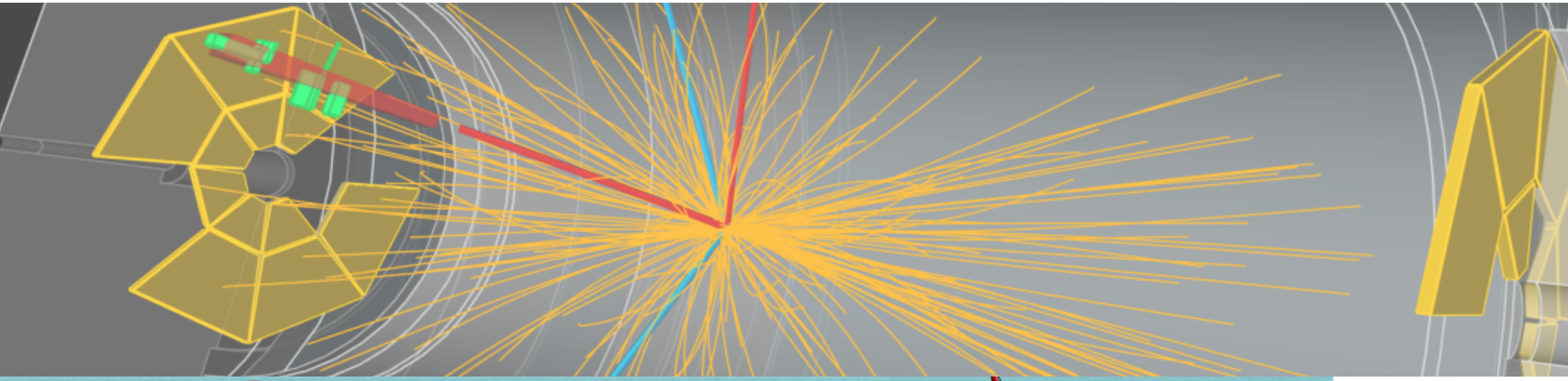
Bosonic SM Higgs decays at ATLAS + CMS

Yanping Huang (*DESY*)

On behalf of the ATLAS & CMS collaboration

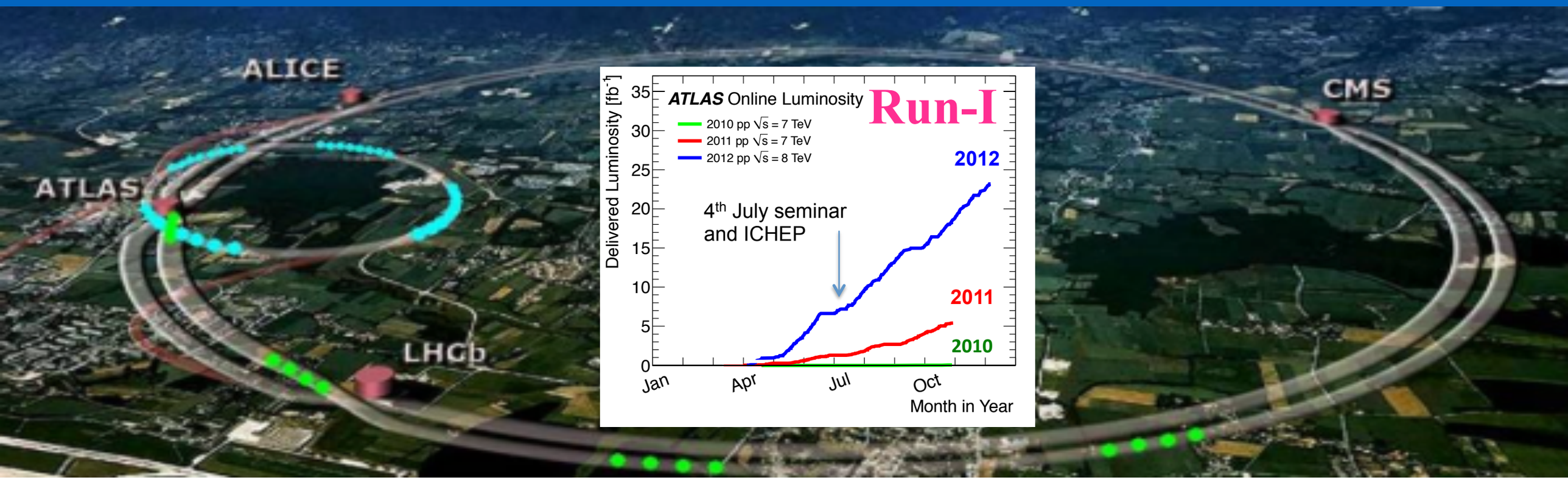


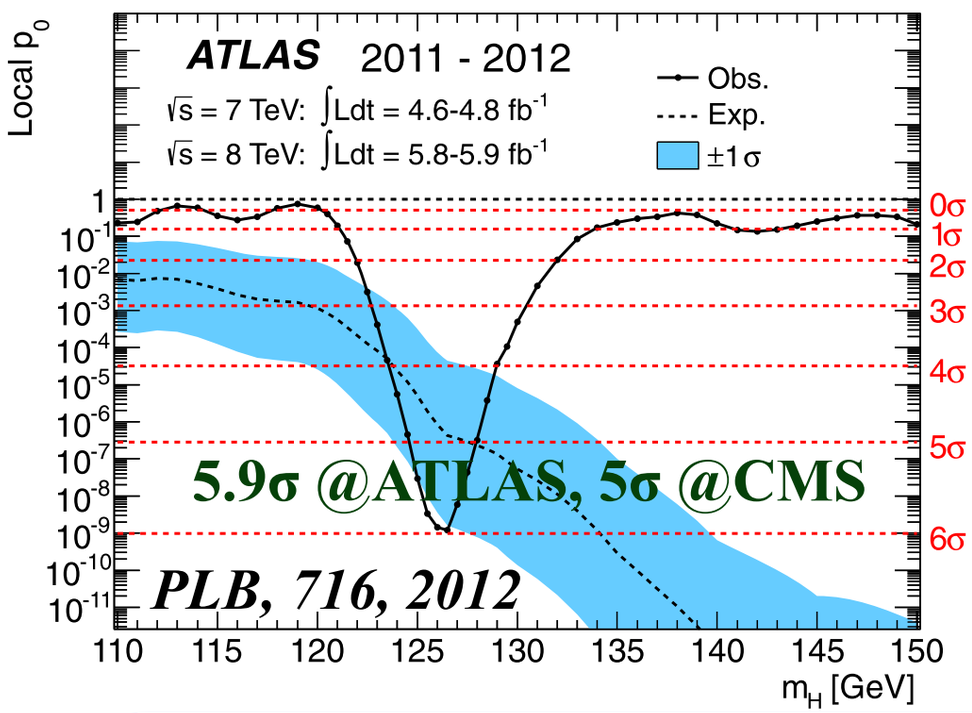
QCD@LHC

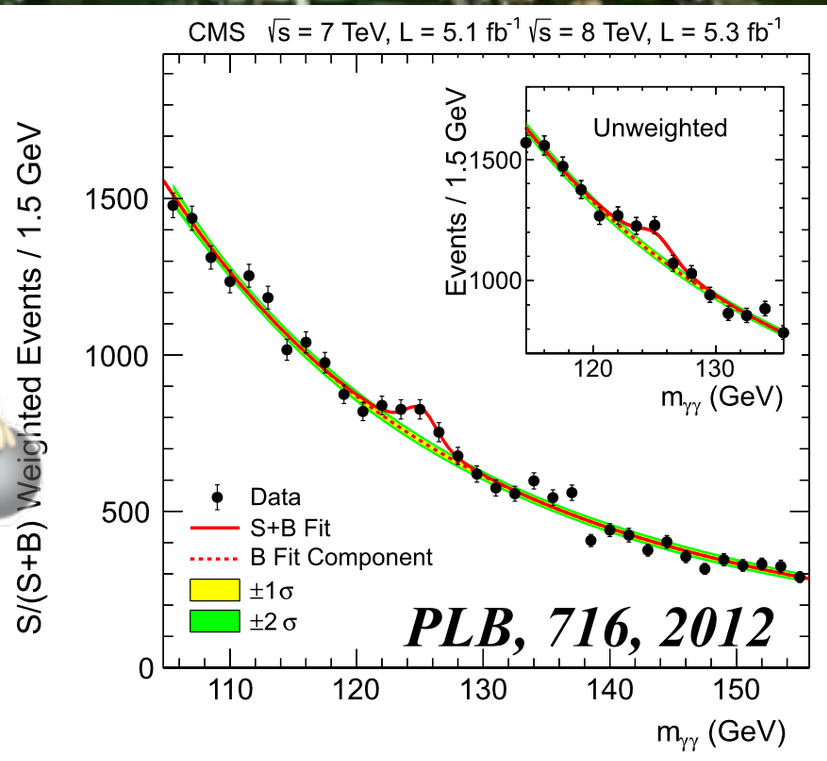
22ND–26TH AUGUST 2016

INTERNATIONAL CONFERENCE ZURICH

LHC and ATLAS/CMS



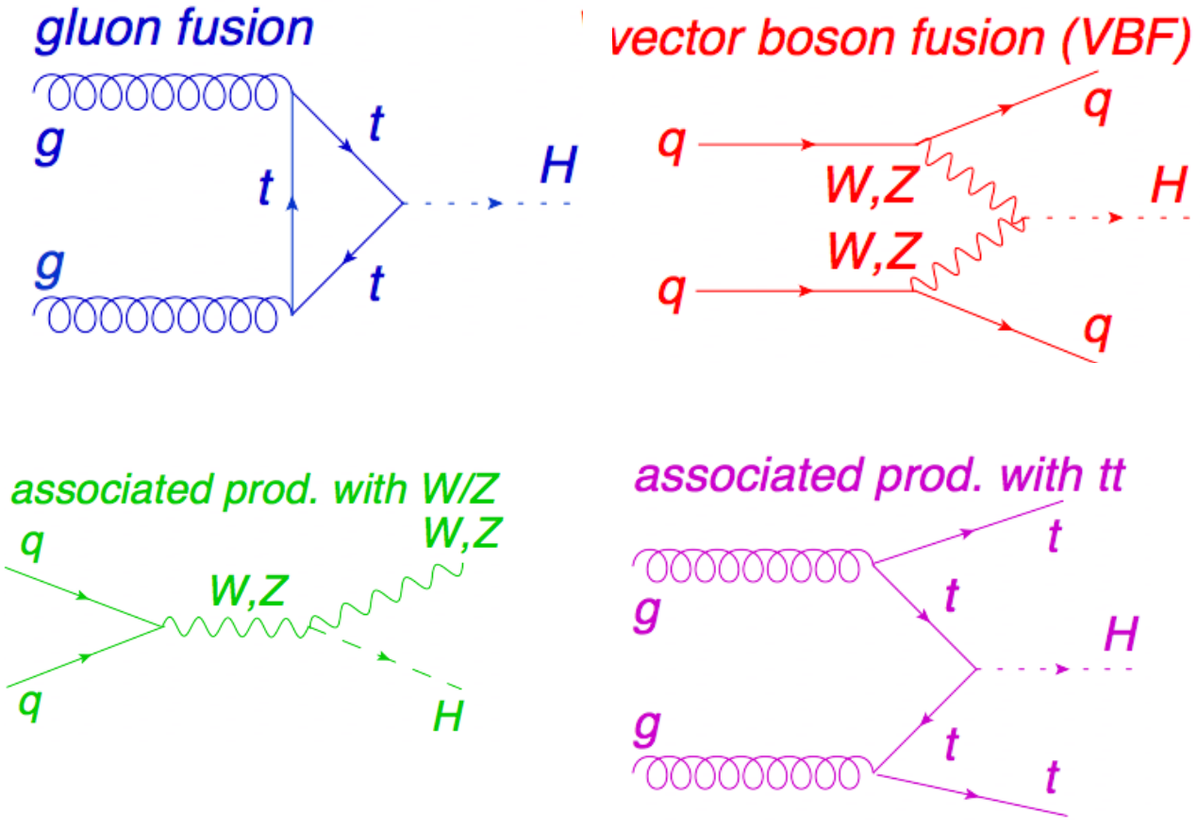




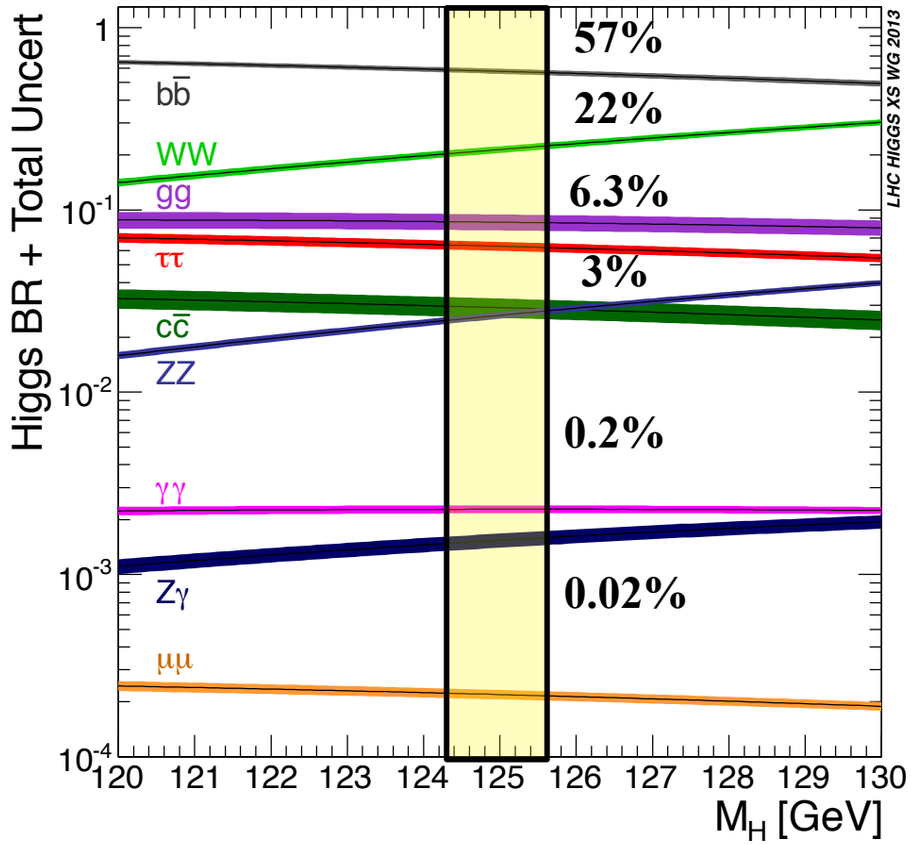
A new era: the transition from discovery to property measurement.

Higgs particle at the LHC

Major Higgs production modes



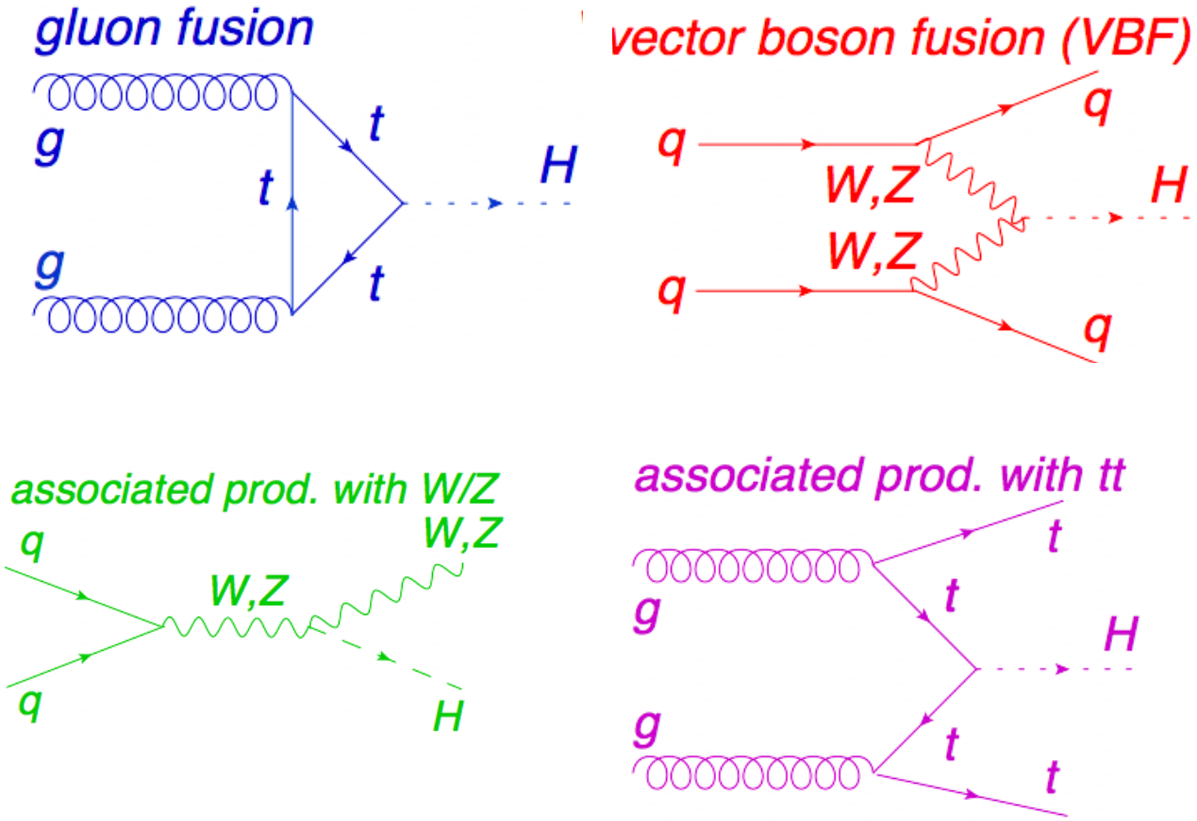
Higgs decays



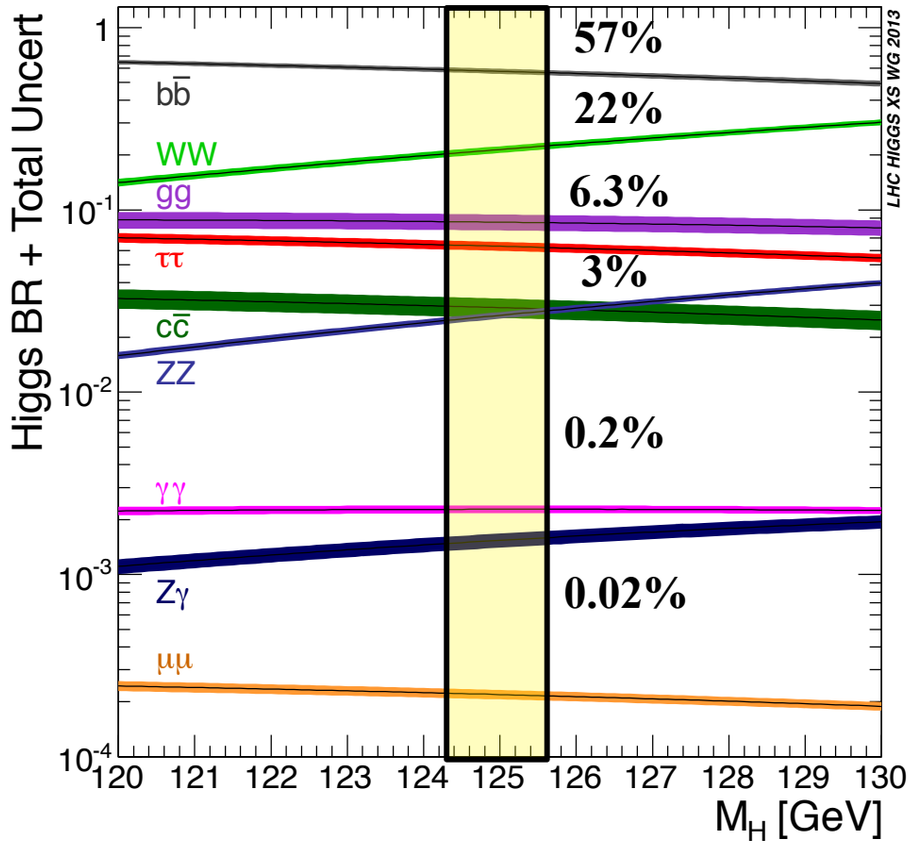
ATLAS (Run1)	Exp. yield	Resolution	S/B
H→γγ	~450	$\sigma(m_H)$~1-2%	~3%
H→ZZ*(4l)	~20	$\sigma(m_H)$~1-2%	~1.6
H→WW*(2l2ν)	~500	$\sigma(m_T)$~20%	~15%
H→ττ	~300	$\sigma(m_H)$~10-20%	~1-30%
H→bb	~400	$\sigma(m_H)$~10-20%	~1-10%

Higgs particle at the LHC

Major Higgs production modes



Higgs decays



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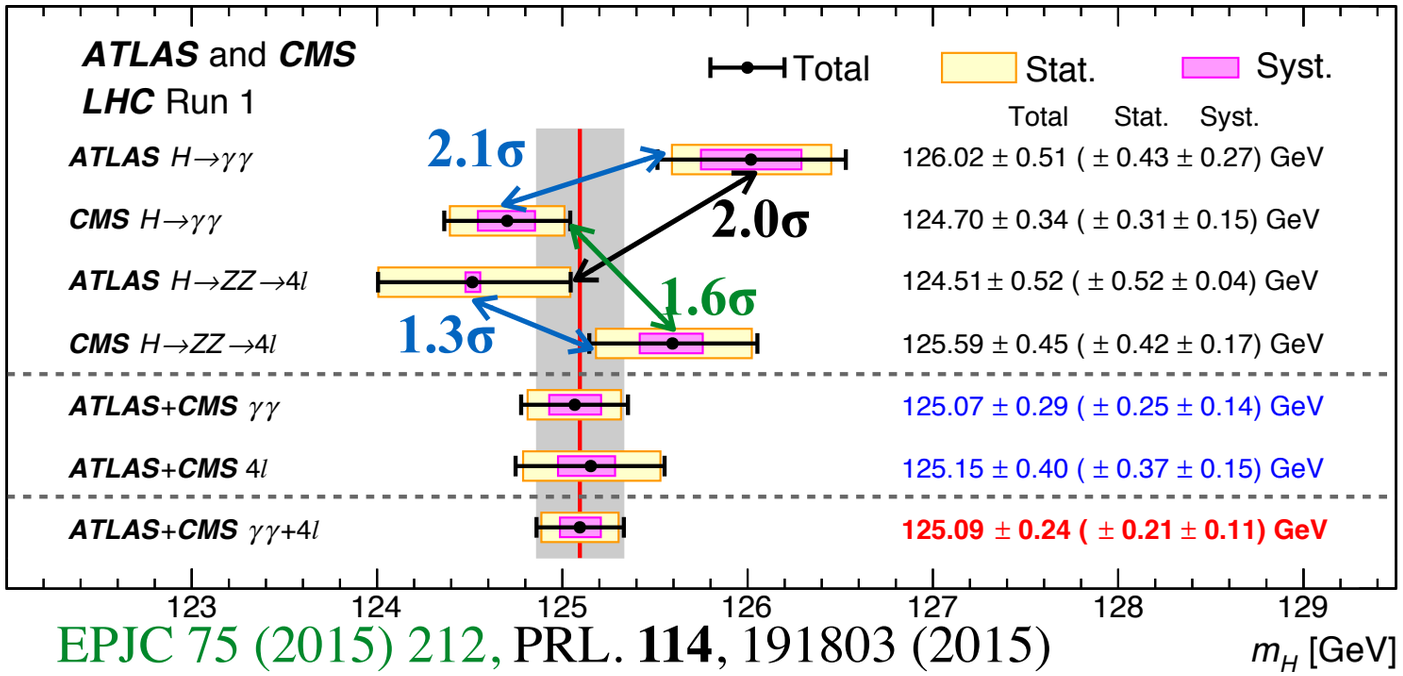
- **Highlight on the Higgs bosonic decays**
- **Channels with excellent mass resolution/signal-to-background ratio or high yield**

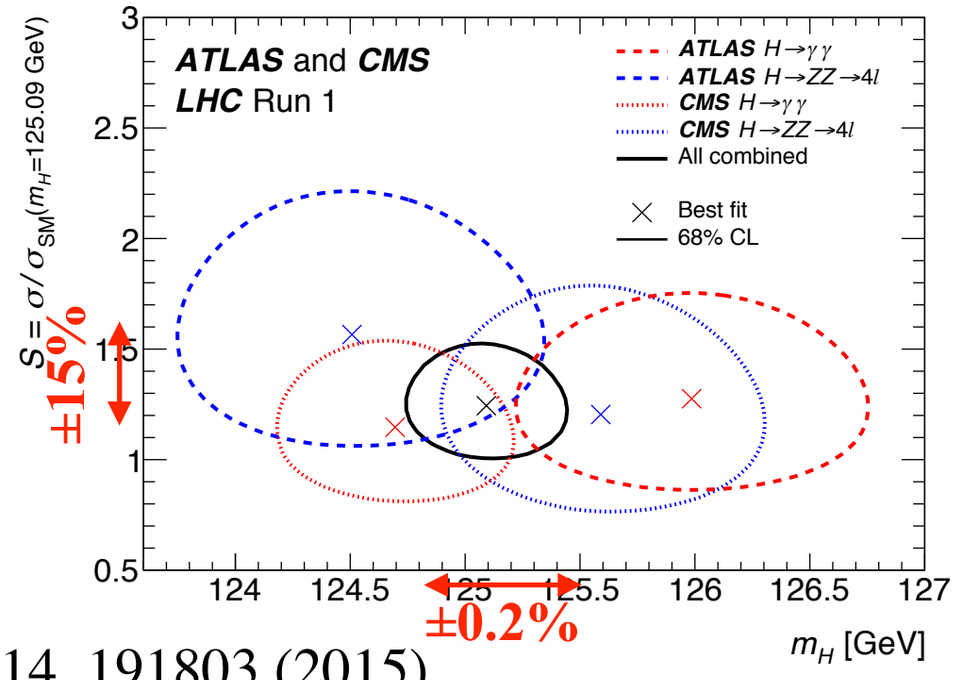
Higgs Mass/Coupling

First ATLAS and CMS Combination: m_H=125.09±0.21(stat.)± 0.11(sys.)GeV

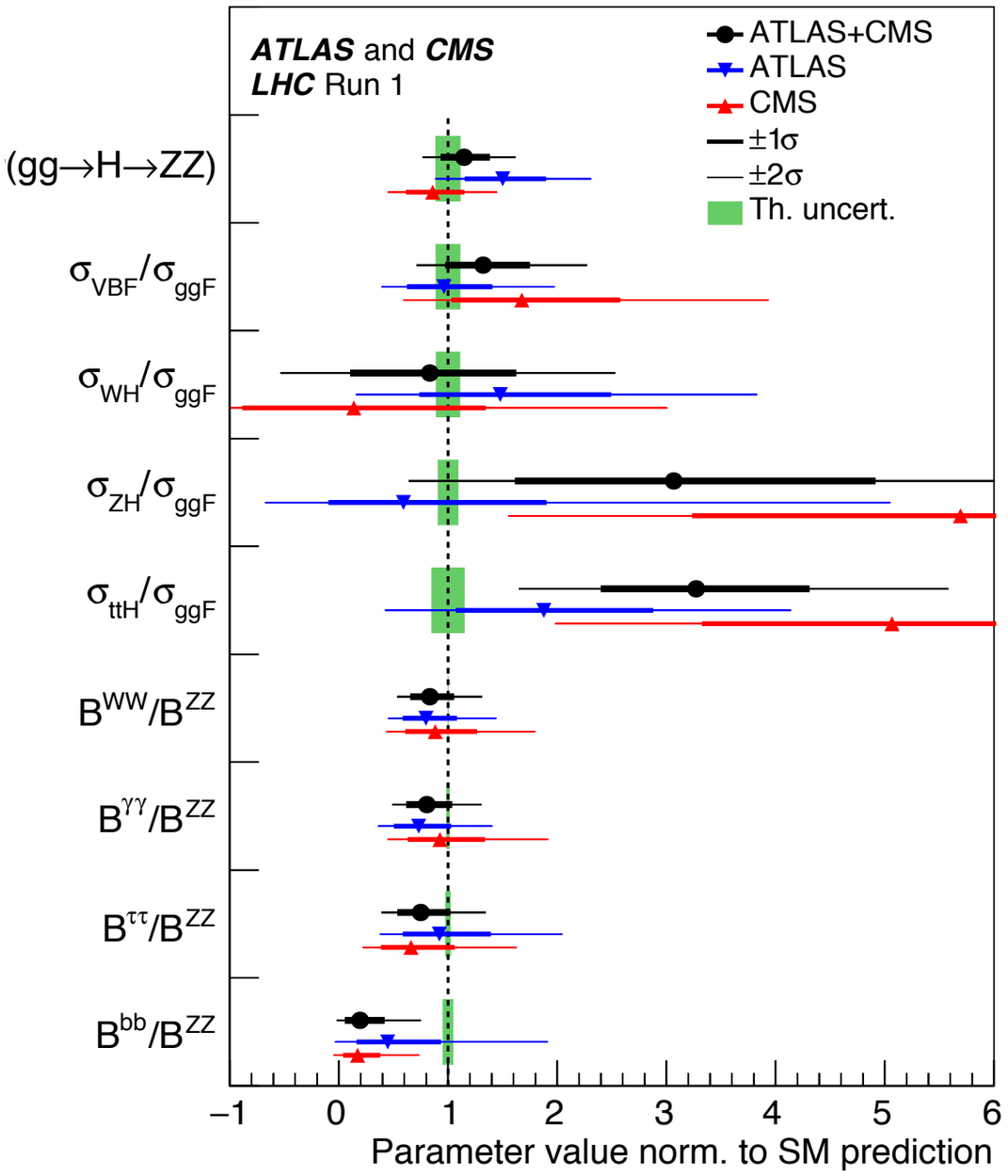
Further combined measurement of Higgs production/decay rates and coupling with m_H=125.09GeV with 6 channels: the global signal strength is 1.09±0.11.



EPJC 75 (2015) 212, PRL. **114**, 191803 (2015)



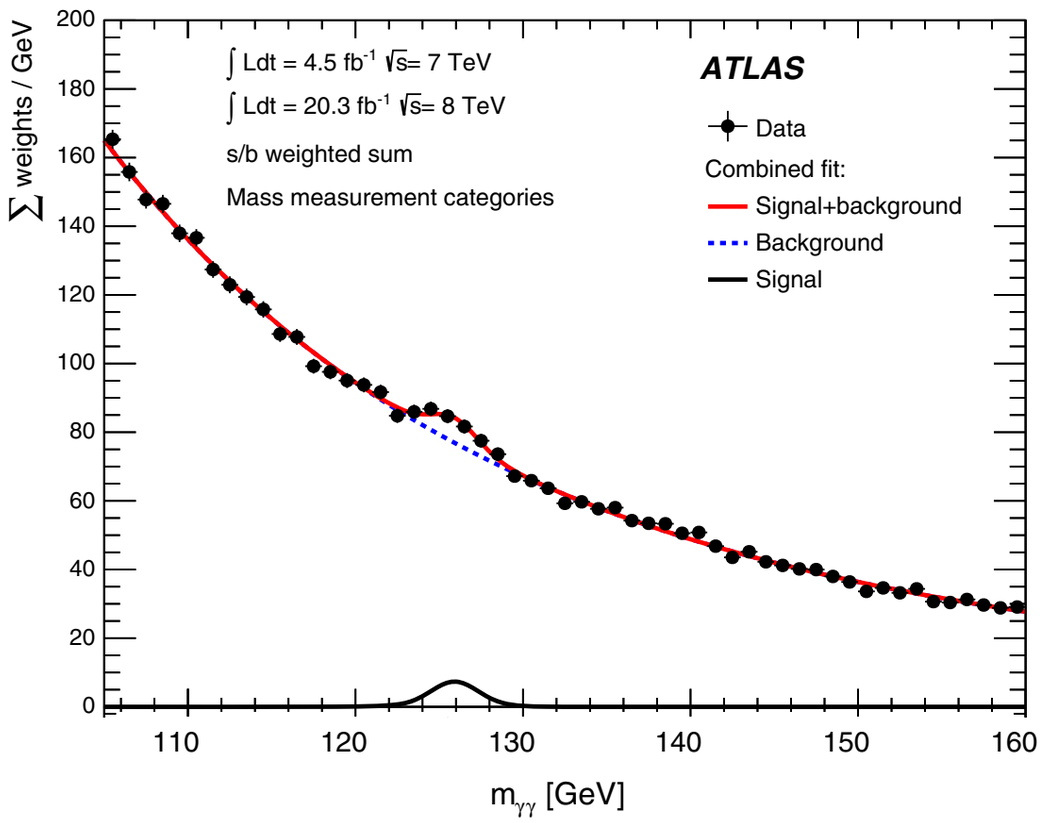
PRL. 114. 191803 (2015)

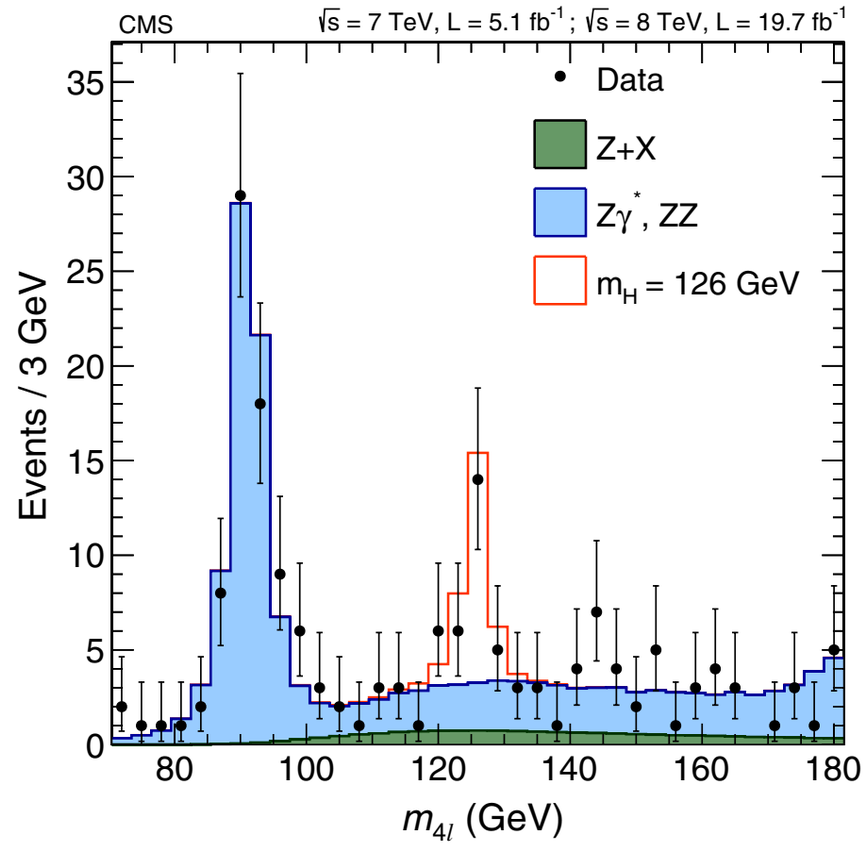


arXiv: 1606.02266

The Higgs Boson width

- **ATLAS and CMS are insensitive to the direct Higgs width measurement (Γ_{SM}~4.2MeV which is too small for the detector resolution)**





Γ: obs.(exp.)@ 95% CL	H→γγ	H→ZZ
ATLAS	5.0 (6.2) GeV	2.6 (6.2) GeV
CMS	2.4 (3.1) GeV	3.4 (2.8) GeV

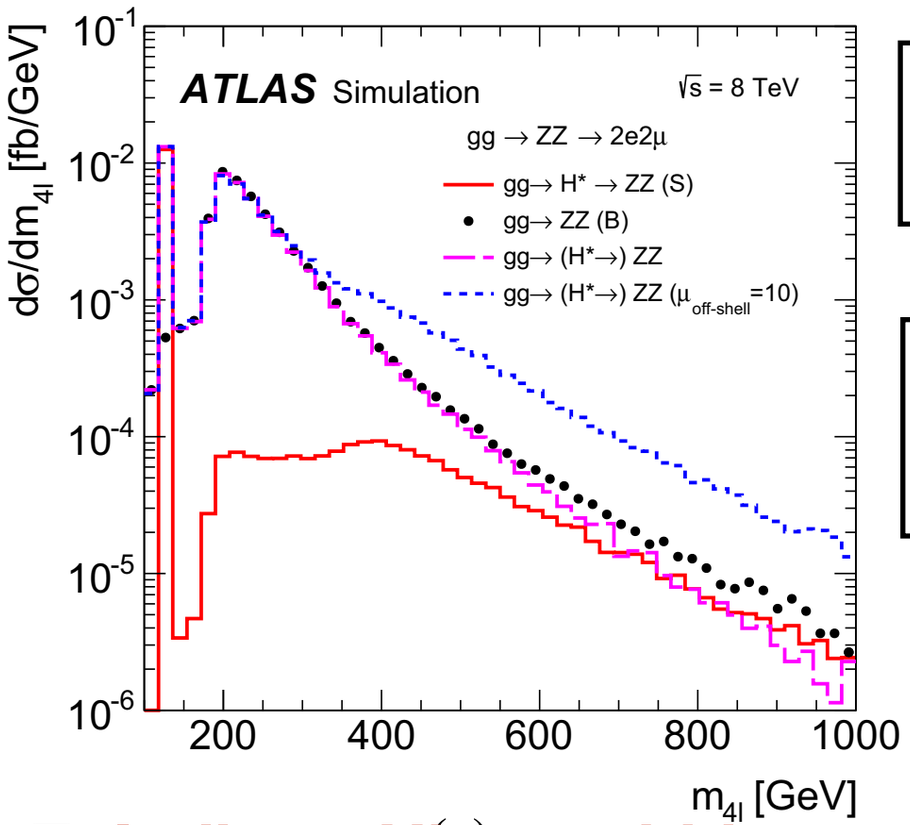
PRD 90, 052004 (2014)

EPJC 75 (2015) 212

3-order of magnitude larger than SM width

Indirect Higgs Boson width constraint

- **At the LHC, it is impossible to extract the coupling and Higgs width separately from on-shell cross section measurement.**



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma^{\text{SM}}_H}$$

$$\mu_{offshell} = \mu_{onshell} \times \Gamma_H / \Gamma_H(SM)$$

- **Indirect Higgs width constraint with the combination between on-shell and off-shell analysis under the following assumptions:**
  - $\mu_{\text{on-shell}} = \mu_{\text{off-shell}}$
  - **No BSM particle or interactions affect the Higgs coupling and SM background expectation**

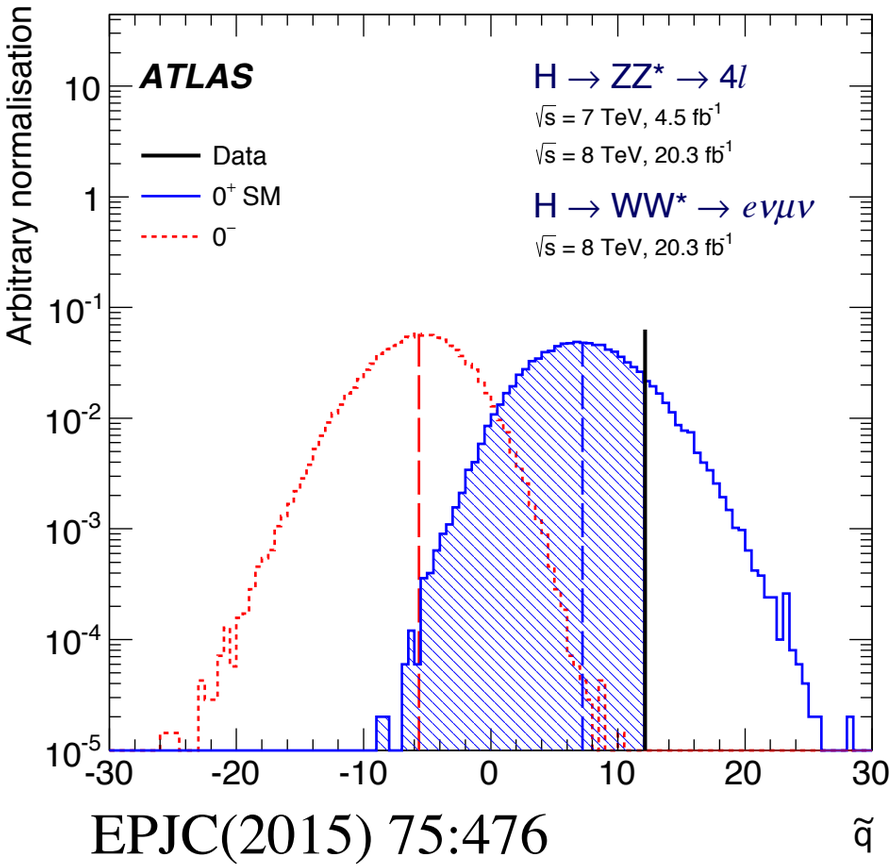
$$R^b_{H^*} = \frac{K_{gg\to VV}}{K_{gg\to H^*\to VV}} = 1$$

arxiv:1605.02329, EPJC 75,335 (2015)

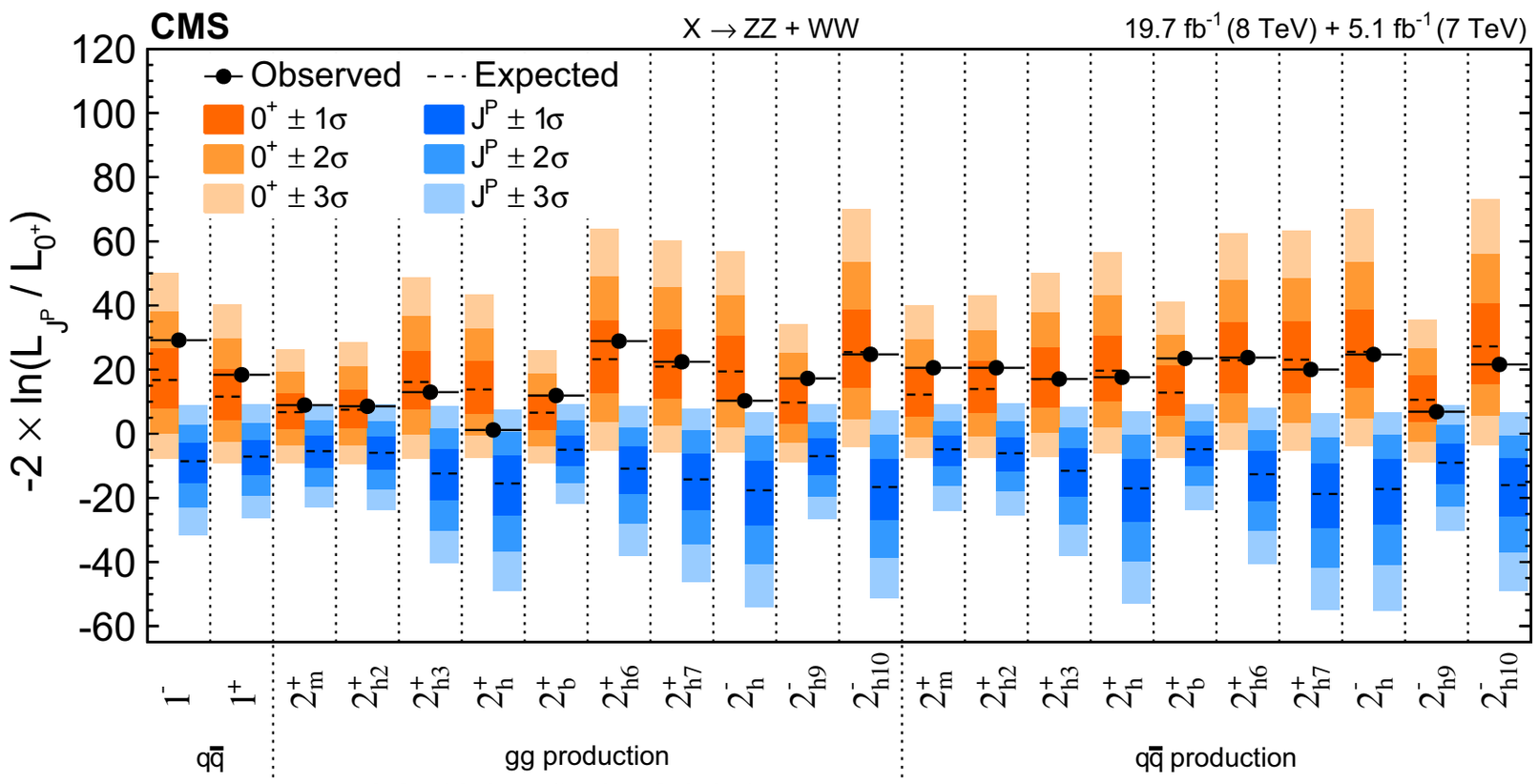
Γ_H =obs.(exp.) 95%CL	CMS	ATLAS
H→ZZ→4l	13(26)MeV	22.7(33.0)MeV
H→ZZ*→2l2ν		
H→WW*→lνlν		

The Spin-Parity of the Higgs Boson

Clear SM prediction for Higgs Boson quantum Numbers: $J^{pc} = 0^{++}$



EPJC(2015) 75:476



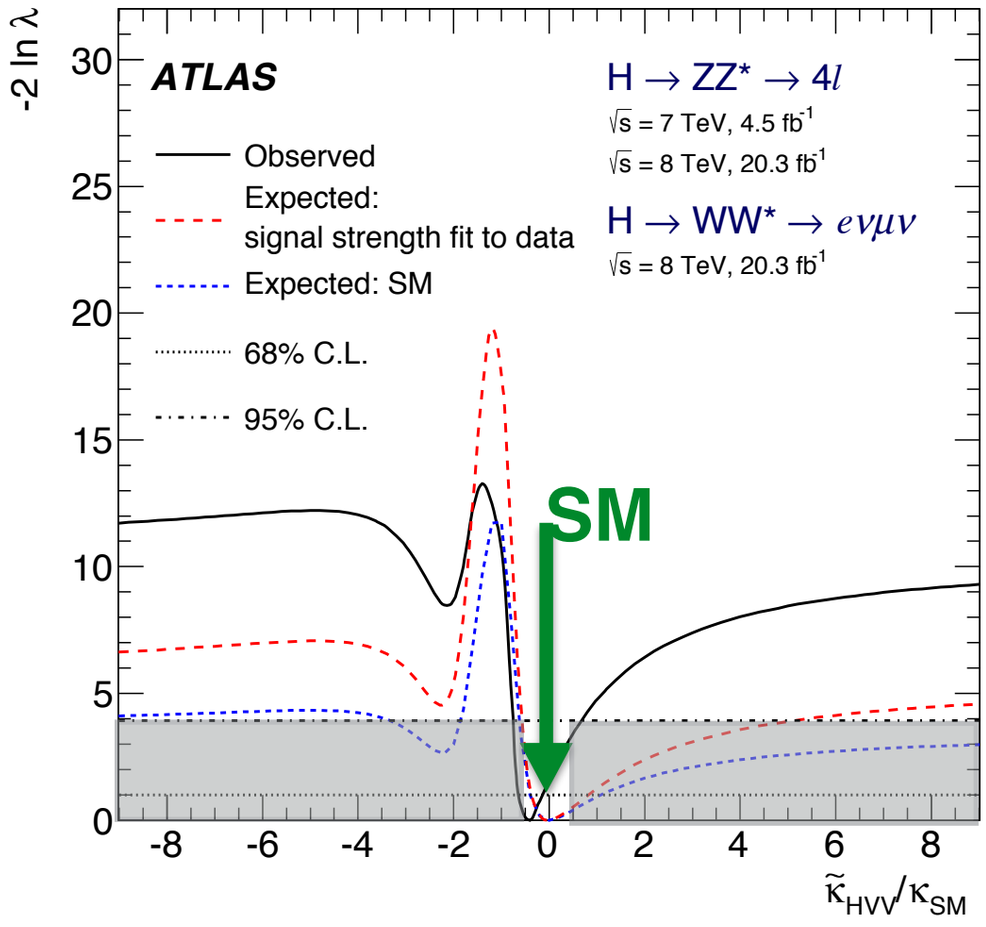
PRD 92 (2015) 012004

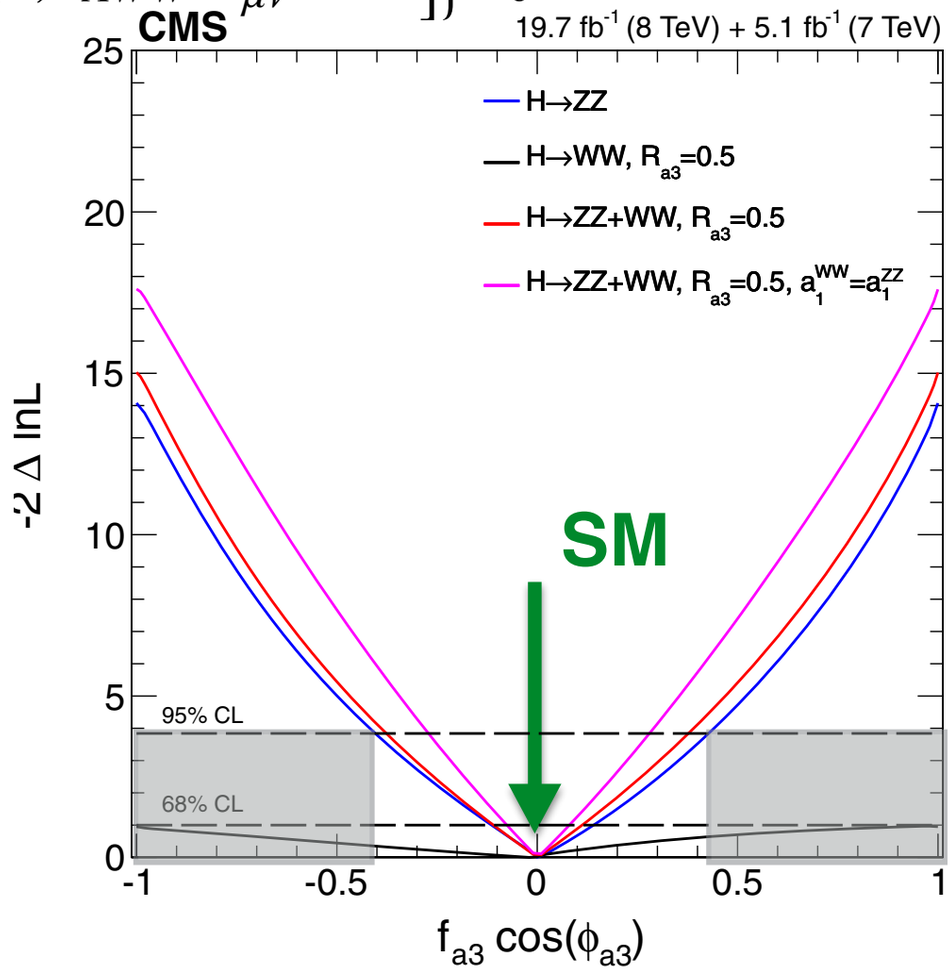
- All alternative hypotheses excluded to more than 99.9% CL.
- The observations are consistent with the expectations for a scalar SM-like Higgs boson

CP Mixing

- Spin0 effective model:

$$\mathcal{L}_0^V = \left\{\cos(\alpha)\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+ W^{-\mu}\right]\right.$$
$$-\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]$$
$$\left.-\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W_{\mu\nu}^+ W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\right\}X_0.$$





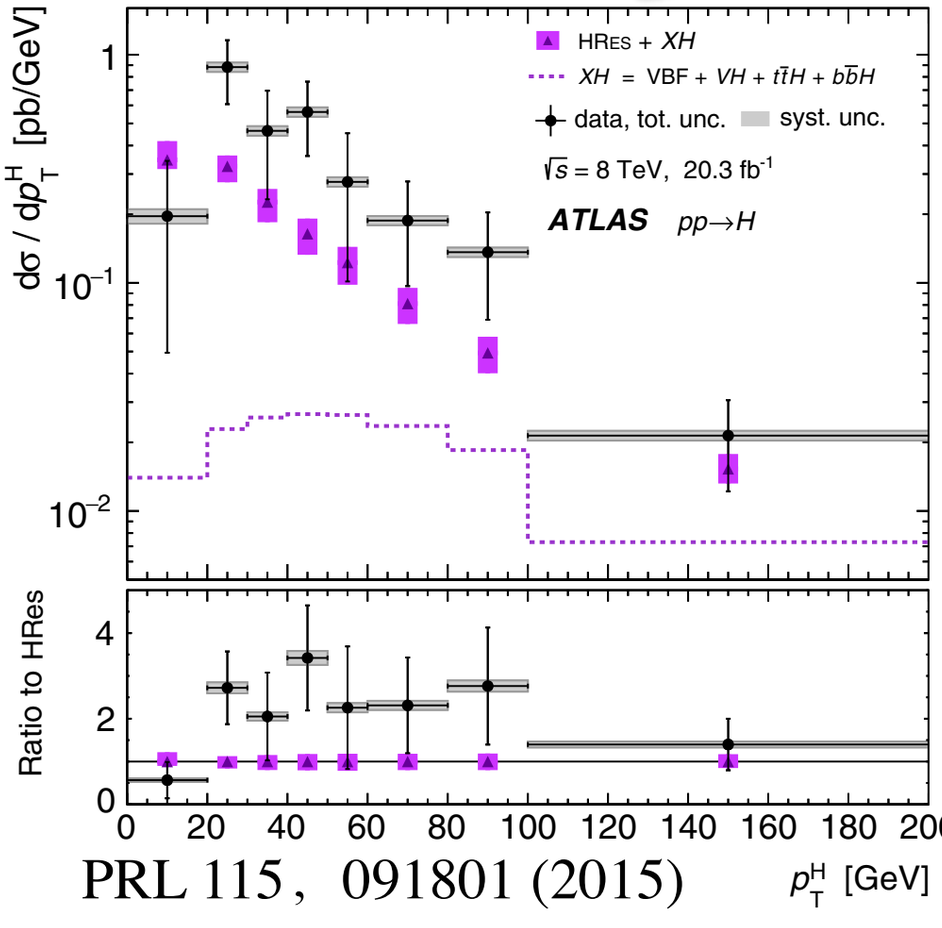
The observed Higgs boson is compatible with a standard CP-even

Fiducial/Differential Cross section measurement

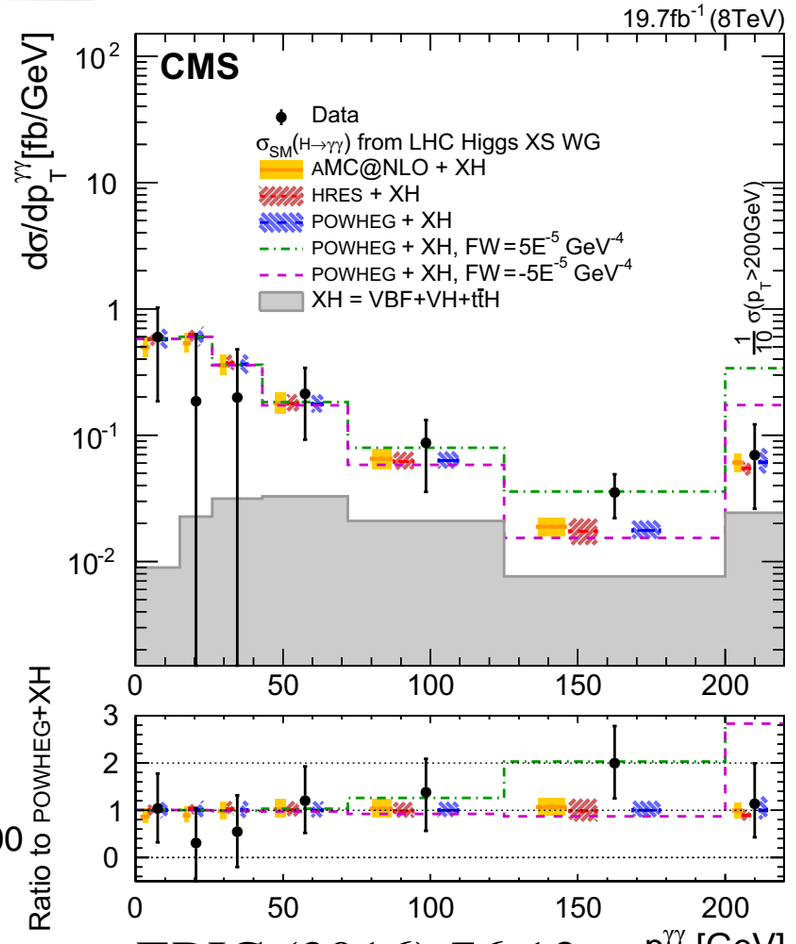
- **Measurement designed as model independent as possible.**
- **Direct comparison with theoretical predictions at particle level.**
- **A wide and diverse range of physical phenomena to be probed:**
  - Higgs boson kinematics, Jet activity, VBF-sensitive variables, Spin-CP sensitive variables
- **Methodology:**

$$\sigma_i = \frac{\nu_i^{sig}}{c_i \times \mathcal{L}_{int}}$$

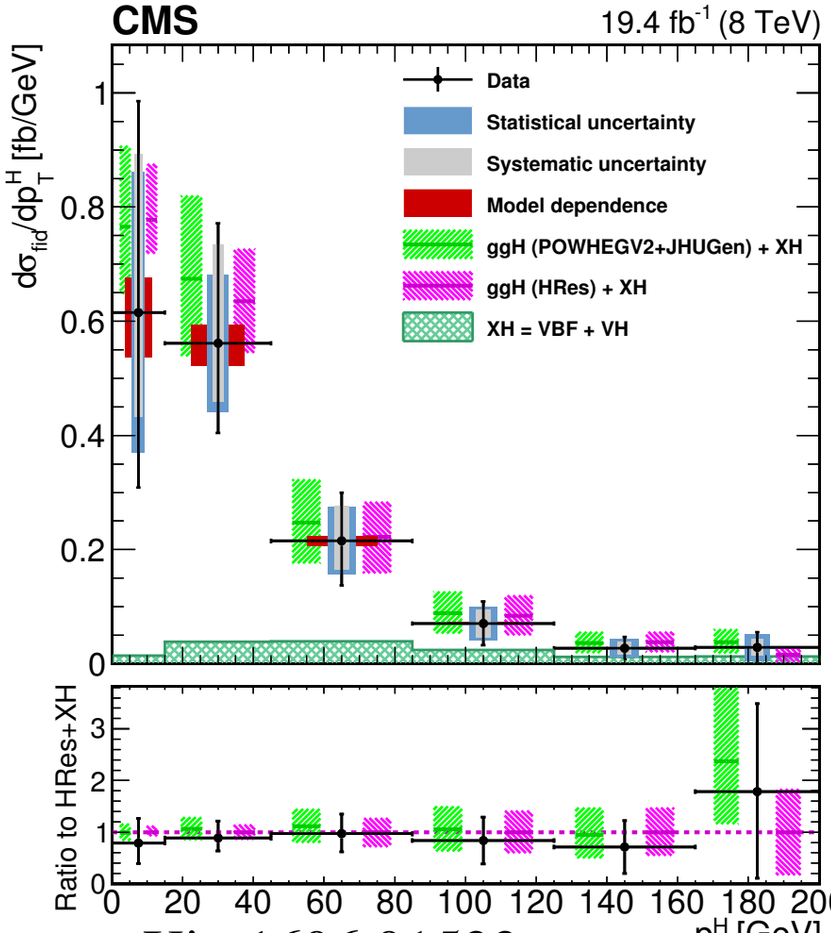
A good agreement with SM prediction.



PRL 115, 091801 (2015)

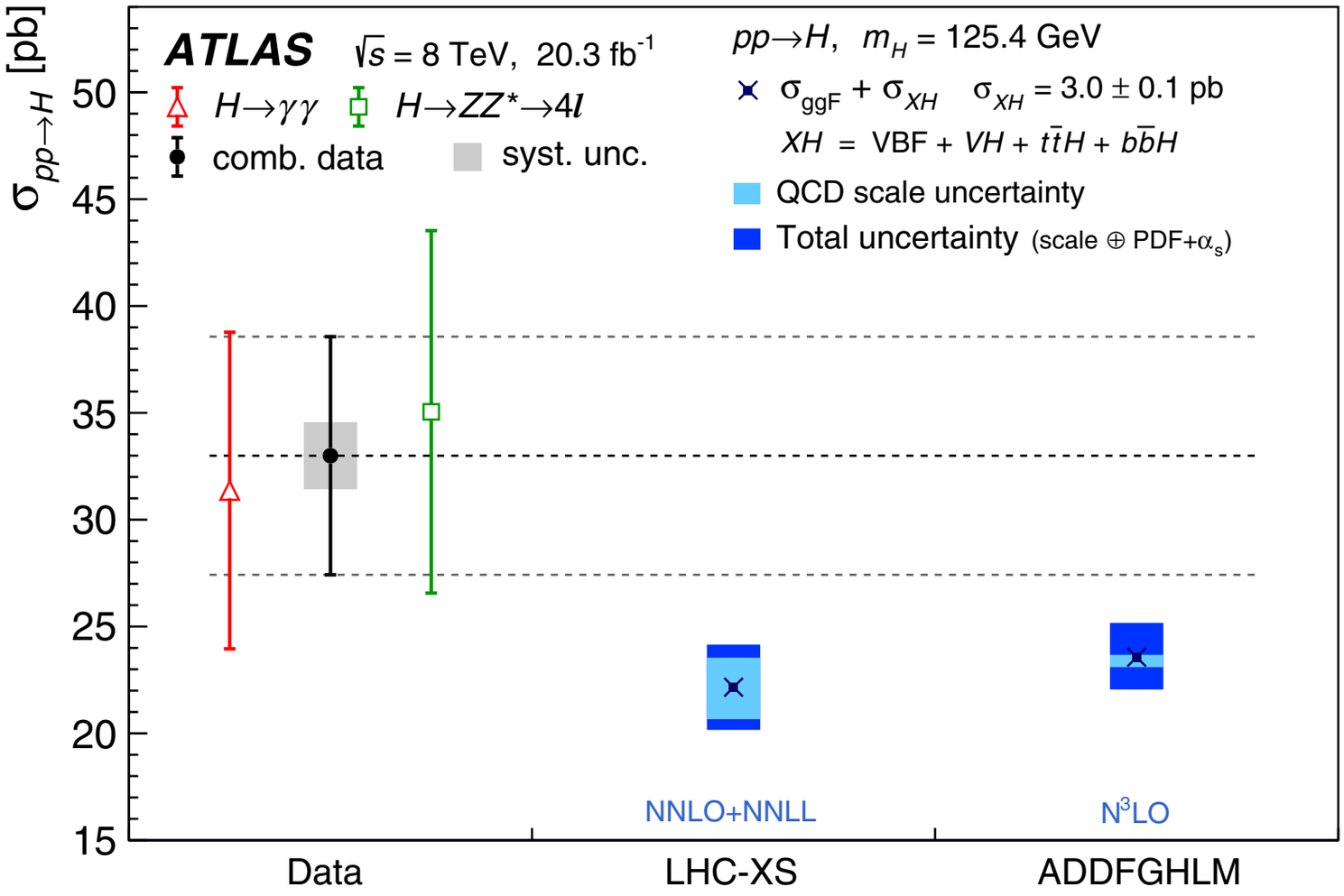


EPJC (2016) 76:13



arXiv:1606.01522

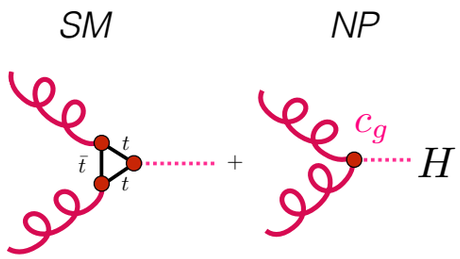
Total Higgs production cross section



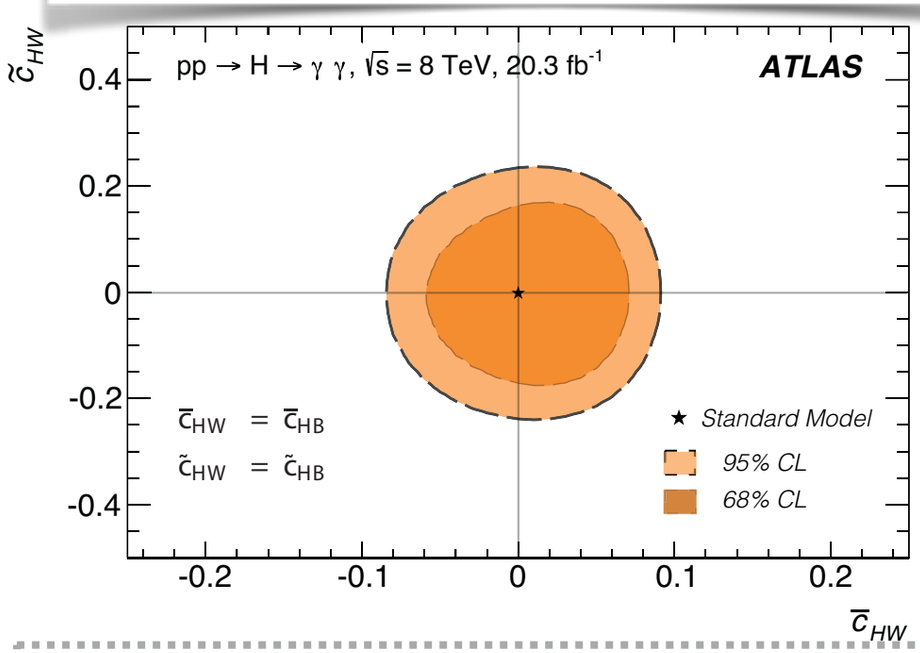
PRL 115，091801 (2015)

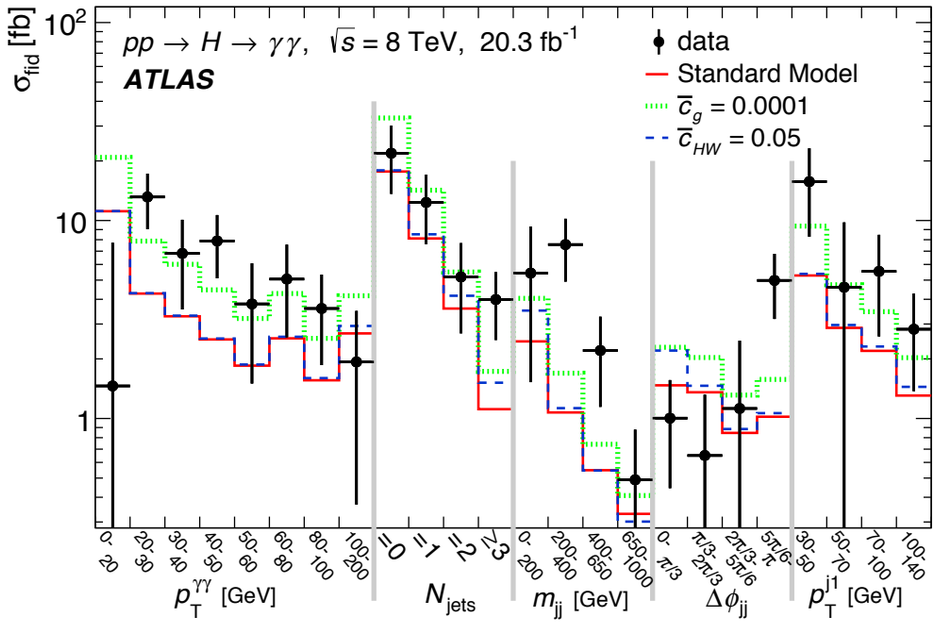
Constraint on non-SM interactions with differential cross sections

- Procedure: simultaneous fit on 5 sensitive differential distributions and set limit on the Wilson coefficients：



$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$





PLB 753 (2016) 69-85

95%CL constraint	κ_{HVV}/κ_{SM}	$(\kappa_{AVV}/\kappa_{SM})\tan\alpha$
H→WW/ZZ	[-0.73, 0.63]	[-2.18, 0.83]
EFT in H→γγ	[-0.08, 0.09]	[-0.22, 0.22]

- **No significant deviation from the SM**
- **More stringent constraint on the HVV Tensor structure with a factor of 7 w.r.t. the dedicated Spin and parity analysis of WW/ZZ decays, due to inclusion of rate and jet kinematic information**

What have we learned from Run1

- Higgs mass determined to 0.2%
- Higgs signal strength ~1, determined to 10%
- Higgs couplings tested for many scenarios and assumptions (consistent with SM).
- Higgs spin-parity is compatible with SM from all studies
- Fiducial/Differential cross-section measurement at 8TeV

Higgs boson is very consistent with SM predictions, but measurements are still statistically limited.

First Stable Beams

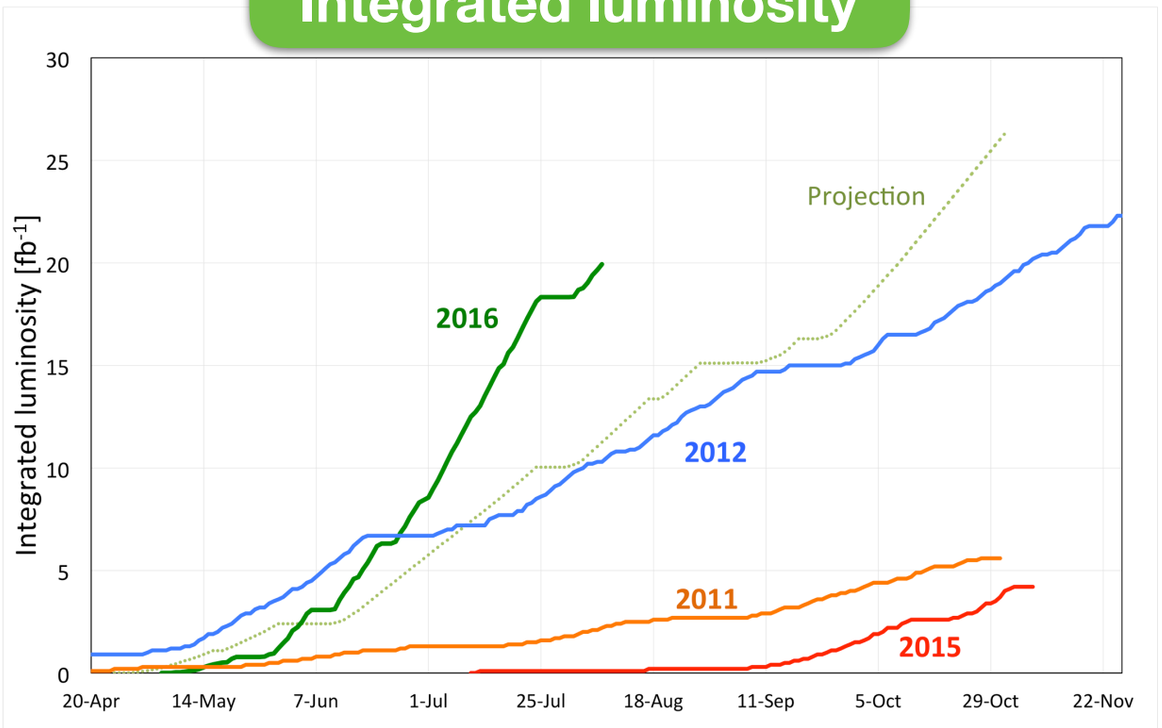
ATLAS EXPERIMENT

Run: 266904
Event: 9393006
2015-06-03 10:40:31 CEST

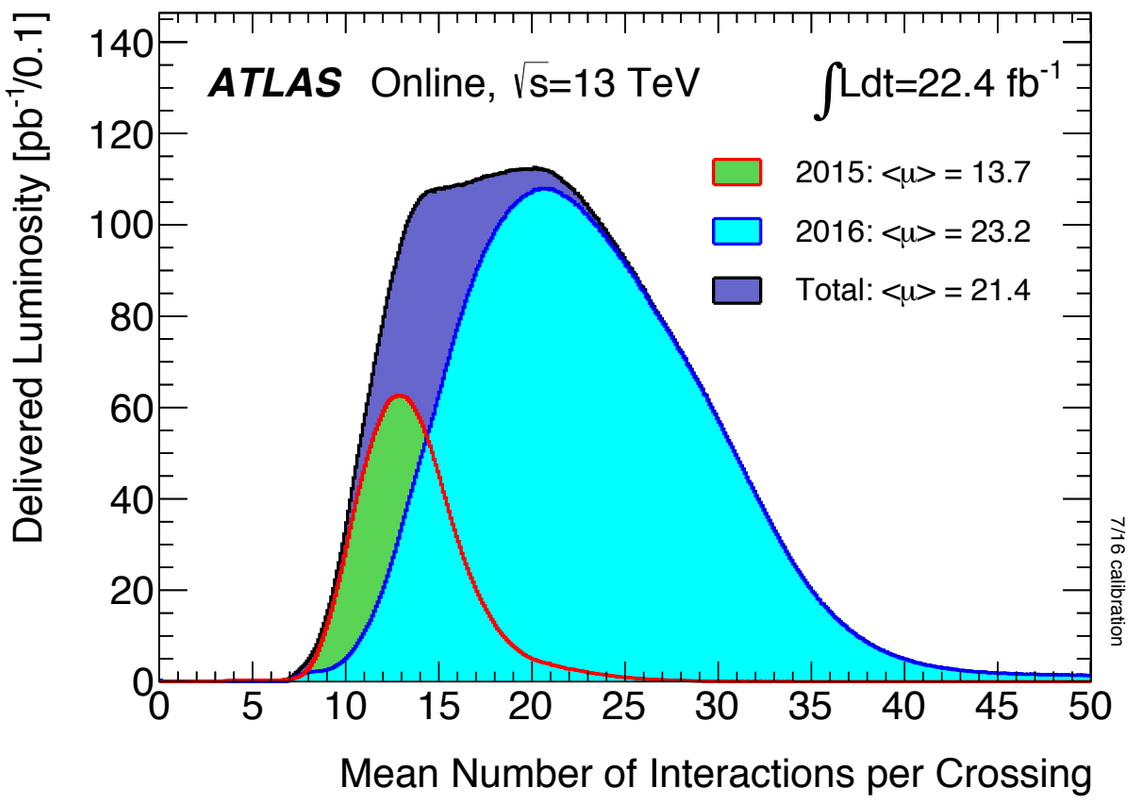
proton-proton collisions at 13 TeV

Run-II Datasets

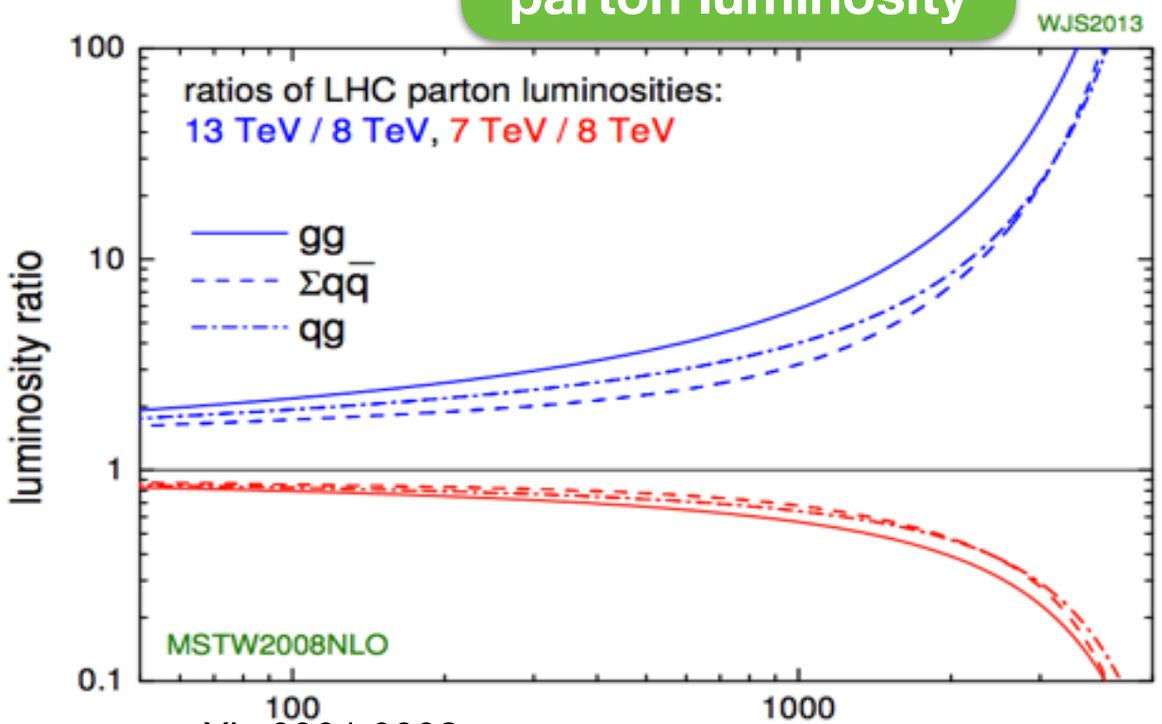
Integrated luminosity



From Mike's talk @ ICHEP2016



parton luminosity

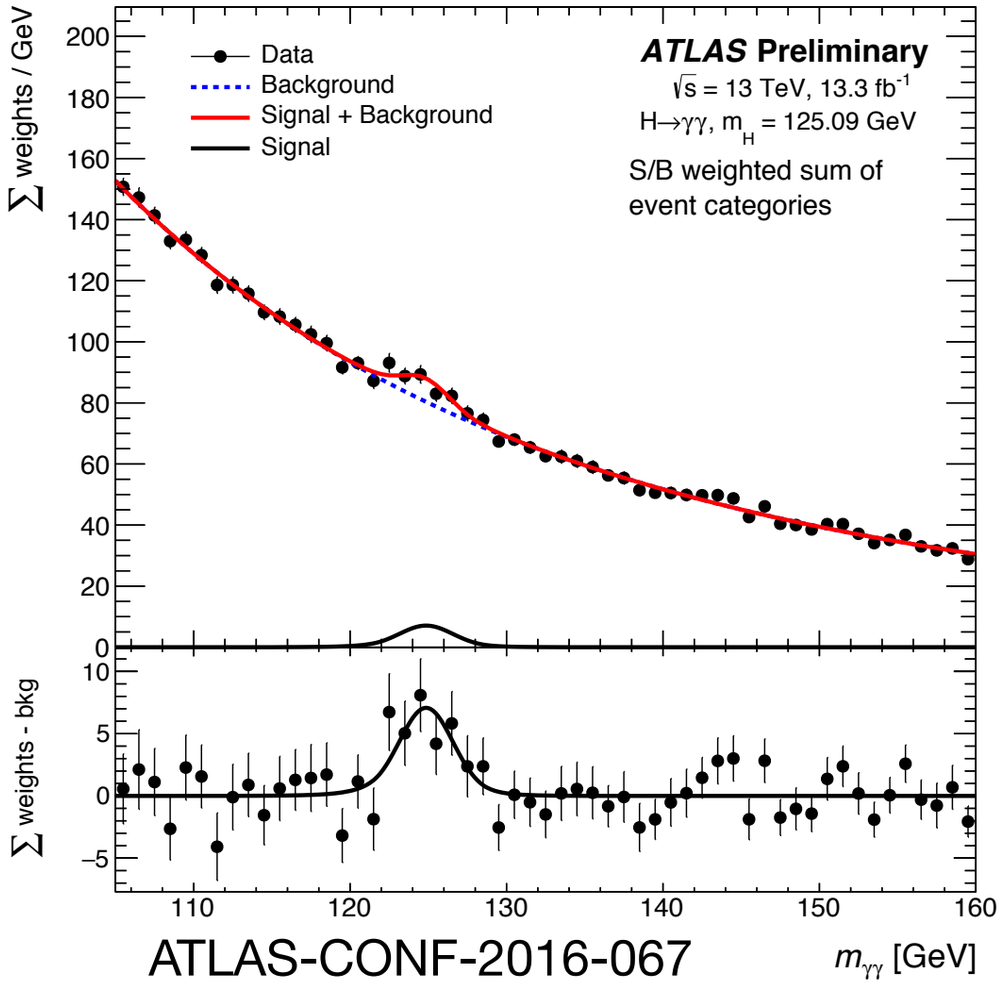


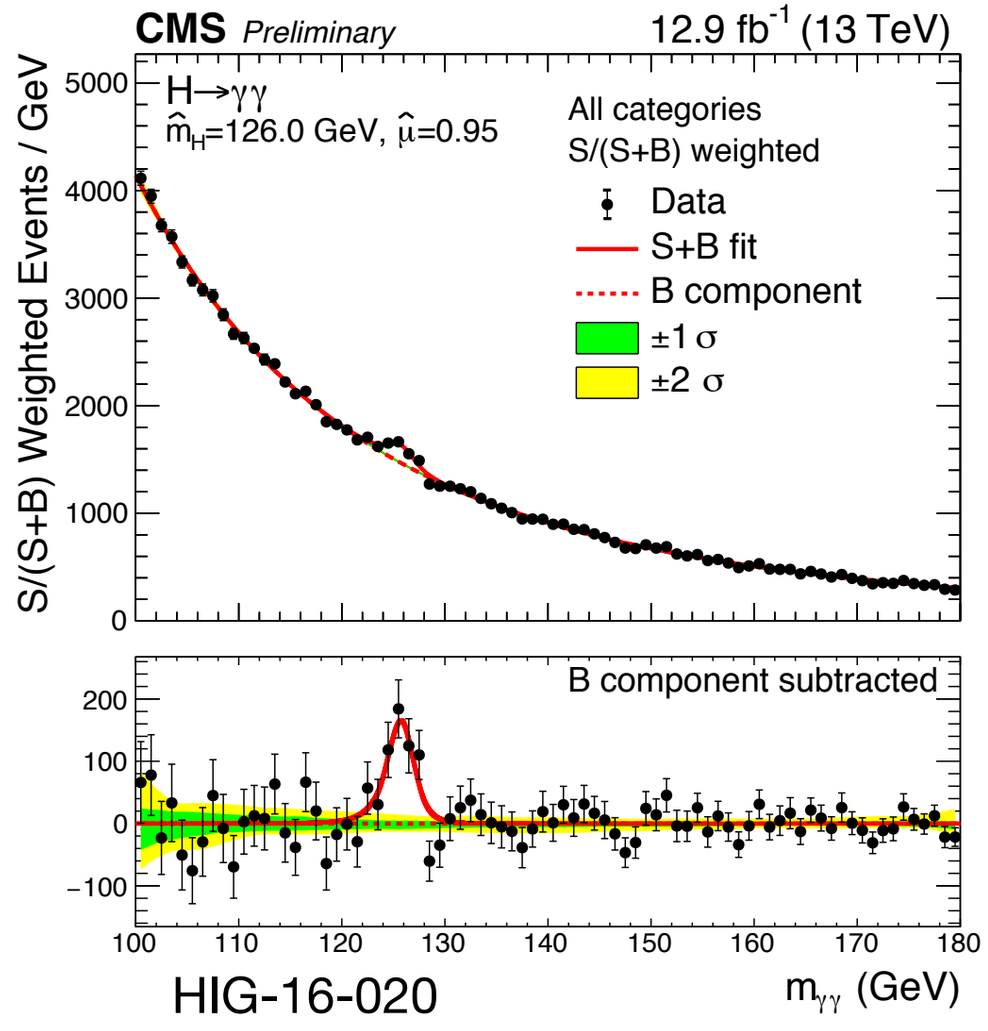
	√s=7 TeV	√s=8 TeV	√s=13 TeV	Ratio 13/8 TeV
ggH	15.3 pb	19.4 pb	44.1 pb	**2.27**
VBF	1.25 pb	1.6 pb	3.8 pb	**2.38**
ttH	88.6 fb	133 fb	507 fb	**3.81**
tt	177 pb	253 pb	832 pb	**3.29**

- **The dataset already collected at 13TeV are comparable to Run-I.**
- **Increased centre-of-mass energy results in much larger cross sections**
- **Pileup robust algorithm developed**

H→γγ

- **Selected events are split into exclusive categories with the optimal separation of the Higgs boson production processes**



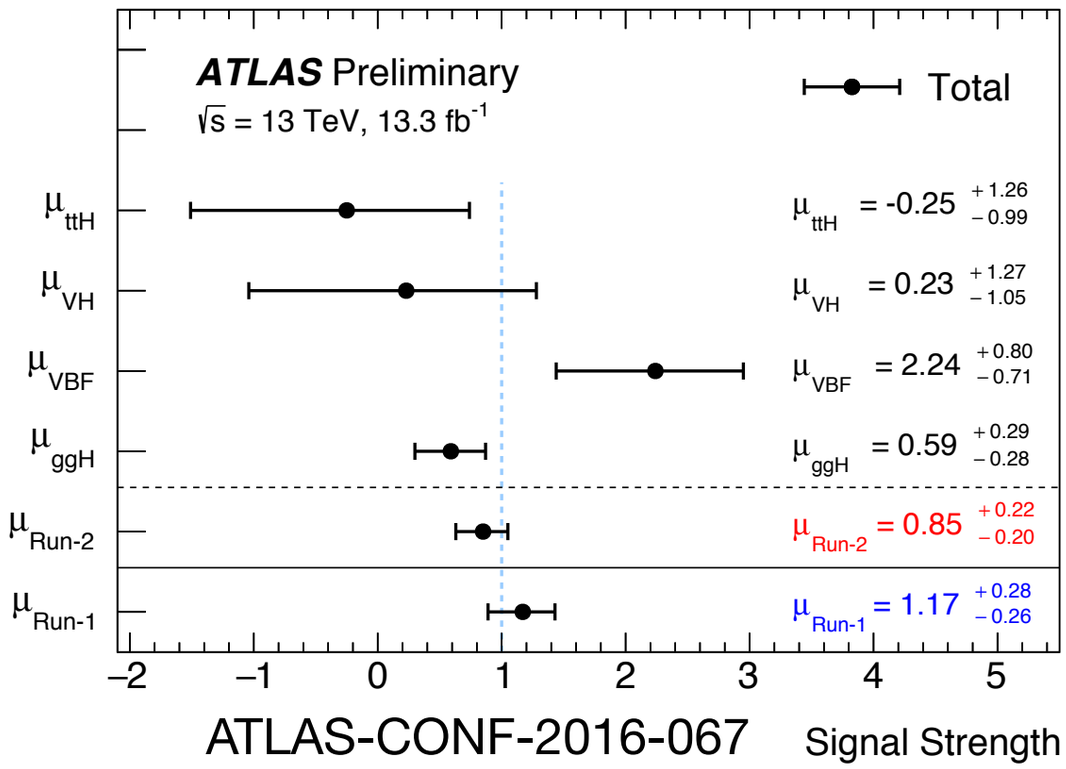


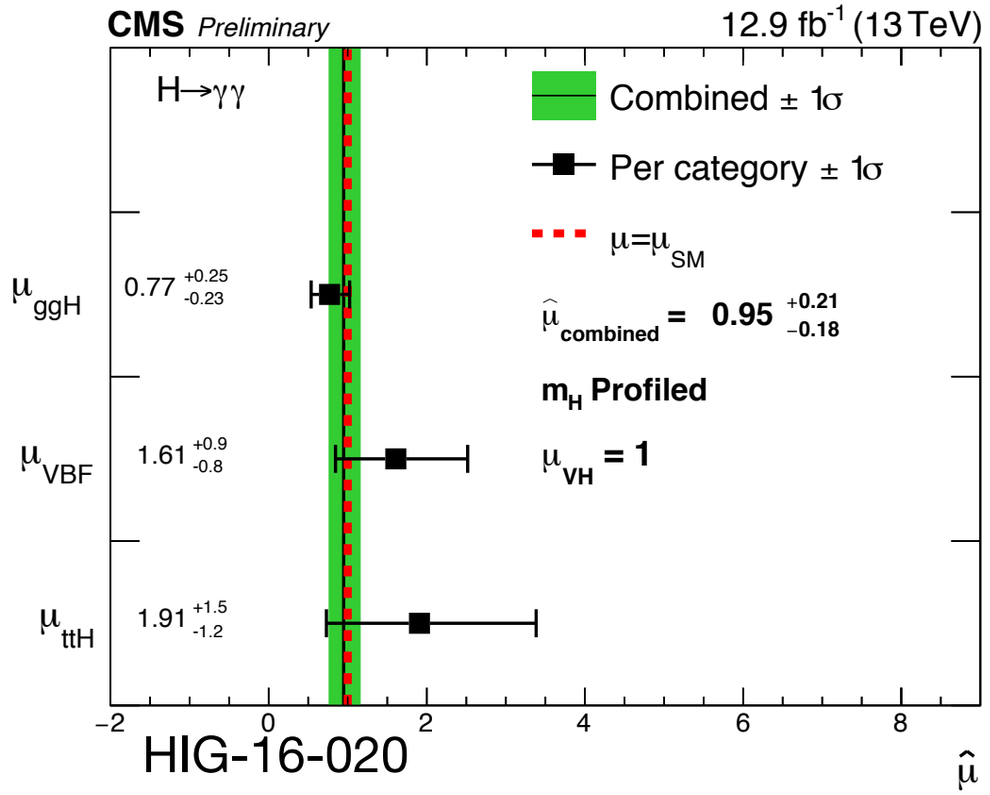
The observed (expected) significance is 4.7 (5.4) σ at mH=125.09GeV

The observed (expected) significance is 5.6 (6.1) σ at mH=125.09GeV

Cross section and signal strength in H→γγ

- **Selected events are split into exclusive categories with the optimal separation of the Higgs boson production processes**





Total Higgs production X-sec

$$\sigma_{ggH} \times \mathcal{B}(H \to \gamma\gamma) = 65\ ^{+32}_{-31}\ \text{fb}$$

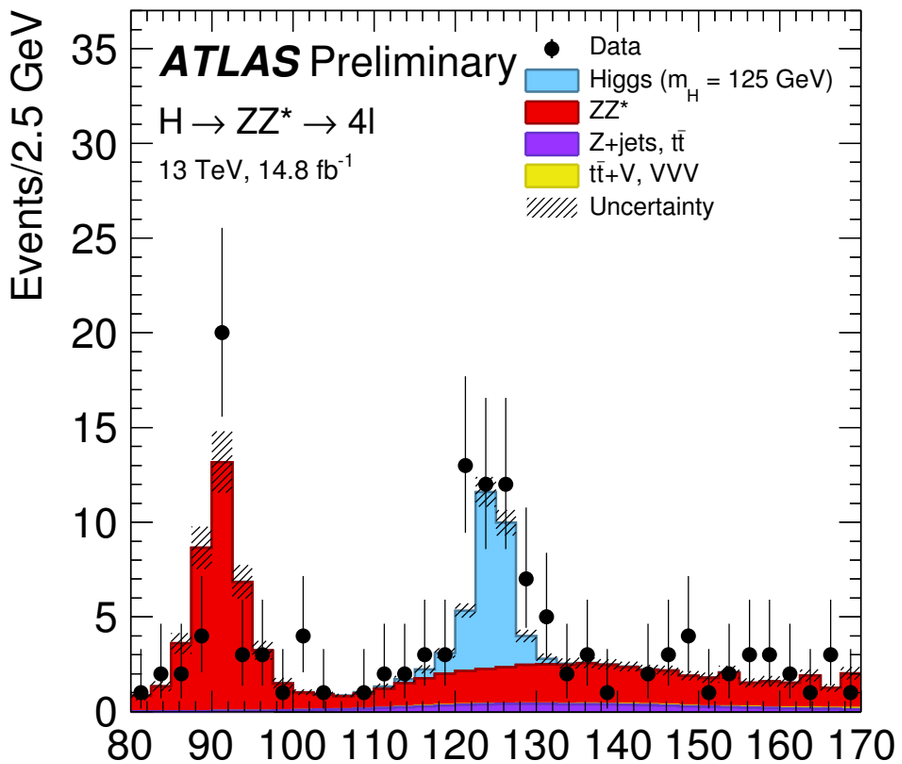
$$\sigma_{\text{VBF}} \times \mathcal{B}(H \to \gamma\gamma) = 19.2\ ^{+6.8}_{-6.1}\ \text{fb}$$

$$\sigma_{VH} \times \mathcal{B}(H \to \gamma\gamma) = 1.2\ ^{+6.5}_{-5.4}\ \text{fb}$$

$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) = -0.3\ ^{+1.4}_{-1.1}\ \text{fb}$$

- **Production cross section and signal strengths probe the Higgs coupling directly**
- **Data in reasonable agreement with the SM predictions**

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



ATLAS-CONF-2016-079

$$\sigma_{\text{tot}} = 81^{+18}_{-16}\ \text{pb}$$

$$\sigma_{\text{ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 1.80^{+0.49}_{-0.44}\ \text{pb}$$

$$\sigma_{\text{VBF}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0.37^{+0.28}_{-0.21}\ \text{pb}$$

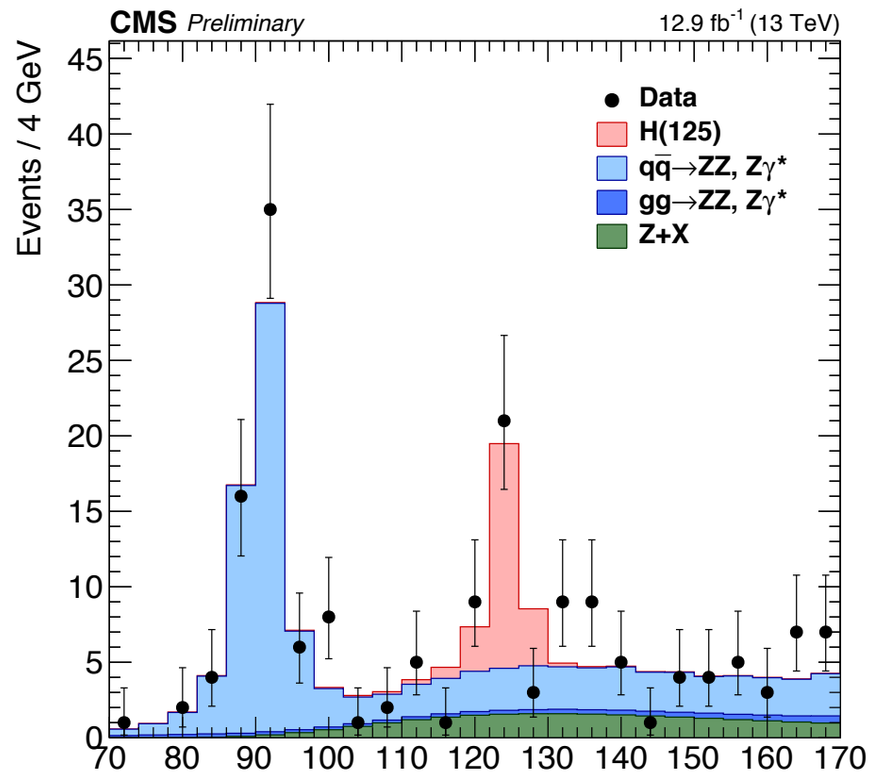
$$\sigma_{\text{VH}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0^{+0.15}\ \text{pb}$$

$$\sigma_{\text{tot,SM}} = 55.5^{+3.8}_{-4.4}\ \text{pb}$$

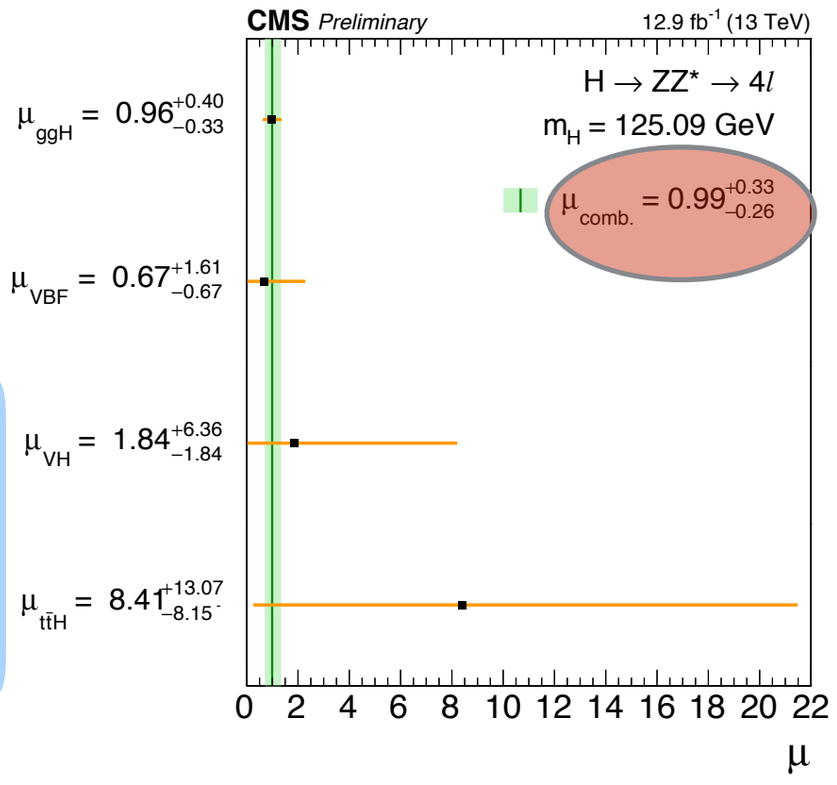
$$\sigma_{\text{SM,ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 1.31 \pm 0.07\ \text{pb}$$

$$\sigma_{\text{SM,VBF}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0.100 \pm 0.003\ \text{pb}$$

$$\sigma_{\text{SM,VH}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0.059 \pm 0.002\ \text{pb}$$

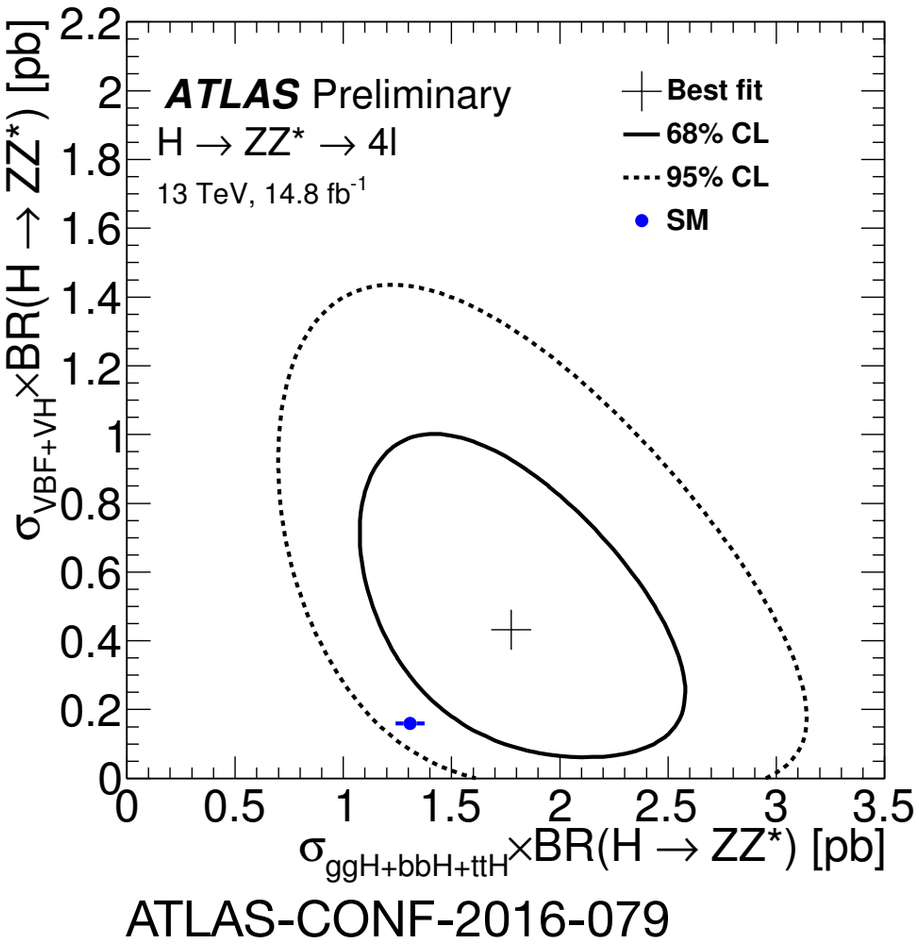


HIG-16-033-pas

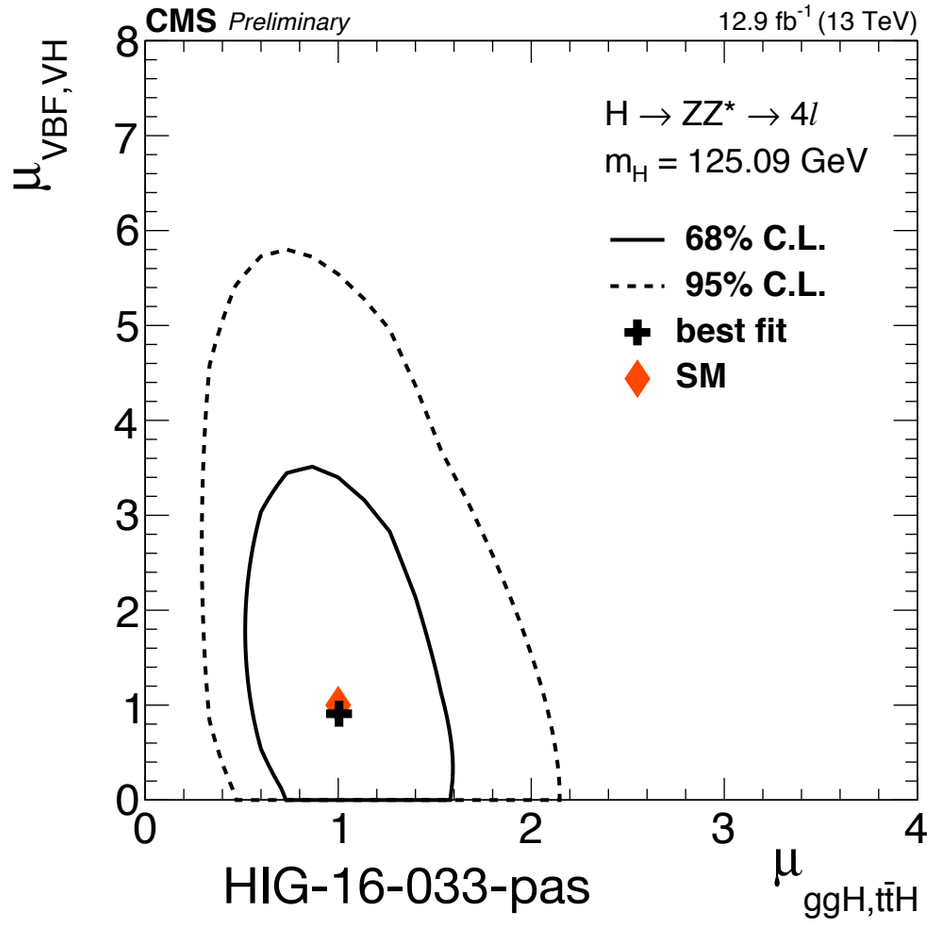


- **First directly measure signal strength/ cross section in different production modes.**
- **The results agree well with SM.**

H→ZZ*→4l



ATLAS-CONF-2016-079

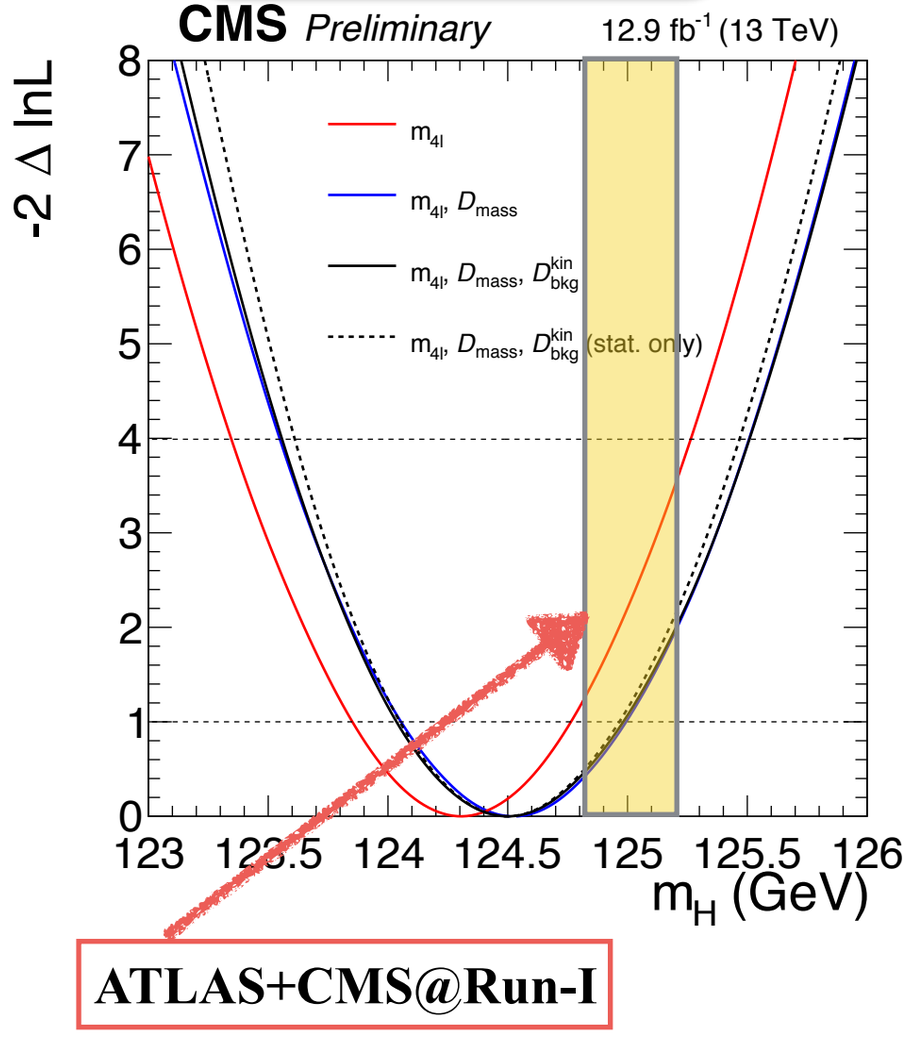


HIG-16-033-pas

- Compatibility to the SM prediction:
  - $\sigma_{ggF+bbH+ttH} \cdot Br(H \to ZZ^*)$ is 1.1σ
  - $\sigma_{VBF+VH} \cdot Br(H \to ZZ^*)$ is 1.4σ
- Observed result is very close to SM prediction.

Mass and width measurement in H→ZZ*→4l @ CMS

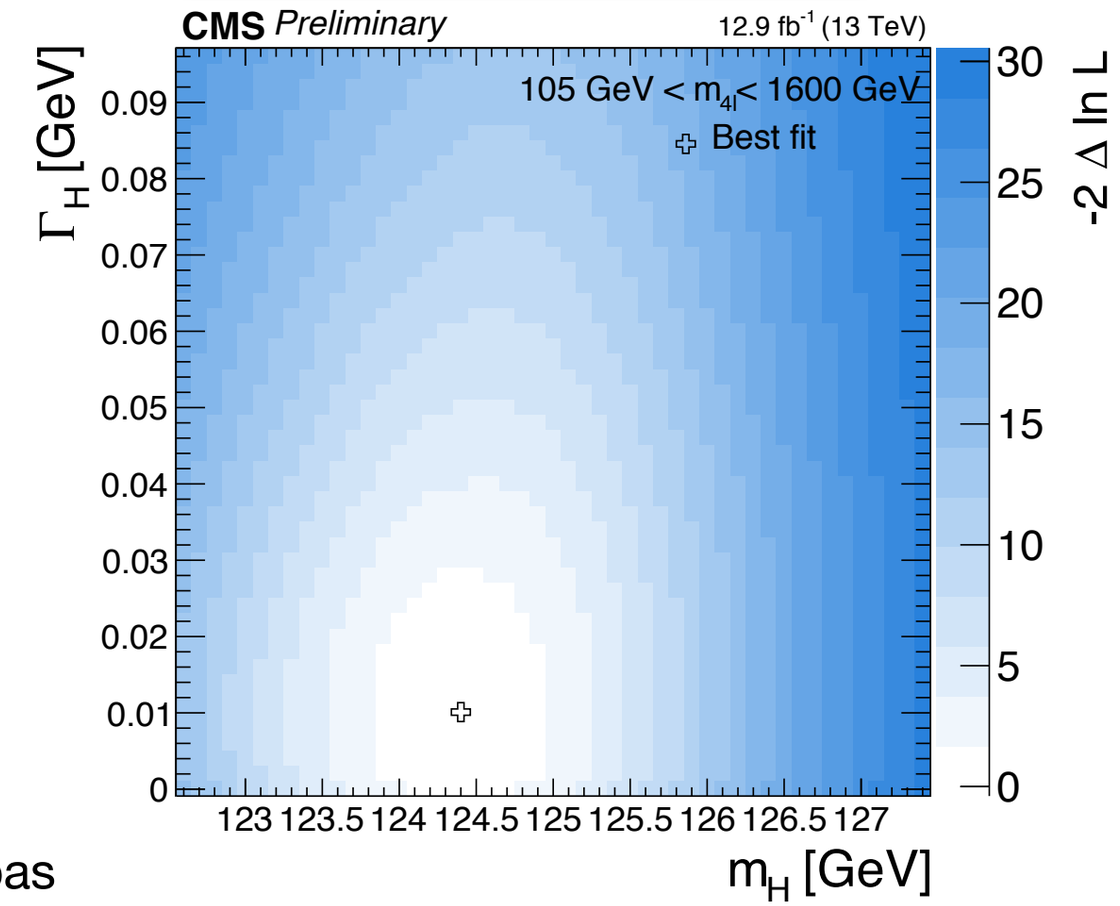
Mass



ATLAS+CMS@Run-I

HIG-16-033-pas

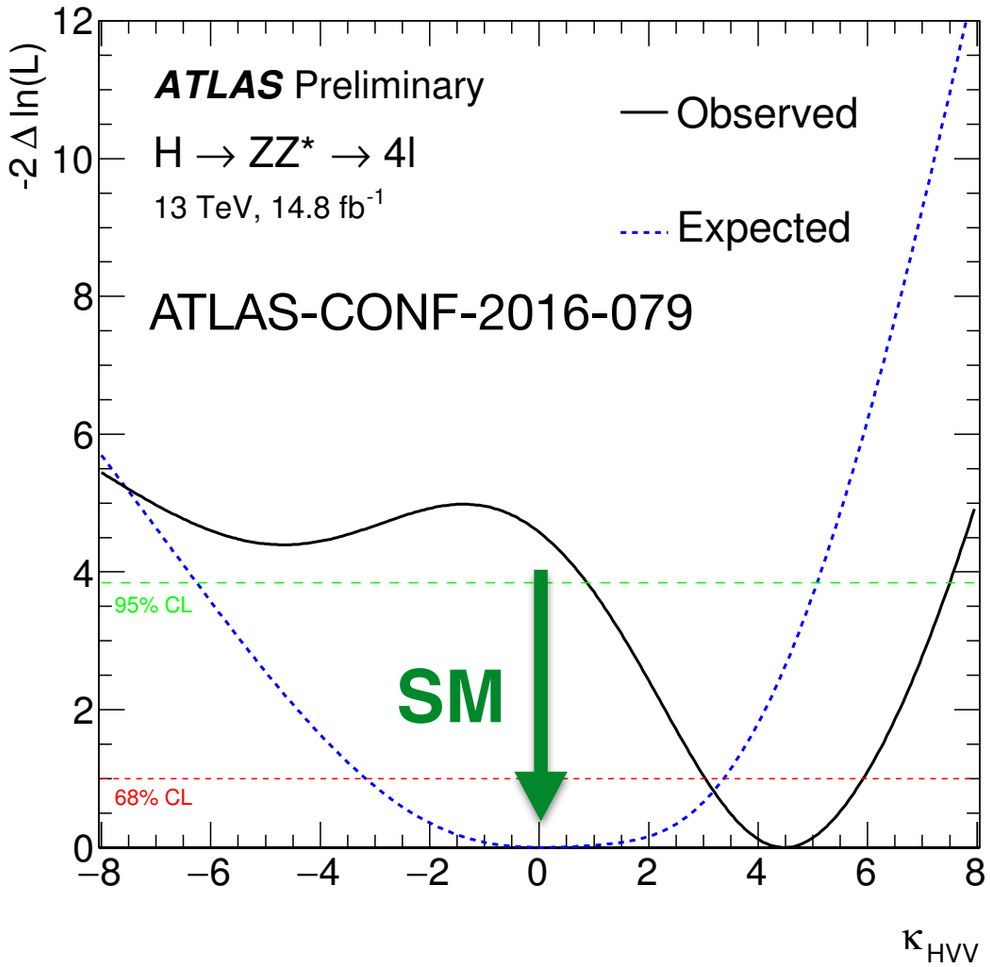
Direct/Indirect Width

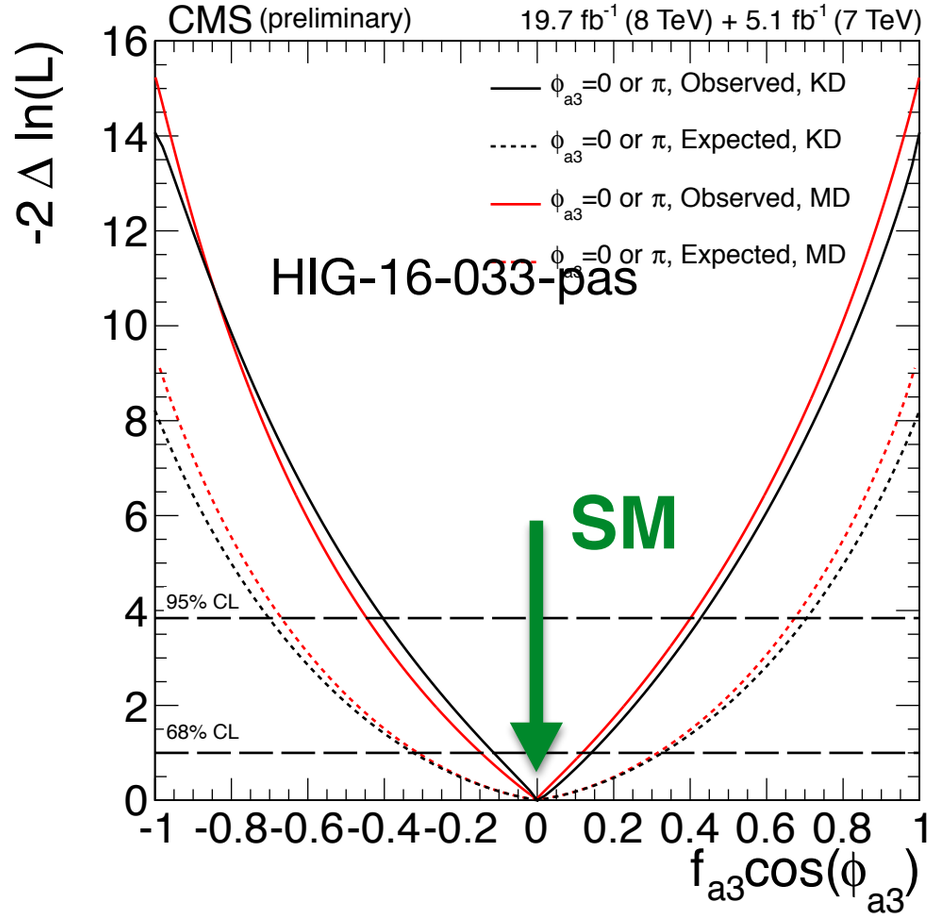


$m_{4\ell}$ range	Observed	Expected
$[100, 1600]$	$0.010^{+0.014}_{-0.010}$ $[0.000, 0.041]$	$0.004^{+0.013}_{-0.004}$ $[0.000, 0.032]$
$[105, 140]$	$0.3^{+1.4}_{-0.0}$ $[0.0, 3.9]$	$0.0^{+1.1}_{-0.0}$ $[0.0, 2.7]$

- **3D mass measurement: m_H=124.50$^{+0.48}_{-0.46}$GeV, comparable with Run-I ATLAS+CMS combination result.**
- **Observed (expected) width is constrained to be Γ_H<41(32) MeV @ 95% CL.**

CP mixing





- Limits on the scalar (κ_{HVV}) and pseudo-scalar ($\kappa_{AVV}\cdot\sin\alpha$) are derived with a fit of the yields in each categories:
  - Compatibility to the SM prediction: κ_{HVV} is 2.1σ, $\kappa_{AVV}\cdot\sin\alpha$ is 1.8σ

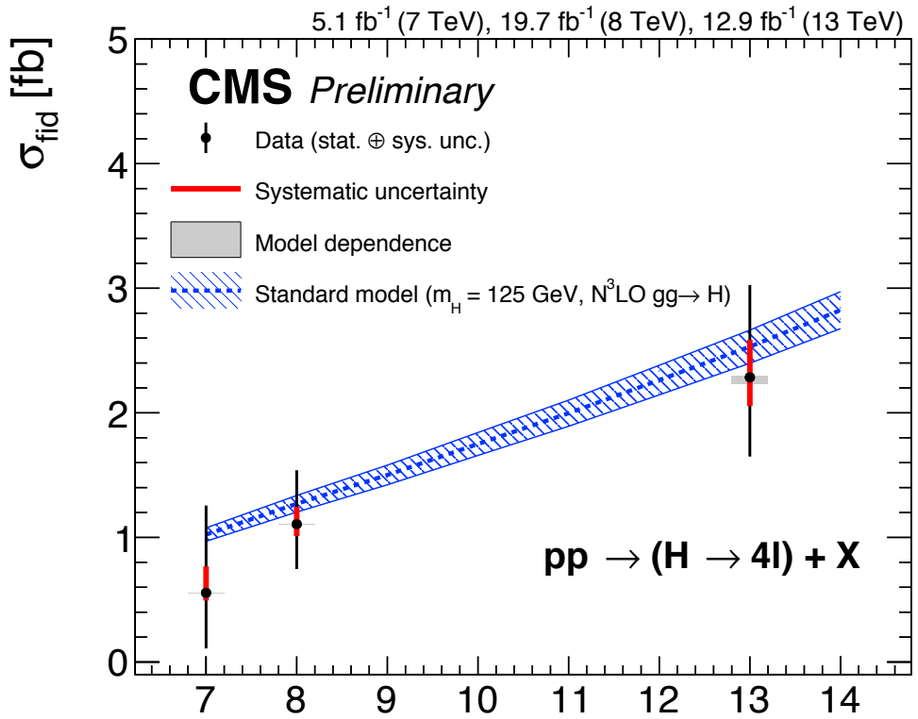
Fiducial cross section measurement

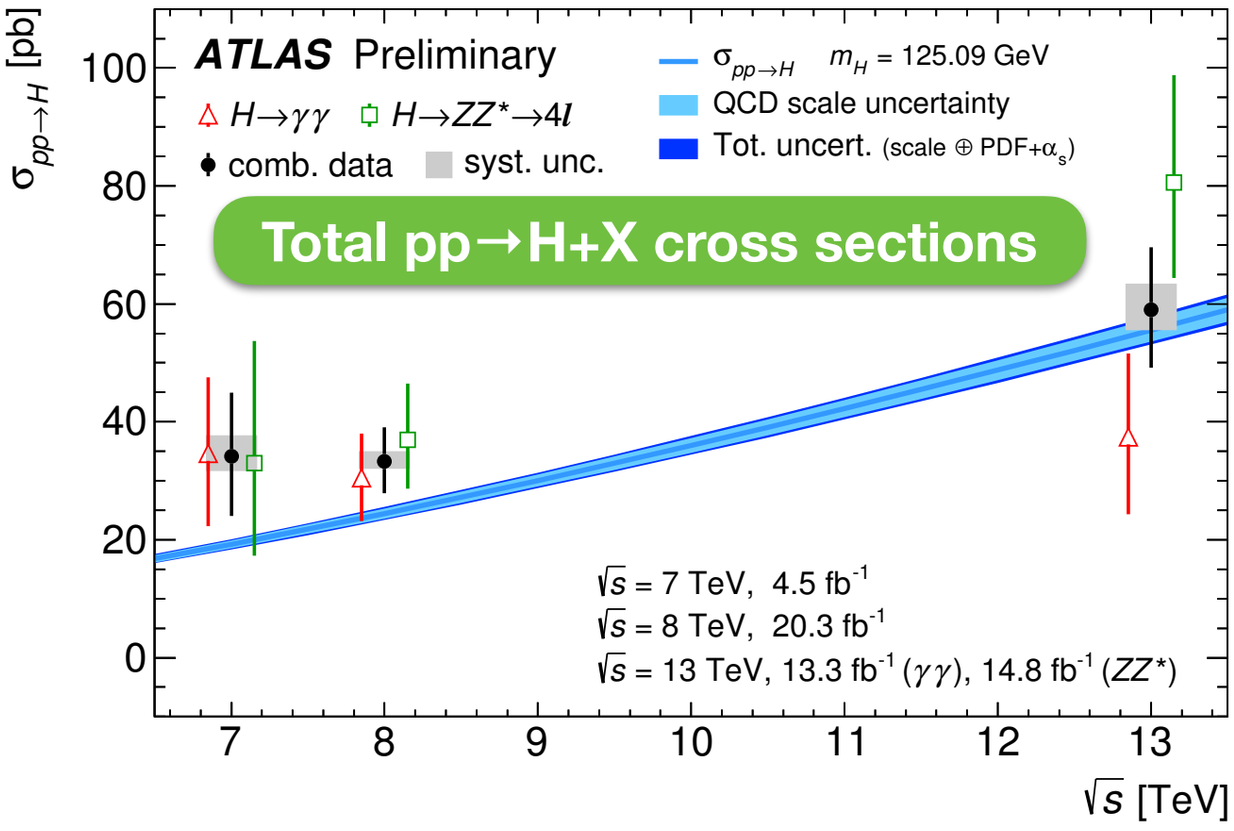
H→γγ

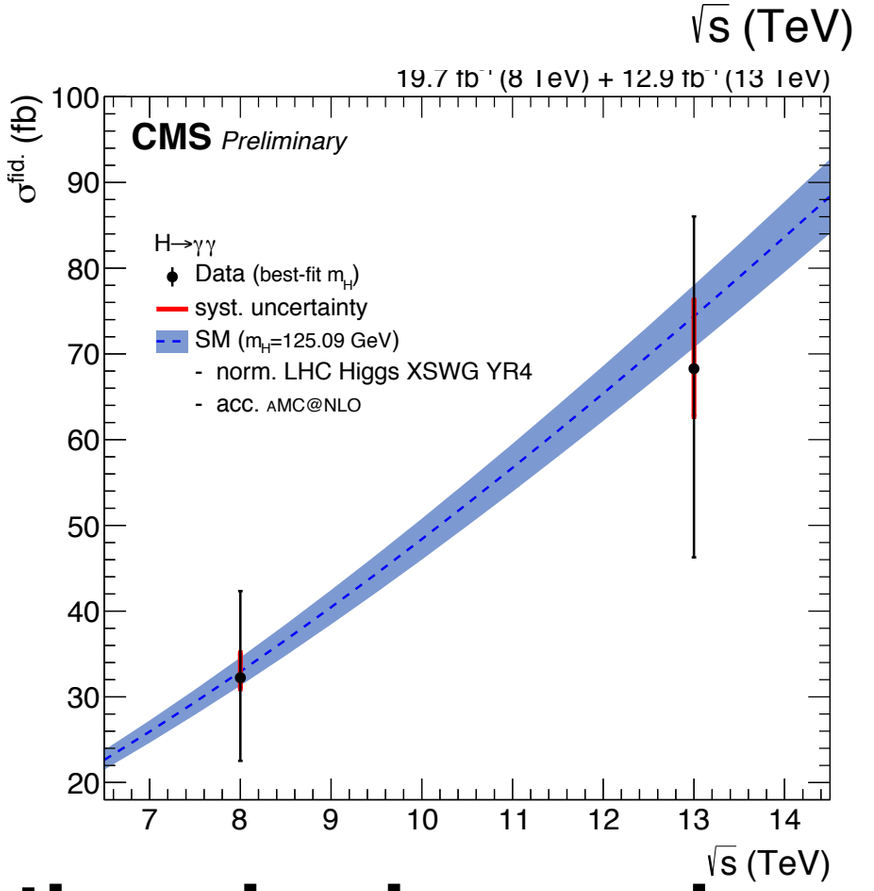
Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	43.2 ± 14.9 (stat.) ± 4.9 (syst.)	$62.8\ ^{+3.4}_{-4.4}$	[N^{3}LO + XH]
VBF-enhanced	4.0 ± 1.4 (stat.) ± 0.7 (syst.)	2.04 ± 0.13	[NNLOPS + XH]
single lepton	1.5 ± 0.8 (stat.) ± 0.2 (syst.)	0.56 ± 0.03	[NNLOPS + XH]

H→ZZ*

Final state	measured σ_{fid} [fb]	$\sigma_{\text{fid,SM}}$ [fb]
4μ	$1.28\ ^{+0.48}_{-0.40}$	$0.93\ ^{+0.06}_{-0.08}$
$4e$	$0.81\ ^{+0.51}_{-0.38}$	$0.73\ ^{+0.05}_{-0.06}$
$2\mu 2e$	$1.29\ ^{+0.58}_{-0.46}$	$0.67\ ^{+0.04}_{-0.04}$
$2e2\mu$	$1.10\ ^{+0.49}_{-0.40}$	$0.76\ ^{+0.05}_{-0.06}$

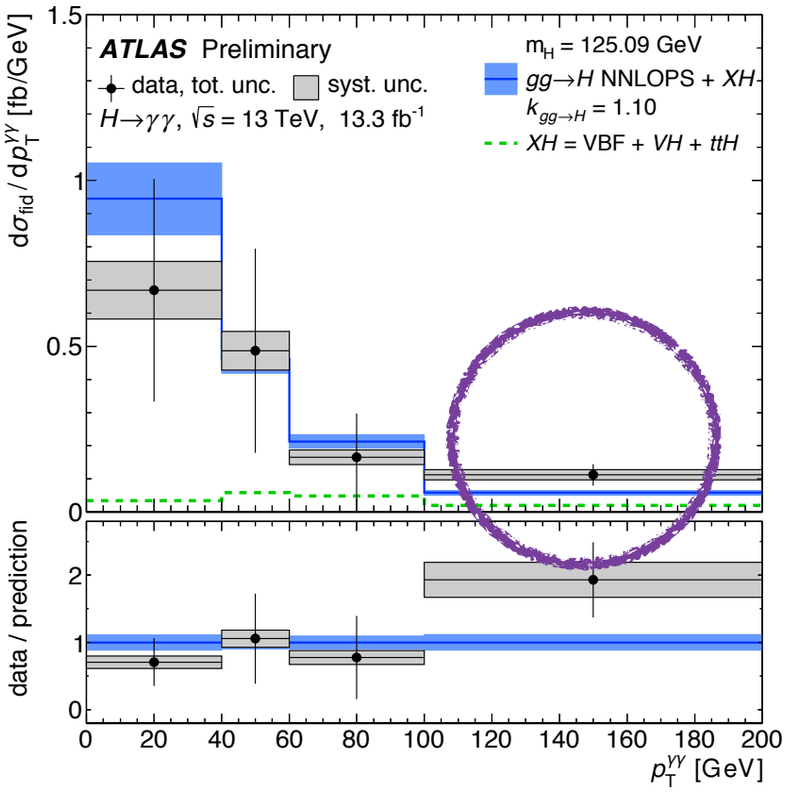






▣ **No deviation from the SM predictions is observed**

Differential cross section measurement



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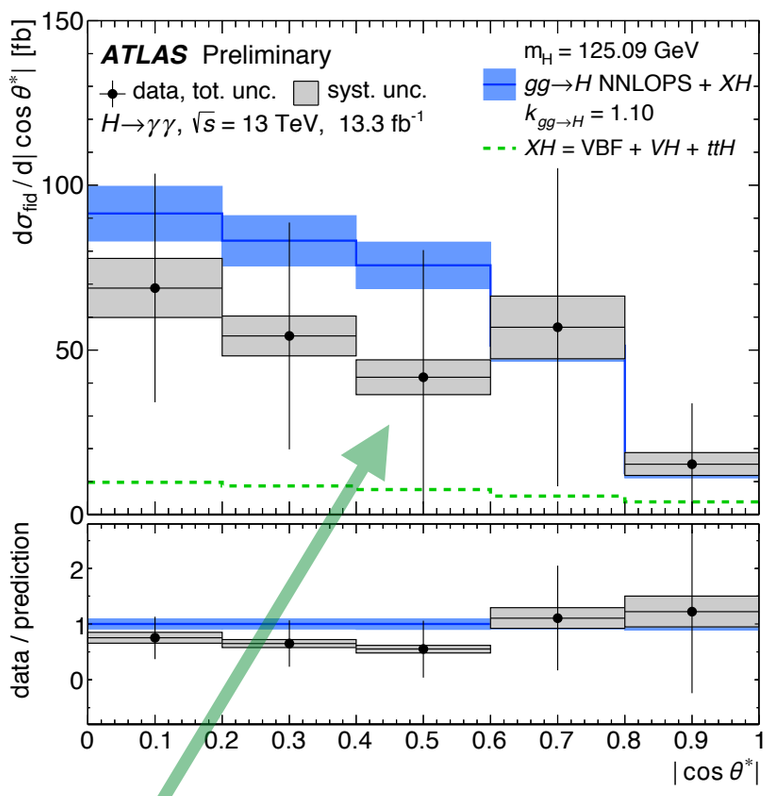
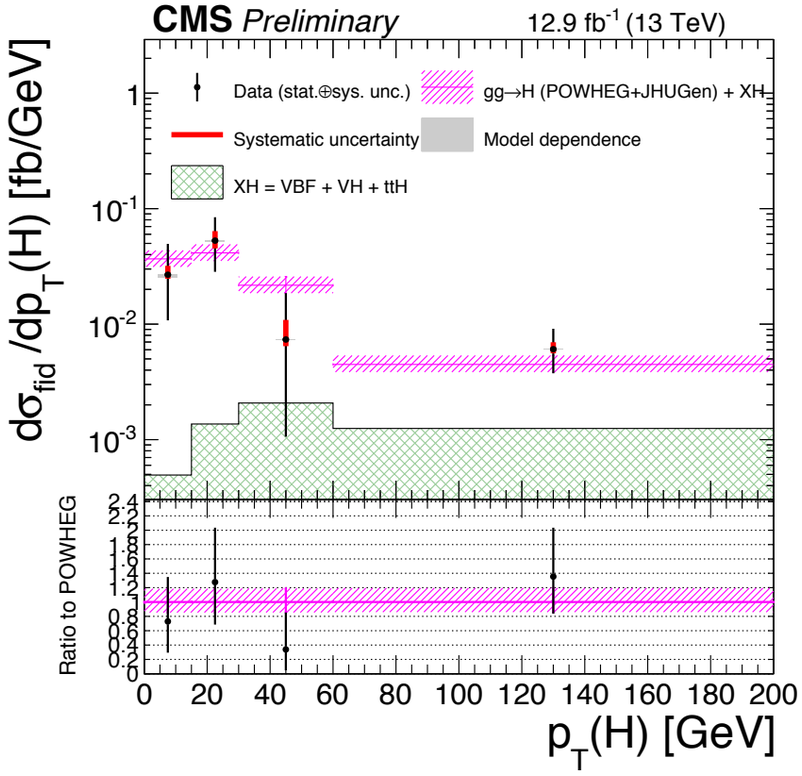
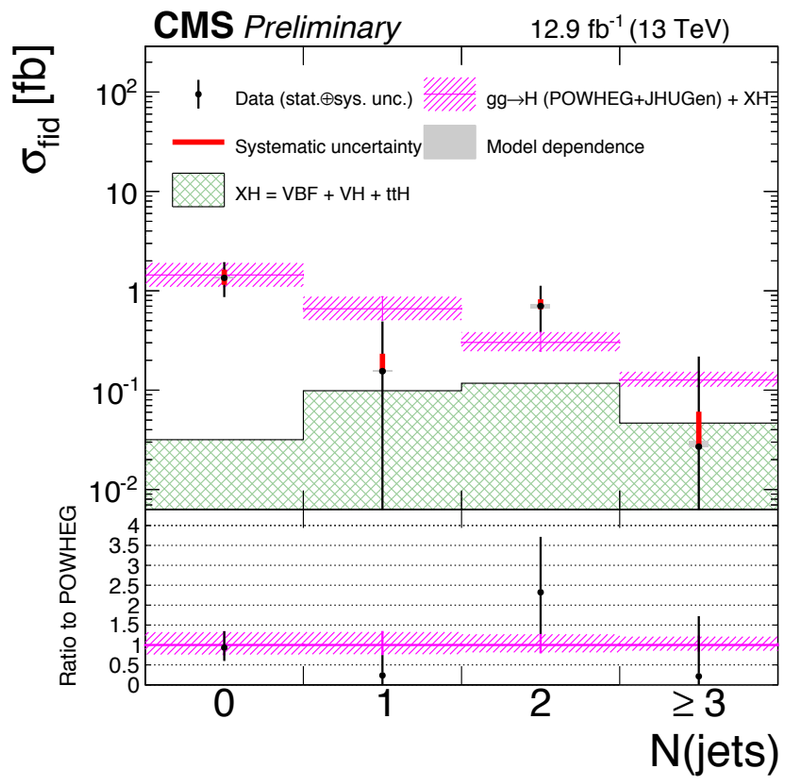


Scalar CP-even



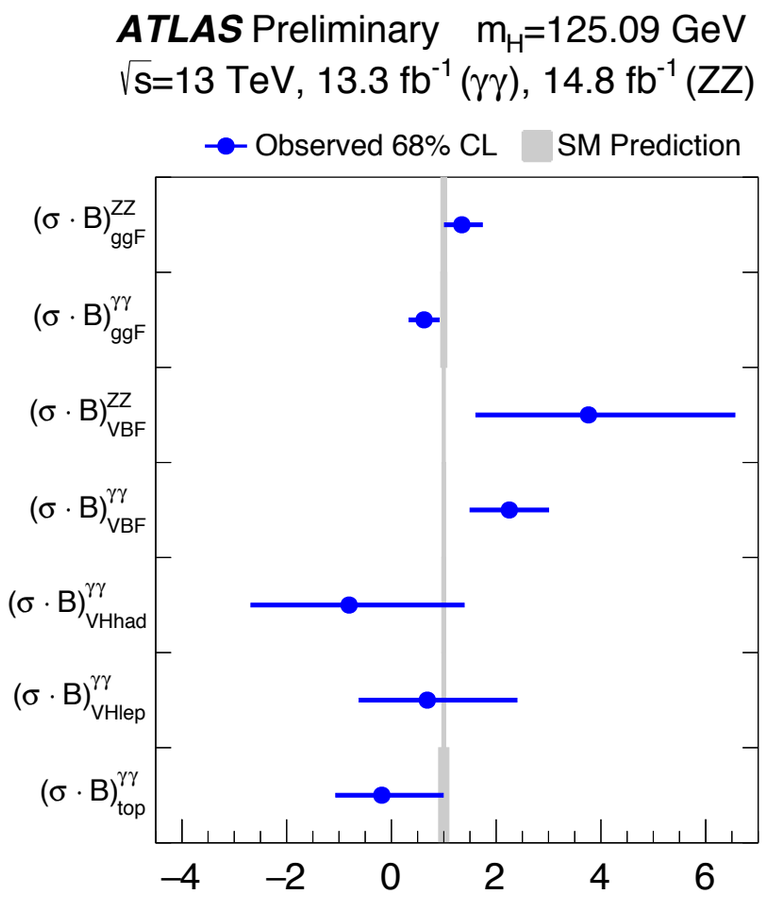


- **Good agreement between data and theory**

First combination of Higgs production and decay rates(Run-II)

- **The combination of H→γγ and H→ZZ*→4l: $\mu=1.13^{+0.18}_{-0.17}$ with observed (expected) significance of 10σ (8σ)**
- **Products of production cross sections and branching ratios:**

Decay mode	ggF	VBF	VHhad	VHlep	top
$H \to \gamma\gamma$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{ggF}}$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{VBF}}$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{VHhad}}$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{VHlep}}$	$(\sigma \cdot \mathrm{B})^{\gamma\gamma}_{\mathrm{top}}$
$H \to ZZ^*$	$(\sigma \cdot \mathrm{B})^{ZZ}_{\mathrm{ggF}}$	$(\sigma \cdot \mathrm{B})^{ZZ}_{\mathrm{VBF}}$	fixed to SM	fixed to SM	fixed to SM



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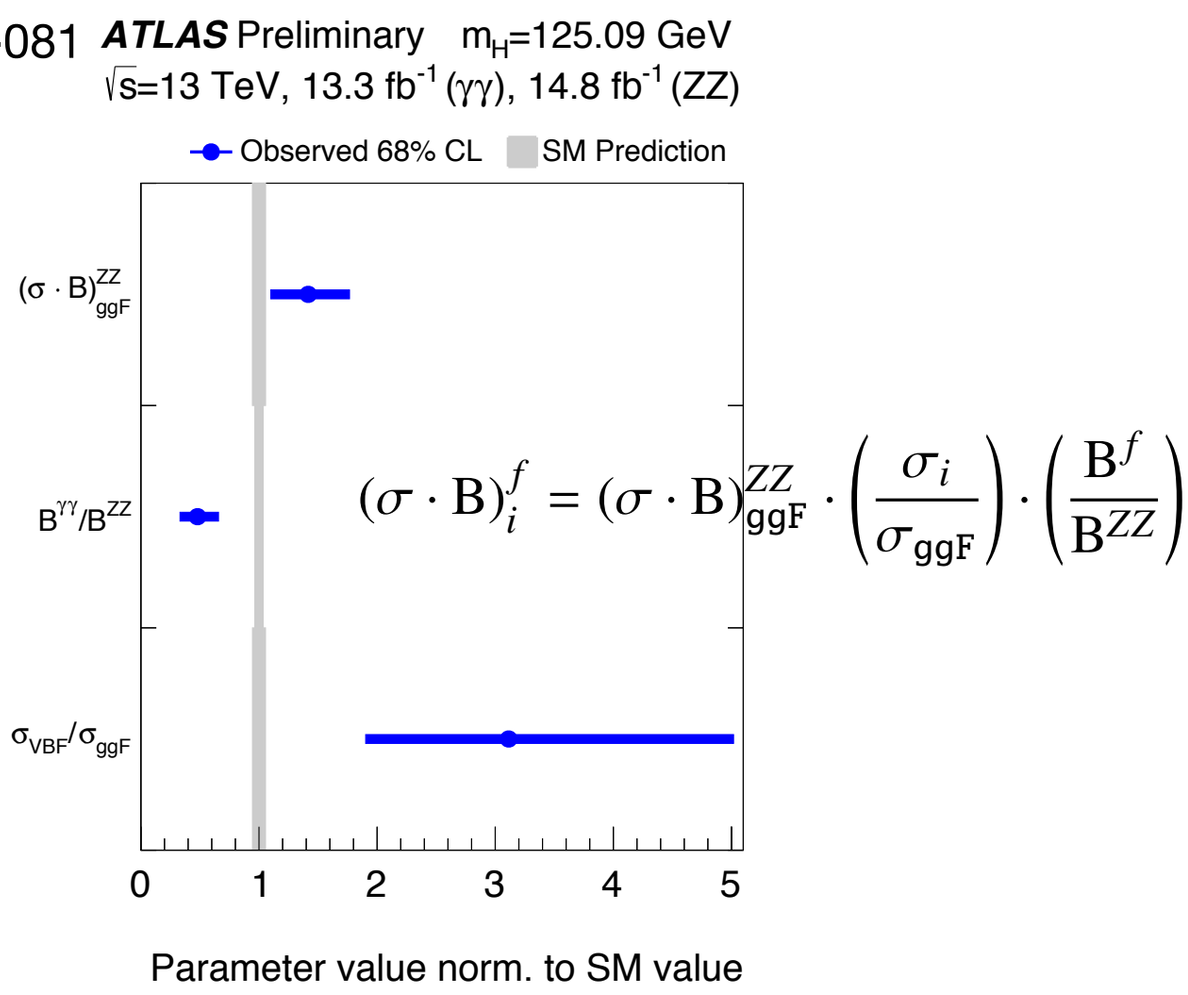
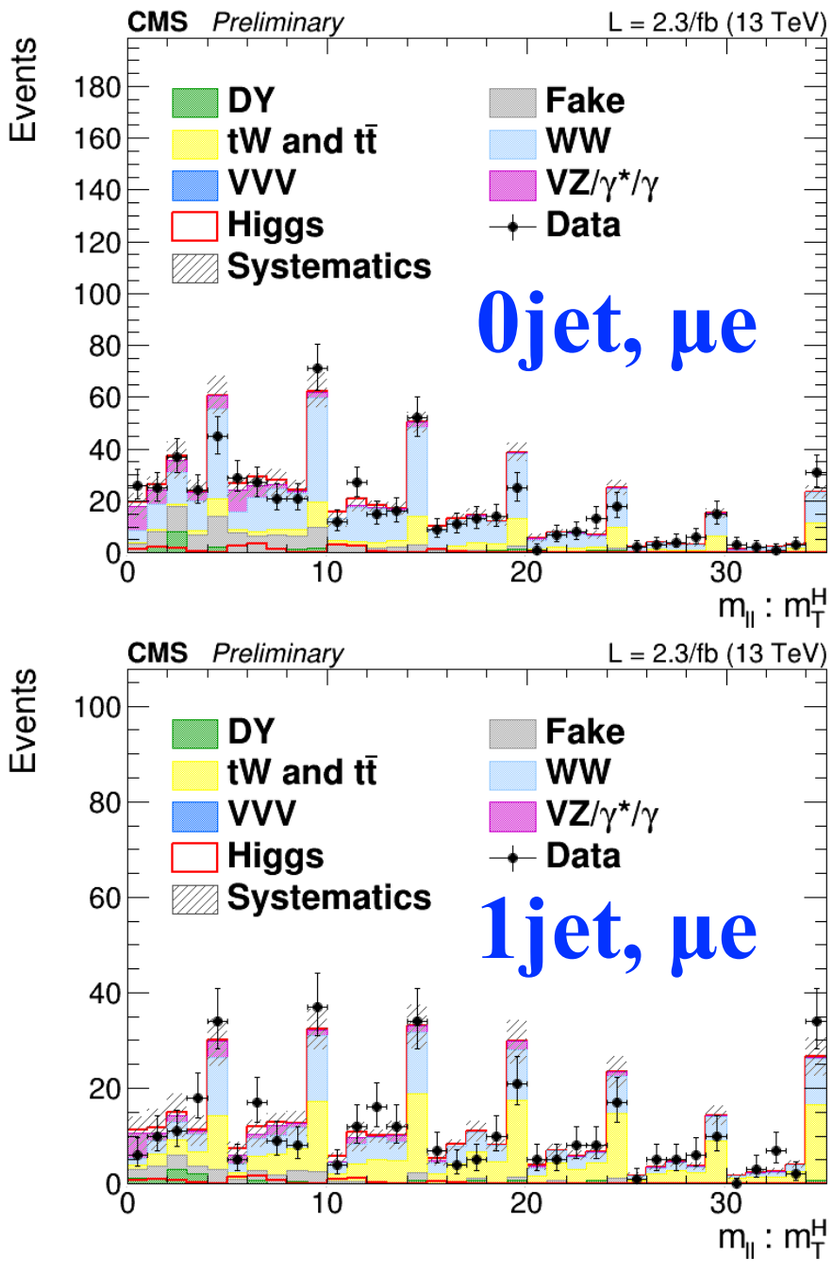


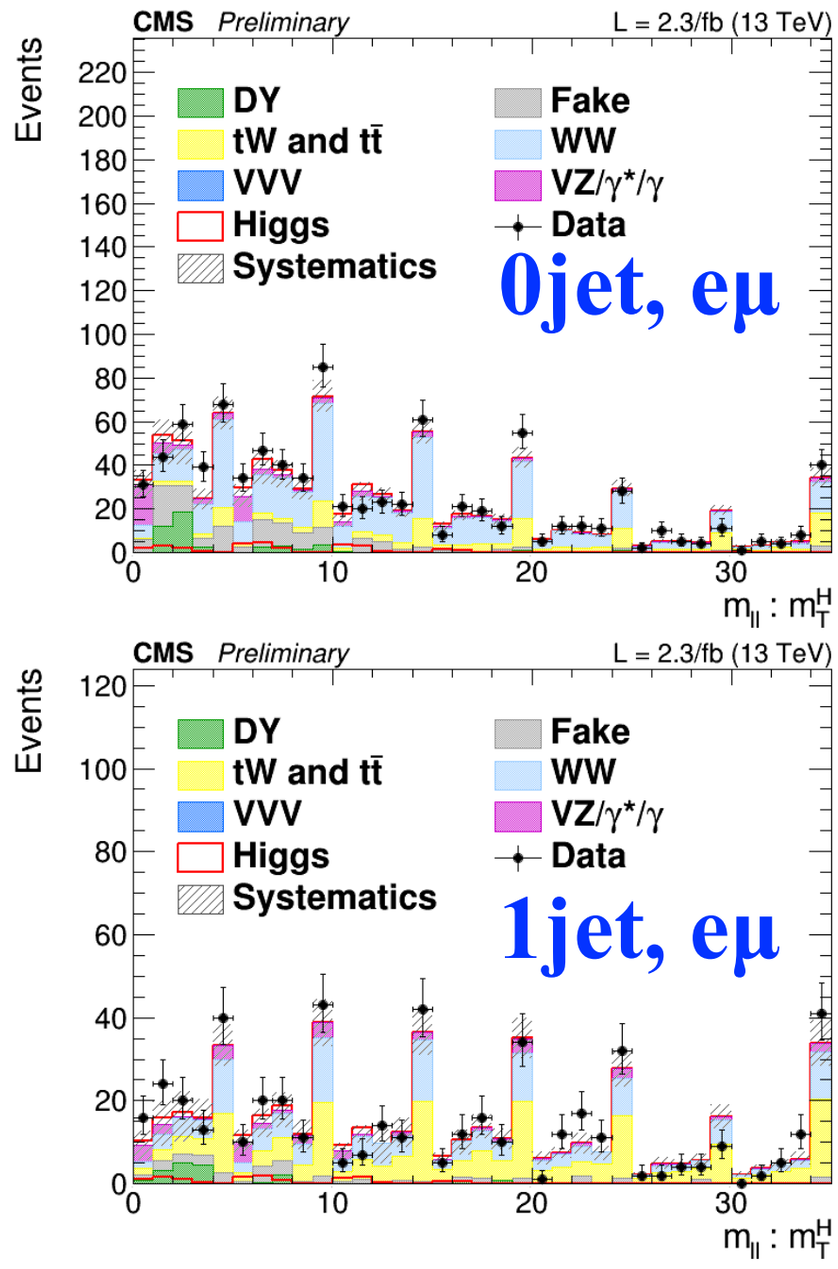
$$(\sigma \cdot \mathrm{B})^{f}_{i} = (\sigma \cdot \mathrm{B})^{ZZ}_{\mathrm{ggF}} \cdot \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \cdot \left(\frac{\mathrm{B}^f}{\mathrm{B}^{ZZ}}\right)$$

No significant deviation from the Standard Model predictions

H→WW→eνμν @ CMS

- Only the eμ final state is studied with the 2.3fb^{-1} early Run-II data
- To disentangle backgrounds, the 0 and 1 jet categories are split.





HIG-15-003

- Signal strength $\sigma/\sigma_{SM} = 0.3 \pm 0.5$
- Significance = 0.7σ (expected 2.0σ)

See more details in Joshuha's talk

Summary

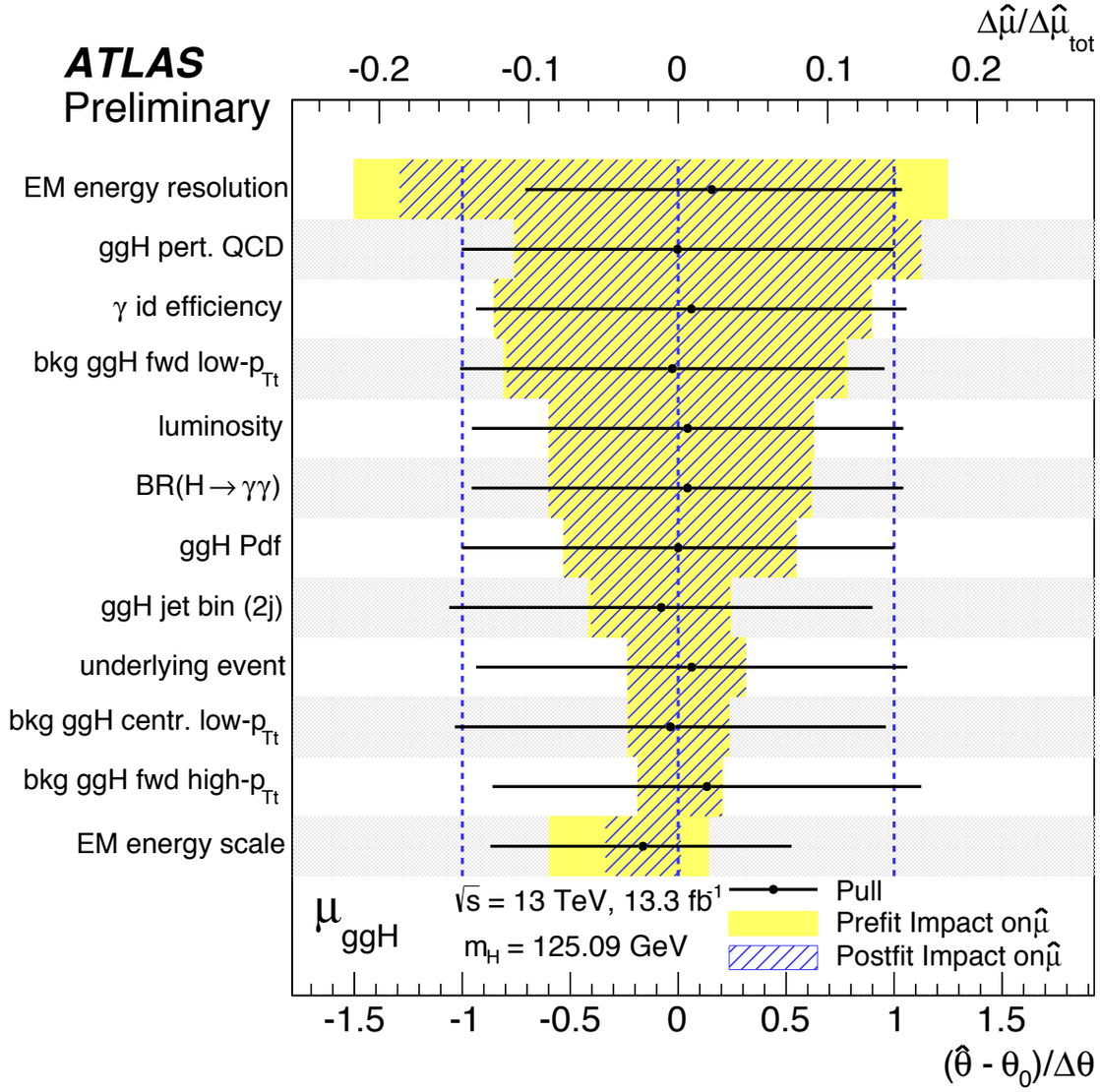
- **Comprehensive Higgs boson property measurement @ Run-I included mass, width, coupling, Spin-parity, cross section measurements etc.**

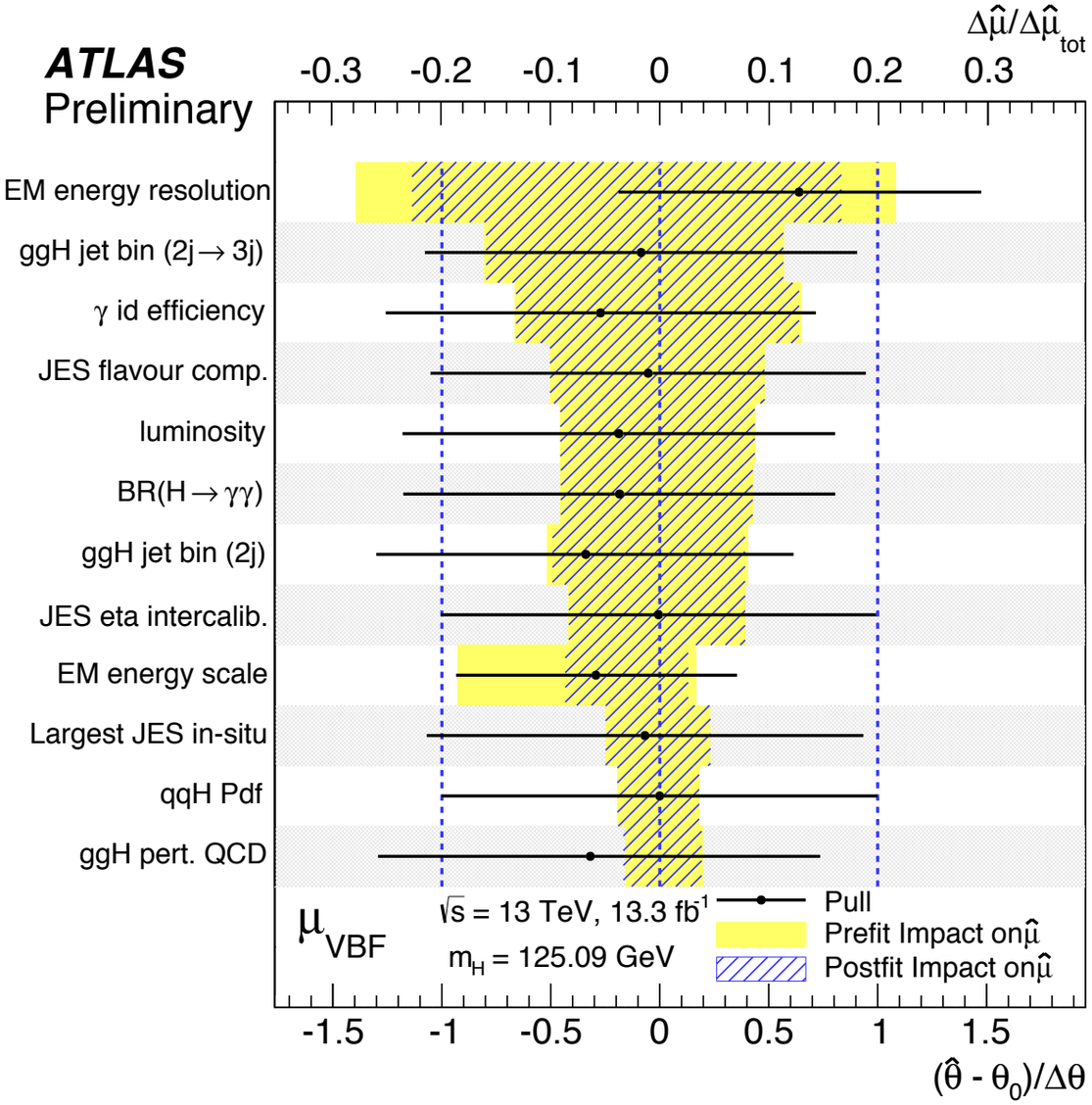
- **With the new 13TeV data, both ATLAS and CMS confirmed the existence of the Higgs boson:**
  - A first measurement of the Higgs boson production cross section: a good agreement with SM prediction

- **More results are coming soon with the increased integrated luminosity.**

Bonus slides

$H \rightarrow \gamma\gamma$





H->ZZ @ ATLAS

Analysis category	Signal ggF + $b\bar{b}H$ + $t\bar{t}H$	Signal VBF	Signal WH	Signal ZH	Background ZZ^*	Background Z + jets, $t\bar{t}$	Total expected	Observed
0-jet	11.2 ± 1.4	0.120 ± 0.019	0.047 ± 0.007	0.060 ± 0.006	6.2 ± 0.6	0.84 ± 0.12	18.4 ± 1.6	21
1-jet	5.7 ± 2.4	0.59 ± 0.05	0.137 ± 0.012	0.091 ± 0.008	1.62 ± 0.21	0.44 ± 0.07	8.5 ± 2.4	12
2-jet VBF enriched	1.9 ± 0.9	0.92 ± 0.07	0.074 ± 0.007	0.052 ± 0.005	0.22 ± 0.05	0.24 ± 0.11	3.4 ± 0.9	9
2-jet VH enriched	1.1 ± 0.5	0.084 ± 0.009	0.143 ± 0.012	0.101 ± 0.009	0.166 ± 0.035	0.088 ± 0.011	1.6 ± 0.5	2
VH-leptonic	0.055 ± 0.004	< 0.01	0.067 ± 0.004	0.011 ± 0.001	0.016 ± 0.002	0.012 ± 0.010	0.16 ± 0.01	0
Total	20 ± 4	1.71 ± 0.14	0.47 ± 0.04	0.315 ± 0.027	8.2 ± 0.9	1.62 ± 0.07	32 ± 4	44