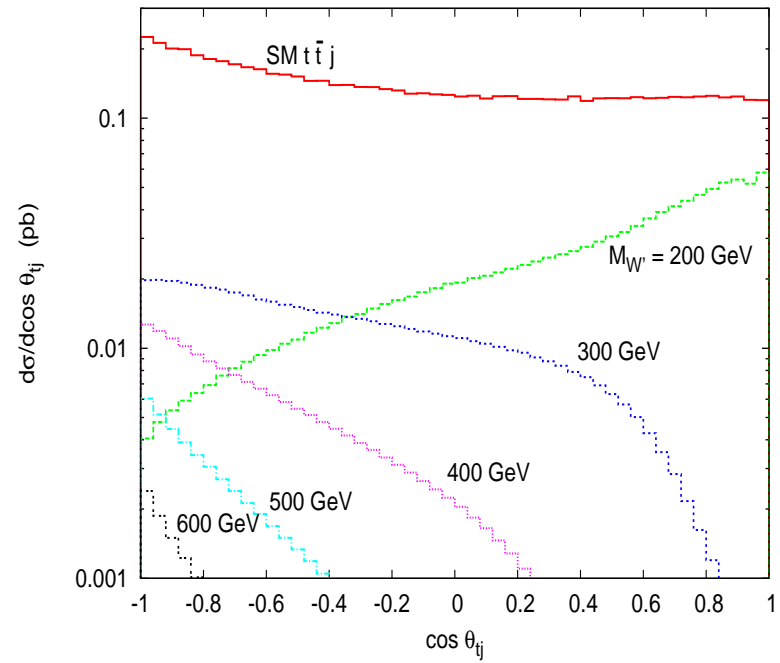
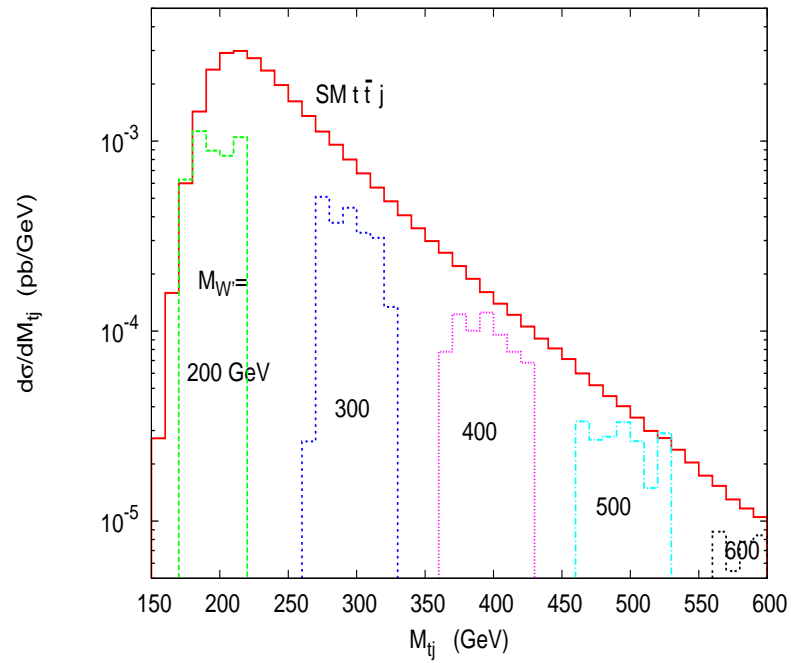
- The  $W'$  decays 100% back into  $t\bar{d}$  or  $\bar{t}d$ . So we reconstruct the invariant mass of one of the top and the jet, it will be right at the  $W'$  mass.
- In the final state, we require to see one hadronic top and one semileptonic top, plus 1 jet. Kinematic cuts for Tevatron (LHC):

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

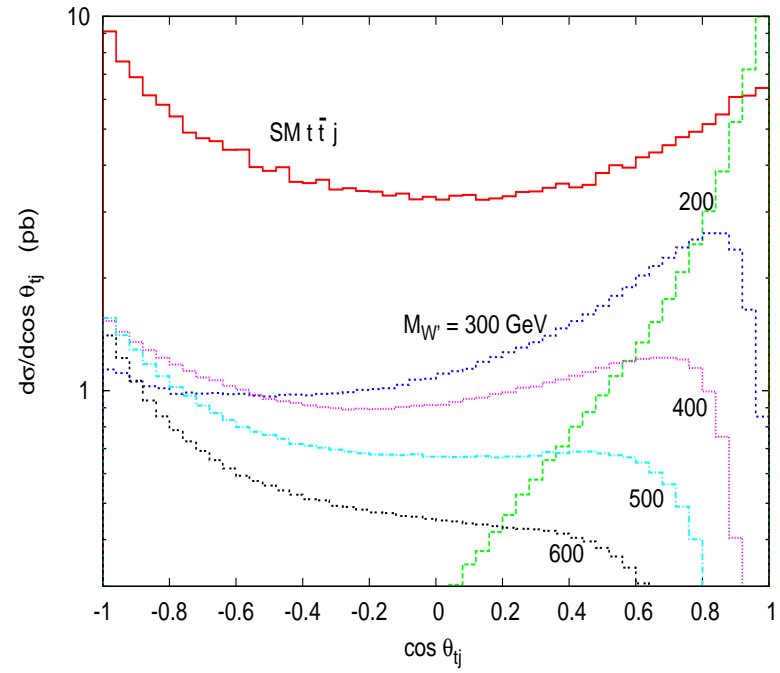
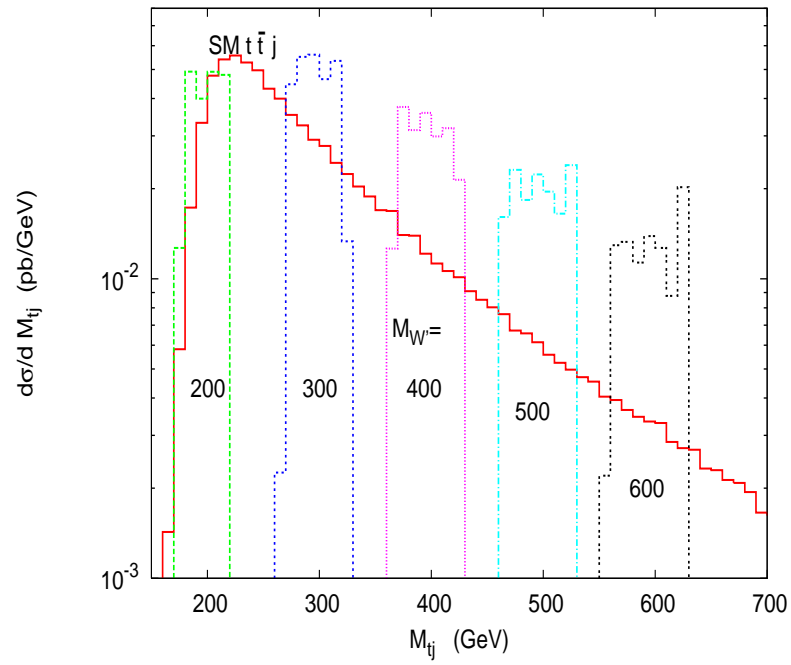
$$p_{T_j} > 15 \text{ (20) GeV}, \quad |\eta_j| < 2 \text{ (2.5)}$$

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





Tevatron



LHC

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

$M_{W'}$ (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 ( $100 \text{ pb}^{-1}$  and  $1000 \text{ pb}^{-1}$ )

$M_{W'}$ (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)

## Conclusions

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- 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  $\Delta y$  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 Tevatron and LHC. Tevatron can observe up to 400 GeV with  $10 \text{ fb}^{-1}$  while the LHC can observe all the way.