Higgs and Standard Model Experimental Measurements at the LHC
Part 3

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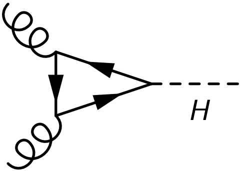
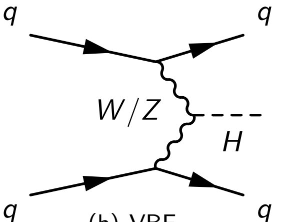
Outline

- Previously:
  - Object reconstruction/identification and Simulation
  - Z as a standard candle
  - Precision measurements with W and Z
  - Measurements with Jets, multiboson production, top physics
- Today:
  - Higgs discovery
  - Overview of Higgs decay channels and analysis strategies
  - Higgs results and interpretation strategies
  - Higgs mass
  - Future prospects

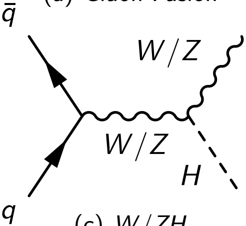
Higgs Production Processes at LHC



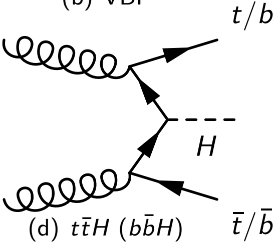
(a) Gluon Fusion



(b) VBF

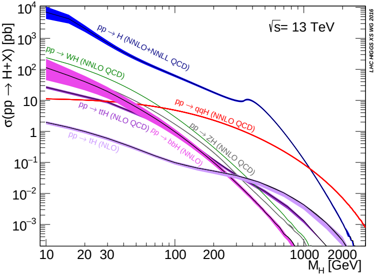


(c) W/ZH

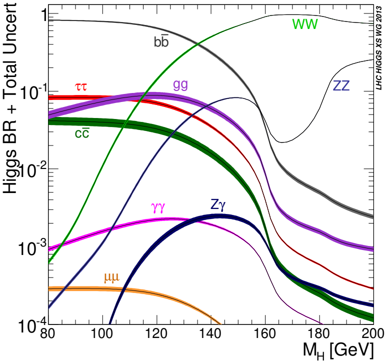


(d) $t\bar{t}H$ ($b\bar{b}H$)

Higgs Production and Decay at LHC



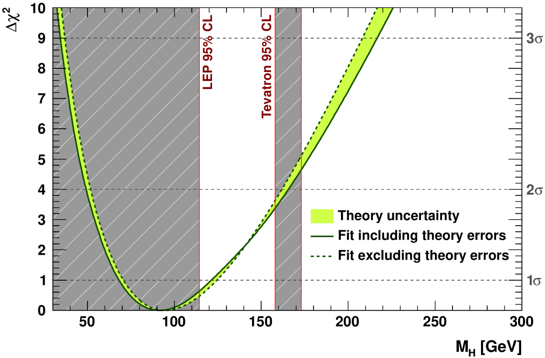
(a) Production Cross Sections



(b) Branching Ratios

- Standard model (+ non-trivial calculations) predict Higgs production cross sections and branching ratios over full range of possible Higgs masses, but m_H itself must be determined experimentally

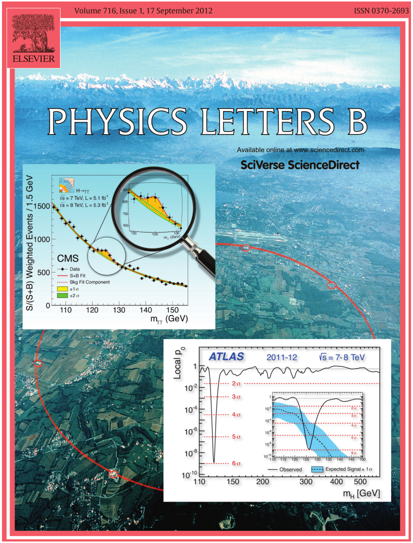
Theoretical and Experimental Constraints Before Discovery



Eur.Phys.J. C72 (2012) 2003

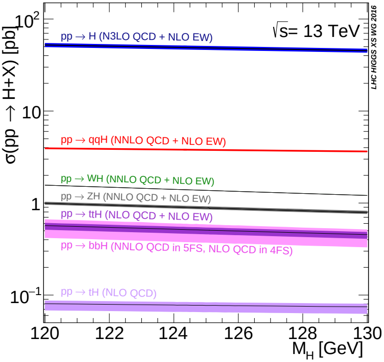
- Prior to discovery, indirect theoretical constraints (Global Electroweak Fit) preferred a light Higgs with large uncertainty
- Theoretical considerations require $M_H \sim< 1$ TeV
- Broad region at low mass excluded by LEP experiments (limited by beam energies together with ZH production mode)
- Small intermediate region excluded by Tevatron experiments

Higgs Discovery

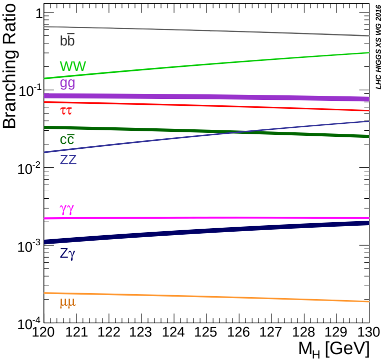


- Discovery of the Higgs announced July 4, 2012

Higgs Production and Decay at LHC



(a) Production Cross Sections



(b) Branching Ratios

- Observed Higgs mass is experimentally fortuitous in that it provides access to a wide range of decay modes and production processes at the LHC

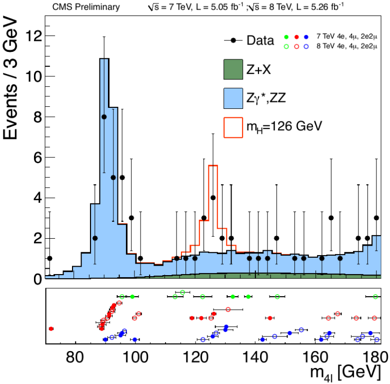
Higgs Search → Discovery

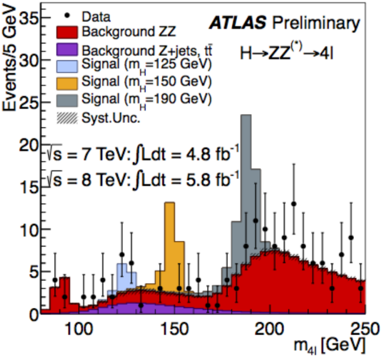
- Two channels played a special role in the search for and discovery of the Higgs at the LHC:
  - $H \rightarrow ZZ \rightarrow 4\ell$ ($\ell = e, \mu$)
  - $H \rightarrow \gamma\gamma$
- **Fully reconstructed final state** (no neutrinos)
- Well reconstructed objects with **excellent energy/momentum resolution** (only tracking and electromagnetic calorimeters)
- (For the same reason, these channels ultimately play a special role in mass and differential cross section measurements as well)

$H \rightarrow ZZ \rightarrow 4\ell$

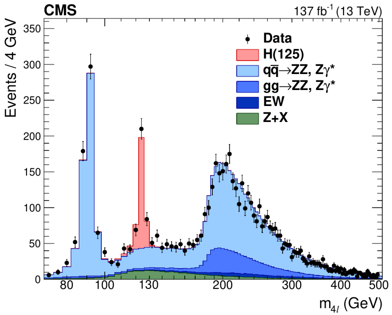
- Total branching fraction, including Z decays to e, μ is small ($\sim 5 \times 10^{-5}$)
- Backgrounds are extremely small
  - **Irreducible background**: $pp \rightarrow ZZ \rightarrow 4\ell$, small cross section, especially for $m_{\ell\ell} < 2M_Z$
  - **Reducible background**: Events with mis-identified leptons (probability of 3 or 4 misidentified leptons is tiny, so these are mostly events with 2 real leptons and 2 mis-identified)
- Some experimental challenges
  - Maximize efficiency and acceptance ($\epsilon = \epsilon_\ell^4$)
  - Effective lepton identification down to low p_T (as low as 5 GeV)
  - Optimize electron and muon resolution (tracker alignment, calorimeter calibration, FSR recovery)
  - Optimal use of kinematic information (Machine learning and/or matrix element discriminants)
  - Estimates for misidentified lepton background

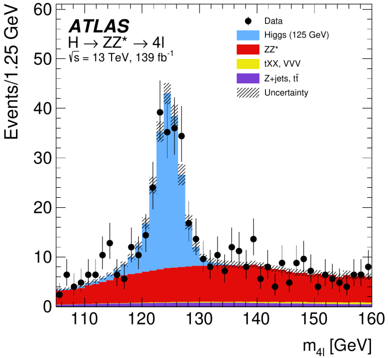
$H \rightarrow ZZ$ At the time of Discovery



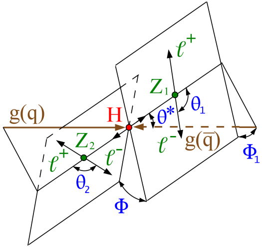


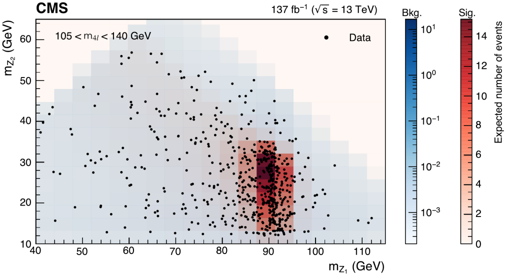
$H \to ZZ$ Full Run 2 Data





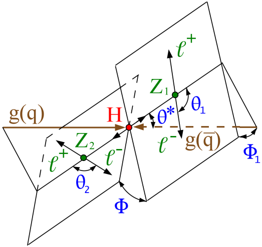
$H \rightarrow ZZ$ Kinematic Discriminants

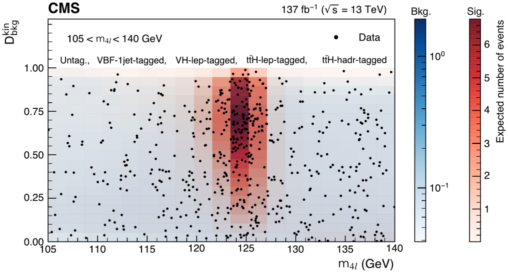




- Masses of lepton pairs and decay angles contain additional information which can discriminate against the background

$H \to ZZ$ Kinematic Discriminants

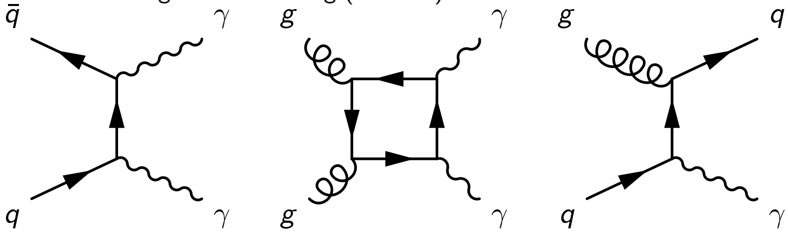




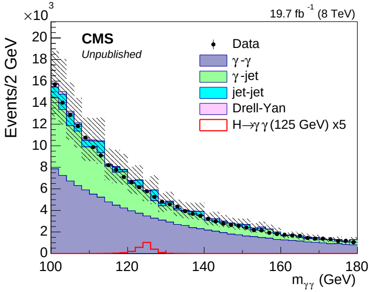
- Masses of lepton pairs and decay angles contain additional information which can discriminate against the background
- Can be optimally used in the analysis e.g. wit Matrix Element likelihood discriminators (or machine learning classifiers)

$H \rightarrow \gamma\gamma$

- Small branching fraction $\sim 2 \times 10^{-3}$ (but larger than $H \rightarrow ZZ \rightarrow 4\ell$
- Significant backgrounds
  - **Irreducible background**: $pp \rightarrow \gamma\gamma$, relatively large cross section
  - **Reducible background**: γ+jets production with one misidentified photon (or multijet production with two misidentified photons). Huge cross sections $\rightarrow$ misidentification rate must be kept under control
- Some experimental challenges
  - **Optimize diphoton mass resolution**
  - Effective photon ID
  - Background modelling (mass fit)



$H \to \gamma\gamma$ Analysis Overview

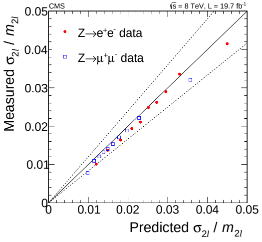


Inclusive selection with coarse binning

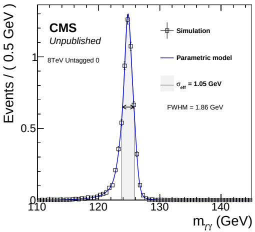
$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta_{12})}$$

- **Basic principle:** Search for a small narrow mass peak on top of a large, smoothly falling background
- Analysis can make extensive use of multivariate techniques to optimize the sensitivity, but **basic principle of "bump hunt" is preserved**
- Analysis is carried out in inclusive, vector-boson-fusion tagged, W/Z, and $t\bar{t}$ associated production tagged channels

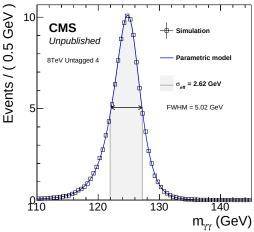
$H \to \gamma\gamma$ CMS example: Per-photon Resolution Estimate



(a) Observed vs predicted σ_m



(b) $H \to \gamma\gamma$ Best Category

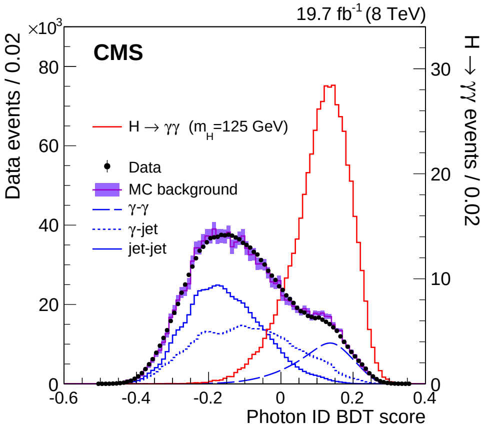


(c) $H \to \gamma\gamma$ Worst Category

- In a resonance search, per-photon resolution estimate can be used to construct a per-event mass resolution estimate $\frac{\sigma_m}{m_{\gamma\gamma}} = \frac{1}{2}\sqrt{\frac{\sigma_{E1}^2}{E_1^2} + \frac{\sigma_{E2}^2}{E_2^2}}$
- Can be used to select or categorize events to make optimal use of highest resolution events (two unconverted photons in the center of the detector, incident on the center of the crystal, far from module boundaries)

$H \to \gamma\gamma$ CMS example: Photon Identification: MVA

- Different background components clearly visible in the ID MVA output distribution (though knowledge of the relative fractions is not required for the analysis)

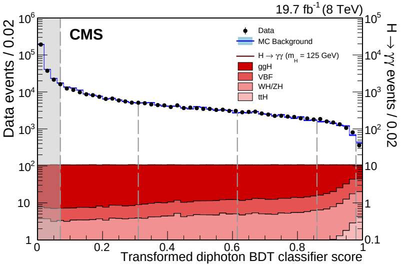


$H \to \gamma\gamma$ CMS example: Di-Photon MVA

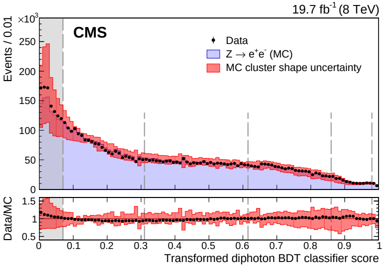
- Basic Strategy: Train di-photon MVA on Signal and Background MC with input variables which are to 1st order independent of $m_{\gamma\gamma}$
- Goal is to encode all relevant information on signal vs background discrimination (aside from $m_{\gamma\gamma}$ itself) into a single variable
- Can then simply categorize on Diphoton MVA output (5 categories, with cut values optimized against expected limit/significance using MC background, plus additional VBF/VH/ttH tagged categories with loose cut on di-photon MVA)
- Input variables cover kinematics (sans mass), per-event mass resolution and vertex probability, and photon ID

$H \to \gamma\gamma$ CMS example: Di-Photon MVA Output

- Lowest score region not included in the analysis
- Diphoton MVA output for signal-like events can be validated with $Z \to ee$ events by inverting electron veto in the pre-selection
- Analysis does not rely on MVA shape of Monte Carlo background

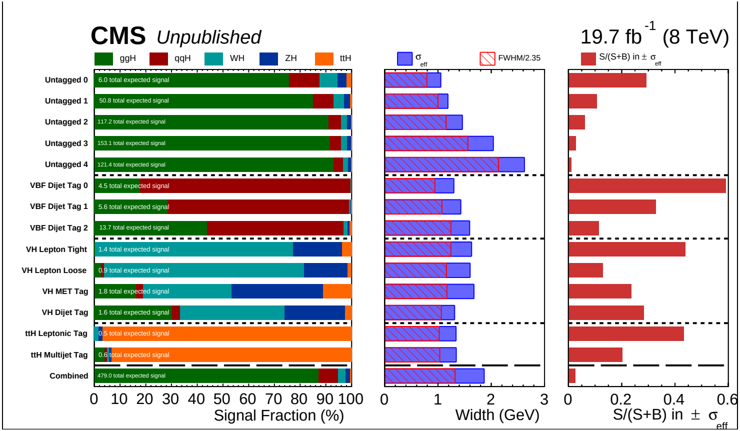


(a) Full Selection



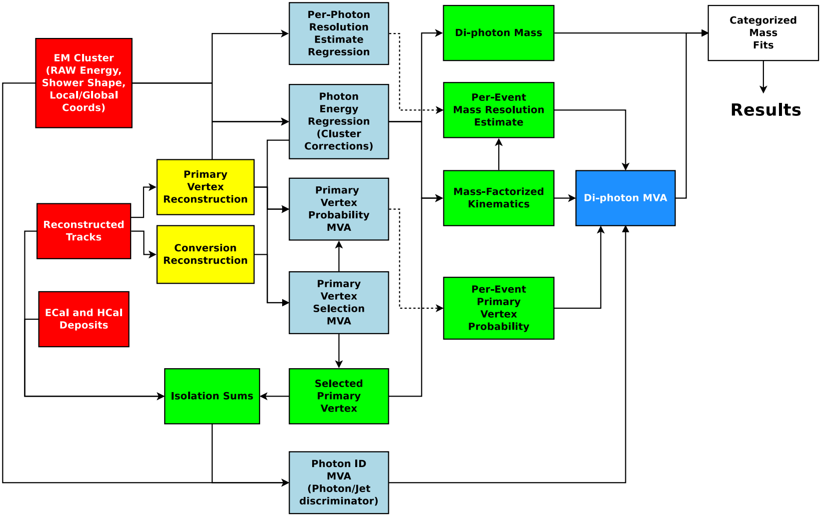
(b) Inverted e-Veto

$H \to \gamma\gamma$ CMS example: Event Classification



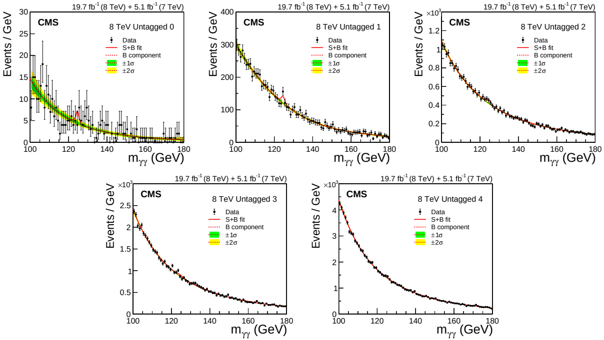
- Events classified according to di-photon MVA output plus tagging of additional objects
- Large variation in resolution and S/B across categories

$H \to \gamma\gamma$ CMS example: All Together



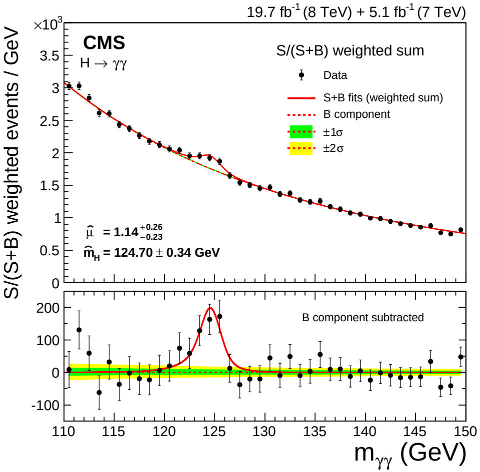
- Strategy: Process available information into quantities with straightforward physical interpretations in order to combine per-event knowledge of expected mass resolution and S/B into a single "Diphoton MVA" variable

$H \to \gamma\gamma$ CMS example: S+B Fits - 8 TeV



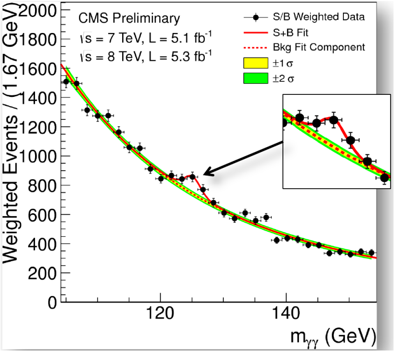
- Plus 20 more distributions for exclusive-tagged modes and 7 TeV

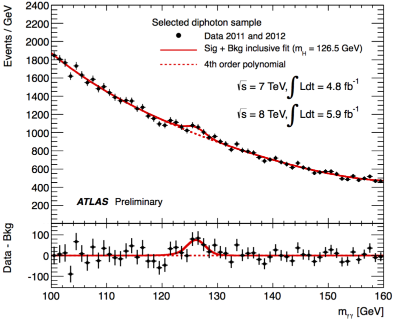
$H \to \gamma\gamma$ CMS example: S+B Fit - Weighted Combination



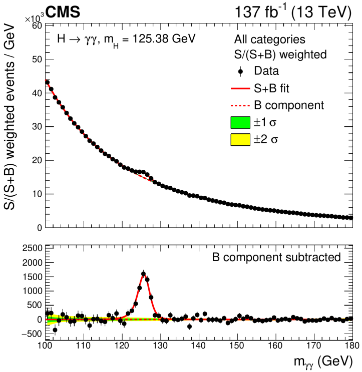
- Results extracted from simultaneous fit to 25 event classes, but combined mass spectrum useful for visualisation
- Combination of all 25 event classes, weighted by $S/(S+B)$ for a $\pm\sigma_{eff}$ window in each event class
- Weights are normalised to preserve the fitted number of signal events

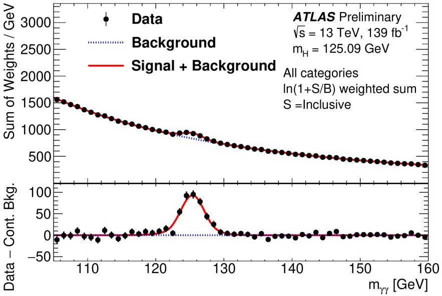
$H \to \gamma\gamma$ At the time of Discovery





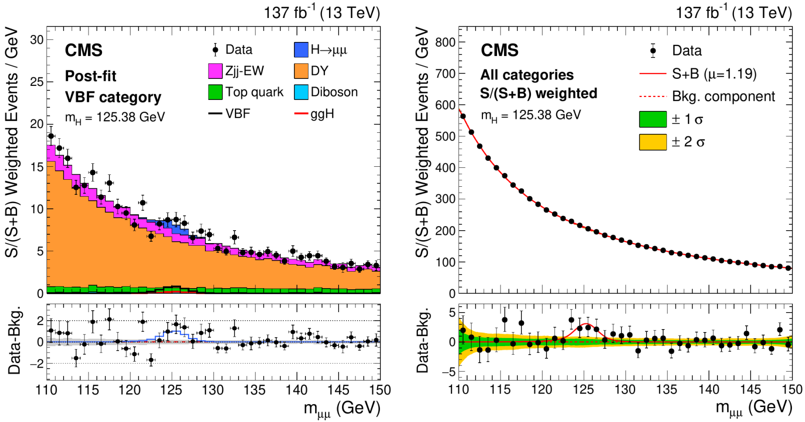
$H \to \gamma\gamma$ Full Run 2 Data





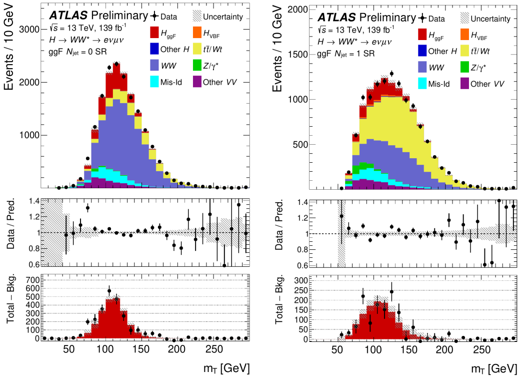
$H \to \mu\mu$

- bump-hunt like $H \to \gamma\gamma$, but tiny branching ratio and large DY ($pp \to \gamma^* \to \mu\mu$) background



$H \to WW \to 2\ell 2\nu$

- Relatively large branching fraction
- Significant backgrounds, mainly from $pp \to WW$, $t\bar{t}$ and W+jets with one misidentified lepton
- Backgrounds with two real leptons estimated from dedicated control regions (kinematic selection for WW, extra b-tagged jet for $t\bar{t}$, m_{ll} consistent with Z mass, etc)

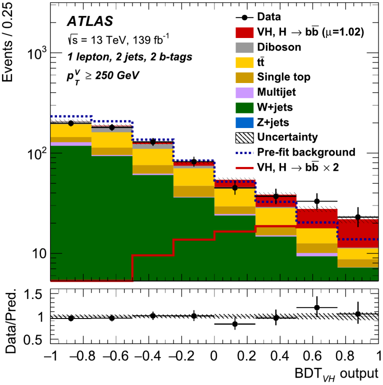


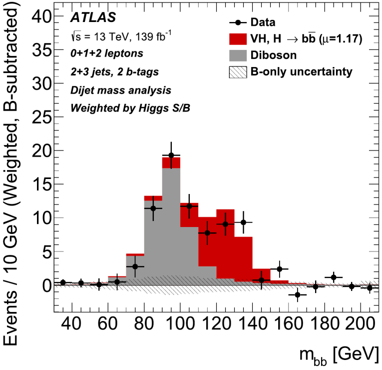
$H \to WW \to 2\ell 2\nu$: Misidentified lepton backgrounds

- Typical procedure for estimating backgrounds with misidentified leptons
  1. Define a "loose" selection and estimate "fake rate" (probability for a misidentified lepton passing the loose selection to also pass the full selection
     - Example: Full lepton selection includes identification and isolation requirements, loose selection drops isolation requirement, fake rate $= p(\text{isolation+id}|id)$ for misidentified leptons
     - Fake rate can be measured from background dominated region (e.g. di-jet events) taking care to suppress or subtract any remaining contamination of events with real leptons (e.g. from W production)
  2. Select events with loose leptons which **fail** the full selection, but otherwise matching the analysis selection, and **extrapolate** to signal region by applying the fake rate (taking care to subtract signal/other prompt lepton contamination)
     - For $H \to WW \to 2\ell 2\nu$ these would be events with one lepton passing the full selection, and one lepton e.g. failing the isolation cut, but otherwise applying all analysis cuts

$H \to bb$

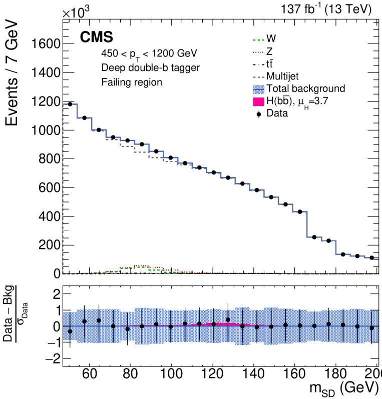
- $H \to bb$ has high branching ratios but huge QCD backgrounds
- To achieve reasonable S/B, historically select $W/Z + H \to \ell\nu\ \ell\ell\ \nu\nu + bb$ events with significant W/Z p_T



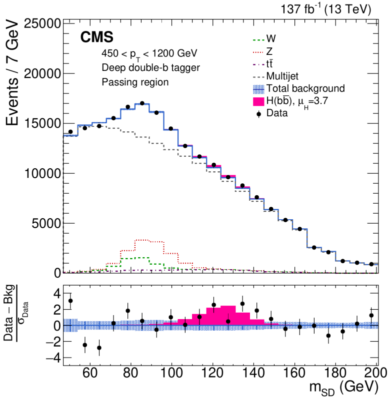


Boosted $H \to bb$

- At very high p_T b-jets from Higgs decay merge into a single large jet
- Very high p_T combined with jet substructure techniques and b-tagging can suppress the QCD background enough to eventually make the gluon fusion production visible



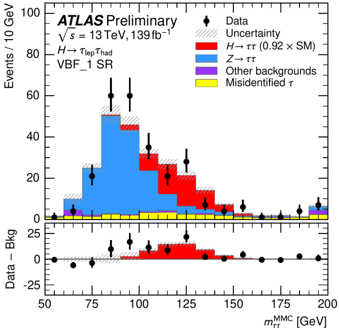
(a) anti b-tagged

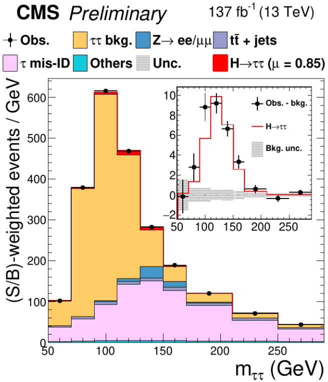


(b) b-tagged

$H \to \tau\tau$

- Events selected in $e\mu$, $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$ final states
- $\tau\tau$ mass reconstructed using various techniques to combine visible products and $\not{E}_T$ (kinematic fit, likelihood constraints on decay kinematics, etc)
- Events further categorized according to production: additional leptons, di-jet VBF tagged, boosted (high lepton or $\tau\tau$ p_T), 0/1 jets , etc



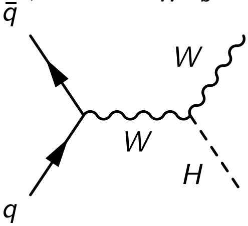


Higgs Combination/Couplings

- The full Higgs experimental program at ATLAS and CMS includes a wide range of decay modes and production modes, split by Higgs final state, additional tagging objects to enhance specific production modes, and other cuts/categorization to enhance S/B which also lead to different combinations of production modes
- These can be used to extract a global picture of the Higgs couplings to SM particles (via a combined maximum likelihood fit of all the channels and/or across experiments)

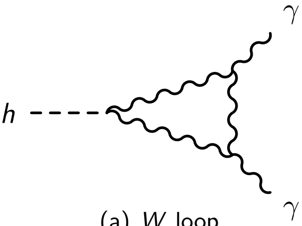
Higgs Combination/Couplings

- General framework for parameterizing compatibility with/small deviations from the Standard Model:
  - $\mu \equiv (\sigma \times \text{BR})_{\text{observed}} / (\sigma \times \text{BR})_{\text{expected}}$
  - κ parameterize the ratio of the **coupling** of the Higgs to a given particle as a ratio to the SM prediction
- **Example:** $\mu_{pp \to WH, H \to bb} = \kappa_W^2 \kappa_b^2$

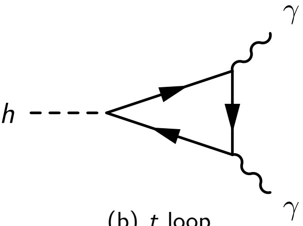


Higgs Combination/Couplings

- Loop-induced couplings κ_g, κ_γ can be expressed individually or decomposed



(a) W loop

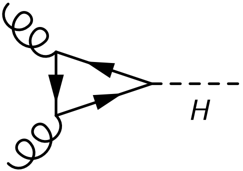


(b) t loop

$$\kappa_\gamma^2 \sim= 1.6\kappa_W^2 - 0.7\kappa_W\kappa_t + 0.1\kappa_t^2$$

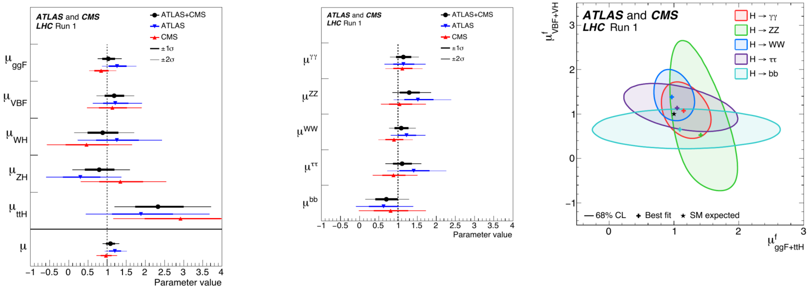
Higgs Combination/Couplings

- Loop-induced couplings κ_g, κ_γ can be expressed individually or decomposed



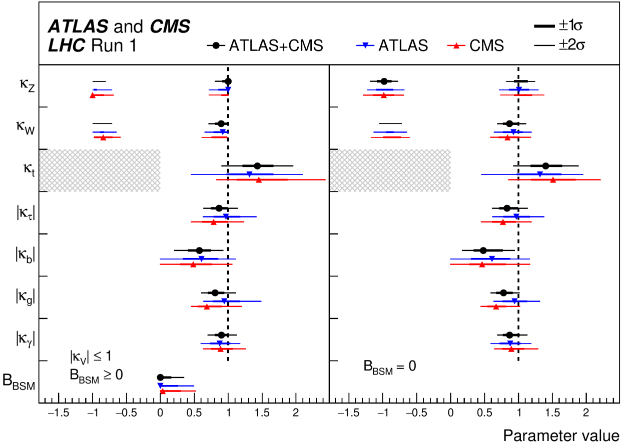
$$\kappa_g^2 \sim= 1.06\kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$$

Higgs Combination/Couplings



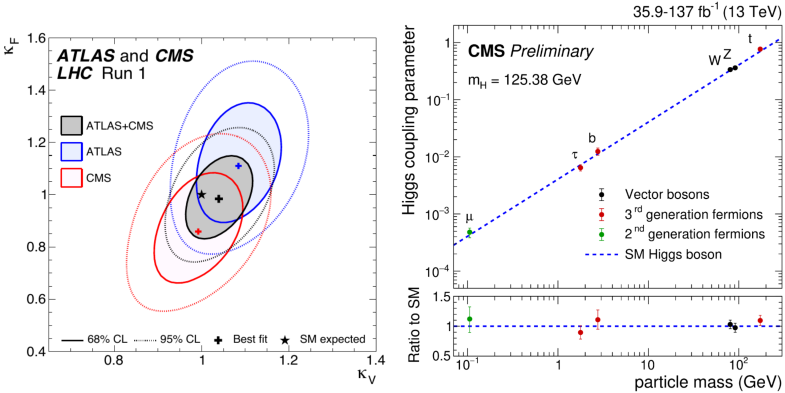
- Results broadly consistent with the Standard Model

Higgs Combination/Couplings



- Results broadly consistent with the Standard Model

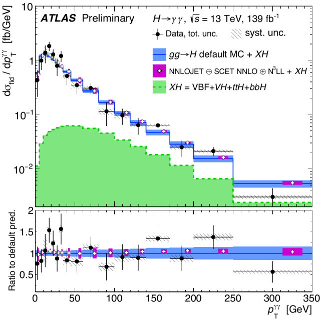
Higgs Combination/Couplings

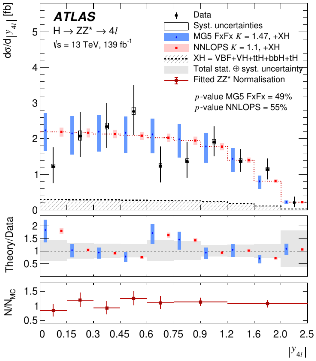


- Both fermion and boson couplings consistent with SM
- Consistent scaling of coupling with fermion mass over many orders of magnitude (so far)

Differential/Fiducial Cross Sections

- In addition to measuring "signal strengths", unfolded fiducial and differential cross sections can be measured (just like for $W, Z, t\bar{t}$, etc production)
- Most straightforward in $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels where Higgs kinematics are fully reconstructed, but also possible in other channels

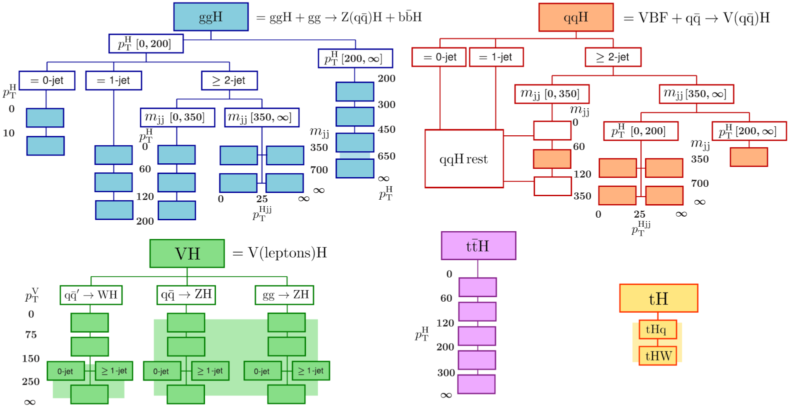




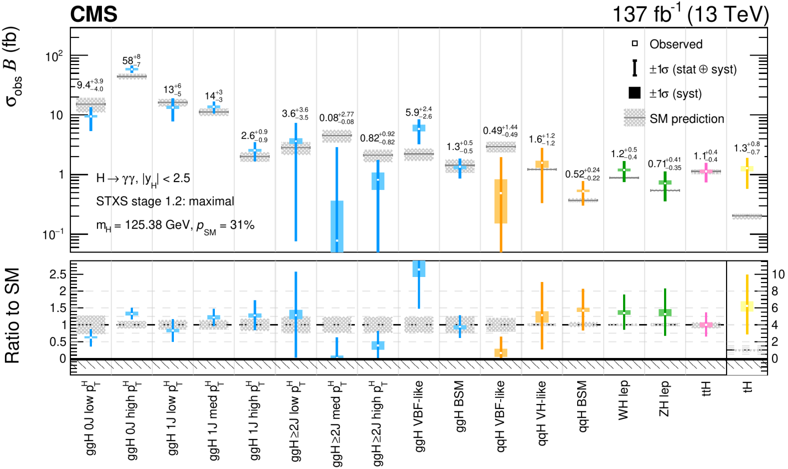
Simplified Template Cross Sections

- Simplified Template Cross sections provide an "intermediate" form for the results, between maximally model-dependent signal strengths and minimally model-dependent fiducial/differential cross sections, via a more fine-grained definition of "processes" via additional splitting by kinematics or extra jets, etc
- This facilitates reinterpration of the results in terms of BSM models
- Precise level of splitting can evolve with integrated luminosity

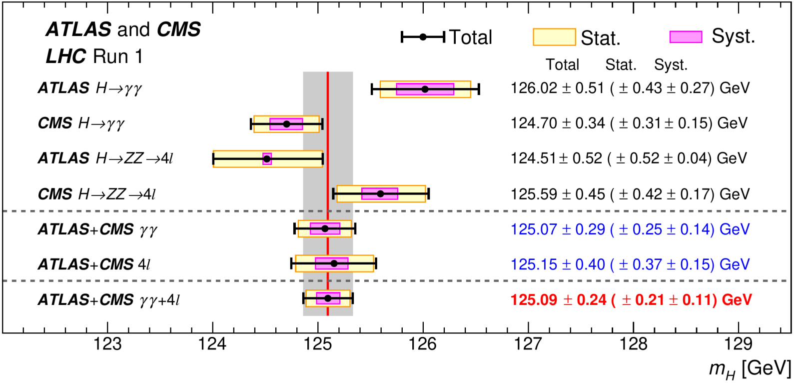
Simplified Template Cross Sections



Simplified Template Cross Sections: Example Result

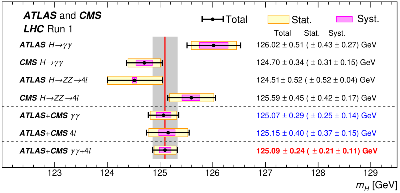


Higgs Mass



- Higgs mass is measured from the peak position in $\gamma\gamma$ and 4ℓ events, already to the per mille level

Higgs Mass



- Higgs mass is measured from the peak position in $\gamma\gamma$ and 4ℓ events, already to the per mille level
- Careful calibration of the photon, electron, muon energy/momentum scale needed, mainly using the Z peak
- $\gamma\gamma$ channel has smaller statistical, but larger systematic uncertainty due to electron$\rightarrow$photon extrapolation $\rightarrow$ mitigate with careful control over calorimeter simulation, material budget, etc
- With full HL-LHC dataset, mass can be measured e.g. from central 4μ events only $\rightarrow$ limited by systematic uncertainty of muon momentum calibration (payoff from current m_W efforts)

Prospects

- Full run 2 Higgs measurements done or being finalized
- ATLAS+CMS Run 2 combinations foreseen for couplings, STXS, mass, etc
- 20 times more data expected for HL-LHC with corresponding precision gains
- Huge further jumps forward possible with future colliders, access to Higgs self-coupling, etc
  (This applies to precision electroweak measurements, PDF constraints, and $\sim$ all other physics studied at the LHC as well)

Conclusions

- Many topics/specifics I could not cover
- Hundreds of papers worth of reference material from the experiments on these topics!