Higgs decays to pairs of Z boson or γ at the LHC

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(On behalf of the ATLAS and CMS collaborations)

Standard Model at the LHC 2017,
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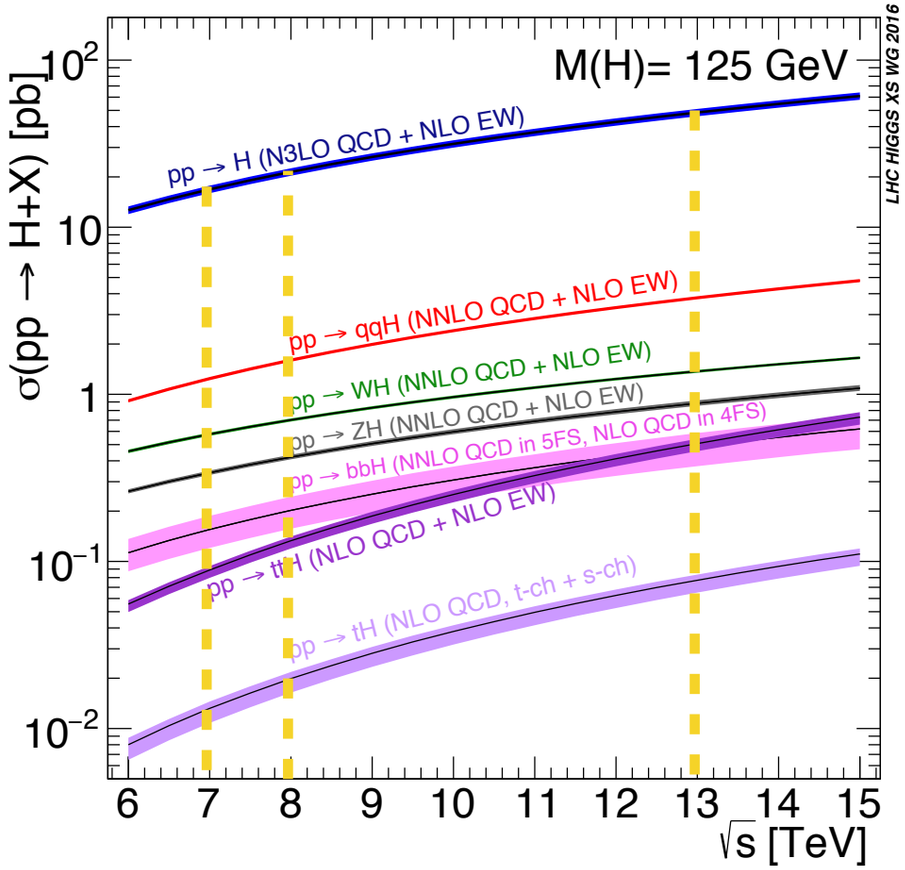
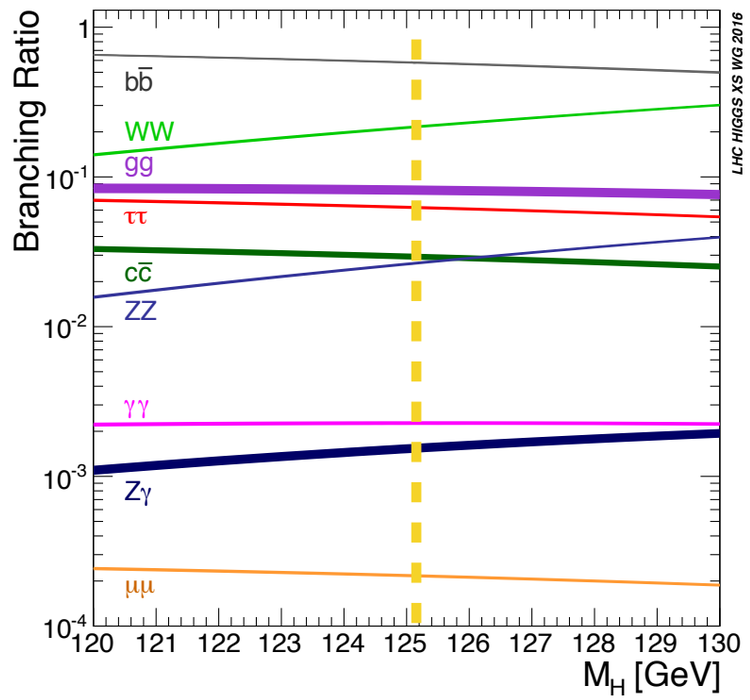
Higgs Production at LHC



Cross section [pb] at √s = 13 TeV & m_H = 125.09 GeV			
ggH	VBF	(W/Z)H	(tt/bb)H
49	3.8	1.4/0.9	0.5/0.5



Branching fraction at m_H = 125.09 GeV:

ZZ: 2.64%

$\gamma\gamma$: 0.23%

√8 TeV (Run 1) ⇒ √13 TeV (Run 2)

σ(pp→H) increased by ~2.5

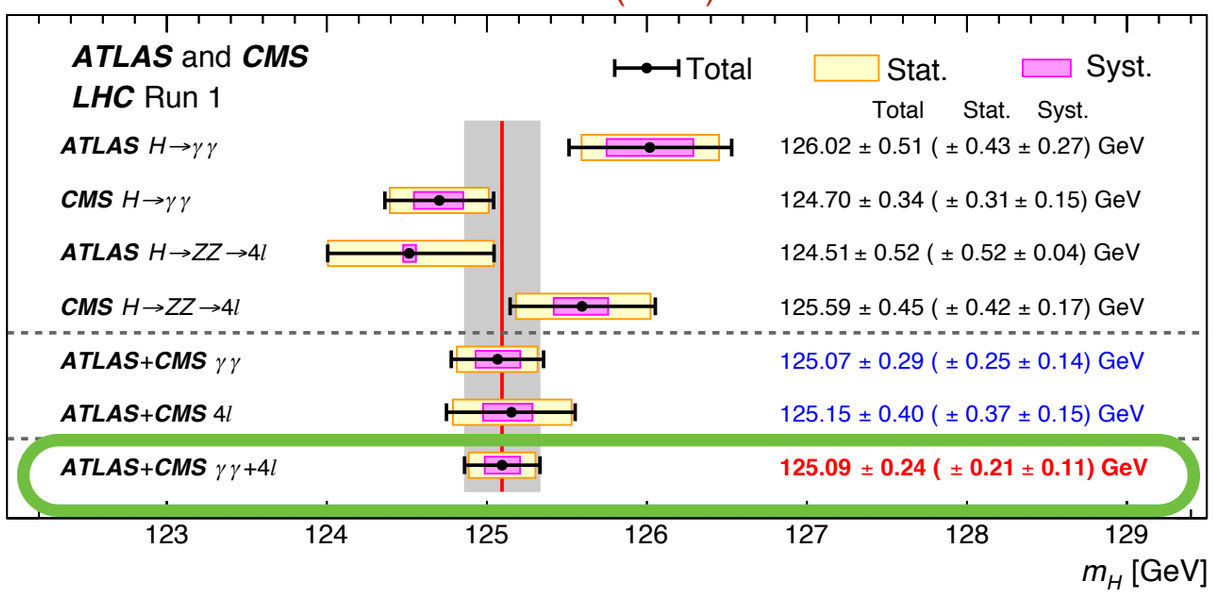
σ(pp→ttH) increased by ~4

- H→ ZZ*→4ℓ and H → $\gamma\gamma$ decays
  - Small branching fraction
  - Final states are fully reconstructable
  - S/B better than 2
  - Look for a narrow peak on a smooth background

Run 1 Legacy (Higgs mass and couplings)

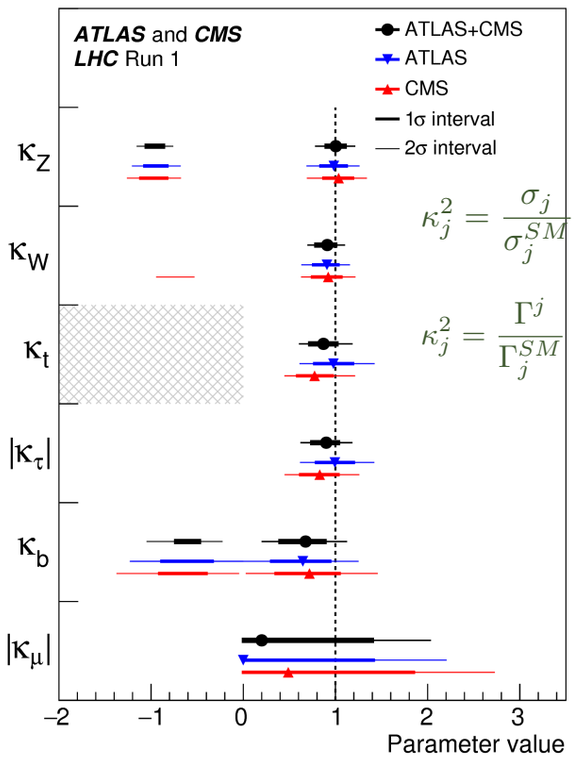
- Combination of H→ 4ℓ and H → $\gamma\gamma$ from ATLAS+CMS results in Run 1 ($\sqrt{s}$ = 7 & 8 TeV, L_{int} = 25 fb^{-1})
  - Higgs mass with ~0.2% uncertainty
  - Higgs boson production and decay rates, constraints on its couplings to vector bosons and fermions

PRL 114 (2015) 191803

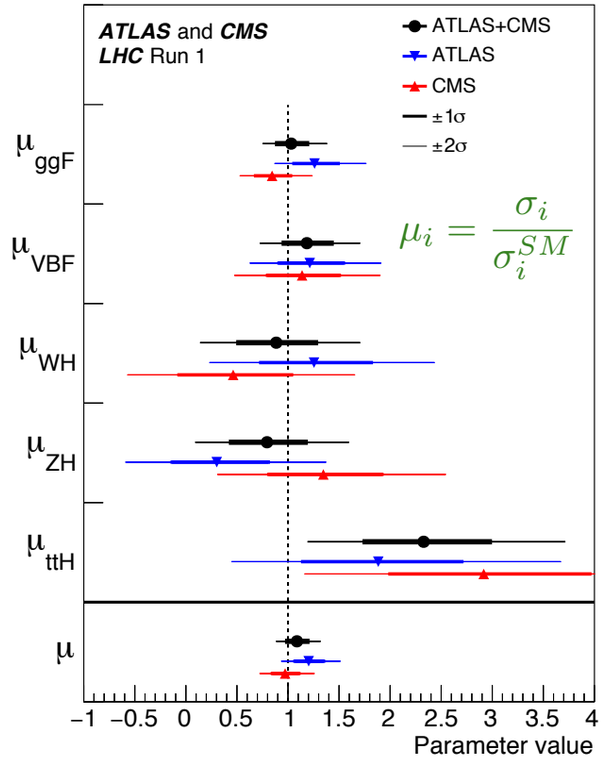


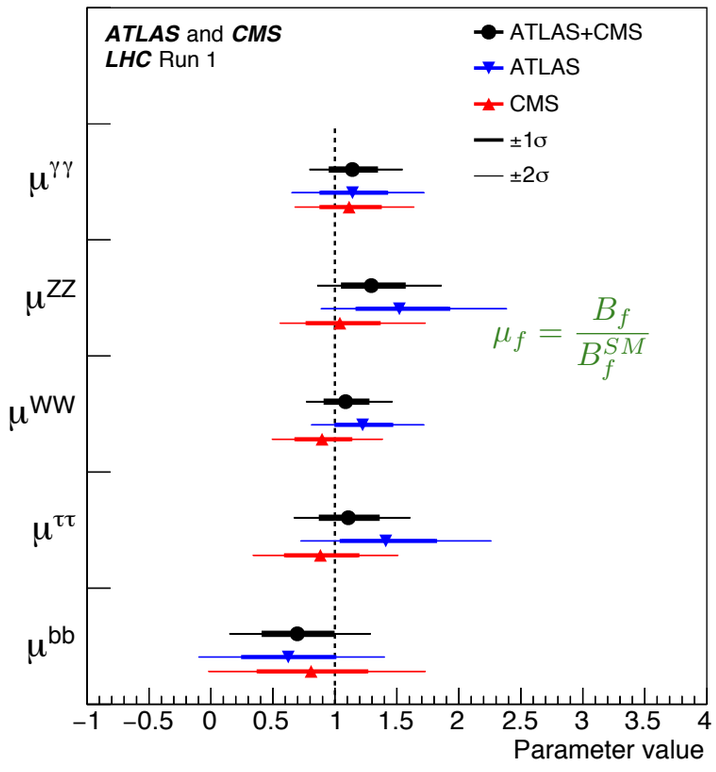
coupling modifiers

JHEP08 (2016) 045



global signal strengths: 1.09 ± 0.07 (stat) ±0.08 (syst)





All the measured the values are consistent with SM

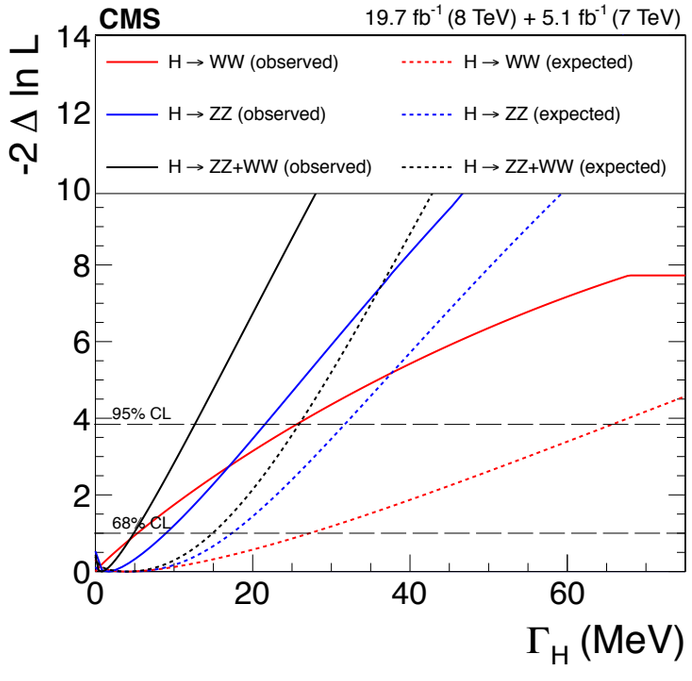
Run 1 Legacy (Higgs width and spin)

- **Higgs Width:** SM expectation on Γ_H is ~ 4 MeV (not directly measurable due to detector resolution)
- From the combined Run 1 H→ 4ℓ and H → $\gamma\gamma$ result, direct Γ_H measurement is based on the observed lineshape.

ATLAS: PRD 90 052004 (2014); CMS: EPJC 75 (2015) 212

	@95 CL Higgs width obs (exp) [GeV]	
	H → $\gamma\gamma$	H→ 4ℓ
ATLAS	5.0 (6.2)	2.6 (6.2)
CMS	2.4 (3.1)	3.4 (2.8)

- **Indirect measurement of Γ_H** from H → ZZ* → 4ℓ or 2ℓ2ν and H → WW :
  - Compare on-shell and off-shell rates, and assuming the couplings of on-shell and off-shell are the same:

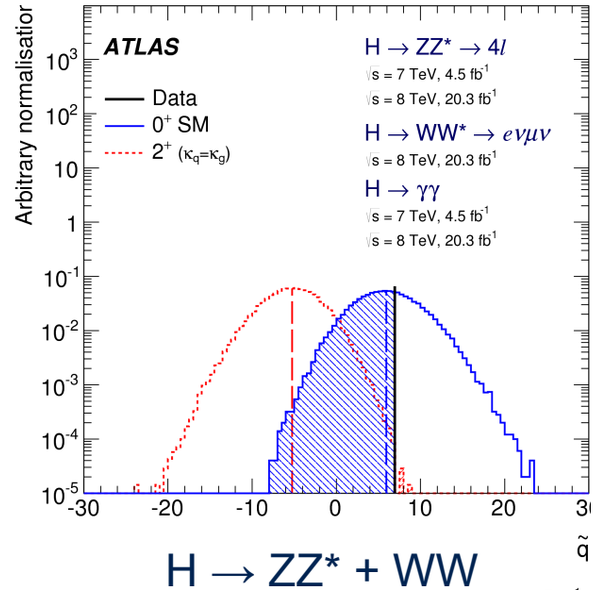


$$\mu_{\text{off-shell}}/\mu_{\text{on-shell}} = \Gamma_H/\Gamma_H^{\text{SM}}$$

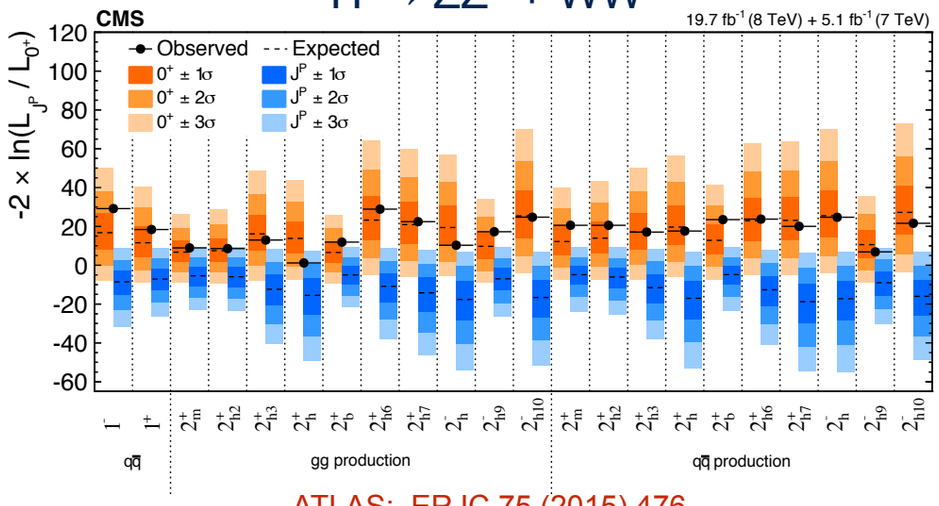
	@95% CL Γ_H obs (exp) [MeV]
ATLAS	22.7 (33)
CMS	13 (26)

ATLAS: ERJC 75 (2015) 335
CMS: JHEP 09 (2016) 051

- **Spin/Parity:** Compare $J^P = 0^+$ with different spin hypotheses:
  - 0+ is favoured and the other hypotheses are excluded > 99.9%
  - Potential CP admixture in spin-zero to be checked with more data



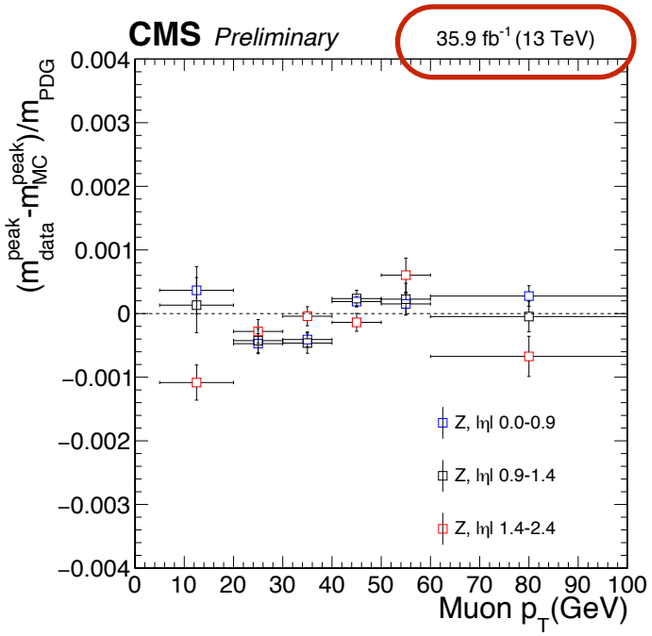
H → ZZ* + WW

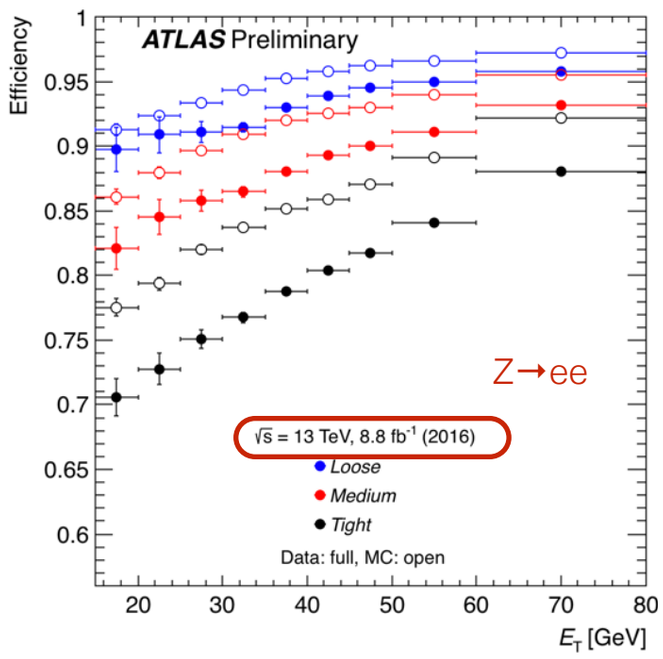


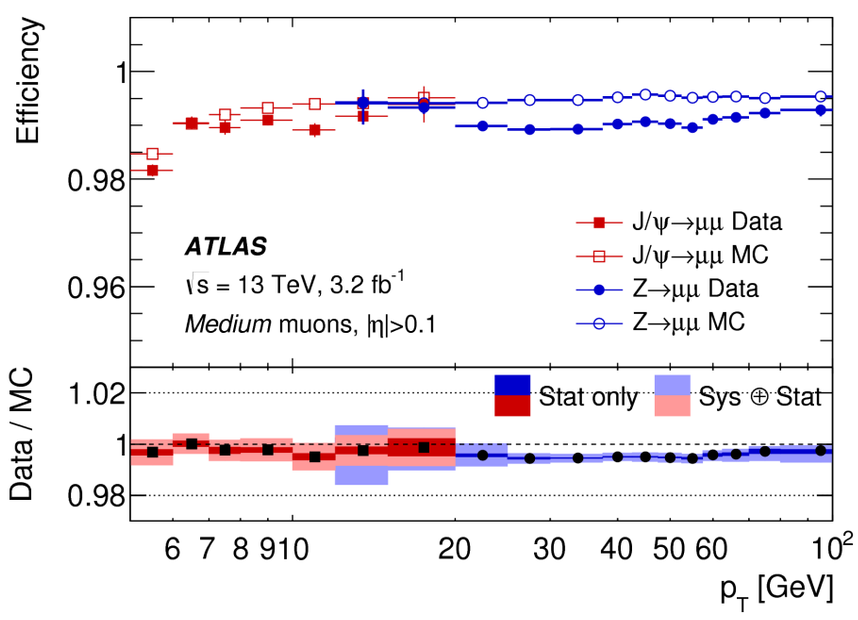
ATLAS: ERJC 75 (2015) 476
CMS: PRD 92 (2015) 012004

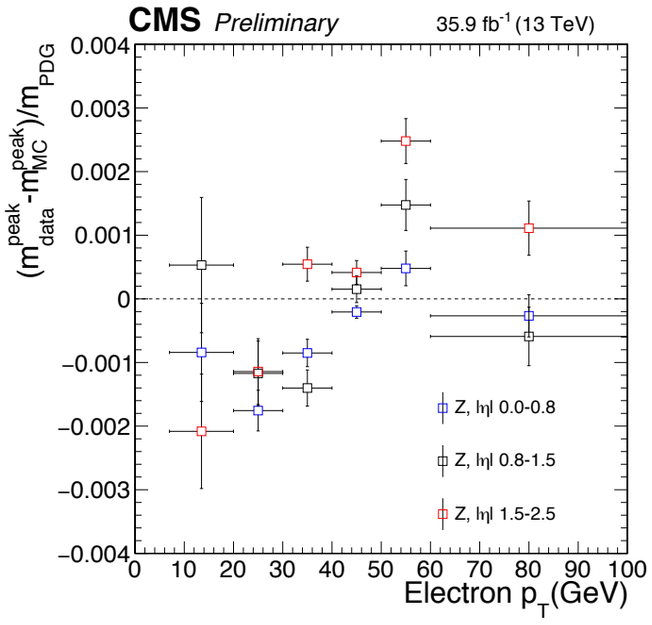
H →ZZ* →4ℓ

- Signal selection
  - 4 isolated leptons (e,μ) : two pairs of same flavour, opposite sign leptons (4e, 4μ, 2e2μ or 2μ2e)
    - p_T > 7 (5) GeV , $|\eta|$ < 2.5 (2.7) for e (μ) at ATLAS
    - p_T > 7 (5) GeV , $|\eta|$ < 2.5 (2.4) for e (μ) at CMS
- Backgrounds
  - SM ZZ* (main background, irreducible); estimated from MC
  - Z+jets, ttbar (reducible); estimated from data-driven methods
- Analyses rely on high lepton reconstruction/identification efficiency & excellent resolution



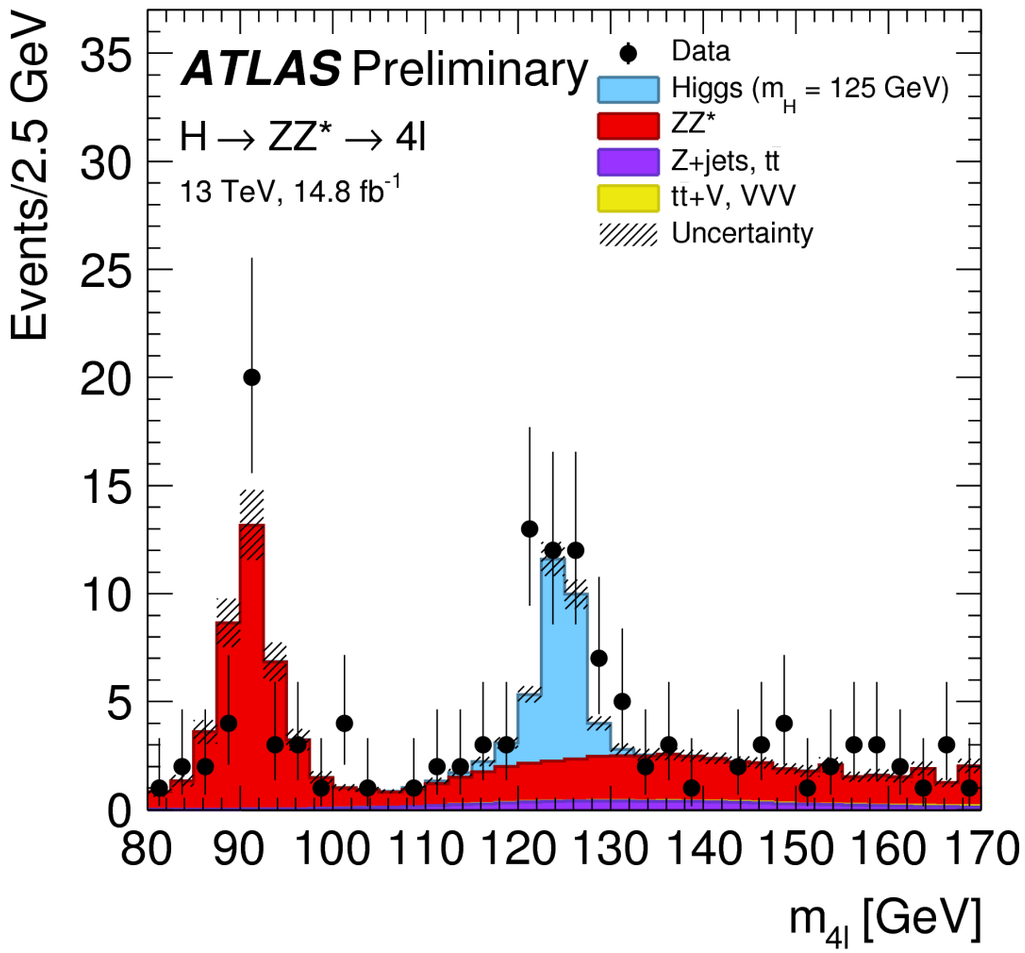




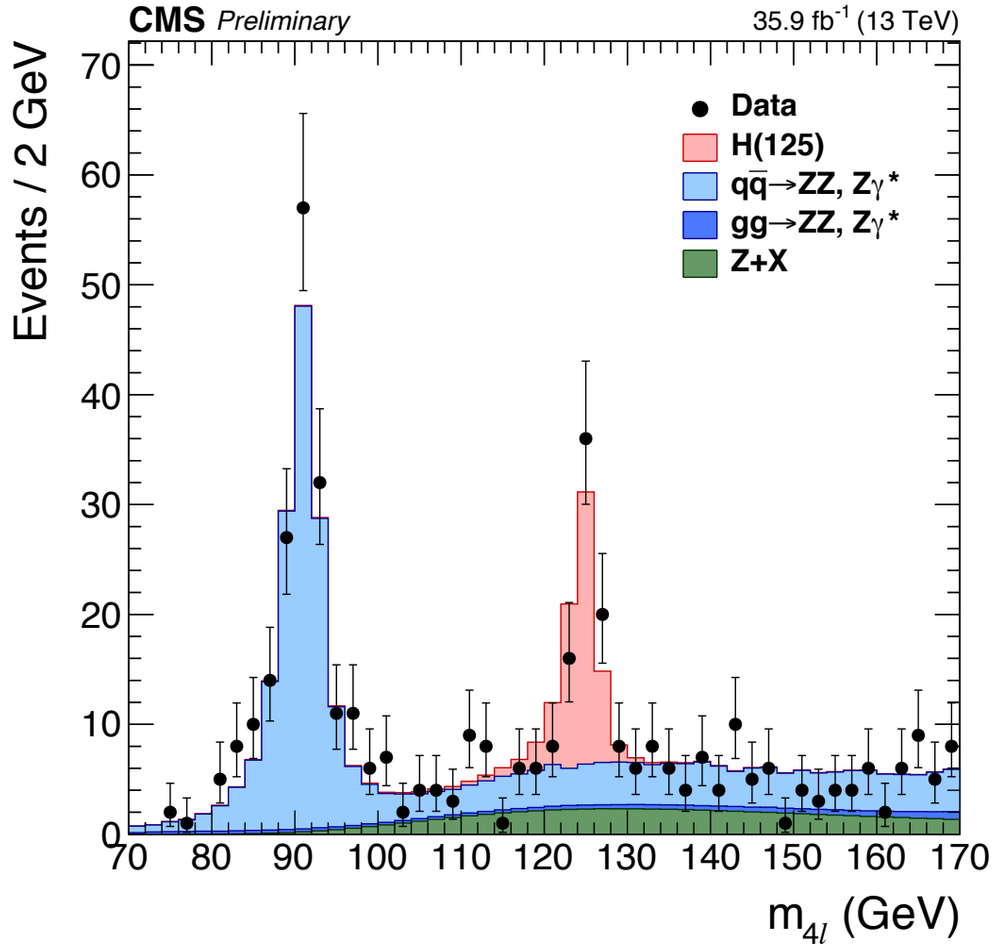


$H \rightarrow ZZ^* \rightarrow 4\ell$

ATLAS-CONF-2016-079

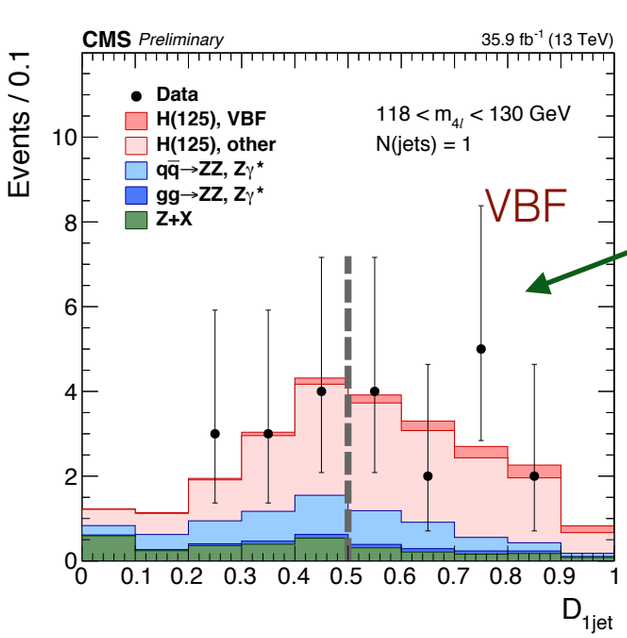


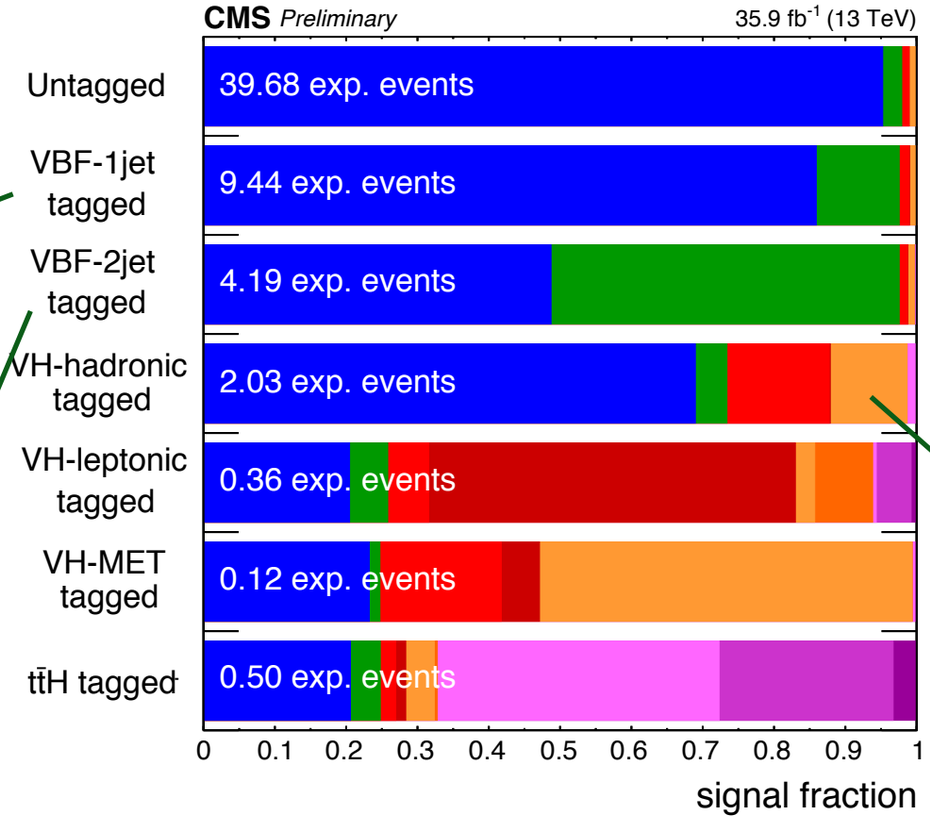
CMS-PAS-HIG-16-041

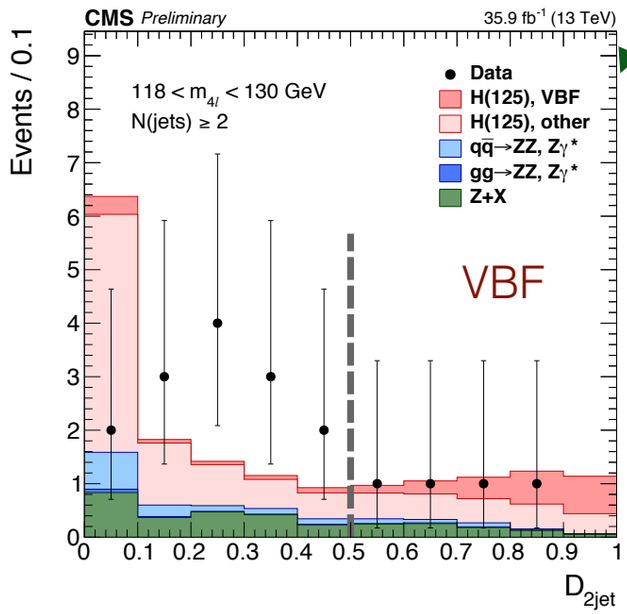


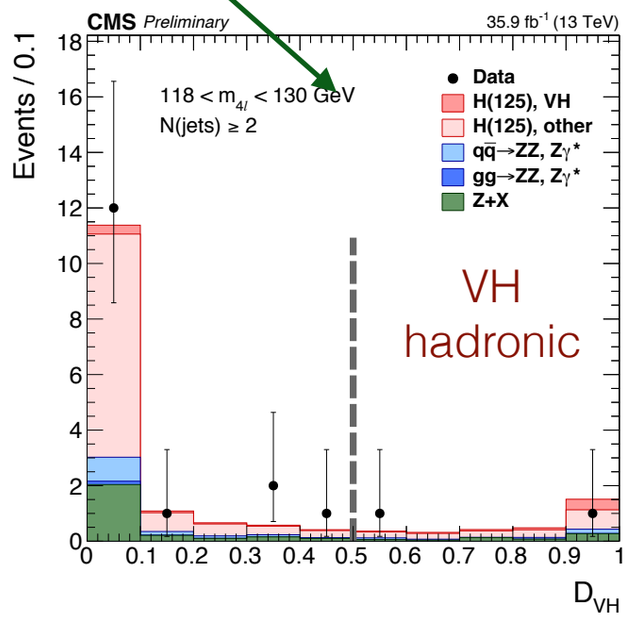
H →ZZ* →4ℓ : Event Categories

- Events are categorised in order to increase sensitivity and assess the cross section of five production processes
- CMS : Events are exclusively divided into seven categories using:
  - Objects information - number of leptons, number of jets and b-tagged jets, missing energy
  - Discriminants (D_{1jet}, D_{2jet} and D_{VH} = max (D_{WH}, D_{ZH})) are calculated from VBF, gluon fusion and VH probabilities







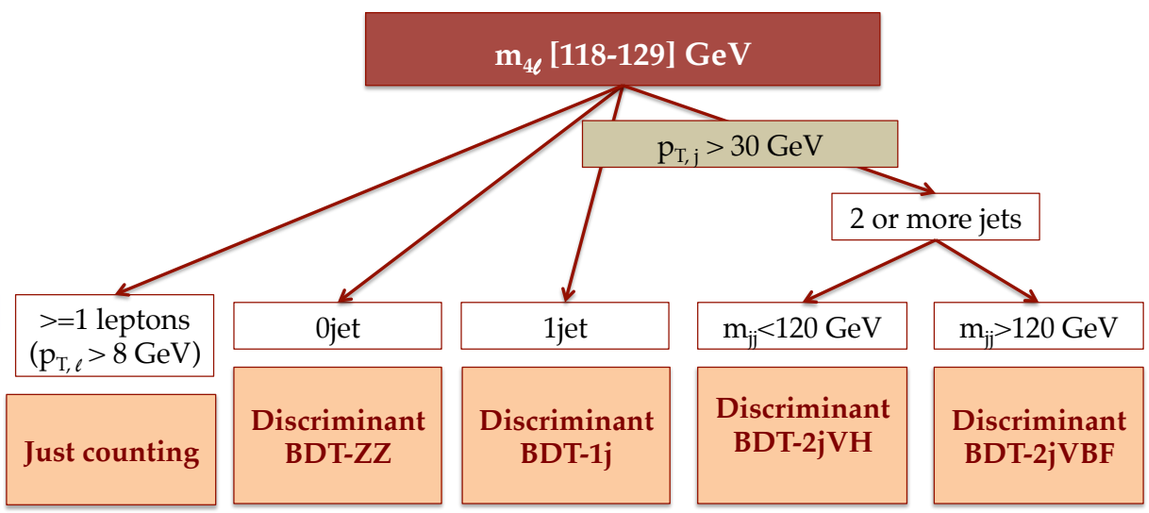


$$\mathcal{D}_{2jet} = \left[1 + \frac{\mathcal{P}_{HJJ}(\vec{\Omega}^{H+JJ}|m_{4\ell})}{\mathcal{P}_{VBF}(\vec{\Omega}^{H+JJ}|m_{4\ell})}\right]^{-1} \qquad \mathcal{D}_{1jet} = \left[1 + \frac{\mathcal{P}_{HJ}(\vec{\Omega}^{H+J}|m_{4\ell})}{\int d\eta_J \mathcal{P}_{VBF}(\vec{\Omega}^{H+JJ}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{WH} = \left[1 + \frac{\mathcal{P}_{HJJ}(\vec{\Omega}^{H+JJ}|m_{4\ell})}{\mathcal{P}_{WH}(\vec{\Omega}^{H+JJ}|m_{4\ell})}\right]^{-1} \qquad \mathcal{D}_{ZH} = \left[1 + \frac{\mathcal{P}_{HJJ}(\vec{\Omega}^{H+JJ}|m_{4\ell})}{\mathcal{P}_{ZH}(\vec{\Omega}^{H+JJ}|m_{4\ell})}\right]^{-1}$$

H →ZZ* →4ℓ : Event Categories

- ATLAS event categorisation:
  - VH leptonic
  - Jet categories: 0j, 1j,
  - 2 or more jets (VH-hadronic and VBF)
- Multivariate discriminants (BDT) are used to improve sensitivity in each production mode

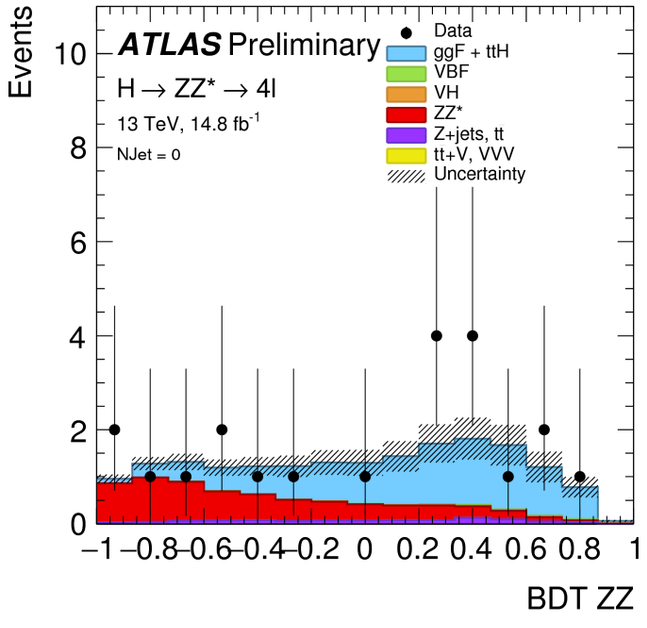


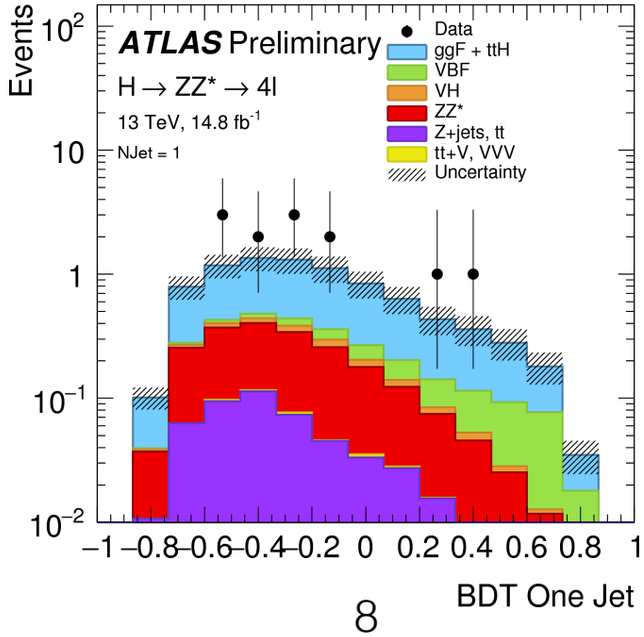
BDT_ZZ:
- $p_{T4\ell}$
- $\eta_{4\ell}$
- KD = $\log(ME_{HZZ}/ME_{ZZ})$

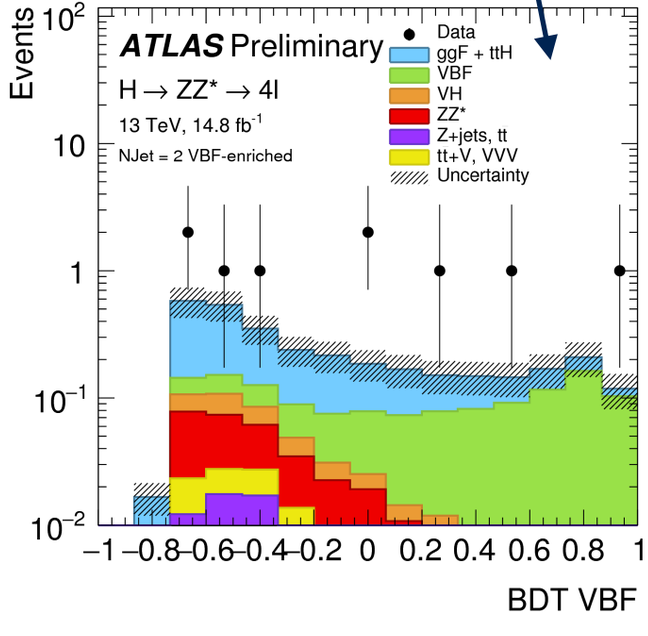
BDT_1jet:
- $p_{T,j}$
- η_j
- $\Delta R_{4\ell j}$

BDT_2jet_VH:
- $p_{T,j1}$
- $p_{T,j2}$
- η_{j1}
- $\Delta\eta_{jj}$
- $\Delta\eta_{4\ell jj}$
- m_{jj}
- $\min(\Delta R_{Zj})$

BDT_2jet_VBF:
- $p_{T,j1}$
- $p_{T,j2}$
- $p_{T,4\ell jj}$
- $\Delta\eta_{jj}$
- $\Delta\eta_{4\ell jj}$
- m_{jj}
- $\min(\Delta R_{Zj})$

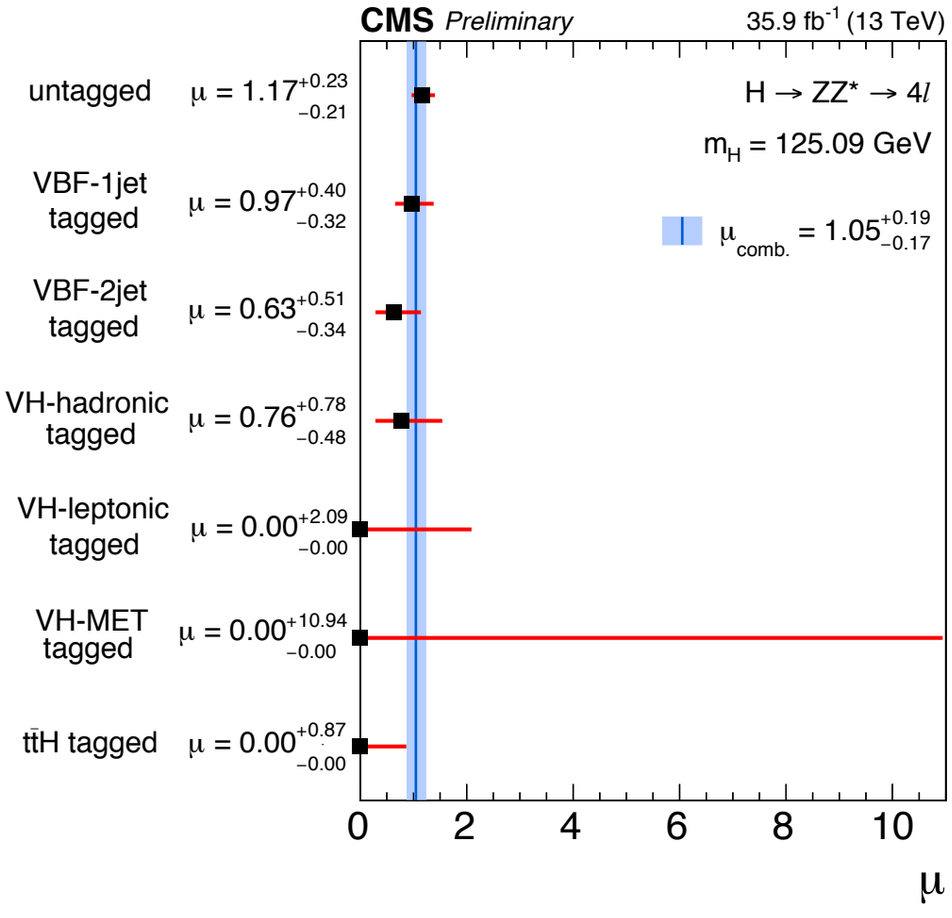


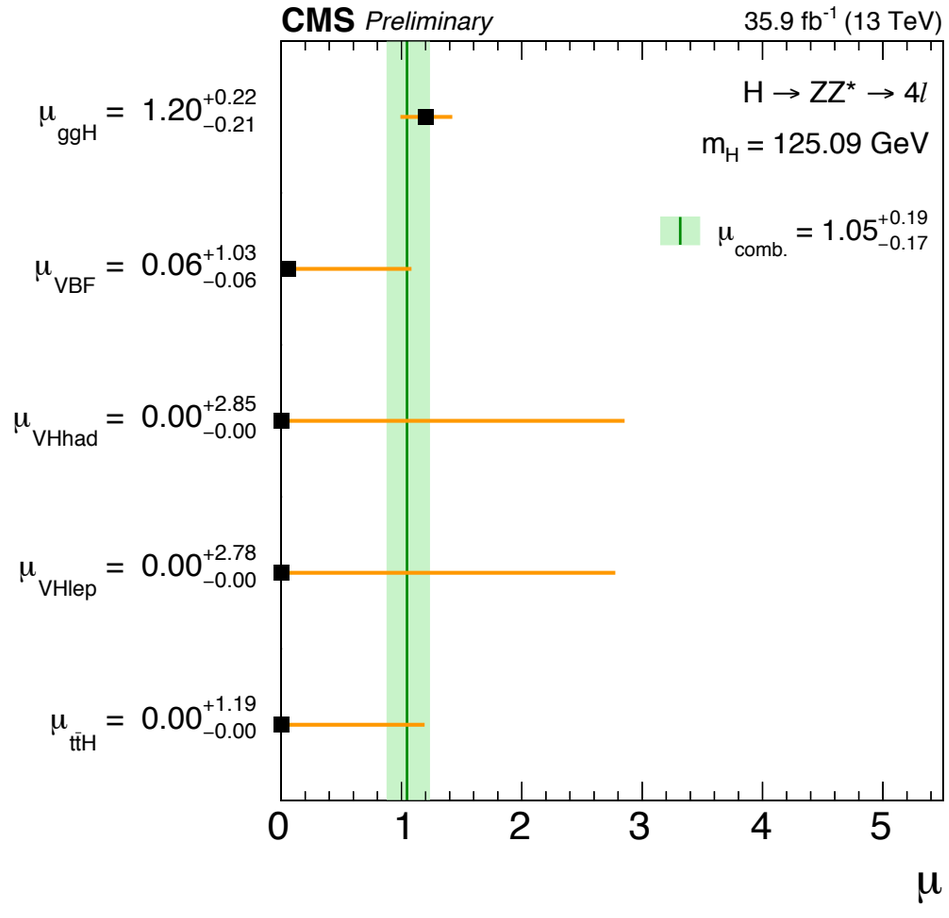




H →ZZ* →4ℓ : Signal Strength (CMS)

- To extract the signal strength 2D simultaneous fit in seven categories: $m_{4\ell}$ and $\mathcal{D}^{\text{kin}}_{\text{bkg}} = \left[1 + \frac{\mathcal{P}^{\text{q}\bar{\text{q}}}_{\text{bkg}}(\vec{\Omega}^{\text{H}\to 4\ell}|m_{4\ell})}{\mathcal{P}^{\text{gg}}_{\text{sig}}(\vec{\Omega}^{\text{H}\to 4\ell}|m_{4\ell})}\right]^{-1}$ (discriminant sensitive to the signal and background kinematics)





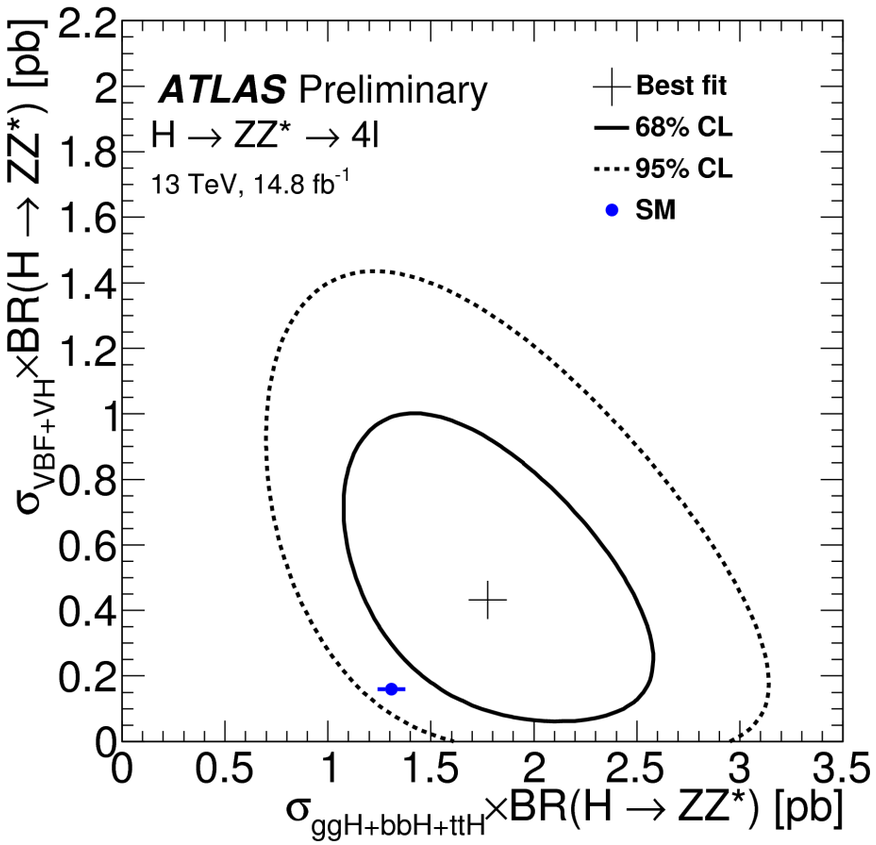
At m_H = 125.09 GeV, combined result:

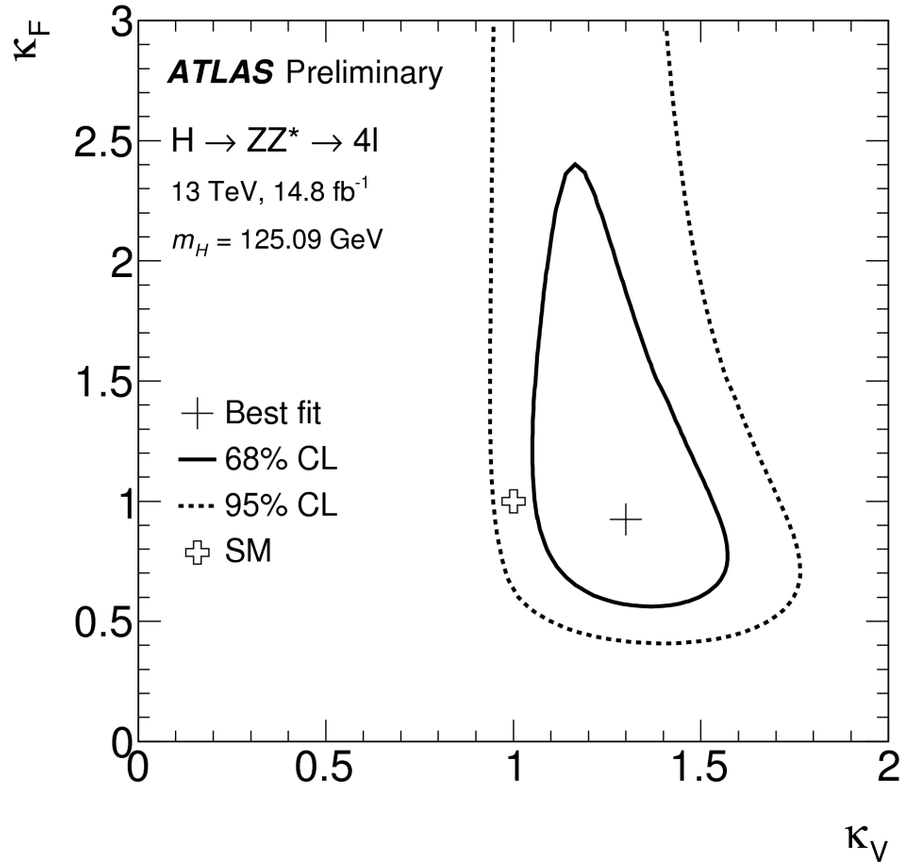
$$\mu = \frac{\sigma}{\sigma_{SM}} = 1.05^{+0.15}_{-0.14}(stat.)^{+0.11}_{-0.09}(sys.)$$

Signal strength associated with fermions and bosons:

$$\mu_{ggH,ttH} = 1.20^{+0.35}_{-0.31} \qquad \mu_{VBF,VH} = 0.00^{+1.37}_{-0.00}$$

H →ZZ* →4ℓ : Cross section per production mode (ATLAS)





Measured

$$\sigma_{\mathrm{ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44}\ \mathrm{pb}$$

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \mathrm{pb}$$

$$\sigma_{\mathrm{VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \mathrm{pb}$$

SM expectation

$$\sigma_{\mathrm{SM,ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.31 \pm 0.07\ \mathrm{pb}$$

$$\sigma_{\mathrm{SM,VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003\ \mathrm{pb}$$

$$\sigma_{\mathrm{SM,VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0.059 \pm 0.002\ \mathrm{pb}$$

Compatibility measurement with the SM:

$\sigma_{\mathrm{ggF+bbH+ttH}}$. B(H→ZZ*) is 1.1$\sigma$ and σ_{VBF}. B(H→ZZ*) is 1.4σ

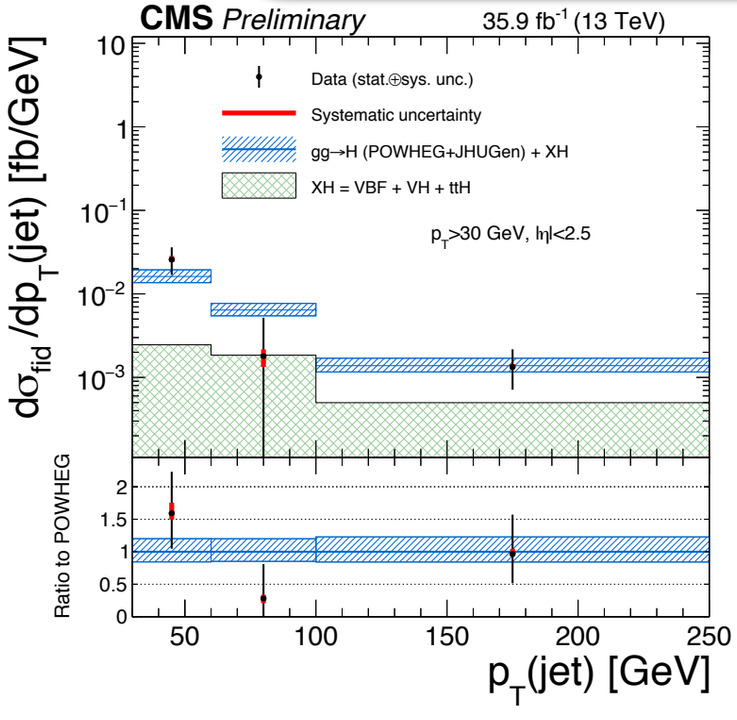
H →ZZ* →4ℓ : Differential and fiducial cross section

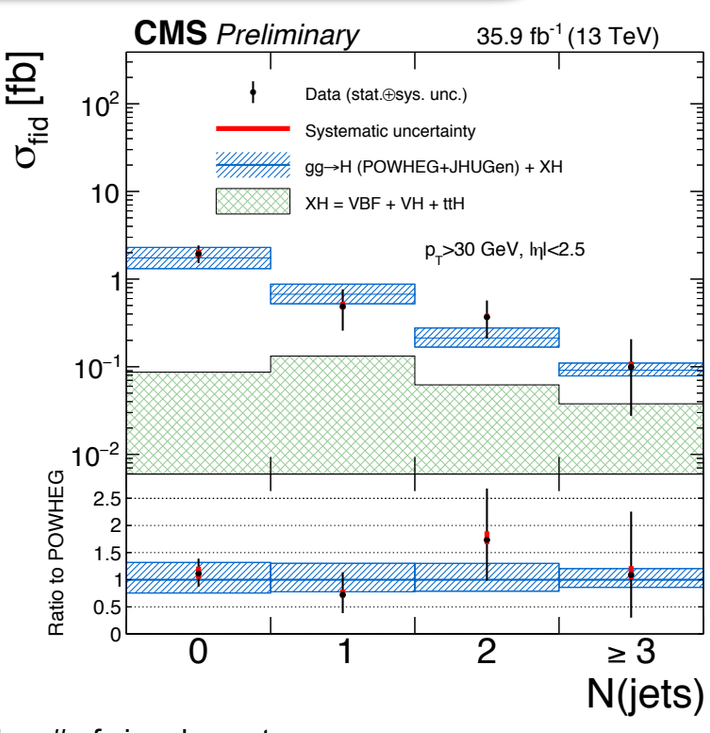
- Model independent measurement
  - No categorisation is used
  - Maximum likelihood fit to the $m_{4\ell}$ distribution to extract the σ_{fid}
    - Detector level bin-by-bin correction applied

CMS: 105 < $m_{4\ell}$ < 140 GeV , m_H = 125 GeV

$$\sigma_{fid} = 2.90^{+0.48}_{-0.44}(stat)^{+0.27}_{-0.22}(sys)\ fb$$

$$\sigma^{SM}_{fid} = 2.72 \pm 0.14\ fb$$

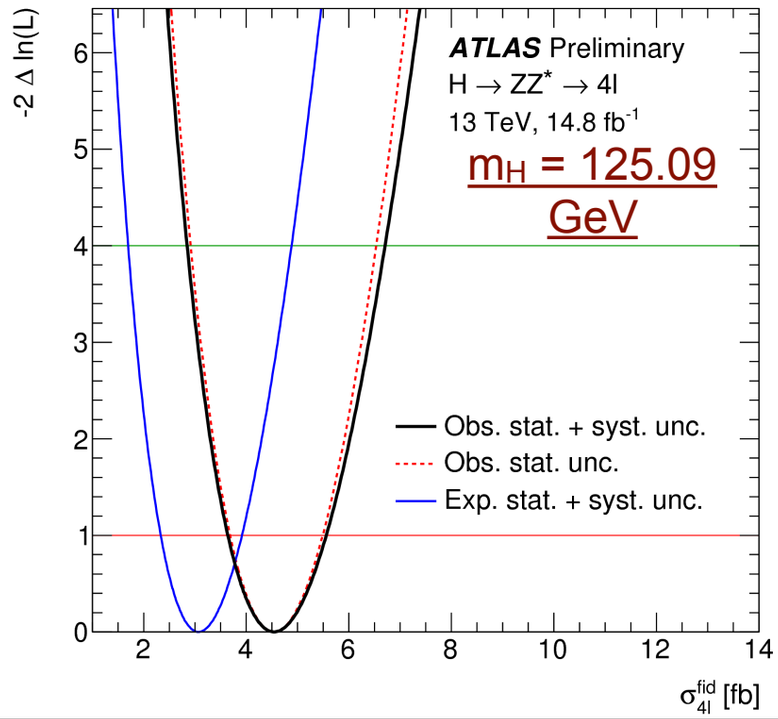




$$\sigma_{tot} = \frac{N_S}{A.C.B.L_{int}} \quad \sigma^i_{fid} = \frac{N_S}{C.L_{int}}$$

N_S = # of signal events
A = Kinematic and geometric acceptance given in fid. volume
C = Detector correction factor

ATLAS: 115 < $m_{4\ell}$ < 130 GeV



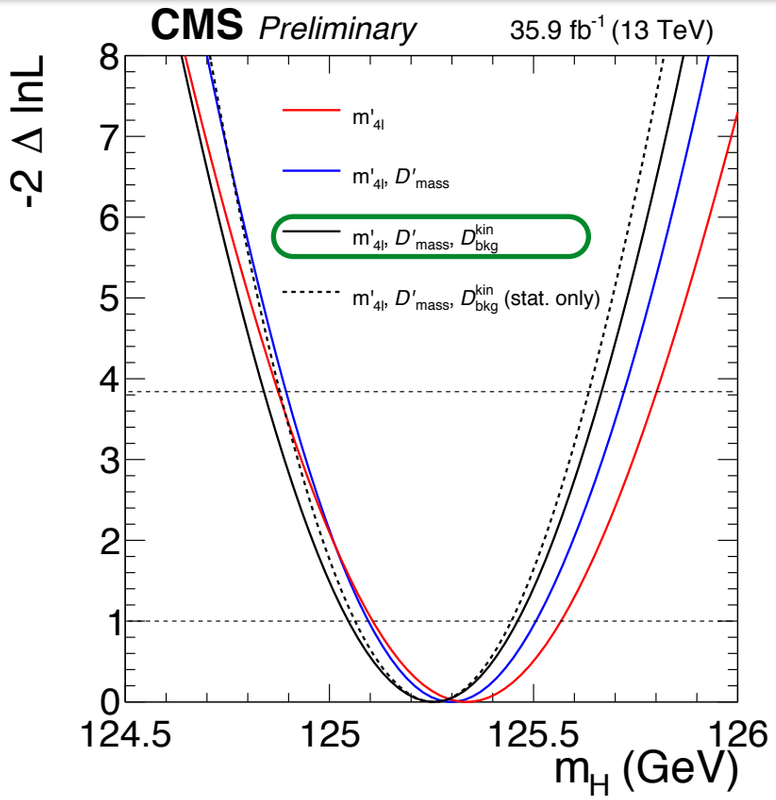
Final state	measured σ_{fid} [fb]	$\sigma_{fid,SM}$ [fb]
4μ	$1.28\ ^{+0.48}_{-0.40}$	$0.93\ ^{+0.06}_{-0.08}$
$4e$	$0.81\ ^{+0.51}_{-0.38}$	$0.73\ ^{+0.05}_{-0.06}$
$2\mu 2e$	$1.29\ ^{+0.58}_{-0.46}$	$0.67\ ^{+0.04}_{-0.04}$
$2e2\mu$	$1.10\ ^{+0.49}_{-0.40}$	$0.76\ ^{+0.05}_{-0.06}$

	Measured	SM exp.
σ_{fid} [fb]	$4.48^{+1.01}_{-0.89}$	$3.07^{+0.21}_{-0.25}$
σ_{tot} [pb]	81^{+18}_{-16}	$55.5^{+3.8}_{-4.4}$

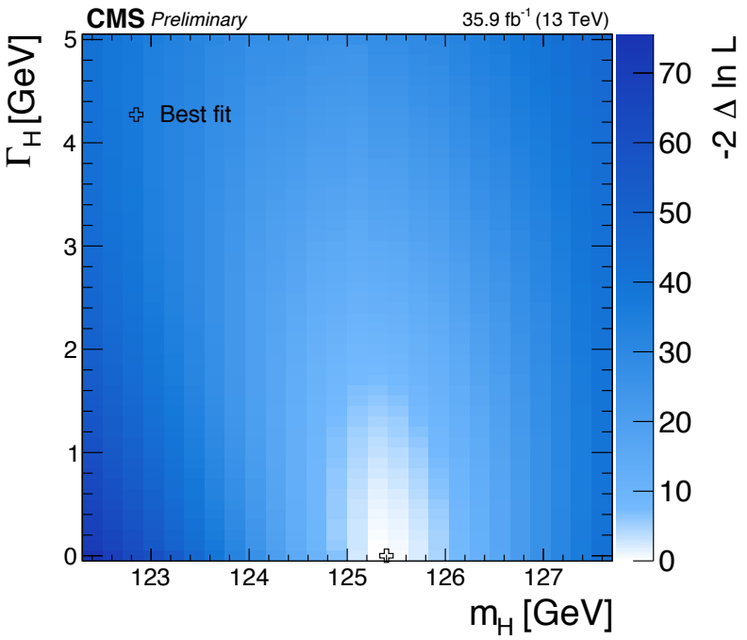
H →ZZ* →4ℓ: Mass and Width (CMS)

- **Mass measurement** is based on 3D fit : invariant mass of four lepton, expected uncertainty on the mass, and the discriminant
  - The on-shell Z is mass constrained
  - Systematic uncertainty dominated by uncertainty in the lepton momentum scale

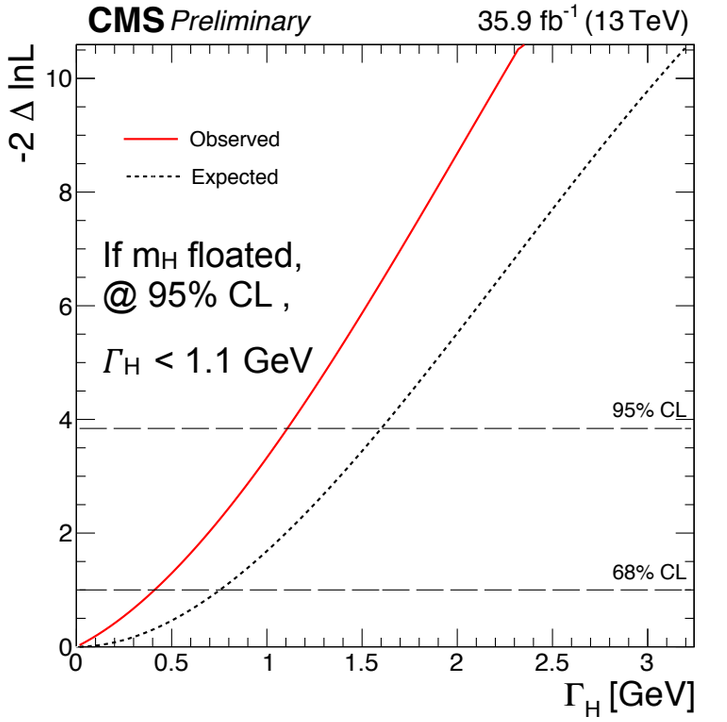
$$m_H = 125.26 \pm 0.20(stat) \pm 0.08(sys)\ GeV$$



Width measurement



Expected ($\mu_{VBF,VH}$ = $\mu_{ggH,ttH}$ and m_H =125 GeV, Γ_H = 0.0041 GeV) and observed values at 68% [95%] CL



Parameter	$m_{4\ell}$ range	Expected	Observed
Γ_H (GeV)	$[105, 140]$	$0.00^{+0.75}_{-0.00}$ $[0.00, 1.60]$	$0.00^{+0.41}_{-0.00}$ $[0.00, 1.10]$

H →ZZ* →4ℓ: Anomalous couplings (CMS)

The scattering amplitude to test the spin-0 Higgs boson with two spin-1 bosons (VV)

$$\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_1+q_2)^2}{\left(\Lambda_{\mathrm{Q}}^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

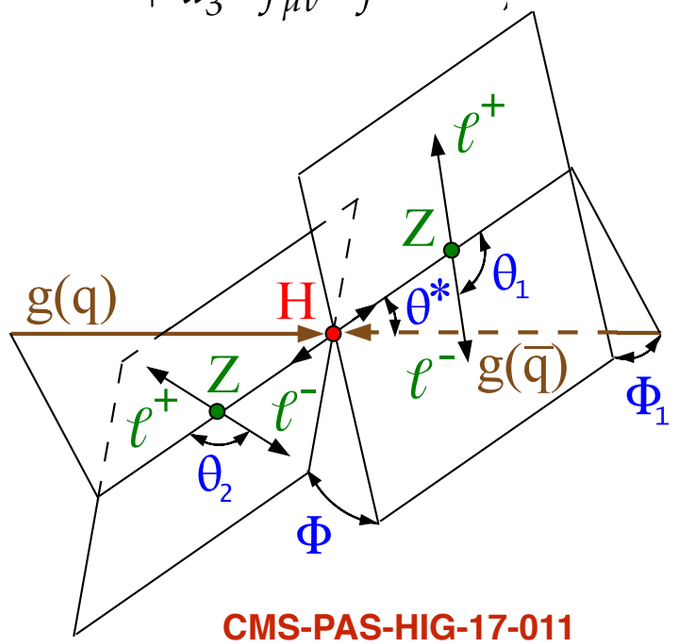
a_i = anomalous coupling

- Same selection as for the mass measurement
  - Only three categories because of small statistics: VBF, VH and untagged
  - Discriminants to suppress background, to separate BSM and SM, and to isolate interference of BSM and SM (Ω - up to 13 observables)

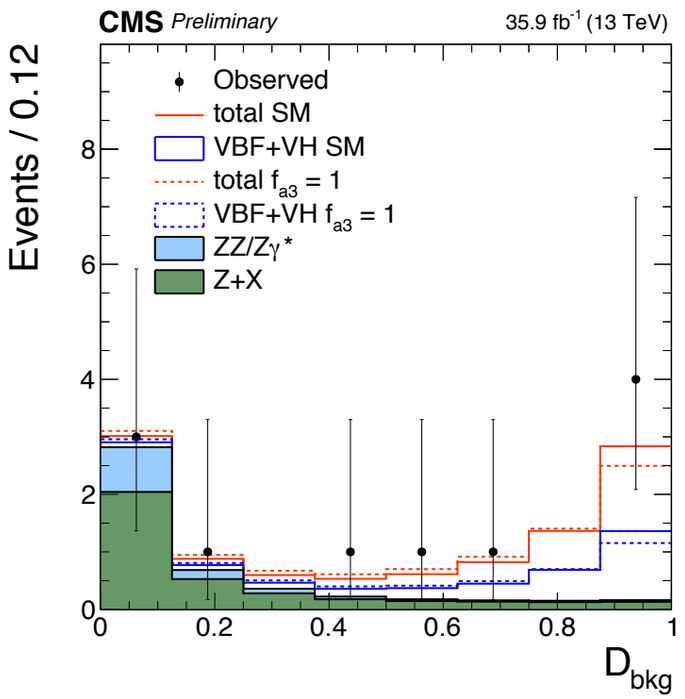
$$\mathcal{D}_{\mathrm{bkg}} = \frac{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{bkg}}(\vec{\Omega})}. \quad \mathcal{D}_{\mathrm{BSM}} = \frac{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})}. \quad \mathcal{D}_{\mathrm{int}} = \frac{\mathcal{P}^{\mathrm{int}}_{\mathrm{SM-BSM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})}$$

Effective cross sections ratio, f_{ai}, phases ϕ_{ai} :
f_{ai} = 0 (1) indicates pure SM (BSM)

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21}$ $[-0.45, 0.66]$	$0.000^{+0.017}_{-0.017}$ $[-0.32, 0.32]$
$f_{a2}\cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04}$ $[-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014}$ $[-0.08, 0.29]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.00^{+0.06}_{-0.33}$ $[-0.92, 0.15]$	$0.000^{+0.014}_{-0.014}$ $[-0.79, 0.15]$
$f_{\Lambda 1}^{Z\gamma}\cos(\phi_{\Lambda 1}^{Z\gamma})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$

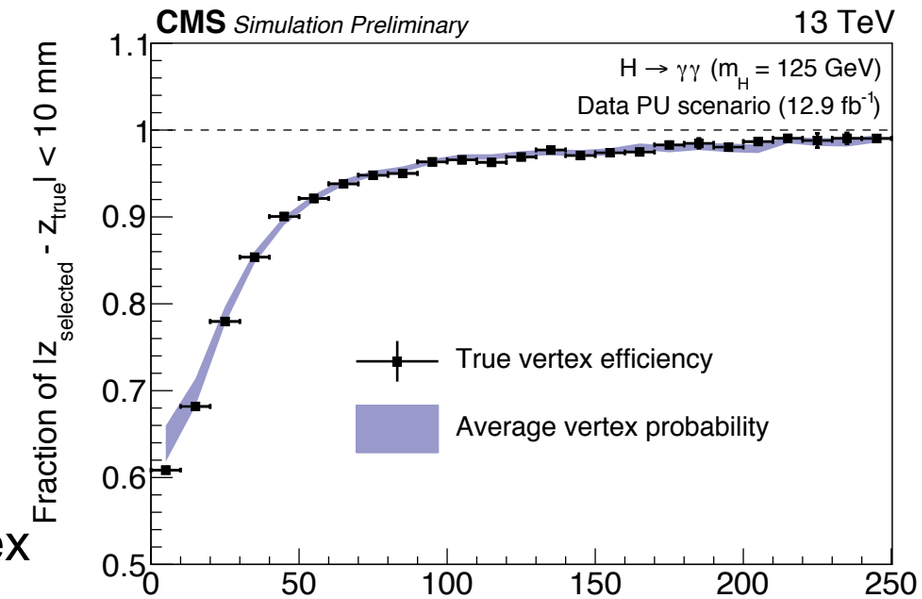


CMS-PAS-HIG-17-011



H → $\gamma\gamma$

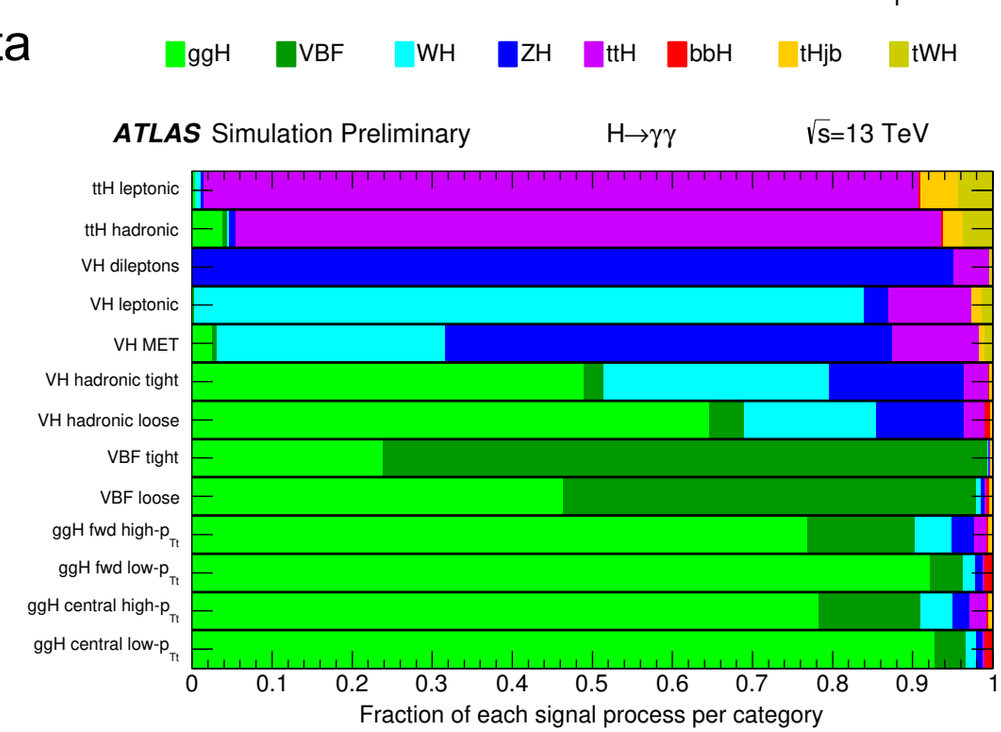
- Signal selection
  - Two isolated and highest E_T photons
    - Leading photon : $E_T/m_{\gamma\gamma}$ > 0.33 (CMS); 0.35 (ATLAS)
    - Subleading photon : $E_T/m_{\gamma\gamma}$ > 0.25 GeV
    - $|\eta|$ < 2.5 (CMS), 2.37 (ATLAS) and exclude transition region
  - Photons originating from the diphoton primary vertex
- Backgrounds
  - Continuum $\gamma\gamma$ (irreducible); estimated from data
  - γ+jet/jet+jet (reducible)



Events are divided in categories based on mass resolution σ_m/m (CMS) /production modes (ATLAS) to maximise the sensitivity

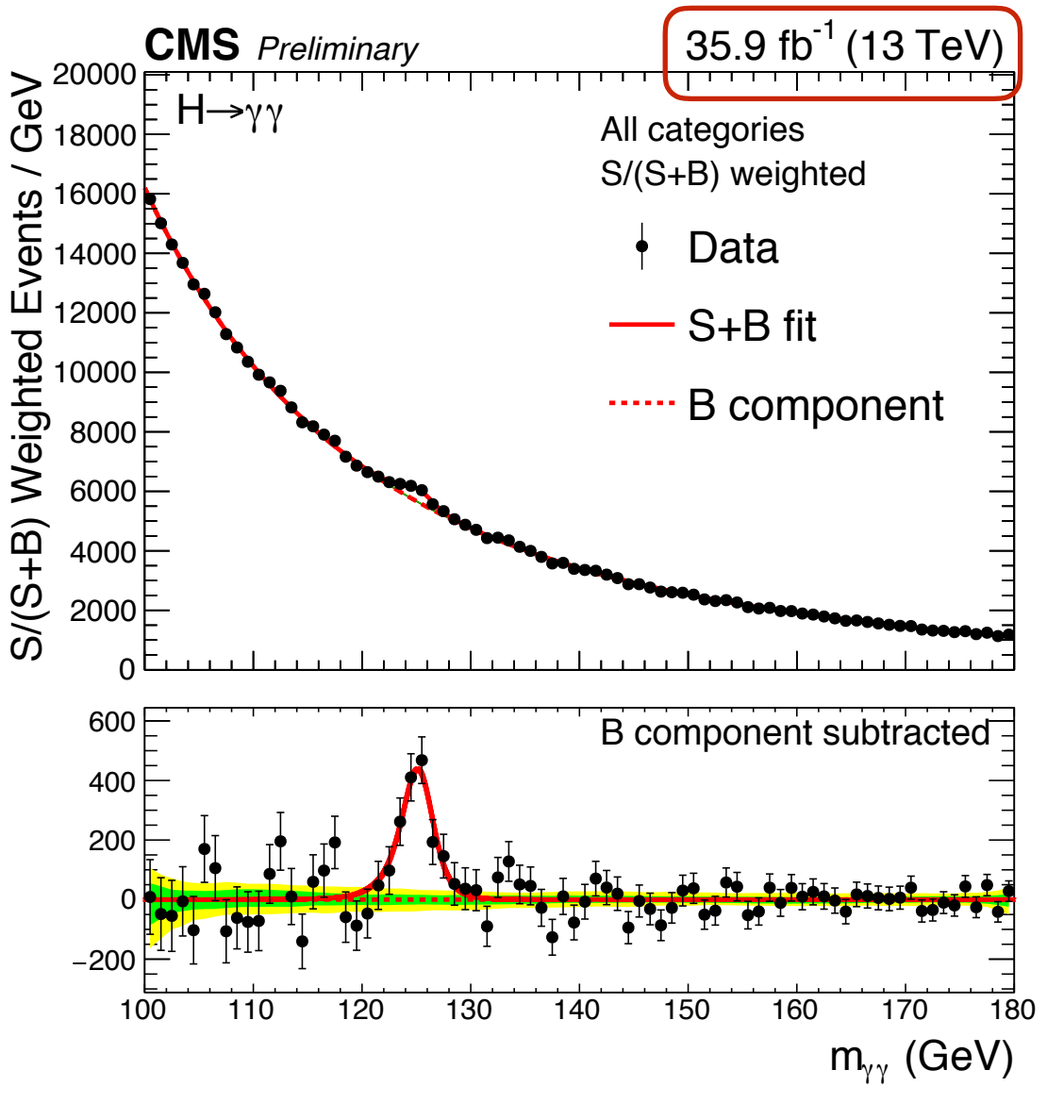
CMS: 3 categories

ATLAS: 13 categories



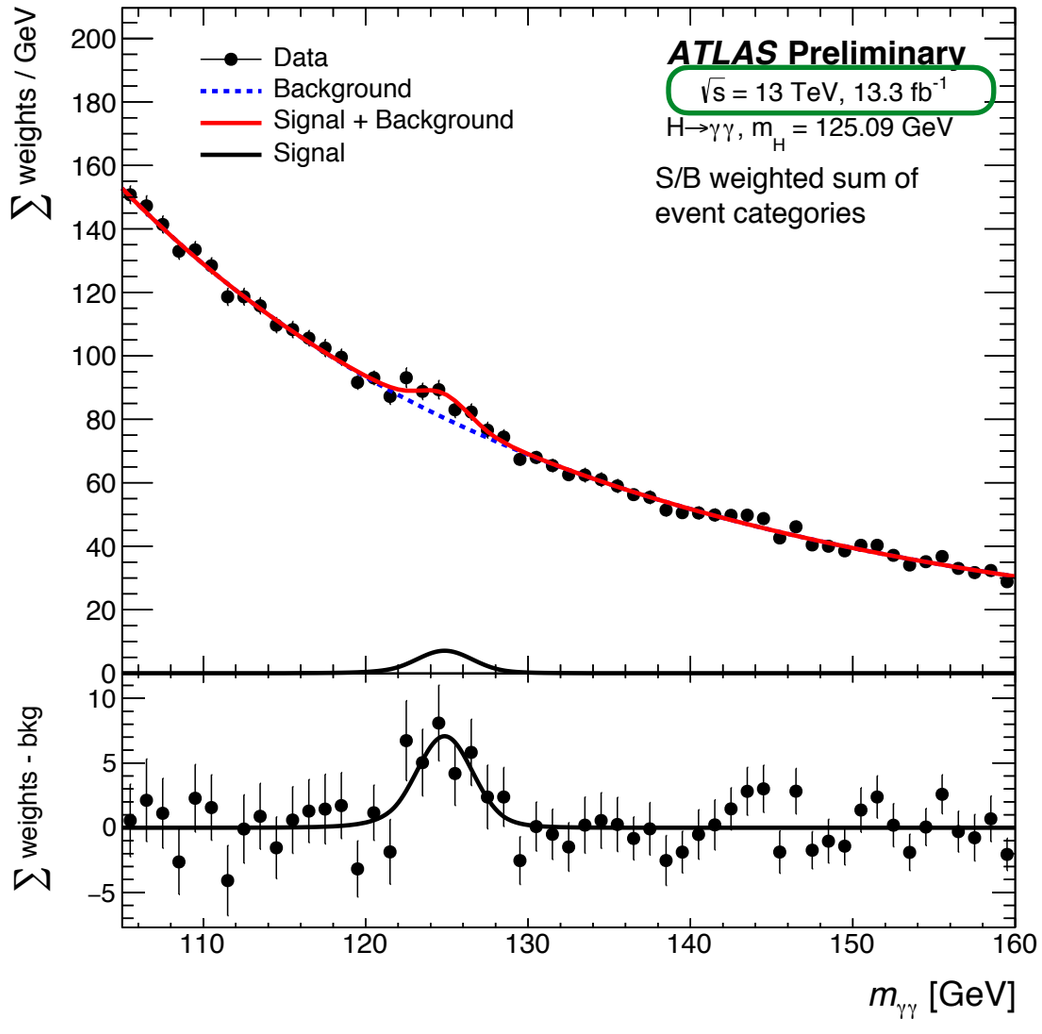
H → $\gamma\gamma$: Diphoton mass distribution

CMS-PAS-HIG-17-015



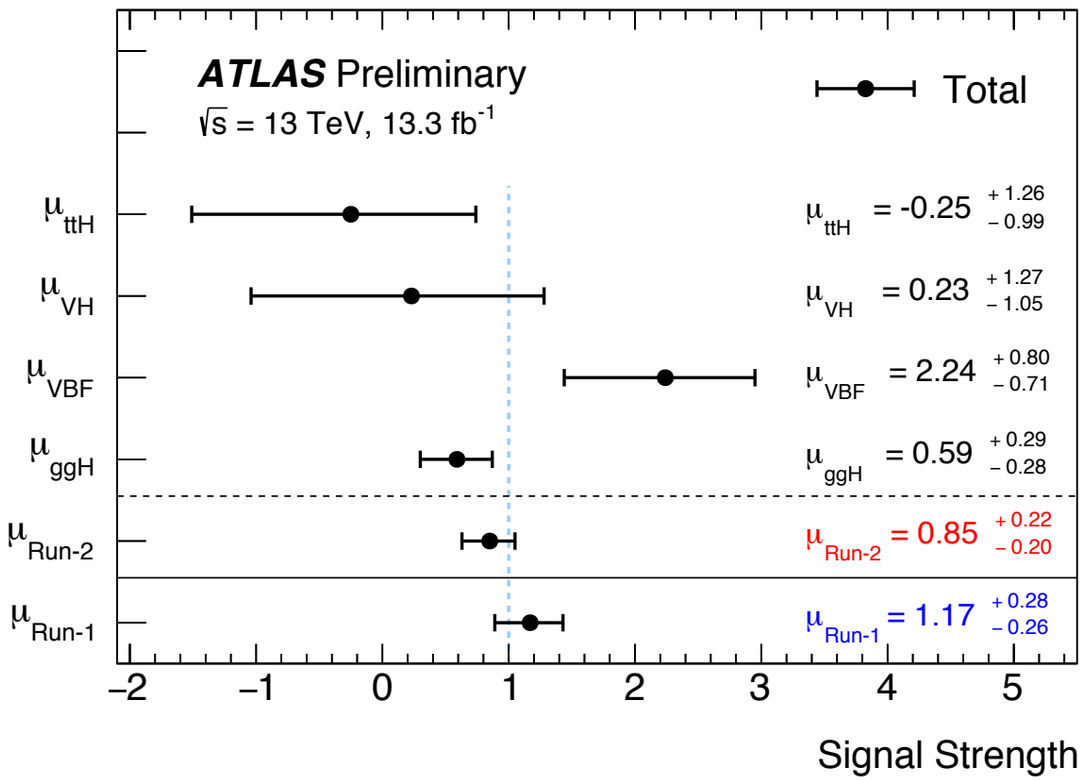
With 12.9 fb^{-1} signal significance:
5.6σ (obs) ; 6.2σ (exp)
at m_H = 125.09 GeV

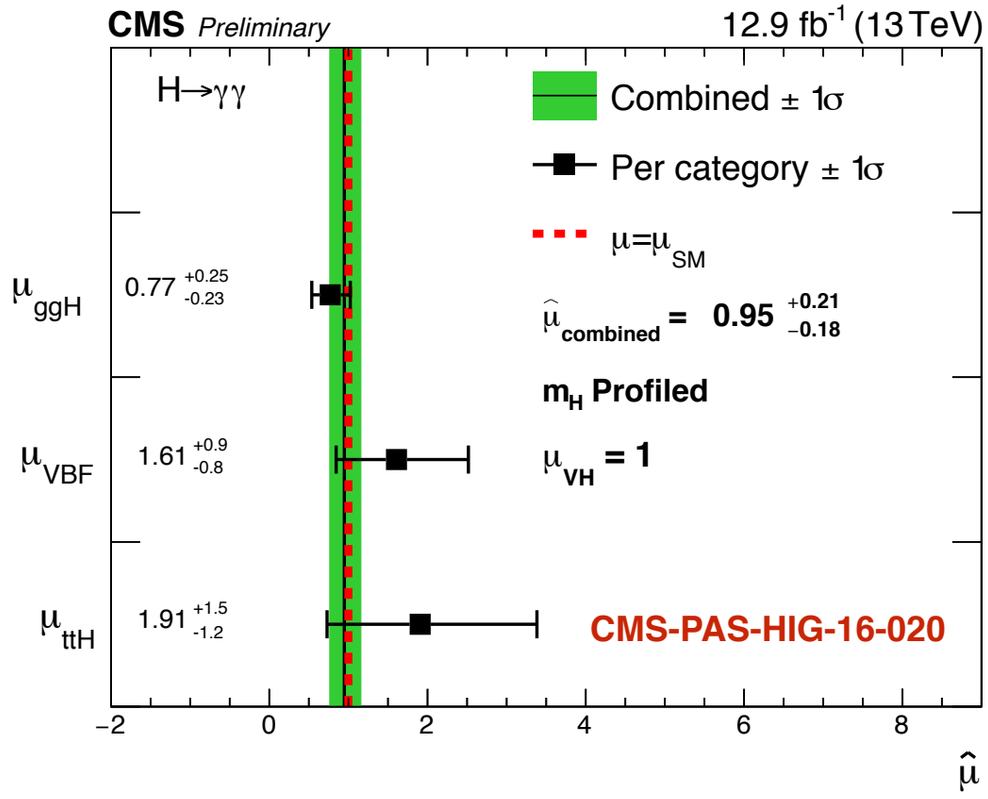
ATLAS-CONF-2016-067



Signal significance : 4.7σ (obs) ;
5.4σ (exp) at m_H = 125.09 GeV

H → $\gamma\gamma$: Signal strength





$\mu_{\text{Run-2}}$ uses an updated ggF theory prediction which is 10% larger than that used for $\mu_{\text{Run-1}}$

ATLAS: m_H = 125.09 GeV, cross section per production mode

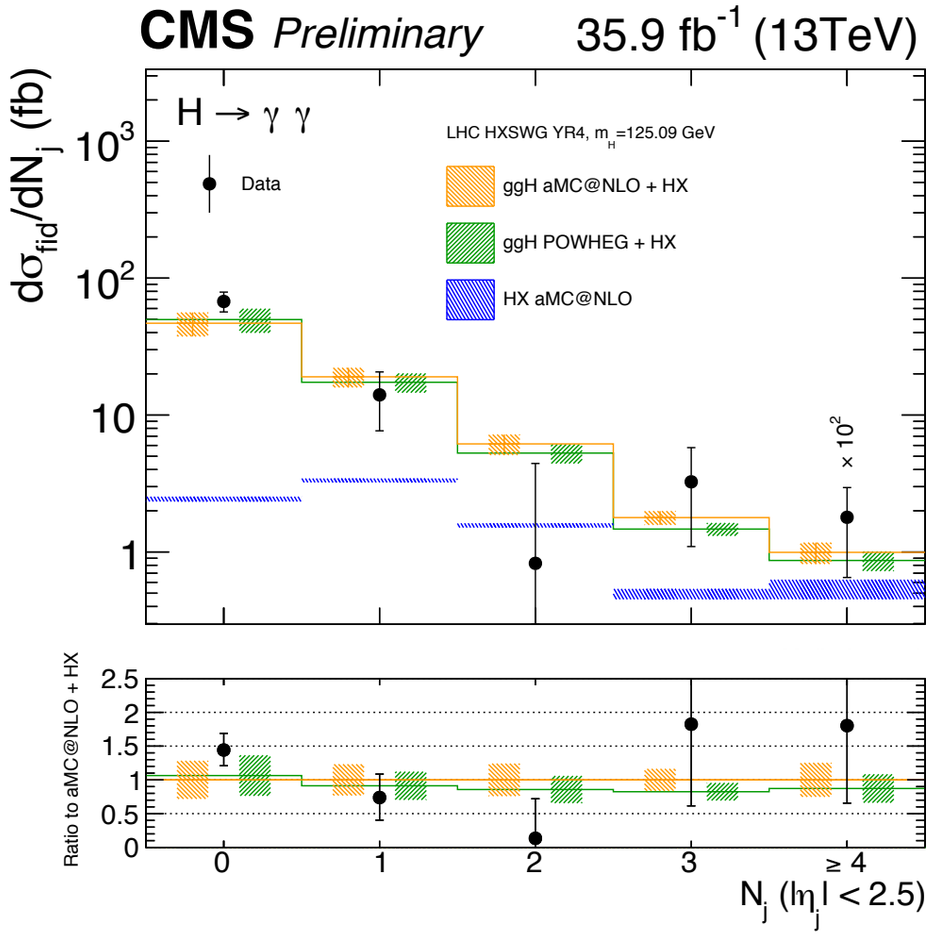
$$\sigma_{ggH} \times \mathcal{B}(H \to \gamma\gamma) = 65\ ^{+32}_{-31}\ \text{fb}$$

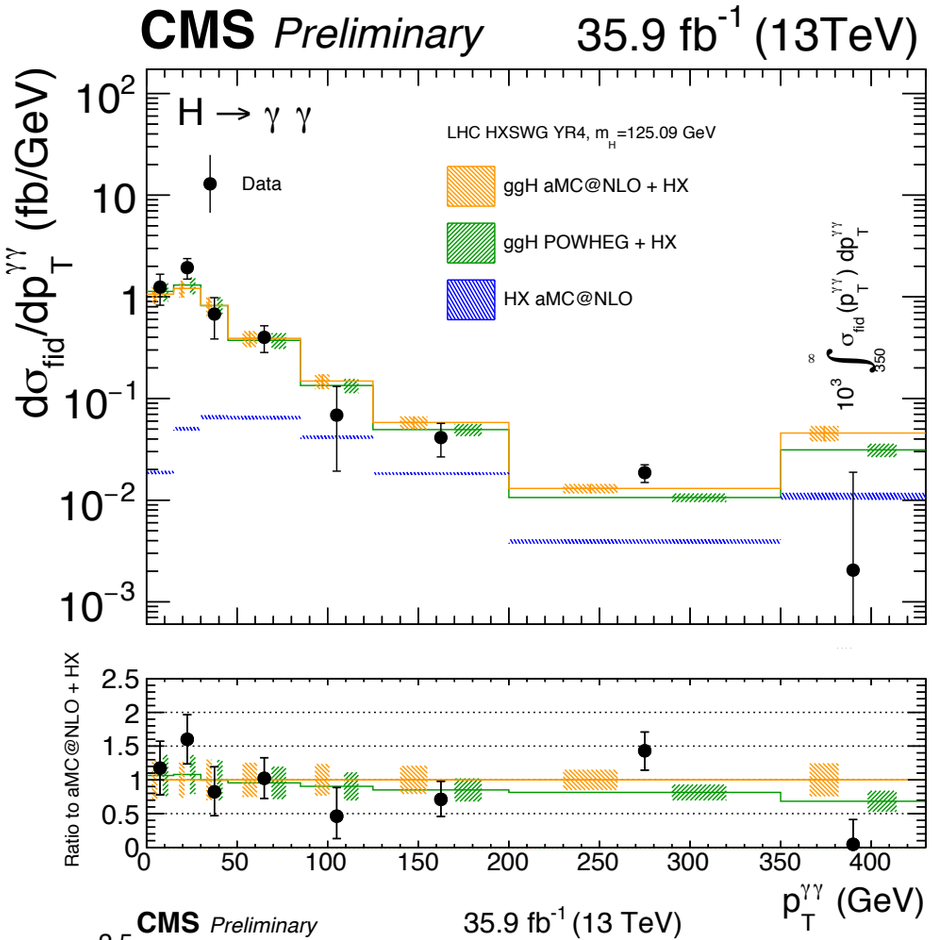
$$\sigma_{\text{VBF}} \times \mathcal{B}(H \to \gamma\gamma) = 19.2\ ^{+6.8}_{-6.1}\ \text{fb}$$

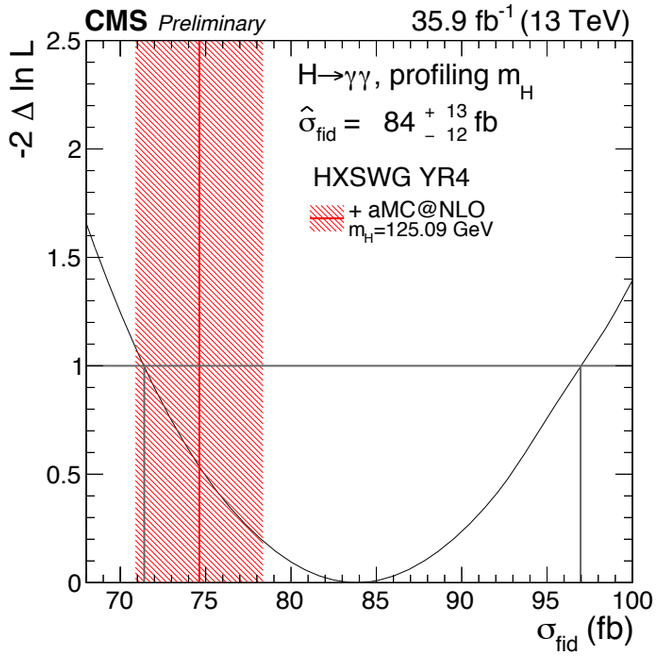
$$\sigma_{VH} \times \mathcal{B}(H \to \gamma\gamma) = 1.2\ ^{+6.5}_{-5.4}\ \text{fb}$$

$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) = -0.3\ ^{+1.4}_{-1.1}\ \text{fb}$$

H → $\gamma\gamma$: Differential fiducial cross section (CMS)





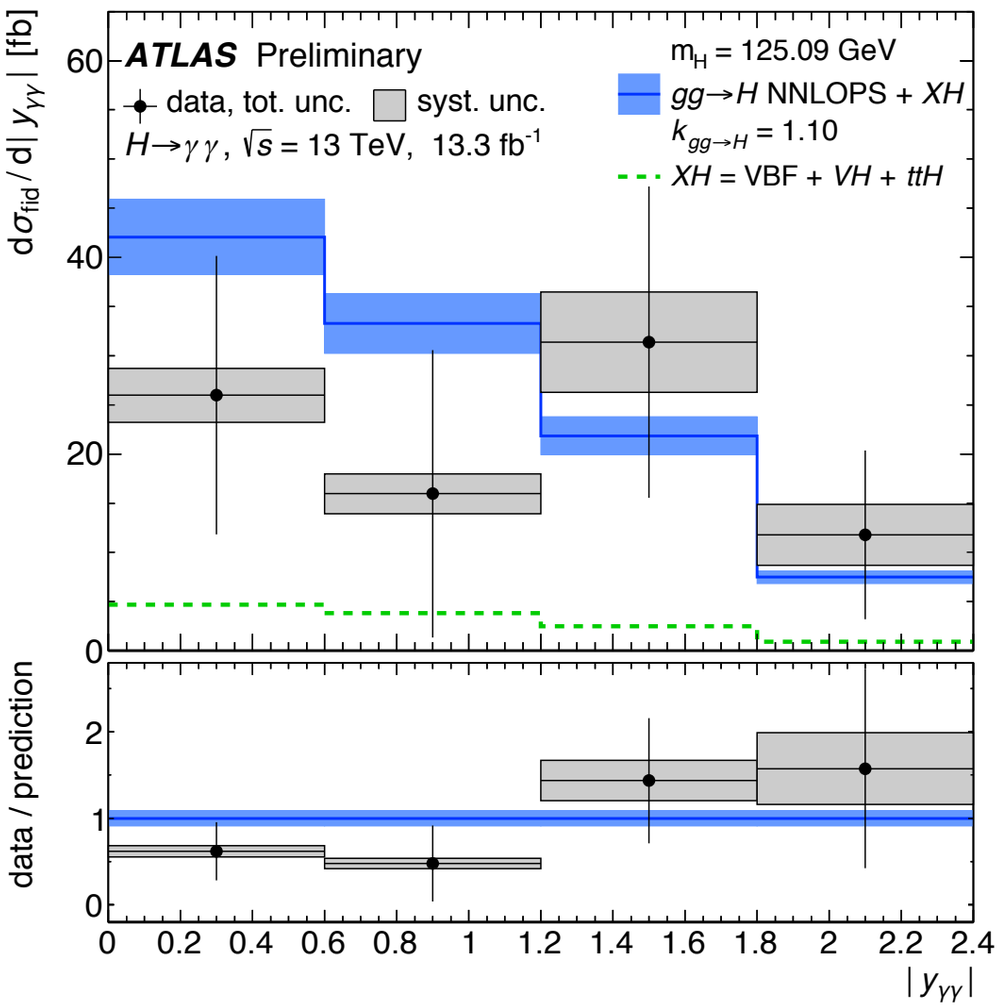


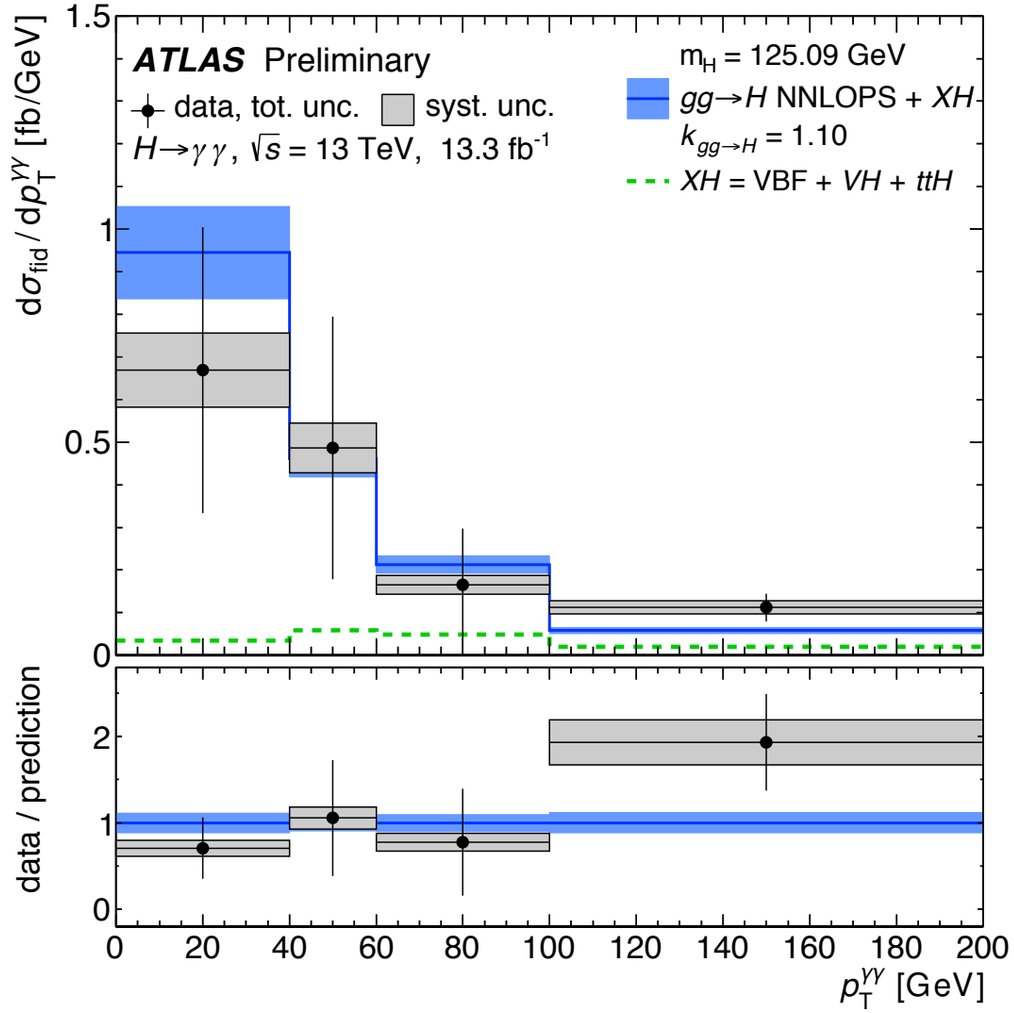
<u>$|\eta_\gamma| < 2.5$, iso < 10 GeV (ΔR = 0.3) and $p_T/m_{\gamma\gamma} > 1/3$ (1/4)</u>

$$\sigma_{fid} = 84 \pm 11(stat) \pm 7(sys)\ fb$$

$$\sigma_{fid}^{SM} = 75 \pm 4\ fb$$

H → $\gamma\gamma$: Differential fiducial cross section (ATLAS)





m_H = 125.09 GeV, $|\eta_\gamma| < 2.37$, and $p_T/m_{\gamma\gamma} > 0.35$ (0.25)

$$\sigma_{fid} = 43.2 \pm 14.9(stat) \pm 4.9(sys)\ fb$$

$$\sigma_{fid}^{SM} = 62.8^{+3.4}_{-4.4}\ fb$$

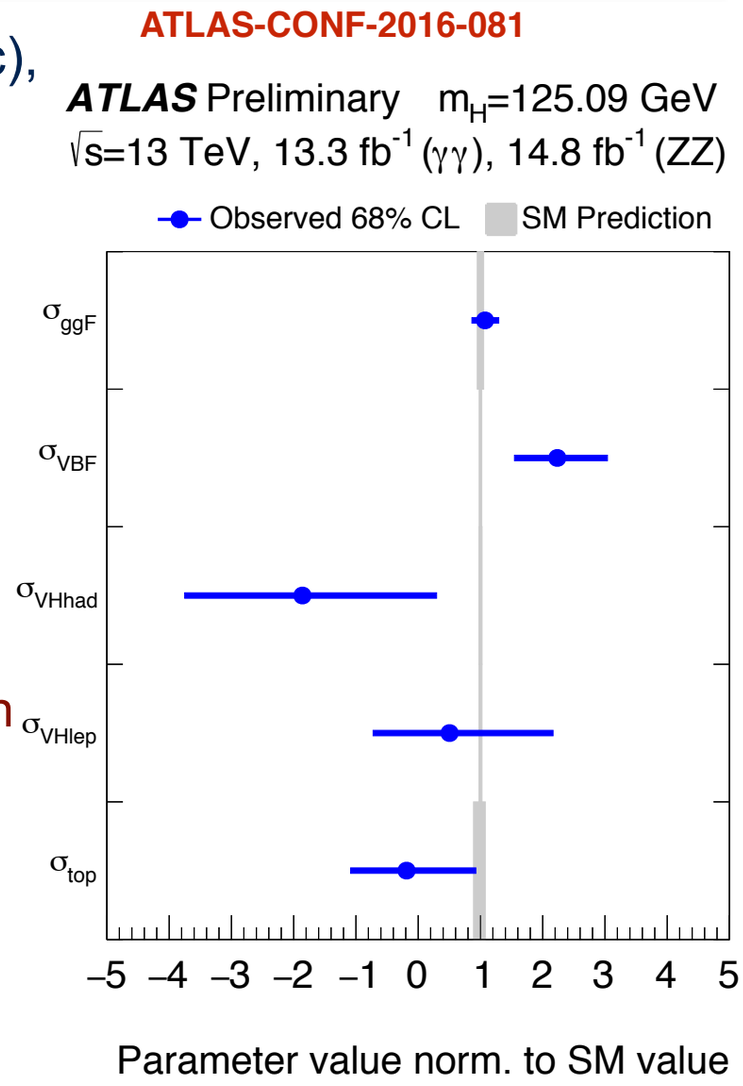
Combination of H → $\gamma\gamma$ and H →ZZ* →4ℓ (ATLAS)

- Combination for $|y_H| < 2.5$ for the ggH, VBF, VH (hadronic), VH (leptonic) and top production processes

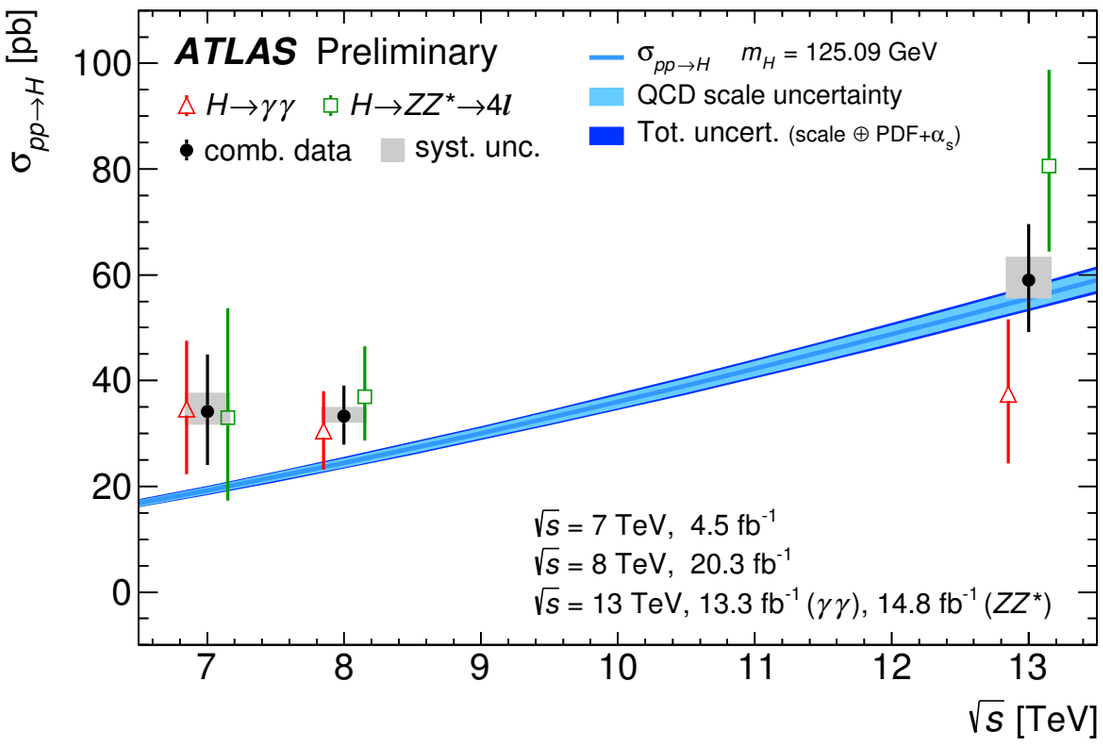
Decay mode	ggF	VBF	VHhad	VHlep	top
$H \to \gamma\gamma$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{ggF}}$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{VBF}}$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{VHhad}}$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{VHlep}}$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{top}}$
$H \to ZZ^*$	$(\sigma \cdot \mathrm{B})^{ZZ}_{\mathrm{ggF}}$	$(\sigma \cdot \mathrm{B})^{ZZ}_{\mathrm{VBF}}$	fixed to SM	fixed to SM	fixed to SM

- The signal strength of $\mu = 1.13^{+0.18}_{-0.17}$
- Observed (expected) significance 10σ (8.6σ)

ATLAS-CONF-2016-081



$\sigma(pp \to H+X)$ in the full phase space is from fiducial cross section



$$\sigma(pp \to H + X) = 59.0^{+9.7}_{-9.2}(stat)^{+4.4}_{-3.5}(syst)\ pb$$

N^{3}LO theory

$$\sigma(pp \to H + X) = 55.5^{+2.4}_{-3.4}\ pb$$

Summary

- A lot was learned on the Higgs boson and its properties with the Run 1 data at 7 & 8 TeV
  - Its mass is known with a precision of 0.2%
  - Its properties ares within the SM expectation

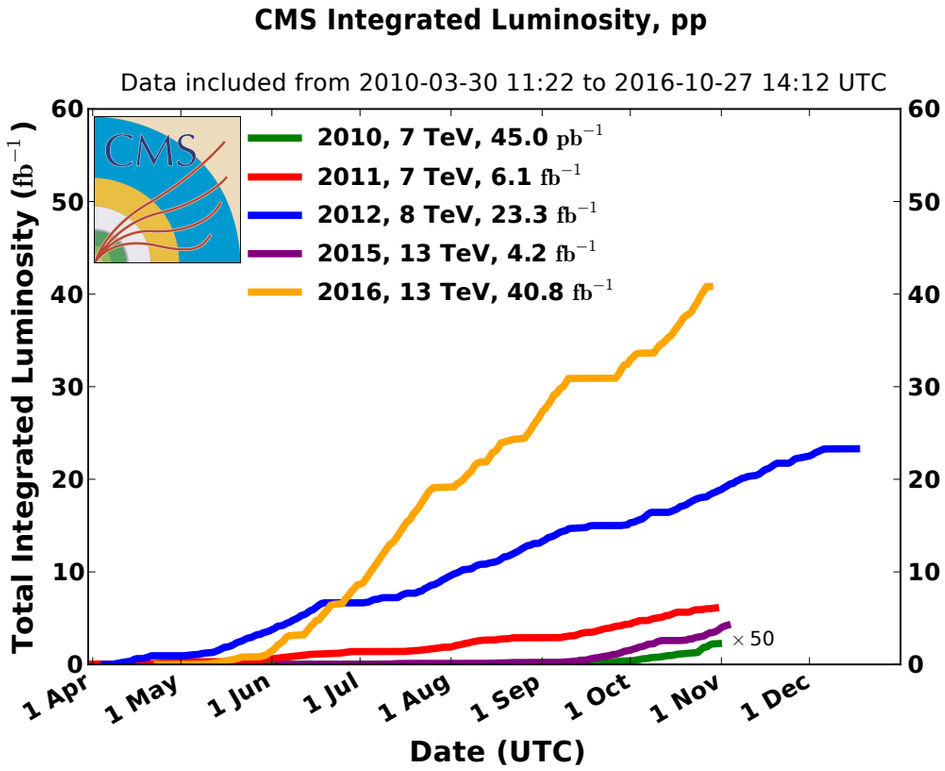
- Latest results from ATLAS (~14 fb^{-1}) and CMS (~36 fb^{-1}) from the Run 2 data at 13 TeV are presented
  - The results are consistent with the Run 1
  - The precision of mass and its properties are about same with the combined ATLAS+CMS result or better
  - The updated results are still statistically limited and consistent with the SM expectations

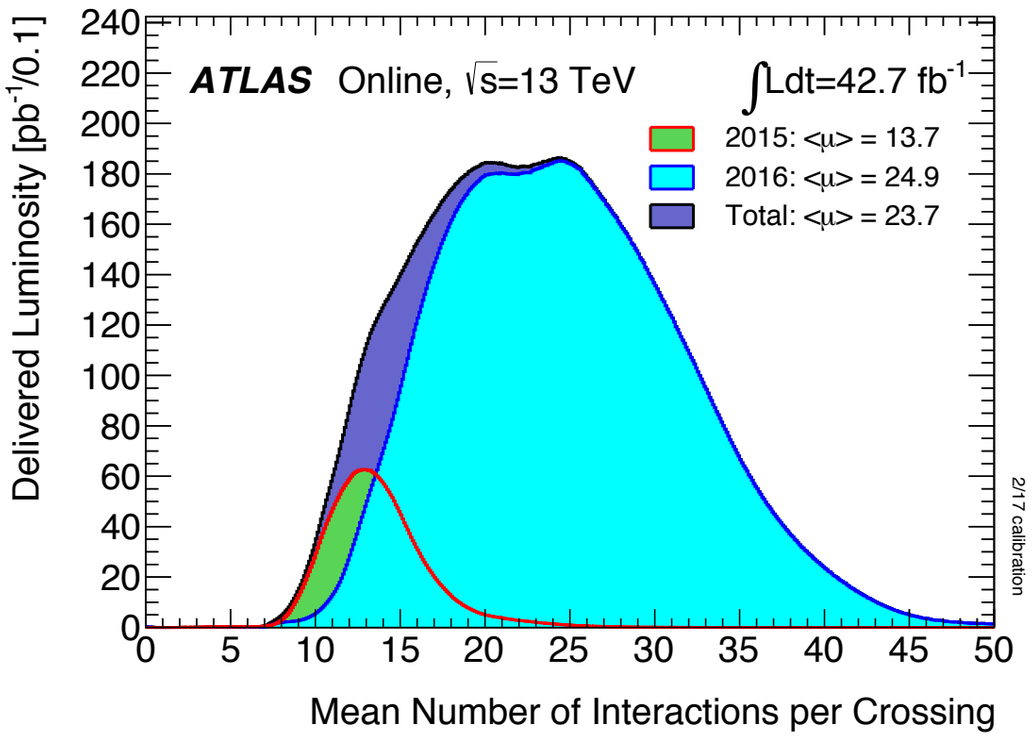
- ATLAS results to be updated soon for the full Run 2 dataset

BACKUP

Run 2 Data

- Very good data taking during 2015 and 2016 (Run 2)
  - Data taking efficiency (> 95%)
- Collected ~ 3 fb^{-1} (2015) and ~33 fb^{-1} (2016)
  - Presented results are from ~36 fb^{-1} (CMS), and ~14 fb^{-1} (ATLAS) (for comparison the CMS results with ~14 fb^{-1} will be shown)





- Pileup (average number of pp interactions per bunch crossing) challenge with 2016 data taking
  - $<\mu>$ ~ 25 (14) in 2016 (2015)

$H \rightarrow ZZ^* \rightarrow 4\ell$

ATLAS: 118 <$m_{4\ell}$ <129 GeV

Final State	Signal full mass range	Signal	ZZ^*	Z + jets, $t\bar{t}$ ttV,VVV, WZ	S/B	Expected	Observed
4μ	8.8 ± 0.6	8.2 ± 0.6	3.11 ± 0.30	0.31 ± 0.04	2.4	11.6 ± 0.7	16
$2e2\mu$	6.1 ± 0.4	5.5 ± 0.4	2.19 ± 0.21	0.30 ± 0.04	2.2	8.0 ± 0.4	12
$2\mu2e$	4.8 ± 0.4	4.4 ± 0.4	1.39 ± 0.16	0.47 ± 0.05	2.3	6.2 ± 0.4	10
$4e$	4.8 ± 0.5	4.2 ± 0.4	1.46 ± 0.18	0.46 ± 0.05	2.2	6.1 ± 0.4	6
Total	24.5 ± 1.8	22.3 ± 1.6	8.2 ± 0.8	1.54 ± 0.18	2.3	32.0 ± 1.8	44

CMS: 35.9 fb^{-1},$m_{4\ell}$ > 70 GeV

Channel	4e	4μ	2e2μ	4ℓ
$q\bar{q} \rightarrow ZZ$	$192.7^{+18.6}_{-20.1}$	$360.2^{+24.9}_{-27.3}$	$471.0^{+32.6}_{-35.7}$	$1023.9^{+68.9}_{-76.0}$
$gg \rightarrow ZZ$	$41.2^{+6.3}_{-6.1}$	$69.0^{+9.5}_{-9.0}$	$101.7^{+14.0}_{-13.3}$	$211.8^{+28.9}_{-27.5}$
Z+X	$21.1^{+8.5}_{-10.4}$	$34.4^{+14.5}_{-13.2}$	$59.9^{+27.1}_{-25.0}$	$115.4^{+31.9}_{-30.1}$
Sum of backgrounds	$255.0^{+23.9}_{-25.1}$	$463.5^{+31.9}_{-33.7}$	$632.6^{+44.2}_{-46.1}$	$1351.1^{+85.8}_{-91.2}$
Signal ($m_H = 125$ GeV)	$12.0^{+1.3}_{-1.4}$	23.6 ± 2.1	30.0 ± 2.6	65.7 ± 5.6
Total expected	$267.0^{+24.9}_{-26.1}$	$487.1^{+33.1}_{-34.9}$	$662.6^{+45.7}_{-47.5}$	$1416.8^{+89.1}_{-94.3}$
Observed	293	505	681	1479

CMS: 12.9 fb^{-1},118 <$m_{4\ell}$ <130 GeV
CMS-PAS-HIG-16-033

Channel	4e	4μ	2e2μ	4ℓ
$q\bar{q} \rightarrow ZZ$	$1.37^{+0.16}_{-0.15}$	$3.09^{+0.27}_{-0.27}$	$3.90^{+0.46}_{-0.43}$	$8.36^{+0.81}_{-0.79}$
$gg \rightarrow ZZ$	$0.16^{+0.03}_{-0.03}$	$0.32^{+0.05}_{-0.05}$	$0.30^{+0.05}_{-0.05}$	$0.77^{+0.12}_{-0.12}$
Z + X	$0.90^{+0.38}_{-0.37}$	$1.40^{+0.52}_{-0.51}$	$2.34^{+0.91}_{-0.89}$	$4.64^{+1.11}_{-1.09}$
Sum of backgrounds	$2.42^{+0.42}_{-0.40}$	$4.81^{+0.59}_{-0.59}$	$6.54^{+1.03}_{-1.00}$	$13.77^{+1.41}_{-1.38}$
Signal ($m_H = 125$ GeV)	$3.90^{+0.53}_{-0.54}$	$7.92^{+0.88}_{-0.93}$	$9.80^{+1.34}_{-1.36}$	$21.61^{+2.63}_{-2.71}$
Total expected	$6.32^{+0.78}_{-0.76}$	$12.73^{+1.21}_{-1.24}$	$16.34^{+1.92}_{-1.90}$	$35.38^{+3.43}_{-3.45}$
Observed	5	12	16	33

H →ZZ* →4ℓ: Mass improvements (CMS)

No $m(\mathrm{Z}_1)$ constraint	3D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\mathrm{mass}}, \mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}})$	2D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\mathrm{mass}})$	1D: $\mathcal{L}(m_{4l})$
Expected m_{H} uncertainty change	+8.1%	+11.2%	+21%
Observed m_{H} (GeV)	125.28±0.22	125.36±0.24	125.39±0.25

With $m(\mathrm{Z}_1)$ constraint	3D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\mathrm{mass}}, \mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}})$	2D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\mathrm{mass}})$	1D: $\mathcal{L}(m'_{4l})$
Expected m_{H} uncertainty change	—	+3.2%	+10.7%
Observed m_{H} (GeV)	125.26±0.21	125.30±0.21	125.34±0.23