The Forward-Backward Asymmetry in Top Quark Pair Production

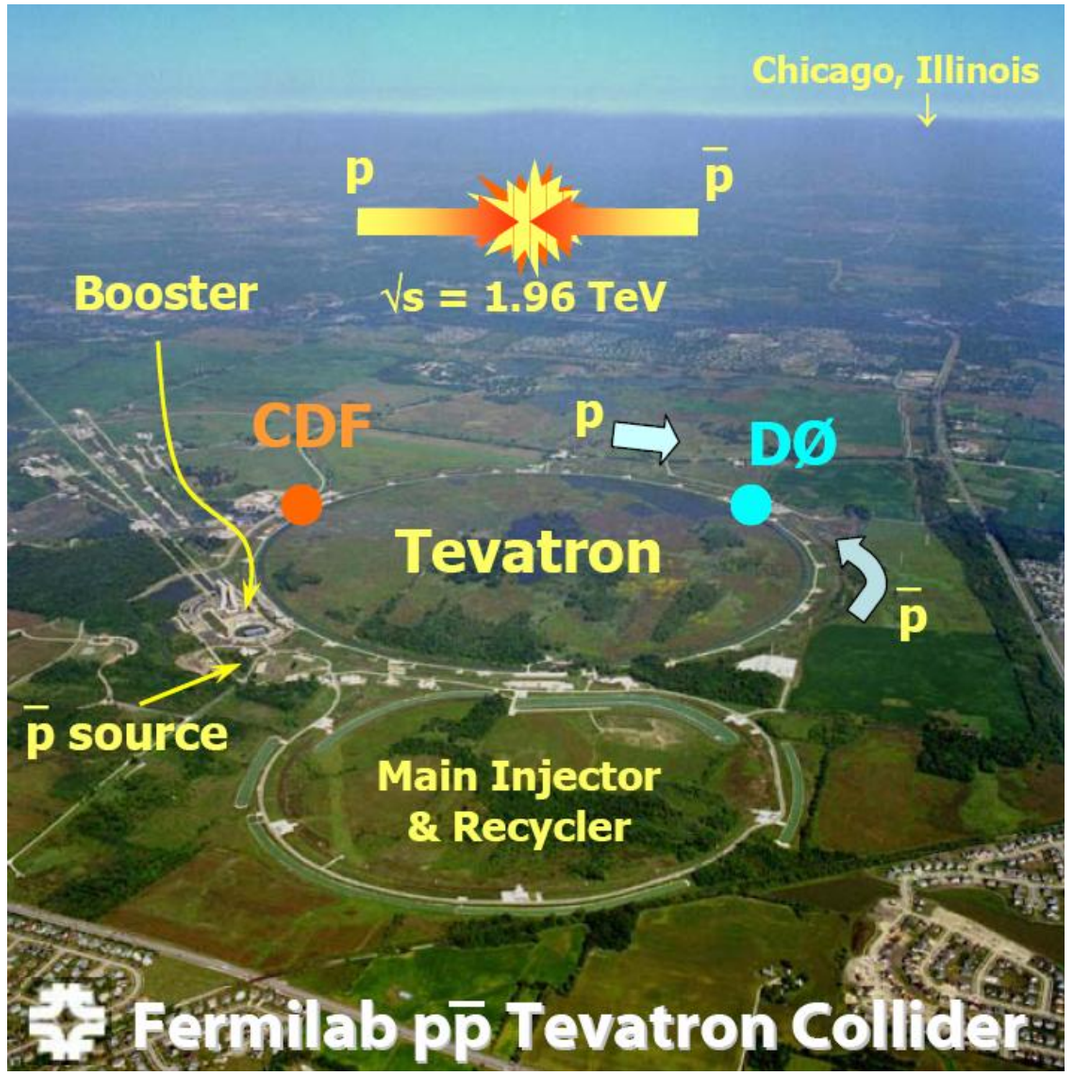
Bryan Webber
Cavendish Laboratory
University of Cambridge

Outline

- Top quark production at Tevatron and LHC
- Standard Model predictions
- Tevatron data
- LHC data and prospects
- Conclusions

Top Production at Tevatron

- $p\bar{p}$ at 1.96 TeV
- CDF & D0
- ~5 fb^{-1}/expt
- $\sigma_{t\bar{t}}$~8 pb



➡ 40,000 $t\bar{t}$

$$t \to Wb$$

$$W \to e\nu_e, \mu\nu_\mu \to l + \not{E}$$

$$(W \to \tau\nu_\tau)$$

$$W \to u\bar{d}, c\bar{s} \to jj$$

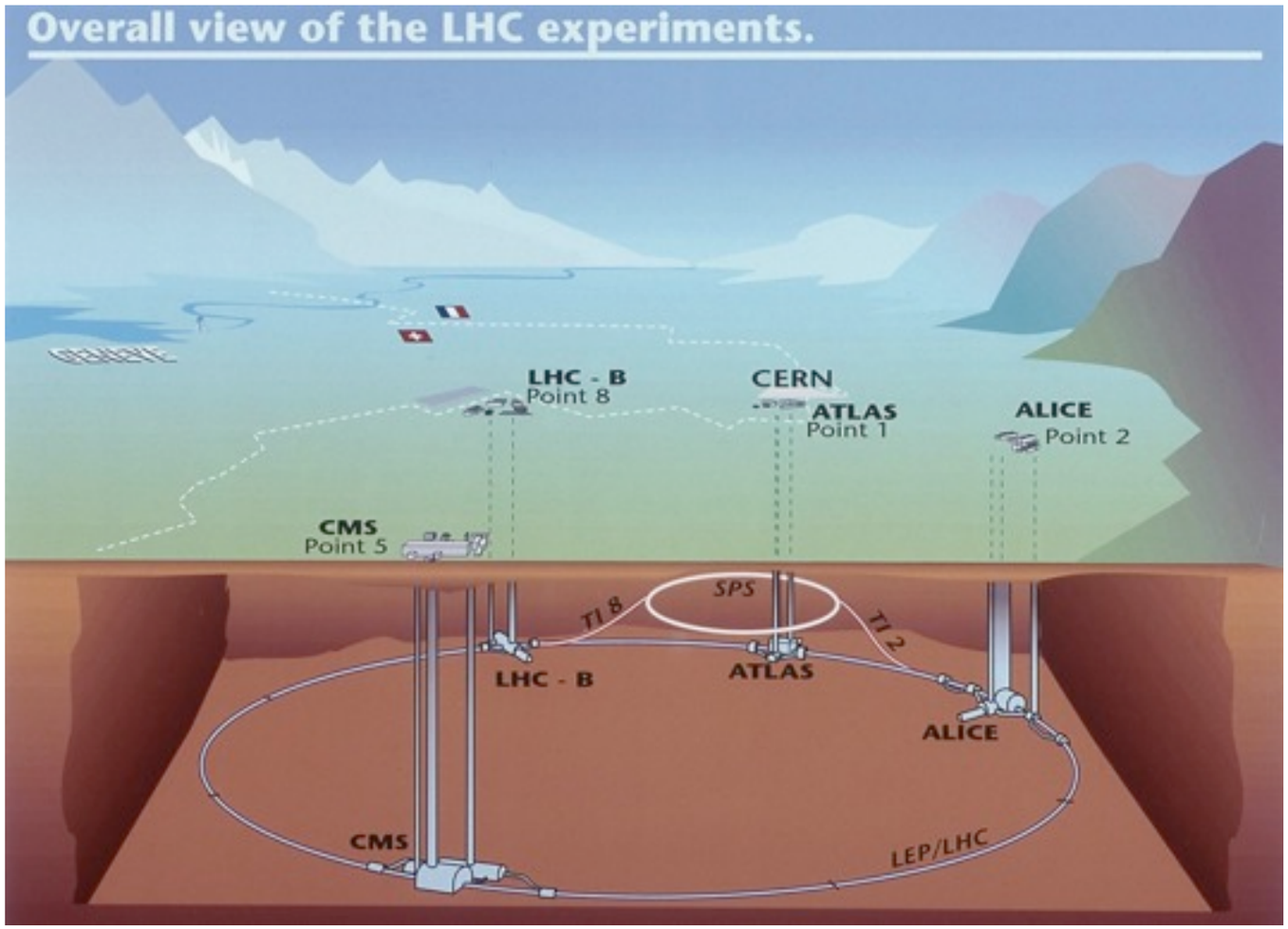
➡ $t\bar{t} \to b\bar{b}l\bar{l} + \not{E}\,(5\%),\ t\bar{t} \to b\bar{b}ljj + \not{E}\,(30\%)$

Top Production at LHC

- pp at 7 TeV
- ATLAS & CMS
- ~2.5 fb^{-1}/expt
- $\sigma_{t\bar{t}}$~160 pb

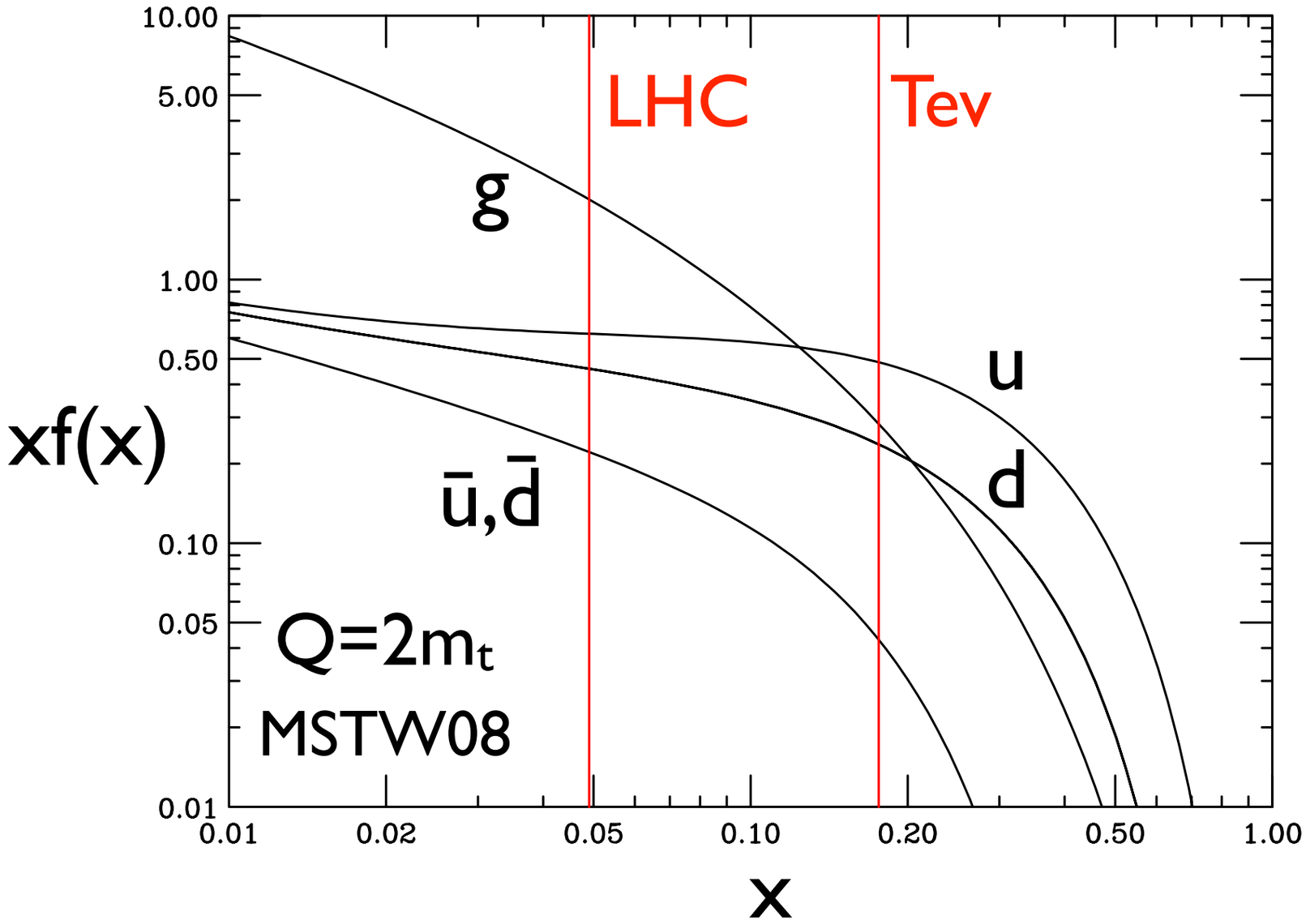
→ 400,000 $\bar{t}t$

- Expect >5 fb^{-1} this run (2012)



But dominated by gg rather than $q\bar{q}$ collisions

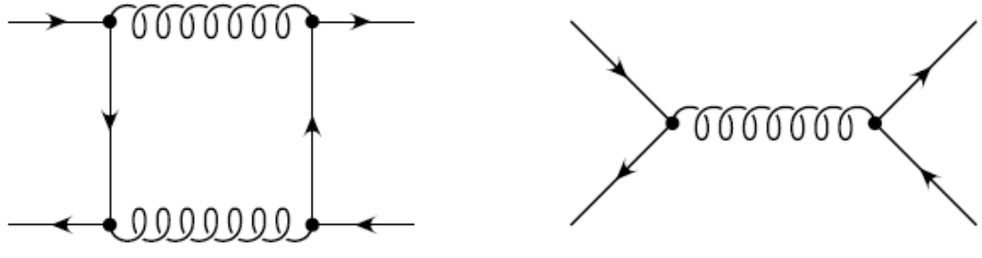
Parton distributions



- uū→tt̄ dominates at Tevatron, gg→tt̄ at LHC

Standard Model prediction

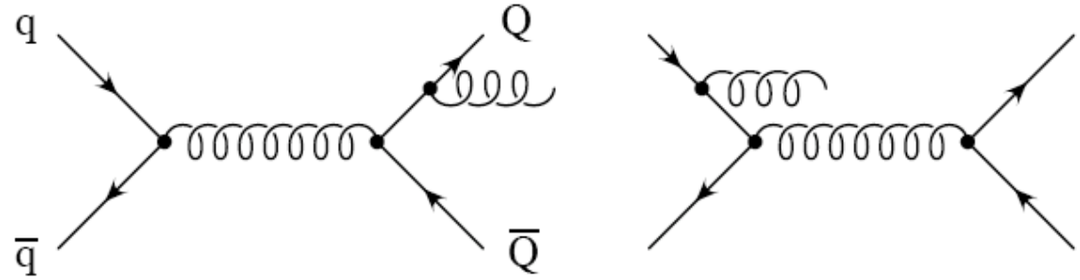
- Only $q\bar{q}$ asymmetric
- NLO effect ~5% at parton level



$A^{t\bar{t}} > 0$ dominant (low $p_T^{t\bar{t}}$)

- t prefers q direction

$$y \equiv \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

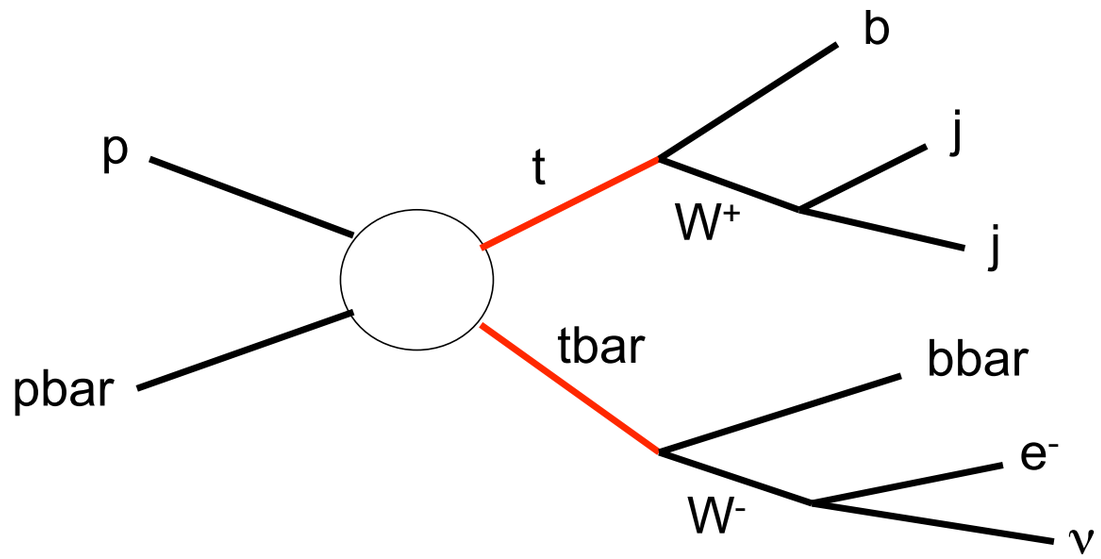


$A^{t\bar{t}} < 0$ if extra jet or high $p_T^{t\bar{t}}$

➡ Expect $y_t > y_{\bar{t}}$

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

Lepton+jets mode



- CDF: 1260 events, i.e. ~10% acceptance
- Acceptance/selection cuts reduce asymmetry
  - Lepton and at least 4 jets (inc. 1 b-jet) with $p_T > 20\,\mathrm{GeV/c}\,,\ \ |\eta| < 2\ \ (|\eta|_b < 1)$
  - Missing $E_T \geq 20\,\mathrm{GeV}$
- Simulate SM with MC@NLO event generator

MC@NLO matching

finite virtual

divergent

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \left[B\left(\Phi_B\right) + V\left(\Phi_B\right) - \int \sum_i C_i\left(\Phi_B, \Phi_R\right) \mathrm{d}\Phi_R\right] \mathrm{d}\Phi_B + R\left(\Phi_B, \Phi_R\right) \mathrm{d}\Phi_B \, \mathrm{d}\Phi_R$$

$$\equiv \left[B + V - \int C \, \mathrm{d}\Phi_R\right] \mathrm{d}\Phi_B + R \, \mathrm{d}\Phi_B \, \mathrm{d}\Phi_R$$

Born phase space

Emission phase space

$$\mathrm{d}\sigma_{\mathrm{MC}} = B\left(\Phi_B\right) \mathrm{d}\Phi_B \left[\Delta_{\mathrm{MC}}\left(0\right) + \frac{R_{\mathrm{MC}}\left(\Phi_B, \Phi_R\right)}{B\left(\Phi_B\right)} \Delta_{\mathrm{MC}}\left(k_T\left(\Phi_B, \Phi_R\right)\right) \mathrm{d}\Phi_R\right]$$

$$\equiv B \, \mathrm{d}\Phi_B \left[\Delta_{\mathrm{MC}}\left(0\right) + \left(R_{\mathrm{MC}}/B\right) \Delta_{\mathrm{MC}}\left(k_T\right) \mathrm{d}\Phi_R\right]$$

Sudakov form factor
(no-emission probability)

$$\mathrm{d}\sigma_{\mathrm{MC@NLO}} = \left[B + V + \int \left(R_{\mathrm{MC}} - C\right) \mathrm{d}\Phi_R\right] \mathrm{d}\Phi_B \left[\Delta_{\mathrm{MC}}\left(0\right) + \left(R_{\mathrm{MC}}/B\right) \Delta_{\mathrm{MC}}\left(k_T\right) \mathrm{d}\Phi_R\right]$$

$$+ \left(R - R_{\mathrm{MC}}\right) \Delta_{\mathrm{MC}}\left(k_T\right) \mathrm{d}\Phi_B \, \mathrm{d}\Phi_R$$

finite

MC starting from no emission

MC starting from one emission

- Expanding gives NLO result

S Frixione & BW, JHEP 06(2002)029
S Frixione, P Nason & BW, JHEP 08(2003)007

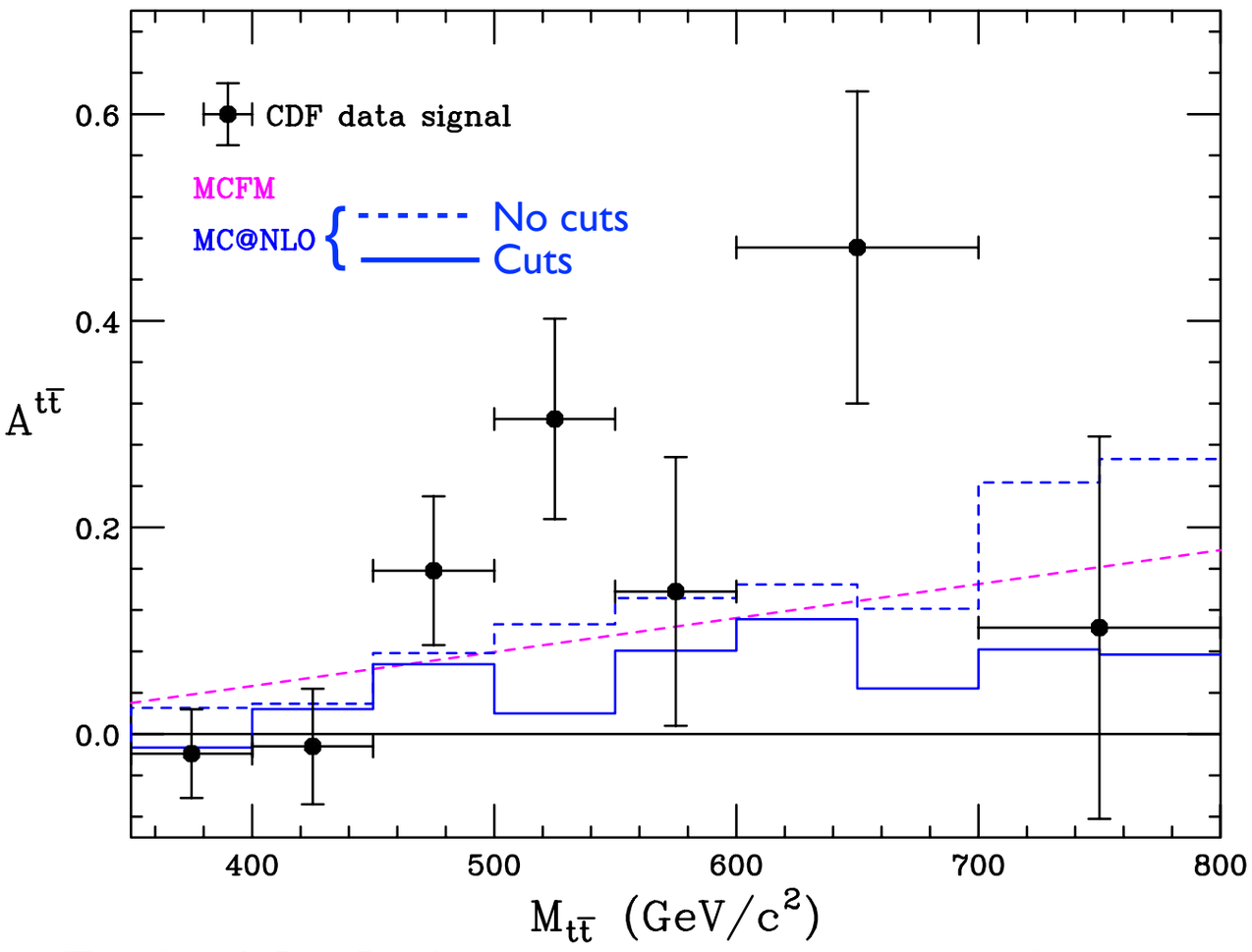
CDF Results

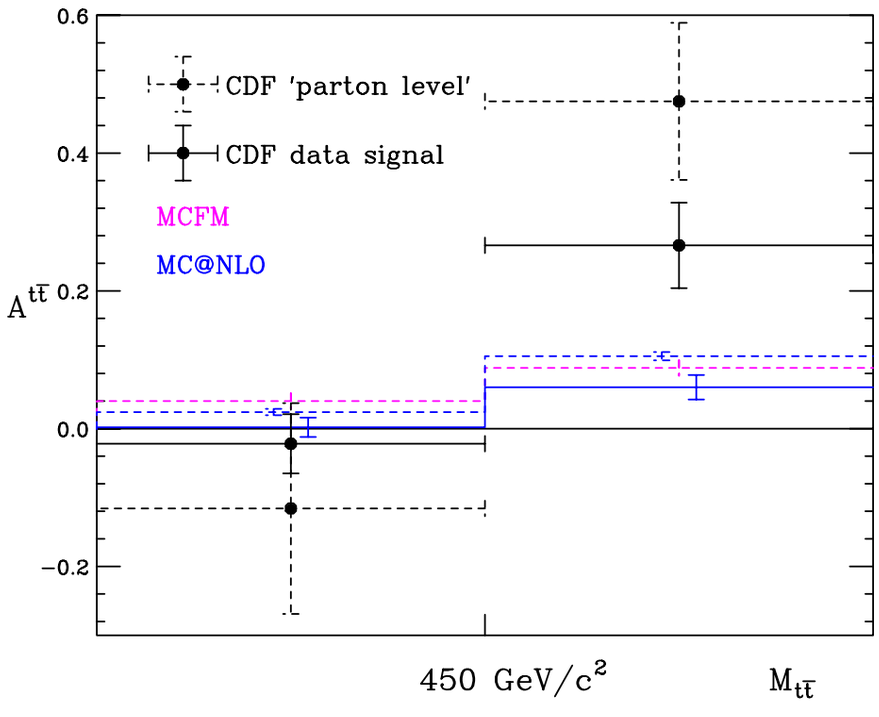
arXiv:1101.0034

- CDF reports a large effect, increasing with $t\bar{t}$ invariant mass
- SM predicts a smaller NLO effect
- MC@NLO and MCFM in good agreement

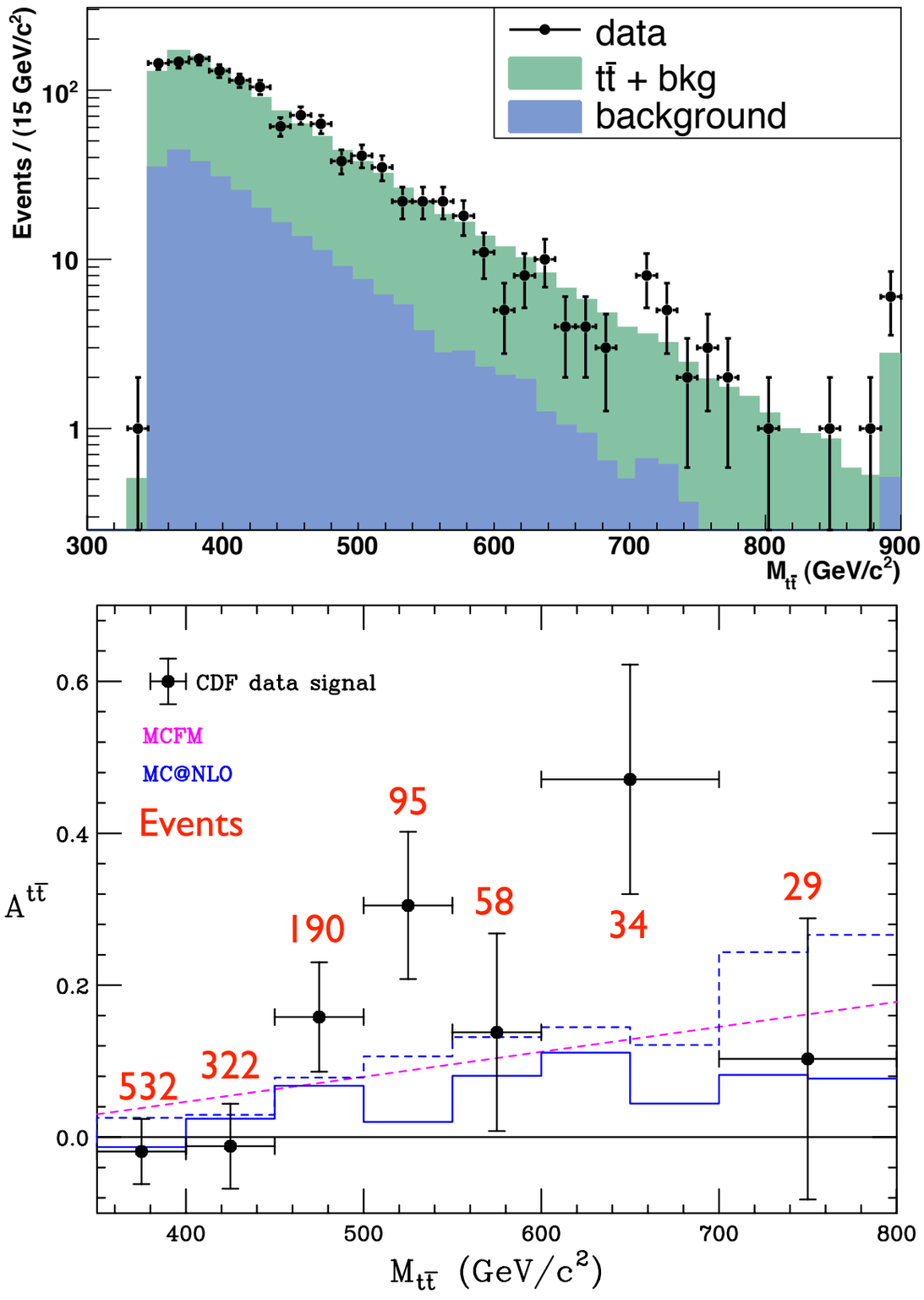
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y_t - y_{\bar{t}} \ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$





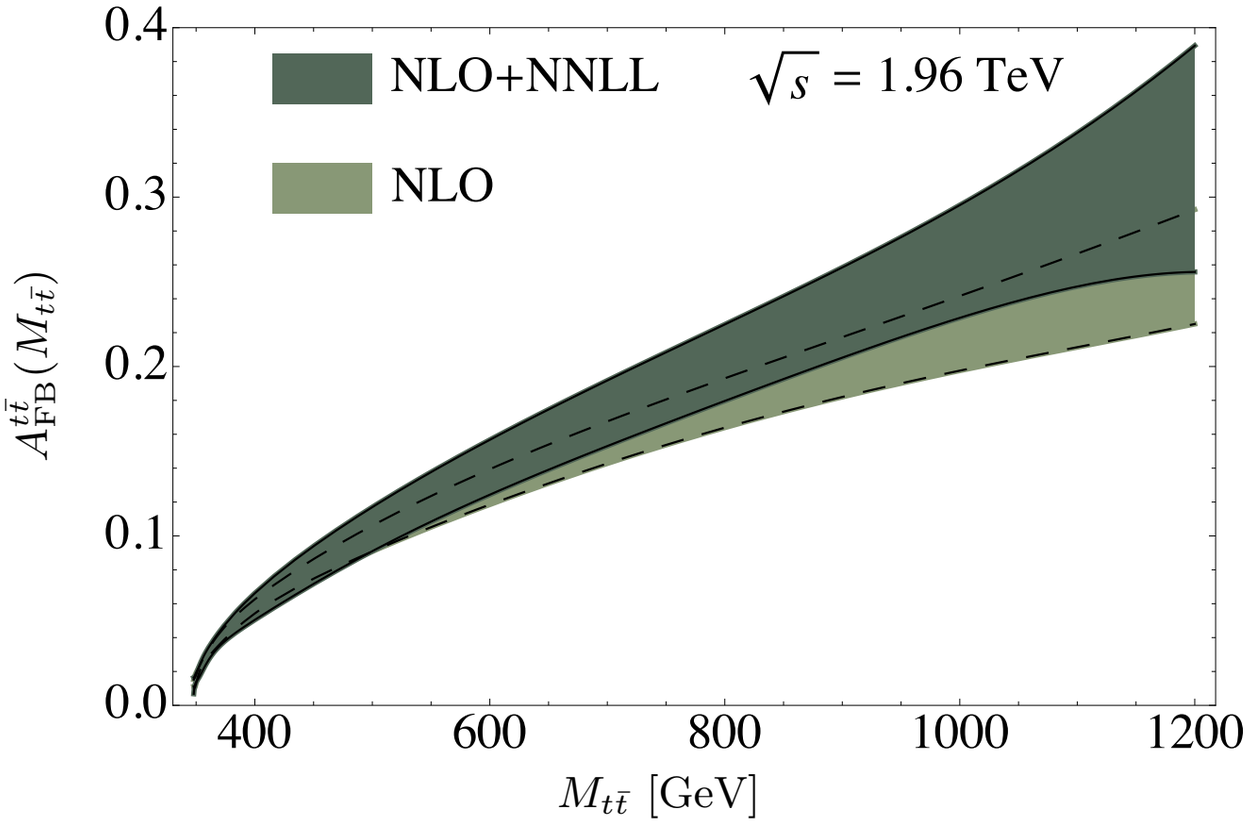
$t\bar{t}$ invariant mass distribution

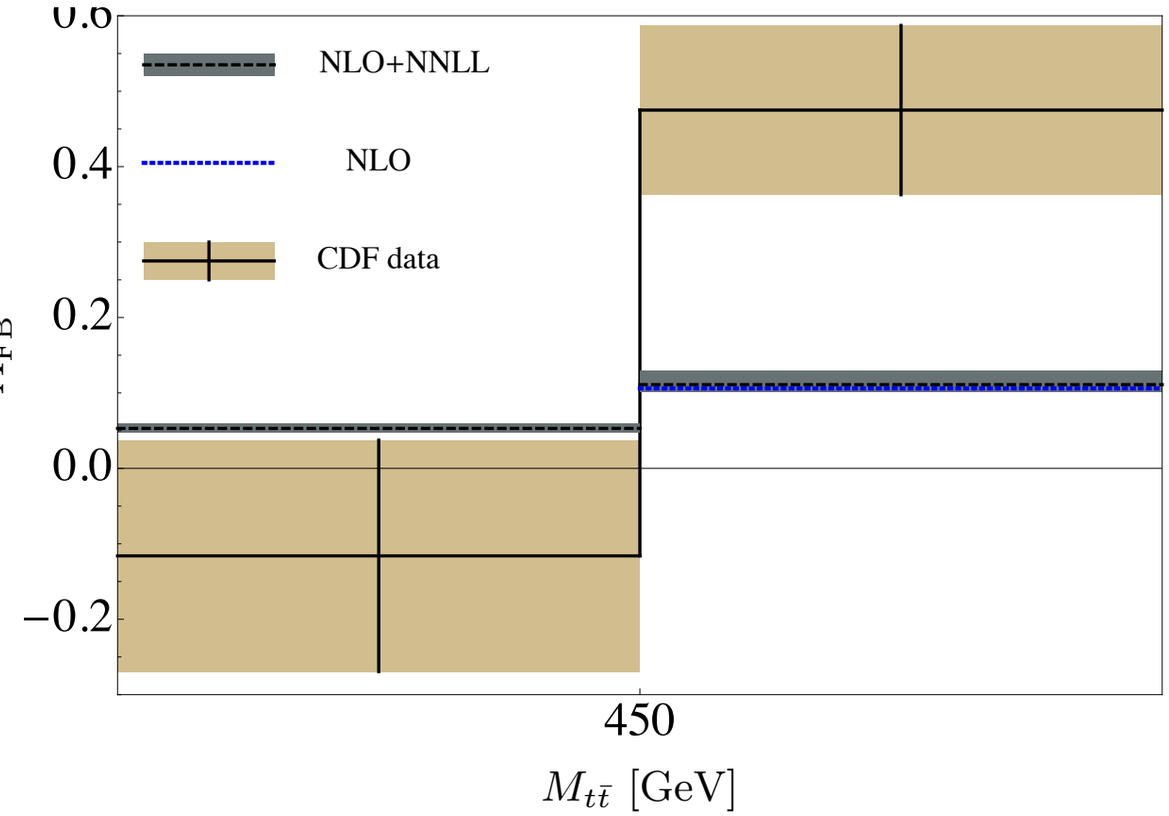


- No sign of bumps or other anomalies
- 2/3 of events below $M_{t\bar{t}}$ = 450 GeV
- 10% disagree with SM
- Claim 3.4 st.dev. above SM at $M_{t\bar{t}}$ > 450 GeV

NLO+NNLL Prediction

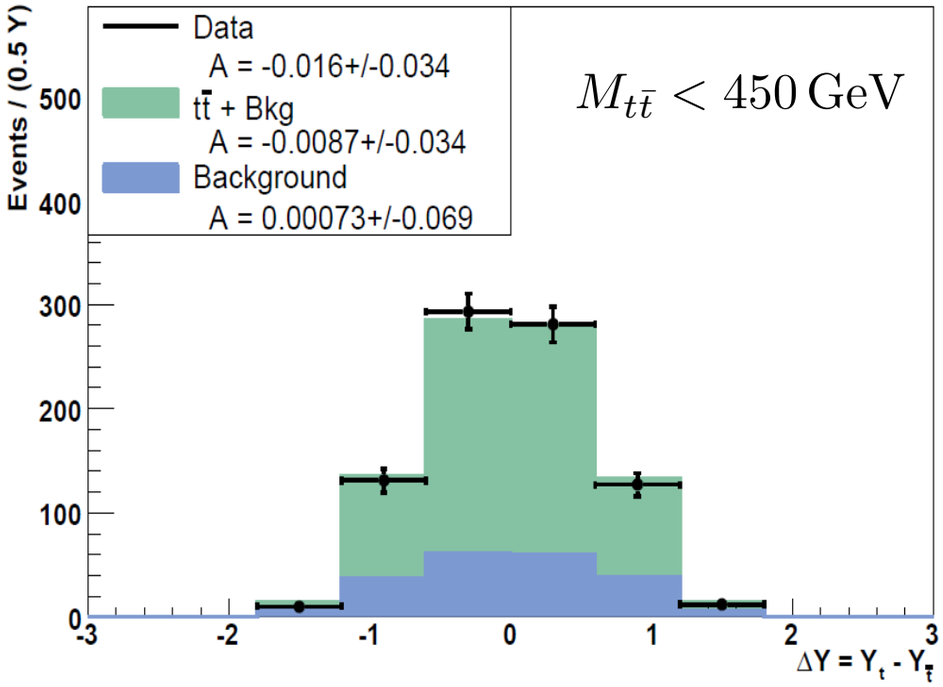
Ahrens, Ferroglia, Neubert, Pecjak, Yang, arXiv:1106.6051

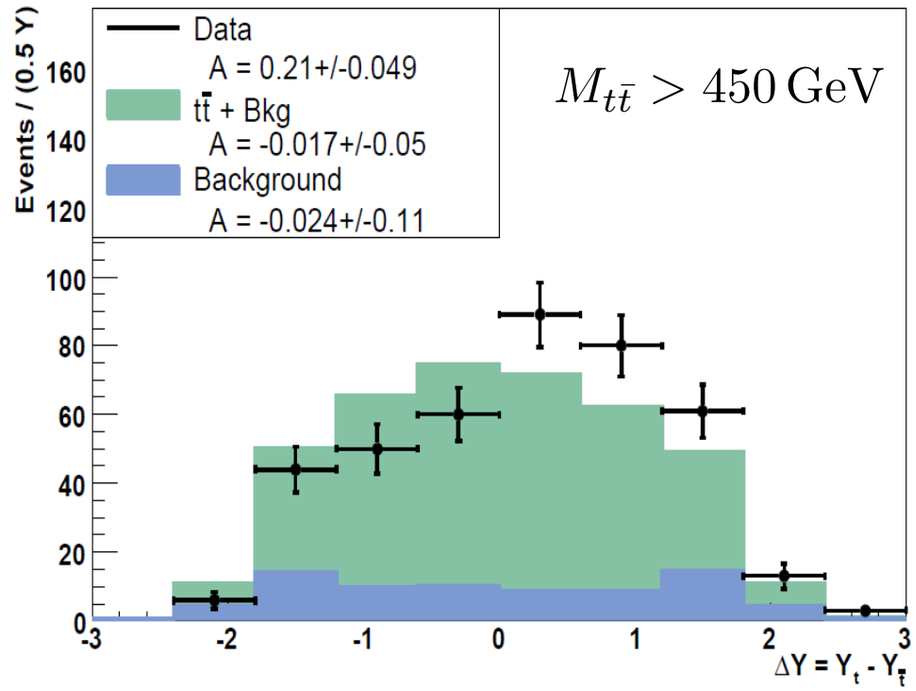




- Stable w.r.t. soft gluon resummation
- Could still be hard NNLO effects

CDF data: low vs high mass

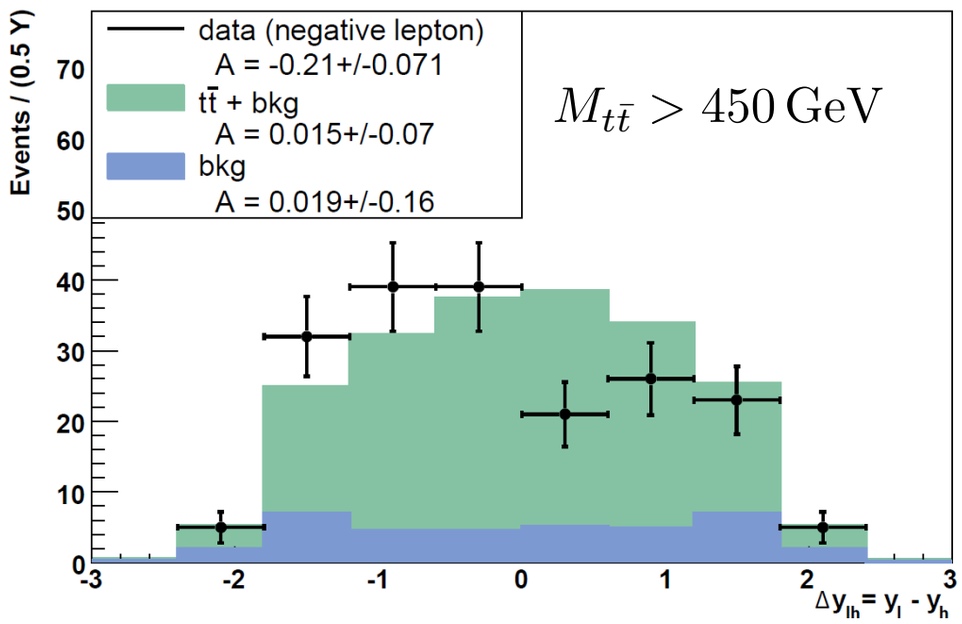


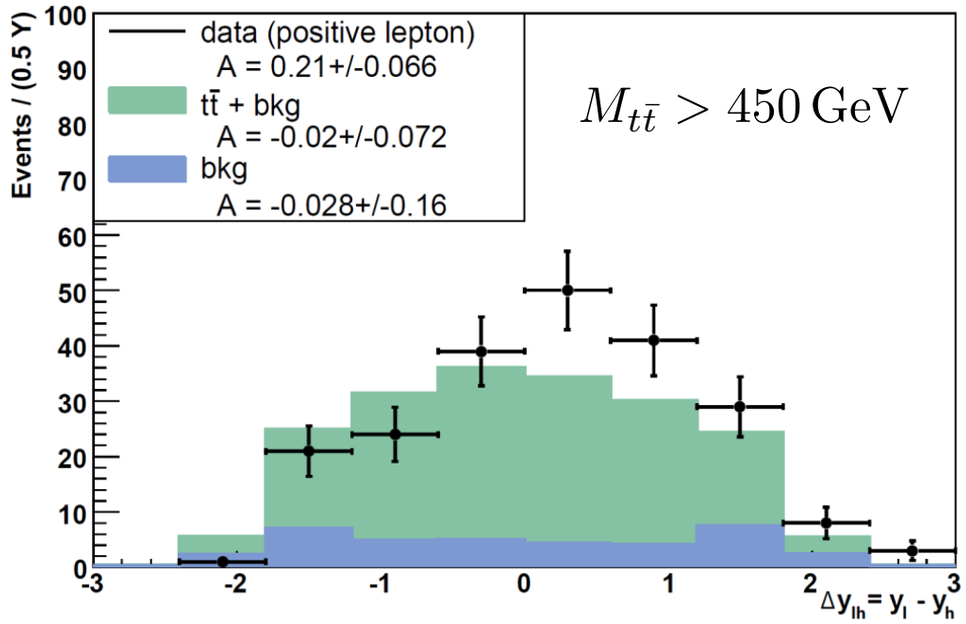


selection	all M	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
reco data	0.057±0.028	-0.016±0.034	0.212±0.049
MC@NLO	0.017±0.004	0.012±0.006	0.030±0.007

- No significant asymmetry below $M_{t\bar{t}} = 450$ GeV

CDF data: lepton charge

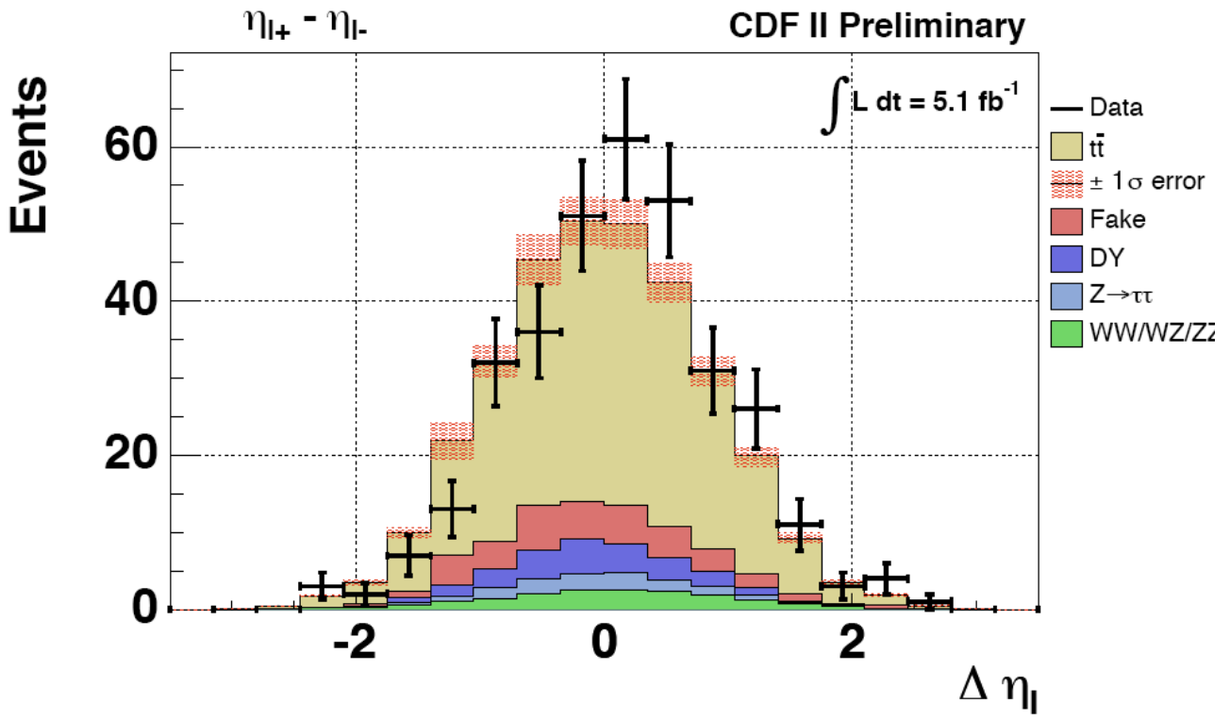


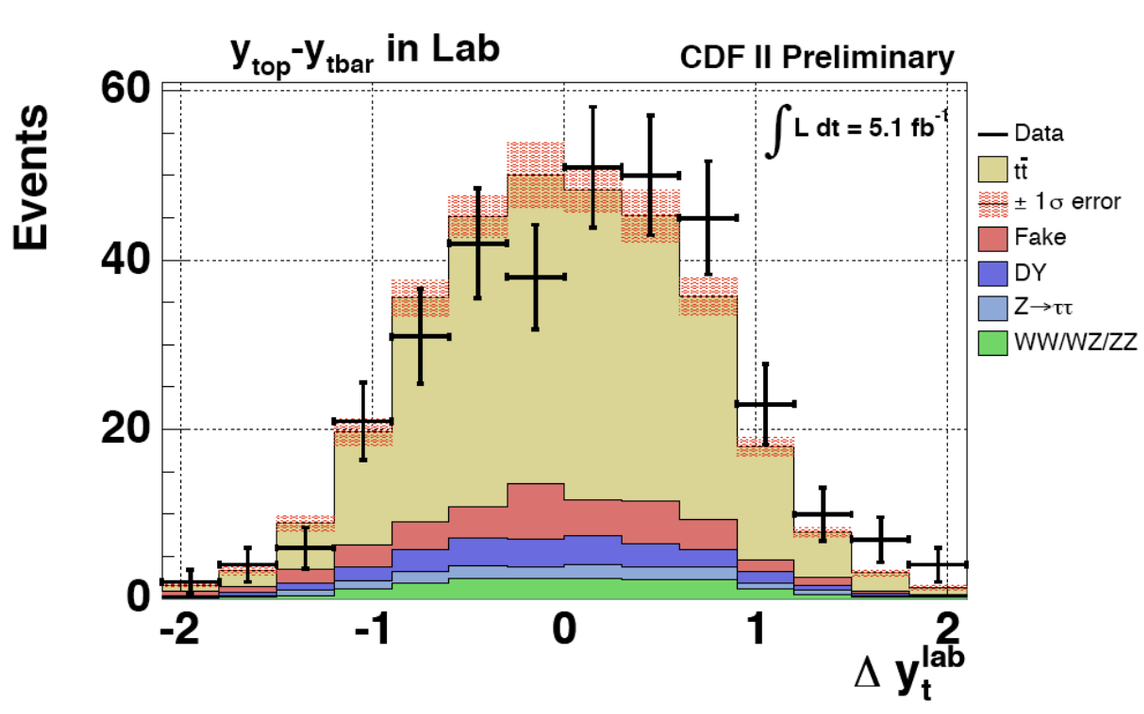


selection	all M	$M < 450\ \mathrm{GeV}/c^2$	$M \geq 450\ \mathrm{GeV}/c^2$
A_{lh}^{+}	0.067±0.040	-0.013±0.050	0.210±0.066
A_{lh}^{-}	-0.048±0.039	0.020±0.047	-0.210±0.071

- Independent data sets are consistent

Dilepton decay mode





$$A_{obs}^{\Delta\eta_l} = 0.138 \pm 0.054$$
$$A_{pred}^{\Delta\eta_l} = -0.022 \pm 0.022$$

$$A_{obs}^{\Delta y_t} = 0.138 \pm 0.054$$
$$A_{pred}^{\Delta\eta_l} = -0.015 \pm 0.023$$

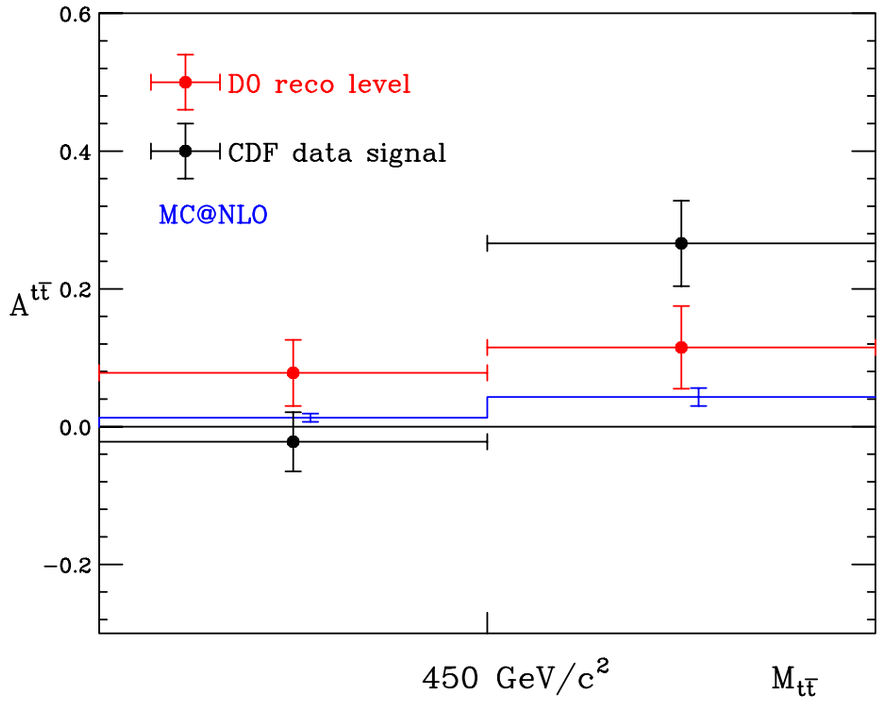
- Consistent with lepton+jets mode

D0 Results

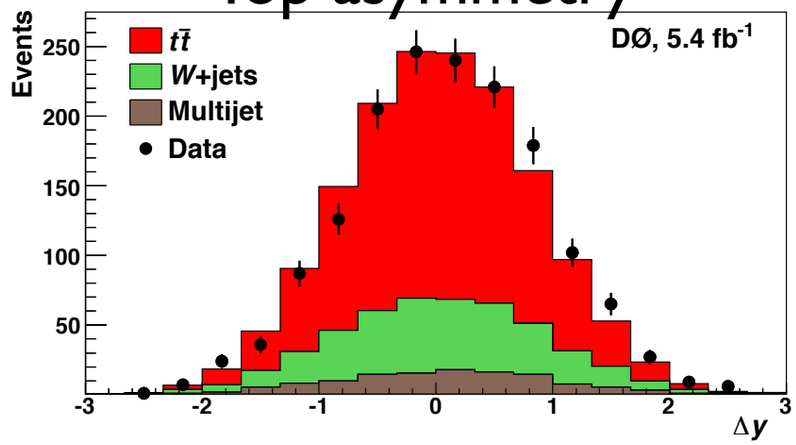
arXiv:1107.4995

TABLE IV. Δy-based asymmetries.

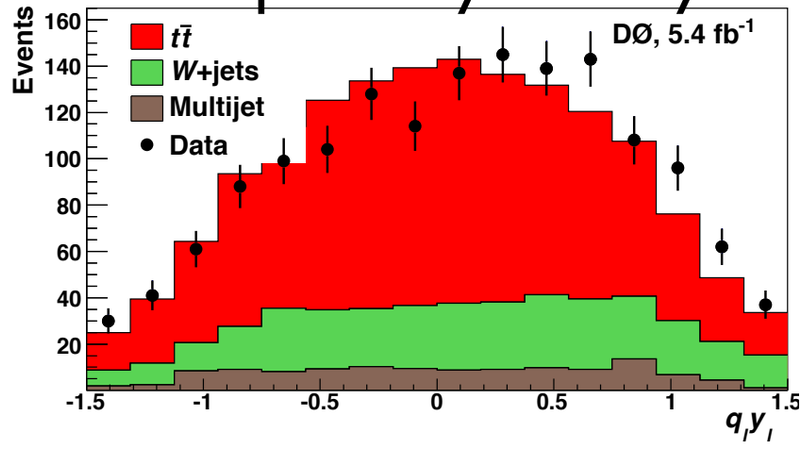
	$A_{\rm FB}$ (%)	
	Reconstruction level	Production level
Data	9.2 ± 3.7	19.6 ± 6.5
MC@NLO	2.4 ± 0.7	5.0 ± 0.1



Top asymmetry

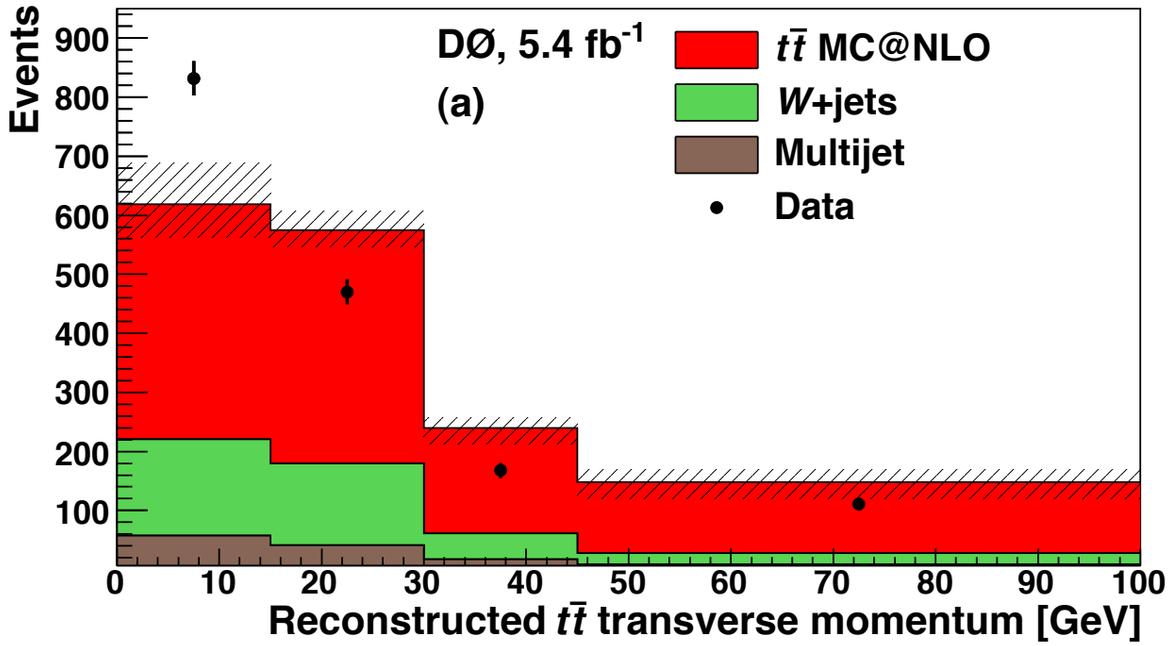


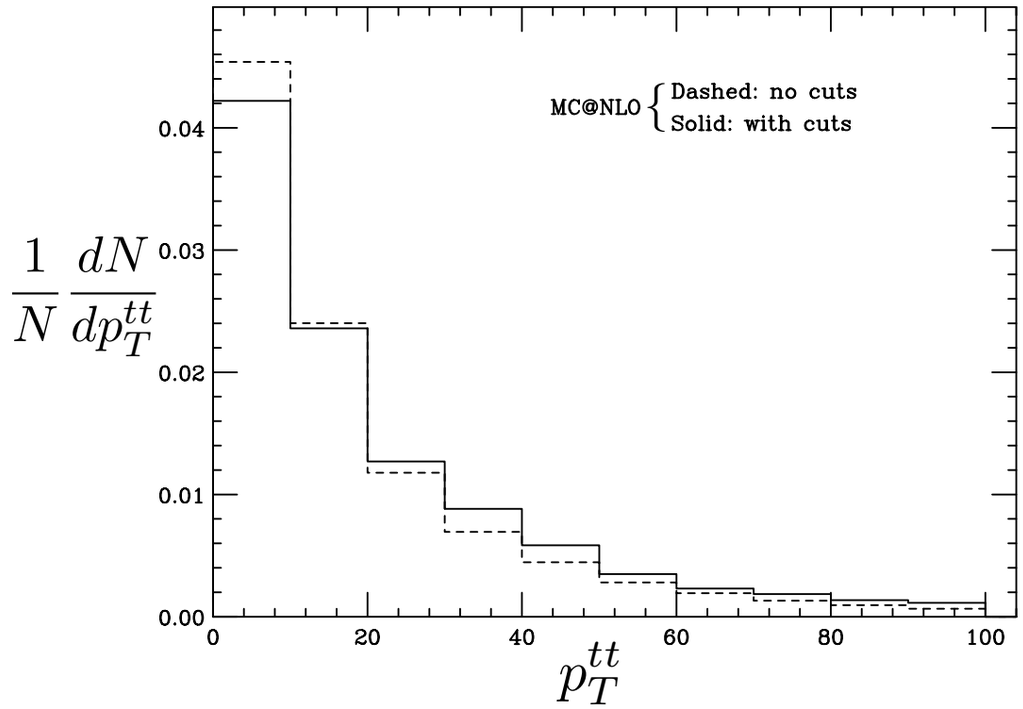
Lepton asymmetry

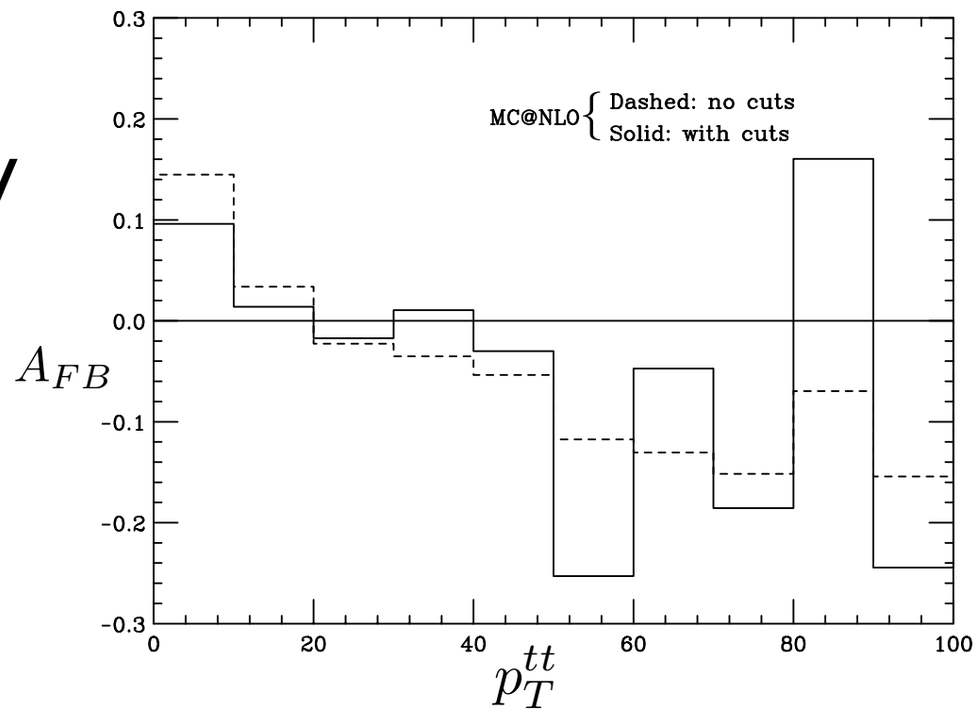


- Disagreement with SM ">3 s.d."
- CDF $M_{t\bar{t}}$ dependence not confirmed

p_T^{tt} dependence



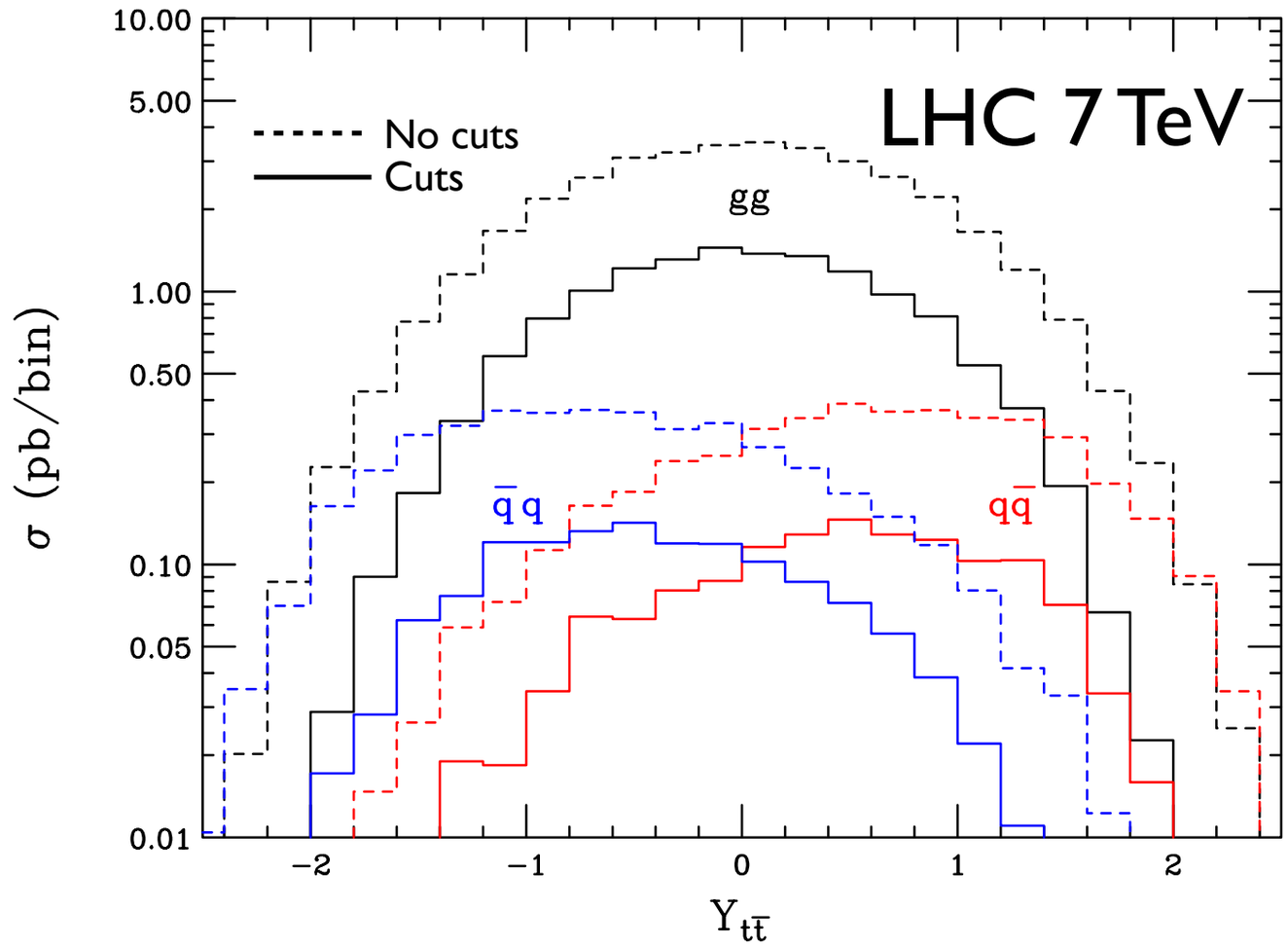




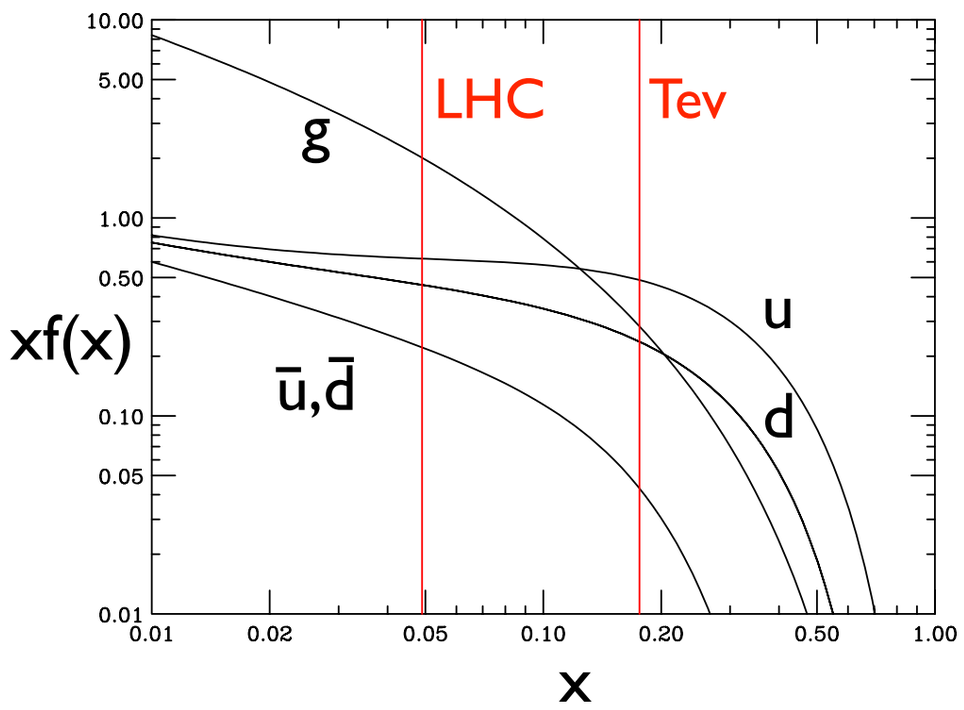
- D0 data disagree with MC@NLO
- Asymmetry changes sign at ~20 GeV
- Loss at high p_T would enhance asymmetry
- What about CDF data?

Top quark asymmetry at LHC

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- SM effect is small (plots show MC truth for 2 fb^{-1})

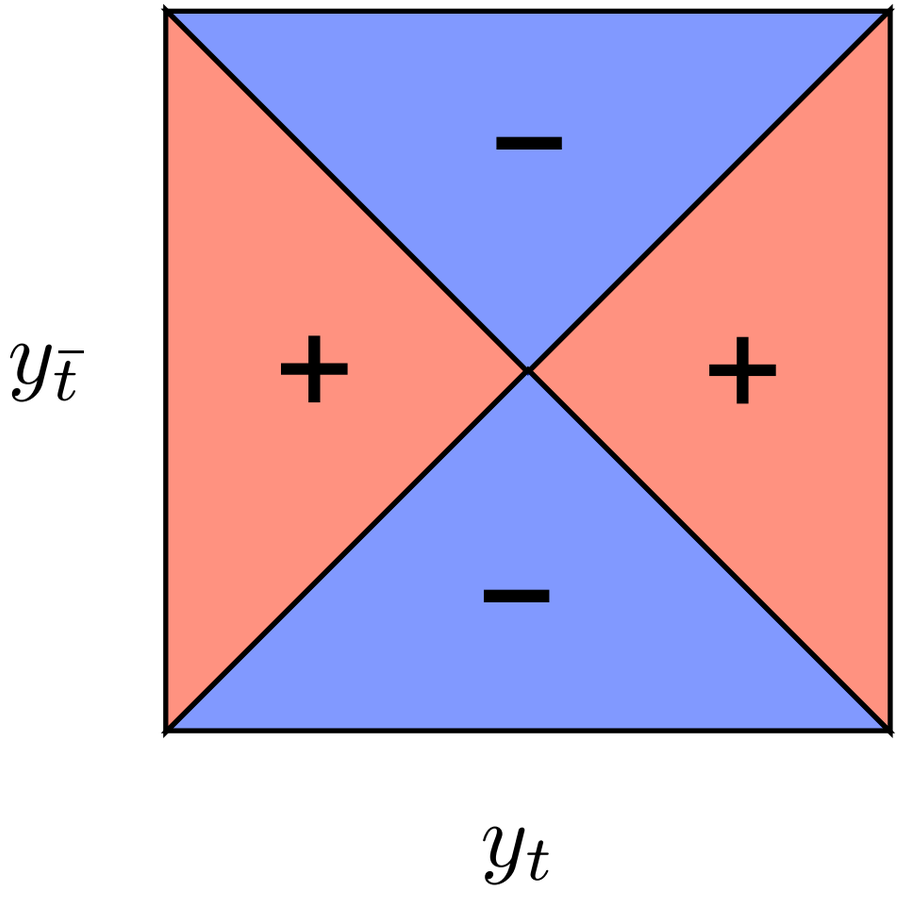


$$\Delta y = y_t - y_{\bar{t}} \ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$



Top quark asymmetry at LHC

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- Rapidity correlation should be as shown below
- Top rapidity distribution should be wider



$$\Delta y = y_t - y_{\bar{t}}\ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$

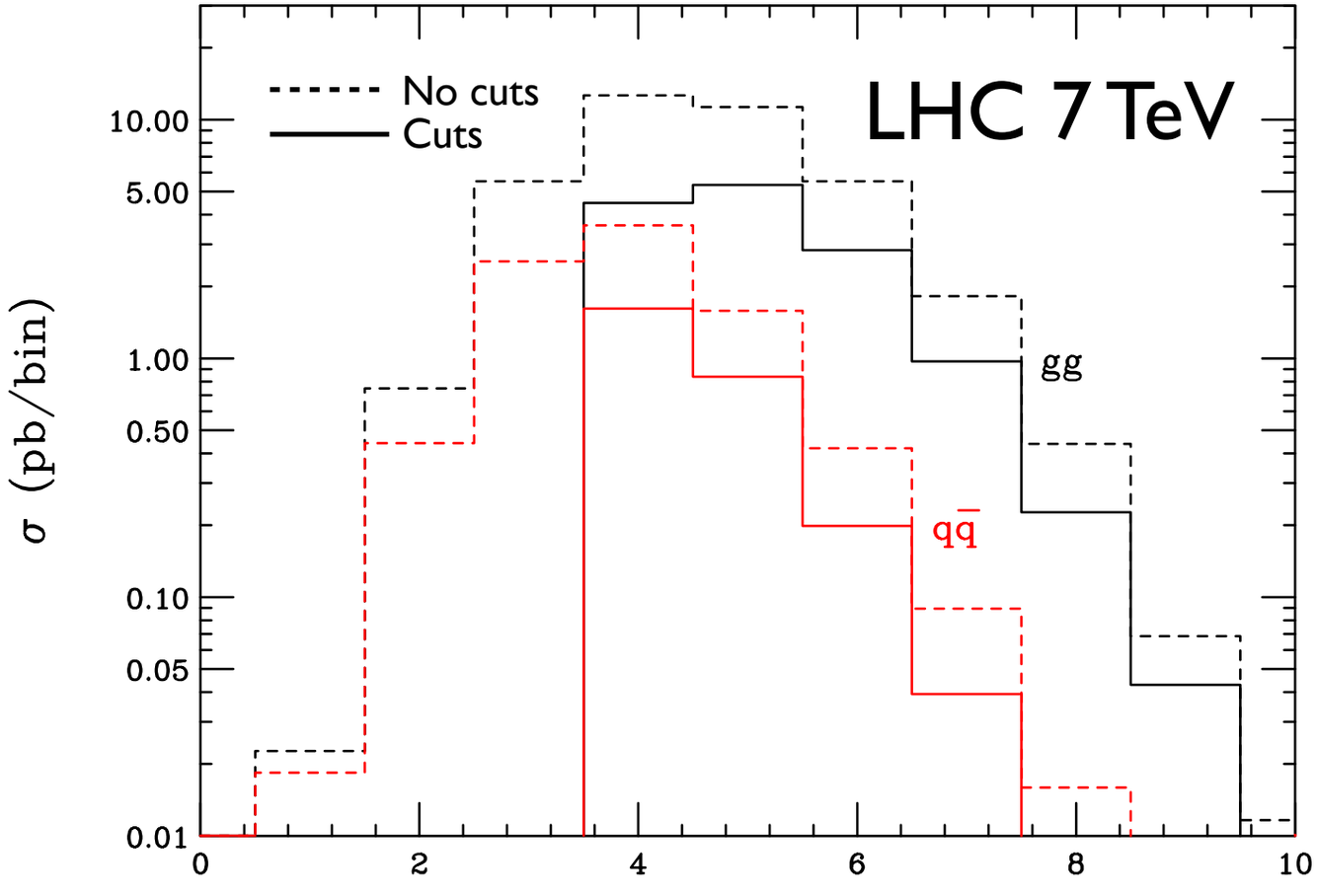
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}| > 0 \quad \Leftrightarrow \quad \Delta y \cdot Y_{t\bar{t}} > 0$$

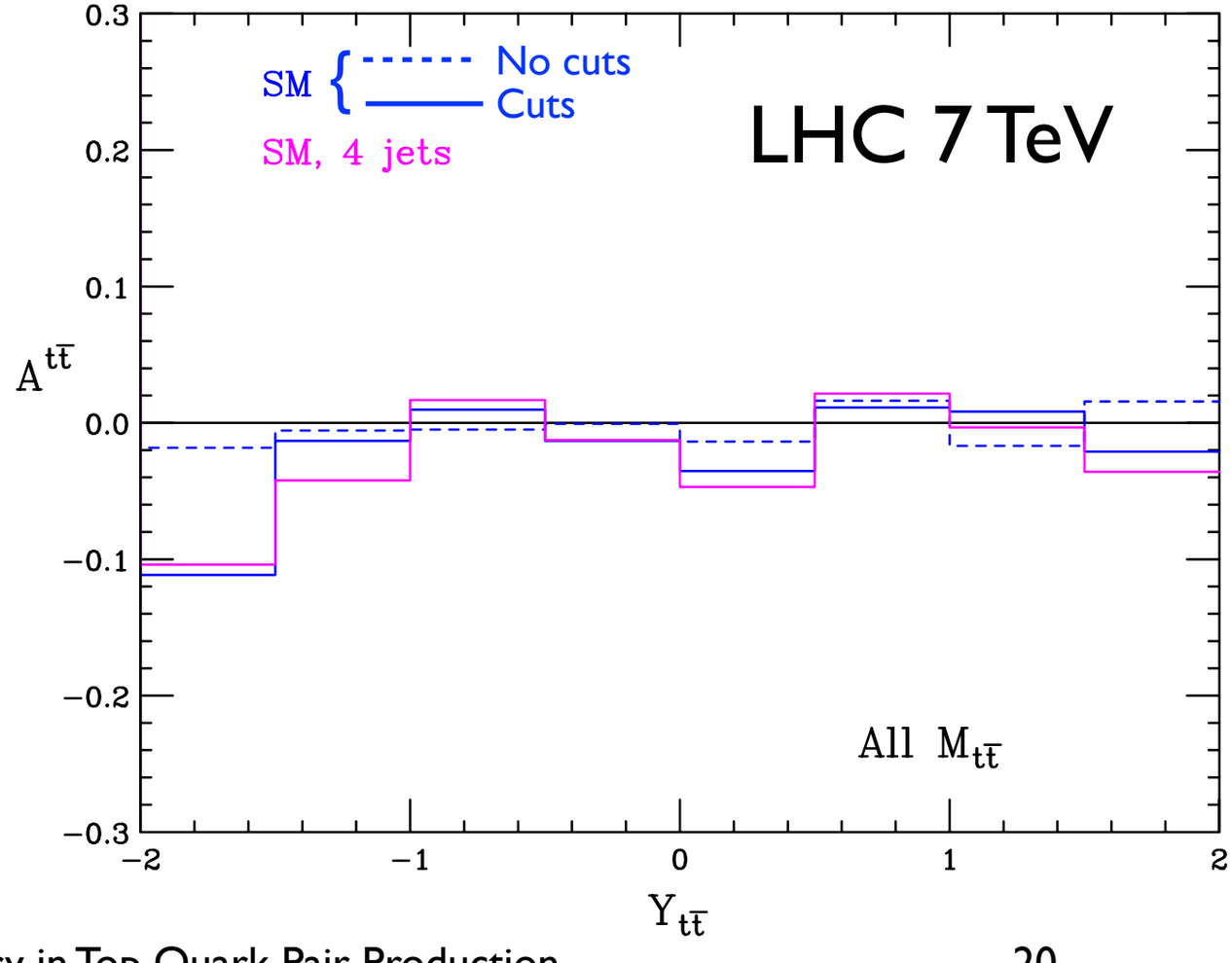
SM asymmetry at LHC

- LHC cuts assumed:
  - 1 charged lepton and at least 4 jets (inc. 2 b's) with $p_T > 20\,\mathrm{GeV/c}\,, \quad |\eta| < 2.5$
  - Missing $E_T > 20\,\mathrm{GeV}$
- 4 jet cut reduces gg contribution



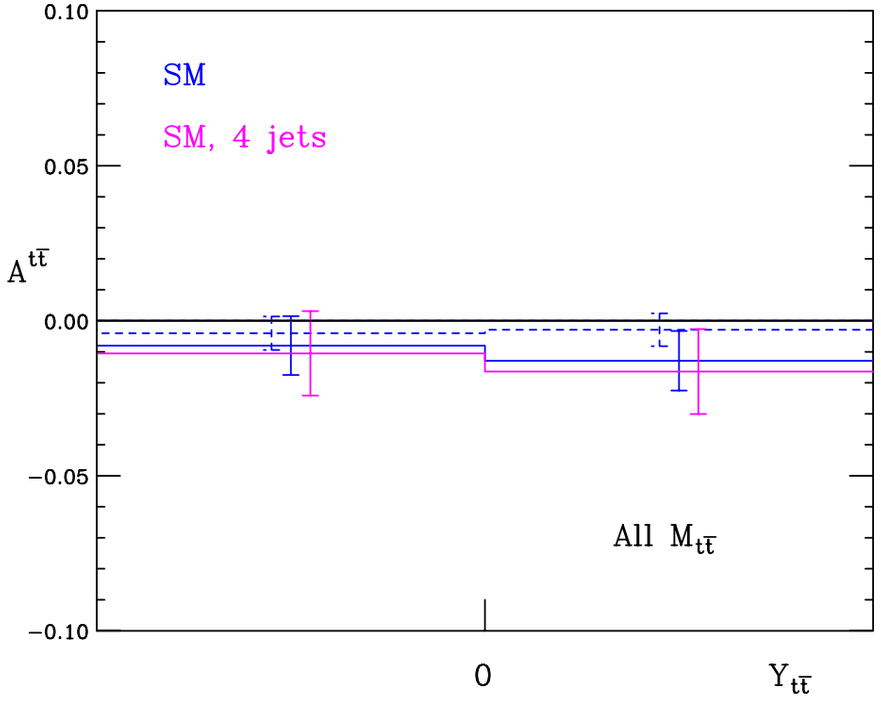
SM asymmetry at LHC

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- SM effect is small (plots show MC@NLO for 2 fb^{-1})



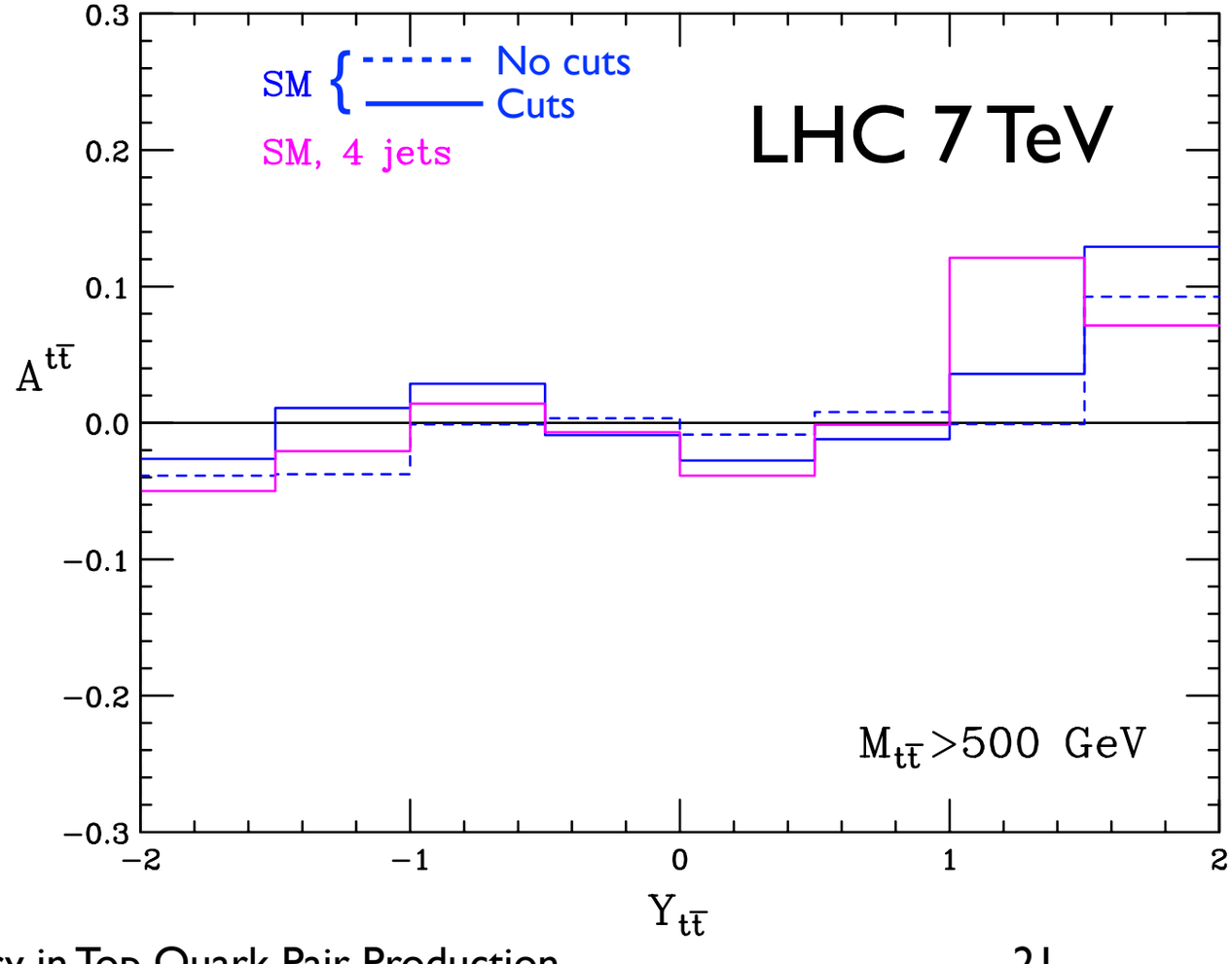
$$\Delta y = y_t - y_{\bar{t}} \ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$

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



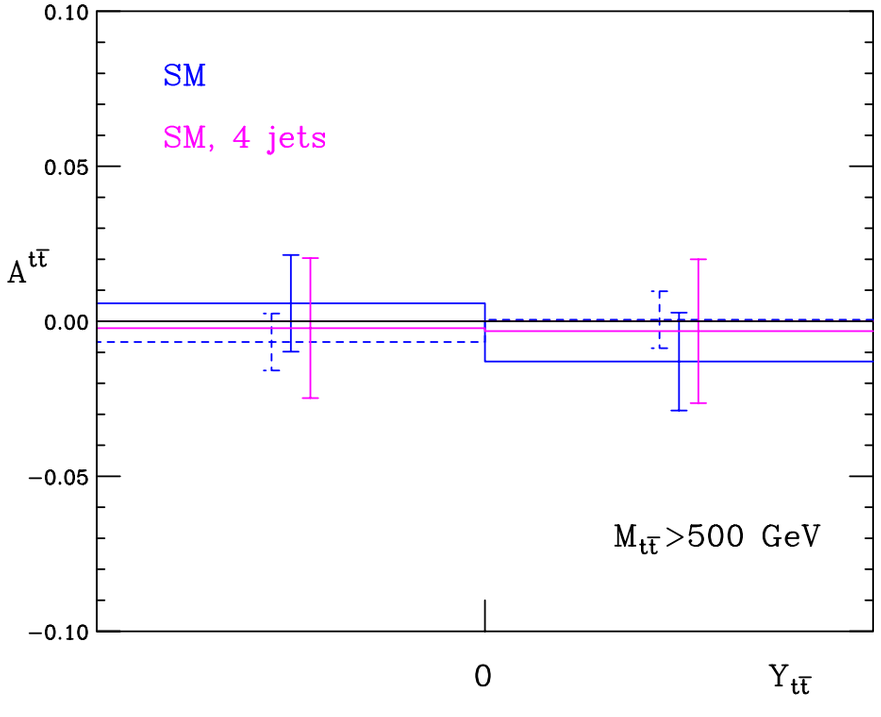
SM asymmetry at LHC

- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- SM effect enhanced by cut on $M_{t\bar{t}}$ (still insignificant)



$$\Delta y = y_t - y_{\bar{t}} \ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$

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

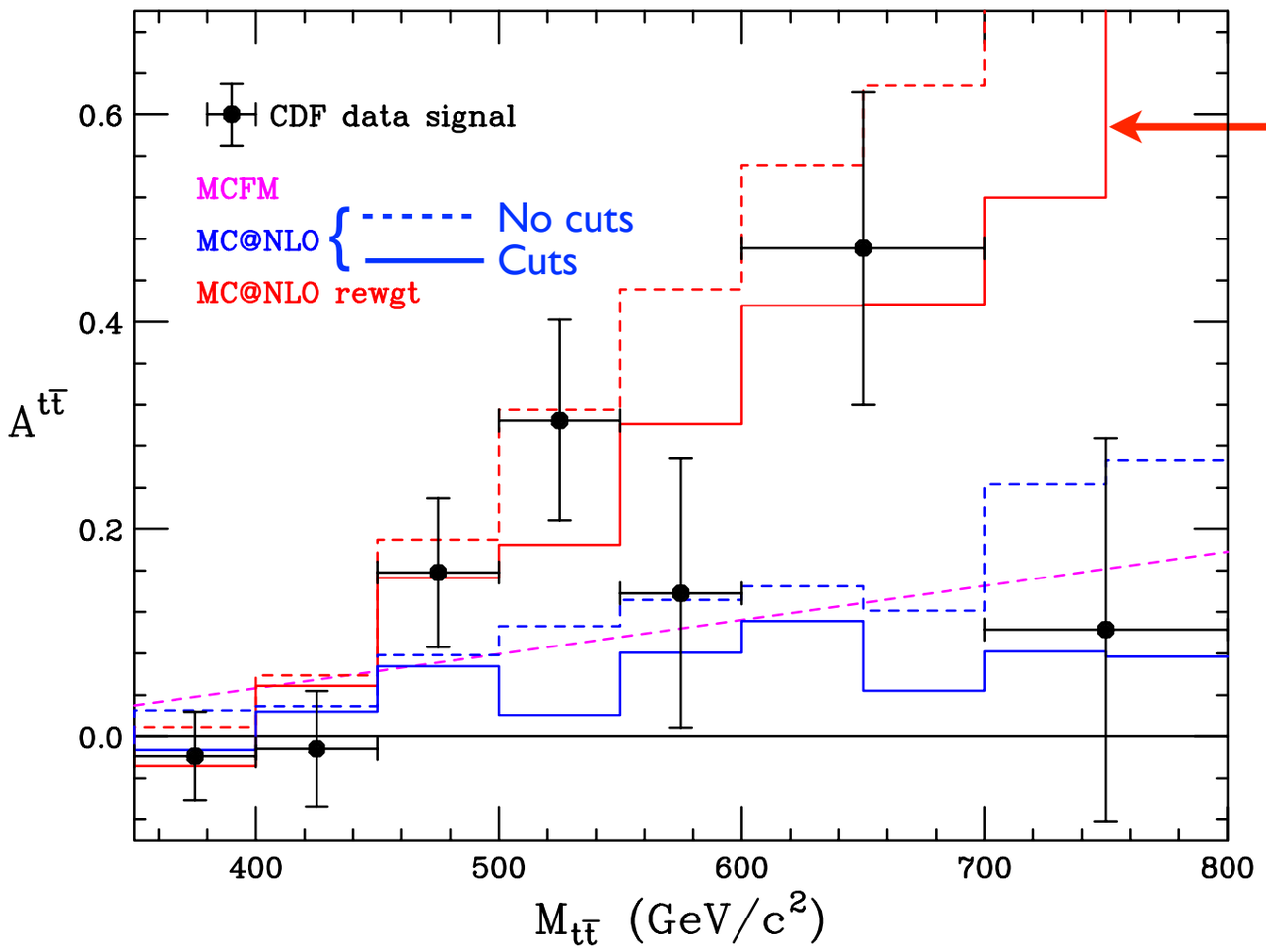


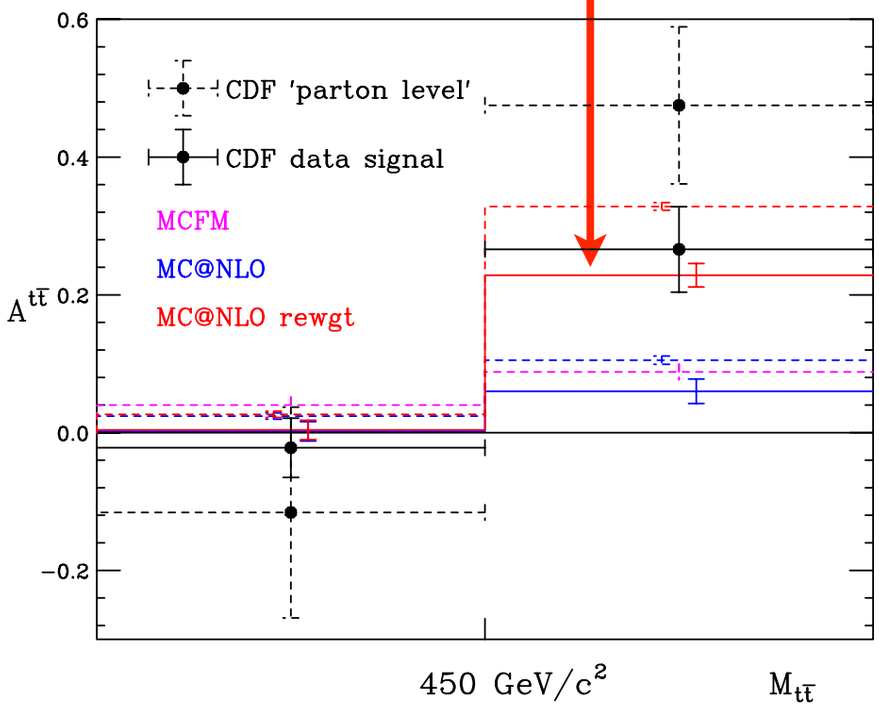
Modelling the CDF asymmetry

- CDF reports a large effect, increasing with $t\bar{t}$ invariant mass
- Suppose this is new physics
- Model it by reweighting $q\bar{q}$ contribution by: $1 + f(M_{t\bar{t}}) \tanh(\Delta y/2)$

$$\simeq 1 + f(M_{t\bar{t}})\beta_t^* \cos\theta_t^*$$

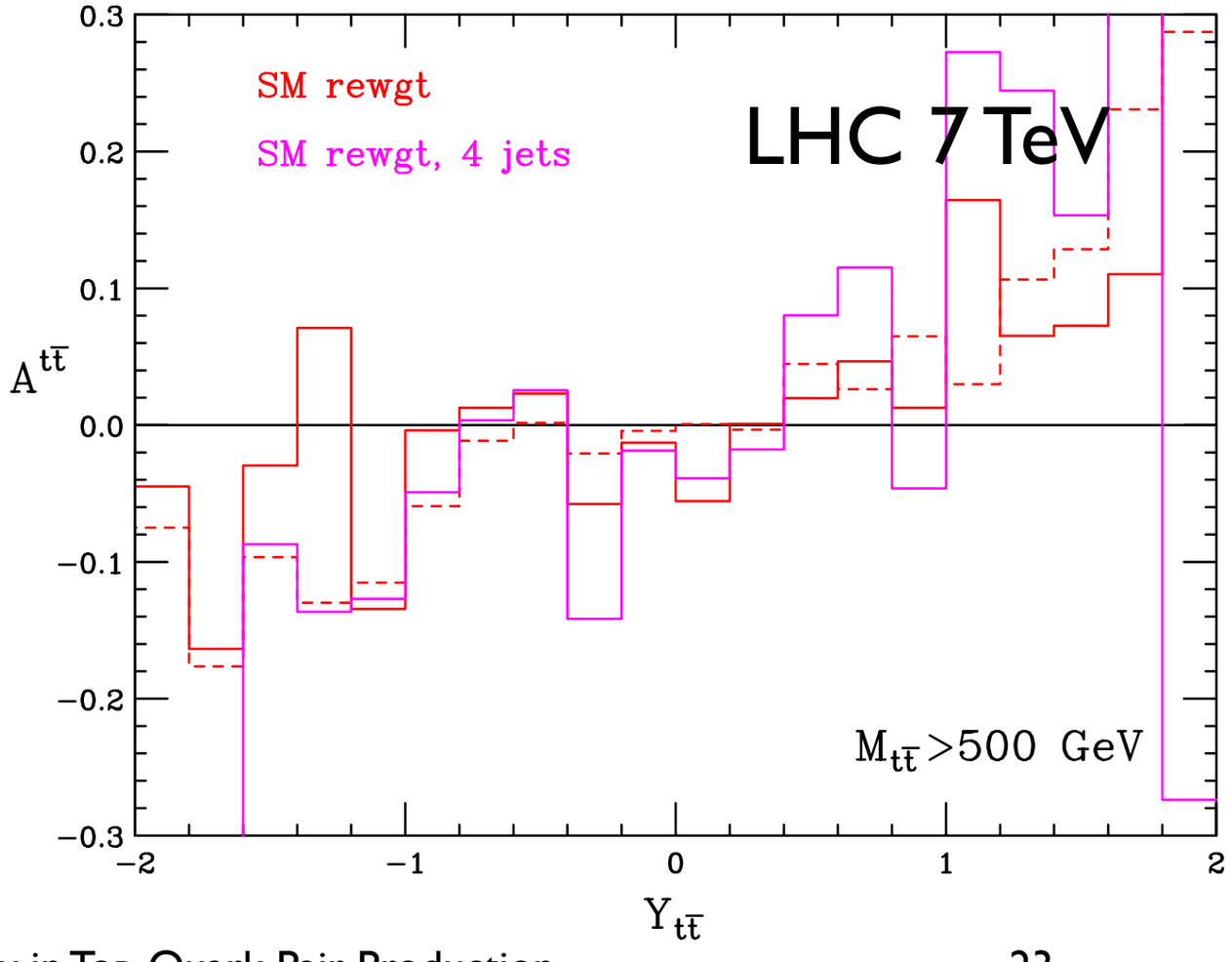
$$f(M_{t\bar{t}}) = M_{t\bar{t}}/200 - 2$$



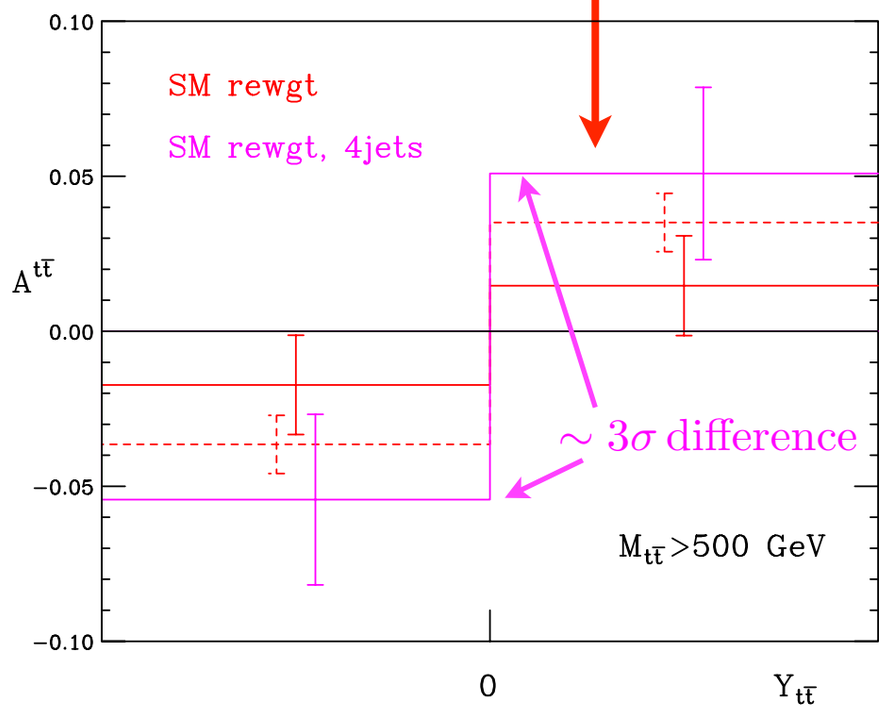


CDF asymmetry at LHC?

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- Model CDF effect by reweighting SM by: $1 + f(M_{t\bar{t}}) \tanh(\Delta y/2)$
$\simeq 1 + f(M_{t\bar{t}})\beta_t^* \cos\theta_t^*$



$f(M_{t\bar{t}}) = M_{t\bar{t}}/200 - 2$

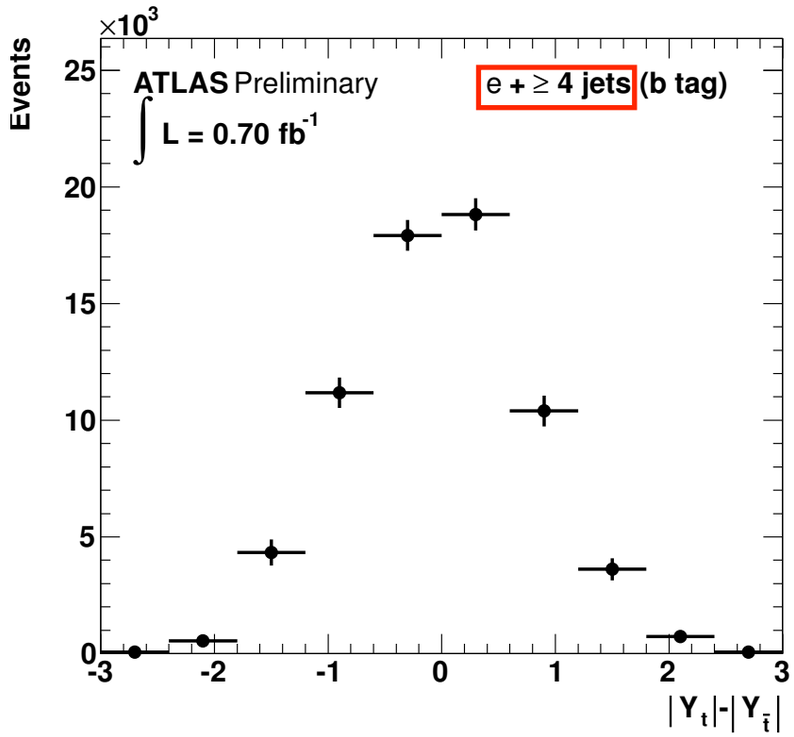


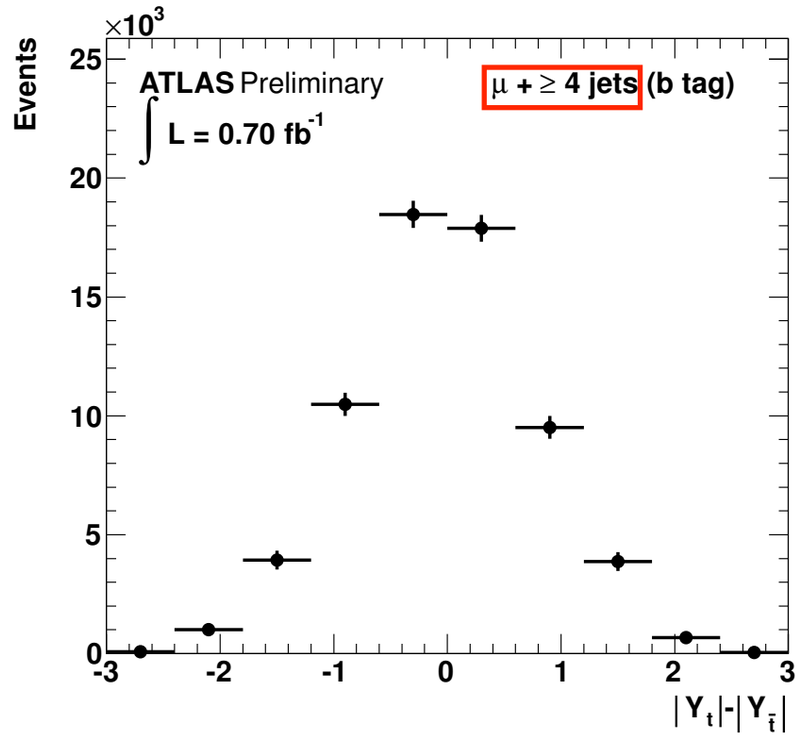
First ATLAS Results

ATLAS-CONF-2011-106

- Looked for $|y_t| - |y_{\bar{t}}| > 0$
- No significant effect: consistent with SM

Asymmetry	detector unfolded	detector and acceptance unfolded
A_C (muon pretag)	-0.020 ± 0.026 (stat.) ± 0.062 (syst.)	-0.016 ± 0.028 (stat.) ± 0.064 (syst.)
A_C (muon b-tag)	-0.030 ± 0.021 (stat.) ± 0.020 (syst.)	-0.028 ± 0.019 (stat.) ± 0.022 (syst.)
A_C (electron pretag)	-0.017 ± 0.031 (stat.) ± 0.067 (syst.)	-0.023 ± 0.034 (stat.) ± 0.065 (syst.)
A_C (electron b-tag)	-0.012 ± 0.026 (stat.) ± 0.030 (syst.)	-0.009 ± 0.023 (stat.) ± 0.032 (syst.)



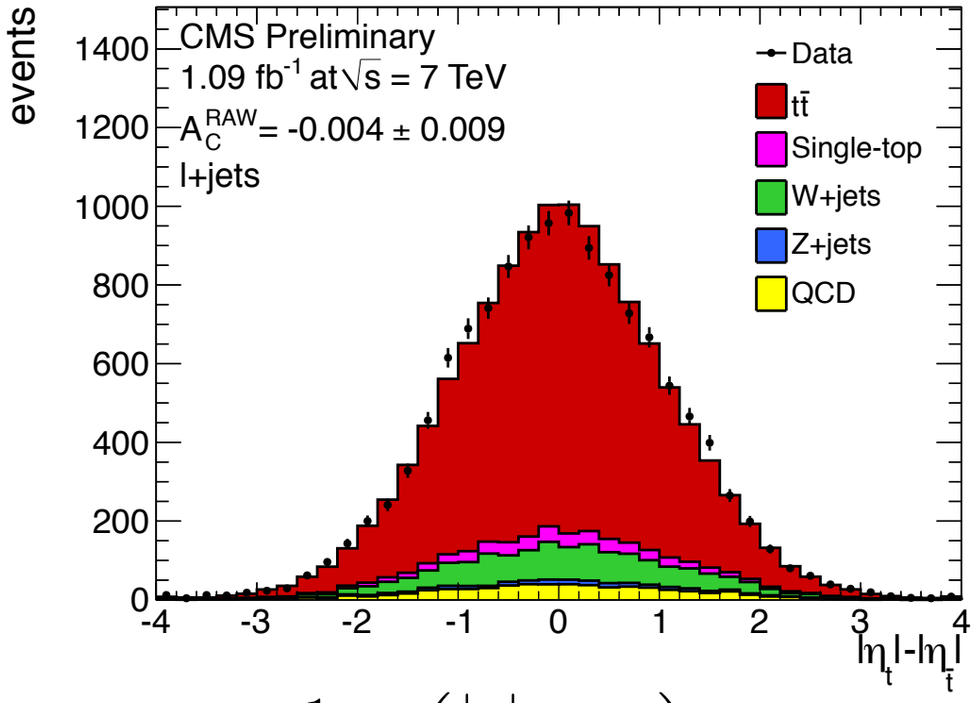


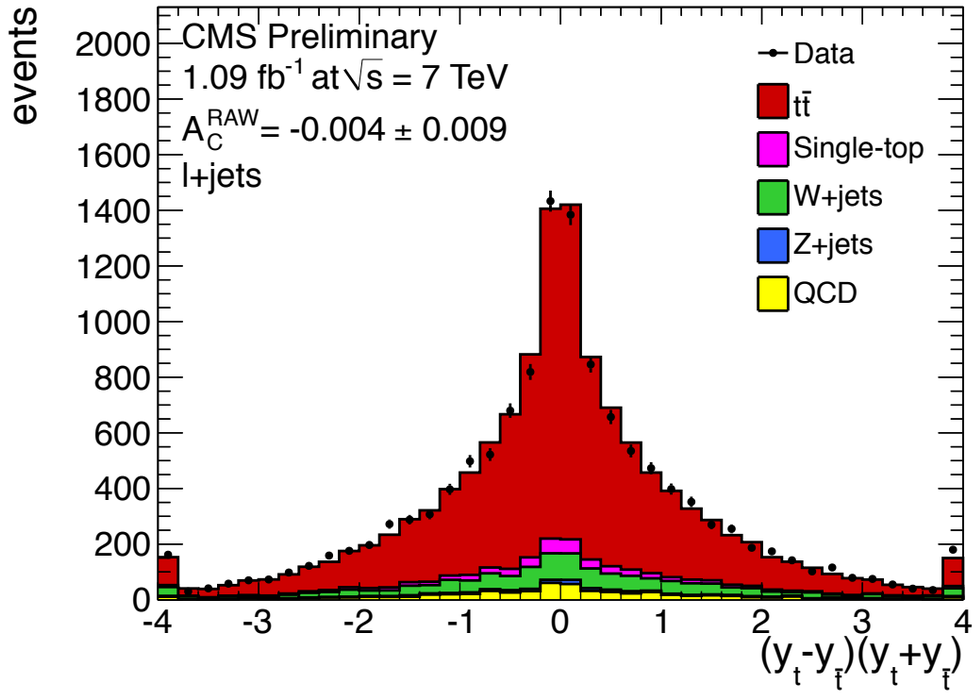
First CMS Results

CMS PAS TOP-11-014

- Looked at $\Delta|\eta|$ and $\Delta y \cdot Y_{t\bar{t}}$
- No significant effect: consistent with SM

Observable	Raw A_C	BG-subtracted A_C	Unfolded (and corrected) A_C	QCD
$\Delta\|\eta\|$	-0.004 ± 0.009	-0.009 ± 0.010	$-0.016 \pm 0.030^{+0.010}_{-0.019}$	+0.013
$\Delta(y^2)$	-0.004 ± 0.009	-0.007 ± 0.010	$-0.013 \pm 0.026^{+0.026}_{-0.021}$	+0.011





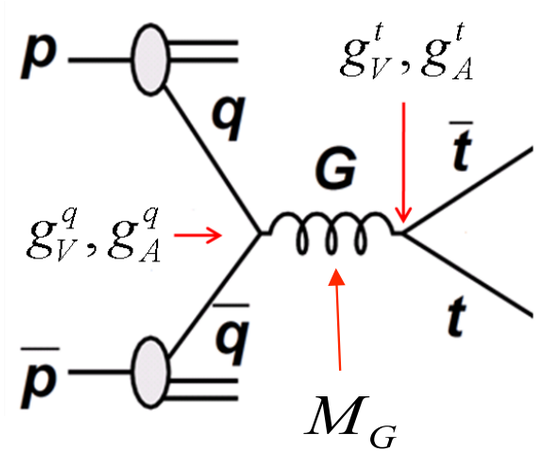
$$\eta \equiv \frac{1}{2} \ln \left(\frac{|p| + p_z}{|p| - p_z} \right)$$

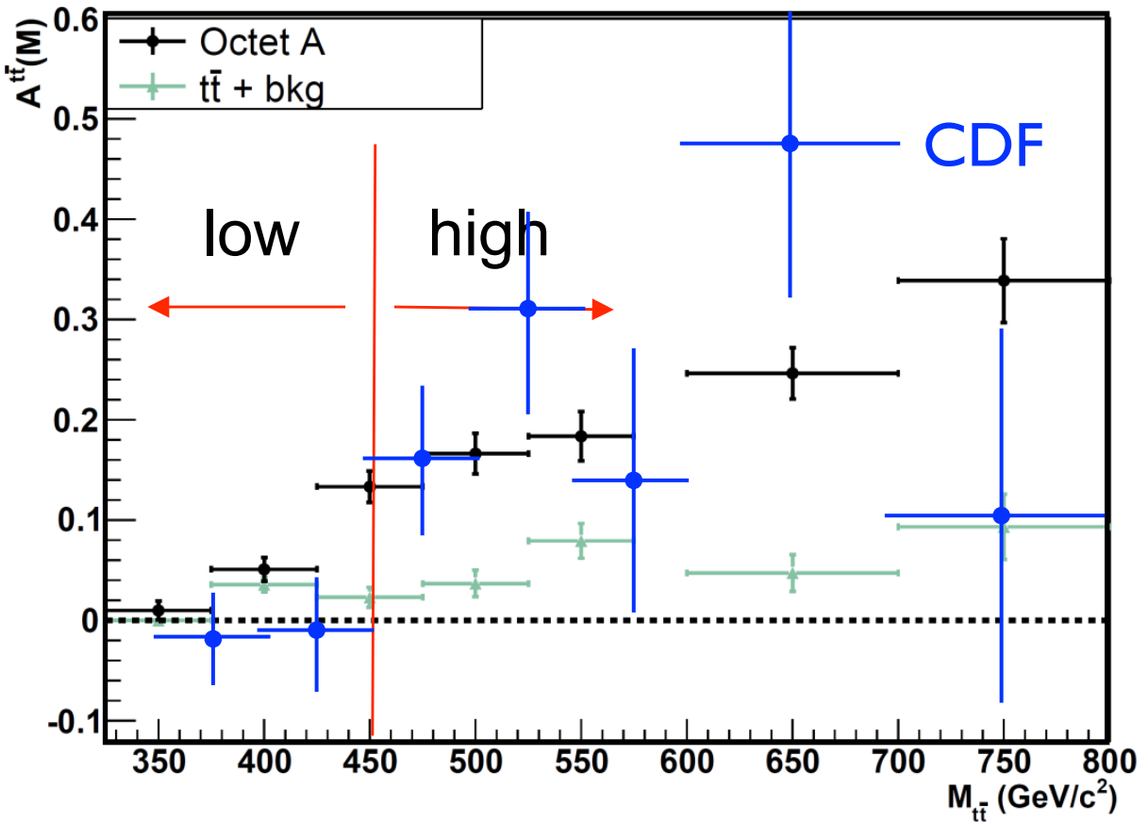
Conclusions

- Asymmetry larger than SM seen by CDF in several independent data sets
- D0 also see this but no mass dependence
- D0 top pair p_T also inconsistent with SM
- Asymmetry at CDF (not SM) level could be seen at LHC in this run
- So far no sign of it

Backup

"Axigluon" model





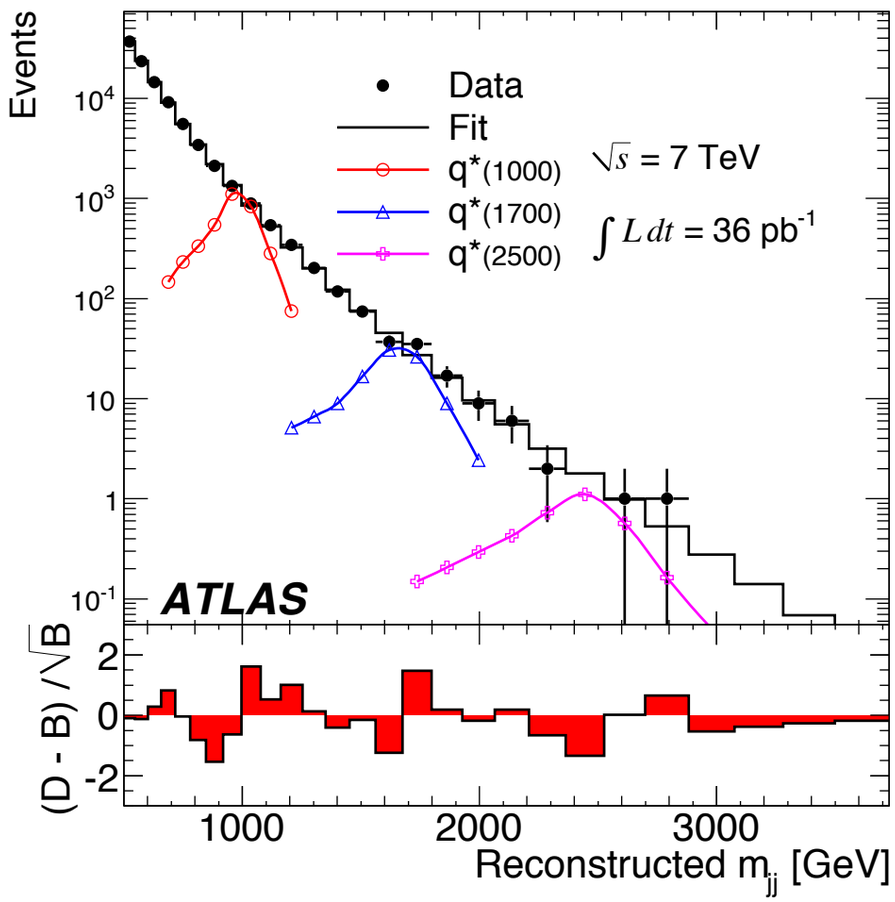
Ferrario & Rodrigo, PRD80(09) 051701

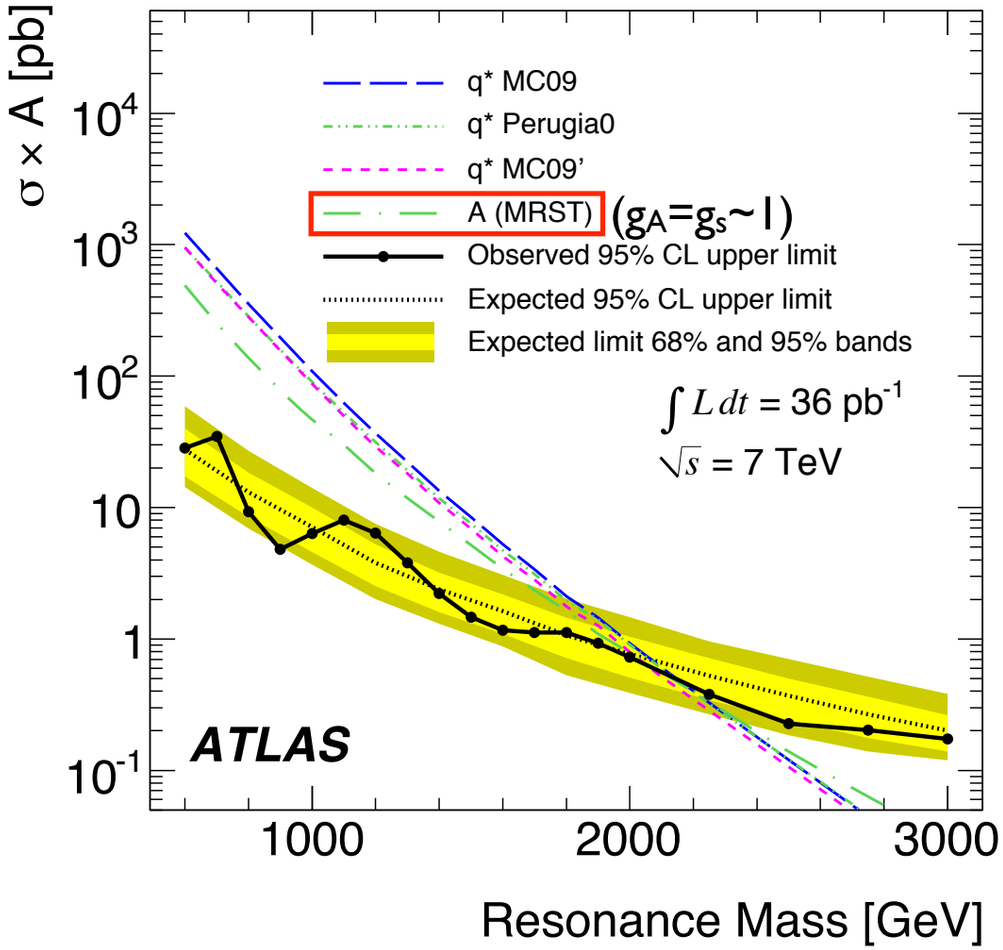
- sample "Octet A"
  - $g_v = 0$, $|g_A = 3|$
  - $g^q_A = - g^t_A$
  - $M_G = 2.0$ TeV
  - xsec ratio: $\sigma/\sigma_{sm} = 1.02$
  - M_{tt} spectrum ~ compares to Pythia
  - Model: Parton $A_{tt} = 0.16$ Reco $A_{tt} = 0.08$
  - Data: Parton $A_{tt} = 0.15$, Reco $A_{tt} = 0.06$

- Can fit CDF $A^{t\bar{t}}$ data
- $M_{t\bar{t}}$ spectrum will differ

Axigluon search in dijets

ATLAS, arXiv:1103.3864

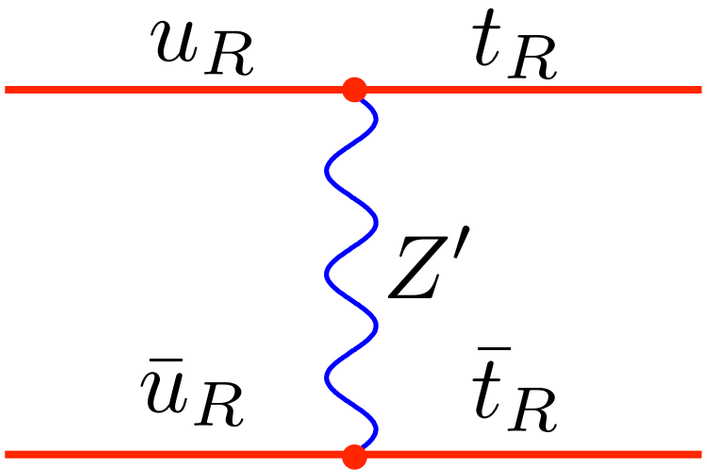


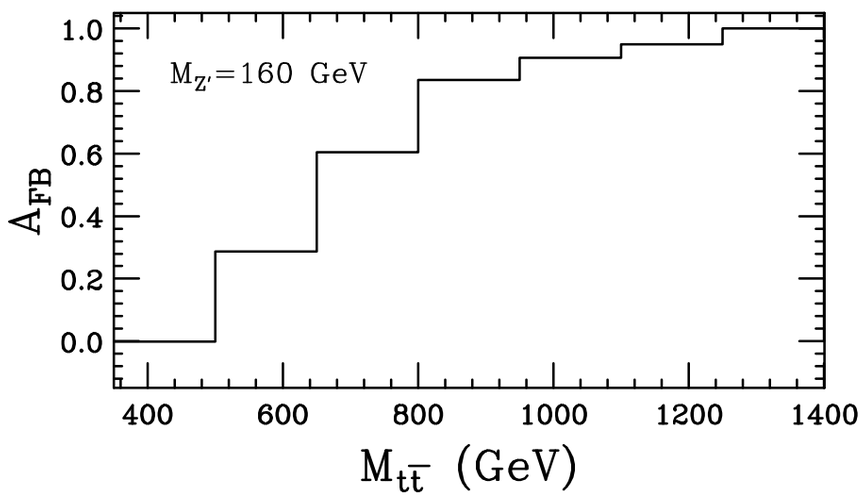


- Resonance bump would be similar to q^*
- Exclude $0.6 < M_G < 2.1$ TeV

Z' exchange models

Jung, Murayama, Pierce, Wells,
PRD81(2010)015004

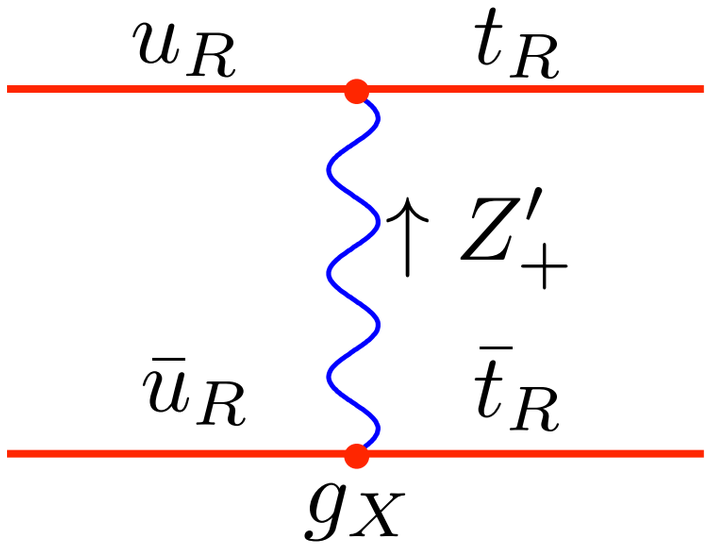




- Rutherford scattering ➔ asymmetry
- Interferes with QCD $u\bar{u} \to g^* \to t\bar{t}$
- RH coupling avoids FCNC constraints
- Data favour light Z' mass, below top
- BUT...
  - Also get $uu \to tt$
  - and $u\bar{u} \to Z'Z' \to t^*\bar{u}t^*\bar{u}$

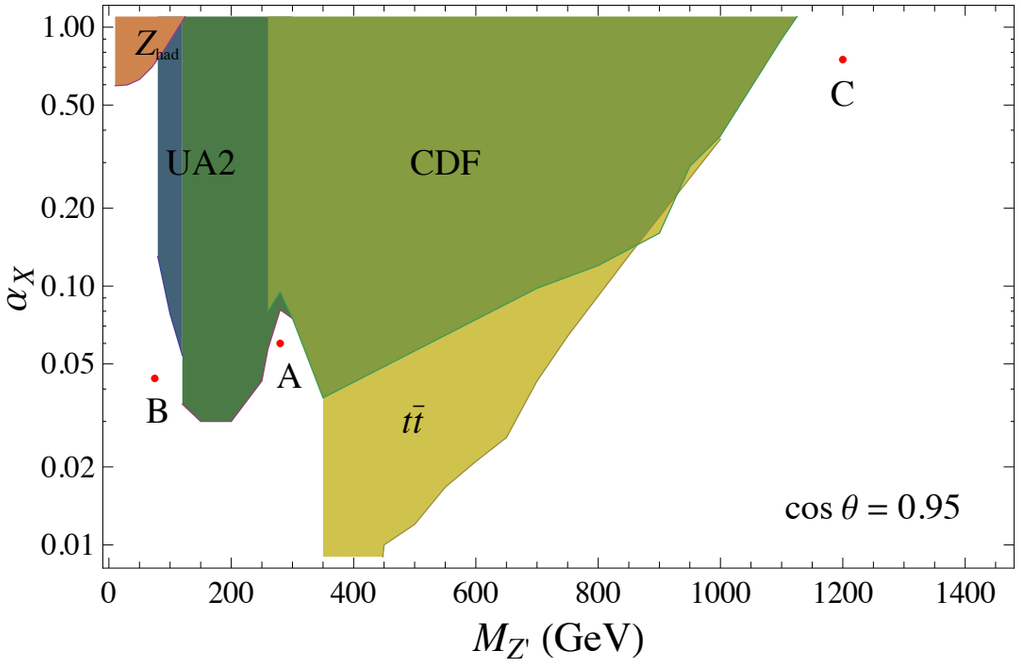
    ➔ need mixing so $Z' \to u\bar{u}$

Nonabelian Z' model



Jung, Pierce, Wells, arXiv:1103.4835

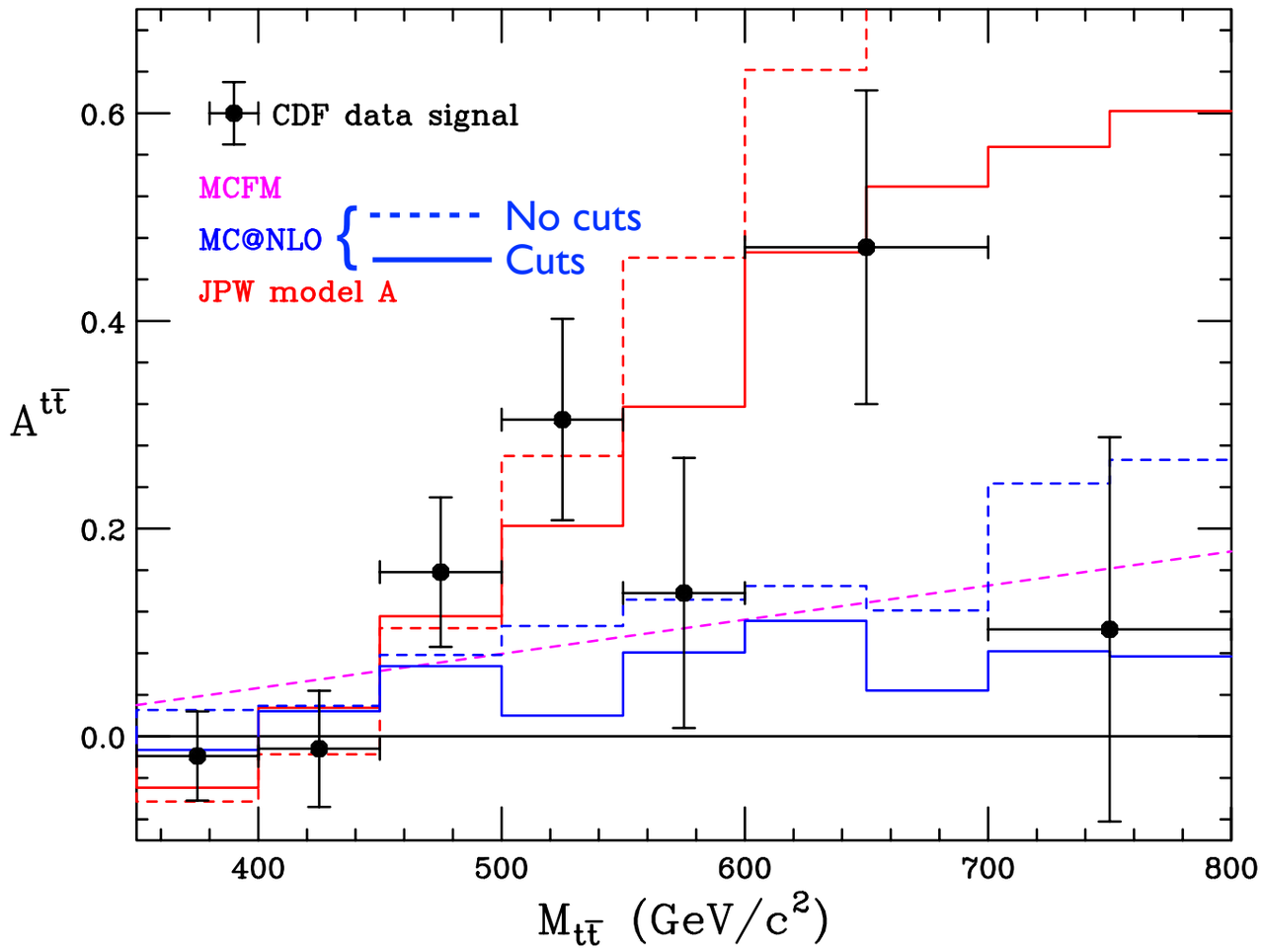
- SU(2)x doublet $\begin{pmatrix} t_R \\ u_R \end{pmatrix}$
- Gauge triplet $Z'_\pm, Z'_0$ (they call W', Z')
- Don't get $uu \to tt$ (when unbroken)

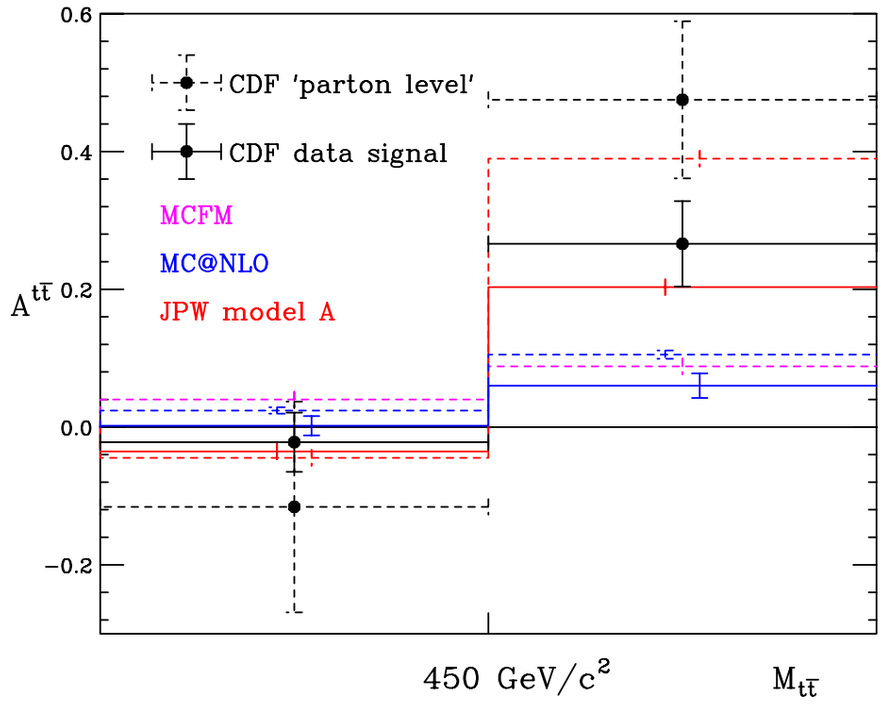


- Flavour mixing reduces $Z'_0 \to u\bar{u}$
- Data favour $m_t < m_{Z'} < 2m_t$ (point A)

Z' model asymmetry

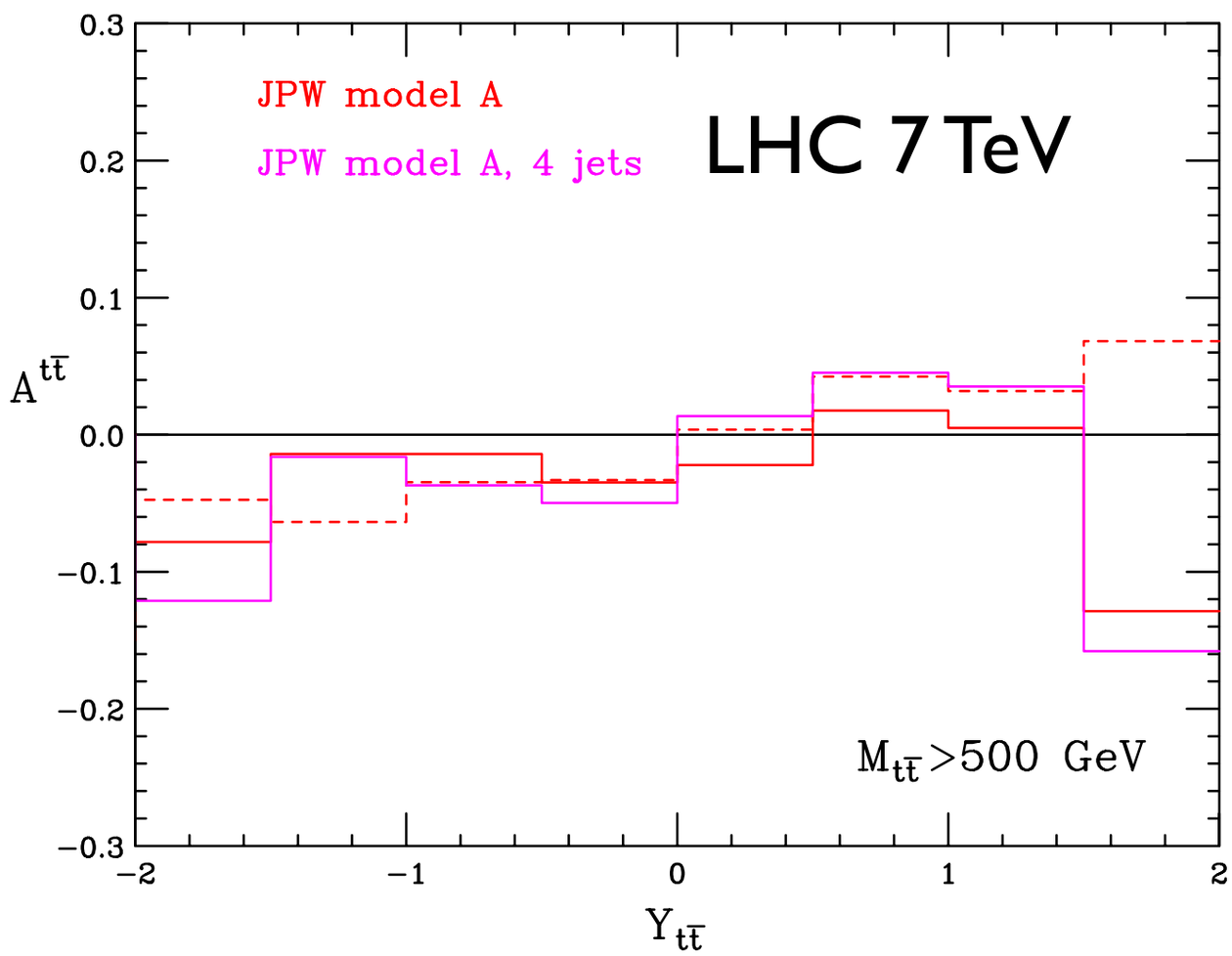
- Jung-Pierce-Wells nonabelain model (point A) can fit data:

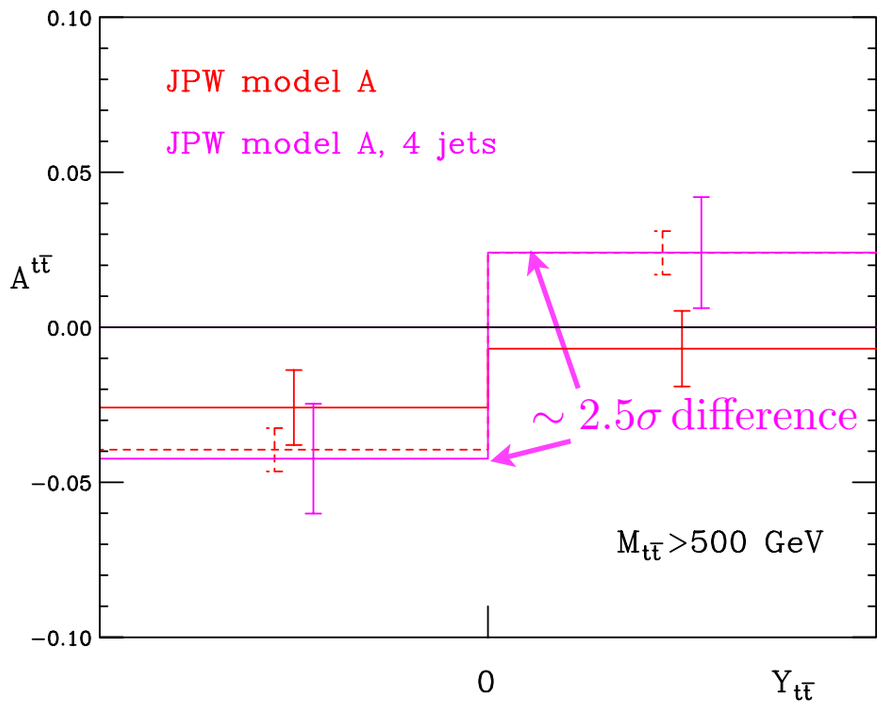




CDF asymmetry at LHC?

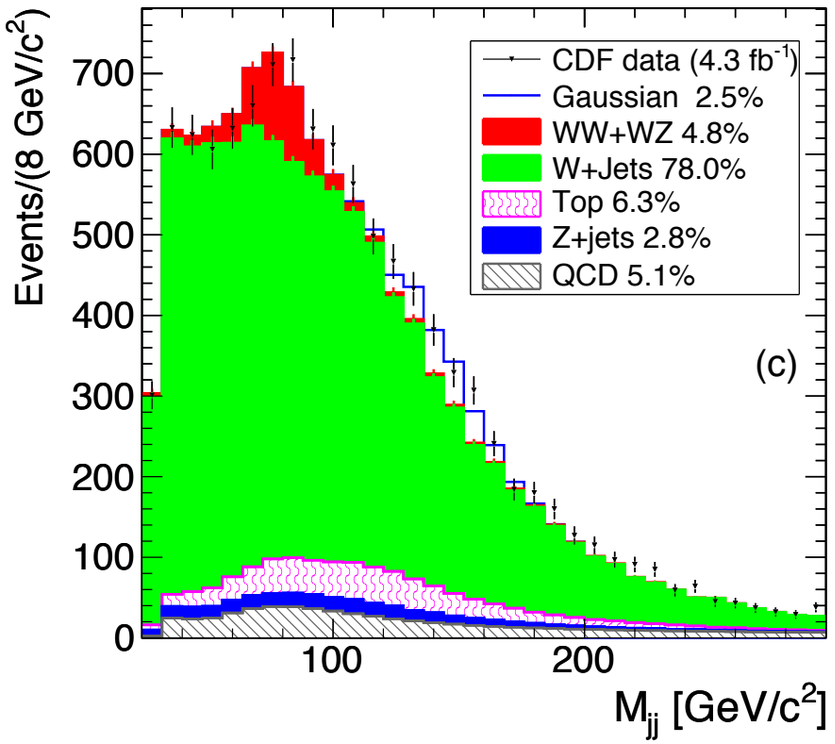
- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- Jung-Pierce-Wells model (point A) → smaller effect ($u\bar{u}$ only)

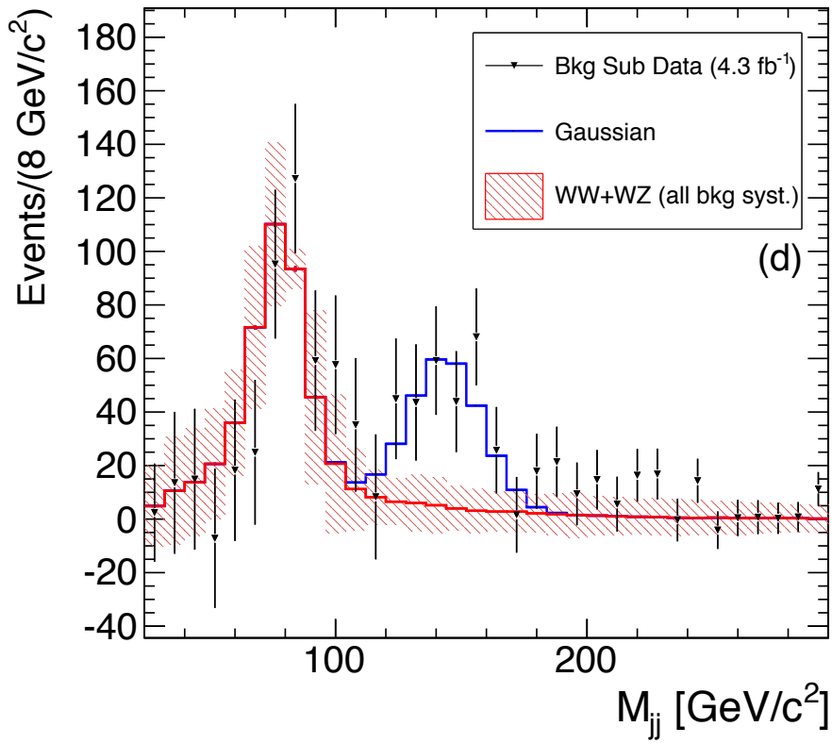




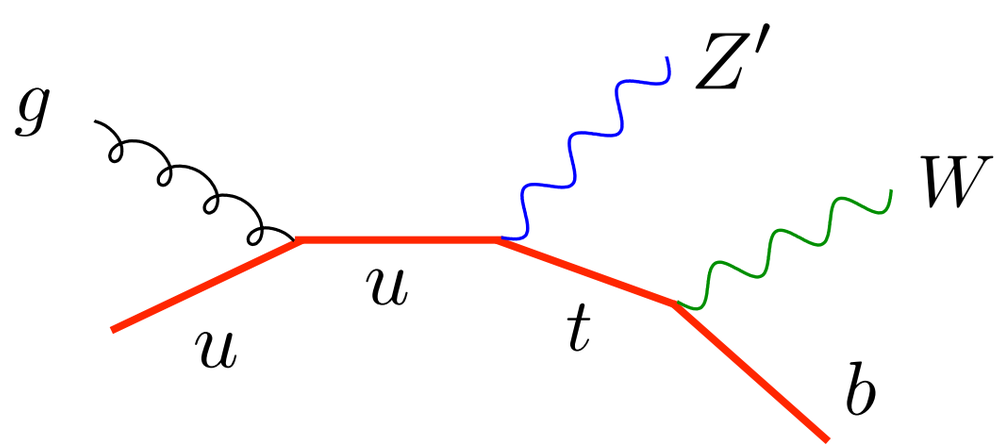
CDF Wjj anomaly

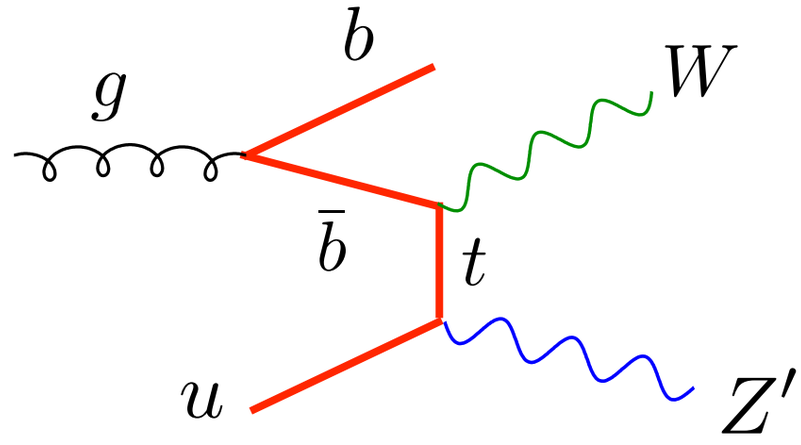
CDF, arXiv:1104.0699





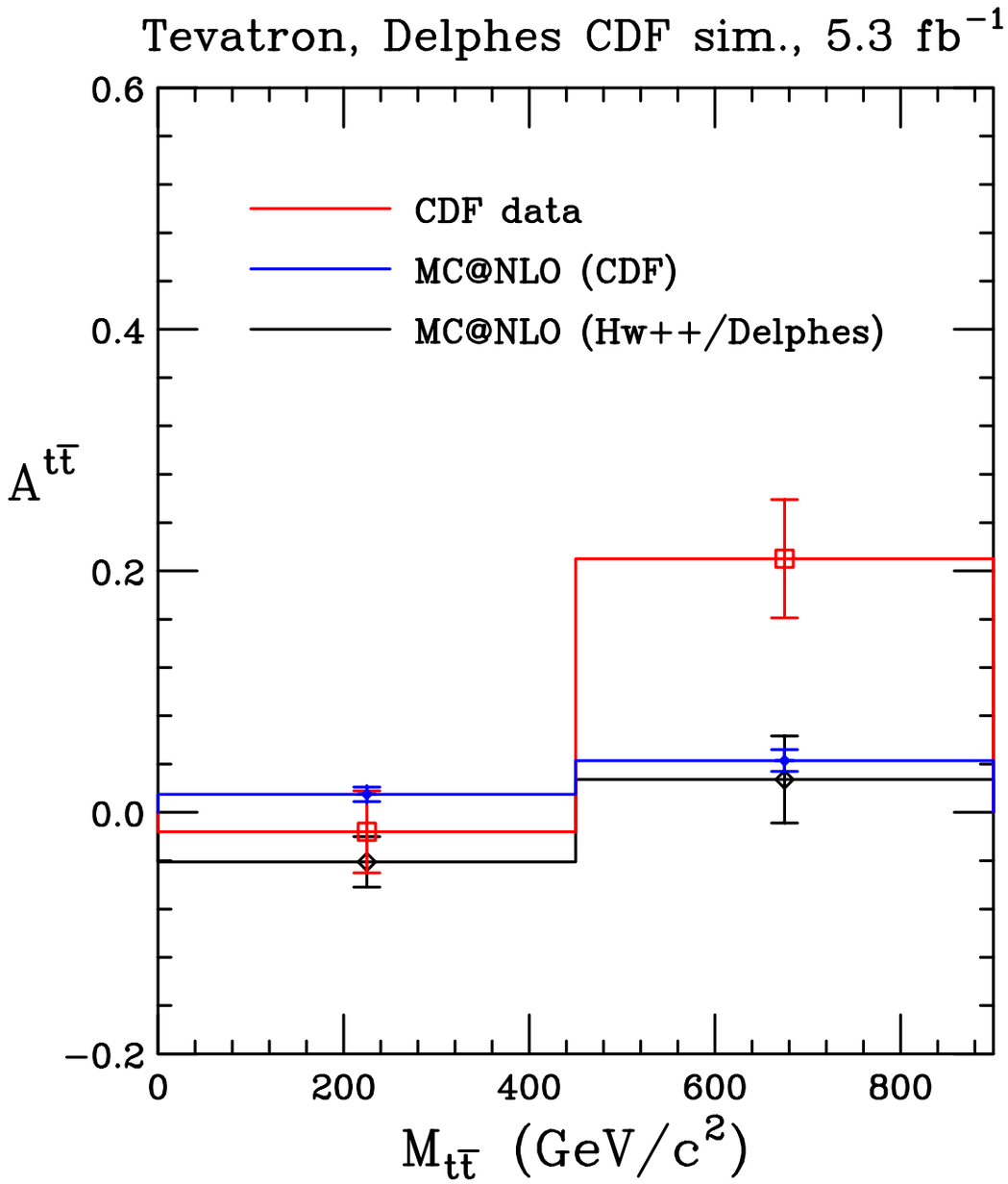
- No anomaly in γjj → flavour-changing Z'?

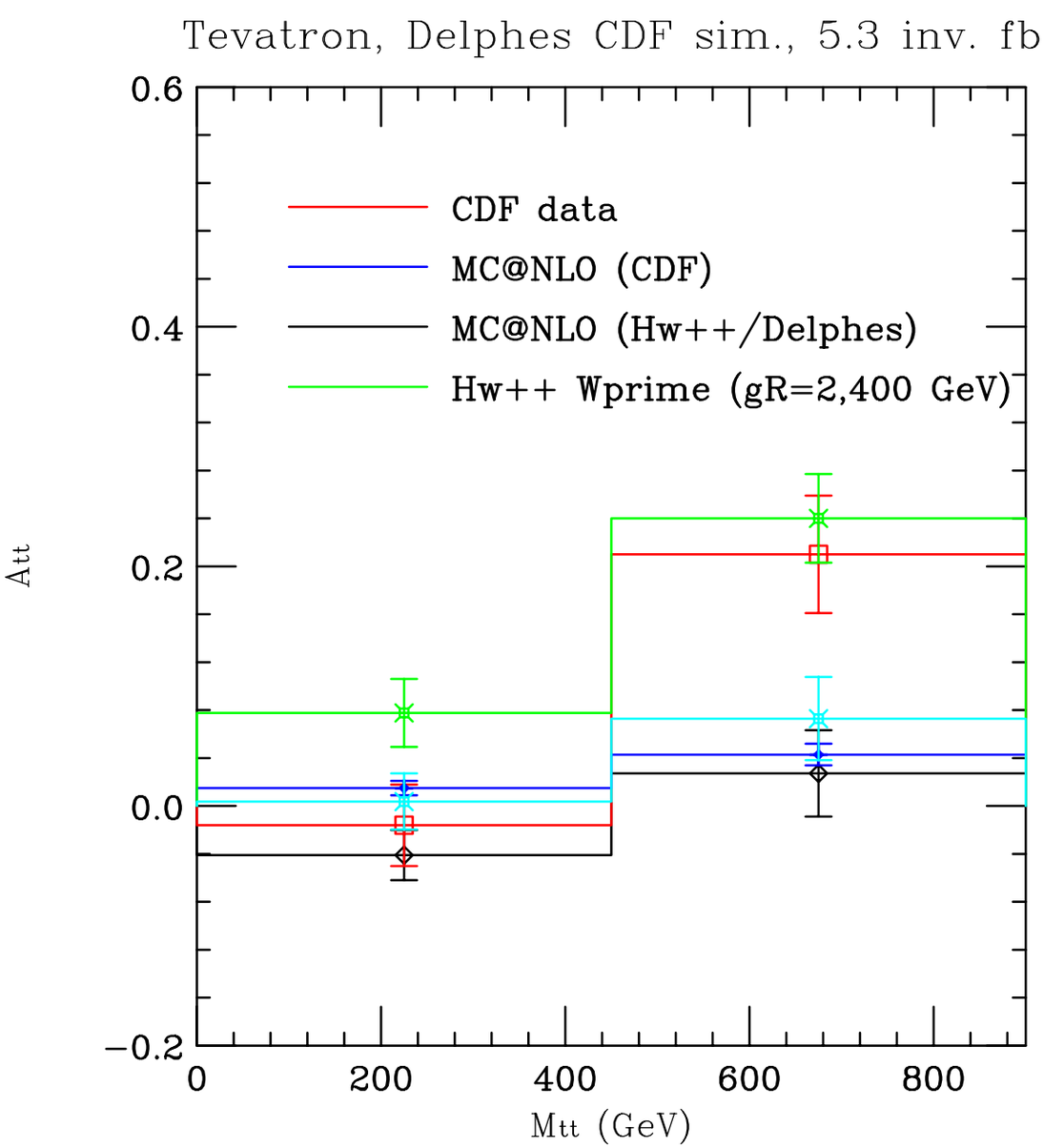




W' model

A Papaefstathiou, in prep.





- Includes simulation of CDF detector