Higgs-boson properties at the LHC: mass, spin and parity

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on behalf of the CMS and ATLAS Collaborations

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Introduction

In 2012, after a 40-year long quest, the ATLAS and CMS collaborations reported the discovery of a resonance compatible with the Higgs boson, as predicted by the Standard Model, at a mass around 125 GeV.

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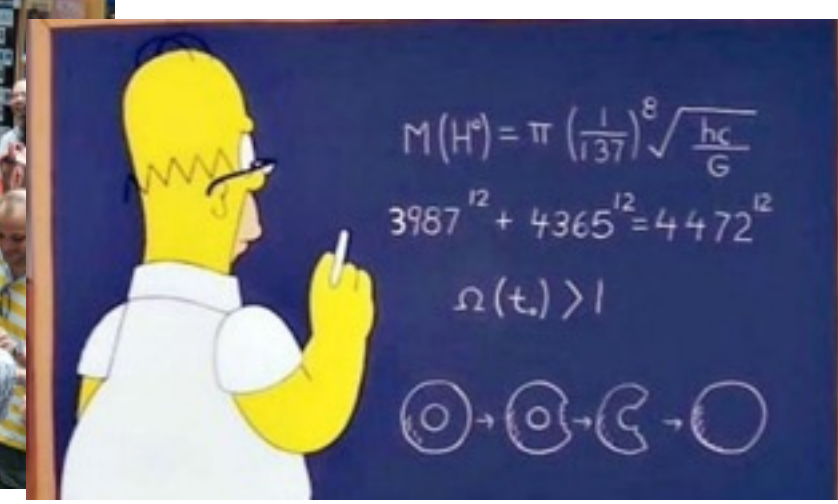
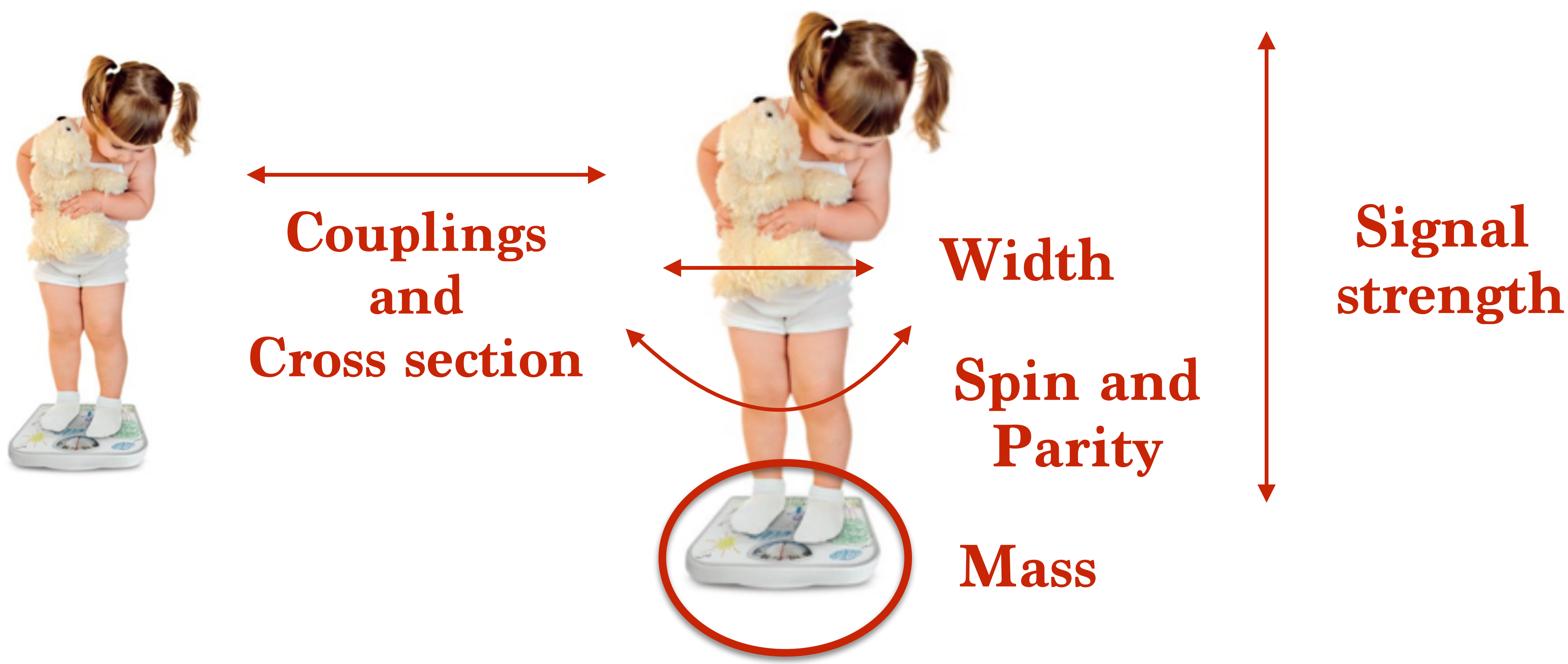


Introduction

In 2012, after a 40-year long quest, the ATLAS and CMS collaborations reported the discovery of a resonance compatible with the Higgs boson, as predicted by the Standard Model, at a mass around 125 GeV.

What have we been able to measure so far?

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



Run1 ATLAS+CMS results

- **Mass**:
  - **ATLAS**: “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)]
  - **CMS**: “Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV” [CERN-PH-EP-2014-288, Eur. Phys. J. C 75 (2015) 212]
  - “**Combined** measurement of the Higgs boson mass in *pp* collisions at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS and CMS experiments” [CERN-PH-EP-2015-075, Phys. Rev. Lett. 114 (2015) 191803]

- **Spin and Parity**:
  - **ATLAS**: “Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector” [CERN-PH-EP-2015-114, submitted to EPJ]
  - **CMS**: “Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV” [CERN-PH-EP-2014-265, Phys. Rev. D 92 (2015) 012004]

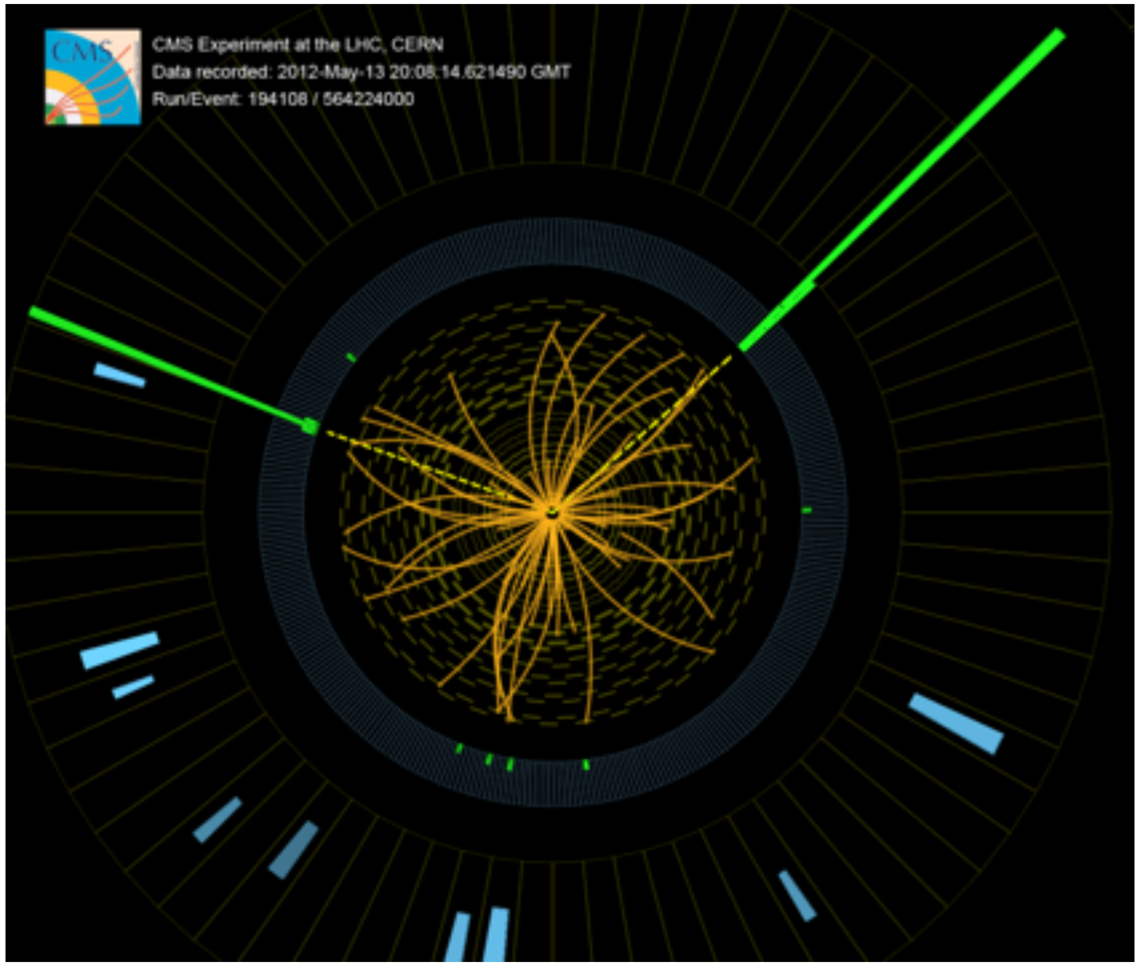
More properties:

- **Couplings** > covered in M. Pieri’s talk
- **On and Off-Shell Width** > covered in R. di Nardo’s talk
- **Total and differential cross section** > covered in K. Tackmann’s plenary talk

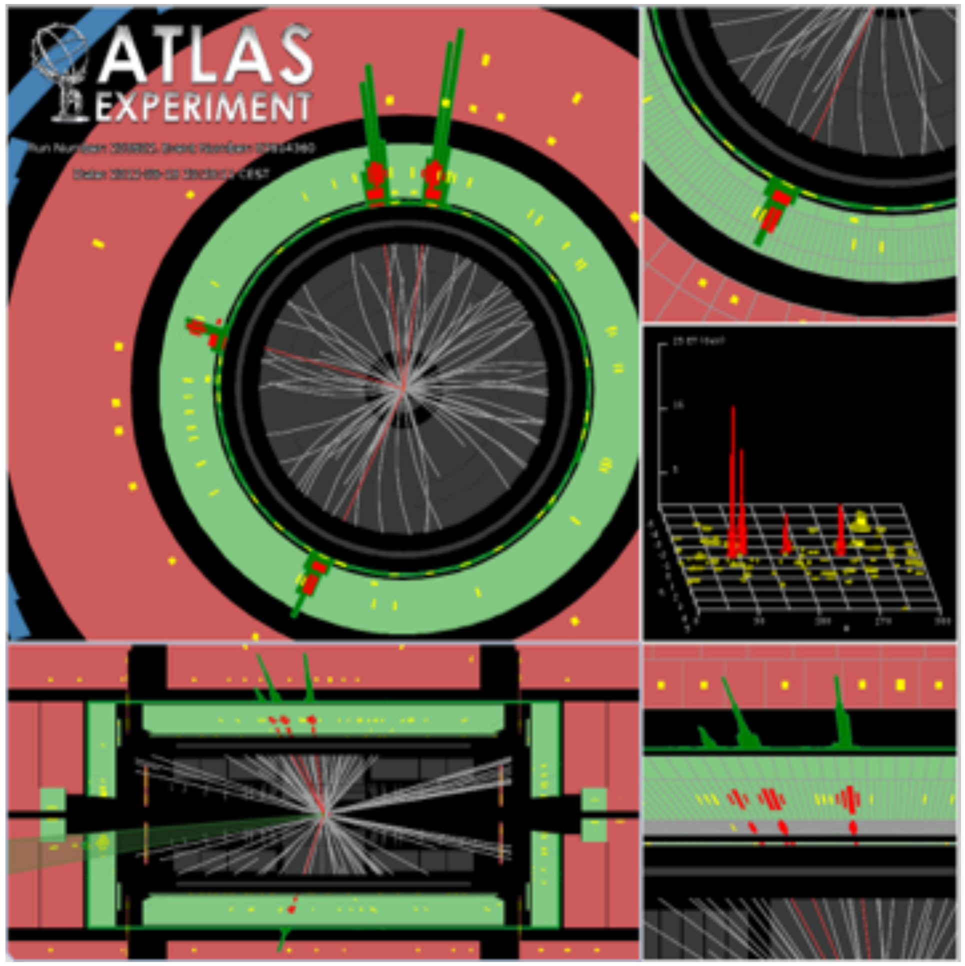
Mass Results

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 (< 2 GeV resolution), over a smoothly falling background
- Golden channels are $\gamma\gamma$ and ZZ



Two unconverted photons

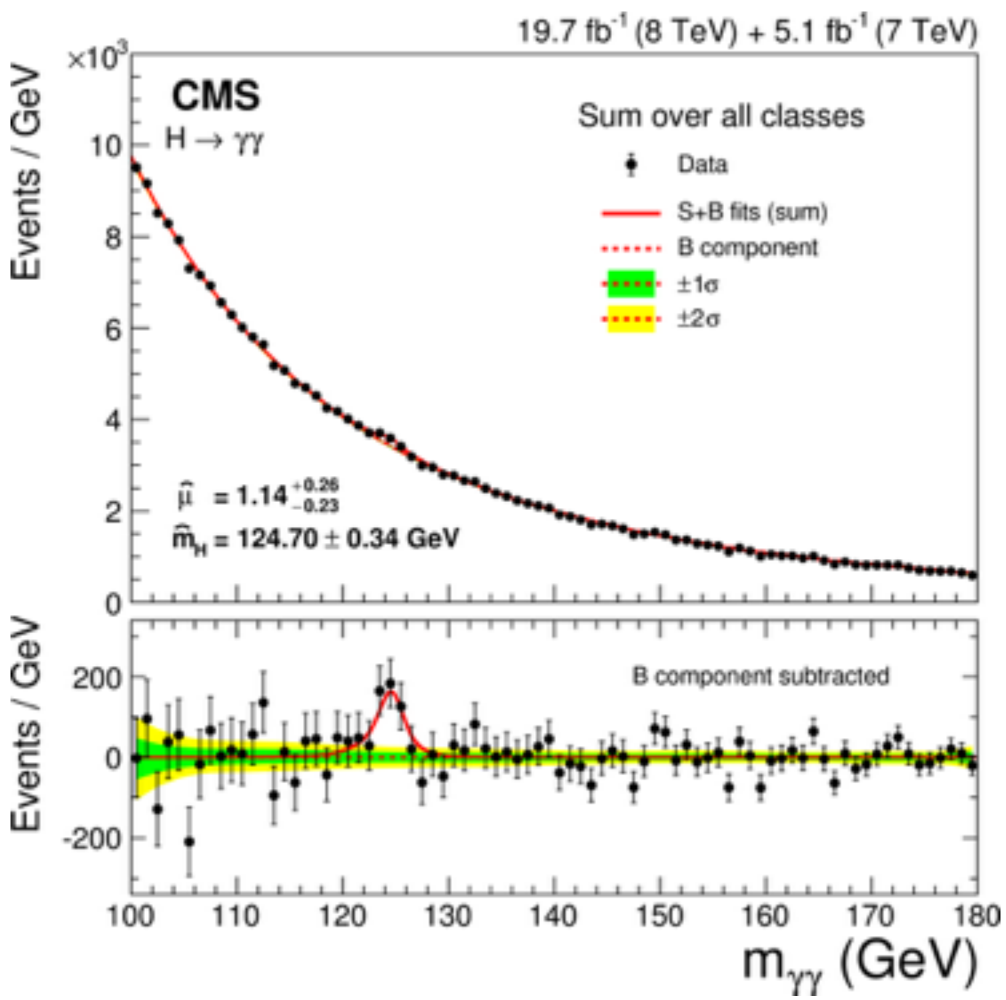


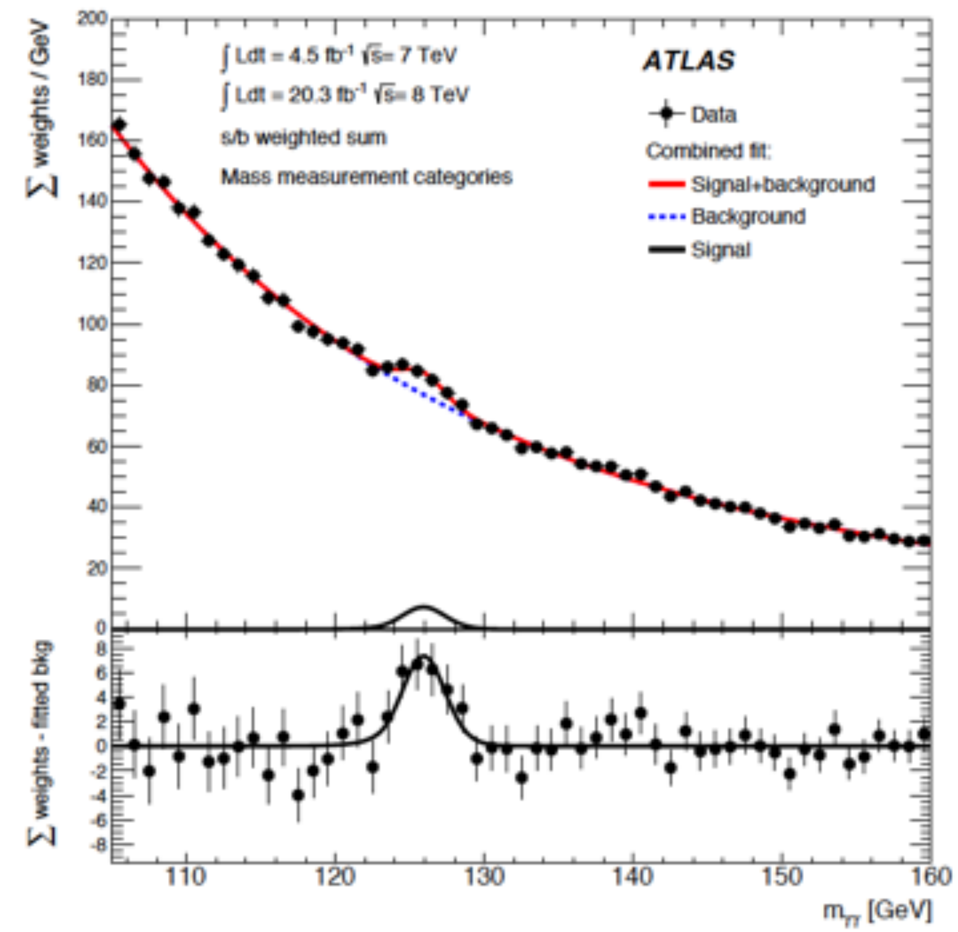
Four electrons, m = 124.6 GeV

High statistics channel, small S/B ratio but excellent mass resolution

To maximise S/B ratio and mass resolution, events are split into categories:

- for ATLAS: photon converted/unconverted $*$ p_T threshold $*$ η range
- for CMS: based on event topology (production mode) + Boosted Decision Tree (**BDT**) classifier





- Combined fit to all categories. Mass and signal strengths treated as parameters of interest
- Background (mostly irreducible SM $\gamma\gamma$) from fit to data

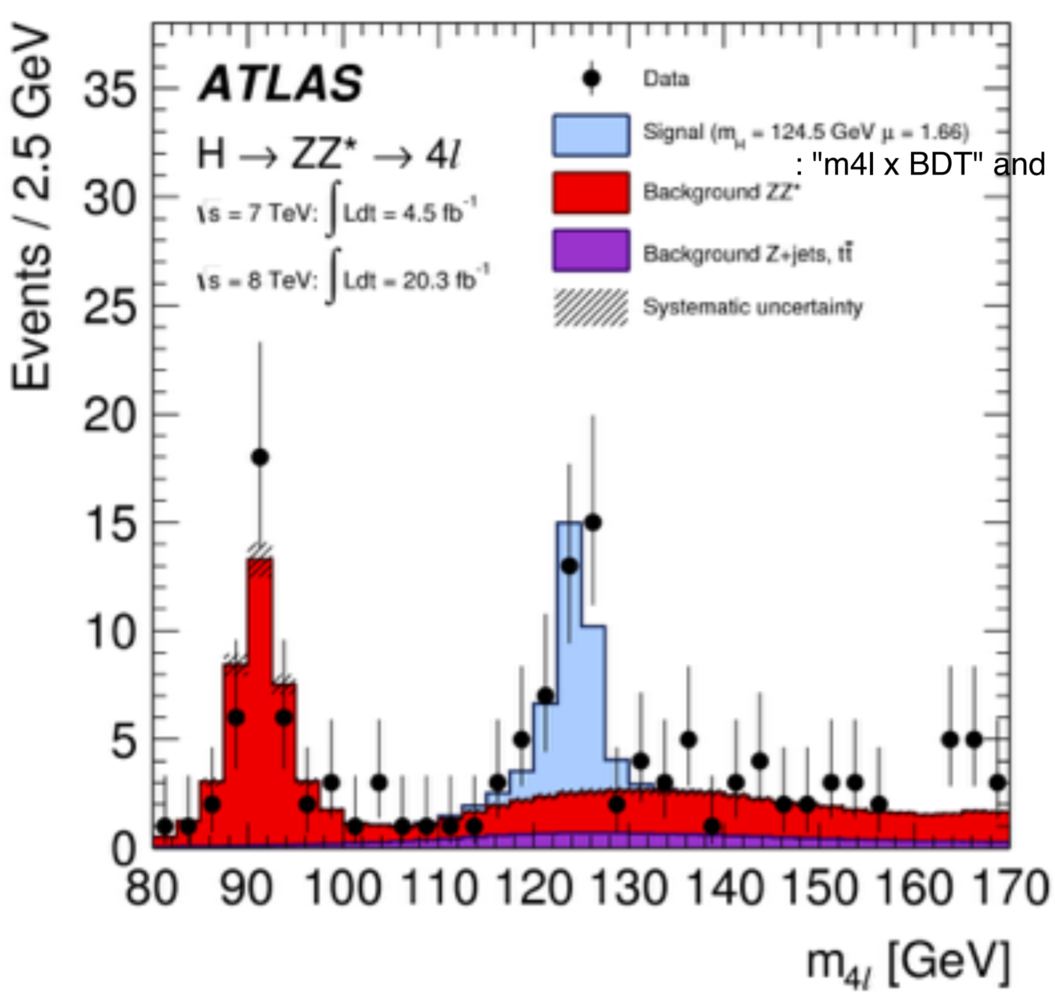
High S/B ratio in this channel (~2 in the mass window 120 - 130 GeV), despite the low statistics, with excellent mass resolution

Both experiments measure the mass fitting m(4ℓ) together with a multivariate discriminant:

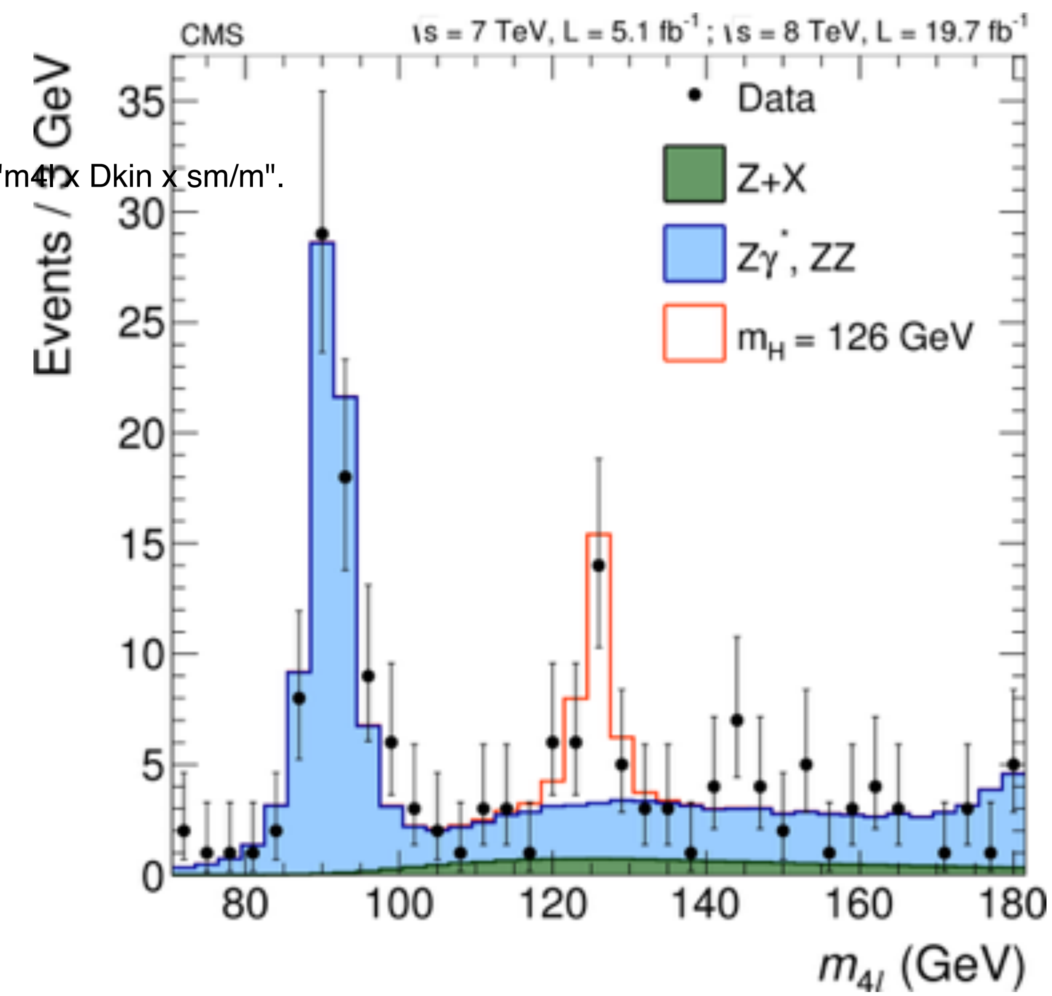
- ATLAS: Combined fit : **m(4ℓ)** $*$ **BDT**
- CMS: Combined fit to : **m(4ℓ)** $*$ **D_{kin}** $*$ **($\sigma_{m(4\ell)}$ / m(4ℓ))**

D_{kin} : kinematical discriminant

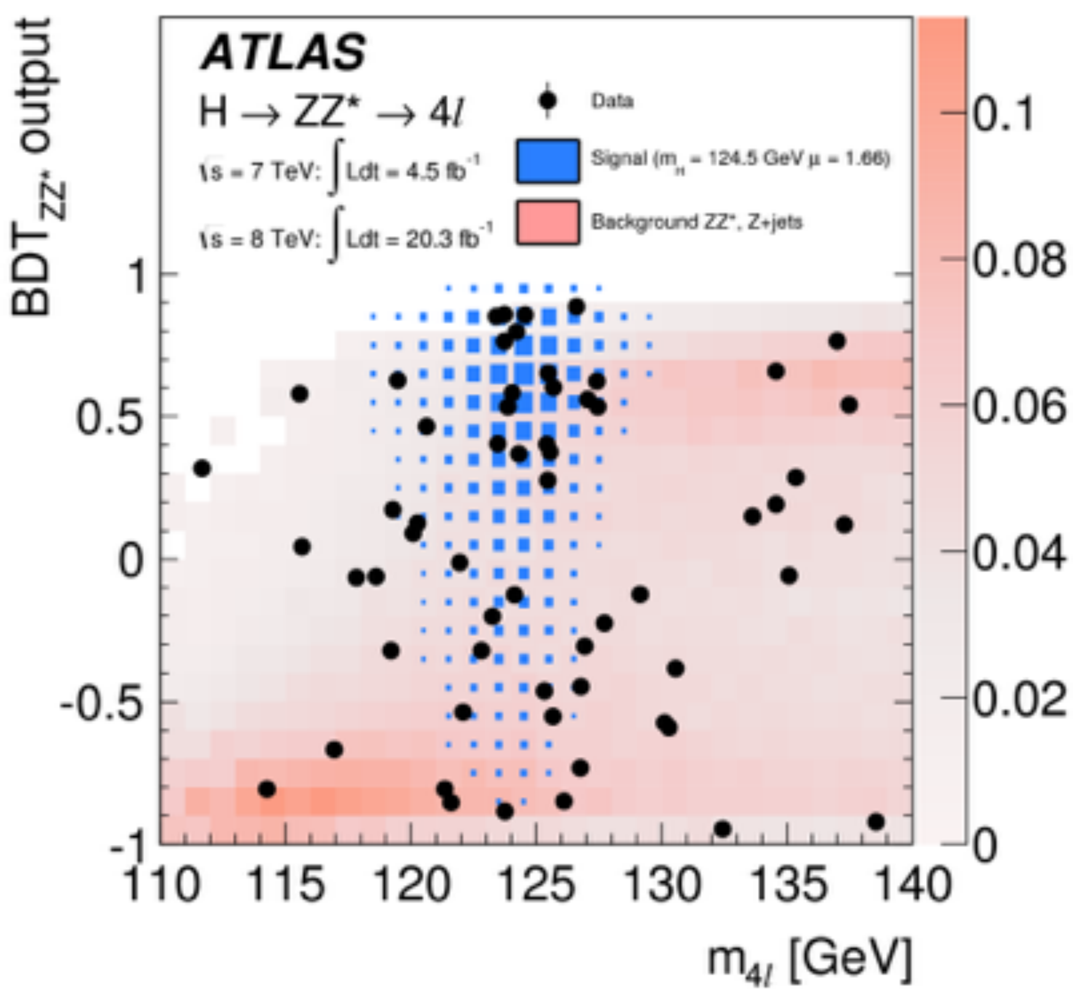
- Data-driven estimations for the reducible backgrounds (tt, Z+jets), MC for ZZ

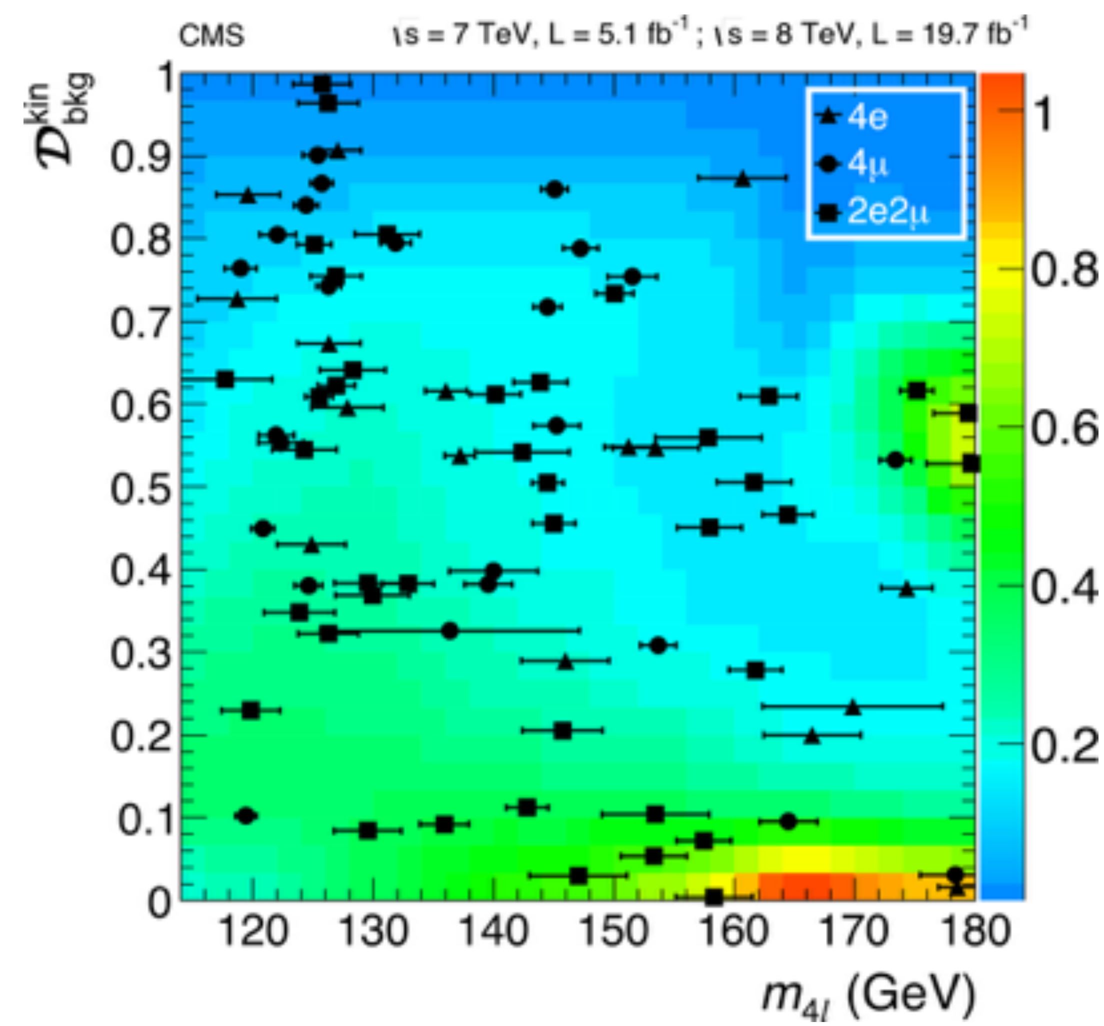


: "m4l x BDT" and "m4l x Dkin x sm/m".



- ATLAS:
  - **BDT** discriminant trained against the irreducible *ZZ** background, input variables:
    - p_T and η of 4ℓ system
    - **Matrix Element discriminant** $D_{ZZ^*} = \ln\left(\frac{|\mathcal{M}_{\rm sig}|^2}{|\mathcal{M}_{ZZ}|^2}\right)$
- CMS:
  - $\mathbf{D_{kin}}$ calculated from masses of the dilepton pairs and five decay angles



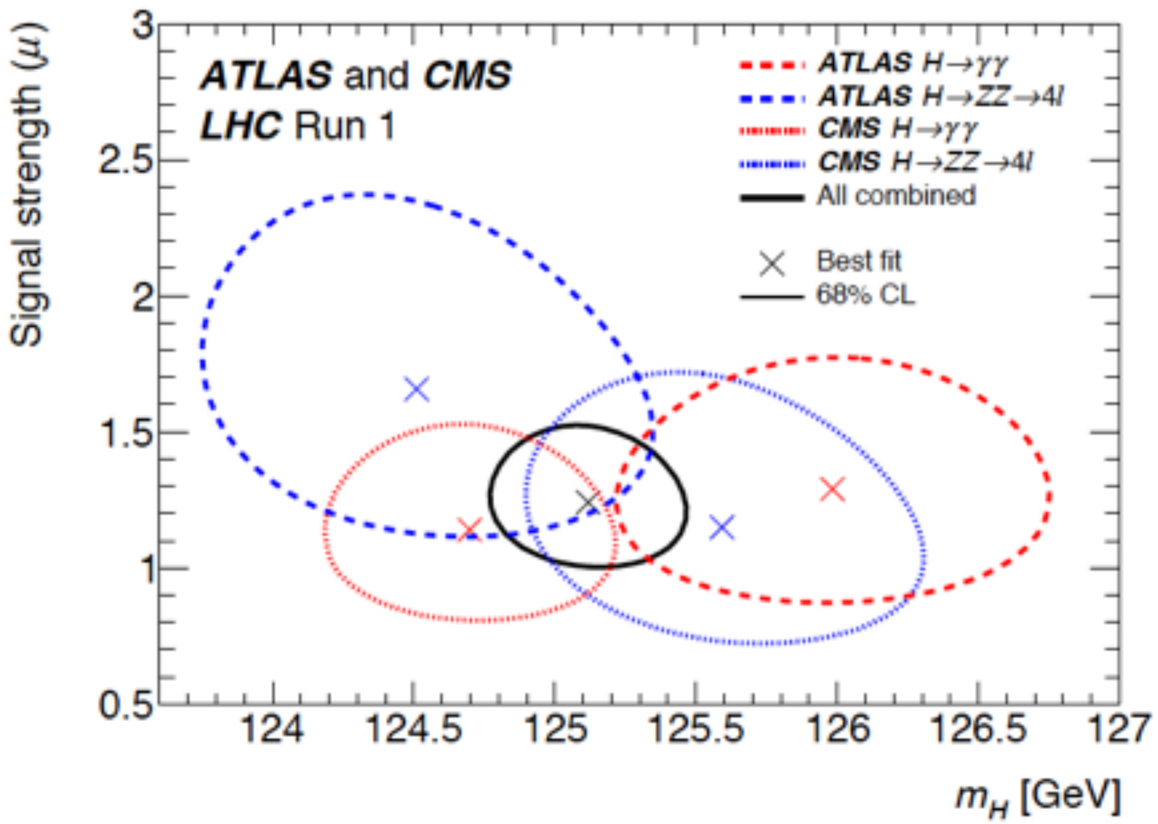


Individual and combined results

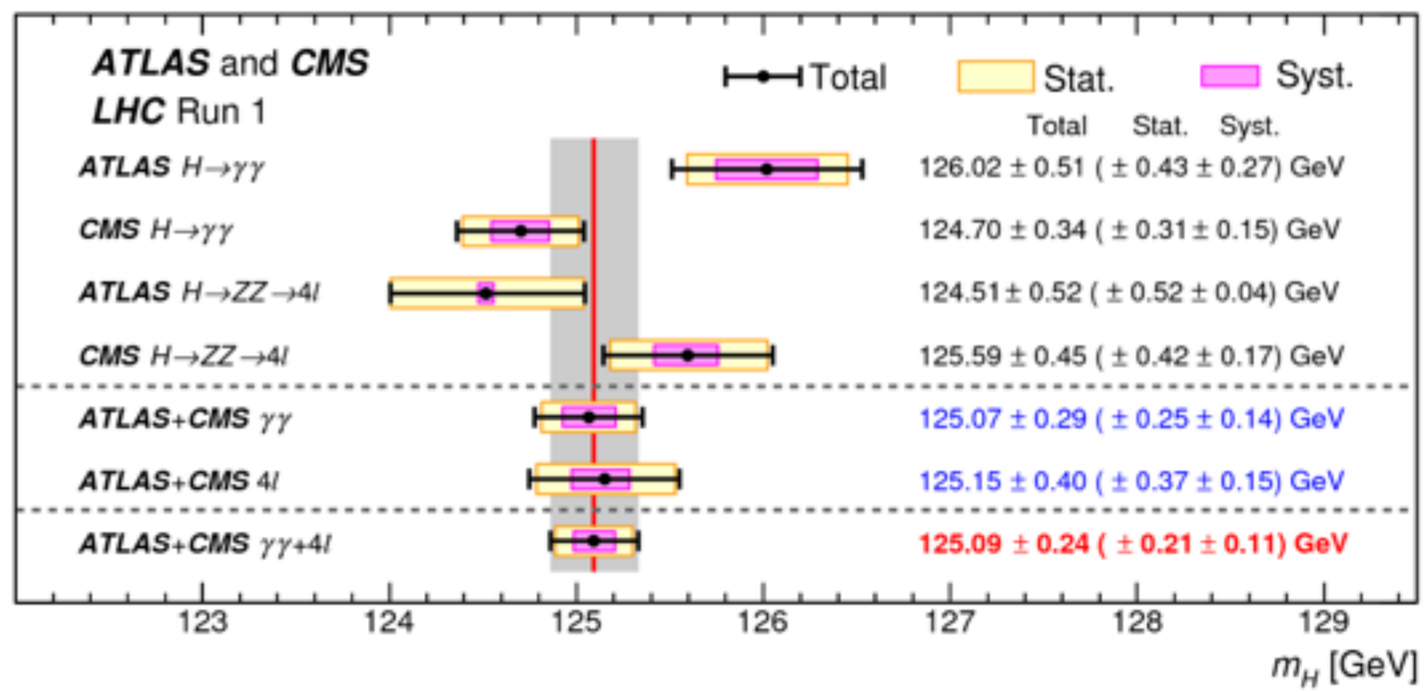
Profile likelihood ratio to be maximised,
in the asymptotic regime:
Signal strengths assumed to be
the same for ATLAS and CMS.

$$\Lambda(m_H) = \frac{L\left(m_H\,,\, \hat{\hat{\mu}}^{\gamma\gamma}_{ggF+t\bar{t}H}(m_H)\,,\, \hat{\hat{\mu}}^{\gamma\gamma}_{\mathrm{VBF}+VH}(m_H)\,,\, \hat{\hat{\mu}}^{4\ell}(m_H)\,,\, \hat{\hat{\theta}}(m_H)\right)}{L(\hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+t\bar{t}H}, \hat{\mu}^{\gamma\gamma}_{\mathrm{VBF}+VH}, \hat{\mu}^{4\ell}, \hat{\theta})}$$

Compatibility of the 4 measurements is 10%



$\gamma\gamma$ sensitive to different production modes

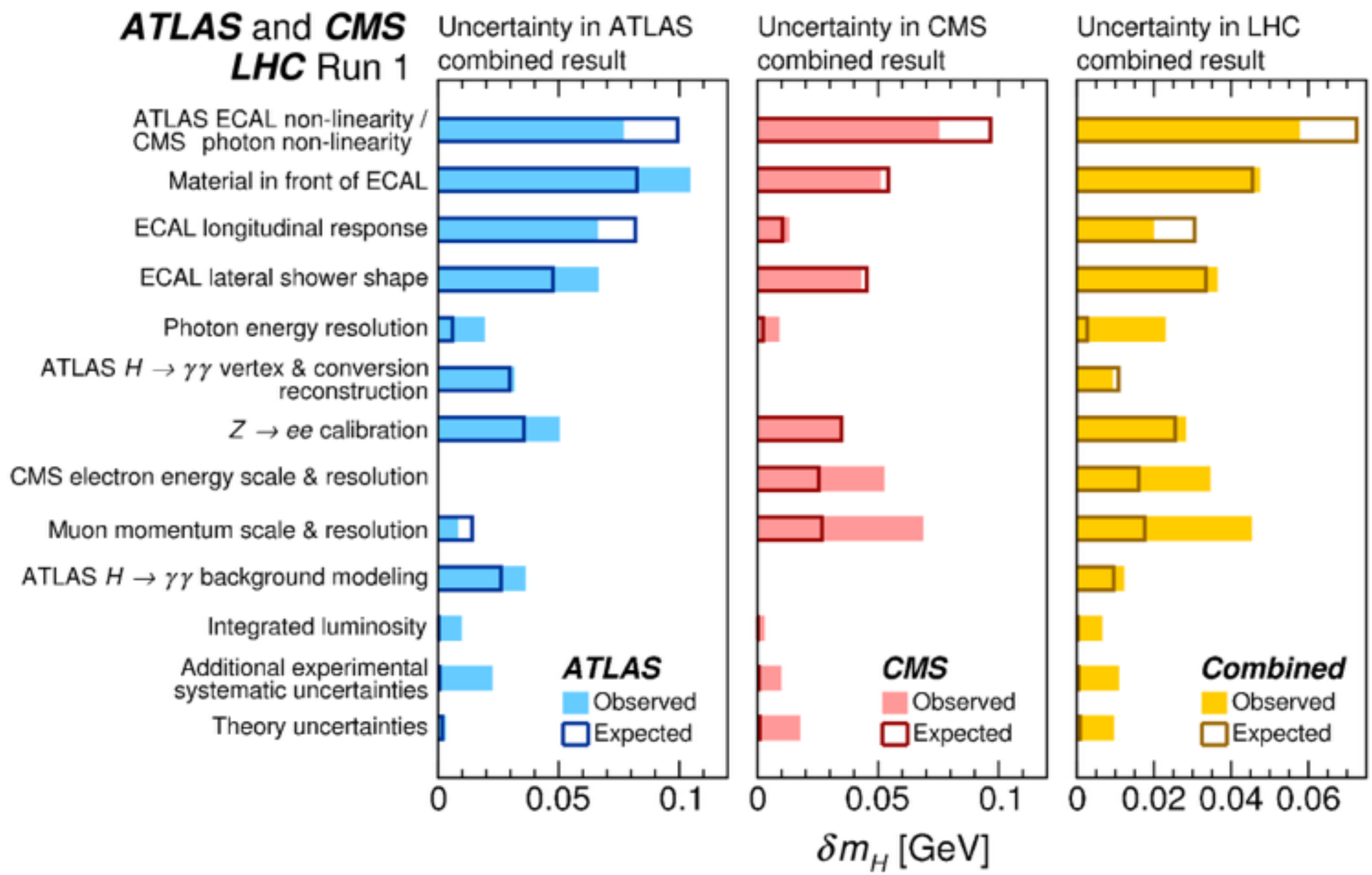


$$m_H = 125.09 \pm 0.21\ (\text{stat.}) \pm 0.11\ (\text{scale}) \pm 0.02\ (\text{other}) \pm 0.01\ (\text{theory})\ \ \text{GeV}$$

Individual and combined mass results

Same dominant uncertainties for the individual experiments and their combination:

- electromagnetic energy scale and resolution
- muon momentum scale and resolution
- theory uncertainties are negligible



Spin and parity quantum numbers measurement in ATLAS

Spin/parity measurement approach: ATLAS

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 (effective field theory, cut-off scale Λ = 1 TeV)
- All bosonic channels used (only *ZZ* and *WW* for spin-1 studies, due to Landau-Yang theorem, and for parity, due to poor discrimination in $\gamma\gamma$)

SM coupling

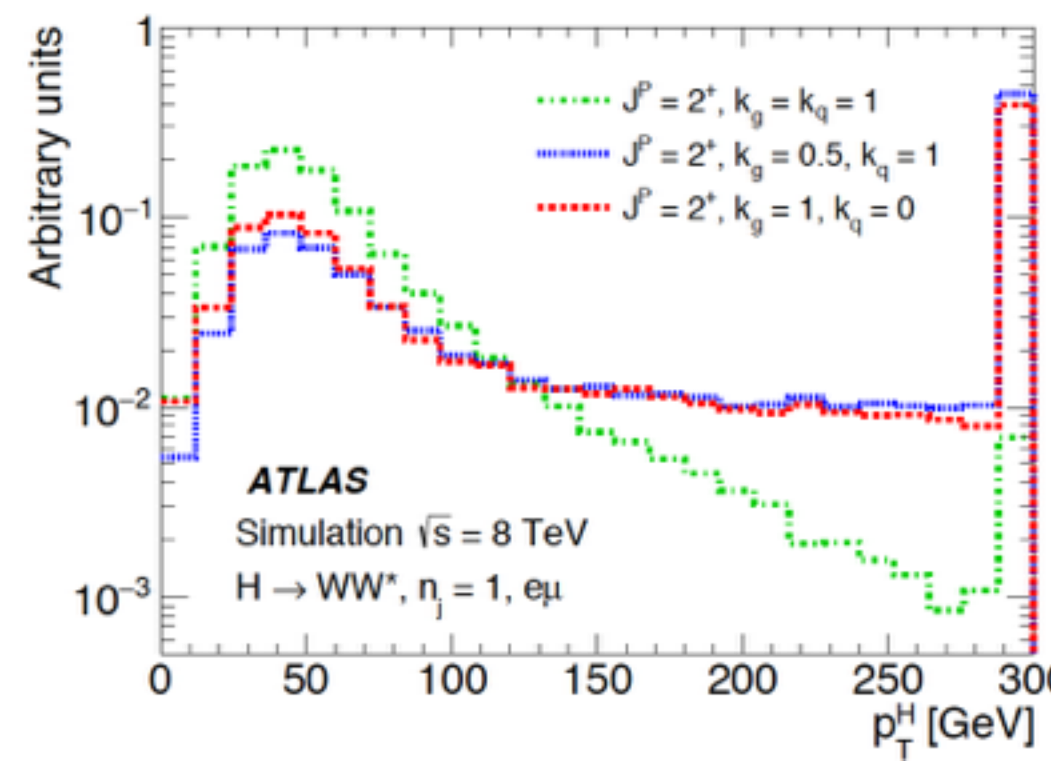
$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu} \right] - \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right] \Big\} X_0.$$

BSM CP-even coupling

BSM CP-odd coupling

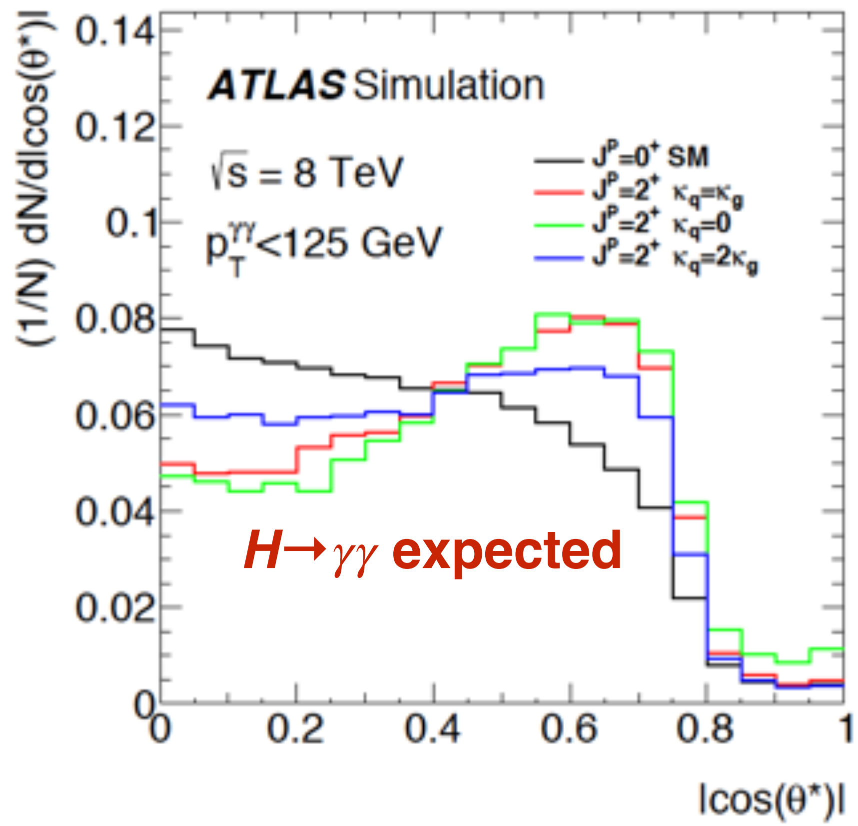
- Spin=2: Higgs-like graviton-inspired resonance, with universal [gravity-like] and non-universal couplings to quarks and gluons (in various k_g, k_q fractions)
  - NLO effects lead to a tail in p_T^H for a spin-2 Higgs-like boson when jets are present
    - cut on p_T^H to stay within EFT validity

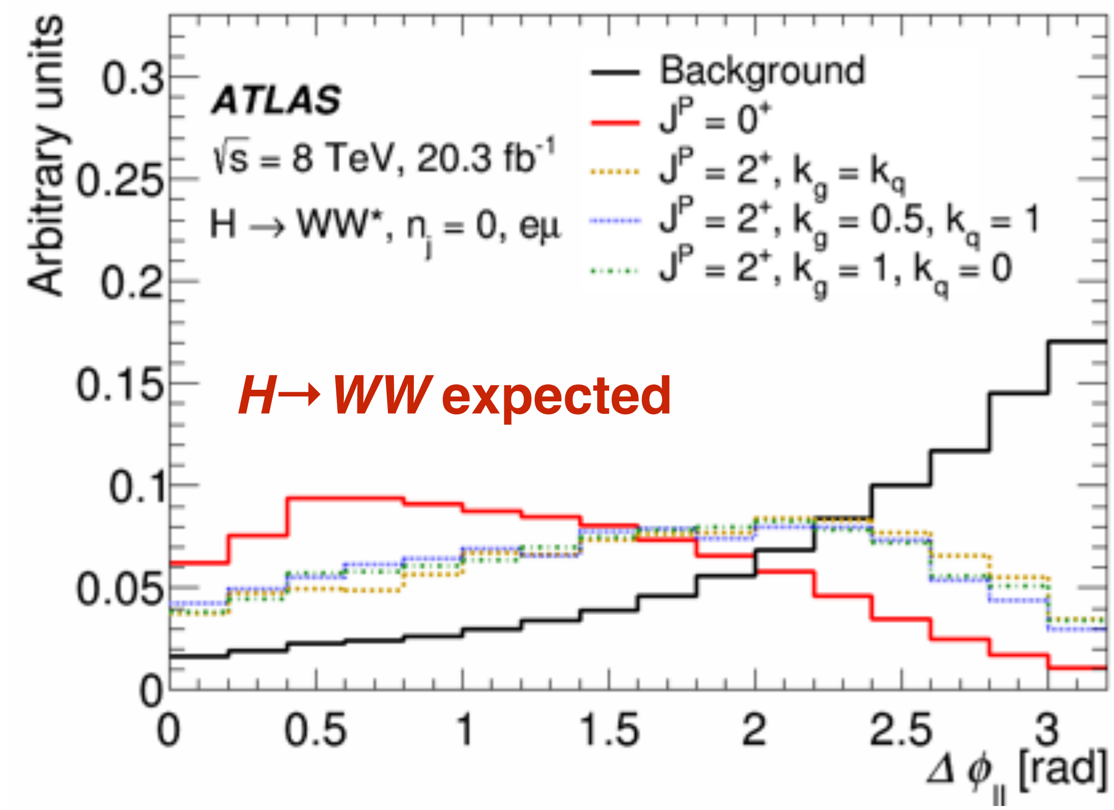
Choice of QCD couplings		p_T^X cut-off (GeV)	
$\kappa_q = \kappa_g$	Universal couplings	–	–
$\kappa_q = 0$	Low light-quark fraction	300	125
$\kappa_q = 2\kappa_g$	Low gluon fraction	300	125

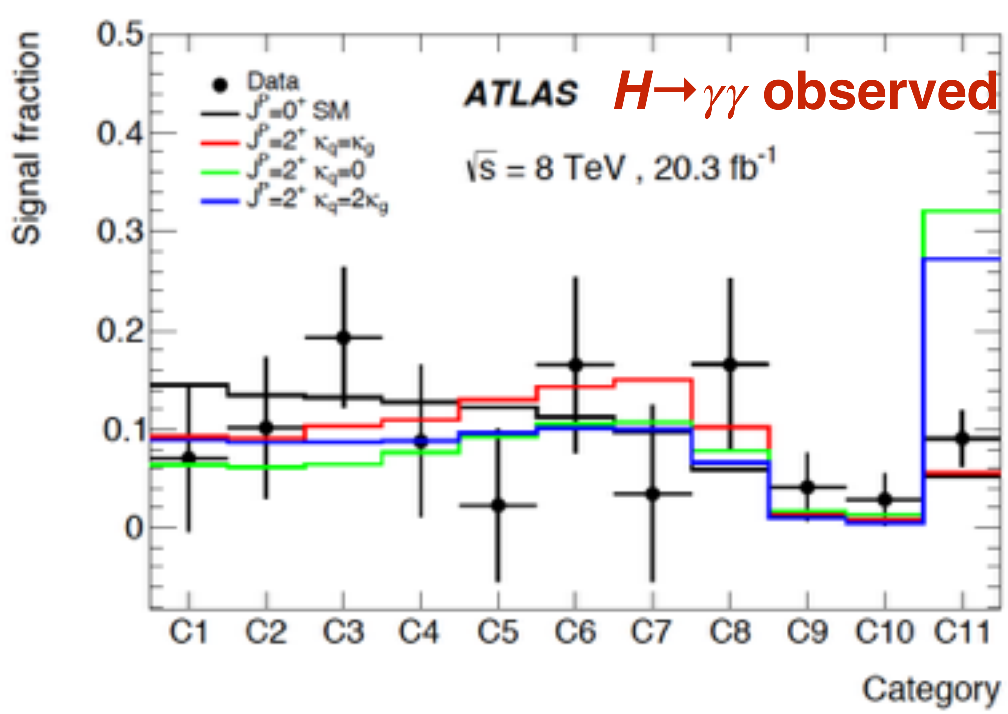


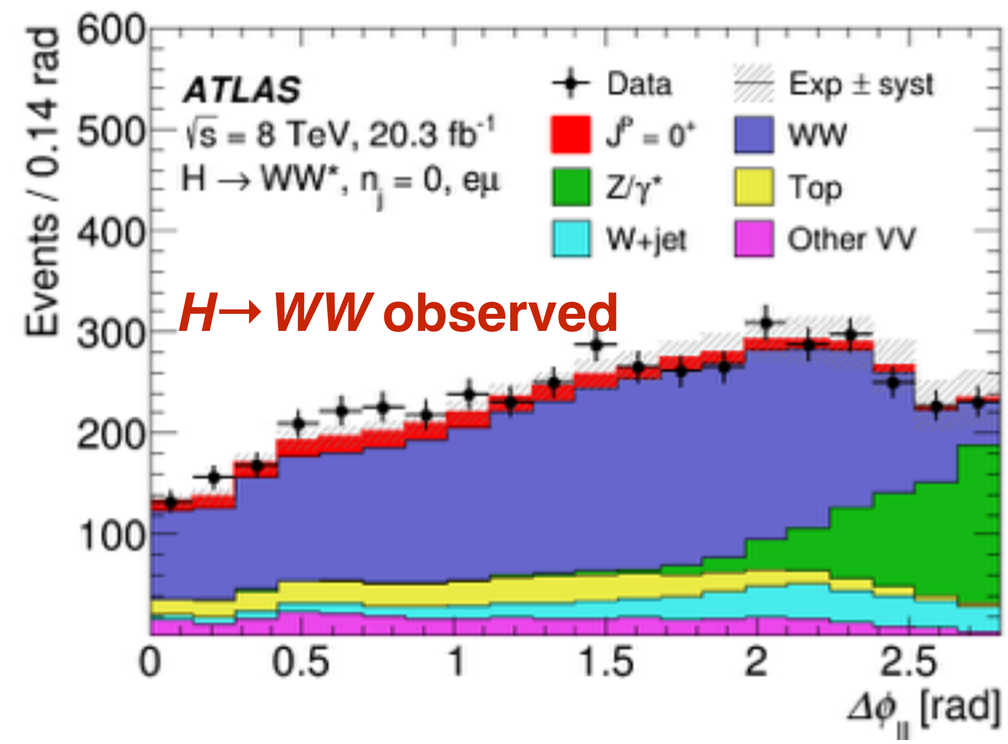
Spin: discriminating variables: ATLAS

Also ZZ used (see slide 17)







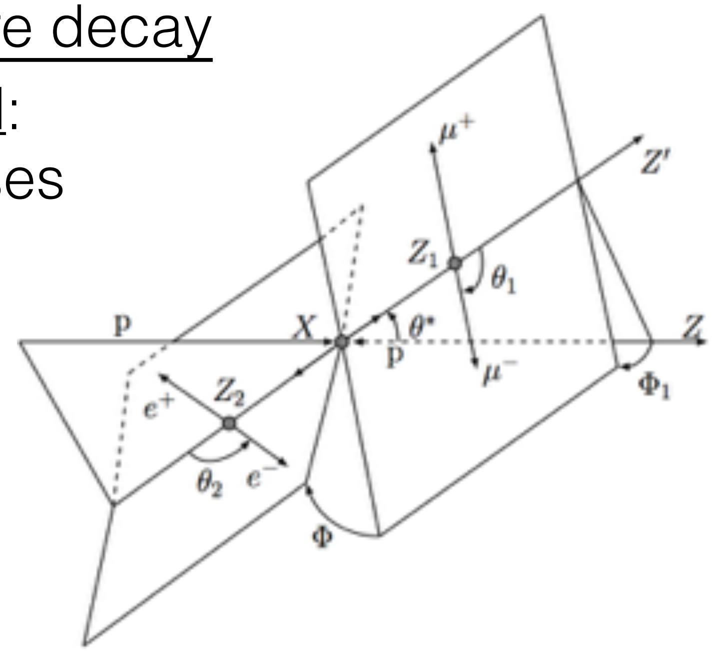


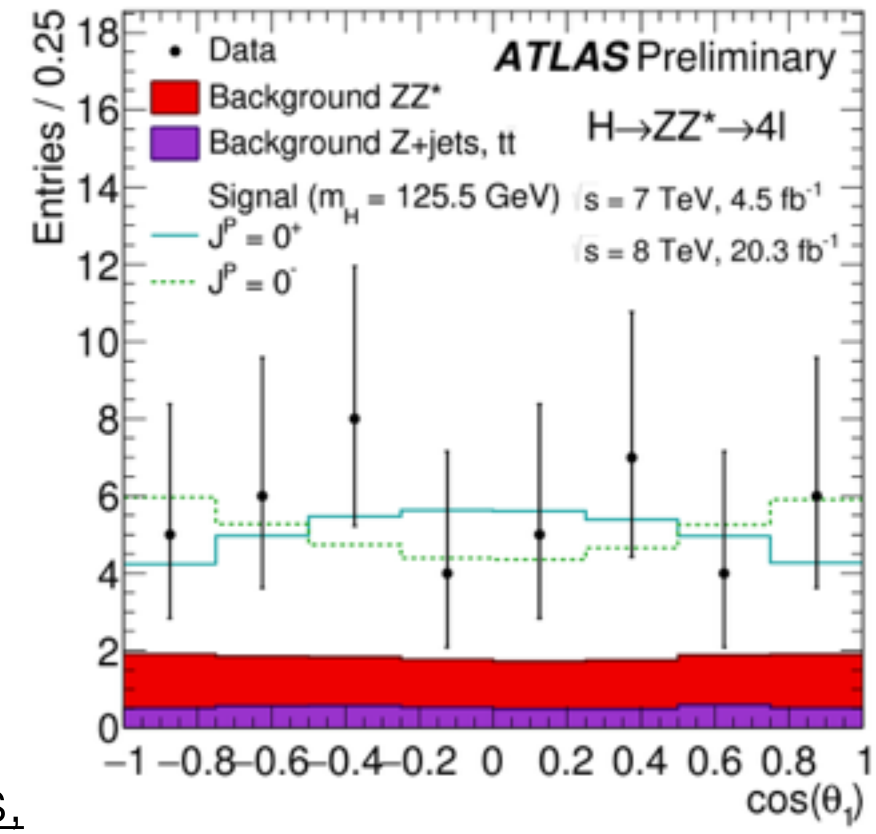
Parity: discriminating variables: ATLAS

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

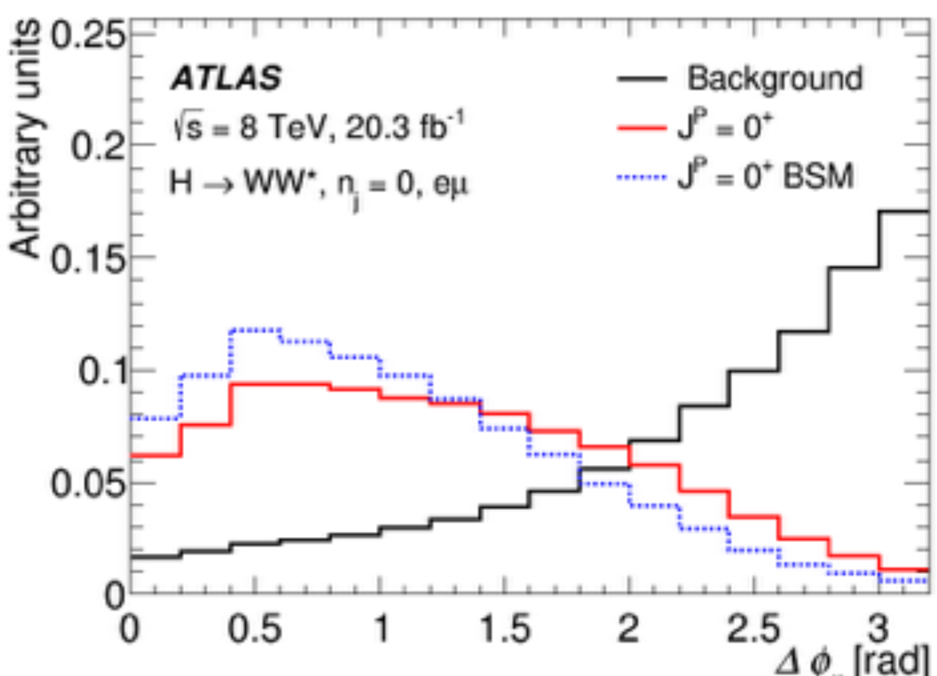
$cos(\theta_1), cos(\theta_2), \Phi, m_{12}, m_{34}$
CP Sensitive

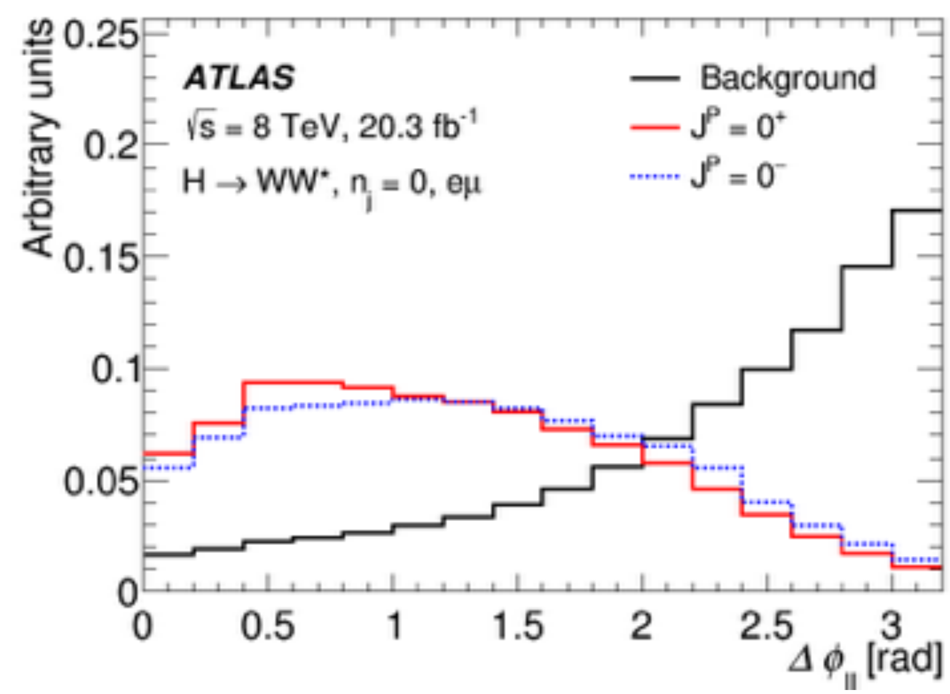
$m_{4l}, cos(\theta^*), \Phi_1$
Background rejecting





WW → *eνμν* is harder due to the presence of the two neutrinos, but the angular difference between *e* and *μ* is sensitive to spin/parity.

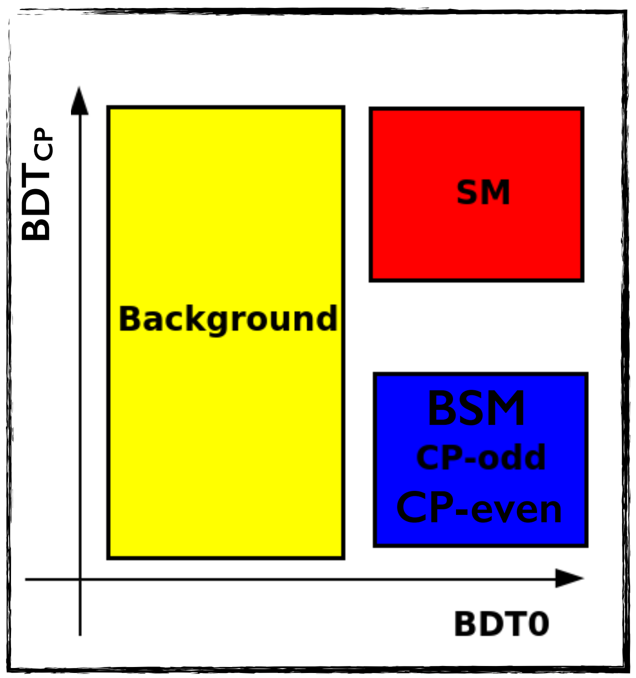


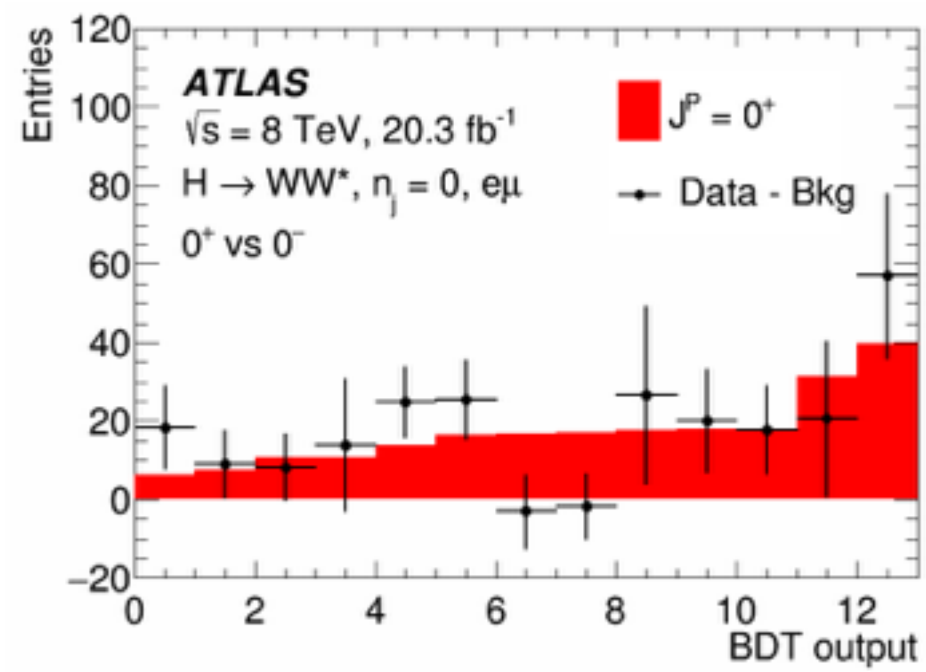


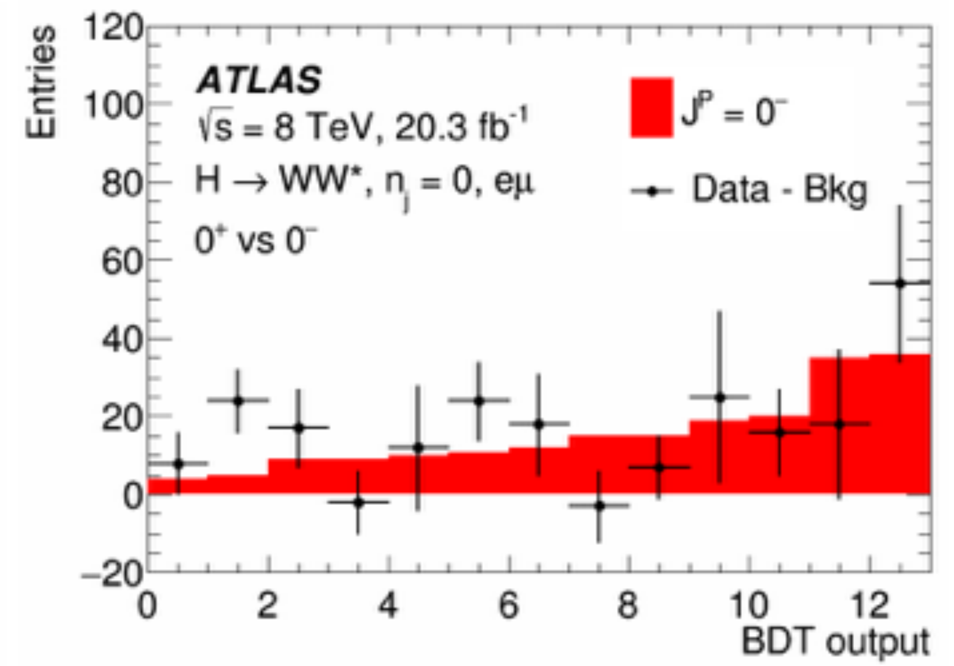
Final discriminants: ATLAS

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

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

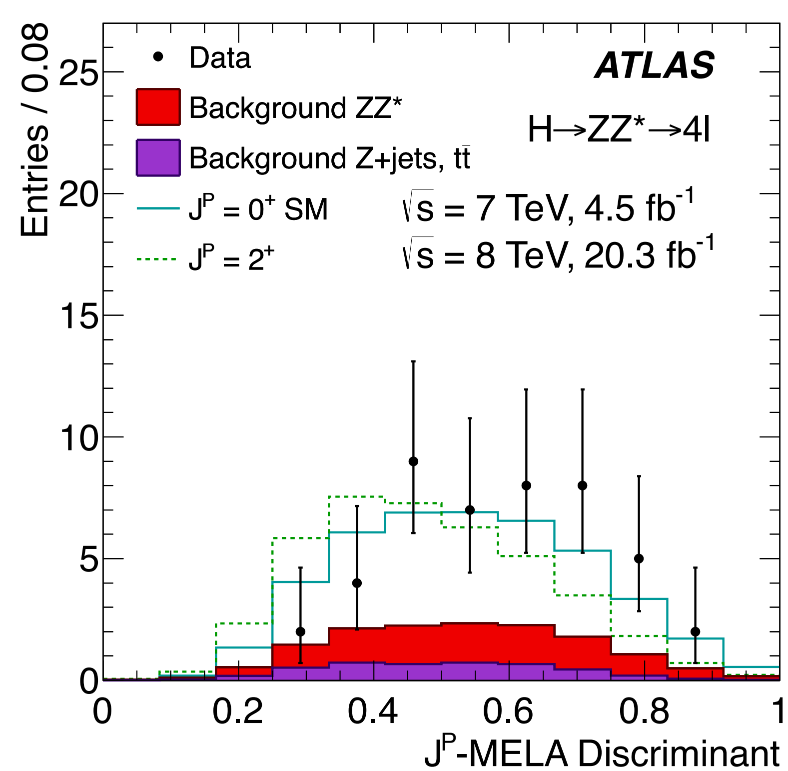


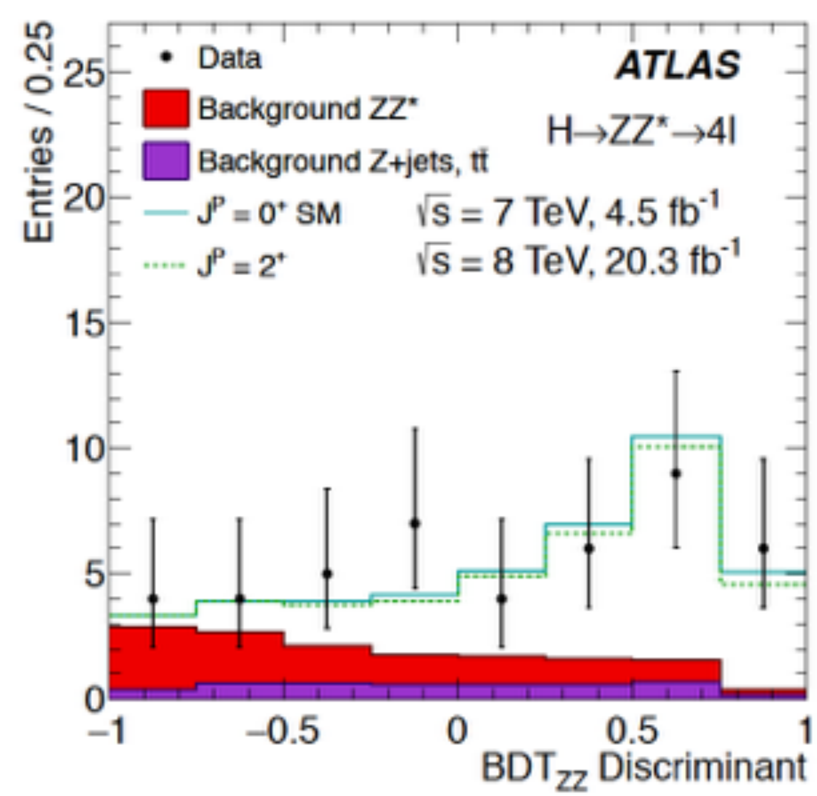




ZZ fits a **Matrix Element** discriminant (**MELA**), in a tight mass window. Optimal observables used as input variables.

In addition, a **BDT** analysis, with similar sensitivity, is performed.





Spin and parity quantum numbers measurement in CMS

CMS chooses the anomalous-couplings approach, expanding the amplitude as:

$$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

SM coupling

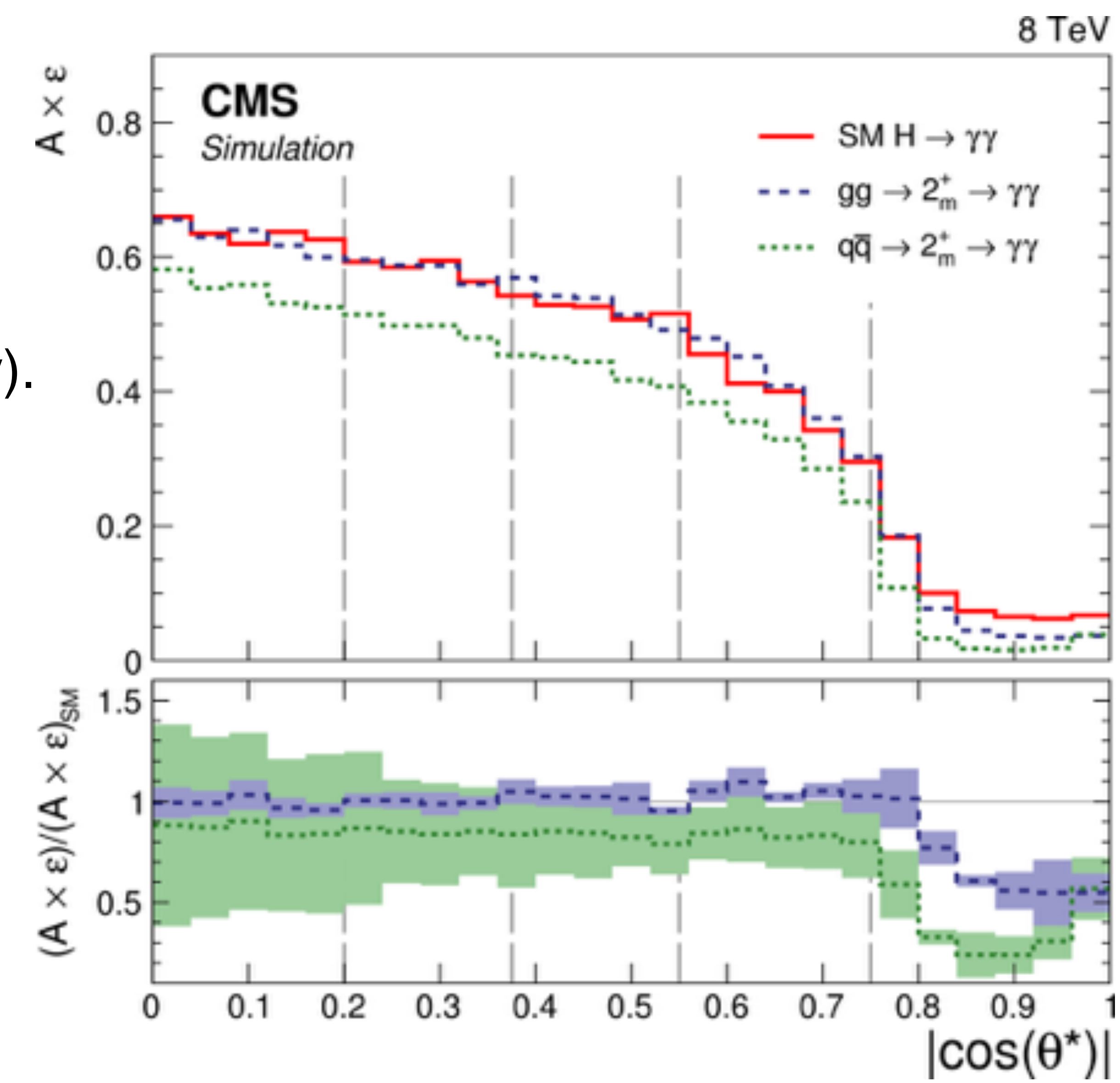
BSM CP-even coupling

BSM CP-odd coupling

The spin analysis investigates the "minimal" spin-2 model and scans over the fraction of qq production, from 0 to 100% (also the case for ATLAS previously).

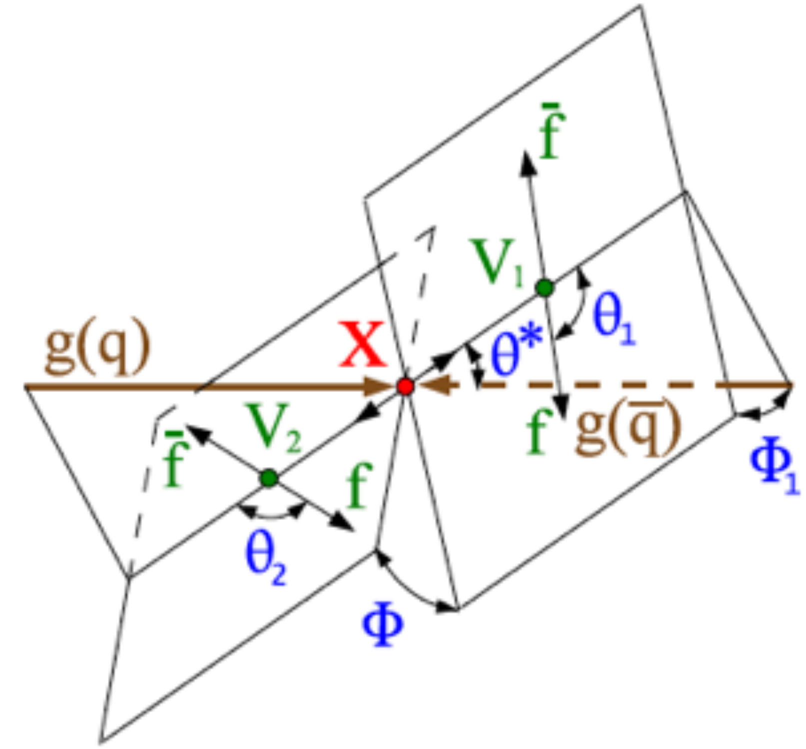
Variable of interest is again the polar angle in the Collins-Soper frame:

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1 + \left(p_T^{\gamma\gamma} / m_{\gamma\gamma}\right)^2}} \frac{2\, p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$



ZZ: spin/parity discriminating variables: CMS

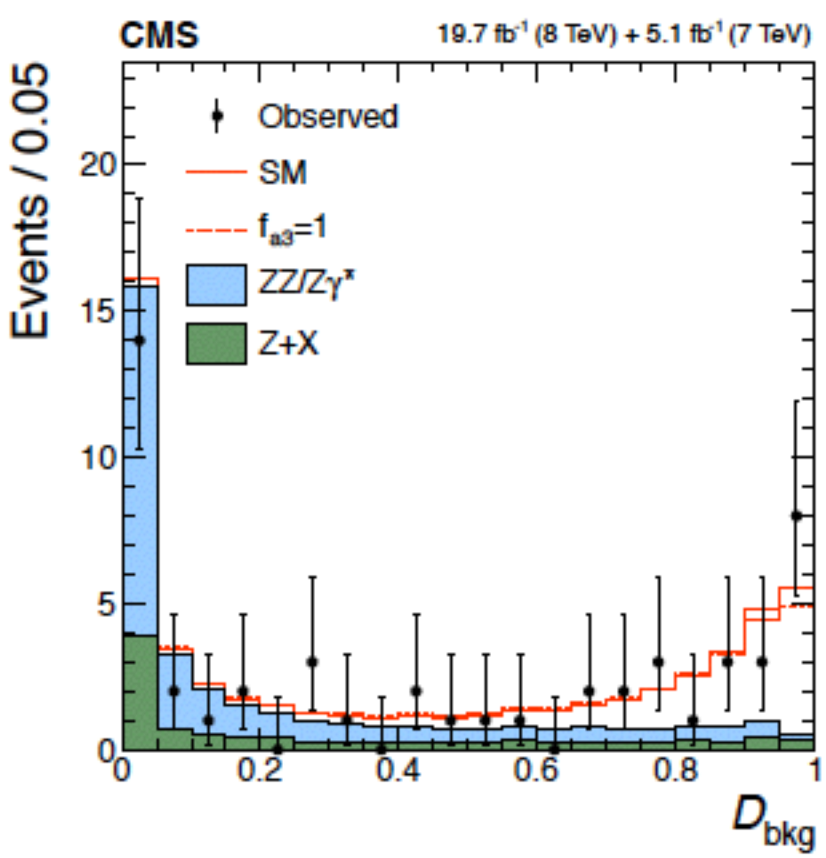
CMS uses the same approach for spin and parity measurement.

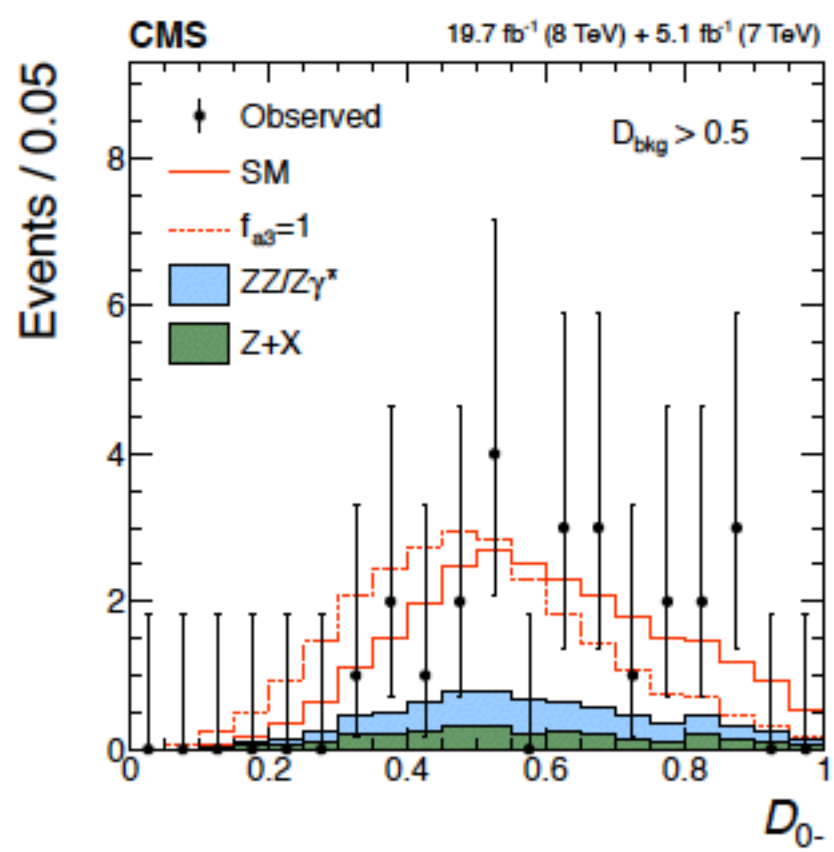


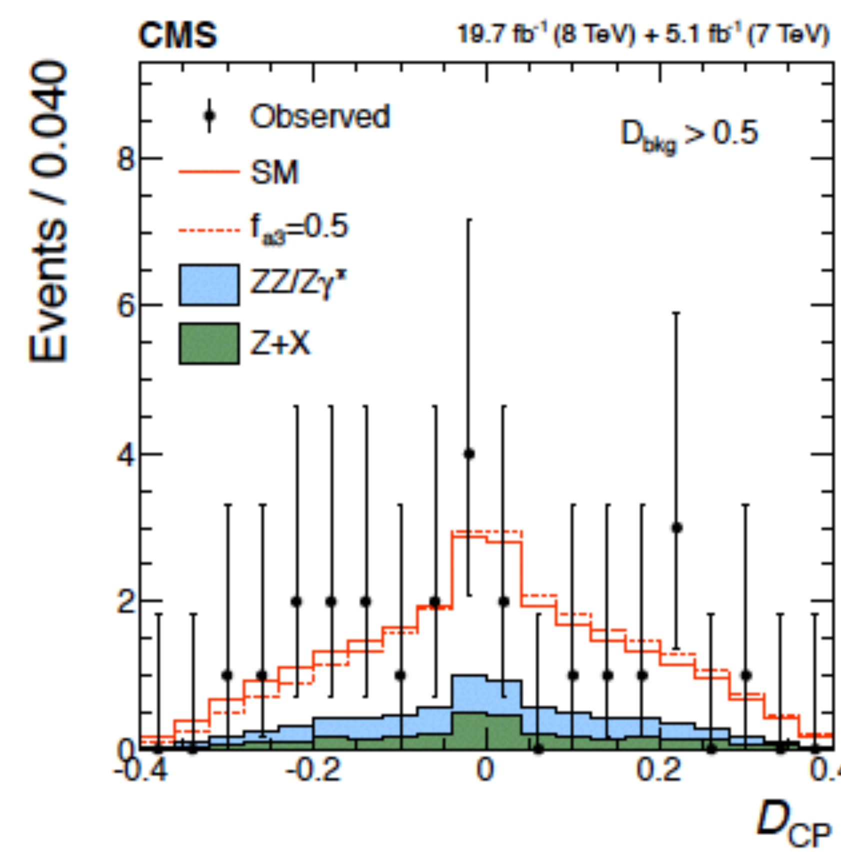
In the ZZ channel, **8** sensitive variables are available:

- 5 decay angles $(\Omega = \theta^*, \phi_1, \theta_1, \theta_2, \phi)$
- 2 invariant masses (for the 2 lepton pairs) (m_1, m_2)
- the total invariant mass of the system $(m_{4\ell})$

A matrix-element discriminant (**MELA**) is used to build templates for the background and the various signal hypotheses:



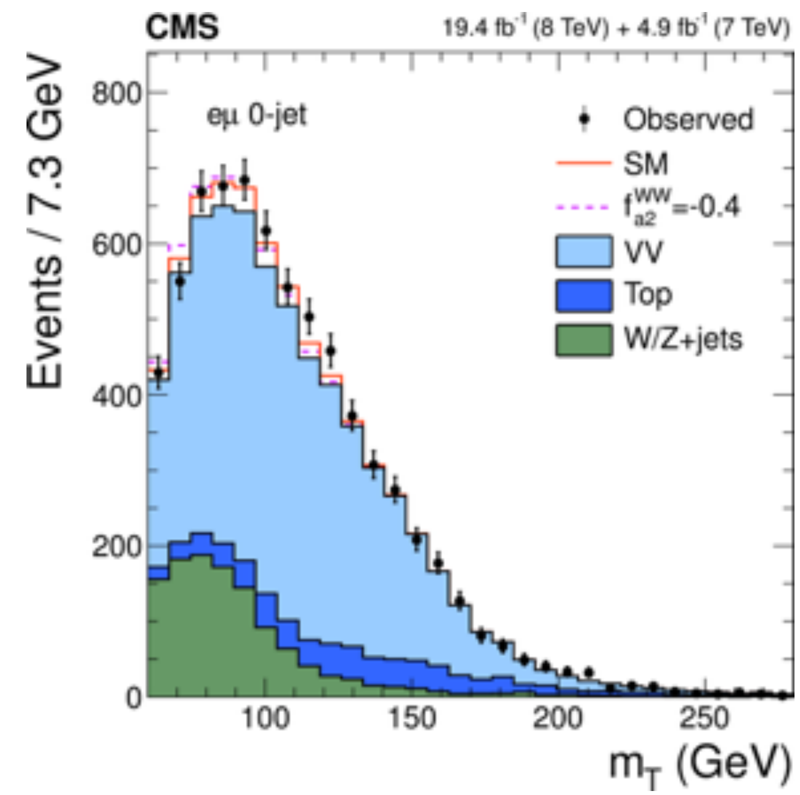




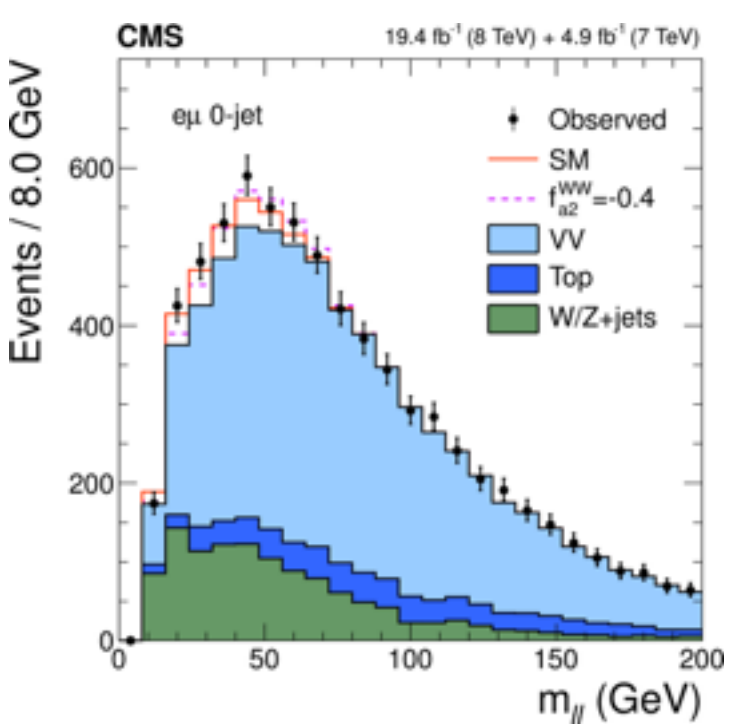
WW: spin/parity discriminating variables: CMS

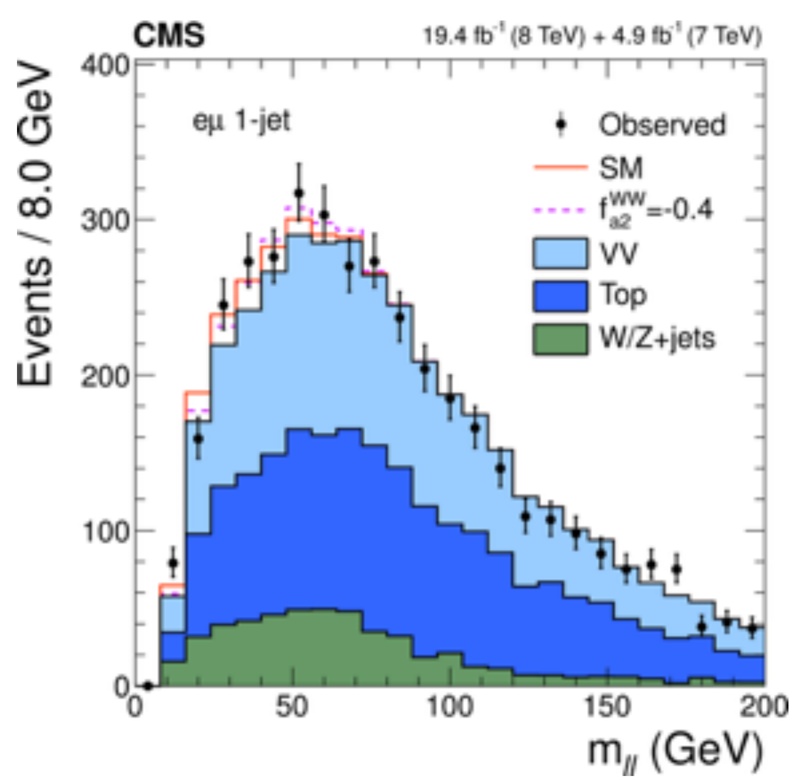
In the WW channel, sensitive variables are the **dilepton mass** and the **transverse mass**, while the **azimuthal angular difference** is disregarded since correlated.

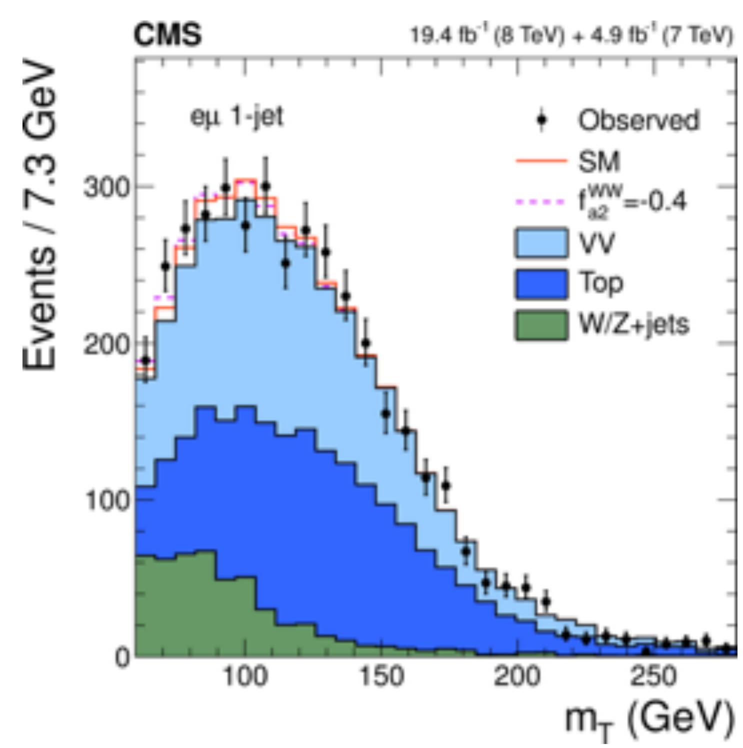
Like in ATLAS, only the *eμ* final state used.
Both 0- and 1-jet final states are taken into account.



$$m_T^2 = 2\, p_T^{\ell\ell}\, E_T^{miss}\, (1\, - \cos \Delta\phi_{\ell\ell,E_T^{miss}})$$





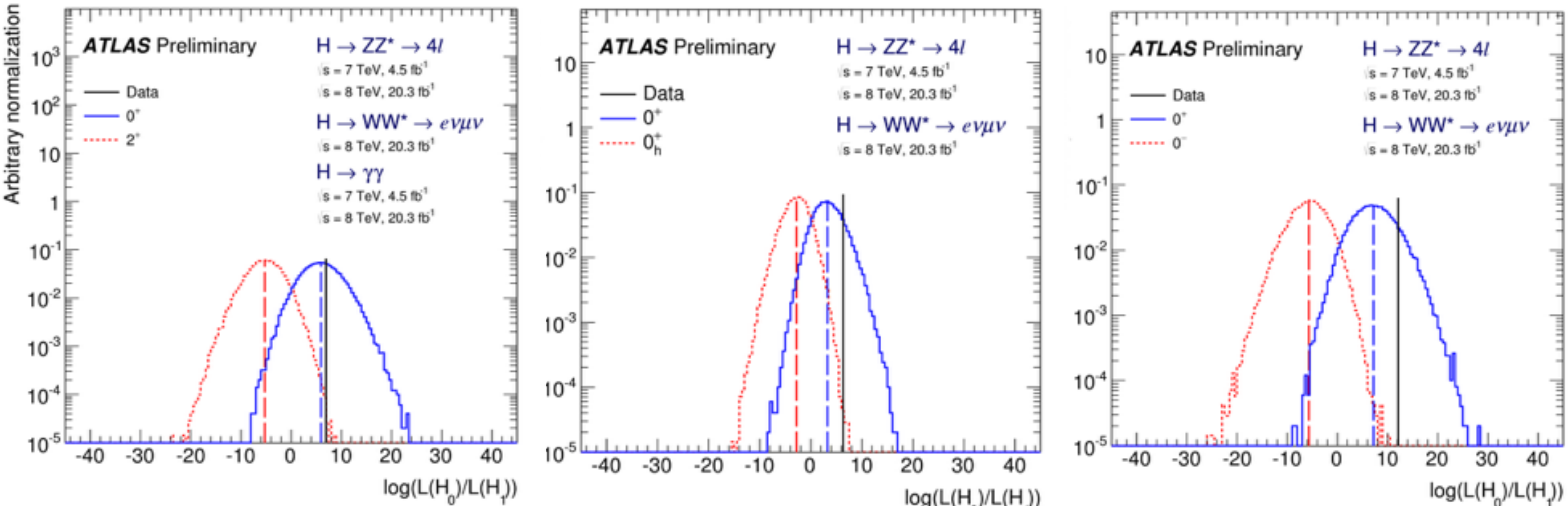


Spin and parity quantum numbers results in ATLAS and CMS

In all cases, the signal rate is fitted independently from the spin/parity hypothesis, in order not to bias properties measurement with constraints on the couplings. In the following slides, "SM 0^+" allows the signal rate to be non-standard.

Fixed-hypothesis results: ATLAS

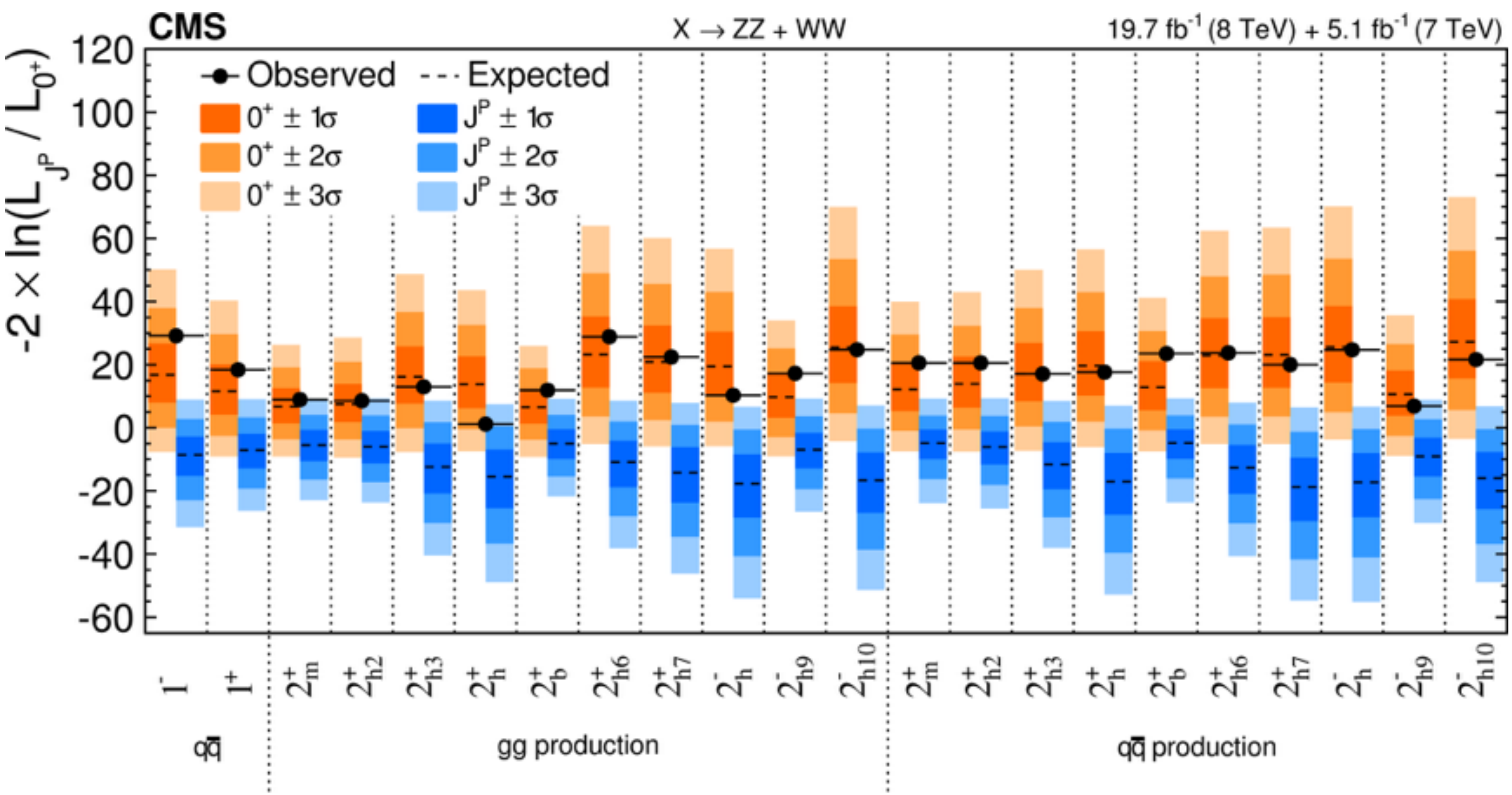
Combined results for SM 0^+ vs a fixed spin-0^-, BSM spin-0^+ or spin-2 hypothesis: all non-SM models excluded at **> 99% CL**



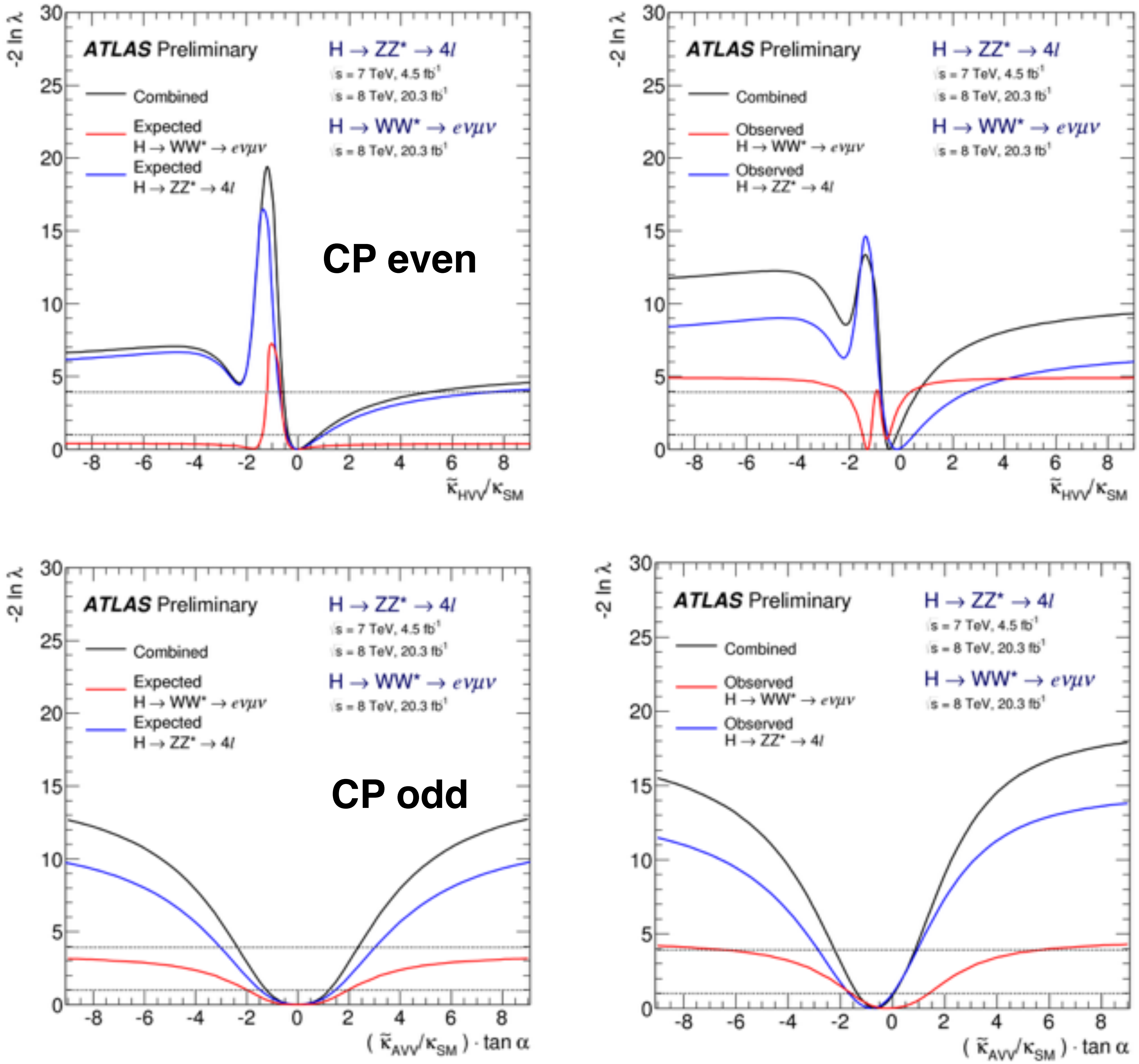
Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL_S (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	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	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

Fixed-hypothesis results: CMS

Combined results for SM 0^+ vs a fixed spin-1 or spin-2 hypothesis:
all non-SM models excluded at **> 99.9% CL**



CP-mixing results: ATLAS

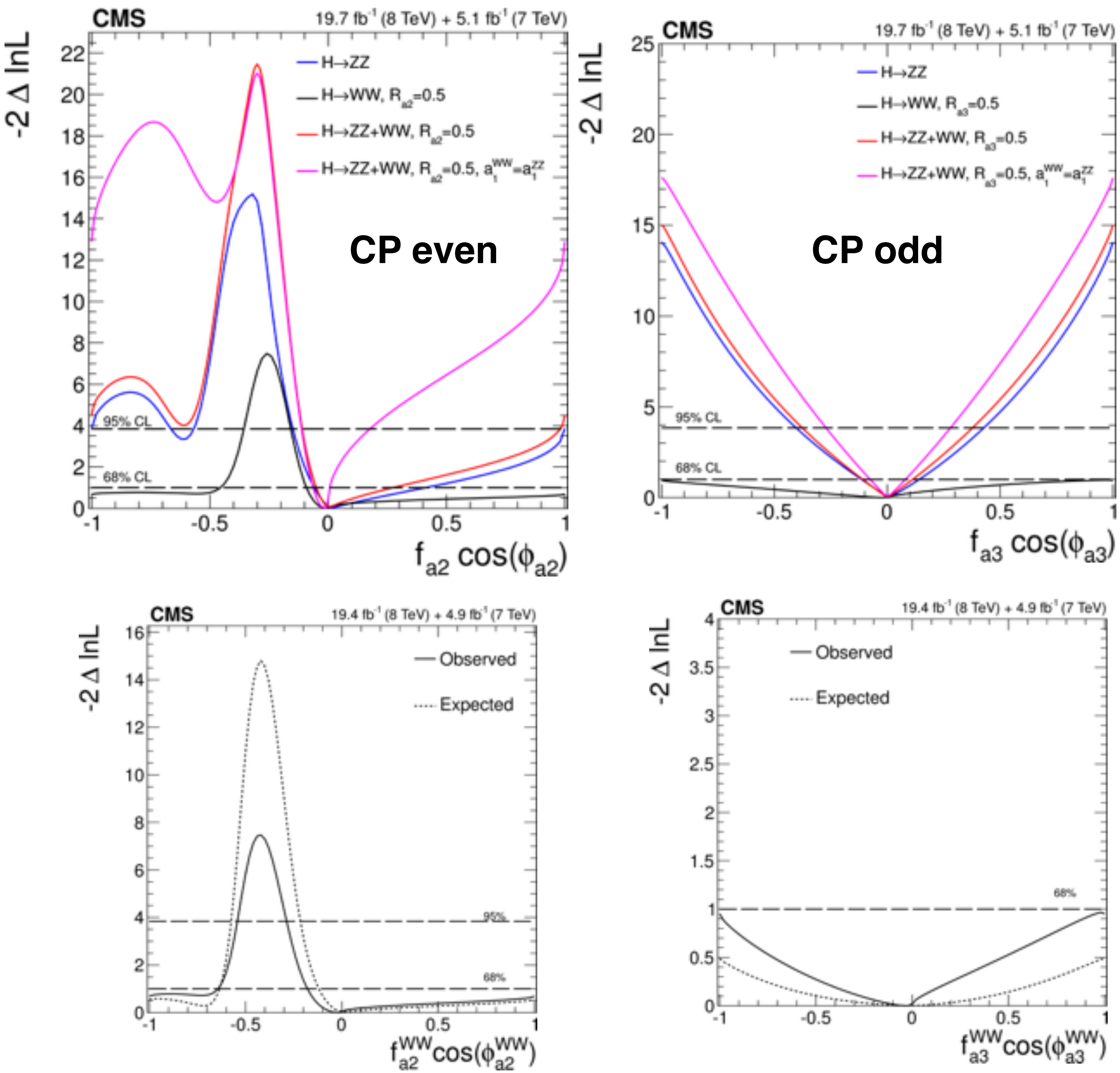


Scanning on possible components of CP-odd or CP-even higher-orders mix with SM (only one at a time).

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

No significant deviation from pure SM composition found.

CP-mixing results: CMS



No significant deviation from pure SM composition found.

Conclusions

The final results for the measurement of the Higgs boson properties, with the full Run1 dataset, collected and analysed by the ATLAS and CMS collaborations, have been presented.

No significant deviation from the Standard Model expectations has been found.

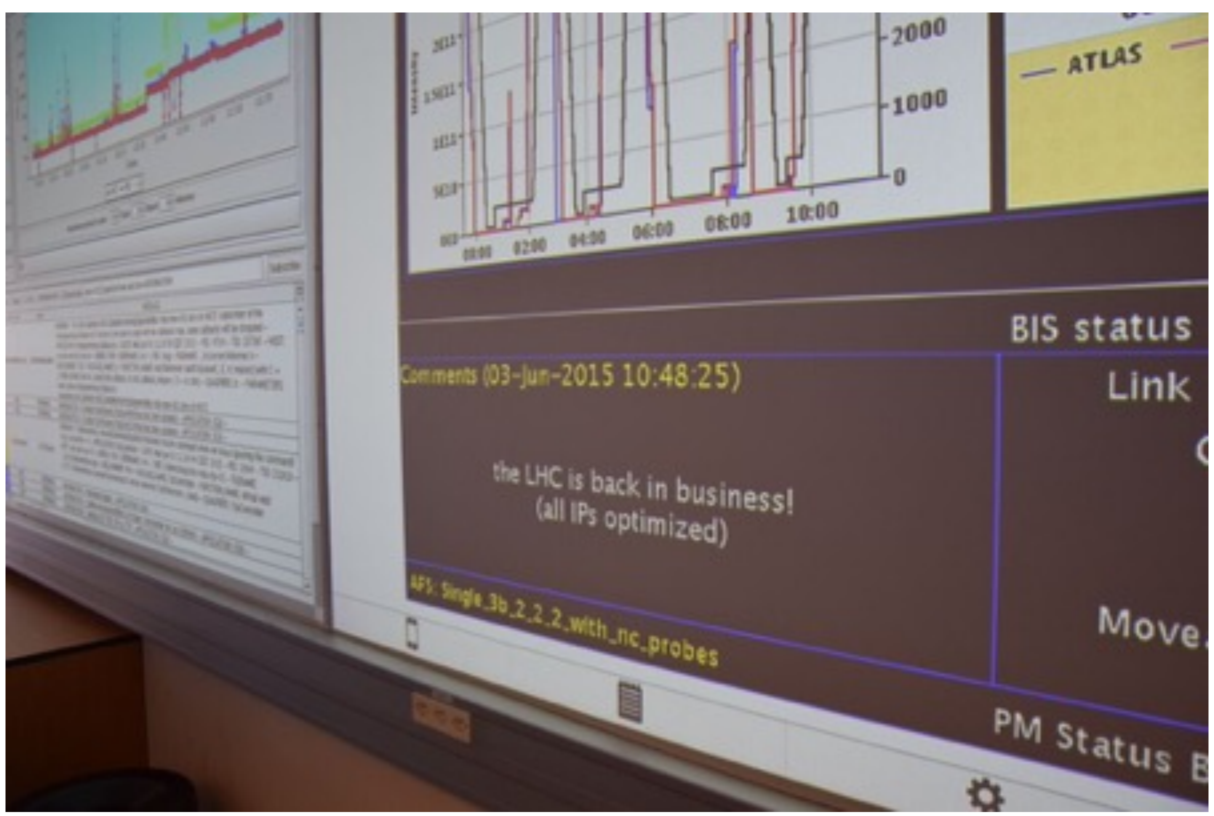
In particular, alternative spin and parity scenarios can be excluded with confidence levels **> 99% in the fixed-hypothesis case.**
No significant deviations from the SM expectation are found **in the CP-mixing case.**

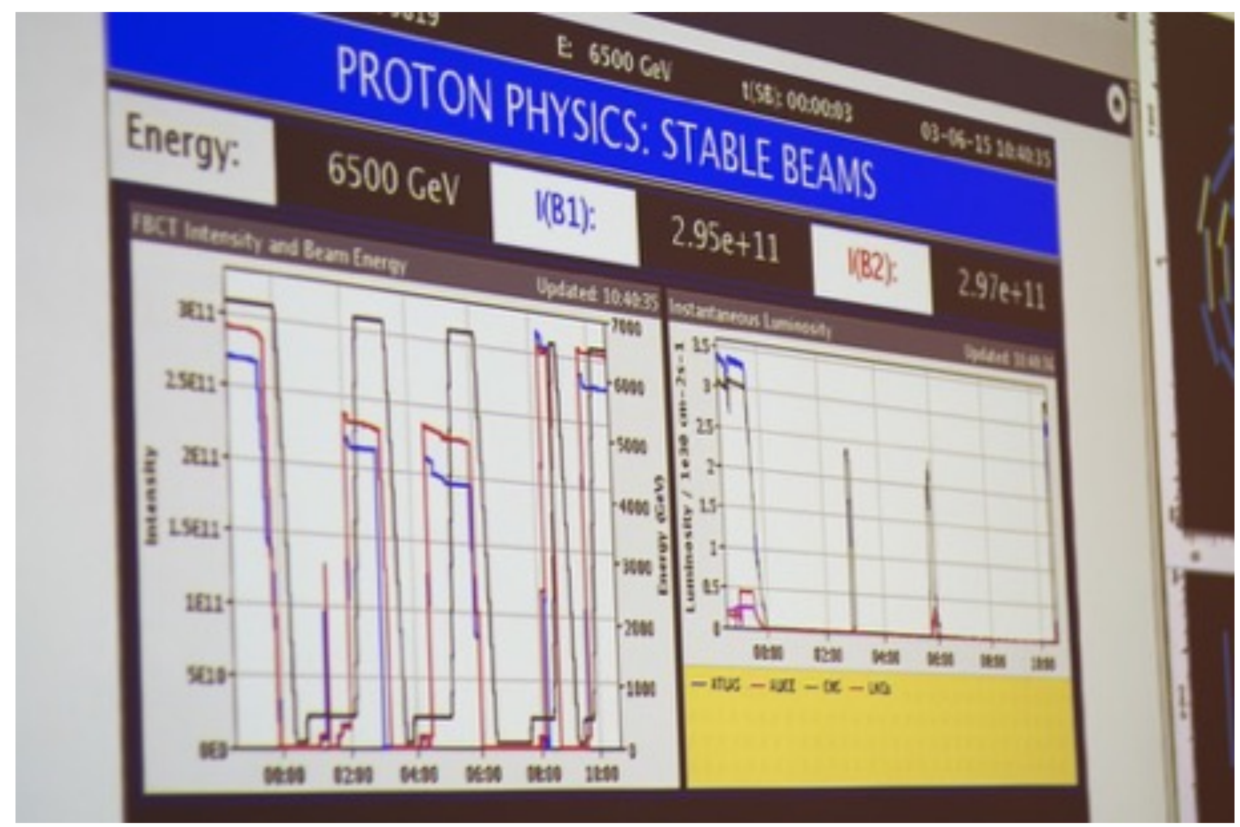
$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{scale}) \pm 0.02\,(\text{other}) \pm 0.01\,(\text{theory})\ \text{GeV}$$

Looking forward to **Run2** results at **13 TeV**, coming up later this year!

Large improvements expected for sensitivity to **CP-mixing** observation.

Thank you!


ATLAS
BIS status
Link
Comments (03-Jun-2015 10:48:25)
the LHC is back in business!
(all IPs optimized)
AFS: Single_3b_2_2_2_with_nc_probes
Move
PM Status


PROTON PHYSICS: STABLE BEAMS
E: 6500 GeV
Energy:
6500 GeV
I(B1):
2.95e+11
I(B2):
2.97e+11
FBCT Intensity and Beam Energy
Instantaneous Luminosity

Back up

Individual and combined mass results

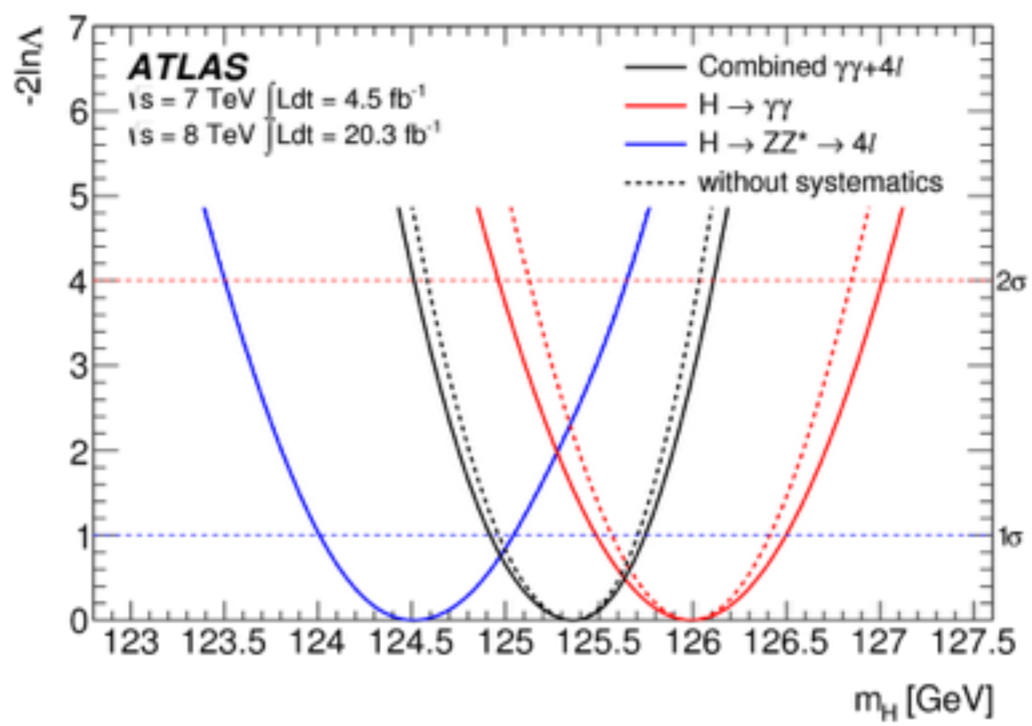
Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ llll$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

Signal strength μ (in terms of SM σ)	Width (GeV) at 95% C.L.
1.29 ± 0.30	< 5.0 (expected 4.2)
1.66 (+0.45, -0.38)	< 2.6 (expected 3.5)

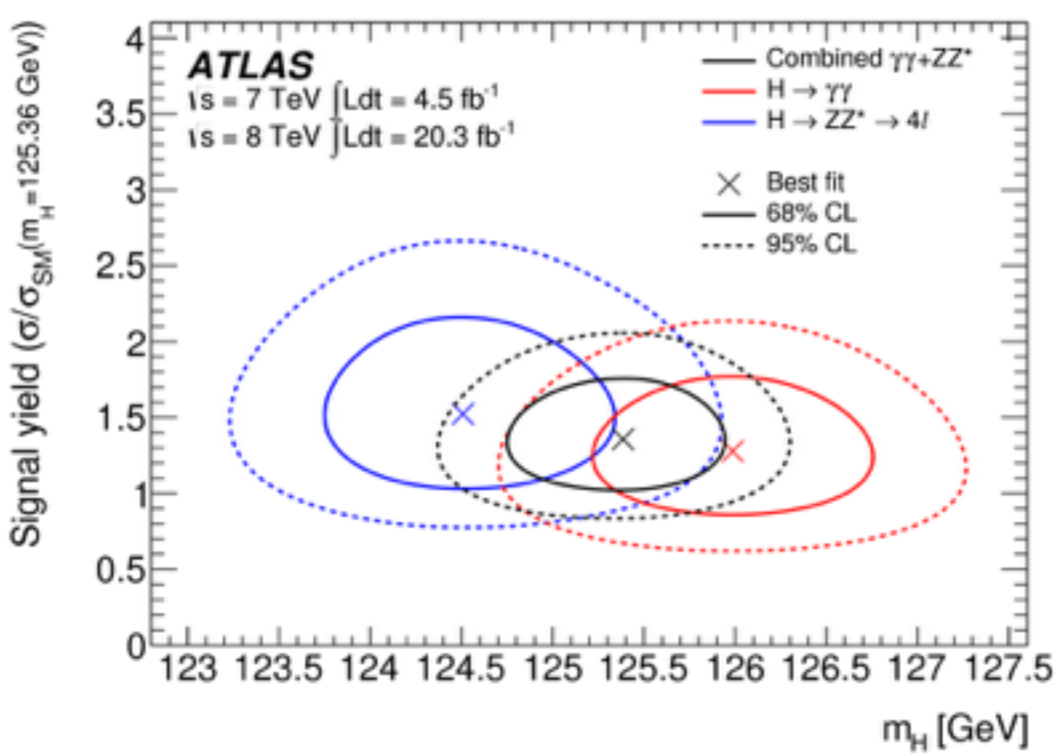
$$\Delta m_H = 1.47 \pm 0.67\,(\text{stat}) \pm 0.28\,(\text{syst})\ \text{GeV}$$
$$= 1.47 \pm 0.72\ \text{GeV}$$
compatible with 0 in 1.97σ

Profile likelihood ratio, treating $\mu(4\ell)$ 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:



Conclusions

The final results for the measurement of the Higgs boson properties, with the full Run1 dataset, collected and analysed by the ATLAS and CMS collaborations, have been presented.

No significant deviation from the Standard Model expectations has been found. 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 couplings excluded $> 99.98\%$ CL 2^+ non-universal couplings excluded $> 99.9\%$ CL
Parity	WW, ZZ	0^- excluded $> 99.95\%$ CL 0^+_h excluded $> 99.97\%$ CL
CP mixing	WW, ZZ	$-2.2 < \tilde{k}_{\rm AVV}/k_{\rm SM}\ \tan\alpha < 0.8$ at 95% CL $-0.7 < \tilde{k}_{\rm HVV}/k_{\rm SM} < 0.6$ at 95% CL
Cross section (8 TeV)	$\gamma\gamma, ZZ$	$\sigma_{pp\to H} = 33.0 \pm 5.5$ pb (exp 24 pb)
Off-shell Width	WW, ZZ	$\Gamma_{\rm H} < 7.5\,\Gamma_{\rm H,\,SM}$

CP violation in the Higgs sector

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{SM} [\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}]$$

$$- \frac{1}{4} [c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \widetilde{A}^{\mu\nu}]$$

$$- \frac{1}{2} [c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \widetilde{A}^{\mu\nu}]$$

$$- \frac{1}{4} [c_\alpha \kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}]$$

$$- \frac{1}{4} \frac{1}{\Lambda} [c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu}]$$

$$- \frac{1}{2} \frac{1}{\Lambda} [c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}]$$

SM

kHWW: Higher order CP-even

kAWW × tgα:
CP violation
in the Higgs sector

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

$$D_{J^P_x} = \left[1 + \frac{\mathcal{P}_2(m_{4\ell}; m_1, m_2, \mathbf{\Omega})}{\mathcal{P}_1(m_{4\ell}; m_1, m_2, \mathbf{\Omega})} \right]^{-1}$$

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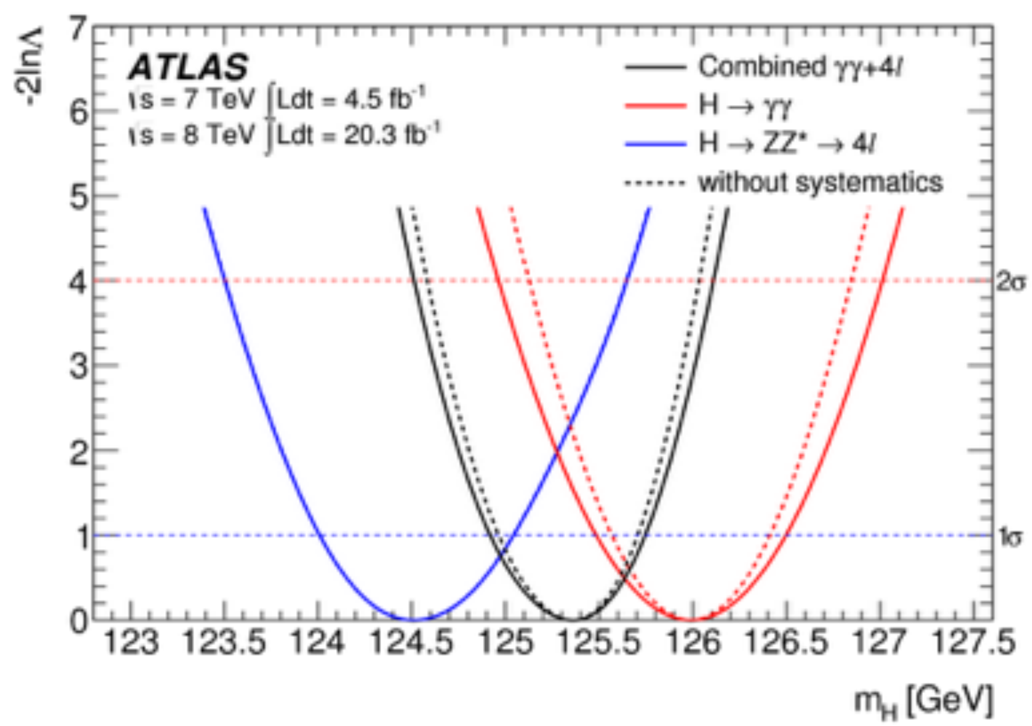

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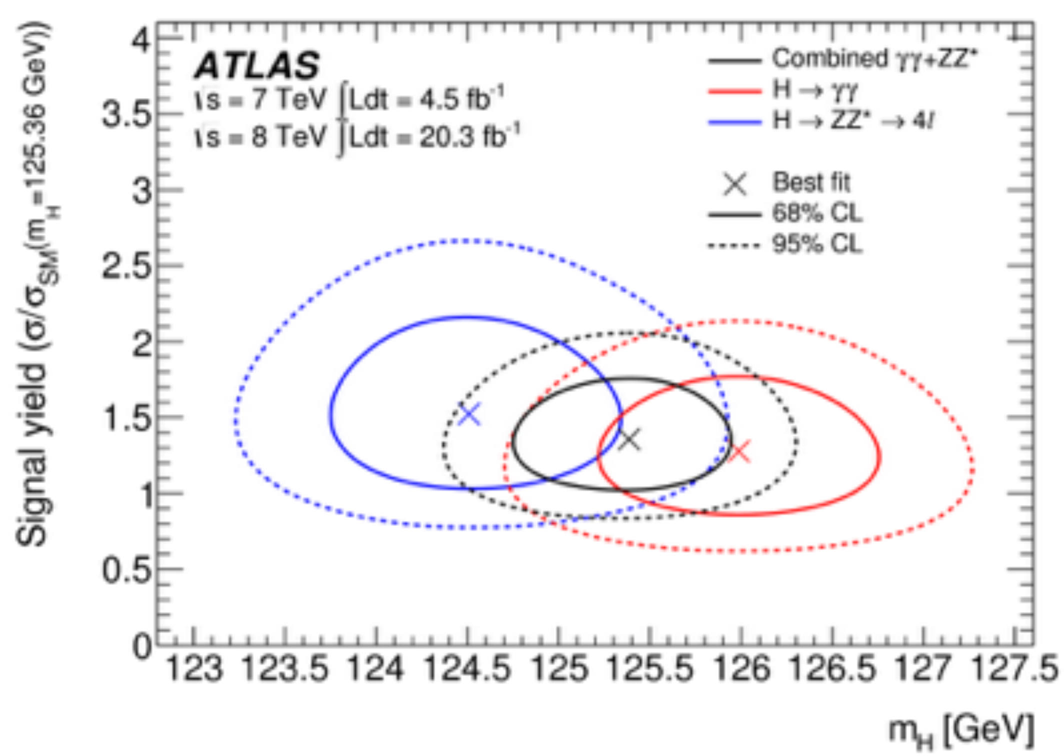
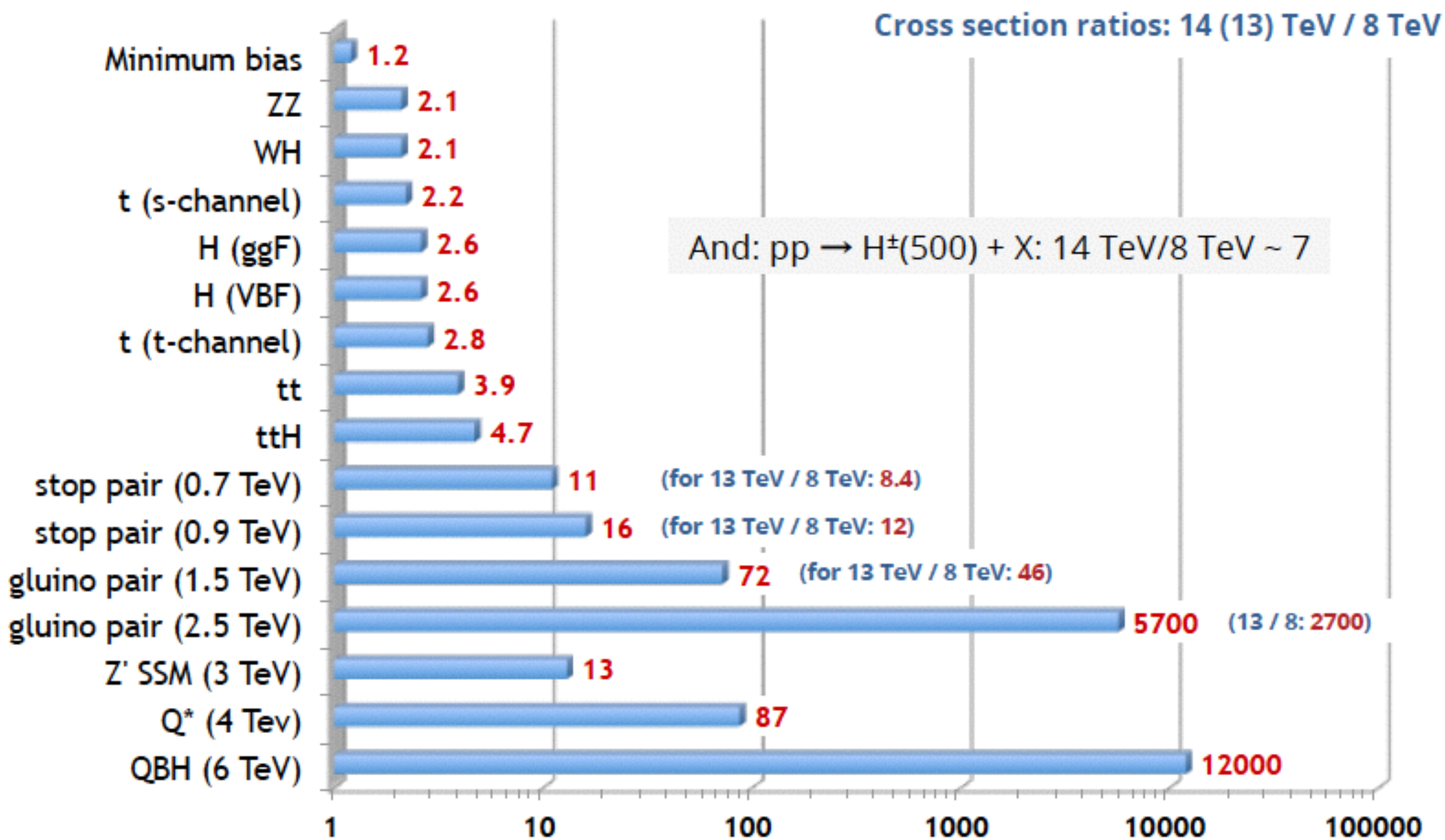



Cross section ratios: 14 (13) TeV / 8 TeV
Minimum bias
ZZ
WH
t (s-channel)
H (ggF)
H (VBF)
t (t-channel)
tt
ttH
stop pair (0.7 TeV)
stop pair (0.9 TeV)
gluino pair (1.5 TeV)
gluino pair (2.5 TeV)
Z' SSM (3 TeV)
Q* (4 Tev)
QBH (6 TeV)
1.2
2.1
2.1
2.2
2.6
2.6
2.8
3.9
4.7
11
(for 13 TeV / 8 TeV: 8.4)
16
(for 13 TeV / 8 TeV: 12)
72
(for 13 TeV / 8 TeV: 46)
5700
(13 / 8: 2700)
13
87
12000
And: pp → H±(500) + X: 14 TeV/8 TeV ~ 7
1
10
100
1000
10000
100000

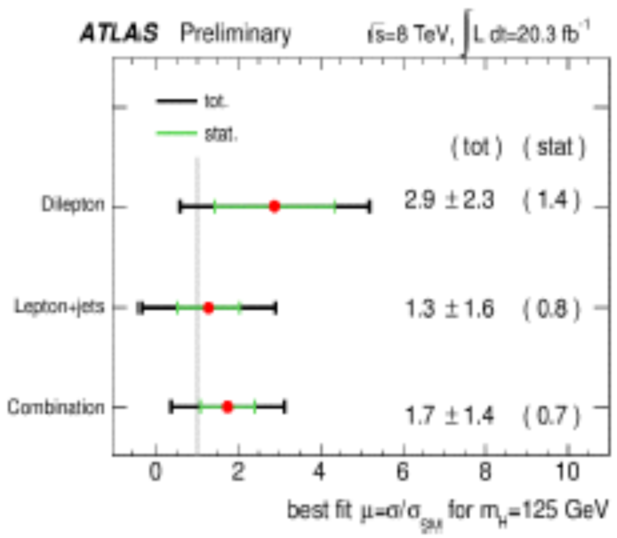
ttH: Motivation and Run-1 results

Want to directly measure top-Higgs Yukawa coupling
(one of the key points of Higgs physics program)

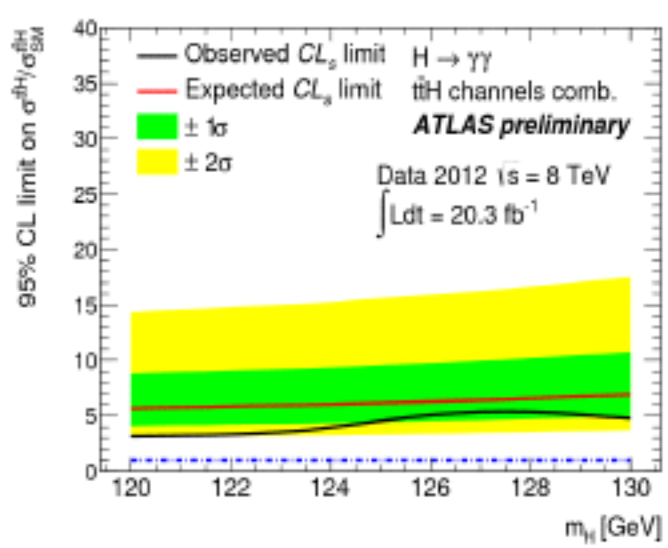
H→bb:
- Most stringent xsec limit
- Dominant decay mode
- Poor mass resolution

H→γγ:
- Low branching ratio (2.28×10^{-3})
- Excellent mass resolution

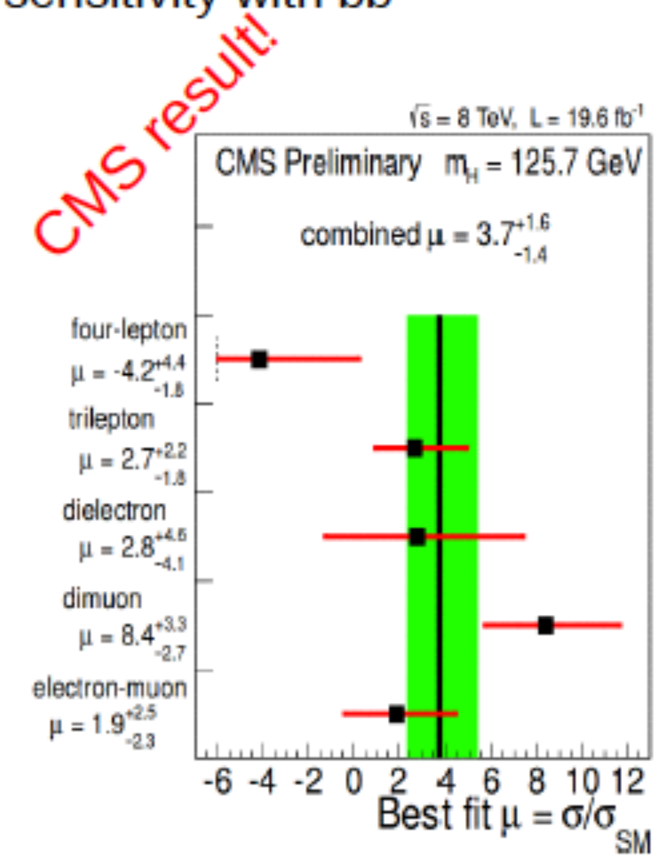
H→multileptons:
- Clean final state
- Can reach competitive sensitivity with bb



ATLAS-CONF-2014-13

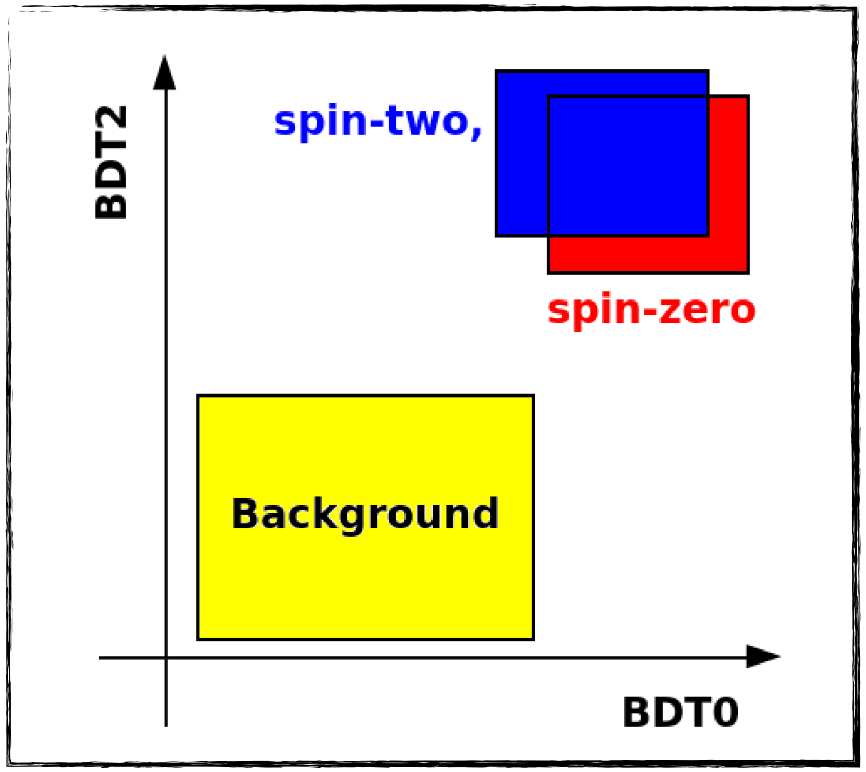


ATLAS-CONF-2013-80



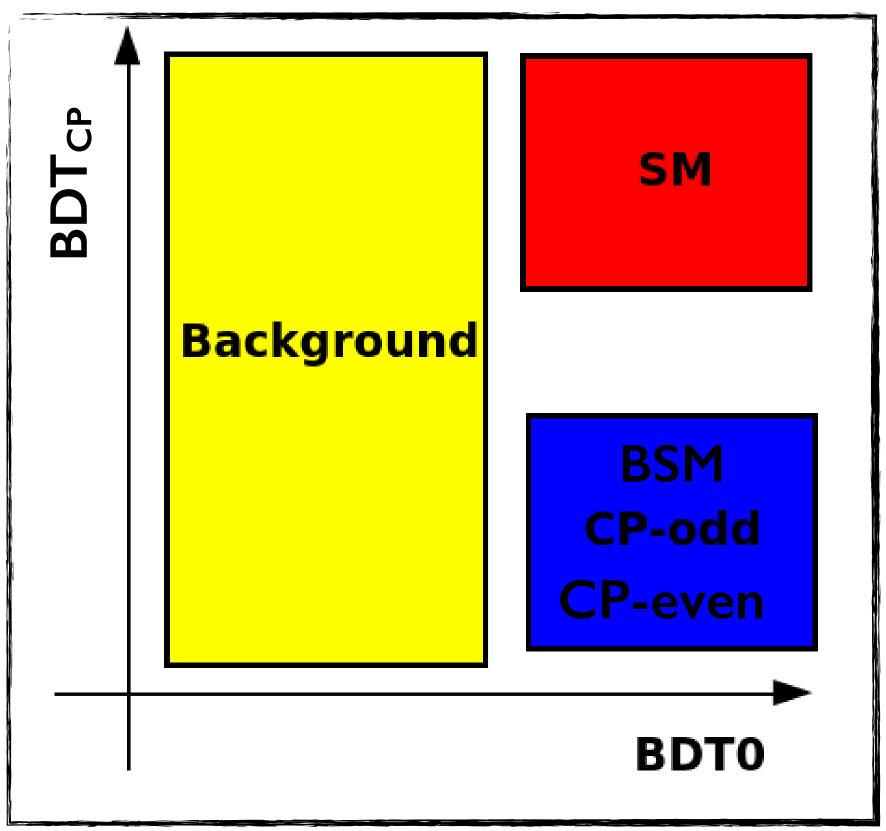
18.04.14 ATLAS Higgs Workshop 3

HWW analysis strategy



Boosted Decision trees used as discriminants:

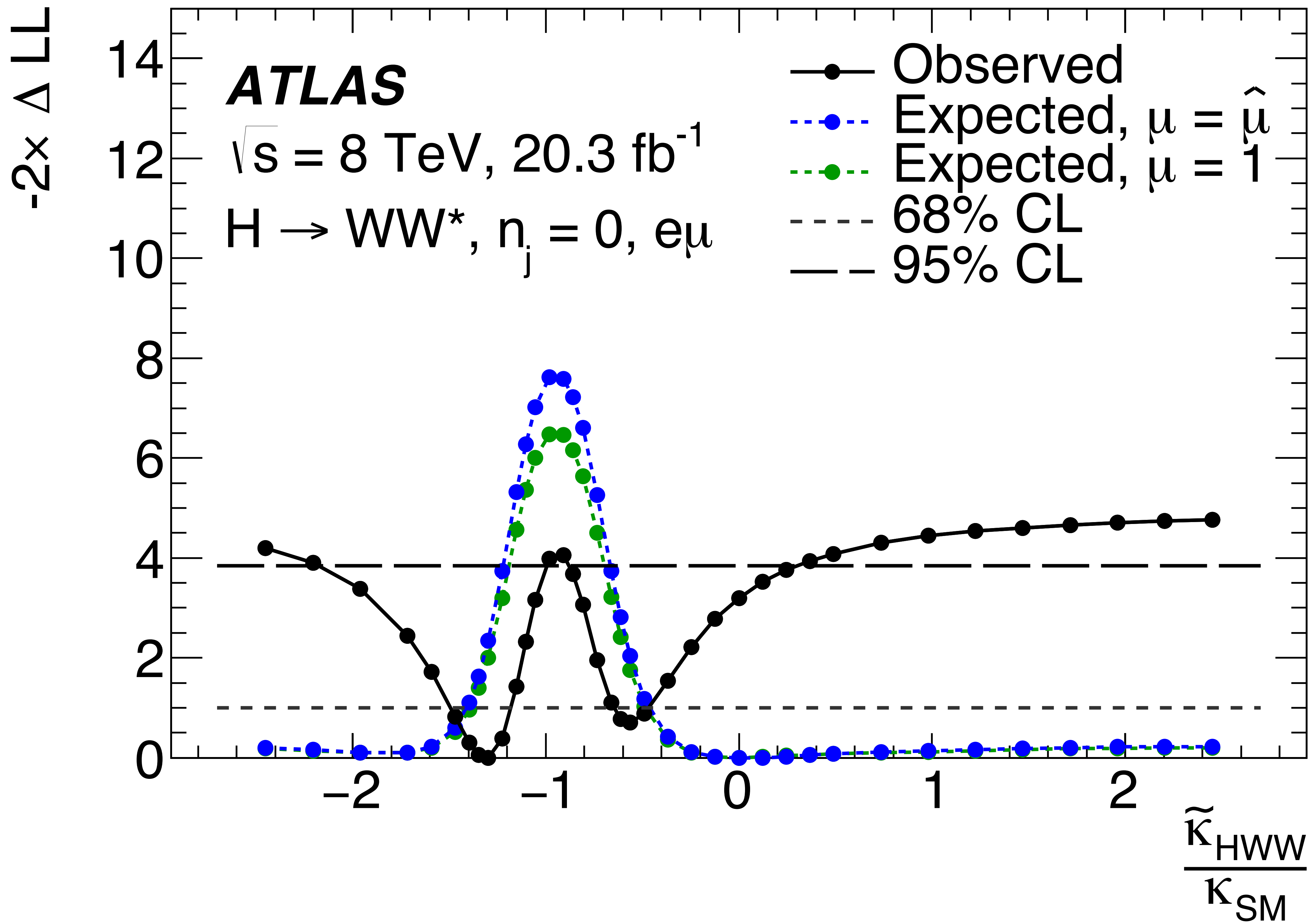
- BDT0: train SM signal vs background
- BDT2: train ALT signal vs background
- Both BDT0 and BDT2 use as input: $m(\ell\ell)$, $\Delta\phi^{\ell\ell}$, $p_T^{\ell\ell}$, m_T^{track}
- Combine (BDT0, BDT2) and fit the 1d projection



- 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, <u>no retraining</u> for the various CP fractions



ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
H → WW*, n_j = 0, eμ
Observed
Expected, $\mu = \hat{\mu}$
Expected, μ = 1
68% CL
95% CL
-2× Δ LL
$\frac{\tilde{\kappa}_{HWW}}{\kappa_{SM}}$