Dark Matter Searches at the LHC

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  • simplified models
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Setting the scene

thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

production at colliders

DM → SM

DM → SM
Setting the scene

break it!

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Setting the scene

shake it!
Setting the scene

make it!

DM ➔ SM ➔ DM

make it!
Collider experiments as DM hunters
Collider experiments as DM hunters

- focus on WIMP-like particles*: no interaction in detector

* the WIMP is not the only type of DM at the LHC, but by far it is the most tested
Collider experiments as DM hunters

- experimental signature is transverse momentum imbalance
  - many tens of publications using MET as key observable

MET + X
Collider experiments as DM hunters

- once we find a deviation, interpretation will be challenging!
  - colliders cannot prove stability beyond the apparatus
  - colliders may not distinguish single from multiple new invisible particles
  - colliders provide poor mass resolution on the invisible (if any)
  - colliders may have no handle on nature of interaction, particle type, quantum numbers,…

- the discovery paper may not mention “Dark Matter” at all

- it's a vast field at LHC
  - but it's only contributing in certain regions of phase space → complementarity!
  - there's a world beyond the WIMP

- I can only touch upon some key messages…
DM production in the lab

LHC search categorisation

DM from cascade decays

- example: SUSY
  - with R parity always 2 LSP's yielding observable momentum imbalance (MET)
DM production in the lab

LHC search categorisation

DM from cascade decays

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DM produced directly

- pair production
  - but back-to-back DM particles are invisible
- ISR diagrams provide probe recoiling against DM pair

\[
\begin{array}{c}
\bar{q} \\
X = g, \gamma, W/Z \\
q \\
\chi \\
\bar{\chi}
\end{array}
\]
DM production in the lab

LHC search categorisation

DM from cascade decays

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artificial distinction?

- example: Higgs portal
  - still large invisible H decay width allowed

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Modelling DM production

- **simplified models**: SM + only few particles
  - new physics restricted to what is relevant for a certain topology
  - aim for maximal experimental coverage of that topology
  - mediator and interactions specified explicitly
  - building blocks for recasting results in full models
  - parameter scans manageable
Modelling DM production

- 13TeV direct DM production searches now standardized on simplified models
- 2015: LHC DM Forum
  - bottom-up guidelines for LHC dark-matter searches at the start of LHC Run-2
  - wide consensus in community summarized in extensive report
  - continues in LPCC Dark Matter Working Group
  - common basis to present LHC results wrt other LHC and non-LHC experiments
  - common basis for comparison of LHC DM searches to visible mediator searches (in dijet and dilepton channels)

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Experimental status

#MoarData

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2018-10-24 04:00 UTC

- 2010, 7 TeV, 45.0 fb\(^{-1}\)
- 2011, 7 TeV, 6.1 fb\(^{-1}\)
- 2012, 8 TeV, 23.3 fb\(^{-1}\)
- 2015, 13 TeV, 4.2 fb\(^{-1}\)
- 2016, 13 TeV, 40.8 fb\(^{-1}\)
- 2017, 13 TeV, 49.8 fb\(^{-1}\)
- 2018, 13 TeV, 68.2 fb\(^{-1}\)
Experimental status

Spectacular spectacular!

E_{miss} = 1.05 \text{ TeV}

p_{Tjet} = 1.04 \text{ TeV}

Mass = 79 \text{ GeV}
Direct DM searches

MonoJet

MonoPhoton

MonoHiggs

MonoZ (leptonic)

MonoW/Z (Hadronic)

MonoW (monoLepton)

BBbar /TTbar

MonoTop
Direct DM searches

Monojet search as poster child example


35.9 fb⁻¹ (13 TeV)

CMS
monojet

Events / GeV

Data
H(125) → inv.
Axial-vector, m_{med} = 2.0 TeV
Z(νν) + jets
W(νν) + jets
WW/ZZ/ZZ
Top quark
Z(γγ)/γγ + jets
QCD

(Dist-Pred.) Data / Pred. → Unc.

(Data-Pred.) Data / Pred. → Unc.

p_{T}^{miss} [GeV]

m_{med} [GeV]

CMS

Vector med, Dirac DM, g_ν = 0.25, g_{Dμ} = 1
- Median expected 95% CL
- ± 1 \sigma_{exp}

Observed 95% CL

Observed ± theory unc

Ω_{χ}\times 10^{−2} ≥ 0.12

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Direct DM searches

Monojet search as poster child example

Direct DM searches

Monojet search as poster child example

- statistically limited
  - needs much bigger datasets
- systematically limited
  - no low-hanging fruits left
  - can only improve with very hard work
  - more difficult at higher lumi
- theoretical uncertainties already incredibly well controlled
  - NLO QCD+EWK
Indirect constraints on DM

Next avenue: link to visible

- interaction may still be probed if dark matter inaccessible
  - quark (jet) final states guaranteed
  - muon and electron pairs possibly too
- thus we can indirectly constrain dark matter models
  - constraints on couplings
  - from searches in dijet and dilepton final states
  - model dependency!

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Interpretation results

Many models, many parameters

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Interpretations beyond LHC

- demonstrates complementarity
- beware: strong model dependency!
What about WIMPs from cascades?

- multitude of searches using SUSY simplified models
- same overall picture on statistics versus systematics

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Higgs as a portal to DM

- analyses targeted on specific production modes
  - also ttH, H→DM interpretations possible

- great progress recently, still room for more
  - but no miracles either

- $\text{BR}(H\rightarrow \text{inv}) < 19\% @95\%\text{CL}$
- limited to $m_{\text{DM}} < m_H/2$
Next frontiers

Venture beyond WIMPs

- WIMPs from long-lived decays
- heavy neutral leptons
- axion-like particles
- dark sector portals (hidden valleys, dark photons,...)
- SIMPs
- ...

Experimental frontiers

- low mass resonances
- long-lived particles
- soft signatures
- ...

- vibrant field: a lot of work on triggers, reconstruction, backgrounds, simulation,...
  - also LHCb and Heavy-Ion community active!
Next frontiers

New exotic signatures!

- only a selection

Emerging Jets

Pedro Schwaller, Daniel Stolarski, Andreas Weiler

Novel signatures for long-lived particles at the LHC

Shankha Banerjee, Geneviève Bélanger, Biplob Bhattacharjee, Fawzi Boudjema, Rohini M. Godbole, Swagata Mukherjee

A Heavy Metal Path to New Physics

Marco Drewes, Andrea Giammanco, Jan Hajar, Michele Lucente, Olivier Mattelaer

Stable Sexaquark

Glennys R. Farrar

Triggering Soft Bombs at the LHC

Simon Knapen, Simone Pagan Griso, Michele Papucci, Dean J. Robinson

Semi-visible Jets: Dark Matter Undercover at the LHC

Timothy Cohen, Mariangela Lisanti, Hou Keong Lou

Discovering True Muonium at LHCb

Xabier Cid Vidal, Philip Ilten, Jonathan Plews, Brian Shuve, Yotam Soreq

Simplified SIMPs and the LHC

Nadir Daci, Isabelle De Bruyn, Steven Lowette, Michel H.G. Tytgat, Bryan Zaldivar
Conclusions

Dark Matter is a hot topic at the LHC

- bread-and-butter signatures intensely searched for
  - LHC is very competitive if mediator can be produced on-shell and/or DM is light
- connection to search for new mediator in visible decay channels
  - dijets, dileptons,...
- branching out to new frontiers
  - beyond the WIMP, beyond experimental comfort zones
- mostly only \(~50/fb\) analysed so far at 13TeV, much more to come
Outlook

LHC / HL-LHC Plan

Run 1 | Run 2 | Run 3 | Run 4 - 5...

LS1 | EYETS | LS2 | LS3

splice consolidation button collimators R2E project

13 TeV

13.5-14 TeV

injection upgrade cryo Point 4 DS collimation P2-11 T dip) Civil Eng. P1-P5

14 TeV

experiment upgrade phase 1

cryolimit interaction regions

cryolimit interaction regions

14 TeV

HL-LHC installation

experiment upgrade phase 2

7 TeV

8 TeV


30 fb⁻¹

150 fb⁻¹

300 fb⁻¹

5 to 7 x nominal luminosity

75% nominal luminosity

nominal luminosity

2 x nominal luminosity

3000 fb⁻¹

integrated luminosity

we are here
3 years to 100 years of dark matter!

FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM

By J. C. KAPTEYN

ABSTRACT

First attempt at a general theory of the distribution of masses, forces, and velocities in the stellar system.—(1) Distribution of stars. Observations are fairly well represented, at least up to galactic lat. 70°, if we assume that the equidensity surfaces are similar ellipsoids of revolution, with axial ratio 5.1, and this enables us to compute quite readily (2) the gravitational acceleration at various points due to such a system, by summing up the effects of each of ten ellipsoidal shells, in terms of the acceleration due to the average star at a distance of a parsec. The total number of stars is taken as 47.4×10⁶. (3) Random and rotational velocities. The nature of the equidensity surfaces is such that the stellar system cannot be in a steady state unless there is a general rotational motion around the galactic polar axis, in addition to a random motion analogous to the thermal agitation of a gas. In the neighborhood of the axis, however, there is no rotation, and the behavior is assumed to be like that of a gas at uniform temperature, but with a gravitational acceleration $G\eta$ decreasing with the distance $\rho$. Therefore the density $\Delta$ is assumed to obey the barometric law: $G\eta = -\frac{\Delta}{\Delta\rho}/\Delta$; and taking the mean random velocity $\bar{u}$ as 10.3 km/sec., the author finds that (4) the mean mass of the stars decreases from 2.3 (sun = 1) for shell II to 1.4 for shell X (the outer shell), the average being close to 1.6, which is the value independently found for the average mass of both components of visual binaries. In the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to $-\frac{\Delta}{\Delta\rho}/\Delta$, $\bar{u}$ is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 30 km/sec., we have a quantitative explanation of the phenomenon of star-streaming, where the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine the amount of dark matter from its gravitational effect. (5) The chief defects of the theory are: that the equidensity surfaces assumed do not agree with the actual surfaces, which tend to become spherical for the shorter distances; that the position of the center of the system is not the sun, as assumed, but is probably located at a point some 550 parsecs away in the direction galactic long. 77°, lat. $-3^\circ$; that the average mass of the stars was assumed to be the same in all shells in deriving the formula for the variation of $G\eta$ with $\rho$ on the basis of which the variation of average mass from shell to shell and the constancy of the rotational velocity were derived—hence either the assumption or the conclusions are wrong, and that no distinction has been made between stars of different types.