Massive Colour-Octet Bosons in Top-Quark Pair Production

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Three playgrounds for massive colour-octet bosons

1.) Theory

- axigluons in chiral colour models
- Kaluza-Klein gluons in warped extra dimensions
- colorons in technicolour models . . .

2.) Phenomenology

- generically have strong couplings to quarks
- interfere with standard-model gluon amplitude

→ large effects in LHC observables

3.) Anomaly

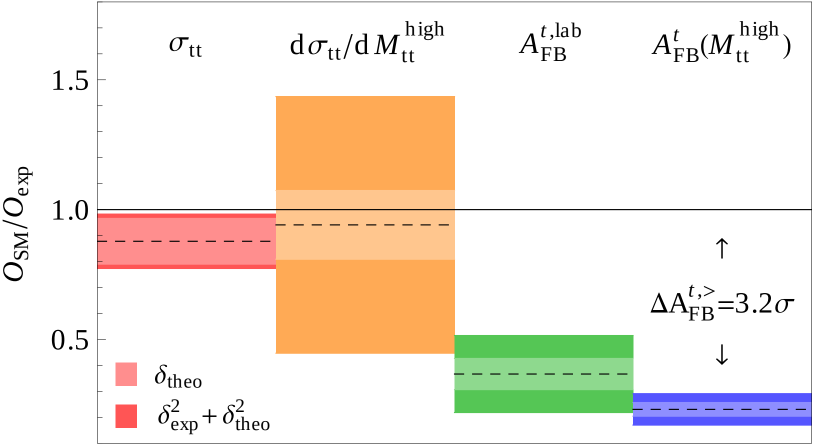
- may exhibit flavour non-universal couplings

→ explain top-quark forward-backward asymmetry at Tevatron

This talk: constraints and effects in $t\bar{t}$ production

Top-quark pair production at the Tevatron

Standard-model predictions O_{SM} versus measurements O_{exp} [CDF '11]

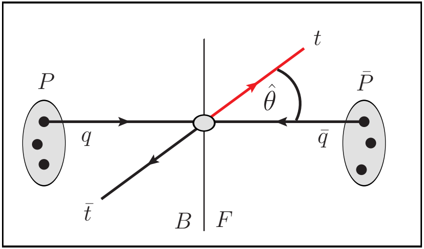


Asymmetric observables lie significantly below the measurement.

Forward-backward asymmetry in $t\bar{t}$ production

Charge-(a)symmetric cross section

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



$$A^t_{\mathrm{FB}} = \frac{N_t(F) - N_t(B)}{N_t(F) + N_t(B)} = \frac{\sigma_a}{\sigma_s}$$

Measurement at Tevatron: inclusive and in bins of invariant mass $M_{t\bar{t}}$

$$(A^{t,\mathrm{lab}}_{\mathrm{FB}})_{\mathrm{exp}} = (15.0 \pm 5.5)\%$$

$$(A^t_{\mathrm{FB}})^{M_{t\bar{t}} > 450\ \mathrm{GeV}}_{\mathrm{exp}} \equiv (A^{t,>}_{\mathrm{FB}})_{\mathrm{exp}} = (47.5 \pm 11.2)\%$$

[CDF '11]

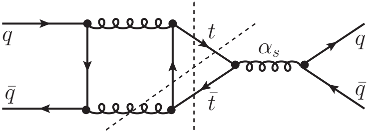
$$(A^t_{\mathrm{FB}})^{M_{t\bar{t}} < 450\ \mathrm{GeV}}_{\mathrm{exp}} \equiv (A^{t,<}_{\mathrm{FB}})_{\mathrm{exp}} = (-11.6 \pm 15.3)\%$$

Large charge asymmetry from massive colour octets

Need amplitude antisymmetric under $t \leftrightarrow \bar{t}$ interchange.

Standard Model: A_{FB}^t at NLO

$$\boxed{\sigma_a \sim \alpha_s^3}$$



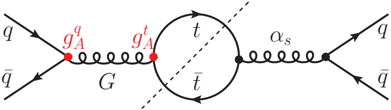
$+$ 10% electroweak corrections

NLO+NNLL: [Ahrens et al. '11]

$$(A_{\text{FB}}^{t,\text{lab}})_{\text{SM}} = 4\% - 5.6\%$$

New physics: A_{FB}^t at tree level

$$\boxed{\sigma_a \sim -\alpha_s\, g_A^q g_A^t}$$



$+$ t- and u-channel new physics

Tree-level effects in cross section:

$$\sigma_s \sim \alpha_s\, g_V^q g_V^t.$$

$$\boxed{\text{Good fit to } t\bar{t} \text{ observables expected for } g_A^q g_A^t < 0 \text{ and } |g_V/g_A| < 1.}$$

Axigluons from chiral colour

Extended colour gauge group [Frampton, Glashow '87][Frampton, Shu, Wang '09]

$$SU(3)_A \times SU(3)_B \xrightarrow{\langle\Sigma\rangle} SU(3)_C$$

with associated gauge fields A_μ, B_μ and couplings g_A, g_B.

Mass eigenstates: axigluon G with $M_G = \mathcal{O}(1\,\text{TeV})$ and massless gluon g

$$\begin{pmatrix} G_\mu \\ g_\mu \end{pmatrix} = \begin{pmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{pmatrix} \begin{pmatrix} A_\mu \\ B_\mu \end{pmatrix}, \qquad \tan\theta = \frac{g_A}{g_B},$$

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

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

$$g_V^\ell = g_V^h$$

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

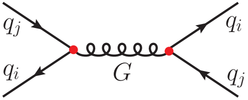
Important for $t\bar{t}$ observables: $\boxed{g_A^\ell g_A^h < 0, \;\; |\frac{g_V}{g_A}| = \cos(2\theta) < 1}$

Constraints on massive colour octets

[Bai, Hewett, Kaplan, Rizzo '11, Haisch, SW '11, et al.]

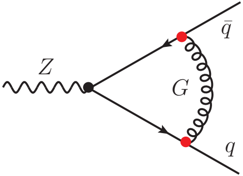
- Flavour-changing neutral currents at tree level

Neutral meson mixing



- Electroweak precision observables

$Zq\bar{q}$ coupling, oblique corr. S, T



- Dijet production at the LHC

[ATLAS, CMS '10,'11]

Resonances in $pp \to G \to jj$ spectrum and angular distribution

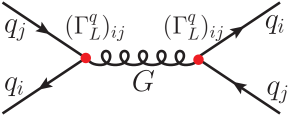
Flavour-changing neutral currents

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

Flavour violation due to misalignment of axigluon- with Yukawa-couplings,

$$\Gamma^{u,d}_L = U^\dagger_{u,d}\widehat{\Gamma}_L U_{u,d} \quad \text{with } \widehat{\Gamma}_L = diag(g^\ell_L, g^\ell_L, g^h_L)\,, \quad (\Gamma^{u,d}_R = \widehat{\Gamma}_R)\,.$$

Neutral meson mixing at tree level:



$$\sim \frac{(g^h_L - g^\ell_L)^2}{M^2_G} = \frac{4}{M^2_G \sin^2(2\theta)}$$

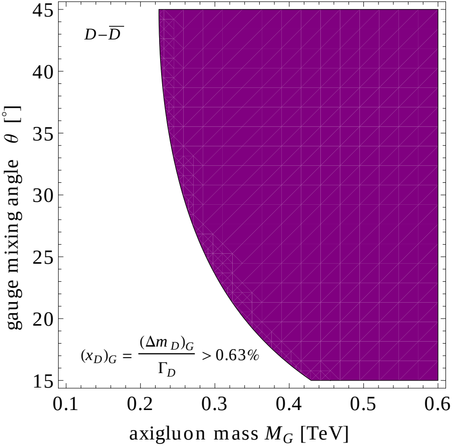
$$\boxed{\text{SM weak charged currents require } U_u = U_d V^\dagger_{\text{CKM}}\,.}$$

Align Γ^d_L with down-quark Yukawa coupling, $U_d = 1$:

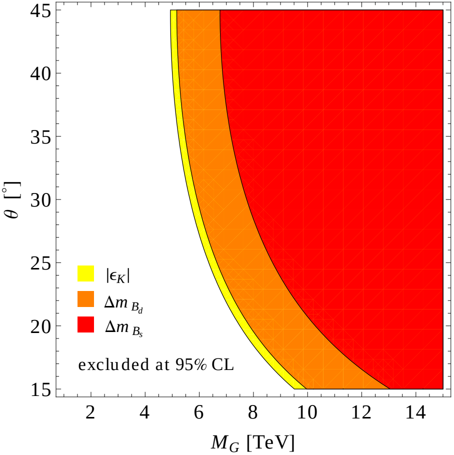
- no flavour violation in $K - \overline{K}$, $B_d - \overline{B}_d$, $B_s - \overline{B}_s$ mixing
- minimal flavour violation in $D - \overline{D}$ mixing $\sim (V^*_{ub} V_{cb})^2$

Constraints on axigluons from meson mixing

Align down-quark sector, $U_d = 1$.



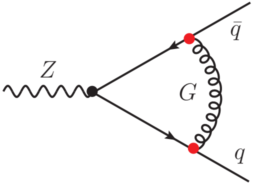
Align up-quark sector, $U_u = 1$.



Minimal constraint from $D - \overline{D}$ mixing: $M_G \sin(2\theta) > 225\,\text{GeV}$

Corrections to electroweak couplings

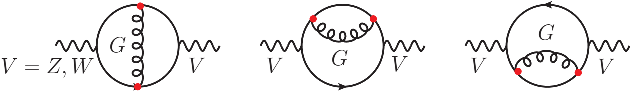
$Zq\bar{q}$ vertex



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

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

Oblique corrections

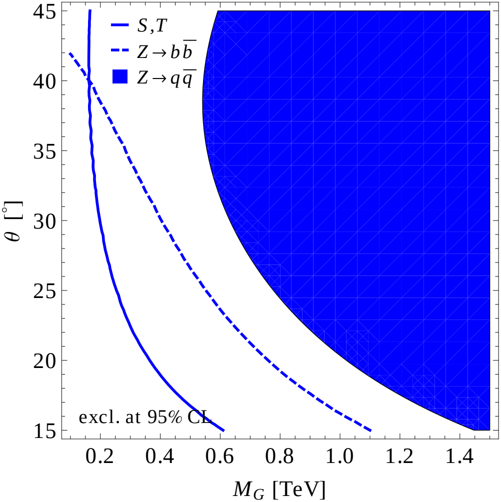


SM: Peskin-Takeuchi parameters $S, T, U = 0$ at reference point.

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

Electroweak precision observables

Measurements at LEP: $e^+e^- \to Z \to q\bar{q}$ at $\sqrt{S} = M_Z$ [LEP EWWG '05]



$Z \to q\bar{q}$ $(\Gamma_Z, \sigma_{\text{had}}, Zb\bar{b})$:

$M_G \gtrsim 500\,\text{GeV}$

$Z \to b\bar{b}$:

combined fit to

- partial decay rate R_b
- asymmetry parameters A_b, A^b_{FB}

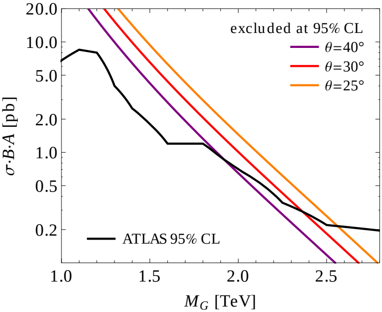
Oblique corrections S, T:

require fine-tuning of 4th quark generation

Dijet production at the LHC

Consider $pp \to G \to jj$ at $\sqrt{S} = 7\,\text{TeV}$. [ATLAS, CMS '10,'11]

- Dijet invariant mass spectrum



constrains $\sigma(pp \to G)\,\mathcal{B}(G \to jj)$ for resonances with $\Gamma_G/M_G \lesssim 15\%$.

Minimal constraints on axigluon mass

$$M_G \gtrsim 1.8\,\text{TeV} \quad \text{at } 95\%\text{CL}\,.$$

- Angular distribution of jets

constrains contact interactions $\mathcal{L}_{4q} = \dfrac{2\pi}{\Lambda^2}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)$,

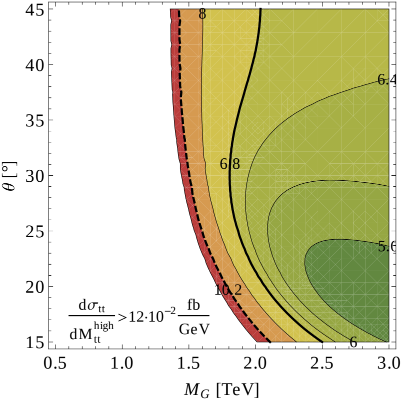
$$\Lambda \gtrsim 5.7\,\text{TeV} \quad \text{at } 95\%\text{CL}\,.$$

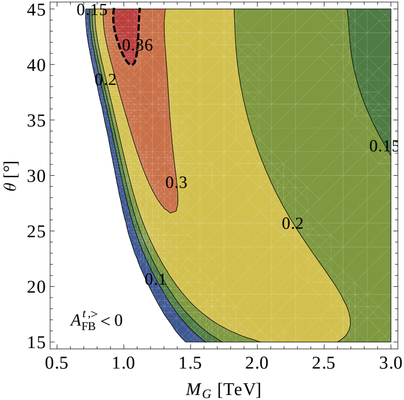
Translated into bound on axigluon: $M_G \gtrsim 1.9\,\text{TeV}$.

Axigluons in top-quark pair production

Consider symmetric and asymmetric cross sections at high $M_{t\bar{t}}$.

$\left(\frac{d\sigma_{t\bar{t}}}{dM^{\text{high}}_{t\bar{t}}}\right)$ prefers $M_G \gtrsim 2\,\text{TeV}$ ↔ $A^{t,>}_{\text{FB}}$ prefers $M_G \simeq 1\,\text{TeV}$

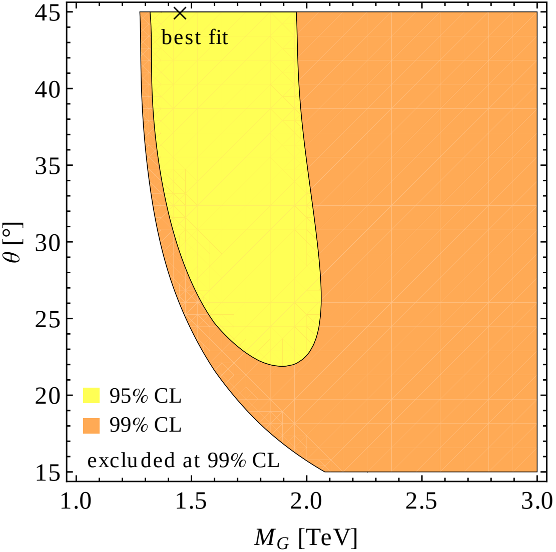




$$\left(\frac{d\sigma_{t\bar{t}}}{dM_{t\bar{t}}}\right)^{M_{t\bar{t}}\in[0.8,1.4]\,\text{TeV}}_{\text{exp}} = (6.8 \pm 3.4)\cdot 10^{-2}\,\frac{\text{fb}}{\text{GeV}}$$

$$(A^t_{\text{FB}})^{M_{t\bar{t}} > 450\,\text{GeV}}_{\text{exp}} = (47.5 \pm 11.2)\%$$

Global fit to $t\bar{t}$ observables $\sigma_{t\bar{t}}$, $\frac{d\sigma_{t\bar{t}}}{dM_{t\bar{t}}^{\text{high}}}$, $A_{\text{FB}}^{t,<}$, and $A_{\text{FB}}^{t,>}$

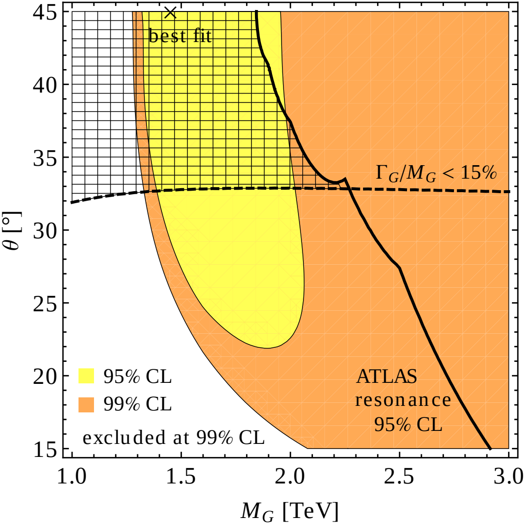


Best fit point x: $\chi^2 = 7.5$
(cf. SM: $\chi^2 = 13.2$)

$$\boxed{M_G = 1.45\,\text{TeV},\ \theta = 45^\circ}$$

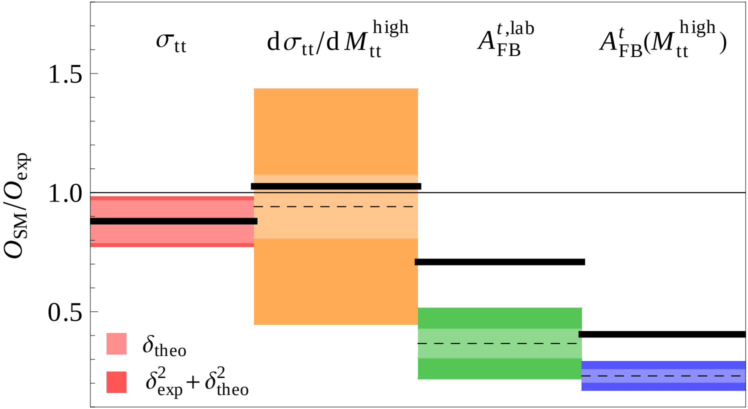
Constraints from resonance search in dijet production

$pp \to G \to jj$ @ $\sqrt{S} = 7\,\text{TeV}$, ATLAS 36pb^{-1}



Axigluons in $t\bar{t}$ observables

consistent w/ all constraints: $M_G = 1.9\,\text{TeV}$, $\theta = 45^\circ$



Tension between $\sigma_{t\bar{t}}$ and A_{FB}^t at high $M_{t\bar{t}}$:

Both increase as M_G decreases.

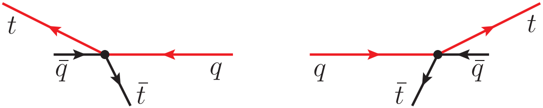
$(A_{FB}^{t,>})_G = 19.2\%$

$(A_{FB}^{t,lab})_G = 11.2\%$

Top-quark charge asymmetry at the LHC

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

Top quarks are preferentially emitted along the beam axis at large rapidity:



Charge-asymmetric contributions to $q\bar{q} \to t\bar{t}$ can be probed by an asymmetry in pseudo-rapidities η, [Antunano, Kühn, Rodrigo '98,'08]

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

$$= 0.060 \pm 0.134_{\text{stat}} \pm 0.026_{\text{syst}}\,.$$

[CMS '11]

To be taken home

Indirect constraints disfavour colour-octet bosons with masses at the weak scale.

For an axigluon with non-universal couplings to quarks:

- $D - \overline{D}$ meson mixing: $M_G \gtrsim 250\,\mathrm{GeV}$
- $Z \to q\bar{q}$: $M_G \gtrsim 500\,\mathrm{GeV}$

The top-quark charge asymmetry can be explained by such an axigluon with $M_G \sim 1.5\,\mathrm{TeV}$.

Direct constraints from dijet production at the LHC challenge this solution by requiring $M_G \gtrsim 1.9\,\mathrm{TeV}$.

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