Axigluon signatures at hadron colliders

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8th International Symposium on Radiative Corrections

APPLICATIONS OF QUANTUM FIELD THEORY
TO PHENOMENOLOGY

Florence - October 1-5, 2007

- **Top quark** is the heaviest known elementary particle ⇨ it plays a fundamental role in many extensions of the Standard Model (SM), production and decay channels are promising probes of new physics.

- The total cross section of top-antitop quark production at LHC is about 100 times larger than at Tevatron ⇨ Millions of top quark pairs per year will be produced even at the initial low luminosity of $\mathcal{L} = 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$(equivalent to 10 fb^{-1}/year integrated luminosity).

- Born processes relevant for top quark production, $qq \rightarrow tt$ and $gg \rightarrow tt$, do not discriminate between final quark and antiquark, thus predicting identical differential distributions also for the hadronic production process.

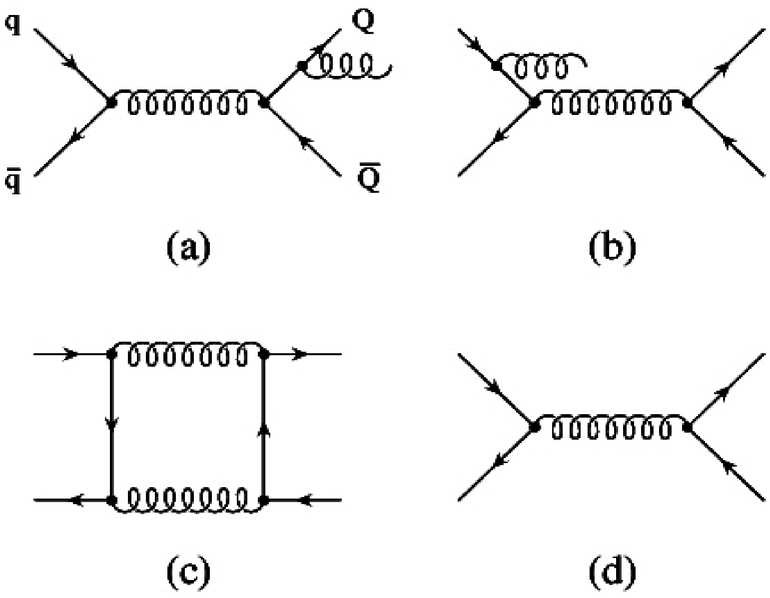
- At $O(\alpha_S^3)$ a **charge asymmetry** is generated and the differential distributions of top quarks and antiquarks are no longer equal. (similar effect leads also to a strange-antistrange quark asymmetry, $s(x) \neq s(x)$, through NNLO evolution of parton densities [Catani et al.])

Some properties of the top quark can be studied at Tevatron through the **forward–backward** asymmetry which originates from the **charge asymmetry**

Outline

- Charge asymmetry and forward—backward asymmetry
- Recent measurements at Tevatron
- Pair asymmetry
- Axigluon signatures, and bounds on the axigluon mass
- Axigluon production at LHC

Inclusive charge asymmetry



(a) (b)

(c) (d)

← Interference of ISR with FSR

LO for tt+jet (NLO see Uwer's talk)

negative contribution

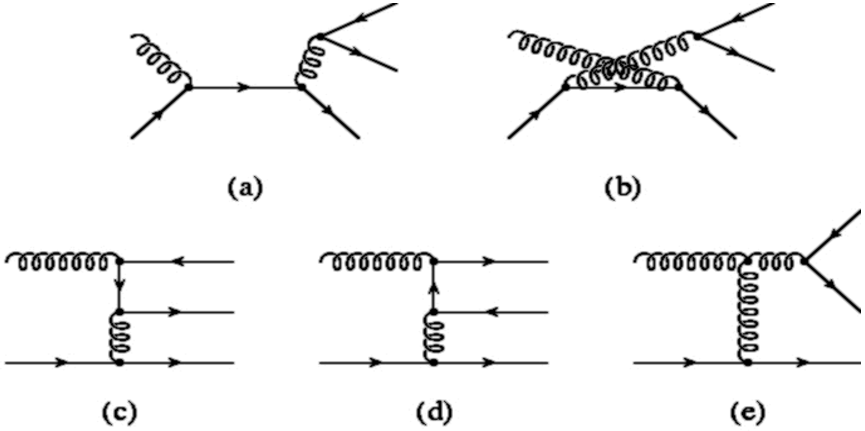
← Interference of box diagrams with Born

positive contribution

- Loop contribution larger than tree level

inclusive asymmetry positive: 5% [Kühn,GR, 98]

quarks are preferentially emitted in the direction of the incoming quark (proton)

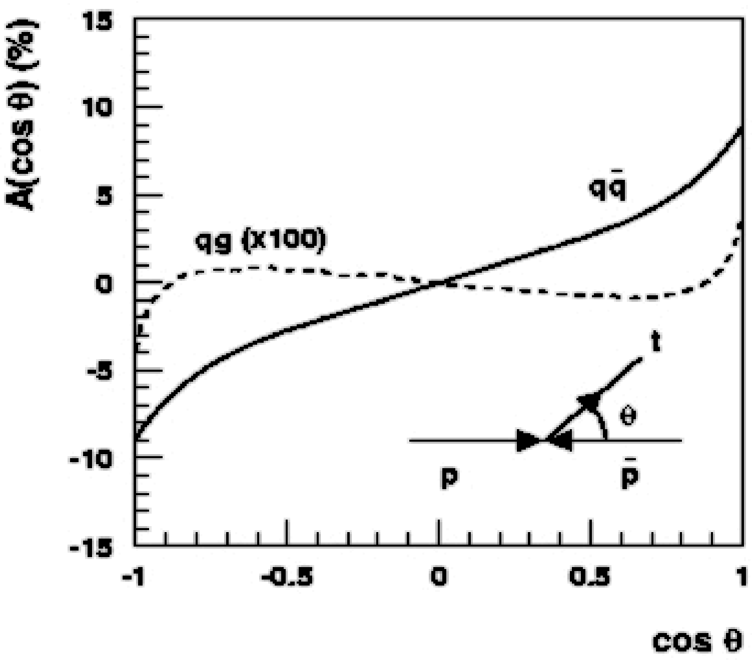


(a) (b)

(c) (d) (e)

← Flavor excitation negligible at Tevatron

Inclusive charge asymmetry at Tevatron



- Differential **charge asymmetry** of the single quark rapidity distribution

$$A(y) = \frac{N_t(y) - N_{\bar{t}}(y)}{N_t(y) + N_{\bar{t}}(y)}$$

y = top (antitop)rapidity in the laboratory frame and *N(y)* = dσ/dy.

- $N_{\bar{t}}(y) = N_t(-y)$ (charge conjugation symmetry)

A(*y*) can also be interpreted as a **forward–backward asymmetry** of the top quark.

[Antuñano, Kühn, GR, arXiv:0709.1652]

- Updated **integrated asymmetry**

with m_t = 170.9 ± 1.9 GeV and MSRT2004

$$A = \frac{N_t(y>0) - N_{\bar{t}}(y>0)}{N_t(y>0) + N_{\bar{t}}(y>0)} = 0.051(6)$$

- mixed QCD-EW interference: factor 1.09 included
- K factor = 1.3 then *A*=0.036(4) ≈ MC@NLO

Asymmetry measurements at Tevatron

- **CDF:** 695 pb^{-1}

T. A. Schwarz, Ph.D. Thesis, University of Michigan, FERMILAB-THESIS-2006-51

$$A_{FB} = 0.20 \pm 0.11(stat) \pm 0.047(sys)$$

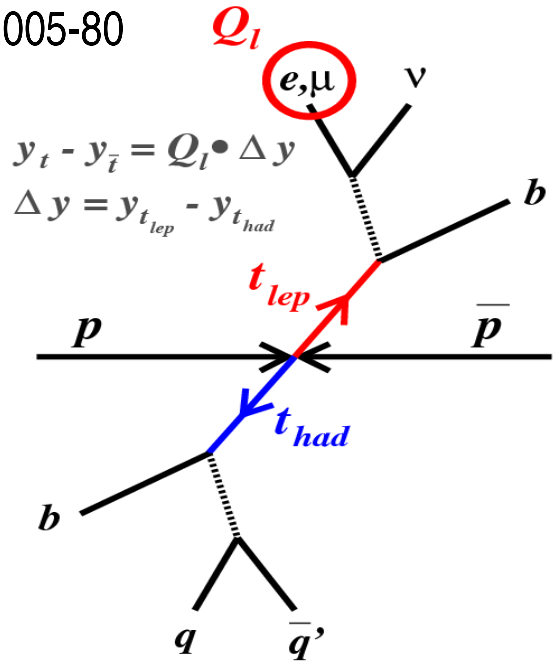
statististical error down to 0.04 with 8 fb^{-1}

- **CDF:** 995 pb^{-1}

J. Weinelt, Masters thesis, Universität Karlsruhe, FERMILAB-MASTERS-2006-05

D. Hirschbühl, Ph.D. Thesis, Universität Karlsruhe, FERMILAB-THESIS-2005-80

$$\begin{aligned} A(\Delta y \cdot Q_l) &= 0.23 \pm 0.12(stat) \pm {}^{0.056}_{0.057}(sys) \\ A^{4j}(\Delta y \cdot Q_l) &= 0.11 \pm 0.14(stat) \pm {}^{0.036}_{0.034}(sys) \\ A^{5j}(\Delta y \cdot Q_l) &= 0.37 \pm 0.30(stat) \pm {}^{0.075}_{0.066}(sys) \end{aligned}$$



rapidity difference of the semileptonically and hadronically decaying top quark x charge of the charged lepton

five-jet sample expected to be negative

Asymmetry measurements at Tevatron

- **D0:** 0.9 fb^{-1}

A. Harel, D0 Note 5393, EPS 2007

$$A_{FB} = 0.12 \pm 0.08(stat) \pm 0.01(sys)$$

uncorrected

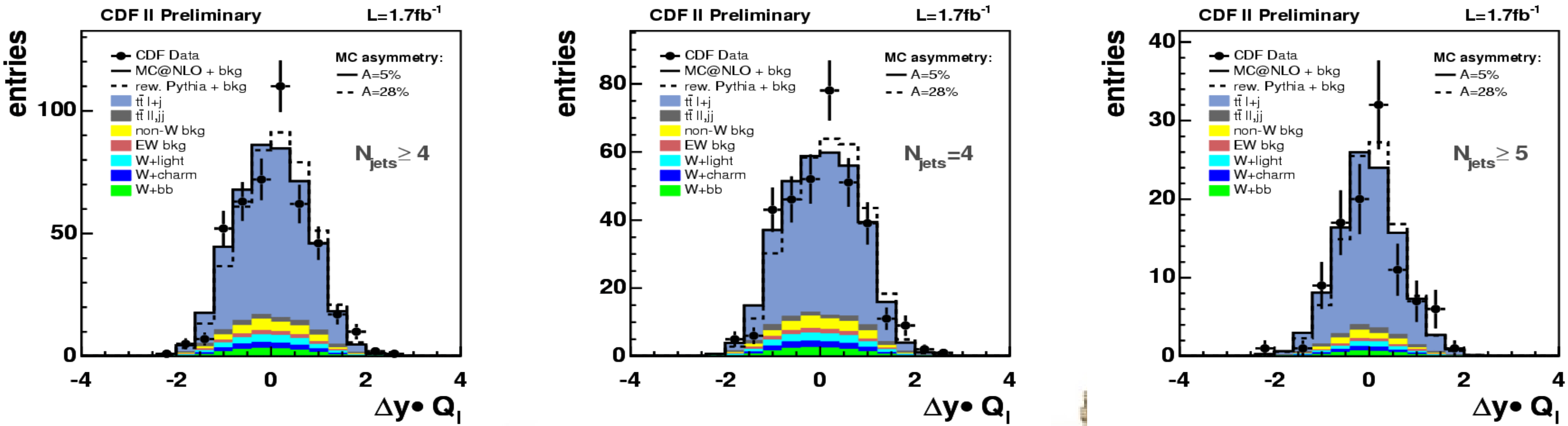
- **CDF:** 1.7 fb^{-1}

D.Hirschbühl, T. Müller, T. Peiffer, J. Wagner, W. Wagner, J. Weinelt, CDF note 8963, Lepton-Photon 2007

$$A^{>4j}(bg\ subt) = 0.144 \pm 0.067(stat)$$
$$A^{4j}(bg\ subt) = 0.156 \pm 0.0.078(stat)$$
$$A^{5j}(bg\ subt) = 0.108 \pm 0.127(stat)$$

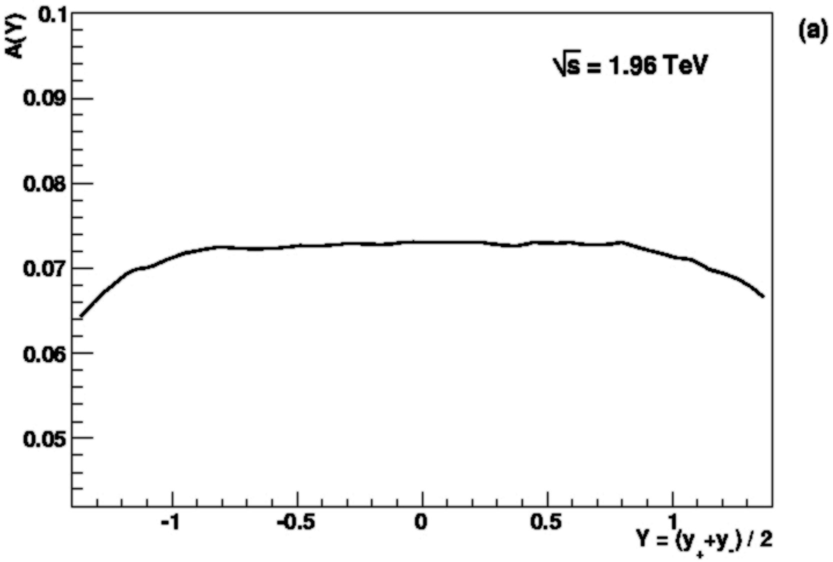
$$A(\Delta y \cdot Q_l) = 0.28 \pm 0.13(stat) \pm 0.05(sys)$$

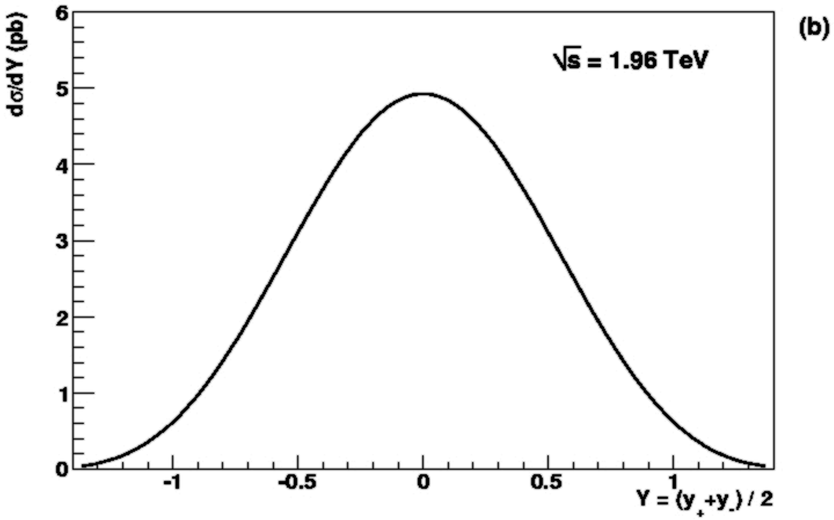
corrected for smearing effects due to non perfect reconstruction and selection eff.



Pair asymmetry

[Antuñano, Kühn, GR, arXiv:0709.1652]





- For events where the rapidities y_+ and y_- of both the top and antitop quarks have been determined, define the **average rapidity**

$$Y = \frac{1}{2}(y_+ + y_-)$$

consider the differential **pair asymmetry $\mathcal{A}(Y)$** for all events with fixed *Y* as a function of *Y*

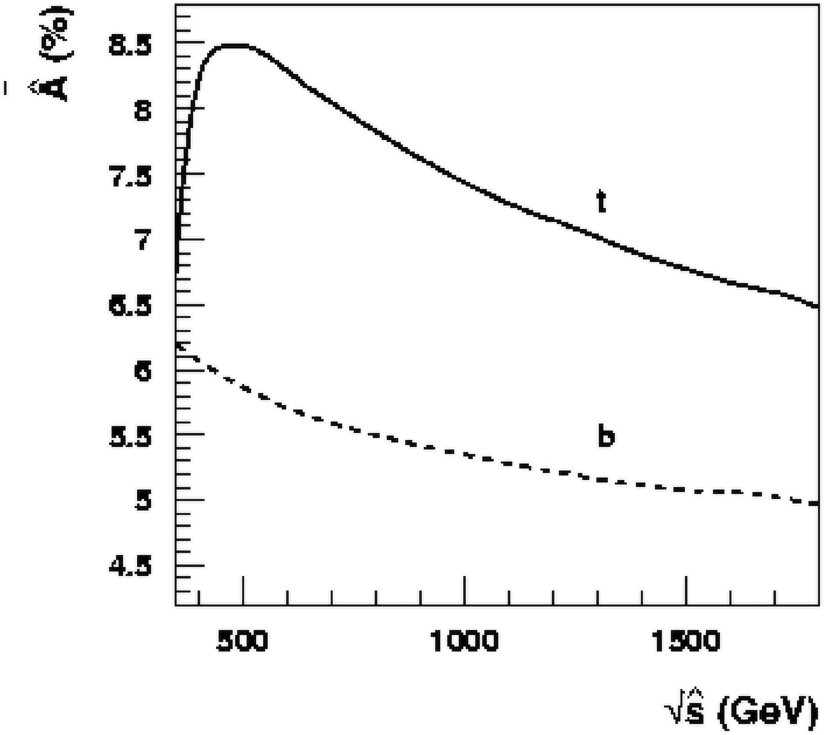
$$\mathcal{A}(Y) = \frac{N_{ev.}(y_+ > y_-) - N_{ev.}(y_+ < y_-)}{N_{ev.}(y_+ > y_-) + N_{ev.}(y_+ < y_-)}$$

integrated pair asymmetry

$$\mathcal{A} = \frac{\int dY\,(N_{ev.}(y_+ > y_-) - N_{ev.}(y_+ < y_-))}{\int dY\,(N_{ev.}(y_+ > y_-) + N_{ev.}(y_+ < y_-))} = 0.078(9)$$

enhancement factor 1.5 !!!

Partonic asymmetry



- The **pair asymmetry** is essentially the forward–backward asymmetry in the **top-antitop rest frame:**

$$A = 7\text{-}8\%$$

events where both top and antitop are produced with positive and negative rapidities do not contribute to the integrated forward–backward asymmetry, which is therefore reduced to around 5%.

- The **integrated pair asymmetry** is equivalent to the integrated asymmetry in $\Delta y \cdot Q_l$

QCD exotics

Chiral Color Models [Pati , Salam, PLB58(75)333; Hall,Nelson, PLB153(85)430; Frampton, Glashow, PLB190(87)157; PRL58(87)2168]

Extend the standard color gauge group to

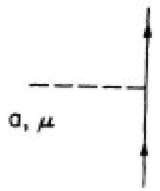
$$SU(3)_L \times SU(3)_R \Rightarrow SU(3)_C$$

- different implementations with new particles in varying representations, but
- model-independent prediction: existence of a massive, color-octet gauge boson: **axigluon**
  - couples to quarks with an **axial-vector** structure and the same strong interaction coupling strength as QCD
  - the **charge asymmetry** that can be generated is maximal.

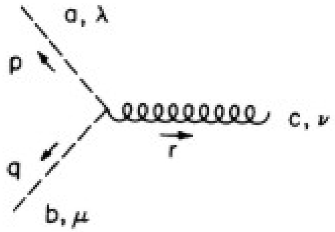
Similar states might appear in other models (technicolor, ...)

Feynman rules for axigluons

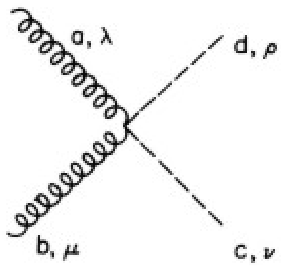
[Bagger, Schmidt, King, PRD37(1987)]



$$qqA = i\, g_s T^a \gamma^\mu \gamma_5$$



$$gAA = -g_s f^{abc} [g_{\mu\nu} (r-q)_\lambda + g_{\mu\lambda} (g-p)_\nu + g_{\lambda\nu} (p-r)_\mu]$$



$$ggAA = -i\, g_s^2 f^{abe} f^{cde} (g_{\lambda\nu} g_{\mu\rho} - g_{\mu\nu} g_{\lambda\rho})$$
$$+ f^{ace} f^{bde} (g_{\lambda\mu} g_{\nu\rho} - g_{\lambda\rho} g_{\mu\nu})$$
$$+ f^{ade} f^{bce} (g_{\lambda\mu} g_{\nu\rho} - g_{\lambda\nu} g_{\mu\rho})$$

Because of parity there are no gluon-axigluon vertices with an **odd number of axigluons**

➔ gluon-gluon fusion to quarks not modifed at tree-level

Top cross-section

Gluon-axigluon interference

- generates charge asymmetry → FB
- vanishes upon integration over charge symmetric regions of phase space

- **Quark-antiquark annihilation**

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos(\theta)}=\alpha_S^2\frac{T_F C_F}{N_C}\frac{\pi\beta}{2s}\left(1+c^2+4\mathrm{m}^2+\frac{4cs(s-m_A^2)+s^2(\beta^2+c^2)}{(s-m_A^2)^2+m_A\Gamma_A^2}\right)$$

where

$$m=m_t/s\,,\qquad \beta=\sqrt{1-4\mathrm{m}^2}\,,\qquad c=\beta\cos(\theta)$$

Squared axigluon amplitude

- contributes to the total cross section
- suppressed by 1/m_A^4

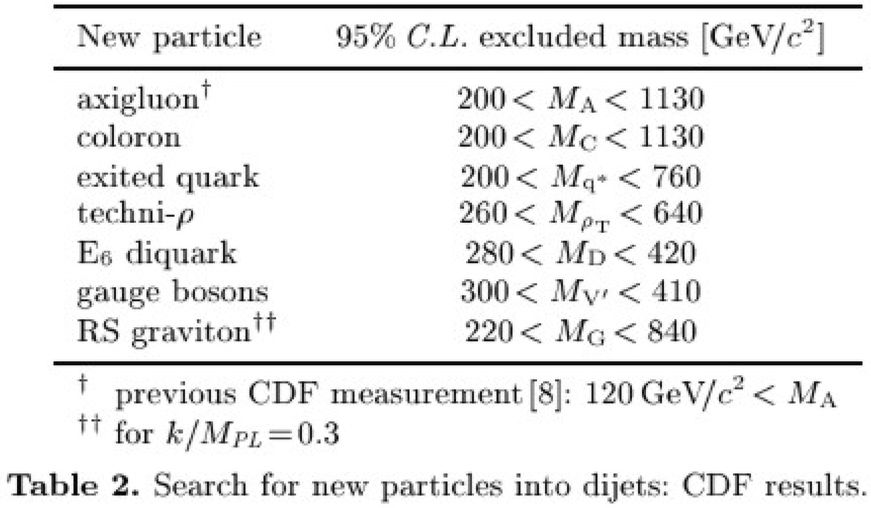
and the width

$$\Gamma_A\equiv\sum\Gamma(A\to q\bar{q})\approx\frac{\alpha_S m_A T_F}{3}\left[5+\left(1-\frac{4\mathrm{m}_t^2}{m_A^2}\right)^{3/2}\right]\approx 0.1\,m_A$$

- **gluon-gluon fusion** at tree-level the same as in the SM

Bounds from the total cross-section

[Giordani, EPS2003]



New particle	95% $C.L.$ excluded mass [GeV/c^2]
axigluon[†]	$200 < M_A < 1130$
coloron	$200 < M_C < 1130$
exited quark	$200 < M_{q^*} < 760$
techni-ρ	$260 < M_{\rho_T} < 640$
E_6 diquark	$280 < M_D < 420$
gauge bosons	$300 < M_{V'} < 410$
RS graviton[††]	$220 < M_G < 840$

[†] previous CDF measurement [8]: $120\,\mathrm{GeV}/c^2 < M_A$

[††] for $k/M_{PL} = 0.3$

Table 2. Search for new particles into dijets: CDF results.

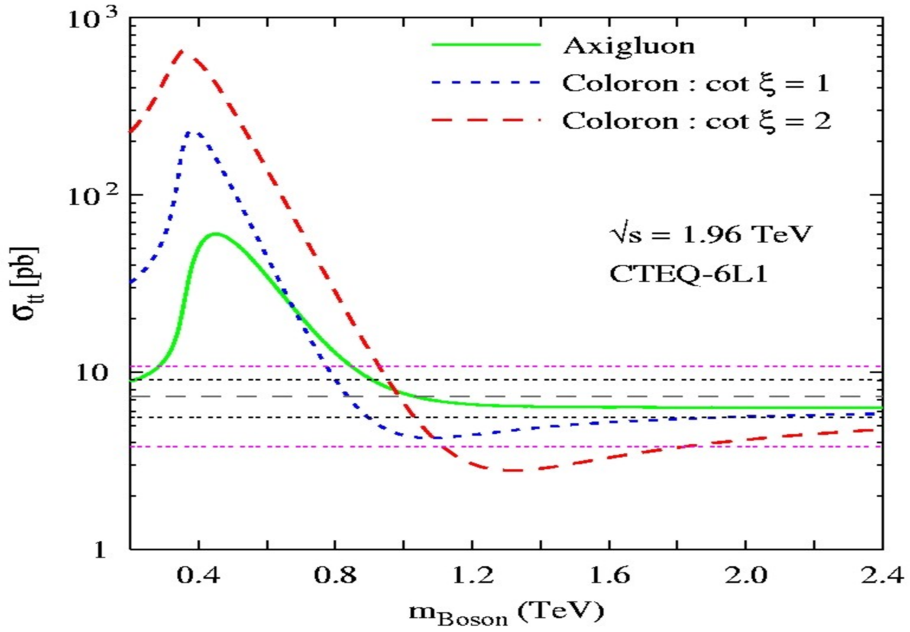
Low mass window for axigluons also excluded [Doncheski,Robinet, 97] from hadronic Z-decays

CDF arXiv:0709.0705

topcolor-assisted technicolor model

leptophobic Z': $M_{Z'} > 725$ GeV @ 95% C.L.

[Choudhury,Godbole,Singh,Wagh, arXiv:0705.1499]



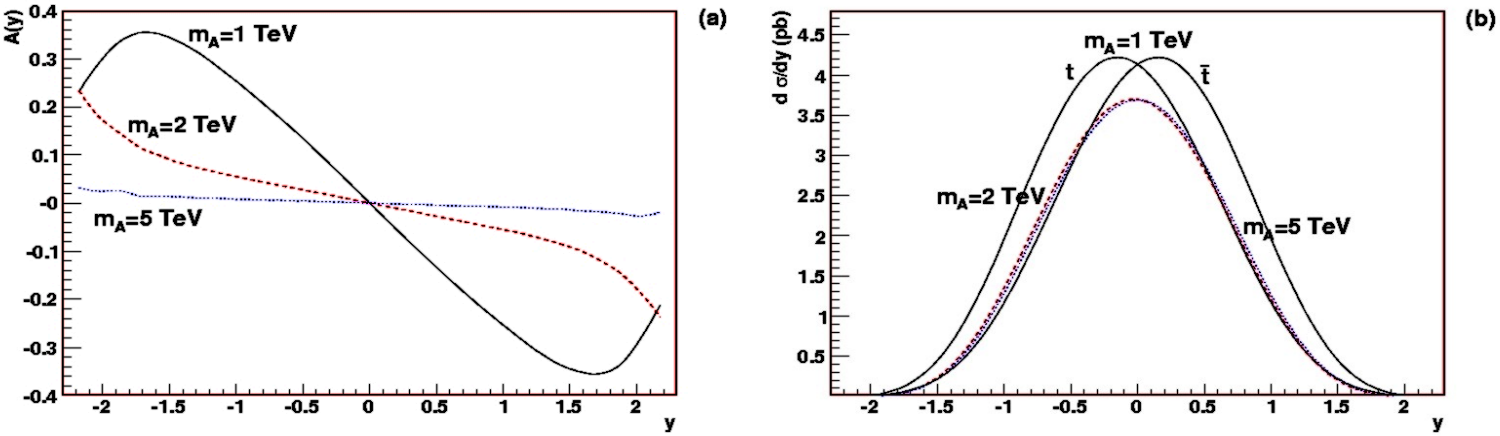
← Better measurement of the top quark cross-section will not lead to a significant improvement in the bound of the axigluon mass

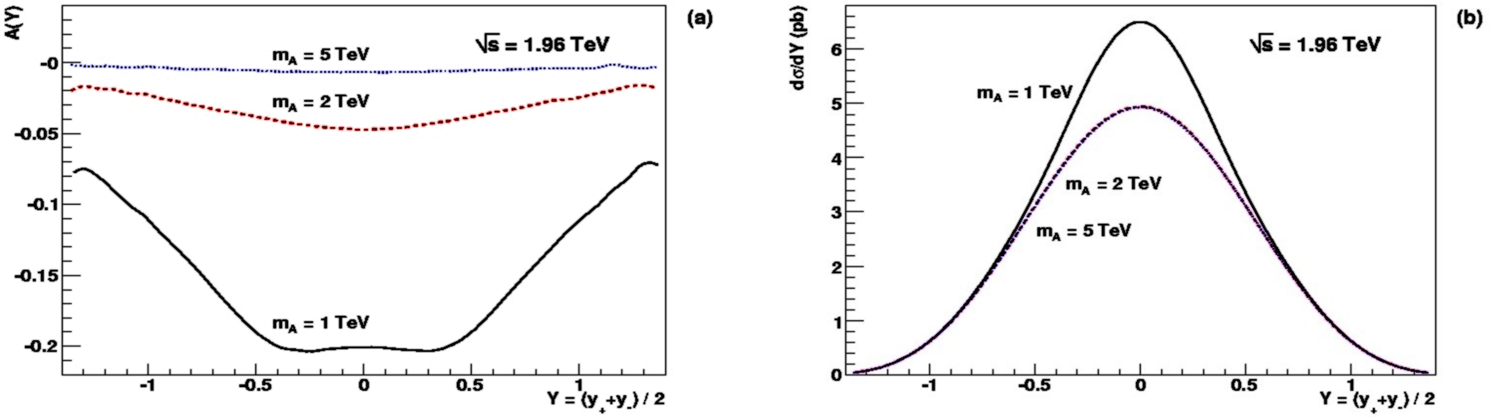
← 2σ and 4σ contours

Axigluon asymmetries at Tevatron

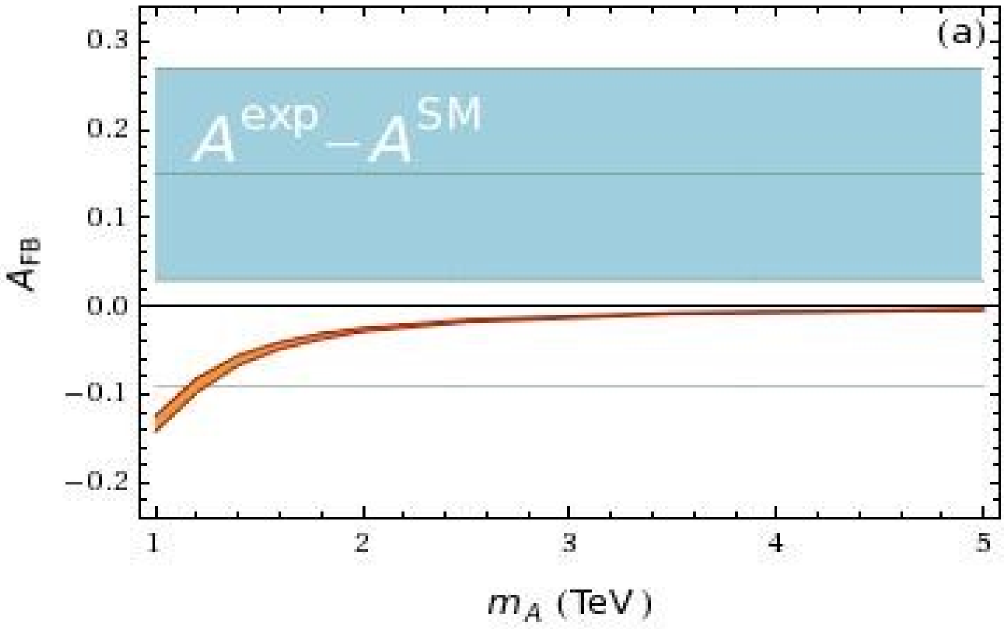
[Antuñano, Kühn, GR, arXiv:0709.1652]

	QCD	m_A=1TeV	m_A=2TeV	m_A=5TeV
A_{FB}	0.051(6)	-0.133(9)	-0.027(2)	-0.0041(3)
$\mathcal{A}$	0.078(9)	-0.181(11)	-0.038(3)	-0.0058(4)





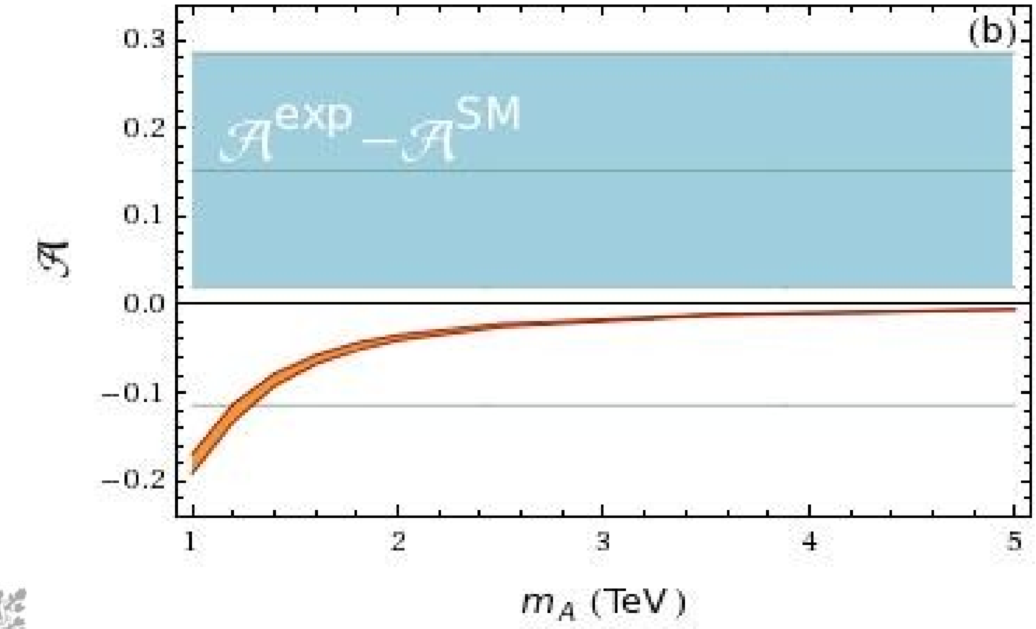
Axigluon mass limits



- **Forward—backward asymmetry**

CDF: 695 pb^{-1}, T. A. Schwarz, Ph.D. Thesis

$$A_{FB} = 0.20 \pm 0.11\,(stat) \pm 0.047\,(sys)$$



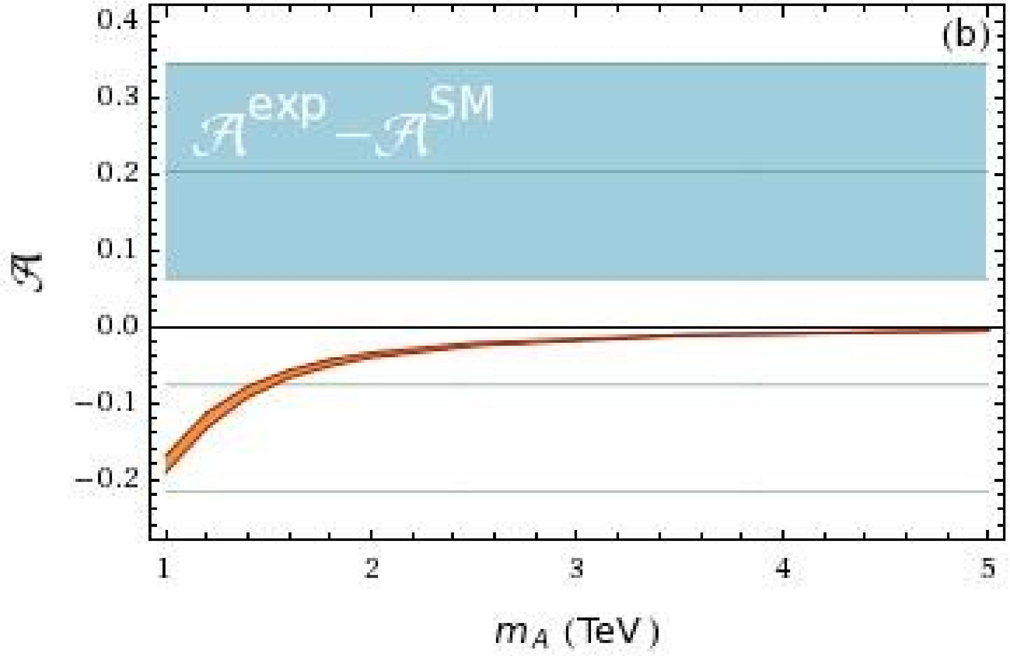
- **Pair asymmetry**

CDF: 995 pb^{-1}, J. Weinelt, Masters thesis

$$A(\Delta y \cdot Q_l) = 0.23 \pm 0.12\,(stat)\ \pm^{0.056}_{0.057}\,(sys)$$

$$m_A > 1.2\,\mathrm{TeV} \quad @ \quad 90\,\%\,C.L.$$

Axigluon mass limits



- **CDF:** 1.7 fb^{-1}, Lepton-Photon 2007

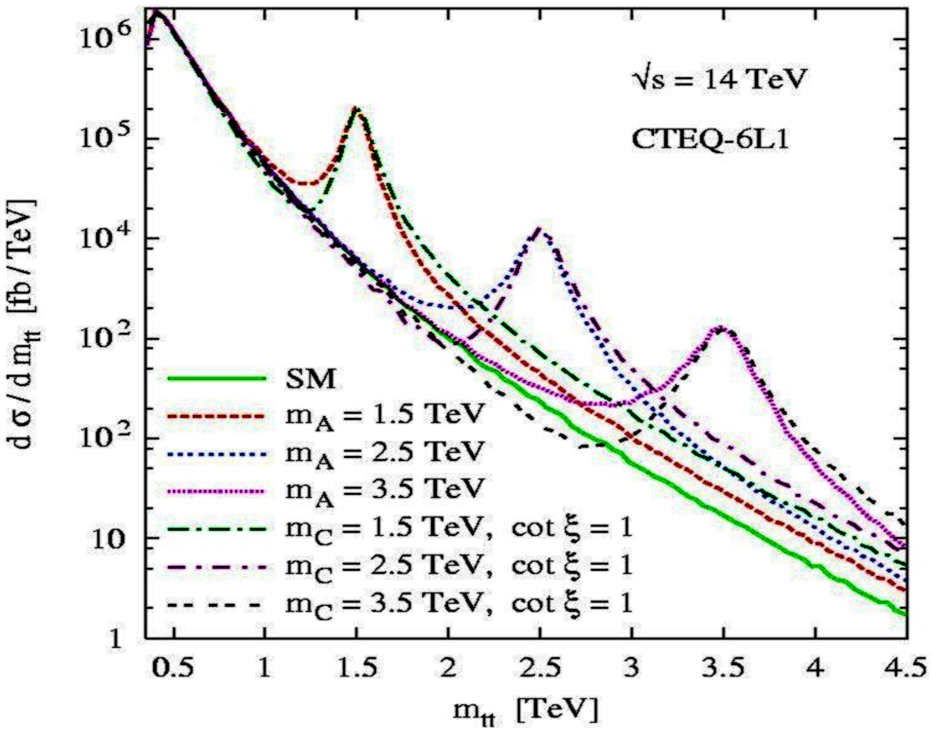
$$A(\Delta y \cdot Q_l) = 0.28 \pm 0.13(stat) \pm 0.05(sys)$$

$$m_A > 1.4\,\mathrm{TeV} \quad @ \quad 90\%\,C.L.$$
$$m_A > 0.9\,\mathrm{TeV} \quad @ \quad 95\%\,C.L.$$

- The largest uncertainty by far is of experimental origin, and statistically dominated
- The FB/pair asymmetry is very sensitive to axigluon masses below 2-2.5 TeV
- Little improvements can lead to a significant change in the lower bound

Axigluon production at LHC

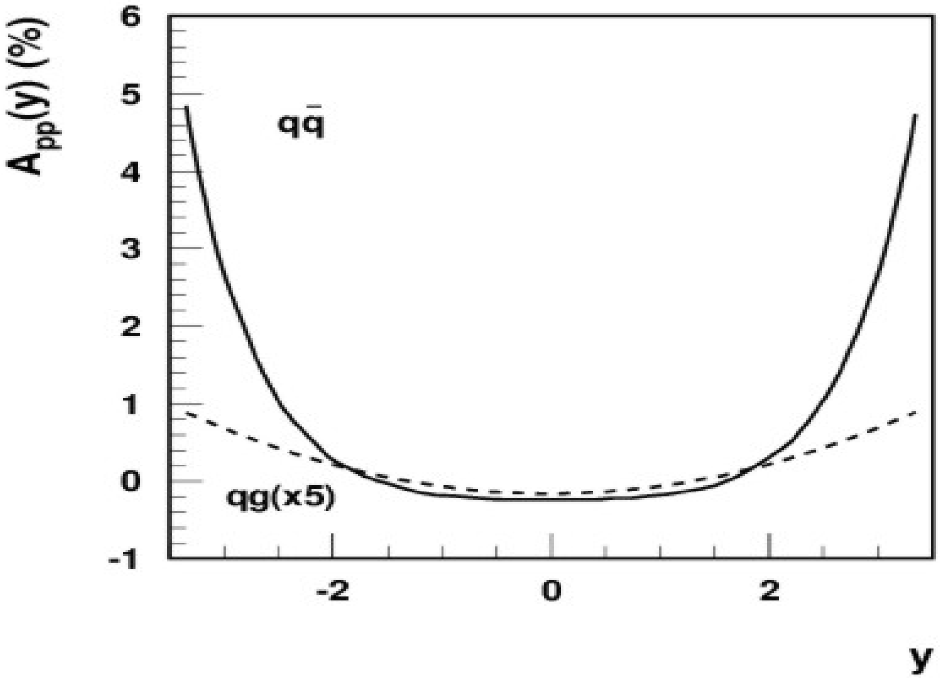
[Choudhury,Godbole,Singh,Wagh, arXiv:0705.1499]

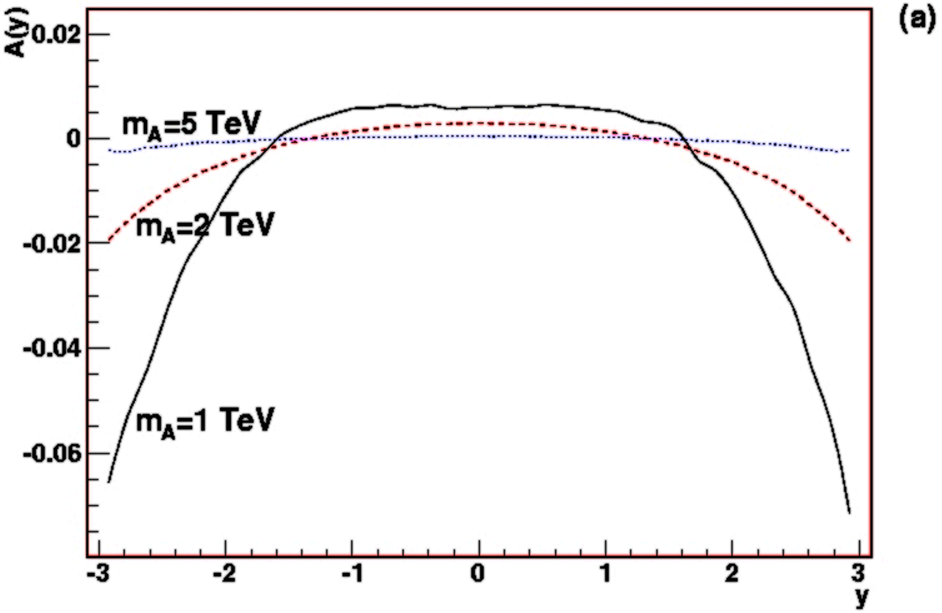


- Exchange of **axigluons** (exotic resonances) will be visible in the top-antitop invariant mass distribution: $1/M^4$ suppressed

- Top quark production at LHC is **forward–backward symmetric** in the laboratory frame as a consequence of the symmetric colliding proton-proton initial state

Differential charge asymmetry at LHC





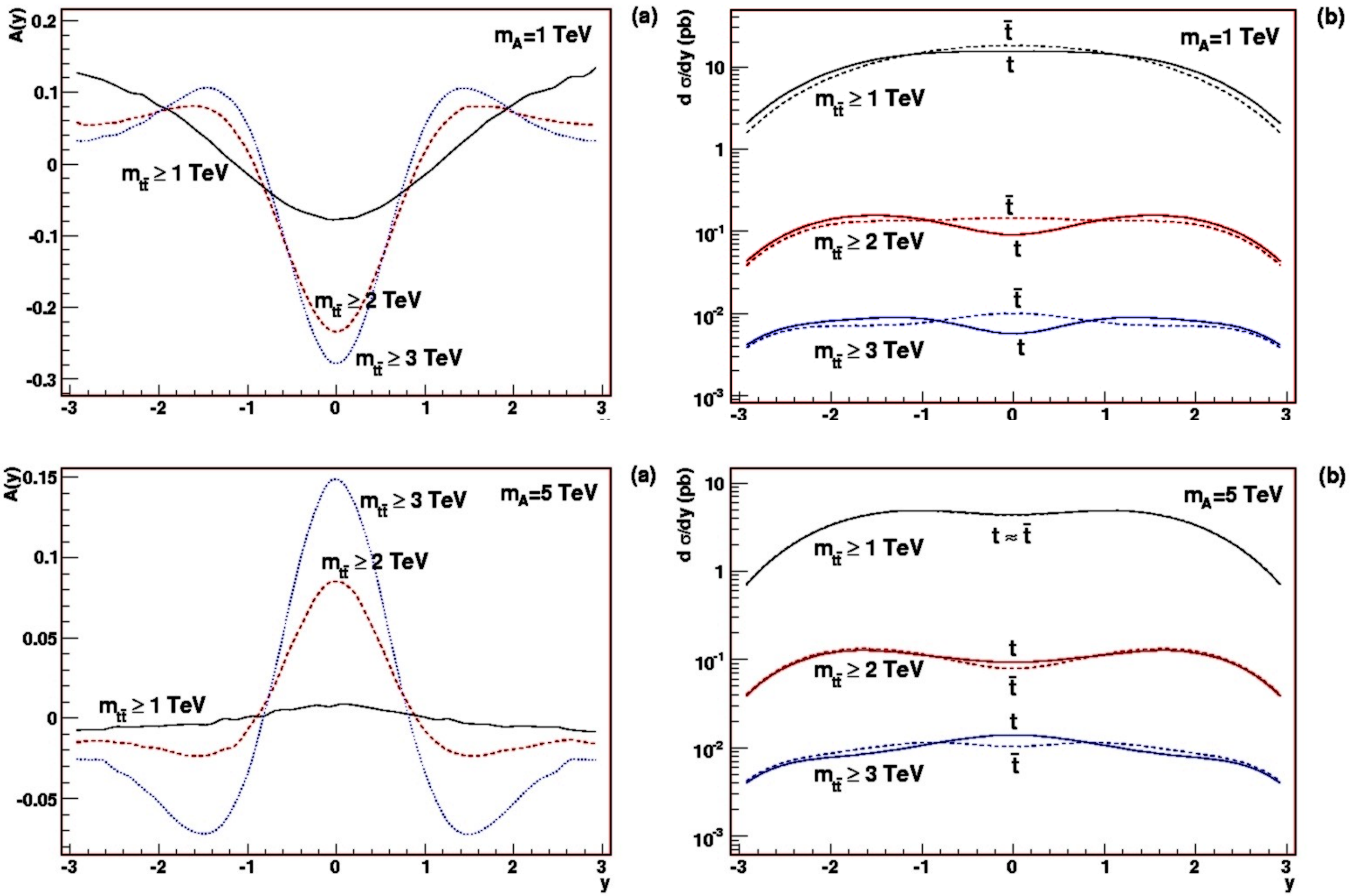
- **charge asymmetry** still visible in suitable distributions, although suppressed because total cross section is dominated by gluon-gluon fusion.

- QCD predicts a slight preference for centrally produced antitop quarks, with top quarks more abundant at very large positive and negative rapidities.

- but sizable in regions with low event rates and large rapidities, where the experimental observation might be difficult.

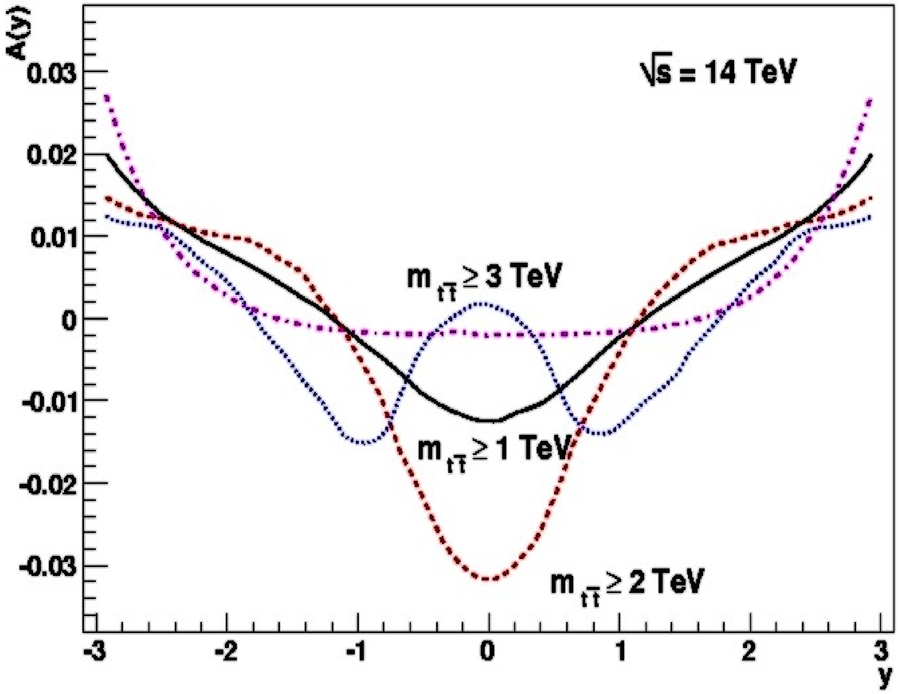
Axigluon asymmetry at LHC

Selecting samples with high invariant masses of the top-antitop pair



Central charge asymmetry at LHC

		QCD	$m_A = 1$ TeV	$m_A = 2$ TeV	$m_A = 5$ TeV
$m_{tt} > 1$TeV	$A_C(y_C=1)$	-0.0086(4)	-0.055(4)	0.025(3)	0.002(1)
	σ_t (lyl <1)	9.7(2.7) pb	34(4) pb	15(2) pb	11(2) pb
$m_{tt} > 2$TeV	$A_C(y_C=1)$	-0.0207(4)	-0.10(2)	-0.048(5)	0.031(9)
	σ_t (lyl <1)	0.19(6) pb	0.28(8) pb	1.7(2) pb	0.26 pb
$m_{tt} > 3$TeV	$A_C(y_C=1)$	-0.0151(7)	-0.10(3)	-0.11(2)	0.057(13)
	σ_t (lyl <1)	0.011(4) pb	0.019(6) pb	0.024(7) pb	0.031(8) pb



Central charge asymmetry

$$A_C(y_C) = \frac{N_t(|y|<y_C) - N_{\bar{t}}(|y|<y_C)}{N_t(|y|<y_C) + N_{\bar{t}}(|y|<y_C)}$$

a maximum is reached at about $y_C=1$

Summary

- We have updated our previous analysis of the inclusive **forward–backward asymmetry** in top quark production at hadron colliders.

- and have proposed a new observable, the **pair asymmetry**, where the effect at Tevatron is flat and about a factor 1.5 larger.

- Top quark production at the LHC is forward–backward symmetric. For samples with large invariant top-antitop mass and rapidities below one, QCD predicts a charge asymmetry of 1-2%

- Preliminary measurements at Tevatron lead to limits on the axigluon mass of about 1.2 – 1.4 TeV @ 90 C.L.

- At LHC large axigluon masses can be explored.