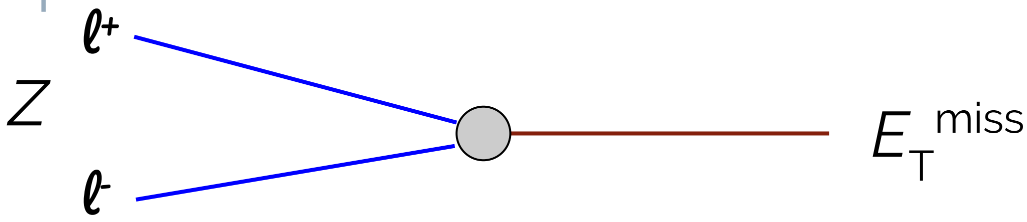
Search for **heavy ZZ resonances**, **invisible-particle decay modes of the Higgs boson** and **dark matter** in di-lepton final state with E_T^{miss} with the ATLAS detector

Higgs Hunting Workshop

Artem Basalaev (PNPI), on behalf of the ATLAS Collaboration

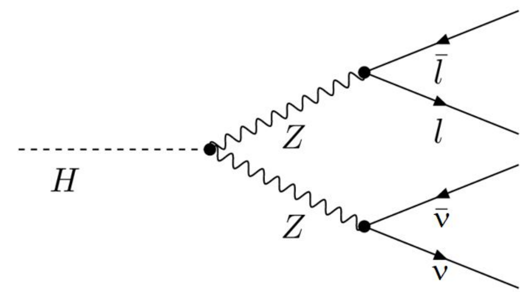
24 July 2018

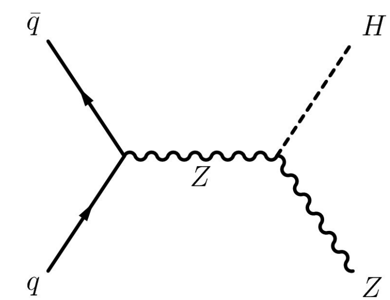
$Z+E_T^{miss}$ signature

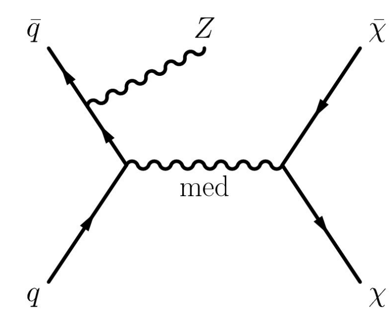


- Many possibilities for new physics: 3 different searches:
  - Heavy ZZ resonances — additional heavy Higgs boson
  - Invisible decay of SM Higgs
  - WIMP dark matter particles
- Same selection (except for a few final cuts), same backgrounds

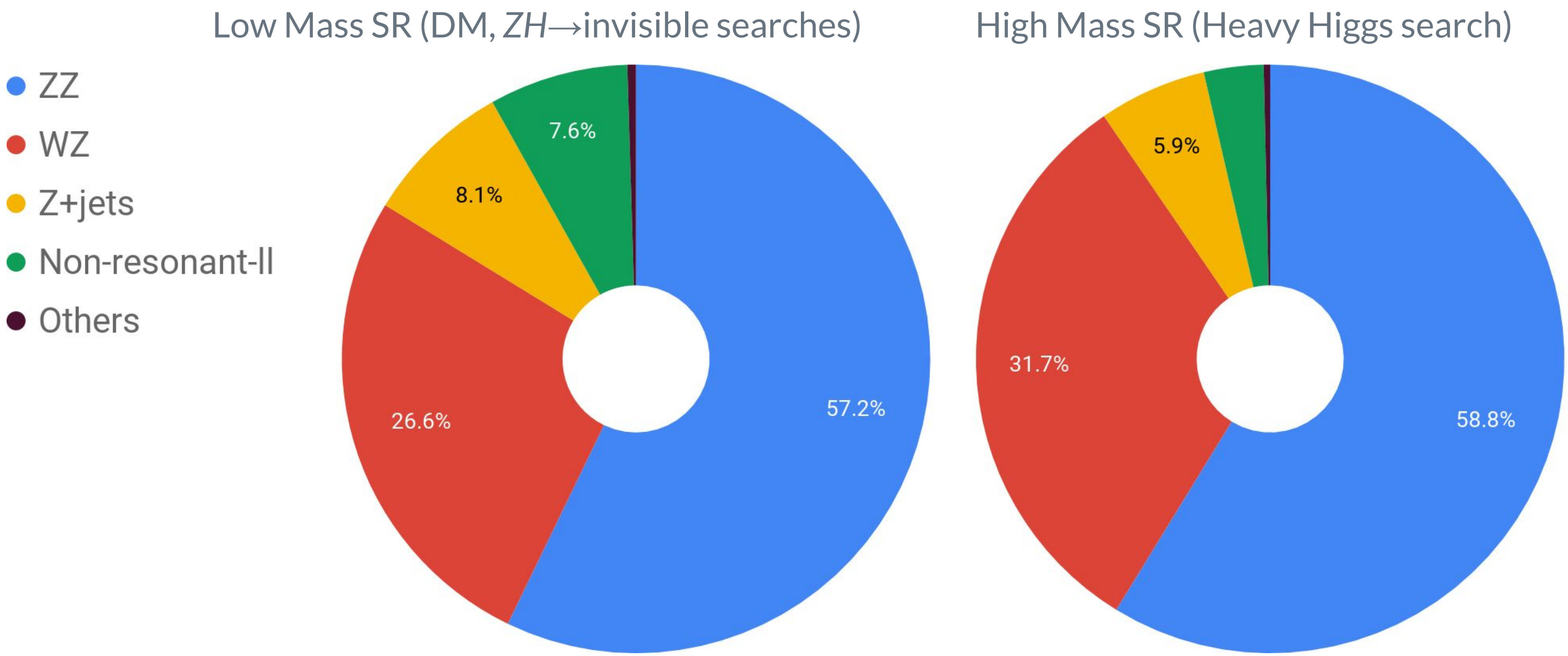
Results presented for 36.1 fb^{-1} of ATLAS Run 2 data at $\sqrt{s}$=13 TeV







Backgrounds



- ▷ Two signal regions, differing by values of a few final cuts
- ▷ ~Same background composition & estimation methods

Background estimation and event selection

- $ZZ \to \ell^+\ell^-\nu\nu$ — **dominant** background, **estimated from NLO QCD MC samples**
    - Irreducible with cuts
- $WZ \to \ell\nu\ell^+\ell^-$ — **data-driven estimation** using 3-lepton CR, where *WZ* dominates
    - Veto events with >2 leptons
- Top, *Wt*, *WW* and $Z \to \tau\tau$ **data-driven estimation** using eμ CR and the ratio ee:μμ:eμ = 1:1:2 and reco efficiency difference between electron and muon.
    - Require E_T^{miss} back-to-back with *Z* boson, max ΔR(l,l) — boosted *Z*, E_T^{miss} balanced in p_T against *Z*
- *Z*+jets — **data-driven estimation** using 3 CRs adjacent to SR in non-correlating variables — the *ABCD* method
    - Cuts above + require min E_T^{miss}, min E_T^{miss}/H_T
- Others — **estimated from MC** (*W*+jets — **data-driven estimation** using *fake-factor* method)

Results: low mass

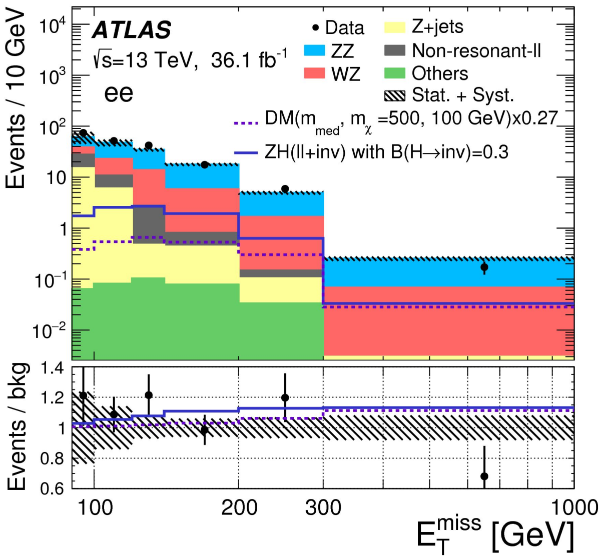
Low mass

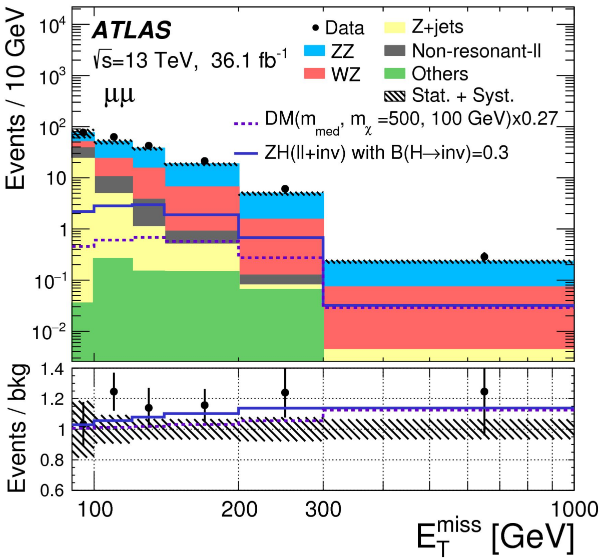
	e^+e^- channel	$\mu^+\mu^-$ channel
Total background	399 ± 6 (stat) ± 34 (syst)	426 ± 6 (stat) ± 28 (syst)
Observed data	437	497

No significant excess over SM prediction

Main uncertainty sources

ZZ (~7% relative, **high absolute**)	PDF choice, perturbative calculation, parton shower modelling
WZ (~6% relative)	SR/CR ratio, data stats
Z+jets **(>50% relative)**	Data-driven method bias, modelling
Non-resonant-ll (~8% relative)	Data-driven method bias, data stats





Results: high mass

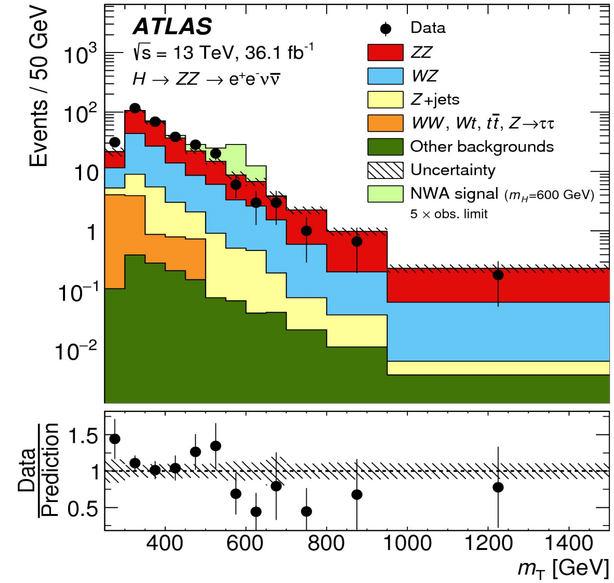
High mass (ggF)

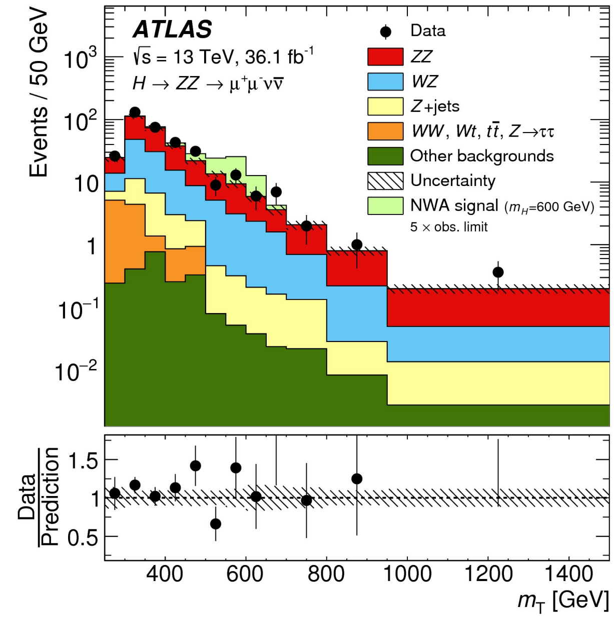
	e^+e^- channel	$\mu^+\mu^-$ channel
Total background	297 ± 4 (stat) ± 24 (syst)	311 ± 5 (stat) ± 27 (syst)
Observed data	320	352

No significant excess over SM prediction

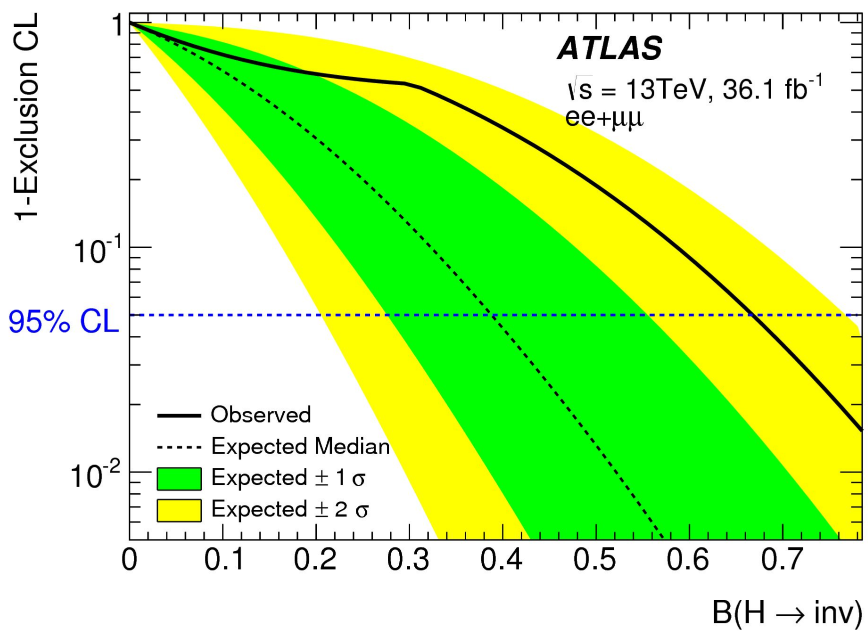
Main uncertainty sources

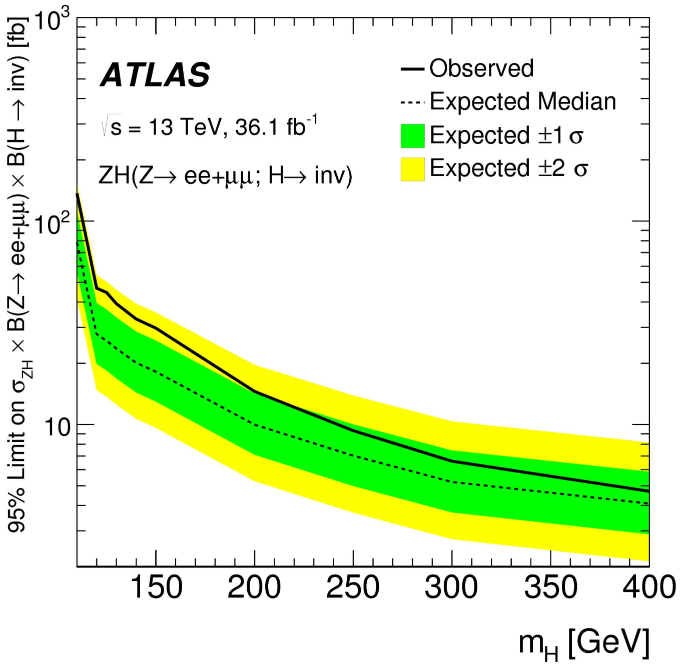
ZZ (~12% relative, **high absolute**)	PDF choice, perturbative calculation, parton shower modelling
WZ (~5% relative)	SR/CR ratio, data stats
Z+jets **(>50% relative)**	Data-driven method bias, modelling
Non-resonant-ll (~7% relative)	Data-driven method bias, data stats





ZH→invisible: 95% CL Limits



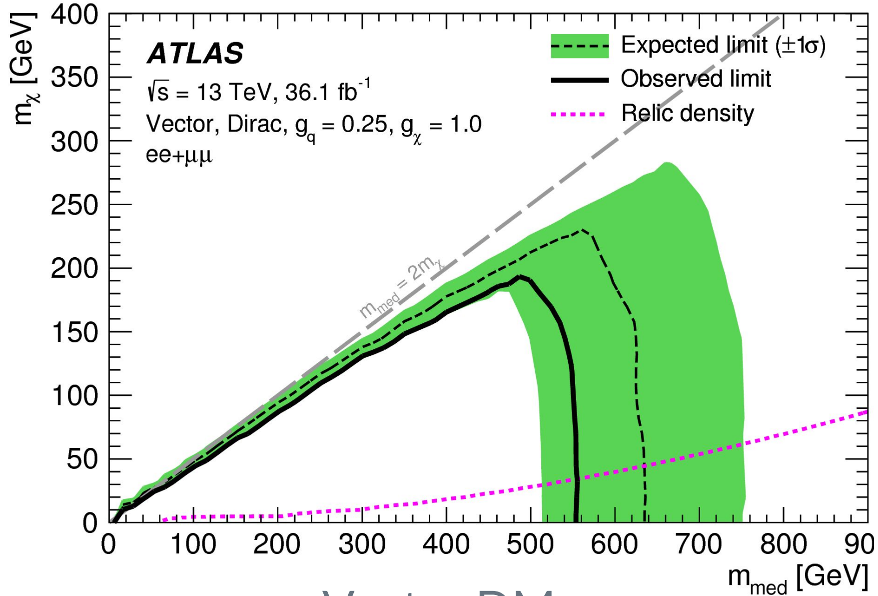


Observed BH→inv limit: **67%**

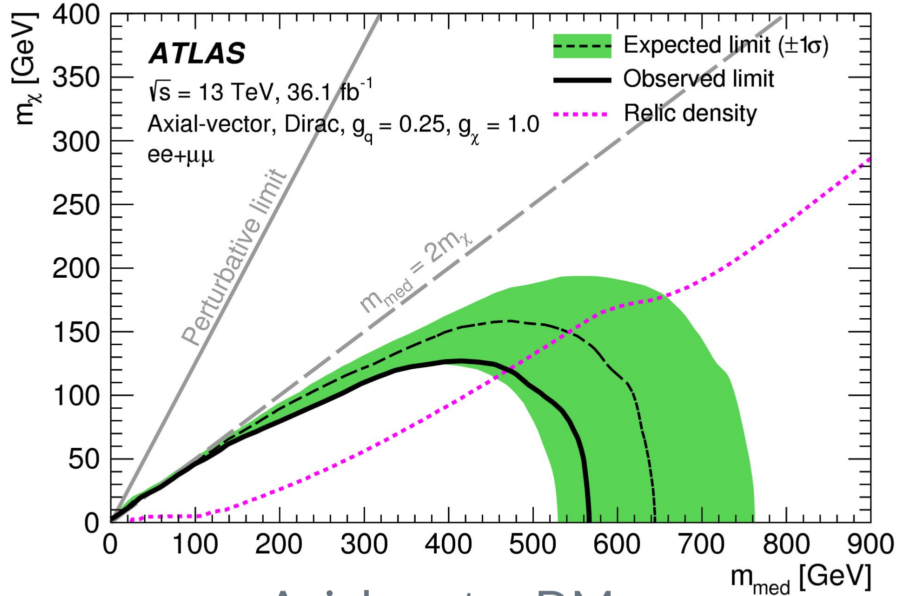
Expected: **39%**

Limits on ZH production cross-section with the prompt Z→ ee and Z→μμ decays and the invisible *H* decays as a function of m_H

DM particles: 95% CL Limits



Vector DM

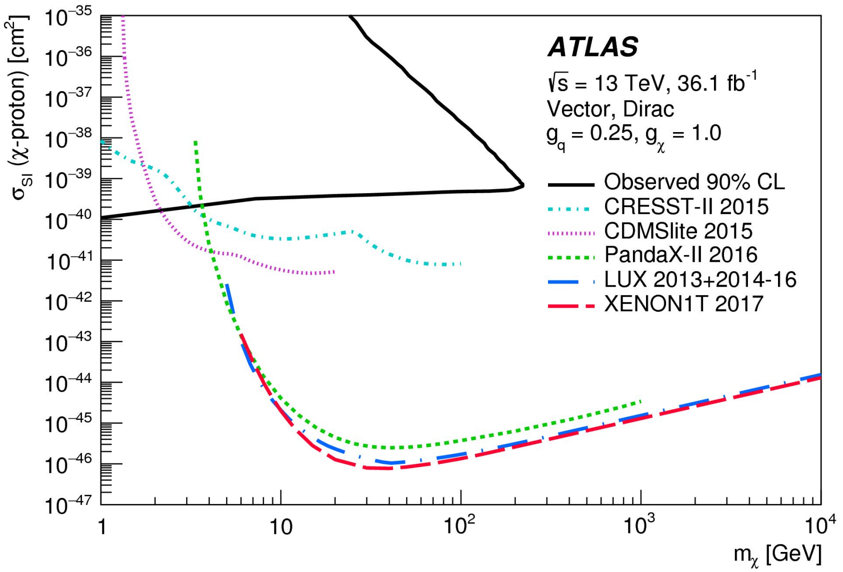


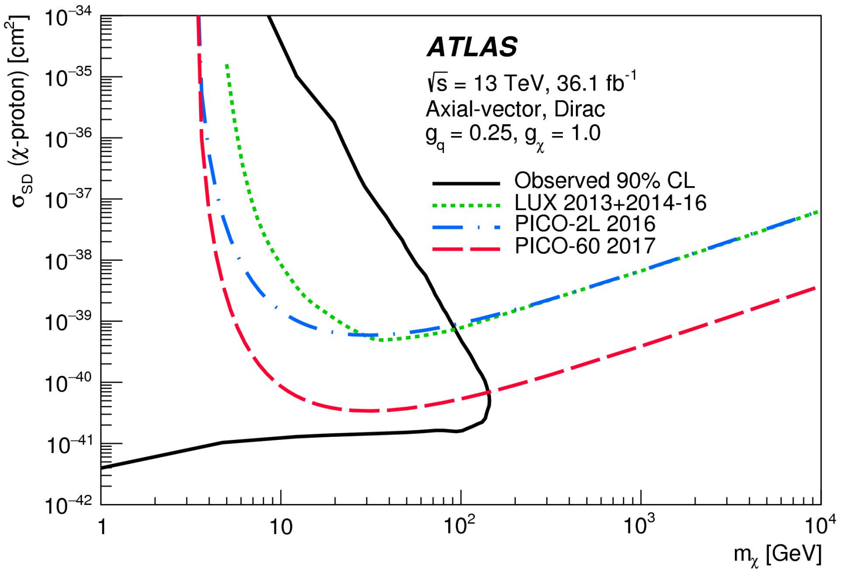
Axial-vector DM

DM exclusion limit in the 2D phase space of WIMP mass m_χ vs mediator mass m_{med}

Area below the curve is excluded

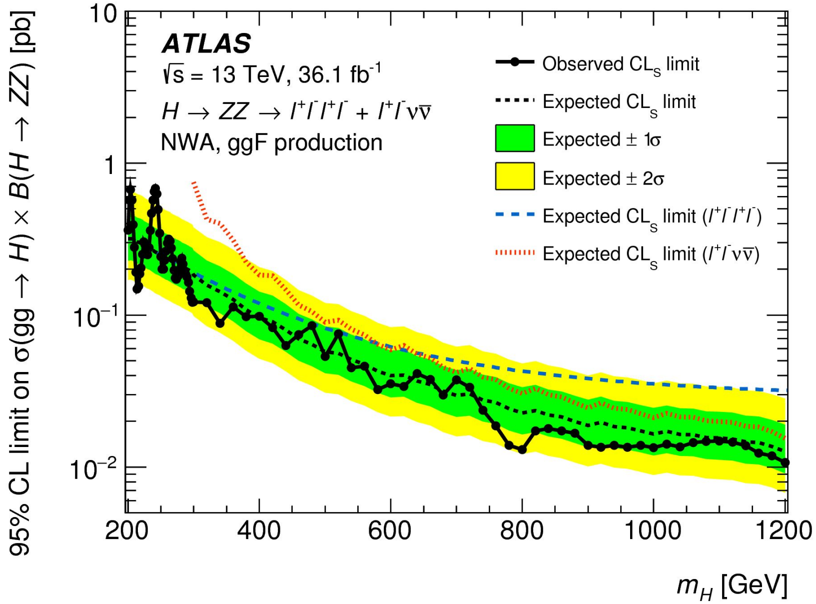
DM particles: 90% CL Limits Comparison with direct searches

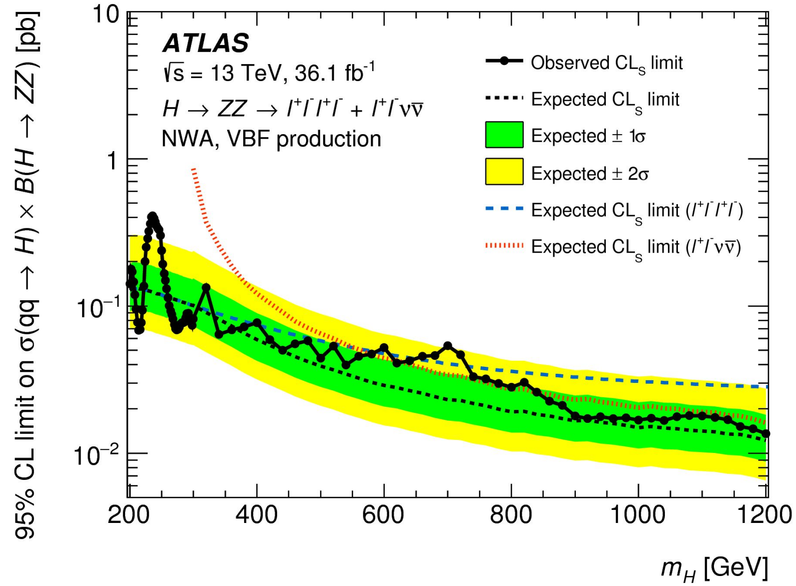




More sensitivity than direct searches for Axial-vector and Vector for low masses

Heavy Higgs: 95% CL Limits (combined with 4-lepton channel)





Limits on the cross section times BR as a function of the heavy resonance mass m_H ggF and VBF production in the case of the NWA

llvv becomes more powerful than 4l at high masses

Thanks for your attention!

Backup

Event Selection: cut-based

Cut	Rationale
Passed single lepton triggers and at least one of the leptons matches them	Select a “good” Z boson (reduce **tt**, $\boldsymbol{WW}\rightarrow\ell\nu\ell\nu$ backgrounds)
Exactly one ee or μμ pair (events with additional leptons are vetoed)	Additional leptons are vetoed to reduce $\boldsymbol{ZZ} \rightarrow \ell^{+}\ell^{-}\ell'^{+}\ell'^{-}$ and $\boldsymbol{WZ} \rightarrow \ell\nu\ell^{+}\ell^{-}$ backgrounds
Both leptons are “medium” LLH, leading p_T>30, sub-leading p_T>20 GeV	
Lepton system fits in Z mass window: 76<m_{ll}<106 GeV	
E_T^{miss}>90 GeV (120 GeV for HM search)	Reduce Z+jets background
$\Delta\varphi(Z,E_T^{miss})>2.7$	E_T^{miss} is back-to-back with Z boson, as expected from signal
$\lvert E_T^{miss,jets}-p_T^{ll}\rvert/p_T^{ll}<0.2$	E_T^{miss} is balanced in p_T against Z boson
$\Delta R(l,l)<1.8$	Z boson is boosted
$E_T^{miss}/H_T>0.6$ (0.4 for HM search)	Reduce Drell-Yan
$\min\Delta\varphi(\mathrm{jet}_{pT>100\ \mathrm{GeV}},E_T^{miss})>0.4$ (only HM search)	Reduce high m_T Drell-Yan
Veto events with b-jets	Reduce heavy flavor background

Background estimation: *WZ* 3-lepton CR

3-lepton CR definition
one ee or μμ pair
one additional lepton with p_T > 20 GeV
$76<M_{ll}<106$ GeV
$m_T(W)>60$ GeV
b-jet veto

Normalization factor

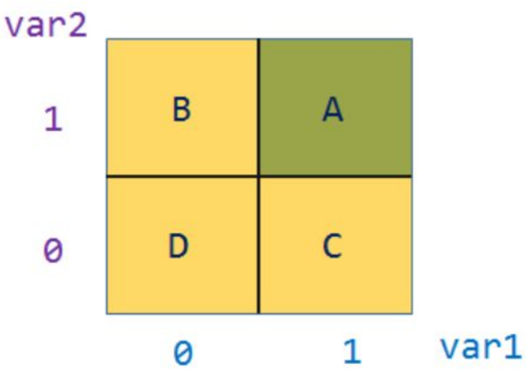
$$N_{est,\,SR} = N_{data,\,CR} \cdot N_{MC,\,SR}/N_{MC,\,CR}$$

Background estimation: *Top, Wt, WW and Z→ ττ*: eμ CR

Reco efficiency difference after Z mass requirement

$$N_{\text{est, SR(ee)}} = 1/2 \cdot N_{ee}/N_{\mu\mu} \cdot N_{\text{data}(e\mu)}$$
$$N_{\text{est, SR}(\mu\mu)} = 1/2 \cdot N_{\mu\mu}/N_{ee} \cdot N_{\text{data}(e\mu)}$$

Background estimation: *Z*+jets *ABCD* method



- Two uncorrelated variables are needed to construct 4 regions: one SR and 3 CRs
- $N_{A,\ data(SR)} = N_{C,\ data} \cdot N_{B,\ data} / N_{D,\ data}$
- In our case, a combination of variables used as a single ***boolean*** variable to increase event count in CRs
- Plus two **additional cuts** for CRs to reduce correlation induced by Z+jets

● var1 = E_T^{miss}>90(120) GeV && E_T^{miss}/H_T>0.6(0.4)
● var2 = $|E_T^{miss,jets} - p_T^{ll}|/p_T^{ll}$<0.2 && $\Delta\varphi(Z, E_T^{miss})$>2.7 && $\Delta R(l,l)$<1.8 && $N_{b\text{-}jets}$=0 (&& $\min\Delta\varphi(jet_{pT>100\ GeV}, E_T^{miss})$>0.4)

Additional cuts: E_T^{miss}>60(30) GeV && E_T^{miss}/H_T>0.12(0.1)

Background estimation: *W*+jets Fake-factor method

- Evaluating the probability for a jet to be mis-identified as a lepton using Tag and Probe method
- Probe: lepton-like jet - fails isolation (or LLH ID for electron)
- Fake-factor (applied to data): ratio of the probability for a jet to satisfy the full lepton ID criteria to the probability to satisfy the lepton-like jet criteria

Event yields: low mass

Final State	ee	$\mu\mu$
Observed Data	437	497
Signal		
$ZH \to \ell\ell + \text{inv}$ ($B_{H\to\text{inv}} = 30\%$)	$32 \pm 1 \pm 3$	$34 \pm 1 \pm 3$
DM ($m_{\text{med}} = 500$ GeV, $m_\chi = 100$ GeV) $\times 0.27$	$10.8 \pm 0.3 \pm 0.8$	$11.1 \pm 0.3 \pm 0.8$
Backgrounds		
$qqZZ$	$212 \pm 3 \pm 15$	$221 \pm 3 \pm 17$
$ggZZ$	$18.9 \pm 0.3 \pm 11.2$	$19.3 \pm 0.3 \pm 11.4$
WZ	$106 \pm 2 \pm 6$	$113 \pm 3 \pm 5$
Z + jets	$30 \pm 1 \pm 28$	$37 \pm 1 \pm 19$
Non-resonant-$\ell\ell$	$30 \pm 4 \pm 2$	$33 \pm 4 \pm 2$
Others	$1.4 \pm 0.1 \pm 0.2$	$2.5 \pm 2.0 \pm 0.8$
Total Background	$399 \pm 6 \pm 34$	$426 \pm 6 \pm 28$

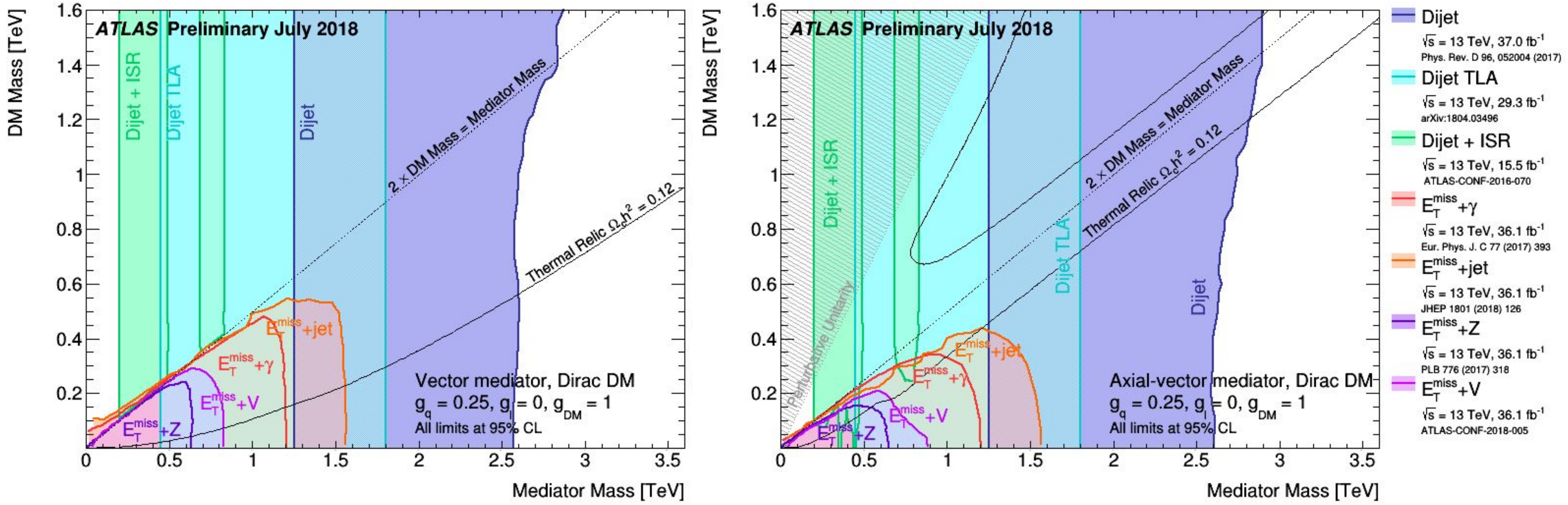
No excess over SM prediction

Event yields: high mass

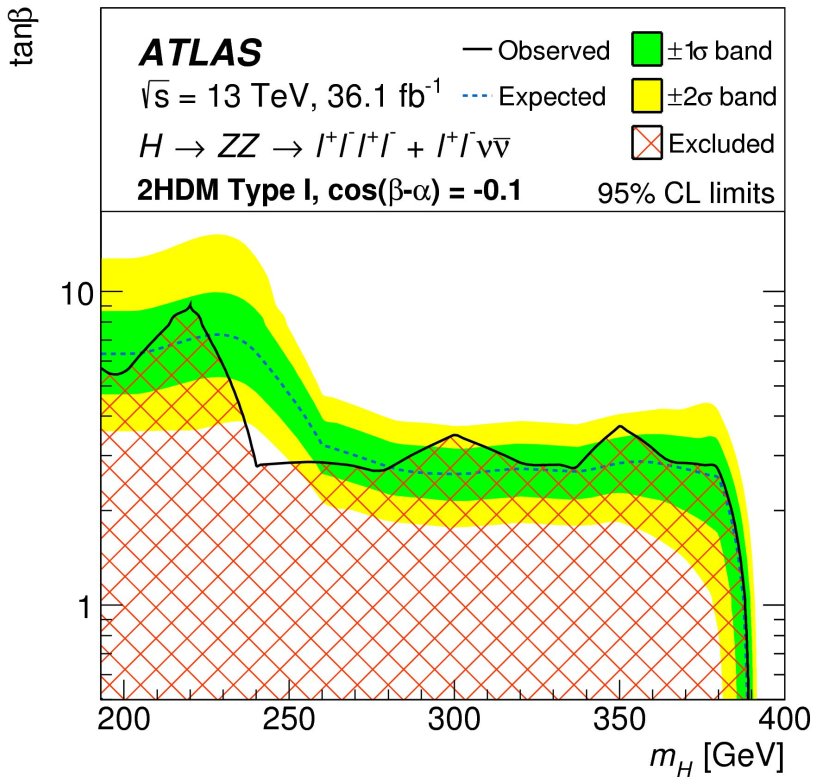
Process	ggF-enriched categories e^+e^- channel	ggF-enriched categories $\mu^+\mu^-$ channel	VBF-enriched category
ZZ	$177 \pm 3 \pm 21$	$180 \pm 3 \pm 21$	$2.1 \pm 0.2 \pm 0.7$
WZ	$93 \pm 2 \pm 4$	$99.5 \pm 2.3 \pm 3.2$	$1.29 \pm 0.04 \pm 0.27$
$WW/t\bar{t}/Wt/Z \to \tau\tau$	$9.2 \pm 2.2 \pm 1.4$	$10.7 \pm 2.5 \pm 0.9$	$0.39 \pm 0.24 \pm 0.26$
Z + jets	$17 \pm 1 \pm 11$	$19 \pm 1 \pm 17$	$0.8 \pm 0.1 \pm 0.5$
Other backgrounds	$1.12 \pm 0.04 \pm 0.08$	$1.03 \pm 0.04 \pm 0.08$	$0.03 \pm 0.01 \pm 0.01$
Total background	$297 \pm 4 \pm 24$	$311 \pm 5 \pm 27$	$4.6 \pm 0.4 \pm 0.9$
Observed	320	352	9

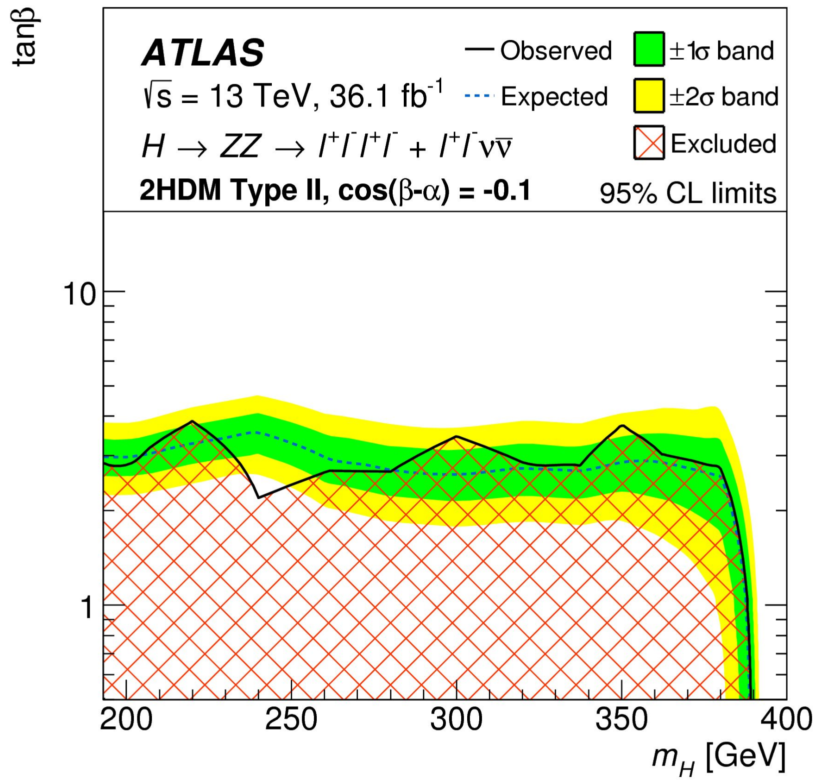
No excess over SM prediction

ATLAS DM limits in different channels



2HDM Type I and II 95% CL limits on tanβ (combined with 4-lepton channel)





ATLAS hMSSM limits in different channels