New Physics Searches in the Top Quark Sector at Hadron Colliders

Pallabi Das
TIFR, Mumbai
Top Pair Event at LHC

t→Wb, W→lν or W→q̅q
LHC pp collisions
Run I: $\sqrt{s} = 7 \, \& \, 8 \, \text{TeV}$
Run II: $\sqrt{s} = 13 \, \text{TeV}$

Scope for many measurements in the top sector.
Physics Beyond the Standard Model

- Standard Model (SM) as a theory is successful, but not the ultimate.

- Models beyond the SM invoke new and heavy particles which have not yet been observed.

- These heavy particles are likely to decay, sometimes even preferentially, through the heavy top quark.

- This implies that the new particles can have large couplings with the top quark, making it suitable for the search of new physics.

- Note: LHC is a top factory, with production rate (~10 top pairs/s at 13TeV).

- High potential for interesting physics at hadron colliders!
Search Strategies with Top Quark

• Via study of Top production (single and pair):
  • Associated production with particle X
    -> look for deviation from SM
  • FCNC production mode

• Via study of Top decays (pair produced where one top decays a la SM):
  • MSSM decays to charged Higgs boson (H^+/^-)
  • FCNC decay to up type quarks

• Massive particles decaying to top quark pairs
• Vector like quarks decaying through top quarks
Top in Massive Vector Boson Decays
**Massive Charged Gauge Boson Decay to Top**

- $W' \rightarrow tb \rightarrow qqbb$ and lepton plus jets final state

- $tb$ invariant mass is reconstructed, search for excess over SM expectation.

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**hadronic**

![Graph](attachment:hadronic_graph.png)

\[ 2.55 \text{ fb}^{-1} (13 \text{ TeV}) \]

**leptonic**

![Graph](attachment:leptonic_graph.png)

\[ 12.9 \text{ fb}^{-1} (13 \text{ TeV}) \]

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**Upper Limit $\sigma_{W'_R} \times B(W'_R \rightarrow tb) [\text{pb}]$**

- **All-Hadronic Channel**

- **Expected limit (95% CL)**
- **Observed limit (95% CL)**

**Invariant Mass Analysis**

- $\sigma(pp \rightarrow W'_R) \times B(W'_R \rightarrow \ell \nu bb) [\text{pb}]$

- $e/\mu + \text{jets } N_b \text{ tags} = 1 \text{ or } 2$

- $M(W'_R) > 2.0 \text{ GeV}$

- $M(W'_R) > 2.67 \text{ GeV}$

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Refer: CMS PAS B2G-16-009, B2G-16-017
Massive Charged Gauge Boson Decay to Top

- $W'\rightarrow tb$ in lepton plus jets and hadronic final states.
- No excess is observed in data over background within the mass range 0.5–3.0 TeV.
- BDT discriminant used to find exclusion limit.


$M_{W'} > 1.92$ TeV assuming right handed coupling

$M_{W'} > 1.8$ (1.7) TeV assuming left handed coupling, without (with) interference with SM $tW$
Massive Charged Gauge Boson Decay to Top

- Charged massive resonance $W^{+/-'}\rightarrow tb$, when $t\rightarrow Wb\rightarrow l\nu b$.
- Events categorized by jet multiplicities and presence of $e/\mu$.
- MVA discriminant is used for analysis.

Refer: PRL 115 061801 (2015)
Chromophilic Heavy Gauge Boson

- $Z' \rightarrow g^* g$, where $g^* \rightarrow t \bar{t}$, leading to the $t \bar{t}g$ final state.

- $Z'$ mass reconstructed in semi-leptonic final state.

40 fb < $\sigma$ < 300 fb for resonances with mass 500-1000 GeV/c$^2$.

Refer: PRD 86 112002
Search for Vector Like Quarks and Invisible Particles
Search for VLQs

* Pair produced VLQs decaying via $T T \rightarrow H t + X$, $T T \rightarrow W b + X$, $B B \rightarrow H b + X$ in the lepton plus jets final state.

$M_T > 730 - 950$ GeV
$M_B > 575 - 813$ GeV

* Singly produced VLQs or excited quarks decaying through top quark.

$M_{b^*} > 1.5$ TeV

Refer: JHEP 08 (2015) 105, JHEP 02 (2016) 110
Search for VLQs

• $Z' \rightarrow T't \rightarrow WbWb$, where $T'$ is a heavy vector like top partner.

• $T'$ and $Z'$ invariant mass reconstructed in all hadronic final state.

• Pair produced VLQs decaying via $T\bar{T} \rightarrow Ht+X$.

Search for Invisible Particle Produced with Single Top Quark

- Single top quark produced in association with MET studied in semi-leptonic final state.

- Upper limits on production x-section are set.

\[ a_{\text{res}} = 0.2 \text{ excluded up to } m(f_{\text{met}}) = 100 \text{ GeV} \]
\[ a_{\text{non-res}} = 0.2 \text{ excluded up to } m(v_{\text{met}}) = 657 \text{ GeV} \]

Refer: EPJC (2015) 75:79
Production of Dark Matter with Top pair

* Dark matter particle produced in association with top quark pair.

* Dilepton final state.

\[ \sigma / \sigma \text{ upper limit on} \]

\[ 10^{-1} \quad 10^{-2} \quad 10^{-3} \quad 10^{-4} \quad 10^{-5} \]

\[ 10 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \]

\[ \text{Scalar, Dirac, } g_1 = 1, \ g_{\text{DM}} = 1, \ M_{\text{DM}} = 1 \text{ GeV} \]

\[ 2.2 \text{ fb}^{-1} (13 \text{ TeV}) \]

\[ M(\varphi/a) > 39 \text{ GeV}, \]

\[ \text{with } M(\text{DM}) = 1 \text{ GeV and } g_q = g_{\text{DM}} = 1 \]

Refer: CMS PAS EXO-16-028
Search for Anomalous Couplings and Four Tops
Higgs Production with Single Top

- Higgs production with a single top studied in both experiments to find deviations in couplings as predicted by SM.

- Interference between contributing diagrams -> hints at anomaly.

Production of Four Tops

* $t\bar{t}t\bar{t}$ production ($\sigma_{SM}\sim1$ fb at 8 TeV) in lepton plus jets final state

* ATLAS limit on cross section: $\sim23\sigma_{SM}$

* CMS limit on cross section at 13 TeV: $\sim10\sigma_{SM}$

Refer: JHEP 08 (2015) 105, CMS PAS TOP-16-016
Anomalous Couplings to Gauge Bosons
Anomalous Wtb Coupling

- Study of the angular properties of the top decay products to constraint the polarization fractions.
- Final state: exactly one charged light lepton, exactly one b tagged jet and exactly one untagged jet.

Refer: JHEP 04 (2016) 023
Anomalous Wtb Coupling

* Single top production in t-channel or in FCNC with one muon and two/three jets in the final state -> Bayesian Neural network analysis.

\[ L = (g/\sqrt{2})\bar{b}Y^\mu (f_L^V P_L + f_R^V P_R) t W^- - (g/\sqrt{2})\bar{b}(i\sigma^{\mu\nu}\partial_W W^\nu - M_W)(f_T^L P_L + f_T^R P_R) t \]

\[ \sigma = ((f_L^V)^2 A_p + (f_R^V)^2 B_p) BR(t\to l, \nu, b) \]

Limits on anomalous coupling:

- \( f^\mu_V > 0.98, |f^R_V| < 0.16 \)
- \( |f^L_T| < 0.057, -0.049 < f^R_T < 0.048 \)

Refer: CMS PAS TOP-14-007
Top Decays to Light Charged Higgs
Light Charged Higgs in Top Decay

- $t\bar{t}$ production with one $t\rightarrow Wb$, another $t\rightarrow H^+b$, with $H^+\rightarrow \tau \nu$.
- Three final states with different decay combinations of $W$ and $\tau$ (all hadronic, semi-leptonic, fully leptonic).

$\text{BR}(t\rightarrow H^+b) < 0.01-0.05$ assuming $\text{BR}(H^+\rightarrow \tau \nu) = 1$
Light Charged Higgs in Top Decay

- $t\bar{t}$ production with one $t\to Wb$, another $t\to H^+b$, with $H^+\to c\bar{s}$.

- Final state: isolated lepton, at least four jets and large MET.

Refer: JHEP 12 (2015) 178
Summary

- Top events at hadron colliders are great place to search for new physics.
- Results from mainly Run I data are presented.
- Till now Standard Model holds strong.
- Large statistics will improve the measurements.
- Stay tuned for Run II results!
Thank You.
Back Up
Light Charged Higgs in Top Decay

- $t\bar{t}$ production with one top decaying through $t\to Wb$, another $t\to H^+b$. 
- $H^+\to cs$, $H^+\to \tau\nu$ channels.

Refer: PLB 682, 278 (2009)
Single Top Production with FCNC

- Study in leptonic final state.
- Neural network analysis.

No significant rate of FCNC single top production is observed. Upper limit is set on BR using Hypothesis test.

Anomalous Single Top Production with Photon

- Search for FCNC in single top production in association with $\gamma$.
- No evidence of the FCNC production is observed.
- Upper limit on $tu_\gamma$ and $tc_\gamma$ anomalous couplings.

Highest constraint put on BR.

$\text{BR}(t \rightarrow u_\gamma) < 1.3 \times 10^{-4}$

$\text{BR}(t \rightarrow c_\gamma) < 1.7 \times 10^{-3}$

Refer: JHEP 04 (2016) 035
Top FCNC Decay to Hq

- Pair produced $tt\rightarrow WbHq$, $H\rightarrow bb$.

- Final state categorized based on number of jets and leptons.

- A discriminant based on probability is used to compare the shape of signal and background.

Refer: JHEP 12 (2015) 061

No significant excess.
Top FCNC Decay to Zq

- Pair produced $tt\rightarrow WbZq$, with $Z\rightarrow ll$, $W\rightarrow l\nu$.

- Top and Z mass are reconstructed after final selection for comparing the data and expected SM background.

- Run I analysis statistics limited.

- Run II results expected soon.

Refer: EPJC 76 (2016) 12

No significant excess.
Top FCNC Decay to Hq

- Pair produced $tt \rightarrow HqWb$, with $H \rightarrow WW$, $ZZ$ and $\tau\tau$ channels.

- Neural network analysis used.

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<th>$B_{\text{obs}}(t \rightarrow Hc)$</th>
<th>$B_{\text{exp}}(t \rightarrow Hc)$</th>
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$|\lambda_{tcl}^H|^2 < 6.9 \times 10^{-3}$ and $|\lambda_{tu}^H|^2 < 9.8 \times 10^{-3}$

Refer: arXiv:1610.04857
Top FCNC Decay to Zq

- $t\bar{t}\rightarrow WbZq$, $Z\rightarrow ll$ and $W\rightarrow l\nu$.

- No anomalous coupling observed in $t_uZ$, $t_cZ$.


No significant excess.
Top FCNC Decay
Anomalous Wtb Coupling

- Study of the angular properties of the top decay products to constraint the polarization fractions with the D0 experiment.

- The analysis is performed in both the leptons plus jets and dilepton final state.

Refer: PLB 713, 165 (2012)