Recent results from dark matter searches at ATLAS and CMS

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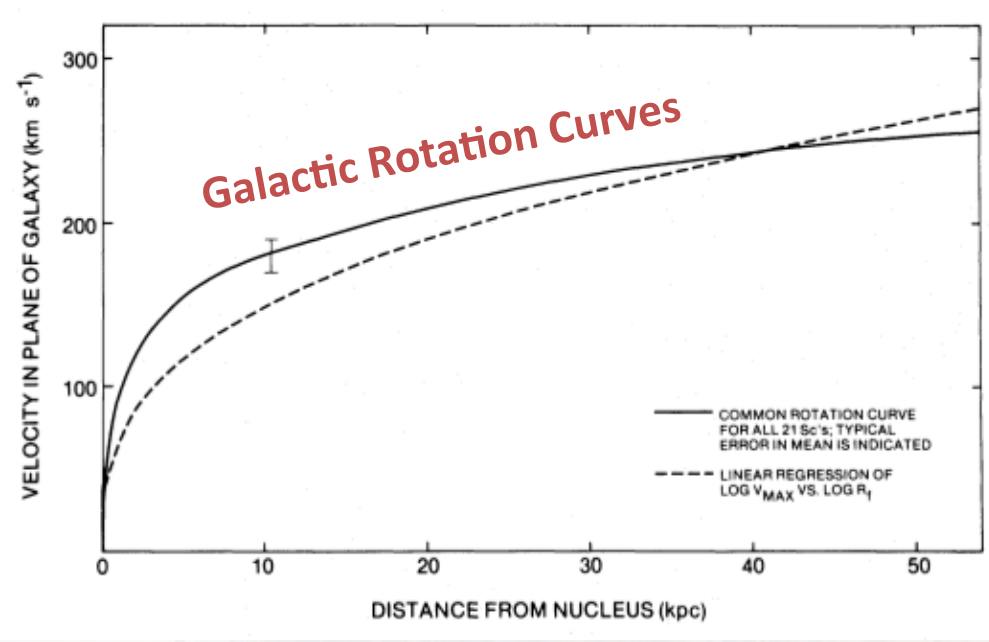
for the ATLAS and CMS collaborations

Dark Matter

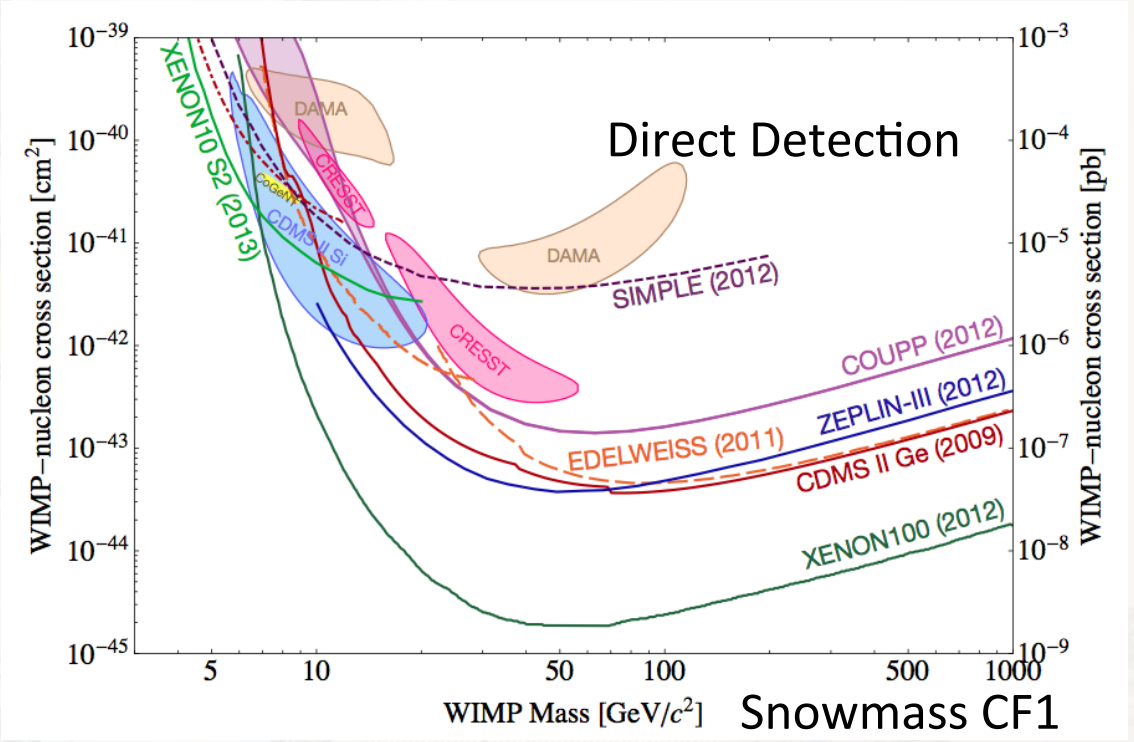
- Dark matter (DM) is one of the best motivated new physics searches at the LHC
- Astrophysical observations have indicated the existence of a new type of matter, but never been directly observed
  - Galactic rotation curves
  - Orbits in galaxy clusters
  - Gravitational lensing
  - CMB anisotropies
- Could be produced at the LHC: stable, weakly interacting, neutral particle



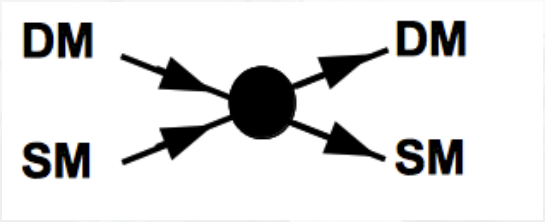
Astrophys. J. 238, 471 (1980)

Searches for dark matter

- Gravitational interactions provided first evidence for dark matter
- Search for weak interactions with ordinary matter
- Three types of searches
- **Collider searches**

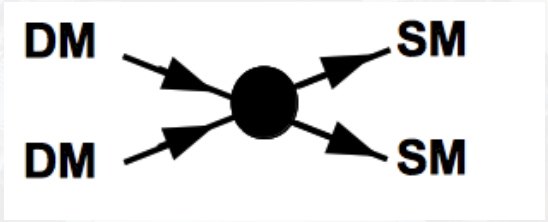


Direct Detection



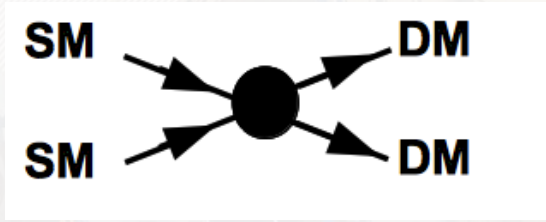
e.g. Xenon, LUX

Indirect Detection



e.g. IceCube

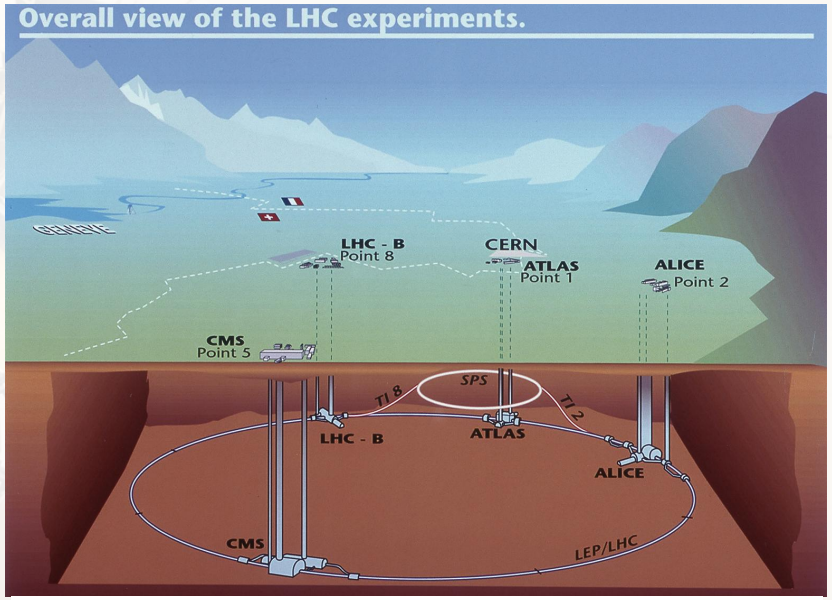
Collider

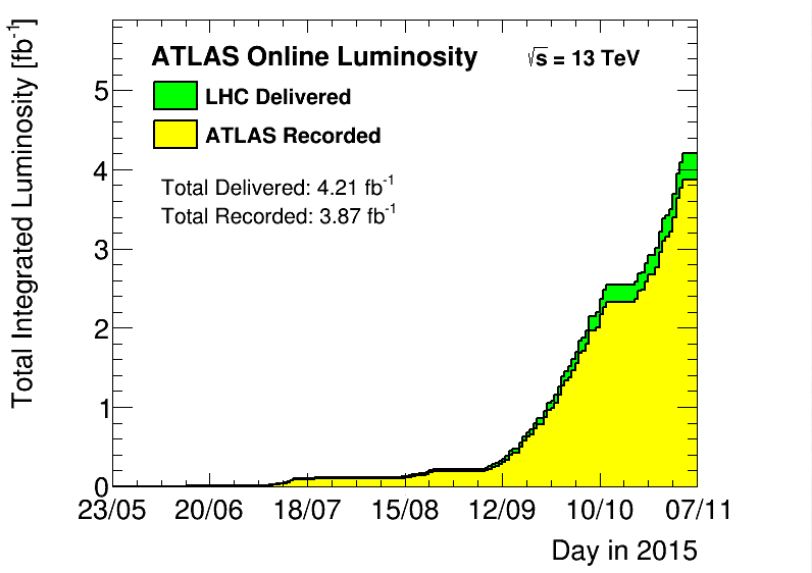


e.g. ATLAS, CMS

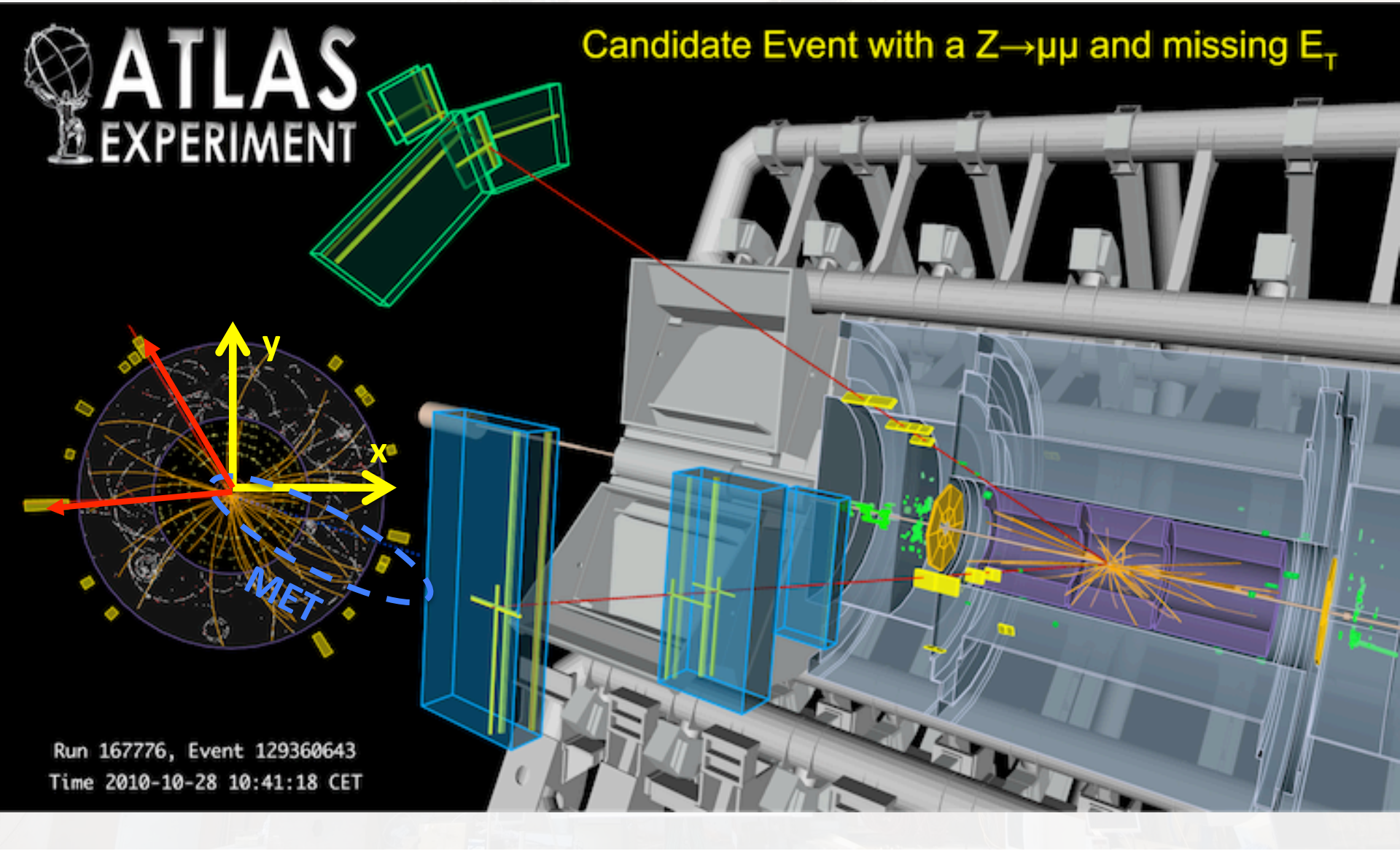
Large Hadron Collider (LHC)

- LHC has 4 detectors stationed at different points along the ring
- **LHC Factoids**
  - 27 km circumference,
  - Maximum instantaneous luminosity achieved in Dec 2012: 7.7×10^{33} $cm^{-2}s^{-1}$
  - Collisions every 25/50 ns
- 20 fb^{-1} at 8 TeV in 2012
- 4 fb^{-1} at 13 TeV in 2015

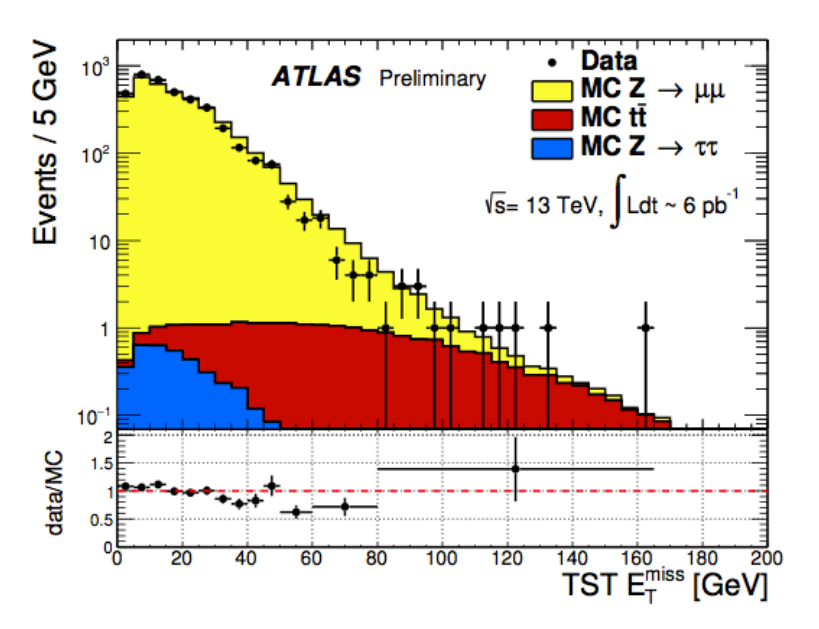


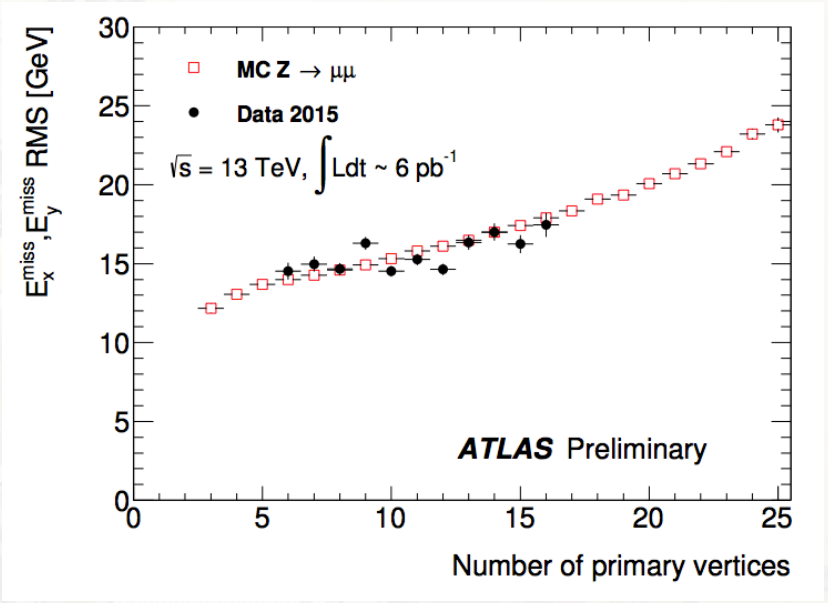


Missing Transverse Energy (MET)



MET Performance



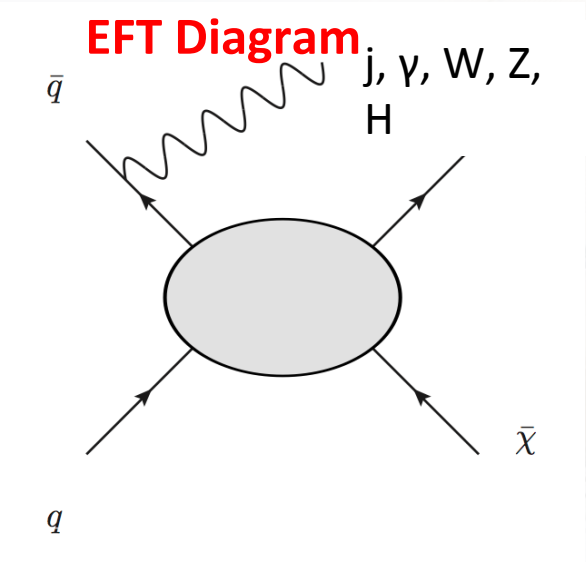


- MET performance for Z➔μμ events
  - Useful for studying MET reconstruction (low real MET)
  - Good indicator of intrinsic resolution

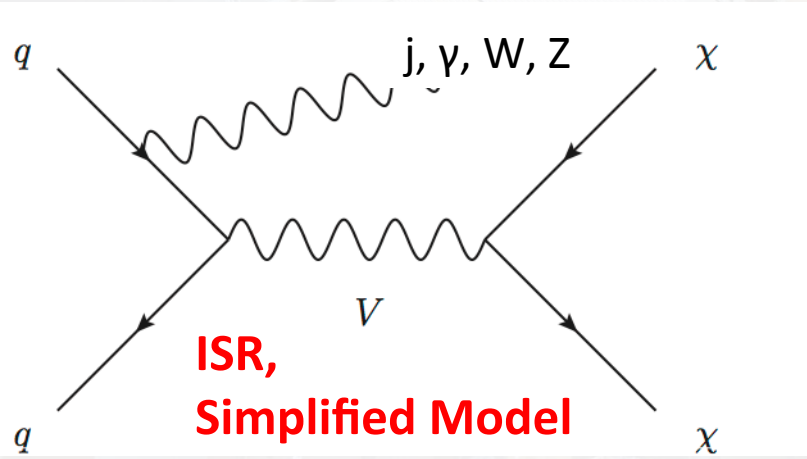
https://cdsweb.cern.ch/record/2037904

Production of DM at colliders

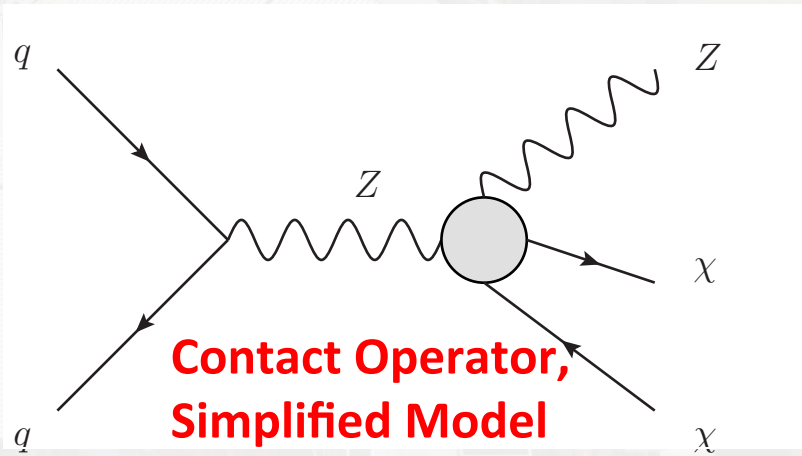
ISR,
EFT Diagram



- Need visible particle in final state
  - Visible particles produced in: initial state radiation (ISR) or in the DM interaction
  - Often search for a single particle: *mono-X: X=jet, b-jet, photon, W, Z, or a Higgs*
- Modeling: Effective field theory or simplified model frameworks
- N.B. EFTs are avoided where possible in new ATLAS and CMS results because of the validity complications that arise when using them
  - Dark Matter Forum **http://arxiv.org/abs/1507.00966**



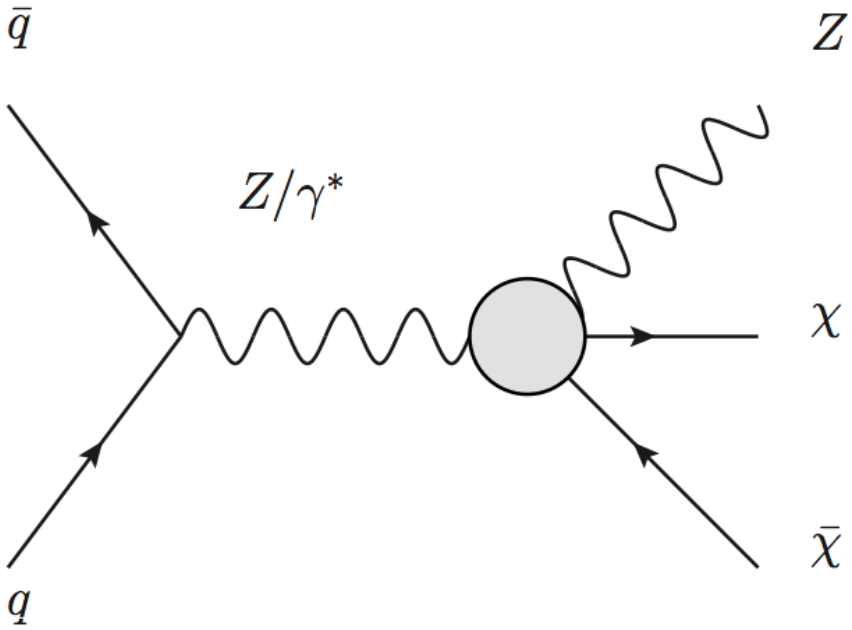
ISR,
Simplified Model



Contact Operator,
Simplified Model

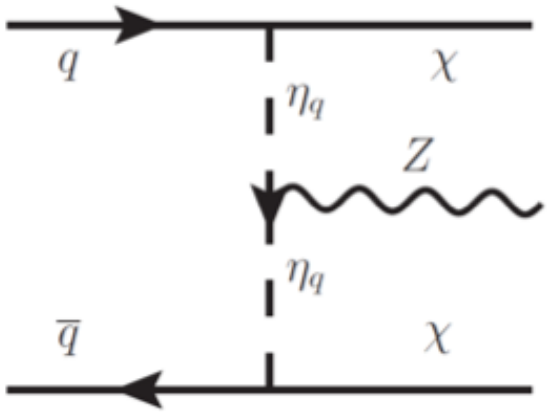
Production of DM in the mono-γ/W/Z/H channel

- We don't know how DM interacts with the Standard Model
- Initial state radiation is dominated by the mono-jet channel
- Other channels may dominate if DM particles interact primarily through them



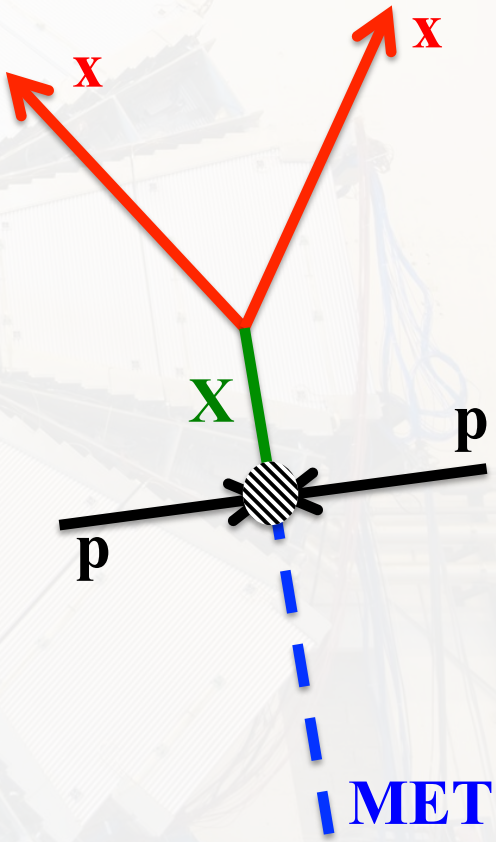
hep-ex/1302.3619. L.Carpenter, AN, C.Shimmin, T.Tait, D.Whiteson

UV complete model



Analysis Strategy

- Single particle is produced and recoils against DM particles
  - *X* is the SM particle, might decay or might be final state particle
- Two types of selections:
  - Require *X* and *MET* to be high quality
- Examples:
  - If *X* is a *W* or *Z*, reconstructed mass within a window
  - $\Delta\phi(X,MET)$ should be large
  - $\Delta\phi(jet,MET)$ should be large to remove events with mismeasured *MET*
  - Veto events with extra particles

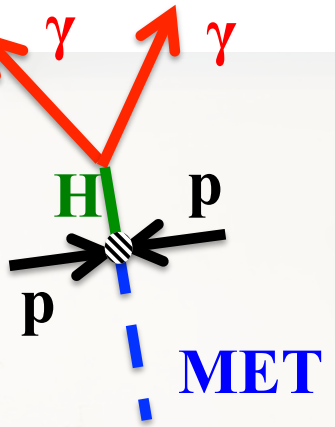


Outline

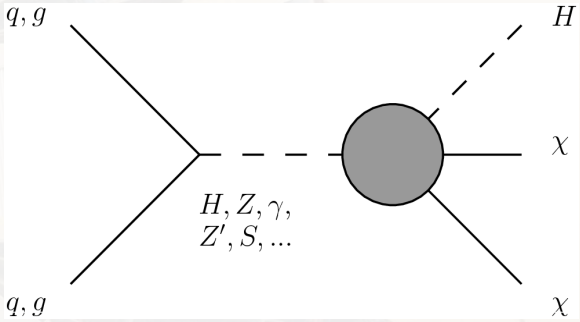
- **DM+Higgs (8 TeV)**
  - **H➔γγ (ATLAS)**
  - **H➔bb (ATLAS)**
- **DM+jets (8 and 13 TeV)**
  - **mono-jet (ATLAS and CMS)**
  - **di-jet (CMS)**
  - **ttbar (heavy-flavor+MET) (ATLAS and CMS)**
- **DM+W/Z (8 and 13 TeV)**
  - **Z➔ll (ATLAS and CMS)**
  - **W➔lν (CMS)**
  - **W/Z➔jj (ATLAS and CMS)**

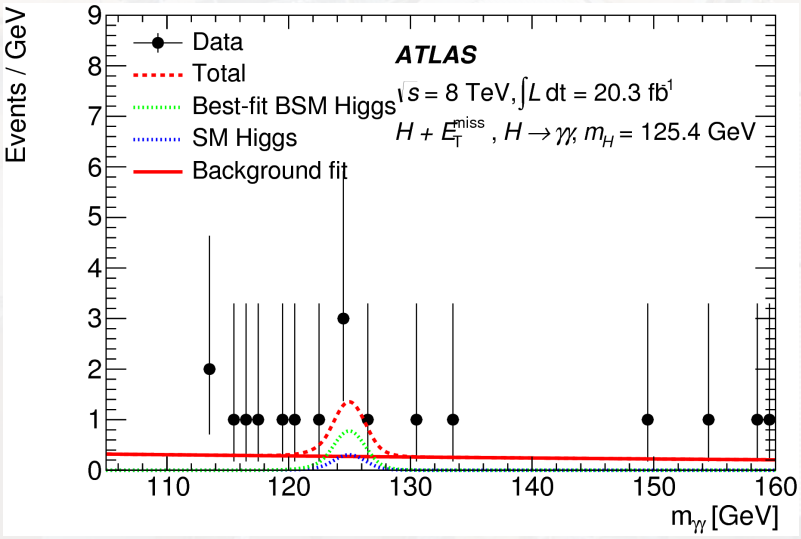
- Many more channels have been explored…

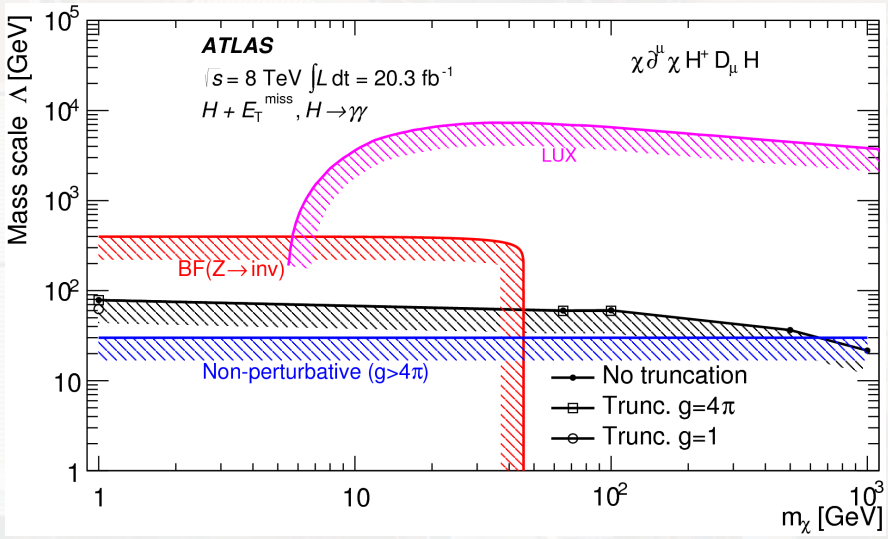
mono-H: γγ channel



- First study of Higgs coupling to DM through heavy mediator (8 TeV analysis)
- Select events with
  - Diphoton trigger
  - Diphoton mass within Higgs window, [105,160]
  - MET>90 GeV
  - photon p_T>90 GeV

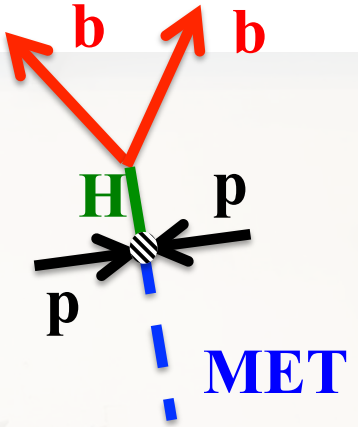






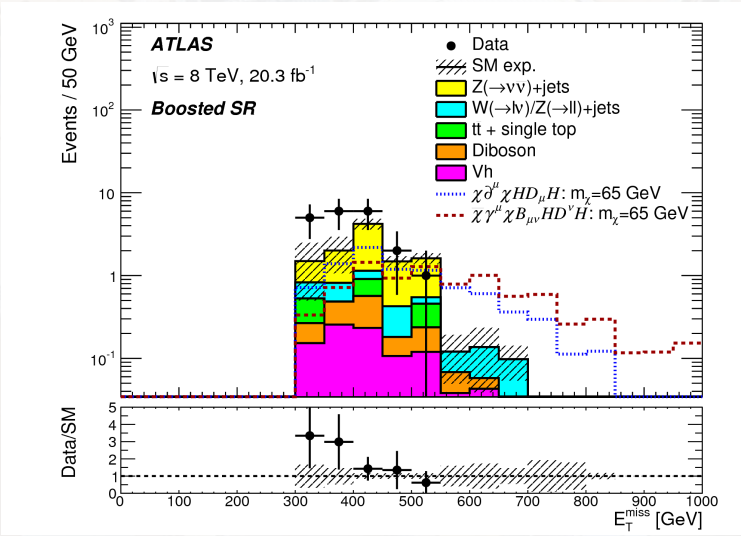
Phys. Rev. Lett. 115, 131801 (2015)

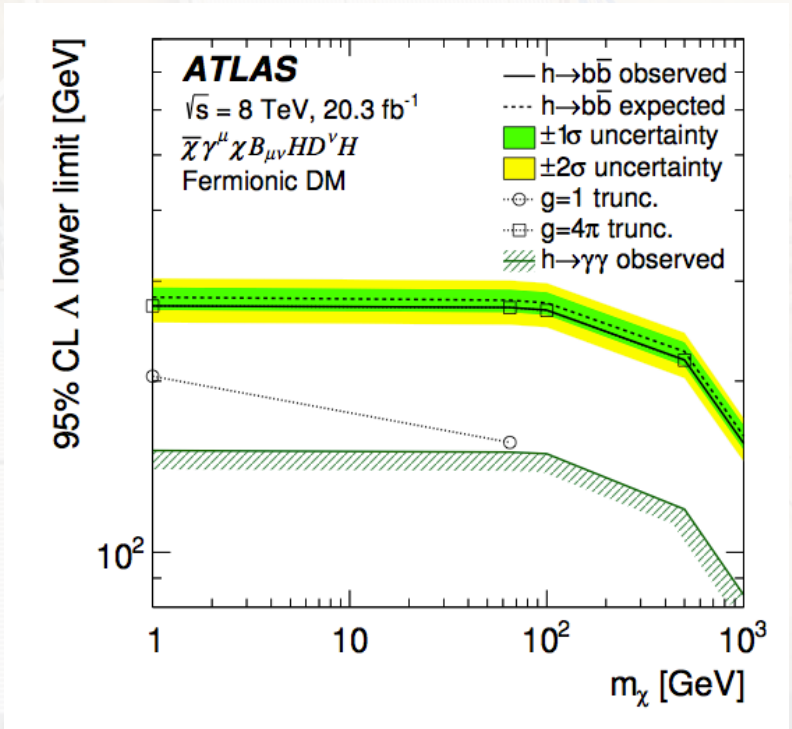
mono-H: bb channel



- Two channels: two small-radius jets (resolved) or one large-radius jet (boosted) (8 TeV analysis)
- For resolved (boosted), events must satisfy
  - Satisfy MET trigger, and large MET
  - 2 b-tagged small-radius jets (track jets)
  - jet p_T>100 (350) GeV
  - Higgs mass [90,150] GeV
  - Angular separation consistent with channel topology

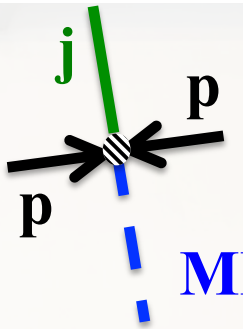
$\Delta R_{bb} \sim 2m_{bb}/p_{T,bb}$



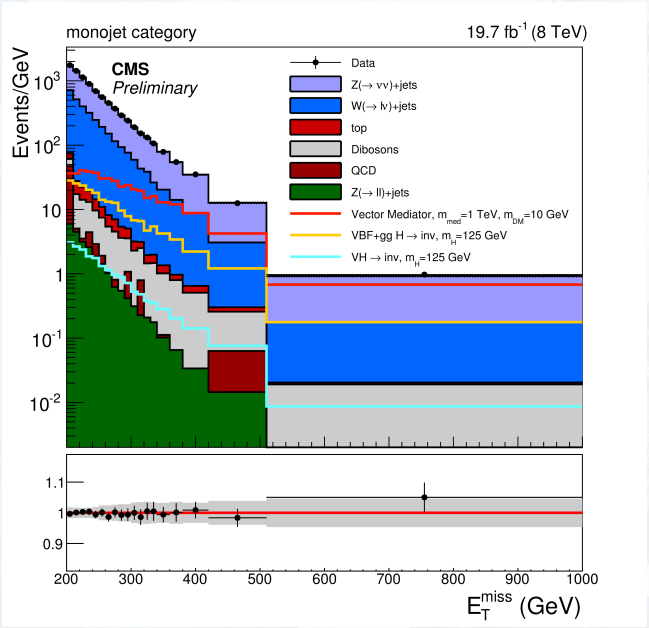


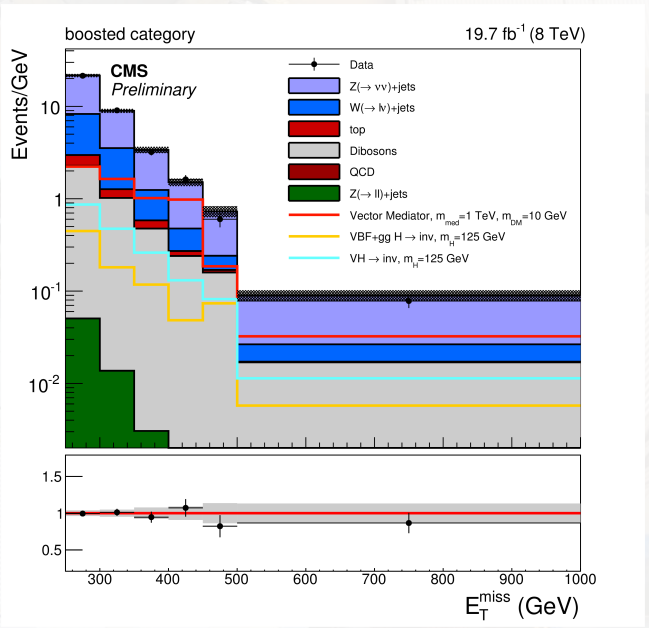
http://arxiv.org/abs/1510.06218

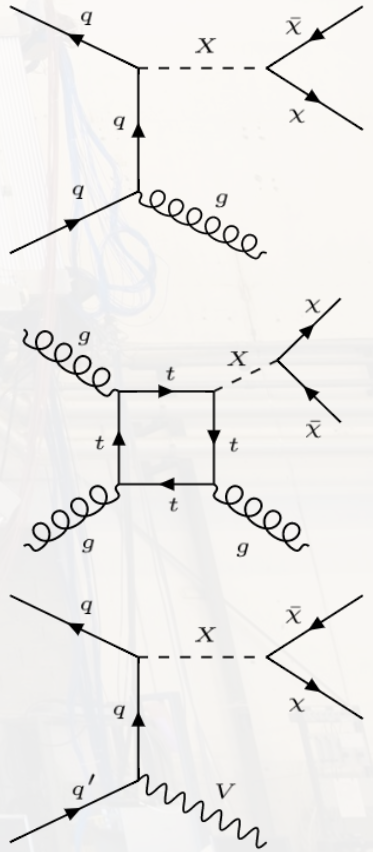
mono-jet



- ATLAS and CMS have studied mono-jet
- MET triggered events with high-quality jet
- Small-radius jet: quark/gluon radiation
- Large-radius jet: boosted W/Z boson

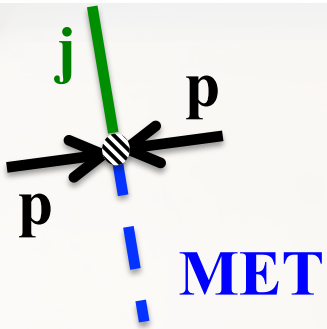




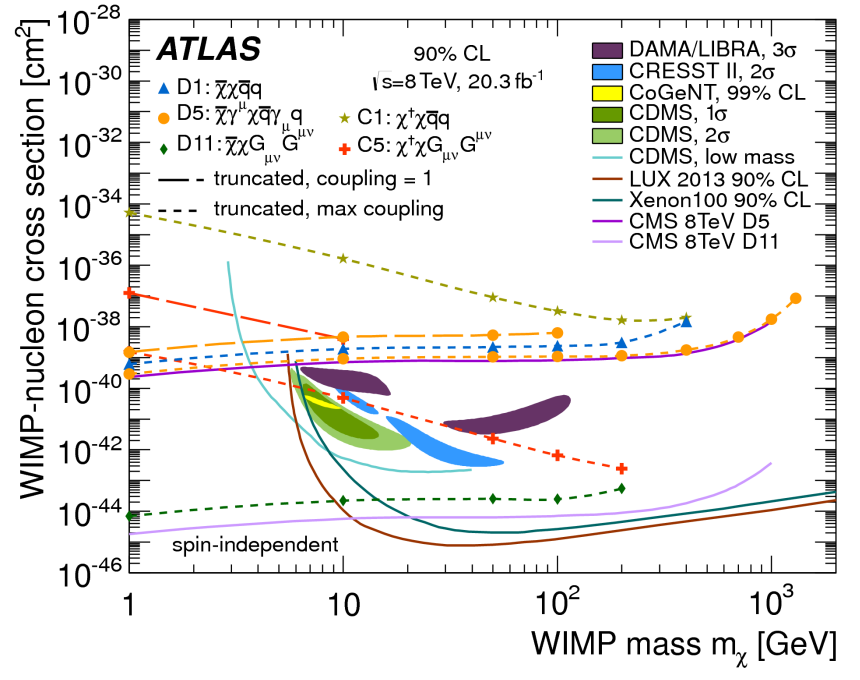


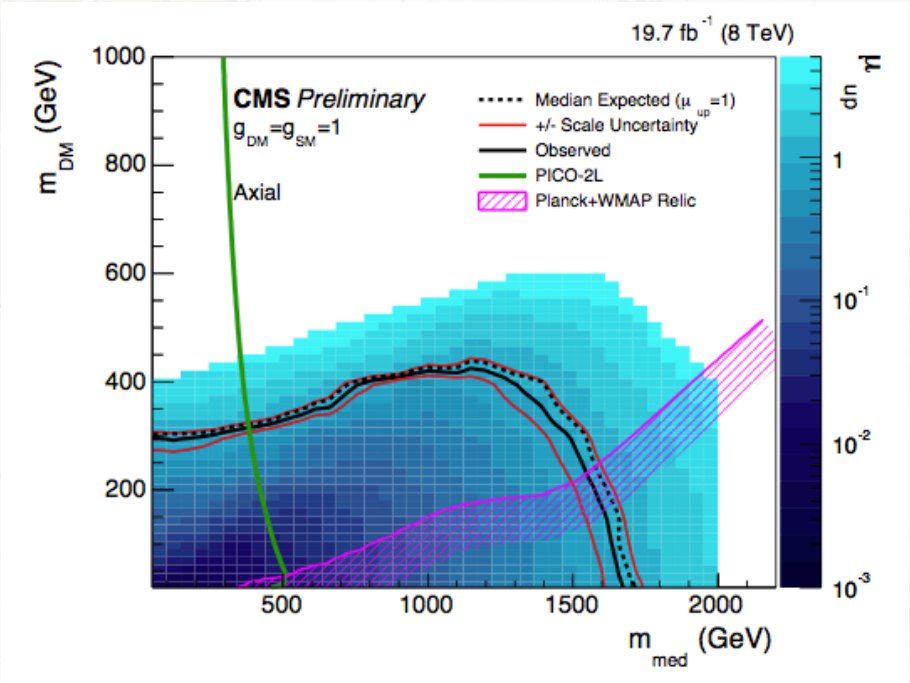
https://cds.cern.ch/record/2036044

mono-jet



- mono-jet limits interpreted in terms of simplified models and EFTs
- CMS combined resolved, boosted, and small-R
- ATLAS reported small-R and large-R separately



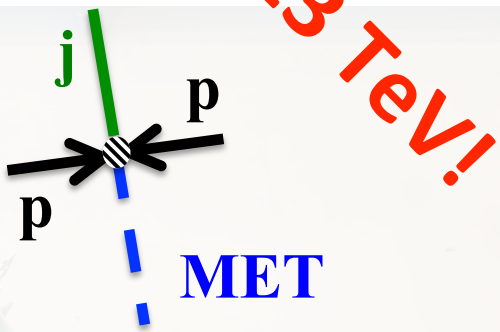


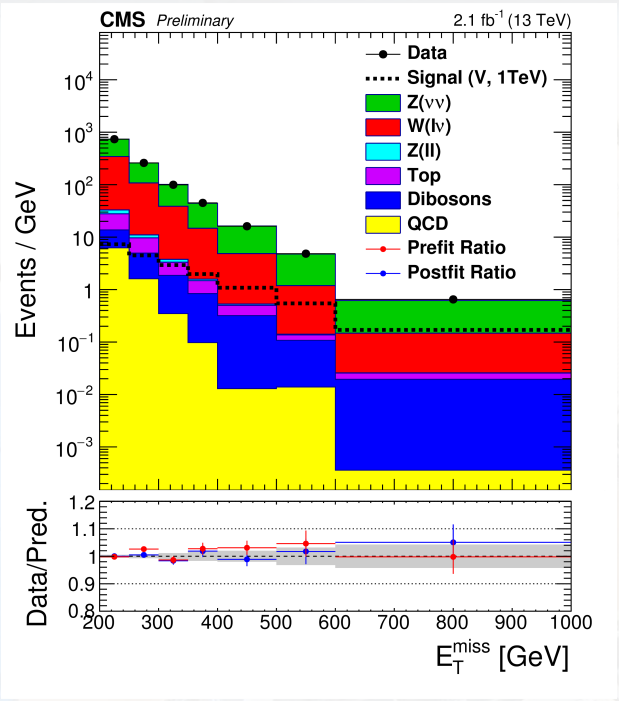
http://arxiv.org/abs/1502.01518

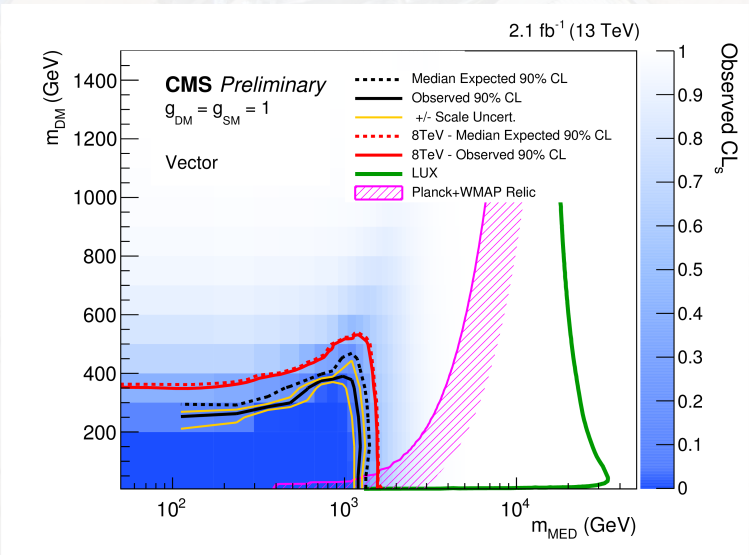
https://cds.cern.ch/record/2036044

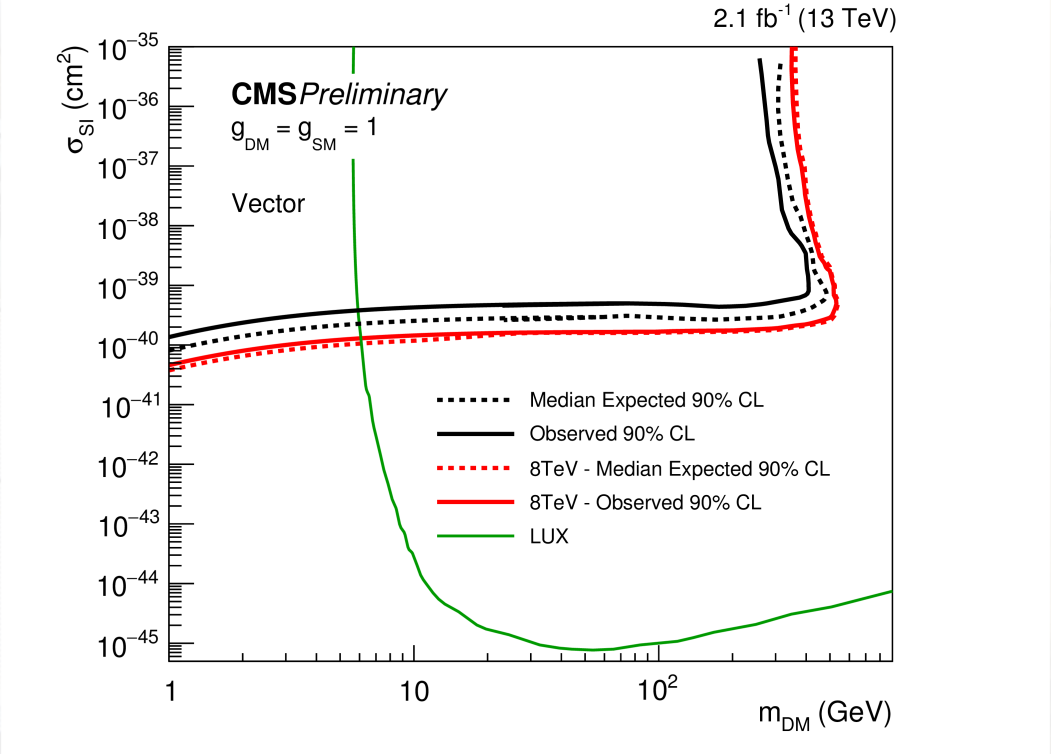
mono-jet

- CMS updated mono-jet (small-radius) search @ 13 TeV





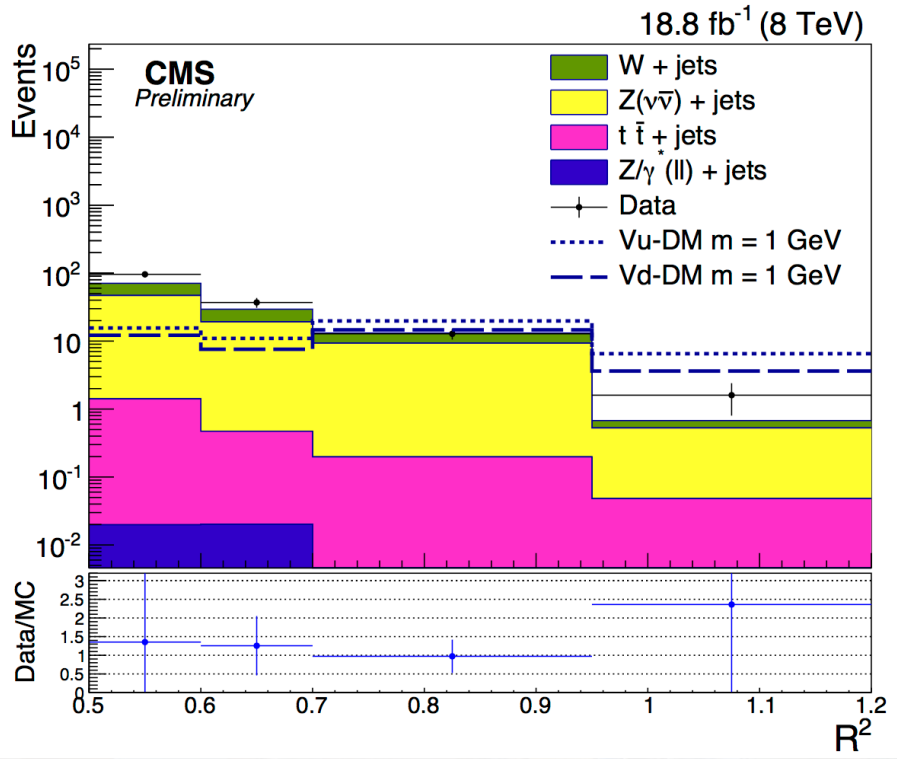


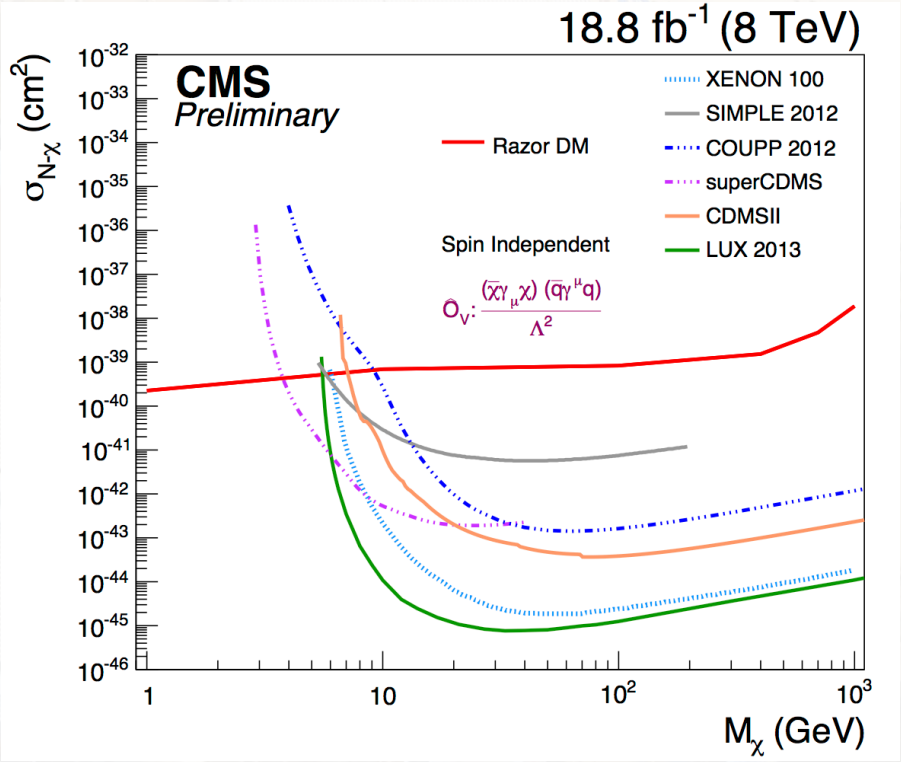


https://cds.cern.ch/record/2114807

Di-jets

- CMS studied events with ≥2 jets with razor variables
- Razor variables: M_R and R
  - M_R represents energy scale of event
  - R is ~1 for co-linear jets, falls exponentially

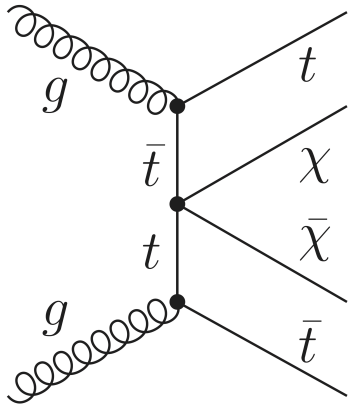




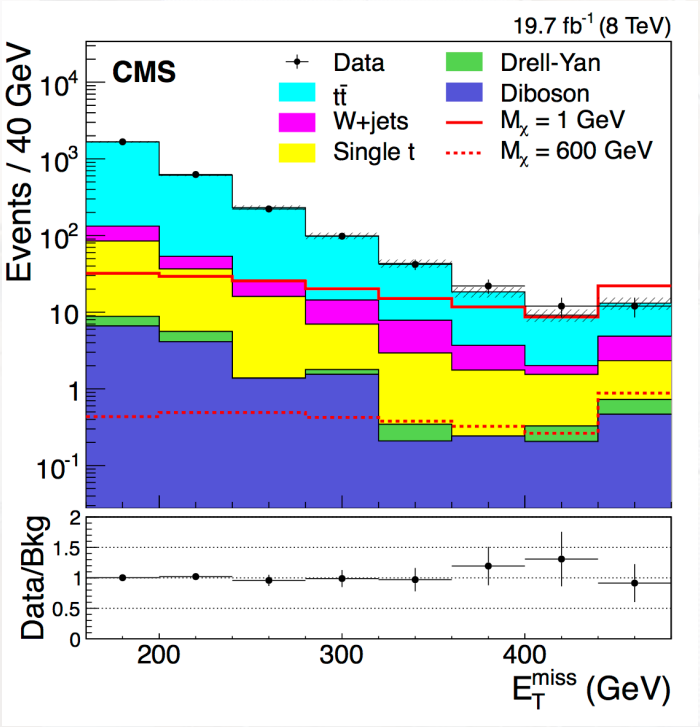
 http://cds.cern.ch/record/2002861

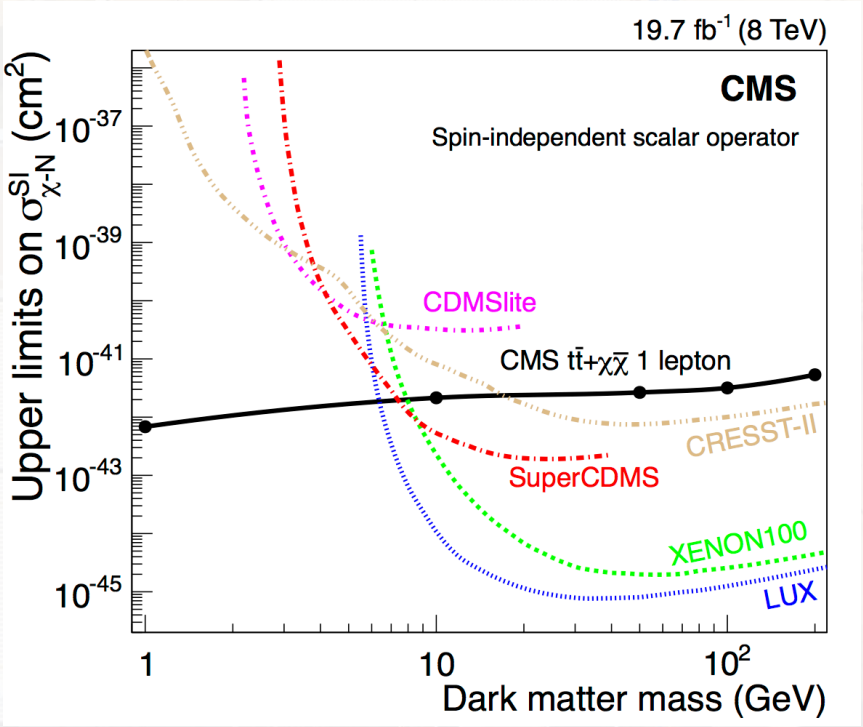
DM+ttbar

- Scalar dark matter interaction proportional to m_q
- ATLAS and CMS have roughly similar sensitivity
- Semi-leptonic ttbar decays

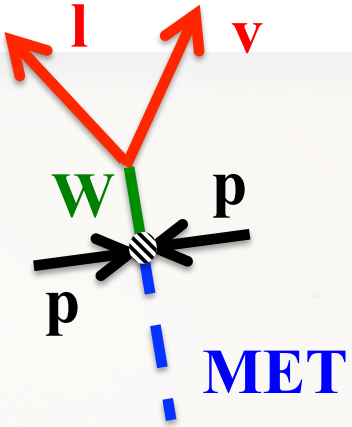


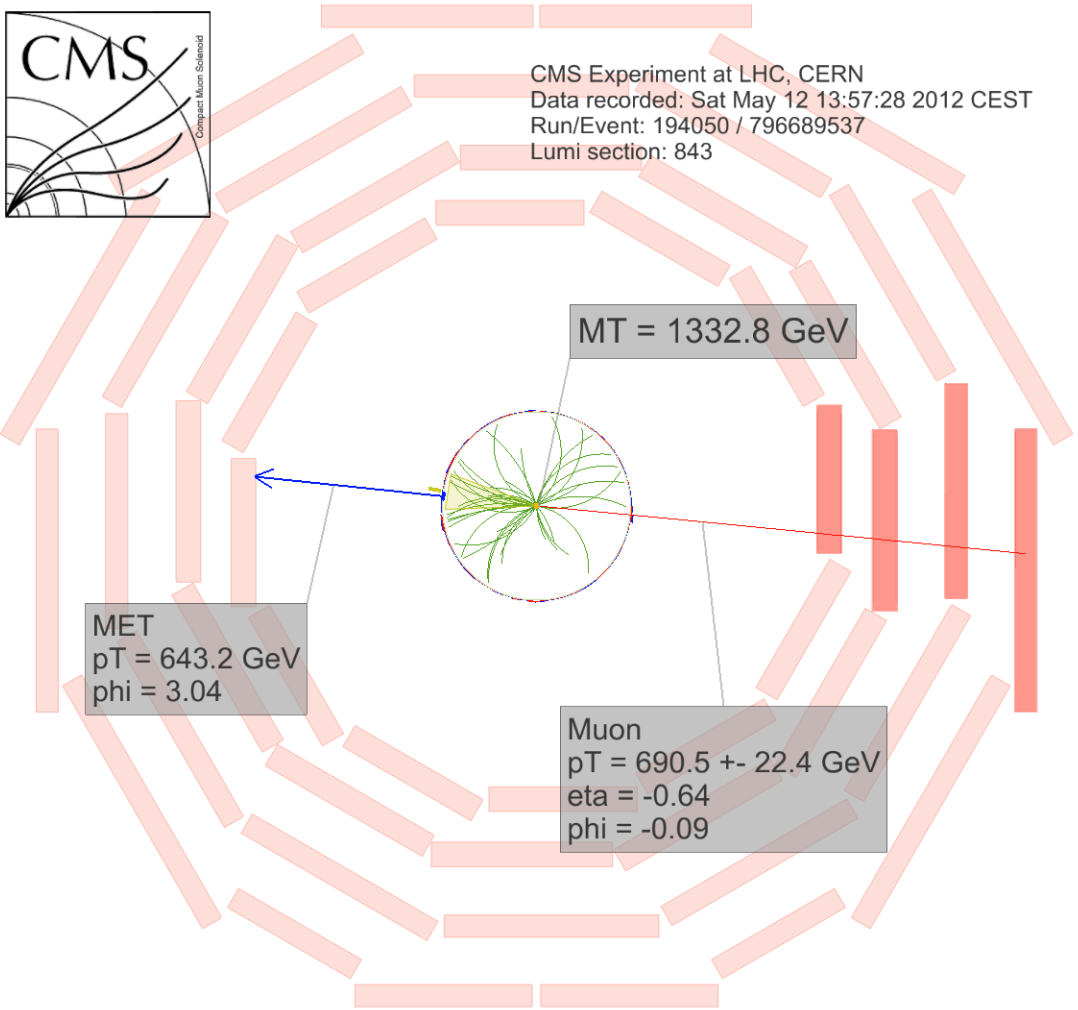
$$L_{\text{int}} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi.$$

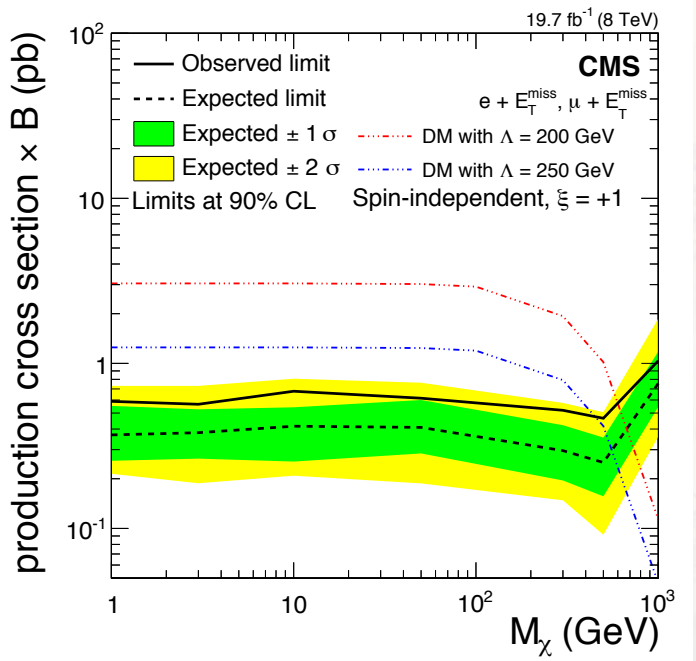




mono-W



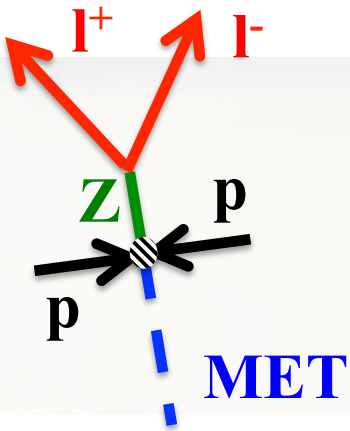


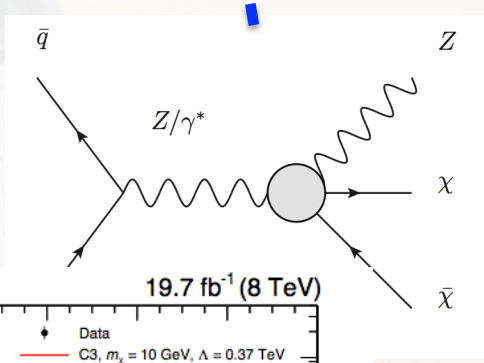


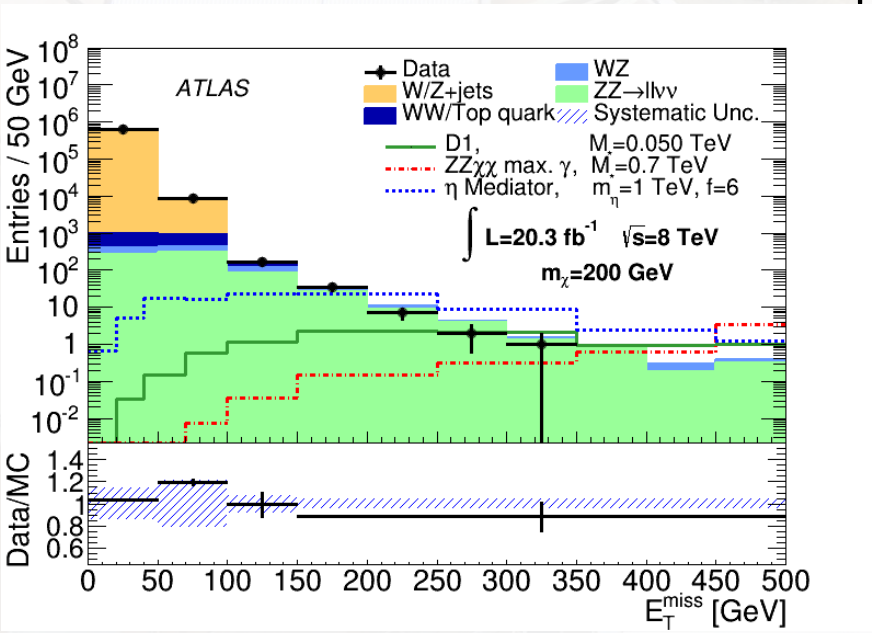
Phys. Rev. D 91, 092005 (2015)

mono-Z: ll channel

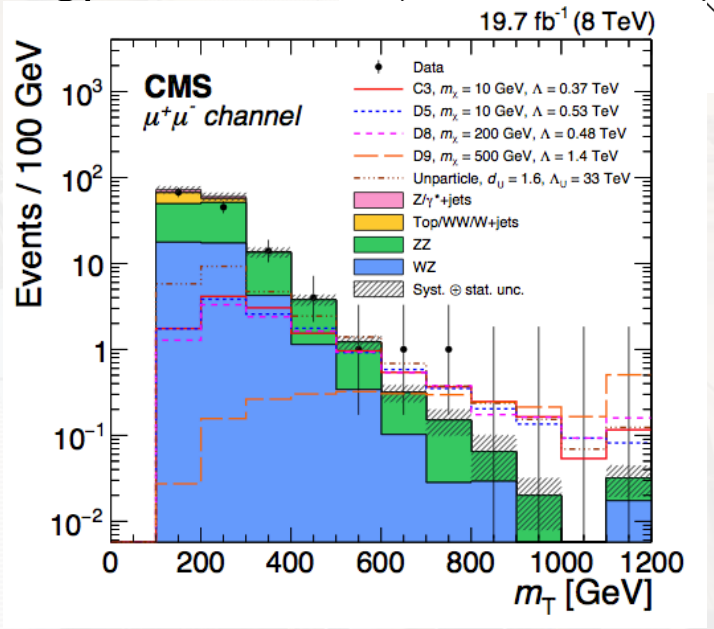
- ATLAS and CMS published searches in this channel
- Select events with
  - Leptonic trigger
  - Large MET
  - Dilepton mass consistent with Z boson
  - Momentum consistent with event topology





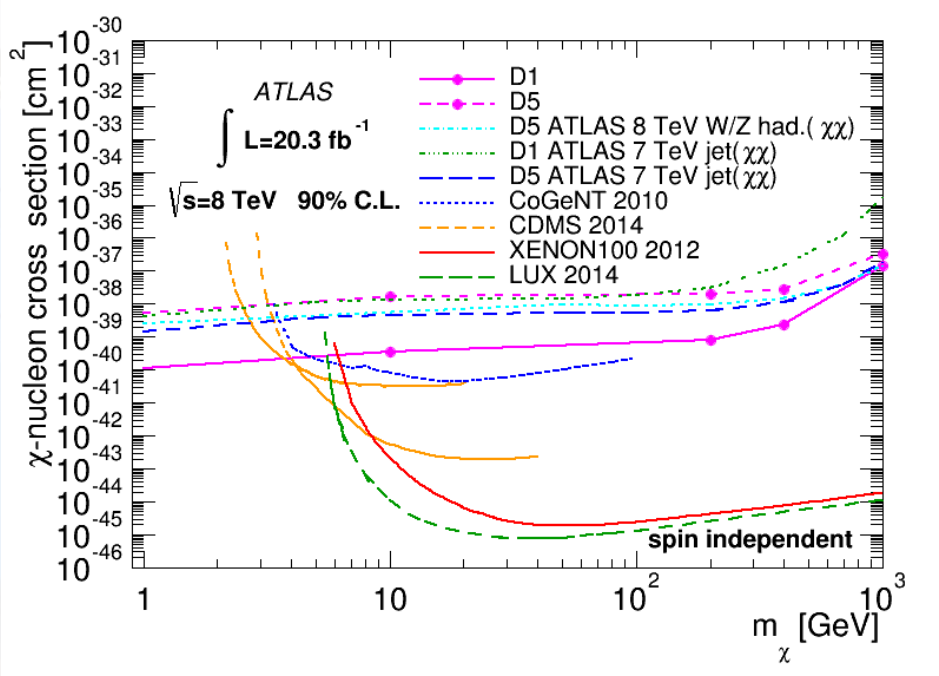


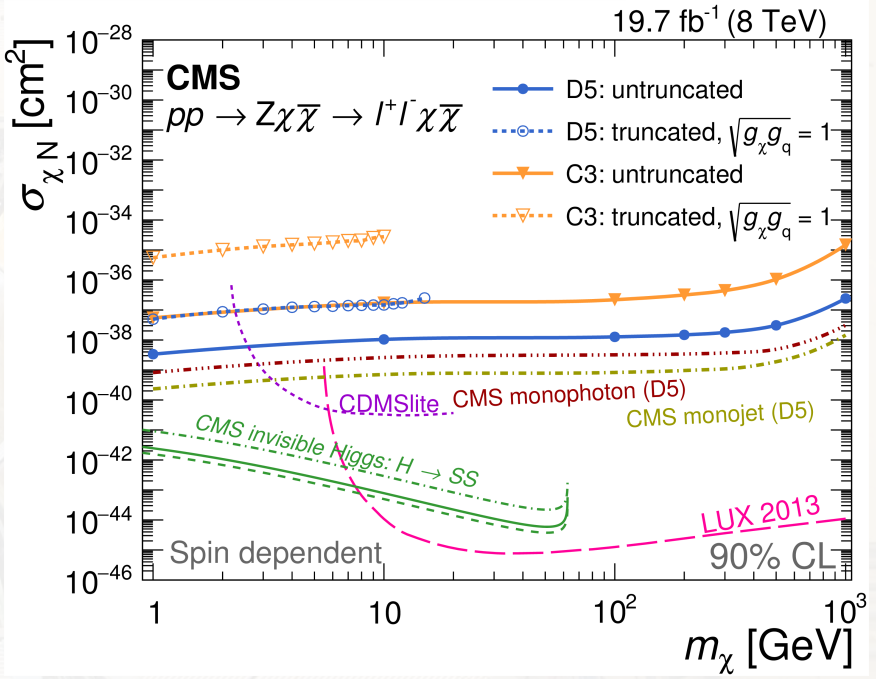
Phys. Rev. D 90, 012004 (2014)



http://arxiv.org/abs/1511.09375

mono-Z, Direct detection limits

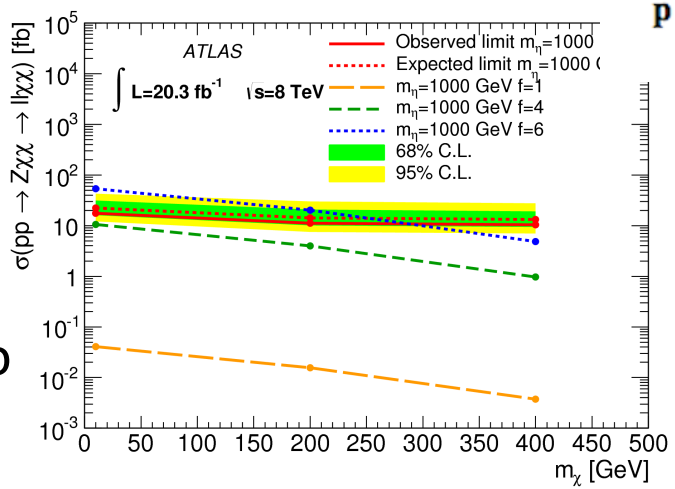


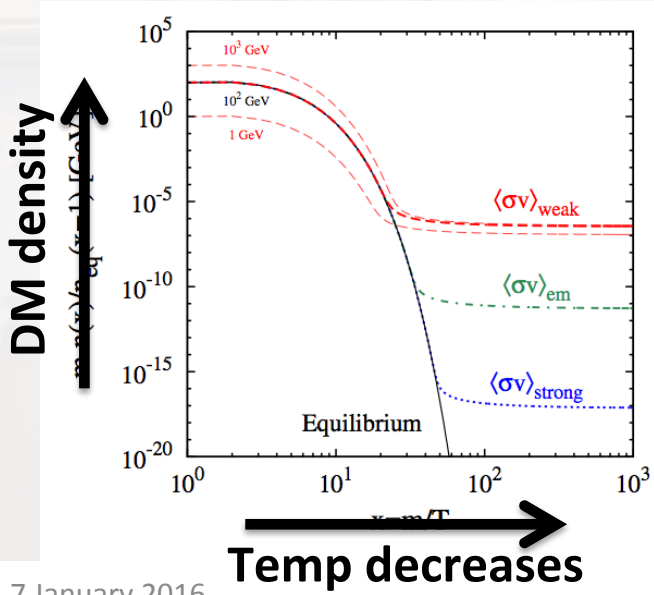


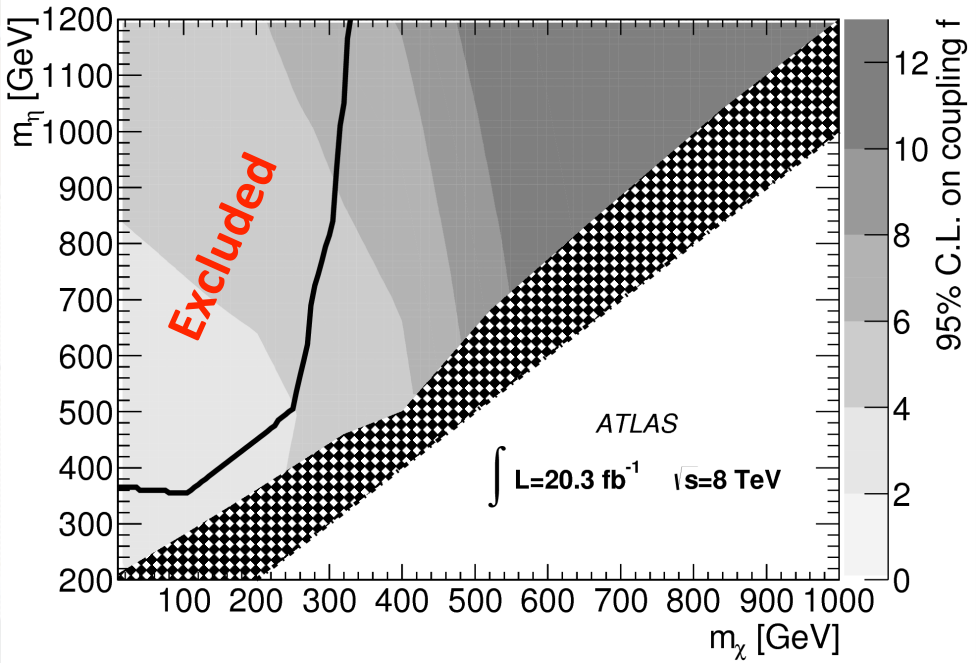
- Transform limits on the EFT scale, M*, into direct detection cross sections
- Complementary to the direct detection searches

Limits on UV complete model

- UV complete model has more parameters than the EFT
  - coupling, f
  - mass of mediator, m_η
  - mass of dark matter m_χ
- Compared an *upper limit* from collider to *lower limit* from relic density
- Certain points have a *upper limit* higher than *lower limit* from relic density: excluded

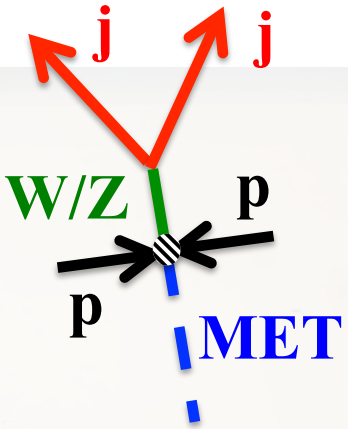


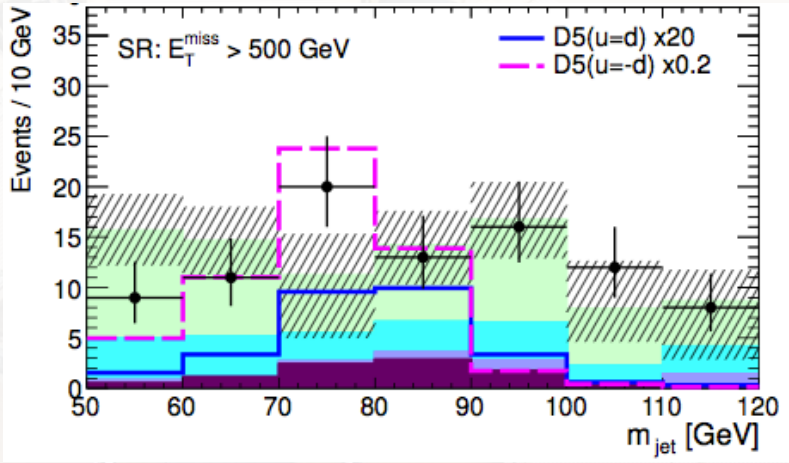


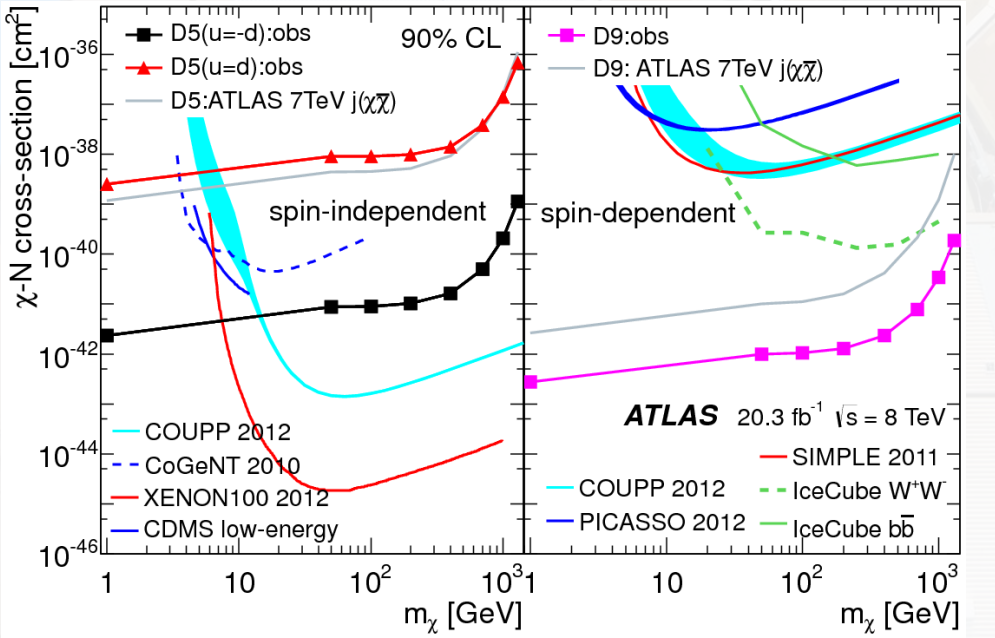


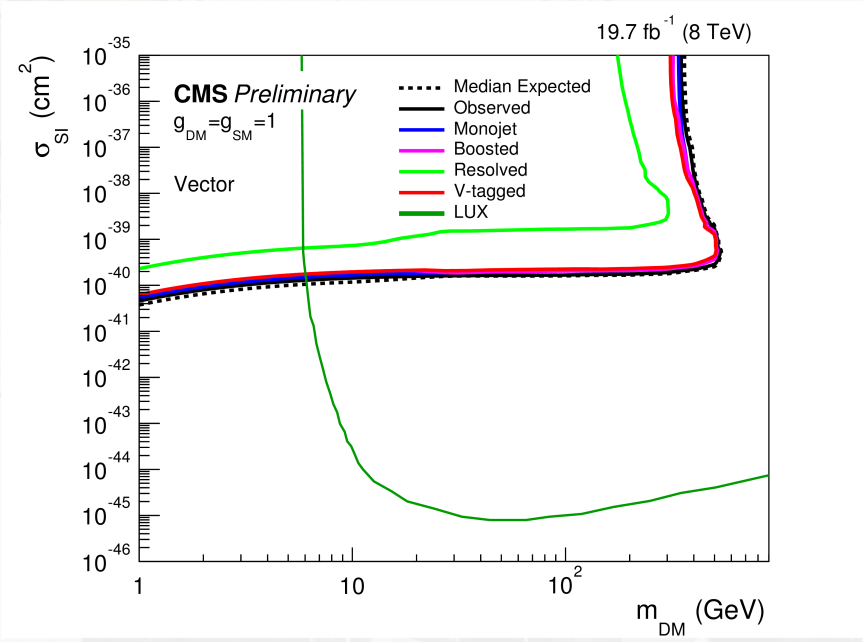
mono-W/Z

- Mono-W/Z
  - Large radius jet
  - W/Z tagging
    - Substructure
    - Grooming







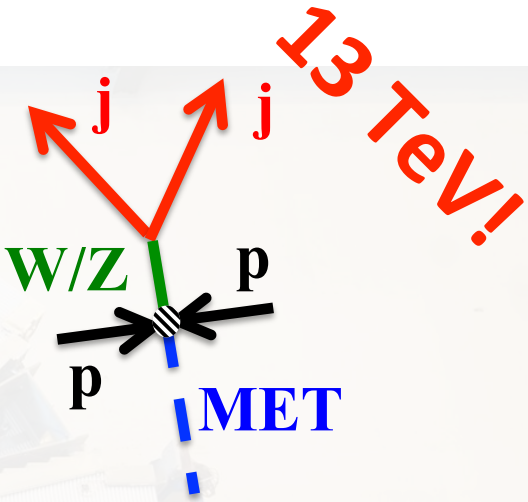


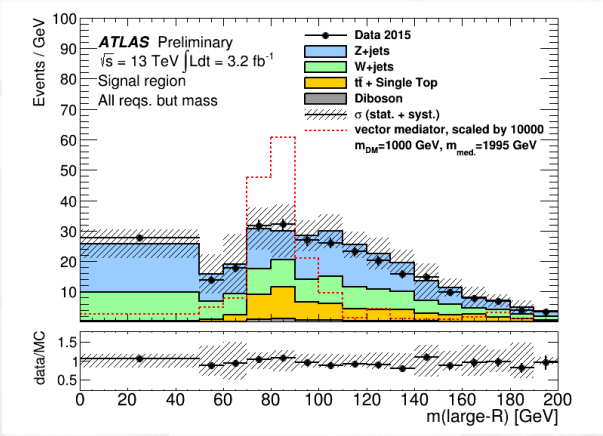
Phys. Rev. Lett. 112, 041802 (2014)

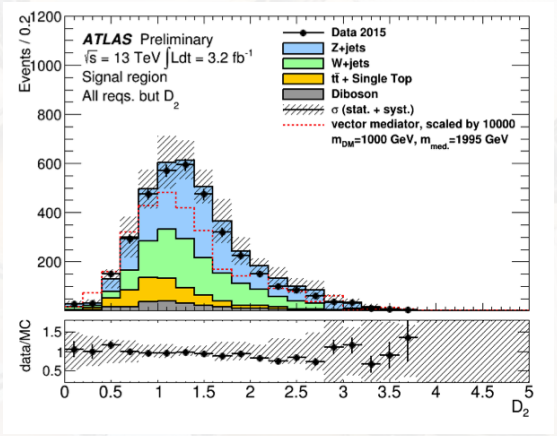
https://cds.cern.ch/record/2036044

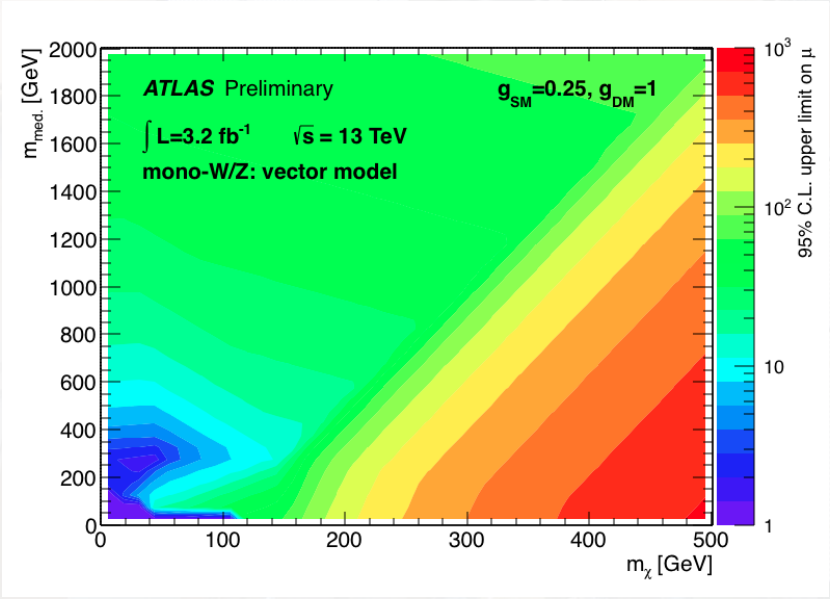
mono-W/Z

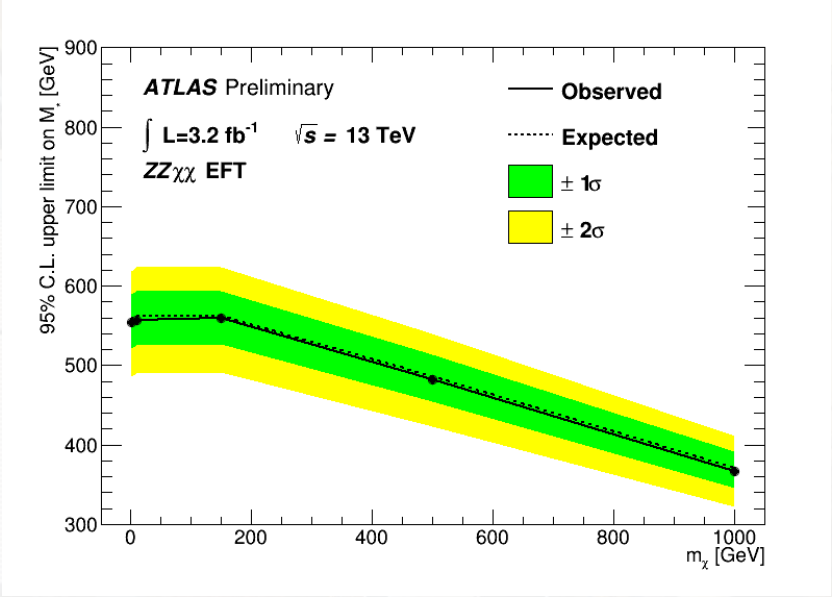
- ATLAS search for mono-W/Z at **13 TeV**









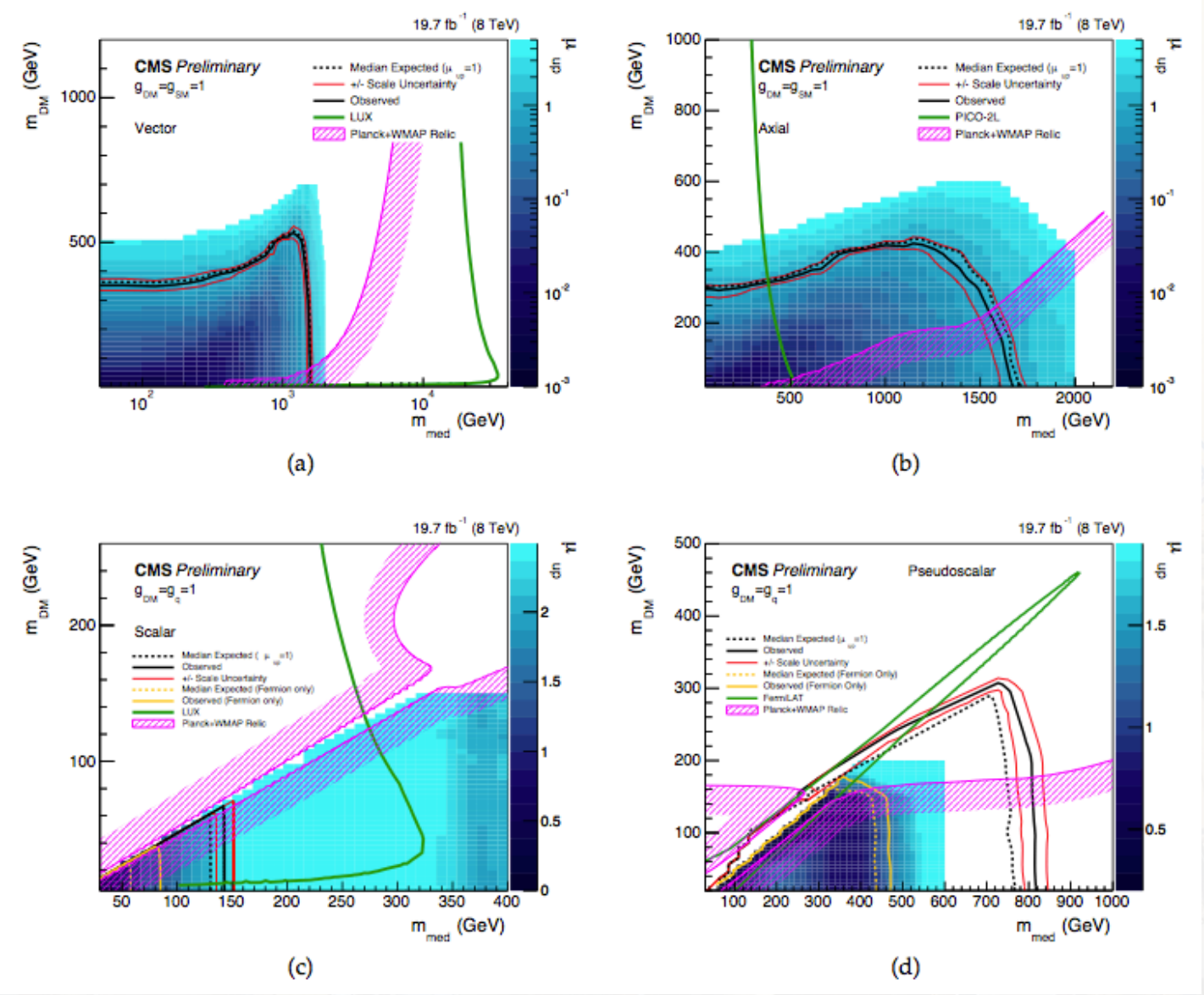


http://cds.cern.ch/record/2114852

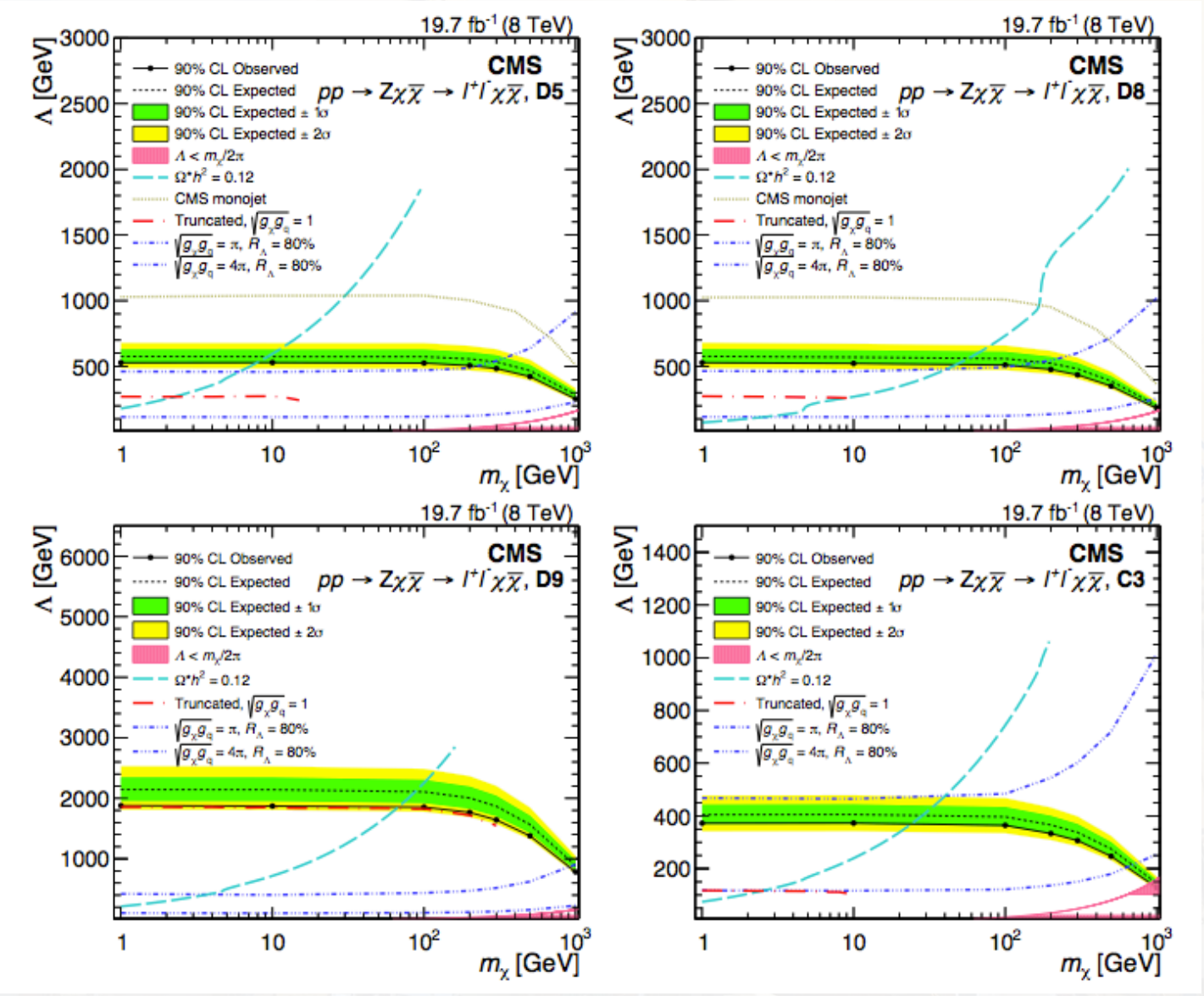
Outlook/Summary

- Colliders are an important part of the search for dark matter
  - Complementary to direct detection and indirect detection techniques
- ATLAS and CMS have explored many channels of dark matter production
- Dark Matter Forum provided common recommendations and models for ATLAS and CMS during the shutdown
  - **http://arxiv.org/abs/1507.00966**
- 13 TeV dark matter searches have just begun!

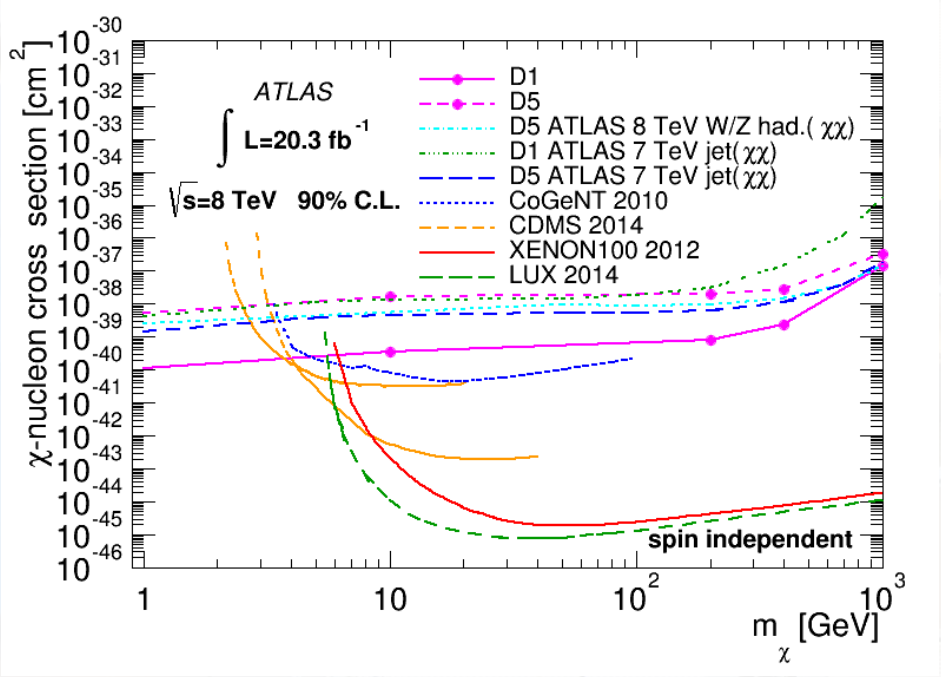
CMS mono-jet

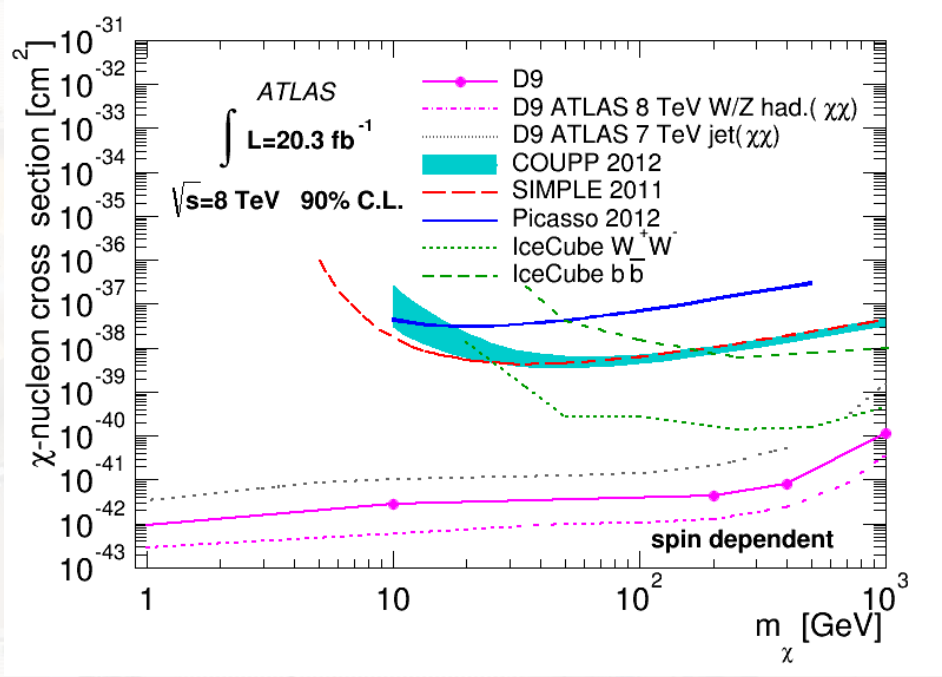

19.7 fb^{-1} (8 TeV)
CMS Preliminary
$g_{DM}=g_{SM}=1$
Vector
Median Expected ($\mu_{\pm\sigma}=1$)
+/- Scale Uncertainty
Observed
LUX
Planck+WMAP Relic
m_{DM} (GeV)
m_{med} (GeV)
dη
(a)
19.7 fb^{-1} (8 TeV)
CMS Preliminary
$g_{DM}=g_{SM}=1$
Axial
Median Expected ($\mu_{\pm\sigma}=1$)
+/- Scale Uncertainty
Observed
PICO-2L
Planck+WMAP Relic
m_{DM} (GeV)
m_{med} (GeV)
dη
(b)
19.7 fb^{-1} (8 TeV)
CMS Preliminary
$g_{DM}=g_{q}=1$
Scalar
Median Expected ($\mu_{\pm\sigma}=1$)
Observed
+/- Scale Uncertainty
Median Expected (Fermion only)
Observed (Fermion only)
LUX
Planck+WMAP Relic
m_{DM} (GeV)
m_{med} (GeV)
dη
(c)
19.7 fb^{-1} (8 TeV)
CMS Preliminary
$g_{DM}=g_{q}=1$
Pseudoscalar
Median Expected ($\mu_{\pm\sigma}=1$)
Observed
+/- Scale Uncertainty
Median Expected (Fermion Only)
Observed (Fermion Only)
FermiLAT
Planck+WMAP Relic
m_{DM} (GeV)
m_{med} (GeV)
dη
(d)

CMS mono-Z


19.7 fb^{-1} (8 TeV)
CMS
$pp \to Z\chi\overline{\chi} \to l^+l^-\chi\overline{\chi}$, D5
90% CL Observed
90% CL Expected
90% CL Expected ± 1σ
90% CL Expected ± 2σ
$\Lambda < m_\chi/2\pi$
$\Omega^* h^2 = 0.12$
CMS monojet
Truncated, $\sqrt{g_\chi g_q} = 1$
$\sqrt{g_\chi g_q} = \pi$, $R_\Lambda = 80\%$
$\sqrt{g_\chi g_q} = 4\pi$, $R_\Lambda = 80\%$
Λ [GeV]
m_χ [GeV]
19.7 fb^{-1} (8 TeV)
CMS
$pp \to Z\chi\overline{\chi} \to l^+l^-\chi\overline{\chi}$, D8
19.7 fb^{-1} (8 TeV)
CMS
$pp \to Z\chi\overline{\chi} \to l^+l^-\chi\overline{\chi}$, D9
19.7 fb^{-1} (8 TeV)
CMS
$pp \to Z\chi\overline{\chi} \to l^+l^-\chi\overline{\chi}$, C3

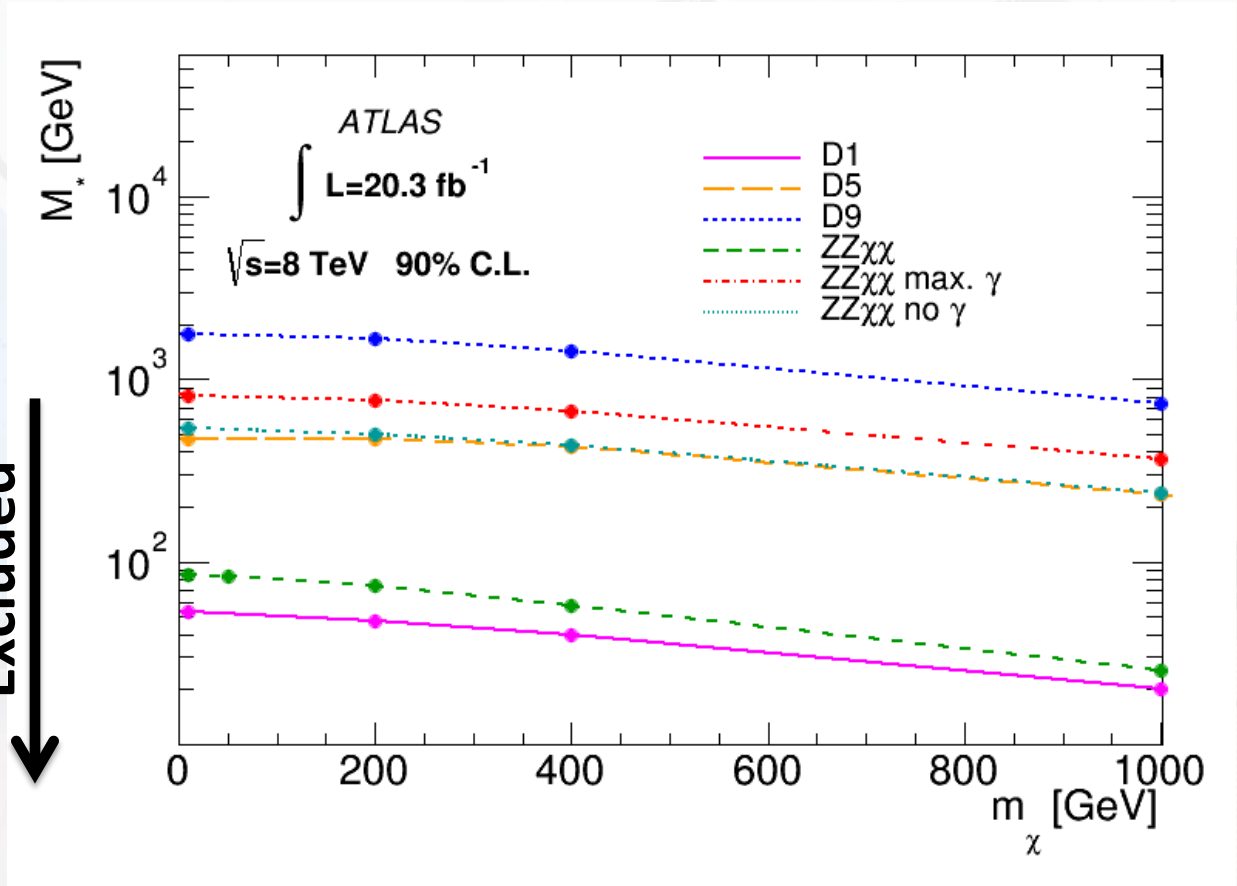
ATLAS mono-Z, Direct detection limits





- Transform limits on the EFT scale, M*, into direct detection cross sections
- Complementary to the direct detection searches

ATLAS mono-Z, Collider limits



- M* → inversely proportional to coupling
- Region <u>below</u> line excluded

- Limits range over an order of magnitude depending on the operator under consideration
  - Free parameters: m_χ, scale M*

Razor Variables

$$M_R \equiv \sqrt{(|\vec{p}_{J_1}| + |\vec{p}_{J_2}|)^2 - (p_z^{J_1} + p_z^{J_2})^2}\,,$$
$$R \equiv \frac{M_T^R}{M_R}\,, \tag{1}$$

with

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{J_1} + p_T^{J_2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{J_1} + \vec{p}_T^{J_2})}{2}}\,. \tag{2}$$

- M_R represents energy scale
- R is razor variable