Searches for Dark Matter plus Heavy Flavor Production at the LHC

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(on behalf of the ATLAS and CMS Collaborations)

DM@LHC Workshop, 3rd – 5th April 2017
Outline

- LHC and ATLAS/CMS
- Theory Framework
- DM+HF results
- Final notes

This talk is focused on dedicated DM searches inspired by simplified models with light mediators

→ Searches for SUSY 3rd generation squarks and mono-H (→ bb) covered by separate talks

DM@LHC Workshop, M. Martinez
LHC Performance (2010-2016)

Spectacular LHC performance (rapid increase of data samples)

LHC performed beyond expectations in 2016 leading to a data samples of about 40 fb-1 (..at the costs of increased pile-up levels)
The experiments collected high-quality data with efficiencies above 92%.

At the moment both experiments are still furiously analyzing the data.
The rotation of the stars around the center of the galaxies is not consistent with the amount of mass observed \((L/M \text{ ratio})_\text{SUN}\).

Spherical dark matter halo

Large distortion of the images of distant galaxies due to gravitation lensing → indication of DM in galaxy clusters

Collisions of clusters of galaxies

Considered the ultimate demonstration of the presence of Dark Matter since this does not involve Newton’s Law

Evidence for Dark Matter
Introductory notes (II)

If Dark Matter turns to be WIMP like (weakly interacting) there is a chance to produce it directly at colliders (Golden channel → Mono-jet final state)

This makes the LHC complementary to direct-detection dedicated experiments underground

Some of the models explored at the LHC are also inspired by the Higgs boson and/or indirect searches at satellites → heavy flavors involved
Benchmark Models

In Run II the ATLAS and CMS experiments moved away from the use of EFT inspired models with questionable validity at high-$Q^2$

A set of well-defined simplified diagrams with heavy mediators is now considered motivated by a number of different considerations (DM Forum: arXiv:1507.00966)

- Simple extensions of SM symmetries
- Minimal Flavor Violation
- Assuming Yukawa couplings $\rightarrow$ favor 3$^{\text{rd}}$ generation
- Some models inspired by satellite “hints”

In some cases a clear overlap with SUSY-inspired simplified models for direct production of 3$^{\text{rd}}$ generation squarks

This talk focused on DM+HF
DM+b/ bb vs=8 TeV, 20.3 fb⁻¹

Mono-b targeted event selection criteria

\( E_T^{\text{miss}} > 300 \text{ GeV} \)
\( p_T (j1) > 100 \text{ GeV} \)
\( N_{\text{jet}} (p_T > 30 \text{ GeV}) < 2 \)

At least one b-tagged jet
\( \Delta \phi (E_T^{\text{miss}}, \text{jets}) > 1.0 \)

Lepton vetoes

Other signal regions target DM+bb (not discussed yet in this slide)

Z(\( \rightarrow \nu\nu \))+jets and W(\( \rightarrow l\nu \))+jets backgrounds constrained in Z+jets, \( \gamma \)+jets and W+jets control regions (tt-bar from MC validated in control regions)

**Good agreement with SM**

<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_g}{M_X^3} \bar{X}Xq\bar{q} )</td>
</tr>
<tr>
<td>D5</td>
<td>qq</td>
<td>vector</td>
<td>( \frac{1}{M_X^2} \bar{X} \gamma^\mu \gamma^\nu q \bar{q} \gamma_\mu q )</td>
</tr>
<tr>
<td>D8</td>
<td>qq</td>
<td>axial-vector</td>
<td>( \frac{1}{M_X^2} \bar{X} \gamma^\mu \gamma^5 \gamma^\nu \gamma^5 q )</td>
</tr>
<tr>
<td>D9</td>
<td>qq</td>
<td>tensor</td>
<td>( \frac{1}{M_X^2} \bar{X} \sigma^{\mu\nu} \gamma_\mu q \bar{q} \sigma_{\mu\nu} q )</td>
</tr>
<tr>
<td>D11</td>
<td>gg</td>
<td>scalar</td>
<td>( \frac{1}{4M_X^3} \bar{X}X\alpha_s (G_{\mu\nu}^a)^2 )</td>
</tr>
</tbody>
</table>
To be read with caution at high DM masses (EFT validity)

Assuming maximum coupling

Complementary sensitivity at very low DM masses

\( \sigma_{\chi N} \) vs. DM mass

\[ \sigma_{\chi N} = \sum_q \frac{1}{M_*^2} \bar{\chi} \sigma^{\mu \nu} \chi \bar{q} \sigma_{\mu \nu} q \]

\[ \sqrt{s} = 8 \text{ TeV}, \ 20.3 \text{ fb}^{-1} \]

\( g + b \)
DM+b

Bottom Flavored DM model (motivated to accommodate Fermi-LAT hints)

Analysis of Fermi-LAT data points to DM mass point of \( \sim 35 \text{ GeV} \)

\[
\Delta \chi^2 = \begin{cases} 
0 & \text{for Inner Galaxy} \\
100 & \text{Galactic Center} \\
80 & \text{Galactic Center, } E > 1 \text{ GeV}
\end{cases}
\]

For a DM mass of 35 GeV, mediator masses in the range 300 – 500 GeV are excluded at 95% CL
DM+bb

Parameters:
Mediator and DM masses (minimal mediator width)
couplings: \( g_{q}\), \( g_{DM} = g = 1 \)

The analysis is optimized for a spin-0 mediator
Final state characterized by
- Two b-jets, no more than 3-jets,
- Large missing transverse energy
- No leptons
- Azimuthal \( E_{T}^{\text{miss}}\)-Jet separation against QCD

As expected SM backgrounds driven by
\( Z(\rightarrow \nu\nu)+bb, W(\rightarrow l\nu)+bb \) and top quark production

Normalization of main background processes are constrained in dedicated control regions in data.
ATLAS-CONF-2016-086

$\sqrt{s} = 13$ TeV, 13.3 fb$^{-1}$

**DM+bb**

Parameters:
Mediator and DM masses (minimal mediator width) 
 couplings: $g_{qr}g_{DM} = g = 1$

The analysis is optimized for relatively light mediators (with mass < 300 GeV) 
and very light DM masses (1 GeV)

Discriminants based on different final state 
topologies between irreducible Z+bb and DM+bb 
from differences in spin and mass.

Signal with well separated jets and b-jets 
and reduced $p_T$-imbalance between them

$$\Delta R_{min} = \min \left( \Delta R_{ij} \right) > 2.8$$

$$Imb(b_1, b_2) = \frac{p_T(b_1) - p_T(b_2)}{p_T(b_1) + p_T(b_2)} > 0.5$$

Good agreement with SM expectations
DM+bb

Good agreement with SM. Analysis still dominated by statistics...
(uncertainties mainly coming from jet energy scale and b-tagging eff.)

<table>
<thead>
<tr>
<th>SR</th>
<th>Observed</th>
<th>Total background</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+jets</td>
<td>1.2 ± 0.8</td>
<td>22.6 ± 5.7</td>
</tr>
<tr>
<td>Z+jets</td>
<td>4.7 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>single top</td>
<td>2.6 ± 1.1</td>
<td></td>
</tr>
<tr>
<td>others</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>pre-fit W+jets</td>
<td>1.2 ± 0.8</td>
<td>20.1 ± 6.0</td>
</tr>
<tr>
<td>pre-fit Z+jets</td>
<td></td>
<td>5.8 ± 1.5</td>
</tr>
<tr>
<td>pre-fit single top</td>
<td>2.7 ± 1.1</td>
<td></td>
</tr>
<tr>
<td>pre-fit others</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

Observed: 33 events
SM prediction: 31.0 ± 6.2

95%CL upper limits w.r.t $\sigma_{\text{signal}} @ g=1$

Cross section limits vs mediator mass
(DM of 1 GeV and g=1)

Model-independent 95% CL limits on visible cross section: 1.38 fb
Analysis targets both DM+bb and DM+tt
Analysis strategy with two signal regions with exclusive 1- and 2-b-jets
Veto on leptons and > 1 additional jet
Imposed azimuthal $E_T^{\text{miss}}$-Jet separation
Signal final state characterized by large missing transverse momentum energetic b-jets (enhanced for DM+tt)
As expected SM backgrounds driven by $Z(\rightarrow \nu\nu)+bb$, $W(\rightarrow l\nu)+bb$ and top quark production
Normalization of dominant background processes are constrained in dedicated control regions in data using a simultaneous fit to data and MC predictions.

A total of 10 control regions with leptons and with same requirements as in signal regions.

Other small background (e.g. single-top, Diboson) taken from simulation.

QCD-multijets data driven.
DM + b/bb \( \sqrt{s}=13 \) TeV, 2.17 fb\(^{-1}\)

Good agreement with SM predictions

(uncertainties dominated by b-tagging efficiency and background modeling)
Upper limits down to \((26) \ 5 \times \frac{\sigma}{\sigma(g_{\chi}g_q=1)}\) are set for models with a generic pseudoscalar (scalar) mediator for low mediator and DM candidate masses.
DM+t

\( \sqrt{s} = 8 \) TeV, 20.3 fb\(^{-1} \)

**Considering Top decay in lepton+jets**

**Resonant channel**
Spin-0 mediator \( \rightarrow t + (\text{invisible}) \) fermion

**Non-resonant channel**
Production of \( t + \text{spin-1 (invisible)} \) particle

No such mono-top process is available in the SM at tree level
\((t+Z (Z \rightarrow \nu\nu) \text{ is GIM suppressed })\)
\( \rightarrow \) Sizable event rate would indicate BSM
**DM+t**

Selection based on
- Large missing transverse energy
- One lepton and exactly one b-tagged jet from the top semi-leptonic decay

SM background dominated by $t\bar{t}$ pairs followed by W+jets processes

Background predictions are taken from simulation and validated in CRs

Good agreement with SM predictions

Systematic uncertainties from Jet energy scale, b-tagging efficiency and MC modeling + x-section uncertainties

**DM@LHC Workshop, M. Martinez**
For a spin-0 mediator mass of 500 GeV
Fermion masses below 100 GeV and
couplings above 0.1 are excluded at 95% CL

In the non-resonant case masses below
400 – 800 GeV are excluded @ 95% CL
depending on the coupling assumed
Reconstruction of the hadronic top decays in boosted configurations using large-R jets (grooming applied to remove soft contributions)

Large missing transverse energy
A fat jet (R=1.5) with $p_T > 250$ GeV
A b-jet identified inside
Jet mass in the range 110-210 GeV
N-subjetettiness compatible with top decays

Veto on additional b-jets outside
Veto on isolated leptons/photons

Dominant background from $t\bar{t}$, $Z(\rightarrow \nu\nu)$+jets and $W(\rightarrow l\nu)$+jets estimated using MC simulations constrained in dedicated control regions

Other small backgrounds (single-top, diboson, QCD-multijets) taken from simulation
Some examples of CRs below:

**Z(\rightarrow \mu\mu)+jets**

**\gamma+jets**

Simultaneous fit **in signal+control regions** to determine SM prediction and identify potential BSM signals → **Good agreement with SM**
For $m_\chi = 10$ GeV FCNC $m_V < 1.5$ TeV excluded at 95% CL (for given couplings)

For $m_\chi = 100$ GeV, $M_\phi < 2.7$ TeV excluded at 95% CL (for given couplings)
Semileptonic:
One high-$p_T$ (30 GeV) lepton, $E_T^{miss} > 160$ GeV
Three or more jets, at least one b-jet
$m_T$ (lepton, $E_T^{miss}$) > 160 GeV, $m_{W,T2} > 200$ GeV
$\Delta \phi (E_T^{miss}, \text{jets}) > 1.2$ (2 leading jets)

Hadronic:
Lepton veto, $E_T^{miss} > 200$ GeV,
Four or more jets, at least 2-bjets
$\Delta \phi (E_T^{miss}, \text{jets}) > 1.0$ (up to 6th jet)

→ Novel top-tagger using NN discriminants
→ Event characterization based on it

Dominant backgrounds($tt$, $W + \text{jets}$) constrained in different control regions (as usual)
A binned maximum likelihood fit is performed simultaneously to the $E_T^{miss}$ distributions → making full use of the shape → good agreement with SM.
Upper limits on the DM production cross section as a function of the DM-particle mass $m_{DM}$ and mediator mass $m_{MED}$ are placed on the ratio to theory cross section $\sigma/\sigma_0$. 95% confidence level (CL) are placed on the ratio to theory cross section $\sigma/\sigma_0$. Sensitivity for exclusion for scalar at low $m_{MED}$ masses.
Considering dilepton channels (ee, µµ, eµ) → Moderate $E_T^{\text{miss}}$, at least one b-jet, multiple jets → Dominated by top production

Most backgrounds from simulation
Data driven background estimations from DY and lepton fakes

Use of the full shape of the $E_T^{\text{miss}}$ to enhance sensitivity

Good agreement with SM prediction
The combination analysis obtains an expected exclusion of scalar mediators with masses up to 39 GeV at 95% CL, with the assumption of Dirac DM particles with $M_{DM}=1$ GeV and $g_q=g_{DM}=1$

In the case of pseudoscalar mediator the expected sensitivity at the edge of that needed for exclusion
DM+tt (hadronic channel)

Large $E_T^{\text{miss}}$ and $E_T^{\text{miss}}$ significance
At least four jets, and 2 b-jets, lepton veto

Reconstruction of two large jets $R=1.2$
with masses above 140 and 60 GeV

Some topological requirements optimized
for a DM signal with $M_{\text{MED}} = 350$ GeV and $M_{\text{DM}} = 1$ GeV

$\Delta R(bb) > 1.5, M_{T,b,\text{min}} > 200$ GeV

$\rightarrow$ Dominated by top production ($tt$ & $Z(\rightarrow \nu\nu)+\text{jets}$)

Background normalizations constrained in dedicated control regions.
Good agreement with SM predictions
95% CL limits on visible cross section of 0.72 fb

Limits on DM models assuming $g = 3.5$
For on-shell scalar/pseudoscalar mediators
masses in the range $300 – 350$ GeV excluded
DM+tt
(semileptonic channel)

Large $E_T^{\text{miss}}$ and $E_T^{\text{miss}}$ significance
At least one lepton
At least four jets, and 1 b-jets
Azimuthal separations: jets, $E_T^{\text{miss}}$, lepton

Some topological requirements based on variants of $m_{T2}$ (arXiv:hep-ph/9906349)

$$m_{T2}(\vec{p}_T,1,\vec{p}_T,2,\vec{q}_T) = \min_{q_{T1}+q_{T2}=q_T} \left\{ \max[ m_T(\vec{p}_T,1,\vec{q}_T,1), m_T(\vec{p}_T,2,\vec{q}_T,2) ] \right\}$$

Background dominated by top processes.

Constrained in control regions via simultaneous fit

Different control regions and validation regions defined in the plane of topological variables and different N b-jets
ATLAS-CONF-2016-050

$\sqrt{s}=13$ TeV, 13.3 fb$^{-1}$

DM+tt

(semileptonic channel)

<table>
<thead>
<tr>
<th>Variable</th>
<th>DM_low</th>
<th>DM_high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of (jets, $b$-tags)</td>
<td>($\geq 4, \geq 1$)</td>
<td>($\geq 4, \geq 1$)</td>
</tr>
<tr>
<td>Jet $p_T &gt; [\text{GeV}]$</td>
<td>(60 60 40 25)</td>
<td>(50 50 50 25)</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>&gt; 300</td>
<td>&gt; 330</td>
</tr>
<tr>
<td>$H_T^{\text{miss}}$</td>
<td>&gt; 14</td>
<td>&gt; 9.5</td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>&gt; 120</td>
<td>&gt; 220</td>
</tr>
<tr>
<td>$amT_2$ [GeV]</td>
<td>&gt; 140</td>
<td>&gt; 170</td>
</tr>
<tr>
<td>$\min(\Delta \phi(p_T^{\text{miss}}, \text{jet}_i))(i \in {1 - 4})$</td>
<td>&gt; 1.4</td>
<td>&gt; 0.8</td>
</tr>
<tr>
<td>$\Delta \phi(p_T^{\text{miss}}, t)$</td>
<td>&gt; 0.8</td>
<td>–</td>
</tr>
</tbody>
</table>

An about $3.3\sigma$ excess (local significance) in one of the signal regions

Nothing seen in Validation Regions
ATLAS-CONF-2016-050

DM+tt

An about 3.3σ excess (local significance) in one of the signal regions (needs more data...)

ATLAS Preliminary
\( p_{\text{T}} = 13 \text{ TeV}, 13.2 \text{ fb}^{-1} \)

DM+tt pseudo-scalar mediator, \( g_{\chi} = g_{q} = g \)

\begin{align*}
\text{Limit on } g & : \\
\text{Expected limit (±1σ_{exp})} & : \\
\text{Contours for } g=3.5 & : \\
\end{align*}

\begin{align*}
\text{Observed limit} & : \\
\text{Expected limit (±1σ_{exp})} & : \\
\text{Contours for } g=3.5 & : \\
\end{align*}

ATLAS Preliminary
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\begin{align*}
\text{Limit on } g & : \\
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\end{align*}

\begin{align*}
\text{Observed limit} & : \\
\text{Expected limit (±1σ_{exp})} & : \\
\text{Contours for } g=3.5 & : \\
\end{align*}
Considering dilepton channels (ee, μμ, eμ) → Moderate $E_T^{\text{miss}}$, at least one b-jet, multiple jets → Topological cuts to enhance signal

<table>
<thead>
<tr>
<th>Variable</th>
<th>DM-SRL</th>
<th>DM-SRH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>$ [GeV] (SF only)</td>
</tr>
<tr>
<td>$b$-jet multiplicity</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>$\Delta \phi_{\text{boost}}$</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>$m_{t2}$ [GeV]</td>
<td>&gt;120</td>
<td>&gt;120</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>&gt; 180</td>
<td>&gt; 260</td>
</tr>
</tbody>
</table>

$m_{t2}(p_T,1,p_T,2,q_T) = \min_{q_T,1+q_T,2=q_T} \{ \max[ m_T(p_T,1,q_T,1), m_T(p_T,2,q_T,2) ] \}$

→ Dominated by top production (tt & tt+Z)

Background normalizations constrained in dedicated control regions.
**Good agreement with SM predictions**

95% CL limits on visible cross section in the range **0.65 fb – 0.43 fb**

Limits on DM models assuming $g=3.5$ ([95% limits on $g$ in the Figures])  

**DM@LHC Workshop, M. Marzénez**
Final notes

• The nature of the Dark Matter remains one of the biggest questions on particle physics and its potential discovery is a pillar of the ATLAS and CMS physics programs.

• The search for Dark Matter in association with heavy flavors at the LHC is well motivated and still statistically limited.

• Exclusion limits on DM strongly depend on model assumptions.

• The LHC is about to resume pp collisions in few months and promises to deliver lots of data in the following years.

• Stay tuned!
In Summary (CMS @ ICHEP2016)

DM + jets/V(qq) $g_{DM}=1, g_q=0.25$
DM + $\gamma$ $g_{DM}=1, g_q=0.25$
DM + Z(\ell\ell) $g_{DM}=1, g_q=0.25$
DM + t $g_{DM}=1, a_{FC}=b_{FC}=0.25$
DM + H(bb/\gamma) $m_A=300\,\text{GeV}, m_{DM}=100\,\text{GeV}$ $g_z=0.8$
DM + jets/V(\ell\ell) $g_{DM}=g_q=1$
DM + tt $g_{DM}=g_q=1, \alpha/\alpha_0 = 2$
DM + bb/tt $g_{DM}=g_q=1, \alpha/\alpha_0 = 5, 30$

Maximal excluded mass [GeV]

Observed limits at 95% CL for considered simplified models
Theory uncertainties not included

V = vector ; AV = axial-vector
S = scalar ; PS = pseudoscalar

DM exclusions
mediator exclusions