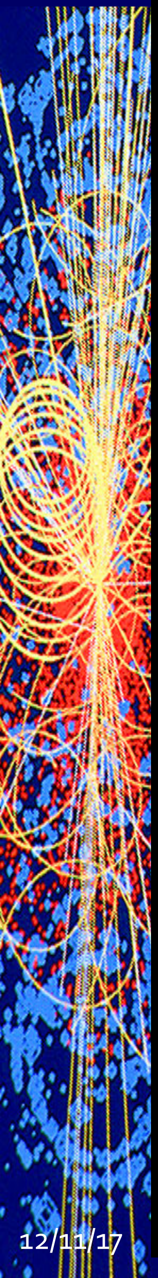
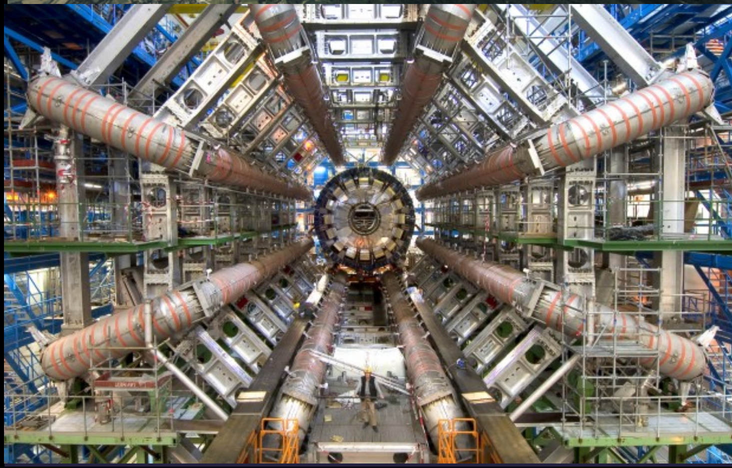


SEARCH FOR NON-STANDARD, RARE OR INVISIBLE DECAYS OF THE HIGGS BOSON WITH THE ATLAS DETECTOR



Daniela Bortoletto

University of Oxford

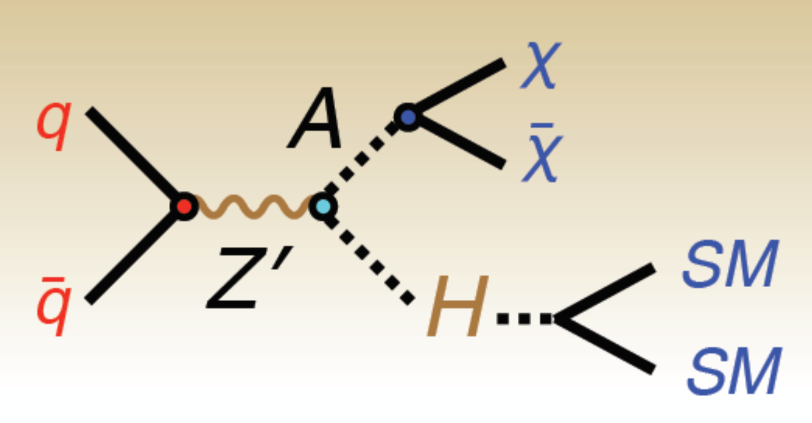
Outline

- The discovery of Higgs has open a new window to search for new physics:
  - Does dark matter interact with baryonic matter through the Higgs?
  - Is there a Higgs portal to dark matter ?
  - Are the couplings of the Higgs to light fermions as expected in the SM?
  - Are there Higgs decay modes forbidden in the SM?
- Focus on Run 2 results

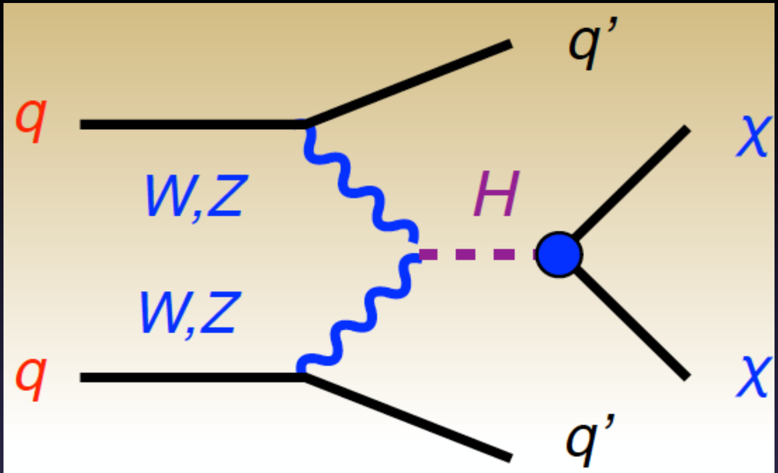
HIGGS AND DARK MATTER

Higgs decays to invisible

Mono-Higgs



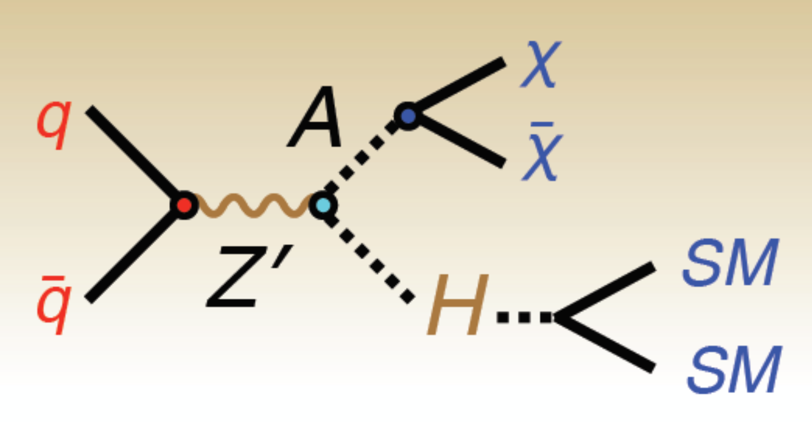
The Higgs recoils against DM



Production modes provide "something" for invisible Higgs to recoil against

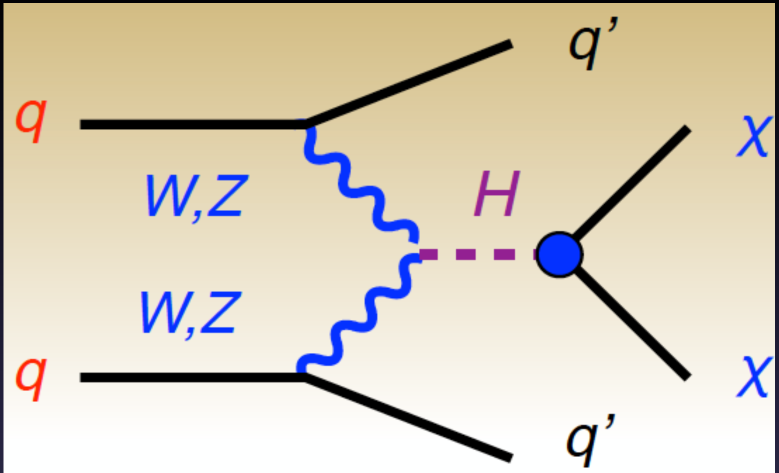
HIGGS AND DARK MATTER

Mono-Higgs



The Higgs recoils against DM

Higgs decays to invisible

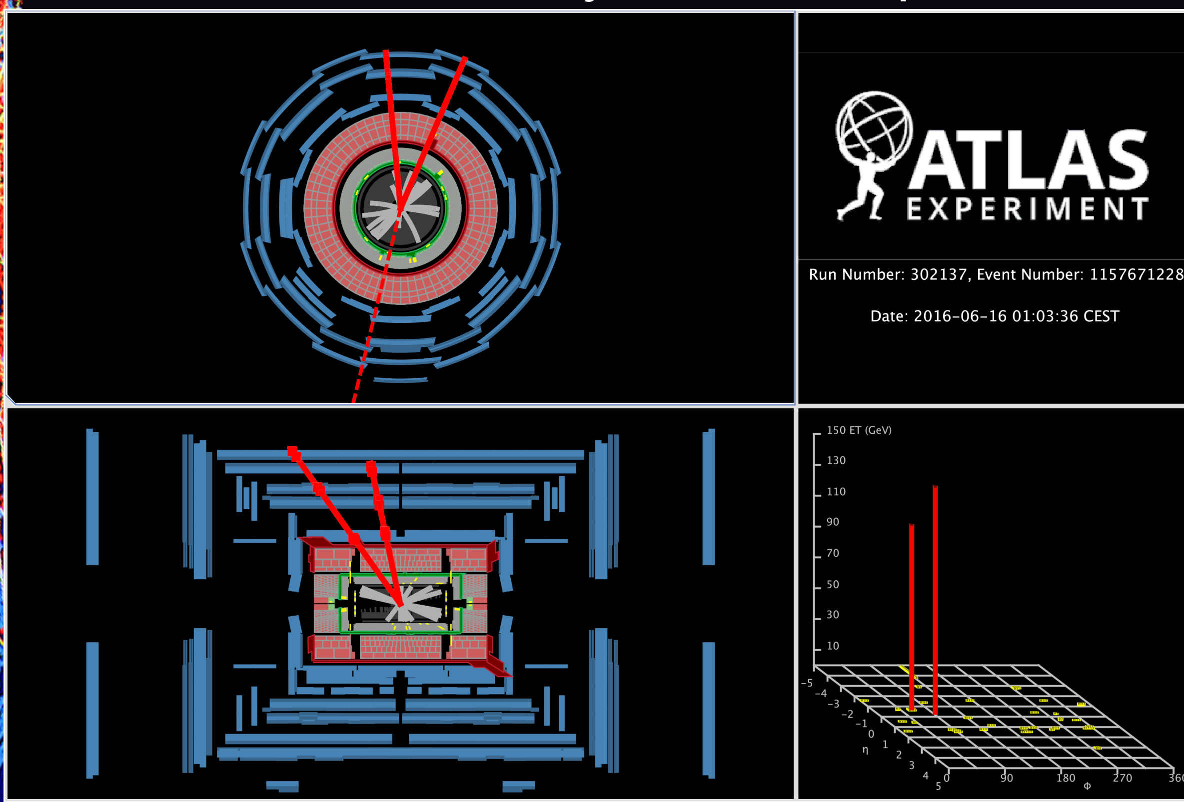


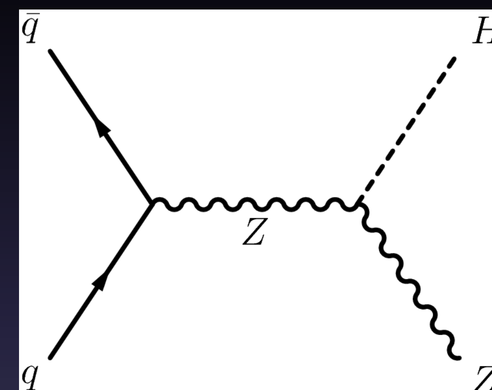
Production modes provides "something" for invisible Higgs to recoil against

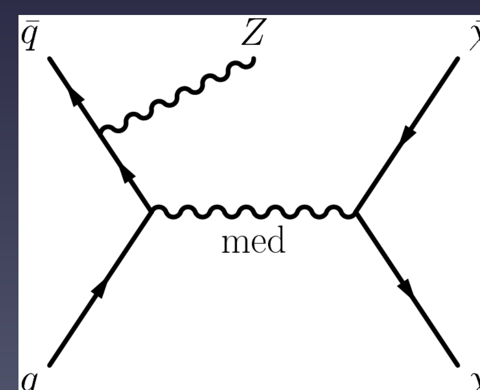
H→ Invisible in ZH $\rightarrow ll$ + E_{Tmiss}
PLB776 (2017)318

H → Invisible in $ZH \rightarrow ll + E_{Tmiss}$

- Clear signature of Z → ee or → μμ plus missing energy
- The invisible decay BR(H → ZZ → νννν)=(1.06 ×10^{-3}) in SM
- Place upper limit on B(H → inv) assuming SM ZH production.
- Limits are also set on DM models with BSM axial-vector mediator that decays to WIMP pair







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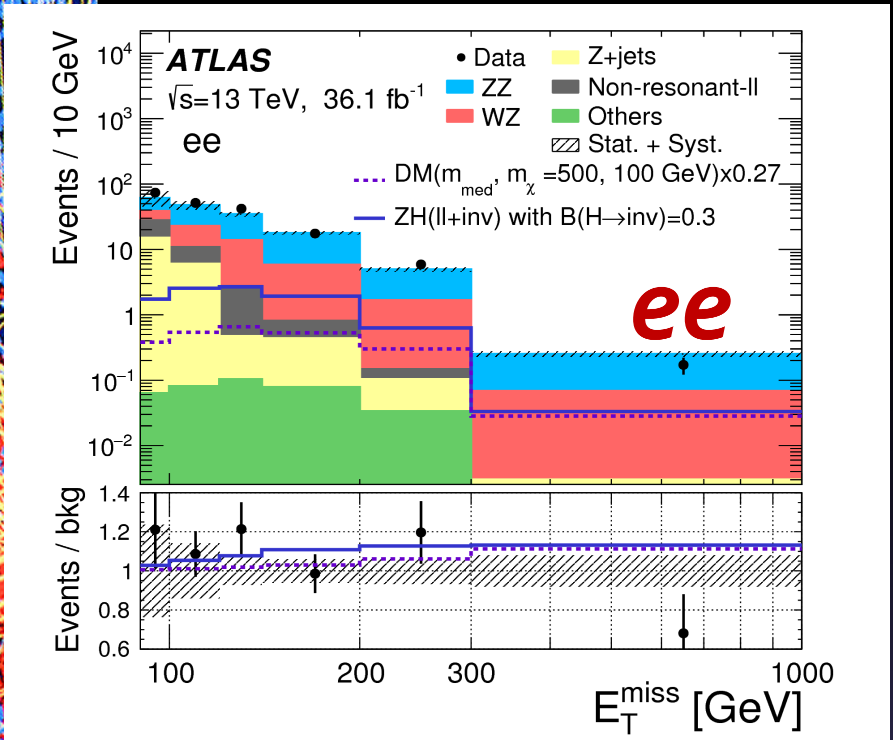
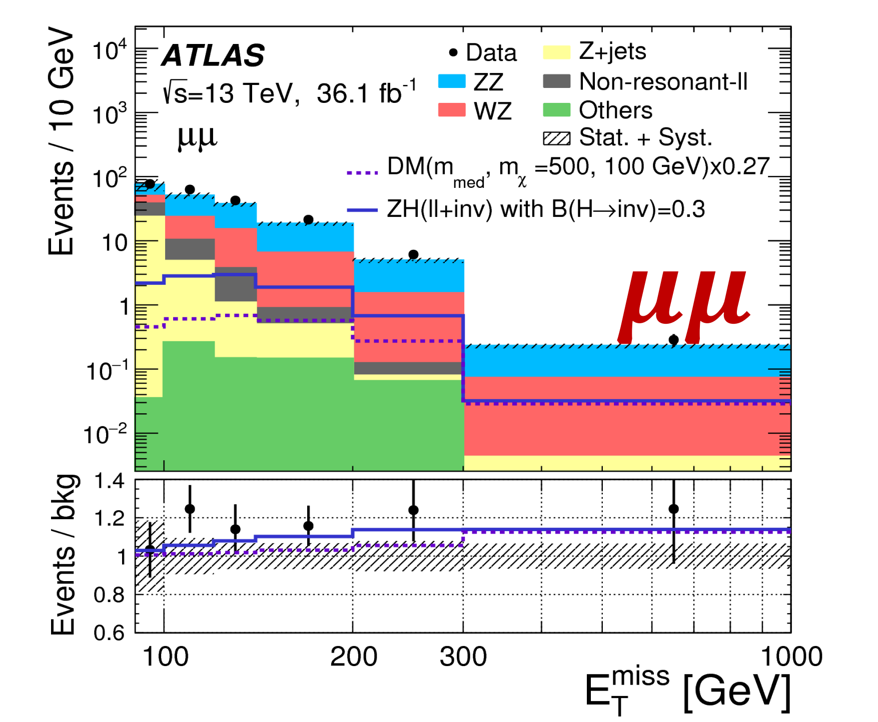
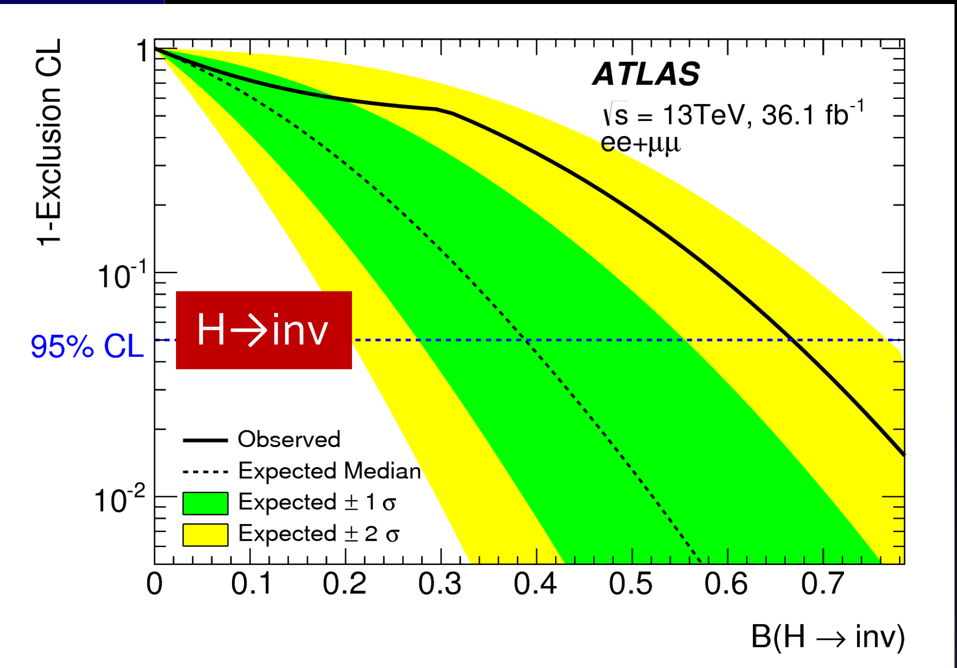
H → Invisible in $ZH \rightarrow ll + E_{Tmiss}$

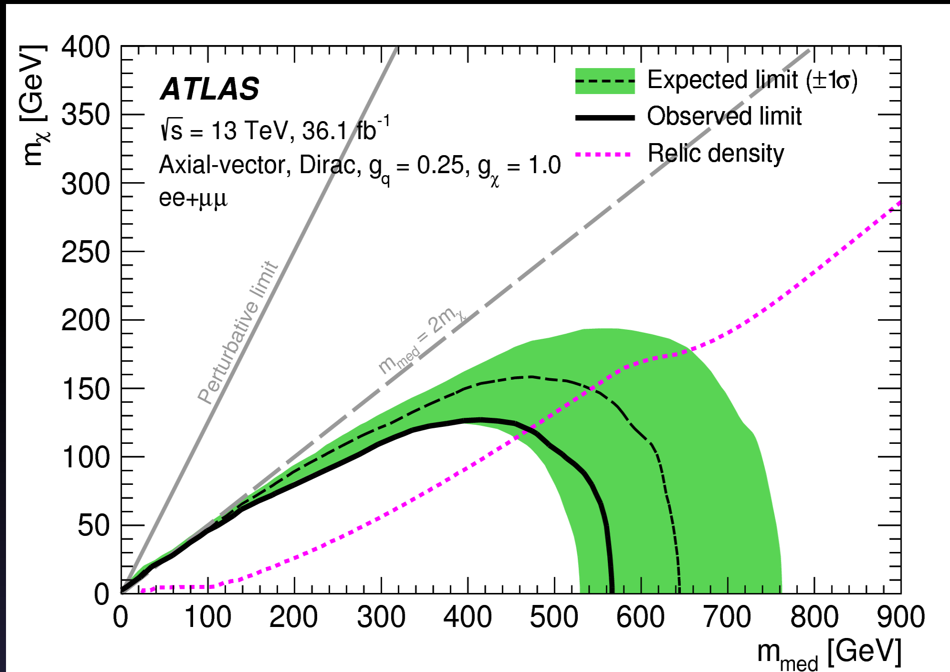




- Main backgrounds: ZZ, WZ and Z+jets. Reducible backgrounds are cut down by removing events with extra leptons or jets containing b-hadrons, and requiring a boosted Z boson which is back to back with MET
- No significant excess wrt SM background (mainly ZZ, WZ at MET>100 GeV)
- Largest systematic uncertainties due to the modelling of ZZ and Z+Jets
- Small excess in μμ (2.2σ) and 1.5σ for combined ee+μμ

H → Invisible in $ZH \rightarrow ll + E_{Tmiss}$





- Exclusion limit on B(H→inv.) assuming SM ZH cross section.
- Observed (Expected) limit of 67% (39%) Run 1 results were 75% (62%)
- Best fit B(H→inv) is found to be (30 ± 20)%, where the data statistical and systematic uncertainties are about 13% and 16%

- 95% CL exclusion limit for DM model with an axial-vector mediator, fermionic WIMPs ($g_\chi = 1$, $g_q = 0.25$)
- Mediator mass m_{med} is excluded up to 560 GeV for a light WIMP
- WIMP mass m_χ is excluded up to 130 GeV for m_{med} = 400 GeV.

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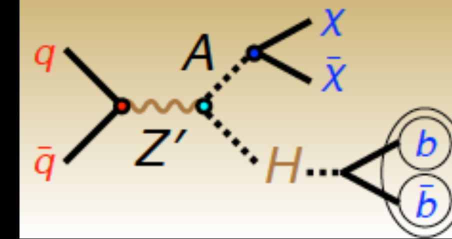
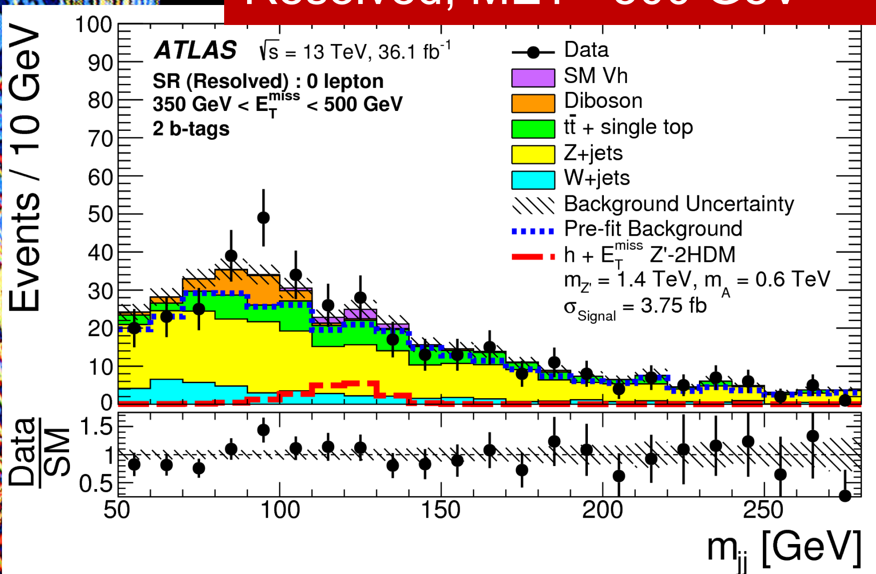
MONO-HIGGS H → bb

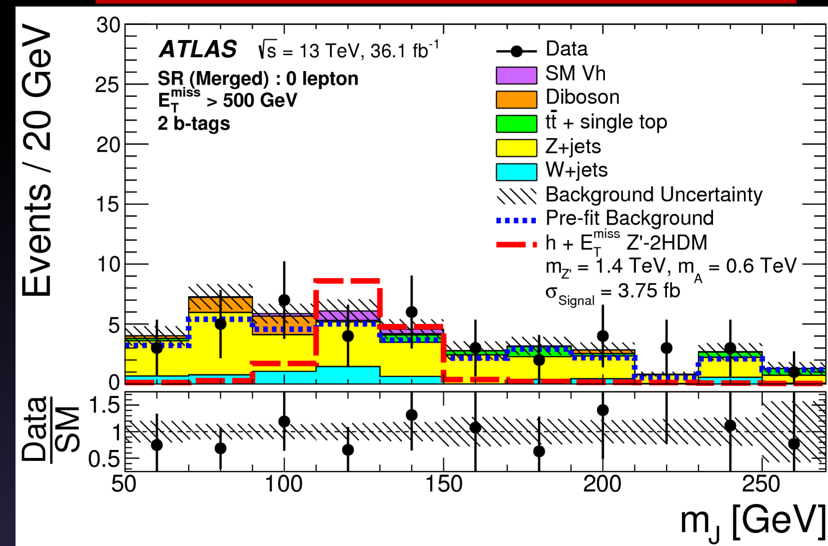


- No isolated e, μ or hadronic τ

Resolved, MET <500 GeV



Boosted, MET >500 GeV

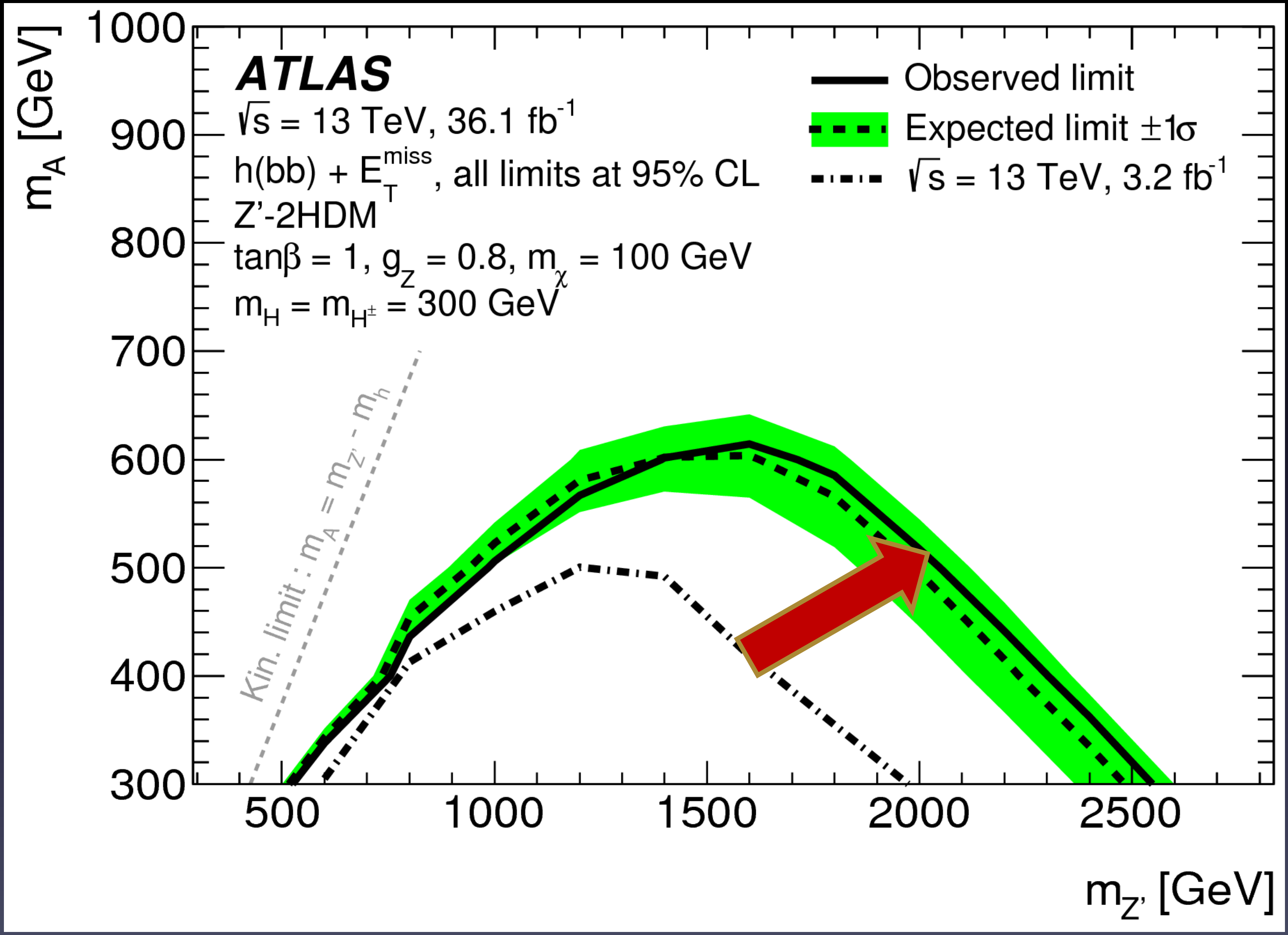


- Dominant backgrounds Z (νν)+jets, W +jets, and tt production
  - (1μ-CR) constrains the tt and W +jets
  - (2l-CR) constrains the Z +jets
- Result statistics limited: Stat. uncertainty 62%
- Dominant systematic errors: MC statistics (22%), calibration b-tagging (17%)
- Most of the sensitivity comes from 2b tags signal region and the highest MET bins

Range in E_T^{miss} [GeV]	$\sigma^{obs}_{vis,h(b\bar{b})+DM}$ [fb]	$\sigma^{exp}_{vis,h(b\bar{b})+DM}$ [fb]	$\mathcal{A}\times\varepsilon$ [%]
[150, 200)	19.1	$18.3^{+7.2}_{-5.1}$	15
[200, 350)	13.1	$10.5^{+4.1}_{-2.9}$	35
[350, 500)	2.4	$1.7^{+0.7}_{-0.5}$	40
[500, ∞)	1.7	$1.8^{+0.7}_{-0.5}$	55

- ATLAS H → bb: PRL 119 181804 (2017)

Exclusion limit



Rare decays

- Rare SM Higgs decays to light fermions
- Lepton flavor-violating H→$\mu\tau$, H→eτ, or H→eμ decays

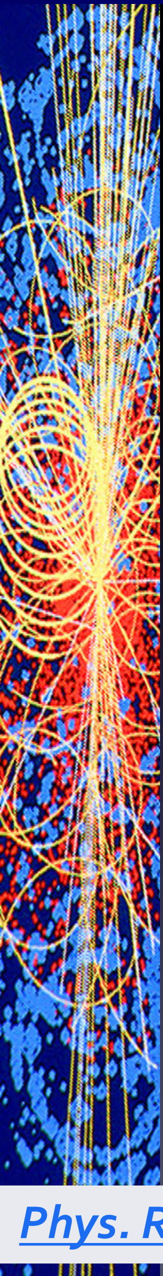
Decay Modes	Data Set	Published	Link
H→ee			
H→$\mu\mu$	36 fb^{-1}, 13 TeV	PRL 119	1705.04582
H→eμ			
H→eτ	20 fb^{-1}, 8 TeV	EPJC 77	1604.07730
H→μτ			
H→Zγ→ℓℓγ	36 fb^{-1}, 13 TeV	JHEP 10	1708.00212
H→γ*γ→ℓℓγ			
H→J/ψ γ	20 fb^{-1}, 8 TeV	PRL 114	1501.03276
H→ Υγ			
H→φγ	36 fb^{-1}, 13 TeV	CONF-17-057	cds:2273873
H→ργ			

Rare decays

$H\rightarrow\mu\mu < 3$ x SM and $H\rightarrow Z\gamma/\gamma^*\gamma < 7$x SM

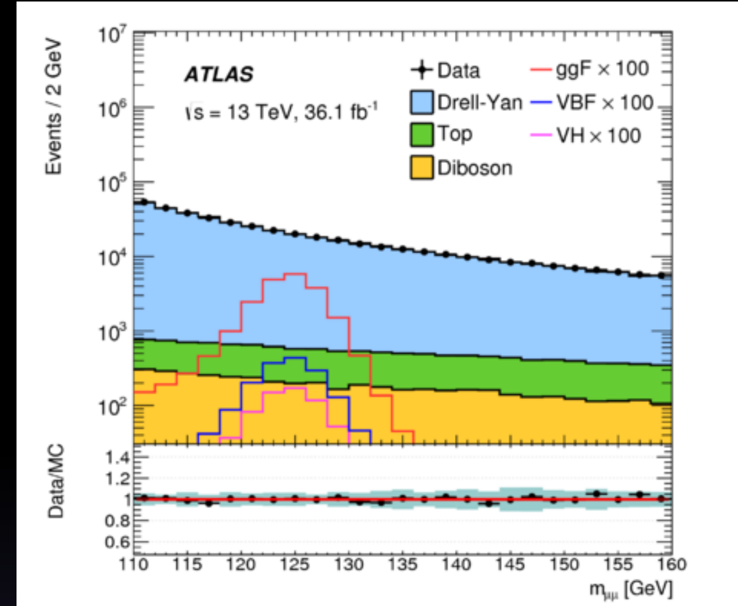
Decay Modes	Data Set	Exp. Limit	Obs. Limit	SM
$H\rightarrow ee$				5×10^{-9}
$H\rightarrow\mu\mu$	36 fb^{-1}, 13 TeV	6.4×10^{-4}	6.4×10^{-4}	2.2×10^{-4}
$H\rightarrow e\mu$				0
$H\rightarrow e\tau$	20 fb^{-1}, 8 TeV	1.2×10^{-2}	1.0×10^{-2}	0
$H\rightarrow\mu\tau$		1.0×10^{-2}	1.4×10^{-2}	0
$H\rightarrow Z\gamma\rightarrow\ell\ell\gamma$	36 fb^{-1}, 13 TeV	4.6×10^{-4}	6.8×10^{-4}	$\sim1.0\times10^{-4}$
$H\rightarrow\gamma^*\gamma\rightarrow\ell\ell\gamma$				1.2×10^{-4}
$H\rightarrow J/\psi\ \gamma$	20 fb^{-1}, 8 TeV	1.2×10^{-3}	1.5×10^{-3}	3.0×10^{-6}
$H\rightarrow \Upsilon\gamma$		$2.5\times10\text{-}^{3}$	2.0×10^{-3}	5.1×10^{-9}
$H\rightarrow\phi\gamma$	36 fb^{-1}, 13 TeV	4.2×10^{-4}	4.8×10^{-4}	2.3×10^{-6}
$H\rightarrow\rho\gamma$		8.4×10^{-4}	8.8×10^{-4}	1.7×10^{-5}

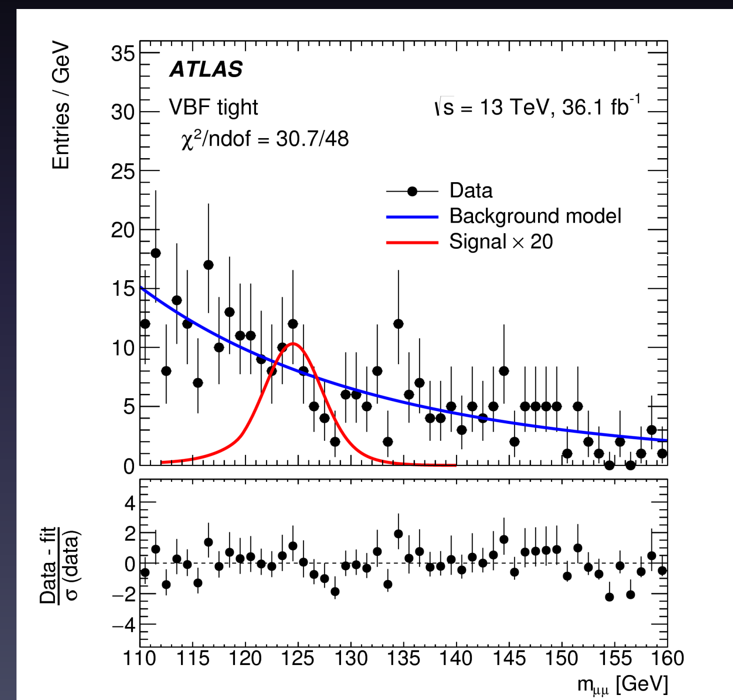
$H \rightarrow \mu^+\mu^-$



Search in VBF and ggF production channels

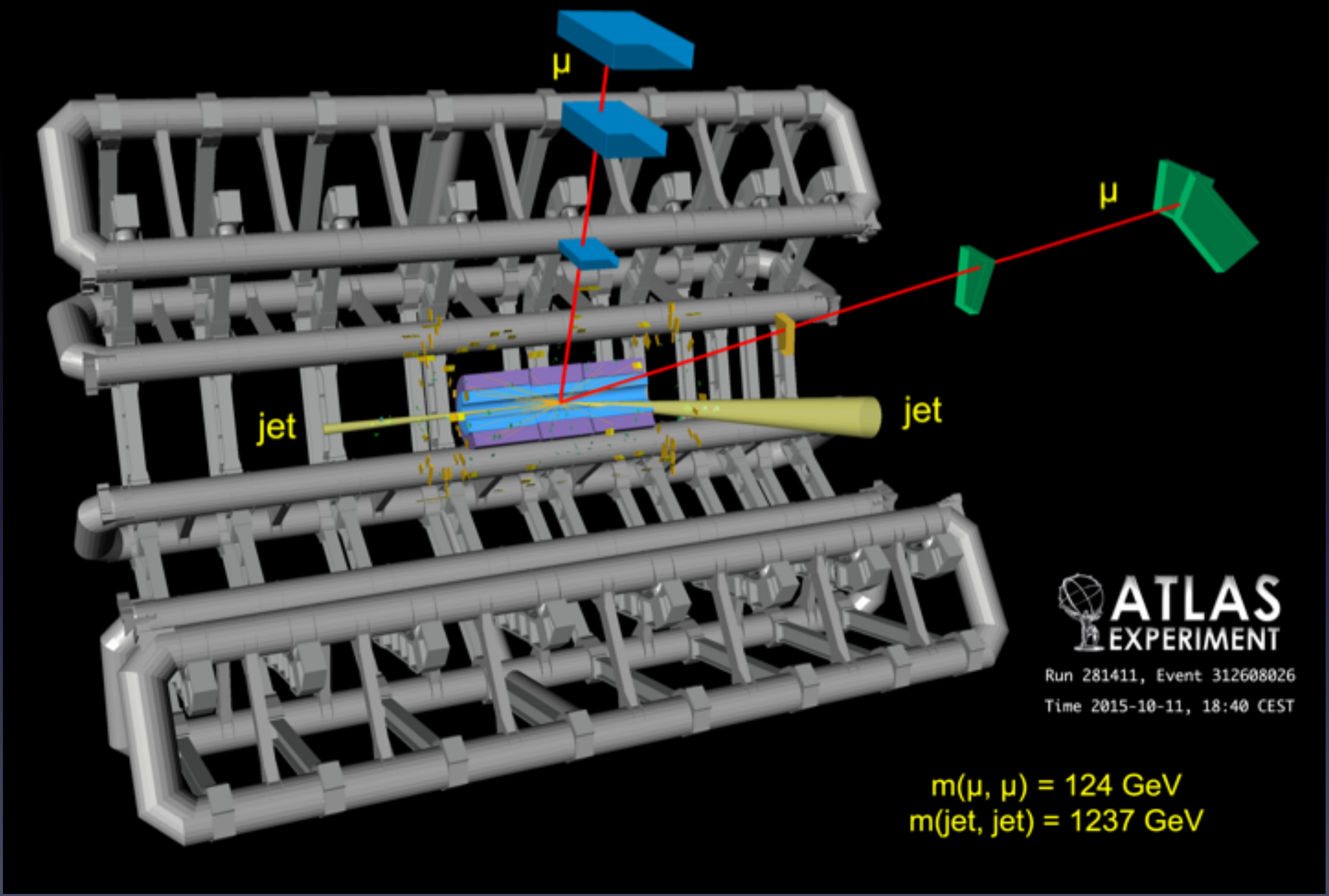
- **VBF:** ≥ 2 jets , multivariate analysis (MVA) to enrich VBF signal region, Categorization in "loose" and "tight"
- **ggF :**
  - If not VBF, categorization based on $p_T(\mu\mu)$ and $\eta(\mu)$
- Simultaneous fit of $m(\mu\mu)$ for all categories
- **μ= -0.1 ± 1.5** upper limit : **μ<3.0 (3.1 exp) @ 95% CL**
- Combined with Run1 **μ= -0.1 ± 1.4** upper limit : **μ<2.8 (2.9 exp) @ 95% CL**
- Limit is driven by the data statistics uncertainty





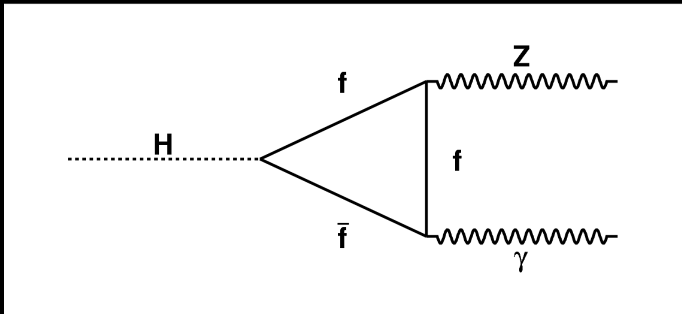
[Phys. Rev. Lett. 119 (2017) 051802]

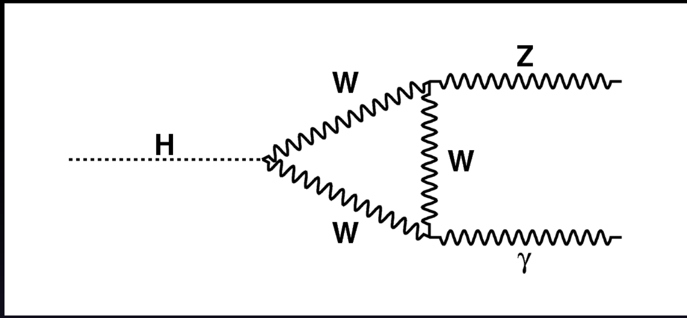
VBF candidate $H \to \mu^+\mu^-$



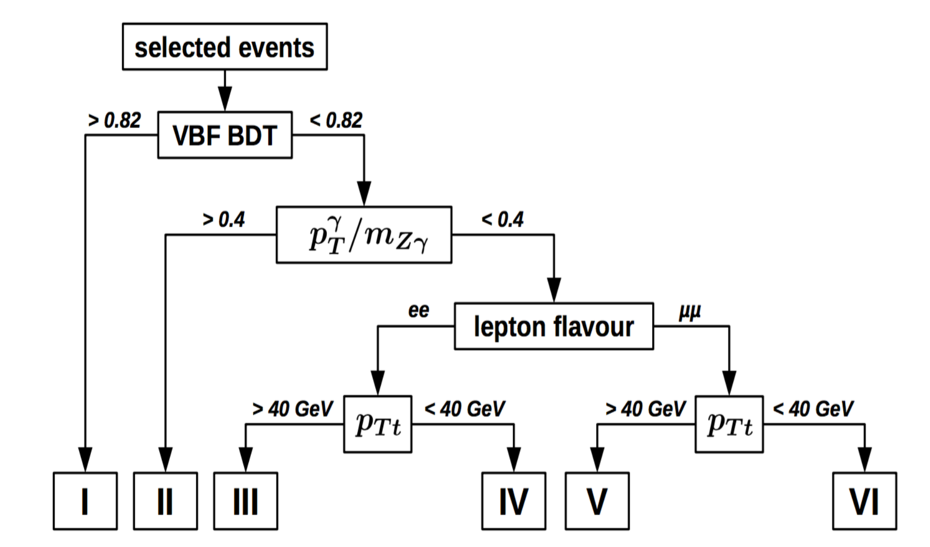
$H \to Z\gamma$

- $H \to Z\gamma$ proceeds by loop diagrams similar to those in $H \to \gamma\gamma$ and has a similar branching ratio.
- Modifications of the $H \to Z\gamma$ branching ratio compared to the SM prediction are expected if:
  - H is a composite state
  - In models with additional colourless charged scalars, leptons or vector bosons coupled to the Higgs boson and exchanged in the $H \to Z\gamma$ loop

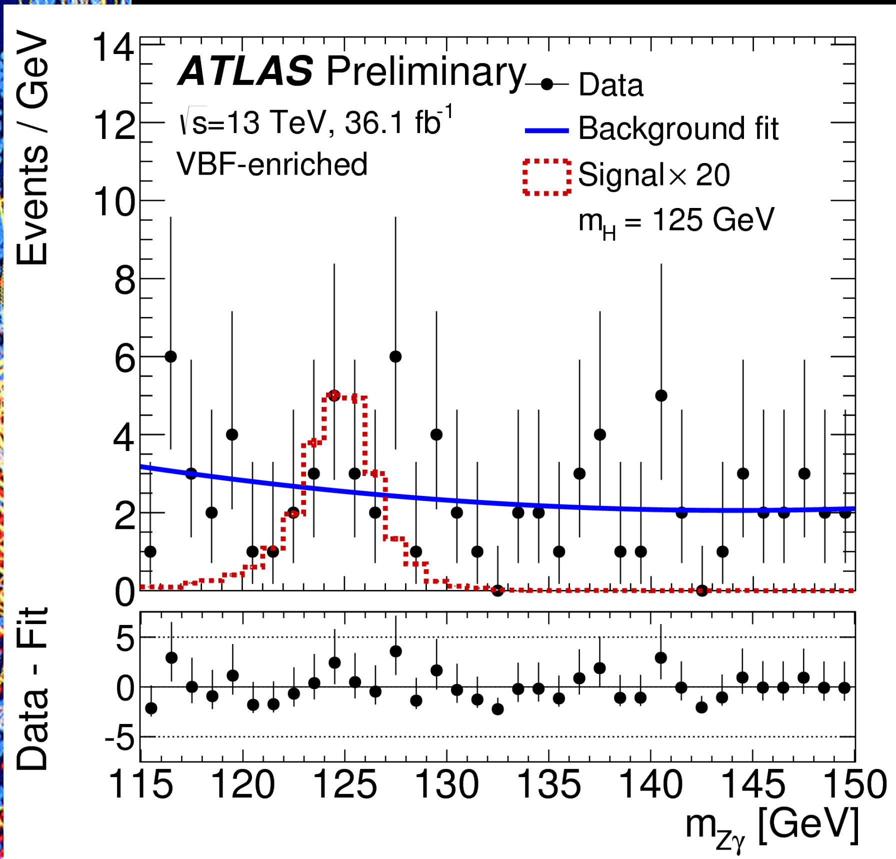


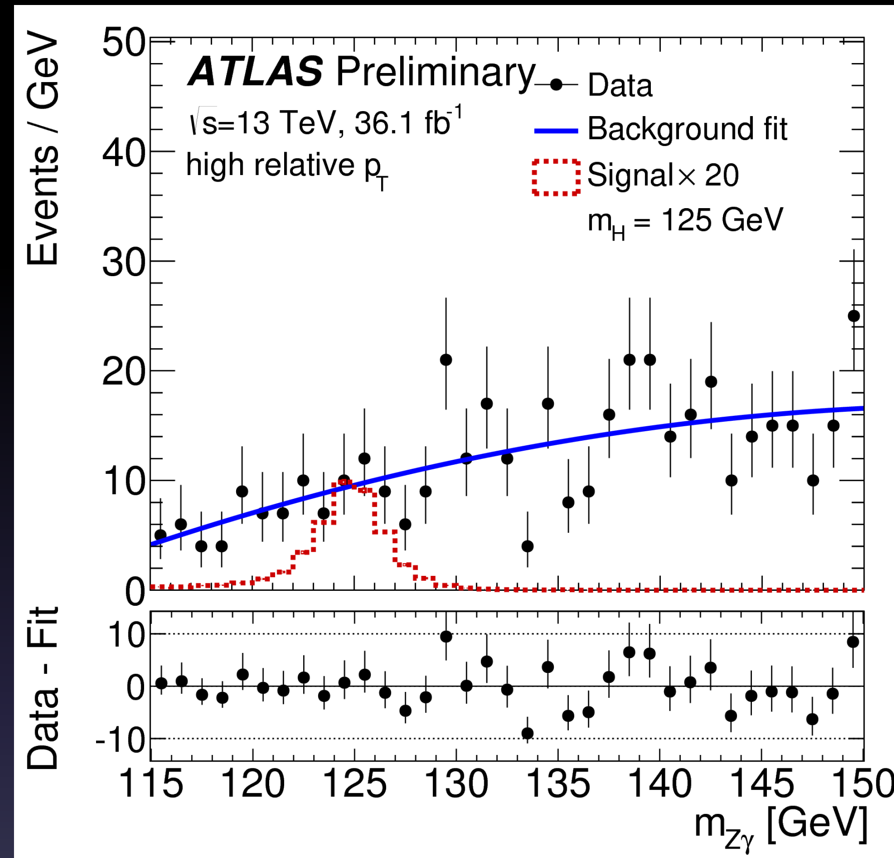


- Signal extracted by fit to $m(Z\gamma)$
- Relies on good mass resolution and Kinematic fit to improves the $m_{\mu\mu\gamma}$ ($m_{ee\gamma}$) resolution by 7% (13%)
- 6 event categories to enhance sensitivity
- Dominant bck.: Non-resonant $Z\gamma$ production Z+jets (jet mis-identified as a γ)



$H \rightarrow Z\gamma$





95% CL Upper limit	Expected without Higgs boson decays	Expected with SM Higgs boson	Observed
$\sigma \cdot BR / (\sigma \cdot BR)_{SM}$	4.4	5.2	6.6

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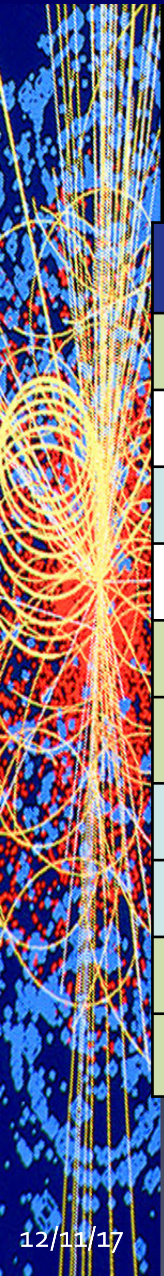


$H \rightarrow$ BSM particle

Eclectic set of final states

Decay Modes	Data Set	Published	Link
$H \rightarrow aa \rightarrow 4b$	3.2 fb^{-1}, 13 TeV	EPJC 76	1606.08391
$H \rightarrow aa \rightarrow \mu\mu bb$			
$H \rightarrow aa \rightarrow \mu\mu\tau\tau$	20 fb^{-1}, 8 TeV	PRD92	1505.01609
$H \rightarrow aa \rightarrow 4\tau$			
$H \rightarrow aa \rightarrow 4\mu$	36 fb^{-1}, 13 TeV	CONF-17-042	cds:2273848
$H \rightarrow Z_{(d)} Z_d \rightarrow 4l$			
$H \rightarrow G\chi \rightarrow GG\gamma$	20 fb^{-1}, 8 TeV	CONF-15-001	cds:1988425
$H \rightarrow \chi\chi \rightarrow G\gamma G\gamma$			
$H \rightarrow f_d f_d \rightarrow 4\ell+\chi$	36 fb^{-1}, 13 TeV	CONF-16-042	cds:2206083
$H \rightarrow f_d f_d \rightarrow 8\ell+\chi$			

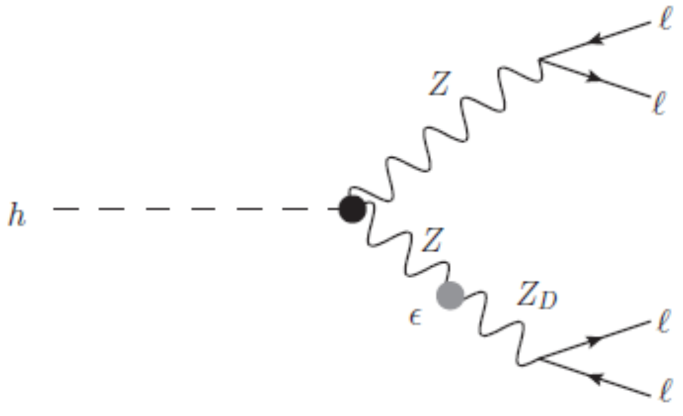
$H \to$ BSM particle

Eclectic set of final states

Decay Modes	Data Set	Published	Link
$H \to aa \to 4b$	3.2 fb^{-1}, 13 TeV	EPJC 76	1606.08391
$H \to aa \to \mu\mu bb$			
$H \to aa \to \mu\mu\tau\tau$	20 fb^{-1}, 8 TeV	PRD92	1505.01609
$H \to aa \to 4\tau$			
$H \to aa \to 4\mu$	36 fb^{-1}, 13 TeV	CONF-17-042	cds:2273848
$H \to Z_{(d)}Z_d \to 4l$			
$H \to G\chi \to GG\gamma$	20 fb^{-1}, 8 TeV	CONF-15-001	cds:1988425
$H \to \chi\chi \to G\gamma G\gamma$			
$H \to f_d f_d \to 4\ell + \chi$	36 fb^{-1}, 13 TeV	CONF-16-042	cds:2206083
$H \to f_d f_d \to 8\ell + \chi$			

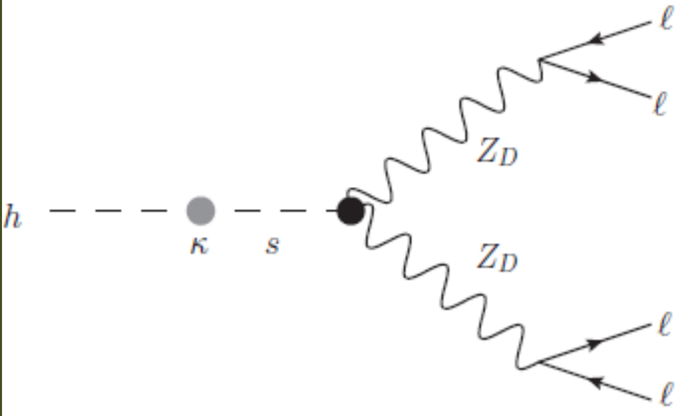
Dark Vector Boson Searches

- Vector Portal: Add a $U(1)_d$ whose massive “dark” gauge boson Z_D mixes with the SM Z



Hidden Abelian Higgs Model (HAHM)

- Higgs Portal: Add dark scalar singlet (S) that spontaneously breaks $U(1)_d$ and mixes with SM Higgs

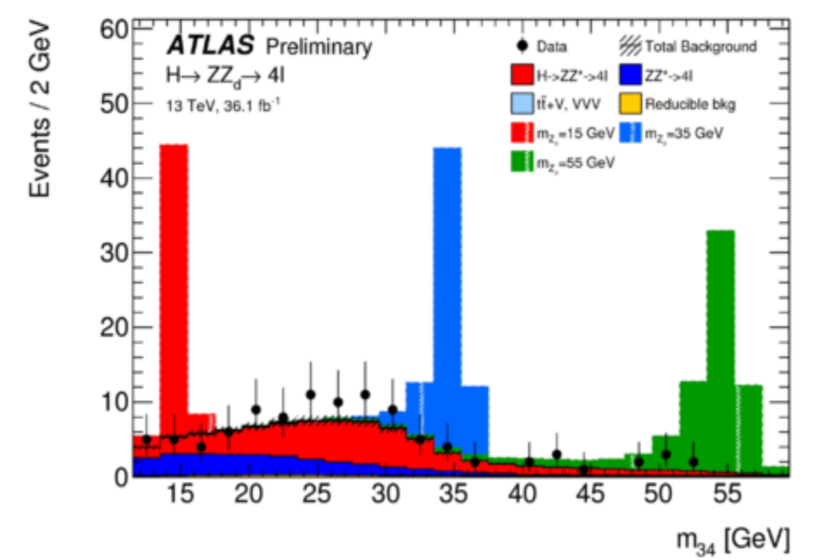


- $H \rightarrow ZZ_d \rightarrow 4\ell$ [$115 < m(4\ell) < 130$ GeV]
  - Denote as m_{12} combination closer to m_Z $50 < m_{12} < 106$ GeV
  - Look for resonances in m_{34} spectrum $12 < m_{34} < 115$ GeV
  - veto J/ψ
  - Dominant Bkg.: $H \rightarrow ZZ^*$, ZZ^*, VVV

- $H \rightarrow Z_dZ_d \rightarrow 4\ell$ [$120 < m(4\ell) < 130$ GeV]
  - Higgs to 2 equal-mass states
  - $10 < m_{12,34} < 64$ GeV (high mass), $0.88 < m_{12,34} < 15$ GeV (low mass)
  - veto J/ψ, Υ, and Z
  - Dominant Bkg.: $H \rightarrow ZZ^*$, ZZ^*, 2b, 4b

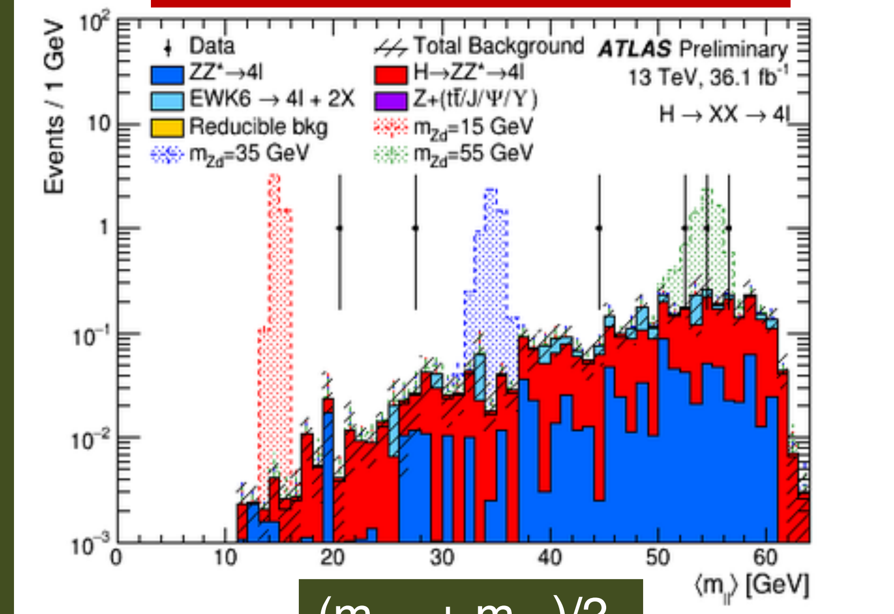
$H \to Z_{(d)} Z_d \to 4\ell$

$H \to Z Z_d \to 4\ell$



- 102 events observed for expected background of 87±7

$H \to Z_d Z_d \to 4\ell$ (high mass)



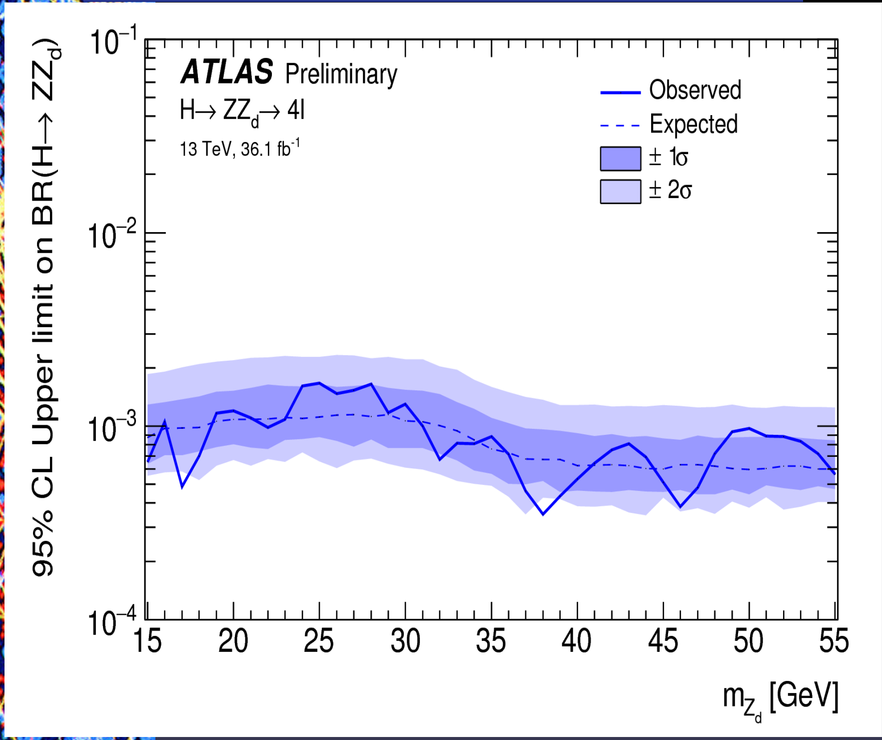
$(m_{12} + m_{34})/2$

- 6 events observed for a prediction of 3.9 ± 0. 3 events (high mass)
- Biggest deviation from SM expectation is the event at $<m_{ll}>$~20 GeV [3.8σ local (2.8σ global) significance].
- 0 events observed for the low mass analysis for a prediction of 0.4 ± 0.1

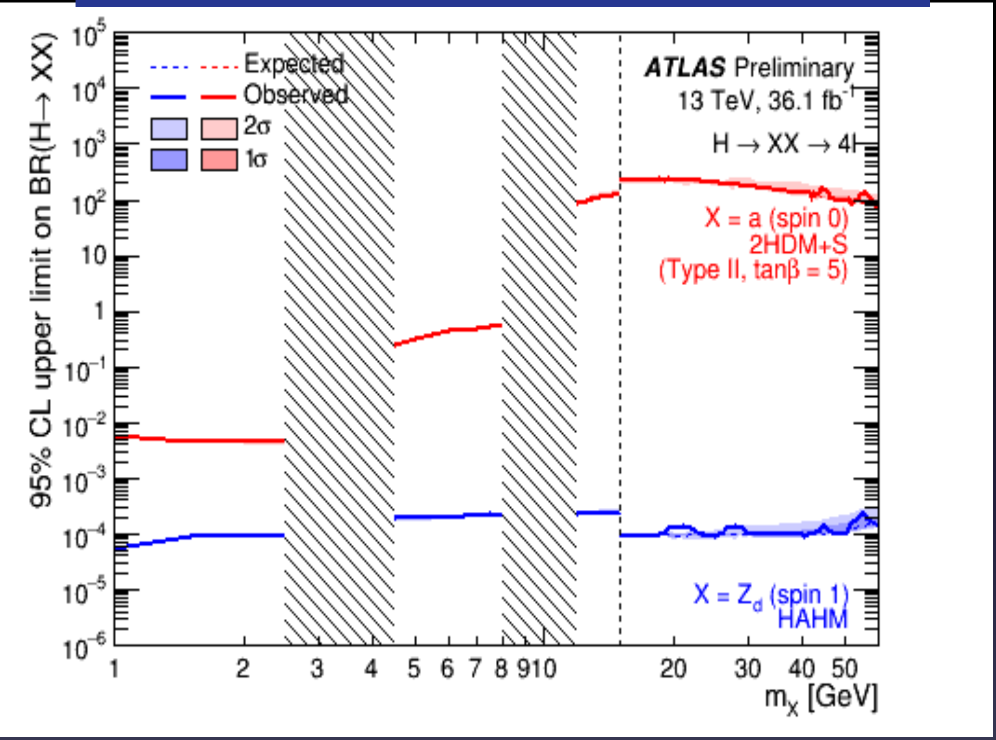
ATLAS-CONF-2017-042

Z_d Limits

$H \to ZZ_d \to 4\ell$



$H \to Z_dZ_d \to 4\ell$



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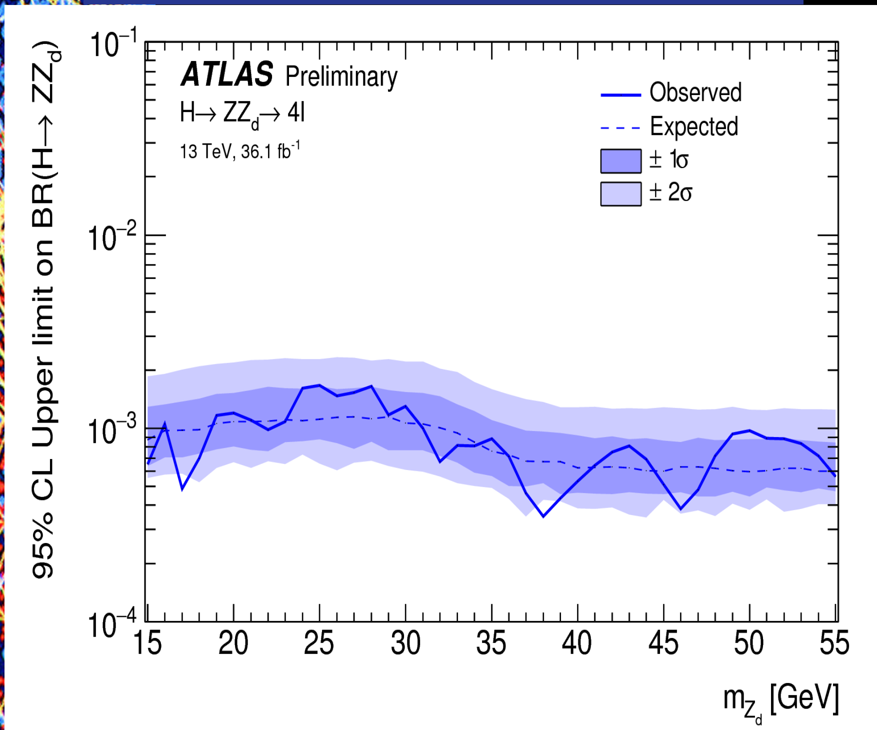
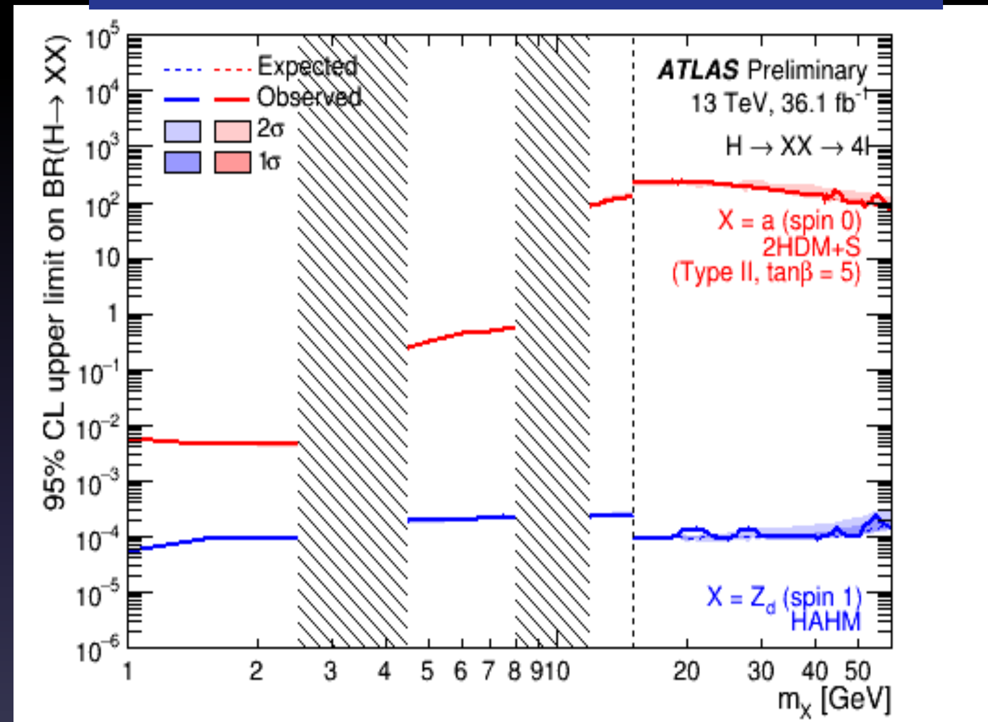
Z_d Limits

$H \rightarrow ZZ_d \rightarrow 4\ell$



$H \rightarrow Z_dZ_d \rightarrow 4\ell$



$H \rightarrow aa \rightarrow 4\ell$

In the two Higgs Doublet with Scalar Singlet Model (2HDM+S) for pseudoscalar a bosons.

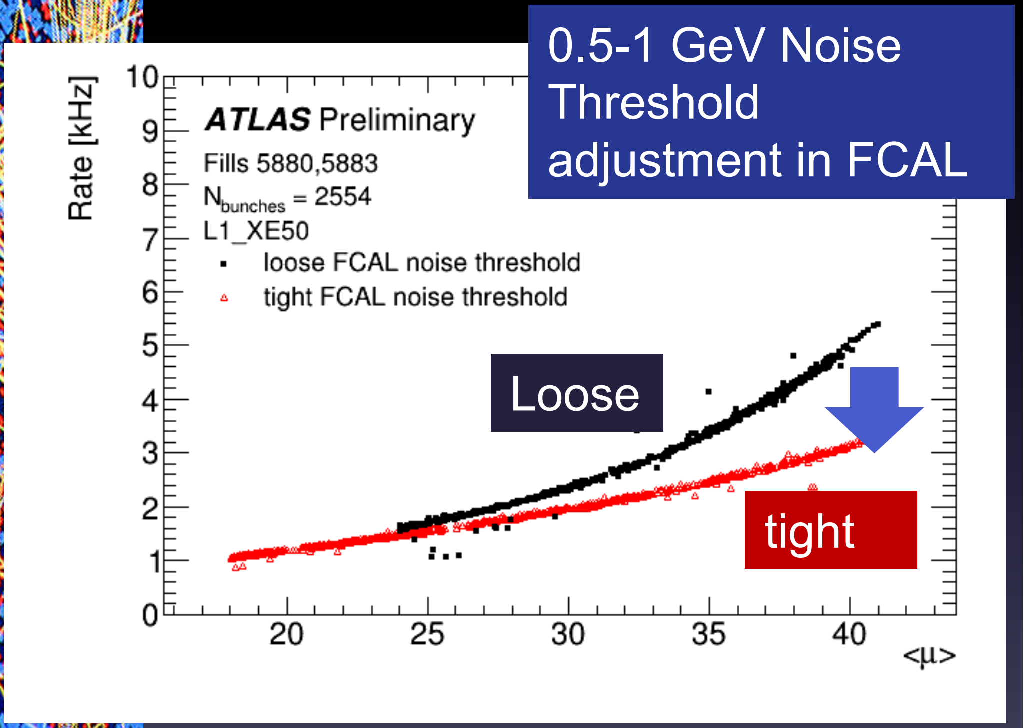
ATLAS-CONF-2017-042

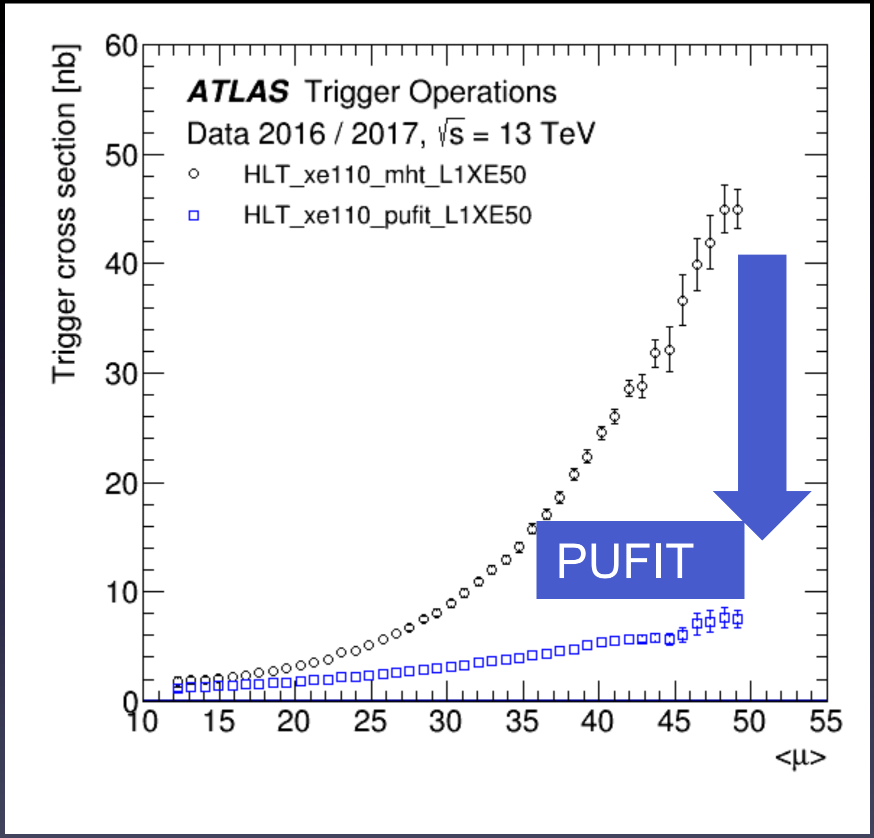
Conclusions

- The SM Higgs boson opens new directions to search for dark matter and a new era of precision physics
- Many rare decays have not been observed yet but may become observable in the next few years
- A wide variety of measurements have been performed at ATLAS
- No evidence for new physics yet

MET Trigger

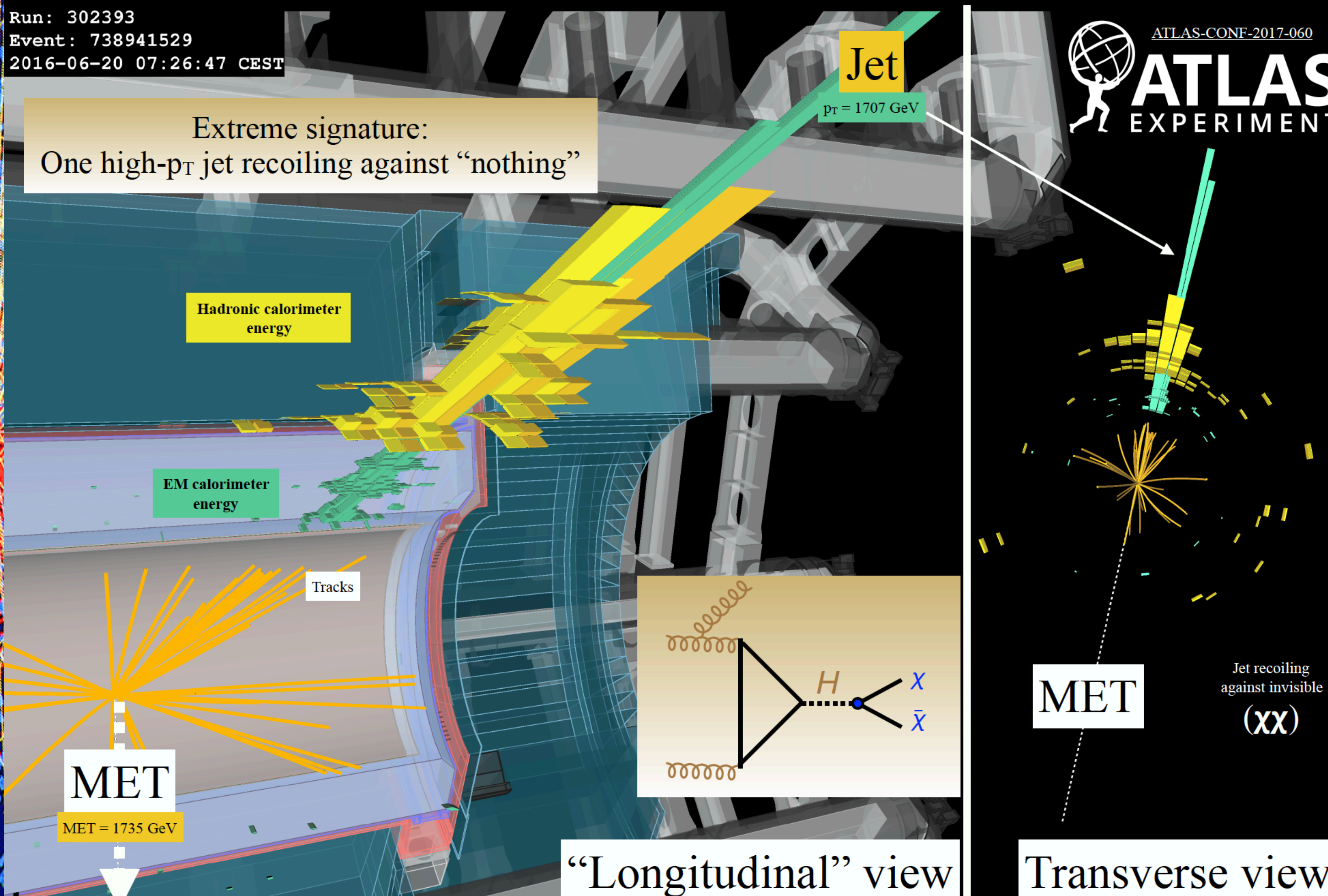
- Critical for dark matter searches
- Higher luminosity and pileup require better trigger algorithms





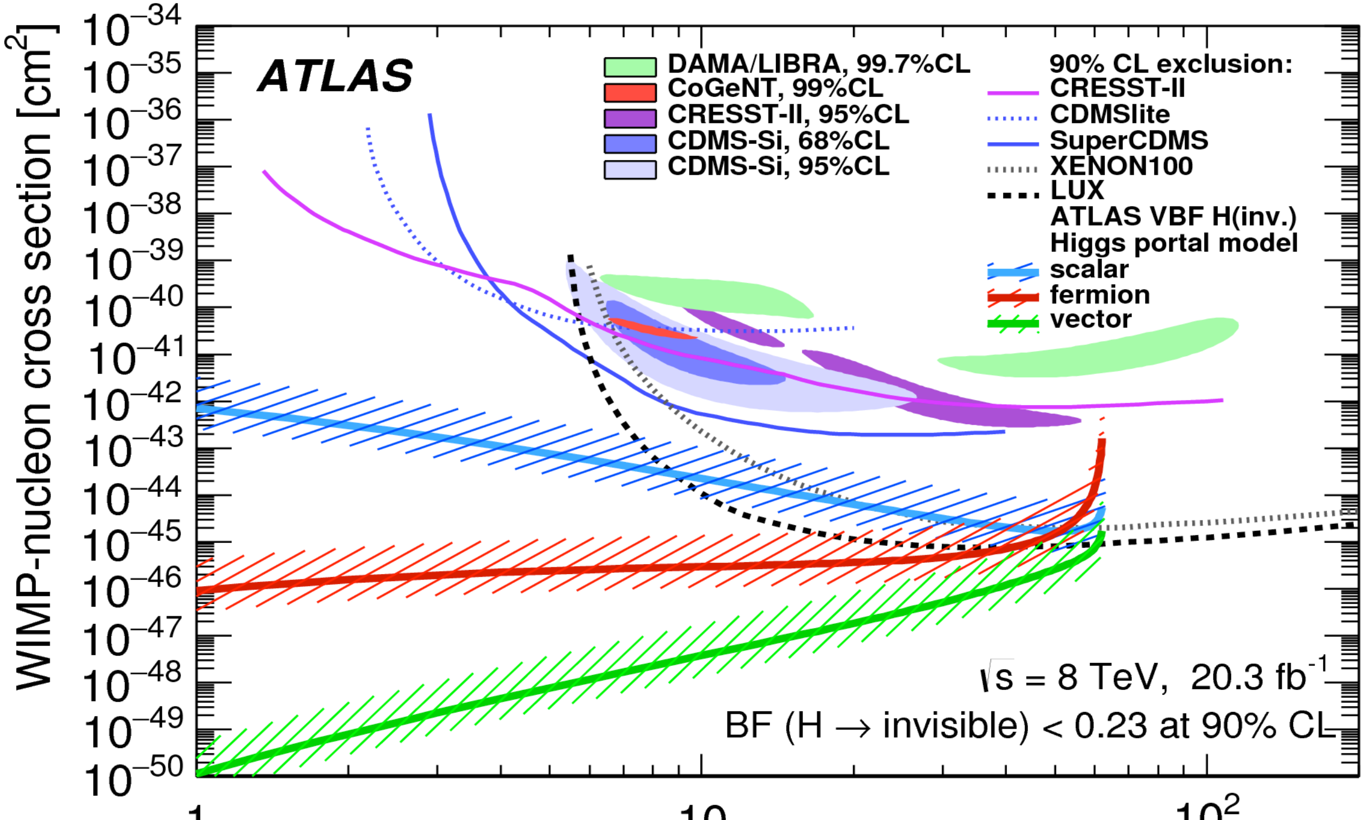
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MissingEtTriggerPublicResults

MONOJET



Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST
Jet
pT = 1707 GeV
Extreme signature:
One high-pT jet recoiling against “nothing”
Hadronic calorimeter energy
EM calorimeter energy
Tracks
MET
MET = 1735 GeV
H
χ
χ̄
“Longitudinal” view
ATLAS-CONF-2017-060
ATLAS EXPERIMENT
MET
Jet recoiling against invisible
(χχ)
Transverse view

Dark matter Interpretation

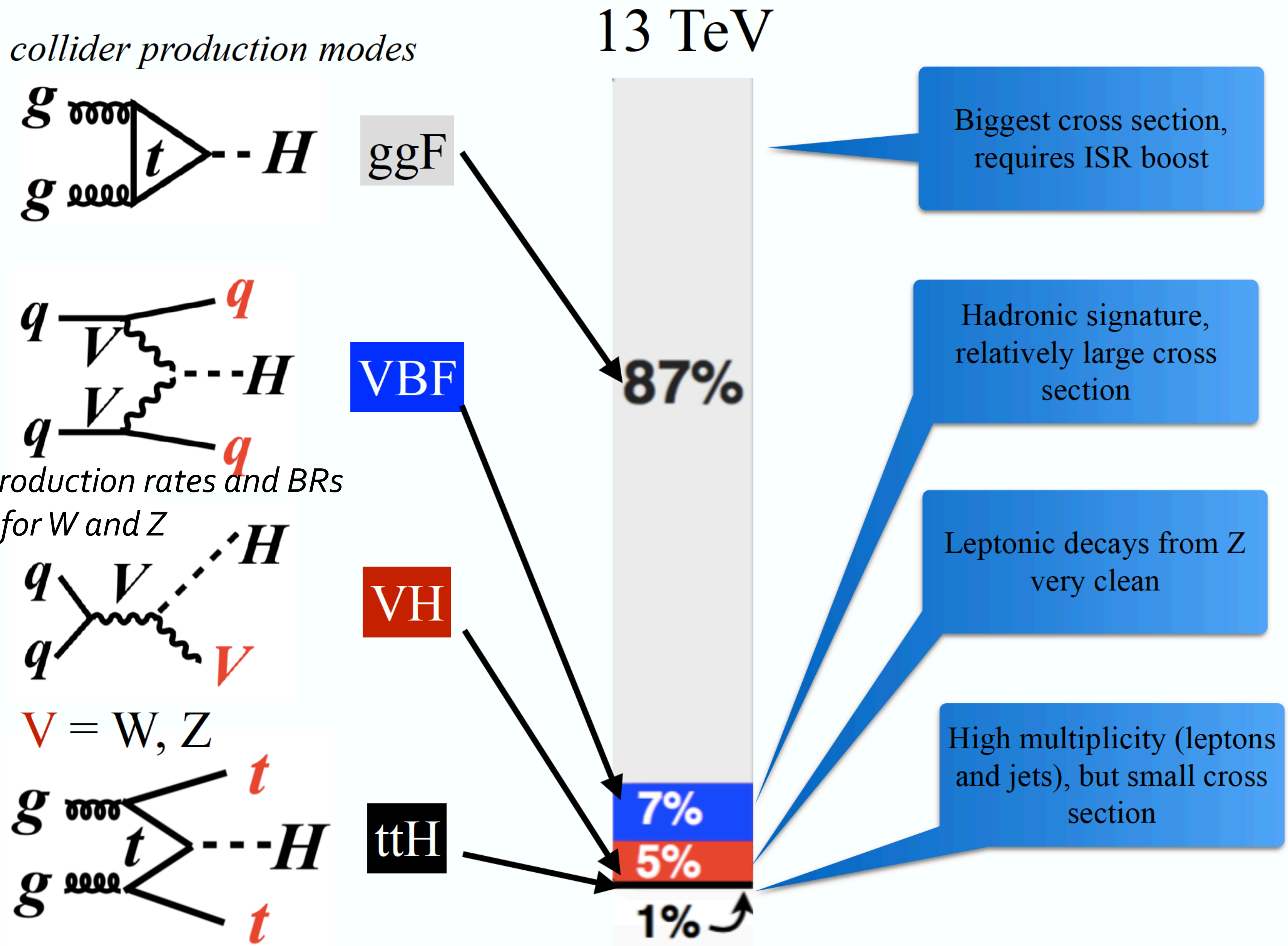


LHC can probe

Direct detection

INVISIBLE HIGGS SEARCHES

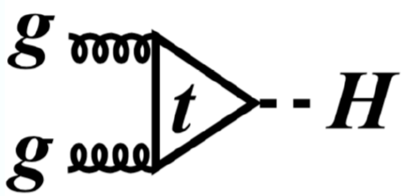
hadron collider production modes



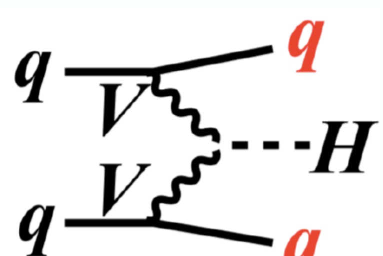
Lower production rates and BRs penalty for W and Z

INVISIBLE HIGGS SEARCHES

hadron collider production modes



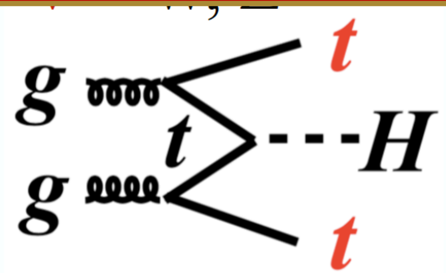
ggF



VBF

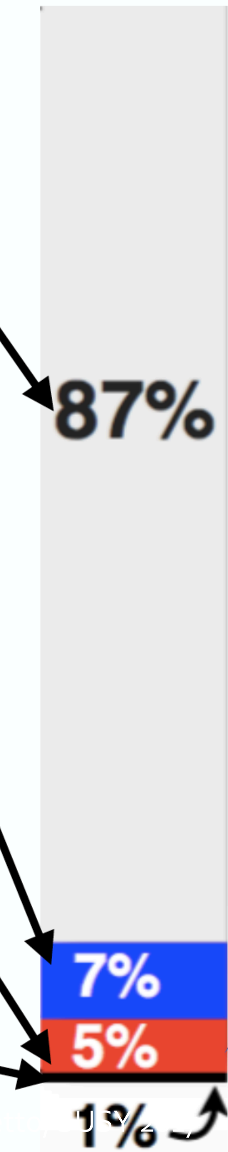
Lower production rates and BRs penalty for W and Z

Recent Result in ZH



ttH

13 TeV



Biggest cross section, requires ISR boost

Hadronic signature, relatively large cross section

Leptonic decays from Z very clean

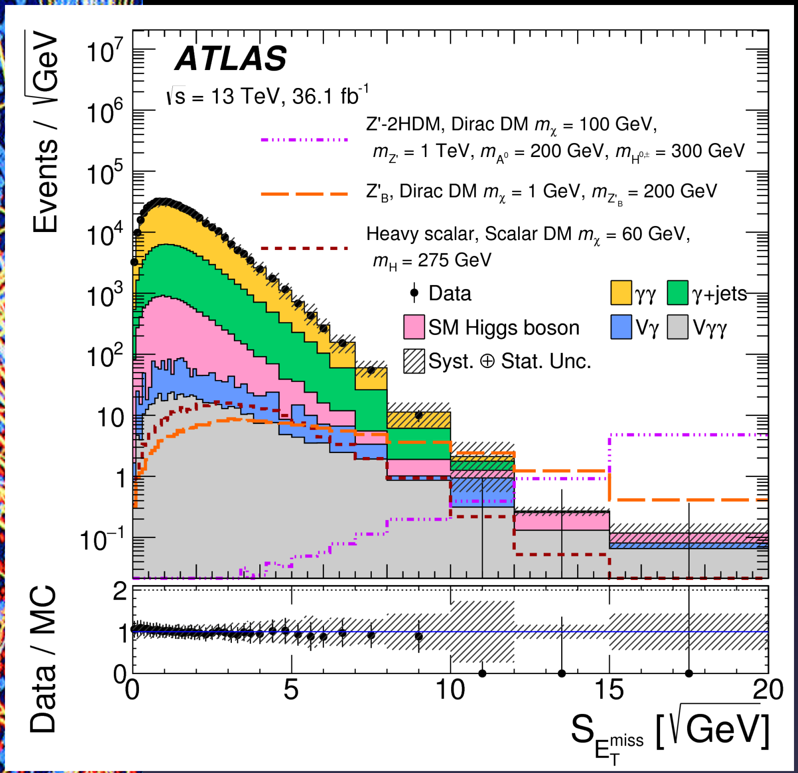
High multiplicity (leptons and jets), but small cross section

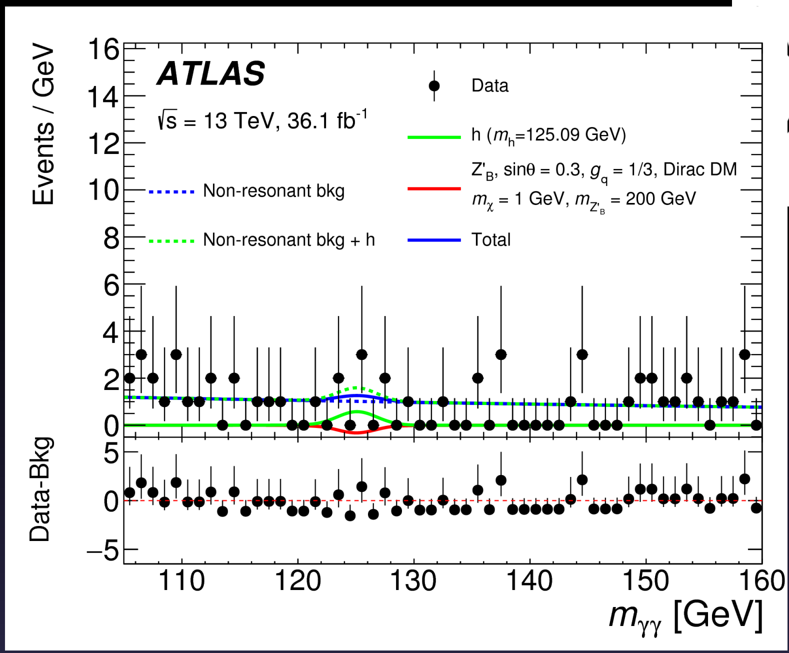
Ben Carlson

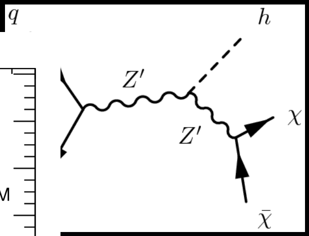
MONO-HIGGS

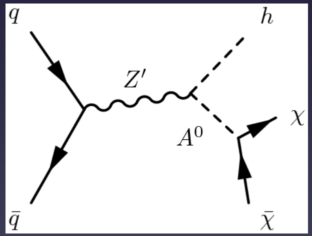
- ATLAS $H \to \gamma\gamma$: HIGG-2016-18

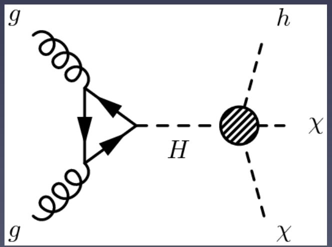
- di-photon mass peak and high MET











Category	Requirements
Mono-Higgs	$S_{E_T^{miss}} > 7\ \sqrt{\text{GeV}}$, $p_T^{\gamma\gamma} > 90$ GeV, lepton veto
High-E_T^{miss}	$S_{E_T^{miss}} > 5.5\ \sqrt{\text{GeV}}$, $\lvert z_{PV}^{highest} - z_{PV}^{\gamma\gamma} \rvert < 0.1$ mm
Intermediate-E_T^{miss}	$S_{E_T^{miss}} > 4\ \sqrt{\text{GeV}}$, $p_T^{hard} > 40$ GeV , $\lvert z_{PV}^{highest} - z_{PV}^{\gamma\gamma} \rvert < 0.1$ mm
Different-Vertex	$S_{E_T^{miss}} > 4\ \sqrt{\text{GeV}}$, $p_T^{hard} > 40$ GeV , $\lvert z_{PV}^{highest} - z_{PV}^{\gamma\gamma} \rvert > 0.1$ mm
Rest	$p_T^{\gamma\gamma} > 15$ GeV

Model Dependent Limits