Dark Matter searches with ATLAS

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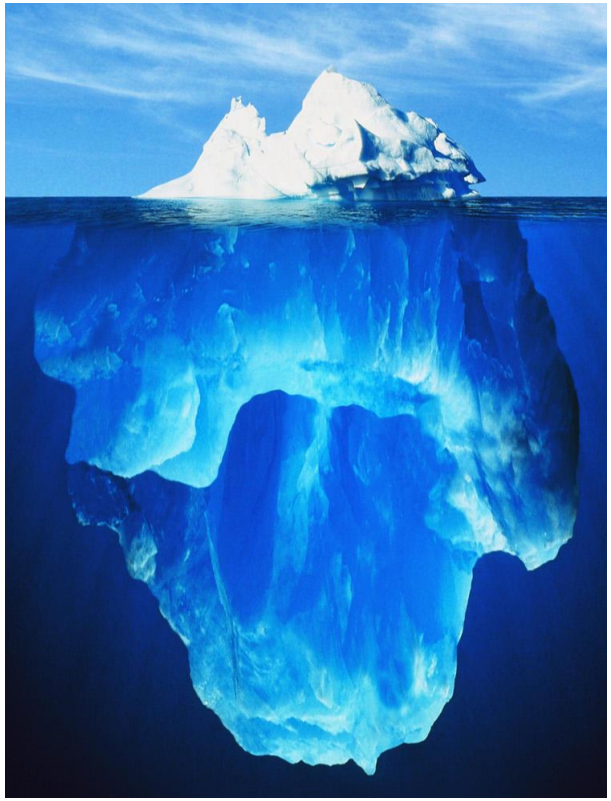
(Werner-Heisenberg-Institut)

on behalf of the
ATLAS collaboration

XXVII International Workshop on
Deep Inelastic Scattering
and Related Subjects

Torino, 9 April 2019



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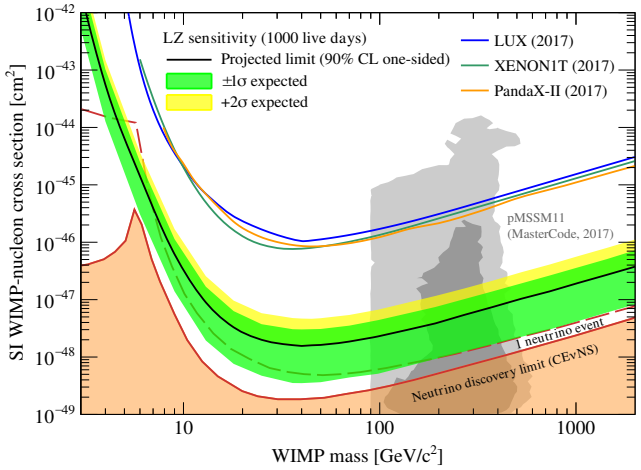

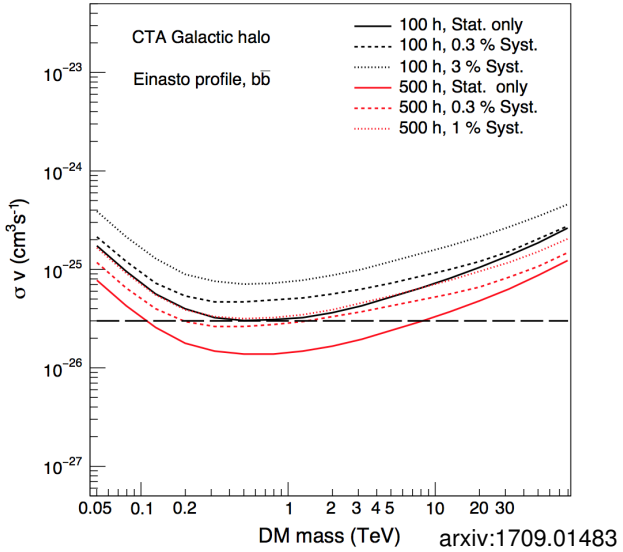

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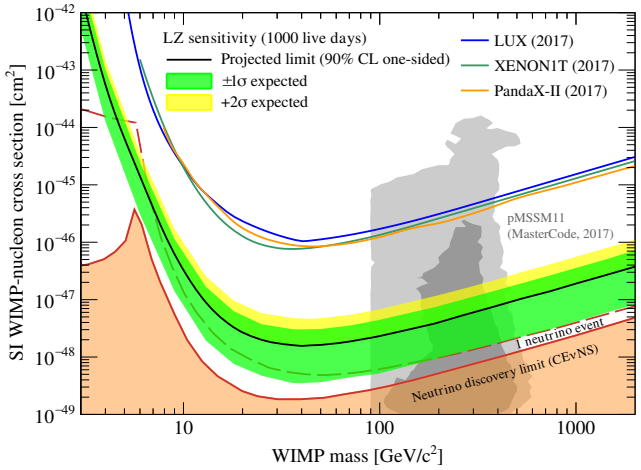

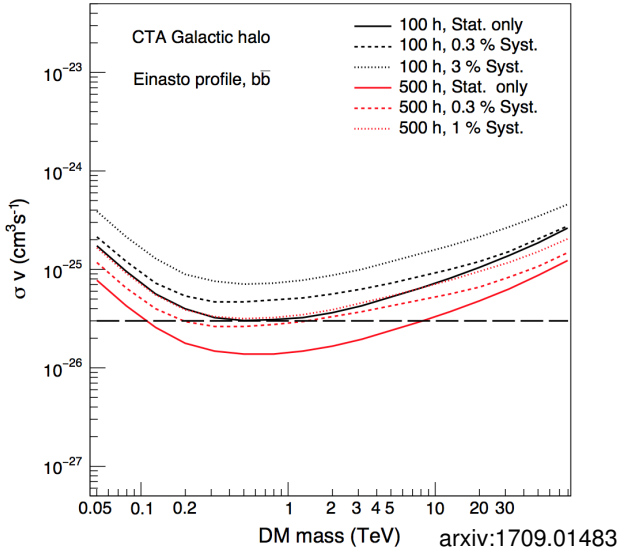

arxiv:1709.01483

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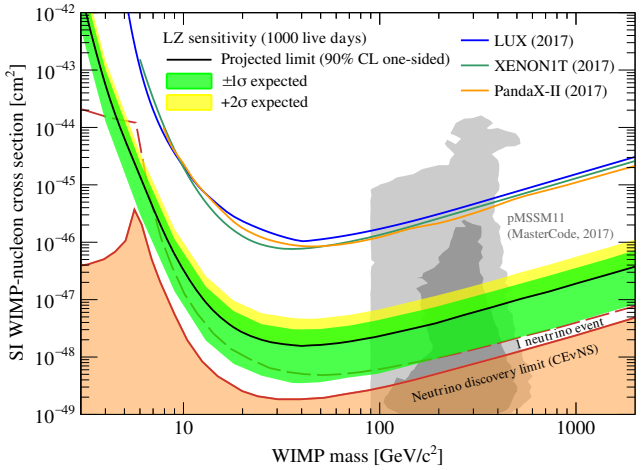

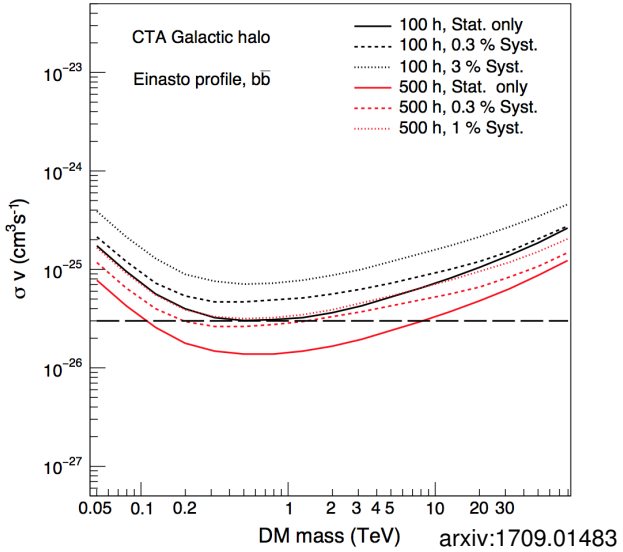

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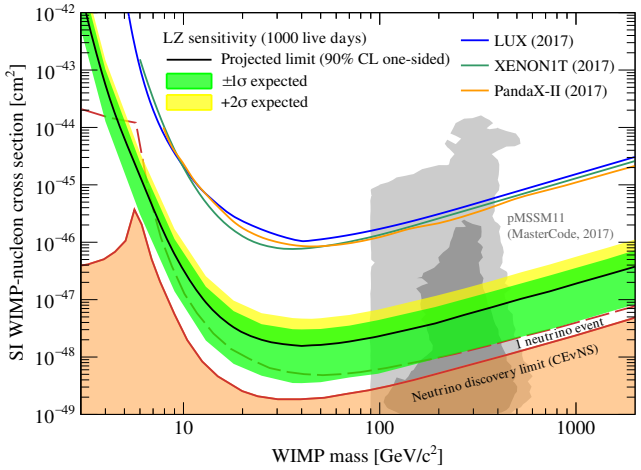

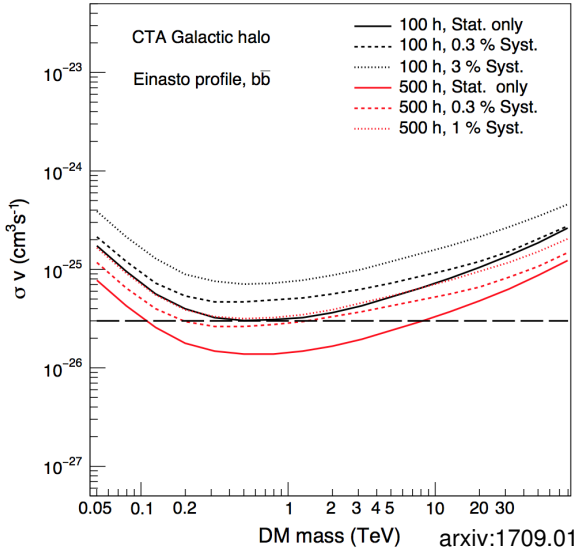

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- How does ATLAS contribute to the search for Dark Matter?

Outline

- Collider approach to Dark Matter
- Dark Matter signatures and searches
- Combinations of Dark Matter searches

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Collider approach to Dark Matter
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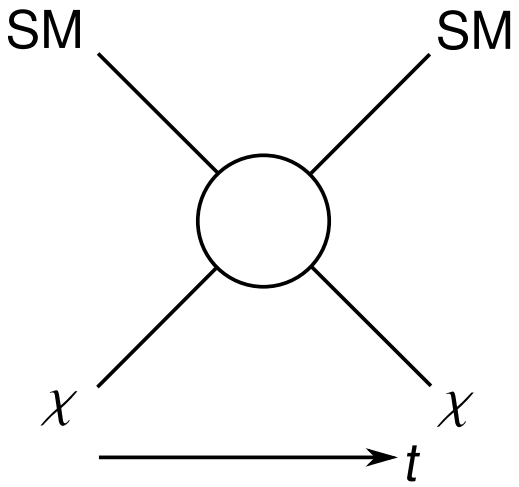
- Direct detection: nuclear recoil from elastic scattering



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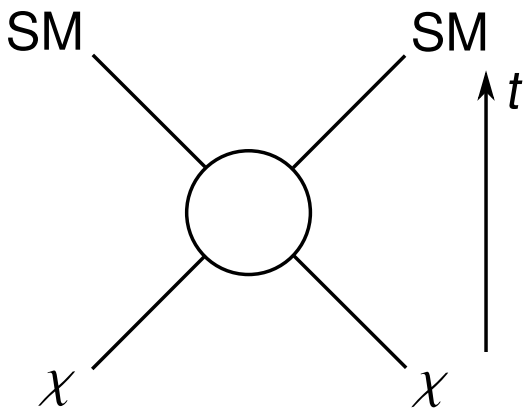

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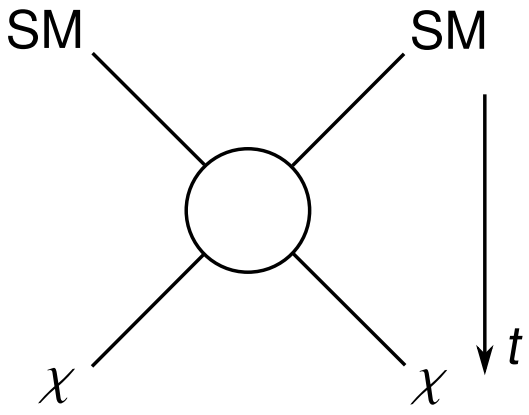

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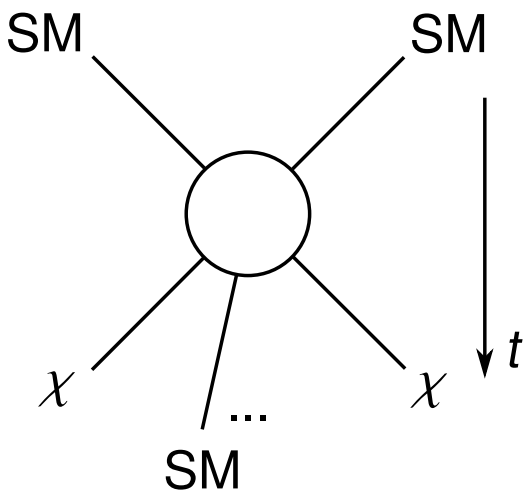

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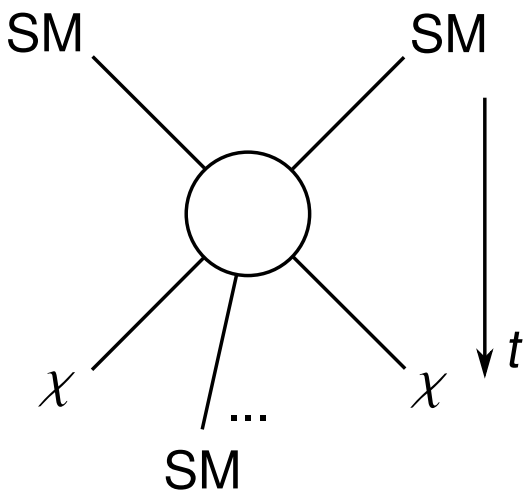

Comparison of search strategies:

	Direct	Indirect	Collider - LHC
Typical mass range	$10\,\text{GeV} < m_\chi < 1\,\text{TeV}$	$10\,\text{GeV} < m_\chi < 100\,\text{TeV}$	$m_\chi \lesssim 1\,\text{TeV}$
Observables beyond m_χ	$\sigma_{\chi N \to \chi N}$	$\sigma_{\chi\chi \to NN}$	many
Model dependence	DM on Earth	DM in space	particle physics

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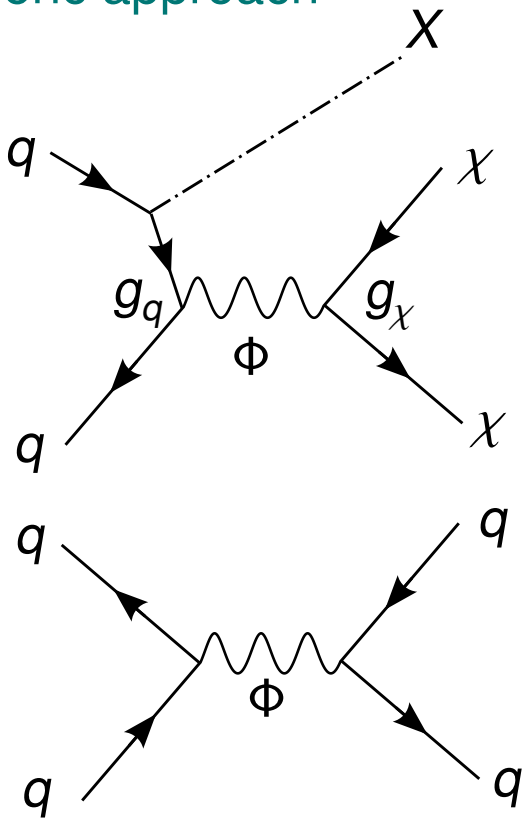

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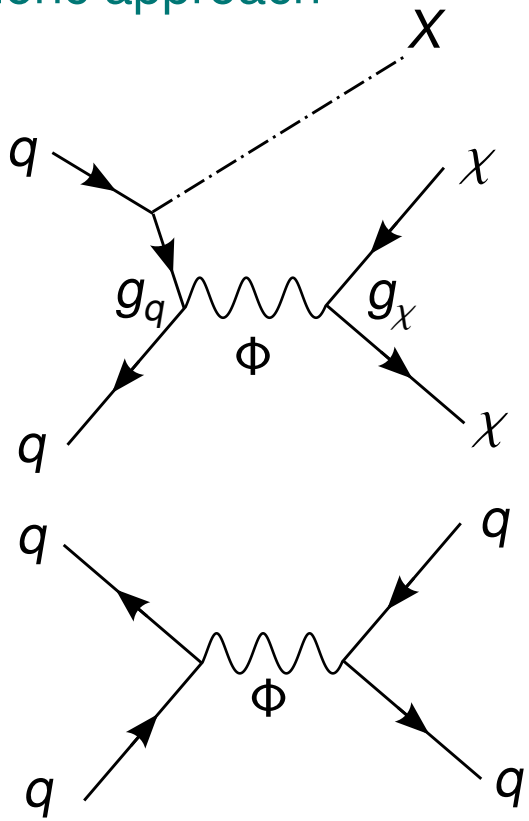

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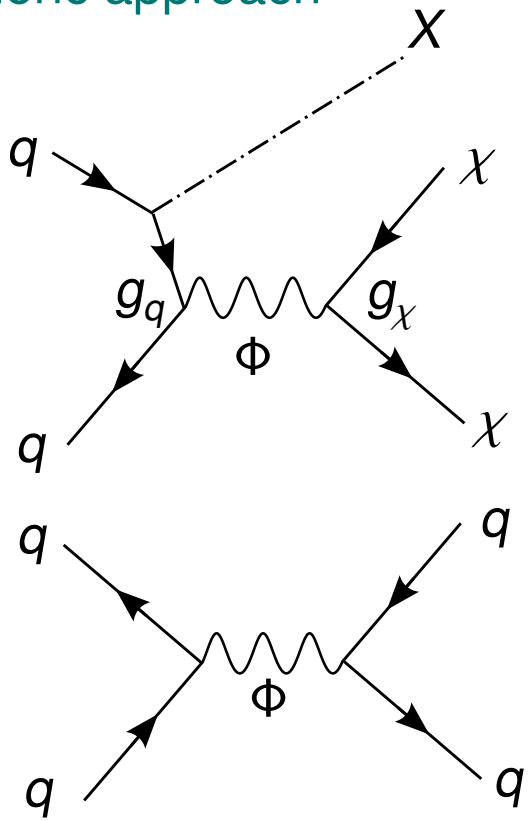

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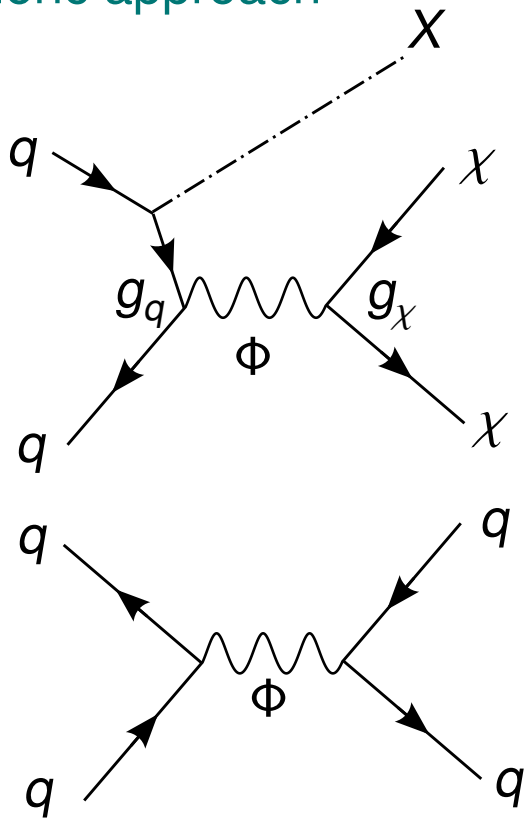

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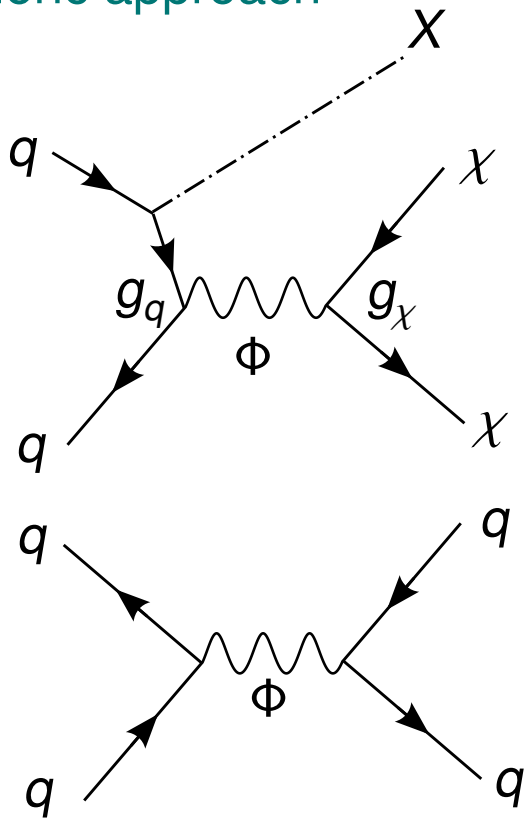


- Dark Matter candidates from Supersymmetry with R-parity conservation (UV-complete models), covered in *tomorrows WG3 sessions*

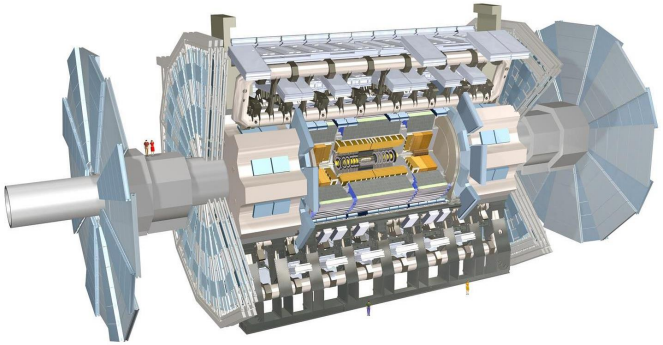
Collider approach to Dark Matter
ATLAS Run 2 Dataset

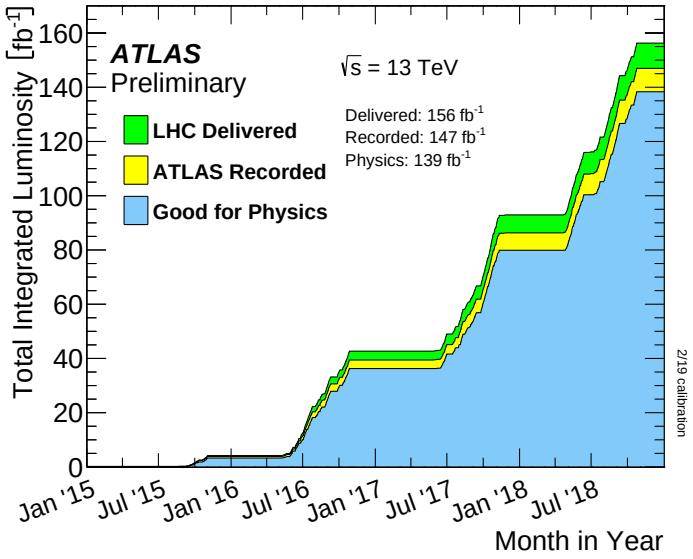
- Large dataset collected by ATLAS in Run 2 (2015-2018):

$$\sqrt{s}_{pp} = 13 \text{ TeV}$$
$$\int L dt = 139 \text{ fb}^{-1}$$

- Analysis of this dataset ongoing; up to 80 fb^{-1} used for the results presented in the following

- E_T^{miss} Trigger used for most Dark Matter searches, fully efficient for $E_T^{miss} \gtrsim 200$ GeV





ATLAS Public Results

Outline

- Collider approach to Dark Matter
- Dark Matter signatures and searches
- Combinations of Dark Matter searches

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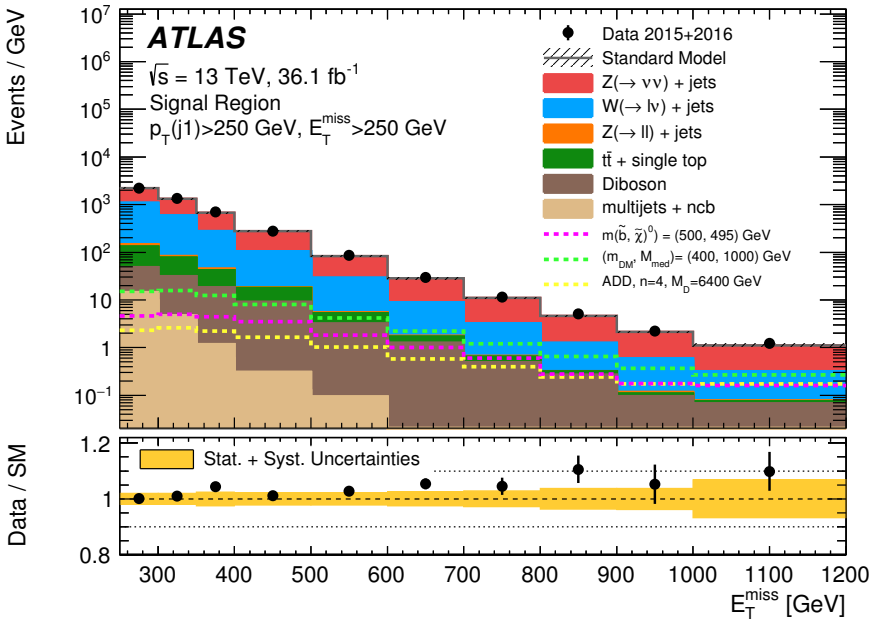
- *Dark Matter signatures and searches:* E_T^{miss} *+*
  - Jet
  - H(bb)
  - W/Z(qq)
  - Z($\ell\ell$)
  - "VBF"
- Combinations of Dark Matter searches

Dark Matter Signatures: Monojet

- $E_T^{miss} > 250$ GeV + up to 4 jets $\Rightarrow$ sensitivity to several new phenomena
- Signal region (no leptons) + $W(e\nu)$, $W(\mu\nu)$, $Z(\mu\mu)$ and top-quark control regions

  - High precision theoretical predictions of W/Z p_T distributions (NLO EWK) $\Rightarrow$ accurate modelling of the E_T^{miss} distribution in the signal region
  - Combined fit of signal and control regions



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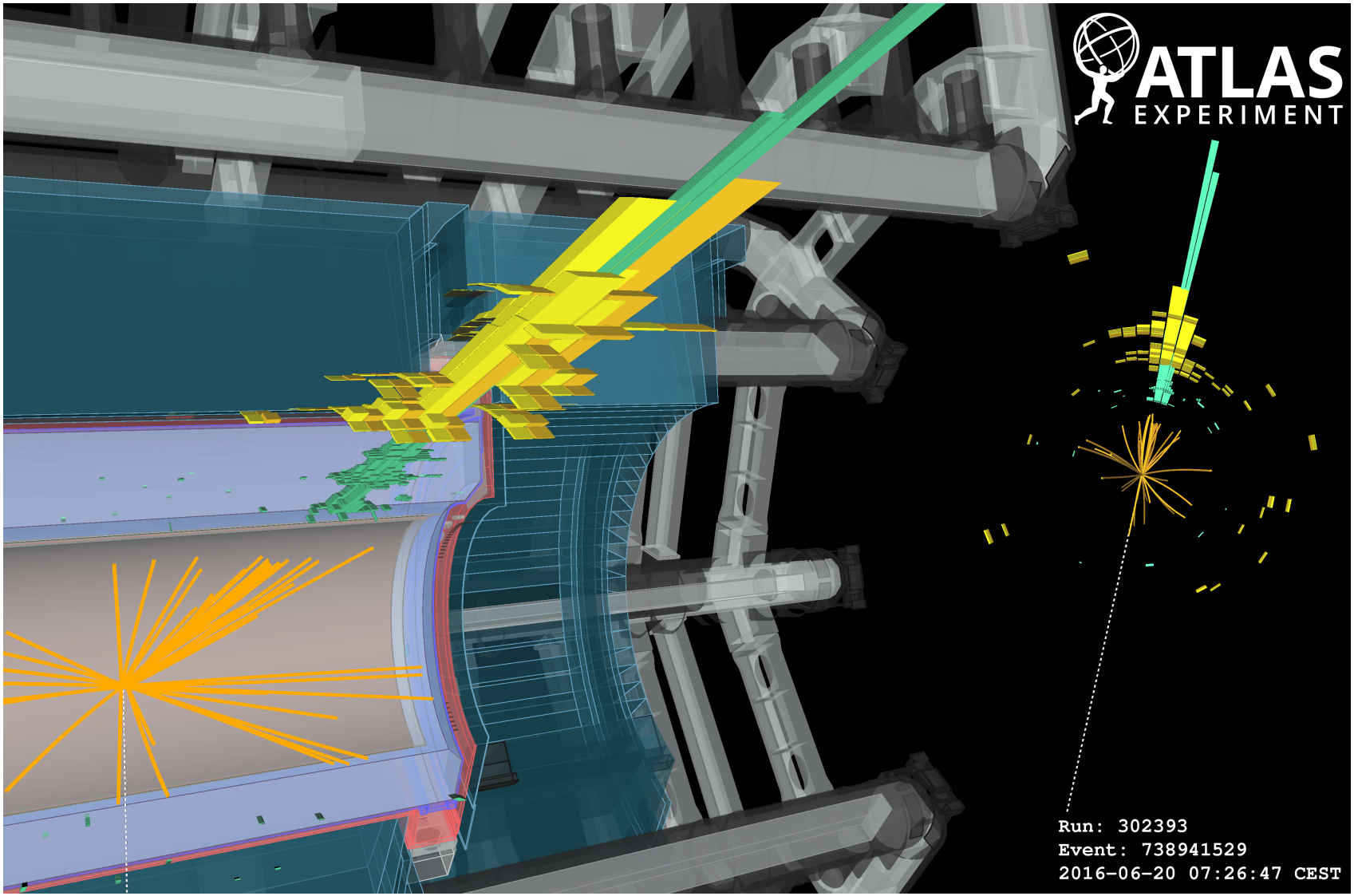

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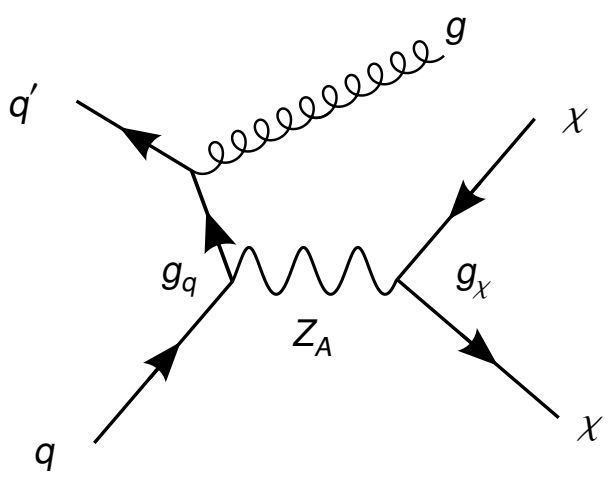
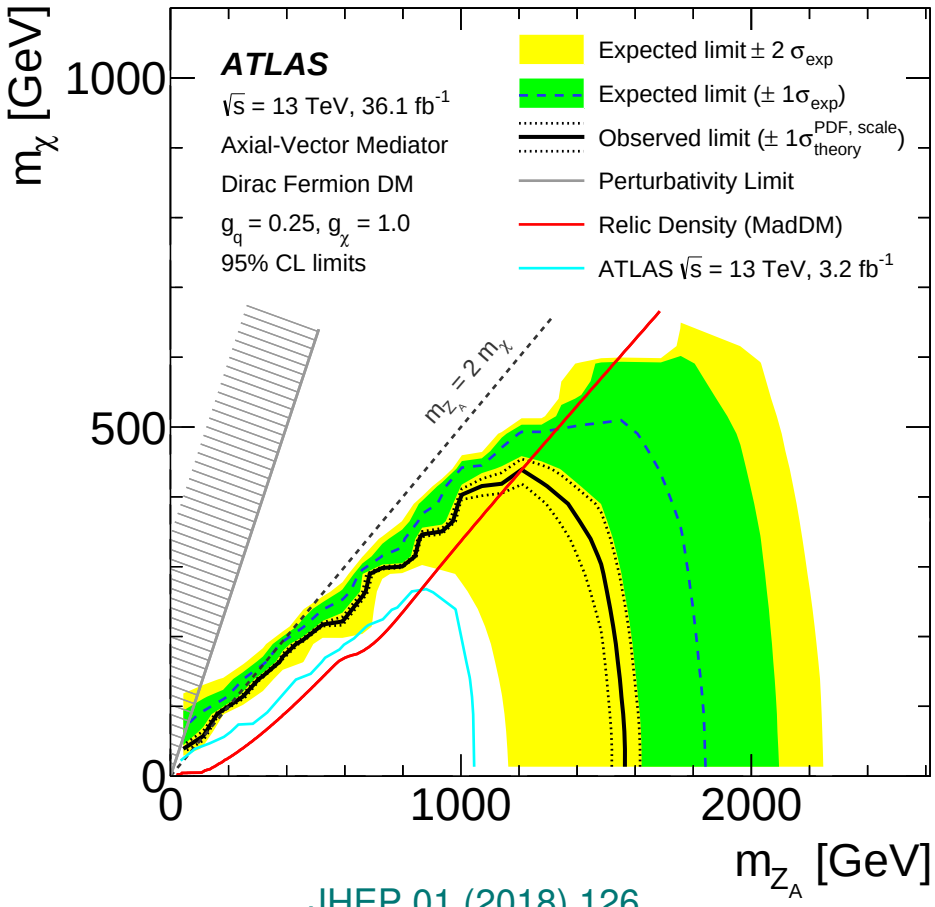


- Interpretation wrt. various signal models. Here: Dark Matter pair production via an axial-vector mediator.



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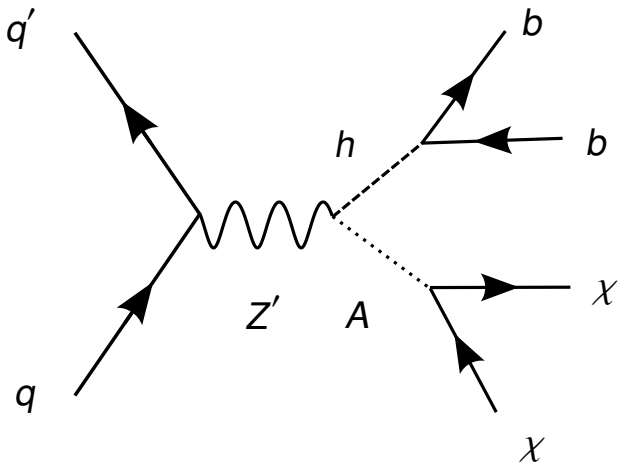
Dark Matter Signatures: Mono-Higgs(bb)



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- Aiming for $h \to bb$ decays (largest branching ratio)

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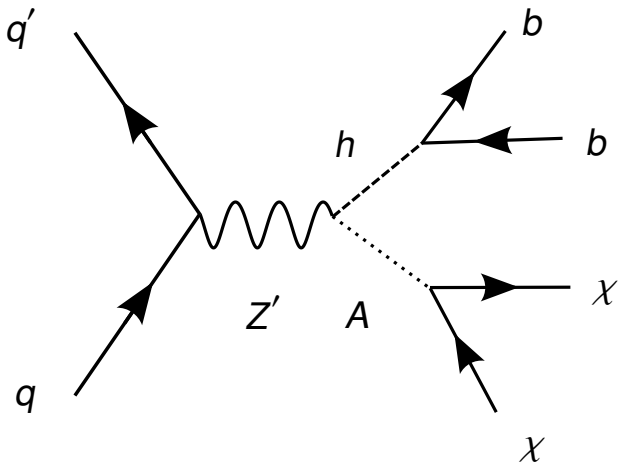
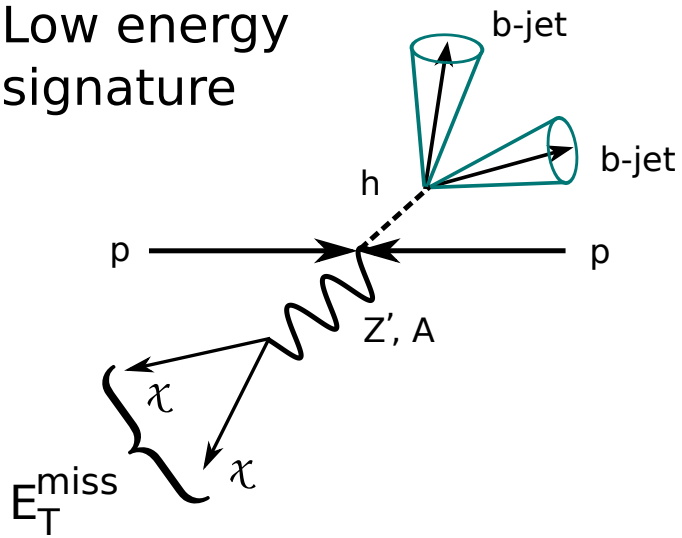
- 2 topologies, depending on the Higgs boson momentum
  - Resolved: Pair of separated jets



Low energy signature



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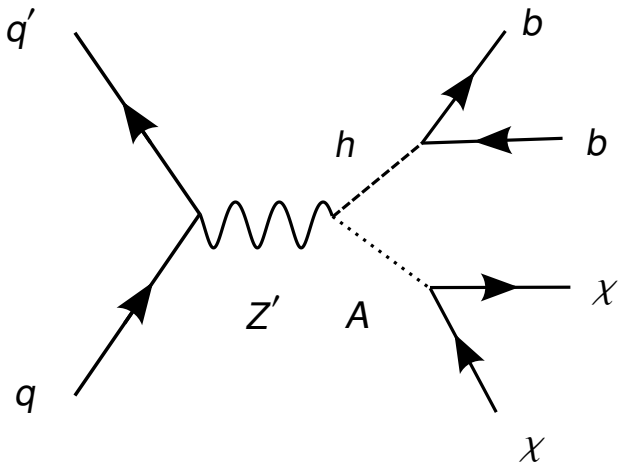
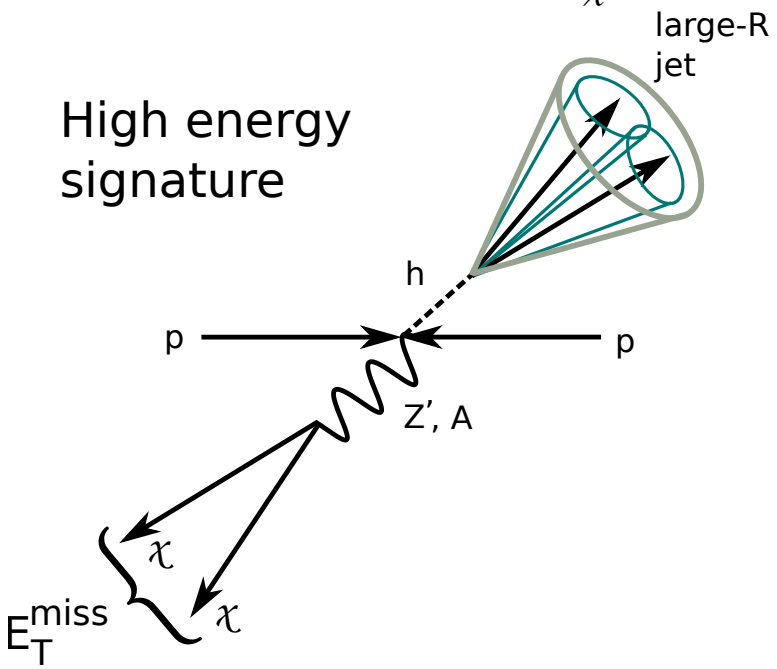
- Aiming for $h \rightarrow bb$ decays (largest branching ratio)
- 2 topologies, depending on the Higgs boson momentum
  - Resolved: Pair of separated jets
  - Boosted: Single large-Radius jet





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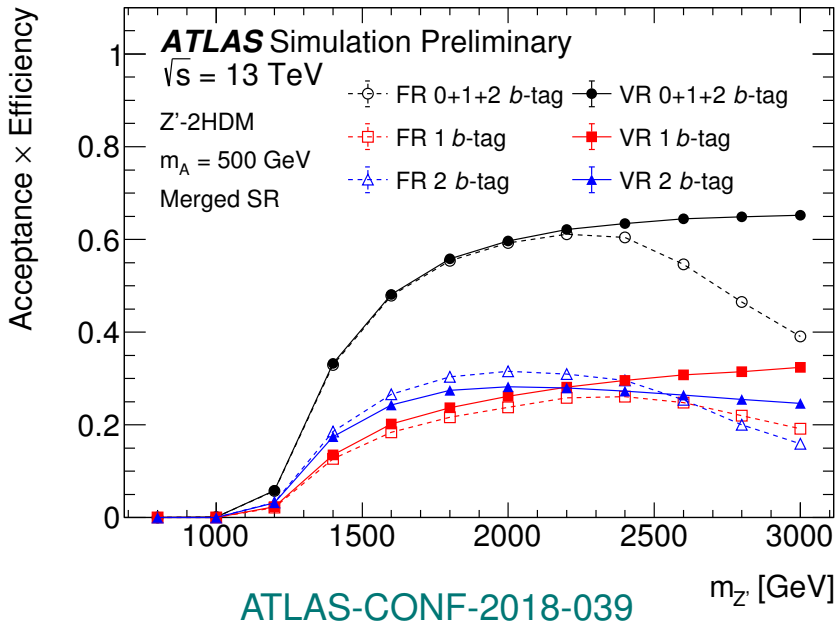

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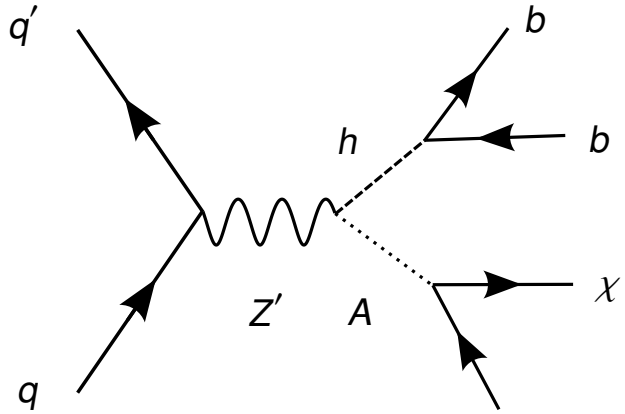
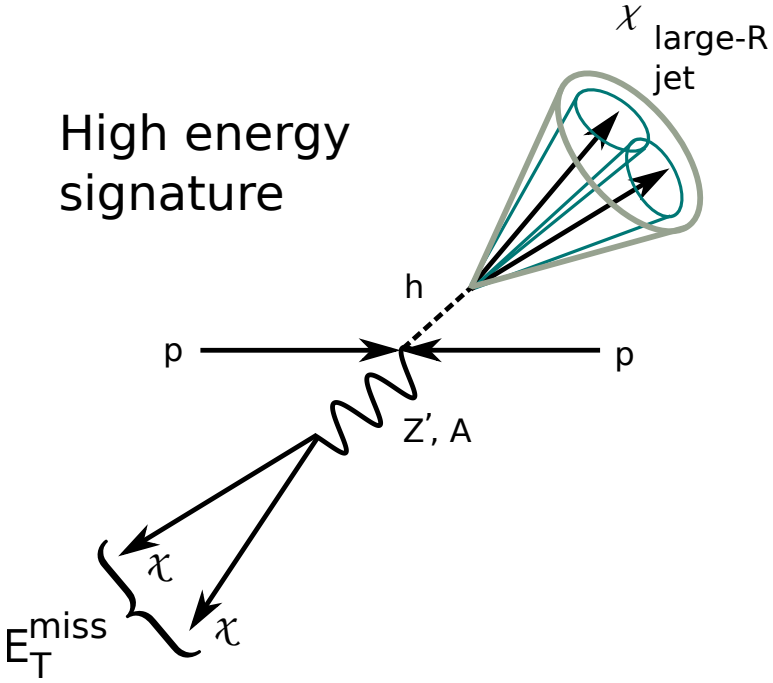
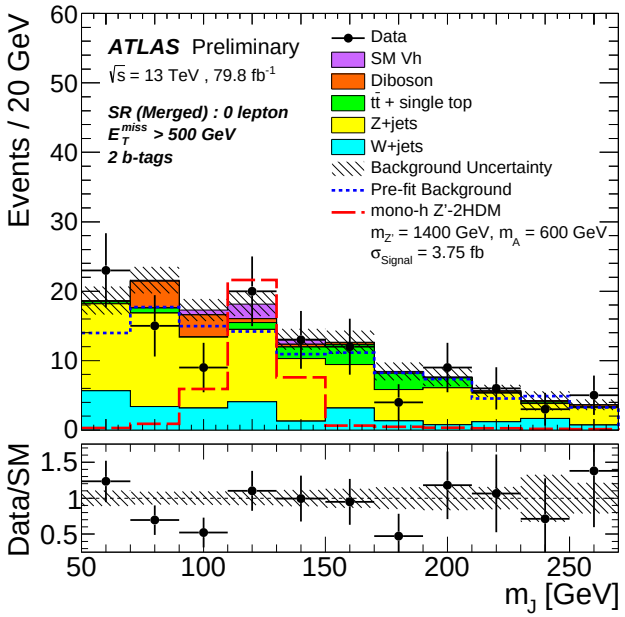


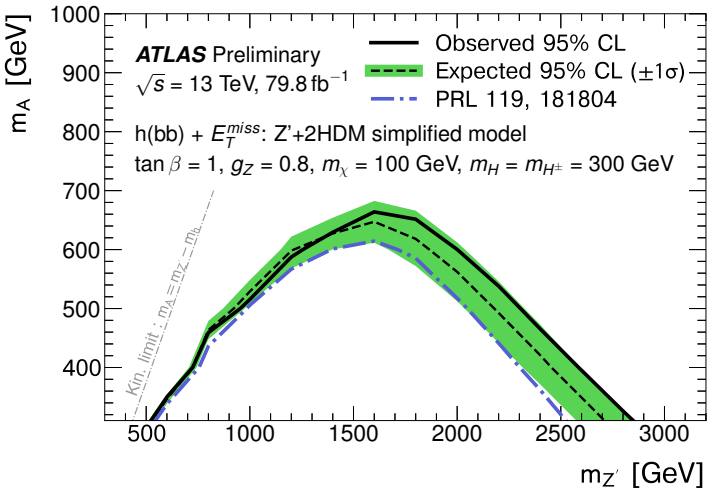


- Boosted topology: using large-R jet sub-structure with two *b*-tagged track jets
- For large p^h: track jets close to each other $\Rightarrow$ Fixed-Radius (FR) track jets merge
- Hence decrease the track jet radius as $p_T^{\text{track jet}}$ increases $\Rightarrow$ Variable-Radius (VR) track jets

Dark Matter Signatures: Mono-Higgs(bb)

- Run 2 data from 2015 - 2017:
  $\int L dt = 80\ \text{fb}^{-1}$
- Discriminating variables:
  di-jet or large-R jet mass, E_T^{miss}
- Interpret results in terms of
  mass limits on new mediators
- Compared to predecessor analysis:
  improvement in particular due to the use of Variable-Radius track jets
  - Relevant also for other searches for new phenomena with ATLAS





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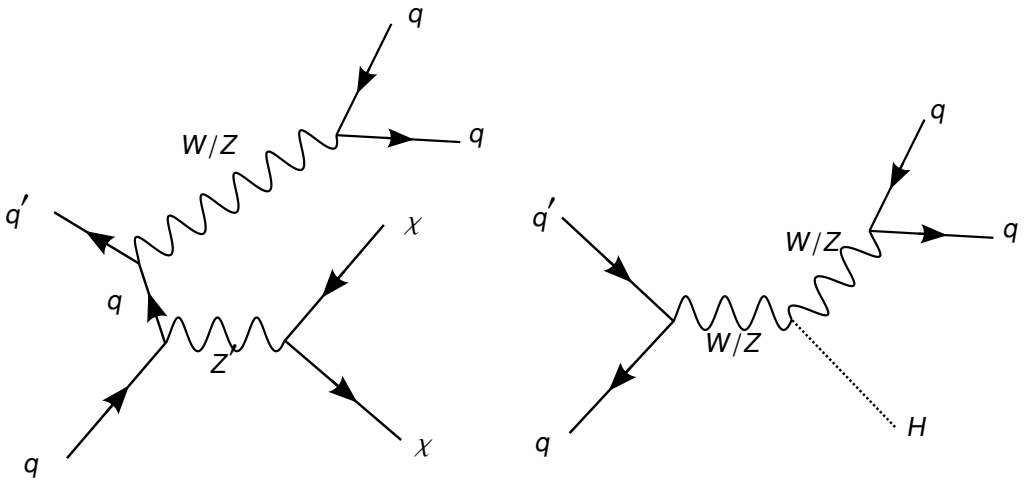
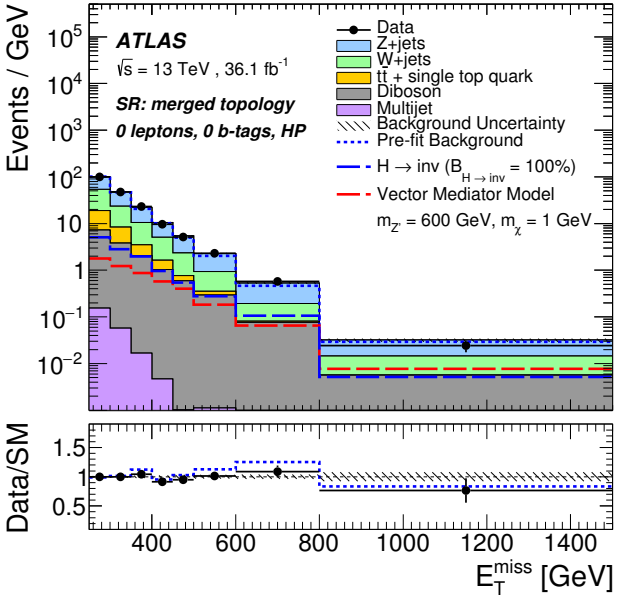
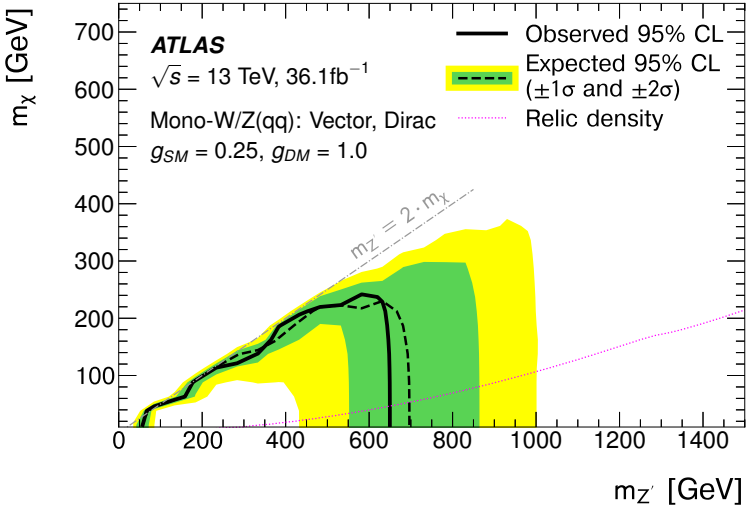
Dark Matter Signatures: $W/Z(qq)+E_T^{miss}$





- Different interpretations, including $H \rightarrow$ inv. decays
- Considering both resolved and boosted $W/Z \rightarrow qq$ - decays
- E_T^{miss} for different b-tag multiplicities as discriminating variable variable



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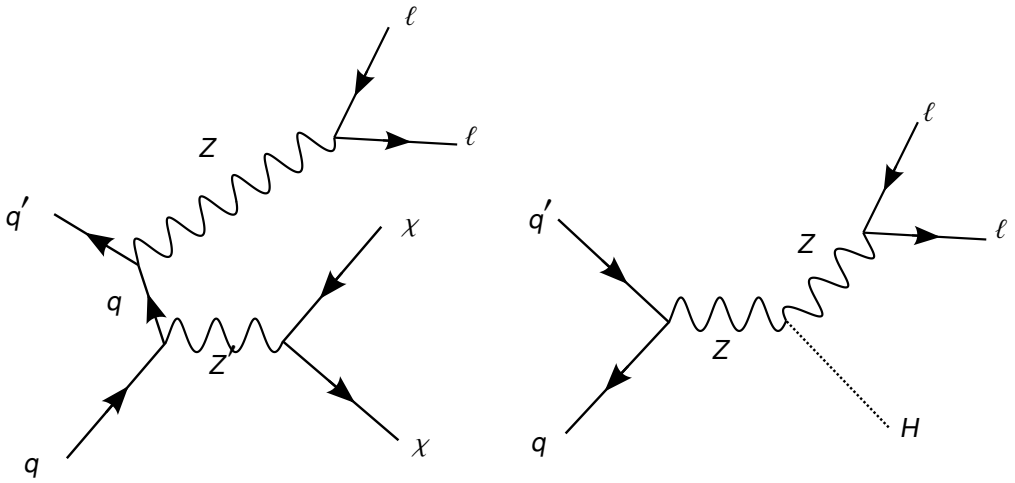
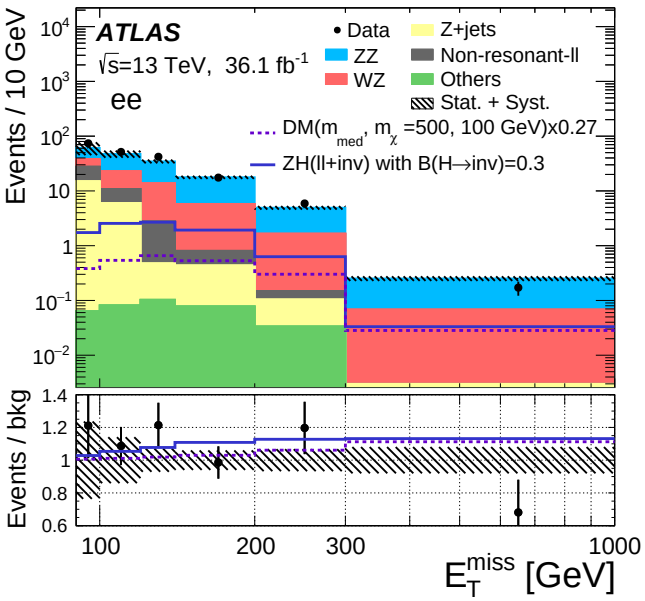
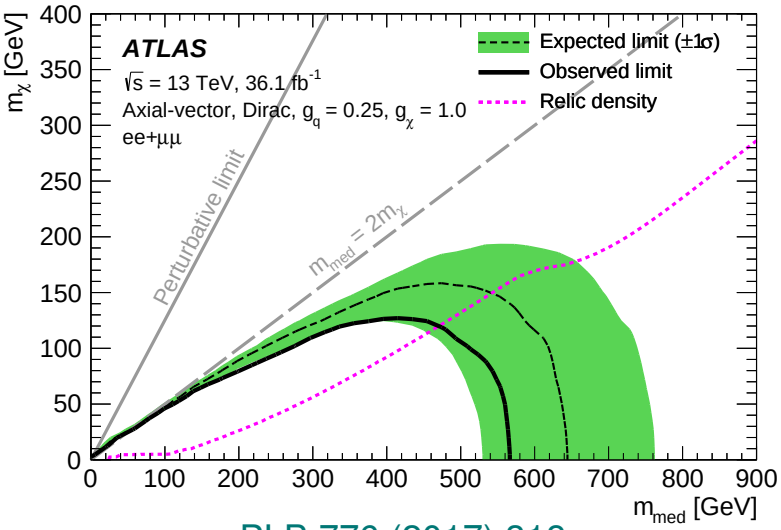
Dark Matter Signatures: $Z(\ell\ell)+E_T^{miss}$





- Different interpretations, including $H \rightarrow$ inv. decays
- Single lepton triggers $\Rightarrow$ sensitivity to signals with lower E_T^{miss}
- E_T^{miss} in ee and $\mu\mu$ signal regions as discriminating variable



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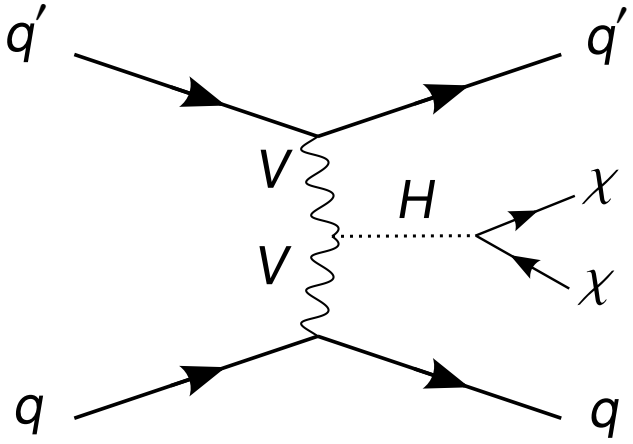
Dark Matter Signatures: VBF+E_T^{miss}

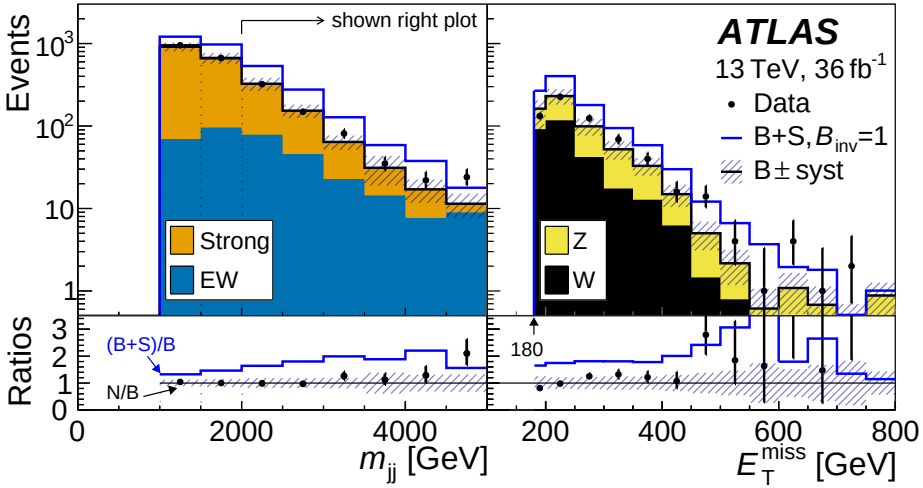
- Events with 2 jets with a rapidity difference $|\Delta\eta_{jj}| > 4.8$ and $E_T^{miss} > 180$ GeV
  $\Rightarrow$ distinct signature
  ("Vector Boson Fusion")



- Background constraints derived from W+jets and Z+jets control regions
- Max. Likelihood Fit using three bins of m_{dijet} starting at 1 TeV
- Resulting observed (expected) limit:

$$\mathcal{B}(\mathrm{H}\rightarrow\mathrm{inv.}) < 0.37\ (0.28^{+0.11}_{-0.08})$$

(without constraints from Higgs boson observations)

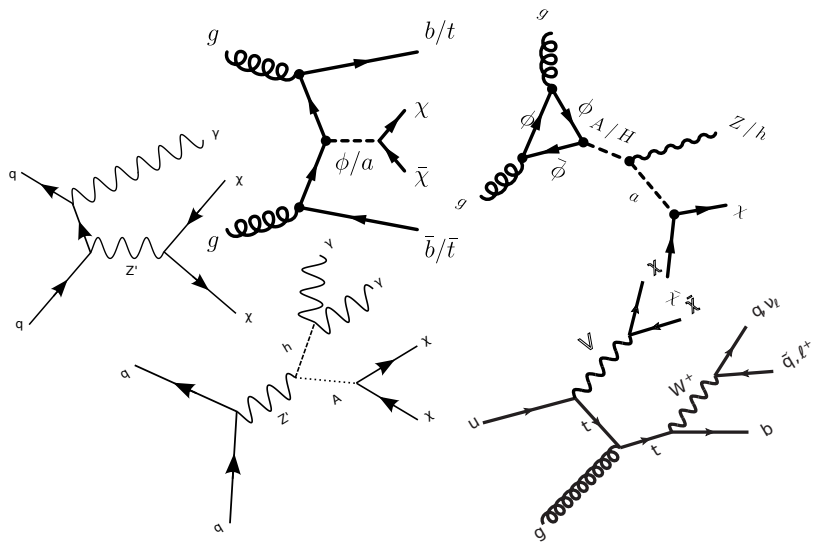


arxiv 1809.06682, subm. to PLB

Dark Matter Signatures: More Searches

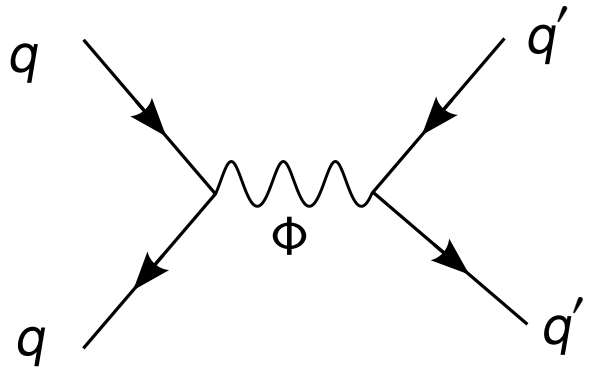
More Mono-X signatures

- Further Dark Matter production modes and alternative Standard Model decays
  - *Mono-Photon*
  - *Mono-H($\gamma\gamma$)*
  - *Mono-Top-Quark*
  - *Dark Matter + heavy flavour pair production*



New Resonances

- Complementary constraints within the simplified model context
- *Dedicated ATLAS talk* by Johannes Erdmann tomorrow



Outline

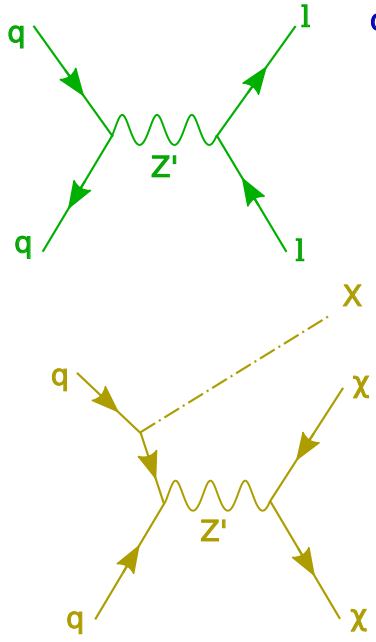
- Collider approach to Dark Matter
- Dark Matter signatures and searches
- Combinations of Dark Matter searches

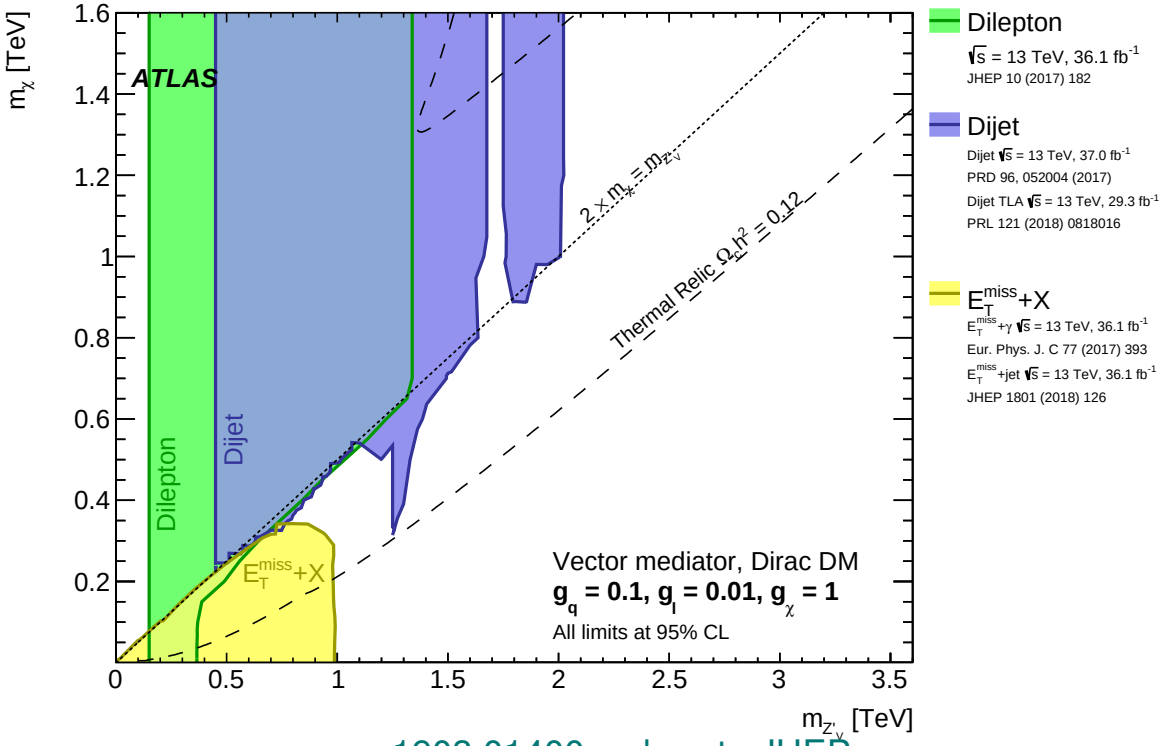
Outline

- Collider approach to Dark Matter
- Dark Matter signatures and searches
- *Combinations of Dark Matter searches*
  - Spin-1 mediators
  - $H \rightarrow$ invisible decays

Combinations of Dark Matter searches

Vector Mediators



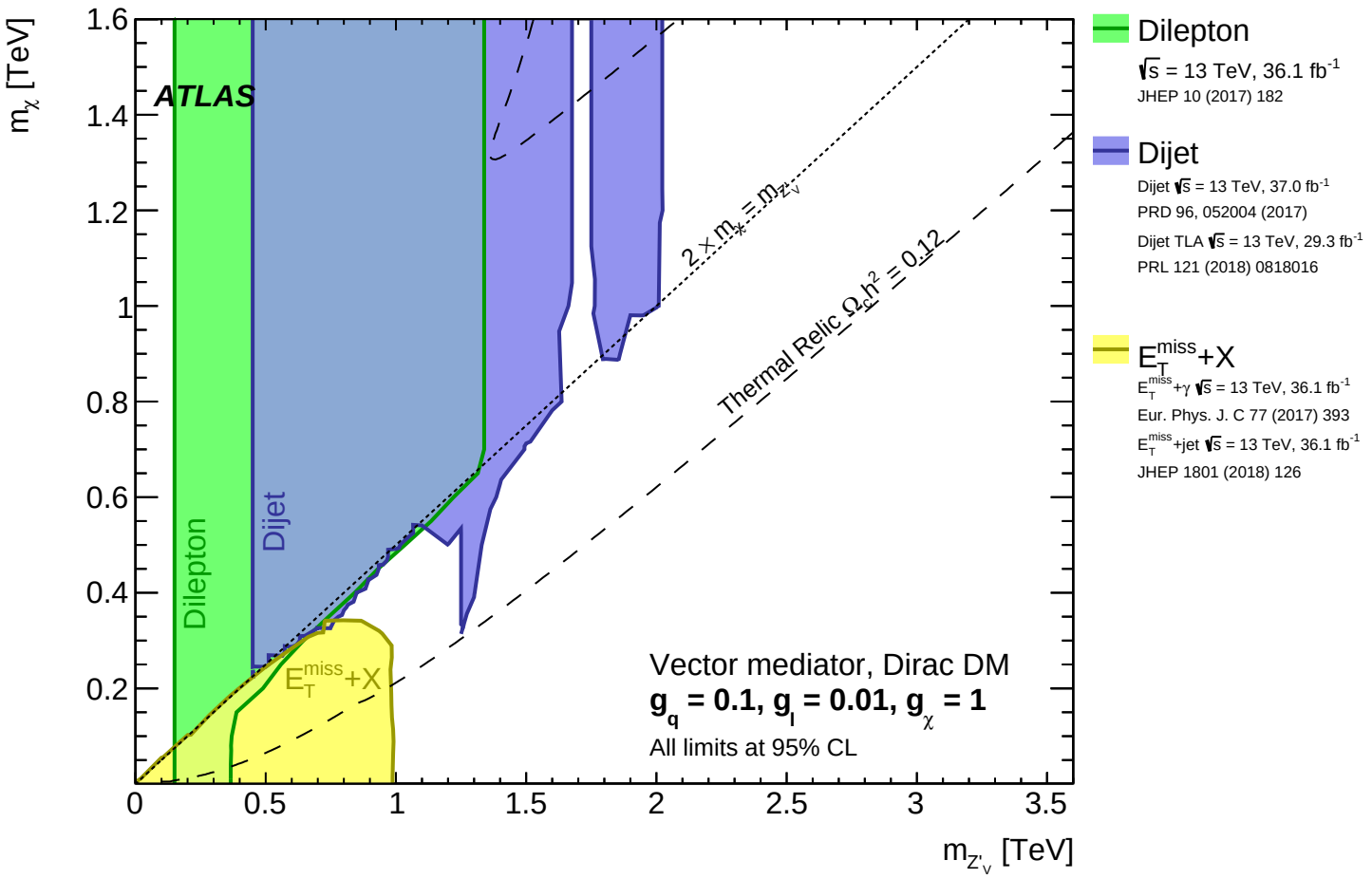


1903.01400, subm. to JHEP

- Summary of exclusion limits of dark matter and resonance searches, both hadronically and leptonically
- Complementarity: large exclusion range achieved via combination
- Similar results for axial-vector mediators

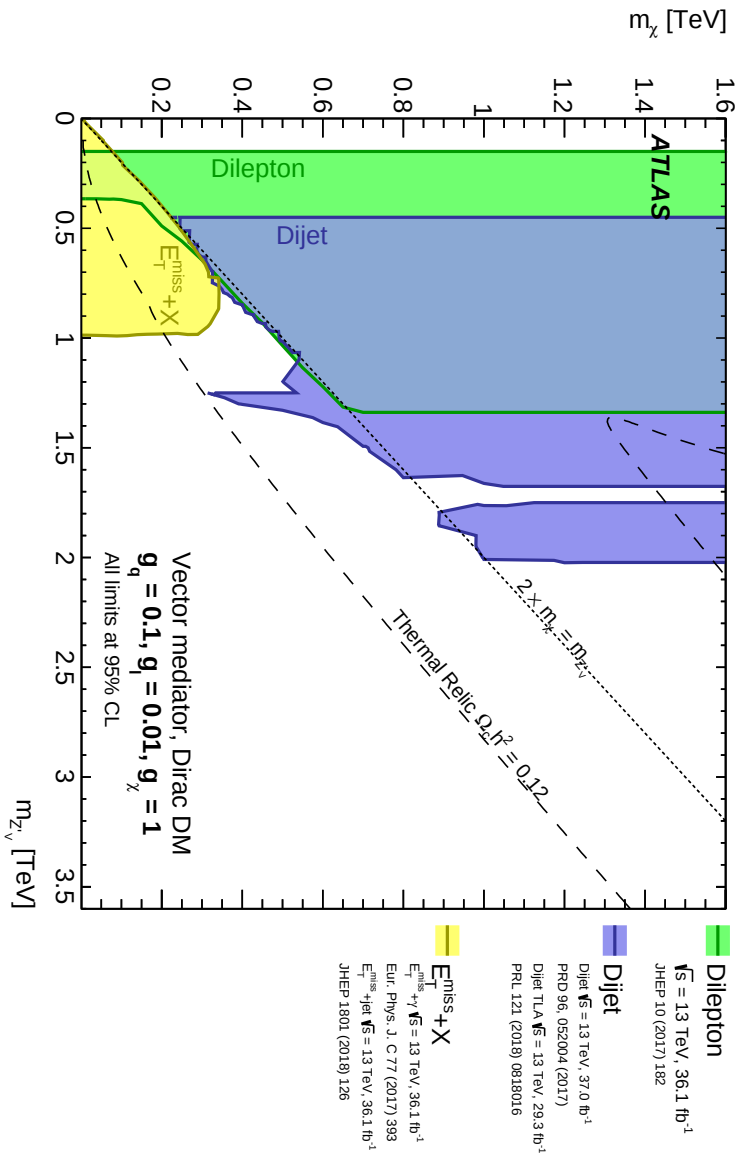
Combinations of Dark Matter searches

Vector Mediators, comparison with direct searches



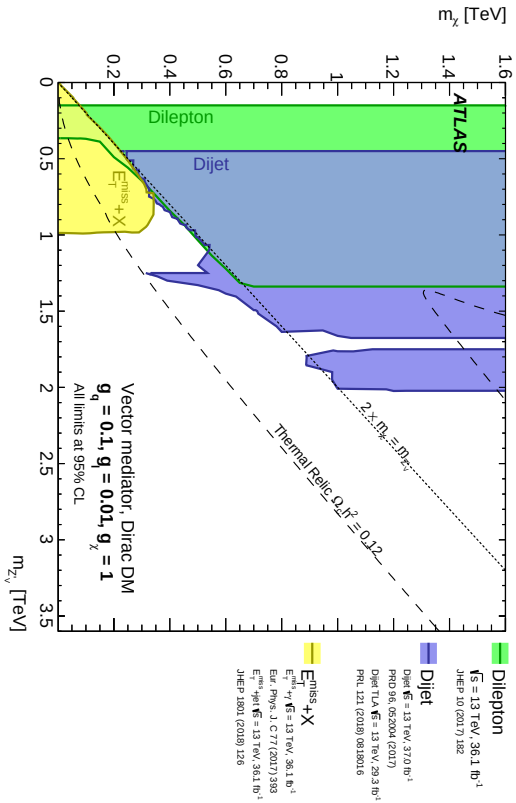
Combinations of Dark Matter searches

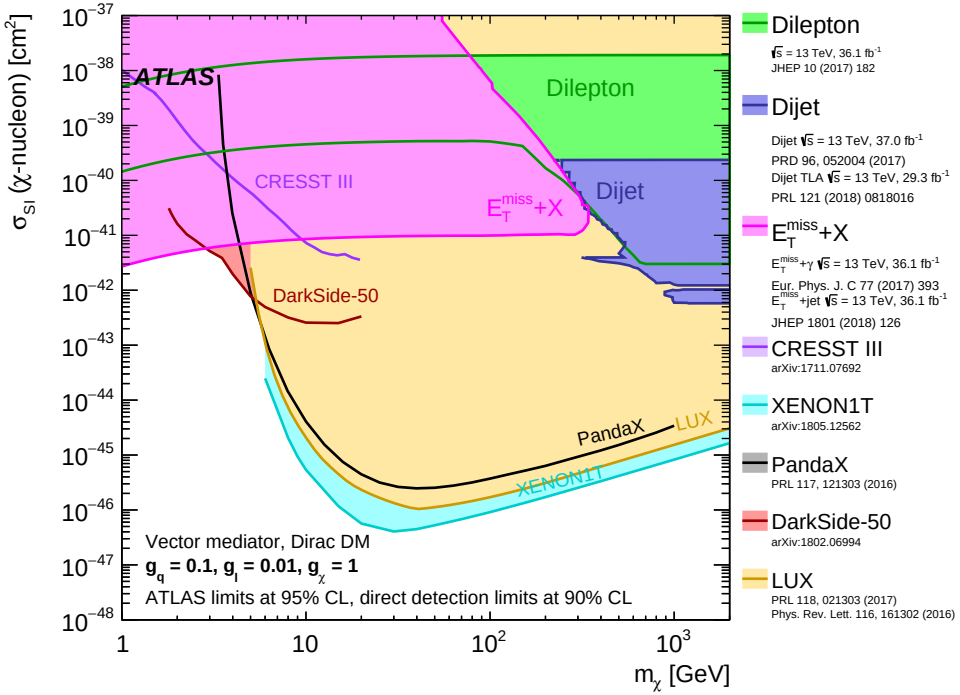
Vector Mediators, comparison with direct searches



Combinations of Dark Matter searches

Vector Mediators, comparison with direct searches



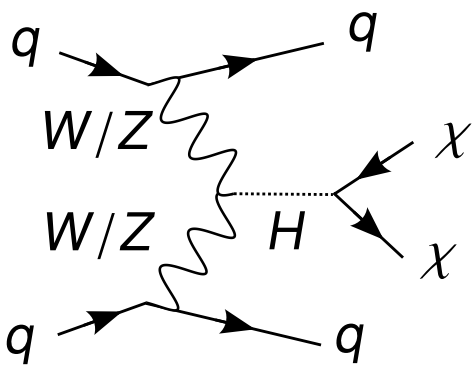


1903.01400, subm. to JHEP

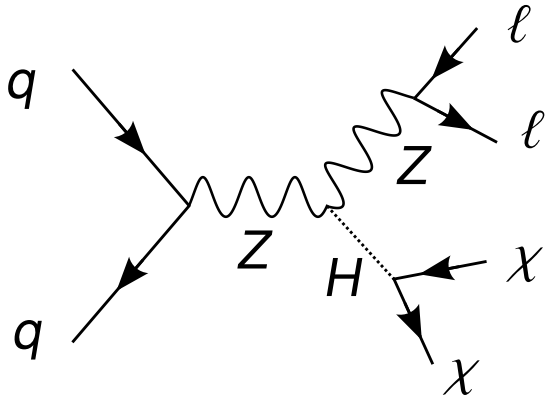
- For the *model parameters chosen here*: higher sensitivity of the E_T^{miss} + jet search compared to direct searches at low values of m_χ (where the χ-nucleon elastic scaterring cross-section is small)

Combinations of Dark Matter searches

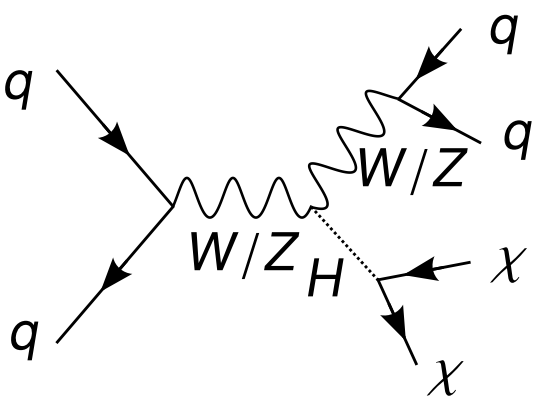
Higgs-boson decays to weakly interacting particles



VBF+MET



Mono-Z(ll)

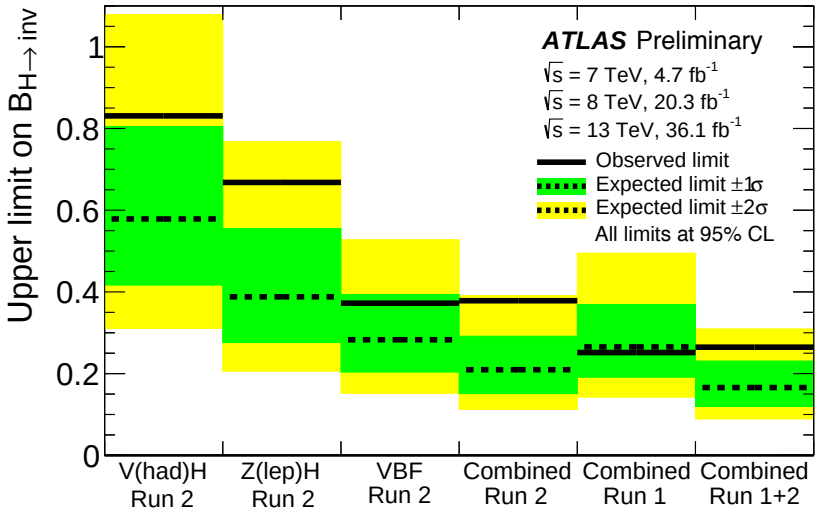


Mono-V(qq)

- Statistical combination of
  - 3 channels
  - Run 1 and Run 2 data up to 2016
- Resulting observed (expected) limit:

$$\mathcal{B}(H \to \text{inv.}) < 0.26(0.17^{+0.07}_{-0.05})$$

(without constraints from Higgs boson observations)



ATLAS-CONF-2018-054

Dark Matter Searches at ATLAS

Summary

- Analysed Run 2 data with up to $\int L dt$ =80 fb^{-1}
- Numerous final states covered
- Interpretation in view of simplified models

Conclusions

1. Complementarity of direct, indirect and collider Dark Matter searches
2. Complementarity of different final states
3. Analysis improvements due to both increased statistics and new analysis techniques, both to come with the analysis of the full Run 2 dataset

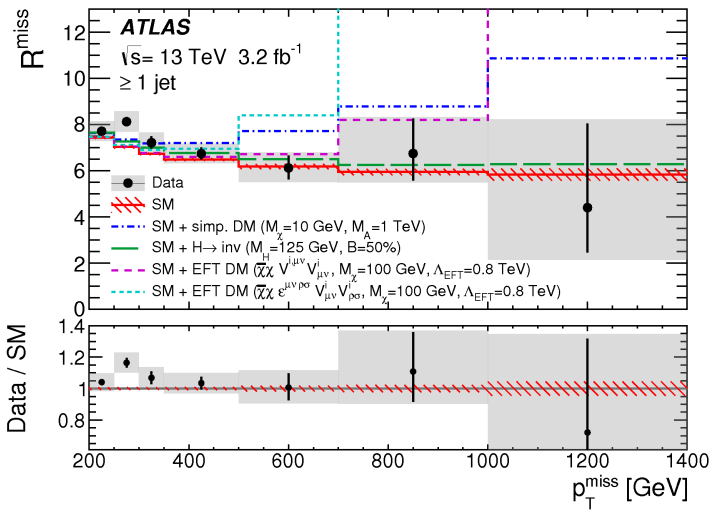
Backup

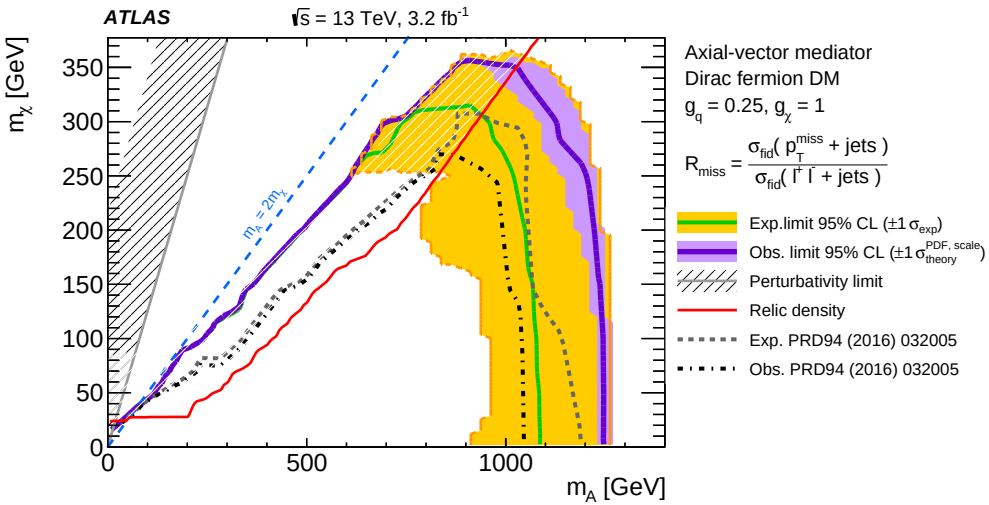
$Z(\nu\nu)/Z(\ell\ell)$ ratio measurement

- Differential measurements of

$$R^{\text{miss}} = \frac{\sigma_{\text{fid}}(Z\to\nu\nu\text{+jets})}{\sigma_{\text{fid}}(Z\to\ell\ell\text{+jets})}$$

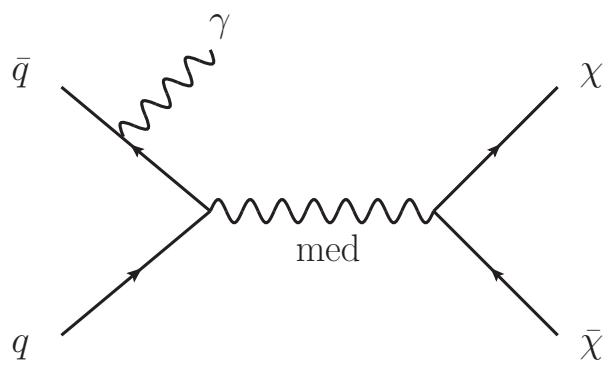
- Two regions with different unfoldings
  - $\geq$1 jet: $E_{\text{T}}^{\text{miss}}$
  - VBF: $E_{\text{T}}^{\text{miss}}$, dijet mass, dijet $\Delta\varphi$
- Allowing to constrain many (future) jets + $E_{\text{T}}^{\text{miss}}$ BSM models

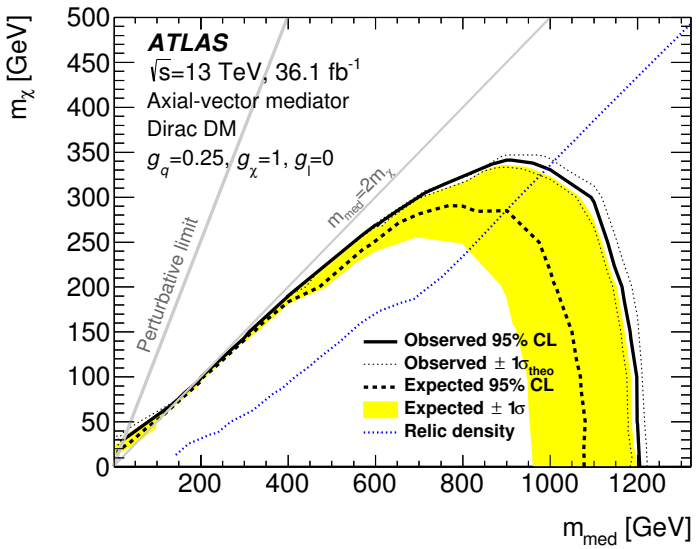


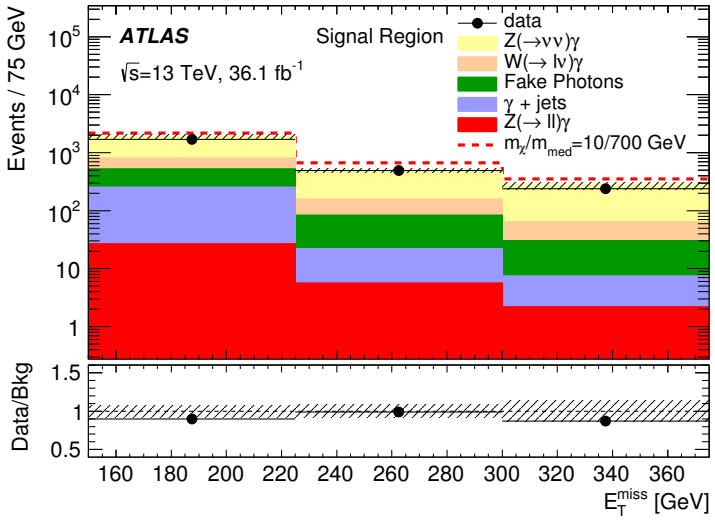


Photon+E_T^{miss}

- E_T^{γ} and E_T^{miss} > 150 GeV + up to one jet
  - Photon trigger allows for lower E_T^{miss} values compared to the mono-jet analysis
- Again, combined fit of signal and control regions using E_T^{miss}

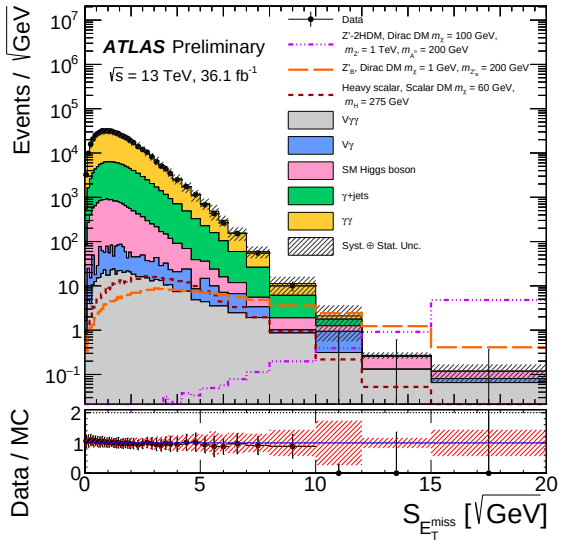


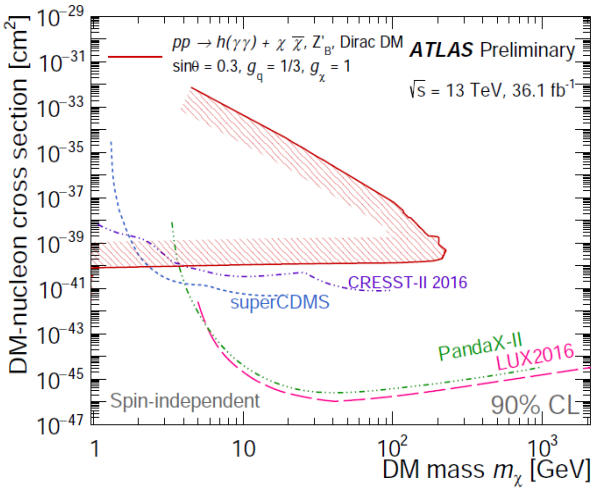


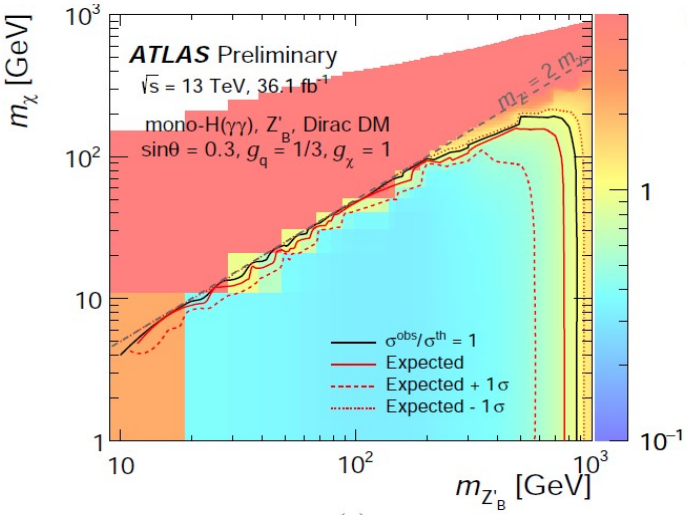


Mono-h($\gamma\gamma$)

- Circumvent E_T^{miss} trigger threshold of the Mono-h(bb) analysis: $h \to \gamma\gamma$
- $\mathcal{BR}(h \to \gamma\gamma) < \mathcal{BR}(h \to bb)$, but better m_h resolution
- Z'+2HDM limits, also referring to the spin-indep. DM-Nucleon cross-section

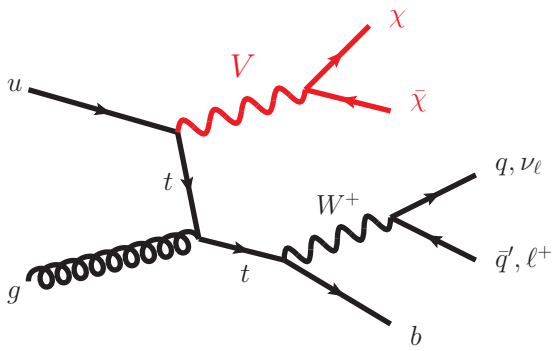


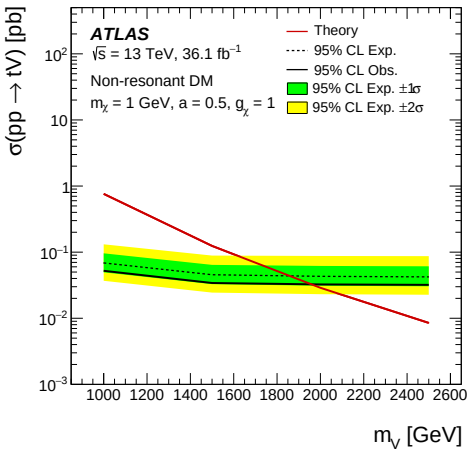


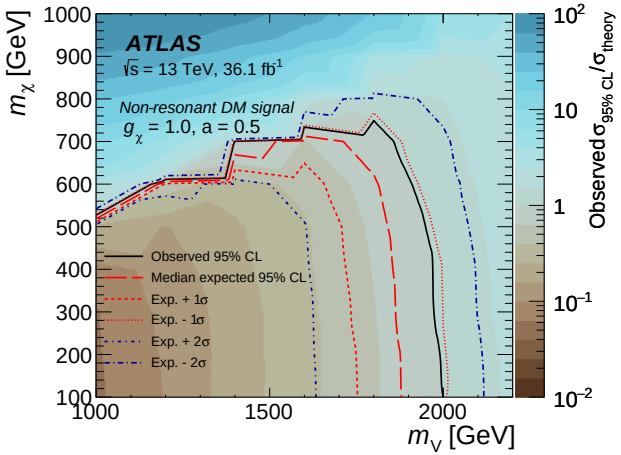


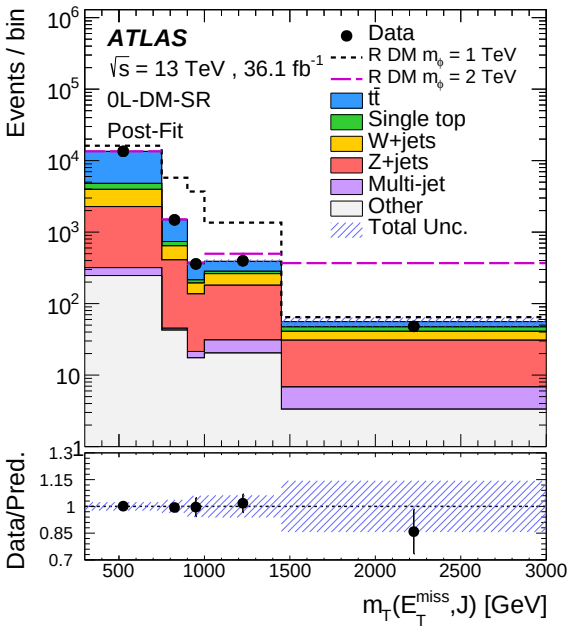
Single top + E_T^{miss}

- Resonant and non-resonant top + dark matter production (+ Vector-like T-quark search with $T \to tZ$ decays)
- Several reducible backgrounds (SM top), negligible irreducible background: FCNCs
- Two approaches: leptonic top decays and boosted hadronic top decays





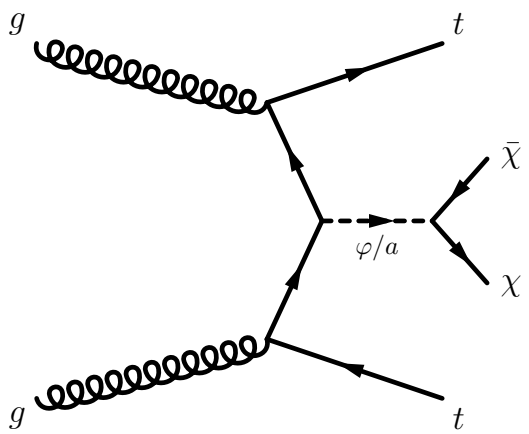


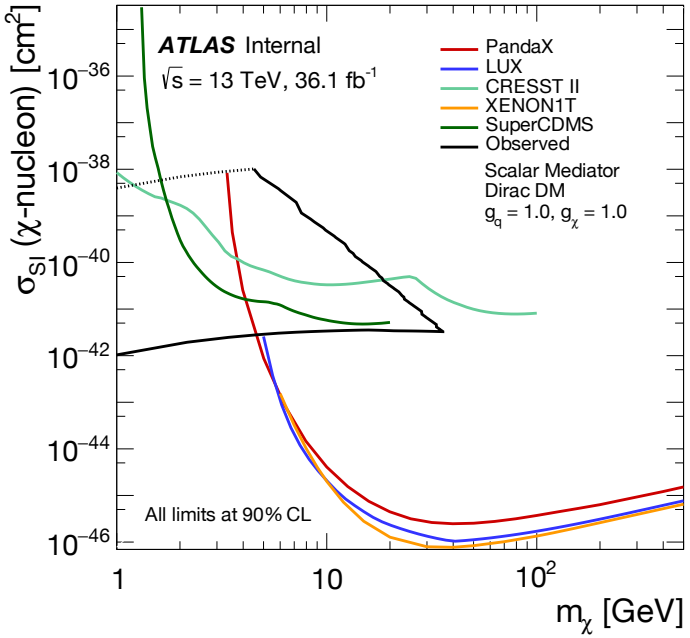


1812.09743, subm. to JHEP

Heavy Flavour Quarks + E_T^{miss}

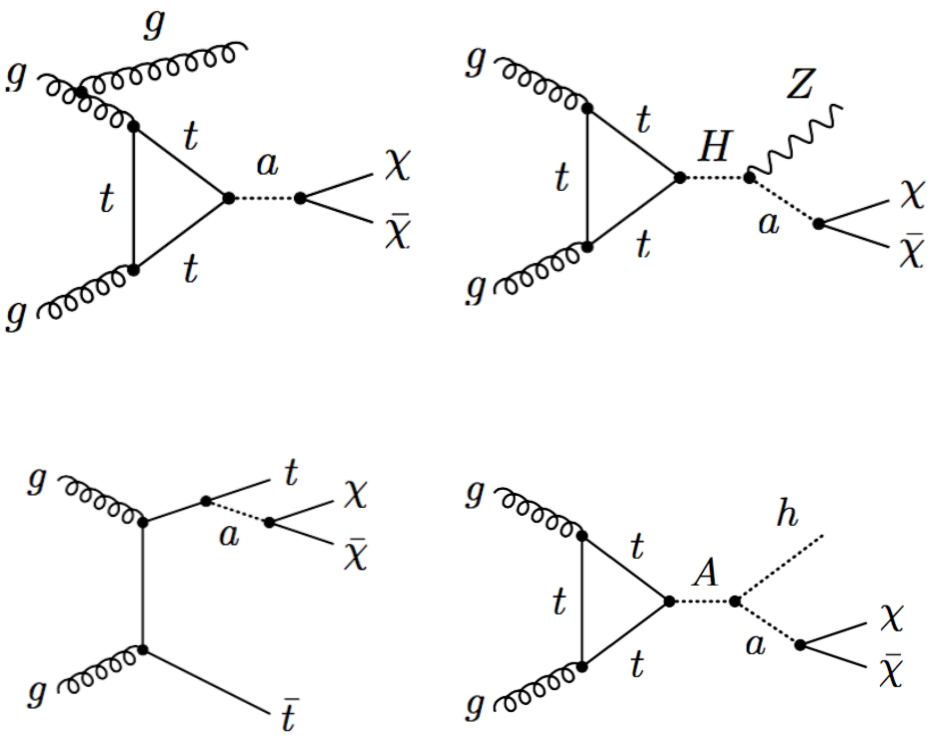
- Several models with new scalar particles mediating between SM and DM particles
- Avoid constraints from flavour physics ⇒ Yukawa couplings set proportional to fermion masses
- Five signal regions sensitive to different BSM scenarios + several control regions for background normalisation
- Limits on new particle masses + model independent limits on detector level cross-sections





2HDM + Pseudoscalar Model

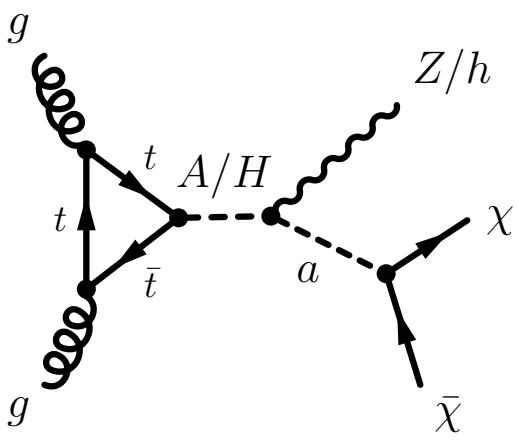
- Careful extension of the SM avoiding numerous constraints, UV complete
- Dark matter: fermion, SM gauge group singlet
- Many relevant production modes; notably including resonant production $H \to aZ$ and $A \to ah$

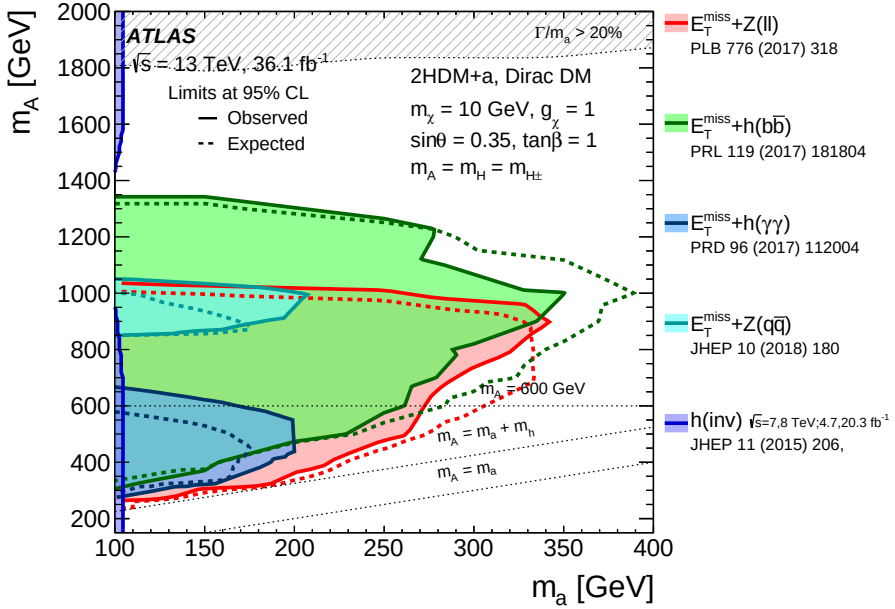


Combinations of Dark Matter searches

2HDM + Pseudoscalar

- UV-complete model, avoiding constraints from direct searches
- Rich phenomenology with several important final states
- Proposed in JHEP05 2017 138, i.e. in the middle of Run 2 ⇒ desire for reinterpretation
  - Rerunning analyses, in case of Mono-H(*bb*) semi-automatically - see this *ATLAS contribution at last week's LHC reinterpretation workshop*
- Ability to perform reinterpretations becoming more important





1903.01400, subm. to JHEP

Mono-Higgs(bb)

Improvement due to VR track jets