ATLAS and CMS: Status and Prospects

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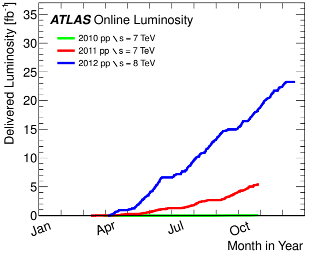
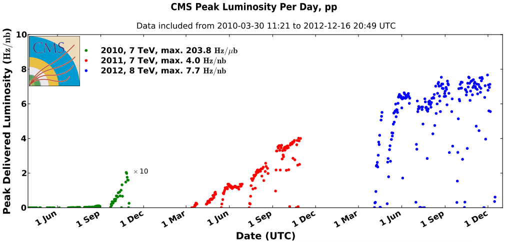
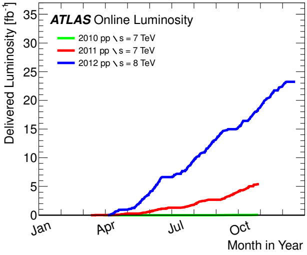
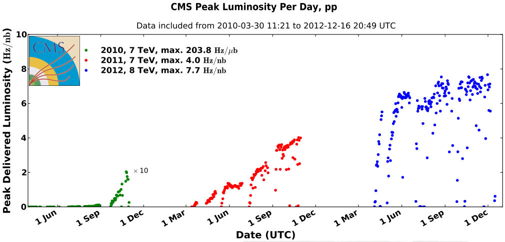
LHC Status: Successes

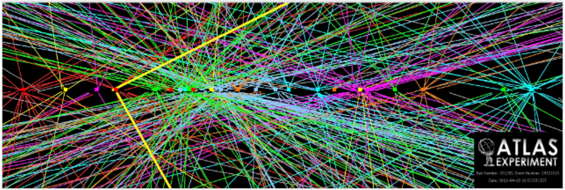




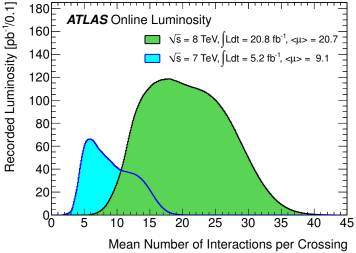
LHC Status: Successes and Challenges



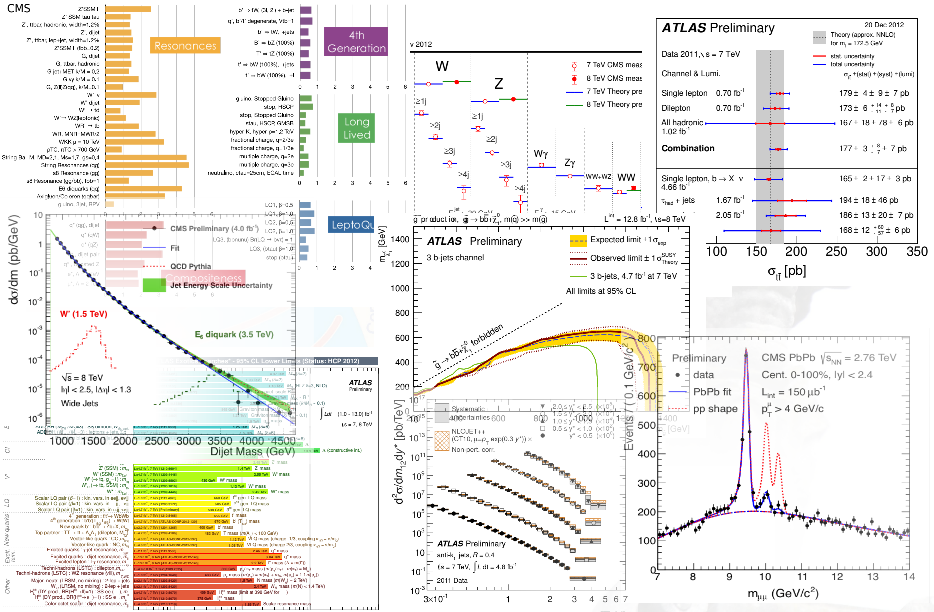




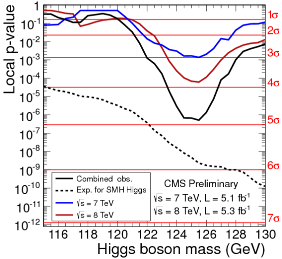
A candidate $Z \to \mu\mu$ event with 25 reconstructed vertices.

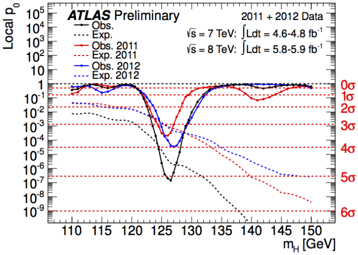


Things I Will Not Be Talking About



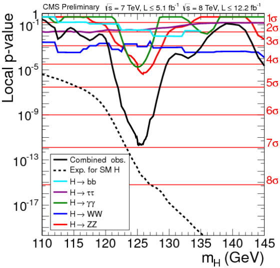
Higgsdependence Day

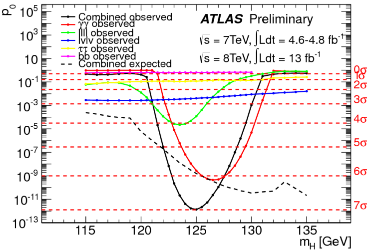




$\lesssim 11\text{fb}^{-1}$	1207.7214 ATLAS	1207.7235 CMS
$H \to \gamma\gamma$	✓	✓
$H \to ZZ \to \ell\ell\ell'\ell'$	✓	✓
$H \to WW \to \ell\nu\ell'\nu'$	✓	✓
$H \to \tau\bar{\tau}$		✓
$H \to b\bar{b}$		✓

Higgsdependence Day and Beyond

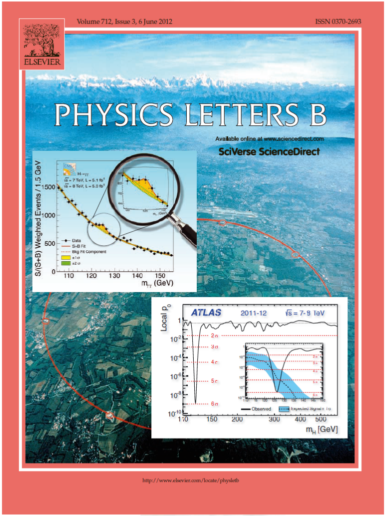




$\lesssim 18\text{fb}^{-1}$	Latest ATLAS	Latest CMS
$H \to \gamma\gamma$	✓	✓
$H \to ZZ \to \ell\ell\ell'\ell'$	✓	✓
$H \to WW \to \ell\nu\ell'\nu'$	✓	✓
$H \to \tau\bar{\tau}$	✓	✓
$H \to b\bar{b}$	✓	✓
$H \to Z\gamma \to \ell\ell\gamma$		✓
$H \to ZZ \to \ell\ell\nu\nu$	✓	✓
$H \to ZZ \to \ell\ell qq$	✓	✓
$H \to WW \to \ell\nu qq$	✓	✓

From Discovery to Measurement

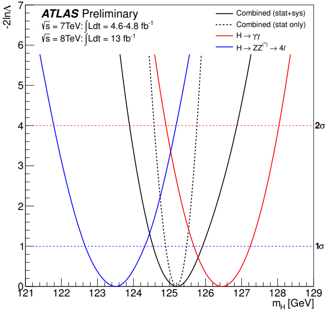
- What is it's mass
- What are its couplings (and self-couplings)
- Does it have spin 0 or 2
- Is it scalar or pseudo-scalar
- Does it have any other non-SM properties

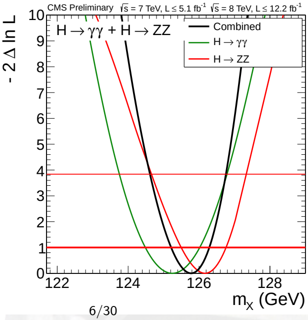


Mass

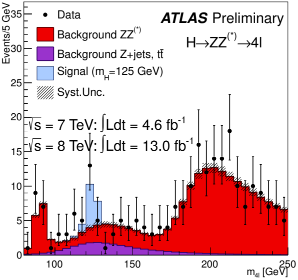
Only missing SM parameter
(modulo neutrino properties)

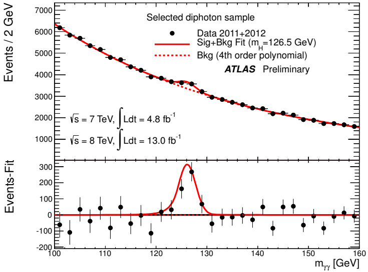
- Measurement from $H \to \gamma\gamma$ and $H \to ZZ \to \ell\ell\ell'\ell'$ where all the four-vectors are preserved with good accuracy.
- ATLAS: $m_H = 125.2 \pm 0.3$ (stat) ± 0.6 (sys) GeV
- CMS: $m_H = 125.8 \pm 0.4$ (stat) ± 0.4 (syst) GeV





Double Peaks



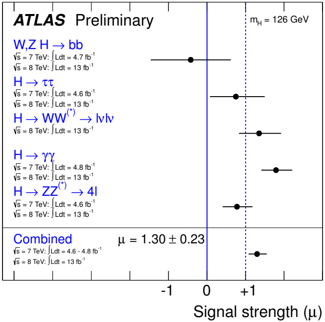


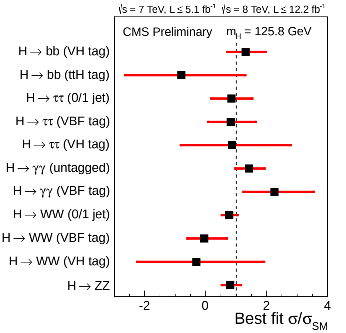
- Taking mass scale systematic uncertainties and their correlations into account, the compatibility of the two measurements is estimated to be at the 2.7σ level.

- CMS *ZZ* mass measurement (126.2 ± 0.6 (stat) ± 0.2 (syst) GeV), is very close to the ATLAS $\gamma\gamma$ mass measurement (126.6 ± 0.3 (stat) ± 0.7 (syst) GeV)

Couplings

- Order 0 excercise: compute the individual and combined signal strength ($\hat{\mu} = \sigma/\sigma_{\rm SM}$) of all available inputs.





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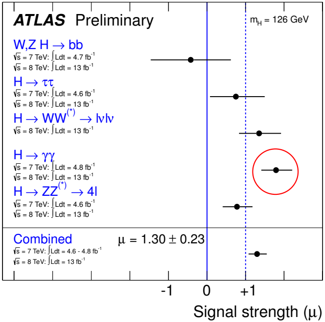
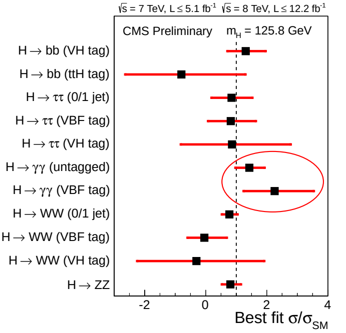
- ATLAS $\hat{\mu} = 1.30 \pm 0.23$
- CMS $\hat{\mu} = 0.88 \pm 0.21$

Couplings

- Order 0 excercise: compute the individual and combined signal strength ($\hat{\mu} = \sigma/\sigma_{\rm SM}$) of all available inputs.





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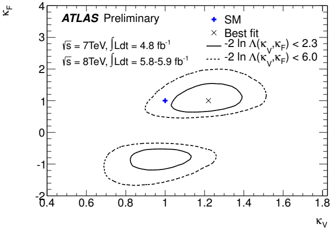
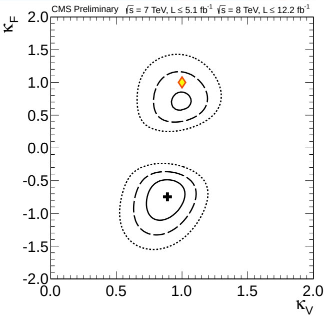
- ATLAS $\hat{\mu} = 1.30 \pm 0.23$
- CMS $\hat{\mu} = 0.88 \pm 0.21$

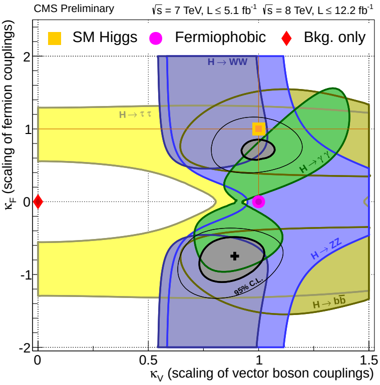
Couplings

- The four main Higgs boson production mechanisms can be associated with either top-quark couplings (gluon-gluon fusion and ttH) or vector boson couplings (VBF and VH).
- Order 1 excercise: Compute couplings of a combination of channels associated with a particular decay mode, explicitly targeting different production mechanisms.

Couplings



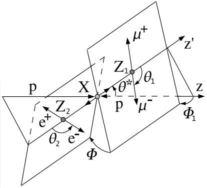


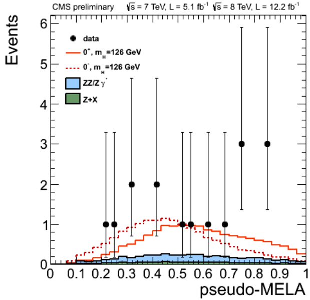


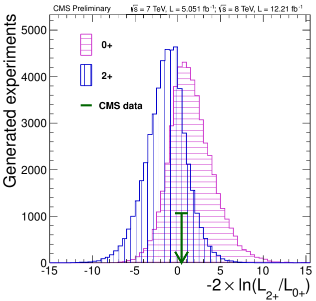
- Couplings look consistent within 2σ for both experiments
- Alternative models heavily constrained: fermiophobic higgs ($k_f = 0$) excluded.

Spin in ZZ

- ZZ^* is sensitive to Spin and CP properties
- CMS uses a Matrix Element-based discriminant of probability ratios



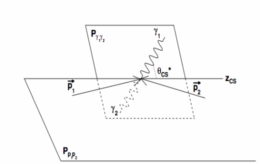


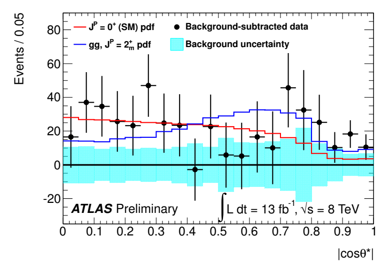


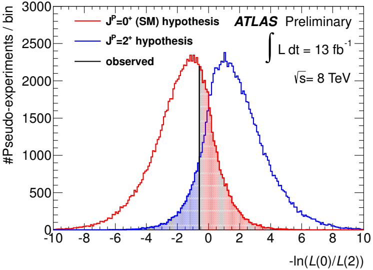
- Find that the spin $J = 0$ hypothesis is compatible with the data.
- 0^+ prefered over 0^- by the data, but both are within 3σ.
- Similar ATLAS $H \rightarrow ZZ$ analysis excludes the 0^- hypothesis at the 99% CL

Spin in $\gamma\gamma$

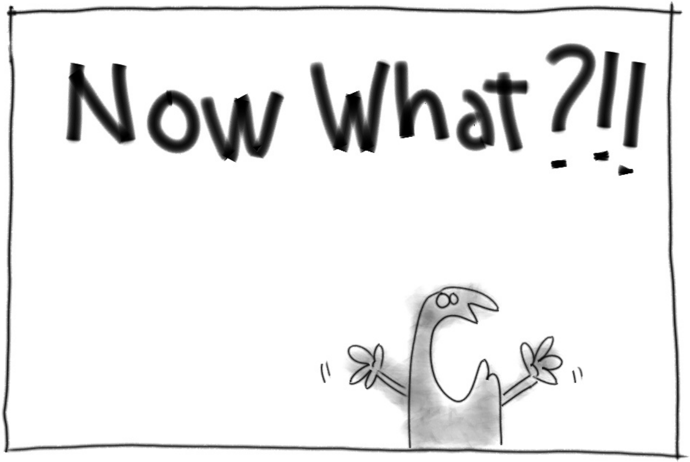
ATLAS probes the spin using the cosine of the polar angle of the largest transverse energy photon in the Collin-Soper di-photon rest frame ($\cos\,\theta^*_{\gamma\gamma}$)







- Exclude the spin 2^+ hypothesis at 91% CL
- Data is compatible with the spin 0 hypothesis within 0.5σ


Now What?!!

LHC Timeline

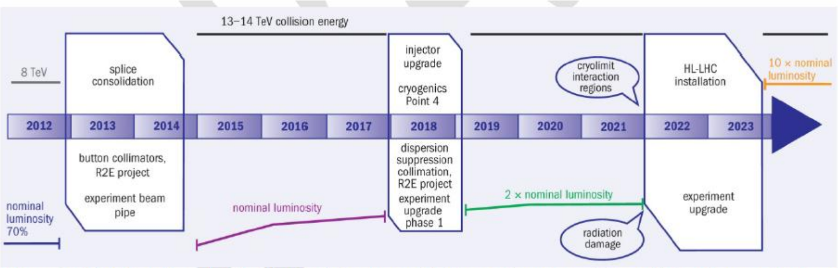
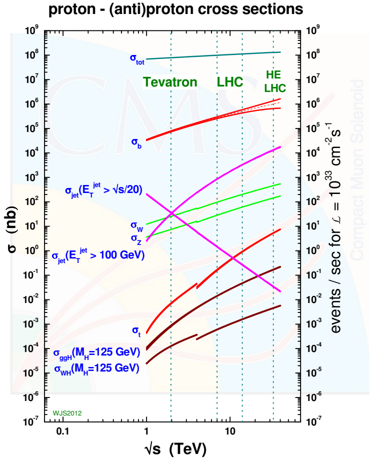


Figure 1: LHC baseline plan for the next ten years. In terms of energy of the collisions (upper line) and of luminosity (lower lines). The first long shutdown 2013-14 is to allow design parameters of beam energy and luminosity. The second one, 2018, is for secure luminosity and reliability as well as to upgrade the LHC Injectors.

- 2009 - 2013: $\sqrt{s} = 7 - 8$ TeV, $L = 6 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$, bunch spacing = 50 ns, 20-25 fb^{-1}
- 2014 - 2018: $\sqrt{s} = 14$ TeV, $L = 1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, bunch spacing = 25 ns, 75-100 fb^{-1}
- 2019 - 2021: $\sqrt{s} = 14$ TeV, $L = 2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, bunch spacing = 25 ns, 350 fb^{-1}
- 2023-2030: $\sqrt{s} = 14$ TeV, $L = 5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, luminosity levelling, 3000 fb^{-1}

Future Prospects



Process	3000fb^{-1} at 14 TeV	300fb^{-1} at 33 TeV
$ggH \rightarrow \gamma\gamma$	350k	123k
$ggH \rightarrow 4\ell$	19k	6.7k
$ttH \rightarrow \gamma\gamma$	42k	30k
$ttH \rightarrow 4\ell$	200	160
$ttH \rightarrow \mu^+\mu^-$	400	300
$HH \rightarrow bb\gamma\gamma$	270	160

- Higher statistics for rare processes at HL-LHC
- Cleaner events (less pile-up, better S/B) at HE-LHC

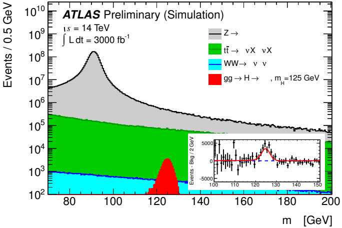
Prospects for Couplings

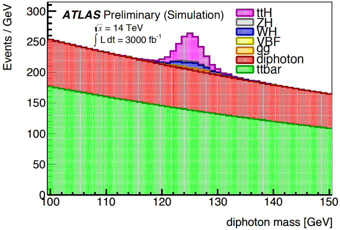
- Post-LS1
  - Continue to measure total signal yield ($\hat{\mu}$)
  - Improve measurement of couplings to Fermion and Vector Bosons
  - Probe loop couplings
- Post-LS2
  - Test down vs up fermion couplings
  - Test lepton vs quark couplings
- Post-LS3:
  - Use ttH for direct measurement of top coupling
  - Use $H \to \mu\mu$ for direct measurement of second generation couplings
  - Measure Higgs trilinear self-couplings, primarily with $gg \to HH \to b\bar{b}\gamma\gamma$

Channels Considered

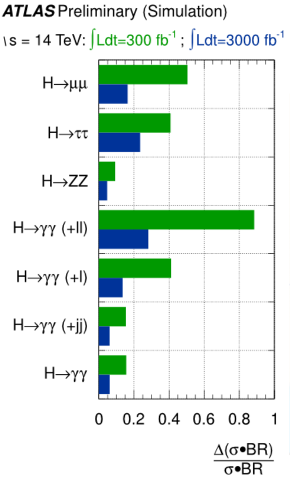
Extrapolations using current performance and MC studies at 14 TeV using Fast-Sim validated up to $<\mu>=70$ with full simulation.

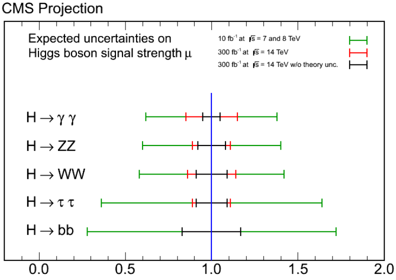
- Current analyses:
  - $H \to \gamma\gamma$ (inclusive, VBF)
  - $H \to \tau\tau$ (all final states)
  - $H \to ZZ \to 4\ell$
  - $H \to WW \to \ell\nu\ell\nu$
  - $VH \to Vbb$
- New final states:
  - $VH \to V\gamma\gamma$, $VH \to VVV$
  - $H \to \mu\mu$
  - $ttH \to \gamma\gamma$
  - $HH \to b\bar{b}\gamma\gamma$





Projected Sensitivity

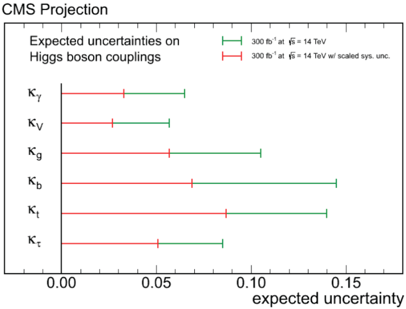




- Scenario 1: same systematics as in 2012
- Scenario 2: no theory systematics (i.e. limits of statistical precision)

Expect measurements of μ to $\sim 10-20\%$ per experiment
Large theory uncertainties on $H \to \gamma\gamma$
Large experimental uncertainties on $H \to b\bar{b}$

Projected Sensitivity



- Scenario 1: same systematics as in 2012
- Scenario 2: theory systematics scaled by a factor 12, other systematics scaled by $1/\sqrt{\mathcal{L}}$

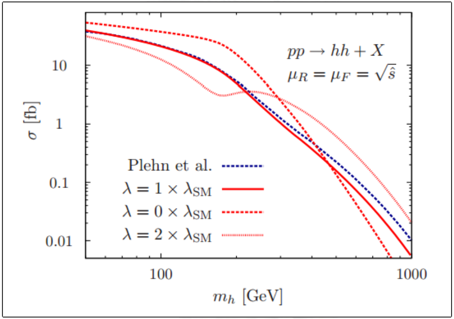
ATLAS	300fb^{-1}	3000fb^{-1}
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

With (without) current theory uncertainties

Several assumptions for each permutation: *e.g.* all bosonic and ferminonic couplings are modified in the same way, or no additional hidden Higgs decays.

Higgs Self-Couplings

- Rely on H pair production via gg fusion
  - CMS studied $HH \to bb\gamma\gamma$ and $HH \to bb\mu\mu$
  - ATLAS studied $HH \to bb\gamma\gamma$ and $HH \to WW$
- Example ATLAS analysis in the $HH \to bb\gamma\gamma$ channel with cut and count
  - $\lambda_{HHH} = 1\times$SM : 15 events
  - $\lambda_{HHH} = 0\times$SM : 26 events
  - Background : 24 events



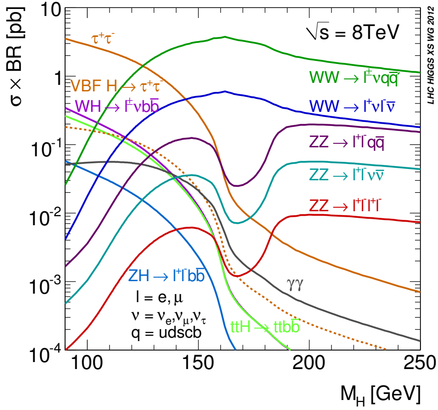
Expect $\sim 2\sigma$ observation for $\lambda_{HHH} = 1\times$SM

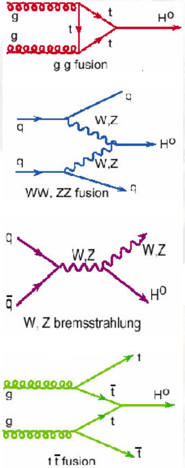
Conclusions

- It's been a phenomenal year for the ATLAS and CMS physics programs (Higgs and otherwise).
  - Observation of a 125 GeV candidate
  - First measurements of spin, parity, global couplings
- Beginning the first of three long shutdowns to improve stability of LHC, reach nominal energy, and various improvements of the detectors
  - Expect continued results throughout 2013/14 as the data is re-analyzed and new channels are added.
- Future prospects depend strongly on ultimate configuration of the LHC and total integrated luminosity.
  - Expect 10-20% measurements of the $\sigma/\sigma_{\rm SM}$
  - Expect $\mathcal{O}(10)\%$ or better measurements of coupling parameters
  - Characterize Higgs CP properties
  - Higgs mass uncertainty to $\sim 50 - 1000$ MeV
  - Fairly conservative extrapolations (not accounting for many new channels, advanced analysis techniques, combination of ATLAS and CMS results, etc...)

Backup Slides

LHC Higgs Boson Production

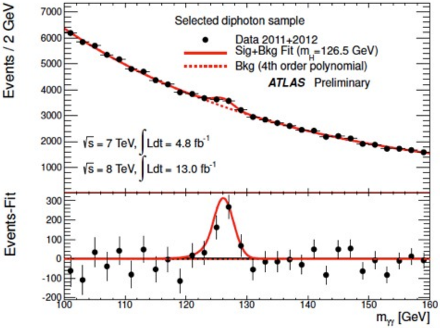




ATLAS $H \to \gamma\gamma$

- Good measurement of $\gamma\gamma$ opening angles thanks to fine longitudinal and lateral segmentation and pointing geometry of the ATLAS EM calorimeter.

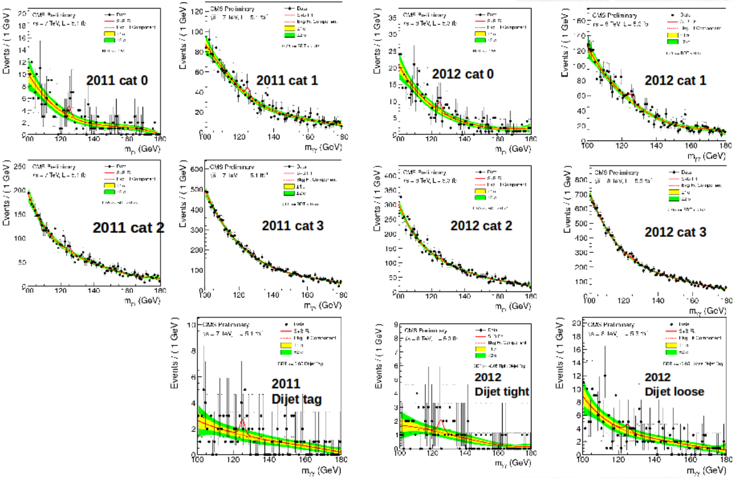
- Overall mass resolution is 1.6 GeV



- Data are split into 12 exclusive categories.
- Fit $m_{\gamma\gamma}$ with exponential or polynomial functions for background plus a sum of Crystal Ball and Gaussian (tails) for signal.

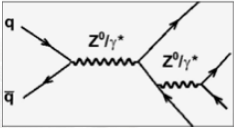
CMS $H \to \gamma\gamma$

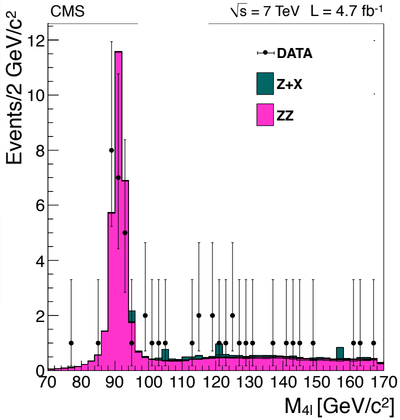
- Boosted Decision Trees for photon ID and event classification
- Fit mass distribution in 6 exclusive categories.

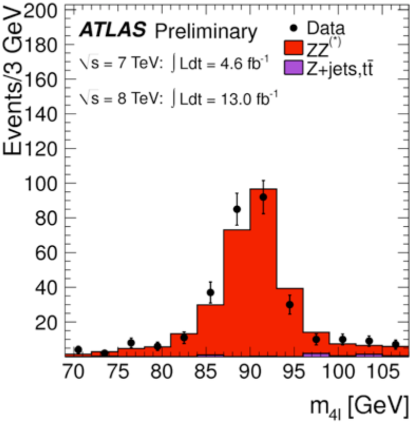


$H \to ZZ$ Validation

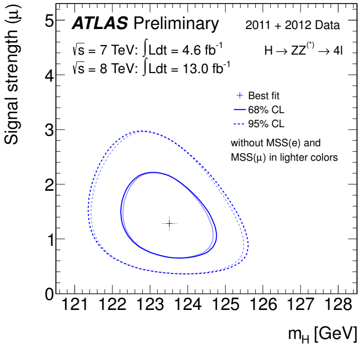
Both ATLAS and CMS validate the four-lepton analysis using the Z resonant peak.

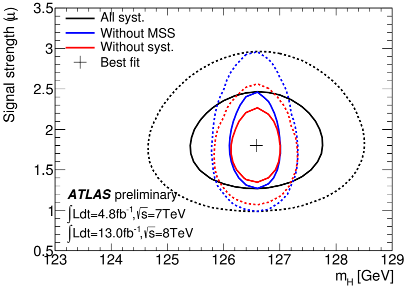






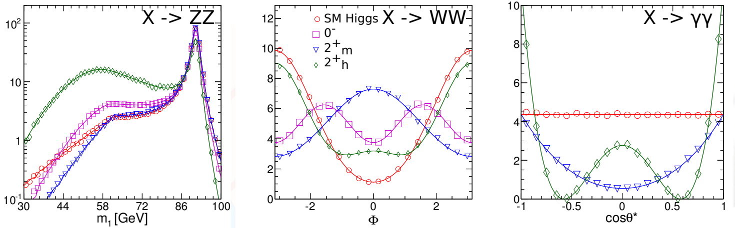
$H \to ZZ$ and $H \to \gamma\gamma$ Mass





- Exhaustive list of systematic uncertainties considered
- Largely uncorrelated
  - Share overall e/γ energy scale
- p-value $=$ 0.6% (2.3% using alternate energy scale systematics)

Spin And Parity



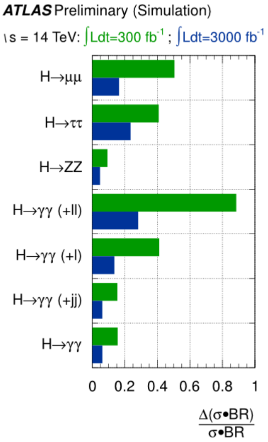
- Discrimination between $0^+/0^-$ and $0^+/2^+$ improves linearly with S/B
  - ZZ best for $0^+/0^-$
  - *WW* and $\gamma\gamma$ best for $0^+/2^+$
- Expect $\geq 4\sigma$ for $\sim 35\text{fb}^{-1}$ for all three channels combined (per experiment)

Couplings Reach

Coupling	Uncertainty (%) 3000 fb^{-1} Scenario 1	Scenario 2
κ_γ	5.4	1.5
κ_V	4.5	1.0
κ_g	7.5	2.7
κ_b	11	2.7
κ_t	8.0	3.9
κ_τ	5.4	2.0

CMS projected uncertainty on the coupling parameters with 3000 fb^{-1} at the HL-LHC

- Scenario 1: 2012 systematics
- Scenario 2: Theory syst $\times 0.5$, Experimental sys $\times 1/\sqrt{\mathcal{L}}$



	300fb^{-1}	3000fb^{-1}
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

With (without) current theory uncertainties

Fitting the Couplings

Follow the recommendations of the LHC Cross-section working group

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases} \quad (3)$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H) \quad (4)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2 \quad (5)$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2 \quad (6)$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2 \quad (7)$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2 \quad (8)$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2 \quad (9)$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2 \quad (10)$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2 \quad (11)$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases} \quad (12)$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases} \quad (13)$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2 \quad (14)$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2 \quad (15)$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2 \quad (16)$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2 \quad (17)$$

Total width

Γ_H ... $\kappa_H^2(\kappa_i, m_H)$