ATLAS searches for Dark Matter at HL/HE-LHC

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FNAL YR Workshop, 4/4/2018

WG3 Table of content

- DM studies are a very important component of YR

The table of content is based on the input collected so far in this online spreadsheet. That does not yet included all experimental studies already done or in progress [being upd

1. **Introduction and overview**
    1. New Physics models
    2. Analysis methods and approaches
    3. Treatment of systematic uncertainties
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        a. Prospects for realistic SUSY models at the HL-/HE-LHC *(S. Heinemeyer et al.)*
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        b. same-sign dilepton SUSY *(CMS)*
    3. SUSY EWK production
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        b. Prospects for chargino pair production at HL- and HE-LHC *(S. Carra' et al. ATLAS)*
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        g. Constraining slepton and chargino through compressed top squark search *(P. Konar et al.)*
        h. light Higgsino ISR + 2leptons and VBS + 2leptons (CMS)
3. **Dark Matter searches**
    1. DM + jets
        a. Prospects for DM interpretations in jet+MET analysis at HL/HE-HLC *(C. Gustavino et al. ATLAS)*
        b. Monojet searches for DM *(CMS)*
    2. DM + ttbar / bbbar
        a. Prospects for associated production of dark matter and top quark pairs at the HL-LHC *(F. Meloni et al. ATLAS)*
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        c. HL/HE-HLC prospect for determining the CP nature of spin-0 mediators in associated production of dark matter and top pairs *(U. Haisch et al.)*
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    4. More models expected to be targeted
        a. Prospects for pure WIMP (pure triplet) Dark Matter at HL-LHC *(L. Carminati et al. ATLAS)*
4. **Long Lived particles**
    a. disappearing tracks
    b. displaced vertex
    c. various interpretations? Other signatures (stable)?
5. **Dark sector: dark photons**
    a. Searching for dark photons via Higgs boson production at the HL-LHC and HE-LHC (S. Biswas et al.)

HL and HE will most probably be put in the same chapter, depending on the topics. Experiments will rather make sure we have a comprehensive and interesting set of HL studies and prospects at HE than vice-versa.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG3

.. [table of content is work in progress]

Outline

- Analyses and models under study so far @ ATLAS
  - Mono-jet DM
  - Mono-top DM
  - DM+bb/DM+tt
  - DM with 2HDM models (also using top-associate production)
  - VBF and mono-photon production
  - More on Dark sector: Search for dark photons using displaced lepton-jet signature (see Laura Jeanty talk for LLP)
- **For discussion:** mostly addressing WIMP-like DM. Should/could we target other cases? E.g. axions?
  - Inputs from theorists would be welcome!

Disclaimer: most of the work is in progress and can't be shown yet

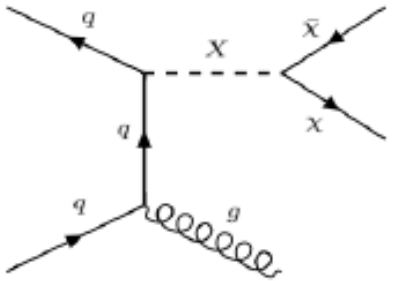
Methodologies in ATLAS

- Experiments use different approaches to perform analyses. In ATLAS
  - **Method 1 - truth + smearing:** truth-level events overlaid with jets (full sim) from pileup library, reconstruct particles (electrons, muons, jets, MET) from truth +overlay and smear their energy and pT using appropriate smearing functions
    - Cross checked with some of the 'real' data analyses
  - **Method 3: projections**
    - Existing signal and background samples (simulated at 13 TeV) scaled to higher luminosity and sqrt(s)=14 TeV. Analysis steps (cuts) from present analyses.
    - Various scenarios for systematics. E.g.: three cases (1) keep present systematics (2) Improved by a fixed factor (3) no systematics, only statistics
- Each approach has pros and cons and results might be very different depending on the assumptions (e.g. on systematic uncertainties, detector performances, contributions from rare background)

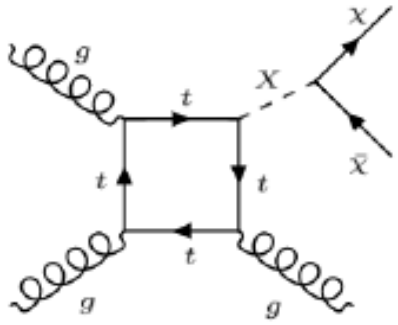
→ AIM to have a coherent approach with CMS and theory studies wherever possible

Mono-jet DM

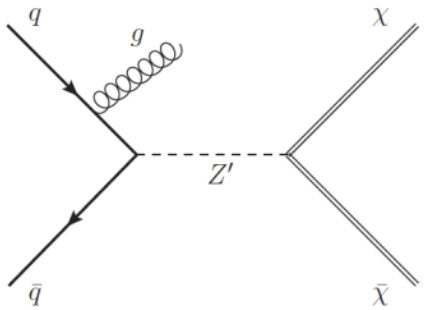
- One of the classic final states considered at colliders
- Sensitive to various DM production models – results also model-dependent



Spin-1 mediator, axialvector assumptions on g_{SM} , g_{DM}



Spin-0 mediator, pseudoscalar assumptions on g_{SM} =1,g_{DM} =1



Z' mediator with axial-vector couplings exchanged in the s -channel.

- **ATLAS Plans:**
  - Projections of most recent mono-jet search JHEP 01 (2018) 126
  - Complemented and cross-checked with 'smearing approach'
    - Status: samples production and independent re-evaluation of analysis on-going

Mono-jet DM (II)

- Projections will be based on current search and increased binning of SRs:
  - Current:

Inclusive (IM)	IM1	IM2	IM3	IM4	IM5	IM6	IM7	IM8	IM9	IM10
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 250	> 300	> 350	> 400	> 500	> 600	> 700	> 800	> 900	> 1000
Exclusive (EM)	EM1	EM2	EM3	EM4	EM5	EM6	EM7	EM8	EM9	EM10
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	250–300	300–350	350–400	400–500	500–600	600–700	700–800	800–900	900–1000	> 1000

  - Main bkg and systematics:

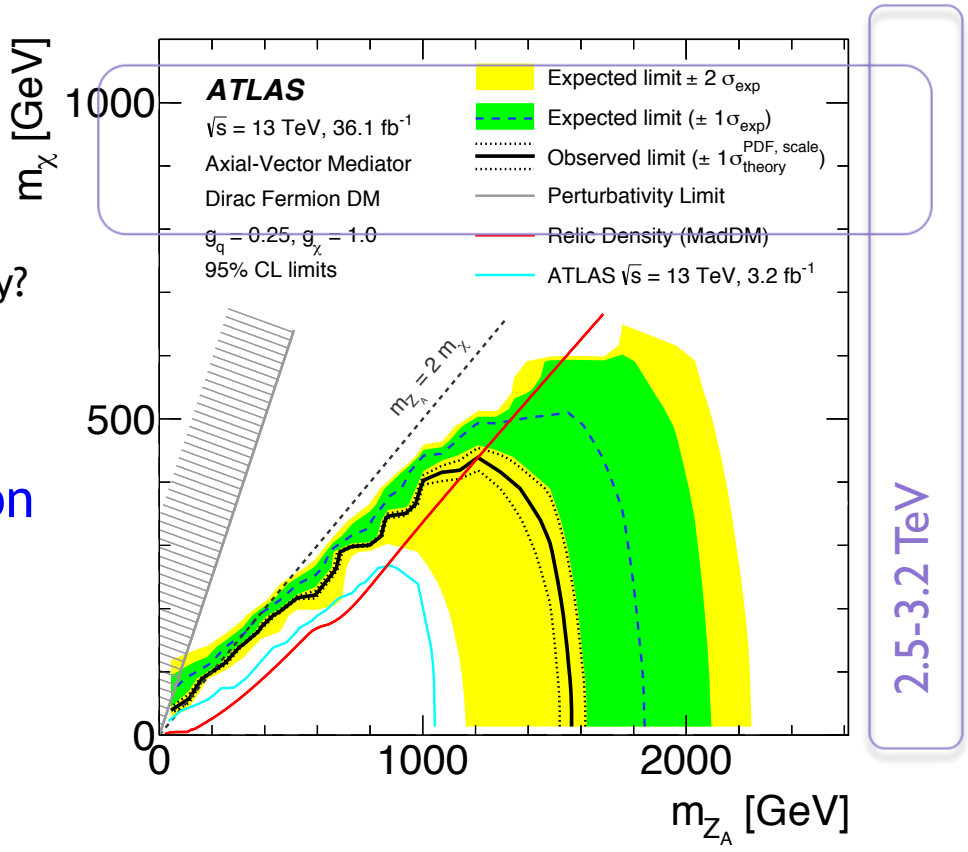
Inclusive Signal Region	IM1	IM3	IM5	IM7	IM10
Observed events (36.1 fb^{-1})	255486	76808	13680	2122	245
SM prediction	245900 ± 5800	73000 ± 1900	12720 ± 340	2017 ± 90	238 ± 23
$W(\rightarrow e\nu)$	20600 ± 620	4930 ± 220	682 ± 33	63 ± 8	7 ± 2
$W(\rightarrow \mu\nu)$	20860 ± 840	5380 ± 280	750 ± 44	115 ± 13	17 ± 2
$W(\rightarrow \tau\nu)$	50300 ± 1500	12280 ± 520	1880 ± 63	261 ± 13	24 ± 3
$Z/\gamma^*(\rightarrow e^+e^-)$	0.11 ± 0.03	0.03 ± 0.01	–	–	–
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$	564 ± 32	107 ± 9	10 ± 1	1.8 ± 0.5	0.2 ± 0.2
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$	812 ± 32	178 ± 8	24 ± 1	3.5 ± 0.5	0.4 ± 0.1
$Z(\rightarrow \nu\bar{\nu})$	137800 ± 3900	45700 ± 1300	8580 ± 260	1458 ± 76	176 ± 18
$t\bar{t}$, single top	8600 ± 1100	2110 ± 280	269 ± 42	26 ± 10	0 ± 1
Diboson	5230 ± 400	2220 ± 170	507 ± 64	88 ± 19	13 ± 4
Multijet background	700 ± 700	51 ± 50	8 ± 8	1 ± 1	0.1 ± 0.1
Non-collision background	360 ± 360	51 ± 51	4 ± 4	–	–

Main exp unc.: JES, up to 6%

Theory unc. on Z(vv) up to 2-3% (conservative unc associated to the last bin, p_T^{recoil} > 1 TeV, due to limited statistics of CR)

Mono-jet DM (III)

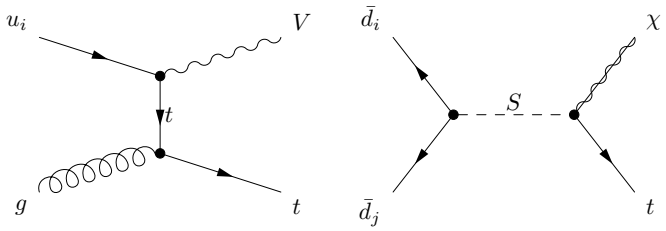
- Expectation on projections
  - multi-jet and Non-Collision Background will not be included in the expected limits (negligible in Run 2 analyses).
  - Different scenarios for systematics (To be discussed):
    - Same as current analysis:
      - too conservative ?
    - Reduced by factor of 2 or 4:
      - experimental and theoretical uncertainties together or separately?
    - Show also MC statistics only ?



- Sensitivity strongly depends on systematic unc. assumptions
  - → ~ 500-700 GeV difference in $m_{Z'}$
  - → ~ 200-300 GeV difference in m_{DM}

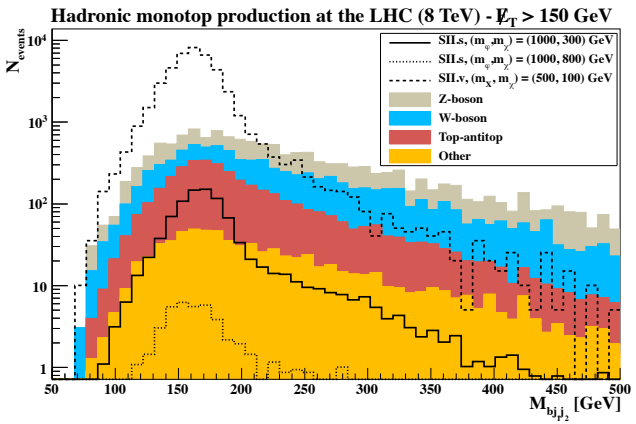
Dark Matter and heavy flavor quarks (I)

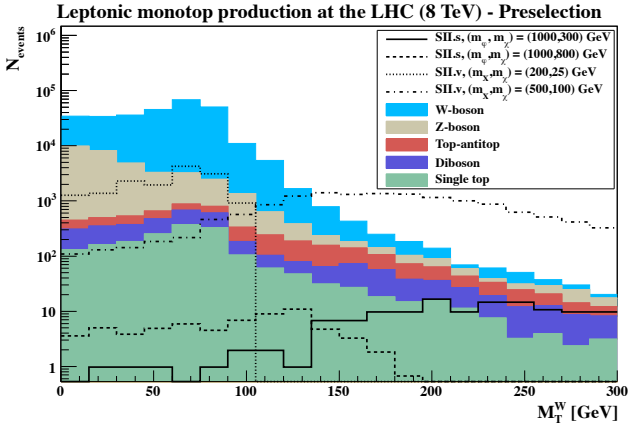
- Many more DM scenarios are actively pursued by ATLAS.
- Mono-top signatures (inspired by **1311.6478**)
- FCNC or exchange of heavy colored scalar field



signature

$$pp \to t + \not{E}_T \to bW + \not{E}_T \to bjj + \not{E}_T \ ,$$
$$pp \to t + \not{E}_T \to bW + \not{E}_T \to b\ell + \not{E}_T \ ,$$



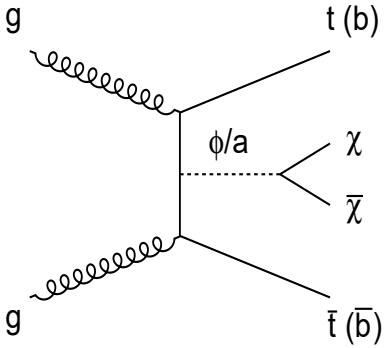


Promising already at 8 TeV!

- Studies in progress (**hadronic and leptonic channels**) for HL and HE
- Smearing-truth based analysis, results expected to be in ~2-3 TeV range for new scalar

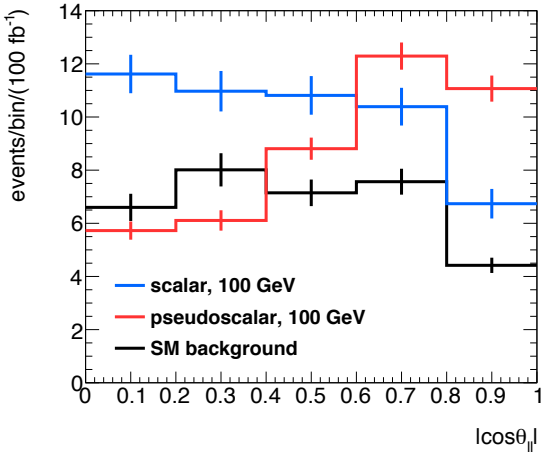
Dark Matter and heavy flavor quarks (II)

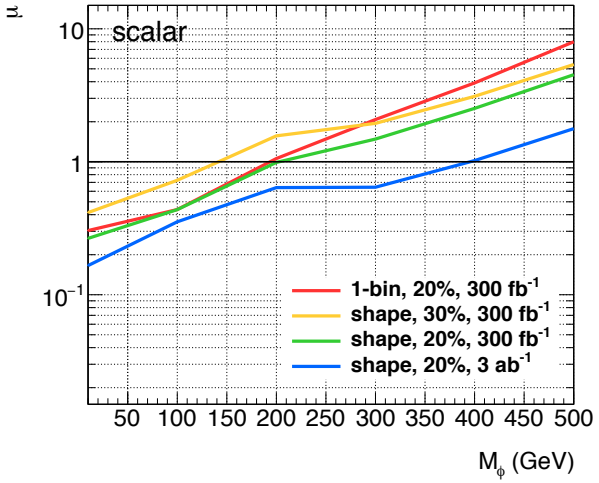
- **DM + bb**: b-jets might be **forward (|η|>2.4)**, analysis could benefit from extended tracking

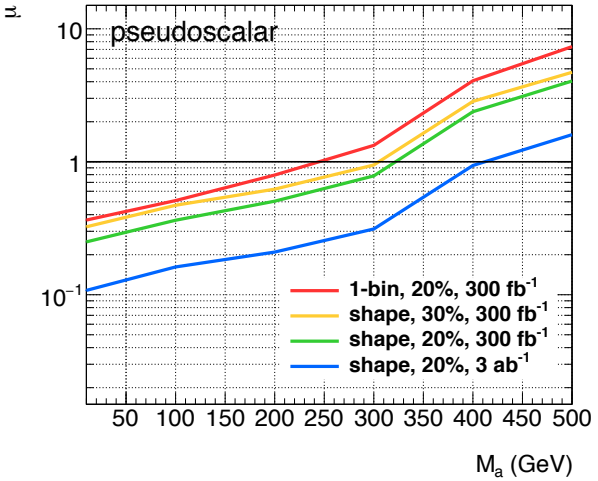


- **DM +ttbar**: studies on-going in the 2L channel
  - Exploit angular correlations of leptons from top decays (2l+2b+MET signatures)
  - Clear improvements with larger HL-LHC dataset

arXiV:1611.09841v2







in progress

Dark Matter and heavy flavor quarks (III)

- **DM + Wt:** from a spin-0 colour-neutral mediator
- Pinna et al.: 1701.05195

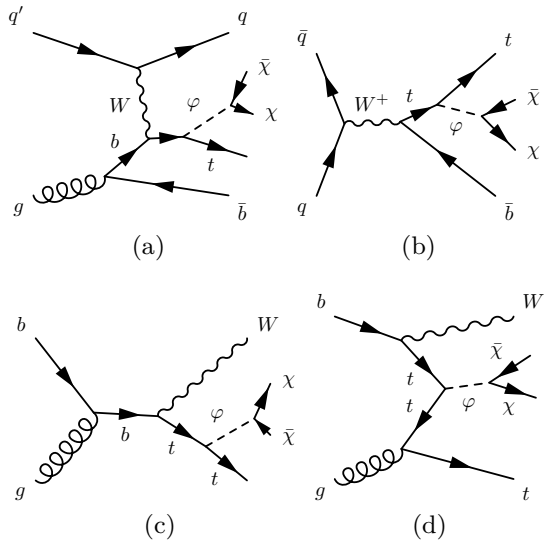
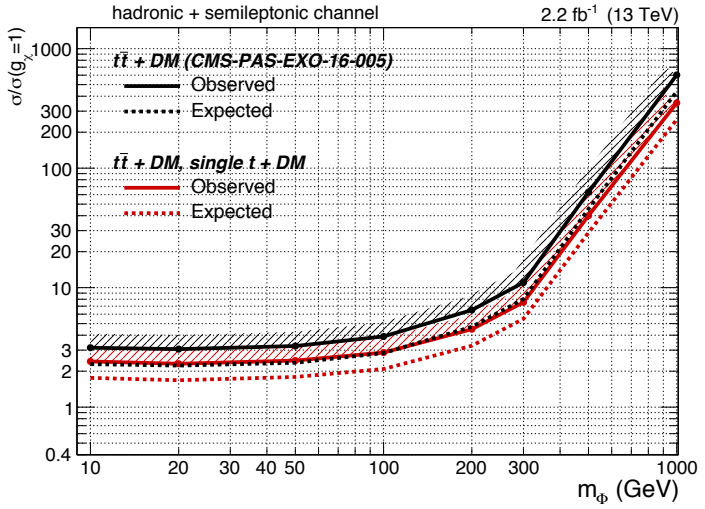


Figure 1: Main production diagrams for the associated production of dark matter with a single top at the LHC: (a) s–channel W boson production, (b) t–channel W boson production, and (c)–(d) associated tW production

Complementary to DM + tt. With CMS data:



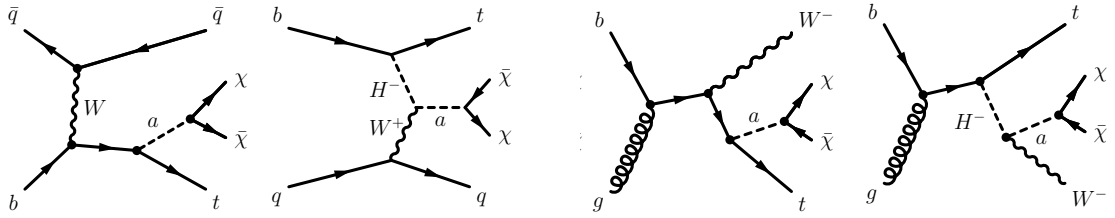
Hadronic and semileptonic channels were considered here. Sensitivity improved wrt using tt+DM only

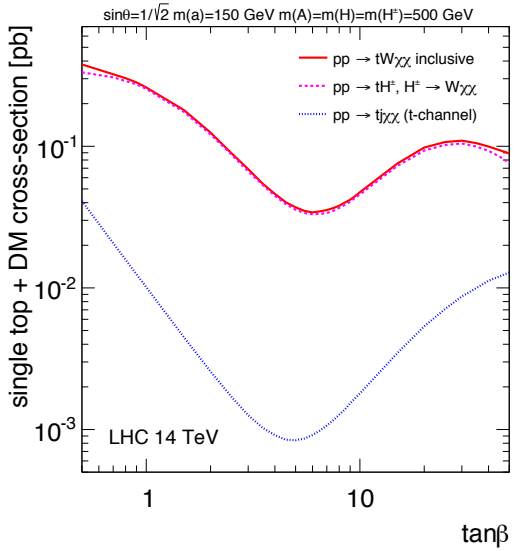
- Signature investigated @ ATLAS: **2L final state**
  - **More handles to extract signal using angular correlations**
  - **More statistics with HL-LHC datasets!**

in progress

more for DM in Wt+MET final states

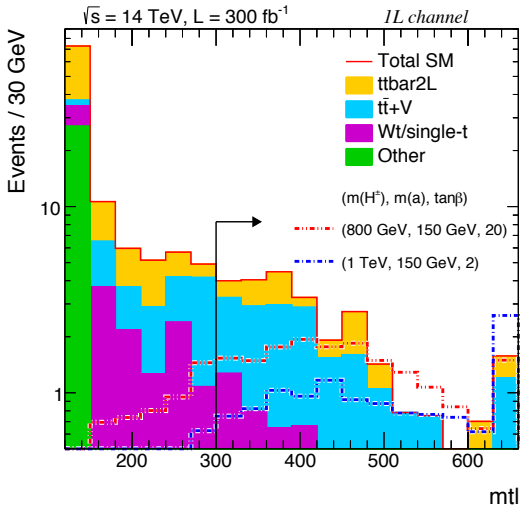
- Modified 2HDMa models lead to Wt+MET signatures

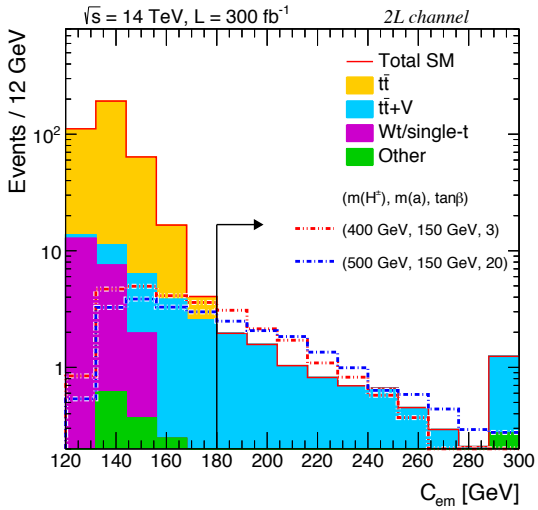


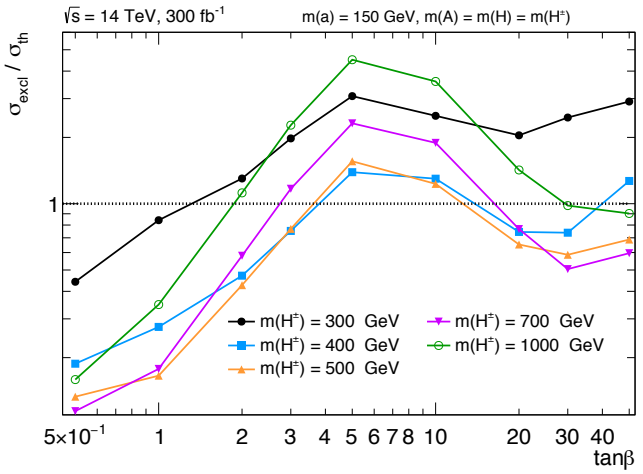


Studies in **1712.03874** performed using 1L and 2L channels

$$C_{\mathrm{em}} \equiv m_{\mathrm{T2}} + 0.2 \cdot E_{\mathrm{T}}^{\mathrm{miss}}$$

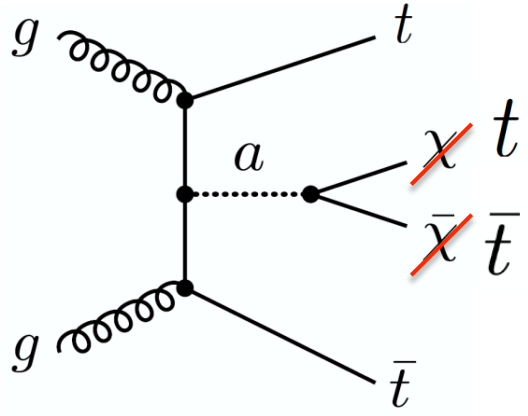






DM with 2HDM+a models

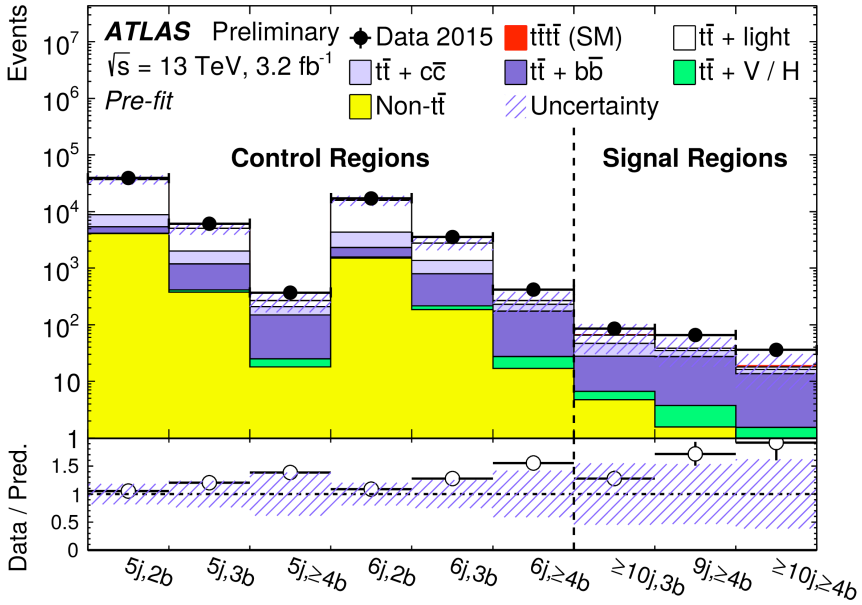
- One more final states being considered: 4-top



Look for final state with at least one lepton, multi-bjets and MET

Scan various sets of parameters:
- e.g. scan in m(a) for benchmark values of m_H

Analysis for Run 2 released with 3.2/fb

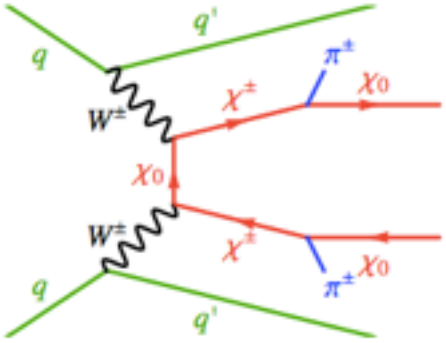


ttbar+bb main background
Difficult to model with MC but we can assume a better understanding of this process at HL-LHC!

VBF and mono-photon

- Targeting models with pure WIMPs. Here
  - pure WIMP triplet, which also corresponds to Wino-like DM
  - Experimentalists working with theorists
  - Based on models in arxiv:1407.7058 (and references therein)
    - Phenomenology like for SUSY where the Wino is the lightest sparticle
    - M(χ_0) < 3 TeV
  - Can be searched for with monojet, disappearing tracks, VBF and mono-γ

VBF:



- Models being produced with Madgraph
- Results strongly depends on the systematic uncertainties and MC statistics

- Using 4/ab and if the systematics are kept to a negligible effect, there is exclusion potential for the lowest masses considered - M(χ) ~100-150 GeV

Results being documented

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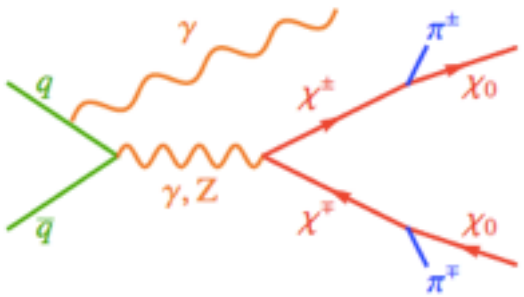
Mono-photon:



Reinterpret ATLAS results @ 13 TeV (36.1/fb)

arxiv:1704.03848

Expect a reach in the order of 300-400 GeV M(chi)
→ Can be improved with improved systematics

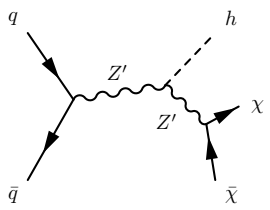
Results being documented

Dark Matter + X: more?

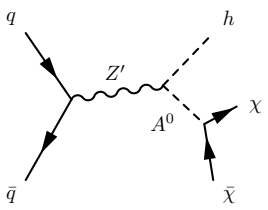
- Mono-W/Z/Higgs so far not considered
- Knowledge of high-MET tails and boosted objects reconstruction very relevant

E.g.: Higgs in bb+ E_T^{Miss}

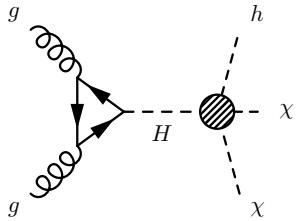
Z' model



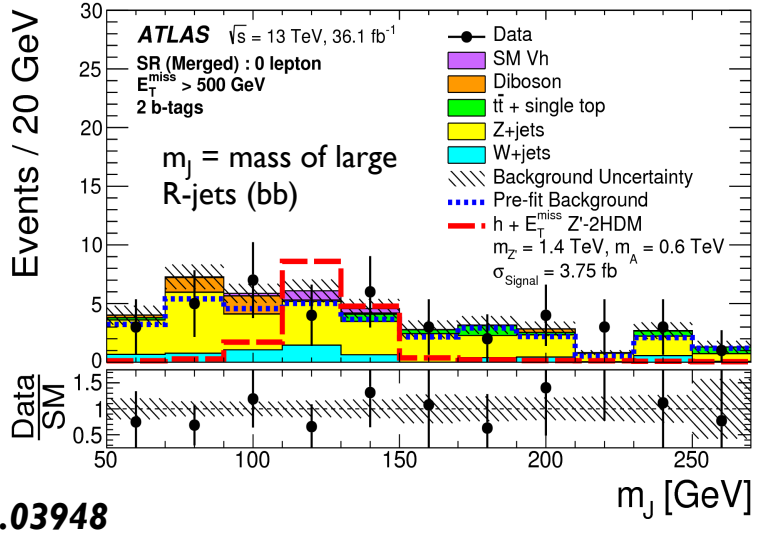
Z'/2HDM model



Heavy scalar model



Higgs: *e.g.* in bb final states



1706.03948

Something to pursue?

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At the moment we have contributions on a number of models/signatures

Higgs portal [either here or in higgs chapter] but no ATLAS efforts on this so far

DM only WIMP ***– any other possibilities? Axions ? More on dark sectors? Synergies with LHCb ?***

Summary

- Several DM models being targeted for YR
- Experiments mostly targeting HL but HE extrapolations being considered
  - Important to agree on approaches, e.g. for what concerns the treatment of systematic uncertainties *[see also Friday's summary]*
    - Reduction of current theory uncertainties
      - Reasonable to expect modelling of ttbar, V+jets, diboson improved by ½ or ¼ (?)
    - Reduction of experimental systematic uncertainties
      - Jet Energy Scale, b-tagging, fake leptons etc.
- **DM studies are not yet fully exploited for HL-LHC and HE-LHC: huge potential for contributions!**
- There is also potential also in terms of complementarities:
  - Push for a synergic approach across HL-LHC experiments in dark matter and dark sectors in general
  - Any idea how to do this concretely ?