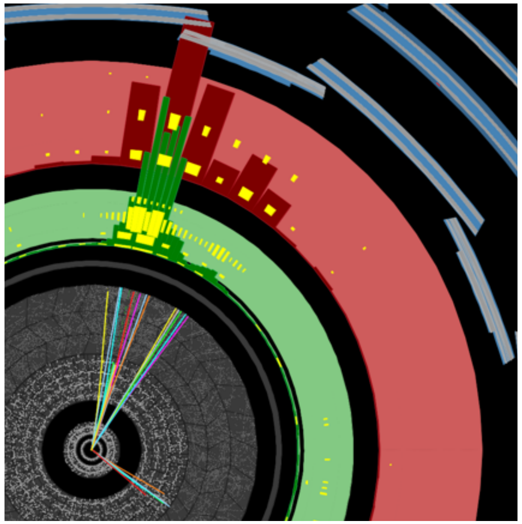
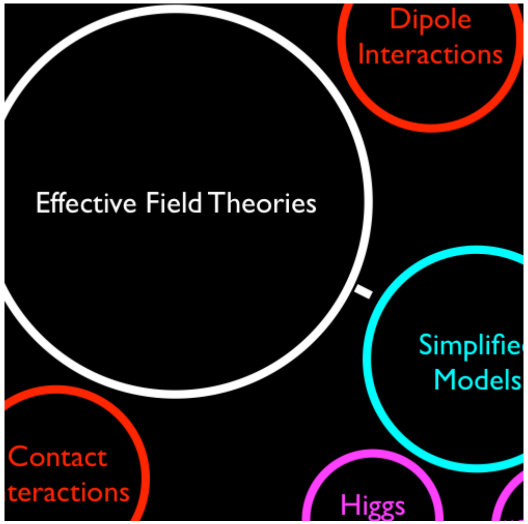
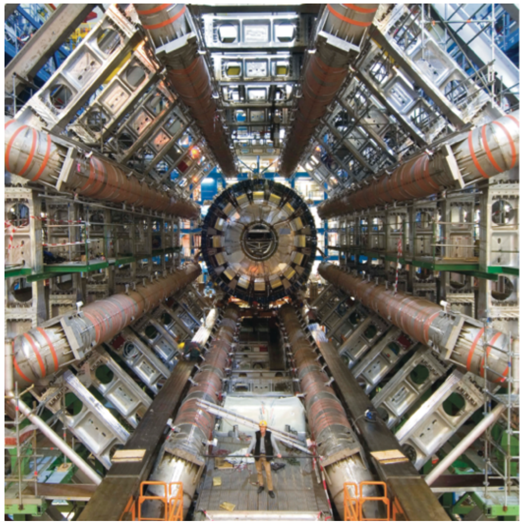
Recent Developments in the Search for Dark Matter @ LHC

Steve Worm
University of Birmingham
June 14, 2017

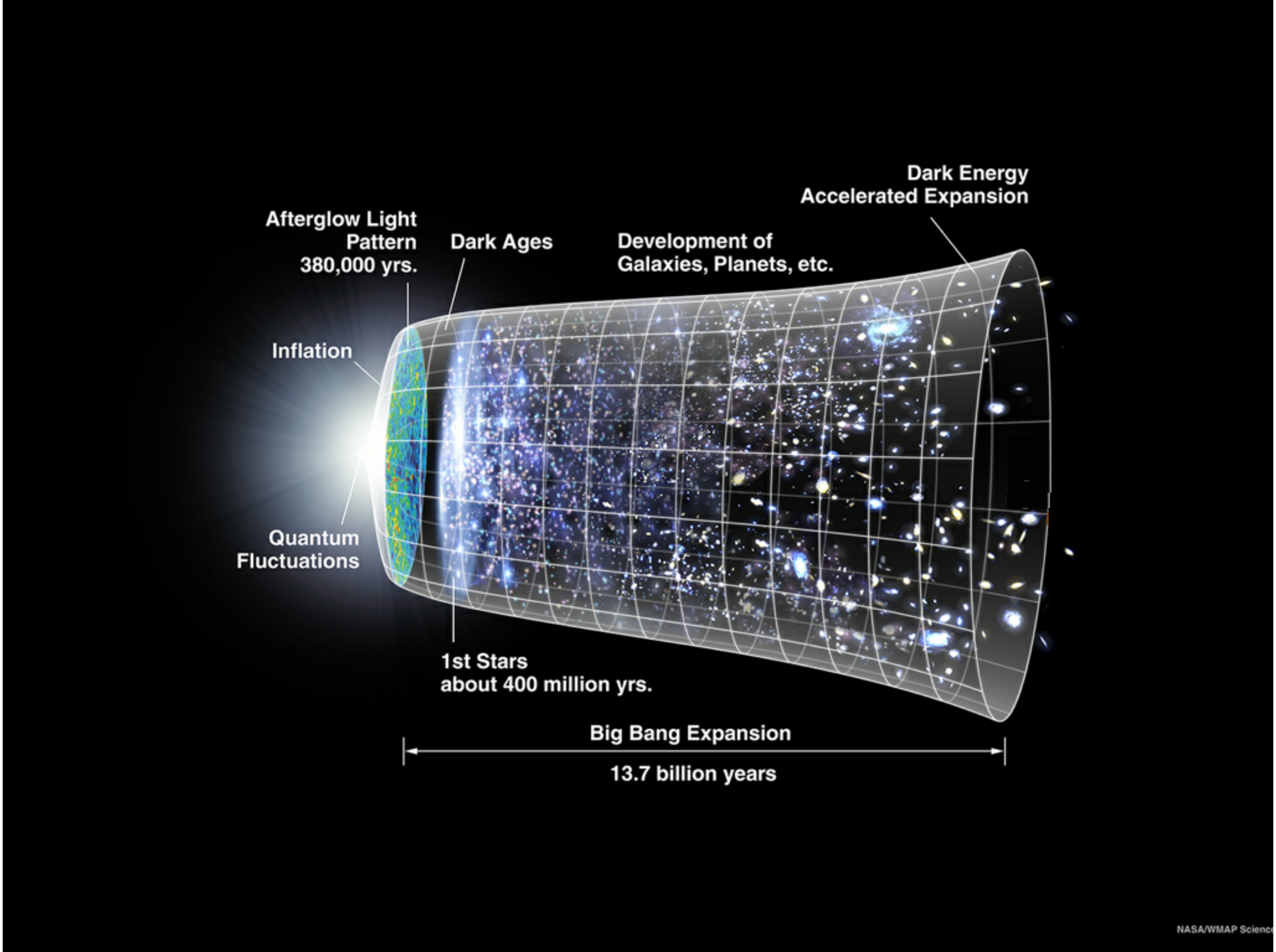




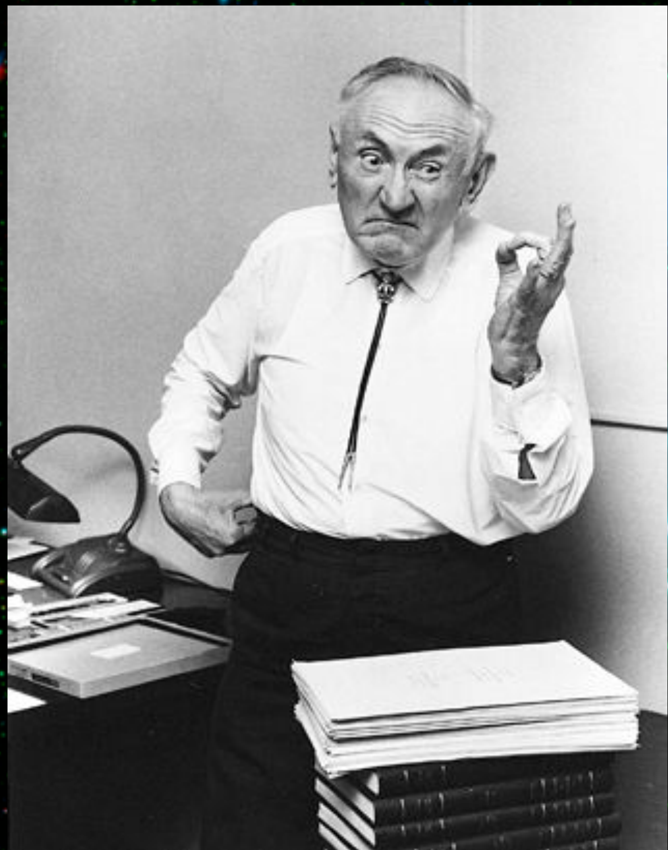


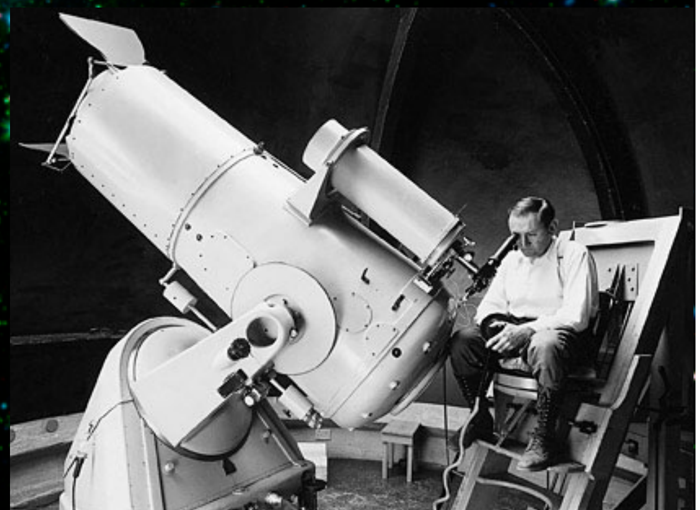
OUTLINE

- Intro to particle Dark Matter
- A bit of history: Monojets in UA1 & CDF
- "Generic" searches for DM at the LHC
- Recent Results I: EFT to Simplified Models
- Recent Results II: Mediator and New Searches
- Conclusions


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science

In 1933, Fritz Zwicky calculated the mass of the Coma cluster using galaxies on the outer edge, and came up with a number 170 times *larger* than expected.





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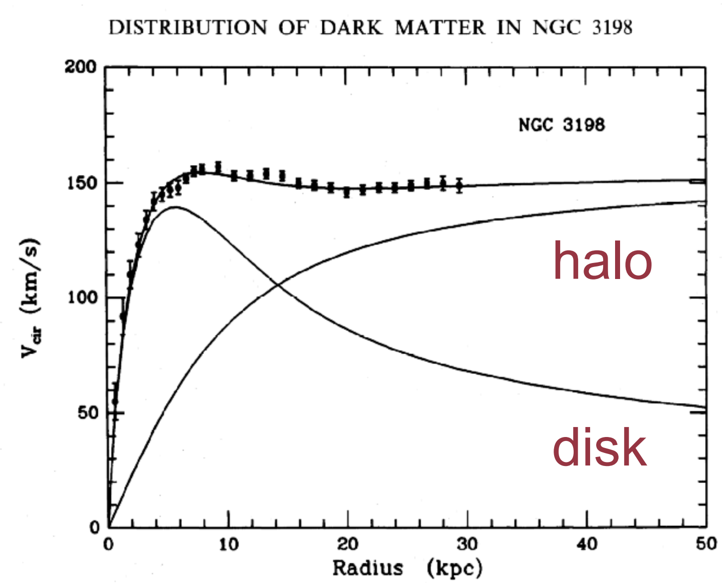
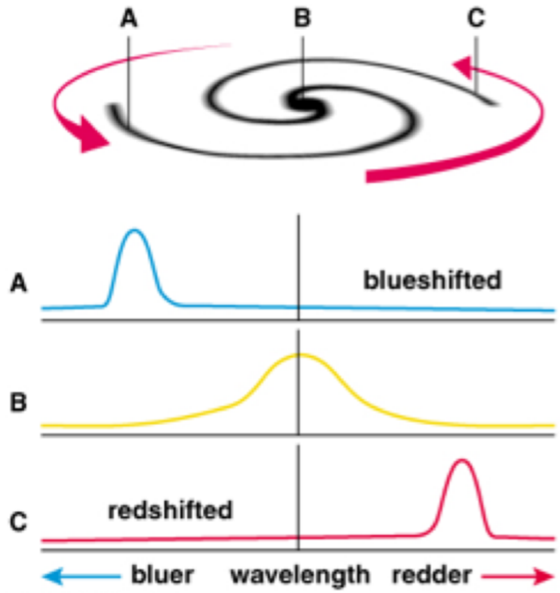
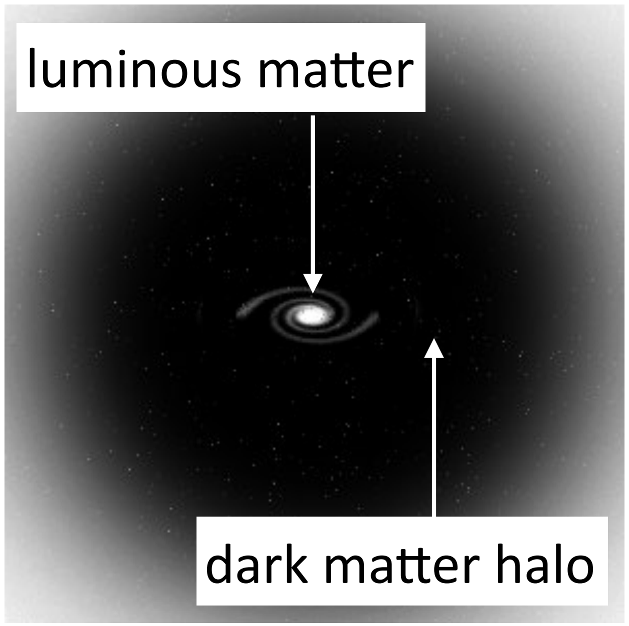
GALACTIC ROTATION

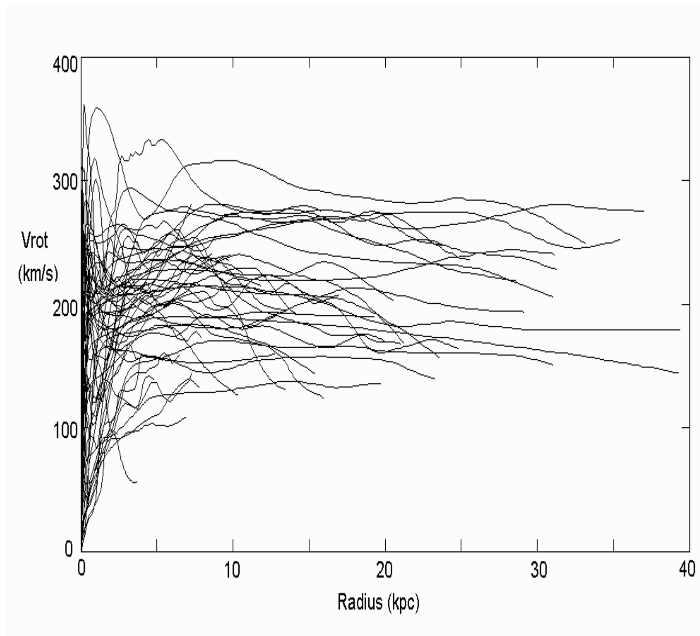
- Starting in the 1970's, measured velocity vs. radius of edge-on spiral galaxies
- They found them to be flat, consistent with ~6x as much "dark" mass...

...and not just one galaxy



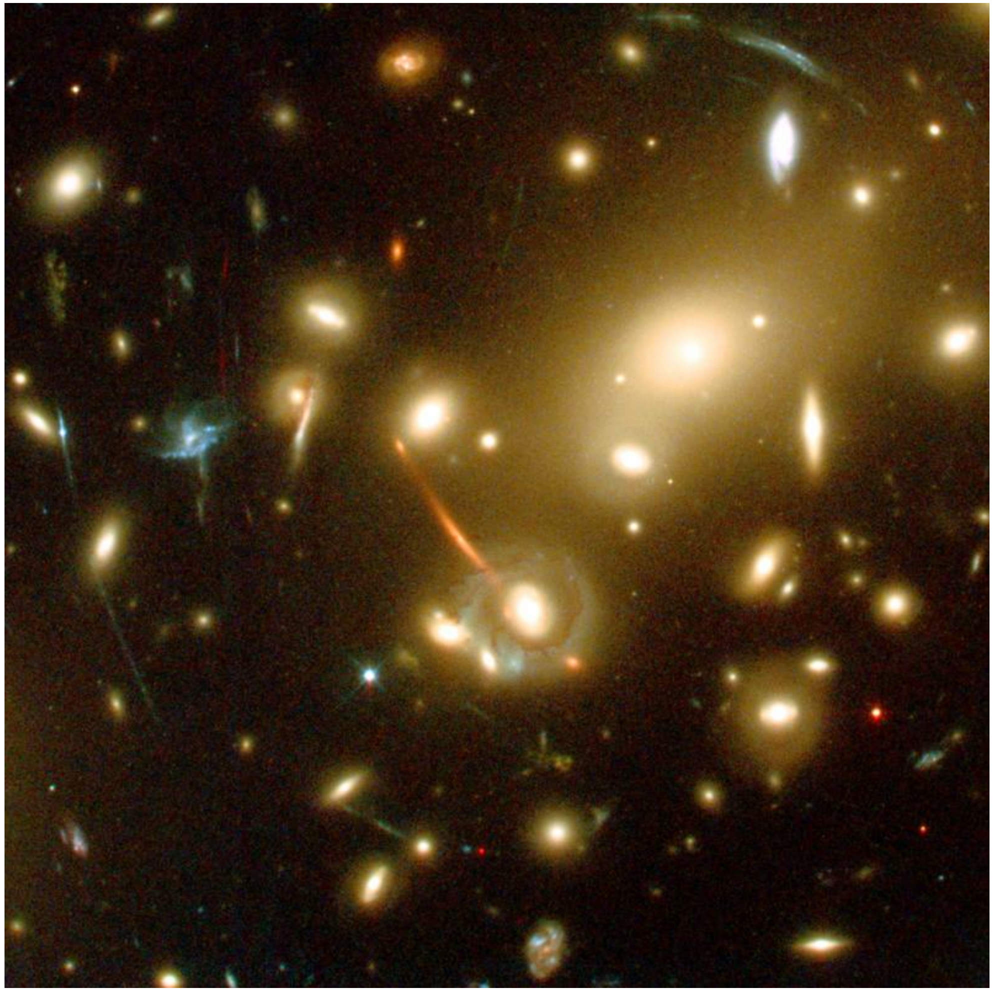


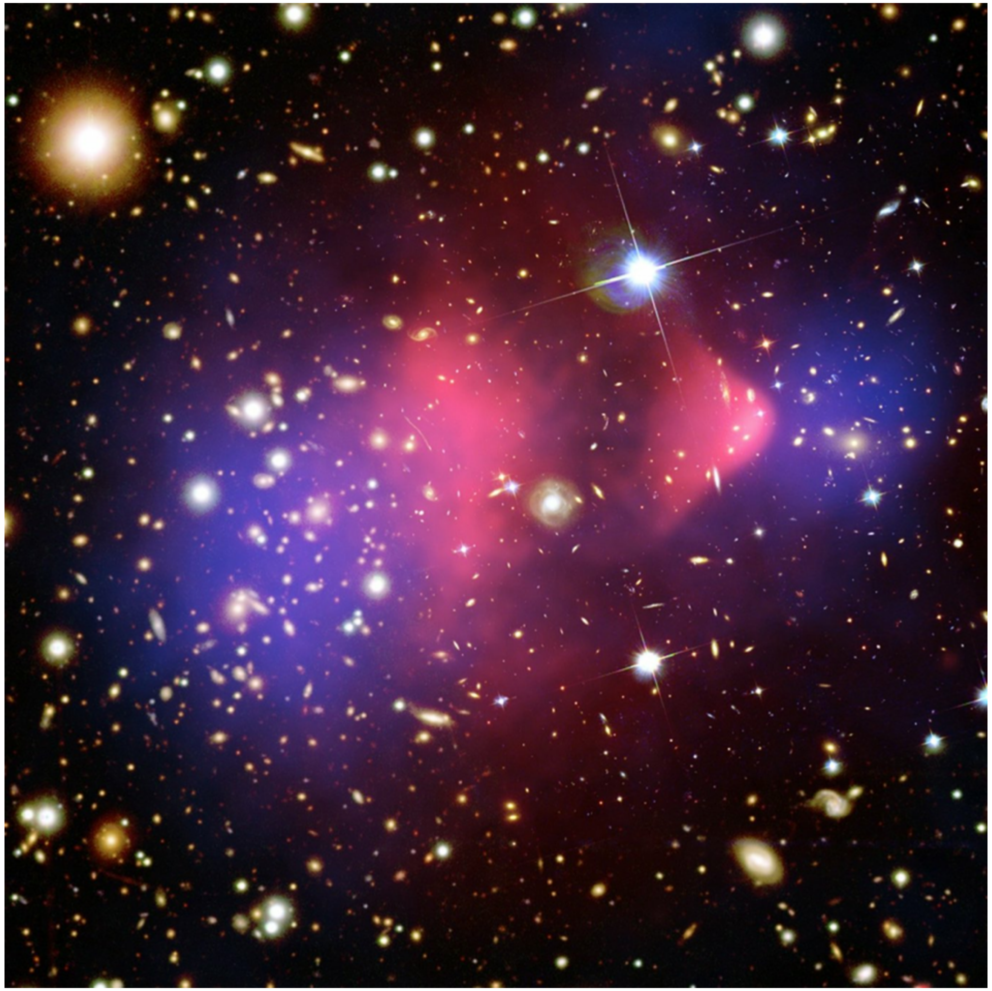




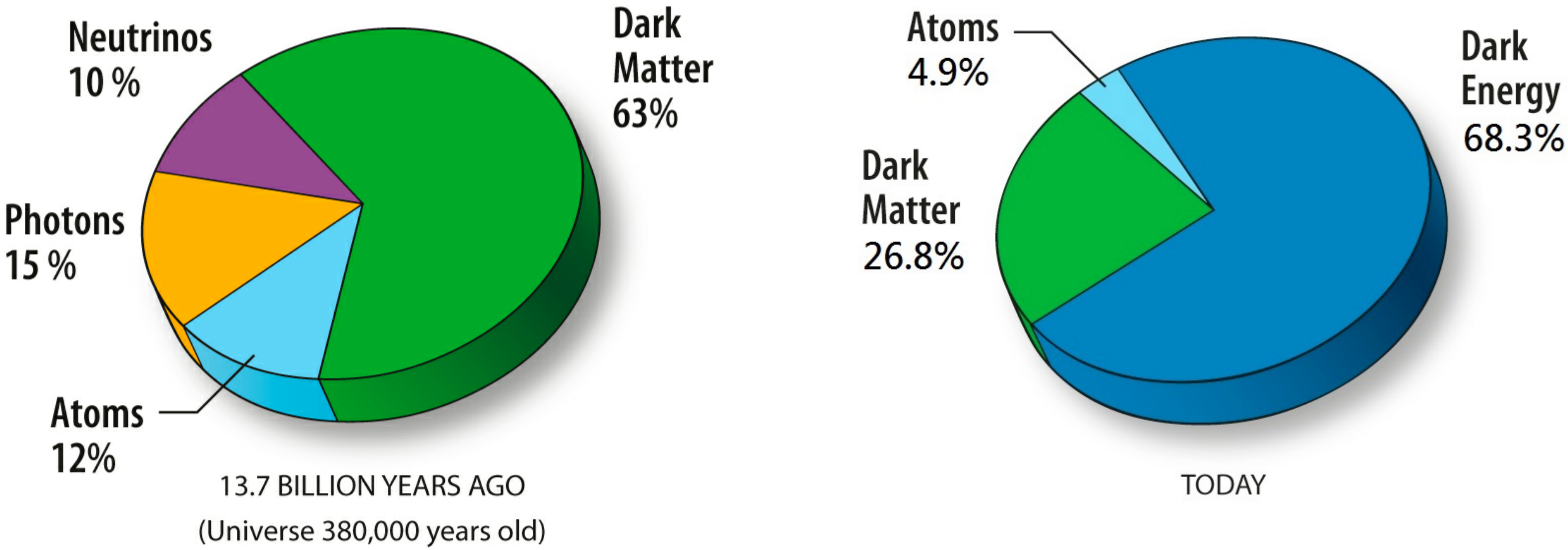
Evidence Piling Up...

- Gravitational Lensing
  - much more lensing than can be explained by visible mass
- Bullet Cluster; colliding galaxies
  - Composite x-ray, visible image, 10x DM
  - Does not really match modified gravity





The Universe, Then and Now



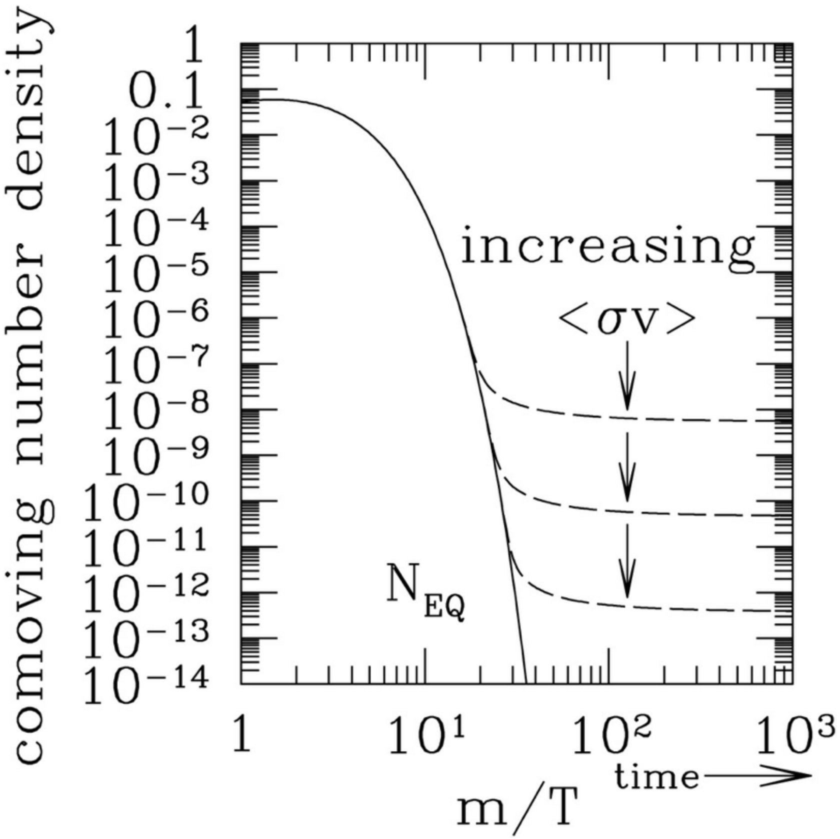
- Strong astrophysical evidence for the existence of dark matter
  - Evidence from bullet cluster, gravitational lensing, rotation curves
  - DM is six times more abundant than baryons
  - Contributes ~1/4 of the total energy budget!

Particle description of DM... testable at the LHC?

WIMPs

- Perhaps Dark Matter is a particle with weak-scale mass?
  - *Weakly Interacting Massive Particles (WIMPs)*
  - Produced in the Big Bang, interact via $\chi + \chi \rightarrow q + q$

- As the universe expands and the temperature drops...
  - WIMPs become diluted, interact less often and ‘freeze out’.
  - Higher cross-section (<σv>) yields lower relic density

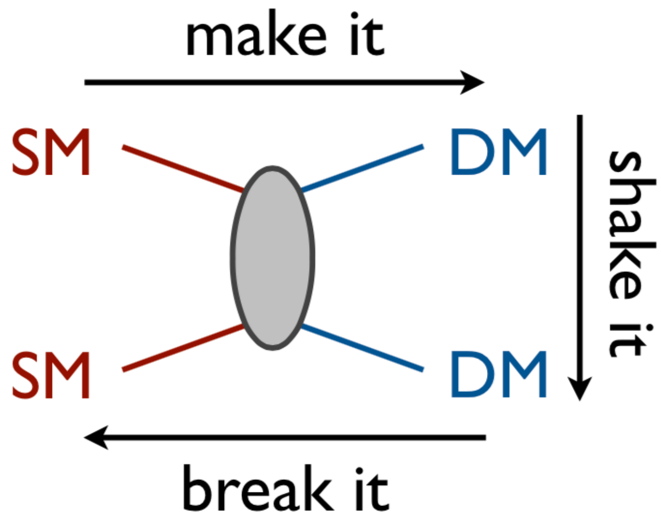


Weakly-interacting massive particles naturally provide the right relic abundance - “WIMP miracle”

Complementarity and Collider Production

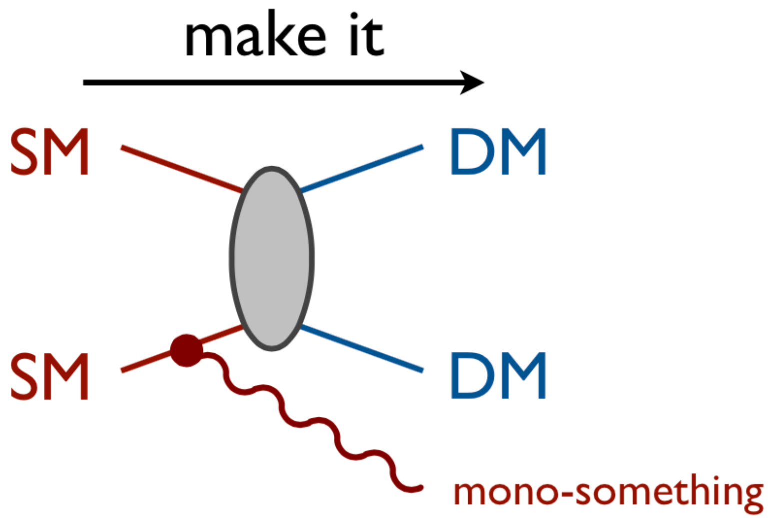
DM complementarity:

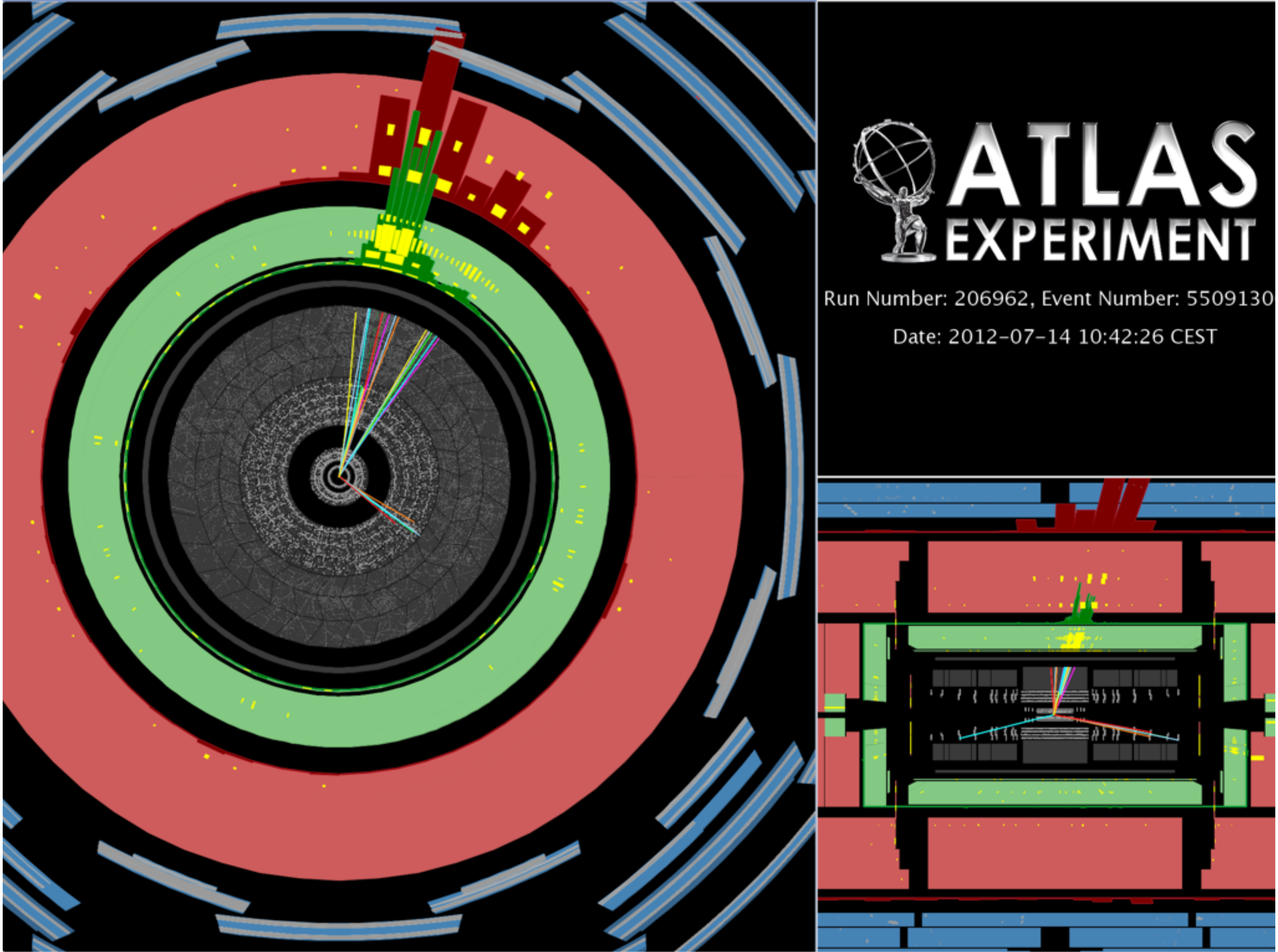
- Colliders make, direct detection shakes, indirect detection breaks… and also CMB (bake it!)



"Generic" Collider searches:

- Dark Matter production gives missing transverse energy (MET)
- Initial-State Radiation results in "mono-something" plus MET




ATLAS
EXPERIMENT
Run Number: 206962, Event Number: 5509130
Date: 2012-07-14 10:42:26 CEST

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON (S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

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SUPERSYMMETRY DISCOVERED in 1984!

Received 30 March 1984

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON (S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

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Supersymmetry theory decaying

Christine Sutton

DOES supersymmetry exist? Theorists in particle physics began to ask that question a few months ago. Initially, the answer seemed to be "maybe". Now it is changing to "maybe not", particularly in the light of recent calculations that show how certain phenomena can mimic some of the predicted effects of supersymmetry.

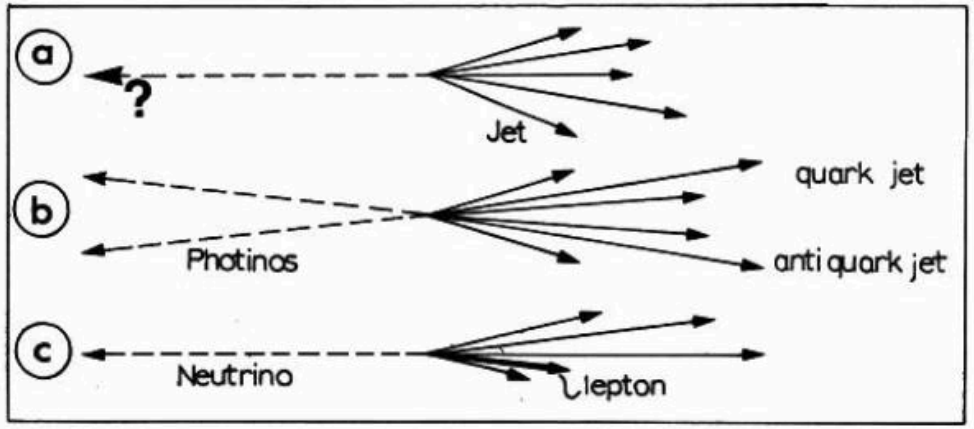
Supersymmetry is symmetry so neat that many physicists want it to be true—the more so because supersymmetry might offer a pathway to a quantum theory of gravity and hence to a completely unified theory of all the fundamental forces (*New Scientist*, 15 March 1984, p 28). The main feature of supersymmetry is that it links the particles of matter—"fermions"—with the particles that carry the fundamental forces—"gauge bosons". The two categories of particle simply become different facets of the same underlying object.

The possible evidence that supersymmetry is a real symmetry which nature respects comes from CERN, the European centre for particle physics. There, an international team of researchers running the experiment known as UA1 discovered a puzzling phenomenon.

The UA1 experiment straddles CERN's main particle accelerator at a point where

theoretical speculation about what they represent; it seemed at first that even as few as five examples were too many to account for by standard theories of particle physics. The proponents of supersymmetry were among those who snatched the monojets to support their cause.

For supersymmetry to link matter particles (fermions) such as quarks, with force carriers (gauge bosons) such as gluons, nature must find new counterparts to all the known particles. For each known fermion (gauge boson) there must exist a bosonic (fermionic) partner. Thus the



A "monojet" (a) is a jet of energetic charged particles, with energy "missing" in the opposite direction, produced when a proton and an antiproton collide. This could, for example, be due to the decay of a squark and antisquark, into two undetected photinos and a quark and antiquark, each of which produce coalescing jets (b). In the alternative scenario, a W particle produced at the same time as a jet (c) will decay into an unseen neutrino and a charged lepton, which may be lost in the jet

each incorporating some hitherto unobserved phenomenon, such as a new kind of neutrino; or quarks built from still smaller entities; or a new type of strong nuclear force, apparent only at the high energies explored in the proton-antiproton collisions at CERN.

Now, some detailed analysis by three physicists at CERN has put an experimental cat among the theoretical pigeons. James Stirling, Ronald Kleiss and Steve Ellis (normally at the University of Washington in Seattle) have looked very carefully into the question of whether conventional physics can explain the monojets. They calculate a higher number of monojets from normal sources than previous studies have suggested. Indeed, they claim that monojets "can arise at a significant rate" from the decays of W and Z particles which are not identified as such (CERN preprint TH.4144/85).

The charged W and neutral Z particles are the carriers of the weak nuclear force, and were observed for the first time in 1983, at CERN, by UA1 and its "sister" experiment, UA2 (*New Scientist*, 27 January 1983, p 221). They are produced in the interaction of a quark and an antiquark. But the other quarks, antiquarks and gluons in the colliding particles can sometimes produce jets, which accompany the W or Z.

UA1 Monojets

Volume 139B, number 1,2 PHYSICS LETTERS 3 May 1984

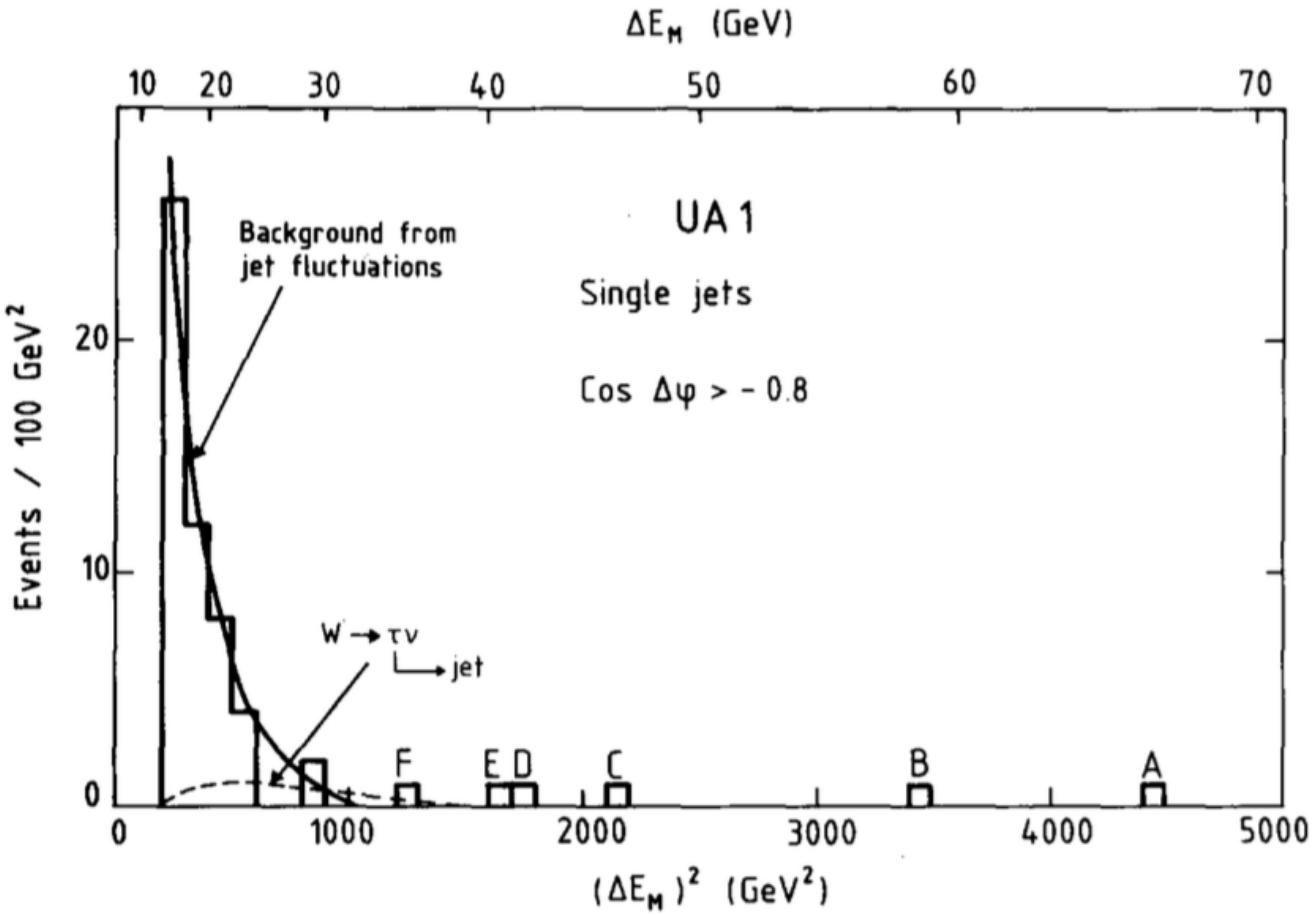


Fig. 6. Distribution of missing transverse energy squared for events with $\cos\Delta\varphi > -0.8$ (see text). The solid curve is the background expected from jet fluctuations. The dashed curve is the expected contribution from $W \to \tau\nu$.

UA1 Monojets

Volume 139B, number 1,2 PHYSICS LETTERS

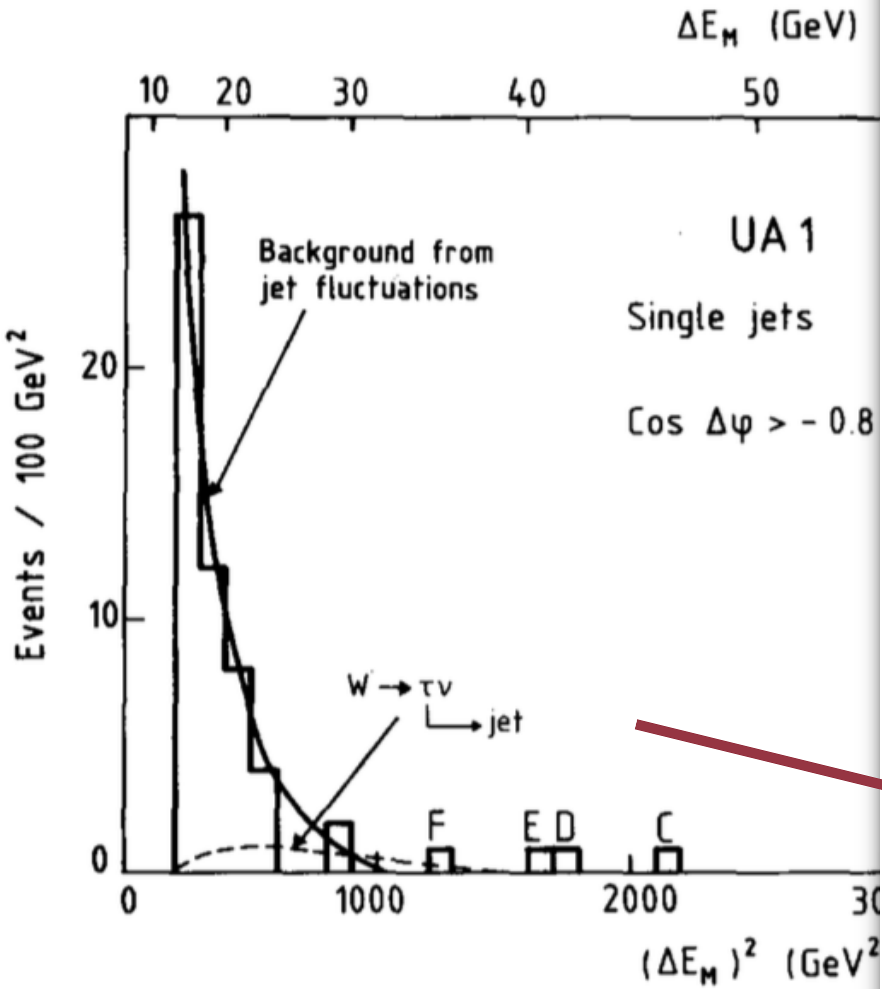


Fig. 6. Distribution of missing transverse energy squared for events with co
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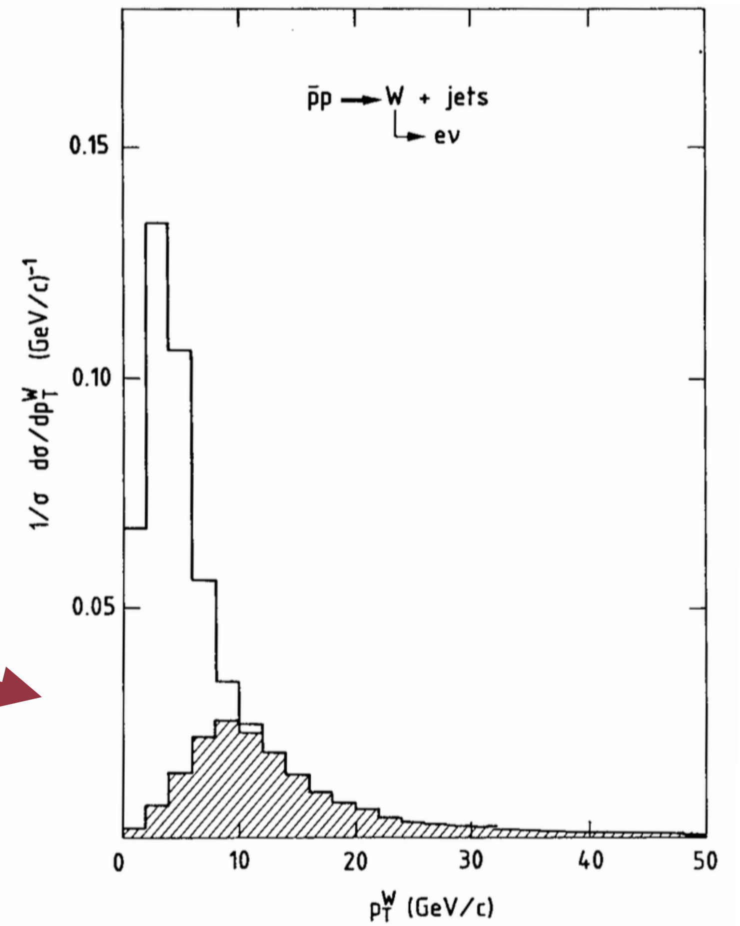
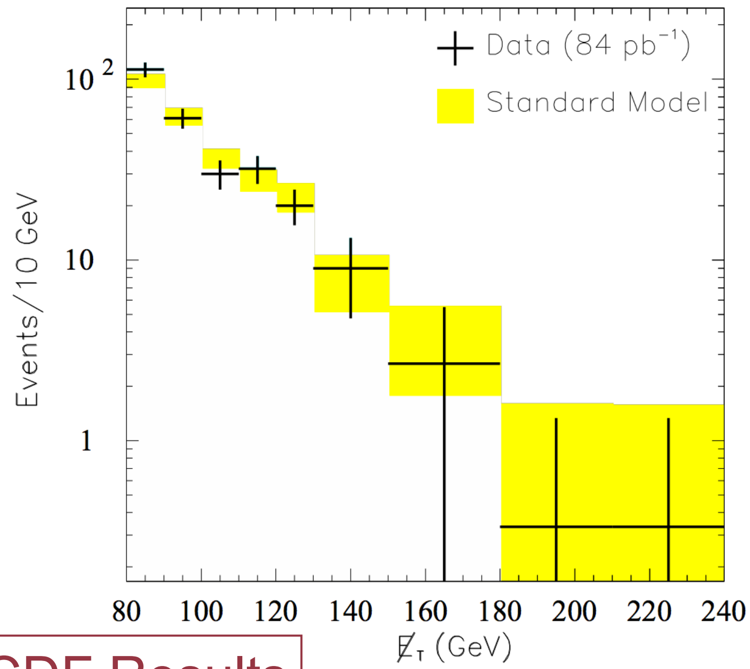
JET ACTIVITY IN $W^{\pm}$, $Z°$ EVENTS - A THEORETICAL ANALYSIS *)

S.D. Ellis**), R. Kleiss and W.J. Stirling
CERN - Geneva



QCD and ISR; Then and Now

[CDF Tevatron Run II: hep-ex/0309051]



CDF Results

Background Source	Predicted Events
$Z(\to \nu\bar{\nu})$+jets	160.2 ± 11.5
$W(\to \tau\nu)$+jets	46.6 ± 5.5
$W(\to \mu\nu)$+jets	23.8 ± 5.0
$W(\to e\nu)$+jets	18.1 ± 4.3
QCD	21.7 ± 6.7
$t\bar{t}$, single t, dibosons	3.9 ± 0.3
Total predicted	274.1 ± 15.9
Observed	284

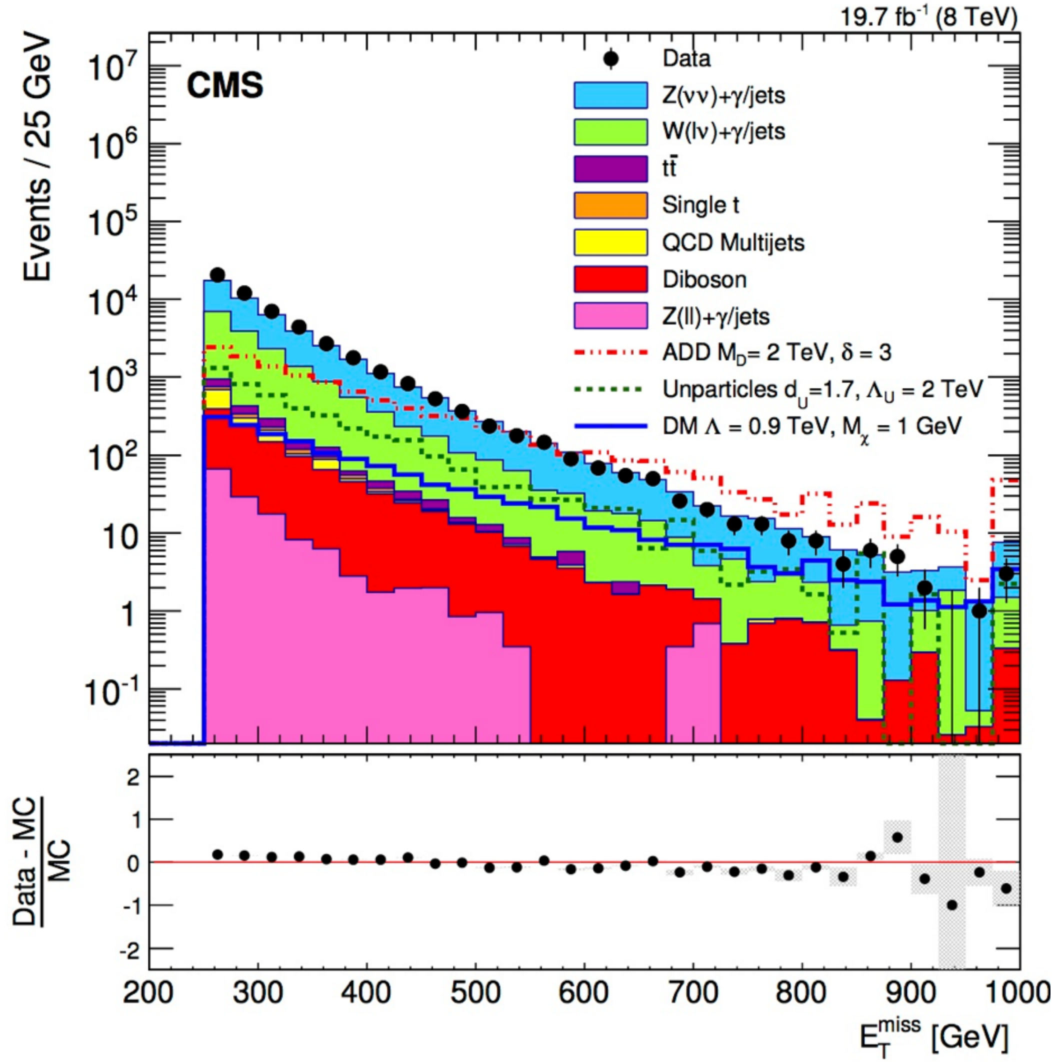
- Multijet events from QCD
  - ~60% in CDF Run 0
  - ~8% in CDF Run 1, 2
  - ~<0.1% in ATLAS & CMS
- Backgrounds from QCD, beam, cosmics
  - suppressed by jet cleanup
  - suppressed by high jet/MET cuts
  - killed by angular and multiplicity cuts
- "Tagging" initial-state radiation (ISR)
  - LHC uses ISR "mono-X" for many searches
  - Generic search for "invisible" new physics

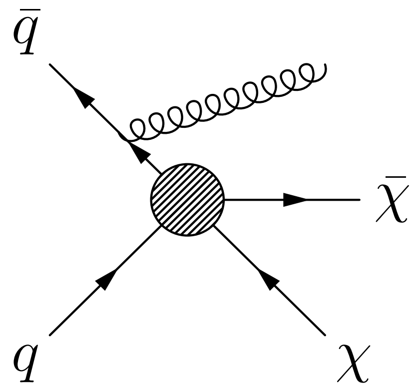
Monojet Dark Matter (CMS Run I)

[arXiv:1408.3583]

- Search for Pair-produced Dark Matter
  - Search for missing energy and radiated jet (or two)
  - Dark Matter will appear as excess events on the tail
- Monojet Event Selection
  - Leading jet p_T > ~120 GeV
  - topological cuts to reduce QCD
  - veto events with isolated leptons
  - primary backgrounds taken from data

Best limits with E_T^{miss} > 500 GeV

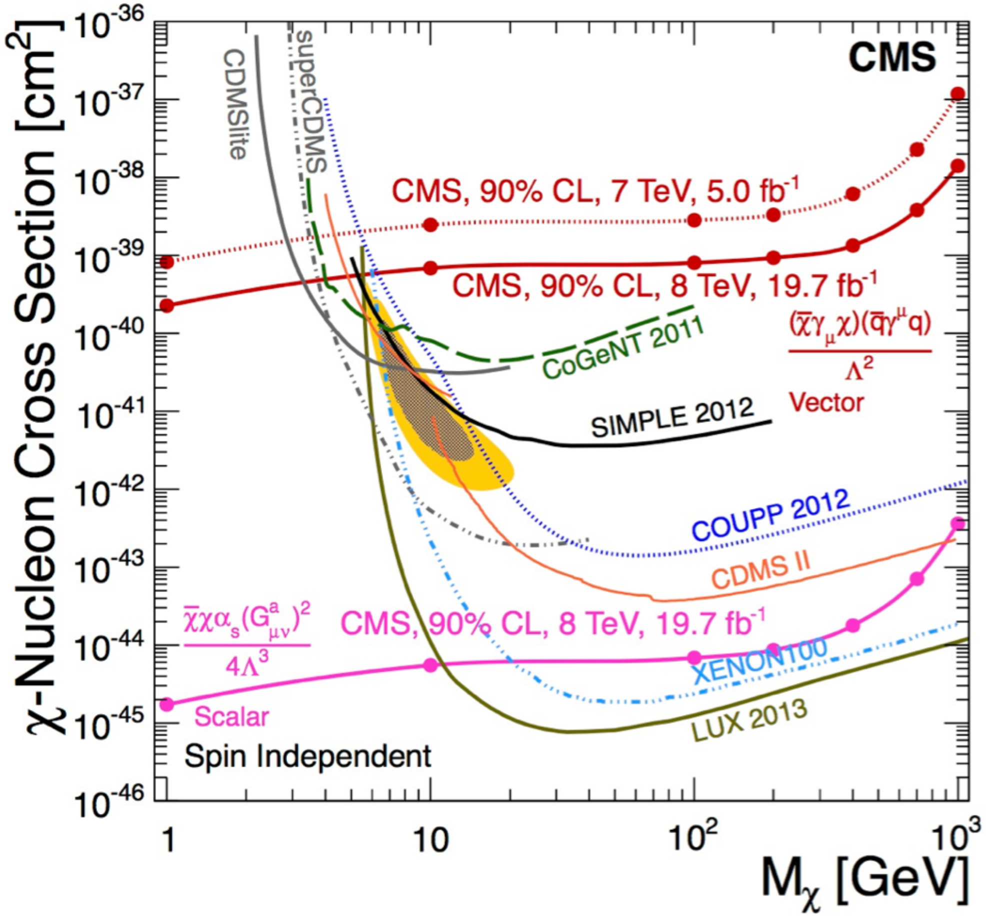


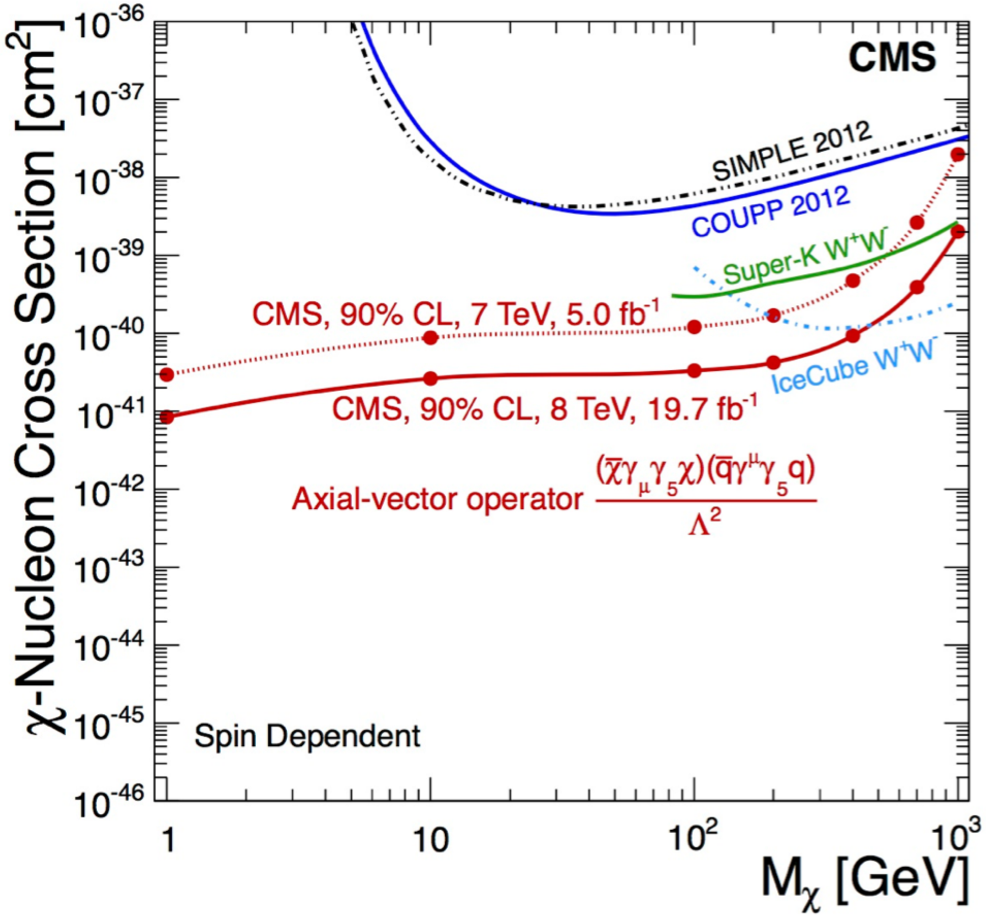


MONOJET DARK MATTER (CMS RUN I)

[arXiv:1408.3583]

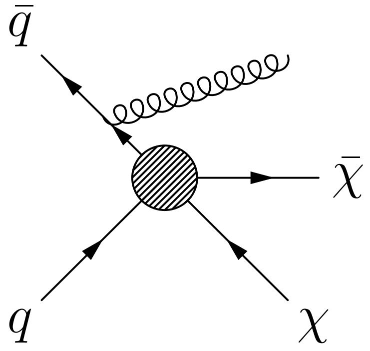
- Derived Effective Field Theory (EFT) limits compared to direct-detection



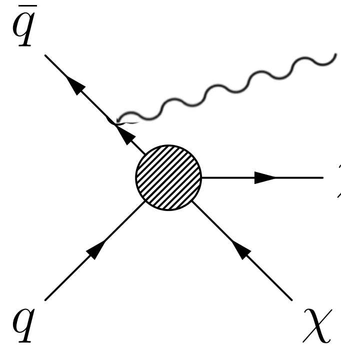


MONO-MANIA!

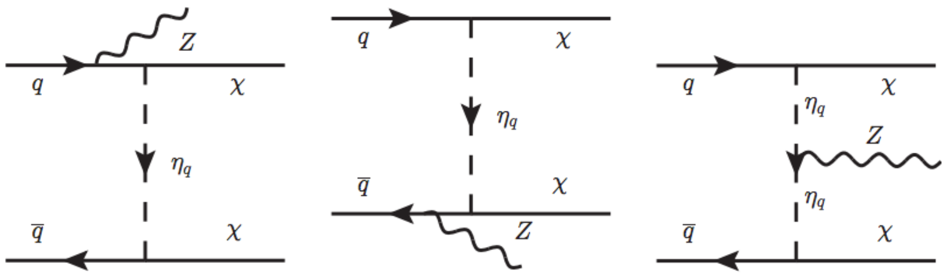
- For the next few years:
  - *Hundreds* of phenomenology papers
  - *Thousands* of citations for collider DM
  - "ISR tagging" established technique for all new particle searches (not just DM)



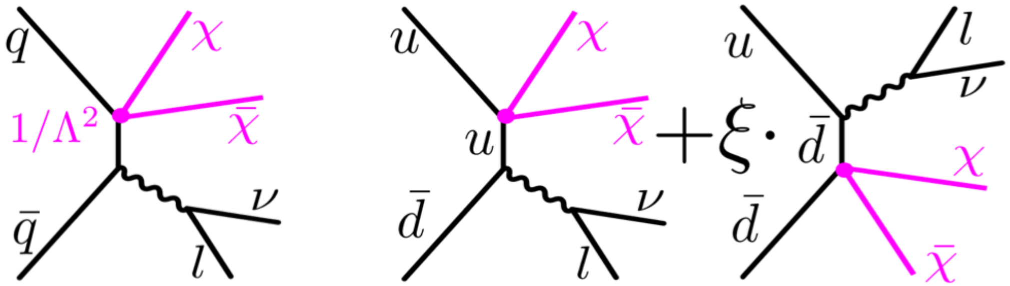
Monojet



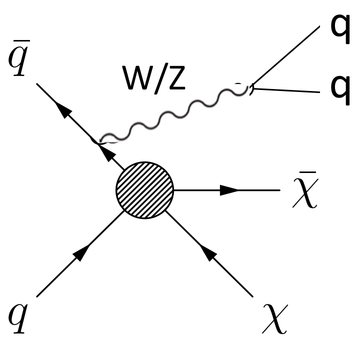
Monophoton



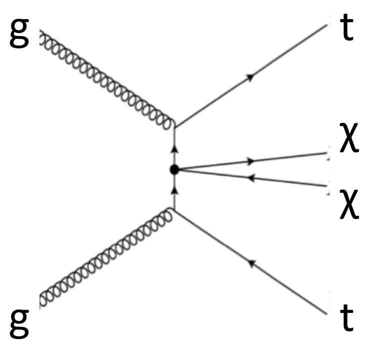
MonoZ



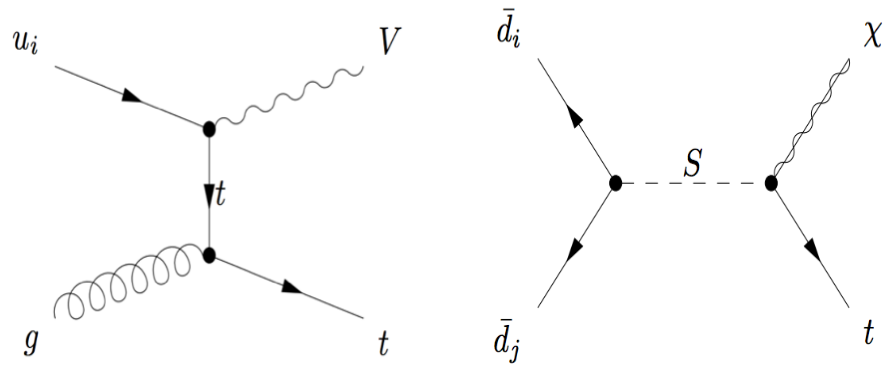
MonoW (Monolepton)



MonoW/Z (hadronic)

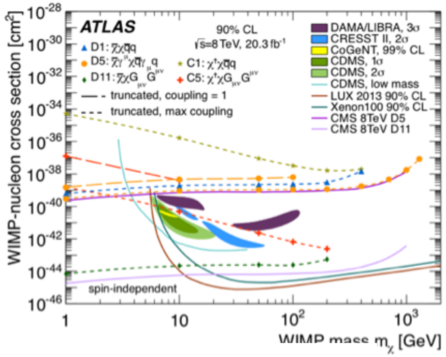


ttbar DM

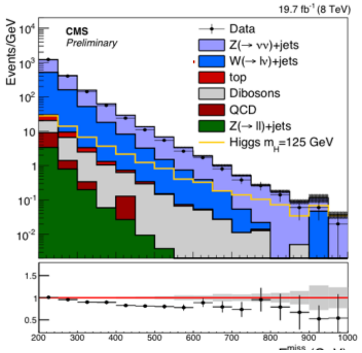


MonoTop

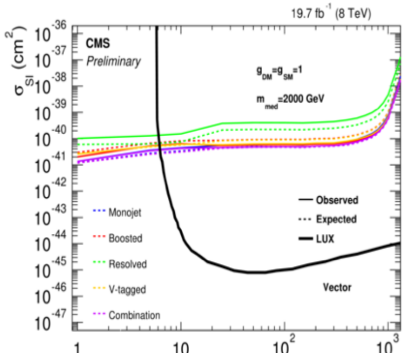
MONO-MANIA!



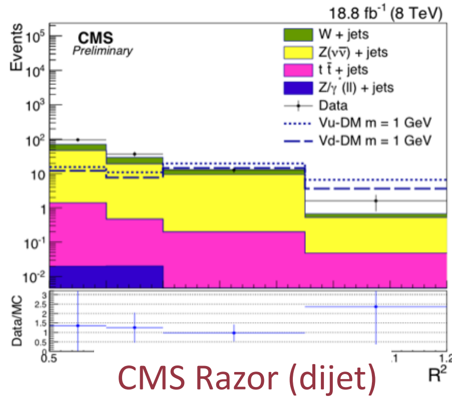
ATLAS Monojet
EPJC (2015) 75:299



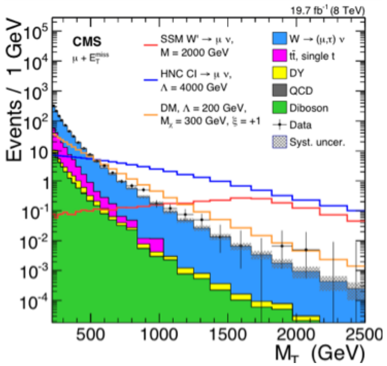
CMS j/V (mono/dijet)
PAS-EXO-12-055



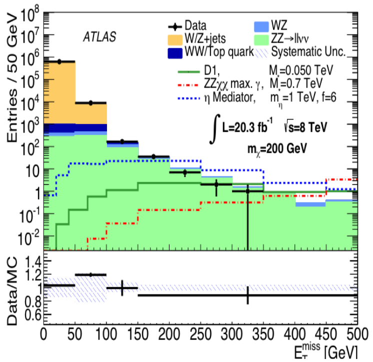
CMS j/V (mono/dijet)
PAS-EXO-12-055



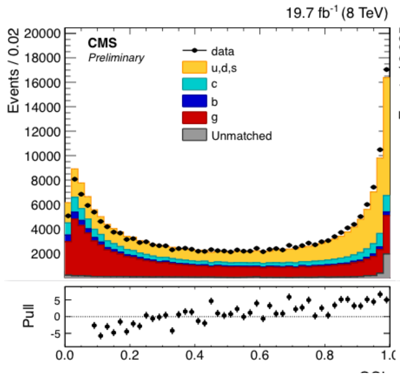
CMS Razor (dijet)
PAS-EXO-14-004



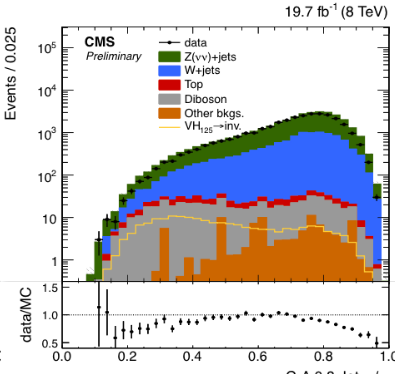
CMS, ATLAS MonoW
PRD 91, 092005, JHEP 09 (2014) 037 (2015)



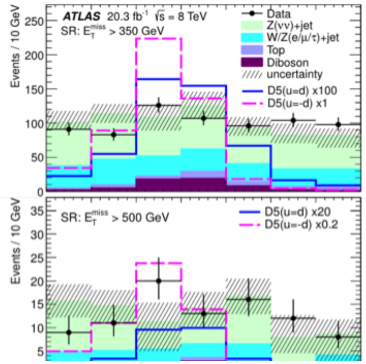
CMS, ATLAS MonoZ
EXO-12-054, PRD 90, 012004 (2014)



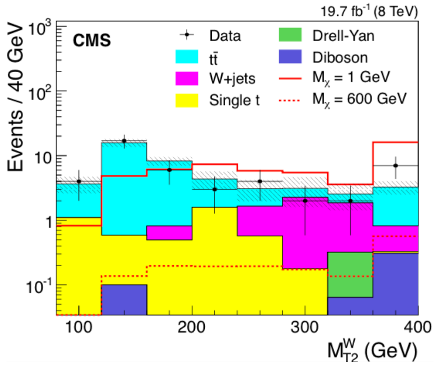
CMS MonoV (resolved)
PAS-EXO-12-005, PAS-JME-14-002



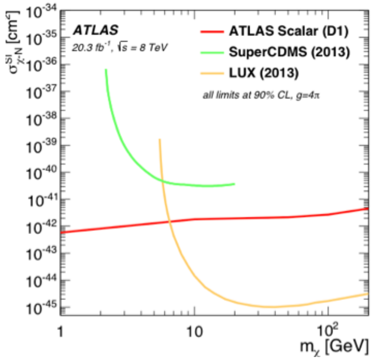
CMS MonoV (boosted)
EXO-12-005/JME-14-002



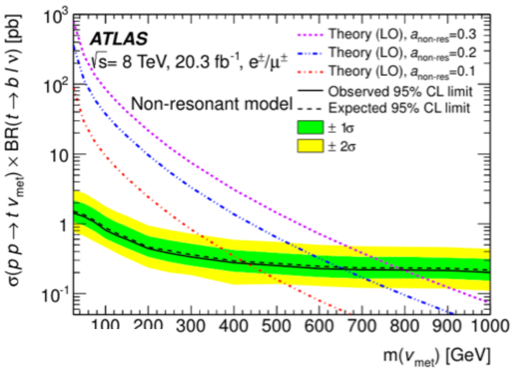
ATLAS MonoV (boosted)
ATLAS, PRL 112, 041802 (2014)



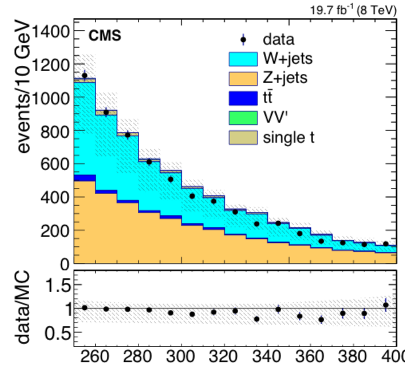
CMS TopPairs
CMS, JHEP 06 (2015) 121



ATLAS TopPairs
ATLAS, EPJC (2015) 75:92



CMS MonoTop
CMS, PRL 114 (2015) 101801



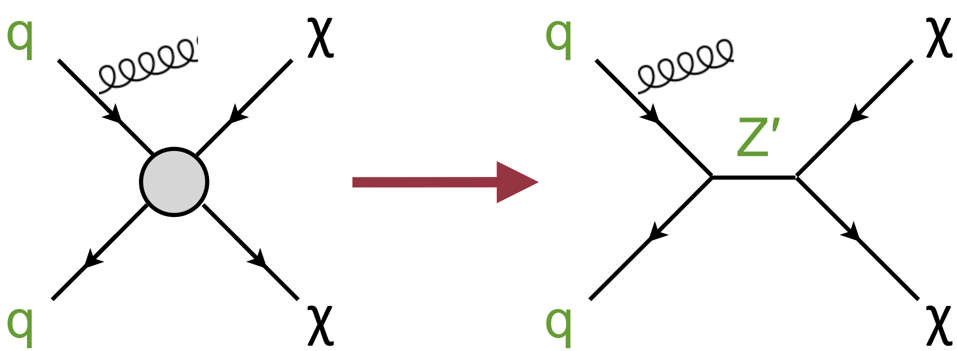
ATLAS MonoTop
ATLAS, JHEP 11 (2014) 118

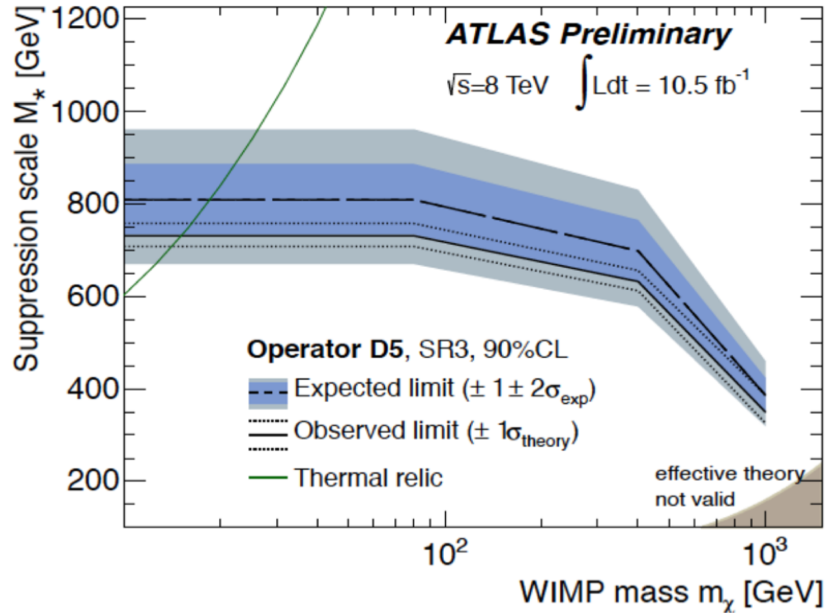
MONOJETS: EFT LIMITS AND STEPS BEYOND

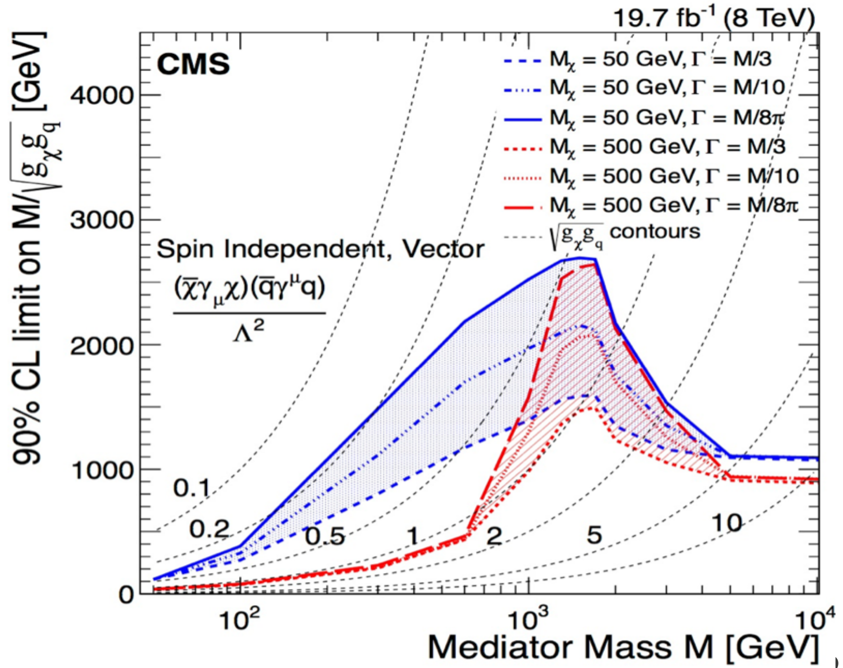
[arXiv:1408.3583, ATLAS-CONF-2012-147]

- Effective Field Theory limit validity
  - Bottom corner: large couplings, small phase space
  - Limits from perturbative bound, unitarity limit
  - Starting to include these bounds in results

- Moving beyond simple EFT
  - Include mediating particle (e.g. s-channel Z'), look at limits vs $m_{Z'}$
  - EFT gives good/conservative results above a few hundred GeV (high M)

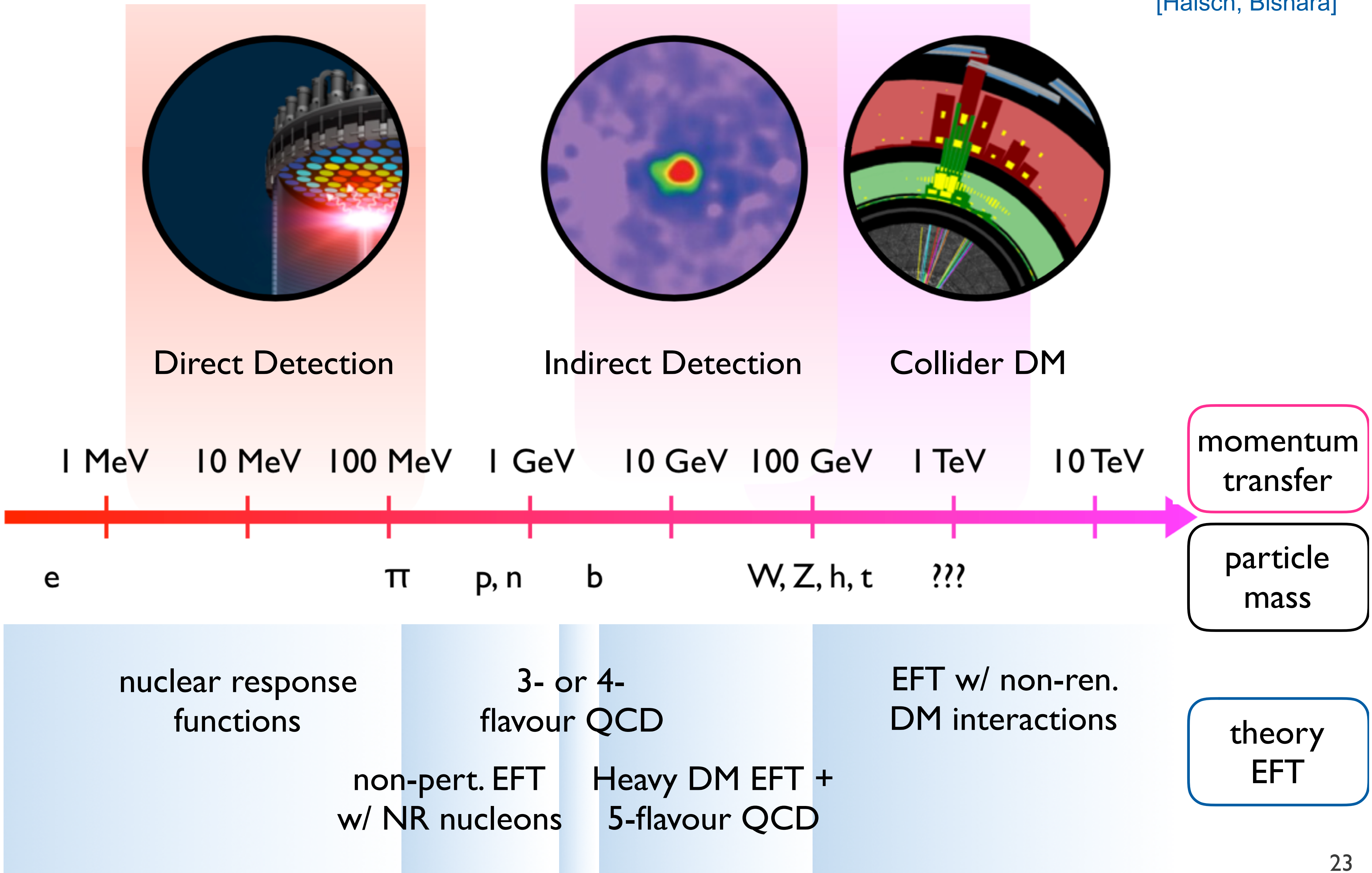






Relevant Scales for DM Searches

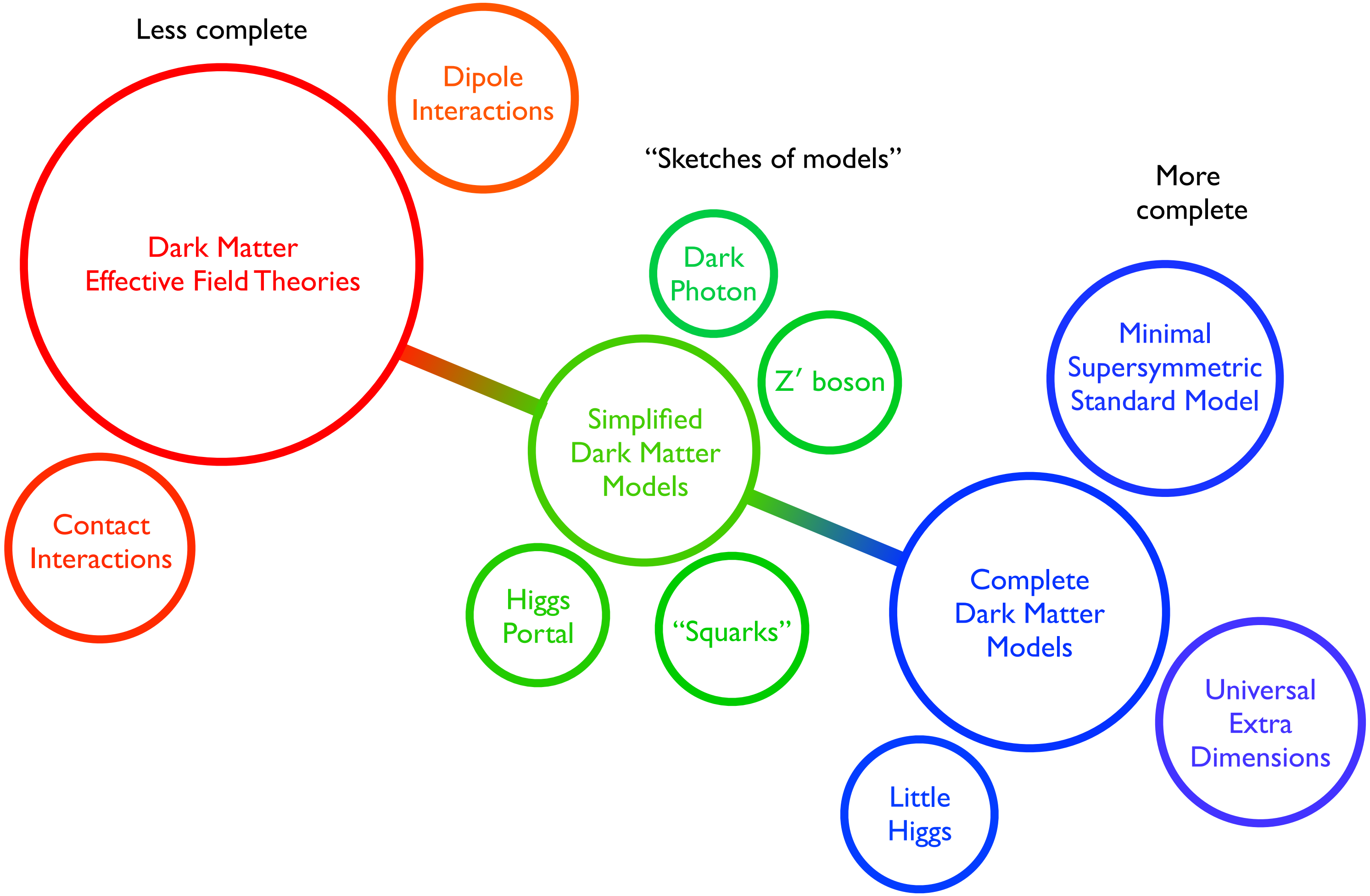
[Haisch, Bishara]



Simplified Models of Dark Matter

[arXiv:1506.03116, 1507.00966]

- Effective Field Theory Interpretation and validity
  - EFT is a simple estimate of LHC sensitivity to an explicit coupling/mediator
  - Good for back-of-envelope, but maybe not the full picture



Simplified Models of Dark Matter

[arXiv:1506.03116, 1507.00966]

- Simplified Models
  - Overcomes (mostly?) the issues of EFT validity
  - More parameters to scan; similar to MSSM in SUSY
  - More information, better way to make a general comparison
- Basic language agreed, and now in use

Simplified Models for Dark Matter Searches at the LHC

Jalal Abdallah (Taiwan, Inst. Phys.) , Henrique Araujo (Imperial Coll., London) , Alexandre Arbey (Lyon U. & Lyon, Ecole Normale Superieure & CERN) , Adi Ashkenazi (Tel Aviv U.) , Alexander Belyaev (Southampton U.) , Joshua Berger (SLAC) , Celine Boehm (Durham U., IPPP) , Antonio Boveia (CERN) , Amelia Brennan (Melbourne U.) , Jim Brooke (Bristol U.) *et al.* Show all 97 authors

Jun 9, 2015 - 16 pages

Phys.Dark Univ. 9-10 (2015) 8-23
(2015-09-05)
DOI: 10.1016/j.dark.2015.08.001
FERMILAB-PUB-15-283-CD, CERN-PH-TH-2015-139
e-Print: arXiv:1506.03116 [hep-ph] | PDF

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

Daniel Abercrombie (MIT) , Nural Akchurin (Texas Tech.) , Ece Akilli (Geneva U.) , Juan Alcaraz Maestre (Madrid, CIEMAT) , Brandon Allen (MIT) , Barbara Alvarez Gonzalez (CERN) , Jeremy Andrea (Strasbourg, IPHC) , Alexandre Arbey (CERN) , Georges Azuelos (TRIUMF) , Patrizia Azzi (INFN, Padua) *et al.* Show all 139 authors

Jul 3, 2015 - 160 pages

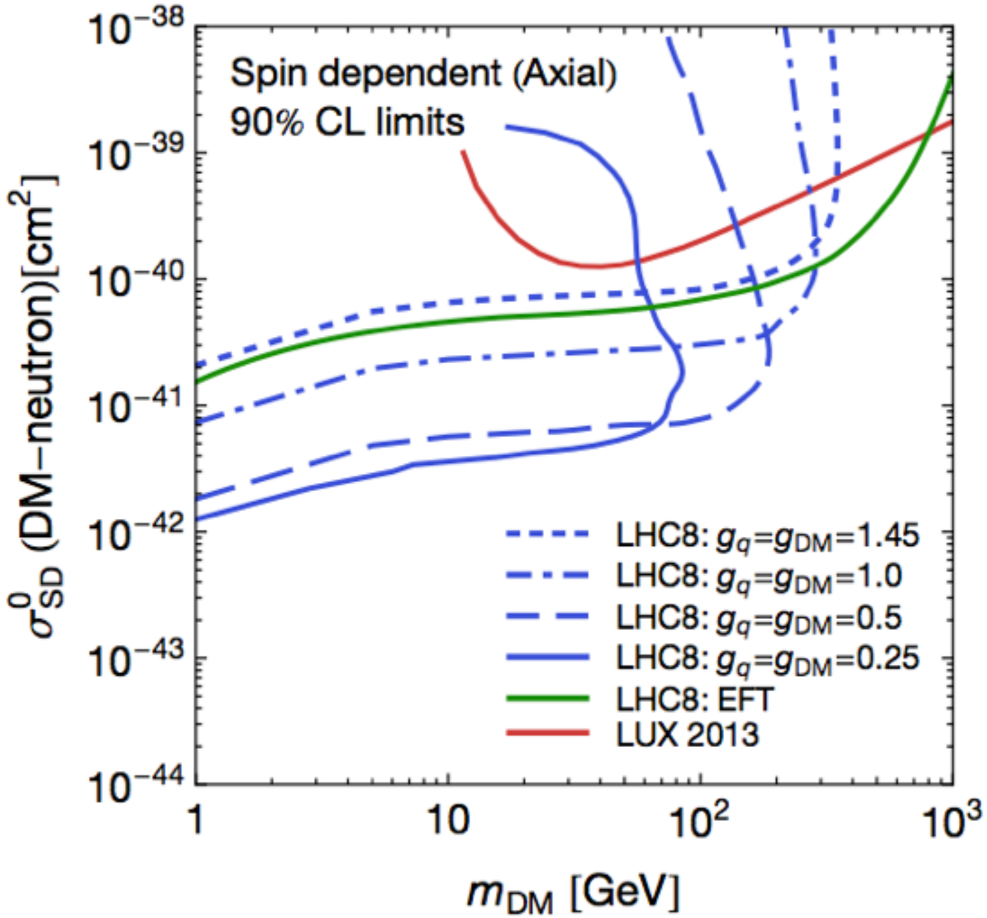
FERMILAB-PUB-15-282-CD
e-Print: arXiv:1507.00966 [hep-ex] | PDF

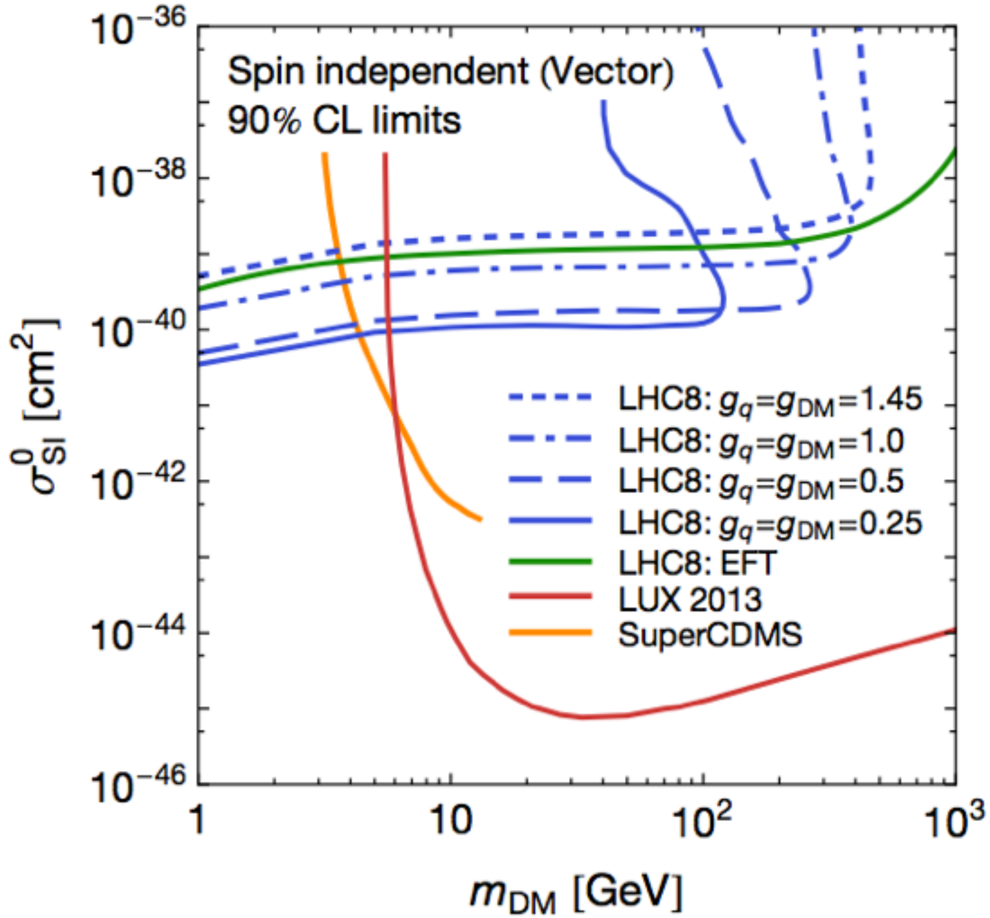
Provides a new language for the Dark Matter field (not just colliders)

SIMPLIFIED MODELS

[arXiv:1408.3583]

Scans of (s-channel) simplified models in m_{DM} vs nucleon xsection (vs coupling)

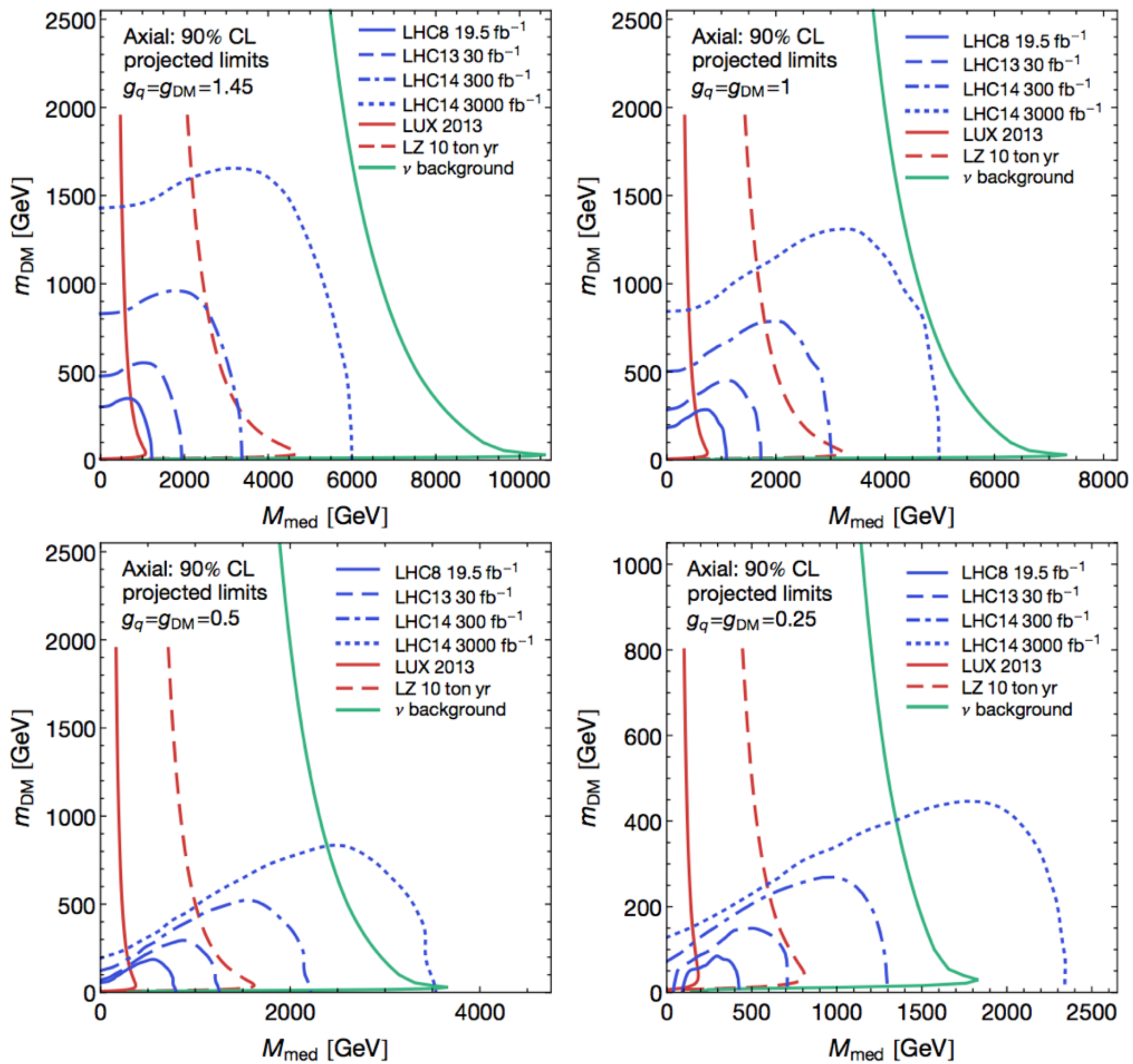




SIMPLIFIED MODELS

[arXiv:1408.3583]

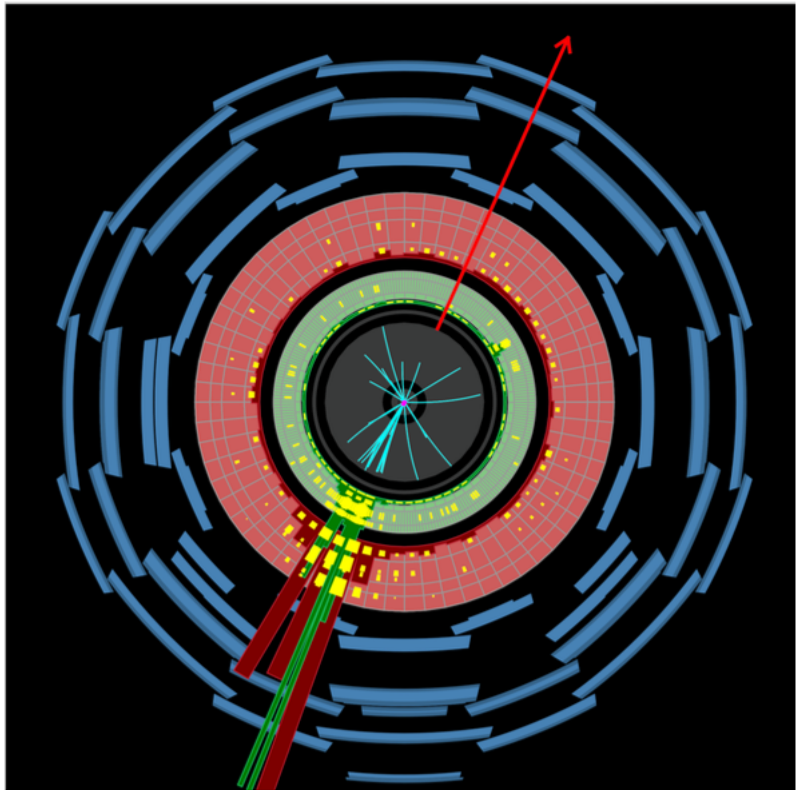
- Plots vs m_{DM}, coupling, M_{Med} etc well-received: *more ways to view the data*
- Below: m_{DM} vs M_{Med} for four different couplings (0.25-1.45)

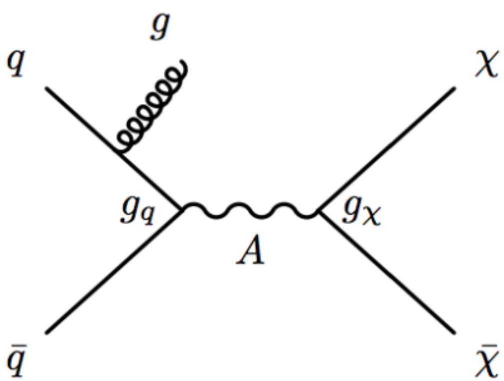


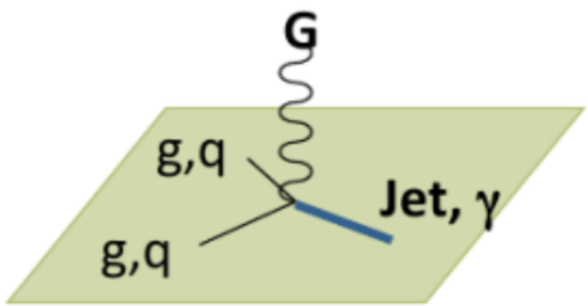
Can we pass the neutrino bound?

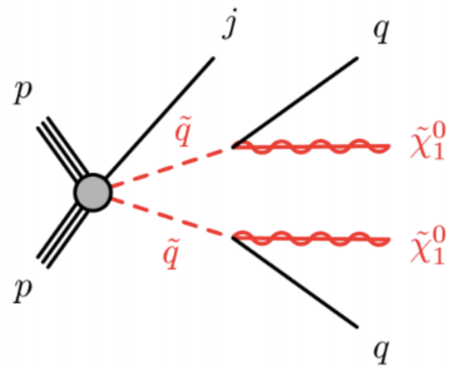
ATLAS MONOJET: OUTLINE

- Signatures:
  - Invisible particles recoiling against high p_T jets
  - Large missing transverse momentum
  - High-p_T jet + up to three jets
- Physics models of interest:
  - DM pair prod via spin 1 and spin 0 mediators
  - SUSY strong prod in compressed scenario
  - ADD gravitons
- 10x sample of new data under study









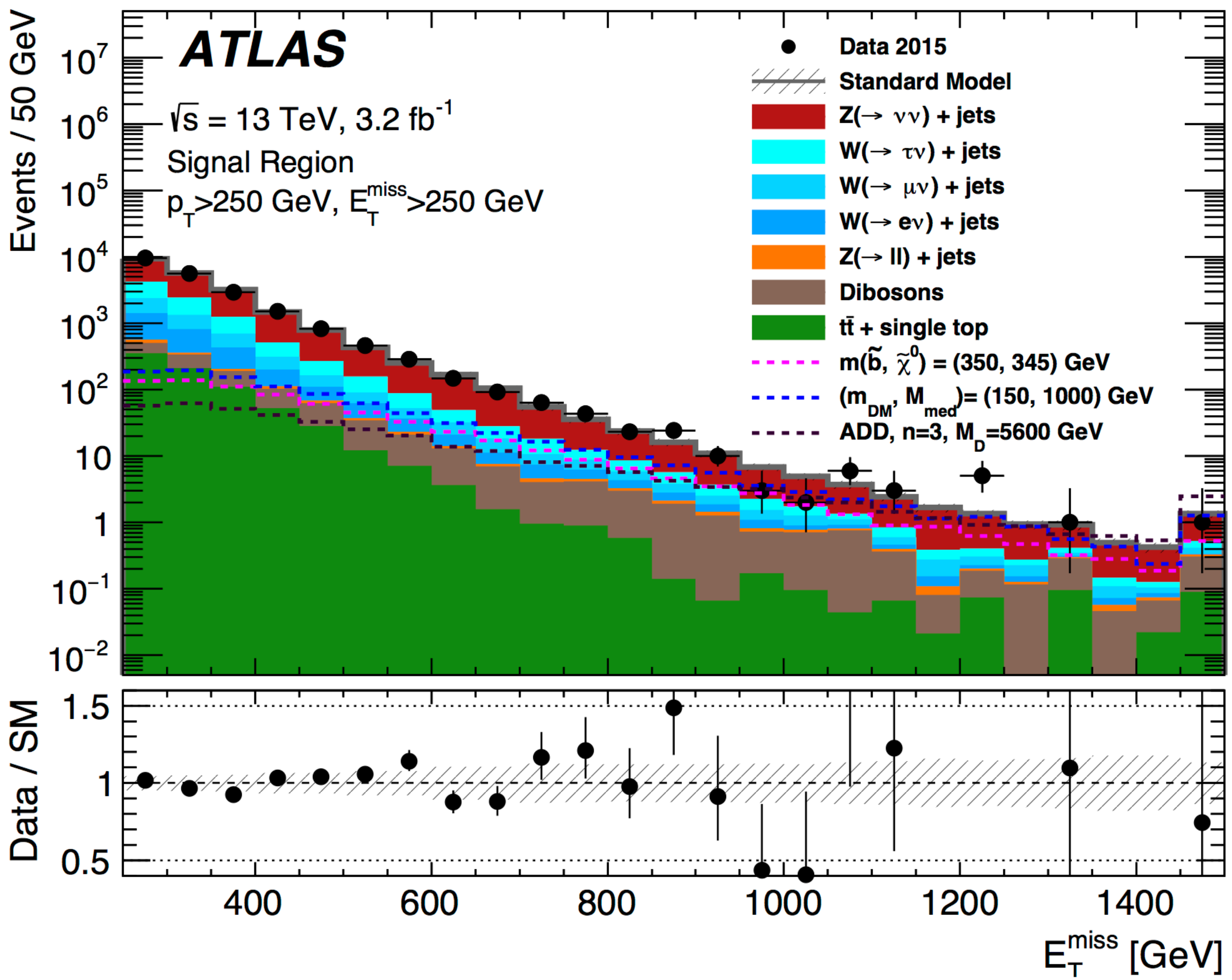
ATLAS MONOJET: DATA

[arXiv:1604.07773]

- Signature:
  high-p_T jet(s), large Missing Transverse Momentum (MET)

- Backgrounds:
  Z(→νν)+jets and W+jets estimated from W(→μν), W(→eν), Z(→μμ)+jets control regions

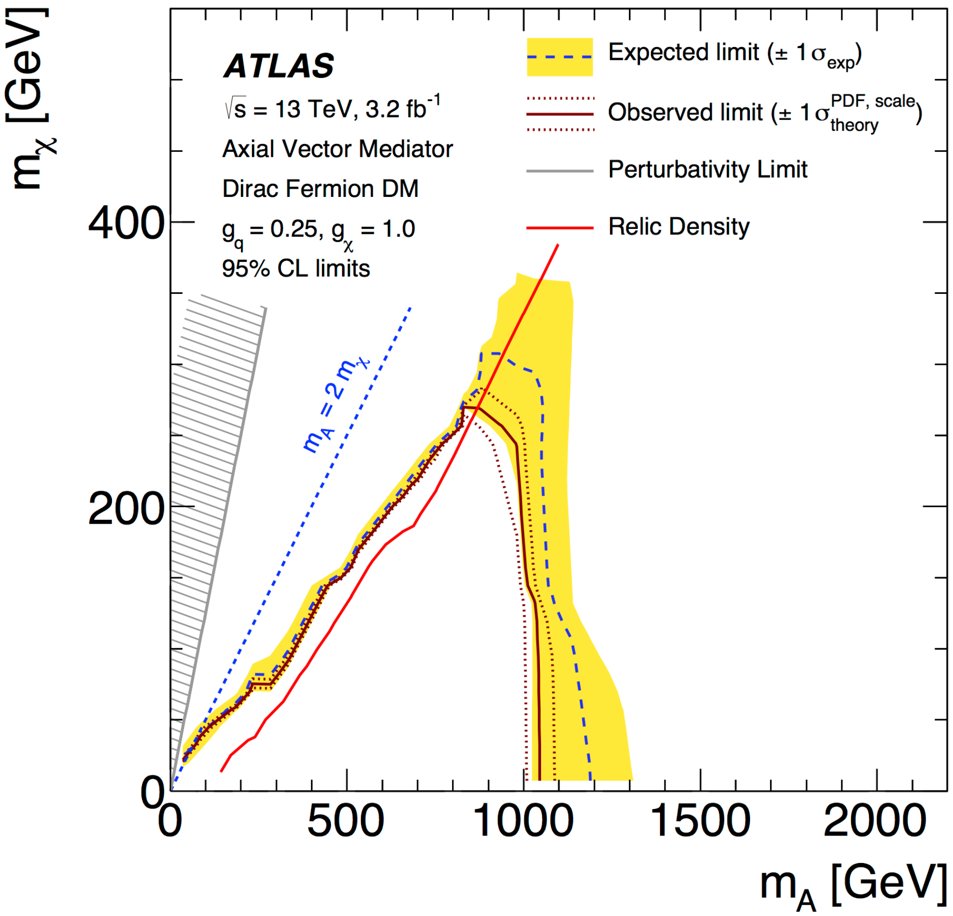
- Results:
  publication on 2015 ($3.2fb^{-1}$), 2015+2016 ($36.1fb^{-1}$) coming soon

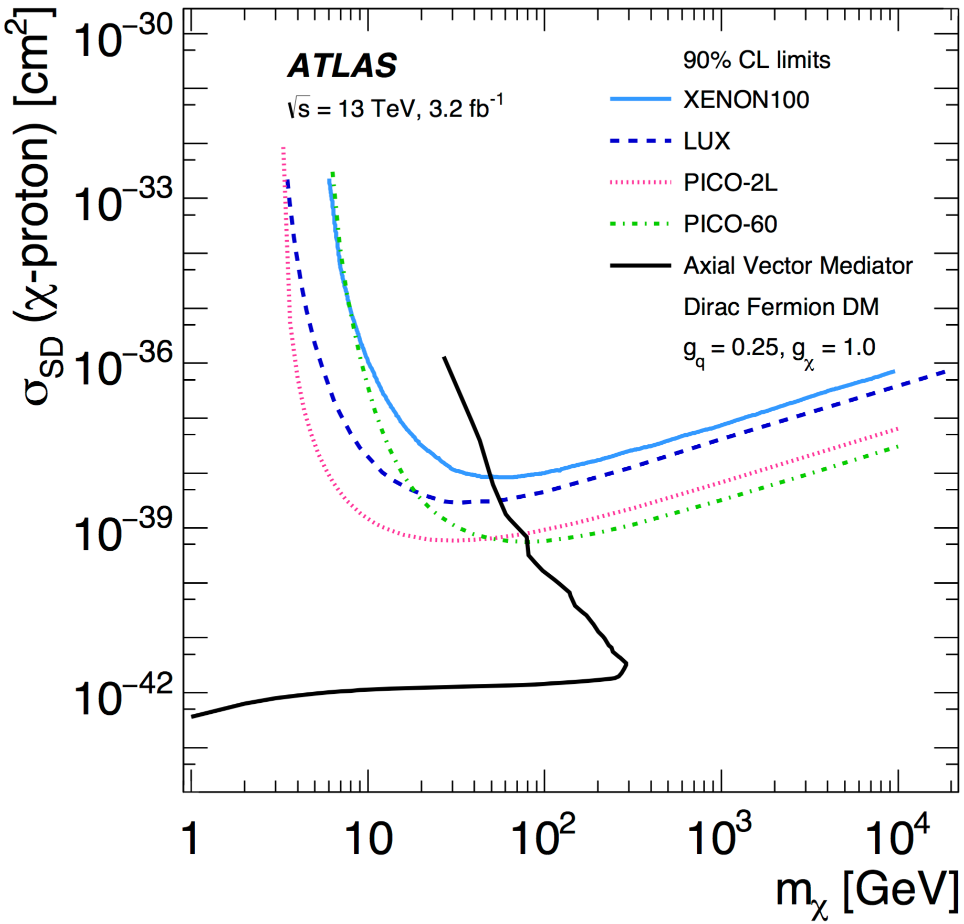


ATLAS Monojet: Results

[arXiv:1604.07773]

- Results for simplified model with Avial Vector mediator





CMS Monojet Simplified Model Scan

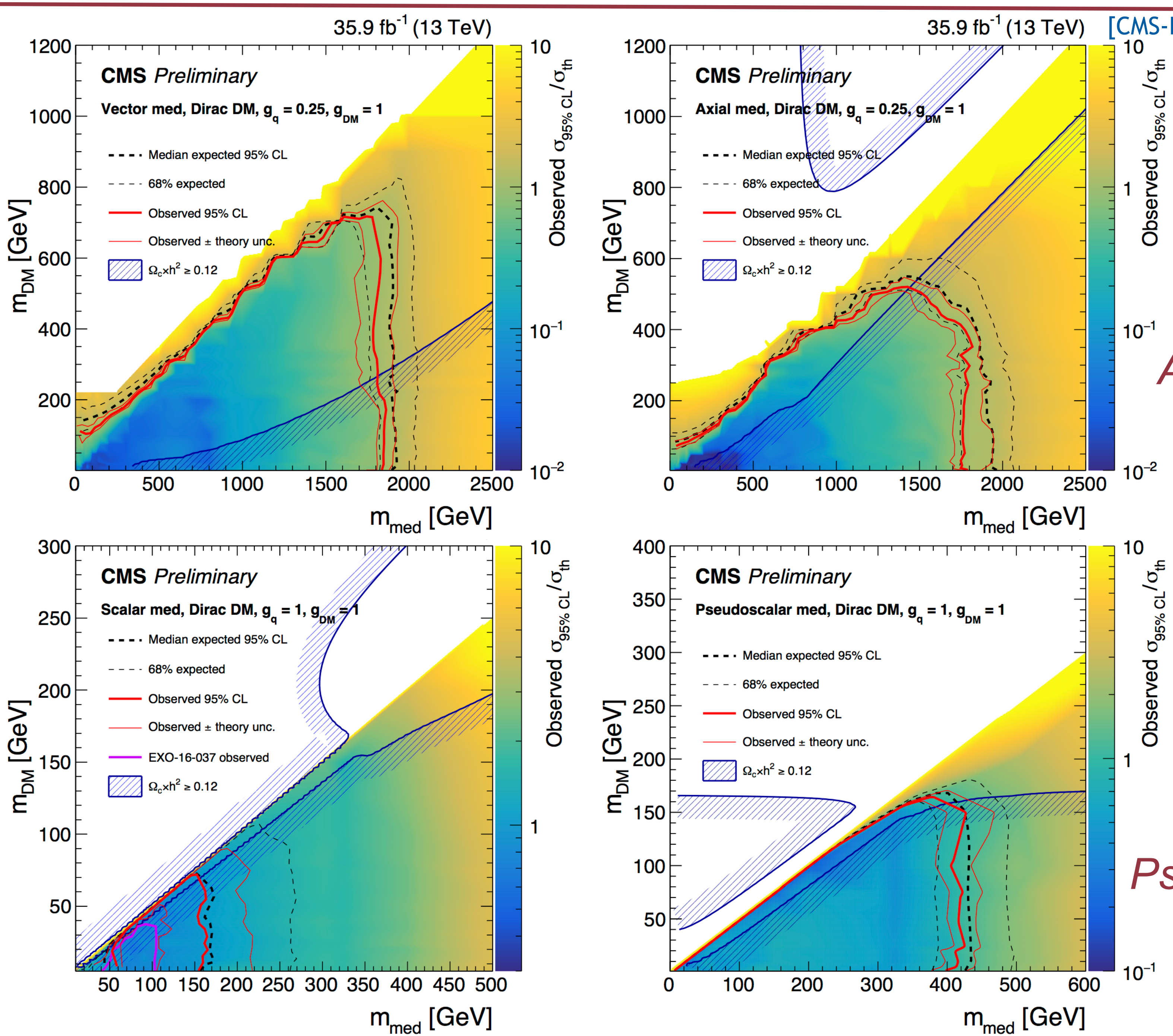
[CMS-PAS-EXO-16-048]

Vector

Axial Vector

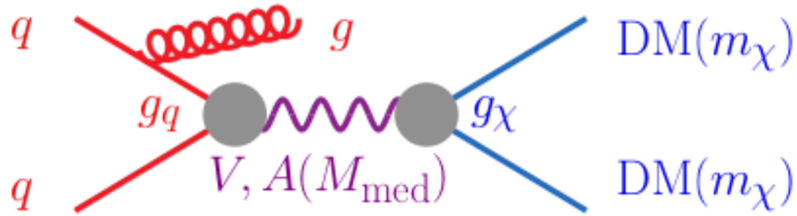
Scalar

Pseudoscalar



New Collider Dark Matter Strategies

- *Mono-X:* look for MET + ISR to "tag" DM pair-production (X = jet, γ, W/Z, H, b$\bar{b}$, t$\bar{t}$)



- *Mediator:* look directly for the mediator instead, to infer limits on DM. Mediator couples to quarks (decays to dijets), leptons, etc.

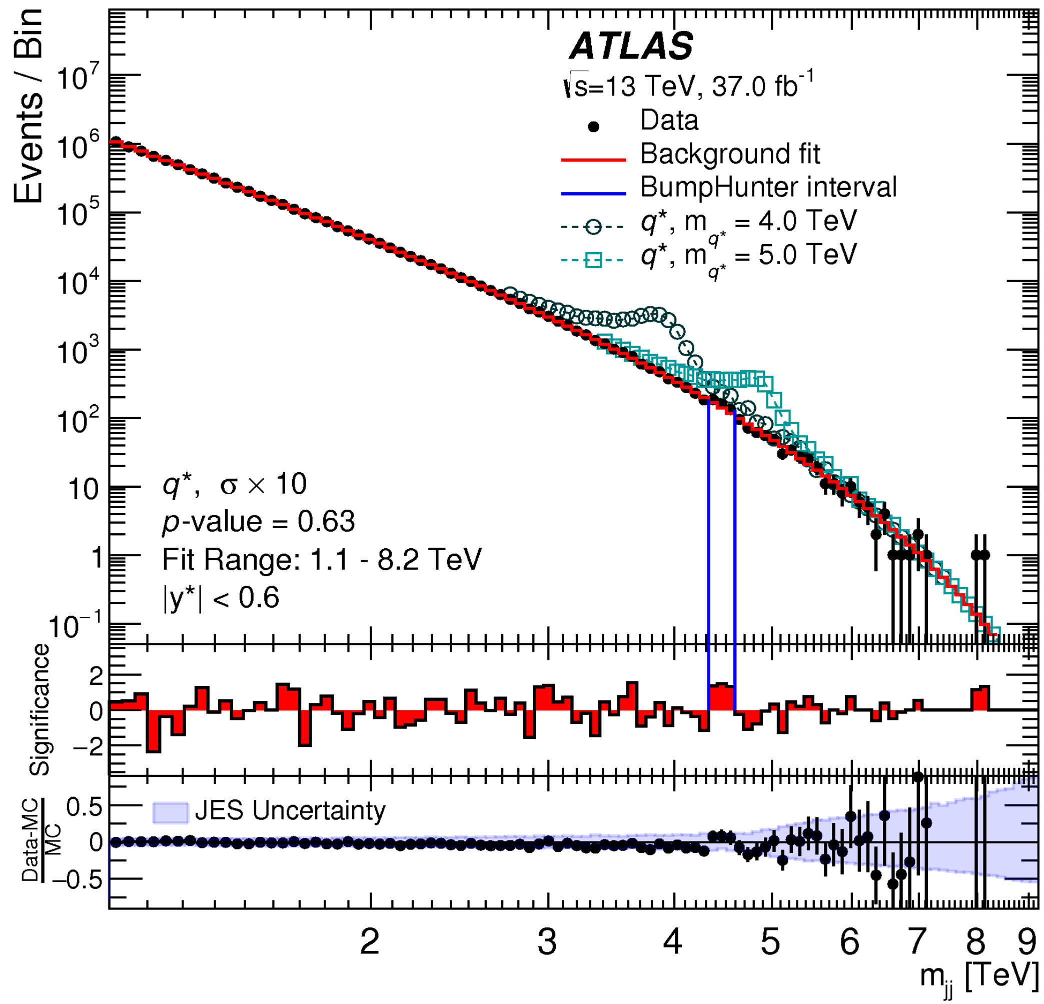
HEAVY RESONANCE DECAYING TO DIJET

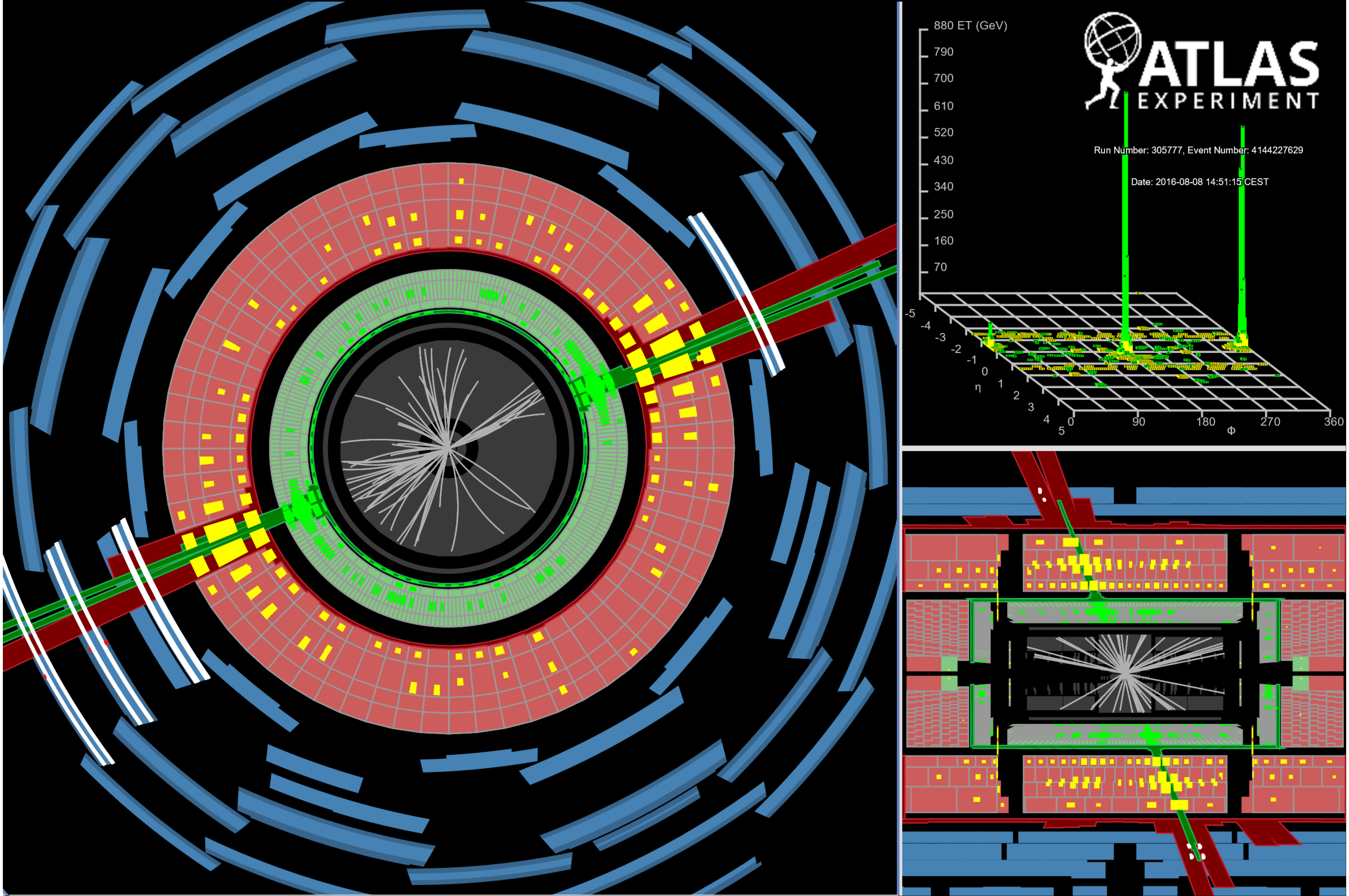
[ATLAS-CONF-2016-069]

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$
$$x \equiv m_{jj}/\sqrt{s}$$

- Dark-Matter mediator, also W'/Z', RS LED, excited quarks, strong gravity
- Large uncertainty on QCD → look for resonance above fit of the data
- Analysis limited by trigger:
  - 1-jet trigger ET~380 GeV
  - implies m(jj) ≳ 1.1 TeV
- Dedicated analysis used for lower-mass resonance search

Strong limits on DM mediator



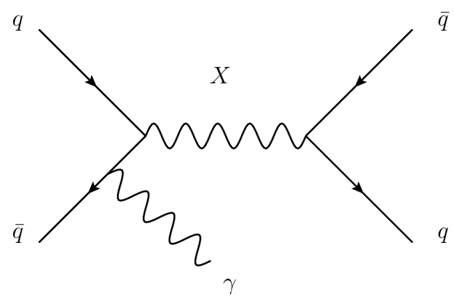


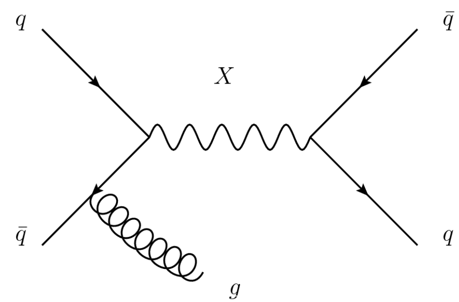
Highest mass dijet event: m(jj) = 8.12 TeV

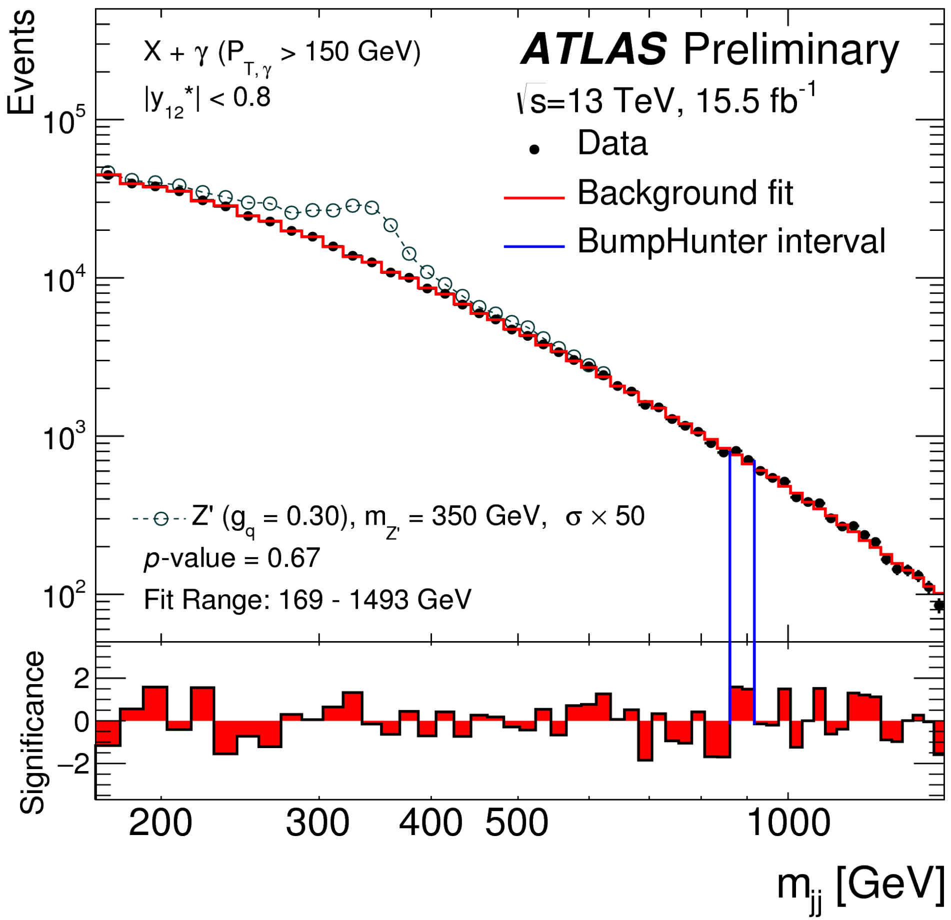
Low-Mass Dijet+ISR Resonance

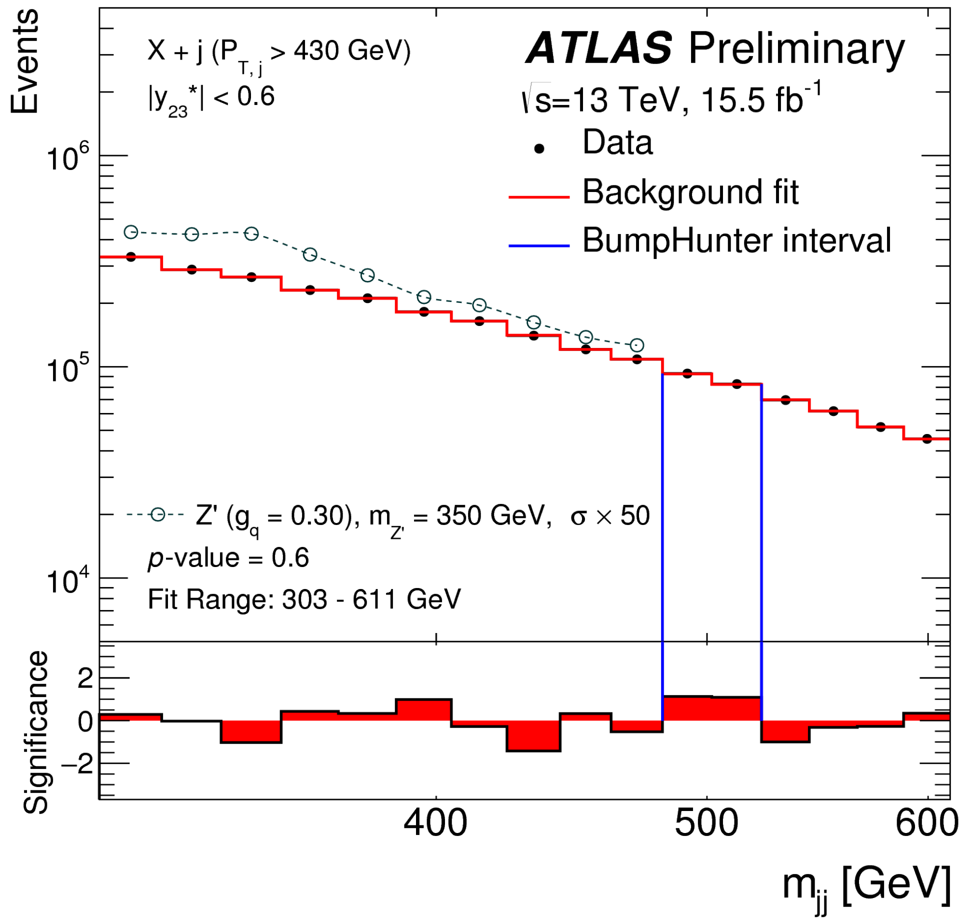
[ATLAS-CONF-2016-070]

- Reaches lower resonance mass by requiring ISR photon or jet
- Same trigger and offline thresholds (jets:380 → 440, photons: 140 → 150)





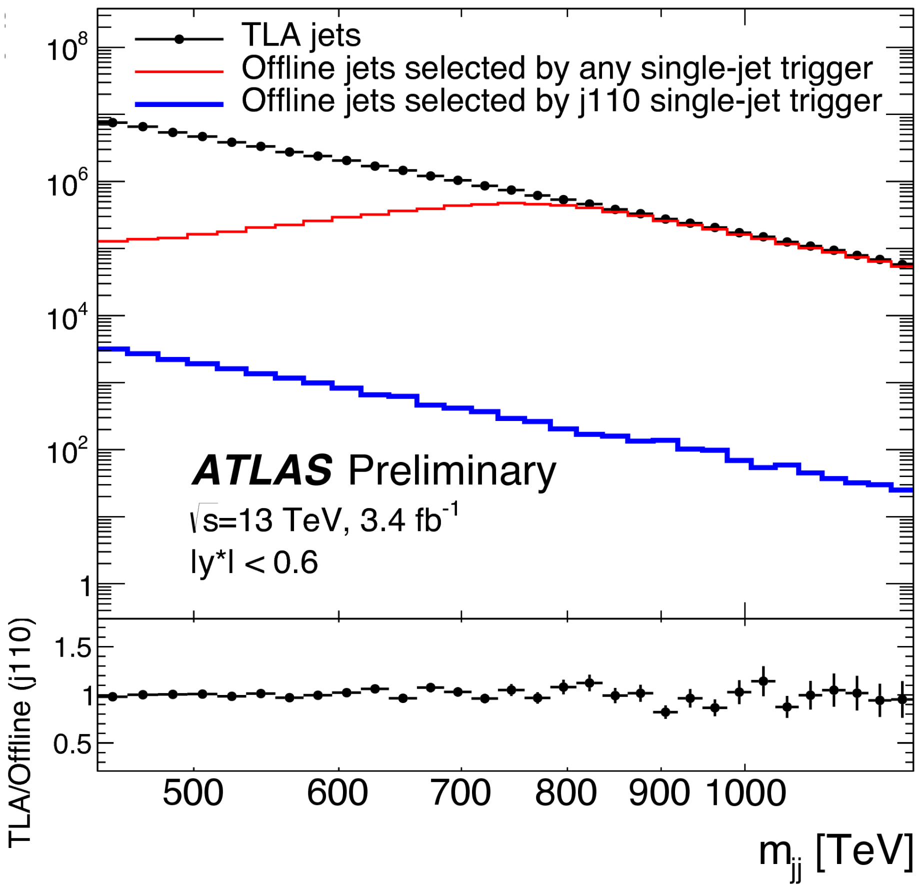


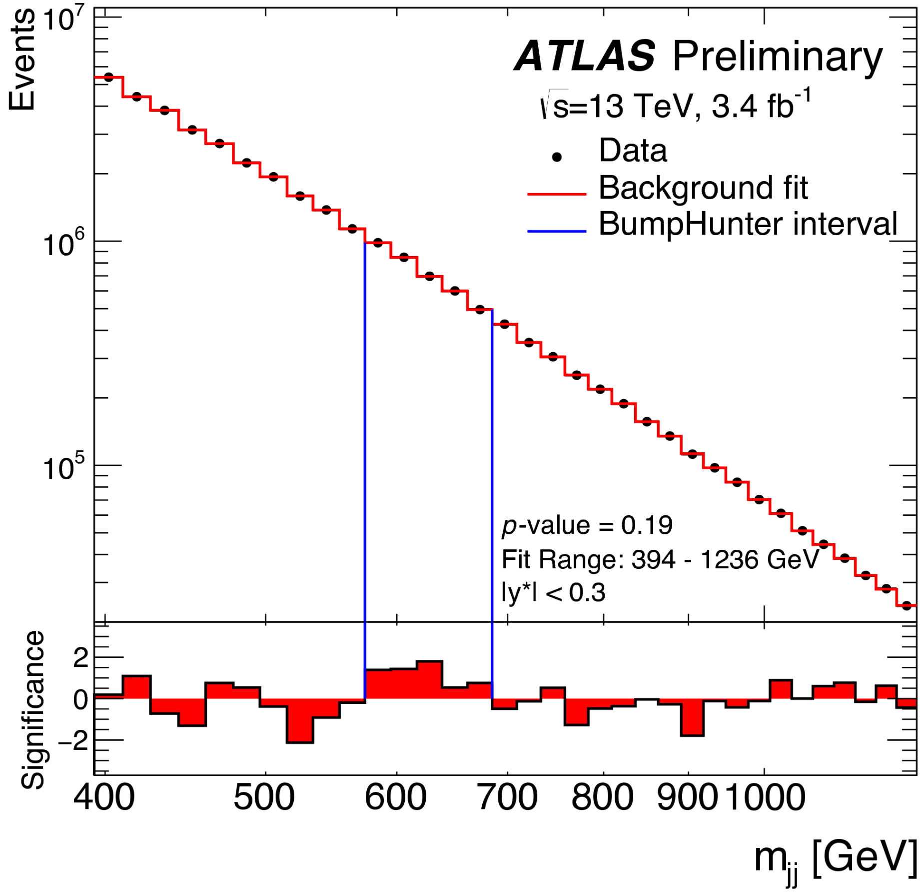


Trigger-Level Dijet Resonance

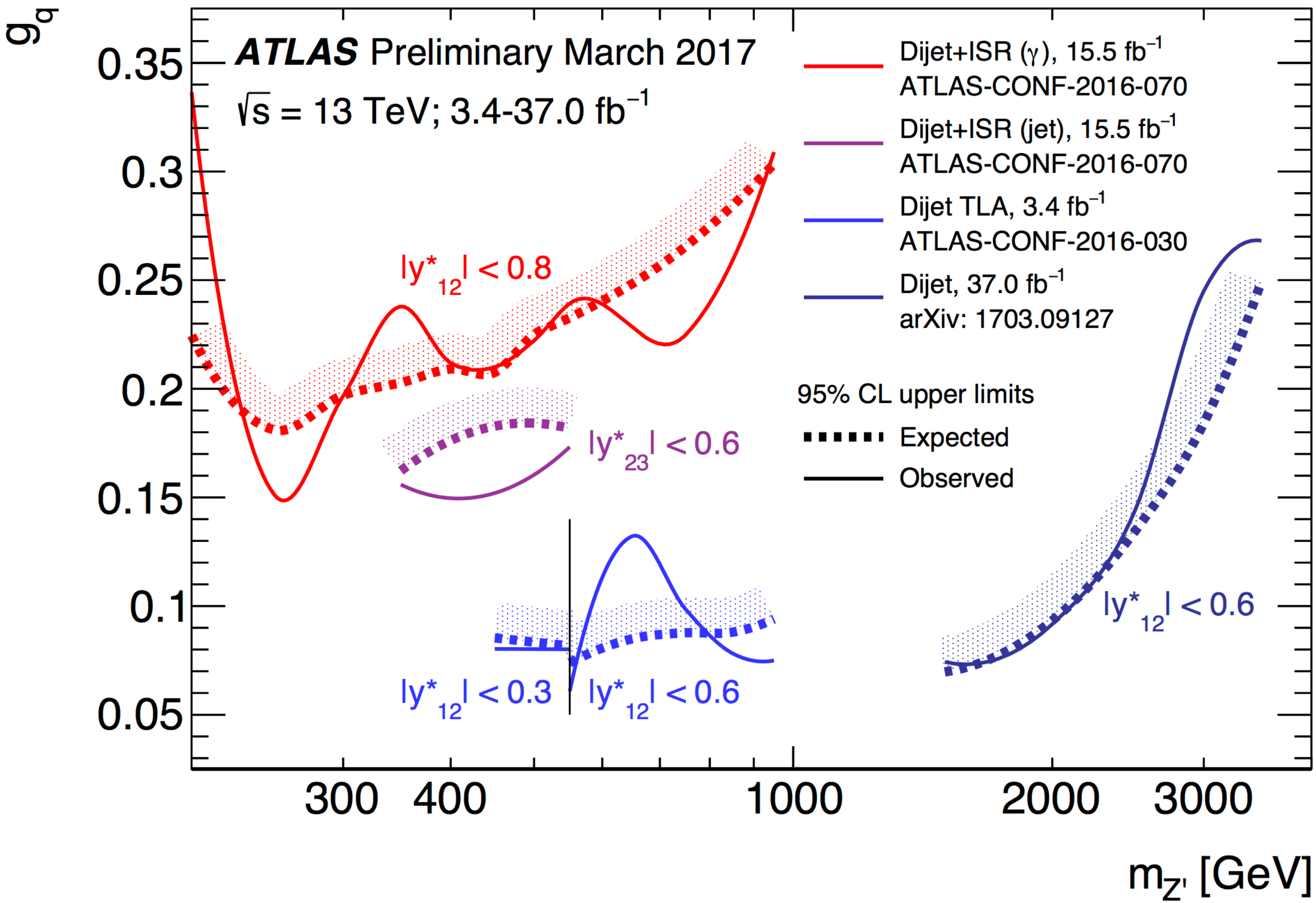
[ATLAS-CONF-2016-030]

- Lower trigger threshold by keeping only partial information for the event
- Additional jet calibration and cleaning applied online



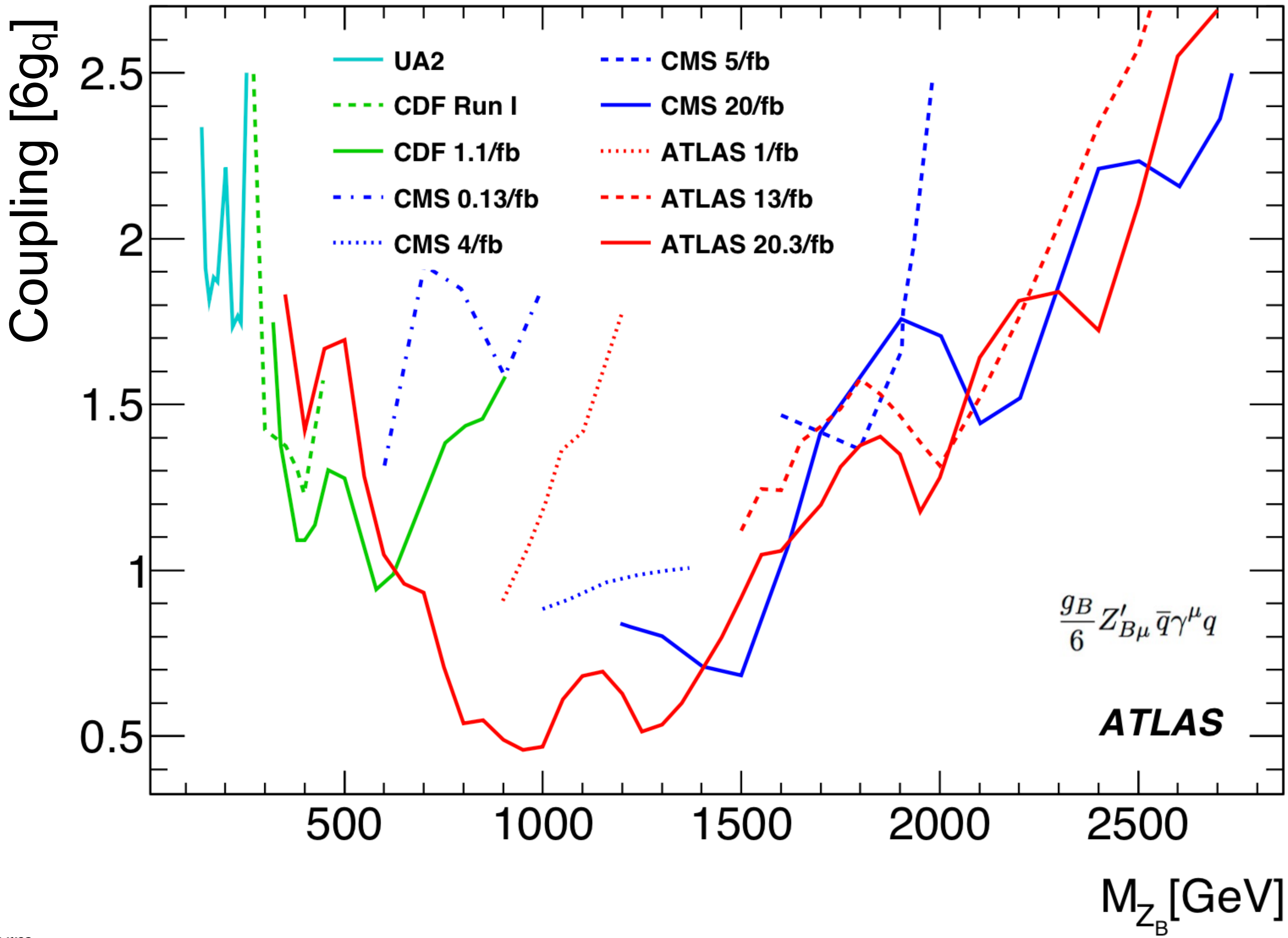


DIJET RESONANCE SEARCHES: SUMMARY

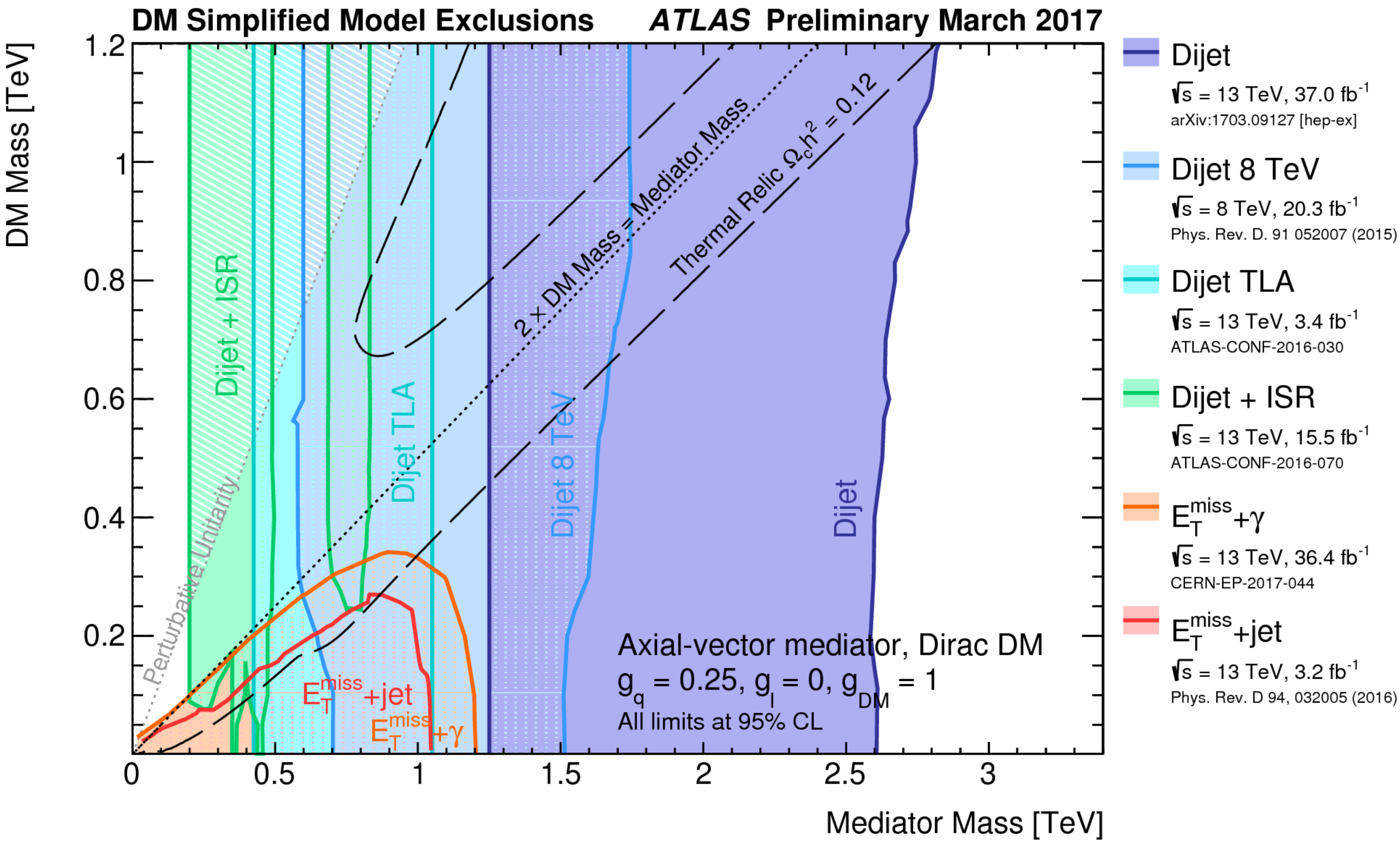


DIJET RESONANCE SEARCHES: SUMMARY

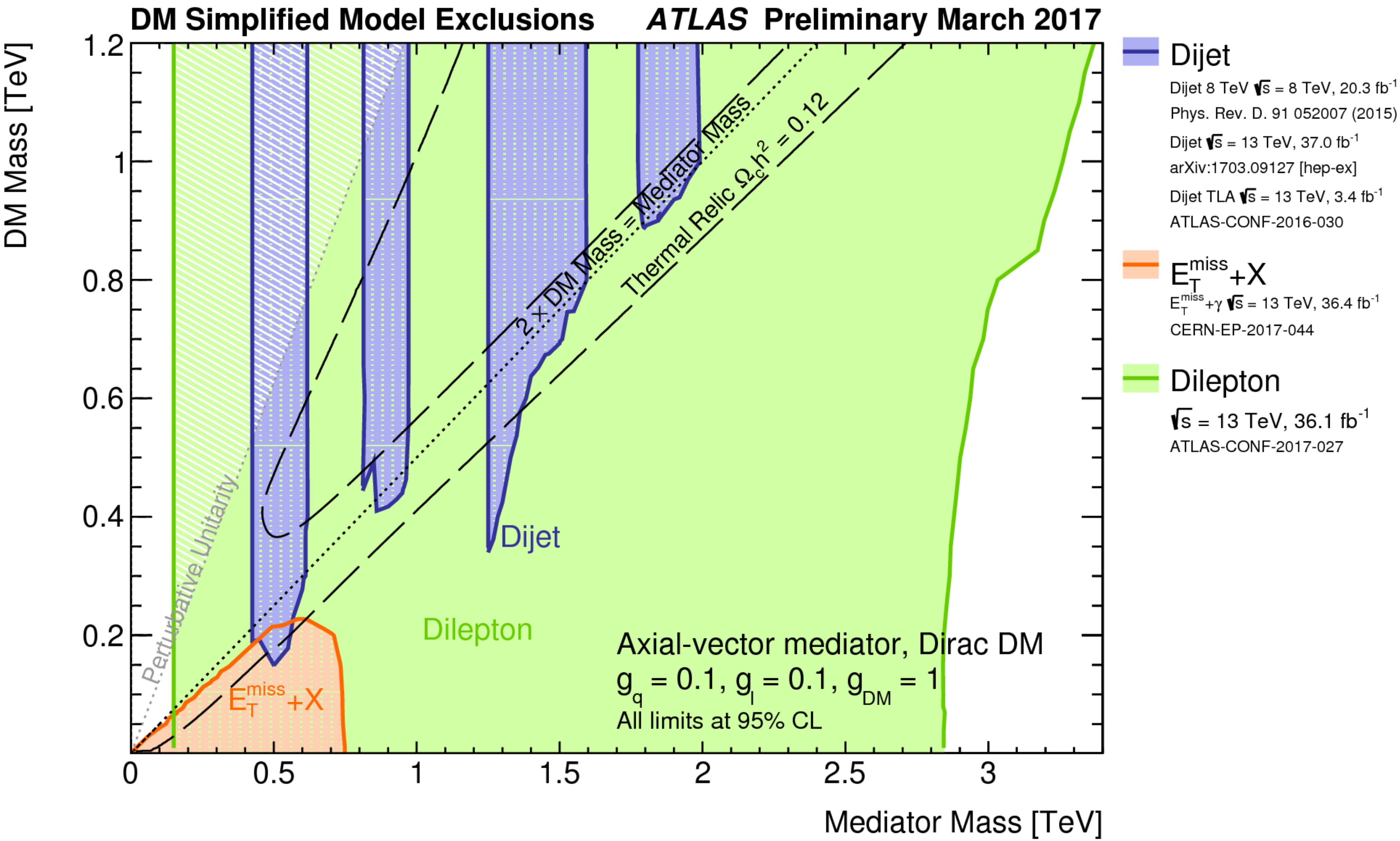
[ATLAS, arXiv:1306.2629]



MONO-X VS. DIJET DARK MATTER

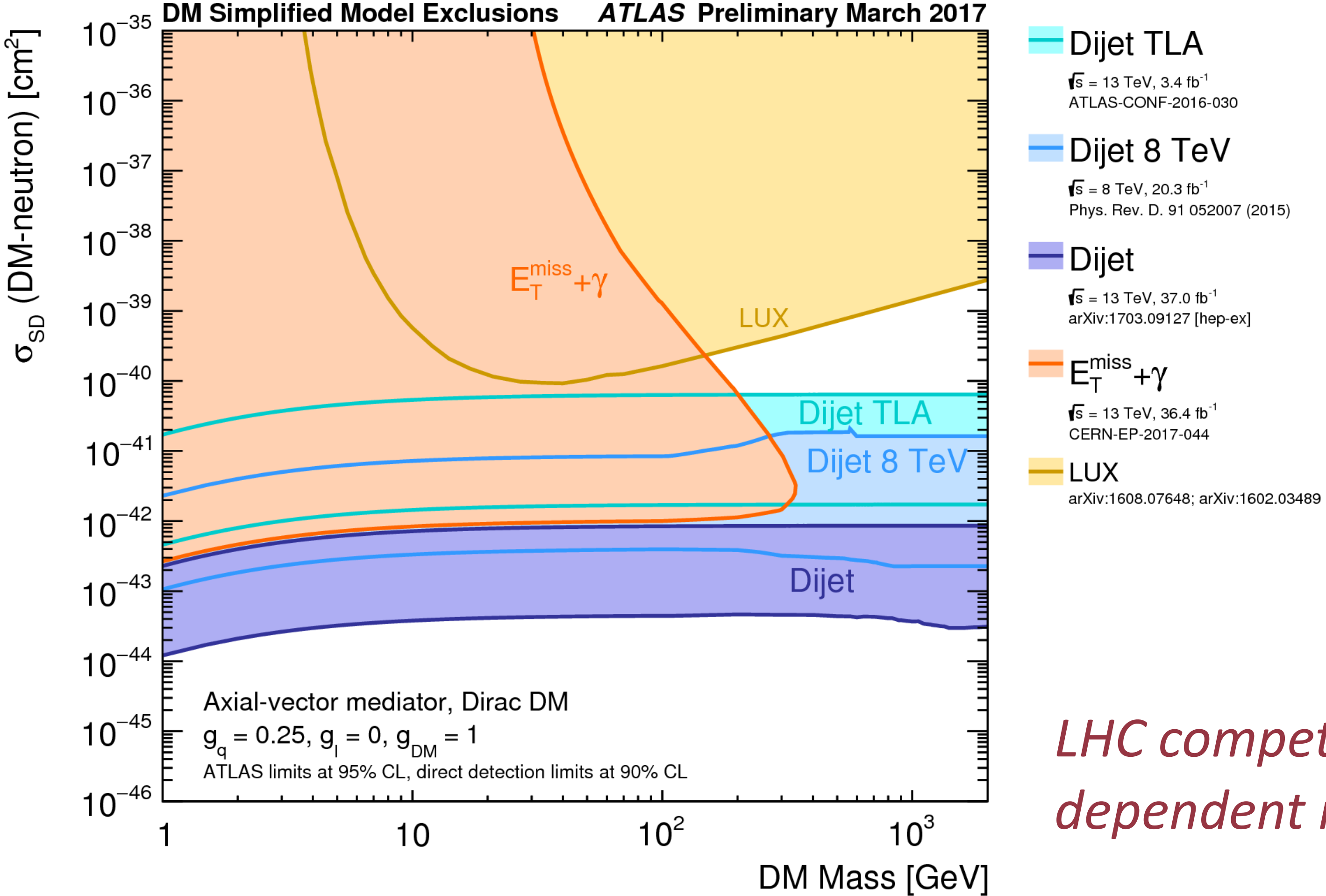


Mono-X vs. Dijet Dark Matter



DARK MATTER: ATLAS VS. LUX

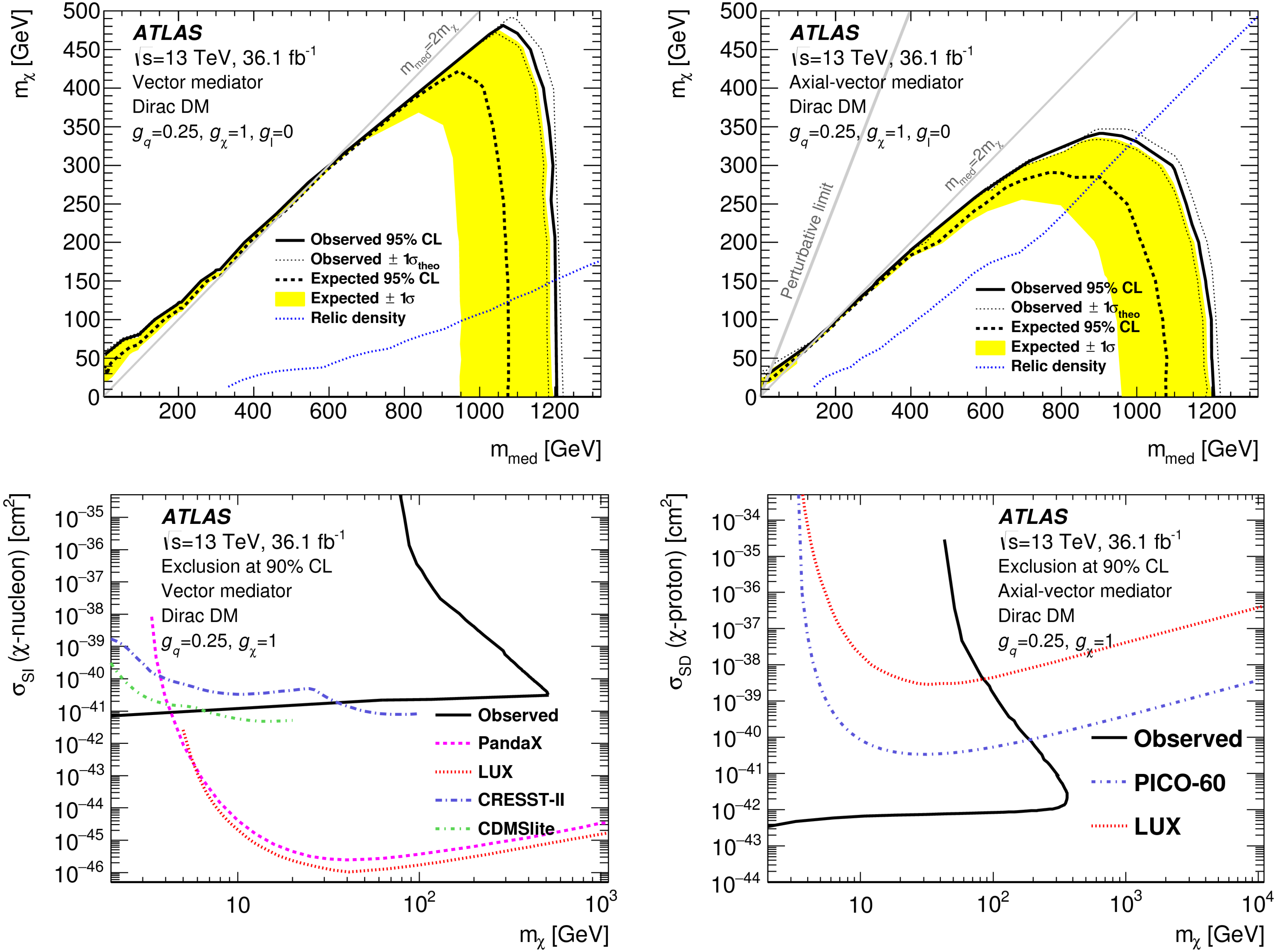
- LHC comparable with direct detection (for specific model assumptions)
- Complementarity approaches:
  - Direct searches loose sensitivity at low mass (nuclear recoil)
  - LHC (Mono-X) searches loose sensitivity at high mass ($\sqrt{s}$)



LHC competitive for spin-dependent interactions

ATLAS Mono-γ Dark Matter

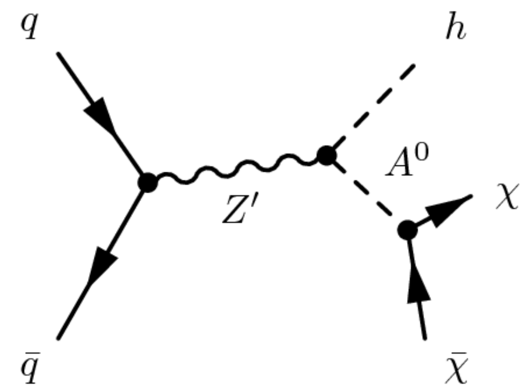
[arXiv:1704.03848]

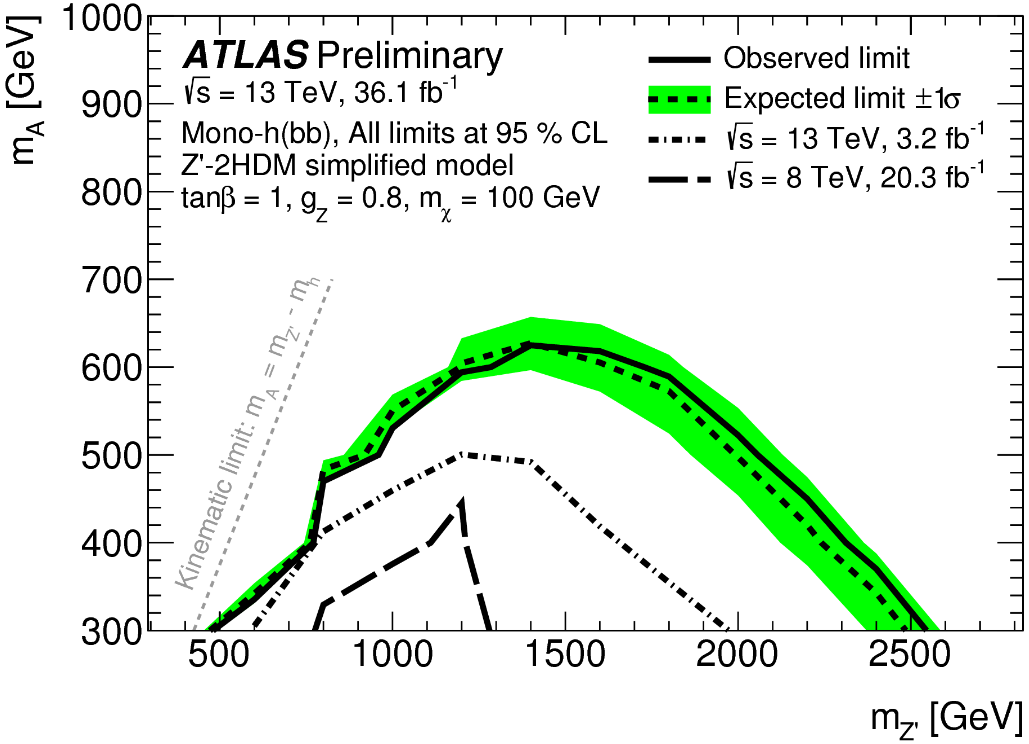


DARK MATTER IN MONO-H

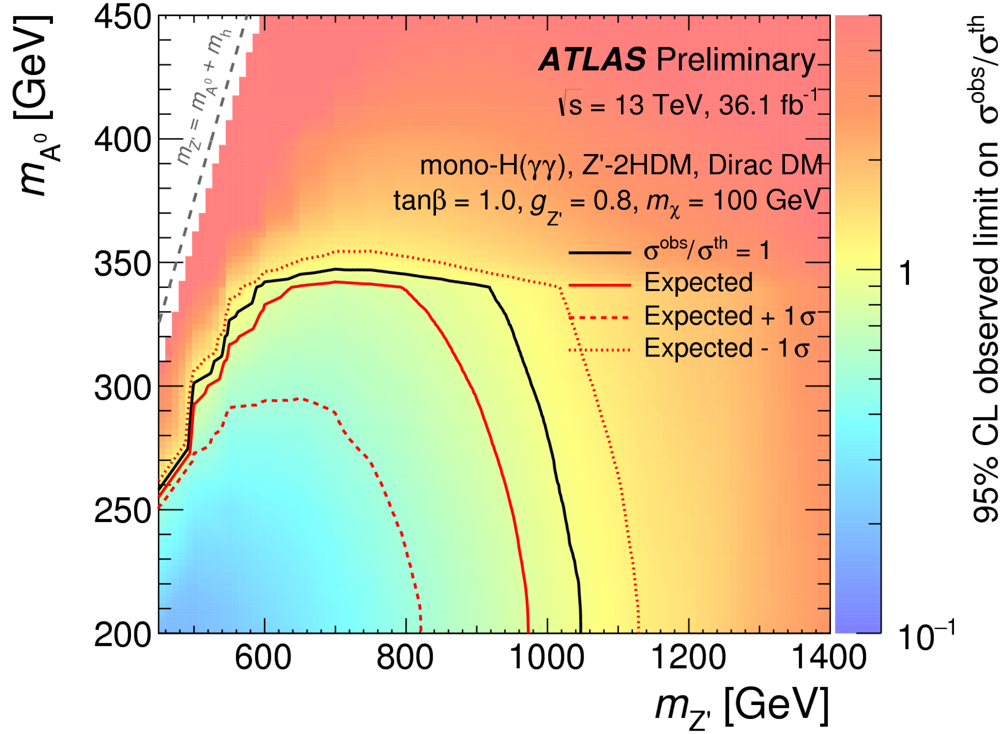
[ATLAS-CONF-2017-028, ATLAS-CONF-2017-024]

- Dark Matter and Mono-Higgs to bb, γγ
- Results for Z'_B, Z'-2HDM, heavy scalar boson models
- Huge improvement over previous search
- Mono-h(bb) better limits for $p_T(h) > 150$ GeV





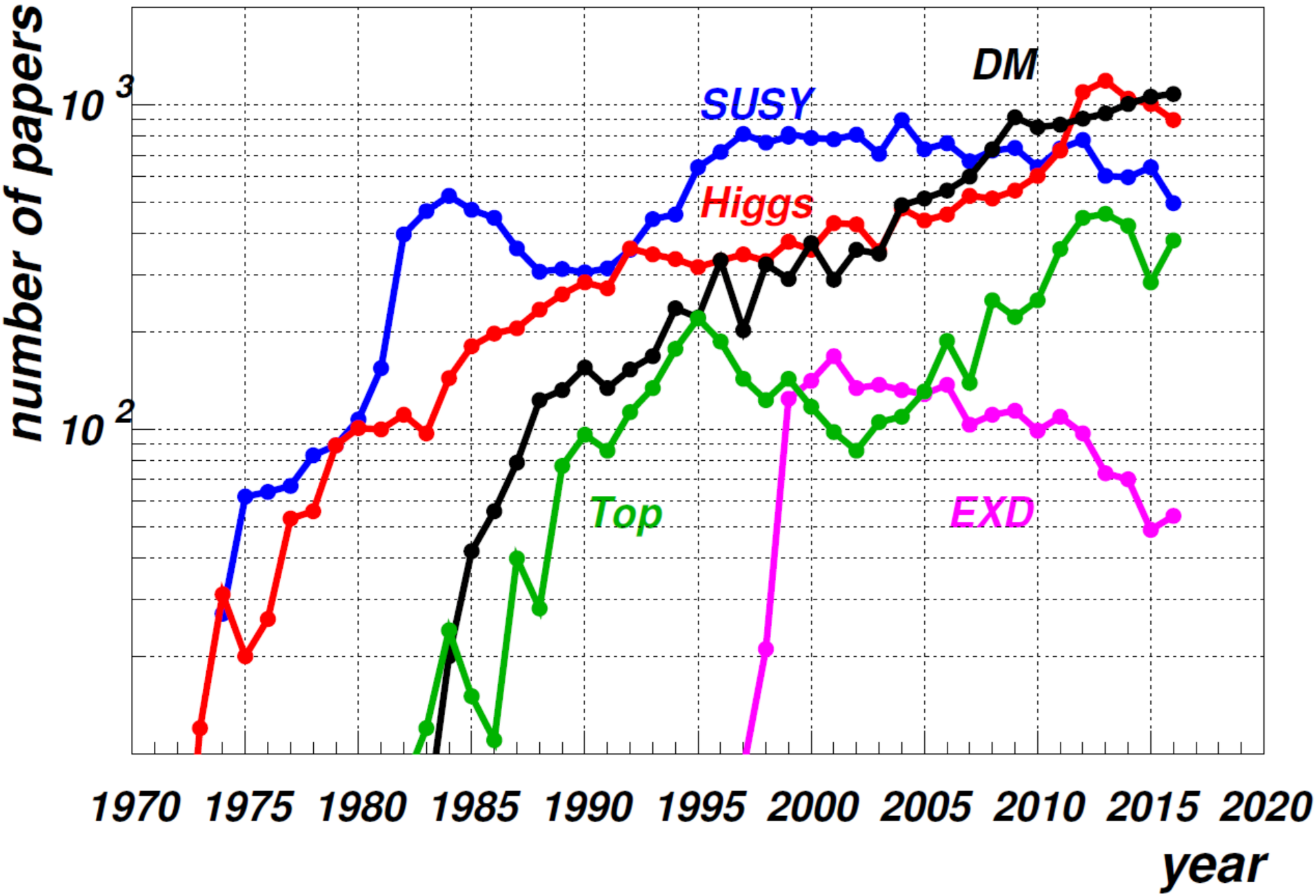
Mono-Higgs to bb



Mono-Higgs to γγ

THEORY PAPERS VS. YEAR

[A. Belyaev]



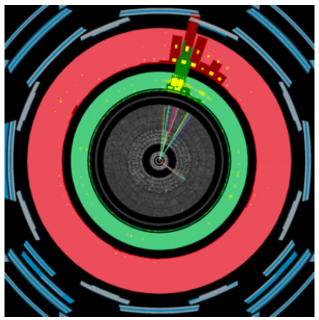
CONCLUSIONS

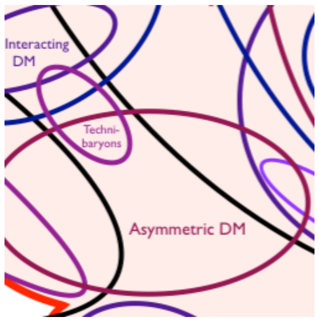
Searches for Dark Matter are thriving at the LHC, *monojet* the flagship

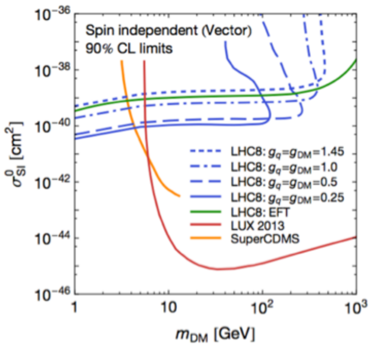
Community using *Simplified Model* interpretation, with focus on mediator

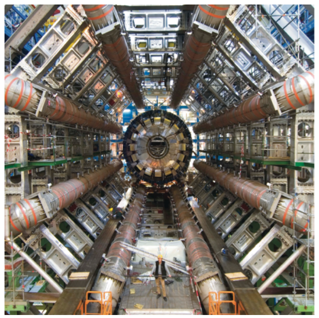
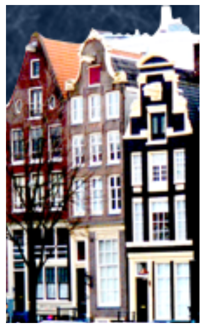
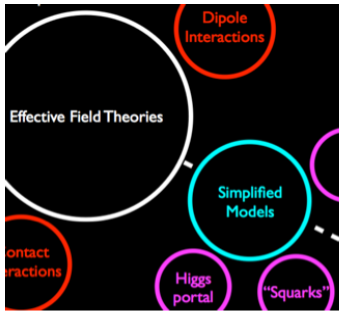
Huge number of new results coming in 13 TeV, across many channels

LHC trying to re-invent itself as a Dark Matter factory!





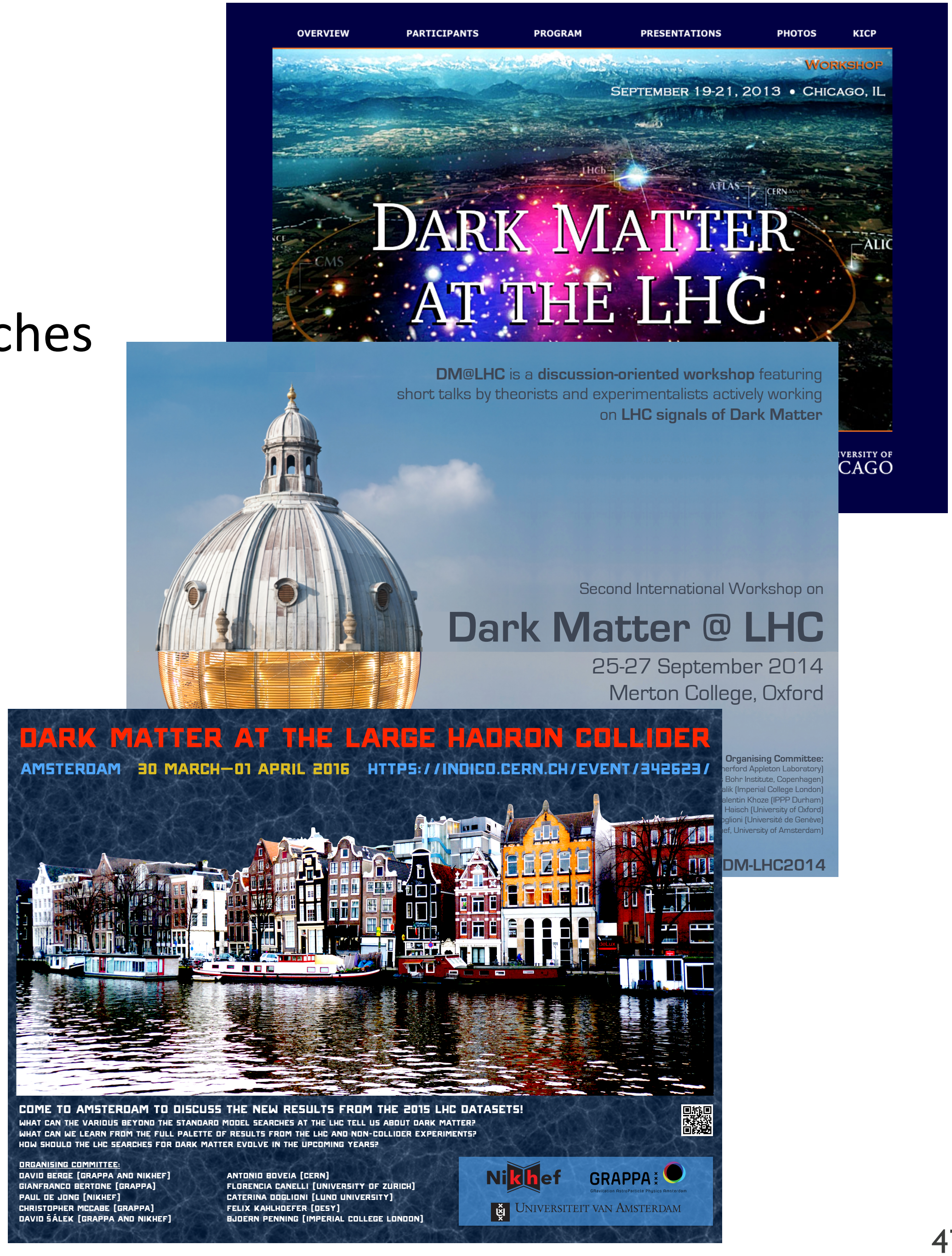


DM@LHC Workshops

- Meeting Themes
  - 1st: Sort out EFTs!
  - 2nd: Adopt set of Simplified Models
  - 3rd: Extend SM's and deploy in searches
  - 4th: Connections

- Many talks on the *connections* to other areas
  - Experiment: DM/BSM overlap
  - Direct/Indirect detection
  - Theory (models) evolving and connecting to more areas; SUSY, cosmological constraints, long lived



DM@LHC 2017

Thanks to our hosts!

- Timothy Tait
- Arvind Rajaraman
- Daniel Whiteson
- Mani Tripathi
- Jan Strudwick*

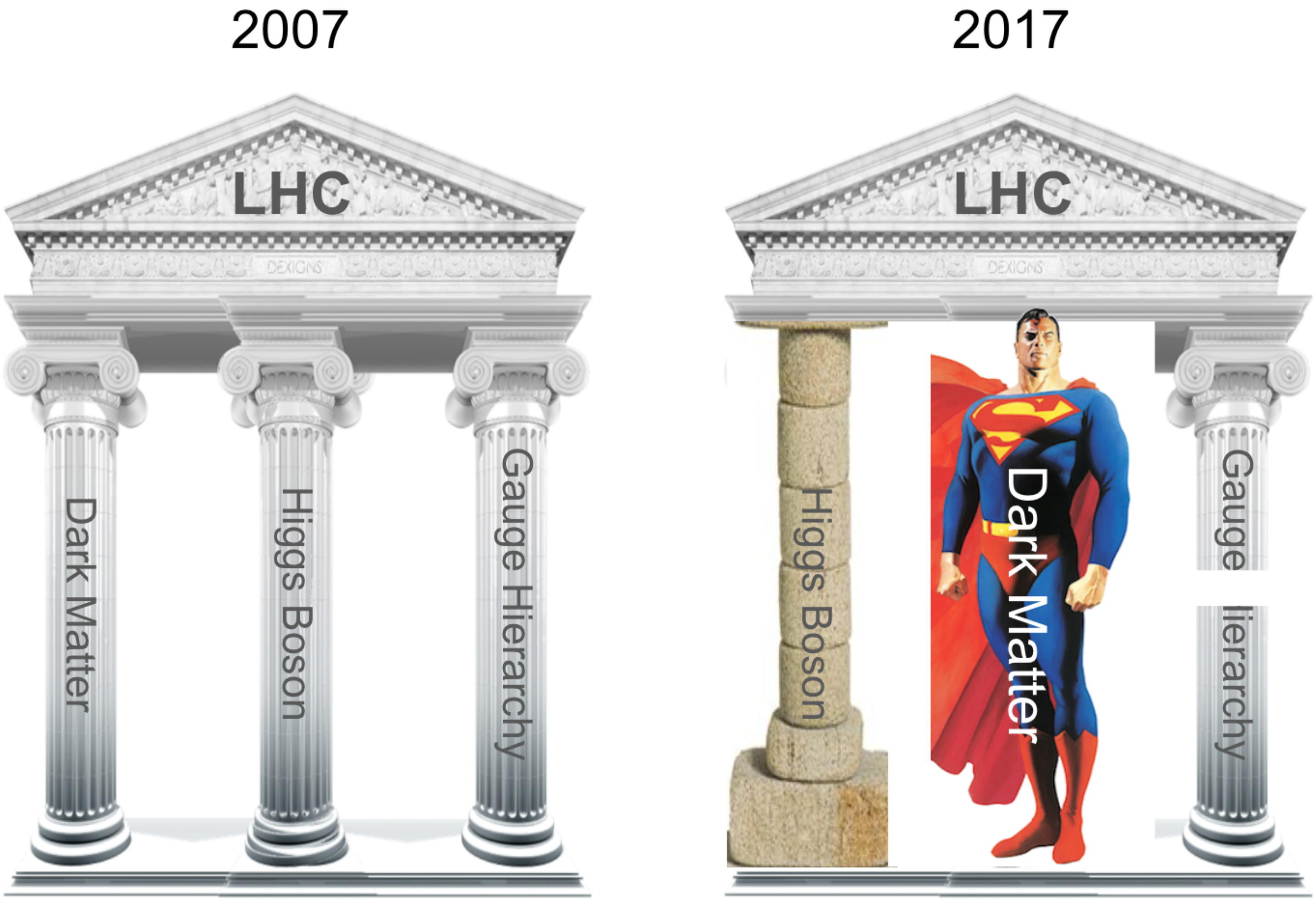
DM@LHC 2017:

- 3 full days of talks
- 45 presentations, 7 posters

Role of DM@LHC

J. Feng

Dark Matter as the central pillar of the LHC programme!



CERN COURIER

CERN COURIER

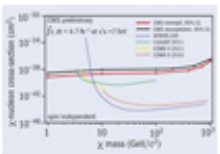
Mar 27, 2012

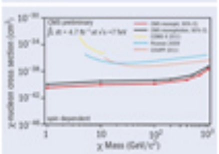
Shedding light on dark matter

Dark matter may constitute 83% of the particles in the universe, but so far there has been no direct observation of its presence in experiments. With its high-energy collisions, the LHC is a promising hunting ground for this elusive form of "matter", either by producing dark-matter particles directly or new particles that decay into dark matter. Recently, the CMS collaboration completed a search for dark matter, sifting through the full 2011 data set of proton collisions at a centre-of-mass energy of 7 TeV.

Dark-matter particles produced at the LHC would presumably escape undetected, yielding "missing momentum" in the event. However, they could be accompanied by a jet or a photon, or some other particle. CMS has looked for evidence of these visible companions by studying "monojet" and "monophoton" data. Within the framework of a simple model for the production of dark matter, the CMS analysis significantly extends the sensitivity of direct searches, which look for tiny interactions of dark-matter particles in very sensitive detectors.

The way that the dark-matter particles (χ) are produced and interact depends on their spin. With respect to direct searches, CMS is sensitive in the low-mass region below 3.5 GeV if the spin of the produced particles is ignored, and it can set the world's best limits at all masses in the spin-dependent case.





The 90% CL upper limits