Title: New strong interactions and the t t-bar asymmetry

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Abstract: The CDF and D0 experiments at Tevatron measure a top-quark forward-backward
 asymmetry significantly larger than the standard-model prediction.
 We construct a model that involves new strong interactions at the electroweak scale
 and can explain the measured asymmetry. Our model possesses a flavor symmetry
 which allows to evade flavor and collider constraints, while it still permits flavor-violating
 couplings of order 1 which are needed to generate the asymmetry via light t-channel vectors.

New strong interactions and the $t\bar{t}$ asymmetry

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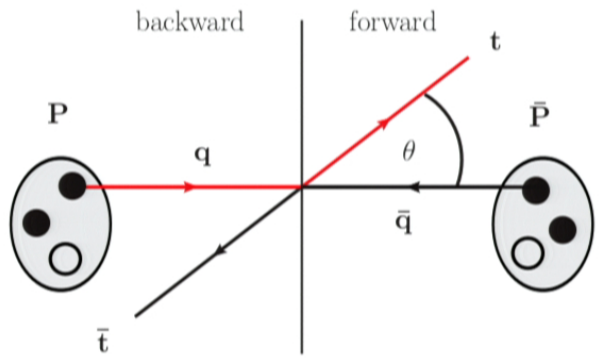
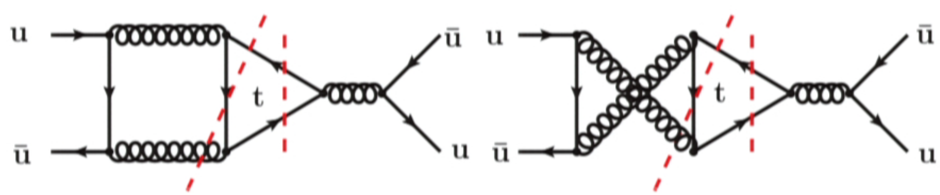
Plan

- Situation
- Flavor-symmetric scenarios
- Strong-interaction realization
- Results

A_{FB} in the standard model



Asymmetry arises at NLO QCD from real and virtual gluons:

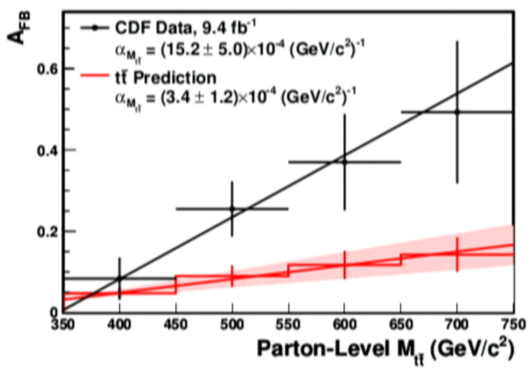


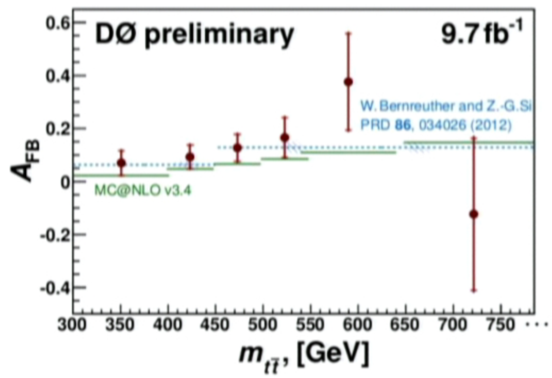
Measurements – Tevatron

$$A_{FB} = \frac{N(y_t > y_{\bar{t}}) - N(y_t < y_{\bar{t}})}{N(y_t > y_{\bar{t}}) + N(y_t < y_{\bar{t}})} = (12.3 \pm 2.5)\%$$

[CDF, arxiv:1211.1003 and D0 March 2014 update, naive average]

$$A_{FB} = (8.8 \pm 0.6)\%$$ [Bernreuther & Si, arxiv:1205.6580]





Measurements – LHC

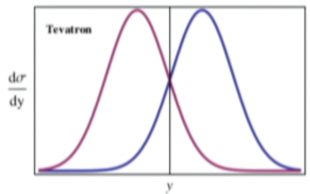
$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

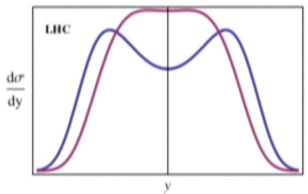
$A_C(7\text{TeV}) = (1.0 \pm 0.8)\%$ [ATLAS, CMS naive average]

$A_C(8\text{TeV}) = (0.5 \pm 0.9)\%$ [CMS]

$A_C(7\text{TeV}) = (1.23 \pm 0.05)\%$ [Bernreuther & Si, arxiv:1205.6580]

$A_C(8\text{TeV}) = (1.11 \pm 0.04)\%$ [Bernreuther & Si, arxiv:1205.6580]

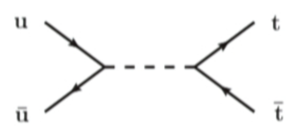


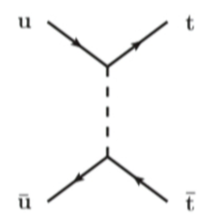


[Ahrens et al., arxiv:1212.5859]

A_{FB} and new physics

- Need interference between NP and SM [Grinstein et al., arxiv:1102.3374]
- Favored scenarios:
  - s-channel: color-octet vector with axial couplings
  - t-channel: color singlet, or colored resonances (Rutherford peak: t-channel propagator $\propto 1/[2E^2(1-\cos\theta)+M^2]$)





t-channel:

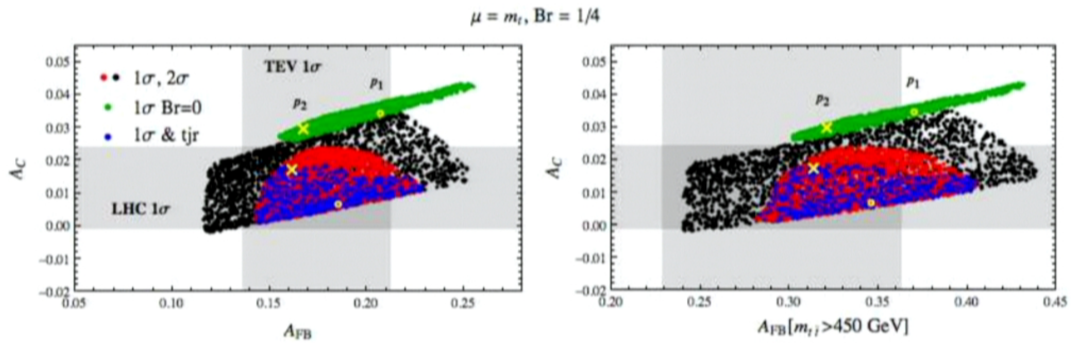
- t-channel vectors with mass of a few hundred GeV yield large A_{FB}, increasing with $M_{t\bar{t}}$ [Jung et al., arxiv:0907.4112]
- A the same time good agreement with measured spectrum at large $M_{t\bar{t}}$ (detector efficiency) [Gresham et al., arxiv:1103.3501]

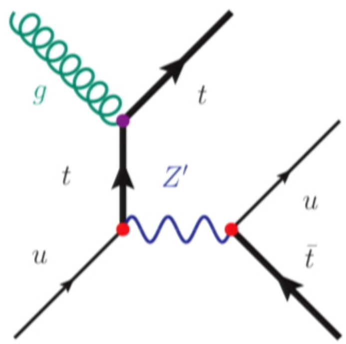
Challenges

- Total and differential cross sections
- Same sign top production $uu \to tt$
- Single top production
- t-channel NP needs large flavor-offdiagonal couplings $Z' - u - t$

  $\Rightarrow$ FCNC's
- Associated production $gq \to t + (Z' \to \bar{t}q)$
  - Contribution to $\sigma_{t\bar{t}}$ at LHC
  - top+jet resonance searches
  - Need suppressed $\mathrm{Br}(Z' \to \bar{t}q)$

Negative contribution to A_C by associate production





- Breaks correlation between A_{FB} and A_C

  [Drobnak et al., arxiv:1209.4872]

- Need other dominant decay mode to obtain $\text{Br}(Z' \to \bar{t}u) \approx 0.25$
- In our case Z' will be K^*_{HC} resonance, main decay $K^*_{\text{HC}} \to \pi_{\text{HC}}\pi_{\text{HC}}$

Flavor symmetric scenarios

- Look at models which are invariant under global

$$G_F = U(3)_{Q_L} \times U(3)_{u_R} \times U(3)_{d_R}$$

- or subgroup

$$H_F = U(2)_{Q_L} \times U(2)_{u_R} \times U(2)_{d_R} \times U(1)^3$$

Flavor symmetric models that

- do not contain breaking of G_F (or H_F) beyond SM Yukawas
- contain new fields in nontrivial representations of G_F or H_F
- have $\mathcal{O}(1)$ couplings to top and light quarks

can avoid

- like-sign top or single top production, FCNCs, e.g., $D^0 - \bar{D}^0$ mixing

while still accounting for A_{FB}. [Grinstein et al., arxiv:1108.4027]

Flavor symmetric scenarios

Simple possibility: $U(3)_{U_R}$ flavor octet vectors coupling only to right-handed up quarks

- t–channel: $(V_\mu^4 - iV_\mu^5)(\bar{t}_R \gamma^\mu u_R) + \ldots$ "K^*"
- s–channel: $V_\mu^8(\bar{u}_R \gamma^\mu u_R + \bar{c}_R \gamma^\mu c_R - 2\bar{t}_R \gamma^\mu t_R)$ "Φ, Ω"
- Phenomenological models with massive vectors not renormalizable
- Two options for UV completion
  - local horizontal symmetry flavor gauge bosons (FGB's)
  - composite vector meson flavor multiplets
- FGB's problematic for low-scale models
- Composite vector mesons naturally have new dominant decay channels $V \to PP$ (needed for $\sigma_{t\bar{t}}$, dijet constraints)

Strong interaction realization

- New confining $SU(3)_{\rm HC}$ "hypercolor" gauge interaction
- Use QCD as a prototype
- Scale $\Lambda \approx 200$GeV
- Add $SU(2)_L$ singlet
  - vectorlike $[SU(2) \times U(1)]_{U_R}$ flavor triplet of hypercolor quarks $(\mathcal{Q}_{L_i}, \mathcal{Q}_{R_i})$
  - flavor singlet hypercolor scalar $\mathcal{S}$
- Transform under $SU(3)_{\rm HC} \times SU(3)_C \times SU(2)_L \times U(1)_Y$ as

$$\mathcal{Q}_{L_i,R_i}(3,1,1,0), \quad \mathcal{S}(\bar{3},3,1,2/3)$$

Setup

$$\mathcal{L}_{\rm NP} = (h_{ij}\bar{u}_{R,i}\,\mathcal{Q}_{L,j}\,\mathcal{S} + \text{H.c.}) + m_{\mathcal{Q}ij}\,\bar{\mathcal{Q}}_i\,\mathcal{Q}_j + m_s^2|\mathcal{S}|^2$$

- $h = \text{diag}(h_1, h_1, h_3)$, $m_{\mathcal{Q}} = \text{diag}(\mu_1, \mu_1, \mu_3)$.
- Take $\mu_1 < \mu_3 \ll \Lambda$, like u, d, s in QCD
- First two generations: "Isospin symmetry"
- Think of as "$(u, d, s) \leftrightarrow (\mathcal{Q}_u, \mathcal{Q}_c, \mathcal{Q}_t)$"
- Hypercolor sector only couples to right-handed quarks due to choice of representations for $\mathcal{Q}, \mathcal{S}$.

Lowest hypercolor resonances

- nonet of $^3S_1$ ($J^{PC} = 1^{--}$) vector resonances $\rho_{\rm HC}$, $K^*_{\rm HC}$, $\phi_{\rm HC}$, $\omega_{\rm HC}$
- nonet of $^3P_1$ ($J^{PC} = 1^{++}$) axial-vector resonances $a_1^{\rm HC}$, $K_{1A}^{\rm HC}$, $f_1^{\rm HC}$
- For simplicity, we neglect the $^1P_1$ nonet ($K_{1A} - K_{1B}$ mixing)
- Kinetic term has chiral $SU(3)_L \times SU(3)_R$ symmetry (as in QCD)
- $\langle \bar{\mathcal{Q}}\mathcal{Q} \rangle \neq 0$ condensates lead to octet of (pseudo-)Nambu-Goldstone bosons $\pi_{\rm HC}$, $K_{\rm HC}$, $\eta_{\rm HC}$
- Neglect singlet $\eta'_{\rm HC}$

Scaling

- Naive scaling relation $\frac{f_\pi^{\rm HC}}{f_\pi} \sim \frac{f_\rho^{\rm HC}}{f_\rho} \sim \frac{m_\rho^{\rm HC}}{m_\rho}, \qquad \frac{f_\rho^{\rm HC}}{m_\rho^{\rm HC}} \sim 0.2$
- A general analysis of A_{FB} suggests $m_\rho^{HC} \sim 200\text{GeV}$
- $\Rightarrow f_\pi^{\rm HC} \sim 20\text{GeV}$
- $\left(m_\pi^{\rm HC}\right)^2 \approx 8\pi f_\pi^{\rm HC} m_{\mathcal{Q}}$
- $\Rightarrow m_\pi^{\rm HC} = \mathcal{O}(100)\text{GeV}$ for HC quark masses $\mathcal{O}(10)\text{GeV}$
- Vector meson dominance (VMD) yields $g_{\rho\pi\pi} \sim M_\rho / f_\rho$

$$\frac{\Gamma(\rho^{\rm HC} \to \pi^{\rm HC}\pi^{\rm HC})}{M_\rho^{\rm HC}} \approx 10\%$$

Resonances containing $\mathcal{S}, \mathcal{S}^*$

- In principle, could have $V^{\mu}_{\text{o,s}}[\mathcal{S}^*\mathcal{S}]$, $u'[\mathcal{S}\mathcal{Q}]$ bound states
- Partonic width $\Gamma(\mathcal{S} \to u_j \bar{\mathcal{Q}}_j) \propto m_{\mathcal{S}} |h_j|^2 \approx 230\,\text{GeV}$ in our benchmark
- Hadronization time governed by $\mathcal{O}(\text{few}) f_\pi \approx 50\,\text{GeV}$
- Lighter $V_{\text{o,s}}$ would lead to large bump in $t\bar{t}$ differential spectrum

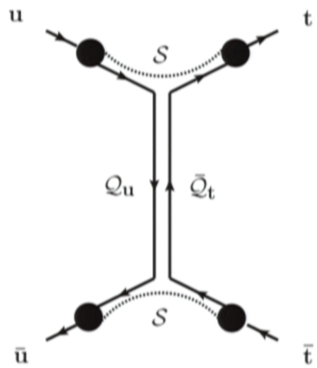
  $\Rightarrow m_{\mathcal{S}} \approx 500\,\text{GeV}$

Mixing and partial compositeness

- Mixing with SM RH up quarks induced by Yukawa couplings $h_i \bar{u}_{R,i} \mathcal{Q}_{L,i} \mathcal{S}$
- Effective width is small for small virtuality
- $t\bar{t}$ production via K^*, K_1, K exchange and $u_i - u_i'$ mixing

$$|u_{R_i(L_i)}\rangle^{\text{mass}} = \cos\theta_{R_i(L_i)} |u_{R_i(L_i)}\rangle^{\text{flav.}} - \sin\theta_{R_i(L_i)} |u'_{R_i(L_i)}\rangle^{\text{flav.}}$$

$$\sin\theta_{R_i} \approx \sqrt{2} h_i \frac{f_{u_i'}}{M_{u_i'}}, \qquad \sin\theta_{L_i} \approx \sqrt{2} h_i \frac{f_{u_i'} m_{u_i}}{M^2_{u_i'}}$$



Couplings to quarks

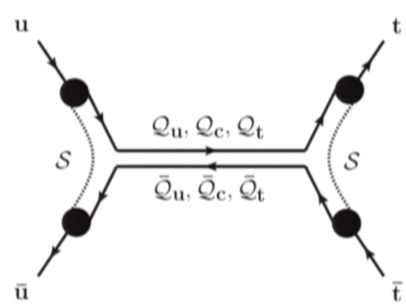
- Use VMD arguments to estimate $g_\rho \approx m_\rho / f_\rho$ (similar for axial vectors)

$$\mathcal{L} = g_\rho \, \rho_\mu^a \, \bar{u}' \, T^a \gamma^\mu u'$$

- $\rho^{\mathrm{HC}} - u_i - u_j$ coupling follows from mixing
  - To get order 1 couplings, need $h \approx 2$. $\Rightarrow \sin\theta_{R_i} \approx 0.2 - 0.4$
  - Main decay channel into HC pions
  - $\mathcal{O}(8)$ tuning of phase space for $K^* \to K\pi$ to get $\mathrm{Br}(K^* \to \bar{u}t) = \mathcal{O}(30\%)$
- $\pi^{\mathrm{HC}} - u_i' - u_j'$ coupling via derivative interactions ("pion - nucleon coupling")
- $\pi^{\mathrm{HC}} - u_i - u_j$ coupling again from mixing
  - HC pions decay into jet pairs

Ideal mixing

- $\psi^8_{\mathsf{HC}} = (\mathcal{Q}_u\bar{\mathcal{Q}}_u + \mathcal{Q}_c\bar{\mathcal{Q}}_c - 2\mathcal{Q}_t\bar{\mathcal{Q}}_t)/\sqrt{6}$ and
  $\psi^1_{\mathsf{HC}} = (\mathcal{Q}_u\bar{\mathcal{Q}}_u + \mathcal{Q}_c\bar{\mathcal{Q}}_c + \mathcal{Q}_t\bar{\mathcal{Q}}_t)/\sqrt{3}$ could contribute in s-channel
- In QCD $\psi^8 = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$ and $\psi^1 = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$ mix into mass eigenstates $\omega \approx (u\bar{u} + d\bar{d})/\sqrt{2}$ and $\phi \approx (s\bar{s})$
- In this case s-channel contribution to A_{FB} and $\sigma_{t\bar{t}}$ vanishes



Quark model fit

To determine meson masses and the mixing angle, we follow [Cheng & Shrock, arxiv:1109.3877]

- ℓ light quarks m_q, one heavier quark m_Q
- For $\ell = 2$, resembles QCD with $m_u = m_d < m_s$
- Fit expressions for meson masses in simple quark model to observed vector meson masses, in dependence of quark masses
- E.g. $M_{\rho_{\rm HC}} = \mu^{\rm HC}(E^{\rm HC} + 2m_{\mathcal{Q}_1})$
- From this determine mixing angle, as well as meson masses for quark masses different from QCD
- Scale up from $\Lambda_{\rm QCD}$ to $\Lambda_{\rm HC}$.

The χ^2 fit

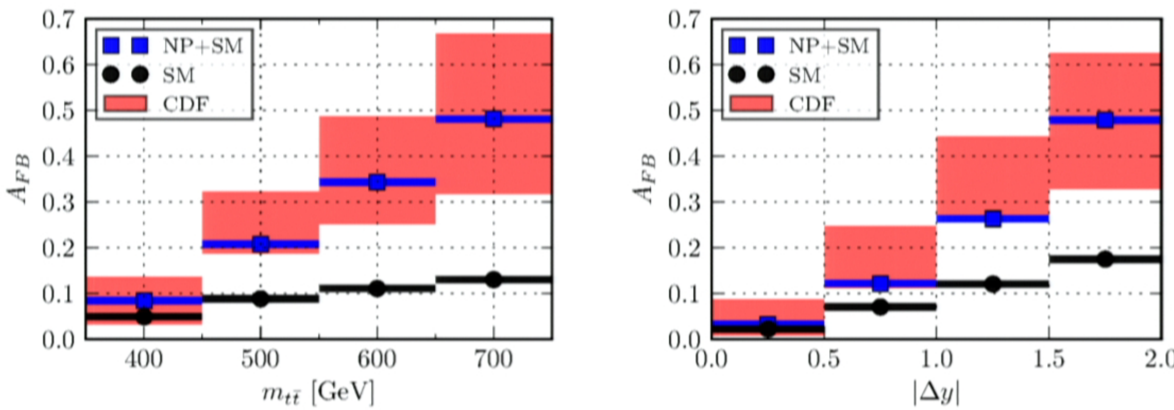
- We minimize the χ^2 of the
  - inclusive, high-, and low-bin Tevatron A_{FB}
  - LHC7 charge asymmetry A_C
  - inclusive LHC and Tevatron $t\bar{t}$ cross section
- We fit for the UV parameters
  - Λ_{HC}
  - HC quark and scalar masses
  - Yukawa couplings
- We also allow for small deviations from QCD scaling

Benchmark

UV input: $\Lambda_{\text{HC}} = 171\text{GeV}$, $m_{\mathcal{Q}_u} = 3.1\text{GeV}$, $m_{\mathcal{Q}_t} = 30.5\text{GeV}$, $M_{\mathcal{S}} = 520\text{GeV}$, $h_1 = 2.0$, $h_3 = 4.4$, plus "fudge factors" of $\mathcal{O}(1)$ for scaling

HC resonance	mass	decay width
π	62 GeV	$4 \cdot 10^{-7}\, m_\pi$
K	143 GeV	≈ 0
η	161 GeV	$1.3 \cdot 10^{-7}\, m_\eta$
ρ	177 GeV	$0.059\, m_\rho$
K^*	211 GeV	$0.002\, m_{K^*}$
$V_H[\phi]$	242 GeV	$8 \cdot 10^{-7}\, m_{V_H}$
$V_L[\omega]$	180 GeV	$0.001\, m_{V_L}$

Resulting A_{FB} from benchmark



$$A_{FB} = 17.3\%$$

$$A_{FB}^{CDF} = (16.4 \pm 4.7)\%$$ [CDF, arxiv:1211.1003]

Resulting A_C from benchmark

- Recall

$$A_C(7\text{TeV}) = (1.0 \pm 0.8)\%$$ [ATLAS, CMS naive average]

$$A_C(8\text{TeV}) = (0.5 \pm 0.9)\%$$ [CMS]

$$A_C(7\text{TeV}) = (1.23 \pm 0.05)\%$$ [Bernreuther & Si, arxiv:1205.6580]

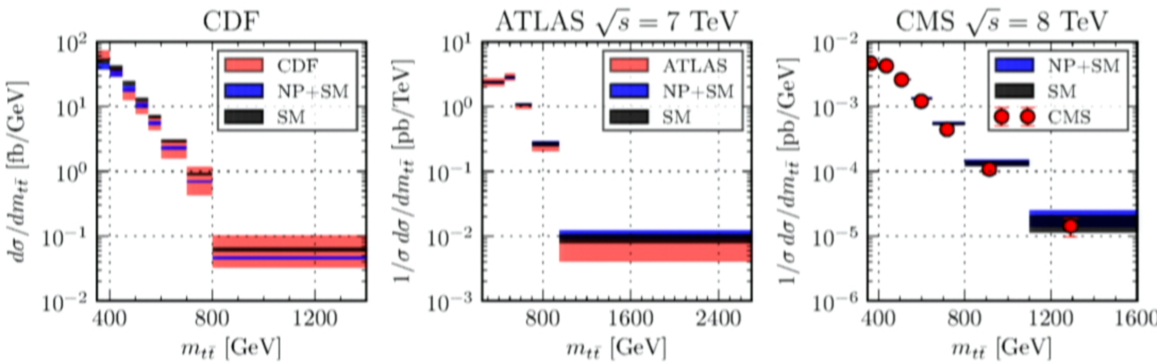
$$A_C(8\text{TeV}) = (1.11 \pm 0.04)\%$$ [Bernreuther & Si, arxiv:1205.6580]

- Our benchmark yields

$$A_C(7\text{TeV}) = 2.45\% \text{ (no associates)} \quad \to \quad 1.37\%$$

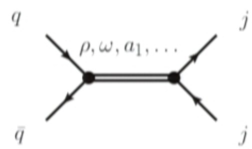
$$A_C(8\text{TeV}) = 2.39\% \text{ (no associates)} \quad \to \quad 1.35\%$$

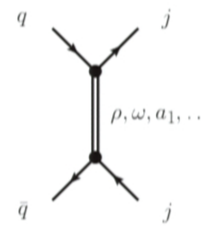
Differential $t\bar{t}$ cross section



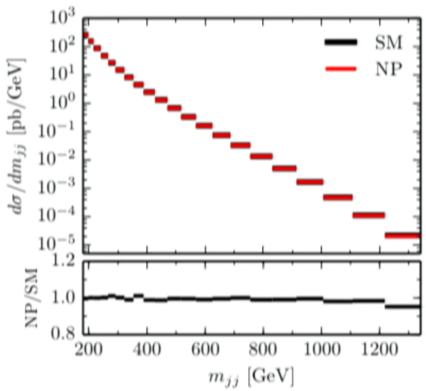
$\sigma_{t\bar{t}}$	SM + NP	exp.
Tevatron	6.38 ± 0.54 pb	7.50 ± 0.48 pb
LHC (7 TeV)	176 ± 15 pb	172.4 ± 8.5 pb
LHC (8 TeV)	251 ± 20 pb	234 ± 8 pb

Dijet m_{jj} spectra

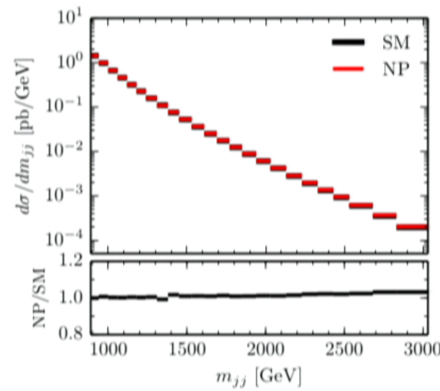




Ratios of benchmark to SM predictions

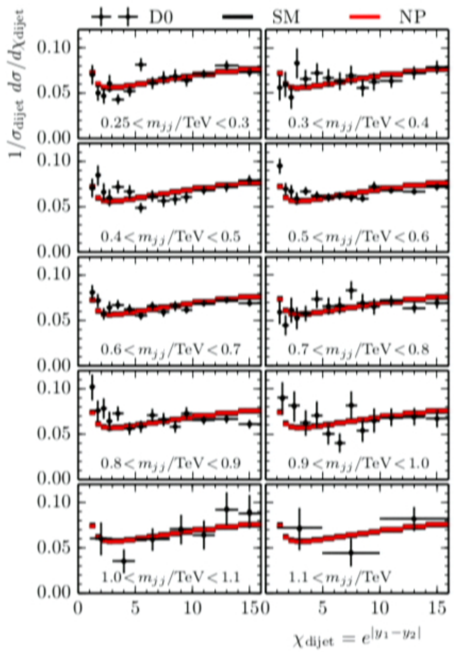


Tevatron (CDF)

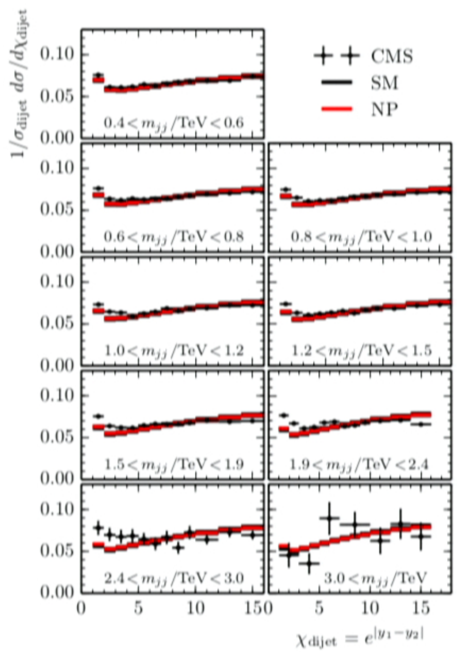


LHC (CMS)

Dijet angular correlations



Tevatron (D0)



LHC (CMS)

CDF dijet pair constraints

- CDF [arxiv:1303.2699] has bounds on $p\bar{p} \to X \to YY \to jj\,jj$
- For $m_\rho = 177$ GeV, $m_\pi = 62$ GeV, $\sigma(p\bar{p} \to \rho \to \pi\pi \to jj\,jj) \approx 35$ pb

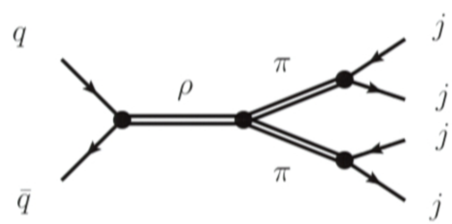
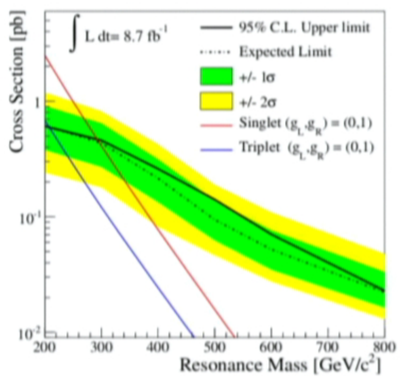


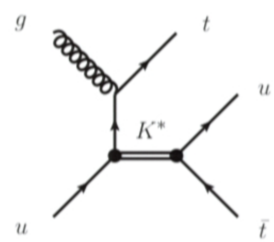
TABLE II: Observed and expected 95% C.L. upper limits on $\sigma(p\bar{p} \to X \to YY \to jj\,jj)$ for several values of m_Y and m_X. Also shown are theoretical predictions for axi-gluon production assuming coupling to quarks of $C_q = 0.4$ [5, 9].

m_X (GeV/c^2)	m_Y (GeV/c^2)	Expected (pb)	Observed (pb)	Axi-gluon (pb)
150	50	641.2	431.1	5600
	70	209.6	270.6	
175	50	66.8	78.9	3500
	70	111.5	163.9	
200	50	13.8	9.5	2200
	70	30.4	91.5	
	90	17.8	100.4	
225	50	18.0	26.0	1750
	70	20.7	25.0	
	90	20.9	25.3	
250	50	6.2	2.0	1000
	70	4.0	3.6	
	90	5.1	2.8	

top – jet resonance searches

CDF arxiv:1203.3894





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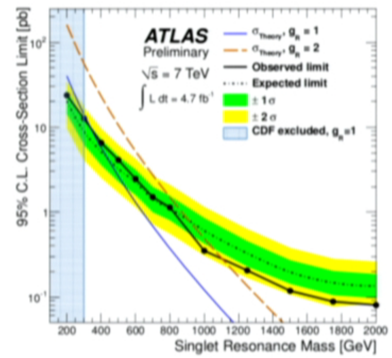


$\sigma_{K*t} \times \text{Br}_{K^* \to \bar{t}j} = 0.07\,\text{pb}$

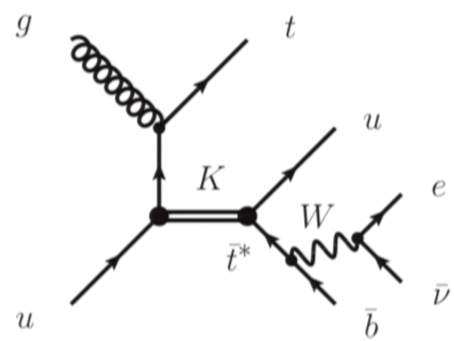
$\sigma_{K_1 t} \times \text{Br}_{K_1 \to \bar{t}j} = 0.008\,\text{pb}$

$\sigma_{K*t} \times \text{Br}_{K^* \to \bar{t}j} = 4.4\,\text{pb}$

$\sigma_{K_1 t} \times \text{Br}_{K_1 \to \bar{t}j} = 0.8\,\text{pb}$

Associated K production

- Recall $M_K = 143\,\text{GeV}$
  - Contribution to single top + W production?
    $\sigma_{tW} < 1.7\,\text{pb}$ (cf. $\sigma_{tW} = 16^{+5}_{-4}\,\text{pb}$ [CMS, arxiv:1209.3489])
  - Contribution to $\sigma_{t\bar{t}}$?
    $\sigma_{t\bar{t}} < 11\,\text{pb}$ (cf. $\sigma_{t\bar{t}} = 239 \pm 13\,\text{pb}$ [CMS, arxiv:1312.7582])
  - $\Rightarrow$ Contributions smaller than current exp. error



Production of resonances @ LHC8

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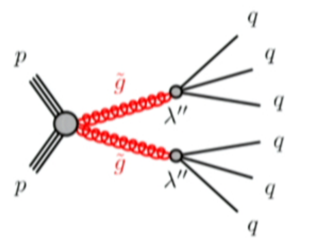
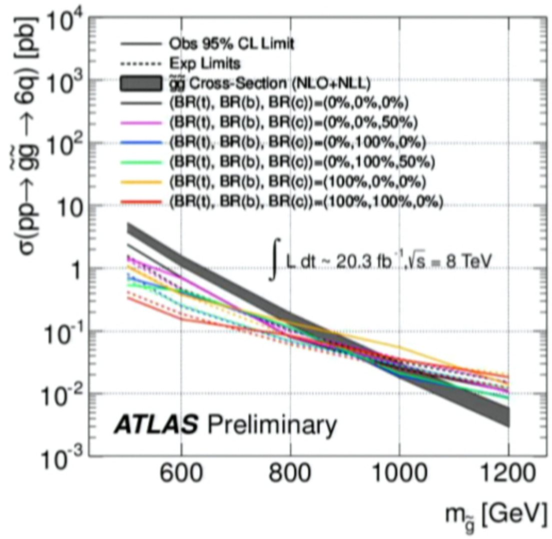
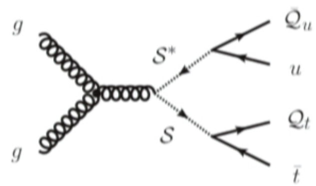


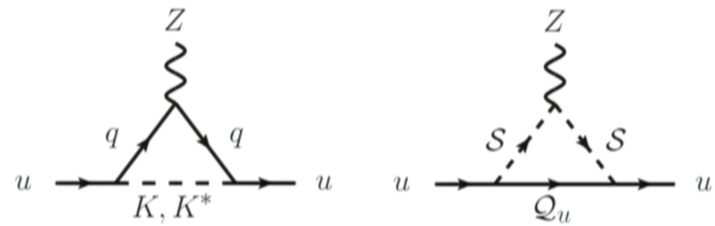




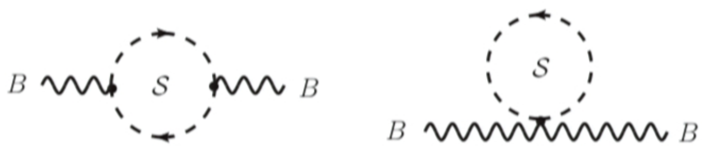
$$\sigma(pp \to \mathcal{S}\mathcal{S}^* \to q\bar{q}\mathcal{Q}_q\bar{\mathcal{Q}}_q) \approx 0.18\,\text{pb}$$
$$\sigma(pp \to \mathcal{S}\mathcal{S}^* \to q\bar{t}\bar{\mathcal{Q}}_q\mathcal{Q}_t + \bar{q}t\mathcal{Q}_q\bar{\mathcal{Q}}_t) \approx 0.6\,\text{pb}$$
$$\sigma(pp \to \mathcal{S}\mathcal{S}^* \to t\bar{t}\mathcal{Q}_t\bar{\mathcal{Q}}_t) \approx 0.6\,\text{pb}$$

Electroweak precision data

- Contributions to atomic parity violation [Gresham et al., arxiv:1203.1320]
- (sub-)permil effects on effective couplings



- $\mathcal{S}$ is $SU(2)$ singlet – no contribution to S parameter
- Diagrams for T parameter cancel (see also [Grimus et al., arxiv:0711.4022])



- Shift in top Yukawa coupling $\lesssim 1\%$ – below current experimental sensitivity

Possible signals

- K^*: $\bar{t}j$ resonances
- K: $\bar{t}^*j$ resonances
- π: $pp \to \rho\rho \to 4\pi$
- HC baryon is a dark matter candidate
  - Accidental Z_2 symmetry
  - Relic density is tiny, $\Omega_B \approx 10^{-8}\Omega_{\rm DM}$
  - Direct detection cross section of order of LUX bound

Summary

- We constructed a model with many low-mass confining resonances
- Currently invisible at LHC
- However, can explain large Tevatron A_{FB}