Status of Higgs Searches at ATLAS and CMS

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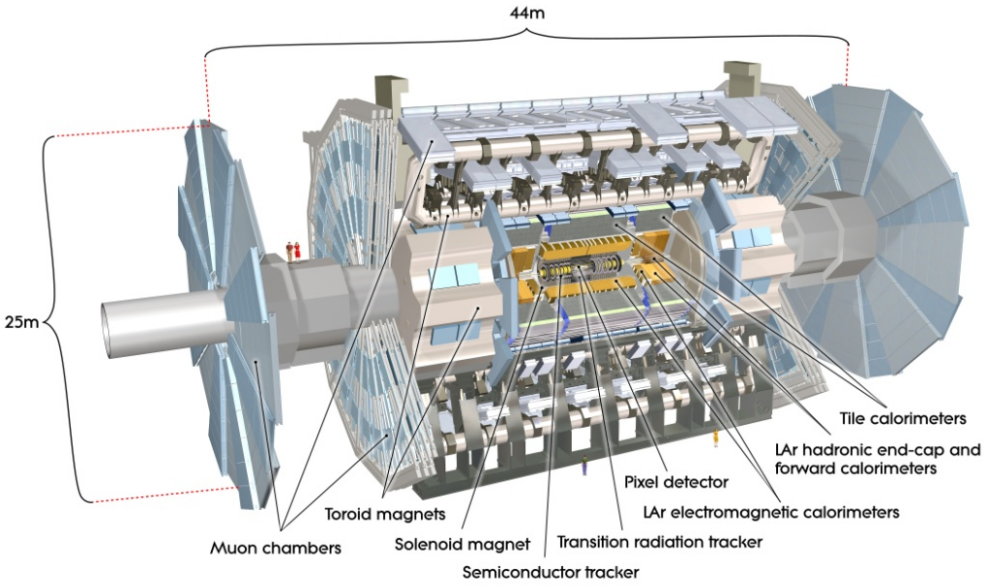
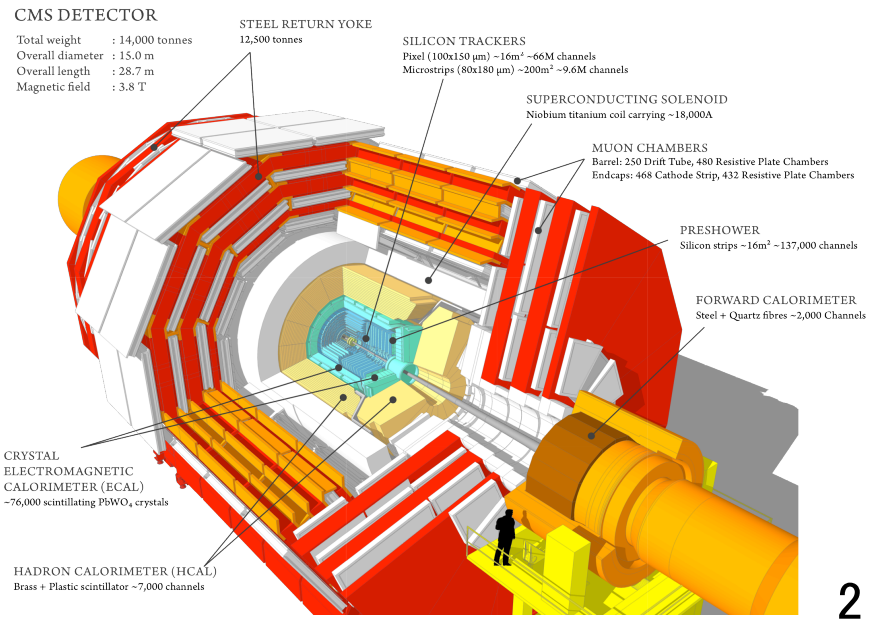
The ATLAS and CMS Experiments at LHC

- LHC at CERN started its operation of the highest energy *pp* collisions since 2010.
  - 7 TeV in 2010 - 2011
  - 8 TeV in 2012

- The ATLAS and CMS detectors are general purpose detectors for Higgs, SUSY, Exotics searches and SM physics.

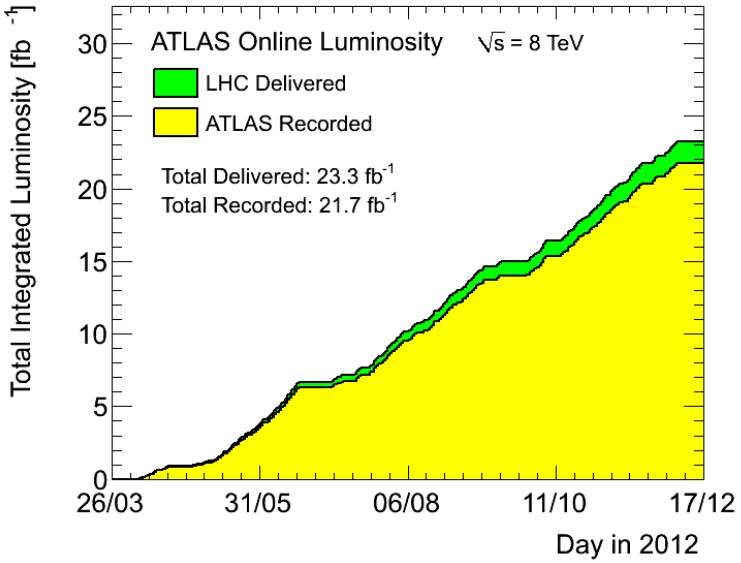
- We report today the status of Higgs searches by ATLAS and CMS.

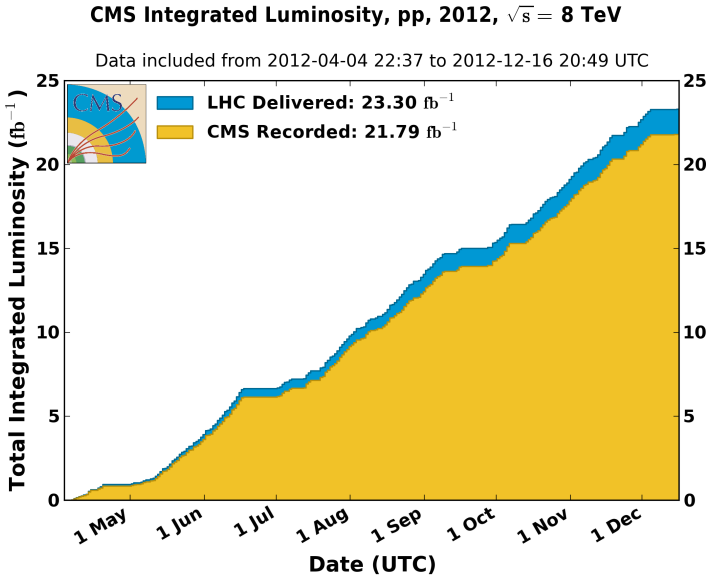




LHC Run I Delivered Data

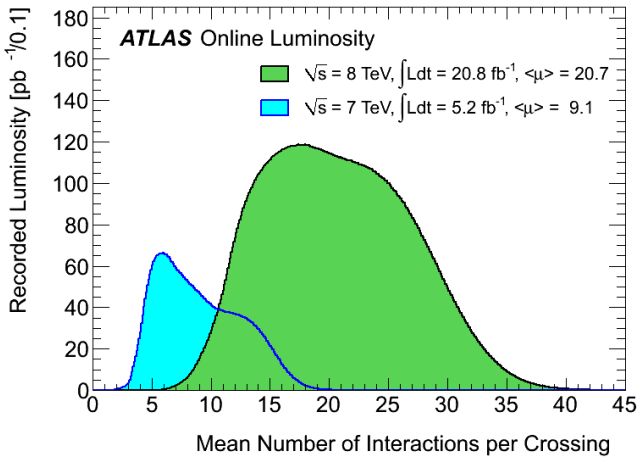
- LHC performed very well to deliver a significant amount of data for Higgs searches in Run I.
- Both ATLAS and CMS experiments kept very high data taking efficiency and use ~90% of delivered data for physics.
  - **2011 : 7 TeV, ~5 fb^{-1}**
  - **2012 : 8 TeV, ~20 fb^{-1}**
- This allowed us to use a wide range of decay and production channels in Higgs searches.



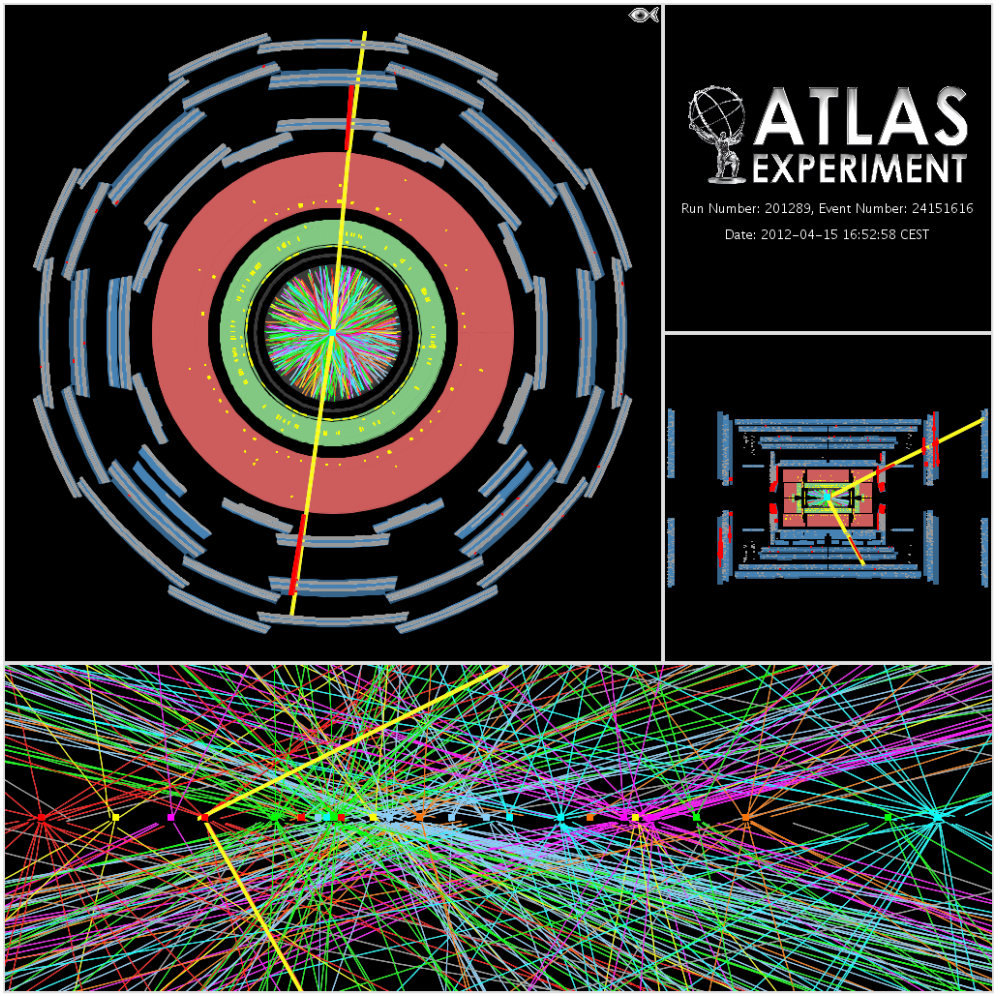


Pileup : Very Harsh Experimental Condition

- High pileup occurs thanks to very high performance of LHC.
- Essential to continuously improve the trigger, reconstruction, object identification in the very harsh condition.



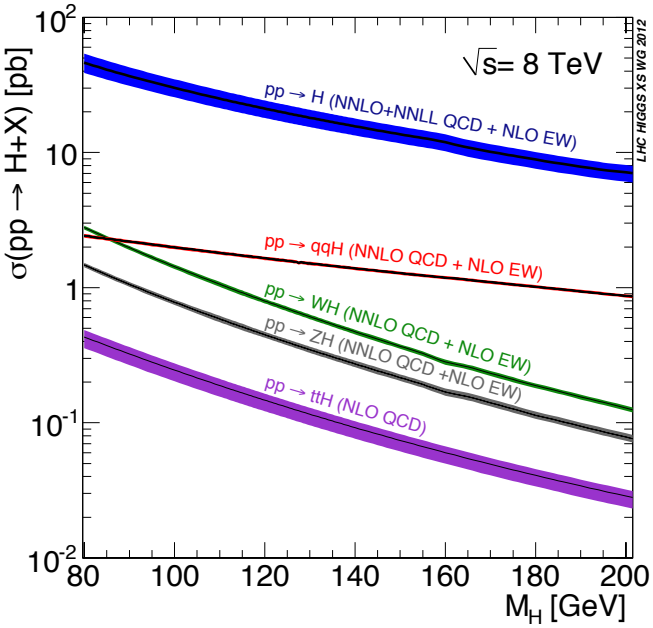
A $Z \rightarrow \mu\mu$ event with 25 reconstructed vertices

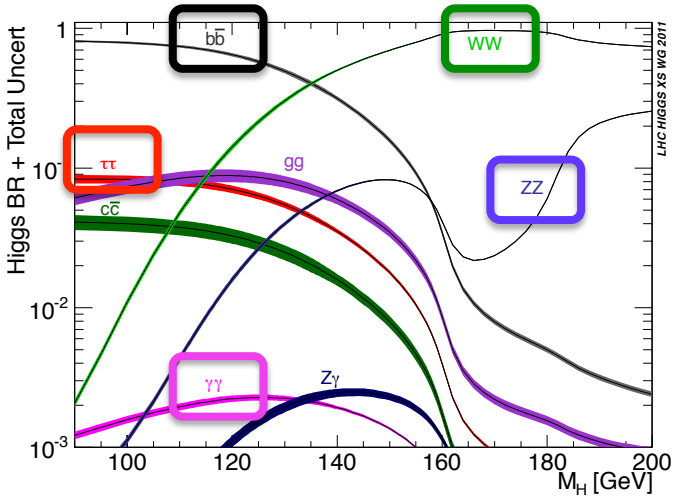


Higgs Productions and Decays

- The production sub-processes
  - **Gluon fusion (*gg*F)**
  - **Vector boson fusion (VBF, *qq*H)**
  - **W/Z-associated production (*VH*, V=*W,Z*)**
  - **Top-associated production (*ttH*)**

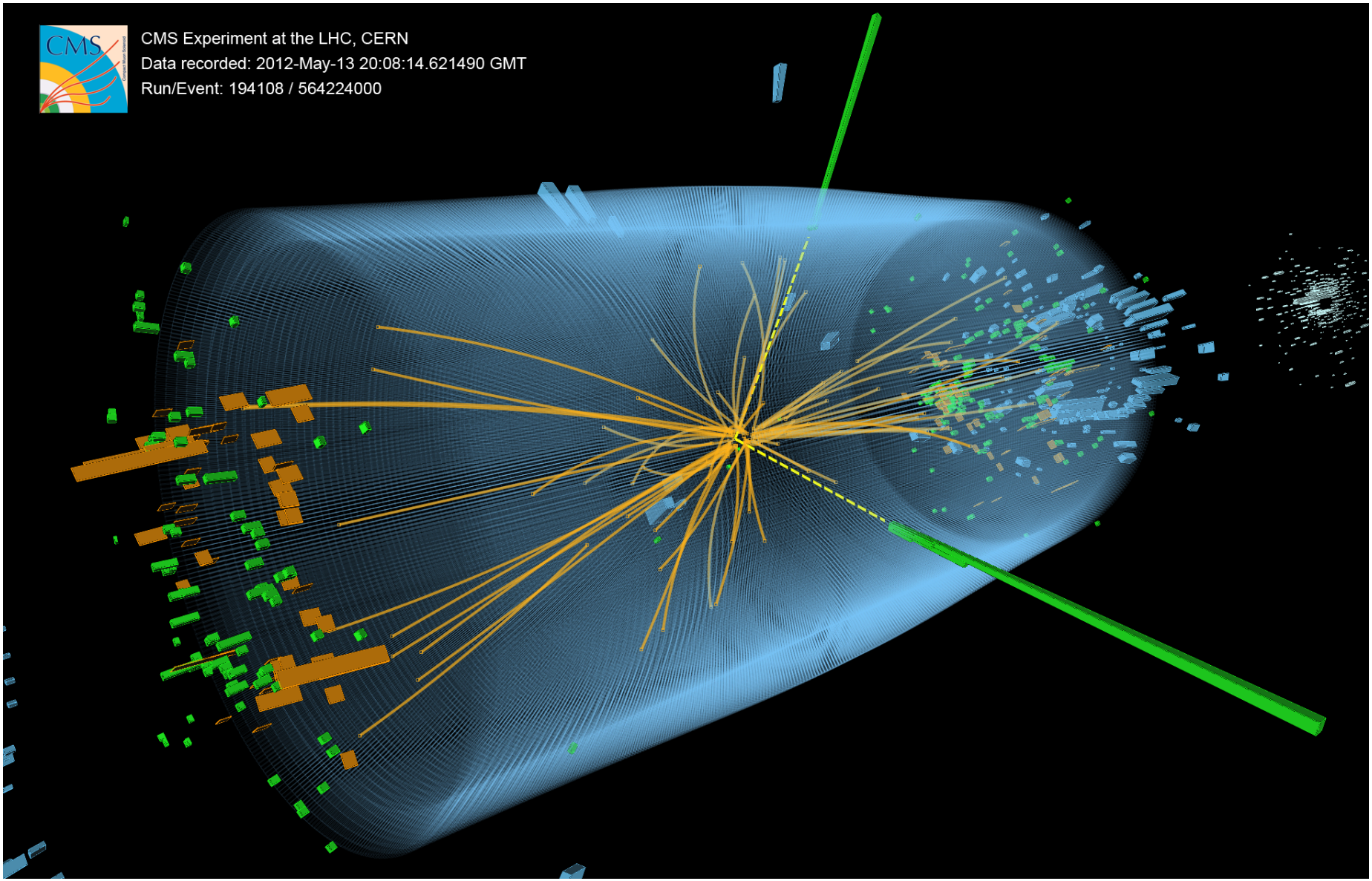
- The Higgs decays accessible in the experiments.
  - ***bb* : large BR, Yukawa coupling**
  - **$\tau\tau$: Yukawa coupling**
  - ***WW* : large BR, gauge boson coupling**
  - ***ZZ* : high S/B, high mass resolution, gauge boson coupling**
  - **$\gamma\gamma$: high mass resolution, loop coupling**





LHC Higgs Cross Section WG : https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

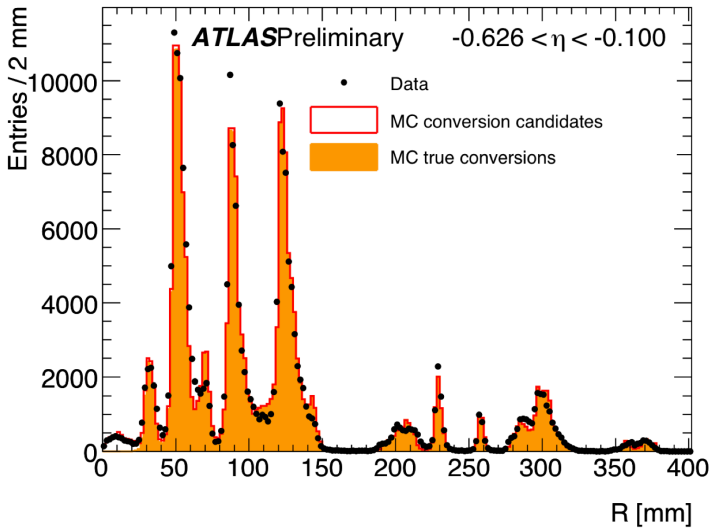
$H \rightarrow \gamma\gamma$



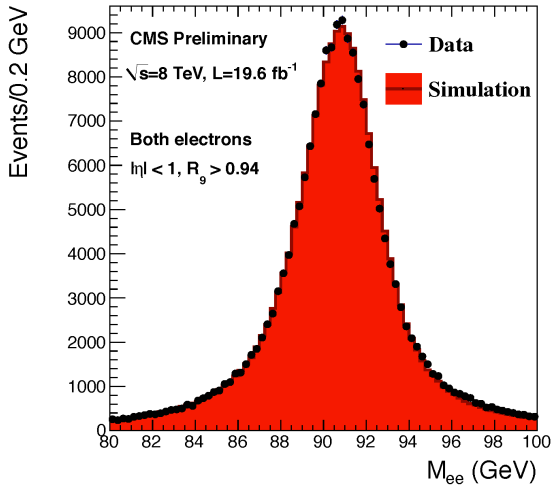
$H \rightarrow \gamma\gamma$

- Searching for excess in di-photon mass spectrum
- Selection of two high p_T isolated photons
  - Both converted and unconverted photons
- EM calorimeter (ATLAS : LAr, CMS : $PbWO_4$) performance is crucial.
  - Calibration, stability against time and pileup, energy resolution, photon pointing (ATLAS)

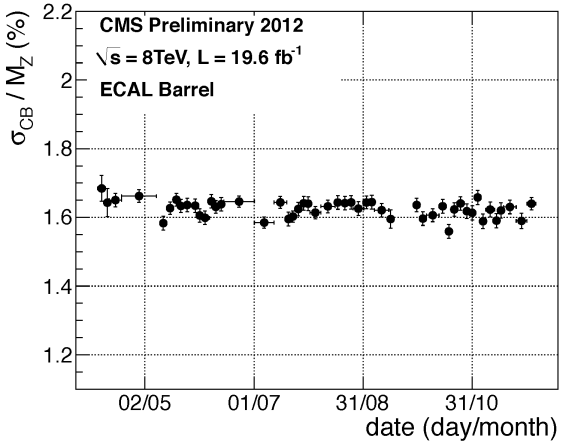
Converted γ in front of calorimeter



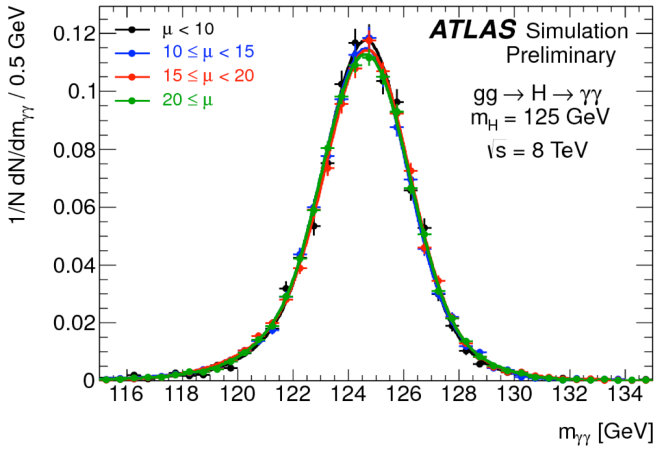
Z→ee in data/MC



Z→ee mass resolution stability

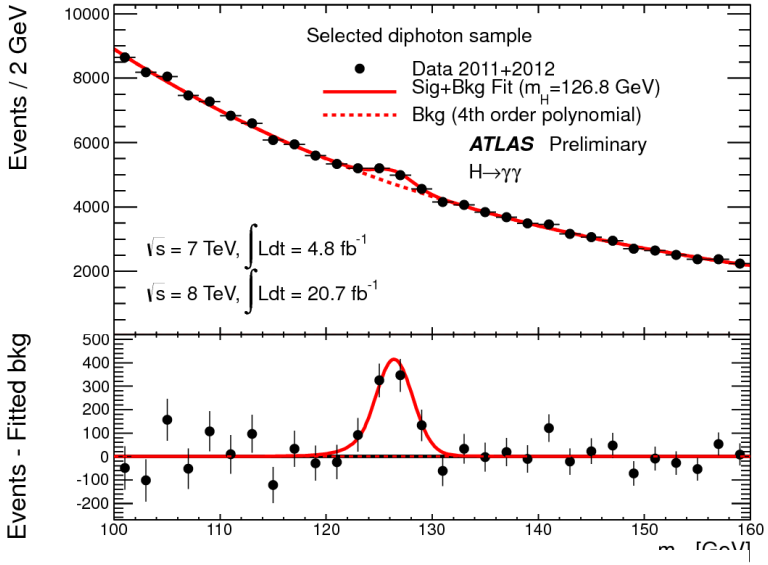


$m_{\gamma\gamma}$ pileup stability (MC)

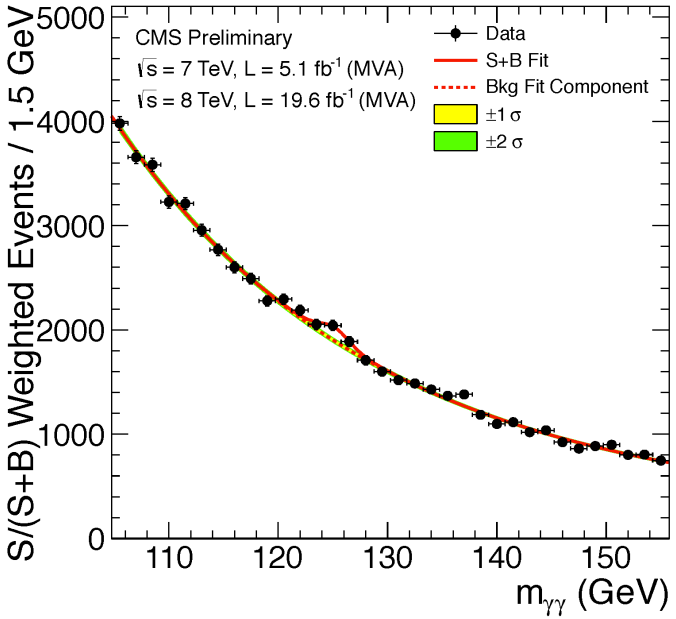


$H \rightarrow \gamma\gamma$

- Excess has been observed by both ATLAS and CMS.
  - **ATLAS**
    - **Significance : 7.4 σ (4.1 σ expected)**
    - **$m_H = 126.8 \pm 0.2(stat) \pm 0.7(syst)$ GeV**
    - **$\sigma/\sigma_{SM} = 1.65 \pm 0.24(stat) \pm 0.22(syst)$**
  - **CMS (MVA analysis)**
    - **Significance : 3.2 σ (4.2 σ expected)**
    - **$m_H = 125.4 \pm 0.5(stat) \pm 0.6(syst)$ GeV**
    - **$\sigma/\sigma_{SM} = 0.78 \pm 0.27$**



- Event categorization to enrich *VH* and VBF channels
  - Lepton, E_T^{miss}, di-jet mass, photons & di-photon p_T



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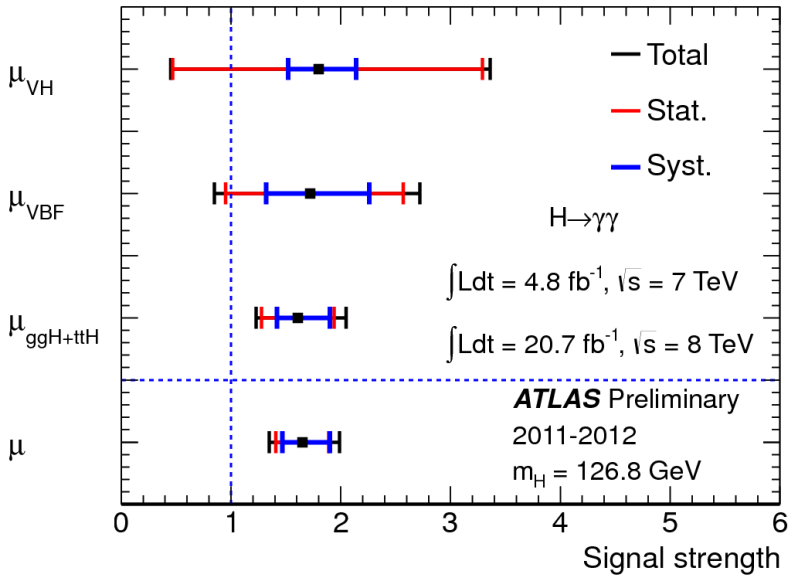

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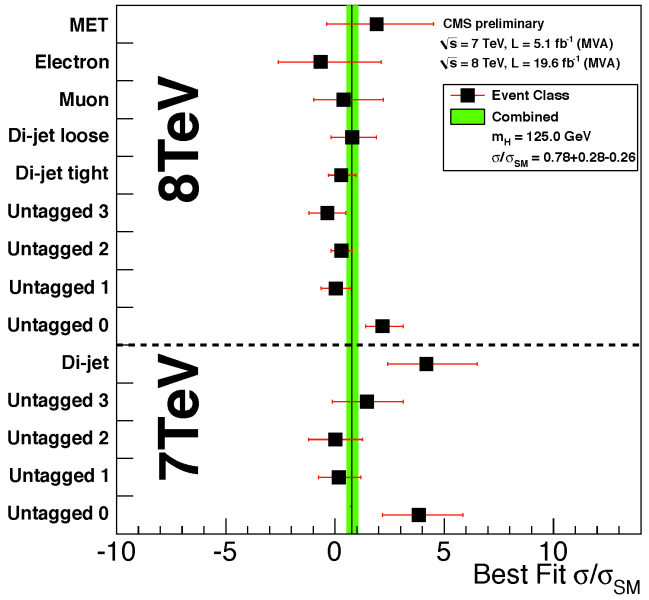
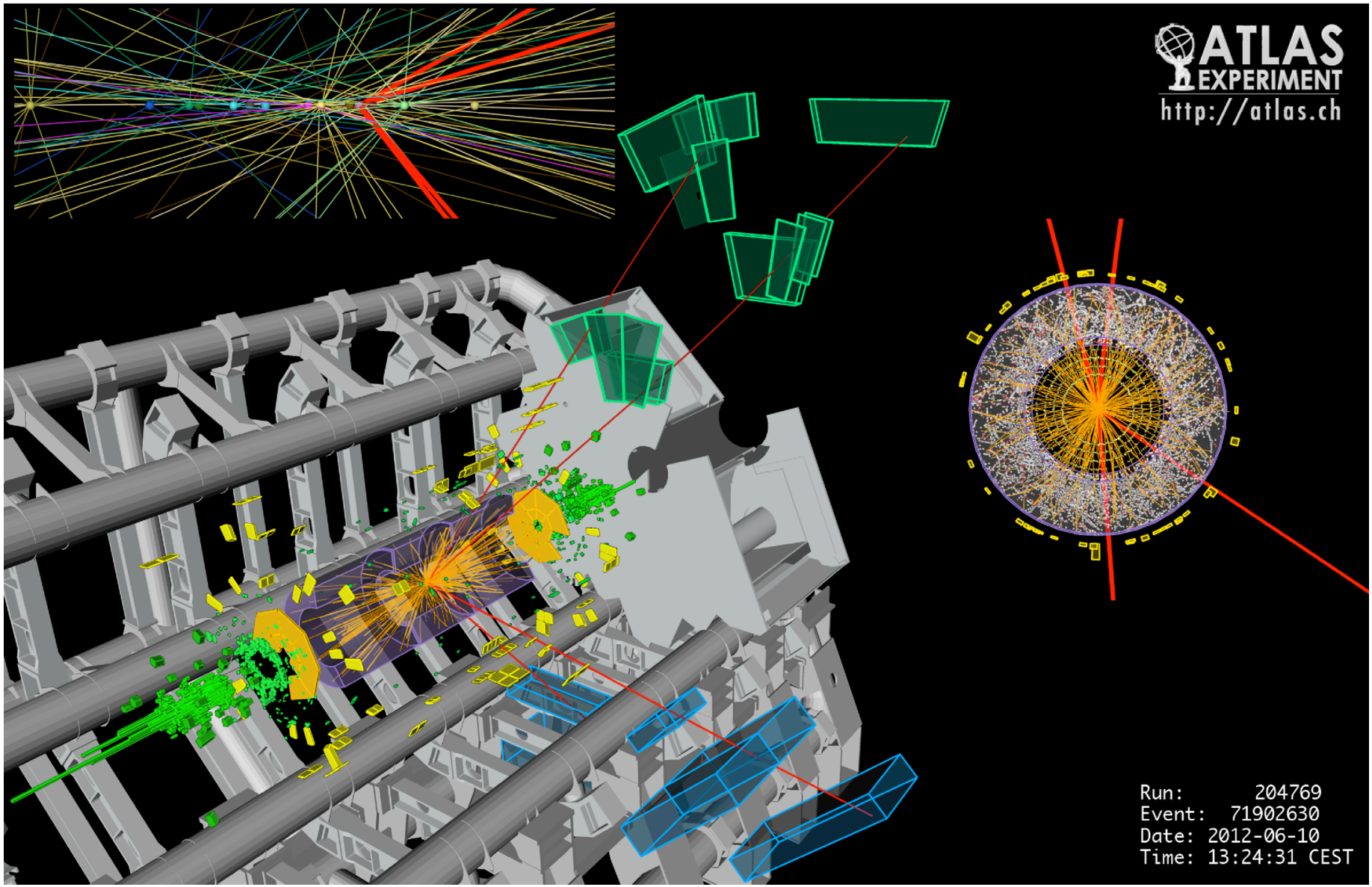


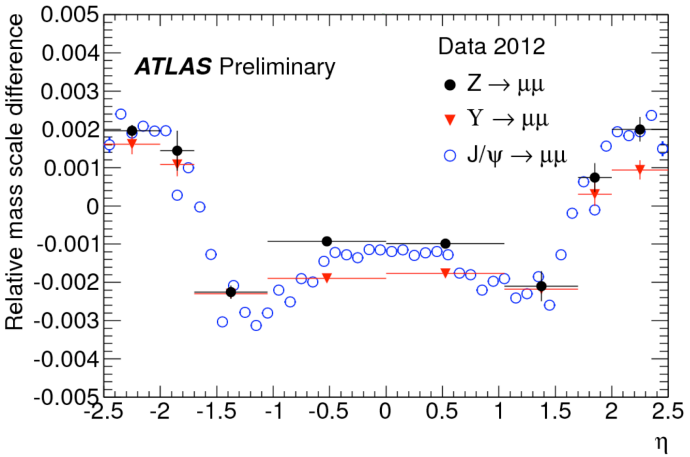
$H \rightarrow ZZ^* \rightarrow 4l$

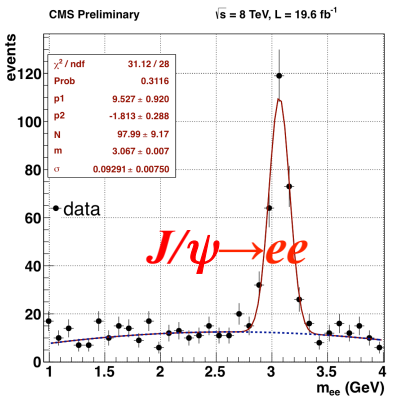


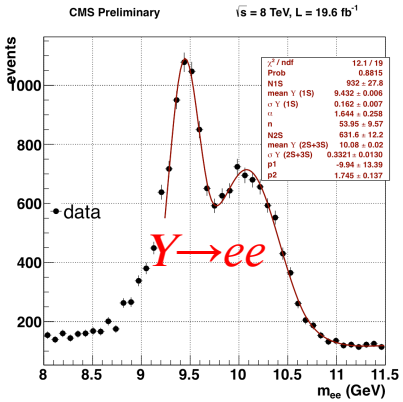
$H \rightarrow ZZ^* \rightarrow 4l$

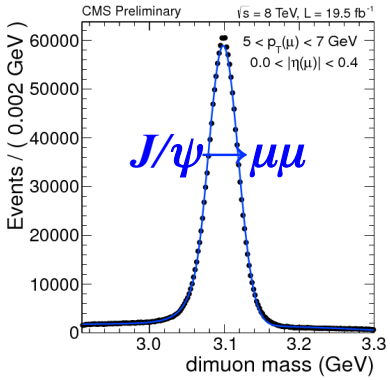
- Searching for excess in four-lepton mass spectrum
  - High mass resolution channel and high S/B
  - BG dominated by SM *ZZ, Zbb, Z+jets*
- Excellent lepton (electron/muon) performance is required.
  - Energy/momentum scale and resolution
  - High reconstruction and identification efficiency at low p_T
  - Validation with Z, Y and J/ψ ($\rightarrow 2l$)
  - Single-resonant Z ($\rightarrow 4l$) for validation

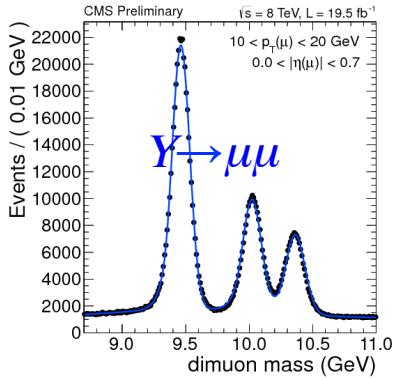
Relative difference from PDG value

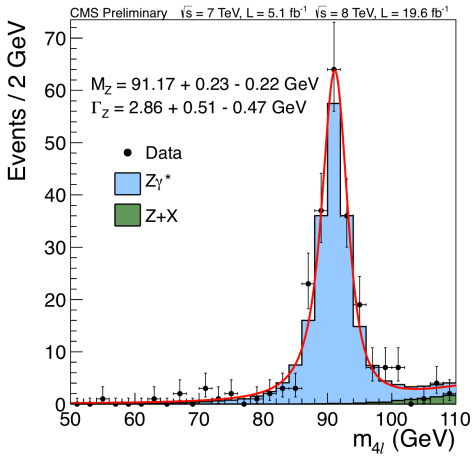












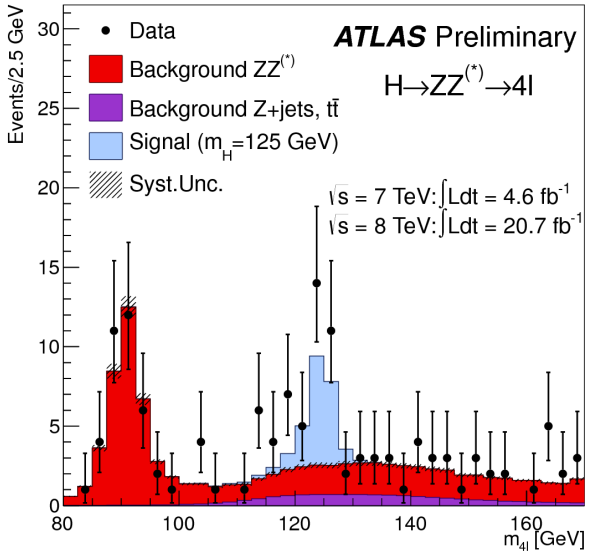
Single-resonant Z decaying to $4l$ in data/MC

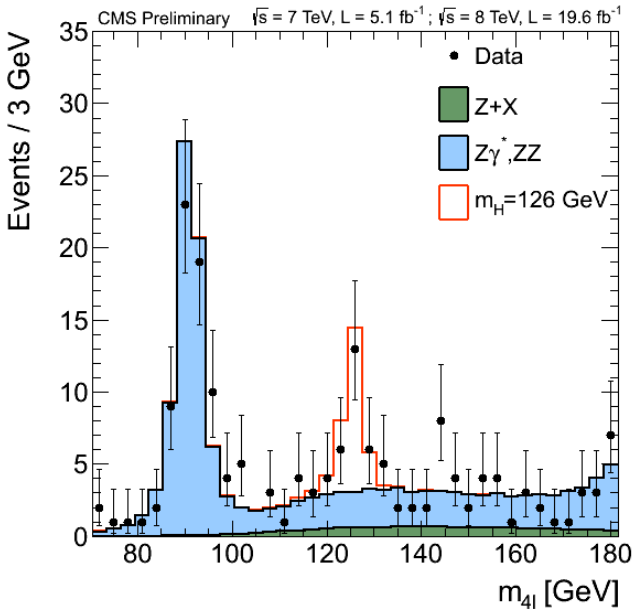
$H \rightarrow ZZ^* \rightarrow 4l$

- Both experiments observed a clear peak together with a single-resonant *Z*.
  - **ATLAS**
    - **Significance : 6.6 σ (4.4 σ expected)**
    - **$m_H = 124.3 \pm 0.6(stat) \pm 0.4(syst)$ GeV**
    - **$\sigma/\sigma_{SM} = 1.7 \pm 0.4$**
  - **CMS**
    - **Significance : 6.7 σ (7.1 σ expected)**
    - **$m_H = 125.8 \pm 0.5(stat) \pm 0.2(syst)$ GeV**
    - **$\sigma/\sigma_{SM} = 0.91\ ^{+0.30}_{-0.24}$**

- Categorization of *gg*F, VBF and *VH* to measure vector boson and fermion coupling in production (to be mentioned later on).

- *Z* boson pair mass correlation as expected





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    - **σ/σ_{SM} = 1.7 ± 0.4**
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    - **m_H = 125.8 ± 0.5(stat) ± 0.2(syst) GeV**
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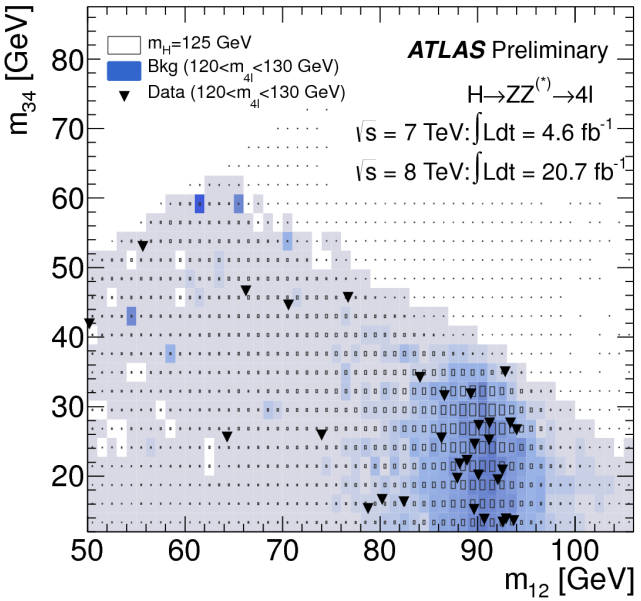
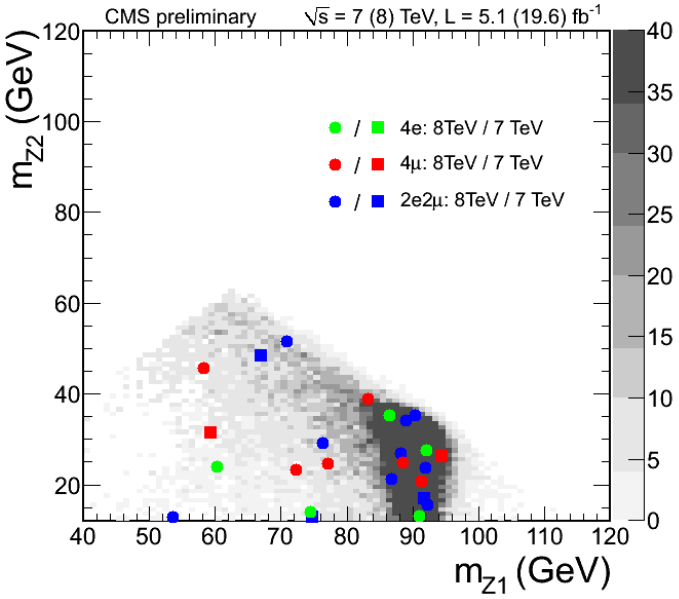
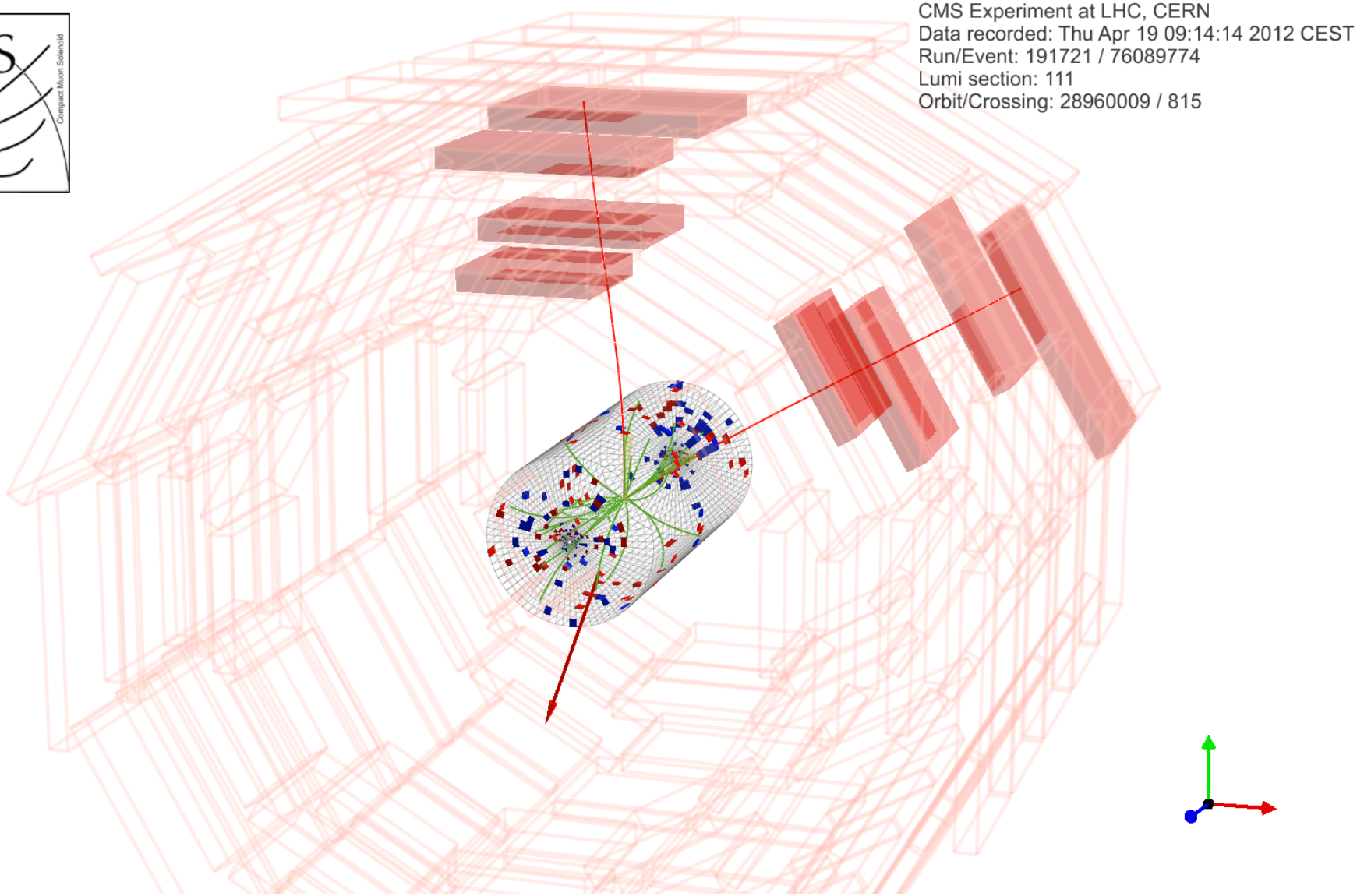




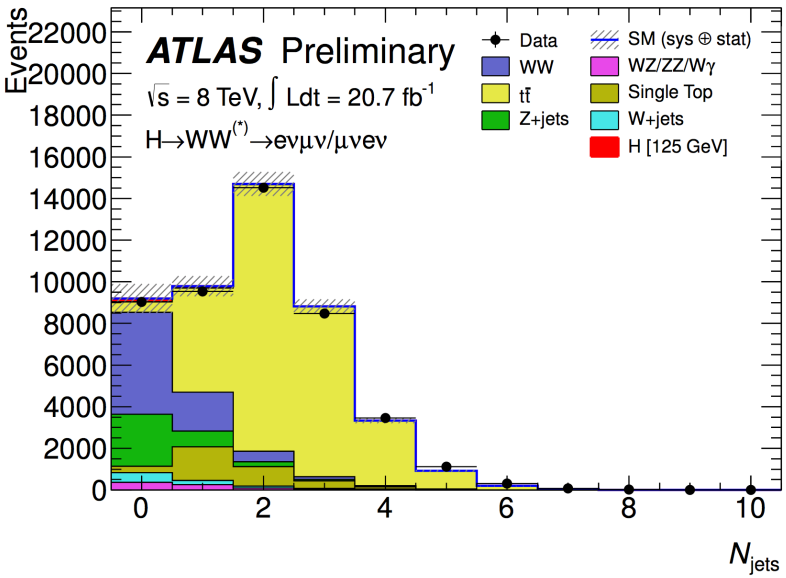
$H \rightarrow WW^* \rightarrow l\nu l\nu$

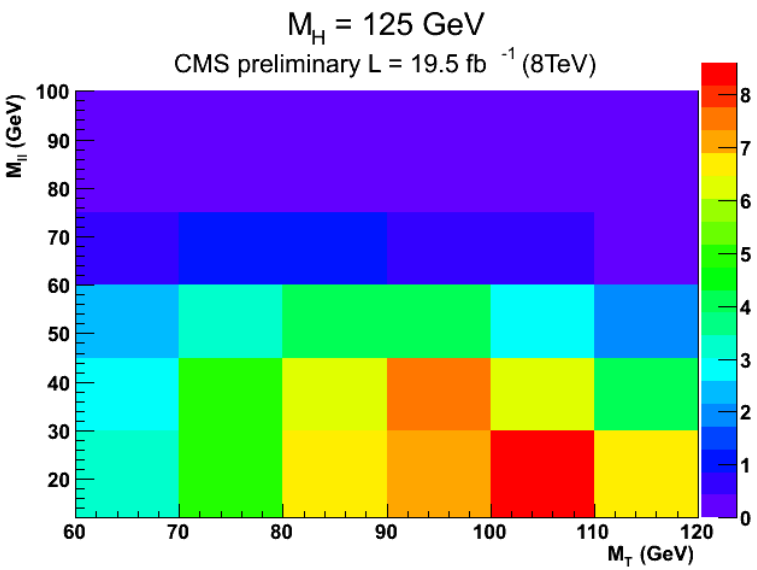


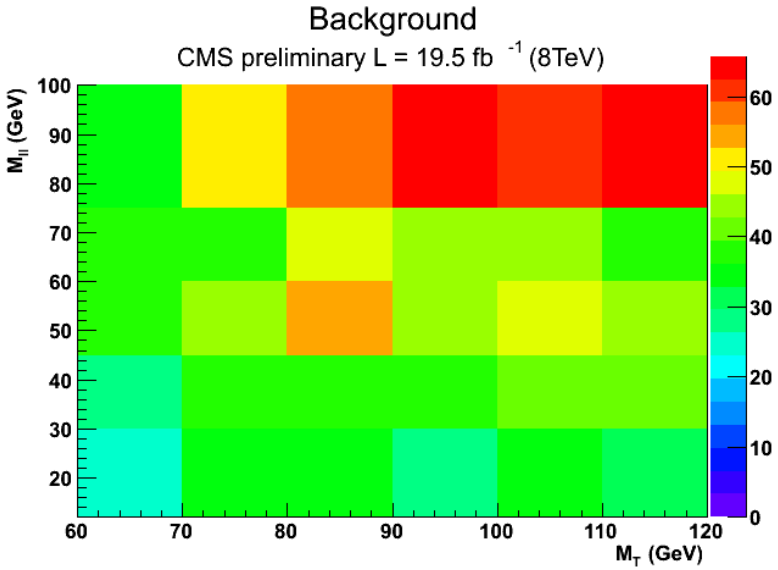
$H \rightarrow WW^* \rightarrow l\nu l\nu$

- Two high p_T isolated leptons + large missing E_T
  - Small opening angle in two leptons
  - Analyses separately in N_{jet} and lepton flavor
  - Searching for excess in m_{ll} and m_T
- Backgrounds
  - Many processes are involved and are estimated by data-driven approach as much as possible.
  - Dominated by SM *WW*, *tt*, *Z+jets* depending on N_{jet} and lepton flavor

Different lepton flavor

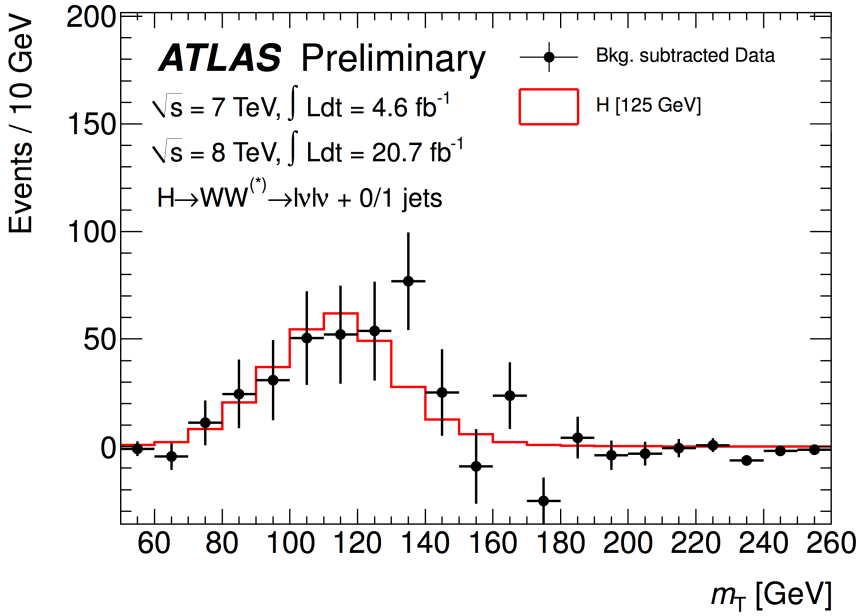


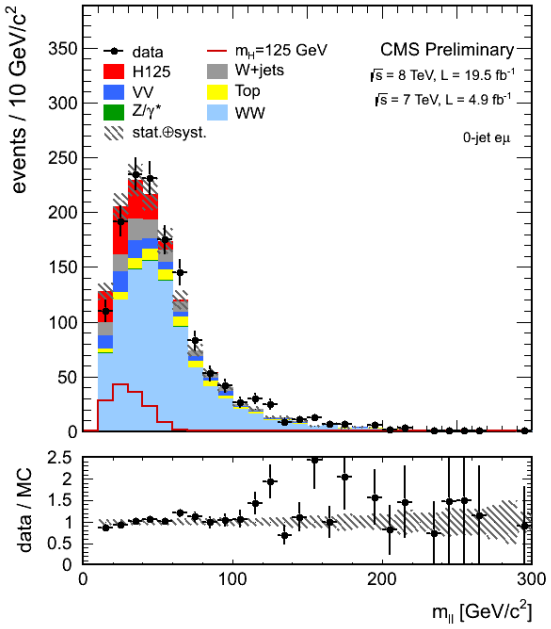


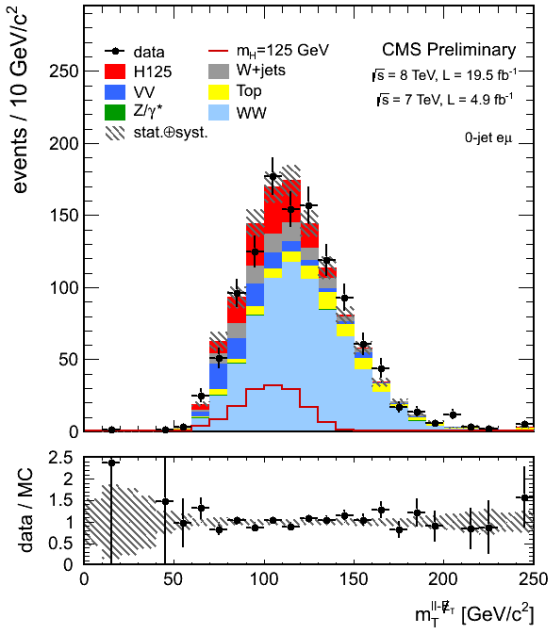


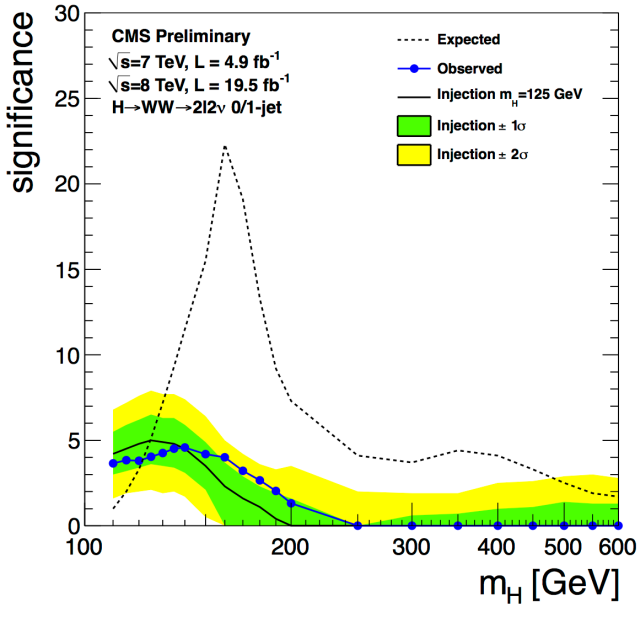
$H \rightarrow WW^* \rightarrow l\nu l\nu$

- Results
  - **ATLAS**
    - **Significance at m_H = 125 GeV :**
      3.8 σ (3.7 σ expected)
    - **$\sigma/\sigma_{SM} = 1.01 \pm 0.31$**
  - **CMS**
    - **Significance at m_H = 125 GeV :**
      4.0 σ (5.1 σ expected)
    - **$\sigma/\sigma_{SM} = 0.76 \pm 0.21$**

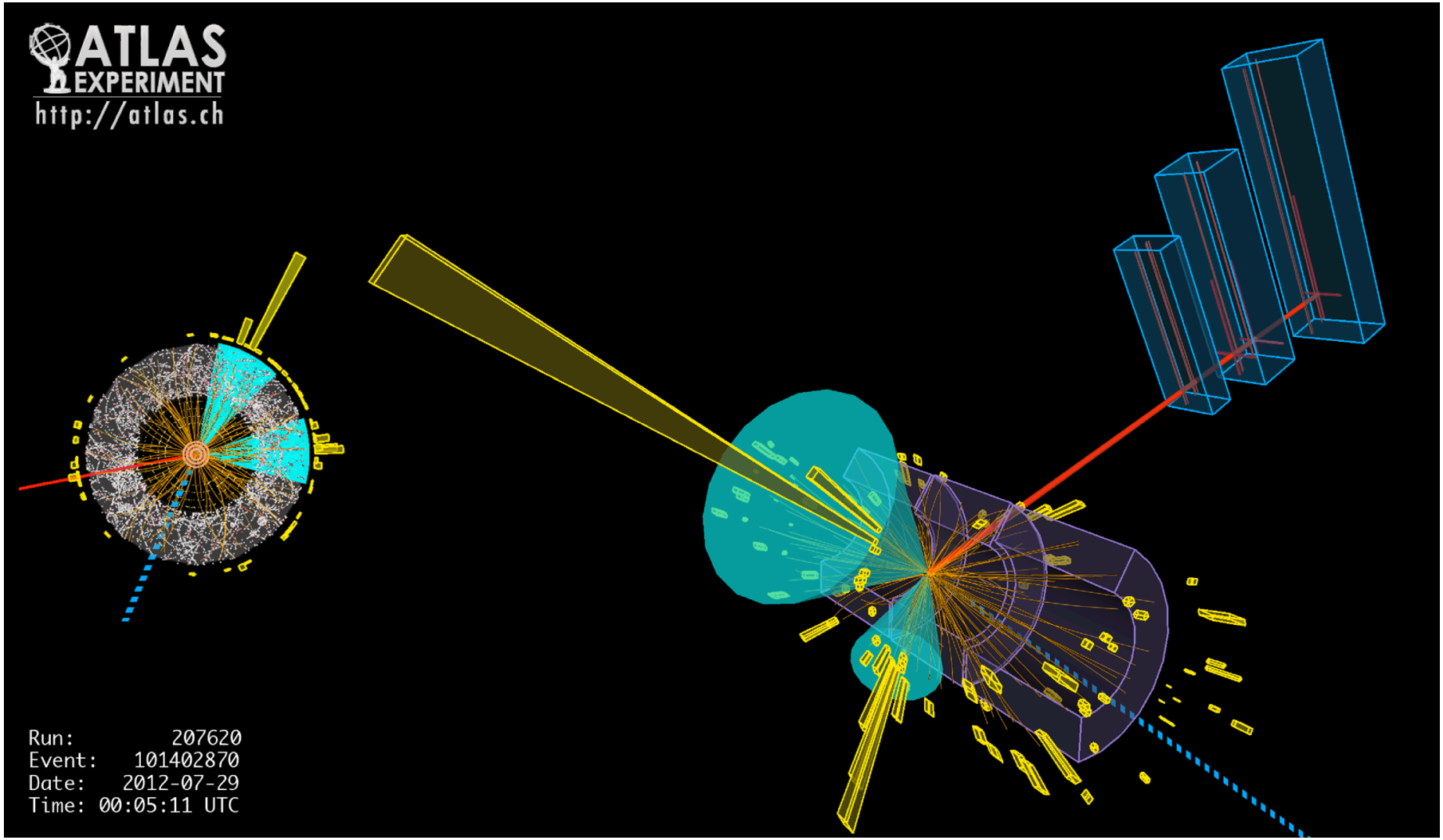








$VH, H \rightarrow bb$

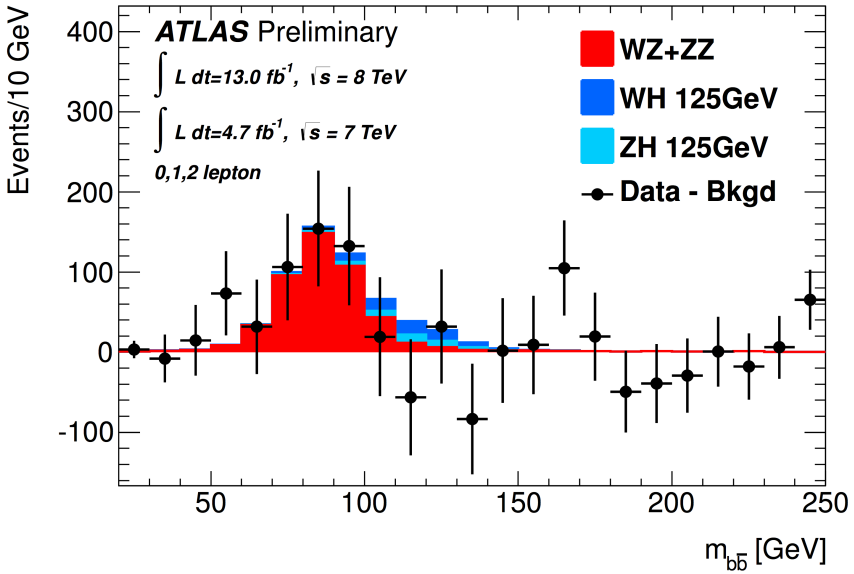


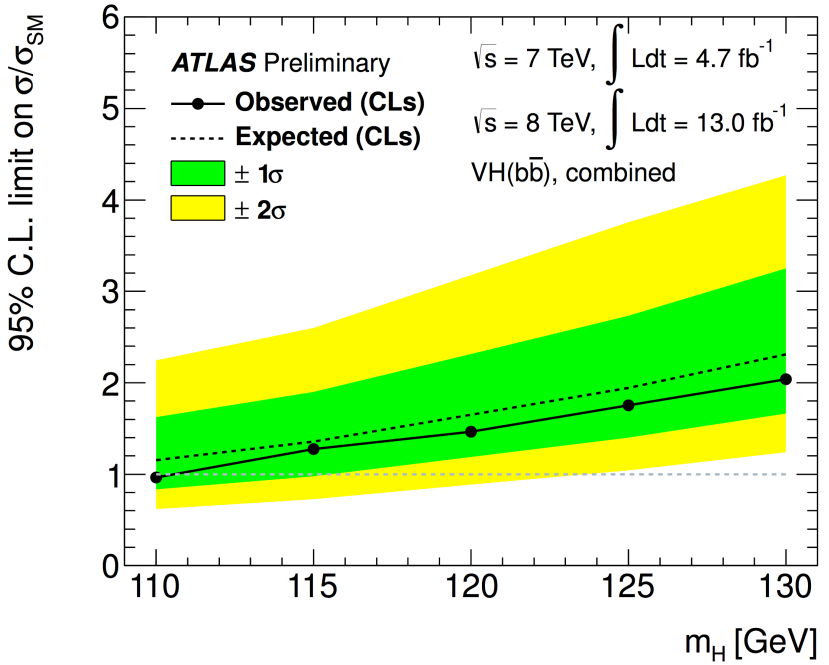
VH, H → bb

- A very important decay mode to measure Bottom-Yukawa coupling, searching for excess in m_{bb} spectrum

- Three search channels categorized by the vector boson type and decay
  - ***WH→lνbb***
  - ***ZH→llbb***
  - ***ZH→ννbb***

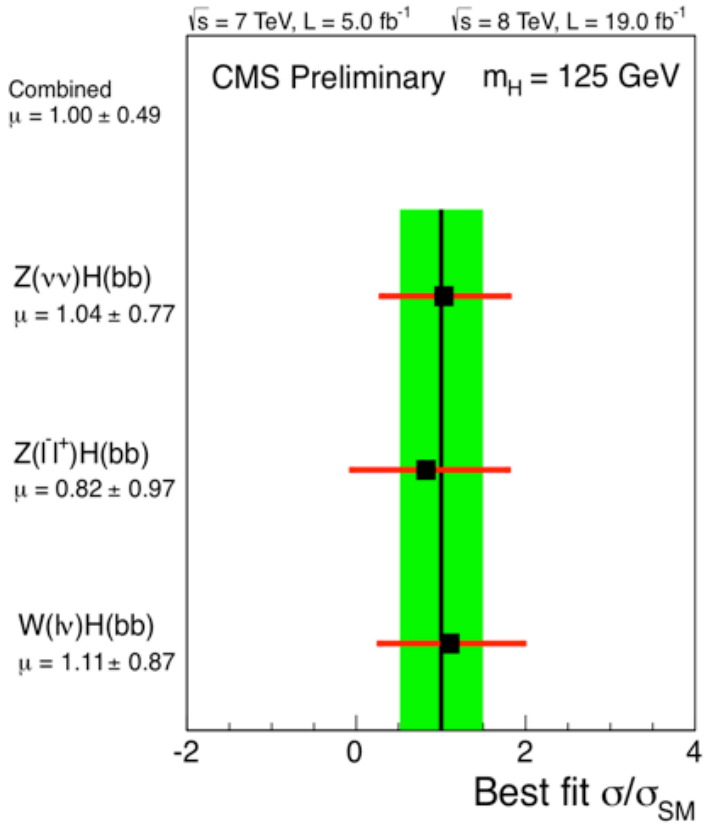
- **ATLAS result**
  - **95% CL limit at 125 GeV :**
    1.8 x σ_{SM} (expected 1.9 x σ_{SM})
  - **σ/σ_{SM} = -0.4 ± 0.7 (stat) ± 0.8 (syst)**

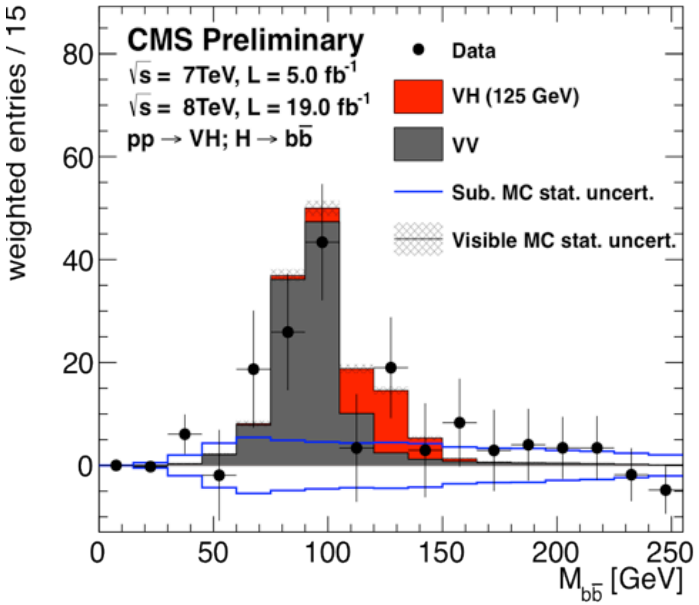


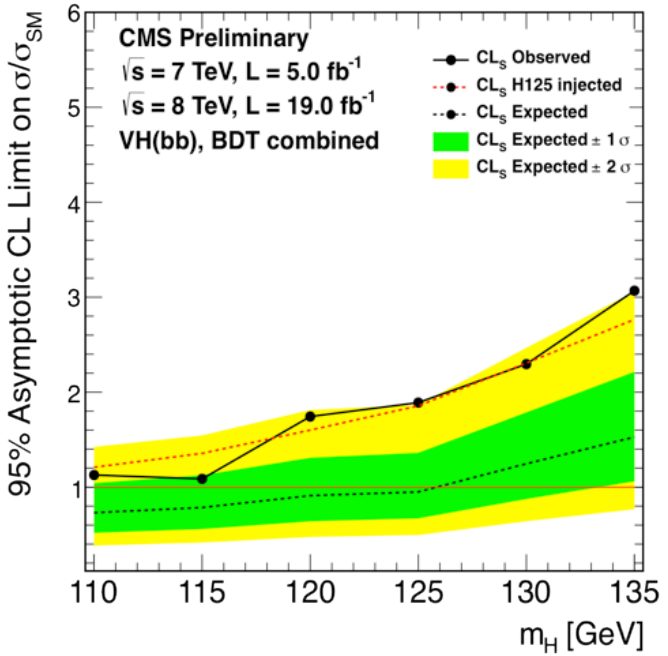


VH, H → bb

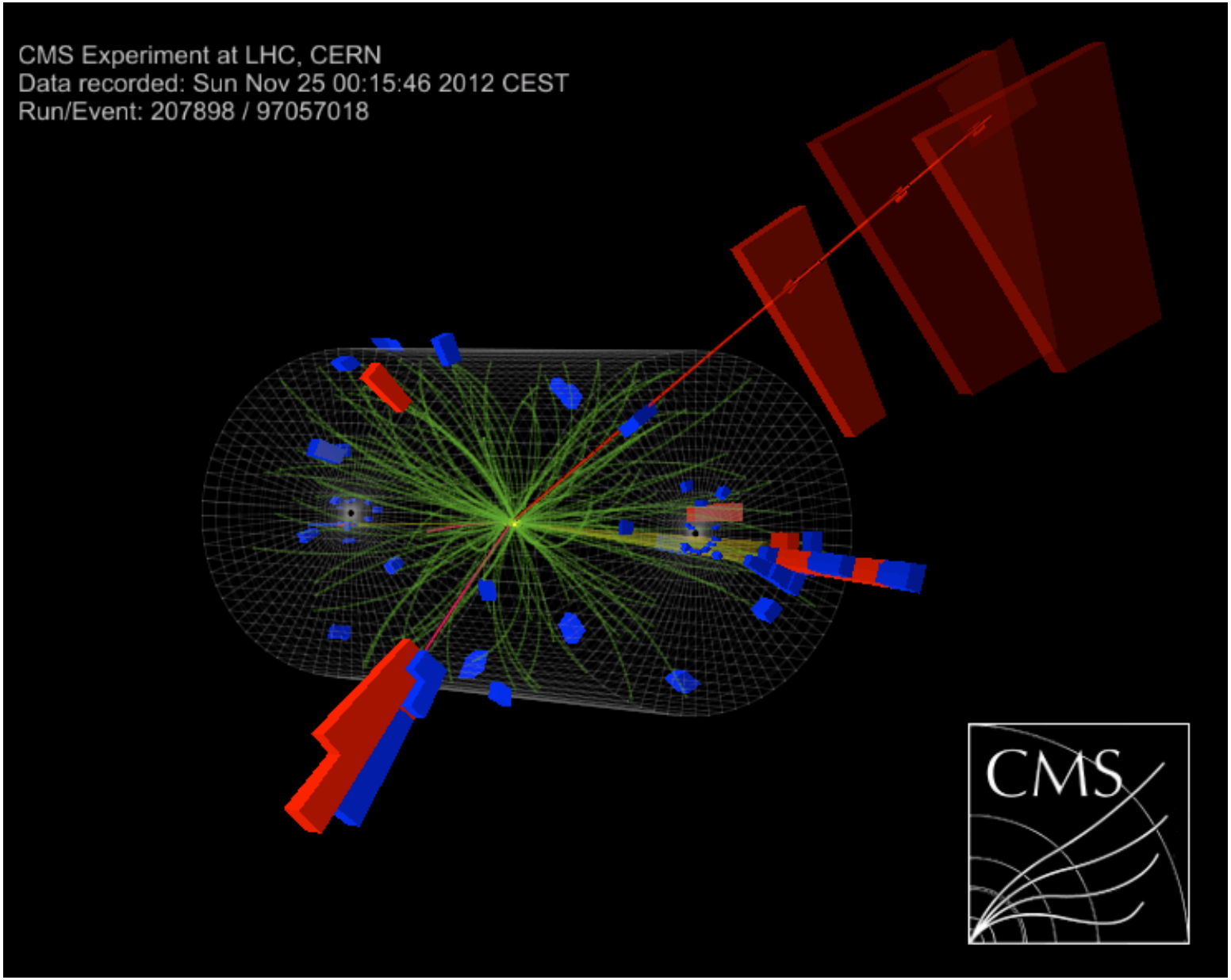
- **CMS result**
  - **Excess was observed above the BG only expectation.**
  - **Significance at m_H = 125 GeV : 2.1 σ**
  - **σ/σ_{SM} = 1.0 ± 0.5**





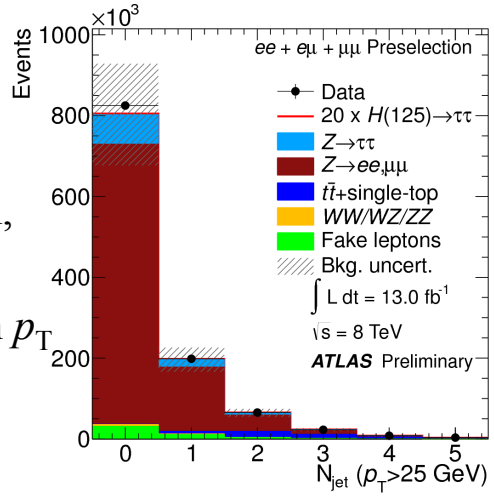


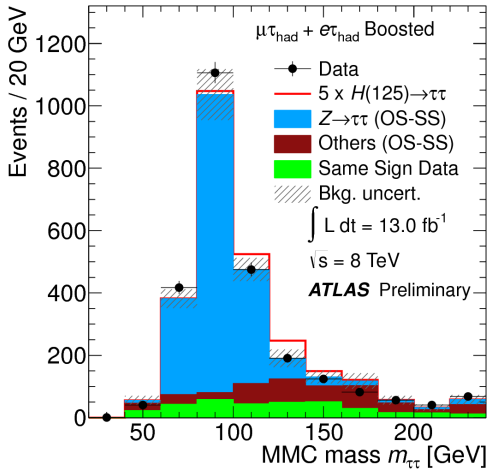
$H \rightarrow \tau\tau$



$H \rightarrow \tau\tau$

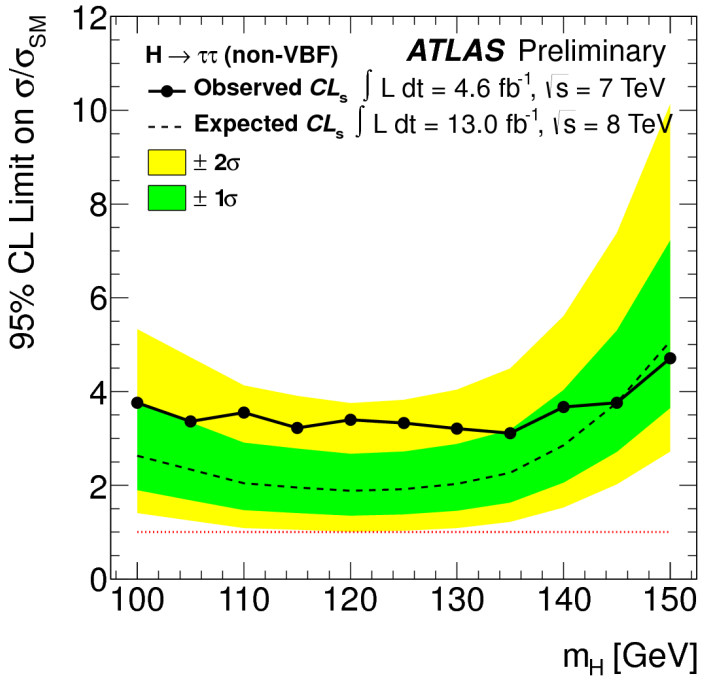
- Higgs search of this decay mode is categorized in the tau-pair decay mode and number of jets.
  - Tau decay : lepton-lepton, lepton-hadron, hadron-hadron
  - Number of jets : 0, 1 (boosted-*H* w/ high p_T jet), 2 (VBF, *VH*)





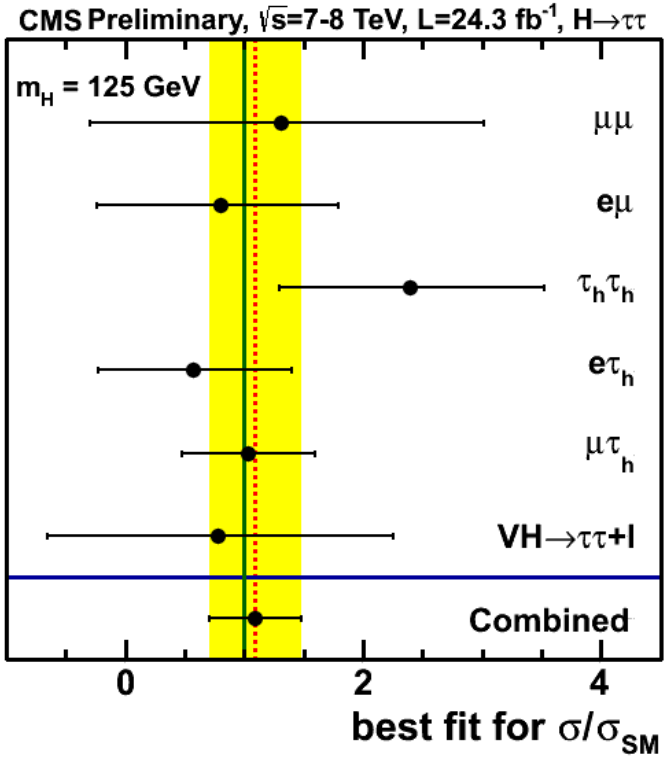
- Searching for excess in $m_{\tau\tau}$ mass spectrum.

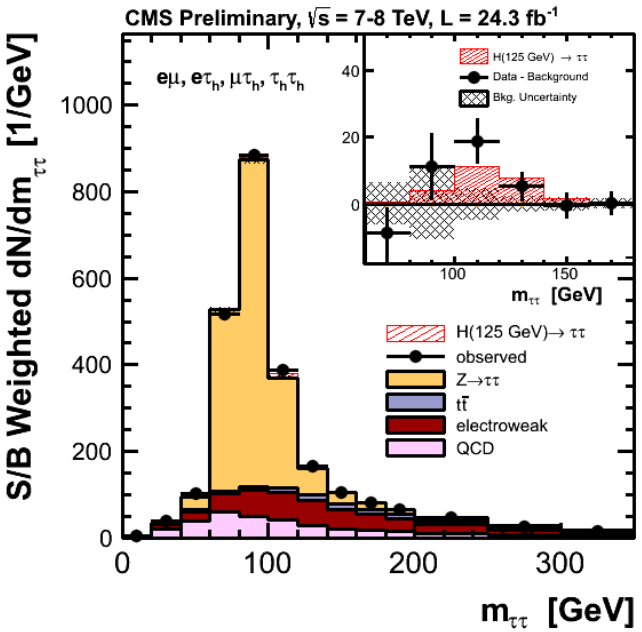
- **ATLAS result**
  - **No excess (yet)**
  - **95% CL limit at 125 GeV :**
    1.9 x σ_{SM} (expected 1.2 x σ_{SM})
  - **$\sigma/\sigma_{SM} = 0.7 \pm 0.7$**

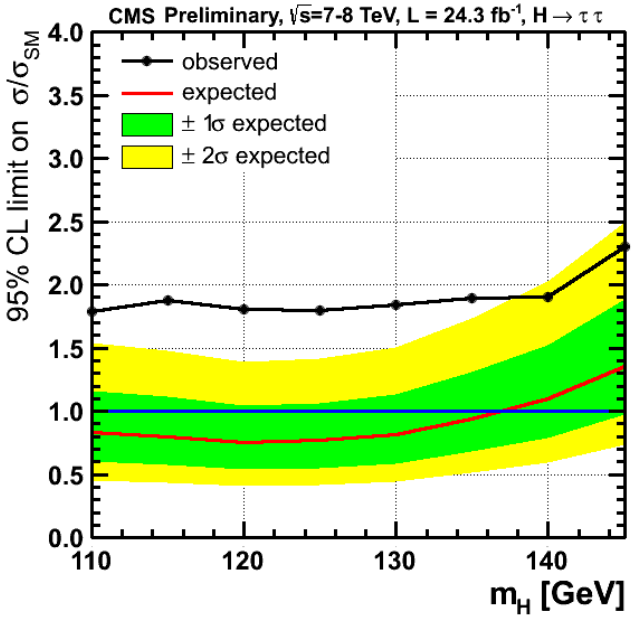


$H \rightarrow \tau\tau$

- CMS result
  - Excess was observed above the BG
  - Significance at $m_H = 125$ GeV : 2.85 σ
  - $\sigma/\sigma_{SM} = 1.1 \pm 0.4$







Higgs Combination

Combining all the channels together
to study the Higgs properties and
its consistency with the SM
(or its inconsistency due to BSM)

Mass

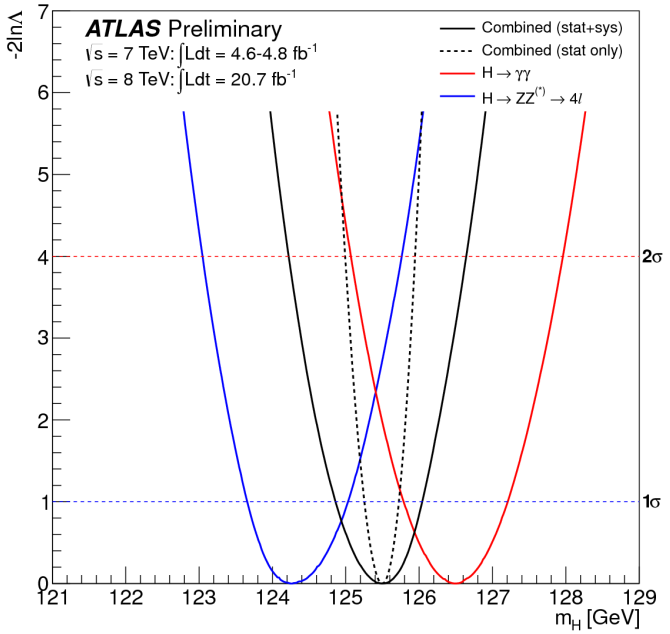
Signal strength

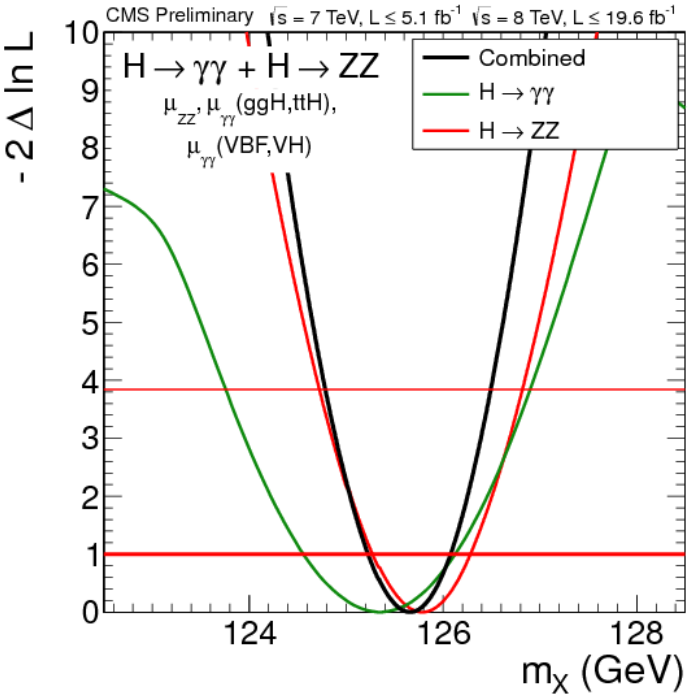
Coupling

Spin

Higgs Combination : Mass

- **Both ATLAS and CMS combined high mass resolution channels of $\gamma\gamma$ and $ZZ^* \rightarrow 4l$.**
- **ATLAS :**
  - **$m_H = 125.5 \pm 0.2(stat) \pm 0.6(syst)$ GeV**
- **CMS**
  - **$m_H = 125.7 \pm 0.3(stat) \pm 0.3(syst)$ GeV**

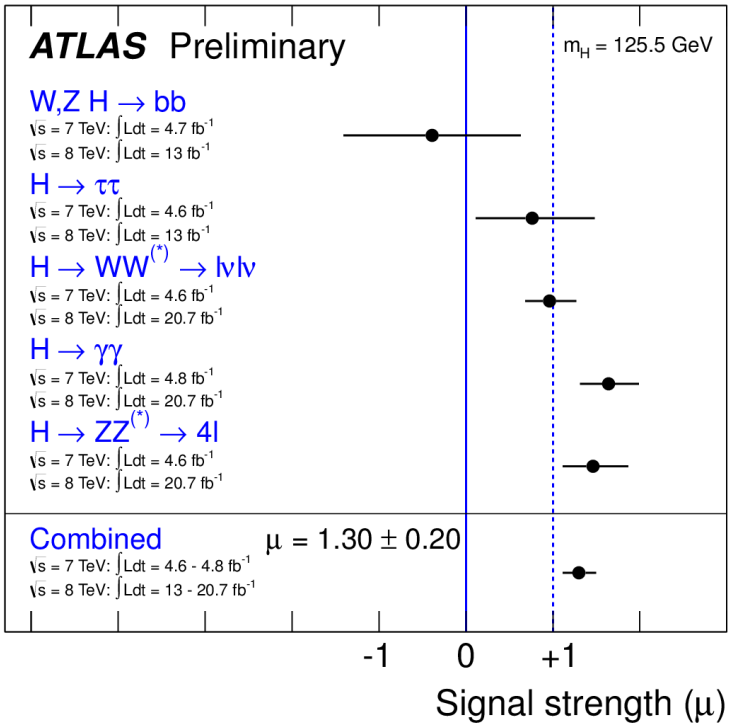


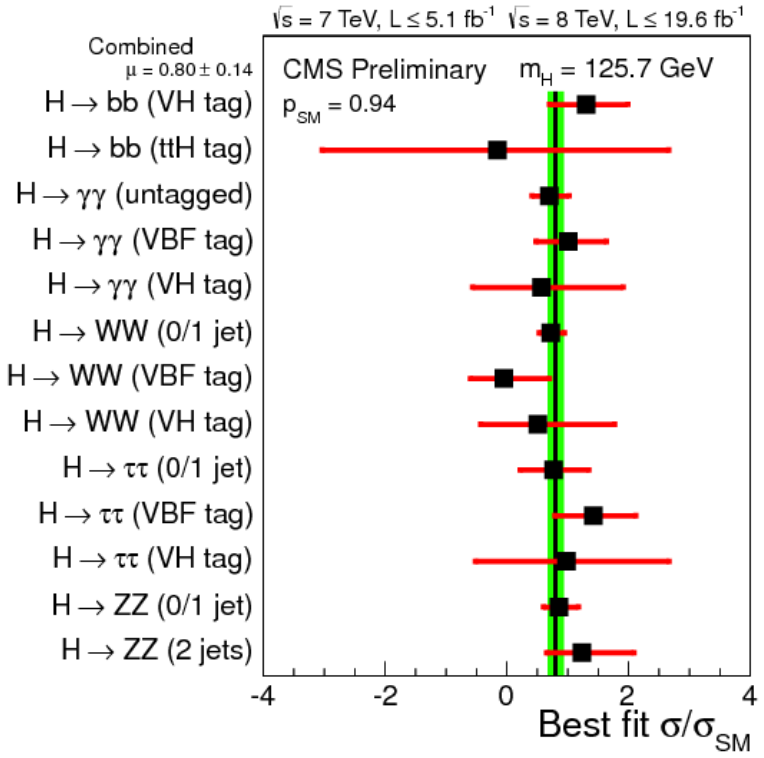


Higgs Combination : Signal Strength

- **Combining all the available channels for signal strength (σ/σ_{SM})**
- **ATLAS :**
  - **$\sigma/\sigma_{SM} = 1.30 \pm 0.20$**
- **CMS**
  - **$\sigma/\sigma_{SM} = 0.80 \pm 0.14$**

Signal strength at the combined mass of each experiment



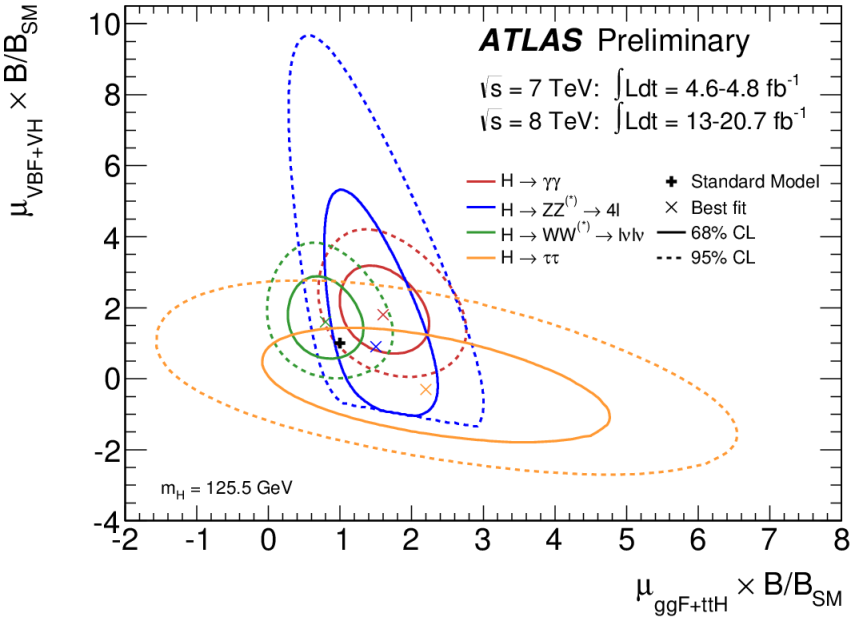


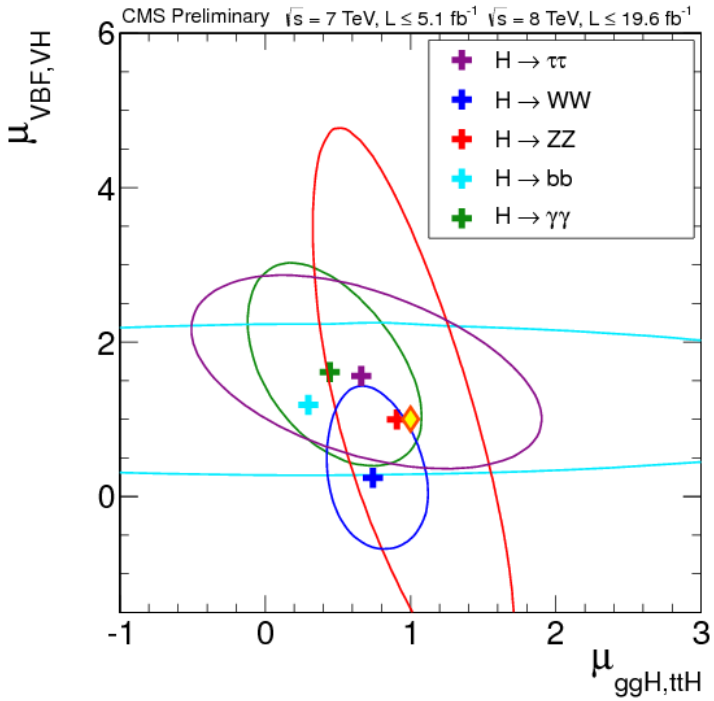
Signal strength consistent in different channels

Higgs Combination : Signal Strength

- **Comparison of the production channels in terms of the signal strength of *gg*F+*ttH* (fermion coupling) vs VBF+*VH* (vector boson coupling)**

- **In both ATLAS and CMS measurements, each production channel is consistent with the SM.**



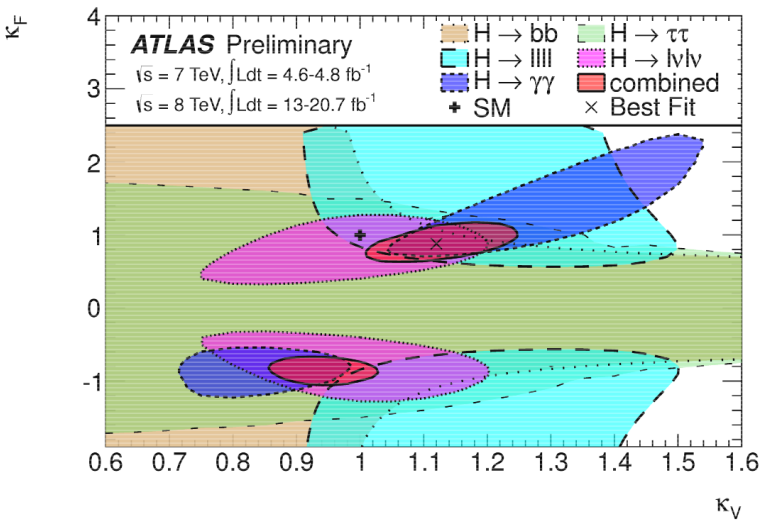


Higgs Combination : Coupling

- Fermion-vs-Vector couplings
  - Coupling scale factor κ_i : modified coupling of Higgs to a SM particle *i*, normalized to 1 for SM Higgs.
  - A benchmark assuming SM contributions only

  Fermion : $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$

  Vector : $\kappa_V = \kappa_W = \kappa_Z$

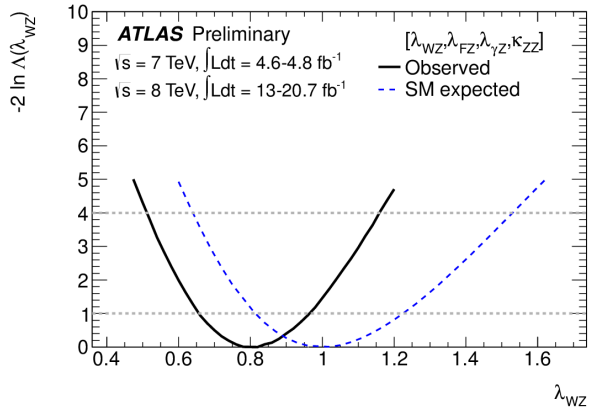


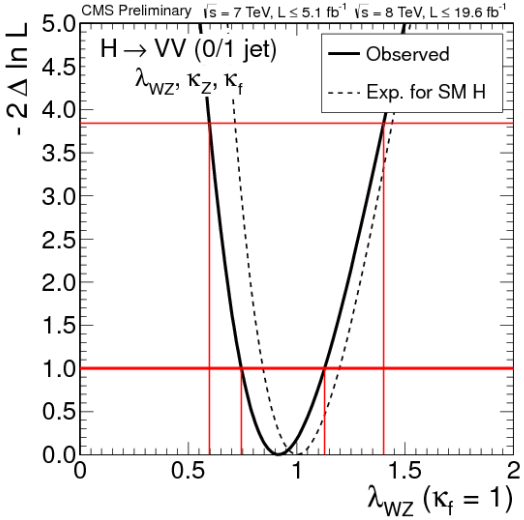
- W-vs-Z coupling ratio :

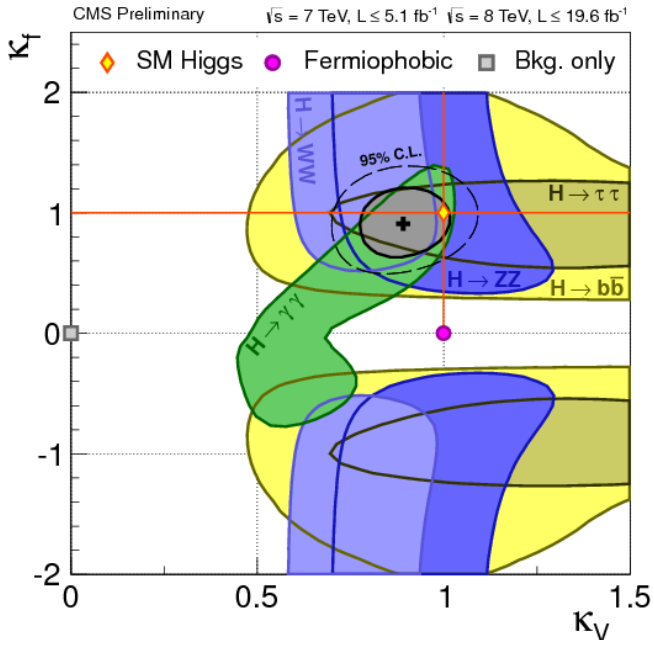
  Custodial symmetry
  - $\lambda_{WZ} = \kappa_W / \kappa_Z$

CMS : 0.73 – 1.00

ATLAS : 0.80 ± 0.15

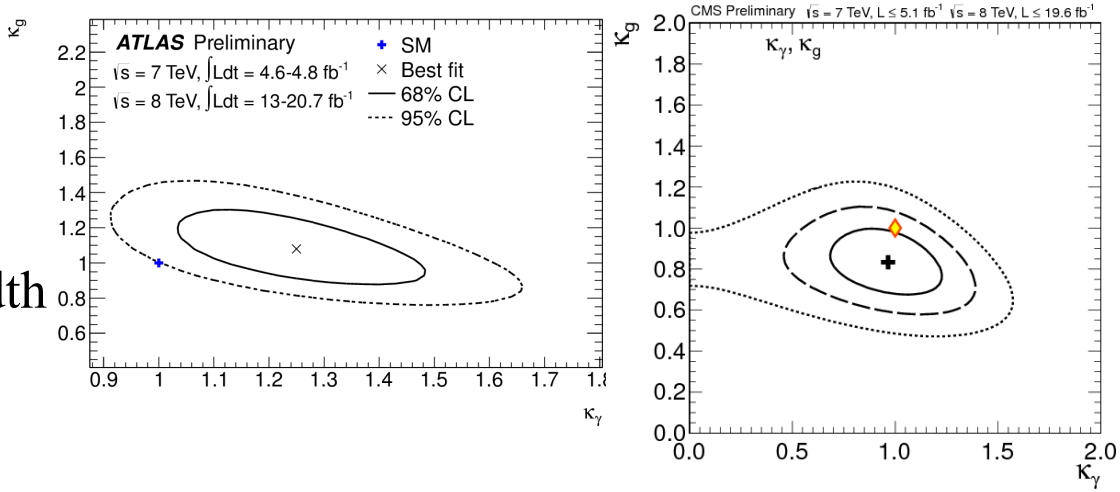






Higgs Combination : Coupling

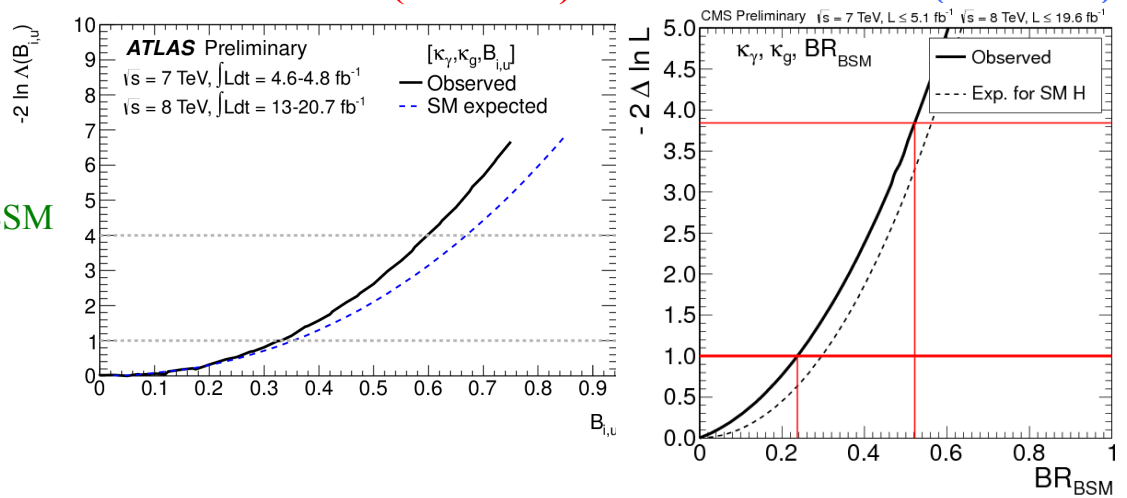
- BSM contribution in loops
  - BSM in loops of $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$
  - Assuming only SM contributions to the total width
  - **Test in κ_g -vs- κ_γ**



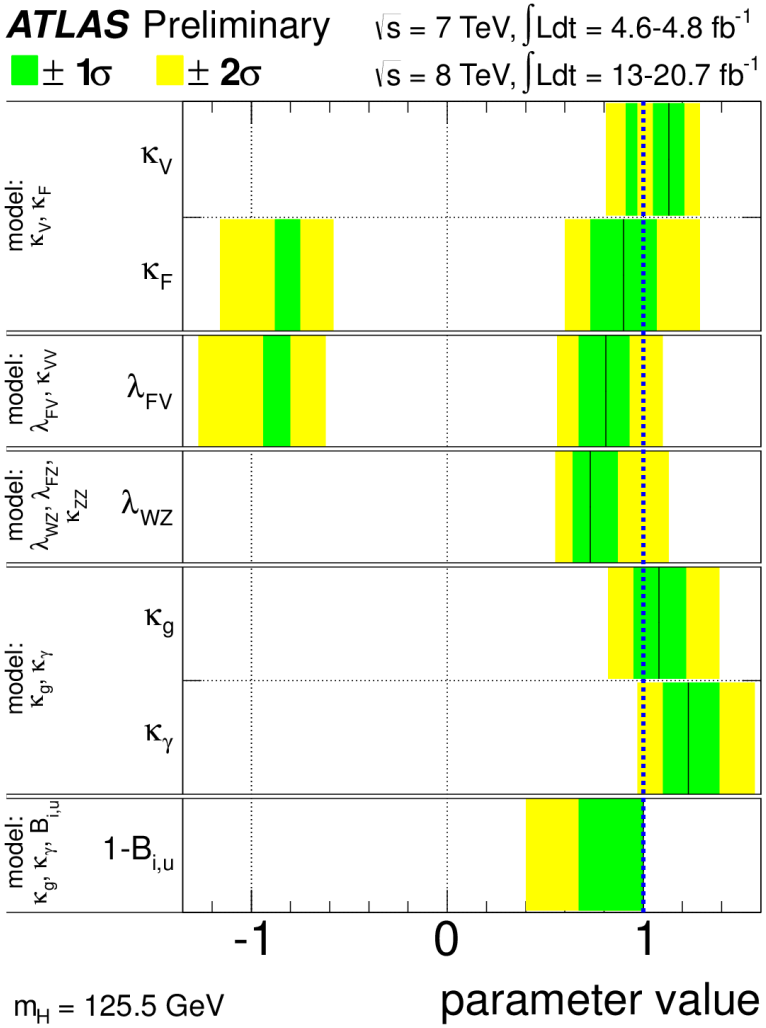
- BSM contribution in total width
  - Test for invisible or undetectable BSM decays
  - $BR(\text{inv.,undet.}) = B_{i,u} = BR_{BSM}$
  - κ_g and κ_γ profiled

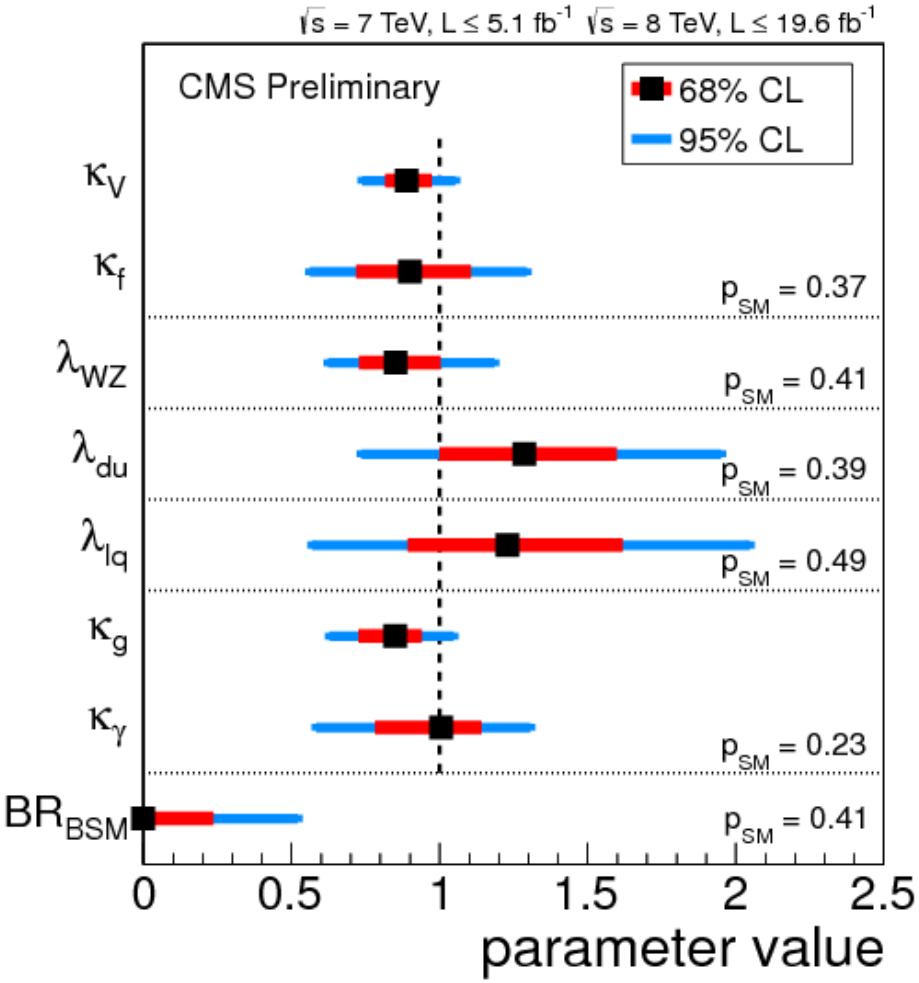
ATLAS : < 0.6 (95% CL)

CMS : < 0.52 (95% CL)



Higgs Combination : Coupling





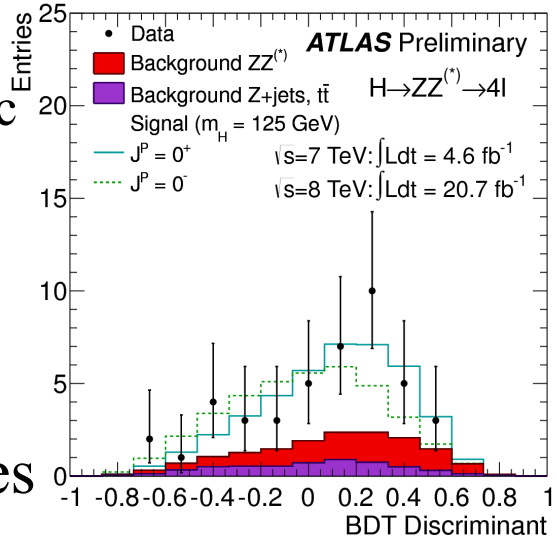
Higgs Combination : Spin

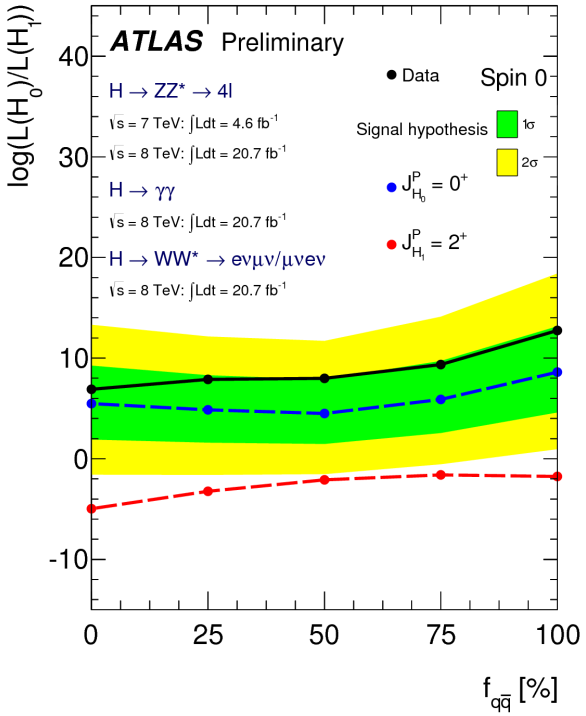
- Spin and parity of the SM Higgs : $J^P = 0^+$
- Test of different Higgs spin-parity hypotheses in kinematic distributions
- $J^P = 0^-$ (ATLAS/CMS), $1^\pm$ (ATLAS)
  - BDT using kinematic variables in $ZZ^* \rightarrow 4l$

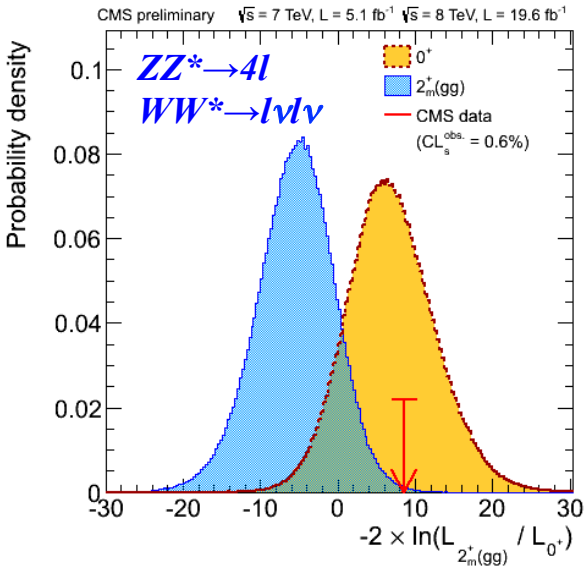
  Excluded 0^- (97.8% CL), 1^+ (99.4% CL), 1^- (94.0% CL)
- $J^P = 2^+_m$: Spin 2 tensor minimal coupling to SM particles
  - **ATLAS**

  Excluded at 99.9% CL
  - **CMS**

  Excluded at 99.4% CL for 100% ggF fraction







Conclusion

- **LHC Run I in 2010 – 2012 delivered a significant amount of data to ATLAS and CMS, allowing us to discover a 125 GeV Higgs Boson.**

- **We are already in a phase to measure the Higgs properties precisely.**
  - **All the properties are consistent with the SM within the uncertainties.**
  - **More updates and results on Run I will come.**

- **In LHC Run II onwards, we will be in another exciting phase for more precise Higgs Physics and BSM search.**