Dark matter searches and prospects at the ATLAS experiment

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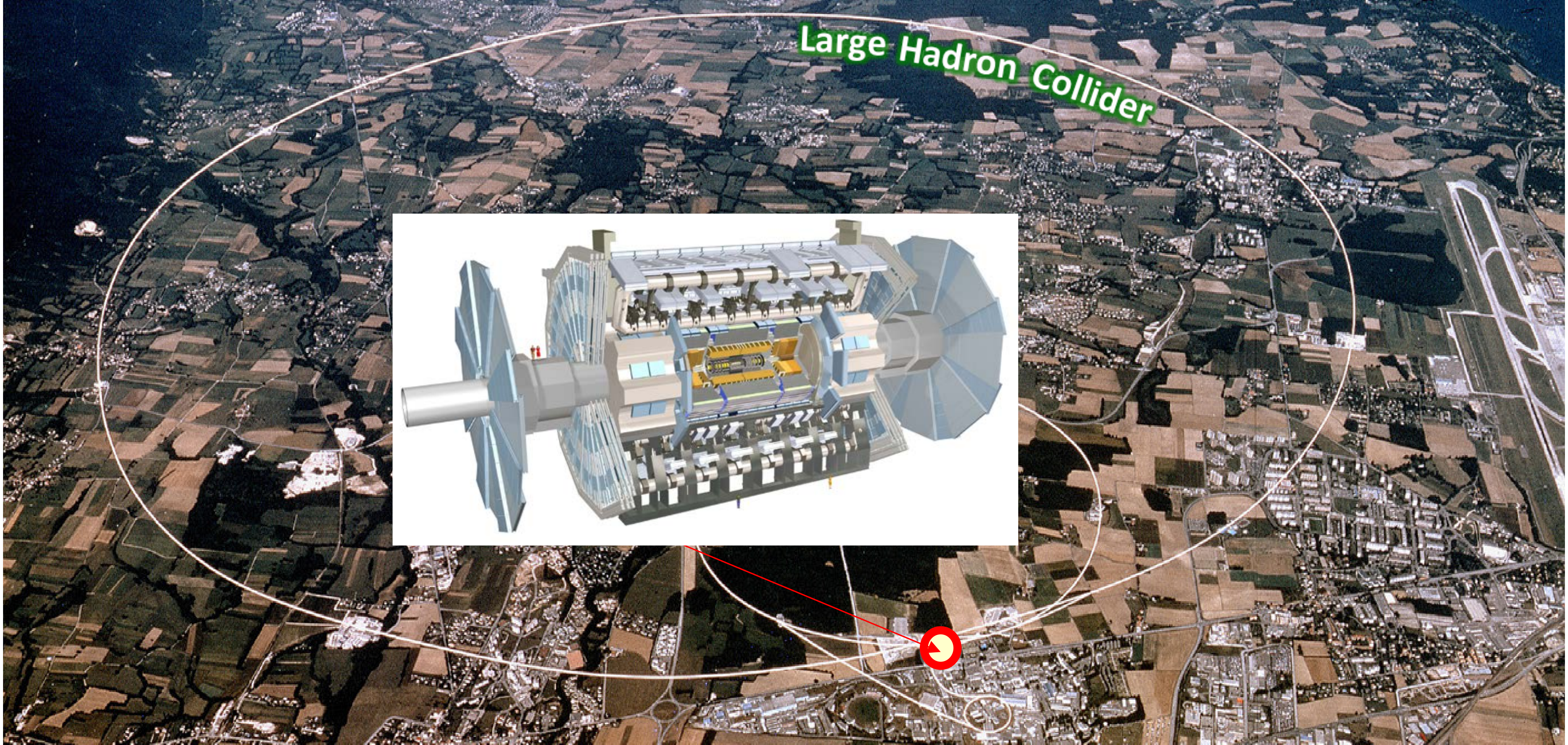
Dark Matter at ATLAS

Use 13 TeV proton-proton collisions in 2015/2016
to search for
Weakly Interacting Massive Particles (WIMP or χ)



Collider Searches Complement Astrophysical DM Experiments

- Direct experiments – aim to detect scattering of galactic DM particles off SM particles
- Indirect experiments – search for astrophysical sources of DM via its decay or annihilation into SM particles
- Collider experiments – search for DM particles pair-produced in collisions of SM particles
  - Interacts weakly with Standard Model (SM) particles (quarks) via non-SM mediator particle
  - Direct probe of interaction between SM and DM particles

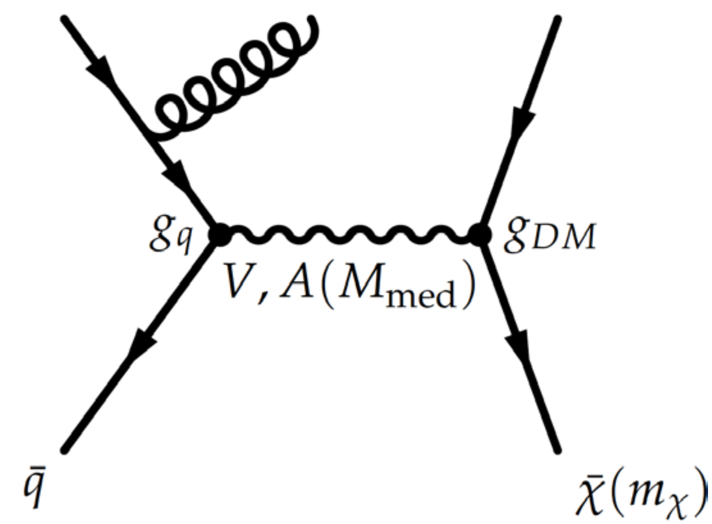
- Interpretations of non-collider results require assumptions on DM relic density
- Collider results require assumptions on production mechanisms

- Collider experiments are sensitive to lower DM masses than most direct detection experiments
- In collider experiments, DM candidate need only be stable long enough to traverse detector

Dark Matter Models

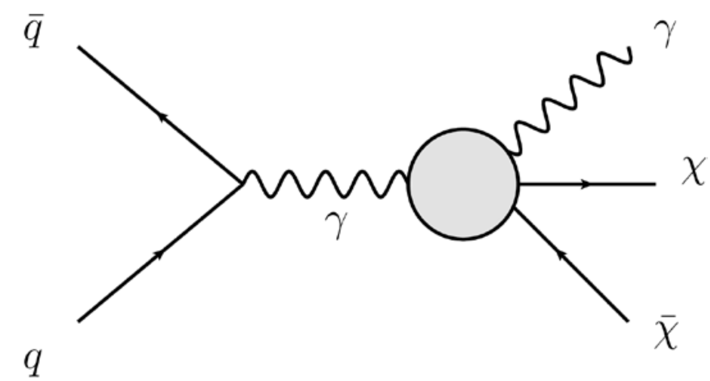
LHC Run 2 dark matter analyses follow recommendations of ATLAS/CMS Dark Matter Forum (arXiv:1507.00966)

- Most analyses interpret results via simplified models with
  - One dark matter particle, χ
  - One non-SM mediator
  - Characterized by 5 parameters:
    - g_{q} – mediator-SM coupling
    - g_{DM}– mediator-DM coupling
    - m_{χ} – dark matter mass
    - M_{med}, Γ_{med} – mediator mass and width

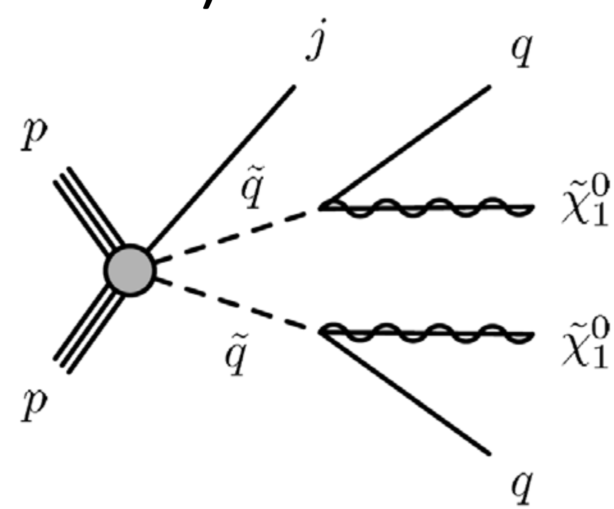


Dark Matter Models

- Effective Field Theory (EFT) used when applicable
  - probes contact interactions but validity range is often limited in Run 2 due to high momentum transfer
  - M^* – effective mass scale of particles that are integrated out
  - m_χ – dark matter mass



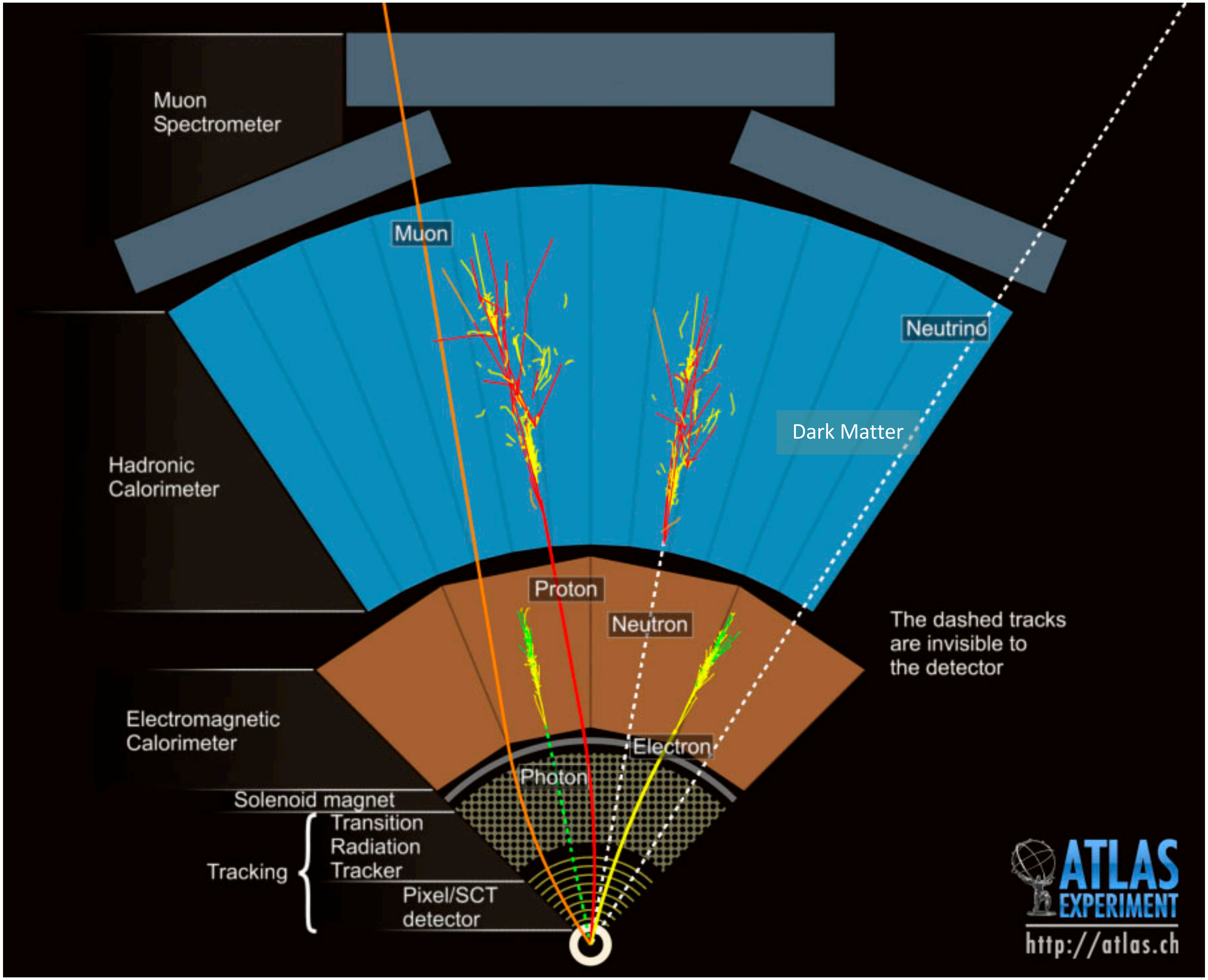
- Lightest Supersymmetric Particles (SUSY LSP) also considered
  - See talk by E. M. Farina



Dark Matter Collider Search Template

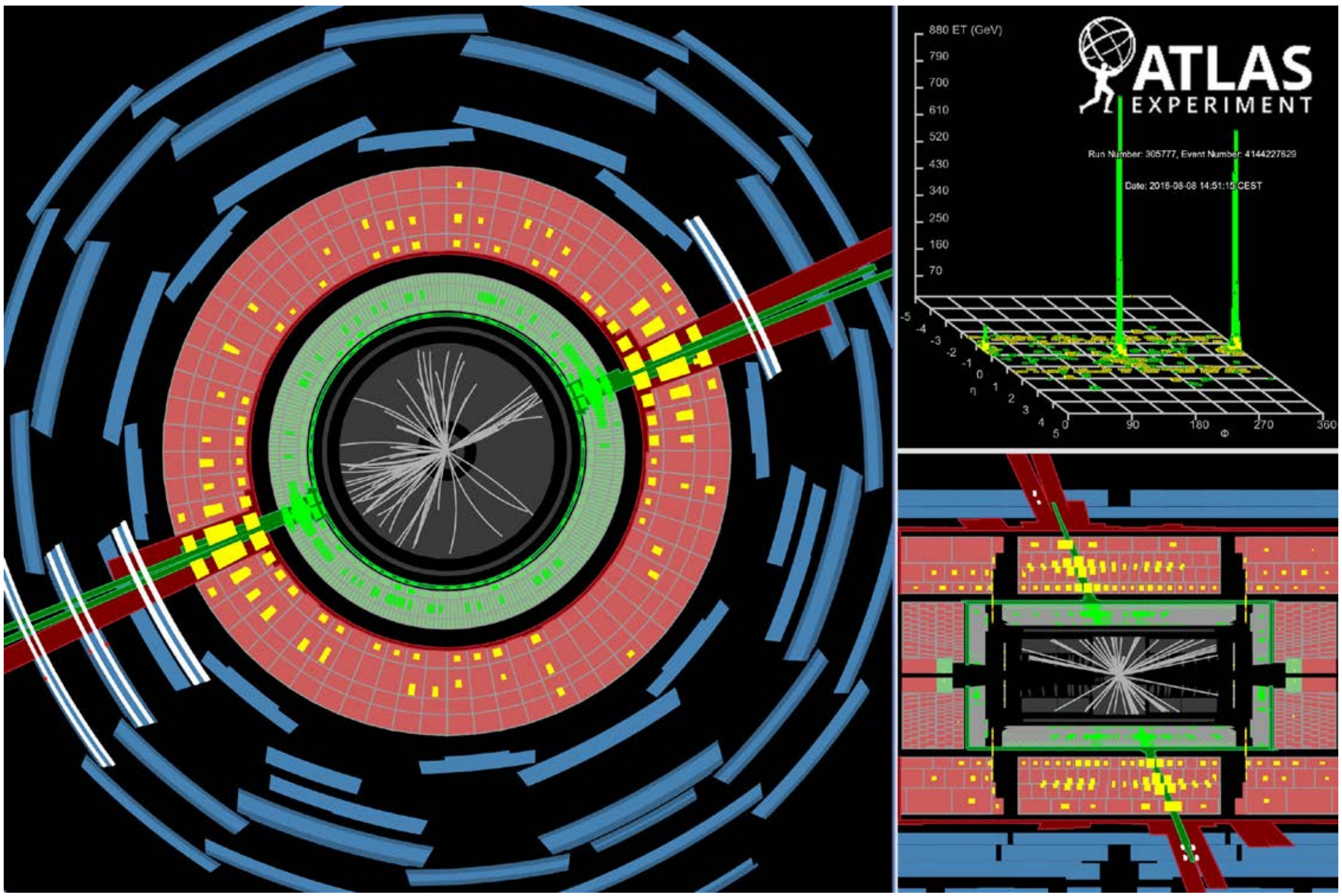
1. Generate Monte Carlo (MC) signal events (kinematic distributions, particle multiplicity, etc.) using simplified model implementations (e.g., MG5_aMC@NLO, JHEP06(2011)128.)
2. Use, e.g., Pythia (Comput.Phys.Commun. 178, 852 (2008),) for decays, parton showering, hadronization and underlying event
3. Simulate event interaction with ATLAS Detector using GEANT4 (NIM 506 (2003) 250.)
4. Simulate/overlay additional interactions (pileup) onto each MC event ($\langle N_V \rangle = 25$)
5. Optimize event selection cuts by maximizing signal to background
6. Implement online trigger algorithm with loose criteria optimized for high signal efficiency and low trigger rates
7. Estimate background (BG) using MC samples normalized to data recorded; use control regions (away from signal) to constrain BG yields in signal region
8. Evaluate systematic uncertainties for background and signal efficiencies and theoretical predictions
9. Perform likelihood fit to get exclusion limits

Dark Matter Signature at ATLAS



Dark Matter Signature at ATLAS

LHC proton beam has momentum p_z=±6.5 TeV and p_x=p_y=0
so collision products must have $\sum p_T$=0

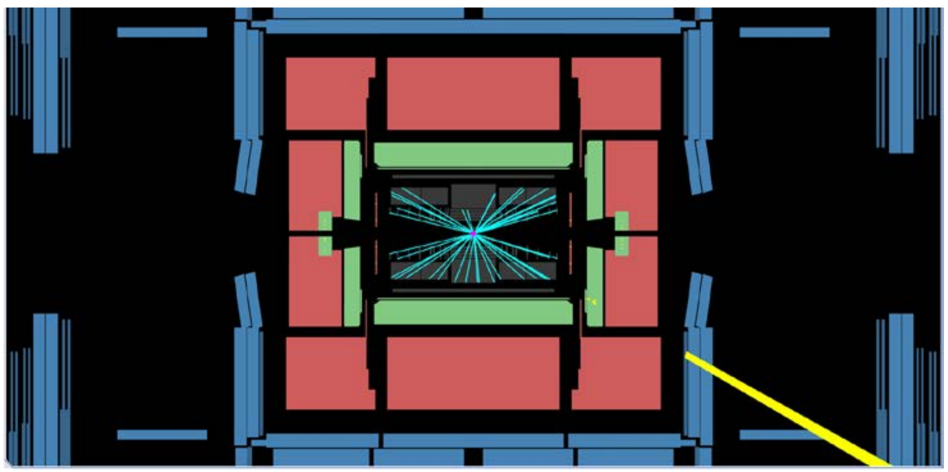


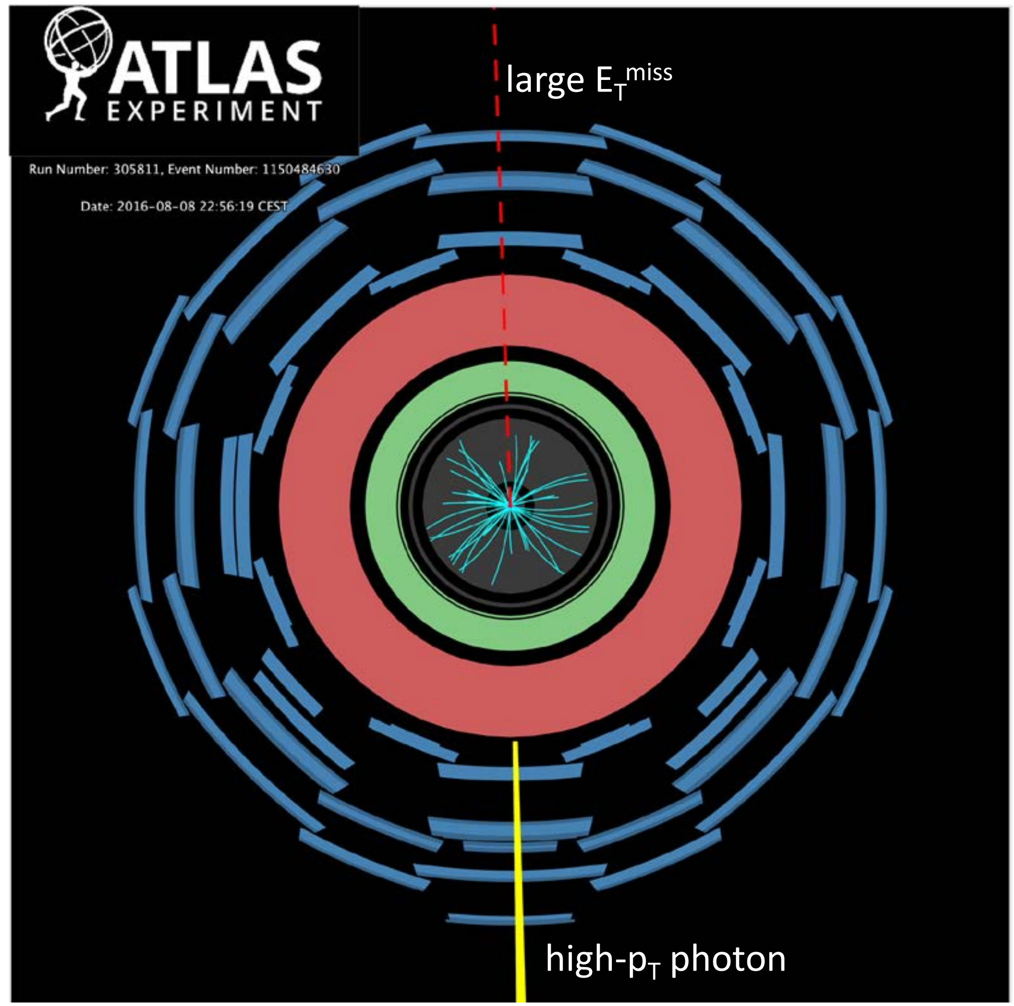
Mass 8.12 TeV dijet event

arXiv:1703.09127

Dark Matter Signature at ATLAS: E_T^{miss}

Dark matter particle itself is not recorded due to low interaction with detector so infer its presence in events that don't conserve p_T





$\gamma + E_T^{miss}$ event, $E_T(\gamma) = 265$ GeV

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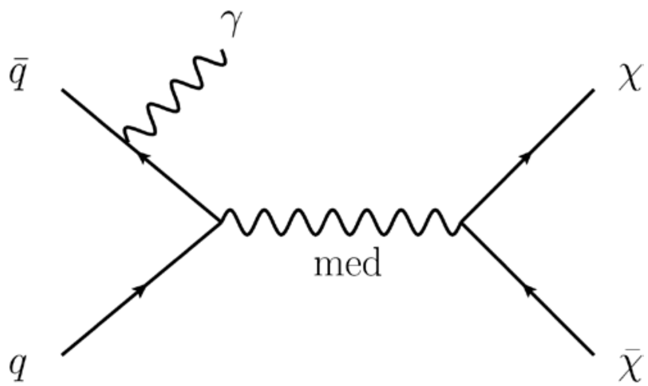
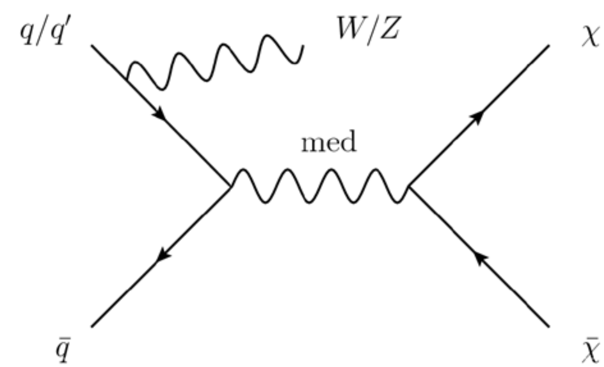
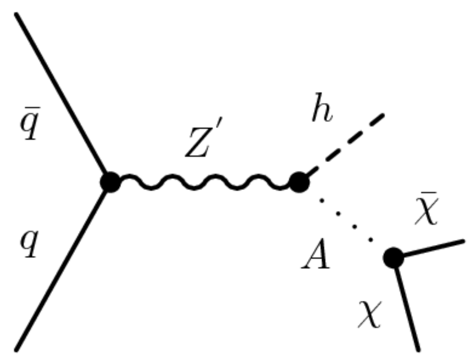
Mono-X Signature of Dark Matter

- Main signature of DM production in ATLAS is $X + E_T^{miss}$
  1. *X*=gluon, photon, *W*/Z from Initial State Radiation (ISR)



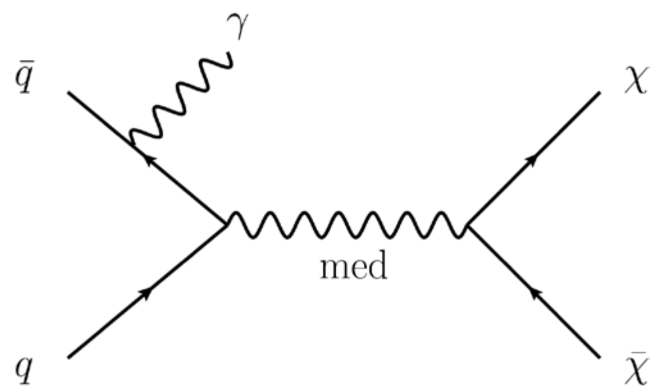


  2. *X*=Higgs: Higgs ISR is Yukawa-suppressed but Higgs can be radiated by mediator directly



- $X + E_T^{miss}$ events readily identified in ATLAS and have low SM rates

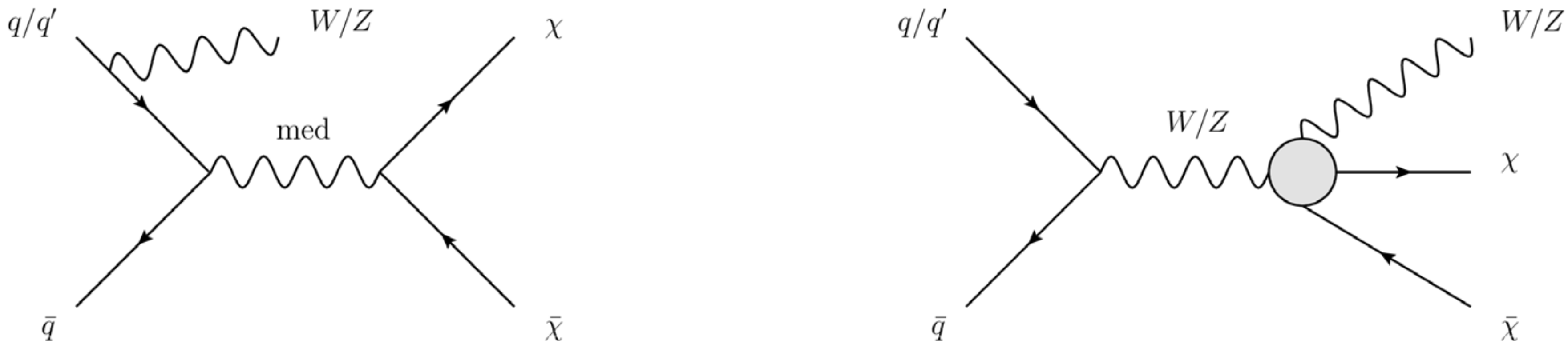
Mono-X Event Reconstruction



- Trigger on E_T^{miss} and/or energy deposit in calorimeter from X
- Reconstruct associated object X offline using more sophisticated algorithm
- Mono-X signature modes presented today
  - Mono-W/Z followed by hadronic decay of W/Z
  - Mono-photon
  - Mono-Higgs decaying to
    - $b\bar{b}$
    - $\gamma\gamma$
  - Mono-jet

Mono-W/Z (hadronic)

- 3.2 fb^{-1} of 13 TeV data collected in 2015
- Simplified model: Dirac-fermion DM pair production via a vector or axial-vector mediator in the *s* channel with ISR [left]

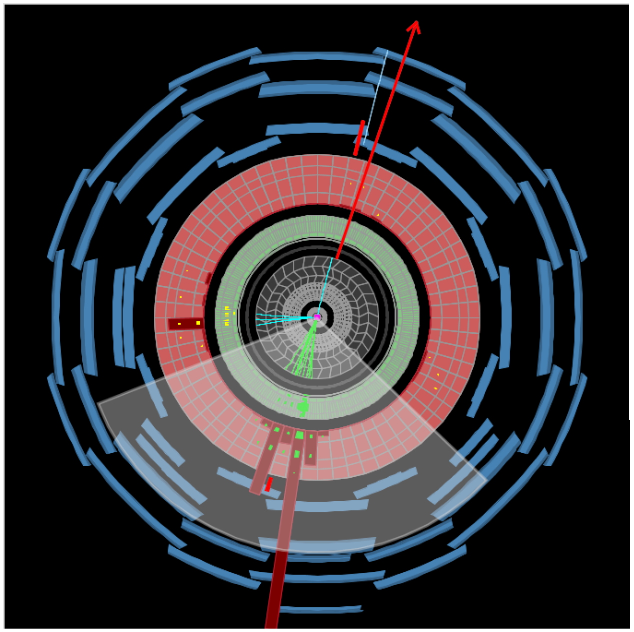


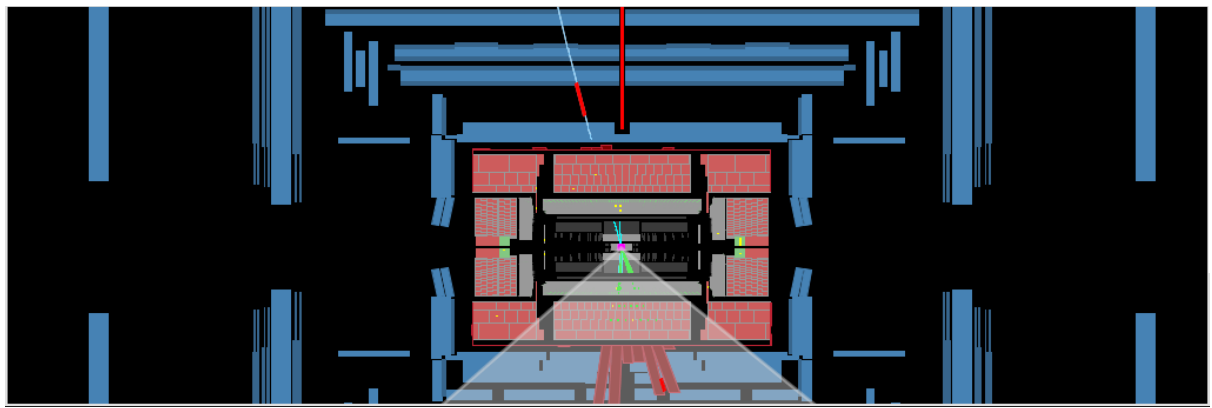
- EFT with $VV\chi\bar{\chi}$ contact interaction [right]
  - effective mass scale M_*
- Hadronically decaying highly boosted W or Z boson

[Phys. Lett. B 763 (2016) 251]

Mono-W/Z (hadronic)

- Inclusive E_T^{miss} online trigger is 99% efficient above 200 GeV
- Offline, $E_T^{miss} > 250$ GeV
- W or Z boson reconstructed as a single jet with $R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} > 1.0$ and $p_T > 200$ GeV





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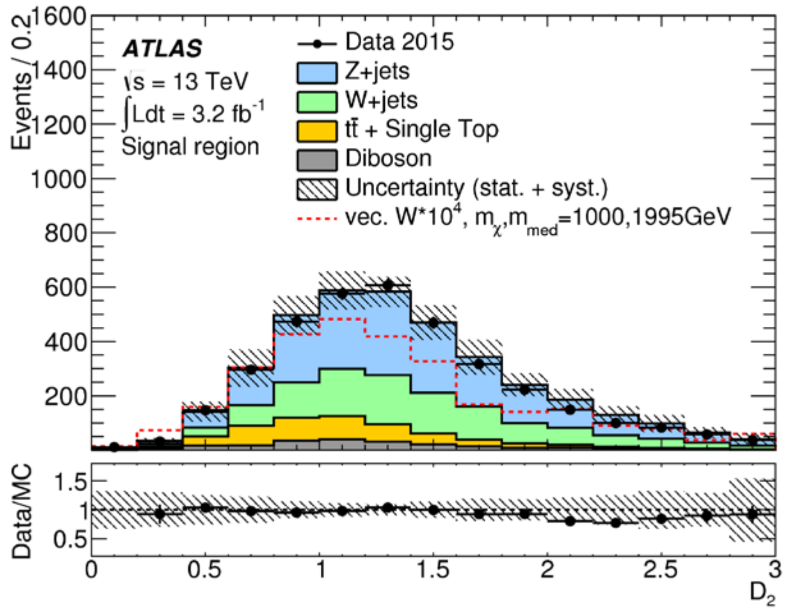
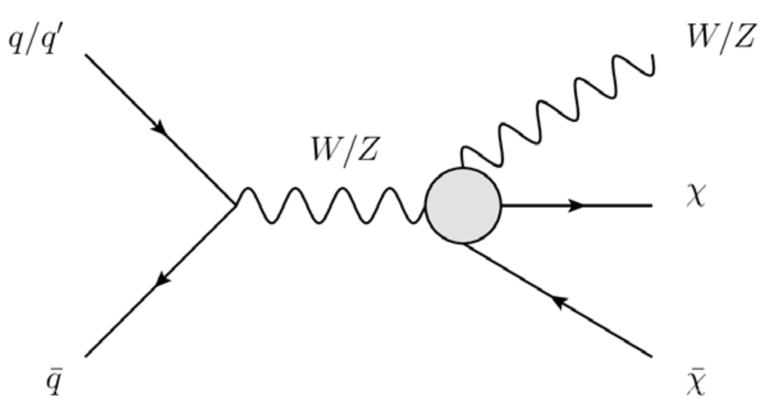
- Jet mass and substructure (i.e., 2 distinct energy deposits) used to tag vector bosons
- Systematic uncertainty on jet tagging efficiency translates into 5-15% uncertainty on signal yield

Mono-W/Z (hadronic)

- Dominant background: $Z(\rightarrow \nu\bar{\nu})$+jets



- EFT $VV\chi\bar{\chi}$ contact interaction



- Background normalizations extracted from profile-likelihood fit to E_T^{miss} distribution

Process	Normalization Factor
Z+jets	1.01 ± 0.16
W+jets	0.90 ± 0.16
$t\bar{t}$	0.91 ± 0.18

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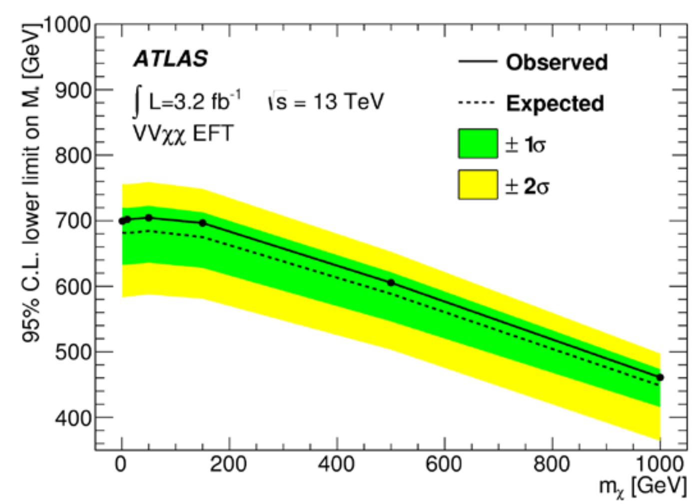
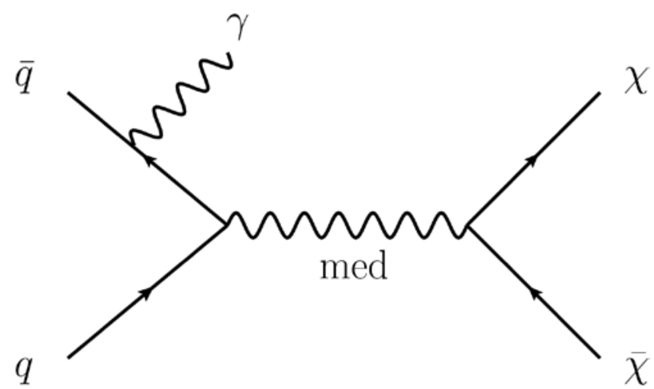


Mono-Photon

- 36.1 fb^{-1} of 13 TeV data collected in 2015/2016
- Simplified model: vector or axial-vector mediator with ISR



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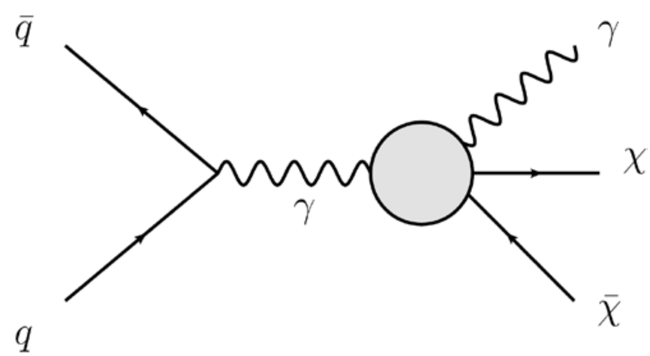
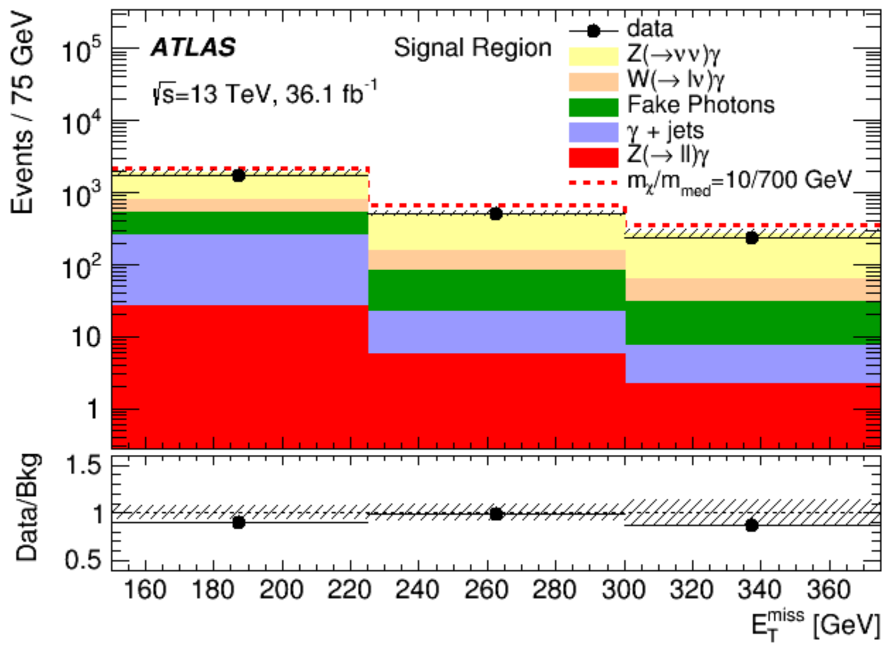
- 7d EFT with $\gamma\gamma\chi\bar{\chi}$ contact interaction
  - effective mass scale M_*



Mono-Photon

- Single photon trigger with $E_{\mathrm{T}}>140$ GeV is 98.5% efficient
- High η granularity in electromagnetic calorimeter (EMcal) $\Rightarrow$ discrimination between single-photon showers and two overlapping photons from π^0 decay
- EMcal energy deposit (without)with matching track in the Inner Detector classifies (un)converted photon candidate
- Energy recorded in the hadronic calorimeter used as a veto
- Dominant background: $Z(\rightarrow \nu\bar{\nu})\gamma$
- Statistical uncertainties dominate
- Jet energy scale and jet fake rate systematics also contribute
- No excess observed over SM



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Mono-Photon

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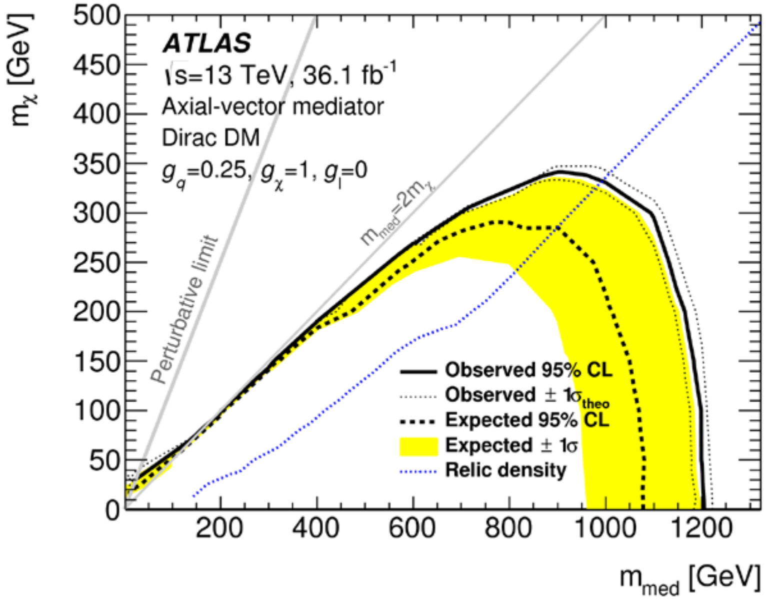
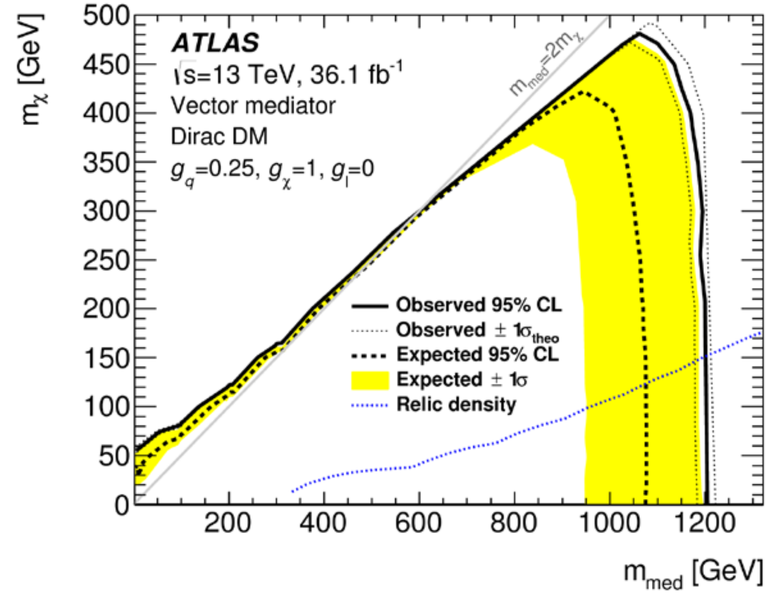
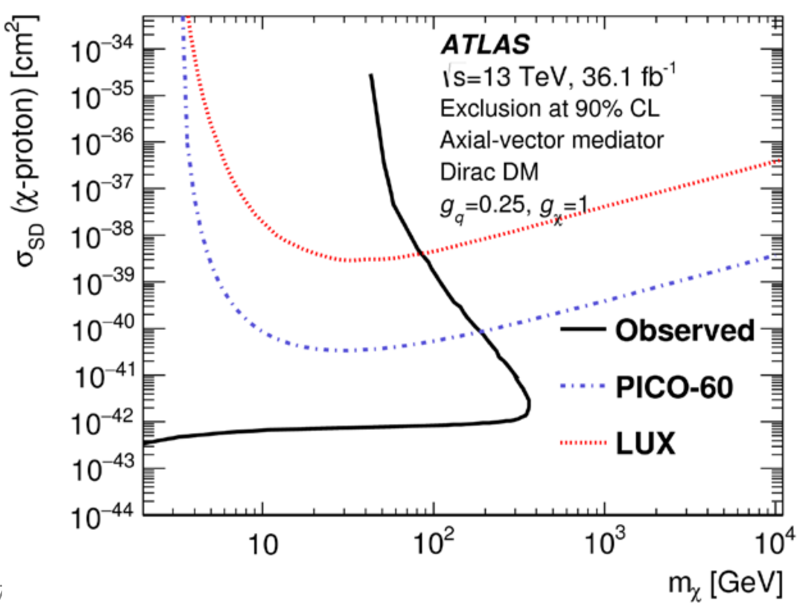
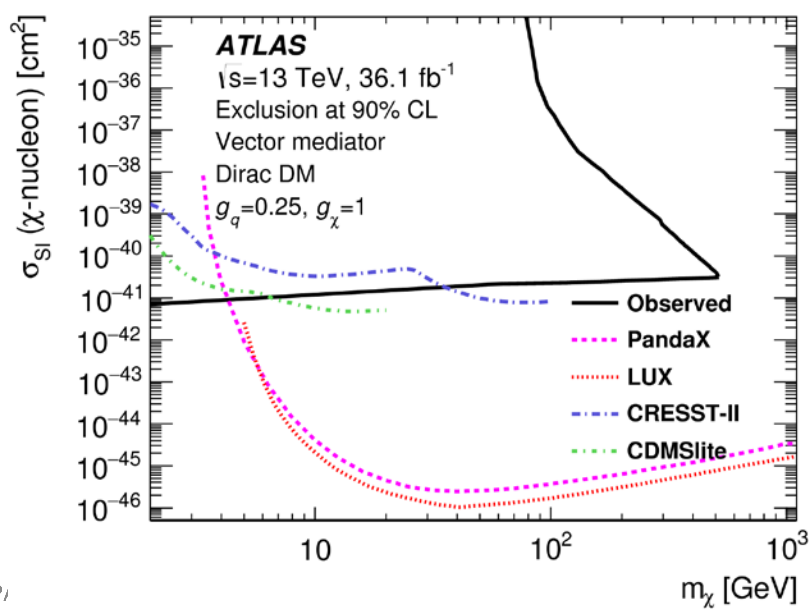
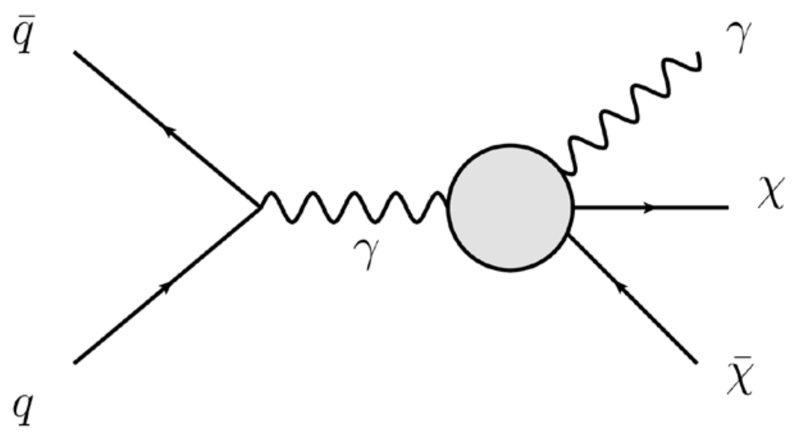


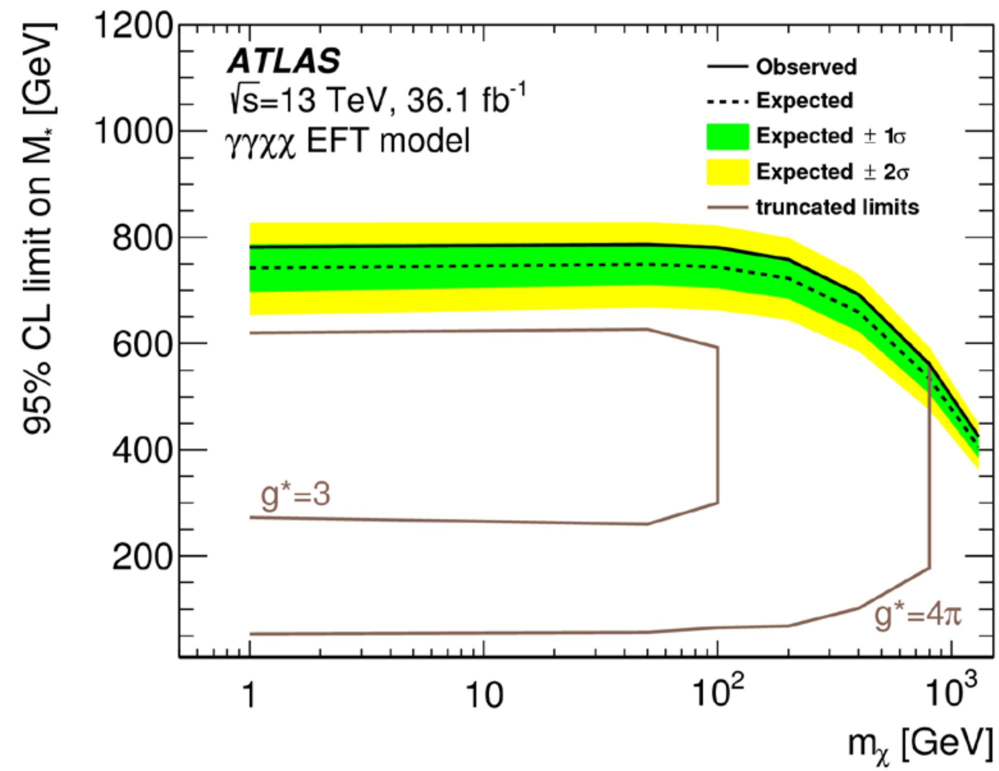






Mono-Photon $\gamma\gamma\chi\bar{\chi}$ Contact Interaction



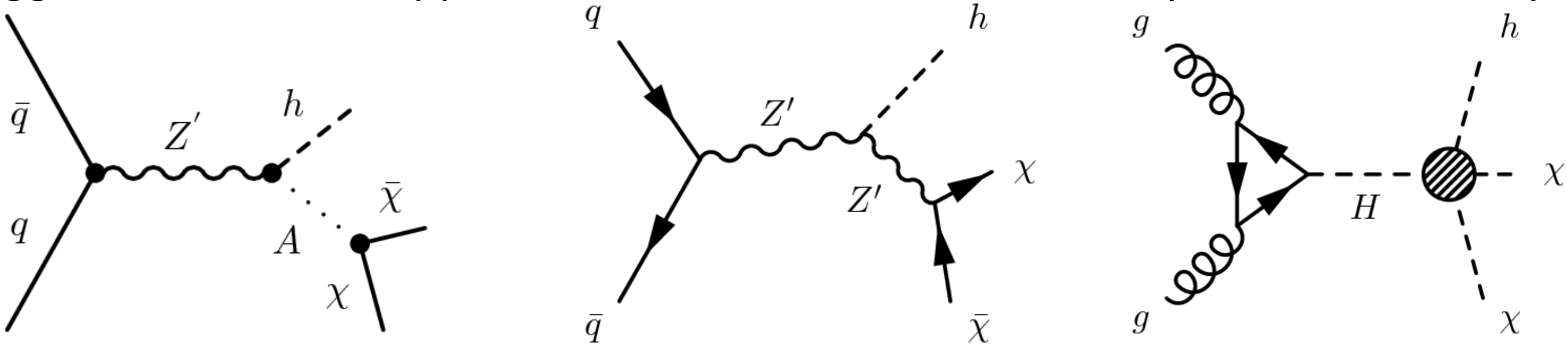


[Eur.Phys.J. C77 (2017) 393]

- Signal events mainly contribute to E_T^{miss}>300 GeV bin
- Set lower limits on effective mass scale M_* vs m_χ
- After removing events that exceed centre-of-mass energy limit for given EFT coupling strength, get truncated limits

Mono-Higgs

- Higgs ISR is Yukawa-suppressed but Higgs can be radiated by mediator directly

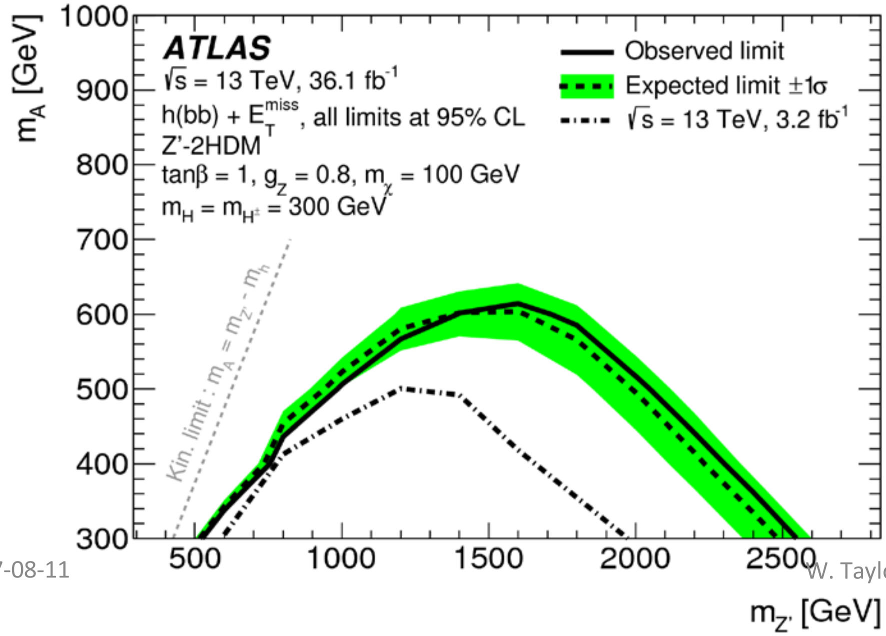


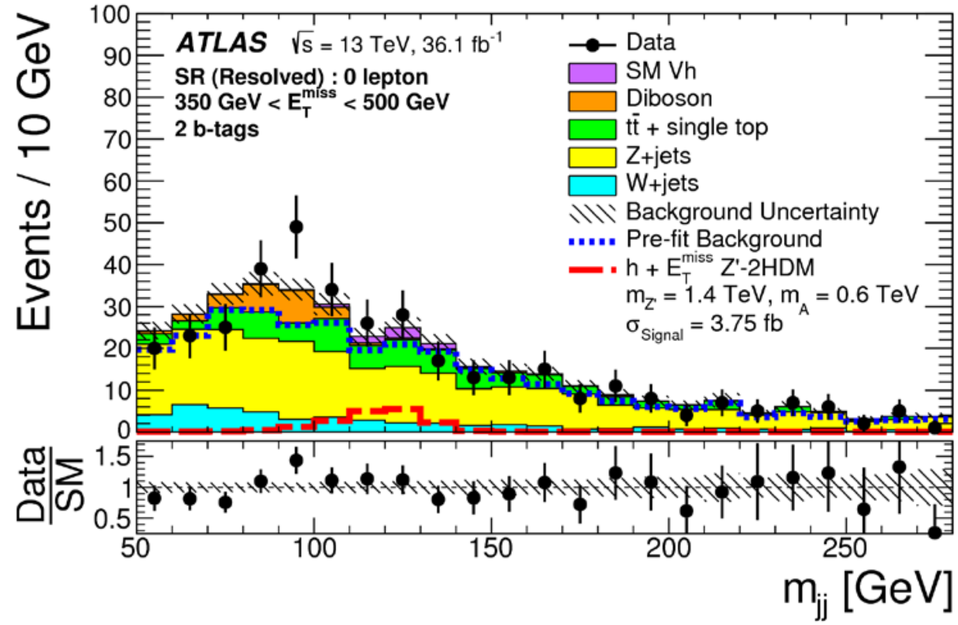
- Example: Type-II two-Higgs doublet model (2HDM) [left]
  - h couples to Z' mediator and pseudoscalar A
  - Large $A \rightarrow \chi\bar{\chi}$ branching ratio
- Also considered: Z'_B [middle] and heavy scalar [right] models

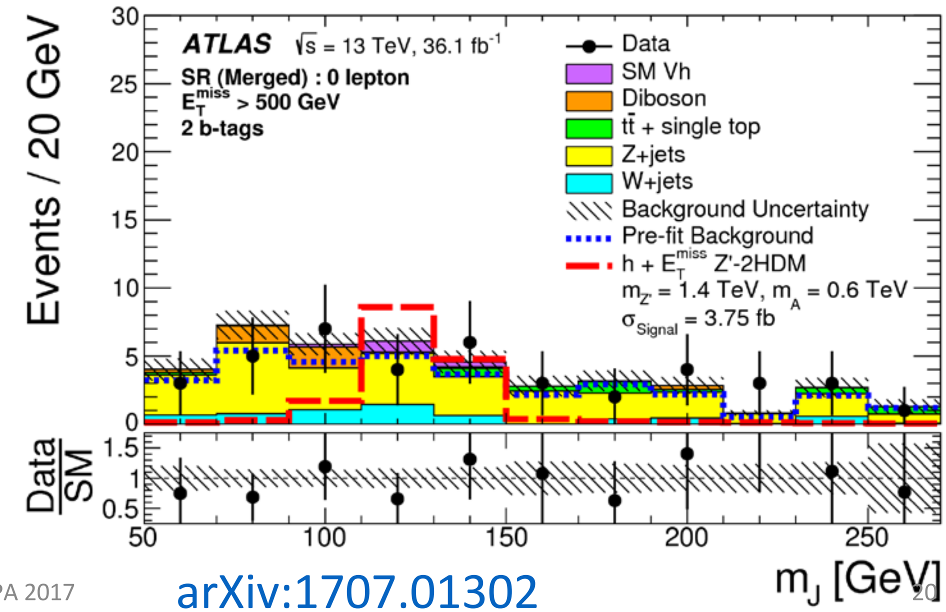
1. $h \rightarrow b\bar{b}$ most sensitive Higgs channel due to large $h \rightarrow b\bar{b}$ branching ratio (57%)
   - Consider two resolved jets or single merged jet
2. $h \rightarrow \gamma\gamma \Rightarrow$ clean event selection with very little background

Mono-Higgs ($h \rightarrow b\bar{b}$)

- 36.1 fb^{-1} of 13 TeV 2015/2016 data
- Trigger on E_T^{miss} in calorimeter
- Offline, reconstruct $b, \bar{b}$ jets via anti-k_t algorithm
- Compute $h \rightarrow b\bar{b}$ invariant mass in four E_T^{miss} bins
  - Jets merged for $E_T^{miss} > 500$ GeV bin
- No significant deviation from SM





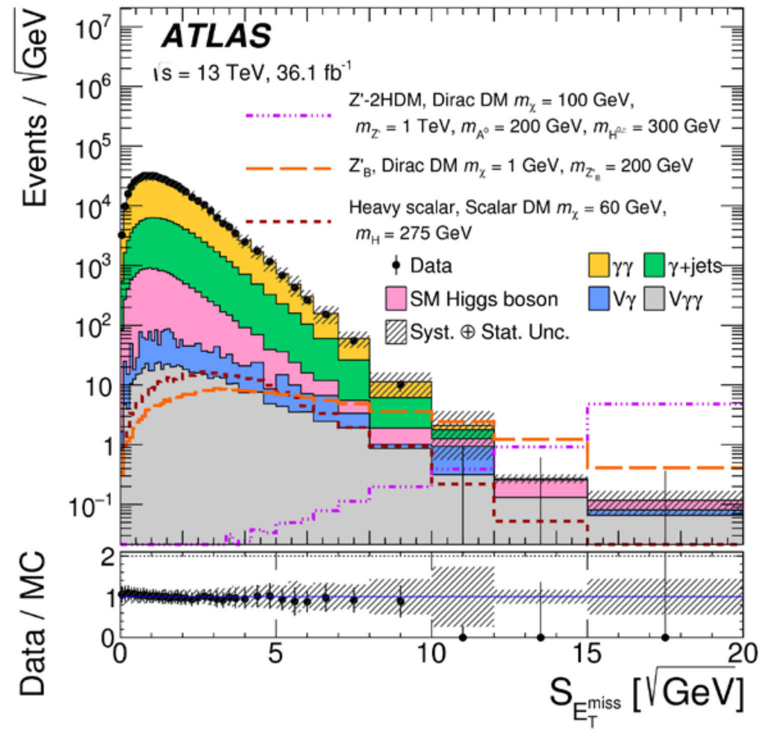


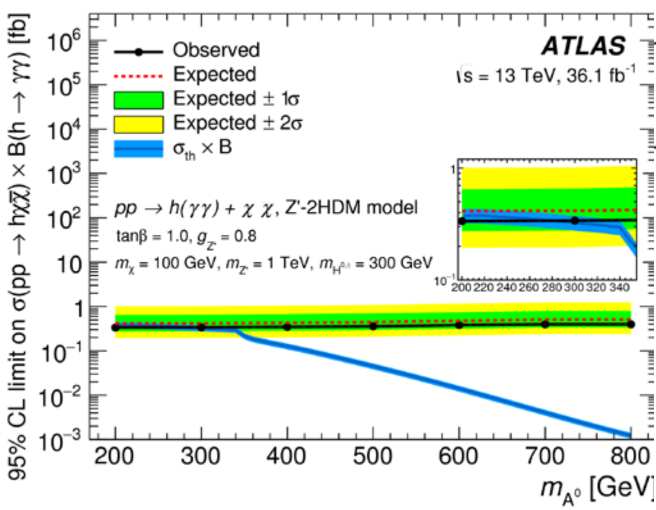
arXiv:1707.01302

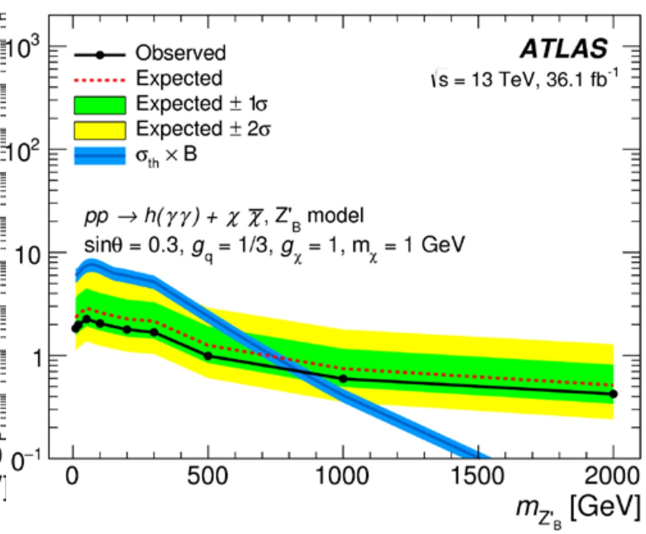
Mono-Higgs ($h \to \gamma\gamma$)

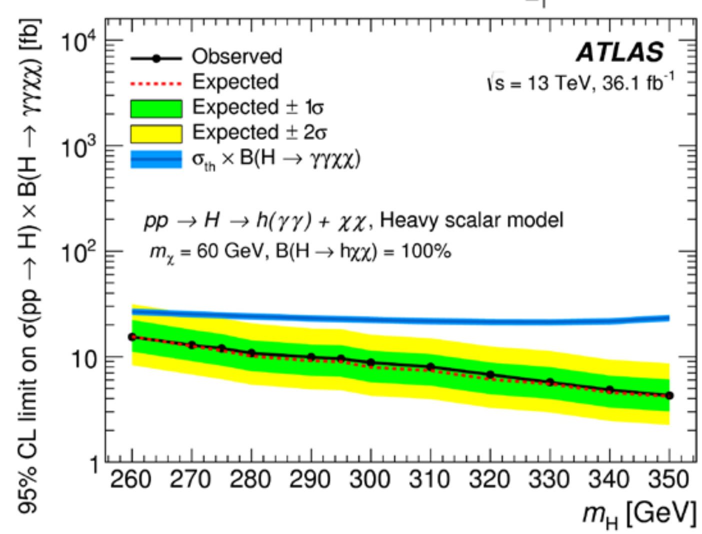
- 36.1 fb^{-1} of 13 TeV 2015/2016 data
- Diphoton trigger
- Offline, categorize photons into (un)converted
- Photon energy calibrated by multivariate algorithm trained on MC samples
- No deviation from SM

arXiv:1706.03948



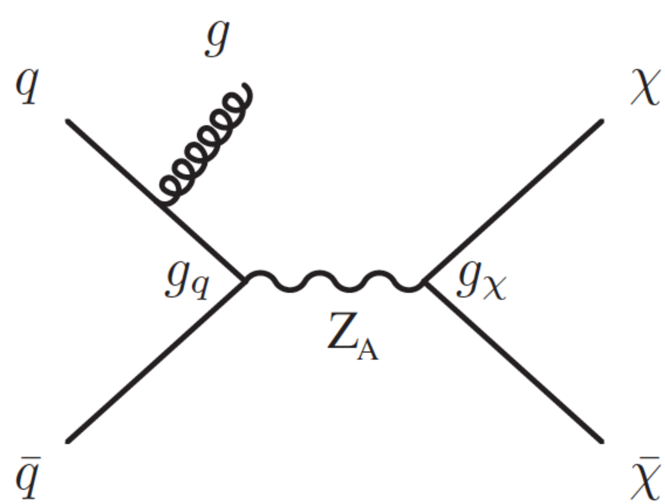






Mono-jet

- 36.1 fb^{-1} of 13 TeV data collected in 2015/2016



- Trigger on events with E_T^{miss}>90 GeV
- Offline, select events with at least one jet with p_T>250 GeV, E_T^{miss}>250 GeV and no leptons

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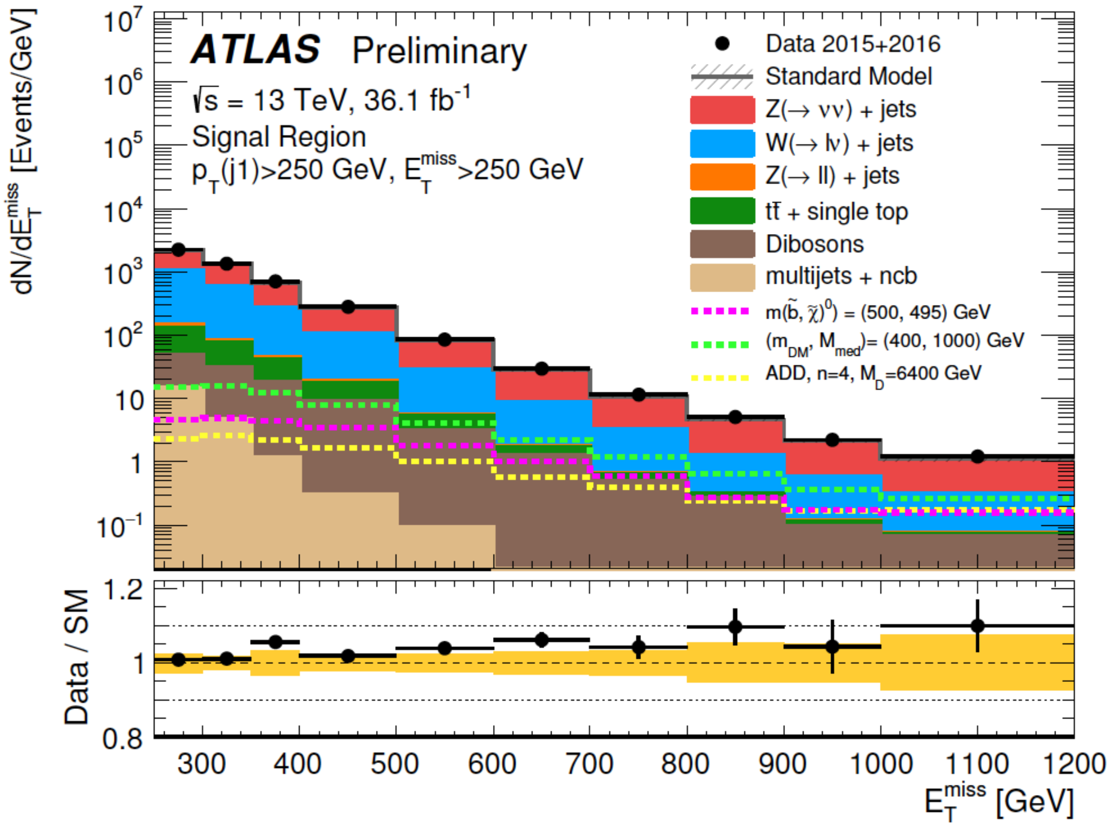
Mono-jet

Precise background modelling needed to reduce systematic uncertainties

- $Z(\rightarrow \nu\bar{\nu})$+jets background dominant and irreducible
- normalize MC samples with data in control regions
- Reweight W+jets and Z+jets MC with NLO EW corrections (arXiv:1705.04664) to determine
  - correlations in scale dependence
  - theory uncertainties

Background-only hypothesis compatible with SM within $1.7 - 2.1\sigma$



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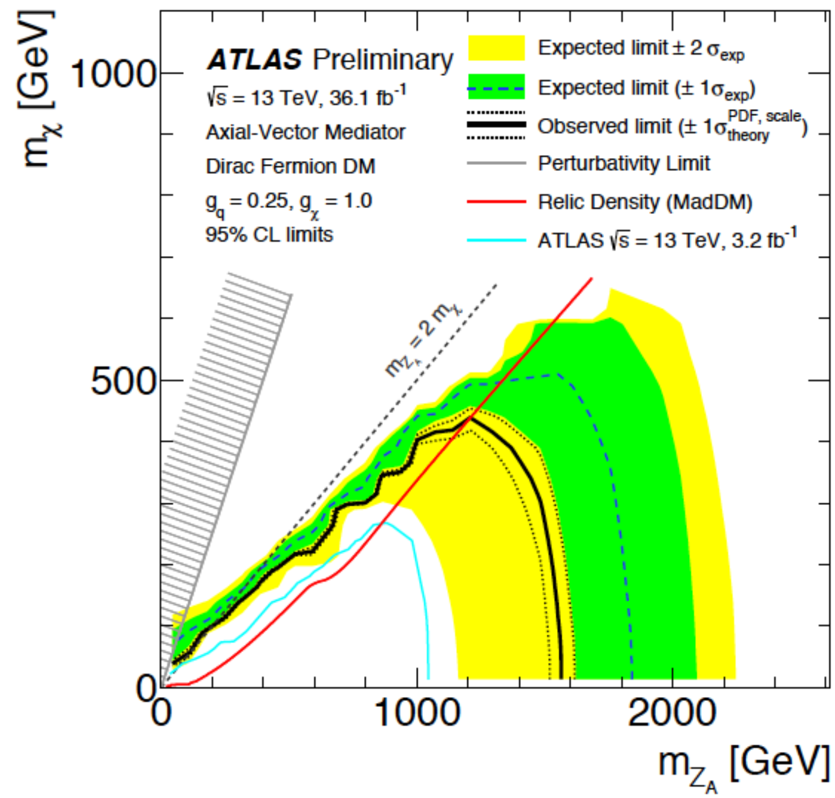
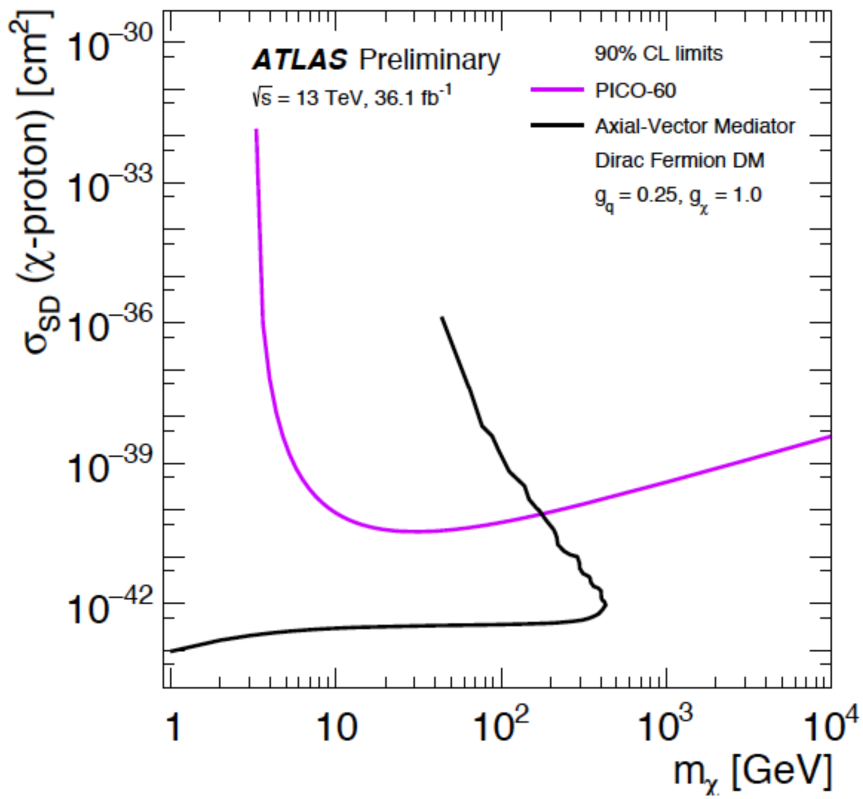
Mono-jet

WIMP signal exclusion limits obtained from simultaneous fit to signal and control regions in bins of E_T^{miss} with independent background normalizations





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Summary

- Several Run 2 ATLAS dark matter searches completed with full 36.1 fb^{-1} 13-TeV 2015/2016 pp collisions
- LHC DM searches are complementary to direct and indirect detection experiments
- Mono-X states yield readily identifiable signature with low SM background
  - Most ATLAS Run 2 dark matter analyses focus on simplified models as per ATLAS/CMS Dark Matter Forum (arXiv:1507.00966)
  - Effective Field Theory can probe contact interactions when applicable
  - No hint yet of excess over Standard Model expectations

Prospects for Future LHC Runs

- Collider DM search program is just beginning
- LHC will deliver 10x luminosity by 2035
  - record of stable luminosity delivered in seven days was set between Aug 1st and 7th with 3.8 fb^{-1}
  - 14.5 fb^{-1} delivered in 2017 so far
  - Additional interactions (pileup): $\langle N_V \rangle = 33$
- Collider searches can be extended to DM models alternative to WIMP, e.g., dark sector with multiple dark matter species