Searches for New Physics in Topologies Containing Beyond-Two-Generations Quarks at CMS

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Top-Like Beyond-the-Standard-model physics at CMS

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Beyond two Generations group

- Gives interesting insight in how collaborations work in practice
- ATLAS has found different solution to same problem
The top quark

- First evidence 1994, CDF
- Discovery by D0 and CDF in 1995
- Heaviest known fundamental particle, $m_t \approx 173\text{ GeV/c}^2$
- Lifetime $\sim 5 \times 10^{-25}\text{ s} \rightarrow$ no hadronization before decay
History of the top quark

**discovery**

- PRL 74, 2632 (1995)
- PRL 74, 2626 (1995)

**today**

- **10000s of events**
- **1995, CDF and DØ experiments, Fermilab**

**LHC: top quark factory**

**precision**

- **searches**

- **Tevatron**

- CMS 2011, 5.0 fb⁻¹ at √s = 7 TeV

**Events/10 GeV**

- Data
- t̅t signal
- t̅t background
- Single top
- Drell-Yan
- Diboson

**Top Quark Mass Uncertainty**

- 1-jets DØ measurement
- Combined DØ measurement
- Tevatron combination
- Projected future uncertainty range

**17 events**

**19 events**
History of the top quark

**discovery**

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17 events

**today**

10000s of events

**precision**

- Tevatron

**searches**

LHC: top quark factory

19 events

1995, CDF and DØ experiments, Fermilab

**LHC: top quark factory**

Data
- t\bar{t} signal
- t\bar{t} background
- Single top
- Drell-Yan
- Diboson
Top pair production at the LHC

- Pair production in 8 TeV pp collisions:

\[ g \rightarrow t \bar{t} \]

\[ q \rightarrow g t \]

\[ g \rightarrow t \bar{t} \]

\[ g \rightarrow q t \]

\[ g \rightarrow \bar{t} \bar{q} \]

\[ g \rightarrow t \bar{q} \]

\[ \sim 90\% \]

\[ \sim 10\% \]
Single Top production

- Electroweak production of top quarks

- Dominant channels at LHC @ 8 TeV:
  - t-channel: 87 pb
  - tW channel: 22 pb
  - s-channel: 5.6 pb
Top pair branching fractions

B-quark identification used to reduce background

"alljets" 44% = six jets

"lepton+jets" 15% = four jets, lepton, MET

dileptons 15% = two jets, two leptons, MET
Top quark – special?

• Many models predict that top is special in order to explain large mass

• Or top quark has special role because of its large mass
**A_{FB} – portal to new physics?**

- **CDF and D0 measure values not consistent with Standard Model**
  - **In multiple decay channels and across multiple experiments**
    - Compelling to explain as new physics

---

### A_{fb} of the Top Quark

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value (90% C.L.)</th>
<th>Cross Section (fb)</th>
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</thead>
<tbody>
<tr>
<td>CDF LM</td>
<td>0.158 ± 0.074 (0.072, 0.017)</td>
<td>5.3 fb^{-1}</td>
</tr>
<tr>
<td>CDF DIL</td>
<td>0.420 ± 0.158 (0.350 ± 0.060)</td>
<td>5.1 fb^{-1}</td>
</tr>
<tr>
<td>CDF combined</td>
<td>0.201 ± 0.067 (0.085 ± 0.018)</td>
<td>≤ 30 fb^{-1}</td>
</tr>
<tr>
<td>D0 LM**</td>
<td>0.196 ± 0.060 ±0.016 -0.026</td>
<td>5.4 fb^{-1}</td>
</tr>
</tbody>
</table>

---

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17 SM parameters do not constrain creativity

- SUSY in all its variations
  - GMSB
  - MSSM, CMSSM etc
- New strong interactions?
  - Technicolor; excited quarks; compositeness; new “contact” interactions
- Exotica:
  - Weird stuff: leptoquarks?
  - New “forces”?
  - New resonances (W-Z-like)
  - More generations?
    - Fourth generation (b’/t’)
  - Gravity descending at the TeV scale?
  - New resonances; missing stuff; black holes; SUSY-like signatures [Universal Extra dimensions]
- SUSY-inspired exotica:
  - Long-lived massive (new) particles?
- Some true inspirations: “hidden valleys”?
Little Hierarchy problem, Naturalness

$Higgs$ 126 GeV

$BSM?$
Motivation

- The CMS and ATLAS collaborations have observed a new boson with mass ~125 GeV.
- Fundamental scalar particles such as the Standard Model Higgs receive divergent corrections to their mass from other SM particles.
- Restricting fine tuning to the 10% level requires new physics which cuts off these divergent contributions.

\[ m_{\text{Higgs}} = 126 \text{ GeV} \]
If fine tuning $\leq 10\%$:  
Restrictions:  
$\Lambda_{\text{quarks}} \sim< 2 \text{ TeV}$  
$\Lambda_{\text{gauge}} \sim< 5 \text{ TeV}$
LHC: search engine

“Physics beyond the standard model” - MSSM

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Vrije Universiteit Brussel
MSSM vs SUSY

- MSSM
- pMSSM
- NMSSM
- U(1)'
- Dirac gauginos
- singlinos
- CMSSM

SUSY

17
LHC performance

The LHC and CMS: outstanding performance during LHC Run 1

Detector performance
Compact Muon Solenoid

CMS Detector

- Pixels
- Tracker
- ECAL
- HCAL
- Solenoid
- Steel Yoke
- Muons

Silicon Tracker
- Pixels (100 x 150 µm²)
- ~1m² 66M channels
- Microstrips (50-100µm)
- ~210m² 9.6M channels

Crystal Electromagnetic Calorimeter (ECAL)
- 76k scintillating PbWO₄ crystals

Preshower
- Silicon strips
- ~16m² 137k channels

Superconducting Solenoid
- Niobium-titanium coil carrying ~18000 A

Steel Return Yoke
- ~13000 tonnes

Hadron Calorimeter (HCAL)
- Brass + plastic scintillator

Muon Chambers
- Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
- Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

Total weight: 14000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

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CMS detector performance

Percentage of CMS active channels

<table>
<thead>
<tr>
<th>CMS Subsystem</th>
<th>CSC</th>
<th>RPC</th>
<th>DT</th>
<th>HCAL Outer</th>
<th>HCAL forw.</th>
<th>HCAL end.</th>
<th>HCAL barrel</th>
<th>Preshower</th>
<th>ECAL end.</th>
<th>ECAL barrel</th>
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<th>Strips</th>
<th>Pixels</th>
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<tr>
<td>% operational Feb 2013</td>
<td>97.2</td>
<td>97.4</td>
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<td>96.9</td>
<td>99.9</td>
<td>99.9</td>
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<td>99</td>
<td>96.8</td>
<td>98.4</td>
<td>99.1</td>
<td>99</td>
<td>97.5</td>
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</table>
Outstanding LHC performance comes at a price:

2011:
- Run A: 5 PU
- Run B: 8 PU

2012:
- Average: 21 PU

CMS Average Pileup, pp, 2012, $\sqrt{s} = 8$ TeV

\[ <\mu> = 21 \]
Particle flow

HCAL deposit

ECAL deposit

Charged hadron

Muon

Photon

Neutral hadron
Particle flow in practice

- PF combines information from all subdetectors in a global event description
  - reconstruct ‘particles’ such as charged/neutral hadrons, photons, muons, electrons
- These particles are used to construct composite objects such as jets, taus, missing transverse energy
  - Reject tracks from non-leading collisions before creating composite objects
  - And make assumptions for background from neutral particles
- Widely used in CMS, LHCb
  - CMS: big improvements in energy resolution jets, MET, tau identification,
Electron efficiency stable vs # vertices

- Substantial effort necessary to achieve this stability
Jets

- For most analyses, CMS uses anti-$k_T$ jets with a distance parameter of 0.5.
- Particle flow algorithm allows very good agreement between data and MC with small jet energy scale uncertainties.
Missing ET

- Particle flow extremely powerful approach for missing ET reconstruction
- Missing ET sensitivity to PU irreducible
  - But well reproduced in MC
Jets with b-tagging

- Long lifetime of b-hadrons in b-jets
  - $\tau = 1.512 \times 10^{-12} \text{s}$
  - $c\tau = 455.4 \mu\text{m}$
- Combination of lifetime information in MVA
- Efficiency measured in top and QCD events (data) using multiple methods
On the momentum of top quarks

- Once boost of top quarks high enough
- Decay products become collimated
  - W->qq in one jet
  - Or t->bqq in one jet
- Special reconstruction algorithms needed:
  - Cambridge-Aachen algorithm with distance parameter 0.8
Jets with substructure

Jet 1: Top Tagging
- pt 589.1 GeV/c
- 3 subjets
- mass = 186.7 GeV/c²
- minMass = 87.2 GeV/c²

Jet 2: Jet Pruning
- pt 484.3 GeV/c
- mass = 68.8 GeV/c²

Jet 3: pt 47.8 GeV/c
b-tag discriminant 4.2

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Jets with substructure
Validation in lepton+jets events

- Algorithm validated using muon+jets selection

- Data shows that W boson and top quark (using di-jet events) can be reconstructed this way and is reasonably well modeled
Top pair production

Production cross section overview

ATLAS+CMS Preliminary
TOPLHCWG

Preliminary

*Tevatron combined* 1.96 TeV (L=8.8 fb⁻¹)
• ATLAS dilepton 7 TeV (L=4.6 fb⁻¹)
• CMS dilepton 7 TeV (L=2.3 fb⁻¹)
• ATLAS l+jets* 7 TeV (L=0.7 fb⁻¹)
• CMS l+jets 7 TeV (L=2.3 fb⁻¹)
• ATLAS dilepton 8 TeV (L=20.3 fb⁻¹)
• CMS dilepton 8 TeV (L=5.3 fb⁻¹)
• ATLAS l+jets* 8 TeV (L=5.8 fb⁻¹)
• CMS l+jets* 8 TeV (L=2.8 fb⁻¹)
  * Preliminary

NNLO+NNLL (pp)
NNLO+NNLL (pA)

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_{top} = 172.5 GeV, PDF+ α_s uncertainties according to PDF4LHC
LHC: Top quark pair factory

- Cross sections \( \sim 225 \) pb
- In combination with 20 /fb datasets:
  - LHC is a top factory
  - Very productive program of Standard Model precision top physics
Top physics: rare decays

- Production of $tt+X$ now used to do measurements to test SM.
Next: undiscovered \texttt{tt\textbar +X} final states

Production of \texttt{tttt} in SM: 1 fb!
Limits now at xsec<32 fb
Very sensitive to QCD-BSM
Heavy resonances decaying to top quark pairs
Investigating $t\bar{t}$ invariant mass distribution

- Differential cross sections now available for 8 TeV sub-set
- Searches in tails of distributions ongoing for 8 TeV full sample
  - Expect results very soon

- $Z'$ scenarios interwoven with natural EXO solutions and $A_{FB}$ explaining models
- $M_{t\bar{t}}$ distribution sensitive to many new physics scenarios

![Graph showing the invariant mass distribution with data points and theoretical predictions.](image)
analysis strategy

• Searches in different top decay channels
  – Dileptons $t\bar{t} \rightarrow \ell^-\ell^+\nu\bar{\nu}b\bar{b}$
  – Semileptonic $\equiv$ lepton+jets $t\bar{t} \rightarrow \ell\nu q\bar{q}b\bar{b}$
  – Hadronic $\equiv$ alljets $t\bar{t} \rightarrow q\bar{q}q\bar{q}b\bar{b}$

• And in different regimes
  – Close to 2x(top mass) threshold
    • Sensitive to shape of SM $M(t\bar{t}b\bar{t})$ distribution
    • Conventional top physics techniques may be used
  – More boosted
    • Sensitive to more massive $M(t\bar{t}b\bar{t})$ BSM physics
    • Dedicated reconstruction techniques may be necessary
Semileptonic, threshold

- Require only one lepton, $\geq 4$ jets and split in b-tag multiplicity

- $\chi^2$ sorting used to select best jet combination

- Using data-driven estimates for falling distribution of top pair mass spectrum above $500\,\text{GeV}/c^2$

- Systematic uncertainties take into account rate and shape changes for signal and background model
Semileptonic, threshold

- Fit to falling distribution in electron/muon final states used to set limits (1 and ≥2 b-tag regions fit simultaneously)
  - **Fully data-driven method, only makes assumptions on resonant shape of signal**
• Alternate analysis: Loosened lepton isolation criteria allow jet/lepton overlap
• Focus on mass tail: require harder cuts on leptons and jets
• Only at least 2 jets+lepton required
• $\chi^2$ sorting used to select best jet combination
• Simultaneous template fit to $M(t\bar{t})$ in different b-tag multiplicities and electron/muon final states used to set limits
• Backgrounds normalized to control region where SM $t\bar{t}$ is dominant
Semileptonic, non-isolated

- Multiple scenarios considered
  - Worlds best limit on production of resonant $ttbar$:
    - $Z'$ (width 1.2%): $m > 2.10 \text{ TeV}$
    - $Z'$ (width 10%): $m > 2.68 \text{ TeV}$
    - KK gluons: $m > 2.69 \text{ TeV}$
    - Resonances in low-mass region: excluded with $\sigma_{xsec} > 1-2 \text{ pb}!!$

All hadronic, boosted, 8 TeV

- Using boosted objects and jet pruning to identify substructure
  - Full merged topology
- Cambridge-Aachen jets
  - ‘top jets’
  - ‘W boson jets’

Type 1 + Type 1

Type 1 + Type 2

Top candidates

W candidate

b candidate

All hadronic, boosted, 8 TeV

- Using boosted objects and jet pruning to identify substructure
  - Full merged topology
- Cambridge-Aachen jets
  - ‘top jets’
  - ‘W boson jets’

2 jets, $p_T > 350$ GeV
- Both jets are top tagged
  - Not type 1 + 1
- Jet 1 $p_T > 350$ GeV, top tagged
- Jet 2 $p_T > 200$ GeV, W tagged
- Jet 3 $p_T > 30$ GeV, form top mass with jet 2

All hadronic, boosted, 8 TeV

- LLH fit to bumps in mass spectrum used to set limits

All hadronic, boosted, 8 TeV

- LLH fit to bumps in mass spectrum used to set limits.

- 95% CL upper limits on increased cross section at high mass:
  \[ \sigma_{NP+SM} < 1.2 \sigma_{SM} \text{ for masses above 1 TeV} \]

Combined limits

- Combining results gives more sensitivity in high mass regime

Heavy top partners
Fourth Generation

- Fourth generation one of more compelling SM extensions
  - Direct and indirect limits on simplest SM4: excluded!
- More elaborate fourth generation models still alive
  - Any SM extension with a Higgs doublet and fourth generation
  - Any models predicting other heavy top partners such as 2HDM
  - Vector-like quarks that are top quark/b quark partners
  - Exotic top partners with different charge
Vector like quarks

- Non-SM fourth generation very hot topic
  - Can enhance CP violation
  - Heavy neutrino as DM candidate

- Vector-like fermions (non-chiral fermions):
  - Not excluded by Higgs cross sections
  - Little Higgs models
  - Warped extra dimensions

- Models benchmark for new physics decaying top-like:
  - Extremely rich phenomenology with final states with multiple gauge bosons, b and t quarks:
    - T->bW,tZ, th
    - B->tW,bZ,bh
  - Current searches mostly pair production
  - Single production also possible
Vector-like quarks:

- Exclude triangles not points

A vector-like heavy quark would have the following decay modes:

- $T' \rightarrow bW$
- $T' \rightarrow tH$
- $T' \rightarrow tZ$
- $B' \rightarrow tW$
- $B' \rightarrow bH$
- $B' \rightarrow bZ$

Similar triangle for B-like VLQ

Possible solution to the hierarchy problem

Combined $t'$ search in $l$+jets and multileptons

- Require one isolated lepton $p_T > 32$ GeV
- And at least 3 jets plus:
  - Fourth jet
  - $W$-tagged CA8 jet in first 3 jets
- $L$+jets analysis employs Boosted Decision Tree to reach maximum sensitivity

src: B2G-12-015, JHEP 06(2014) 125
Combined t' search in l+jets and multileptons

- In multilepton channels events are separated by backgrounds
  - 12 categories, cut and count experiment in each

- Example:
  - same-sign dilepton events
  - Opposite sign same flavor leptons + one extra lepton
Search for $b'$ pair production in $l+\text{jets}$

- Single lepton, at least 4 jets, one $b$-tag
- Again, focus on boosted (vector-boson-tagged) jets
- Only ST considered to be more model-independent
- Sensitive to $tWtW$, $tWbZ$, $tWbH$, $bZbZ$, $bZbH$, $bHbH$ final states

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Observed limits:

<table>
<thead>
<tr>
<th>BR(bZ)</th>
<th>BR(bH)</th>
<th>BR(bW)</th>
<th>Obs (GeV)</th>
<th>Exp (GeV)</th>
<th>±1σ (GeV)</th>
<th>±2σ (GeV)</th>
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</thead>
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<td>700</td>
<td>689</td>
<td>[586,782]</td>
<td>[516,851]</td>
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<td>582</td>
<td>&lt;450</td>
<td>[&lt;450,495]</td>
<td>[&lt;450,566]</td>
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<td>[&lt;450,557]</td>
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<td>[450,732]</td>
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Combined result in BR plane: t’

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<thead>
<tr>
<th>Scenario</th>
<th>T→BW</th>
<th>T→H</th>
<th>T→tZ</th>
<th>expected limit (GeV)</th>
<th>observed limit (GeV)</th>
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src: B2G-12-015, JHEP 06(2014) 125
**Top partner with charge 5/3e**

- Focus on same-sign dilepton channel
  - Leptonic $W$ bosons from same $T_{5/3}$
- Understanding same-sign fake and prompt lepton background
  - Non-prompt background determined on data
  - Prompt: rare decays from MC:
    - $WW$, $ZZ$, $ttbarW$, $ttbarZ$, $WWW$

Top partner with charge 5/3e

- Very busy environment: require same-sign leptons outside Z boson window and HT>900 GeV
- High-mass leads to merging of objects:
  - Substructure considered as V-tagged jets or top-tagged jets
- Cross section limits exclude q=5/3e top partners with mass up to 770 GeV/c^2

CMS ttbar+DM

- Searches for threshold ttbar production with low missing ET
- Complementary to more SUSY-inspired searches that for example focus on stop+LSP pair production

CMS-B2G-13-004, (19.6 fb^{-1} @ 8 TeV)
• Production of one top quark recoiling against DM candidate
• Signature: one hadronic top quark + $E_T\text{miss}$
• Complementary to typical ‘mono-$X$’ signatures
• Signature favoured in DM scenarios with modified couplings to heavy flavour
• Analysis investigates $E_T^{\text{miss}}$ and invariant mass of three-jet system recoiling against $E_T^{\text{miss}}$

• After b-tagging the signal should be visible as a peak at the top quark mass

• No excess observed above SM background, dominated by $t\bar{t}$bar and $Z$ boson+3 jet production
CMS monotops

- Limits set for Scalar and vector couplings
- No mapping to flux or coupling strength limits as in monojet/monophoton searches

CMS-B2G-12-022, hep-ex:1410.1149, submitted to PRL, (19.7 fb⁻¹@ 8 TeV)
Conclusion & Outlook

• CMS has dedicated searches program in the top sector
  – Top-like Exotica
    = Beyond two generations (B2G)

• Pushing the envelope:
  – very stringent limits
  – spearheading new reconstruction techniques

• Some ‘final word’ papers in pipeline – but these techniques will really flourish at 13 TeV
3.3 Background estimate

Since this analysis focuses on signatures with high-\(p_T\) jets, the main backgrounds expected are from SM non-top multijet production and \(t\bar{t}\) production. The background from NTMJ production is estimated from sidebands in the data as described below. For the \(Z_0\) masses considered in this analysis, the irreducible SM \(t\bar{t}\) component is significantly smaller than the NTMJ background contribution, and is therefore estimated from MC simulation using the same correction factors as found for the \(Z_0\) MC described in Sec. 3.2. It is normalized to the approximate next-to-next-to-leading-order (NNLO) cross section for inclusive \(t\bar{t}\) production, taken to be 163 pb [48–50].

Figure 2: (a) The mass of the highest-mass jet (W-jet), and (b) the mass of the Type-2 top candidate (W+\(b\)), in the hadronic hemisphere of moderately boosted semimuonic \(t\bar{t}\) events. The data are shown as points with error bars, the \(t\bar{t}\) Monte Carlo events in dark red, the W+jets Monte Carlo events in lighter green, and non-W multijet (non-W MJ) backgrounds are shown in light yellow (see Ref. [46] for details of non-W MJ distribution derivation). The jet mass is fitted to a sum of two Gaussians in both data (solid line) and MC (dashed line), the latter of which lies directly behind the solid line for most of the region.