Hightlight of Higgs boson measurements with boson final states @ LHC

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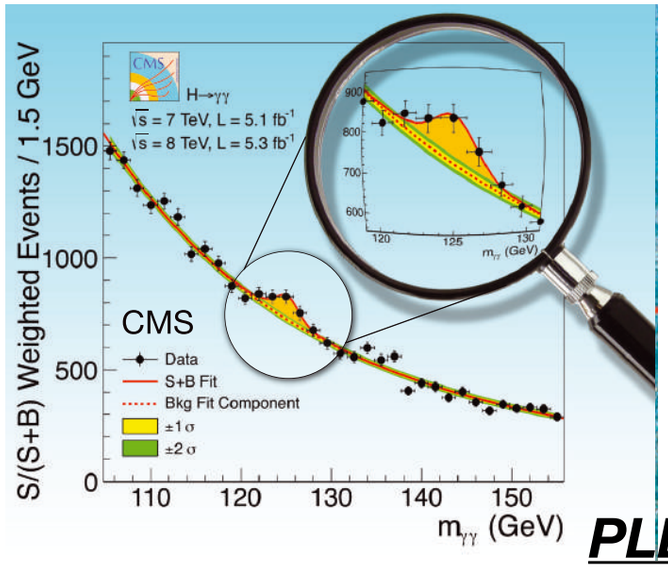
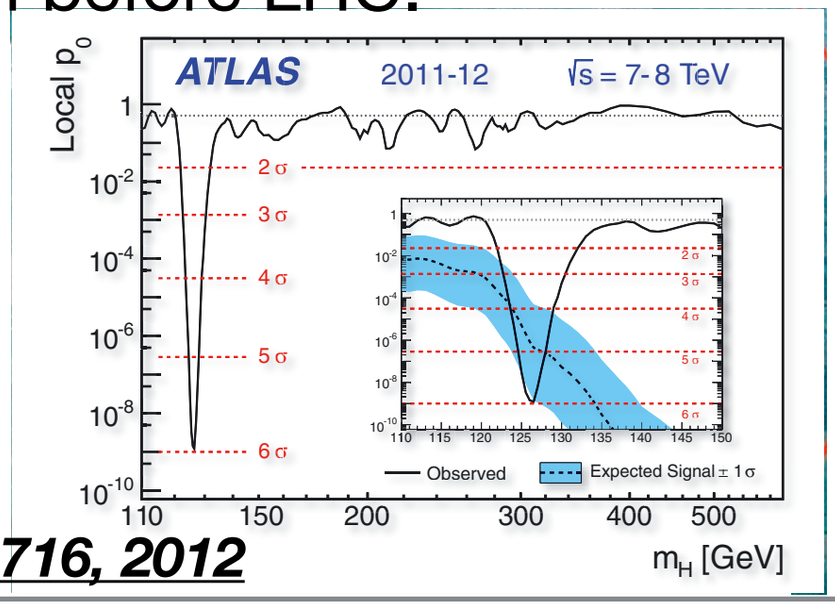
Higgs particle

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





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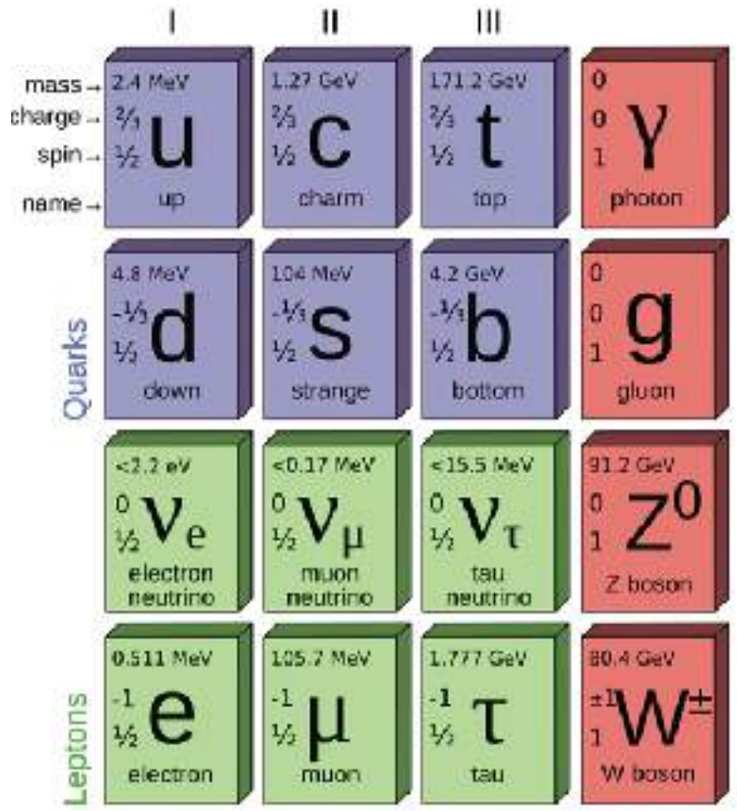
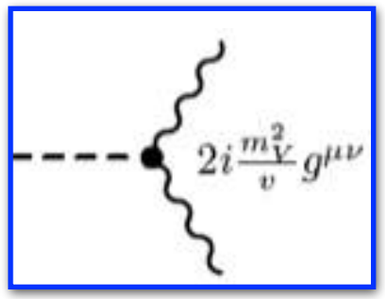


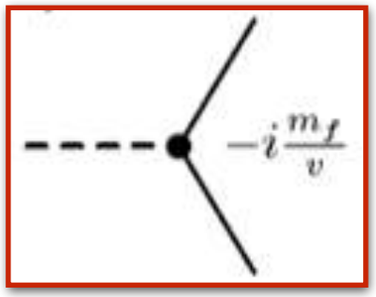
Higgs discovery: A new era of particle physics — measure the properties of the new particle

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

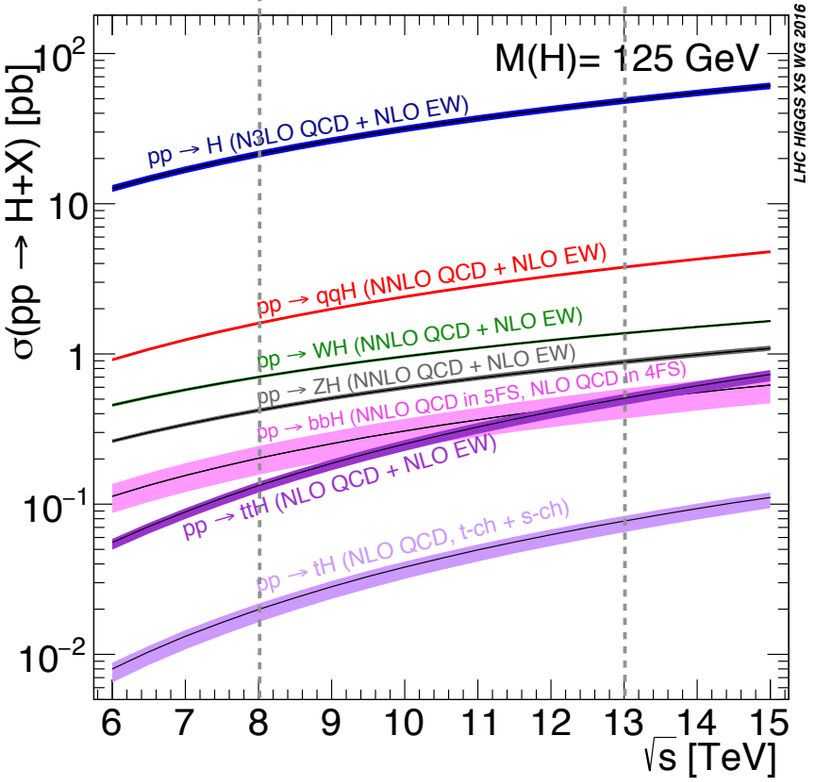
Gauge coupling

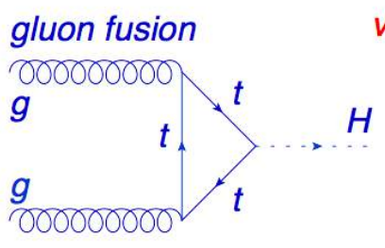


Yukawa coupling

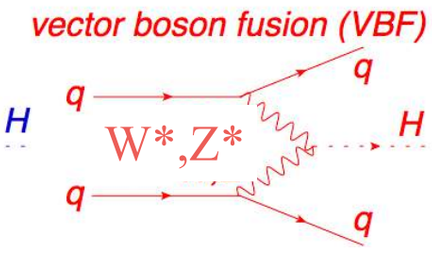


Higgs boson production and decays

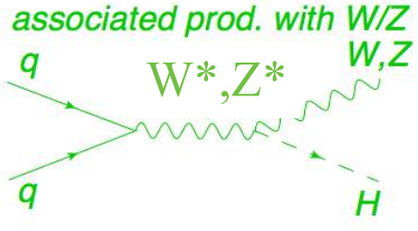




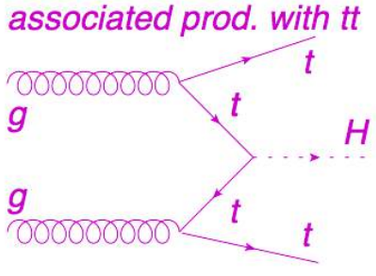
~48.6 pb (88%)



~3.8 pb (7%)

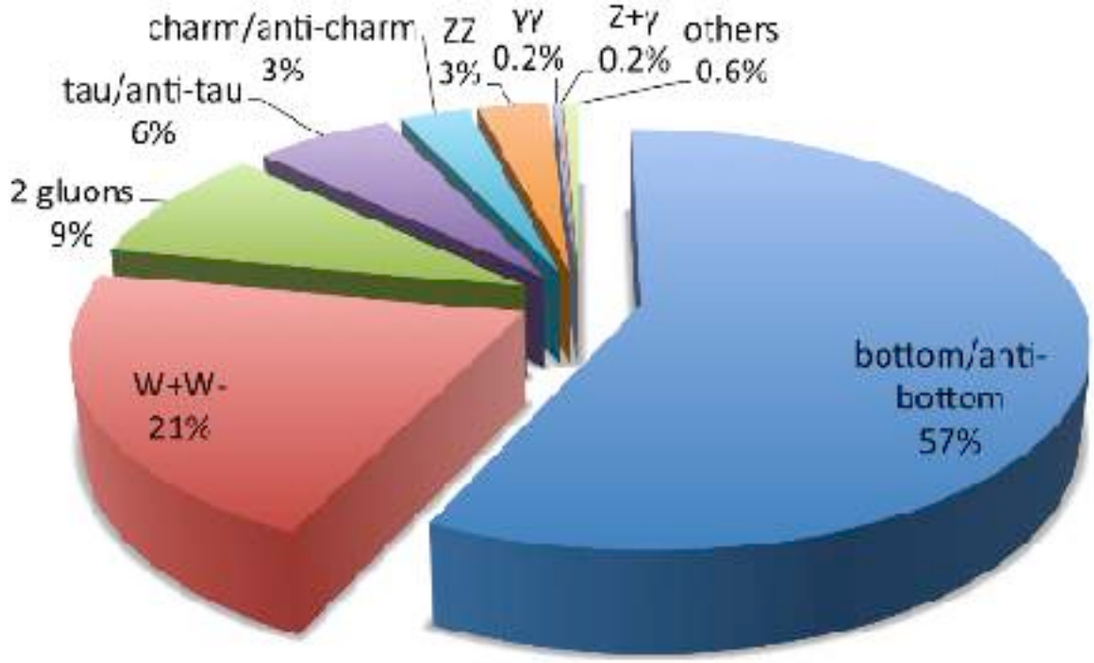


~2.3 pb (4%)



~0.5 pb (1%)

Many decay modes accessible with different properties



ZZ* and γγ: high resolution and precise differential measurements

WW*: high BR but low mass resolution

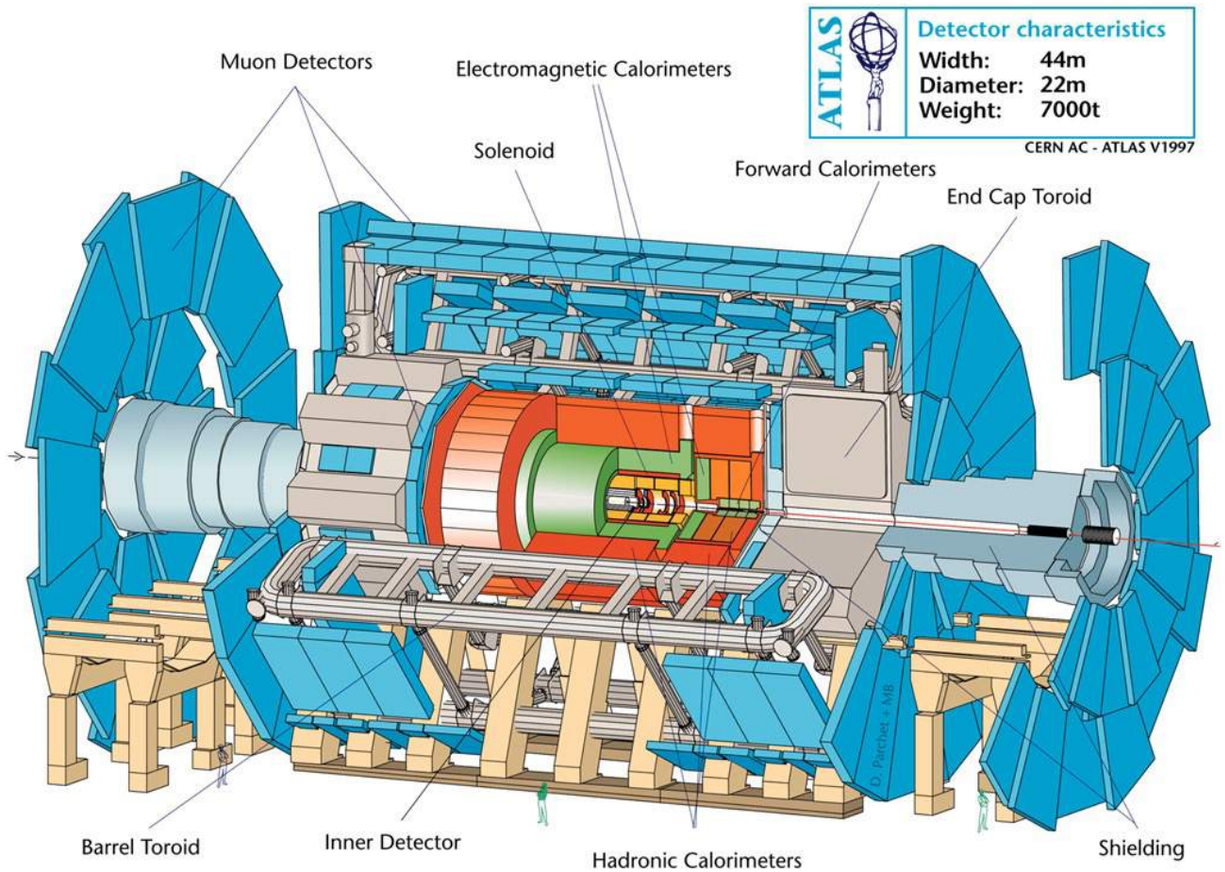
ττ and bb: high BR but low S/B, important to directly probe Yukawa coupling with 3rd generation

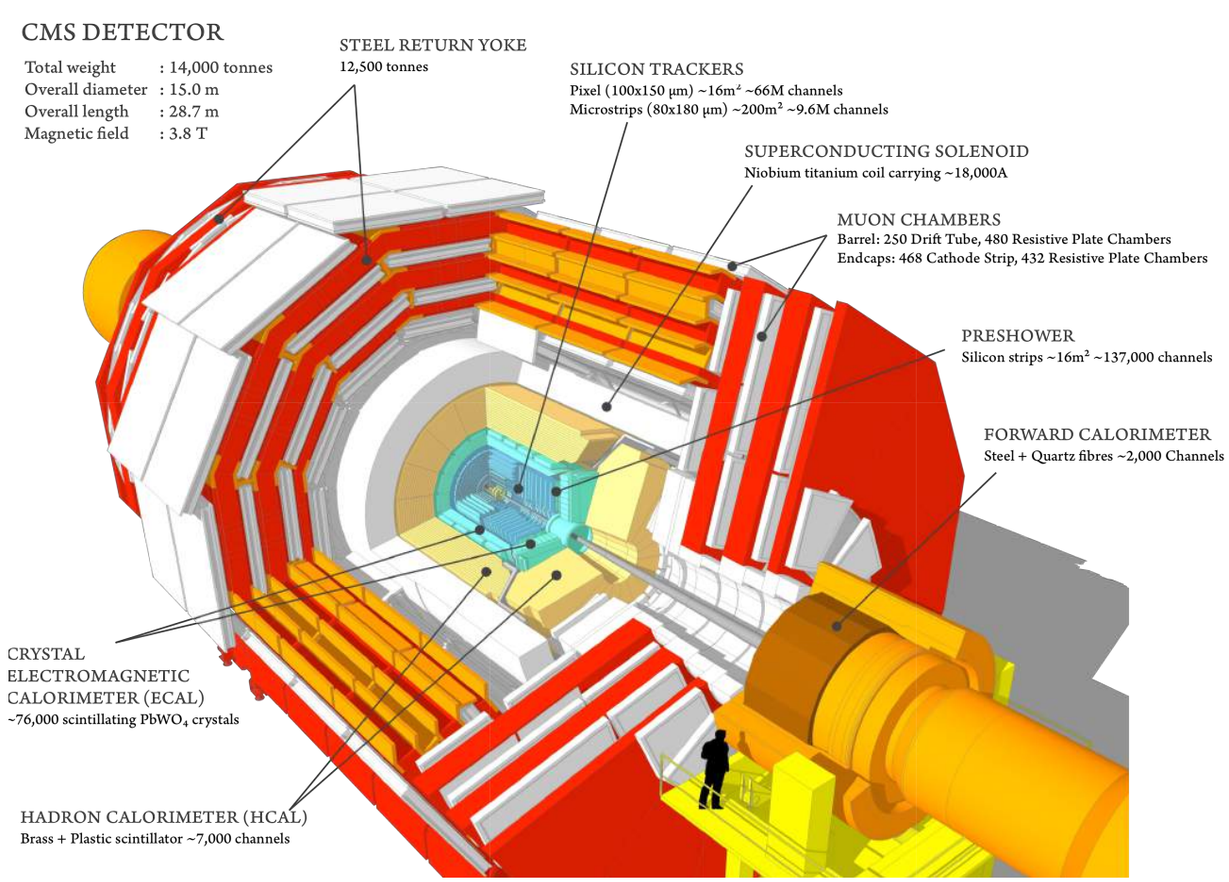
μμ: very small BR but access to Yukawa coupling with 2nd generation fermions

ATLAS and CMS

Upgrades for run-2 (starting 2015)

- new innermost pixel layer (ATLAS)
- pixel detector replacement in 2017 (CMS)
- trigger improvements to cope with high pp interaction rate



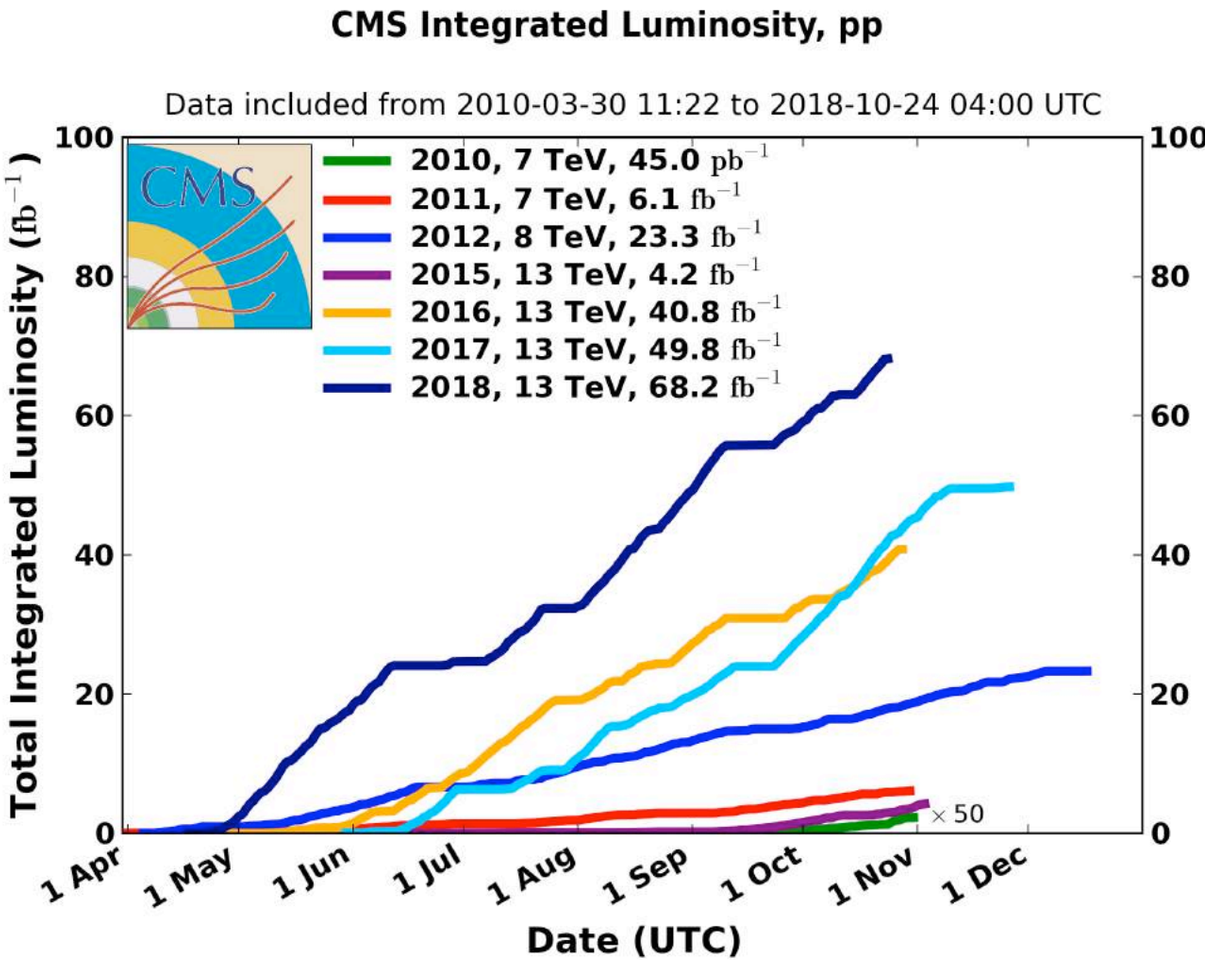


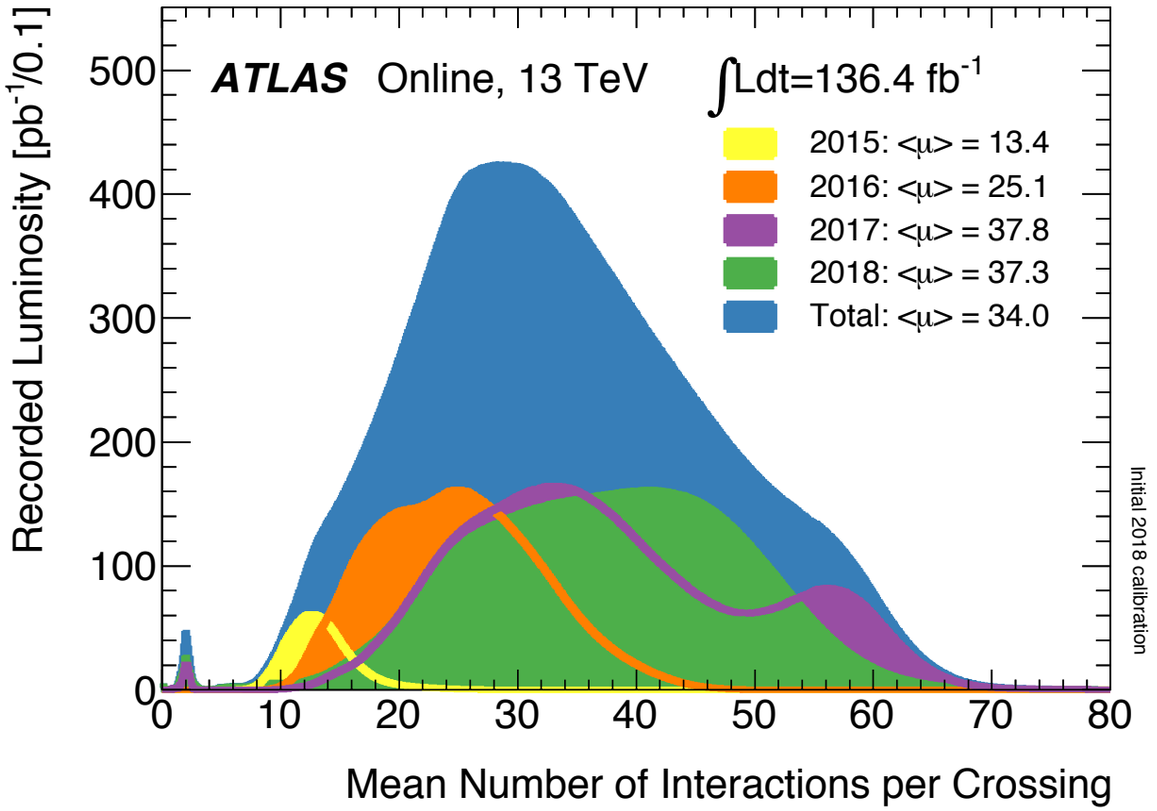
Run-2 dataset

Full Run2 data-taking finished (~ 140 fb^{-1}): 13 TeV, 25 ns bunch spacing

Peaking luminosity ~2.1×10^{34} cm^{-2}s^{-1} (twice design)

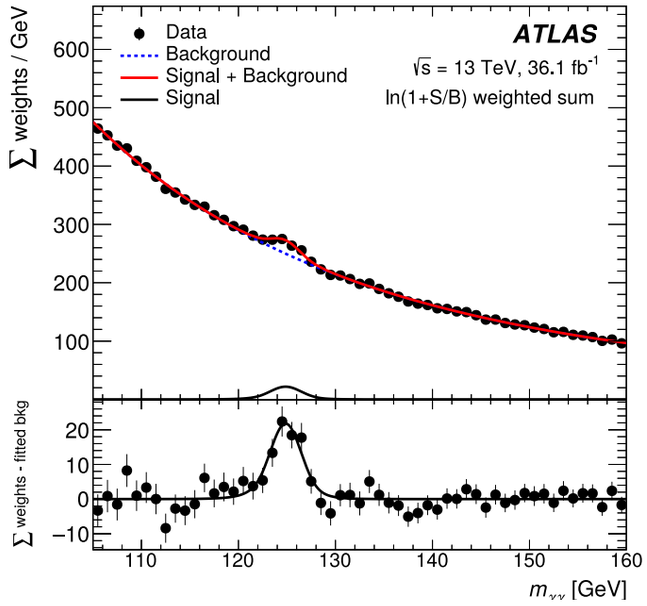
- Up to ~60 pp interaction per bunch crossing

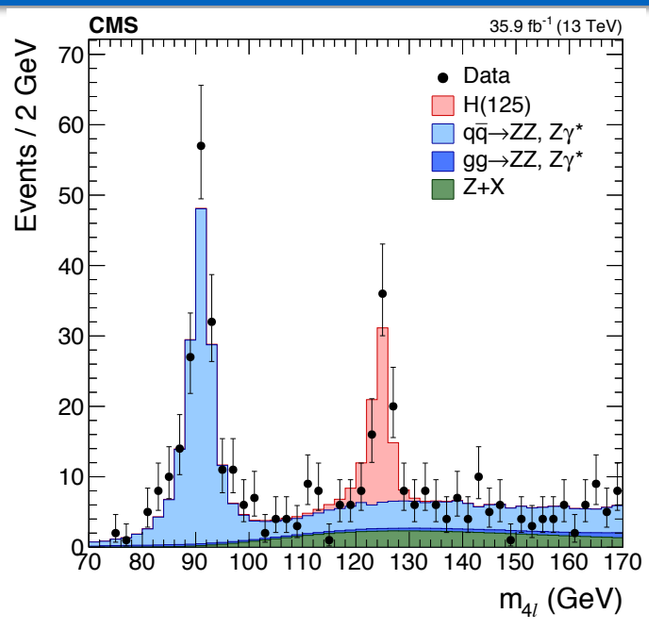




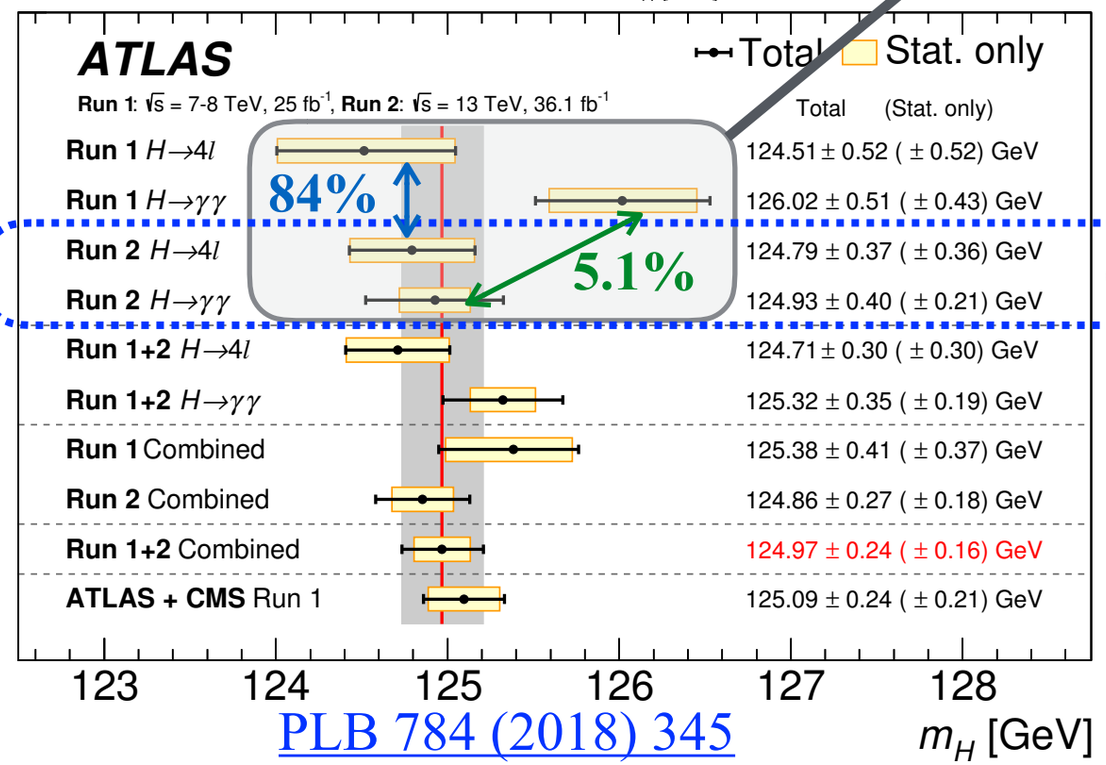
Results presented are based on the analyses of ~ 36 fb^{-1} to ~80 fb^{-1} of 13 TeV data

Higgs Mass





Compatible with 12.3%



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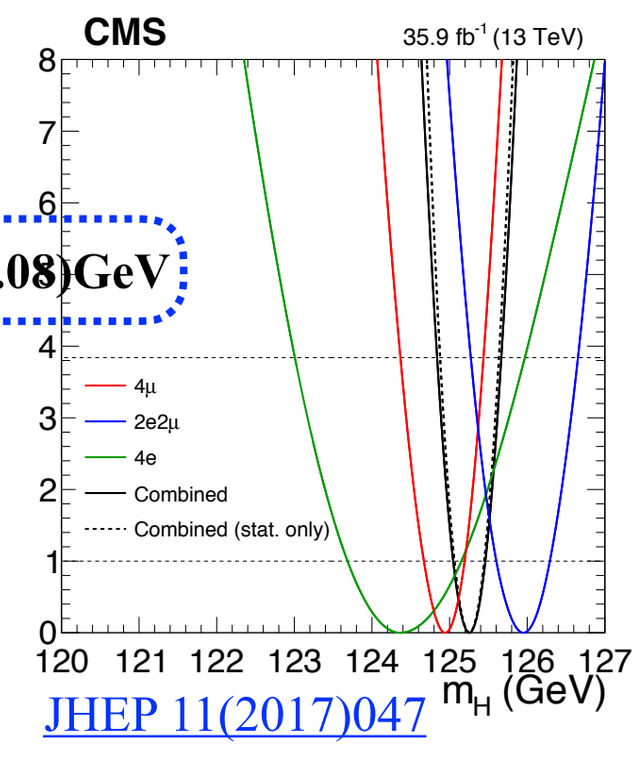
3D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\rm mass}, \mathcal{D}^{\rm kin}_{\rm bkg})$
With Z-constraint

CMS :125.26±0.21(±0.20±0.08)GeV



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- Precise measurements with excellent detector performance : **$\sigma(m_H)/m_H$ ~ 0.17% (CMS) and 0.21% (ATLAS),** are better/comparable w.r.t. **ATLAS+CMS Run-1 combination 0.19%**
- Still dominated by statistical uncertainties, uncertainty on coupling ~ 0.5%

Higgs Width

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

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

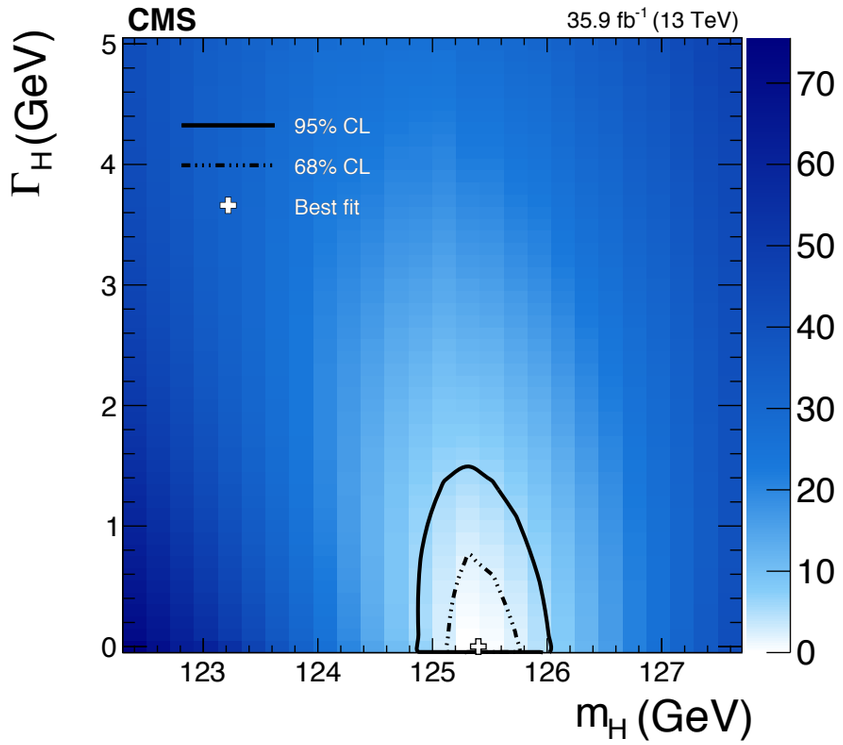
SM: $m_H = 125\text{GeV} \rightarrow \Gamma_H = 4.07\text{MeV}$
Γ_H cannot be accessed directly due to the experiment resolution

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



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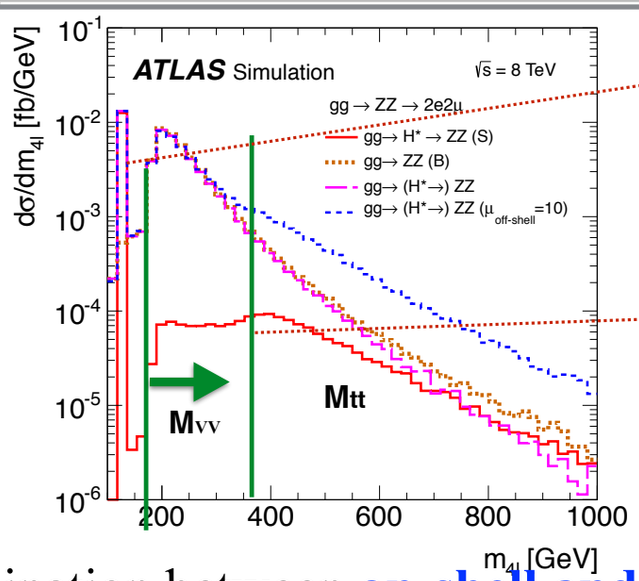
Indirect Higgs Width Measurement



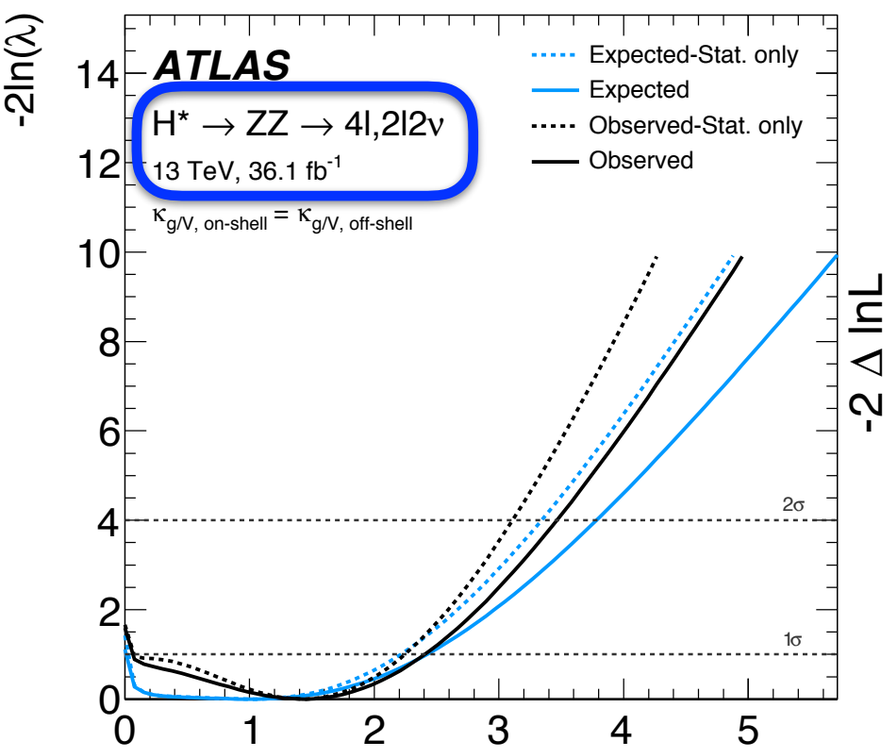
$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

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

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

With the combination between **on-shell and off-shell analyses**

- **Assuming the on-shell coupling modifiers are the same as the off-shell coupling modifiers**
- Assuming NP modifying off-shell coupling **without the modification of other background and signal expectation.**



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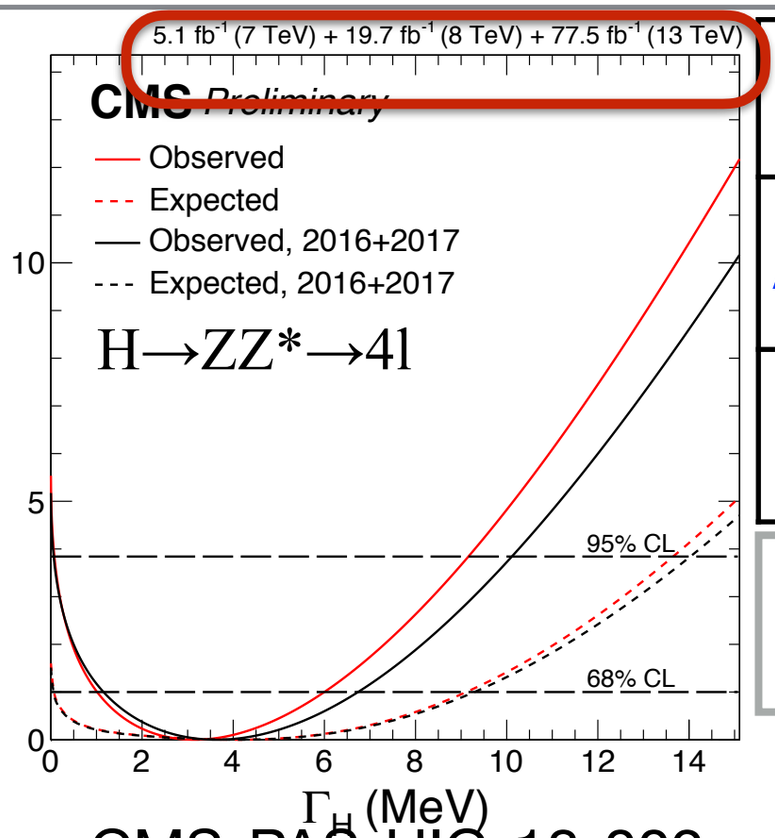


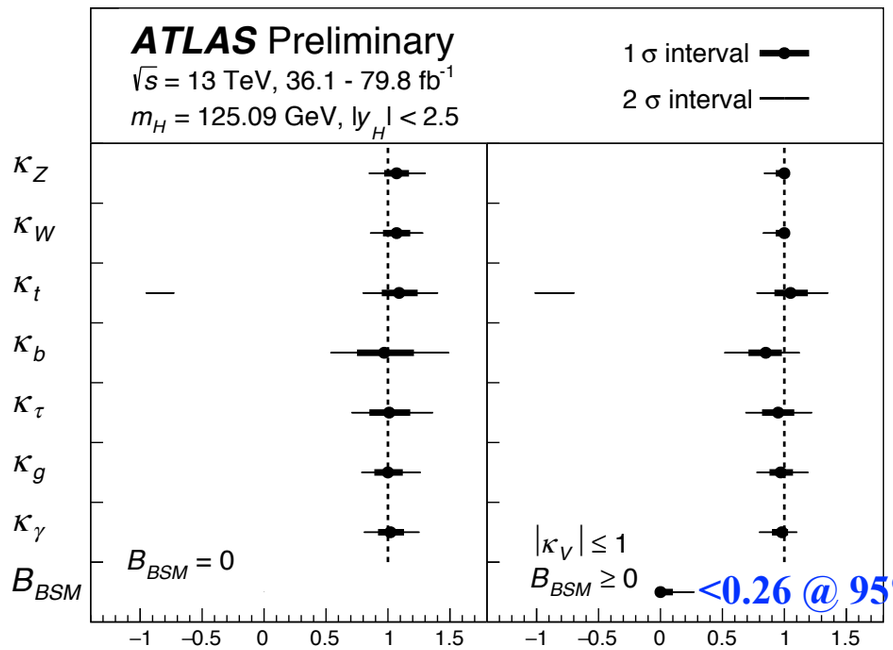
CMS-PAS-HIG-18-002

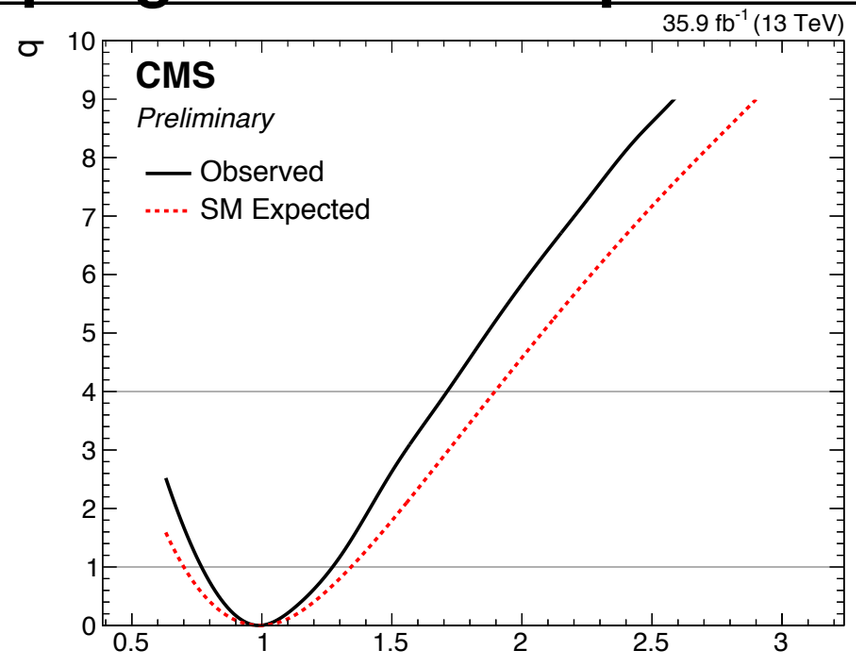
Γ_H	Obs. (Exp.) @95 CL.
ATLAS	14.4 (15.2) MeV 3.8 (3.4) ×Γ_{SM}
CMS	9.16 (13.7) MeV 2.2 (3.3) ×Γ_{SM}

Improves on Run1 expected limits by ~ factor 2

Indirect Higgs Width Measurement

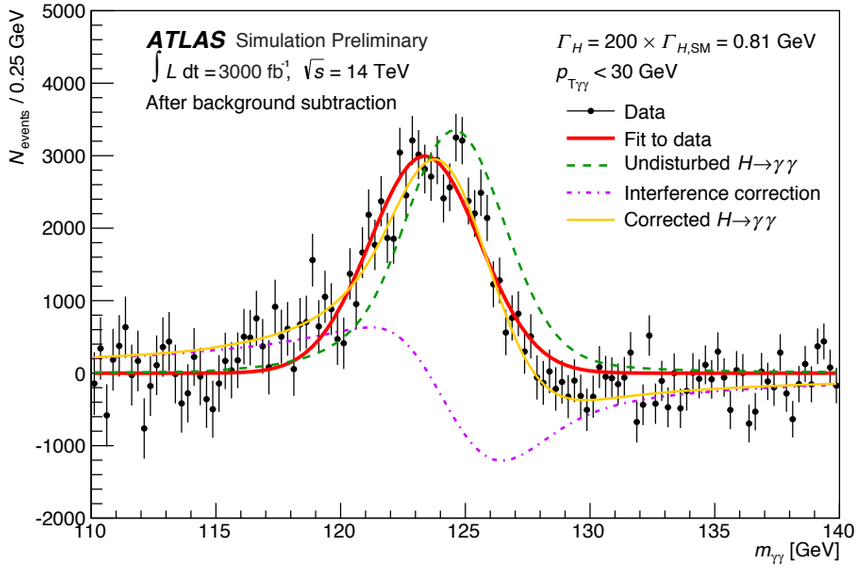
Introduce the BSM contribution in the Coupling combination parametrization

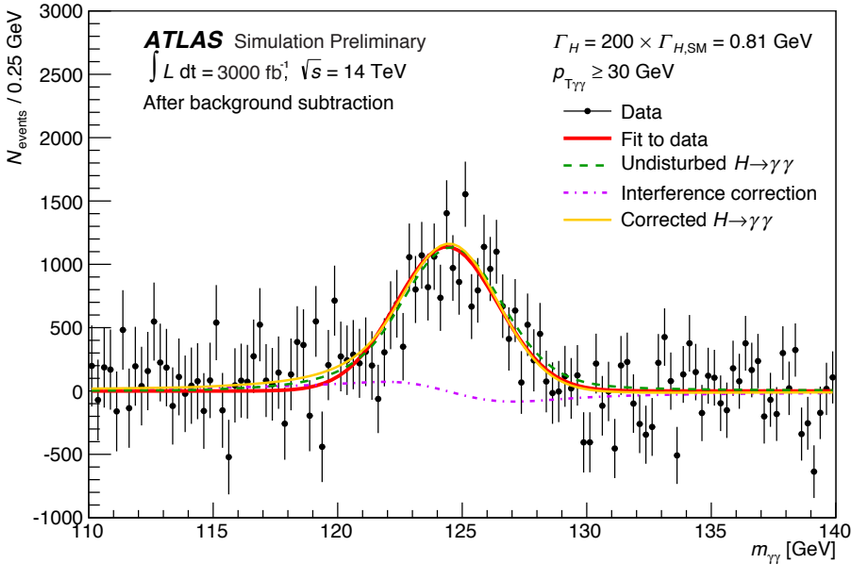




<0.26 @ 95% CL

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)





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

Higgs Measurement Methodology

Run 1-style coupling measurements: μ, kappa

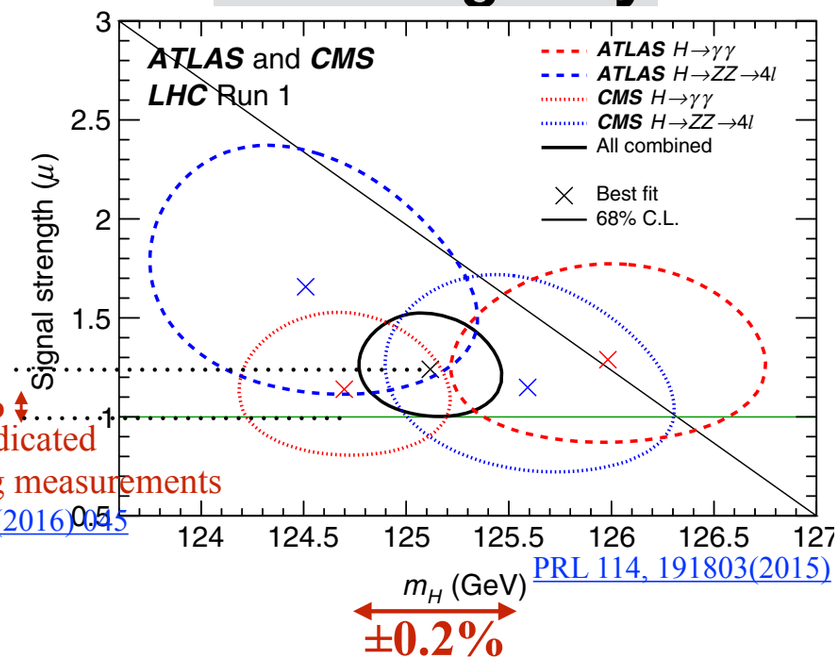
Simplified template cross sections

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

Individual channel:

- H→γγ
- H→ZZ
- H→WW

Combination: (addition of H→ττ/bb/μμ and ttH)

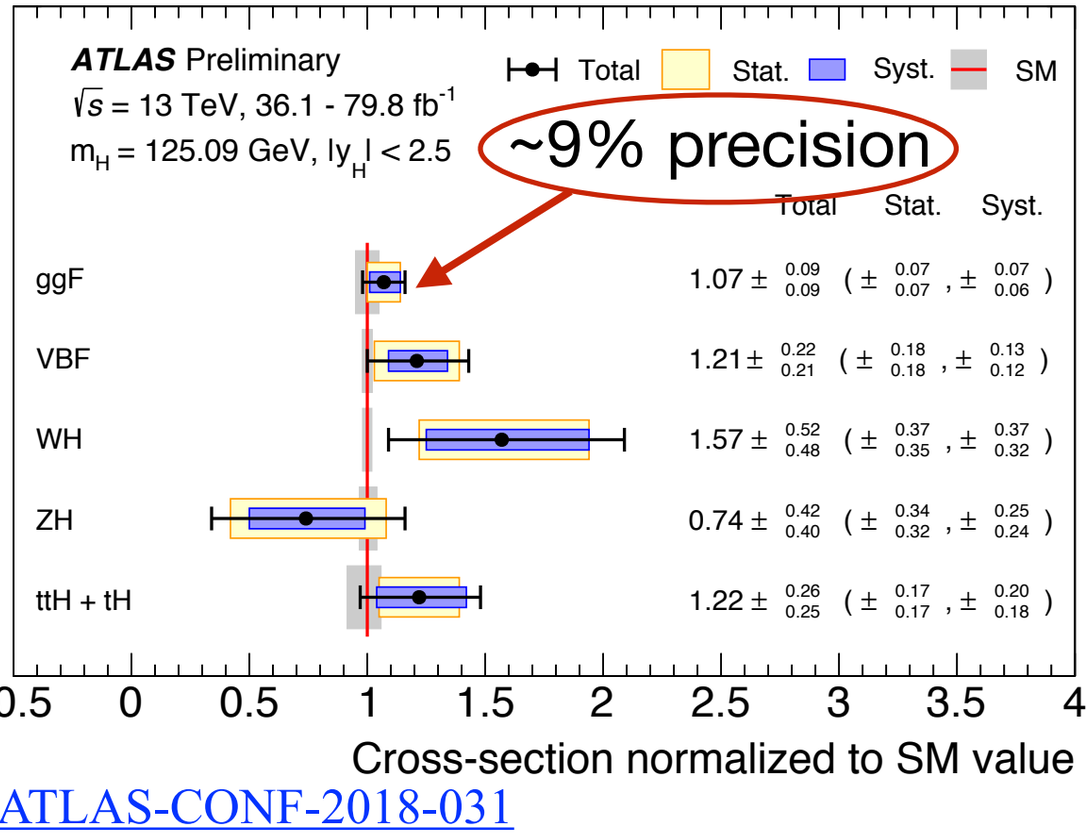
- **ATLAS: (36.1 - 80fb^{-1})**
- **CMS: (36.1fb^{-1})**

Bosonic channels

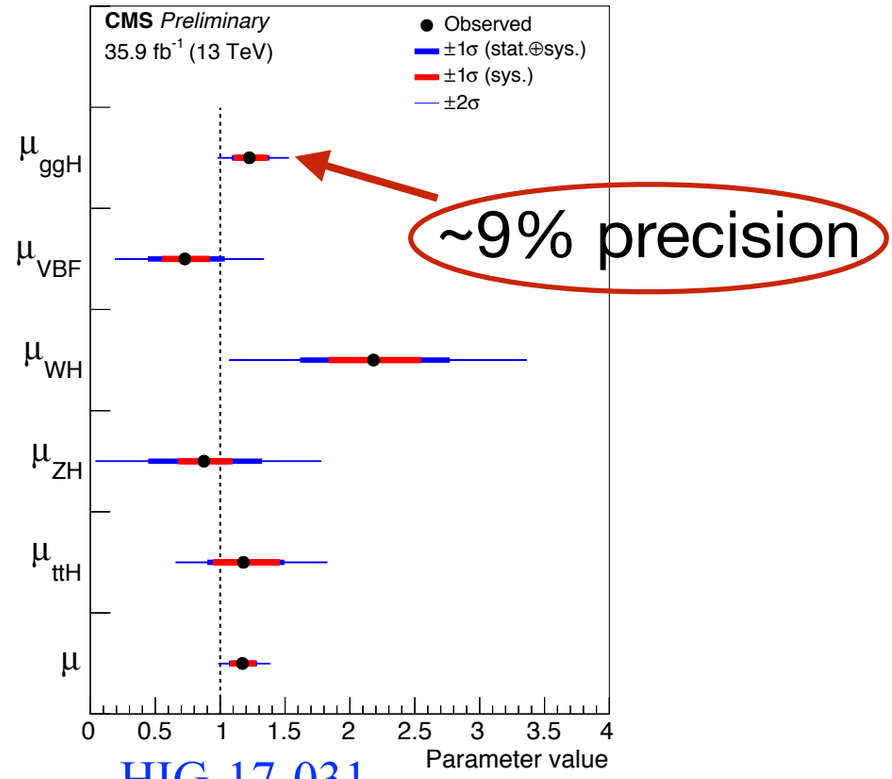
	Global signal strength			
		H→γγ	**H→ZZ**	**H→WW**
Run-2	ATLAS	$1.06^{+0.14}_{-0.12}$ ATLAS-CONF-2018-028	$1.19^{+0.16}_{-0.15}$ ATLAS-CONF-2018-018	μ_{ggF}: $1.21^{+0.22}_{-0.21}$ μ_{VBF}:$0.62^{+0.37}_{-0.36}$ ATLAS-CONF-2018-018
		Combination: 1.13±0.05(stat.)±0.05(exp)$^{+0.05}_{-0.05}$(sig. th.)±0.03(bkg) ATLAS-CONF-2018-031		
	CMS	$1.16^{+0.15}_{-0.14}$ HIG-16-040	$1.10^{+0.19}_{-0.17}$ HIG-18-001	μ_{ggF}: $1.19^{+0.16}_{-0.15}$ HIG-16-014
		Combination: 1.09±0.09(stat.)$^{+0.06}_{-0.05}$(exp)$^{+0.06}_{-0.05}$(th.) HIG-17-031		
Run-1 ATLAS+CMS		**1.09±0.07(stat.)$^{+0.04}_{-0.04}$(exp)$^{+0.07}_{-0.06}$(th.)$^{+0.03}_{-0.03}$(other sys)**		

- ATLAS and CMS overall **consistent in** the **3 bosonic decay modes with each other** and **with SM prediction**
- Data precision will be **<10% with full Run2 data** for **γγ and ZZ**
- **H→WW**: systematic uncertainties dominate

Signal strength and production XS from combination



ATLAS-CONF-2018-031



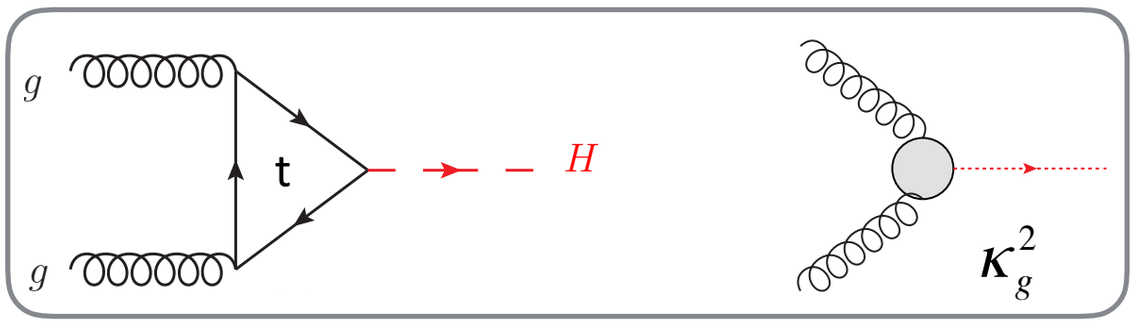
HIG-17-031

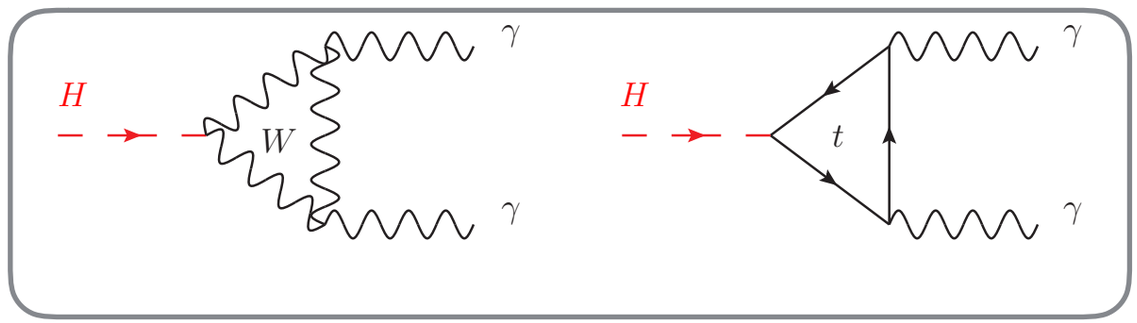
Observe all main production modes.

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)

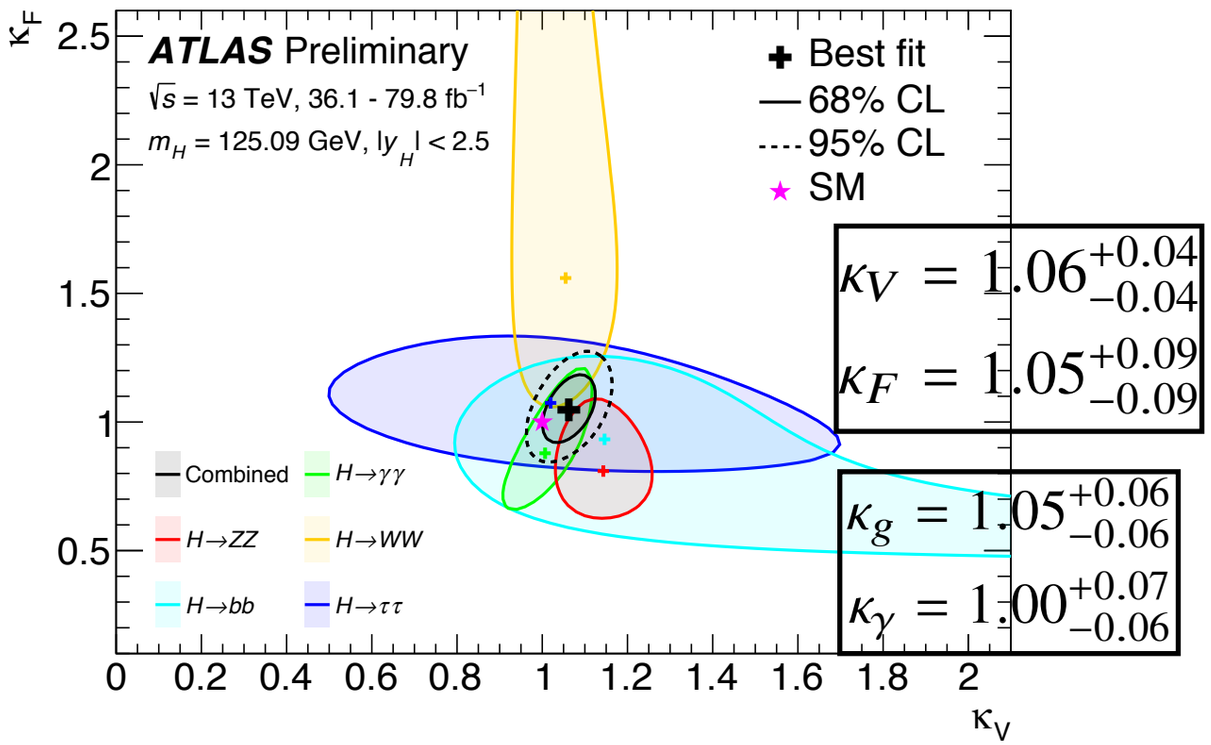
κ-framework

- **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 $\{\kappa_x\}$

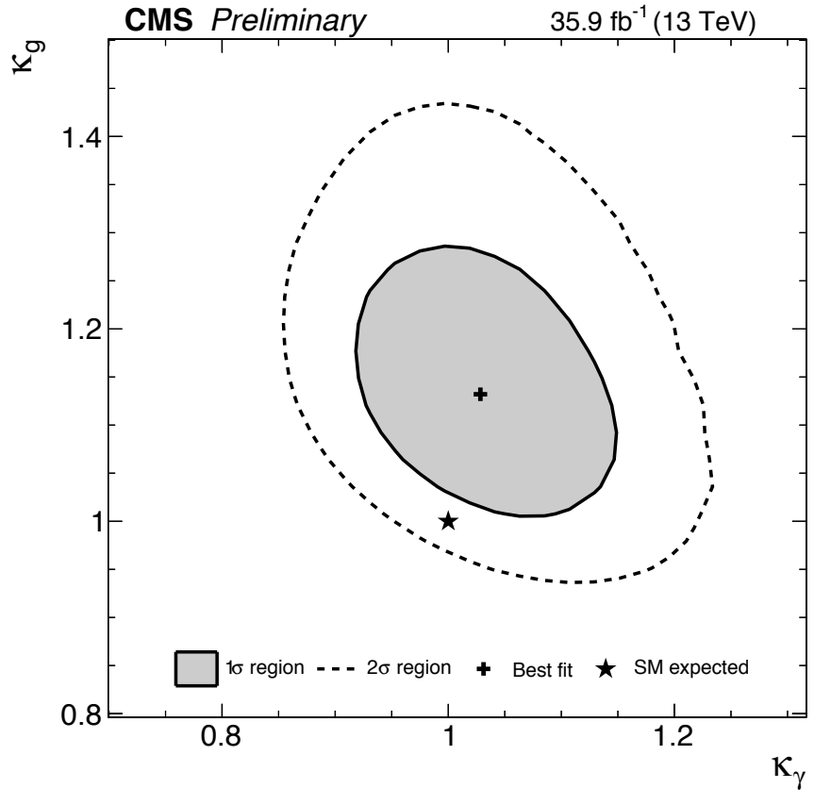




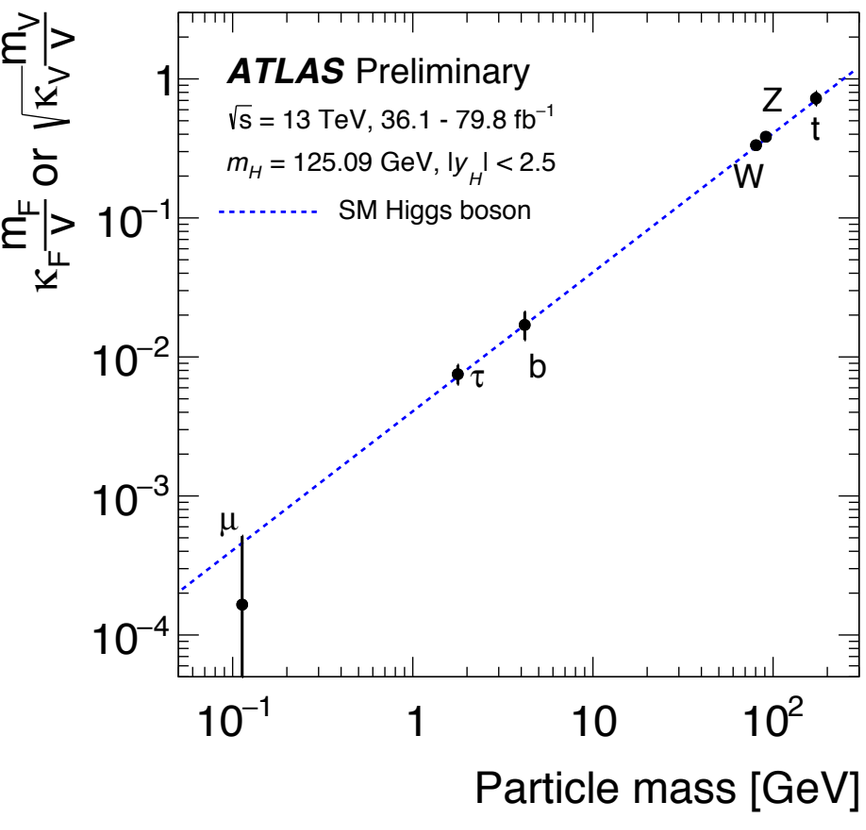
$\kappa_g^2 = 1.042\kappa_t^2 + 0.002\kappa_b^2 - 0.040\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0005\kappa_b\kappa_c + 0.00002\kappa_c^2$

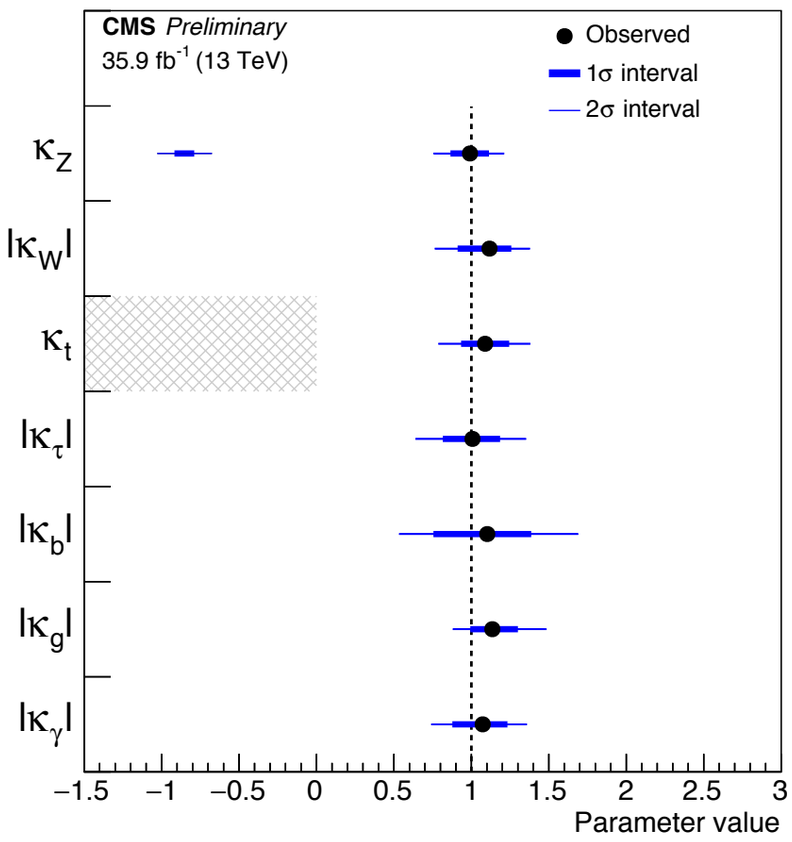


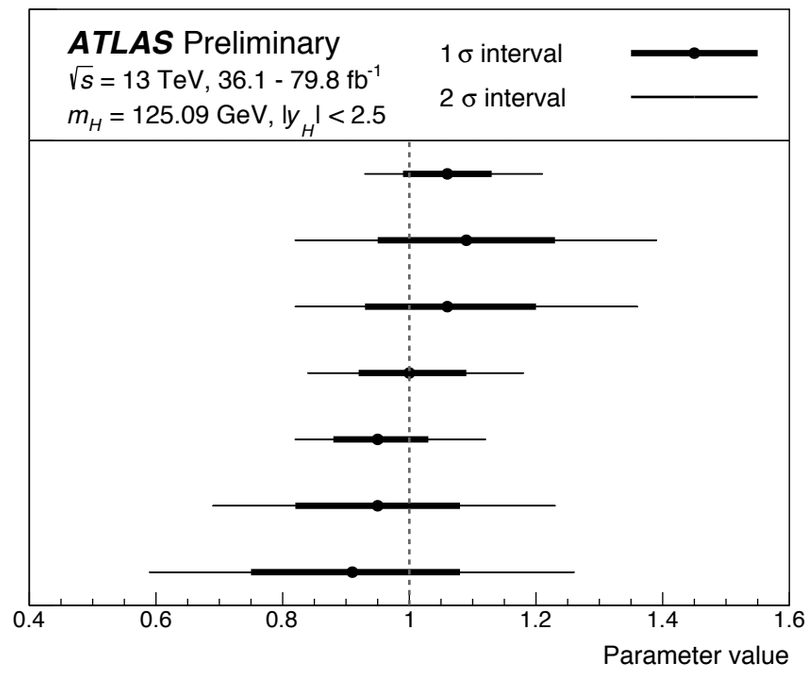
$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t\kappa_W + 0.1 \times \kappa_t^2$



κ-framework

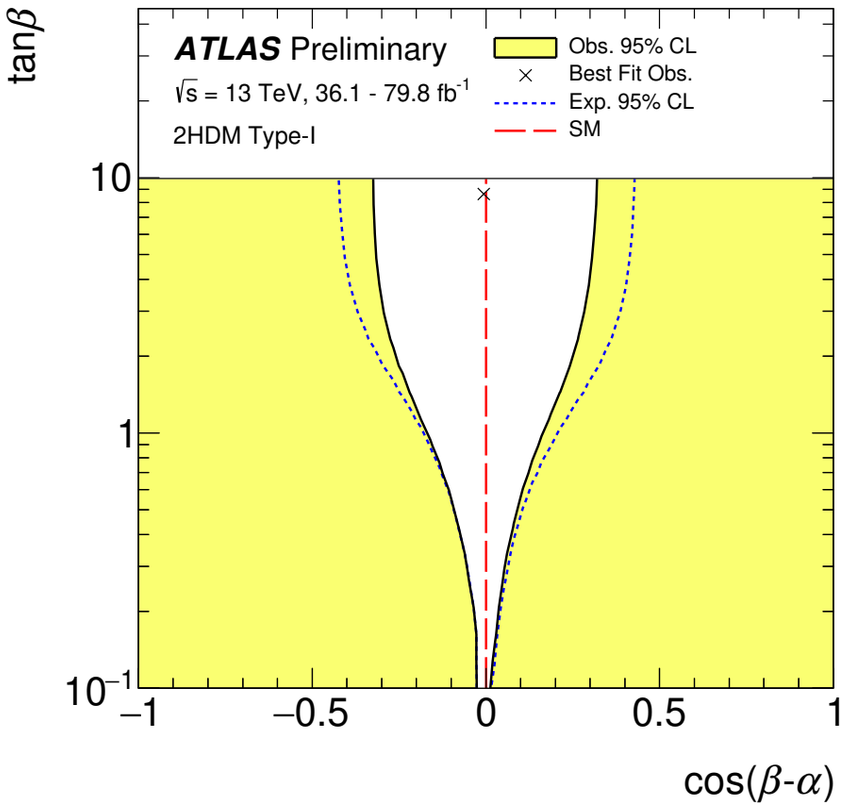


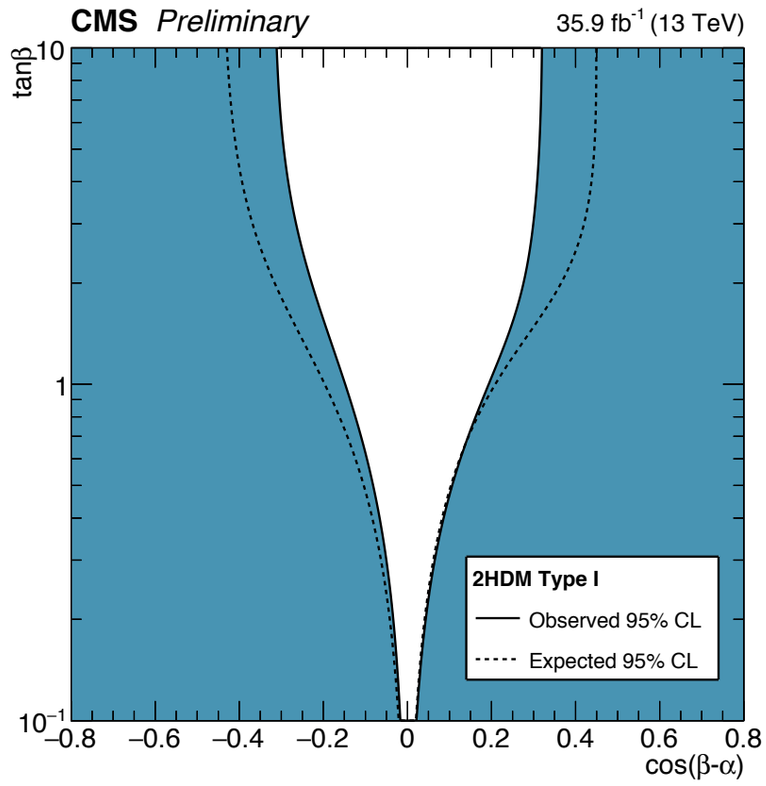




- Good agreement with the SM prediction
- Interactions with vector bosons and (heavy) fermions are already probed at 10-30% level
- A wide measurement on the ratio parametrization, e.g. λ_{tg} ~ 13%

Constraints on New Phenomena



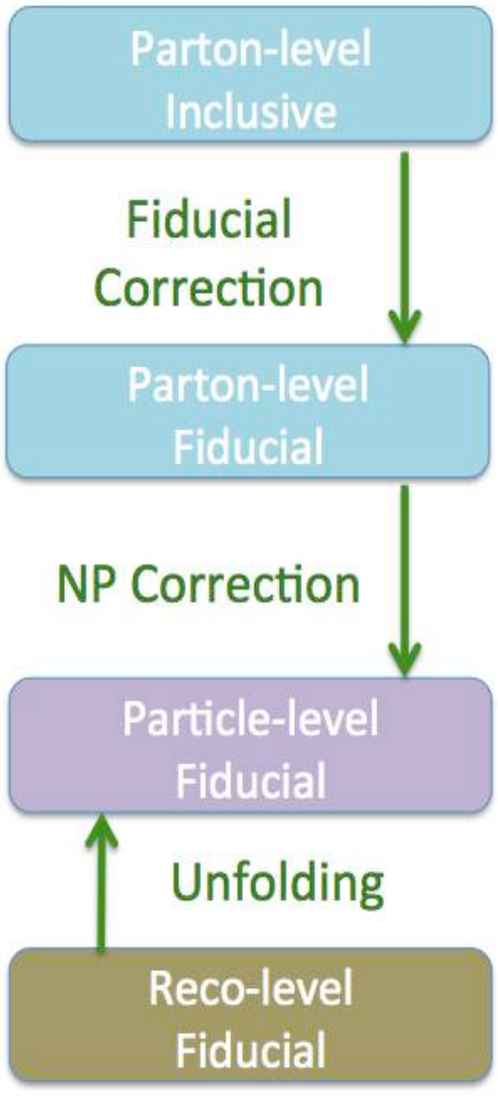


In benchmark 2HDM, (κ_V, κ_u, κ_d, κ_l) can be expressed as the function of α and tanβ.

- The Higgs boson couplings are same as the SM predictions for cos(β-α)
- The observation provides more stringent constraint than SM expectation.

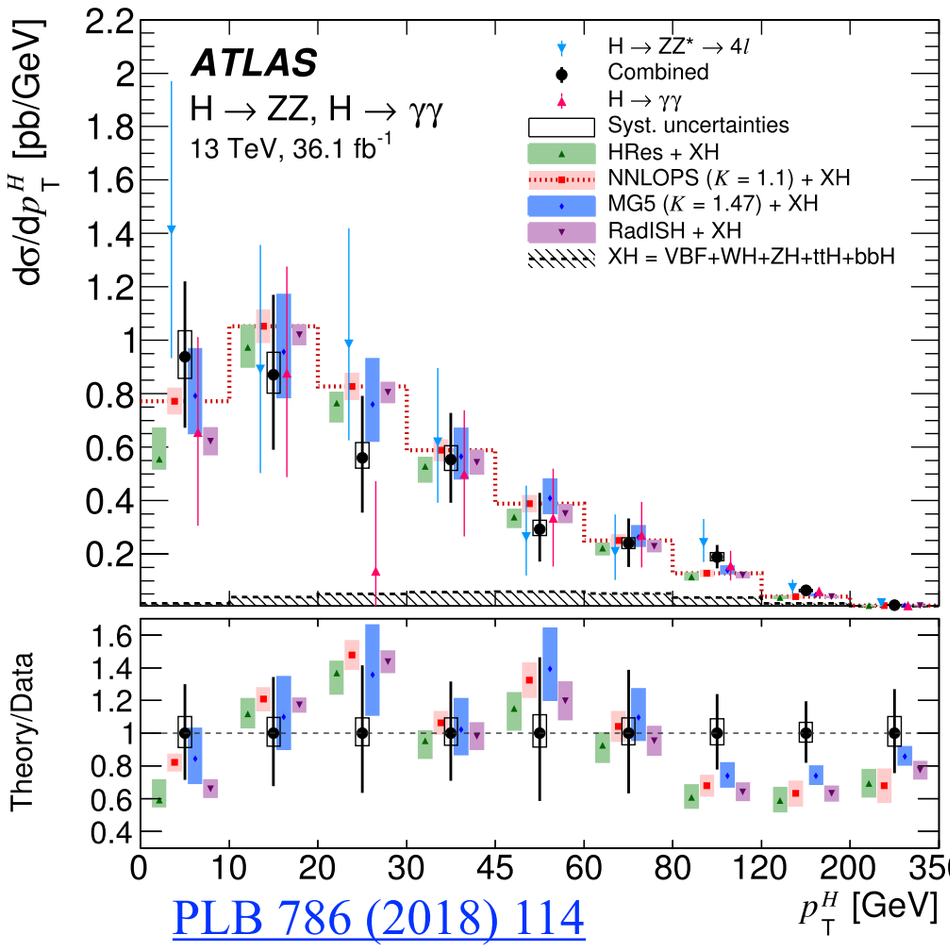
Fiducial and differential cross section

- Measurement designed as model independent as possible.
- Direct comparison with theoretical predictions at particle level with unfolding method (Bin-by-bin method @ ATLAS, matrix method @ CMS).
- A wide and diverse range of physical phenomena to be probed:



- **Differential X-sections (20 variables):**
  - ***Higgs kinematic*:** $p_{T,H}$ $|y_H|$ pTt
  - ***Jet activity*:** N_{jets} p_{Tj1} N_{jets_50} H_{Tjet} $|y_{j1}|$ p_{Tj2} p_{tj3} $|y_{j2}|$ τ_j $\sum\tau_j$ N_{bjets}
  - ***VBF - sensitive variables*:** $\Delta\varphi_{H,jj}$ m_{jj} Δy_{jj} p_{THjj}
  - ***Spin - CP variables*:** $cos\theta^*$ $\Delta\varphi_{jj}$ Δy_H
  - ***2D variables:*** $p_{T,H} \times N_{jets}$ $p_{T,H} \times cos\theta^*$
- **Fiducial X-sections:**
  - ***1- / 2- / 3- jet and inclusive regions***
  - ***Inclusive 1-lepton / MET / VBF / VH enriched regions***

Cross Section Measurement



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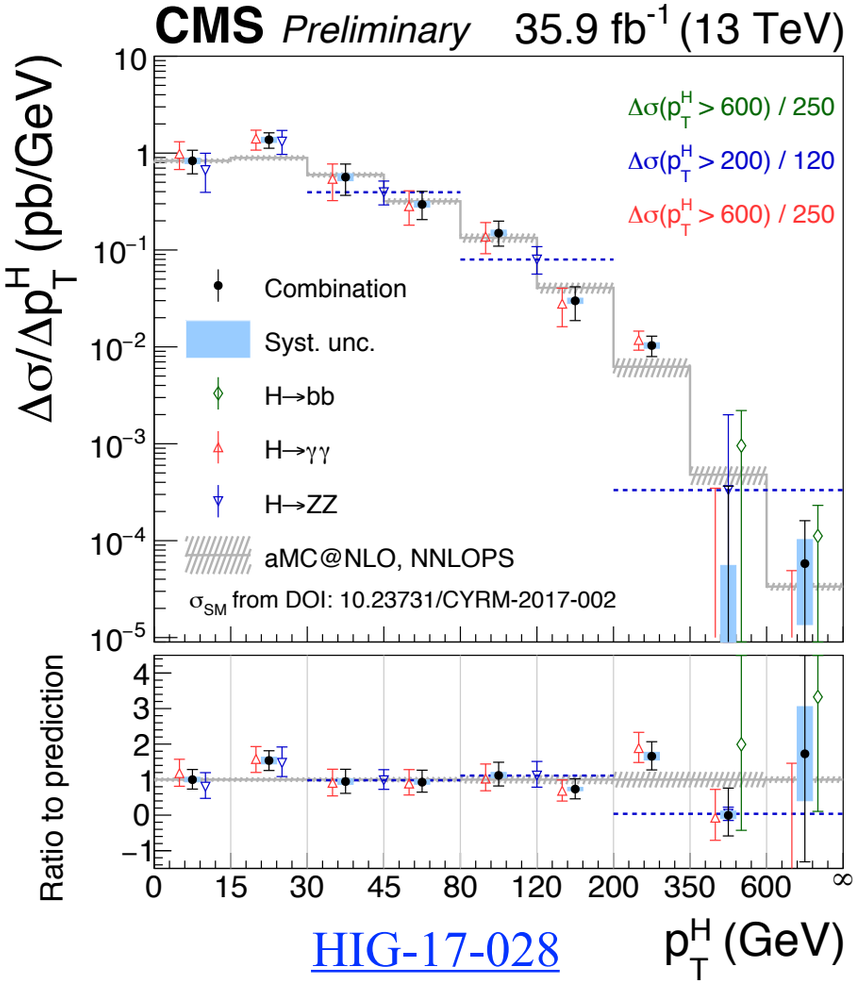
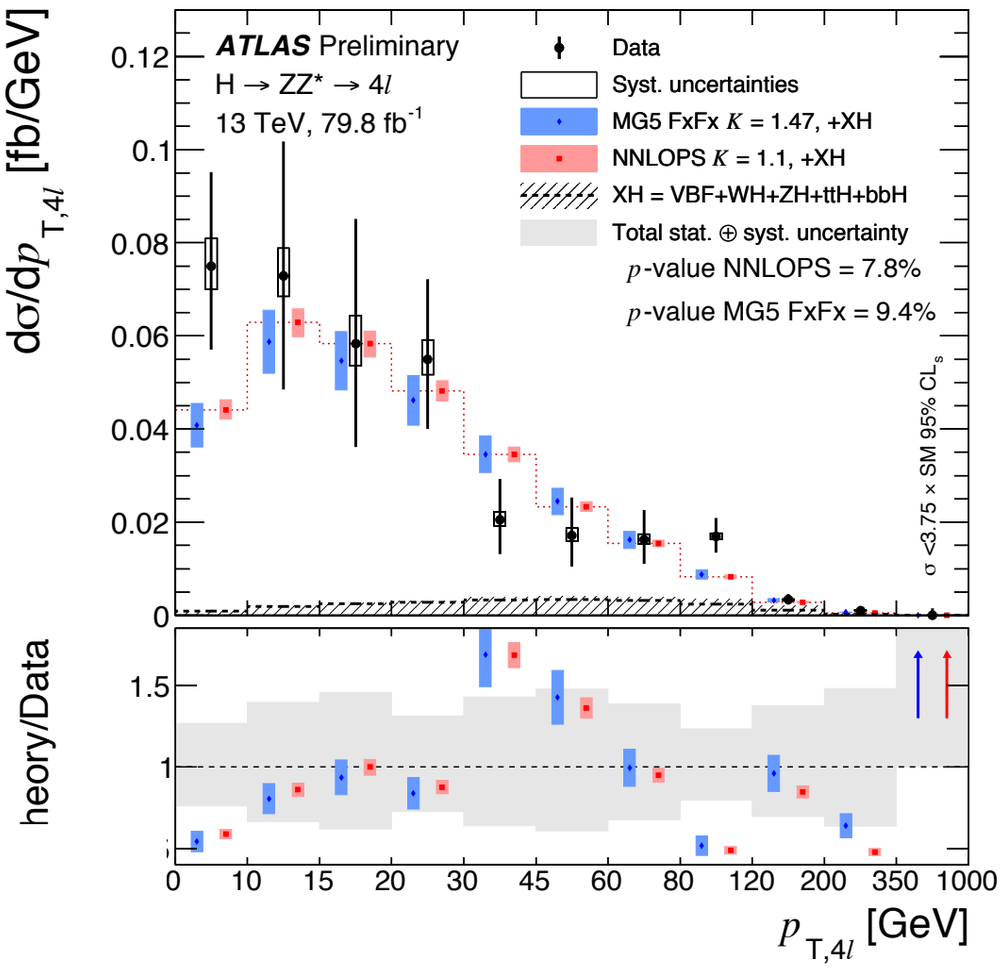
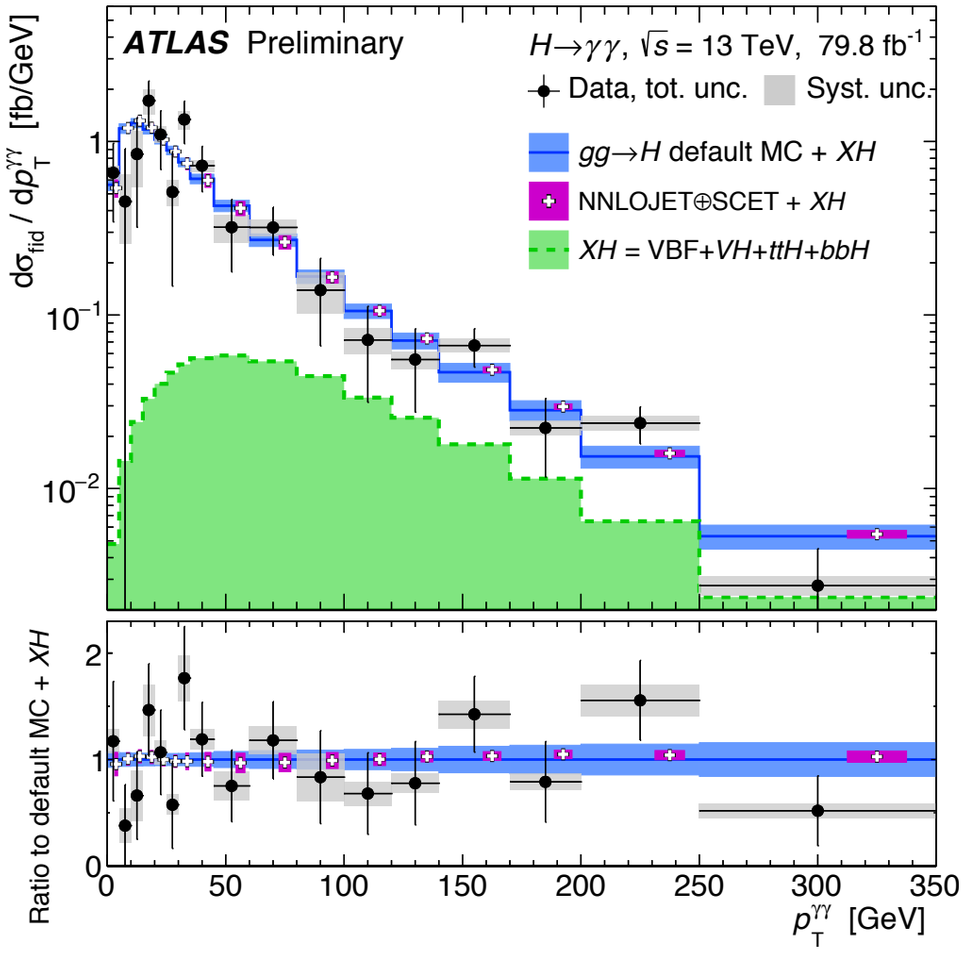


HIG-17-028

- Similar accuracy in γγ and 4l channels, and consistent with SM predictions within uncertainties
- Significance uncertainty reduction compared to Run1 with finer binning
- Boosted gg→H→bb search sensitive to the high pT(H) bin

Cross Section Measurement

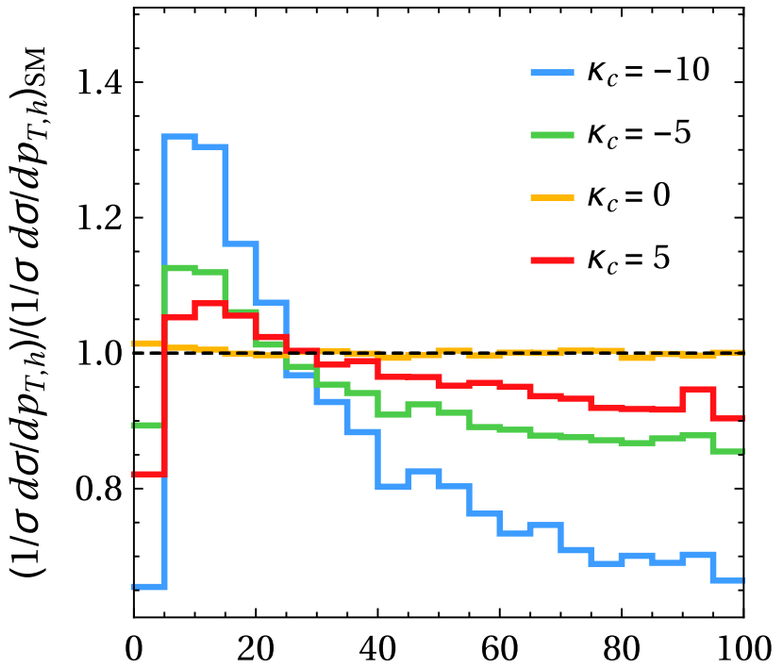




- Similar accuracy in $\gamma\gamma$ and 4l channels, and consistent with SM predictions within uncertainties
- Significance uncertainty reduction compared to Run1 with finer binning
- Boosted gg→H→bb search sensitive to the high pT(H) bin

Interpretation from differential cross section

$p_{T,H}$ sensitive to c-Yukawa due to interference between c- and t-mediated contributions in ggF



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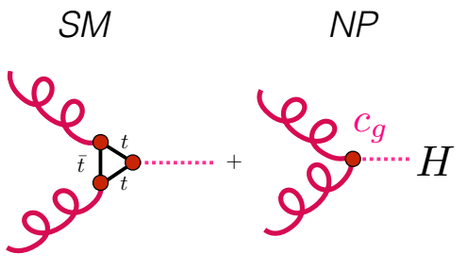
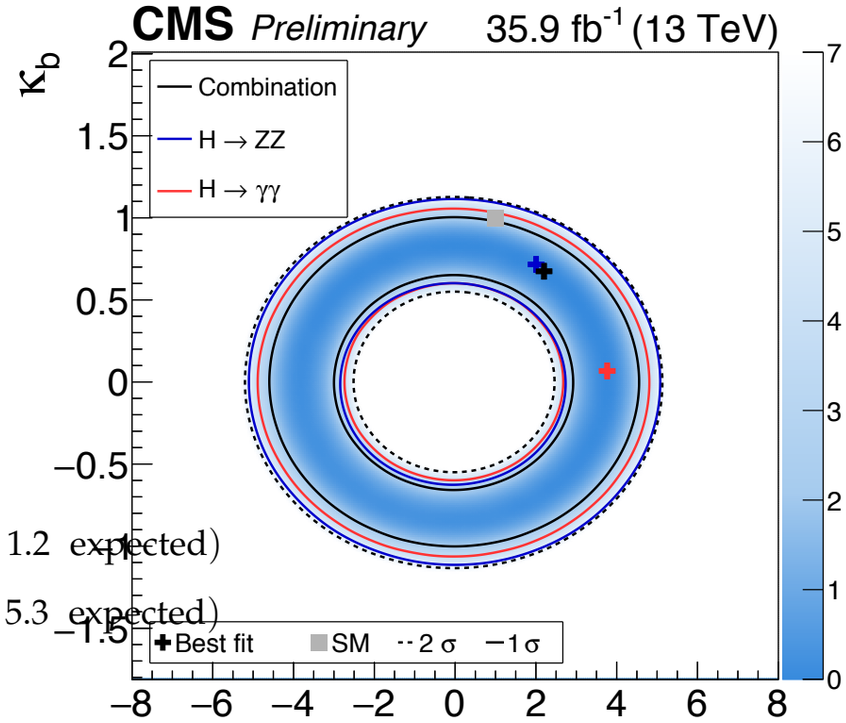
EFT approach with differential cross sections



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

No significant deviation from SM



$-0.9 < \kappa_b < 0.9 \quad (-1.2 < \kappa_b < 1.2$ expected)

$-4.3 < \kappa_c < 4.3 \quad (-5.4 < \kappa_c < 5.3$ expected)

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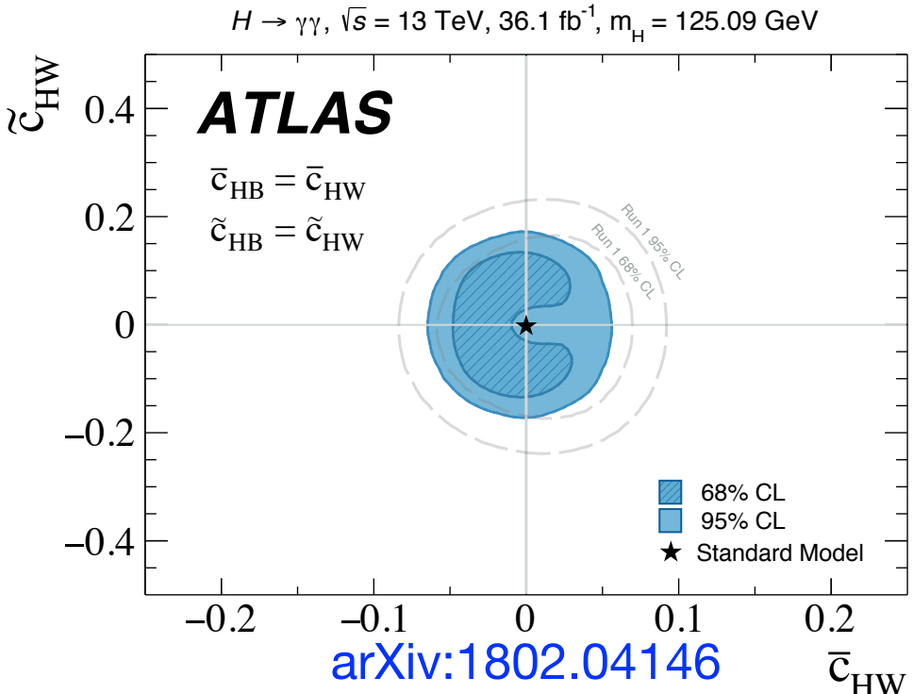
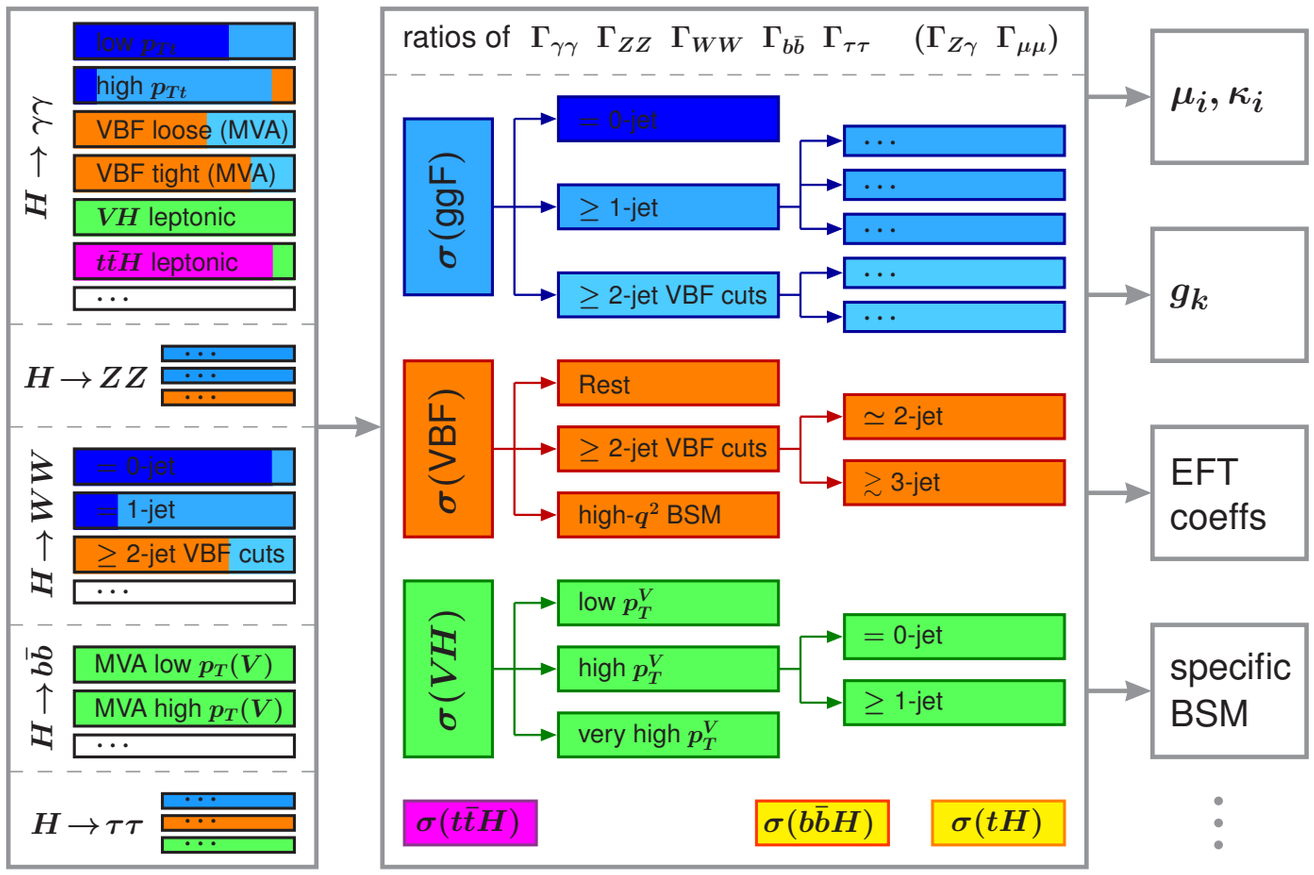
5 variables: $p_T^{\gamma\gamma}$ N_{jets} m_{jj} $|\Delta\phi_{jj}|$ $p_T^{j_1}$



arXiv:1802.04146

Simplified template cross section



- **Fiducial volumes based on properties of production but not of decay**
- **Less model dependence**
- **Make use of Rec. optimization for sensitive improvement**
- **Further combination and interpretation**

The signal yield in each category c is the sum over the yields from the STXS bins

Stage-0: production mode separation

H→γγ

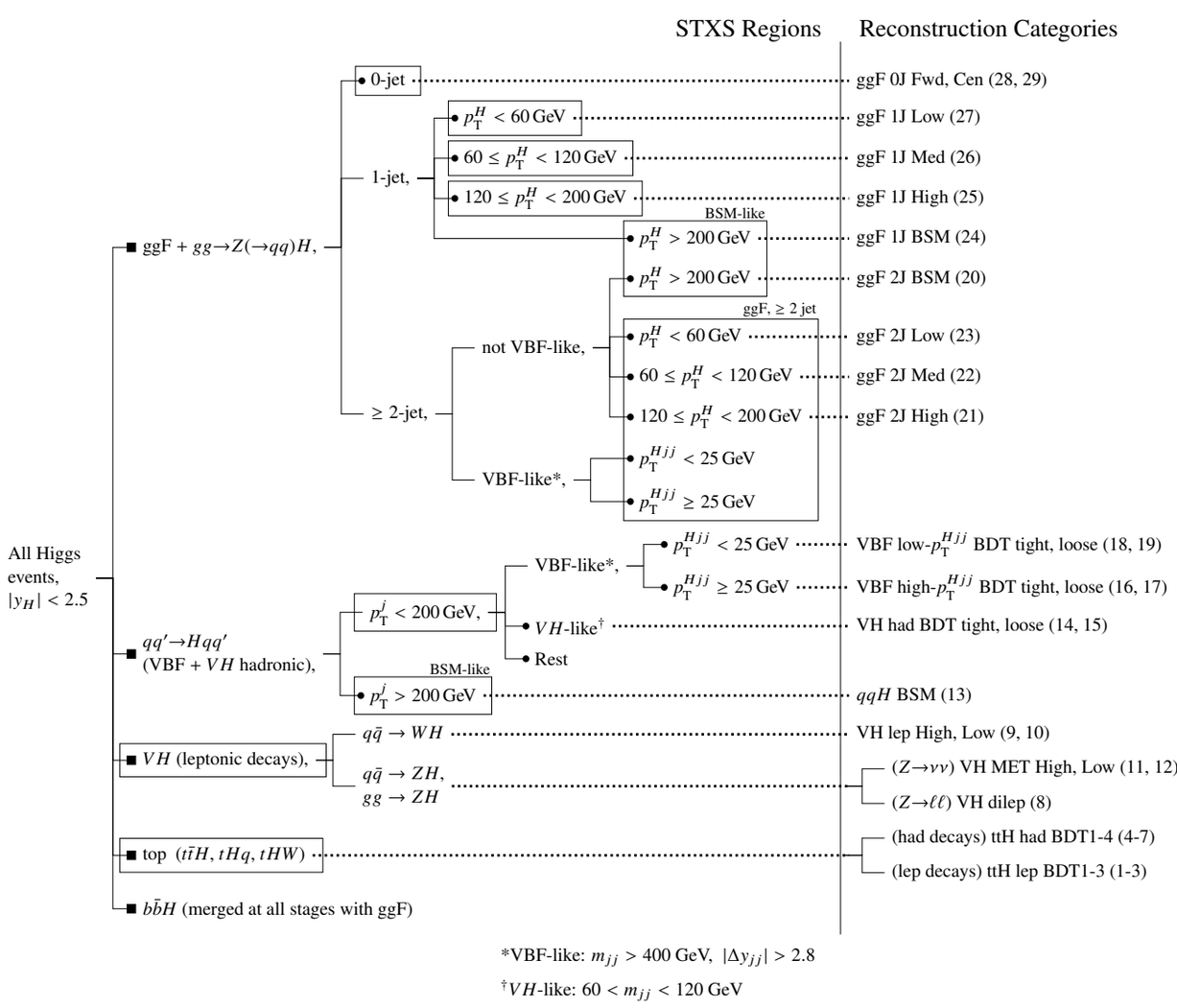
Process ($\lvert y_H\rvert < 2.5$)	Result [fb]	Uncertainty [fb] Total	(Stat.	Exp.	Theo.)	SM prediction [fb]
ggF	98	$^{+15}_{-14}$	(± 11	$^{+9}_{-8}$	$^{+4}_{-3}$)	$102\ ^{+5}_{-7}$
VBF	11.2	$^{+3.4}_{-3.0}$	($^{+2.6}_{-2.4}$	$^{+1.3}_{-1.2}$	$^{+1.9}_{-1.1}$)	8.0 ± 0.2
VH	4.9	$^{+2.7}_{-2.5}$	($^{+2.4}_{-2.2}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$)	4.5 ± 0.2
Top	1.5	$^{+0.6}_{-0.5}$	($^{+0.5}_{-0.4}$	± 0.2	$^{+0.2}_{-0.1}$)	1.3 ± 0.1

H→ZZ

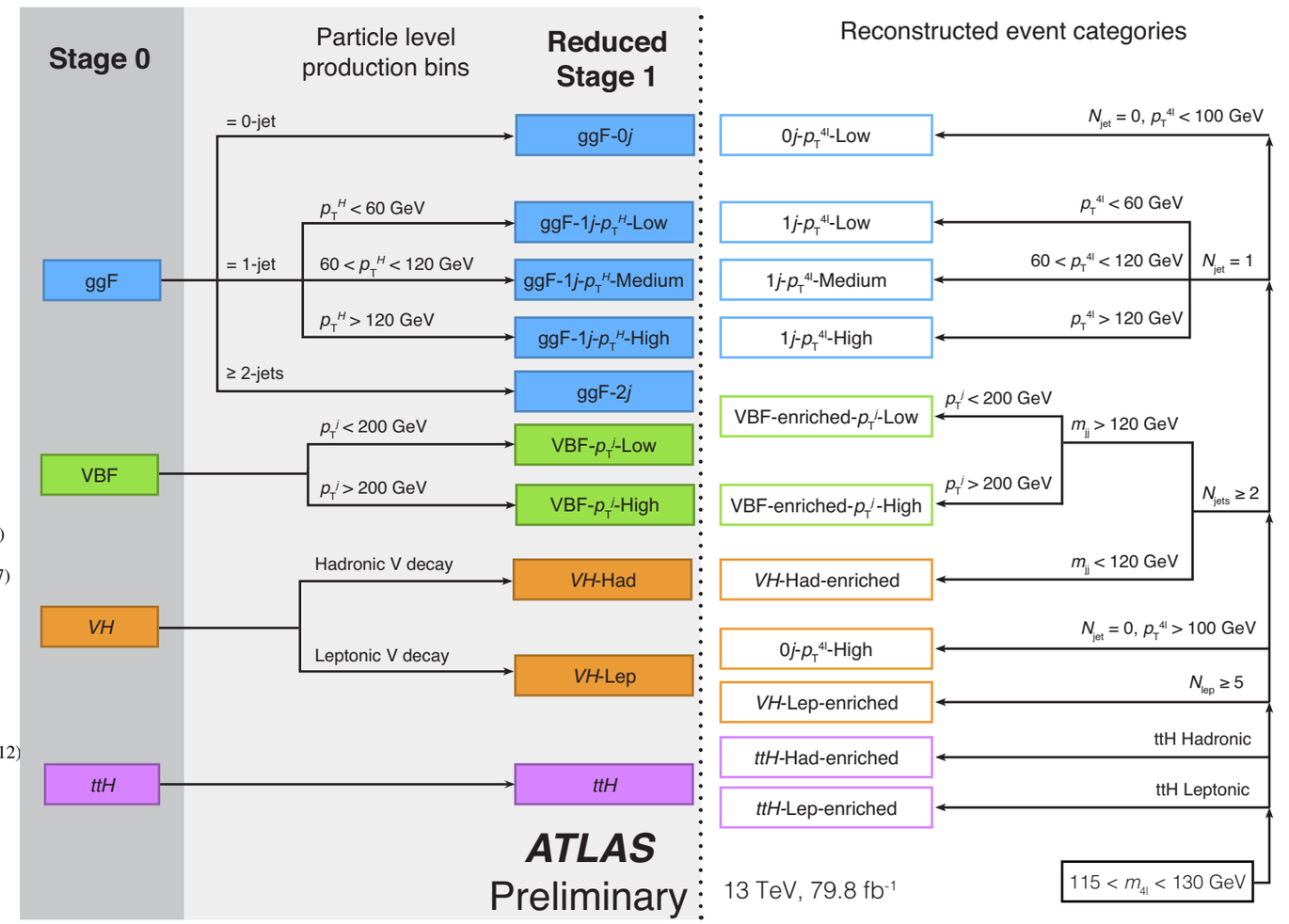
Production bin	Cross section ($\sigma \cdot \mathcal{B}$) [pb] SM expected	Observed	$(\sigma \cdot \mathcal{B})/(\sigma \cdot \mathcal{B})_{\mathrm{SM}}$ Observed
Inclusive production, $\lvert y_H\rvert < 2.5$			
	1.33 ± 0.09	$1.57 \pm 0.16 \pm 0.07 \pm 0.04$	$1.18 \pm 0.12 \pm 0.05 \pm 0.03$
Stage-0 production bins, $\lvert y_H\rvert < 2.5$			
ggF	1.17 ± 0.08	$1.22 \pm 0.17 \pm 0.07 \pm 0.04$	$1.04 \pm 0.14 \pm 0.06 \pm 0.03$
VBF	0.0917 ± 0.0028	$0.25 \pm 0.08 \pm 0.02 \pm 0.01$	$2.8 \pm 0.9 \pm 0.2 \pm 0.2$
VH	$0.0524^{+0.0026}_{-0.0047}$	$0.05 \pm 0.05 \pm 0.01 \pm 0.01$	$0.9 \pm 1.0 \pm 0.1 \pm 0.1$
ttH	$0.0154^{+0.0011}_{-0.0016}$	< 0.07	< 4.04

Event categorization

H→γγ



H→ZZ

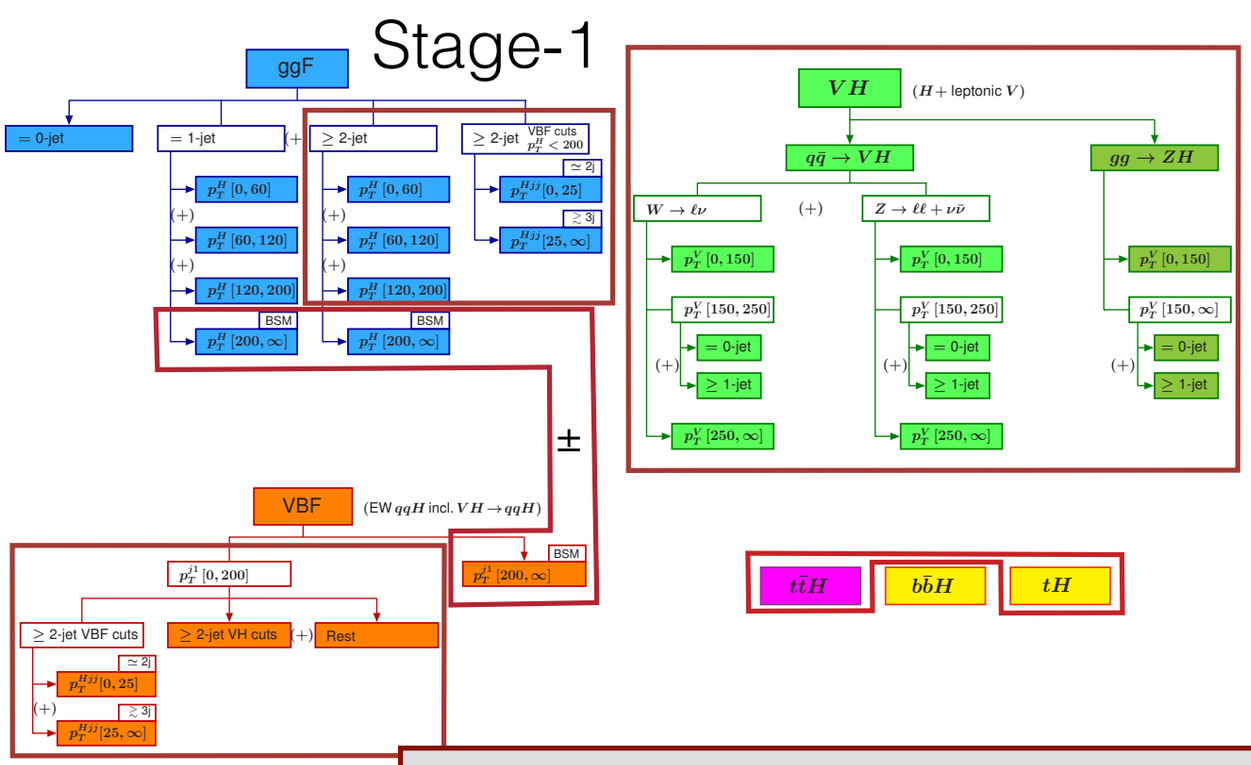


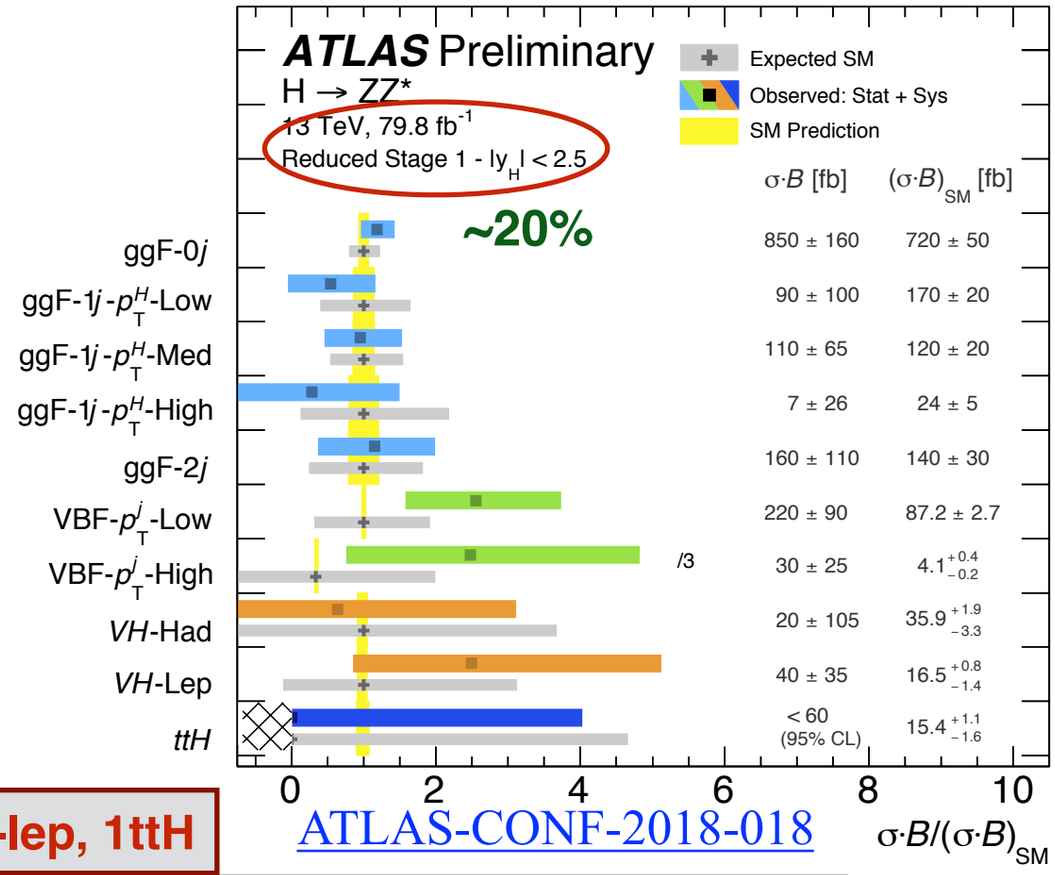
- **Event categories are defined based on kinematic properties of the γγ/4l system + extra particles in the event**
- **Good sensitivity to main production modes / stage-1 regions**

Simplified template cross section (Stage-1)

Less model dependence: separate the theory uncertainties in measurements

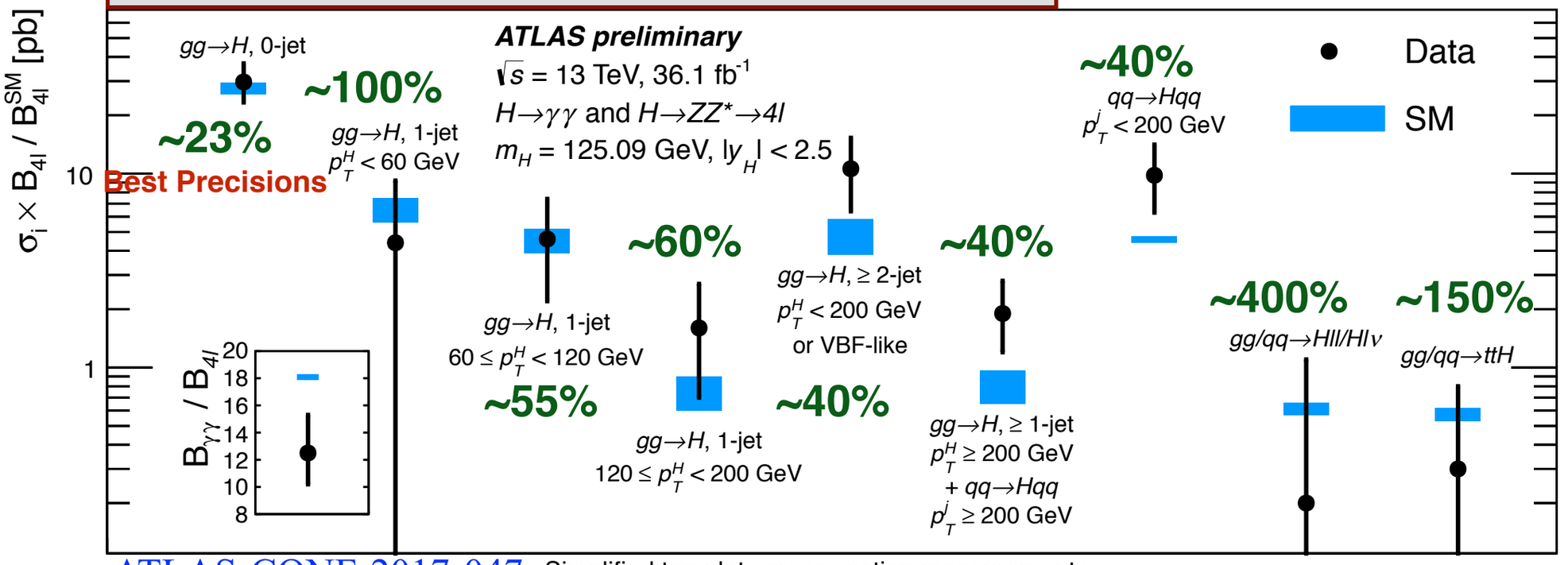
ATLAS preliminary





ATLAS-CONF-2018-018

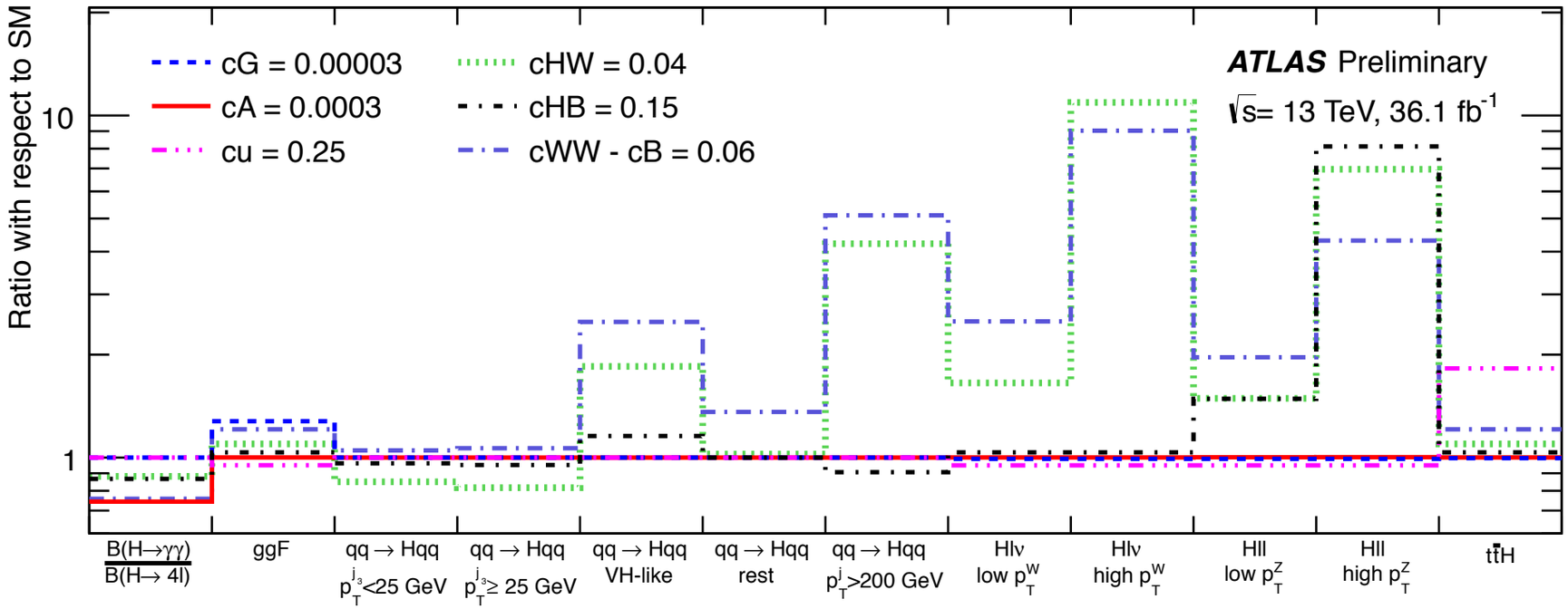
Merged strategy: 5 ggH, 1BSM, 1VF, 1VH-lep, 1ttH



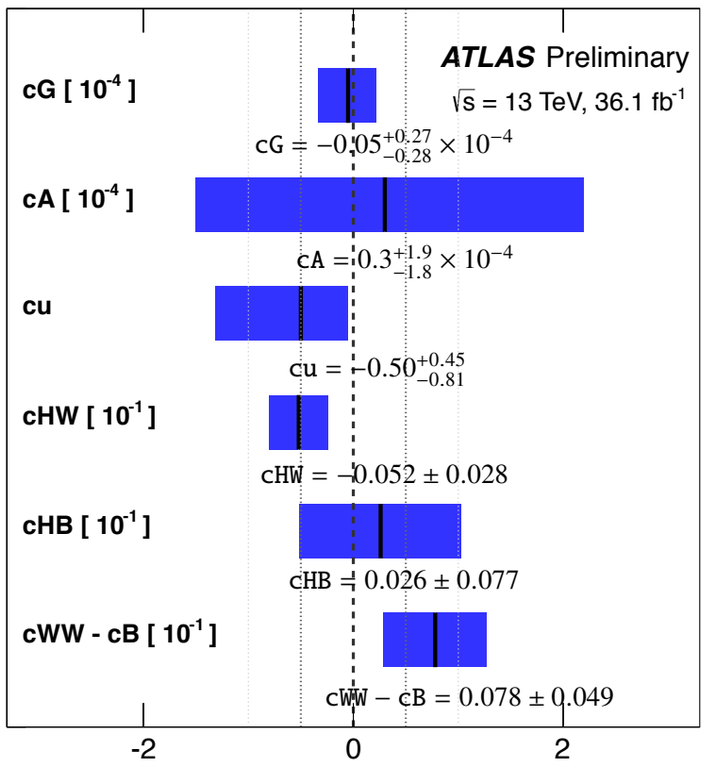
ATLAS-CONF-2017-047 Simplified template cross section measurements

Interpretation with EFT framework

The relationship between EFT parameters and STXS



Observed HEL constraints with $H \to ZZ^*$ and $H \to \gamma\gamma$

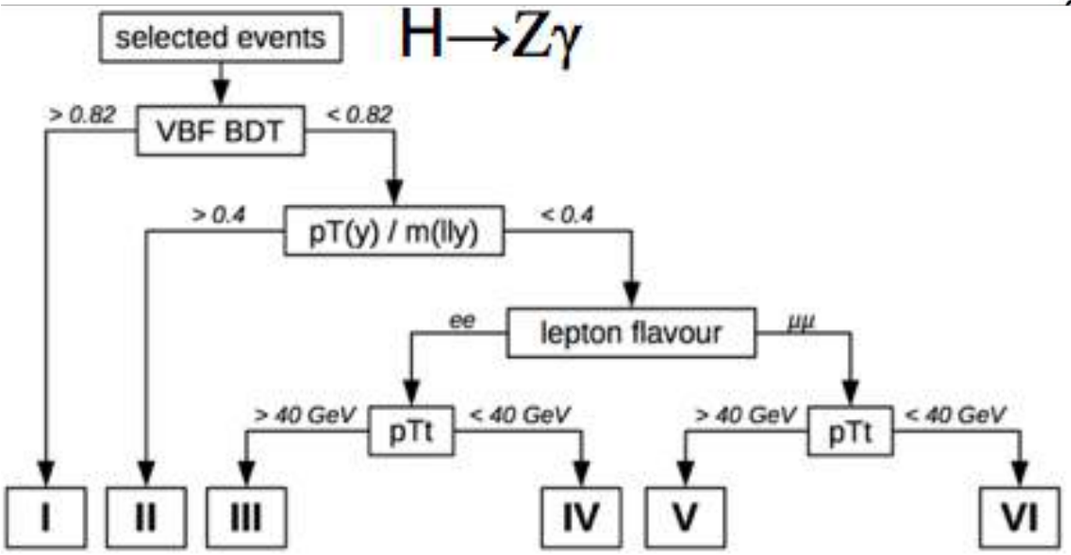


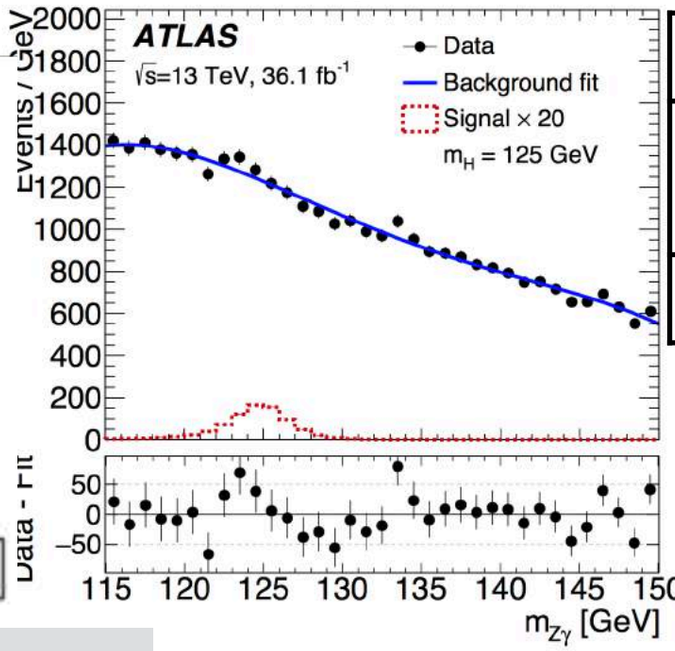
- A general procedure for moving beyond κ framework into a more general EFT framework
- Most stringent constraints on the effective couplings to photons and gluons w.r.t. global fit to data from Tevatron and Run1
- More precise constraint is expected with more measurements and more robust theoretical tools.

ATL-PHYS-PUB-2017-018

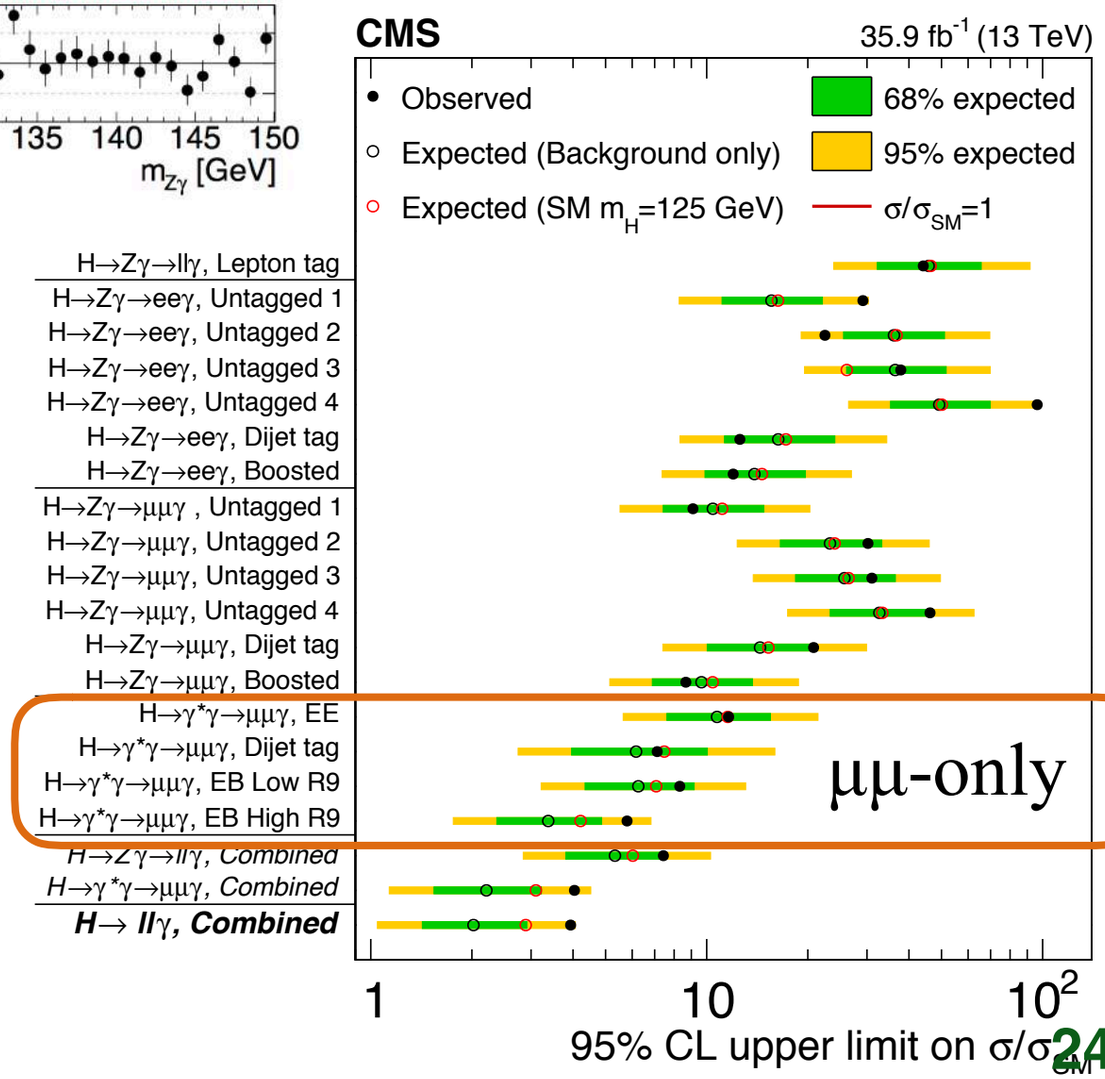
Search for H→Zγ

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

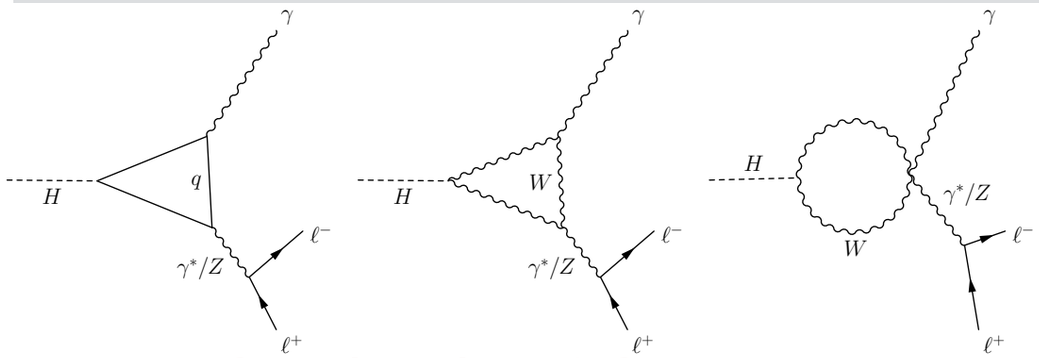




@95%CL	Obs./Exp.
σ(pp→H) ×B(H→Zγ)	6.6/4.4 SM
μ (Run1)	11



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



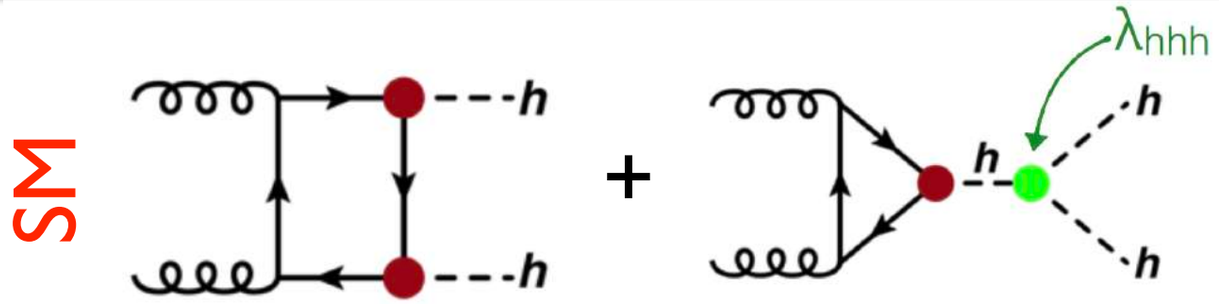
Obs. (Exp.) 95% CL limit

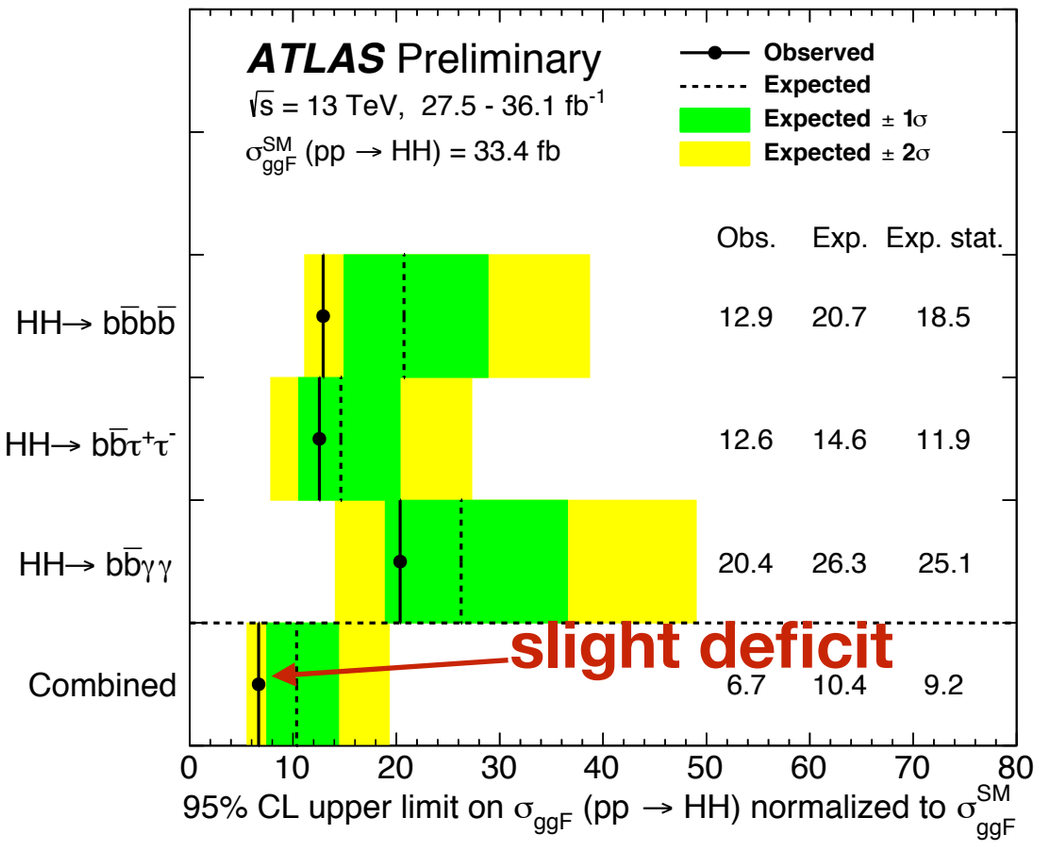
BR(H → Zγ → ℓℓγ) < 8.0 (5.8) x SM

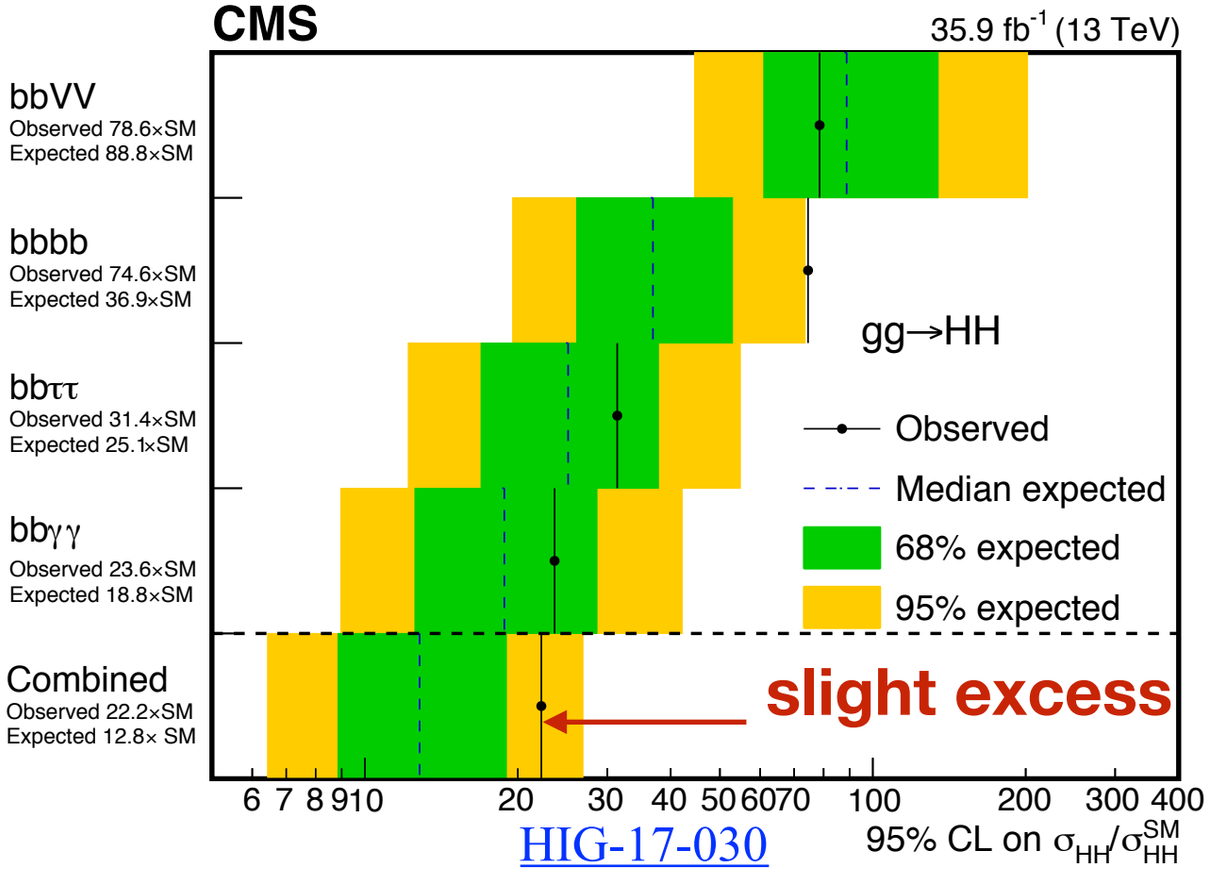
BR(H → γ*γ → ℓℓγ) < 4.0 (2.2) x SM

Combination: σ(pp→H) < 3.9 (2.0) × SM

Di-Higgs search



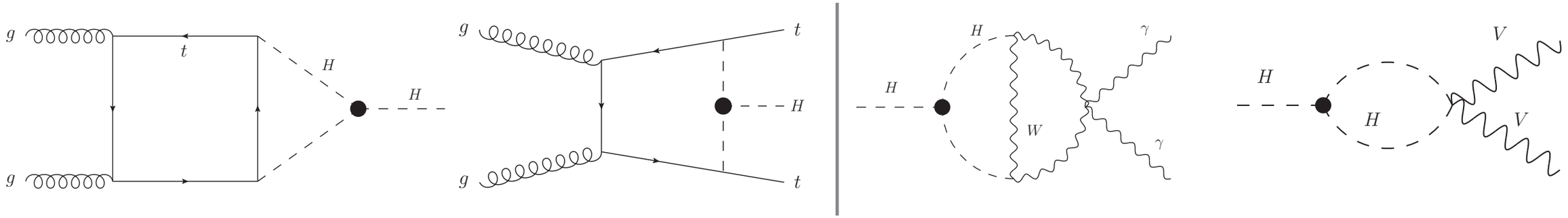




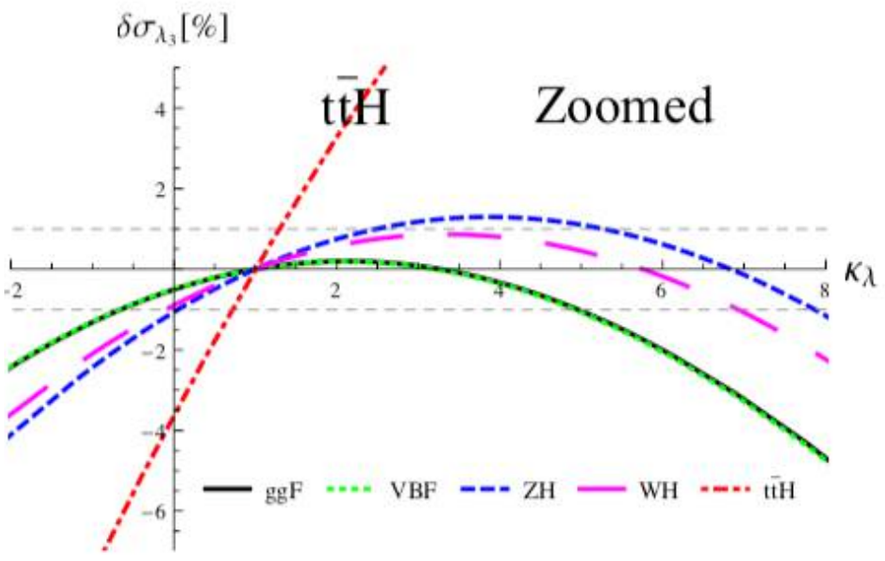
- Getting close to **10*SM rate** for Di-Higgs production
- Constraint on **self-coupling (obs/exp) @ 95% CL:**
  - **ATLAS :** $-7.1<\kappa_\lambda<13.6$ / $-11.8<\kappa_\lambda<18.8$
  - **CMS:** $-5.8<\kappa_\lambda<12.0$ / $-5<\kappa_\lambda<12.1$

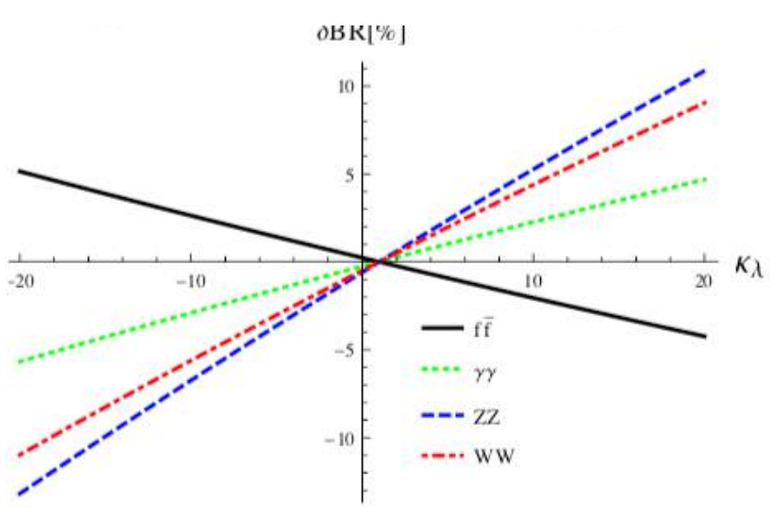
Self-coupling from single Higgs

All the single Higgs production and decay processes are affected by an anomalous trilinear (**not quartic**) Higgs self coupling, parametrized by κ_λ.

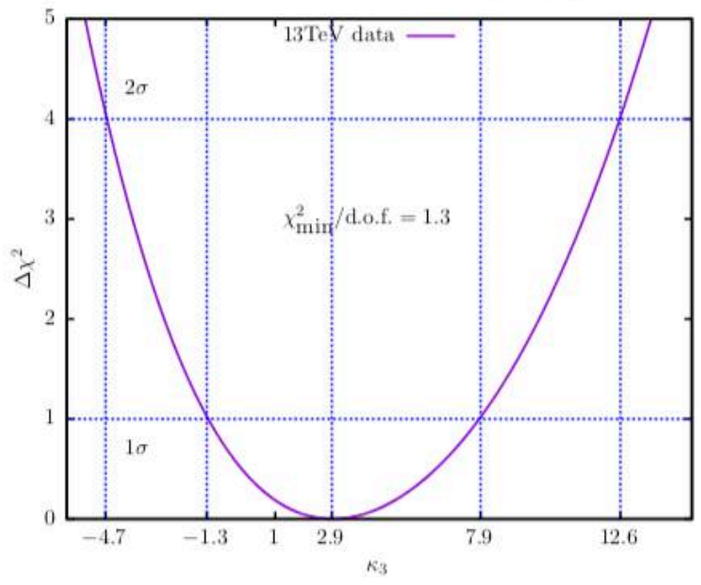


All the different signal strengths μ_i^f have a different dependence on a single parameter κ_λ, which can thus be constrained via a global fit.





Based on HIG-17-031



Enhancement for ttH and H->VV @ small κ_λ

$$\kappa_\lambda^{\text{best}} = 2.9\,, \qquad \kappa_\lambda^{1\sigma} = [-1.3, 7.9]$$

From Davide's talk @ HC2018

Summary

- Main boson decay channels now entering precision era
- **Comprehensive Higgs property measurements:** mass, width, fiducial/differential cross section, simplified template cross section: everything is in good agreement with SM
- Still missing: Zγ (current limit σ*BR < 6*SM with 36fb-1)
- Run-2 data collection was done. It is promising in the next year.