Massive Gluons in Top-Quark Pair Production

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Massive gluons and top quarks

might both be messengers of physics related to the

Origin of mass

Massive gluons

may exhibit strong couplings to top quarks in models of

- technicolor (topcolor)
- extra dimensions

Top quarks

have special properties among quarks, such as

- large mass $m_t \approx M_{\text{EW}}$
- Yukawa coupling $y_t \approx 1$

Probe interplay of massive gluons and top quarks at hadron colliders in

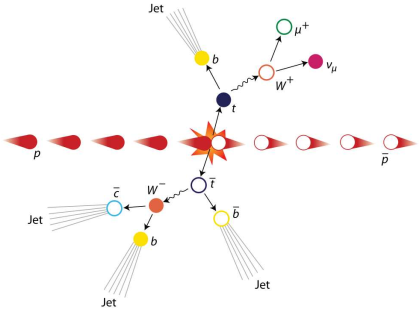
Top-quark pair production

This talk: generic constraints on massive gluons and effects in top-quark pair production.

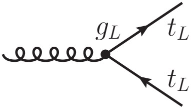
Top-quark pair production at the Tevatron

Proton-antiproton collisions
at $\sqrt{s} = 1.96$ TeV.

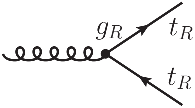
$q\bar{q} \rightarrow t\bar{t}$: 90%
$gg \rightarrow t\bar{t}$: 10%



Test Quantum Chromodynamics (QCD):
Universal quark-gluon vector coupling, in particular

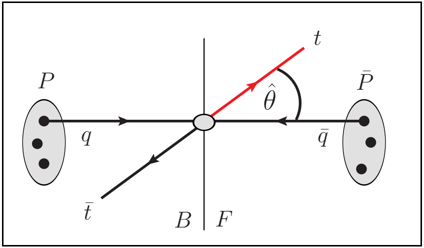


$g_L = g_R \equiv g_s$



Top-quark forward-backward asymmetry

In a theory with CP-conserving couplings, the forward-backward asymmetry is equal to a top-quark charge asymmetry.



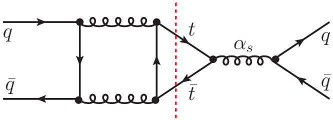
$$A_{\text{FB}}^t = \frac{N_t(F) - N_t(B)}{N_t(F) + N_t(B)} = \frac{\sigma_a}{\sigma_s}$$

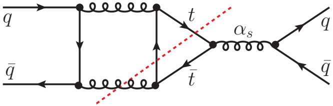
Charge-(a)symmetric cross section

$$\sigma_{a(s)} = \int_0^1 \cos\hat{\theta} \left[\frac{d\sigma(p\bar{p} \to t\bar{t}X)}{d\cos\hat{\theta}} - (+) \frac{d\sigma(p\bar{p} \to \bar{t}tX)}{d\cos\hat{\theta}} \right]$$

Asymmetry in the Standard Model

In QCD, the charge asymmetry arises at next-to-leading order:





Small standard-model (SM) prediction

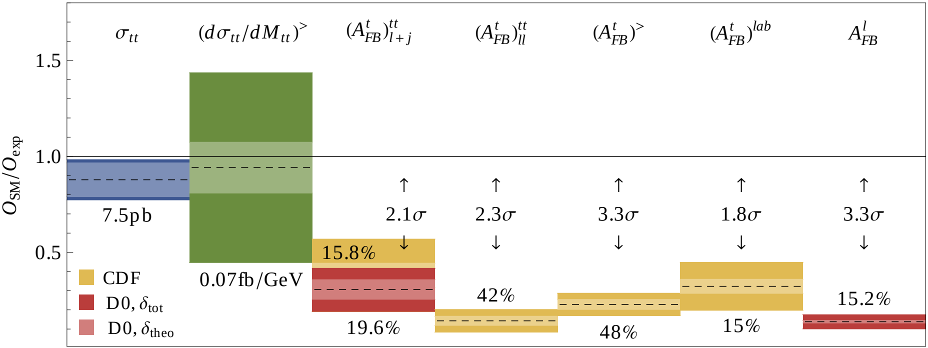
$$(A_{\mathrm{FB}}^t)^{\mathrm{lab}} = 0|_{\alpha_s^2} + \text{few}\,\%|_{\alpha_s^3} + \text{few}\,‰|_{\alpha\alpha_s^2}$$ [Kühn & Rodrigo, Phys.Rev.D59:054017,1999]

$$= (4.8 \pm 0.5)\% + \mathcal{O}(\alpha)$$ [Ahrens et al., arXiv:1106.6051]

- expected to be robust under higher-order QCD corrections.
  [Melnikov & Schulze, Nucl.Phys.B840:129,2010][Ahrens et al., arXiv:1106.6051]
- enhanced by electroweak corrections of about 20%.
  [Hollik & Pagani, arXiv:1107.2606]

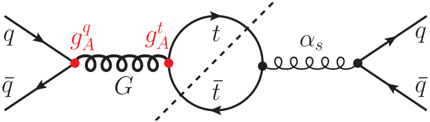
Evidence for new physics at the Tevatron

Standard-model predictions O_{SM} versus measurements O_{exp}



Tension between charge-symmetric and -asymmetric observables.

Axigluons in top-quark pair production



Axigluon contributions to $t\bar{t}$ production at tree level

$$\sigma_a^{\rm INT} \sim g_A^q\, g_A^t\, \frac{1}{M_{t\bar{t}}^2 - M_G^2}\,, \qquad \sigma_s^{\rm NP} \sim (g_A^q)^2 (g_A^t)^2 \frac{M_{t\bar{t}}^2}{(M_{t\bar{t}}^2 - M_G^2)^2}\,.$$

A positive charge asymmetry $\sigma_a^{\rm INT} > 0$ requires

- $M_G > M_{t\bar{t}}$: flavor non-universal axigluon couplings,
- $M_G < M_{t\bar{t}}$: flavor universal axigluon couplings.

Upper limit on $|g_A^q\, g_A^t|/M_G^2$: effect on total cross section $\sigma_{t\bar{t}} \sim \sigma_s^{\rm NP}$
and resonance in spectrum $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$.

Chiral color

Spontaneous breaking of an extended color gauge group,

$$SU(3)_L \times SU(3)_R \to SU(3)_{QCD} \,,$$

with associated gauge fields L_μ, R_μ and couplings g_L, g_R,

yields massless gluon g and massive axigluon G,

$$\begin{pmatrix} G_\mu \\ g_\mu \end{pmatrix} = \begin{pmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{pmatrix} \begin{pmatrix} L_\mu \\ R_\mu \end{pmatrix} \,, \qquad \tan\theta = \frac{g_L}{g_R}.$$

Two parameters

$$\boxed{\text{gauge mixing angle } \theta \in [0^\circ, 45^\circ] \text{ and axigluon mass } M_G = \mathcal{O}(1\,\text{TeV})}$$

[Frampton & Glashow, Phys.Lett.B190:157,1987][Frampton et al., Phys.Lett.B683:294,2010]

Axigluon couplings to quarks

The cancellation of chiral anomalies requires additional fermions.

Assign charges to light ($\ell = q_{1,2}$) and heavy ($h = q_{3,4}$) quarks

	$Q_{1,2}$	$u^c_{1,2}$	$d^c_{1,2}$	$Q_{3,4}$	$u^c_{3,4}$	$d^c_{3,4}$
$SU(3)_L$	3	1	1	1	$\bar{3}$	$\bar{3}$
$SU(3)_R$	1	$\bar{3}$	$\bar{3}$	3	1	1

Flavour non-universal axial-vector couplings to quarks

$$g_V^\ell = g_V^h = -g_s \cot(2\theta)\,, \qquad g_A^\ell = -g_A^h = g_s / \sin(2\theta)\,.$$

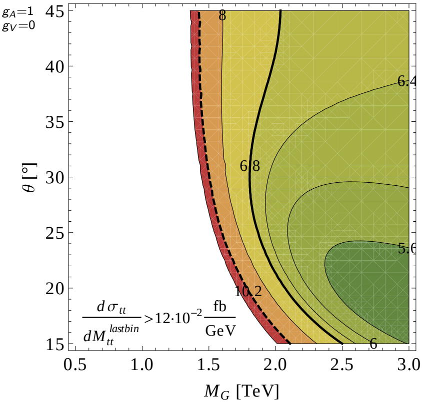
Good for $t\bar{t}$ observables: $\boxed{g_A^\ell g_A^h < 0, \;\; |\frac{g_V}{g_A}| = \cos(2\theta) < 1}$

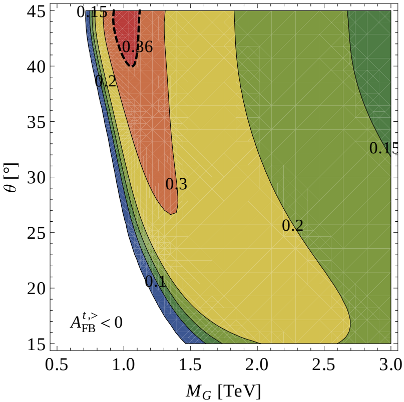
Axigluon effects in top-quark pair production

Tension between charge-symmetric and -asymmetric cross sections at high invariant mass $M_{t\bar{t}}$ (CDF):

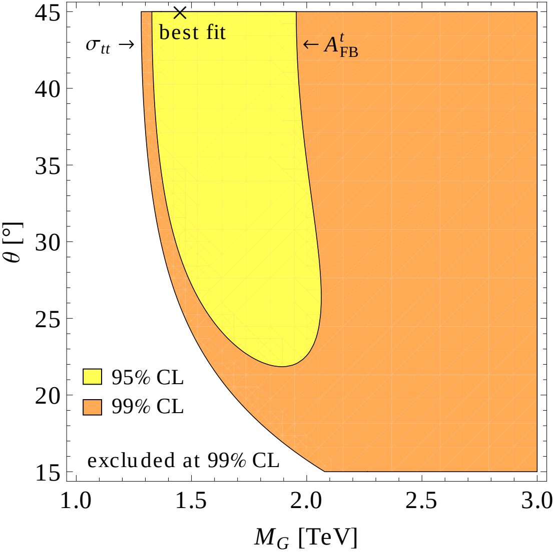
$(d\sigma_{t\bar{t}}/dM_{t\bar{t}})^{>}$ prefers $M_G \gtrsim 2\,\text{TeV}$ $\leftrightarrow$ $(A^t_{\text{FB}})^{>}$ prefers $M_G \simeq 1\,\text{TeV}$

$\downarrow$ $\downarrow$





Global fit to $\sigma_{t\bar{t}}$, $(d\sigma_{t\bar{t}}/dM_{t\bar{t}})^>$, $(A^t_{\text{FB}})^<$, and $(A^t_{\text{FB}})^>$



Axigluon best-fit point x:

$M_G = 1.5\,\text{TeV}$, $\theta = 45°$

Significant improvement with respect to fit in the Standard Model.

Maximal asymmetry from SM gluon + axigluon:

$(A^t_{\text{FB}})^> = 26\%$

Flavor constraints on axigluons

$$\mathcal{L} \supset -(Y_u)_{ii}\overline{Q}^i_L\, H\, u^i_R + g_s\left[(\Gamma^L_u)_{ij}\,\bar{u}^i_L \not{G}\, u^j_L + (\Gamma^R_u)_{ij}\,\bar{u}^i_R \not{G}\, u^j_R + (u \leftrightarrow d)\right]$$

Flavor-changing neutral currents at tree level $\sim (g_L^h - g_L^\ell)^2$
due to misalignment of Yukawa and axigluon couplings Y_q and Γ_q.

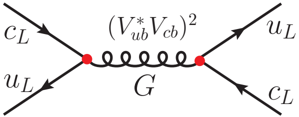
Minimal constraints: Align Y_d and Γ_d.

- No effects in down-quark sector, i.e. $K - \overline{K}$ and $B_{d,s} - \overline{B}_{d,s}$ mixing.
- Minimal flavor violation in up-quark sector.

Constraints from D meson mixing (Δm_D):

$M_G \gtrsim 200\,\text{GeV}$ $\quad (g_L^\ell = 1 = -g_L^h)$

[Bai et al., JHEP1103:003,2011][Haisch & SW, JHEP1108:088,2011]

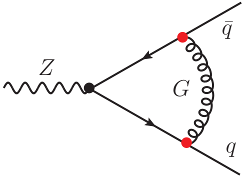


No constraints for flavor-universal axigluon couplings.

Constraints from electroweak precision observables

Effective coupling $Zq\bar{q}$ $(m_q = 0)$

$$\delta\, \mathcal{G}^{\ell,h}_{L,R} \sim (g^{\ell,h}_{L,R})^2 \frac{M_Z^2}{M_G^2} \log\left(\frac{M_Z^2}{M_G^2}\right)$$



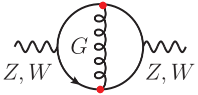
$Zb\bar{b}$, Γ_Z , $\sigma_{\rm had}$: $\boxed{M_G \gtrsim 500\,\text{GeV}}$

[Hill & Zhang, Phys.Rev. D51 (1995) 3563][Haisch & SW, JHEP1108:088,2011]

Oblique corrections

$$\{S, T\} \sim \{1, \frac{m_t^2}{M_Z^2}\} \left[(g_L^t)^2 + 2\,(g_R^t)^2\right] \frac{m_t^2}{M_G^2} \log^2\left(\frac{m_t^2}{M_G^2}\right)$$

$\boxed{M_G \gtrsim \text{few}\,100\,\text{GeV}}$ (model-dependent)



T constraints are important for massive gluons with large g_R^t.

Dijet production at the LHC

$pp \to G \to 2\,\text{jets at } \sqrt{s} = 7\,\text{TeV}.$

[ATLAS, arXiv:1108.6311, New J.Phys.13:053044,2011]
[CMS, arXiv:1107.4771, Phys.Rev.106:029902,2011]

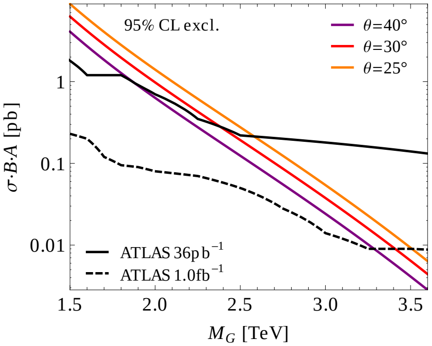
Resonance search in dijet invariant mass spectrum:

Bounds on $\sigma(pp \to G)\,\mathcal{B}(G \to q\bar{q})$

ATLAS $36\,\text{pb}^{-1}$: $M_G > 1.9\,\text{TeV}$

ATLAS $1.0\,\text{fb}^{-1}$: $M_G > 3.3\,\text{TeV}$

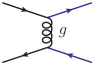
Results apply for narrow resonances, $\Gamma/M \lesssim 15\%$, and $|g^{q,t}_{L,R}| = 1$.



Evade dijet constraints by suppressing axigluon couplings to light quarks,

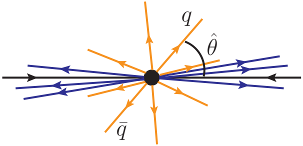
$|g^q_{L,R}| \to \xi |g^q_{L,R}|$, $|g^t_{L,R}| \to |g^t_{L,R}|/\xi$ (need $\xi \lesssim 0.5$ for $M_G < 2\,\text{TeV}$).

Angular distribution of jets

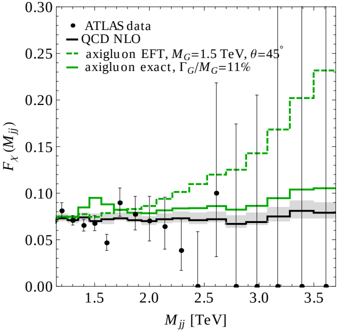


QCD:
forward scattering

Axigluon:
rather uniform distribution



Search for additional dijet events in the central region.



ATLAS 36 pb^{-1}: $M_G > 1.7$ TeV

$$F_\chi(M_{jj}) = \frac{\sigma(\chi < 3.3, M_{jj})}{\sigma(\chi < 30, M_{jj})}$$

$$\chi = (1 + |\cos\hat{\theta}|)/(1 - |\cos\hat{\theta}|)$$

[ATLAS, New J.Phys.13:053044,2011]

$t\bar{t}$ resonance search at the LHC

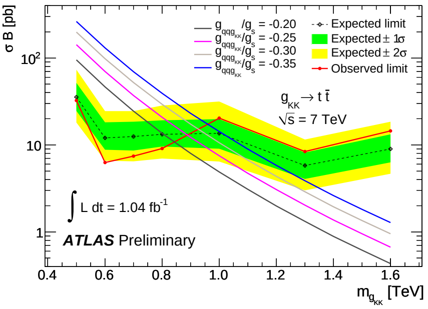
Search for resonances in dilepton $t\bar{t}$ final-state events constrains $\sigma_G \cdot \mathcal{B}(G \to t\bar{t}) \sim (g^q)^2\,(g^t)^2$.

Massive gluon with couplings $g^q_{L,R} = 0.35,\ g^{t,b}_L = 1,\ g^t_R = 4$:

$M_G > 1.0\,\text{TeV}$ [ATLAS-CONF-2011-123]

Strongly collimated top-quark decay products for $M_G \gtrsim 1\,\text{TeV}$

$\Rightarrow$ resolve top-jet topologies.

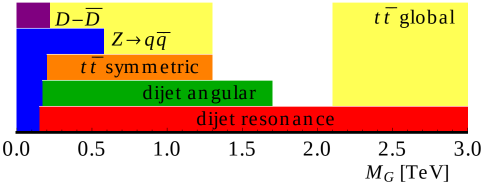


Compare with dijet resonance search: $\sigma_G \cdot \mathcal{B}(G \to q\bar{q}) \sim (g^q)^2\,(g^q)^2$.

$M_G > 1.9\,\text{TeV}$ for $g^q_{L,R} = 0.35,\ g^{t,b}_{L,R} = 1$.

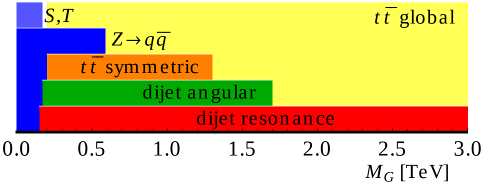
Axigluon constraints at 95% CL – Summary

- Flavor non-universal axigluon



$$g_A^\ell = -g_A^h = 1$$

- Flavor universal axigluon



$$g_A^\ell = g_A^h = 1$$

Similar constraints for massive gluons with vector couplings to quarks.
Exception $\sigma_{t\bar{t}}$: SM – G interference.

Top asymmetry from axigluons

Heavy axigluon

[Ferrario & Rodrigo, Phys.Rev.D80:051701,2009][Haisch & SW, JHEP1108:088,2011]

Flavor non-universal couplings $g_A^q = -g_A^t = 1$, $M_G = 1.5\,\text{TeV}$, $\Gamma_G/M_G = 10\%$.

- Global best fit for $t\bar{t}$ production: $(A_{\text{FB}}^t)^{>}_{\text{SM+NP}} = 26\%$.
- The "minimal" axigluon solution to A_{FB}^t with strong couplings $|g_A^q| = 1$ is ruled out by dijet resonance searches at the LHC.

Light axigluon

[Tavares & Schmaltz, arXiv:1107.0978][see also Barcelo et al., arXiv:1106.4054]

Flavor universal couplings $g_A^q = g_A^t = 1/3$, $M_G = 400\,\text{GeV}$, $\Gamma_G/M_G \gtrsim 10\%$.

- Evade bounds from dijet production (g_A^q) and T parameter (g_A^t).
- Need large width Γ_G to suppress resonance in $M_{t\bar{t}}$ spectrum $\rightarrow$ additional matter in axigluon decay, e.g. vector quarks.

$$\boxed{(A_{\text{FB}}^t)^{>}_{\text{NP}} \approx 30\%}$$

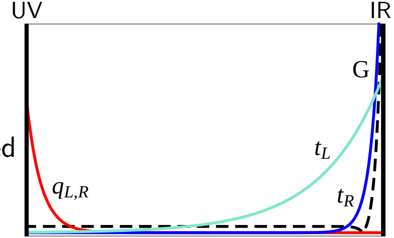
Top asymmetry in Randall-Sundrum models

Kaluza-Klein gluons in a warped extra dimension (ED) act as axigluons.

Anarchic flavor structure [Bauer et al., JHEP 1011:039,2010]

Fermion masses and mixings determine their localization in the ED.

$g_A^q = g_L^q - g_R^q$
strongly suppressed



$g_A^t = g_L^t - g_R^t$
large

No enlarged forward-backward asymmetry.

Relaxed flavor anarchy [Djouadi et al., Phys.Lett.B701:458,2011][Barcelo et al., Phys.Rev.D84:014024,2011]

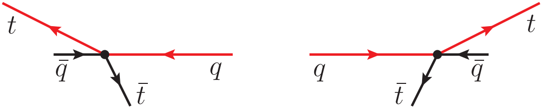
Light quarks are more IR-localized $\rightarrow g_A^q$ increased.
But: need flavor protection to avoid strong flavor constraints.

[Delaunay et al., Phys.Lett.B703:486,2011]

Top-quark charge asymmetry at the LHC

The process $pp \to t\bar{t}$ is symmetric $\Rightarrow$ no forward-backward asymmetry.

But: more boosted valence quarks q than sea quarks $\bar{q}$ inside the proton.
$\Rightarrow$ Excess of boosted top quarks along the beam axis.



Charge-asymmetric contributions to $q\bar{q} \to t\bar{t}$ can be probed by an asymmetry in pseudo-rapidities $\eta = -\ln(\tan\hat{\theta}/2)$,

[Antuñano et al., Phys.Rev.D77:014003,2008]

$$A_\eta^t = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}\,, \quad \Delta\eta = |\eta_t| - |\eta_{\bar{t}}|\,,\ A_\eta^{t,\mathrm{SM}} = 0.0130(11)$$

$$= -0.016 \pm 0.030_{\mathrm{stat}}{}^{+0.010}_{-0.019}{}_{\mathrm{syst}}$$

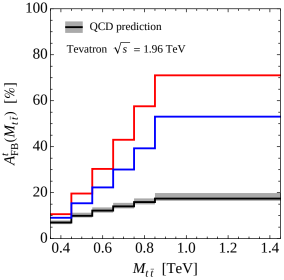
[CMS PAS TOP-11-014: l+jets, 1.09 fb^{-1}]

$$A_y^t = -0.024 \pm 0.016_{\mathrm{stat}} \pm 0.023_{\mathrm{syst}}$$

[ATLAS-CONF-2011-106: l+jets, 0.70 fb^{-1}]

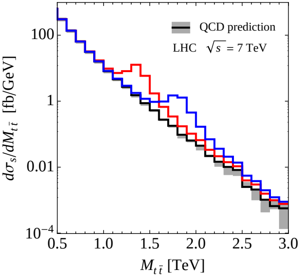
Model distinction from top observables

Shape of $A_{\mathrm{FB}}^{t}(M_{t\bar{t}})$



[Aguilar-Saavedra & Perez-Victoria, arXiv:1107.2120]

Resonances in $\sigma_{t\bar{t}}(M_{t\bar{t}})$



[Hewett et al., arXiv:1103.4618]

Top-quark polarization: departures from QCD vector coupling

[Choudhury et al., Phys.Rev.D84:014023,2011][Krohn et al., arXiv:1105.3743]

Large-p_T observables: high sensitivity to TeV-scale new physics

[Delaunay et al., JHEP 1108:031,2011]

To be taken home

Massive gluons with strong couplings to quarks

- ✘ are banished to reside well above the EW scale.
  (flavor and electroweak precision observables)
- ✘ cannot yield a large forward-backward asymmetry A^t_{FB}.
  (dijet and $t\bar{t}$ resonances vs. T parameter)

Massive gluon survivors

- ✔ have suppressed couplings to light quarks.
- ✔ need additional accompanying matter.
  (enlarged decay width prevents dijet and $t\bar{t}$ resonances)