Higgs property Measurement @ ATLAS

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Higgs particle

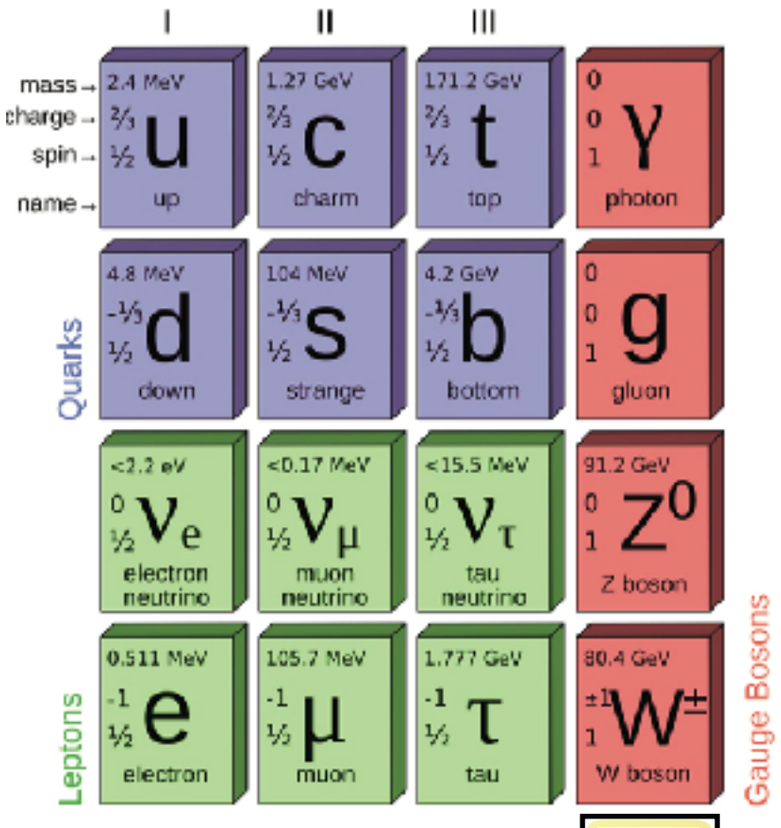
- The Higgs particle is **responsible for the masses of elementary particles**, while was the **missing corner stone** of the SM before LHC.

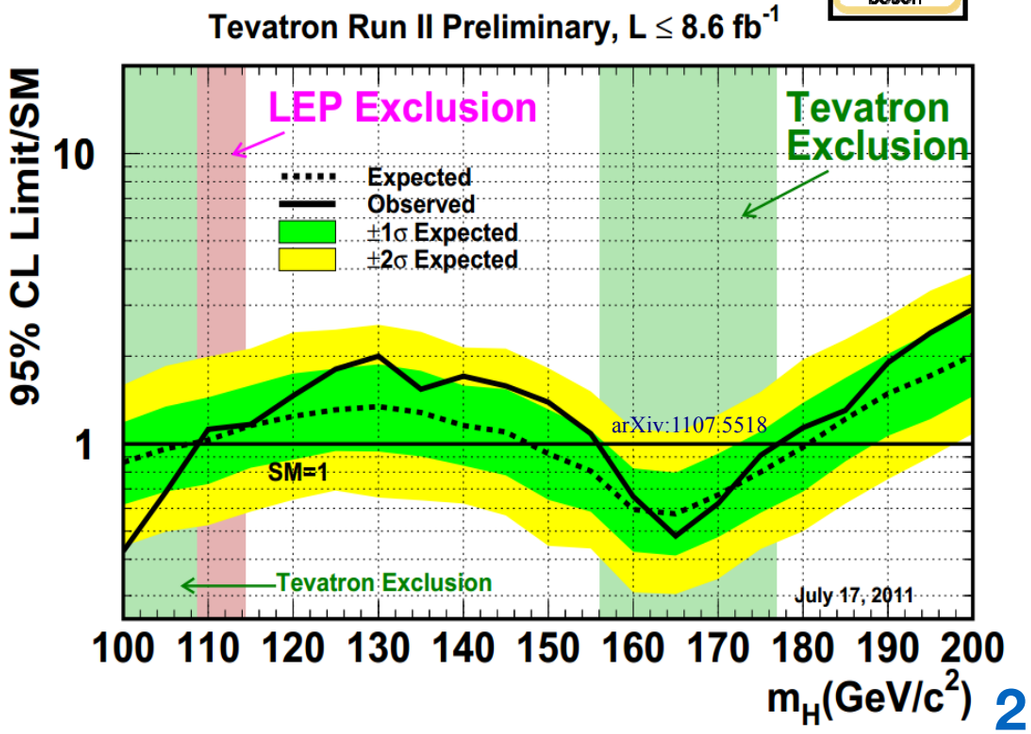
- **Great effects** of both the **theoretical and experimental** HEP Higgs community **before LHC**

  - **precise predictions** from the theory community (early days to LHCHXWG)

  - **excellent tools** due to previous experiments (e.g. PDFs from HERA)

  - **restrictions on the m_H** phase space





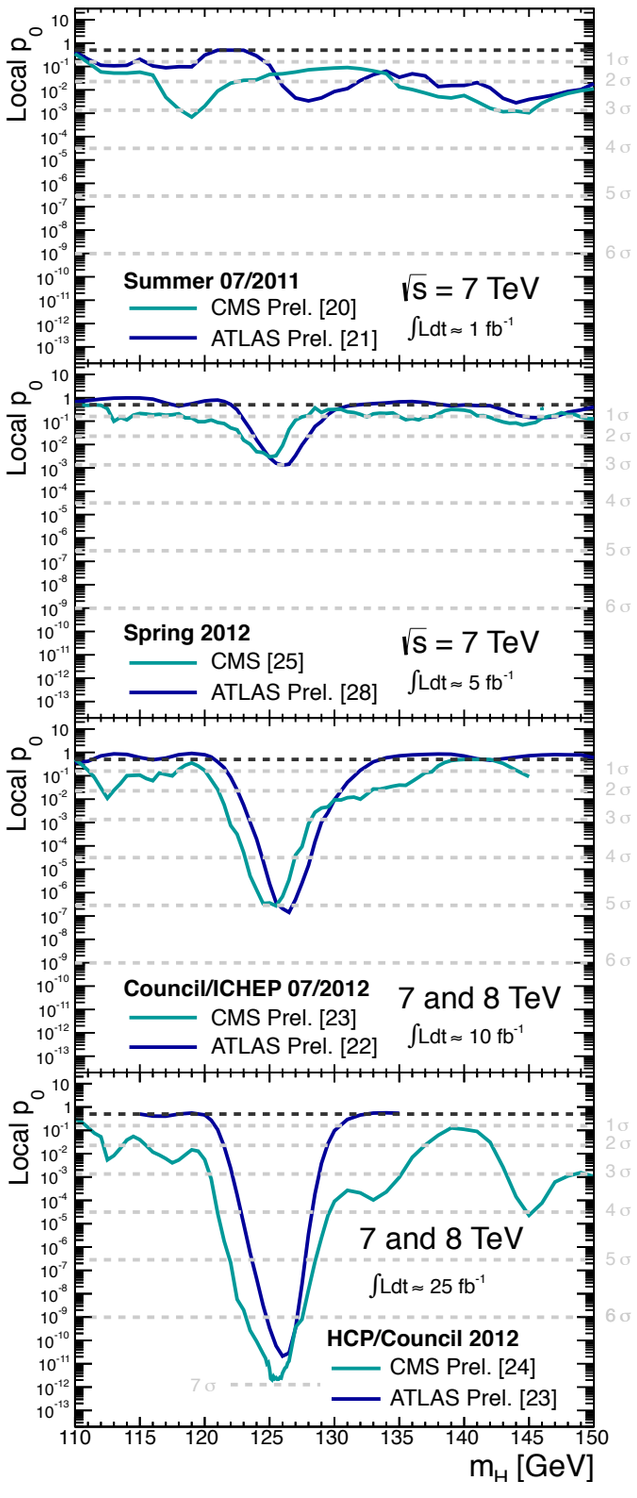
Before LHC:

$m_H > 15$ GeV (NA31, 1989)

$m_H > 114.4$ GeV (LEP, 2000)

$m_H < 156$ GeV OR $m_H > 177$ GeV (Tevatron, 2011)

LHC Timely Discovery



- ✦ **Summer 2011: EPS and Lepton-Photon**

  First (and last) focus on limits (scrutiny of the p_0)

- ✦ **December 2011: CERN Council**

  First hint

- ✦ **Summer 2012: CERN Council and ICHEP**

  Discovery on 4th of July 2012:

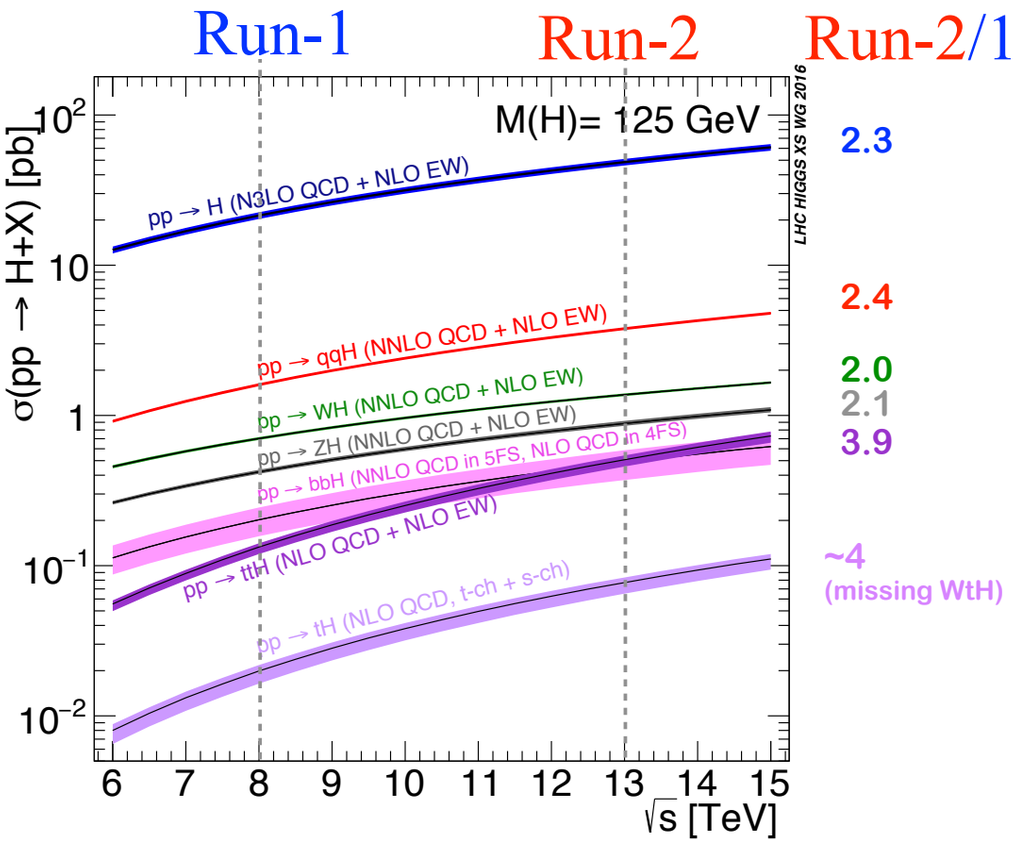
  - **Higgs-like boson at ~125GeV**
  - **5.9σ @ATLAS, 5σ @CMS (*PLB, 716, 2012*)**

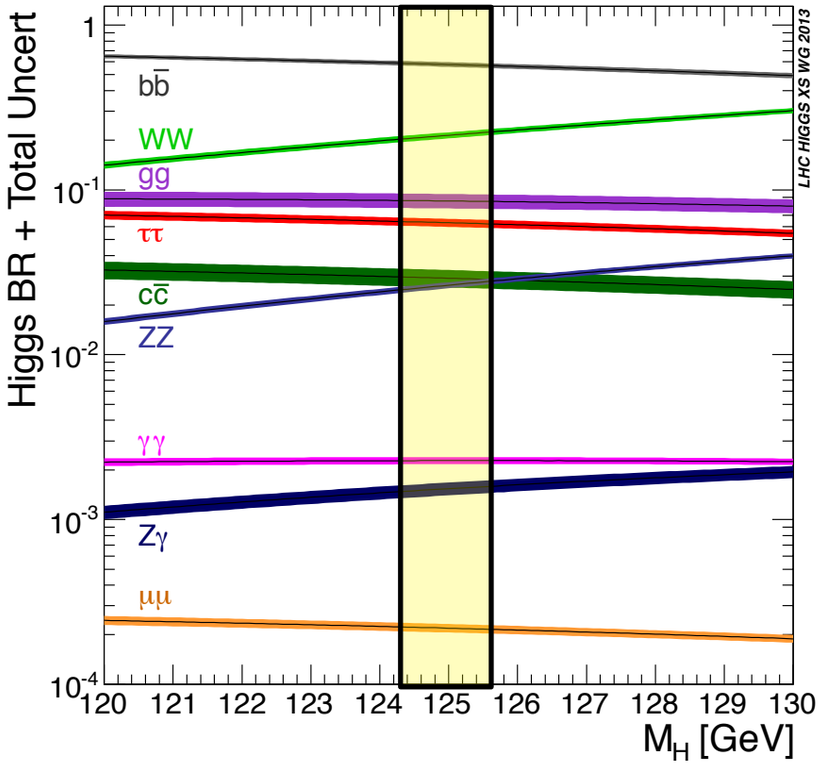
- ✦ **December 2012: CERN Council**

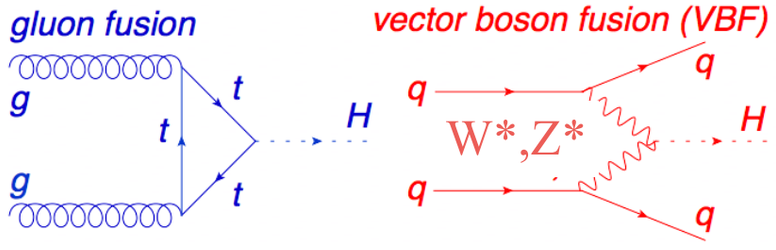
  A new era of particle physics — measure the properties of the new particle

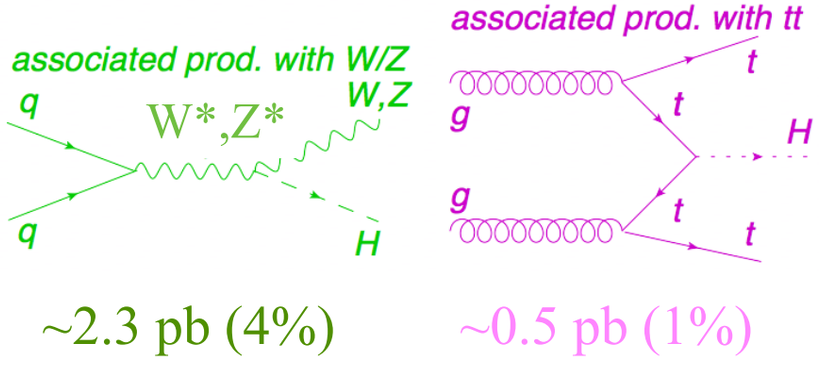
✦ October 2013: **Nobel prize** to Englert and Higgs

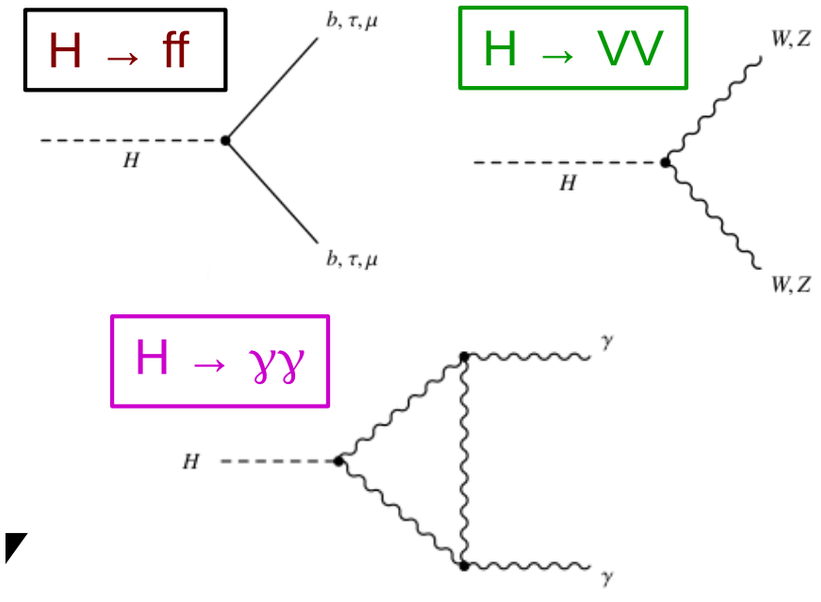
Higgs production and decay @ LHC



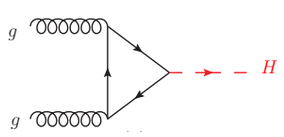
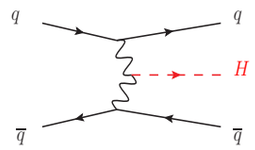
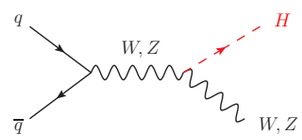
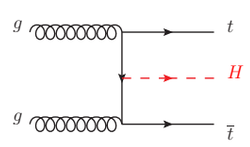






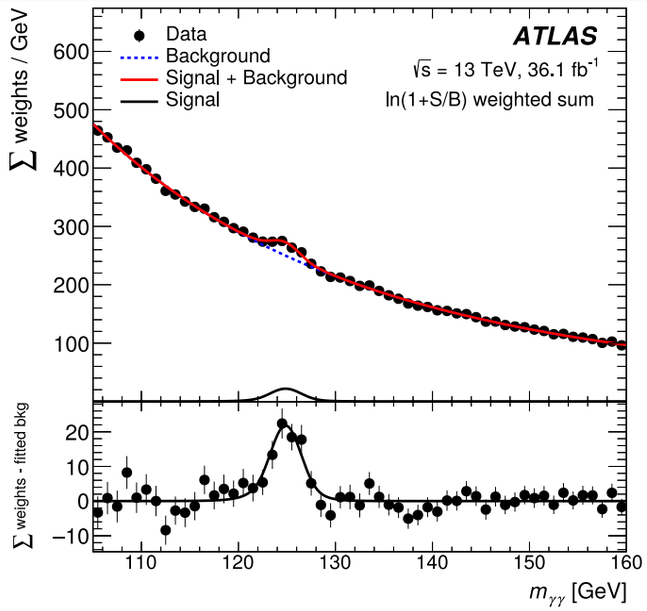


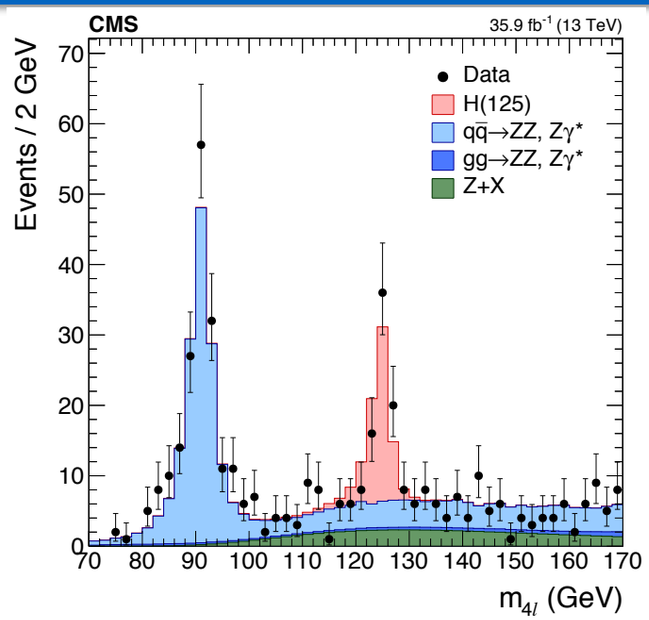
Panorama of Higgs analysis

Channel ATLAS√ CMS√	ggF 	VBF 	VH 	ttH 	Mass	CP	X-sec.	Width
γγ	√ √	√ √	√ √	√ √	√ √	√ √	√ √	√ √
ZZ*(4l)	√ √	√ √	√ √	√ √	√ √	√ √	√ √	√ √
WW*(lvlv)	√ √	√ √	√ √	√ √		√ √	√ √	√ √
ττ	√ √	√ √		√ √		√	√	
bb	√	√ √	√ √	√ √				
Zγ	√ √	√ √						
γ*γ	√	√						
μμ	√ √	√ √						
invisible	√ √	√ √	√ √					

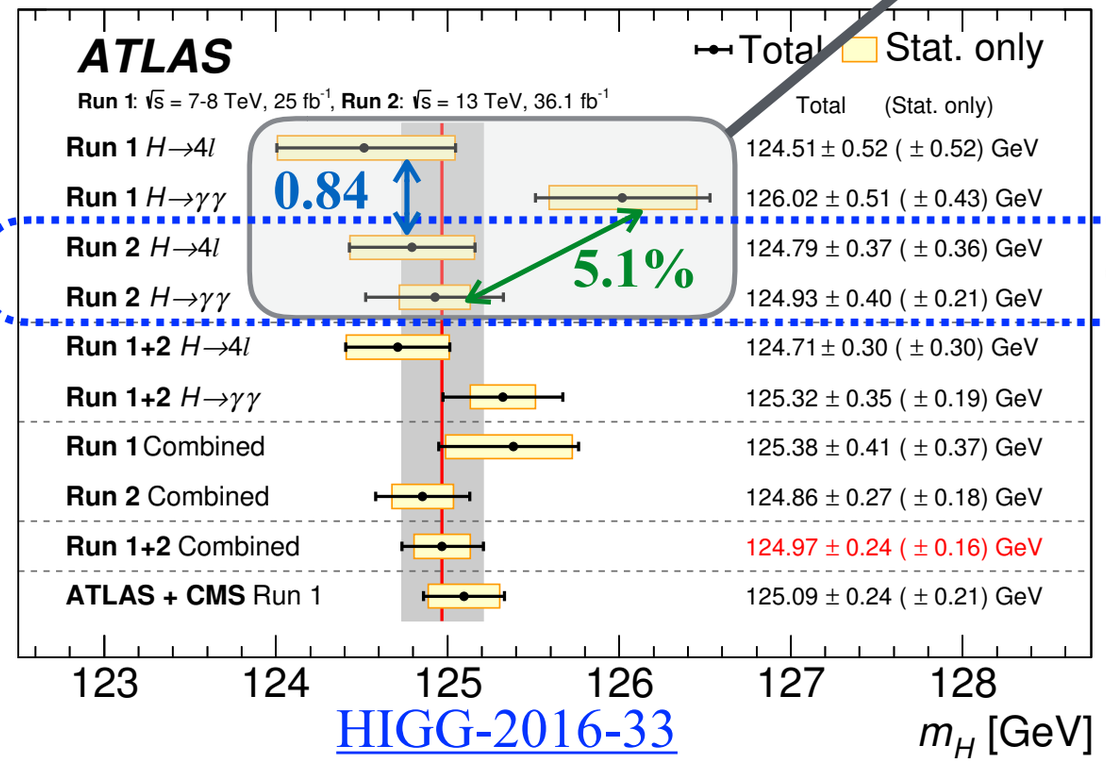
√ ready @run1, but no yet @ run2, √ still on the way

Higgs Mass





Compatible with 12.3%

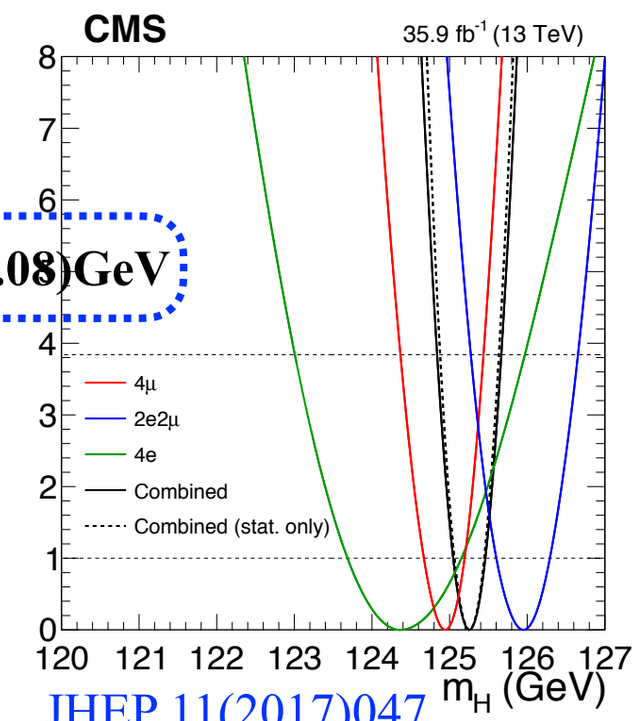


HIGG-2016-33

$3D: \mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$

With Z-constraint

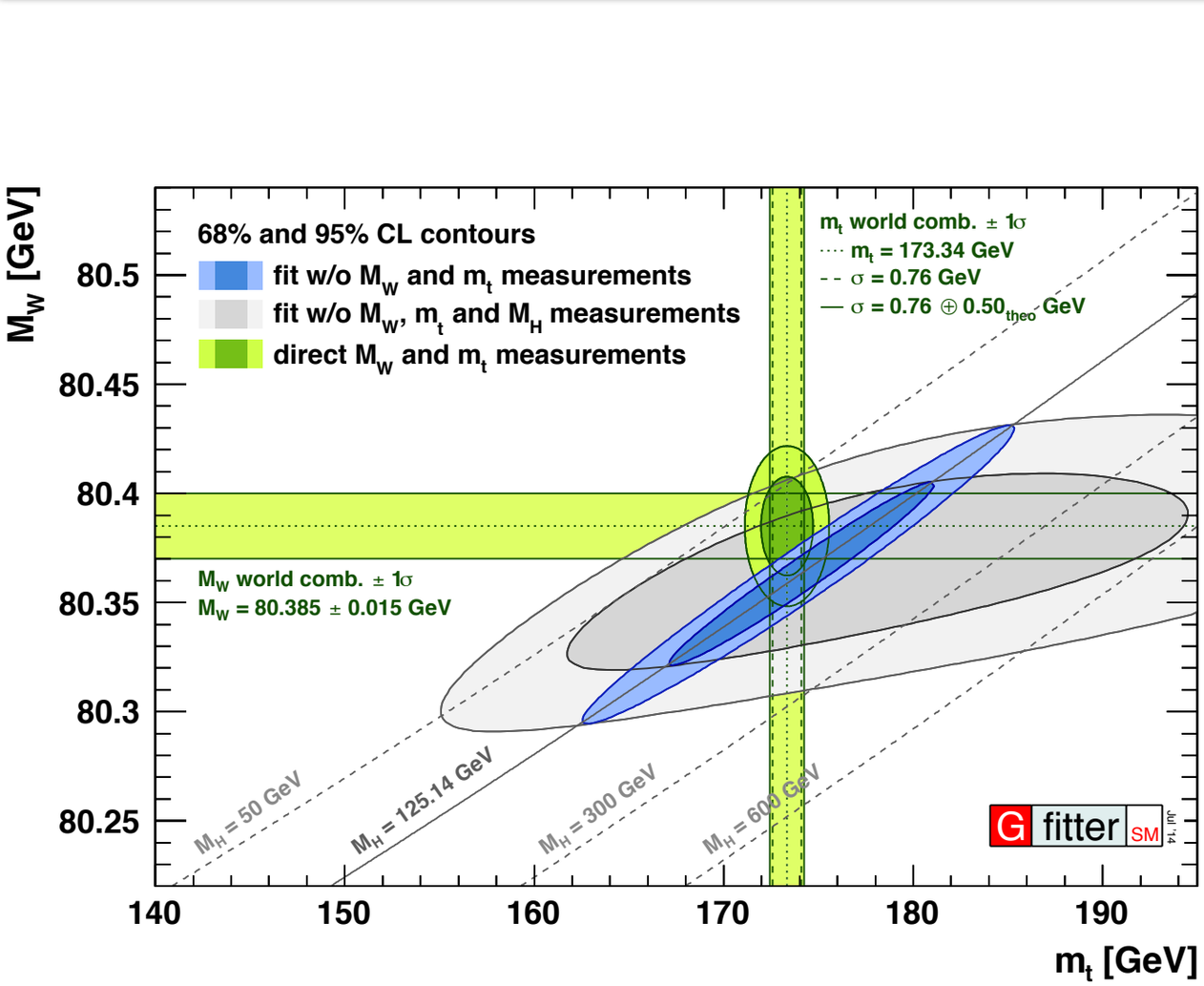
CMS :125.26±0.21(±0.20±0.08)GeV

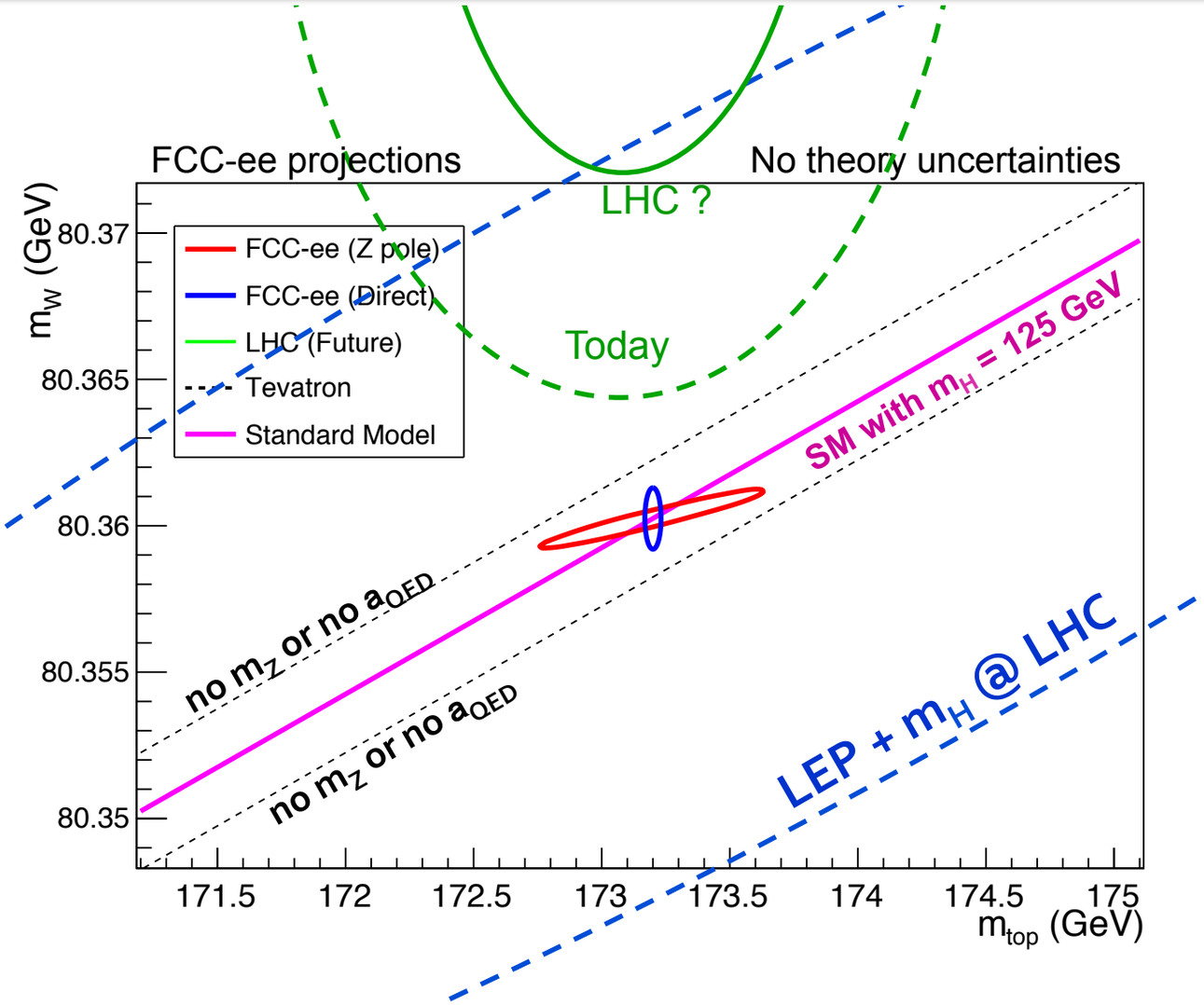


JHEP 11(2017)047

- Precise measurement with excellent detector performance : $\sigma(m_H)/m_H \sim 0.17\%$.
- Single experiments are better/comparable w.r.t. ATLAS+CMS Run-1 combination
- Still dominated by statistical uncertainties, uncertainty on coupling ~ 0.5%

Mass Measurement: Applications





- More precise measurements become sensitive to other particles /NP in the loops
- More stringent requirement for the theoretical calculations.

Higgs Width

It is impossible to extract the coupling and Higgs width separately from on-shell cross section measurement → Importance of Γ_H measurement.

$$\sigma_{i\to H\to f}^{on-shell}(SM) \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

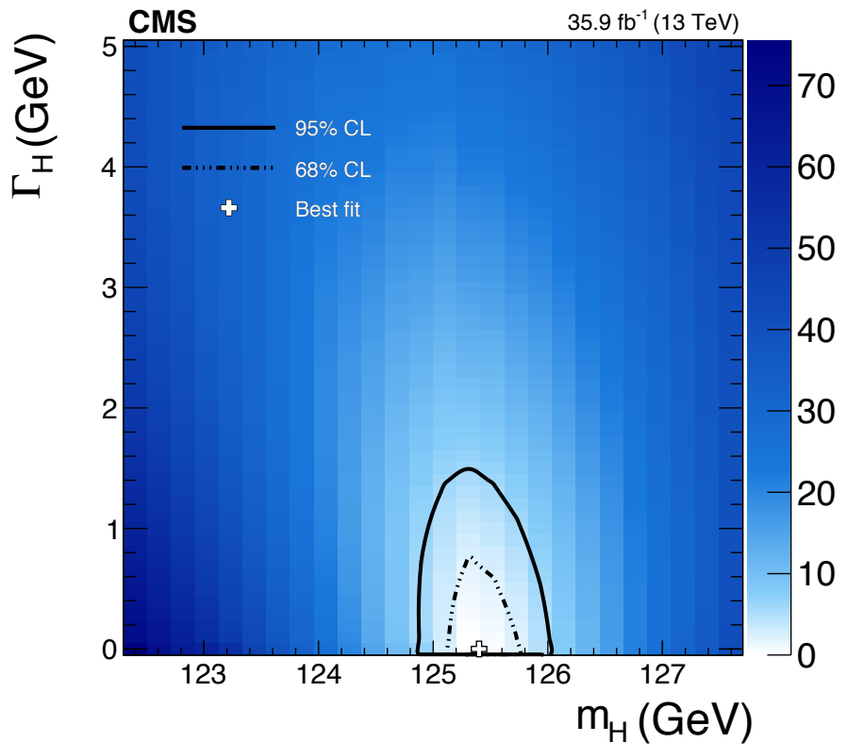
$m_H = 125\text{GeV} \rightarrow \Gamma_H = 4.07\text{MeV}$
Γ_H cannot be accessed directly due to the experiment resolution

Run-1 direct Higgs width measurement:

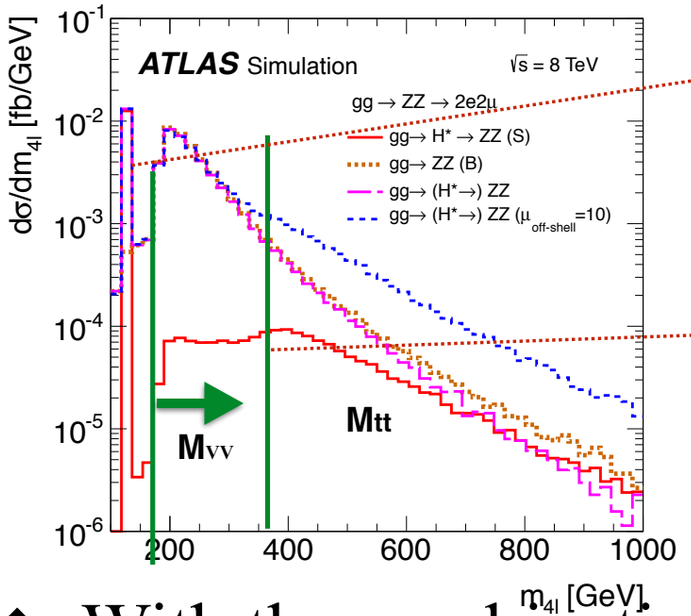
Γ: obs.(exp.) @ 95% CL	H→γγ	H→ZZ
ATLAS	5.0 (6.2) GeV	2.6 (6.2) GeV
CMS	2.4 (3.1) GeV	3.4 (2.8) GeV

Latest CMS: 1.1 (1.6) GeV

3 orders of magnitude larger than SM width



Indirect Higgs Width Measurement



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

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

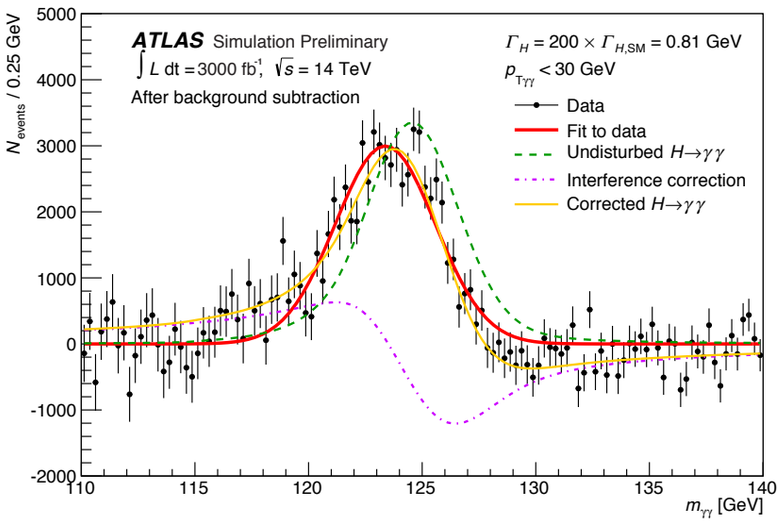
$$\mu_{offshell} = \mu_{onshell} \times \Gamma_H / \Gamma_H(SM)$$

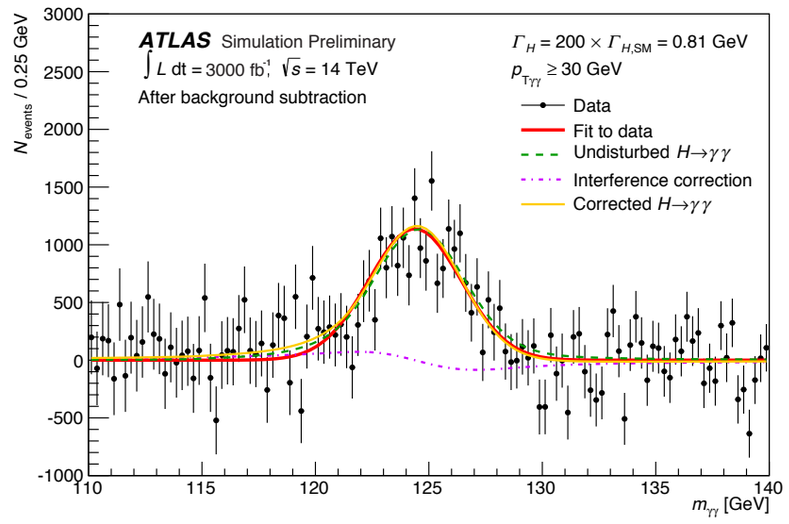
Obs (Exp) @ 95% CL:
CMS: Γ_H < 22 (33)MeV
ATLAS: Γ_H < 14 (15)MeV

PLB 736 (2014) 64
EPJC (2015) 71:335
HIGG-2017-06

ATLAS @ 3000 fb^{-1}:
$4.2^{+1.5}_{-2.1}$ MeV

- With the combination between **on-shell and off-shell analyses**:
  - **Assuming the on-shell couplings are the same as the off-shell couplings**
  - Assuming NP modifying off-shell coupling **without the modification of other background and signal expectation.**



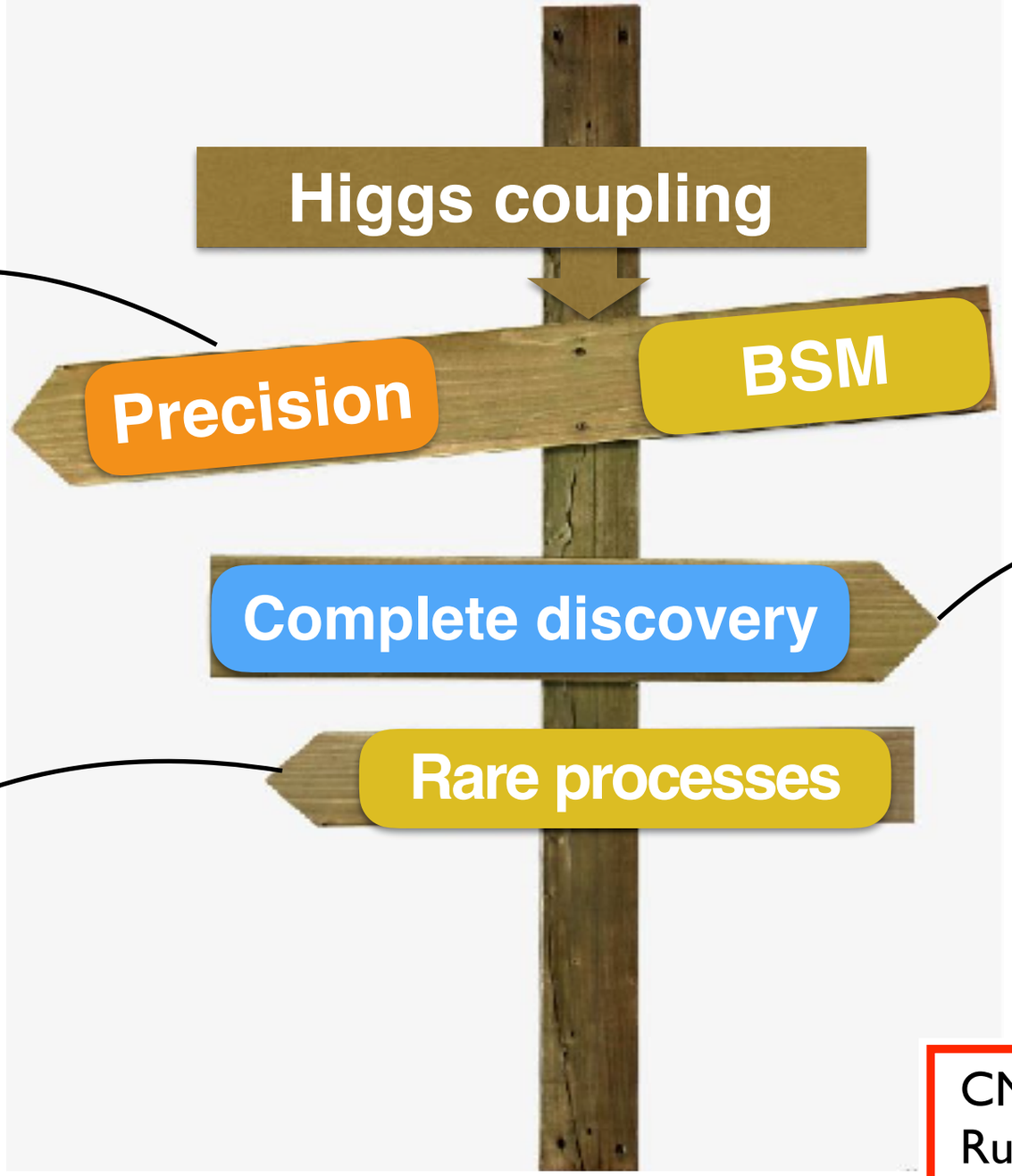


ATLAS @ 3000 fb^{-1}:
<160MeV @95%

- Extract the Higgs width with **the mass shift from the interference** of the H→γγ w.r.t the continuum background (gg→γγ box diagrams)

Comprehensive Measurements @ Run2

H→γγ/ZZ/WW
…
Combination
Methodology



H→bb observation

Significance:
5.4σ observed
(5.5σ expected)

New : ★
H→bb,ttH,VH

H→μμ/Zγ/inv*
HH …

ttH observation

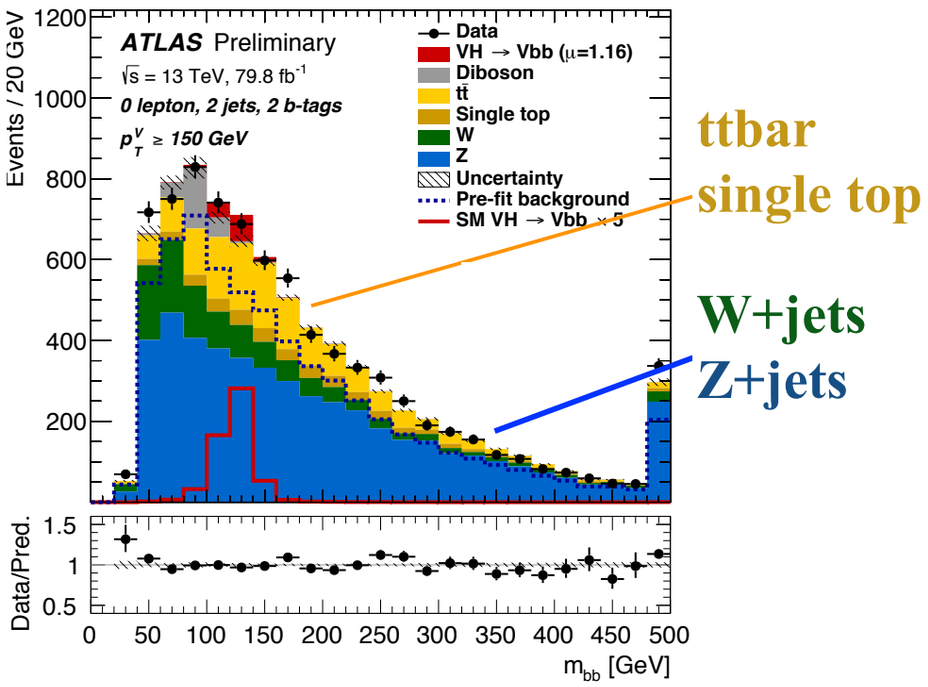
CMS
Run-1+Run-2: **5.2σ** (4.2σ exp.)

VH observation

5.3σ observed
(4.8σ expected)

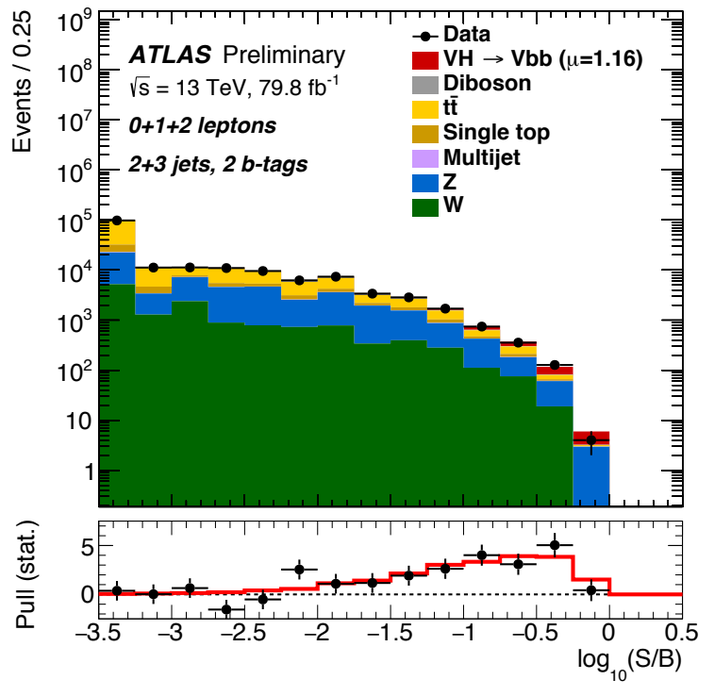
ATLAS (up to 80 fb^{-1})
Run-2: **5.8σ** (4.9σ exp.)
Run-1+Run-2: **6.3σ** (5.1σ exp.)

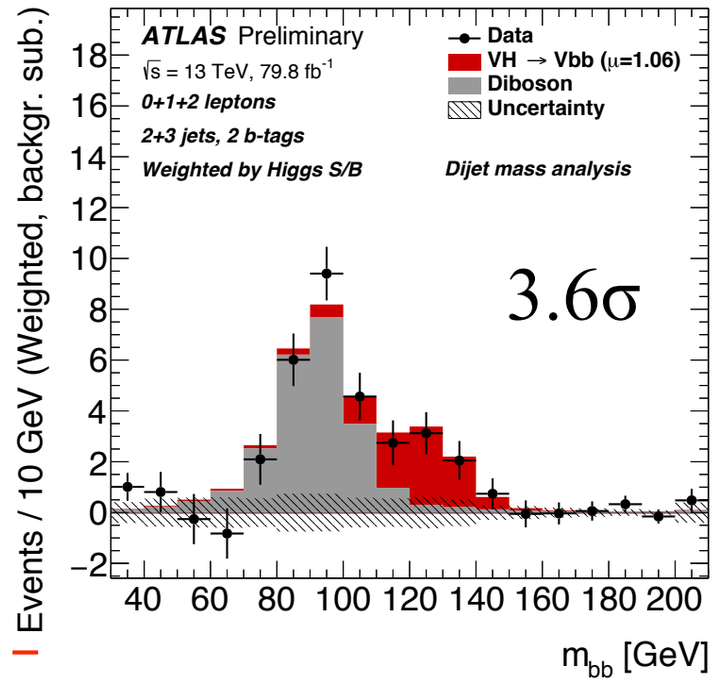
Observation of H→bb



ttbar
single top

W+jets
Z+jets





Fit result with 79.8 fb^{-1} of Run-2 data

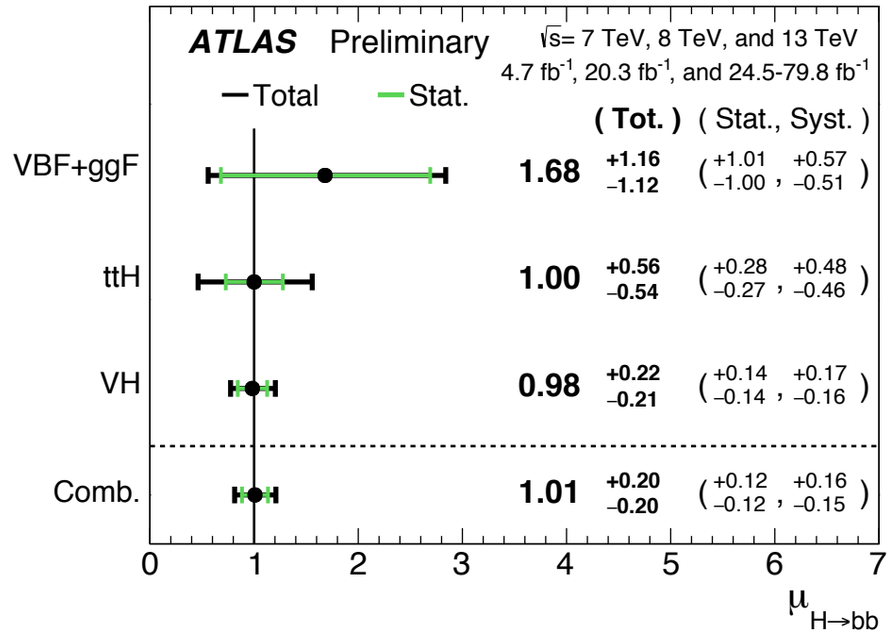
$$\mu = \sigma_{\mathrm{meas}}/\sigma_{\mathrm{SM}} = 1.16^{+0.27}_{-0.25}$$

Significance: **4.9σ** (4.3σ expected)

Combination with Run-1:

$$\mu = 0.98 \pm 0.14(\mathrm{stat.})^{+0.17}_{-0.16}(\mathrm{syst.})$$

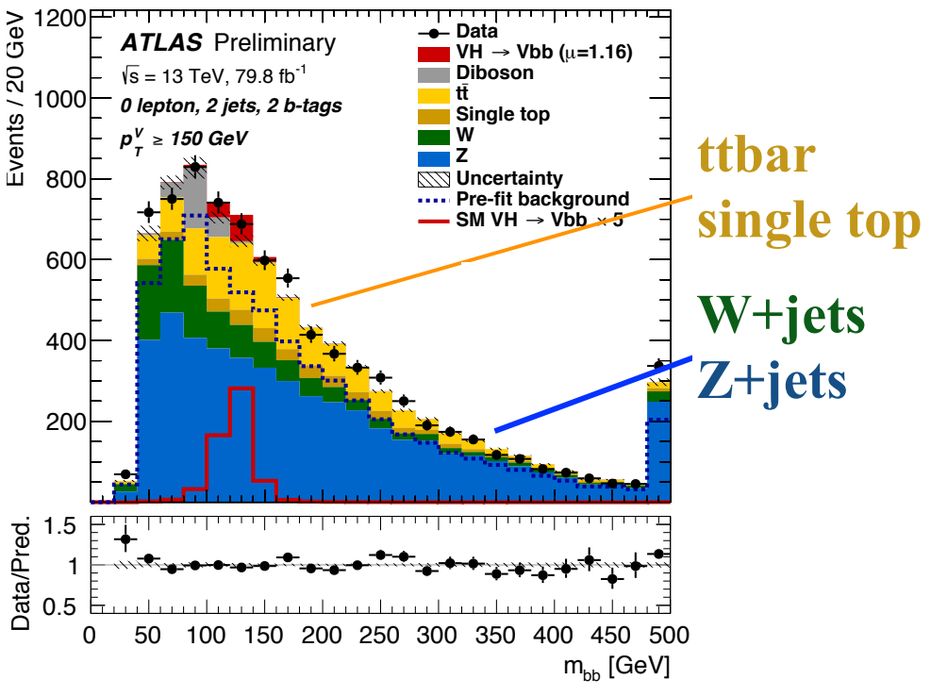
Significance: **4.9σ** (5.1σ expected)



Significance:
5.4σ observed
(5.5σ expected)

VH observation **5.3σ** observed (4.8σ expected)

Observation of H→bb

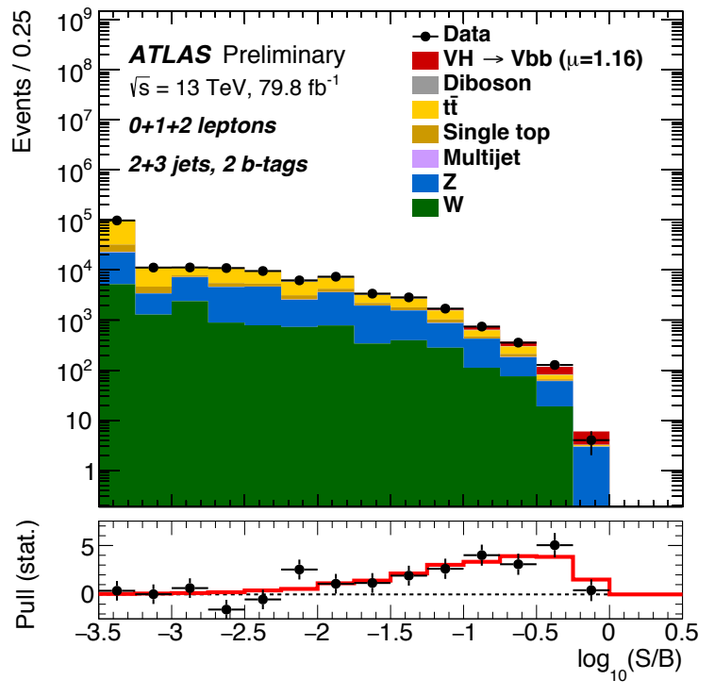


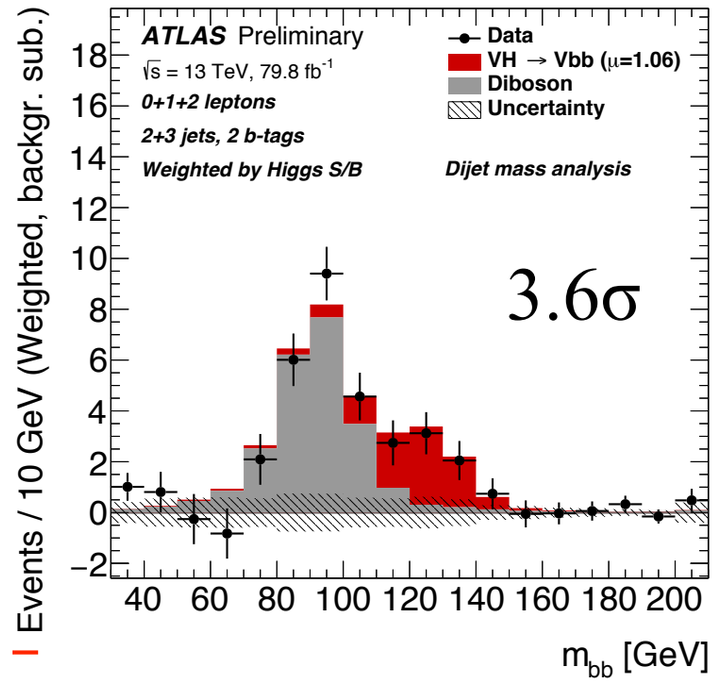
ttbar

single top

W+jets

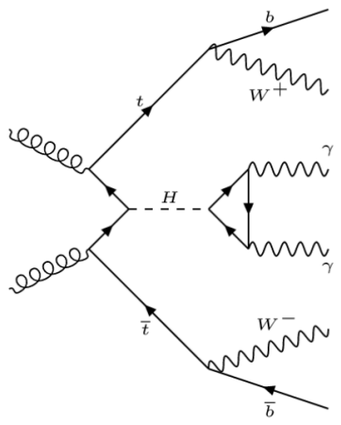
Z+jets



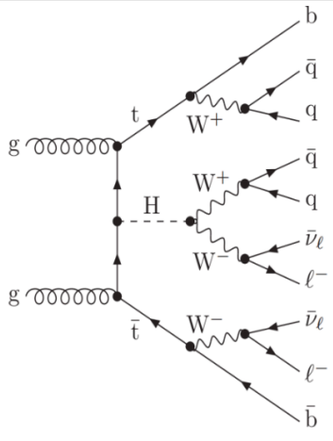


- More precise measurements in future?
  - Differential / Fiducial cross section measurement (limited by the sensitivity)
  - Branch ratio measurement for H→bb
  - Heavy resonance search in ZH channel

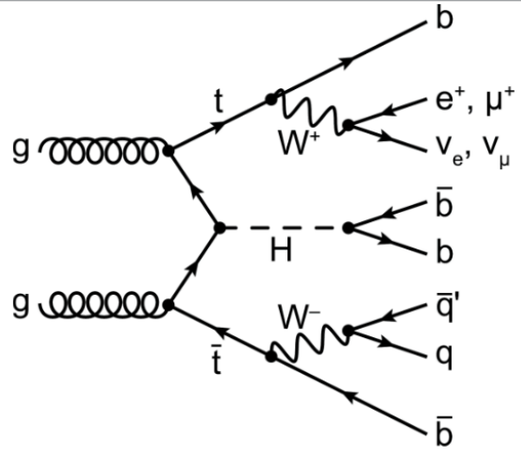
ttH Discovery



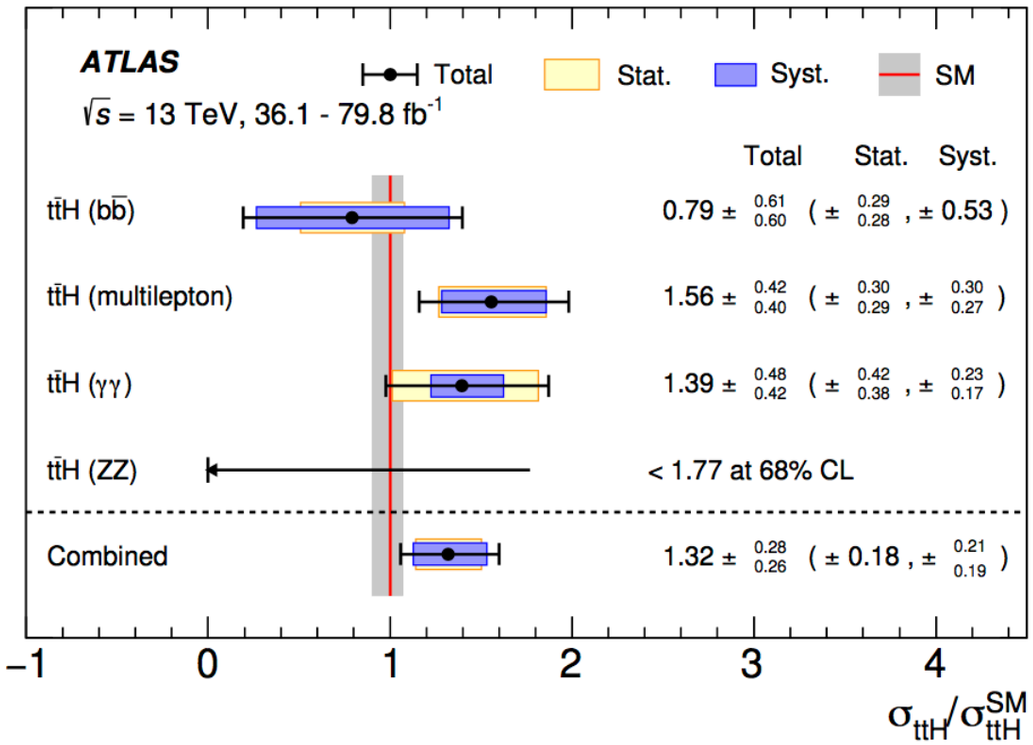
$H \to ZZ^* \to 4\ell$
$H \to \gamma\gamma$



$H \to WW^* \to \ell\nu\ell\nu$
$H \to \tau\tau$
(multi-leptons)



$H \to b\bar{b}$

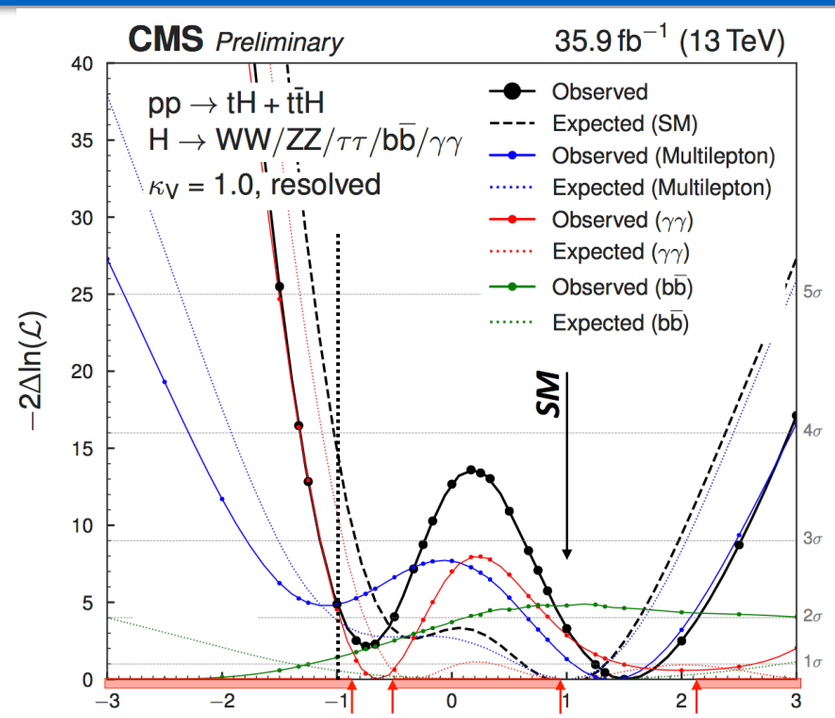


ATLAS (up to 80 fb^{-1})
Run-2: **5.8σ** (4.9σ exp.)
Run-1+Run-2: **6.3σ** (5.1σ exp.)

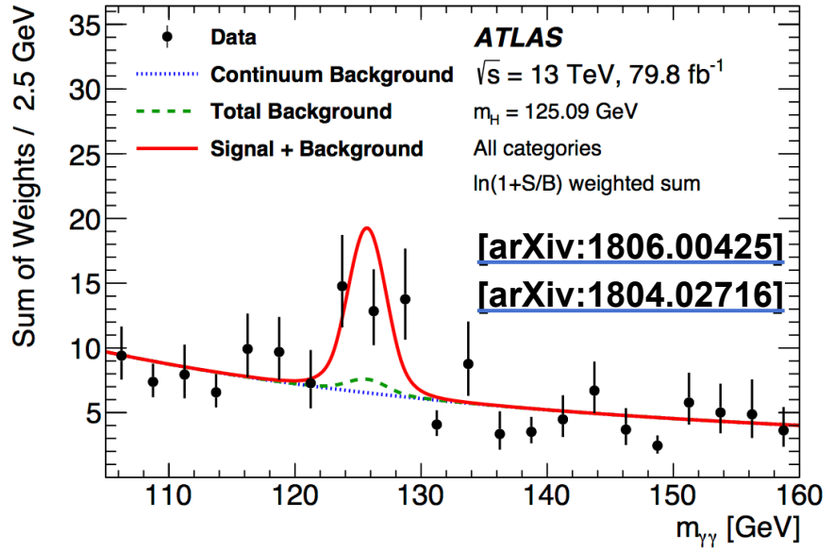
CMS
Run-1+Run-2: **5.2σ** (4.2σ exp.)

More study in ttH

- The discovery in each individual channel
  - ✦ H→γγ： dominated by the Stats. Un.
  - ✦ H→multi-lepton: size theoretical uncertainty and mis-modeling effect
  - ✦ H→bb : Large background contamination
- Further constraint on the κ_t sign
- CP measurement
- bbH



Single top+Higgs for the κ_t sign constraint



Higgs Measurement Methodology

Run 1-style coupling measurements: μ, kappa

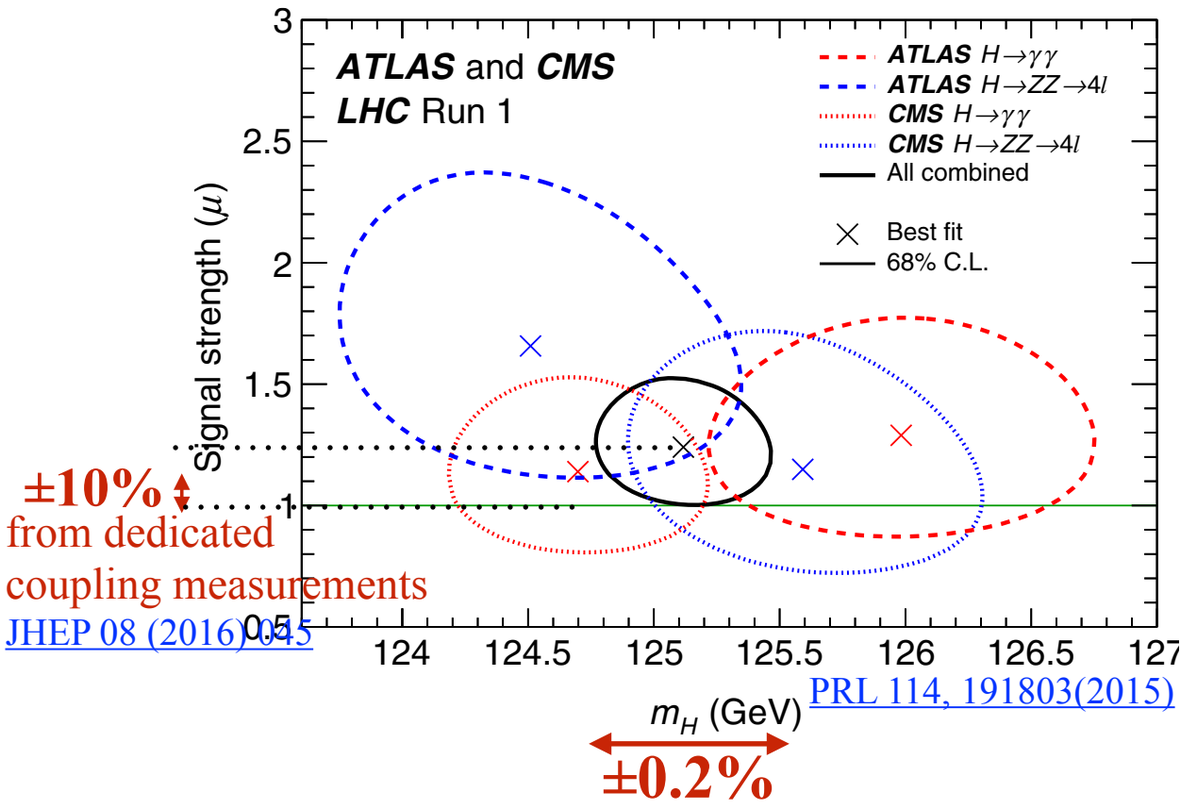
Simplified template cross sections

Fiducial/differential cross sections

Model independence

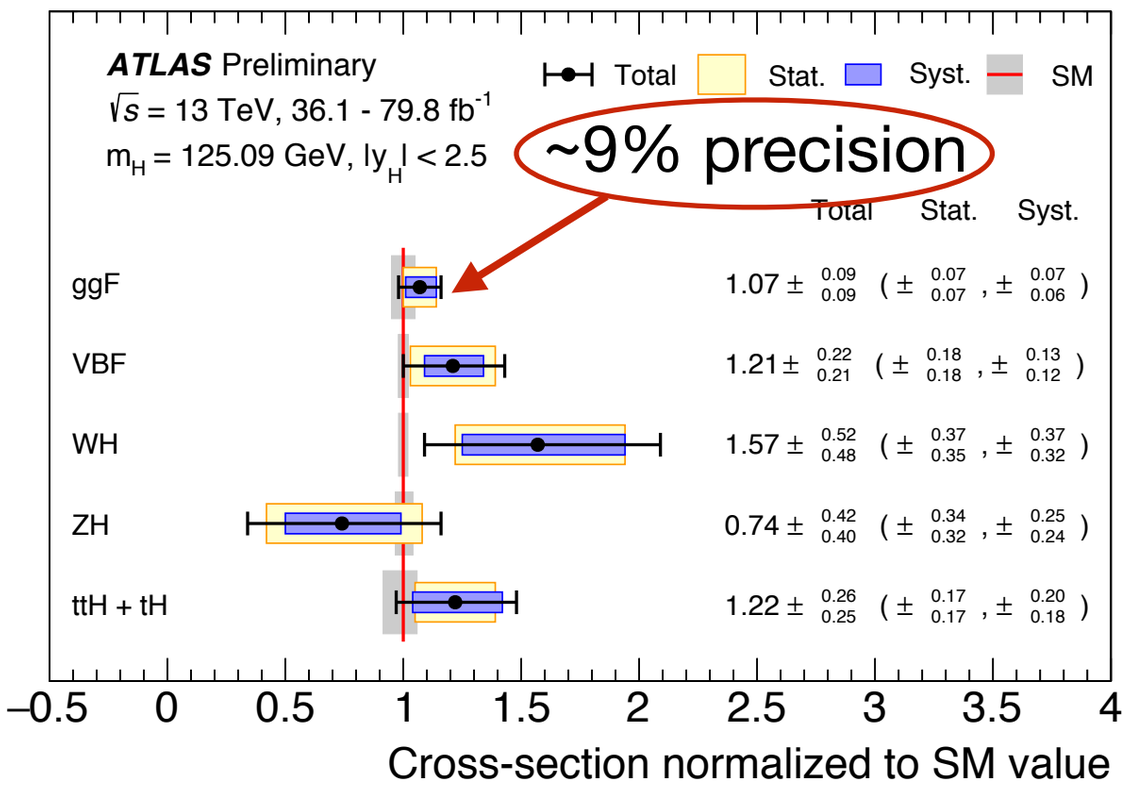
Analysis power

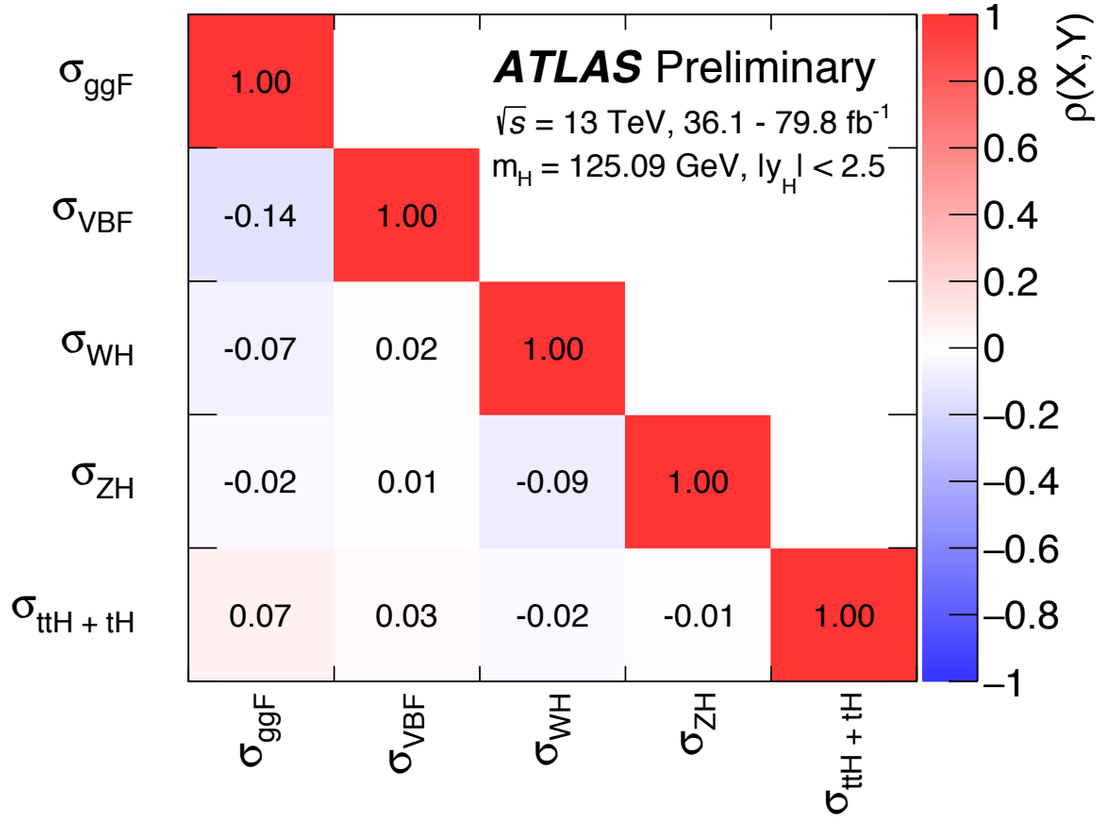
Run1 legency



Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Signal strength



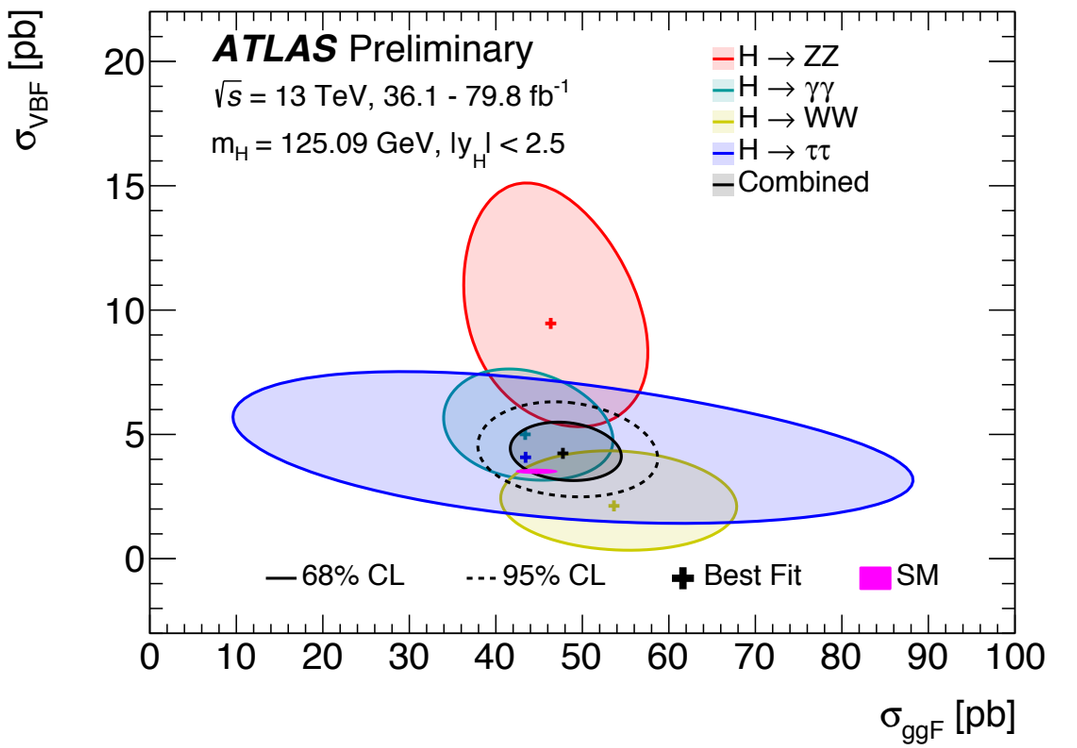


$$\mu = 1.13^{+0.09}_{-0.08}$$

$$= 1.13 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.})$$

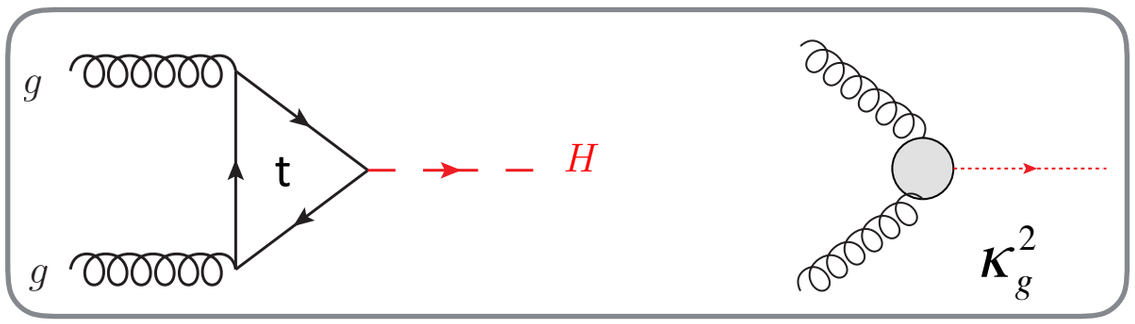
Observe all main production modes.

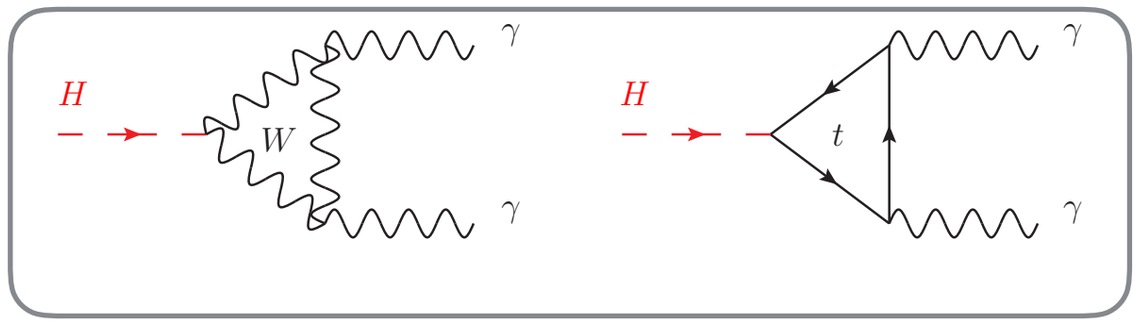
Significance obs (exp.)	**ATLAS+CMS Run-I**	**ATLAS** (single exp)
VBF	**5.4σ** (4.6σ)	**6.5σ** (5.3σ)
VH	**3.5σ** (4.2σ)	**5.3σ*** (4.8σ)
ttH	**4.4σ** (2.0σ)	**5.8σ** (5.3σ)



κ-framework

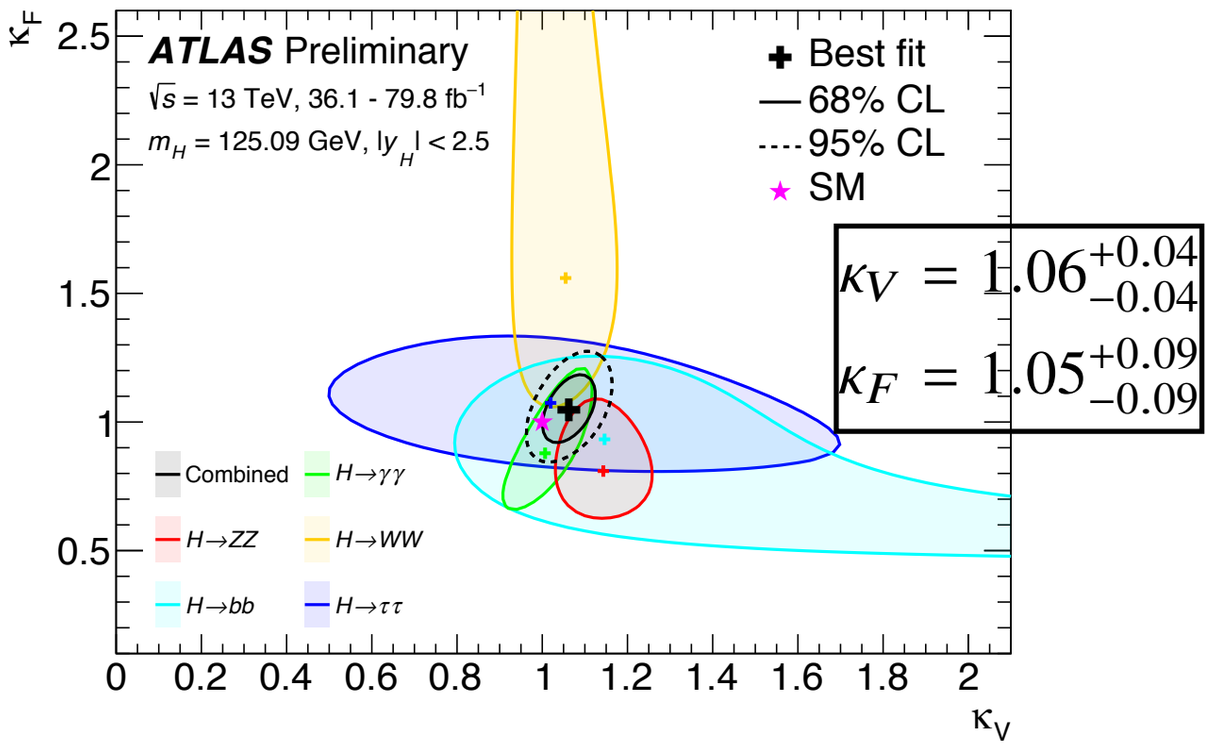
- **Assumptions:**
  - Single state, spin 0 and CP-even.
  - Narrow-width approximation: $(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \dfrac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$
- **Methodology:** parametrize deviations with coupling scale factors $\{\kappa_x\}$

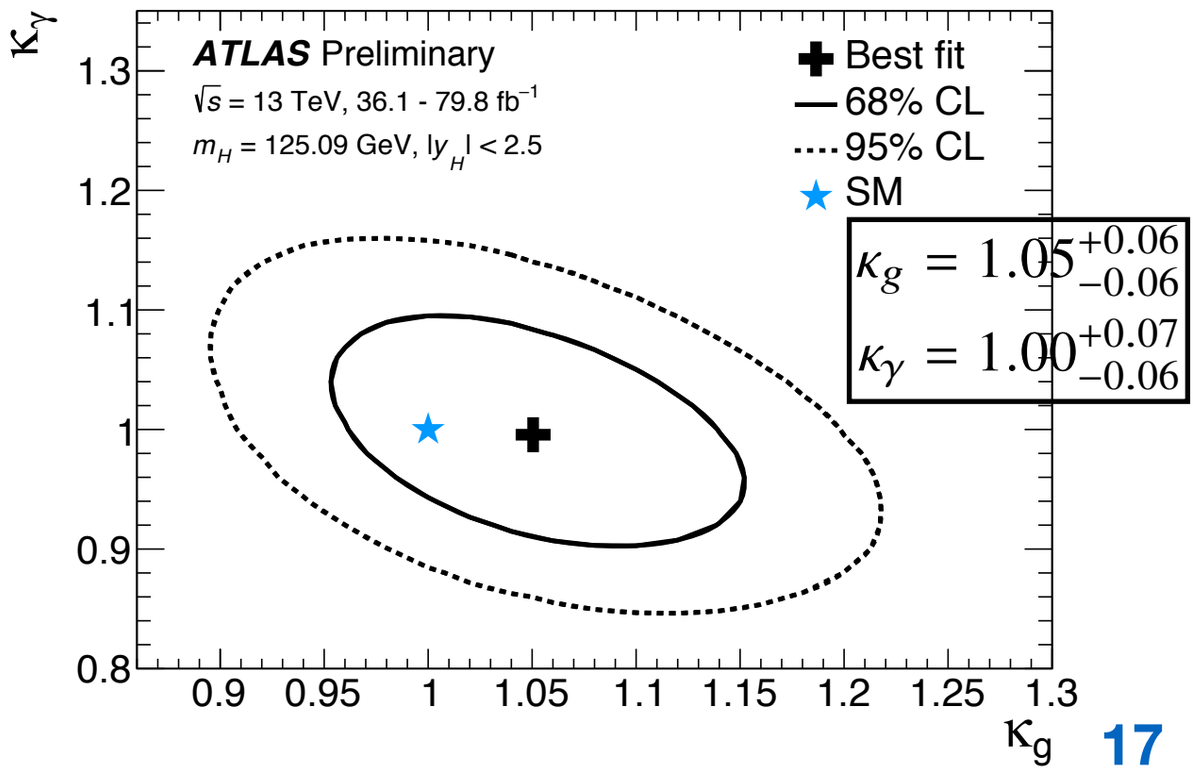




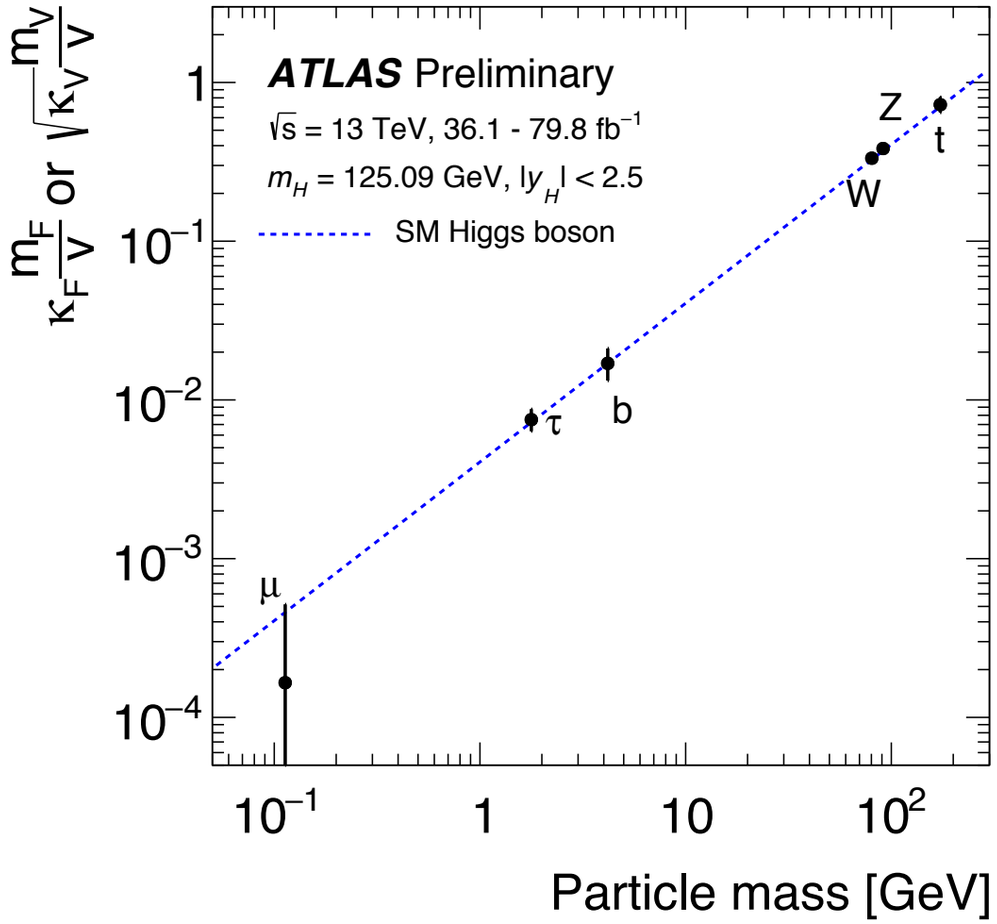
$\kappa_g^2 = 1.042\kappa_t^2 + 0.002\kappa_b^2 - 0.040\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0005\kappa_b\kappa_c + 0.00002\kappa_c^2$

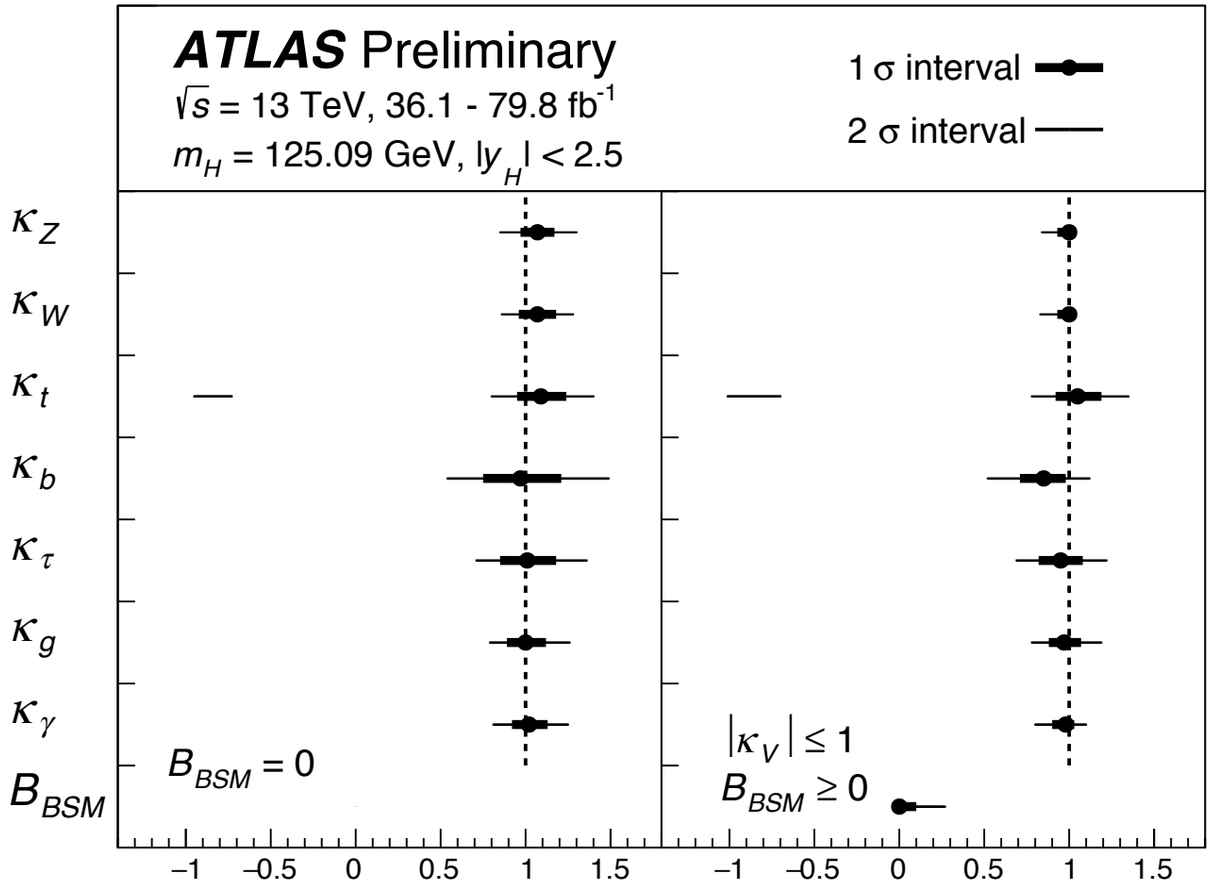
$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t\kappa_W + 0.1 \times \kappa_t^2$





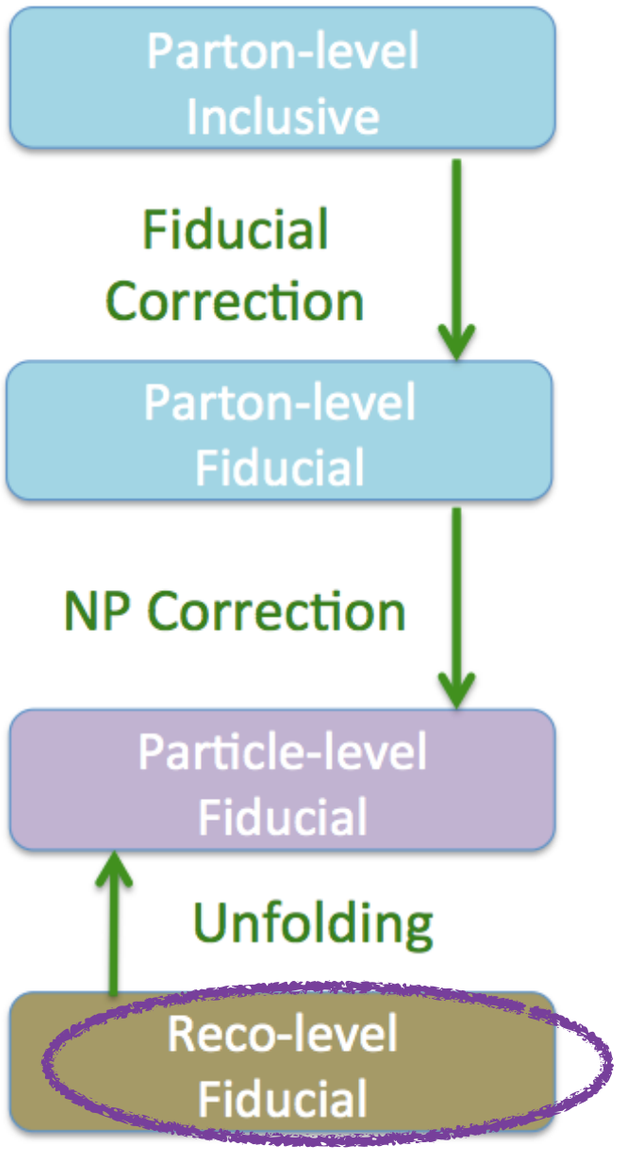
κ-framework

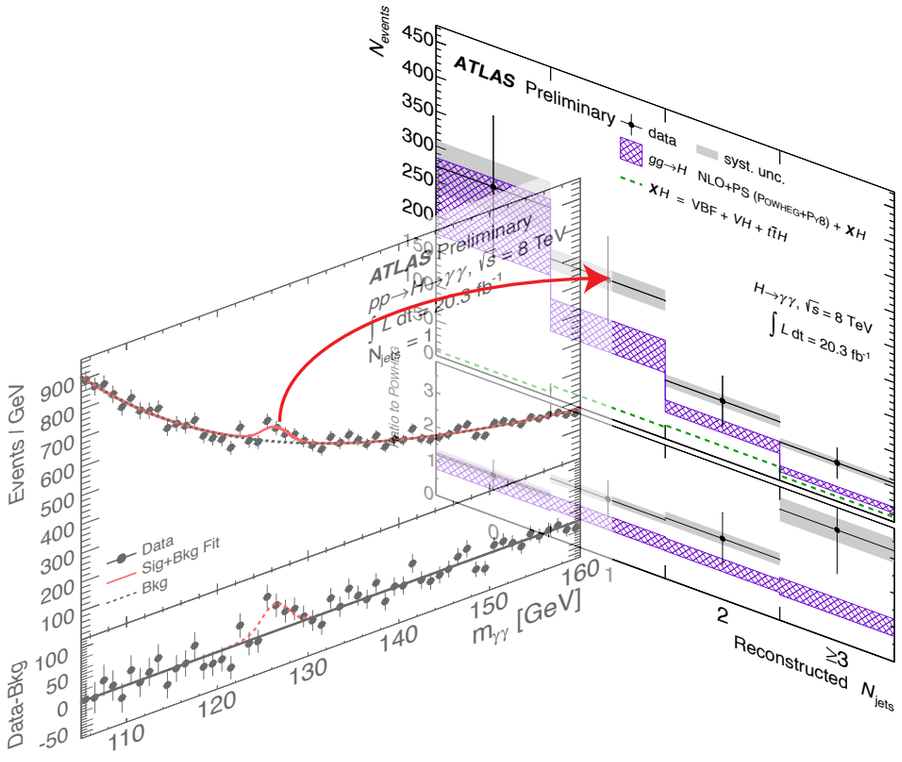


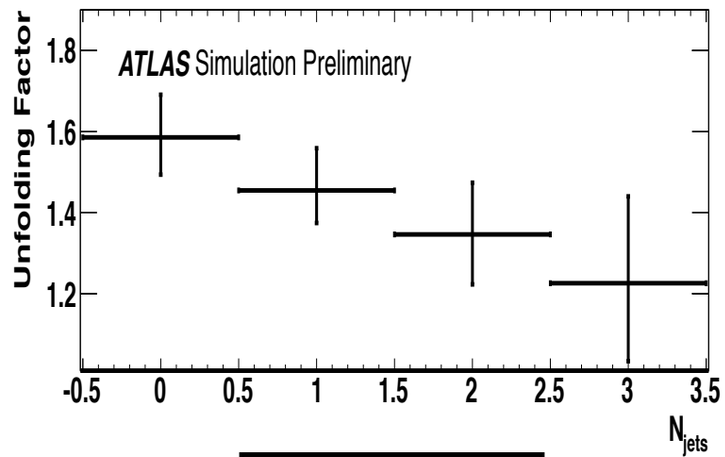


Good agreement with the SM prediction

Fiducial and differential cross section



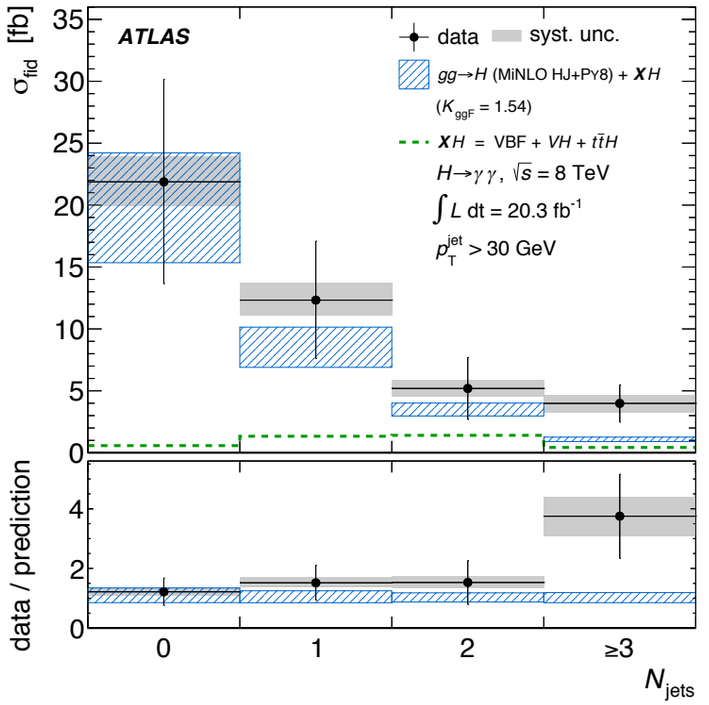




$$\sigma_i^{fid} = \frac{n_i^{sig}}{c_i \mathcal{L}}$$

Basic fiducial region :

- 2 isolated photons
- ($|\eta|$<2.37) excluding creak region
- $pT_{\gamma 1}(pT_{\gamma 2})/m_{\gamma\gamma}$>0.35(0.25)
- 105<$m_{\gamma\gamma}$<160GeV



Cross section combination between H→γγ and H→ZZ*

H→γγ data signal

$$n_i^{sig}$$

H→ZZ data signal

unfolding, $c_i\mathcal{L}$

H→γγ fiducial particle level

$$\sigma_i^{fid} = \frac{n_i^{sig}}{c_i\mathcal{L}}$$

H→ZZ fiducial particle level

extrapolation, $\mathcal{A}_i^{fid}\mathcal{B}$

Photon selection	
Kinematic:	$E_T > 25$ GeV, $\|\eta\| < 2.37$
Isolation:	$E_T^{iso} < 14$ GeV
Event selection	
Two photons	
Cut on invariant mass	$m_{\gamma\gamma} \in [105, 160)$
Leading photon	$p_T/m_{\gamma\gamma} > 0.35$
Subleading photon	$p_T/m_{\gamma\gamma} > 0.25$

Combined inclusive cross sections

$$\sigma_i^{incl} = \frac{n_i^{sig}}{c_i\mathcal{L}\mathcal{A}_i^{fid}\mathcal{B}}$$

Lepton selection	
Muons:	$p_T > 6$ GeV, $\|\eta\| < 2.7$
Electrons:	$p_T > 7$ GeV, $\|\eta\| < 2.47$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair:	Remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$118 < m_{4\ell} < 129$ GeV

Fiducial and 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

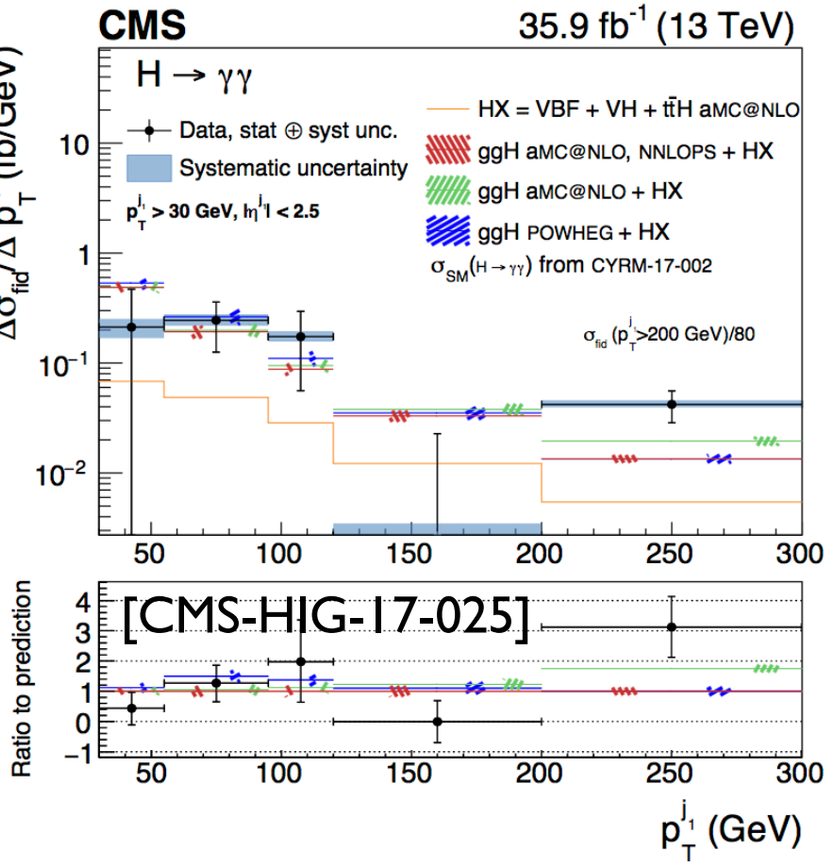
- **Differential X-sections (20 variables):**

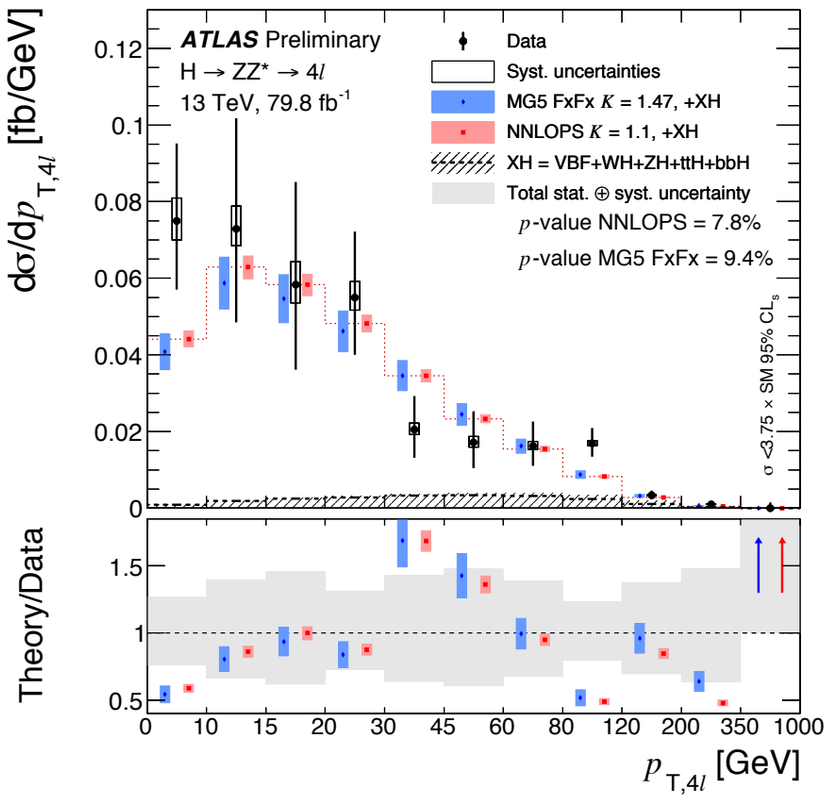
	EPS variable		Auxiliary	
• *Higgs kinematic*:	$p_{T\gamma\gamma}$ $\lvert y_{\gamma\gamma}\rvert$		pTt	
• *Jet activity*:	N_{jets} p_{Tj1}	N_{jets_50} H_{Tjet} $\lvert y_{j1}\rvert$ p_{Tj2}	p_{tj3} $\lvert y_{j2}\rvert$ τ_j $\sum\tau_j$	
• *VBF - sensitive variables*:		$\Delta\varphi_{\gamma\gamma,jj}$ m_{jj}	Δy_{jj} p_{THjj}	
• *Spin - CP variables*:	$cos\theta^*$ $\Delta\varphi_{jj}$		$\Delta y_{\gamma\gamma}$	

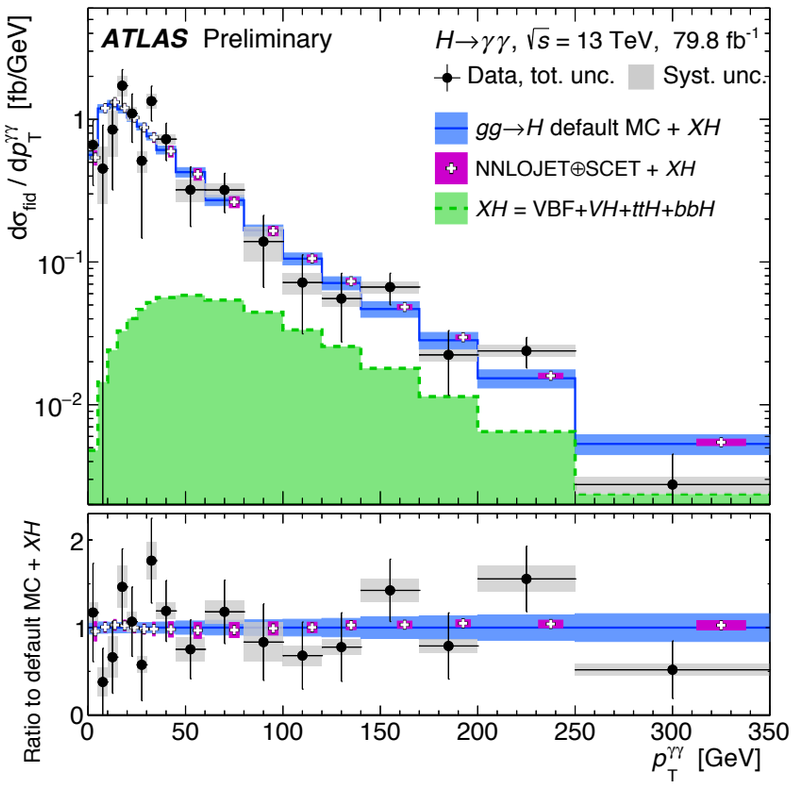
- *2D variables:* $p_{T\gamma\gamma} \times N_{jets}$ $p_{T\gamma\gamma} \times cos\theta^*$

- **Fiducial X-sections:**
  - *1- / 2- / 3- jet and inclusive regions*
  - *Inclusive 1-lepton / MET / VBF / VH enriched regions*

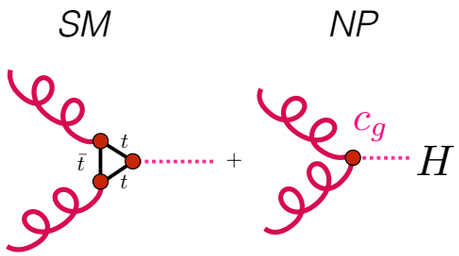
Cross Section Measurement







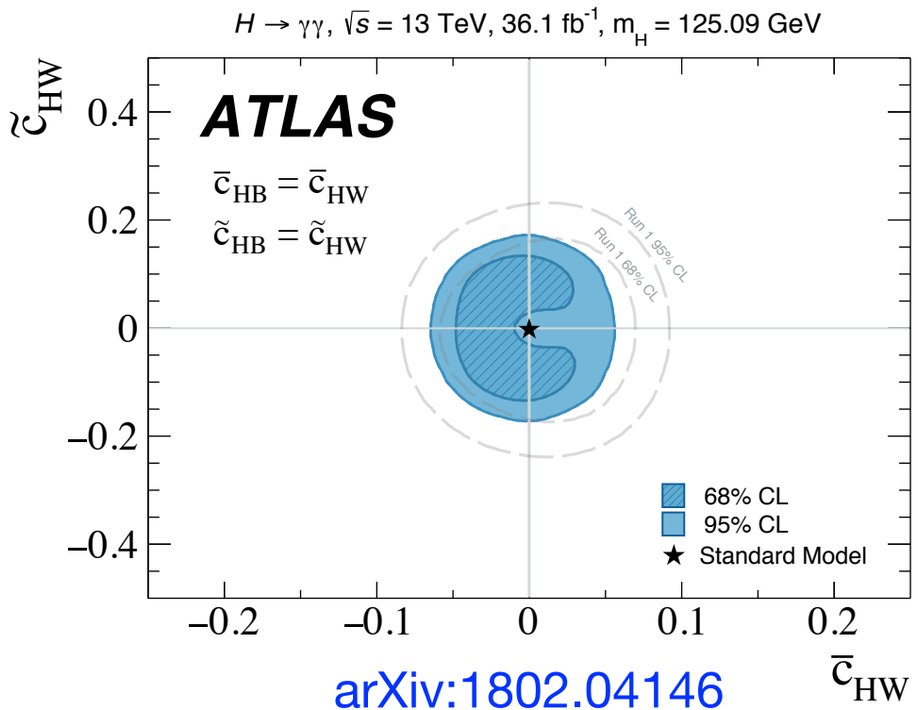
EFT approach with differential cross sections



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

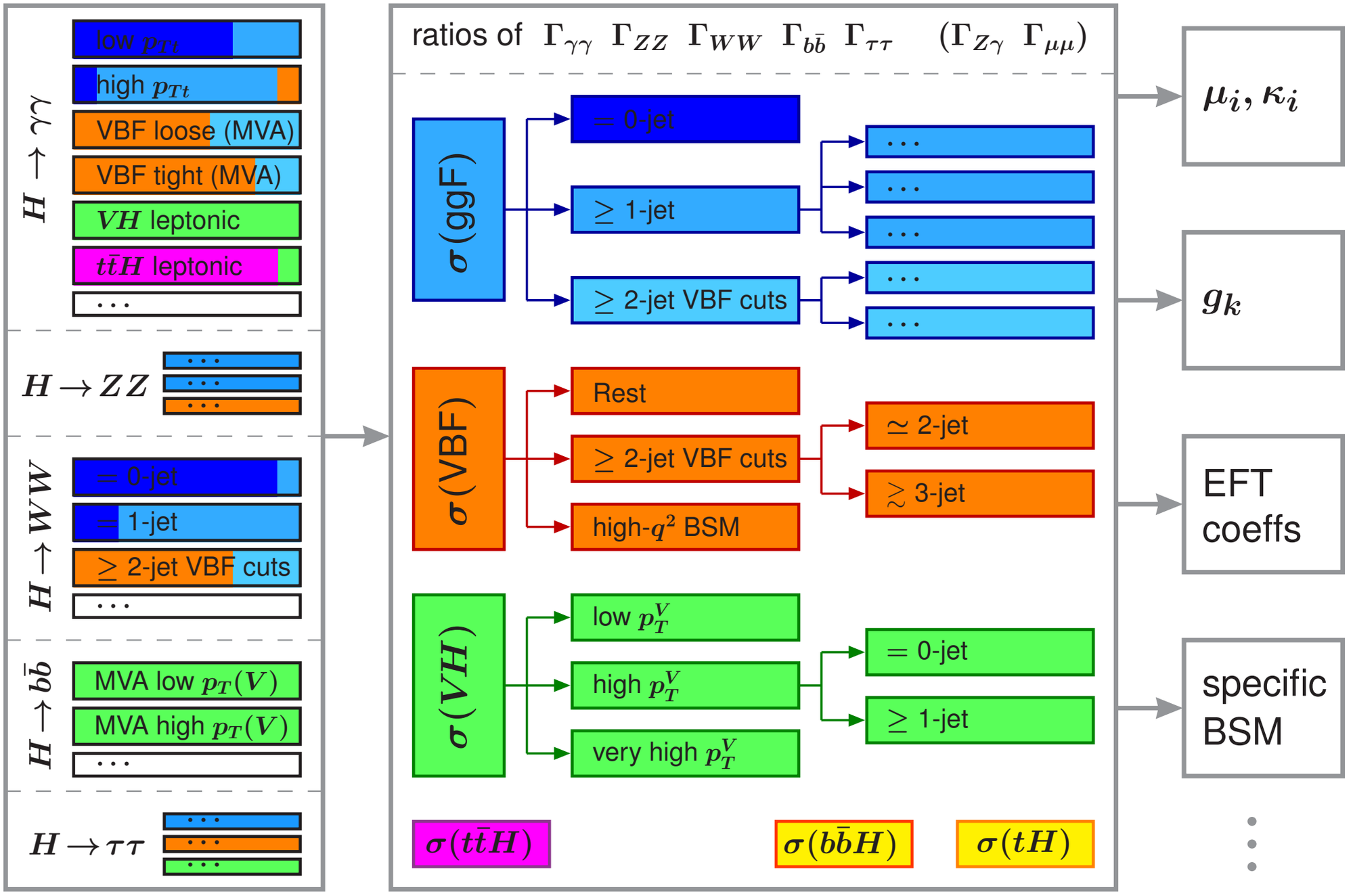
No significant deviation from SM

5 variables: $p_T^{\gamma\gamma}$ N_{jets} m_{jj} $|\Delta\phi_{jj}|$ $p_T^{j_1}$



arXiv:1802.04146

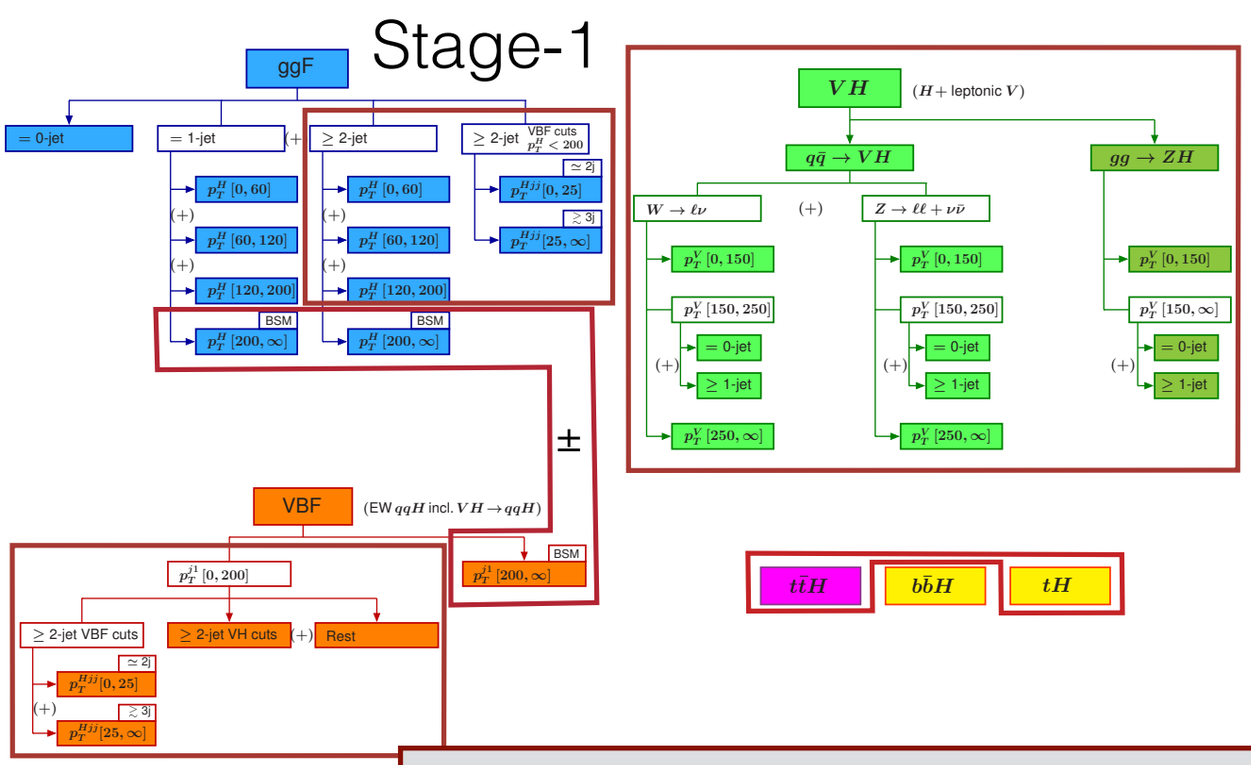
Simplified template cross section

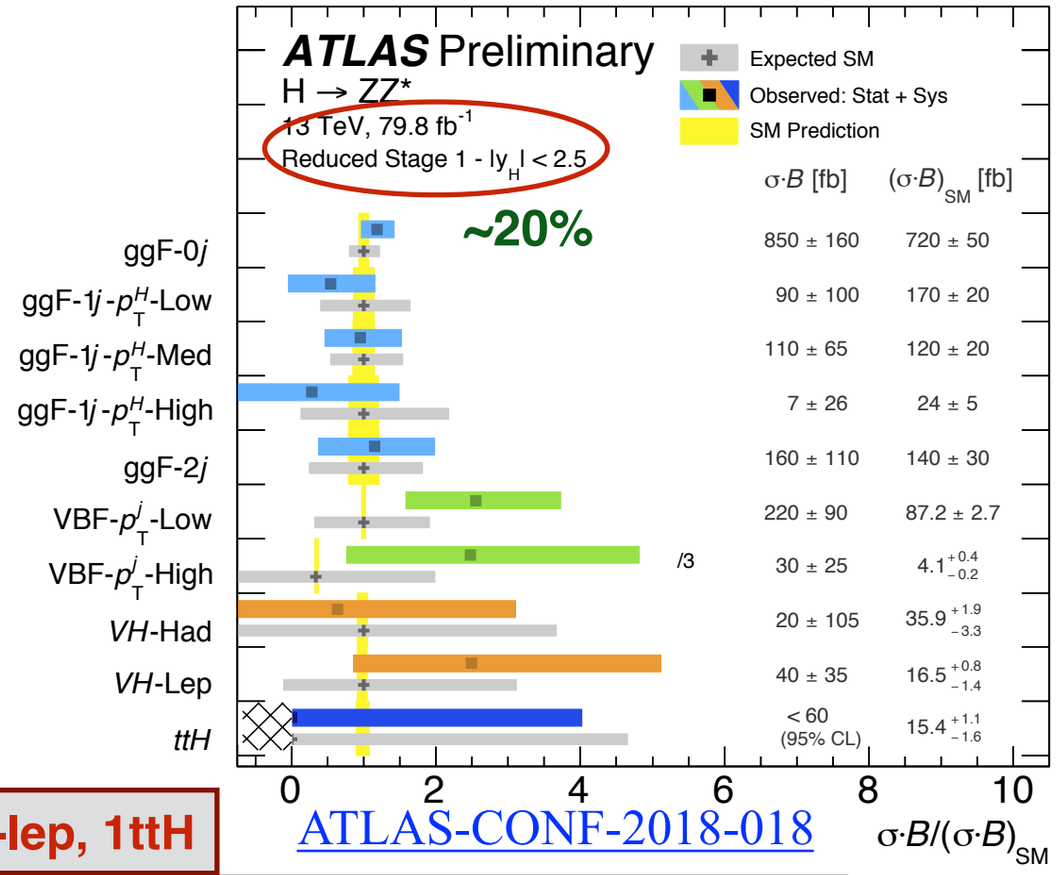


Simplified template cross section

Less model dependence: separate the theory uncertainties in measurements

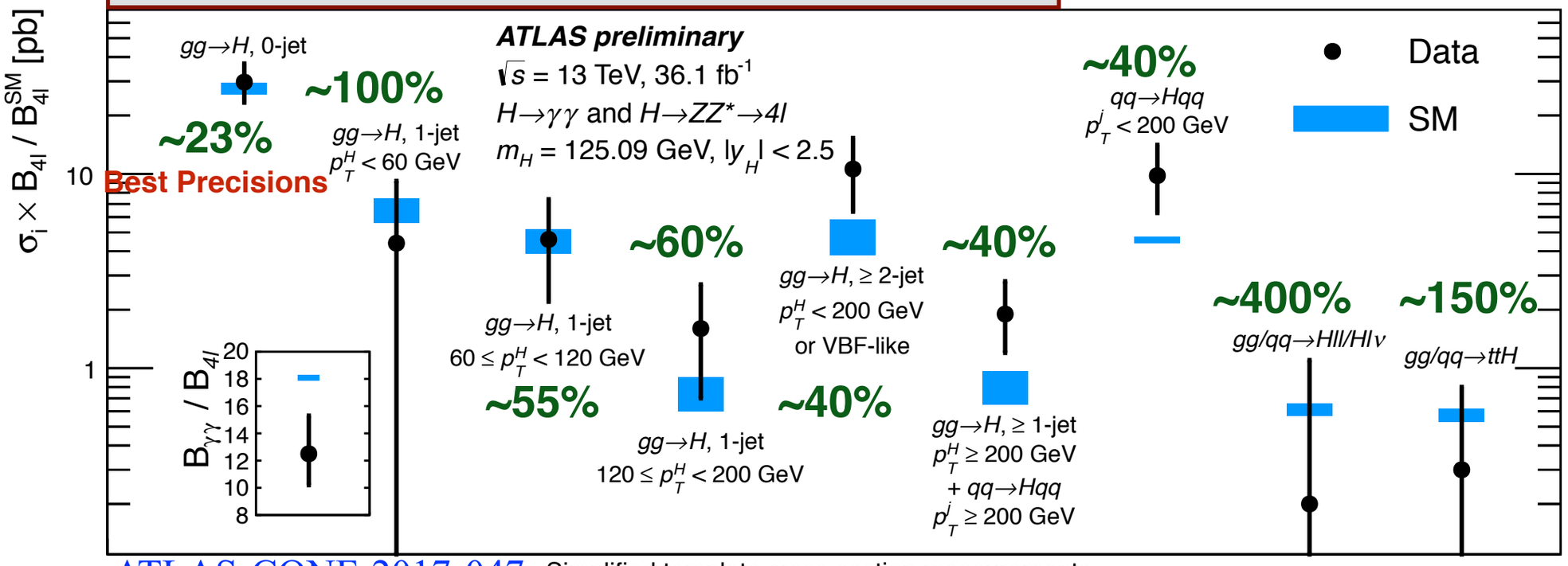
ATLAS preliminary





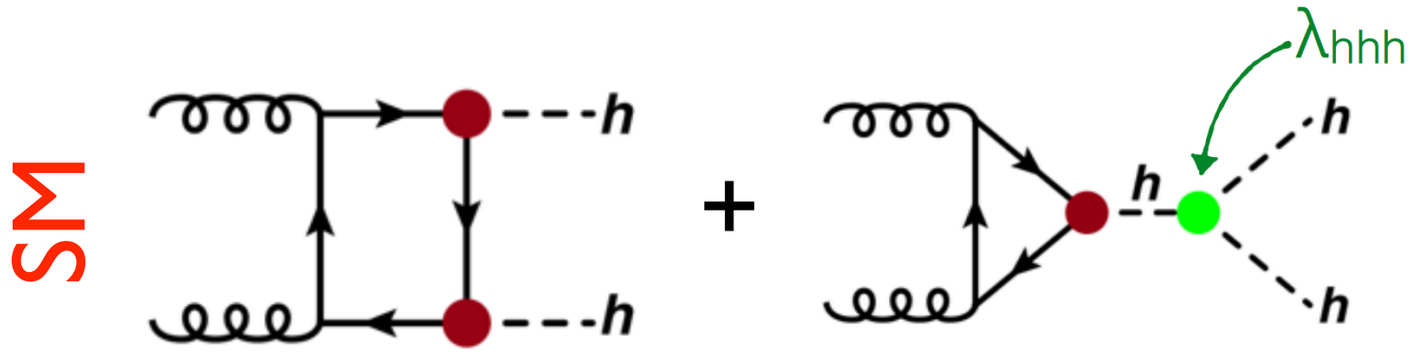
ATLAS-CONF-2018-018

Merged strategy: 5 ggH, 1BSM, 1VF, 1VH-lep, 1ttH

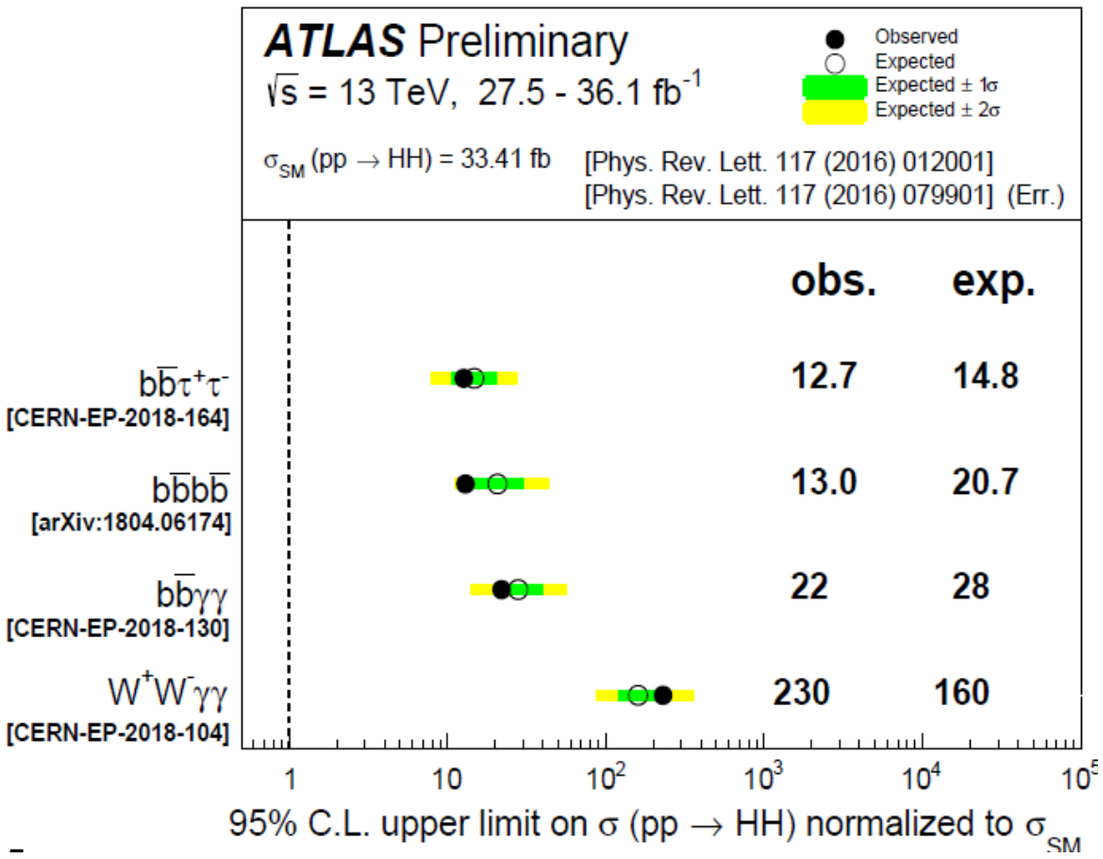


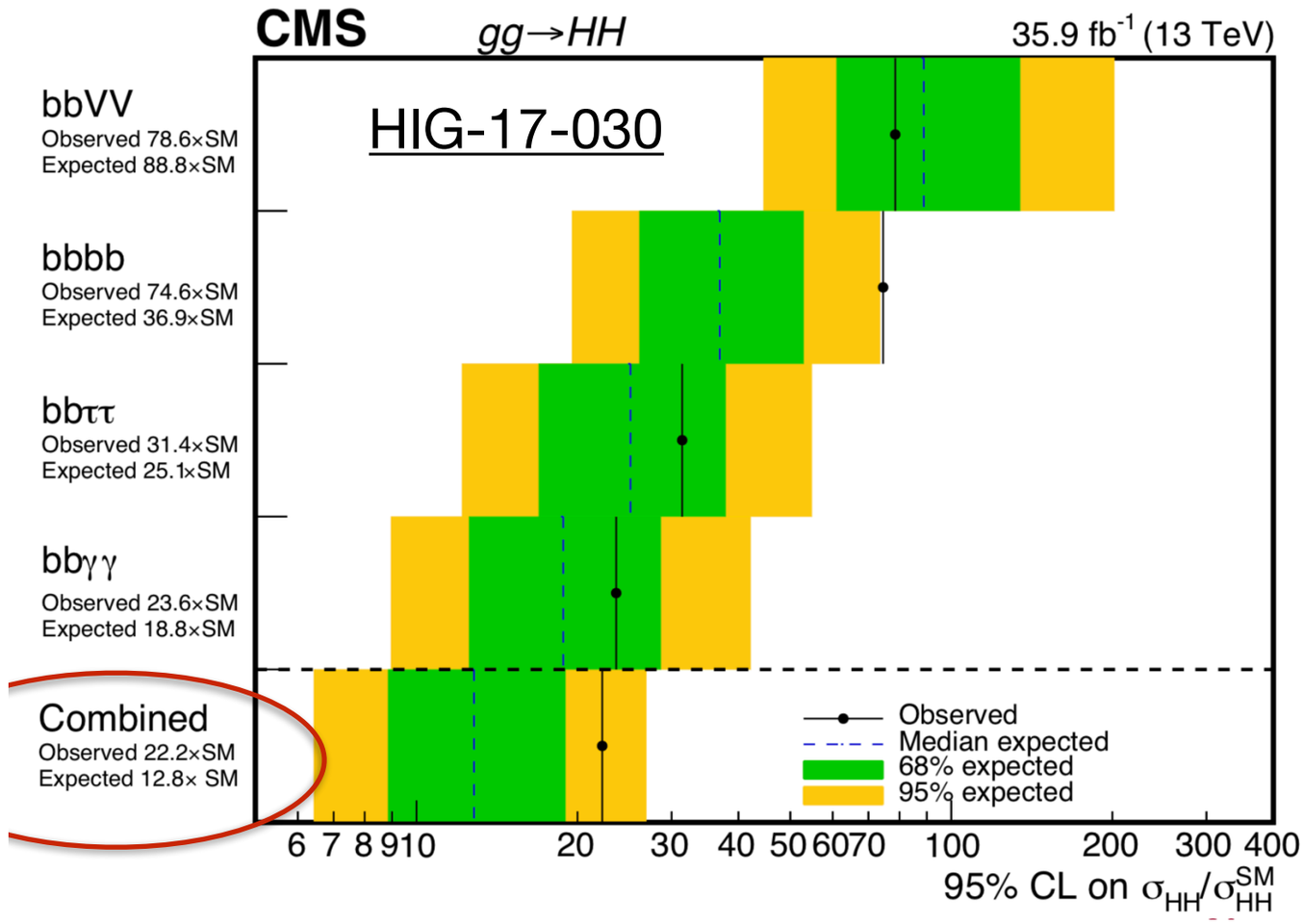
ATLAS-CONF-2017-047 Simplified template cross section measurements

Di-Higgs search



$$-11.8 < k_\lambda < 18.8$$
$$(-7.1 < k_\lambda < 13.6 \text{ exp.})$$
@ 95% CL

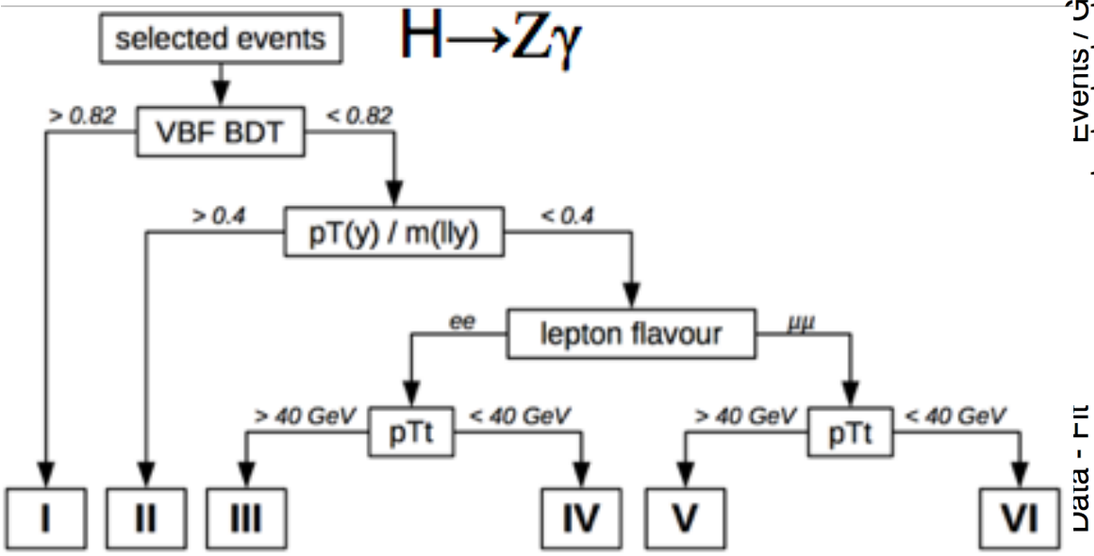


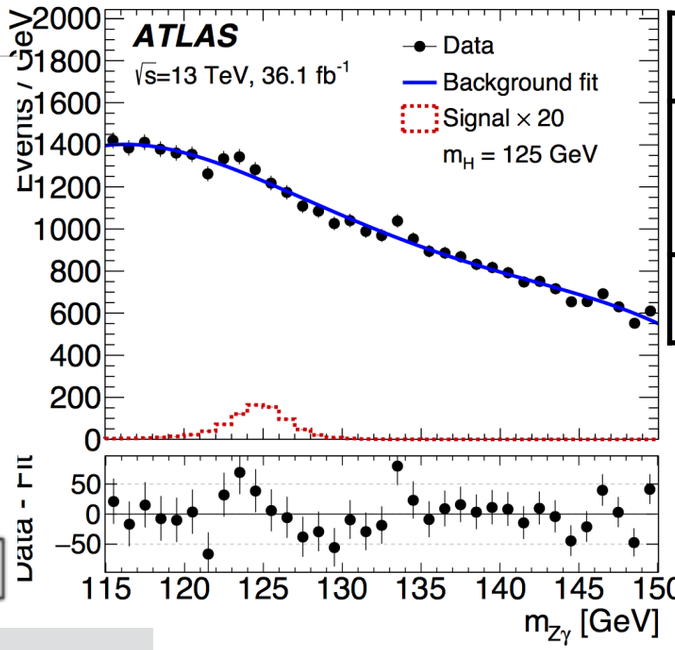


- Getting close to 10*SM rate for Di-Higgs production

H→Zγ

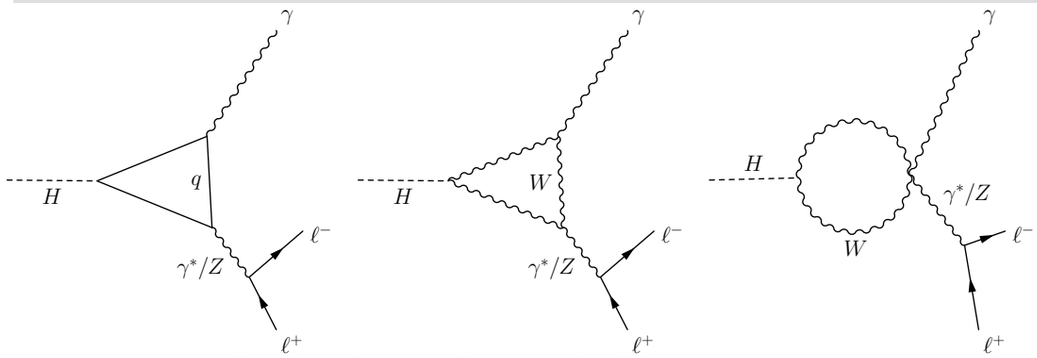
- Similar to H→γγ ones via **loop interaction** (BR(H→Zγ) =0.15%, BR(H→γγ) =0.22%) : probe BSM contribution in loops





@95%CL	Obs./Exp.
σ(pp→H) ×B(H→Zγ)	6.6/4.4 SM
μ (Run1)	11

Split H→Zγ / γ*γ measurements with mll=50GeV

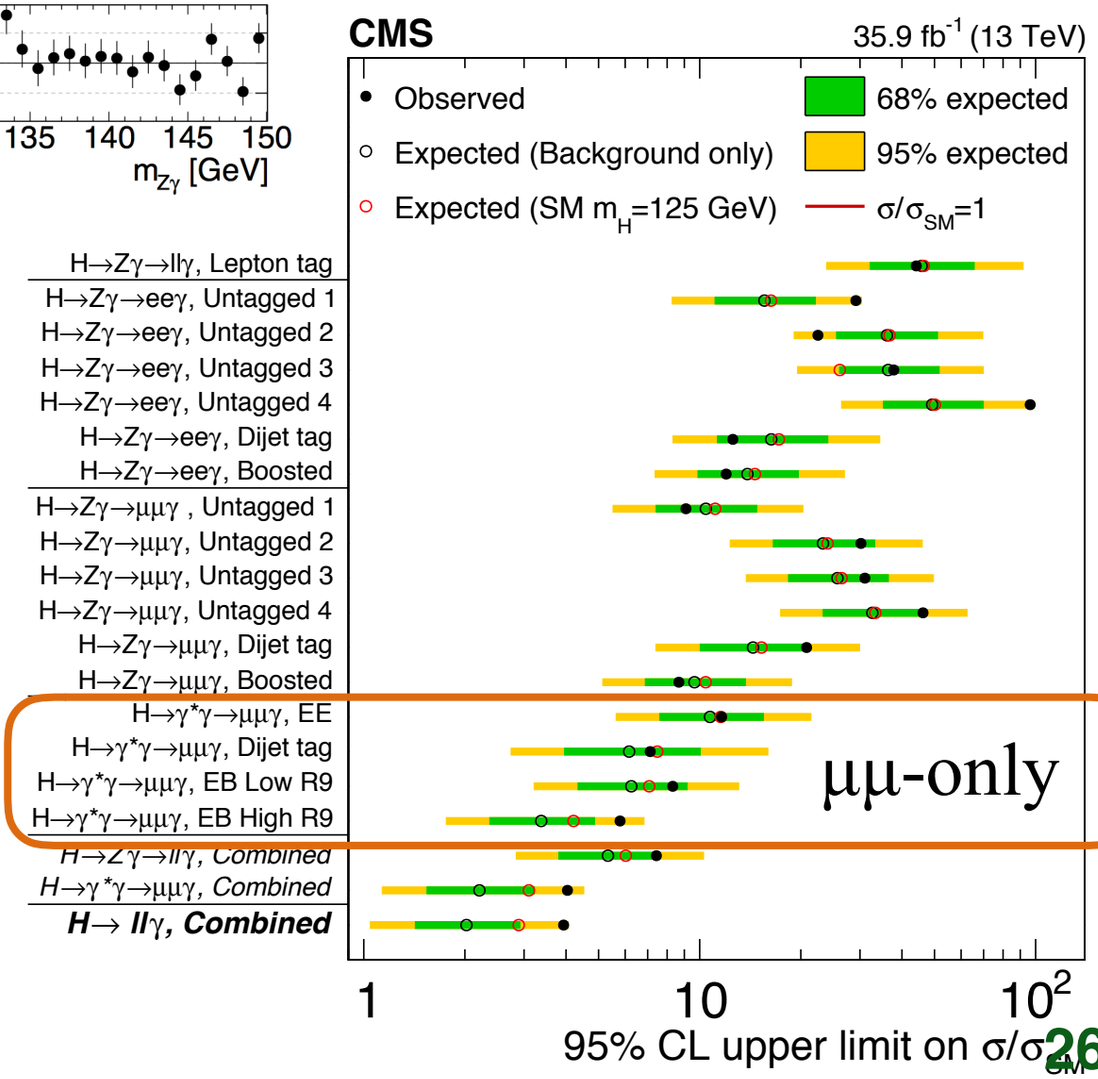


Obs. (Exp.) 95% CL limit

BR(H → Zγ → ℓℓγ) < 8.0 (5.8) x SM

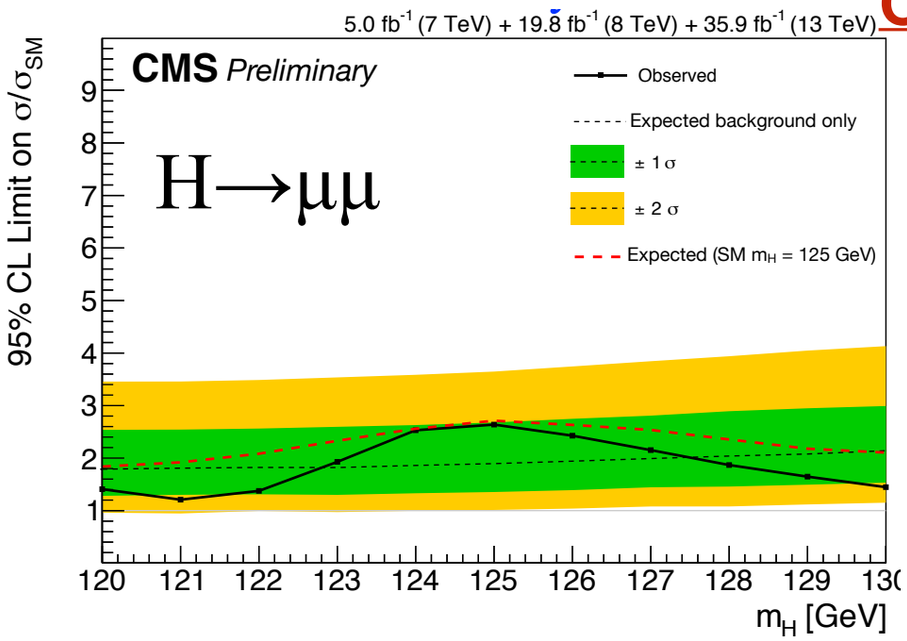
BR(H → γ*γ → ℓℓγ) < 4.0 (2.2) x SM

Combination: σ(pp→H) < 3.9 (2.0) × SM



More SM Higgs searches

Coupling to 2nd generation

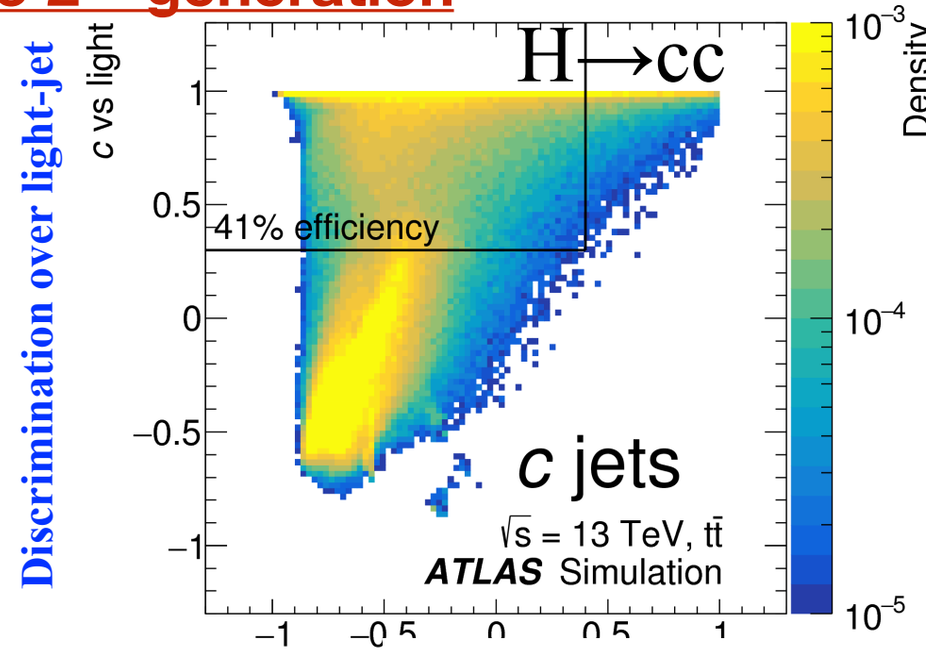


PRL 119(2017) 051802, CMS-HIG-17-019

Run-1+Run-2:

ATLAS: Obs.(Exp.) < 2.8(2.9)@95%CL

CMS: Obs.(Exp.) < 2.6(1.9)@95%CL

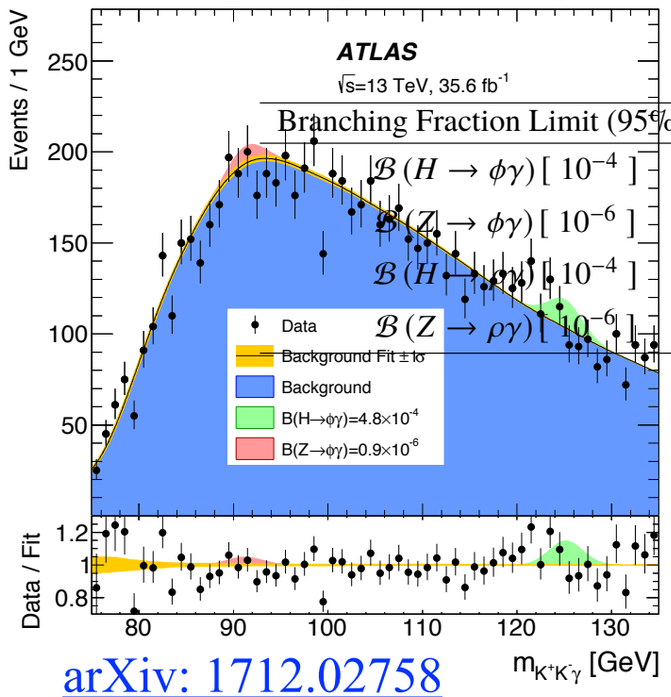


arXiv: 1802.04329

Obs.(Exp.) σ(pp→ZH)B(H→cc)< 2.7(3.9)@95%CL

→110(150)×SM

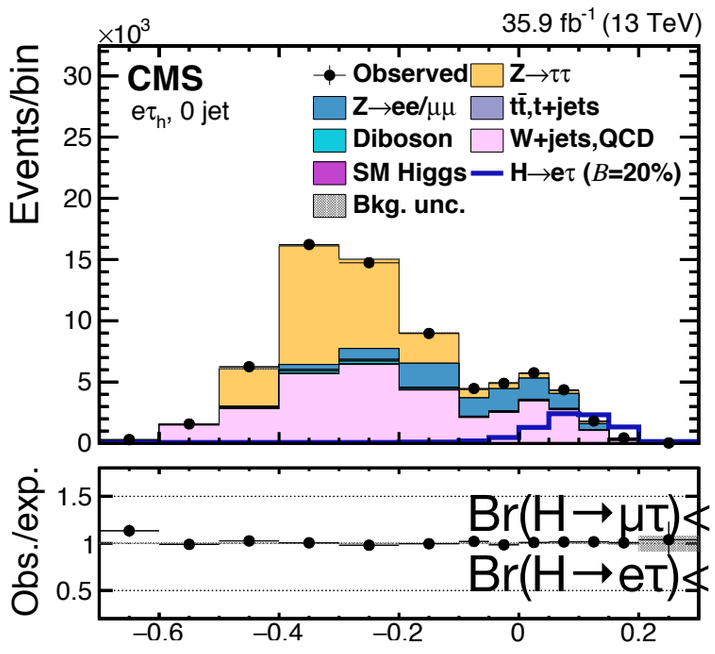
Coupling to 1st generation



Branching Fraction Limit (95% CL)	Expected	Observed	
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8	~208×SM
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9	~87×SM
$\mathcal{B}(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8	~52×SM
$\mathcal{B}(Z \to \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25	~597×SM

arXiv: 1712.02758

Lepton Flavor Violation



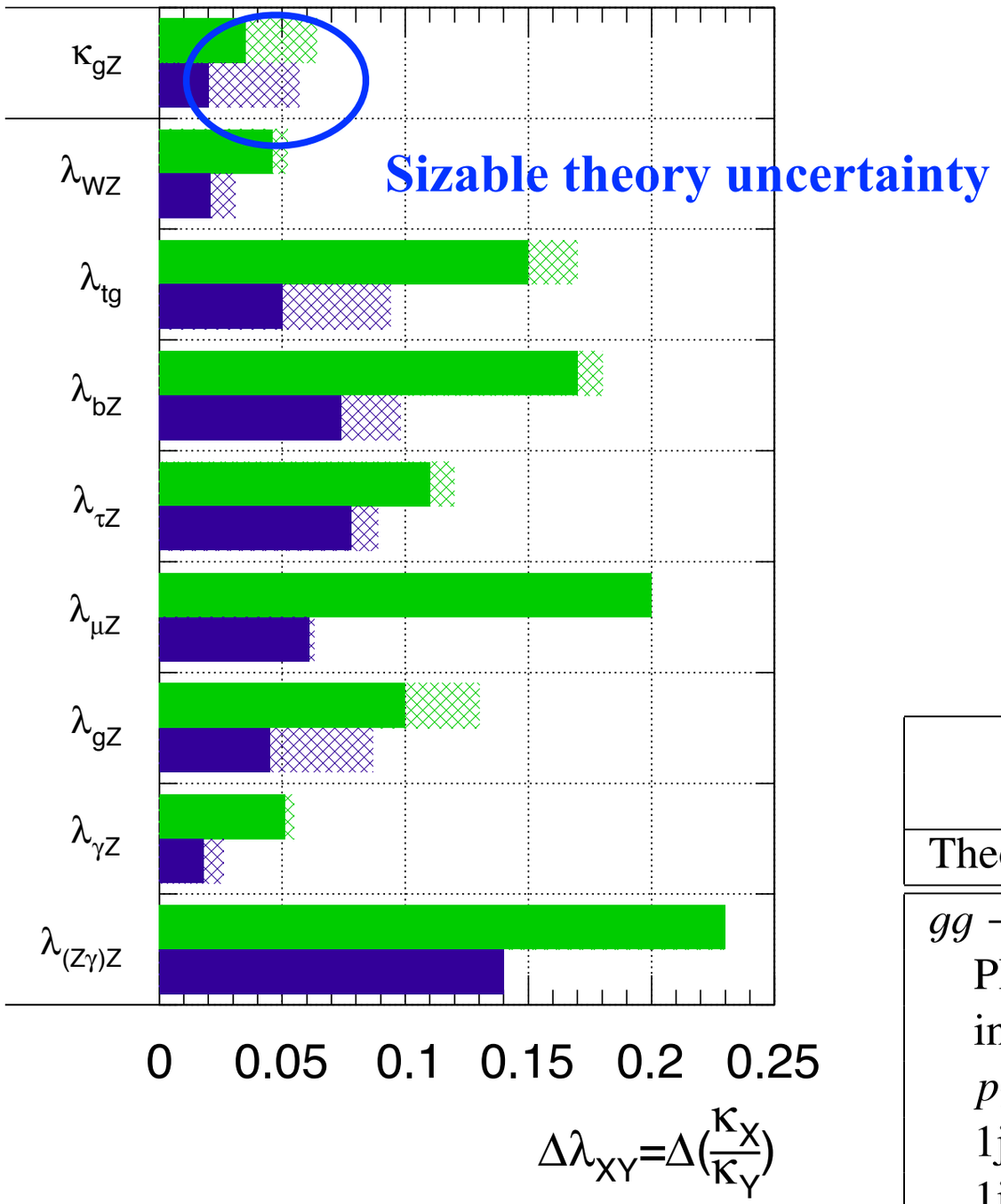
H→eτ

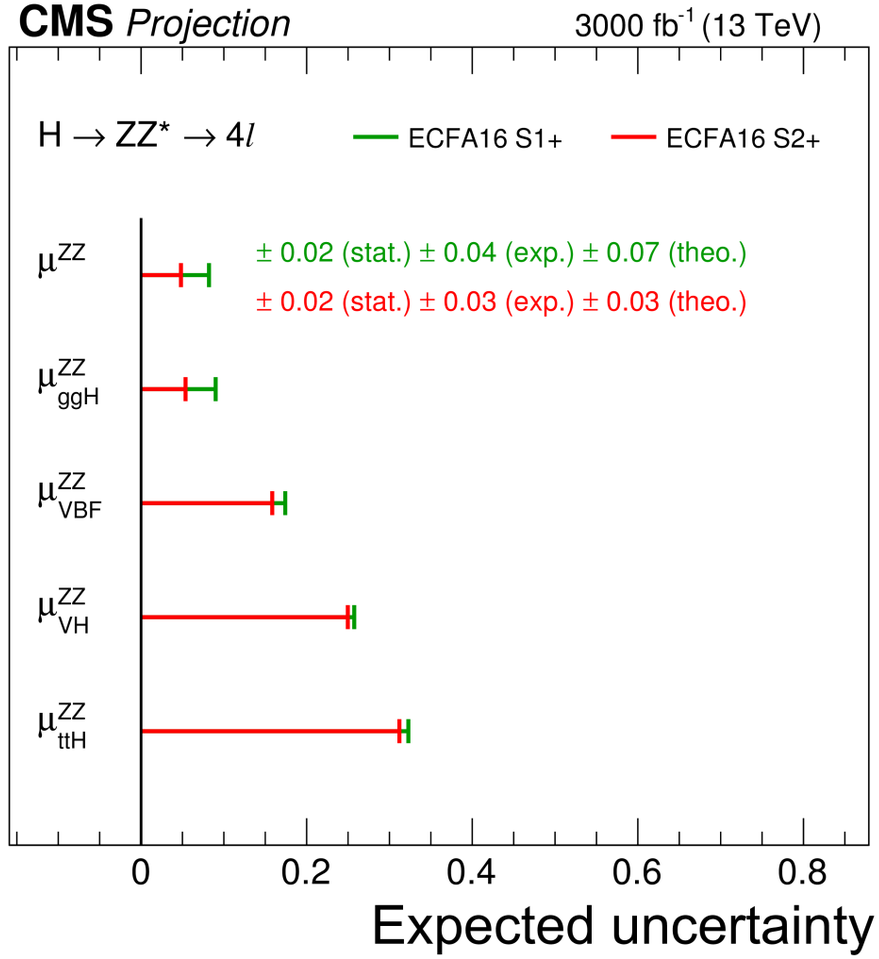
Br(H→μτ)< 0.25(0.25)@95%CL

Br(H→eτ)< 0.61(0.37)@95%CL

CMS-HIG-17-001 BDT discriminator

Higgs Projection @ HL_LHC





Scenario	ainty to increase total uncertainty by ≲10% for 3000 fb^{-1}				
Theory uncertainty (%)	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$					
PDF	1.3	-	-	-	-
incl. QCD scale (MHOU)	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	-	1.5–3	-	-	-
1j → 2j mig.	-	3.3–7	-	-	-
1j → VBF 2j mig.	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	-	-	-	6–19	-

Summary

- **Comprehensive Higgs property measurements:** mass, width, fiducial/differential cross section, simplified template cross section.
- **Principal production modes:**
  - Observation: ggH, VBF, ttH, VH
- **Principal decay modes:**
  - Observation: γγ, WW, ZZ, ττ, bb
  - Probe coupling to 2nd / 1st generation
- **Excellent agreement with SM so far.**

Plan to have **a regular theory-experiment discussion**:

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Contactor: Minshui Chen, Yanping Huang, Hao Zhang