



Search for the Higgs Boson rare and exotic decay modes with the ATLAS detector

2nd CLHCP @ Peking University, Beijing, December 16-19, 2016

Bo Liu



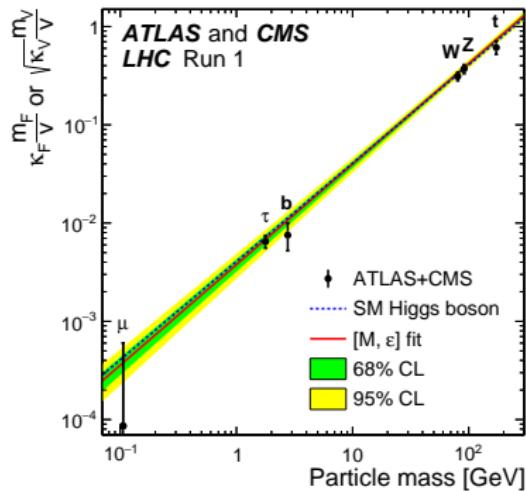
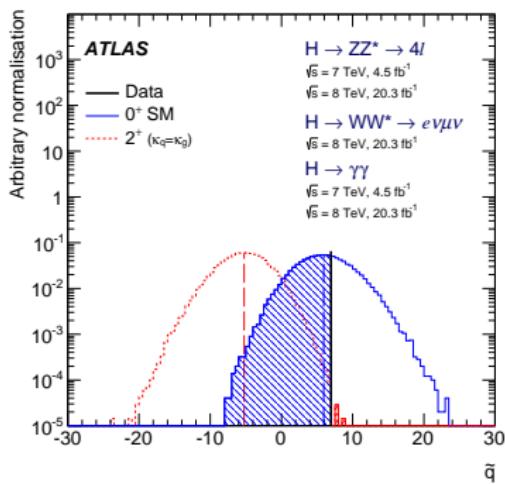
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Introduction



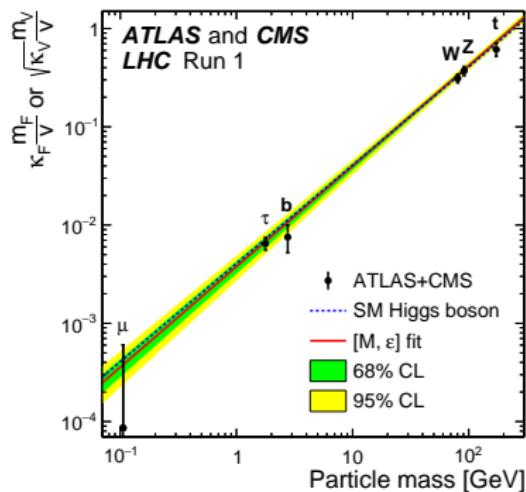
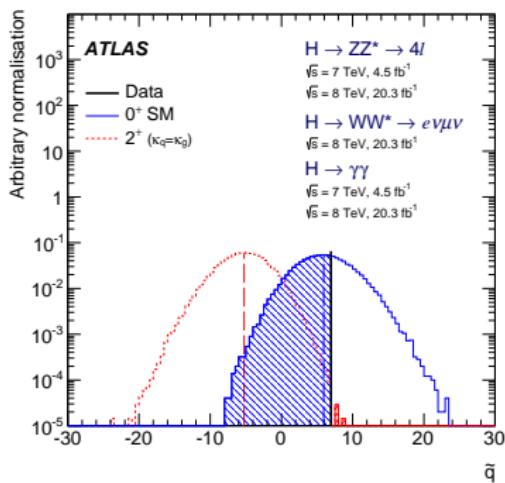
- The Higgs boson is observed in many decay channels.
 - Recent results on Higgs boson properties are consistent with the SM predictions.



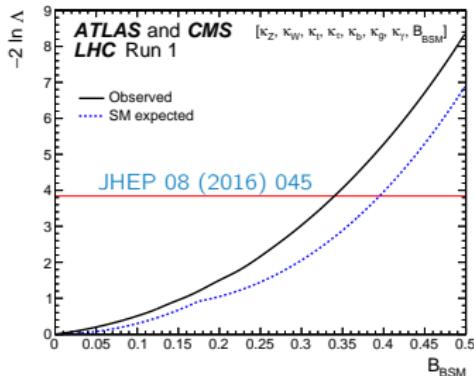
Introduction



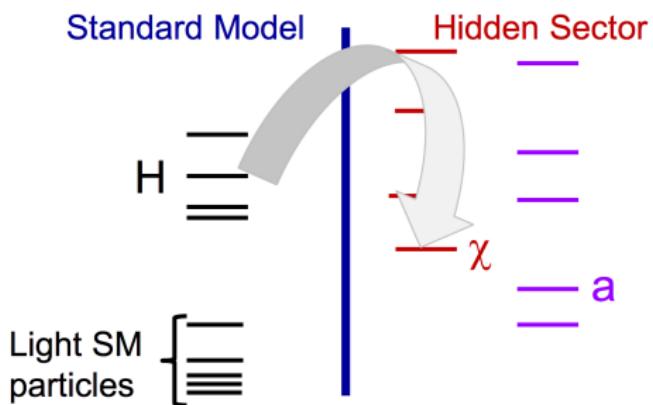
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 - Recent results on Higgs boson properties are consistent with the SM predictions.
- The Higgs boson rare decay modes have not been observed yet.
 - New physics could modify the coupling \Rightarrow derivations from the SM predictions



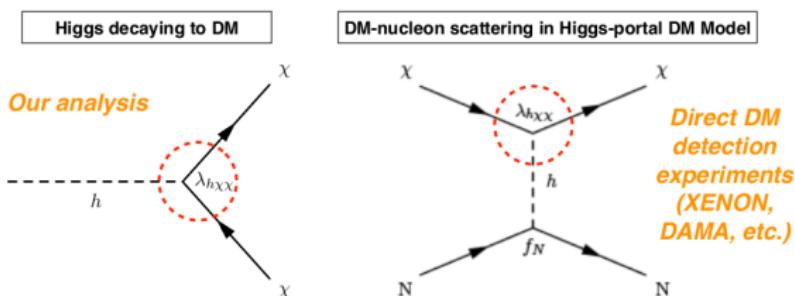
- The Higgs boson is observed in many decay channels.
 - ☞ Recent results on Higgs boson properties are consistent with the SM predictions.
- The Higgs boson rare decay modes have not been observed yet.
 - ☞ New physics could modify the coupling \Rightarrow derivations from the SM predictions
- The constraints on parameters using LHC run-I data are still relatively loose
 - ☞ $\mathcal{B}(H \rightarrow \text{BSM}) < 0.34$: still some rooms for BSM decay mode
 - ☞ Any observed non-SM decay mode would be the sign of new physics
 - ☞ The Higgs boson can be a portal to new physics.



- The SM Higgs has very small invisible decay BR: $BR(H \rightarrow ZZ^* \rightarrow 4\nu) \approx 0.001$
- Some BSM models enhance the invisible decay of Higgs e.g. MSSM with neutralino, extra dimension and Higgs portal model for dark matter. \rightarrow any observed deviations from SM prediction on invisible decay BRs indicate the existence of new physics.



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- In particular, the Higgs invisible decay searches provide the complementary results to directly search of dark matter.



Higgs invisible decay

$$\Gamma(h \rightarrow \chi\chi)$$

$$BR(h \rightarrow \chi\chi) = \frac{\Gamma(h \rightarrow \chi\chi)}{\Gamma(h \rightarrow \chi\chi) + \Gamma(h \rightarrow SM)}$$

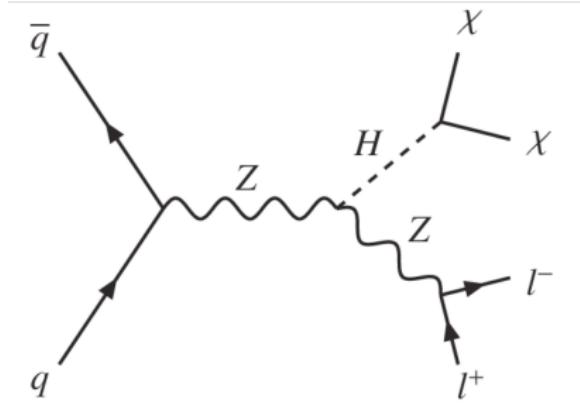
Higgs-DM coupling

$$\Leftrightarrow \lambda_{h\chi\chi}^2$$

DM-nucleon xsec

$$\sigma N\chi$$

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- In particular, the Higgs invisible decay searches provide the complementary results to directly search of dark matter.
- Search for an invisible decaying Higgs boson, which is produced in association with a Z boson, where the Z boson decays to two leptons.
- ATLAS ConfNote with 13.3 fb^{-1} 13 TeV data: [ATLAS-CONF-2016-056](#)



Variable	Value
Di-Lepton Selection	Exactly one ee or $\mu\mu$ pair (as defined above) with leading (subleading) lepton $p_T > 30$ (20) GeV. Opposite charge is required for both $\mu\mu$ and ee pairs.
Third lepton	Veto any additional leptons with $p_T > 7$ GeV .
$m_{\ell\ell}$	76 - 106 GeV
E_T^{miss}	> 90 GeV
$\Delta R_{\ell\ell}$	< 1.8
$\Delta\phi(p_T^Z, E_T^{\text{miss}})$	> 2.7
Fractional p_T Difference *	< 0.2
Number of b-jet	0
$\min\Delta\phi(E_T^{\text{miss}}, \text{jet}_{p_T > 25})$	> 0.7
p_T^Z / m_T **	< 0.9

* Fractional p_T Difference: $|p_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$, $p_T^{\text{miss,jet}} = |\vec{E}_T^{\text{miss}} + \sum_{\text{jet}} \vec{p}_T^{\text{jet}}|$.

** $m_T = \sqrt{2p_T^Z E_T^{\text{miss}} \cos(\Delta\phi(p_T^Z, E_T^{\text{miss}}))}$



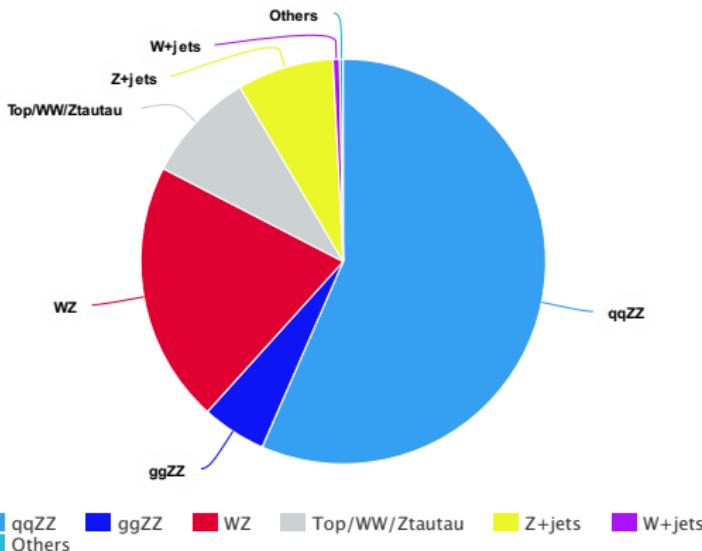
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Di-Lepton Selection	Exactly one ee or $\mu\mu$ pair (as defined above) with leading (subleading) lepton $p_T > 30$ (20) GeV. Opposite charge is required for both $\mu\mu$ and ee pairs.
Third lepton	Veto any additional leptons with $p_T > 7$ GeV . <i>reduce WZ</i>
$m_{\ell\ell}$	76 - 106 GeV <i>Topo. cut</i>
E_T^{miss}	> 90 GeV <i>reduce Z+jets</i>
$\Delta R_{\ell\ell}$	< 1.8 <i>Topo. cut</i>
$\Delta\phi(p_T^Z, E_T^{\text{miss}})$	> 2.7 <i>Topo. cut</i>
Fractional p_T Difference *	< 0.2 <i>Topo. cut</i>
Number of b-jet	0 <i>reduce Top</i>
$\min\Delta\phi(E_T^{\text{miss}}, \text{jet}_{p_T > 25})$	> 0.7 <i>reduce Z+jets</i>
p_T^Z / m_T **	< 0.9 <i>reduce Z+jets</i>

* Fractional p_T Difference: $|p_T^{\text{miss,jet}} - p_T^{\ell\ell}| / p_T^{\ell\ell}$, $p_T^{\text{miss,jet}} = |\vec{E}_T^{\text{miss}} + \sum_{\text{jet}} \vec{p}_T^{\text{jet}}|$.

** $m_T = \sqrt{2p_T^Z E_T^{\text{miss}} \cos(\Delta\phi(p_T^Z, E_T^{\text{miss}}))}$



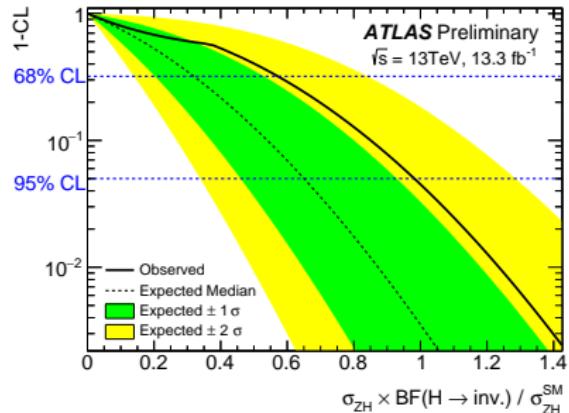
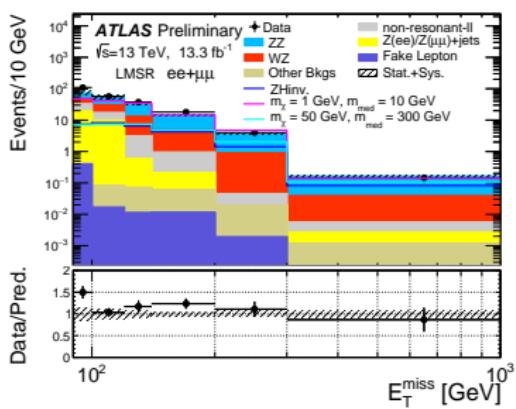
- SM ZZ: $ZZ \rightarrow ll\nu\nu$ is main irreducible background. Full MC based
- WZ: second dominant background in high E_T^{miss} region. Normalization is derived from three lepton CR. Use MC-based shape.
- Z+jet: Yield is estimated using ABCD method. Use MC-based shape.
- Top/Z $\rightarrow \tau\tau$ /WW: estimated using $e\mu$ CR considering the flavor symmetry. Shape from MC
- W+jets: fake factor method.
- ttV(V)/triboson: small backgrounds, estimated from theory predictions.



* The fraction of each background in final signal region, the numbers are calculated based on MC samples.

- E_T^{miss} shape is used as input for statistical analysis
- limit on $BR(H \rightarrow \text{inv.})$: 98% obs. (65% exp.)

Low Mass Signal Region		ee	$\mu\mu$
Data		220	236
Signals			
ZH ($m_H = 125$ GeV) with $BF(H \rightarrow \text{invisible})=100\%$		$40.5 \pm 1.2 \pm 4.1$	$41.7 \pm 1.2 \pm 4.4$
Mono-Z ($m_\chi = 1$ GeV, $m_{\text{med}} = 10$ GeV)		$175 \pm 24 \pm 14$	$169 \pm 21 \pm 22$
Mono-Z ($m_\chi = 50$ GeV, $m_{\text{med}} = 300$ GeV)		$43.7 \pm 2.3 \pm 2.8$	$49.1 \pm 2.6 \pm 4.2$
Backgrounds			
$qqZZ$ (MC-based)		$95.0 \pm 1.5 \pm 5.8$	$102.1 \pm 1.6 \pm 8.0$
$ggZZ$ (MC-based)		$5.6 \pm 0.1 \pm 3.3$	$5.7 \pm 0.1 \pm 3.4$
WZ (Data-driven)		$44.0 \pm 1.1 \pm 3.3$	$50.5 \pm 1.2 \pm 3.3$
$Z(\rightarrow ee, \mu\mu) + \text{jets}$ (Data-driven)		$23 \pm 5 \pm 11$	$16.9 \pm 5.2 \pm 6.7$
non-resonant- $\ell\ell$ (Data-driven)		$16.9 \pm 2.8 \pm 1.0$	$20.7 \pm 3.4 \pm 1.2$
fake-lepton (Data-driven)		$0.18 \pm 0.04 \pm 0.03$	$0.36 \pm 0.46 \pm 0.08$
$t\bar{t}V/VVV$ (MC-based)		$0.44 \pm 0.02 \pm 0.06$	$0.43 \pm 0.02 \pm 0.06$
Total background		$185 \pm 6 \pm 13$	$196 \pm 7 \pm 12$



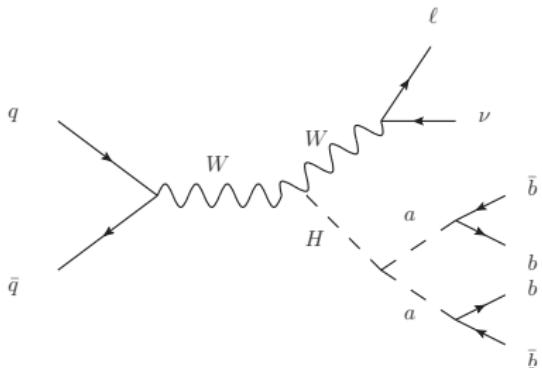
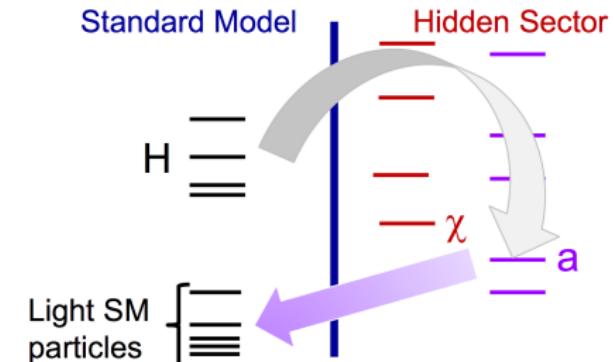
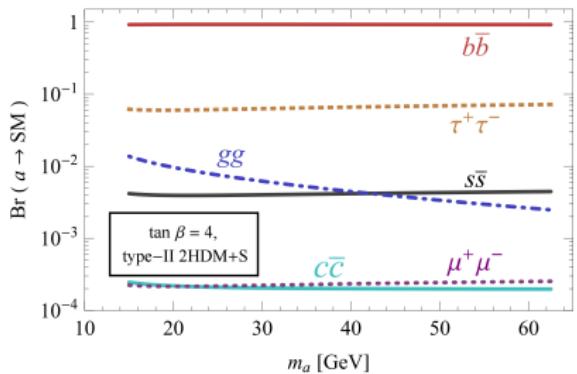
- Many theories motivate using Higgs boson as portal to explore the hidden sector, where the hidden sector decays to light SM particles.

Arxiv: [1412.4779](#)

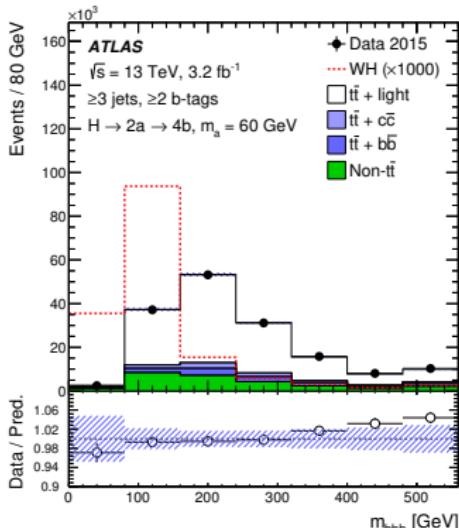
Arxiv: [1312.4992](#)

- Performed a search for this hidden sector in $WH \rightarrow \ell\nu + 4b$ channel with 3.2 fb^{-1} data.

Eur. Phys. J. C 76 (2016) 605

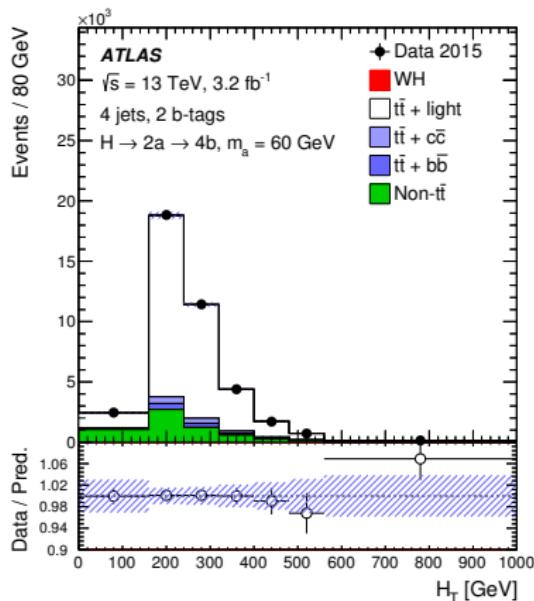
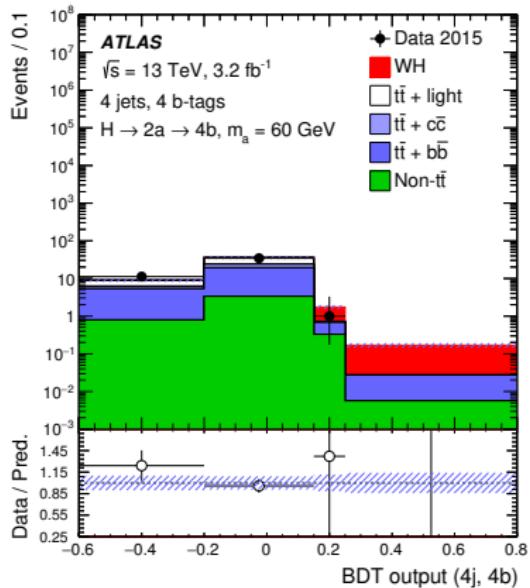


- Search for scalar a in a mass range: $20 < m_a < 60$ GeV
- Analysis strategy
 - Require 1e or 1 μ , $E_T^{\text{miss}} > 25$ GeV and $m_T^W > 50$ GeV.
 - Perform BDT in three signal regions (3j3b, 4j3b, 4j4b) to separate signal and $t\bar{t}$ bkg.

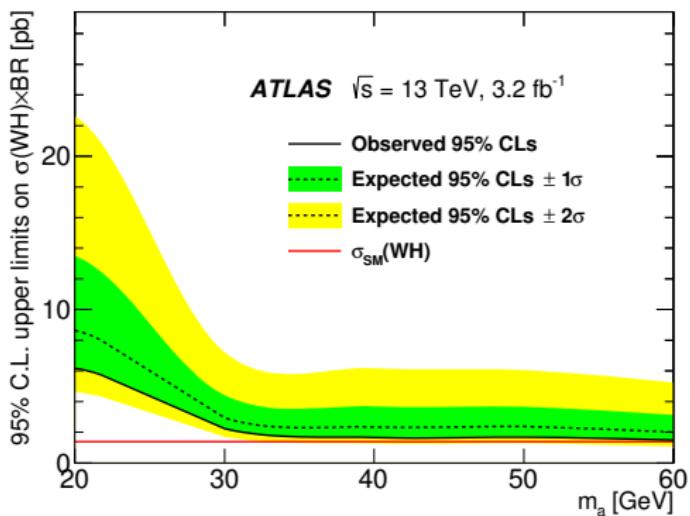


Process	(3j, 3b)	(4j, 3b)	(4j, 4b)
$t\bar{t} + \text{light}$	1089 ± 76	2940 ± 180	53 ± 16
$t\bar{t} + c\bar{c}$	70 ± 28	280 ± 110	21 ± 11
$t\bar{t} + b\bar{b}$	172 ± 55	610 ± 160	74 ± 15
$t\bar{t} + \gamma/W/Z$	0.8 ± 0.1	4 ± 1	0.4 ± 0.1
$W + \text{jets}$	93 ± 31	129 ± 40	2 ± 1
$Z + \text{jets}$	18 ± 12	14 ± 10	–
Single-top-quark	135 ± 13	208 ± 17	8 ± 1
Multijet	48 ± 20	67 ± 28	4 ± 2
Dibosons	4 ± 1	9 ± 1	0.6 ± 0.4
$t\bar{t} + H$	0.7 ± 0.1	4 ± 1	0.8 ± 0.2
Total	1640 ± 58	4270 ± 130	165 ± 15
Data	1646	4302	166
$WH, H \rightarrow 2a \rightarrow 4b$			
$m_a = 60$ GeV	10 ± 2	9 ± 1	3 ± 1
$m_a = 40$ GeV	11 ± 2	10 ± 2	2 ± 1
$m_a = 20$ GeV	6 ± 1	5 ± 1	0.7 ± 0.2

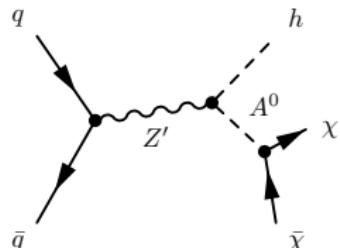
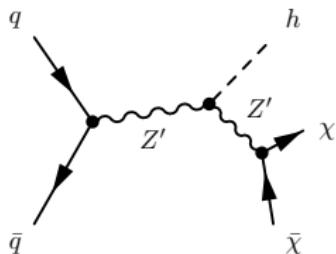
- A combined SR+CR fit is performed to test the signal.
 - 👉 BDT output distributions in three SRs
 - 👉 H_T distributions in 5 CRs ($3j2b$, $4j2b$, $\geq 5j2b$, $\geq 5j3b$, $\geq 5j \geq 4b$)



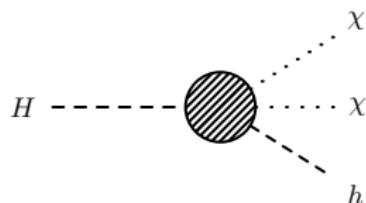
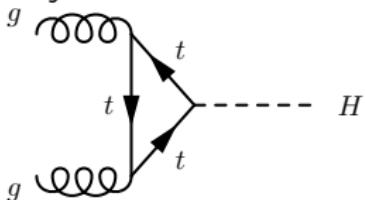
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 - ☞ BDT output distributions in three SRs
 - ☞ H_T distributions in 5 CRs ($3j2b$, $4j2b$, $\geq 5j2b$, $\geq 5j3b$, $\geq 5j \geq 4b$)
- Upper limit on $\sigma(WH) \times BR$: 6.2 pb@ $m_a = 20$ GeV,
1.5 pb@ $m_a = 60$ GeV.



- Simplified models of dark matter production in association with a Higgs boson



- Heavy scalar model

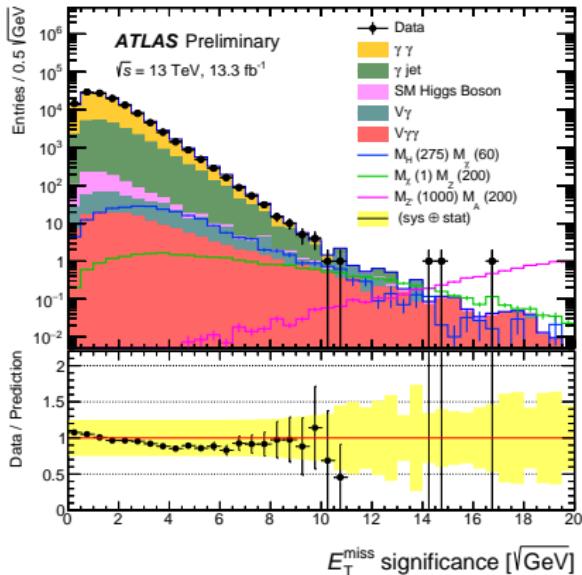


- Perform search with 13.3 fb^{-1} data: ATLAS-CONF-2016-087

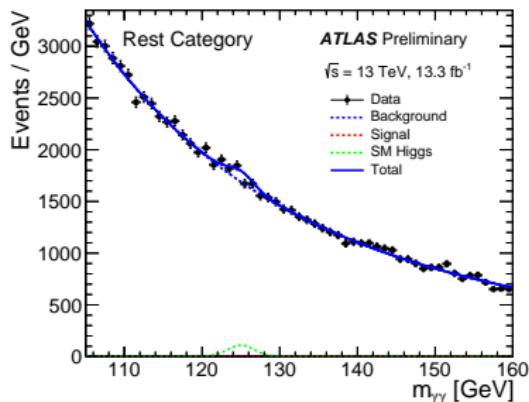
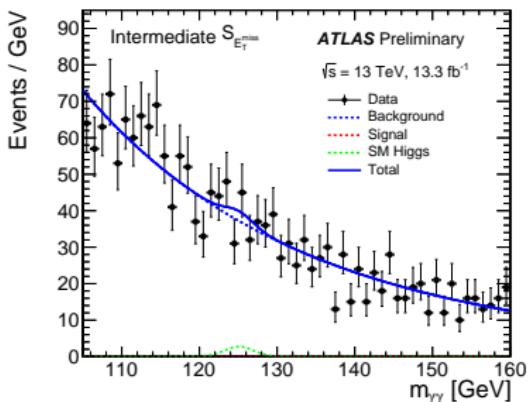
- Leading (subleading) photon with $E_T^\gamma/m_{\gamma\gamma} > 0.35$ (0.25)
- $105 < m_{\gamma\gamma} < 160$ GeV
- Separate into different categories based on $S_{E_T^{\text{miss}}}^*$ and $p_T^{\gamma\gamma}$

Category	$S_{E_T^{\text{miss}}} [\sqrt{\text{GeV}}]$	$p_T^{\gamma\gamma} [\text{GeV}]$
High $S_{E_T^{\text{miss}}}$, high $p_T^{\gamma\gamma}$	> 7	> 90
High $S_{E_T^{\text{miss}}}$, low $p_T^{\gamma\gamma}$	> 7	≤ 90
Intermediate $S_{E_T^{\text{miss}}}$	> 4 and ≤ 7	> 25
Rest	-	> 15

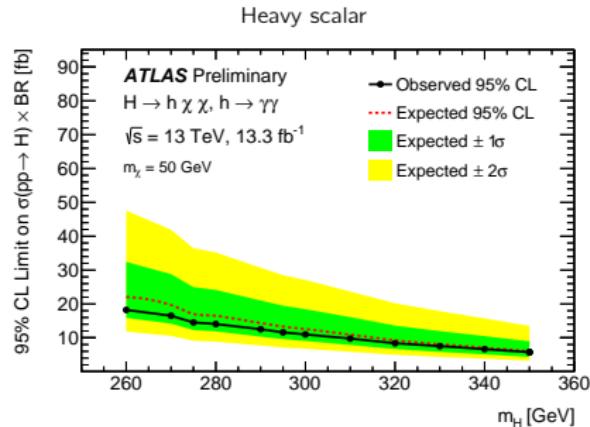
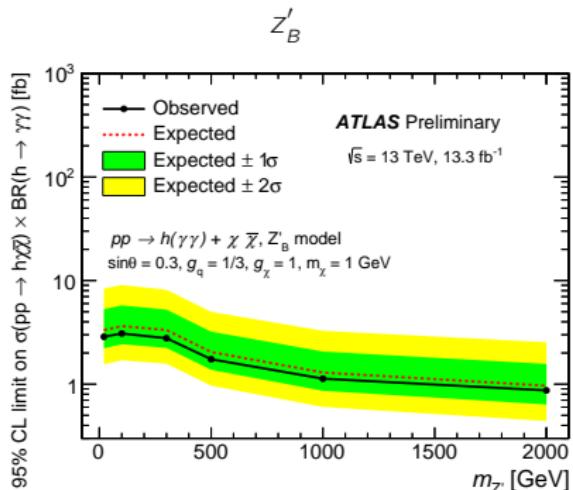
$$* S_{E_T^{\text{miss}}} = E_T^{\text{miss}} / \sum E_T$$



- Perform unbinned likelihood fit with events in certain categories.
 - ☞ Z'_B and Z' -2HDM model: use category with high $S_{E_T^{\text{miss}}}$ and $p_T^{\gamma\gamma}$.
 - ☞ Search for heavy scalar: use all categories



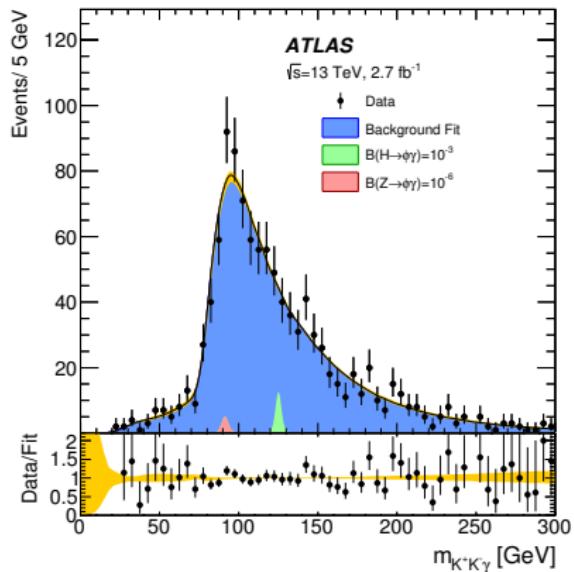
- Perform unbinned likelihood fit with events in certain categories.
 - Z'_B and Z' -2HDM model: use category with high $\mathcal{S}_{E_T^{\text{miss}}}$ and $p_T^{\gamma\gamma}$.
 - Search for heavy scalar: use all categories
- No significant excess is observed, derive upper limit on $\sigma \times BR$



- A probe of Yukawa coupling of the Higgs boson to s quark.
 ↳ $\mathcal{B}(H \rightarrow \phi\gamma) = 2.3 \pm 0.1 \times 10^{-6}$
- Some BSM models modify this coupling
 → explore new physics.
- Also perform a search for $Z \rightarrow \phi\gamma$ decay mode.
 ↳ $\mathcal{B}(Z \rightarrow \phi\gamma) = 1.17 \pm 0.08 \times 10^{-8}$
- Use $K^+K^-\gamma$ final state
 - $\Delta\phi(K^+K^-, \gamma) > 0.5$
 - $m_{K^+K^-\gamma}$ dependent $p_T^{K^+K^-}$ threshold
- Unbinned fit to $m_{K^+K^-\gamma}$ distribution.
- No significant excess is observed
- Publication:

Phys. Rev. Lett. 117, 111802

Observed (Expected) Background		Expected Signal	
Mass Range [GeV]		Z	H
All	81–101	$120\text{--}130$	$\mathcal{B}[10^{-6}]$
1065	288 (266 ± 9)	89 (87 ± 3)	6.7 ± 0.7
			13.5 ± 1.5



Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \rightarrow \phi\gamma) [10^{-3}]$	$1.5^{+0.7}_{-0.4}$	1.4
$\mathcal{B}(Z \rightarrow \phi\gamma) [10^{-6}]$	$4.4^{+2.0}_{-1.2}$	8.3

Conclusion



- ATLAS has performed several searches for rare and non-SM decay modes of the Higgs boson using run-II data.
- No hints for these modes are found from recent data.
- Expect more excited results with full 2015+2016 data and furthermore with full run-II data ($\sim 100 \text{ fb}^{-1}$).
 - More precision measurements on SM processes \Rightarrow higher chance to observe small signals.
 - More stringent constraints on parameter space.

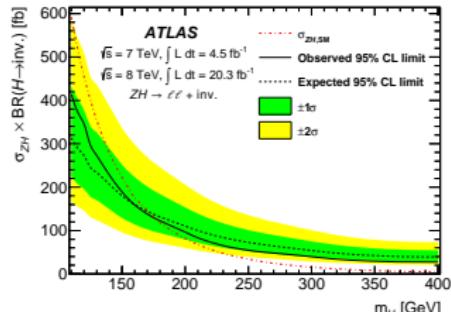


Backup

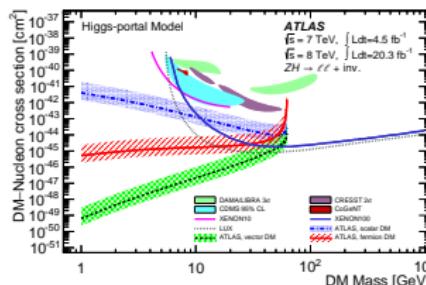


$ZH \rightarrow ll + inv.$

- The ATLAS performed the search using 7 and 8 TeV data. No significant deviations are observed and 95% C.L. upper limit on $BR(H \rightarrow inv.) = 0.75$ (0.62 exp.) @ $m_H = 125.5$ GeV



Phys. Rev. Lett. 112, 201802 (2014)



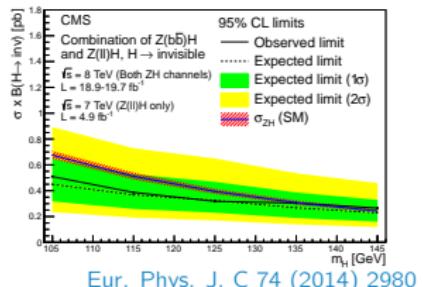
Phys. Rev. Lett. 112, 201802 (2014)

$$\sigma_{\chi N}^{\text{Scalar}} = \frac{\lambda_{h\chi\chi}^2 \text{Scalar}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\sigma_{\chi N}^{\text{Vector}} = \frac{\lambda_{h\chi\chi}^2 \text{Vector}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\sigma_{\chi N}^{\text{Majorana}} = \frac{\lambda_{h\chi\chi}^2 \text{Majorana}}{4\pi\Lambda^2 m_h^4} \frac{m_\chi^2 m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

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- The CMS performed the search using 7 and 8 TeV data and give the 95% C.L. upper limit on $BR(H \rightarrow inv.) = 0.83$ (0.86 exp.). The CMS also performed the preliminary results using 13 TeV data and set the 95% C.L. upper limit on $BR(H \rightarrow inv.)$ to 1.28 (1.28 exp.)



Eur. Phys. J. C 74 (2014) 2980

