DM@LHC2016: Workshop Impressions

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Introduction

M. Buckley

DARK MATTER

Optical Dark Matter X-ray Gas

Most of the universe can't even be bothered to interact with you.

M. Buckley

Andreas Korn

DM@LHC2016, 30th March
Introduction

What do we know?

- How much: $\Omega_{DM} \approx 0.26$
- Likely particle with non-gravitational interactions
- Dark:
  - Electrically neutral - probably
  - Colour neutral – (H-dibaryon...)
- Cold: nonrelativistic during structure formation
- Sufficiently long-lived
- Non-baryonic (from BBN – $\Omega_B \approx 0.04$)

Candidate within the Standard Model of particle physics?

- Neutrinos
  - Correspond to hot DM
  - Cannot account for the observed dark matter density

$$\sum \Omega_{\nu} h^2 \approx m_{\nu_i}/93\text{eV}$$

Physics beyond the Standard Model!

Many candidates (theorists are inventive...)
Introduction

Particle physics candidates

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Introduction

Freeze out - WIMPs

(1) Assume dark matter $X$ is initially in thermal equilibrium:

$$XX \leftrightarrow SM \; SM$$

(2) Universe cools:

$$XX \rightarrow SM \; SM$$

(3) Universe expands:

$$XX \rightarrow SM \; SM$$

The abundance is determined by the annihilation cross section!

Works just fine for weak scale masses and couplings → WIMP miracle

Unitarity bound: $m_{DM} \leq 100$ TeV
Introduction

- Dark Matter (DM) well established:
  - Galaxy rotation
  - CMB measurements

- Three detection methods
  - Direct
  - Indirect
  - Production in collisions → LHC

Direct detection
DM-nucleon scattering

Indirect detection
DM annihilation/decay

Collider Production
Indirect Detection: Challenges

Astrophysical backgrounds = Large Systematic Uncertainties

Challenging to model theoretically (e.g., cosmic ray diffusion)

New surprises as experimental sensitivities continue to improve (e.g., millisecond pulsars)

How will we ever know that we have discovered dark matter?

Signal detection in more than one target

Correlate gamma-ray signal with large-scale structure that traces the DM signal

ML, Mishra-Sharma, Rodd, Safdi [in progress]

Mariaangela Lisanti
InDirect Detection

GeV Photon Excess

Observed at the Galactic Center and Inner Galaxy (≤ 10°)

Constitutes ≈10% total flux

High statistical significance

Goodenough and Hooper [0910.2998]
Hooper and Goodenough [1010.2752]
Boyarsky, Malyshev, Ruchayskiy [1012.5839]
Hooper and Linden [1110.0006]
Abazajian and Kaplinghat [1207.6047]
Gordon and Macias [1306.5725]
Abazajian et al. [1402.4090]
Daylan et al. [1402.6703]
Calore, Cholis, and Weniger [1409.0042]
Fermi Collaboration [1511.02938]

Mariaangela Lisanti

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Introduction

direct detection

- vector(DM)-vector(SM)
  - stringent limits from spin-independent direct detection
  - best limit: $\mathcal{O}(10^{-45}\text{cm}^2)$ by LUX

- axial(DM)-axial(SM)
  - not quite so stringent limits from spin-dependent direct detection
  - best limit neutron $\mathcal{O}(10^{-40}\text{cm}^2)$ by LUX
  - best limit proton $\mathcal{O}(10^{-39}\text{cm}^2)$ by PICO

- vector(DM)-axial(SM)
  - $\sigma \propto v^2$ or $q^2$ and direct detection very suppressed
  - essentially no limit (see Del Nobile, Cirelli, Panci 1307.5955 for actual limit)

- axial(DM)-vector(SM)
  - $\sigma \propto v^2$ or $q^2$ and direct detection very suppressed
  - essentially no limit
Direct Detection

Phonons
- CRESST I
- CUORE
- TeO$_2$, Al$_2$O$_3$, LiF
- 10 meV/ph
- 100% energy

Ionization
- CDMs
- EDELWEISS
- Ge, Si
- ~ 10 eV/e
- 20% energy

Scintillation
- CLEAN
- DAMA
- DEAP
- NAIAD
- ZEPLIN I
- XMASS
- Xe, Ar, Ne

~ 1 keV/y
- few % energy

ArDM
- DarkSide
- LUX
- WARP
- XENON
- ZEPLIN II, III
- Xe, Ar, Ne

S1

S2

Drift time indicates depth

Time

E field

LUX

Image by C. Hanlon (Brown)

Julien Billard
Direct Detection: Direction!

Directional detection

*Directional detection aims at measuring both the recoil energy and direction using gas TPC*

Leading experiments are: DRIFT, DM-TPC, MIMAC and Newage

Great experimental challenges:

- Intrinsic angular resolution: ~20 degrees RMS
- Thresholds: 1 keV (energy), 10 keV (directional)
- Exposure: ~100 g (DRIFT)
- Target: Fluorine (excellent spin-dependent coupling)

- Thanks to the rotation of Solar System around Galactic Center, WIMPs are coming from Cygnus
- Solar neutrinos are coming from … the Sun

Julien Billard

Andreas Korn

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Direct Detection

The neutrino background

Julien Billard
Direct Detection

Julien Billard
DM at the LHC

1. Monojet
   - Strategy: reconstruction, analysis & interpretation

2. Other Mono-X
   - Mono-V/γ
   - Mono-H
   - DM+HF
   - H→inv

3. Alice+LHCb
   - Dark photons
   - Dark sectors

4. Cosmological constraints
   - For LHC & FCC

5. Resonances constraints
Gathering the community for a view of the landscape


Determined recommended benchmark models for LHC Run 2 searches: emphasis on mediators that could be produced and discovered in the next few years

Joint ATLAS/CMS/theory discussion forum

- Classify benchmark models (simplified models) according to final state signatures
- Propose a small set of simplified models for early Run-2 LHC searches
- Review tools and implementations, state-of-the-art calculations
- Maintain model repository

A. Boveia/S. Malik
LHC Dark Matter Working Group (2015–)

The LHC Dark Matter Working Group (LHC DM WG) brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC.

The LHC DM WG develops and maintains close connections with theorists and other experimental particle DM searches (e.g. Direct and Indirect Detection experiments) in order to help verify and constrain particle physics models of astrophysical excesses, to understand how collider searches and non-collider experiments complement one another, and to help build a comprehensive understanding of viable dark matter models.

Pilot effort: translation of LHC simplified model results into DM-nucleon cross-section plane (DD/ID)
Higgs → invisible

- This Higgs boson thing seems like it could be useful
  \[ pp \rightarrow (h^{(*)} \rightarrow \chi\chi) + X \]
- Or through extra Higgs(es) in non-minimal models
- Combined limit on \( \text{BR}(H_{125} \rightarrow \text{inv.}) \lesssim 0.25 \)

Brooke, Buckley, Dunne, Penning, Tamanas, Zgubic 1603.07739

M. Buckley/P.Dunn
More exotic searches

Displaced jets

- $H \rightarrow \pi_\nu(bb)\pi_\nu(bb)$
  - Hidden valley - long-lived particles
- **Low mass**
  - 25 GeV – 50 GeV
- **Displaced bb**
  - 0.4 mm – 4.8 mm

LHCb advantages

- **Triggers**: low-mass $p_T$
  - Upgrade: full software trigger
- **Vertex resolution**
  - Critical for displaced searches

LHCb: see Swagata Mukherjee for Atlas+CMS long lived


Tristan du Pree (CERN), DM@LHC (1 April 2016)
DM: Latest results in the mono-jet and di-jet channels

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Introduction

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  \( \rightarrow \) LHC
DM at LHC: Models

- Common: Effective Field Theory (EFT)
- Limited validity: $m_{\text{mediator}} >> E(\chi)$
- Integrate mediator out, Fermi constant $G_F$ like coupling:

$$G_{DM} = \frac{\sqrt{g_q g_{DM}}}{M_{\text{mediator}}} = \frac{1}{(M_*)^n}$$

- Now mostly superseded
DM at LHC: Models

- Move towards simplified models
- → recommendations from DM@LHC14 (arXiv:hep-ph/1506.03116)
- Parameters: $m_{DM}$, $m_{\text{mediator}}$, $g_{DM}$, $g_{q}$
- Benchmark models
- $m_{DM}$ vs $m_{\text{mediator}}$ plane, couplings
- Vector: $g_{DM} = 1$; $g_{q} = 0.25$
- Axial-Vector: $g_{DM} = 1$; $g_{q} = 0.25$
- Scalar: $g_{DM} = 1$; $g_{q} = 1$
- Pseudo-Scalar: $g_{DM} = 1$; $g_{q} = 1$

$$\mathcal{L}_{\text{vector}} = g_{q} \sum_{q=u,d,s,c,b,t} Z'_{\mu} \bar{q} \gamma^{\mu} q + g_{\chi} Z'_{\mu} \bar{\chi} \gamma^{\mu} \chi$$

$$\mathcal{L}_{\text{axial-vector}} = g_{q} \sum_{q=u,d,s,c,b,t} Z'_{\mu} \bar{q} \gamma^{\mu} \gamma^{5} q + g_{\chi} Z'_{\mu} \bar{\chi} \gamma^{\mu} \gamma^{5} \chi.$$
DM at LHC

- DM $\chi$ couples loosely to SM particles (quarks $q$) through a mediator
  $\rightarrow$ mediator couples to DM $\chi$ with $g_{DM}$ and to SM quark with $g_q$
- Can't reconstruct DM in detector
  $\rightarrow$ need accompanying signature
- Mediator can decay into quark (jet) pairs

- Mono-jets
- Di-jets

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DM@LHC2016, 30th March
DM at LHC

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\[ 2^*m = m \]

\[ m = m_{\chi\chi} = m_{\chi DM} = m_{\chi q} \]

\[ \chi \]

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Other DM signals at the LHC

- Can't reconstruct DM in detector
  → missing momentum → need accompanying signature
- Differentiate channels by accompanying signature

\[ H \rightarrow jj + \text{MET} \]
\[ Z \rightarrow jj + \text{MET} \]
\[ W \rightarrow jj + \text{MET} \quad \rightarrow \text{see Kenji Hamano's talk} \]

SUSY DM candidates → see George Redlingers talk
Missing transverse Energy MET

Plane transverse to the beam direction

Visible particles

MET
Missing transverse Energy MET

Plane transverse to the beam direction

Visible particles

MET
Mono-Jet

CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 20:41:32 2012 CEST
Run/Event: 204553 / 26729384
Lumi section: 31

Mono-jet +MET

Jet 0,
et = 921.98
eta = -0.463
phi = 2.508

MET 0,
pt = 913.68
eta = 0.000
phi = -0.657
Mono-Jet: Backgrounds

- MET hard to model
- Estimate/measure invisible decays ($\nu$'s)
- use $Z \rightarrow ll$ & $W \rightarrow l\nu$
- Detector effects & non-collision bkgs are very important too!
- Distributions rather well described

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, $3.2$ fb$^{-1}$

Signal Region

$p_T^{jet} > 250$ GeV, $E_T^{miss} > 250$ GeV

Data 2015

- Standard Model
- $Z \rightarrow \nu\nu +$ jets
- $W \rightarrow l\nu +$ jets
- $W \rightarrow \nu\nu +$ jets
- $W \rightarrow l\nu +$ jets
- Dibosons
- $Z \rightarrow \nu\nu +$ single top

CMS

Data

- $Z\nu\nu+$jets
- $W\nu\nu+$jets
- $W\nu\nu+$jets
- Single $t$
- QCD Multijets
- Dibosons

$Z\nu\nu+$jets

$E_T^{miss} > 100$ GeV

Before cleaning
Mono-Jet

- Vector mediator: $g_{DM} = g_{SM} = 1$
- Selection:
  - Leading jet: $p_T > 100$ GeV; $|\eta| < 2.5$
  - $E_T^{miss} > 200$ GeV, Input Jets: $|\eta| < 5$

CMS PAS EXO-15-003

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Mono-Jet

- Axial Vector Mediator: $g_{\text{DM}} = 1$, $g_{\text{SM}} = 0.25$
- Selection
  - Leading jet: $p_T > 250$ GeV; $|\eta| < 2.8$
  - $E^{\text{miss}}_T > 250$ GeV, Input Jets: $p_T > 20$ GeV; $|\eta| < 4.9$

EXOT-2015-03
Comparison with Direct Detection

- Translate into DM-nucleon cross sections
- Spin dependent (SD) or independent (SI) according to mediator model used
- Note: Comparisons model dependent!
- LHC experiments provide complementary coverage!
DiJet Events
Look for resonant qq, gq and gg states
Benchmark search for new physics
Construct dijet mass
Fit smooth spectrum
Look for deviations
→ Bumphunter
→ Tailhunter
Limits on acceptance times x-section and specific models
Dijet resonances

- Selection
  - $p_T > 440$ GeV
  - $|y^*| = \frac{1}{2} |y_1 - y_2| < 0.6$
- Background from fit
- BumpHunter indicates most discrepant interval (not so exciting at all)

ATLAS

\[ s = 13 \text{ TeV}, \ 3.6 \text{ fb}^{-1} \]
- Data
- Background fit
- BumpHunter interval
- $q^*, m_{q^*} = 4.0$ TeV
- $q^*, m_{q^*} = 5.0$ TeV

$q^*, \sigma \times 3$
$p$-value $= 0.67$
Fit Range: 1.1 - 7.1 TeV
$|y^*| < 0.6$

http://dx.doi.org/10.1016/j.physletb.2016.01.032
 Limits on Dijet resonances

- Limits on benchmark models
  - Excited quarks q* (5.2 TeV)
  - Extra Gauge Bosons
    - Z'-Boson
    - W'-Boson (2.6 TeV)
- Quantum Black Holes (QBH)
  - Randall-Sundrum
  - QBH generator (5.3 TeV)
  - Arkani-Hamed-Dimopoulous-Dvali
    - QBH generator (8.3 TeV)
  - BlackMax generator (8.1 TeV)

http://dx.doi.org/10.1016/j.physletb.2016.01.032
Limits on Dijet resonances

- Limits on benchmark models
  - Extra Gauge Z'-Boson
  - Leptophobic model
  - Provides dark matter mediator candidate
- Limits on coupling $g_q$ for different $Z'$ masses

http://dx.doi.org/10.1016/j.physletb.2016.01.032
Limits on Dijet resonances

- Limits on Gaussian contributions to observed cross section
- Model independent approach
- Narrow width approximation
- Apply selection
  - leading jet $p_T > 440$ GeV
  - $|y^*| < 0.6$
- Truncate signal to approximate Gaussian core
  → useful to translate limit to other models not considered

http://dx.doi.org/10.1016/j.physletb.2016.01.032
Limits on Dijet resonances

Excluded masses: String resonance (7.0 TeV), scalar di-quark (6.0 TeV), axigluon (5.1 TeV), excited quark q* (5.0 TeV), Heavy W' (2.6 TeV)
Dijet Events at low mass

- At low mass → low jet $p_T$ threshold
- Data rate too high to write out

→ **Online data scouting**

**Trigger Level Analysis**

---

**Figure:**

- CMS Preliminary
- ATLAS Preliminary

- $\sqrt{s} = 13$ TeV, 6.25 pb$^{-1}$
- 2015 Data: Single Run
Di-beauty-Jets

- Third Generation (top & bottom) heavy, might be special → investigate couplings to b
- Needs identification of jets containing bottom hadrons → b-tagging
- Depending on decay (bb, bq, bg) → at least 1 or 2 b-tags
  - Possible qg background reduction also for X → qq modes
**Di-beauty-Jets**

- Same selection as dijets ($p_T > 440$ GeV, $|y^*| = \frac{1}{2} |y_1 - y_2| < 0.6$)
- Limit $|\eta| < 2.5$, to tracking coverage for b-tagging

---

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Di-beauty-Jets

- **Limits on benchmark models**
- **Excited quarks** $b^* \rightarrow bg$
  - $\geq 1$ b-tag
  - Excluded masses 1.1-2.1 TeV
- **Extra Gauge Bosons** $Z'$
  - 2 b-tag
  - Leptophobic $Z'$
  - Excluded masses 1.1-1.5 TeV
- **Sequential Standard Model (SSM) $\rightarrow$ SM couplings**
  - Not enough data to exclude Sequential SM $Z'$

---

arXiv:1603.08791v1 [hep-ex]
Di-b-Jets: what about 750 GeV?

- Needs different trigger strategy
- Di-b-jet trigger $p_T > 175$ GeV & $p_T > 60$ GeV
- Limits on benchmark model Extra Gauge Bosons $Z'$
  - Sequential Standard Model (SSM) → SM couplings
  - Exclude 0.3-0.02 pb in the mass range 0.65-1.15 TeV

ATLAS-CONF-2016-031
Summary

DM Simplified Model Exclusions  
ATLAS Preliminary  
March 2016

Axial-vector mediator, Dirac DM  
\( g_q = 0.25, \ g_{DM} = 1 \)

Mono-\( \gamma \) 13 TeV  
Mono-jet 13 TeV

Dijet 8 TeV

Dijet 13 TeV

\( \Omega_c h^2 < 0.12 \)  
\( 2 \times \text{DM Mass} = \text{Mediator Mass} \)  
 Thermal relic \( \Omega_c h^2 = 0.12 \)

Mediator Mass [TeV]

DM Mass [TeV]
Putting it together: Global Fits!

Evidence from Astroparticle physics
- Dark Matter
- Assumptions

Theoretical connections
- Supersymmetry
- Extra Dimensions
- …, ??

Consequences for LHC
- LHC phenomenology
- Model testing

S. Caron
Putting it together: Global Fits!

GAMBIT: a second-generation global fit code

GAMBIT: The Global And Modular BSM Inference Tool

Overrinding principles of GAMBIT: flexibility and modularity

- General enough to allow fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just small modifications to constrained MSSM (NUHM, etc), and not just SUSY!
- Extensive observable/data libraries (likelihood modules)
- Many statistical options – Bayesian/frequentist, likelihood definitions, scanning algorithms
- A smart and fast LHC likelihood calculator
- Massively parallel
- Full open-source code release

Pat Scott
The Future of Simplified Models

Tables, tables, tables

<table>
<thead>
<tr>
<th>ID</th>
<th>X</th>
<th>$\alpha + \beta$</th>
<th>$M_s$</th>
<th>Spin</th>
<th>$(SM_1, SM_2)$</th>
<th>$X-DM-SM_3$</th>
<th>$M_s-X-X$</th>
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<tr>
<td>SU1</td>
<td>$(1, 1, 0)$</td>
<td>$0$</td>
<td>B</td>
<td>$(u_R \bar{u}_R, (d_R \bar{d}_R, (\ell_R \bar{\ell}_R))$</td>
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<td>SU2</td>
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<td>$(1, 3, 0)^{N \geq 2}$</td>
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<td>$(1, -3)$</td>
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<td>$(L_L \bar{H})$</td>
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<td>B</td>
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<td></td>
<td>✓</td>
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</tr>
</tbody>
</table>

Tally

In total 161 simplified models (defined by representations of DM, X and M)

49 s-channel, 105 t-channel, 7 hybrid

DM in $(1, N, \beta)$ representation of $SU(3) \times SU(2) \times U(1)$

X coannihilation partner

$M_s$ s-channel mediator

$SM_1, SM_2$ SM particles in coannihilation $DM + X \rightarrow SM_1 SM_2$

$SM_3$ Possible additional vertex $DM-X-SM_3$
Conclusion

- The hunt for Dark Matter continues
- Very nice and constructive workshop https://indico.cern.ch/event/342623
- ATLAS and CMS have new interesting results
- Just the beginning of 13 TeV running ...
- LHC searches complementary to direct searches
- Jet channels are particularly sensitive
- Search for both DM and mediator candidates
- Model dependence in Interpretation
  - LHCDMWG Recommendations should unify approaches and help comparisons
- Hope presenting hard work on LHC measurements has the right consequences ....
Consequences

Andreas Korn: "Ways to find dark matter: make it, break it, or shake it."
(colliders, indirect detection, direct detection)
#DMatLHC
Bonus Slides
ATLAS: a particle detector at the LHC

- **Inner tracker**
  - 2T solenoid
  - $|\eta|<2.5$
  - Silicon pixel
  - Silicon strips
  - straw tracker
- **Muon system**
  - 0.5-2T toroid
  - $|\eta|<2.7$
  - Precision & trigger chambers

- $\sigma_{Pt}/Pt \sim 0.05\% Pt[GeV] \oplus 1.5\%$
- $\sim 10 \mu m$ impact parameter resolution

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The narrow-width approximation

width, even for resonances normally considered narrow. The extreme end of this tail due to the PDFs is sometimes suppressed in the searches by requiring the partons to be have mass close to the pole mass, within a few standard deviations on the dijet mass resolution. This is generally a reasonable solution for the shapes, as the QCD background overwhelms the signal at low dijet mass. However, the way that this tail from PDFs is handled can significantly affect the total resonance cross section quoted for specific models, as we discuss in Appendix A.

Narrow width approximation:

- Approximate the true resonance shape with a delta function
- This avoids low-mass tails as PDFs will act only in the surrounding of the peak

$$\sigma_{had}(m_R) = 16\pi^2 \times N \times A_{\cos \theta^*} \times BR \times \left[ \frac{1}{s} \frac{dL(\bar{y}_{\text{min}}, \bar{y}_{\text{max}})}{d\tau} \right]_{\tau = m_R^2/s} \times \frac{\Gamma_R}{m_R}, \quad (44)$$

where the parton luminosity $\frac{dL}{d\tau}$ is calculated at $\tau = m_R^2/s$, and constrained in the inelastic range $[\bar{y}_{\text{min}}, \bar{y}_{\text{max}}]$. 

Searches for Dijet Resonances at Hadron Colliders
Robert M. Harris, Konstantinos Kousouris
arXiv:1110.5302
Rapidity distribution, Selection

- $|y^*| < 1.7$, $|y_B| < 1.1$, implied: $|y_{1,2}| < 2.8$, $p_T > 80$ GeV

boost $y_B = 0.5*(y_1 + y_2) = 0.5\ln(x_1/x_2)$
Beauty-jets and missing $E_T$
Direct Detection
Mono-Jet

ATLAS, $\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$

relic abundance

$M_{\text{med}}$ [TeV]

$10^{-1}$

$10^{-2}$

$m_\chi$ [GeV]

$10^{-1}$

$10^{2}$

$10^{3}$

$10^{4}$

$10^{5}$

$10^{6}$

95% CL upper limit on $\sqrt{g_{\chi q}}$

DOI 10.1140/epjc/s10052-015-3517-3

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Mono-Jet

![Graph showing WIMP-nucleon cross section vs. WIMP mass](image_url)
Mono-Jet

ATLAS

WIMP-nucleon cross section [cm²]

90% CL

1s=8 TeV, 20.3 fb⁻¹

- DAMA/LIBRA, 3σ
- CRESST II, 2σ
- CoGeNT, 99% CL
- CDMS, 1σ
- CDMS, 2σ
- CDMS, low mass
- LUX 2013 90% CL
- Xenon100 90% CL
- CMS 8TeV D5
- CMS 8TeV D11

WIMP mass m_χ [GeV]

- truncated, coupling = 1
- truncated, max coupling

- spin-independent

ATLAS

WIMP-nucleon cross section [cm²]

90% CL

1s=8 TeV, 20.3 fb⁻¹

- COUPP 90% CL
- SIMPLE 90% CL
- PICASSO 90% CL
- Super-K 90% CL
- IceCube W⁺W⁻ 90% CL
- CMS 8TeV D8

WIMP mass m_χ [GeV]

- truncated, coupling = 1
- truncated, max coupling

- spin-dependent

DOI 10.1140/epjc/s10052-015-3517-3
Mono-Jet

DOI 10.1140/epjc/s10052-015-3451-4
- Gaussian limits: model independent approach
Di-Jet

http://dx.doi.org/10.1016/j.physletb.2016.01.032