QUEST FOR DARK MATTER AT COLLIDERS AND BEYOND

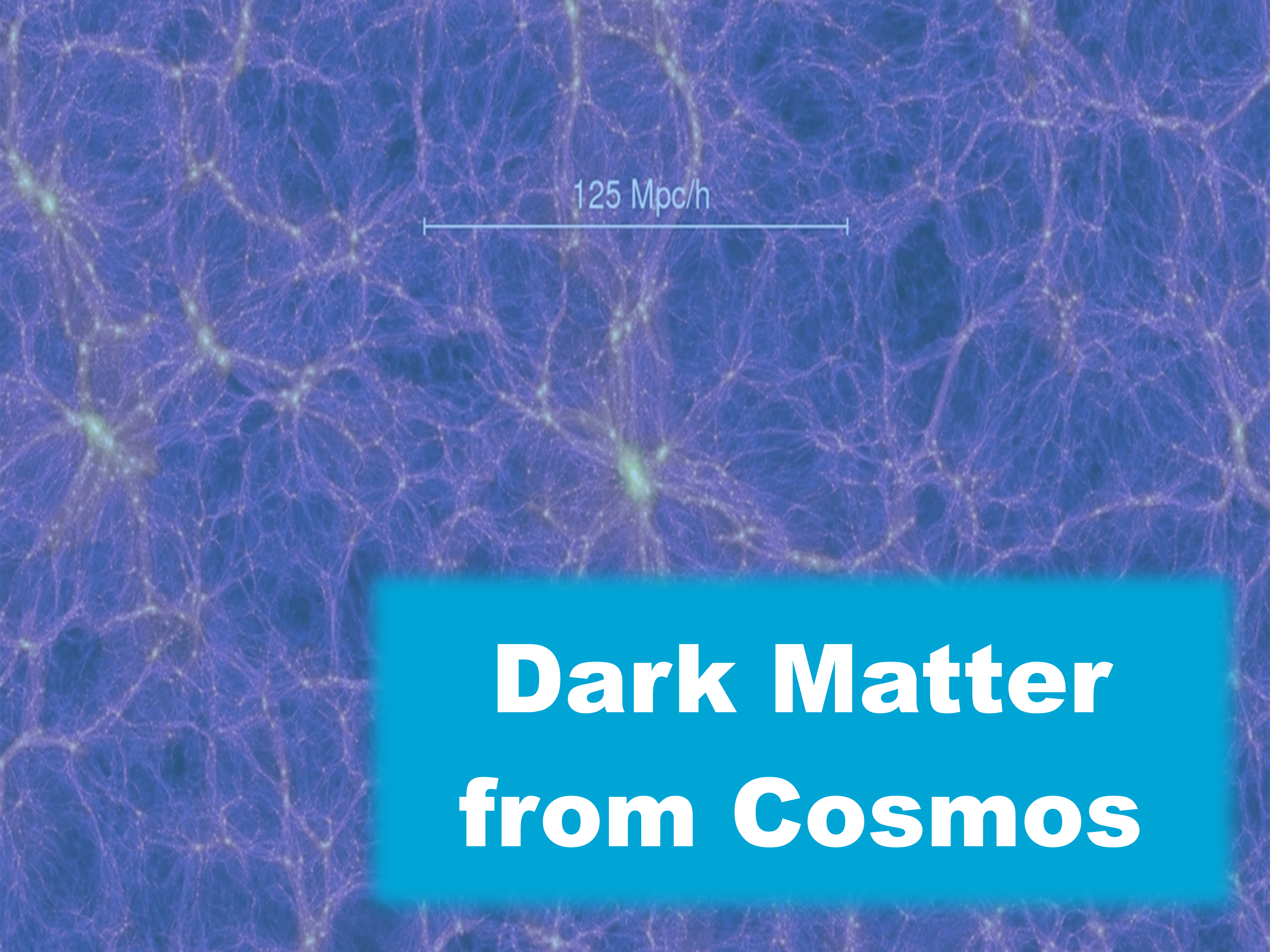
Greg Landsberg

DESY Colloquium

October 30, 2018

Outline

- Evidence for Dark Matter
- WIMP Miracle
- Status of Direct Detection Searches
- Indirect Detection Results
- Dark Matter at Colliders
  - EFT Approach
  - Simplified models of Dark Matter
  - Latest results
- Outlook



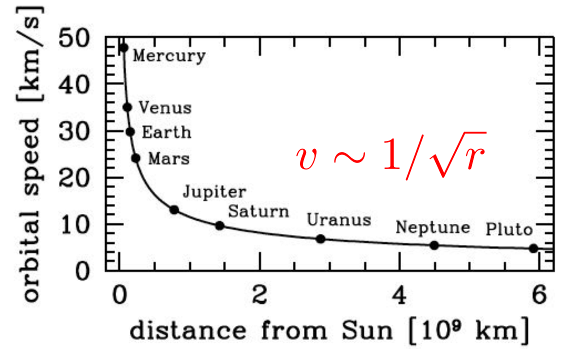
Dark Matter from Cosmos

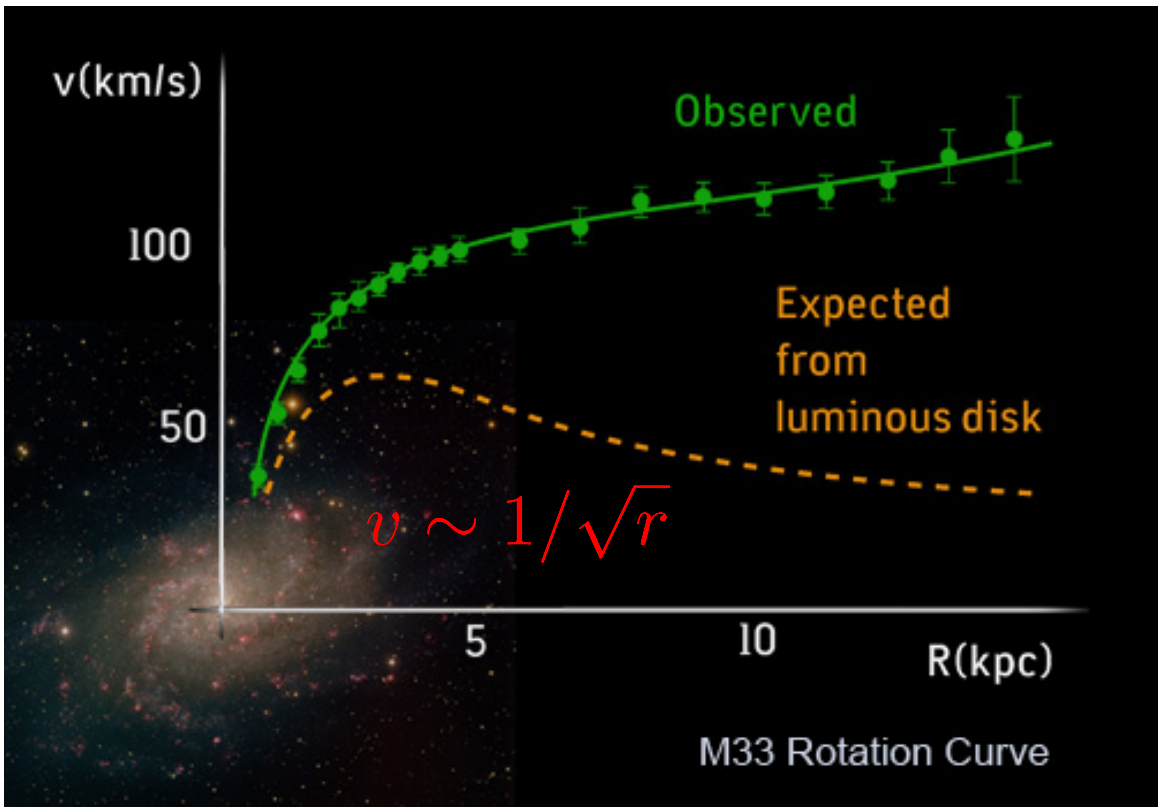
Dunkle Materie

- Fritz Zwicky was first to suggest the possibility of DM in the 1930-ies by observing the Coma cluster of galaxies and comparing the velocities to the ones expected from the virial theorem: $\frac{GM_{\odot}m}{r} = mv^2$
- Found that galaxies move too fast to remain bound unless there is additional invisible mass (DM)
- N.B. Similar technique as used by Le Verrier in 1846 to predict the existence of Neptune from the distortion of the Uranus orbit

Galaxy Rotation Curves

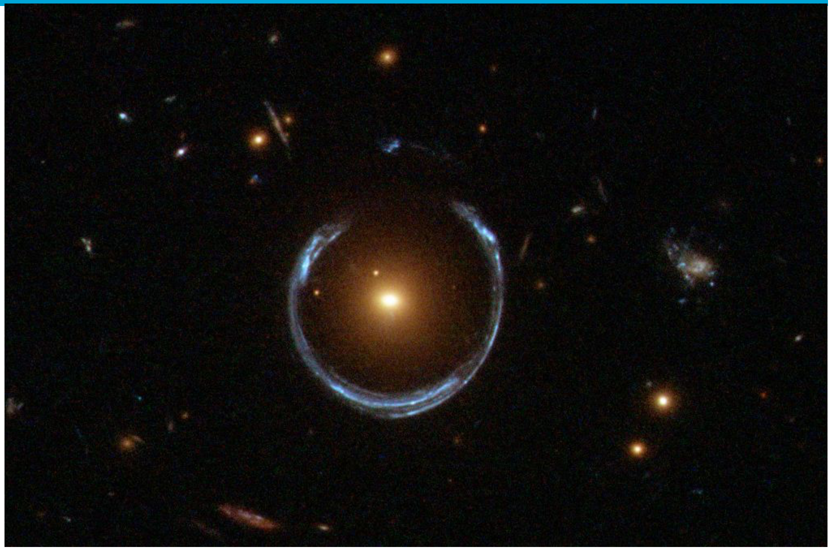
- ✦ In the 1970-ies, Vera Rubin has measured rotation curves in a number of spiral galaxies, only to find flat distribution, indicative of hidden mass

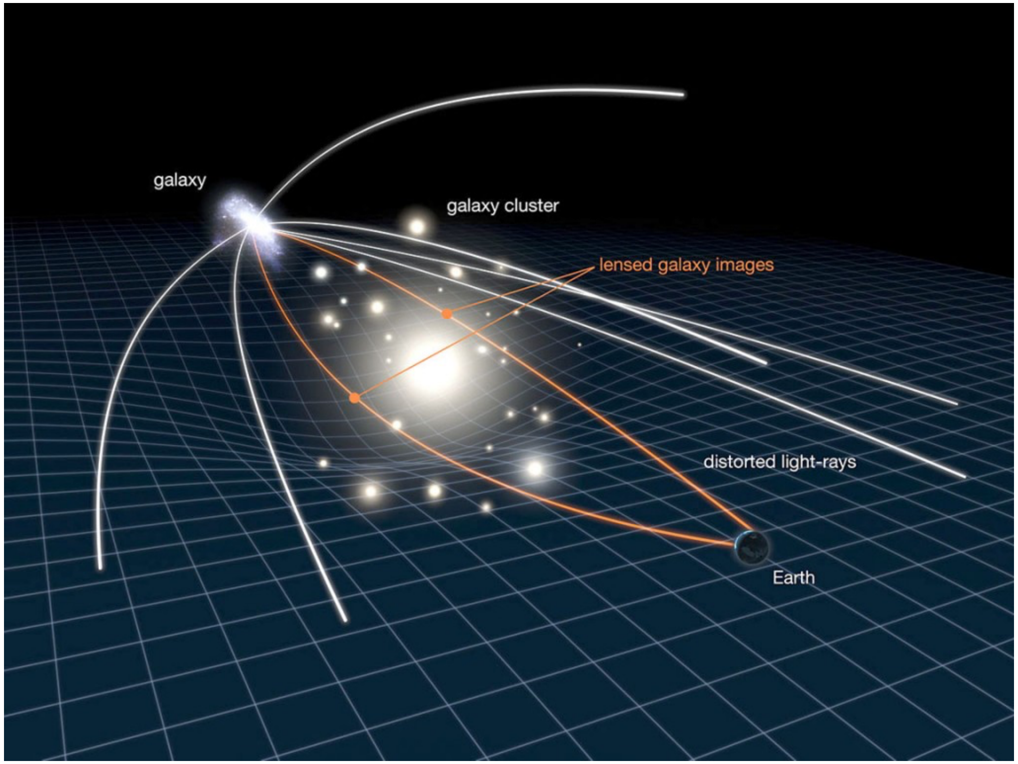


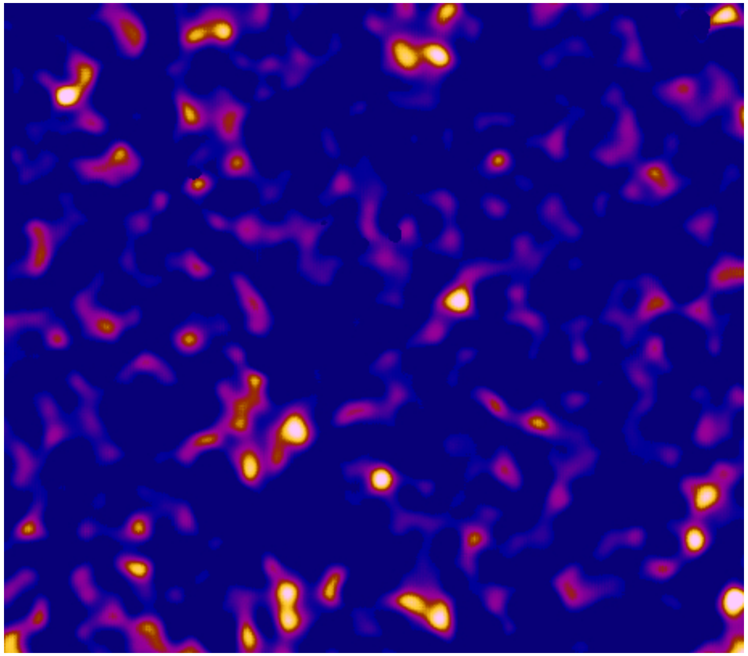


Gravitational Lensing

- One can also infer about the distribution of dark matter mass using weak or strong lensing

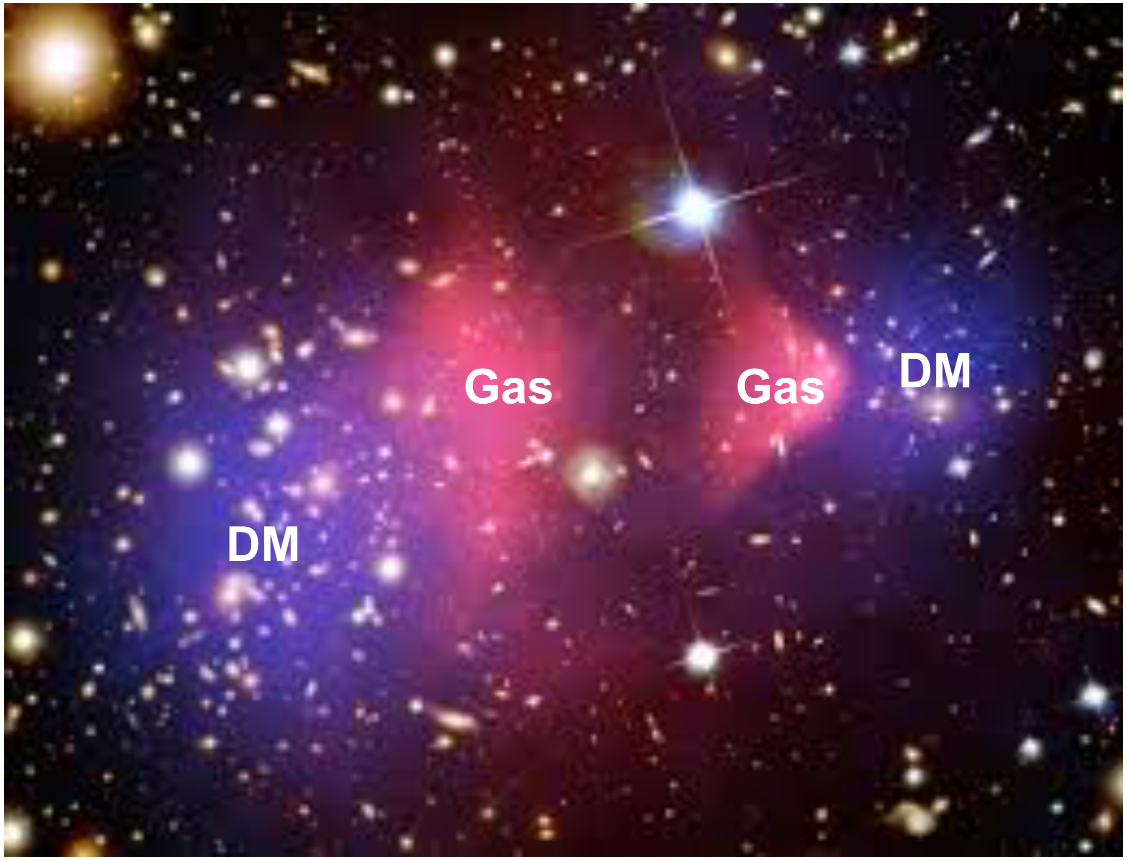






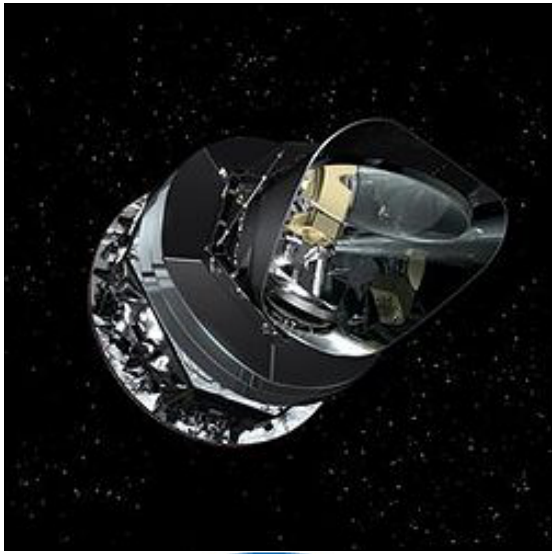
Other Observations

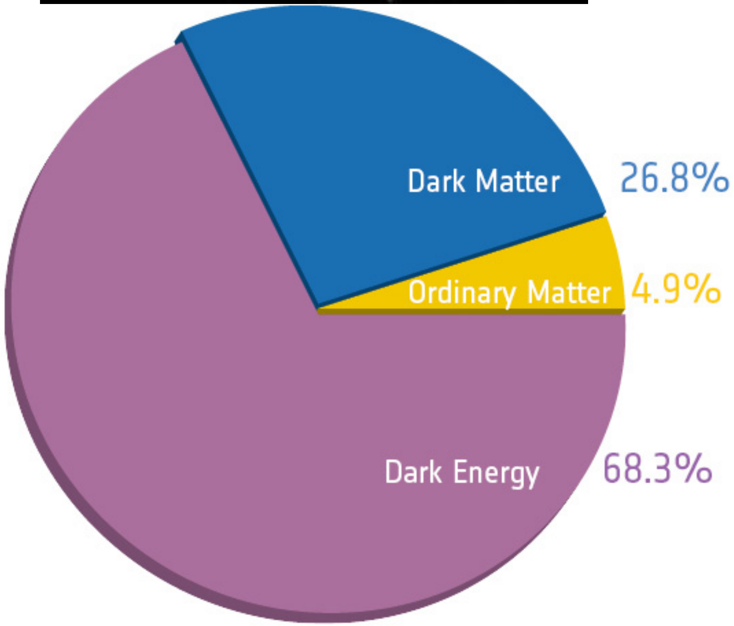
- Observation of the Bullet cluster by the Chandra X-ray satellite showed that hot matter is left behind the clouds of dark matter (reconstructed via gravitational lensing)



Abundance Measurements

- The leading model of cosmology is Λ_{CDM}, favored by cosmic microwave background measurements, baryon acoustic oscillations, gravitational lensing and other observations
- Latest CMB data dominated by the Planck satellite results suggest the following components of the energy balance in the universe





WIMP Miracle

- With the development of SUSY in the 1970-ies, it was quickly realized that a neutral, weakly interacting particle with the mass of ~100 GeV can naturally serve as a DM candidate
- This is known as "WIMP Miracle" and is one of three miracles of SUSY (the other two being a natural solution to the hierarchy problem and the unification of couplings)
- As the universe expands and cools down, WIMPs thermally decouple (i.e., can't annihilate any longer), giving fixed DM abundance:

$$\Omega_{\mathrm{DM}} h^2 = \frac{0.2 \times 10^{-9} \mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \Rightarrow \Omega_{\mathrm{DM}} \sim 0.2$$

$$\langle \sigma v \rangle \sim 10^{-9} \mathrm{GeV}^{-2}$$ (weak cross section)

Relic Abundance

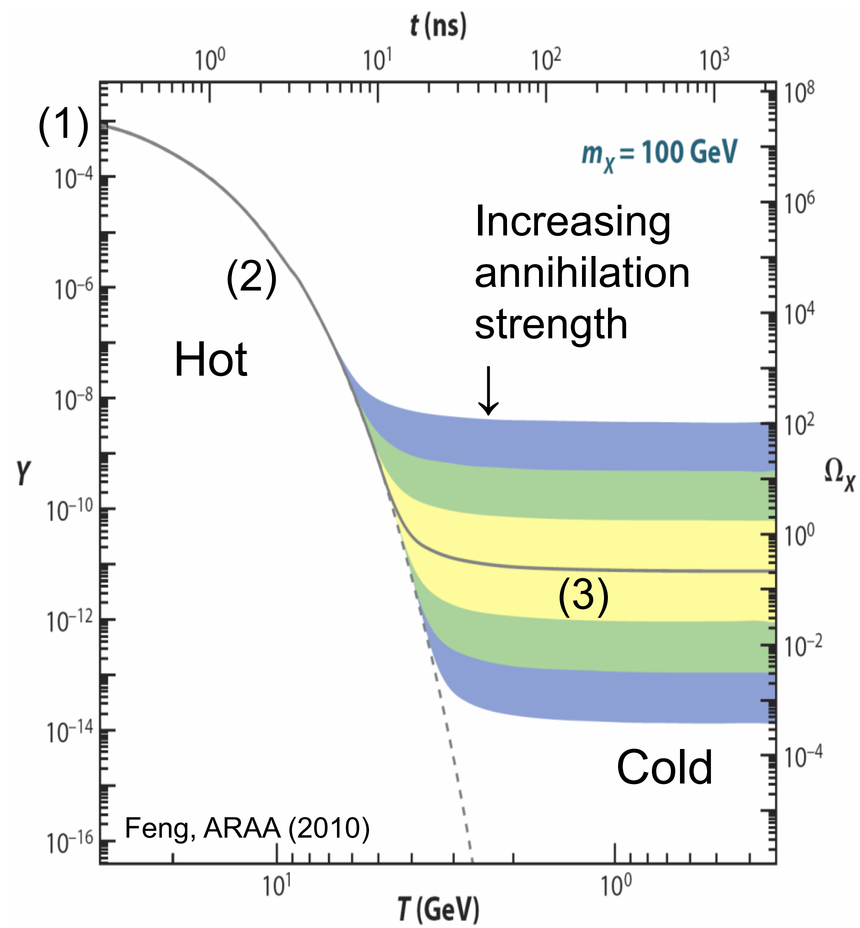
- When DM is in thermal equilibrium w/ matter, both the formation and annihilation are possible and equal:

$$\chi\chi \rightleftarrows q\bar{q}$$

- As the universe cools down, the formation is not possible, and only annihilation remains:

$$\chi\chi \rightarrow q\bar{q}$$

- As the universe further expands, the annihilation is no longer possible: DM freezes out
- This DM is non-relativistic (cold) with typical velocity ~300 km/s



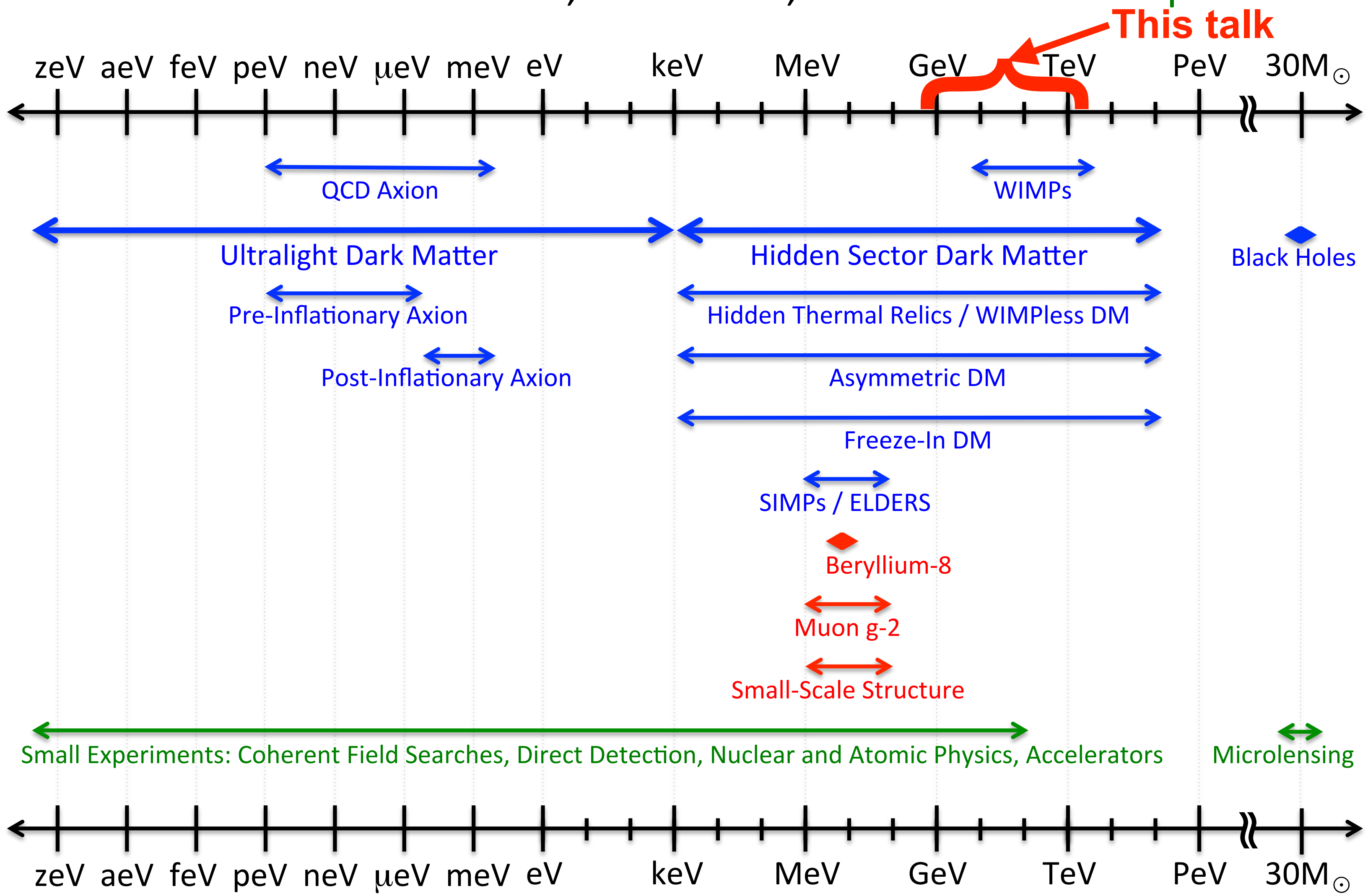
$$\Omega_{\rm DM}h^2 = 0.12$$

Nota Bene

- While WIMPs are the most sought and theoretically preferred DM candidates, they are not the only known possibility:
  - Axions (very light axial-vector particles proposed to solve the "strong CP" problem, could also serve as DM candidate
  - Dark sector (DM has complicated structure and is found in the dark sector, which only communicates to SM particles weakly)
  - Compact astronomical objects and primordial particles, such as super-heavy monopoles, could also be DM candidates
- Finally, while a single DM source is economic, the nature may have opted for a more complex solution, and there may be several sources of DM
- In what follows we will nevertheless focus on WIMP DM, predicted not only by SUSY, but also by other new physics models attempting to solve the hierarchy problem of the standard model (e.g., models with extra dimensions in space)
- Generally speaking, any model that predicts a stable, weakly interacting massive particle, whose stability must be ensured by a certain symmetry (e.g., R-parity in SUSY), could be a good DM candidate

Dark Matter Landscape

Dark Sector Candidates, Anomalies, and Search Techniques



Battaglieri et al., rXiv:1707.04591

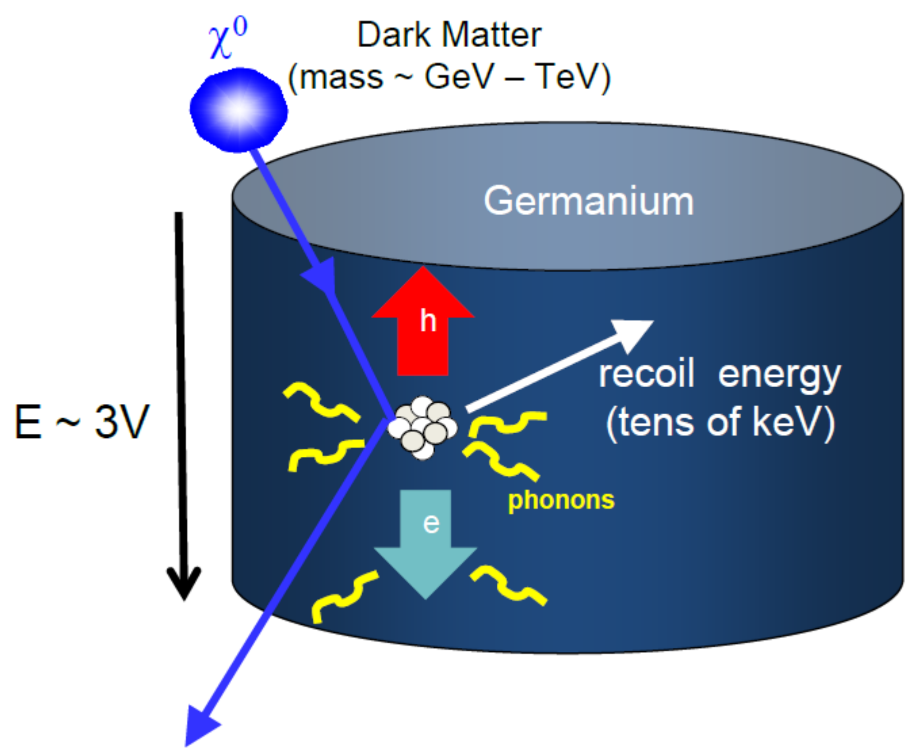
BROWN

Known Unknowns

- While the true origin of DM is unknown, several things about DM are well understood
- Assuming that DM has particle origin we know that:
  - It has to be a neutral particle
  - It's unlikely that it carries color (strong interactions)
  - It must be stable on a cosmological timescale
  - It must have the right abundance, which sets constraints on its decay channels, couplings, and mass
    - For example, ordinary neutrinos can't be a sole source of DM, despite having mass
    - In order to achieve the right abundance, DM must be able to interact with the SM particles, which is usually achieved by introducing a "mediator" a particle coupled to both SM species and DM

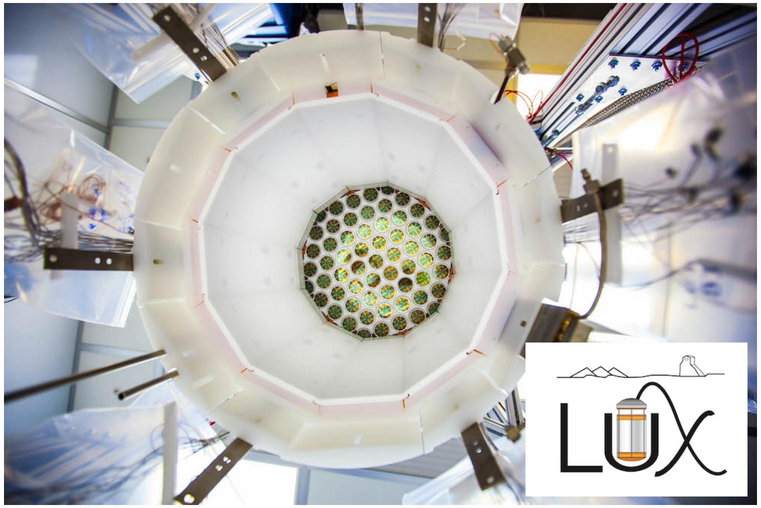
Searching for Dark Matter

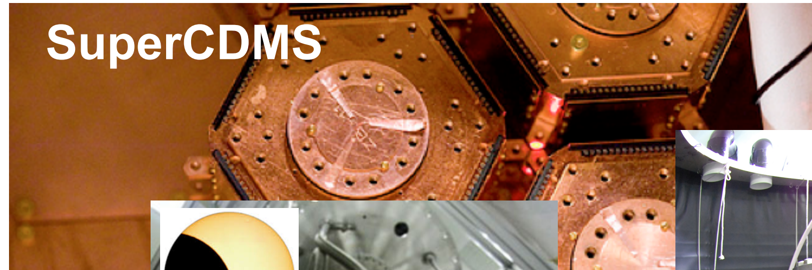
- A clever way of searching for DM is to look for a recoil of DM from a heavy nucleus
- These types of experiments use very cold targets and are conducted deep underground to shield cosmic rays
- The sensitivity drops dramatically for a light DM, as there is not much of a recoil!
- Latest generation of experiments uses Xe as the target (LUX, Xenon1T, PandaX, LZ)
  - As the dominant Xe isotope has spin 0, these experiments are sensitive mainly to spin-independent (SI) scattering and benefit from a resonant enhancement ~A^2
  - Other targets are used to probe spin-dependent (SD) scattering (C_4F_{10}, CF_3Br, etc)

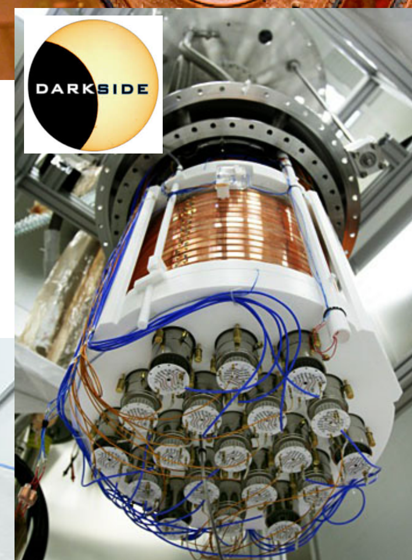


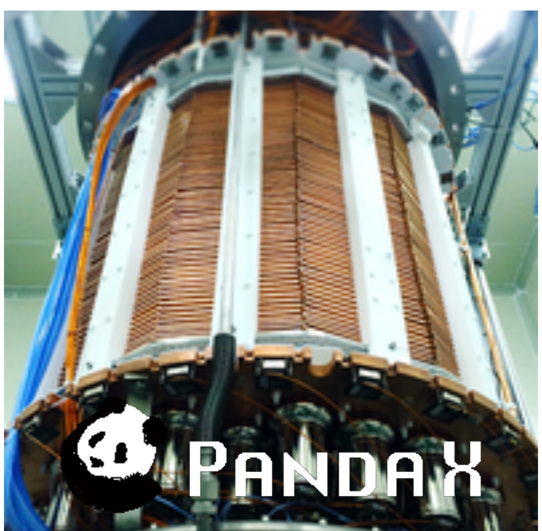
BROWN

Direct Detection Experiments



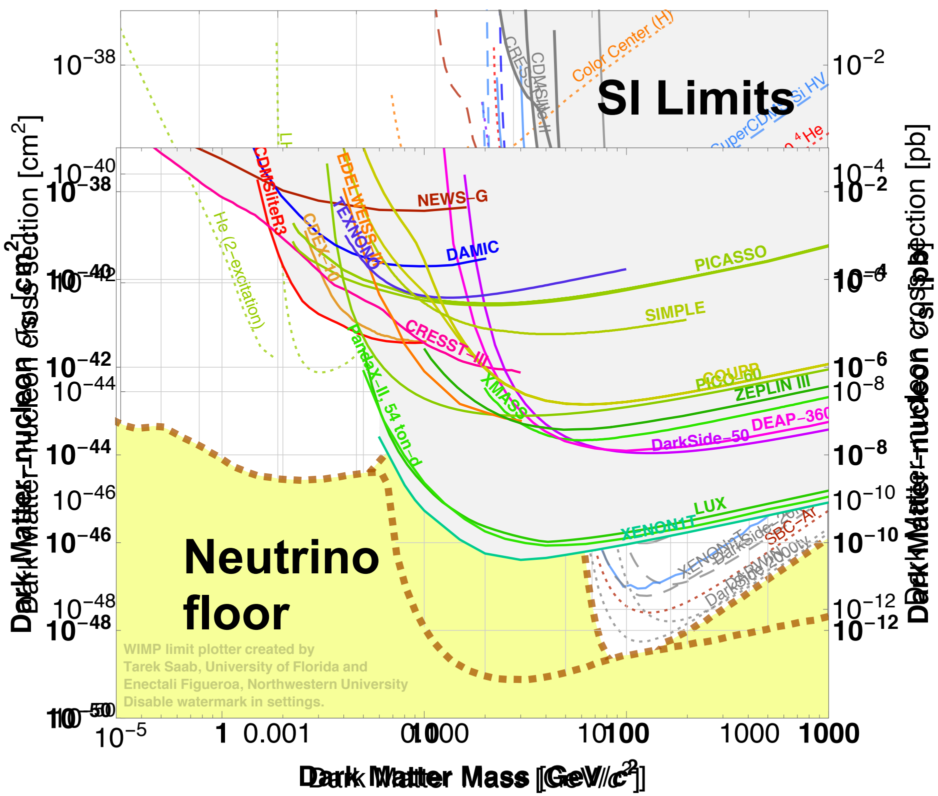


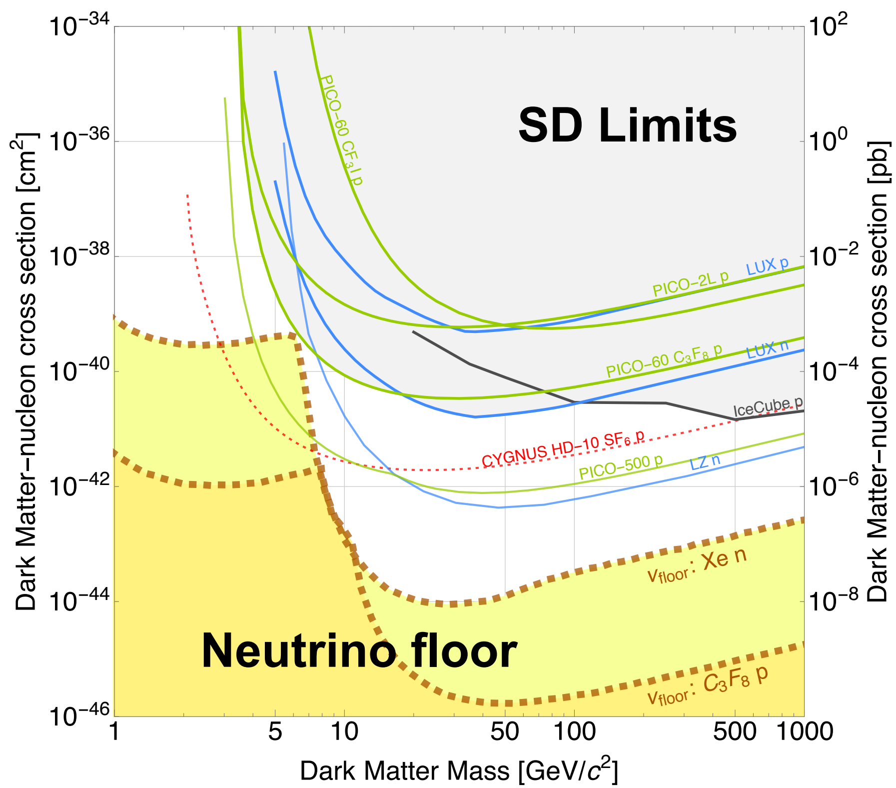




Direct Detection Constraints

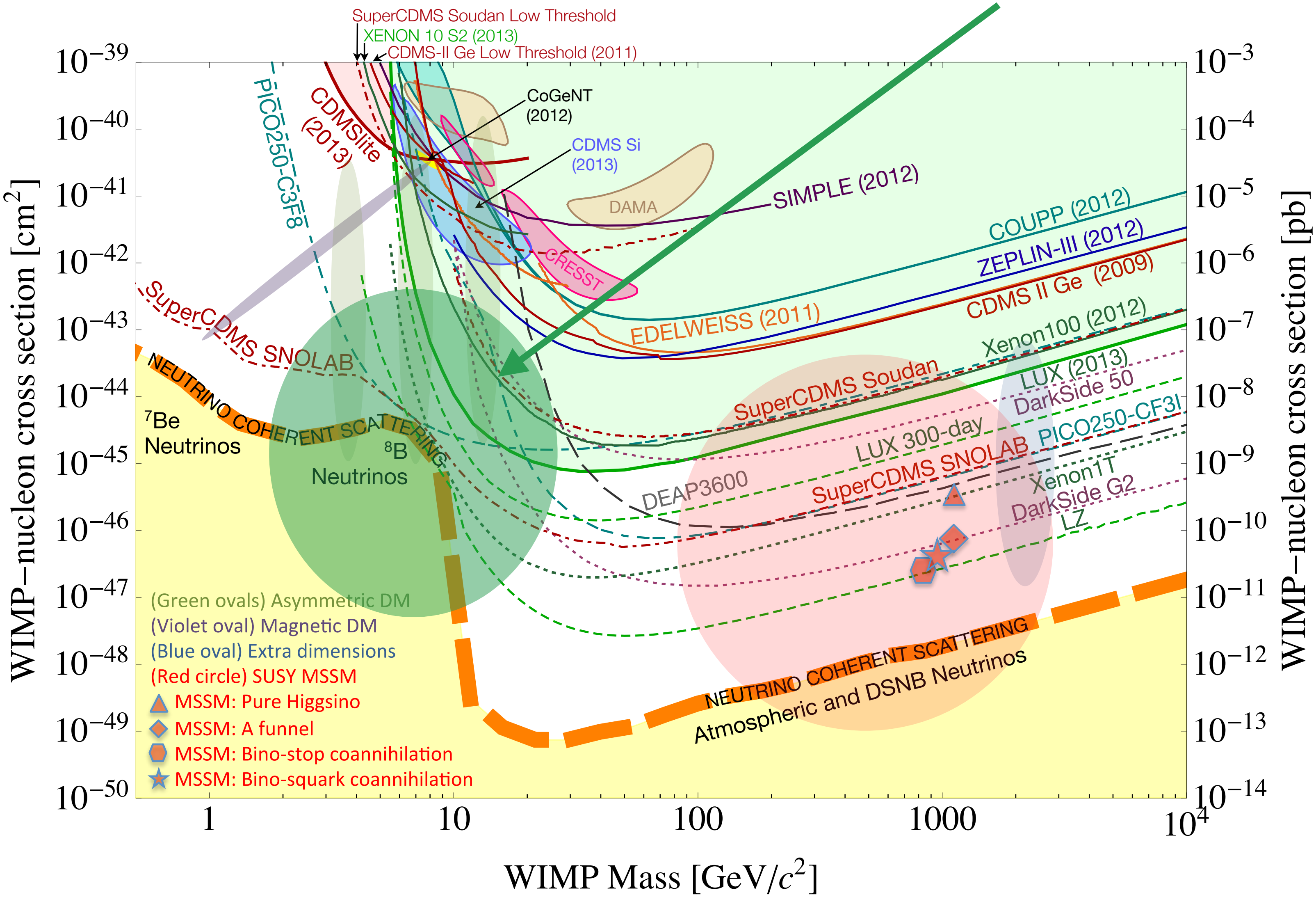
- State of the art results dominated by the latest Xenon 1T result, with Lux & PandaX-II being close second/third (SI) and PICO (SD)
- Large neutrino detectors (IceCube, SuperK) are also sensitive to DM via annihilation inside the Sun or (very slow) decay
- Note the SD limits are ~6 orders of magnitude weaker than the SI ones





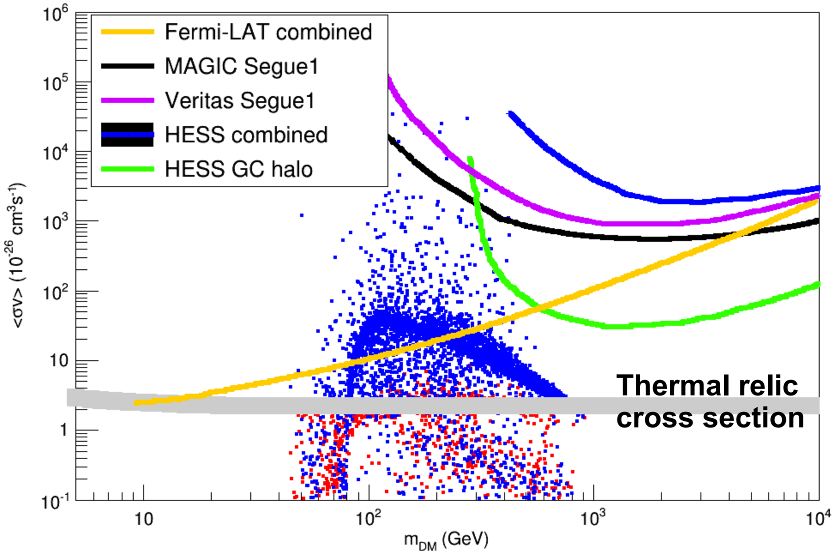
Future of Direct Detection

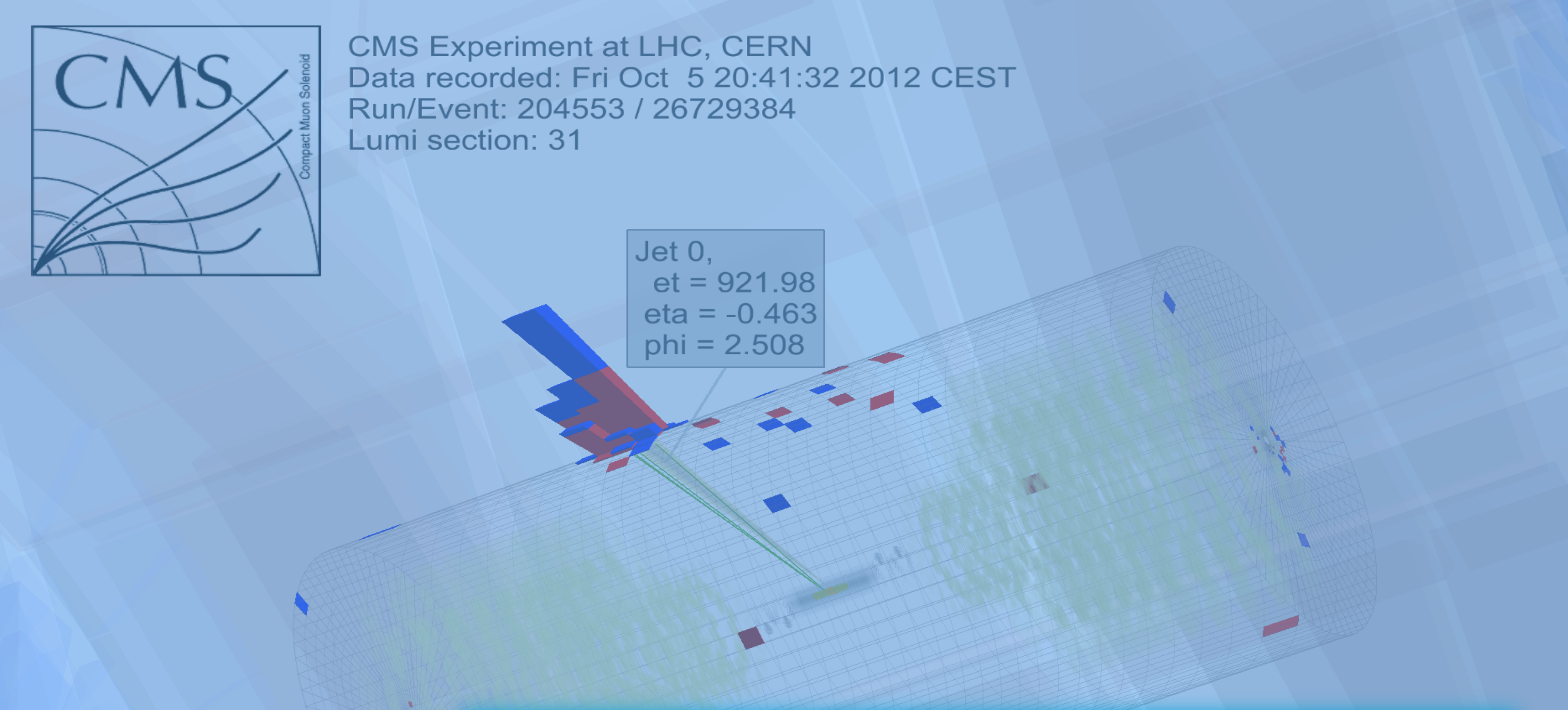
- Next generation of DD experiments will reach the "ν floor"



Indirect Detection

- Look for DM annihilation in SM particles, further decaying to lighter species (bb, $\tau\tau$, ...)
  - Every time a π^0 is created, it decays into two photons - look for an excess of γ rays in the sky
- Number of ground-based (HESS, Magic, Veritas) and space-based (Fermi-LAT) instruments
  - Look for γ ray emission from the center of galaxy, cluster of galaxies, dwarf galaxies, etc.
  - Certain hints (galactic center, dwarf galaxies) have been reported, but no definitive observation (yet)
  - Could also look for positron emission (AMS, Pamela)
  - Results reported in terms of velocity-averaged annihilation cross section

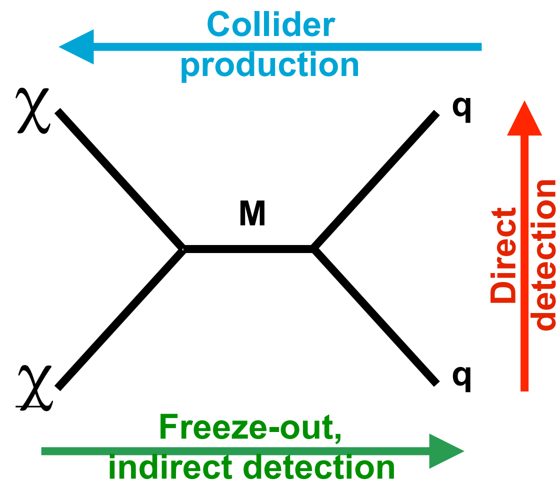


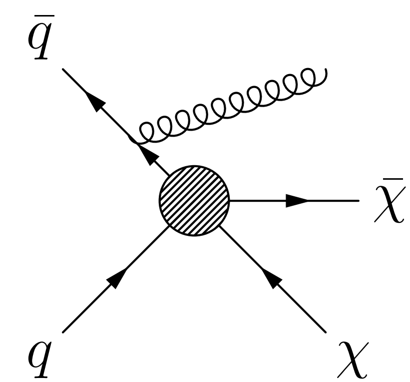


Monomania, or LHC as a Dark Matter Factory

Make It, Break It, or Shake It!

- There are three main approaches to detect dark matter (DM):
  - DM-nucleon scattering (direct detection, or DD)
  - Annihilation (Indirect detection, or ID)
  - Pair production at colliders
- All three processes are nothing but topological permutations of one and the same Feynman diagram:
  - But: how to trigger on a pair of DM particles at colliders?
  - Initial-state radiation (ISR: g, γ, W/Z, H, …) to rescue!
- Original idea - to use ISR - appeared eight years ago:
  - Beltran, Hooper, Kolb, Krusberg, and Tait, "Maverick Dark Matter at Colliders" arXiv:1002.4137 (299 citations)





Monojet + MET

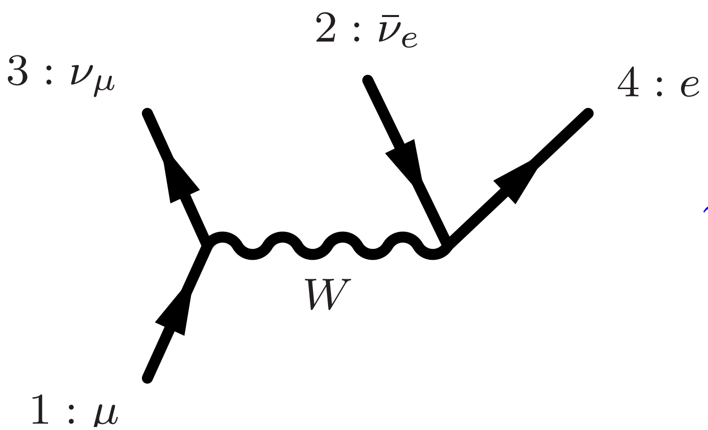
BROWN

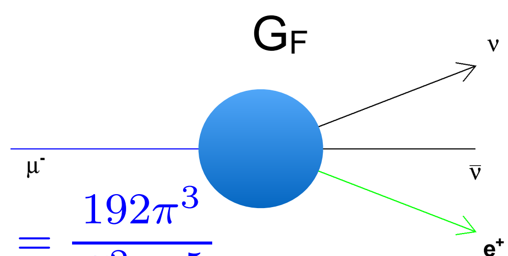
Mono-Mania

- More phenomenological follow-ups sparked interest from the collider community:
  - Goodman et al, arXiv:1005.1286, 359 citations
  - Bai, Fox, Harnik, arXiv:1005.3797, 361 citations
  - Goodman et al, arXiv:1008.1783, 574 citations
  - Fox, Harnik, Kopp, Tsai, arXiv:1103.0240, 238 citations - LEP reinterpretation
  - Fox, Harnik, Kopp, Tsai, arXiv:1109.4398, 424 citations - LHC case
- The first experimental search came from the CDF collaboration:
  - Mono-top, arXiv:1202.5653, 27 citations
  - Monojets, arXiv:1203.0742, 85 citations
- Was quickly followed and superseded by ATLAS and CMS:
  - CMS, Monophotons, arXiv:1204.0821, 188 citations
  - CMS, Monojets, arXiv:1206.5663, 274 citations
  - ATLAS, Monophotons, arXiv:1209.4625, 170 citations
  - ATLAS, Monojets, arXiv:1210.4491, 248 citations
- ...and then the hell broke loose with dozens of other mono-X searches

Effective Field Theory

- Effective Field Theory (EFT) is a convenient simplified description of a complicated process via effective operator (and effective coupling)
- Most well-known example: Fermi theory of muon decay





$$\tau_\mu = \frac{192\pi^3}{G_F^2 m_\mu^5}$$

$$G_F = \frac{\sqrt{2} g_w^2}{8 M_W^2}$$

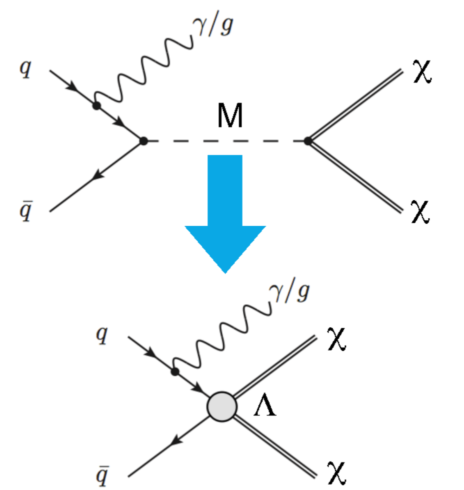
$$\left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_w^4}{M_W^4} m_\mu^2 E_2 (m_\mu - 2E_2)$$

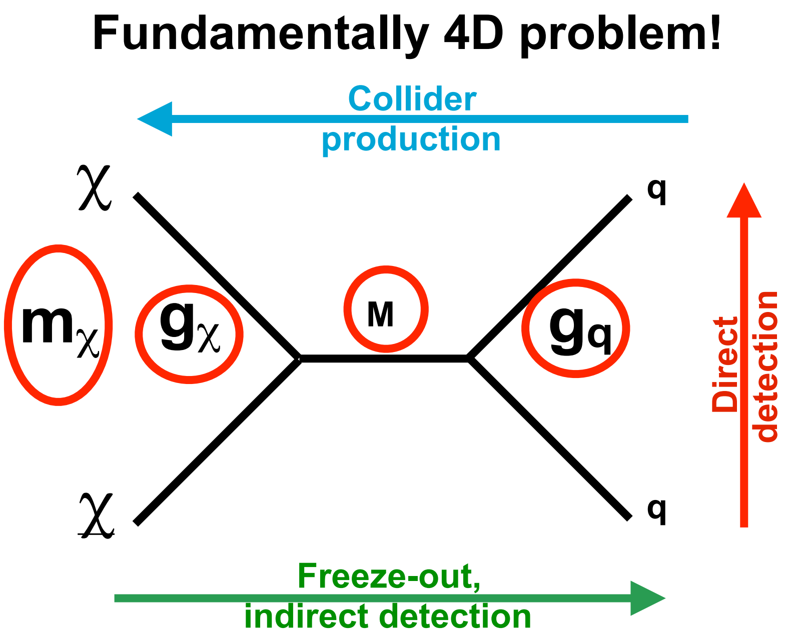
$$\Gamma_\mu = \left(\frac{g_w}{M_W}\right)^4 \frac{m_\mu^2}{2(4\pi)^3} \int_0^{m_\mu/2} E^2 \left(1 - \frac{4E}{3m_\mu}\right) dE = \frac{1}{6144\pi^3} \left(\frac{g_w}{M_W}\right)^4 m_\mu^5$$

- But, just like applying Fermi theory to describe W production at the LHC would fail completely, one has to be very careful about applicability of effective theory

Dark Matter Interactions

- Early DM searches: EFT based
  - Since then understood the fundamental limitations of EFT and moved to simplified models
- Moving away from EFT allows for a more fair LHC vs. DD/ID experiments comparison and emphasizes the complementarity of the two approaches



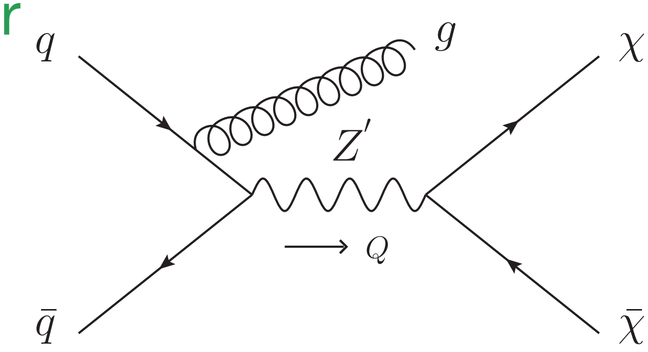


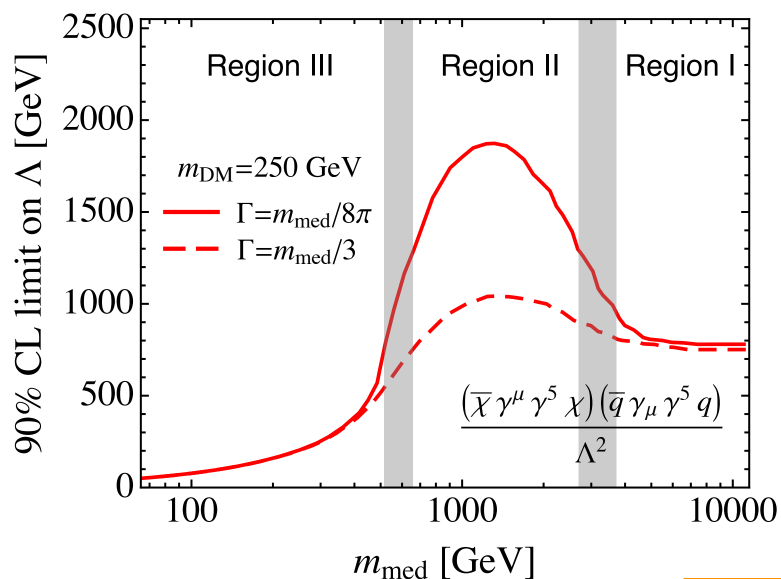
BROWN

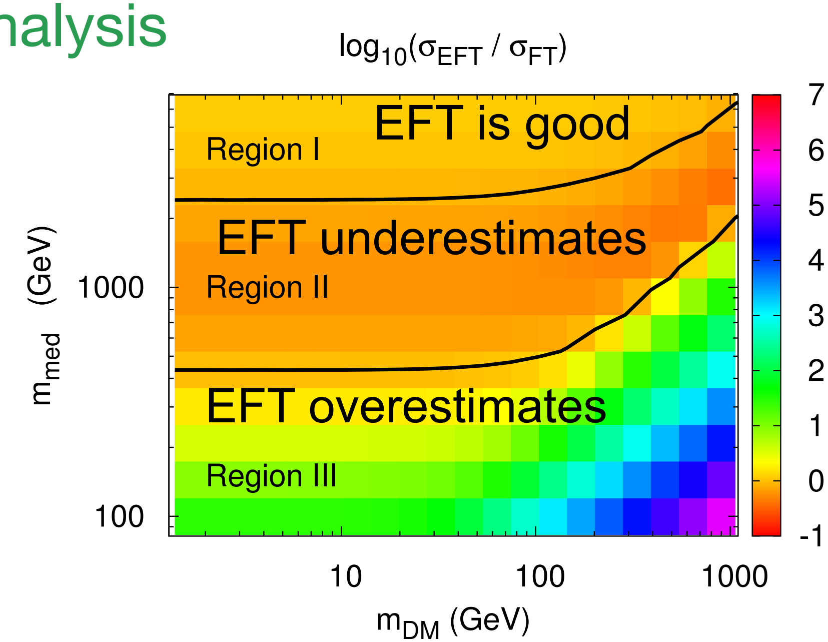
Realistic Example

- The couplings and the width are in fact interrelated
- Let's take a toy example of an axial vector particle exchange: $\frac{\Gamma}{m_{\rm med}} = \frac{N_C\, g_f^2}{12\pi}\left(1 - \frac{4m_f^2}{m_{\rm med}^2}\right)^{3/2}$

  where N_C = 1 for a color-singlet mediator
- Now let's consider the limits for a typical case based on the CMS monojet analysis



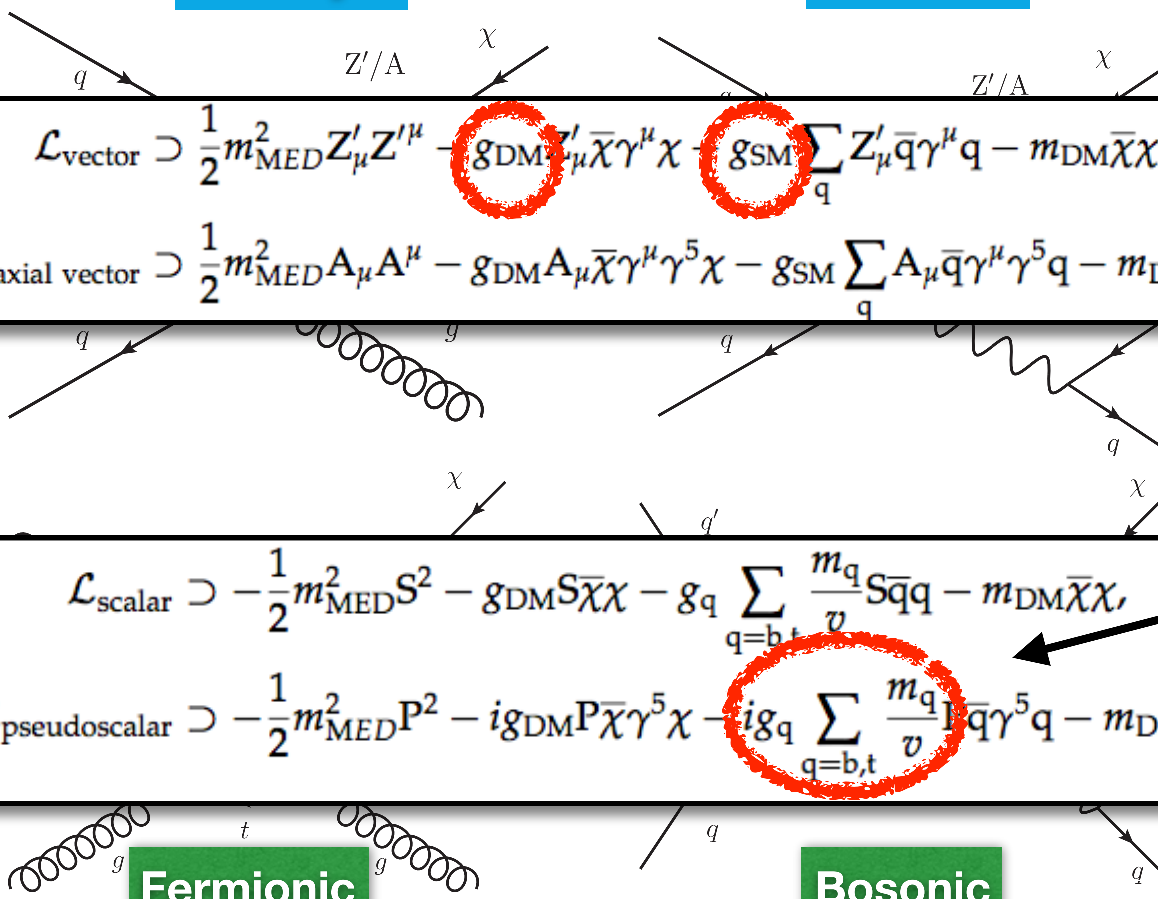




Buchmuller, Dolan, McCabe, arXiv:1308.6799

Simplified Models to Rescue

- Combined monojet and mono-V(jj) (boosted) analysis
- Probes scalar and pseudoscalar mediators, in addition to (axial) vector ones



$$\mathcal{L}_{\text{vector}} \supset \frac{1}{2} m_{\text{MED}}^2 Z'_\mu Z'^\mu - g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - g_{\text{SM}} \sum_q Z'_\mu \bar{q}\gamma^\mu q - m_{\text{DM}}\bar{\chi}\chi,$$

$$\mathcal{L}_{\text{axial vector}} \supset \frac{1}{2} m_{\text{MED}}^2 A_\mu A^\mu - g_{\text{DM}} A_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - g_{\text{SM}} \sum_q A_\mu \bar{q}\gamma^\mu\gamma^5 q - m_{\text{DM}}\bar{\chi}\chi,$$

(Axial) Vector

$g_q = 0.25$, $g_\chi = 1$

$$\mathcal{L}_{\text{scalar}} \supset -\frac{1}{2} m_{\text{MED}}^2 S^2 - g_{\text{DM}} S\bar{\chi}\chi - g_q \sum_{q=b,t} \frac{m_q}{v} S\bar{q}q - m_{\text{DM}}\bar{\chi}\chi,$$

$$\mathcal{L}_{\text{pseudoscalar}} \supset -\frac{1}{2} m_{\text{MED}}^2 P^2 - i g_{\text{DM}} P\bar{\chi}\gamma^5\chi - i g_q \sum_{q=b,t} \frac{m_q}{v} P\bar{q}\gamma^5 q - m_{\text{DM}}\bar{\chi}\chi,$$

Higgs-like couplings to SM fields

(Pseudo) Scalar

Yukawa couplings

Monojets: the Classics

Monojet Searches

- Monojet analysis is a classical search for a number of new physics phenomena
  - Smoking gun signature for supersymmetry, large extra dimensions, dark matter production, ...
  - Was pursued since early 1980s
- The signature is deceptively simple, yet it's not
  - Backgrounds from instrumental effects
  - Irreducible $Z(\nu\nu)$+jet background
  - Reducible backgrounds from jet mismeasurements and W+jets with a lost lepton
- Number of techniques have been developed since the first search by UA1; will show the state-of-the-art results from CMS

Monojet Searches

- ✦ We've come a long way since Carlo Rubbia's first attempt!

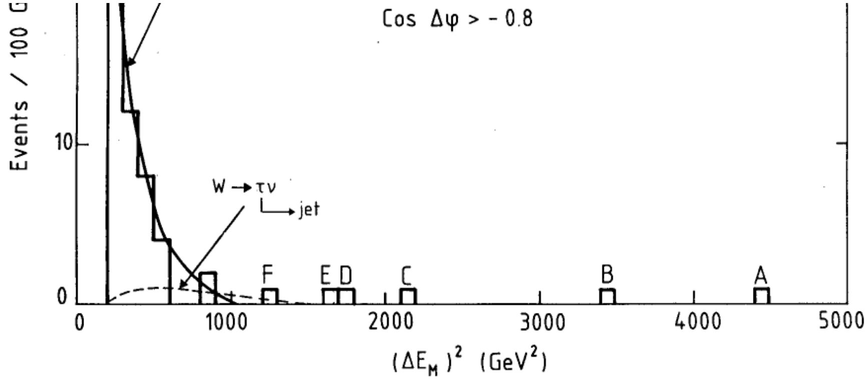
EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

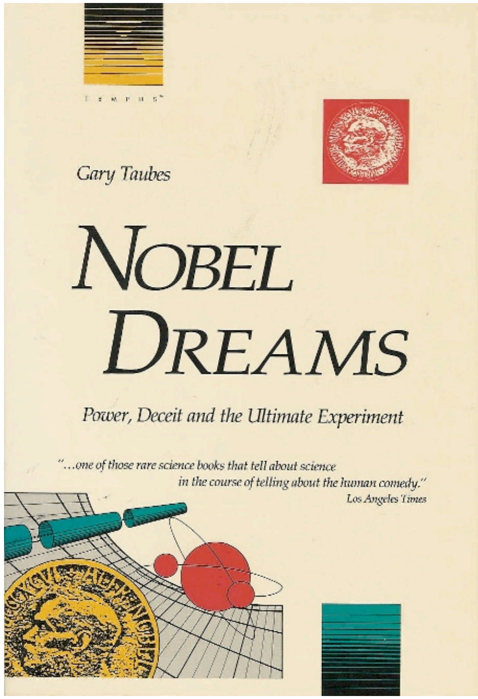
[PL, **139B**, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland

Abstract

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.

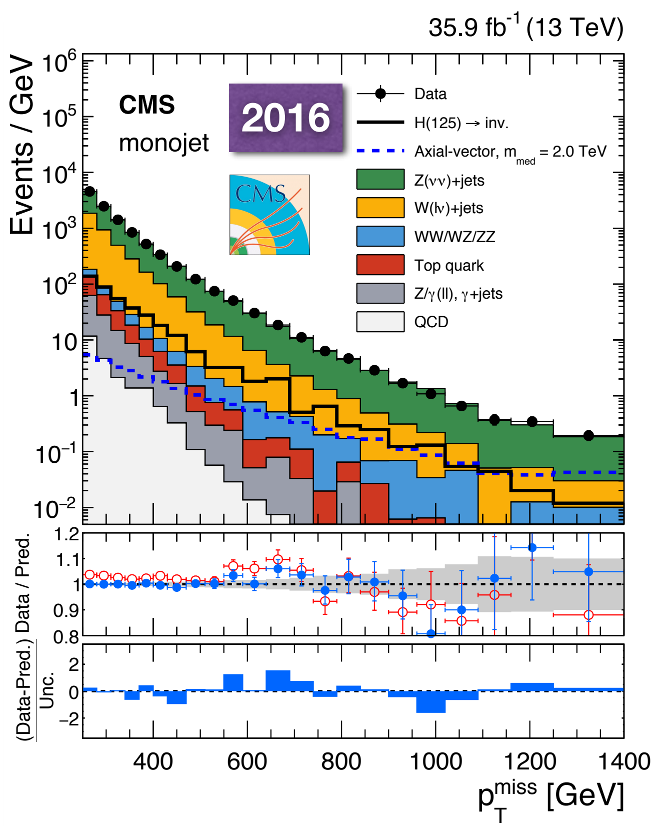


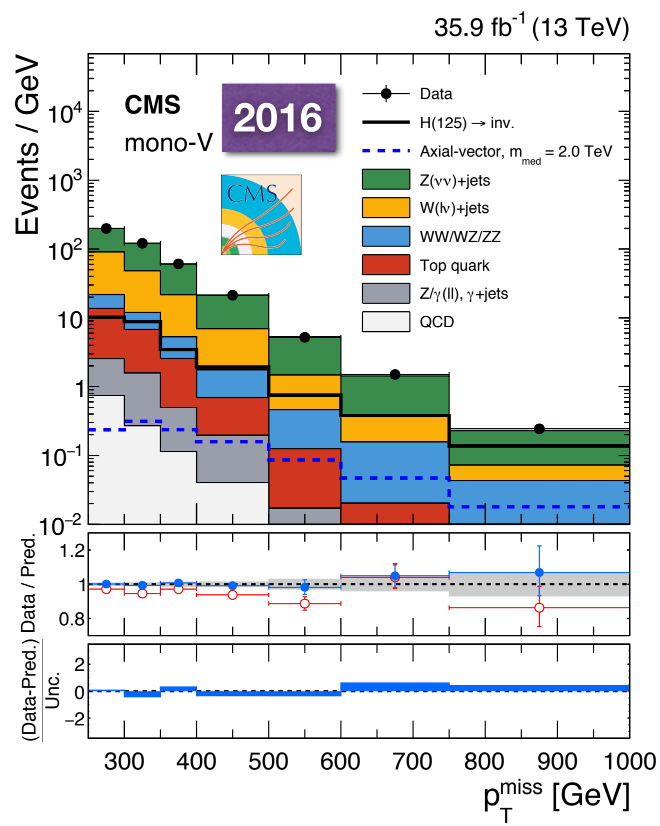


CMS Monojet/Mono-V Analysis

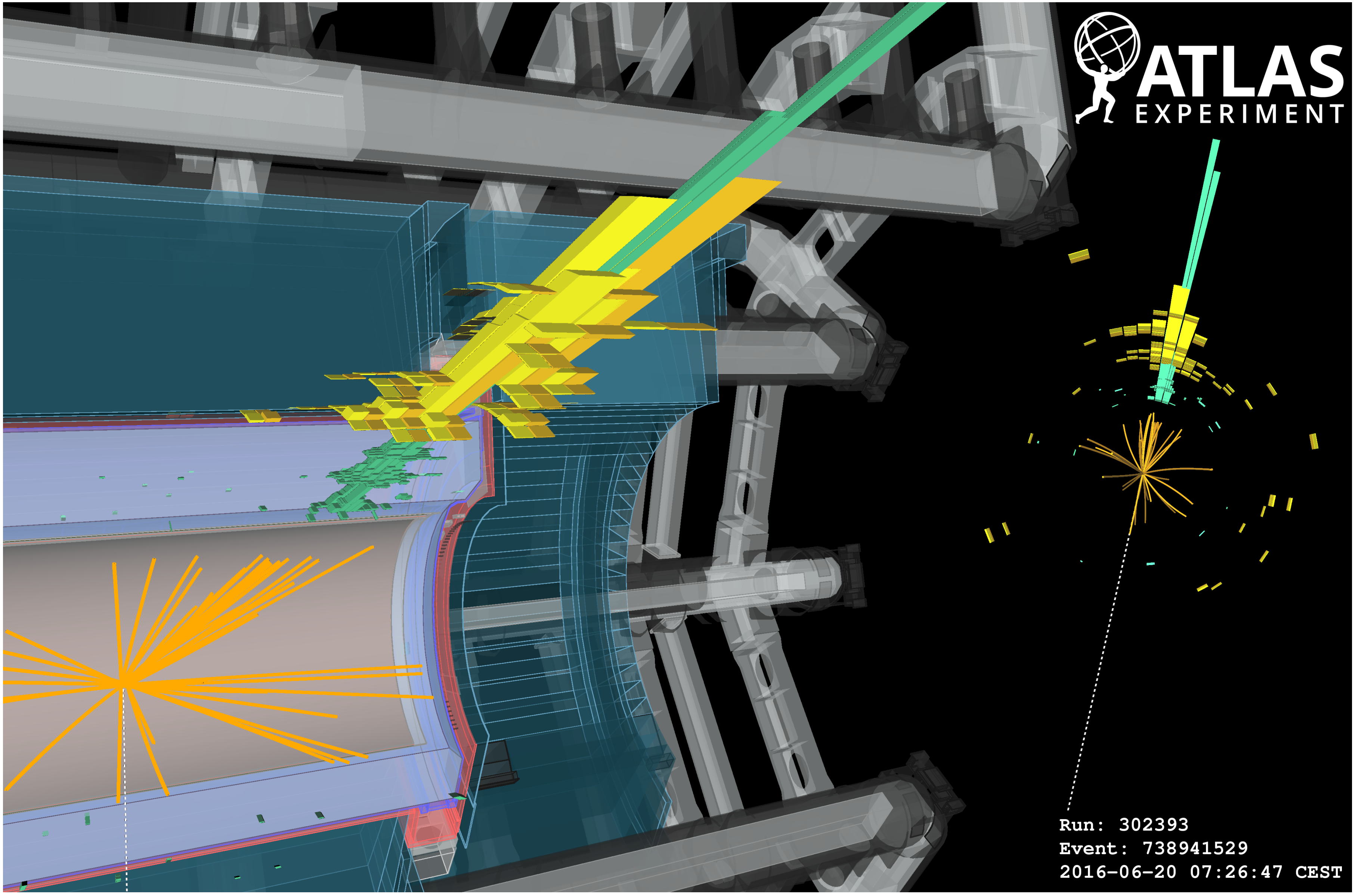
- ✦ The latest Run 2 analysis is built on the Run 1 techniques
  - Five control regions (l+jets, ll+jets, γ+jets) to fix major backgrounds
  - Theoretically consistent treatment of NLO EW/QCD corrections to SM V+jets processes, after Lindert et al., arXiv:1705.04464

CMS arXiv:1712.02345

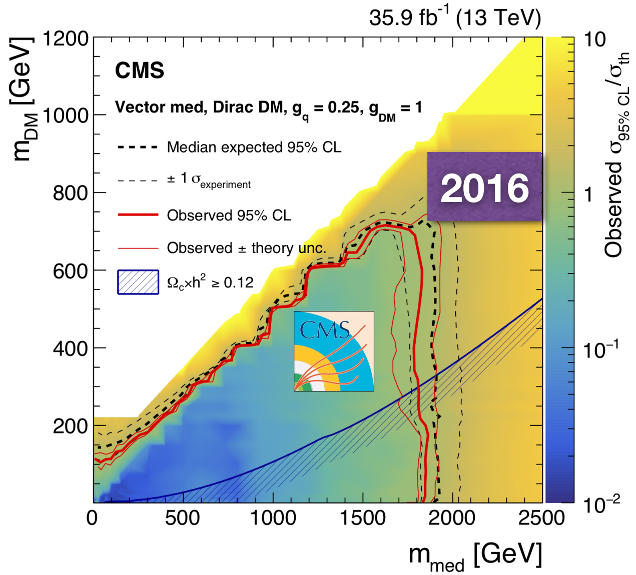


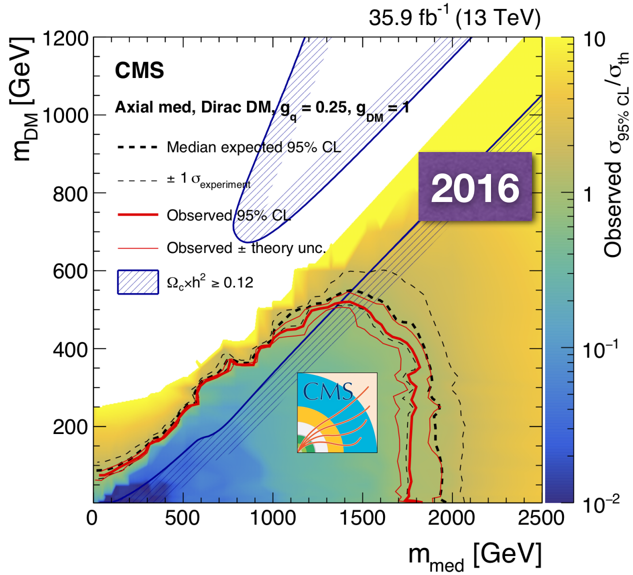


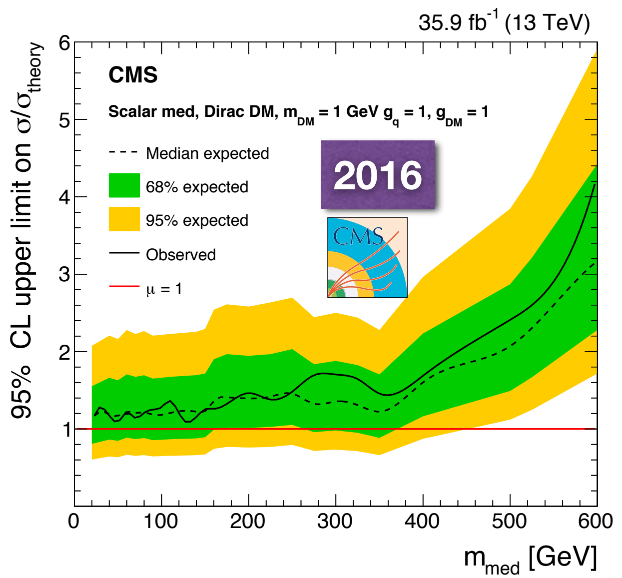
A Monojet Event

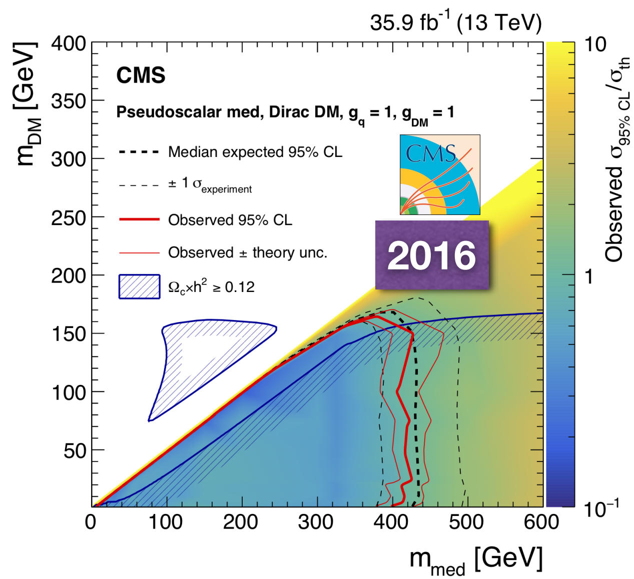


DM Interpretation







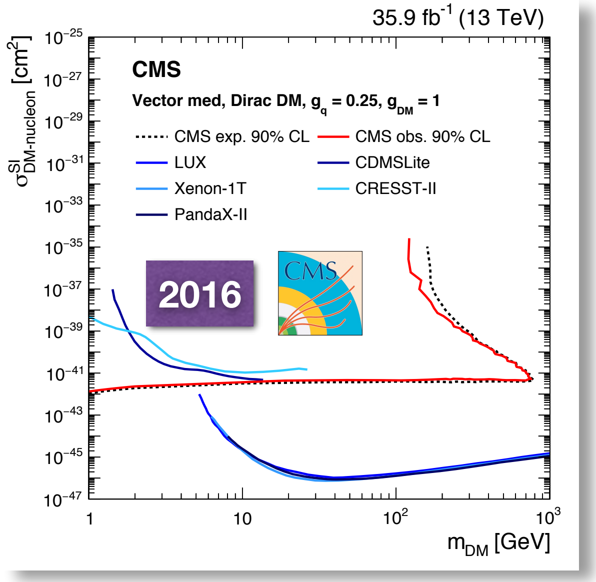


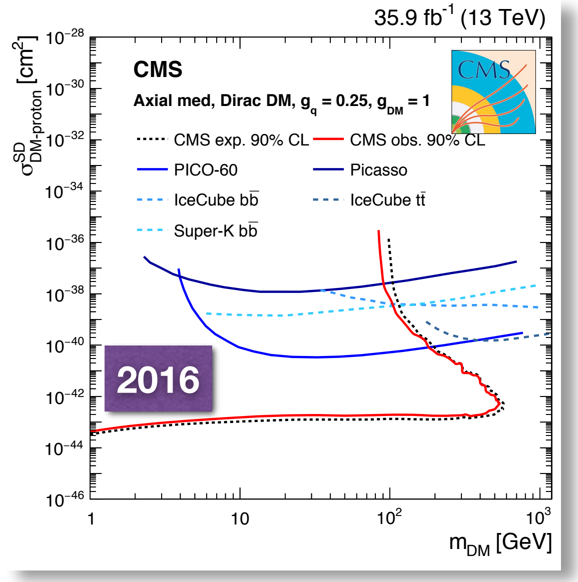
Fully compliant w/ LHC DM WG [arXiv:1603.04156] recommendations

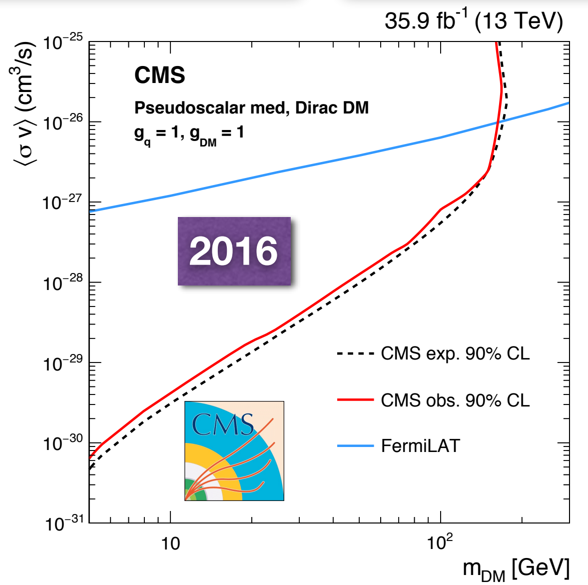
CMS arXiv:1712.02345

Complementarity w/ I/DD

CMS arXiv:1712.02345





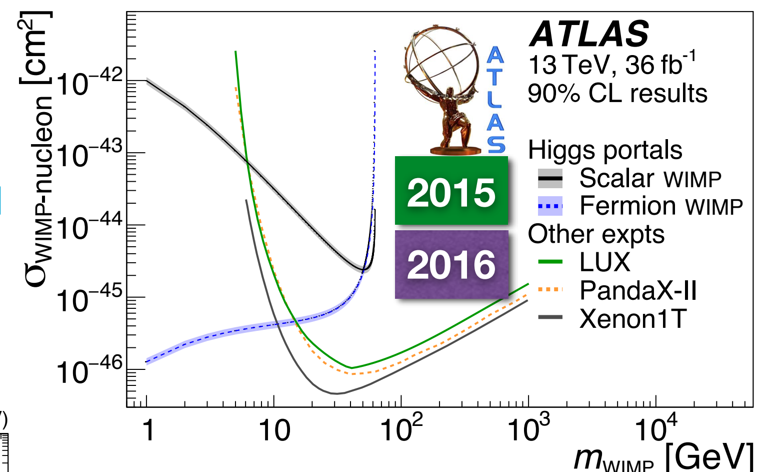


Beyond Monojets

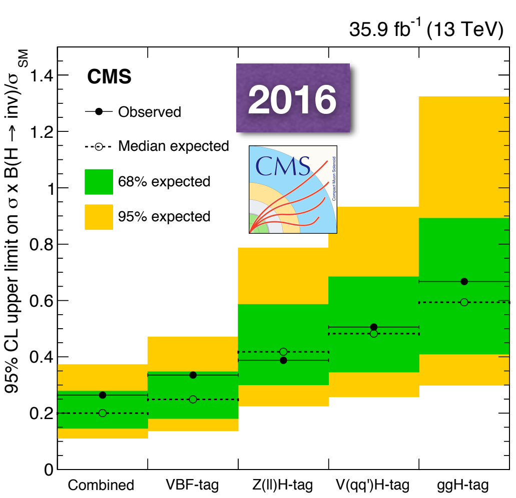
H(inv.) Limis

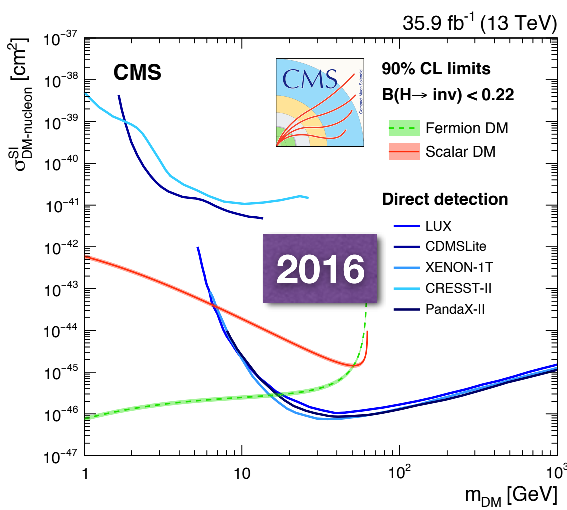
- The monojet and mono-V results can be interpreted as limits on invisible Higgs boson decays
- They can be further combined with the dedicated H(inv.) searches in associated production (ZH) and vector boson fusion H+jj
  - **ATLAS:**
    - **$B(H \to inv.) < 0.37\ (0.28)$ @ 95% CL - VBF**
      $< 0.67\ (0.39)$ @ 95% CL - ZH
  - **CMS:**
    - **$B(H \to inv.) < 0.26\ (020)$ @ 95% CL - combined**

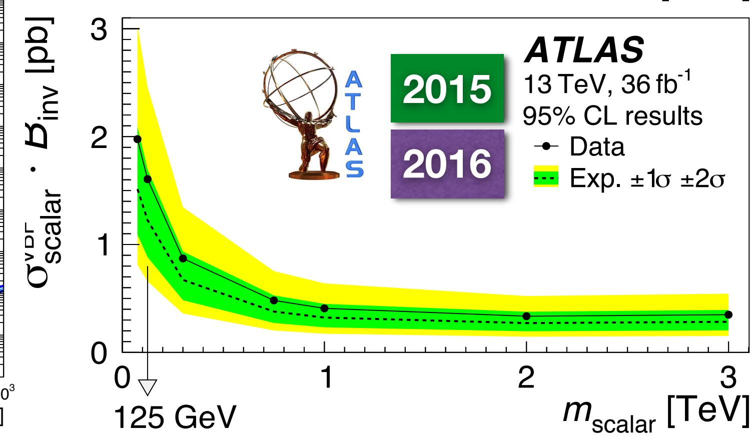
ATLAS arXiv:1809.06682



CMS arXiv:1809.05937



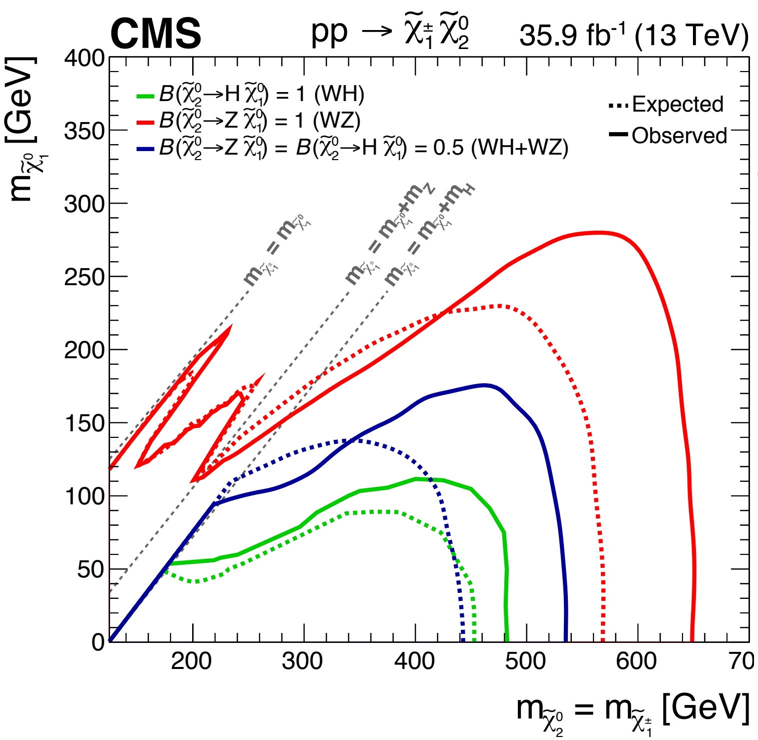




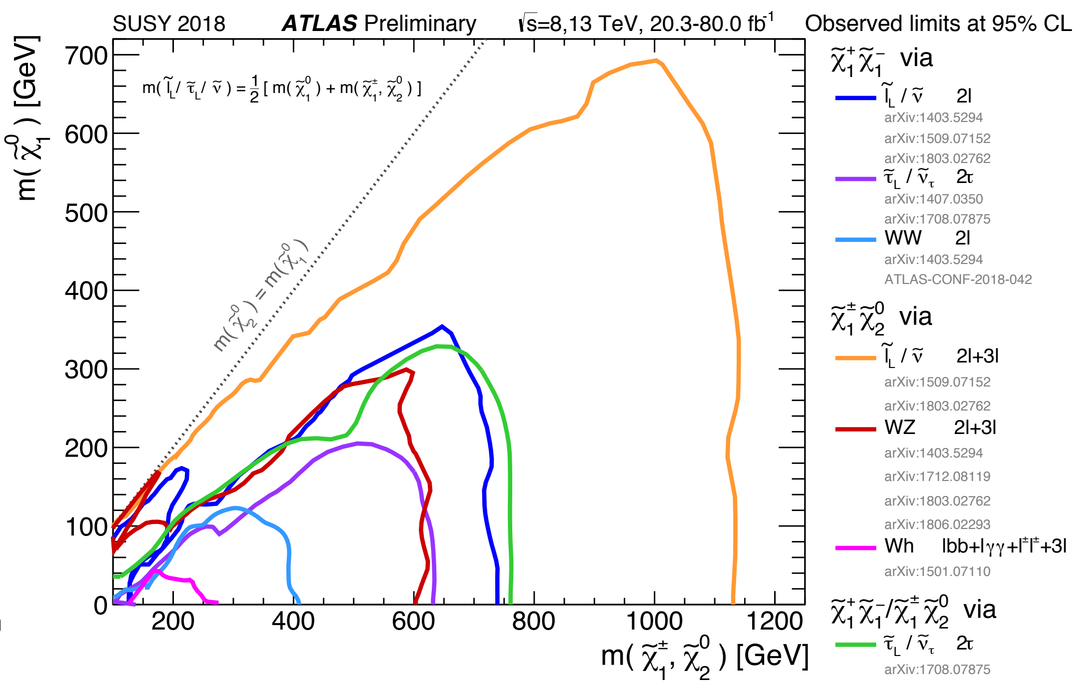
Direct SUSY Searches

- Since SUSY gives a perfect WIMP candidate, direct searches for neutralino production set limit on DM
    - Depending on the nature of the neutralino (wino, bins, Higgsino), limits are still not very strong, particularly if sleptons are heavy

CMS arXiv:1801.03957

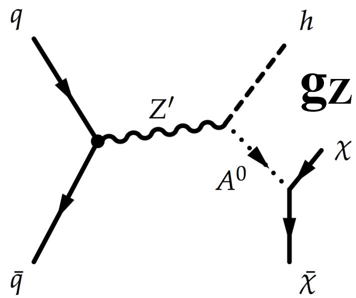


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

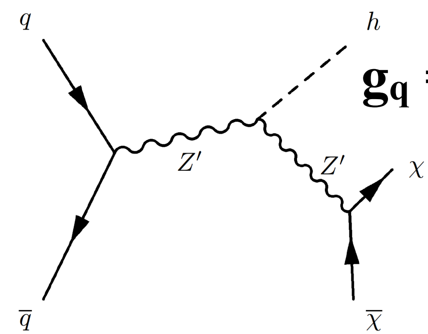


Mono-Higgs Production

- ✦ Mono-Higgs analysis in the context of 2HDM-Z' and baryonic Z' models
- ✦ Explore the dominant H(bb) decay mode

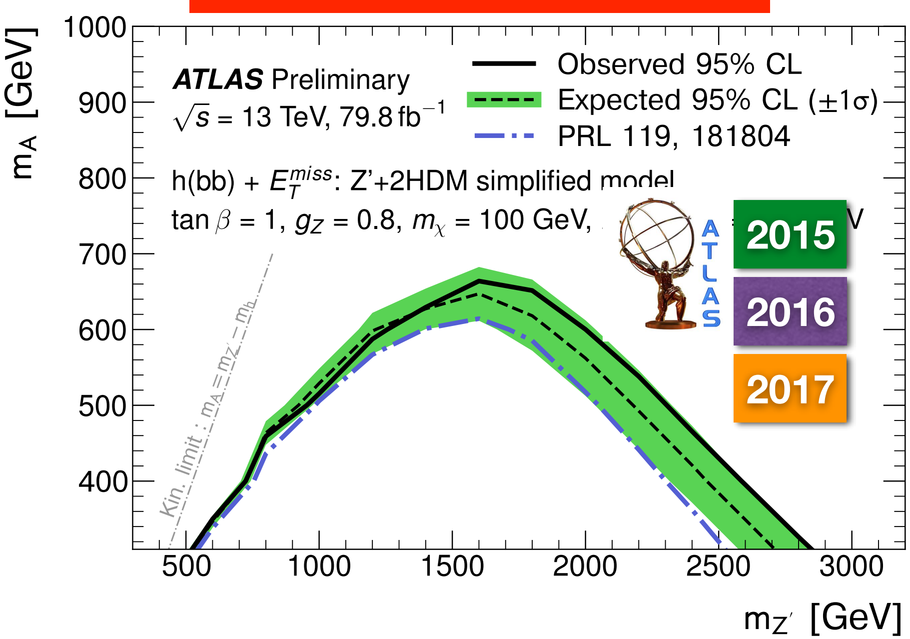


$g_{Z'} = 0.8, \tan\beta = 1$

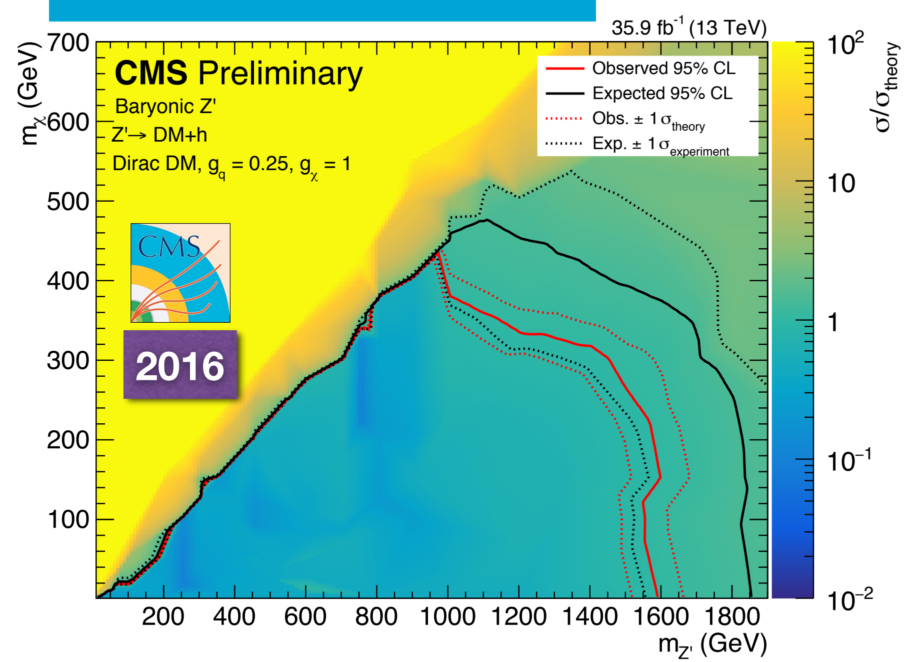


$g_q = 0.25, g_\chi = 1$

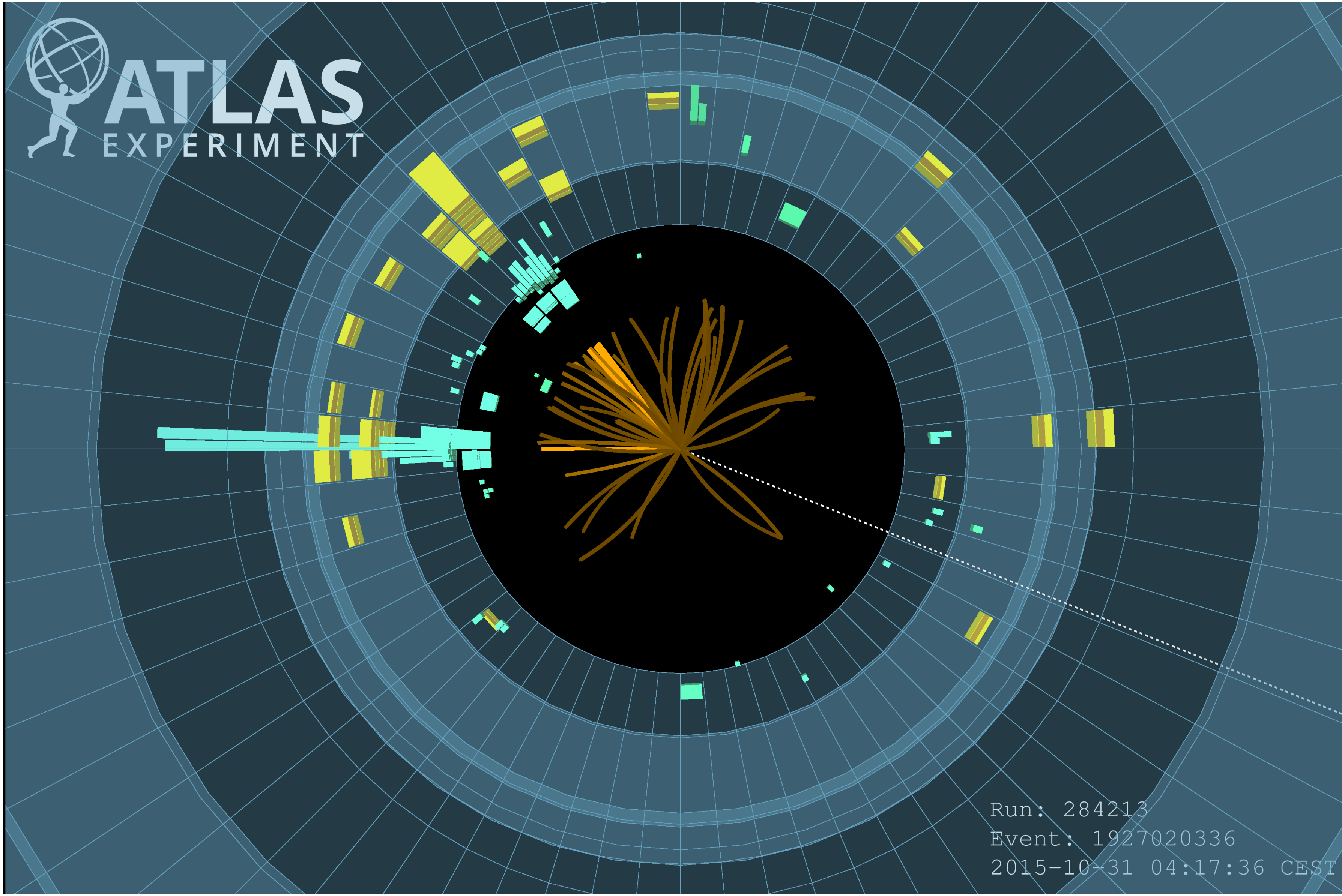
ATLAS-CONF-2018-039



CMS PAS EXO-16-050

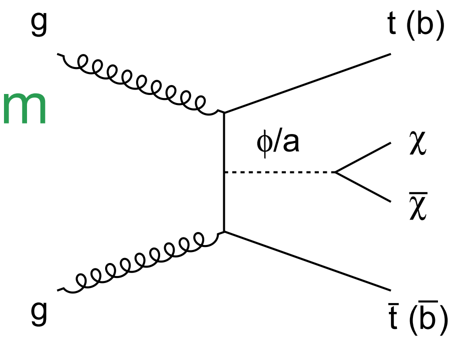


Mono-H Event Display

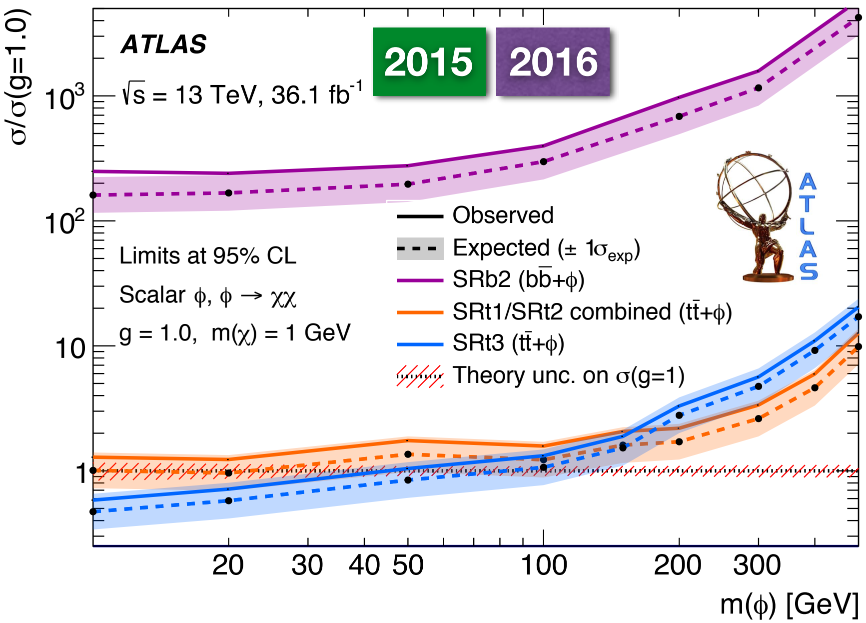


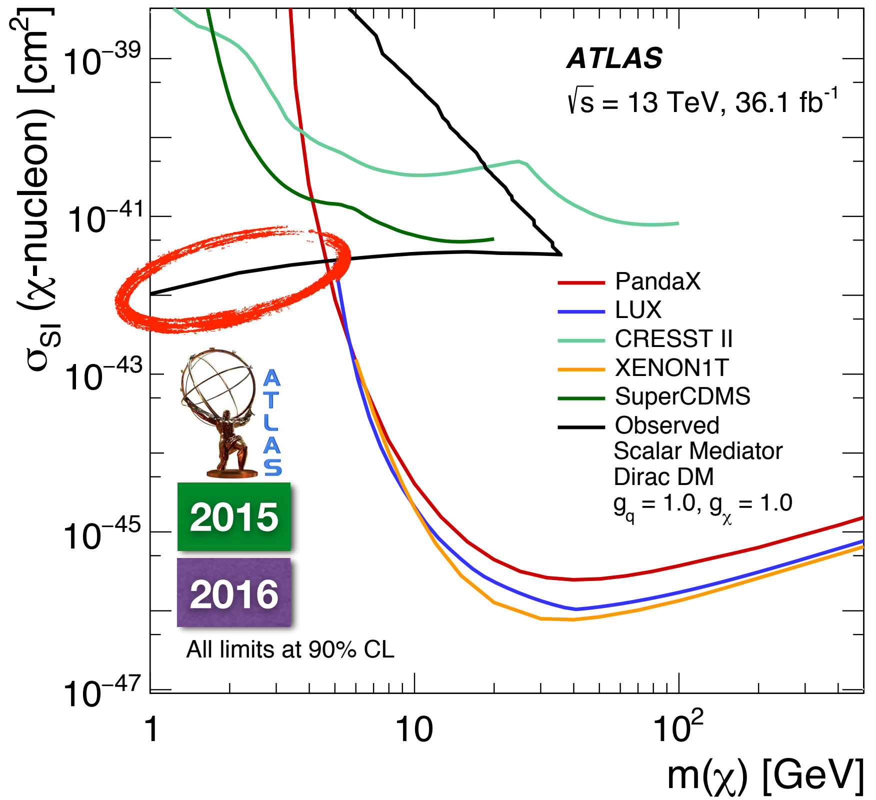
Mono-tt/bb Production

- Dedicated tt/bb+X search for a Higgs-like mediator
- Search based on all-hadronic decays of the tt system or b-tagged bb system
- Not yet sensitive to bb+ϕ/a production, but set first limits on (pseudo)scalar mediator in bb+ϕ/a production



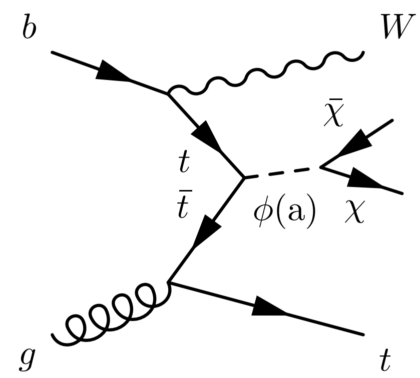
ATLAS arXiv:1710.11412



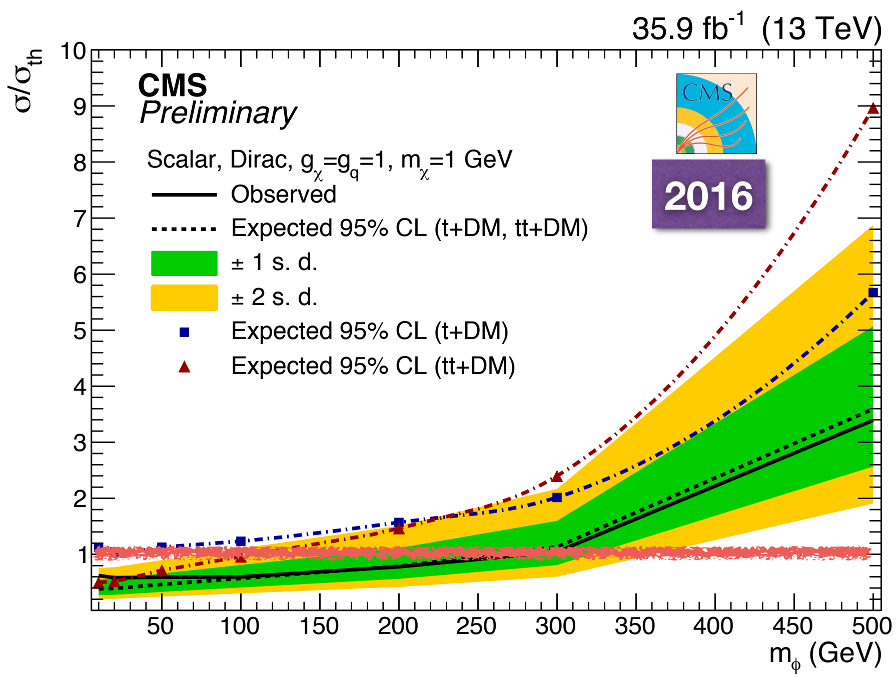


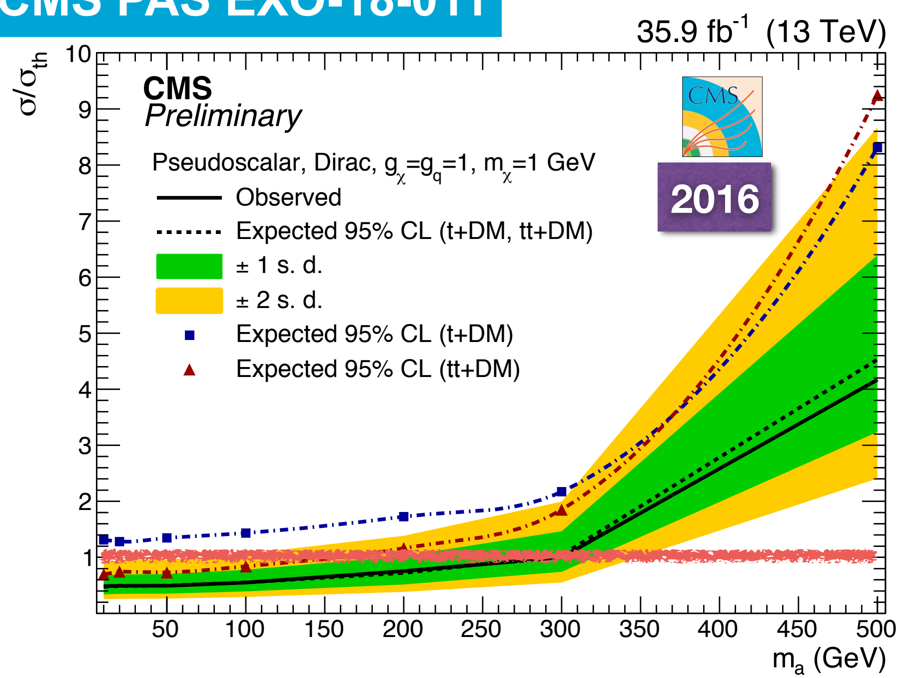
Mono-t and Mono-tt

- New analysis from CMS explores associated production with single top quark in addition to the tt diagram
- Aids sensitivity, particularly at high masses
- Excludes (pseudo)scalars with masses below ~300 GeV



CMS PAS EXO-18-011

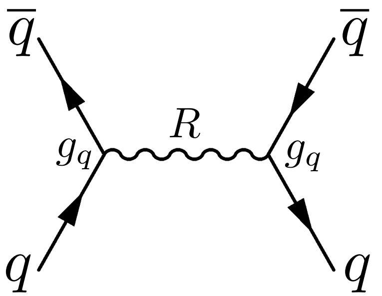





Searches for
the Mediator

Search for the Mediator

- One doesn't need to produce DM at the LHC to look for a mediator

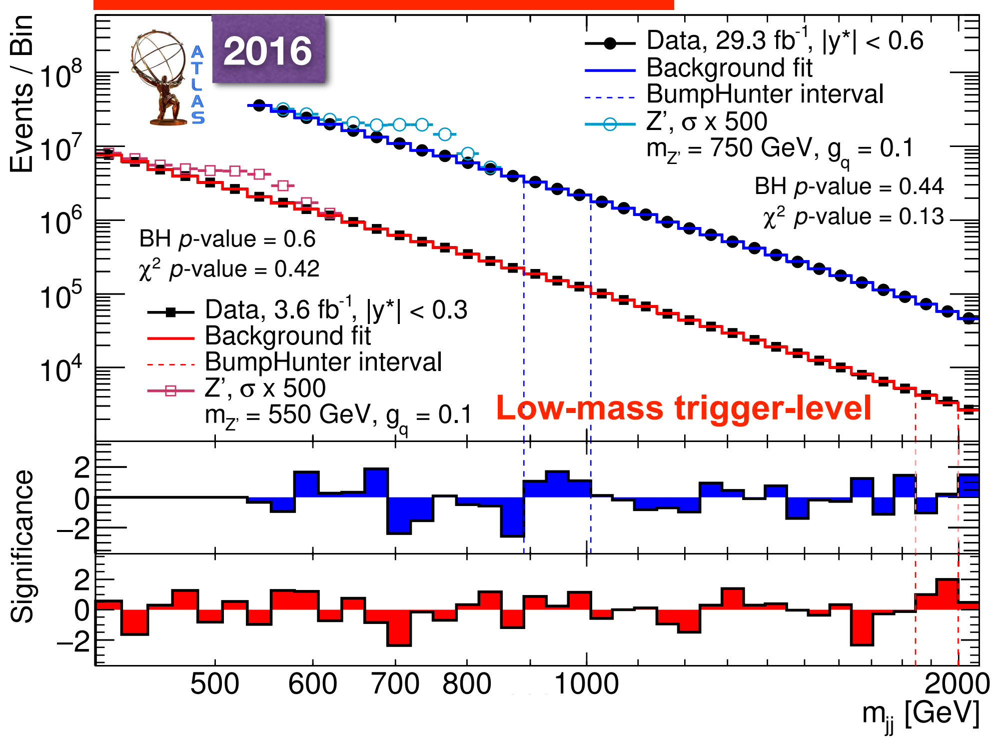


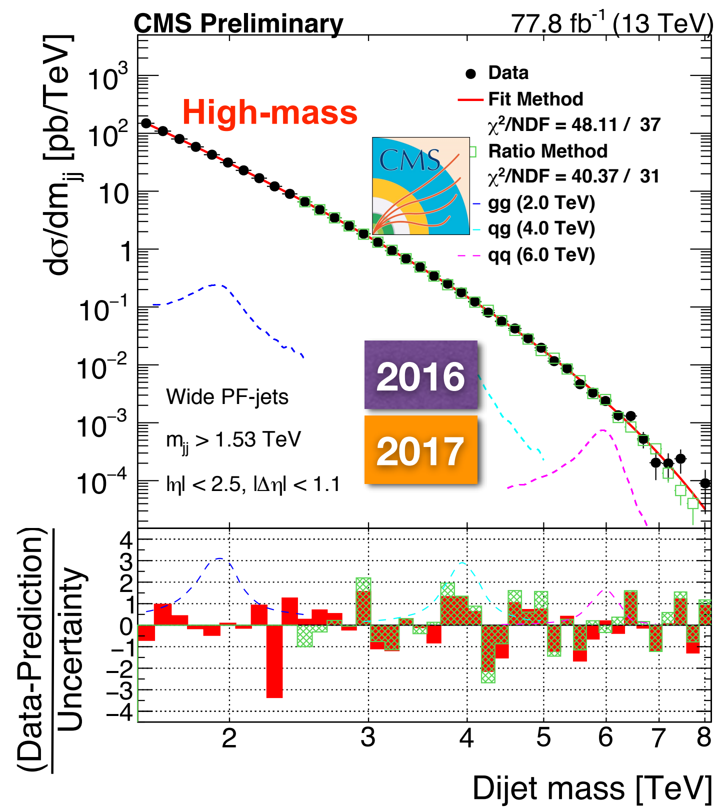
- Since it's coupled to the initial state, one could look for dijet decays of the mediator by "recycling" dijet resonance searches
  - Also possible to reinterpret dilepton searches if the mediator couples to leptons in addition to quarks

Dijet Resonance Searches

- Standard search to do at any new energy
  - Recent additions to the dijet search portfolio:
    - Scouting (trigger-level) analysis based on low-threshold triggers writing only very limited information about the event

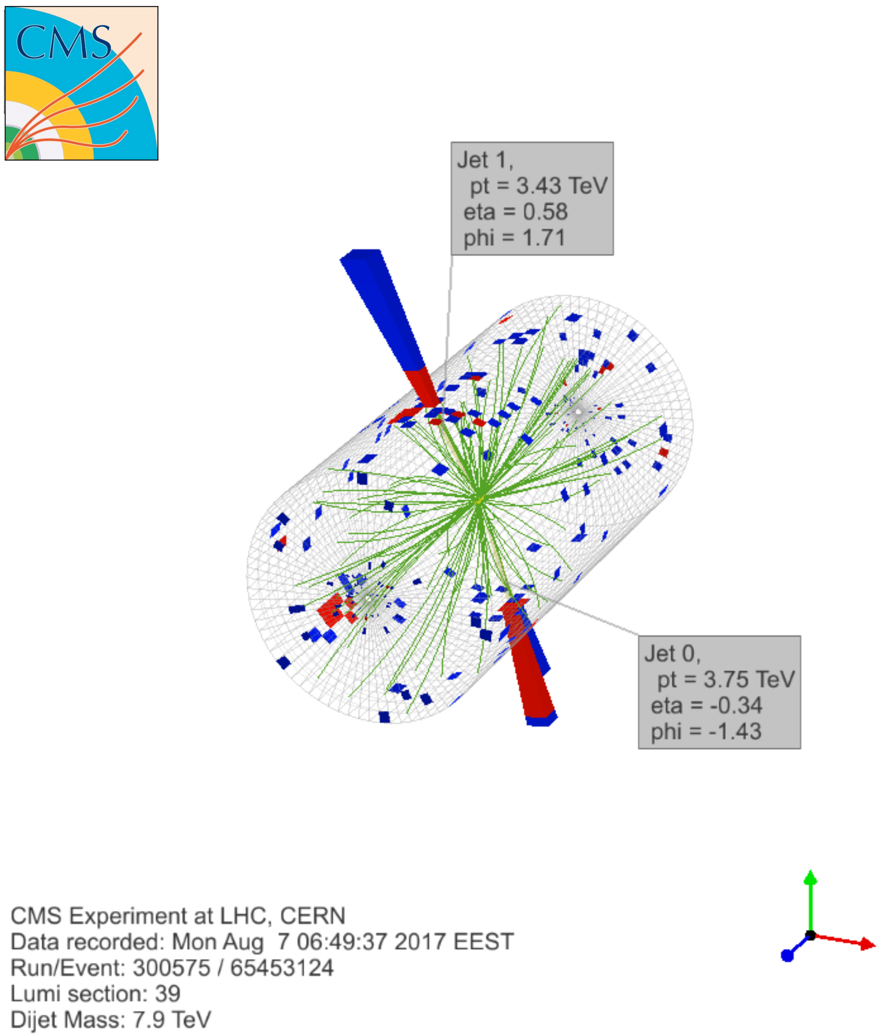
ATLAS arXiv:1804.03496

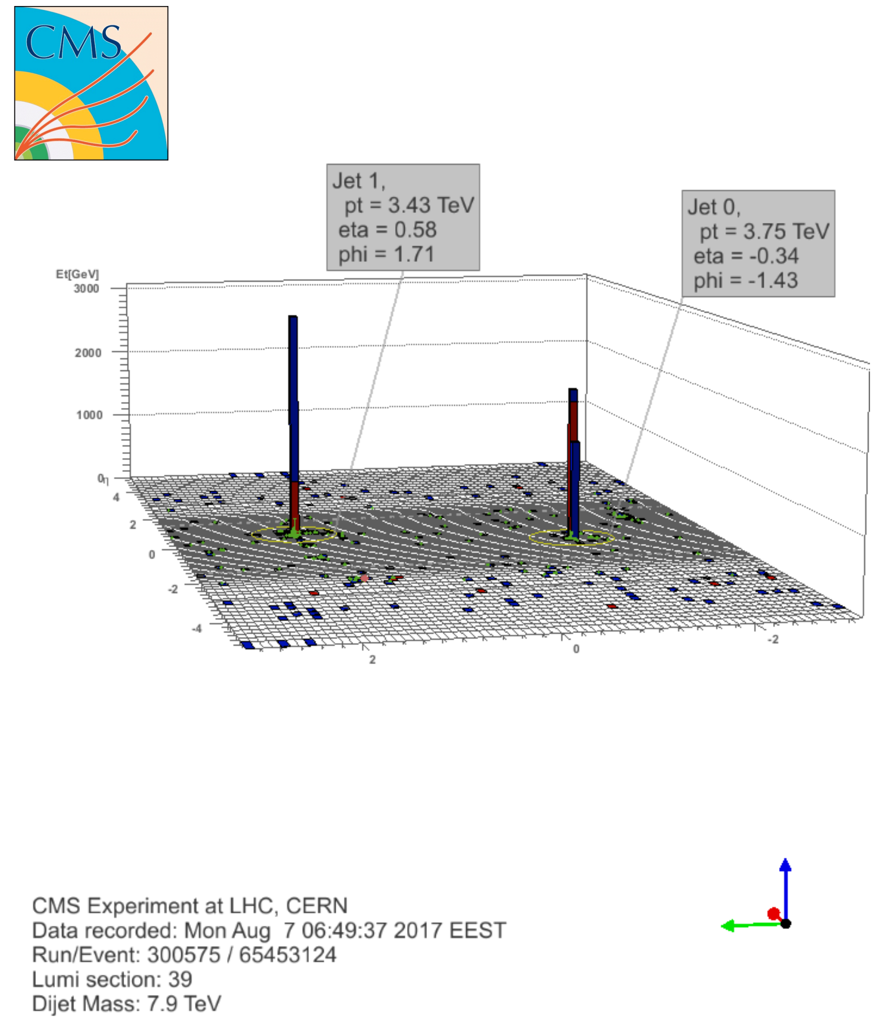




CMS PAS EXO-17-026

Dijet Event Display

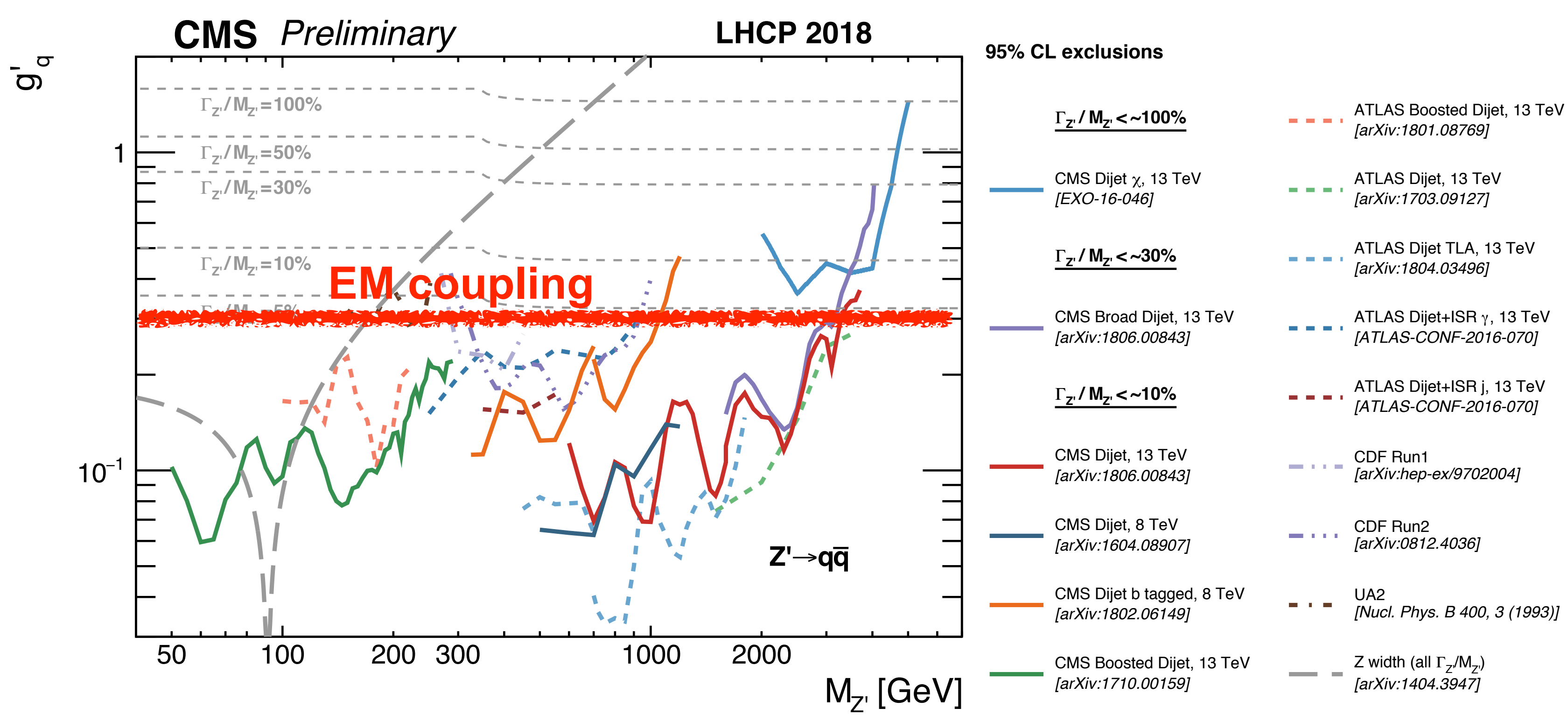




BROWN

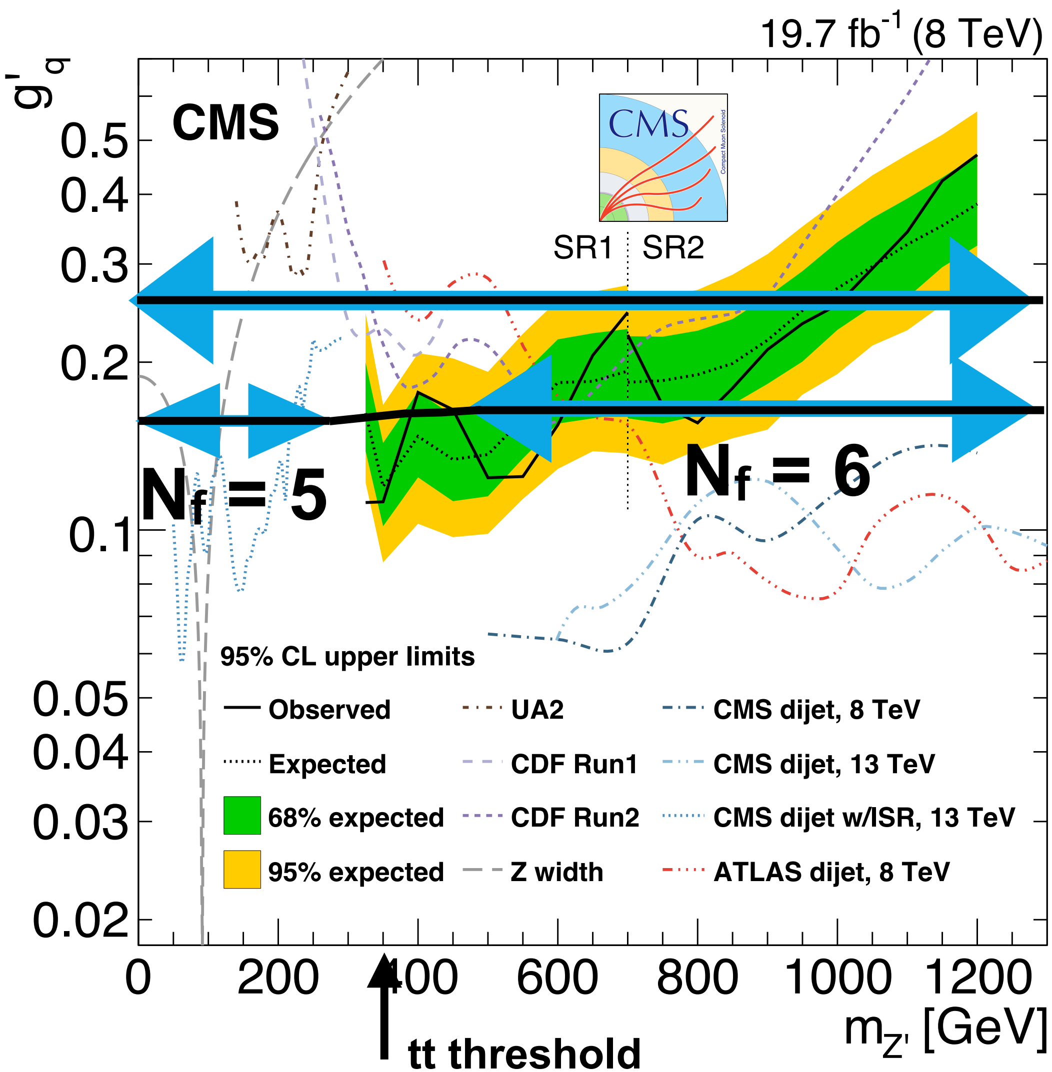
Dijets: Convenient Language

- For many applications, it's convenient to express limits in terms of a Z'_B like object with a coupling g_B to a baryon number [Dobrescu, Yu, arXiv:1306.2629] given by $\frac{g_B}{6} Z'_{B\mu}\bar{q}\gamma^{\mu}q$, $\alpha_B = g_B^2/4\pi$
- The decay width: $\Gamma(Z'_B \to jj) = \frac{5\alpha_B}{36} M_{Z'_B}\left(1+\frac{\alpha_s}{\pi}\right)$
- Parameterize everything as a function of $g'_q = g_B/6$



Using the g'$_q$ Plot

- Reading M_{med} limits from the g'$_q$ plot:



$m_{DM} = \infty$: g'$_q$ = 0.25

$m_{DM} = 0$: g'$_q$ = 0.174-0.182

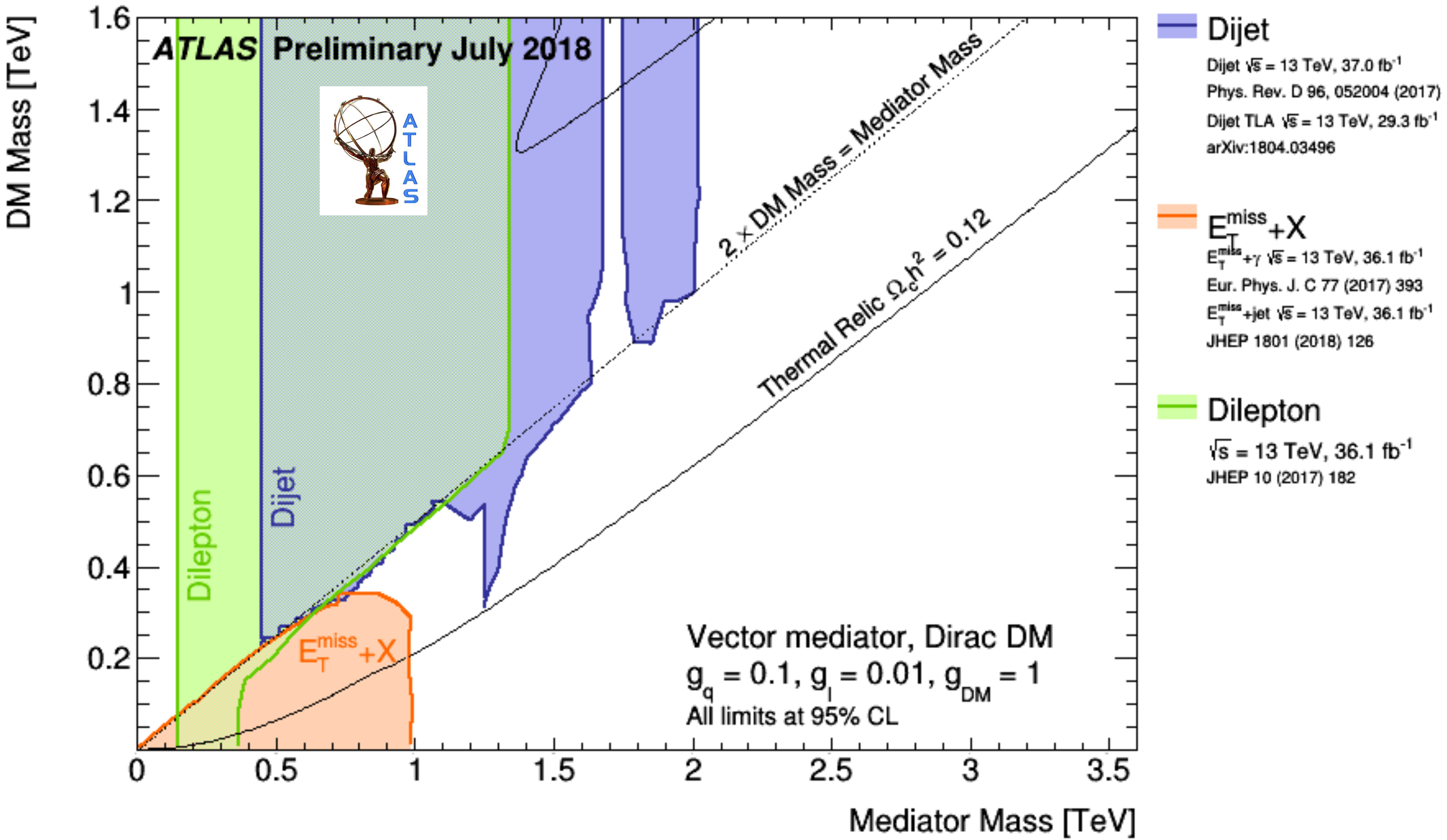
For q_g = 0.25, taking into account additional width from decays to DM:

$$g'_q = \frac{1/4}{\sqrt{1 + \frac{16}{3N_f}\left[1 - 4\left(\frac{m_{DM}}{M_{med}}\right)^2\right]}}$$

CMS arXiv:1802.06149

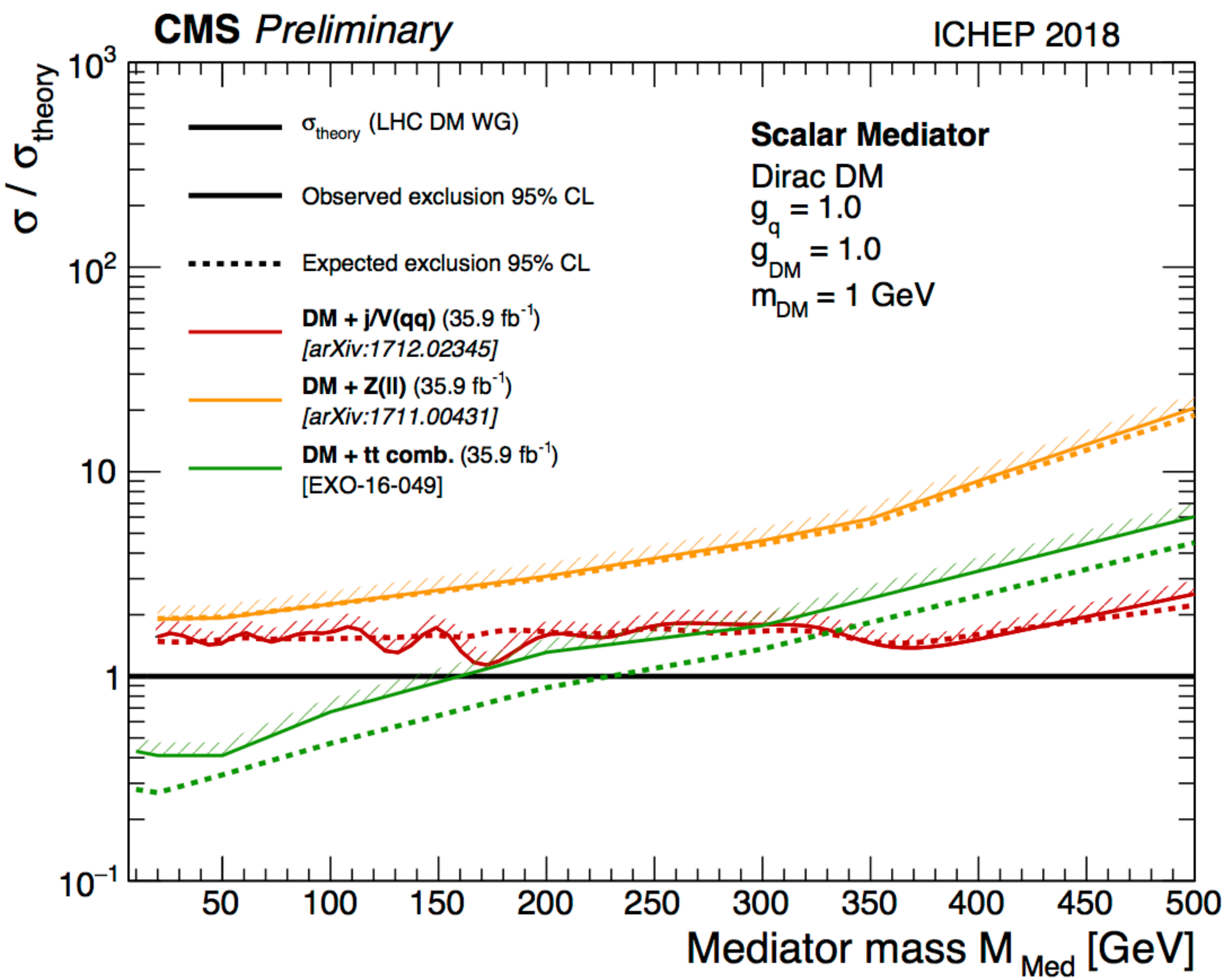
Big Picture: Spin 1

- Analogous limits for axial vector mediators
  - The complementarity depends significantly on the coupling values!



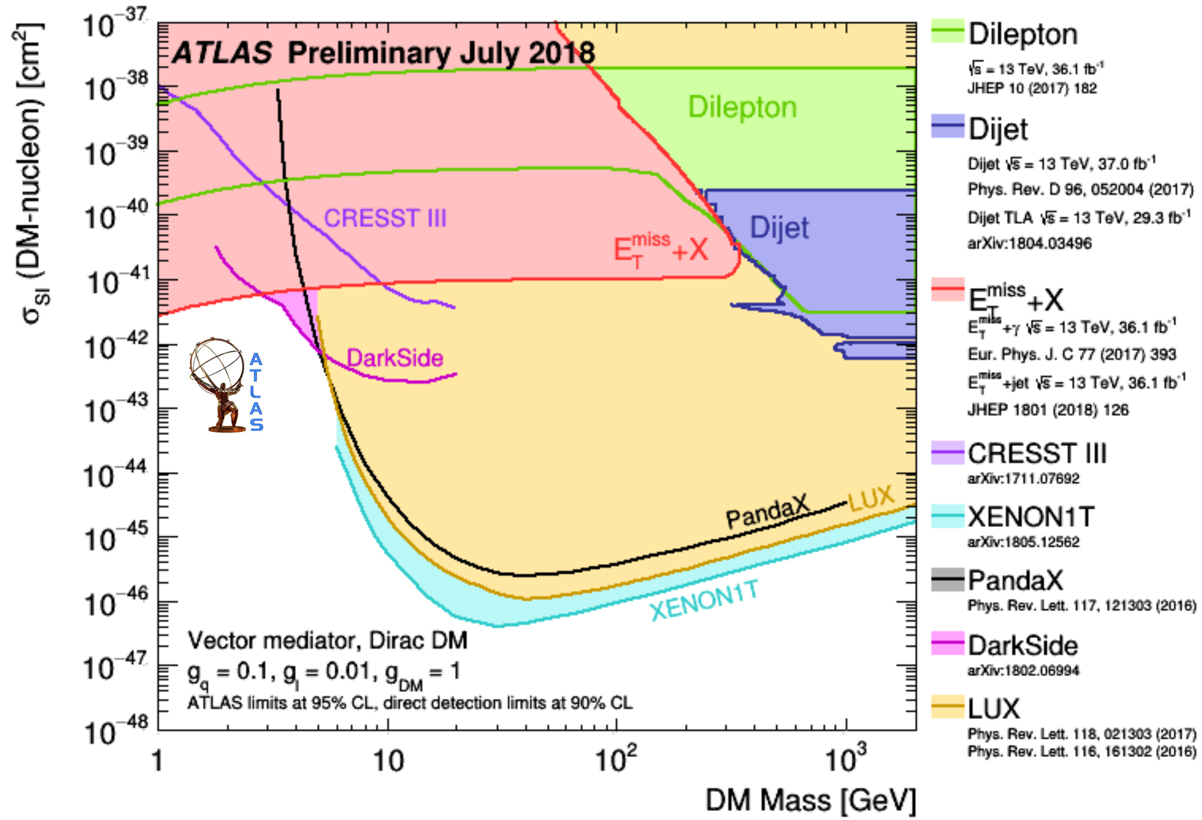
Big Picture: Spin 0

✦ For the first time started probing spin-0 mediators



Comparison w/ Direct Detection

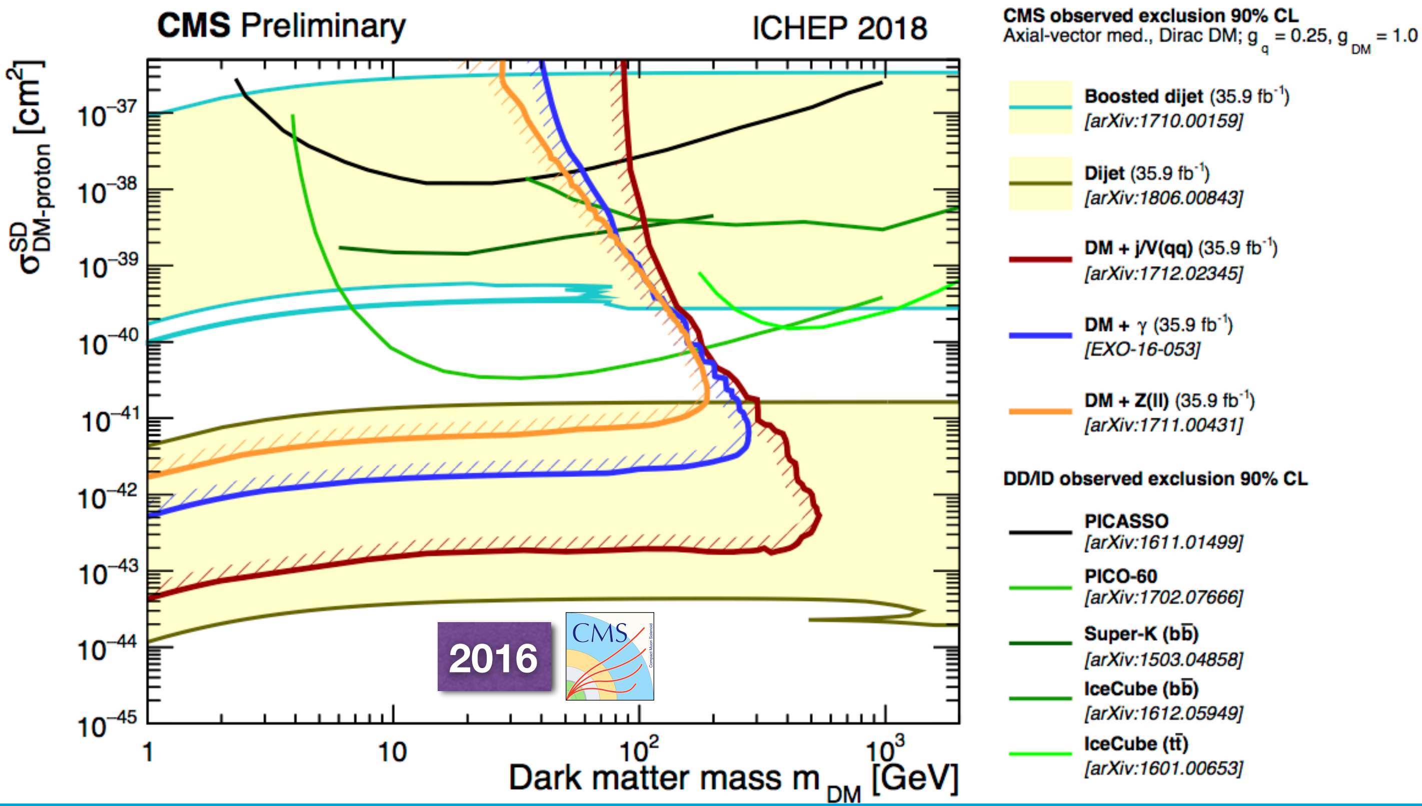
- Vector mediators
  - DD experiments get a resonant enhancement on a nucleus due to spin-independent scattering cross section
  - Colliders only win at low DM masses



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

Comparison w/ Direct Detection

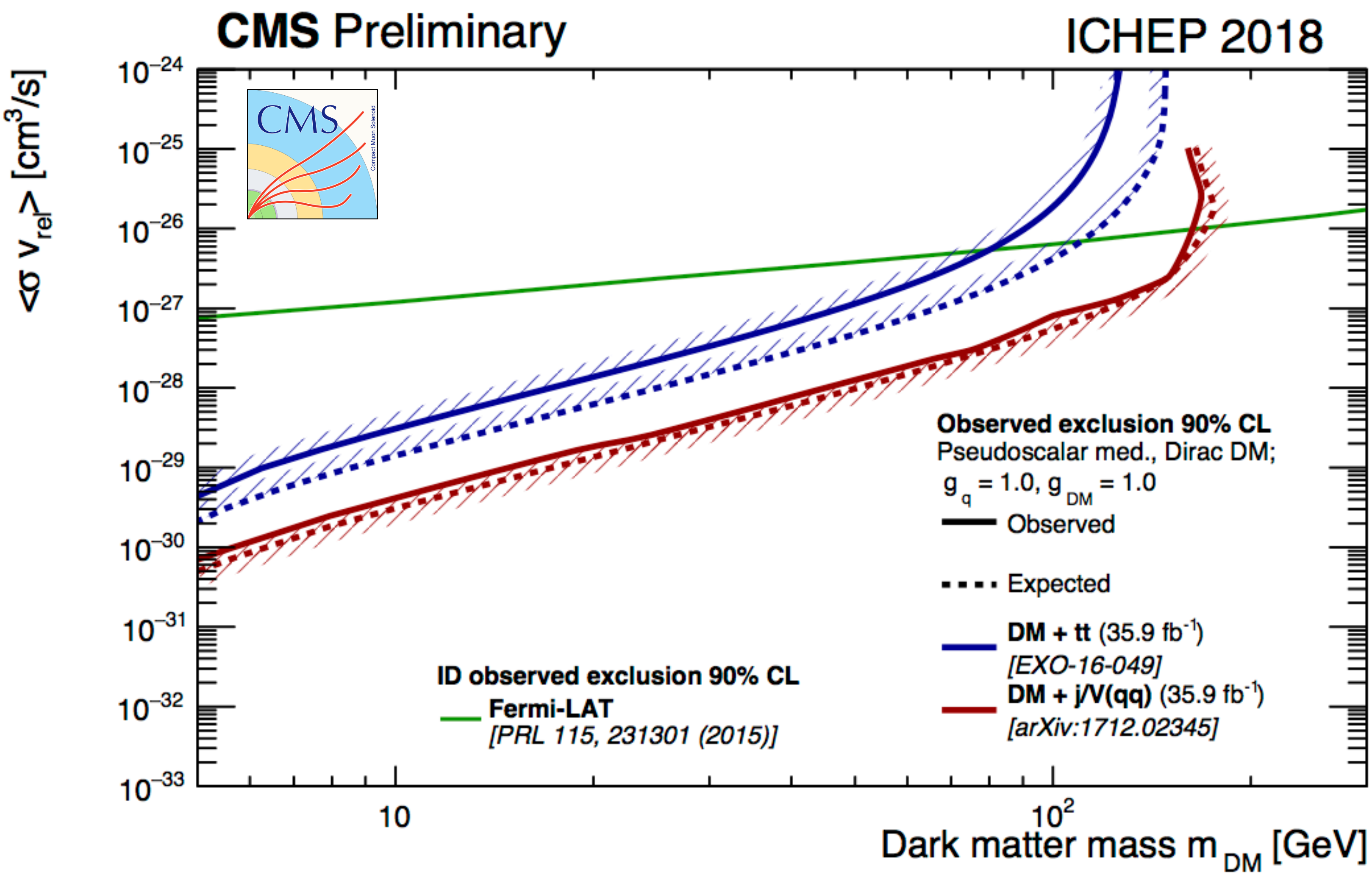
- Axial vector mediators
  - No resonant enhancement due to spin-dependent cross section
  - Colliders typically win over the DD experiments up to a few hundred GeV DM masses



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Dark_Matter_Summary_plots

Comparison w/ Indirect Detection

✦ Also nice complementarity with γ-ray experiments



DM: Quo Vadis?

- We hope that the multi-prong attack on the DM will bear fruit
  - DD experiments are moving to a multi-ton mass range and will soon reach neutrino floor
  - Many new ideas of non-WIMP and light DM searches (electron recoil, CCD detectors, etc.)
  - New generation of axion searches curbing the available parameter space
  - New indirect detection experiments coming online, and exciting hints from the present ones
  - Collider experiments are processing large amount of Run 2 data and move toward more sophisticated models of dark matter, including hidden-sector searches

Conclusions

- There is overwhelming evidence that dark matter exists and outweighs ordinary matter by a factor of four
  - While there is no guarantee that dark matter has particle physics origin, this is certainly a compelling possibility
  - If exist, dark matter particles could be produced at the LHC, leading to exciting mono-X signatures
  - In addition, LHC can look directly for the dark matter mediators
- A lot of theoretical and experimental progress in the past few years - an exciting and rapidly developing subject
- LHC searches are complementary to both direct and indirect detection and offer unique sensitivity for pseudoscalar mediator and/or very light dark matter particles
- Many searches ongoing with the large data sets accumulated in the last few years - stay tuned!

Dark Matter Day

DARK MATTER DAY

DON'T BE AFRAID OF THE DARK

Showing in the Universe Near You Tomorrow!