

# Higgs boson measurements with photons

Workshop on Photons Physics at the LHC, 18-  
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*Pasquale Musella (ETH Zurich)*  
**on behalf of the CMS and ATLAS collaborations**



ETH Institute for  
Particle Physics



CMS

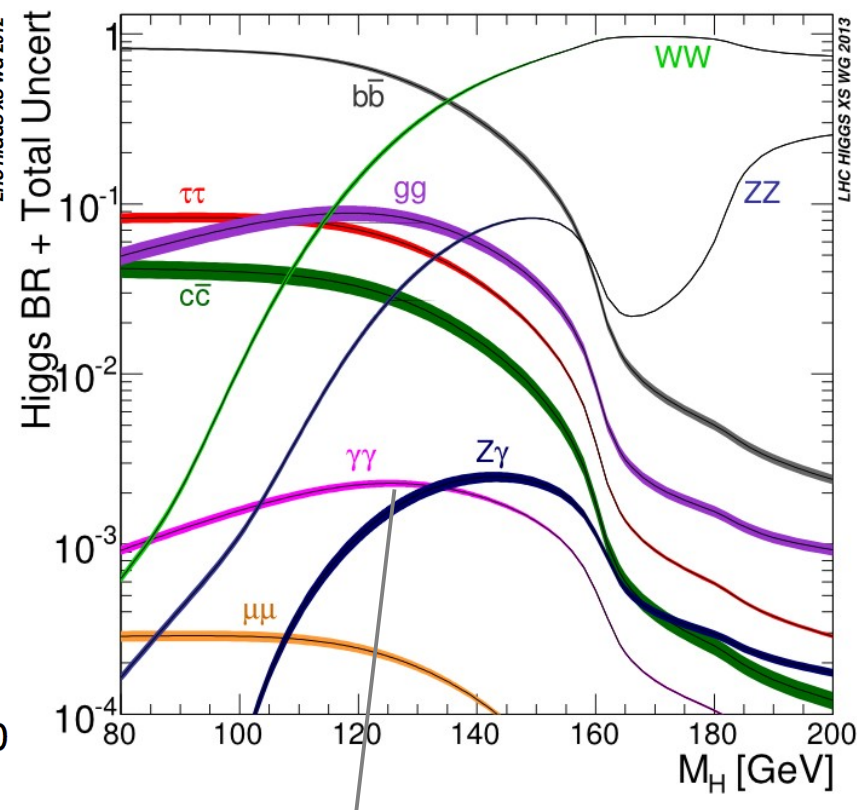
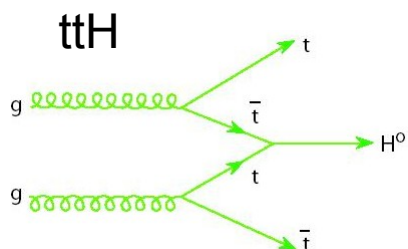
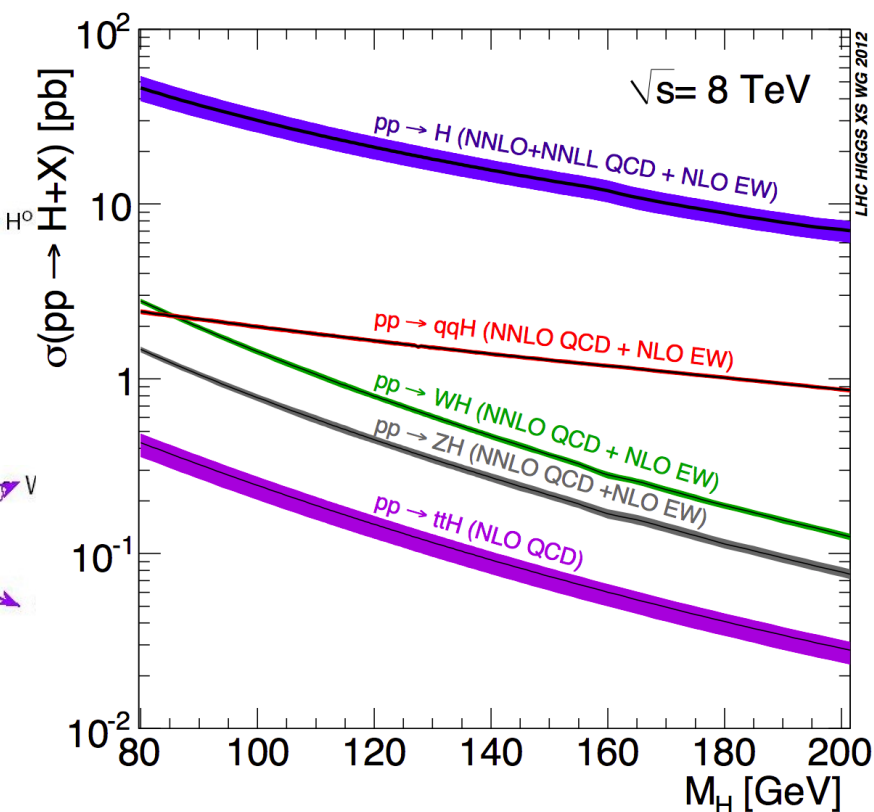
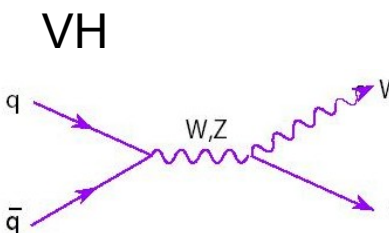
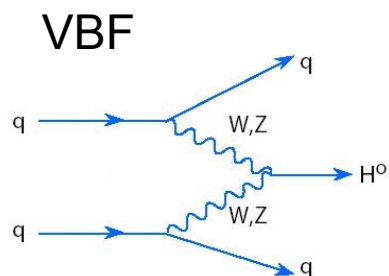
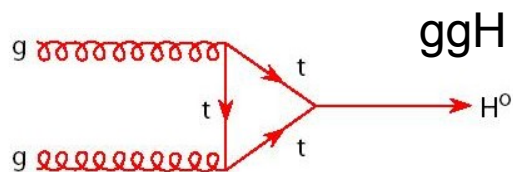


# Which Higgs physics with photons?



- ▶ Several important channels for Higgs physics contain photons in the final state.
  - ▶  $H \rightarrow \gamma\gamma$  decay
    - ▶ One of the most sensitive channels at the LHC.
    - ▶ Loop-mediated decay: measurement of  $H\gamma\gamma$  coupling sensitive to BSM physics.
  - ▶  $H \rightarrow l\bar{l}\gamma$  decay
    - ▶ Loop-mediated  $H \rightarrow Z\gamma$  decay: small branching fraction but sensitive to BSM effects.
    - ▶ Charm-mediated  $H \rightarrow J/\psi \gamma$ : extremely challenging experimentally, but may give information on  $Hcc$  couplings.
  - ▶ Double Higgs production through  $HH \rightarrow b\bar{b} \gamma\gamma$ 
    - ▶ Sensitive to Higgs self-coupling.

# Higgs production and decays at the LHC

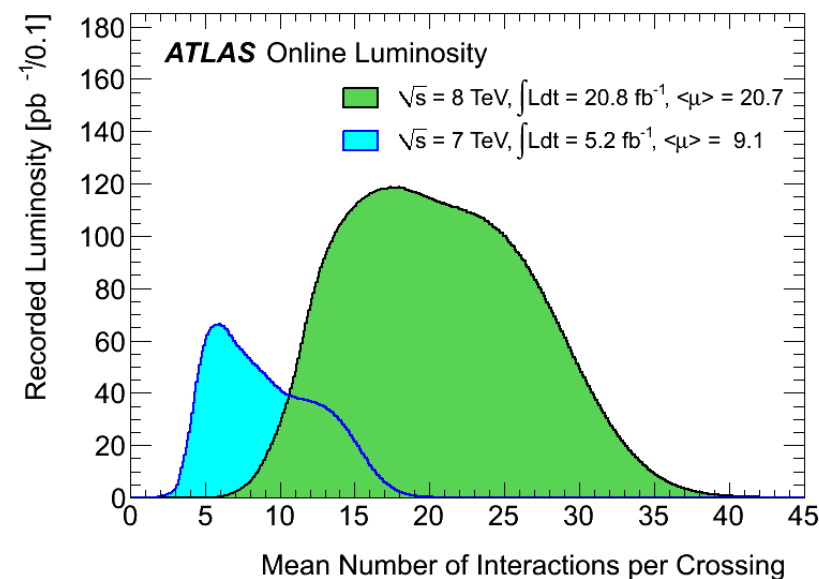
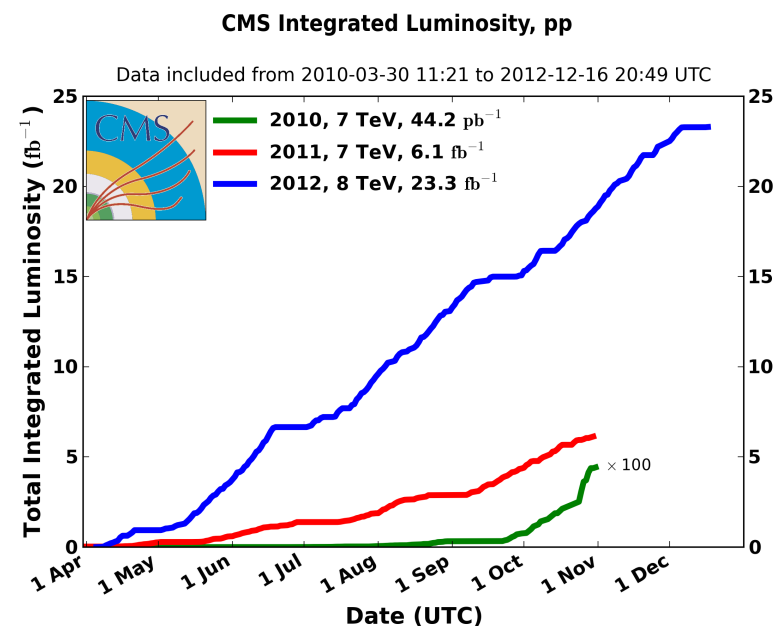


@  $m_H = 125$  GeV

$BR(H \rightarrow \gamma\gamma) \sim 2 \times 10^{-3}$

$BR(H \rightarrow l\bar{l}\gamma) \sim 10^{-6}$

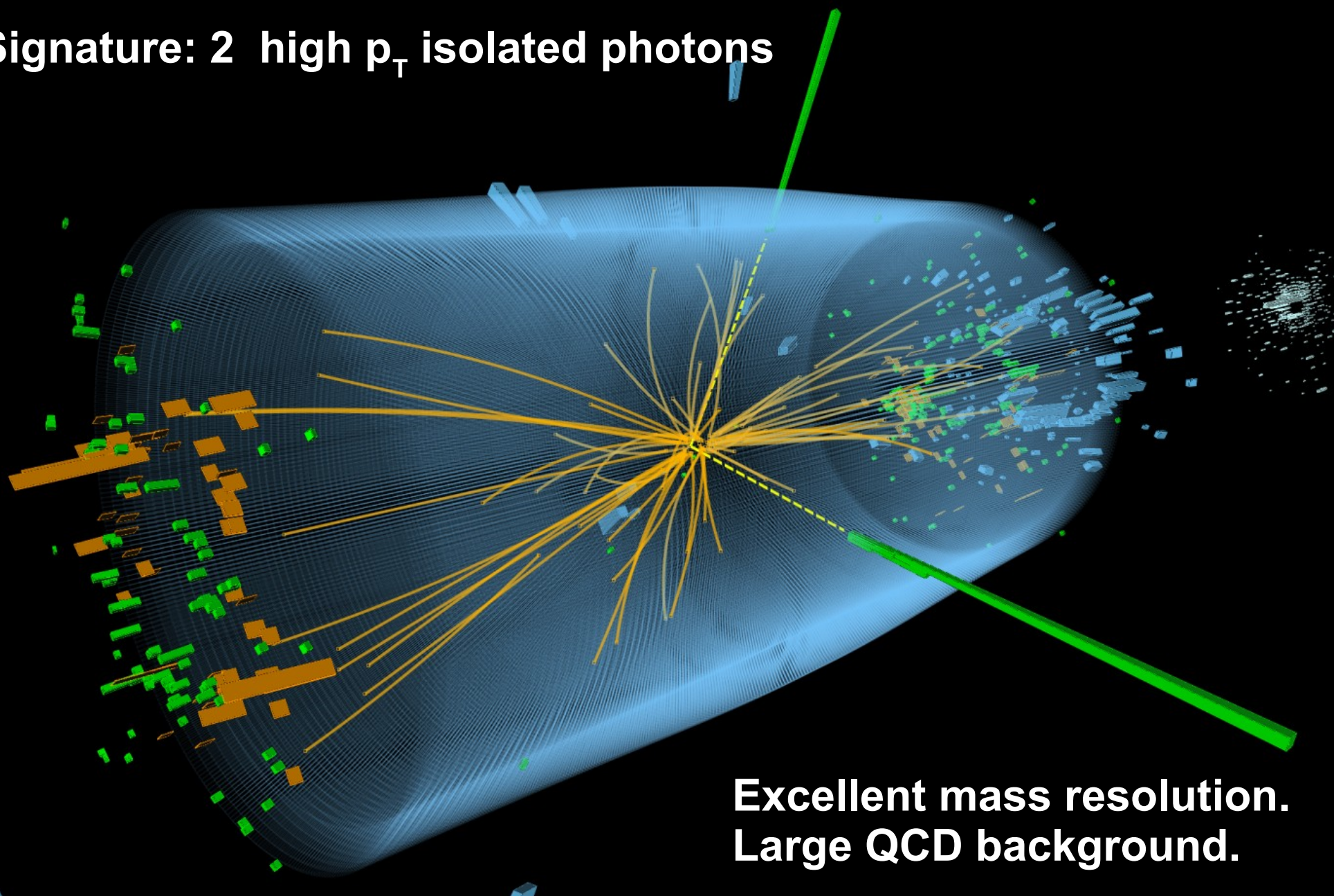
- ▶ Excellent performance of the LHC machine throughout the Run 1.
- ▶ Also excellent performance of the CMS and ATLAS detectors
  - ▶ ~90% of the delivered data available for offline analysis.
- ▶ Available dataset:
  - ▶  $\sim 5\text{fb}^{-1} \sqrt{s}=7\text{TeV} + \sim 20\text{fb}^{-1} \sqrt{s}=8\text{TeV}$
- ▶ Challenging pile-up conditions.
  - ▶ Up to 30 average interactions per bunch-crossing.
  - ▶ Ingenious ideas needed to keep detector performances.



$$H \rightarrow \gamma\gamma$$

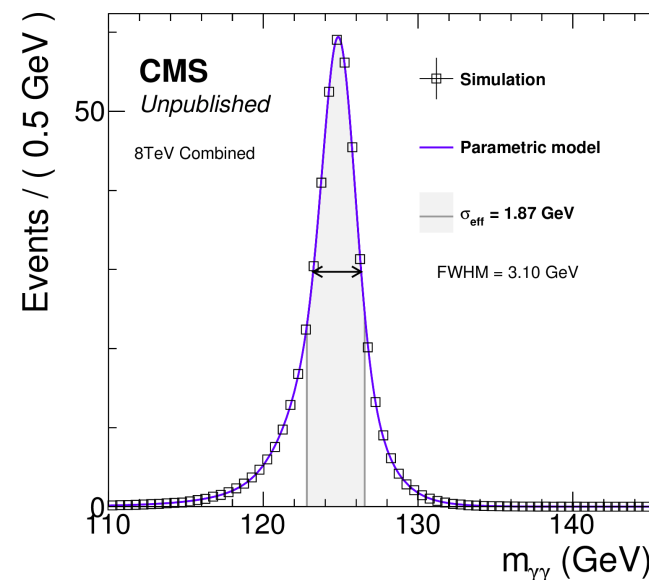
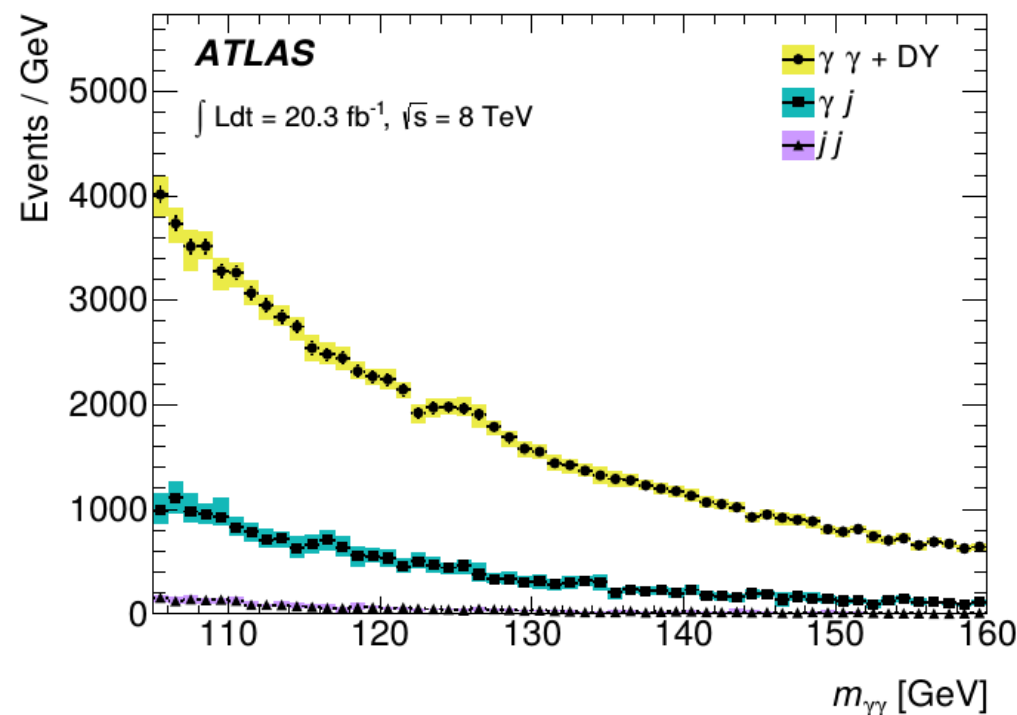


**Signature: 2 high  $p_T$  isolated photons**



**Excellent mass resolution.  
Large QCD background.**

- ▶ Narrow peak on large smoothly falling background.
  - ▶ QCD production of  $\gamma\gamma$ , but also  $\gamma j$  and  $jj$ , with jet misidentified as photon.
- ▶ Particle identification very important to reject reducible background.
- ▶ Mass resolution crucial to minimize effective QCD background.
  - ▶ Energy resolution.
  - ▶ Primary vertex identification (angular resolution).
- ▶ Signal modelling through nearby standard candles.
  - ▶  $Z \rightarrow ee$ ,  $Z \rightarrow \mu\mu$ ,  $Z \rightarrow l\bar{l}\gamma$



# Analysis strategy



Both CMS and ATLAS analysis employ event categories to enhance sensitivity.

CMS:

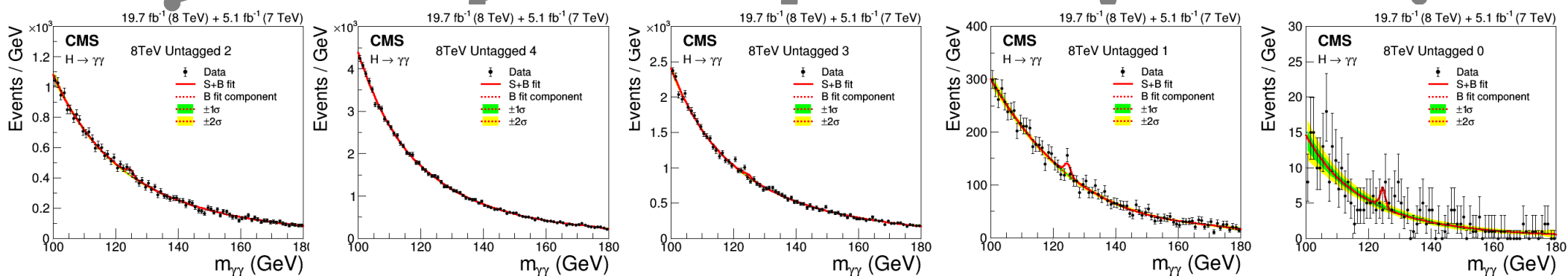
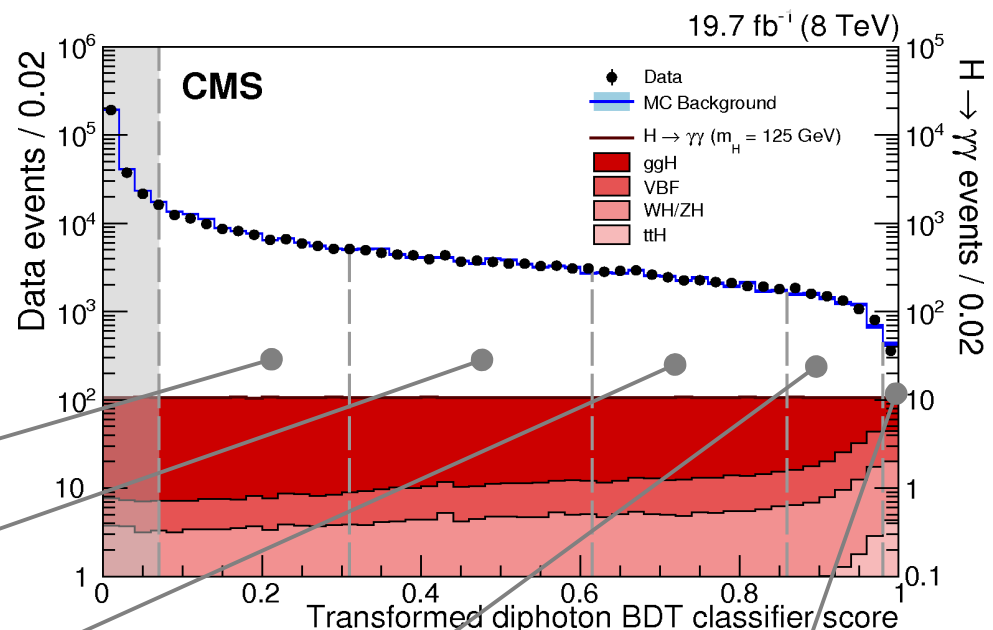
Event classification based on BDT combining kinematics and mass resolution.

Classify events according to kinematics and mass resolution.

“Exclusive categories” defined in terms of additional object in event (jets, leptons missing  $E_T$ ) to enhance sensitivity to VBF and associated production.

ATLAS:

Cut-based categorization based on photon candidate rapidity and diphoton  $p_T$ . Use BDT classifier for VBF categories



# Analysis strategy (2)

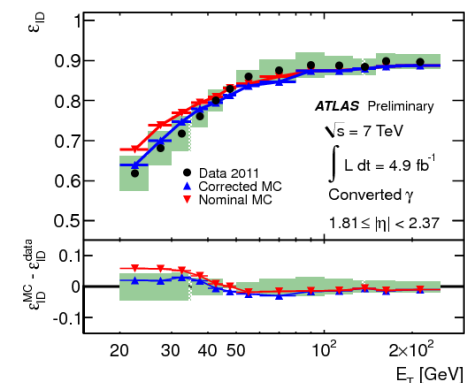
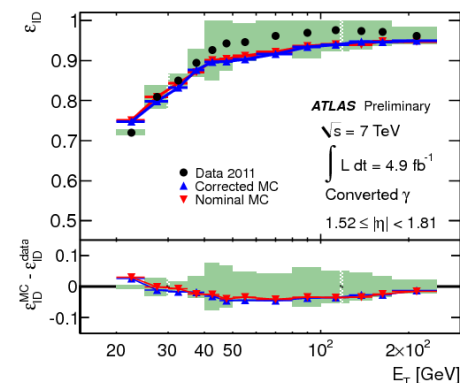
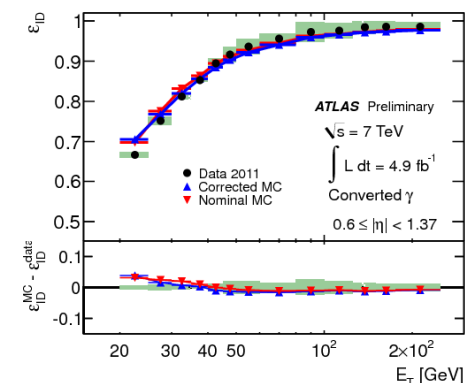
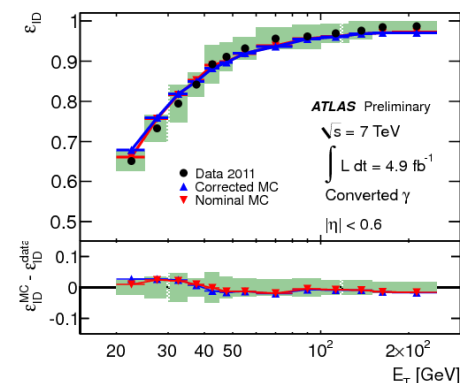
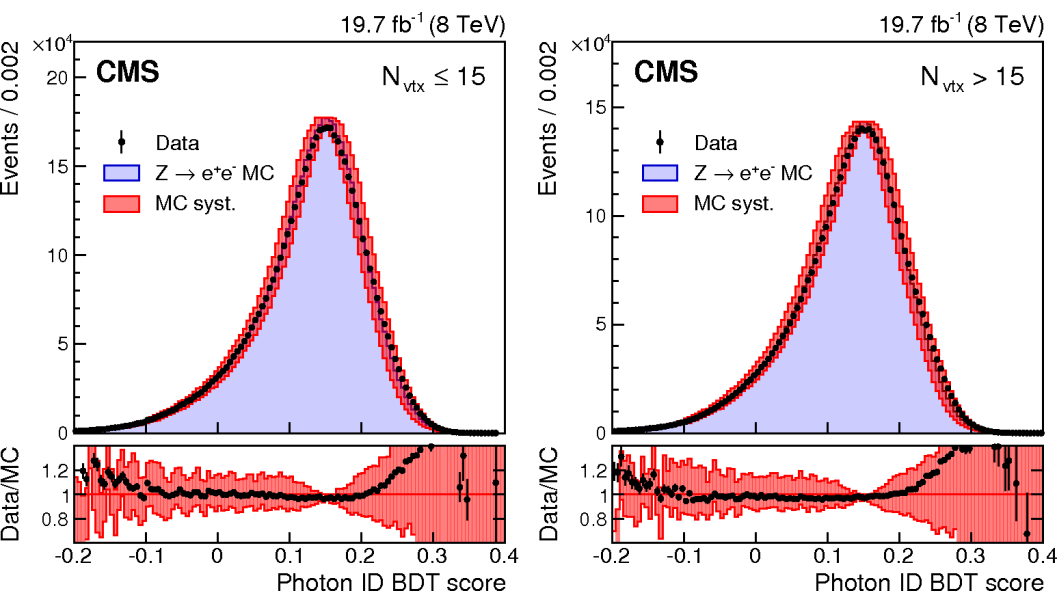
## Photon identification:

(See also S.Zenz presentation yesterday)

► Categorized cut-based for ATLAS.

► Using BDT classifier for CMS (also cross check with categorized cut-base ID).  
No explicit cut: fed-forward into event-classification BDT.

## Modelling in data using $Z \rightarrow ee$ and $Z \rightarrow l\bar{l}\gamma$



# Analysis Strategy (3)



► Vertex identification crucial to achieve good mass resolution.

► Angular term negligible if  $\delta z < 1\text{cm}$ .

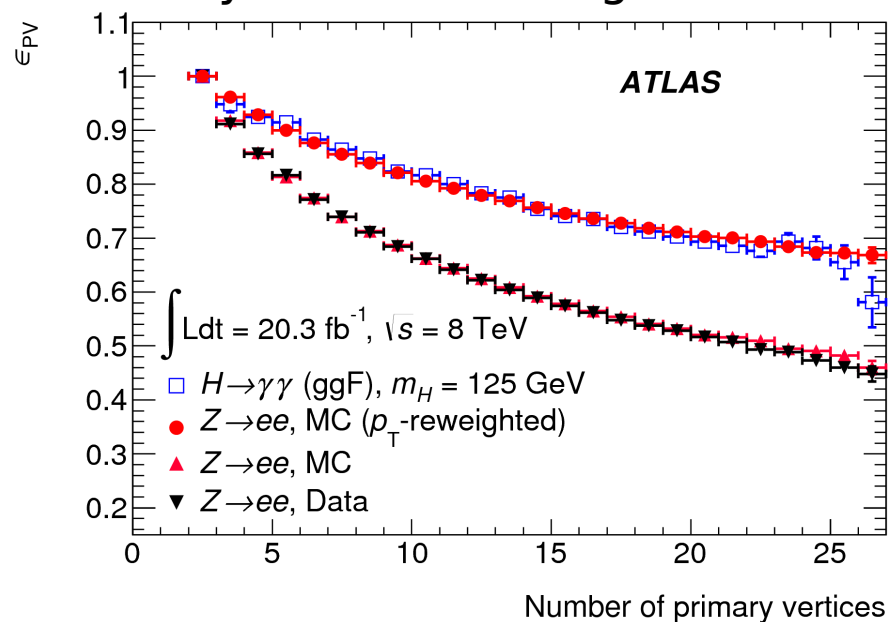
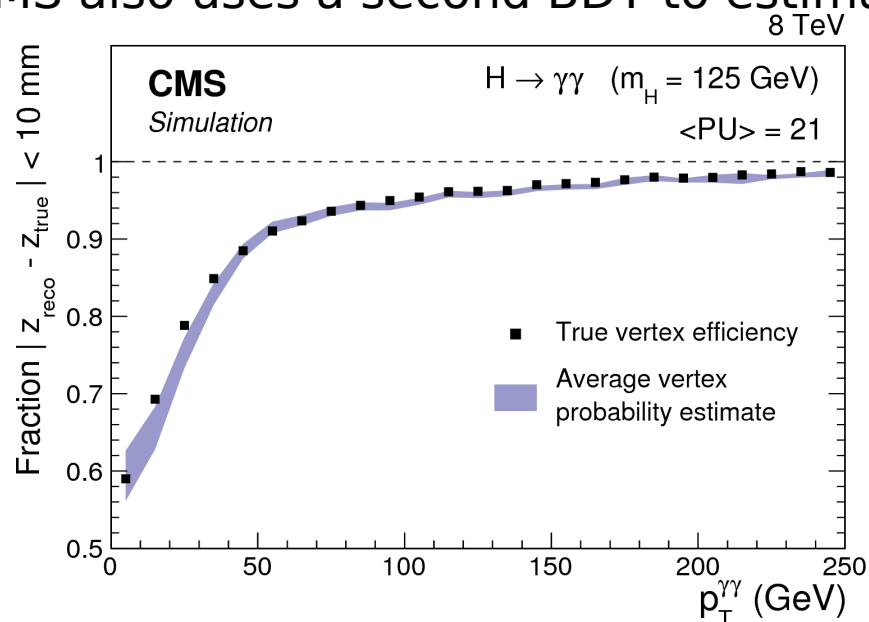
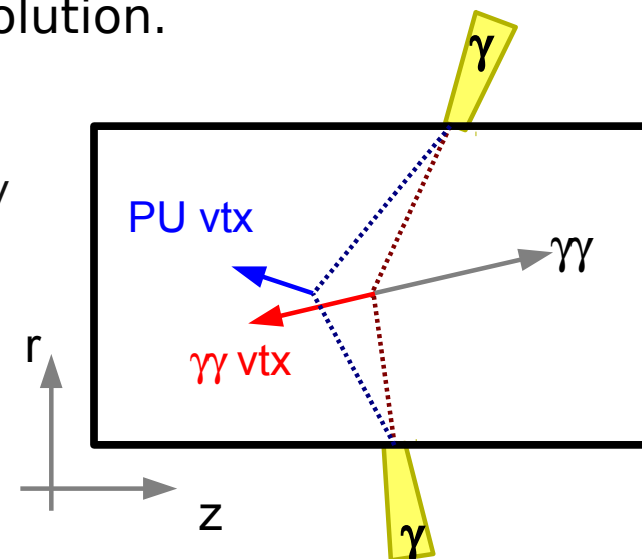
► Also important to compute isolation sums in high multiplicity environments.

► Intrinsic difference between ATLAS and CMS: pointing capability.

► Both collaborations use BDT classifier to identify primary vertex.

► Vertex tracks  $\Sigma p_T^2$ , recoil information, pointing information (@CMS only for converted photons).

► CMS also uses a second BDT to estimate probability of correct assignments.



# Analysis strategy (4)

Background modelling very important for accurate estimation of signal strength.

Both collaborations use  $m_{\gamma\gamma}$  sidebands to constrain background.

Choice of background functional form is arbitrary.

Make sure that potential biases are small (namely <15-20% of the statistical uncertainty).

Dedicated model for each event category.

CMS

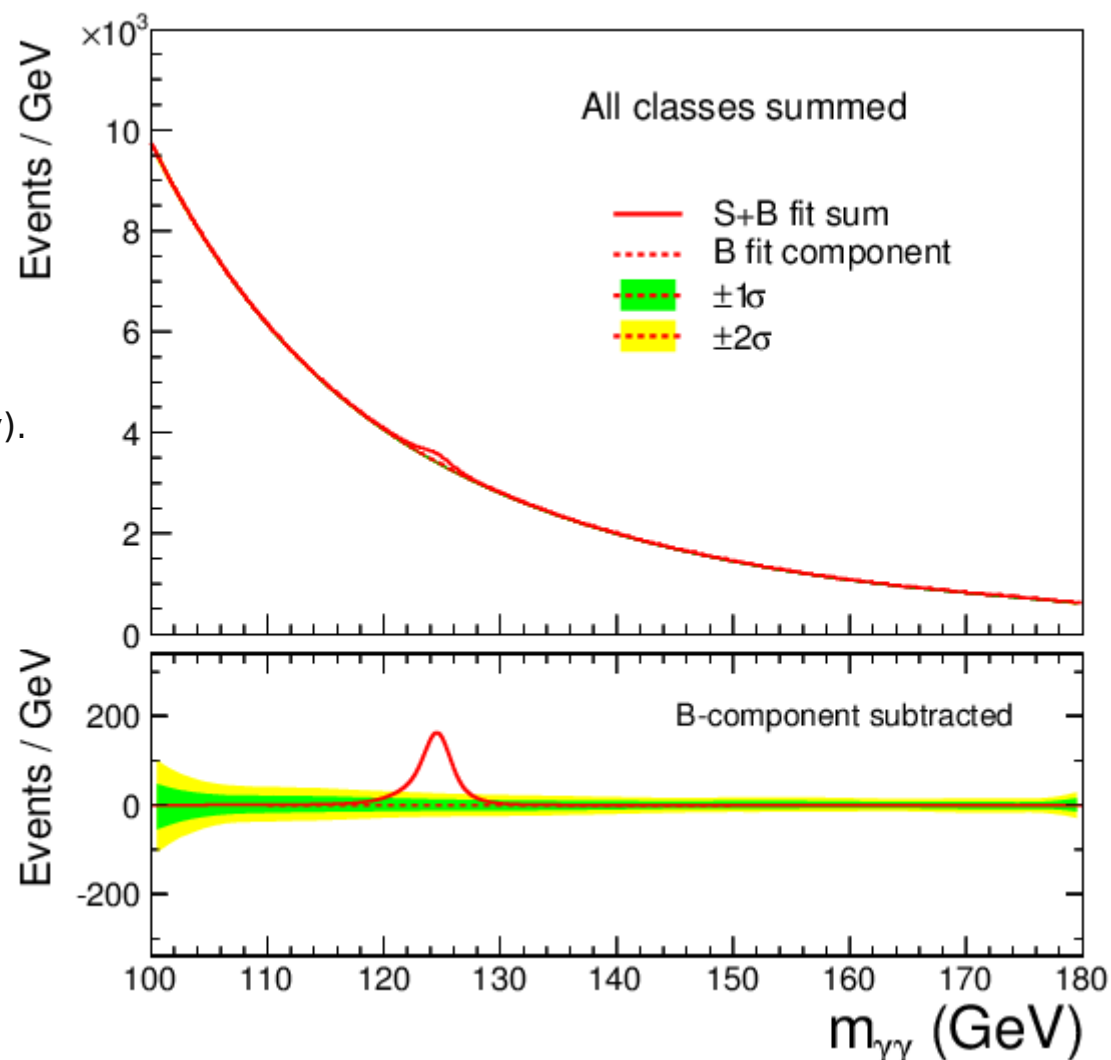
Discrete profiling method: choice of background model as a discrete nuisance parameter (difference between models included in uncertainties).

Ensure that the resulting model is equivalent to other possible choices allowed by the data.

ATLAS

Pick background model from a pool of possible parametrizations, ensuring that chosen parametrization reproduces well the background shape in MC simulation.

Difference between background shape in MC and background model (allowed to be as large as 10% of the expected signal) included in uncertainties.



# Higgs measurements from $H \rightarrow \gamma\gamma$

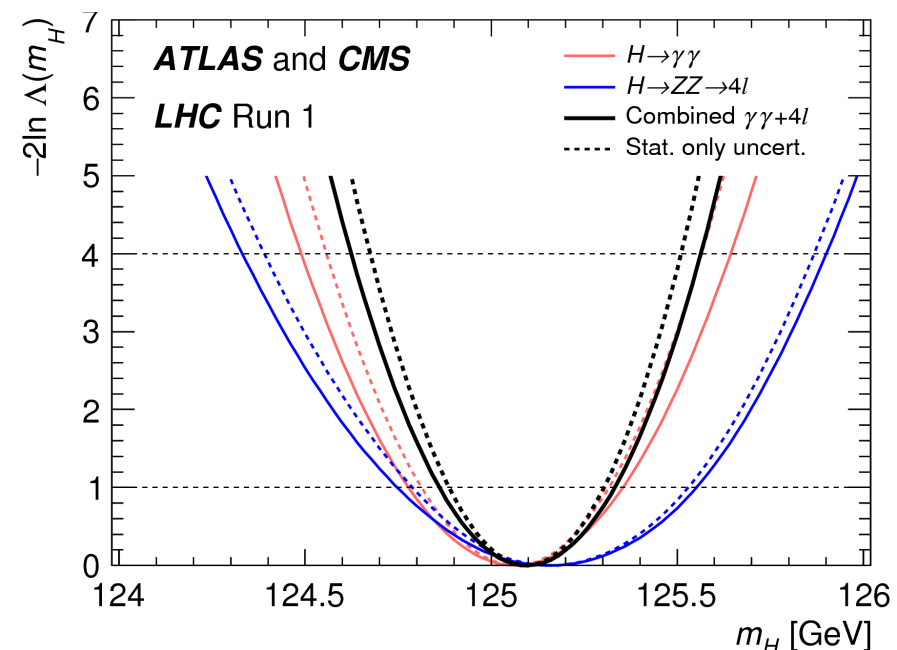
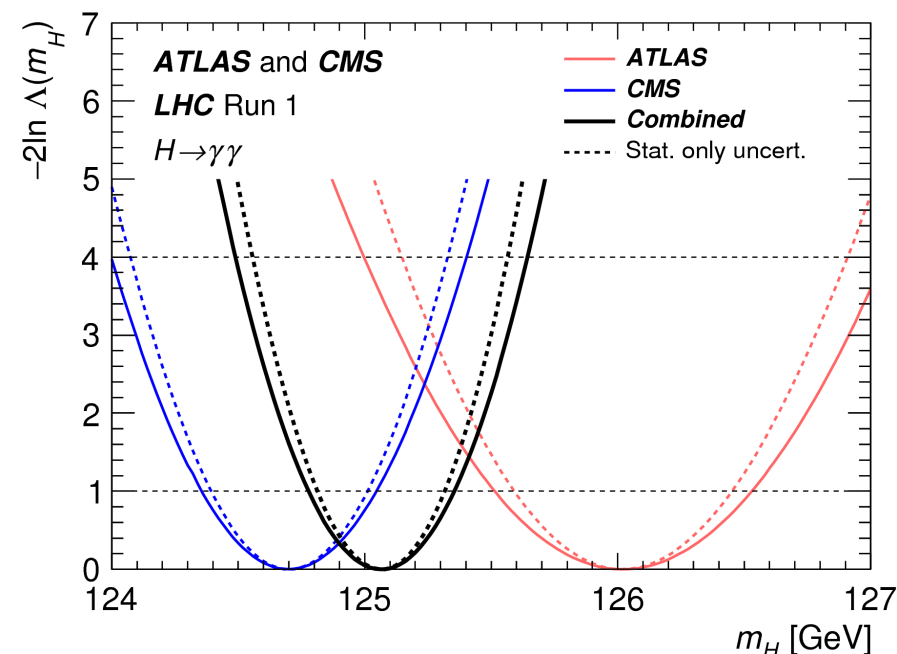


- ▶ Mass.
- ▶ Signal strength and couplings.
- ▶ Fiducial cross sections.

# Higgs mass measurement

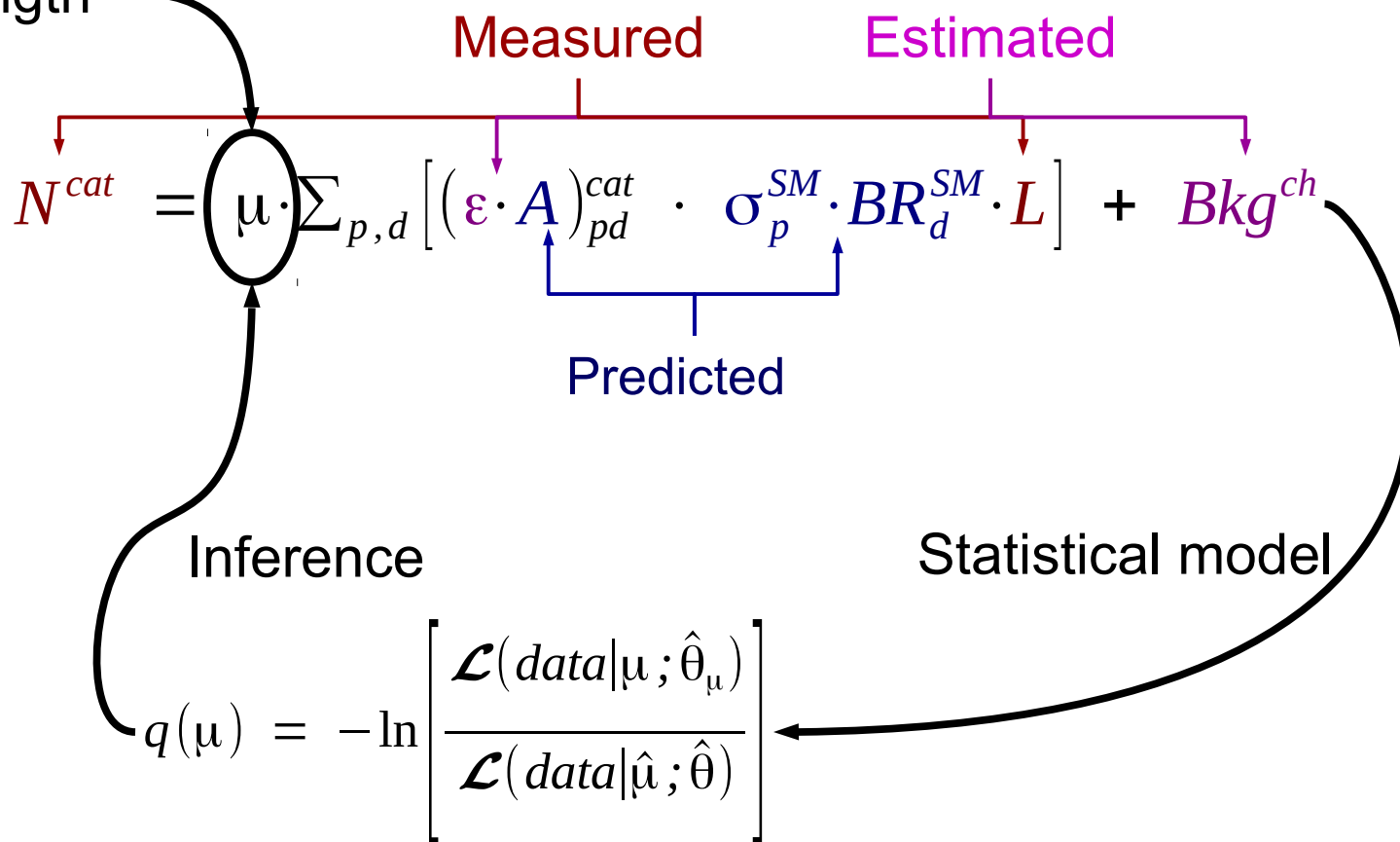


- ▶ Higgs boson mass is a fundamental parameter for the determination of its properties.
  - ▶ SM predictions fully specified, once it's determined.
- ▶  $H \rightarrow \gamma\gamma$  channel provides the best measurement of  $m_H$ .
  - ▶ ATLAS:
    - ▶ Dedicated analysis for  $m_H$ , avoiding use of exclusive categories.
  - ▶ CMS:
    - ▶ Consistent analysis for mass and couplings.
    - ▶ Minimize model dependence allowing production modes signal strengths to float independently.



- ▶ Properties of the Higgs boson can be inferred correlating the event rates measured in different channels.
- ▶ Being able to probe several production mechanisms,  $H \rightarrow \gamma\gamma$  provides very important informations

“Signal strength”



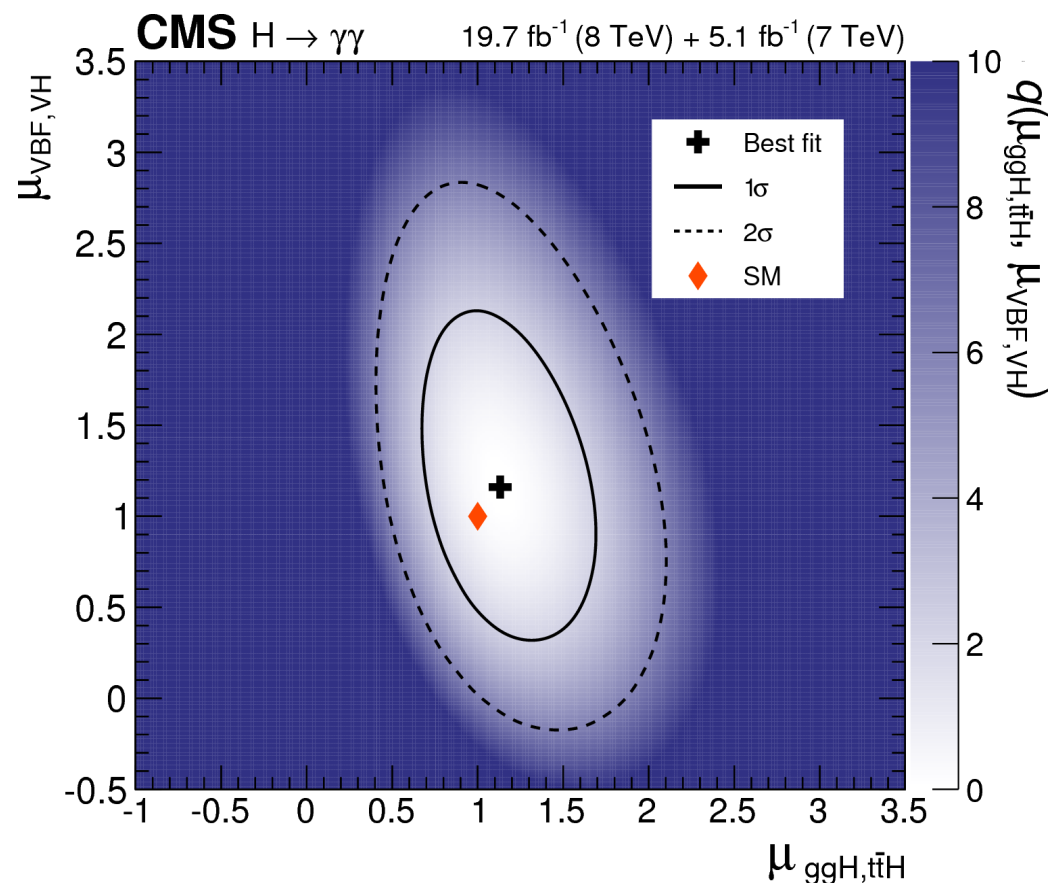
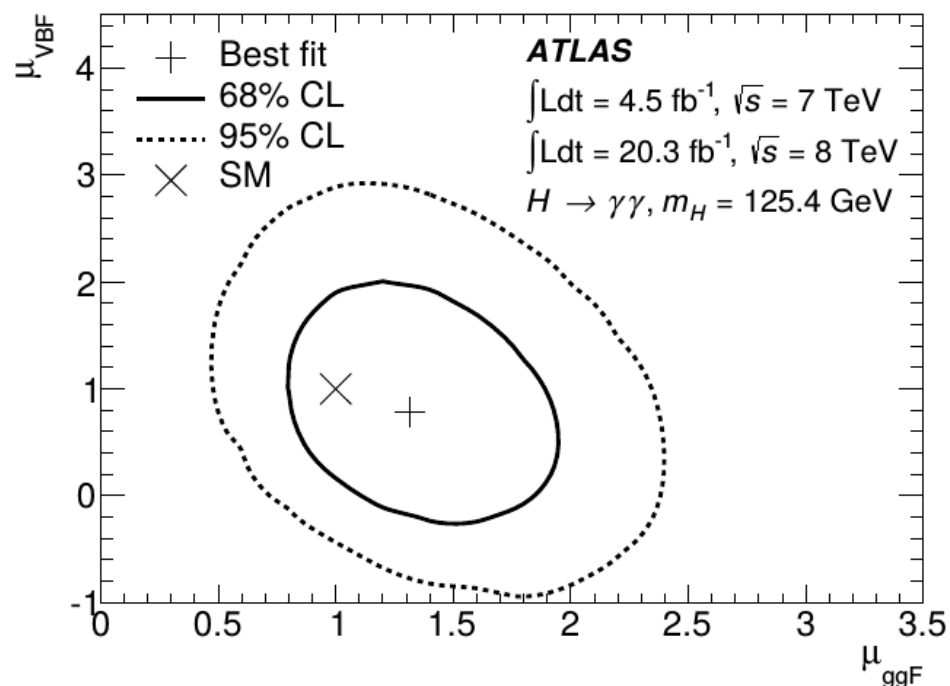
► Well in agreement with SM predictions.

$$\hat{\mu}_{CMS}(m_H = 124.7 \text{ GeV}) = 1.14 \pm 0.24 \left[ \pm 0.21 (stat)_{-0.05}^{+0.09} (theo)_{-0.09}^{+0.13} (syst) \right]$$

$$\hat{\mu}_{ATLAS}(m_H = 125.4 \text{ GeV}) = 1.17 \pm 0.27 \left[ \pm 0.23 (stat)_{-0.08}^{+0.12} (theo)_{-0.08}^{+0.12} (syst) \right]$$

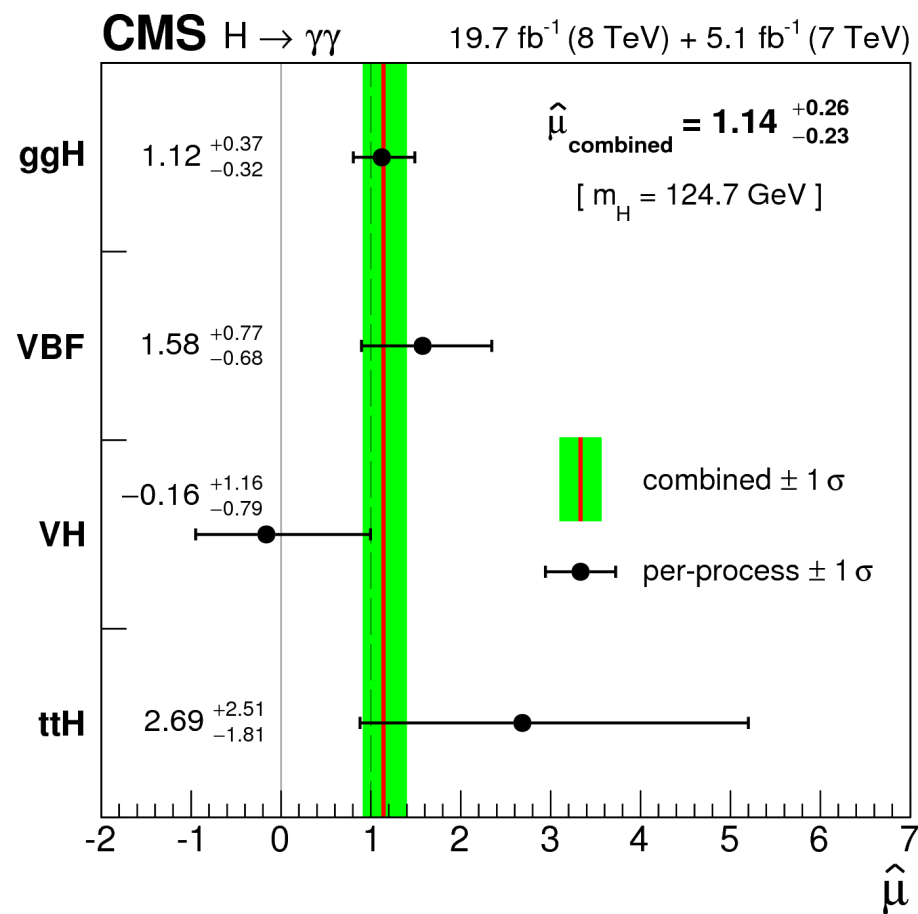
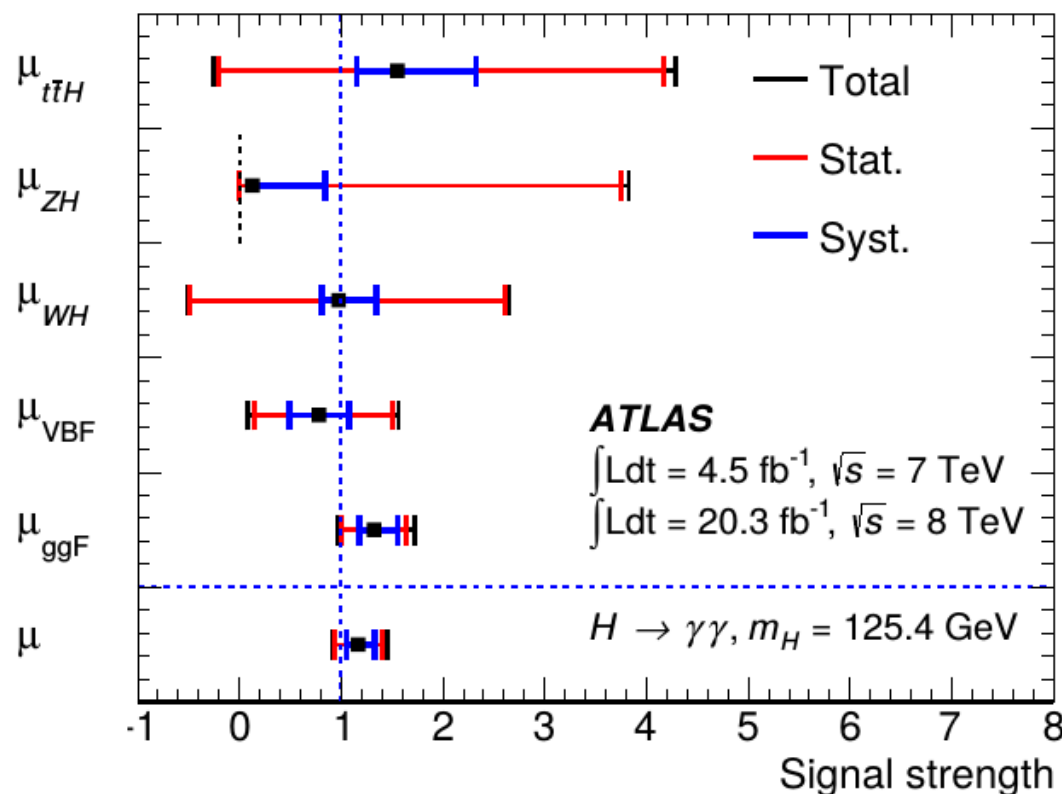
# “Fermionic” vs “Bosonic modes”

$$N^{ch} = \sum_{p,d} \left[ \mu_{pd} \cdot (\varepsilon \cdot A)_{pd}^{ch} \cdot \sigma_p^{SM} \cdot BR_d^{SM} \cdot L \right] + Bkg^{ch}$$



# Per production mechanism

- ▶ Finest possible breakdown.
  - ▶ Worsening in precision.
  - ▶ Well in agreement with SM predictions





- ▶ Simplest parametrization of Higgs-couplings deviations from SM values.

- ▶ Strengths modifications from SM amplitudes (LO EWK, NLO QCD).
- ▶ Assume kinematics unmodified.
- ▶ Motivated for small deviations from SM.

$$\sigma_p \cdot BR_d = \sigma_p \cdot \frac{\Gamma_d}{\Gamma_{tot}} = \frac{k_p^2 \cdot k_d^2}{k_H^2} \cdot \sigma_p^{SM} \cdot \frac{\Gamma_d^{SM}}{\Gamma_{tot}^{SM}}$$

- ▶ Parametrise  $\mu$ 's in terms of k's

- ▶ Can test different assumptions on relation between k's.

$$\mu_{pd} = \frac{k_p^2 \cdot k_d^2}{k_H^2}$$

- ▶  $k_H$  parametrises change in total width:

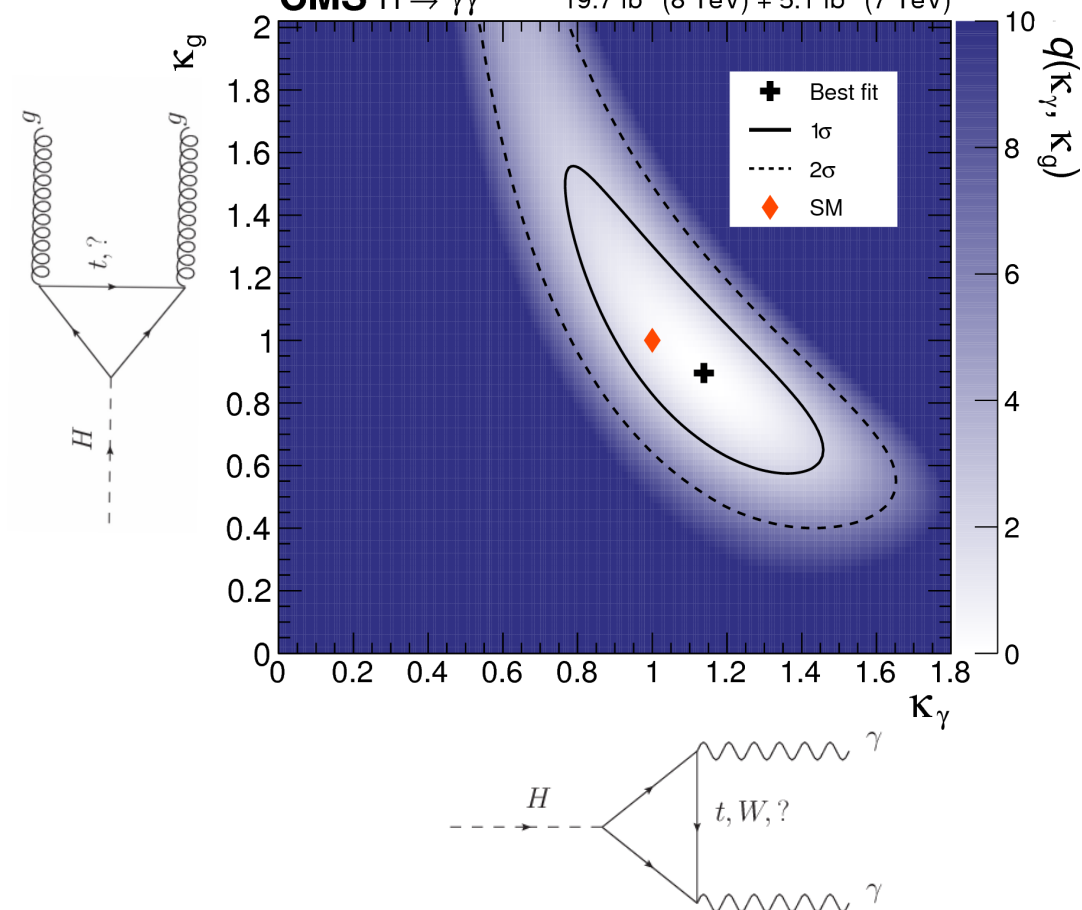
- ▶ As an independent parameter or as a function of the other k's

# Constraints on loop-induced couplings

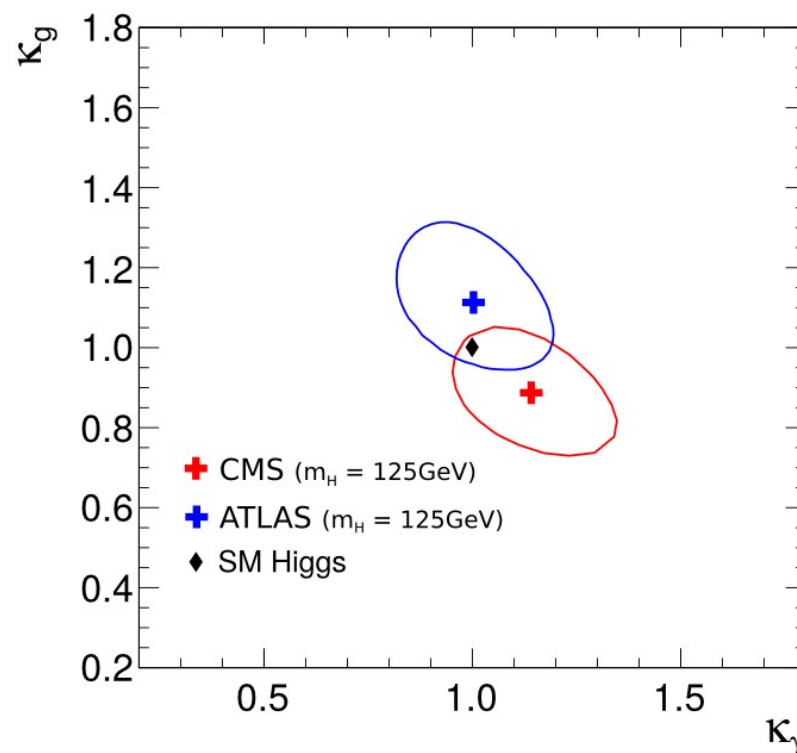


$H \rightarrow \gamma\gamma$  channel alone (CMS)

**CMS**  $H \rightarrow \gamma\gamma$  19.7 fb<sup>-1</sup> (8 TeV) + 5.1 fb<sup>-1</sup> (7 TeV)



Combining also other H decay modes

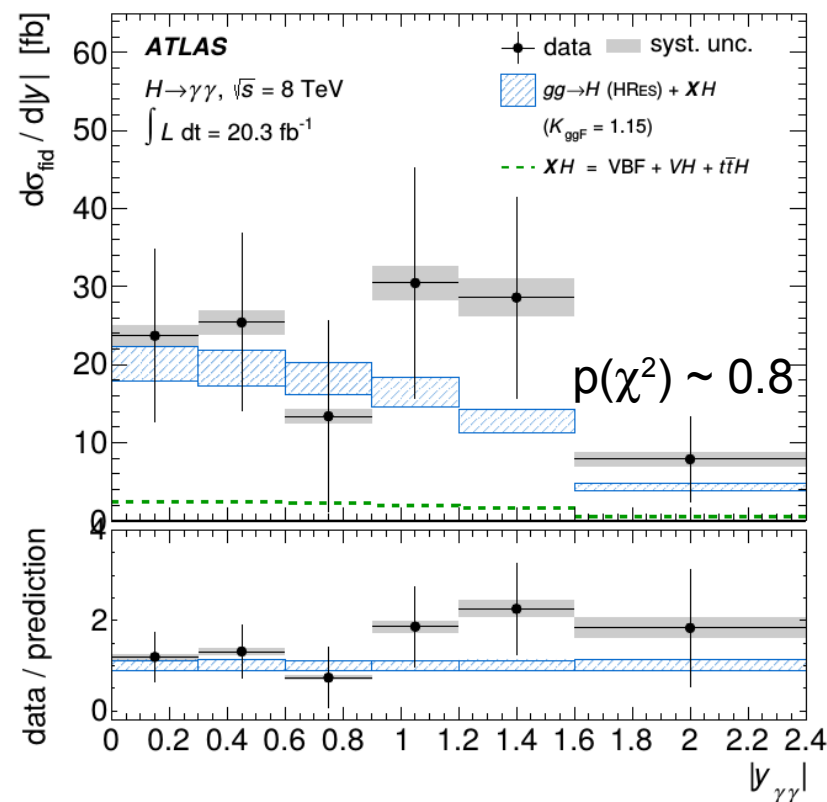
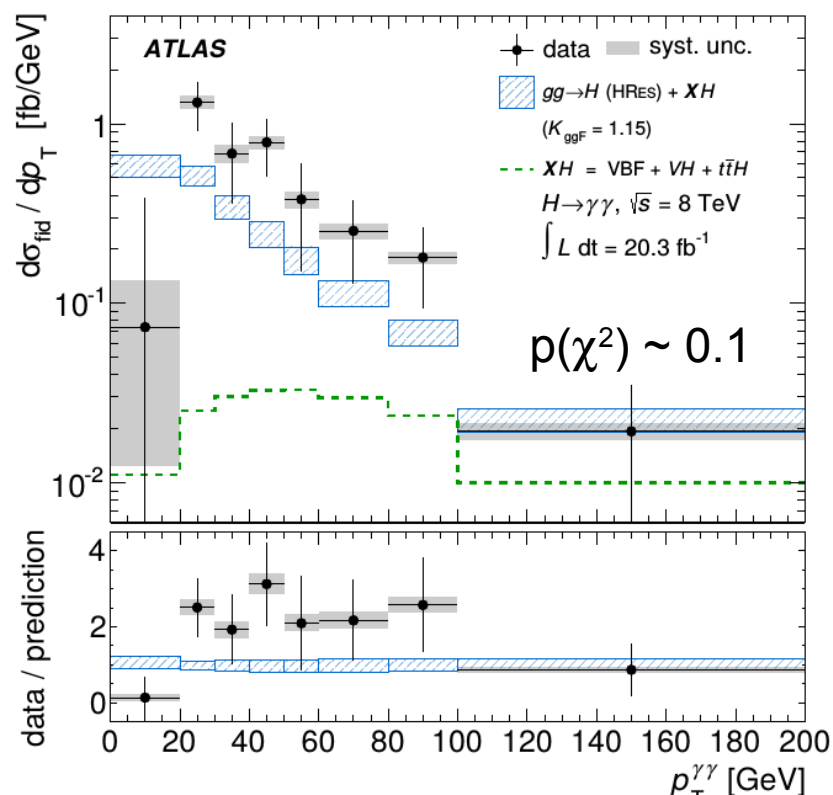


Expect to assess deviations on  $k_\gamma$  at 3-5% level in Run 2.

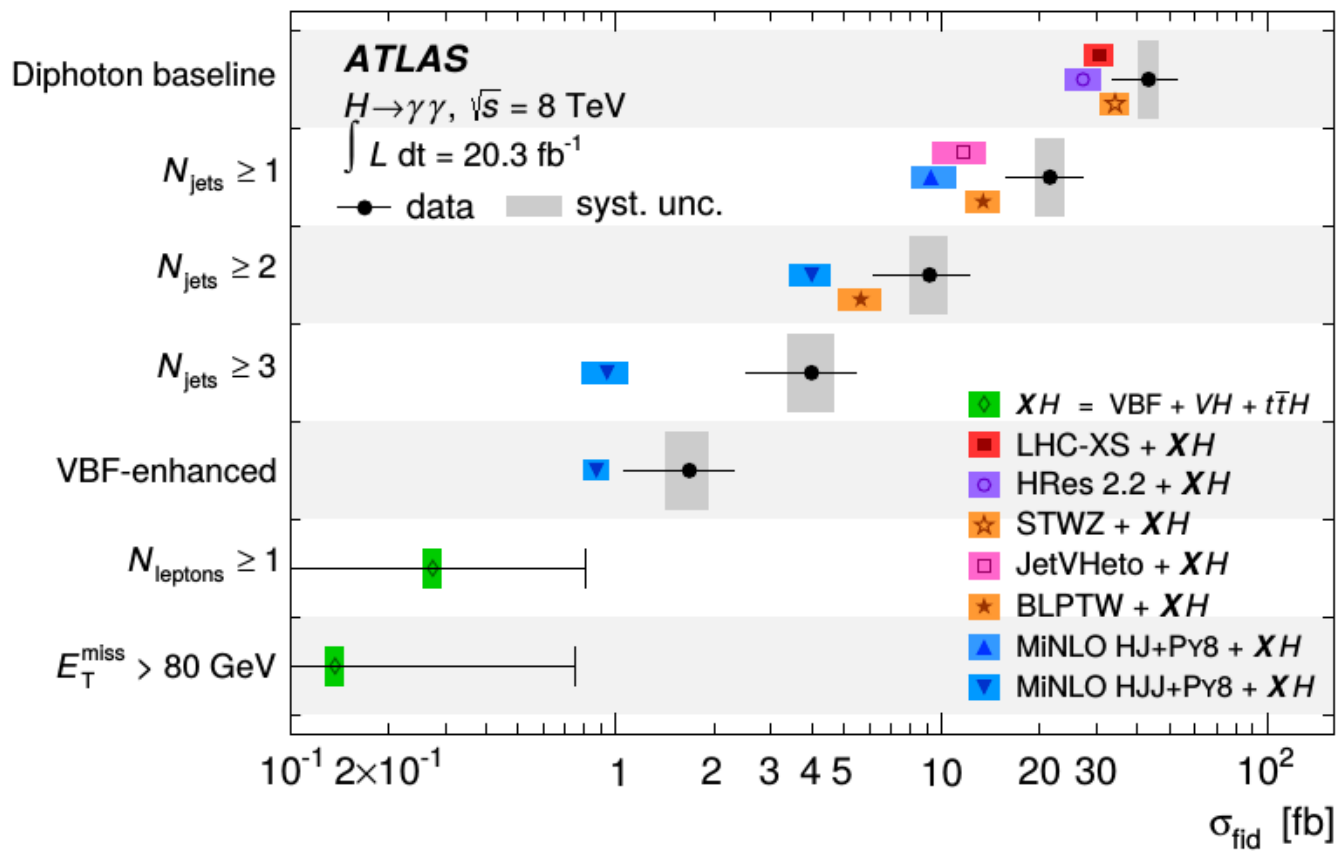
- ▶ Analysis presented so far use the most advance techniques for event selection and classification.
  - ▶ Maximal amount of information extracted.
  - ▶ Assumption: signal kinematics is SM one.
- ▶ Complementary approach is to measure fiducial cross section.
  - ▶ Simple definition of fiducial region.
  - ▶ Assumptions on signal kinematics much reduced.
  - ▶ Reduced precision.

$$\begin{array}{c}
 \text{Detector level observable} \\
 \downarrow \\
 \Delta N(O_j) = \sum_j \left[ \underset{\substack{\text{Fiducial cross-section} \\ \nearrow}}{\Delta \sigma(O_i^*)} \cdot \left( \frac{\varepsilon \cdot A_{fd}}{A} \right)_j^i \cdot \underset{\substack{\text{Detector response matrix} \\ \nearrow}}{L} \right] + \Delta Bkg(O_j) \\
 \begin{array}{c}
 \nearrow \text{Particle level observable} \\
 \text{Particle level observable}
 \end{array}
 \end{array}$$

- Fiducial phase-space.
  - $p_T(g1) > p_T(g2) > |h| < \text{ISO}_{0.3} <$
- Differential cross-section measured as a function of several observables.
  - Overall good agreement with SM predictions.
- CMS measurement on the way to publication.



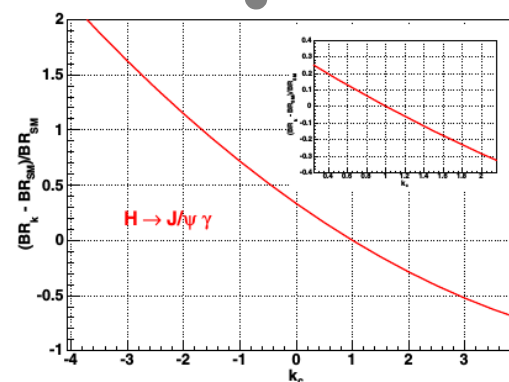
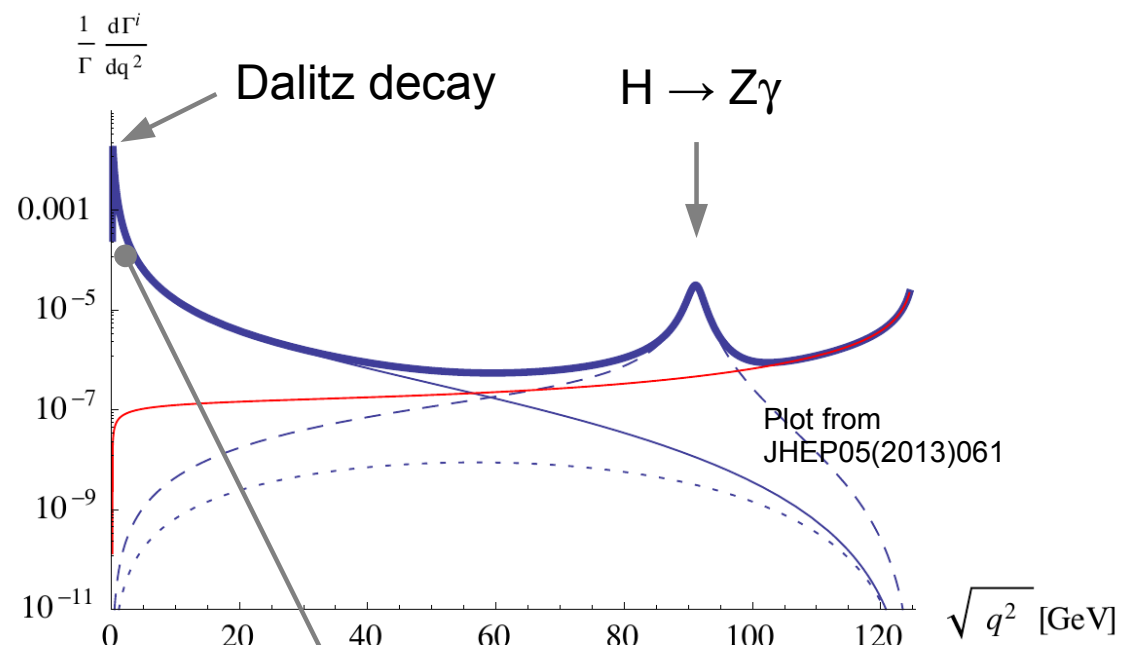
# Fiducial cross sections: grand summary



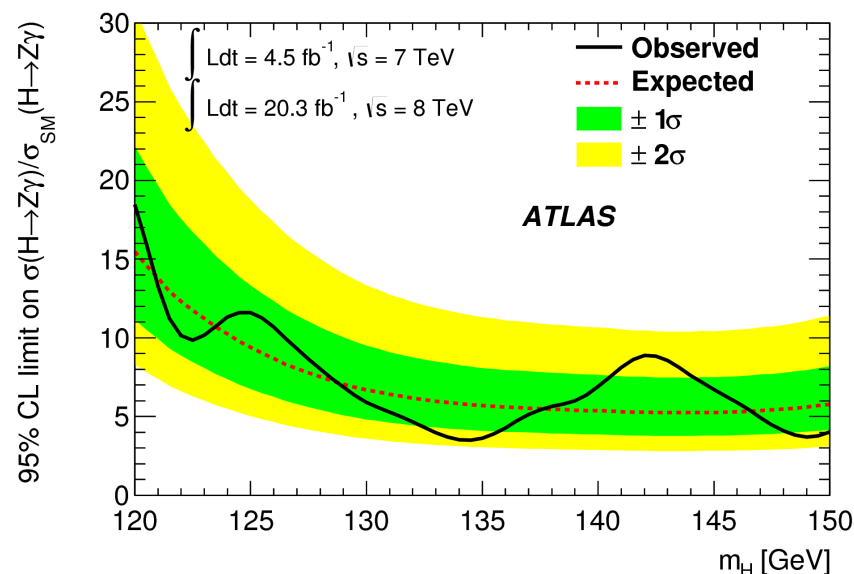
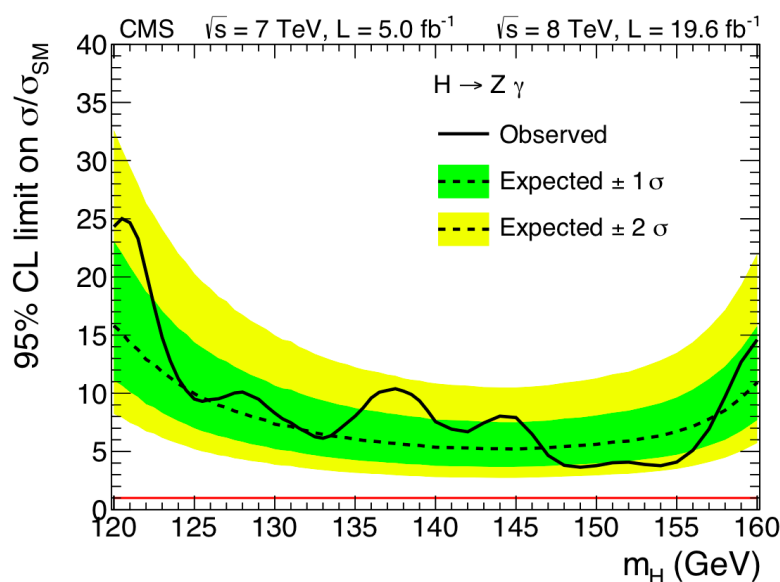
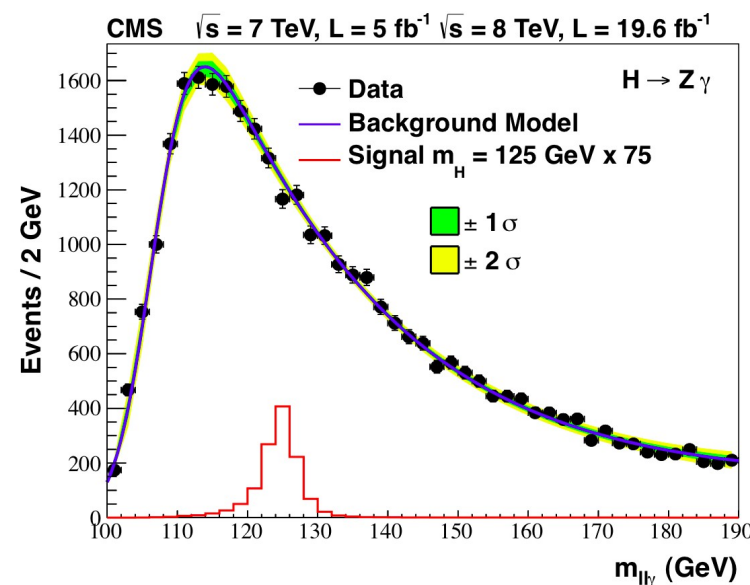
- Higgs decay channels with 2 leptons and a photon not as sensitive as  $H \rightarrow \gamma\gamma$  channel.

- Important to study.

- Loop mediated  $HZ\gamma$  coupling.
- $H \rightarrow J/\psi \gamma$



- ▶ Similar strategy to  $H \rightarrow \gamma\gamma$ .
  - ▶ Events categorized according to resolution.
  - ▶ CMS also uses VBF selection.
  - ▶ Limit from simultaneous fit to  $m_{ll\gamma}$ .
- ▶ Exclusion sensitivity  $\sim 10 \times$  SM for each experiment.
- ▶ Will probe branching ratios close to SM by the end of LHC Run 2.



# Dalitz decay and quarkonia



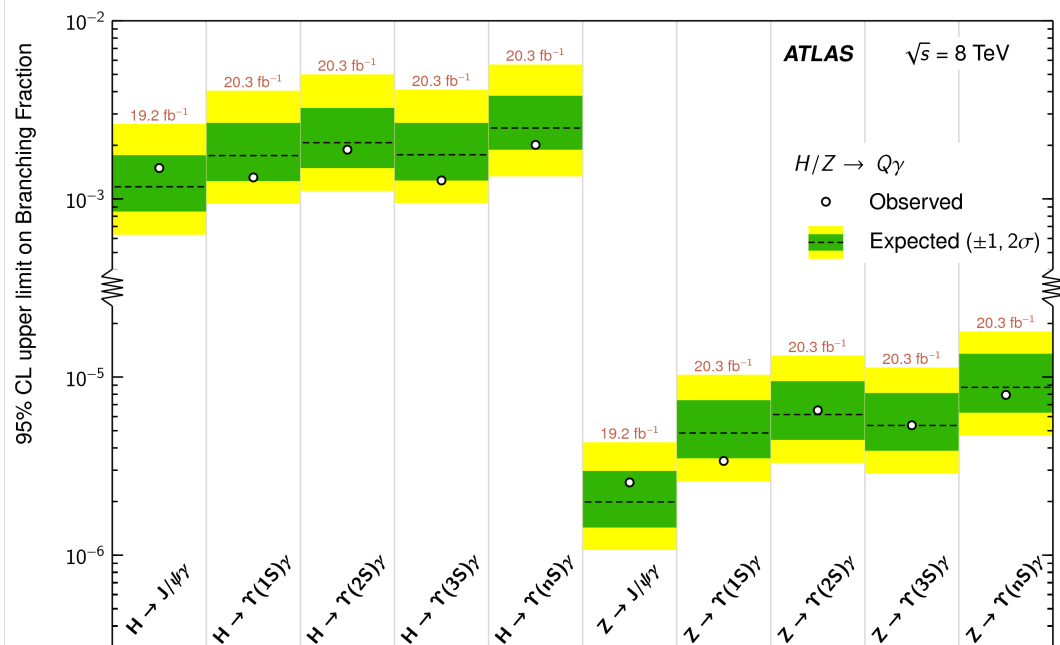
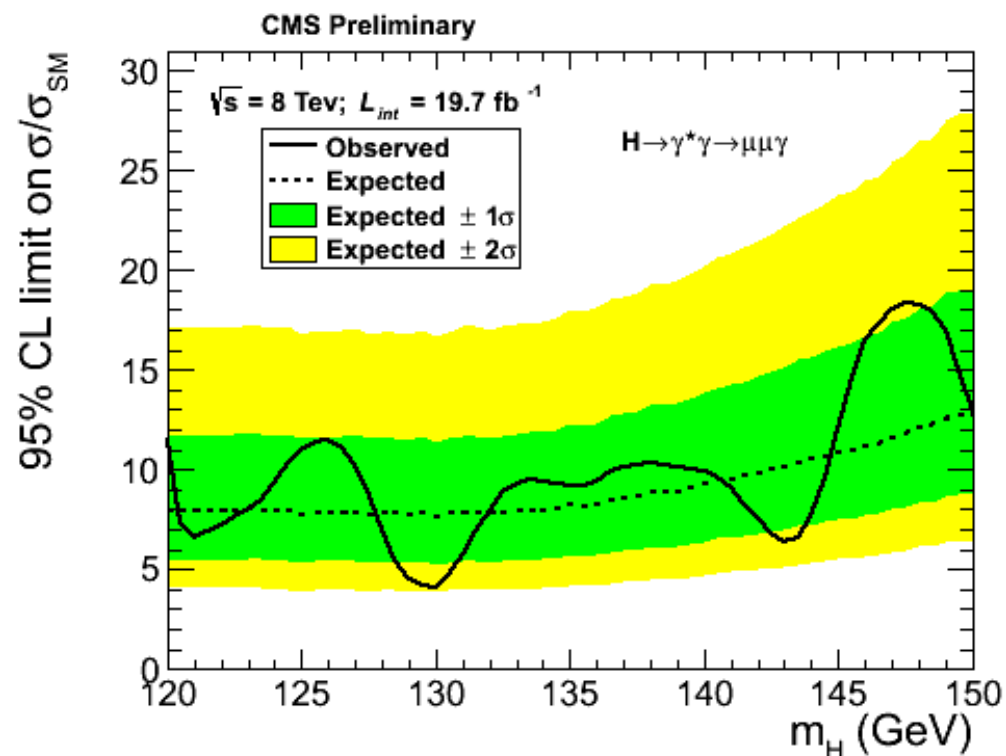
## ► CMS:

- Search for  $H \rightarrow g^*g \rightarrow llg$  (no the road to  $H \rightarrow J,Y g$ ).

## ► ATLAS:

- Search for  $H \rightarrow J,Y g$  and  $Z \rightarrow J,Y g$ .

► Decays with quarkonia final states extremely challenging even for HL-LHC



# Double Higgs production



► Long term goal is to constrain Higgs field self-coupling.

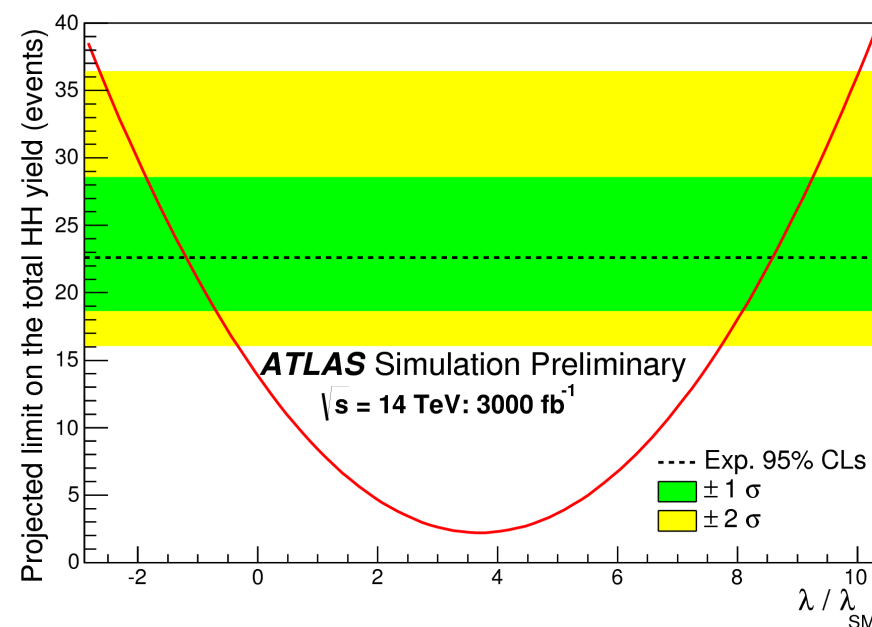
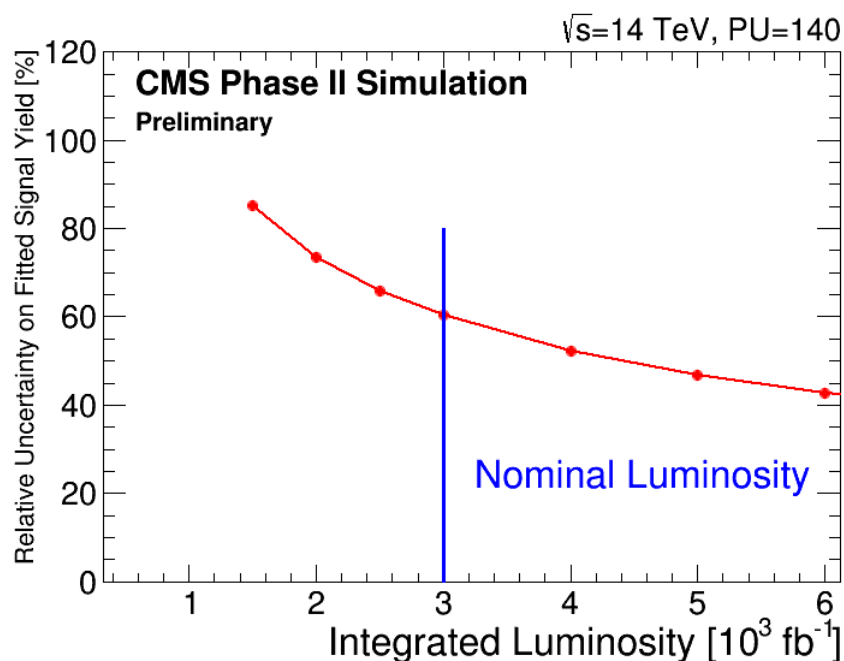
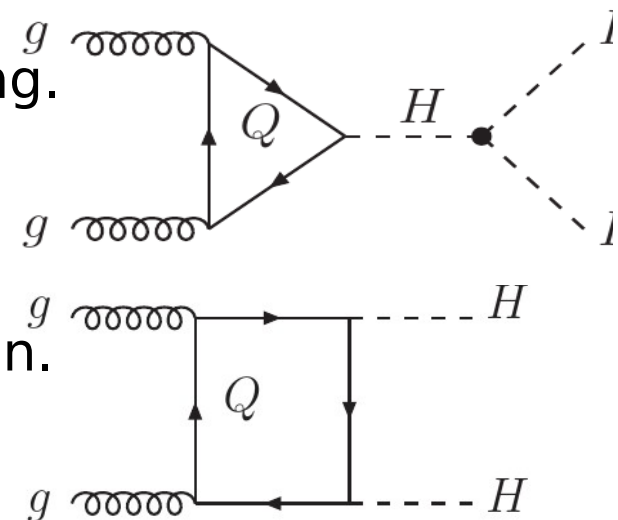
►  $HH \rightarrow bb \gamma\gamma$  is the most promising channel.

► Expect  $1-2\sigma$  sensitivity for  $3ab^{-1}$ .

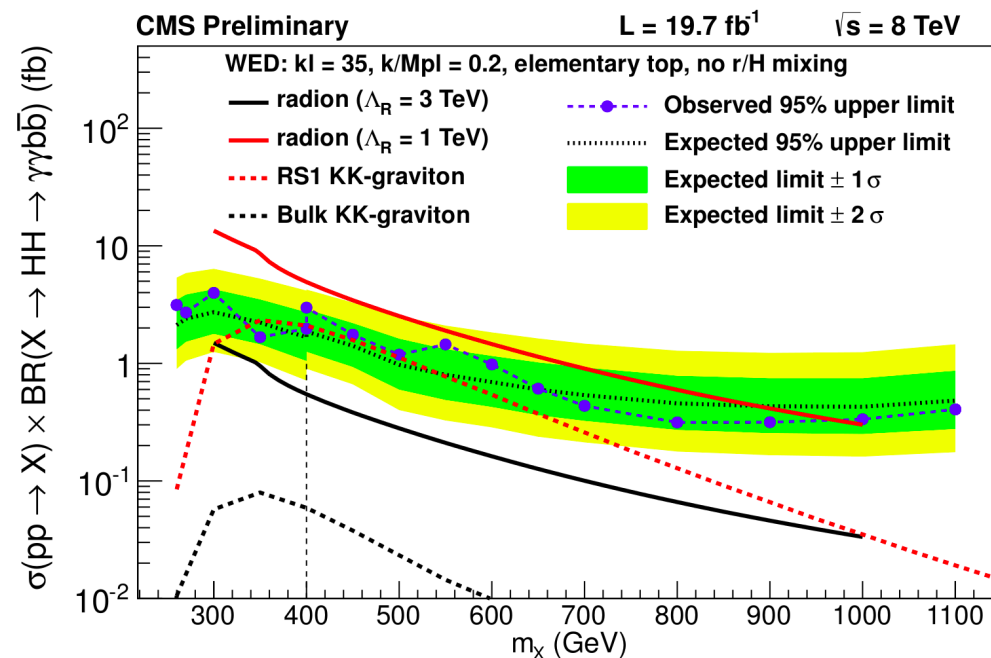
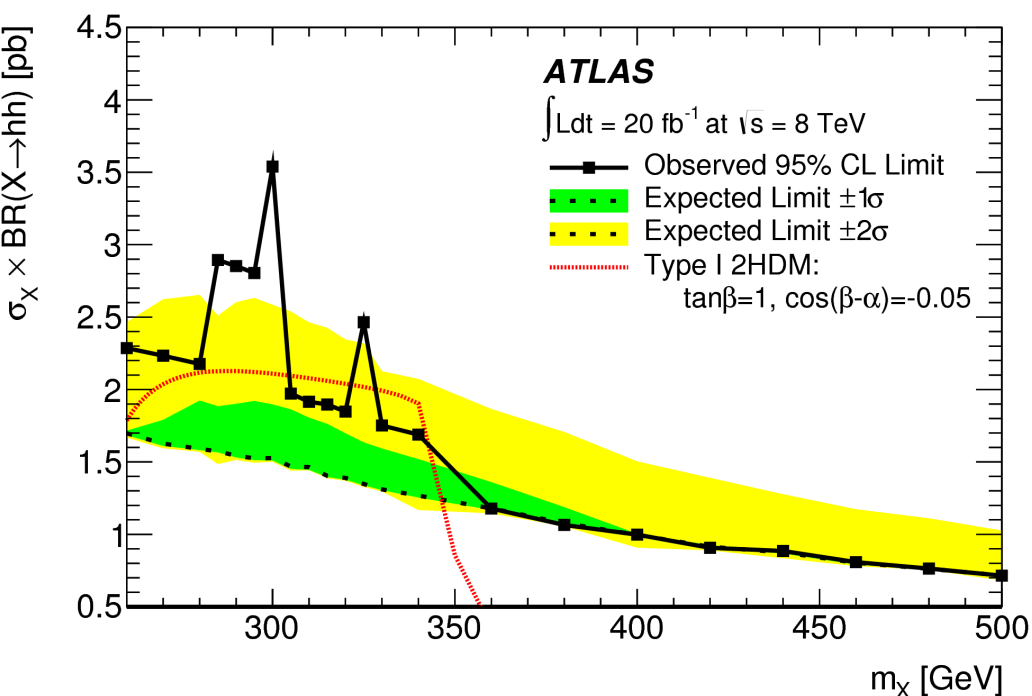
► For LHC Run 1 (and 2) focus is on resonant production.

► First step towards non-resonant production.

► Set limit on exotic physics and extended Higgs sector.



- ▶ Results interpreted in terms of 2HDM or extradimensional models.
  - ▶ Comparable sensitivities for CMS and ATLAS.
  - ▶ Moderate excess in ATLAS search, not seed in CMS one.



- ▶ Final states with photons are a very important part of the LHC Higgs program.
- ▶  $H \rightarrow \gamma\gamma$  channel is one of the most sensitive ones and allows precise determination of the Higgs sectors parameters.
  - ▶ Best determination of  $m_H$  comes from  $H \rightarrow \gamma\gamma$  channel.
  - ▶ Measurement of signal strength(s) is among the most precise ones. Perspectives for LHC Run 2 is to constrain  $H\gamma\gamma$  couplings at a few % level.
  - ▶ Best measurement of differential fiducial cross section also from  $H \rightarrow \gamma\gamma$ . Higher statistics in LHC Run 2 will considerably improve precision.
- ▶ Search for rare decays of  $H \rightarrow l\gamma$  allow to constrain BSM contributions to Higgs decay loops.
- ▶ In the long run  $HH \rightarrow b\bar{b}\gamma\gamma$  expected to provide information on the Higgs field self-coupling.

# Thank you for your attention



## References.

### ATLAS Collaboration

*“Measurement of the Higgs boson mass from the  $H \rightarrow \gamma \gamma$  and  $H \rightarrow ZZ^{*} \rightarrow 4 \ell$  channels with the ATLAS detector at the LHC”, Phys. Rev. D. 90, 052004 (2014).*

*“Search for Higgs Boson Pair Production in the  $\gamma \gamma b \bar{b}$  Final State using  $pp$  Collision Data at  $\sqrt{s} = 8$  TeV from the ATLAS Detector”, Phys. Rev. Lett. 114, 081802 (2015).*

*“Measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel at  $\sqrt{s} = 8$  TeV with ATLAS”, JHEP09(2014)112.*

*“Measurement of Higgs boson production in the diphoton decay channel in  $pp$  collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector”, Phys. Rev. D. 90, 112015 (2014).*

*“Measurements of the Higgs boson production and decay rates and couplings using  $pp$  collision data at  $\sqrt{s} = 7$  and 8 TeV in the ATLAS experiment”, ATLAS-CONF-2015-007.*

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### CMS Collaboration

*“Observation of the diphoton decay of the Higgs boson and measurement of its properties”, EPJ C 74 (2014) 3076.*

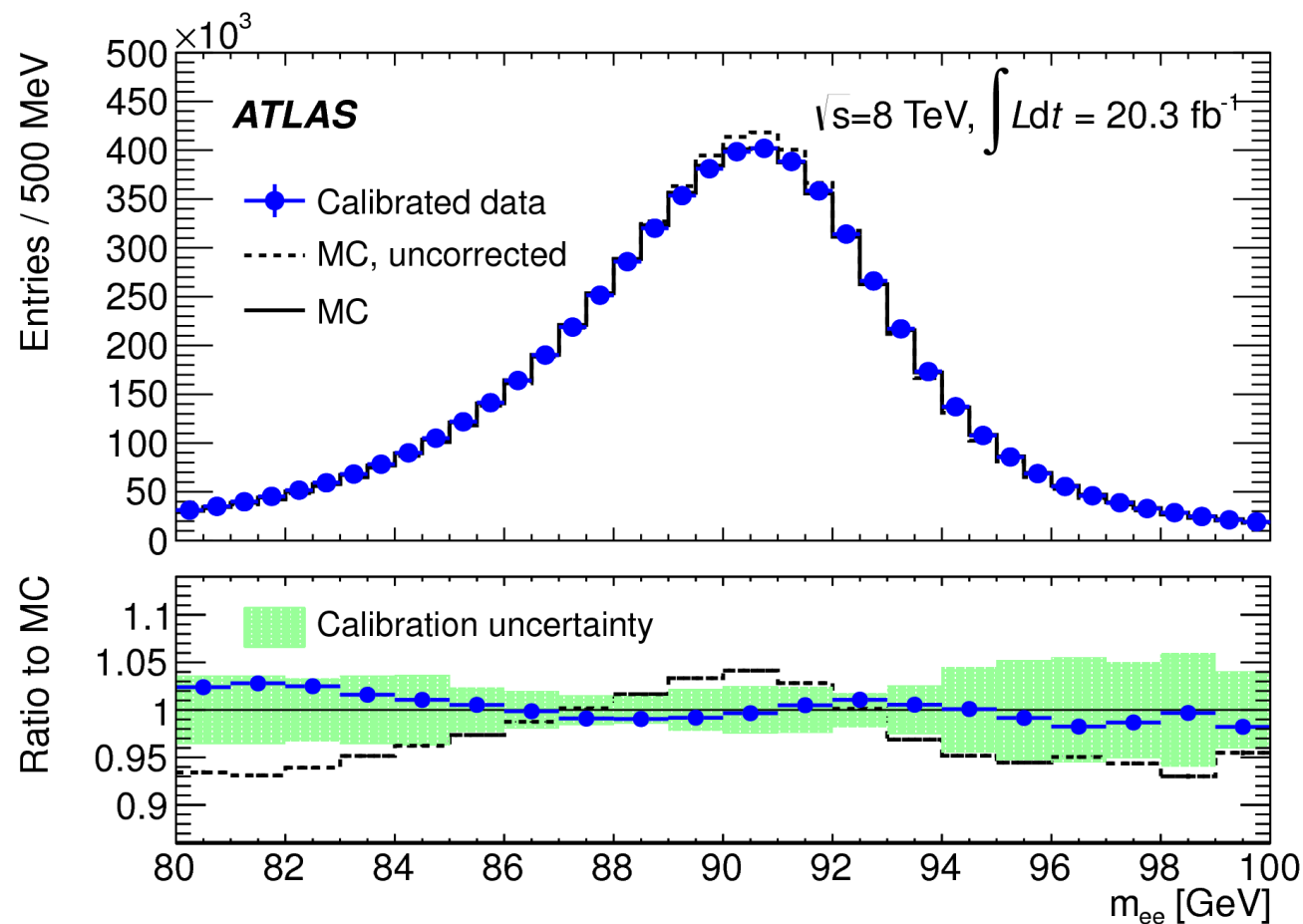
*“Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV”, arXiv:1412.8662 accepted by EPJ C.*

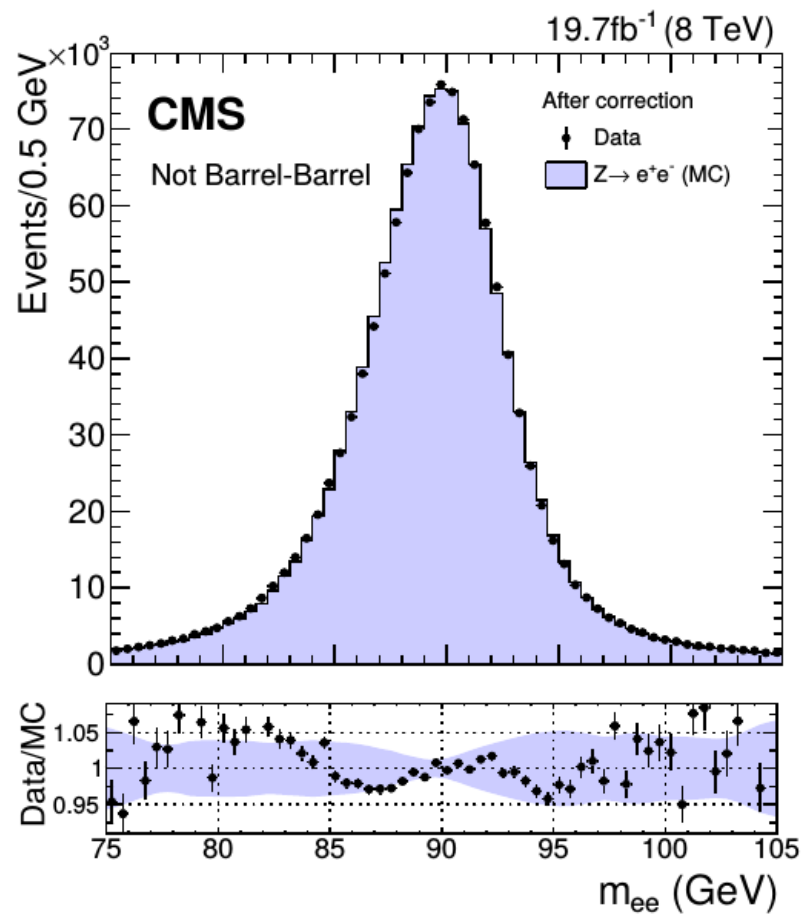
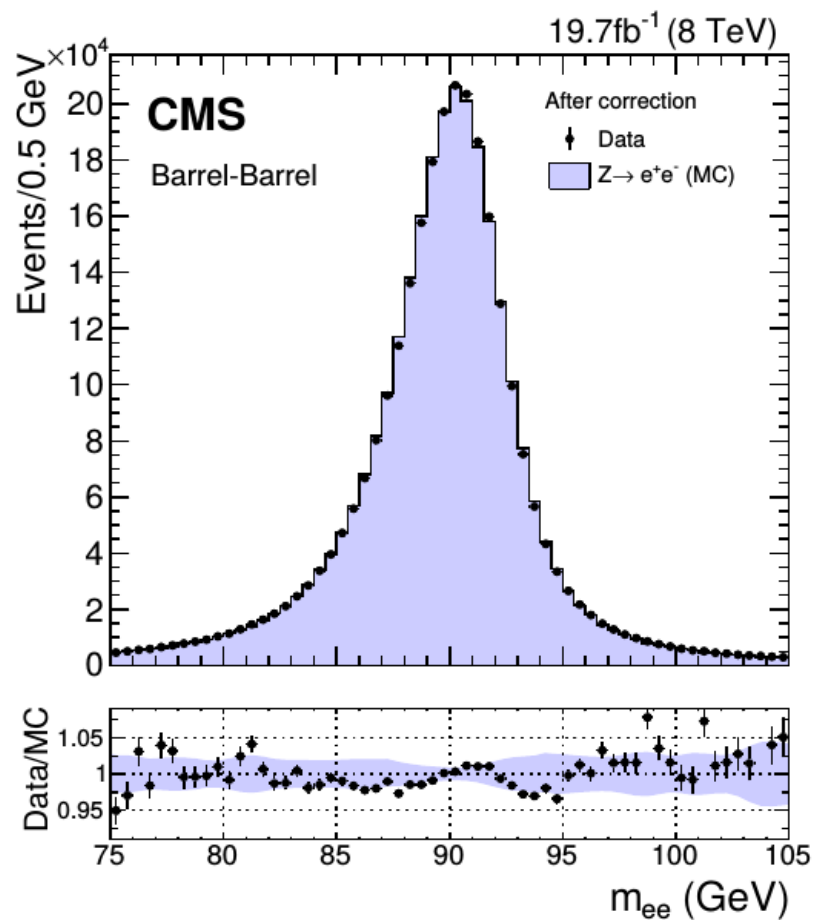
*“Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, arXiv:1502.02702, submitted to JHEP*

### CMS and ATLAS Collaborations

*“Combined Measurement of the Higgs Boson Mass in  $pp$  Collisions at  $\sqrt{s} = 7$  and 8 TeV with the ATLAS and CMS Experiments”, arXiv:1503.07589, accepted by Phys Rev Lett*





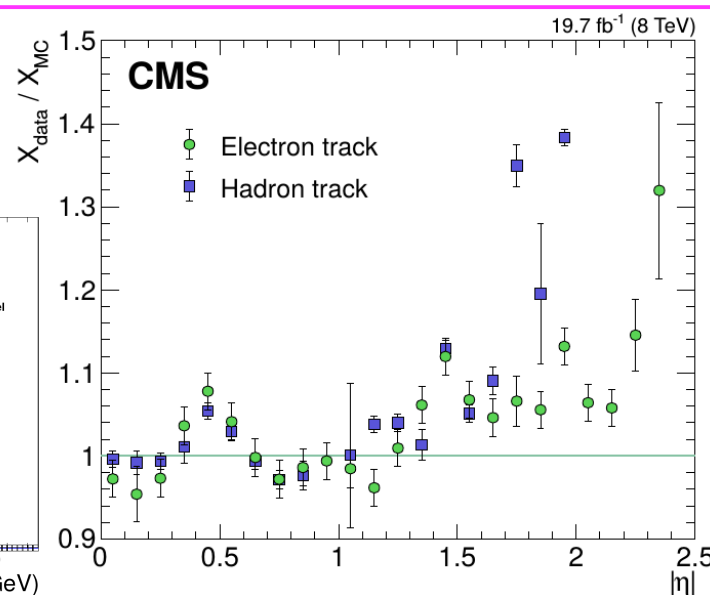
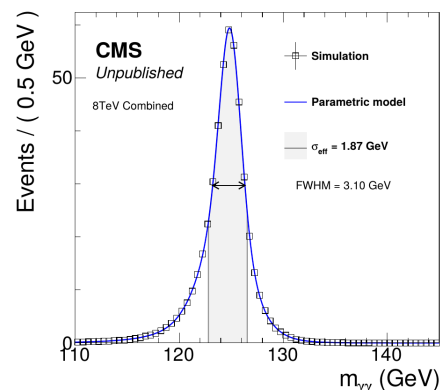
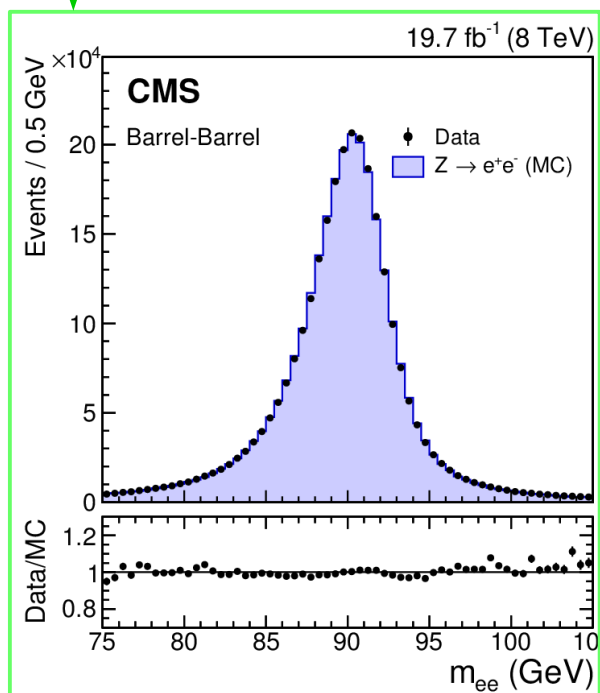
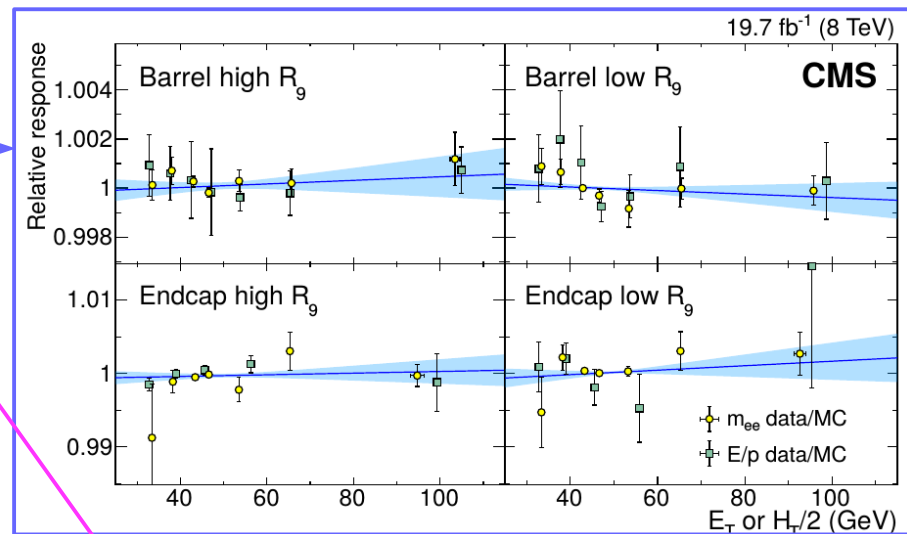


# Photon energy scale uncertainties



- Photon energy scale and resolution corrections derived from  $Z \rightarrow ee$  events.

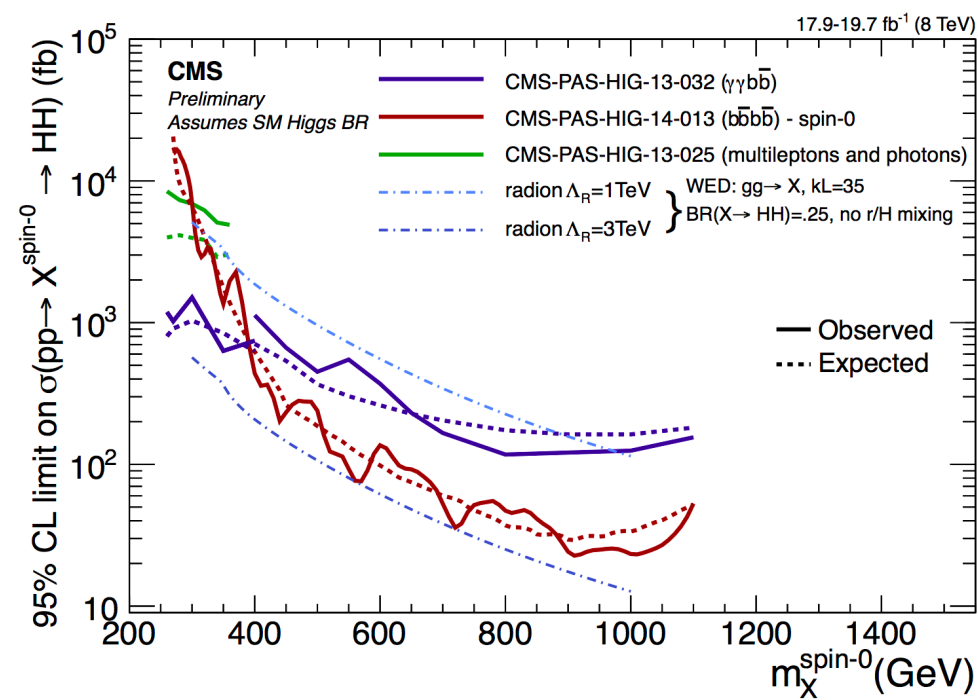
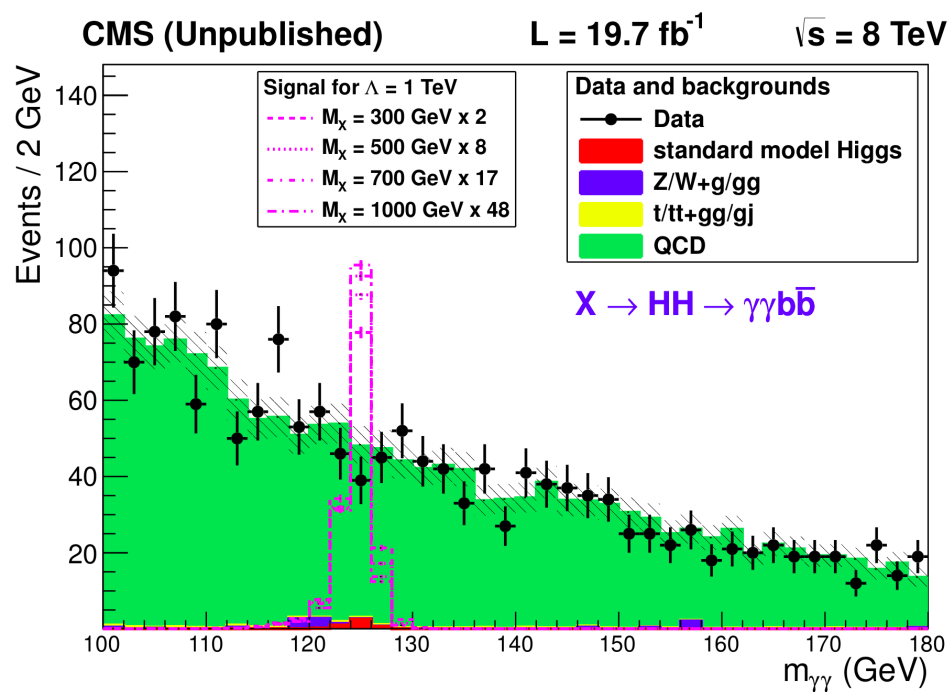
- Extrapolation to higher  $p_T$  through boosted Z production.
- Extrapolation from electrons to photons through MC simulation ( $Z \rightarrow l\gamma$  low- $E_T$  cross-check)

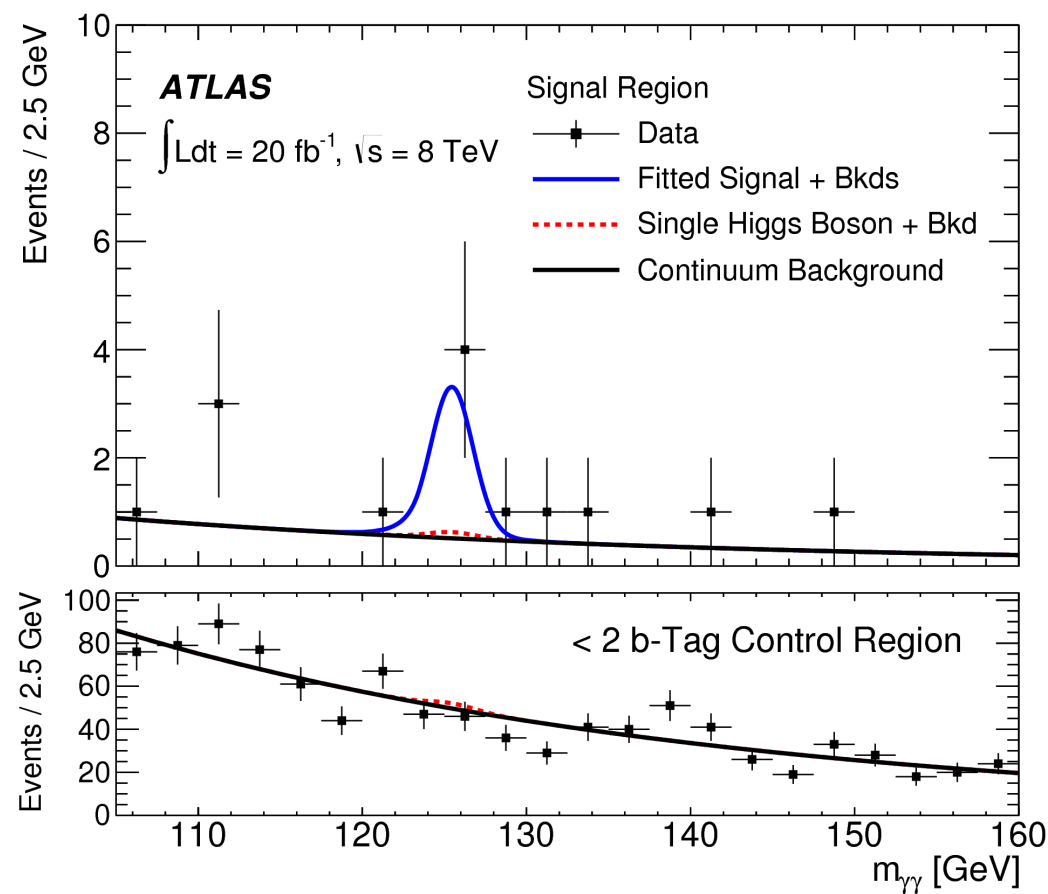
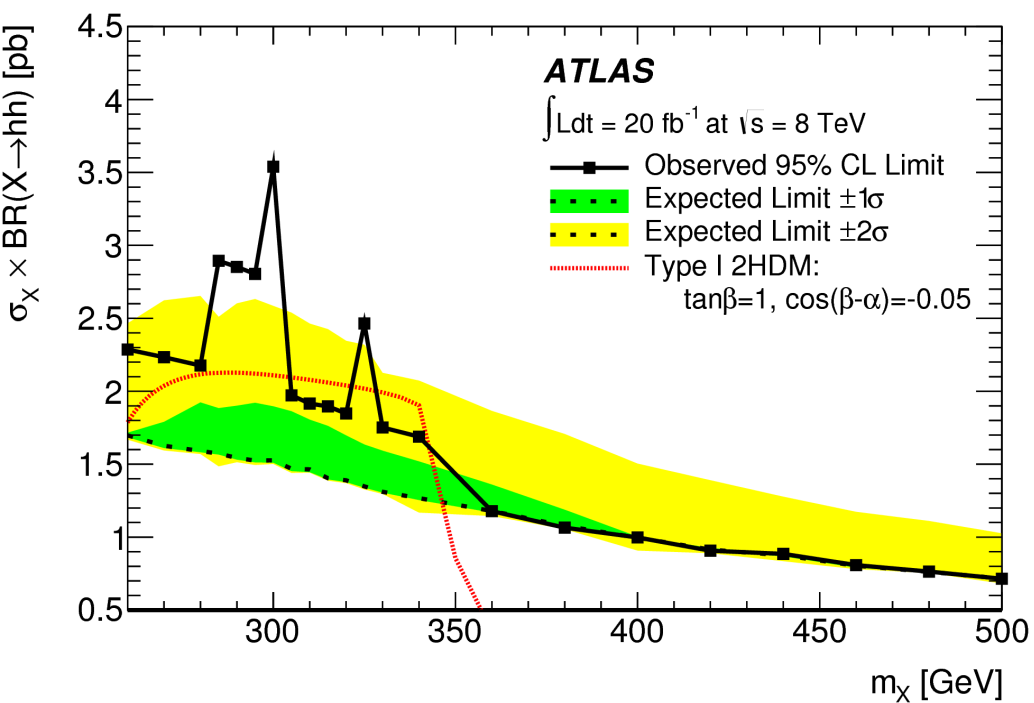


► Contributions to systematic uncertainties on  $m_H$  in GeV.

► Observed (expected) uncertainties are quoted.

	ATLAS	CMS
Non-linearity	0.14 (0.16)	0.10 (0.13)
Material in front of ECAL	0.15 (0.13)	0.07 (0.07)
ECAL longitudinal response	0.12 (0.13)	0.02 (0.01)
ECAL lateral shower shape	0.09 (0.08)	0.06 (0.06)
Photon energy resolution	0.03 (0.01)	0.01 (<0.01)
$Z \rightarrow ee$ calibration	0.05 (0.04)	0.05 (0.05)
Total	0.27 (0.27)	0.15 (0.17)





Can also exploit destructive interference between  $gg \rightarrow \gamma\gamma$  and  $gg \rightarrow H \rightarrow \gamma\gamma$ .

- Generate effective mass shift, which magnitude varies as a function of the boson  $p_T$ .
- Constraint of the width from measurement of  $m_H$  vs  $p_{TH}$ .
- Projected sensitivity for  $3ab^{-1}$   $\Gamma < 30 \Gamma_{SM}$  (95% CL).

