

Update on the top quark charge asymmetry

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The top quark

The top quark is the heaviest known elementary particle: it plays a fundamental role in many extensions of the Standard Model (SM) / alternative mechanisms of EWSB.

Huge statistics from top-antitop quark pair production

Tevatron: $\sigma = 7.6$ (5) pb

Integrated luminosity of 10 fb^{-1} :

7×10^4 top quark pairs

LHC @14 TeV: $\sigma = 940$ (80) pb

with $10 \text{ fb}^{-1}/\text{year}$:

millions of top pairs per year

LHC @7 TeV: $\sigma = 160$ (10) pb

45 pb^{-1} (1 fb^{-1}) by the end of 2010 (2011): 6×10^3 (10^5) top quark pairs



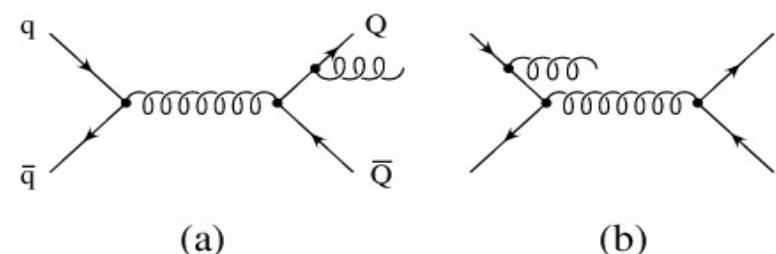
Production and decay channels are promising probes of new physics.

Charge asymmetry in QCD

At $O(\alpha_s^2)$: top and antitop quarks have identical angular distributions

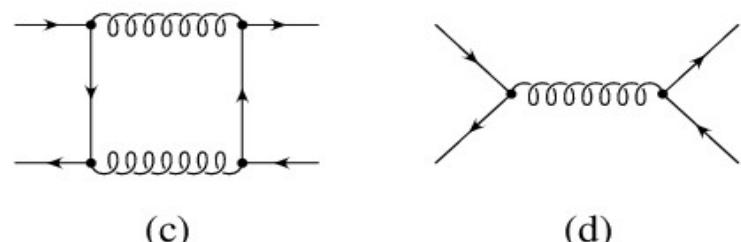
A charge asymmetry arises at $O(\alpha_s^3)$

Interference of ISR with FSR
LO for ttbar+jet
negative contribution



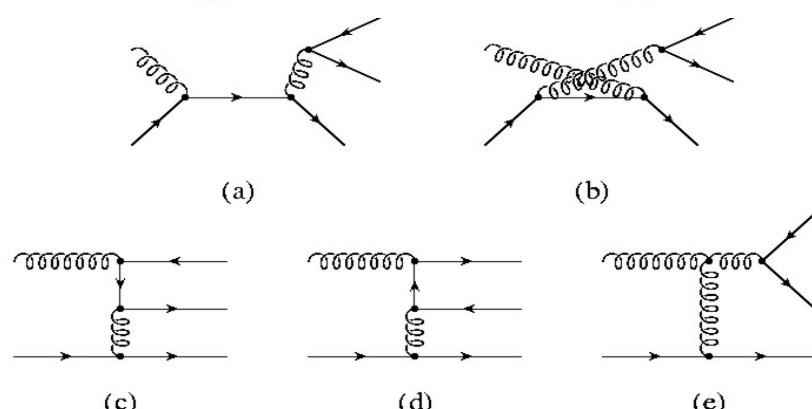
[Kühn, GR, 1998]

Interference of box diagrams with Born
positive contribution



- color factor d_{abc}^2 : pair in color singlet
- Loop contribution larger than tree level
top quarks are preferentially emitted in the direction of the incoming quark

Flavor excitation (qg channel) much smaller



Inclusive asymmetry at Tevatron

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

→ forward-backward

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

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = 0.078(9) \quad \Delta y = y_t - y_{\bar{t}}$$

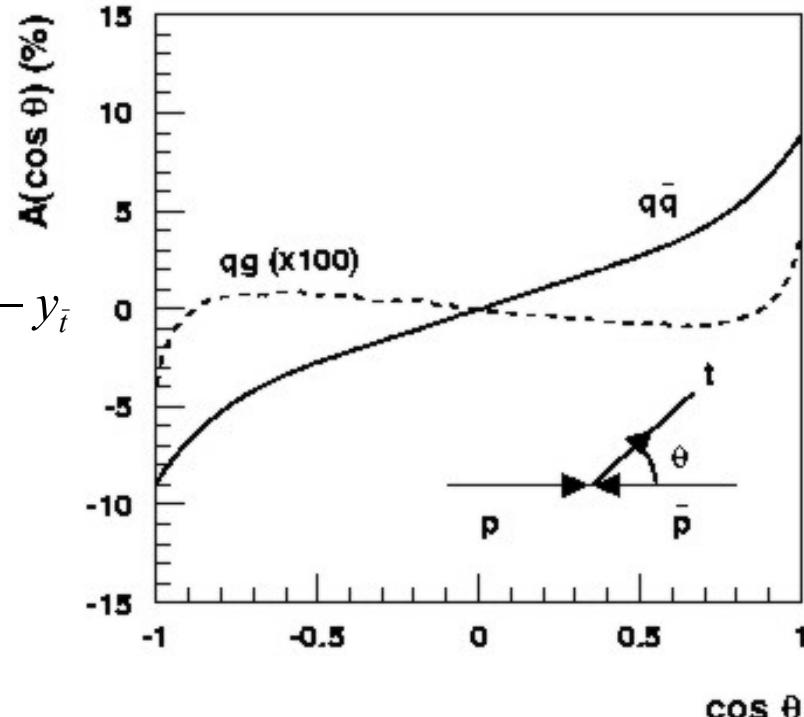
- mixed QCD-EW interference: factor 1.09 included
- stable to NLL threshold resummations (one per mille) [Almeida, Sterman, Vogelsang, 2008]

■ NNLL threshold resummations

[Ahrens, Ferroglia, Neubert, Pecjak, Yang, 2010]

Not expanding the asymmetry in α_s : the asymmetry decreases by 20% at NLO (K factor), but only by 5% at NLO+NNLL

[Kühn, GR, 1998; Antuñano, Kühn, GR, 2008]



* CP violation arising from electric or chromoelectric dipole moments do not contribute to the asymmetry

Asymmetry measurements at Tevatron

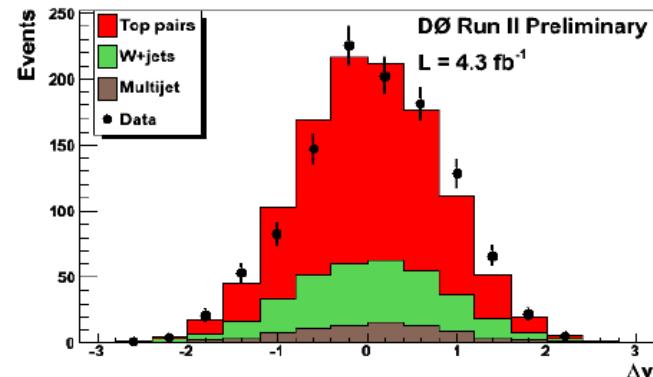
D0 [Conf. Note 6062, PRL101(2008)202001]

uncorrected

ttbar rest frame

$$A_{FB}^{\text{ttbar}} = 0.08 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)} \quad 4.3 \text{ fb}^{-1}$$

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



CDF [Conf. Note 10185 and 9724, PRL101(2008)202001]

ppbar rest frame

$$A_{FB}^{\text{ppbar}} = 0.150 \pm 0.050 \text{ (stat)} \pm 0.024 \text{ (syst)} \quad 5.3 \text{ fb}^{-1}$$

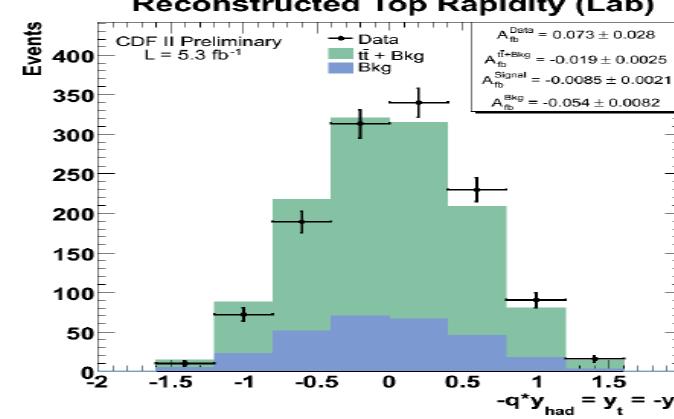
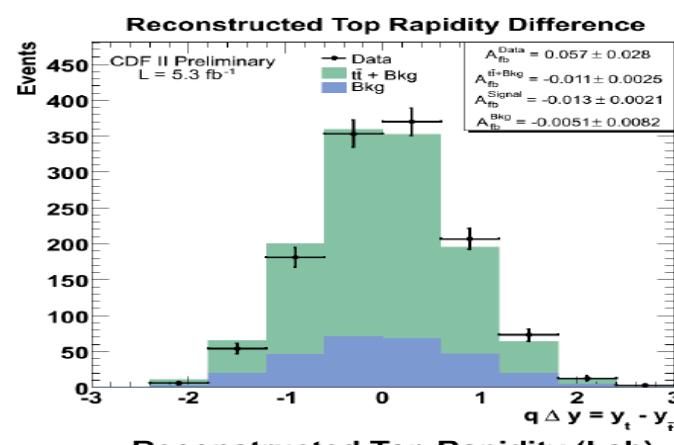
$$A_{FB}^{\text{ppbar}} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (syst)} \quad 3.2 \text{ fb}^{-1}$$

$$A_{FB}^{\text{ppbar}} = 0.17 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (syst)} \quad 1.9 \text{ fb}^{-1}$$

ttbar rest frame

$$A_{FB}^{\text{ttbar}} = 0.158 \pm 0.072 \text{ (stat)} \pm 0.017 \text{ (syst)} \quad 5.3 \text{ fb}^{-1}$$

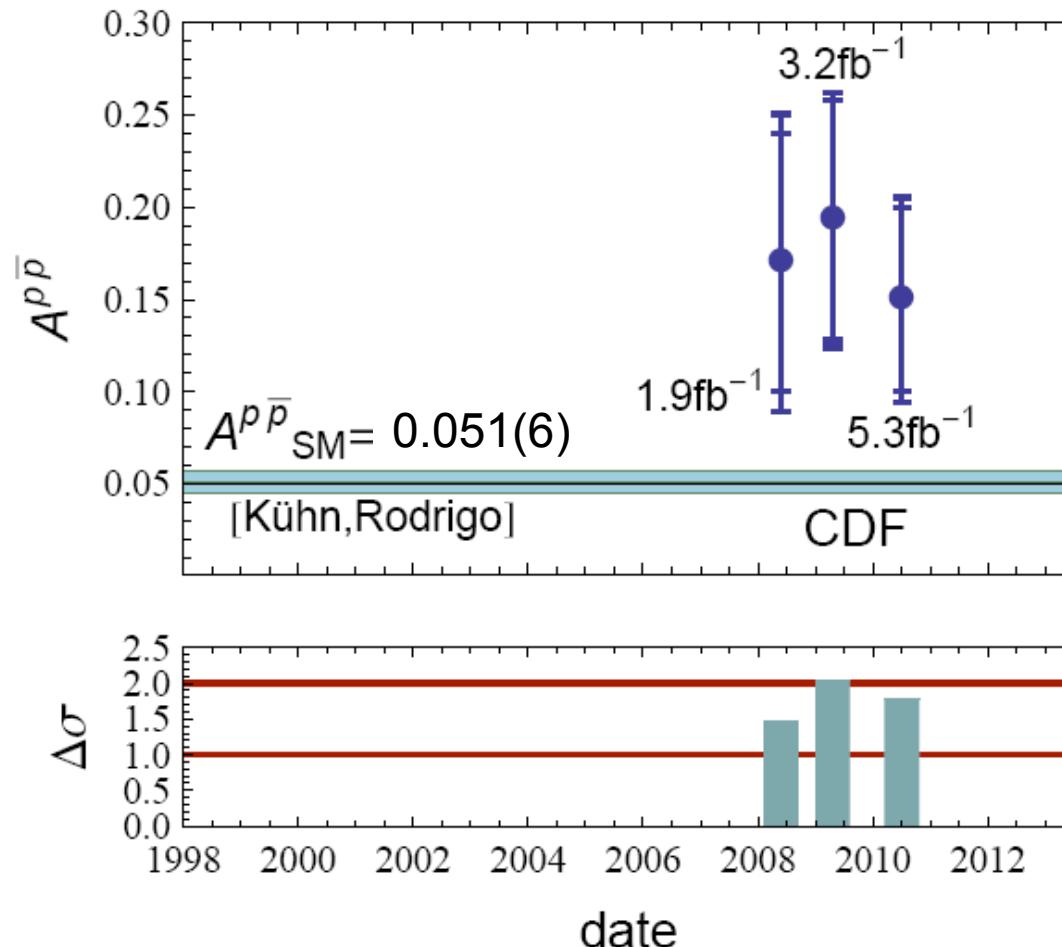
$$A_{FB}^{\text{ttbar}} = 0.24 \pm 0.13 \text{ (stat)} \pm 0.04 \text{ (syst)} \quad 1.9 \text{ fb}^{-1}$$



2.7 σ from zero, $(A^{\text{exp}} - A^{\text{SM}})_{\text{ppbar}} = 0.099 \pm 0.055$

room for BSM within 2 σ

Evolution with time



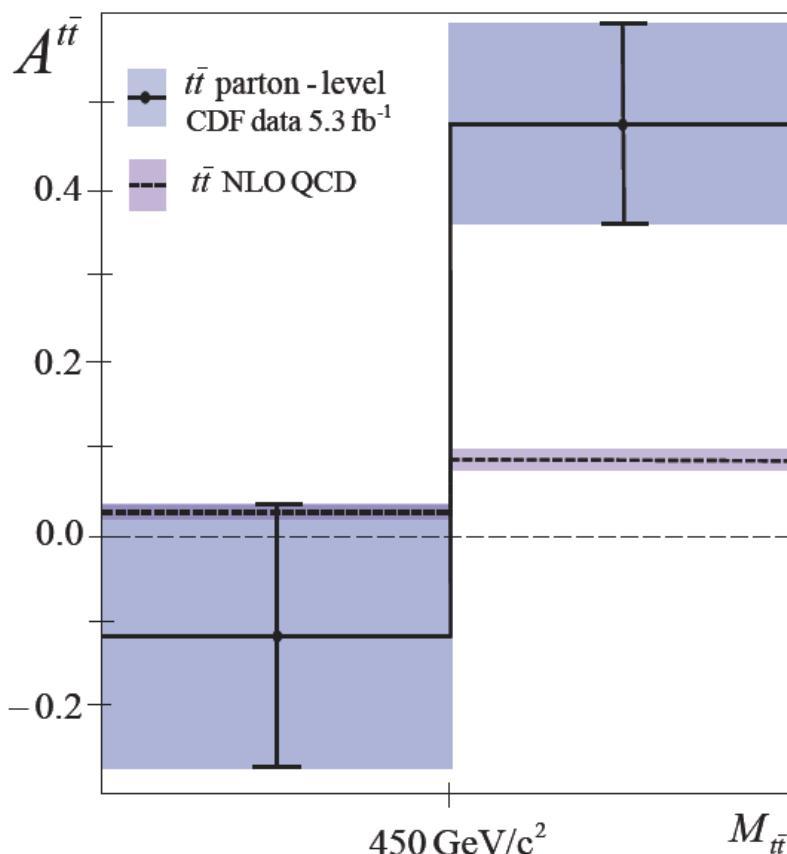
- last measurement, down from 2σ to 1.7σ (lab frame)
- and only 1σ from the measurement in the $t\bar{t}$ rest frame
(and more room for negative contributions BSM)

Invariant mass dependent charge asymmetry

CDF [arXiv:1101.0034] ttbar rest frame 5.3 fb^{-1}

$$A_{\text{FB}}^{\text{ttbar}} (M_{\text{ttbar}} < 450 \text{ GeV}) = -0.116 \pm 0.146 \text{ (stat)} \pm 0.047 \text{ (syst)}$$

$$A_{\text{FB}}^{\text{ttbar}} (M_{\text{ttbar}} > 450 \text{ GeV}) = 0.475 \pm 0.101 \text{ (stat)} \pm 0.049 \text{ (syst)}$$

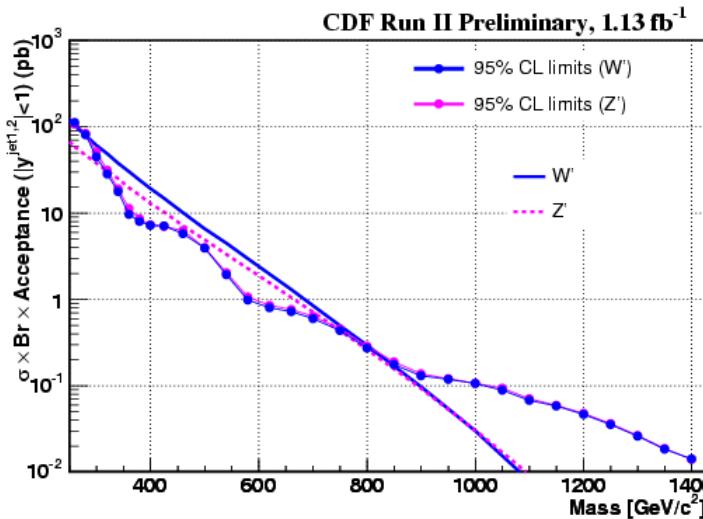
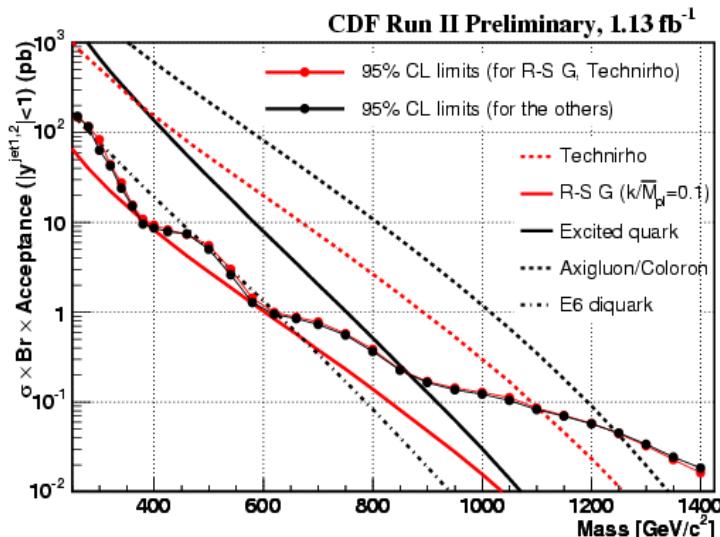


- **below 450 GeV:** negative asymmetry but still compatible with the SM within 1σ
- **above 450 GeV:** positive asymmetry, disagrees with the SM at 3.4σ

Which model BSM



BSM Mass exclusion from Tevatron



Dijet channel CDF arXiv:0812.4036

260-870 GeV/c ²	Excited quark ($f=f'=fs=1$)
260-1100 GeV/c ²	Color-octet technirho [top-color-assisted technicolor (TC2) couplings, $M'_8=0$, $M(\pi_{22}^8)=5M(\rho)/6$, $M(\pi_{22}^1)=M(\pi_{22}^8)/2$, $M_8=5M(\rho)/6$]
260-1250 GeV/c ²	Axigluon and flavor-universal coloron (mixing of two SU(3)'s, $\cot(\theta)=1$)
290-630 GeV/c ²	E_6 diquark
280-840 GeV/c ²	W' (SM couplings)
320-740 GeV/c ²	Z' (SM couplings)

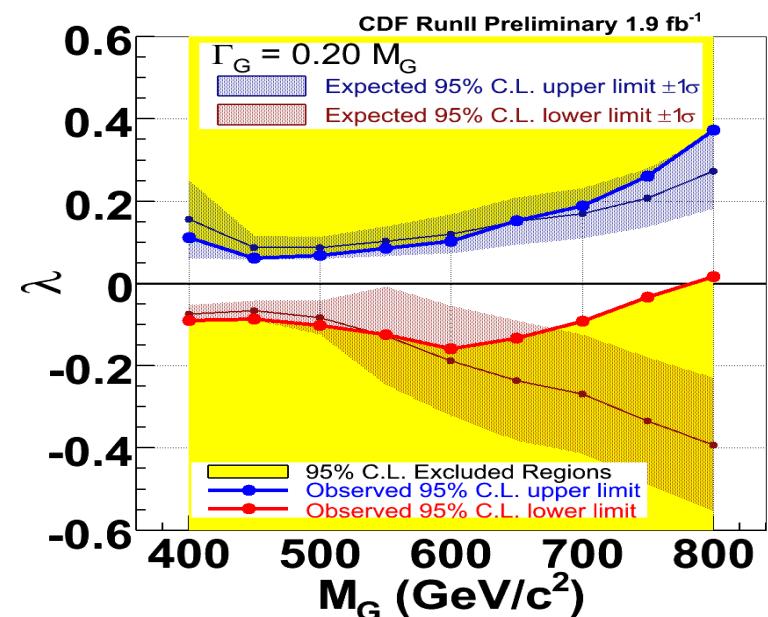
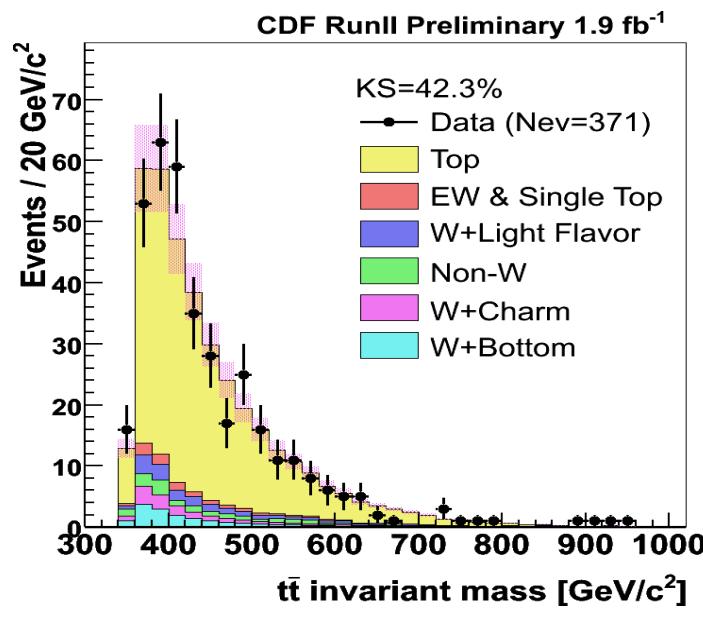
* Low mass window for axigluons also excluded [Doncheski, Robinet, 97] from hadronic Z -decays

Other channels CDF

WW/WZ (evjj)	$m_{Z'} > 545$ GeV $m_{W'} > 515$ GeV $m_{\text{graviton}} > 606$ GeV	2.9 fb ⁻¹
ZZ	$m_{\text{graviton}} > 491$ GeV ($k/M_{\text{Pl}} = 0.1$)	3.0 fb ⁻¹
tb	$m_{W'} > 800$ GeV for $m_{W'} > m_{vR}$ $m_{W'} > 825$ GeV for $m_{W'} < m_{vR}$	1.9 fb ⁻¹

ttbar channel at Tevatron

D0	Lepton+jet	topcolor-assisted technicolor, leptophobic $m_{Z'} > 820 \text{ GeV}$	3.6 fb^{-1}
CDF	All hadronic	$m_{Z'} > 805 \text{ GeV}$ (SM couplings)	2.8 fb^{-1}
CDF	Lepton+jet	Topcolor leptophobic $m_{Z'} > 720 \text{ GeV}$ Out of range of sensitivity to SM Z'	1 fb^{-1}
CDF	Lepton+jet	Limits on massive gluon coupling $\lambda = g_V^q g_V^t$ as a function of width	1.9 fb^{-1}



Chiral Color Models

[Pati , Salam, PLB58(1975)333; Hall,Nelson, PLB153(1985)430;
Frampton, Glashow, PLB190(1987)157; PRL58(1987)2168]

Extend the standard color gauge group to

$$\mathbf{SU(3)_L \times SU(3)_R \rightarrow SU(3)_C}$$

- different implementations with new particles in varying representations (anomaly cancellation requires extra fermions), but
- model-independent prediction: existence of a massive color-octet axial-vector 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.
- because of parity a single axigluon do not couple to gg
- **Asymmetric Chiral Color** [Cuypers, ZPC48(1990)639]: chiral color with different couplings ξ_1, ξ_2 : $g_V = g_S \cot 2\theta, g_A = g_S / \sin 2\theta$

Colorons

[Hill, PLB266(1991)419; Hill, Parke, PRD 49(1994)4454;
Chivukula, Cohen, Simmons, PLB380(1996)92]

Extend the standard color gauge group to

$$\mathbf{SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C}$$

- with gauge couplings ξ_1 , ξ_2 and $\xi_1 \ll \xi_2$
- massive gluons / color-octet vector boson (colorons)
- coupling to quarks $g_S \cot \theta = g_S (\xi_2 / \xi_1) > g_S$
- no **charge asymmetry**

GUT theories

- Grand Unified Theories (GUT) based on larger gauge groups, e.g., E6 and SO(10), or left-right symmetric models often introduce additional gauge bosons, such as W' and Z' , which decay to $f\bar{f}$ and $f\bar{f}$, respectively.
- The E6 GUT model also predicts the presence of a diquark (colored scalars) which decays to qq or $q\bar{q} q\bar{q}$.
- colored scalars (singlet, triplet, sextet and octet) in SU(5) GUT
$$5_H = H_1 + T = (\mathbf{1}, \mathbf{2}, 1/2) + (\mathbf{3}, \mathbf{1}, -1/3)$$
$$24_H = \Sigma_i = (\mathbf{8}, \mathbf{1}, 0) + (\mathbf{1}, \mathbf{3}, 0) + (\mathbf{3}, \mathbf{2}, -5/6) + (\mathbf{3}\bar{\mathbf{2}}, \mathbf{2}, 5/6) + (\mathbf{1}, \mathbf{1}, 0)$$
$$45_H = (\mathbf{8}, \mathbf{2}, 1/2) + (\mathbf{6}\bar{\mathbf{2}}, \mathbf{1}, -1/3) + (\mathbf{3}, \mathbf{3}, -1/3) + (\mathbf{3}\bar{\mathbf{2}}, \mathbf{2}, -7/6) + (\mathbf{3}, \mathbf{1}, -1/3) + (\mathbf{3}\bar{\mathbf{2}}, \mathbf{1}, 4/3) + (\mathbf{1}, \mathbf{2}, 1/2)$$
- e.g., **scalar color-octet in Adjoint SU(5)** [Fileviez et al., 2008]

$$\Phi_1 = (\mathbf{8}, \mathbf{2}, 1/2) \subset 45_H$$

Unification and proton decay $M_{\Phi_1} < 440$ TeV

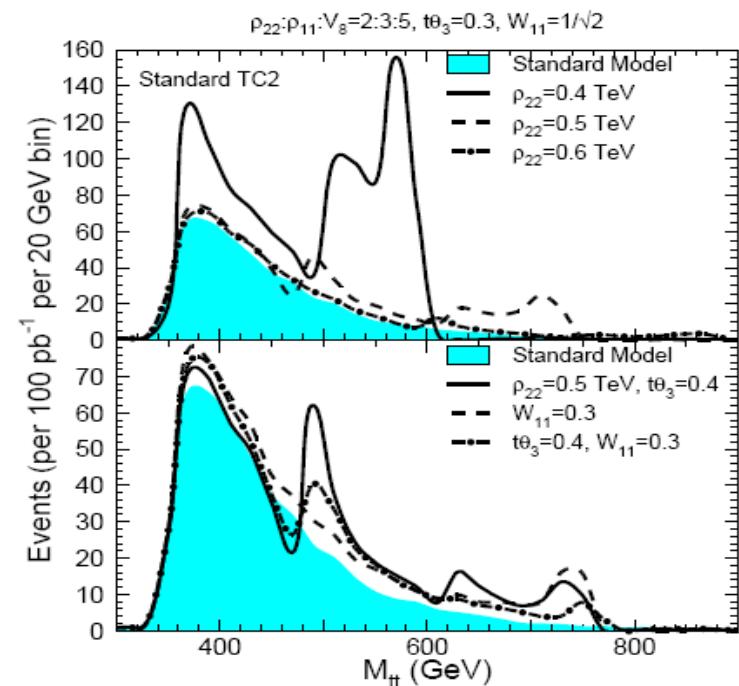
Top color assisted technicolor (TC2)

[Hill, PLB345(1995)483; Lane, Ramana, PRD 44 (1991) 2678;
Lane, Mrenna, PRD67(2003) 115011]

Combine extended technicolor and topcolor assisted technicolor

$$G_{ETC} \times [SU(3)_1 \times U(1)_1] \times [SU(3)_2 \times U(1)_2] \times SU(2)_L \rightarrow SU(3)_C \times U(1)_{EM}$$

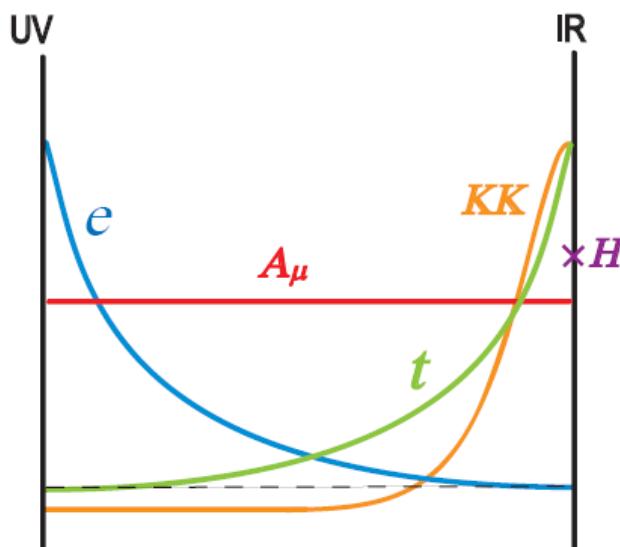
- where $SU(3)_1 \times U(1)_1$ couples preferentially to the third generation, and the weaker $SU(3)_2 \times U(1)_2$ to the first and second
- Z' (leptophobic or not), 8 colorons and 4 color-octet technirho vector mesons (ρ_{T8}) which decays to $q\bar{q}$ or gg



Warped extra dimensions

[Randall, Sundrum, PRL 83, 3370 (1999);
Dicus, McMullen, Nandi, PRD65 (2002) 076007]

- The RS model of a warped extra dimension offers a solution for the hierarchy between the electroweak scale and Planck scale M_{Pl} by introducing an extra spacial dimension. Predicts a **Kaluza-Klein** tower of graviton states (**RS gravitons**) which decay to $\text{f}\bar{\text{f}}$ or gg .
- **RS Kaluza-Klein gauge bosons (KK g^* , Z' , W')**: explains mass hierarchy between top and light quarks, with preferential couplings to top quarks, no couplings to gg (odd number of g^*), suppression of FCNC



Interactions are given by wave function overlap

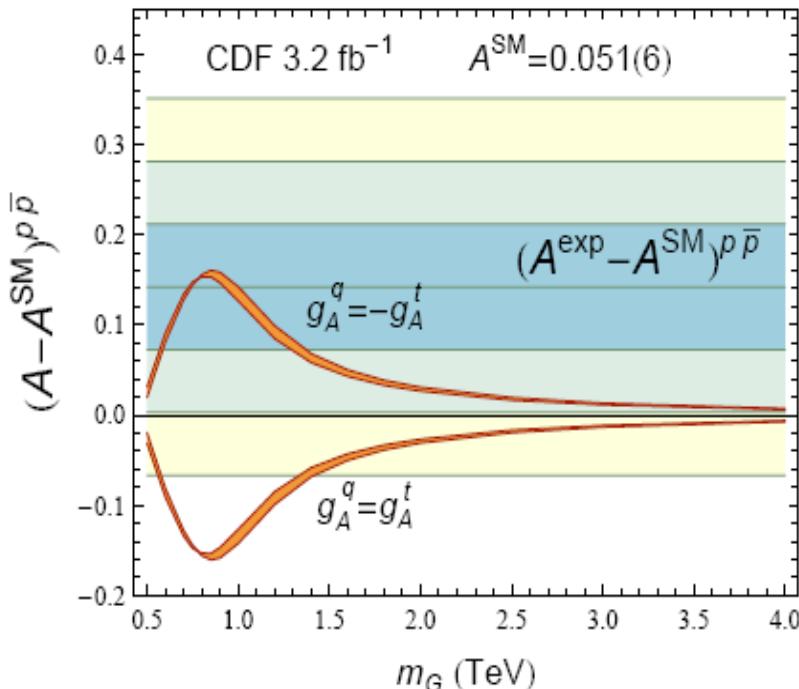
- The top quark: close to Higgs profile
- KK modes have masses $\text{O}(1 \text{ TeV})$: localized near the IR brane too: preferential couplings to top quarks
- EW precision measurements: $M_{Z'} > 3 \text{ TeV}$
[Agashe et al. 2003]

save the axigluon 2009

Color-octet resonances might produce a charge asymmetry at LO

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

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

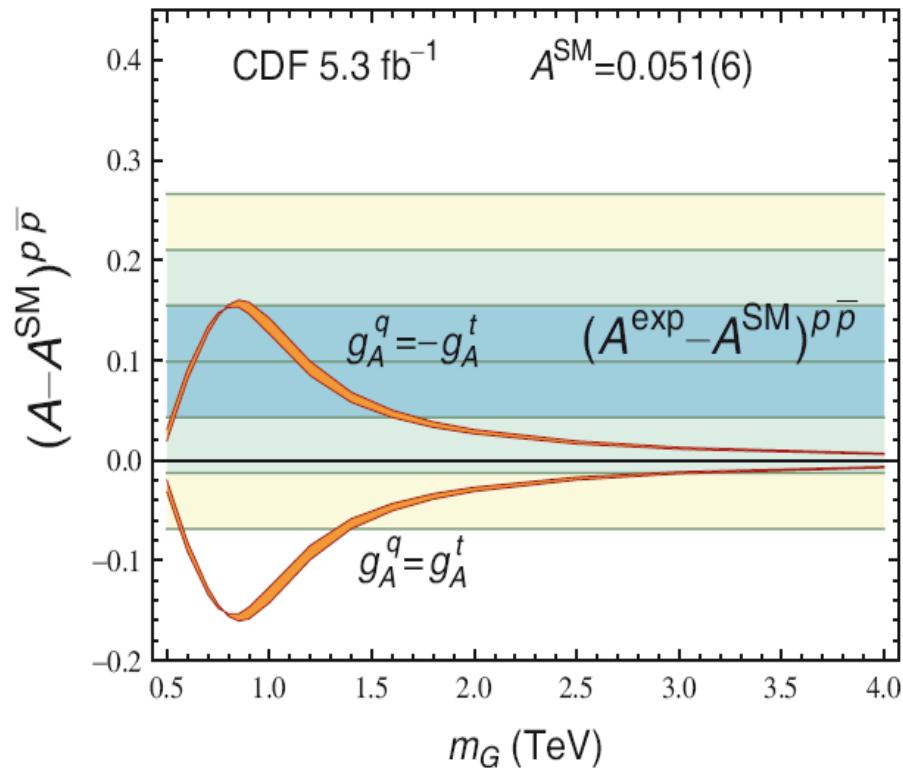
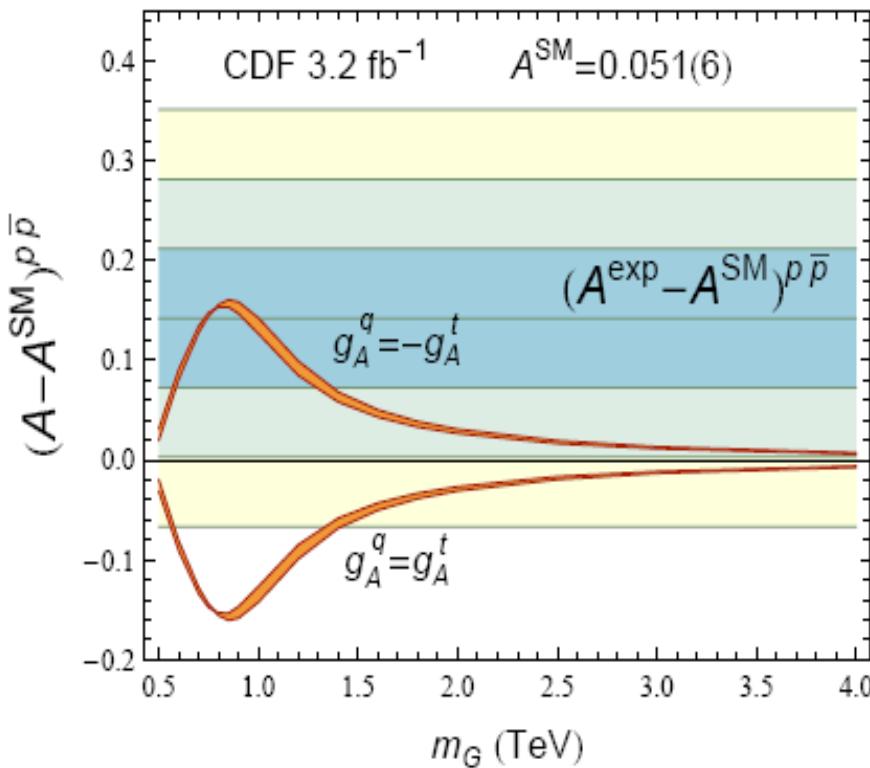


- The FB asymmetry disfavoured at 2σ vanishing or negative contributions (axigluons or colorons)
- $m_G > 1.6 \text{ TeV}$ at 99% C.L. ($g_V=0, g_A=1$)
- Larger exclusion limit than dijet channel.
- It is still possible to generate a positive asymmetry if $\text{sign}(g_A^q) = -\text{sign}(g_A^t)$

[Ferrario, GR, arXiv:0906.5541]

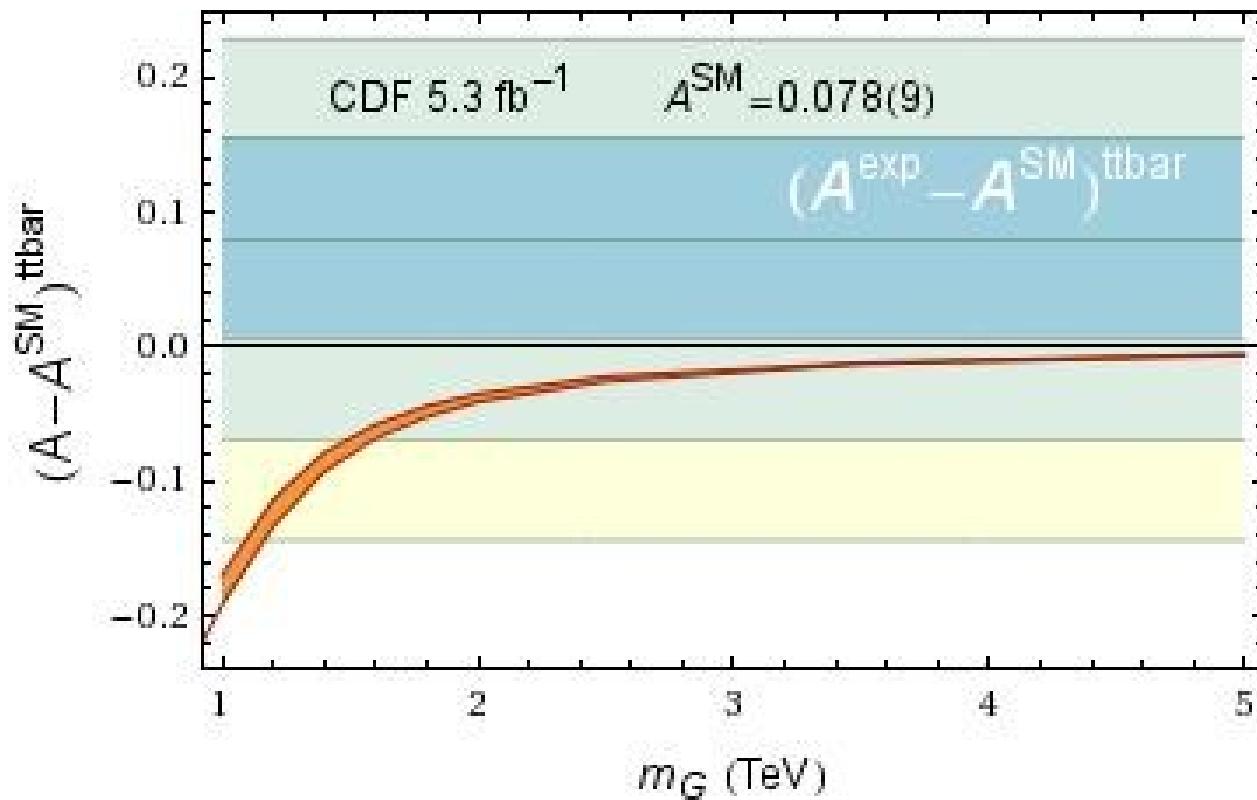
[Frampton, Shu, Wang, arXiv:0911.2955]

save the axigluon 2010

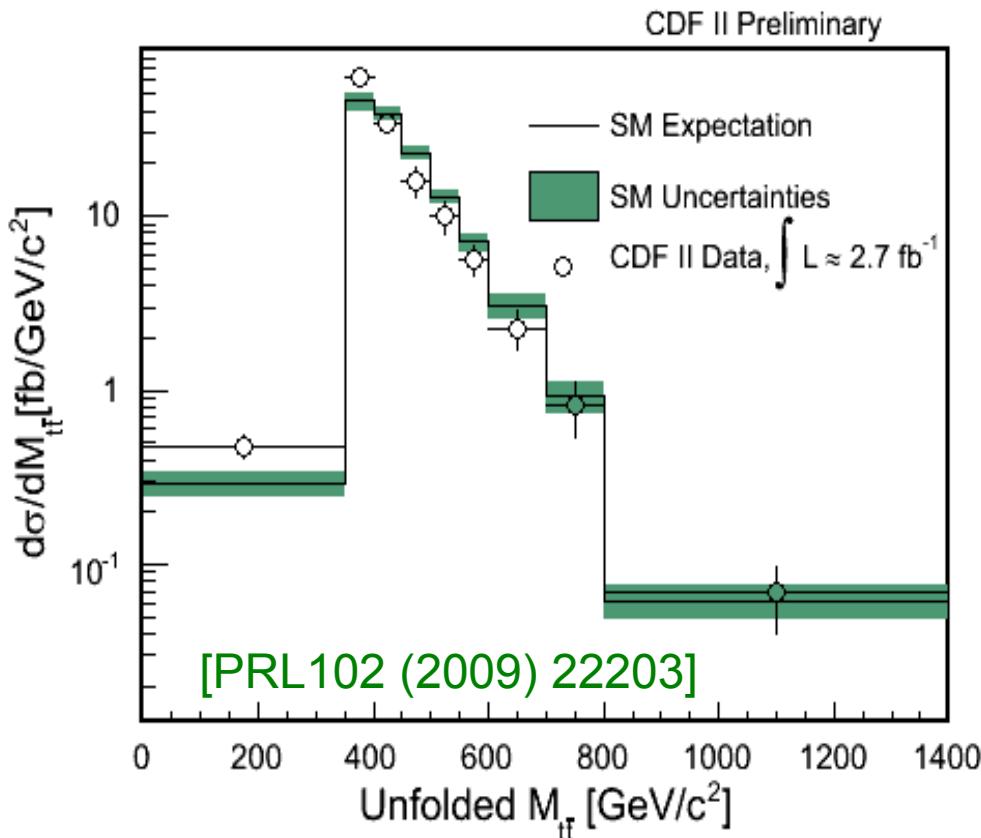


■ still some room for negative or vanishing contributions within 2 σ

$m_G > 2.5 \text{ TeV}$ at 95% C.L. ($g_V=0, g_A=1$)



The invariant mass distribution



- larger charge asymmetry with smaller resonant mass: sets upper bound
- The last bin of $d\sigma/dM_{t\bar{t}}$ is the most sensible to masses of $O(1\text{TeV})$: sets lower bound on the mass
- Total cross section less sensible

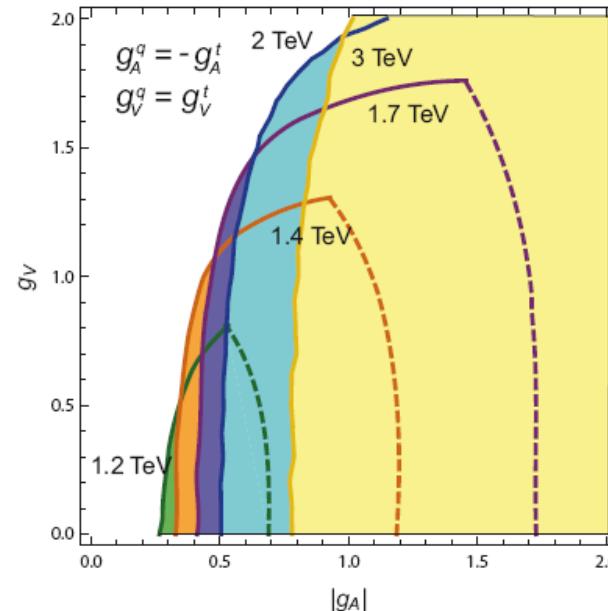
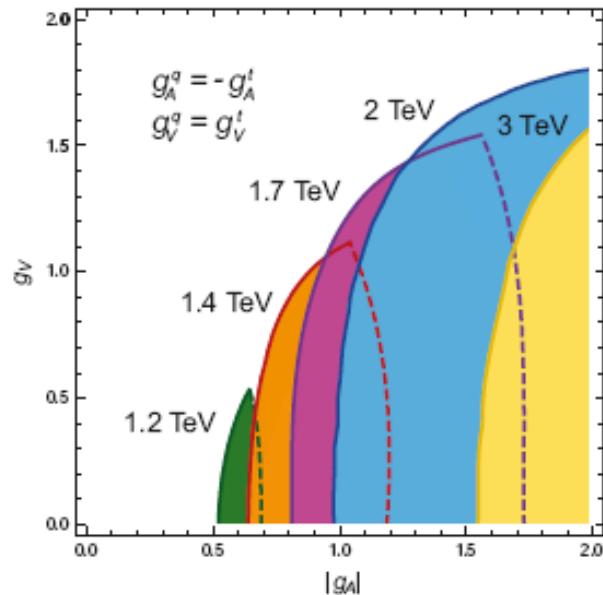
$$d\sigma/dM_{t\bar{t}}(0.8\text{--}1.4\text{TeV}) = \\ 0.07 \pm 0.032_{stat} \pm 0.015_{sys} \pm 0.004_{lum} (\text{fb GeV}^{-1})$$

Flavour non-universal axigluon 2009/2010

[Ferrario, GR, arXiv:0906.5541,arXiv:1007.3284]

- Combining limits on the charge asymmetry (solid lines) and the invariant mass distribution (dashed)

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



- 3.2 fb⁻¹, 90 % C.L. contours

Fixing the couplings sets **lower** and **upper** bounds on the mass

$$|g_A| = 1 \quad 1.33 \text{ TeV} < m_G < 2 \text{ TeV} \quad @90\% \text{C.L.}$$

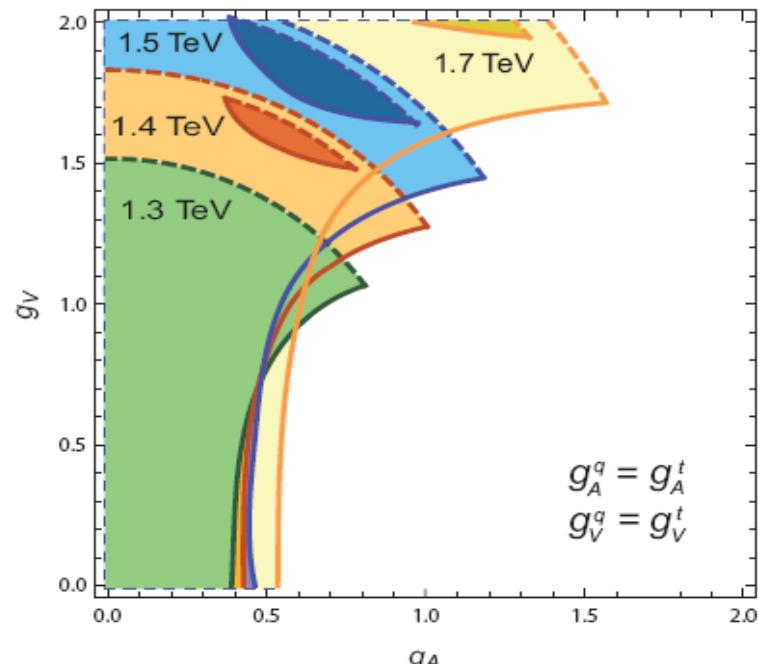
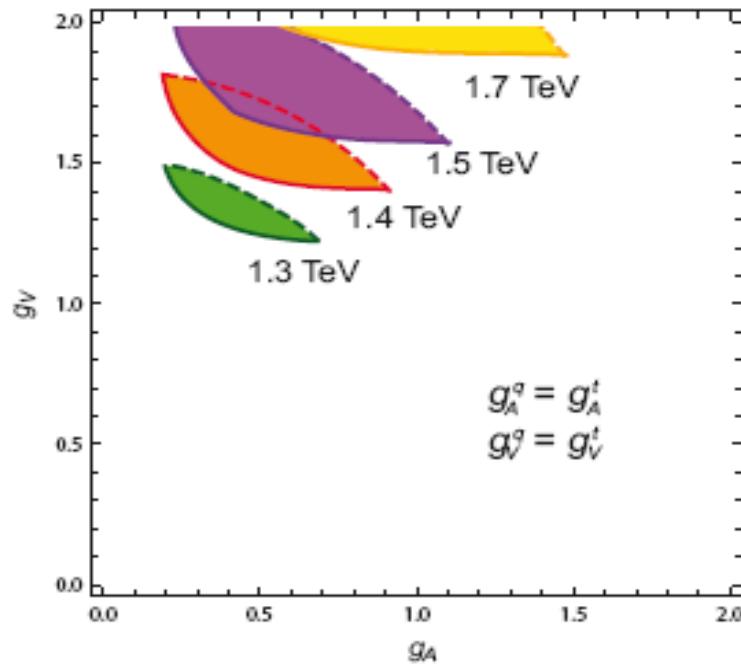
■ 5.3 fb⁻¹

■ Frampton model ($g_V = g_S \cot 2\theta$, $|g_A| = g_S / \sin 2\theta$) constrained by neutral Bd-meson mixing [Chivukula, Simmons, Yuang, arXiv:1007.0260, 3.2 fb⁻¹]

Flavour universal axigluon 2009/2010

[Ferrario, GR, arXiv:0906.5541,arXiv:1007.3284]

- positive BSM asymmetry if squared resonance amplitude dominates, which is proportional to $g_V^q g_V^t g_A^q g_A^t$
- Combining limits on the charge asymmetry (solid lines) and the invariant mass distribution (dashed)



- 3.2 fb^{-1} no overlapping region @ 90 % C.L.
 $m_G > 1.2 \text{ TeV}$ @ 95 % C.L.

$$|g_A| = 1 \quad \{m_G > 1.44 \text{ TeV} \quad g_V > 1.45$$

- 5.3 fb^{-1}
90 % and 95 % C.L. contours
 $m_G > 1.3 \text{ TeV}$ @ 90 % C.L.

Z' and W' in the t-channel

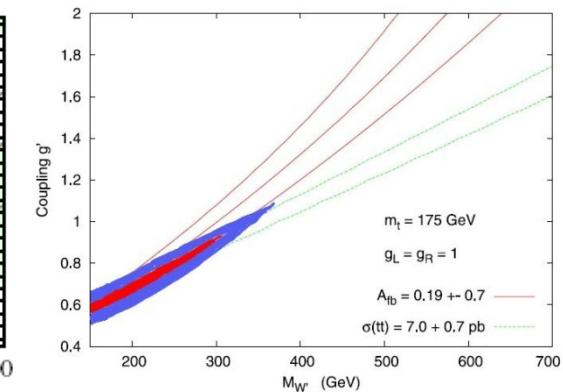
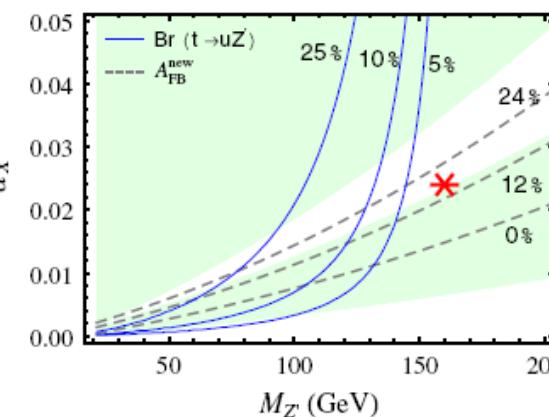
Flavour violating weak vector bosons in the t-channel (mostly):

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

$$L = g_X Z'_\mu (\bar{u} \gamma^\mu P_R t + \epsilon_X \bar{u}_i \gamma^\mu P_R u_i)$$

best fit: $m_{Z'} = 160$ GeV , $\alpha_X = 0.024$

light to avoid $uu \rightarrow tt$ (same sign dileptons)
 $\epsilon_X \neq 0$ to suppress $uubar \rightarrow Z'Z'$ (like sign tt)



- [Cheung,Keung,Yuan, arXiv:0908.2589]

$$L = -g' W'_\mu \bar{t} \gamma^\mu (g_V + g_A \gamma_5) d$$

- Third generation enhanced LR model $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$: $uubar \rightarrow Z' \rightarrow ttbar$
[[Cao,Heng,Wu,Yang, arXiv:0912.1447](#)] No u_R - t_R mixing (s-channel) ✗, with mixing (t-channel) ✓

- Asymmetric LR model $SU(2)_L \times (SU(2)' \times U(1)' \rightarrow U(1)_Y)$: Z' (s-channel) and W' (t-channel)
[[Barger,Keung,Yu, arXiv:1002.1040](#)]: $m_{Z'} = 190$ GeV , $m_{W'} = 175$ GeV

- [[Cao,McKeen,Rosner,Saughnessy,Wagner, arXiv:1003.3461](#)]: W' large couplings and large amount of fine tuning



Requires light Z' and W' : $O(200$ GeV)
or large flavour violating couplings

Scalars in the t-channel

Flavour violating scalars in the t-channel: uubar \rightarrow ttbar

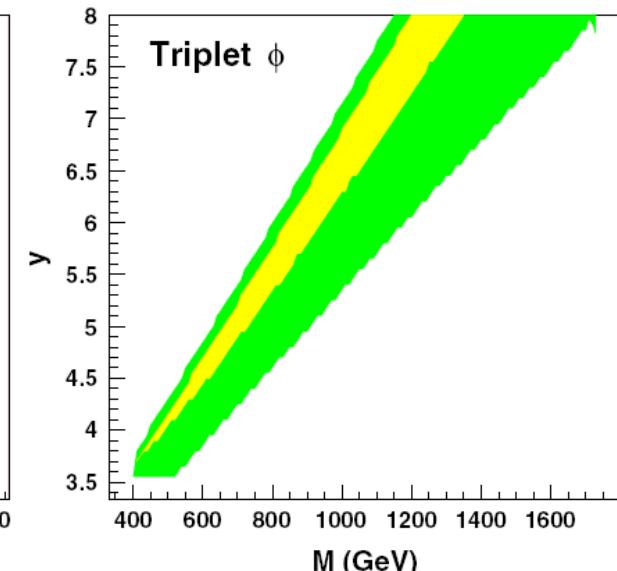
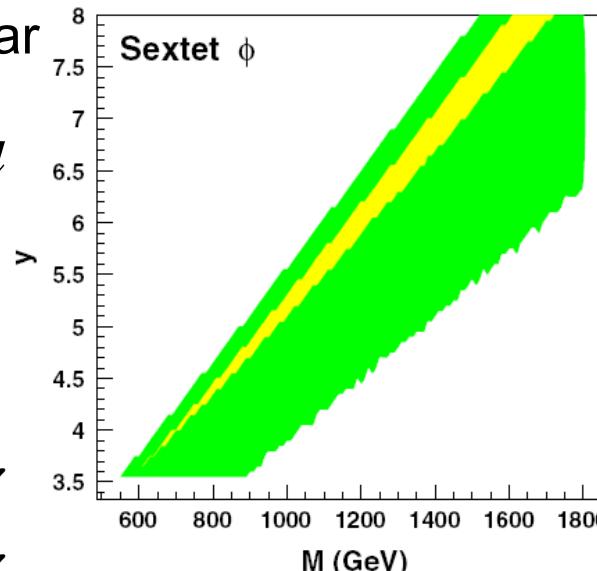
$$L = \phi^a \bar{t} T^a (g_S + g_P \gamma_5) u$$

$$y = \sqrt{g_S^2 + g_P^2}$$

- Singlet (1,2,-1/2) ✗
- Triplet (3bar,1,4/3) ✓
- Sextet (6,1,4/3) ✓
- Octet (8,2,-1/2) ✗

* (6,3,1/3) and (3bar,3,1) more constrained from flavour observables

[Shu,Tait,Wang, arXiv:0911.3237]



Requires large flavour violating couplings
Potential uu \rightarrow tt (same sign dileptons):
singlet and octet; sextet in the s-channel

R-parity violating MSSM: sleptons (singlet) ✗, and squarks (triplet) ✓, in ddbar \rightarrow ttbar

[Cao,Heng,Wu,Yang, arXiv:0912.1447]

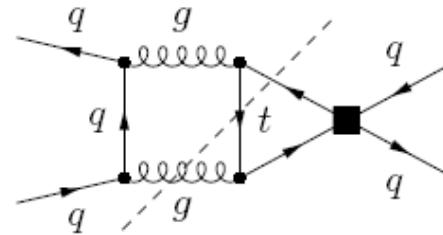
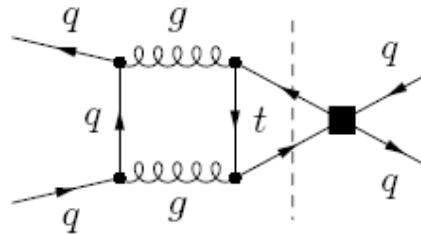
GUT: triplet (3bar,1,4/3) ✓ ($M_{tt\bar{b}} \rightarrow m_\phi < O(\text{TeV})$), octet (8,2,-1/2) ✗ [Dorsner et.al. arXiv:0912.0972]

Triplet ✓ and sextet ✗ [Arhrib,Benbrik,Chen,arXiv:0911.4875]

EFT: singlet ✓, triplet ✗, sextet ✗, octet ✓ [Jung,Ko,Lee,Nam,arXiv:0912.1105]

EFT

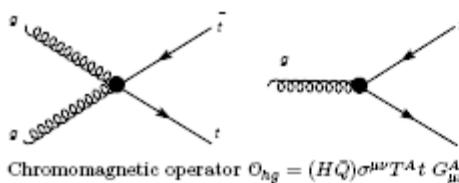
- [Bauer, Goertz, Haisch, Pfoh, Westhoff, arXiv:1008.0742] RS models



Large FB has to arise from tree-level effects (s or t-channel)

- [Zhang, Willenbrock, arXiv:1008.3869] Next talk

- [Degrande, Gerard, Grojean, Maltoni, Servant, arXiv:1010.6304] Full set of dimension six operators (only interference with SM)

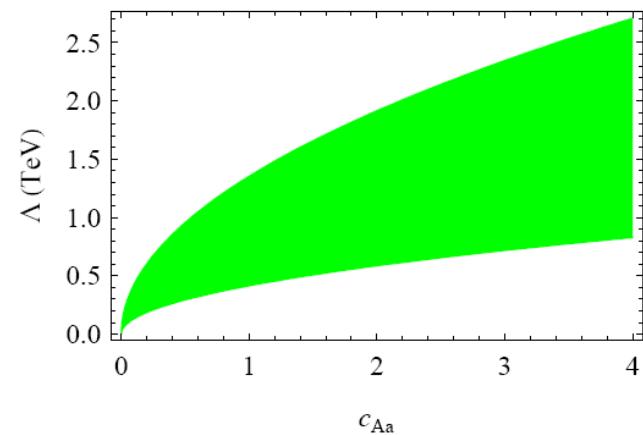


Chromomagnetic operator $\mathcal{O}_{hg} = (H\bar{Q})\sigma^{\mu\nu}T^A t G_{\mu\nu}^A$

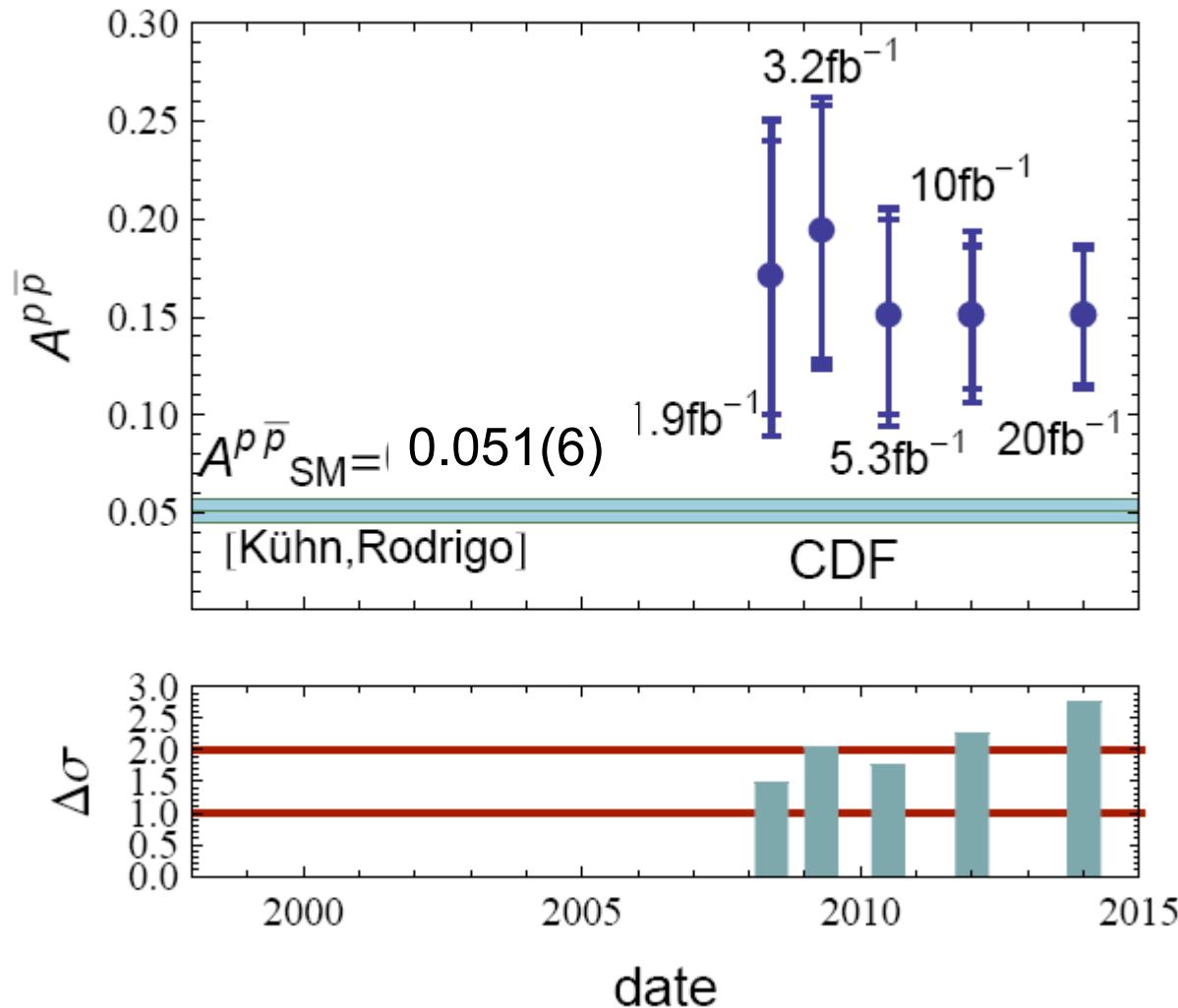


Translation to flavour universal axigluon

$$c_{Aa} / \Lambda^2 = -2 g_s^2 / m_A^2$$



Prospects for future evolution

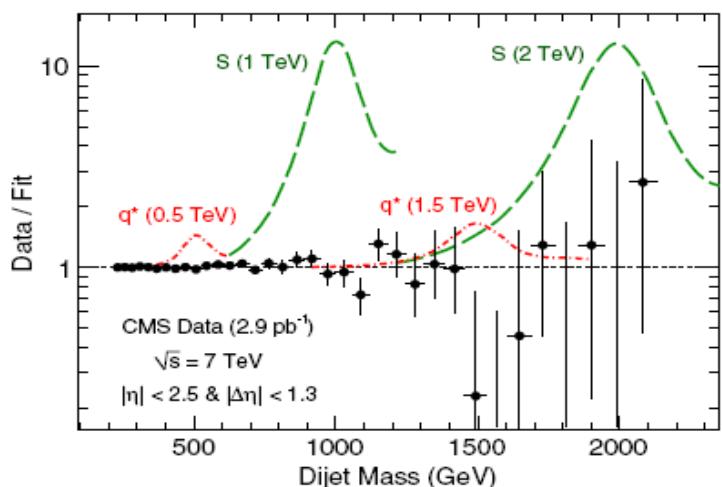
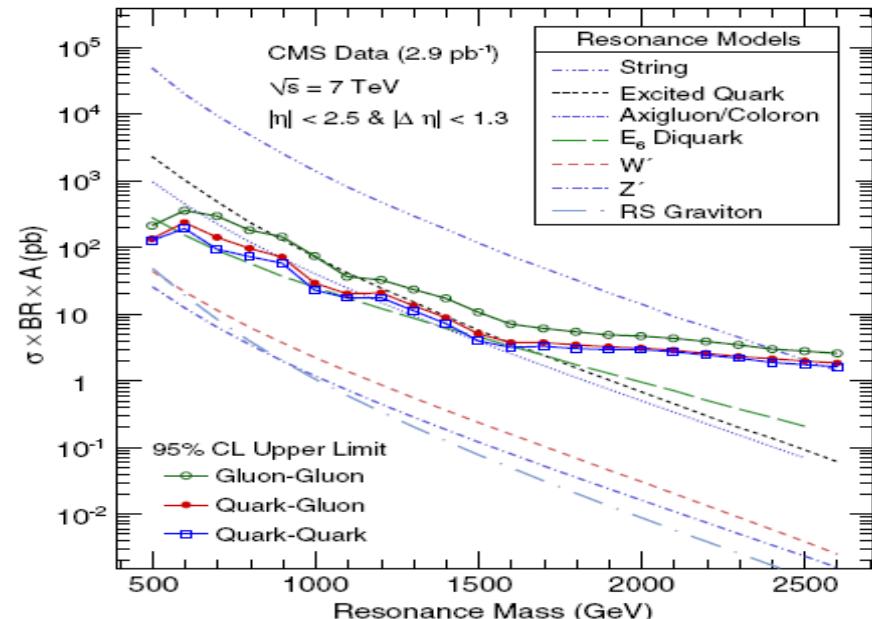
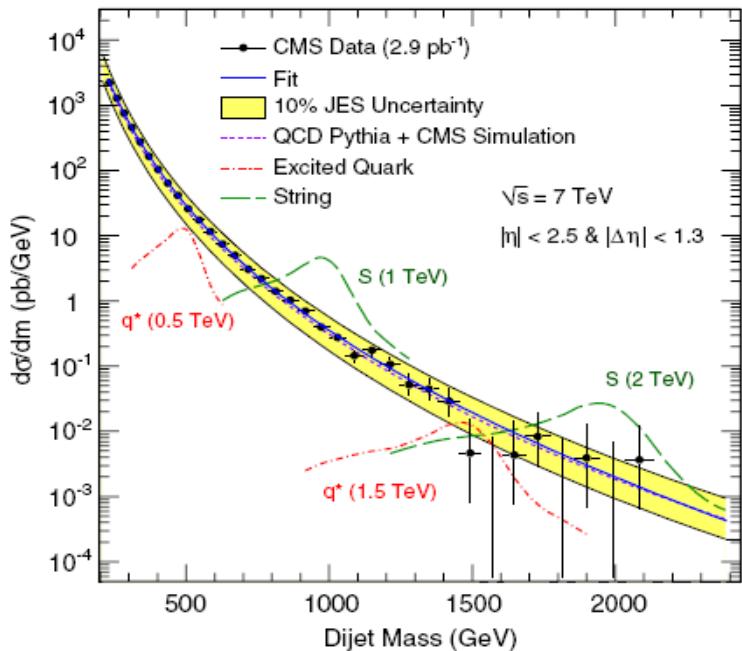




@ the LHC

CMS: dijet mass distribution

[PRL 105 (2010) 211801]

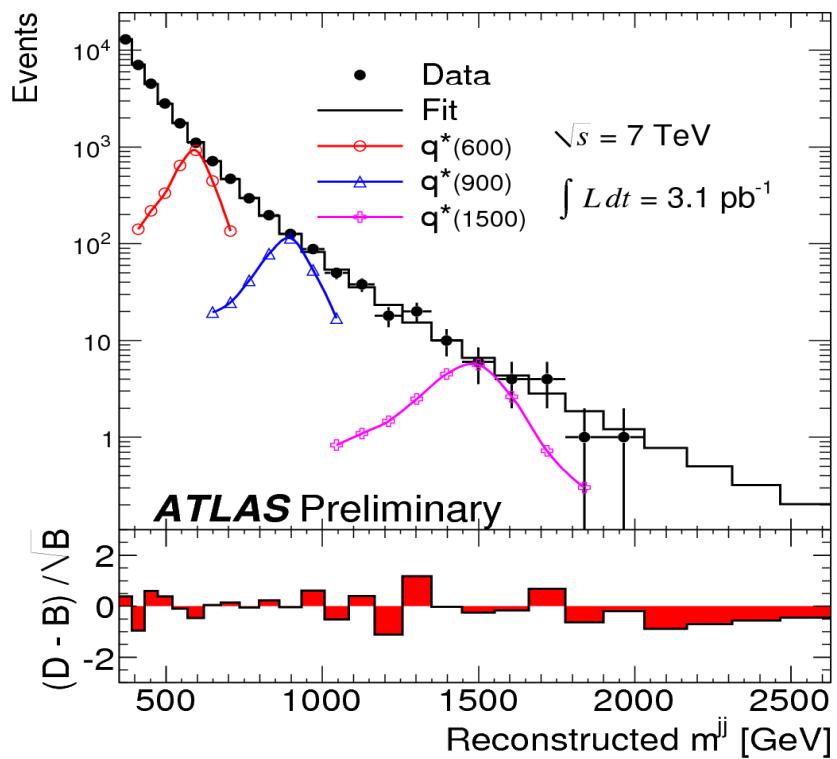


Extended Tevatron limits:

- | | |
|-------------------|------------|
| String resonances | > 2.5 TeV |
| excited quarks | > 1.58 TeV |
| axigluons | > 1.52 TeV |
| E6 diquarks | > 1.60 TeV |

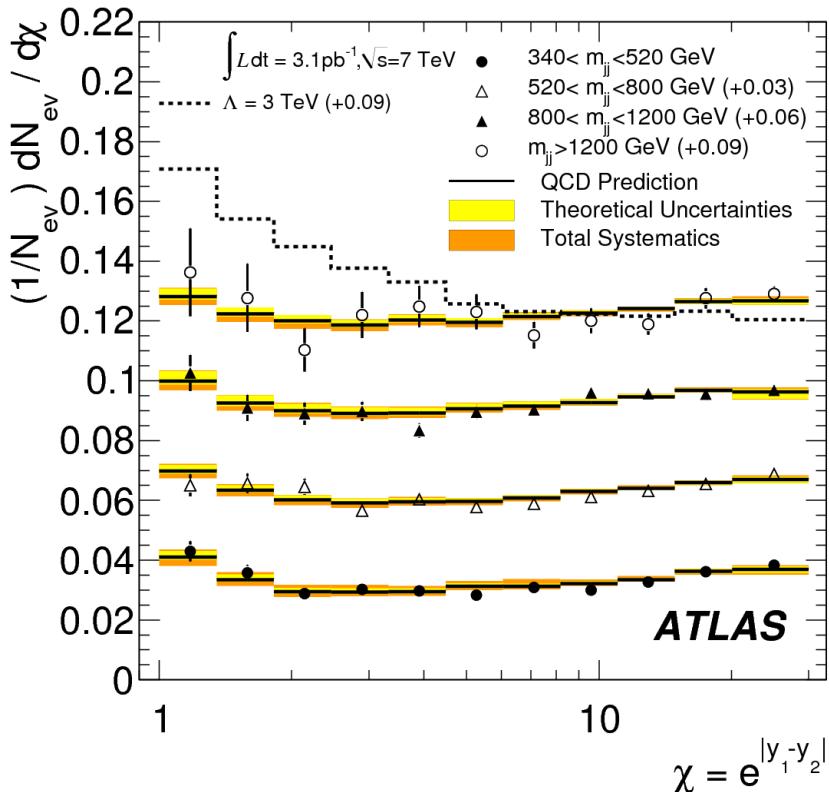
ATLAS: dijet mass and ang.distribution

**0.50 < m(q^*) < 1.53 TeV
excluded @ 95% C.L.**



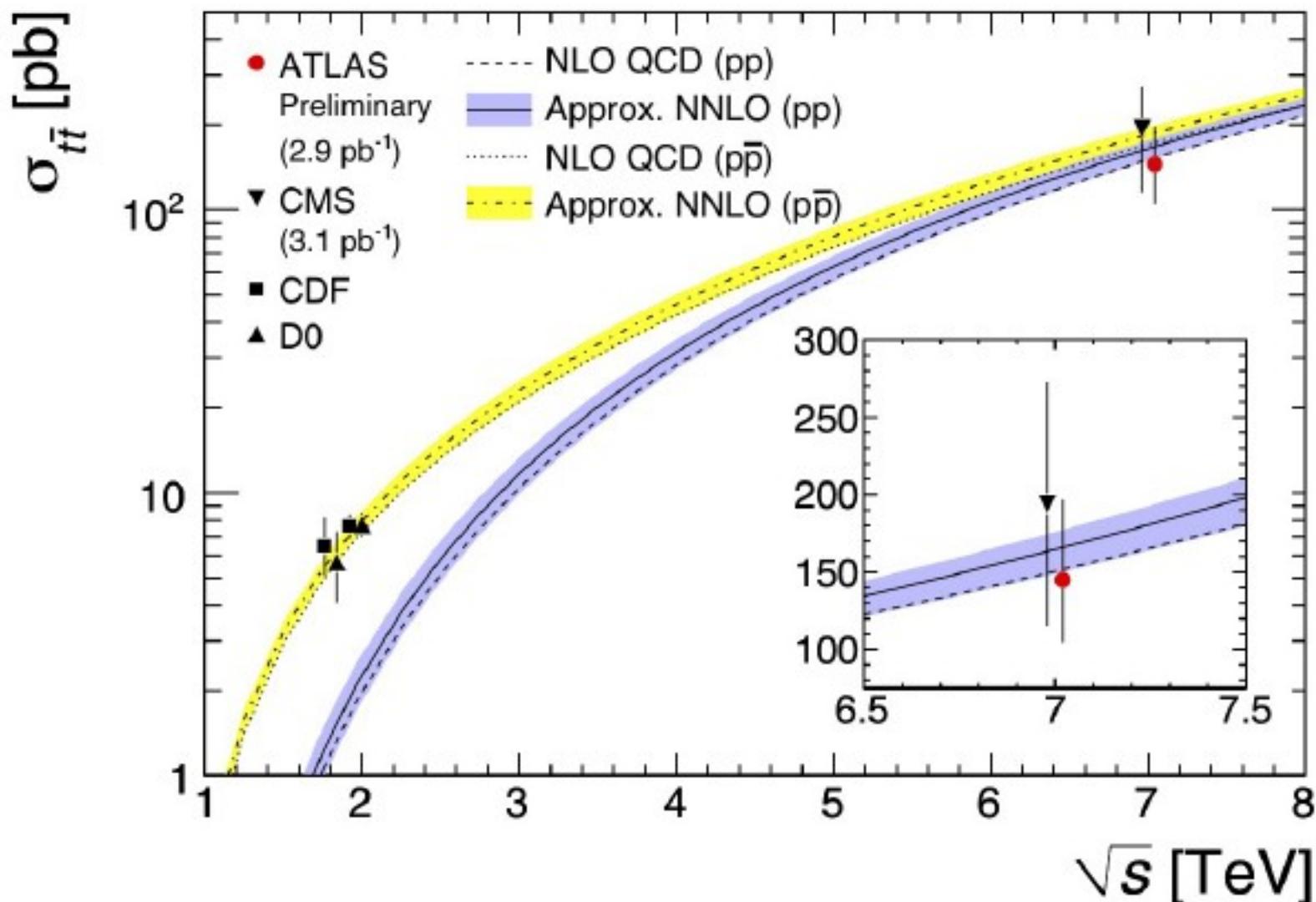
Latest CDF published limit:
 $260 < M (q^*) < 870 \text{ GeV}$

**Quark contact interactions with scale
 $\Lambda < 3.4 \text{ TeV}$ excluded @ 95% C.L.**



D0 limit: $\Lambda < 2.8 \text{ TeV}$
[PRL103(2009)191803]

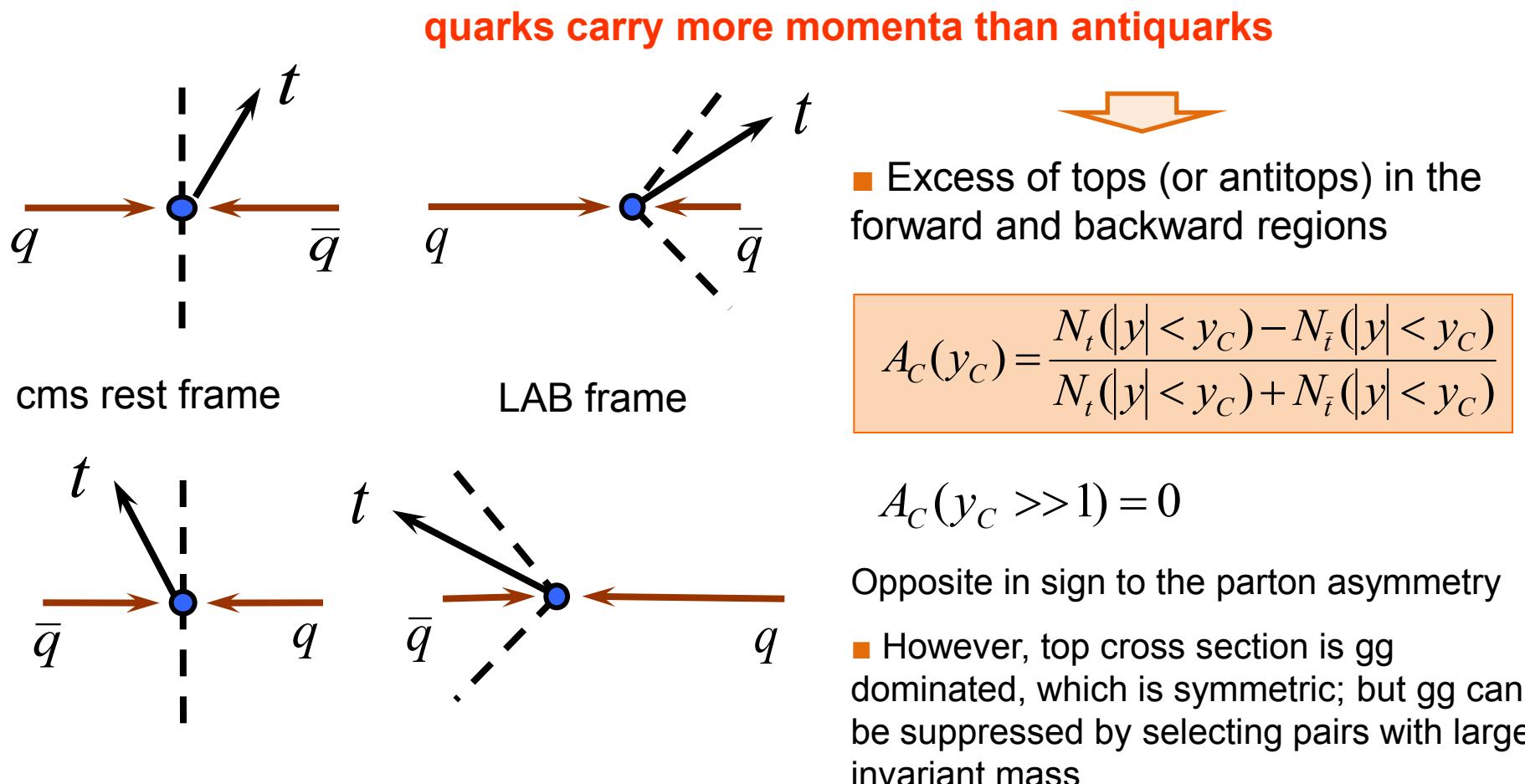
Top quarks at the LHC



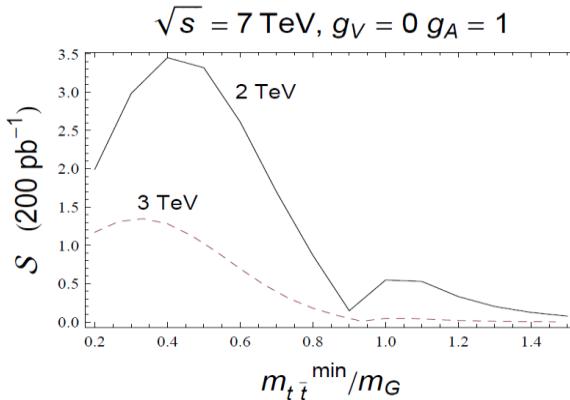
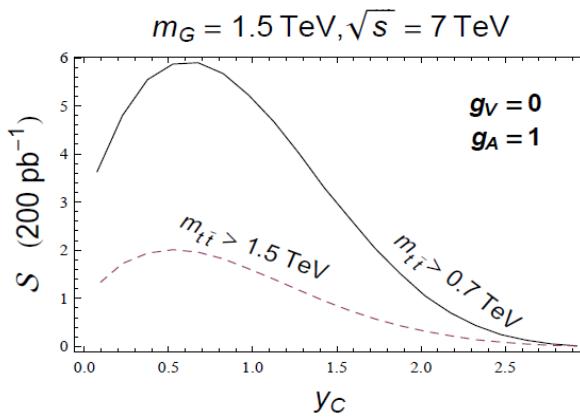
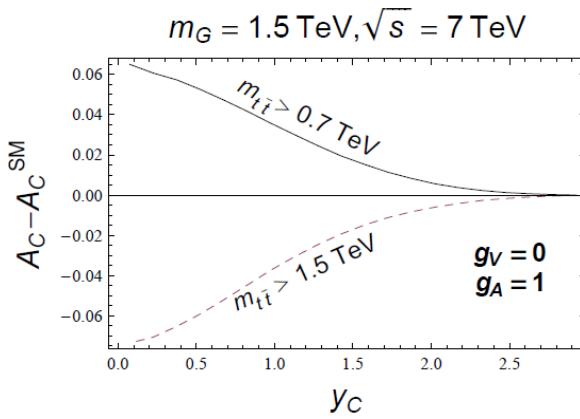
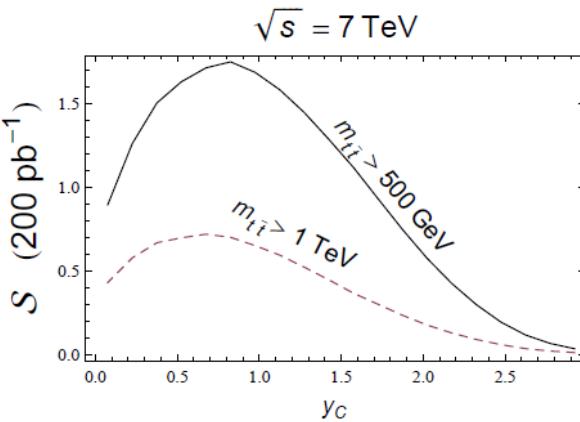
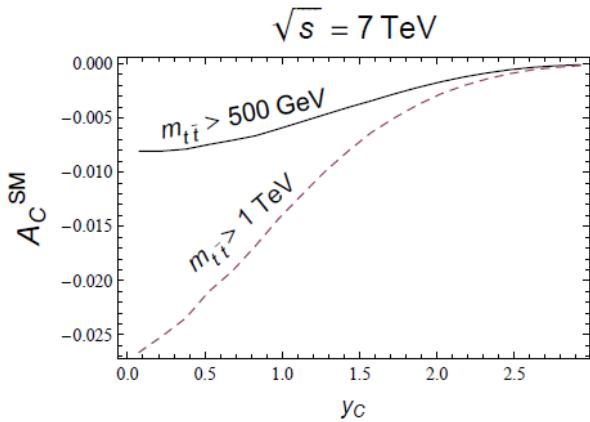
Charge asymmetry at LHC

LHC is symmetric \rightarrow no forward-backward

But suppose that there is a charge asymmetry at parton level
(QCD predicts that tops are preferentially emitted in the direction of incoming quark,
resonance asymmetry can be positive or negative)



[Ferrario, GR, arXiv:0809.3354]

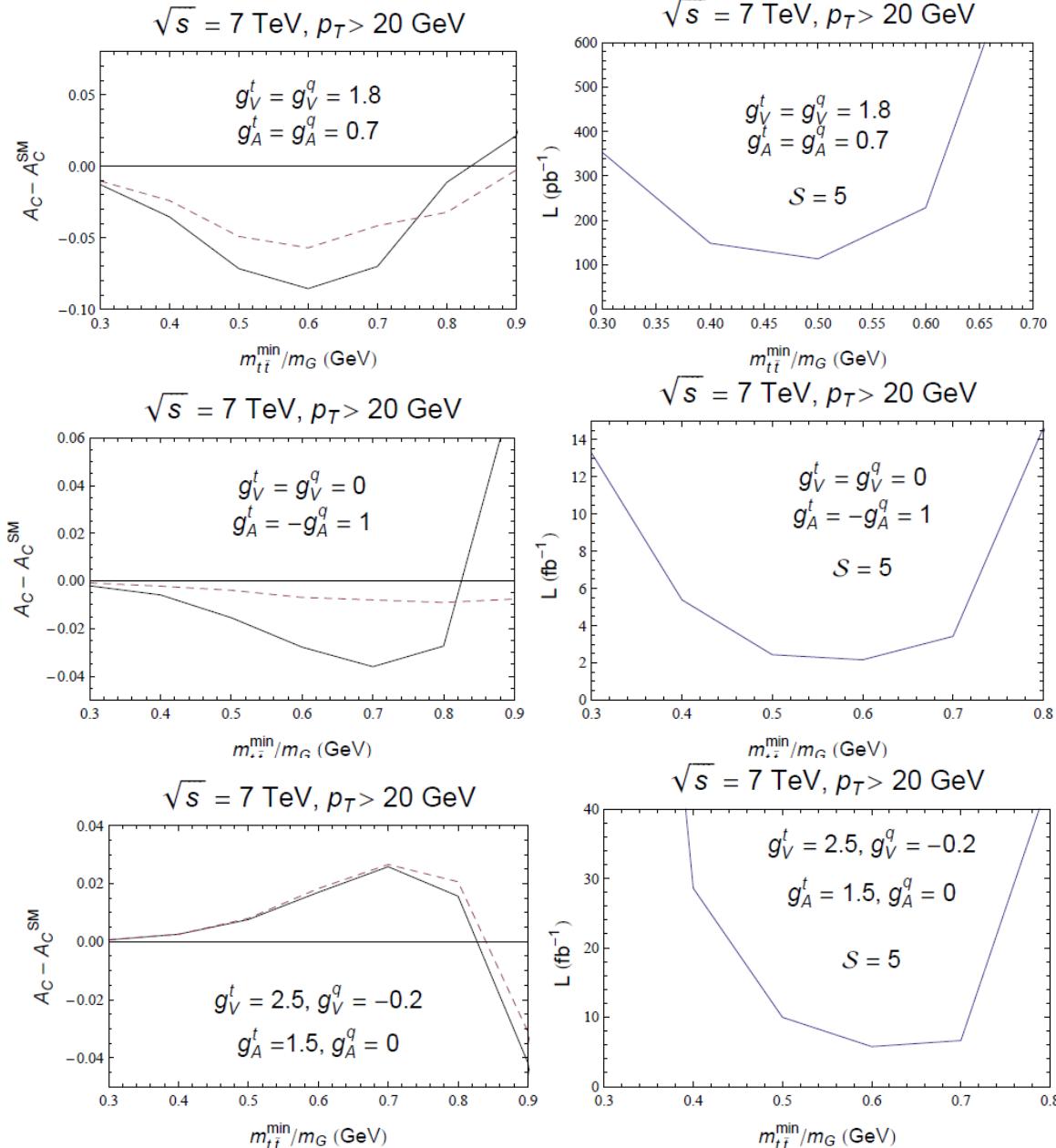


- Charge asymmetry suppressed by gg-fusion (90% @14TeV) but statistical significance can be maximized by tuning y_C and m_{tt}^{\min}

- smallness of QCD asymmetry compensated by statistics at low m_{tt}^{\min}

- Color-octet resonance: maximum statistical significance at about $m_G/2$ (less boosted tops)

ttbar + jet @ LHC



[Ferrario, GR, arXiv:0912.0687]

- QCD asymmetry washed out in ttbar+jet @ NLO

[Dittmaier, Uwer, Weinzierl, 2007]

$$A_{t\bar{t}+jet}^{p\bar{p}} = -0.07 \xrightarrow{NLO} -0.015(15)$$

- f_{abc}^2 contributions (color octet state) too in ttbar+jet

- d_{abc}^2 contributions (color singlet state) dashed

Conclusions

■ New measurements from Tevatron reduce room for BSM to 1.7σ (in the lab frame) from the measurement of the top quark charge asymmetry (forward-backward), early to claim new physics, but, together with $d\sigma/dM_{t\bar{t}bar}$, allows to set/revisit constrains in the top quark sector

- ✓ Flavour Universal axigluons with (large) vector couplings or large mass
- ✓ Flavour non-Universal axigluons: $\text{sign}(g_A^q) = -\text{sign}(g_A^t)$
- ✓ Flavour violating Z' and W' relatively light $O(200 \text{ GeV})$
- ✓ Flavour violating scalars in the t-channel: triplet or sextet

statistically dominated, still room for improvements

■ The charge asymmetry can be measured at the LHC too, and is a good observable to discriminate among different models (about 45 pb^{-1} recorded)

Top Events
of Switzerland

Kick-off meeting of the LHCPhenoNet Initial Training Network

from 31 January 2011 to 04 February 2011 (Europe/Madrid)

**Centre
Cultural
Bancaixa,
Valencia**

[Home](#)

The goal of the meeting is to review and to discuss the state-of-the-art and future developments in the research field of higher order perturbative corrections in the Standard Model and beyond, with emphasis on phenomenology at the LHC, and the development of customized open source software for precision physics at colliders. This is the first meeting organized with the support of the **LHCPhenoNet Initial Training Network**, but is also open to non-members of the network.

Dates: from 01 February 2011 09:00 to 04 February 2011 14:30

Location: *Centre Cultural Bancaixa, Valencia*
Room: Sala Ausias March

<http://www.lhcphenonet.eu/valencia2011>

Backup

Massive gluon diff cross section

Color octet resonances might produce a charge asymmetry at LO

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

- Quark-antiquark annihilation

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

where

resonance-resonance amplitude
• generates charge asymmetry too

$$m = \frac{m_t}{\sqrt{\hat{s}}}$$

$$c = \beta \cos\theta = \sqrt{1 - 4m^2} \cos\theta$$

$$\frac{\Gamma_G}{m_G} \approx \frac{\alpha_s}{6} \sum_{i=q,t} \left((g_V^i)^2 + (g_A^i)^2 \right)$$

- **gluon-gluon fusion** at tree-level the same as in the SM (gauge invariance, parity, orthonormality of field profiles in extra dimensions)