Searching for Dark Matter and Dark Sectors at the LHC

Spåtind, Skeikampen, Jan 2-7, 2018

Christian Ohm

Intentions

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- Show the breadth of program at the LHC looking for DM
- Try to give everyone something:
  - Half of you work on the LHC
  - Half of you **do not**
- Focus on more recent results

Intentions and disclaimers

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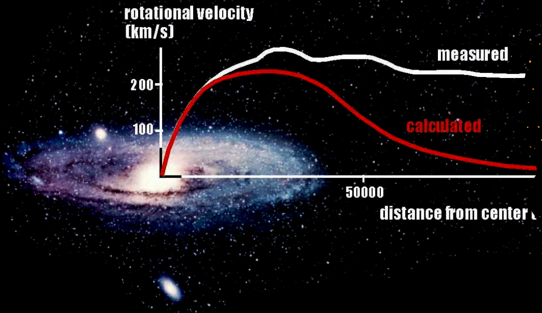
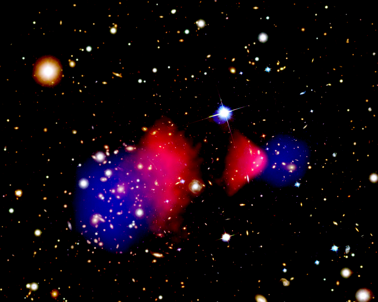
Disclaimers:

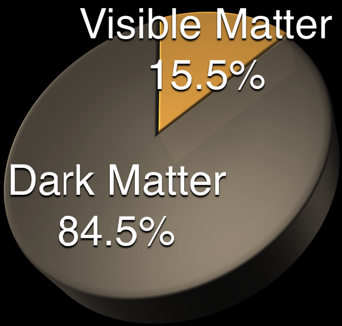
- With a very wide DM program, it is impossible to cover all searches in 45 minutes
- I will not have time to go into much detail, links to full papers/notes throughout!
- The two LHC experiments with the biggest DM programs are ATLAS and CMS, and they're quite similar $\Rightarrow$ strong bias towards ATLAS in results shown (sorry, Finland. . .)





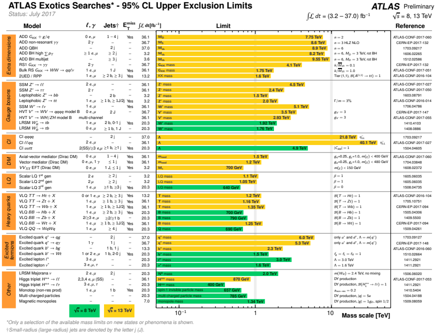
Bullet Cluster (astro-ph/0608407)

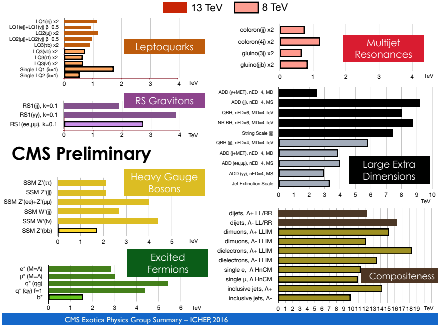
- Strong evidence for Dark Matter from astronomy and observational cosmology
- What is it made up of?
  We don't know.
- Can we produce it at the LHC?

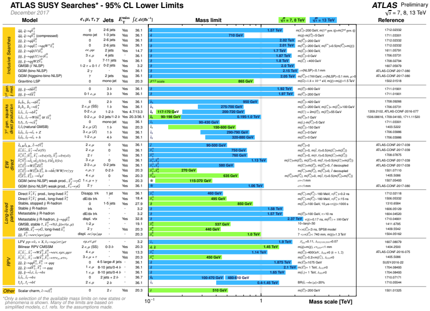


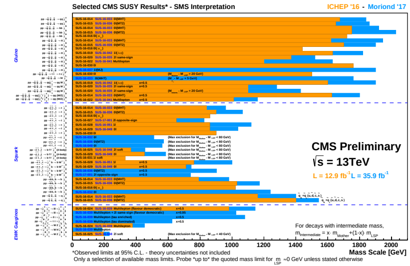
(Planck: 1502.01589)

BSM results from ATLAS and CMS - *many* DM related!



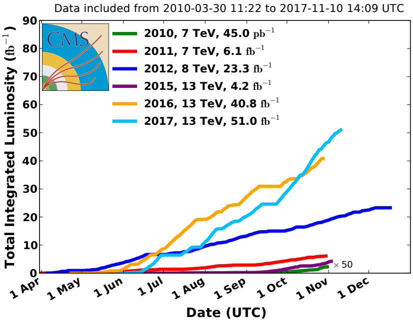


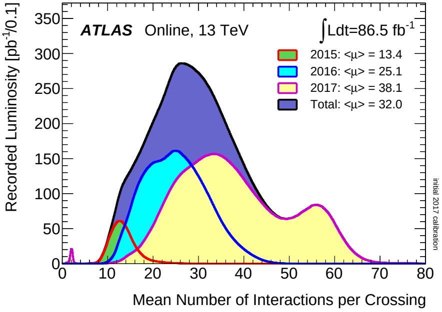




ATLAS Run II 13 TeV dataset

The LHC has performed extremely well in Run II,
2017 was certainly no exception!





All results shown today use at most $\int \mathcal{L}\, dt = 36\ \text{fb}^{-1}$

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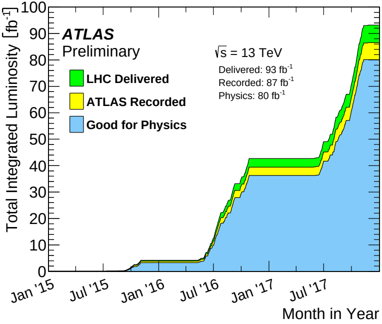

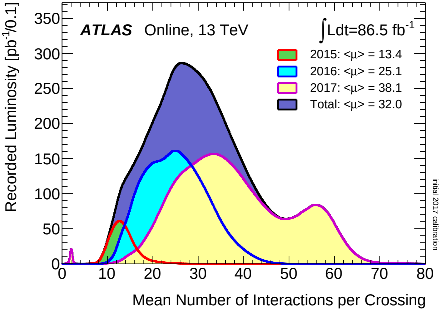

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Assumptions we make about the Dark Matter

WIMP:

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- Weakly interacting (WI)

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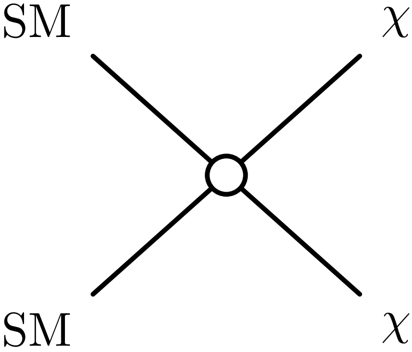
If not interacting via weak force, it needs to have some small ("feeble") coupling to be produced at the LHC

SM-DM interactions



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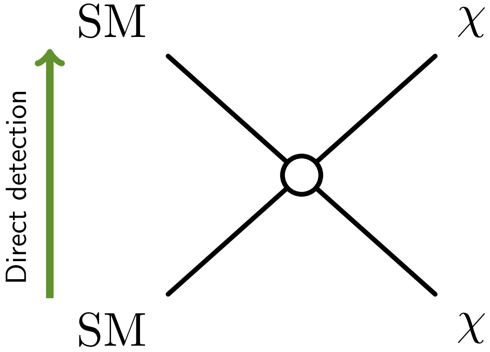

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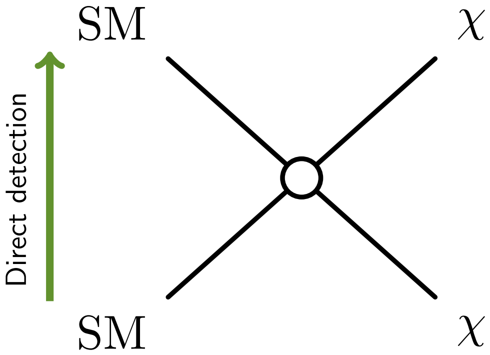
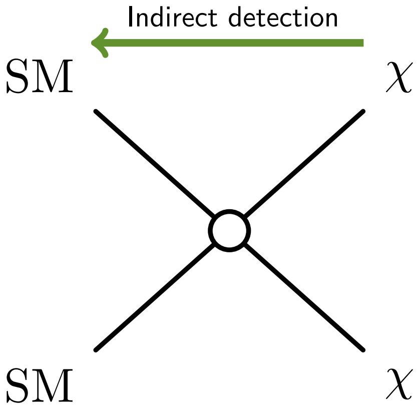


What Jan just told us about!

SM-DM interactions



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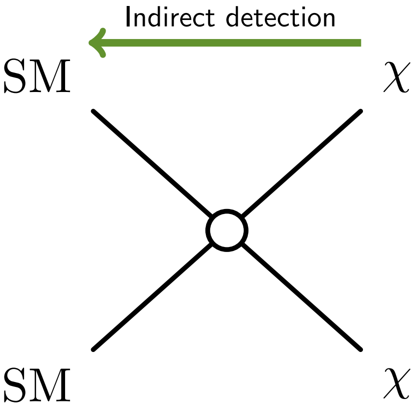
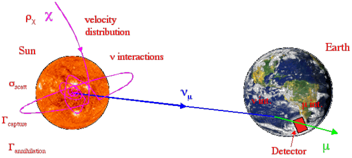
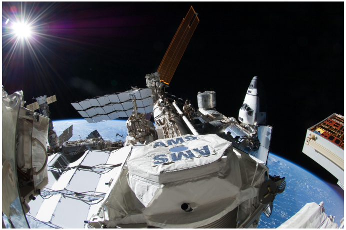
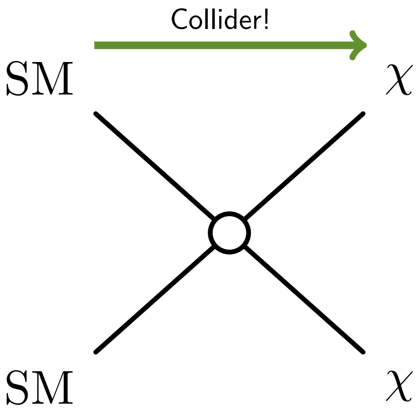






E.g. IceCube, AMS, Fermi LAT, . . .

SM-DM interactions



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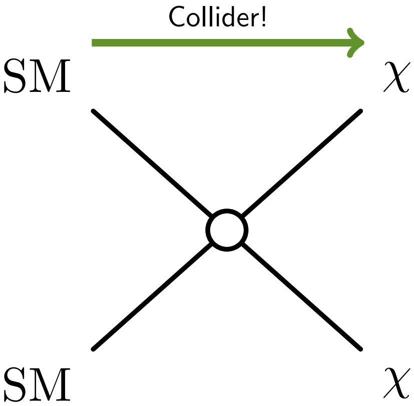
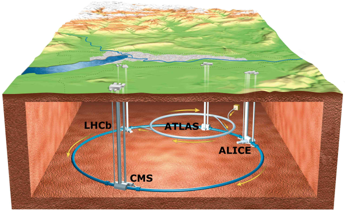
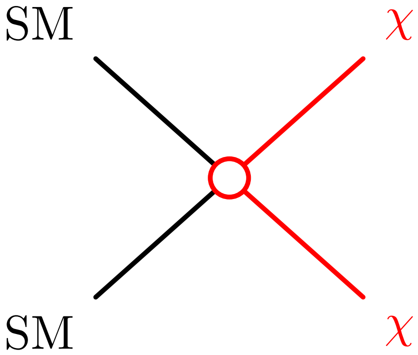




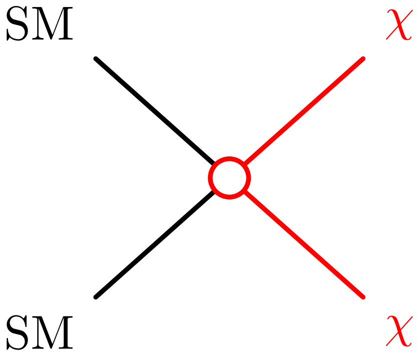
Produce our own DM!

SM-DM interactions



Beyond-SM physics

SM-DM interactions

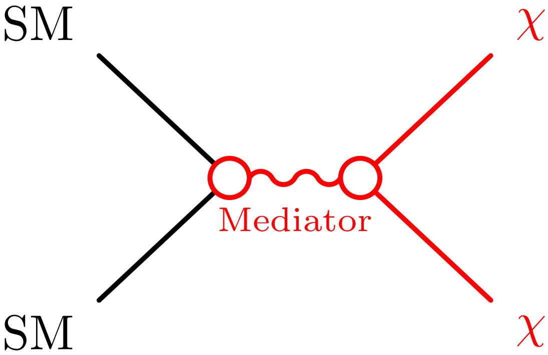


Beyond-SM physics

Easiest implementation: EFT "blob"

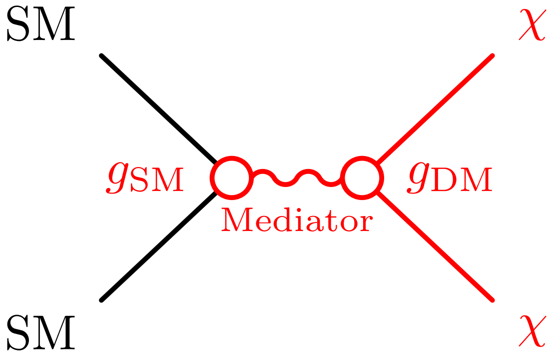
Valid for $q^2 << \mu_{\mathrm{cutoff}} \Rightarrow$ problematic in Run 2

SM-DM interactions



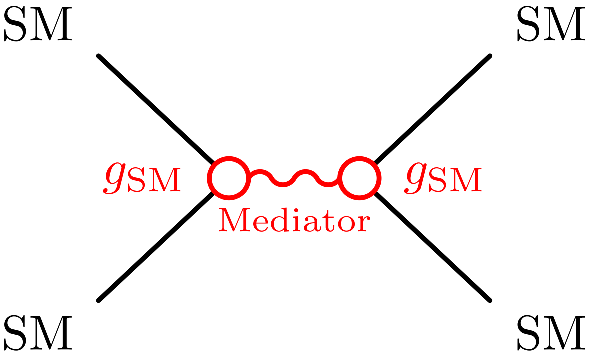
Simplified model with mediator

SM-DM interactions



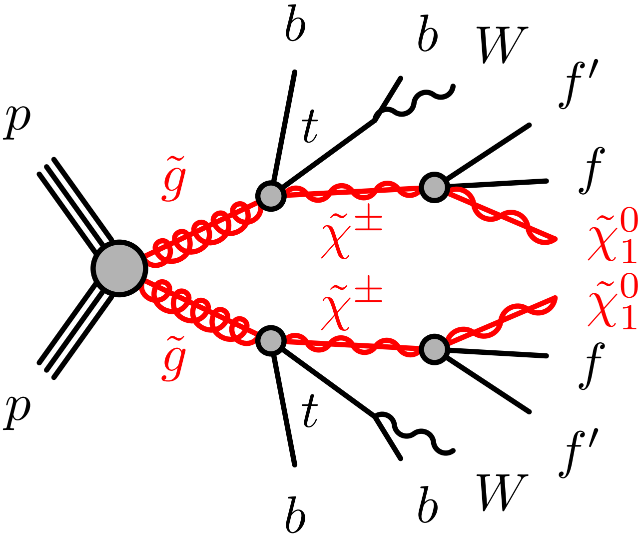
Simplified model with mediator
Parameters: two couplings, two masses

SM-DM interactions



Look for decay of mediator back to SM

SM-DM interactions



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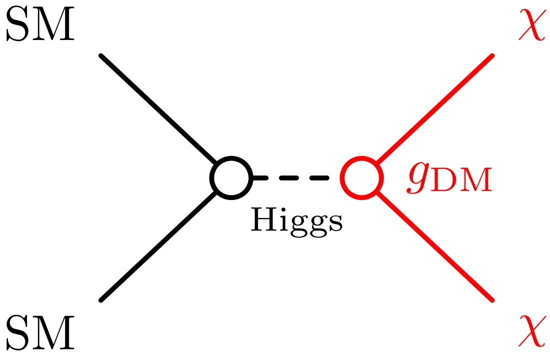
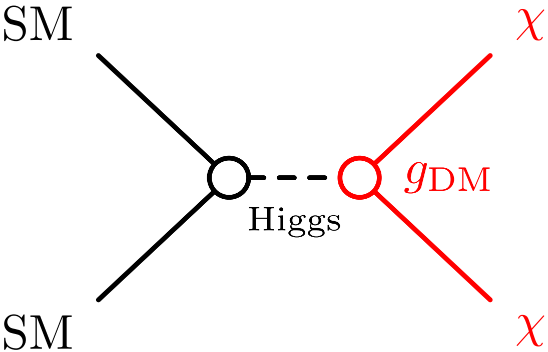


Invisible decay of $H(125)$

SM-DM interactions

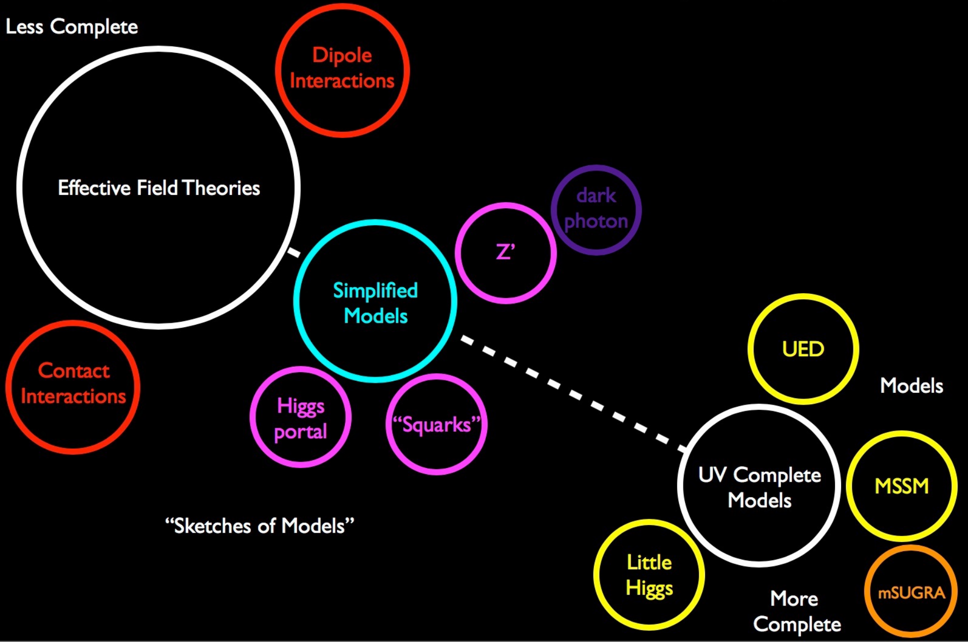


Invisible decay of $H(125)$

CMS: BR($H\rightarrow$inv) $< 24\%$, 1610.09218

Spectrum of Theory Space

Tim M.P. Tait



10 s description of most relevant simplified DM models

DM particle:

- Dirac Fermion DM

Mediator particle options:

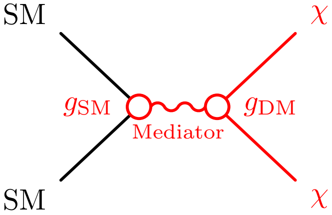
- Spin-1: vector or axial-vector
- Spin-0: scalar or pseudo-scalar

$\Rightarrow$ Four parameters + mediator:
$m_\chi,\ m_{\text{med.}},\ g_{\text{SM}},\ g_{\text{DM}}$

(See 1507.00966 for details)

$E_T^{miss} + X$ searches

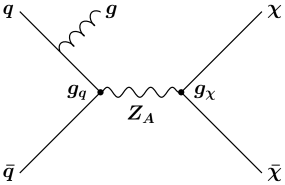
Target: DM production via mediator



How to measure the invisible

- DM particles weakly interacting
  $\Rightarrow$ not detected!

  If recoiling against visible system
  $\Rightarrow E_{\mathrm{T}}^{\mathrm{miss}}$, need additional radiation (ISR)
- Most ISR from strong radiation at hadron collider, only "pay" α_s



Missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$:

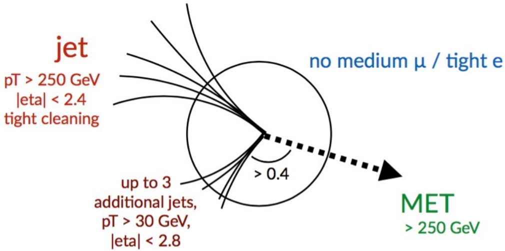
$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$

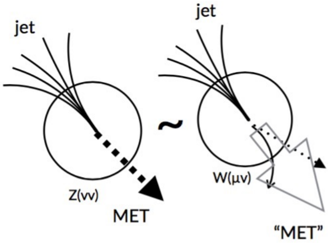
where $E_{x(y)}^{\mathrm{miss}} = -\sum E_{x(y)}$ summed over all calibrated e, γ, μ, τ and jets plus a track-based "soft" term

$E_{\mathrm{T}}^{\mathrm{miss}}$+jet (aka “mono-jet”), 1711.03301

Selection:

- One jet $p_{\mathrm{T}} > 250$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV (no close jets)





Main backgrounds:

- High-p_{T} W/Z+jets dominant
- Strategy: measure visible W/Z in data, normalize invisible MC

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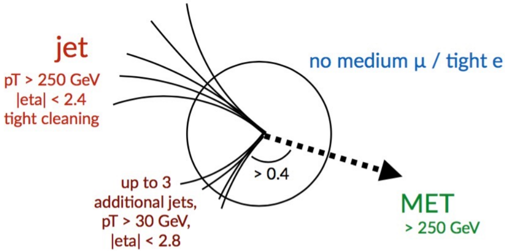

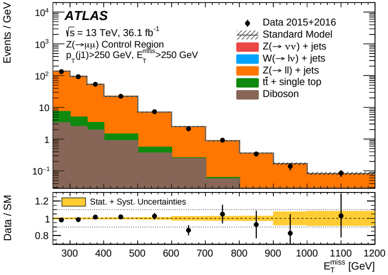

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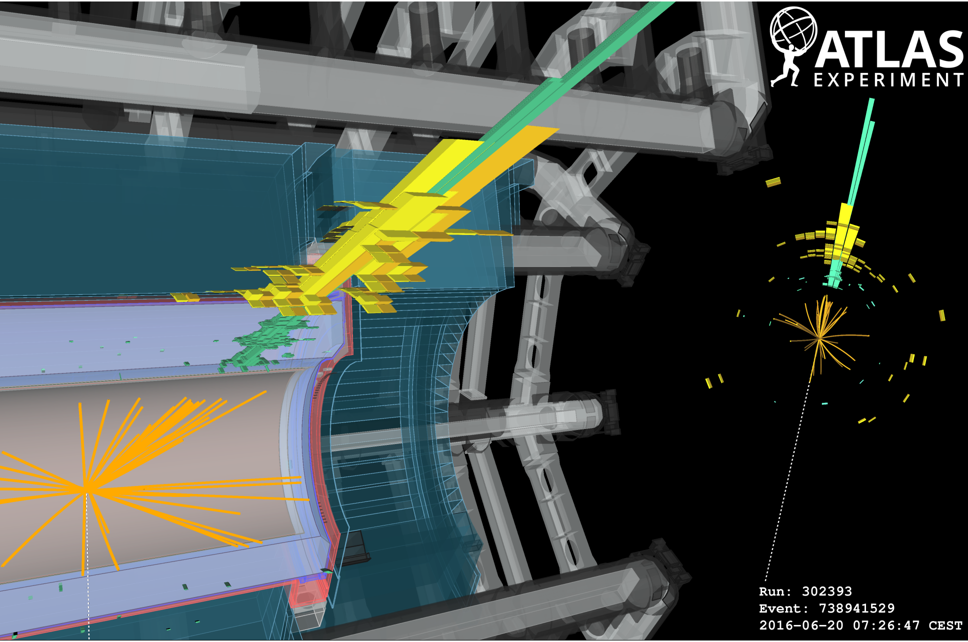
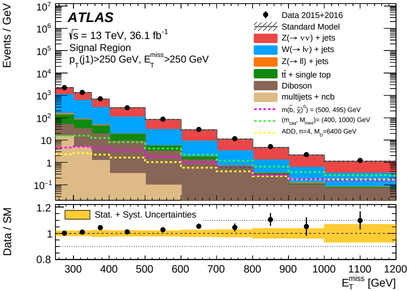
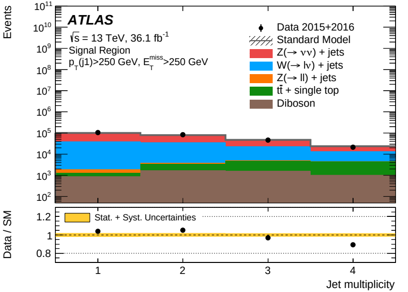

ATLAS
EXPERIMENT
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

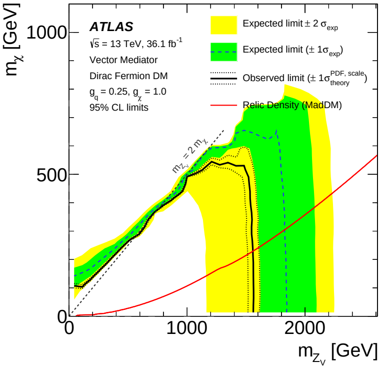
$E_{\mathrm{T}}^{\mathrm{miss}}$+jet (aka "mono-jet"), 1711.03301

Signal region yields:





Obs. agrees with bg-only hypothesis ⇒ exclusion limits



Example: Dirac DM, vector mediator

$$g_q = 0.25, \; g_{\mathrm{DM}} = 1$$

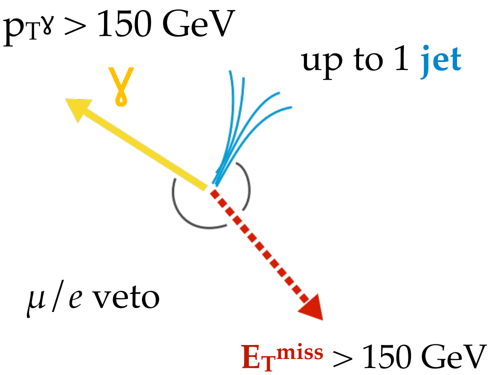
E_T^{miss}+γ, 1704.03848

Cleaner final state, at

higher cost for ISR (α_{EM})

Selection:

- Photon trigger threshold
  $\Rightarrow$ reach lower E_T^{miss}
- One photon
  $p_T > 150$ GeV
- $E_T^{miss} > 150$ GeV



Main backgrounds:

- W/Z+γ measured in lepton CRs
- Fake-photon bg from e/jet measured in data

$E_T^{\mathrm{miss}}+\gamma$, 1704.03848

$p_T^\gamma > 150$ GeV

up to 1 **jet**

Clea

highe

Selec

- Ph

  $\Rightarrow$

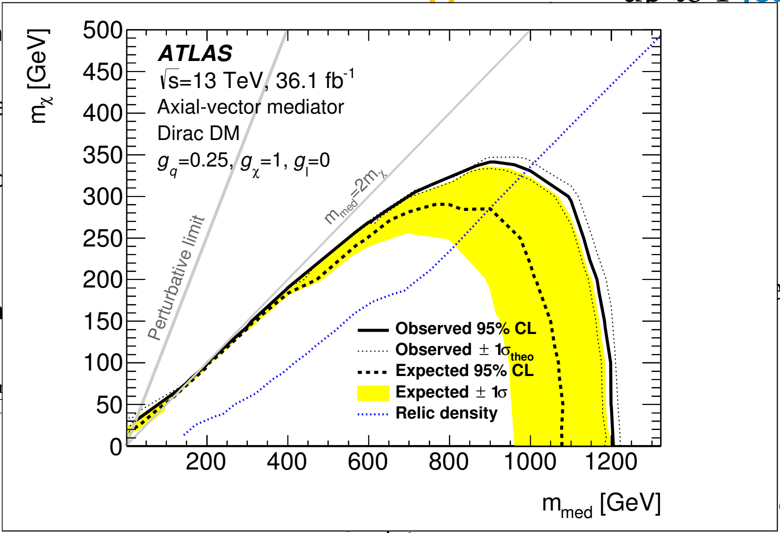
- On

  p_T

- E_T^{n}

eV

d



in data

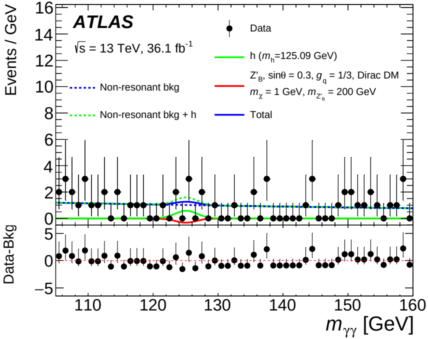
$E_{\mathrm{T}}^{\mathrm{miss}}+H(\gamma\gamma)$, 1706.03948 (also $b\bar{b}$, 1707.01302)

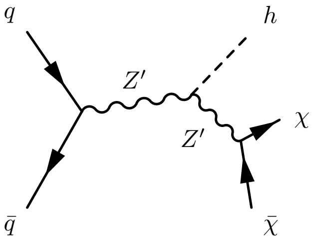
Use Higgs in same way!

Couples to mass:

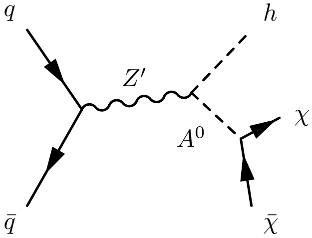
- ISR dramatically suppressed
- Heavy mediator $\Rightarrow$ Higgs-strahlung

Even cleaner!





Simplified model with Z' mediator



2HDM+pseudo-scalar model

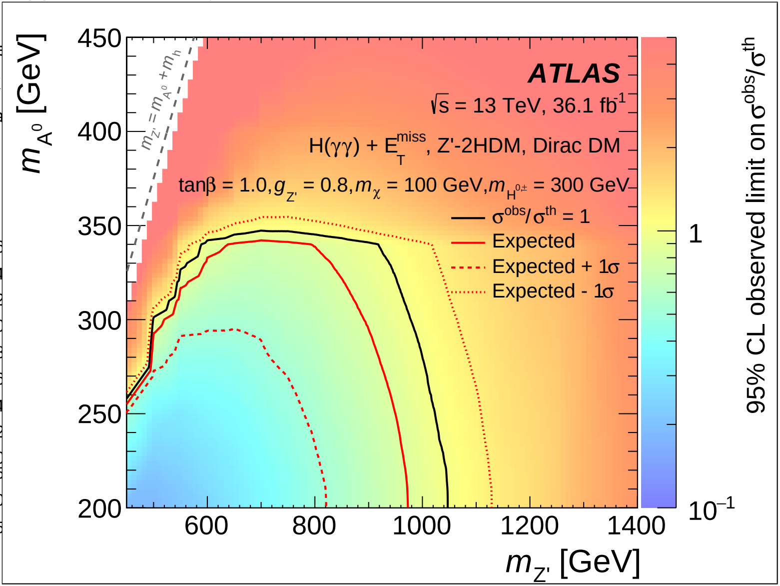
$E_T^{miss} + H(\gamma\gamma)$, 1706.03948 (also $b\bar{b}$, 1707.01302)

Use Higgs in same way!

Couple

- ISR
- Hea

Even



You get the picture.

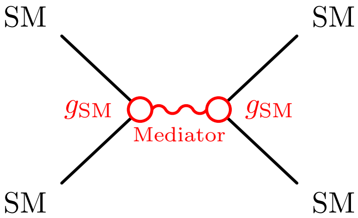
Skipping:

- $E_{\mathrm{T}}^{\mathrm{miss}}+Z(\ell\ell)$ with 36 fb^{-1}, 1708.09624
- $E_{\mathrm{T}}^{\mathrm{miss}}+V$(had) with 3.2 fb^{-1}, 1608.02372

(. . . and the corresponding CMS results . . .)

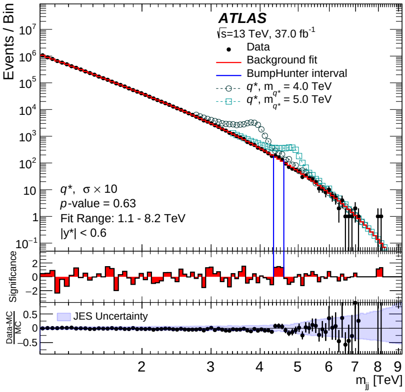
Di-X resonance searches

Target: DM mediator



Dijet resonance searches

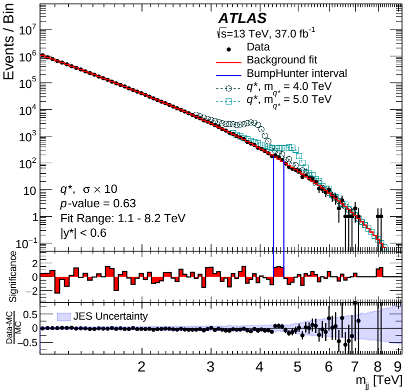
- Search for bump in m_{jj} spectrum
- Vector Z' mediator, strongly dependent on g_q



Dijet resonance searches

1. Standard (1703.09127):
   - Leading jet $p_T > 440$ GeV
   - $|y^*| = |y_1 - y_2|/2 < 0.6$
   - $m_{jj} > 1.1$ TeV

- Search for bump in m_{jj} spectrum
- Vector Z' mediator, strongly dependent on g_q



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2. ISR-assisted (ATLAS-CONF-2016-070/): Trigger on jet/γ from ISR $\Rightarrow$ access lower m_{jj}

- Search for bump in m_{jj} spectrum
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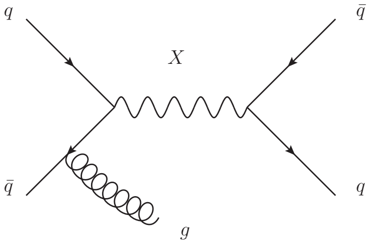

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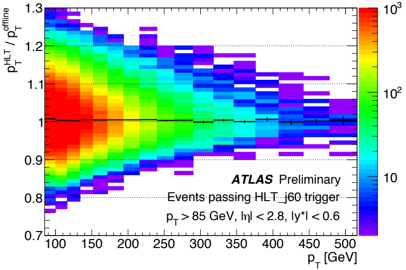
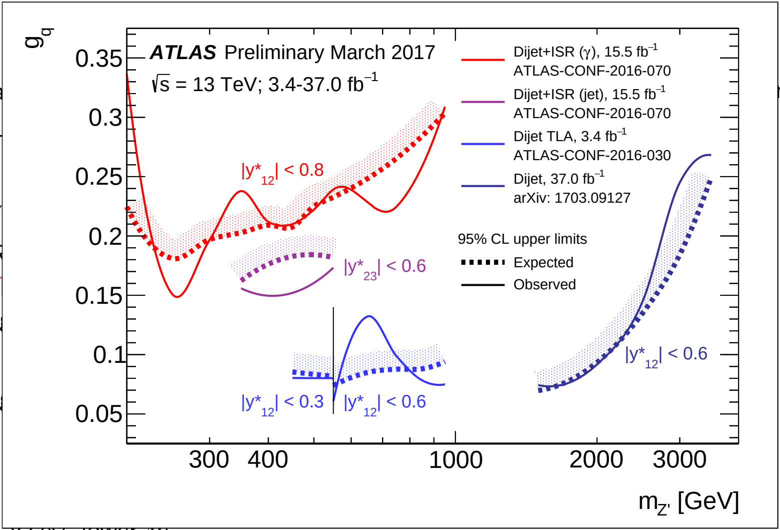
2. ISR-assisted (ATLAS-CONF-2016-070/):
   Trigger on jet/γ from ISR
   $\Rightarrow$ access lower m_{jj}
3. Trigger-level analysis (TLA):
   Only write out trigger jets
   $\Rightarrow$ Small per-event size
   $\Rightarrow$ afford lower threshold
   $\Rightarrow$ access lower m_{jj}

- Search for bump in m_{jj} spectrum
- Vector Z' mediator, strongly dependent on g_q



Dijet resonance searches

1. Sta
   - L
   - |
   - m



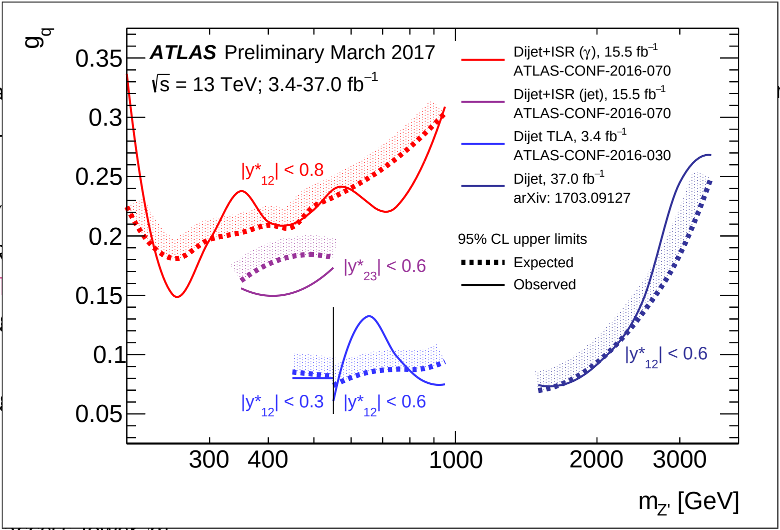
m

2. ISR
(AT
Trig
⇒

3. Trig
On
⇒
⇒
⇒ access lower m_{jj}

Dijet resonance searches

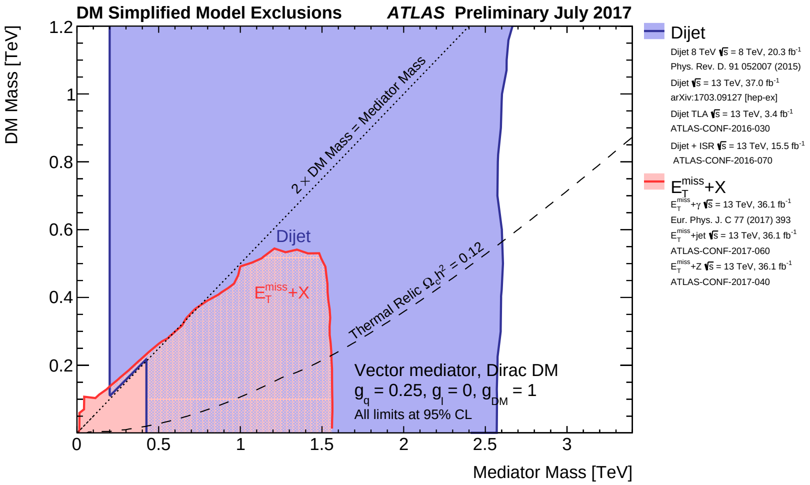
1. Sta… m
   - L…
   - |…
   - m…
2. ISR…
   (AT…
   Trig…
   ⇒ …
3. Tri…
   On…
   ⇒ …
   ⇒ …
   ⇒ access lower m_{jj}



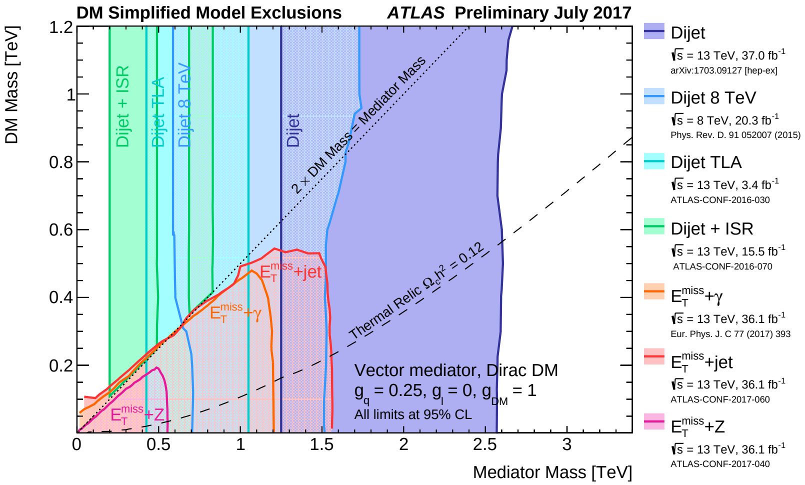
Skipping dilepton (1707.02424) and $t\bar{t}$ (ATLAS-CONF-2016-014/) Z' searches

Combining the exclusion limits

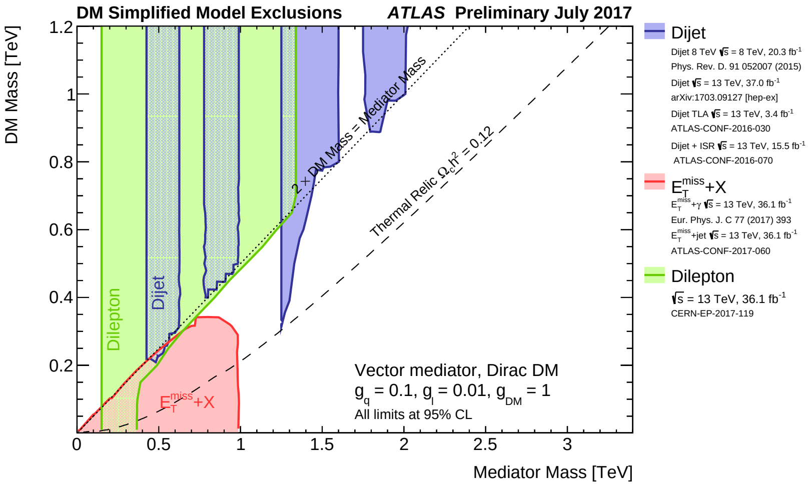
Combined exclusions: vector mediator



Combined exclusions: vector mediator

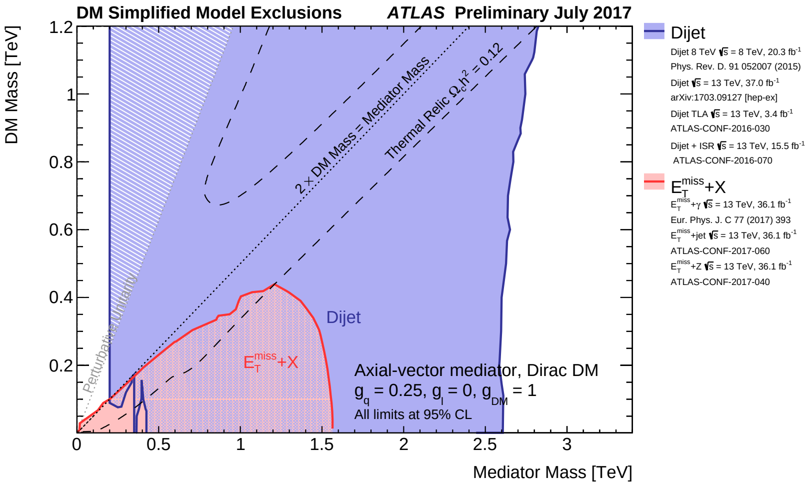


Combined exclusions: vector mediator

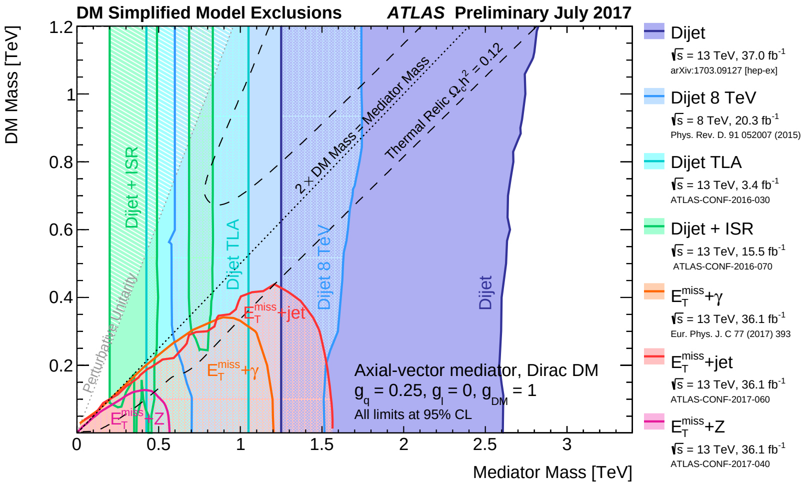


Turn on ℓ coupling $\Rightarrow g_\ell : 0 \rightarrow 0.01,\ \ g_q : 0.25 \rightarrow 0.1$

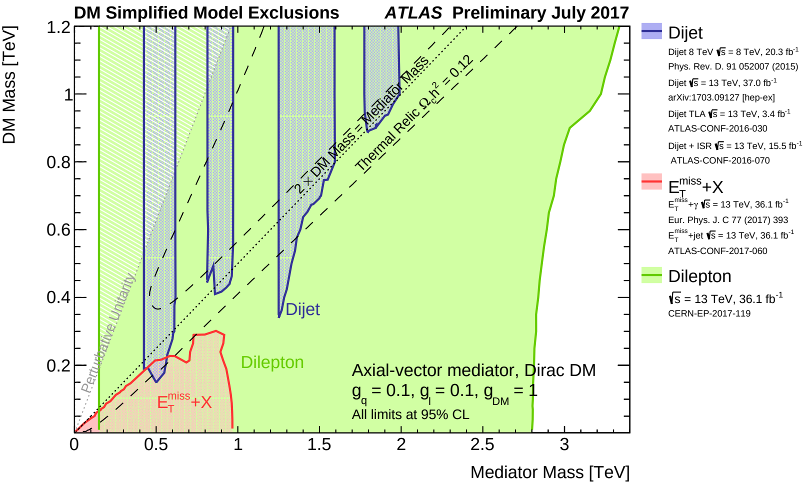
Combined exclusions: axial-vector mediator



Combined exclusions: axial-vector mediator

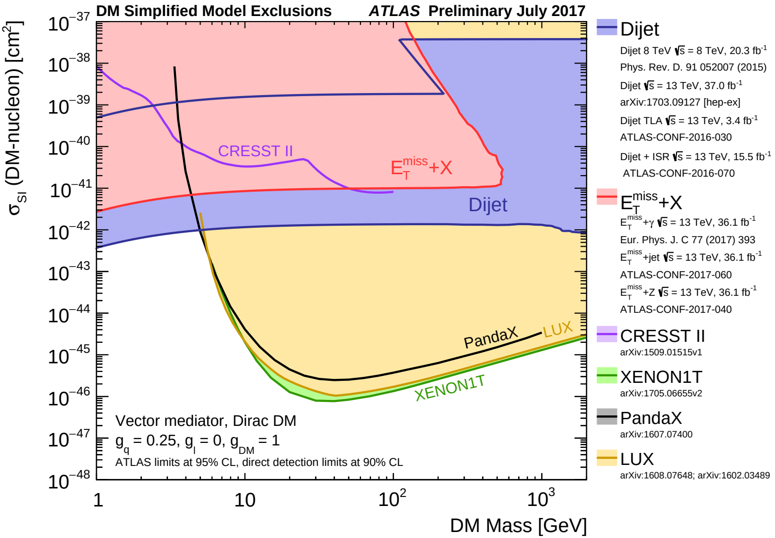


Combined exclusions: axial-vector mediator

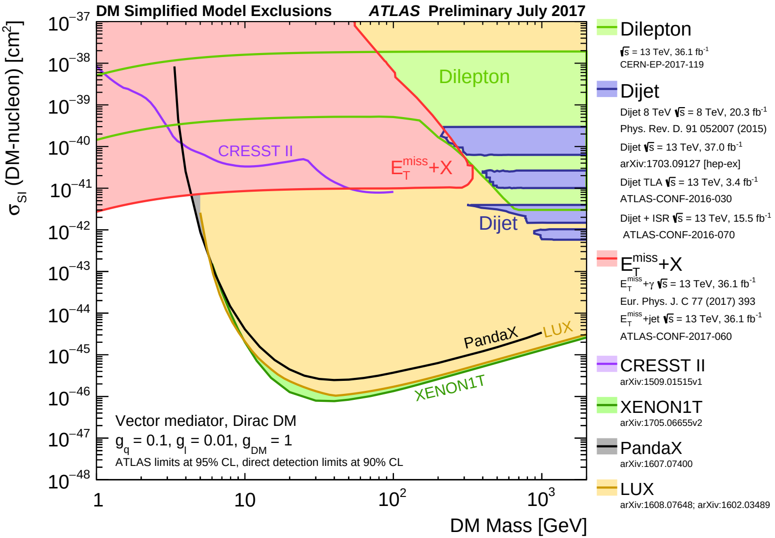


Turn on ℓ coupling $\Rightarrow g_\ell : 0 \rightarrow 0.1,\ \ g_q : 0.25 \rightarrow 0.1$

Comparing to direct-detection results (spin-independent)



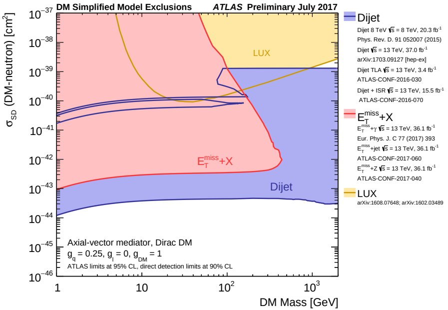
Comparing to direct-detection results (spin-independent)



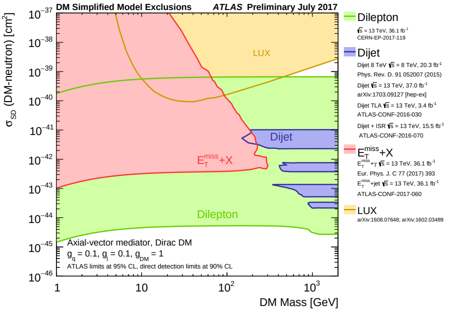
Turn on ℓ coupling $\Rightarrow g_\ell : 0 \to 0.01,\ g_q : 0.25 \to 0.1$

Comparing to direct-detection results (spin-dependent)

Leptophobic

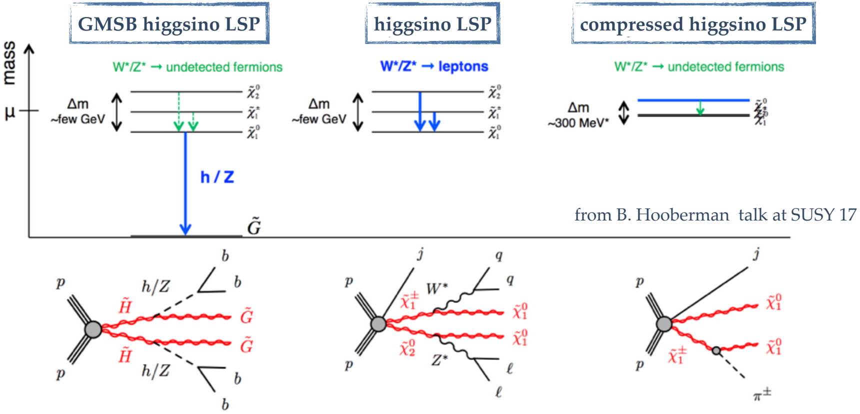


$g_q = 0.1, \; g_\ell = 0.1$



Selected SUSY DM results

Higgsino-like LSP as DM - brand new results for SUSY17



ATLAS-CONF-2017-081

$E_{\mathrm{T}}^{\mathrm{miss}} + hh/hZ/ZZ$

$E_{\mathrm{T}}^{\mathrm{miss}}$ and b-jet trigger

1712.08119

$E_{\mathrm{T}}^{\mathrm{miss}} + Z * (\ell\ell)$

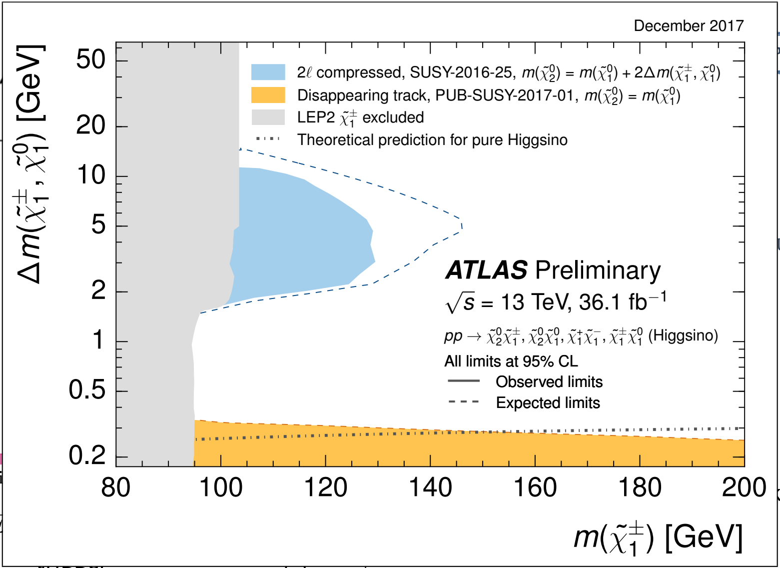
Soft leptons,

$p_{\mathrm{T}} > 4/4.5$ GeV

ATL-PHYS-PUB-2017-019

Disappearing track from decaying $\tilde{\chi}^{+}$

Higgsino-like LSP as DM - brand new results for SUSY17

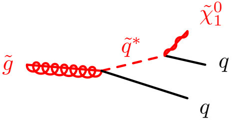


Dark Matter via long-lived particles and Dark Sectors

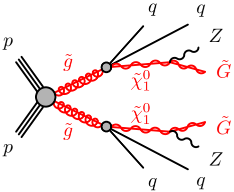
What if things are more complicated?

Instead start from a well-motivated theory, e.g. SUSY:

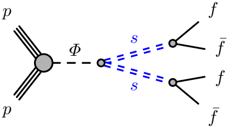
- Split SUSY: long-lived gluinos (e.g. hep-th/0405159, 1212.6971)



- GMSB: displaced Z decays (hep-ph/9601367)



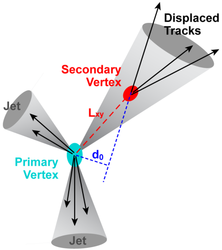
- Co-annihilation: displaced vertices, $\tilde{B}$-$\tilde{g}$ (1504.00504), $\tilde{B}$-$\tilde{W}$ (1506.08206)



Or models with a Hidden Valley (hep-ph/0604261) that does not take part in the SM gauge interactions but exert gravitational pull.

Couples to the SM via a portal particle, e.g. Higgs-like heavy scalar to LLPs

Example: displaced vertices + $E_{\mathrm{T}}^{\mathrm{miss}}$, 1710.04901

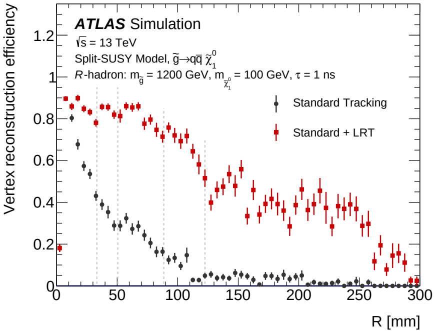


Selection

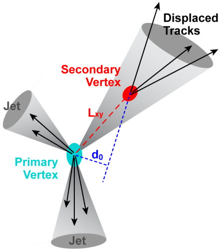
- $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV (trigger)
- Vertex in $R < 300$ mm
  $m > 10$ GeV, $n_{\mathrm{trk}} \geq 5$

- **Problem**: Tracking most CPU-intensive in offline reco
  ⇒ limited to prompt tracks
  ⇒ displaced vertices missed!

- **Solution**: preselect small sample at raw-data level and run more expensive processing
  1. tracking with relaxed cuts
  2. special vertexing alg for displaced vertices



Example: displaced vertices + $E_{\mathrm{T}}^{\mathrm{miss}}$, 1710.04901



- **Problem**: Tracking most CPU-intensive in offline reco
  $\Rightarrow$ limited to prompt tracks
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- $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV (trigger)
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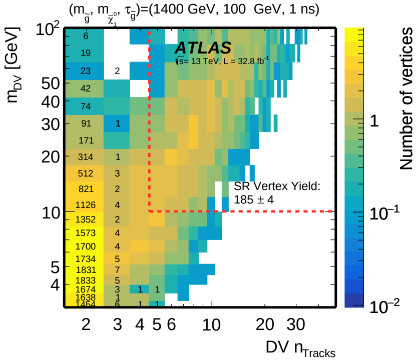
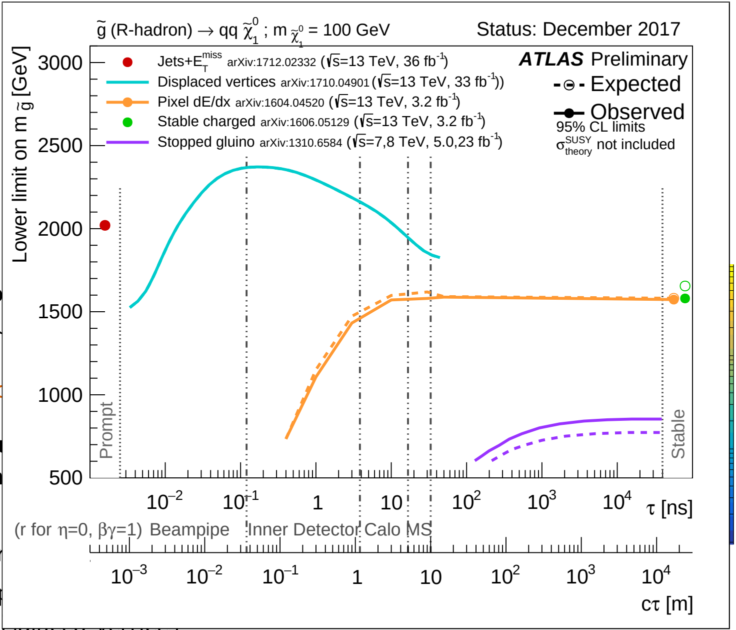
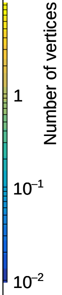


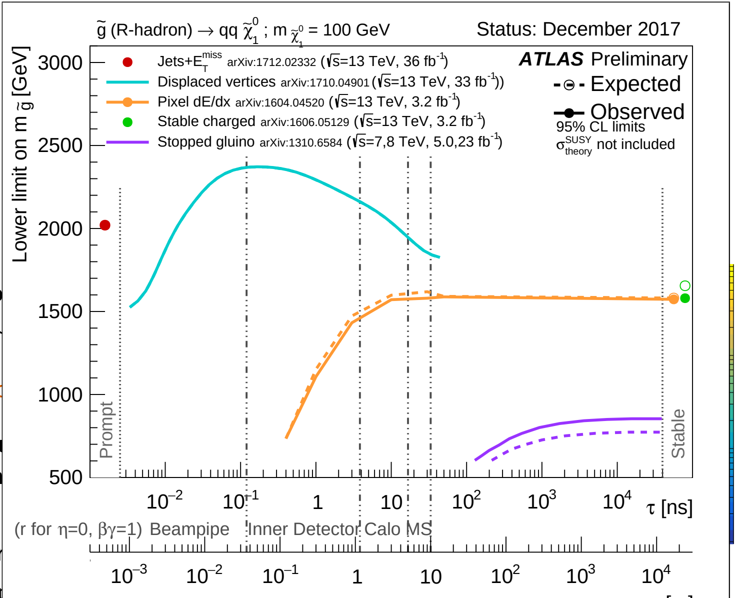
Example: displaced vertices + $E_{\mathrm{T}}^{\mathrm{miss}}$, 1710.04901



- **Pro**
  CPU
  ⇒ I
  ⇒ c
- **Solu**
  sam
  run
  1. tr
  2. sp
  displaced vertices

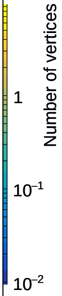


Example: displaced vertices + $E_{\mathrm{T}}^{\mathrm{miss}}$, 1710.04901



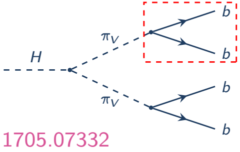
Parameterized sel. effs available for reinterpretation!

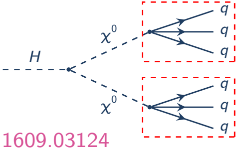
- ▶ **Pro**
  CPU
  ⇒ I
  ⇒ c
- ▶ **Sol**
  sam
  run
  1. tr
  2. sp
  displaced vertices

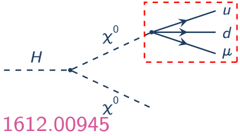


What about LHCb?

LHCb specializes in low-mass resonances - can do decaying LLPs!
Hidden Valley: LLPs in decays of Higgs(-like) particles:



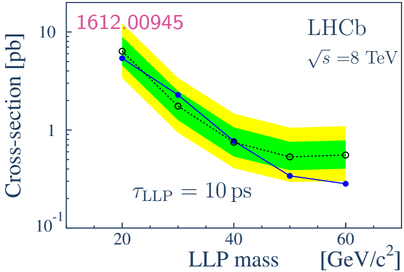




Complements ATLAS/CMS:

- Lifetimes down to $\sim$1 ps
- Lower mass LLPs

Limits on $\sigma \times BR$ (95% CL) $\Rightarrow$



A few words about LHC-wide organization

LPCC Dark Matter Working Group (LPCC website)

"Theorists and experimentalists define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for DM at the LHC"

- MO: Focused efforts leading to arxiv write-ups:
  - Summer 2015: *Dark Matter Benchmark Models for Early LHC Run-2 Searches*, 1507.00966
  - Winter 2015/2016: *Recommendations on presenting LHC searches for $E_{\mathrm{T}}^{\mathrm{miss}}$ signals using simplified s-channel models of DM*, 1603.04156
  - Winter 2016/2017: *Comparing LHC searches for heavy mediators of DM production in visible and invisible decay channels*, 1703.05703
  - Spring 2017: *Precise predictions for V+jets DM backgrounds*, 1705.04664
- Recent meeting on Dec 18 (indico)

LHC DM WG: WG on Dark Matter Searches at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about meetings and available documents, go to
http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg

A second mailing list is used for more technical exchanges related to the ongoing work of the WG. To subscribe, go to
http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg-contributors

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. As examples, the group develops and promotes well-defined signal models, specifying the assumptions behind them and describing the conditions under which they should be used. It works to improve the set of tools available to the experiments, such as higher- precision calculations of the backgrounds. It assists theorists with understanding and making use of LHC results.
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 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.

The WG activity builds on the experience of the previous ATLAS-CMS Dark Matter Forum, whose findings are documented in this paper

WG documents and meeting agendas: see links in the right menu

LHC WORKING GROUPS

Dark Matter WG
- WG Meetings
- WG documents

Electroweak WG
- WG Documents
- WG meetings

Forward Physics WG
- WG TWIKI PAGE
- WG documents
- WG meetings

Heavy Flavour WG
- WG Documents
- WG Meetings

MB & UE WG
- WG meetings
- WG documents

Machine Learning WG
- WG meetings
- iml web page

Top WG
- WG meetings

High Energy Physics – Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

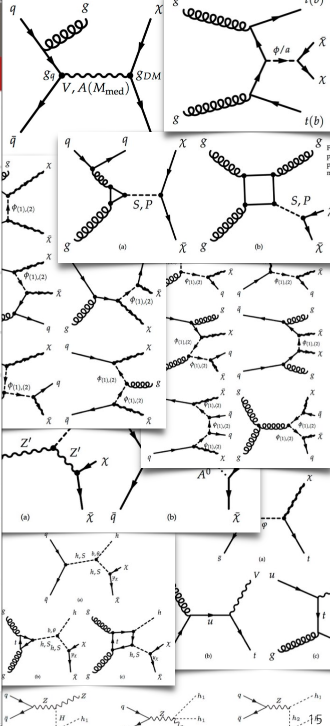
Subjects: **High Energy Physics – Experiment (hep-e**
(hep-ph)

Cite as: **arXiv:1507.00966 [hep-ex]**
(or **arXiv:1507.00966v1 [hep-ex]** for this v

Dirac WIMP mediators:
t- and s-channel exchange
vector/axial-vector/scalar/pseudo-scalar (MFV)
MET+heavy flavor, W, Z, and Higgs

Submission history

From: Antonio Boveia [view email]
[v1] Fri, 3 Jul 2015 16:54:32 GMT (3860kb,D)



Workshop on the physics of HL-LHC, and perspectives at HE-LHC

18-20 June 2018
CERN
Europe/Zurich timezone

Search...

Contact for administrative assistance

hllhc-physics.support@c...

This is the second of a series of meetings, running throughout 2018, with plenary events and intermediate periods of working group activities.

The main goal of the Workshop is to review, extend and further refine our understanding of the physics potential of the High Luminosity LHC.
The workshop aims to stimulate new ideas for measurements and observables, to extend the LHC discovery reach, to improve the modeling of LHC phenomena towards measurements at ultimate precision, and to prepare to exploit the HL-LHC data to the fullest possible extent.

The Workshop will also provide the opportunity to begin a more systematic study of physics at the HE-LHC, a new pp collider in the LHC ring with CM energy in the range of 27 TeV.

The activity of the Workshop will extend over a one year period, driven by working groups covering the following areas:

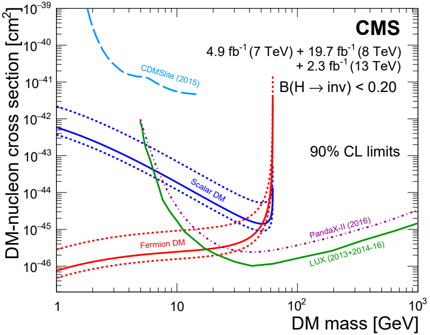
1. **QCD, EW and top quark physics**
2. **Higgs and EWSB**
3. **BSM**
4. **Flavour**
5. **Heavy Ions**

Summary

- The LHC searches for Dark Matter in *a lot of different ways*:
  - Production of DM in association with visible SM particles ($E_{\mathrm{T}}^{\mathrm{miss}}$+X)
  - Mediator: di-X resonance
  - SUSY search program (R-parity conserving scenarios $\Rightarrow$ DM)
  - Dedicated efforts for DM-motivated but experimentally challenging scenarios: LLPs (Dark Sector models, SUSY, ...)
- Exclusion limits for simplified DM models can be compared with direct-detection experiments
  - Complementary sensitivity for both SI/SD if $m_\chi \lesssim 10$ GeV
  - Improved sensitivity for SD for $\mathcal{O}(1)$ GeV$< m_\chi < \mathcal{O}(1)$ TeV
- Insensitive to: local DM distribution, fraction of DM made of WIMPs
- Found nothing yet $\Rightarrow$ exclusion limits! But more data coming, 5x shown today end 2018, 100x with HL-LHC

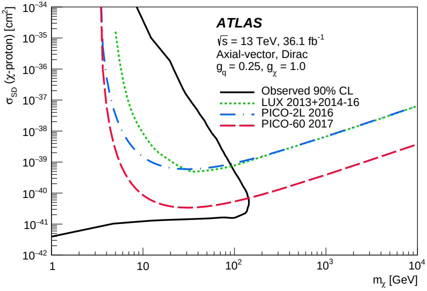
Backup slides

$H \to$ invisible: CMS

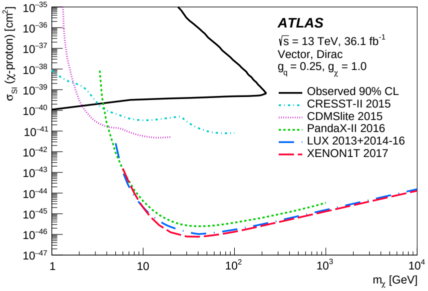


- CMS: BR($H \to$inv) $< 24\%$, 1610.09218
- Combines 7, 8 and 13 TeV data and ggF, VBF and VH production
- ATLAS paper on 13 TeV data, only for ZH production

$H \to$ invisible: ATLAS



Axial-vector mediator, spin-dependent

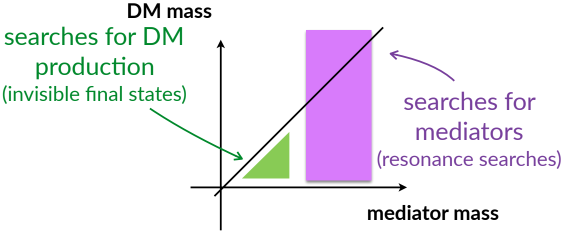


Vector mediator, spin-independent

- ATLAS paper 1708.09624 only on 13 TeV data and ZH prod.
- Excludes BR($H \to$inv) $< 67\%$ $(39\%$ expected)

Projecting to direct-detection plane

1. take LHC results (high Q²) at fixed values of the couplings



2. extrapolate to low Q² of direct detection (EFT)

caveat: 1605.04917

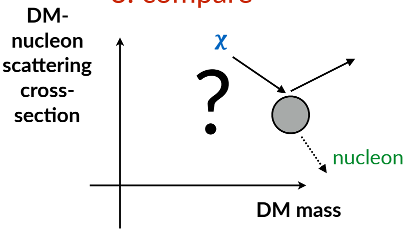
0^+ $\sigma_{\rm SI} \approx 1.1 \times 10^{-39}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$

0^- $\sigma_{\rm SI} \approx 0$ (suppressed by velocity dependent terms)

1^+ $\sigma_{\rm SI} \approx 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{125\ {\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$

1^- $\sigma^{\rm SD} \approx 3.8 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$

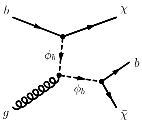
3. compare

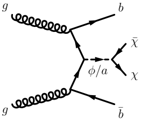


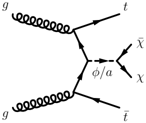
SUSY production of DM in association with HF

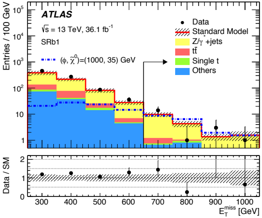
Search for **dark matter** produced in association with **top or bottom quarks**

- Favoured if couplings are Yukawa-like
- Scalar or pseudo-scalar mediators

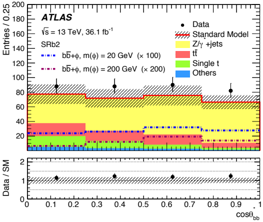




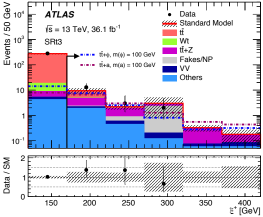




mono-b selection plus MET



two b-jets plus MET
use angle of b-jet with beam-pipe
as discriminator



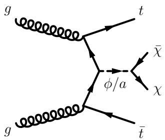
consider all decay modes
reject top pairs background with
top reconstruction (hadronic), mT2-based
variables for 1 and 2 leptons channel

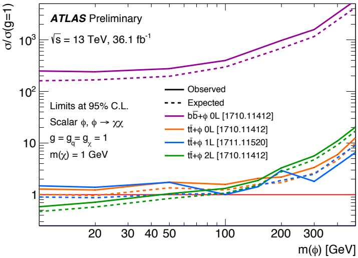
1710.11412, 1711.11520

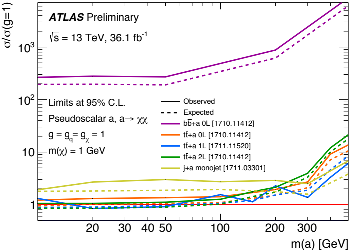
SUSY production of DM in association with HF

Scalar

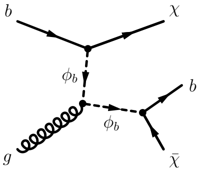
Pseudo-scalar

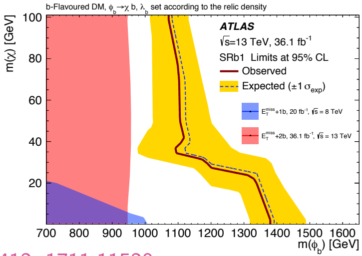






b-flavored DM





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