Higgs Boson Results from the LHC Run-2

Jonas Strandberg (KTH)

on behalf of the ATLAS and CMS collaborations

Introduction

- After the Higgs discovery in 2012, the emphasis shifted towards measuring the properties of this new particle.
  - The mass, the only free parameter in the Higgs sector in the SM.
  - The width, very challenging as the intrinsic width around 4 MeV.
  - Spin and parity, is it 0^+ as expected in the SM?
  - Couplings, several models for physics beyond the SM predict (small) deviations in the couplings for the Higgs boson. Not covered in this talk.
- This talk will review the latest results using the Run 2 dataset.
  - Comparing this with the Run 1 results, in most cases the analysis strategy is following closely what was done in Run 1.
  - Increased collision energy (13 TeV) means an increased cross section for signal and background, with the most significant gain for processes involving heavy particles like multiple top quarks.
  - The luminosity (~3 fb-1) from the first year of Run 2 means that most results are not competitive with the Run 1 results yet.

Production and Decay

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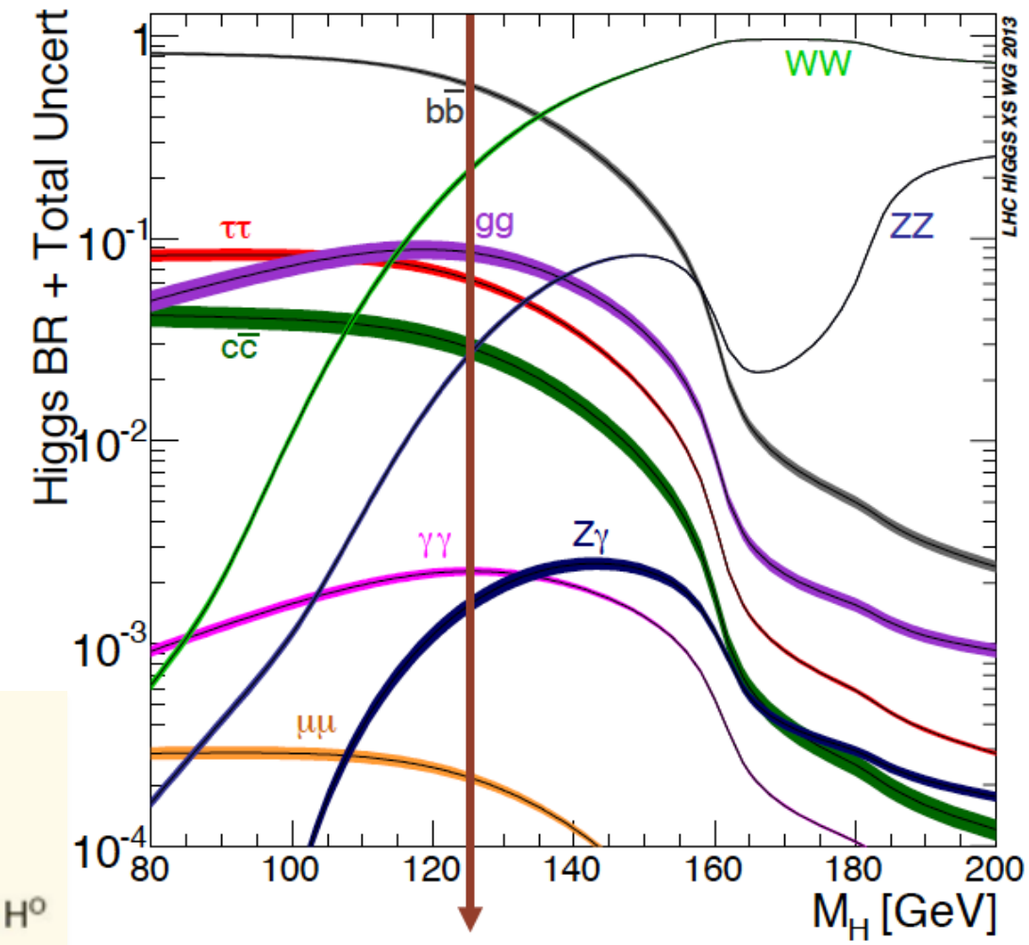
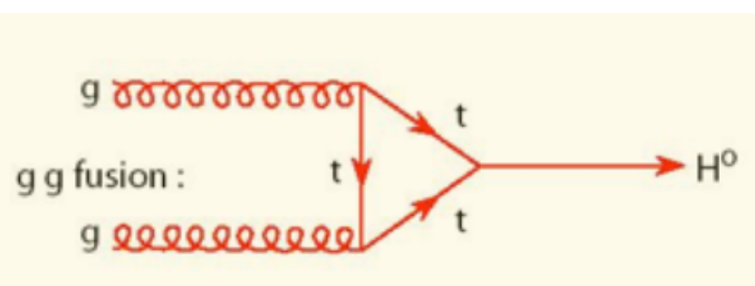
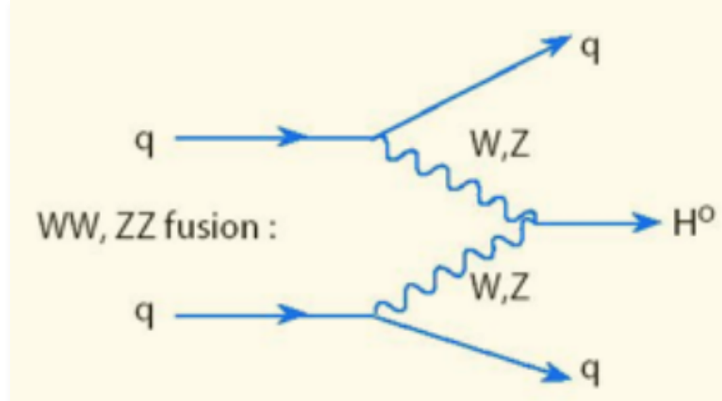
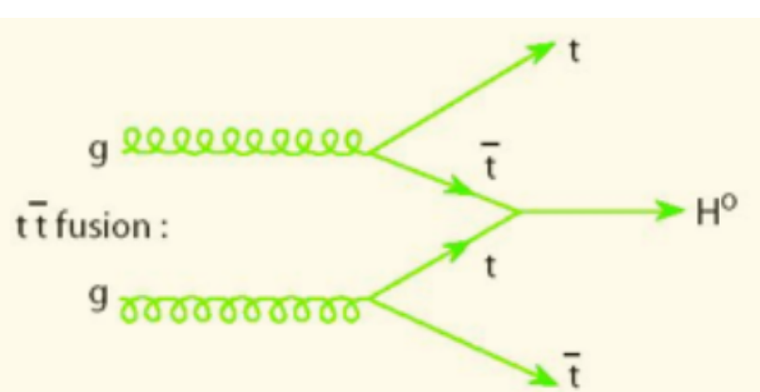
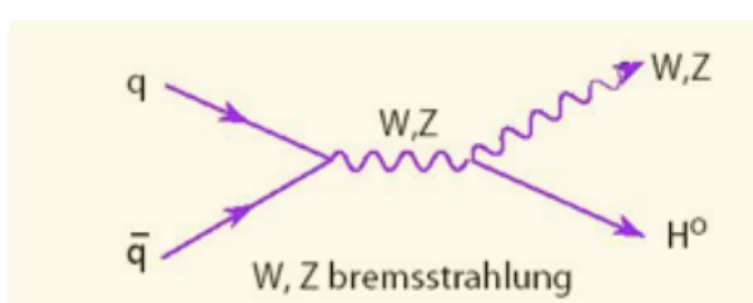
- Given the mass of 125 GeV, we know the branching fractions from theory.
- Several production modes of the Higgs boson possible at the LHC, sometimes with associated particles.
  - Highlighted production and decay modes will be mentioned in this talk.











Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

LHC Higgs XS Working Group

Run 1 and Run 2 Datasets

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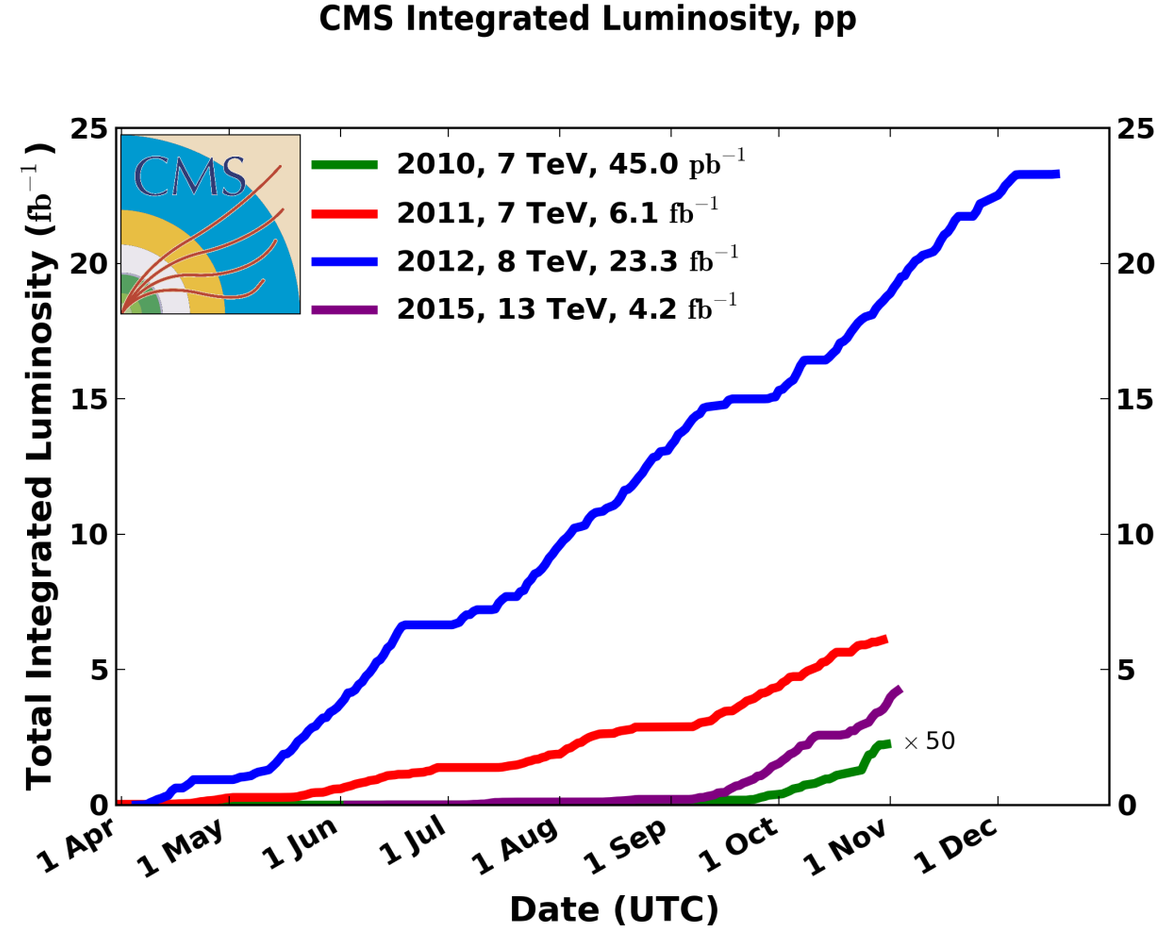
- Essentially three years of data taking used in analyses covered here:
  - 2011, at 7 TeV, with $\int \mathscr{L} \approx 5$ fb^{-1} for analysis.
  - 2012, at 8 TeV, with $\int \mathscr{L} \approx 20$ fb^{-1} for analysis.
  - 2015, at 13 TeV, with $\int \mathscr{L} \approx 3$ fb^{-1} for analysis.
- The higher collision energy in Run 2 leads to an increase of σ for both signal and backgrounds.

	√s=7 TeV	√s=8 TeV	√s=13 TeV	Ratio 13/8 TeV
ggH	15.3 pb	19.4 pb	44.1 pb	**2.27**
VBF	1.25 pb	1.6 pb	3.8 pb	**2.38**
ttH	88.6 fb	133 fb	507 fb	**3.81**
tt	177 pb	253 pb	832 pb	**3.29**



The H→ZZ*→4ℓ Channel in Run I

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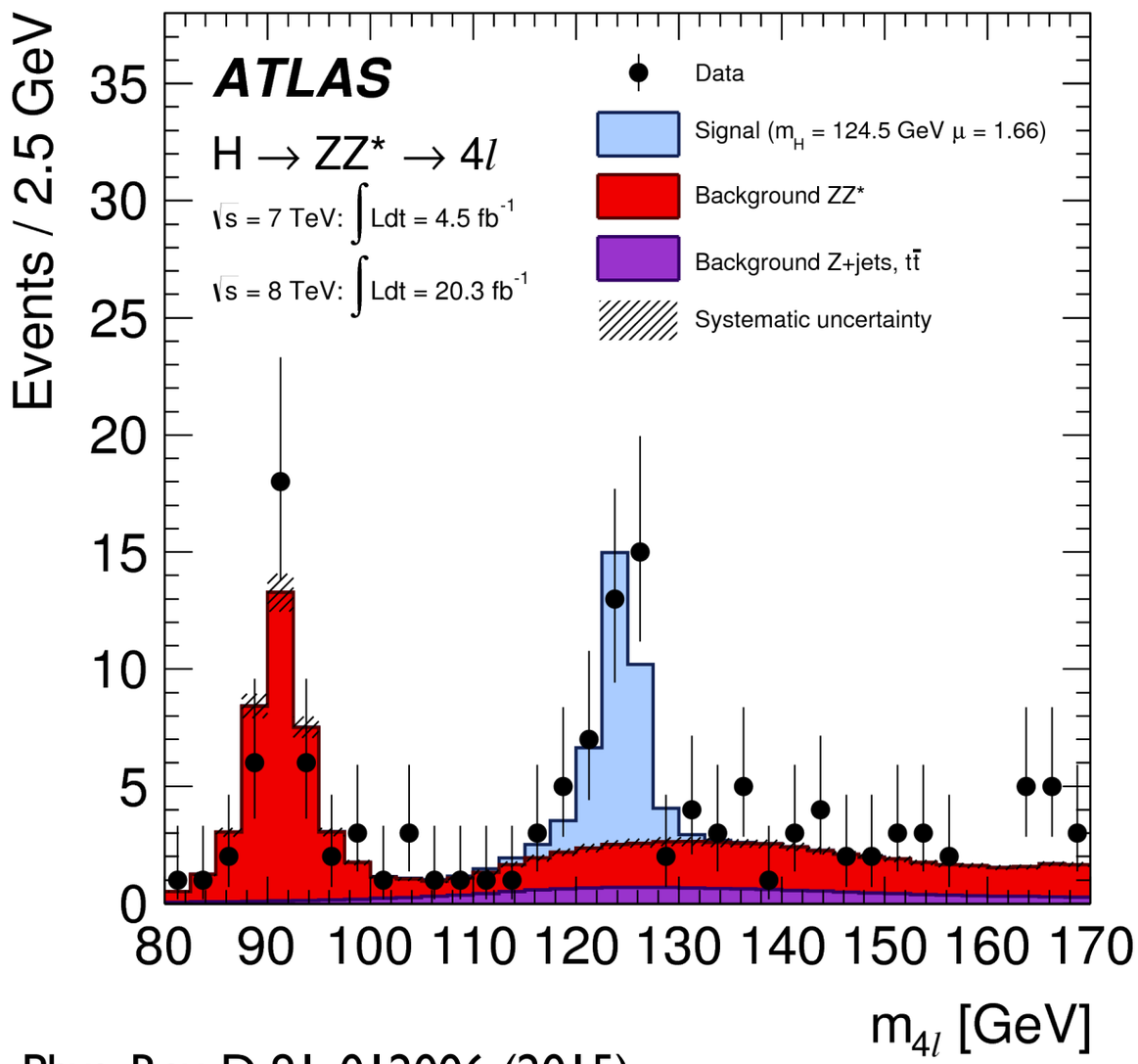
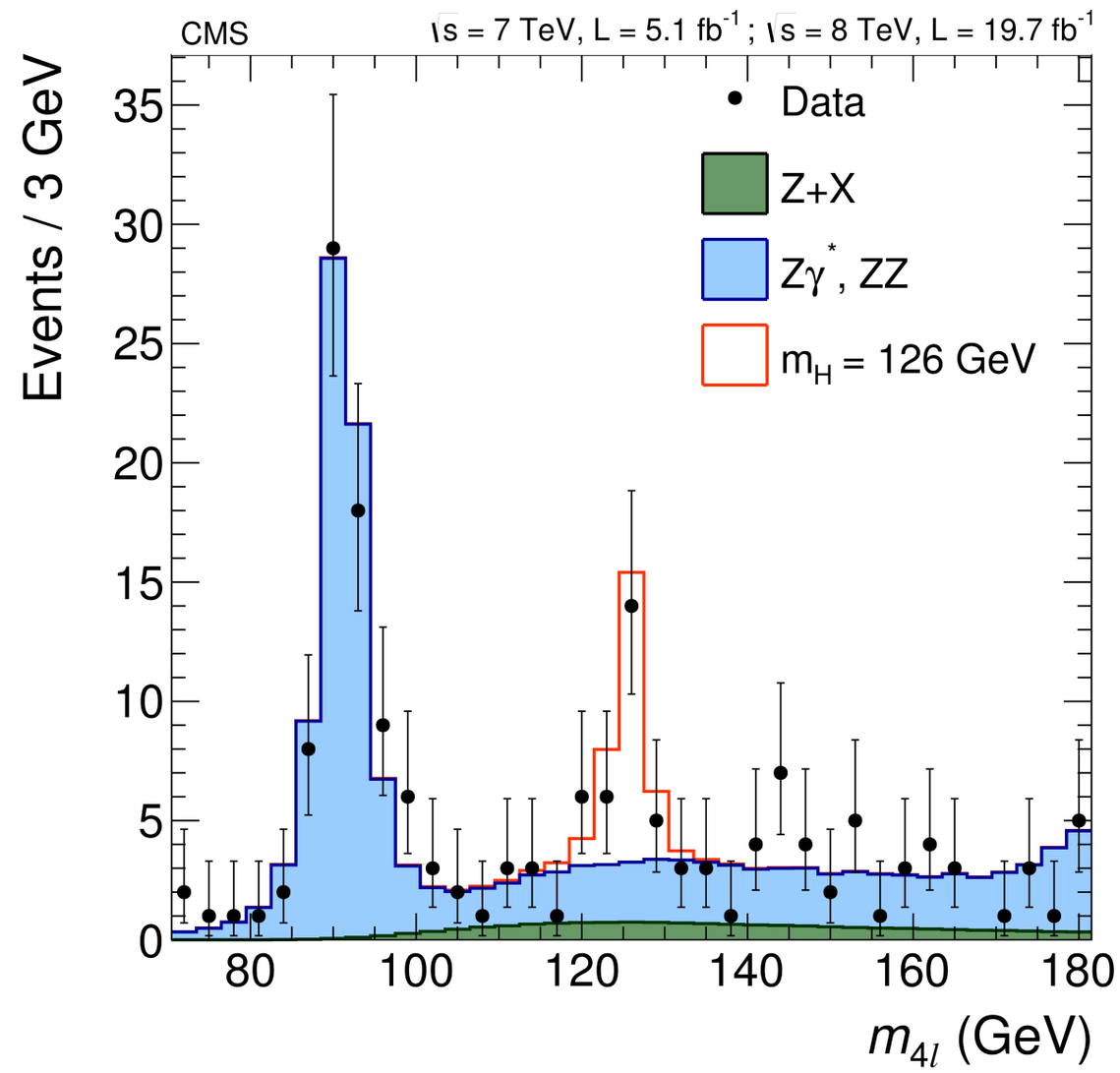
- Look for two pairs of leptonically decaying Z bosons, one off-shell.
  - Invariant mass of the 4 leptons should peak at the Higgs boson mass.
  - Very clean channel, but statistics limited, main background from SM ZZ production.
  - Use data (Z→ℓℓ, J/ψ) for calibration of energy and momentum of leptons.



Phys. Rev. D 91, 012006 (2015)



Phys. Rev. D 89 (2014) 092007

The H→γγ Channel in Run I

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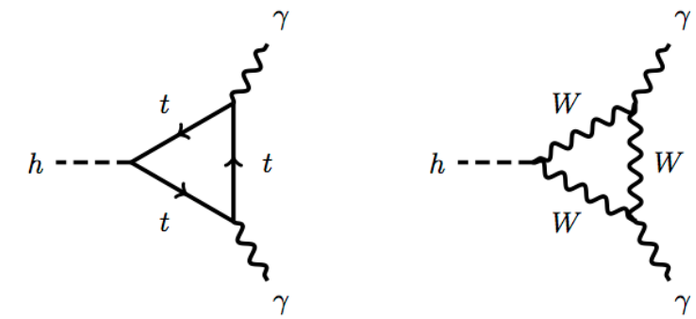
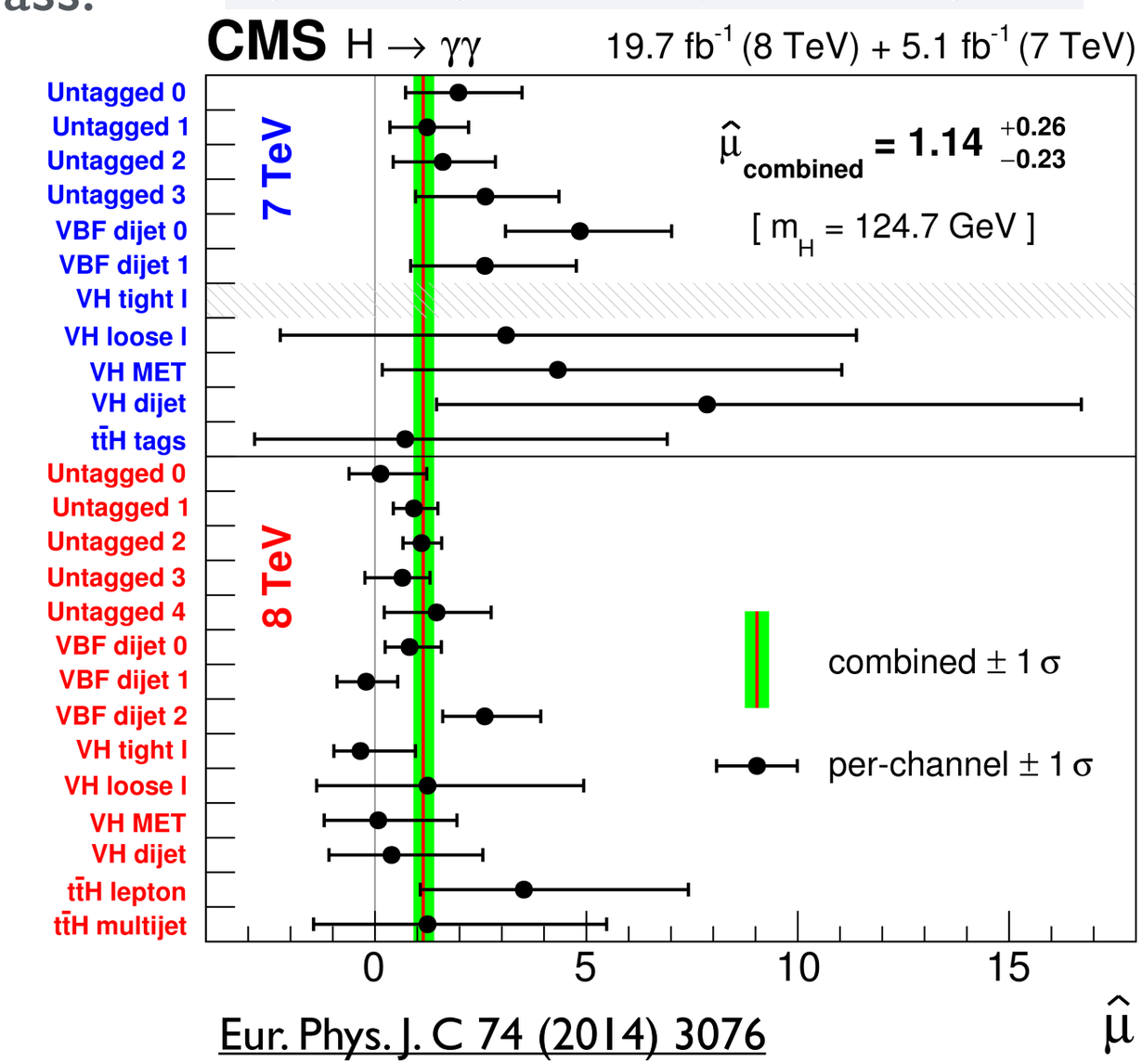
- The Higgs boson can decay to a pair of photons through a loop of heavier particles.
  - Low branching ratio, but good signal to background and invariant mass of the two photons should peak at the Higgs boson mass.



- To increase the sensitivity, events are divided into categories according to associated particles from the production mode and the quality of the photons.
  - When combining categories, effective S/(S+B) ratio is taken into account.
- Main backgrounds from SM γγ production and γj production.

Signal strengths in CMS γγ event categories:



Eur. Phys. J. C 74 (2014) 3076

The H→γγ Channel in Run I

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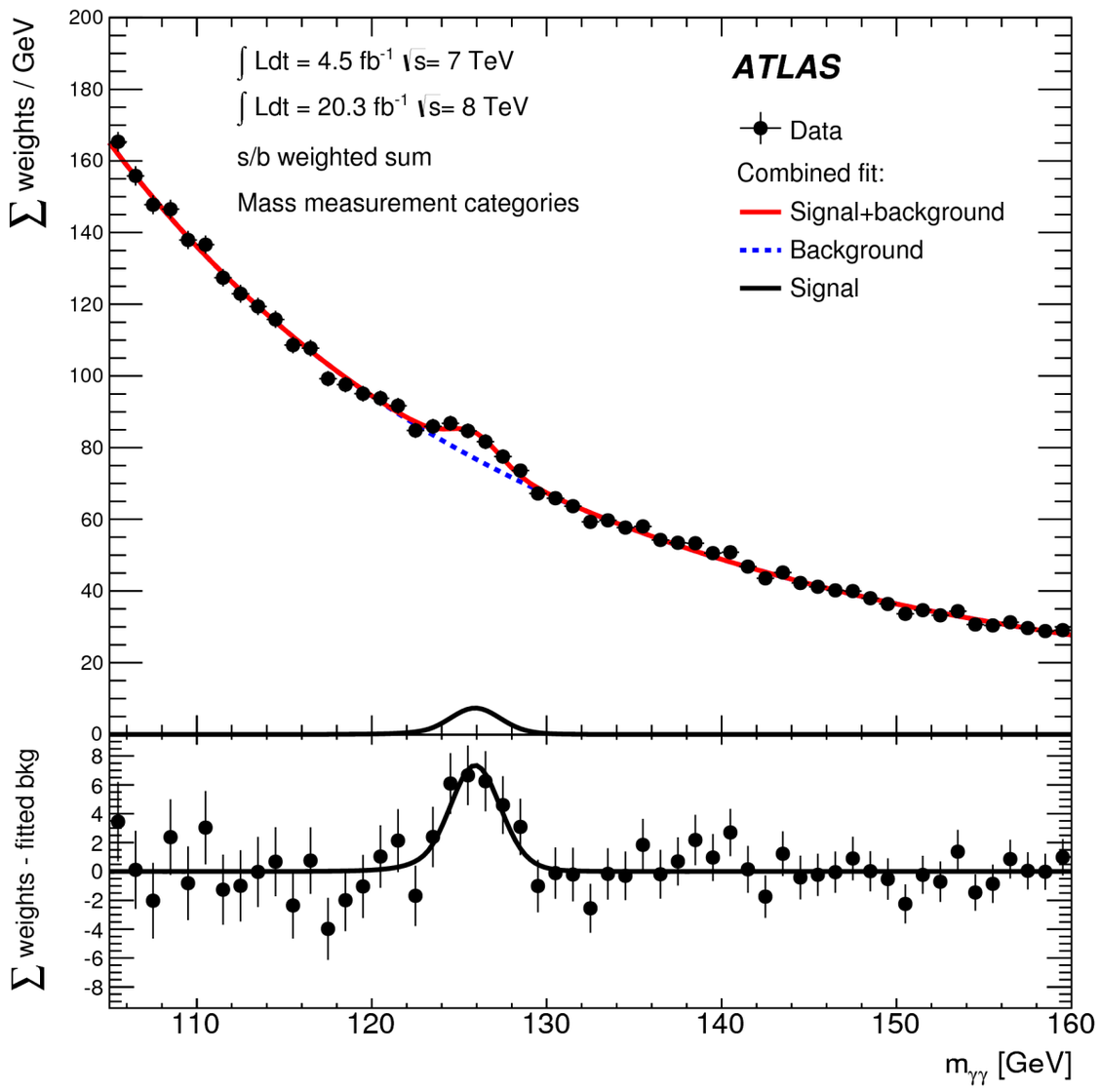
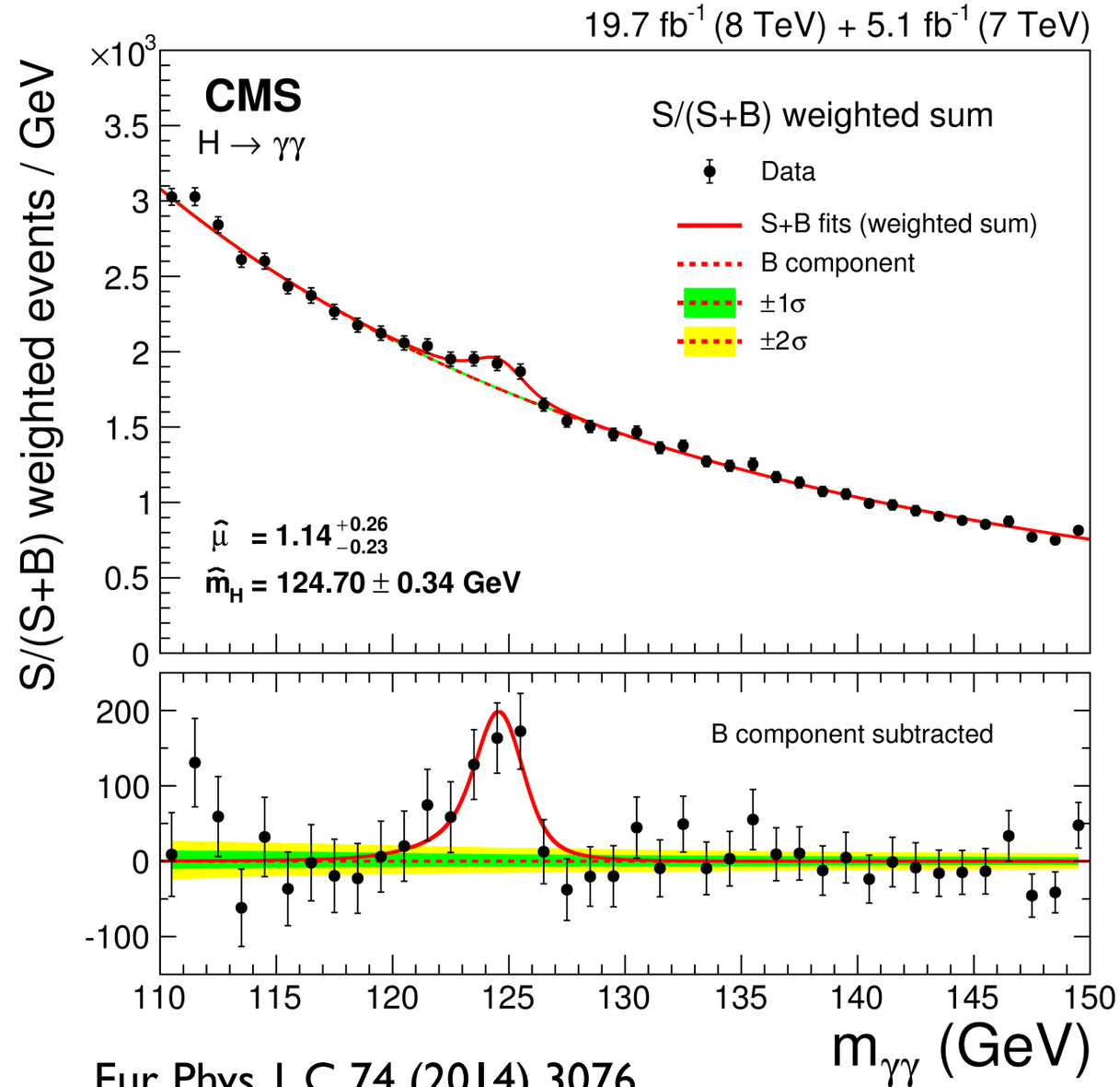
- The Higgs boson signal clearly visible on top of the continuous γγ background. Background can be extracted from a fit to the sidebands.
- Mass peak with events weighted according to their expected S and B:



Phys. Rev. D. 90, 052004 (2014)



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The Higgs Boson Mass

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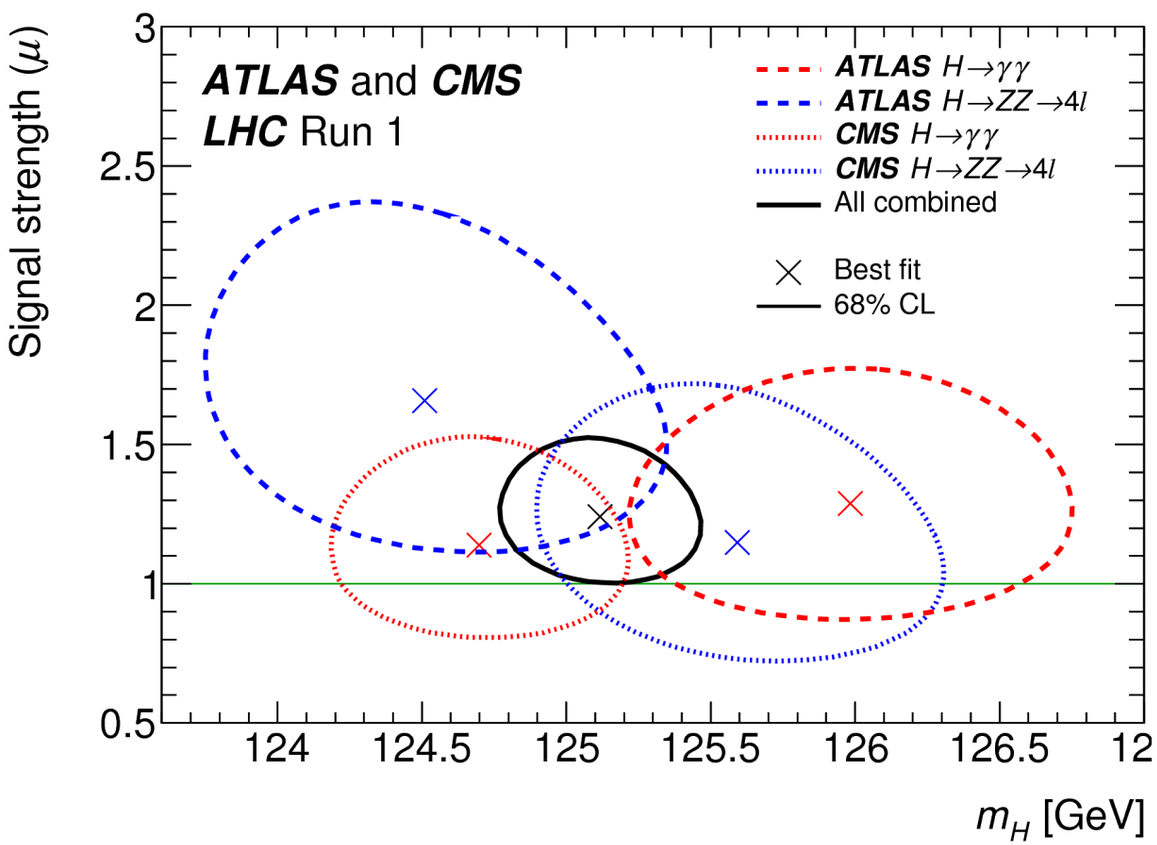
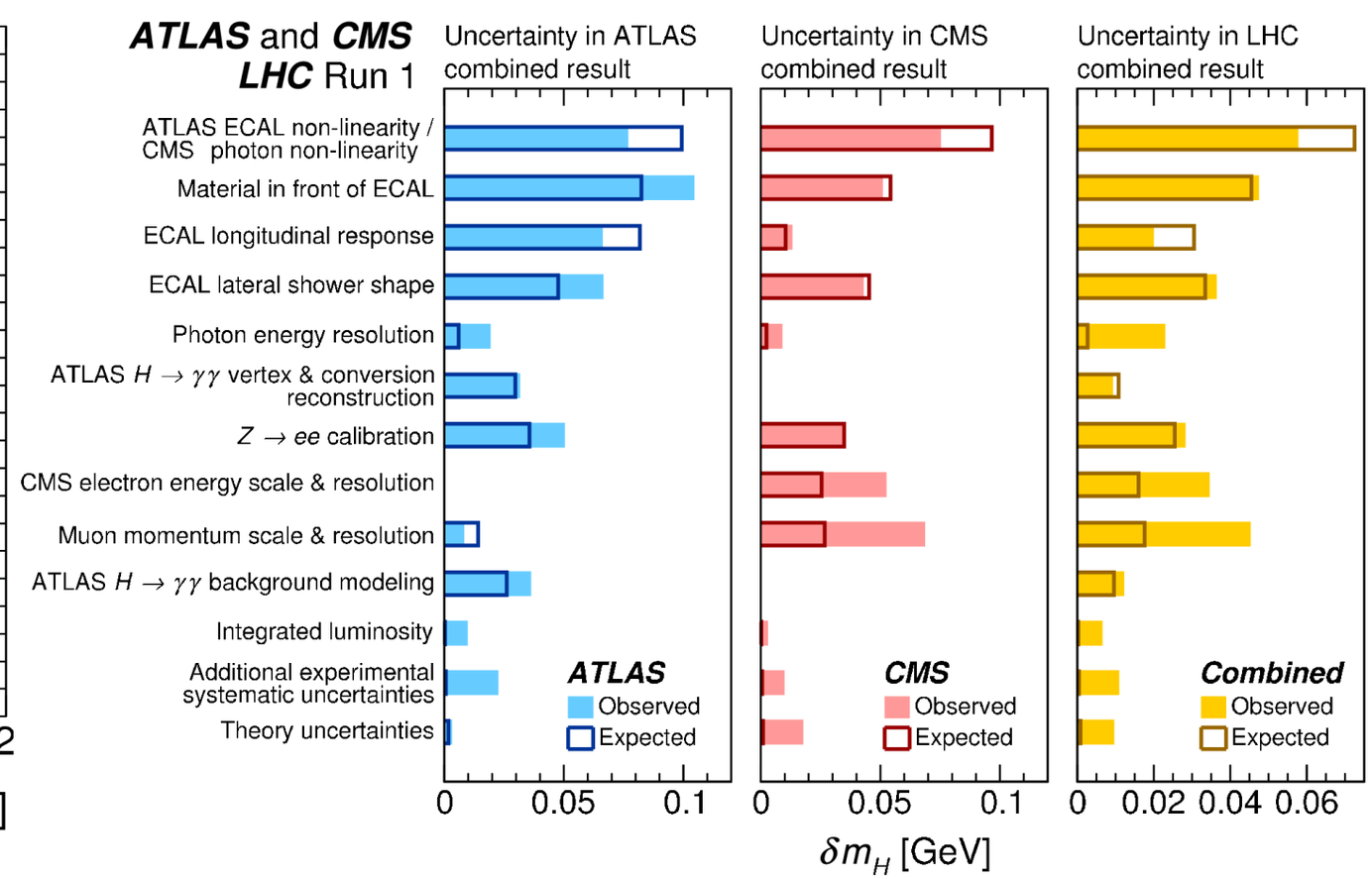
- The Higgs boson mass is estimated from a combination of the four results in the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels for ATLAS and CMS.
  - The four measurements compatible with a p-value of 10%.
- The total systematic uncertainty on the combined Higgs boson mass is dominated by the contribution from the photon energy scale.





Phys. Rev. Lett. 114, 191803

The Higgs Boson Mass

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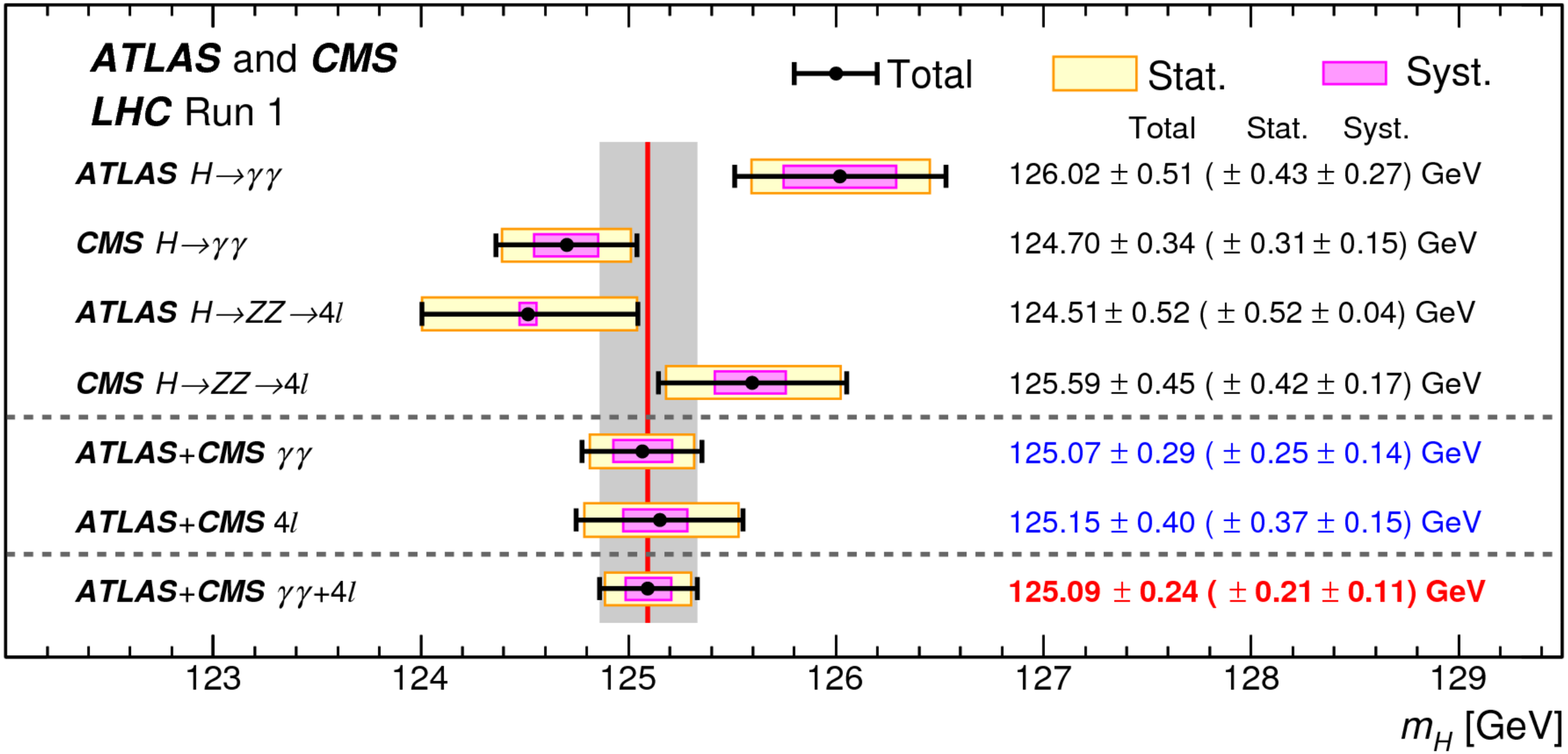

- Combined ATLAS and CMS best estimate of the Higgs boson mass: m_H = 125.09 ± 0.24 GeV (uncertainty dominated by statistical component).

Phys. Rev. Lett. 114, 191803

Run 2 H→ZZ and H→γγ (CMS)

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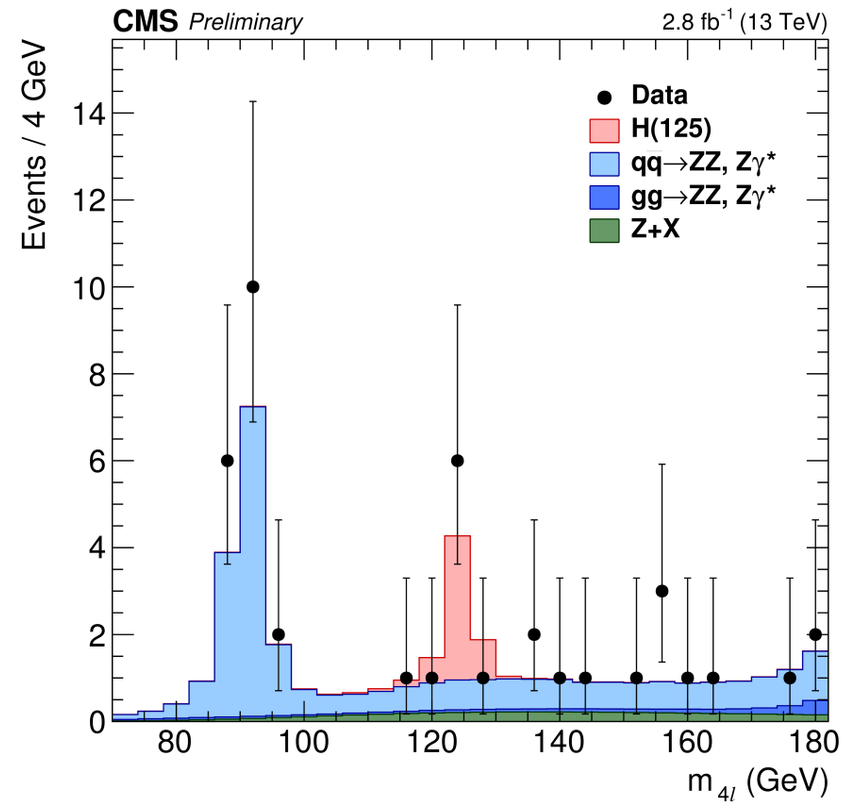
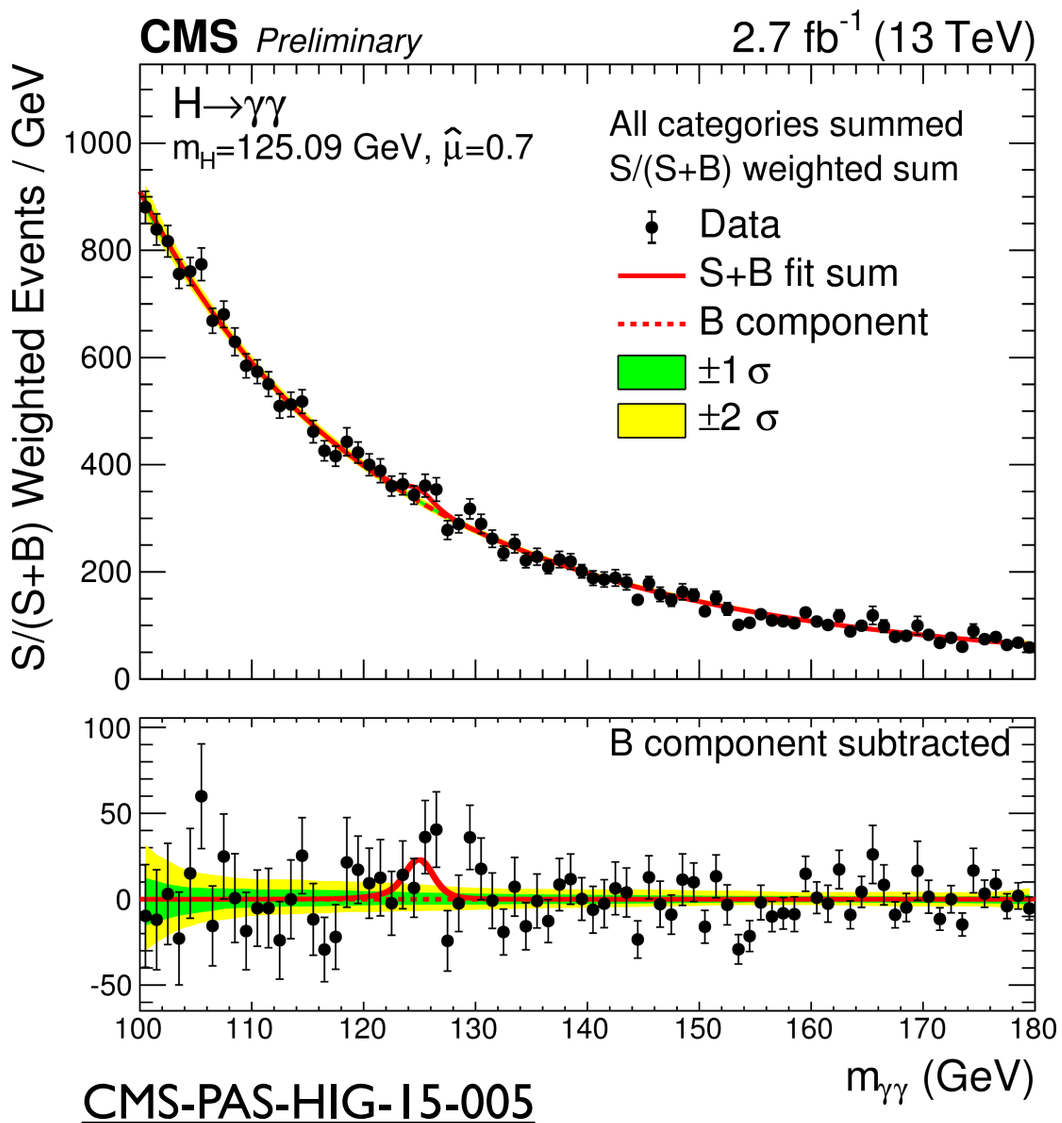
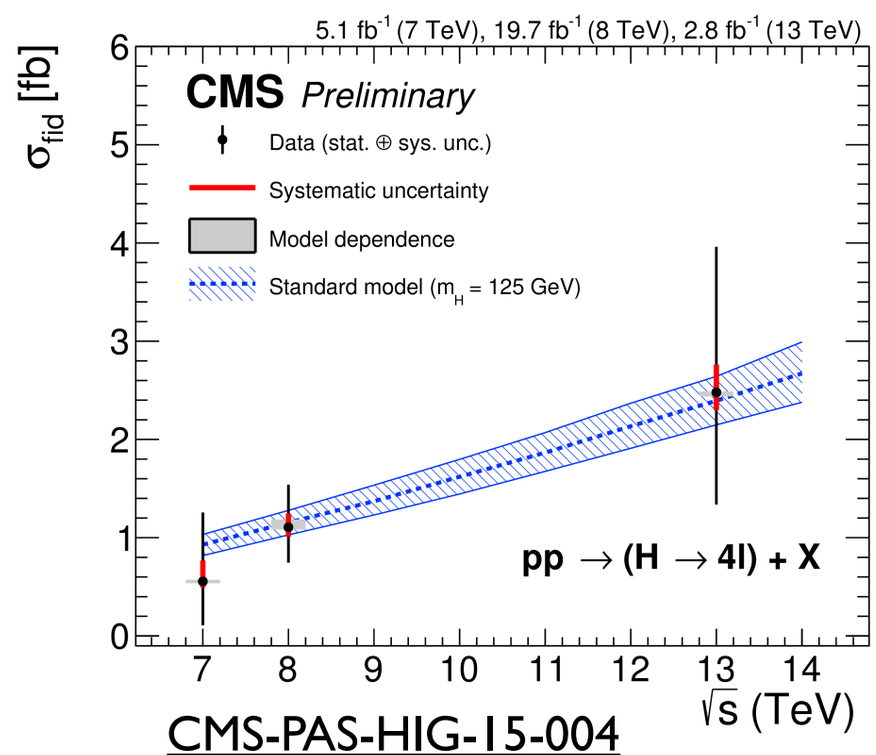
- Limited luminosity in 2015 compared to Run 1 means that the results for the traditional Higgs channels are still significantly less sensitive in Run 2.





CMS-PAS-HIG-15-005



CMS-PAS-HIG-15-004

Run 2 H→ZZ and H→γγ (ATLAS)

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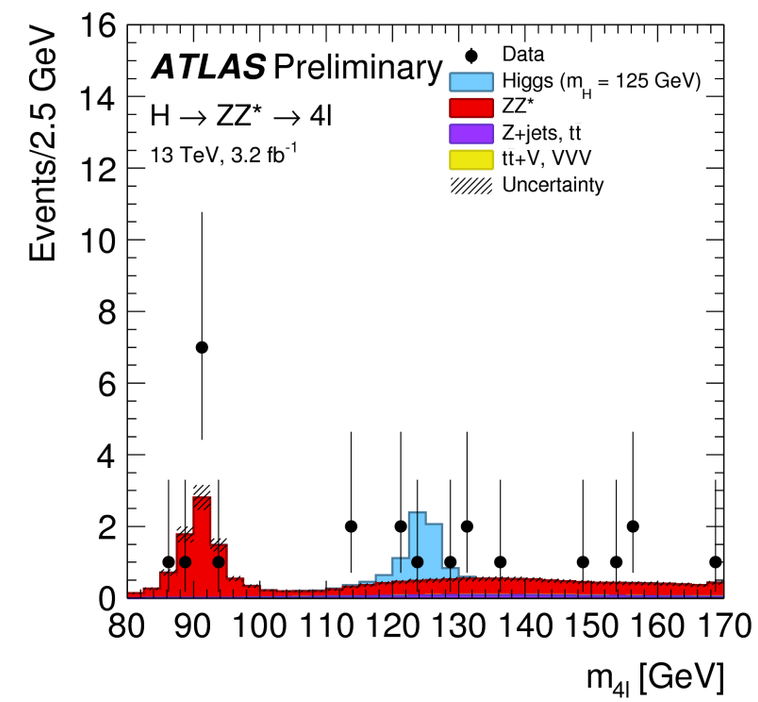
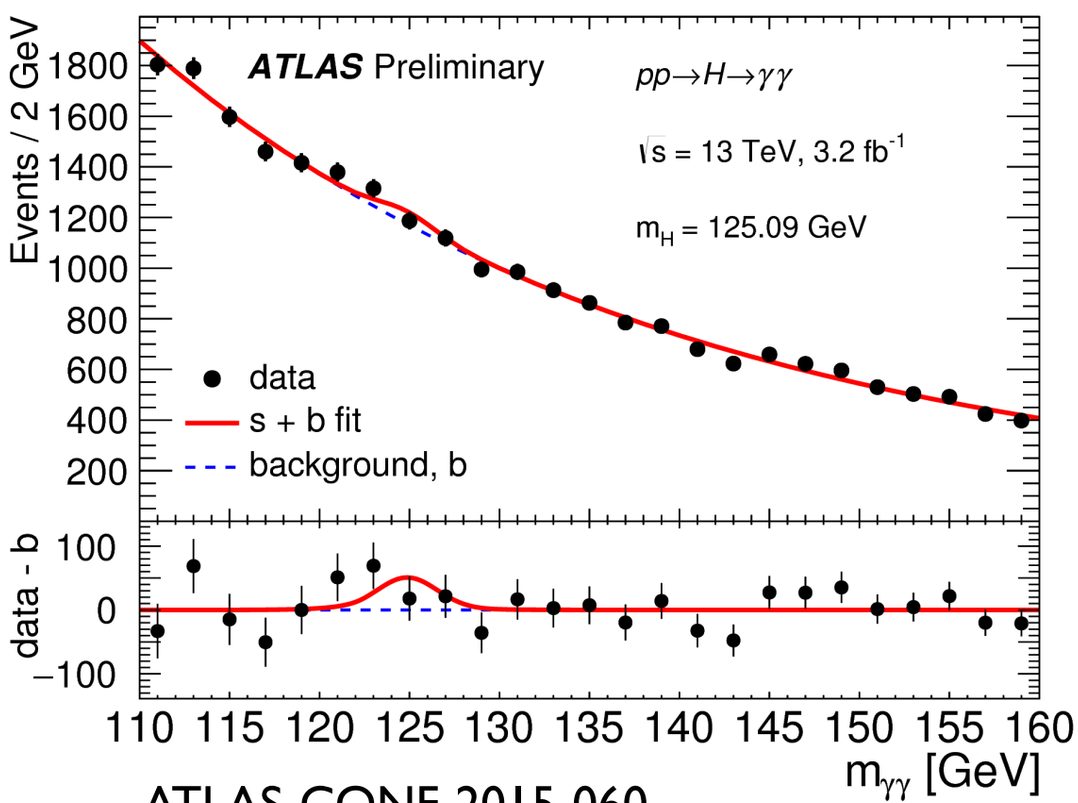
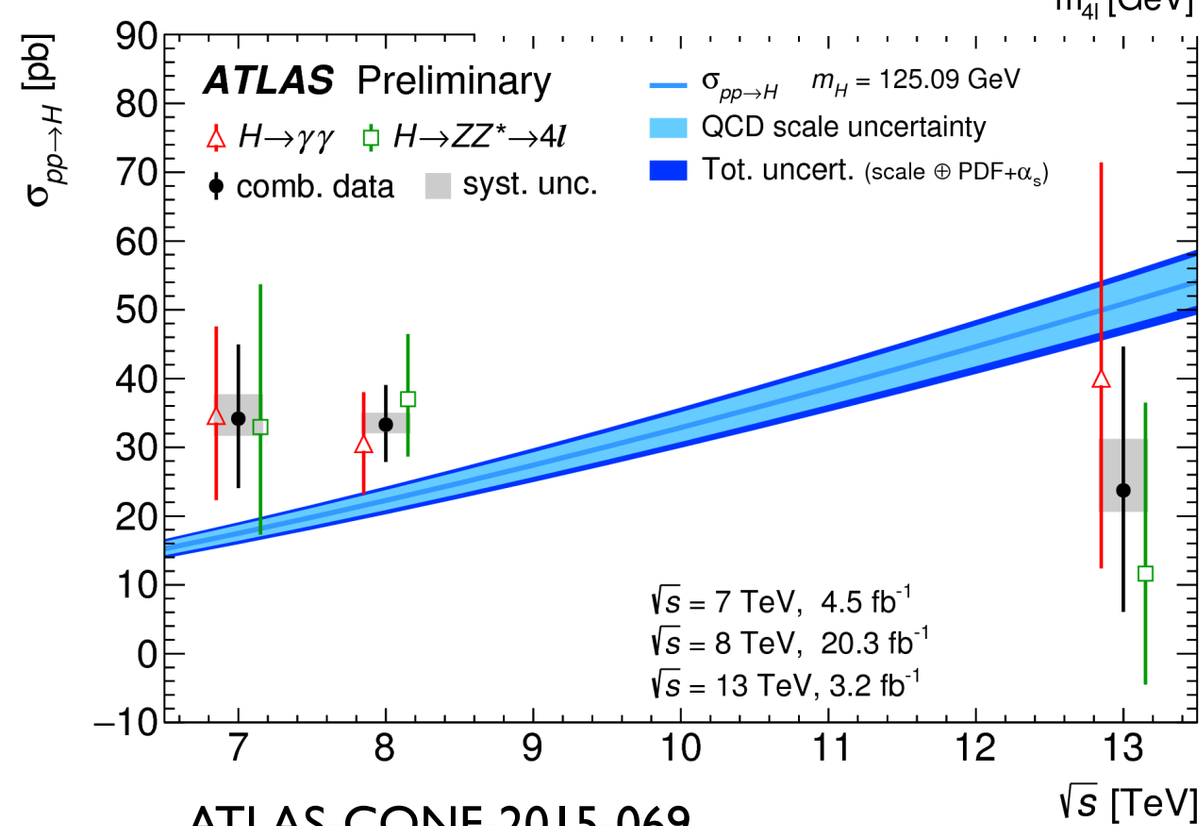
- ATLAS seeing a downward fluctuation in the yield in the signal region for both the H→ZZ*→4ℓ and the H→γγ channels.
  - In Run 1 there was instead a slight excess compared to SM expectations in both channels.
  - The H→γγ channel still to make use of the full event categorisation in Run 2.





ATLAS-CONF-2015-060



ATLAS-CONF-2015-069

The H→WW*→$\ell\nu\ell\nu$ Channel in Run I

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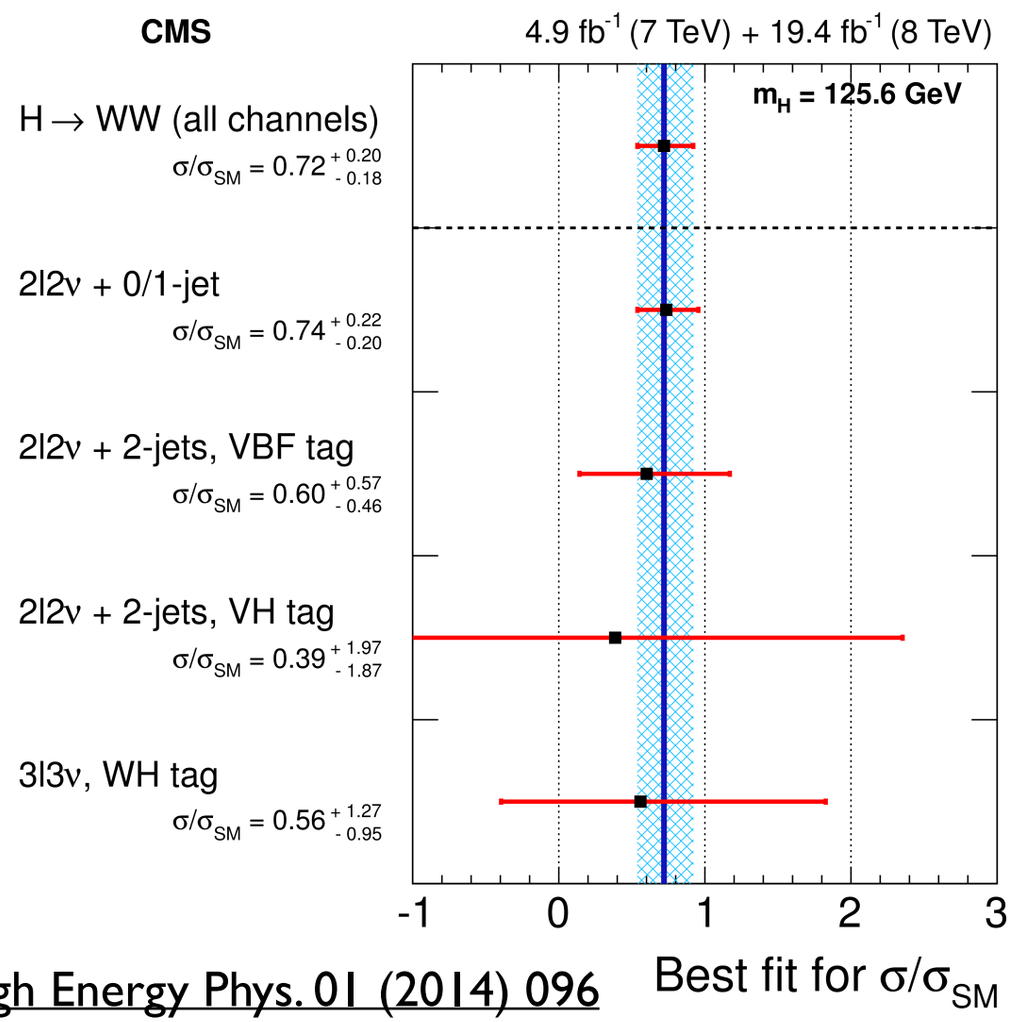
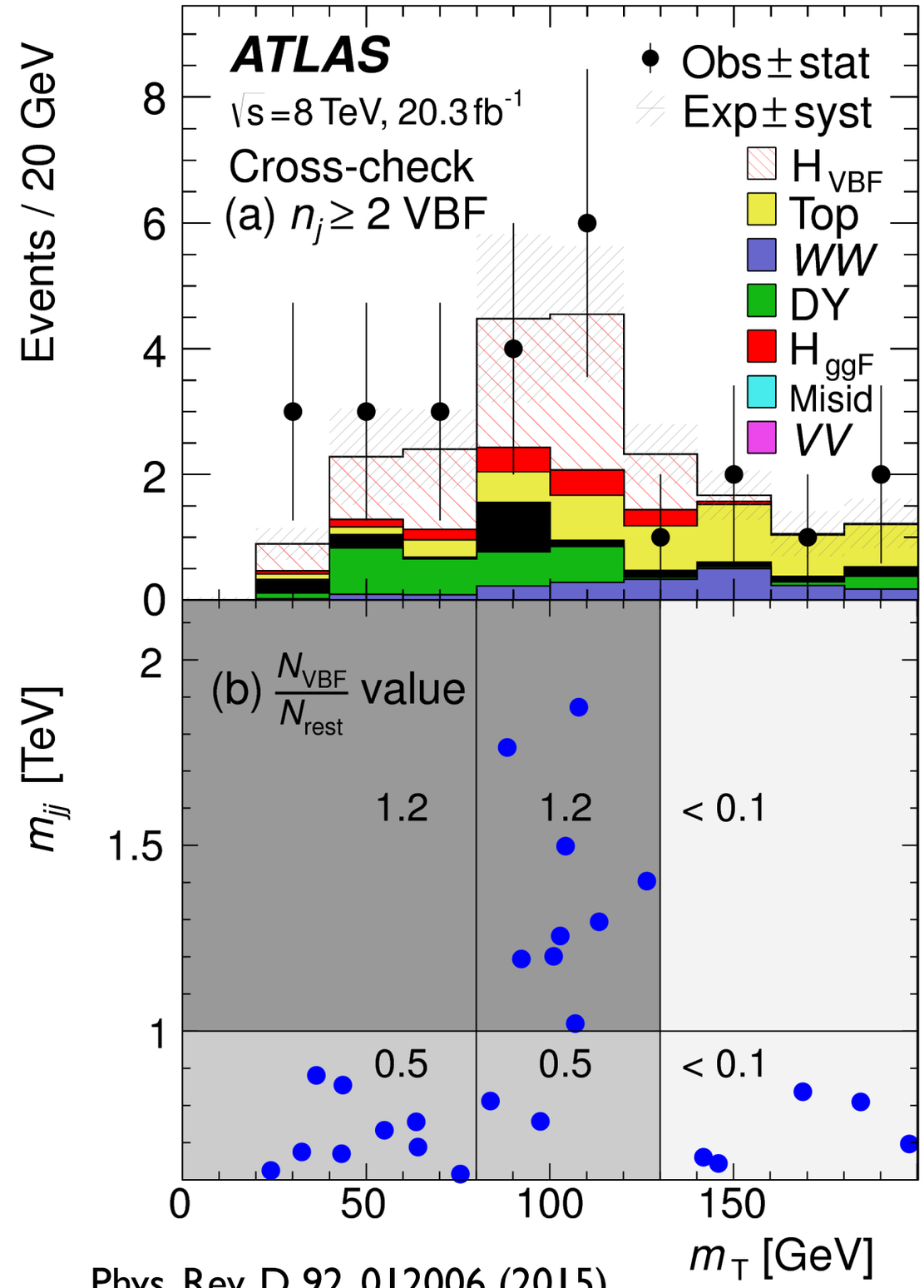
- Look for pair of leptons and high E_T^{miss}.
  - To cope with ttbar background, divide analysis according to jet multiplicity.
- High BR, good S/B, poor mass resolution.
- Uncertainty dominated by theoretical knowledge of the WW background.



J. High Energy Phys. 01 (2014) 096



Phys. Rev. D 92, 012006 (2015)

The Higgs Boson Width

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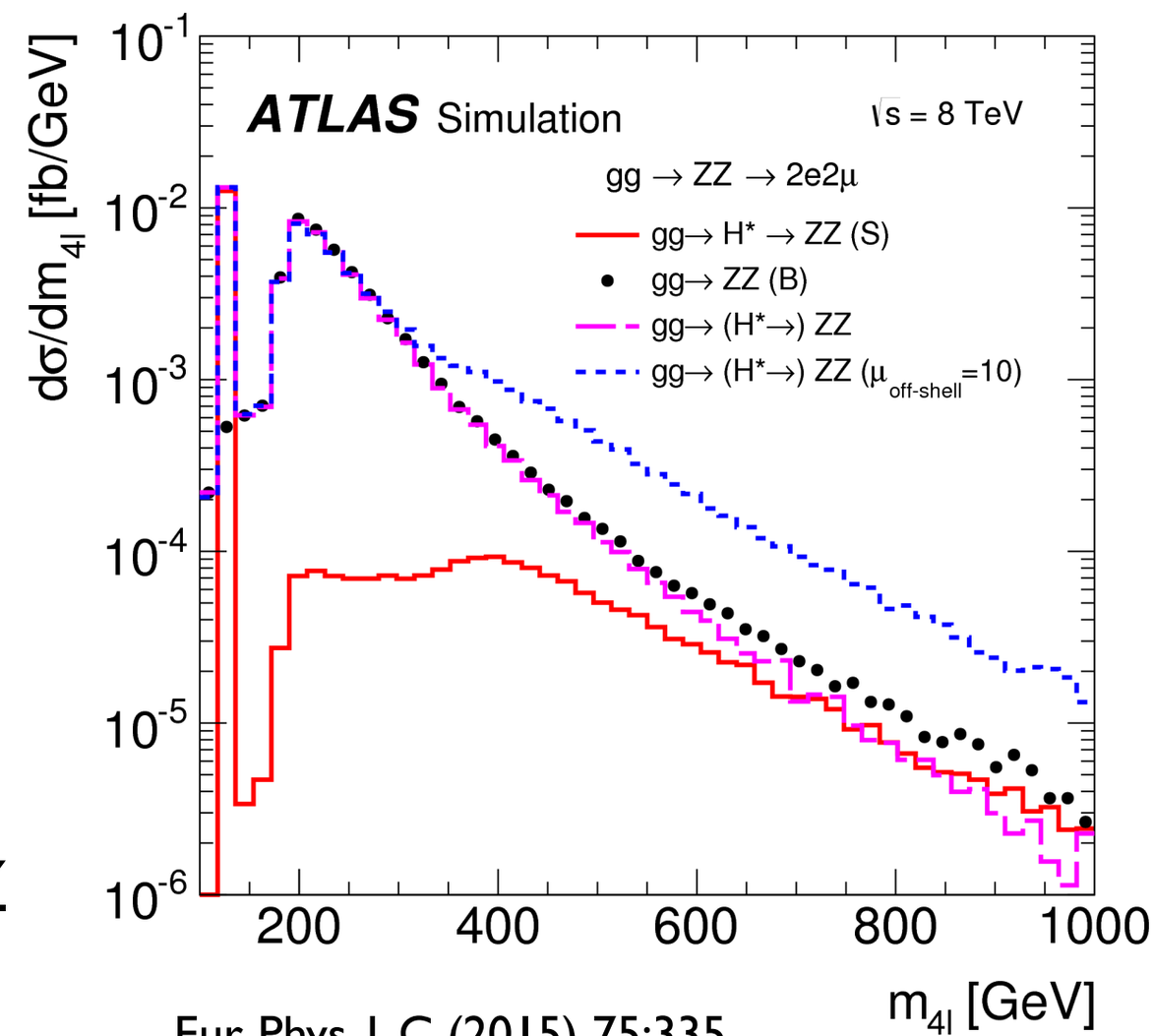
- In the standard model, $\Gamma_H \sim 4.1$ MeV (for $m_H = 125$ GeV).
  - Limited by the experimental resolution, ~1-2%.
  - Direct upper limit on $\Gamma_H < 1.7$ GeV (CMS). Eur. Phys. J. C 75 (2015) 212
- The high mass region (>$2m_V$, with V=W,Z) is sensitive to off-shell Higgs boson production and background interference effects.
- Limit on Γ_H under the assumptions:
  - $q \sim m_H$ (on shell) → $\sigma \sim$ (couplings)/Γ_H
  - $q >> m_H$ (off shell) → $\sigma \sim$ (couplings)
  - Ratio ~ Γ_H.
- Negative interference with gg→ZZ taken into account.
- Results derived using both the H→ZZ and the H→WW channels.



Eur. Phys. J. C (2015) 75:335

The Higgs Boson Width

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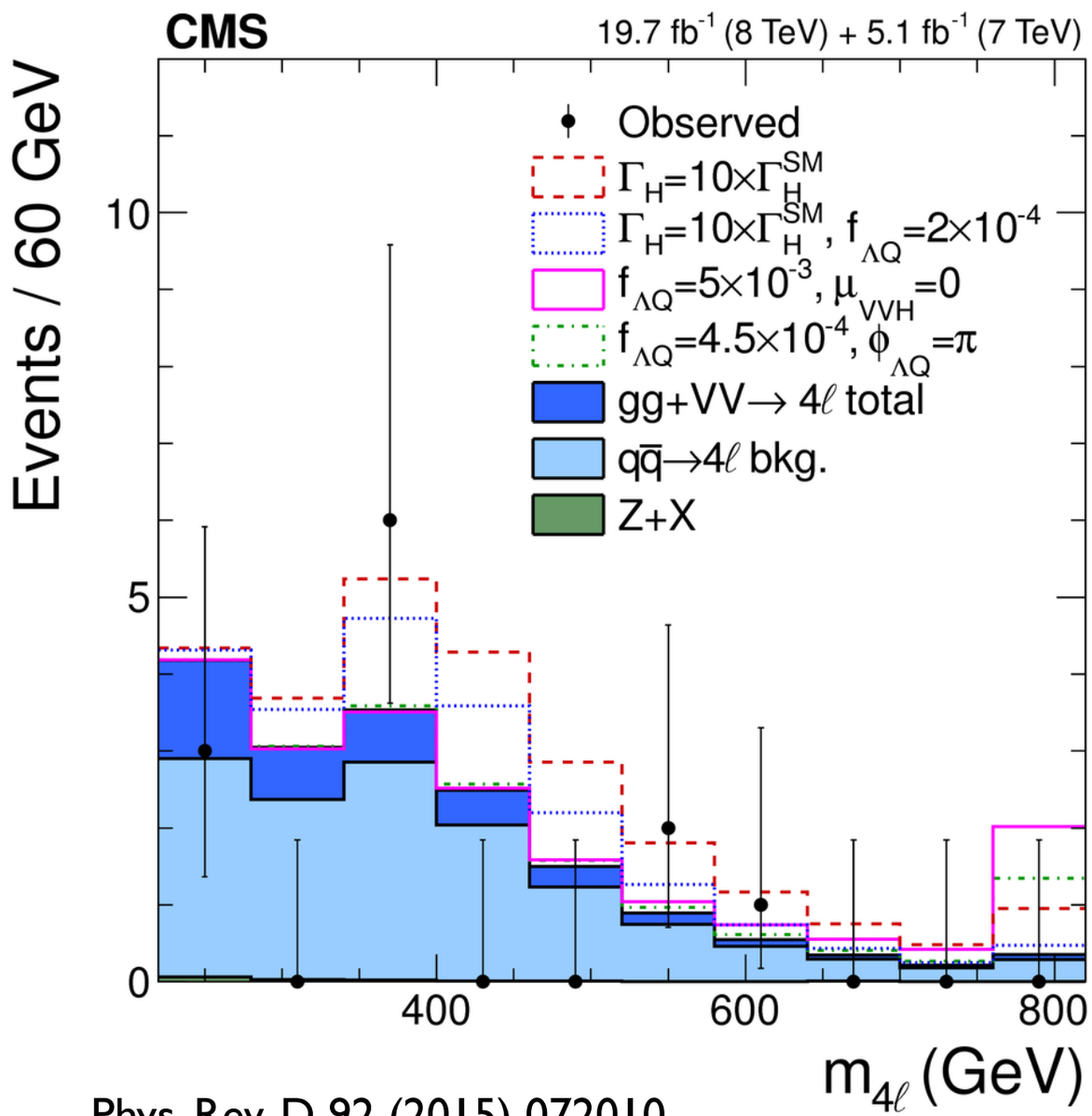
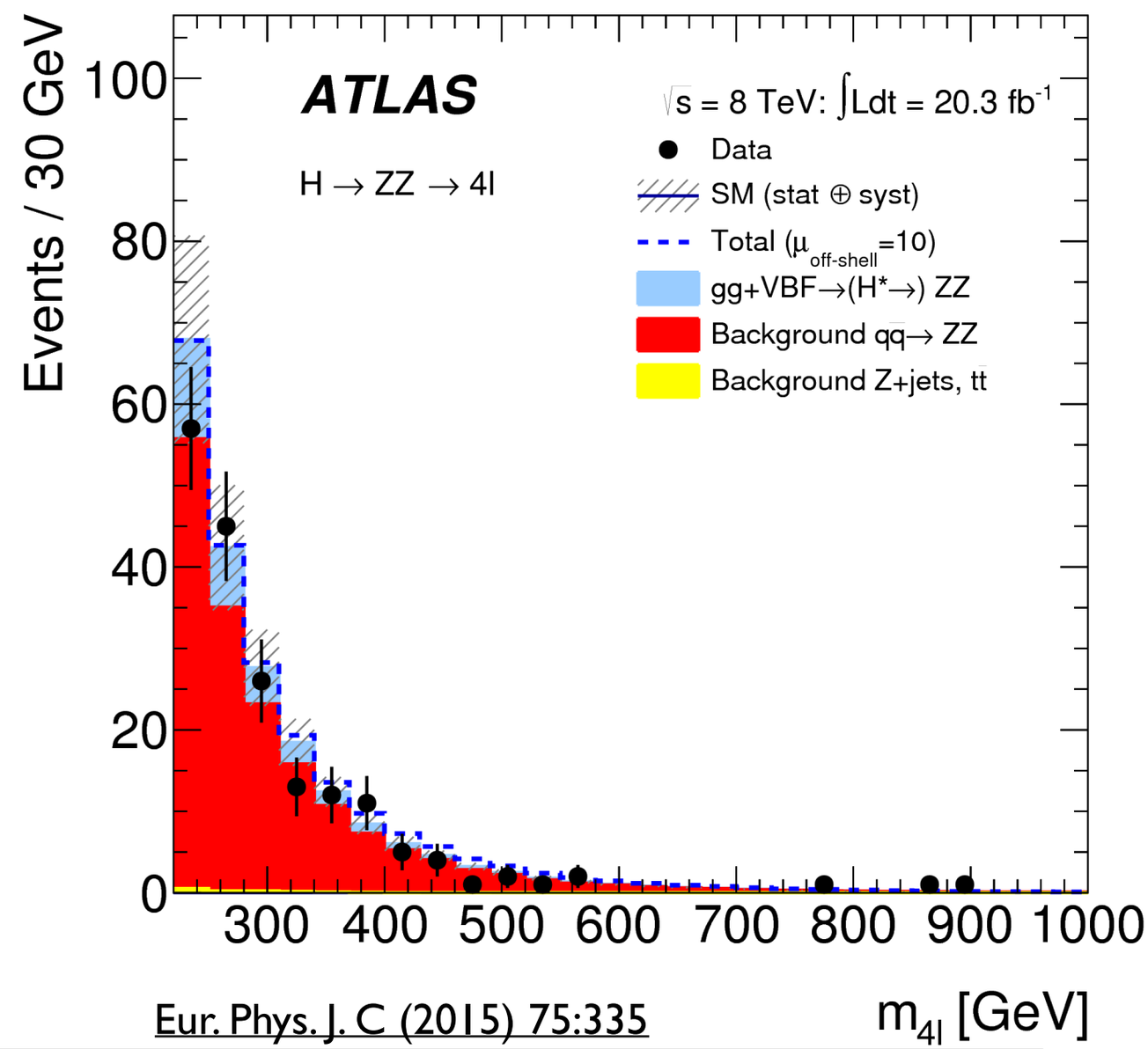
- Limits Γ_H < 22.7 MeV (ATLAS) and Γ_H < 26 MeV (CMS) derived assuming no change in couplings and no new physics at high mass.
  - Analyses can eventually probe off-shell couplings as a function of 4ℓ mass.

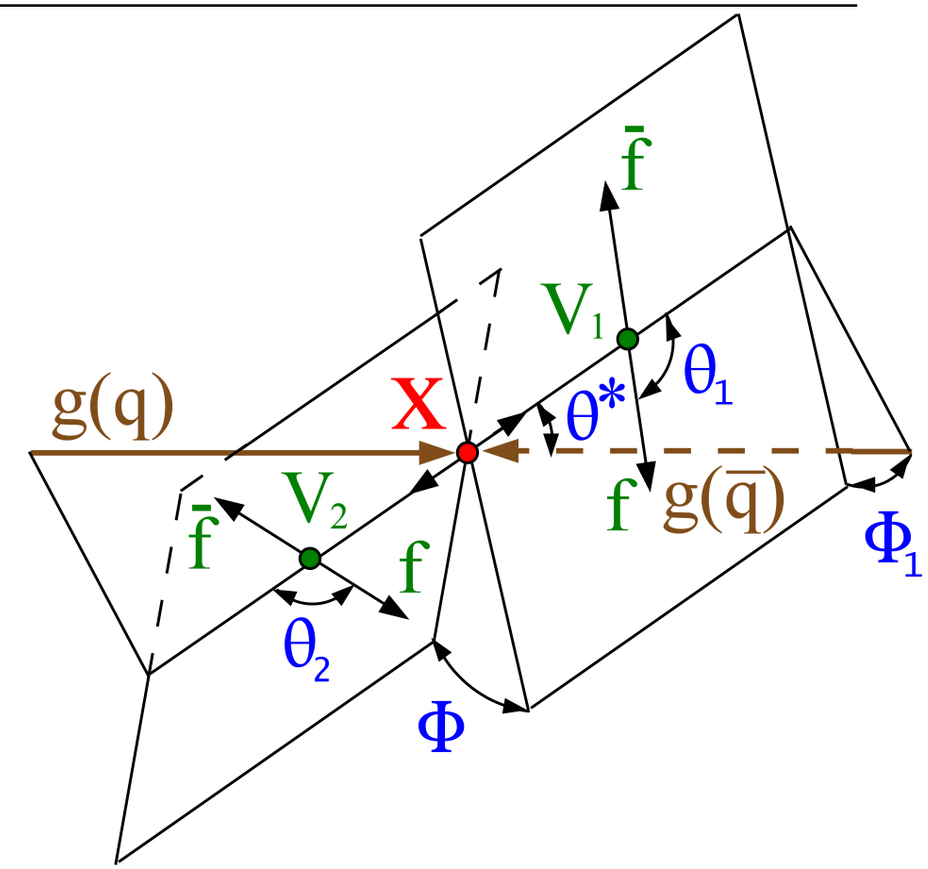


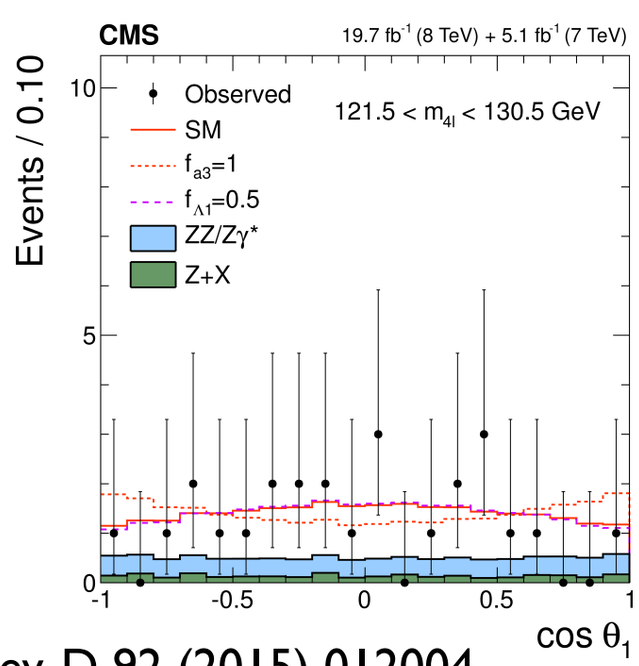
Phys. Rev. D 92 (2015) 072010

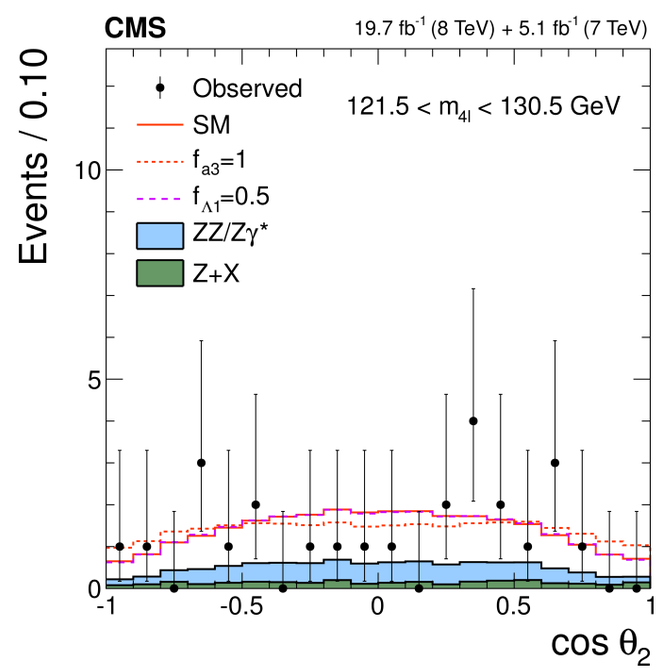


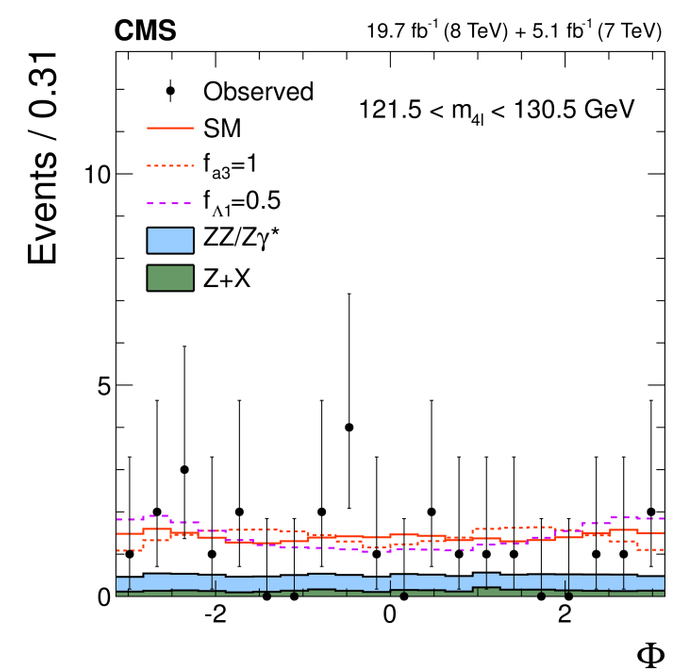
Eur. Phys. J. C (2015) 75:335

- Test various alternative spin-parity options against the SM hypothesis $J^P = 0^+$ using angular and kinematic distributions in Higgs decays to diboson final states.
  - $H \to \gamma\gamma$ (sensitivity to 2^+, excludes spin 1).
  - $H \to ZZ^* \to 4l$ (sensitivity to all spin/parity).
  - $H \to WW^* \to l\nu l\nu$ (sensitivity to spin 1 and 2).









Phys. Rev. D 92 (2015) 012004

The Spin of the Higgs Boson

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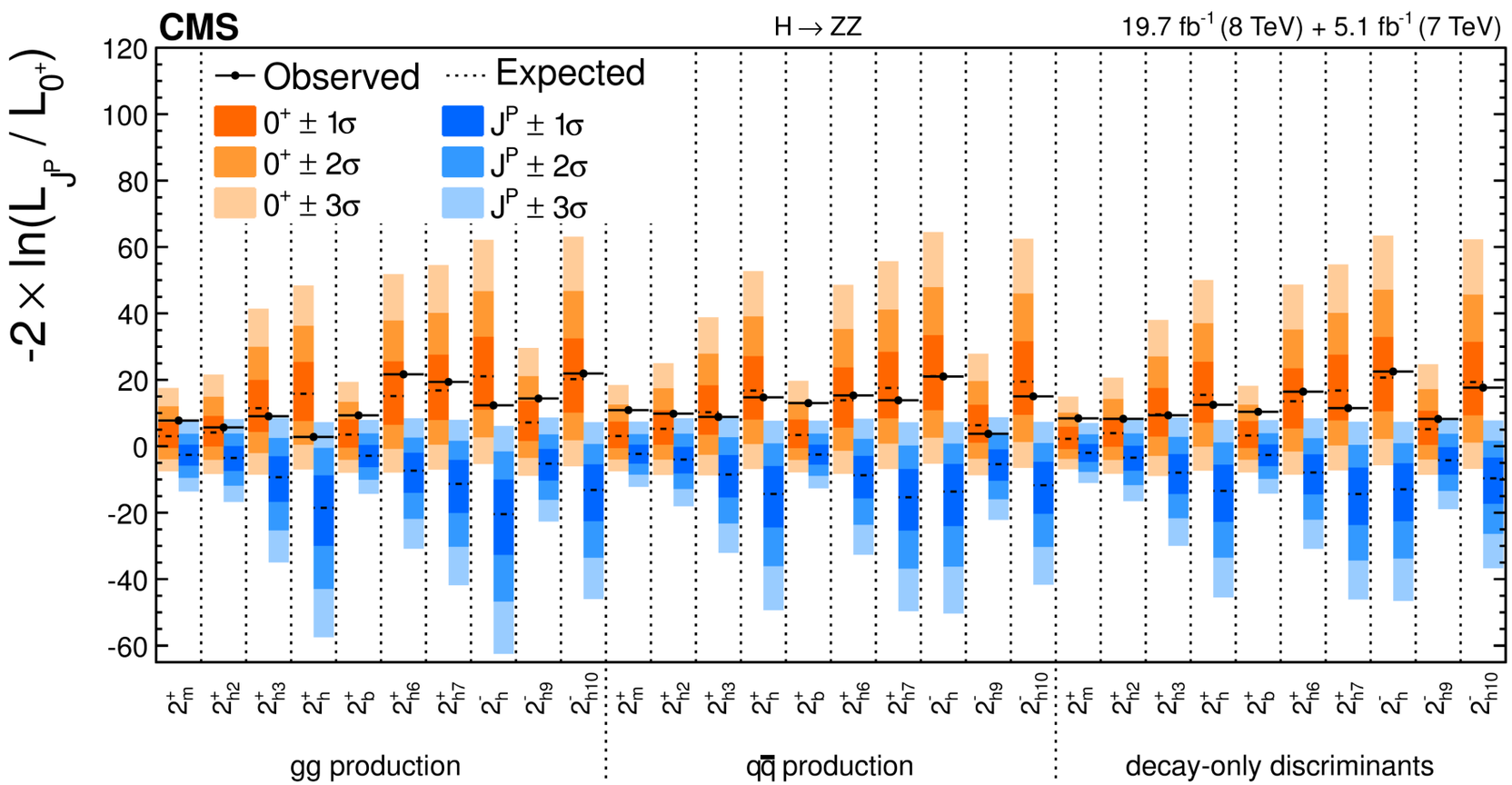
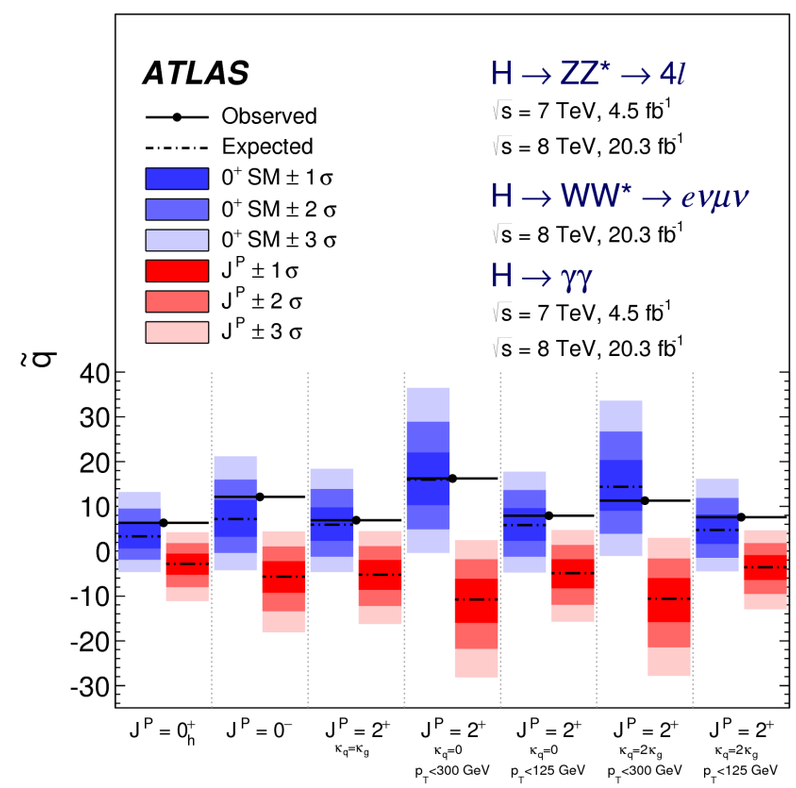
- All pure alternative spin-parity hypotheses are strongly disfavoured compared to the SM 0^+ scenario.
  - With the larger dataset foreseen in Run 2 expect to be sensitive to various mixing scenarios, e.g. with small anomalous J^P admixture.





Phys. Rev. D 92 (2015) 012004

Eur. Phys. J. C75 (2015) 476

Differential Cross Sections

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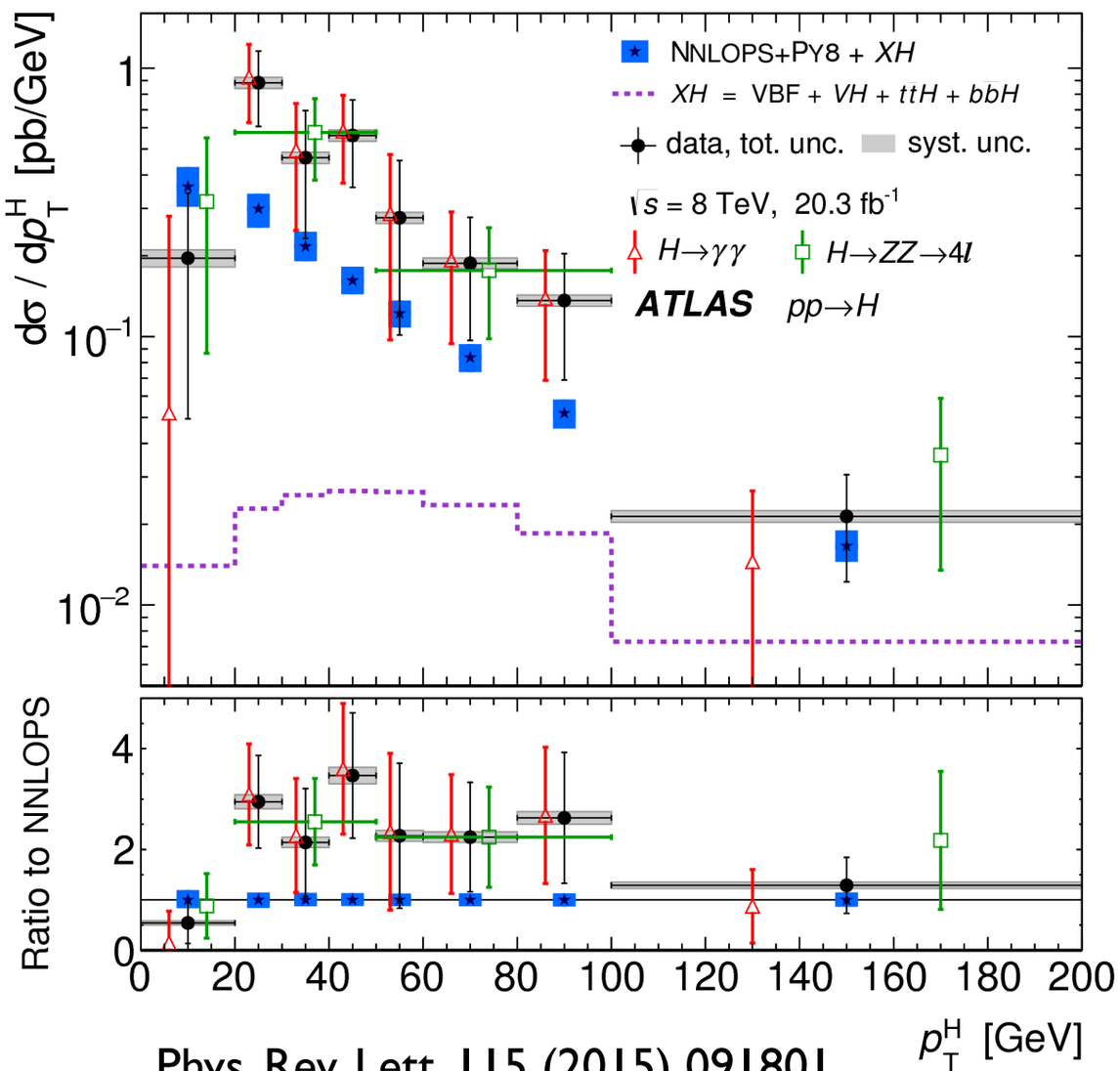
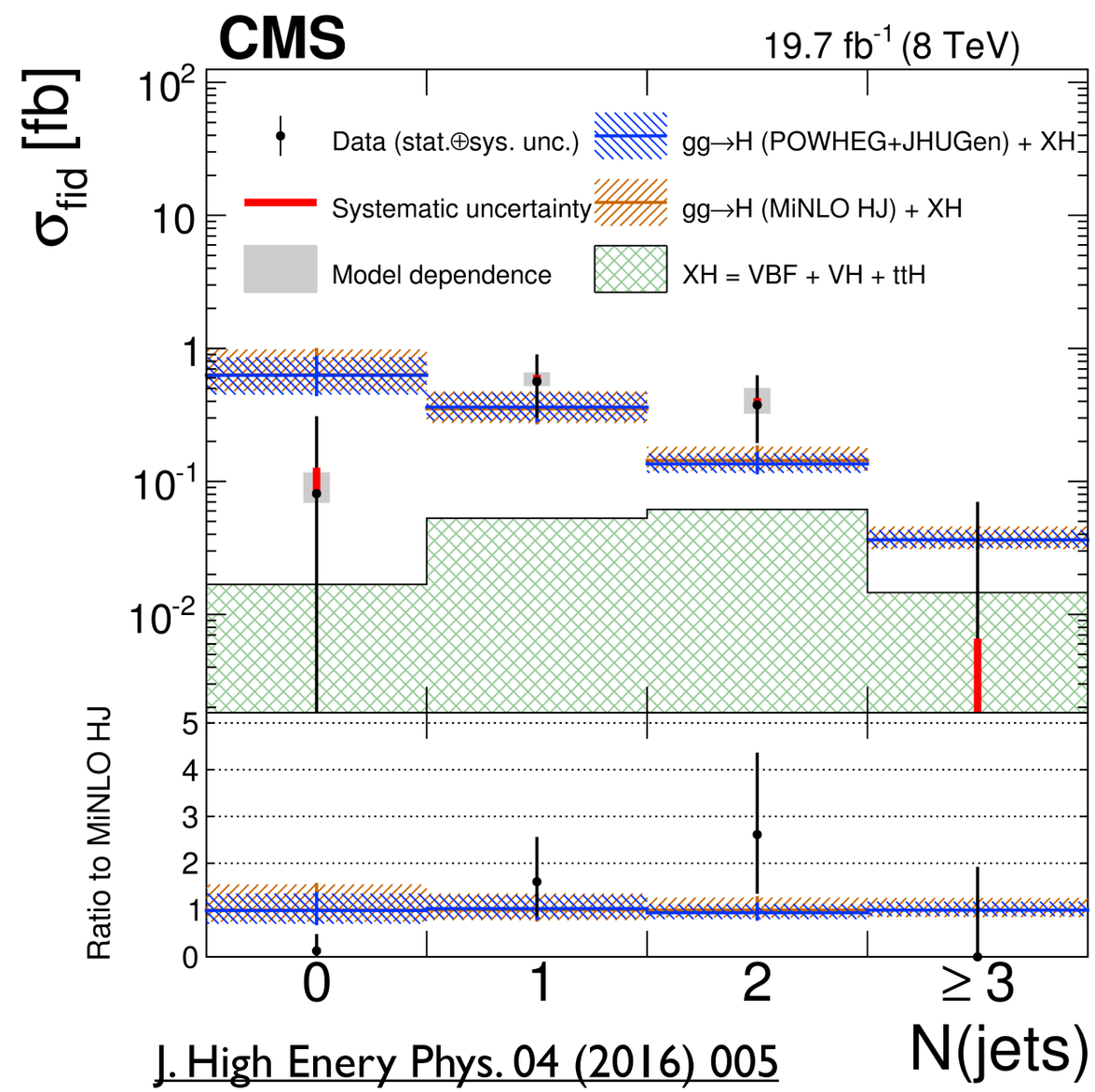
- Differential cross-sections for quantities like $p_T(H)$, $|y_H|$ and jet multiplicity, unfolded to the particle level, have also been measured.
  - Statistical uncertainties (23%-75%) still dominate all the differential measurements.



Phys. Rev. Lett. 115 (2015) 091801



J. High Enery Phys. 04 (2016) 005

Differential Cross Sections in H→WW

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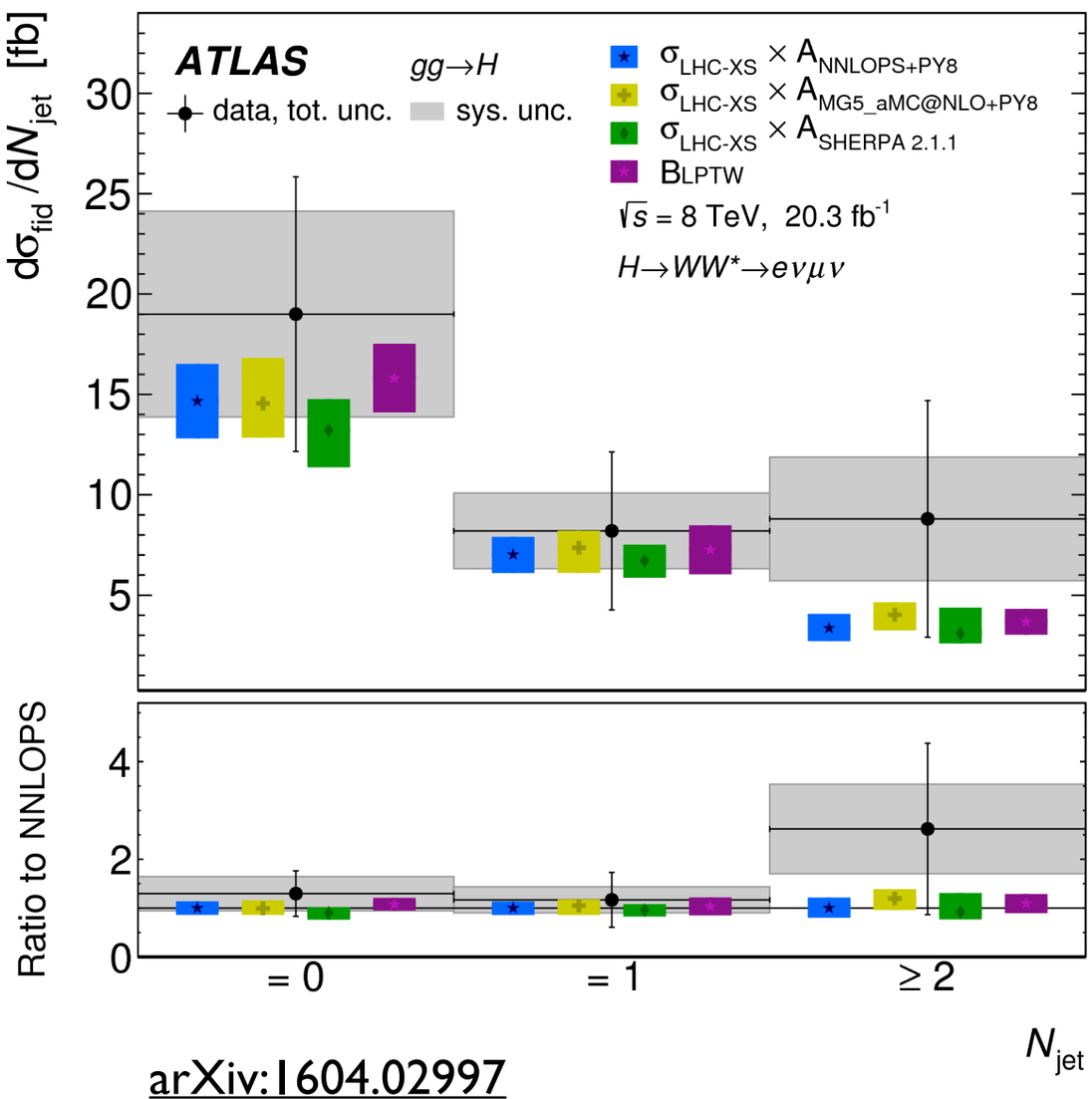
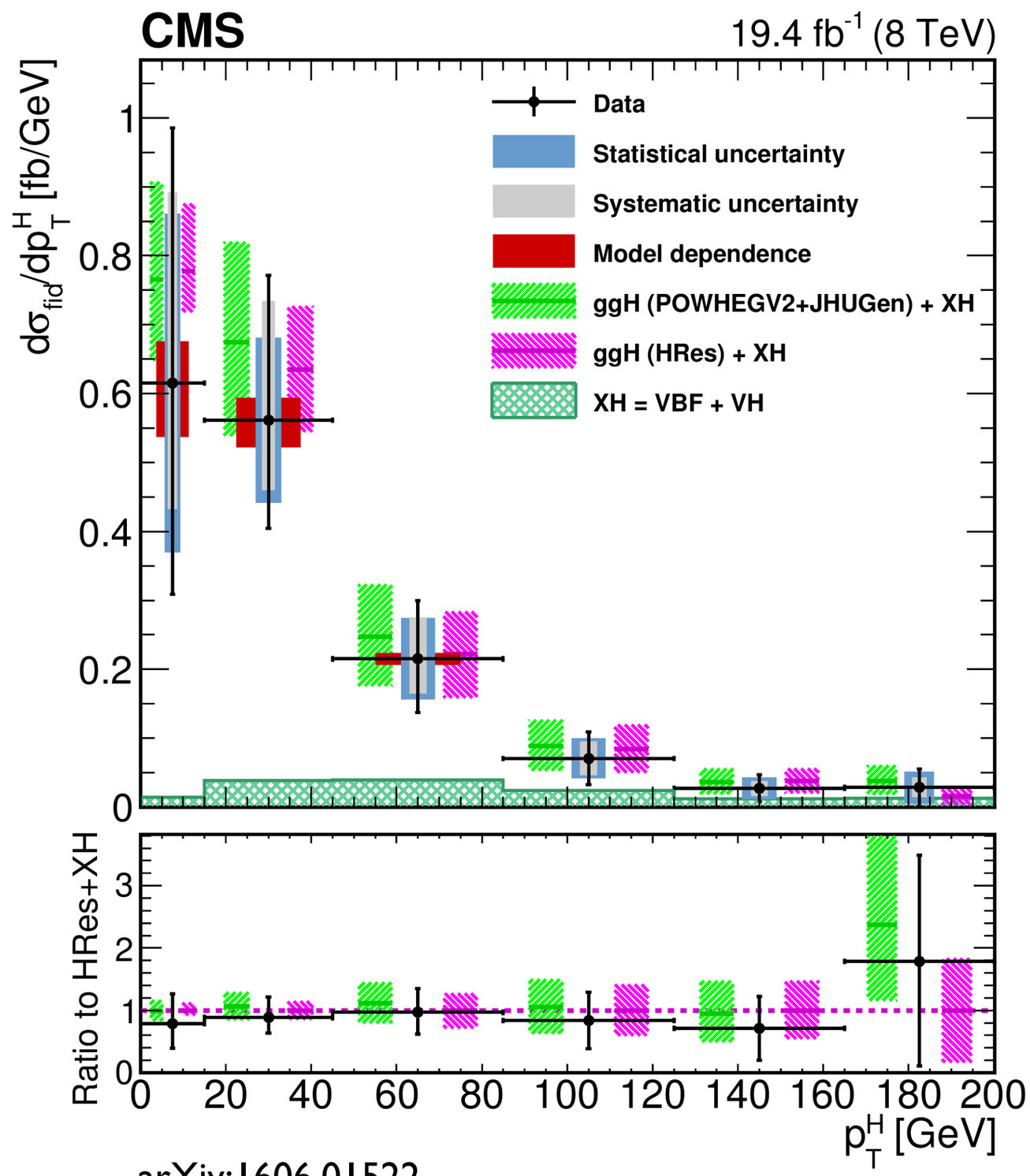
- ATLAS and CMS recently released the first differential measurements in the H→WW channel.



arXiv:1604.02997



arXiv:1606.01522

The H→ττ Channel in Run I

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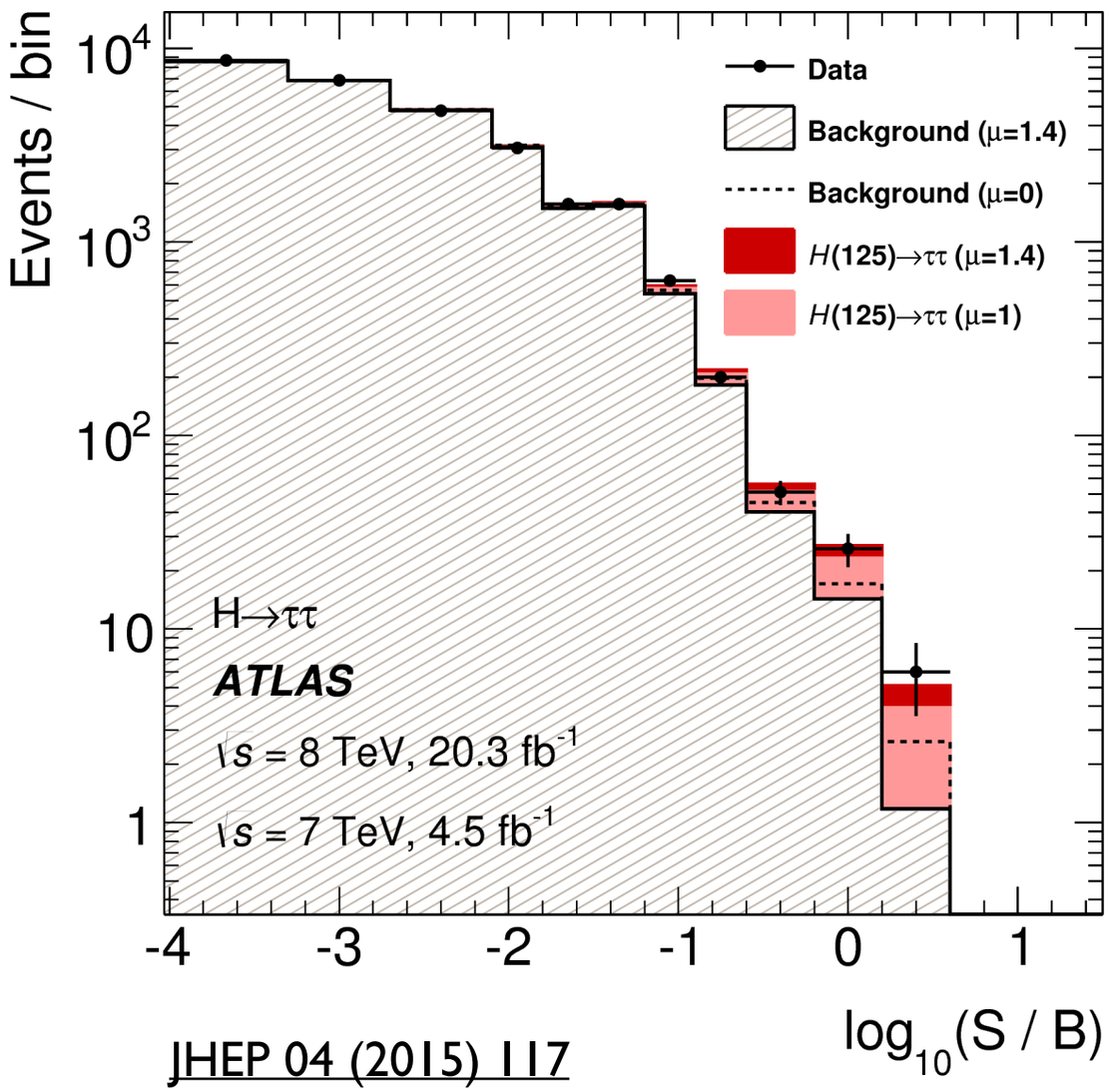
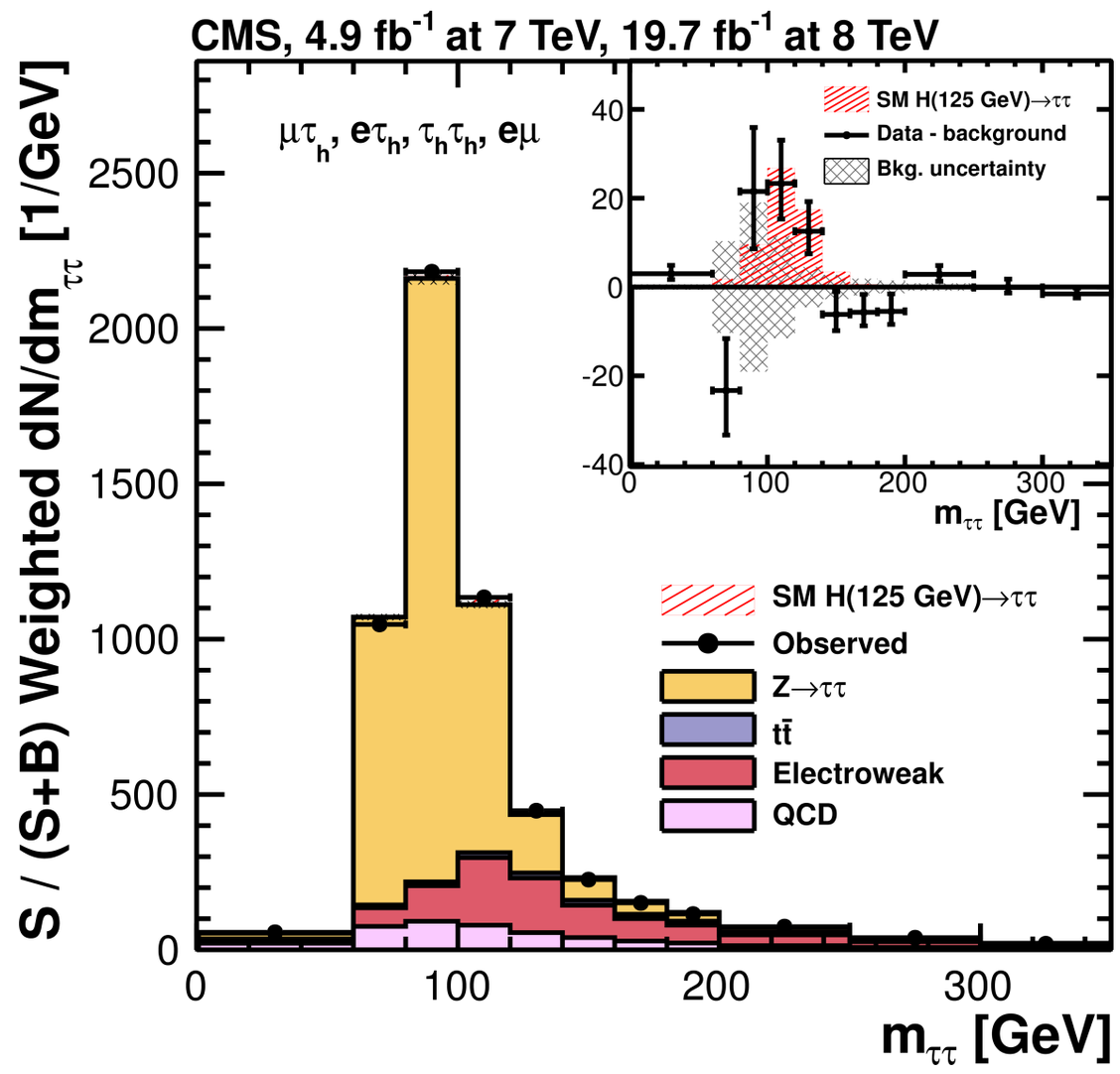
- The most sensitive of the fermionic Higgs boson decay modes.
  - Events classified in categories depending on decays of the two τ leptons.
- Analysis also binned in jet multiplicity and the p_T of the leptons.



JHEP 04 (2015) 117



J. High Energy Phys. 05 (2014) 104

ttH(→bb) Production in Run I

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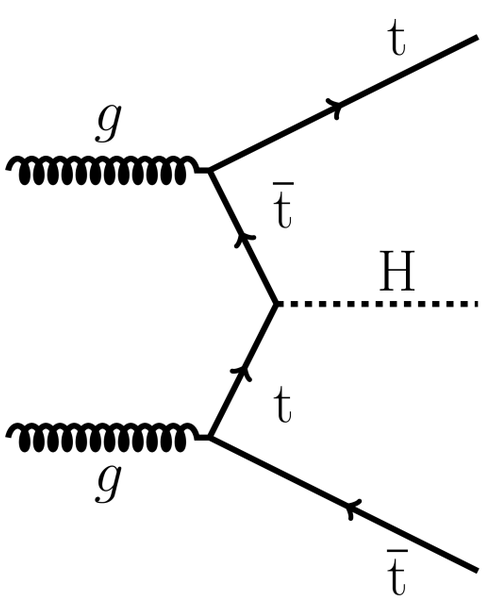
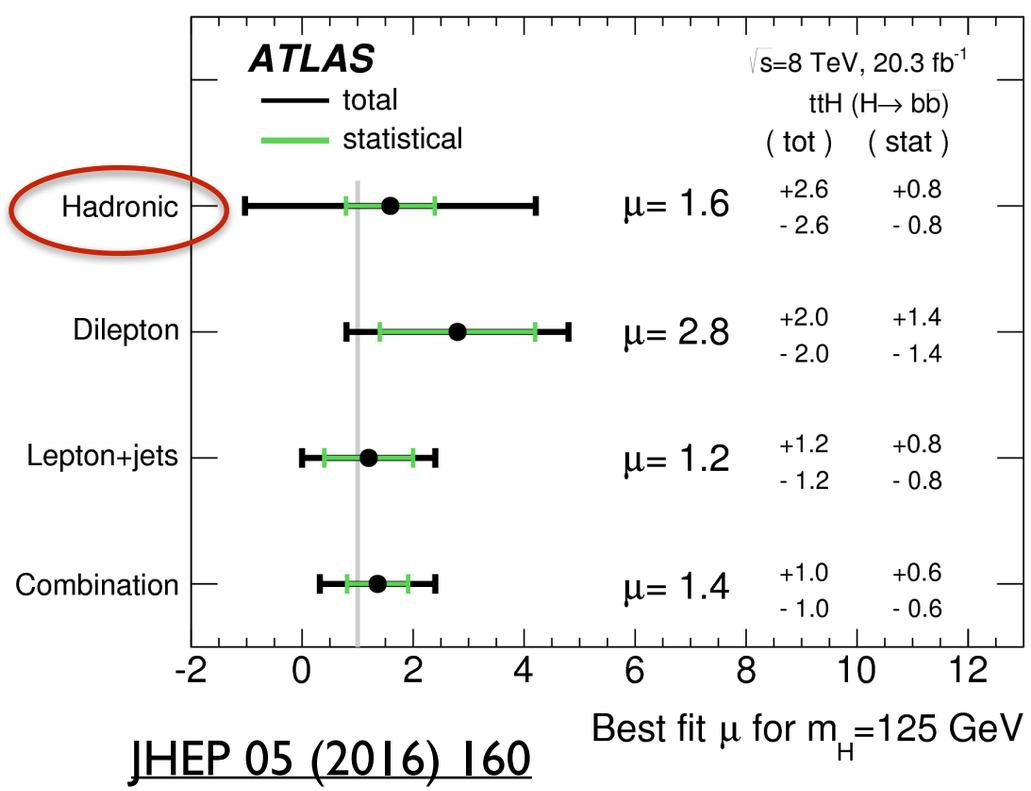
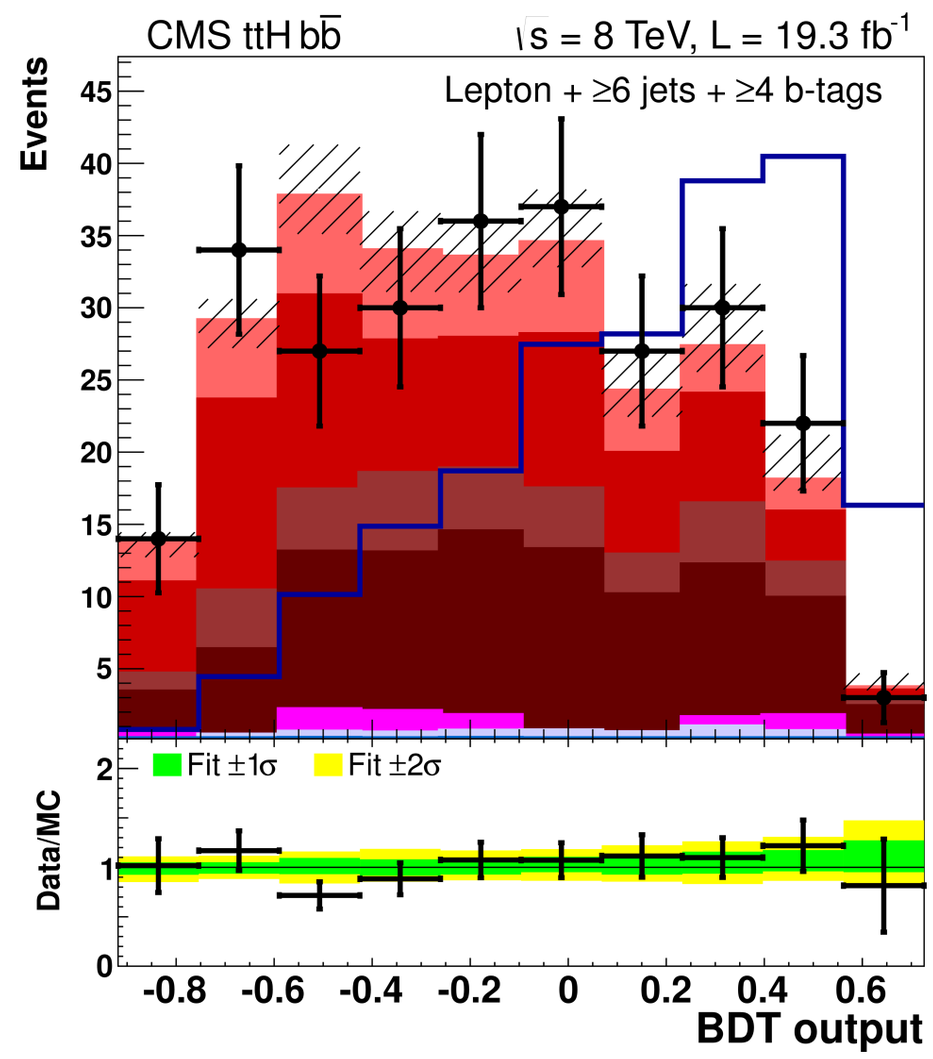
- The ttH production mode is important to directly probe the coupling between the Higgs boson and the top quark.
  - Crucial for probing for new particles contributing to the loops in the Higgs boson production or decay.
- Very rich experimental signature, depending on the decay of the top quarks and the Higgs boson.
  - Critical to model the ttbar background, in regions of phase-space that are not simple.





JHEP 05 (2016) 160



J. High Energy Phys. 09 (2014) 087

ttH(→multilepton) Production in Run 1

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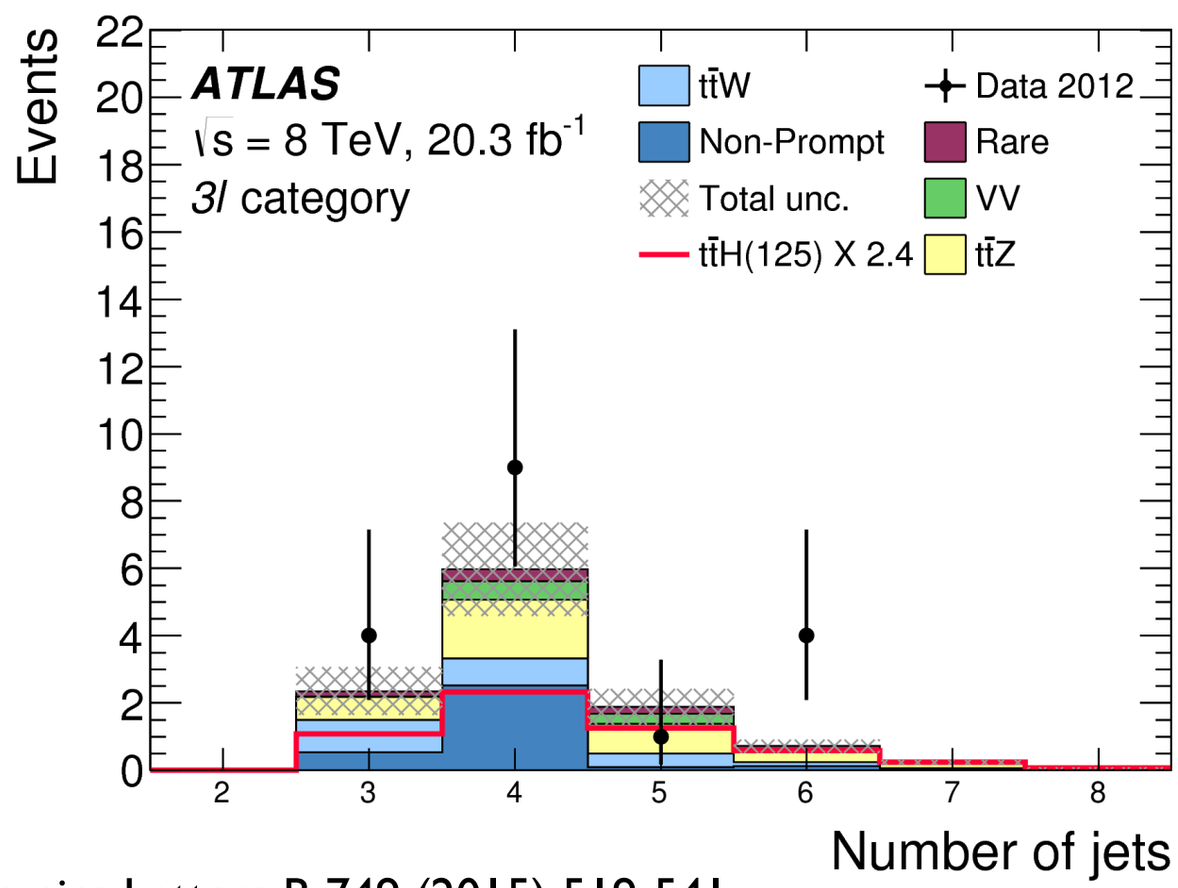
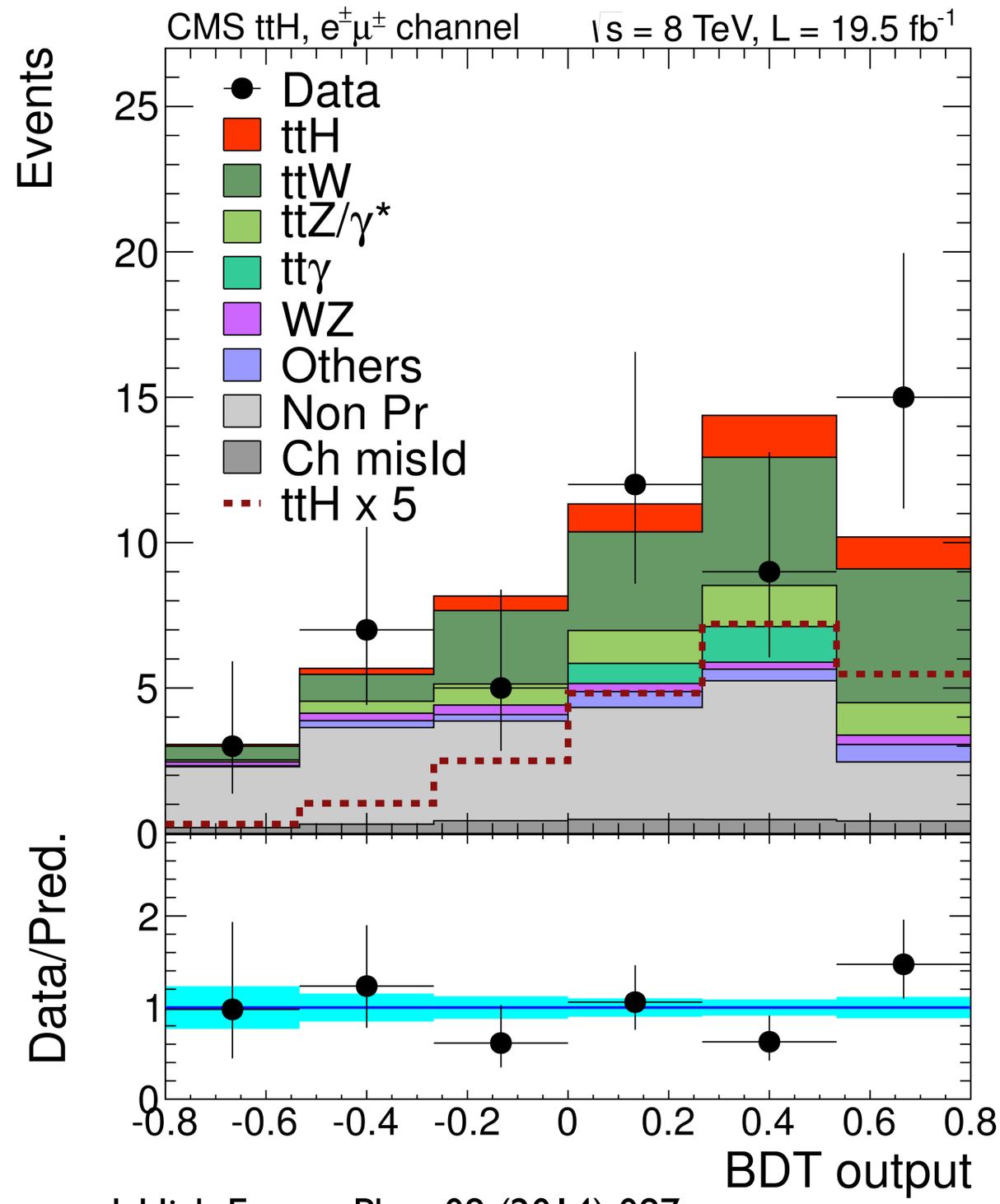
- Higgs boson decays to WW, ZZ or $\tau\tau$ can be probed in multilepton final states.
  - For example 3 leptons, or requiring a pair of same-charge leptons.
  - Can additionally require b-tagged jets to further increase the signal to background.



Physics Letters B 749 (2015) 519-541

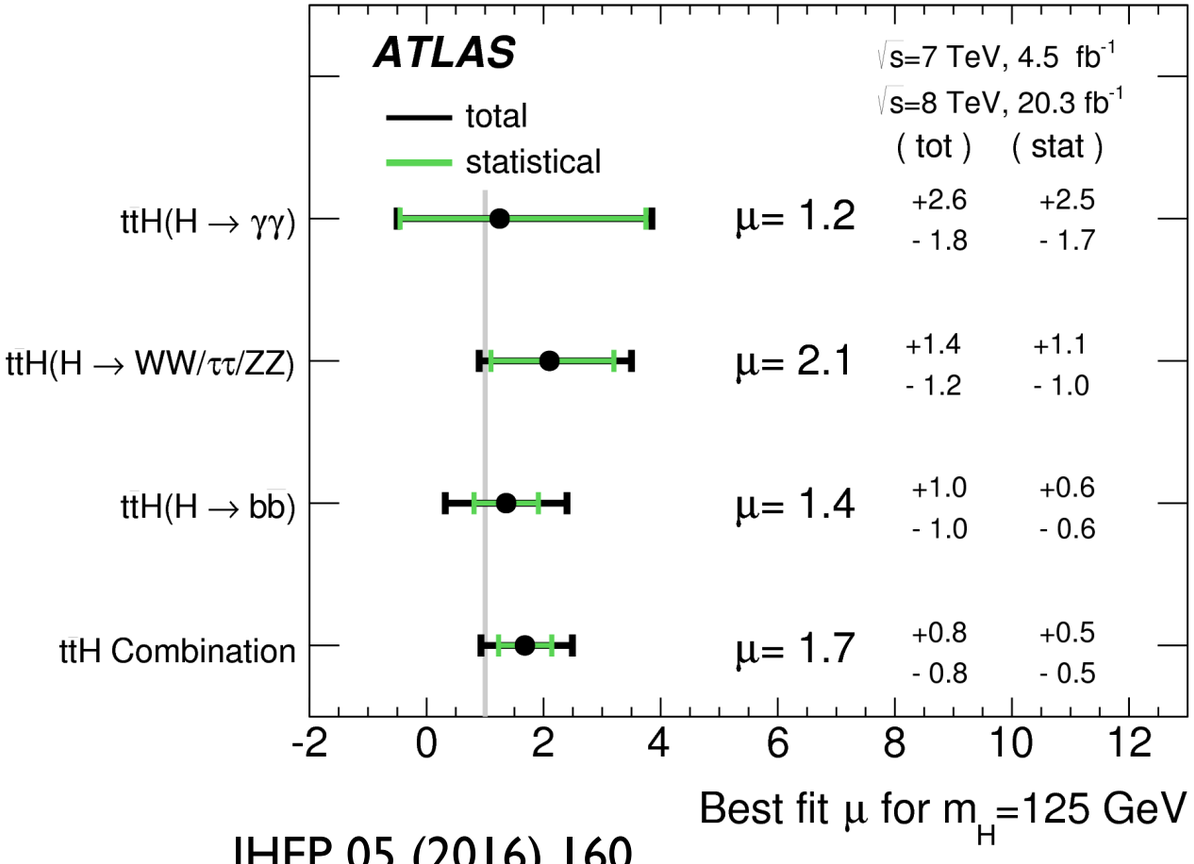


J. High Energy Phys. 09 (2014) 087

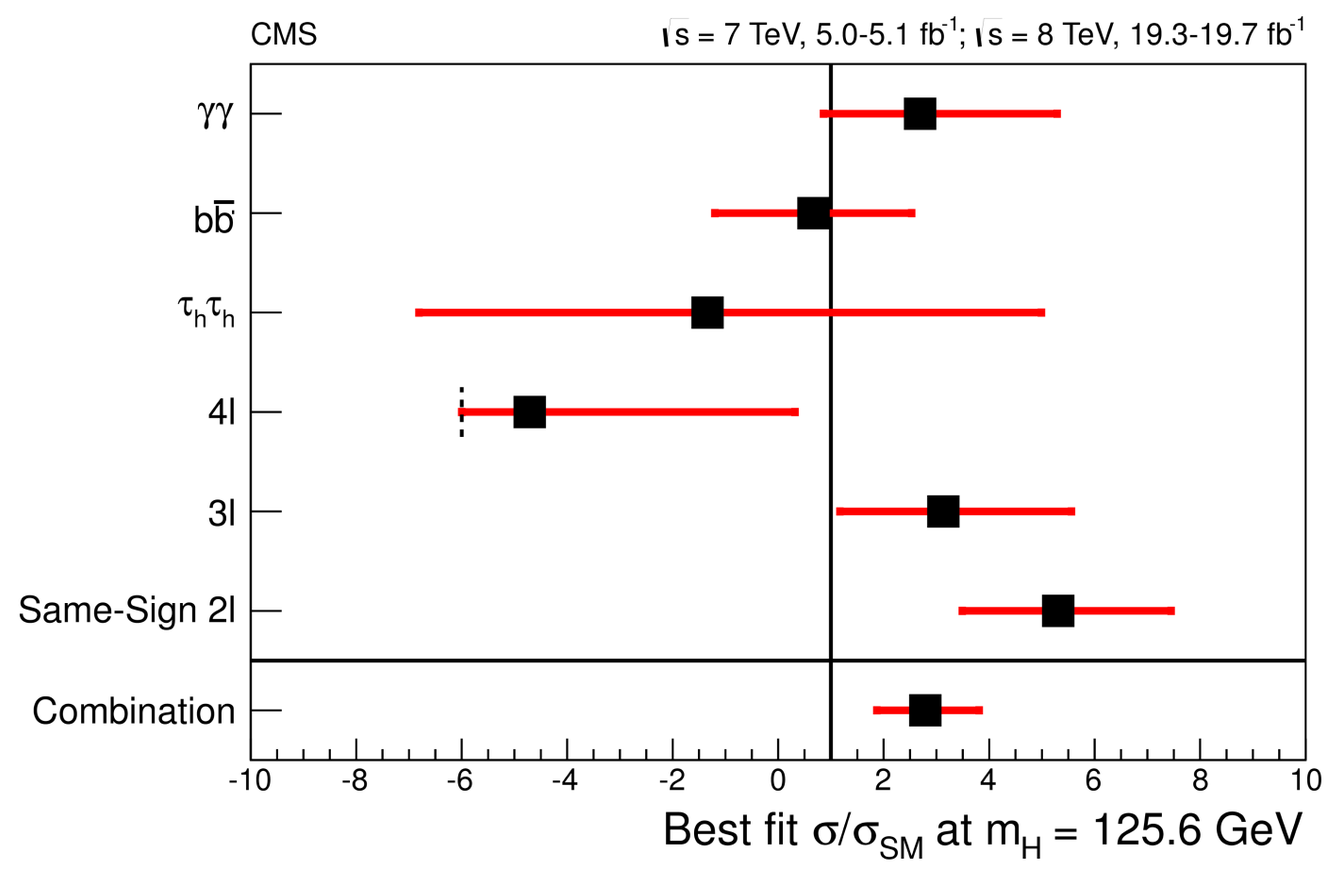
ttH Run 1 Results

Jonas Strandberg

- Even combining the results for all different ttH channels, the observed significance in Run 1 was only a few standard deviations.
  - Still an important input to determining the Higgs boson couplings.
- Below are a summary of the results in the γγ, bb and various multi-lepton final states, and the results when combining all ttH channels together.



JHEP 05 (2016) 160



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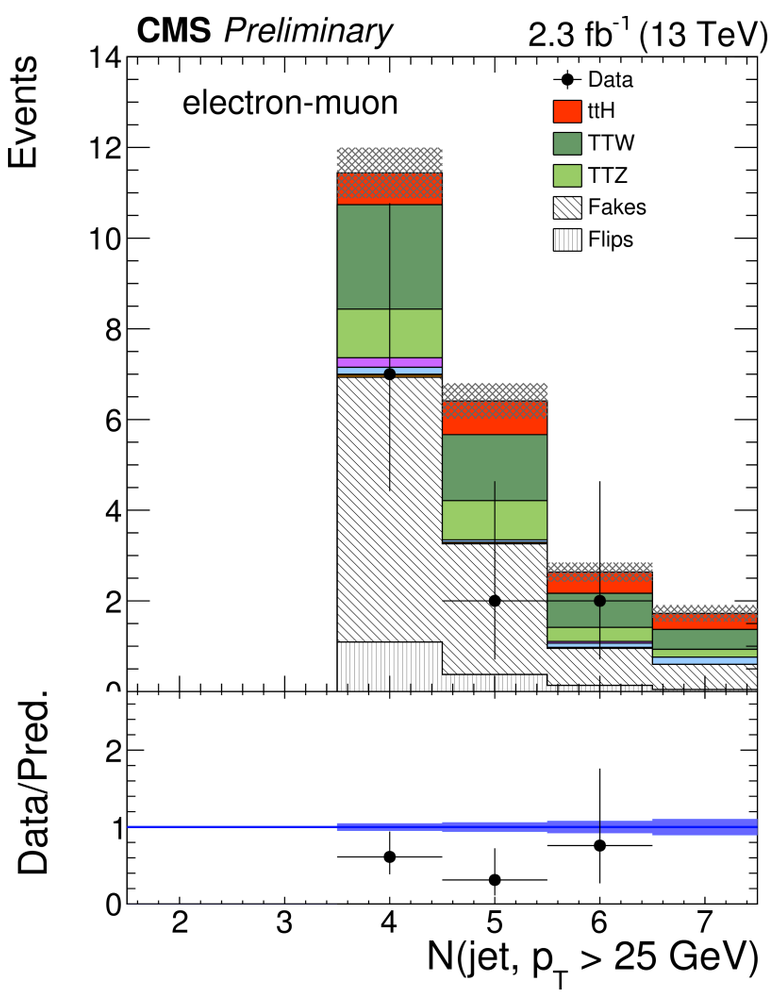
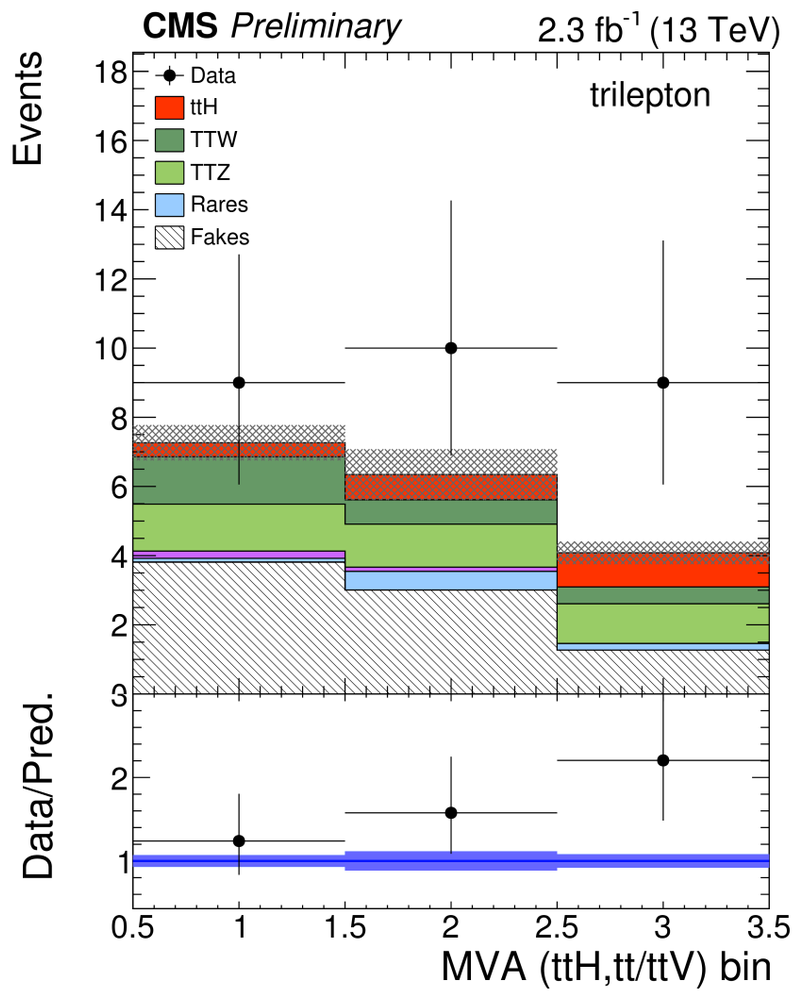
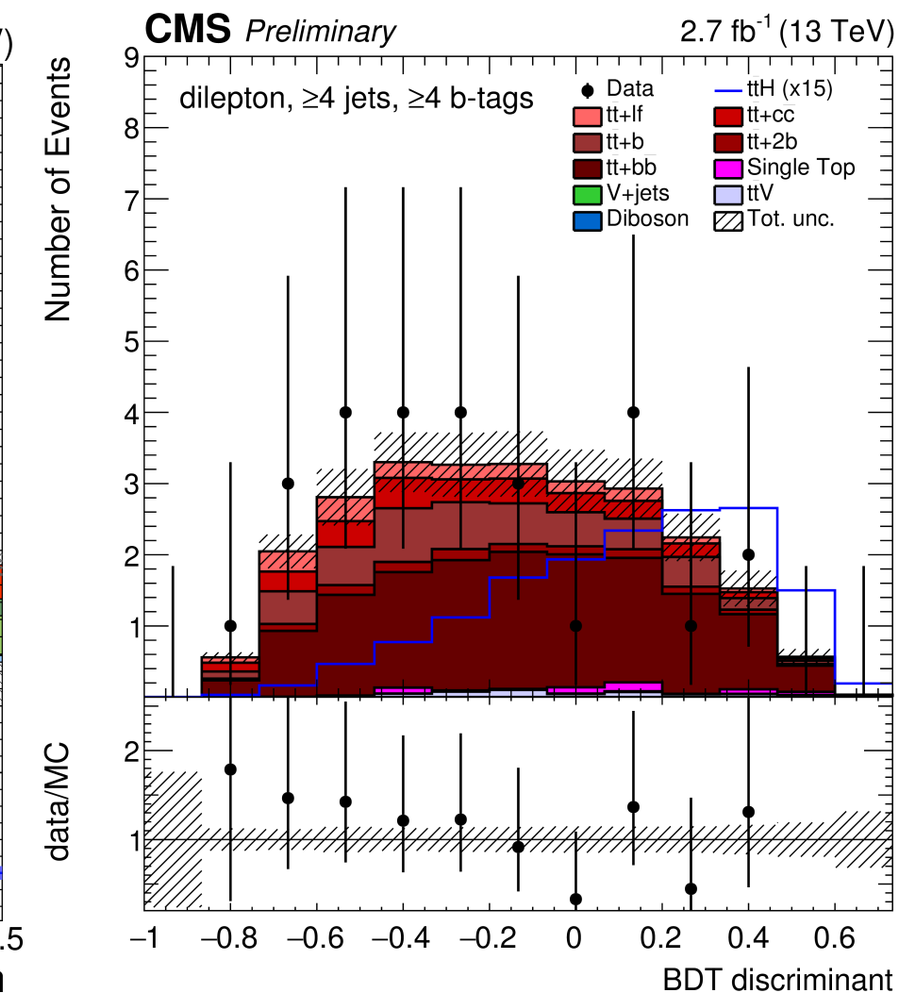
CMS ttH in Run 2

Jonas Strandberg

- The ttH channels get a boost by almost a factor of 4 in LHC Run 2.
  - So far studied H→bb, H→γγ and H→WW, each then gets divided into multiple sub-channels depending on the decays of the two W bosons from the top quark decays and the potential additional W bosons from the Higgs decay.







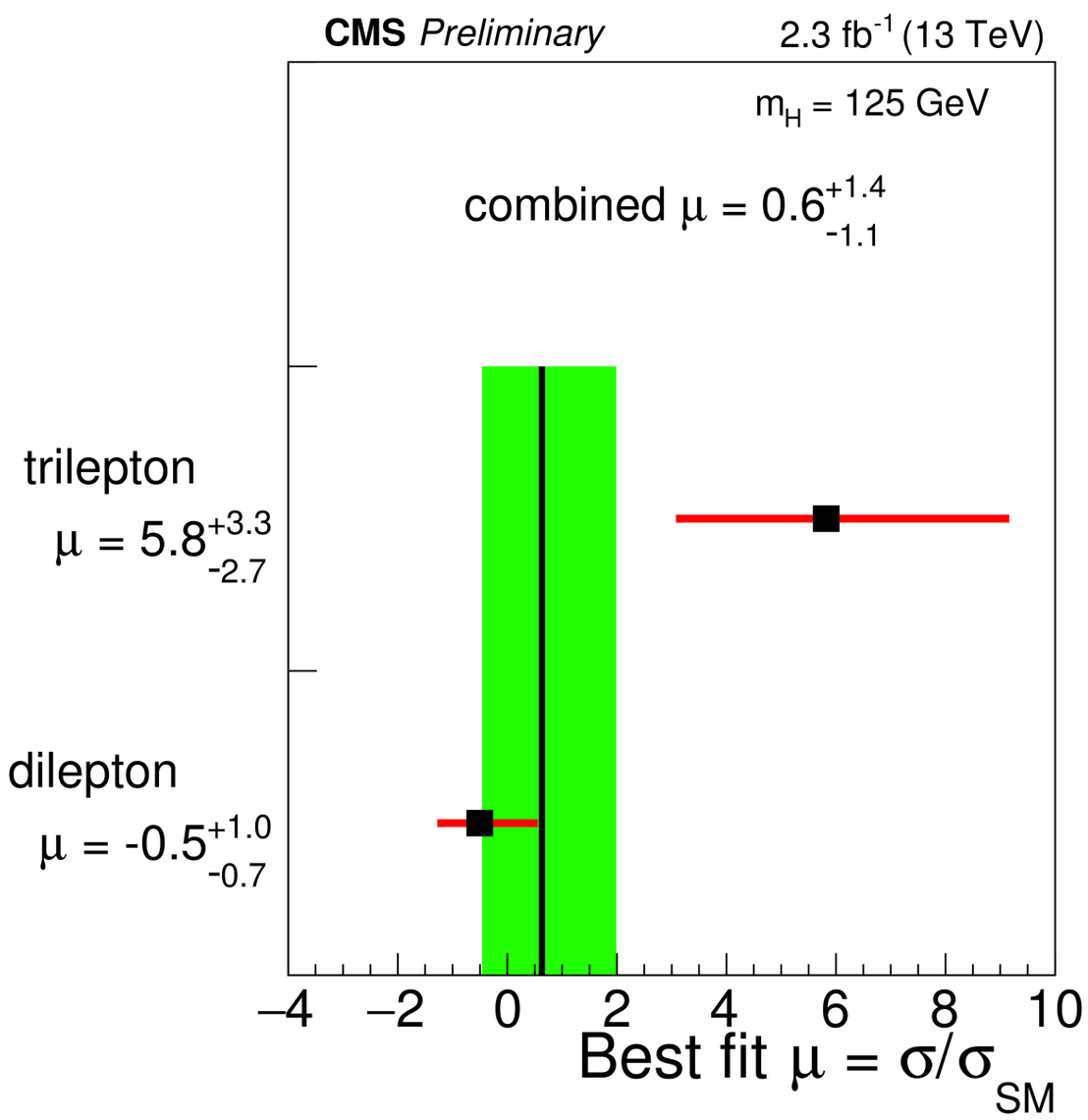
CMS-PAS-HIG-15-008

CMS-PAS-HIG-16-004

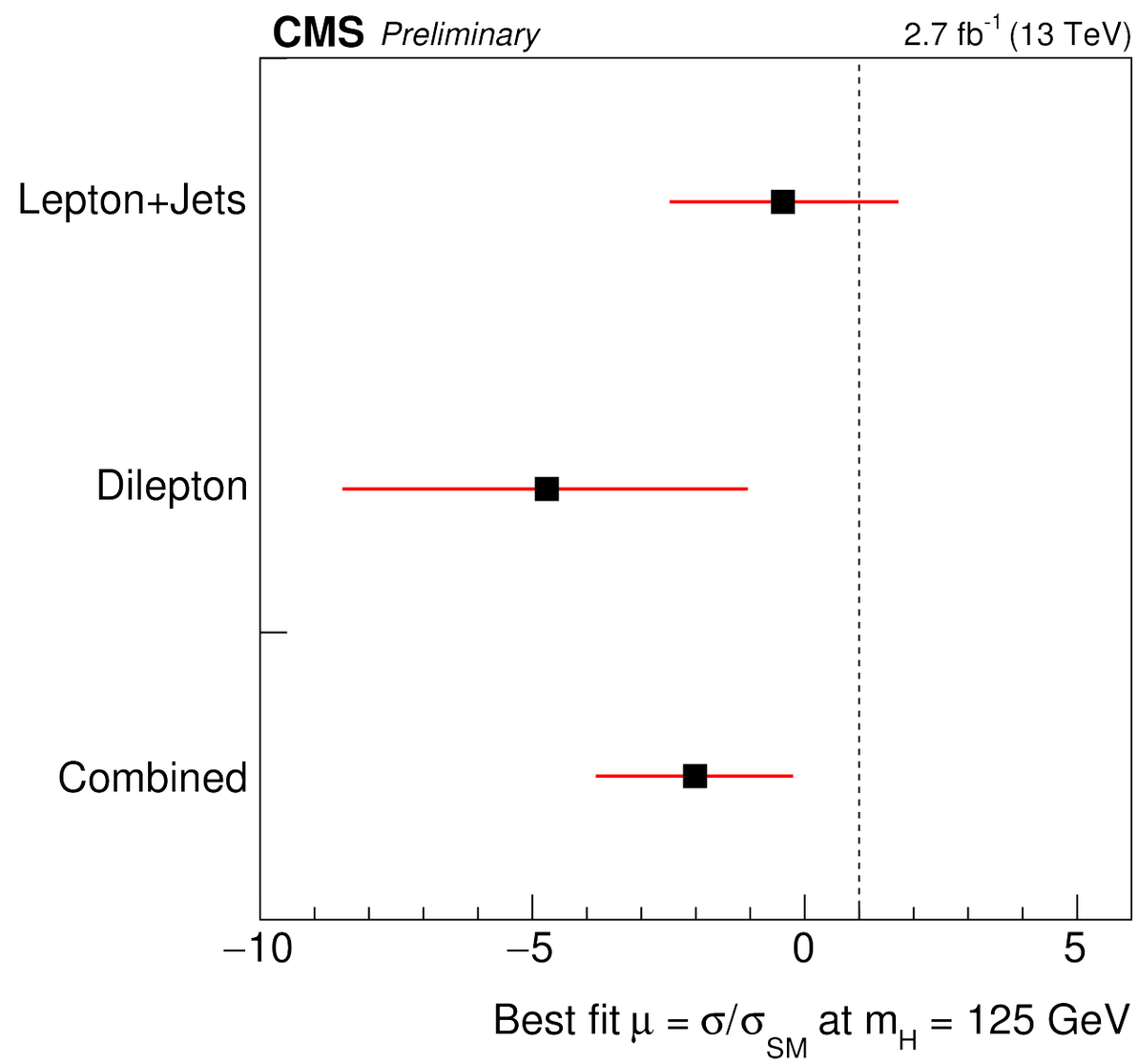
CMS ttH Run 2 Result

Jonas Strandberg

- So far all results consistent with the standard model.
  - Slight deficits in data for the analyses targeting H→bb decays.
  - Similar sensitivity as with the full Run 1 dataset.



CMS-PAS-HIG-15-008



CMS-PAS-HIG-16-004

Conclusions

Jonas Strandberg

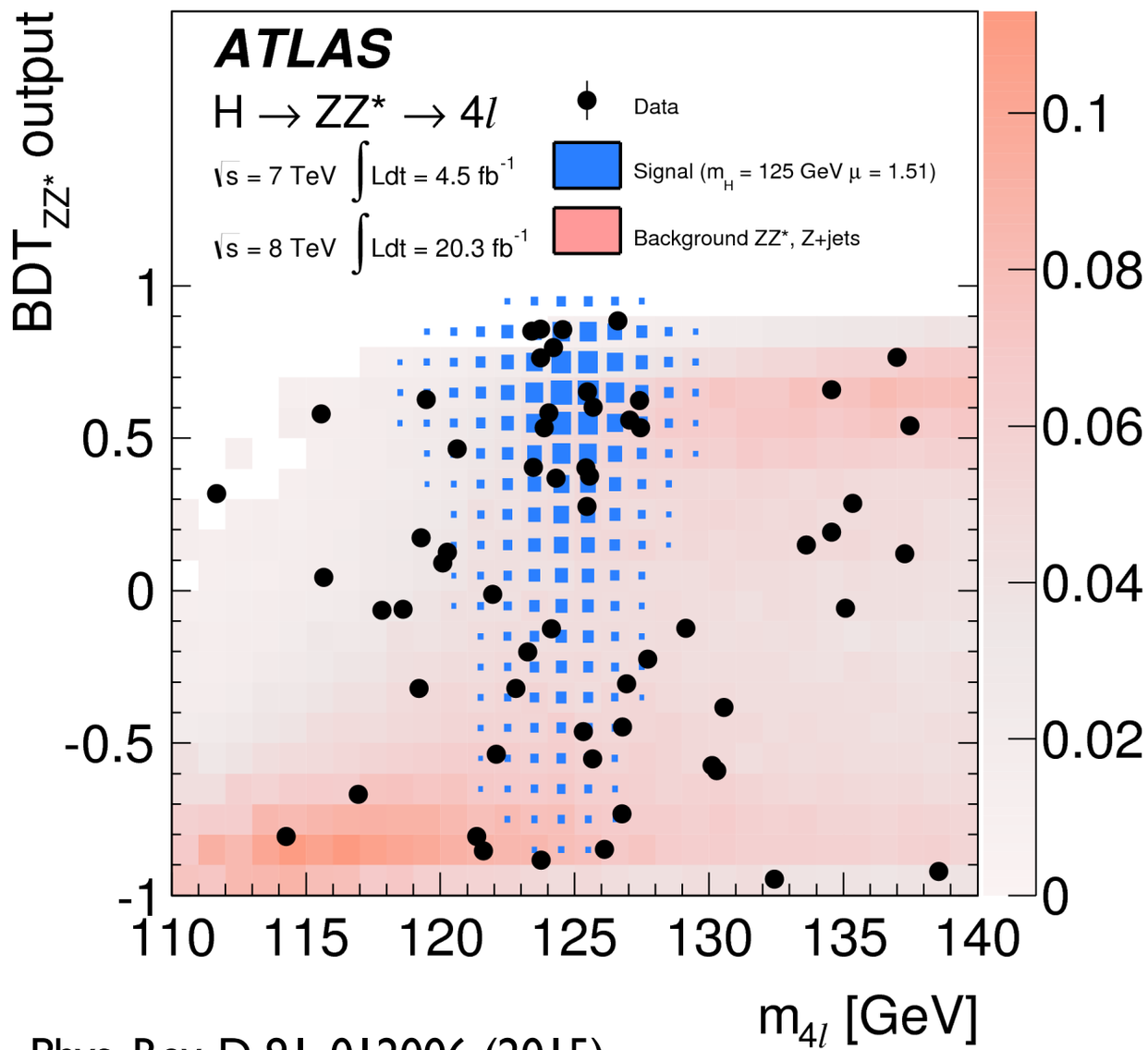
- From the Run 1 data, all Higgs boson properties are consistent with the expectations from the standard model:
  - The spin and parity confirmed to be according to the SM.
  - The mass, not predicted by the SM, is measured to a precision of a few ‰.
- A combination of all the results in the various Higgs boson channels can be used to determine the Higgs boson couplings to other particles.
  - You will hear much more about that in the next talk by Silvio!
- The 2015 data does not have the sensitivity of Run 1 but have been used by ATLAS and CMS to re-establish the analysis of the Higgs boson.
  - The channel that gains the most from the increased collision energy, ttH production, start to have comparable sensitivity to Run 1 already.
- With the 2016 data (around 20-25 fb^{-1}) the sensitivity of all analyses will significantly improve compared to the Run 1 results.
  - Just waiting for more data now. Very encouraging start so far this year!

Backup

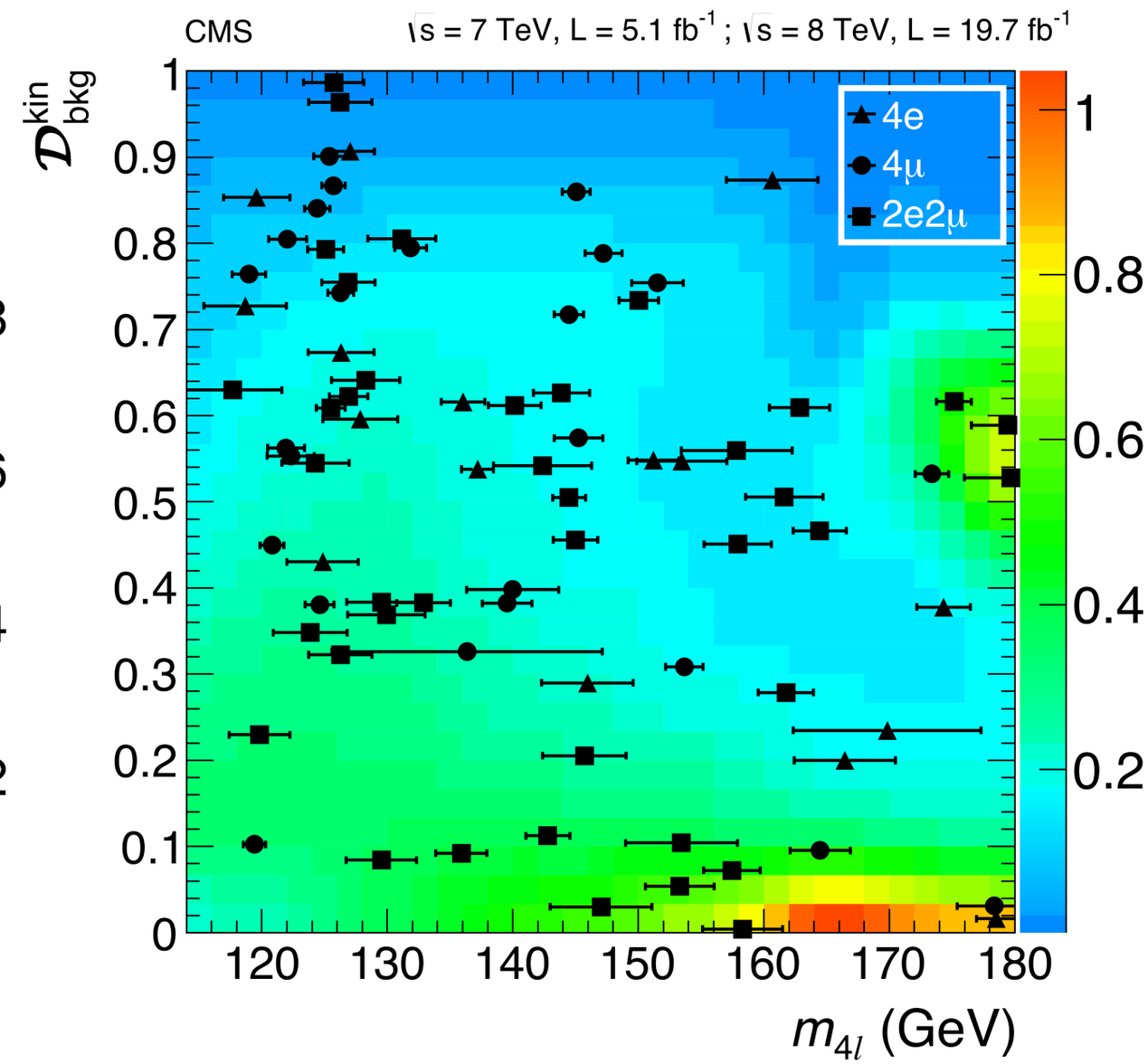
The H→ZZ*→4ℓ Channel in Run I

Jonas Strandberg

- Both experiments also define multi-variate discriminants to further increase the separation between the signal and the background.
  - Discriminant values for events passing the analysis selections shown below.



Phys. Rev. D 91, 012006 (2015)

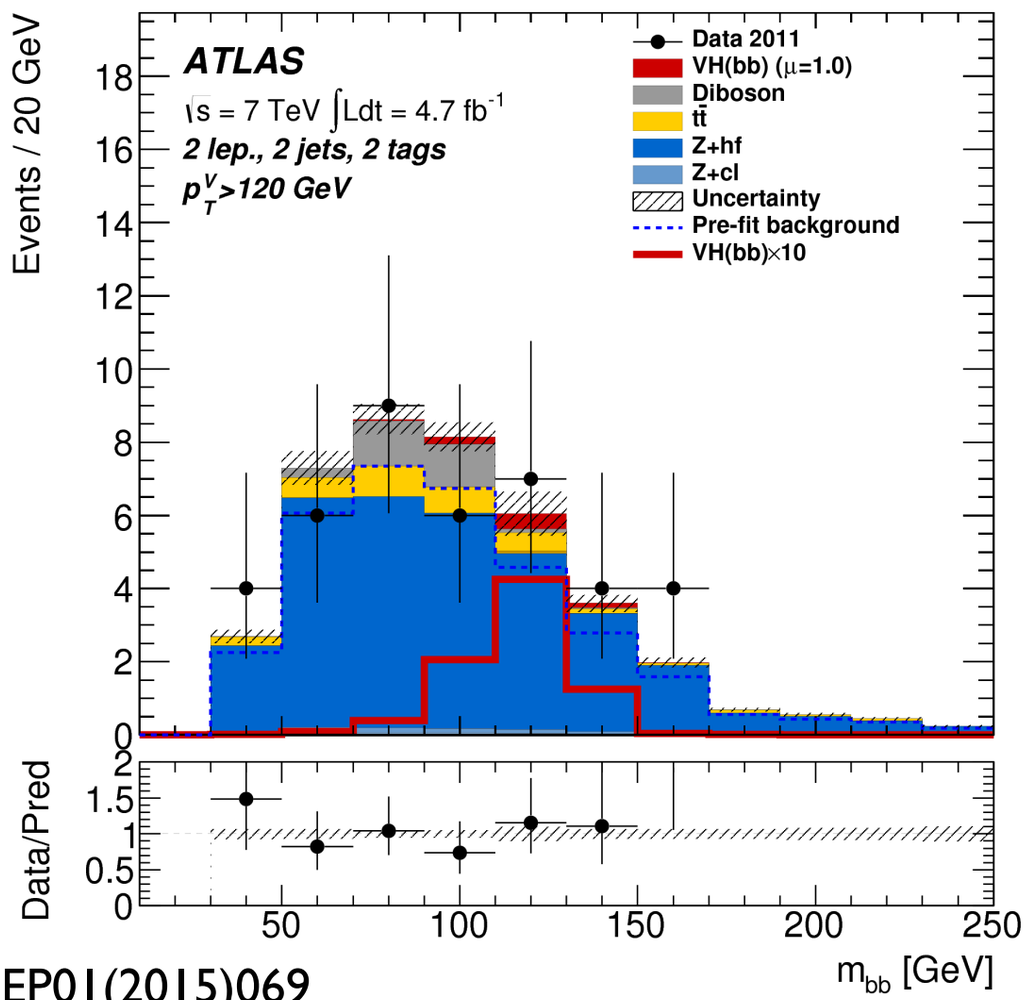


Phys. Rev. D 89 (2014) 092007

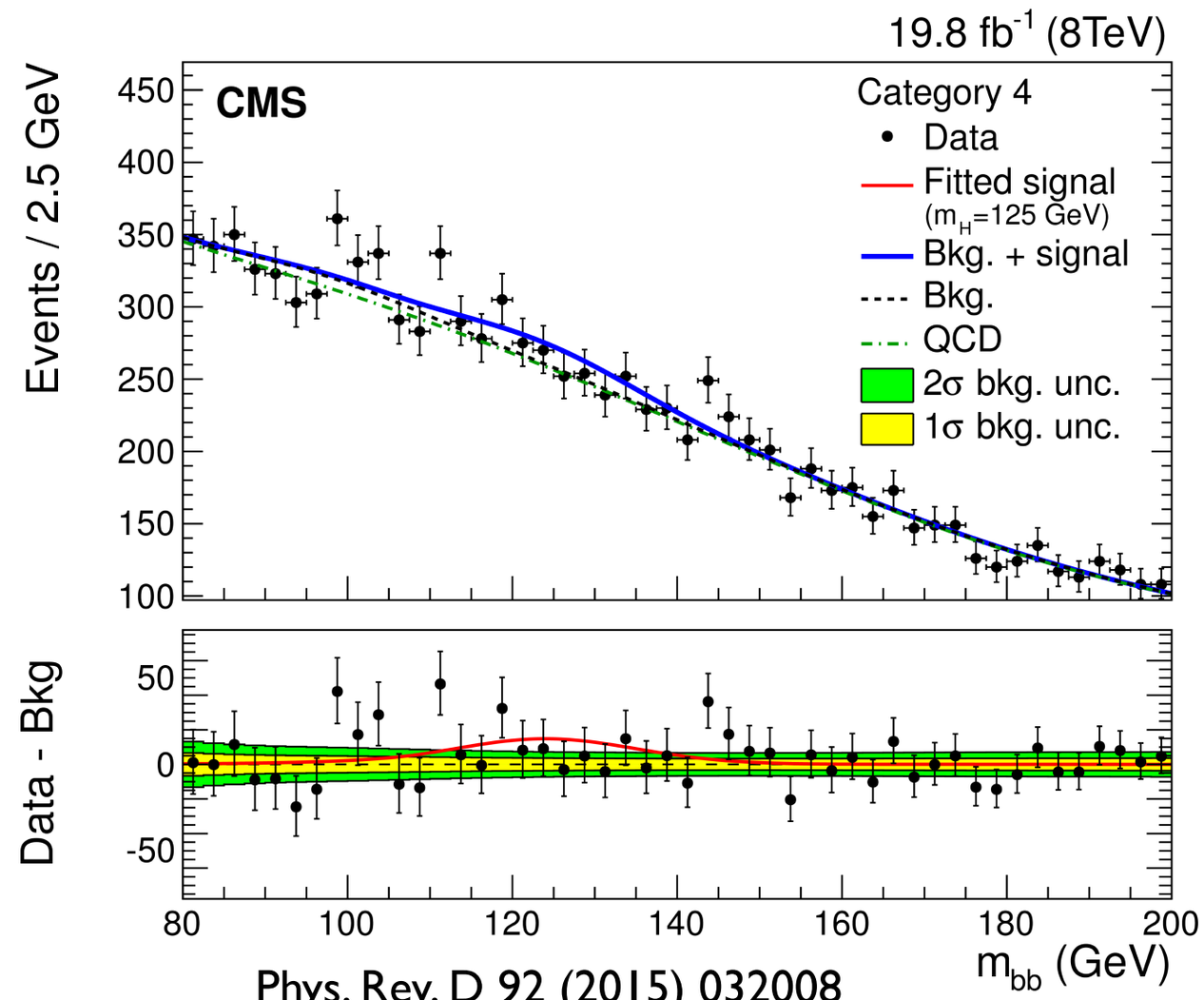
The H→bb Channel in Run I

Jonas Strandberg

- The H→bb decay channel has the highest branching ratio, but is swamped by SM bb production at the LHC.
  - Make use of the rarer production modes, where the associated particles give additional handles for background rejection.
  - Tagging efficiency for b-quarks and jet-jet invariant mass resolution critical.



JHEP01(2015)069

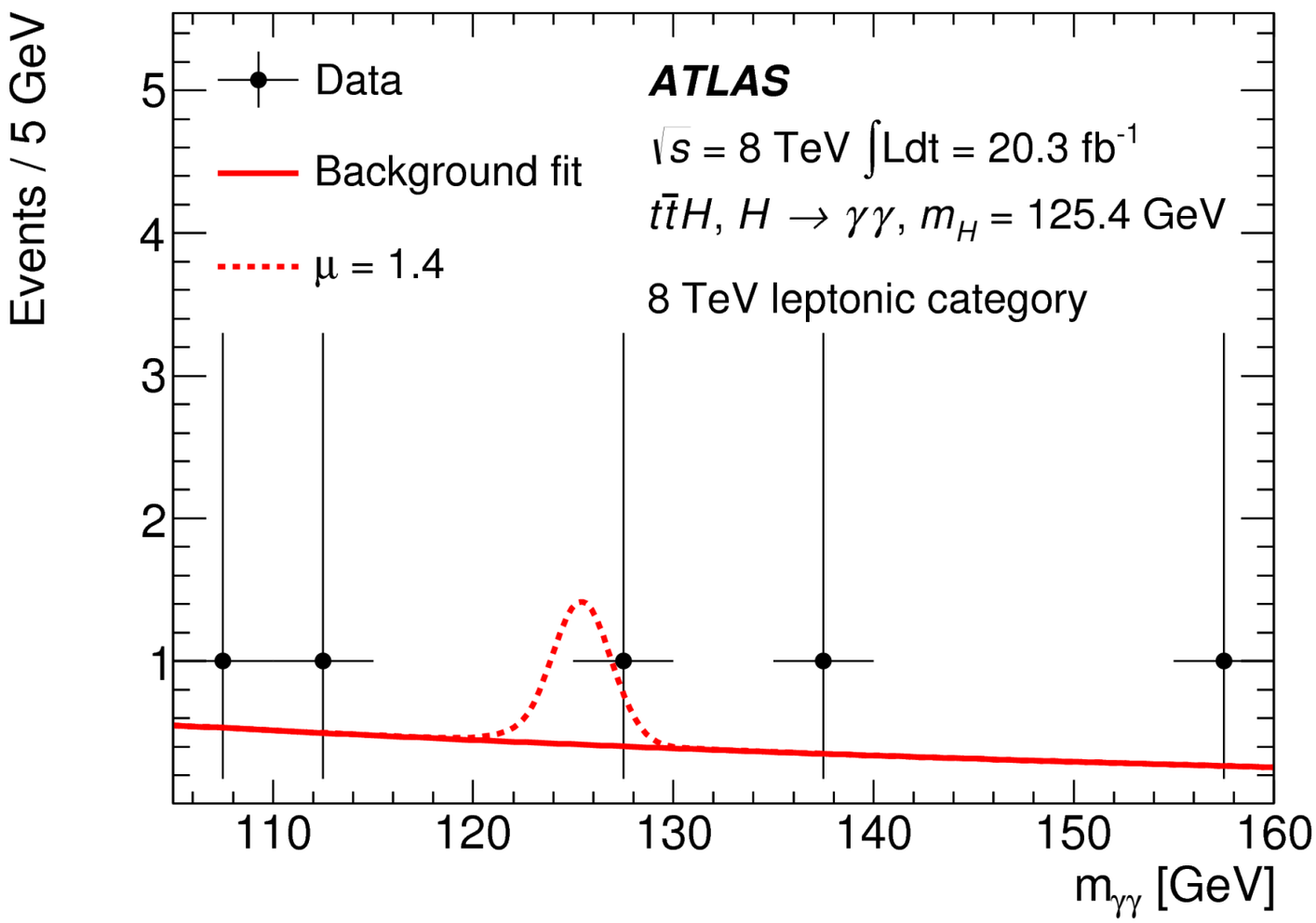


Phys. Rev. D 92 (2015) 032008

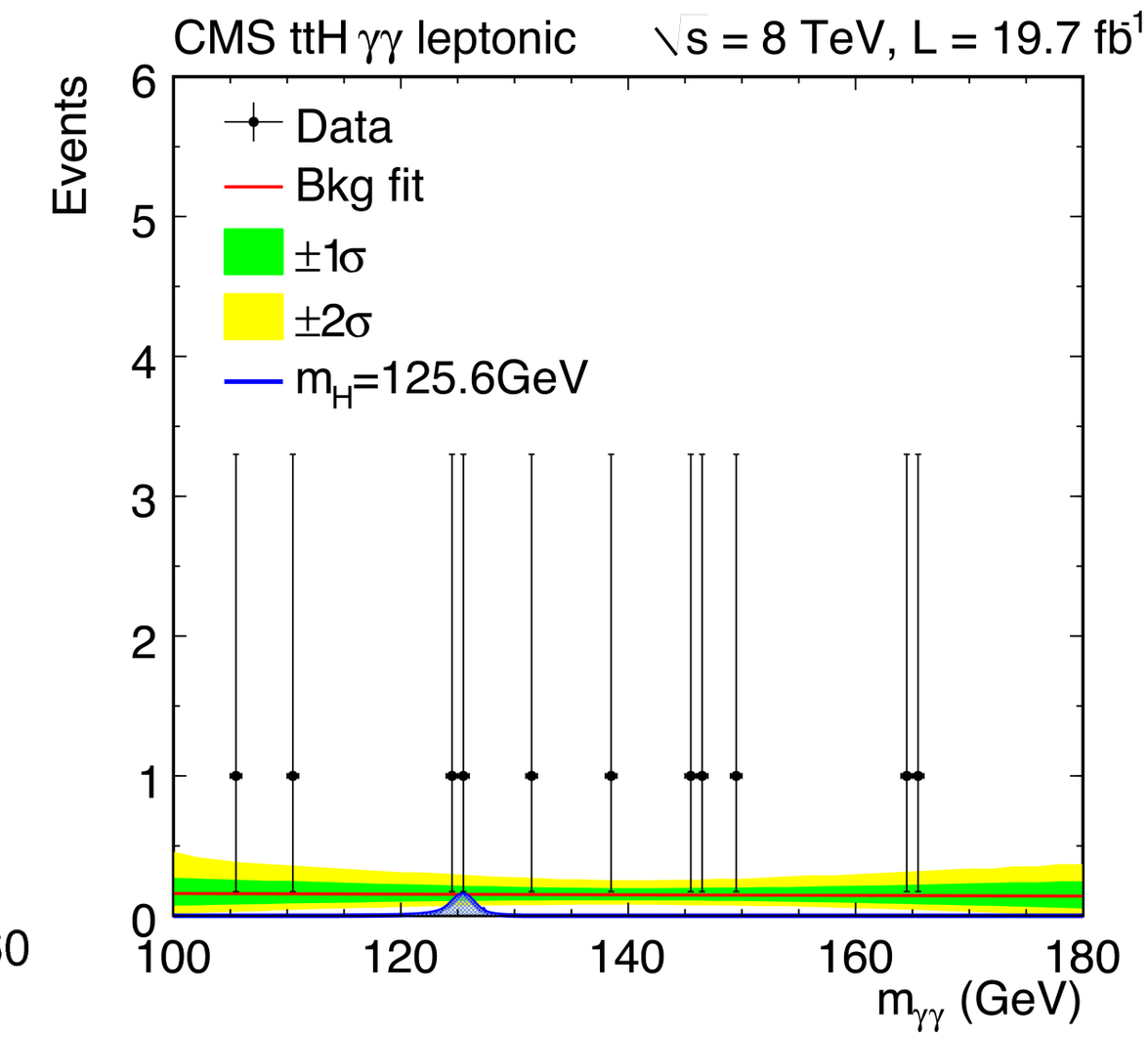
ttH(→γγ) Production in Run 1

Jonas Strandberg

- Higgs boson decays to γγ suffers from low statistics due to the small branching fraction but gives a very clean signal.
  - Expected to become an increasingly important channel in Run 2 and beyond.



Physics Letters B 740 (2015) 222-242



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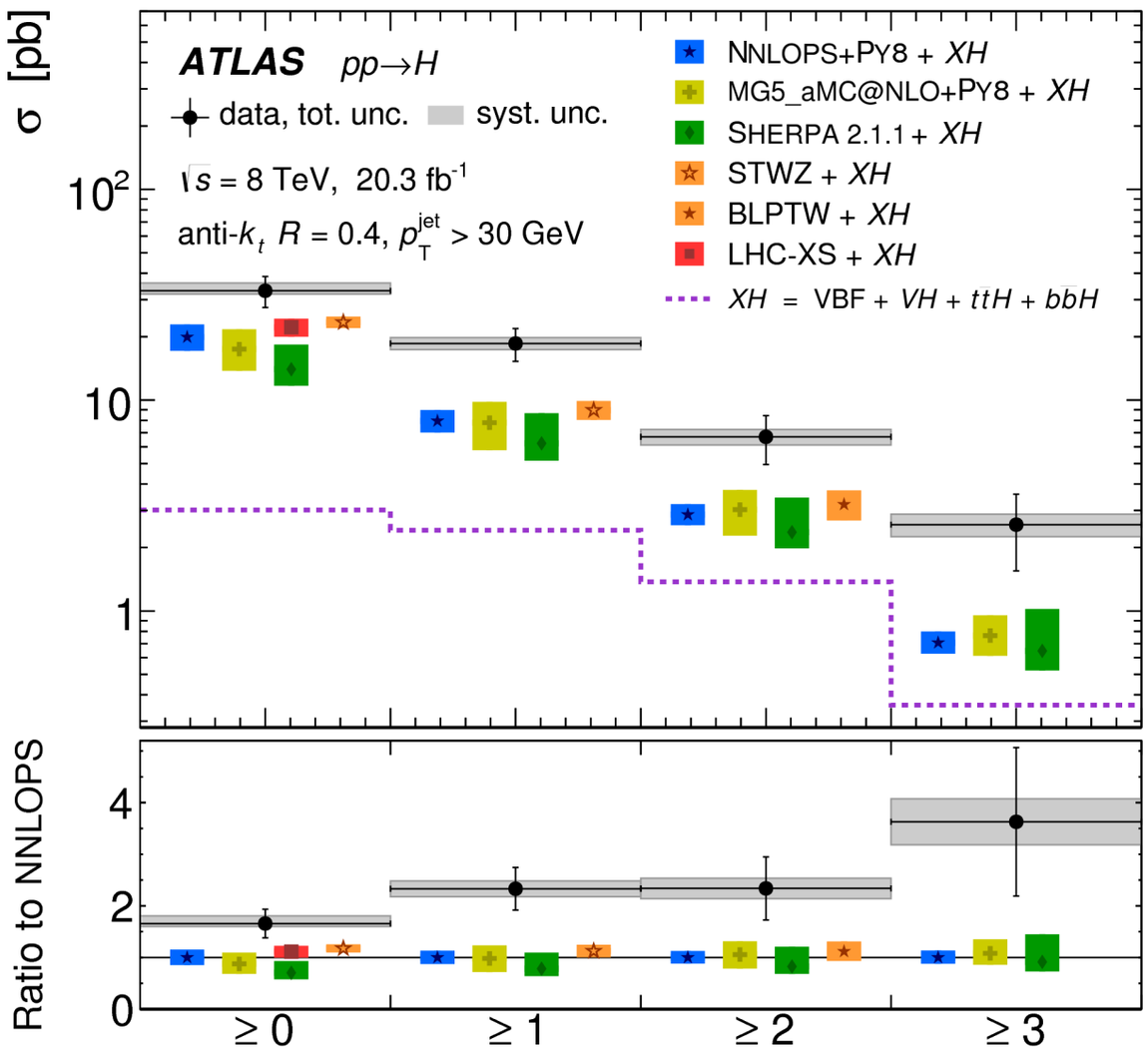
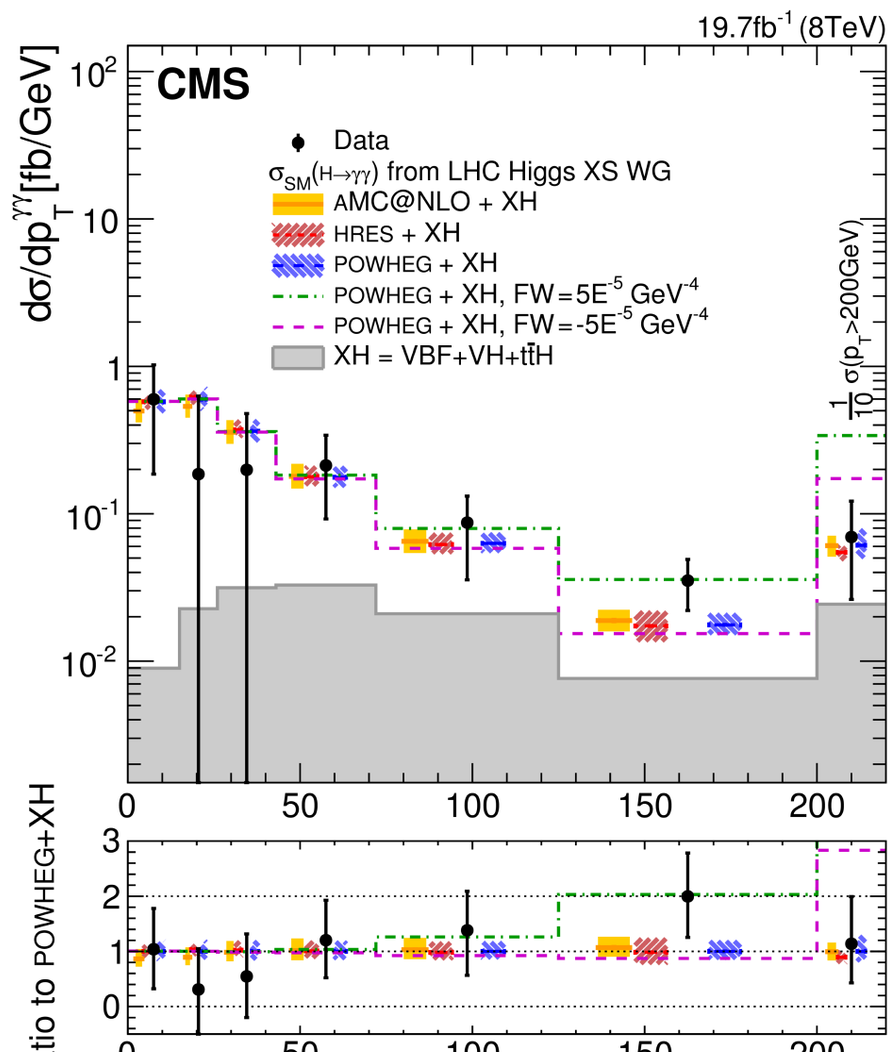
Differential Distributions

Jonas Strandberg

- Differential cross-sections for quantities like $p_T(H)$, $|y_H|$ and jet multiplicity, unfolded to the particle level, have also been measured.
  - Statistical uncertainties (23%-75%) still dominate all the differential measurements.



Phys. Rev. Lett. 115 (2015) 091801



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