Searches for rare Higgs decays and production modes at the LHC

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On behalf of ATLAS and CMS collaborations

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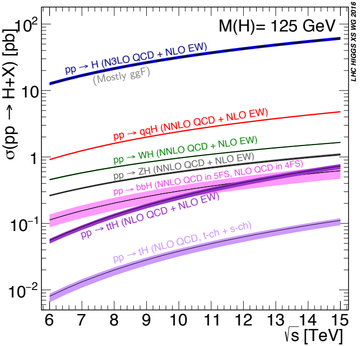
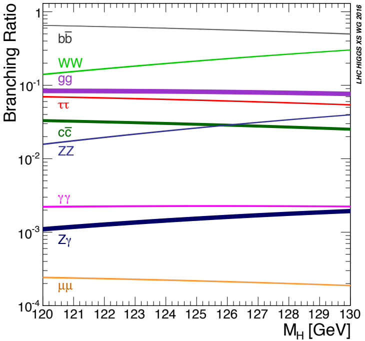
Les rencontres de physique de la vallée d'Aoste

La Thuile, 10–16 Mar 2019

Production and decays of the Higgs boson

- At a mass of $\approx 125\,\mathrm{GeV}$, many production and decay modes are available





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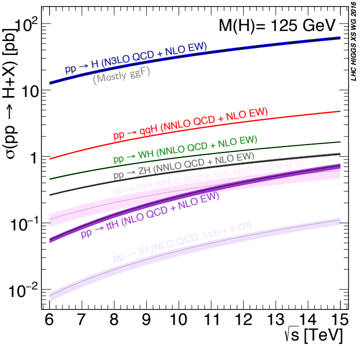

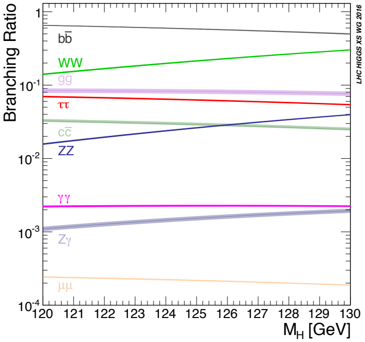

- Many have been observed already (talk by Antonio De Maria)

Content

- Will discuss rare decays and production

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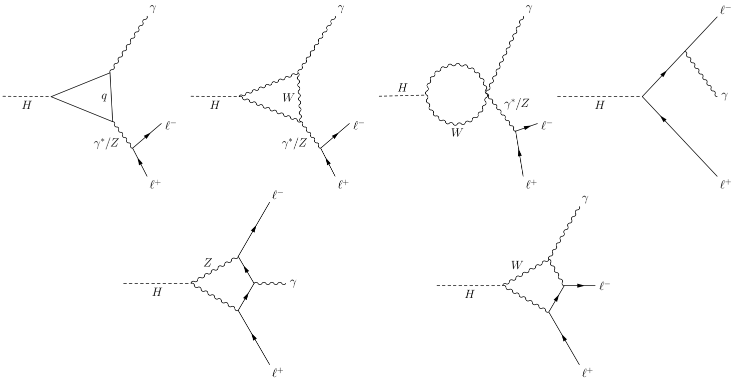
- Already presented:
  - $t\bar{t}H$ and $H \to \mu\mu \Rightarrow$ Antonio De Maria
  - FCNC $t \to Hq \Rightarrow$ Danny Noonan

Content

- Will discuss rare decays and production
- Already presented:
  - $t\bar{t}H$ and $H \to \mu\mu \Rightarrow$ Antonio De Maria
  - FCNC $t \to Hq \Rightarrow$ Danny Noonan
- A selection of recent results:
  - $H \to \ell\ell\gamma$ (includes $Z\gamma$), CMS
    - JHEP 11 (2018) 152
  - H decaying to quarkonium and photon, ATLAS
    - PLB 786 (2018) 134
  - $H \to$ invisible, ATLAS
    - arXiv:1809.06682, submitted to PLB
  - $pp \to tH$, CMS
    - arXiv:1811.09696, submitted to PRD

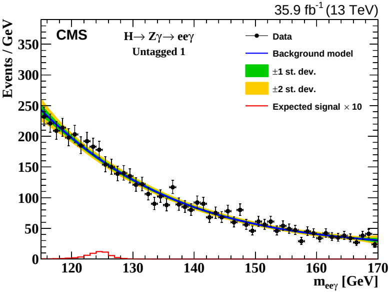
$H \to \ell\ell\gamma$

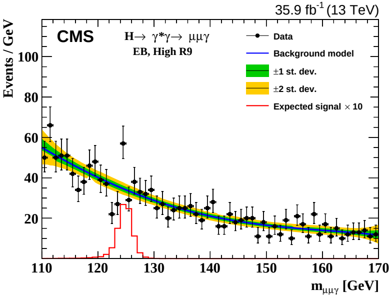
- Decay $H \to \ell\ell\gamma$ involves loops and can be sensitive to BSM particles running in them
  - SM $\mathcal{B}(H \to \ell\ell\gamma) \approx 1.8 \times 10^{-4}$



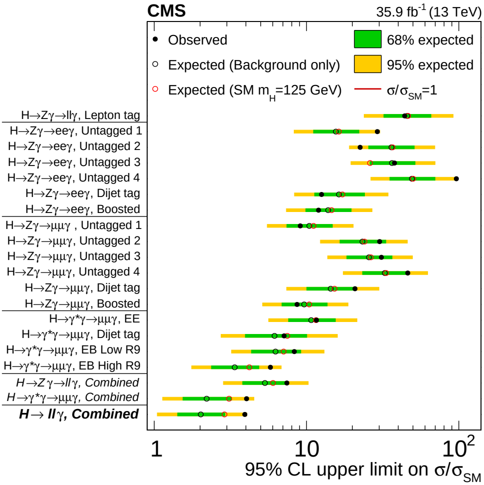
$H \to \ell\ell\gamma$

- CMS search for $H \to \ell\ell\gamma$ with $36\,\text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
- Two channels:
  - $H \to Z\gamma$, $Z \to \ell\ell$ ($\ell = e, \mu$) with $m_{\ell\ell} > 50$ GeV
  - $H \to \gamma^*\gamma$, $\gamma^* \to \mu\mu$ with $m_{\mu\mu} < 50$ GeV (and veto quarkonium decays)
  - A number of subcategories based on jets, 3rd lepton, p_T^H, photon ID...
- Fit a peak in $m_{\ell\ell\gamma}$ on top of a smooth background





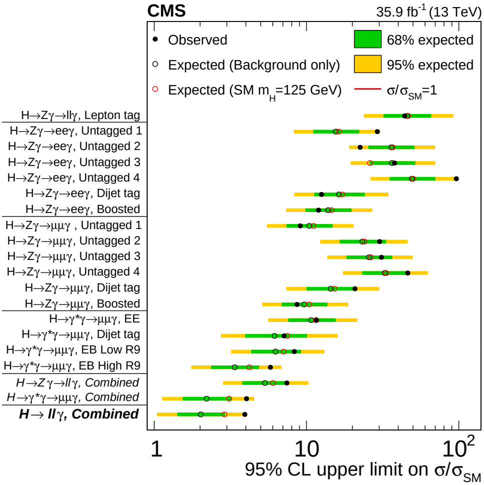
$H \to \ell\ell\gamma$



- For $m_H = 125\,\text{GeV}$ put upper limit $\sigma/\sigma_{\text{SM}} < 3.9$ at 95% CL

$H \to \ell\ell\gamma$

JHEP 11 (2018) 152

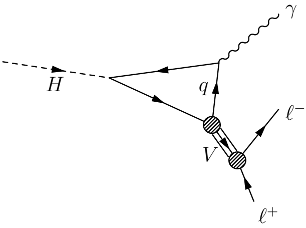


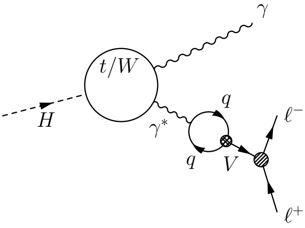
- For $m_H = 125\,\text{GeV}$ put upper limit $\sigma/\sigma_{\text{SM}} < 3.9$ at 95% CL
- Related ATLAS search[1]
  - Largely similar but specifically targets $H \to Z\gamma$ channel
  - Observed upper limit is $\sigma/\sigma_{\text{SM}} < 6.6$

[1] JHEP 10 (2017) 112

Quarkonium and photon

- $H \to \mathcal{Q}\gamma$ provides an alternative way to probe couplings to quarks
  - In SM $\mathcal{B}(H \to \psi(nS)\,\gamma) \sim 10^{-6}$, $\mathcal{B}(H \to \Upsilon(nS)\,\gamma) \sim 10^{-9}$
  - Destructive interference between direct and indirect production[1]
    - They are of similar size for $\Upsilon \Rightarrow$ Access to the relative phase of Hbb coupling



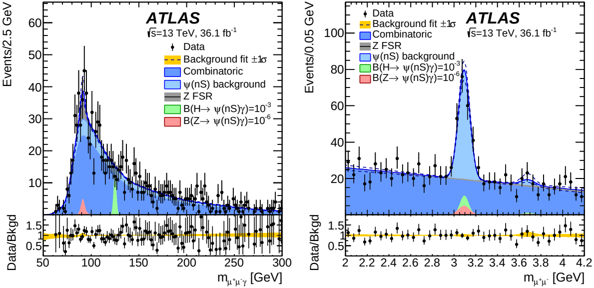


[1] Bodwin et al., PRD 88 (2013) 053003

Quarkonium and photon

PLB 786 (2018) 134

- ATLAS search for $H \to \mathcal{Q}\gamma$, $\mathcal{Q} = J/\psi, \psi(2S), \Upsilon(nS)$, $n = 1, 2, 3$
  - $\mathcal{Q} \to \mu\mu$
  - $36\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
- Unbinned 2D fit to distribution of $(m_{\mu\mu\gamma}, m_{\mu\mu})$
  - Non-parametric model for continuum bkg from region with loosened event selection



Quarkonium and photon

- Upper limits on $\mathcal{B}(H \to \mathcal{Q}\gamma)$ at 95% CL

Decay	Observed [10^{-4}]	Expected [10^{-4}]
$H \to J/\psi\,\gamma$	3.5	$3.0^{+1.4}_{-0.8}$
$H \to \psi(2S)\,\gamma$	19.8	$15.6^{+7.7}_{-4.4}$
$H \to \Upsilon(1S)\,\gamma$	4.9	$5.0^{+2.4}_{-1.4}$
$H \to \Upsilon(2S)\,\gamma$	5.9	$6.2^{+3.0}_{-1.7}$
$H \to \Upsilon(3S)\,\gamma$	5.7	$5.0^{+2.5}_{-1.4}$

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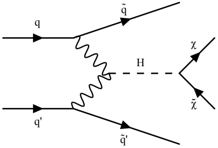
- CMS recently updated their search for $H \to J/\psi\,\gamma$[1]
  - Observed (expected) upper limit: $\mathcal{B}(H \to J/\psi\,\gamma) < 7.6\ (5.2^{+2.4}_{-1.6}) \times 10^{-4}$

[1] Eur. Phys. J. C 79 (2019) 94

$H \to$ invisible

- In SM $\mathcal{B}(H \to ZZ \to 4\nu) \approx 1.0 \times 10^{-3}$
  - Gets enhanced if H decays to invisible BSM
  - Higgs portal to dark matter



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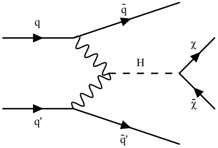
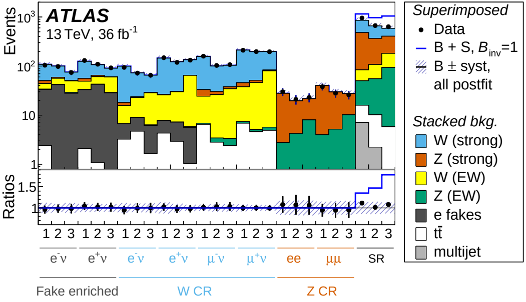
arXiv:1809.06682

- In SM $\mathcal{B}(H \to ZZ \to 4\nu) \approx 1.0 \times 10^{-3}$
  - Gets enhanced if H decays to invisible BSM
  - Higgs portal to dark matter
- Focus on a recent result from ATLAS
  - $36\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$
- VBF topology with a large $p_{\text{T}}^{\text{miss}}$
  - Jets with large η gap, not back-to-back, $m_{jj} > 1\,\text{TeV}$
  - Bins in m_{jj}
- Main backgrounds are $Z(\to \nu\nu) + \text{jets}$ and $W(\to \ell\nu) + \text{jets}$
  - Estimated from dedicated CR





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  - Expected upper limit is 0.28

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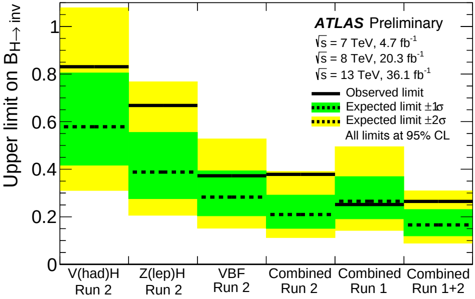
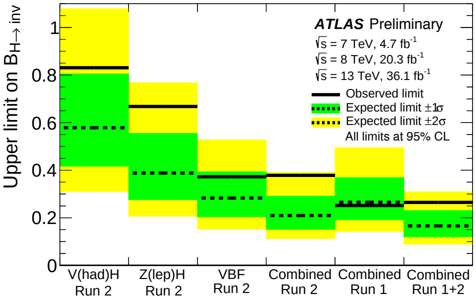
- In ATLAS combination[1] with other modes and Run 1 $\mathcal{B}(H \to \text{inv}) < 0.26$ (0.17) is observed (expected)



[1] ATLAS-CONF-2018-054

$H \to$ invisible

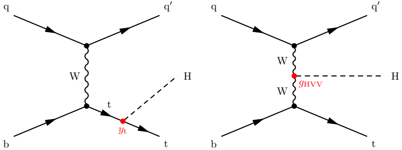
- Observed upper limit $\mathcal{B}(H \to \text{inv}) < 0.37$ at 95% CL
  - Expected upper limit is 0.28
- In ATLAS combination[1] with other modes and Run 1 $\mathcal{B}(H \to \text{inv}) < 0.26$ (0.17) is observed (expected)
- Combined CMS result[2] is $\mathcal{B}(H \to \text{inv}) < 0.26$ (0.20)



[1] ATLAS-CONF-2018-054 [2] arXiv:1809.05937

tH production

- Destructive interference between dominant amplitudes
  - Sensitive to strengths of *HWW* and *Htt* couplings and relative phase[1]
  - SM cross section around 90 fb

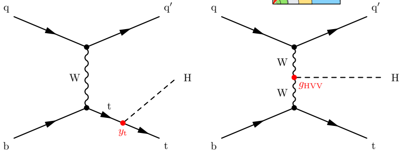


[1] Maltoni et al., PRD 64 (2001) 094023,
Farina et al., JHEP 05 (2013) 022

tH production

arXiv:1811.09696

- Destructive interference between dominant amplitudes
  - Sensitive to strengths of HWW and Htt couplings and relative phase[1]
  - SM cross section around 90 fb
- Searched for in CMS
  - $36\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13\,\mathrm{TeV}$
  - Multitude of Higgs decays utilized



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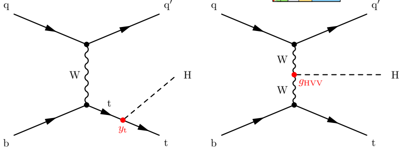
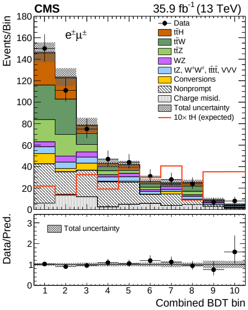
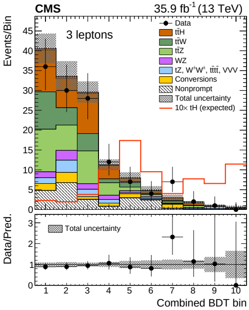


- Multilepton channels target $H \to WW$, $t \to b\ell\nu$
  - $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$, 3ℓ channels
  - Main bkg with non-prompt leptons is data-driven
  - MV classification against $t\bar{t}V$ and $t\bar{t}$ + jets





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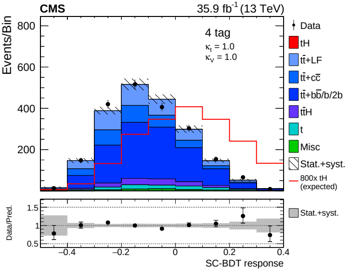
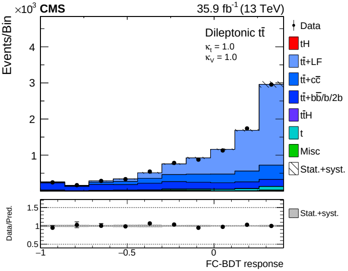
tH production

arXiv:1811.09696

- $H \to b\bar{b}$, $t \to b\ell\nu$ channel
  - MV jet assignment under tHq, tHW, and $t\bar{t}$ + jets hypotheses
    - E. g. which jets correspond to $H \to b\bar{b}$?
  - MV discrimination against dominant $t\bar{t}$ bkg
  - $t\bar{t}$ + HF constrained in situ
    - $\ell^{\pm}\ell'^{\mp}$ CR enriched in $t\bar{t}$
    - MVA to distinguish $t\bar{t}$ + LF and $t\bar{t}$ + HF





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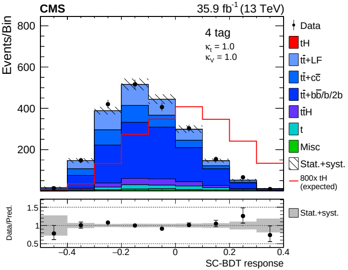
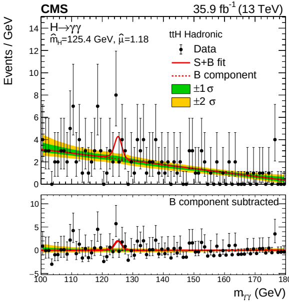
    - MVA to distinguish $t\bar{t}$ + LF and $t\bar{t}$ + HF
- $H \to \gamma\gamma$ channel
  - Reinterpreted from a measurement of Higgs properties in $H \to \gamma\gamma$[1]
  - Fit a peak on top of smooth bkg in $m_{\gamma\gamma}$



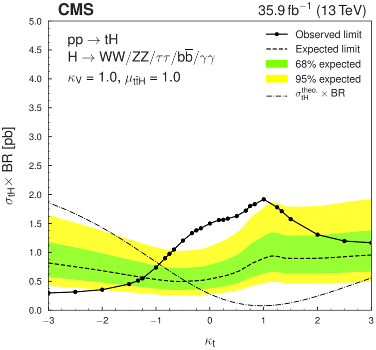


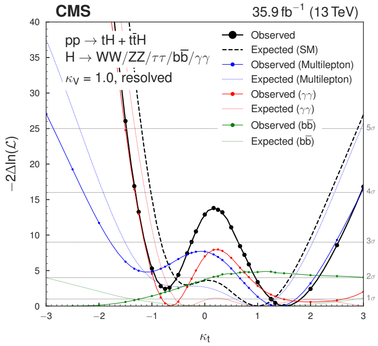
[1] JHEP 11 (2018) 185

tH production

arXiv:1811.09696

- Scan over $\kappa_t = y_t / y_t^{\text{SM}}$
- For SM, obs. (exp.) upper limit is about 25 (12) $\times\, \sigma_{\text{SM}}(pp \to tH)$





  - There is $\approx 2\,\sigma$ excess stemming from multilepton and $\gamma\gamma$ channels
  - Consistent with the excess observed for $t\bar{t}H$

Outlook

- With main modes of production and decays of the Higgs boson established, interest to rare processes increases
  - These are corners in which new physics can still be hiding
- We are just in the beginning of the journey
  - All results shown here are with 2016 data set — stay tuned for full Run 2
  - Looking forward Run 3 and HL-LHC

Additional slides

Categorization in CMS $H \to Z\gamma \to \ell\ell\gamma$

JHEP 11 (2018) 152

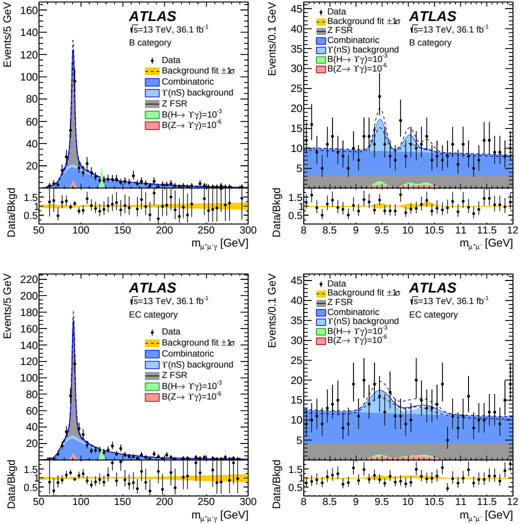
Category	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
Lepton tag	Additional electron ($p_T > 7\,\text{GeV}$) or muon ($p_T > 5\,\text{GeV}$)	
Dijet tag	At least 2 jets required	At least 2 jets required
Boosted	$p_T(ee\gamma) > 60\,\text{GeV}$	$p_T(\mu\mu\gamma) > 60\,\text{GeV}$
Untagged 1	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 1.4442$ $R_9 > 0.94$	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 2.1$ and one lepton $0 < \|\eta\| < 0.9$ $R_9 > 0.94$
Untagged 2	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 1.4442$ $R_9 < 0.94$	Photon $0 < \|\eta\| < 1.4442$ Both leptons $0 < \|\eta\| < 2.1$ and one lepton $0 < \|\eta\| < 0.9$ $R_9 < 0.94$
Untagged 3	Photon $0 < \|\eta\| < 1.4442$ At least one lepton $1.4442 < \|\eta\| < 2.5$ No requirement on R_9	Photon $0 < \|\eta\| < 1.4442$ Both leptons in $\|\eta\| > 0.9$ or one lepton in $2.1 < \|\eta\| < 2.4$ No requirement on R_9
Untagged 4	Photon $1.566 < \|\eta\| < 2.5$ Both leptons $0 < \|\eta\| < 2.5$ No requirement on R_9	Photon $1.566 < \|\eta\| < 2.5$ Both leptons $0 < \|\eta\| < 2.4$ No requirement on R_9

Uncertainties in CMS $H \to Z\gamma \to \ell\ell\gamma$

Sources	$\mathrm{H} \to \mathrm{Z}\gamma \to \ell\ell\gamma$	$\mathrm{H} \to \gamma^*\gamma \to \mu\mu\gamma$
Theory		
– ggH cross section (scale)	3.9%	3.9%
– ggH cross section (PDF)	3.2%	3.2%
– VBF cross section (scale)	$+0.4\% - 0.3\%$	$+0.4\% - 0.3\%$
– VBF cross section (PDF)	2.1%	2.1%
– WH cross section (scale)	$+0.5\% - 0.7\%$	$+0.5\% - 0.7\%$
– WH cross section (PDF)	1.9%	1.9%
– ZH cross section (scale)	$+3.8\% - 3.1\%$	$+3.8\% - 3.1\%$
– ZH cross section (PDF)	1.6%	1.6%
– $\mathrm{t\bar{t}H}$ cross section (scale)	$+5.8\% - 9.2\%$	—
– $\mathrm{t\bar{t}H}$ cross section (PDF)	3.6%	—
Underlying event and parton shower		
– Muon channel	3%	4.7%
– Electron channel	3%	—
Branching fraction	5.7%	6%
Integrated luminosity	2.5%	2.5%
Lepton identification and isolation		
– Muon channel	0.6%	2%
– Electron channel	1.2%	—
Photon identification and isolation		
– Muon channel	2.3%	1.6%
– Electron channel	2.2%	—
Pileup reweighting		
– Muon channel	0.6%	0.3%
– Electron channel	0.9%	—
R_9 reweighting		
– Muon channel	6.5%	9%
– Electron channel	6.8%	—
Trigger		
– Muon channel	1.3%	4%
– Electron channel	1%	—
Energy and momentum (muon channel)		
– Signal mean	0.04%	0.08%
– Signal resolution	4%	5%
Energy (electron channel)		
– Signal mean	0.15%	—
– Signal resolution	4%	—
Jet energy scale		
– Muon channel	2.5%	3.8%
– Electron channel	2.7%	—
Jet energy resolution		
– Muon channel	0.3%	0.7%
– Electron channel	0.3%	—

Distributions for $H \to \Upsilon\gamma$ in ATLAS

PLB 786 (2018) 134

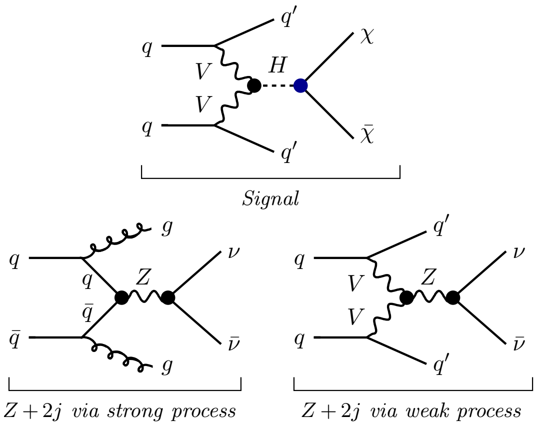


Uncertainties in ATLAS $H \to \mathcal{Q}\gamma$

PLB 786 (2018) 134

Source of systematic uncertainty	Yield uncertainty $H(Z) \to \mathcal{Q}\,\gamma$
Total $H(Z)$ cross section	7.0% (2.9%)
Integrated luminosity	2.1%
$H(Z)$ QCD modelling	1.8% (6%)
Trigger efficiency	2.0%
Photon identification	1.4%
Muon reconstruction	2.8%
Photon energy scale	0.3%
Muon momentum scale	0.2%

Example diagrams for VBF $H \to$ inv



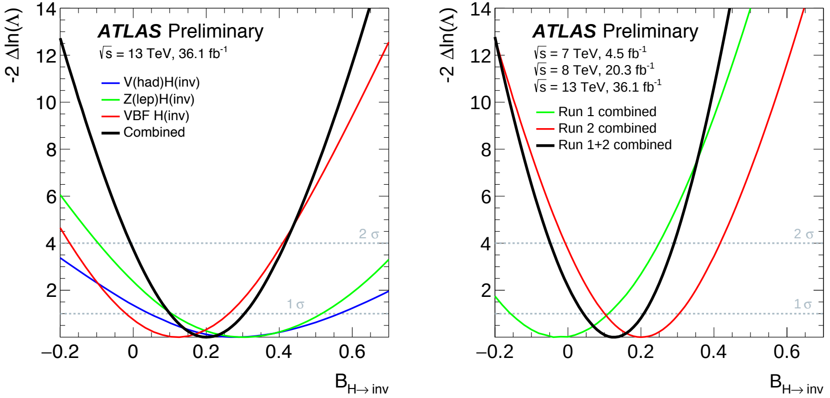
Uncertainties in ATLAS VBF $H \to$ inv

arXiv:1809.06682

Source	$\mathcal{B}_{\text{inv}}$ improve. [%] using all m_{jj} bins		Yields, α changes (%) in $1 < m_{jj} < 1.5$ TeV				
	Δ	visual	S	B^Z_{SR}	B^Z_{CR}	α_Z	α_W
Experimental (†)							
Jet energy scale	10		12	7	8	8	6
Jet energy resol.	2		2	0	1	1	4
$E_{\text{T}}^{\text{miss}}$ soft term	1		2	2	2	2	2
Lepton id., veto	2		-	-	-	-	4
Pileup distrib.	1		3	1	2	3	1
Luminosity	0		2	2	2	-	-
Theoretical (‡)							
Resum. scale	1		-	2	3	0	2
Renorm., fact.	2		-	20	19	1	2
CKKW matching	4		-	2	3	1	5
PDF	0		1	1	2	1	1
3rd jet veto	2		7	-	-	-	-
Statistical							
MC sample (★)	12		4	5	9	10	9
Data sample	21		6	5	12	12	6
Combined							
All † sources	17						
All ‡ sources	10						
Combine †, ‡	28						
Combine †, ‡, ★	42						

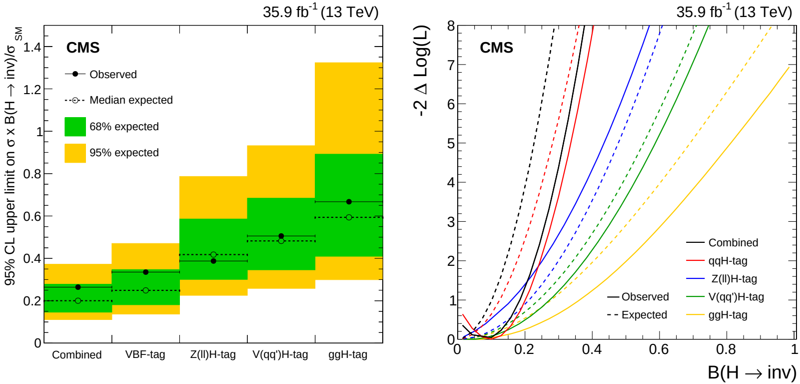
Combination of ATLAS $H \to$ inv

ATLAS-CONF-2018-054



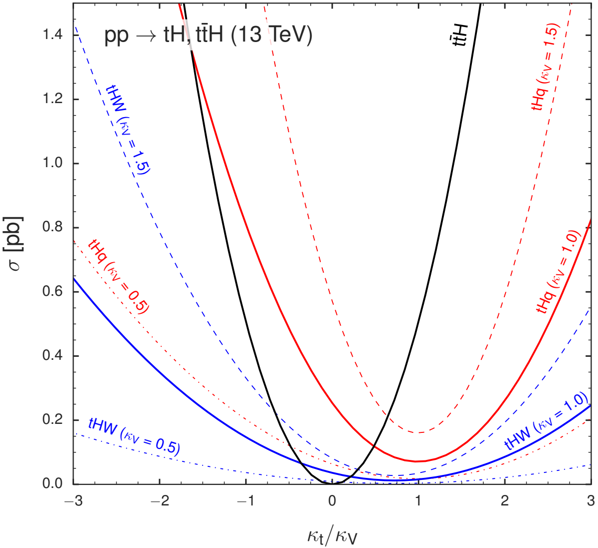
Combination of Run 2 CMS $H \to$ inv

arXiv:1809.05937



tH cross sections

arXiv:1811.09696



Main uncertainties in CMS search for tH

arXiv:1811.09696

Source	Uncertainty [%]	$\Delta\mu/\mu$ [%]
e, μ selection efficiency	2–4	17
b tagging efficiency	2–15	6
Jet energy calibration	2–15	3
Forward jet modeling	10–35	3
Integrated luminosity	2.5	10
Reducible background estimate	10–40	14
Theoretical sources	$\approx$10	14
$t\bar{t}$+HF normalization	$\approx$50	7
PDFs	2–6	8

LFV decays

- Tightest constraints on $H \to \mu\tau$ and $H \to e\tau$ are from CMS
  - $36\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$
  - Categorization based on τ decays and jets, multivariate classifier
  - Observed (expected) upper limits on branching fractions:
    - $\mathcal{B}(H \to \mu\tau) < 0.25\%\ (0.25\%)$
    - $\mathcal{B}(H \to e\tau) < 0.61\%\ (0.37\%)$