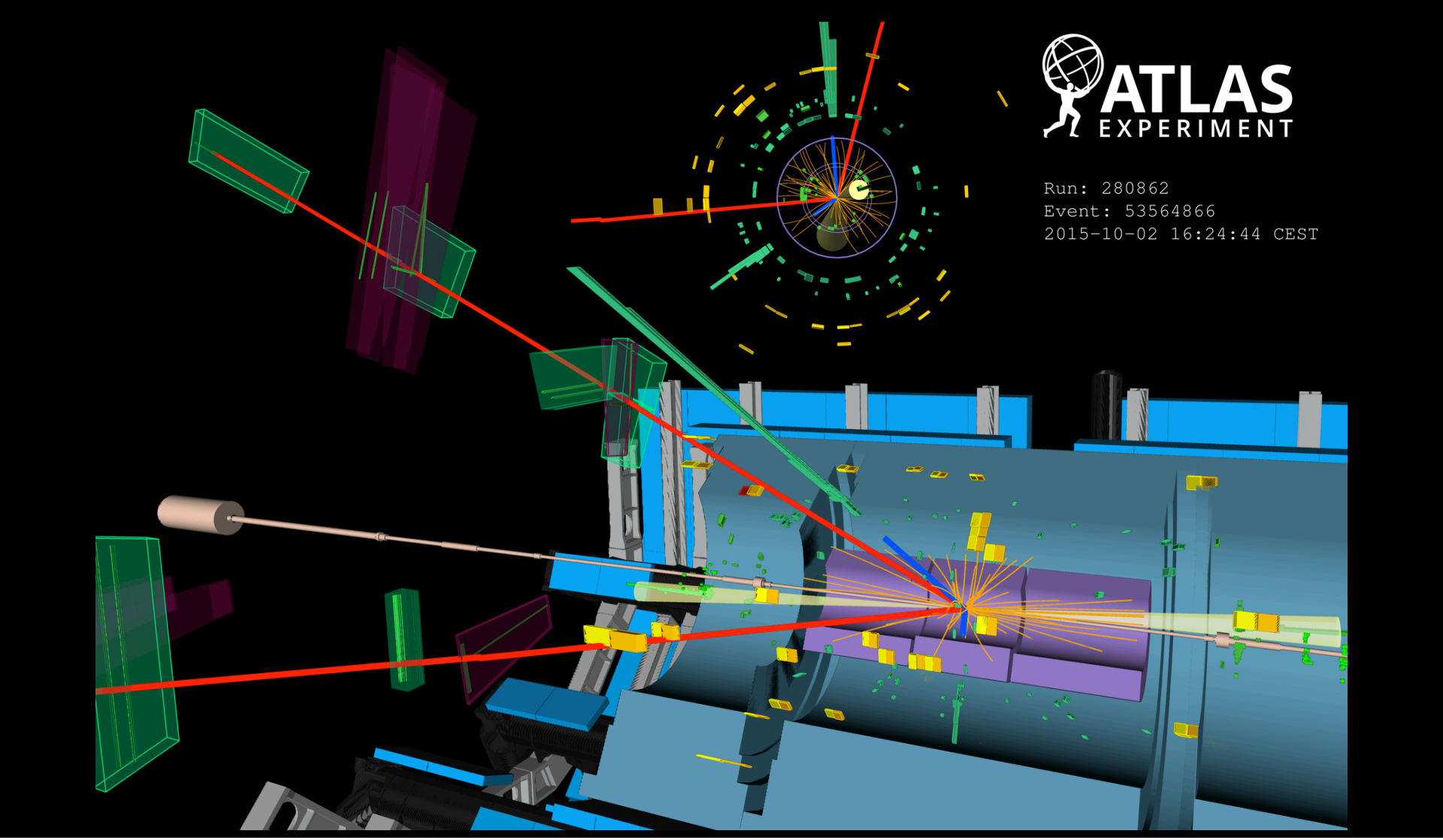


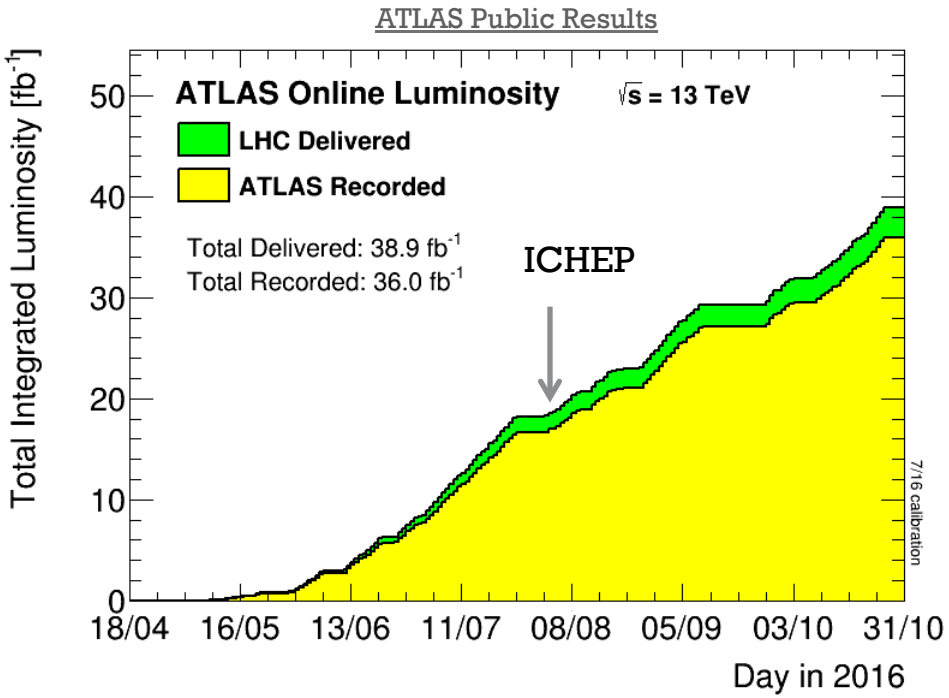
Measurement of Cross Sections and Properties of the Higgs Boson Using the ATLAS Detector

Stephan Hageböck
On behalf of the ATLAS Collaboration
20.02.2017, Lake Louise, Canada

universitätbonn

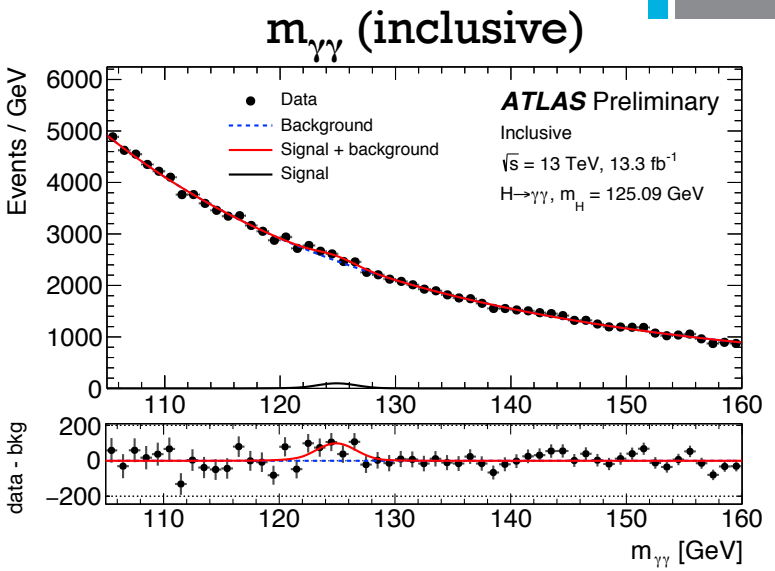
Run 2 Higgs Results from ATLAS

- Run 2 so far:
  - 2015: 3.2 fb^{-1}
  - 2016: ~ 36 fb^{-1} on disk
  - Available for ICHEP 2016: ~ 13 fb^{-1}
- Cross sections:
  - H→γγ
  - H→ZZ
  - H→WW: WH and VBF production
- Updates / refinements of searches:
  - H→μμ / bb
  - ttH production
- Combinations:
  - H→γγ / ZZ
  - 3 channels on ttH production



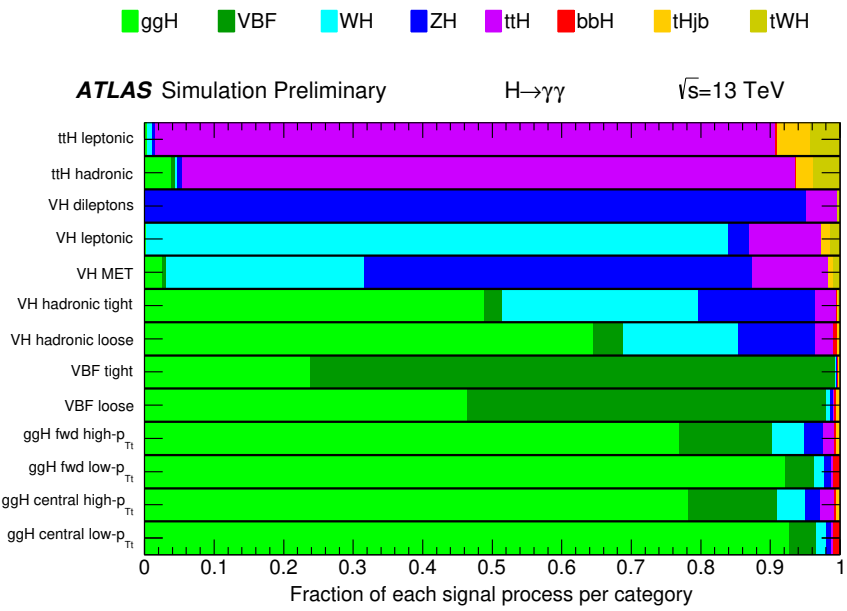
H→γγ

- As in Run 1: Fit S+B model in $m_{\gamma\gamma}$ spectrum (m_H = 125.09 GeV)
- Split into 13 categories:
  - Optimise background model: Data-driven, backed by MC
  - Probe production channels: ttH / VH / VBF / gg

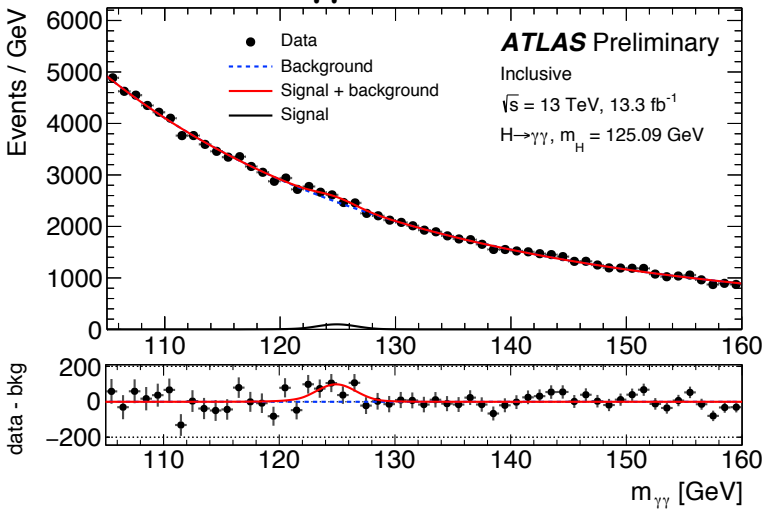


H→γγ

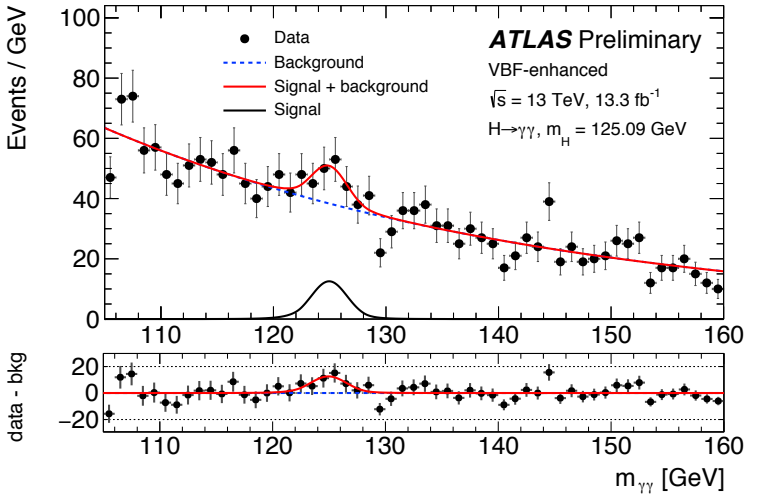
- As in Run 1: Fit S+B model in $m_{\gamma\gamma}$ spectrum (m_H = 125.09 GeV)
- Split into 13 categories:
  - Optimise background model: Data-driven, backed by MC
  - Probe production channels: ttH / VH / VBF / gg



$m_{\gamma\gamma}$ (inclusive)



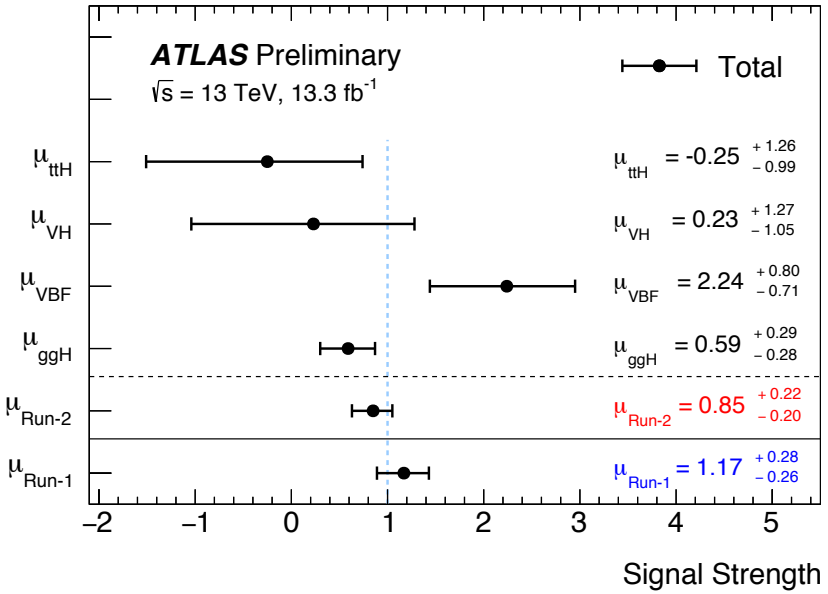
$m_{\gamma\gamma}$ (VBF)



H→γγ

- „Simplified template cross sections“
  Stage 0: add $|y_H| < 2.5$ arxiv:1610.07922

$$\sigma_{ggH} \times \mathcal{B}(H \to \gamma\gamma) = 63\ ^{+30}_{-29}\ \text{fb}$$
$$\sigma_{\text{VBF}} \times \mathcal{B}(H \to \gamma\gamma) = 17.8\ ^{+6.3}_{-5.7}\ \text{fb}$$
$$\sigma_{\text{VHlep}} \times \mathcal{B}(H \to \gamma\gamma) = 1.0\ ^{+2.5}_{-1.9}\ \text{fb}$$
$$\sigma_{\text{VHhad}} \times \mathcal{B}(H \to \gamma\gamma) = -2.3\ ^{+6.8}_{-5.8}\ \text{fb}$$
$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) = -0.3\ ^{+1.4}_{-1.1}\ \text{fb}$$



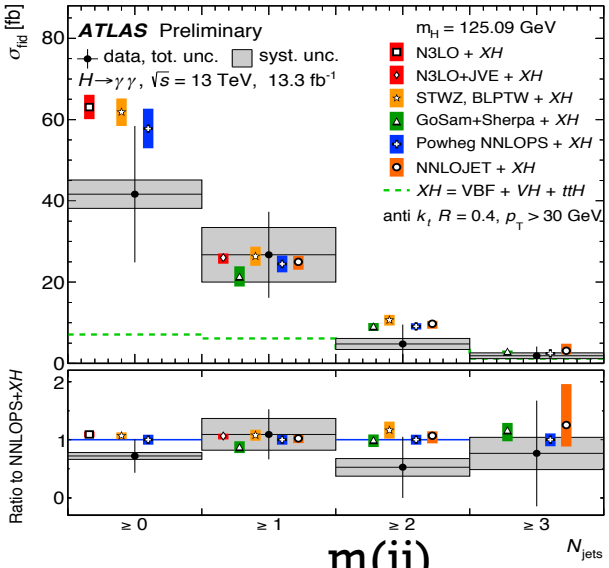
- For each category:
  - Fit N^{sig}
  - Use efficiencies and acceptance corrections to extract cross section x BR

$$N_k^{\text{sig}} = \sum_i \sigma_i \cdot \mathcal{B}(H \to \gamma\gamma) \cdot \epsilon_{ik} \cdot A_{ik} \cdot \int L\,\mathrm{d}t$$

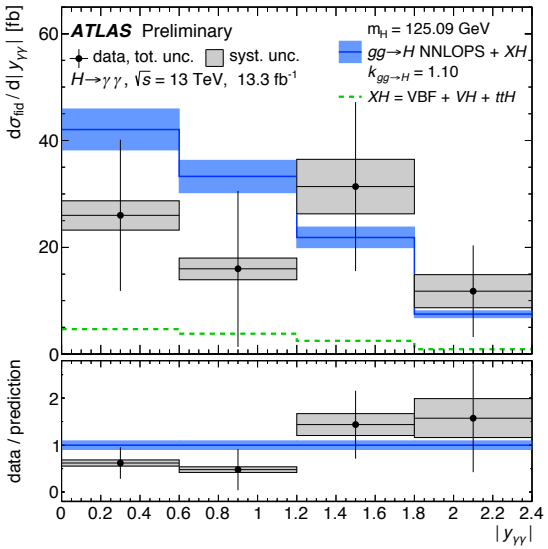
H→γγ

- Not splitting into production modes: Differential cross sections
- Restricted to fiducial region to reduce model dependencies →backup
- 7 variables:
  dN(jet), dy(H), $dp_T(H)$, $d\cos(\theta^*)$
  dm(jj), $dp_T(j1)$, $d\Phi(jj)$
- Limited by data statistics

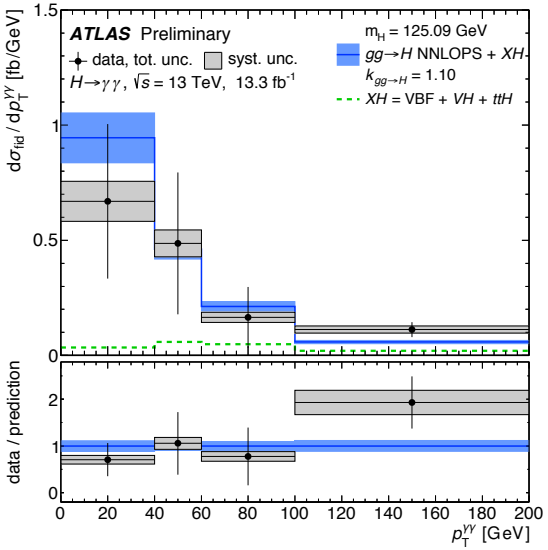
N(jet)



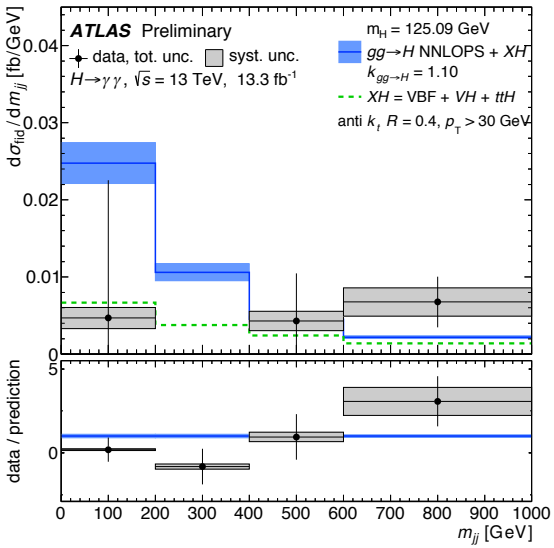
y(H)



$p_T(H)$



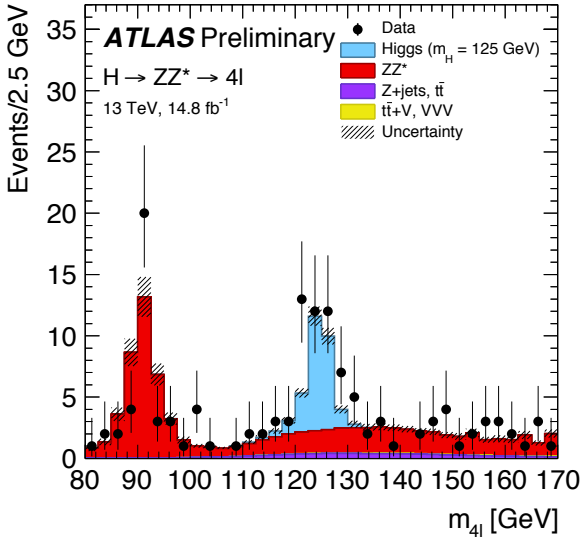
m(jj)

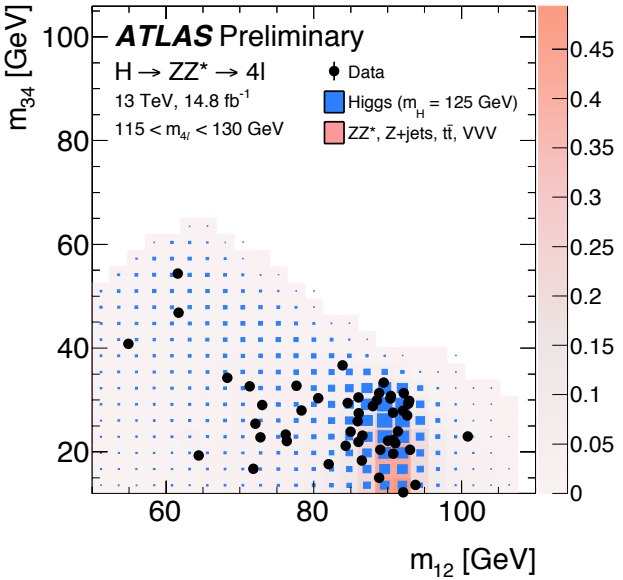


H → ZZ → 4l

- Search for two pairs of oppositely charged leptons
  - Very clean: S/B ≈ 2
  - Mostly ZZ background
- Fiducial cross sections:
  - Total:
    $\sigma^{4\ell}_{\text{fid,sum}} = 4.48^{+1.01}_{-0.89}$ fb SM: 3.1±0.2
  - Per decay channel:

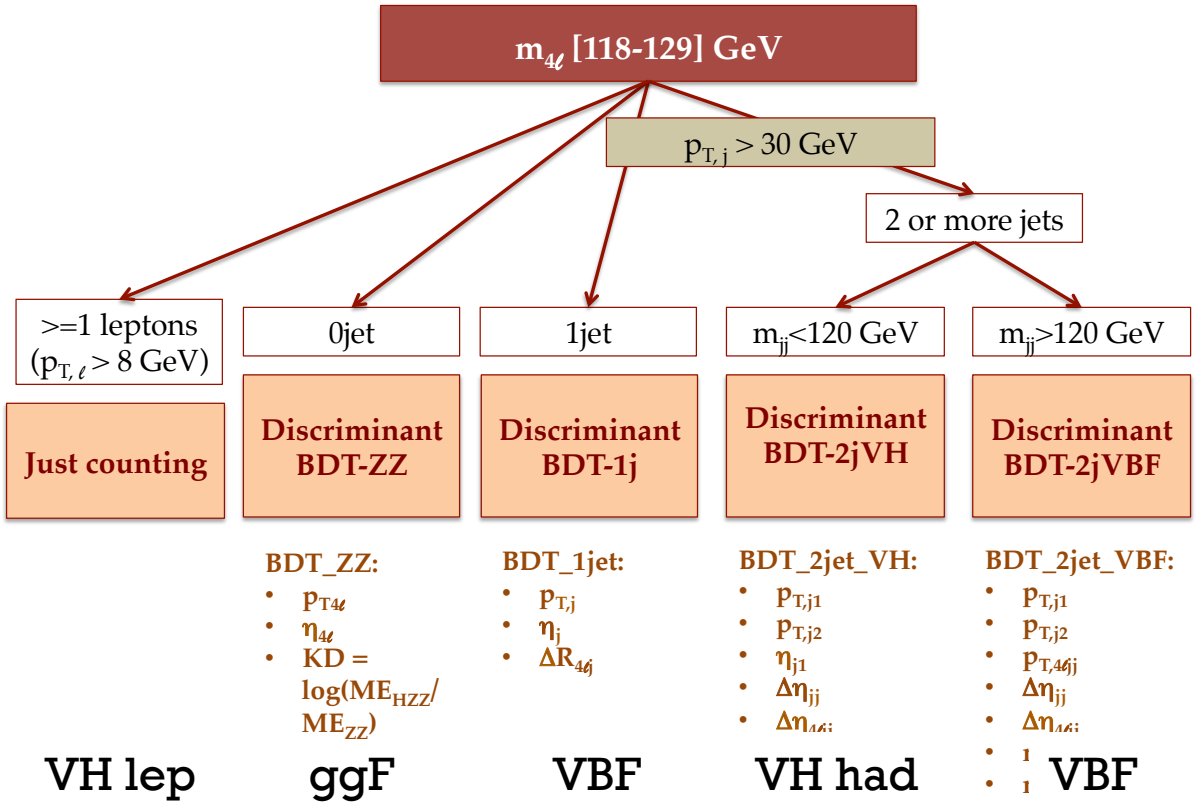
Final state	measured σ_{fid} [fb]	$\sigma_{\text{fid,SM}}$ [fb]
4μ	$1.28\ ^{+0.48}_{-0.40}$	$0.93\ ^{+0.06}_{-0.08}$
$4e$	$0.81\ ^{+0.51}_{-0.38}$	$0.73\ ^{+0.05}_{-0.06}$
$2\mu 2e$	$1.29\ ^{+0.58}_{-0.46}$	$0.67\ ^{+0.04}_{-0.04}$
$2e2\mu$	$1.10\ ^{+0.49}_{-0.40}$	$0.76\ ^{+0.05}_{-0.06}$





H → ZZ → 4l

- Also:
  Cross sections of
  gg / VBF / VH
- Low statistics
  → Train BDTs to select different modes
- Compatibility with SM:
  - ggF: 1.1 σ
  - VBF: 1.4 σ



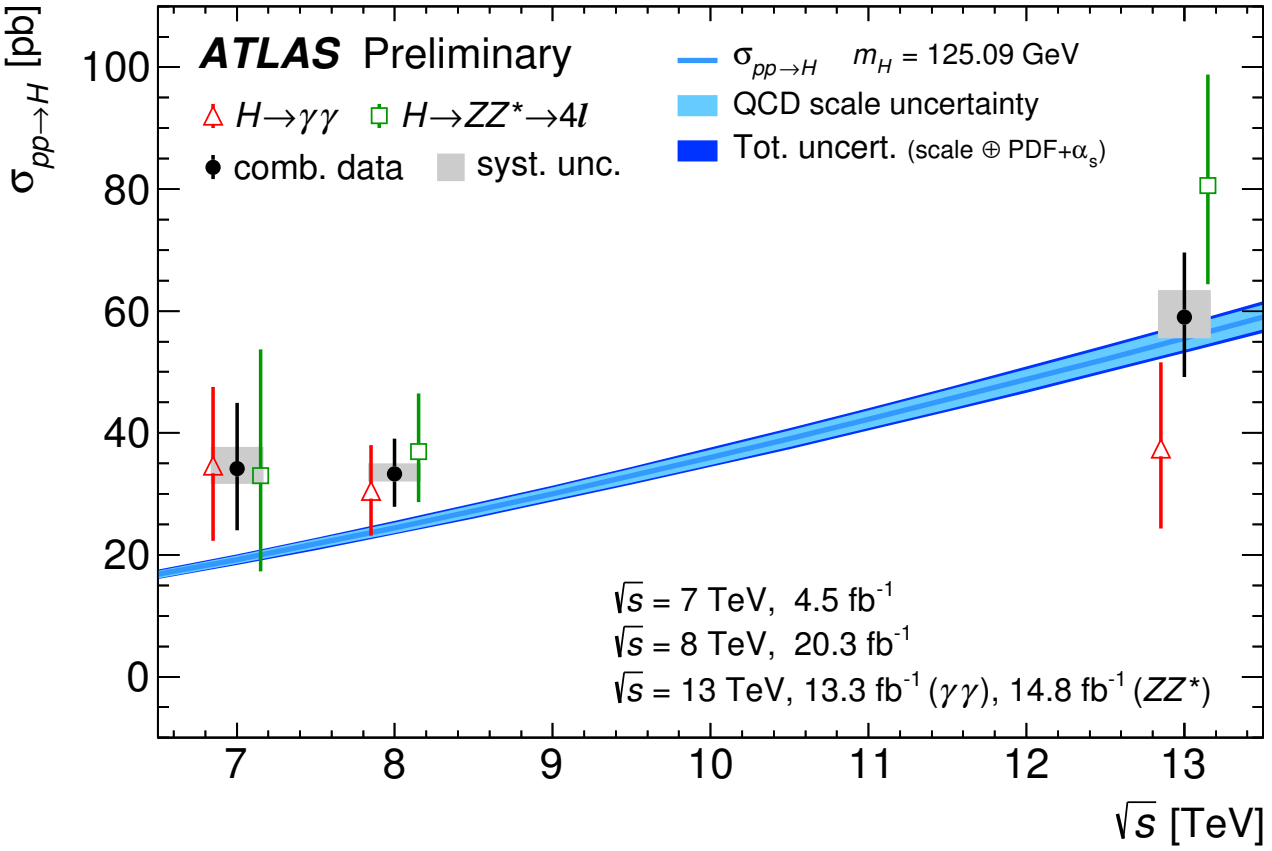
$$\sigma_{\mathrm{ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44}\ \mathrm{pb} \quad \textbf{SM: } 1.31 \pm 0.07\ \mathrm{pb}$$

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \mathrm{pb} \quad 0.100 \pm 0.003\ \mathrm{pb}$$

$$\sigma_{\mathrm{VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \mathrm{pb} \quad 0.059 \pm 0.002\ \mathrm{pb}$$

Combine H → ZZ, H → γγ

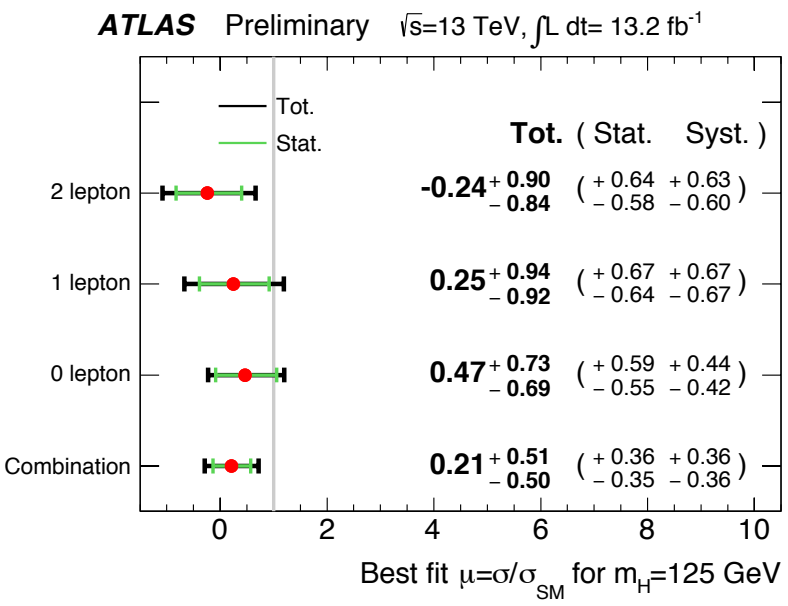
- Full combination (13 TeV)
  - μ = 1.13 ± 0.18
  - Higgs "re-discovered" ~ 10 σ (8.6 exp.)

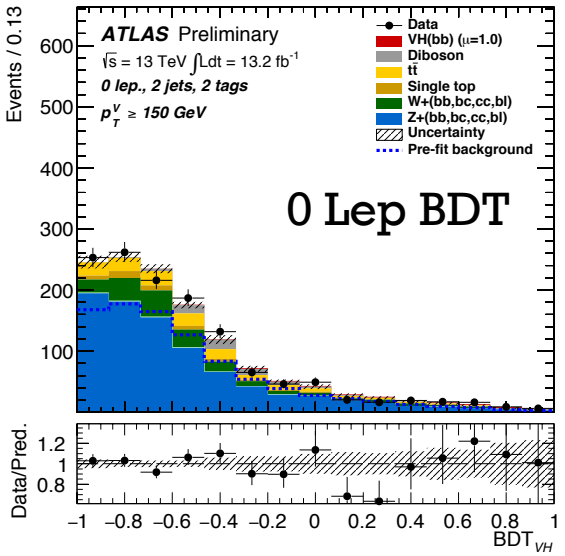


Searches

H → bb

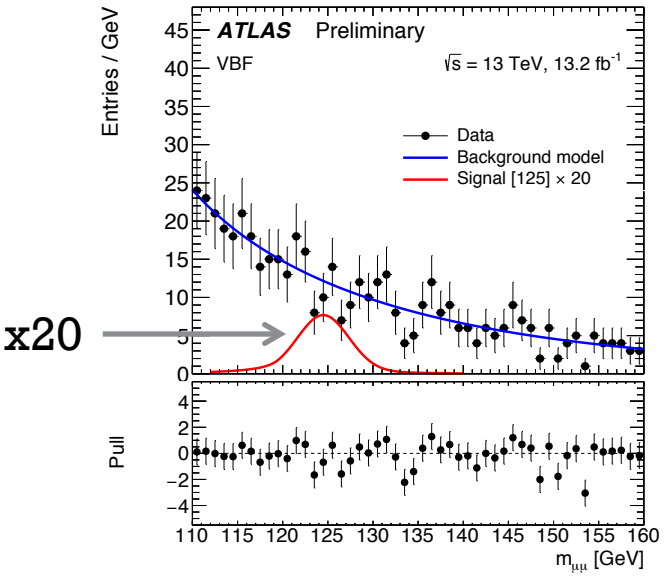
- Highest branching fraction, but not observed so far:
  Run 1, ATLAS+CMS:
  2.6 σ (includes ttH)
- Challenging backgrounds:
  - Focus on VH
    - 0 lep: $Z \rightarrow \nu\nu$
    - 1 lep: $W \rightarrow l\nu$
    - 2 lep: $Z \rightarrow ll$
  - Restrict 0 & 1 lepton to $p_T^V > 150$ GeV
  - Heavy usage of BDTs in all categories
- Higgs: $\mu = 0.2 \pm 0.5$
  - Diboson cross-check: $\mu = 0.9 \pm 0.4$
- Also VBF + γ:
  $\mu = -3.9 \pm 2.8$

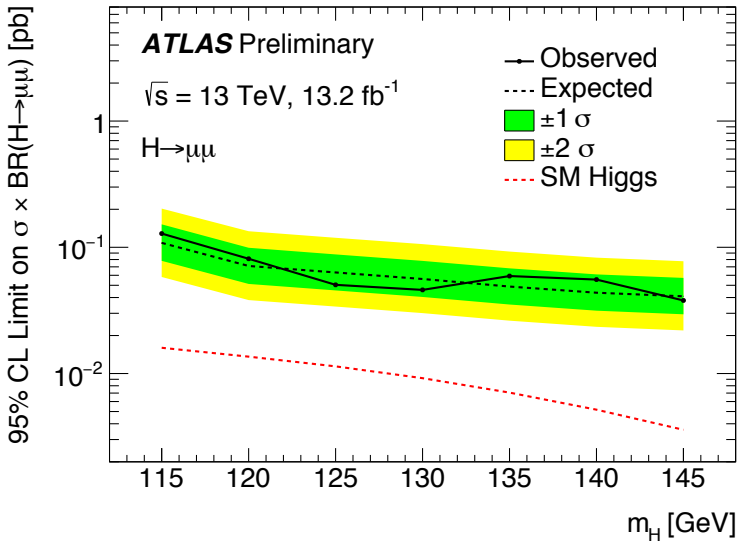




H → μμ

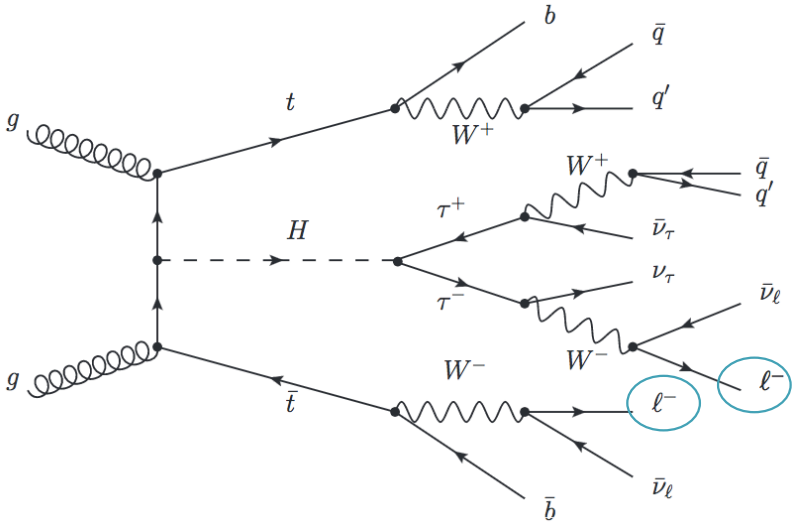
- Challenging:
  - Tiny branching fraction (0.02 %)
  - High Drell-Yan background
- Strategy:
  - Fit $m_{\mu\mu}$ in opposite charge μμ events
  - Several categories for higher sensitivity:
    VBF / $p_T^{\mu\mu}$ / η_μ
- 95 % CL limits on μ (m_H = 125.9 GeV):
  - Run 2: 4.4 (5.5)
  - Run 1+2: 3.5 (4.3)

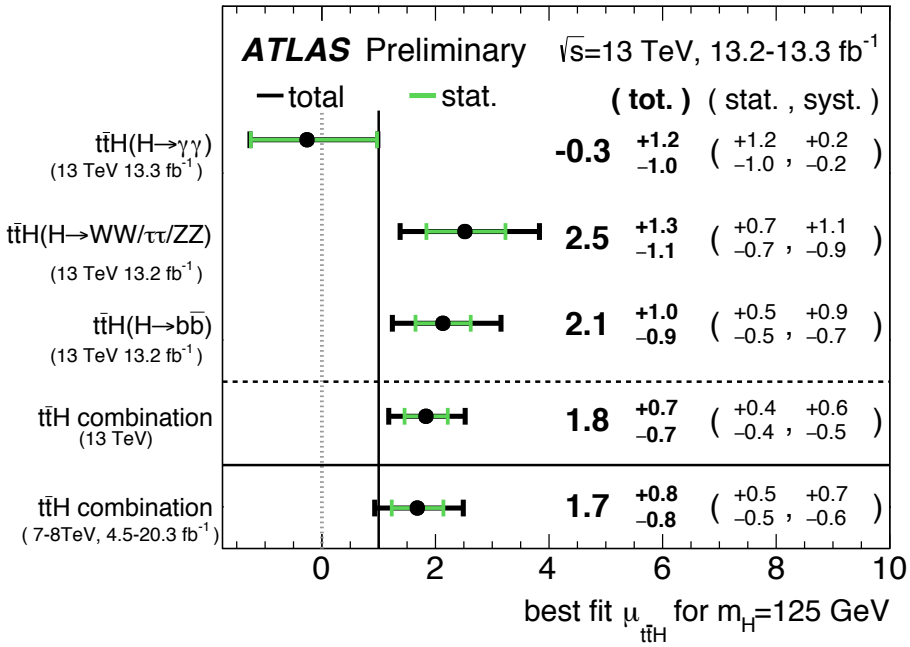




Combination of ttH Measurements

- ttH massively benefits from 13 TeV
  $\sigma_{13\,TeV} = 3.9 \times \sigma_{8\,TeV}$
- But: Challenging final states
- 3 new results:
  - ttH, H→γγ
  - ttH, 2 → 4 lepton final states
    - Mostly H→ WW / ττ (/ ZZ)
  - ttH, H→bb
- Significance:
  - 2.8 σ (exp. 1.8 σ)
  - Run 1: exp. 1.5 σ
- Compatibility of 3 channels: 7%





Summary

- Run 2: First results available
- Cross sections
  - Fiducial
  - Production modes / differential
- Searches: Updates from
  - H→bb: VH, VBF+γ
  - H→μμ
  - ttH
- All consistent with SM
- More to come:
  ~ 33 fb^{-1} "good for physics" in 2016

Overview of Run 2 results from ATLAS

Channel	μ
γγ + ZZ	1.13 ± 0.18
• γγ	0.85 ± 0.22
• ZZ → 4l	1.37 ± 0.40
• γγ + ZZ (VBF)	2.24 ± 0.80
bb	0.21 ± 0.51
μμ	< 4.4 (95 % CL)
ttH (γγ + Multilep + bb)	1.8 ± 0.7
WW (VBF)	1.7 ± 1.1

Backup

H→WW

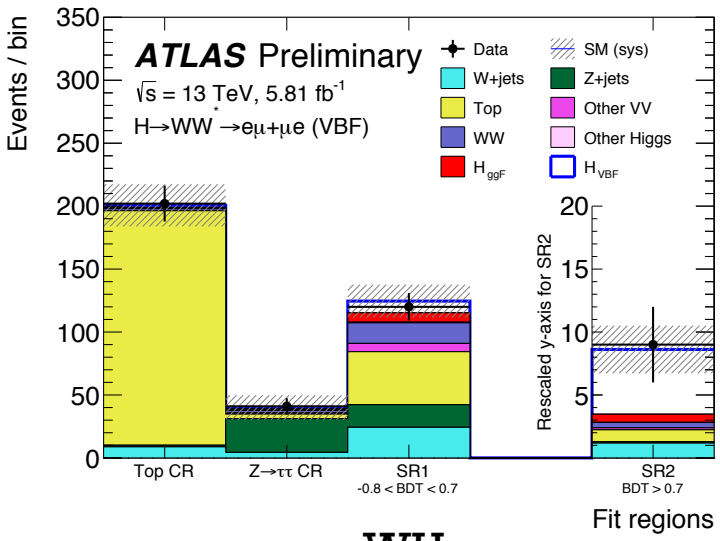
- Relatively small dataset: 5.8 fb^{-1}
- Restrict to distinctive production channels:
  - VBF: 2 leptons + forward jets
  - WH: 3 isolated leptons
- Create signal and background control regions and fit yields
- Results:

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 1.4^{+0.8}_{-0.6}(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{sys})\ \mathrm{pb}$$

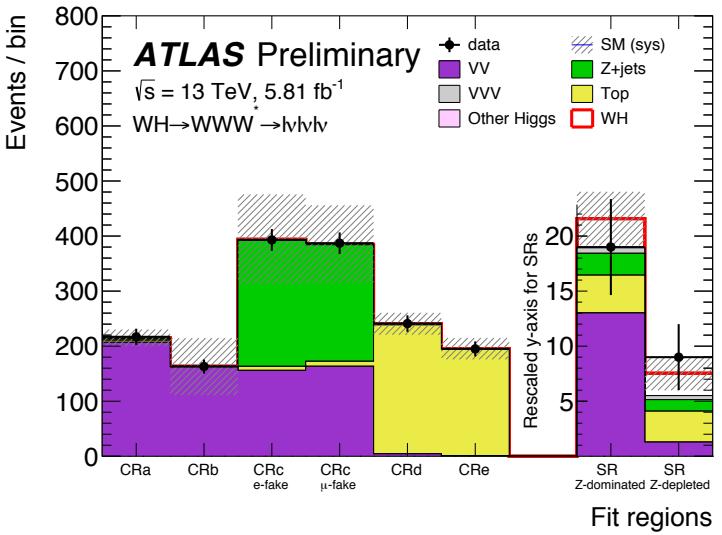
$$\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*} = 0.9^{+1.1}_{-0.9}(\mathrm{stat})^{+0.7}_{-0.8}(\mathrm{sys})\ \mathrm{pb}$$

- SM
  VBF: 0.81 ± 0.02 pb
  WH: 0.293 ± 0.007 pb

VBF



WH

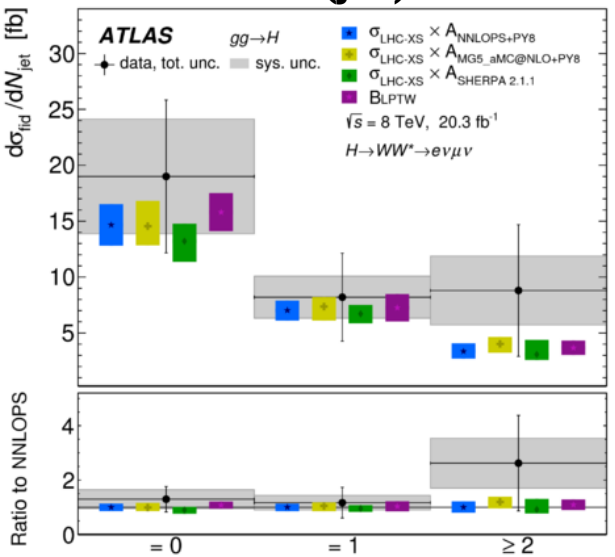


H→WW

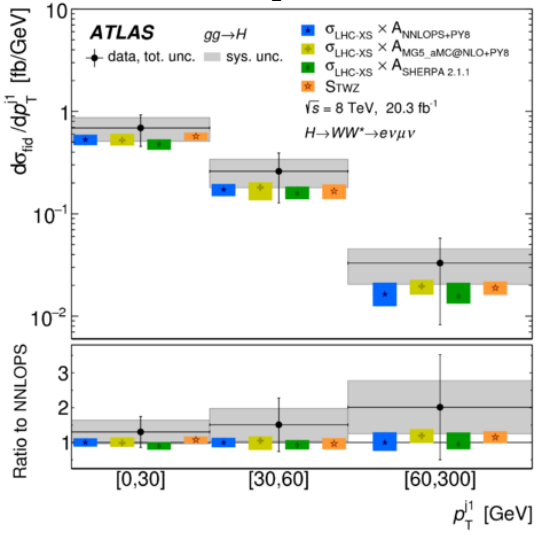
JHEP08 (2016) 104

- Differential cross sections with 8 TeV data
- Restricted to H → WW → eνμν

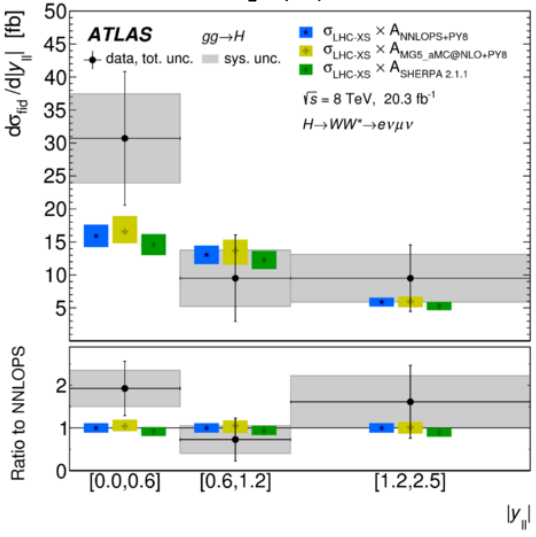
N(jet)



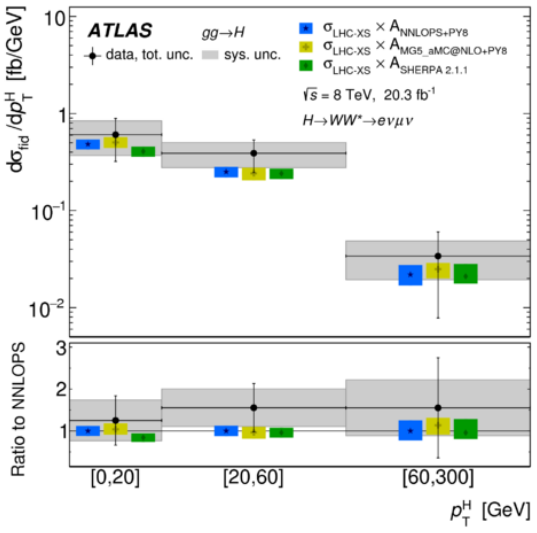
$p_T(j^1)$



y(ll)

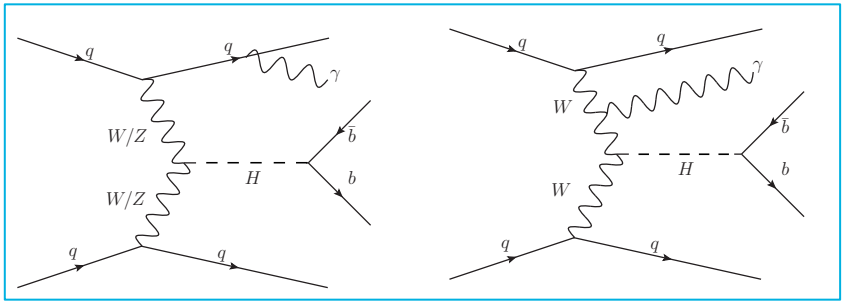


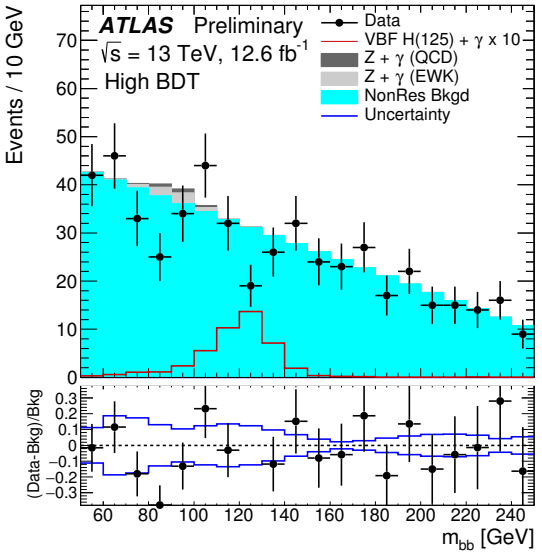
$p_T(H)^{N_{jet}}$

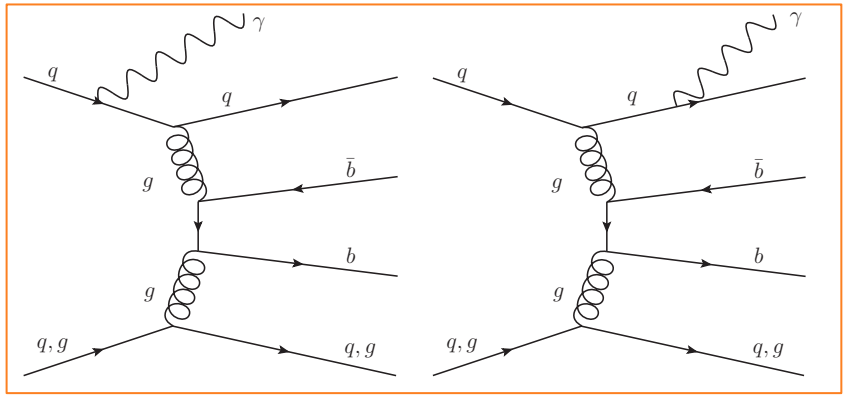


H → bb: VBF with γ

- VBF signature in H→bb: large bbjj backgrounds
  - Run 1: μ = -0.8 ± 2.3 (using MVAs)
- VBF + γ: Better background suppression
  - gg collisions won't radiate γ → VBF production enhanced
  - Destructive interference in qq-induced backgrounds



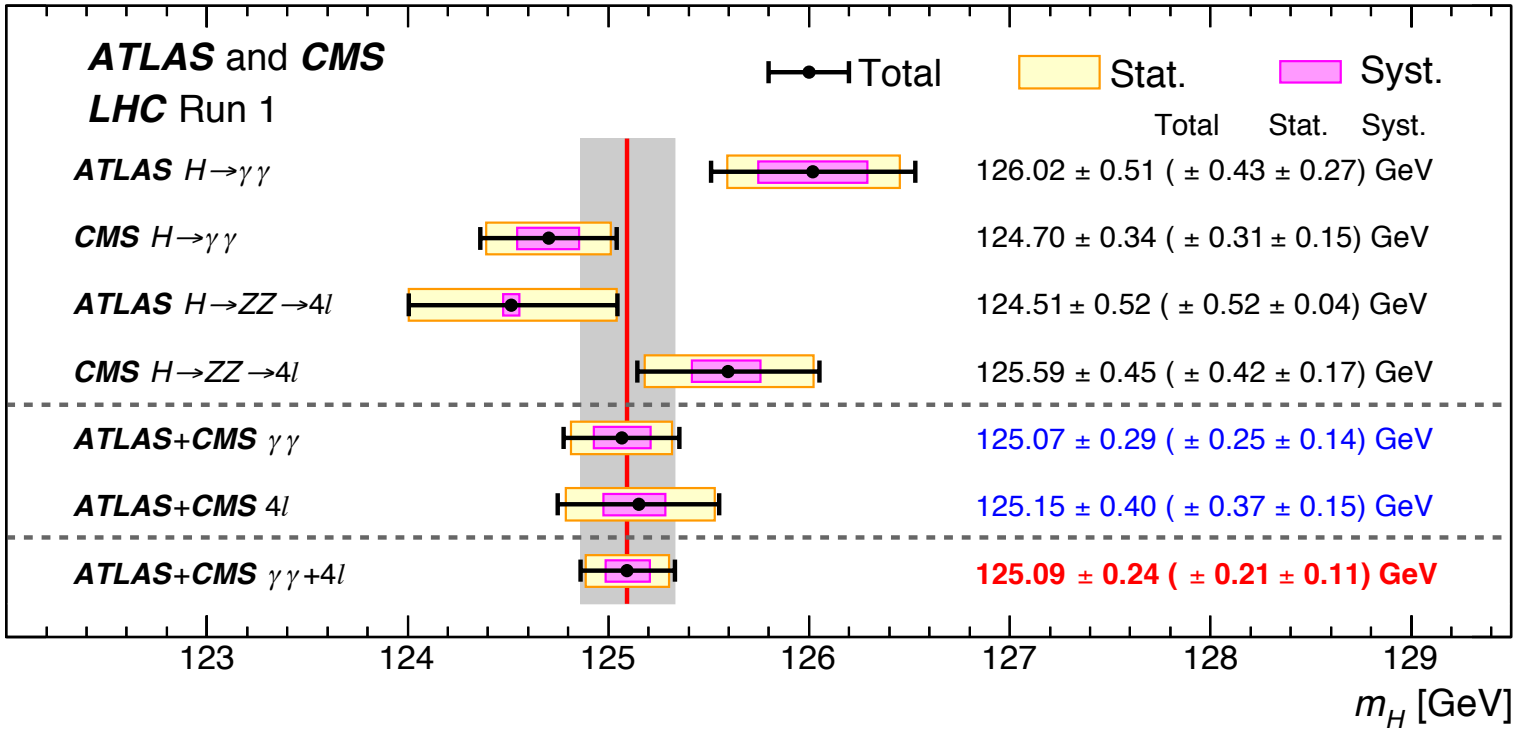




BDT analysis:
μ = -3.9 ± 2.8
- NB: 50% of Run 1 lumi

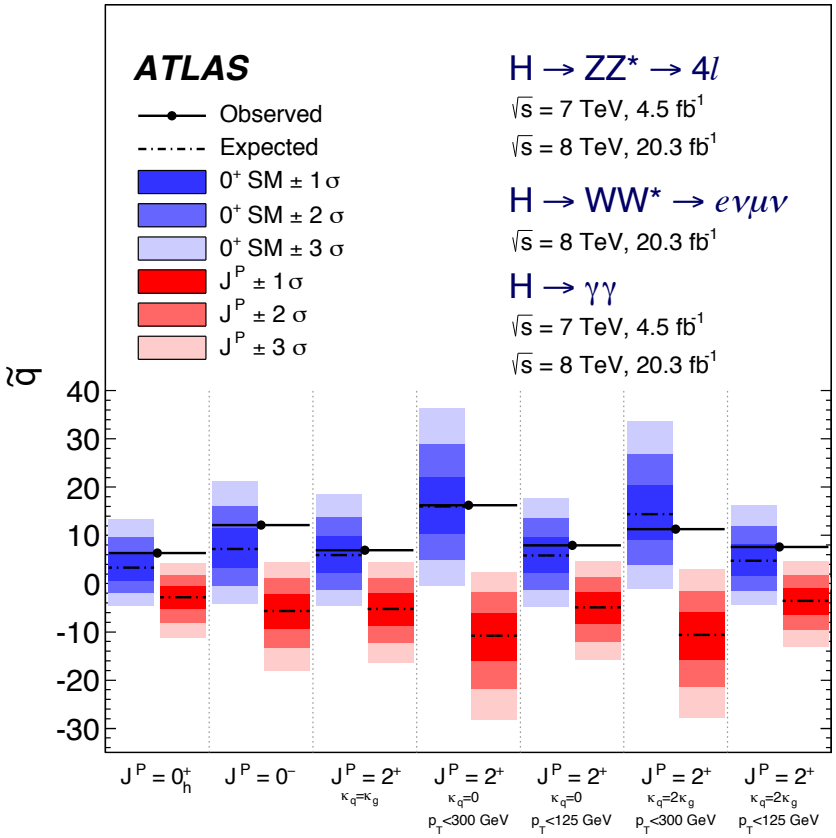
Higgs Mass

- Best measurement by combining ATLAS & CMS Run 1 data
- Limited by statistical uncertainty
- → Update only makes sense with more data



Higgs CP Measurements: Bosons

- Analysis of spin-sensitive observables with 7/8 TeV data
  - H → γγ
  - H → ZZ → 4l
  - H → WW → eνμν
- Pure CP-eigenstate hypotheses:
  - $J^P = 0^+$ (>99.9% CL)
- Also test admixture of BSM terms in HVV interactions:
  - Compatible with no admixture



Coupling ratio	Best-fit value	95 % CL exclusion regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\mathrm{SM}}$	−0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\mathrm{SM}}) \cdot \tan\alpha$	−0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

Fiducial Cross Sections: H→γγ

ATLAS-CONF-2016-067

	diphoton baseline	VBF enhanced	single lepton
Photons	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$ $p_{\mathrm{T}}^{\gamma_1} > 0.35\, m_{\gamma\gamma}$ and $p_{\mathrm{T}}^{\gamma_2} > 0.25\, m_{\gamma\gamma}$		
Jets	- - -	$p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\|y\| < 4.4$ $m_{jj} > 400\,\mathrm{GeV}$, $\|\Delta y_{jj}\| > 2.8$ $\|\Delta\phi_{\gamma\gamma,jj}\| > 2.6$	- - -
Leptons	-	-	$p_{\mathrm{T}} > 15\,\mathrm{GeV}$ $\|\eta\| < 2.47$

Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	$43.2 \pm 14.9\,(\mathrm{stat.}) \pm 4.9\,(\mathrm{syst.})$	$62.8\,^{+3.4}_{-4.4}$	[N^{3}LO + XH]
VBF-enhanced	$4.0 \pm 1.4\,(\mathrm{stat.}) \pm 0.7\,(\mathrm{syst.})$	2.04 ± 0.13	[NNLOPS + XH]
single lepton	$1.5 \pm 0.8\,(\mathrm{stat.}) \pm 0.2\,(\mathrm{syst.})$	0.56 ± 0.03	[NNLOPS + XH]

Fiducial Cross Sections: H→ZZ

ATLAS-CONF-2016-079

Lepton definition	
Muons: $p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.7$	Electrons: $p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection	
Lepton kinematics:	Leading leptons $p_{\mathrm{T}} > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same(opposite)-flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115 < m_{4\ell} < 130$ GeV

Diboson CP Measurements

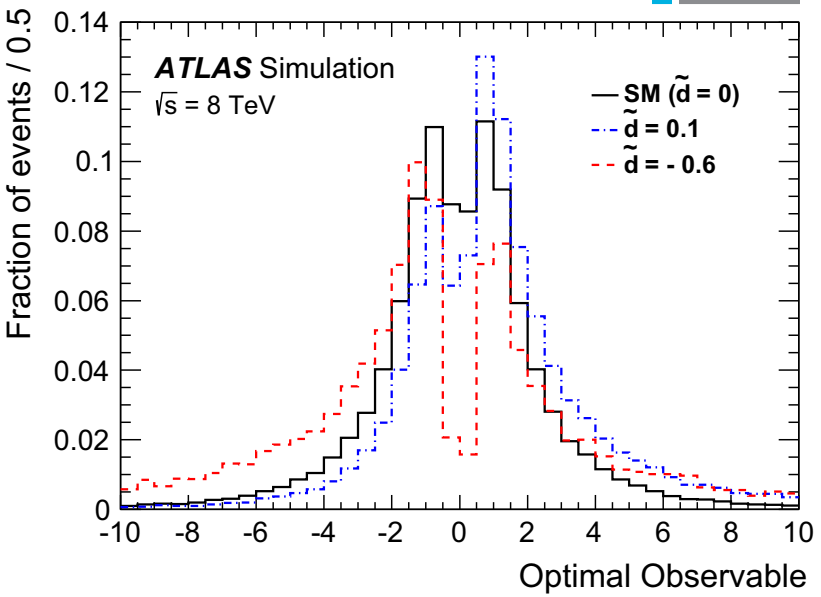
- Probe possible admixture of BSM spin-0 states to SM 0^+
- Use effective field theory interaction Lagrangian

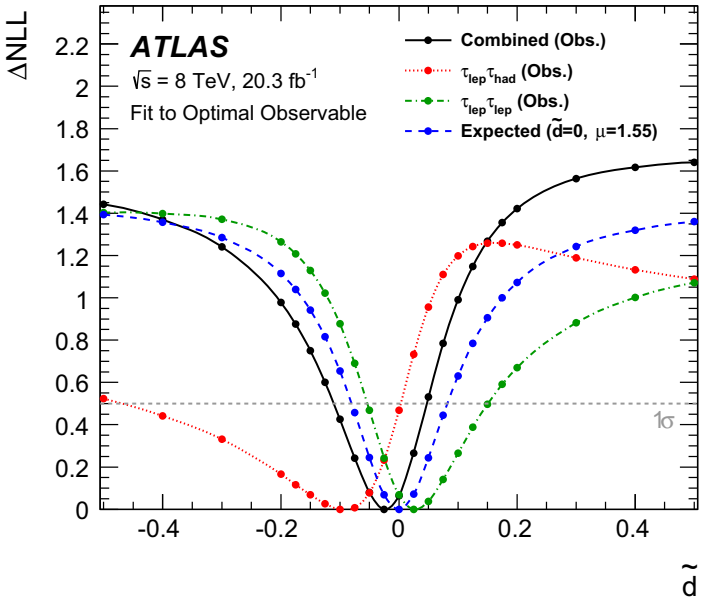
$$\begin{aligned}\mathcal{L}_0^V = \Big\{ & \cos(\alpha)\kappa_{\rm SM}\left[\frac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+ W^{-\mu}\right] \\ & -\frac{1}{4}\frac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & -\frac{1}{2}\frac{1}{\Lambda}\Big[\cos(\alpha)\kappa_{HWW}W_{\mu\nu}^+ W^{-\mu\nu} \\ & + \sin(\alpha)\kappa_{AWW}W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\Big]\Big\} X_0. \end{aligned} \quad (1)$$

J^P	Model	Values of tensor couplings			
		$\kappa_{\rm SM}$	κ_{HVV}	κ_{AVV}	α
0^+	SM Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

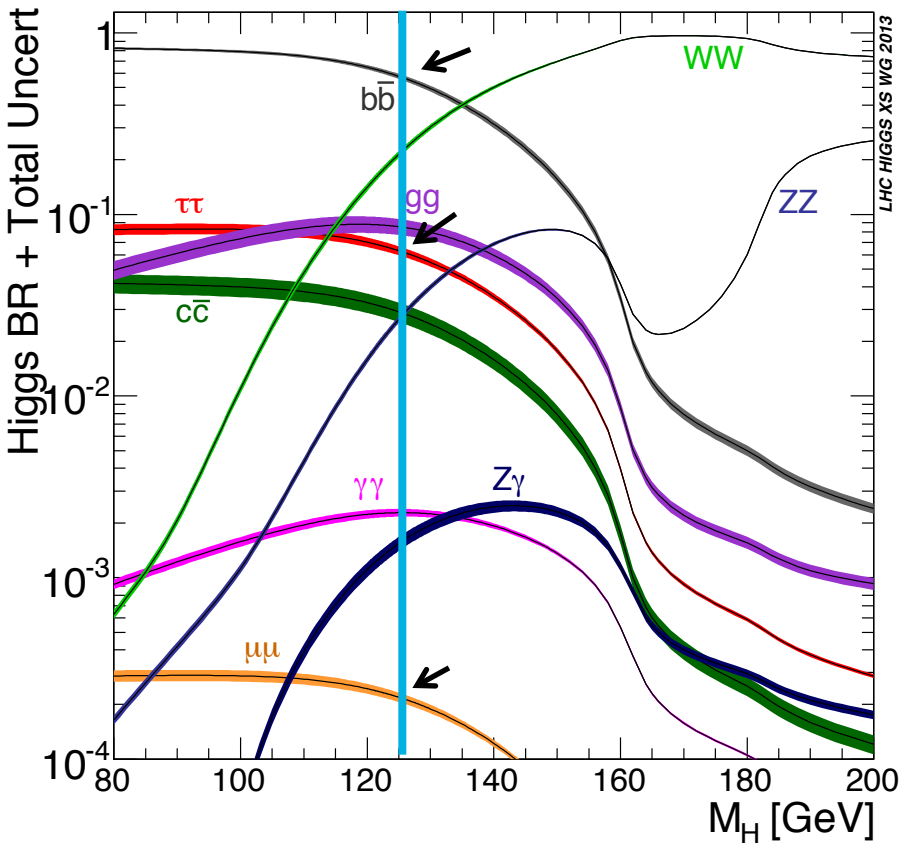
Higgs CP Measurements: VBF & ττ

- Test CP invariance in VBF production: ττ very sensitive
- Closely follows 8 TeV H→ττ analysis
- Add CP-violating contribution to SM matrix element:
  $\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}}$
- Interference term is CP-odd:
  $|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$
- Yields "optimal observable":
  $\mathcal{OO} = \frac{2\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$
- No sign of CP violation:
  $-0.11 < \tilde{d} < 0.05$ (68% CL)





Higgs Branching Fractions



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG