Search for rare or non-standard production and decay modes of the Higgs boson with the ATLAS detector

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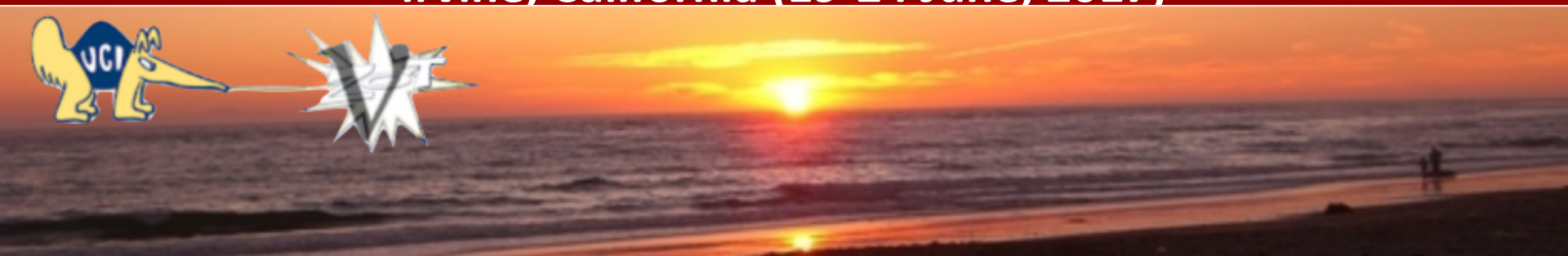


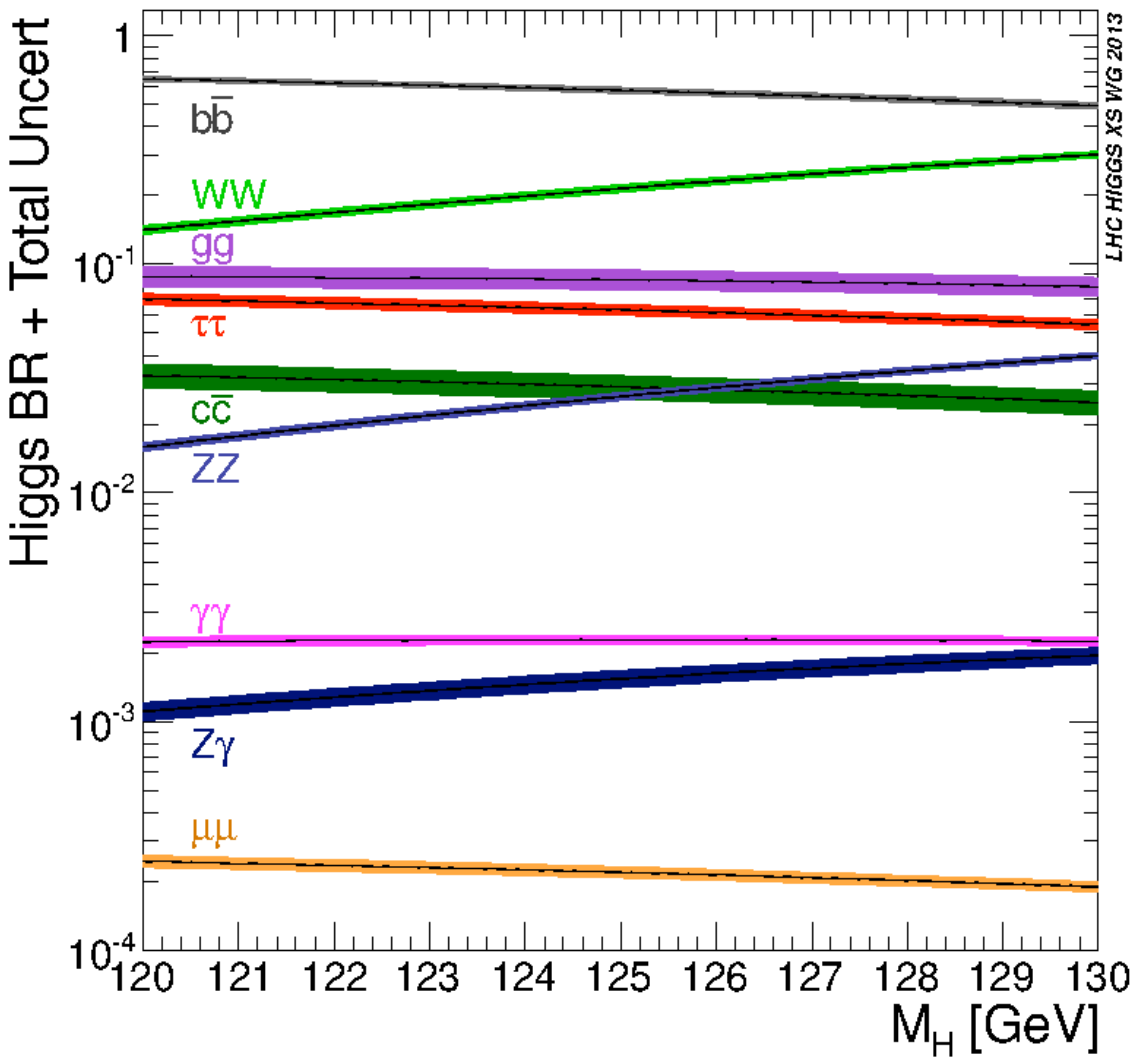
Outline

- Motivation
- Rare production modes ("new" results only)
  - Pair production: $pp \rightarrow hh$
  - Associated with Dark Matter: $pp \rightarrow h\chi\chi$
  - In decays of pair-produced top squarks: $pp \rightarrow \tilde{t}_1\tilde{t}_1;\ \tilde{t}_1 \rightarrow ht\widetilde{\chi_1^0}$
- Rare decay modes
  - Di-muon: $h \rightarrow \mu\mu$
  - Mesonic: $h \rightarrow \phi\gamma$
  - Invisible: $h \rightarrow \chi\chi$
- Summary and outlook

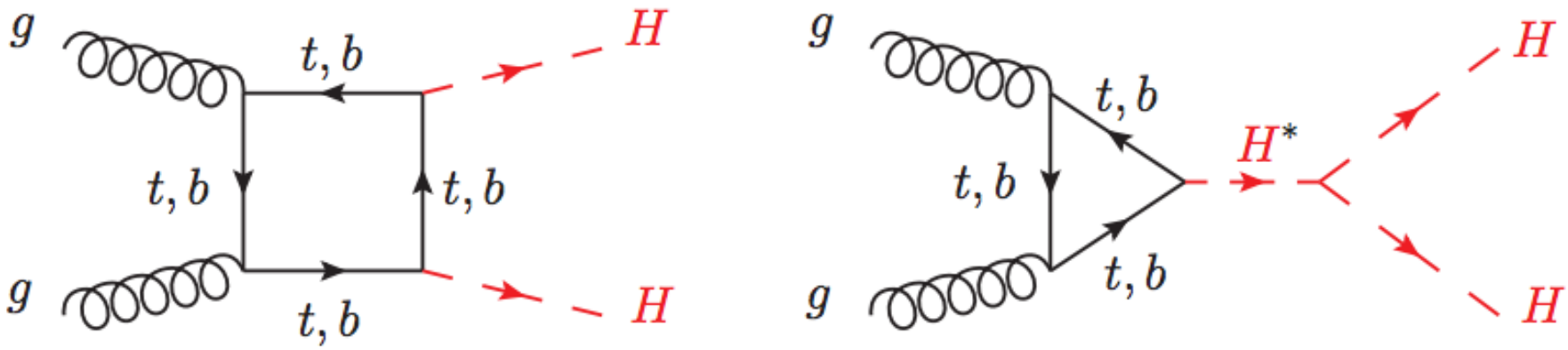
Motivation

- Since its discovery at the LHC 5 years ago, studies of Higgs boson properties has been the highest priority for both ATLAS and CMS.
- A number of BSM theories can affect Higgs production or decay.
- Although all measurements so far are in line with SM predictions, it is possible that BSM alterations to production and decay modes that are rare in SM are hiding in experimental uncertainties.
- $B(h \rightarrow BSM)$<0.34 : constraint from Run 1. JHEP08 (2016) 045
- Measurement of a well-chosen set of processes allows us to address a diverse set of BSM scenarios.

SM Higgs branching fractions

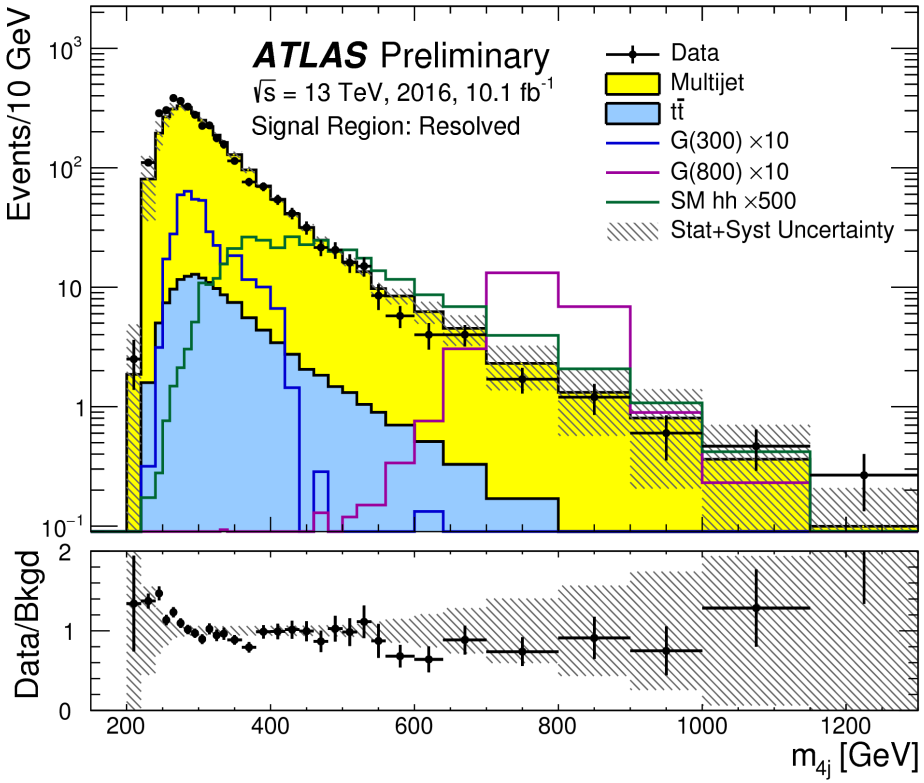


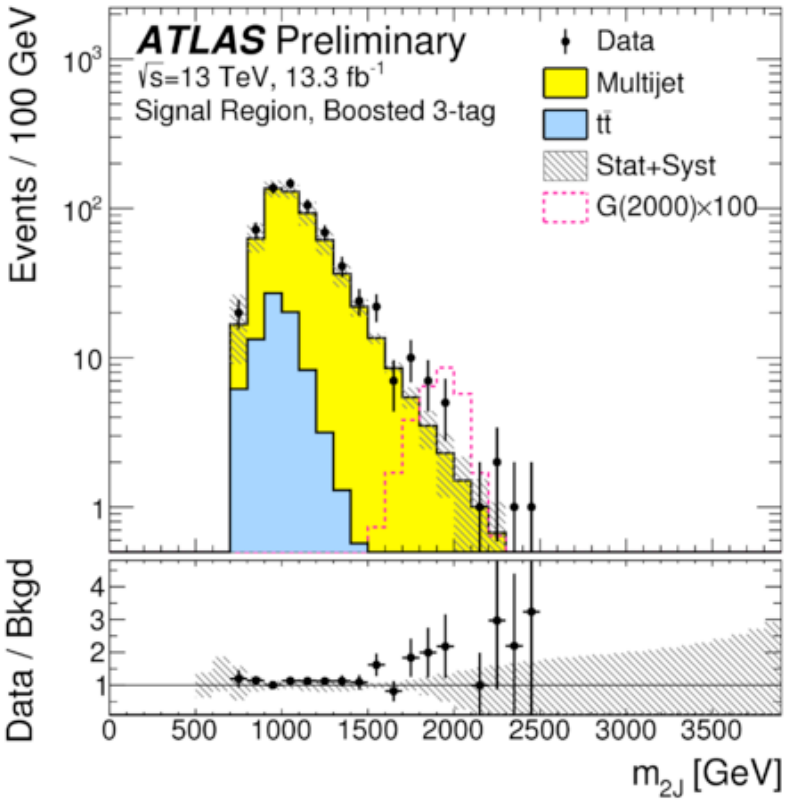
Pair production: $pp \rightarrow hh$



- Higgs trilinear self-coupling λ_{hhh} can be extracted from $\sigma(pp \rightarrow hh)$
- SM prediction: 33.4 fb at $\sqrt{s} = 13$ TeV
  - Suppressed by destructive interference between the two processes.
- Rate enhancement is possible in several extensions of the SM
  - Resonant: discovery of $pp \rightarrow X \rightarrow hh$ if m_X is kinematically accessible.
  - Non-resonant: new interaction or modification of λ_{hhh}.

Pair production: $pp \rightarrow hh \rightarrow bbbb$ (1/2)





- Resolved regime: reconstruct ≥ 4 b -tagged jets, R=0.4; 10.1 fb^{-1}.
  - aiming at non-resonant production or $m_X < 1000$ GeV
- Boosted regime: 2 fat jets containing ≥ 3 b-tags, R=1.0; 13.3 fb^{-1}.
  - aiming at $m_X > 1000$ GeV

ATLAS-CONF-2016-049

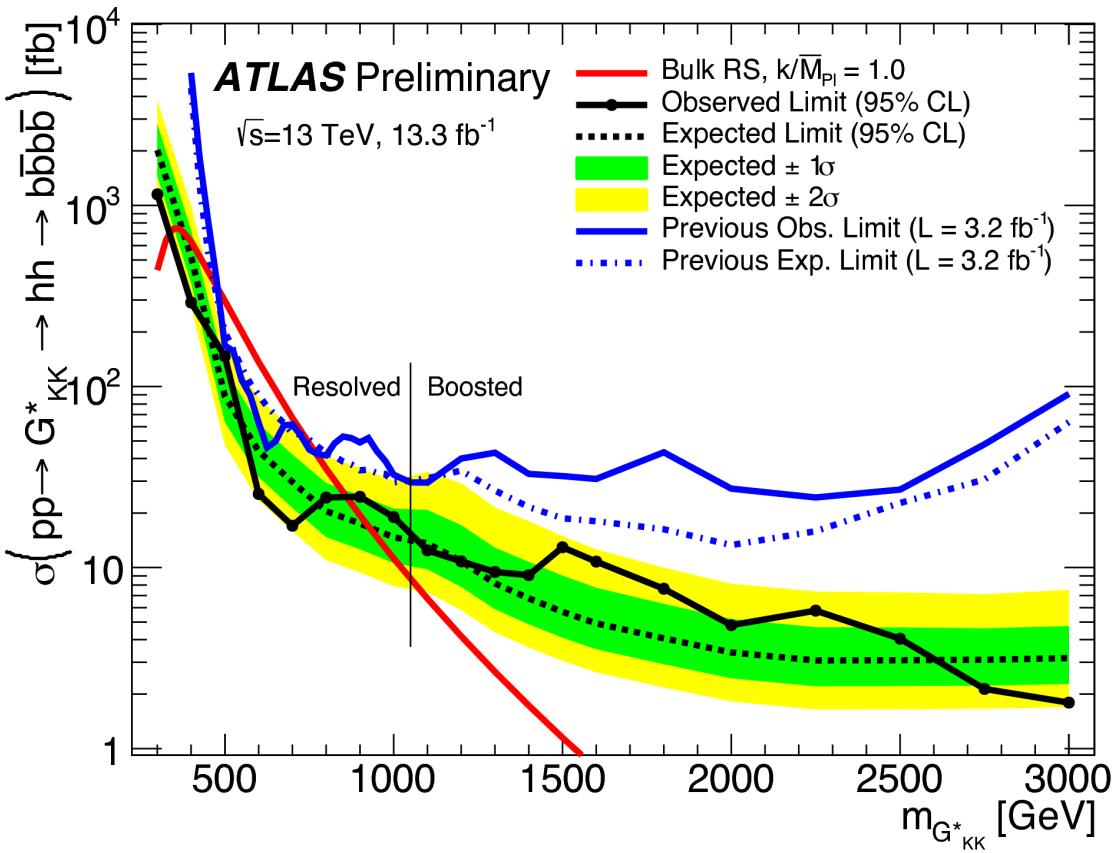
Pair production: $pp \rightarrow hh \rightarrow bbbb$ (2/2)

- Upper limit on non-resonant production (430 fb expected):

$$\sigma(pp \rightarrow hh) \times B(hh \rightarrow bb) < 330 \text{ fb at } 95\% \text{ CL}$$

- Resonant production: upper limit on the rate through the first excitation of a KK graviton in the bulk RS model.

ATLAS-CONF-2016-049

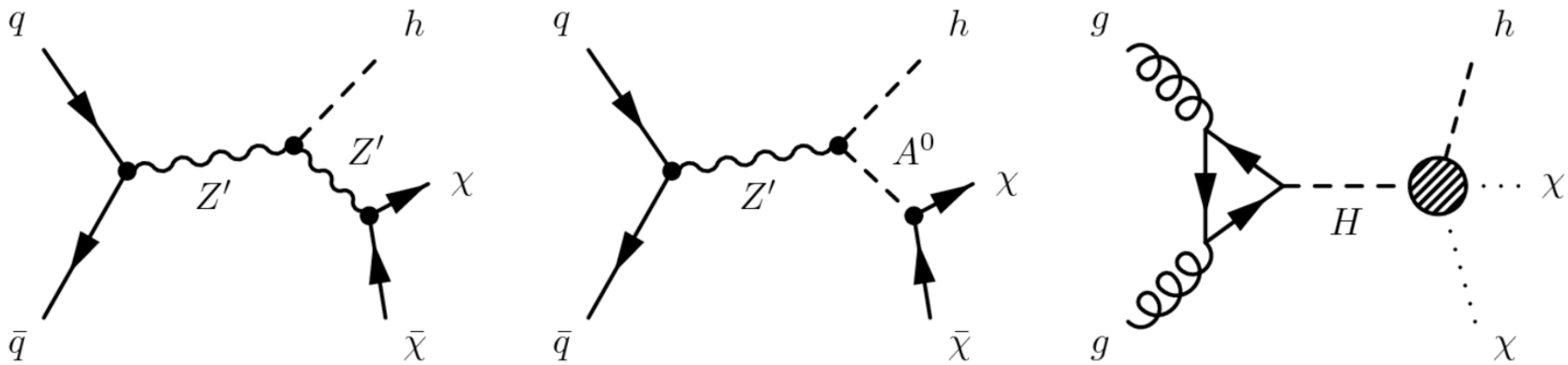


Pair production: $pp \rightarrow hh$ summary

Channel	$\int \mathcal{L}\, dt$ (fb^{-1})	Obs. (exp.) 95% C.L. limit on σ/σ_{SM}	
$bbbb$	13.3	29 (38)	ATLAS-CONF-2016-049
$bb\gamma\gamma$	3.2	117 (161)	ATLAS-CONF-2016-004
$\gamma\gamma WW$	13.3	747 (386)	ATLAS-CONF-2016-071

- Analyses in different channels complementary strengths.
- Analyses of other channels such as $bb\tau\tau$ and $bbWW$ at $\sqrt{s} = 13$ TeV are in progress.

Dark-matter-associated production



(a) (b) (c)

- (a): Z'_B model, the $U'(1)_B$ baryon symmetry ensures stability of χ.
- (b): Z'-2HDM, A^0 is the pseudoscalar Higgs state.
- (c): Heavy scalar model: $2m_h < m_H < 2m_t$, $m_\chi \approx \frac{m_h}{2}$ ensures validity of assumption $B(H \to h\chi\chi) = 1$.
- The DM candidate is a Dirac fermion in (a) and (b), scalar in (c).

$pp \to h\chi\chi \to \gamma\gamma E_{\mathrm{T}}^{\mathrm{miss}}$ (1/3)

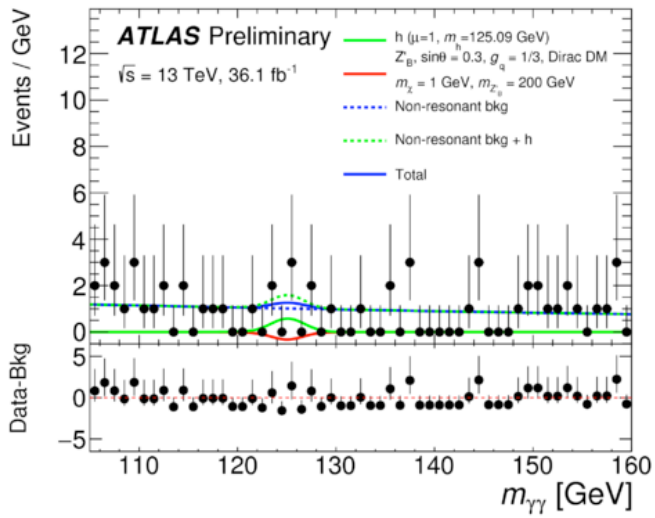
- Look for $h \to \gamma\gamma$, so the final state signature consists of two high-p_T isolated photons and significant $E_{\mathrm{T}}^{\mathrm{miss}}$ (measured by $S_{E_{\mathrm{T}}^{\mathrm{miss}}}$).
- Selected events are split into 5 categories with complementary sensitivities (events in each category are removed from all below it):

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

$\int \mathcal{L}\, dt$ = 36.1 fb^{-1}

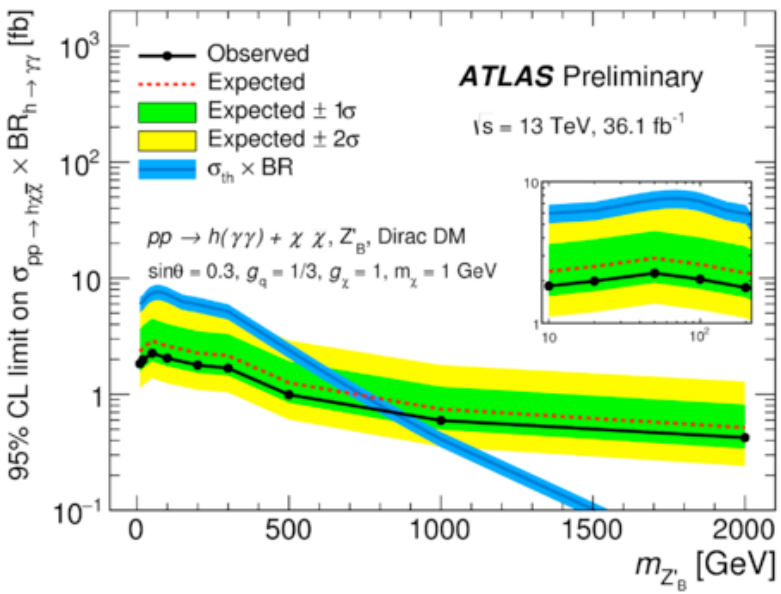
arXiv:1706.03948

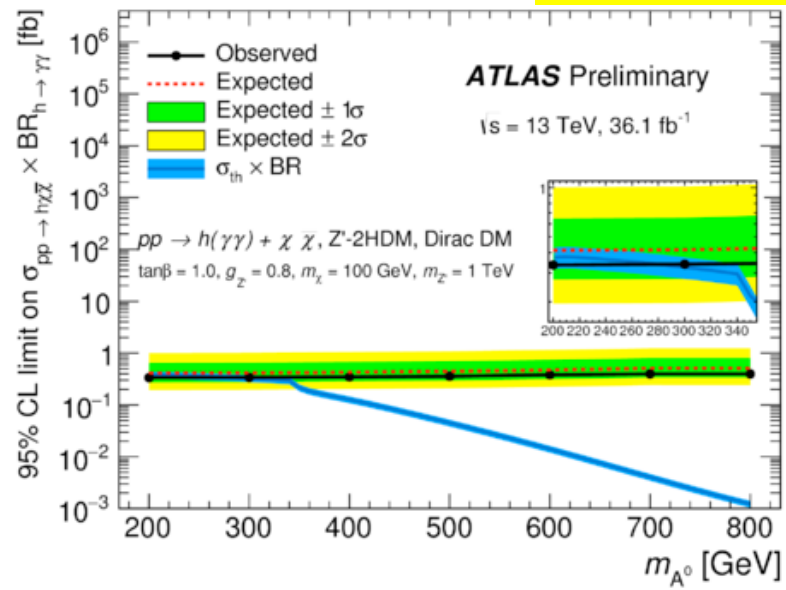
$pp \to h\chi\chi \to \gamma\gamma E_{\mathrm{T}}^{\mathrm{miss}}$ (2/3)



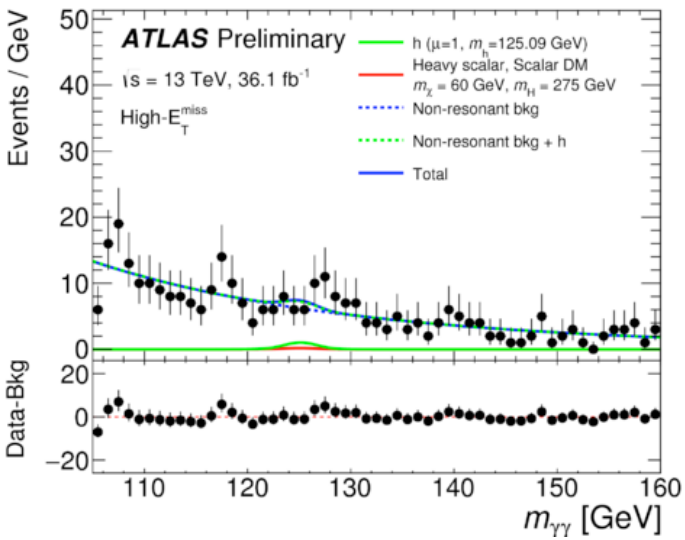
- $m_{\gamma\gamma}$ distribution of data, SM bkg, and Z'_B signal in the mono-Higgs category.
- Good agreement between data and SM constrains Z'_B and Z'-2HDM rates.

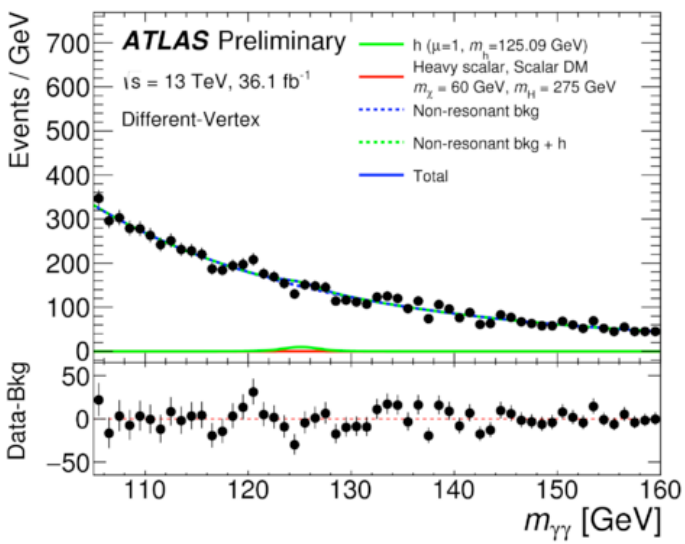
arXiv:1706.03948



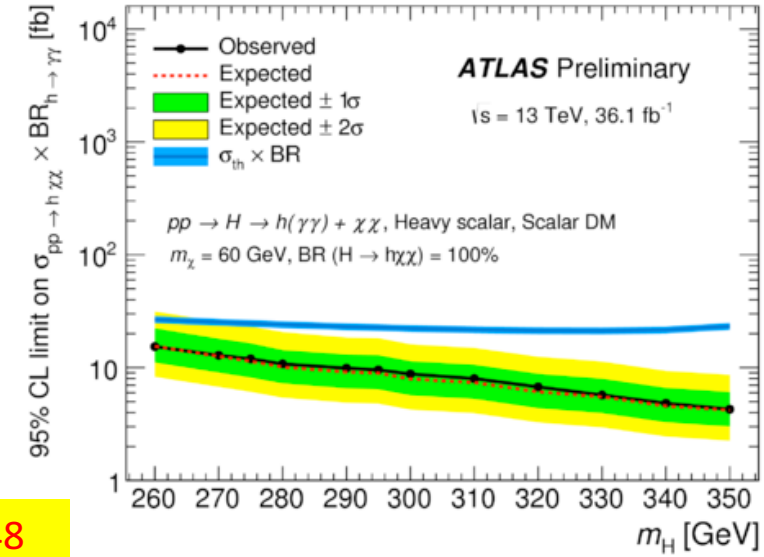


$pp \to h\chi\chi \to \gamma\gamma E_T^{miss}$ (3/3)





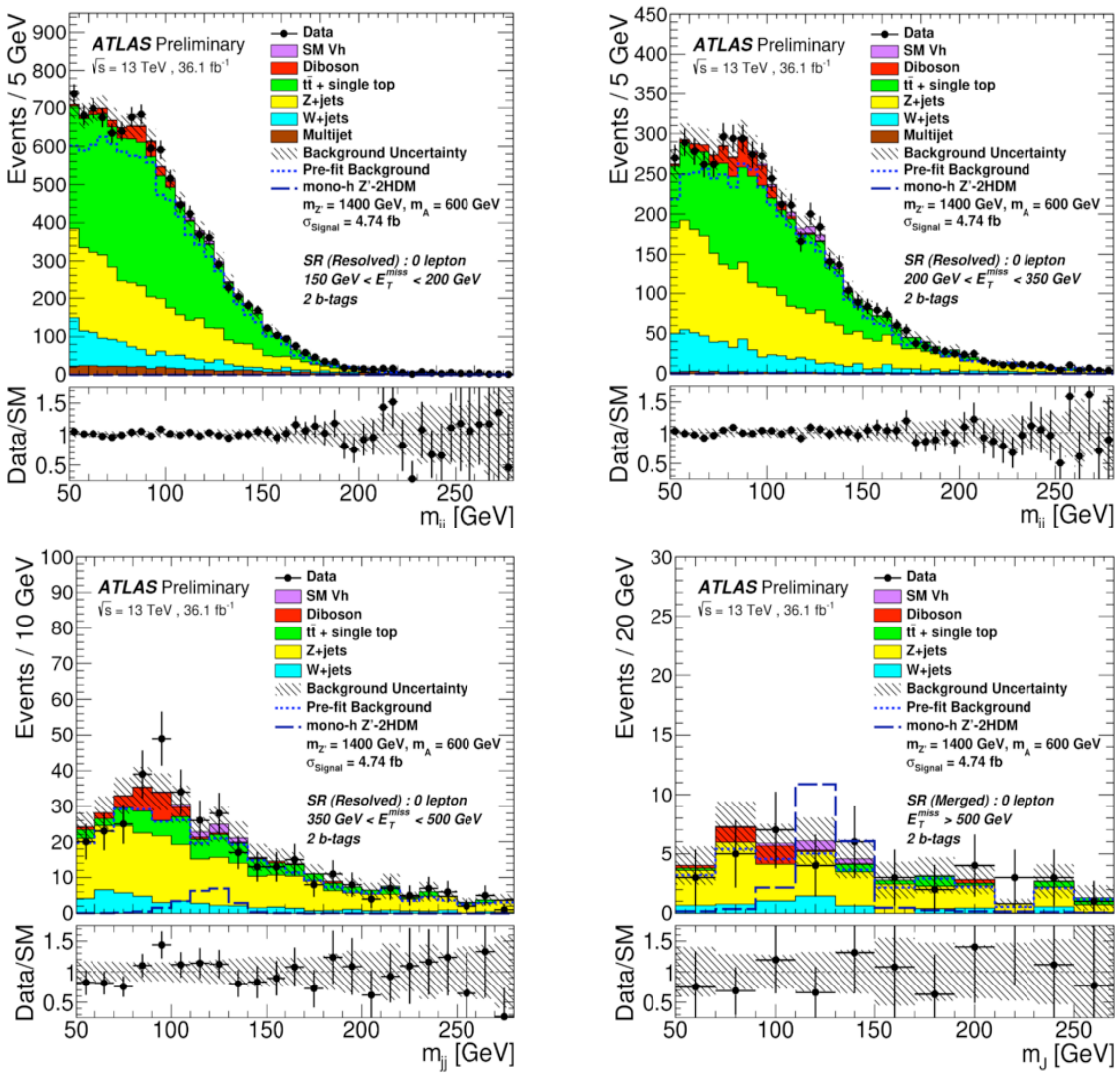
- $m_{\gamma\gamma}$ distribution of data, SM bkg, and heavy Higgs signal in "High-E_T^{miss}" (top) and "Different-Vertex" categories.
- Good agreement between data and SM constrains $\sigma(pp \to h\chi\chi) \times B(h \to \gamma\gamma)$.



arXiv:1706.03948

$pp \to h\chi\chi \to bbE_{\mathrm{T}}^{\mathrm{miss}}$ (1/2)

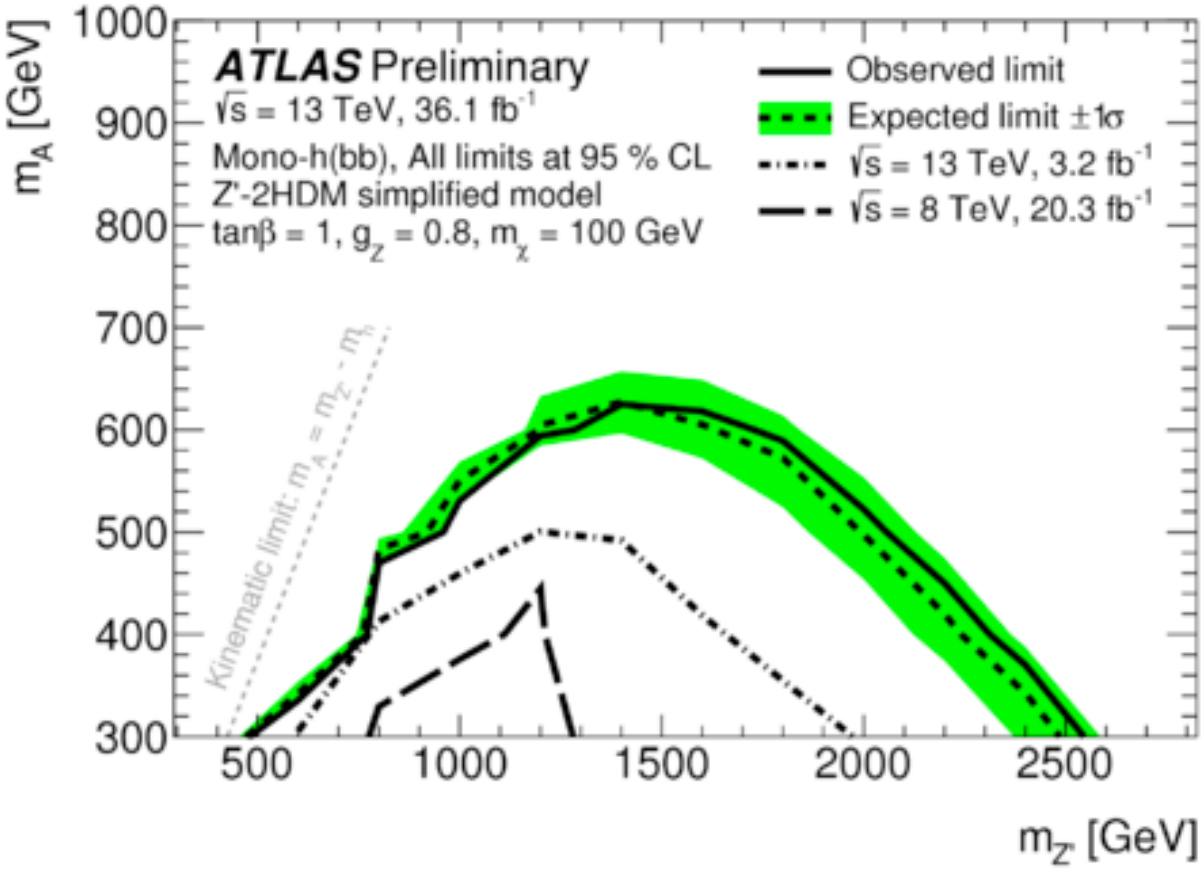
- Z'-2HDM only.
- Complements $\gamma\gamma E_{\mathrm{T}}^{\mathrm{miss}}$ search, which is more effective in the low-mass, $E_{\mathrm{T}}^{\mathrm{miss}}$ regime.
- Fit to dijet mass in four bins of $E_{\mathrm{T}}^{\mathrm{miss}}$.
- A single "fat" jet is used in the highest $E_{\mathrm{T}}^{\mathrm{miss}}$ bin.



ATLAS-CONF-2017-028

$pp \to h\chi\chi \to bbE_{\mathrm{T}}^{\mathrm{miss}}$ (2/2)

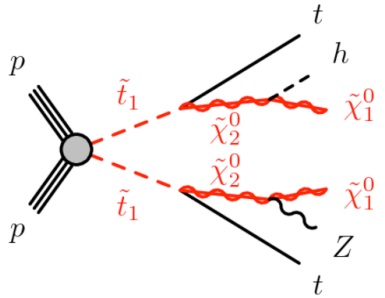
- The lack of any significant disagreement between SM predictions and data leads to exclusion of the $m_{Z'}, m_A$ parameter space.

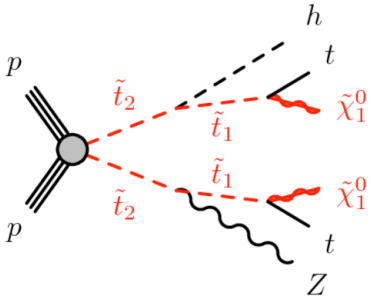


$\int \mathcal{L}\, dt$ = 36.1 fb^{-1}

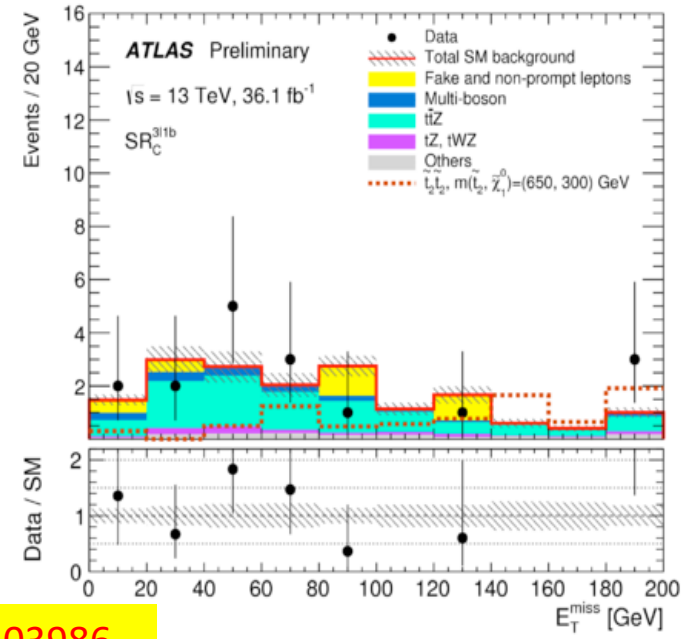
ATLAS-CONF-2017-028

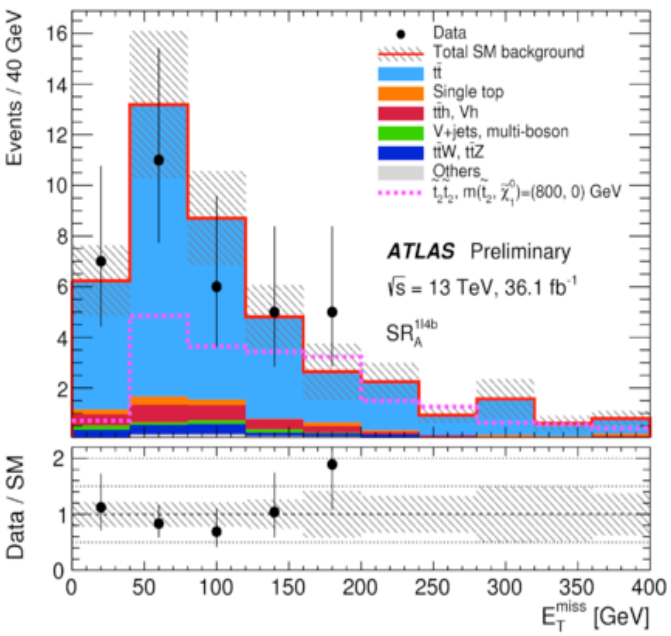
Higgs in decay of top squarks (1/2)





- In addition to multiple (jets, candidate events must have, at least, <u>either</u> 3 leptons and 1 b-tags ($3l1b$) <u>or</u> 1 lepton and 4 b-tags ($1l4b$).



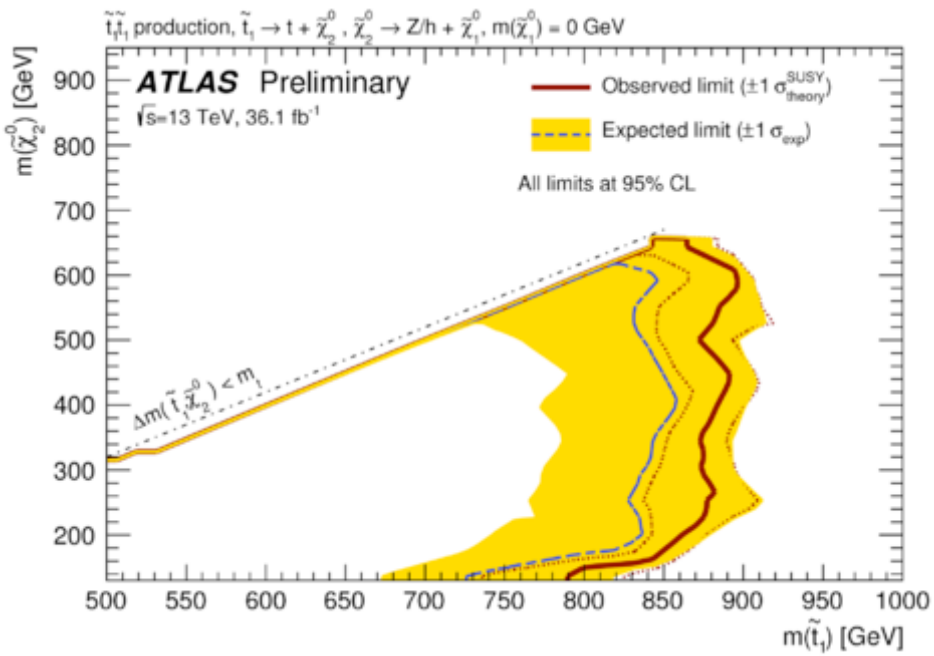


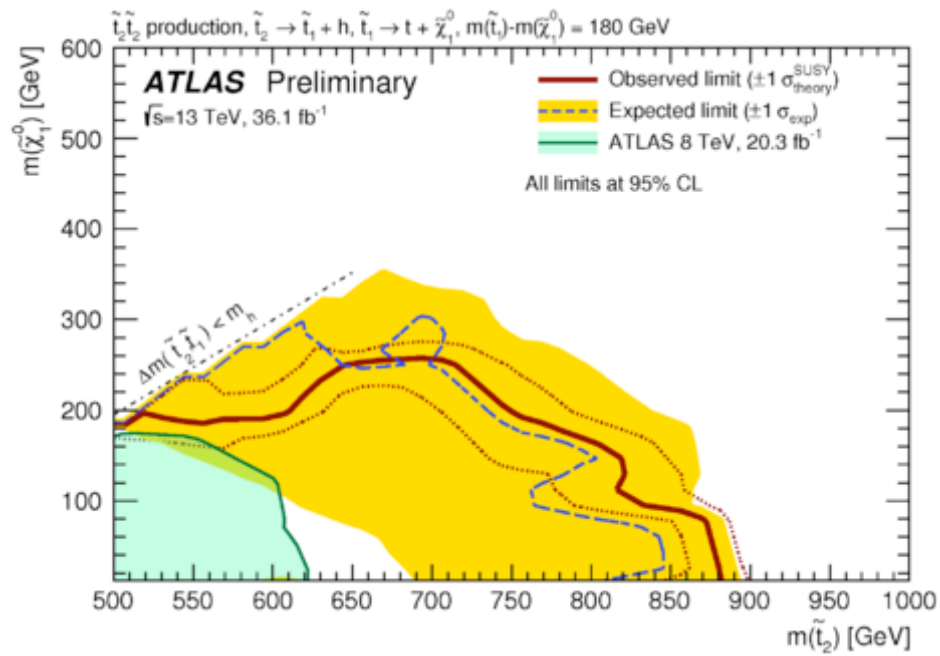
arXiv:1706.03986

Higgs in decay of top squarks (2/2)

assuming $\mathrm{BR}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = \mathrm{BR}(\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0) = 0.5$.

assuming $\mathrm{BR}(\tilde{t}_2 \to h\tilde{t}_1) = 1$.



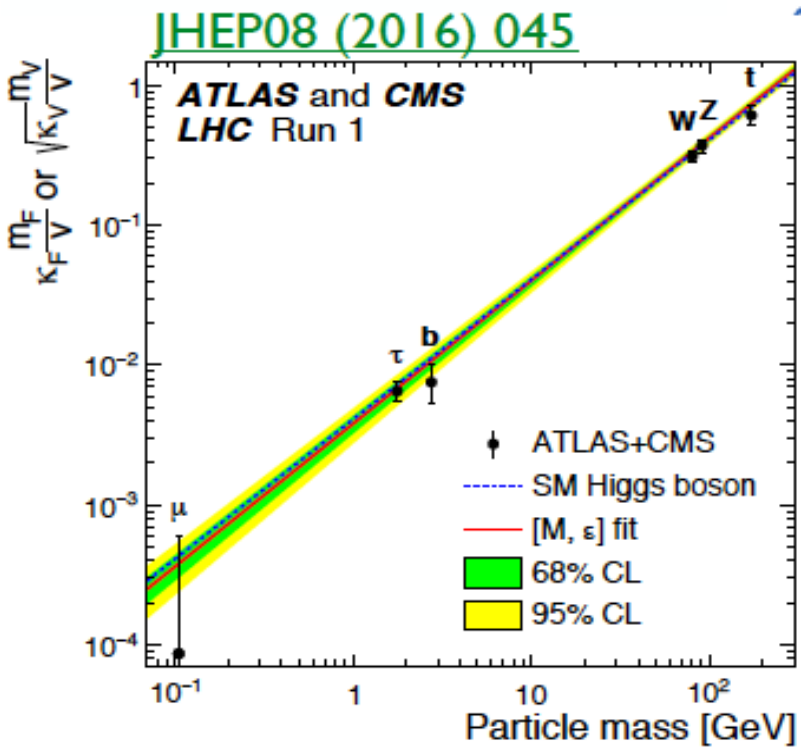


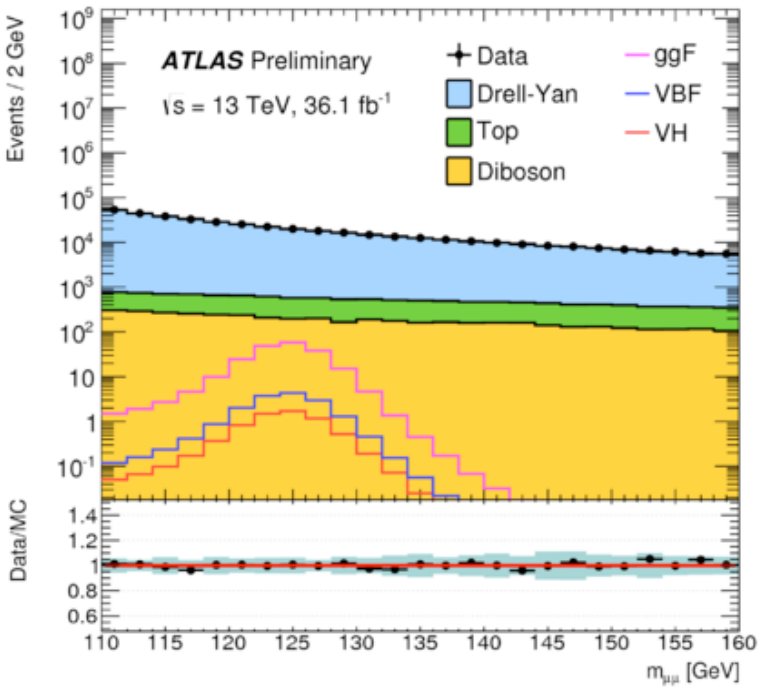
$\int \mathcal{L}\, dt = 36.1\ \mathrm{fb}^{-1}$

arXiv:1706.03986

Rare decay: $h \to \mu\mu$ (1/2)

- Cleanest channel to study Higgs coupling to 2nd generation fermions.
- SM: $B(h \to \mu\mu) = 2.2\times10^{-4} \approx 0.1\times B(h \to \gamma\gamma)$
- Dominated by irreducible background from $Z/\gamma^* \to \mu\mu$.



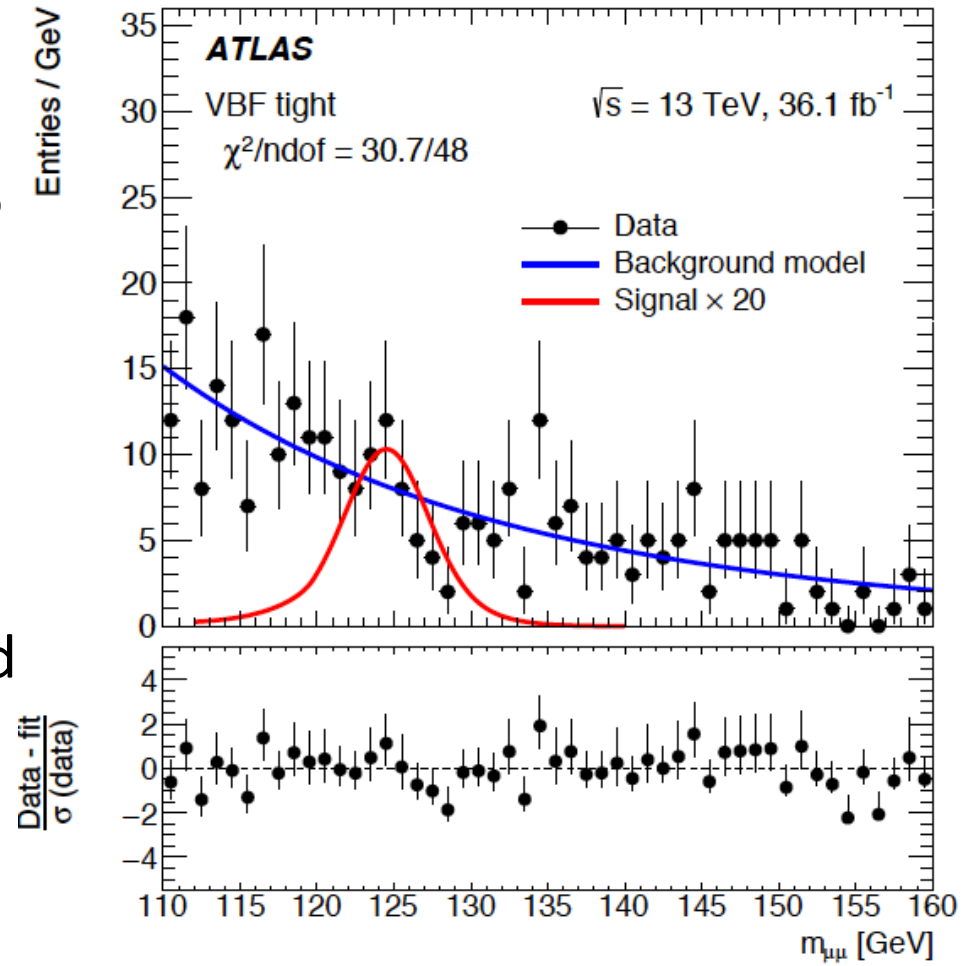


arXiv:1705.04582

Rare decay: $h \to \mu\mu$ (2/2)

- Run 2 observed (expected) 95% CL upper limit on $B(h \to \mu\mu)$: 3.0 (3.1) × SM prediction.
- Combined with Run 1:

$B(h \to \mu\mu) < 2.8\ (2.9) \times$ SM pred

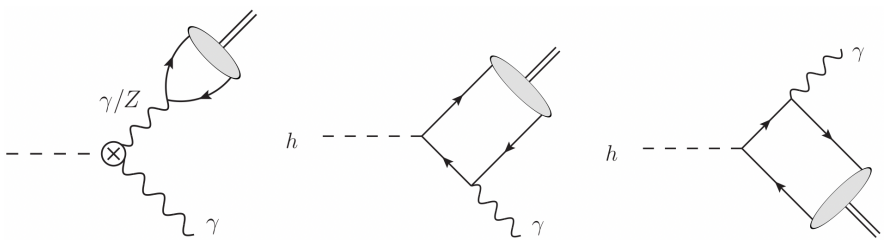


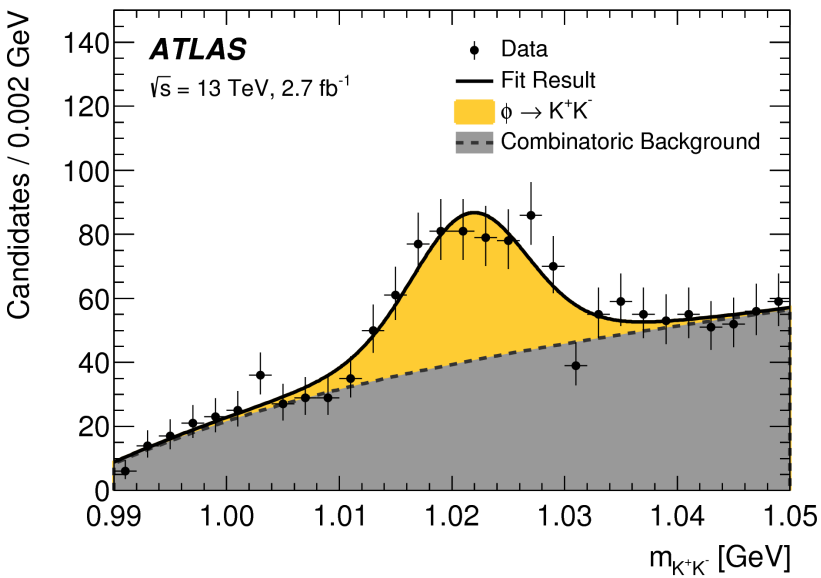
$\int \mathcal{L}\, dt$ = 36.1 fb^{-1}

arXiv:1705.04582

Rare decay: $h \to \varphi\gamma$ (1/2)

- Sensitive to Yukawa coupling of the strange quark.
- Reconstruct $\phi \to K^+ K^-$ $(B = 0.49)$
- Two high-p_T (>20, 15 GeV) tracks with $\Delta R < 0.05, m(KK) \approx m_\varphi$ recoiling against a high-p_T γ (> 35 GeV).
- Dedicated trigger ($\epsilon \approx 0.78 \times$ offline).
- Data-driven background modeling using templates (non-parametric).



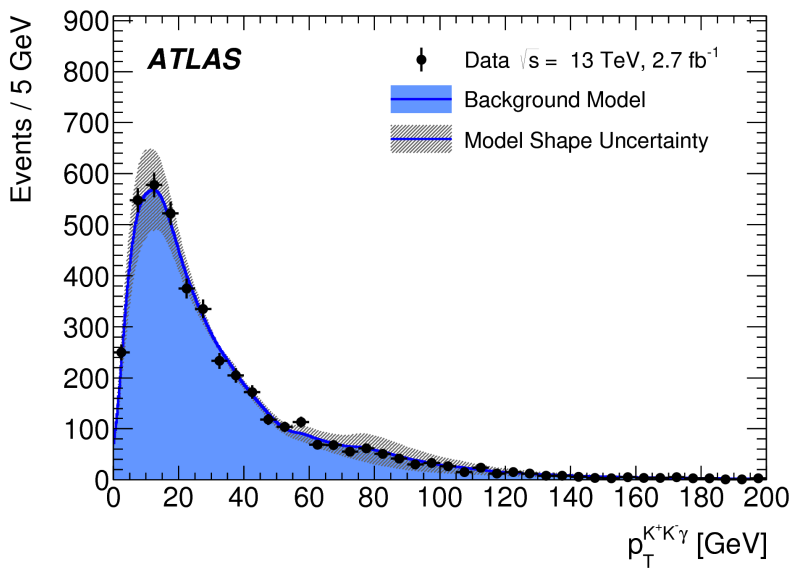


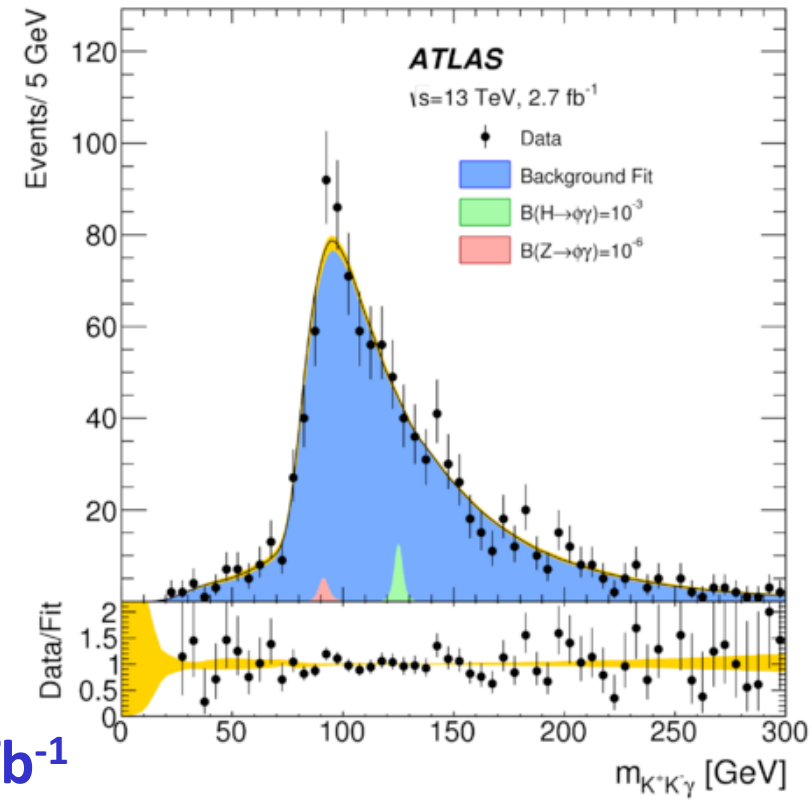
Phys. Rev. Lett. 117, 111802 (2016)

Rare decay: $h \to \varphi\gamma$ (2/2)

- Unbinned maximum-likelihood fit to $m(KK\gamma)$

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





- SM prediction:
  - $B(h \to \phi\gamma) = (2.3 \pm 0.1)\times 10^{-6}$
  - $B(Z \to \phi\gamma) = (1.17 \pm 0.08)\times 10^{-8}$

Phys. Rev. Lett. 117, 111802 (2016)

$\int \mathcal{L}\, dt$ = 2.7 fb^{-1}

Invisible decay: $h \to \chi\chi$ (1/2)

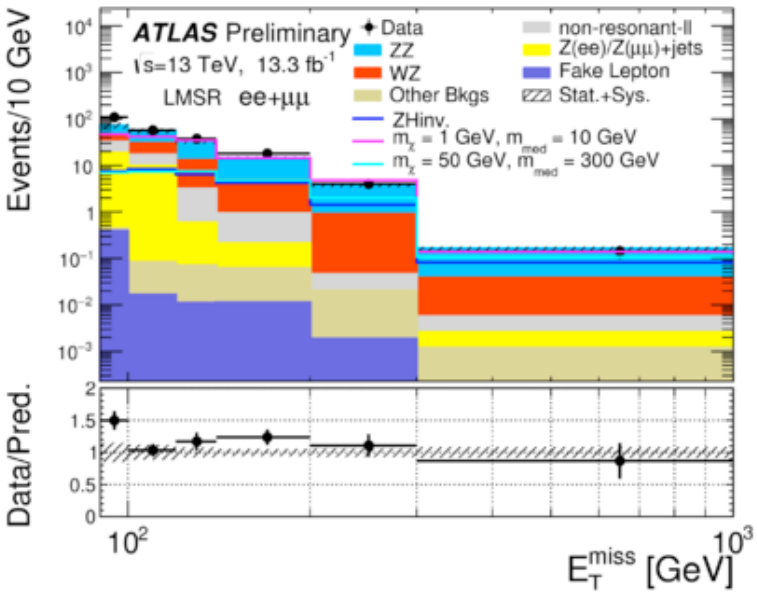
- Look for $pp \to Zh \to ll + E_{\mathrm{T}}^{\mathrm{miss}}$

ATLAS-CONF-2016-056

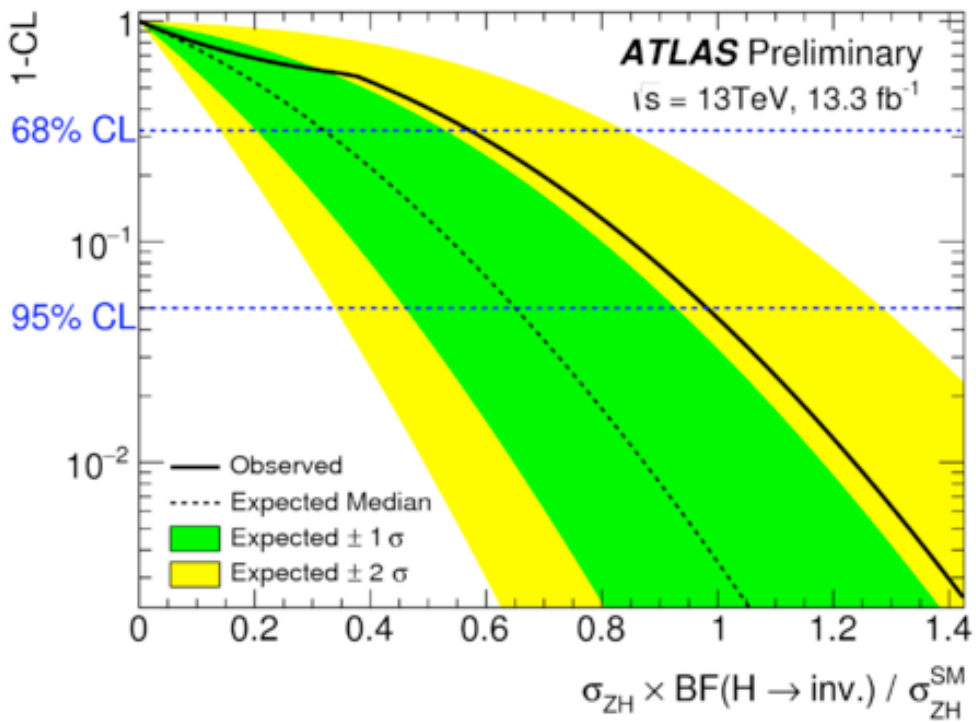
- SM: $\sigma(pp \to Zh) \times B(Z \to ll) \approx 89$ fb at $\sqrt{s} = 13$ TeV.

Low Mass Signal Region	ee	$\mu\mu$
Data	220	236
Signals		
ZH ($m_H = 125$ GeV) with BF($H \to$ invisible)=100%	$40.5 \pm 1.2 \pm 4.1$	$41.7 \pm 1.2 \pm 4.4$
Mono-Z ($m_\chi = 1$ GeV, $m_{\mathrm{med}} = 10$ GeV)	$175 \pm 24 \pm 14$	$169 \pm 21 \pm 22$
Mono-Z ($m_\chi = 50$ GeV, $m_{\mathrm{med}} = 300$ 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)	$44.0 \pm 1.1 \pm 3.3$	$50.5 \pm 1.2 \pm 3.3$
$Z(\to ee, \mu\mu)$+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	$185 \pm 6 \pm 13$	$196 \pm 7 \pm 12$

Invisible decay: $h \rightarrow \chi\chi$ (2/2)



- Good agreement between data and SM prediction constrains the rate of $pp \rightarrow Zh \rightarrow ll + E_{\mathrm{T}}^{\mathrm{miss}}$



$\int \mathcal{L}\, dt$ = **13.3 fb^{-1}**

ATLAS-CONF-2016-056

Summary and outlook

- Extensive studies of Higgs production and decay properties – rates and kinematics – constitute a rich program of physics at the LHC.
- Most processes that the SM predicts too rare to be accessible yet remain unobserved, but we remain vigilant for any sign of enhancements predicted by a variety of BSM scenarios.
- Improved statistics, analysis techniques, inclusion of new channels, combination of different channels have improved, and will continue to improve, results. Several new analyses are underway.
- HL-LHC will improve sensitivity of statistically limited analyses.

BACK-UP

Dark-matter-associated production (2/4)

Category	Mono-Higgs	High-E_T^{miss}	Intermediate-E_T^{miss}	Different-Vertex	Rest
Data	9	72	464	1511	46804
Backgrounds					
SM Higgs boson	2.43 ± 0.22	4.2 ± 0.6	11.9 ± 2.7	44 ± 10	1360 ± 110
Non-resonant	9.9 ± 1.9	62 ± 5	418 ± 10	1490 ± 18	45570 ± 110
Total background	12.3 ± 1.9	67 ± 5	430 ± 10	1535 ± 21	46930 ± 170
Heavy scalar, $m_H = 275$ GeV, $m_\chi = 60$ GeV					
Expected yields	10.9 ± 1.4	23.8 ± 3.2	43 ± 5	33 ± 5	222 ± 20
$A \times \epsilon$ (%)	1.22 ± 0.07	2.67 ± 0.10	4.82 ± 0.14	3.65 ± 0.13	24.9 ± 0.4
Z'_B model, $m_{Z'_B} = 200$ GeV, $m_\chi = 1$ GeV					
Expected yields	20.0 ± 4.5	–	–	–	–
$A \times \epsilon$ (%)	17.4 ± 0.2	–	–	–	–
Z'-2HDM model, $m_{Z'} = 1000$ GeV, $m_{A^0} = 200$ GeV, and $m_\chi = 100$ GeV					
Expected yields	28.0 ± 5.3	–	–	–	–
$A \times \epsilon$ (%)	70.7 ± 0.2	–	–	–	–