The 3rd generation quarks in warped models: LHC predictions from LEP/Tevatron anomalies

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with
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PRD 2010; PLB 2011
I) Introduction: a warped model

II) \( A_{FB}^t \) and \( t\bar{t} \) cross section @ Tevatron

III) \( A_{FB}^b \) and EW precision tests @ LEP

IV) Constraints and predictions @ LHC

V) Other scenarios explaining \( A_{FB}^t \) ?

VI) Conclusions
I) Introduction: a warped model

The Randall-Sundrum (RS) scenario with bulk fields:

- RS addresses the gauge hierarchy:
  \[ M_{\text{grav}} \approx TeV \approx Q_{\text{EW}} \]
  Randall, Sundrum (1999)

- RS generates the mass hierarchies:
  \[ m_e \ll m_t \]
  Gherghetta, Pomarol (2000)

Planck–brane  TeV–brane
I) Introduction: a warped model

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- RS generates the mass hierarchies:
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  Gherghetta, Pomarol (2000)

New Physics effects in the heavy fermion sector!
+ attractive features of the RS scenario with bulk fields (= dual via AdS/CFT to composite Higgs & top models) :

- WIMP candidates for the dark matter of universe: a LKP stable due to a possible KK-parity \( (\text{like in UED}) \)

- Unification of gauge couplings \( (\text{as in ADD}) \) at high-energies

- Extra-Dimensions = necessary ingredients for higher-energy string theories
Bulk gauge bosons/fermions mix with their KK excitations
=> tree-level contributions to EW observables

Ways out to respect the constraints from EW precision data for $M_{KK} \sim \text{TeV}$:
Bulk gauge bosons/fermions mix with their KK excitations
=> tree-level contributions to EW observables

Ways out to respect the constraints from EW precision data for $M_{KK} \approx \text{TeV}$:

~> **Gauge custodial symmetry in the bulk**

\[
\begin{align*}
O(4) & \quad SU(2)_L \times SU(2)_R \\
\downarrow & \quad \approx \\
O(3) & \quad SU(2)_V \times P_{LR}
\end{align*}
\]


~> **Brane-localized kinetic terms for fermions/gauge fields**


~> **Modification of the AdS metric in the vicinity of the IR brane**

Cabrera, Gersdorff, Quiros (2010)
Minimal representations under $SU(2)_L \times SU(2)_R \times U(1)_X$:

$$H = (2,2)_0$$

$$\left( \begin{array}{ccc} t_{1L} & b_L' & q_{-4/3L}' \\ b_{1L} & q_{-4/3L}' & q_{-7/3L}' \end{array} \right)_{-5/6} \quad \left( b_R, q_{-4/3R}' \right)_{-5/6} \quad \left( \begin{array}{cc} q_{5/3L}' & t_{2L} \\ t_L' & b_{2L} \end{array} \right)_{2/3} \quad (t_R)_{2/3}$$

SU($2)_R \rightarrow U(1)_R$

U($1)_R \times U(1)_X \rightarrow U(1)_Y$

$W_R^3 \rightarrow B_Y$ ( + $Z'$ KK )
**Minimal** representations under $SU(2)_L \times SU(2)_R \times U(1)_X$:

\[
\begin{pmatrix}
  t_{1L} & b'_L & q'_{-4/3L} \\
  b_{1L} & q''_{-4/3L} & q'_{-7/3L}
\end{pmatrix}
\begin{pmatrix}
  b_R & q'_{-4/3R} & -5/6 \\
  q'_{-7/3L} & t_{2L} & -2/3
\end{pmatrix}
\begin{pmatrix}
  q'_{5/3L} \\
  t'_L \\
  b_2L
\end{pmatrix}
\]

<table>
<thead>
<tr>
<th>SU(2)$_R$</th>
<th>$\rightarrow$</th>
<th>U(1)$_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U(1)$_R \times U(1)_X$</td>
<td>$\rightarrow$</td>
<td>U(1)$_Y$</td>
</tr>
</tbody>
</table>

$W^3_R$, $B_X \rightarrow B_Y$ ( + $Z'_{KK}$)

$Z'$ charges ($I_{3R}$ isospin) and coupling ($g_{Z} \sim 2$) $\Rightarrow$ Zbb couplings addressing $A^b_{FB}$

t$_R$ singlet: no custodian top partners $\Rightarrow$ possible large $g^{KK}t\bar{t}$ couplings favor $A^t_{FB}$
II) $A_{FB}^t$ and $t\bar{t}$ cross section @ Tevatron

$A_{FB}^t$ at Tevatron

« What is the Forward-Backward asymmetry for the top quark? »

$A_{FB}^t \neq 0$ with Parity-violating couplings

$$A_{FB}^t = \frac{\sigma^F - \sigma^B}{\sigma^F + \sigma^B} = \frac{\sigma[\cos \theta_t^* : 0 \rightarrow 1] - \sigma[\cos \theta_t^* : -1 \rightarrow 0]}{\sigma[\cos \theta_t^* : 0 \rightarrow 1] + \sigma[\cos \theta_t^* : -1 \rightarrow 0]} = \frac{\sigma[y_t > 0] - \sigma[y_t < 0]}{\sigma[y_t > 0] + \sigma[y_t < 0]}$$

( $t\bar{t}$ rest frame )

Rapidity : $y_t = \frac{1}{2} \ln[(E + p_z)/(E - p_z)] = \Delta y/2$
the data we use cause: most recent, unfolded and the only ones on rapidity dependence

01-2011 CDF in the lepton+jets channel with $5.3 \text{fb}^{-1}$:

$A_{FB}^t = 0.158 +/- 0.075$ ($+1.3 \text{ sigma}$ from SM prediction)

**Graphs:**
- Left: The event probability in the standard data (+ lepton) and the statistical errors only; in the table the uncertainty contains both the statistical and data (− lepton).
- Right: The $\bar{t}t$ parton-level, CDF data $5.3 \text{fb}^{-1}$, and $\bar{t}t$ NLO QCD with the only ones on rapidity dependence.
\[
A^{t\bar{t}} = \frac{N(1 > \Delta y > 0) - N(-1 < \Delta y < 0)}{N(1 > \Delta y > 0) + N(-1 < \Delta y < 0)}, \quad A_{FB}^{|\Delta y| > 1} = \frac{N(\Delta y > 1) - N(\Delta y < -1)}{N(\Delta y > 1) + N(\Delta y < -1)}
\]

\[|\Delta y| < 3\]

+1.9 standard deviation from SM
$A^t_{FB}$ in the considered warped model

$q \xrightarrow{KK gluon} t$

$- +$ interferences with SM

(negligible EW gauge contrib.)

$A^t_{FB}$ non-vanishing (Parity violation)

\[
\begin{align*}
&g_s \, Q(c_{t_L}) \neq g_s \, Q(c_{t_R}) \\
&g_s \, Q(c_{q_L}) \neq g_s \, Q(c_{q_R})
\end{align*}
\]

slightly closer to TeV-brane:

$c_{u_L}, c_{d_L} \lesssim 0.5$

EW tests not so far treated in this setup

$A^t_{FB}$ significant

$\Rightarrow M_{KK} \sim 1.5 - 2 \text{ TeV}$

5D mass: $c_k$

$M_{KK}$
$A_{FB}^t$ in the considered warped model

$KK$ gluon

$q$ \quad $\bar{q}$

$t$ \quad $\bar{t}$

$+ \text{ interferences with SM}$

(negligible EW gauge contrib.)

$A_{FB}^t$ non-vanishing

(Parity violation)

\[
\begin{align*}
g_s Q(c_{t_L}) & \neq g_s Q(c_{t_R}) \\
g_s Q(c_{q_L}) & \neq g_s Q(c_{q_R})
\end{align*}
\]

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to TeV-brane:
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$M_{KK} \sim 1.5 - 2 \text{ TeV}$

EW tests not so far treated in this setup

We will show that EW fits are OK for:

$c_{u/d_L} \sim 0.44, c_{u/d_R} \sim 0.8, c_{c/s_L} \sim 0.6, c_{c_R} \sim 0.6,$

$c_{s_R} \sim 0.49, c_{t/b_L} \sim 0.51, c_{b_R} \sim 0.53, c_{t_R} \sim -1.3$
Asymmetry at parton level (neglecting 2nd/3rd generation + gluon initial state)...
Asymmetry at parton level (neglecting 2\textsuperscript{nd}/3\textsuperscript{rd} generation + gluon initial state)...

\[ \hat{A}^{LO}_{FB}(\hat{s}) = a_q a_t \frac{4\pi \alpha_s^2(\mu_r) \beta_t^2 |D|^2}{9} \left[ (\hat{s} - M_{KK}^2) + 2v_q v_t \frac{\hat{s}}{\hat{s}} \right] \]

\[ \hat{A}^{NLO}_{FB}(\hat{s}) = \frac{(\hat{\sigma}^F_{SM-LO}(\hat{s}) + \hat{\sigma}^F_{RS+inter.-LO}(\hat{s})) - (\hat{\sigma}^B_{SM-LO}(\hat{s}) + \hat{\sigma}^B_{RS+inter.-LO}(\hat{s}))}{\hat{\sigma}^F_{SM-NLO}(\hat{s}) + \hat{\sigma}^F_{RS+inter.-LO}(\hat{s})} \]

\[ \approx \hat{A}^{LO}_{FB}(\hat{s}) + \hat{A}^{SM-NLO}_{FB}(\hat{s}) \]

\[
\left[
\begin{array}{l}
a_q = (Q(c_{qR}) - Q(c_{qL}))/2, \\
a_t = (Q(c_{tR}) - Q(c_{tL}))/2, \\
v_q = (Q(c_{qR}) + Q(c_{qL}))/2, \\
v_t = (Q(c_{tR}) + Q(c_{tL}))/2,
\end{array} \right.
\]

For our parameters such that:
\[ a_q a_t = -1.4 \quad v_q v_t = 0.7 \]

⇒ Positive \( A^{LO}_{FB} \) in RS at low \( M_{tt} \) as wanted!
Full asymmetry after convolution with MSTW-2008…

\[ \mu_f = \mu_r = m_t = 172.5 \text{ GeV} \]

CDF data unfolded

<table>
<thead>
<tr>
<th>( A'_{FB} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
</tr>
<tr>
<td>0.4</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.0</td>
</tr>
<tr>
<td>-0.2</td>
</tr>
</tbody>
</table>

RS + SM

SM(NLO)

+ EW corr. => ~ -1.3 \( \sigma \)

Hollik et al. (2011)

\[ M_{t\bar{t}} = 450 \text{ GeV} \]

rest of the discrepancy : RS @ NLO ?
Full asymmetry as a function of rapidity…

\[ \mu_f = \mu_r = m_t = 172.5 \text{ GeV} \]

CDF data unfolded

RS + SM

SM(NLO)

44% uncertainty

\[ \Delta y = 1 \]

additional positive test of the model
One must take care of the differential $t\bar{t}$ production cross section in good agreement with the SM…

$$\frac{d\sigma_{SM-NNLO}}{dM_{t\bar{t}}}(1 + \frac{d\sigma_{RS+inter.-LO}}{dM_{t\bar{t}}}/\frac{d\sigma_{SM.-LO}}{dM_{t\bar{t}}})$$

$-1.7\sigma$ $-1.4\sigma$

$2.7\text{ fb}^{-1}$

CDF data unfolded

RS + SM

$\chi^2_{RS} \rightarrow 6.3$

$\chi^2_{SM} \rightarrow 6.8$

In SM:

$\chi^2_{SM}/d.o.f. = 6.8/8$

In RS:

$\chi^2_{RS}/d.o.f. = 6.3/8$

$m_t = 175\text{ GeV}$

$\mu_f = \mu_r = m_t$
What about the **whole integrated top quark asymmetry and cross section**?

- **Tevatron data** [5]: 0.158 ± 0.075
  - SM [NLO] [5]: 0.058 ± 0.009 (−1.33σ)
  - RS+SM: 0.189 ± 0.010 (+0.42σ)

- **Theoretical (HATHOR)**: \( \sigma(p\bar{p} \rightarrow tt) = 6.62 \pm 1 \text{ pb} \)
  - \( \mu_R = \mu_F = m_t = 172.5 \text{ GeV} \)
  - MSTW PDF NNLO

- **Experimental (Tevatron)**: 7.50 ± 0.48 pb  
  - CDF Collaboration, Note 9913, Run II, October 2009.

OK as heavy KK gluon with broad resonance.
III) $A^b_{FB}$ and EW precision tests @ LEP

$A^b_{FB}$: a NP effect in the b sector?

$$A^b_{FB}(\text{pôle}) = \frac{\int_0^1 \sigma_{\theta} d \cos \theta - \int_{-1}^0 \sigma_{\theta} d \cos \theta}{\sigma_0(e^+e^- \rightarrow \gamma/Z \rightarrow b\bar{b})}$$

$$= \frac{3 (Q_Z^L)^2 - (Q_Z^R)^2}{4 (Q_Z^L)^2 + (Q_Z^R)^2}$$

$$\times \frac{(Q_L^b)^2 - (Q_R^b)^2}{(Q_L^b)^2 + (Q_R^b)^2}$$

$R_b = \frac{\Gamma(Z \rightarrow b\bar{b})}{\Gamma(Z \rightarrow \text{hadrons})}$

$$= \frac{(Q_L^b)^2 + (Q_R^b)^2}{\sum_{q \neq t} [(Q_Z^q)^2 + (Q_Z^{qR})^2]}$$
Interpretation in a generic extra-dimensional model… (difficult in SUSY)
Interpretation in a generic extra-dimensional model…
(difficult in SUSY)

Coupling $Z'_{KK} f_i f_i$ << Coupling $Z'_{KK} b b$

$\left| \delta Q_Z^{f_i f_i} \right| \approx 1\%/00 \ll \left| \delta Q_Z^{b L/R} \right| \approx -1.5/30\%$

$m_{b'}(c_{t_{R}}) \ll m_f(c_{light})$

$m_t(c_{t_{R}}) \uparrow \Rightarrow m_{b'}(c_{t_{R}}) \downarrow$

'natural' conditions within the RS model
Summary of the EW observables…

<table>
<thead>
<tr>
<th>Observable</th>
<th>SM</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{FB}^b(m_Z)$</td>
<td>2.7σ</td>
<td>1.2σ</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.8σ</td>
<td>1.2σ</td>
</tr>
<tr>
<td>$A_{FB}^c(m_Z)$</td>
<td>0.9σ</td>
<td>0.9σ</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.0σ</td>
<td>0.5σ</td>
</tr>
<tr>
<td>$A_{FB}^s(m_Z)$</td>
<td>0.6σ</td>
<td>0.2σ</td>
</tr>
<tr>
<td>$\Gamma_{had}(Z)$</td>
<td>1.3σ</td>
<td>1.0σ</td>
</tr>
<tr>
<td>$\Gamma_{tot}(W)$</td>
<td>0.2σ</td>
<td>0.2σ</td>
</tr>
<tr>
<td>$\langle Q_{FB} \rangle$</td>
<td>1.1σ</td>
<td>0.1σ</td>
</tr>
<tr>
<td>$C_{1u} + C_{1d}$</td>
<td>0.2σ</td>
<td>0.8σ</td>
</tr>
<tr>
<td>$C_{1u} - C_{1d}$</td>
<td>1.1σ</td>
<td>0.1σ</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>25.3/17</td>
<td>19.8/17</td>
</tr>
</tbody>
</table>

- no more $A_{FB}^b$ anomaly at the $Z^0$ pole
- whole fit improved
- still fits well
- + Zuu/Zdd OK from Tevatron Run I & II & HERA (H1,ZEUS)
IV) Constraints and predictions @ LHC

Comparison of the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$

- in RS+SM (HATHOR) NNLO
- $\mu_F = \mu_R = m_t = 173$ GeV
- $\sqrt{s} = 7$ TeV
- $\mathcal{L} = 35$ pb$^{-1}$

\[
\sigma(pp \rightarrow t\bar{t}) \quad \text{at } -0.86\sigma \\
\quad \text{SM at } -0.81\sigma
\]

from the ATLAS measurement, $180 \pm 18.5$ pb

\[
\sigma(pp \rightarrow t\bar{t}) \quad \text{at } +0.36\sigma \\
\quad \text{SM at } +0.31\sigma
\]

from the CMS measurement, $158 \pm 19$ pb

OK as major contribution from the gg initial state
Blob constraints from dijets

- **Axigluon - SU(3)$_L \times$SU(3)$_R**

  - *Frampton et al. (1987)*
  - *Bagger et al. (1987)*

- ★ now including the width effect between 0.7 $M_{KK}$ and 1.3 $M_{KK}$

- ★ we have also checked the angular distribution constraints

- Computing the ratio RS/Axigluon

  => $KK$ gluon exchange @ 0.023 pb
Constraints from dijets

**Axigluon - SU(3)\_L x SU(3)\_R**

Frampton et al. (1987)  
Bagger et al. (1987)

- Now including the width effect between 0.7 M\_KK and 1.3 M\_KK
- We have also checked the angular distribution constraints

**Computing the ratio RS/Axigluon**

=> KK gluon exchange @ 0.023 pb

**Coupling g\^{(1)}\_tt > g\^{(1)}\_qq**

RS addresses A\^{t}_{FB}

+ passes dijet bounds
 KK gluon searches at LHC

June 5, 2011

KK gluon searches at LHC

June 5, 2011

ATLAS Preliminary

interesting $\sim 1.5\sigma$ effect seen at $M_{KK} \sim 1.6$ TeV (!)

rescaling to our KK couplings

$\Rightarrow$ KK gluon exchange @ 2.3 pb (conservative due to our larger $g_{KK}$ width)
An observed intriguing high-mass ($M_{tt} \sim 1.6$ TeV) candidate event with boosted top quarks...
$\mu_f = \mu_r = m_t = 173$ GeV
What does the RS model predicts at the expected luminosity of 1 fb⁻¹?

..a KK gluon resonance

\[ \Gamma_{g^{(1)}} \approx 40\% M_{KK} \]

assuming 100 GeV bins

integration of the cross section e.g. over [1050, 1750] GeV

\[ \frac{\text{Signal}}{\sqrt{\text{Background}}} \approx 13.9 \]

An excess should be clearly visible.
A great excess even simulating the $M_{t\bar{t}}$ experimental resolution:

### Table 8 - Quantities

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Reference Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptonic Top Mass</td>
<td>8.57 GeV</td>
</tr>
<tr>
<td>Hadronic Top Mass</td>
<td>8.52 GeV</td>
</tr>
<tr>
<td>Hadronic W Mass</td>
<td>8.75 GeV</td>
</tr>
<tr>
<td>$p_T$ of $t\bar{t}$ System</td>
<td>7 GeV</td>
</tr>
<tr>
<td>$H_T$ Fraction</td>
<td>85%</td>
</tr>
</tbody>
</table>

The $H_T$ Fraction is the scalar sum of the transverse energy in the selected jets divided by the scalar sum of the transverse energy in all jets.

### Figure 8 - Resolution

- **Resolution:** $M_{t\bar{t}}$ as a function of generated $M_{t\bar{t}}$ for muon plus jets ($\ell + jets$) and electron plus jets ($e + jets$) events.

**Background Estimation**

We divide the SM backgrounds into three categories and, where possible, use the data to constrain both the rates and kinematic shapes of each. These contributions are QCD multijet events, $W$ boson - Drell-Yan plus jets events, and $t\bar{t}$ events. We also account for the small contribution from single top quark production.

- **7.1 QCD Multijet Events**
  - QCD multijet events can be mis-reconstructed as a lepton plus jets signatures, even though this is highly suppressed by the isolation requirement.
  - Although semileptonic and leptonic decays of hadrons contribute to both channels, energetic photon conversions will only contaminate the electron channel.
  - The contribution of this background to muon plus jets and electron plus jets samples is therefore determined separately.
  - The yields in the muon sample are determined with a matrix method.
  - A loose region which is a superset of the tight region containing the signal is first defined, in this case by relaxing the cut on the relative isolation from 0.7 to 0.8.
  - The number of QCD events in the signal region can then be calculated from the total number of events in the loose region, the fraction of muons from QCD events in the loose region that are also in the tight region, and the fraction of muons from non-QCD events in the loose region that are also in the tight region.
  - The fraction of muons from QCD events falling in the tight region is calculated from a control region; the fraction in non-QCD events is taken from simulation and verified using the tag-and-probe method.

---

**LHC 7 TeV**

Luminosity 1 fb$^{-1}$

---

**Smearing effect**
V) Other scenarios explaining $A^t_{FB}$?

Messages from the effective operator approach…
(trying to fit $A^t_{FB}$ and $\sigma_{tt}$)

Extra scalar field – color octet [t-channel] : impossible

```
  - color triplet [t-channel] : possible (diquark FC couplings)
```

Extra vector boson – color octet [s-channel] : possible (Axigluon / KK gluon)

```
  - color singlet [s- & t-channel] : difficult
```

Extra vector boson – color octet [s-channel] : possible (Axigluon / KK gluon)

```
  - color singlet [s- & t-channel] :
tensions as no Z',W' interferences with the SM contributions (QCD@LO)
```

Possibility: t-chan. exchange of a non-abelian Z' (with Z'urRtR couplings)

Aguilar-S. et al. (2011)
Delaunay et al. (2011)
Degrande et al. (2011)
Hewett et al. (2011)
Shu et al. (2010), ...
Giudice et al. (2011)
Jung et al. (2011)
VI) Conclusions

The ‘warped paradigm’, with theoretical motivations, predicts deviations from SM in the 3rd generation sector => $A^b_{FB}$, $A^t_{FB}$ = early indications?

We suggest a geometrical RS realization addressing both $A^b_{FB}$ and $A^t_{FB}$.

The several constraints on the parameter space render this RS scenario quite predictive on the effects in the $t\bar{t}$ invariant mass distribution @ LHC.

One must wait for more data (Tevatron, LHC) in order to discriminate between the main $A^t_{FB}$ interpretations: Z/W’, KK gluon, Axigluon, stop…

This RS model addressing $A^b_{FB}$, $A^t_{FB}$ predicts a KK gluon resonance

Other RS models usually with light custodians copiously producable (‘no-lose signal’ theorem in warped pheno. @ LHC )
Back up
Some useful formula’s...

\[
\cos \theta_t^* = \sqrt{1 + \frac{4m_t^2}{\hat{s} - 4m_t^2}} \tanh y_t
\]

\[
\frac{1}{\mathcal{D}} = \hat{s} - M_{KK}^2 + i \frac{\hat{s}}{M_{KK}^2} \sum_q \Gamma_{KK}^{q(1)\rightarrow q\bar{q}} M_{KK} \frac{\beta_q [v_q^2 (3 - \beta_q^2)]/2 + a_q^2 \beta_q^2}{v_q^2 + a_q^2}
\]

\[
\beta_t = \sqrt{1 - 4m_t^2/\hat{s}}
\]

\[
\sqrt{\hat{s}_0} \simeq \frac{M_{KK}}{(1 + \Gamma_{KK}^2/M_{KK}^2)^{1/4}}
\]
\[
\frac{d\hat{\sigma}_{RS-LO}}{d \cos \theta_t^*}(\hat{s}) = \frac{\pi \alpha_s^2(\mu_r) \beta_t}{9 \hat{s}} \times \\
\hat{s}^2 |D|^2 \left[ 8 v_q v_t a_q a_t \beta_t \cos \theta^* + (a_q^2 + v_q^2) \left( v_t^2 (2 - \beta_t^2 \sin^2 \theta^*) + a_t^2 \beta_t^2 (1 + \cos^2 \theta^*) \right) \right]
\]

\[
\frac{d\hat{\sigma}_{inter.-LO}}{d \cos \theta_t^*}(\hat{s}) = \frac{\pi \alpha_s^2(\mu_r) \beta_t}{9 \hat{s}} 4 \hat{s} \text{Re}(D) \left[ v_q v_t \left( 1 - \frac{1}{2} \beta_t^2 \sin^2 \theta^* \right) + a_q a_t \beta_t \cos \theta^* \right]
\]

\[
\left( \frac{d\hat{\sigma}_{SM-LO}}{d \cos \theta_t^*}(\hat{s}) \right)_{q\bar{q}} = \frac{\pi \alpha_s^2(\mu_r) \beta_t}{9 \hat{s}} \left\{ 2 - \beta_t^2 \sin^2 \theta^* \right\}
\]
« How is $A^t_{FB}$ measured at Tevatron in lepton+jet channels? »

$$\Delta y = y_t - \bar{y}_{\bar{t}} \quad y_t = (y_t - \bar{y}_{\bar{t}})/2$$

$$\Delta y = q(y_l - y_h) = q\Delta y_{lh}$$

$t \rightarrow W^+ b \quad t \rightarrow W^+ b$

in the laboratory frame

$$A^t_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = \frac{N(q\Delta y_{lh} > 0) - N(q\Delta y_{lh} < 0)}{N(q\Delta y_{lh} > 0) + N(q\Delta y_{lh} < 0)}$$

Other asymmetries...

$$A^{p\bar{p}}_{FB} = \frac{\sigma[y^p_{t}\bar{p} > 0] - \sigma[y^p_{\bar{t}}\bar{p} < 0]}{\sigma[y^p_{t}\bar{p} > 0] + \sigma[y^p_{\bar{t}}\bar{p} < 0]} \quad A^t_C = \frac{\sigma_t[y_t > 0] - \sigma_{\bar{t}}[y_t > 0]}{\sigma_t[y_t > 0] + \sigma_{\bar{t}}[y_t > 0]} \quad A^t_C = A^t_{FB} \implies CP$$. 
The five-dimensional parameter set is mainly composed by the SM gauge group being the extra $U_{fpg}$ part of $SU_{fpg}$ broken to all $NLO$. We will call this the parton level $i$ based on our own studies. Any modifications by detector acceptance and resolution greatly from that $t$ production is an anomaly probably not fully explained by QCD errors $\sim 0.01$.

In the near-threshold form of the cross section $[l]$ the $t\bar{t}$ asymmetry for inclusive production is an anomaly probably not fully explained by QCD errors $\sim 0.01$.

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Measurements of $A_t^{FB}$ at Tevatron

**07-2010** D0 in the lepton+jets channel with (0.9 fb$^{-1}$ then) 4.3 fb$^{-1}$

(ttbar frame, not unfolded = no subtracting bckgrd & effic. + no ttbar level) :

$A_t^{FB} = 0.08 +/- 0.04 +/- 0.01$  (+1.7 sigma from SM prediction)

**03-2009** CDF in the lepton+jets channel with (1.9 fb$^{-1}$ then) 3.1 fb$^{-1}$

(lab frame, unfolded) :

$A_t^{FB} = 0.193 +/- 0.065 +/- 0.024$  (+2.1 sigma from SM prediction)

**01-2011** CDF in the dilepton channel with 5.1 fb$^{-1}$

(lab frame, unfolded) :

$A_t^{FB} = 0.42 +/- 0.15 +/- 0.05$  (+2.3 sigma from SM prediction)

(large error => +1.7 sigma from lept.+jets channel)

(lab frame, not unfolded) :

$A_t^{FB} (M_{tt}<450 GeV)= 0.104 +/- 0.066$  (+1.6 sigma from SM prediction)

$A_t^{FB} (M_{tt}>450 GeV)= 0.212 +/- 0.096$  (+2.6 sigma from SM prediction)

now 5.1 fb$^{-1}$: see F.Badaud’s talk
The way to compute it...

\[
A^t_{\text{FB}} = \frac{(\sigma^F_{SM} + \sigma^F_{RS} + \sigma^F_{\text{inter.}}) - (\sigma^B_{SM} + \sigma^B_{RS} + \sigma^B_{\text{inter.}})}{(\sigma^F_{SM} + \sigma^F_{RS} + \sigma^F_{\text{inter.}}) + (\sigma^B_{SM} + \sigma^B_{RS} + \sigma^B_{\text{inter.}})}
\]

\[\Leftrightarrow A^t_{\text{FB}} = A^R_{\text{FB}} \times R + A^S_{\text{FB}} \times (1 - R)\]

Cao et al. (2010)

\[
A^R_{\text{FB}} = \frac{(\sigma^F_{RS-LO} + \sigma^F_{\text{inter.}-LO}) - (\sigma^B_{RS-LO} + \sigma^B_{\text{inter.}-LO})}{(\sigma^F_{RS-LO} + \sigma^F_{\text{inter.}-LO}) + (\sigma^B_{RS-LO} + \sigma^B_{\text{inter.}-LO})}
\]

with

\[
R = \frac{\sigma^\text{total}_{RS-LO}}{\sigma^\text{total}_{SM-LO} + \sigma^\text{total}_{RS-LO} + \sigma^\text{total}_{\text{inter.-LO}}}
\]

ex: \[
\sigma^F_{RS-LO} = \sigma_{RS-LO}[\cos \theta^*_t : 0 \rightarrow 1] = \\
\sum_{ij} \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} d\tau \left[ \int_0^1 d\cos \theta^*_t \left( \frac{d\hat{\sigma}_{RS-LO}}{d\cos \theta^*_t} (\tau s) \right)_{ij} \right] \left\{ \int_\tau^1 dx f_i(x, \mu_f) f_j (\frac{\tau}{x}, \mu_f) \right\}
\]

\[
\tau_{\text{min/max}} = \hat{s}_{\text{min/max}} / s
\]

MSTW-2008-NLO
Looking at the effect of MSTW uncertainties [@ 90%C.L.]…

\[ \mu_f = \mu_r = m_t = 172.5 \text{ GeV} \]

CDF data unfolded

RS + SM

SM(NLO)

\( M_{tt}(\text{GeV}) \)

no significant dependence as well on \( \mu_f, \mu_r \) and \( m_t \)

\( M_{tt} = 450 \text{GeV} \)
Appendix in incompatible with the LHC data as in our scenario also has a vectorial component one can check whether the LHC limits.

The SM quark-quark scattering is governed by gluon exchange in the $t$-channel with a propagator varying like $l^{-\Delta}$. By selecting values of $\cos \theta^* = 0$.

KK gluon produces less than 10% deviation.

KK gluon of mass $M_{KK}$ which is precisely the end of the mass domain explored by ATLAS and CMS in $m_{jj}$.

Using Ref. [pn], which give quark-quark scattering.

To increase the asymmetry, $c_\chi$ decreases.

$\sqrt{2} M_{KK} \sim 2$ TeV.

$t = -M_{jj}^2/2$.

$M_{jj} = \sqrt{2} M_{KK}$.

$1/(t - M_{KK}^2) \leq M_{KK}^2$.

$\cos \theta^* = 0$.
Global $A_{FB}^{b}$ fit @ and off the Z pôle :

$$A_{FB}^{b}(s \simeq M_Z^2)$$

$\sqrt{s}$ [GeV]

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>$A_{FB}^{b}(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>89</td>
<td>0.04</td>
</tr>
<tr>
<td>90</td>
<td>0.06</td>
</tr>
<tr>
<td>91</td>
<td>0.08</td>
</tr>
<tr>
<td>92</td>
<td>0.13</td>
</tr>
<tr>
<td>93</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>$A_{FB}^{b}(s)$</th>
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<tbody>
<tr>
<td>20</td>
<td>-0.4</td>
</tr>
<tr>
<td>40</td>
<td>-0.4</td>
</tr>
<tr>
<td>60</td>
<td>0.2</td>
</tr>
<tr>
<td>80</td>
<td>0.6</td>
</tr>
<tr>
<td>100</td>
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<tr>
<td>120</td>
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<tr>
<td>140</td>
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<tr>
<td>160</td>
<td>0.6</td>
</tr>
<tr>
<td>180</td>
<td>0.6</td>
</tr>
<tr>
<td>200</td>
<td>0.6</td>
</tr>
</tbody>
</table>

$\chi^2$ $= 24$  
$\chi^2$ $= 20$  
$\chi^2$ $= 14$

$b_R$ under $SU(2)_L \times SU(2)_R \times U(1)_X$: 

- RSa:  
  $$Q_X = (B - L)/2 \Rightarrow I_R^3 = -1/2$$

- RSb:  
  $$Q_X = -5/6 \Rightarrow I_R^3 = +1/2$$
Improved goodness-of-fit

EW observables are expressed in terms of oblique parameters encoding the New Physics...

$$m_h = 190 \text{ GeV}$$
$$m_h = 115 \text{ GeV}$$

$$m_h = 190 \text{ GeV}$$
$$m_h = 115 \text{ GeV}$$

p-value 10.3% $\Leftrightarrow \chi^2 / 11 = 1.56$

p-value 37.3% $\Leftrightarrow \chi^2 / 10 = 1.08$
Better quality of fit in RS than in SM cause.

1) positive contribution $T_{RS}$ (custodial symmetry breaking)

2) SM fit degraded by the $\sin^2 \theta_W$ measurement derived directly from $A_{FB}^b$:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{FB}^{0,l}$</td>
<td>0.23099 ± 0.00053</td>
</tr>
<tr>
<td>$A_{l}(P_{\tau})$</td>
<td>0.23159 ± 0.00041</td>
</tr>
<tr>
<td>$A_{l}(SLD)$</td>
<td>0.23098 ± 0.00026</td>
</tr>
<tr>
<td>$A_{FB}^{0,b}$</td>
<td>0.23221 ± 0.00029</td>
</tr>
<tr>
<td>$A_{FB}^{0,c}$</td>
<td>0.23220 ± 0.00081</td>
</tr>
<tr>
<td>$Q_{FB}^{had}$</td>
<td>0.2324 ± 0.0012</td>
</tr>
<tr>
<td>Average</td>
<td>0.23153 ± 0.00016</td>
</tr>
</tbody>
</table>

$\chi^2$/d.o.f.: 11.8 / 5

$\sin^2 \theta_{eff}^{lept}$ vs $m_H$
**AdS / CFT correspondence (98’)**:

**WARPED H-DIM. SCENARIOS / STRONGLY COUPLED MODELS**

<table>
<thead>
<tr>
<th><strong>5D holographic version</strong></th>
<th><strong>4D dual interpretation</strong></th>
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<tbody>
<tr>
<td><strong>RS with bulk fields</strong></td>
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</tr>
<tr>
<td><strong>gauge-Higgs unification</strong></td>
<td><strong>composite Higgs pseudo-Goldstone boson of a global symmetry</strong> (as for little Higgs with T parity)</td>
</tr>
<tr>
<td><strong>Higgsless models</strong></td>
<td><strong>technicolor models</strong></td>
</tr>
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