Composite t' triplets from QCD-like dynamics and $t\bar{t}$ asymmetries

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Probing the Standard Model and New Physics at Low and High Energies
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Introduction

Gregory: "Is there any other point to which you would wish to draw my attention?"
Holmes: "To the curious incident of the dog in the night-time."
Gregory: "The dog did nothing in the night-time."
Holmes: "That was the curious incident."

[Arthur Conan Doyle, "Silver Blaze"]

Introduction

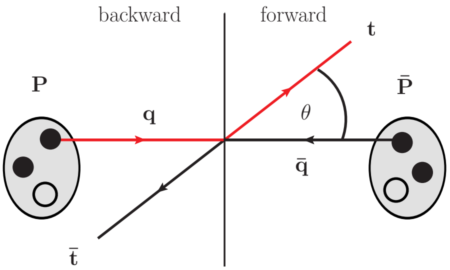
Gregory: "Is there any other point to which you would wish to draw my attention?"
Holmes: "To the curious incident of the t's at colliders."
Gregory: "The t's have not been seen at colliders."
Holmes: "That was the curious incident."

[based on Arthur Conan Doyle, “Silver Blaze”]

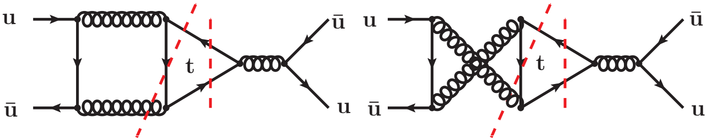
Outline

- Situation
- Flavor-symmetric models
- Strong-interaction realization
- Preliminary results

A_{FB} in the standard model



Asymmetry arises at NLO QCD from real and virtual gluons:



Standard-model predictions

$$A_C^{\text{exp}} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$$

- Tevatron:

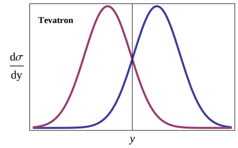
  $A_C^{\text{exp}} = A_{FB}^t \qquad \Delta y = y_t - y_{\bar{t}} \qquad A_C^{\text{TEV}} = (7.16^{+1.05}_{-0.68})\% \times 1.22_{\text{EW}}$

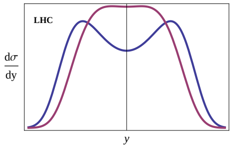
  [Ahrens et al., arxiv:1106.6051; Hollik, Pagani, arxiv:1107.2606]

- LHC:

  $A_C^{\text{exp}} = A_C^{|y|} \qquad \Delta y = |y_t| - |y_{\bar{t}}| \qquad A_C^{\text{LHC7}} = (1.15 \pm 0.06)\%$

  [Kühn, Rodrigo, arxiv:1109.6830]





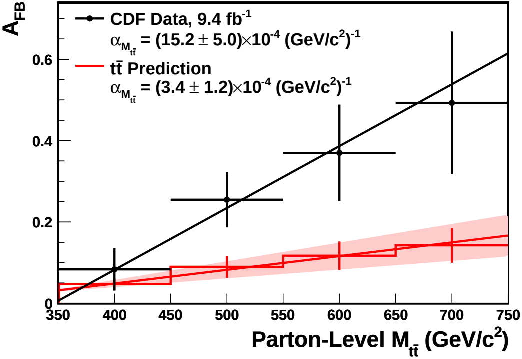
[Ahrens et al., arxiv:1212.5859]

Measurements – Tevatron

Inclusive parton level

$$A_{FB} = \frac{N(y_t > y_{\bar{t}}) - N(y_t < y_{\bar{t}})}{N(y_t > y_{\bar{t}}) + N(y_t < y_{\bar{t}})} = \left[17.4 \pm 3.8\right]\%$$

[CDF & D0, naive average]



Measurements – LHC

$$A_C(\ell j) = (0.4 \pm 1.0 \pm 1.1)\%$$ [CMS, arxiv:1207.0065]

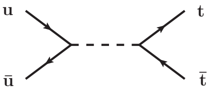
$$A_C(\ell\ell) = (5.0 \pm 4.3^{+1.0}_{-3.9})\%$$ [CMS, PAS-TOP-12-010]

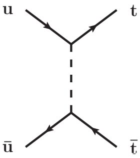
$$A_C(\ell j) = (-1.9 \pm 2.8 \pm 2.4)\%$$ [ATLAS, arxiv:1203.4211]

$$A_C(\ell\ell) = (5.7 \pm 2.4 \pm 1.5)\%$$ [ATLAS-CONF-2012-057]

A_{FB} in models of 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 models:

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

Flavor symmetric models

- Look at NP 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]

Strong interaction realization

- New confining $SU(N)_{\text{HC}}$ "hypercolor" gauge interaction
- Naturally translate a UV symmetry to the u_R sector
- Use QCD as a prototype
- Scale $\Lambda \approx 300\text{GeV}$
- $SU(2)_L$ singlet, vectorlike $SU(3)_{U_R}$ or $(SU(2) \times U(1))_{U_R}$ flavor triplet of hypercolor quarks $(\omega_{L_i}, \omega_{R_i})$, flavor singlet hypercolor scalar $\mathcal{S}$

Transforms under $SU(N)_{\text{HC}} \times SU(3)_C \times SU(2)_L \times U(1)_Y$ as

$$\omega_{L_i,R_i}(N,1,1,a), \quad \mathcal{S}(\bar{N},3,1,b), \quad a+b=2/3\,(\text{choose})$$

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

- Kinetic term has chiral $SU(3)_L \times SU(3)_R$ symmetry (as in QCD)

Setup

- $h = \mathrm{diag}(h_1, h_1, h_3)$, $m_\omega = \mathrm{diag}(\mu_1, \mu_1, \mu_3)$.
- Take $\mu_1 \sim \mu_3 \ll \Lambda$, like u, d, s in QCD
- Think of as "$(u, d, s) \leftrightarrow (\omega_u, \omega_c, \omega_t)$"
- Hypercolor sector only couples to right-handed quarks due to choice of representations for $\omega, \mathcal{S}$.
- To be specific, take $N = 3, a = 0$ (hypercolor quarks have no charge).

Effective theory

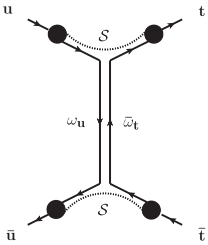
- Spontaneous symmetry breaking $\rightarrow$ octet of massless goldstone bosons (as in QCD)
- (Hyper-)quark masses break symmetry explicitly $\Rightarrow$ small nonvanishing Goldstone-boson masses
- Construct effective chiral Lagrangian for Goldstone bosons
- Include resonances

Physical particle content:

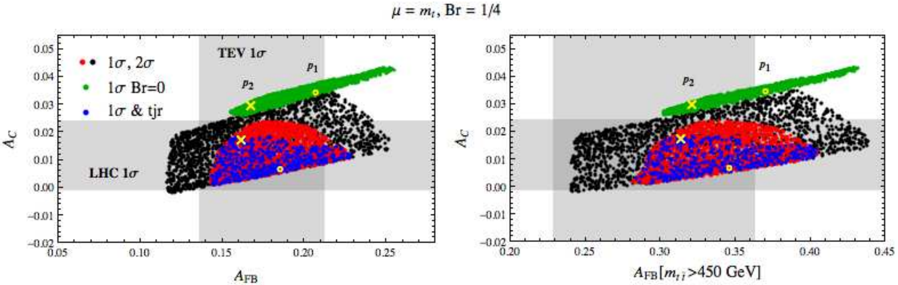
- HC pion octet $\pi^a_{\text{HC}}[\bar{\omega}\omega]$; singlet η'_{HC}
- Lowest HC resonance nonets: $\rho^a_{\text{HC}}[\bar{\omega}\omega]$ vector, $a^a_{1,\text{HC}}[\bar{\omega}\omega]$ axial vector, ...
- Composite quarks $u'_i[\mathcal{S}\omega_i]$
- Color octet vector $V^o_\mu[\mathcal{S}^*\mathcal{S}]$, color singlet vector $V^s_\mu[\mathcal{S}^*\mathcal{S}]$

A_{FB} from t-channel exchanges

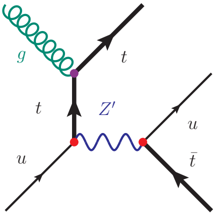
- flavor triplet of weak singlet vectorlike up-quarks $u'[\mathcal{S}\omega_u]$, $c'[\mathcal{S}\omega_c]$, $t'[\mathcal{S}\omega_t]$
- Yukawa couplings $h_i \bar{u}_{R,i}\,\omega_{L,i}\,\mathcal{S}$ induce mixing with SM RH up quarks
- K^*_{HC} t-channel exchange contributes to A_{FB}.

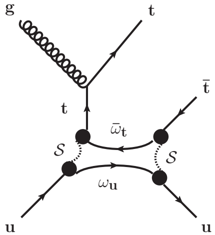


A_C from associate production



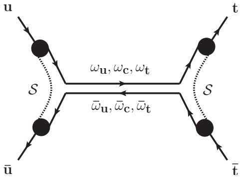
See talk by Jure Drobnak yesterday [Drobnak et al., arxiv:1209.4872]





A_{FB} from s-channel exchanges

- $\psi^8_{\mathrm{HC}} = (\omega_u\bar{\omega}_u + \omega_c\bar{\omega}_c - 2\omega_t\bar{\omega}_t)/\sqrt{6}$ and $\psi^1_{\mathrm{HC}} = (\omega_u\bar{\omega}_u + \omega_c\bar{\omega}_c + \omega_t\bar{\omega}_t)/\sqrt{3}$ could contribute in s-channel
- Contribution to A_{FB} vanishes for "ideal mixing": $\Omega_{\mathrm{HC}} = (\omega_u\bar{\omega}_u + \omega_c\bar{\omega}_c)/\sqrt{2}$ and $\Phi_{\mathrm{HC}} = \omega_t\bar{\omega}_t$



Physical parameters

$$\Lambda_{\mathrm{HC}} \approx 300\,\mathrm{GeV}$$

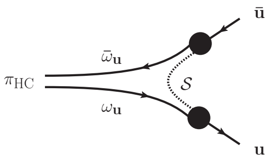
- Get couplings, decay constants, etc. essentially by naive scaling from QCD
- E.g. $M_{\pi_{\mathrm{HC}}} \propto \frac{\Lambda_{\mathrm{HC}}}{\Lambda_{\mathrm{QCD}}} 2m_{\omega_1}$

Resonance masses and mixing angle à la [Cheng & Shrock, arxiv:1109.3877]:

- Fit expressions for QCD meson masses in simple quark model to observed vector meson masses, in dependence of quark masses
- Determine mixing angle, meson masses for general quark mass dependence
- Scale up to Λ_{HC}
- E.g. $M_{\rho_{\mathrm{HC}}} = \mu^{\mathrm{HC}}(E^{\mathrm{HC}} + 2m_{\omega_1})$

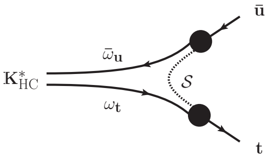
HC pions

- Goldstones: $M_\pi, M_\rho \sim 100\,\text{GeV}$
- Main decay channel into jets
- K_{HC}s can be long-lived
  – can they be seen in pixel detectors?



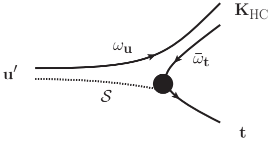
HC ρs

- $M_\rho, M_{K^*} \sim 200\,\text{GeV}$
- Main decay channel into HC pions
- Enhance branching ratio $K^* \to \bar{u}t$ for associate production of t



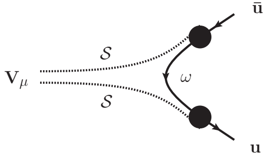
HC quarks

- Heavier than ρ, K^* because of $\mathcal{S}$ contribution: $m_{u'} \sim 700\,\mathrm{GeV}$
- They decay via $u' \to \pi^a + t$
- $\Gamma/M \approx 100\%$, compare with $\approx 1\%$ for the top quark



HC vectors

- Naturally heavy because of $\mathcal{S}$ contribution: $M_V \sim 1300\,\text{GeV}$
- Helps to avoid a bump in $t\bar{t}$ cross section!
- Decays dominantly into u, u'
- Very broad!, $\Gamma/M \approx 50\%$



Preliminary Benchmark

UV input: $\Lambda_{\mathrm{HC}} = 178\mathrm{GeV}$, $m_{\omega_u} = 3.7\mathrm{GeV}$, $m_{\omega_t} = 20.2\mathrm{GeV}$, $m_{\mathcal{S}} = 520\mathrm{GeV}$, $h_1 = 1$, $h_3 = 1.5$, plus "fudge factors" of $\mathcal{O}(1)$ for scaling (here all equal 1)

HC resonance	mass	decay width
π	68 GeV	$10^{-6} m_\pi$
K	123 GeV	$\approx 10^{-7} m_K$
η	137 GeV	$\approx 10^{-7} m_\eta$
ρ	185 GeV	$0.1 M_\rho$
K^*	207 GeV	$\approx 0 M_{K^*}$
Φ	188 GeV	$\approx 0 M_\Phi$
Ω	227 GeV	$\approx 0 M_\Omega$
$a_1, K_1, \ldots$	$\sim$ 350 GeV	$(0.1 - 0.5) M_{a_1}$
$u_i', \ldots$	$\sim$ 700 GeV	$\approx m_{u_i'}$
V_o	1302 GeV	$0.4 M_{V_o}$
V_s	1302 GeV	$0.4 M_{V_s}$

$\cos\theta_{R,1} \approx 0.96$

$\cos\theta_{R,3} \approx 0.92$

$\cos\theta_{L,1} \approx 1$

$\cos\theta_{L,3} \approx 0.995$

$\kappa(\rho)_R \approx 0.56$

Resulting A_{FB} from benchmark

Parton level $M_{t\bar{t}}$ [GeV]	A_{FB}(stat.)(syst.)	NLO (QCD + EW)
< 450	0.078(54)	0.062(4)
≥ 450	0.296(67)	0.129(7)
inclusive	0.174(38)	0.088(6)

Table: Tevatron measurements [arxiv:1211.1003]

Parton level $M_{t\bar{t}}$ [GeV]	A_{FB}
< 450	0.139
≥ 450	0.297
inclusive	0.162

Table: A_{FB} from our preliminary benchmark

Differential $t\bar{t}$ cross section

- Blue $\to$ SM
- Purple $\to$ SM + NP
- Black dots $\to$ Tevatron measurement

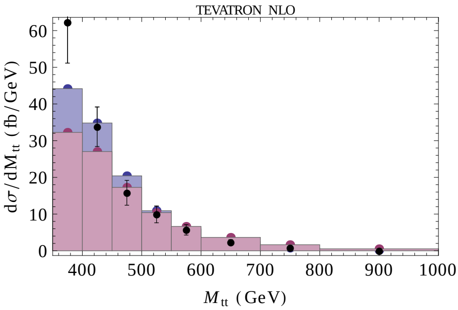


Figure: Tevatron

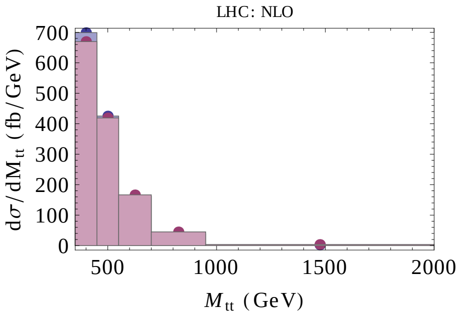


Figure: LHC @ 7TeV

Summary and outlook

- Large Tevatron A_{FB} can be explained by NP
- Hypercolor model yields natural realization of NP models with flavor symmetry
- Check more collider constraints: dijets, t jet resonances, jet multiplicities, ...
- Find LHC signatures