Recasting four top quark searches
the sgluon case

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From LD, Fuks, Goodsell, 1805.xxxx
Outline

Introduction

Recasting CMS 1710.10614 in MadAnalysis 5

The pseudo-scalar octet case

Conclusion
Introduction

four top searches and New physics
Four top signatures and New Physics

• Focuses on top quarks (heaviest SM particle, often coupled to NP,...)

• The process $pp \rightarrow t\bar{t}t\bar{t}$ has a small cross-section in the SM $\sigma_{pp\rightarrow 4t} \sim 10\text{fb}$

• This signature occurs fairly often in BSM models,
  • typically pair-production of new strongly charge particle
  • Decay chain then involved tops
  • For instance: SUSY (gluino), Dirac gaugino (sgluon), composite models, etc...

Typical SM diagram

Scalar Octets, sgluon 1 TeV
$\sigma_{pp\rightarrow 4t} \sim 40\text{fb}$
Recasting CMS same-sign lepton 4t search (1710.10614) with MadAnalysis5
The CMS 4t analysis (1710.10614)

Search for standard model production of four top quarks with same-sign and multilepton final states in proton-proton collisions at 13 TeV

→ SM-like searches, needs recast to get reliable NP bound

- Several Signal Regions, based on number of jets/leptons ...
- Backgrounds include $t\bar{t}W$, $t\bar{t}Z$, non-prompt leptons etc ...
- Measured $16.9^{+13.8}_{-11.4}$ fb

<table>
<thead>
<tr>
<th>$N_{\text{lep}}$</th>
<th>$N_b$</th>
<th>$N_{\text{jets}}$</th>
<th>Region</th>
<th>Total</th>
<th>Observed</th>
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<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>$\leq 5$</td>
<td>CRW</td>
<td>$85.6 \pm 8.6$</td>
<td>86</td>
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<tr>
<td></td>
<td></td>
<td>6</td>
<td>SR1</td>
<td>$8.6 \pm 1.2$</td>
<td>7</td>
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<tr>
<td></td>
<td></td>
<td>7</td>
<td>SR2</td>
<td>$3.2 \pm 0.6$</td>
<td>4</td>
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<tr>
<td></td>
<td></td>
<td>$\geq 8$</td>
<td>SR3</td>
<td>$0.8 \pm 0.4$</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>5, 6</td>
<td>SR4</td>
<td>$5.4 \pm 0.9$</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\geq 7$</td>
<td>SR5</td>
<td>$1.6 \pm 0.6$</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\geq 4$</td>
<td>SR6</td>
<td>$1.7 \pm 0.6$</td>
<td>0</td>
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<tr>
<td>$\geq 3$</td>
<td>2</td>
<td>$\geq 5$</td>
<td>SR7</td>
<td>$2.9 \pm 0.6$</td>
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<tr>
<td></td>
<td>$\geq 3$</td>
<td>$\geq 4$</td>
<td>SR8</td>
<td>$2.1 \pm 0.6$</td>
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</table>
MadAnalysis 5 implementation (1)

Validation by generating Standard Model signal:

Step 1: Generating events

• MG5_aMC@NLO ($p p \rightarrow t \bar{t} t \bar{t}$ [QCD])
• MadSpin (inclusive decay, $t \rightarrow w^+ b$, $w^+ > all all$)
• PYTHIA 8

→ Cards and parameters provided by CMS, publically available

Step 2: Implementing the analysis

• MadAnalysis5 (using Delphes (MA5 tune) for detector simulation)

→ Implement the cuts/signal regions and the tune Delphes to the efficiencies of the analysis
B-tagging implementation

• Signal regions depend crucially on number of b-tagged jets
  • E.g., for sgluon, strongest bounds from SR6 (with all 4 jets b-tagged)

• Reproduce the efficiency of DeepCSV algorithm, medium working point in Delphes (MA5 tune)

LD, Fuks, Goodsell 1805.xxxx
MadAnalysis 5 implementation (2)

→ Some challenges

• « Loose » isolation criterium (defined back in CMS’ 1605.0317)
• Relatively strong cuts (sizeable MC dataset required)
• No cutflows
• On the other hand, many histograms pre-fits ($H_T$, $p_T^\text{miss}$, $N_{\text{jets}}$, $N_b$ ...) included by CMS
• Overall good agreement
Summary: PAD

- Implemented CMS 1710.10614 $t\bar{t}t\bar{t}$ SM search in MadAnalysis 5
- Included in the Public Analysis Database of MadAnalysis 5 (cf this morning talk) allows recasting of your own model straightforwardly
  - Available online (inspirehep.net/record/1672876), validation note soon ready

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CMS analyses, 13 TeV

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Short Description</th>
<th>Implemented by</th>
<th>Code</th>
<th>Validation note</th>
<th>Version</th>
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<tbody>
<tr>
<td>CMS-SUS-16-052</td>
<td>SUSY in the 1l + jets channel (36 fb-1)</td>
<td>D. Sengupta</td>
<td>Inspire</td>
<td>Inspire</td>
<td>v1.6/Delphes3</td>
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<tr>
<td>CMS-SUS-17-001</td>
<td>Stops in the OS dilepton mode (35.9 fb-1)</td>
<td>S.-M. Choi, S. Jeong, D.-W. Kang, J. Li et al.</td>
<td>Inspire</td>
<td>Inspire</td>
<td>v1.6/Delphes3</td>
</tr>
<tr>
<td>CMS-EXO-16-010</td>
<td>Mono-Z-boson (2.3 fb-1)</td>
<td>B. Fuks</td>
<td>Inspire</td>
<td>Inspire</td>
<td>v1.6/Delphes3</td>
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<tr>
<td>CMS-EXO-16-012</td>
<td>Mono-Higgs (2.3 fb-1)</td>
<td>S. Ahn, J. Park, W. Zhang</td>
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<td>v1.6/Delphes3</td>
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<td>CMS-EXO-16-022</td>
<td>Long-lived leptons (2.6 fb-1)</td>
<td>J. Chang</td>
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<td>Inspire</td>
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<tr>
<td>CMS-TOP-17-009</td>
<td>SM four-top analysis (35.9 fb-1)</td>
<td>L. Darmé and B. Fuks</td>
<td>Inspire</td>
<td>To appear</td>
<td>v1.7/Delphes3</td>
</tr>
</tbody>
</table>

[Conte et al.(CPC’12); Conte et al. (EPJC’14) Dumont et al. (EPJC ’15)]
A Dirac gaugino-inspired example: pseudo-scalar octet
Pseudo-scalar octet, Dirac gauginos

- Supersymmetric model -> makes gauginos Dirac fermions instead of Majorana (various additional properties: supersoftness, ... etc)
  - For $SU(3)_C$, it means we need a new chiral multiplet, which contains half of the gluino degrees of freedom and a new, color octet complex scalar

\[
O = \frac{O_R + iO_I}{\sqrt{2}}
\]

The scalar octet $O_R$
- Typically heavier, (gluino mass)
- Couples to squarks and gluino at tree-level

The pseudo-scalar octet $O_I$
- Typically light (mass not correlated to gluino)
- Only couples to gluinos at tree-level
Sgluon decay channels

- We focus in the case in which the squarks/gluinos are heavier than sgluon
  → Only loop decay allowed

\[ \mathcal{L}_{\text{int}} = \bar{q}^i \left[ y^L_{8\,ij} P_L + y^R_{8\,ij} P_R \right] O q^j + h.c. + g_8 d_{abc} O^a G^{\mu\nu, b} G^{\mu\nu, c} \]

- For pseudo-scalar, only available decay is into quarks
  → Mainly into tops (light quark mass-suppressed)
  → Focus on this field for now
Recasting setup

• Simple recasting chain:
  - **FeynRules + NLOCT**
    [Christensen & Duhr (CPC ’09); Alloul et al. (CPC’14); Degrande (CPC’16)]
  - **MG5_aMC@NLO**
    Alwall et al. (JHEP’14)
  - **MadSpin**
    Artoisenet et al. (JHEP’13)
  - **PYTHIA 8**
    Sjostrand et al. (CPC’15)
  - **MadAnalysis 5**
    [Conte et al. (CPC’12); Conte et al. (EPJC’14); Dumont et al. (EPJC ’15)]

Implement effective model with:

\[
\mathcal{L} \supset \frac{1}{2} D_\mu O^a D^\mu O_a - \frac{1}{2} m_O^2 O^a O_a + y_8 \bar{t} \gamma^5 t O
\]

Generate \( pp \rightarrow OO \) at NLO

Decay the sgluon into tops, then the tops inclusively \( t > w^+ b \), \( w^+ > \) all al

The cross-section/signal shape depends only on the sgluon mass

→ Scan over it
Bounds based on SR6

- The signal SR6 (at least 4 b-tagged jets) is typically the most populated.
- Downward fluctuation (SM+bkd $1.2 \pm 0.4$ expected but 0 seen).
- We increase by almost factor 2 the reach in $\sigma \times Br$ compared to SM-related CMS bound.

![Graph showing bounds based on SR6](image-url)
Going beyond: kinematic discriminant

- The process generating $t\bar{t}t\bar{t}$ is completely different between SM and sgluon (pair production)
  
  → starkly different kinematics

- Even a very rough criterium, e.g. a signal region with $H_T > 800$ GeV could enhance the bounds
Conclusion
Conclusion

• Fast experimental progress on $t\bar{t}t\bar{t}$ searches
  → hopefully more to come soon (e.g, opposite sign search @ CMS)

• CMS search 1710.10614 now implemented in PAD
  • Recast is available for every NP models with similar signature
  • Validated and first example: most stringent current bounds on pseudo-scalar sgluon → 1.1 TeV

• Time to go beyond the SM measurement and actively start searching for NP signatures in this channel
  → Recasting also help designing next experimental searches
Back-up slides
Dirac gauginos -- couplings

- The idea → replace Majorana gauginos masses by Dirac masses
  - Add chiral multiplets $S$, $T^i$ and $O^a$ in adjoint representations of the gauge groups
  - Dirac masses given by e.g.:

$$\mathcal{L} \supset \int d^2 \theta \sqrt{2} \theta^\alpha m_{1D} \text{tr} S W_Y,$$

- The above operator gives $\mathcal{L} \supset -m_{1D} \lambda_Y \chi_S$ but also D-term contribution

$$D_1 = -\sqrt{2} m_{1D} (S + S^*) + D_Y^{(0)} \quad \text{with} \quad D_Y^{(0)} = -g_Y \sum_j Y_j \varphi_j^\dagger \varphi_j$$

- We have new trilinears $\mathcal{L} \supset -\sqrt{2} g_Y m_{1D} (S + S^*) \sum_j Y_j \varphi_j^\dagger \varphi_j$
Scalar vs pseudo-scalar octet

- No differences in production mechanism (pair production)
- Main difference → the scalar can decay into a pair of gluon
- Focusing on $t\bar{t}t\bar{t}$ it simply means that we have

$$\sigma \times Br_{O_R} \propto (\sigma \times Br)_{O_I} \times Br(O_R \rightarrow t\bar{t})$$

- In other words, the bounds can be directly applied, even though typically, $Br(O_R \rightarrow t\bar{t})$ is of percent level or below, so that the bounds are severely weakened
# Selection cuts

<table>
<thead>
<tr>
<th>Kinematic requirements</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electrons</td>
<td>Muons</td>
<td>Jets</td>
<td>b-tagged jets</td>
</tr>
<tr>
<td>$p_T$ (GeV)</td>
<td>$&gt; 20$</td>
<td>$&gt; 20$</td>
<td>$&gt; 40$</td>
<td>$&gt; 25$</td>
</tr>
<tr>
<td>$\eta$ (GeV)</td>
<td>$&gt; 2.5$</td>
<td>$&gt; 2.4$</td>
<td>$&gt; 2.4$</td>
<td>$&gt; 2.4$</td>
</tr>
</tbody>
</table>

**Isolation**/ Loose isolation criterium: Based on [27], all jets used in the lepton isolations criterium are discarded.

<table>
<thead>
<tr>
<th>Baseline selection</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets</td>
<td>$H_T &gt; 300$ GeV, $p_T^{\text{miss}} &gt; 50$ GeV, at least two jets and two b-tagged jets</td>
</tr>
<tr>
<td>Leptons</td>
<td>Same charge pair of isolated leptons, with the first satisfying $p_T &gt; 25$ GeV.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Further vetoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vetoed</td>
</tr>
<tr>
<td>In CRZ</td>
</tr>
</tbody>
</table>
Jets distributions

LHC13 - 35.9 fb$^{-1}$

$m_{O} = 1$ TeV

$m_{O} = 1.2$ TeV

Bkd and SM $t\bar{t}t\bar{t}$
Validation – SM modeling

- Slightly underestimating hadronic activity, but overall very good agreement
Same-sign vs Opposite-sign search

- Implemented a toy opposite sign lepton analysis (of course lack background estimate)
- Typically expects more jets and 2x more events
- With similar signal region, we found:
  - 2x more events in SR5-SR6
  - 3x more in SR3
CMS data – pre-fits

CMS

Data/Pred. vs $N_{\text{jets}}$

- Data
- $t+W$
- $t+H$
- Nonprompt lep.
- $t+Z / \gamma^*$
- $t+VV$
- $X\gamma$
- Rare
- Charge misid.
- $t+t t x 5$

CMS

Data/Pred. vs $H_T$ (GeV)

- Data
- $t+W$
- $t+H$
- Nonprompt lep.
- $t+Z / \gamma^*$
- $t+VV$
- $X\gamma$
- Rare
- Charge misid.
- $t+t t x 5$