Dark Matter searches in ATLAS: Run 1 results and Run 2 prospects

Lashkar Kashif

University of Wisconsin

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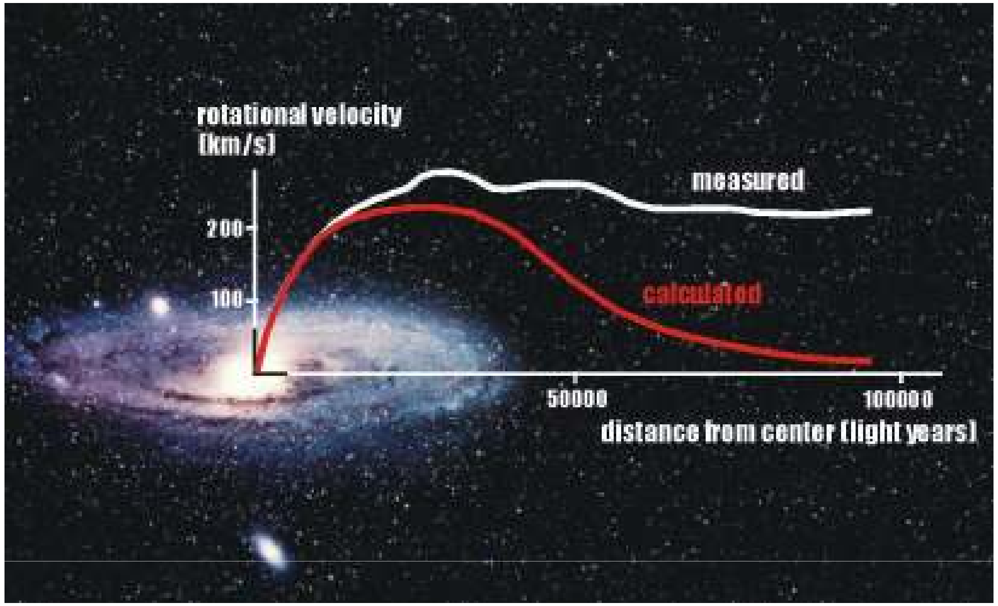
Outline

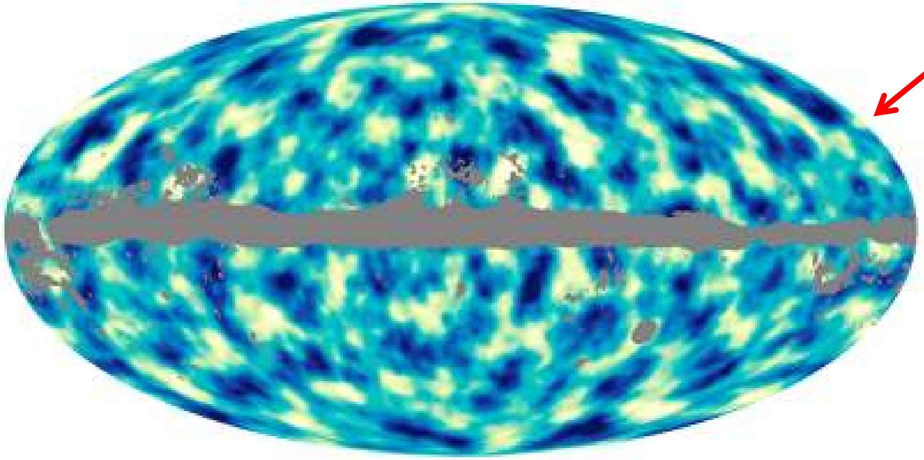
- Motivation and theories of dark matter production
- Collider searches for dark matter
- Dark matter searches in mono-object channels:
  - Jet + E_T^{miss}
  - Photon + E_T^{miss}
  - $H \rightarrow \gamma\gamma$ + E_T^{miss}
  - Heavy flavor + E_T^{miss}
  - *W/Z* + E_T^{miss}
- Dark matter searches in invisible Higgs decays
  - VH, VBF
  - Combination
- Run 2 prospects
- Conclusion & outlook

Dark Matter exists…



Galactic rotation curves

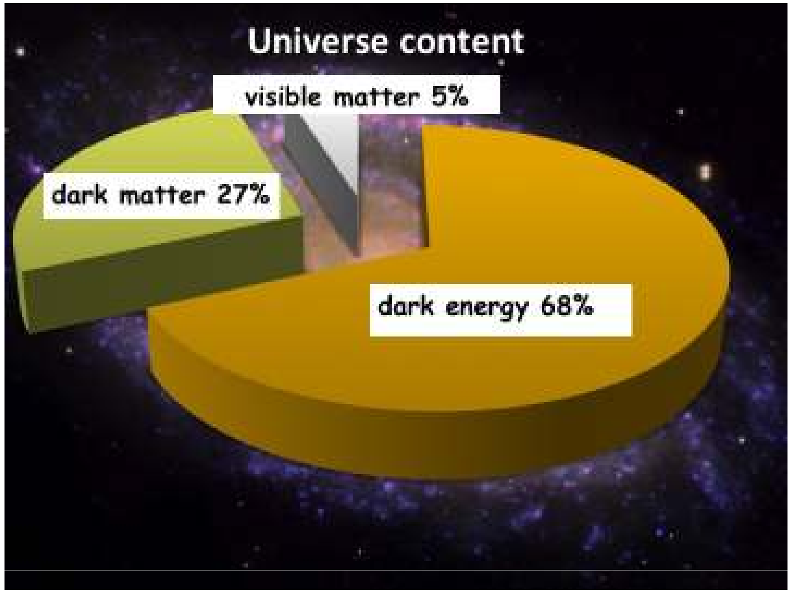
Gravitational lensing



CMB anisotropy

…and there's a lot of it

- But what is it?
- Nothing in the Standard Model of particle physics
- Weakly Interacting Massive Particles (WIMPs) good candidates
  - mass *O*(GeV) to *O*(TeV)
  - falls in well with Standard Model of cosmology (ΛCDM)



…and there's a lot of it

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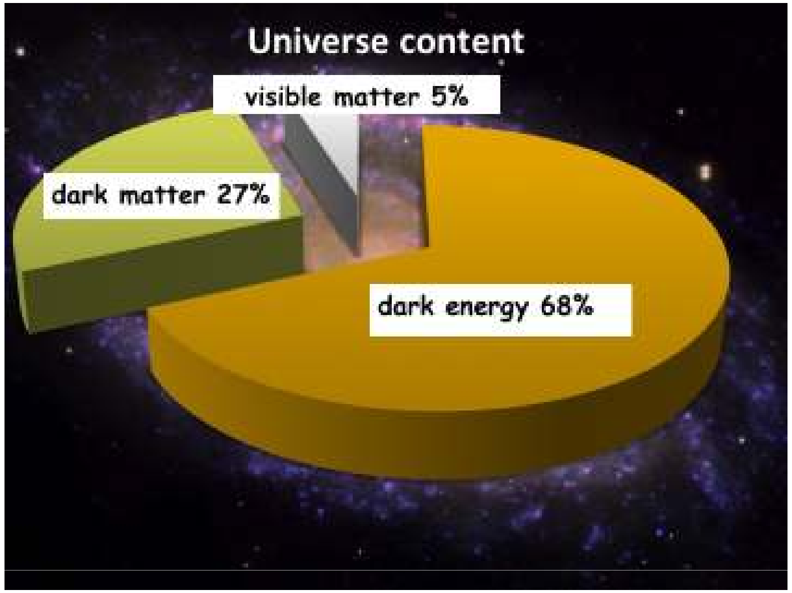
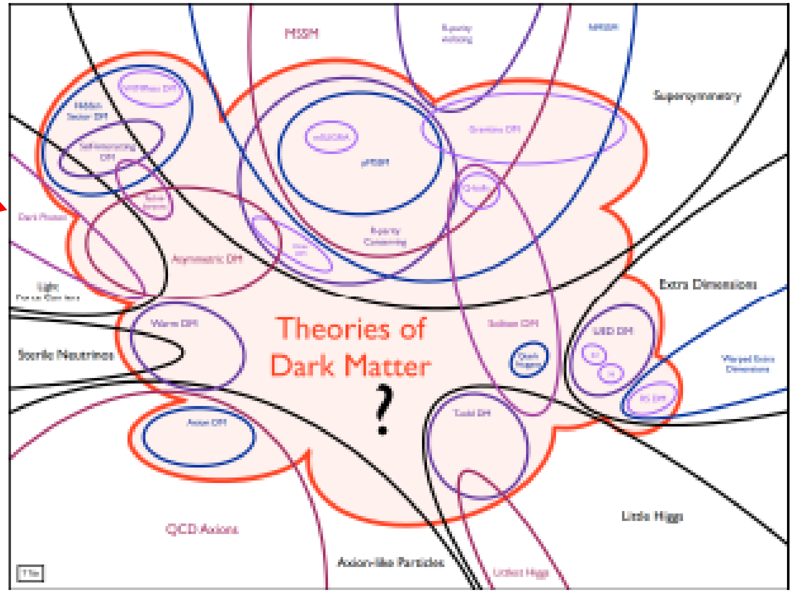
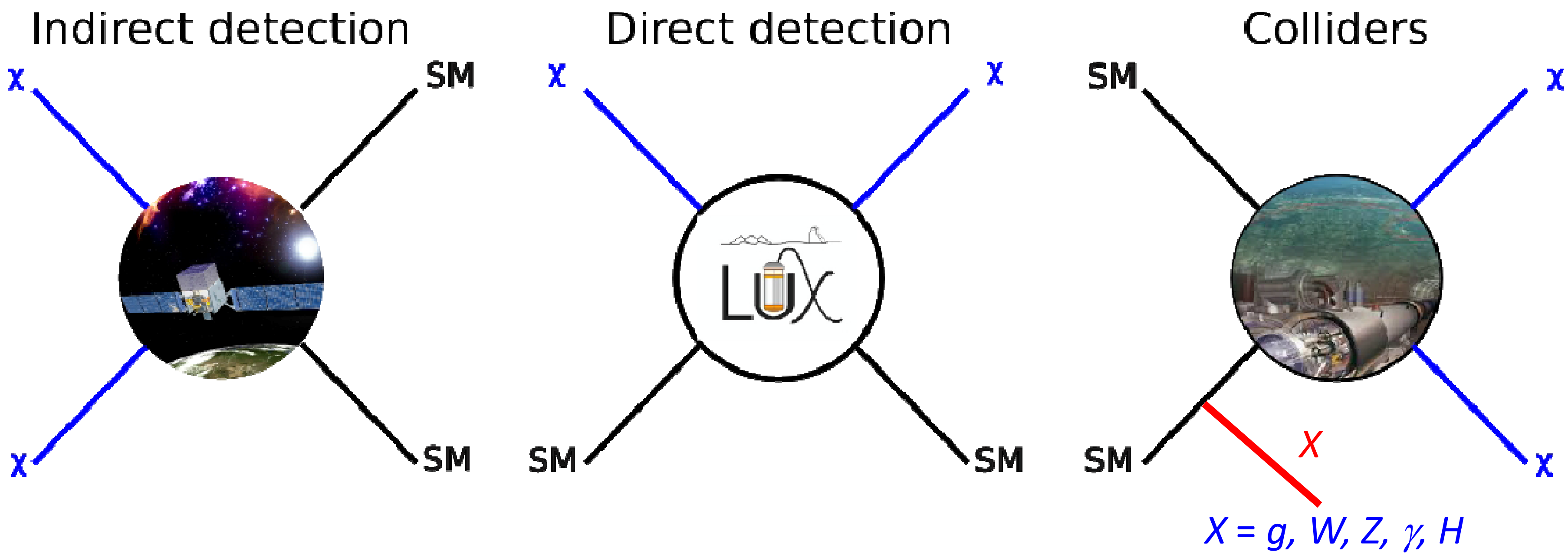
- Nothing in the Standard Model of particle physics
- Weakly Interacting Massive Particles (WIMPs) good candidates
  - mass *O*(GeV) to *O*(TeV)
  - falls in well with Standard Model of cosmology (ΛCDM)
- *Many* promising theoretical scenarios
- No one type of detection strategy can be robust over entire mass range of WIMPs
  - but we have complementary methods!





Indirect, direct & collider searches for dark matter

C. Doglioni at Moriond2015

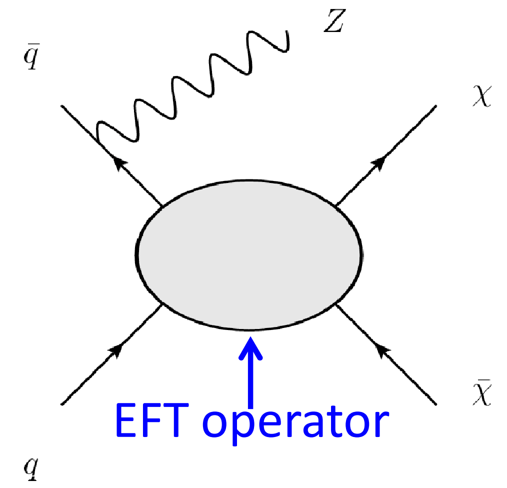


- Collider search: DM escapes detector, leading to events with large transverse momentum imbalance (E_T^{miss})
- In absence of any other interesting particle, difficult to trigger on event
- But what if there is an energetic jet, or γ, or *W/Z* boson, or even a Higgs in the event?

→ these constitute mono-*X* + E_T^{miss} channels for DM search

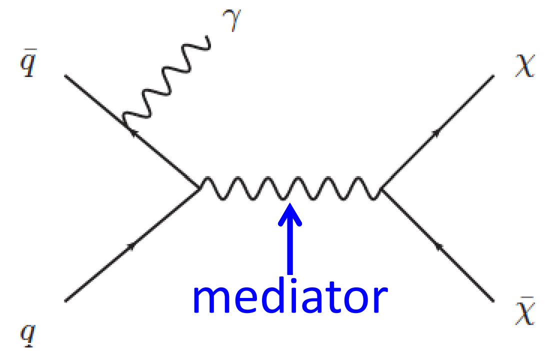
Models of dark matter production @ colliders

- ➢ Effective Field Theories (EFTs) traditionally used to interpret DM searches
  - searches can then be largely model-independent
  - easy to compare results with those from direct detection experiments



- But EFTs suffer from validity issues at LHC energies
  - mediator can be produced on-shell or close

- ➢ Simplified models using explicit mediators becoming popular
  - searches more model-dependent, but models valid at all energies



- ATLAS searches using Run 1 data interpreted in both types of models

Mono-X dark matter searches in ATLAS

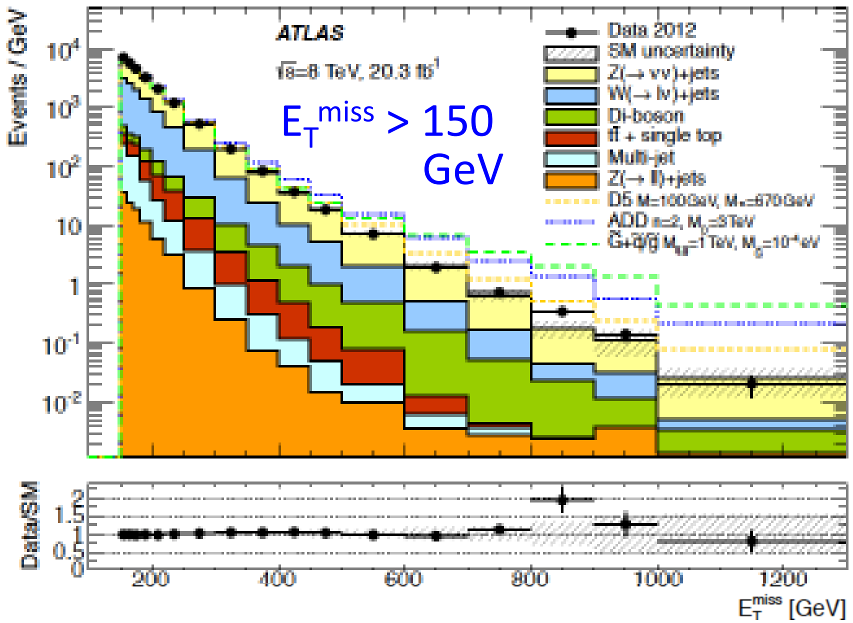
Jet + E_T^{miss}

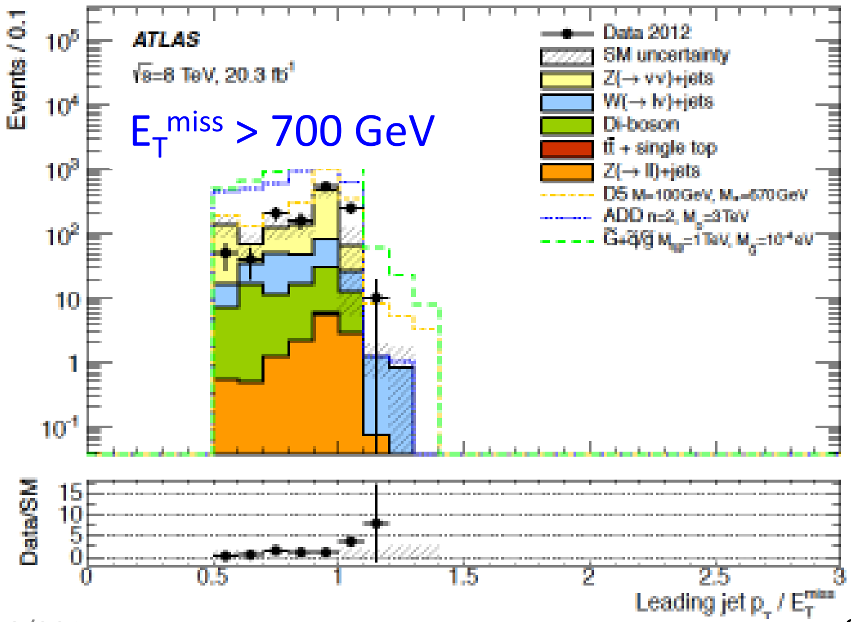
EPJC 75 (2015) 299

- Most sensitive of the mono-*X* channels

➢ Selection:

- Events categorized in 9 E_T^{miss} bins: E_T^{miss} > 150, … , 700 GeV
- Leading jet p_T: $p_T(j^{lead})$ > 120 GeV
- Jet recoils against DM pair
  → ratio $p_T(j^{lead})/E_T^{miss}$ expected to be close to 1
  - require $p_T(j^{lead})$ / E_T^{miss} > 0.5
- Azimuthal separation b/w jet and E_T^{miss}: $\Delta\phi(p_T, E_T^{miss})$ > 1.0
- Veto events with leptons and isolated tracks

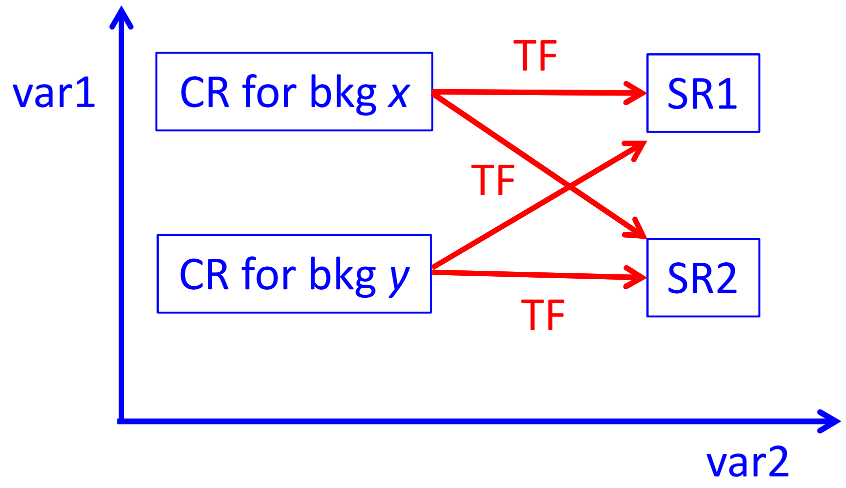




Jet + E_T^{miss}: backgrounds

EPJC 75 (2015) 299

- Main backgrounds are EW processes with intrinsic E_T^{miss}, accompanied by jets
- $Z(\nu\nu)$ + jet/s: irreducible bkg
- $W(l\nu)$ + jet/s with unreconstructed or unidentified lepton



- Both estimated from data using leptonic *Z* or *W* control regions (CRs)
- In this case, CRs are $Z(ll)$ + jets and $W(l\nu)$ + jets events with identified leptons
- Event count from CR extrapolated to signal regions (SRs) using transfer factors
- Major advantage: many theoretical and most experimental uncertainties cancel out in transfer factor

Jet + E_T^{miss}: results

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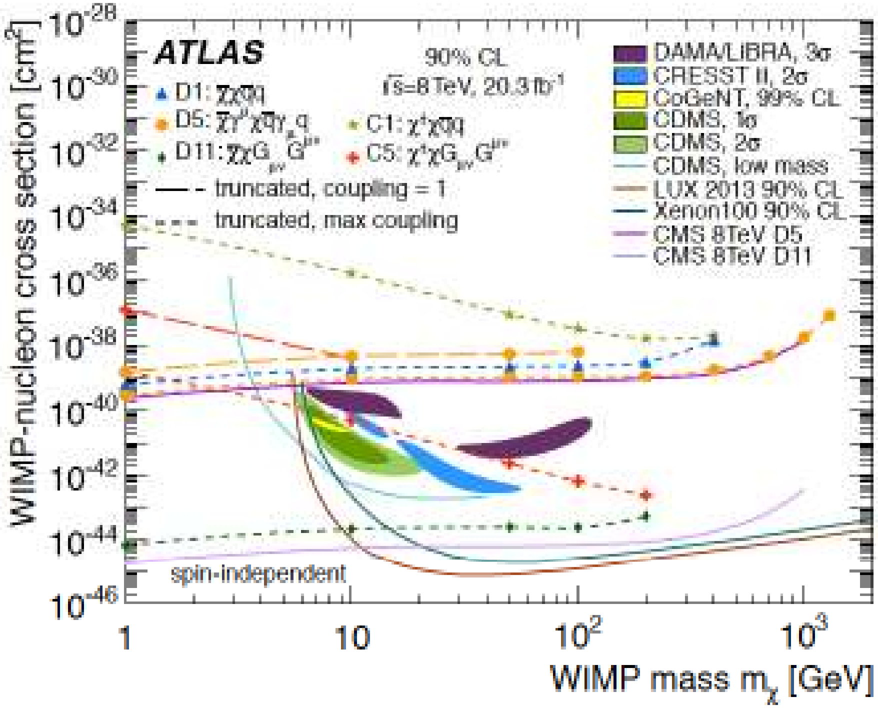
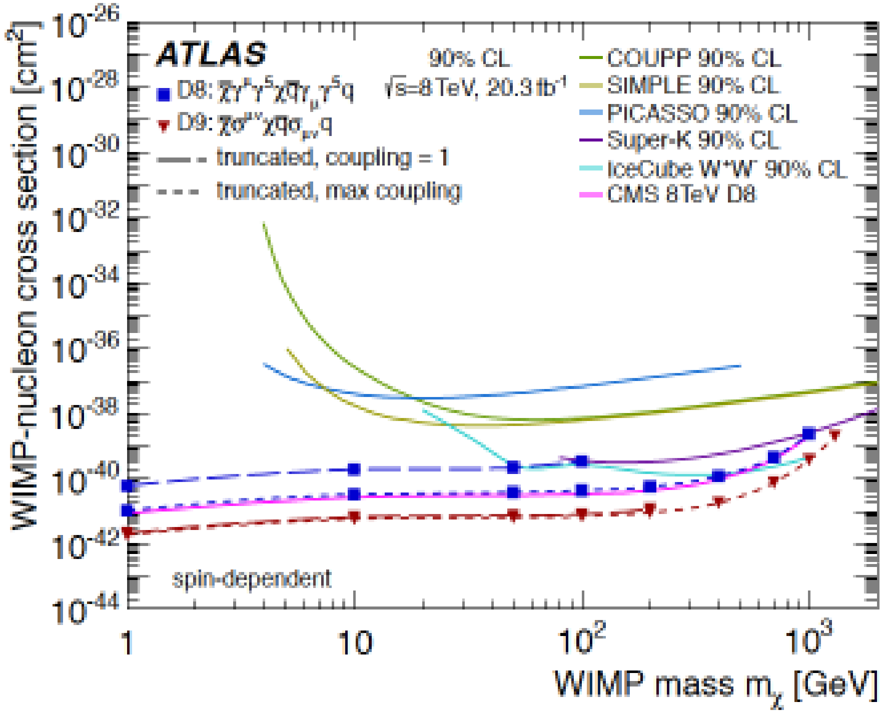




- Limits on number of DM events can be translated to limits on cross section of DM-nucleon scattering

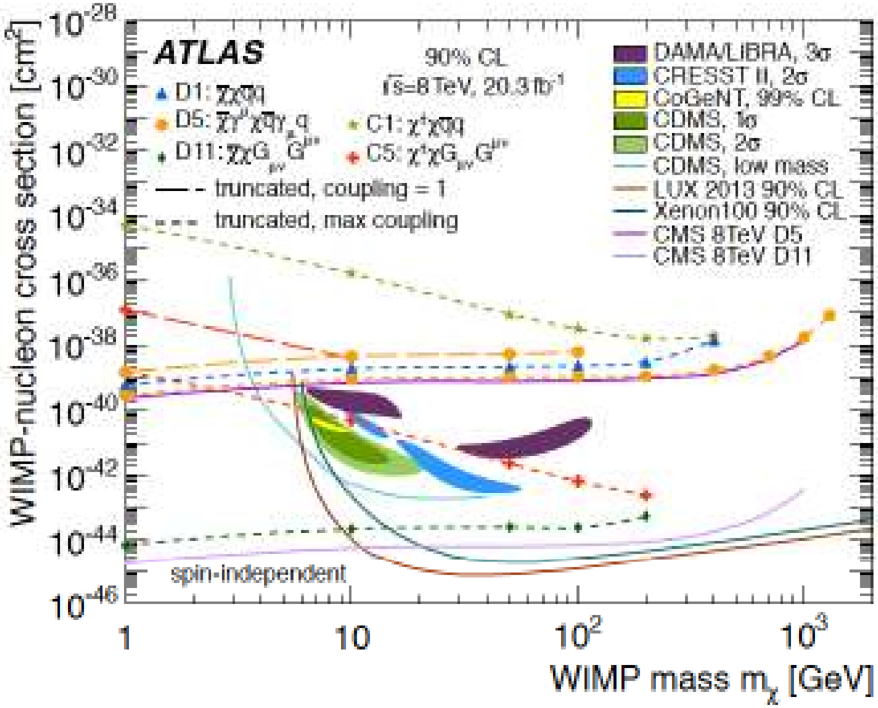
  - convenient for comparing with results of direct detection searches

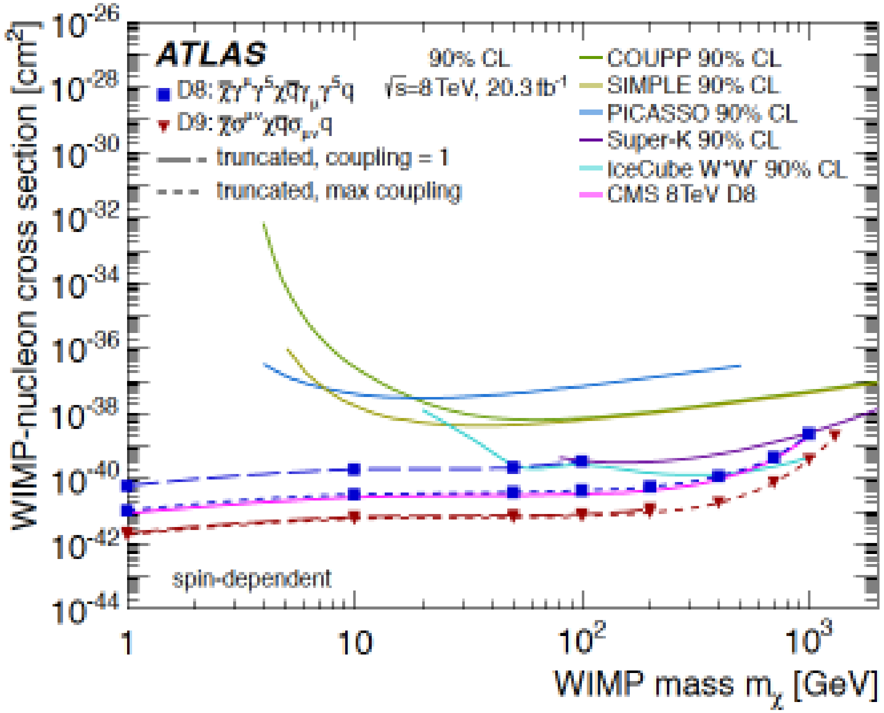
- ATLAS limits shown by dashed lines

- CMS, direct (DD) and indirect (InD) detection results shown by solid lines and contours

Jet + E_T^{miss}: results

EPJC 75 (2015) 299





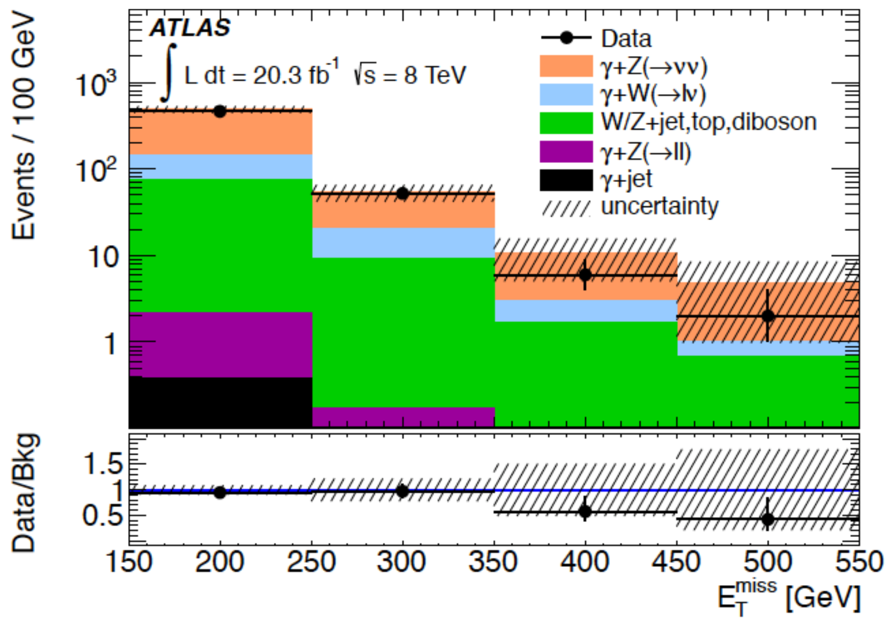
- ATLAS limits shown for several EFT operators
- Spin-independent case (left): collider limits better than DD limits at low DM masses, where the latter have little sensitivity

  - great complementarity!
- Spin-dependent case (right): collider limits significantly better than DD, InD limits over ~full mass range

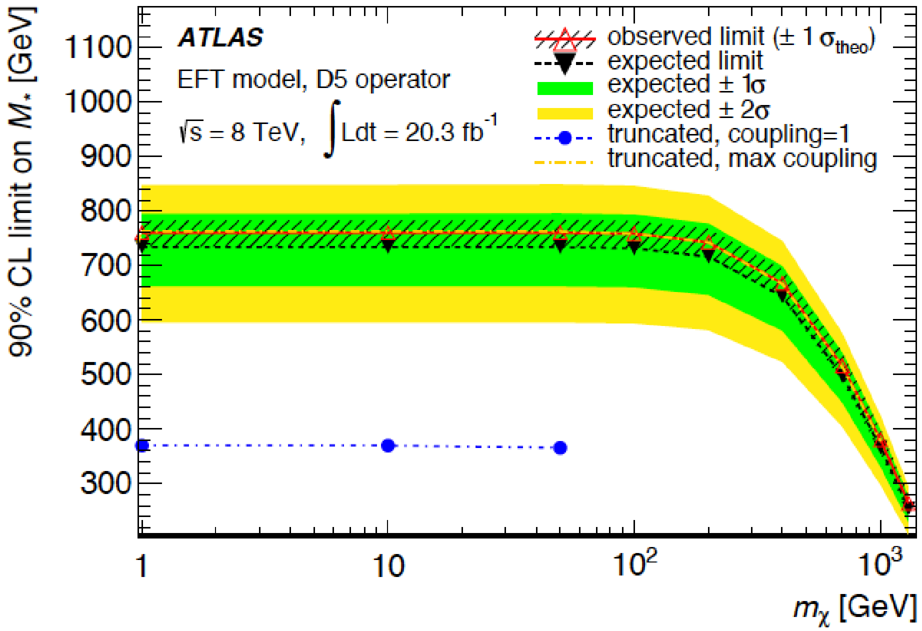
Photon + E_T^{miss}

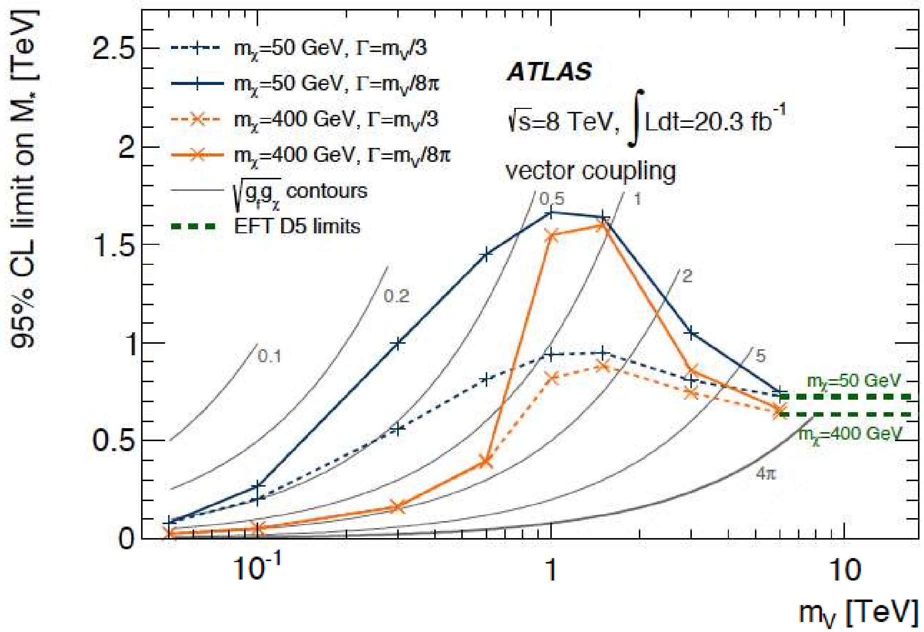
PRD 91, 012008 (2015)

- Sensitive channel because of well-measured γ and mostly EW bkgs
- Selection:
  - At least 1 isolated γ: $p_T(\gamma) > 125$ GeV
  - $\Delta\phi(p_T(\gamma^{lead}), E_T^{miss}) > 0.4$
  - 1 jet allowed: if $N_{jet} > 1$ or $\Delta\phi(p_T(\text{jet}), E_T^{miss}) > 0.4$, event vetoed
  - Also veto events with leptons
  - $E_T^{miss} > 150$ GeV
- Major backgrounds:
  - $Z(\nu\nu) + \gamma$, $W(l\nu) + \gamma$: estimated in data control regions
  - W/Z + jets: estimated using data-driven jet → γ misID factor
- No excess observed in signal region



Photon + E_T^{miss}: results PRD 91, 012008 (2015)





- Limit on suppression scale M_* *vs* DM mass in EFT (D5 operator)
- M_*: mass of mediator / √(product of its couplings to SM and DM)
- 'truncated' refers to truncation of phase space because of EFT validity
- Limit on M_* *vs* mediator mass in a model with vector mediator
- Curves correspond to various DM masses and mediator widths
- For very high mediator mass, limits should approach EFT limits (green dashed lines)

Higgs($\gamma\gamma$) + E_T^{miss}

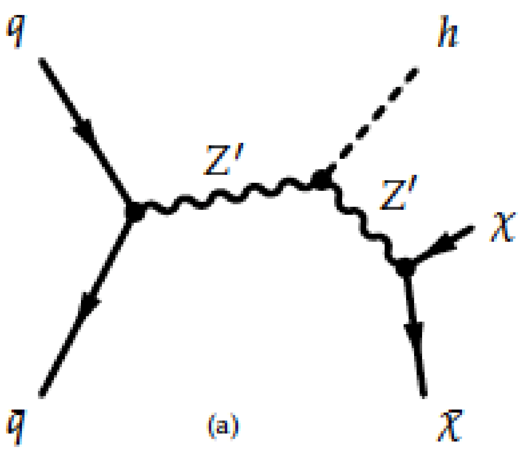
arXiv:1506.01081
Accepted by PRL

- Following Higgs discovery, mono-Higgs production in association with dark matter provides very interesting final states

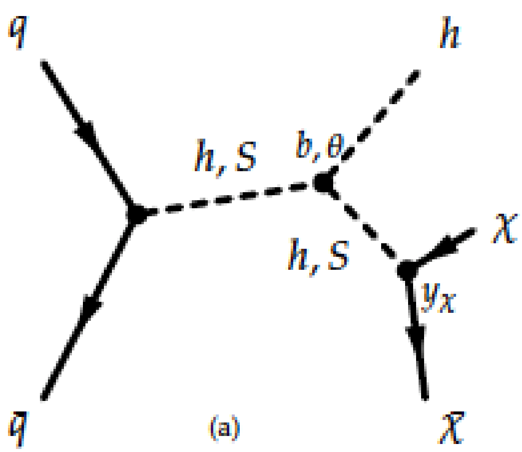
- Higgs not emitted from initial-state quarks, but from physics related to DM production

  → observation of such events can probe new physics directly

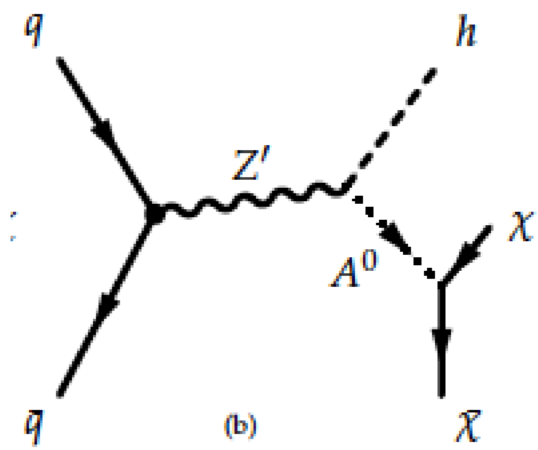
- $H \rightarrow \gamma\gamma$ branching fraction small ($2.3 * 10^{-3}$ @ 125 GeV), but very clean signature owing to good mass resolution



Z'_B mediator



scalar mediator

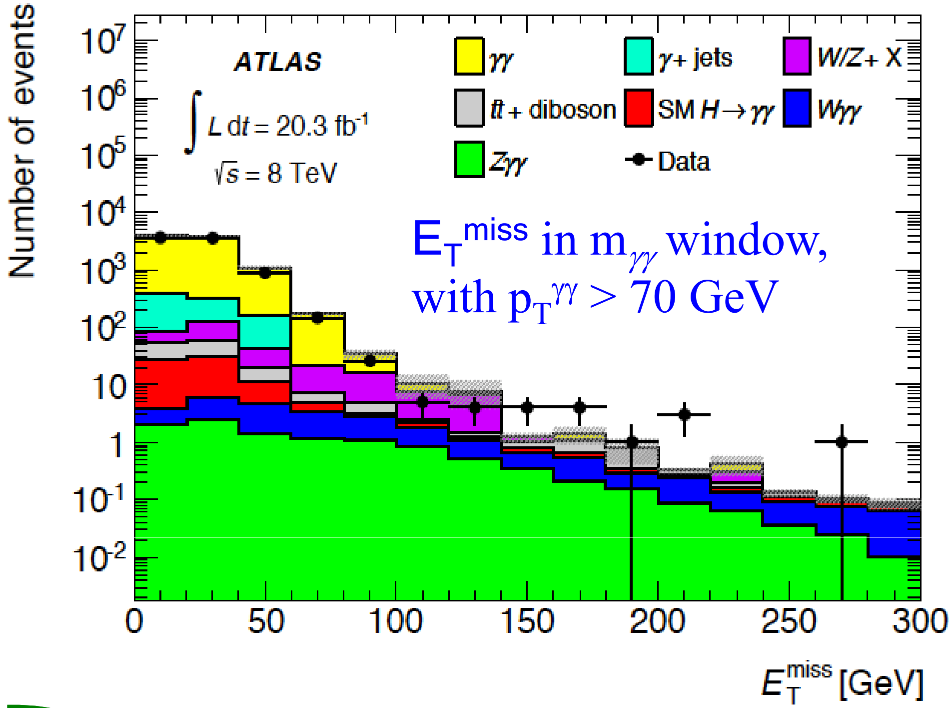


Z' mediator in 2HDM

Higgs($\gamma\gamma$) + E_T^{miss}

arXiv:1506.01081
Accepted by PRL

- Selection
  - 2 isolated, well-identified γ's
  - $p_T(\gamma^{lead})/m_{\gamma\gamma} > 0.35$, $p_T(\gamma^{sublead})/m_{\gamma\gamma} > 0.25$
  - $p_T^{\gamma\gamma} > 90$ GeV
  - $E_T^{miss} > 90$ GeV

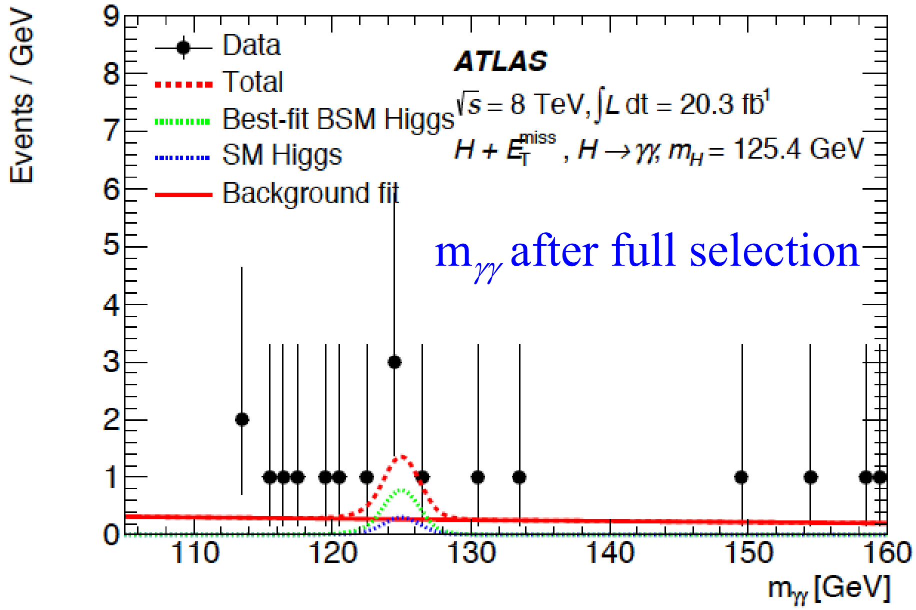


- Major backgrounds:
  - Non-resonant $\gamma\gamma$, $V\gamma\gamma$ production
  - γ+jet with jet misidentified as γ
  - *W(eν)*γ, *Z(ee)*γ, *e* misID'd as γ
  - *Z(νν)H, W(lν)H, ttH*

estimated from sidebands in $m_{\gamma\gamma}$ distribution (first three)

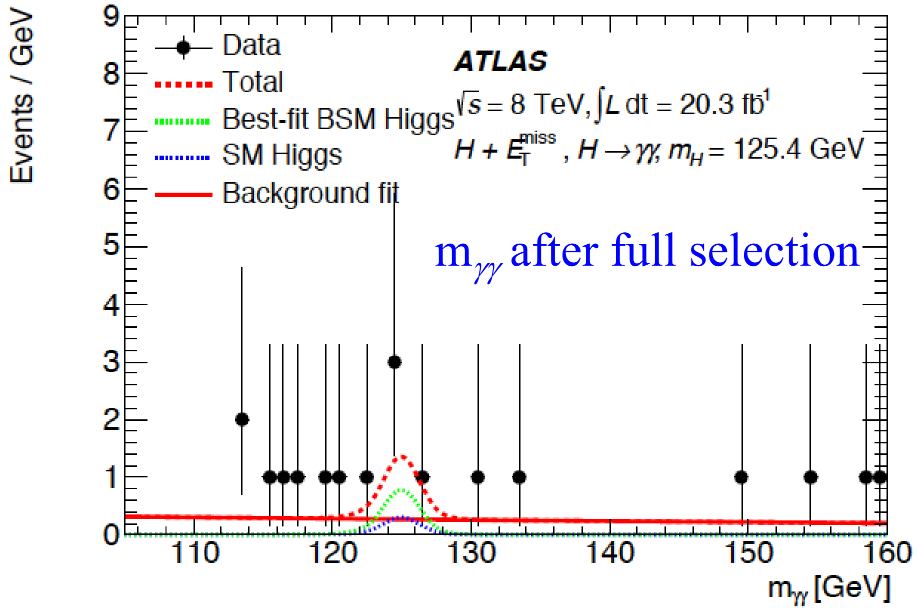
estimated from simulation (last)

Higgs($\gamma\gamma$) + E_T^{miss}: results



- Observed upper limit on fiducial cross section of $H \rightarrow \gamma\gamma + E_T^{miss}$ events: 0.70 fb
- Small excess: 1.4σ deviation from bkg-only hypothesis

Higgs($\gamma\gamma$) + E_T^{miss}: results



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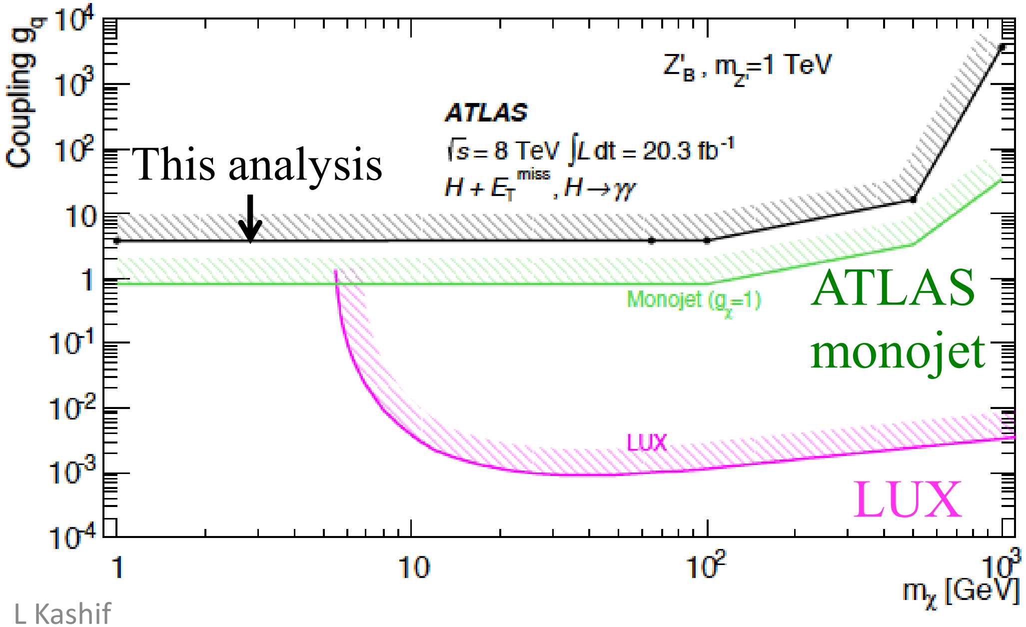
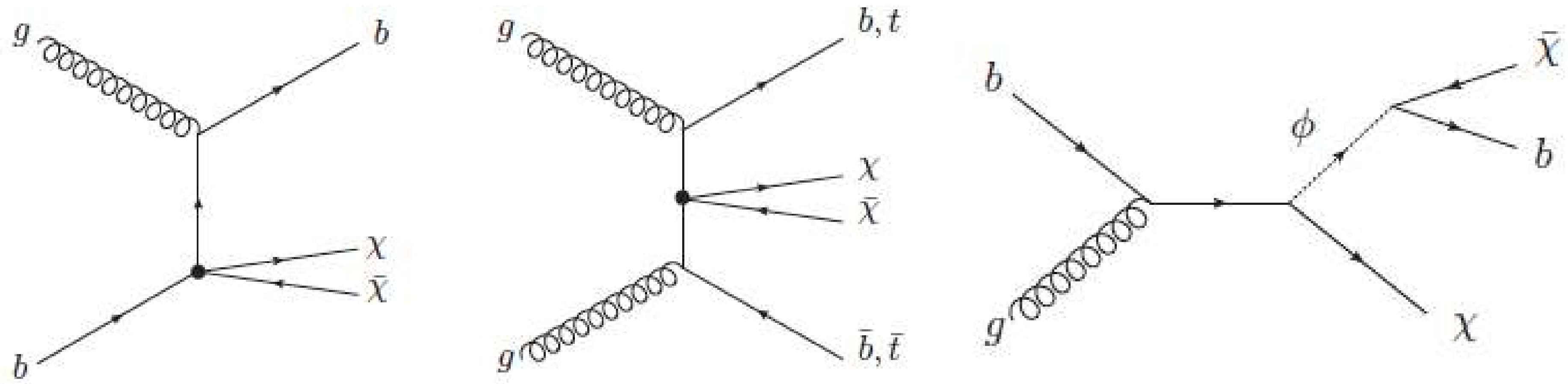


Interpretation in *Z'* mediator model

- Limits on mediator-quark coupling as function of m_{DM}
- Region above curves excluded
- Significant constraint on models for m_{DM} < ~5 GeV

Heavy flavor + E_T^{miss}

EPJC 75 (2015) 92



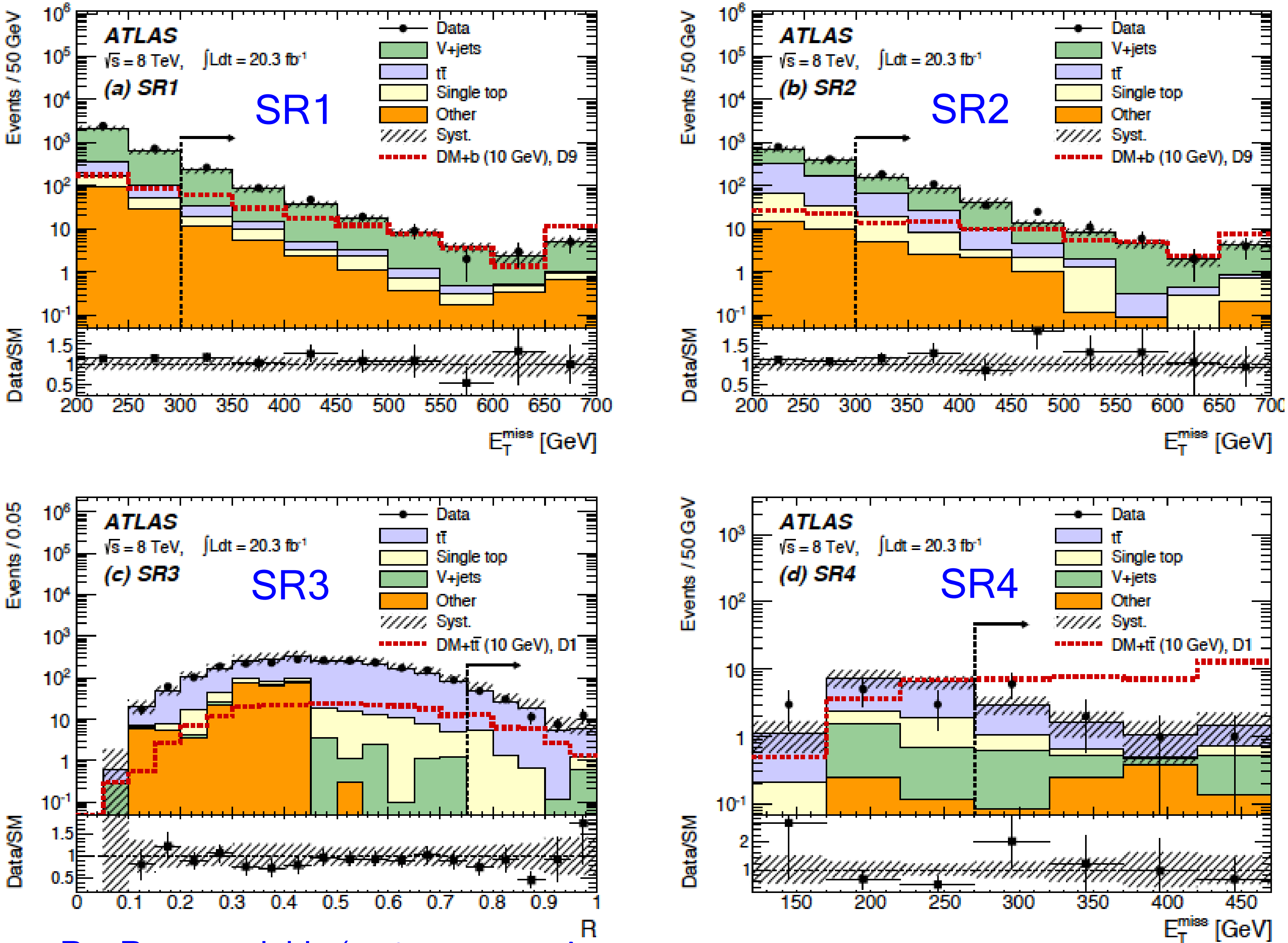
In effective scalar-mediated interactions, DM couplings largest to massive quarks

b-flavored DM (*b*-FDM) model, motivated by Fermi-LAT excess

- DM search in final states with heavy flavor motivated on a variety of grounds
- Analysis uses 4 signal regions defined to target DM production with:
  - 1 or 2 *b* quarks
  - *tt* pair with all-hadronic or semi-leptonic decays
- Selection in each region optimized *wrt* targeted final state and bkgs

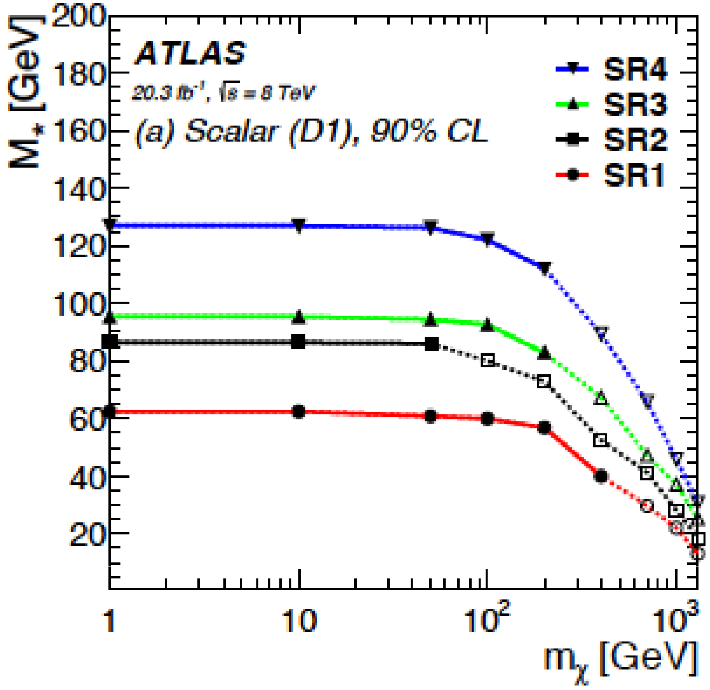
Heavy flavor + E_T^{miss}

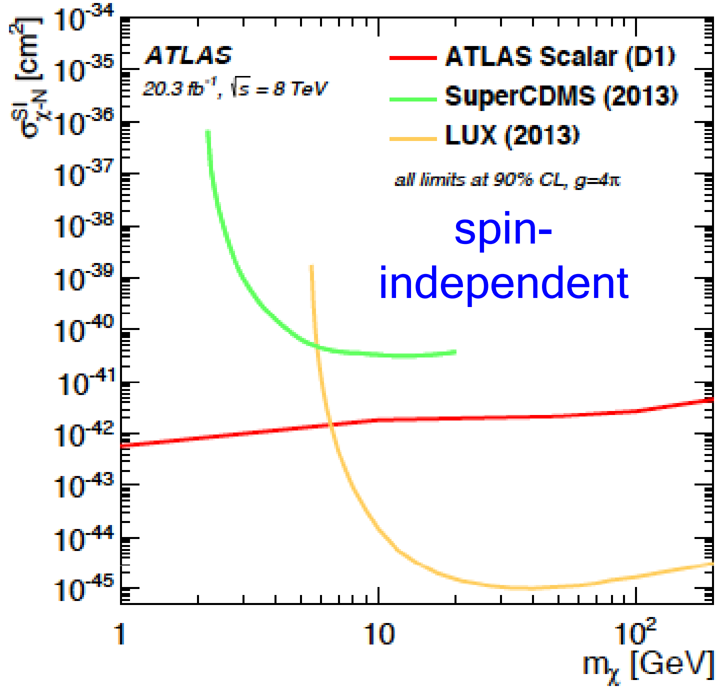
[EPJC 75 (2015) 92]



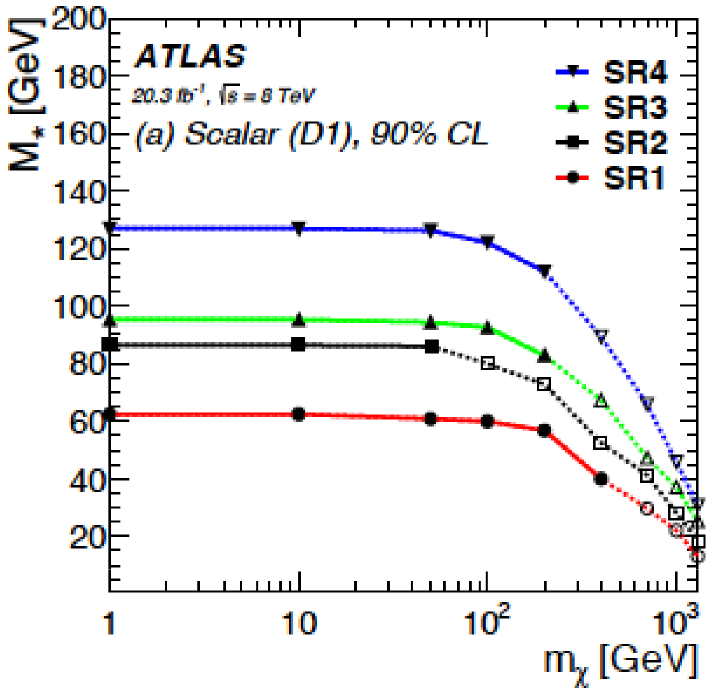
R = Razor variable (**arXiv:1006.2727**)

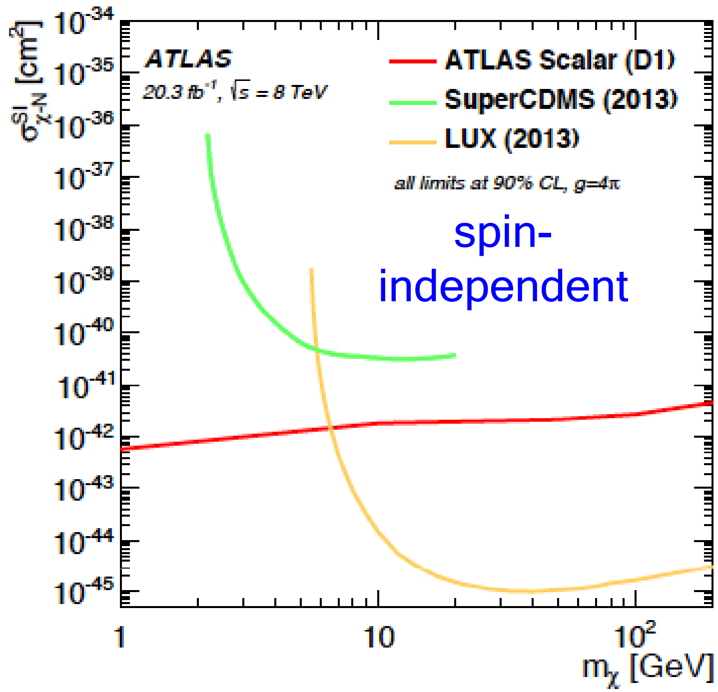
Heavy flavor + E_T^{miss}: results

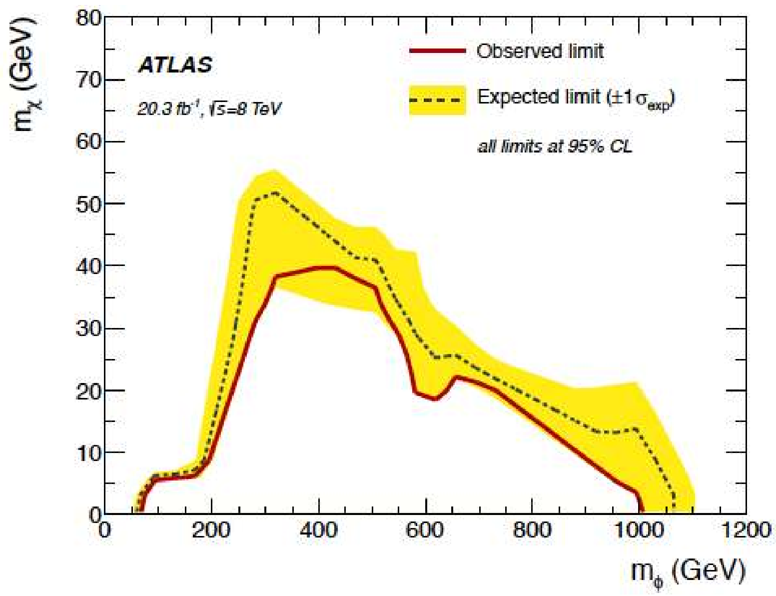




Heavy flavor + E_T^{miss}: results







Exclusion contour in *b*-FDM model:

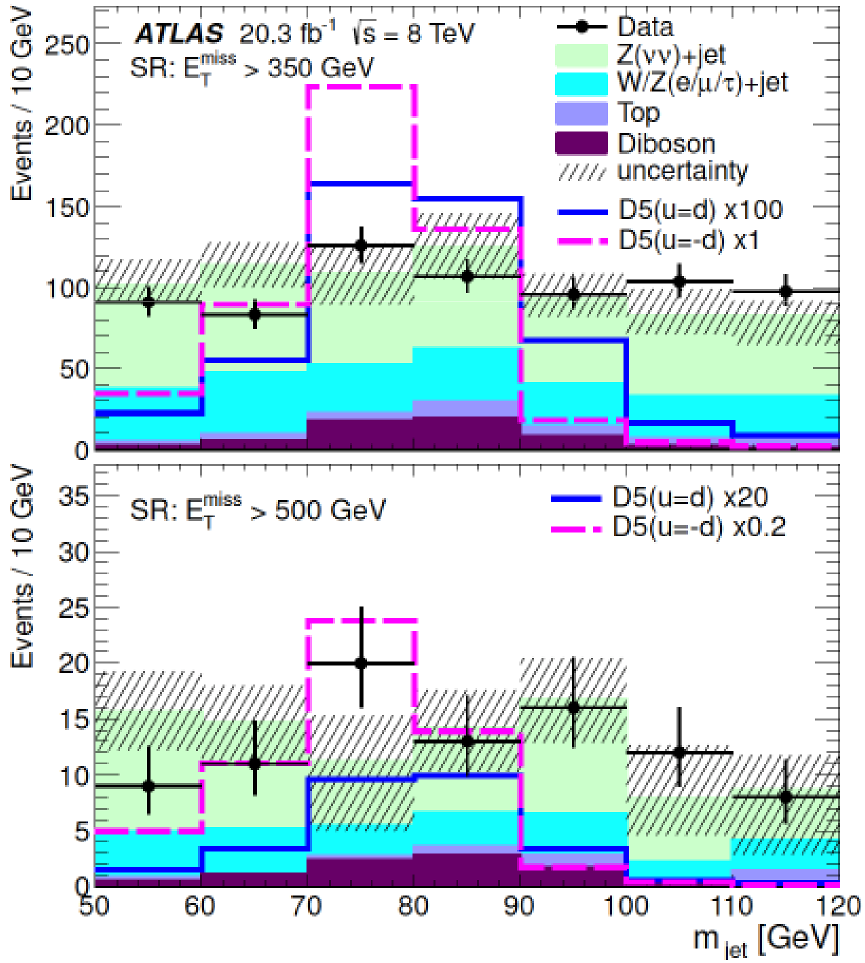
- Fermi-LAT interpretation suggests $m_{DM} \sim 35$ GeV
- For this m_{DM}, mediator masses in range [~300, ~500] GeV excluded by this analysis

W/Z (hadronic) + E_T^{miss} [PRL 112, 041802 (2014)]

- ‘Boosted’ analysis: *W/Z* have large enough p_T that decay jets merge into a large-radius jet J (*fat jet*)
- Mass of fat jet required to be broadly consistent with *W/Z* mass:
  $50 < m_J < 120$ GeV
- $p_T(J) > 150$ GeV
- Veto events with:
  - lepton or photon
  - narrow jet of $p_T > 40$ GeV that does not overlap with fat jet
- 2 signal regions defined using
  $E_T^{miss} > 350, 500$ GeV

➢ Main backgrounds:

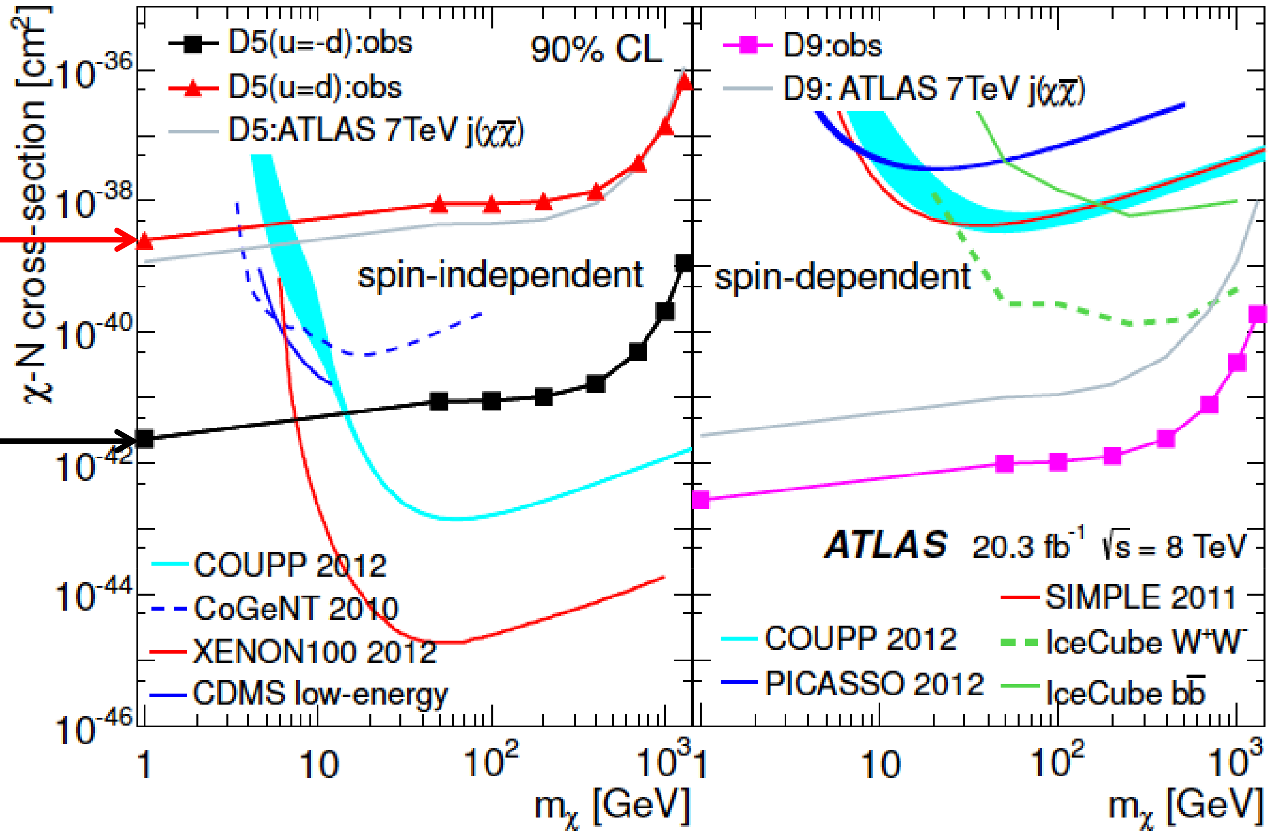
- $Z(\nu\nu)$ + jets, $W/Z(e/\mu/\tau)$ + jet
- Estimated from data control region



W/Z (hadronic) + E_T^{miss}: results

Same-sign couplings of *W* to *u* and *d* quarks → -ve interference

Opposite-sign couplings of *W* to *u* and *d* quarks → +ve interference

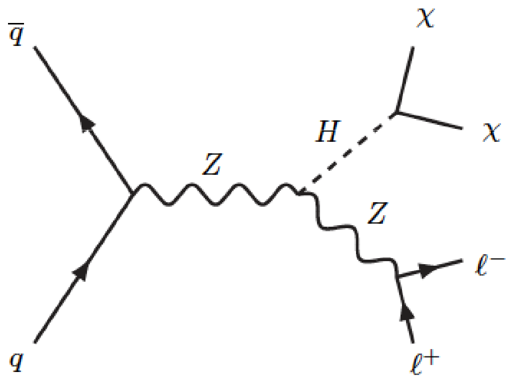


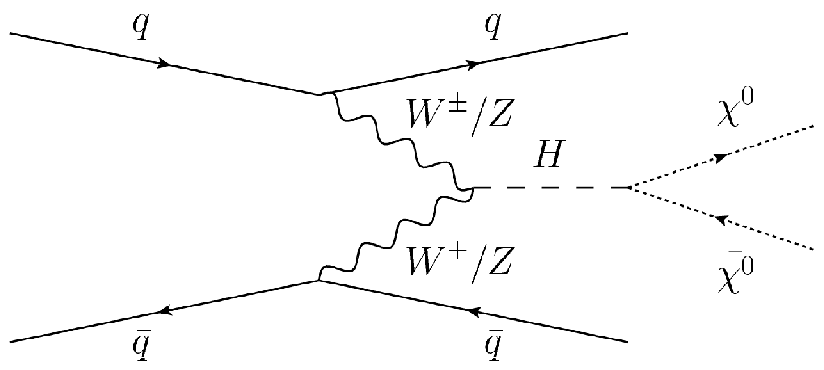
- When up-type and down-type couplings of *W* have opposite signs, rate of mono-*W* >> rate of all other mono-boson production
  → strong limits
- EFT validity not taken into account in these results

Dark matter searches in Higgs boson decays

Higgs decays into invisible final states

- If Higgs couples to dark matter (Higgs Portal models), Higgs can decay into DM pair provided that $m_{DM} < m_H/2$
- This would be an invisible decay of Higgs
- Conversely, limits on branching fraction of Higgs into invisible final states can be interpreted as limits on DM production

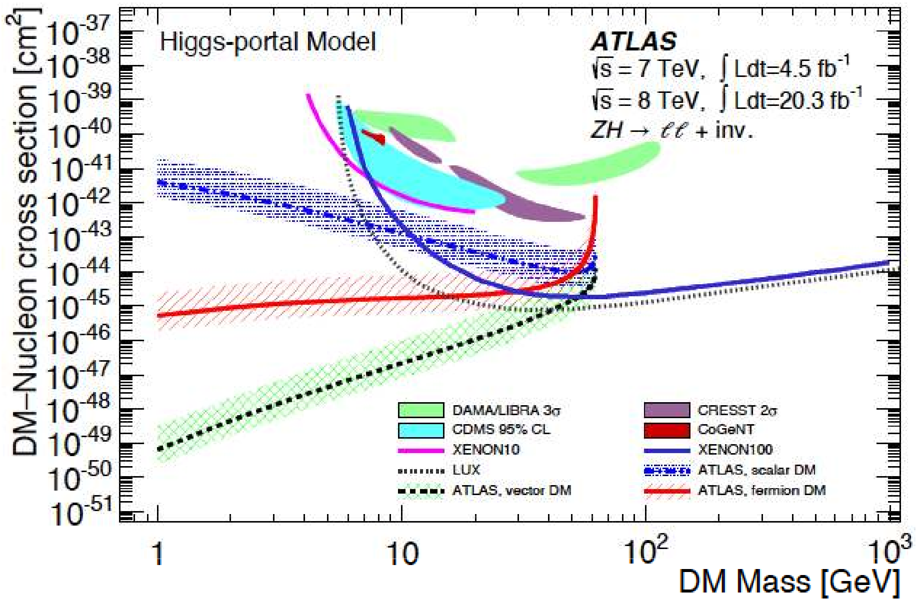


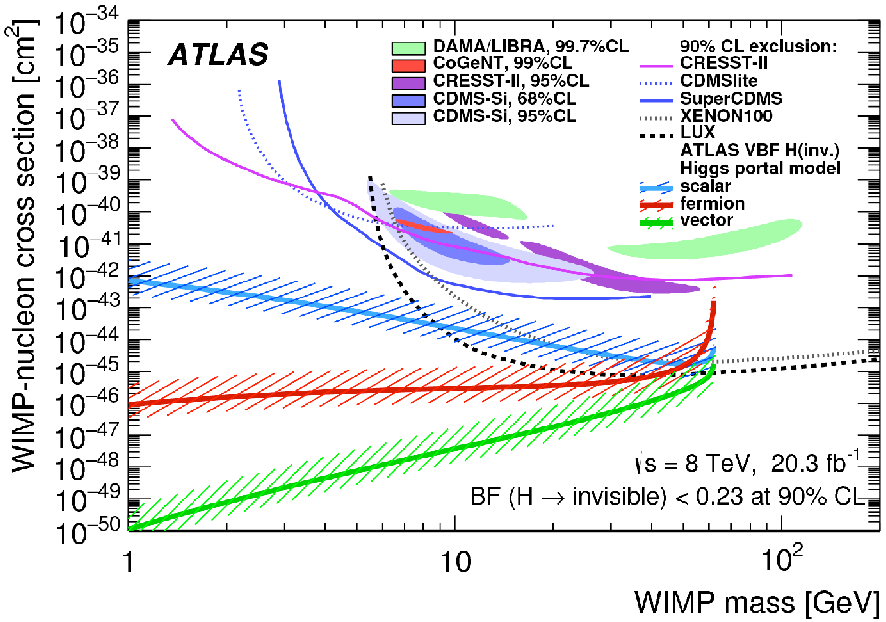


➢ ATLAS has searched for invisible Higgs decays in

- Assoc production with a *Z* boson, *Z*(*ll*)*H* — PRL112, 201802 (2014)
- Assoc production with a *W/Z* boson, *V*(*jj*)*H* — EPJC (2015) 75:337
- Vector boson fusion (VBF) production — arXiv:1508.07869 Submitted to JHEP

Constraints on DM production



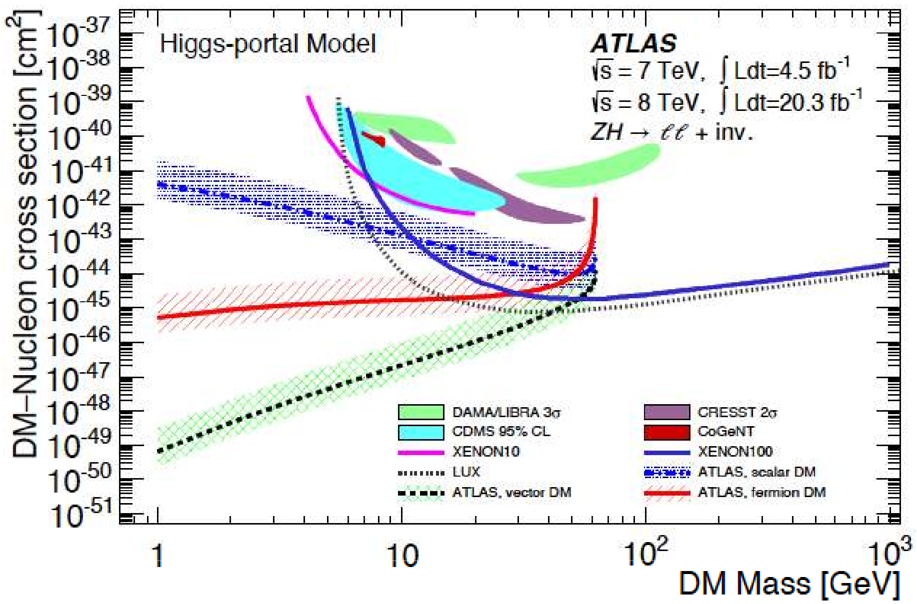


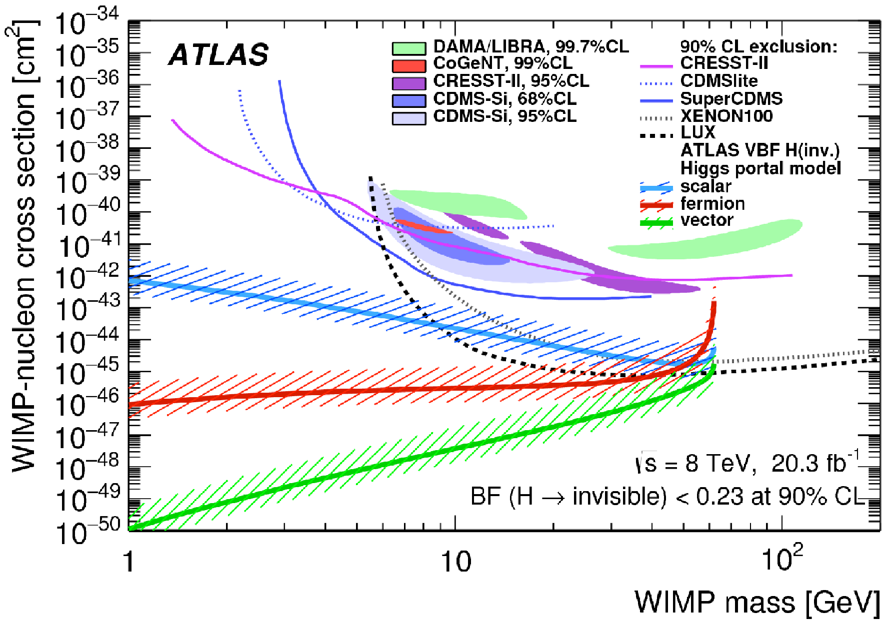
Z(*ll*)*H*: BR(*H* → inv) < 75% at 95% CL

VBF: BR(*H* → inv) < 28% at 95% CL

V(*jj*)*H*: BR(*H* → inv) < 78% at 95% CL

Constraints on DM production





Z(*ll*)*H*: BR(*H* → inv) < 75% at 95% CL   VBF: BR(*H* → inv) < 28% at 95% CL

V(*jj*)*H*: BR(*H* → inv) < 78% at 95% CL

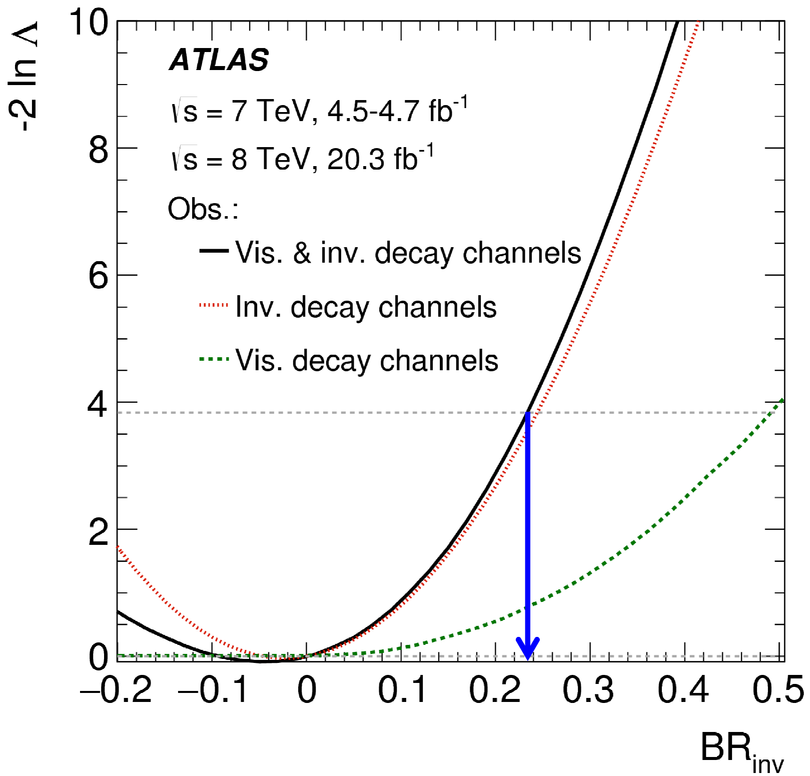
- Combination of all visible and invisible Higgs decay channels in ATLAS yields strong constraint:

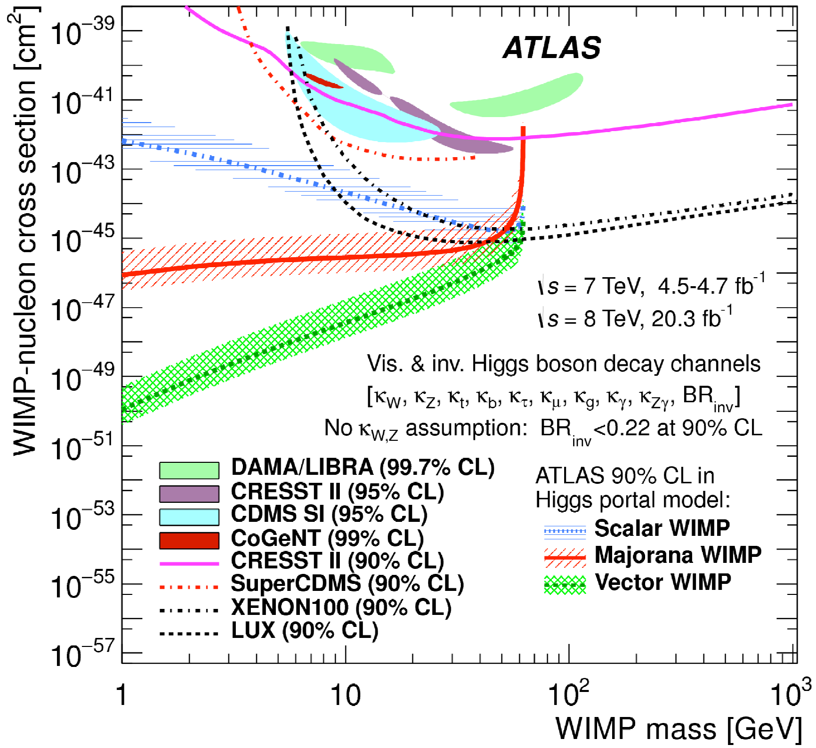
BR(*H* → inv) < 23% at 95% CL

arXiv:1509.00672
Submitted to JHEP

Constraints on DM production: Higgs combination

arXiv:1509.00672, submitted to JHEP



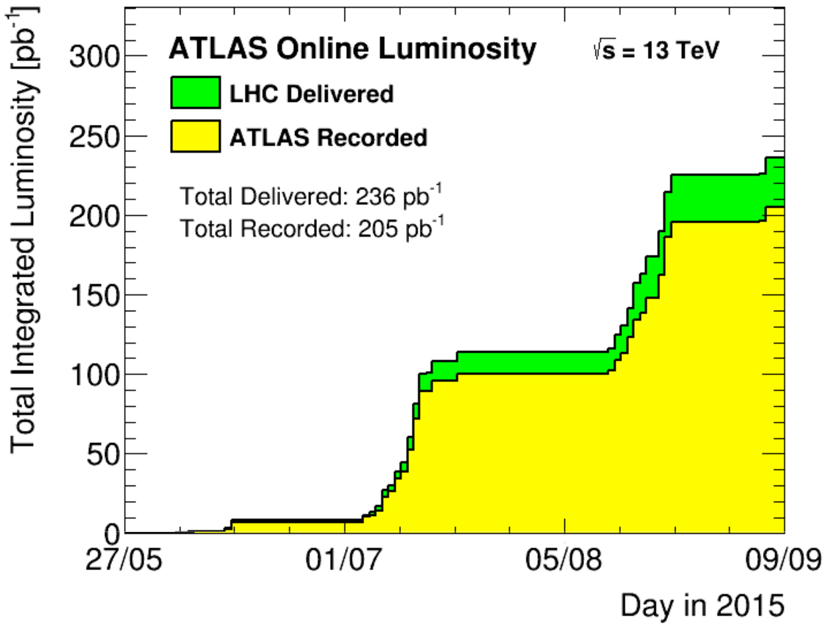


- Likelihood scan as a function of BR($H \rightarrow$ inv)
- $-2\ln\Lambda = 3.84$ gives 95% CL upper limit on BR($H \rightarrow$ inv)

- Interpretation as limits on WIMP - nucleon scattering cross section
- Dominated by VBF $H \rightarrow$ inv channel

Toward LHC Run 2

Run 2 is underway



Nice stairway profile, leading up to some place great!

Benchmark models for dark matter search in Run 2

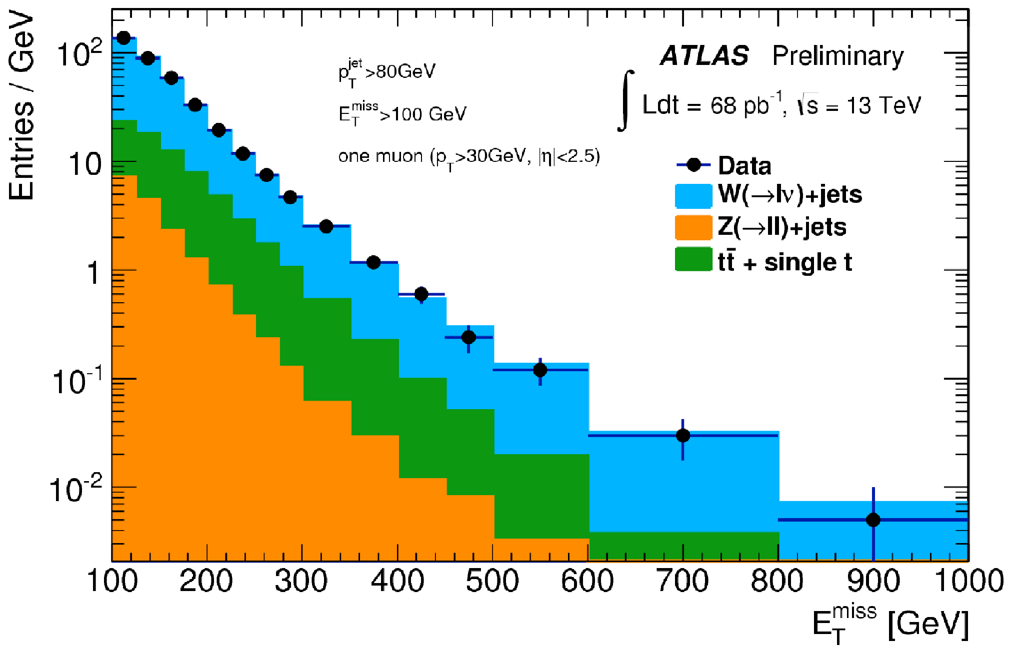
- Models for early DM searches in Run 2 set out in the LHC Dark Matter Forum report:

  http://arxiv.org/pdf/1507.00966.pdf

- Trend is to move away from EFTs, focus on simplified models as much as possible

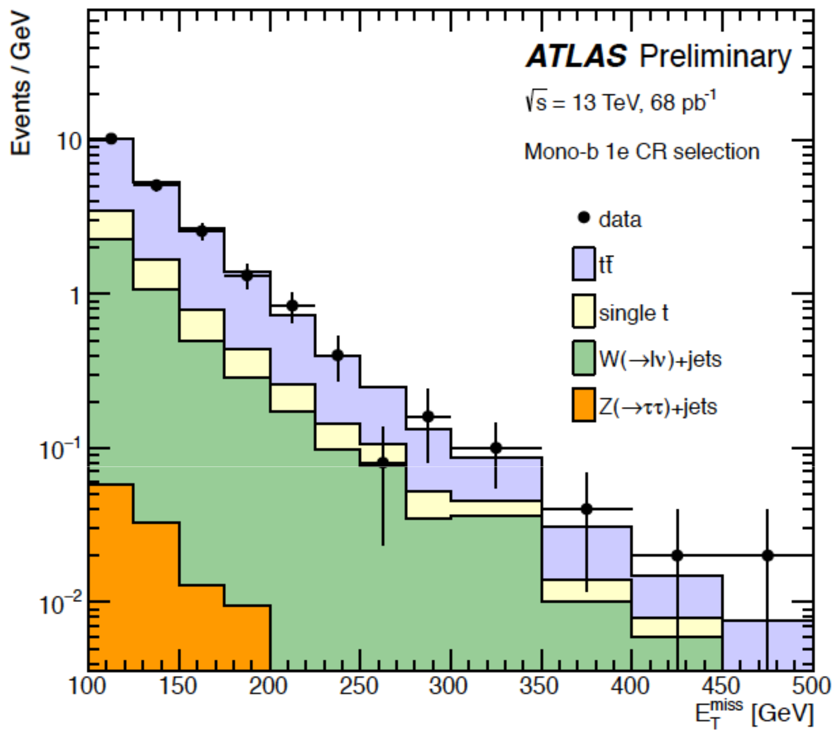
Early dark matter analysis plots from Run 2

Jet + E_T^{miss}: EXOT-2015-005



- E_T^{miss} in $W \rightarrow \mu\nu$ control region
- 68 pb^{-1} of data at 13 TeV
- Prediction normalized to data

mono-*b* + E_T^{miss}: EXOT-2015-007



- E_T^{miss} in 1*e* control region
- 68 pb^{-1} of data at 13 TeV
- Prediction normalized to data

Conclusion & outlook

- Dark matter searches in ATLAS using LHC Run 1 data has been *very* successful!

  - to the extent that you can call non-discovery a success ☺

- The workhorses have been mono-object channels and constraints on invisible Higgs decays
- Significant regions of parameter space of many models excluded
- Excellent complementarity b/w ATLAS results and those from direct and indirect dark matter search experiments

Conclusion & outlook

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- The workhorses have been mono-object channels and constraints on invisible Higgs decays
- Significant regions of parameter space of many models excluded
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- And now Run 2 is upon us

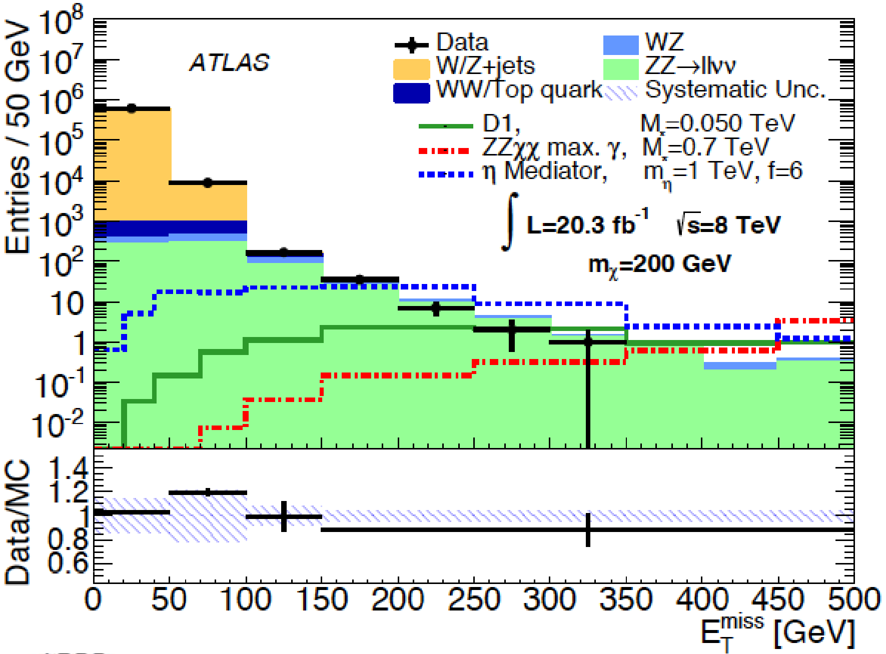
- Some channels will overtake Run 1 sensitivity with 1 - 5 fb^{-1} of data
- We will keep climbing those stairs, hopefully finding dark matter at the top

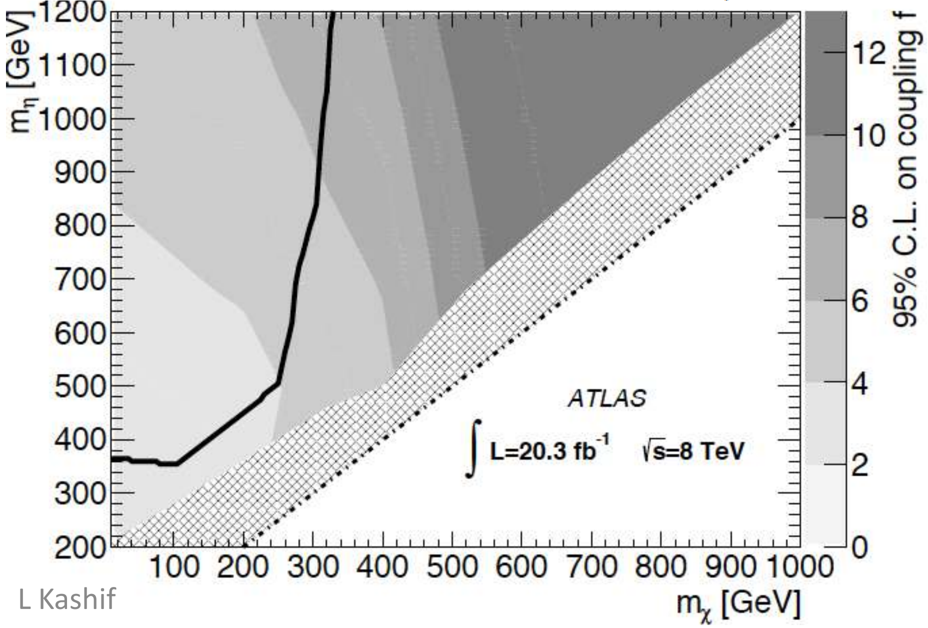
So let's keep our fingers crossed. Thank you!

Extra slides

$Z(ll)$ + E_T^{miss}

PRD 90, 012004 (2014)





- Complements hadronic Z decay channel
- $76 < m_{ll} < 106$ GeV
- $\Delta\phi(p_T^{ll}, E_T^{miss}) > 2.5$
- Veto events with more l's or jets
- 4 signal regions defined with $E_T^{miss} > 150, 250, 350, 450$ GeV

Interpretation in model with scalar mediator η

- Limits on coupling f b/w DM and η
- White region: model invalid
- Region above black line: lower limit from relic abundance > upper limit from this analysis

$W(l\nu)$ + E_T^{miss}

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- Strategy: look for excess in transverse mass distribution, defined as

$$m_T = \sqrt{2 p_T E_T^{miss}(1-\cos\varphi_{l\nu})}$$

- **Electron channel:**
  $p_T(e) > 125$ GeV, $E_T^{miss} > 125$ GeV
- **Muon channel:**
  $p_T(\mu) > 45$ GeV, $E_T^{miss} > 45$ GeV

- Backgrounds:
- Multijet: estimated from data using matrix method
- Top and diboson: estimated from simulation

- No excess seen in data