The Top-Quark Forward-Backward Asymmetry

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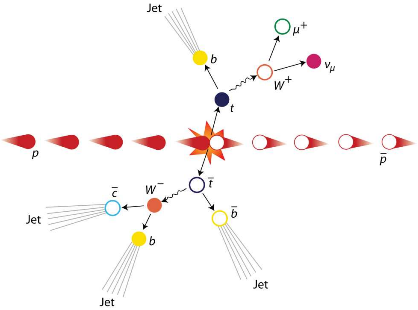
EPS 2011, July 23rd, 2011 – Grenoble, France

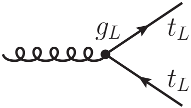
Top-quark pair production at the Tevatron

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

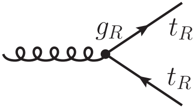
$q\bar{q} \to t\bar{t}$: 90%
$gg \to t\bar{t}$: 10%



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

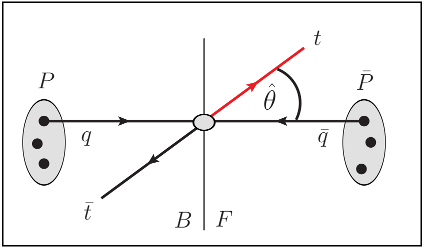


$g_L = g_R \equiv g_s$



Top-quark forward-backward asymmetry

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



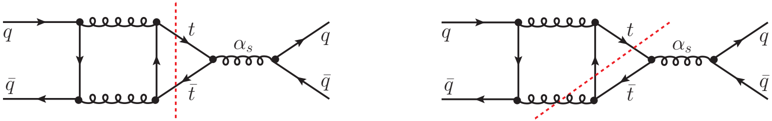
$$A_{\mathrm{FB}}^{t} = \frac{N_t(F) - N_t(B)}{N_t(F) + N_t(B)} = \frac{\sigma_a}{\sigma_s}$$

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] [EPS: Pecjak, Top & EW, 21/7]

- enhanced by electroweak corrections of about 20%.

  [Hollik & Pagani, arXiv:1107.2606]

Evidence for new physics in $t\bar{t}$ production

CDF lepton + jets channel [CDF, Phys.Rev.D83:112003,2011] [EPS: CDF, Top & EW, 23/7]

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

$$(A^t_{FB})^{t\bar{t}}_{exp} = (15.8 \pm 7.4)\%$$

$$(A^t_{FB})^{>}_{exp} \equiv A^t_{FB}[M_{t\bar{t}} > 450\,\mathrm{GeV}] = (47.5 \pm 10.1_{stat.} \pm 4.9_{syst.})\%$$

$$(A^t_{FB})^{lab}_{SM} = (4.8^{+0.6}_{-0.5})\%$$

$$(A^t_{FB})^{t\bar{t}}_{SM} = (7.3^{+0.9}_{-0.8})\%$$

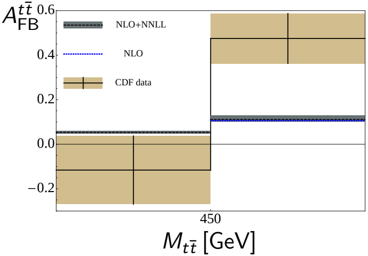
$$(A^t_{FB})^{>}_{SM} = (10.8^{+1.0}_{-0.8})\%$$

CDF dilepton channel [CDF note 10398, 2011]

$$(A^t_{FB})^{t\bar{t}} = (42 \pm 15_{stat.} \pm 4_{bkg.\text{-}shape})\%$$

D0 lepton + jets channel [D0 note 6062-CONF, 2010]

$$(A^t_{FB})^{obs.}_{exp} = (8 \pm 4_{stat.} \pm 1_{syst.})\%$$

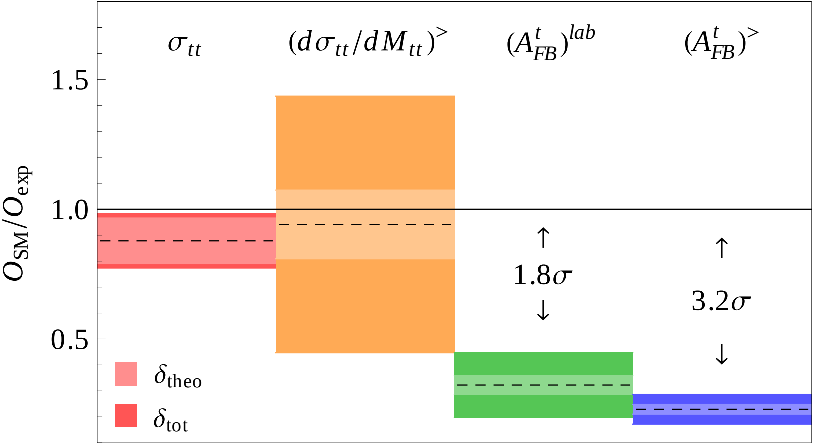


[EPS: Verzocchi, Top & EW, 23/7]

[SM: Ahrens et al., arXiv:1106.6051]

Observables at the Tevatron

Standard-model predictions $O_{\rm SM}$ versus measurements $O_{\rm exp}$



Tension between charge-symmetric and -asymmetric observables.

New physics in top-antitop production

First approach: Effective theory for new physics (NP) at $\Lambda > M_{t\bar{t}}$.

- The dominant partonic process $u\bar{u} \to t\bar{t}$ is mediated by 8 vector, 8 scalar, and 2 tensor dimension-six operators of $\mathcal{O}(\Lambda^{-2})$.

[Delaunay et al., arXiv:1103.2297][Aguilar-Saavedra & Perez-Victoria, JHEP 1105:034,2011]

- Operators interfering with the Standard Model,

$$\mathcal{O}_V^8 = (\bar{u}\gamma_\mu T^a u)(\bar{t}\gamma^\mu T^a t)\,, \quad \mathcal{O}_A^8 = (\bar{u}\gamma_\mu\gamma_5 T^a u)(\bar{t}\gamma^\mu\gamma_5 T^a t)\,,$$
$$\mathcal{O}_S^3 = (\bar{t}\, T_3 u)(\bar{u}\, T^3 t)\,, \quad \mathcal{O}_P^3 = (\bar{t}\, T_3\gamma_5 u)(\bar{u}\, T^3\gamma_5 t)\,, \quad T_3 = \epsilon_{abc}\,.$$

Hint towards $A_{\rm FB}^t$ from SM-NP interference effect:

- The data on $(A_{\rm FB}^t)^> \sim \sigma_{t\bar{t}}^F - \sigma_{t\bar{t}}^B$ and $\sigma_{t\bar{t}}^> = \sigma_{t\bar{t}}^F + \sigma_{t\bar{t}}^B$ prefer $(\sigma_{t\bar{t}}^F)_{\rm NP} > 0$ and $(\sigma_{t\bar{t}}^B)_{\rm NP} < 0$ with a significance of 2σ.

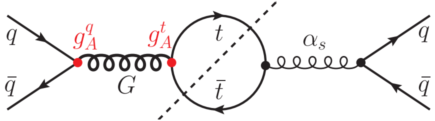
[Grinstein et al., Phys.Rev.Lett.107:012002,2011]

Since a large asymmetry requires $\Lambda \lesssim \mathcal{O}(1\,\text{TeV})$, resonance and width effects of the new particle are important.

Candidates for a large asymmetry

A massive vector boson can generate a charge asymmetry at tree level from the interference with the standard gluon amplitude.

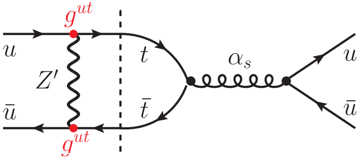
<u>s channel</u>: axial-vector couplings $g_A = g_L - g_R$



$$\sigma_a \sim \frac{\alpha_s \, g_A^q \, g_A^t}{s - M_G^2}$$

$$M_G = \mathcal{O}(1\,\text{TeV})$$

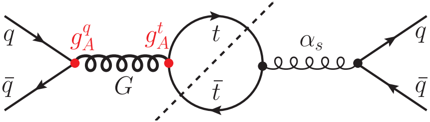
<u>t and u channels</u>: flavor-changing couplings g^{ut}



$$\sigma_a \sim \frac{\alpha_s \, (g^{ut})^2}{t - M_{Z'}^2}$$

$$M_{Z'} = \mathcal{O}(\text{few}\,100\,\text{GeV})$$

New physics in s channel: color-octet vectors (axigluons)



Axigluon contributions to $t\bar{t}$ production

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

A positive charge asymmetry $\sigma_a^{\text{NP}} > 0$ 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 $\sigma_{t\bar{t}} \sim \sigma_s^{\text{NP}}$
and resonance in spectrum $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$.

Indirect constraints on axigluons

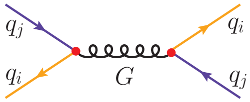
- Flavor-changing neutral currents at tree level

($|g_A^q| = 1 = |g_A^t|$)

D meson mixing: $\boxed{M_G \gtrsim 200\,\text{GeV}}$

(flavor non-universal couplings)

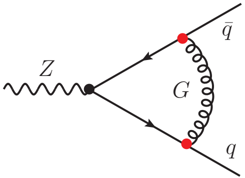
[Bai et al., JHEP 1103:003,2011][Haisch & SW, arXiv:1106.0529]



- Electroweak precision observables

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

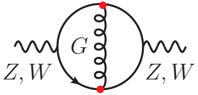
[Hill & Zhang, Phys.Rev. D51 (1995) 3563][Haisch & SW, 1106.0529]



Oblique corrections S, T:

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

[Haisch & SW, arXiv:1106.0529]



T constraints are important for large g_A^t.

Direct constraints: dijet production at the LHC

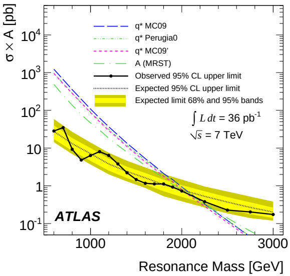
Consider $pp \to G \to 2\,\text{jets}$ at $\sqrt{s} = 7\,\text{TeV}$. $\qquad (|g^q_{L,R}| = 1,\ \Gamma_G/M_G = 10\%)$

Resonance search
in dijet invariant mass spectrum:
bounds on $\sigma(pp \to G)\,\mathcal{B}(G \to q\bar{q})$

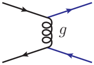
$$\to \boxed{M_G > 2.0\,\text{TeV}}$$

(only for narrow resonances, $\Gamma/M \lesssim 15\%$)

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

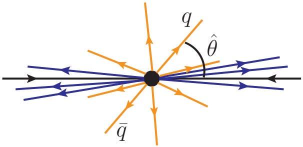


Angular distribution of jets: $\boxed{M_G > 1.7\,\text{TeV}}$



QCD:
forward scattering

Axigluon:
rather uniform distribution



[ATLAS, New J.Phys.13:053044,2011][CMS, Phys.Rev.Lett.106:201804,2011]

Theory: [Bai et al., JHEP 1103:003,2011][Haisch & SW, arXiv:1106.0529][Ligeti et al., JHEP 1106:109,2011]

Chiral color

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

Spontaneous breaking of an extended color gauge group,

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

gives rise to a massive axigluon $G_\mu = \frac{1}{\sqrt{2}}(L_\mu - R_\mu)$.

Heavy axigluon [Ferrario & Rodrigo, Phys.Rev.D80:051701,2009][Haisch & SW, arXiv:1106.0529]

Flavor non-universal couplings $g_A^q = -g_A^t = 1$, $M_G = 2\,\text{TeV}$, $\Gamma_G/M_G = 10\%$.

- Effects limited by dijet production (g_A^q).

$$(A_{\rm FB}^t)^>_{\rm max} = 20\%$$

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
  $\to$ additional matter in axigluon decay.

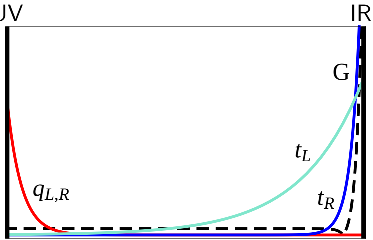
$$(A_{\rm FB}^t)^>_{\rm NP} \approx 30\%$$

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

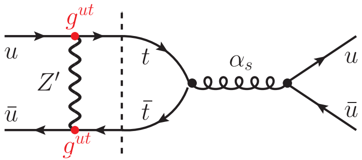
No enlarged forward-backward asymmetry.

Relaxed flavor anarchy [Djouadi et al., Phys.Lett.B701:458,2011][Barcelo et al., arXiv:1105.3333]

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

[Delaunay et al., arXiv:1101.2902]

New physics in t channel: color-singlet vectors (Z', W')

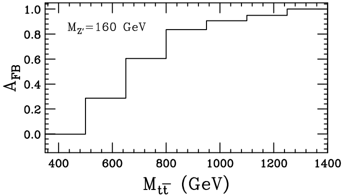


Z' contributions to $t\bar{t}$ production

$$\sigma_a^{\text{INT}} \sim a \cdot \frac{(g_L^{ut})^2 + (g_R^{ut})^2}{t - M_{Z'}^2}, \qquad \sigma_s^{\text{INT}} \sim b \cdot \frac{(g_L^{ut})^2 + (g_R^{ut})^2}{t - M_{Z'}^2} + c \cdot \frac{g_{L,R}^{u\bar{u}}\, g_{L,R}^{t\bar{t}}}{t - M_{Z'}^2}.$$

Rutherford enhancement at high $M_{t\bar{t}}$:

Excess of forward-scattered top quarks in both A_{FB}^t ✔ and $\sigma_{t\bar{t}}(M_{t\bar{t}})$ ✘.



[Jung et al., Phys.Rev.D81:015004,2010]

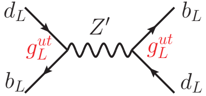
- $\sigma_a^{\text{INT}} < 0 \;\Rightarrow\; \sigma_a^{\text{NP}} \sim (g^{ut})^4/M_{Z'}^4$ relevant, need $g^{ut} = \mathcal{O}(1)$.
- $\sigma_{t\bar{t}}(M_{t\bar{t}})$ sets upper bound on $M_{Z'}$.

Indirect constraints on Z' bosons

Universal Z' couplings to left-chiral quarks in $SU(2)_L$ doublets,

$$\mathcal{L} \supset g_L^{ut}\,(\overline{u,d})_L \gamma^\mu Z'_\mu \binom{t}{b}_L \quad \Rightarrow \quad g_L^{ut}\,\overline{d}_L (V_{ud}^* V_{tb}) \gamma^\mu Z'_\mu\, b_L\,.$$

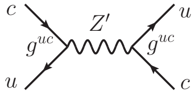
- g_L^{ut} constrained by $B_d - \overline{B}_d$ meson mixing: [Cao et al., Phys.Rev.D81:114004,2010]



$$g_L^{ut} < 3.5 \times 10^{-4} \left(\frac{M_{Z'}}{100\,\text{GeV}} \right)$$

Generically, coupling g^{ut} implies g^{uc} and g^{ct}.

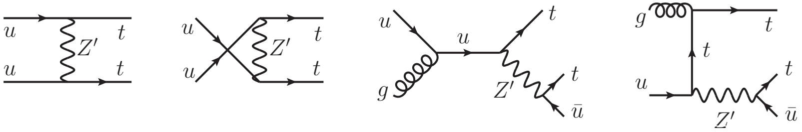
- $g_{L,R}^{uc}$ constrained by $D - \overline{D}$ mixing: [Jung et al., Phys.Rev.D81:015004,2010]



$\Rightarrow$ impose ut flavor symmetry.

Natural motivation for large g_R^{ut}: top condensates. [Cui et al., arXiv:1106.3086]

Direct constraints: same-sign top production



Tevatron: $\sigma(tt + \bar{t}\bar{t}) \lesssim 0.7\,\text{pb}$. [CDF, Phys.Rev.Lett.102:041801,2009][CDF PUBLIC 10466,2011]

Excludes part of the parameter space $(M_{Z'}, g_R^{ut})$ that fits $t\bar{t}$ data.

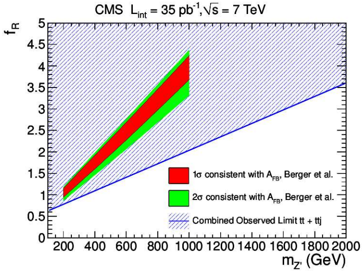
[Berger et al., Phys.Rev.Lett.106:201801,2011][Aguilar-Saavedra & Perez-Victoria, Phys.Lett.B701:93,2011]

LHC: [CMS, arXiv:1106.2142] $f_R = g_R^{ut}/g_W$

High abundance of uu parton density $\rightarrow$ increased tt production rate.

Search for $pp \rightarrow tt$ or $pp \rightarrow ttj$ in dilepton channel.

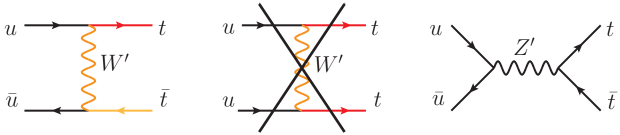
Z' for A_{FB}^t excluded at 95% CL.



Non-abelian flavor symmetry

Add (spont. broken) $SU(2)_{ut}$ gauge symmetry: [Jung et al., Phys.Rev.D83:114039,2011]

$$\mathcal{L} = (\overline{u,t})_R \, \gamma^\mu \, \frac{g}{2} \tau^a W^a_\mu \, \binom{u}{t}_R$$
$$= \frac{g}{\sqrt{2}} \left(\overline{u}_R \gamma^\mu t_R W'^t_\mu + \overline{t}_R \gamma^\mu u_R W'^{\bar{t}}_\mu \right) + \frac{g}{2} \left(\overline{u}_R \gamma^\mu u_R - \overline{t}_R \gamma^\mu t_R \right) Z'_\mu$$

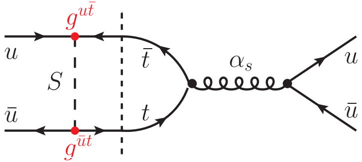


- Same-sign top production suppressed by flavor isospin conservation.
- Dangerous: Z' effects in dijet production $\rightarrow$ increase $M_{Z'}$.

$\boxed{(A^t_{\text{FB}})^> \approx 30\%}$ with $M_{W'} = 200\,\text{GeV}, \; M_{Z'} = 280\,\text{GeV}, \; \alpha = g^2/4\pi = 0.06.$

Lost W' events in forward direction due to selection cuts.
$\rightarrow$ Observed asymmetry reduced to $(A^t_{\text{FB}})^> \approx 22\%$.

New physics in u channel: colored scalars



$$(SU(3)_C, SU(2)_L)_{U(1)_Y} : \; S_6 = (6,1)_{4/3} \text{ or } S_{\bar{3}} = (\bar{3},1)_{4/3}$$

No Rutherford enhancement due to spin correlation (top backwards).

$\rightarrow$ A^t_{FB} smaller than from t-channel NP. [Shu et al., Phys.Rev.D81:034012,2010]

$\rightarrow$ stronger constraints from $\sigma_{t\bar{t}}(M_{t\bar{t}})$ for fixed A^t_{FB}.

Same-sign top production forbidden by electric charge conservation.

Color symmetry dictates flavor symmetry: [Ligeti et al., JHEP 1106:109,2011]

S_6: $g^{ij} = g^{ji}$ ruled out by dijet production, $uu \rightarrow S_6 \rightarrow uu$.

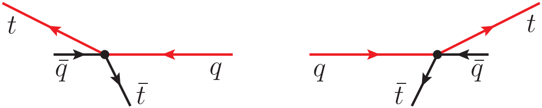
$S_{\bar{3}}$: $g^{ij} = -g^{ji}$ moderate dijet bounds, $uc \rightarrow S_{\bar{3}} \rightarrow uc$.

Light $S_{\bar{3}}$ motivated by grand unification (45_H). [Dorsner et al., Phys.Rev.D81:055009,2010]

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 [EPS: Deisher, Top & EW, 21/7]

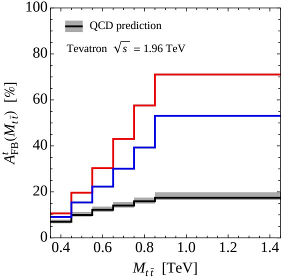
[see also Khachatryan et al., CMS-PAS-TOP-10-010]

$$= -0.023 \pm 0.015_{\mathrm{stat}} \pm 0.021_{\mathrm{syst}}$$

ATLAS [EPS: Ferrari, Top & EW, 21/7]

Model distinction from top observables

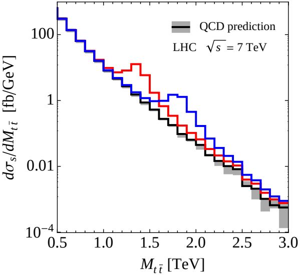
Shape of $A_{FB}^{t}(M_{t\bar{t}})$ [s, t, u]



[Jung et al., Phys.Rev.D81:015004,2010]

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

Resonances in $\sigma_{t\bar{t}}(M_{t\bar{t}})$ [s]
and enhanced tail at high $M_{t\bar{t}}$ [t, u]



[Gresham et al., Phys.Rev. D83 (2011) 114027]

[Hewett et al., arXiv:1103.4618]

Top-quark polarization: departures from QCD vector coupling

[Choudhury et al., arXiv:1012.4750][Krohn et al., arXiv:1105.3743]

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

[Delaunay et al., arXiv:1103.2297]

Top asymmetry - to be taken home

Candidates

s channel: color-octet vector axigluons
t channel: color-singlet vector Z', W'
u channel: color-triplet scalar $S_{\bar{3}}$

Constraints

Dijet production
Same-sign top production
$\sigma_{t\bar{t}}(M_{t\bar{t}})$ tail

Tests

Resonances in $t\bar{t}$ production
Top decay patterns
Direct production of new particles