Probing New Physics with Polarised Top Quark

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Based on the works in collaboration with
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Top-quark: a new physics window

(The heaviest particle in the SM, the only “normal” quark)

Top quark is possibly uniquely related to unknown fundamental electroweak physics
Top quark as a probe of new physics

**Extra Gauge Bosons**
- $Z'$
- $W'$
- $G'$

**New Heavy Quarks**
- Vector Quark
- 4th Gen
- Gluino

**Heavy Quark Production via pQCD**

**Exotic Coloured States**

**Charge Higgs**

**CP**

**AFB**

**Color Sextet**
Top-quark: a new physics window

Top quark is quite common in decays of NP resonances and it is often polarised.

Top quark polarisation can tell us the chirality structure of top quark couplings to NP Resonances.
Top-quark: a new physics window

Top quark is quite common in decays of NP resonances and it is often polarised.

Top quark polarisation can tell us the chirality structure of top quark couplings to NP Resonances.

\[ gb \rightarrow tH^- \rightarrow t\bar{t}b \]

in Type-II 2HDB

\[ H^+ \]

\[ \tan \beta \]

\[ \bar{b} \]

\[ \sqrt{s}=14\text{TeV}, M_H=400\text{GeV} \]

- \( D_{\text{decay}} \)
- \( 2A_{\text{FB}} \)

V. CONCLUSION AND DISCUSSION

The charged Higgs boson, an undoubted signal of new physics, appears in many new physics models. In the type-II two-Higgs-doublet model the chirality structure of the coupling of charged Higgs boson to the top and bottom quarks is very sensitive to the value of \( \tan \beta \). As the polarization of the top quark can be measured experimentally from the top quark decay products, one could make use of the top quark polarization to determine the value of \( \tan \beta \). In this work we perform a detailed analysis of measuring top quark polarization in the charged Higgs boson production channels \( gb \rightarrow tH^- \rightarrow t\bar{t}b \) and \( g\bar{b} \rightarrow \bar{b}tH^+ \). We calculate the helicity amplitudes of the charged Higgs boson production and decay. Our calculation shows that the top quark from the charged Higgs boson decay provides a good...
Top-quark: the only bare quark in SM
( the only “bizarre” quark in the SM )

- Short lifetime:

  \[
  \begin{align*}
  t & \rightarrow W \rightarrow b, \\
  \frac{1}{m_t} & = 5 \times 10^{-27} \text{ s}, \\
  \frac{1}{\Gamma_t} & = 5 \times 10^{-25} \text{ s}, \\
  \frac{1}{\Lambda_{QCD}} & = 3 \times 10^{-24} \text{ s}
  \end{align*}
  \]

- “bare” quark:
  spin info well kept among its decay products
Charged lepton: the top-spin analyser

- The charged-lepton tends to follow the top-quark spin direction.

- In top-quark rest frame

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_{\text{hel}}} = \frac{1 + \lambda_t \cos \theta_{\text{hel}}}{2}
\]

\(\lambda_t = +\) right-handed

\(\lambda_t = -\) left-handed

\[
\ell^+ \quad \theta_{\text{hel}} \quad \vec{p}_t \quad (\text{c.m.s.})
\]

Czarnecki, Jezabek, Kuhn, NPB351 (1991) 70

reconstruction of top quark kinematics
Top quark reconstruction

- The charged leptons produced always in association with an invisible neutrino

\[ p_x^\nu = E_T(x) \quad p_y^\nu = E_T(y) \quad m_\nu = 0 \]

- Unknown

- \( W \)-boson on-shell condition

\[ m^2_W = (p_\ell + p_\nu)^2 \]

\[ p_z^\nu = \frac{1}{2(p_T^e)^2} \left[ A p_T^e \pm E_e \sqrt{A^2 - 4 (p_T^e)^2 \ E_T^2} \right] \]

\[ A = m^2_W + 2 \vec{p}_T^e \cdot \vec{E}_T \]
Top quark production in NP

(1) Top-quark pair production + semi-leptonic decay

One invisible particle in the final state
Top-quark Forward-backward Asymmetry at the Tevatron

It is induced at the loop level in the SM

Kuhn and Rodrigo
PRL 81 (1998) 49

\[
A^{\bar{p}p} = \frac{N_t(y > 0) - N_{\bar{t}}(y > 0)}{N_t(y > 0) + N_{\bar{t}}(y > 0)} = 0.051(6)
\]

\[
A^{\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = 0.078(9) \quad \Delta y = y_t - y_{\bar{t}}
\]
Top-quark $A_{FB}$ at the Tevatron

CDF (8.7 fb$^{-1}$):

- $A_{FB}^{\text{inclusive}} = 0.162 \pm 0.041 \pm 0.022$
- $A_{FB}^{NLO+EW} = 0.066$

CDF: 1101.0034

- Forward-Backward Top Asymmetry, %
- Reconstruction Level
- $m_{t\bar{t}} < 450$ GeV
  - DØ, 5.4 fb$^{-1}$
  - CDF, 5.3 fb$^{-1}$
  - $7.8 \pm 4.8$
- $m_{t\bar{t}} > 450$ GeV
  - DØ, 5.4 fb$^{-1}$
  - CDF, 5.3 fb$^{-1}$
  - $26.6 \pm 6.2$

S. Frixione and B.R. Webber, JHEP 06, 029 (2002)
Forward-Backward asymmetry of the charged lepton from top-quark decay $A_{FB}^{\ell}$
\( A_{FB}^t \) versus \( A_{FB}^\ell \)

**D0:**
\[
\begin{align*}
A_{FB}^t &= 0.196 \pm 0.065 \\
A_{FB}^\ell &= 0.152 \pm 0.040
\end{align*}
\]

**CDF:**
\[
\begin{align*}
A_{FB}^t &= 0.085 \pm 0.025 \\
A_{FB}^\ell &= 0.066 \pm 0.025
\end{align*}
\]

\[
\frac{A_{FB}^\ell}{A_{FB}^t} \bigg|_{D0} \sim \frac{3}{4}
\]

\[
\frac{A_{FB}^\ell}{A_{FB}^t} \bigg|_{\text{inc}} \sim \frac{3}{5}
\]

SM predictions at the NLO
\[
\begin{align*}
A_{FB}^t &= 0.051 \pm 0.001 \\
A_{FB}^\ell &= 0.021 \pm 0.001
\end{align*}
\]

\[
\frac{A_{FB}^\ell}{A_{FB}^t} \bigg|_{\text{SM}} \sim \frac{1}{2}
\]

Bernreuther and Si, NPB837 (2010) 90
\( A^t_{FB} \) and \( A^\ell_{FB} \) are connected by the spin correlation between the top-quark and charged lepton

\[
A^\ell_{FB} \approx \rho_{t_L} A^t_{FB} \times (2R^t_{C} - 1) + \rho_{t_R} A^t_{FB} \times (2R^t_{C} - 1)
\]

\[
A^t_{FB} \approx [\rho_{t_L} A^t_{FB} + \rho_{t_R} A^t_{FB}]
\]

\[
A^\ell_{FB}(t_L/R) = 2R^t_{C} - 1
\]

\[
R^\lambda_t(\beta, y_t) = \begin{cases} 
\frac{1}{2} + \frac{1}{2 (1 + \gamma^{-2} \coth^2 y_t)^{1/2}} + \frac{\lambda_t \coth^2 y_t}{4\beta \gamma^2 (1 + \gamma^{-2} \coth^2 y_t)^{3/2}}, & (y_t > 0) \\
\frac{1}{2} - \frac{1}{2 (1 + \gamma^{-2} \coth^2 y_t)^{1/2}} - \frac{\lambda_t \coth^2 y_t}{4\beta \gamma^2 (1 + \gamma^{-2} \coth^2 y_t)^{3/2}}, & (y_t < 0)
\end{cases}
\]
dependence on top kinematics

\[ A_{FB}^\ell \]

\[ (a) \quad E_t = 200 \text{GeV} \]

\[ (b) \quad E_t = 600 \text{GeV} \]

\[ A_{FB}^\ell (\beta, y_t) = 2R_{FB}^{\ell, \lambda_t} (\beta, y_t) - 1 \]
Invariant mass spectrum of top quark pair

CDF collaboration, PRL 102 (2009) 222003
$A_{FB}^t$ and $A_{FB}^\ell$ are connected by the spin correlation between the top-quark and charged lepton.

Berger, QHC, Chen, Yu, Zhang, PRL 108 (2012) 072002

\[
A_{FB}^\ell \approx \rho_{t_L} A_{FB}^{t_L} \times \left(2R_{C}^{t_L} - 1\right) + \rho_{t_R} A_{FB}^{t_R} \times \left(2R_{C}^{t_R} - 1\right)
\]

\[
A_{FB}^t \approx \left[\rho_{t_L} A_{FB}^{t_L} + \rho_{t_R} A_{FB}^{t_R}\right]
\]

\[
A_{FB}^\ell(t_{L/R}) = 2R_{C}^{t_{L/R}} - 1
\]

SM: \[\rho_{t_L} = \rho_{t_R} = \frac{1}{2}\]

\[
\left. \frac{A_{FB}^\ell}{A_{FB}^t}\right|_{SM} \approx \frac{1}{2}
\]

\[
R_{F}^{\lambda_t}(\beta, y_t) = \begin{cases} 
\frac{1}{2} + \frac{1}{2 (1 + \gamma^{-2} \coth^2 y_t)^{1/2}} & + \frac{\lambda_t \coth^2 y_t}{4\beta \gamma^2 (1 + \gamma^{-2} \coth^2 y_t)^{3/2}}, \quad (y_t > 0) \\
\frac{1}{2} - \frac{1}{2 (1 + \gamma^{-2} \coth^2 y_t)^{1/2}} & - \frac{\lambda_t \coth^2 y_t}{4\beta \gamma^2 (1 + \gamma^{-2} \coth^2 y_t)^{3/2}}, \quad (y_t < 0)
\end{cases}
\]
$A_{FB}^t$ and $A_{FB}^\ell$ are connected by the spin correlation between the top-quark and charged lepton.

Berger, QHC, Chen, Yu, Zhang, PRL 108 (2012) 072002

Unpolarised top-quark

Right-handed top-quark

$A_{FB}^\ell \approx 0.47 \times A_{FB}^t + 0.25\%$

$A_{FB}^\ell \approx 0.75 \times A_{FB}^t - 2.1\%$

Cheung, Keung, Yuan, PLB 682 (2009) 287
(2) **Same-Sign** top-quark pair production (or top-antitop pair production in dileptonic decay)

Two invisible particles in the final state
Top quark is often polarised in NP

- Flavour changing gauge boson

\[ u_R \rightarrow Z' \rightarrow t_R \]

- Exotic coloured particles
  (diquark scalar/vector)

\[ 3 \otimes 3 = 6 \oplus \bar{3} \]

References:

- Jung, Murayama, Pierce, Wells,
  PRD81 (2010) 015004

- Cakir and Sahin,
  PRD72 (2005) 115011

- Mohapatra, Okada, Yu,
  PRD77 (2008) 011701

- C.-R. Chen, Klemm, Rentala, Wang,
  PRD79 (2009) 054002

Measuring top-quark polarisation in same-sign top quark pair production in color sextet scalar/vector model

\[ \phi_6^{(1,3)} \rightarrow t_L t_L \quad \phi_6^{(1)} \rightarrow t_R t_R \]

Full kinematics reconstruction

Four unknowns and Four on-shell conditions

Quartic equation
(correct l-b pairing is necessary)

\[ p_x^4(\nu_1) + a \ p_x^3(\nu_1) + b \ p_x^2(\nu_1) + c \ p_x(\nu_1) + d = 0 \]

Two complex, two real solutions

Sonnenschein, PRD73 (2006) 054015
\[ \ell^+ - b \] pairing: MT2-assisted method

MT2 variable of lepton-b clusters and MET

Two combinations of lepton-b clusters

Choose smaller MT2 (correct combination found with nearly 100% probability)

MT2 - Lester and Summers, PLB 463 (1999) 99
Neutrino momentum reconstruction

- Strong correlation between the true $p^{\nu_1}_x$ and reconstructed $p^{\nu_1}_x$
- Top quark polarisation can be measured after neutrino reconstruction.

**s-channel 700GeV resonance**

- **True** $p^{\nu_1}_x$
- **Reconstructed** $p^{\nu_1}_x$ (GeV)
Top quark production in NP

(3) Top-quark pair + dark matter candidates

Three invisible particles in the final state
Top-quark pair plus missing energy

Typical collider signature in several NP models

- Minimal Supersymmetric extension of the Standard Model (MSSM)

- Little Higgs Model with T-parity (LHT)

- Universal Extra Dimension Model (UED)
Charged lepton distribution

- In the rest frame of the top-quark

\[
\frac{d\Gamma}{dx \, d\cos \theta} = \frac{\alpha^2_W m_t}{32 \pi A B} \left[ x (1-x) \arctan \left( \frac{Ax}{B-x} \right) \right] \frac{1 + s_t \cos \theta}{2}
\]

Czarnecki, Jezabek, Kuhn, NPB351 (1991) 70

The energy and angle are correlated when top is boosted.
Lepton energy is sensitive to top-polarization

\[
\frac{d\Gamma(\hat{s}_t)}{dx} = \frac{\alpha_W^2 m_t}{64\pi AB} \int_{z_{\text{min}}}^{z_{\text{max}}} x\gamma^2 \left[1 - x\gamma^2 (1 - z\beta)\right]
\times \left(1 + \hat{s}_t \frac{z - \beta}{1 - z\beta}\right) \arctan \left[\frac{A x\gamma^2 (1 - z\beta)}{B - x\gamma^2 (1 - z\beta)}\right] dz
\]

\[A = \frac{\Gamma_W}{m_W}, \quad B = \frac{m_W^2}{m_t^2} \approx 0.216\]

\[\gamma = \frac{E_t}{m_t}, \quad \beta = \sqrt{1 - 1/\gamma^2}\]

\[z_{\text{min}} = \max[(1 - 1/\gamma^2 x)/\beta, -1]\]

\[z_{\text{max}} = \min[(1 - B/\gamma^2 x)/\beta, 1]\]
Lepton energy and top-quark polarization

Identical decay chains

\[ x'_\ell = \frac{2E_{\ell^+}}{E_{\tilde{t}}} \]
Lepton energy and top-quark polarisation

Define a variable $\mathcal{R}$ to quantify the difference between $t_L$ and $t_R$

$$\mathcal{R}(x_c) \equiv \frac{\text{Area}(x_\ell < x_c)}{\text{Area(tot)}} = \text{Area}(x_\ell < x_c)$$

![Graph showing the distribution of $1/\Gamma d\Gamma/dx$ for different energies $E_t$ and polarisations $t_L$ and $t_R$.](image)
Toy model mimicking MSSM

- MSSM like:

\[ \mathcal{L}_{\tilde{t}\tilde{t}\tilde{\chi}} = g_{\text{eff}} \tilde{t}\tilde{\chi}(\cos \theta_{\text{eff}} P_L + \sin \theta_{\text{eff}} P_R) t \]

Collider signature

- Major SM backgrounds
Collider simulation

• Basic selection cuts
  \[ p_T^\ell > 20 \text{ GeV} \quad p_T^j > 25 \text{ GeV} \]
  \[ E_T > 25 \text{ GeV} \quad \Delta R_{jj,\ell j} > 0.4 \]
  \[ |\eta_{\ell,j}| < 2.5 \]

• Hard cuts
  \[ E_T > 100 \text{ GeV} \quad H_T > 500 \text{ GeV} \]

\[ H_T = p_T^\ell + p_T^{j_1} + p_T^{j_2} + p_T^b + p_T^{\bar{b}} + E_T \]

• \( \bar{t} \to 3j \) reconstruction (Minimal-\( \chi^2 \) method)
  Loop over all jet combinations and pick up the one minimize

\[ \chi^2 = \frac{(m_W - m_{jj})^2}{\Delta m_W^2} + \frac{(m_t - m_{jjj})^2}{\Delta m_t^2} \]

\[ m_{\tilde{t}} = 360 \text{ GeV} \quad m_{\tilde{\chi}} = 50 \text{ GeV} \]
Signal versus Backgrounds

- Cross section (fb) of signal and backgrounds at 14TeV LHC

<table>
<thead>
<tr>
<th></th>
<th>Basic</th>
<th>$t_{had,,recon.}$</th>
<th>Hard</th>
<th>$E_T$ sol.</th>
<th>$\epsilon_{cut}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal</td>
<td>22.26</td>
<td>18.46</td>
<td>8.87</td>
<td>6.51</td>
<td>11.6 %</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>4347.08</td>
<td>3596.75</td>
<td>154.47</td>
<td>0.91</td>
<td>0.00556%</td>
</tr>
<tr>
<td>$t\bar{t}Z$</td>
<td>1.25</td>
<td>1.03</td>
<td>0.34</td>
<td>0.22</td>
<td>5.9 %</td>
</tr>
</tbody>
</table>

- $E_T$ solution cut

$$p_T^{\nu} = \frac{1}{2(p_T^e)^2} \left[ A p_T^e \pm E_e \sqrt{A^2 - 4(p_T^e)^2 E_T^2} \right]$$

$$A = m_W^2 + 2 p_T^e \cdot E_T$$

$$A^2 - 4 (p_T^e)^2 E_T^2 \leq 0$$

Han, Mahbubani, Walker, Wang, JHEP 0905 (2009) 117
$\mathcal{R}'$ distribution

t$_L$ and t$_R$ are separated

LHC
14 TeV
100fb$^{-1}$
Conclusion

TOP QUARK POLARISATION

Anomaly

Discovery

TH Precision

NP Theory

Exp Precision
Conclusion

- Top-quark polarisation provides additional information about new physics structure

One invisible particle in the final state
Conclusion

- Top-quark polarisation provides additional information about new physics structure

Two invisible particles in the final state
Conclusion

• Top-quark polarisation provides additional information about new physics structure

Three invisible particles in the final state
THANK YOU!
Back-up slides
$R(x_c)$ versus $R'(x_c)$

$x_\ell = 2E_{\ell+} / E_\ell \quad \rightarrow \quad x'_\ell = 2E_{\ell+} / E_{\ell}^\prime$

\(x_c = 2E_{\ell+} / E_{\ell} \quad \rightarrow \quad x'_c = 2E_{\ell+} / E_{\ell}^\prime\)

(a) \(t_L\) and \(t_R\)

- \(t_L\): \(x_\ell\) in lab
- \(t_R\): \(x'_\ell\) in lab
- \(t_L\): \(x'_\ell\) in lab
- \(t_R\): \(x'_\ell\) in lab

\(R(x_c)\)
\(R'(x_c)\)

\(x_c\)
Measuring top-quark polarisation

Traditional method of measuring top-quark polarisation is through the angle between the charged lepton and top-quark spin.

The charged-lepton tends to follow the top-quark spin direction.