Dark Matter Searches at ATLAS and CMS

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  - simplified models
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  - searches for direct DM production
  - interpretation; comparison beyond LHC
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- The next horizon
- Outlook

Setting the scene

dark matter

Examples   Word Origin

noun

1. a hypothetical form of matter invisible to electromagnetic radiation, postulated to account for gravitational forces observed in the universe.

Origin of dark matter

1985-1990

1985-90

source: dictionary.com

Setting the scene

FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM[1]

BY J. C. KAPTEYN[2]

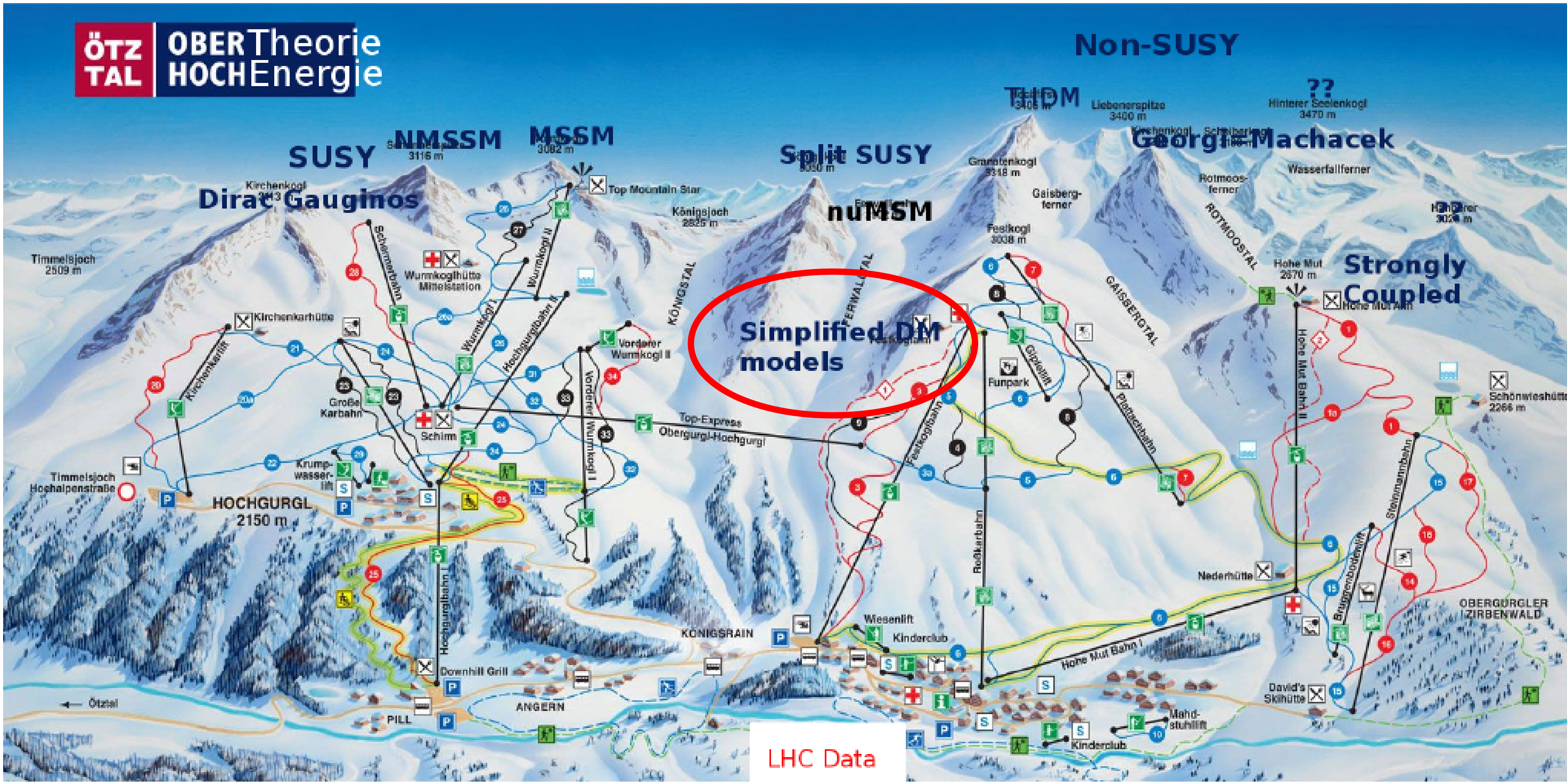
ABSTRACT

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 47.4×10^9. (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 ρ. Therefore the density Δ is assumed to obey the barometric law: $G\eta = -\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$; 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 2.2 (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 $-\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$, $\bar{u}$ 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 39 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 650 parsecs away in the direction galactic long. 77°, lat. −3°; 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 ρ 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.

Astrophysical Journal 55 (1922) 302

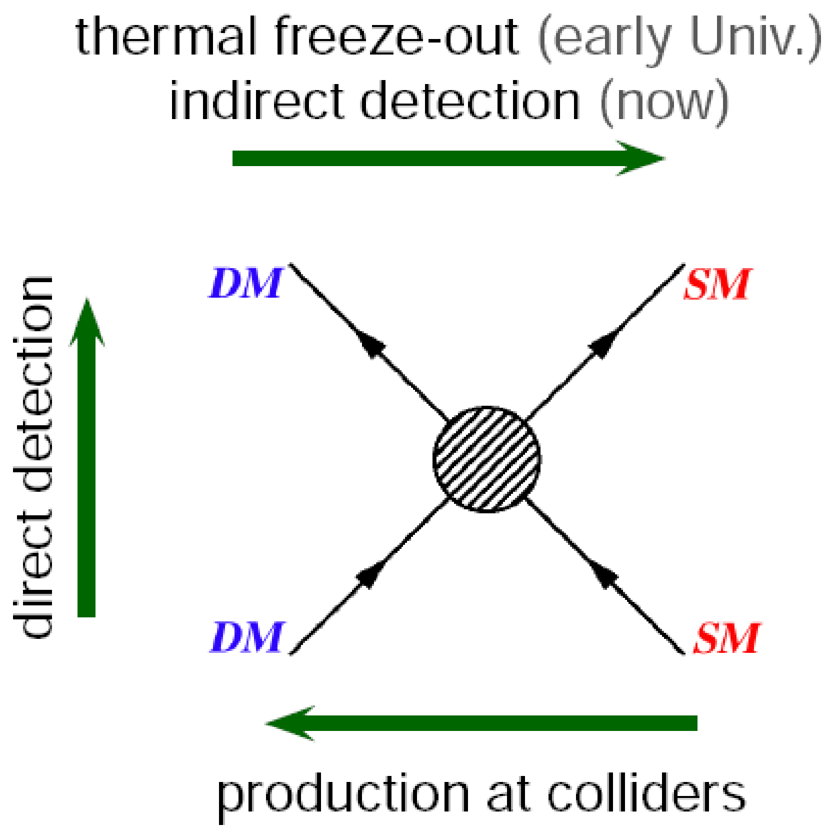
5 years to 100 years of dark matter!

Setting the scene



Mark D. Goodsell

Setting the scene



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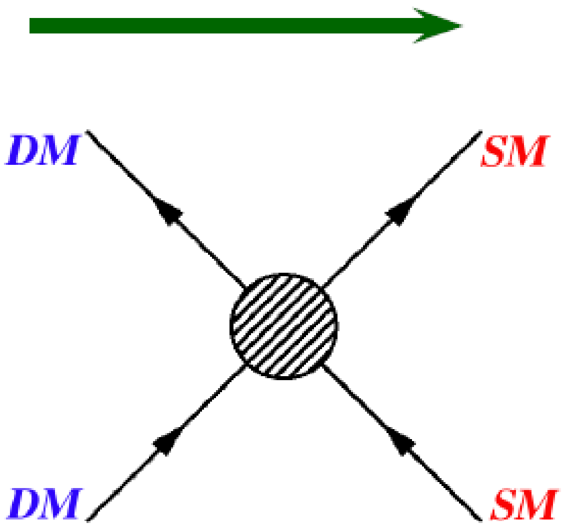
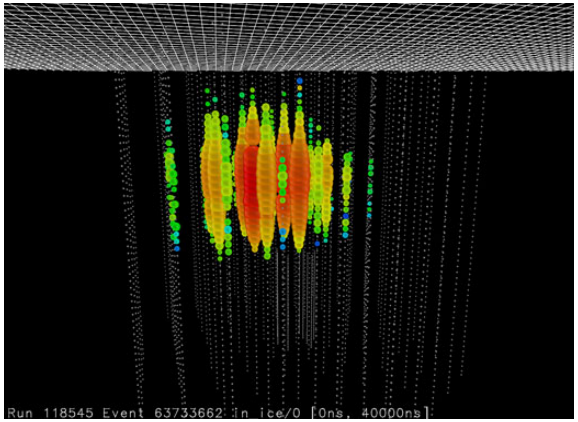
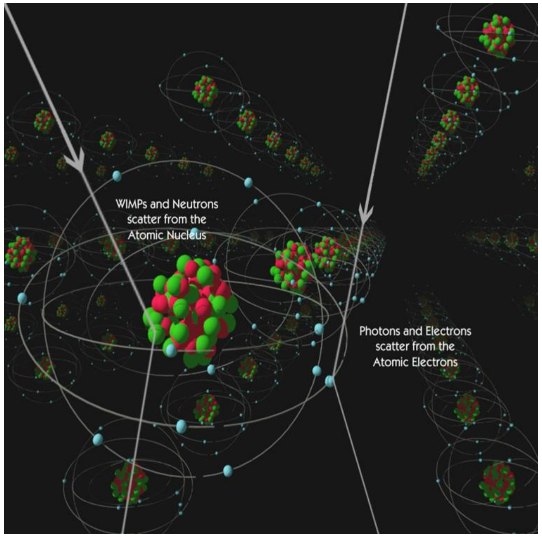
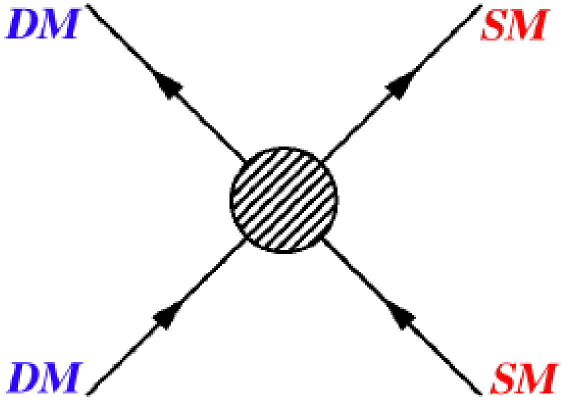




break it!

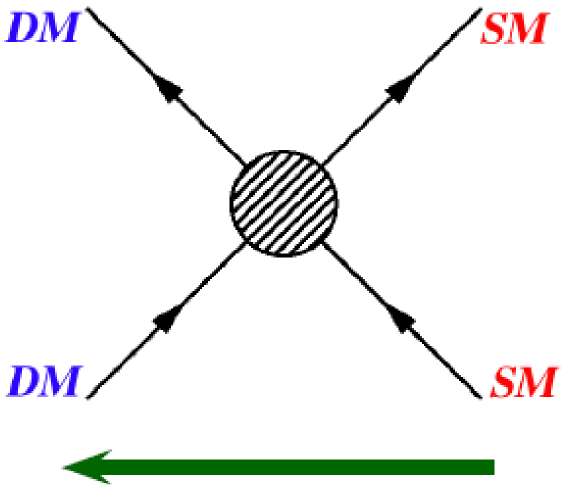
Setting the scene





shake it!

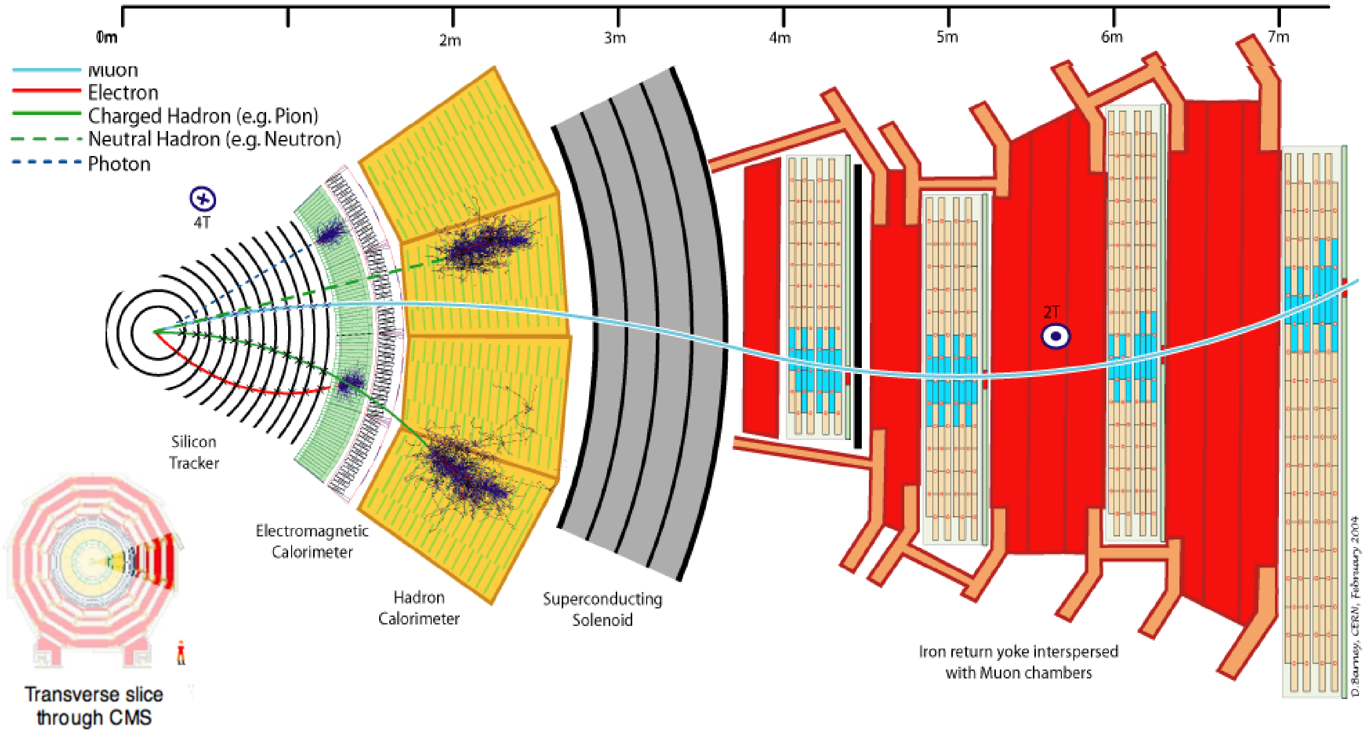
Setting the scene



make it!

Setting the scene

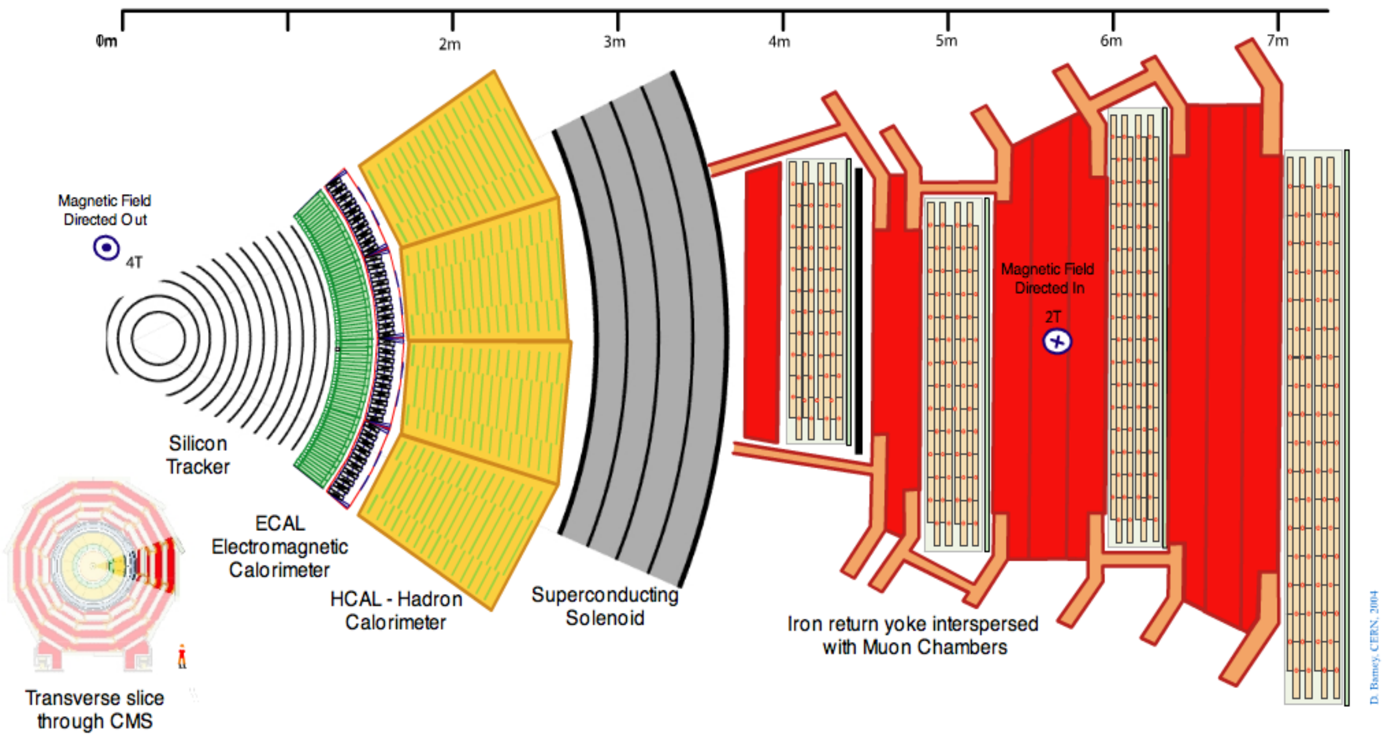
Collider experiments as DM hunters



Setting the scene

Collider experiments as DM hunters

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



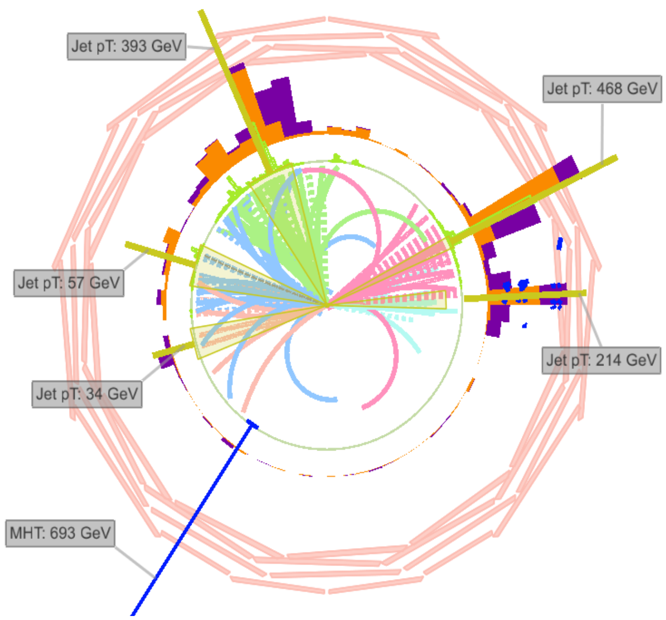
(*) though a whole world beyond the WIMP, also in ATLAS/CMS

Setting the scene

Collider experiments as DM hunters

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

MET + X



CMS-PAS-SUS-10-005

- note: DM → MET is obvious ; MET → DM interpretation much harder!

DM production in the lab

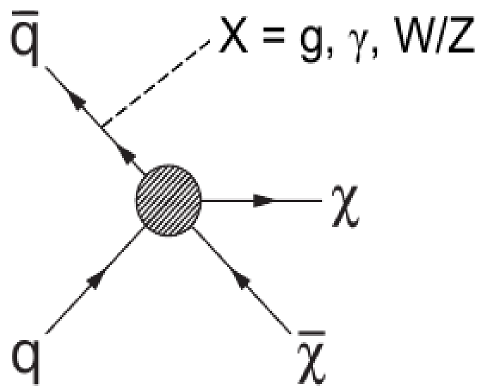
LHC search categorisation

DM from cascade decays

- example: SUSY
  - with R parity always 2 LSP's yielding observable momentum imbalance (MET)

DM produced directly

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



DM production in the lab

LHC search categorisation

DM from cascade decays

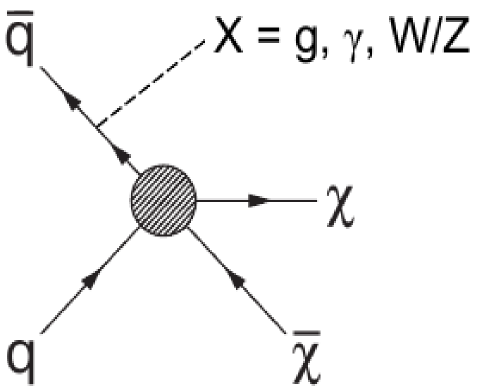
- example: SUSY
  - with R parity always 2 LSP's yielding observable momentum imbalance (MET)

artificial distinction?

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

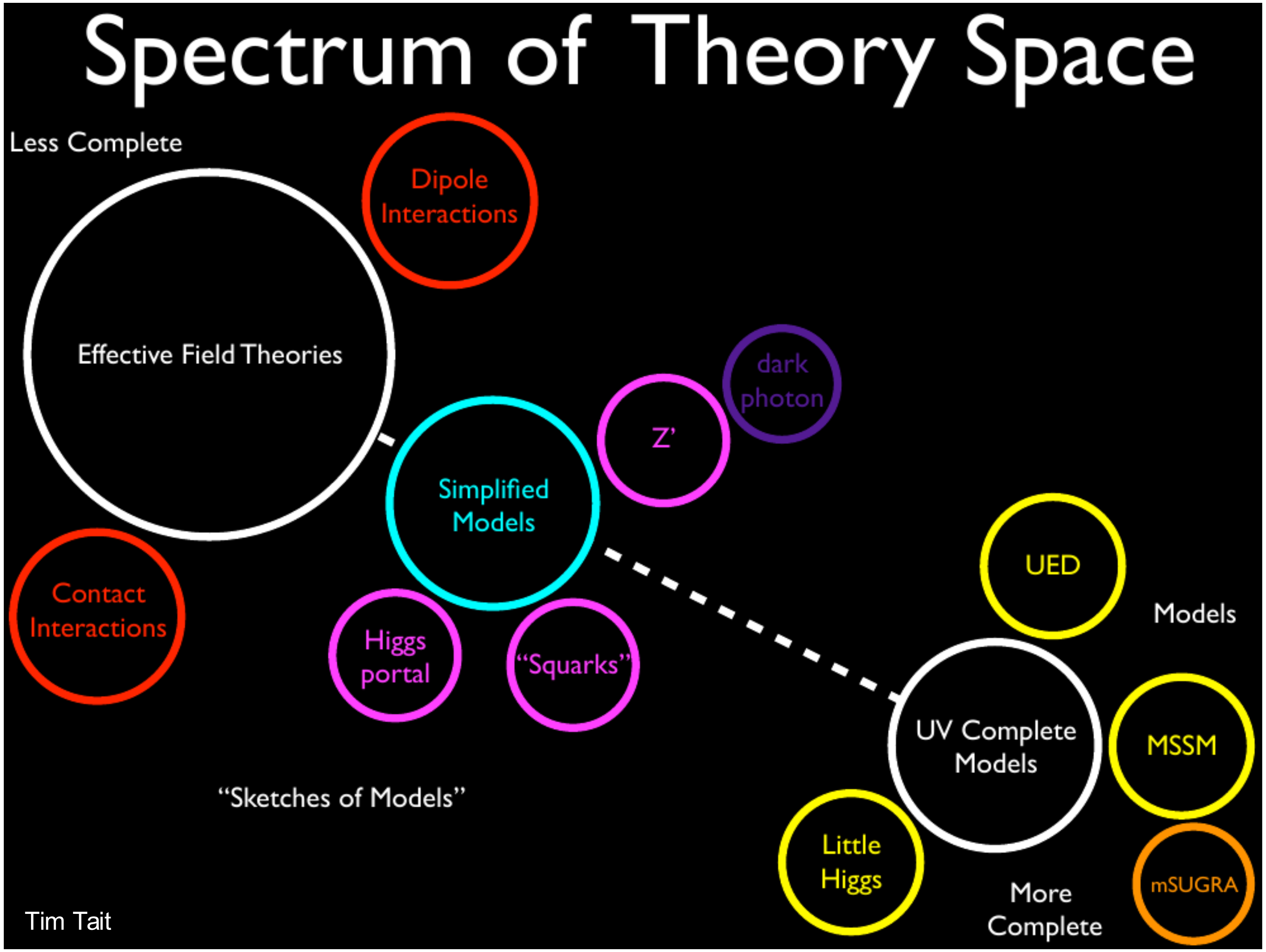
DM produced directly

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



Modelling DM production

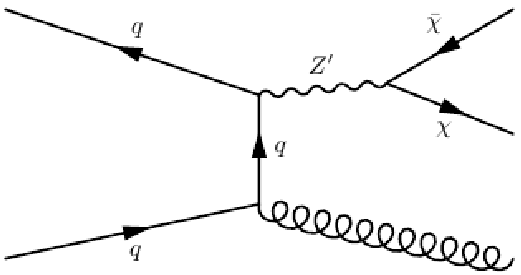
Use models to guide experimental strategies

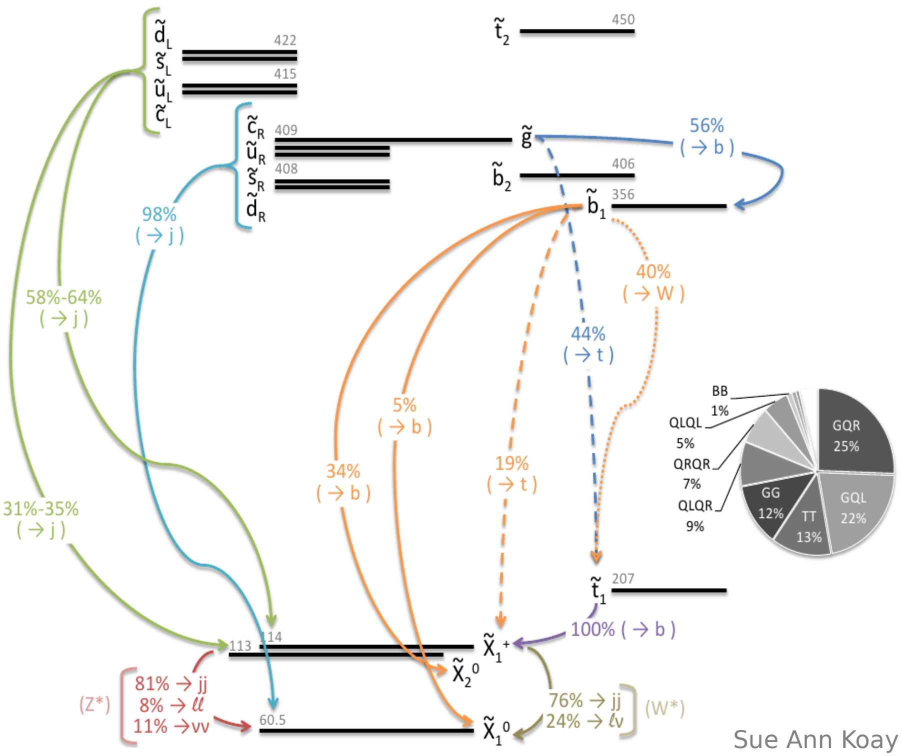


Modelling DM production

- 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

    caveats apply
  - parameter scans manageable



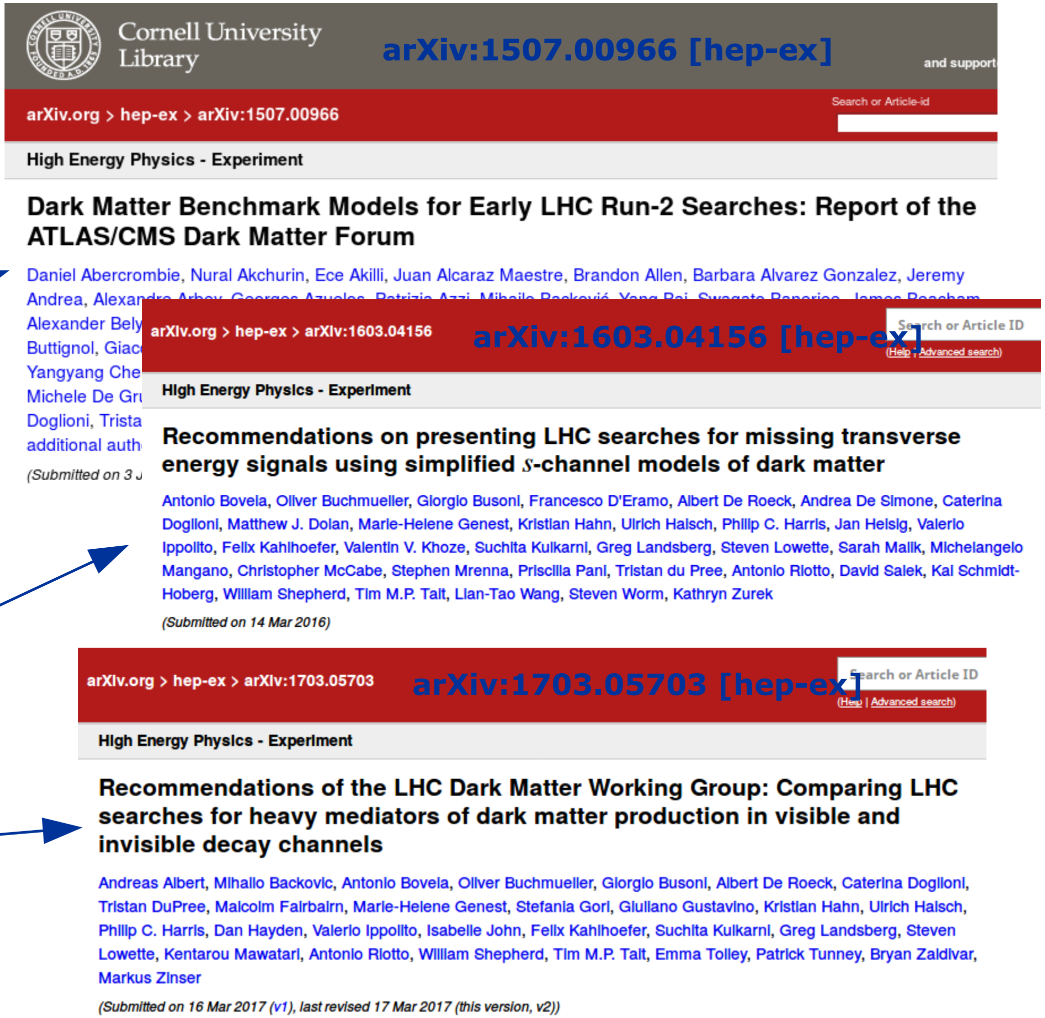


Breakdown of an example SUSY benchmark point

Sue Ann Koay

Modelling DM production

- simplified models were standardized in 7/8TeV LHC SUSY searches
- 13TeV direct DM production now also 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
  - https://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg
  - 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)


Cornell University Library

arXiv:1507.00966 [hep-ex]

and support

arXiv.org > hep-ex > arXiv:1507.00966

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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, Alexan… Alexander Bely… Buttignol, Giac… Yangyang Che… Michele De Gru… Doglioni, Trista… additional auth…

(Submitted on 3 J…

arXiv.org > hep-ex > arXiv:1603.04156

arXiv:1603.04156 [hep-ex]

Search or Article ID

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High Energy Physics - Experiment

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Antonio Boveia, Oliver Buchmueller, Giorgio Busoni, Francesco D'Eramo, Albert De Roeck, Andrea De Simone, Caterina Doglioni, Matthew J. Dolan, Marie-Helene Genest, Kristian Hahn, Ulrich Haisch, Philip C. Harris, Jan Heisig, Valerio Ippolito, Felix Kahlhoefer, Valentin V. Khoze, Suchita Kulkarni, Greg Landsberg, Steven Lowette, Sarah Malik, Michelangelo Mangano, Christopher McCabe, Stephen Mrenna, Priscilla Pani, Tristan du Pree, Antonio Riotto, David Salek, Kai Schmidt-Hoberg, William Shepherd, Tim M.P. Tait, Lian-Tao Wang, Steven Worm, Kathryn Zurek

(Submitted on 14 Mar 2016)

arXiv.org > hep-ex > arXiv:1703.05703

arXiv:1703.05703 [hep-ex]

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High Energy Physics - Experiment

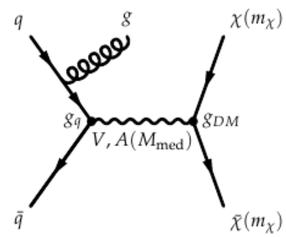
Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

Andreas Albert, Mihailo Backovic, Antonio Boveia, Oliver Buchmueller, Giorgio Busoni, Albert De Roeck, Caterina Doglioni, Tristan DuPree, Malcolm Fairbairn, Marie-Helene Genest, Stefania Gori, Giuliano Gustavino, Kristian Hahn, Ulrich Haisch, Philip C. Harris, Dan Hayden, Valerio Ippolito, Isabelle John, Felix Kahlhoefer, Suchita Kulkarni, Greg Landsberg, Steven Lowette, Kentarou Mawatari, Antonio Riotto, William Shepherd, Tim M.P. Tait, Emma Tolley, Patrick Tunney, Bryan Zaldivar, Markus Zinser

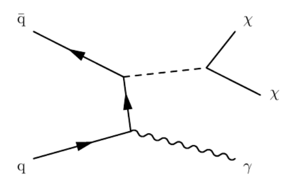
(Submitted on 16 Mar 2017 (v1), last revised 17 Mar 2017 (this version, v2))

Experimental status

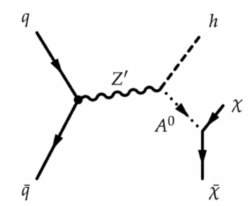
Searches for direct DM production



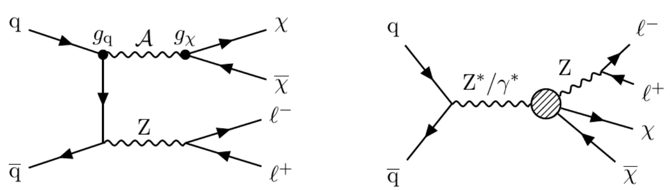
MonoJet



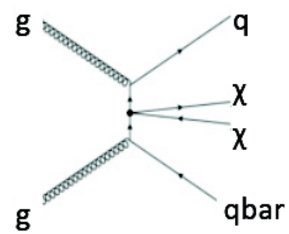
MonoPhoton



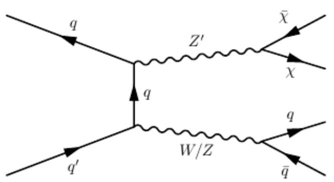
MonoHiggs



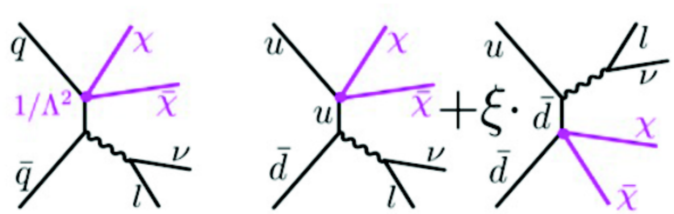
MonoZ (leptonic)



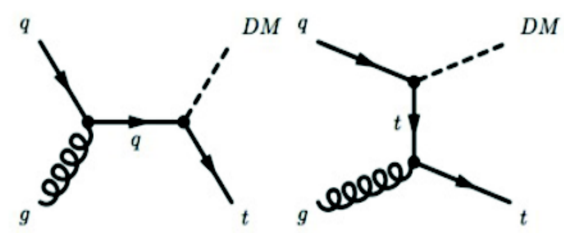
BBbar /TTbar



MonoW/Z (Hadronic)



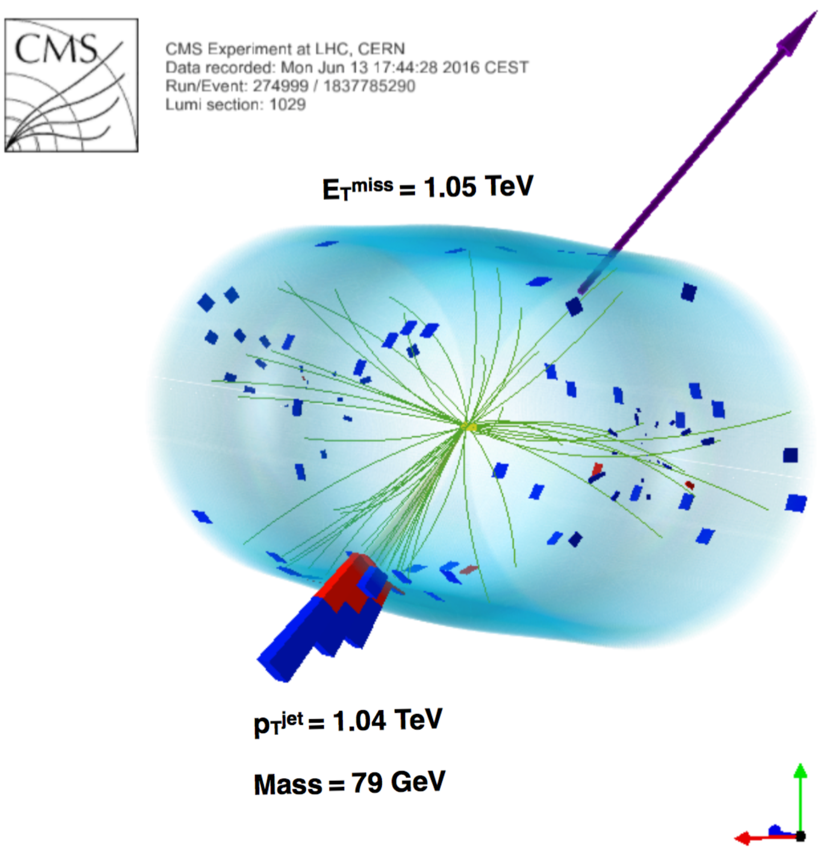
MonoW (monoLepton)

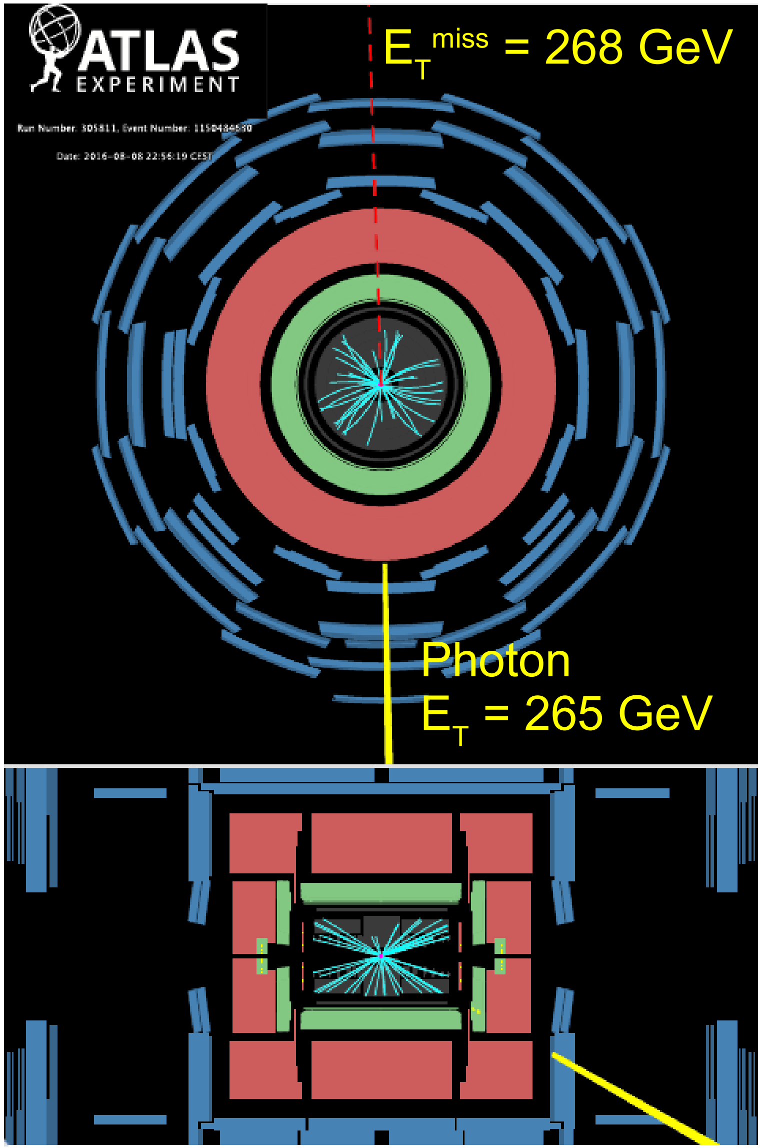


MonoTop

Experimental status

Spectacular signatures!





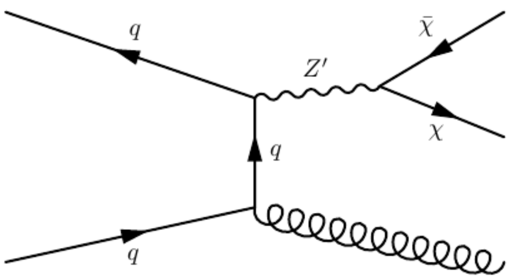
Experimental status

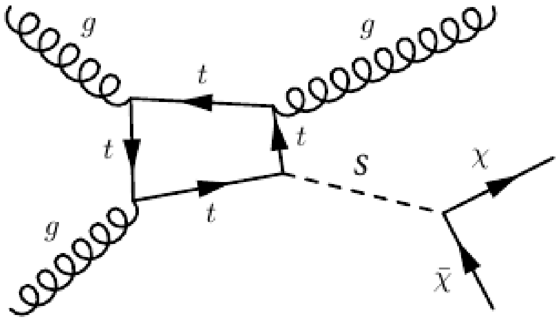
"Classic" search: mono-jet

CMS, arXiv:1703.01651 [hep-ex], 12.9fb^{-1}

ATLAS, Phys. Rev. D94 (2016) 032005, 3.2fb^{-1}

- DM recoils against a jet from QCD ISR
- selection highlights (ex. from CMS)
  - MET as sensitive observable,
    lowest cut driven by trigger (200GeV)
  - at least one central high-momentum jet
    away from MET (pT>100GeV)
  - electron/muon/tau/b/photon vetoes
  - suppress large jet mismeasurements:
    Δφ(jet 1..4, MET)>0.5
  - control fake jets and instrumental MET
- irreducible Z→νν dominant
  after selection
  - W→lν subdominant



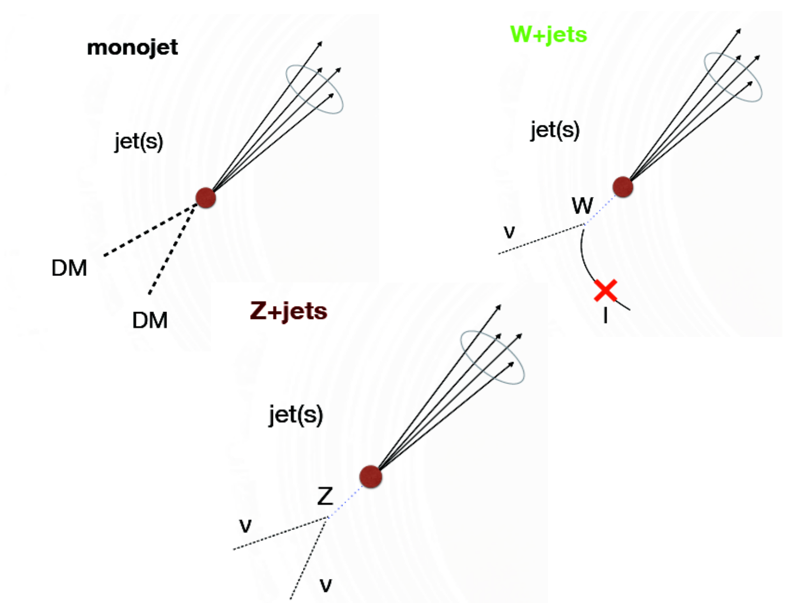


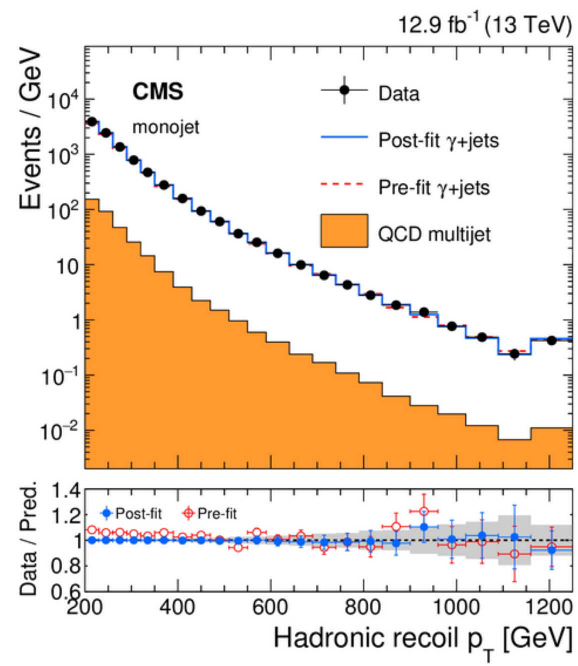
Experimental status

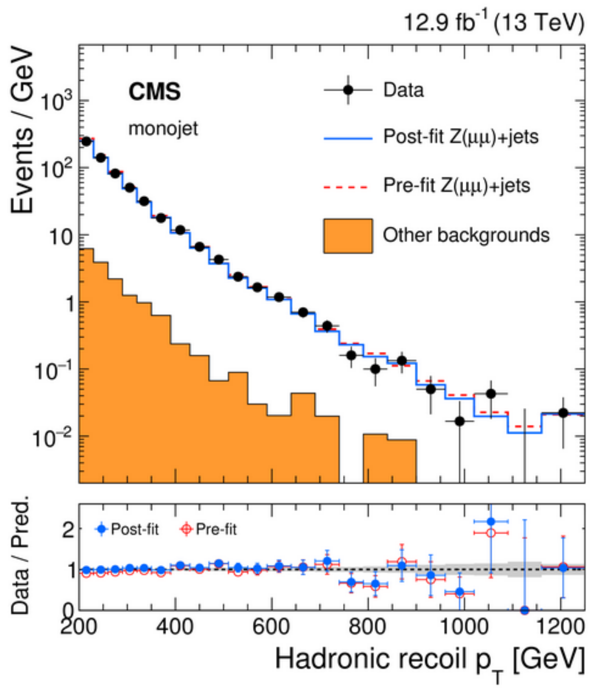
"Classic" search: mono-jet

CMS, arXiv:1703.01651 [hep-ex], 12.9fb^{-1}

- backgrounds well controlled with global fit over several data control regions
  - Z→νν constrained from Z→μμ, Z→ee and photon+jets
  - W→lν background constrained from W→μν and W→eν
  - Z/W cross section ratio constraint added







example: Z(→μμ)+jets CR

example: γ+jets CR

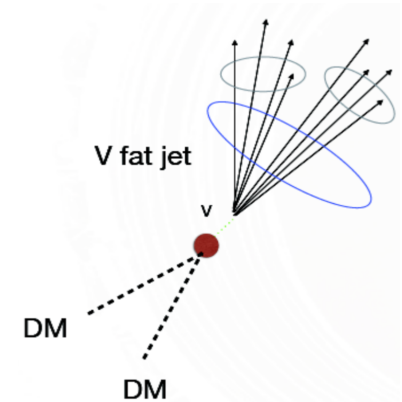
Experimental status

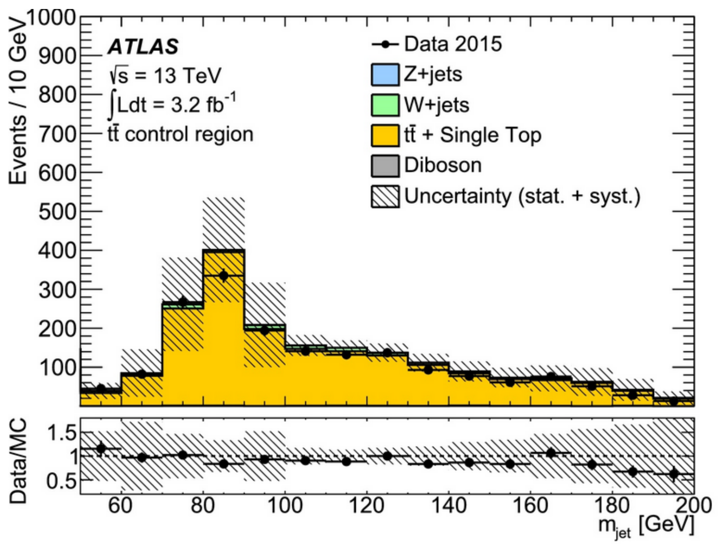
Extension to hadronic mono-V

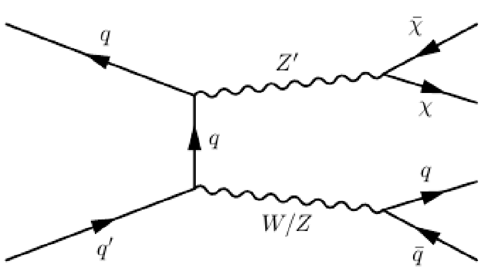
- DM recoils against a hadronically decaying W or Z
- estimate boson mass from a single large merged jet with substructure
- otherwise, analysis similar to monojet
- particularly interesting in production a la Higgs-strahlung, with (pseudo)scalar mediator
  - ISR W/Z production always smaller than monojet

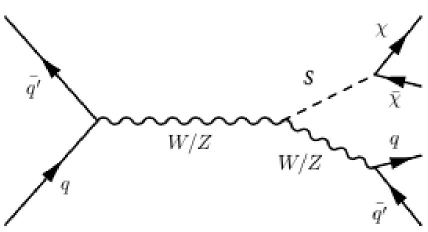
CMS, arXiv:1703.01651 [hep-ex], 12.9fb^{-1}

ATLAS, Phys.Lett. B763 (2016) 251, 3.2fb^{-1}







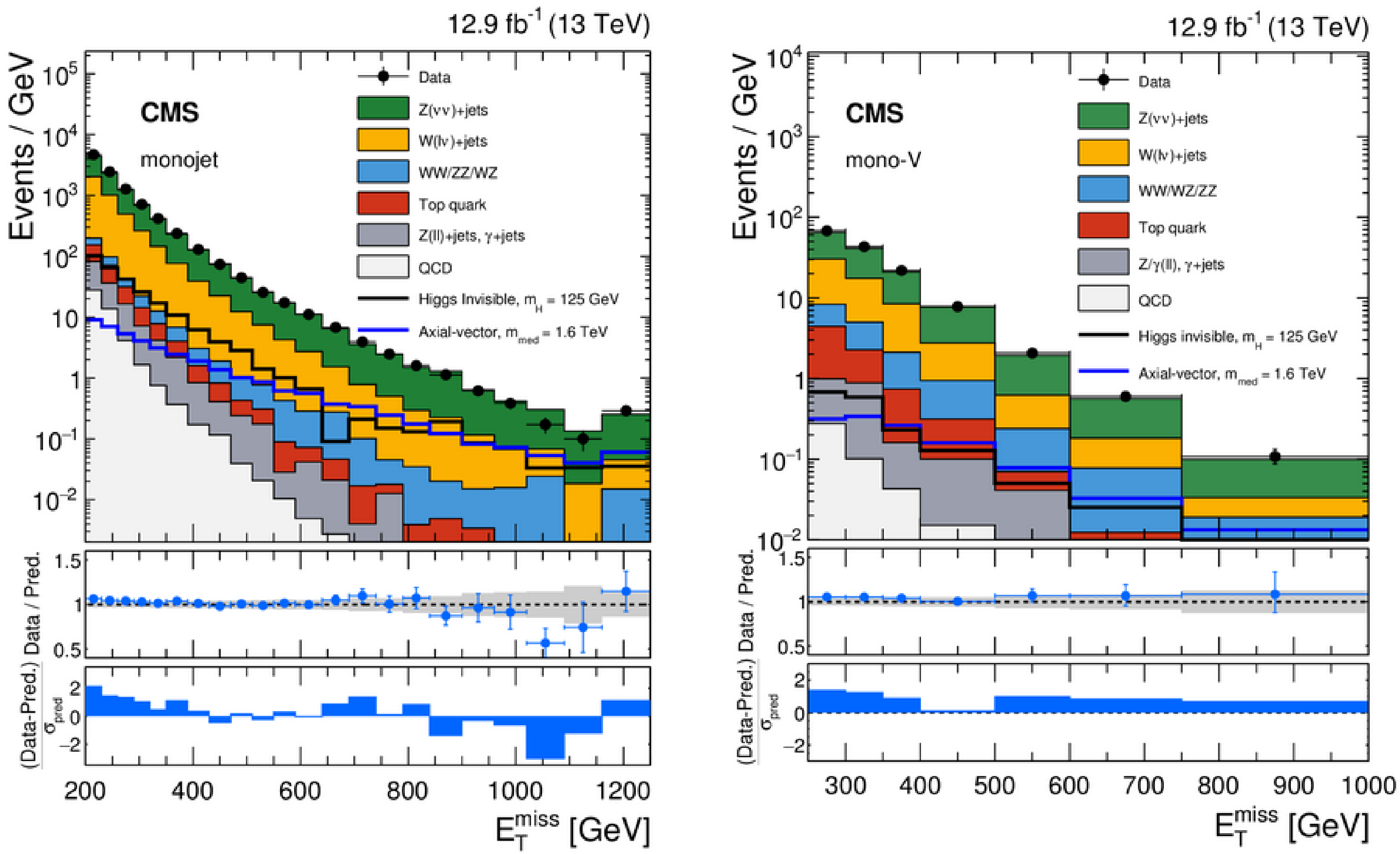


Experimental status

Mono-(V)jet

CMS, arXiv:1703.01651 [hep-ex], 12.9fb^{-1}

- (relatively) good match of data to background prediction



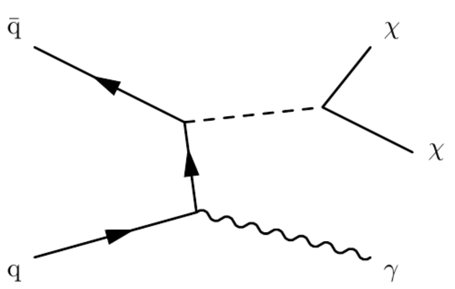
Experimental status

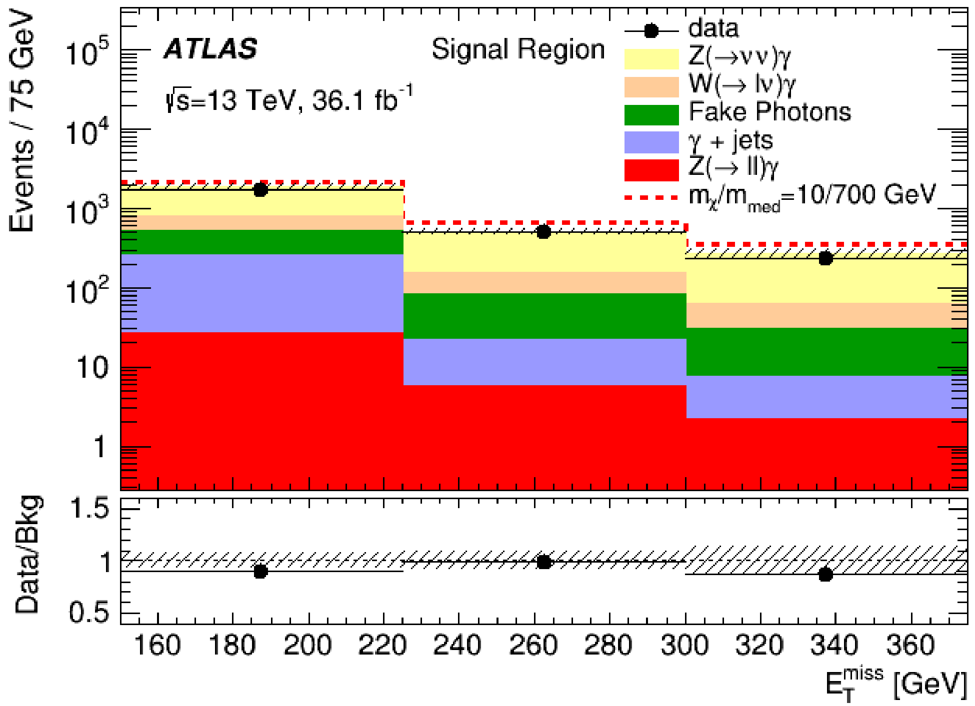
Mono-photon

ATLAS, arXiv:1704.03848 [hep-ex], 36.1 fb^{-1}

CMS-PAS-EXO-16-039, 12.9 fb^{-1}

- DM recoils against a photon from QED ISR
  - clean signal, but $\alpha_{QED} < \alpha_{QCD}$
- difficult instrumental backgrounds
  - jet and electron fakes, beam halo (CMS), spikes (CMS)…
  - all subdominant
- good match of data to background prediction





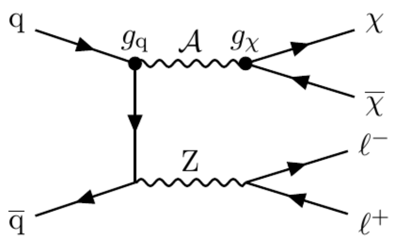
Experimental status

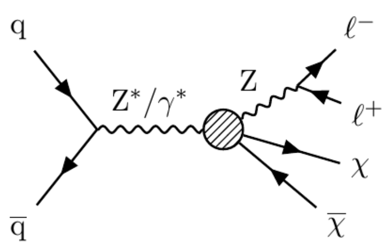
Mono-Z(→ll)

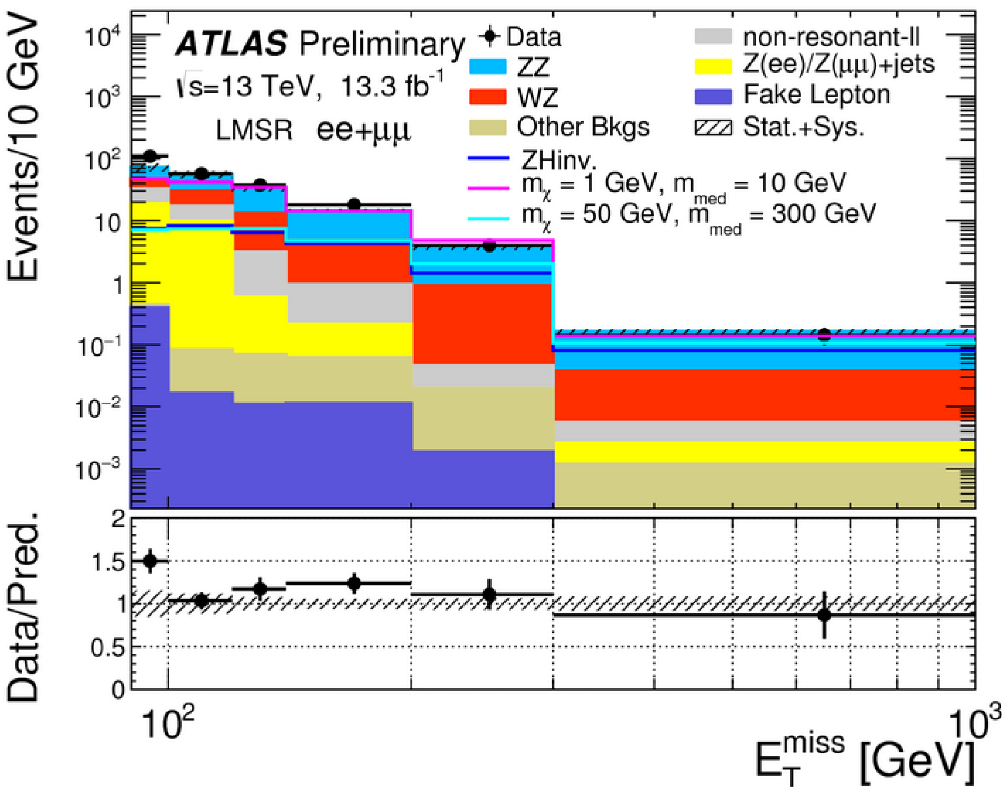
ATLAS-CONF-2016-056, 13.3fb^{-1}

CMS-PAS-EXO-16-038, 12.9fb^{-1}

- DM recoils against a Z boson
  - can arise from "EWK ISR" or from "DM-strahlung"
- very clean backgrounds
  - except at low MET:
    DY + jet mismeasurements
- good match of data to background prediction







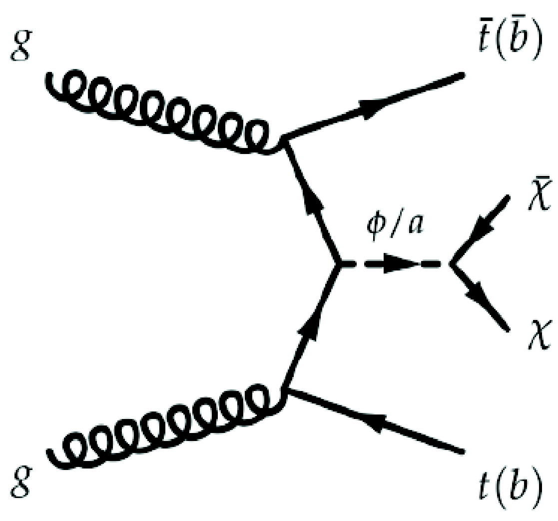
Experimental status

MET + tt

ATLAS-CONF-2016-077/050/076, 13.3fb^{-1}

CMS-PAS-EXO-16-005/028, 2.2fb^{-1}

- DM produced in association with t quarks
- of interest for (pseudo)scalar interactions with Yukawa-like couplings
  - Higgs-like production



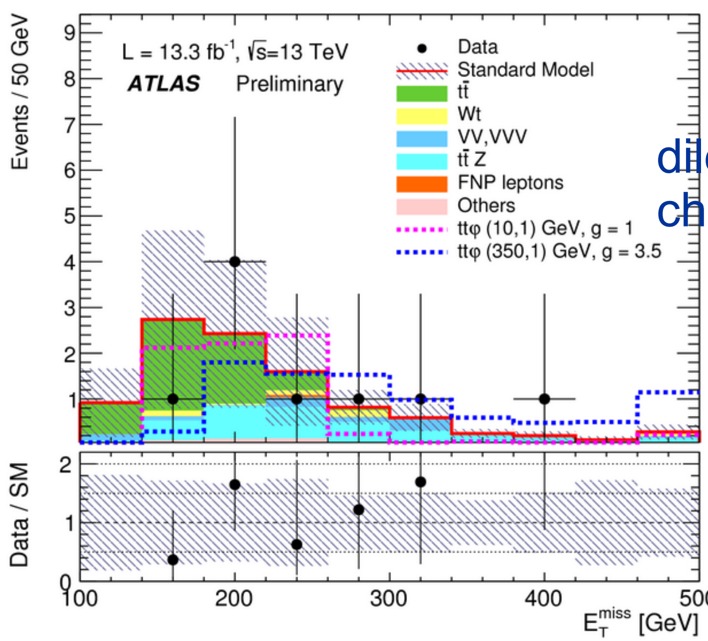
- MET as sensitive observable
- all 3 channels searched in
  - hadronic, lepton+jets, dilepton
- jet substructure being used
- currently sensitive at low mediator mass
  - means low MET, means quite similar to SM ttbar
  - or high coupling

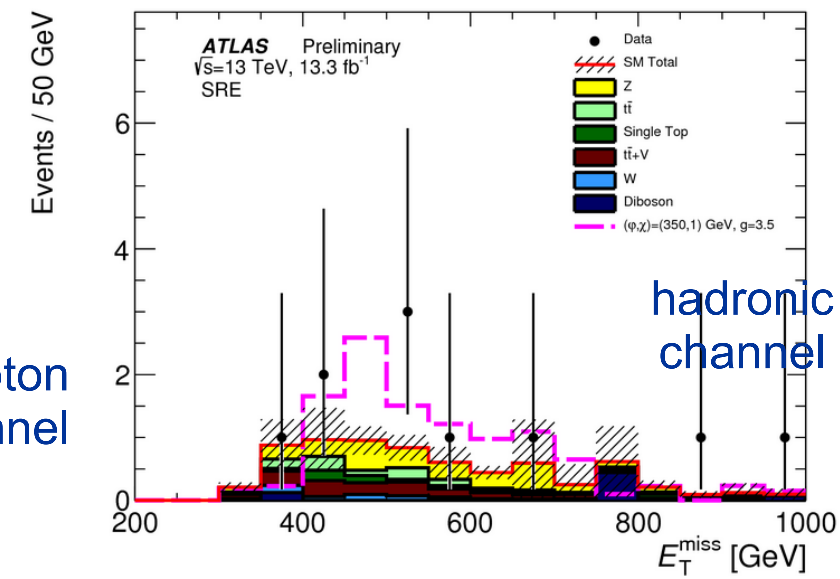
Experimental status

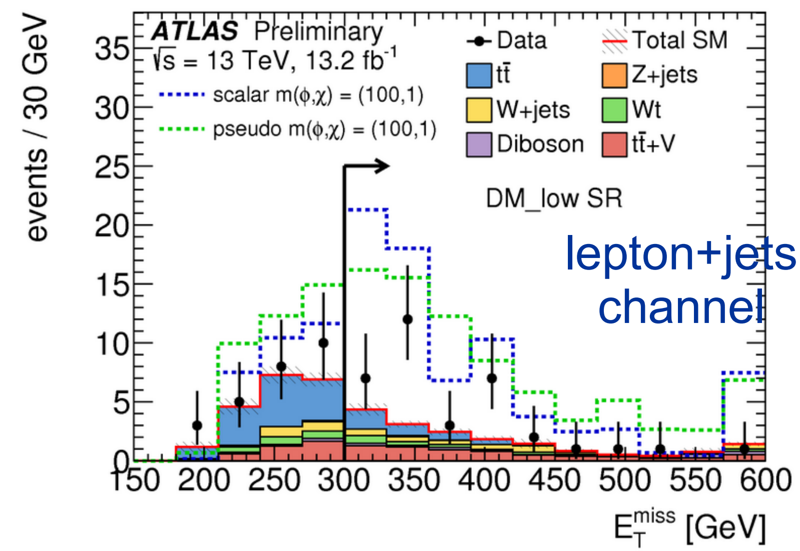
ATLAS-CONF-2016-077/050/076, 13.3fb^{-1}

MET + tt

- good match of data to background prediction







- channels with lots of progress expected in 2017!

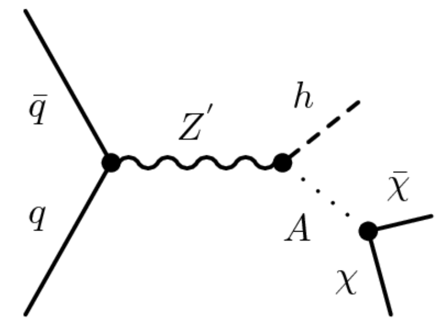
Experimental status

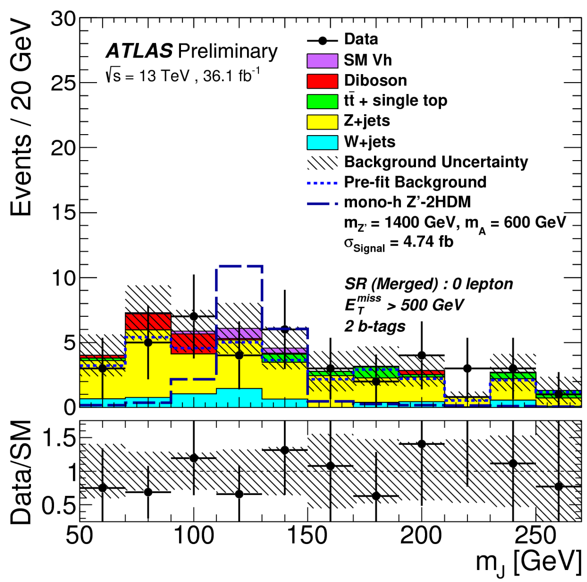
Mono-H(→bb) and mono-H(→γγ)

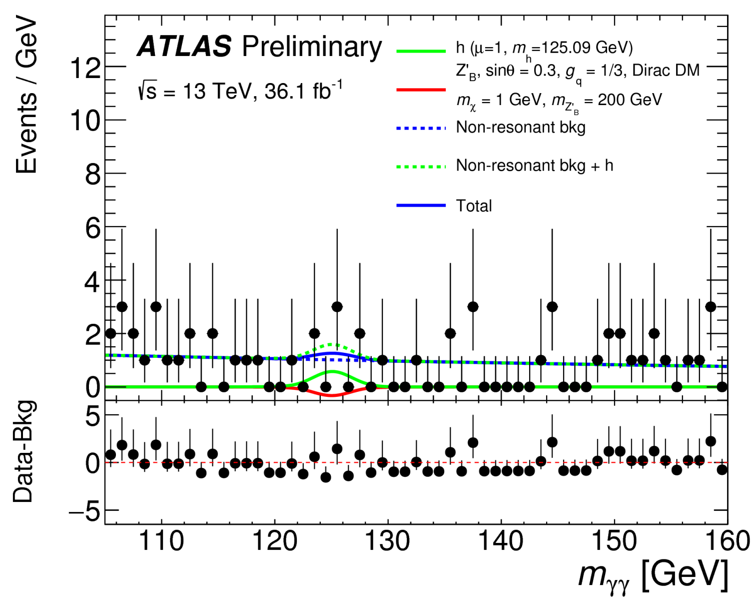
ATLAS-CONF-2017-028/024, 36.1fb^{-1}

CMS, arXiv:1703.05236, 2.3fb^{-1}

- DM recoils against a Higgs boson
- need to boost production cross section with dedicated models (eg. Z'-2HDM)
  - Higgs initial state radiation as good as zero
- H(→bb): resolved m(jj) and merged m(J)
- H(→γγ): fit to m(γγ) spectrum







$E_t^{miss}/\sqrt{\Sigma E_T} > 7\sqrt{GeV}$

$p_T^{\gamma\gamma} > 90GeV$

Experimental status

Other searches for direct DM production

- mono-top: DM recoils against a single top quark
  - specific flavour-changing simplified model, resonant and non-resonant
  - background shared between Z(→vv) and ttbar

  CMS-PAS-EXO-16-040, 12.9fb^{-1}

- b(b)+MET: DM recoils against b quarks
  - MET>150GeV, jets far apart
  - very tough signal due to small fiducial cross section

  ATLAS-CONF-2016-068, 13.3fb^{-1}

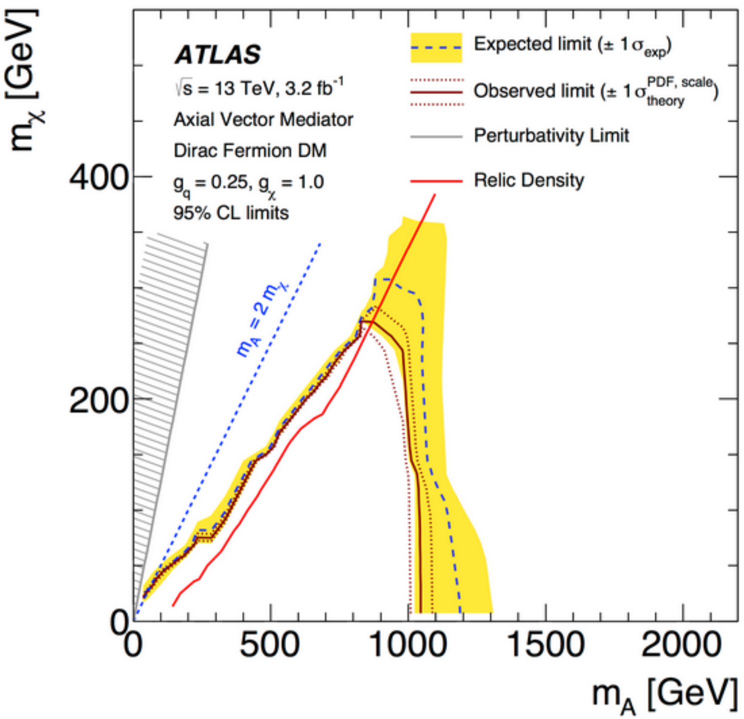
- + others

Interpretation of results

- all analyses found data compatible with background expectation
- provide exclusion limits on assumed signal models → simplified models!

- simplified models allow to map out all mediator masses
  - resonant enhancement when mediator produced on-shell (s-channel)
  - limits suppressed when going off-shell for $m_{med} < 2*m_{DM}$
  - cross section drops at high mediator mass

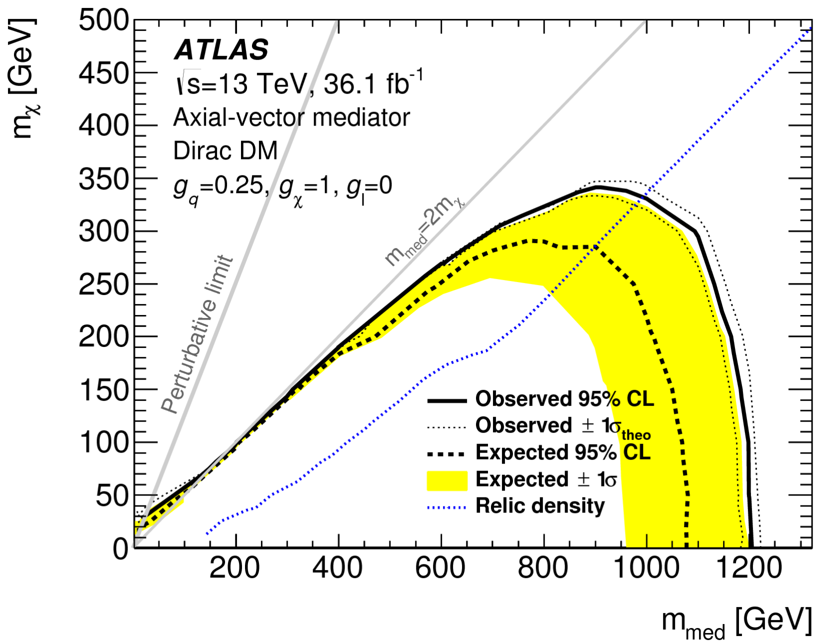
- always mind assumptions:
  - mediator type
  - coupling values
  - …



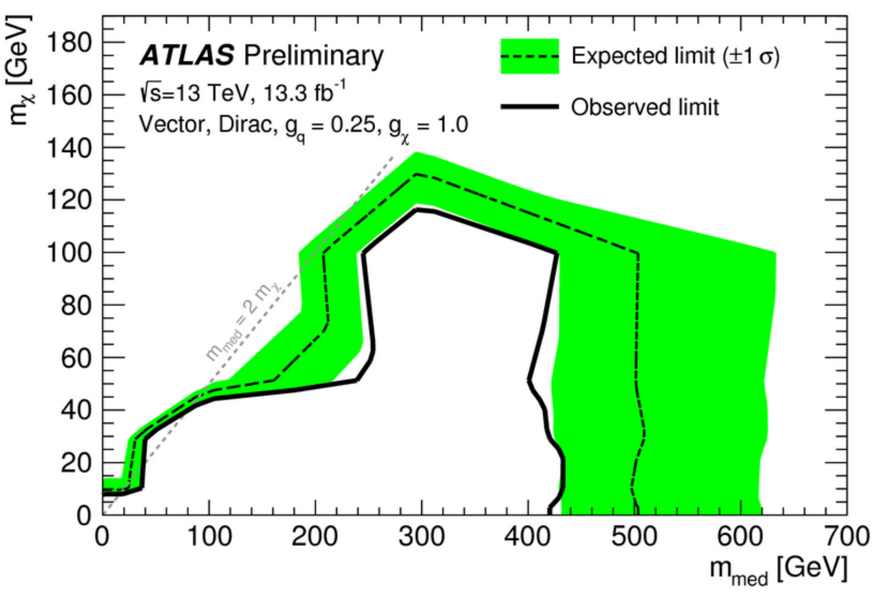
mono-jet
Phys. Rev. D94 (2016) 032005

Interpretation

mono-photon
arXiv:1704.03848 [hep-ex]

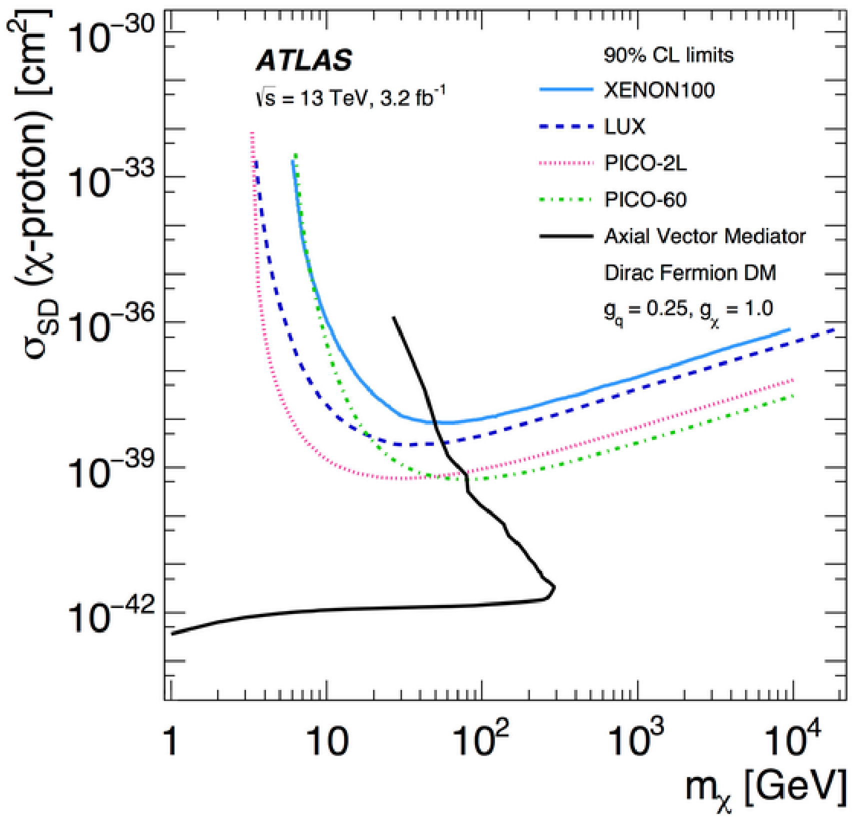


mono-Z(→ll)
ATLAS-CONF-2016-056



Interpretation

- the comparison of simplified models in the WIMP-DM cross section versus DM mass plane can be done unambiguously
  - advantage: visualizes the complementarity of the collider and DD/ID searches → eg. low versus high mass, vector versus axial-vector, etc
  - disadvantage: must be careful, oversimplification can lead to misinterpretation → must properly specify model, parameters and assumptions



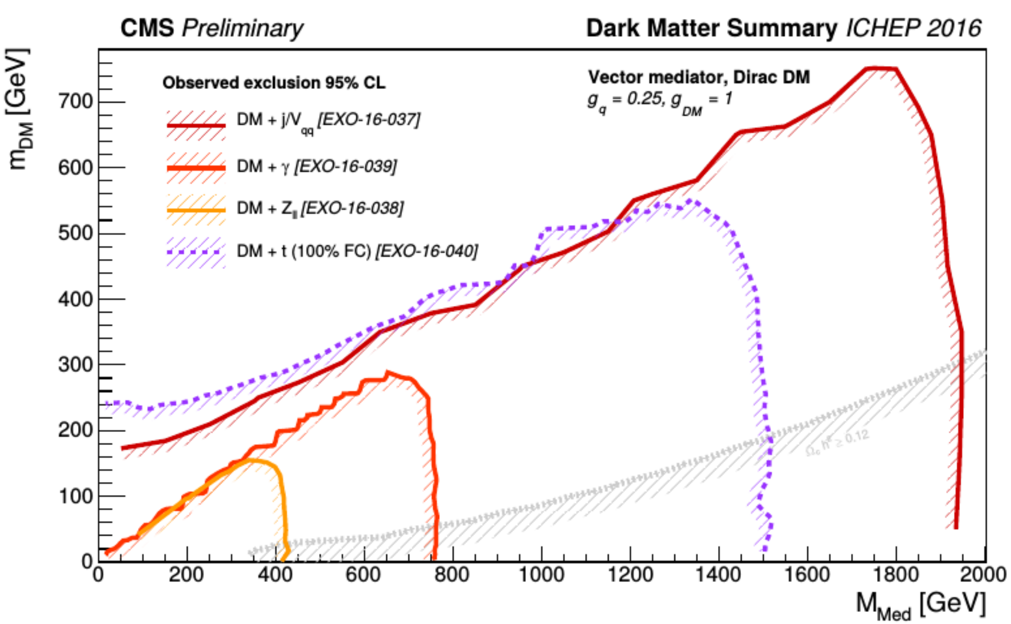
- comparison standardization by the LHC DM WG
  - arXiv:1603.04156 [hep-ex]

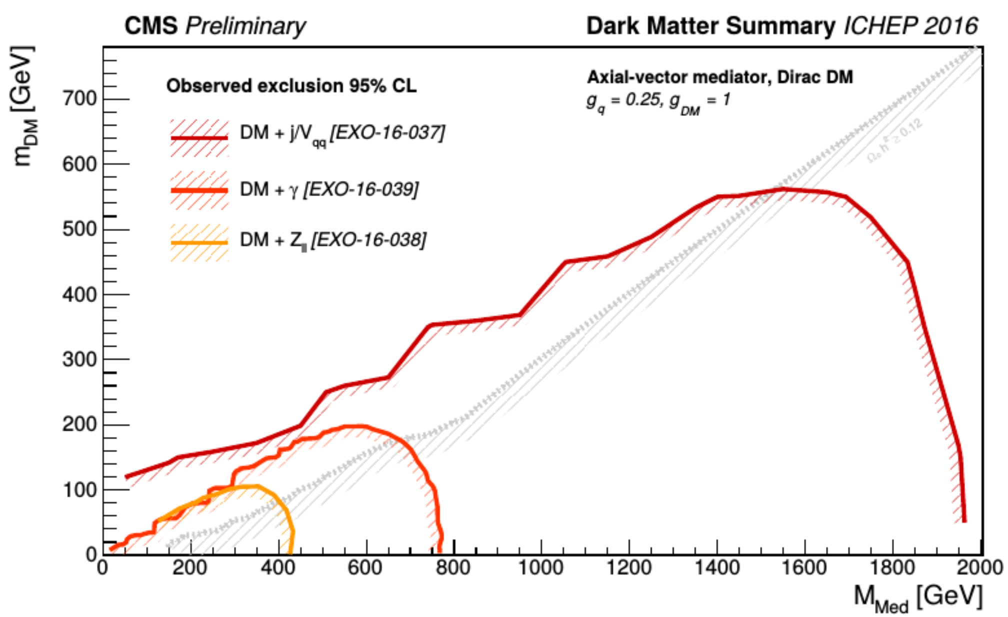
    "Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter"

Interpretation

Summary of spin-1 channels

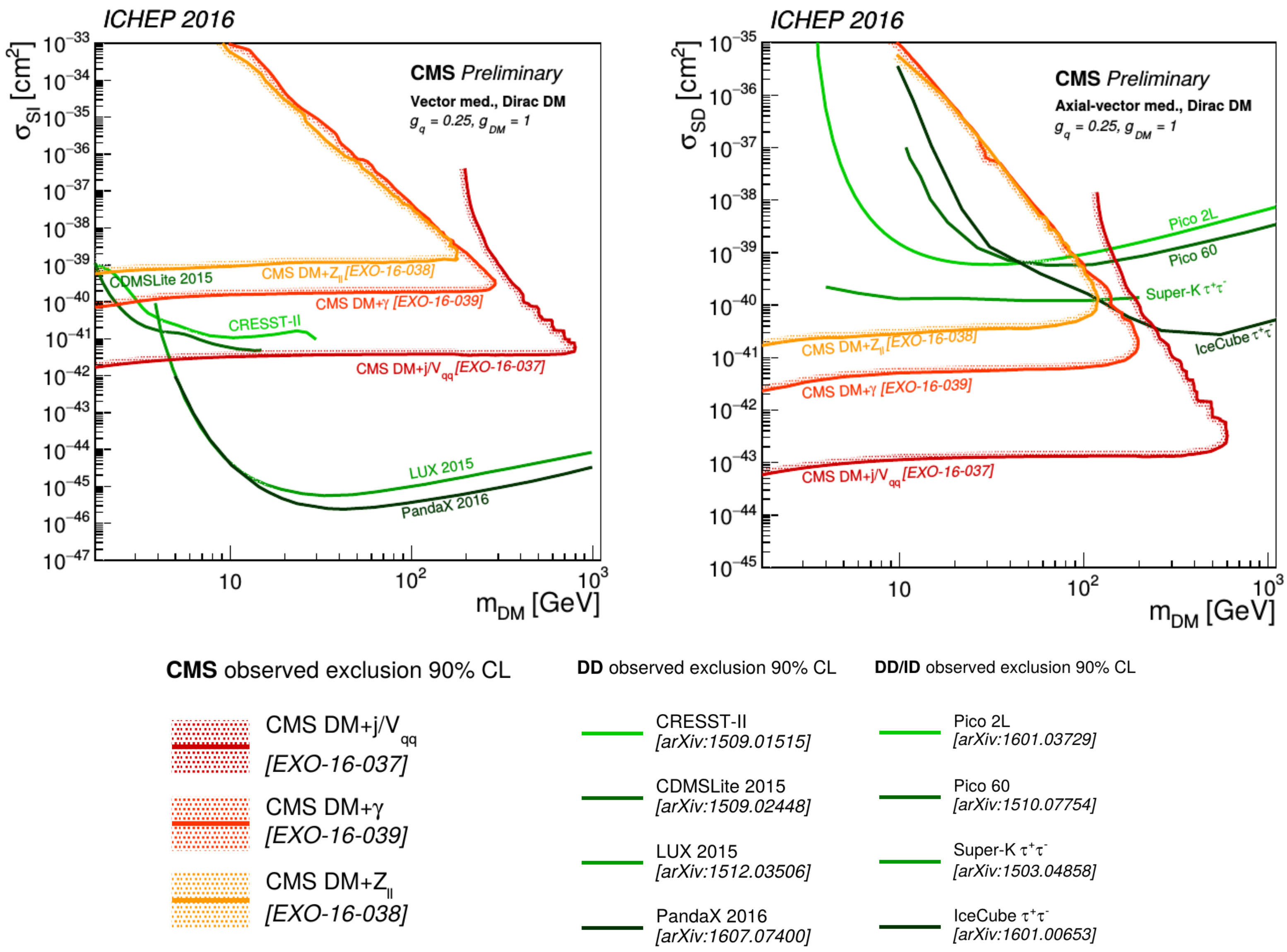
- monojet most sensitive because of “H” in LHC acronym
- reached 2TeV → further jumps in reach need much more luminosity
  - or significantly lower couplings
  - or a higher-energy collider





Interpretation

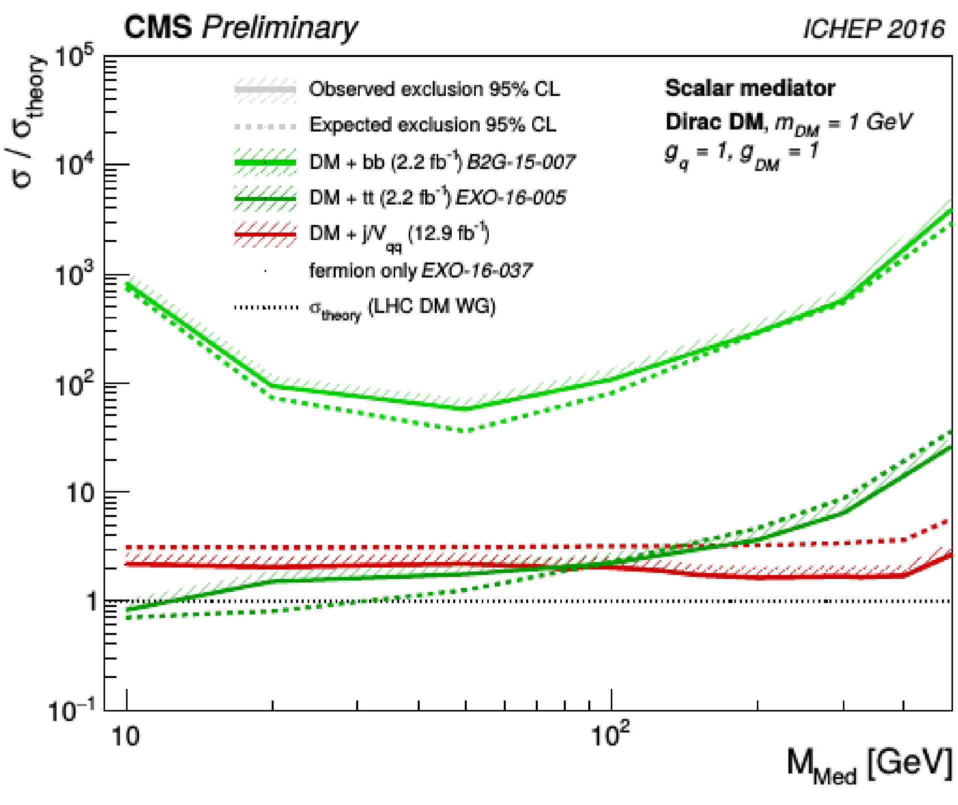
- translation to direct-detection plane

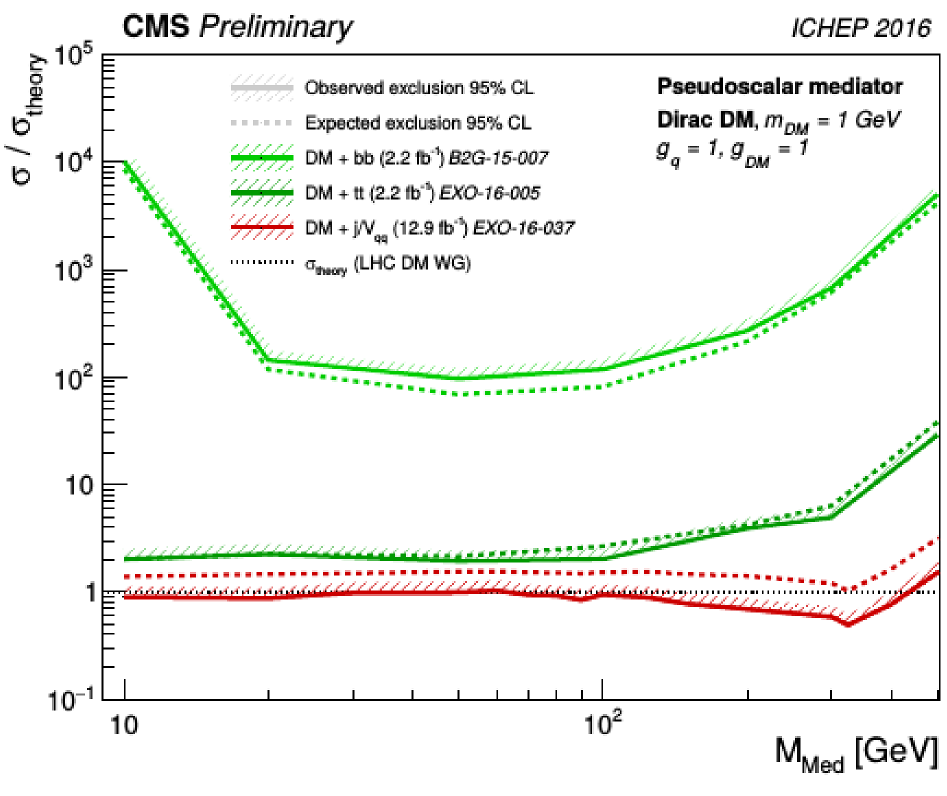


Interpretation

Summary of spin-0 channels

- ttbar most sensitive at low mass, monojet at high mass
- only scratched the surface so far → lots of progress expected in 2017

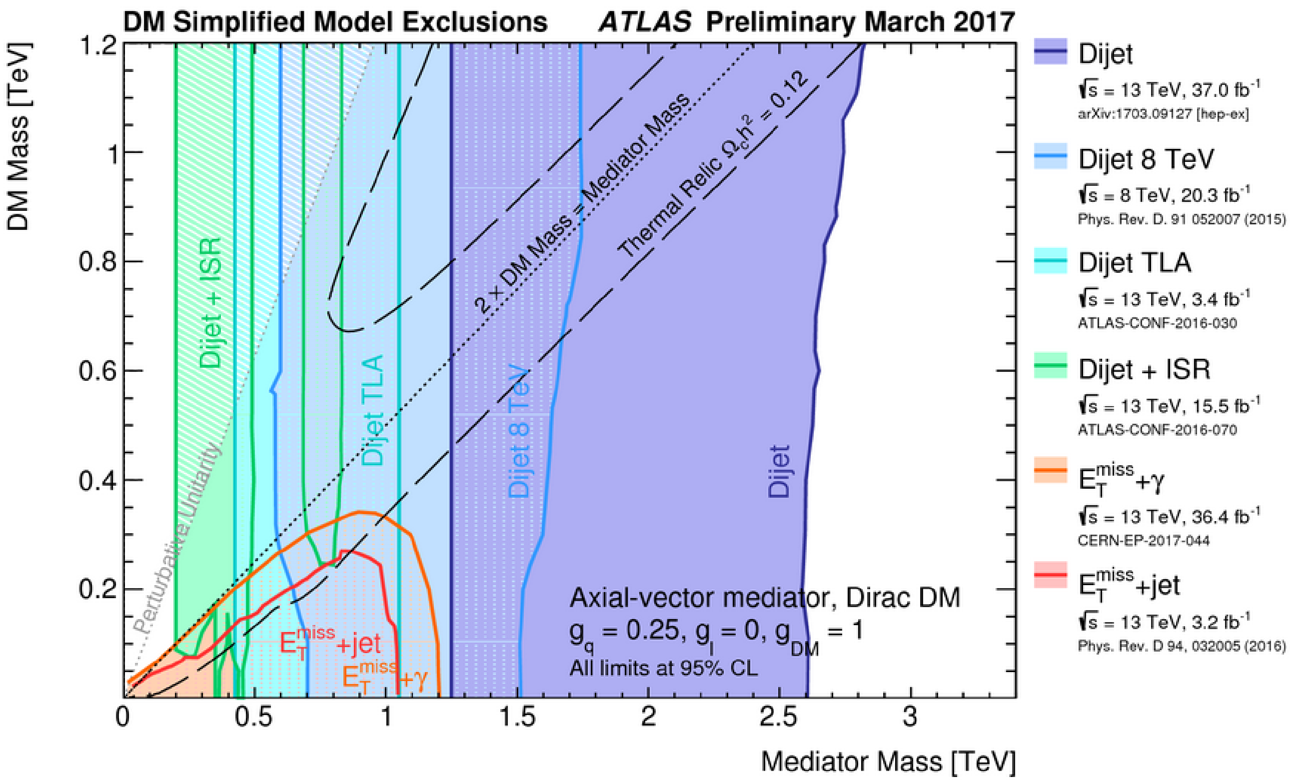




Other searches

Visible mediator searches

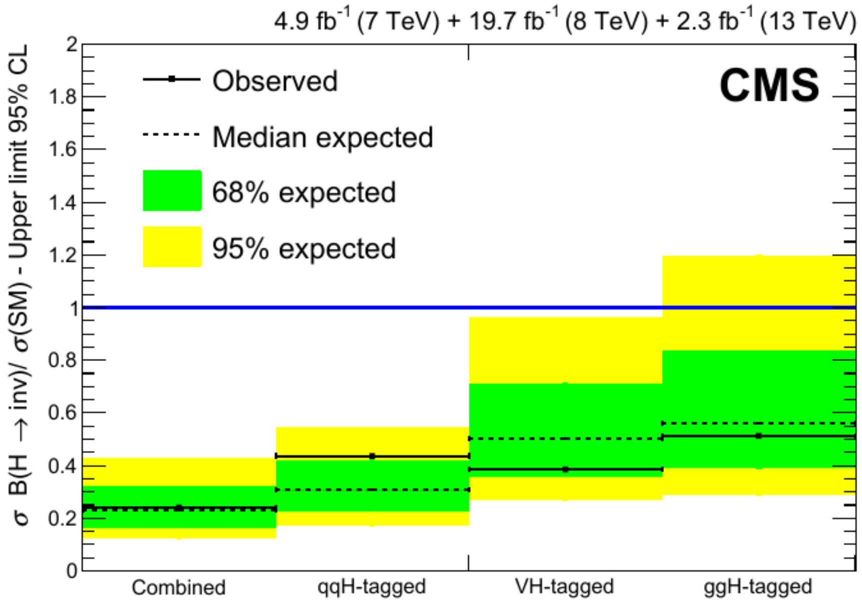
- dark matter searches can be constrained by visible decays of the mediator
  - complementary information to the invisible decays into Dark Matter
- guaranteed: dijets – possibly: dileptons
  - coupling choices very important!

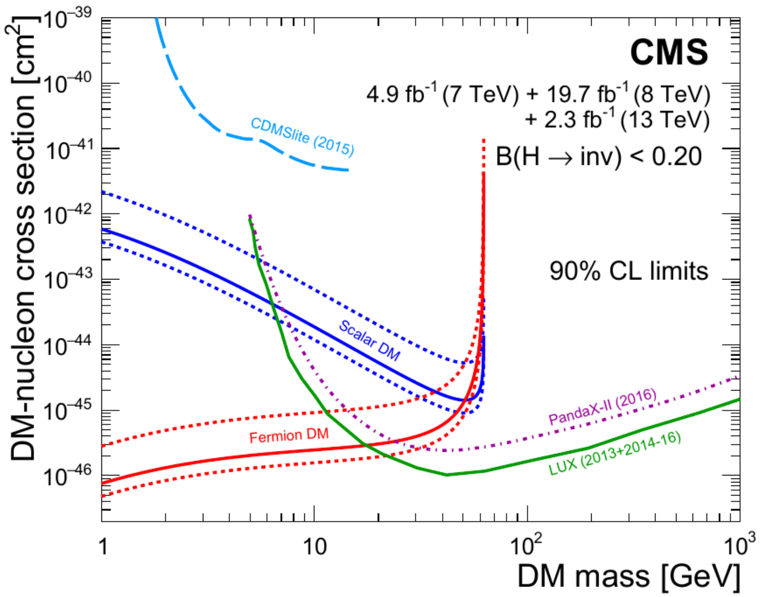


Other searches

DM from Higgs decay

- H → invisible: DM production through the Higgs portal
  - for DM mass below $m_H/2$
- 3 channels:
  - qqH VBF production
  - Z(→ll) H(→inv)
  - latest addition: monojet
- BR(H→inv) < 24%
- both ATLAS and CMS results still dominated by 8TeV
  - lots of progress to be made





arXiv:1610.09218 [hep-ex]

ATLAS-CONF-2016-056

The next horizon

Beyond minimal models

- simplified models were great for initial exploration
  - "done with V and AV"
- now things are moving towards more realism/complexity in scalar sector
  - extra scalar with H mixing (arXiv:1607.06680 [hep-ex])
  - current 2HDM exploration in LPCC DM WG
  - t-channel production
  - ideas beyond MFV
  - beyond the WIMP
  - …

Outlook

- The LHC has a large dark matter program
  - missing momentum signatures and visible mediator searches
  - complementarity to direct and indirect searches
  - a top priority for LHC
- LHC Run-II going full speed
  - analysis of 2016 data intensely proceeding
  - factor 3 more collisions during LHC Run-II
- many developments in the pipeline
  - scalar sector exploration
  - beyond simplest simplified models
  - more exotic scenarios

Thank You

"I'm sorry I know so little.
I'm sorry we all know so little.
But that's kind of the fun, isn't it?"

(Vera Rubin)