Couplings and mass with 13 TeV data and expectations

Susumu Oda (Kyushu University)

On behalf of the ATLAS and CMS Collaborations

2017-03-19, La Thuile, Italy

52nd Rencontres de Moriond EW 2017

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I will present results of diboson final states.
Difermion and other final states will be covered by the following speakers.

Introduction

- The BEH scalar boson was the last undiscovered particle in the Standard Model of particle physics.
- Couplings to the BEH scalar field determine the particle masses.

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}, \langle 0|\Phi|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v\end{pmatrix}$$

$$\mathcal{L}_{\text{BEH}} = \left|\left(\partial_\mu - \frac{i}{2}g'B_\mu - \frac{i}{2}g\tau^a W_\mu^a\right)\Phi\right|^2 + \mu^2\Phi^+\Phi - \frac{\lambda}{2}(\Phi^+\Phi)^2$$

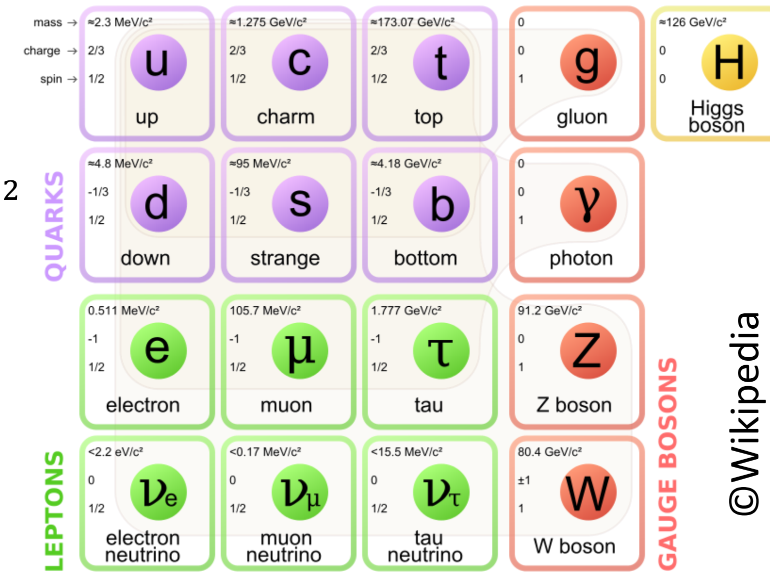
$$m_W = \frac{gv}{2}, m_Z = \frac{\sqrt{g^2+g'^2}v}{2}, m_H = \sqrt{\lambda}v, v = \sqrt{\frac{2\mu^2}{\lambda}}$$

$$\mathcal{L}_{\text{lepton}}^{\text{mass}} = \sum_{j=e,\mu,\tau}(-f_j)[(\bar{L}_j\Phi)R_j + \bar{R}_j(\Phi^+L_j)]$$

$$m_j = \frac{f_j v}{\sqrt{2}}$$

$$\mathcal{L}_{\text{quark}}^{\text{mass}} = \sum_{f=d,s,b}(-f_f)[(\bar{L}_f\Phi)R_f + \bar{R}_f(\Phi^+L_f)] + \sum_{F=u,c,t}(-f_F)[(\bar{L}_F\tilde{\Phi})R_F + \bar{R}_F(\tilde{\Phi}^+L_F)]$$

$$m_f = \frac{f_f v}{\sqrt{2}}, m_F = \frac{f_F v}{\sqrt{2}}$$



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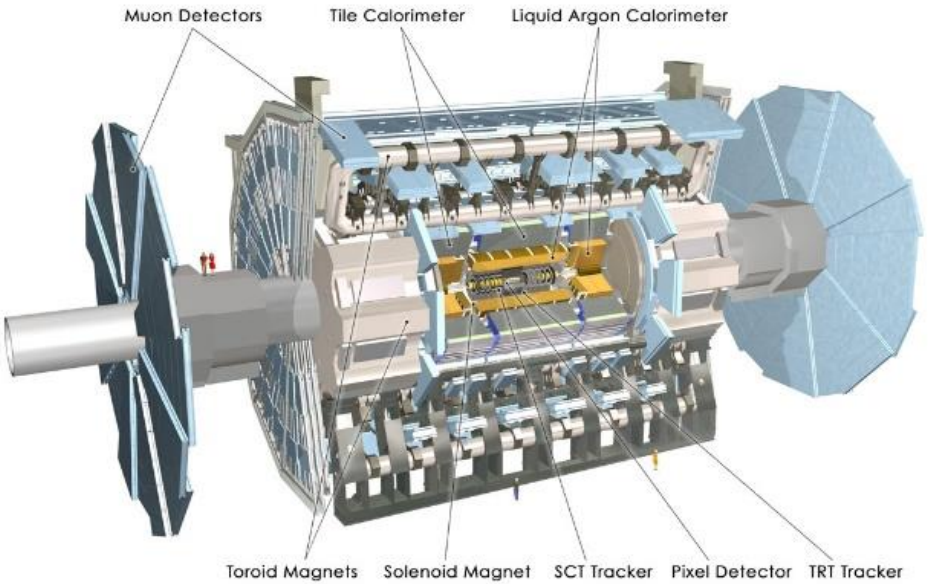
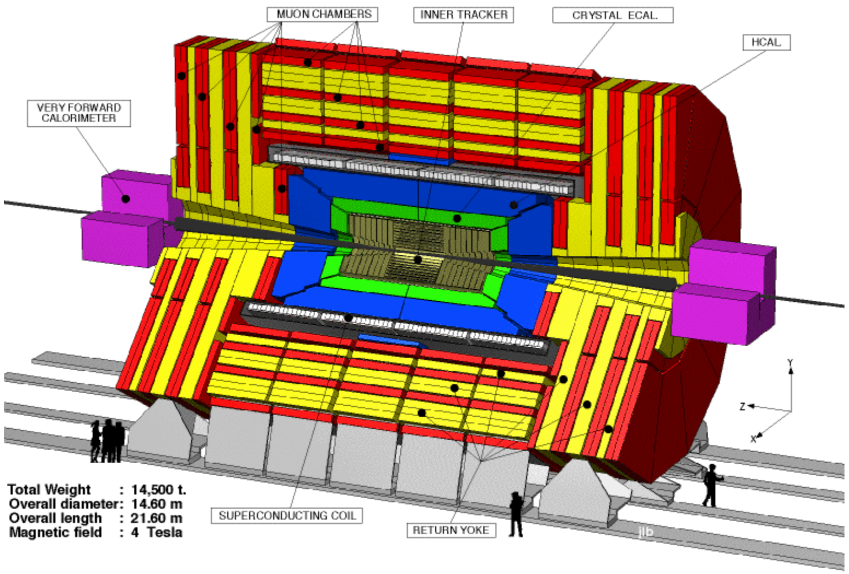
LHC, ATLAS and CMS

- Large Hadron Collider (LHC) is the world's largest collider at CERN.
  - Proton-proton collider
- ATLAS and CMS detectors located at the LHC are for general purpose.



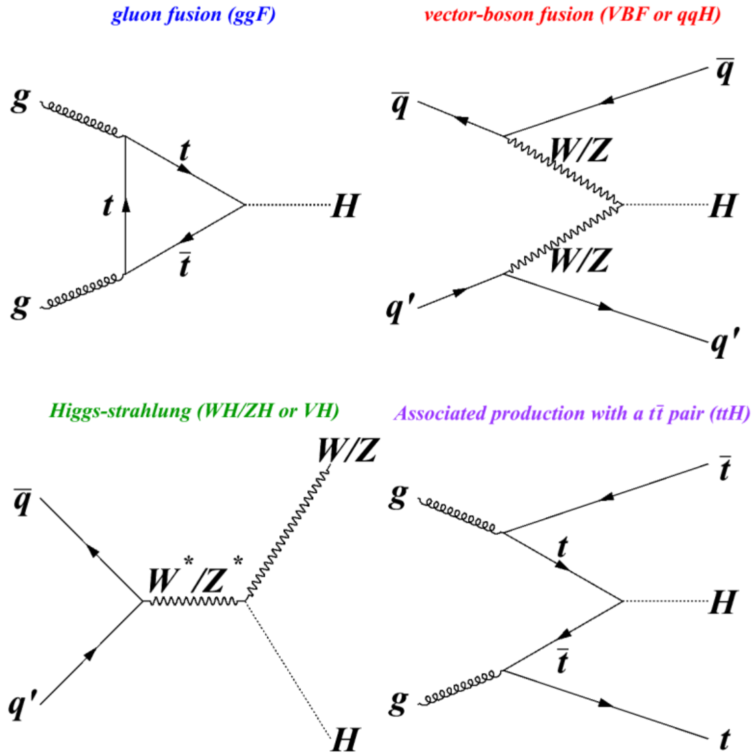
44 m x 25 m, 7,000 tons

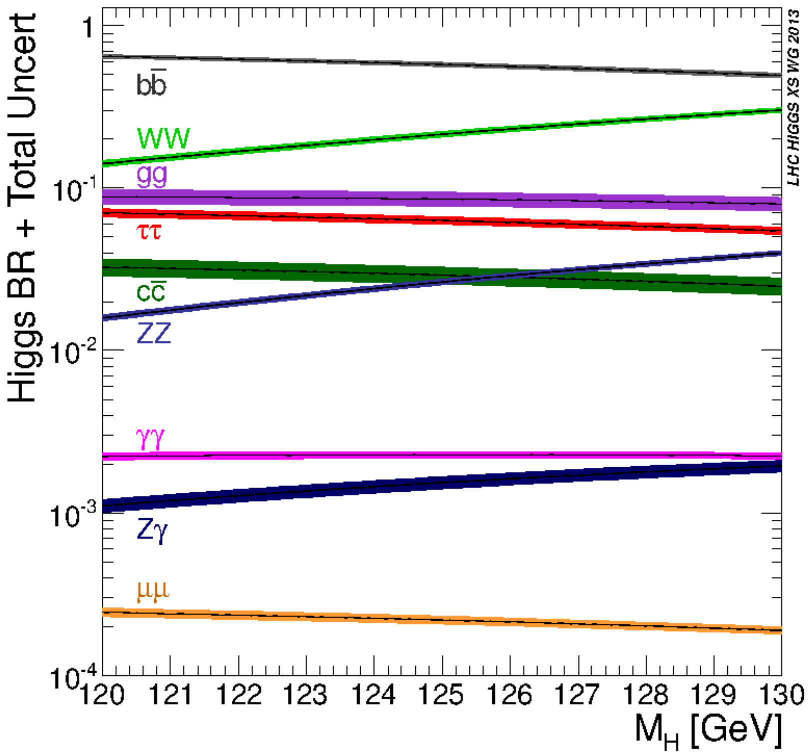


29 m x 15 m, 14,000 tons

Production and decay

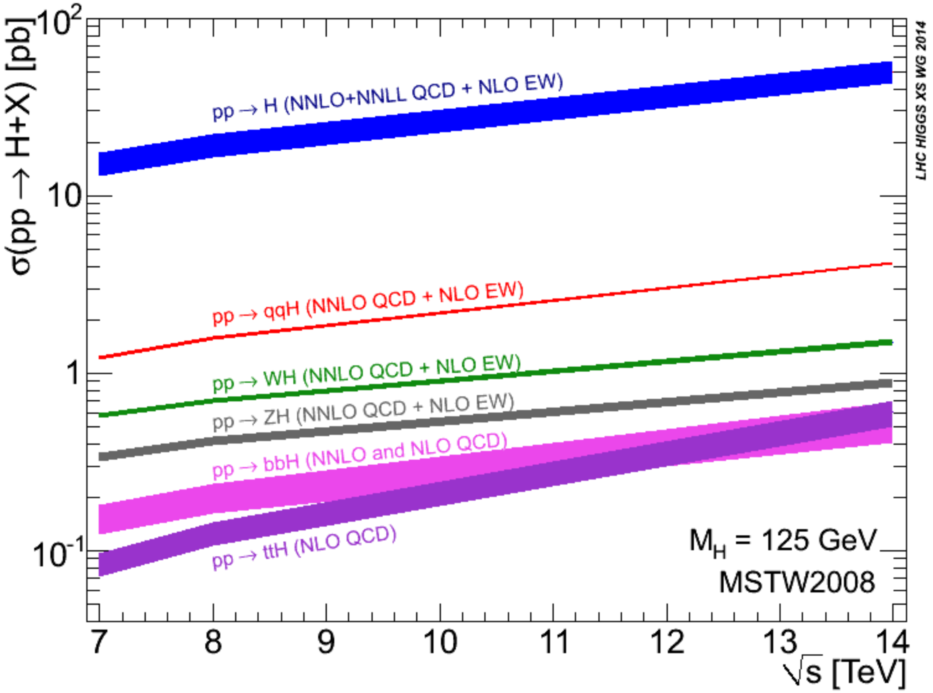
- Gluon fusion (ggF) is the dominant production channel of the Standard Model scalar boson at the LHC.
  - Fermionic production (production via top quark loop)
- Vector boson fusion (VBF or qqH) and vector boson associated production (WH and ZH or VH)
  - Bosonic production
- Many decay modes are accessible at M_H~125 GeV.





LHC Run 2 at 13 TeV

- Cross sections are increased by ~2.3 except for ttH 3.8 from 8 TeV to 13 TeV.
- More than 100 fb^{-1} is expected in Run 2.
  - ~25 fb^{-1} in Run 1
- We expect 10 times more the BEH scalar events than Run 1.
- In this talk, results with 2—36 fb^{-1} data are presented.



Cross section [pb] @125.09 GeV	ggF	VBF	WH	ZH	ttH	bbH
8 TeV	21.39	1.600	0.701	0.4199	0.1326	0.2015
13 TeV	48.52	3.779	1.369	0.8824	0.5065	0.4863
Ratio	2.27	2.36	1.95	2.10	3.82	2.41

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

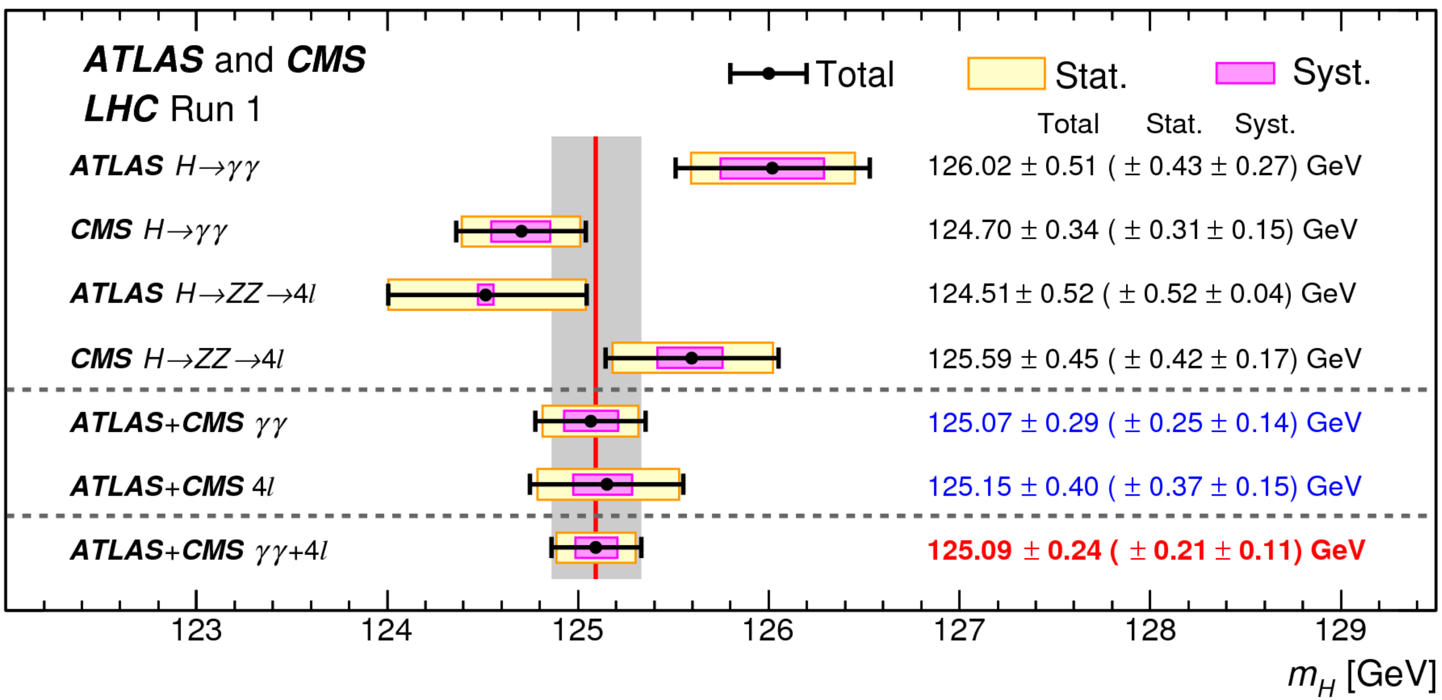
Run 1 mass results

Phys. Rev. Lett. 114, 191803

- $m_H = \sqrt{\lambda} v$
  - Determination of the BEH potential.
  - Not predicted by the theory.
- Combination of ATLAS and CMS results is

$$125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV.}$$

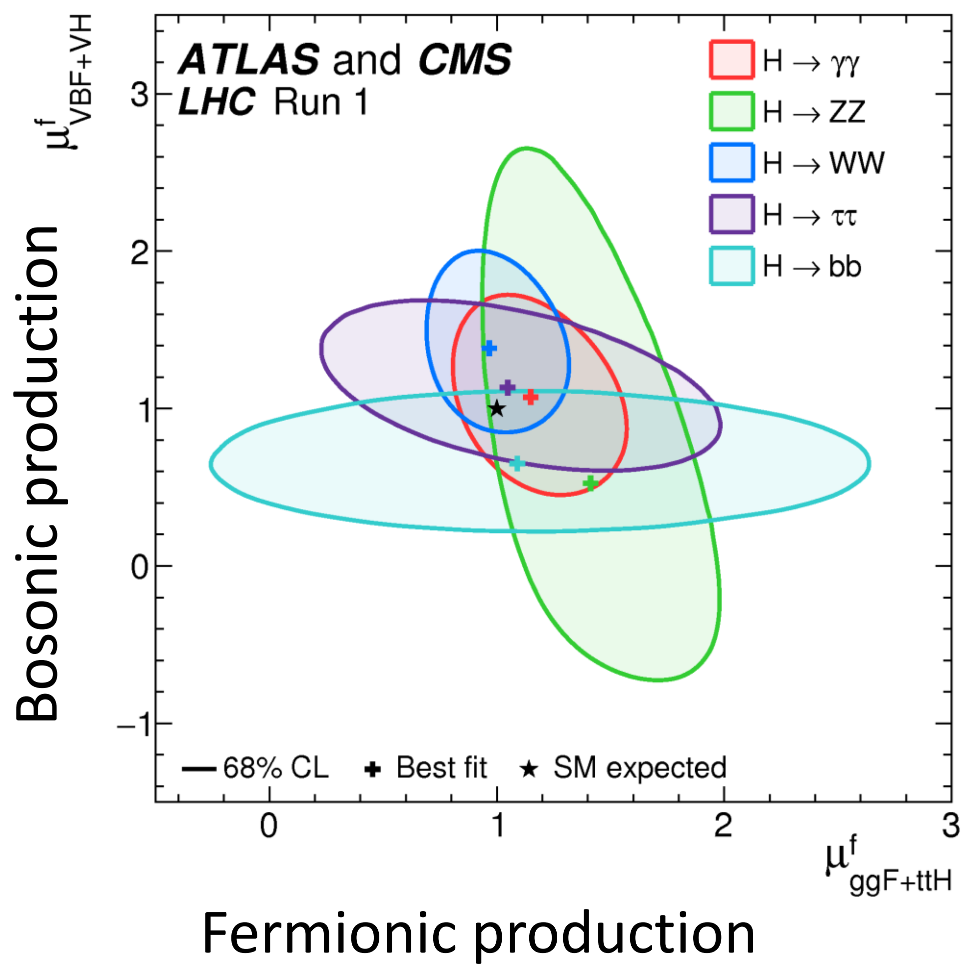
- Still dominated by statistical uncertainties



Run 1 coupling results

JHEP 08 (2016) 045

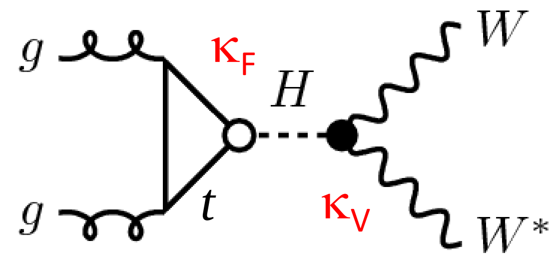
- Signal strength: $\mu = \sigma_{obs}/\sigma_{SM}$
  - μ=1 means that data observation is compatible with the SM expectation.
  - μ=0 means that no signal is observed.

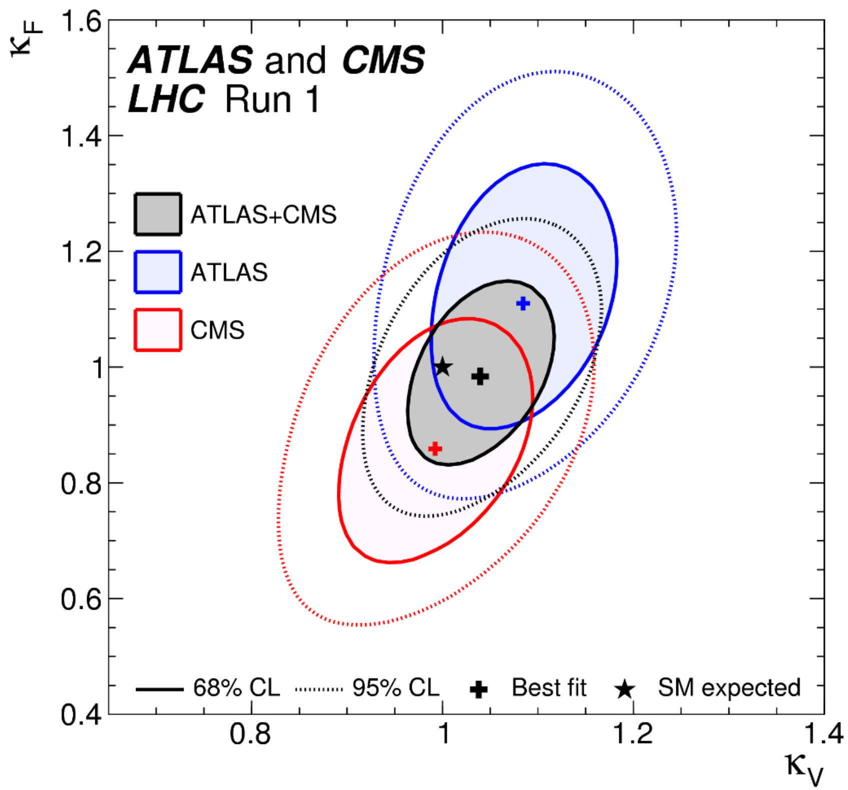


Run 1 coupling results

JHEP 08 (2016) 045

- Scale factors κ_j are introduced to quantify deviations of couplings from the SM.
- One benchmark model uses two scale factors of κ_V for vector bosons and κ_F for fermions.
- The SM corresponds to κ_V=1 and κ_F=1.
- Result is consistent with the SM expectations.

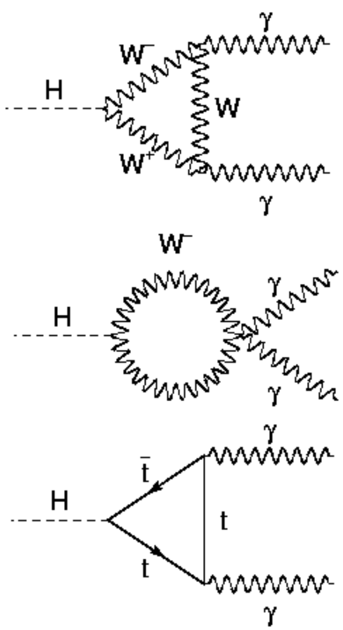


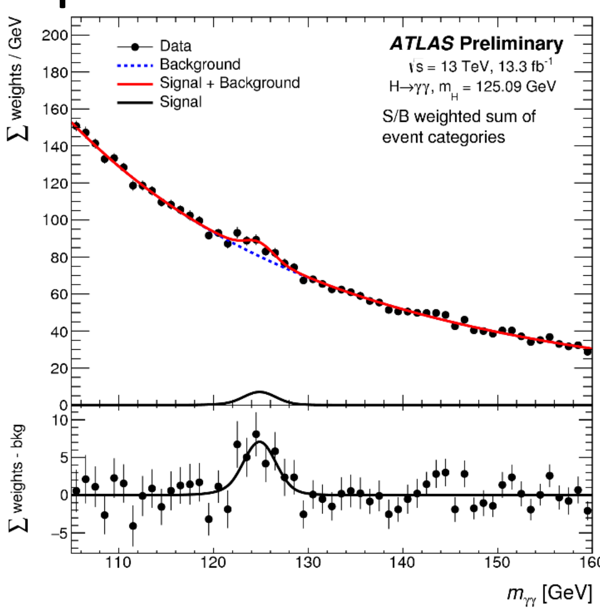


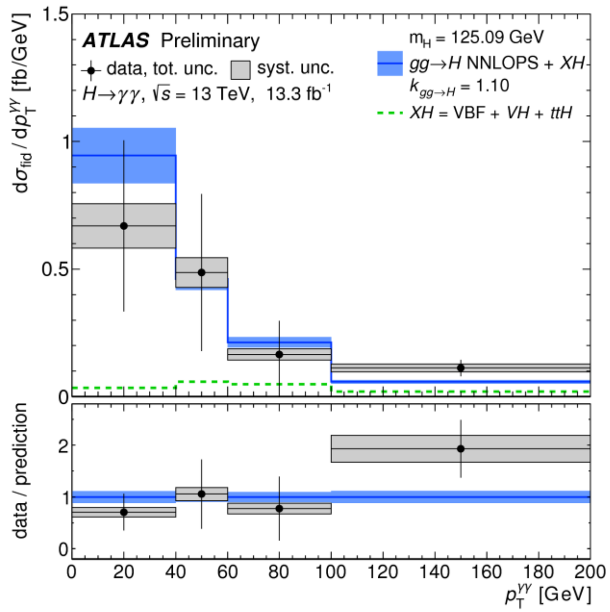
Assuming no BSM particles in the loops and there are no BSM decays.

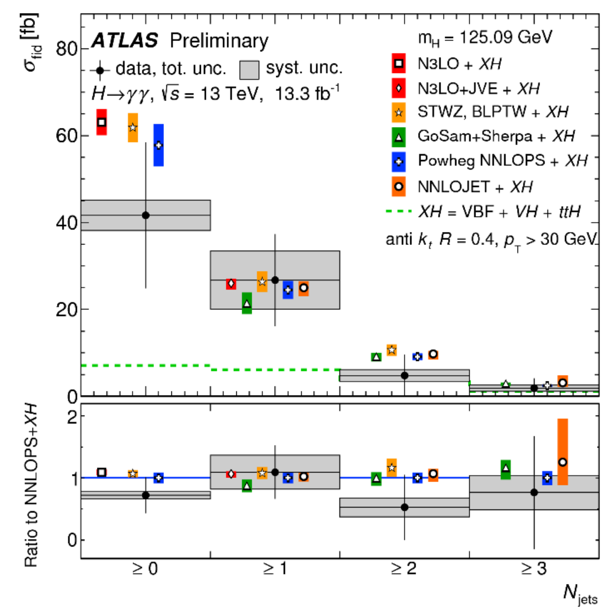
$H \to \gamma\gamma$ by ATLAS

- Signals are extracted by fitting of the diphoton invariant mass spectrum.
  - Observed significance is 4.7σ.
- Transverse momentum (p_T) of diphoton
  - Good agreement between data and theory
  - Data slightly undershoot (overshoot) the theory prediction at low (high) p_T.
- N_{jets}: Data are in agreement with state-of-art theory predictions.



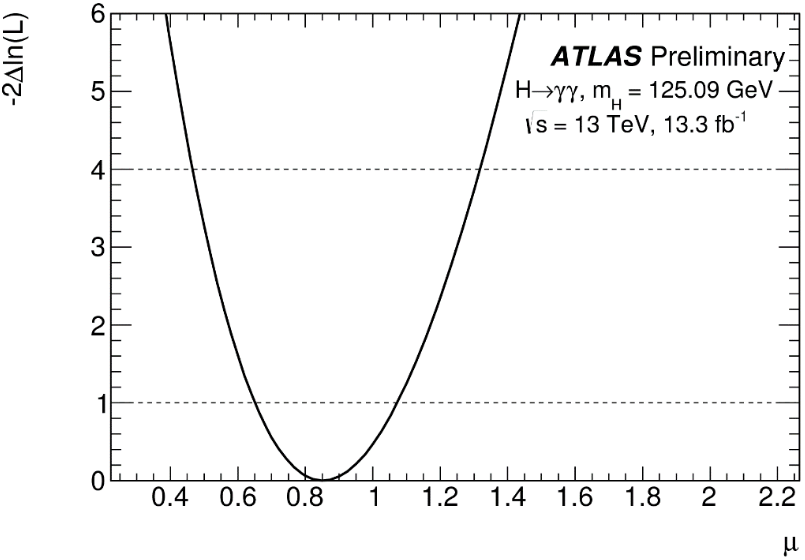


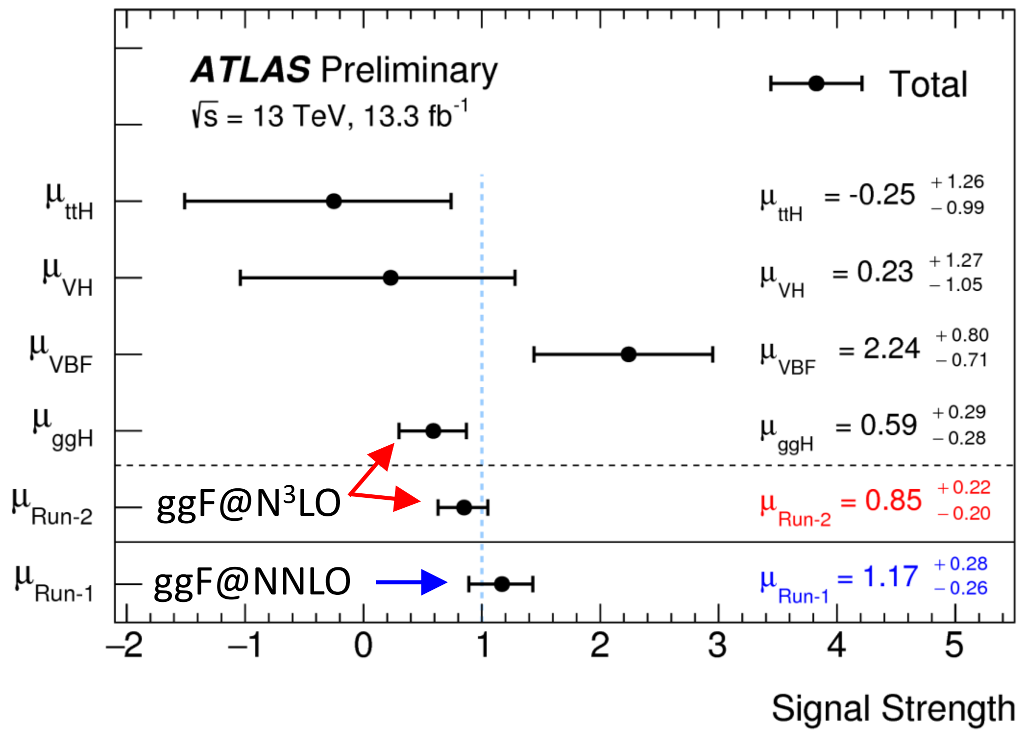




$H \to \gamma\gamma$ by ATLAS

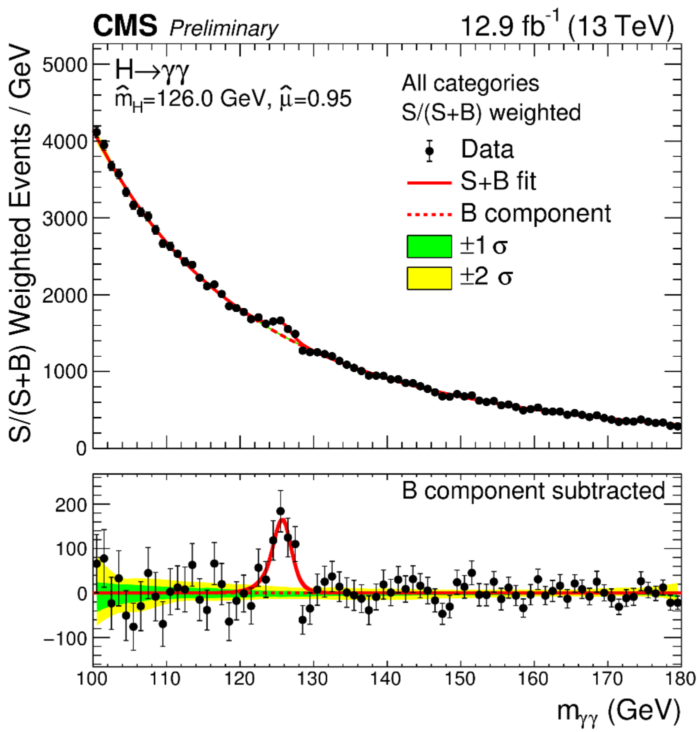
- Signal strength is obtained for each production mode.
- No significant deviation from the SM expectations is observed.
- Run 2 (Run 1) result uses N^{3}LO (NNLO) calculation for ggF.
- If N^{3}LO calculation is used for Run 1, the theory prediction for σ_{ggF} is increased by approximately 10%.

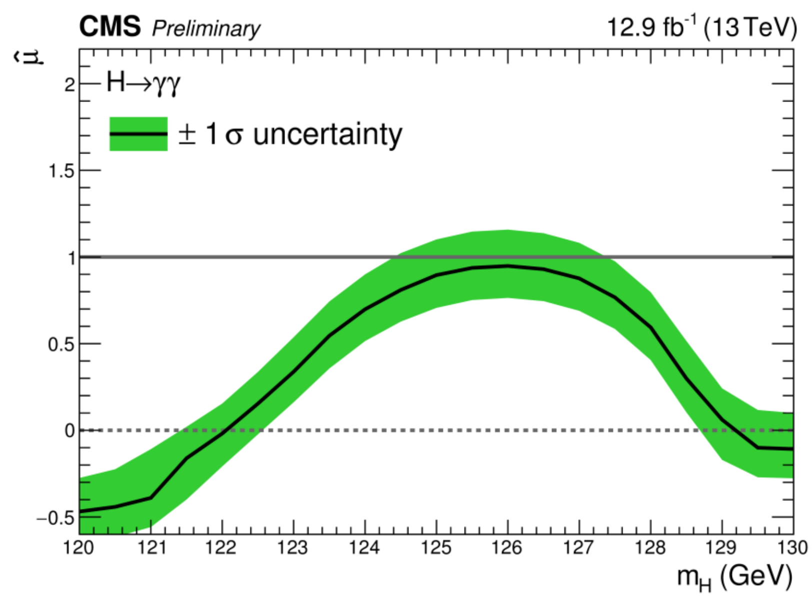




$H \to \gamma\gamma$ by CMS

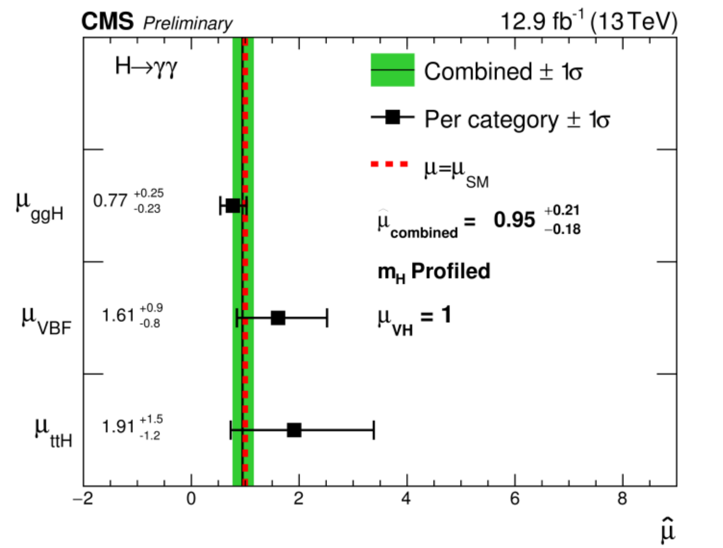
- CMS and ATLAS use very similar approaches.
- Look for bump on diphoton invariant mass spectrum.
- Categorize events by sensitivity and production topology using additional objects in the events.
- The maximum observed significance is 6.1σ at 126 GeV.
- $\mu = 0.95 \pm 0.20$

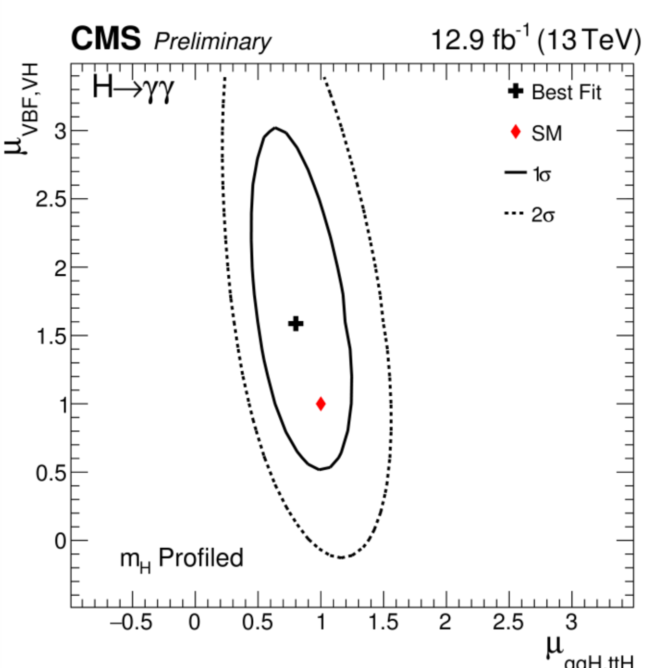


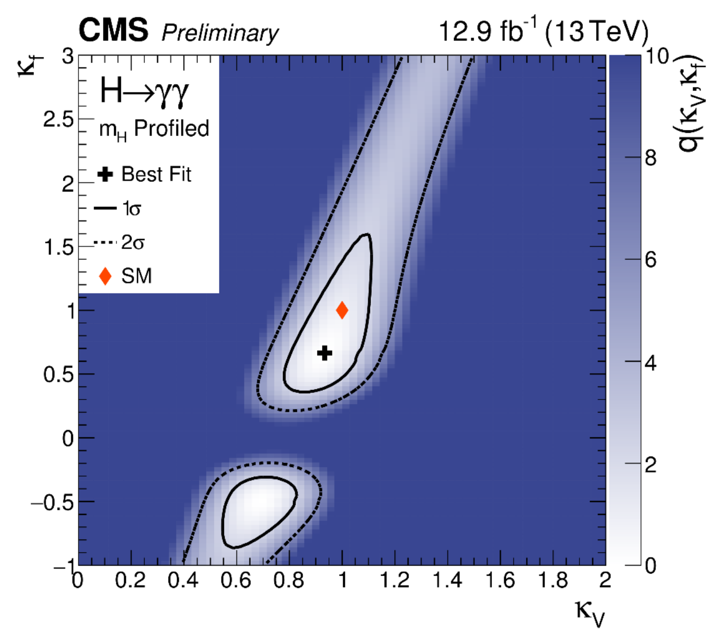


$H \to \gamma\gamma$ by CMS

- Signal strengths of individual production modes are consistent with the SM expectations.
- Couplings, κ_V and κ_F, are also consistent with the SM expectation.



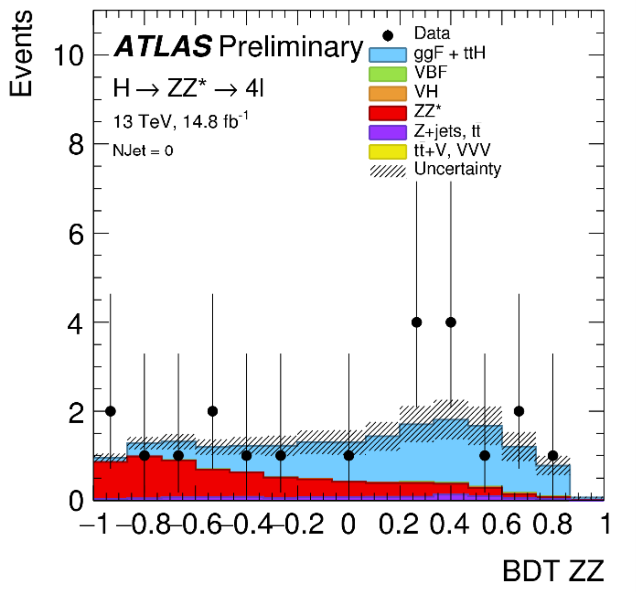


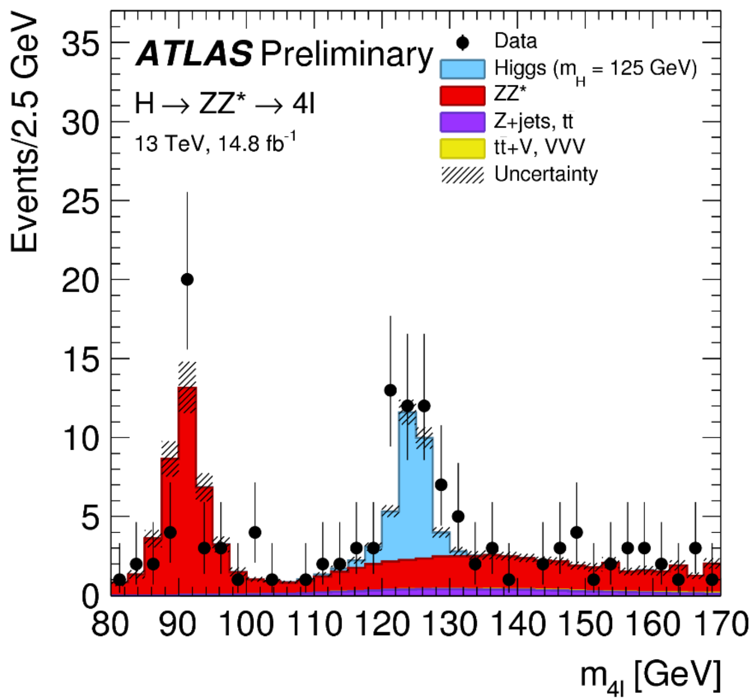


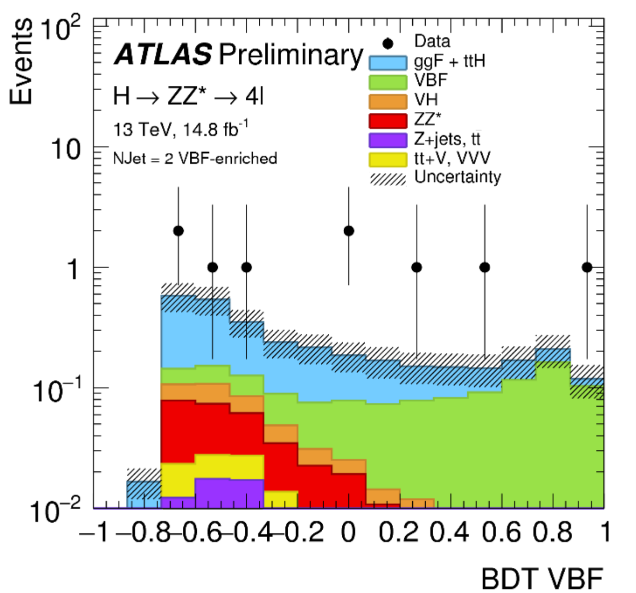
$H \to ZZ^* \to 4\ell$ by ATLAS

ATLAS-CONF-2016-079

- Events are categorized.
  - To measure cross section per production mode
  - To provide sensitivity to BSM interactions
- Signals are extracted through a likelihood fit to the shape of discriminants (Boosted Decision Tree) in each category.

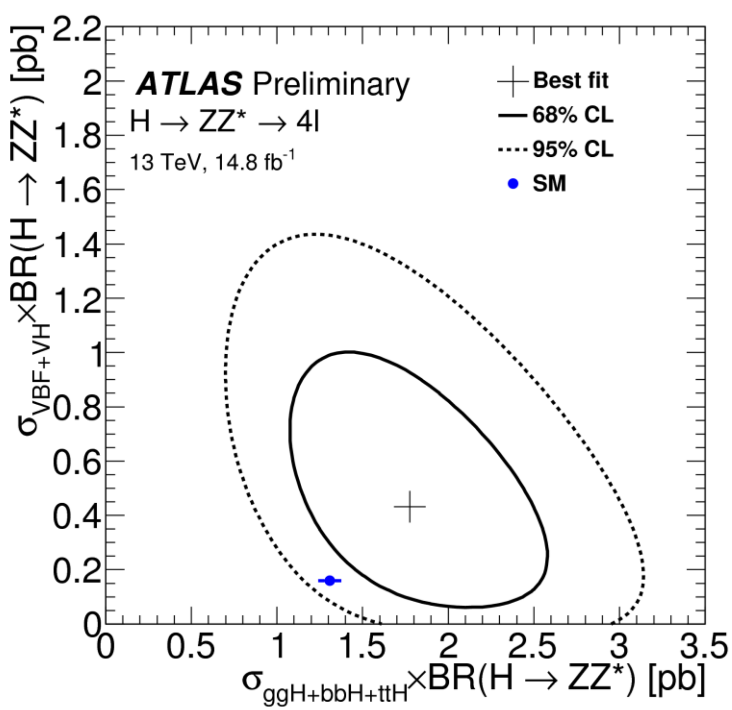


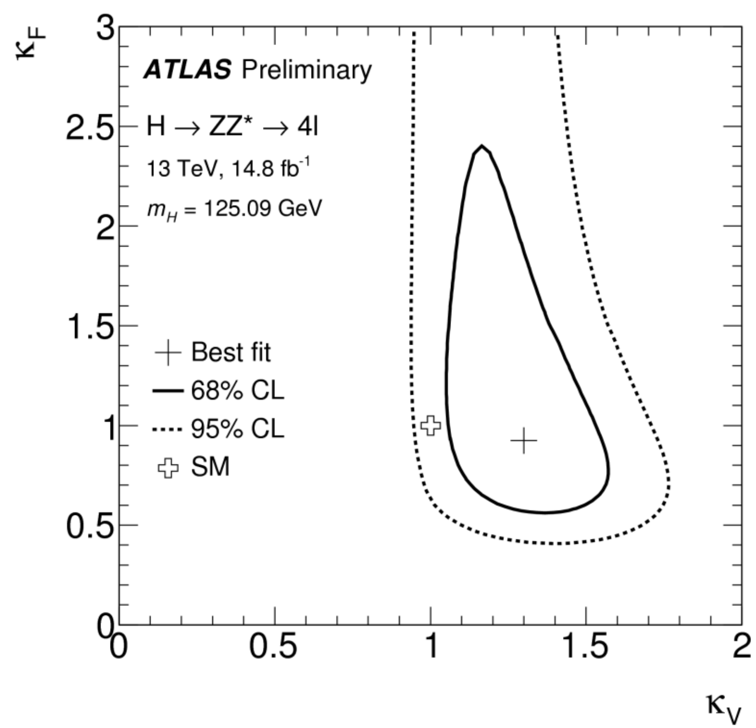




$H \to ZZ^* \to 4\ell$ by ATLAS

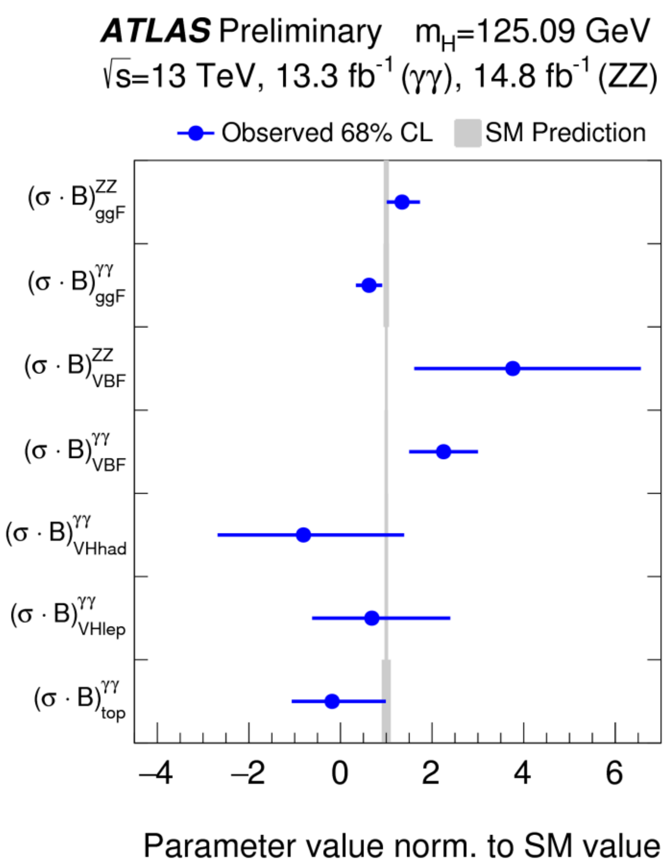
- Measured cross sections and couplings are consistent with the SM expectations within 2σ.
- Mass is fixed to m_H=125.09 GeV.
- No undetected or invisible decays are assumed to exist.

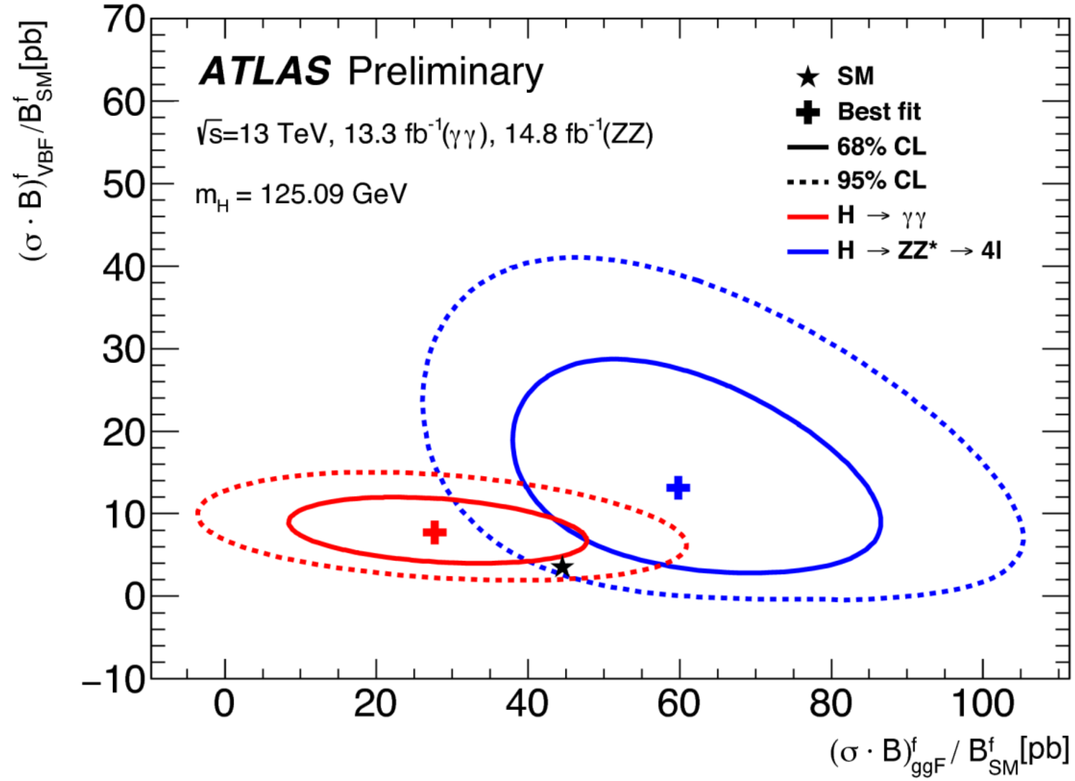




Combination by ATLAS

- Combined Run 2 $\gamma\gamma$ and ZZ^* results
- Simplified template cross sections are for $|y_H|<2.5$.
- Inclusive: $\mu = 1.13^{+0.18}_{-0.17}$

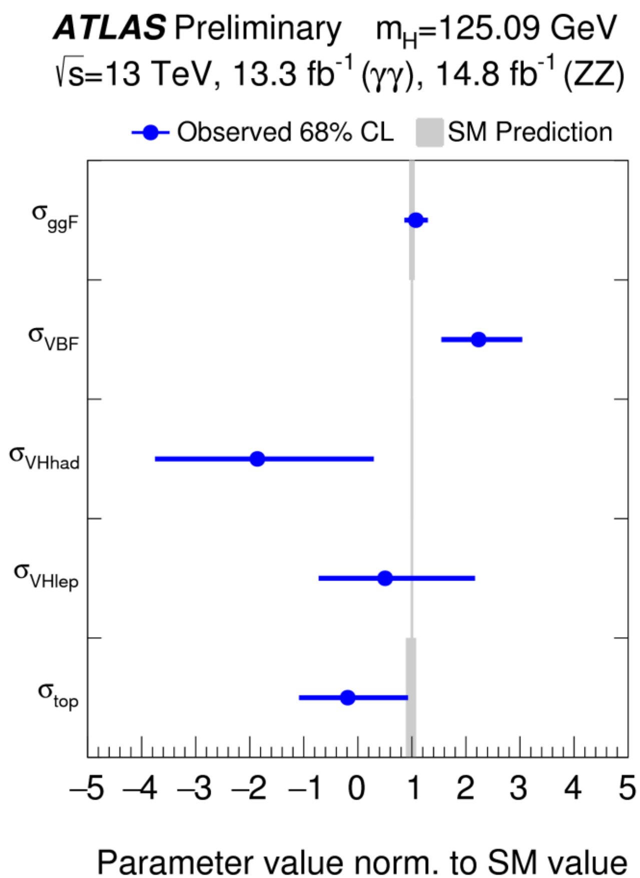


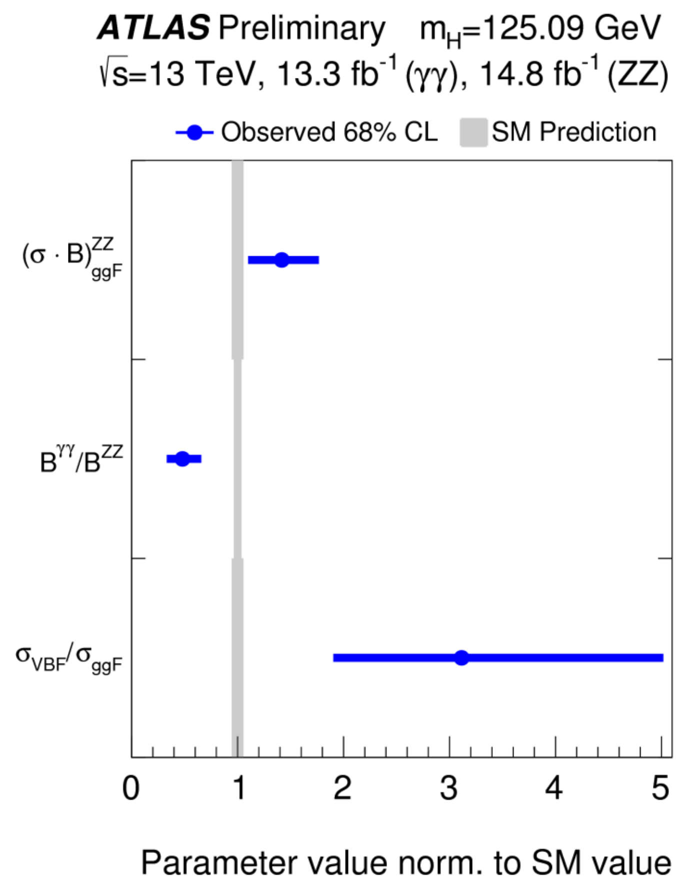


Combination by ATLAS

ATLAS-CONF-2016-081

- Vector Boson Fusion production mode
  - Local significance is about 4σ.
- No significant deviations from the SM expectations are observed.



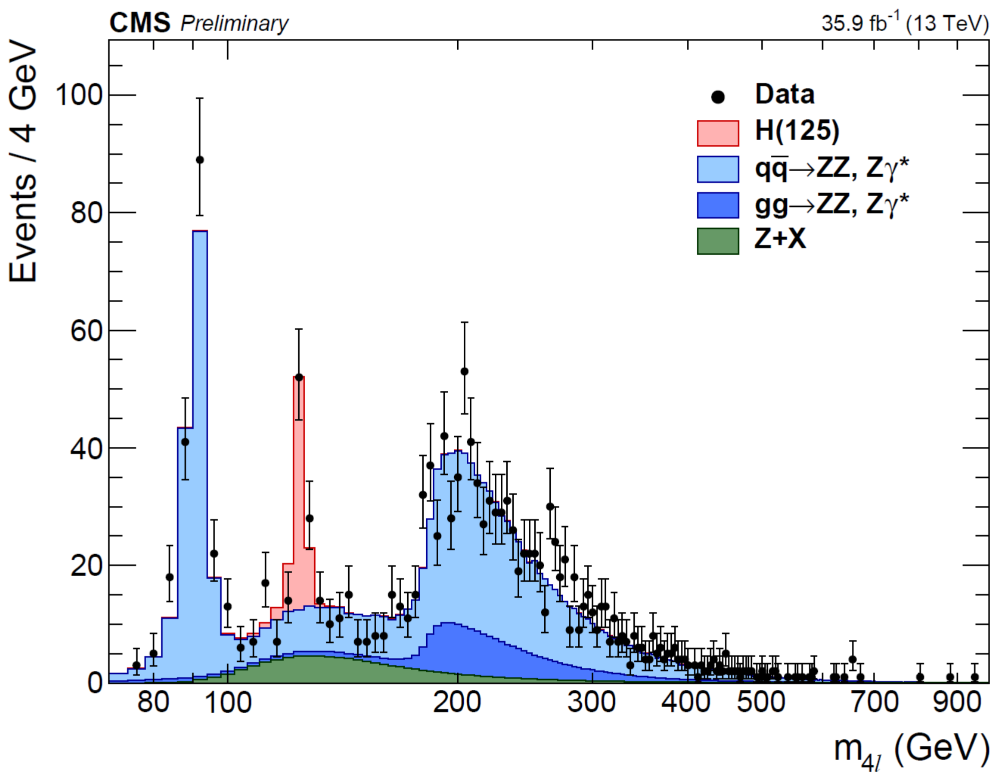


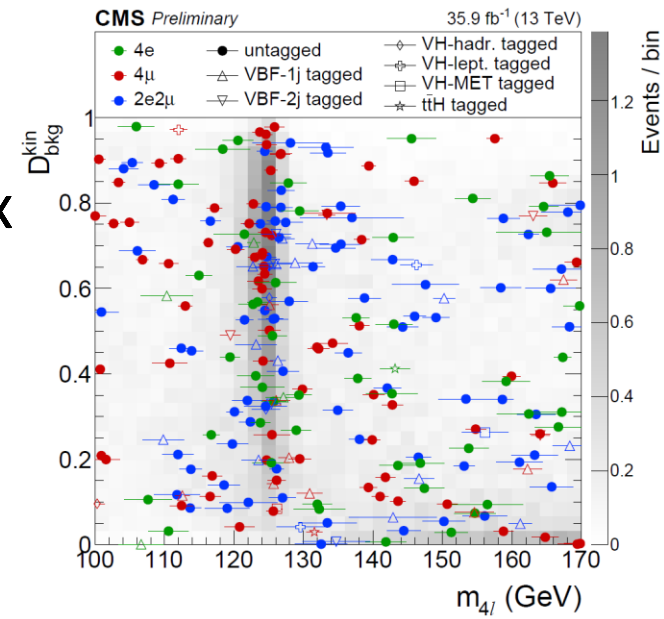
$H \rightarrow ZZ^{*} \rightarrow 4\ell$ by CMS

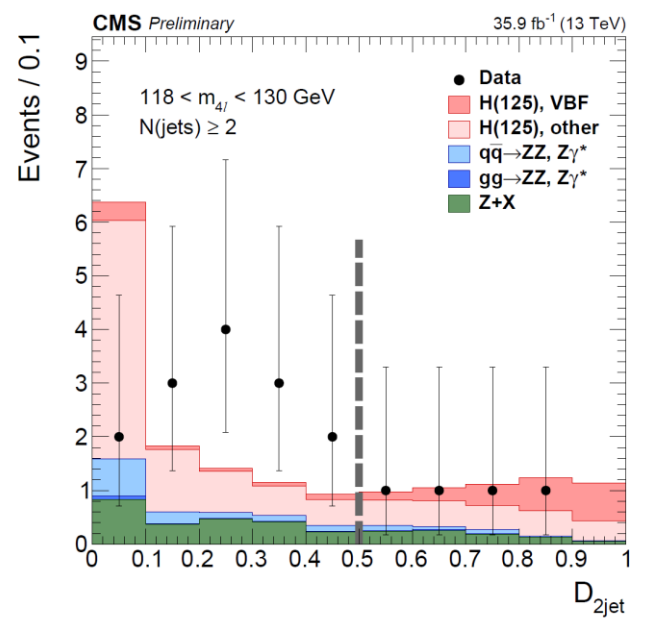
CMS-PAS-HIG-16-041

NEW

- Probing 4 (ggH, VBF, VH, ttH) production modes with 7 event categories.
- Make kinematic discriminants using matrix elements with inputs of kinematic properties to reject background events and categorize signal events.





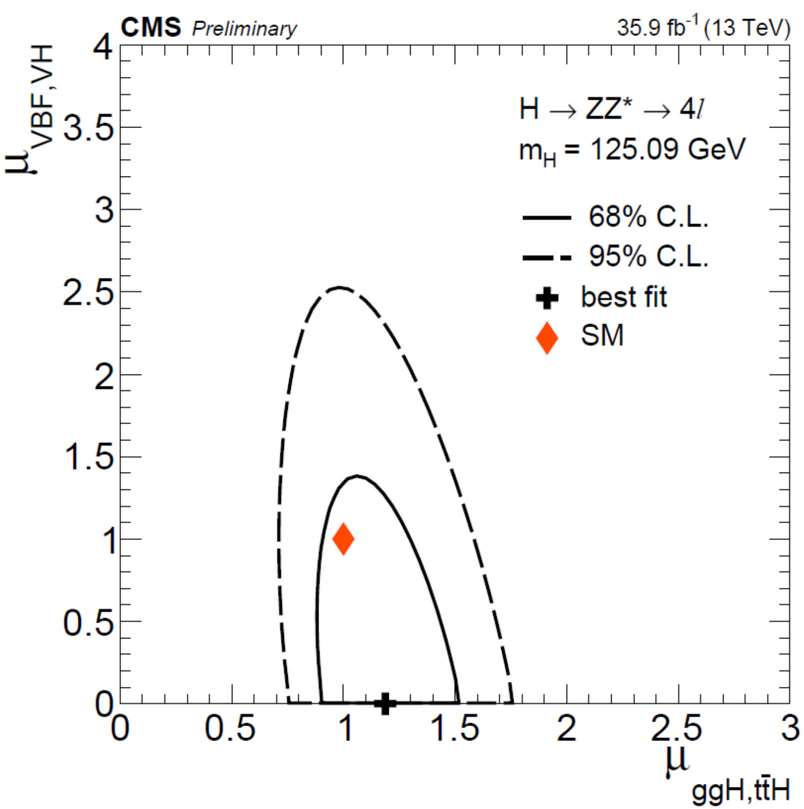


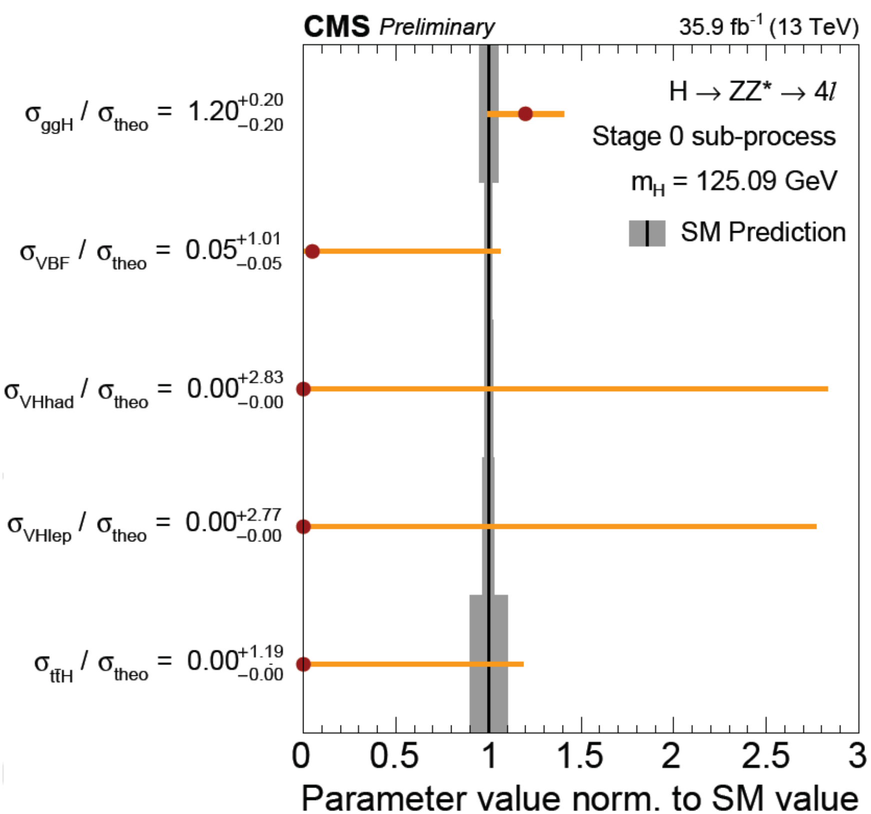
$H \rightarrow ZZ^* \rightarrow 4\ell$ by CMS

CMS-PAS-HIG-16-041

NEW

- $\mu = 1.05^{+0.15}_{-0.14}(\text{stat.})^{+0.11}_{-0.09}(\text{syst.})$
  - Combined signal strength at m_H=125.09 GeV.
- Simplified template cross sections for $|y_H|$<2.5.



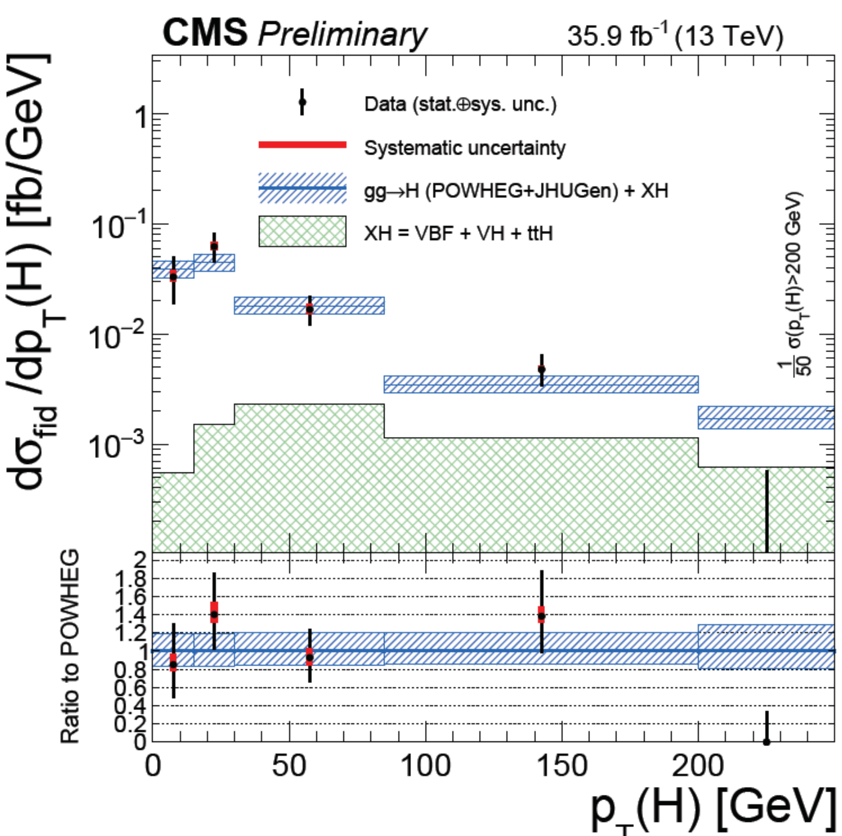


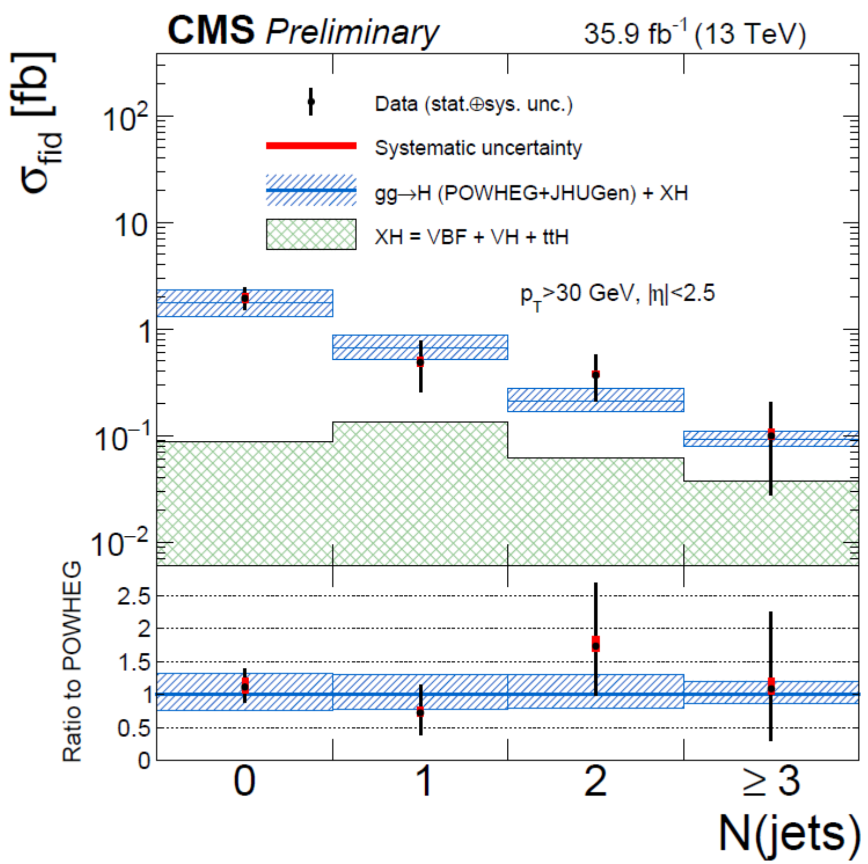
$H \to ZZ^* \to 4\ell$ by CMS

CMS-PAS-HIG-16-041

NEW

- Differential cross-section with respect to $p_T(H)$ and the number of jets.
- Consistent with the SM expectations within uncertainty.





Mass by CMS

CMS-PAS-HIG-16-041

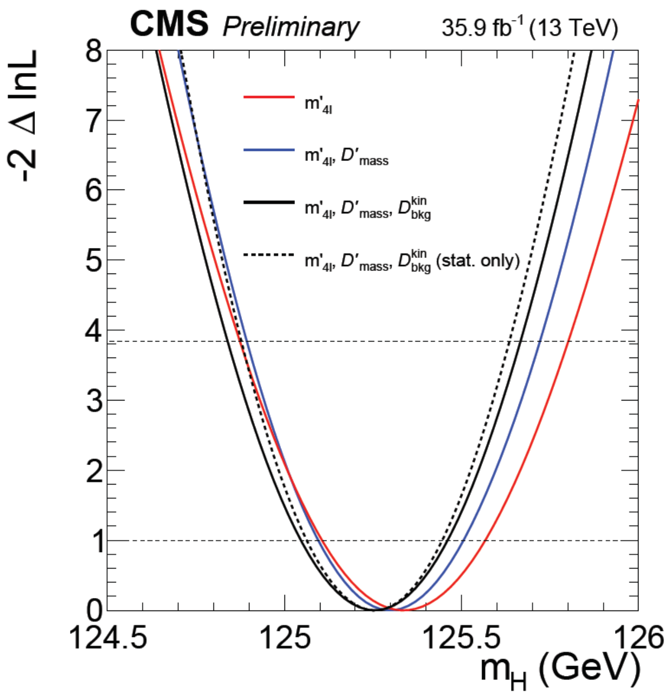
NEW

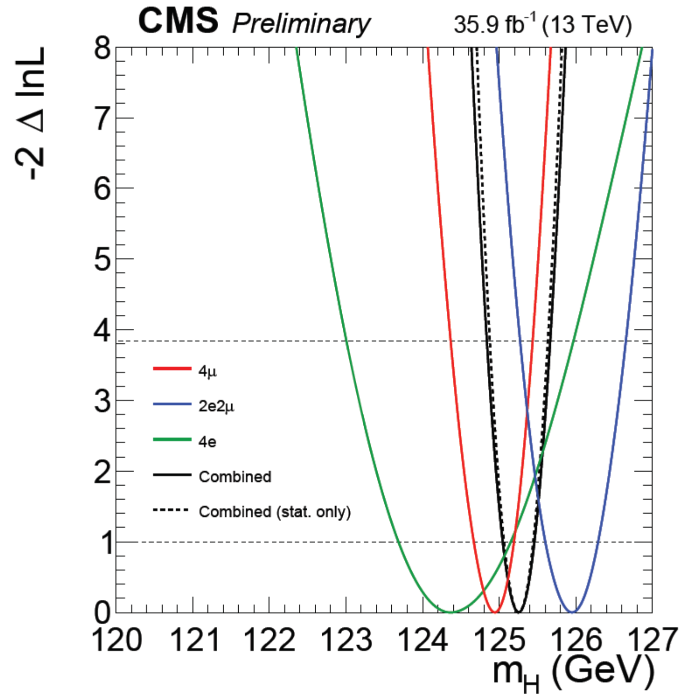
- Mass is determined by 3D measurement with $m(Z_1)$ constraint.
  - Invariant mass: $m'_{4\ell}$
  - Mass error: D'_{mass}
  - Discriminant for $qq/gg \rightarrow 4\ell$: $D^{\mathrm{kin}}_{\mathrm{bkg}}$

YSF1 (this afternoon)
Hualin Mei

- $m_H = 125.26 \pm 0.20\,(\mathrm{stat.}) \pm 0.08\,(\mathrm{syst.})$ GeV
  - Run 1 ATLAS and CMS combination

$m_H = 125.09 \pm 0.21\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{syst.})$ GeV

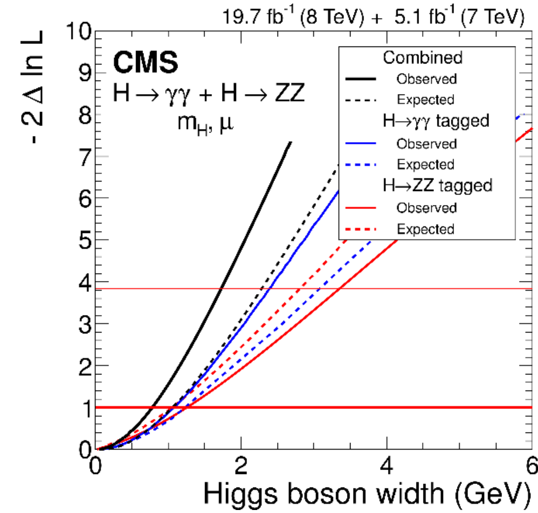




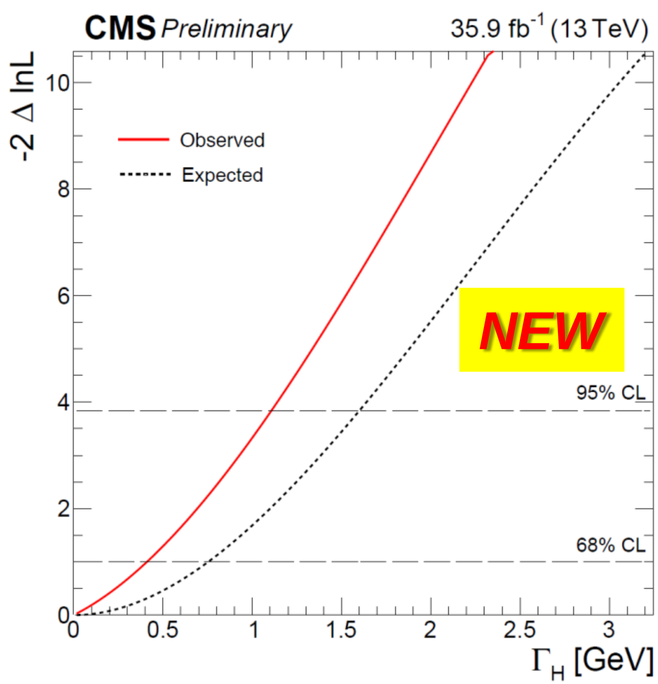
Width by CMS

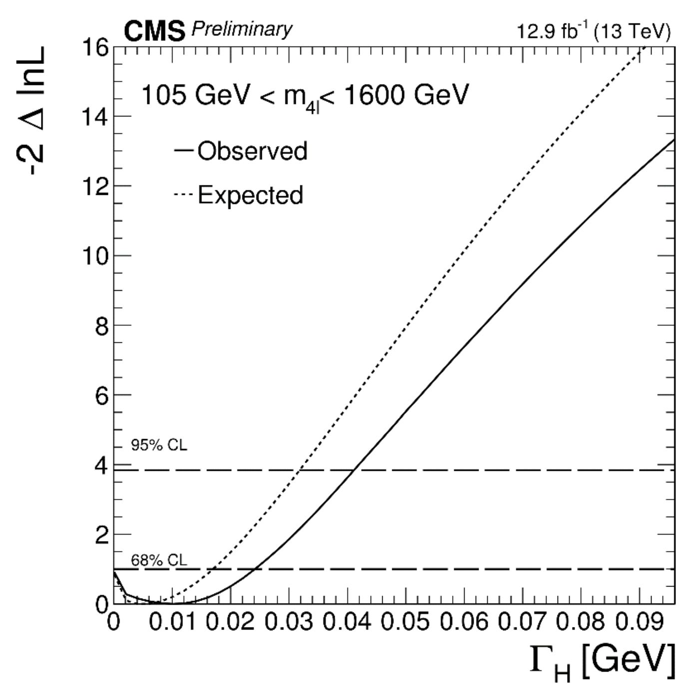
CMS-PAS-HIG-16-041
CMS-PAS-HIG-16-033

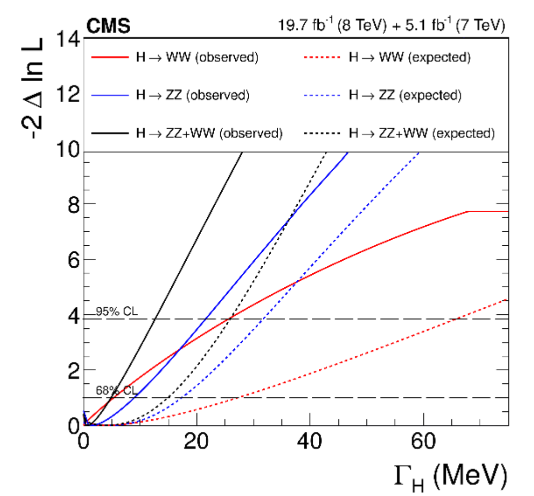
- Mass width is measured with two very different methods.
- $\Gamma_H = 0.00^{+0.41}_{-0.00}$ GeV with only on-shell
  - Tighter limit than Run 1
- $\Gamma_H = 10^{+14}_{-10}$ MeV with both on-shell and off-shell
  - With strong theory assumptions
  - With only 12.9 fb^{-1}



EPJC 75 (2015) 212







JHEP 09 (2016) 051

Anomalous HVV interactions

CMS-PAS-HIG-17-011

NEW

- Scattering amplitude for a spin-0 boson and two spin-1 gauge bosons VV $(= ZZ^*, Z\gamma^*)$

$$\underbrace{\left[\underbrace{a_1^{VV}}_{\text{SM (CP+)}} + \underbrace{\frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV} (q_1+q_2)_1^2}{\left(\Lambda_Q^{VV}\right)^2}}_{\text{BSM (CP+)}}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^*}_{} + \underbrace{a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\text{BSM (CP+)}} + \underbrace{a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{BSM (CP-)}}$$

Anomalous Coupling	Coupling Phase	Effective Fraction	Translation Constant
a_3	ϕ_{a3}	f_{a3}	$\sigma_1/\sigma_3 = 6.53$
a_2	ϕ_{a2}	f_{a2}	$\sigma_1/\sigma_2 = 2.77$
Λ_1	$\phi_{\Lambda 1}$	$f_{\Lambda 1}$	$\sigma_1/\tilde{\sigma}_{\Lambda 1} = 1.47 \times 10^4\ \text{TeV}^{-4}$
$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$	$\sigma_1'/\tilde{\sigma}_{\Lambda 1}^{Z\gamma} = 5.80 \times 10^3\ \text{TeV}^{-4}$

Effective fractions

$$f_{aj} = \frac{\left|a_j\right|^2 \sigma_j}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\,\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\,\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}$$

Coupling phases

$$\phi_{aj} = \arg\left(\frac{a_j}{a_1}\right)$$

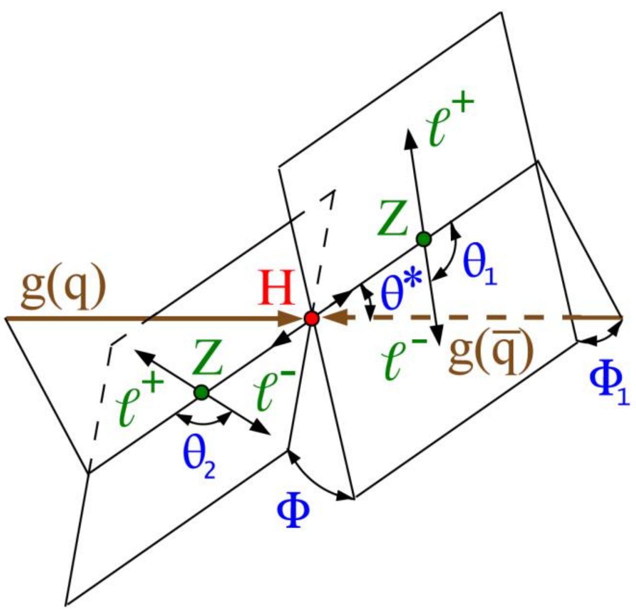
$$\phi_{\Lambda 1}$$

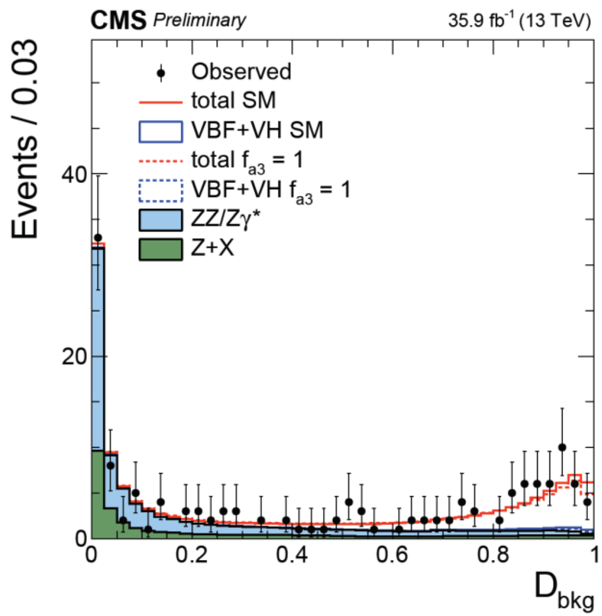
Anomalous HVV interactions

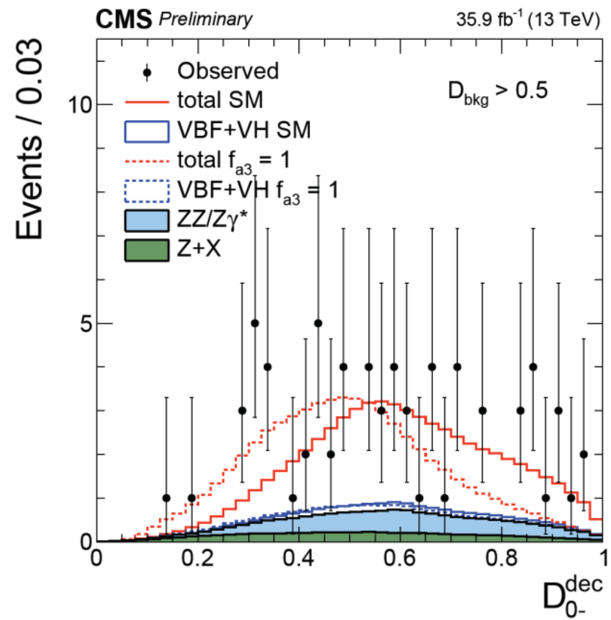
CMS-PAS-HIG-17-011

NEW

- The full kinematic information from each event using either the spin-0 boson **<u>decay</u>** or associated particles in its **<u>production</u>** is extracted using matrix element calculations.
  - Up to 13 observables
- Three types of discriminants are defined for either production or decay.
  - Separate signal and background
  - Separate SM and BSM contributions
  - Isolate SM-BSM interference contributions







Anomalous HVV interactions

CMS-PAS-HIG-17-011

NEW

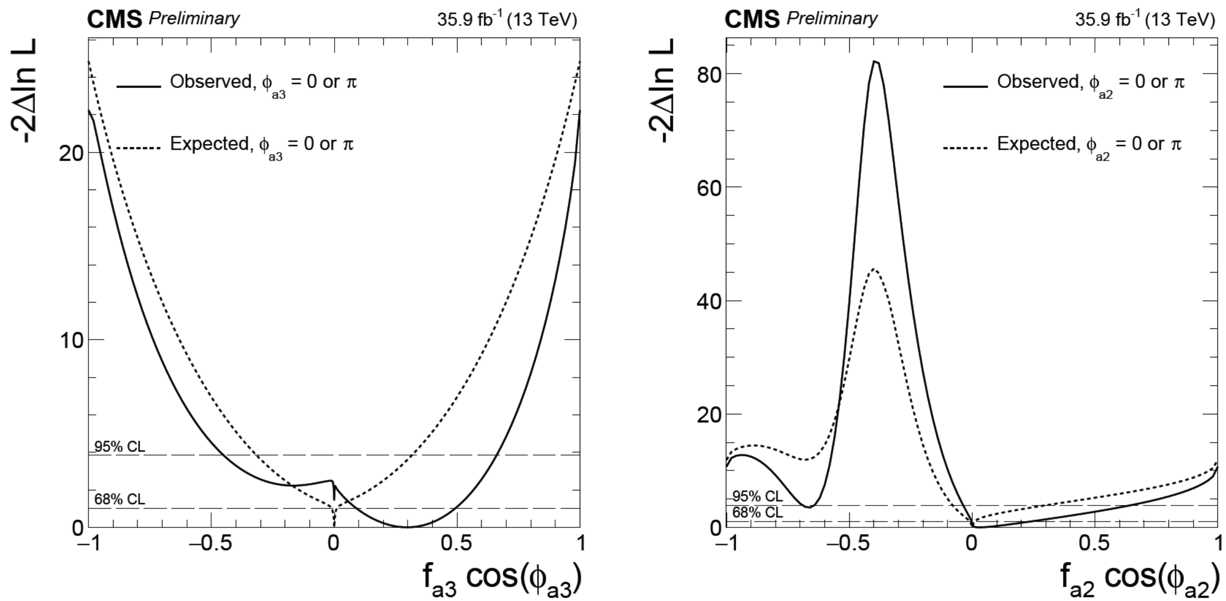


Table 5: Summary of allowed 68% CL (central values with uncertainties) and 95% CL (ranges in square brackets) intervals on anomalous coupling parameters in HVV interactions under the assumption that all the coupling ratios are real ($\phi_{ai}^{VV} = 0$ or π). The expected results are quoted for the SM signal production cross section ($f_{an} = 0$ and $\mu_V = \mu_f = 1$).

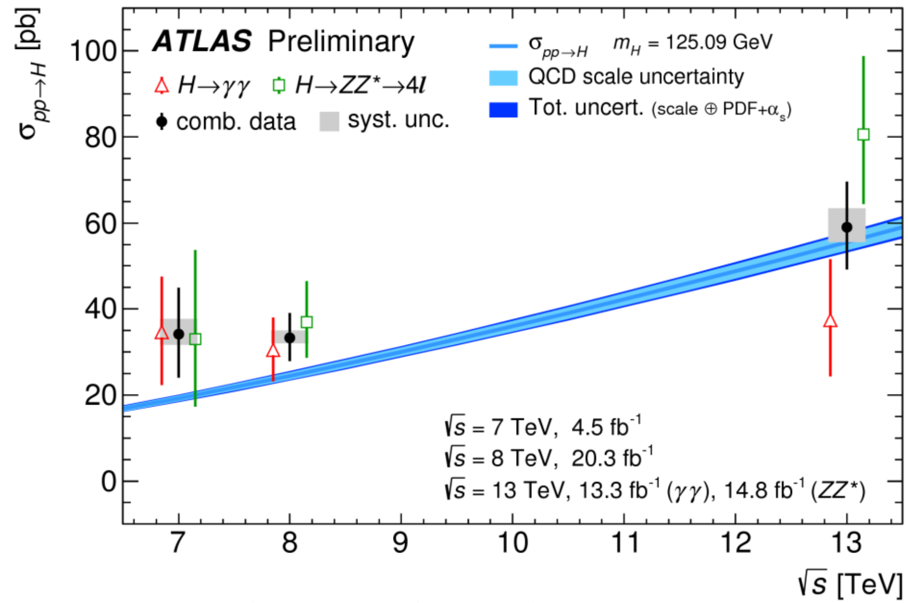
Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21}$ $[-0.45, 0.66]$	$0.000^{+0.017}_{-0.017}$ $[-0.32, 0.32]$
$f_{a2}\cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04}$ $[-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014}$ $[-0.08, 0.29]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.06}_{-0.33}$ $[-0.92, 0.15]$	$0.000^{+0.014}_{-0.014}$ $[-0.79, 0.15]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$

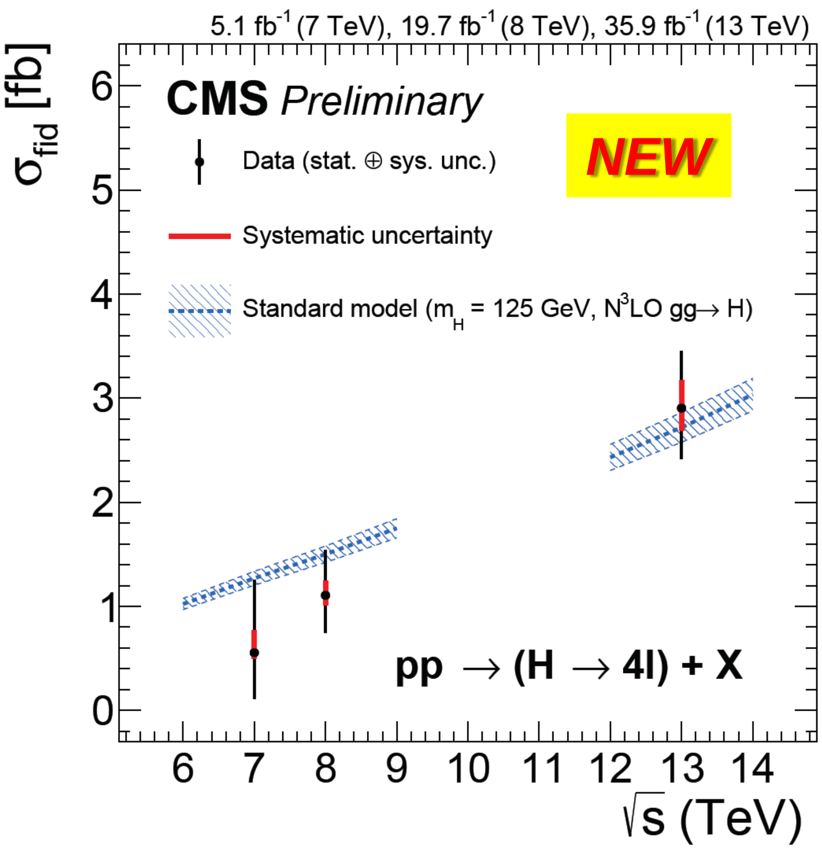
All observations are consistent with the SM expectations.

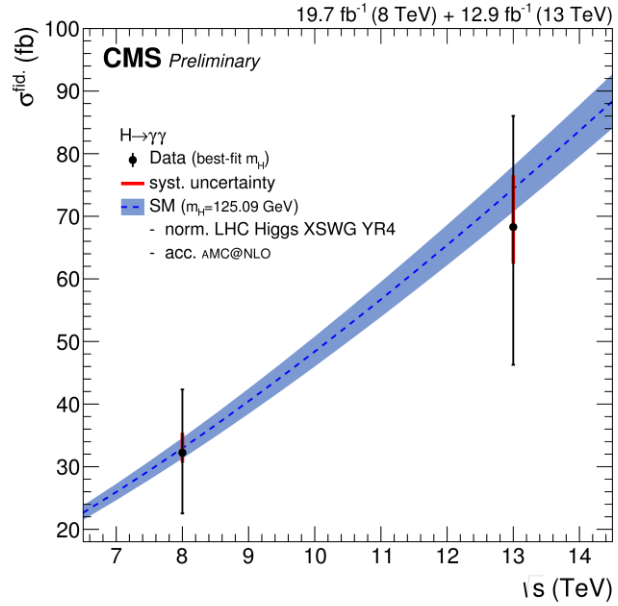
Total/fiducial cross section

ATLAS-CONF-2016-081
CMS-PAS-HIG-16-020
CMS-PAS-HIG-16-041

- Total (ATLAS) and fiducial (CMS) cross sections are consistent with N^3LO QCD calculation with NLO electroweak corrections.



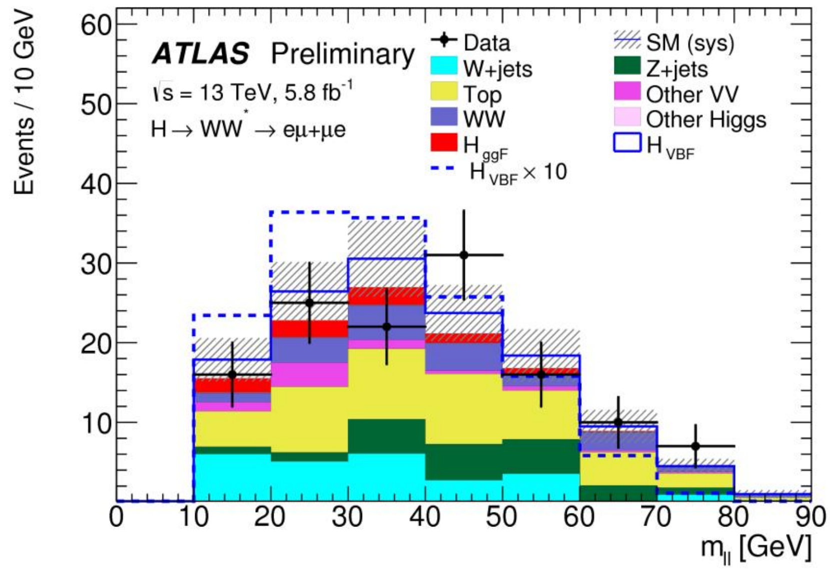


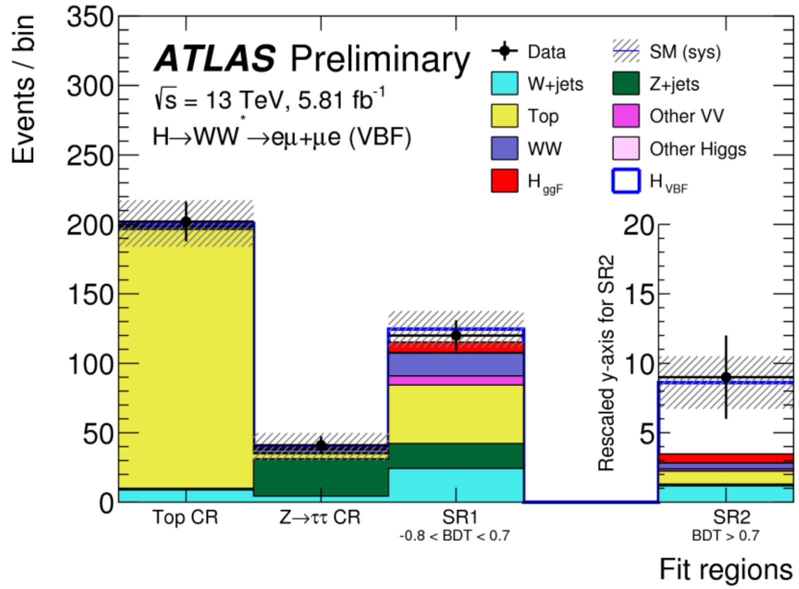


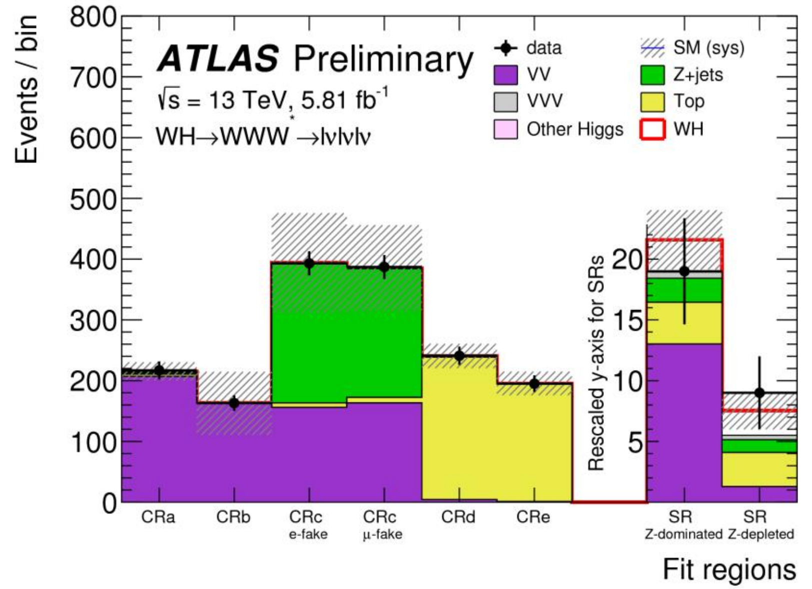
$H \to WW^*$ by ATLAS

ATLAS-CONF-2016-112

- VBF and WH production modes are studied.
- Events are categorized based on jet and lepton multiplicity.
- $\mu_{VBF} = 1.7^{+1.1}_{-0.9}$, $\mu_{WH} = 3.2^{+4.4}_{-4.2}$
  - Consistent with the SM

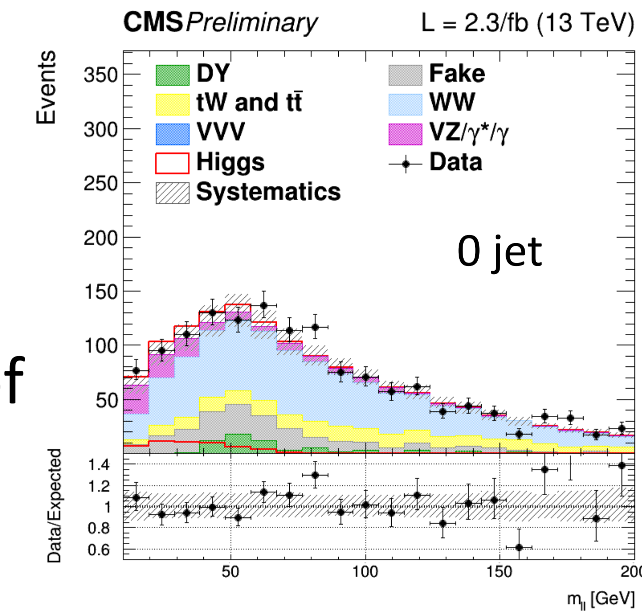


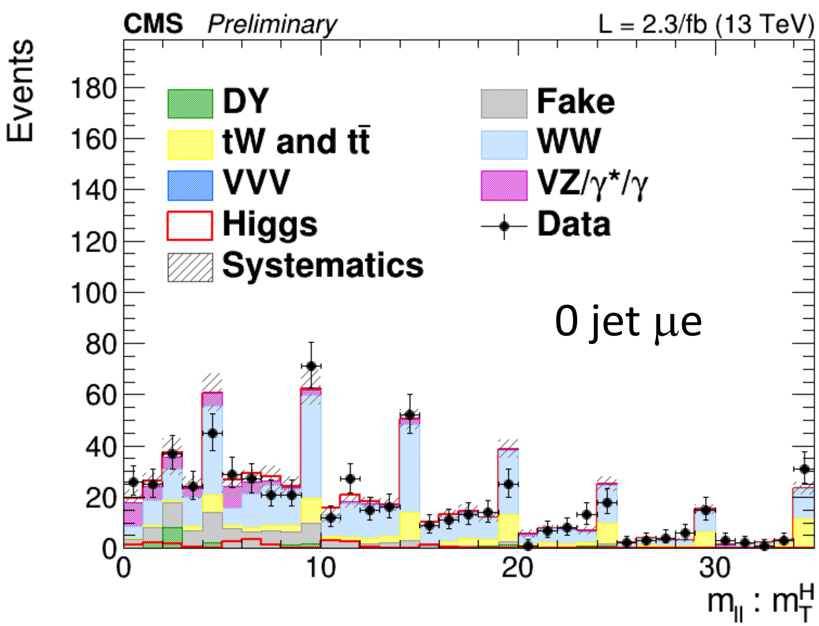


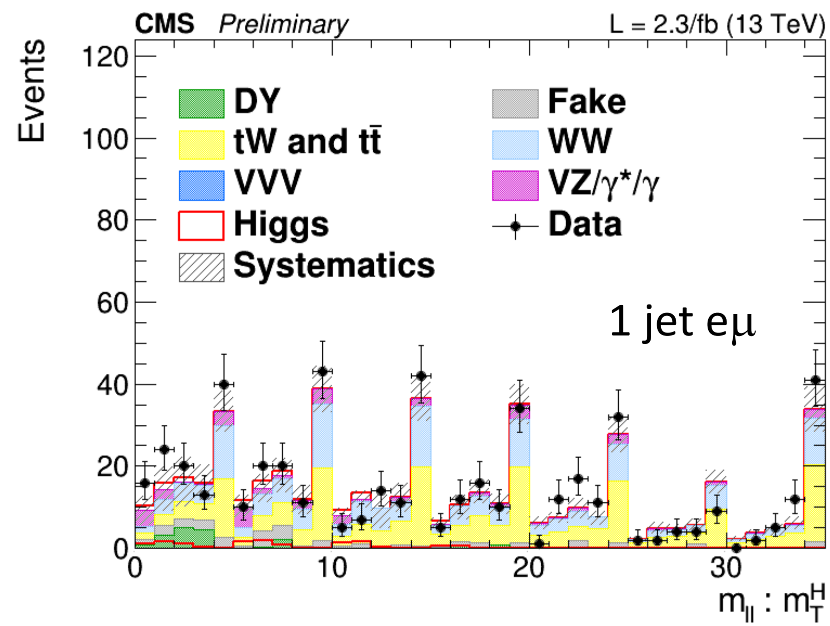


$H \to WW^*$ by CMS

- ggF production mode is the target.
- Event categorization is based on
  - 0 jet or 1 jet
  - eμ or μe (p_T ordered)
- Binned fit using template histograms of unrolled distributions of $m_{\ell\ell}$ and m_T^H
- $\mu = 0.3 \pm 0.5$

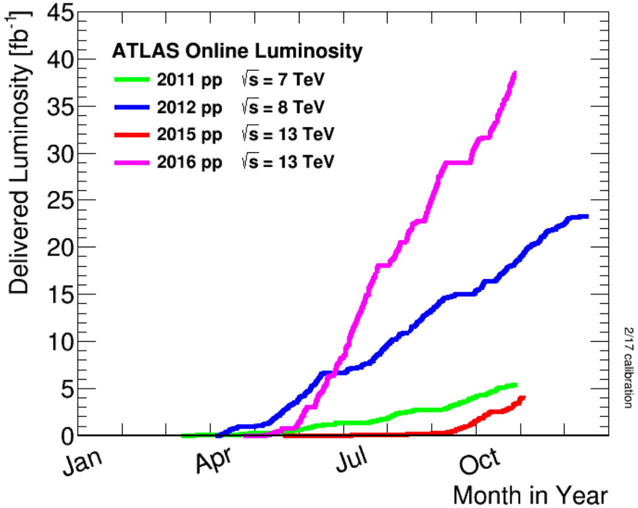




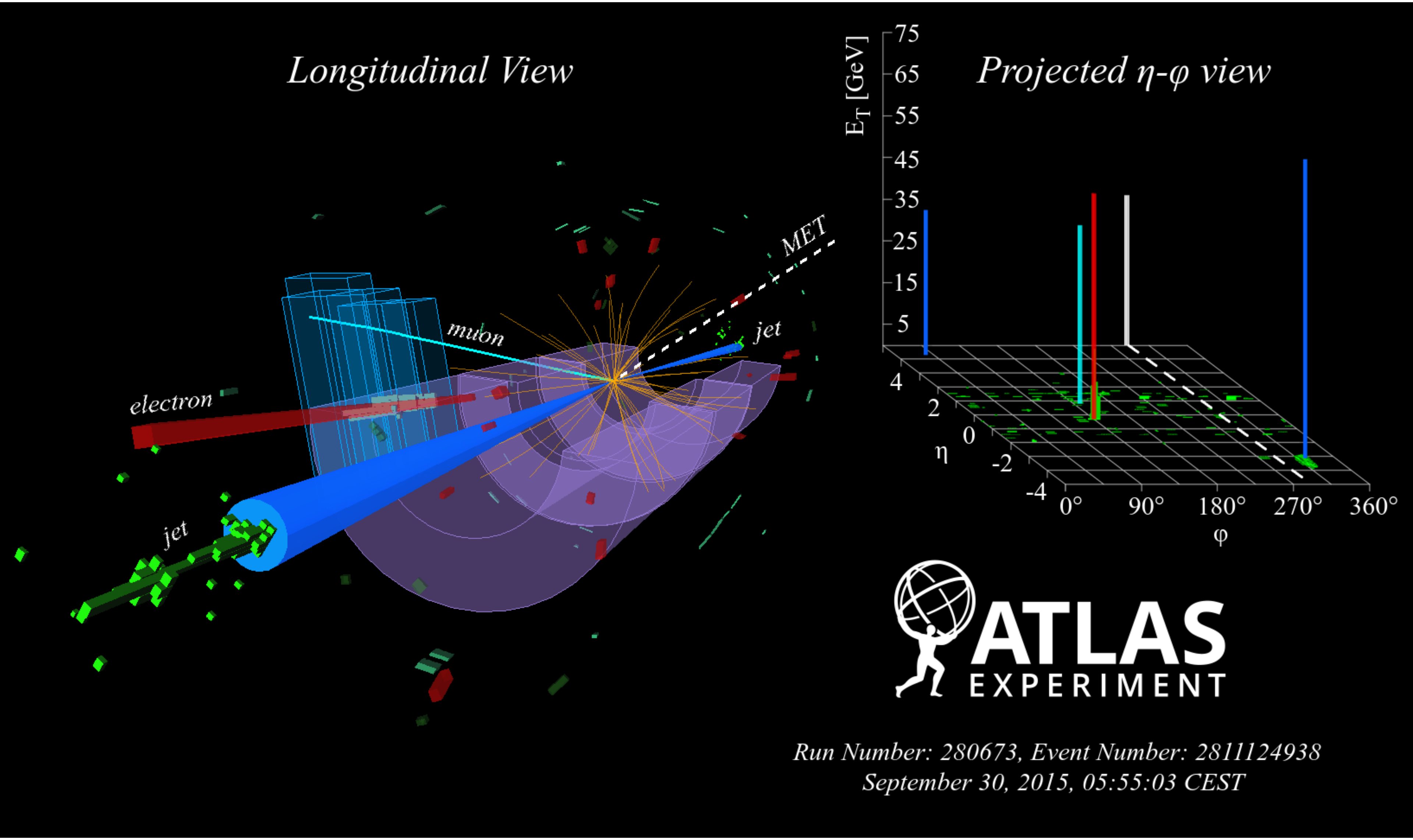


Summary

- Measurement of couplings and mass plays a key role to test the BEH mechanism and to find deviations.
- Results with Run 2 data at 13 TeV are shown.
- All results are compatible with the SM expectations.
- Uncertainties with Run 2 are getting smaller than ones with Run 1.
- New CMS ZZ^* results with the full dataset taken by 2016 are shown.
- Other analyses with the full dataset are ongoing.



Back-up slides



arXiv:1605.04692 [hep-ph]

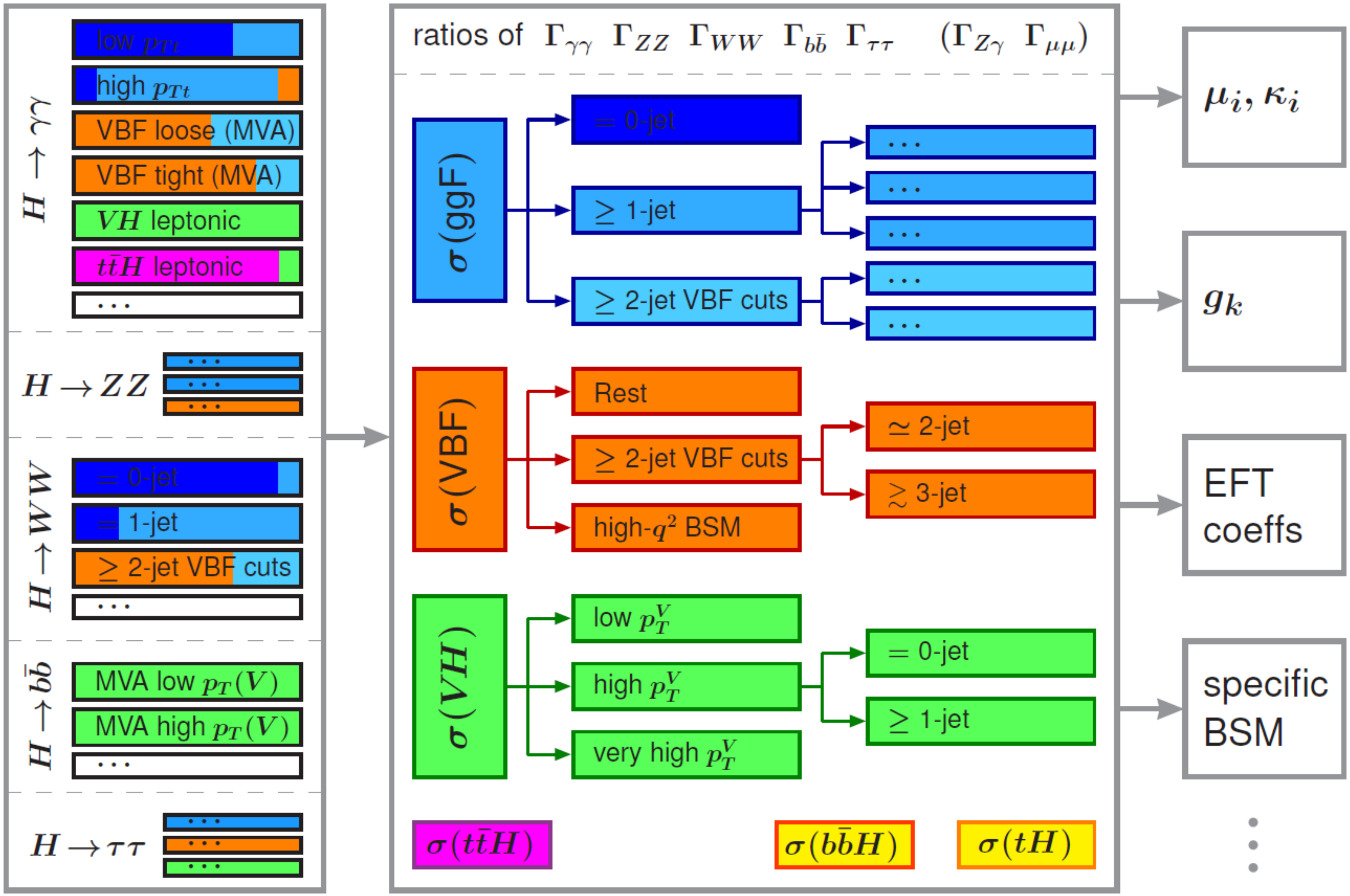


Fig. III.4: Schematic overview of the simplified template cross section framework.