Dark Matter produced in association with top quark pair

Deborah Pinna
on behalf of the CMS Collaboration

50th Rencontres de Moriond EW: YSF
La Thuile, March 14th - 21st 2015
Introduction

- Dark Matter (DM) empirical evidence for new physics beyond Standard Model (SM)
  - large variety of DM candidates: WIMP mostly studied
  - essential model-independent DM searches
    Effective Field Theory (EFT), interaction parametrized by effective operators
  - EFT approach valid when the momentum transferred $Q_{tr}$
    small cutoff scale $M^*$

- Discovery potential in different experiments:
  - direct and indirect searches
  - searches for production of DM at colliders

See C. Doglioni’s talks

G. Busoni et al., 1402.1275
Effective Field Theory

- Assuming DM is a Dirac fermion $\chi$, example of SM-DM effective operators

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_q}{M^3} \chi \bar{q}q$</td>
</tr>
</tbody>
</table>

- **Scalar interaction**  
  T. Lin et al., 1303.6638

  proportional to quark mass, better constraints when DM couples to heavy quarks

**Study of production of DM in association with top quark pair**

- Searches performed using data collected by CMS experiment during 2012, $\sqrt{s} = 8$ TeV, 19.7 fb$^{-1}$:

  DM+tt single-lepton channel CMS-PAS-B2G-14-004
DM + tt ($\rightarrow blv, bjj$): event selection

**Analysis strategy**

1. **Selection of topology**
   - 1 lepton, at least 3 jets, at least 1 b-tagged

2. **Rejection of background**

3. **Extract normalization for background**
   - $tt$-jets, $W$+jets: from data
   - Drell-Yan, single top, Di-boson: simulation
DM + tt (\(\rightarrow blv, bjj\)): event selection

**Analysis strategy**

(1) Selection of topology

- 1 lepton, at least 3 jets, at least 1 b-tagged

(2) Rejection of background

- signal has large MET from DM particles which escape detector

\[
\text{MET} > 320 \text{ GeV}
\]

(3) Extract normalization for background

- **tt+jets, W+jets**: from data
- **Drell-Yan, single top, Di-boson**: simulation
DM + tt (\(\rightarrow blv, bjj\)): event selection

**Analysis strategy**

1. **Selection of topology**
   - 1 lepton, at least 3 jets, at least 1 b-tagged

2. **Rejection of background**
   - Most W+jets and tt+jets semi-leptonic events \(M_T < M_W\). Signal events distribution peaks at higher values

\[
M_T = \sqrt{2p_T^{lep} E_T^{miss}(1 - \cos(\Delta \phi))} > 160 \text{ GeV}
\]

3. **Extract normalization for background**
   - **tt+jets, W+jets**: from data
   - **Drell-Yan, single top, Di-boson**: simulation
DM + tt ($\rightarrow blv, bjj$): event selection

Analysis strategy

(1) Selection of topology

1 lepton, at least 3 jets, at least 1 b-tagged

(2) Rejection of background

- The jets and the MET tends to be more separated in $\Phi$ in signal events than in tt and in single top events

$\min(\Delta\Phi_{j1,\text{MET}}, \Delta\Phi_{j2,\text{MET}}) > 1.2 \text{ GeV}$

(3) Extract normalization for background

$\text{tt+jets, W+jets}$: from data

$\text{Drell-Yan, single top, Di-boson}$: simulation
DM + tt ($\rightarrow bl\nu, bjj$): event selection

Analysis strategy

(1) **Selection of topology**

1 lepton, at least 3 jets, at least 1 b-tagged

(2) **Rejection of background**

- For most tt+jets di-leptonic events $M_{T2W} < M_{top}$. Signal events distribution shows higher tails

$$M_{T2W} > 200 \text{ GeV}$$  (see slide 20)

(3) **Extract normalization for background**

- tt+jets, W+jets: from data
- Drell-Yan, single top, Di-boson: simulation
DM + tt ($\rightarrow bl\nu, bjj$): event selection

**Analysis strategy**

(1) Selection of topology

1 lepton, at least 3 jets, at least 1 b-tagged

(2) Rejection of background

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET</td>
<td>&gt; 320 GeV</td>
</tr>
<tr>
<td>$M_T = \sqrt{2p_T^{lep} E_T^{miss}(1 - \cos(\Delta\phi))}$</td>
<td>&gt; 160 GeV</td>
</tr>
<tr>
<td>$\min(\Delta\Phi_{j1,\text{MET}}, \Delta\Phi_{j2,\text{MET}})$</td>
<td>&gt; 1.2</td>
</tr>
<tr>
<td>$M_{t2W}$</td>
<td>&gt; 200 GeV</td>
</tr>
</tbody>
</table>

(3) Extract normalization for background

- **tt+jets, W+jets**: from data
- **Drell-Yan, single top, Di-boson**: simulation
DM + tt (→blv,bjj): results

(4) Final yields

<table>
<thead>
<tr>
<th>Source</th>
<th>Yield (± stat. ± syst. unc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>18</td>
</tr>
<tr>
<td>Signal</td>
<td>38.3 ± 0.7 ± 2.1</td>
</tr>
<tr>
<td>Total Bkg</td>
<td>16.4 ± 2.2 ± 2.7</td>
</tr>
<tr>
<td>tt̄</td>
<td>8.2 ± 0.6 ± 1.9</td>
</tr>
<tr>
<td>W</td>
<td>5.2 ± 1.7 ± 0.6</td>
</tr>
<tr>
<td>Single top</td>
<td>2.3 ± 1.1 ± 1.1</td>
</tr>
<tr>
<td>Di-boson</td>
<td>0.5 ± 0.2 ± 0.2</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>0.3 ± 0.3 ± 0.1</td>
</tr>
</tbody>
</table>

Main systematics on total background
13% from background estimation

(5) Results

- 90% CL lower limits on interaction scale \( M^* \) for scalar interaction
  
  Assuming 100 GeV mass DM particle, \( M^* \) below 118 GeV is excluded

- 90% CL upper limits on \( tt+\text{DM} \) production cross section
  
  Cross sections higher than 55 fb for 1 GeV and higher than 20 fb for 1 TeV DM mass are excluded
DM + tt ($\rightarrow blv, bjj$): results

(4) Final yields

<table>
<thead>
<tr>
<th>Source</th>
<th>Yield ($\pm$ stat. $\pm$ syst. unc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>18</td>
</tr>
<tr>
<td>Signal</td>
<td>38.3 ± 0.7 ± 2.1</td>
</tr>
<tr>
<td>Total Bkg</td>
<td>16.4 ± 2.2 ± 2.7</td>
</tr>
<tr>
<td>$tt$</td>
<td>8.2 ± 0.6 ± 1.9</td>
</tr>
<tr>
<td>W</td>
<td>5.2 ± 1.7 ± 0.6</td>
</tr>
<tr>
<td>Single top</td>
<td>2.3 ± 1.1 ± 1.1</td>
</tr>
<tr>
<td>Di-boson</td>
<td>0.5 ± 0.2 ± 0.2</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>0.3 ± 0.3 ± 0.1</td>
</tr>
</tbody>
</table>

Main systematics on total background
13% from background estimation

(5) Results

- 90% CL lower limits on interaction scale $M^*$ for scalar interaction

Assuming 100 GeV mass DM particle, $M^*$ below 118 GeV is excluded

Cross sections higher than 55 fb for 1 GeV and higher than 20 fb for 1 TeV DM mass are excluded

What is next?
DM + tt ($\rightarrow bl\nu, bjj$): results

(4) Final yields

<table>
<thead>
<tr>
<th>Source</th>
<th>Yield ($\pm$ stat. ± syst. unc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>18</td>
</tr>
<tr>
<td>Signal</td>
<td>$38.3 \pm 0.7 \pm 2.1$</td>
</tr>
<tr>
<td>Total Bkg</td>
<td>$16.4 \pm 2.2 \pm 2.7$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$8.2 \pm 0.6 \pm 1.9$</td>
</tr>
<tr>
<td>$W$</td>
<td>$5.2 \pm 1.7 \pm 0.6$</td>
</tr>
<tr>
<td>Single top</td>
<td>$2.3 \pm 1.1 \pm 1.1$</td>
</tr>
<tr>
<td>Di-boson</td>
<td>$0.5 \pm 0.2 \pm 0.2$</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>$0.3 \pm 0.3 \pm 0.1$</td>
</tr>
</tbody>
</table>

Main systematics on total background
13% from background estimation

(6) Run 2

- Simplified models, EFT kept as benchmark
- Proton collisions from the LHC can shed light on the mysterious DM

See C. Doglioni’s and U. Haisch’s talks
DM + tt ($\rightarrow blv, bjj$): results

(4) Final yields

<table>
<thead>
<tr>
<th>Source</th>
<th>Yield ($\pm$ stat. $\pm$ syst. unc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>18</td>
</tr>
<tr>
<td>Signal</td>
<td>$38.3 \pm 0.7 \pm 2.1$</td>
</tr>
<tr>
<td>Total Bkg</td>
<td>$16.4 \pm 2.2 \pm 2.7$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$8.2 \pm 0.6 \pm 1.9$</td>
</tr>
<tr>
<td>W</td>
<td>$5.2 \pm 1.7 \pm 0.6$</td>
</tr>
<tr>
<td>Single top</td>
<td>$2.3 \pm 1.1 \pm 1.1$</td>
</tr>
<tr>
<td>Di-boson</td>
<td>$0.5 \pm 0.2 \pm 0.2$</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>$0.3 \pm 0.3 \pm 0.1$</td>
</tr>
</tbody>
</table>

main systematics on total background
13% from background estimation

(6) Run 2

- Simplified models, EFT kept as benchmark
- Proton collisions from the LHC can shed light on the mysterious DM
Thank you!
Backup slides
Introduction

- Evidence at different observable length scales for Dark Matter (DM)
  - dispersion velocity of galaxies in galactic cluster too large to be explained by luminous matter
  - rotation curves on singular galaxies constant beyond luminous region
    velocity is expected to go like $r^{-1/2}$
    differences explained by existence of dark matter

- Studies at different scales provide measurements that universe is composed mainly of non-baryonic matter
  Dark matter abundance ~24% of the universe, five times the amount of baryonic matter

- Evidence based on gravitational interactions, no information of what is the nature of Dark Matter
Introduction

• Most studied DM candidate: **Weakly Interacting Massive Particle (WIMP)**
  - neutral particle
  - mass in the range ~10 GeV - TeV
  - weak interactions
  - correct relic density
  - may be detected in different ways

• Studies at largest and smallest observable length scales
  - **indirect searches:** products of DM annihilations or decays
  - **direct searches:** scattering DM-heavy nucleons
  - **collider searches:** signature of DM production
Dark Matter signatures at LHC

- In p-p collisions Dark Matter could be produced
  very stable weakly interacting particle which escape detector

  - Missing Transverse Energy (MET)

    Energy imbalance will be observed in the plane transverse to the colliding proton beams

    initial transverse momenta of partons considered negligible, rules of conservations can be applied

\[
MET = \sqrt{\left(\sum_n E_x\right)^2 + \left(\sum_n E_y\right)^2}
\]

- Recoil

  searches for DM need also visible particles in the event to which DM particle recoil against

  searches classified depending on type of visible particles used to “tag” the event
DM+tt semi-leptonic backup
DM + tt (→blv, bjj): background

Dominant background (tt+jets, W+jets)

Scale Factors (SFs) extracted in CRs enriched in background composition and negligible signal contribution fitting simultaneously two simulated template distributions to data

**MET in W+jets enriched CR**
(pre-selection + $M_T > 160$ GeV)

| $SF(tt+jets)$  | 1.11 ± 0.02 (stat) |
| $SF(W+jets)$   | 1.26 ± 0.06 (stat) |

**$M_T$ in tt+jets enriched CR**
(pre-selection but 0 b-tag + $M_T > 160$ GeV)

predicted background yields and uncertainties propagated from CR to SR

Good agreement between data and simulation is observed after SFs are applied.
Most irreducible background from **tt di-leptonic**
- Large MET can arise from neutrinos and missing lepton
- $M_T$ higher than W mass because of additional missing particles

**Transverse mass $M_{T2}$ can be used to reject background event**
- minimal mother particle mass compatible with assumed event topology and daughter particle mass

A variable where the intermediate $W$ are considered on shell can be used

$$M_{T2}^W = \min \left\{ m_y \text{ consistent with: } \begin{cases} \overline{p}_1^T + \overline{p}_2^T = \overline{E}_T^{\text{miss}}, & p_1^2 = 0, (p_1 + p_\ell)^2 = p_2^2 = M_{W}^2, \\ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{cases} \right\}$$

it adds other kinematical info w.r.t to other $M_{T2}$ variables

**Bai, Cheng, Gallichio, Gu**
*JHEP 07 (2012) 110*
Data-simulation agreement

Agreement between data and MC samples is used to check the validity of this estimate

- In all distributions good agreement between data and background prediction is observed after SFs applied

CR1 (tt enriched)
Data-simulation agreement

Agreement between data and MC samples is used to check the validity of this estimate.

- In all distributions good agreement between data and background prediction is observed after SFs applied.
Systematic uncertainties

- **Uncertainties on backgrounds**
  
  normalization uncertainties covered by SFs
  shape uncertainties constrained in CRs and SFs propagated in SR

- **Uncertainties on signal**: 5-6%

<table>
<thead>
<tr>
<th>Source of systematic uncertainties</th>
<th>Relative error on total background (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% normalization error of other bkg in deriving SFs</td>
<td>10</td>
</tr>
<tr>
<td>Statistical error of SF_{W+jets}</td>
<td>1.5</td>
</tr>
<tr>
<td>tt+jets jet-parton matching</td>
<td>8.2</td>
</tr>
<tr>
<td>tt+jets Q^2</td>
<td>6.6</td>
</tr>
<tr>
<td>tt+jets top p_T reweighting</td>
<td>3.9</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>4.0</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>3.0</td>
</tr>
<tr>
<td>b-tagging correction factor (heavy flavor)</td>
<td>1.0</td>
</tr>
<tr>
<td>b-tagging correction factor (light flavor)</td>
<td>1.8</td>
</tr>
<tr>
<td>Pileup model</td>
<td>2.0</td>
</tr>
</tbody>
</table>

- Limits are calculated using the CL_S technique with ROOSTATS software package. Frequentist treatment of nuisance parameters
Results: lower limits on $M^*$

- Values below the observed limit are excluded

- The grey area represents only minimal requirement on $M^*$ for the EFT to be valid. There could be other areas on the plane where the EFT breaks down.
Results: cross section limits

- Can be translated in upper limits on DM-nucleon cross section for comparison with results from direct detection experiment

\[ \sigma_0^{D1} = 1.60 \times 10^{-37} \text{ cm}^2 \left( \frac{\mu_X}{1 \text{ GeV}} \right)^2 \left( \frac{20 \text{ GeV}}{M_*} \right)^6 \]

\( \mu_X \) reduced mass DM-nucleon system

Excluded dark matter-nucleon cross sections higher than \( 1 - 2 \times 10^{-42} \text{ cm}^2 \) for DM masses from 1 to 6 GeV
**Physics objects**

- **Trigger**: single-lepton triggers: single-electron, single-muon with $p_T > 24$ and 27 GeV

<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Muons</th>
<th>Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reconstruction</strong></td>
<td>ECAL driven algorithm</td>
<td>Tracker and global muon algorithms</td>
<td>anti-$k_T$ clustering algorithm with a cone size of $\Delta R = 0.5$</td>
</tr>
<tr>
<td></td>
<td>standard muon identification criteria</td>
<td>standard muon identification criteria</td>
<td></td>
</tr>
<tr>
<td><strong>Selection</strong></td>
<td>Loose $p_T \geq 30$ GeV, $</td>
<td>\eta</td>
<td>&lt;2.5$</td>
</tr>
<tr>
<td></td>
<td>$I_{rel}&lt;0.1$ in $\Delta R=0.3$</td>
<td>$I_{rel}&lt;0.12$ in $\Delta R=0.4$</td>
<td>b-tagging with medium working point CSV algorithm $</td>
</tr>
</tbody>
</table>
# Physics objects

## MUON IDENTIFICATION CUTS

<table>
<thead>
<tr>
<th>Variables</th>
<th>cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>isGlobalMuon</td>
<td>true</td>
</tr>
<tr>
<td>isPFMuon</td>
<td>true</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Number of muon hits</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>Number of pixel hits</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>Number of matched stations</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>Number of tracker layers</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>$d_{xy}(vtx)$</td>
<td>&lt; 0.2 cm</td>
</tr>
<tr>
<td>$d_z(vtx)$</td>
<td>&lt; 0.5 cm</td>
</tr>
<tr>
<td>pfIso04/$p_T$, $\Delta \beta$ corr.</td>
<td>&lt; 0.12</td>
</tr>
</tbody>
</table>

## JET IDENTIFICATION CUTS

<table>
<thead>
<tr>
<th>PF Jet ID</th>
<th>Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral hadron fraction</td>
<td>&lt; 0.99</td>
</tr>
<tr>
<td>Neutral EM fraction</td>
<td>&lt; 0.99</td>
</tr>
<tr>
<td>Number of constituent</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>Below for $</td>
<td>\eta</td>
</tr>
<tr>
<td>Charged hadron fraction</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>Charged multiplicity</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>Charged EM fraction</td>
<td>&lt; 0.99</td>
</tr>
</tbody>
</table>

## ELECTRON IDENTIFICATION CUTS

<table>
<thead>
<tr>
<th>Variables</th>
<th>tight cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_0(vtx)$</td>
<td>&lt; 0.02 cm</td>
</tr>
<tr>
<td>$d_z(vtx)$</td>
<td>&lt; 0.1 cm</td>
</tr>
<tr>
<td>$\sigma_{\eta}\eta$</td>
<td>&lt; 0.01 (barrel), &lt; 0.03 (endcap)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi</td>
</tr>
<tr>
<td>$H/E$</td>
<td>&lt; 0.12 (barrel), &lt; 0.10 (endcap)</td>
</tr>
<tr>
<td>$</td>
<td>1/E - 1/p</td>
</tr>
<tr>
<td>pfIso03/$p_T$</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Matched conversion?</td>
<td>false</td>
</tr>
<tr>
<td>Missing hits</td>
<td>0</td>
</tr>
</tbody>
</table>
Pileup reweighting

Pileup distribution different in MC w.r.t data

- MC number pileup reweighted to match data
- Data distribution re-calculated with ±5% variation on cross section to cover pileup mis-modelling syst. unc.

Good agreement data-MC after pileup reweighting

![Graph showing pileup distribution comparison](image1)

![Graph showing data-MC agreement after reweighting](image2)
Top $p_T$ reweighting

$p_T$ distribution of leptons and jets from tops softer in data w.r.t Madgraph simulation

- Top differential cross section measurement provide SFs for correction
- Each event weighted by geometric mean of SFs from 2 tops (assumed flat $> 400$ GeV)
- Syst. unc.: no SF, SF applied twice

\[ SF = e^{0.156 - 0.00137 \times p_T} \]
Physics objects: b jets

b jets

b-tagging algorithm: Combined Secondary Vertex (CSV)

- Standard CMS b-tagging algorithm
- Used to identify jets likely to come from b quarks fragmentation-adronization
- Exploits long lifetime of b hadrons
  - large impact parameter and presence of a secondary vertex as input
- Continuous output: allows selection of optimal working points

Efficiencies, mis-tag rates

<table>
<thead>
<tr>
<th>CSV threshold</th>
<th>b quark tag</th>
<th>c quark tag</th>
<th>light quark tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSV &gt; 0.90</td>
<td>50%</td>
<td>6%</td>
<td>0.15%</td>
</tr>
<tr>
<td>CSV &gt; 0.50</td>
<td>72%</td>
<td>23%</td>
<td>3%</td>
</tr>
</tbody>
</table>
Effective Field Theory backup
Effective Field Theory

- Supposing a heavy mediator of mass $M$ in the s-channel coupling to DM and SM with couplings $g_1$, $g_2$.

Considering only the lowest order operators in the EFT approach is connected to the propagator expansion

\[
\frac{g_1 g_2}{Q_{tr}^2 - M^2} = -\frac{g_1 g_2}{M^2} \left( 1 + \frac{Q^2}{M^2} + \mathcal{O} \left( \frac{Q_{tr}^4}{M^4} \right) \right) \approx -\frac{g_1 g_2}{M^2} \quad \text{for} \quad Q_{tr}^2 \ll M^2
\]

the coefficient of the effective operator should match to reproduce the UV theory, i.e. for D1

\[
M_* = \left( \frac{m_q M^2}{g_1 g_2} \right)^{1/3}
\]
Effective Field Theory

• In general the EFT field theory is valid when \( Q_{tr} << M_* \)

• The validity of the truncation of the propagator expansion requires

\[
Q_{tr} < M
\]

from the assumed UV details (heavy mediator, s-channel)

from kinematics

assuming most strongly coupled scenario in the perturbative regime

\[
\sqrt{\frac{M_*^3}{m_q}} > \frac{M_\chi}{2\pi}
\]

• This is a very minimal requirement on \( M_* \) and it depends on the details of the UV completion

\[
M_* = \left( \frac{m_q M^2}{g_1 g_2} \right)^{1/3}
\]

\[
Q_{tr} > 2m_\chi
\]

\[
\sqrt{g_1 g_2} < 4\pi
\]