Measurement of the Higgs boson properties with the ATLAS experiment

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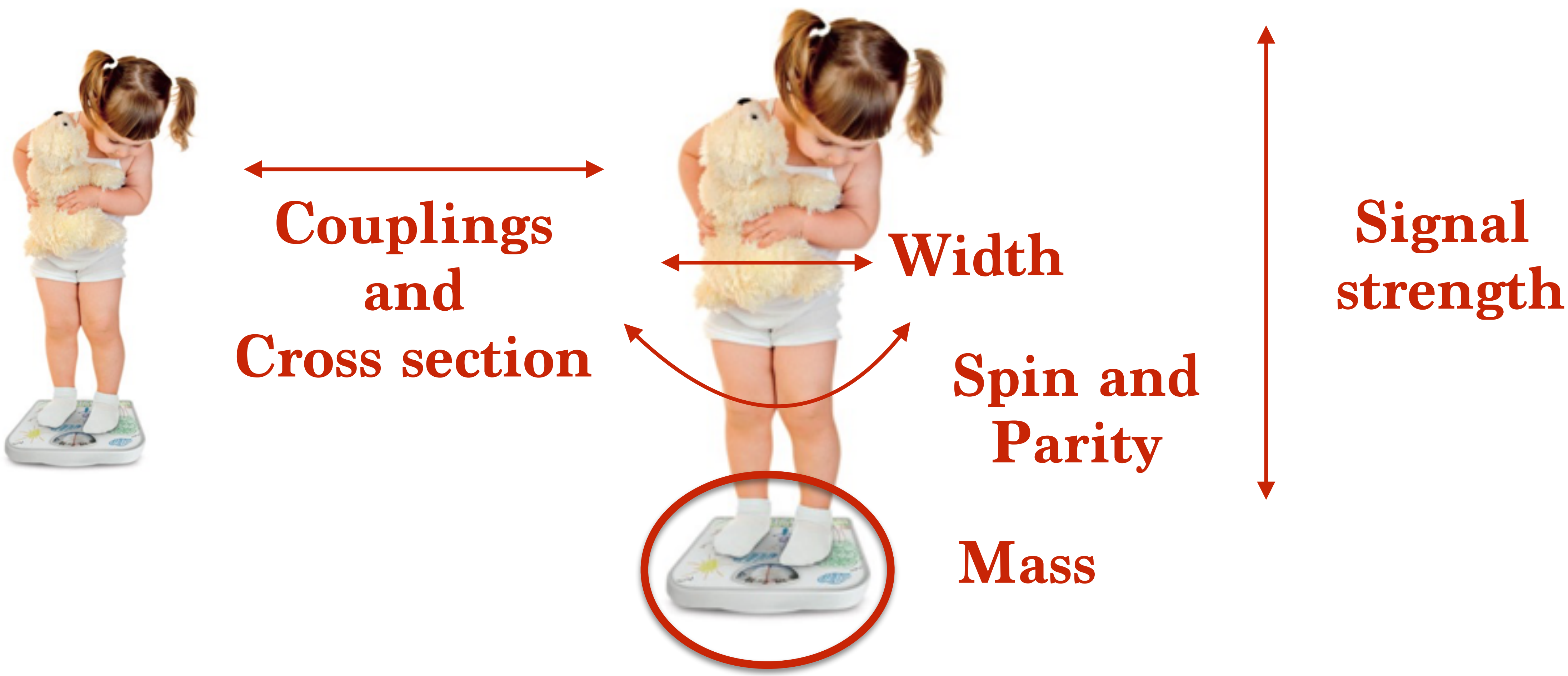
Introduction

In 2012, the ATLAS collaboration reported the discovery of a resonance compatible with the Higgs boson, as predicted by the Standard Model, at a mass around 125 GeV.

Results with the full Run1 dataset (25 fb^{-1} at $\sqrt{s}$ = 7 and 8 TeV) on the properties of the new resonance will be presented here, for the individual decay channels and their combination.



Latest/final ATLAS results for Run1

- **Mass**:
  - Measurement of the Higgs boson mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels with the ATLAS detector at the LHC [Phys.Rev. D90, 052004 (2014)]

- **Spin and Parity**:
  - Combination of the Higgs boson spin and parity analyses of the Higgs boson in the $H \to ZZ^* \to 4\ell$, $H \to WW^* \to \ell\nu\ell\nu$ and $H \to \gamma\gamma$ final states [ATLAS-CONF-2015-008]

- **Couplings**:
  - Measurements of the Higgs boson production and decay rates and couplings using *pp* collisions data at $\sqrt{s}$ = 7 and 8 TeV in the ATLAS experiment [ATLAS-CONF-2015-007]

- **Off-Shell Width**:
  - Determination of the off-shell Higgs boson signal strength in the high-mass *ZZ* and *WW* final states with the ATLAS detector [arXiv:1503.01060]

- **Total and differential cross section**:
  - Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ Decay Channels at $\sqrt{s}$ = 8 TeV with the ATLAS Detector [arXiv:1504.05833]

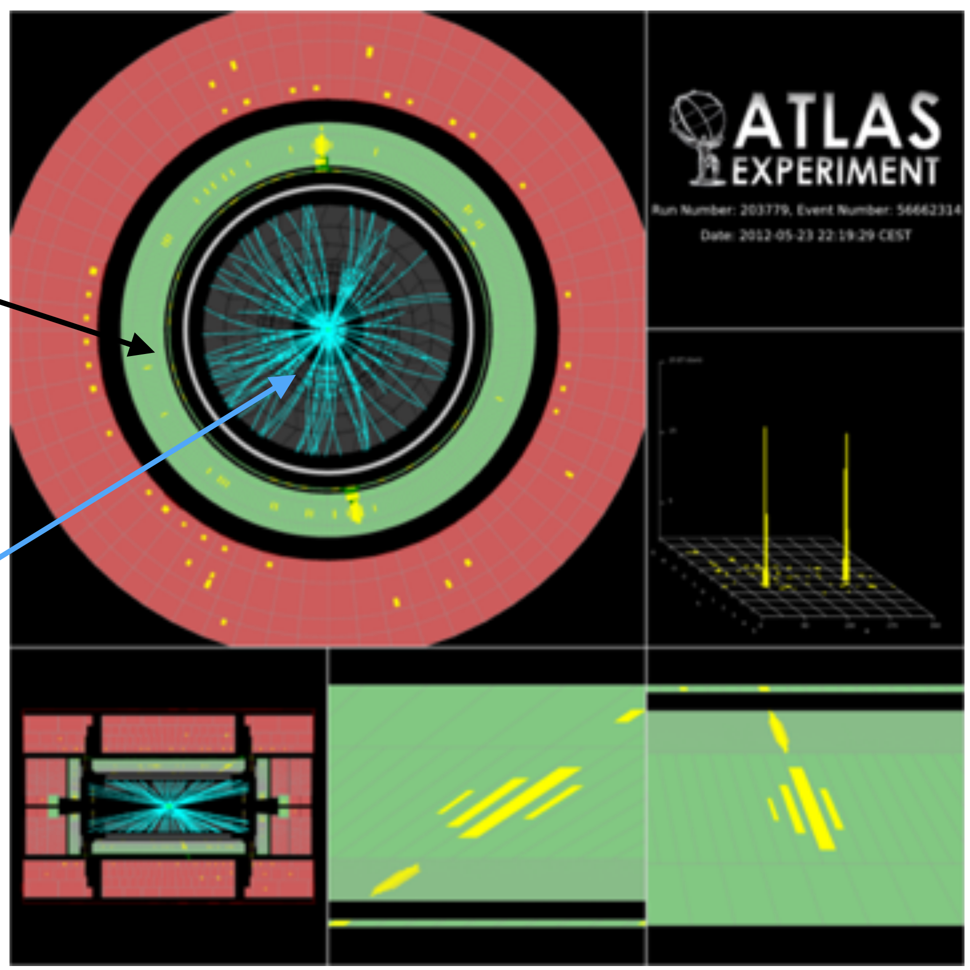
Mass Results

Mass measurement approach

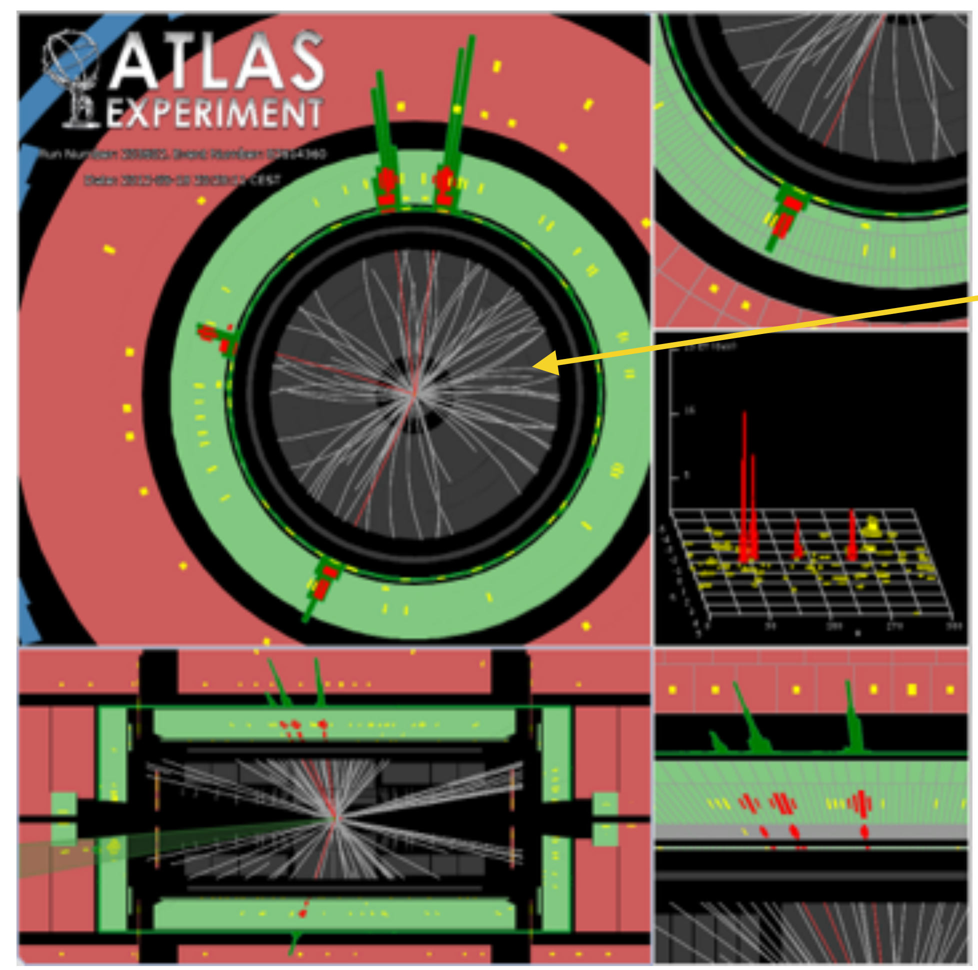
- Model-independent measurement
  - fit the spectra of the reconstructed invariant masses, without assumptions on signal production and decay yields
- Narrow peak expected in both channels (1.6 - 2 GeV resolution), over a smoothly falling background
- Final Run1 results (25 fb^{-1} $\sqrt{s}$ = 7+8 TeV) improve with respect to previous publications on electron and photon calibration, muon momentum scale uncertainty, event categorisation

EM calorimeter

Primary vertex



Two unconverted photons, m = 126.9 GeV

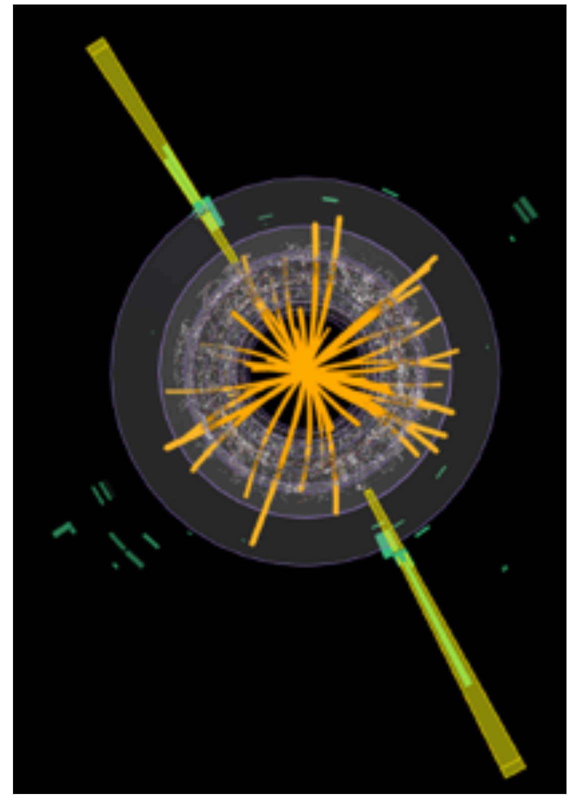


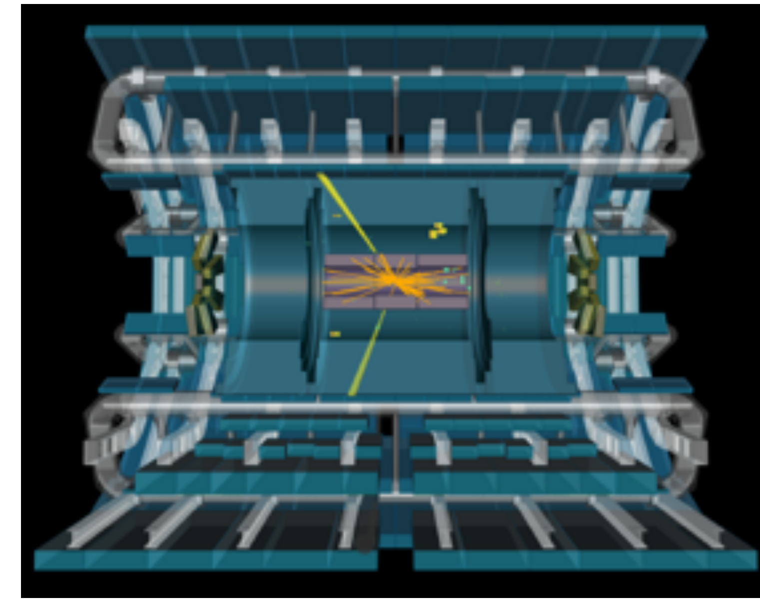
Tracks in the Inner Detector

Four electrons, m = 124.6 GeV

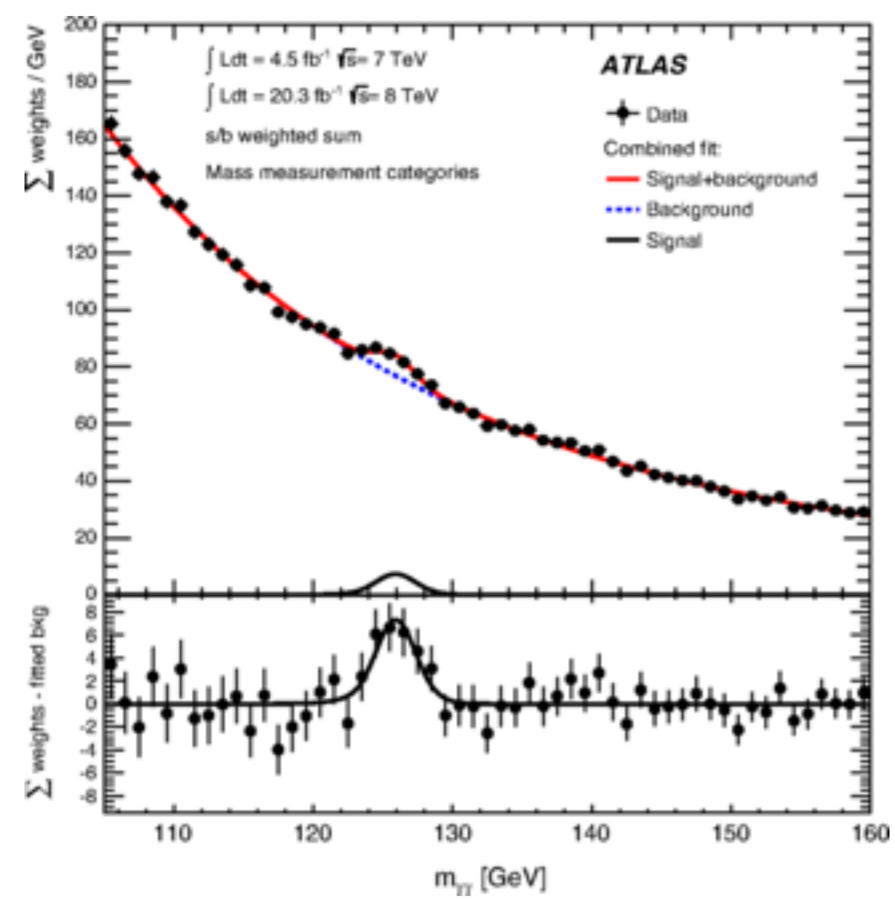
$H \rightarrow \gamma\gamma$

- Excellent identification and measurement (energy, direction) of photons thanks to the design of the EM calorimeter





- Selection:
  - Two photons in $|\eta| < 2.37$
    - $p_T > 20$ GeV (7 TeV data)
    - $p_T > 25, 35$ GeV (8 TeV)
  - Tight identification criteria (shower shape), isolation, association with primary vertex
  - Further cuts on the diphoton E_T
  - Mass window (105,160) GeV

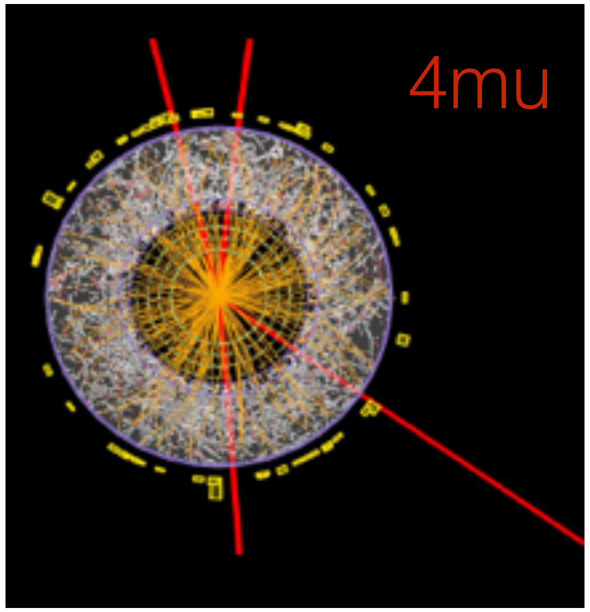


- 95k (17k) candidates in 8(7) TeV data, split into ten categories:
  - converted/unconverted x p_T criteria x η range
  - maximising S/B ratio and mass resolution
- <u>Signal model: Crystal Ball for the bulk + wide Gaussian for the tails</u>
- <u>Background (mostly irreducible SM $\gamma\gamma$) model: fit to data</u>

- <u>Combined fit to the ten categories</u>, in the S+B hypothesis
- Mass and signal strength (assuming gluon fusion only) are treated as parameters of interest

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

- High S/B ratio in this channel (~2 in the mass window 120 - 130 GeV), despite the low statistics, and excellent mass resolution
- *4μ* (1.6 GeV mass resolution), *4e* (2.2 GeV), *2μ2e*, *2e2μ*

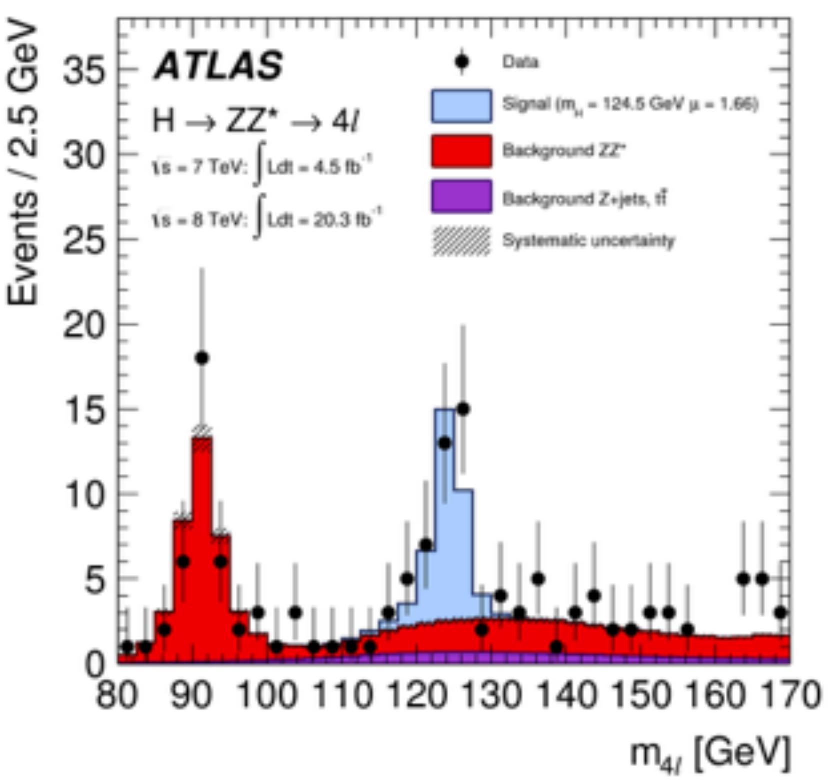


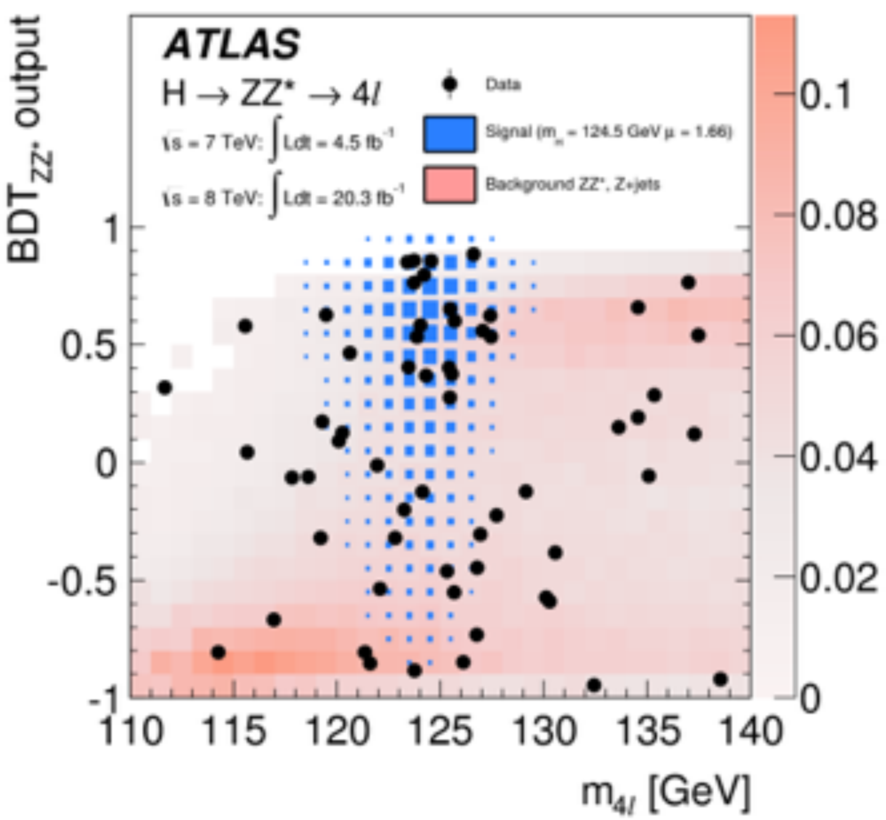
- Selection:
  - Four leptons, quality criteria applied
  - Muons in |η| < 2.7, electrons is |η| < 2.47
  - p_T > 20, 15, 10, 6 (7 if electron) GeV
  - Invariant masses of same-sign pairs must be close to *Z* mass

- Data-driven estimations for the backgrounds
- **BDT** discriminant trained against the irreducible *ZZ** background, input variables:
  - p_T and eta of 4ℓ system
  - **Matrix Element discriminant**

$$D_{ZZ^*} = \ln\left(\frac{|\mathcal{M}_{sig}|^2}{|\mathcal{M}_{ZZ}|^2}\right)$$

- Combined fit to (BDT, m(4ℓ)) in the mass window (110,140) GeV





Individual and combined results

Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ$llll	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

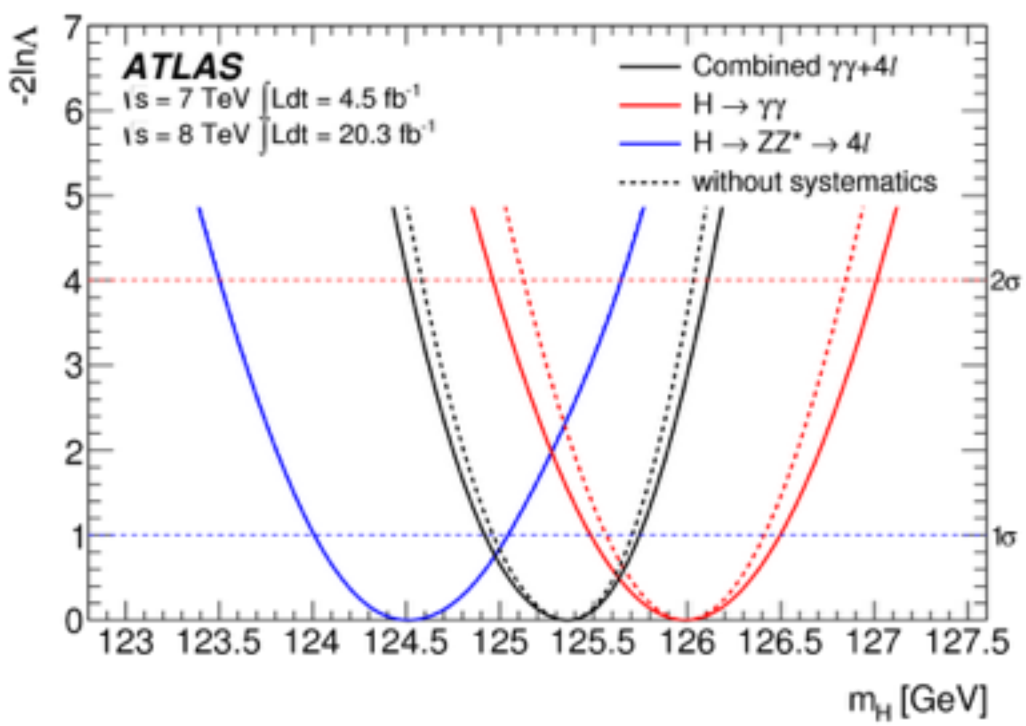
Signal strength (in terms of σ	Width (GeV) at 95% C.L.
1.29 ± 0.30	Γ (expected 4.2)
1.66	Γ (expected 3.5)

$$\Delta m_H = 1.47 \pm 0.67\,(\text{stat}) \pm 0.28\,(\text{syst})\ \text{GeV}$$
$$= 1.47 \pm 0.72\ \text{GeV}$$

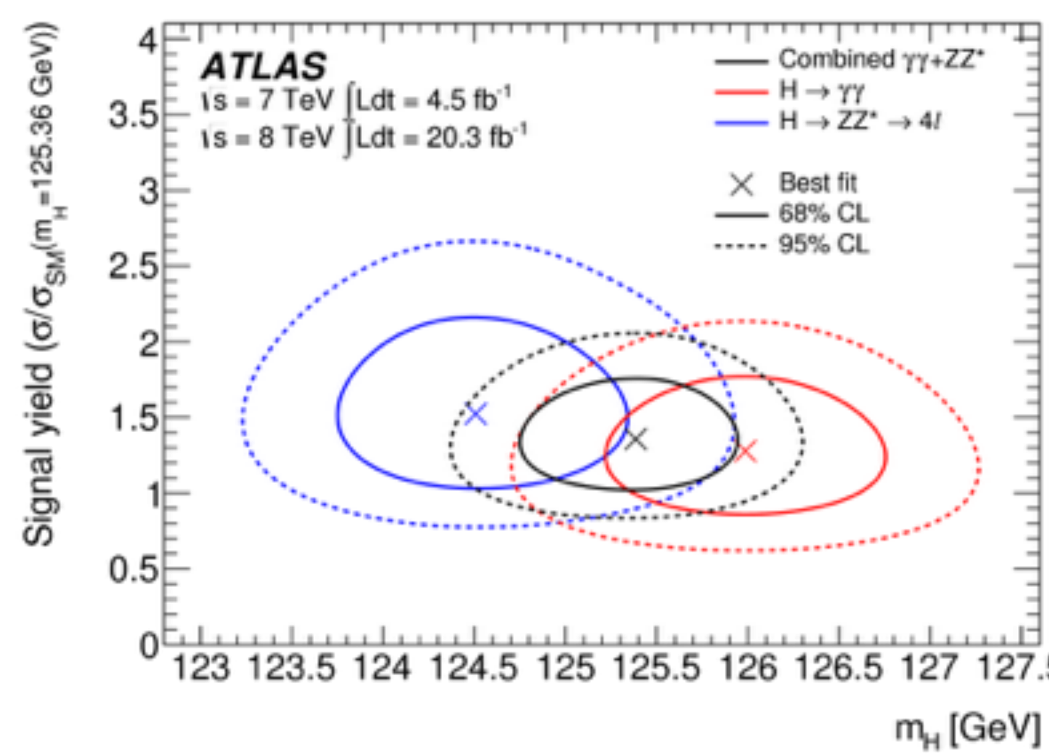
compatible with 0 in 1.97σ

Profile likelihood ratio, treating mu(4ℓ) and mu($\gamma\gamma$) as independent nuisance parameters:

$$\Lambda(m_H) = \frac{L(m_H\,,\,\hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(m_H)\,,\,\hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\theta})}$$



Mass measurement uncorrelated to the signal yield:



Combination of signal strengths and couplings

The Kappa Framework

Assumptions

Handbook of LHC Higgs Cross Sections: 3. Higgs Properties [arXiv:1307.1347]

- All observed signals originate from a single, narrow resonance
  - due to the narrow-width approximation, production and decay factorise
- The tensor structure is the one predicted by the SM, $J^{PC}=0^{++}$
- Also assuming SM production and decay kinematics
- The production/rate decay can vary, according to the signal strength $$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{obs}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$
- The couplings can also vary, according to $$g_{Hii} \to \kappa_i \cdot g_{Hii}$$

Thus in general:

$$\sigma \cdot \mathrm{BR}(i \to H \to f) = \frac{\sigma_i^{\mathrm{SM}} \cdot \Gamma_f^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}} \cdot \frac{\kappa_i^2 \kappa_f^2}{\kappa_{\mathrm{H}}^2}$$

- Combine all available channels using a simultaneous maximum likelihood fit with the following test statistic (in the asymptotic approximation):

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}_\alpha)}{L(\hat{\alpha}, \hat{\theta})}$$

Parameters of interest can be **μ, m_H, k and their ratios λ**

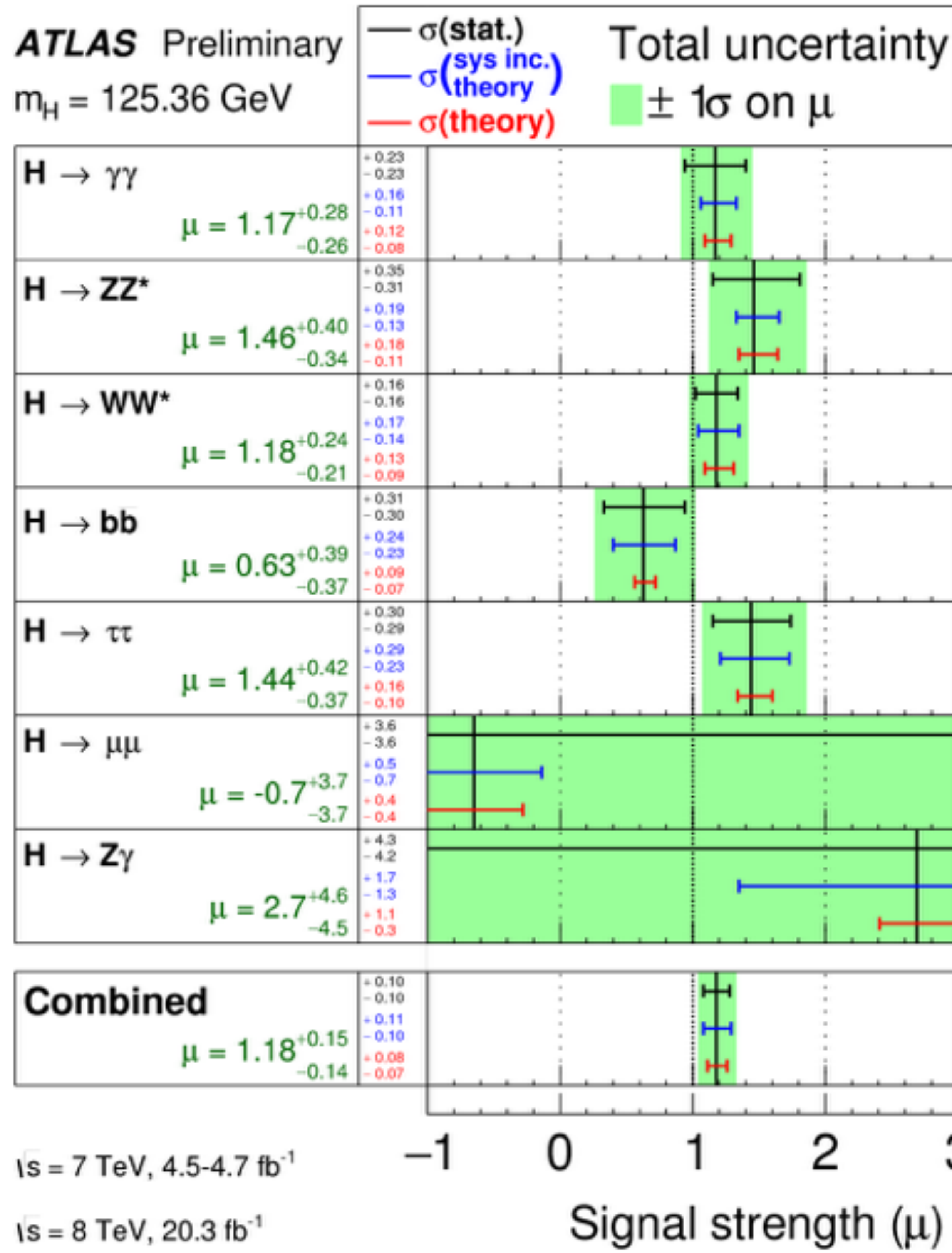
Nuisance parameters are the systematic uncertainties, correlated among all analyses

Combined signal strengths

Combined result at m_H = 125.36 GeV:

$$\mu = 1.18\,^{+0.15}_{-0.14} = 1.18 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{expt.})\,^{+0.08}_{-0.07}\,(\text{theo.})$$

fixed →



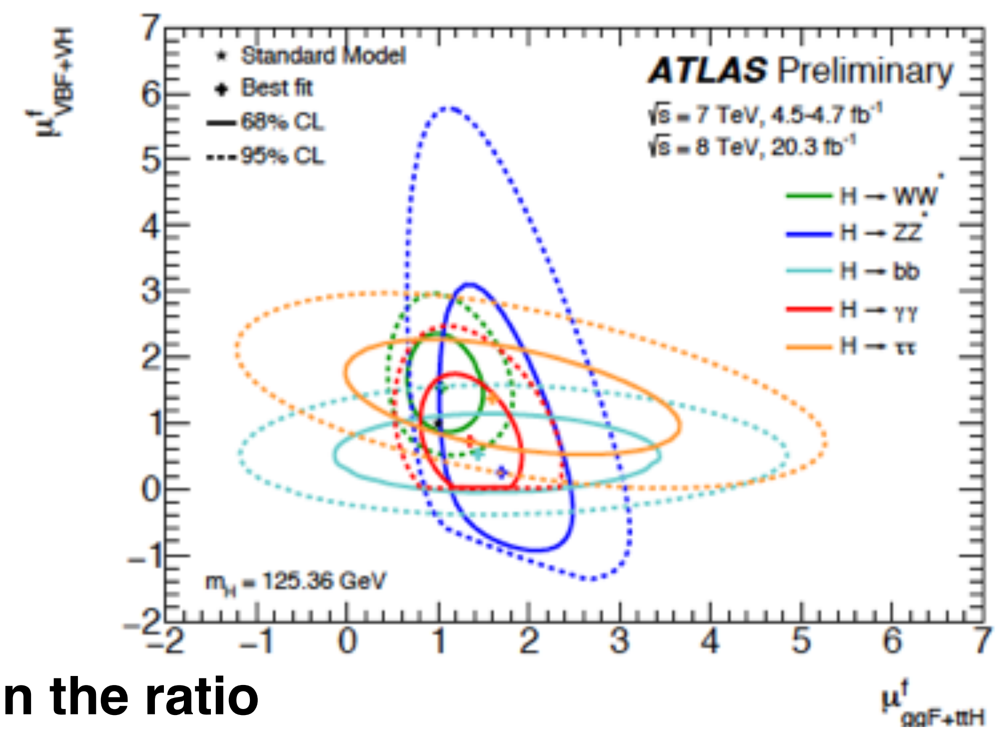
- **compatibility with SM (μ=1): p-value = 18%**
- **compatibility with a single narrow resonance: p-value = 76%**
- main theoretical uncertainties are on SM production cross section and decay branching ratios - at the level of our experimental precision

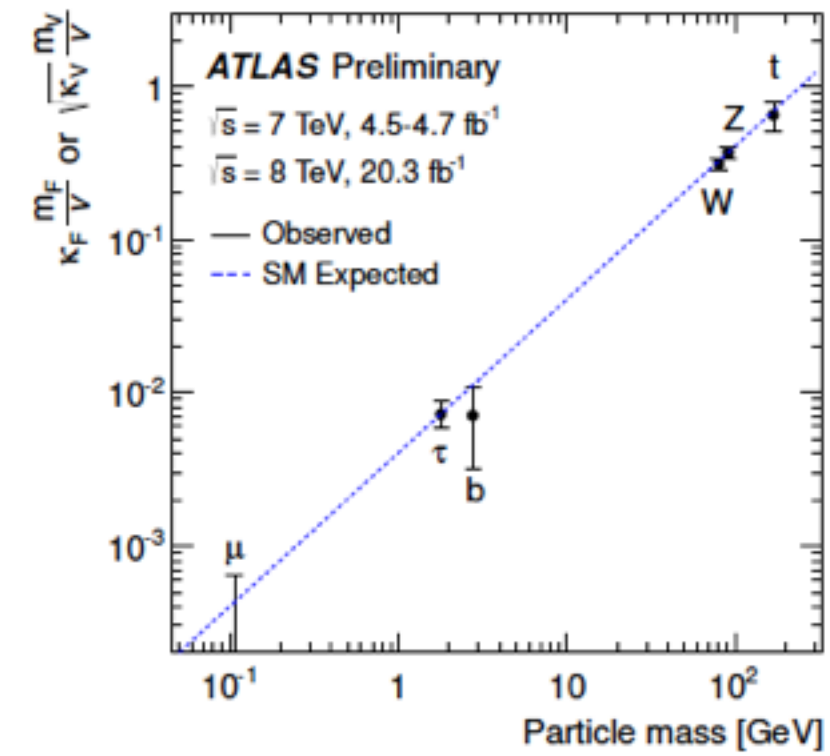
Combined results on couplings

Many interesting results in several different scenarios, just a few examples here

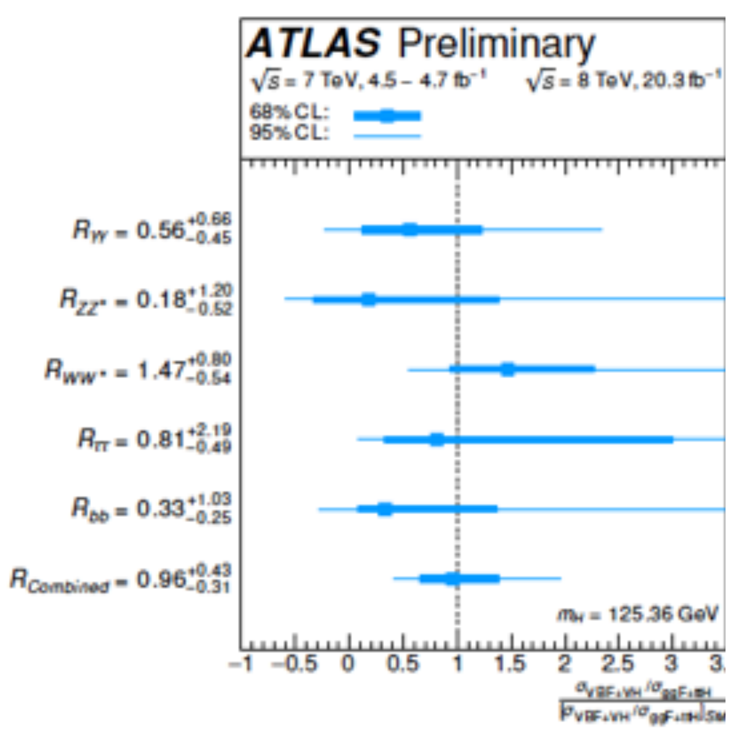
Production mechanism: Higgs coupling to fermions (ggf, ttH) or vector bosons (VBF, VH)

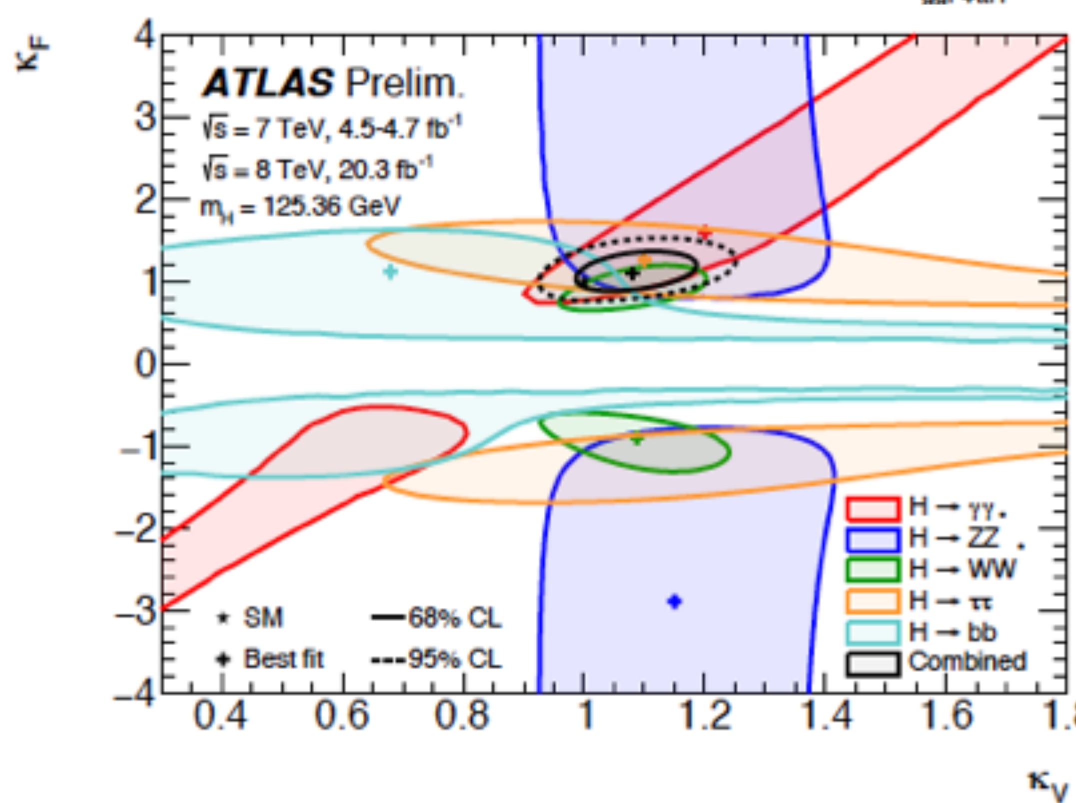
$$\mu_{\mathrm{ggH,ttH}} = \mu_{\mathrm{ggH}} = \mu_{\mathrm{ttH}}$$
$$\mu_{\mathrm{VBF,VH}} = \mu_{\mathrm{VBF}} = \mu_{\mathrm{VH}}$$



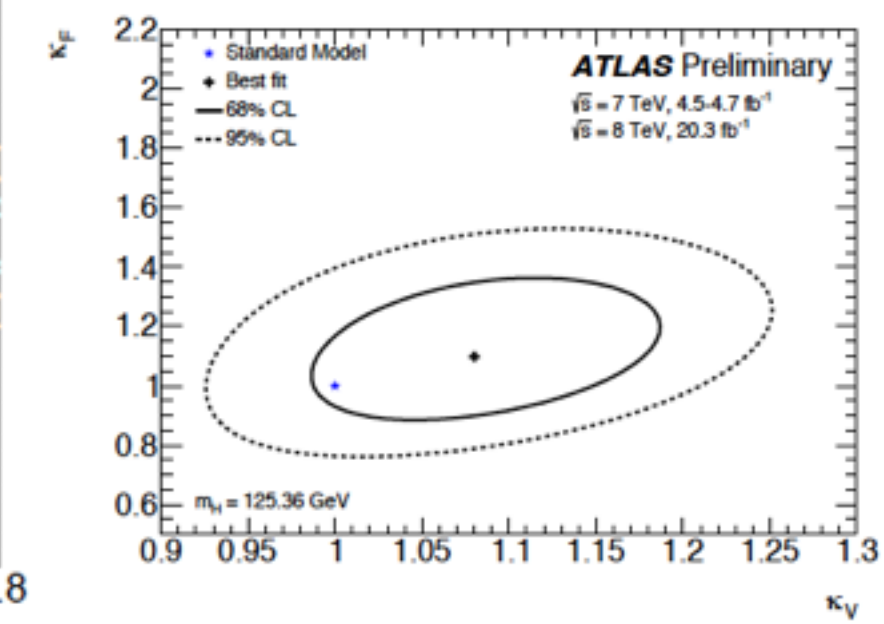


Branching fractions cancel in the ratio





Couplings to fermions and bosons



Spin and Parity Quantum Numbers

Spin/parity measurement approach

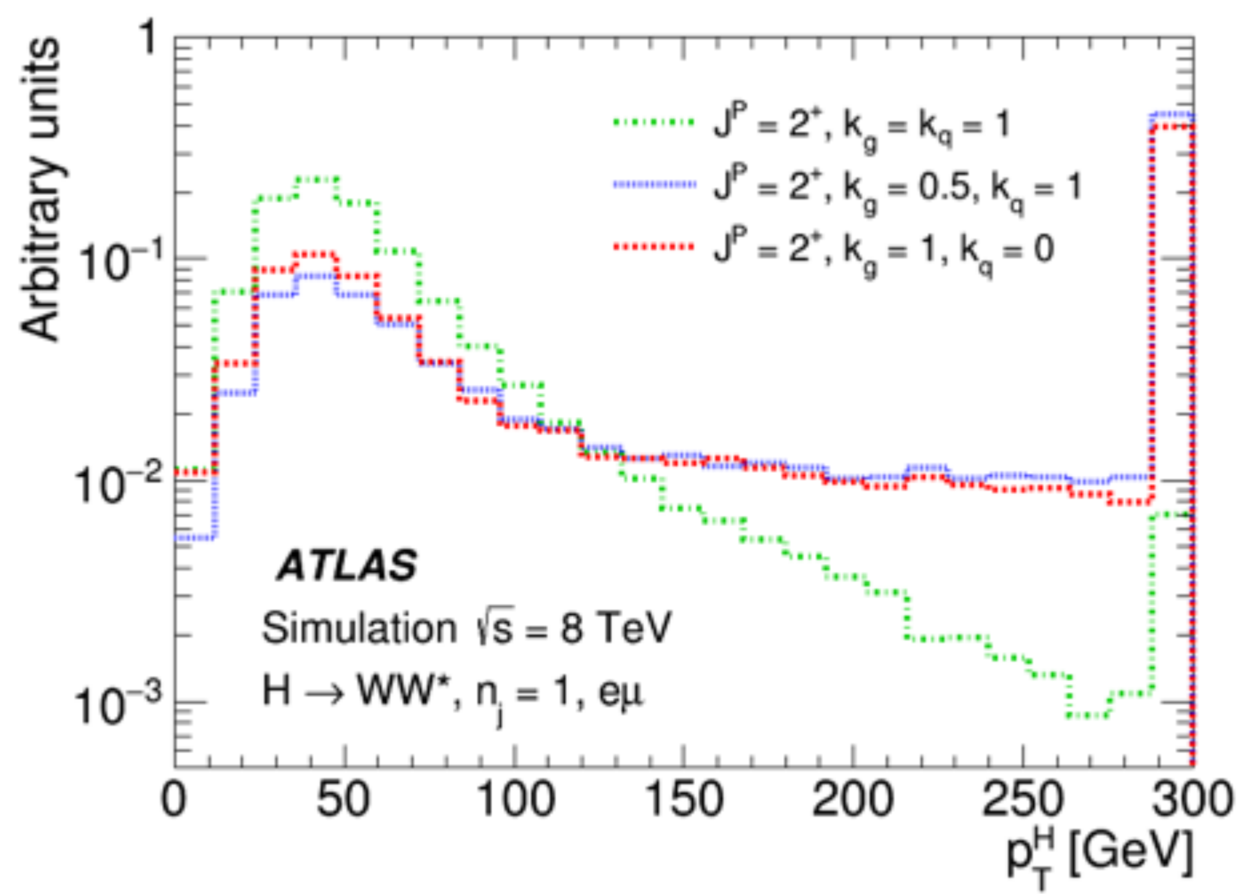
The spin/parity SM assignment, $J^P=0^+$, can be tested against alternative models:
fixed-hypothesis test: 2^+, 0^-, 0^+ with higher-order operators,
CP mixing: mixture of spin-0 states, implying CP violation in the Higgs sector

- Higgs characterization Model from Madgraph5 (effective field theory, cut-off scale Λ = 1 TeV)
- All bosonic channels used (only *ZZ* and *WW* for spin-0 studies)
    - in all cases, only the most sensitive categories are used

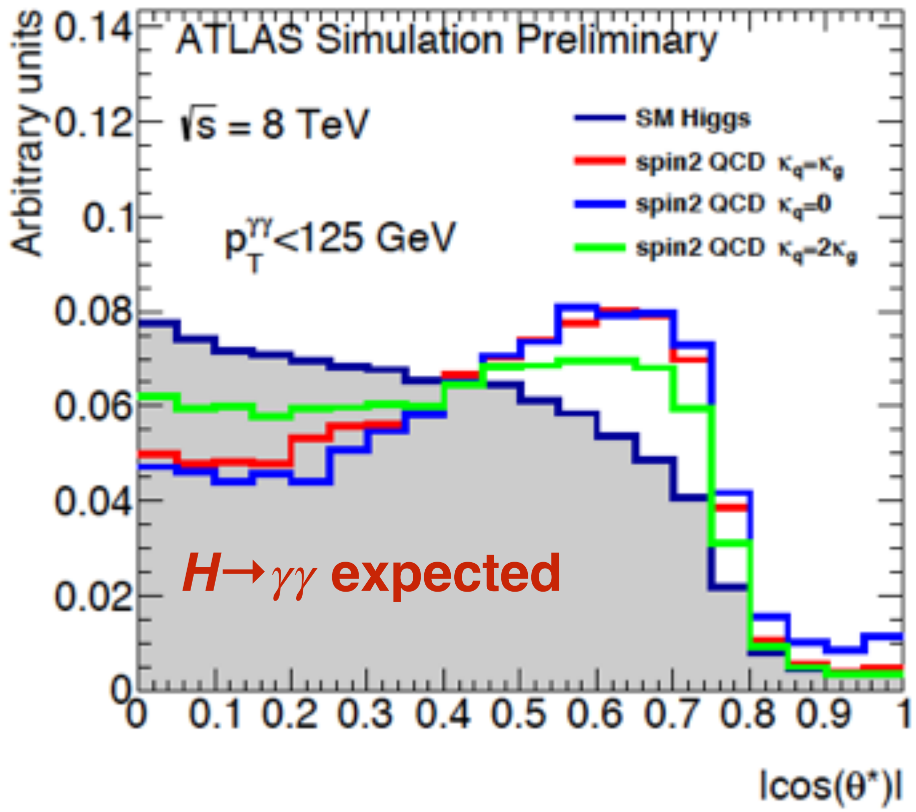
- Spin=2: Higgs-like graviton-inspired resonance, with universal [gravity-like] and non-universal couplings to quarks and gluons (in various k_g, k_q fractions)

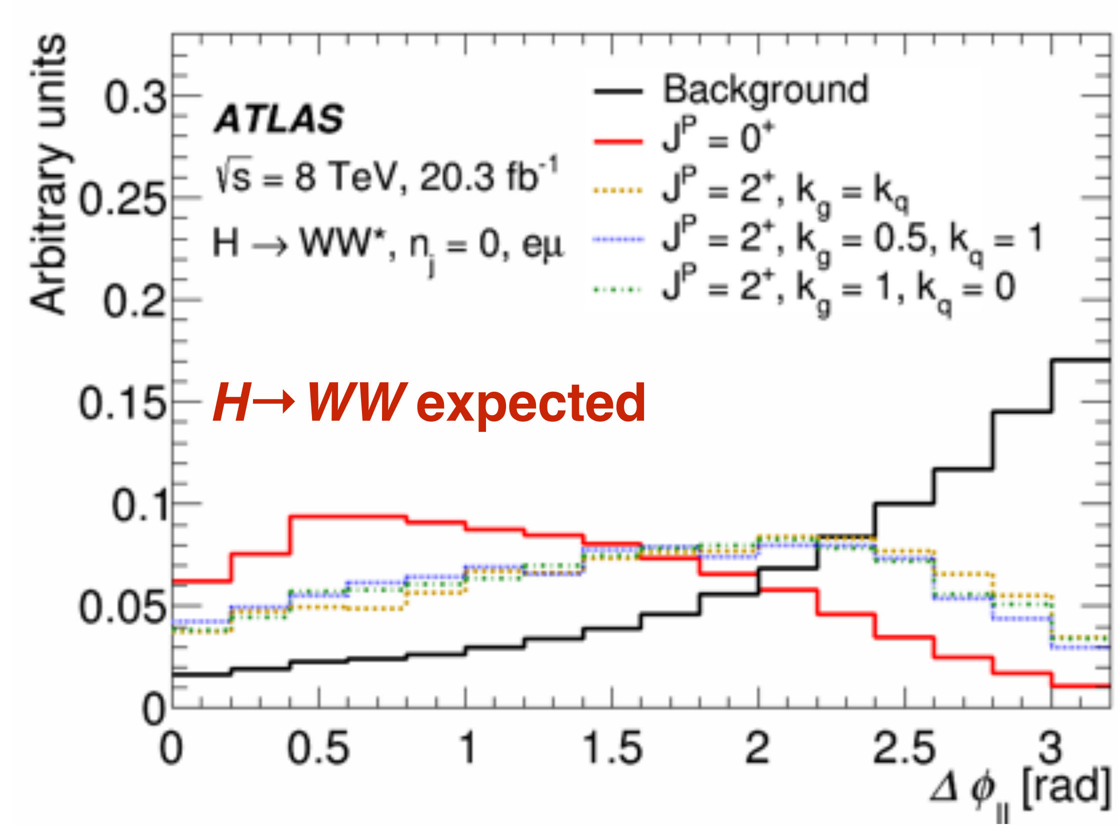
- **NLO effects lead to a tail in p_T^H for a spin-2 Higgs-like boson when jets are present > cut on p_T^H to preserve unitarity**

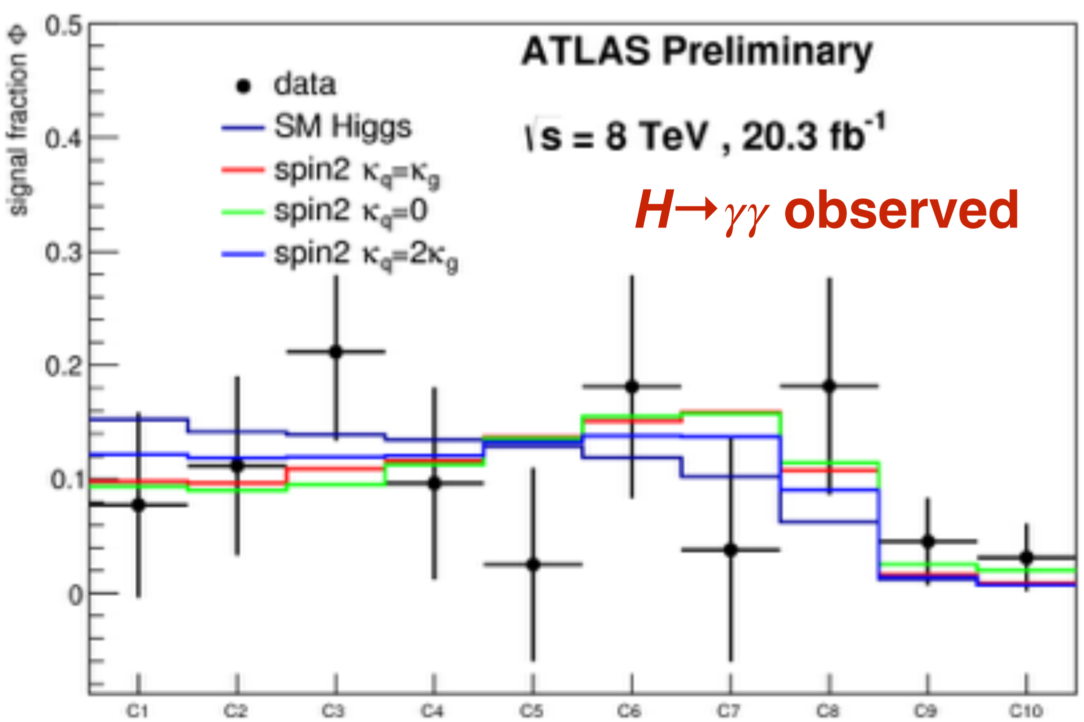
Choice of QCD couplings		p_T^X cut-off (GeV)	
$\kappa_q = \kappa_g$	Universal couplings	–	–
$\kappa_q = 0$	Low light-quark fraction	300	125
$\kappa_q = 2\kappa_g$	Low gluon fraction	300	125

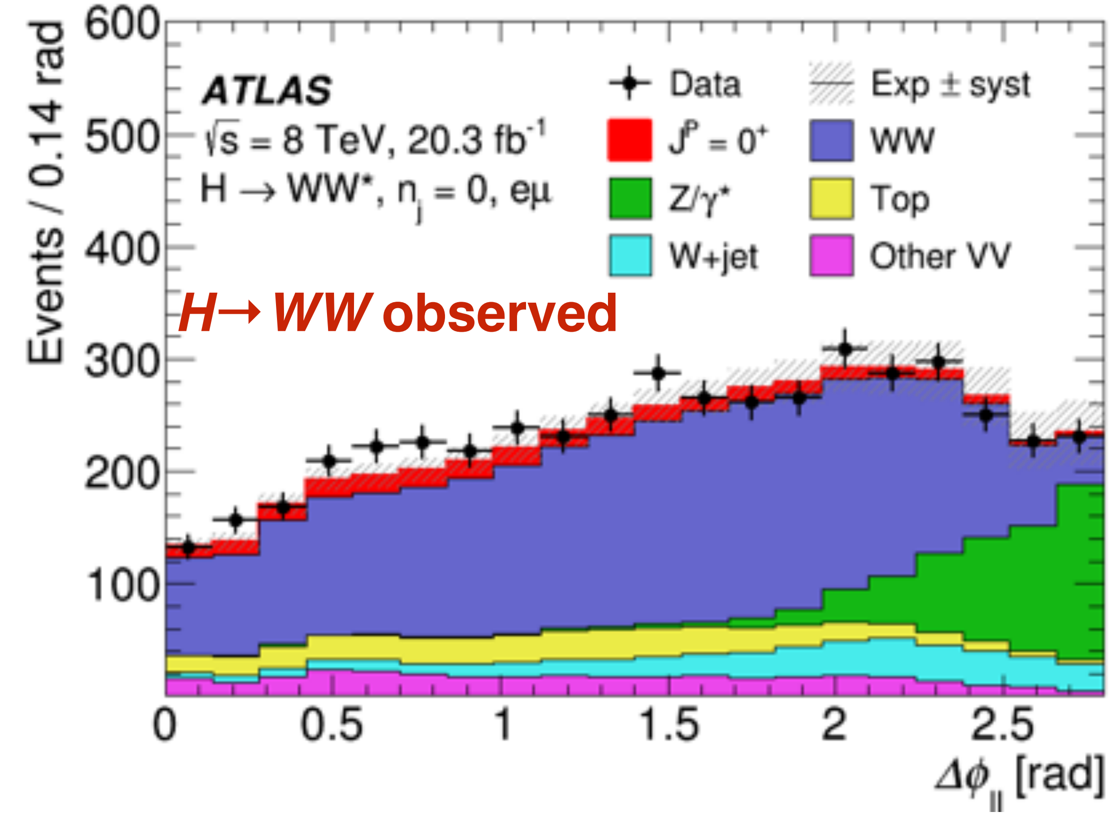


Spin: sensitive variables









Parity: sensitive variables

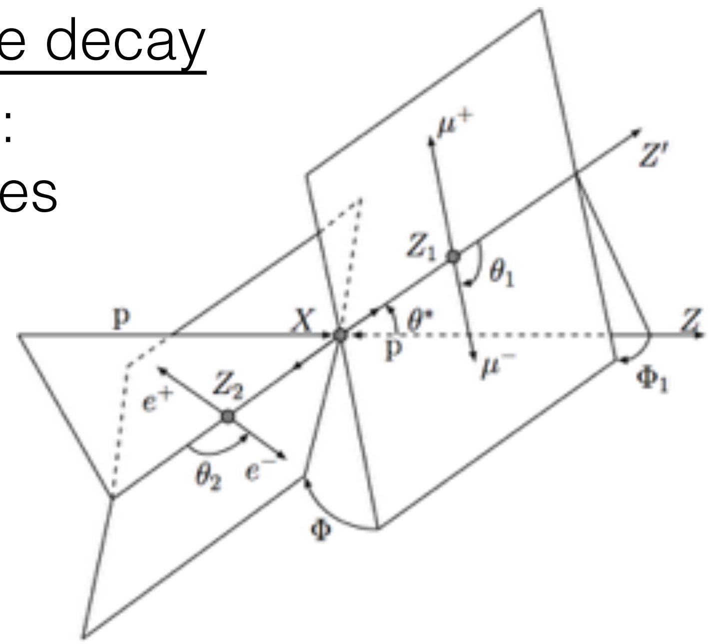
In the $ZZ^* \rightarrow 4\ell$ case, the entire decay topology can be reconstructed:
decay angles + invariant masses
= 8 degrees of freedom

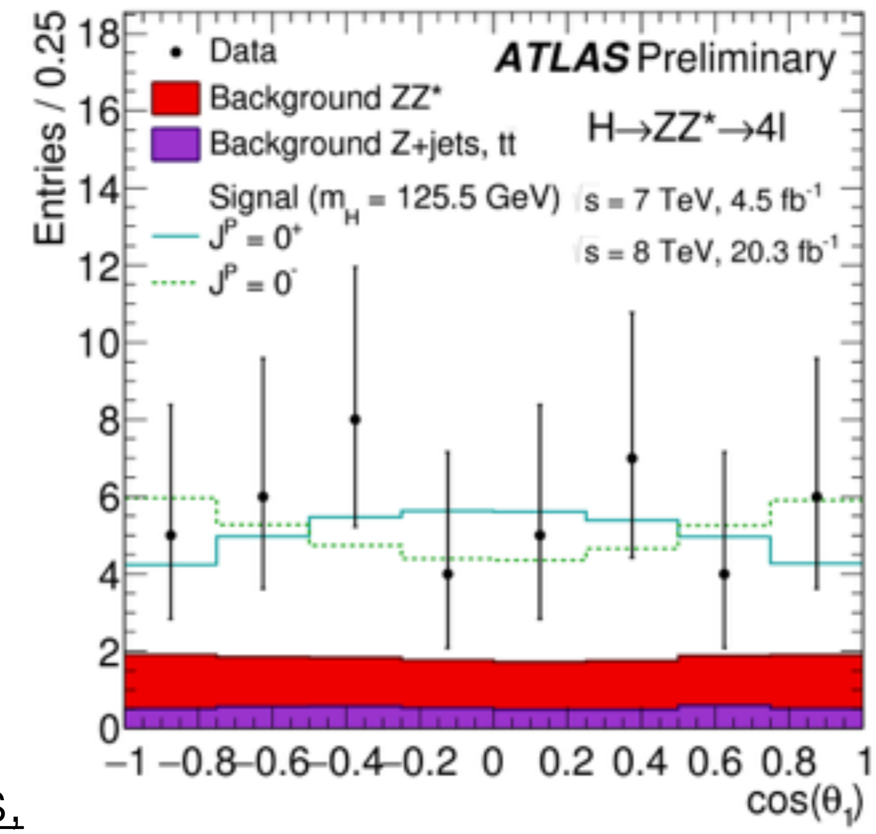
$cos(\theta_1), cos(\theta_2), \Phi, m_{12}, m_{34}$

CP Sensitive

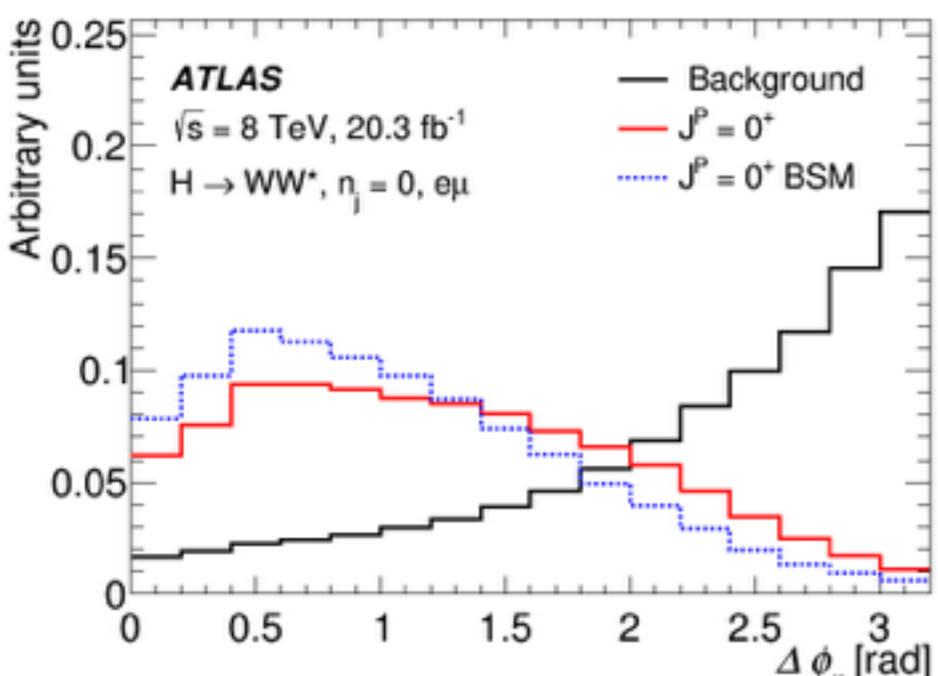
$m_{4l}, cos(\theta^*), \Phi_1$

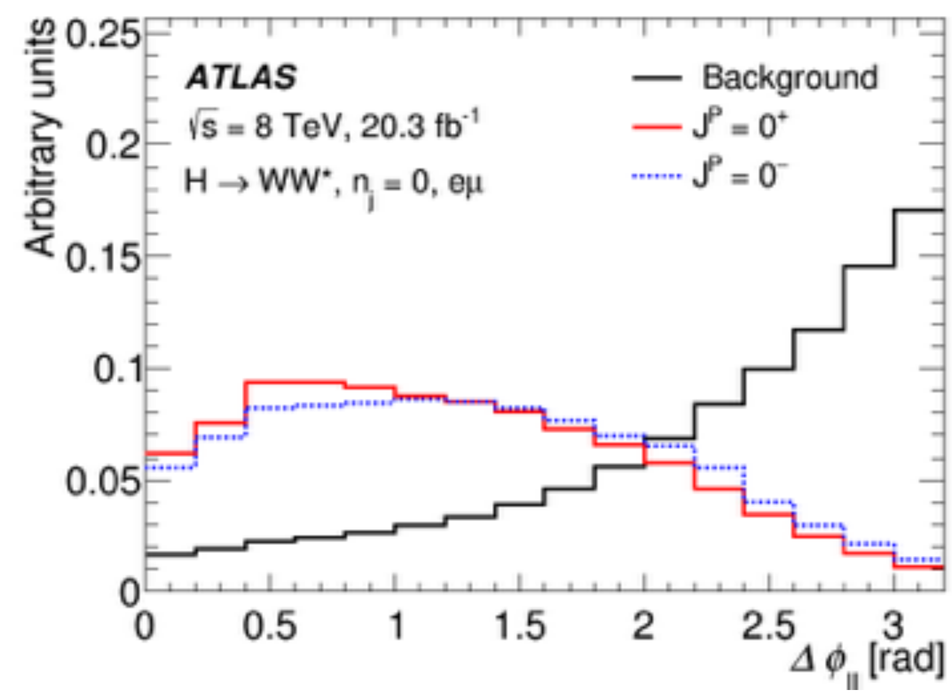
Background rejecting





$WW \rightarrow e\nu\mu\nu$ is harder due to the presence of the two neutrinos, but the angular difference between e and μ is sensitive to spin/parity.

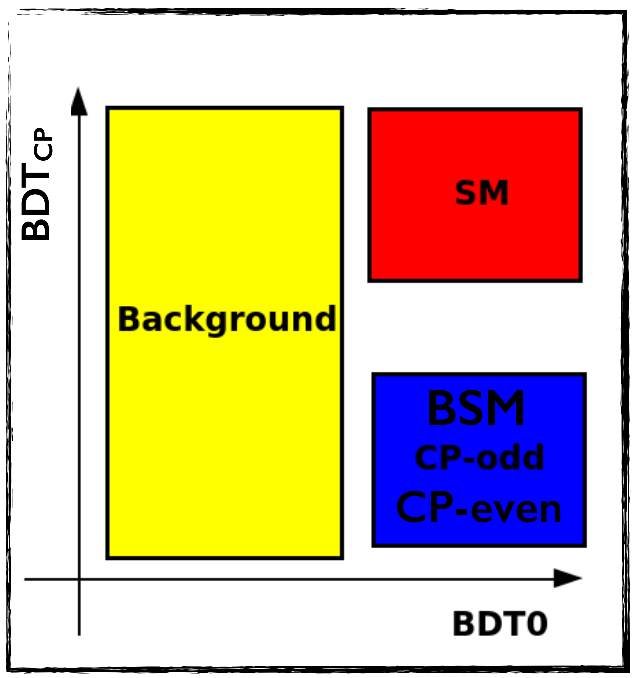


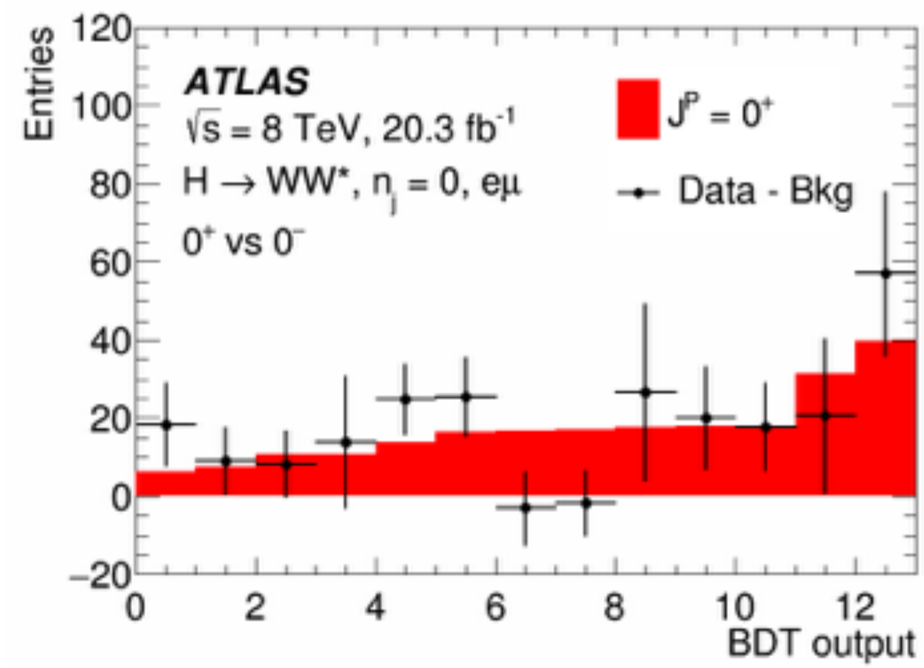


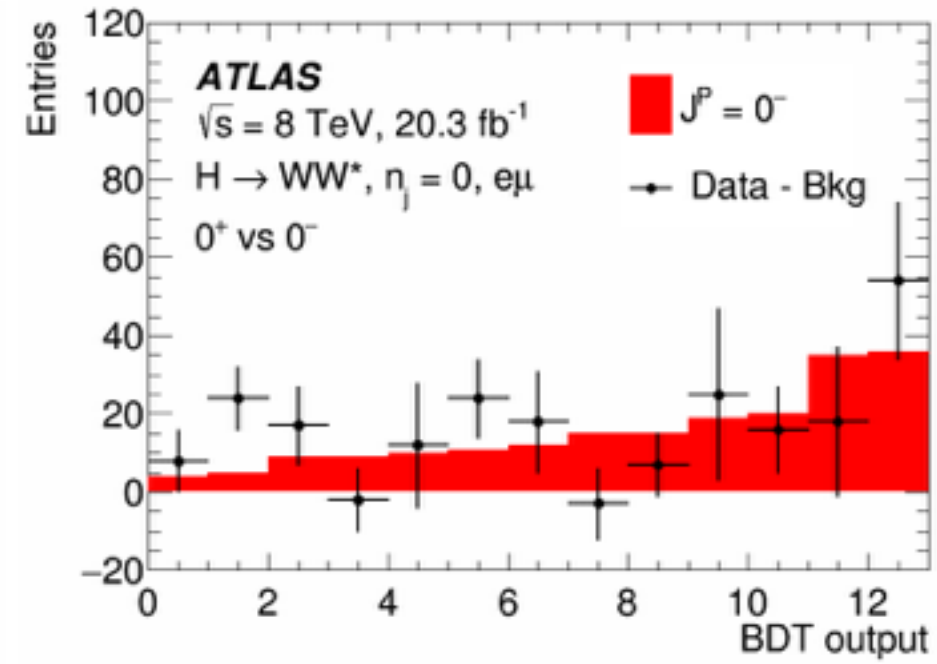
Final discriminants

Most sensitive bins of the BDT discriminant after subtracting post-fit background from the data:

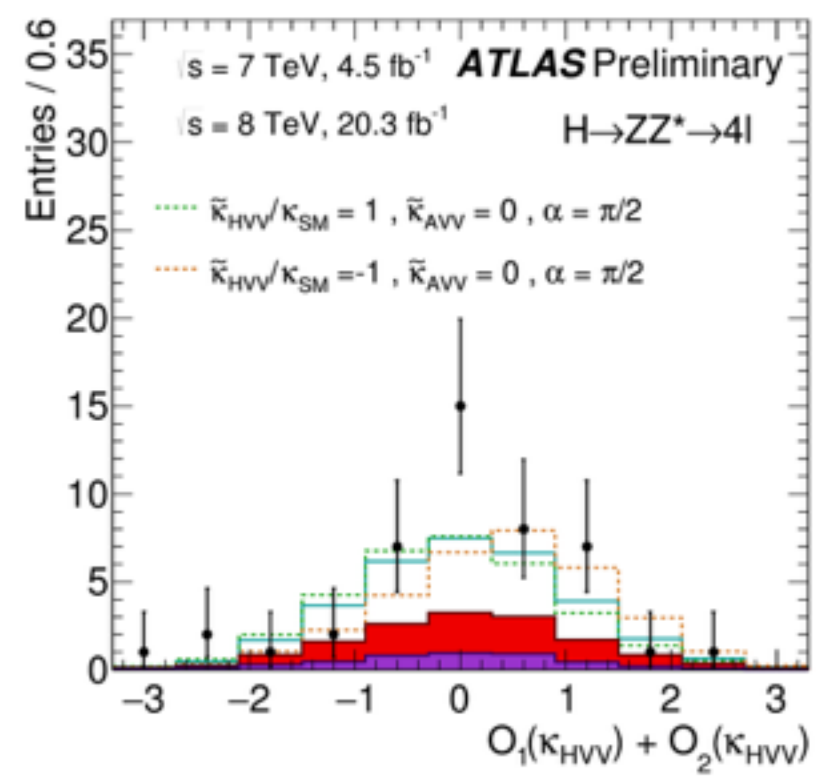
Boosted Decision trees used as discriminants in ***WW***:





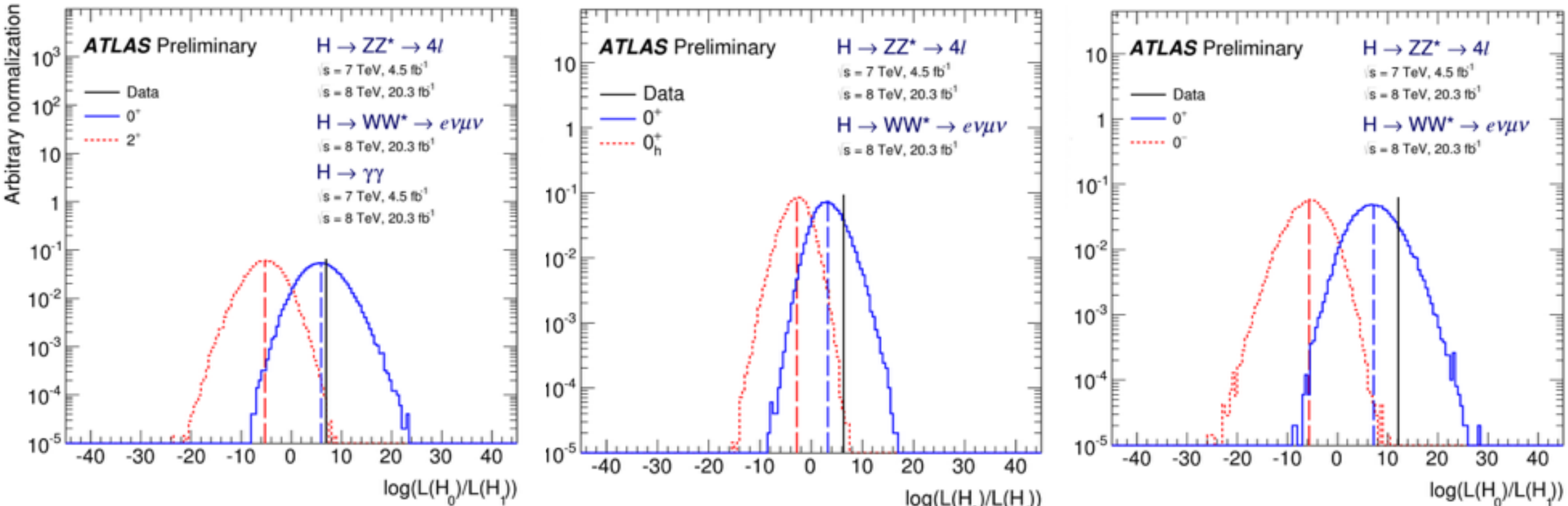


***ZZ* uses the Matrix Element** method in a tight mass window, fed with optimal observables



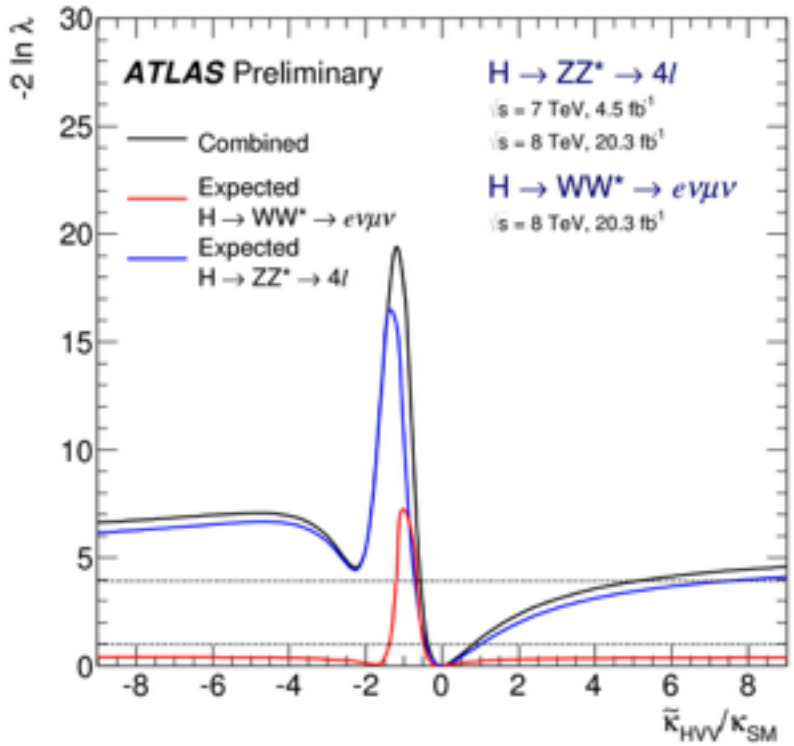
Fixed-hypothesis results

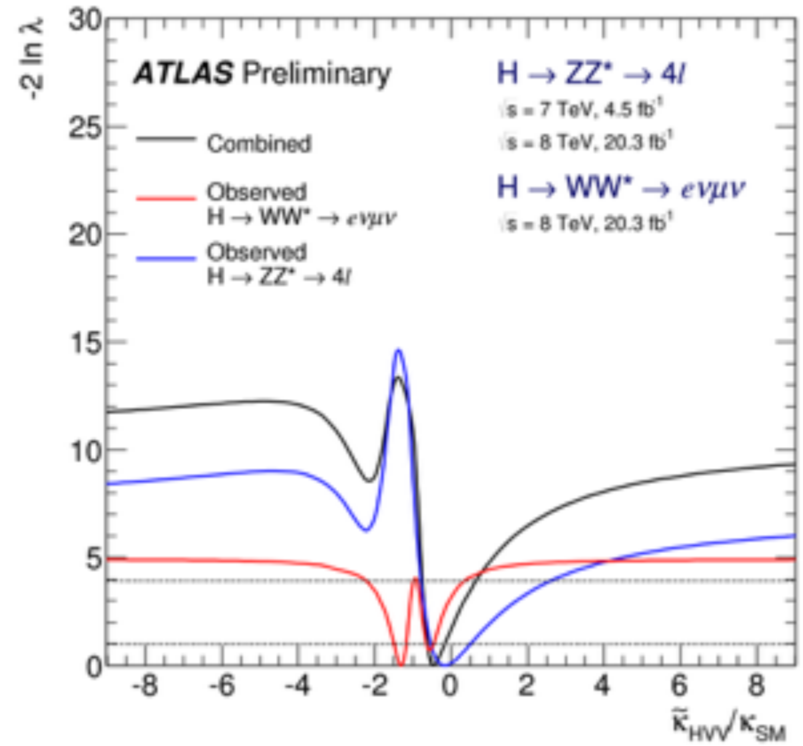
Combined results for SM 0^+ vs a fixed alternative hypothesis:
all non-SM models excluded at **> 99% CL**



Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL_S (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

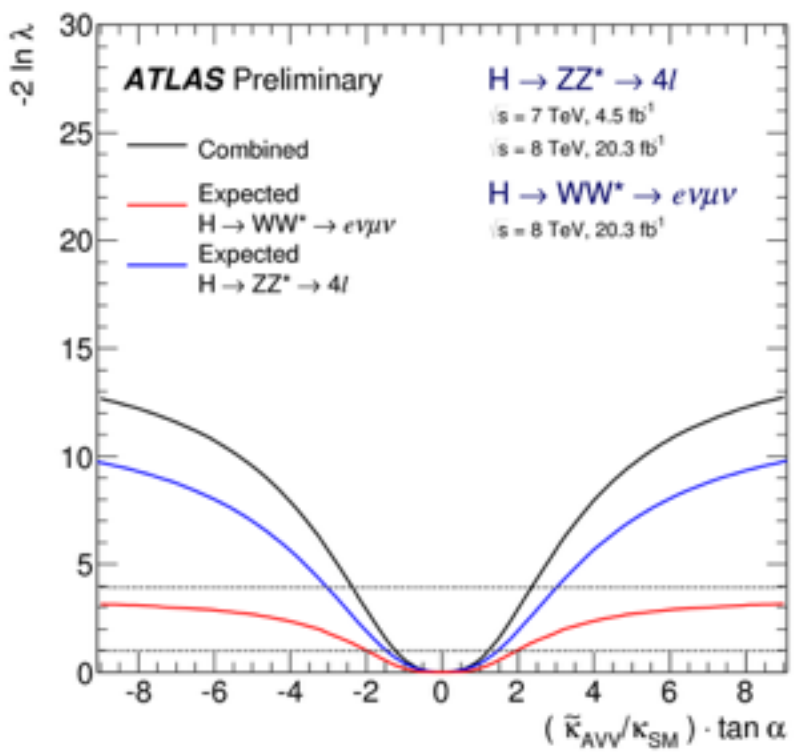
CP-mixing results

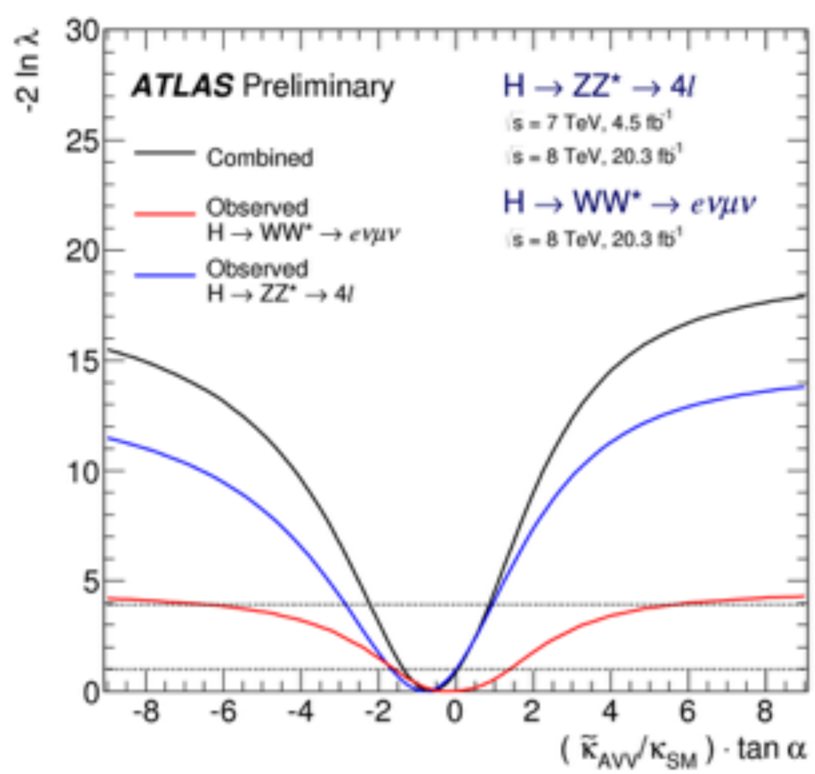




Scanning on possible components of CP-odd or CP-even higher-orders mix with SM (only one at a time).

Same BSM couplings assumed for *ZZ* and *WW*.





No significant deviation from pure SM composition found.

Off-Shell width results

Off-shell width approach

For high masses ($m_{VV} > 2m_V$), sensitivity to Physics beyond the SM can be achieved via off-shell Higgs boson production and interference effects, negligible around 125 GeV.

$\sigma^{gg\to H^*\to VV}_{\text{off-shell}}$ independent from the total width Γ_H:

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

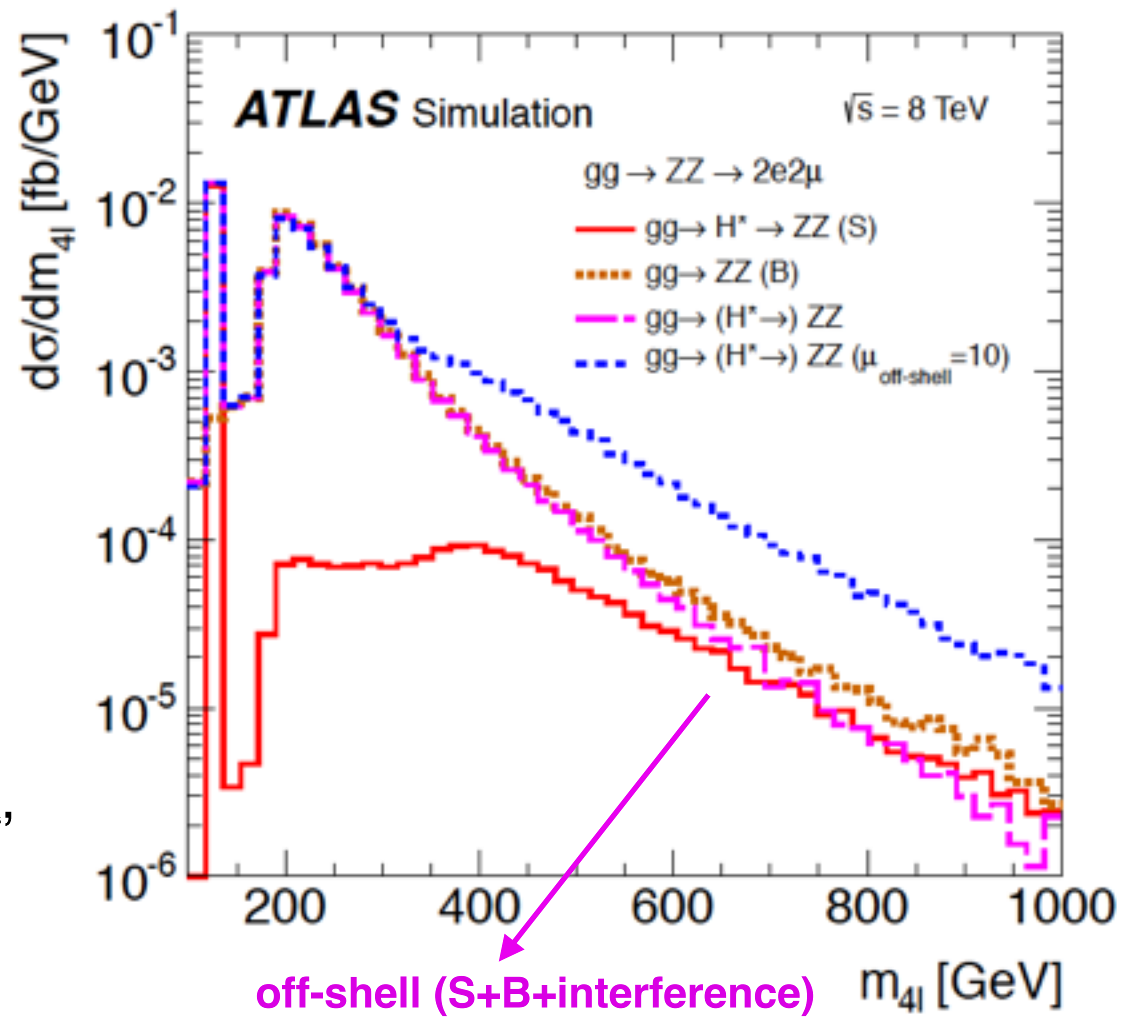
while the on-shell term depends on Γ_H:

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

- Therefore, assuming identical on/off-shell couplings k, the total width Γ_H can be indirectly constrained

- Alternatively, assuming this only for VBF but not ggF, and fixing $\Gamma_H = \Gamma_{H,SM}$, the gluon ratio can be constrained:

$$R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$$

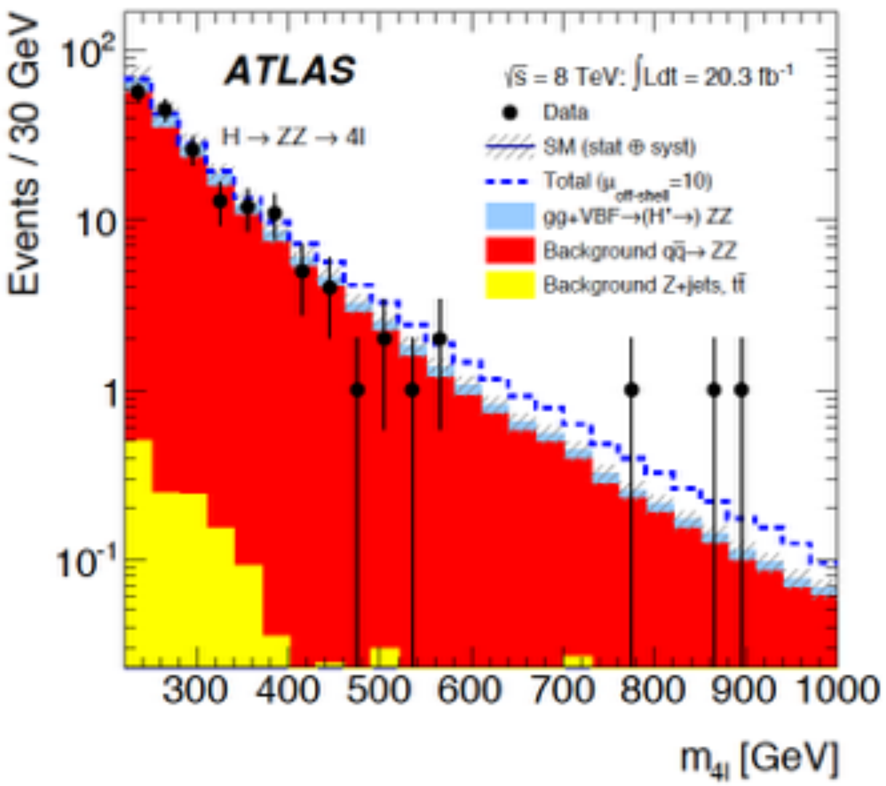


Interference is negative over the whole mass range

SM Γ_H = 4.12 MeV at m_H=125.4 GeV

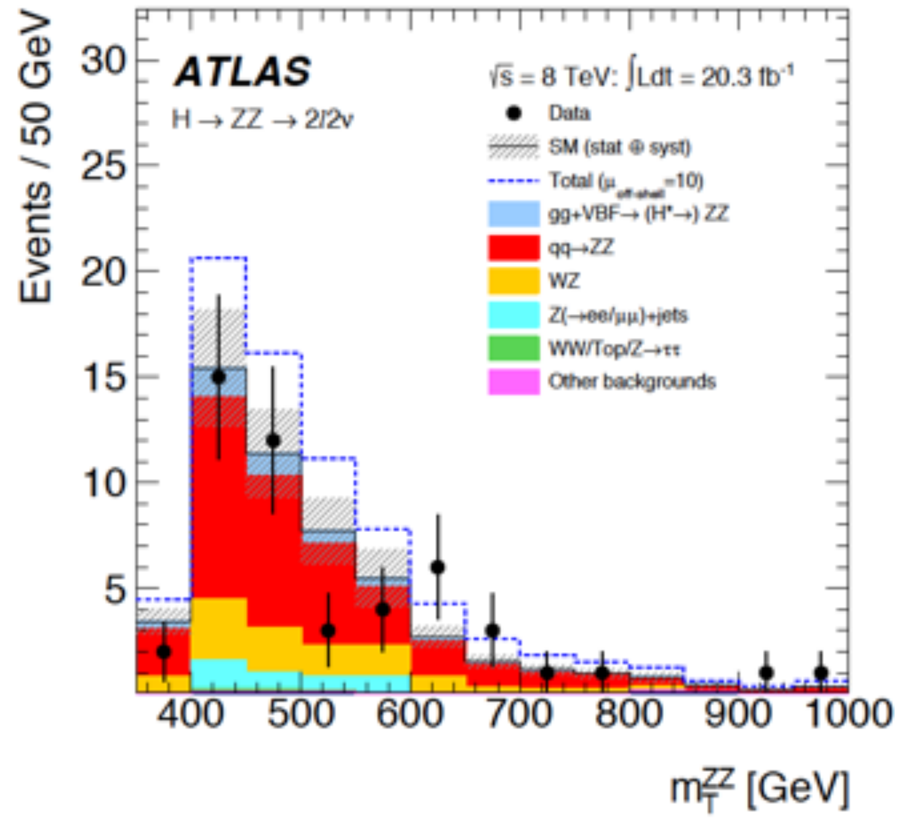
High-mass spectra of $H \to ZZ, WW$

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



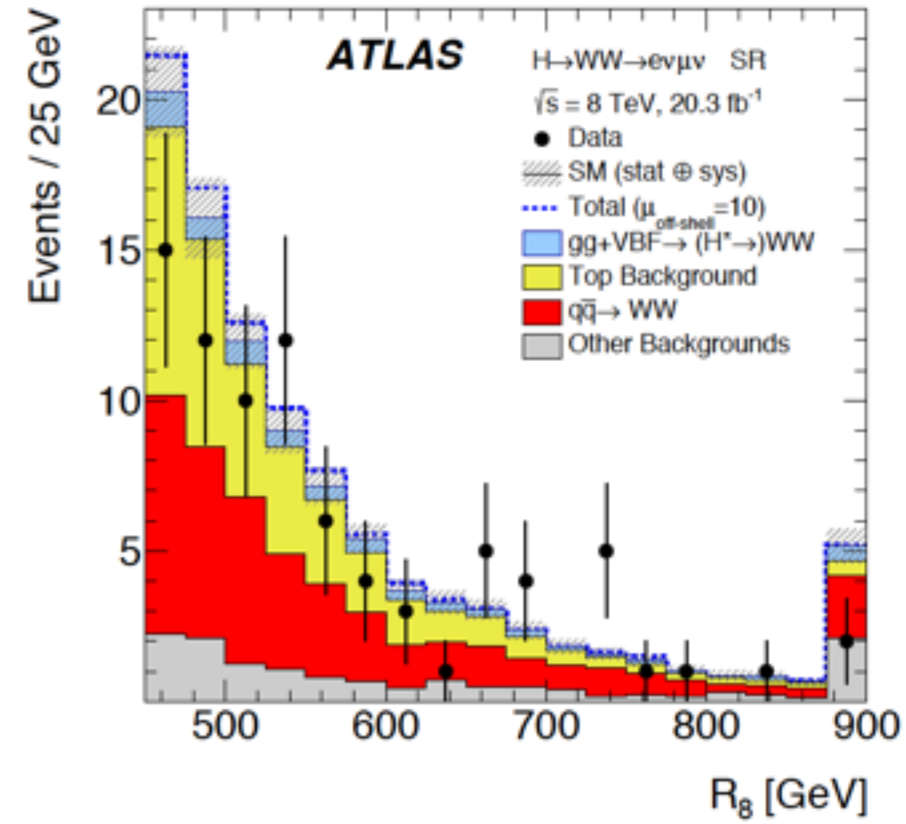
Matrix element discriminant built with the topological observables

$H \to ZZ^* \to 2\ell 2\nu$



Transverse mass to account for the presence of neutrinos

$H \to WW^* \to e\nu\mu\nu$ +jets



New variable $R_8 > 450$ GeV:

$$R_8 = \sqrt{m_{\ell\ell}^2 + \left(a \cdot m_T^{WW}\right)^2}.$$

to reject on-shell Higgs boson decays

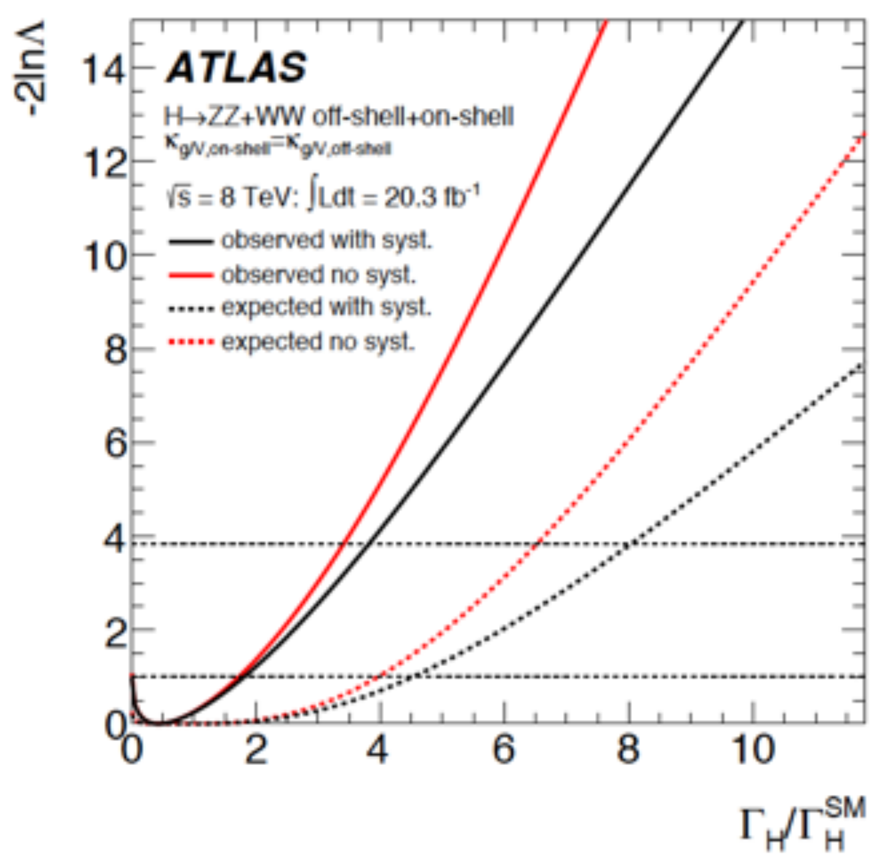
Combination of on- and off-shell results

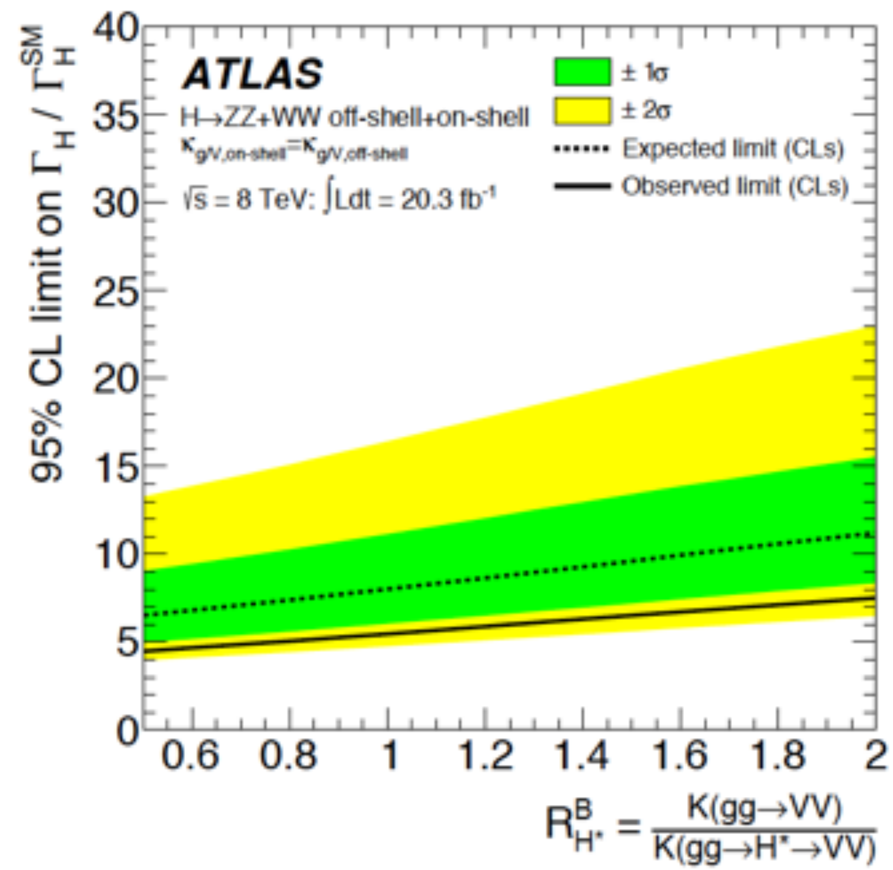
Measurement of Γ_H/Γ_H^{SM} assuming $\kappa_g = \kappa_{g,\text{on-shell}} = \kappa_{g,\text{off-shell}}$ and $\kappa_V = \kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}$ for both ggF and VBF, as in the SM.

There is no prediction for NLO corrections to the $gg \to VV$ background at high mass, thus results are given as a function of R^B, in the range (0.5, 2).

$R^B_{H^*}$	Observed 0.5	Observed **1.0**	Observed 2.0	Median expected 0.5	Median expected **1.0**	Median expected 2.0	Assumption
Γ_H/Γ_H^{SM}	4.5	**5.5**	7.5	6.5	**8.0**	11.2	$\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$

For $R^B = 1$
$\Gamma_H < 22.7$ (exp 33.0) MeV



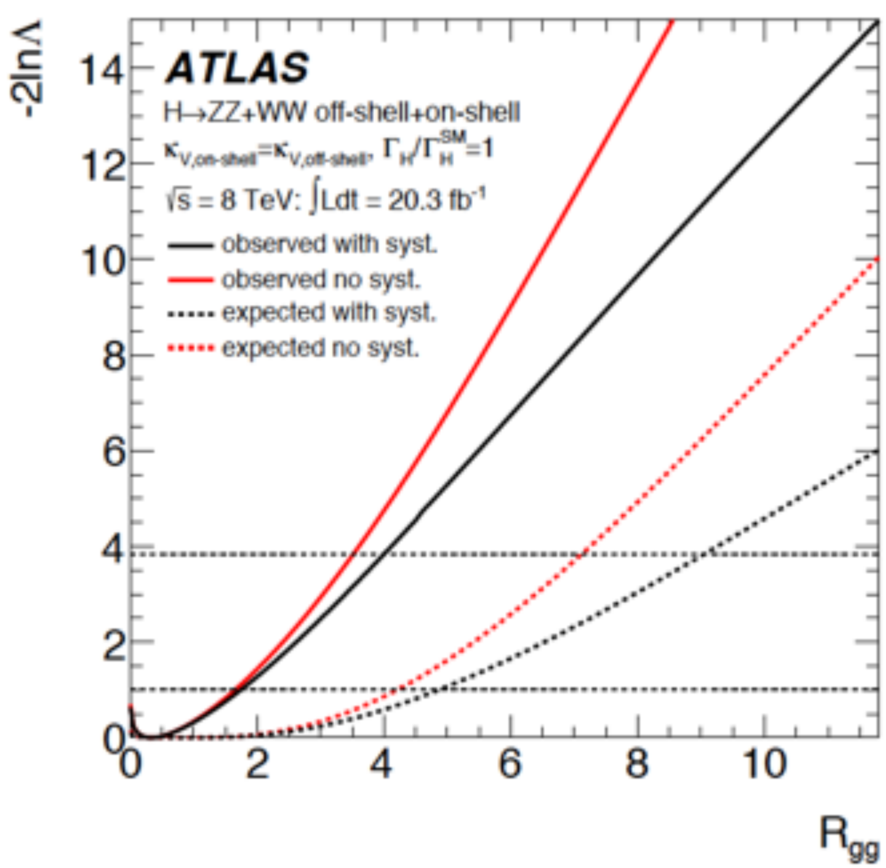


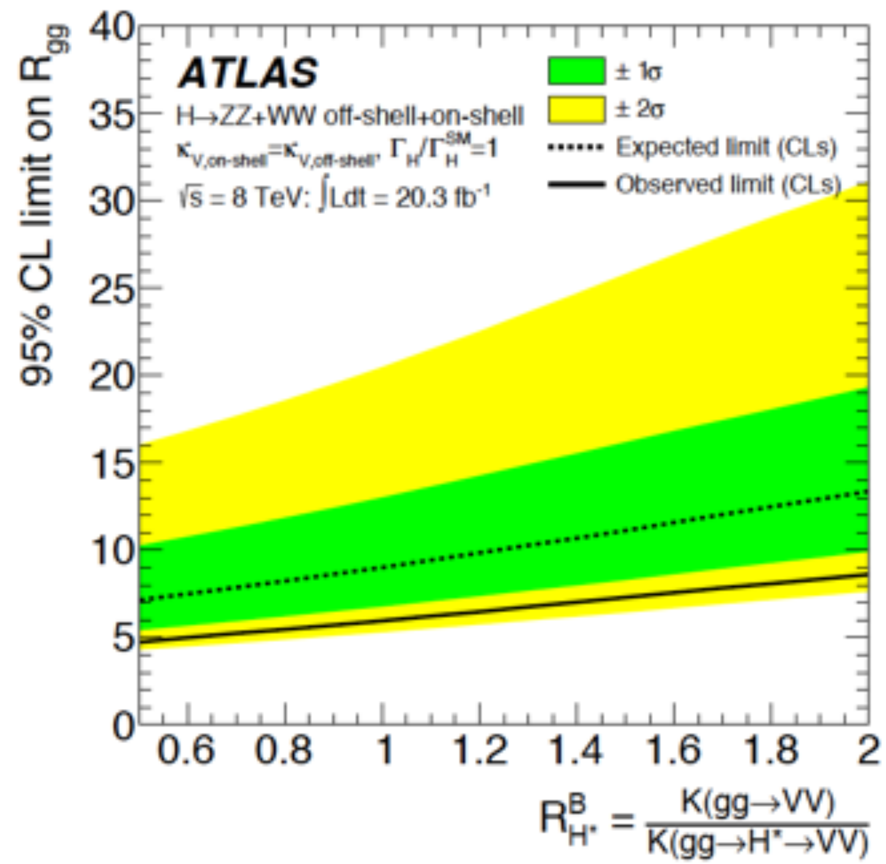
Combination of on- and off-shell results

Measurement of $R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$ assuming $\kappa_V = \kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}$ for VBF only, while ggF can deviate (different k_g on/off shell). Also assuming $\Gamma_H = \Gamma_H$ (SM).

Like before, results as a function of RB.

$R^B_{H^*}$	Observed 0.5	Observed 1.0	Observed 2.0	Median expected 0.5	Median expected 1.0	Median expected 2.0	Assumption
$R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$	4.7	**6.0**	8.6	7.1	**9.0**	13.4	$\kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}, \Gamma_H/\Gamma_H^{SM}=1$





Production Cross Section at $\sqrt{s}$ = 8 TeV

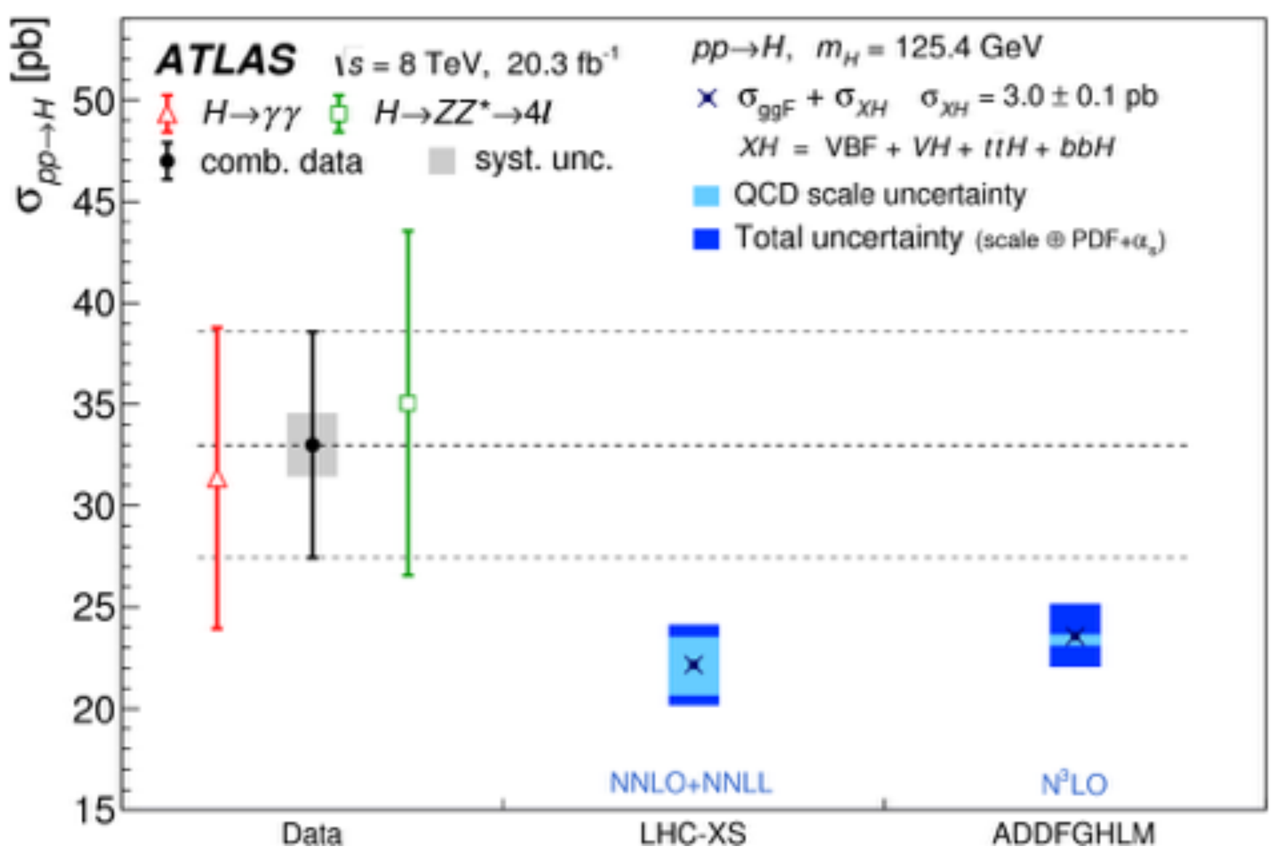
Total cross section

Combination of *ZZ* and $\gamma\gamma$ measurements at 8 TeV, ~30% improvement on individual results. Common mass of 125.36 GeV assumed.

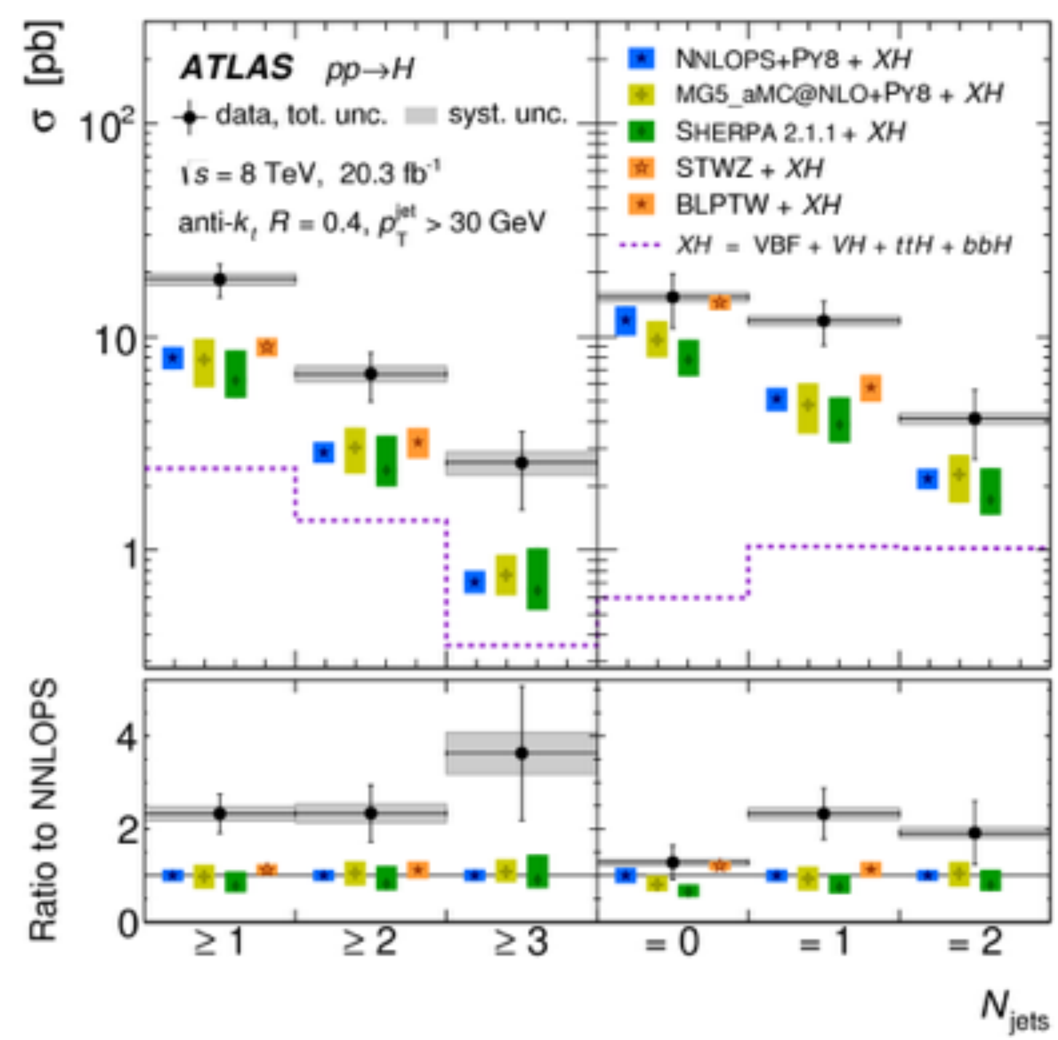
$$\sigma_{pp\to H} = 33.0 \pm 5.3(\text{stat}) \pm 1.6(\text{sys})\ \text{pb}$$

THEO-EXP compatibility:

- p-value = 5.5% for LHC-XS
- 9% for ADDFGHLM

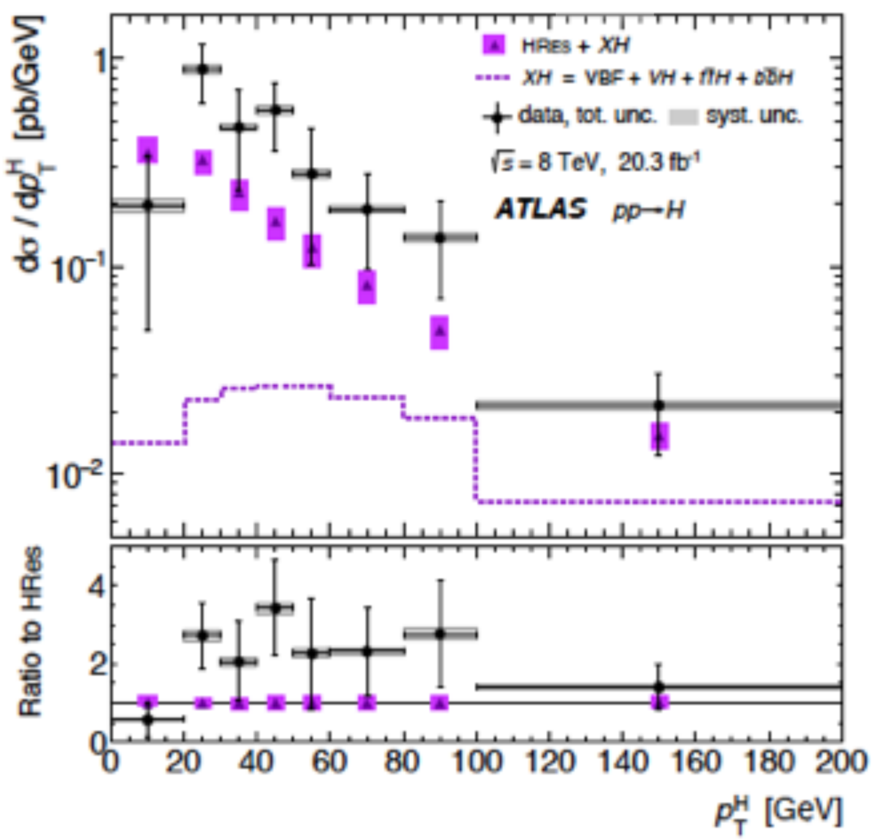


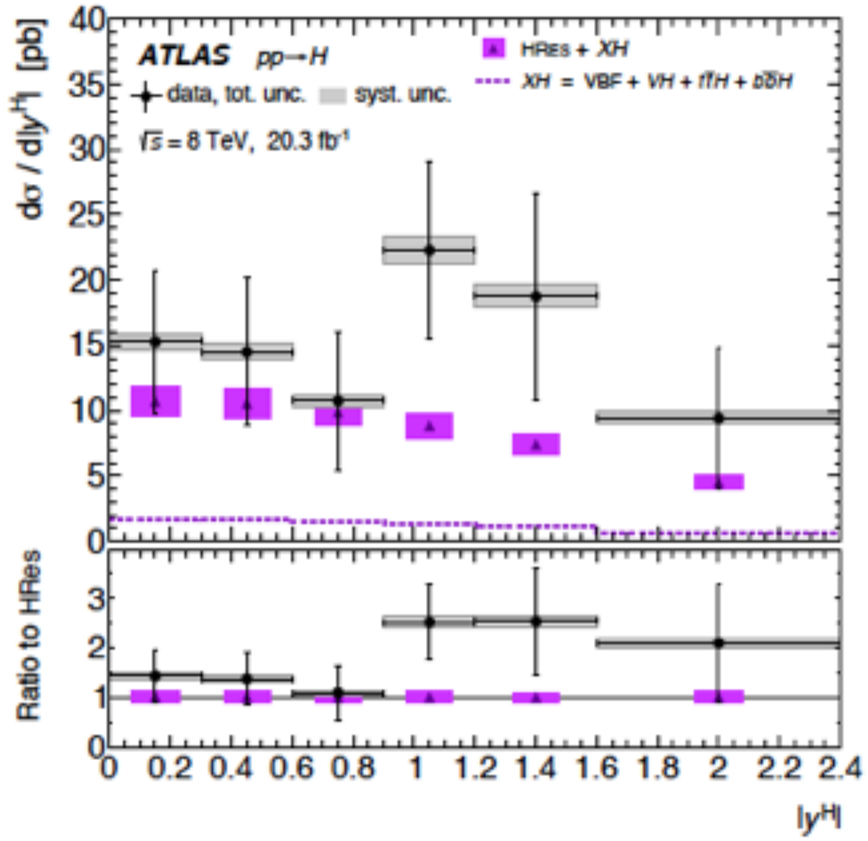
Same trend as a function of $N_{jets} > 1$: exp > theo:

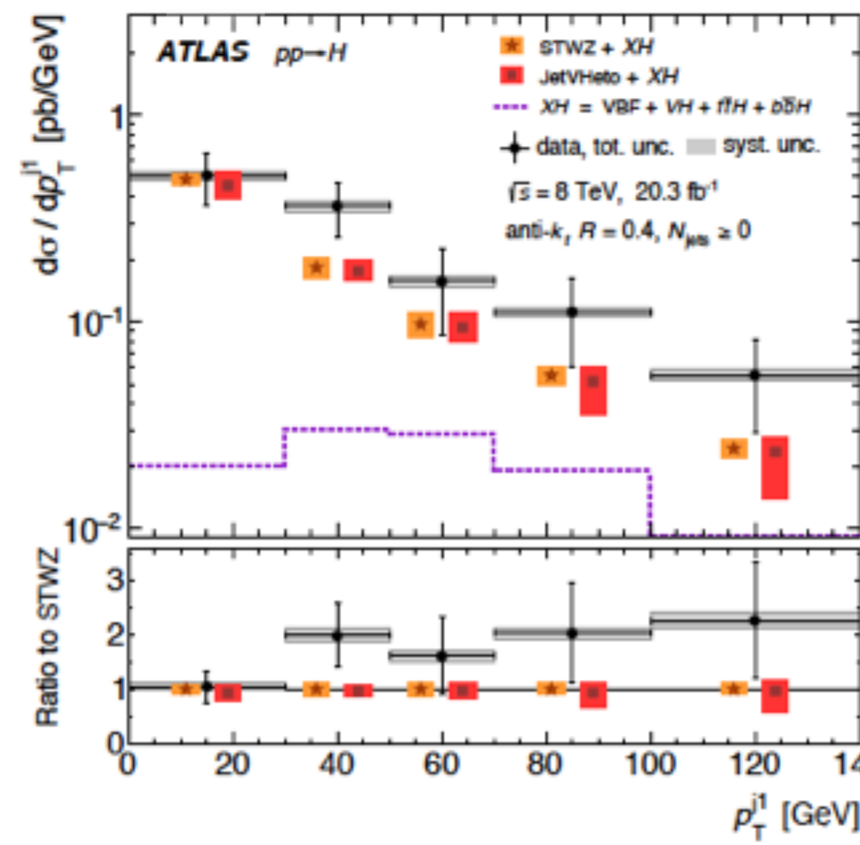


Differential cross sections

- Measured as a function of the Higgs p_T and |y|, and of leading jet p_T.
- Comparison to NNLO computations.
- Need more data to study the shapes and verify the observed deviations.







Conclusions

The final results for the measurement of the Higgs boson properties, with the full Run1 dataset (25 fb^{-1} at sqrt(s)=7 and 8 TeV) collected and analysed by the ATLAS collaboration, have been presented.

All the aspects of the Higgs boson physics have been explored, finding no significant deviation from the Standard Model expectations. Looking forward to Run2 results at 13 TeV, coming up later this year!

	Combination of channels	Results
Mass	$\gamma\gamma$, ZZ	**125.36 ± 0.41 GeV**
Spin	$\gamma\gamma$, WW	• **2^+ universal** • **2^+ non-universal**
Parity	WW, ZZ	• **0^-** excluded • **0^+_h**
CP-mixing	WW, ZZ	• $\tilde{K}_{AVV}/K_{SM}$ tan(α) in **(-2.2, 0.8)** at 95% CL • $\tilde{K}_{HVV}/K_{SM}$ in **(-0.7, 0.6)** at 95% CL
Cross section (8 TeV)	$\gamma\gamma$, ZZ	σ_{pp}
Off-shell width	WW, ZZ	Γ_H

Outlook to Run2

Much more on Run2 prospects in Pierre Savard's plenary talk on Thursday

Run2 Higgs analyses will be dominated by **systematic** uncertainties

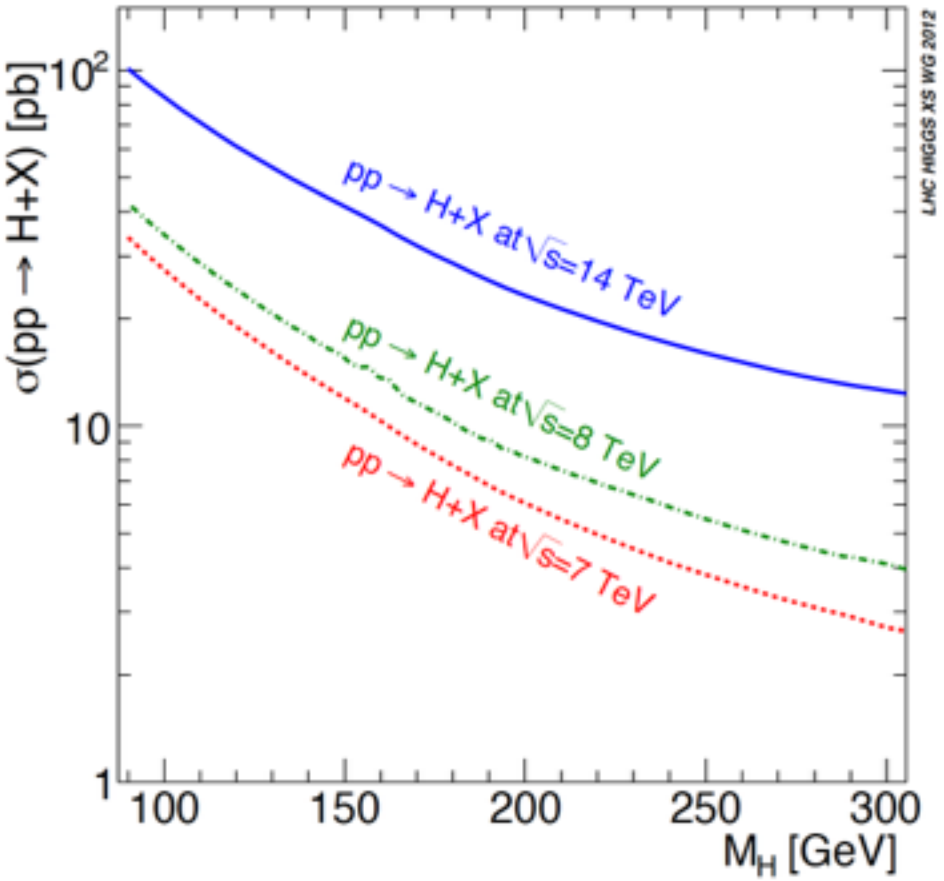
$\sigma_{pp\to H} = 33.0 \pm 5.3(\text{stat}) \pm 1.6(\text{sys})$ pb

→ **± 5.5 pb total** **Run1**

→ **± 2.3 pb total** **Run2** **(stats x10)**

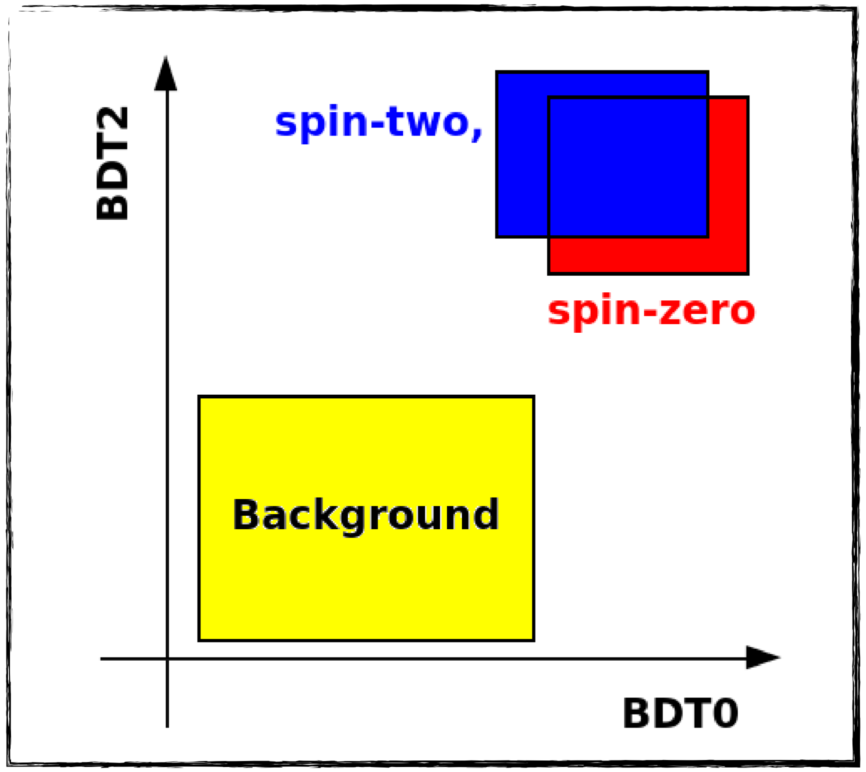
from LHC Higgs XS WG

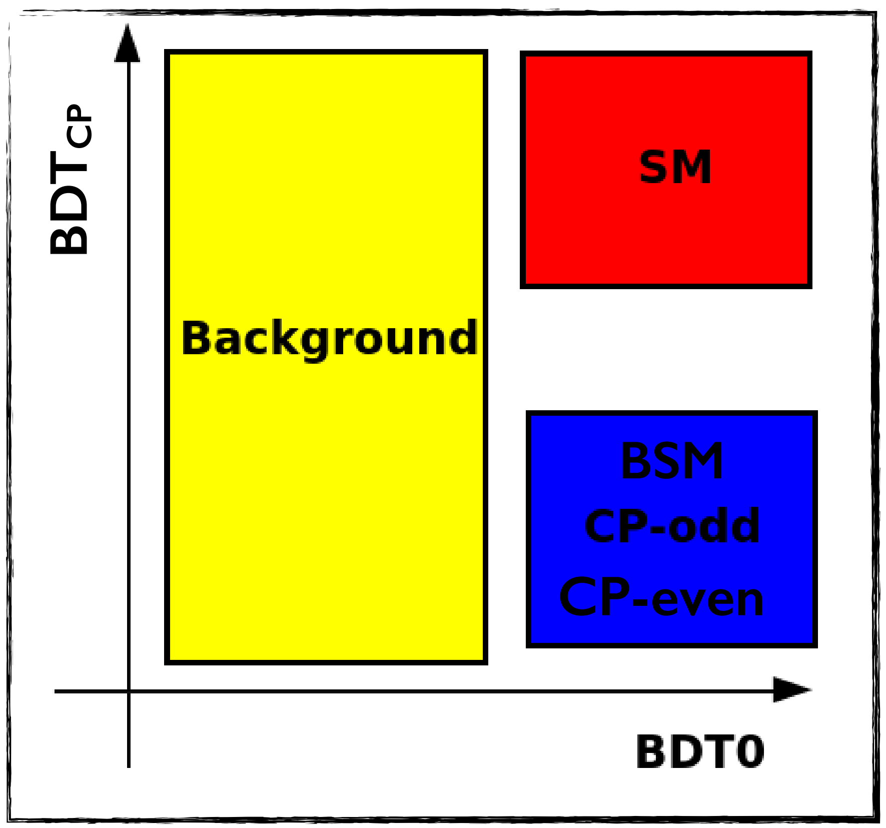
	σ(8 TeV)	σ(13 TeV)	ratio
gg→H	19.3	43.9	**2.3**
VBF	1.58	3.75	**2.4**
WH	0.70	1.38	**2.0**
ZH	0.42	0.87	**2.1**
ttH	0.13	0.51	**3.9**



Back up

HWW analysis strategy





Boosted Decision trees used as discriminants:

- BDT0: train SM signal vs background
- BDT2: train ALT signal vs background
- Both BDT0 and BDT2 use as input: $m(\ell\ell)$, $\Delta\phi^{\ell\ell}$, $p_T^{\ell\ell}$ m_T^{track}
- Combine (BDT0, BDT2) and fit the 1d projection

- BDT0: train SM signal vs background (as for spin)
- BDT$_{CP}$: train SM signal vs ALT signal:
  - BSM CP-odd: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $E_{\ell\ell\nu\nu}$ and Δp_{T}
  - BSM CP-even: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $p_{\mathrm{T}}^{\ell\ell}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$

$$E_{\ell\ell\nu\nu} = p_{\mathrm{T}}^{\ell_1} - 0.5 p_{\mathrm{T}}^{\ell_2} + 0.5 E_{\mathrm{T}}^{\mathrm{miss}} \qquad \Delta p_{\mathrm{T}} = \left| p_{\mathrm{T}}^{\ell_1} - p_{\mathrm{T}}^{\ell_2} \right|$$

Training performed for the pure CP hypothesis only, no retraining for the various CP fractions

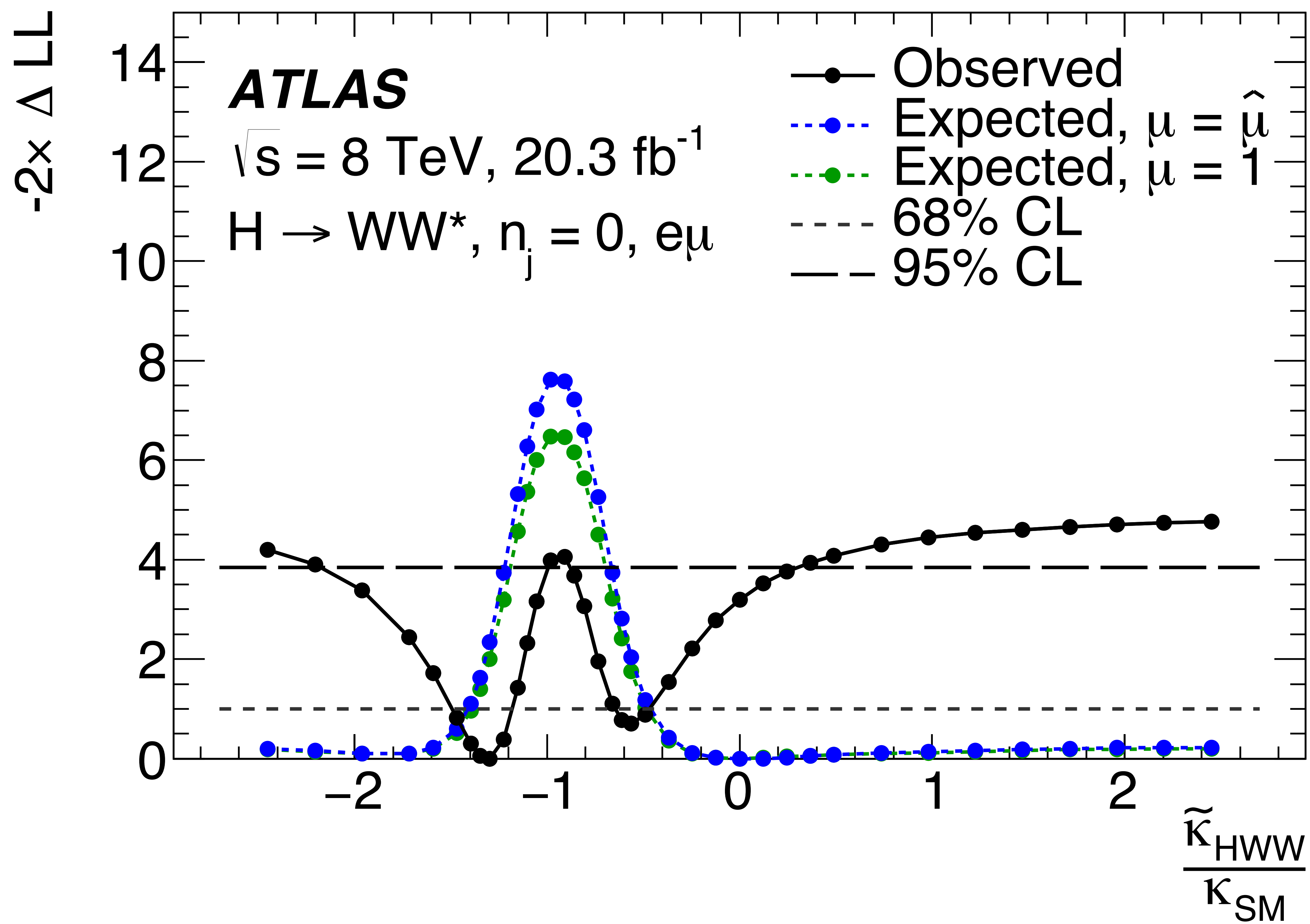
CP violation in the Higgs sector

$$
\begin{aligned}
\mathcal{L}_0^V = & \left\{ c_\alpha \kappa_{\rm SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \right. \\
& - \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \widetilde{A}^{\mu\nu} \right] \\
& - \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \widetilde{A}^{\mu\nu} \right] \\
& - \frac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \widetilde{G}^{a,\mu\nu} \right] \\
& - \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \right] \\
& - \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu} \right]
\end{aligned}
$$

SM

kHWW: Higher order CP-even

kAWW × tgα:
CP violation
in the Higgs sector


ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$H \rightarrow WW^*$, n_j = 0, eμ
Observed
Expected, $\mu = \hat{\mu}$
Expected, μ = 1
68% CL
95% CL
$-2\times \Delta$ LL
$\tilde{\kappa}_{HWW} / \kappa_{SM}$
14
12
10
8
6
4
2
0
−2
−1
0
1
2