Dark matters at the LHC
and their mediators

This talk:
ATLAS
CMS

LHCP, Shanghai
May 18, 2017
http://indico.cern.ch/e/517784

Tae Min Hong

University of Pittsburgh
Dark matter at LHC is a hit
I wrote a macro to do scour the arXiv

"Dark matter + LHC" is among the most popular topics

Search terms in title

LHC + Higgs

LHC + DM
DARK MATTER

300 total!

LHC + SUSY
SUPERSYMMETRY

Scaled up 2017 since it’s < ½ over

"Dark matter + LHC" is among the most popular topics
This talk

≥ ⅔ of attendees have “CERN” in registration, so not introducing LHC, ATLAS, CMS.

Objectives

• Complementarity
• Searches
• Tools: trigger, boosted jets, …

Homework

• See parallel talks
• Visit websites
  CMS [ see p24, 39 ]
  ATLAS [ see p24, 40 ]
• Ask me! [ tmhong@pitt.edu ]

Hong
Pittsburgh

Dark matter

Mono-x \[ x = j, \gamma, Z, W, H, b, t \]
jet
EW BOSONS
H. FLAVOR

Mediators

Via di-jets
Higgs

DM simplified models
Exp’t DM in CMS
Exp’t DM in ATLAS
Theory LHC pheno. of DM coannih’n
Exp’t Heavy reson. w/ lep.+γ at LHC
Exp’t Other pheno. w/ lep.+γ at LHC
Zen of dark matter

WIMP miracle is guide. Freeze out gives ~ relic density.

LHC designed to probe the weak scale, suitable here.

Complementary in approaches
Neutral third party

**Features of mediator**

<table>
<thead>
<tr>
<th></th>
<th>spin 0</th>
<th>spin 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge $Q$</td>
<td>$Q_{\text{med}} = 0$ for s-channel</td>
<td></td>
</tr>
<tr>
<td>Mass $m$</td>
<td>unknown</td>
<td></td>
</tr>
<tr>
<td>Dark sector</td>
<td>$H$</td>
<td>$\gamma, Z, Z'$</td>
</tr>
<tr>
<td>bosons similar to</td>
<td>$[1609.09079]$</td>
<td></td>
</tr>
<tr>
<td>Lorentz structure</td>
<td>scalar 1 pseudosc. $\gamma_5$</td>
<td>vector $\gamma^\mu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>axial v. $\gamma^\mu \gamma_5$</td>
</tr>
<tr>
<td>Coupling “$g$”</td>
<td>$\propto$ mass</td>
<td>$\propto$ charge</td>
</tr>
<tr>
<td>Consequences</td>
<td>$m_b \gg m_d$</td>
<td>$Q_b = Q_d$</td>
</tr>
<tr>
<td>Example chan.</td>
<td>mono-$b$</td>
<td>di-jet</td>
</tr>
</tbody>
</table>

**Complementary in channels**

**Lagrangian parameters**

```
$q$                        |
\hline
mediator
```

```
$q\bar{q}A$ $g_{\text{DM}} \bar{\chi}\chi A$
```

```
$g_q \bar{q}qA$ $g_{\text{DM}} \bar{\chi}\chi A$
```

```
$g_q m_q m_{\text{med}}$ $g_{\text{DM}} m_{\text{DM}} m_{\text{med}}$
```

```
known redundant
```

Matrix element = 4 parameters

2d plots must assume 2 other param.
Complementarity non-LHC v. LHC

Generic features for benchmark \((g_{DM} = 1, g_q = \frac{1}{4})\)

CERN-LPCC-2016-001

Overlay

Assumptions
- Particle types
  - Dirac DM
  - Leptophobic Axial vector
- Coupling val.
  - \(g_q = 0.25\)
  - \(q_{DM} = 1\)

Cartoon of cross-section v. DM

No lower bound
- exp’t limit \(\approx O(1)\) GeV

No upper bound
- \(m_{mediator} \approx O(100)\) GeV

Also have complementarity among various LHC results
**Much ado about “x”**

Search $pp \rightarrow \chi \bar{\chi} + “x”$

- MET is recoil against “x”
- $Z_{\nu\bar{\nu}} \leftrightarrow A_{\chi \bar{\chi}}$ indistinguishable

**General**

- Estimate with $\gamma$ and/or $W_{lv}$ control sample

  **Drell-Yan**
  - $W - Z$ similarity
  - Very high stats
  - QCD produced

  **Weak bosons**
  - Higher stats
  - Can produce EW

- “x” can be
  - Single object or res., e.g., jet, $\gamma$, $W_{lv}$, $W_{q\bar{q}}$, $Z_{ll}$, $H_{b\bar{b}}$
  - System of non-resonant objects, e.g., $b\bar{b}_{non-res}$

<table>
<thead>
<tr>
<th>$\chi$</th>
<th>objects</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jet</strong></td>
<td>$P_T \approx 100$&lt;br&gt;$MET \approx 200$</td>
<td>classic</td>
</tr>
<tr>
<td><strong>Photon</strong></td>
<td>$P_T \approx 200$&lt;br&gt;$MET \approx 200$</td>
<td>low rate</td>
</tr>
<tr>
<td><strong>Weak bosons</strong></td>
<td>$t^+ t^-$</td>
<td>clean</td>
</tr>
<tr>
<td></td>
<td>$q\bar{q}$</td>
<td>rate, boosted</td>
</tr>
<tr>
<td><strong>Higgs boson</strong></td>
<td>$b\bar{b}$</td>
<td>60%</td>
</tr>
<tr>
<td><strong>Heavy flavors</strong></td>
<td>$\gamma\gamma$</td>
<td>clean 0.5% lower trig.</td>
</tr>
<tr>
<td></td>
<td>$b, b\bar{b}$</td>
<td>Fermi-LAT?</td>
</tr>
<tr>
<td></td>
<td>$t, t\bar{t}$</td>
<td>3rd gen.</td>
</tr>
</tbody>
</table>
Dark matter + mono-jet

**Mono-jet**

**Signal models**

- Higgs invisible
- Axial-vector
  - $m_{\text{med}} = 2 \text{ TeV}$
  - (more later)

**MET $\approx 200 \text{ GeV}$ v. largest processes**

- Kills di-jet, multi-jet
- Kills $t\bar{t}$
- Kills $W, Z, \gamma$

**MET kills**
MET + mono-jet

MET → 954 GeV

jet → 973 GeV

transverse view

unrolled cylinder

longitudinal view

Hong Pittsburgh

March 2016,

Run Number: 279284, Event Number: 606734214
Date: 2015-09-14 12:05:34 CEST
Dark matter + mono- (jet, photon)

Exclude in \((m_{\text{med}} \text{ v. } m_{\text{DM}})\) 2d plane, must fix \((g_{\text{DM}}, g_q)\)

Complementary coverage regions

Overlay of mediator v. DM

Cartoon of mediator v. DM

Legend for 6 results

- Dijet
- Dijet 8 TeV
- Dijet TLA
- Dijet + ISR
- \(E_T^{\text{miss}}\) + jet
- \(E_T^{\text{miss}} + \text{jet}\)

ATLAS Prelim. Mar. 2017
DM Simplified Model Exclusions

Legend for 6 results

- Dijet
- Dijet 8 TeV
- Dijet TLA
- Dijet + ISR
- \(E_T^{\text{miss}}\) + jet
- \(E_T^{\text{miss}} + \text{jet}\)

ATLAS Prelim. Mar. 2017
DM Simplified Model Exclusions


Complementary coverage regions
Dark matter + mono-photon

Exclude in \((\sigma_{\text{DM-proton}} \text{ v. } m_{\text{DM}})\) 2d plane [see also p34]

- \(\sigma\) is function of \(m_{\text{med}}\), see right

\[
\sigma_{\text{SD}} \sim \left( g_q \cdot g_{\text{DM}} \cdot \frac{m_{\text{DM-p}}}{(m_{\text{med}})^2} \right)^2
\]

mediator is on-off-shell

mediator v. DM

cross-section v. DM

ATLAS
\(\sqrt{s}=13\ \text{TeV}, 36.1\ \text{fb}^{-1}\)

April 2017
[1704.03848]

Non-LHC

LUX

Pico-60

excluded by LHC

excluded by LHC

LHC sensitive

overlap

non-LHC
Dark matter + mono-Higgs

**Challenges**
- $\sigma_{\text{Higgs}} \sim O(\text{pb})$
- Gap in $m_A - m_{Z'}$
- Large par. space

**Solutions**
- Channels: boosted…
- MET trigger threshold
- Fix $\tan \beta$ ($m_A$ v. $m_{Z'}$)
- Consider DM sector

**Distribution of boosted jet**

**Two mediators: $A$ v. $Z'$**

**Modeling**
- Background Uncertainty
- Pre-fit Background
- mono-h $Z'$-2HDM
- $m_Z = 1400$ GeV, $m_A = 600$
- $\sigma_{\text{Signal}} = 4.74$ fb

**Signal**

**ATLAS**
$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

**Channel**
SR (Merged) : 0 lepton
$E_T^\text{miss} > 500$ GeV
2 $b$-tags

**Composition**
- Data
- SM Vh
- Diboson
- $t\bar{t} + \text{single top}$
- $Z$+jets
- $W$+jets

**Limit details**
- Observed limit
- Expected limit $\pm 1\sigma$
- $\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
- $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$\Delta R = \frac{2m_H}{P_T}$

$Z'$-2HDM simplified model
$\tan \beta = 1$, $g_z = 0.8$, $m_\chi = 100$

$Z'$ off-shell

$Z'$-2HDM simplified model
$\tan \beta = 1$, $g_z = 0.8$, $m_\chi = 100$

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

April 2017
[ATL-CONF-2017-028]
Joke

Once you have a collider,

every problem starts to look like a particle.

your analysis
dark matter
Mediator via di-jet

Challenges

• Di-jets high rate
• $m_{\text{jet-jet}}$ threshold

Solutions

• ISR jet / photon
• Boosted jet-jet
• Save trig.-level (more later)

Display of event here next slide
Di-jet (no MET!)

Invariant mass
- \( m_{\text{jet-jet}} = 7.7 \text{ TeV} \)
- among the highest recorded
**Trigger-level**

New tools, reach lower

Full event, 1 MB
- Rate increase

Jet info, 1 kB
- CMS scouting
- ATLAS trigger-level


---

CMS
12.9 fb⁻¹ (13 TeV)
Nov. 2016 [1611.03568]

Preliminary
36 fb⁻¹ (13 TeV)

Plot similar to p14 with legends removed here [CDS: 2256873]

---

Dijet mass [TeV]

9

8

7

6

5

4

3

2

1

0

-1

-2

-3

-4

-5

-6

-7

-8

-9

-10

m_{jet-jet} [TeV]

|< 2.5, |

| |< 1.3

Wide Calo-jets

0.45 < m_{jj} < 2.04 TeV

| < 2.5, | |< 1.3

gg (0.75 TeV)

qg (1.20 TeV)

qq (1.60 TeV)

---

detector

full data buffer

save?

trigger

reduced data

storage

save reduced data

16
Exclude in \((m_{\text{med}} \text{ v. } m_{\text{DM}})\) 2d plane, must fix \((g_{\text{DM}}, g_q)\)

**Overlay of mediator v. DM**

<table>
<thead>
<tr>
<th>Legend for 6 results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dijet</td>
</tr>
<tr>
<td>Dijet 8 TeV</td>
</tr>
<tr>
<td>Dijet TLA</td>
</tr>
<tr>
<td>Dijet + ISR</td>
</tr>
<tr>
<td>E_{Tmiss} + jet</td>
</tr>
<tr>
<td>E_T^{miss} + jet</td>
</tr>
</tbody>
</table>

**Cartoon of mediator v. DM**

- **Cartoon of mediator v. DM**
- **Overlay of mediator v. DM**

**Legend for 6 results**
- Dijet
- Dijet 8 TeV
- Dijet TLA
- Dijet + ISR
- E_{Tmiss} + jet
- E_T^{miss} + jet

**Cartoon of mediator v. DM**
- mediator is on-shell
- mediator is off-shell

**Vertical lines:** \(q\bar{q} \rightarrow A \rightarrow q\bar{q} \text{ is independent of } m_{\text{DM}}\)

Below diagonal:

\(A \rightarrow \chi \bar{\chi} \text{ allowed, wider } \Gamma_{\text{med}} \text{ due to phase space} \)
Alternate \((g_{DM}, g_q, g_{lep})\) alters conclusions [also see p36, 37]

Decrease \(g_q = \frac{1}{10}\), Turn-on \(g_{lep} = \frac{1}{100}\)

Increase \(g_{lep} = \frac{1}{10}\)

No overlap in on-shell

Dilepton results more imp’t

Overlapping coverages important for robustness
Challenges

- Not many var. for VBF
- MET trigger has higher pileup dependence, left

Solutions

- Background est. imp’t
- Keep MET trigger threshold v. pileup
- Can trig. on jets, right

Figure 2: Distributions of $M_{jj}$ (top left), $D_{hjj}$ (top right), $D_{fjj}$ (bottom left), and central jet $p_T$ (bottom right) in background and signal MC simulation. The distributions are shown after requiring two jets with $p_{T1}, p_{T2} > 50 \text{ GeV}$, $|h| < 4.7$, $h_{j1}, h_{j2} < 0$, $M_{jj} > 150 \text{ GeV}$, and $E_{\text{miss}} > 130 \text{ GeV}$.

The arrows correspond to the thresholds applied for the final selection, after optimization.

CMS simulation

$\sqrt{s} = 8 \text{ TeV}, L = 19.5 \text{ fb}^{-1}$

VBF $m_H = 125 \text{ GeV}$,

B($H \rightarrow \text{inv}$) = 100%

- EWK
- QCD

Higgs

QCD

From [1404.1344], also Mar. 2017 [1610.09218]
Search for invisible or measure Higgs decays
Higgs mediator

- General area of disputed signals
- Scalar $\sim m^2$
- Fermion $\sim \text{const.}$
- Vector $\sim m^2$

LHC can probe

- overlap:
  - Exp't limit
  - Direct detection

- For $B_{\text{inv}} = 0.22$, LHC exclude for models

- Complementary: LHC v. direct det.
Many interesting topics not discussed here, e.g.,

- Scalars with color
- Dark $\gamma / Z$ with long lifetime
- SUSY that conserves $R$ parity
Extra
<table>
<thead>
<tr>
<th>References cited</th>
<th>Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slide</td>
<td>Links</td>
</tr>
<tr>
<td>1, 12</td>
<td><a href="http://www.newyorker.com/cartoons/a18624">http://www.newyorker.com/cartoons/a18624</a></td>
</tr>
<tr>
<td>3</td>
<td><a href="http://indico.cern.ch/event/517784/sessions/223842/#all.detailed">http://indico.cern.ch/event/517784/sessions/223842/#all.detailed</a></td>
</tr>
<tr>
<td>4</td>
<td><a href="http://arxiv.org/abs/1507.00966">http://arxiv.org/abs/1507.00966</a></td>
</tr>
<tr>
<td>5</td>
<td><a href="http://arxiv.org/abs/1609.09079">http://arxiv.org/abs/1609.09079</a></td>
</tr>
<tr>
<td>8</td>
<td><a href="http://arxiv.org/abs/1703.016511">http://arxiv.org/abs/1703.016511</a></td>
</tr>
<tr>
<td>9, 17, 37</td>
<td><a href="http://cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_DarkMatter_Summary">http://cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_DarkMatter_Summary</a></td>
</tr>
<tr>
<td>10</td>
<td><a href="http://arxiv.org/abs/1703.016511">http://arxiv.org/abs/1703.016511</a></td>
</tr>
<tr>
<td>12</td>
<td><a href="http://arxiv.org/abs/1704.03848">http://arxiv.org/abs/1704.03848</a></td>
</tr>
<tr>
<td>14</td>
<td><a href="http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-21/">http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-21/</a></td>
</tr>
<tr>
<td>15</td>
<td><a href="http://cds.cern.ch/record/2203615">http://cds.cern.ch/record/2203615</a></td>
</tr>
<tr>
<td>Extra</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td><a href="http://dx.doi.org/10.1007/JHEP01(2015)037">http://dx.doi.org/10.1007/JHEP01(2015)037</a></td>
</tr>
<tr>
<td>27</td>
<td><a href="http://arxiv.org/abs/1704.03848">http://arxiv.org/abs/1704.03848</a></td>
</tr>
<tr>
<td>29</td>
<td><a href="http://cds.cern.ch/record/2208044">http://cds.cern.ch/record/2208044</a></td>
</tr>
<tr>
<td>30</td>
<td><a href="http://dx.doi.org/10.1140/epjc/s10052-014-2980-6">http://dx.doi.org/10.1140/epjc/s10052-014-2980-6</a> [ <a href="http://arxiv.org/abs/1404.1344">http://arxiv.org/abs/1404.1344</a> ]</td>
</tr>
<tr>
<td>31</td>
<td><a href="http://arxiv.org/abs/1603.07739">http://arxiv.org/abs/1603.07739</a></td>
</tr>
<tr>
<td>32</td>
<td><a href="http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-21/">http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-21/</a></td>
</tr>
<tr>
<td>33</td>
<td><a href="http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-32/">http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-32/</a></td>
</tr>
<tr>
<td>34</td>
<td><a href="http://arxiv.org/abs/1703.01651">http://arxiv.org/abs/1703.01651</a></td>
</tr>
<tr>
<td>35</td>
<td><a href="http://arxiv.org/abs/1702.07666">http://arxiv.org/abs/1702.07666</a></td>
</tr>
<tr>
<td>36</td>
<td><a href="http://indico.cern.ch/event/623880">http://indico.cern.ch/event/623880</a> contribution from C. Doglioni</td>
</tr>
<tr>
<td>39</td>
<td><a href="http://cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO">http://cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO</a></td>
</tr>
<tr>
<td>40</td>
<td><a href="http://cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults">http://cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults</a></td>
</tr>
</tbody>
</table>
m_{DM} reach TeV at HL-LHC

Non-LHC: LUX '13, LZ 10 ton yr

Buchmueller, Dolan, Malik, et al., JHEP 01 (2015) 037

Axial vector
Projected 90% CL limits
\( g_q = g_{DM} = 1 \)

Complementarity continues
Improved understanding of the dark matter sector

Effective field theory

Simplified models

\[ \frac{g_{\text{init}} \cdot g_{\text{final}}}{(m_{\text{mediator}})^2} \]

dark matter

dark matter mediator

Improved understanding of the dark matter sector
Dark matter + mono-photon

**Search** $pp \rightarrow \chi \bar{\chi} + \gamma$

- "$\chi$" = $\gamma$ for recoil
- Irreducible $Z_{\gamma\gamma} \leftrightarrow M_{\chi \bar{\chi}}$
- Estimate using $Z_{ll}$

**Experimental**

- $O(100)$ events will improve with data
- $\gamma$ trigger > 140 GeV

**MET distribution:** signal enhanced, $\mu\mu$ control.

(top) $m_{\chi}/m_{med} = 10/700$ GeV

(bottom) $E_{T}^{miss}$ [GeV]
Mediator via di-jet

Last year’s result (with blip) for pedagogy

\[ m_{\text{jet-jet}} \]

Little blip

Limit

Exclusion excludes blip

Assumptions on 2 params.
Many direct detection results

LHC measurement

\[ \sigma \sim \Gamma_{\text{inv}} \cdot \begin{cases} \langle m_\chi \rangle^2 \\ \langle m_\chi \rangle^0 \\ \langle m_\chi \rangle^{-2} \end{cases} \]

DM interpretation

DM model
9 Dark matter interactions

We now interpret the experimental upper limit on $B(H \rightarrow \text{inv})$, under the assumption of SM production cross section, in the context of a Higgs-portal model of DM interactions [7–9]. In these models, a hidden sector can provide viable stable DM particles with direct renormalizable couplings to the Higgs sector of the SM. In direct detection experiments, the elastic interaction between DM and nuclei exchanged through the Higgs boson results in nuclear recoil which can be reinterpreted in terms of DM mass, $M_X$, and DM-nucleon cross section. If the DM candidate has a mass below $m_H/2$, the invisible Higgs boson decay width, $\Gamma_{\text{inv}}$, can be directly translated to the spin-independent DM-nucleon elastic cross section, as follows for scalar (S), vector (V), and fermionic (f) DM, respectively [8]:

$$\sigma_{\text{SI}}^{\text{S-N}} = \frac{4\Gamma_{\text{inv}}}{m_H^2 v^2 \beta (M_X + m_N)^2} \frac{m_N^4 f_N^2}{m_H^4},$$  \hspace{1cm} (8)$$

$$\sigma_{\text{SI}}^{\text{V-N}} = \frac{16\Gamma_{\text{inv}} M_X^4}{m_H^2 v^2 \beta (m_H^4 - 4M_X^2 m_H^2 + 12M_X^4)} \frac{m_N^4 f_N^2}{(M_X + m_N)^2},$$  \hspace{1cm} (9)$$

$$\sigma_{\text{SI}}^{\text{f-N}} = \frac{8\Gamma_{\text{inv}} M_X^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(M_X + m_N)^2}.$$  \hspace{1cm} (10)$$

Here, $m_N$ represents the nucleon mass, taken as the average of proton and neutron masses, 0.939 GeV, while $\sqrt{2}v$ is the Higgs vacuum expectation value of 246 GeV, and $\beta = \sqrt{1 - 4M_X^2/m_H^2}$. The dimensionless quantity $f_N$ [8] parameterizes the Higgs-nucleon coupling; we take the central values of $f_N = 0.326$ from a lattice calculation [69], while we use results from the MILC Collaboration [70] for the minimum (0.260) and maximum (0.629) values. We convert the invisible branching fraction to the invisible width using $B(H \rightarrow \text{inv}) = \Gamma_{\text{inv}}/(\Gamma_{\text{SM}} + \Gamma_{\text{inv}})$, where $\Gamma_{\text{SM}} = 4.07$ MeV.
Luminosity projections

CMS Run-2 VBF results with 2.3 fb⁻¹
- Limit 69% (62%)
- Z norm’d w/ W

ATLAS Run-1 VBF
- Limit 28% (31%)
- Z norm’d w/ W

Run 2 target
Run 3+ target

Need 10 fb⁻¹ of 13 TeV reach Run 1
We’ll try for < 20% in Run 2
Maybe possible? < 10% in Run 3
Di-jet (no MET!)

Jet
3.8 TeV

Jet
3.8 TeV

From Mar. 26, 2017,
http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-21/

m_{jet-jet} = 8.1 TeV
highest recorded

Run: 305777
Event: 4144227629
2016-08-08 08:51:15

ATLAS EXPERIMENT
MET + photon

MET 268 GeV

Photon 265 GeV


Run Number: 305811, Event Number: 1150484630
Date: 2016-08-08 22:56:19 CEST
Mono-jet CMS version of p11

Exclude in \((\sigma_{\text{DM-proton}} \text{ v. } m_{\text{DM}})\) 2d plane

- \(\sigma\) is function of \(m_{\text{med}}\), see right

mediator is off-shell, \(\sigma\) on-shell

\[
\sigma_{\text{SD DM-p}} \sim \left( \frac{g_q \cdot g_{\text{DM}}}{m_{\text{DM-p}} / (m_{\text{med}})^2} \right)^2
\]

Fix

Scan

cross-section v. DM

mediator v. DM

To \(m_{\text{med}} = 1.7\) TeV

LHC sensitive

overlap

non-LHC

Mar. 2017

[1703.01651]
FIG. 5. PICO-60 constraints (blue) on the mediator coupling to dark matter (purple) [9], and PICO-60 constraints (thick blue) [10].

FIG. 6. Exclusion limits at 95% C.L. in the $m_{\text{med}} - m_{\text{DM}}$ 2d plane. PICO-60 constraints (thick blue) are compared against collider constraints from CMS for an axial-vector mediator using the monojet/mono-V (red) [32] and mono-photon (orange) [33] channels. A similar analysis by ATLAS can be found in [52].
Illustartive examples
Results depending on coupling assumptions

Axial Vector mediator, Dirac DM
(g_q = 0.25, g_{DM} = 1)

 Axial Vector mediator, Dirac DM
(g_q = 0.1, g_{DM} = 1, g_{lep} = 0.01)

 Axial Vector mediator, Dirac DM
(g_q = 0.1, g_{DM} = 1, g_{lep} = 0.01)

Legends
- Searches for DM particles
- Dijet searches for DM mediators
- Low-mass dijet searches for DM mediators
- Dilepton searches for DM mediators

Dark matter particle mass [TeV]
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4 3.6 3.8 4.0 4.2 4.4 4.6 4.8 5.0 5.2 5.4 5.6 5.8 6.0 6.2 6.4 6.6 6.8 7.0 7.2 7.4 7.6 7.8 8.0 8.2 8.4 8.6 8.8 9.0 9.2 9.4 9.6 9.8 10.0
Alternate $(g_{DM}, g_q, g_{lep})$ alters conclusions [also see p36]

Same plot as p17
- $(g_{DM} = 1, g_q = 1/4, g_{lep} = 0)$

Modify coupling assumptions
- Keep $g_{DM} = 1$, decr. $g_q = 1/10$, incr. $g_{lep} = 1/100$

Overlapping coverages important for robustness
Pile-up dependence of MET trigger

**ATLAS** Trigger Operations

Data 2016, $\sqrt{s} = 13$ TeV

- $E_T^{\text{miss}} (\text{mht}) > 110$ GeV
- $E_T^{\text{miss}} (\text{mht}) > 130$ GeV
- $E_T^{\text{miss}} (\text{pufit}) > 110$ GeV
- $E_T^{\text{miss}} (\text{mht}) > 110$ GeV and $E_T^{\text{miss}} (\text{cell}) > 70$ GeV

Average number of interactions per bunch crossing = Pile-up = $\langle \mu \rangle$

Trigger rate / bunch luminosity = Trigger cross section [nb]

NB.

- A flat line on the right plot = linear dependence for rate
- A non-flat line on the right plot = polynomial / exponential dependence for rate

Notice of new CMS results

Past week (http://cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO)

CMS PAS EXO-16-048  Search for new physics in final states with an energetic jet or a hadronically decaying W or Z boson using 35.9 fb⁻¹ of data at √s = 13 TeV

A search for dark matter and extra dimensions are presented using events containing an imbalance in transverse momentum and one or more energetic jets. The data of proton-proton collisions at the LHC were collected with the CMS detector, and correspond to an integrated luminosity of 35.9 fb⁻¹. Results are presented in terms of limits on the dark matter production in association with jets or vector bosons in a simplified models, nonthermal dark matter models, and fermion portal dark matter models. Results are also interpreted in terms of the decay of the standard model Higgs boson to invisible particles and as limits on the Planck scale in the ADD model with large extra spatial dimensions.

CMS PAS EXO-16-052  Search for dark matter, invisible Higgs boson decays, and large extra dimensions in the ll + E_{T}^{miss} final state using 2016 data

A search for new physics in events with a Z boson produced in association with large missing transverse momentum with the CMS experiment at the LHC is presented. The search is based on the 2016 data sample of proton-proton collisions at √s = 13 TeV corresponding to an integrated luminosity of 35.9 fb⁻¹. The results of this search are interpreted in terms of a simplified model of dark matter production with spin-0 or spin-1 mediators, a standard model Higgs boson decaying invisibly and produced in association with the Z boson, as well as a model with large extra spatial dimensions. For all models, no significant deviation from the background expectation is found, and limits are set with respect to relevant model parameters.

CMS PAS EXO-16-054  Search for dark matter produced in association with a Higgs boson decaying to two photons

A search for the associated production of dark matter with a Higgs boson which decays into two photons is presented. The search uses data from proton-proton collisions at a center-of-mass energy of 13 TeV, collected with the CMS detector at the LHC in 2016, corresponding to an integrated luminosity of 35.9 fb⁻¹. Results are interpreted in the context of two dark matter models: a two-Higgs-doublet-Z’ model where the Z’ decays to a pseudoscalar and a standard model-like Higgs Boson and a baryonic Z’ simplified model. The search is performed categorizing the events based on the amount of missing transverse momentum in order to also be sensitive to hypothetical signals with small amounts of missing transverse momentum. After the final selection, no significant evidence for dark matter particle production has been observed. Two-Higgs-doublet-Z’ signals with a pseudoscalar mass of 300 GeV are excluded at 95% of CL for Z’ masses below 900 GeV. Baryonic Z’ models with a dark matter mass of 1 GeV are excluded at 95% of CL for Z’ masses below 800 GeV.
Search for dark matter at \( \sqrt{s}=13 \text{ TeV} \) in final states containing an energetic photon and large missing transverse momentum with the ATLAS detector

Results of a search for physics beyond the Standard Model in events containing an energetic photon and large missing transverse momentum with the ATLAS detector at the Large Hadron Collider are reported. As the number of events observed in data, corresponding to an integrated luminosity of 36.1 fb\(^{-1}\) of proton-proton collisions at a centre-of-mass energy of 13 TeV, is in agreement with the Standard Model expectations, exclusion limits in models where dark-matter candidates are pair-produced are determined. For dark-matter production via an axial-vector or a vector mediator in the s-channel, this search excludes mediator masses below 750-1200 GeV for dark-matter candidate masses below 230-480 GeV at 95% confidence level, depending on the couplings. In an effective theory of dark-matter production, the limits restrict the value of the suppression scale M, to be above 790 GeV at 95% confidence level. A limit is also reported on the production of a high-mass scalar resonance by processes beyond the Standard Model, in which the resonance decays to Z\( \gamma \) and the Z boson subsequently decays into neutrinos.

Search for new high-mass phenomena in the dilepton final state using proton-proton collisions \( \sqrt{s}=13 \text{ TeV} \) with the ATLAS detector

A search is conducted for new resonant and non-resonant high-mass phenomena in dielectron and dimuon final states. The search uses 36.1 fb\(^{-1}\) of proton-proton collision data, collected at \( \sqrt{s}=13 \text{ TeV} \) by the ATLAS experiment at the LHC in 2015 and 2016. The dilepton invariant mass is used as the discriminating variable. No significant deviation from the Standard Model prediction is observed. Upper limits at 95% credibility level are set on the cross-section times branching ratio for resonances decaying to dileptons, which are converted into lower limits on the resonance mass, up to 4.1 TeV for the E6-motivated Z\( \gamma \)\( \chi \)\( \chi \). Lower limits on the \( \ell \ell qq \) contact interaction scale are set between 23.5 TeV and 40.1 TeV, depending on the model.

Search for Dark Matter Produced in Association with a Higgs Boson Decaying to b\( \bar{b} \) at \( \sqrt{s}=13 \text{ TeV} \) with the ATLAS detector

Several extensions of the Standard Model predict associated production of Dark Matter particles with a Higgs boson. Such processes are searched for in final states with missing transverse momentum and a Higgs boson decaying to a b\( \bar{b} \) pair with the ATLAS detector using 36.1 fb\(^{-1}\) of pp collisions at a center-of-mass energy of 13~TeV at the LHC. The observed data are in agreement with the Standard Model and limits are placed on the associated production of Dark Matter particles and a Higgs boson for a simplified Dark Matter model and without extra model assumptions.
Increase $pp$ luminosity
Why need pile-up

Why dislike pile-up
Experimental difficulty

$\sigma_{pp \rightarrow \text{inelastic}} = (\gg 10^{10}) \cdot \sigma_{pp \rightarrow \text{DM}}$

$\sigma_{pp \rightarrow \text{DM}} \cdot L = N_{pp \rightarrow \text{DM}}$

LHC timeline

Run-1
$\sqrt{s} = 8$ TeV


Long shutdown

Run-2
$\sqrt{s} = 13$ TeV

pile-up of 20±10
(Higgs found!)

15±3 25±10 50±10?
starts this month

DM Benchmark Models for Early LHC Run-2 Searches
Report of the ATLAS/CMS Dark Matter Forum
July 2015, revised Aug. 2016 [1507.00966]
I thank Philip for discussions on collider dark matter searches, dijet strengths and limitations, invisible Higgs, and general outlook.

I thank Javier for discussions on dijets in dark matter, data-scouting, and the implications of findings in DM exclusions.

I thank Sam for discussions on mono-x and Higgs-DM in extended theories, exotic Higgs, and boosted jets.

I thank Alex for discussions on quarkphobic / leptophillic DM models that evade previous results.

I thank Ben for discussions on invisible Higgs, MET triggers, and trigger rates.