Recent Results and Future Prospects of Higgs Physics at the LHC

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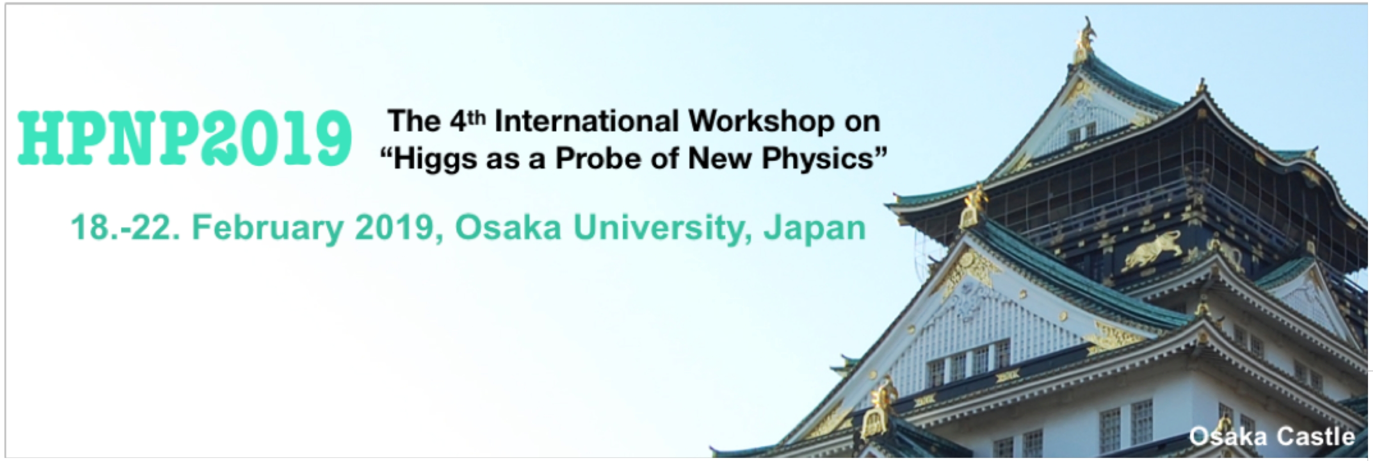

東京大学
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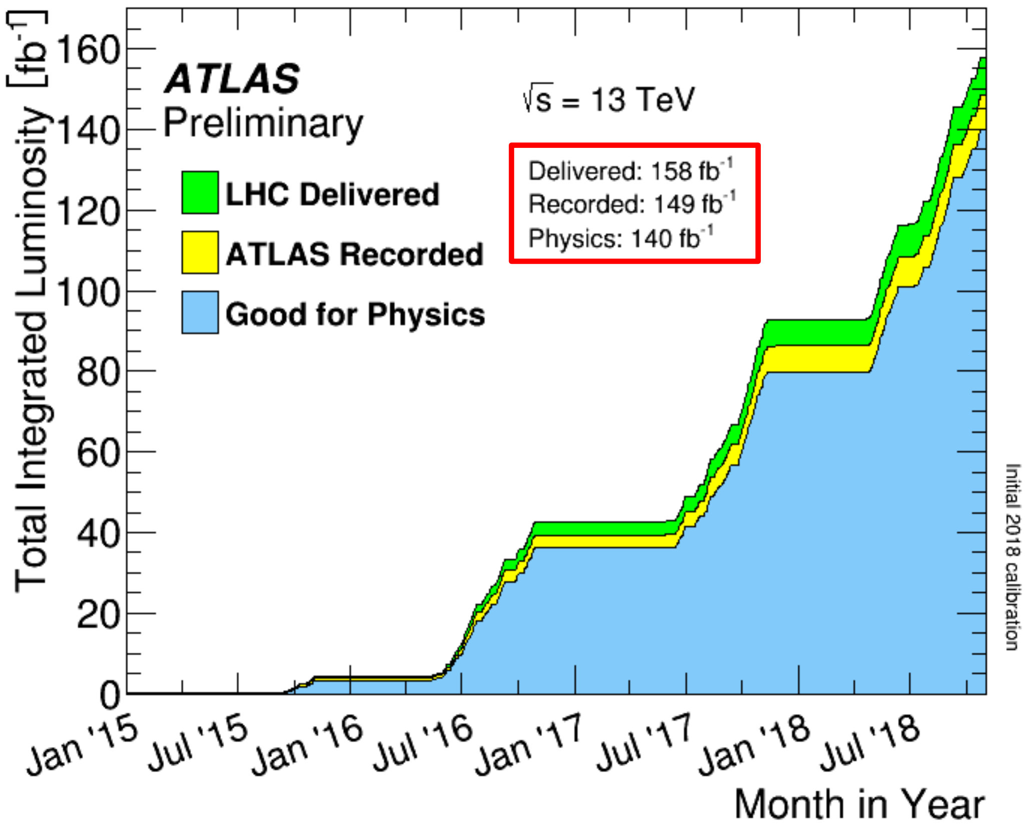
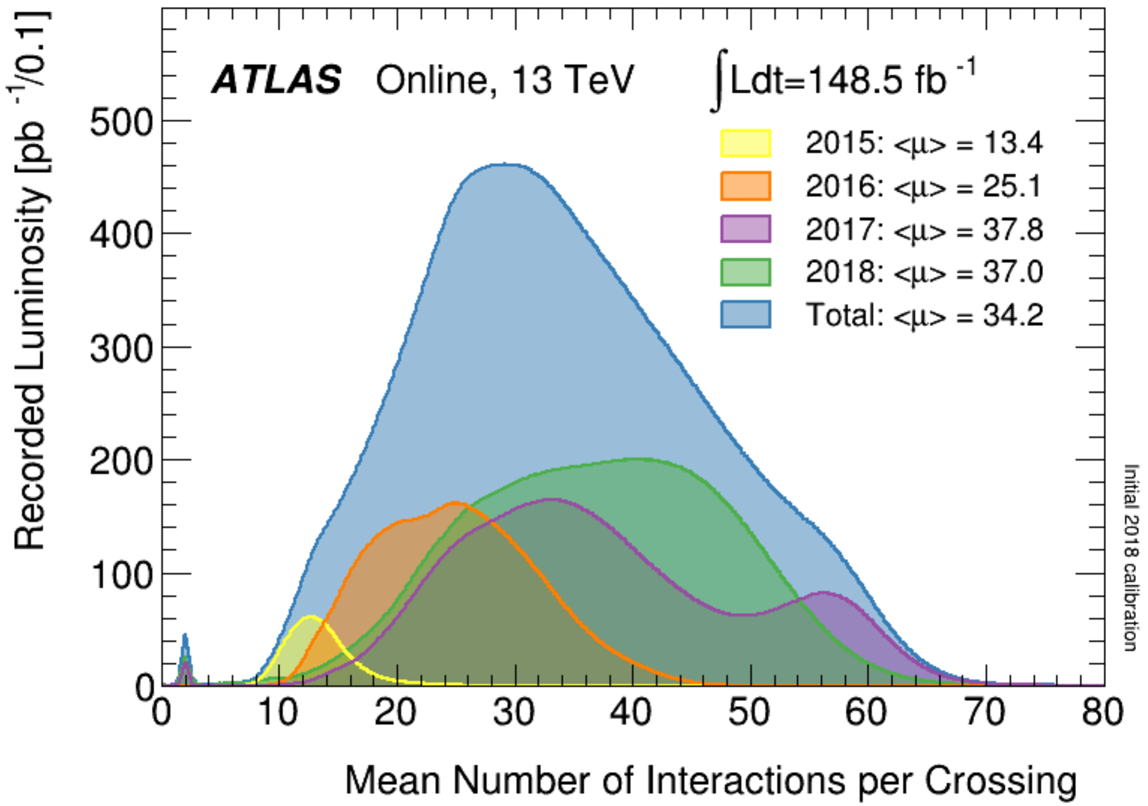
ATLAS EXPERIMENT

CMS Compact Muon Solenoid

LHC Run2 Status

- LHC Run2 physics program successfully finished in 2018!!
- ATLAS and CMS recorded ~150fb^{-1} (**140fb^{-1} for physics**) at s=√13 TeV



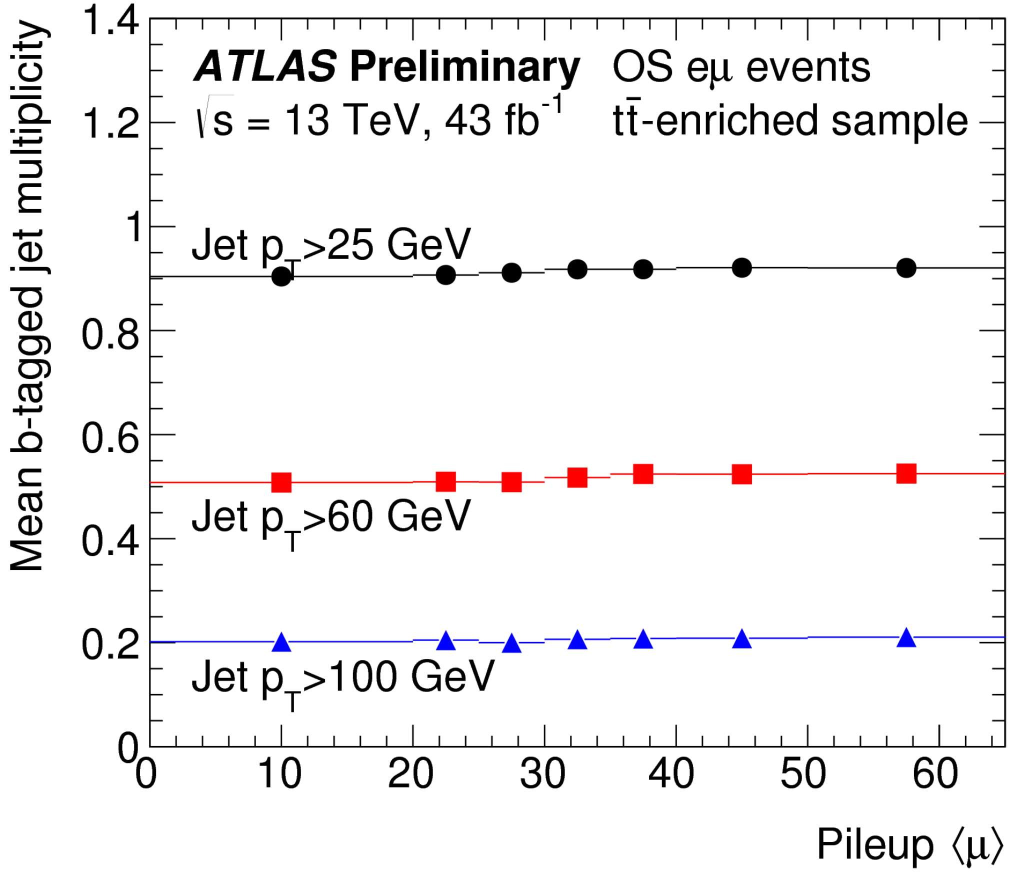


Pile-up increased significantly ➔ Severe condition for experiment (higher trigger rate, performance degradation)

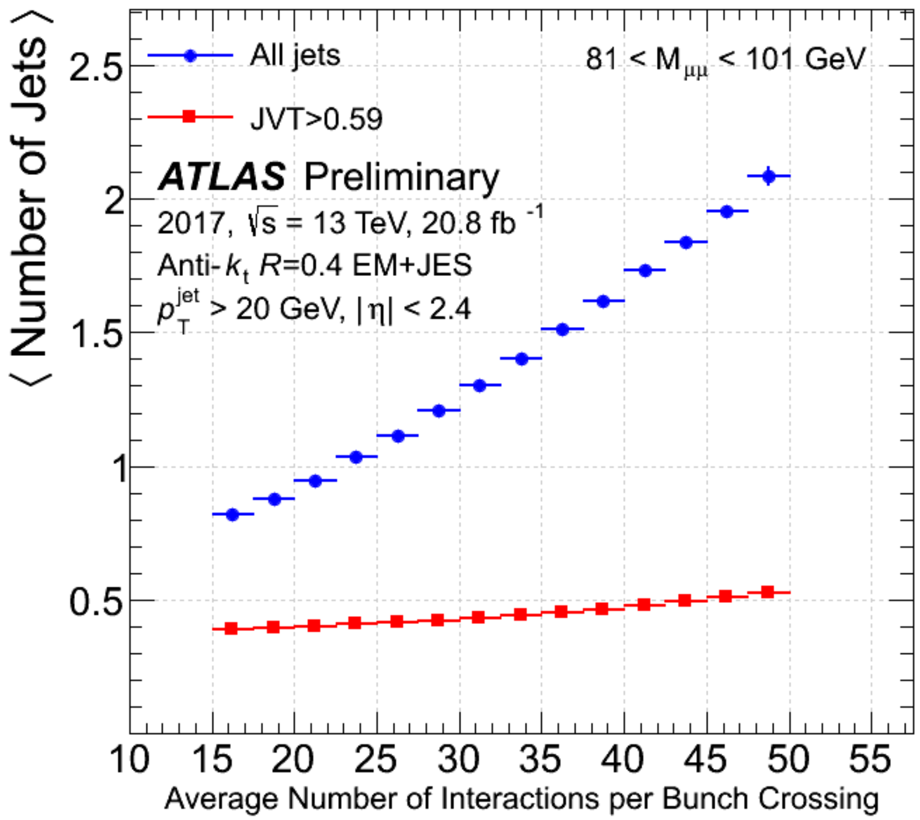
Highlight of Experimental Performance

- Physics object performances are under control in <μ> 50~60!!

b-tagging efficiency

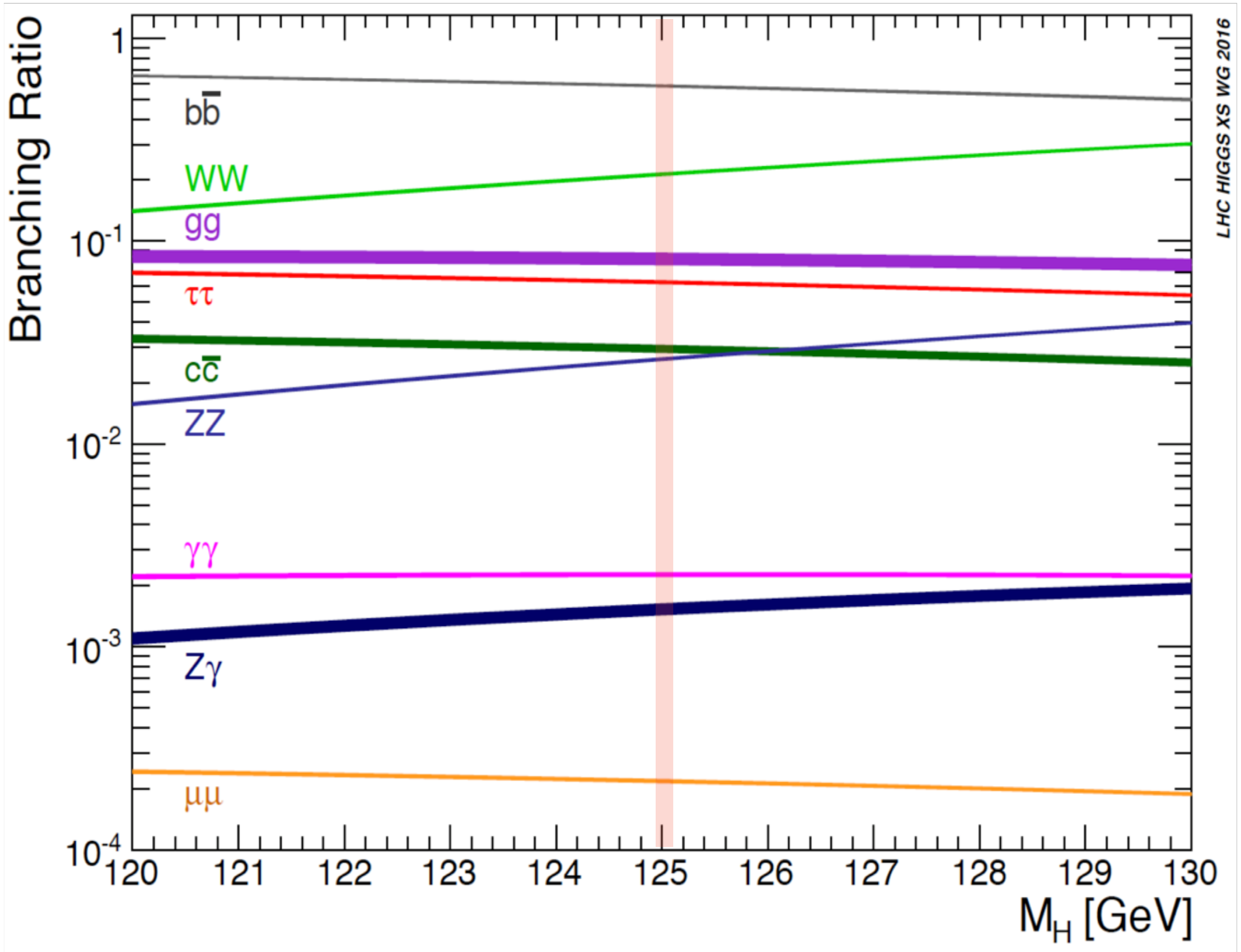


pile-up jet mitigation



Higgs Decay Branching Ratio

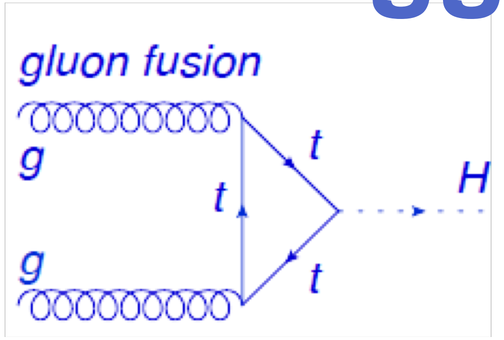
125 GeV Higgs is "miracle" → Accessible to various decay modes!!

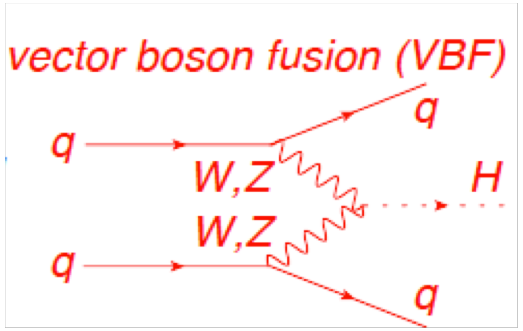


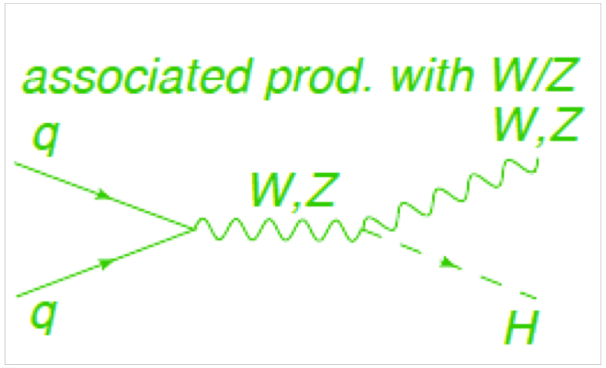
	Branding Ratio @ 125 GeV	
H→WW	21.4%	Observed in Run1 (clean final state)
H→ZZ	2.62%	
H→γγ	0.23%	
H→ττ	6.27%	
H→bb	58.2%	Observed in Run2
H→cc	2.89%	Run3 - HL-LHC
H→μμ	0.022%	
H→Zγ	0.015%	

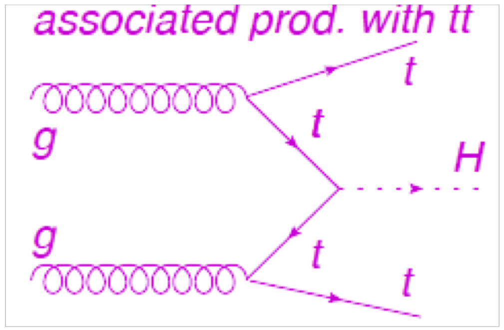
Reaching more difficult and lower decay mode

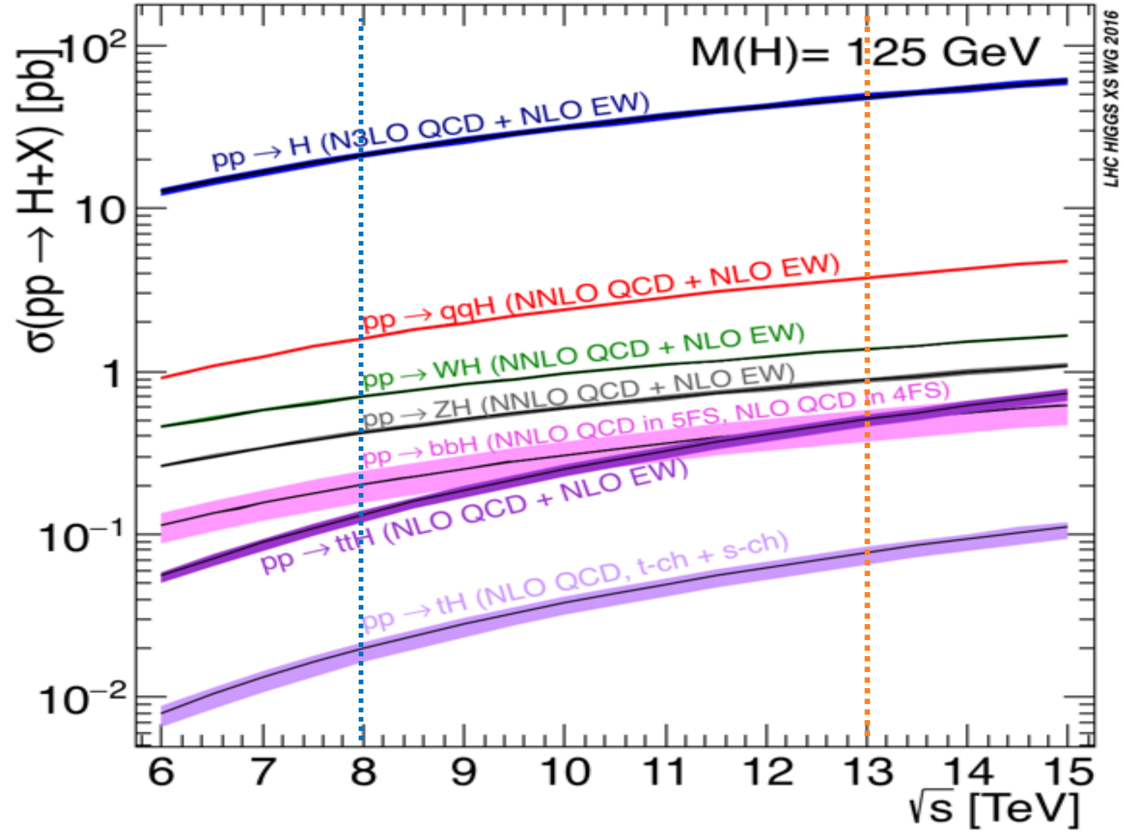
Higgs Production at LHC











	Production Cross Section
ggF	49pb
VBF	3.8pb
WH	1.3pb
ZH	0.88pb
ttH	0.51pb

Observed in Run1 (bosonic, ττ decay mode) (ggF, VBF)

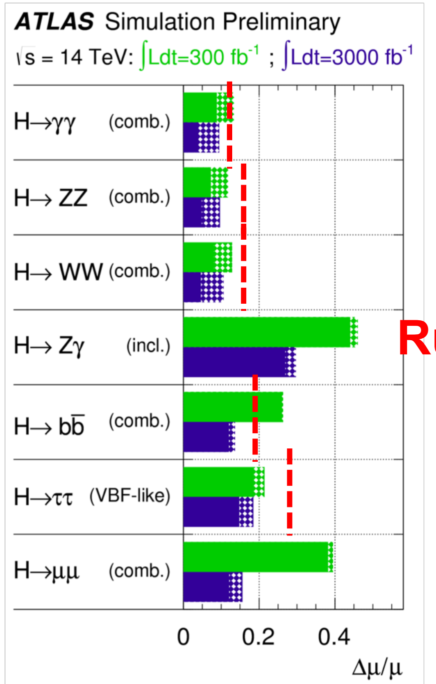
Observed in Run2 (WH, ZH, ttH)

Reaching more difficult and lower production channels

Outline

- **Run2 achievements (so far)**
  - Higgs Yukawa sector
  - Higgs precise measurement
    - Cross section measurement (inclusive/differential, “simplified template cross section”)
    - Coupling measurement (combination)
  - Higgs-pair production
  - BSM Higgs search
- **HL-LHC Prospect**
  - 125 GeV Higgs boson measurement
  - Higgs-pair production
  - BSM Higgs Search

	ggF	VBF	VH	ttH
H→WW	★	★	✔	✔
H→ZZ	★	✔	✔	✔
H→γγ	★	✔	✔	★
H→ττ	✔	★	✔	✔
H→bb	✔	✔	★	✔
H→cc			✔	
H→μμ	✔	✔		



Extrapolation based on Run1 analysis

Run2 results

Pessimistic!!

Outline

	ggF	VBF	VH	ttH
H→WW	★	★	✔	✔

- **Run2 achievements (so far)**

A lot of Higgs (Search/Measurement) results in Run2

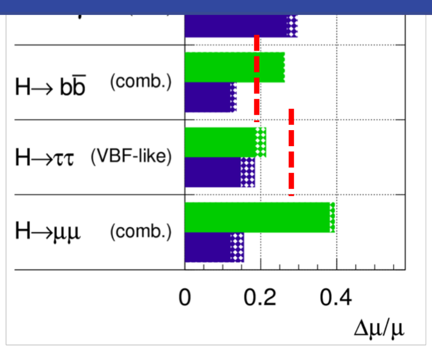
✓ Main results using 36fb^{-1} or 80fb^{-1} (up to 2017 data)

➔ Full Run2 results (~140fb^{-1}) will come soon

✓ HL-LHC Prospect are updated based on improved Run2 analysis

Impossible to cover all results (show selected(biased) results)

- Higgs-pair production
- BSM Higgs Search

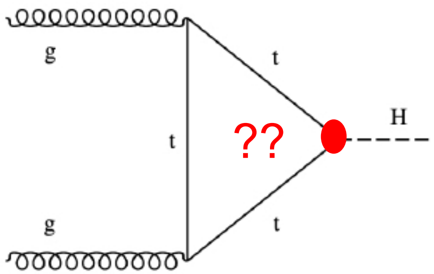


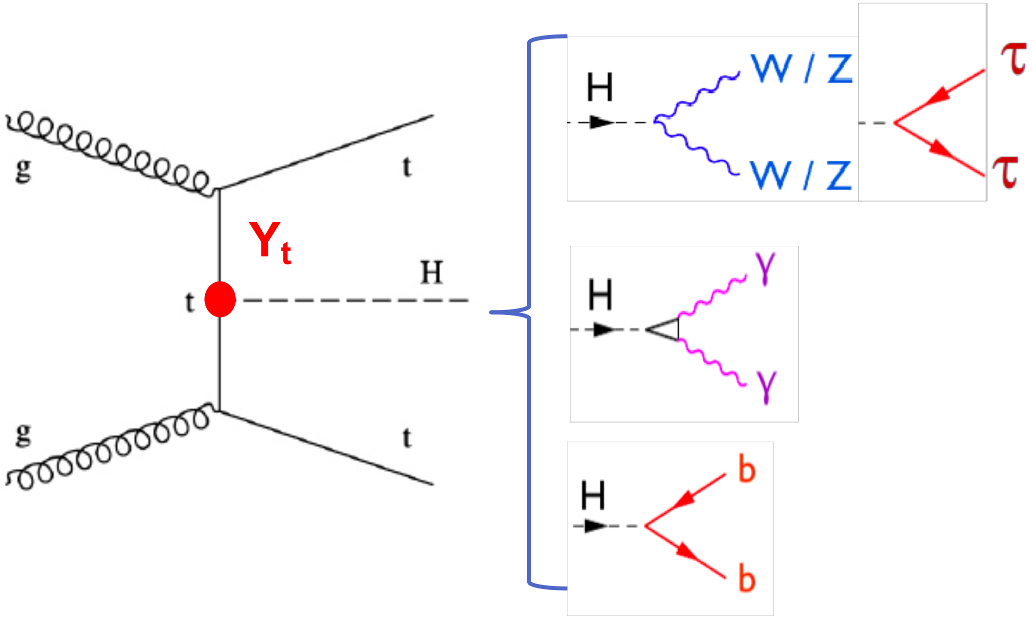
Pessimistic!!

Run2 Recent Results
(Higgs-Yukawa Sector)

Search for ttH Production

- Provide direct top-Yukawa interaction
- 13 TeV ttH cross section is ×3.8 higher than 8 TeV
- Experimentally final state is quite complex (ttH→WbWb+Higgs decay product)





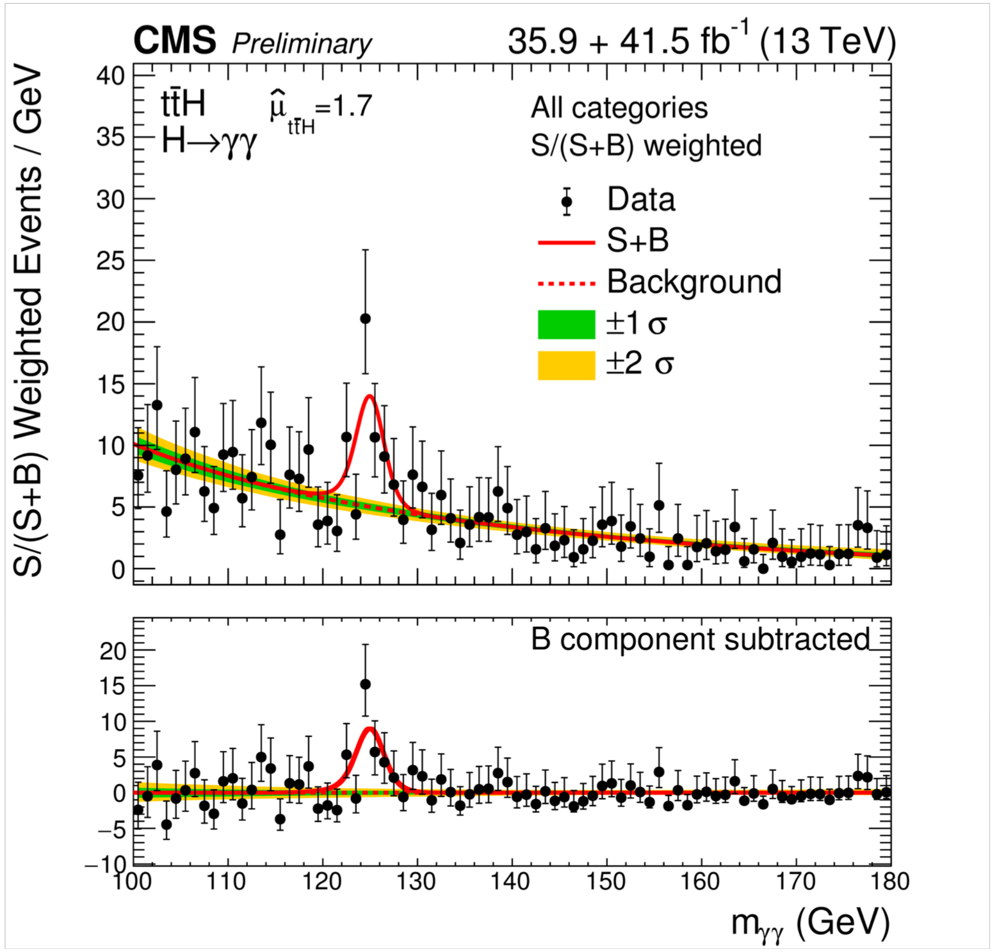
Various Higgs decay modes used

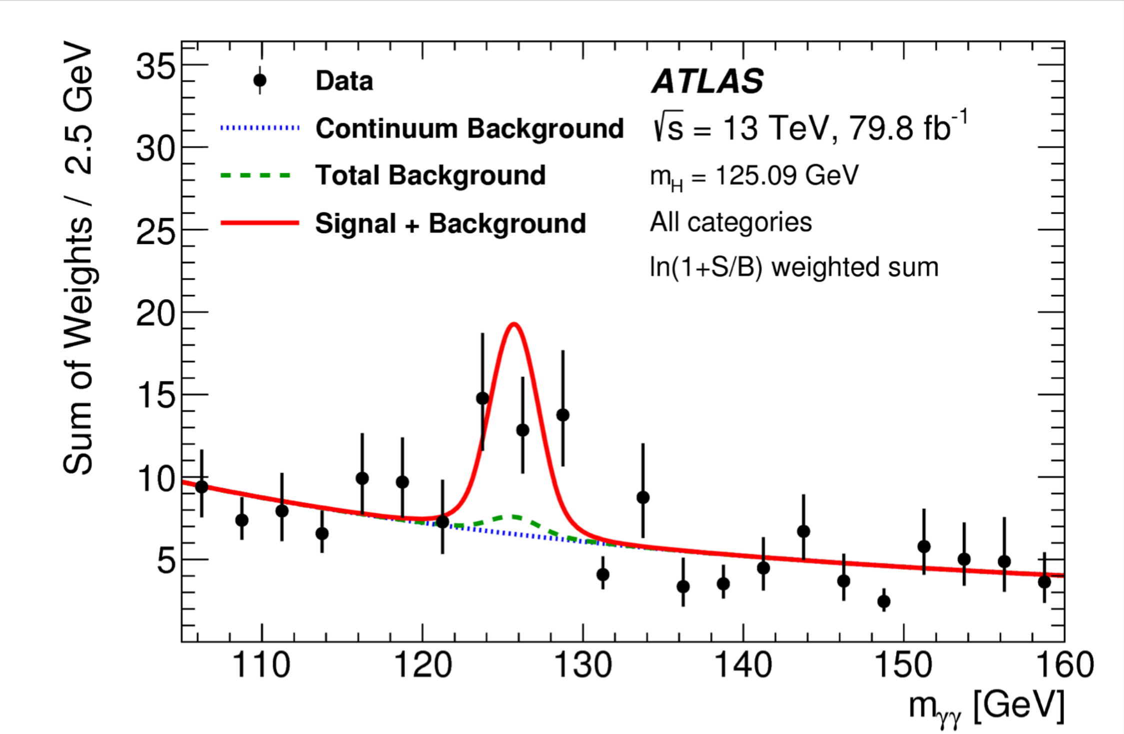
✓ H→WW/ZZ/ττ (multi-lepton)
  ✓ Use leptonic decay from W/Z or τ
    ➔ Relatively clean
  ✓ Difficult to reconstruct m_H
✓ H→γγ (Golden channel)
  ✓ Clear m_H peak can be observed
  ✓ Statistics is quite limited
✓ H→bb
  ✓ High statistics
  ✓ Difficult to reconstruct m_H due to wrong b-jet assignment
  ✓ tt+HF bkg modeling is extremely difficult

Search for ttH Production

$$\mu = \frac{(\sigma \times BR)_{meas}}{(\sigma \times BR)_{SM}}$$

- **H→γγ : ATLAS, CMS update with 80fb^{-1}**
  - ✓ ttH events categorized by number of lepton (ttH Had, ttH Lep)
  - ✓ MVA(BDT) performed for each category to discriminate from non-ttH background



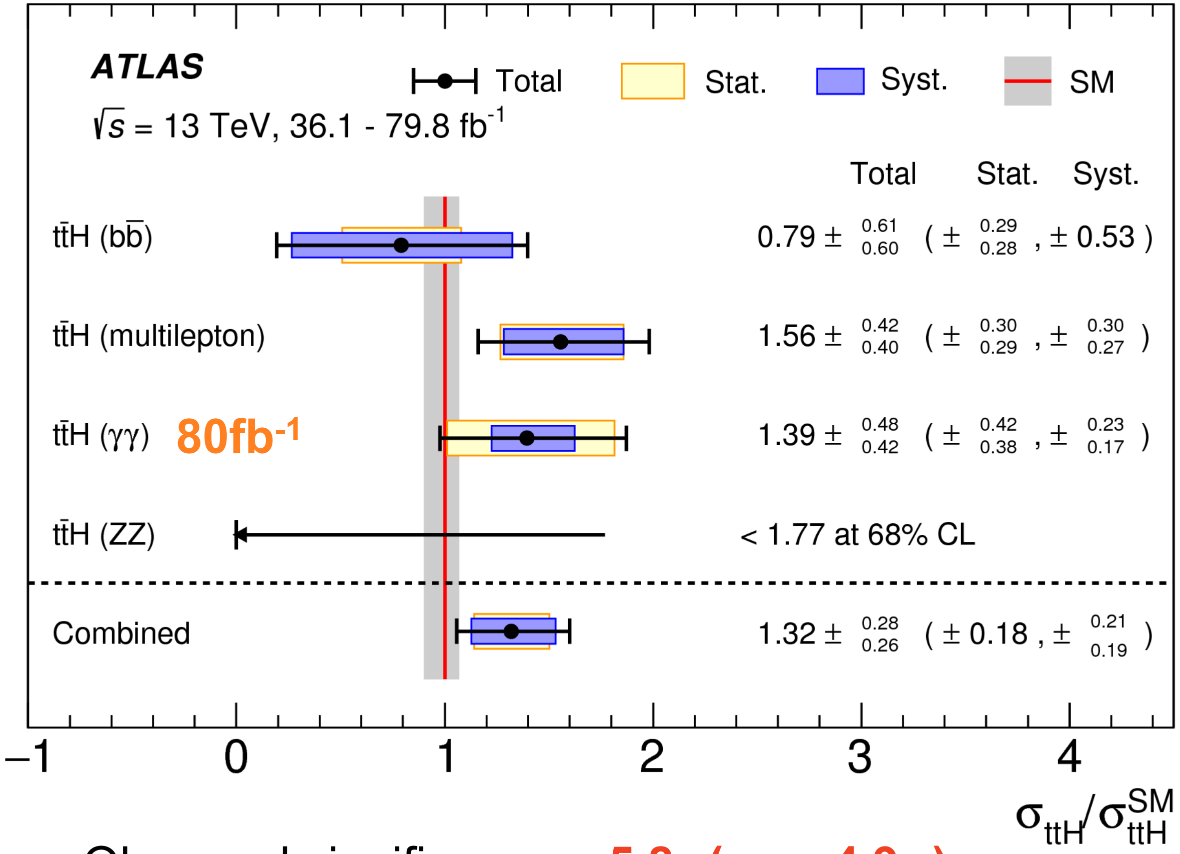


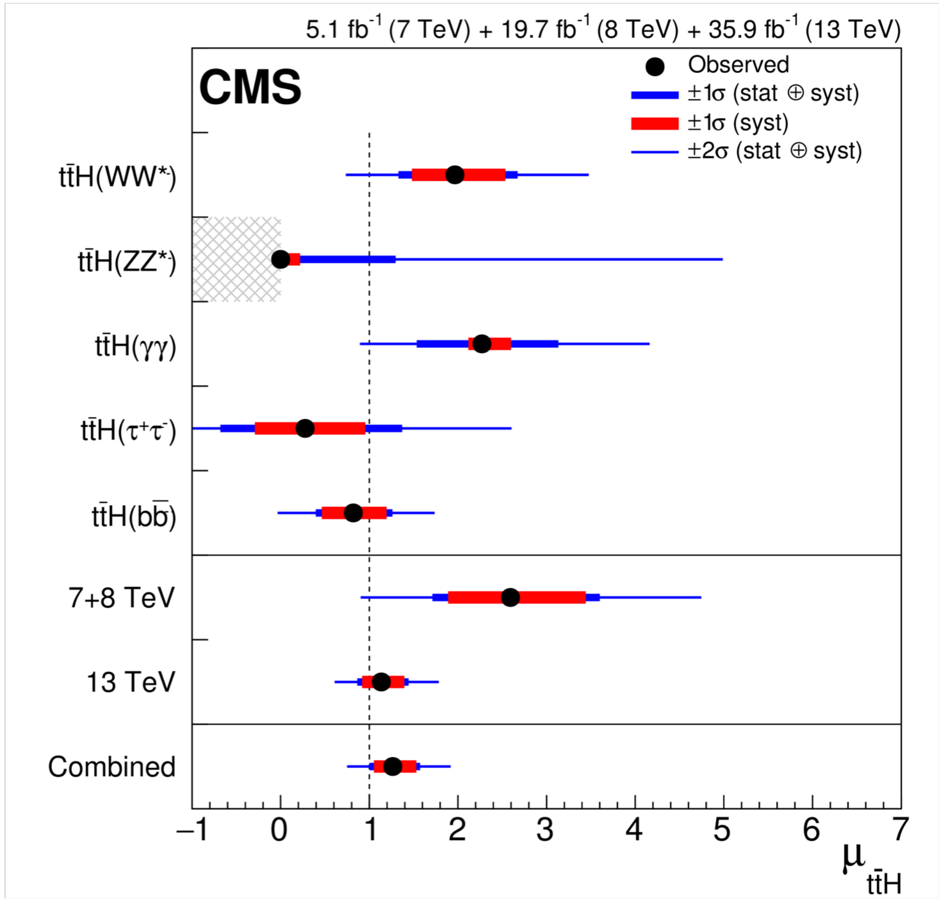
CMS $\mu_{\mathrm{ttH}} = 1.7^{+0.6}_{-0.5}$ **Obs. significance 4.1σ** (exp. 2.7σ)
ATLAS $\mu_{\mathrm{ttH}} = 1.4^{+0.5}_{-0.5}$ **Obs. significance 4.1σ** (exp. 3.7σ)
Sensitivity is still statistically limited

ttH Observation in Run2

- Combined all decay modes
  - ttH→γγ : statistically limited
  - ttH ML, ttH→bb : systematically limited

*ttH ML, ttHγγ 80fb^{-1} not included





Observed significance : **5.8σ(exp. 4.9σ)**
signal strength : $1.32^{+0.28}_{-0.26}$

Observed significance : **5.2σ(exp. 4.2σ)**
signal strength : $1.26^{+0.31}_{-0.26}$

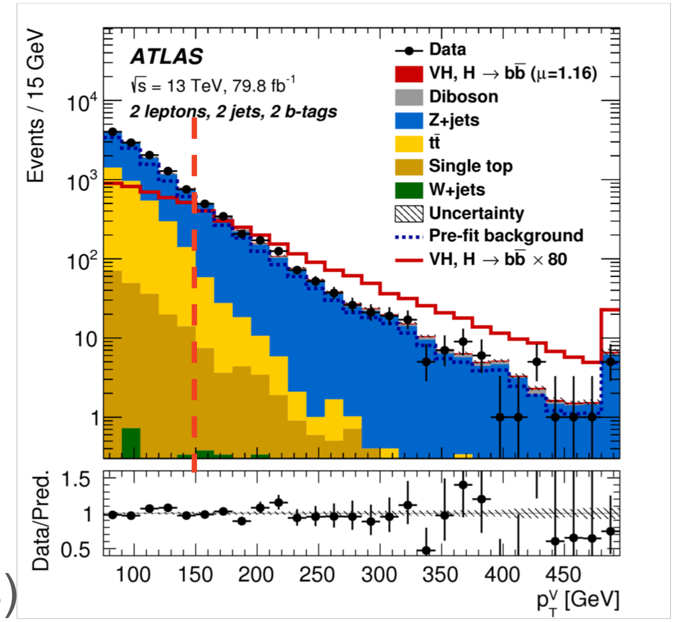
Both experiments observed slightly high signal strength (~still 1σ level)

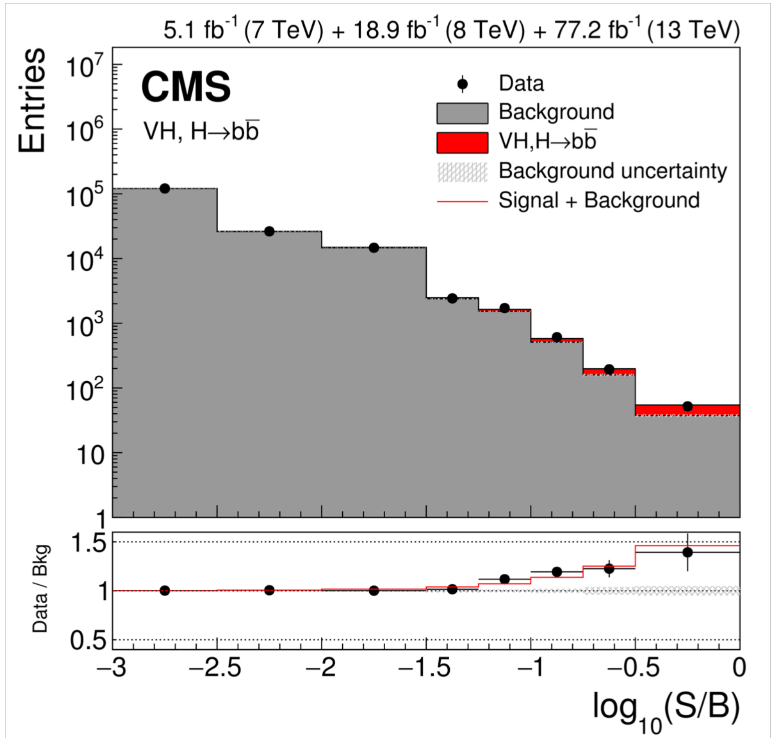
H→bb Measurement

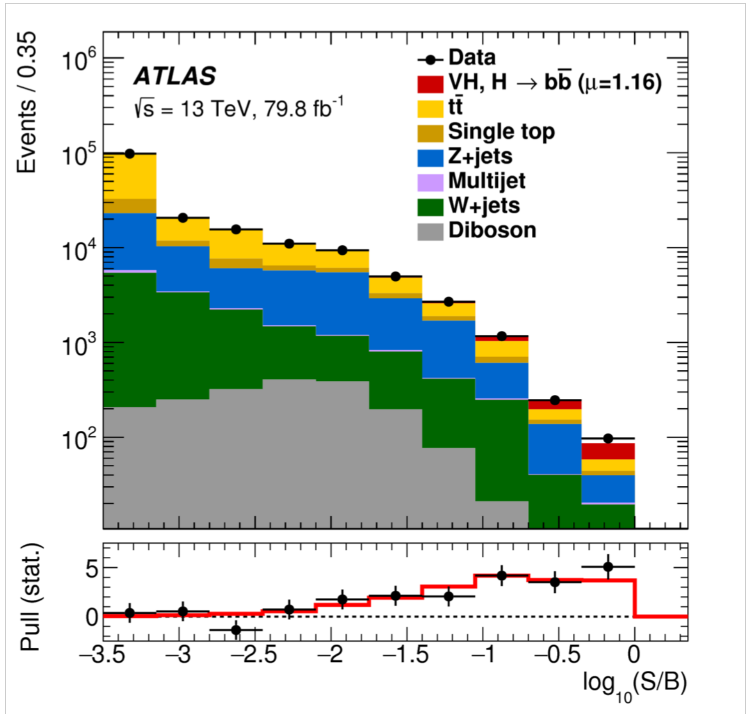
- VH channel is most sensitive for H→bb measurement
  - Lepton from weak boson can eliminate huge QCD background, make trigger easy (lepton and MET trigger)
  - Sensitive to High-p_T^V region (higher S/B)

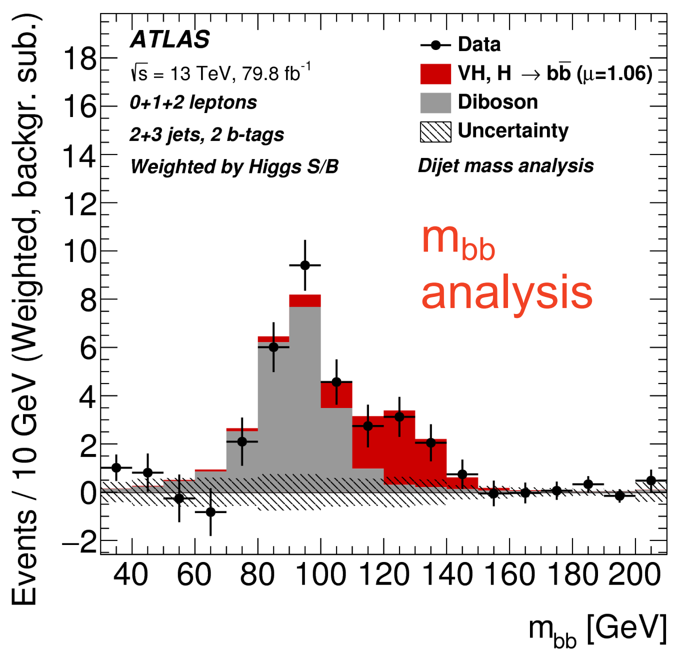
p_T^V	0lep	1lep	2lep	
ATLAS	>150 GeV	>150 GeV	75-150 GeV	>150 GeV
CMS	>170 GeV	>150 GeV	50-150 GeV	>150 GeV

  - MVA discriminants used to extract signal (m_{bb}, p_T^V, m_{top} and jet kinematics)



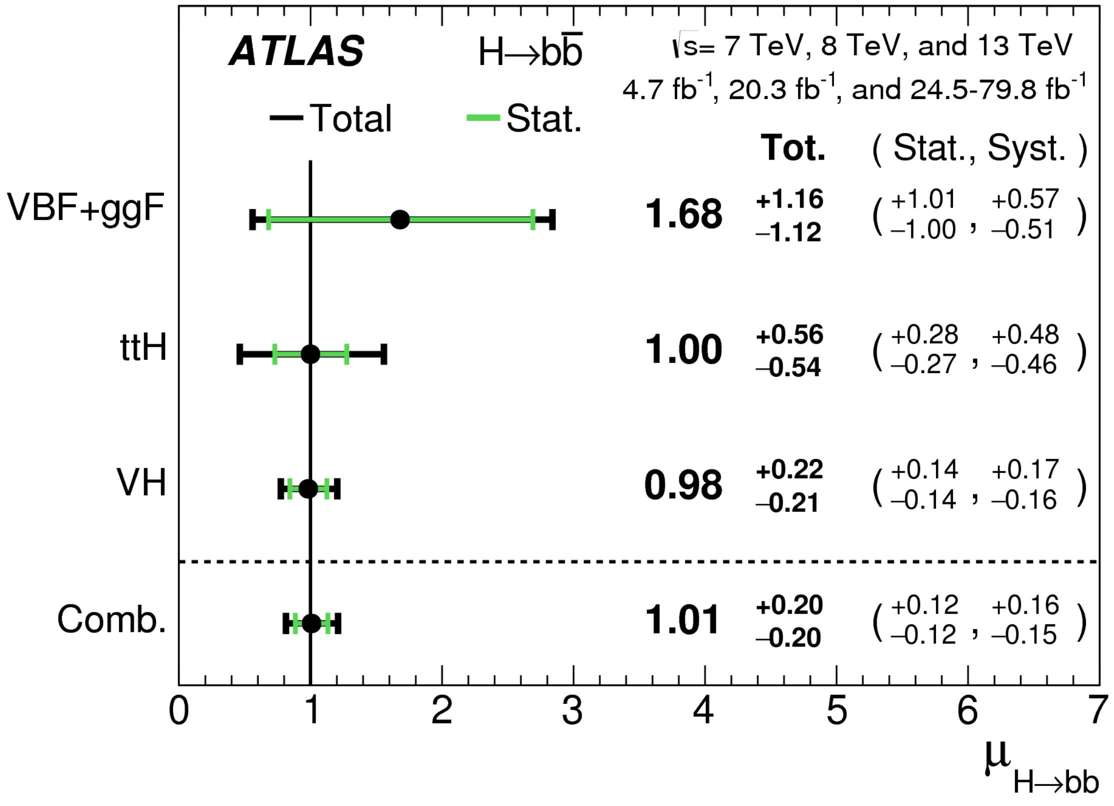


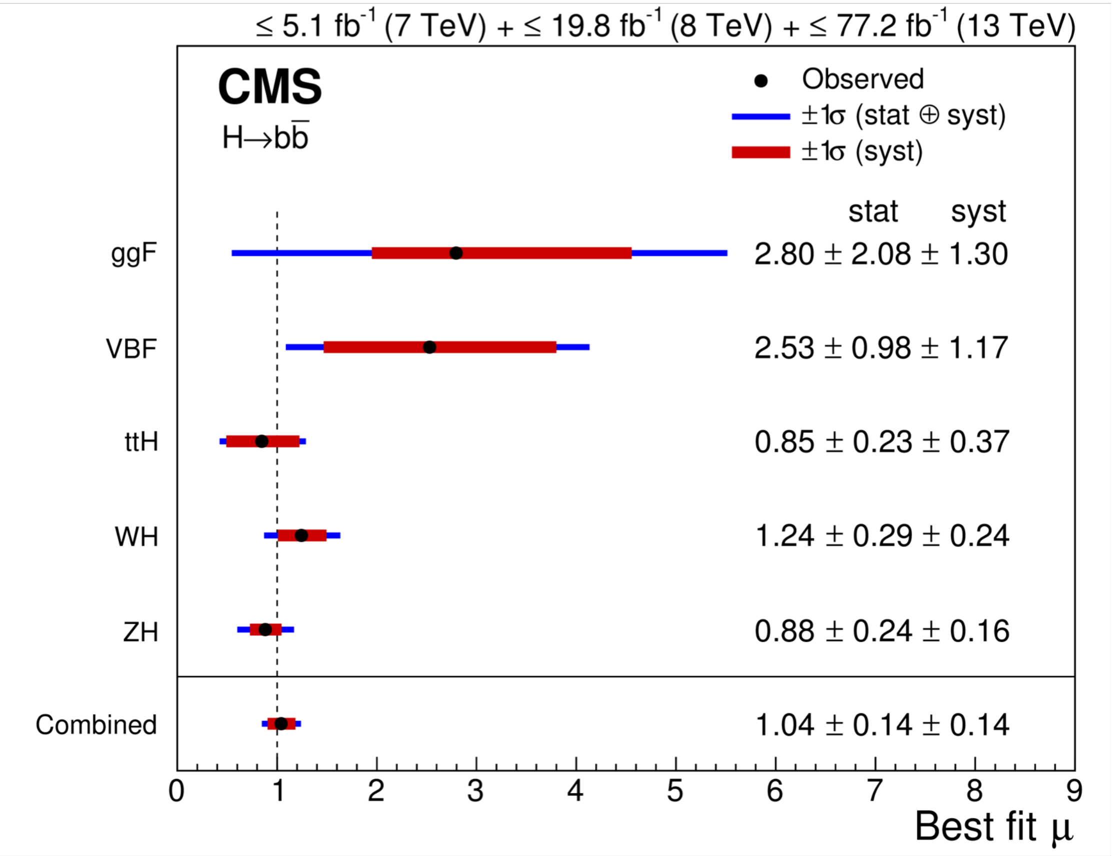




H→bb Observation

- Both experiments combined other production modes
- Sensitivity is quite similar



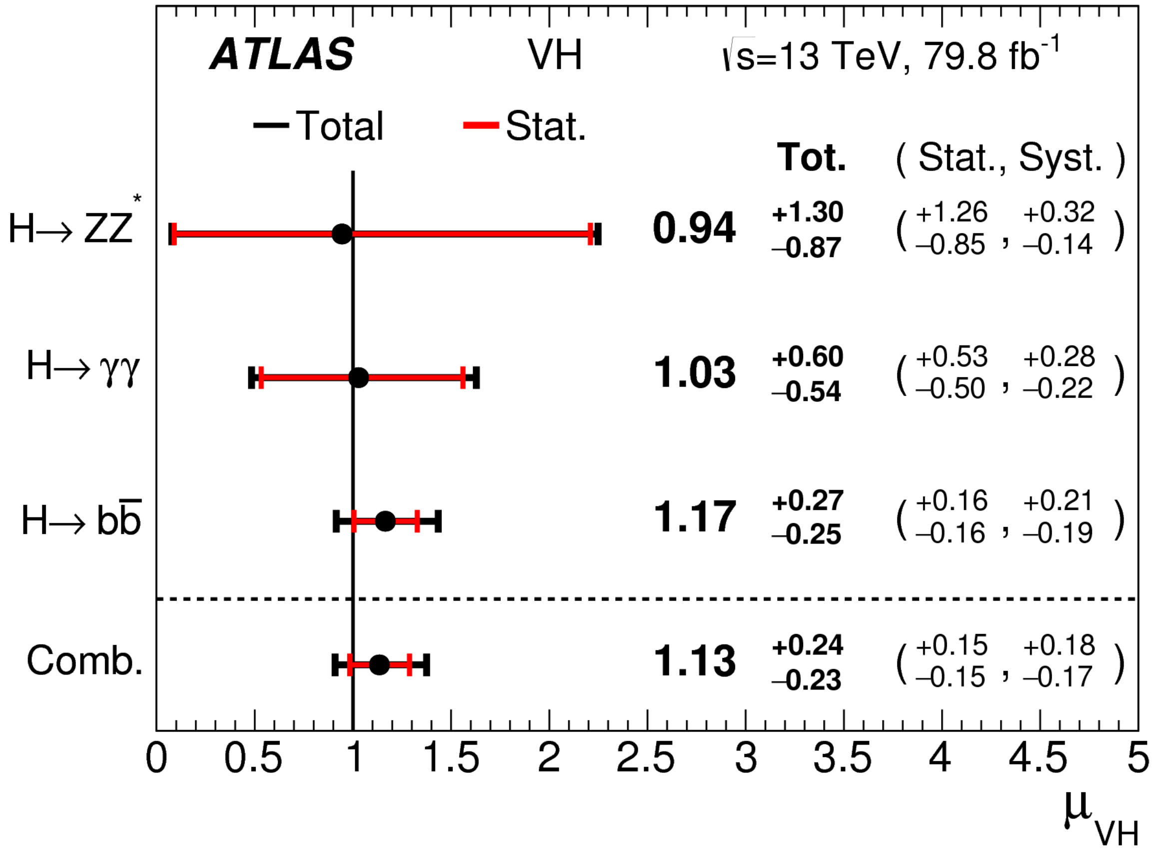


Observed significance **5.4σ (5.5σ)**
Signal strength **$\mu=1.01\pm0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$**

Observed significance **5.4σ (5.5σ)**
Signal strength **$\mu=1.04\pm0.14(\text{stat.})\pm0.14(\text{syst})$**

VH Production Observation

- ATLAS claims an observation of VH production mode
  - Combined with H→ZZ, H→γγ

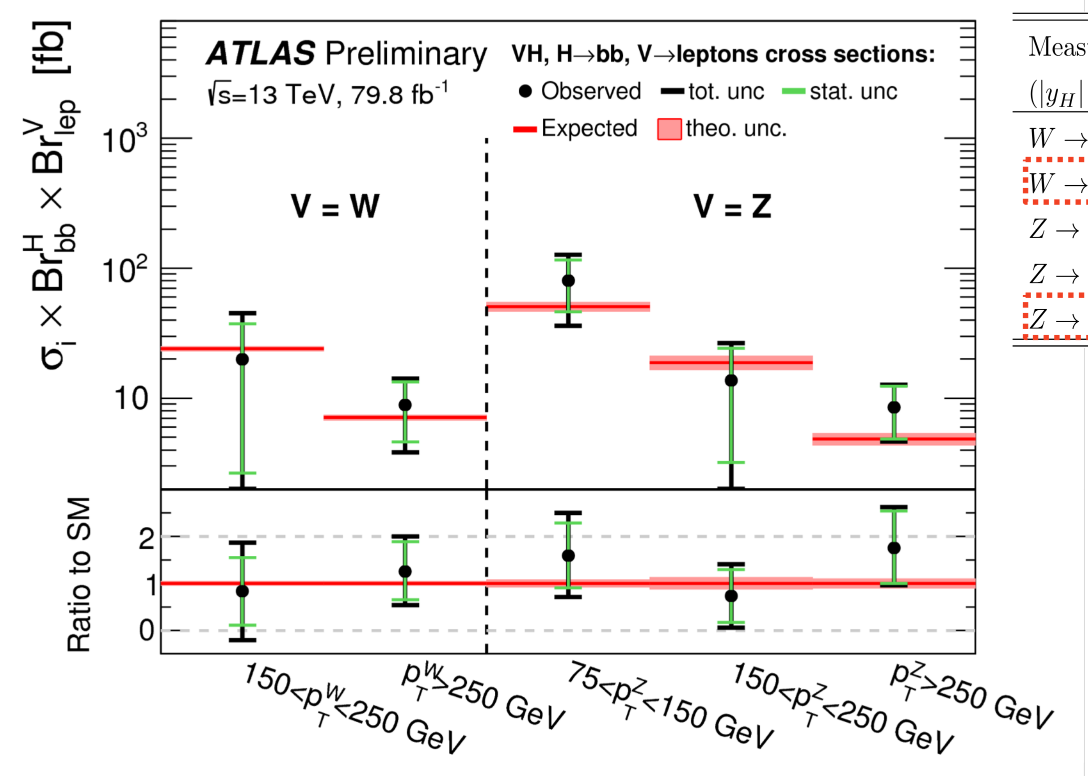


Observed significance **5.3σ (exp. 4.8σ)**

Channel	Significance Exp.	Significance Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3

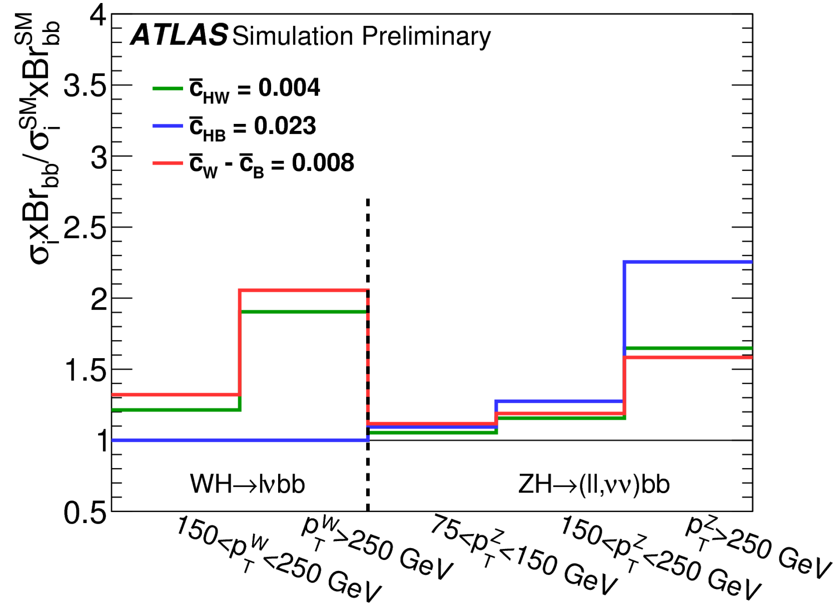
VH Cross Section Measurement

- ATLAS measured "differential" cross section in the context of Simplified Template Cross Section (STXS)



Measurement region ($|y_H| < 2.5$, $H \to b\bar{b}$)	SM prediction [fb]			Result [fb]			Stat. Unc. [fb]		Syst. Unc. [fb] Th. Sig.		Th. Bkg.		Exp.	
$W \to l\nu, 150 < p_T^V < 250$ GeV	24.0	±	1.1	20	±	25	±	17	±	2	±	13	±	9
$W \to l\nu, p_T^V > 250$ GeV	7.08	±	0.34	8.8	±	5.2	±	4.4	±	0.5	±	2.5	±	0.9
$Z \to ll, \nu\nu, 75 < p_T^V < 150$ GeV	50.6	±	4.1	81	±	45	±	35	±	10	±	21	±	19
$Z \to ll, \nu\nu, 150 < p_T^V < 250$ GeV	18.8	±	2.4	14	±	13	±	11	±	1	±	6	±	3
$Z \to ll, \nu\nu, p_T^V > 250$ GeV	4.9	±	0.5	8.5	±	4.0	±	3.7	±	0.8	±	1.2	±	0.6

5 p_T^V-bin : highest p_T^V bin still statistically limited



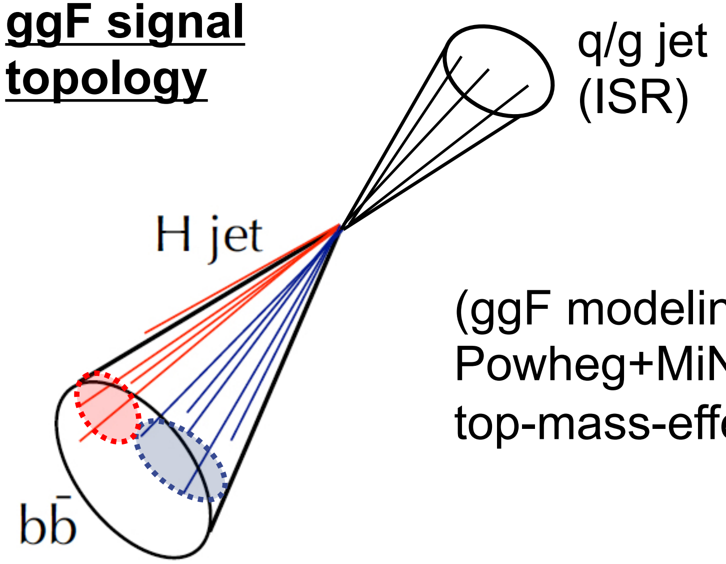
Only Dimension=6 operator considered (linear+quad term)

Parameter	Expected 95% CL intervals	Observed 95% CL intervals
$\bar{c}_{HW}$	$[-0.018,\ 0.004]$	$[-0.019, -0.010] \cup [-0.005,\ 0.006]$
$\bar{c}_{HB}$	$[-0.082,\ 0.023]$	$[-0.092, 0.029]$
$\bar{c}_W - \bar{c}_B$	$[-0.034,\ 0.080]$	$[-0.036, -0.024] \cup [-0.009,\ 0.010]$

Boosted H→bb analysis (ATLAS)

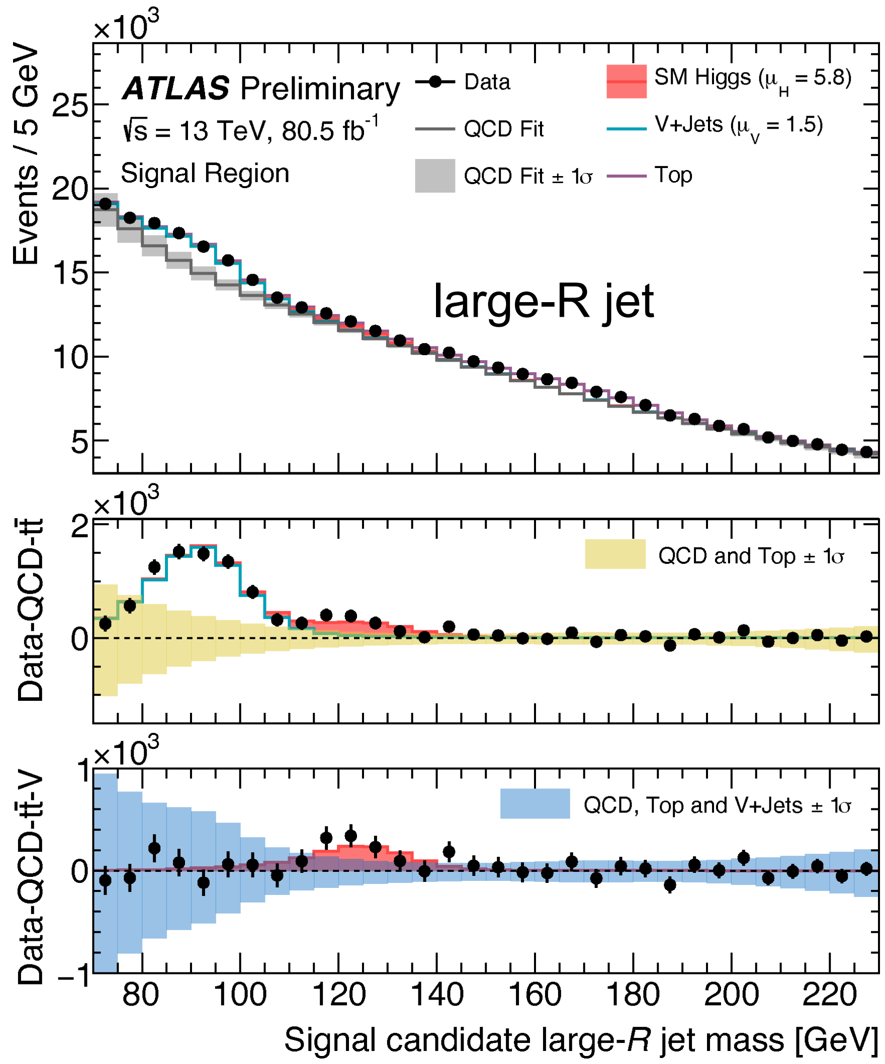
- Search for highly boosted H→bb associated with ISR jet
- Require two jets (R=1.0), p_T>480 GeV, 250 GeV
- Higgs candidate is leading large-R jet with two b-tagged track-jets
- QCD background m_J modeling : polynomial exponential function (validated by loose b-tagged control region)

ggF signal topology



Signal process	Fraction
ggF	53%
VBF	25%
VH	22%

(ggF modeling : Powheg+MiNLO with finite top-mass-effect correction)

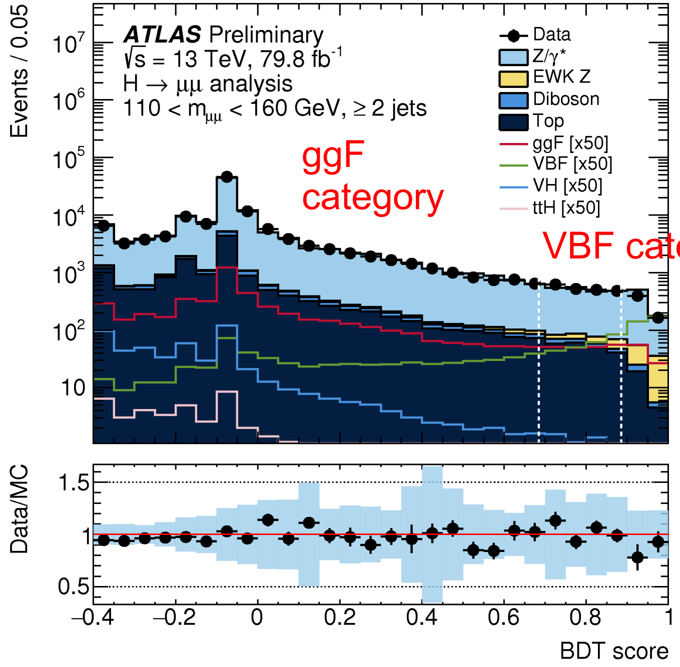


$$\mu_V = 1.5 \pm 0.22(stat)^{+0.29}_{-0.25}(syst) \pm 0.18(th)$$: obs. 5σ

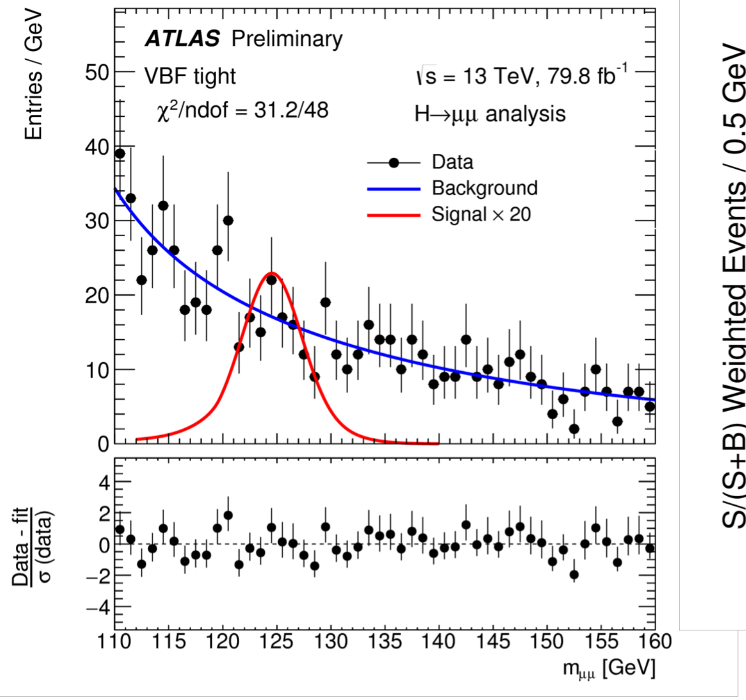
$$\mu_H = 5.8 \pm 3.1(stat) \pm 1.9(syst) \pm 1.7(th)$$: obs. 1.6σ

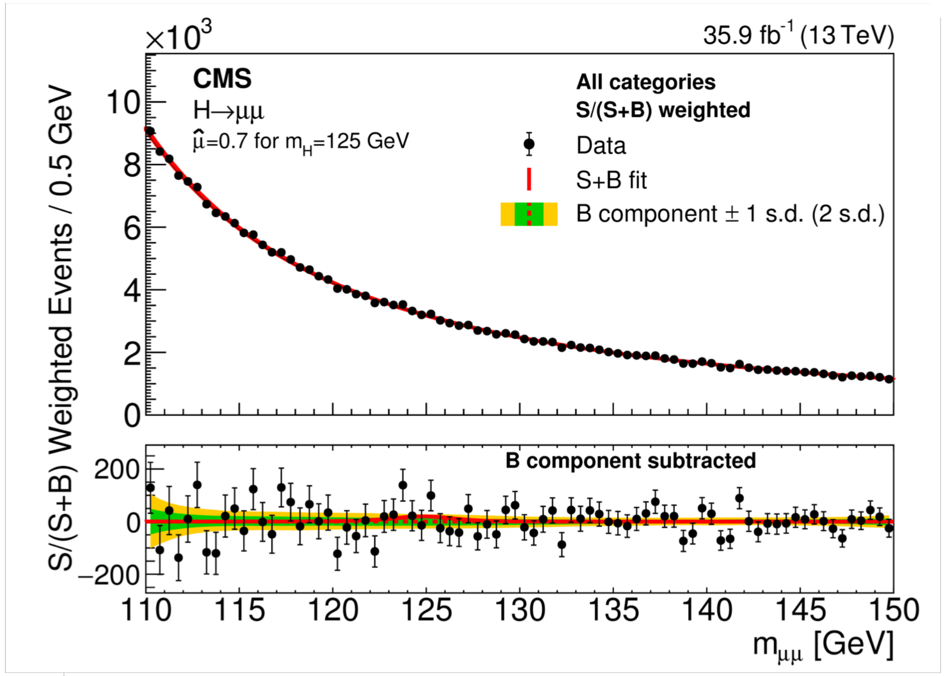
Search for H→μμ

- Direct search for interaction of Higgs with **2nd gen. fermion**
- Extremely small BR(H→μμ) : 0.022%
  - High statistics is required
  - Narrow peak $m_{\mu\mu}$ can be observed (Analysis is simple!)
  - Extract VBF-like signature by BDT categorization ➔ Separate high S/B region



VBF category





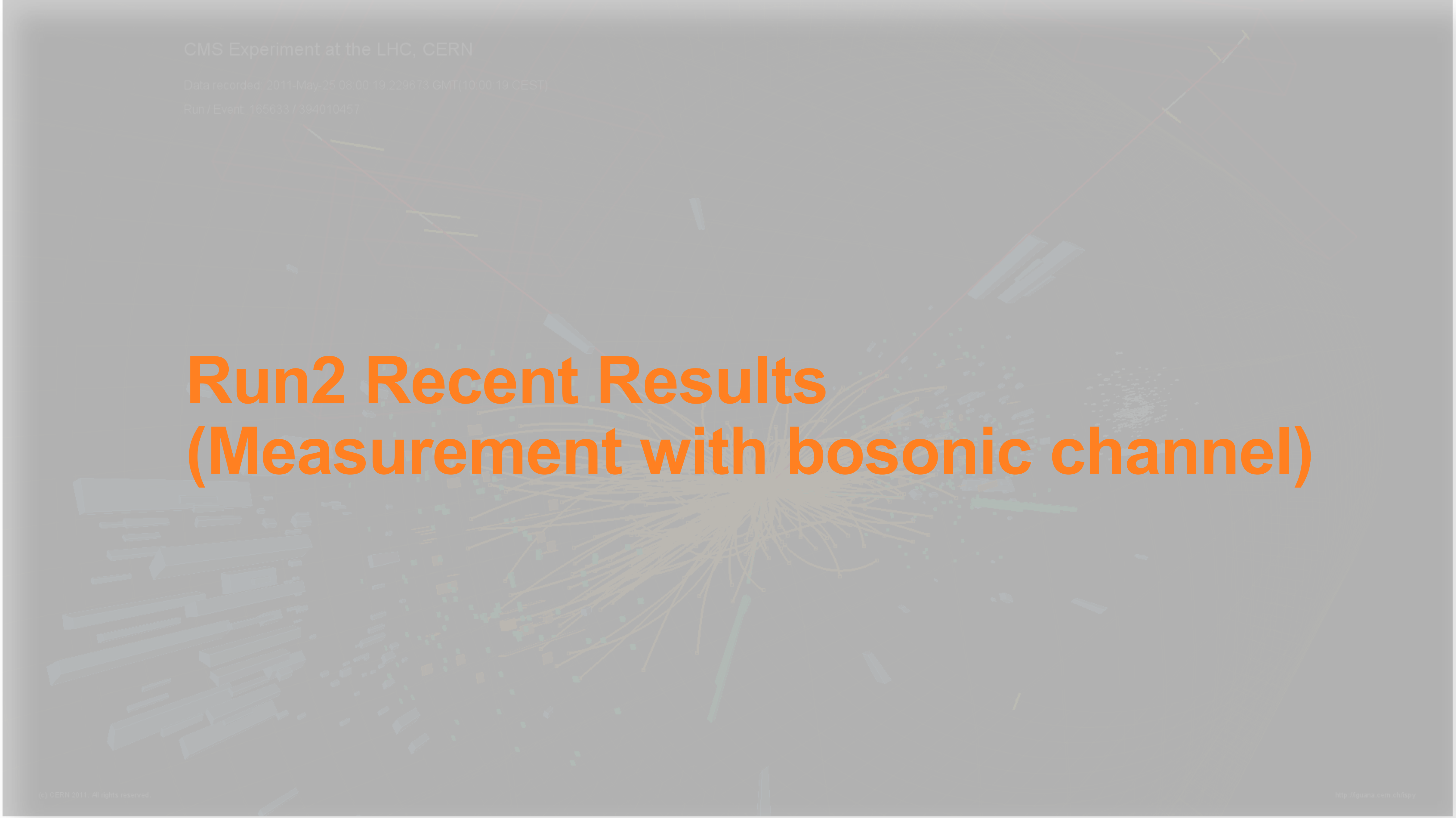
No significant excess yet

ATLAS (80fb^{-1})
Obs. 0σ (Exp. 0.9σ)

CMS (36fb^{-1})
Obs 0.9σ (Exp. 1.0σ)

Statistically limited analysis

Possible to reach to SM cross section in Run2



Run2 Recent Results (Measurement with bosonic channel)

Measurement of Higgs Properties

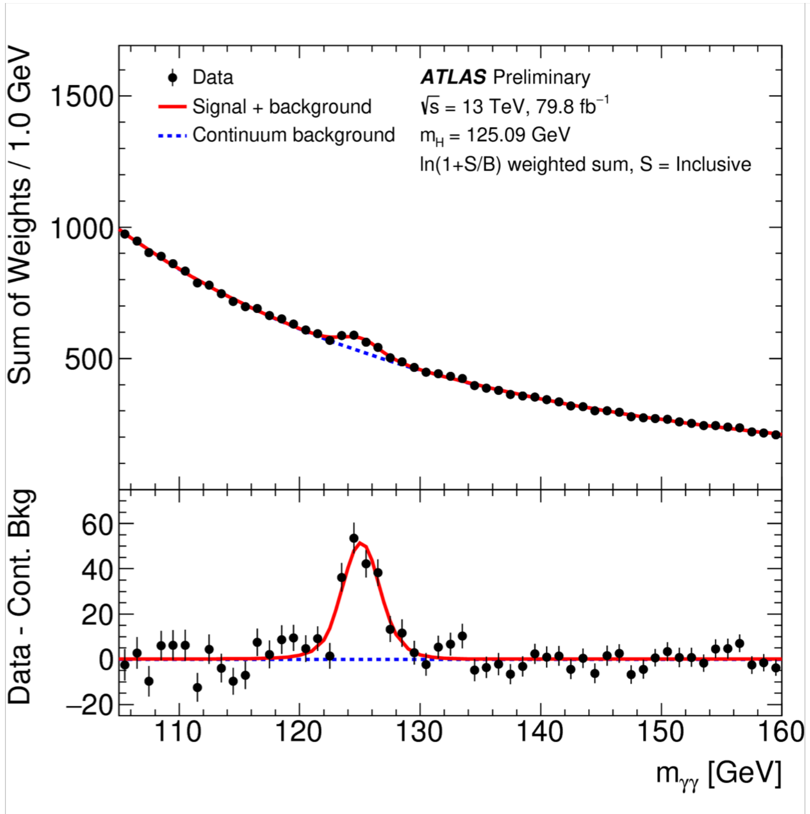
- H→γγ and H→ZZ→4l are golden channels to measure Higgs boson precisely

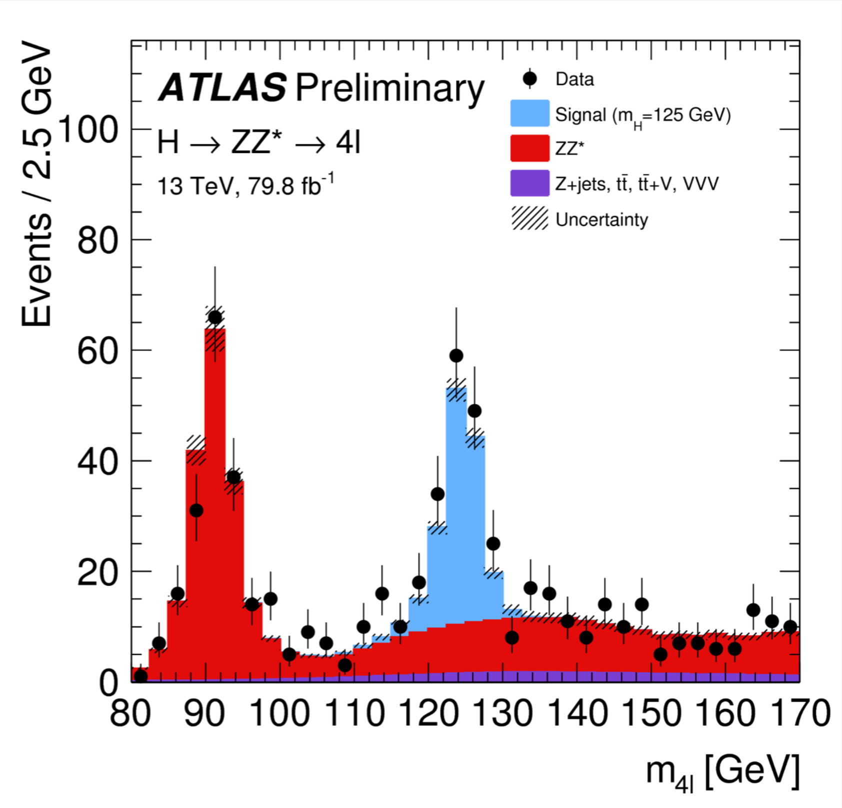
<u>H→γγ</u>

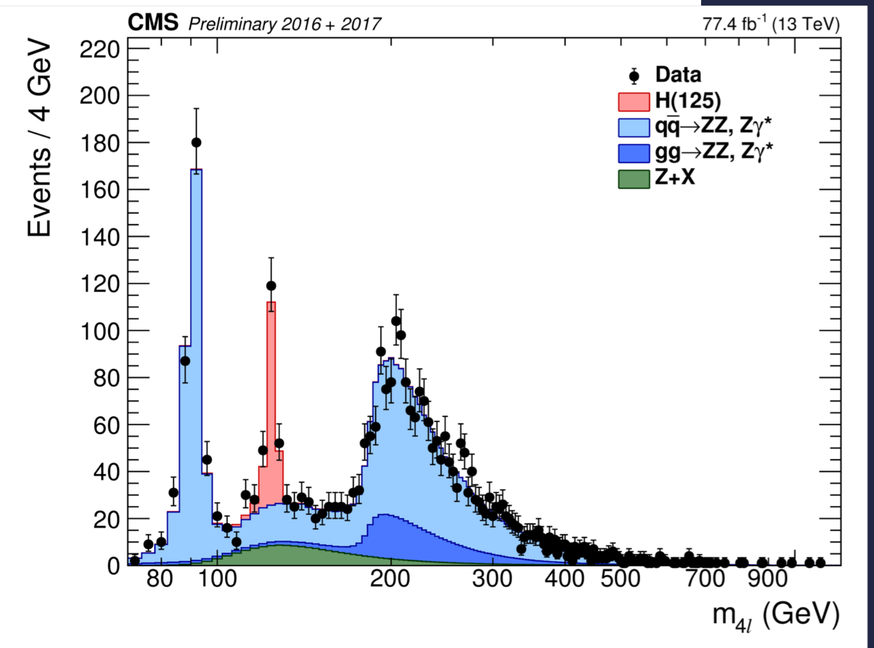
- Branching Ratio ~0.2%
- Narrow $m_{\gamma\gamma}$ peak : σ~1-2GeV
- Background can be determined by data side-band

<u>H→ZZ→4l</u>

- Tiny Branching Ratio ~0.012%
- Very clean (4e, 4μ 2e2μ), high S/B ~(2/1)
- Narrow 4lepton mass peak : m_{4l} resolution

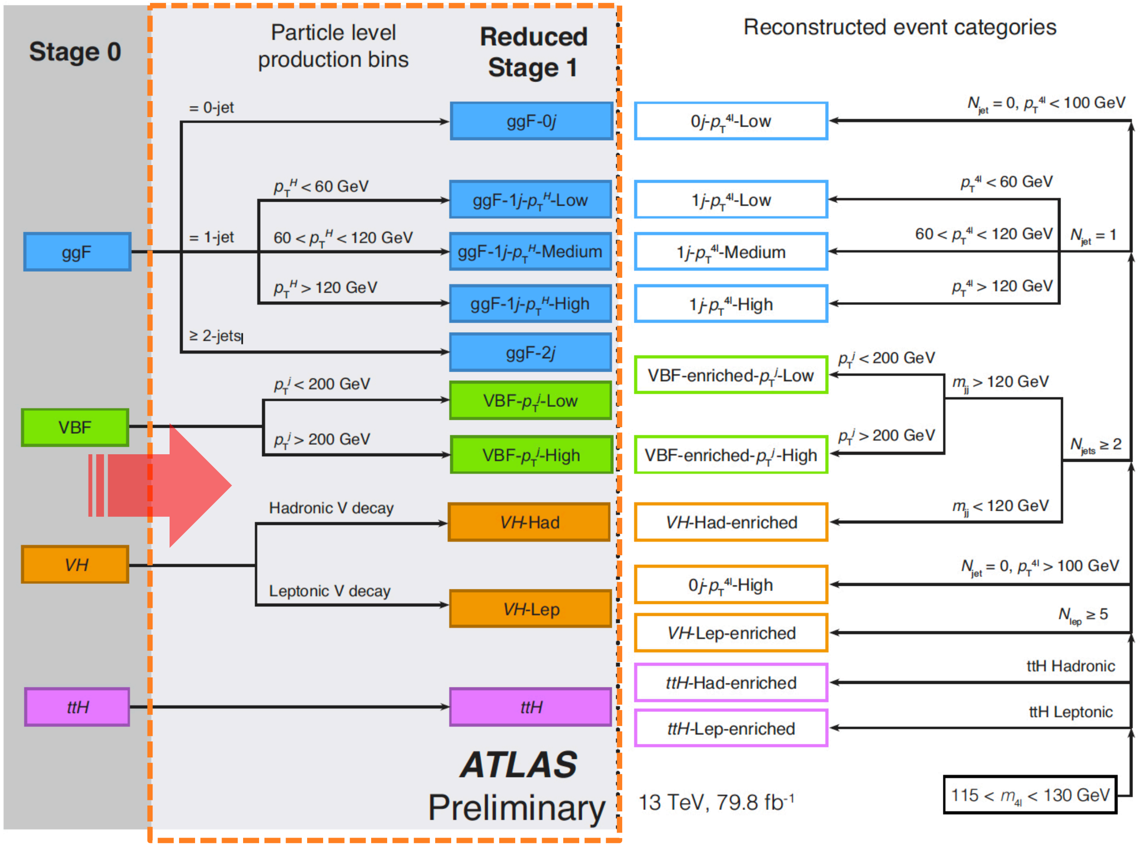


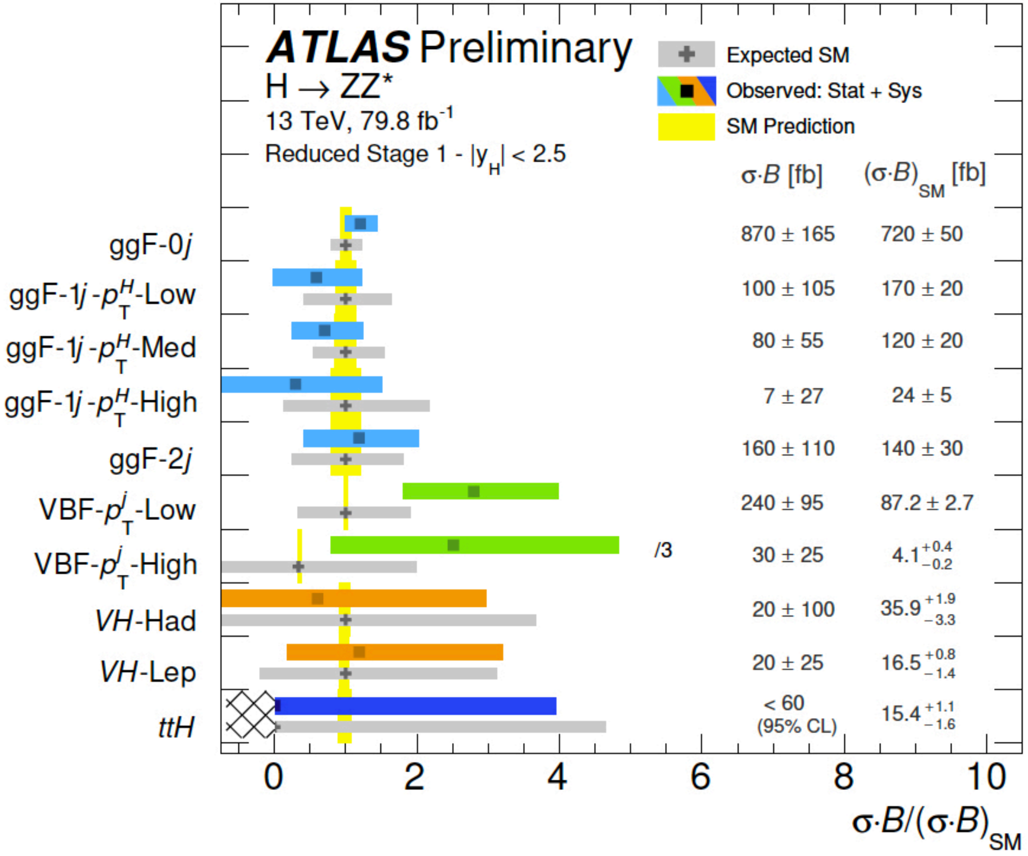




Cross Section Measurement (H→ZZ→4l)

- Cross section measurement using Simplified Template Cross Section (STXS)
- Reconstructed event categories matches with "reduced" Stage 1 bin to maximize precision in the current statistics
  - ggF and VBF bins are divided by p_T^H and particle-level jet (p_T>30 GeV)

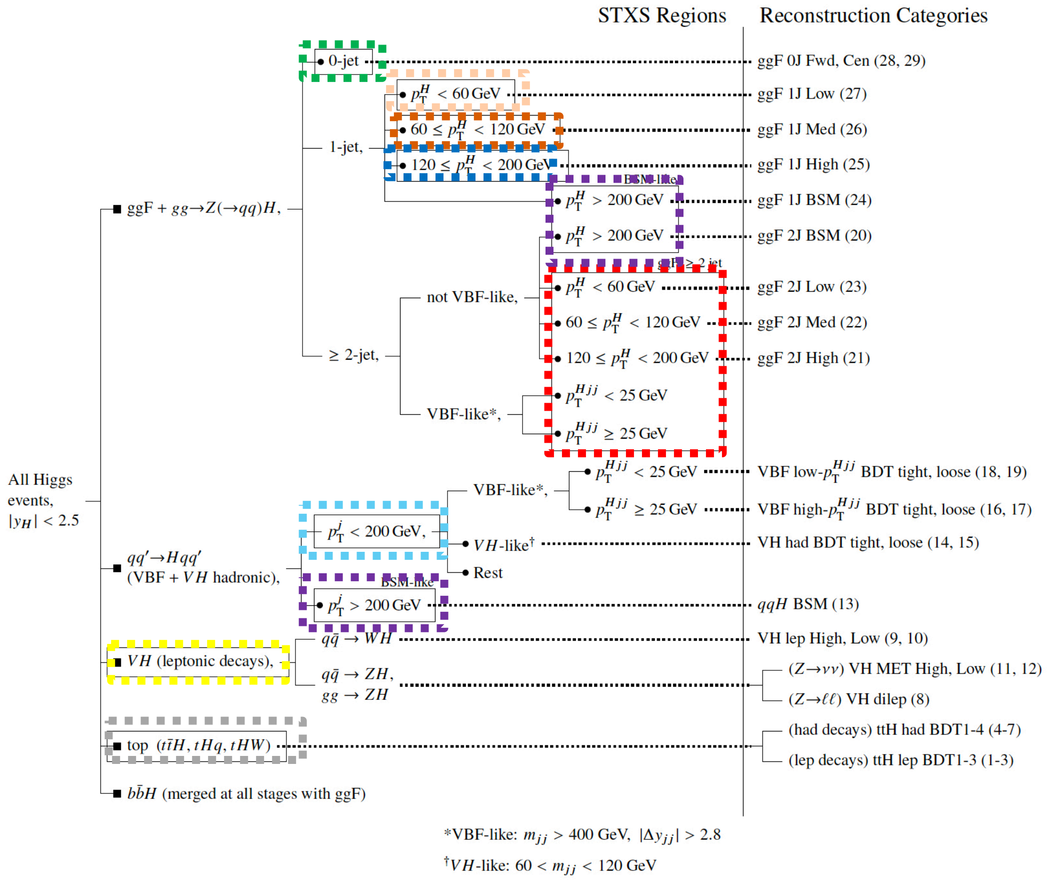


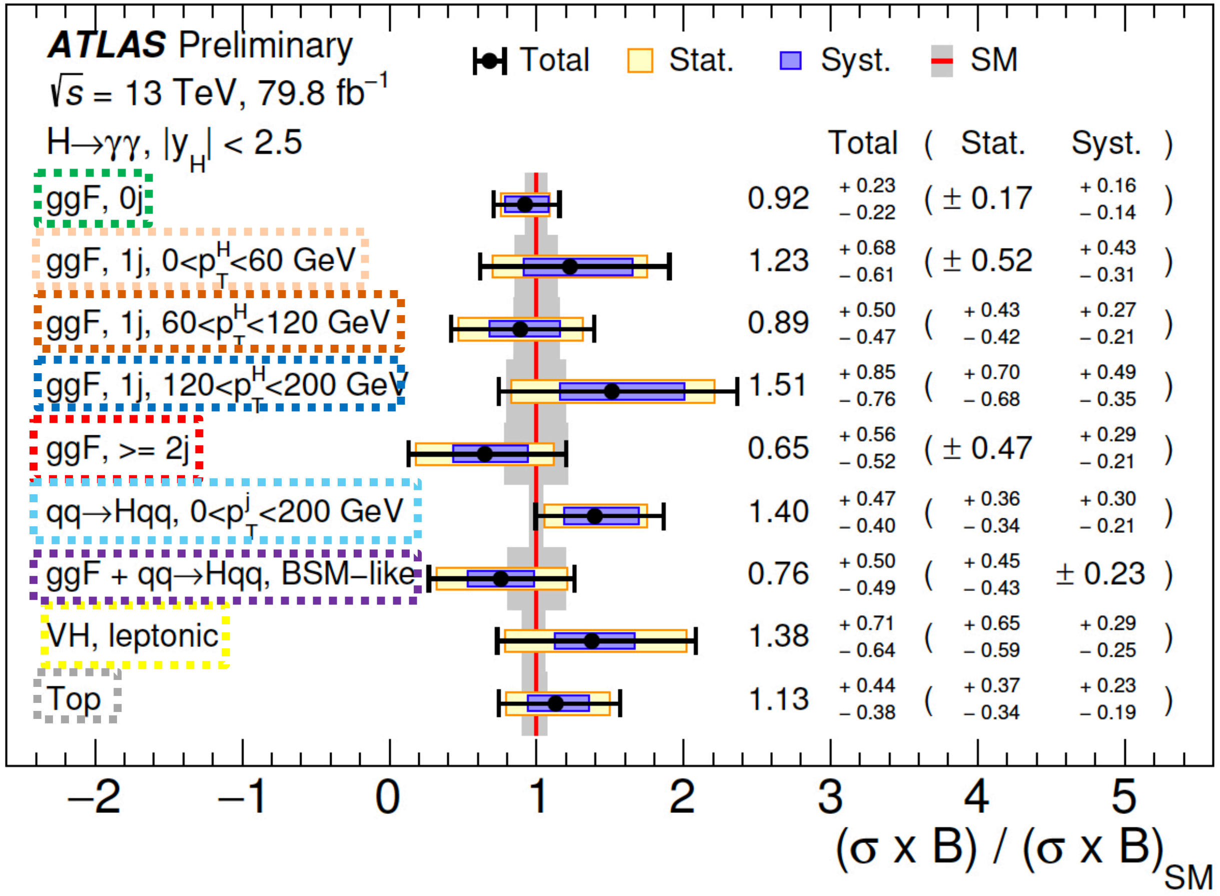


Measurement is still dominated by data statistics

Cross Section Measurement (H→γγ)

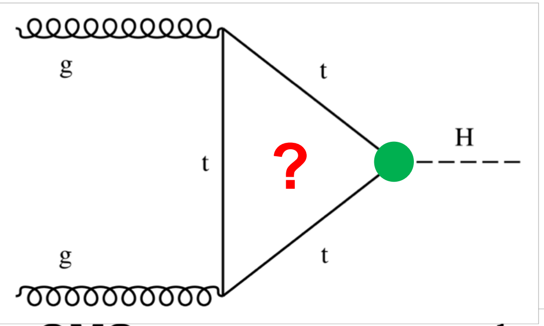
- Cross section measurement using Simplified Template Cross Section (STXS)
- Reconstructed event categories matches with “reduced” Stage 1bin to maximize precision in the current statistics
  - ggF and VBF bins are divided by p_T^H and particle-level jet (p_T>30 GeV)

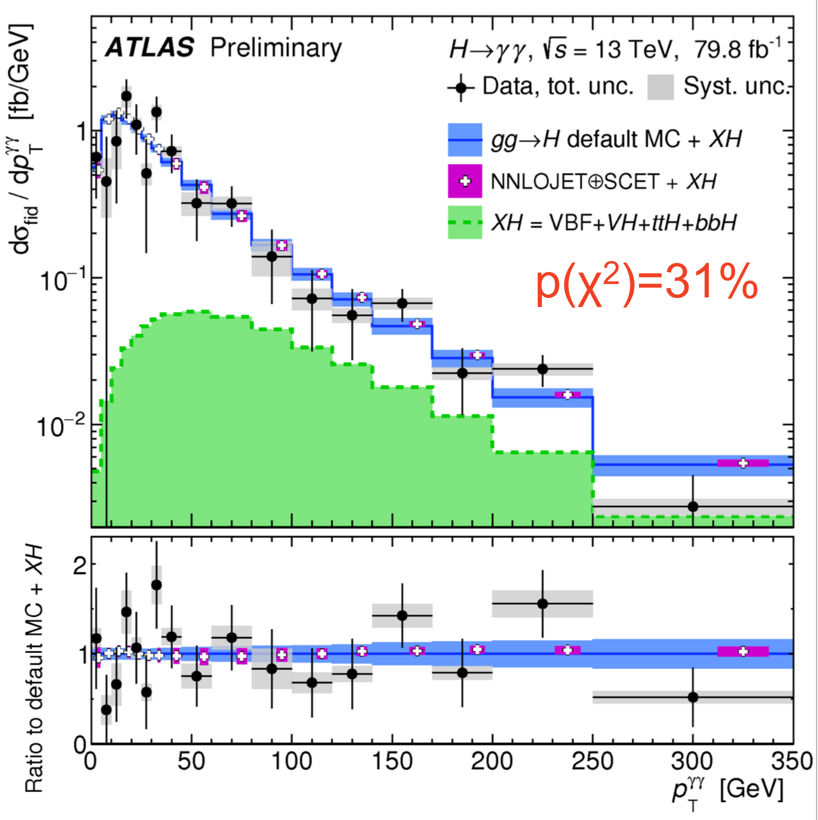


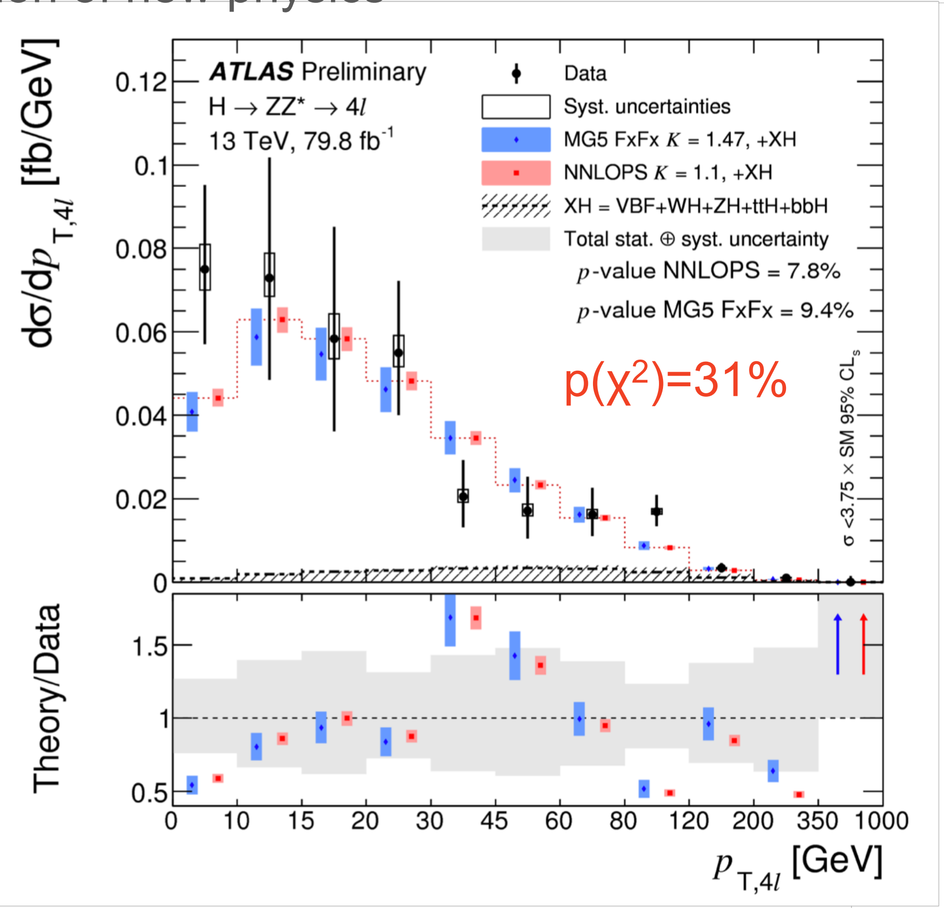


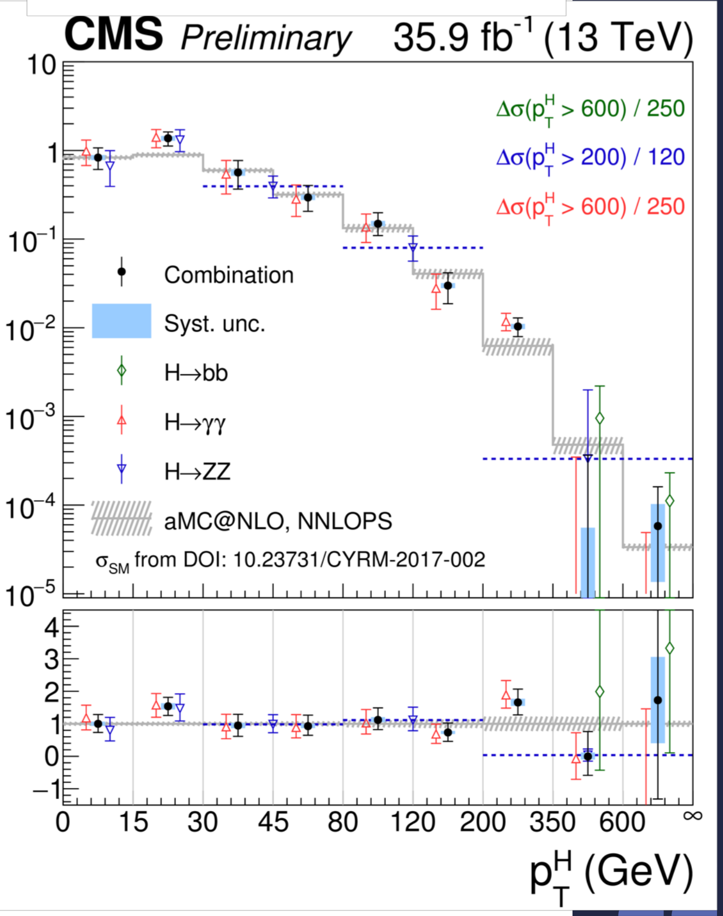
Different Cross-section measurement

- $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$ signal regions are dominated by ggF
- Higgs p_T is sensitive to perturbative QCD and new particle effect in loop and deviation of Yukawa coupling
  - High p_T^H is sensitive to contribution of new physics

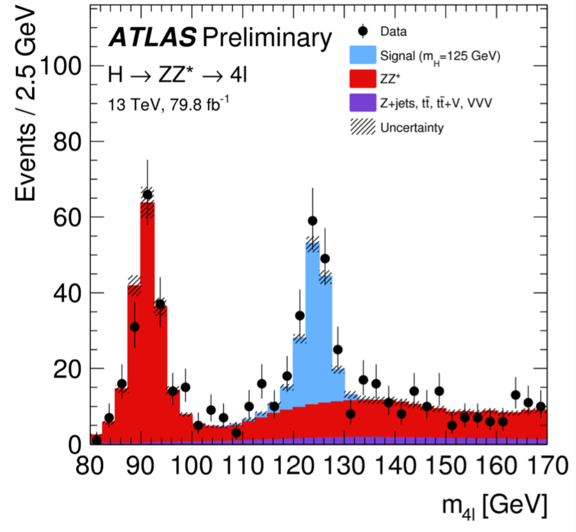


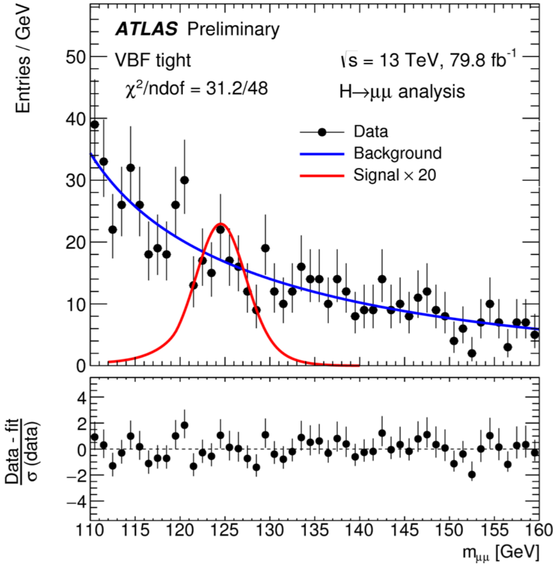


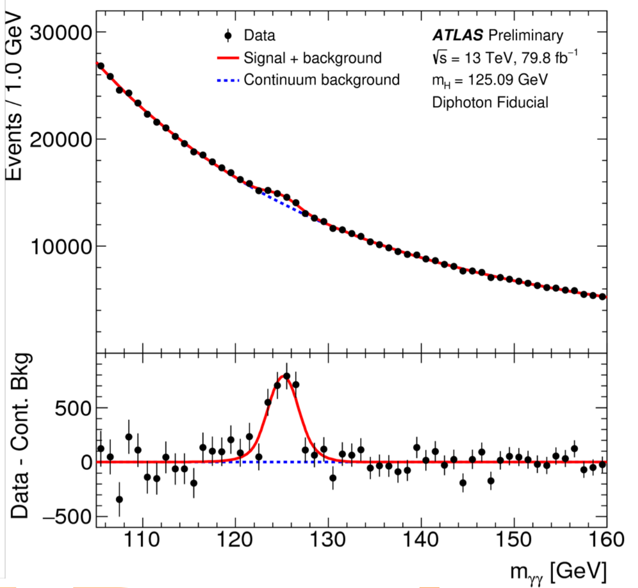


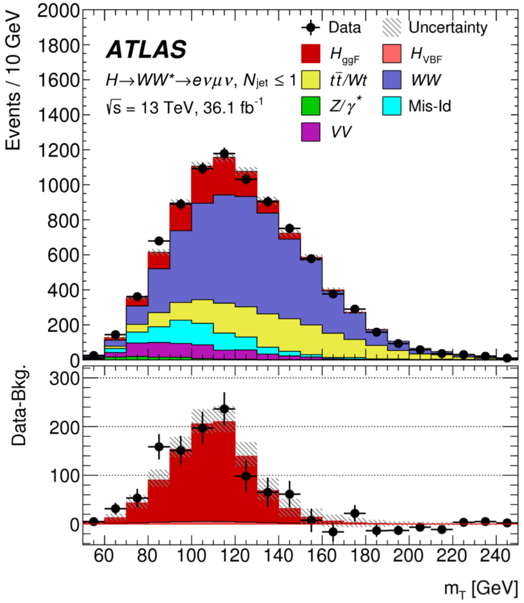


Distribution compared to state-of-art theory predictions

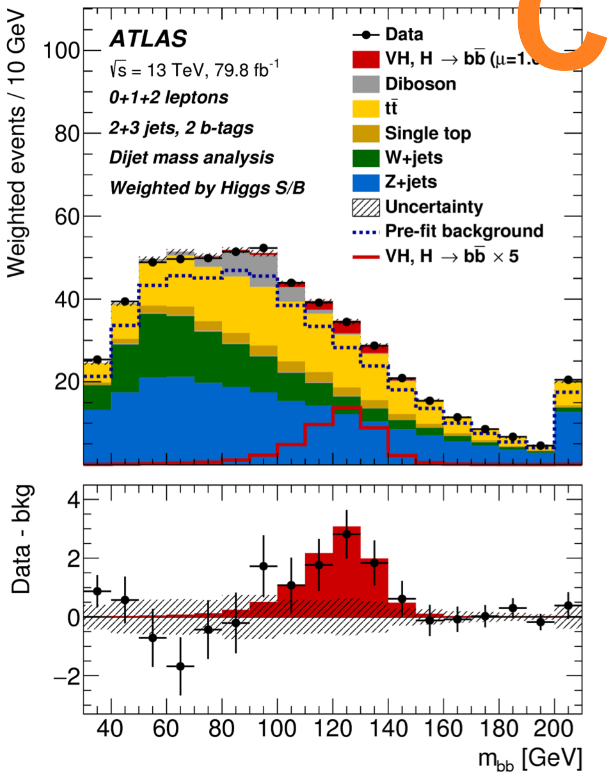


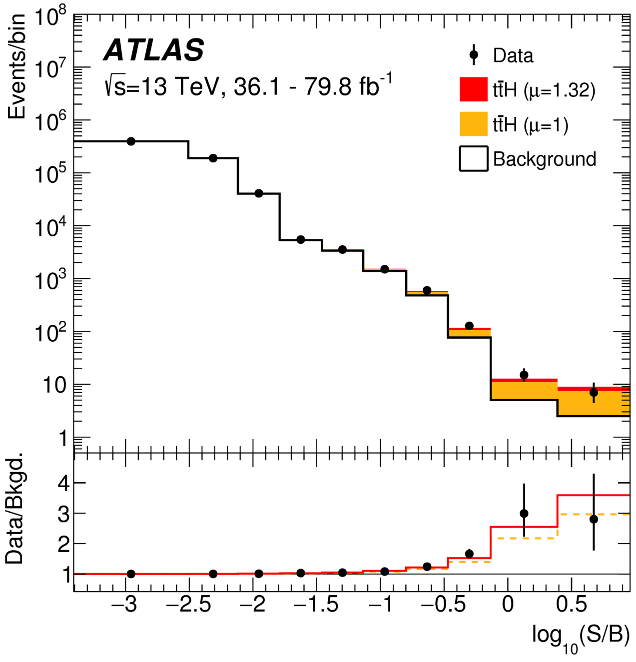


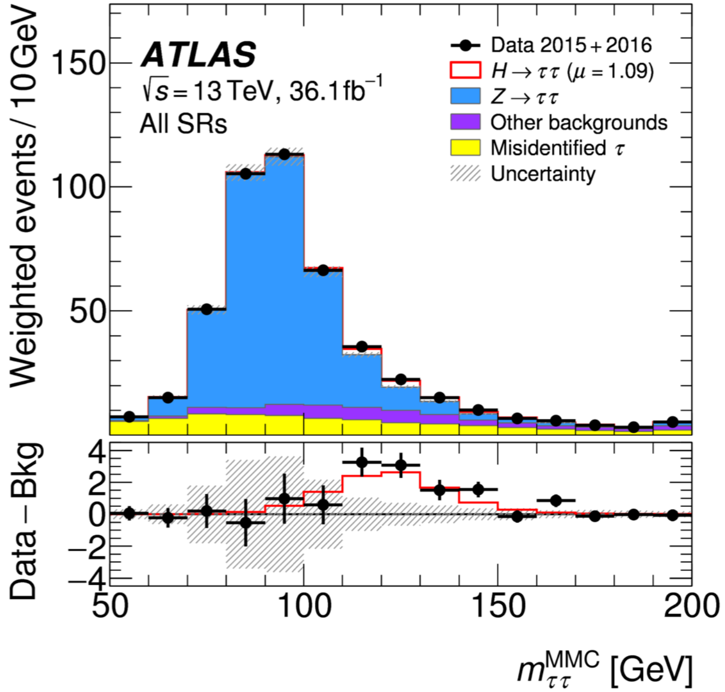




Combined Results







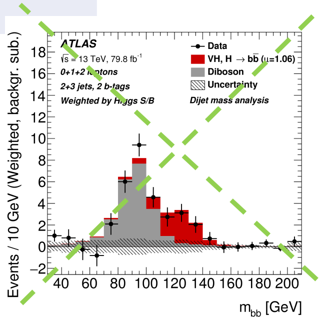
Higgs Global Combination

- Higgs properties measure with many production and decay channel

	H→γγ		H→ZZ		H→ττ		H→bb		H→μμ	
	ATLAS	CMS	**ATLAS**	CMS	ATLAS	CMS	ATLAS	CMS	**ATLAS**	CMS
ggF	○	○	○	○	○	○			○	○
VBF	○	○	○	○	○	○			○	○
WH	○	○	○	○			○	○		
ZH	○	○	○	○			○	○		
ttH	○	○	○	○	○	○	○	○		

○ : 80fb-1 results included

5σ results not included



$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

<u>Inclusive signal strength measurement</u>

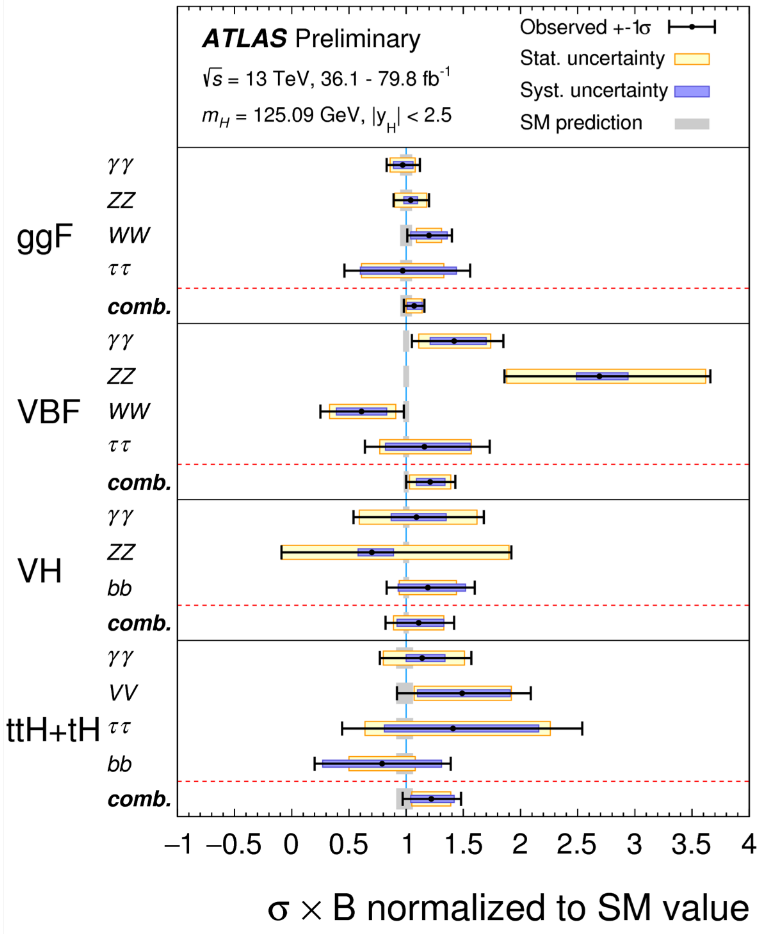
ATLAS : $\mu = 1.13^{+0.09}_{-0.08} = 1.13 \pm 0.05(stat.) \pm 0.05(exp.)^{+0.05}_{-0.04}(sig.th.) \pm 0.03(bkg.th.)$

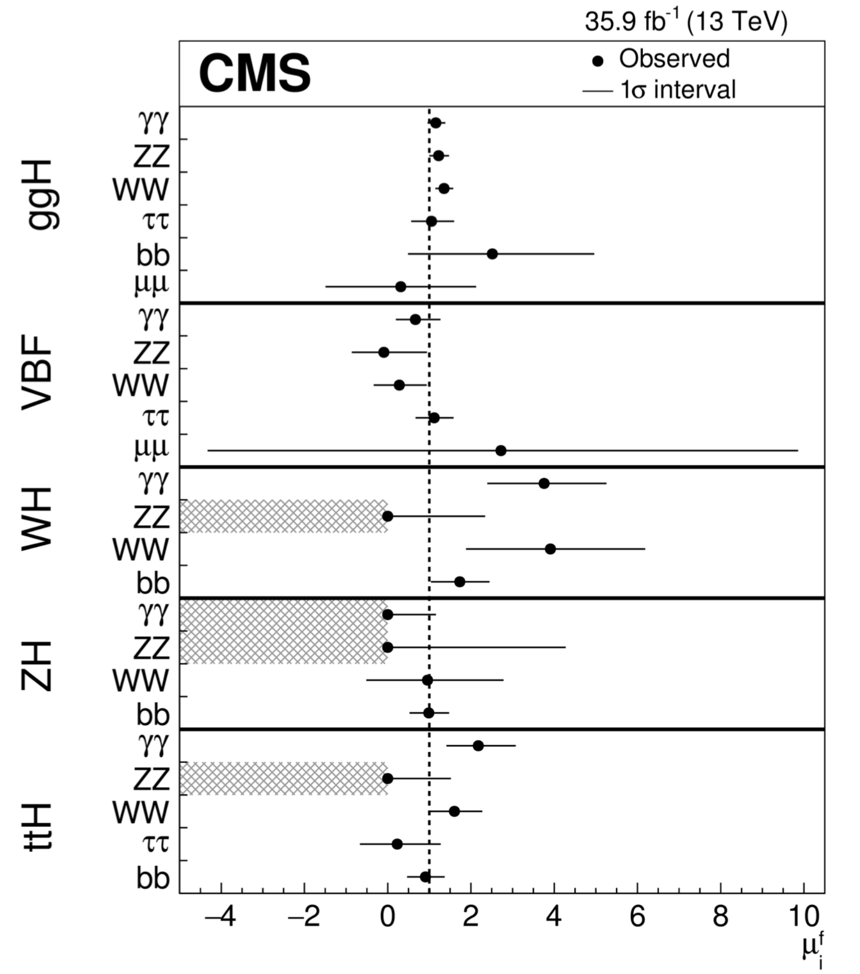
CMS : $\mu = 1.17 \pm 0.10 = 1.13 \pm 0.06(stat.)^{+0.05}_{-0.04}(sig.th.) \pm 0.06(other)$

Both experiments show slightly high signal strength (~1σ level)

Production Cross Section

- Most generic parametrization : one signal strength for each production and decay mode (μ_i^f) (ggF, VBF, WH, ZH, ttH)×(γγ, ZZ, WW, ττ, bb, (μμ))
- The parameter not having sensitivity is merged or fixed in SM





Consistent with SM

No significant trend between ATLAS and CMS

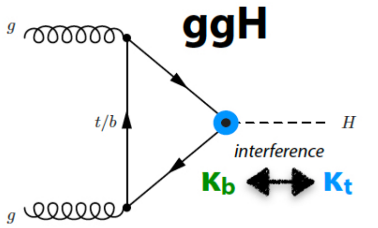
<u>Uncertainties on production cross section (ATLAS)</u>

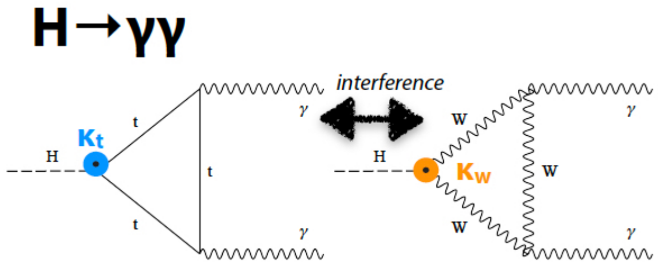
σ (ggF) ~8% accuracy
σ(VBF) ~18%
σ(VH) ~30-40% (new Hbb results are not included)
σ(ttH) ~20%

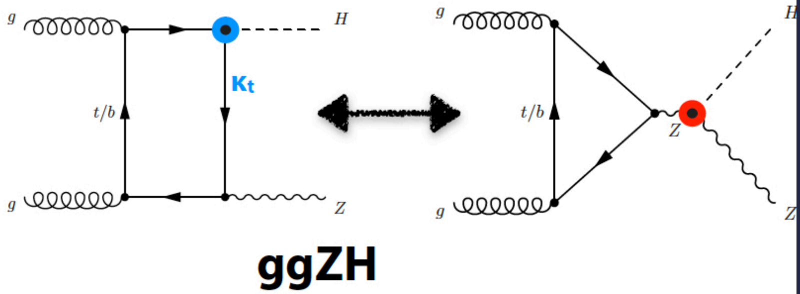
Coupling measurement in κ-framework

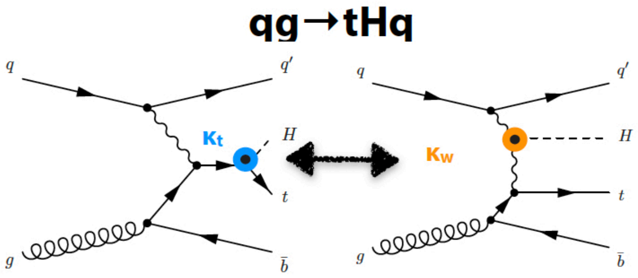
$$(\sigma \times B)_{if} = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_H^2 \Gamma_H^{SM}}$$

Production	Effective modifier	Resolved modifier
σ_{ggF}	κ_g^2	$1.04\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.04\,\kappa_t\kappa_b$
σ_{VBF}	-	$0.73\,\kappa_W^2 + 0.27\,\kappa_Z^2$
$\sigma_{qq/qg\to ZH}$	-	κ_Z^2
$\sigma_{gg\to ZH}$	-	$2.46\,\kappa_Z^2 + 0.46\,\kappa_t^2 - 1.90\,\kappa_Z\kappa_t$
σ_{WH}	-	κ_W^2
$\sigma_{t\bar{t}H}$	-	κ_t^2
σ_{tHW}	-	$2.91\,\kappa_t^2 + 2.31\,\kappa_W^2 - 4.22\,\kappa_t\kappa_W$
σ_{tHq}	-	$2.63\,\kappa_t^2 + 3.58\,\kappa_W^2 - 5.21\,\kappa_t\kappa_W$
$\sigma_{b\bar{b}H}$	-	κ_b^2
Partial decay width	**Effective modifier**	**Resolved modifier**
$\Gamma_{\gamma\gamma}$	κ_γ^2	$1.59\,\kappa_W^2 + 0.07\,\kappa_t^2 - 0.67\,\kappa_W\kappa_t$
Γ_{ZZ}	-	κ_Z^2
Γ_{WW}	-	κ_W^2
$\Gamma_{\tau\tau}$	-	κ_τ^2
Γ_{bb}	-	κ_b^2
$\Gamma_{\mu\mu}$	-	κ_μ^2
Γ_{gg}	κ_g^2	$1.11\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.12\,\kappa_t\kappa_b$
$\Gamma_{Z\gamma}$	$\kappa_{(Z\gamma)}^2$	$1.12\,\kappa_W^2 - 0.12\,\kappa_W\kappa_t$
Total width	**Efective modifier**	**Resolved modifier**
Γ_H	κ_H^2	$(0.58\,\kappa_b^2 + 0.22\,\kappa_W^2 + 0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2 + 0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2 + 0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2)/(1 - B_{BSM})$



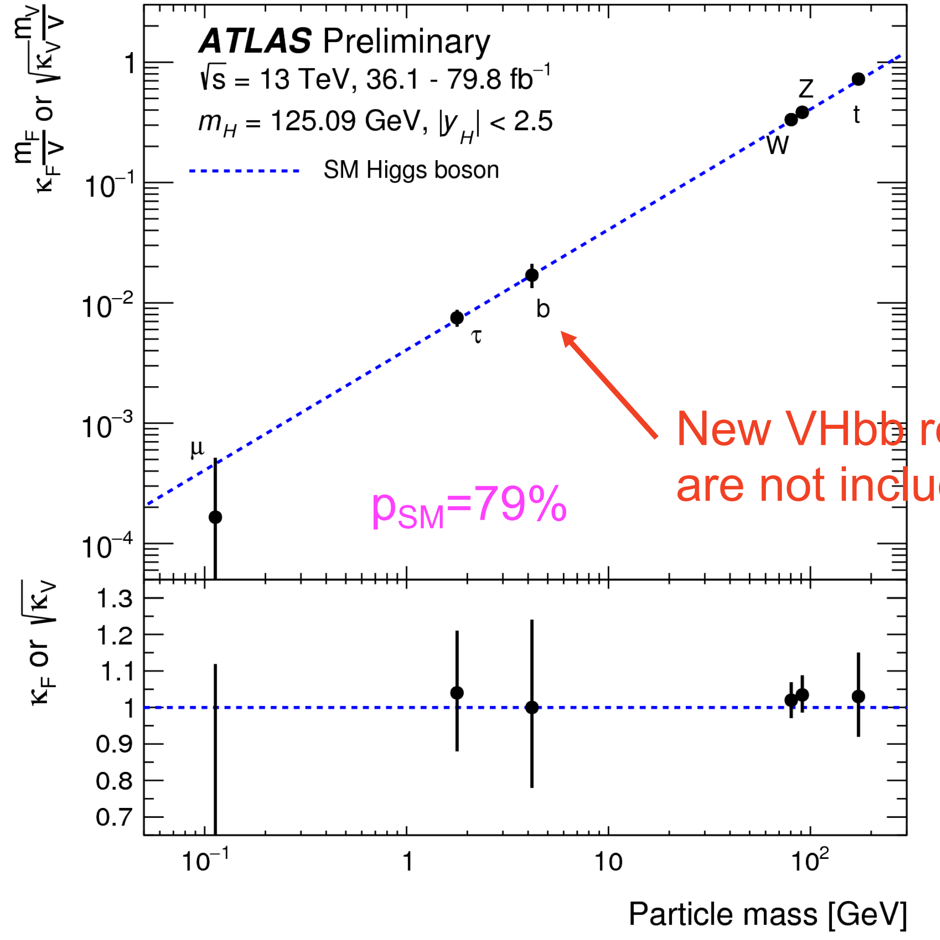




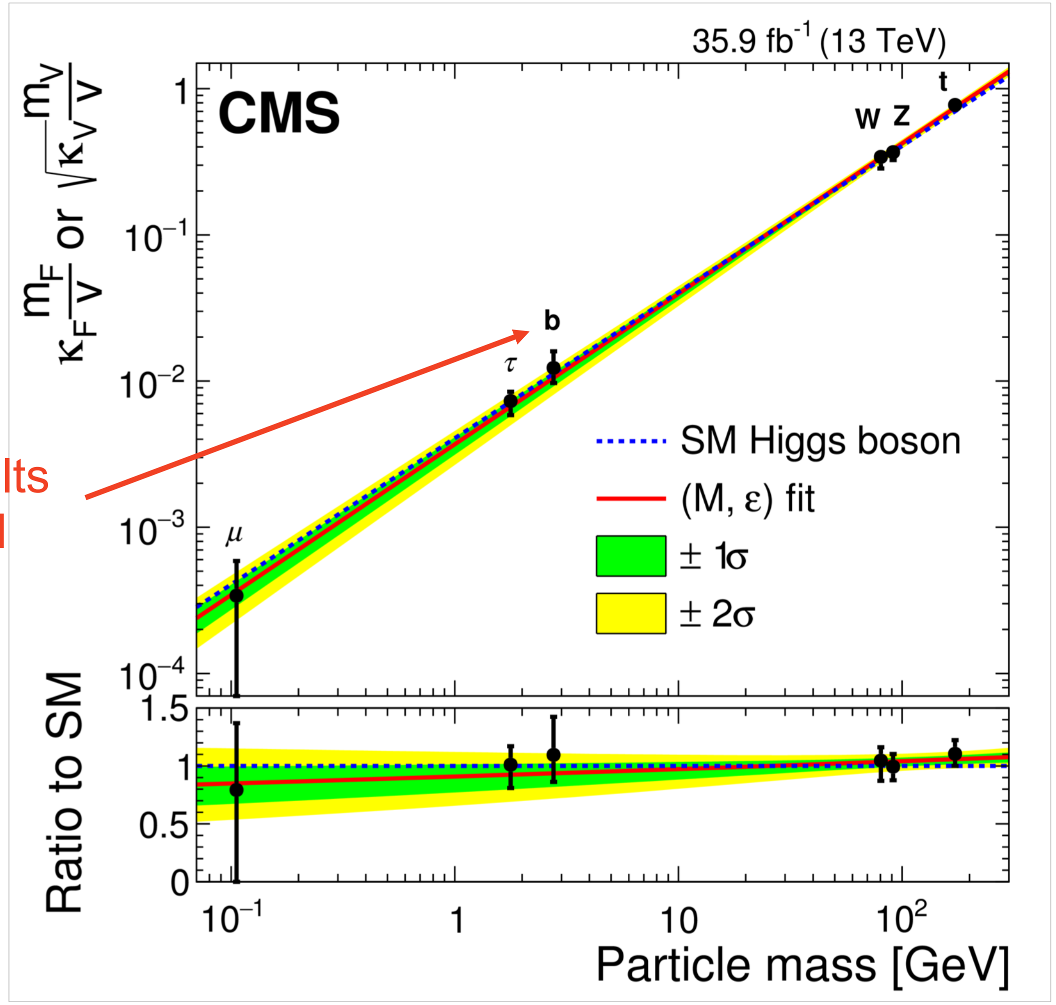


Coupling Measurement (test of SM)

- Assuming no BSM particle in the loop (resolved H→γγ and ggF loop)
- Parameter : reduced coupling strength modifier ($\kappa_F \frac{m_F}{v}$, $\sqrt{\kappa_V}\frac{m_V}{v}$)

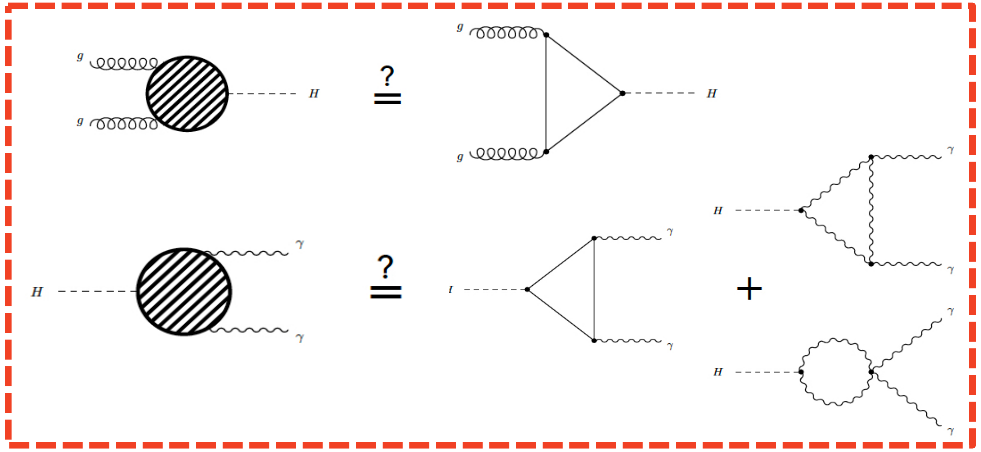


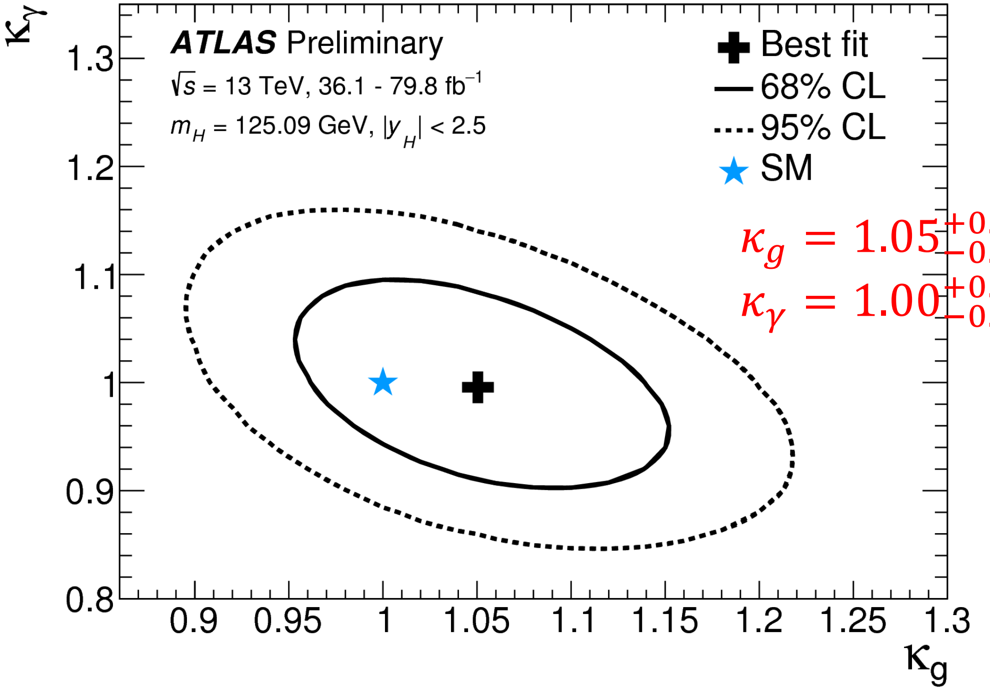
New VHbb results are not included



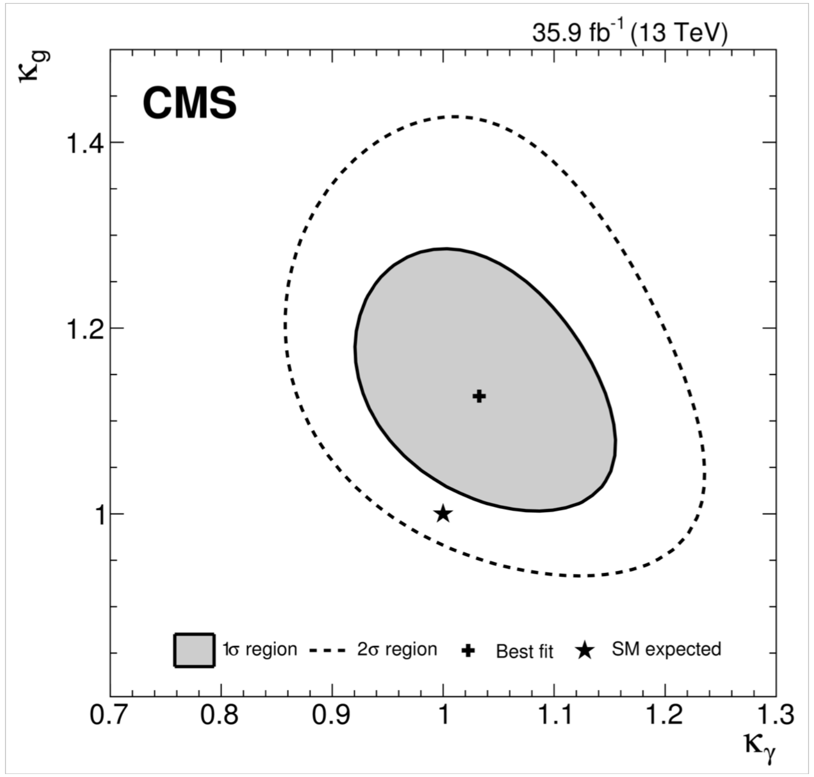
Coupling Measurement (effective loop)

- Test effective modifier κ_g, κ_γ
- ggF, H→γγ induce loop in the SM
  ➔ κ_g, κ_γ may derivate from the SM if new particle contributes to the loop induced process
- All other couplings are fixed to SM





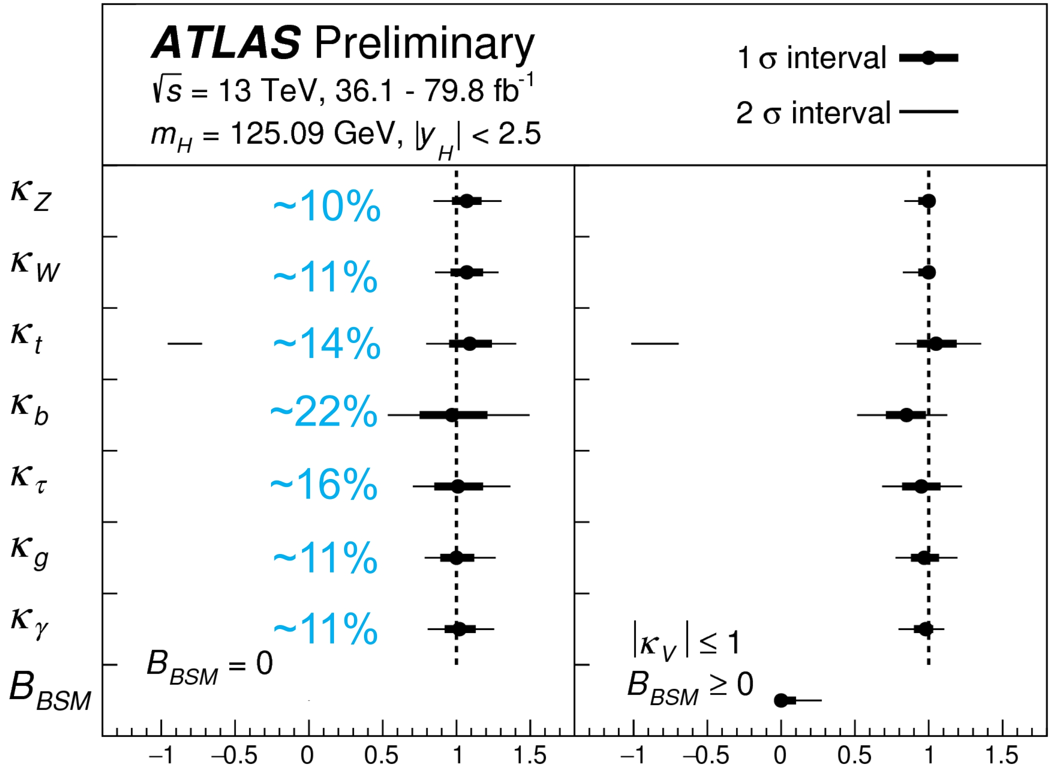
$\kappa_g = 1.05^{+0.06}_{-0.06}$
$\kappa_\gamma = 1.00^{+0.07}_{-0.06}$

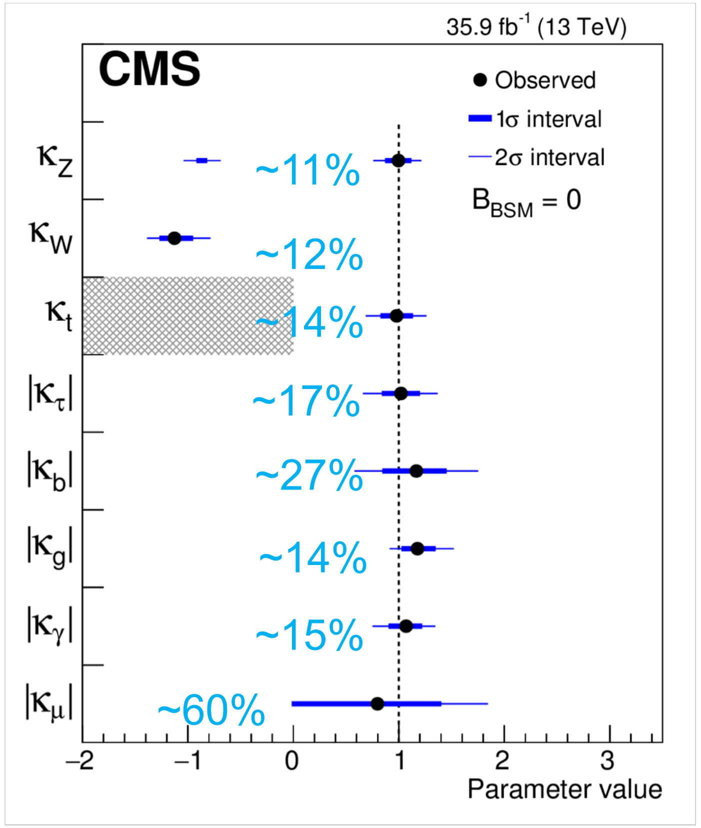


Coupling Measurement with effective loop (with/without BSM contribution)

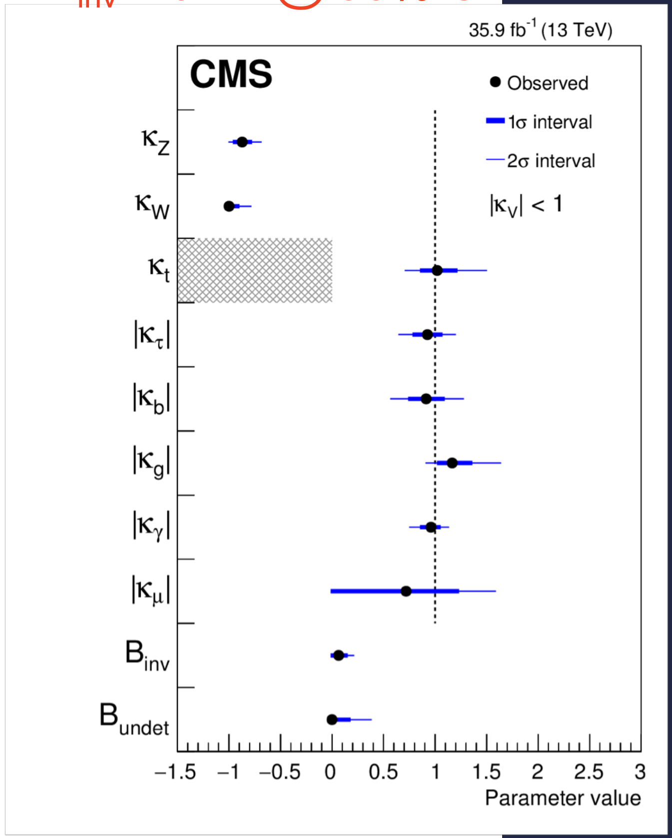
- $B_{BSM} = 0$: No BSM contribution to the total width
- $B_{BSM}(B_{inv}) \geq 0$: Allow BSM contribution to total width

$B_{BSM} < 0.26$ @ 95% CL





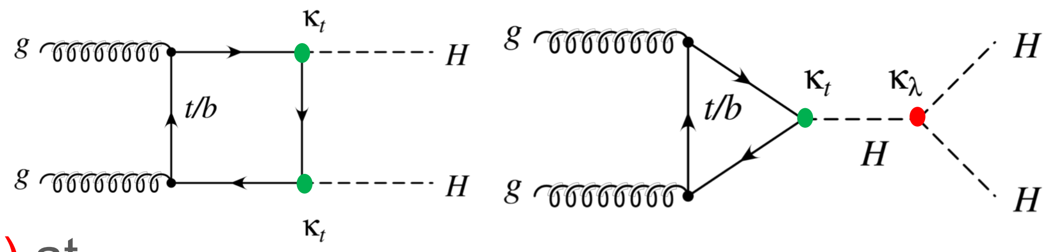
$B_{inv} < 0.22$ @ 95% CL

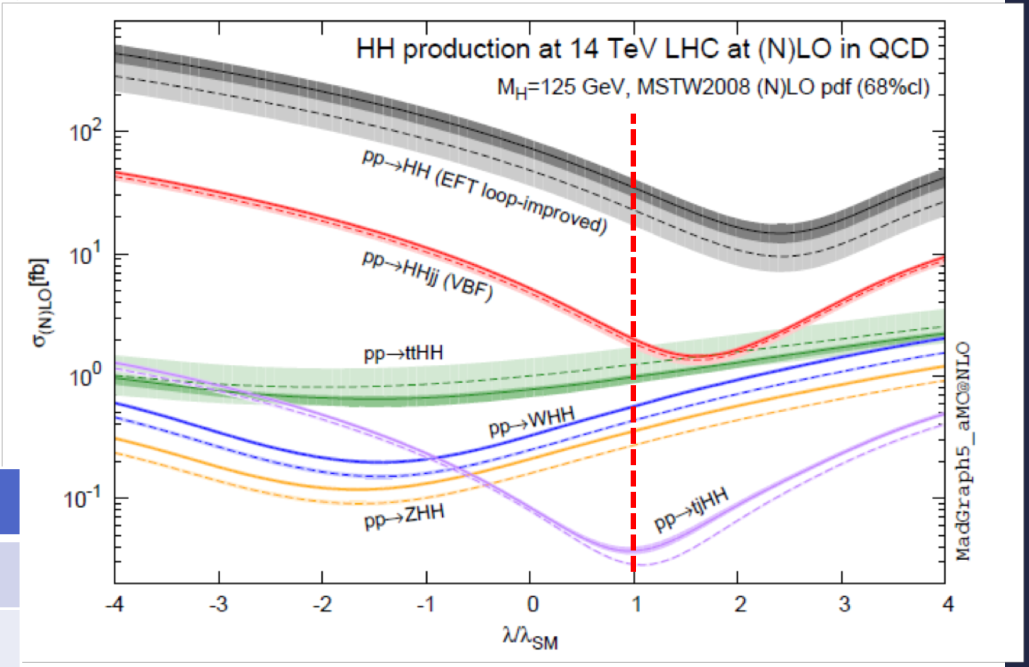


Added H→inv search results
➔ separate B_{inv}, B_{undet}

Higgs pair-production in Run2

- Search for Higgs pair production
- Destructive interference between diagrams
  - SM cross section σ(pp→HH) = 33fb(NNLO+NNLL) at 13 TeV
    ➔ **Super tiny at LHC**
  - If trilinear coupling (λ_{HHH}) deviates from SM, signal cross section ($\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$) can be increased/decreased
  - No unique strong channel, combine all of them



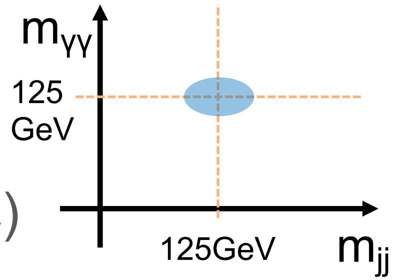


Decay	bb	γγ	ττ	WW
bb	**4b (34%)**			
γγ	**bbγγ (0.27%)**	4γ(0.0005%)		
ττ	**bbττ (7.2%)**	ττγγ(2.9%)	4ττ(0.4%)	
WW	**bbWW (24%)**	**γγWW(0.1%)**	ττWW(2.6%)	4W(4.4%)

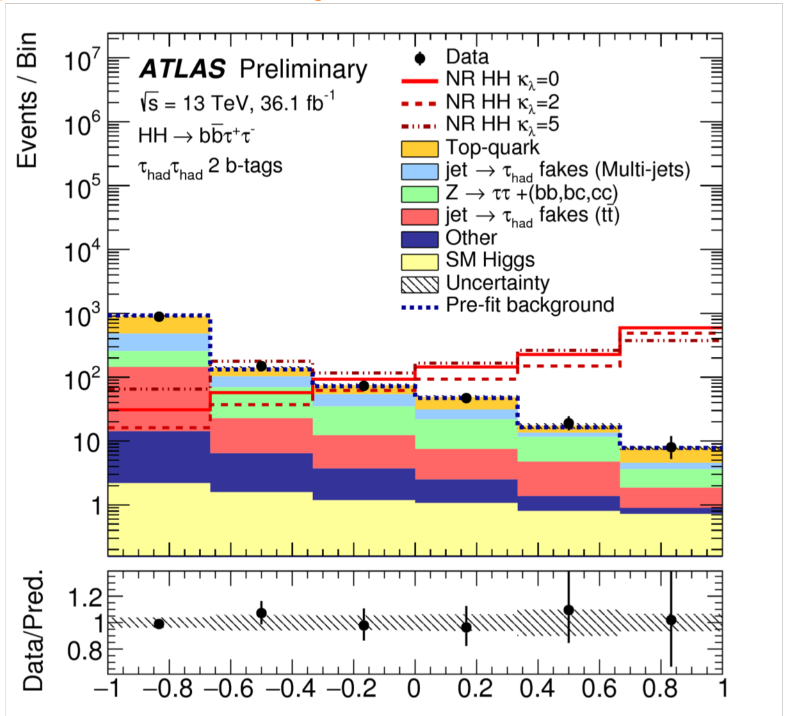
- Sensitive channel is HH→bb+X having high branching ratio (HH→4b, bbγγ, bbττ)

final states are complicated
➔ Still room to improve analysis

Selected Di-higgs analysis

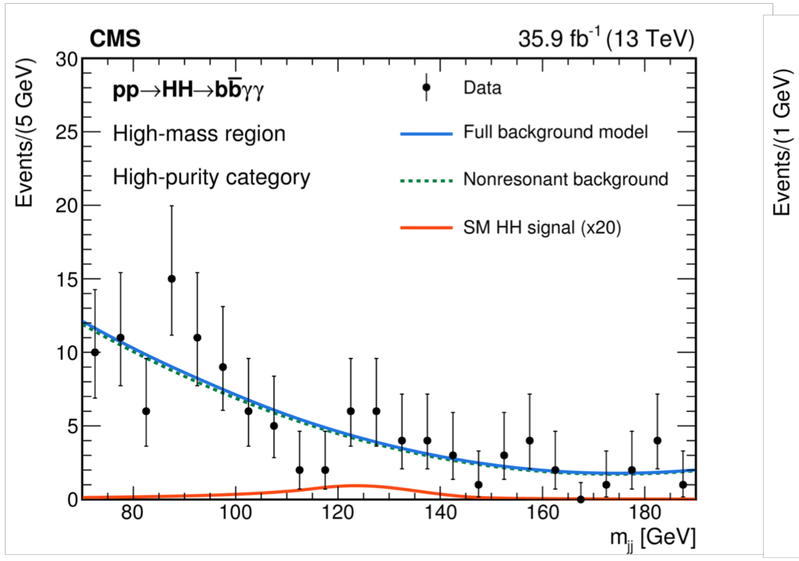


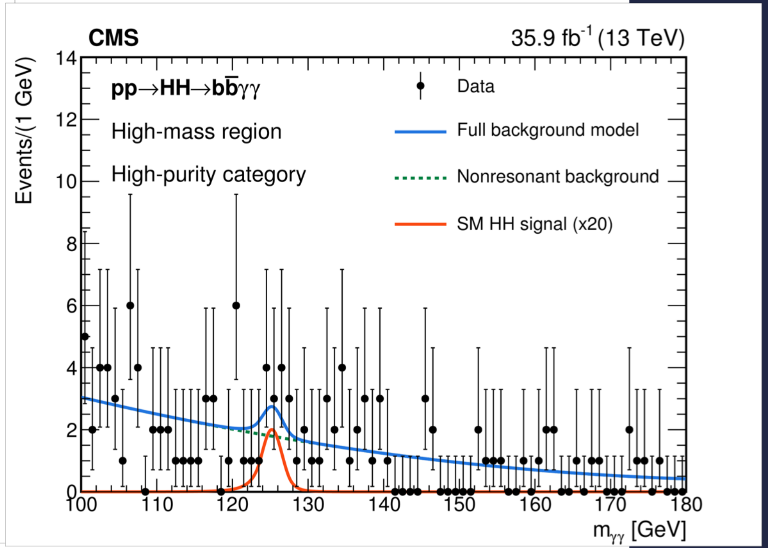
- **bbττ (ATLAS) at 36fb^{-1}**
  - Optimize analysis $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$, separately
  - Introduced BDT as final discriminants (m_{HH}, $m_{\tau\tau}$, m_{bb}, MET, and angle correlation)
    ➔ Sensitivity improved by factor of 2 from previous analysis



BDT shape varied by κ_λ

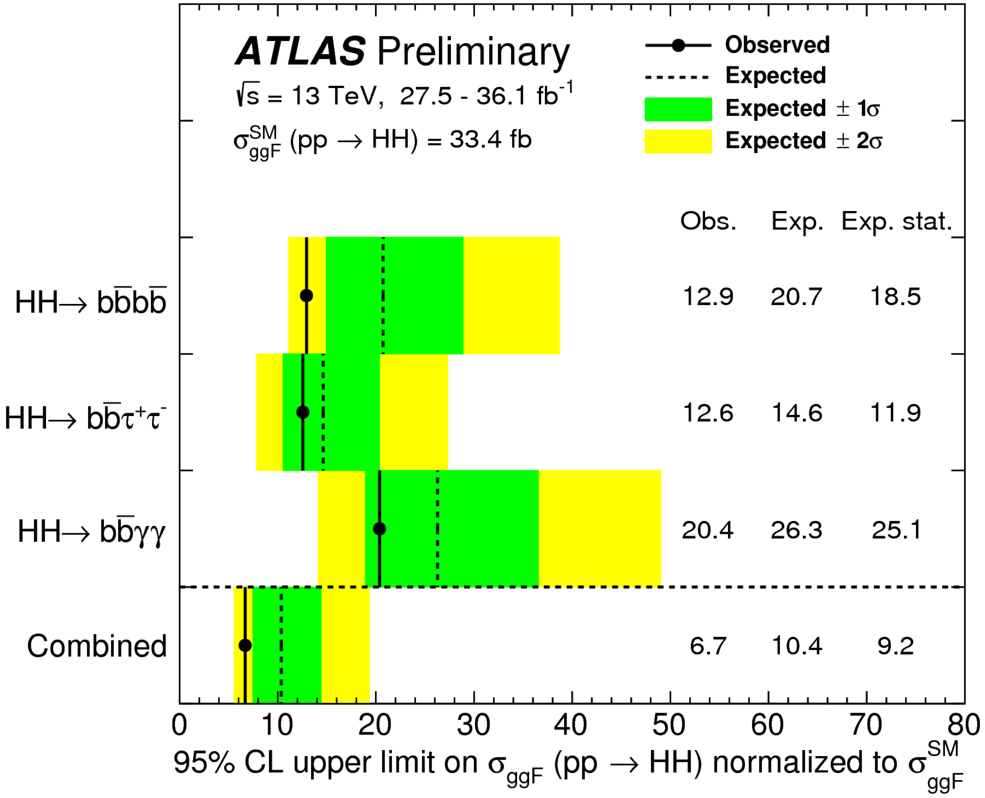
- **bbγγ (CMS) at 36fb^{-1}**
  - Perform 2D fitting ($m_{jj(bb)}$ vs $m_{\gamma\gamma}$) to mitigate single Higgs+jets production
  - Selected 2b+2γ events are further categorized by $M_{\gamma\gamma jj}$ distribution and BDT (b-tagging variable, Helicity angle and HH transverse balance)
  - non resonance background estimated from sideband

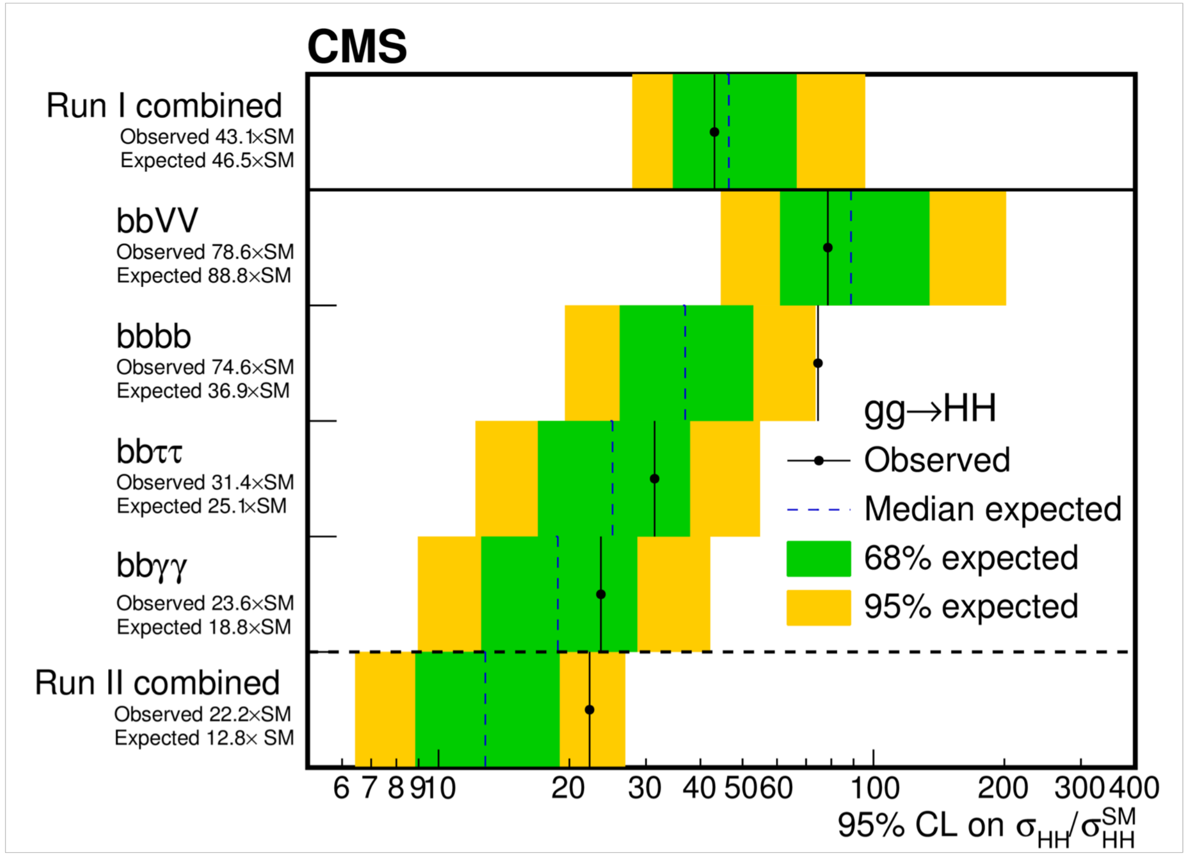




Search for Higgs pair production in Run2

- First Run2 combined results ($36fb^{-1}$)



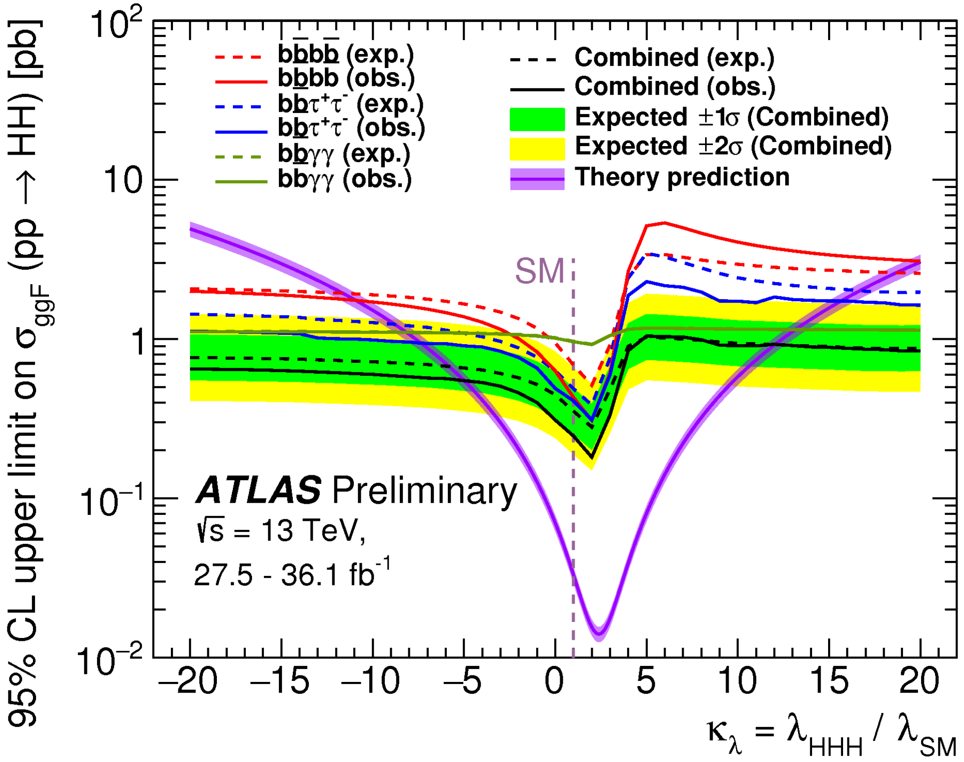


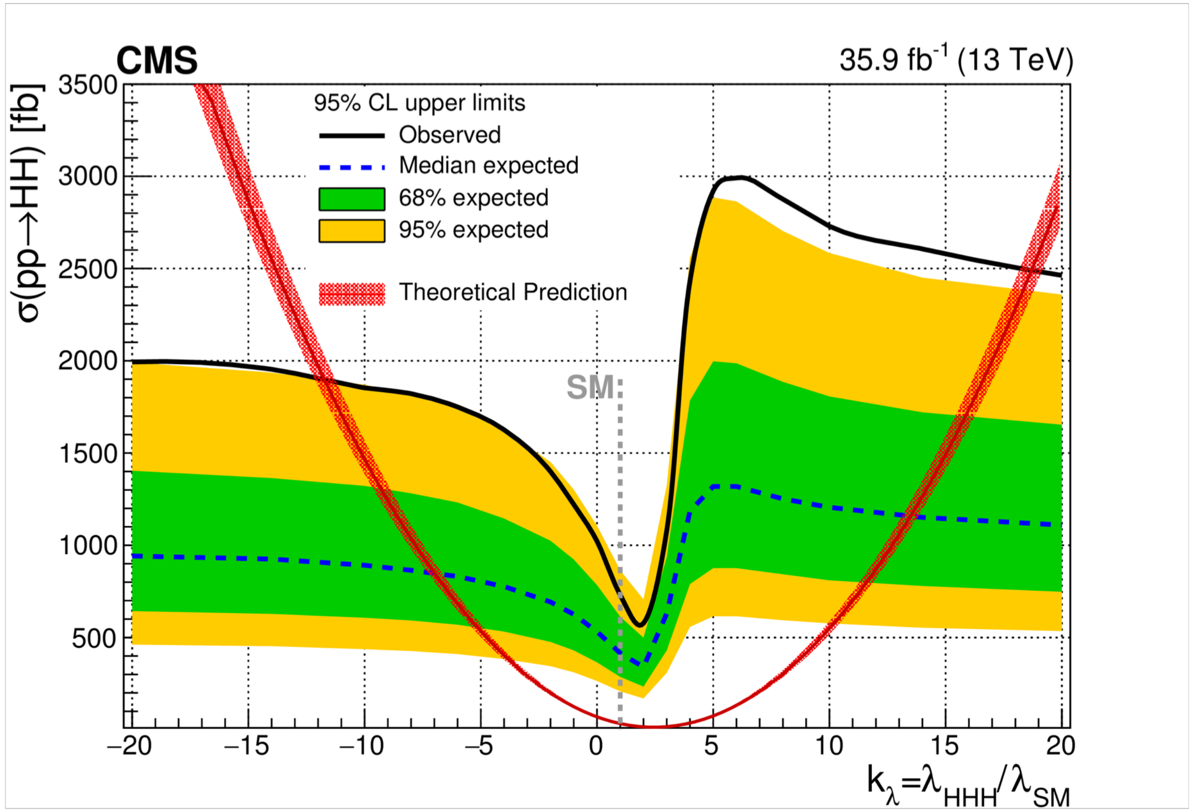
upper limit on Higgs pair production cross-section
Observed **0.22 pb(exp. 0.35pb) ➔ 6.7(10.4) × SM**
$-5.0 < \kappa_\lambda < 12.1$ ($-5.8 < \kappa_\lambda < 12.1$)

Observed **22.2(12.8) × SM**
$-11.8 < \kappa_\lambda < 18.8$ ($-7.1 < \kappa_\lambda < 13.6$)

Upper limit on trilinear coupling

- Run2 combined results ($36 fb^{-1}$)





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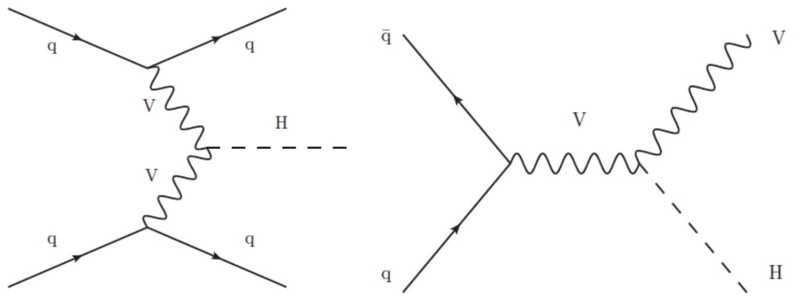
Observed **22.2(12.8) × SM**

$-11.8 < \kappa_\lambda < 18.8$ ($-7.1 < \kappa_\lambda < 13.6$)

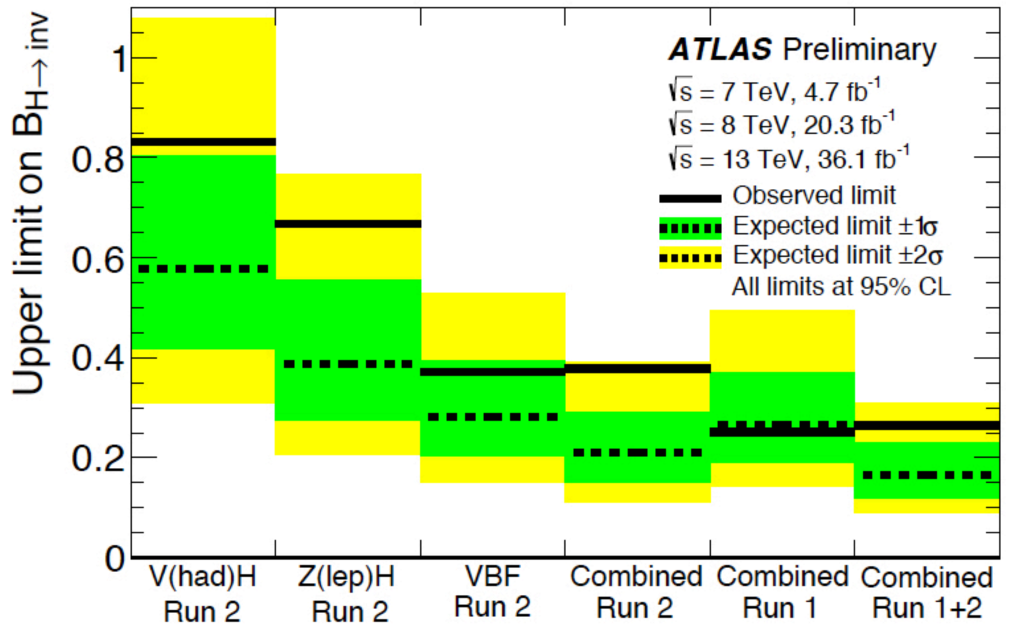
Search for H→ invisible

- ATLAS recently combined three H→invisible searches
  - Invisible BR in SM is very small (ZZ→4ν), 0.1%
    ➔ any observation would be evidence of new physics
  - VBF channel gives stringent upper limit in Run2
    - MET trigger ($MET_{offline}$ > 180 GeV), VBF topology ($\Delta\eta_{jj}$>4.8, m_{jj} > 1 TeV)
    - VBF topology dominant background : W→lν+jets, Z→νν+jets (estimated in the dedicated control region)

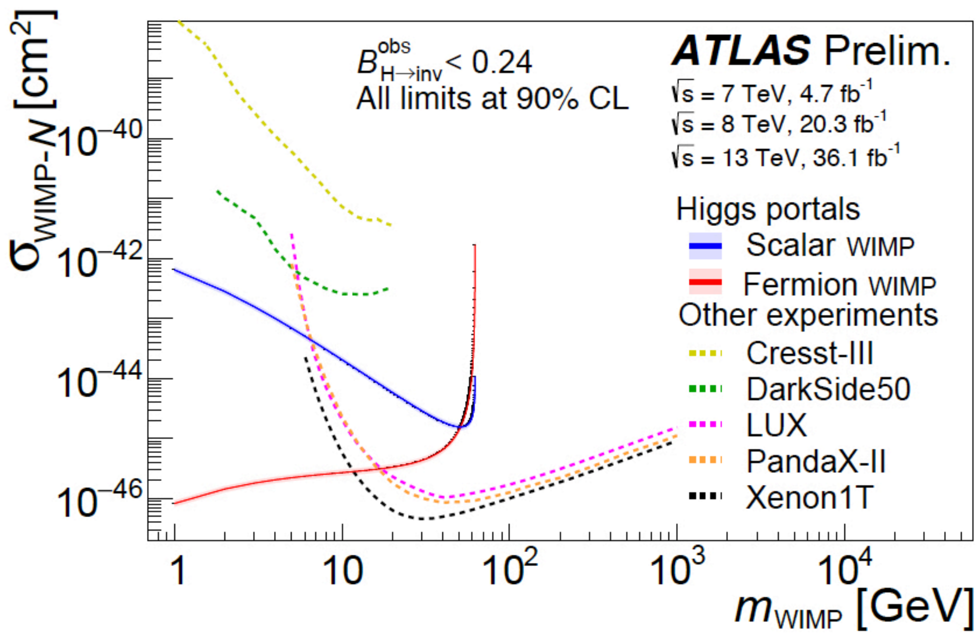
Main production modes



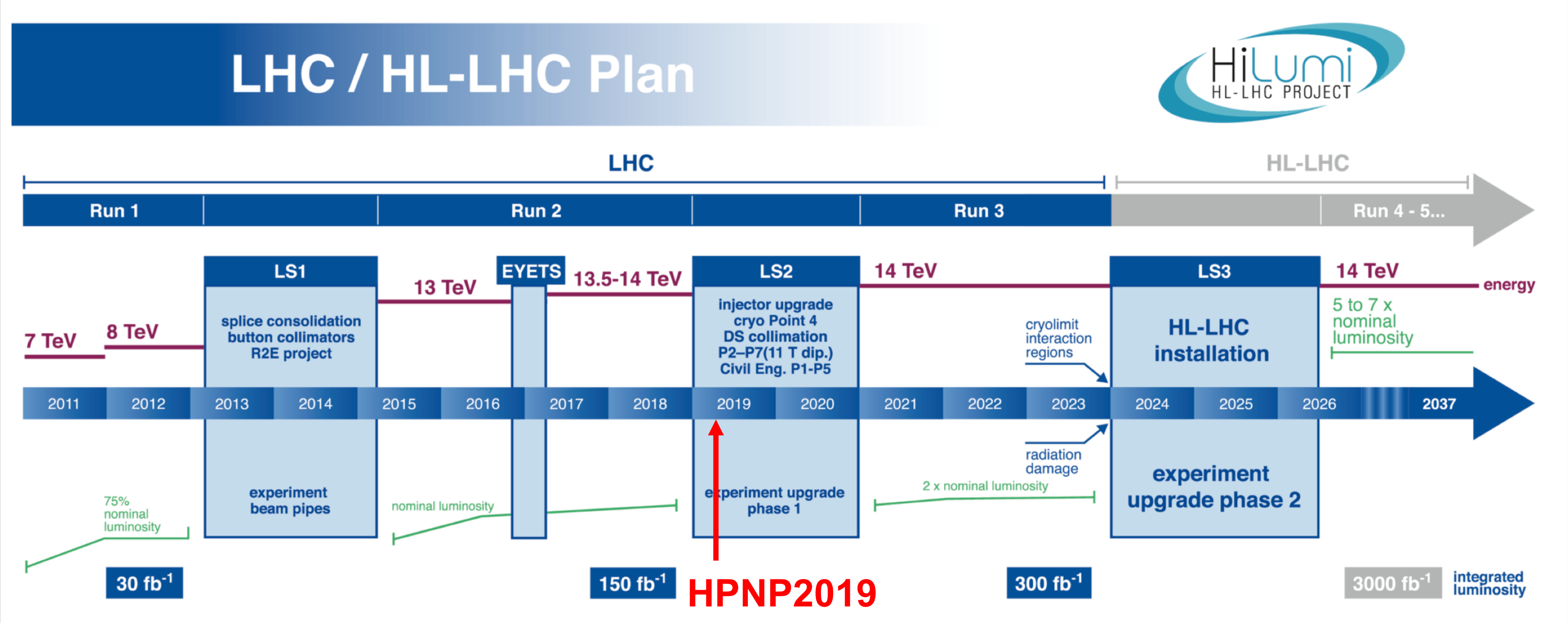
VBF(2jet)+MET   Z/W(→qq/ll)+MET



Obs. BR(H→inv) < 0.26 (exp. 0.17)@95% CL



Higgs poral interpretation



- So far, no clear hint (both direct, indirect) of new physics at LHC
- HL-LHC starts ~2026, $\sqrt{s}$=14 TeV, accumulate **3000fb^{-1}** in 10 years
  - We're at most only analyzing 80fb^{-1} **(~3% of total expected data!!)**
- HL-LHC is Higgs factory : 180M single higgs, 110K di-higgs
  - Accessible to corner of phase space, rare production/decay mode
- Recently Yellow Report published : https://arxiv.org/abs/1902.00134
  - Cross section/coupling measurement
  - higgs pair production/BSM Higgs search

I can't cover all of them....

125 GeV Higgs Precision Measurement at HL-LHC

- Extrapolate results from Run2 analysis ($36fb^{-1}$ or $80fb^{-1}$) to $3000fb^{-1}$
  - It is not straightforward to extrapolate from inaccessible phase space in Run2

Extrapolation assumptions

✓ Signal and background cross sections increase to 14 TeV

✓ Assume experimental condition (reconstruction eff, resolution and fake rate) is similar to Run2 (Harsh pile-up condition compensated by detector upgrade

✓ Assume enough MC statistics ➔ neglect MC stat.

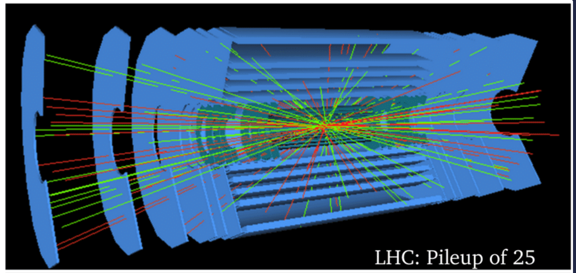
Baseline for systematic uncertainties (Reduced systematic : S2)

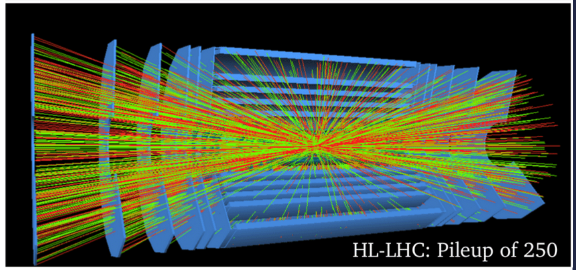
✓Signal and background theory systematic uncertainties are halved

✓Experimental systematic uncertainties ➔ Reduced

✓Luminosity uncertainty 2.5% → 1.0%

➔ Not precise extrapolation but reasonable assumptions





Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

Several exceptions :

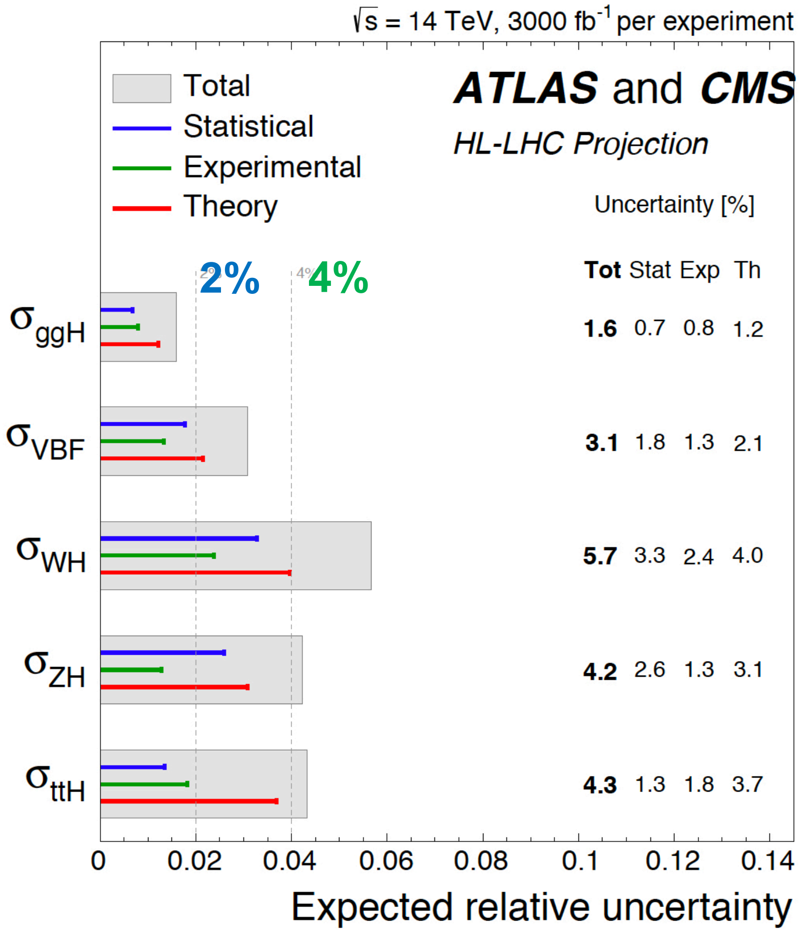
✓ PDF uncertainty reduced more than half

✓ HH analysis consider acceptance increase of b-tagging $|\eta|<2.5$ → $|\eta|< 4.0$

125 GeV Higgs Precision Measurement at HL-LHC

- Combination of ATLAS and CMS results based on extrapolation from Run2

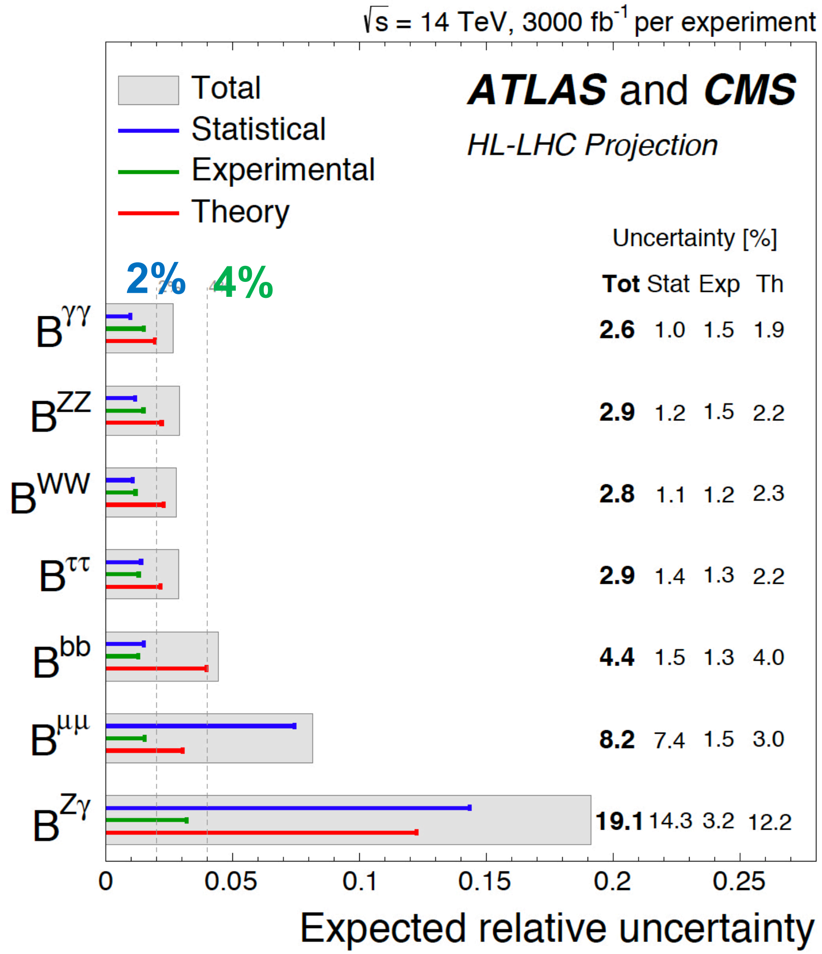
Higgs production cross section (S2)



2-5% precision@3000fb-1 : 5-10 times better than Run2

ttH dominated by signal+bkg theory uncertainty

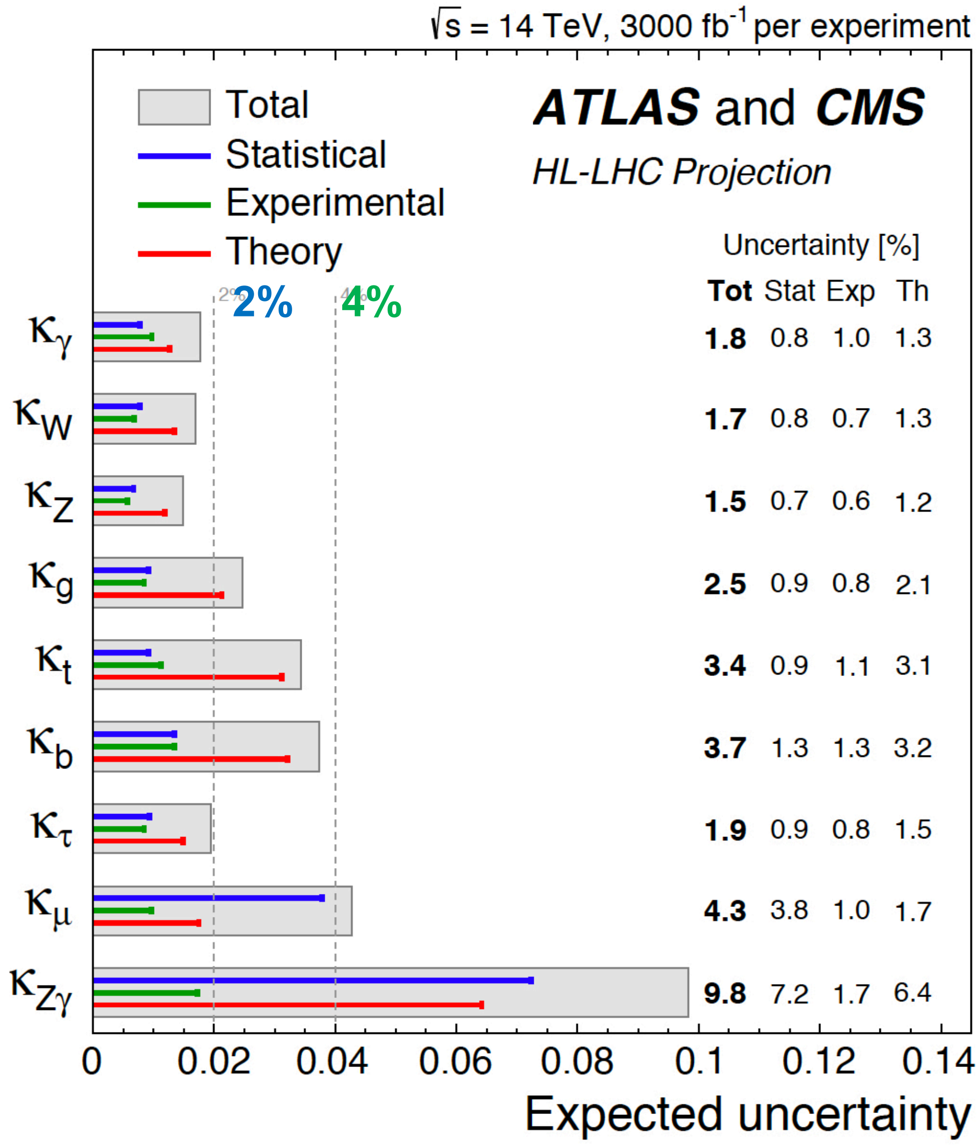
Higgs Branching Fraction (S2)



2-4% precision for main decay modes

< 10(20)% for H→μμ(Zγ)

Coupling Measurement at HL-LHC



Combination of ATLAS and CMS extrapolation from Run2 analysis

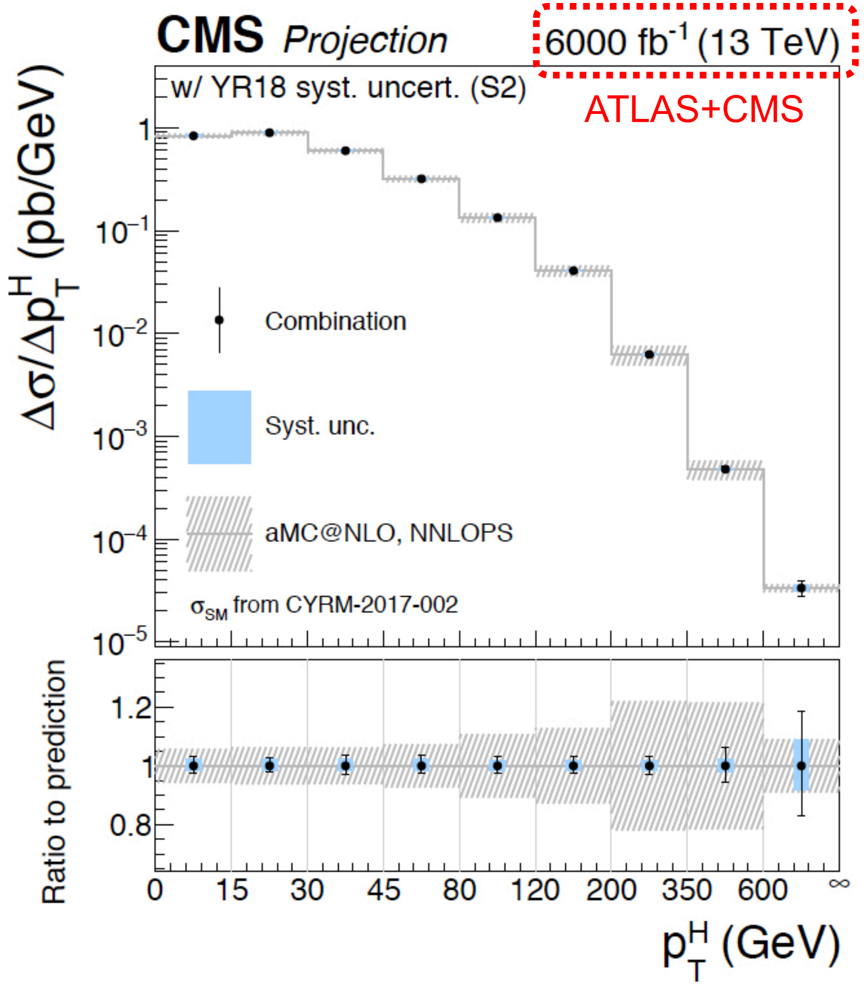
* Expected uncertainty on κ-framework (coupling modifiers)

Dominant coupling modifier parameters can be measured **2-4%** level (limited by theoretical systematic)

Statistically limited

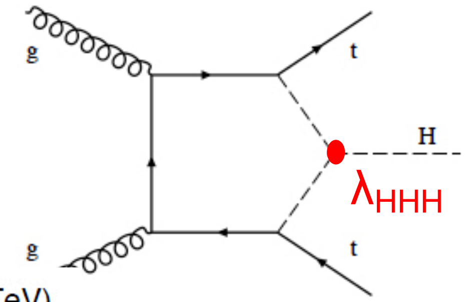
Differential cross section measurement at HL-LHC

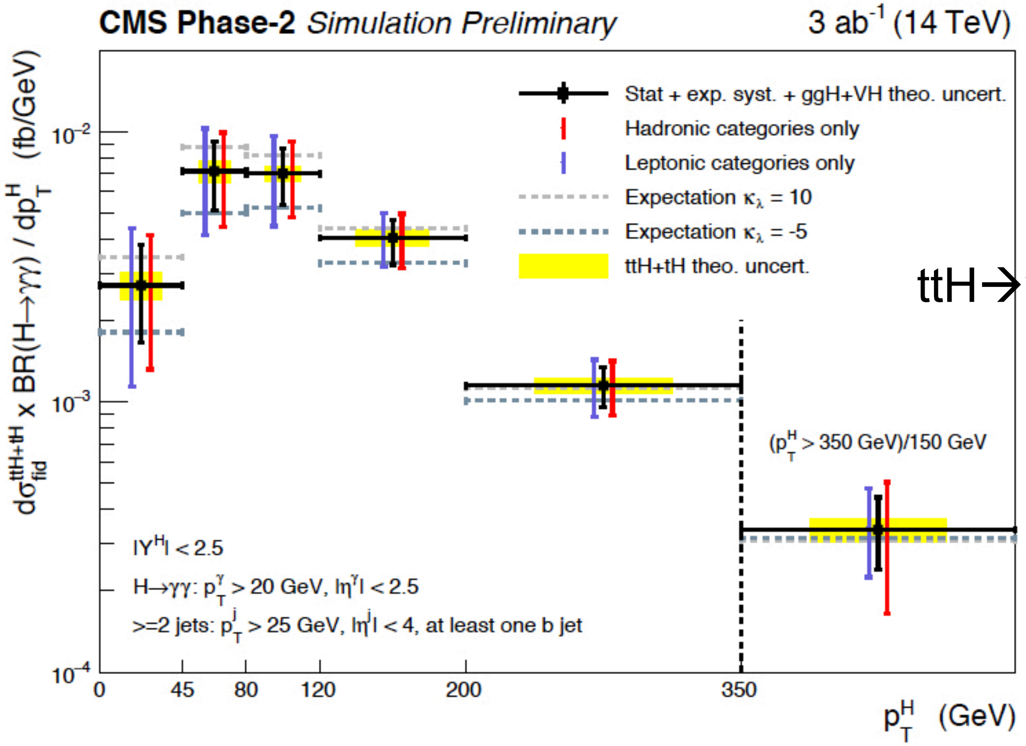
- p_T^H measurement combined H→γγ, H→ZZ, H→bb



3-6% accuracy in p_T^H<600 GeV
~18% p_T^H>600 GeV (stat dominant)

- p_T^H measurement in ttH+tH production using H→γγ
- Single Higgs production is also sensitive to self-coupling ➔ indirect measurement
  - p_T^H distribution depends on on $\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

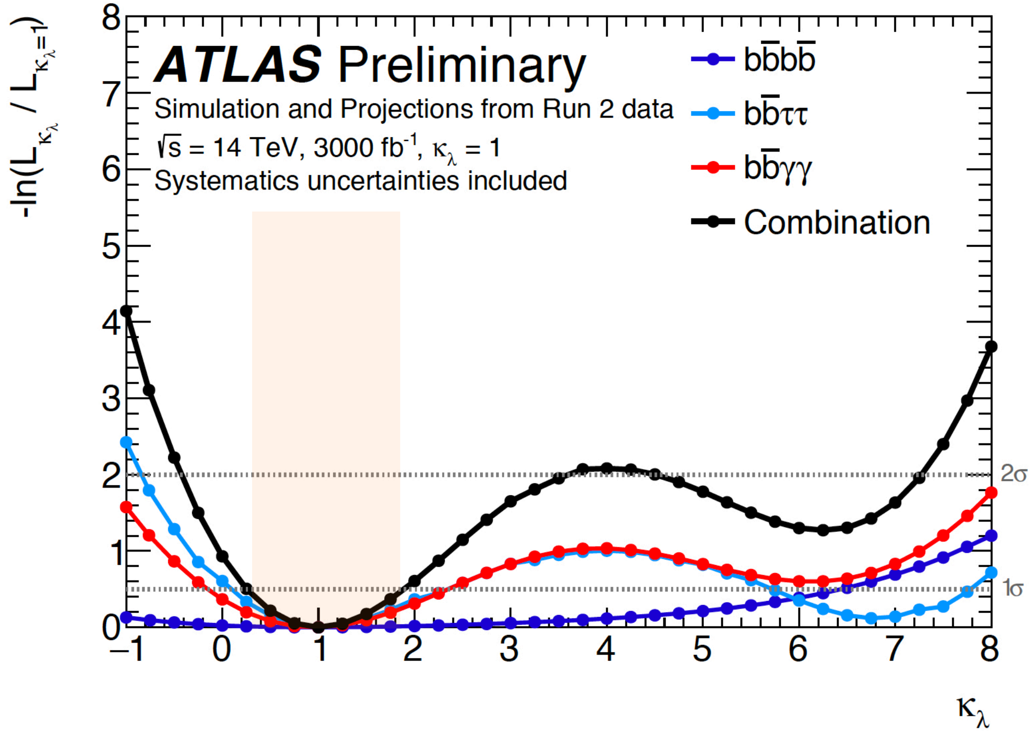




68% Confidence interval $-2 < \kappa_\lambda < 5.5$
Complimentary with the direct dihiggs production

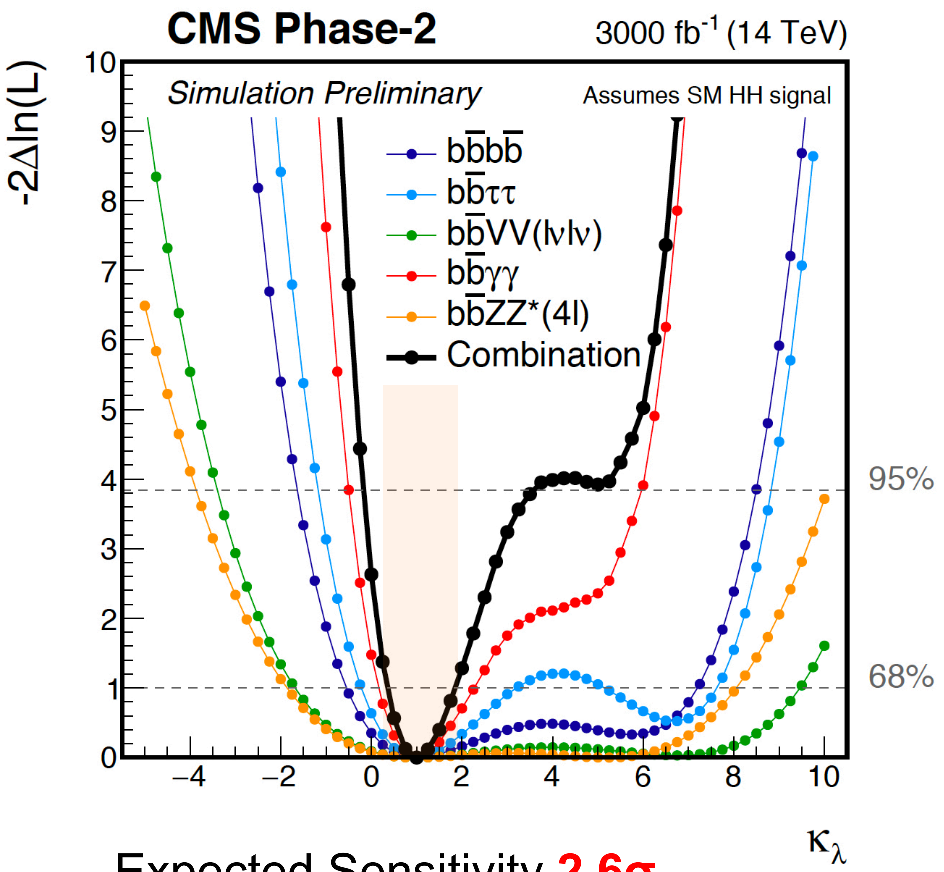
Di-Higgs/Higgs Self-coupling at HL-LHC

- ATLAS Combined analysis : HH→4b, bbττ, bbγγ



Combined measurement (with systematic)
Expected Sensitivity **3.0σ**
uncertainty on μ **40% (1.0±0.4)**
68% Confidence interval on κ_λ **$0.25 < \kappa_\lambda < 1.9$**

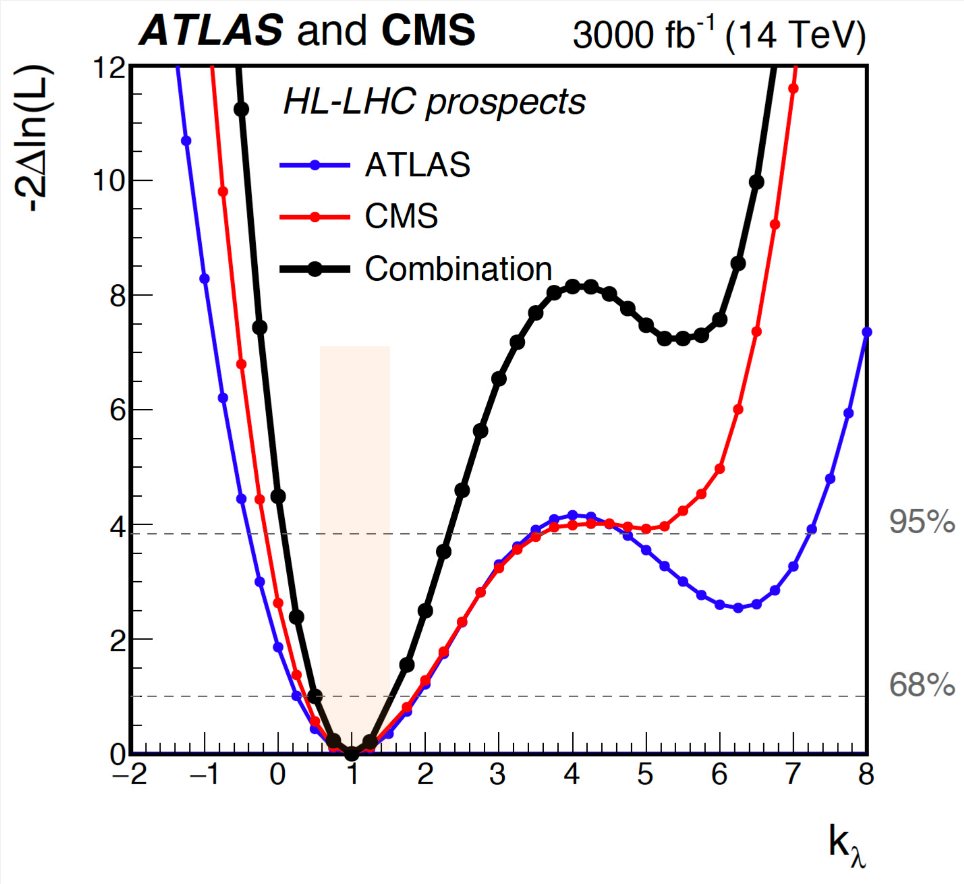
- CMS Combined analysis : HH→4b, bbττ, bbγγ, bbVV, bbZZ



Expected Sensitivity **2.6σ**
Uncertainty on μ **40%**
68% confidence interval on κ_λ **$0.35 < \kappa_\lambda < 1.9$**

Di-Higgs/Higgs Self-coupling at HL-LHC

ATLAS+CMS Combination



Expected significance (κ_λ=1)

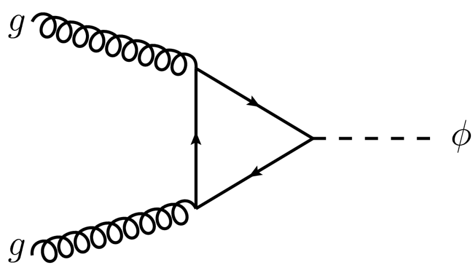
4.0σ (with systematic)

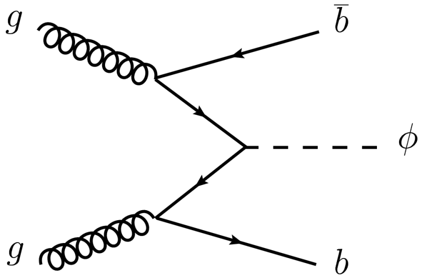
68% Confidence interval

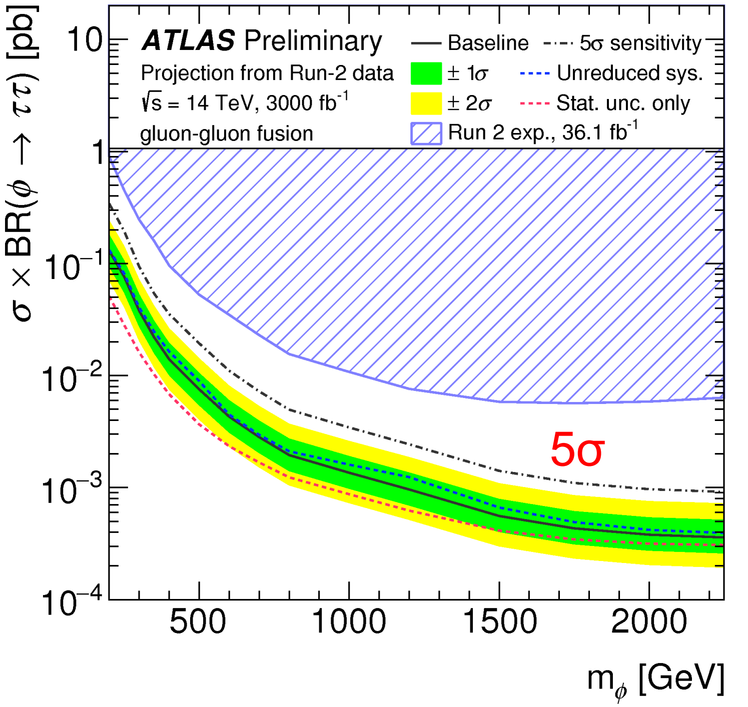
$0.52 < \kappa_\lambda < 1.5$

BSM Higgs Search at HL-LHC

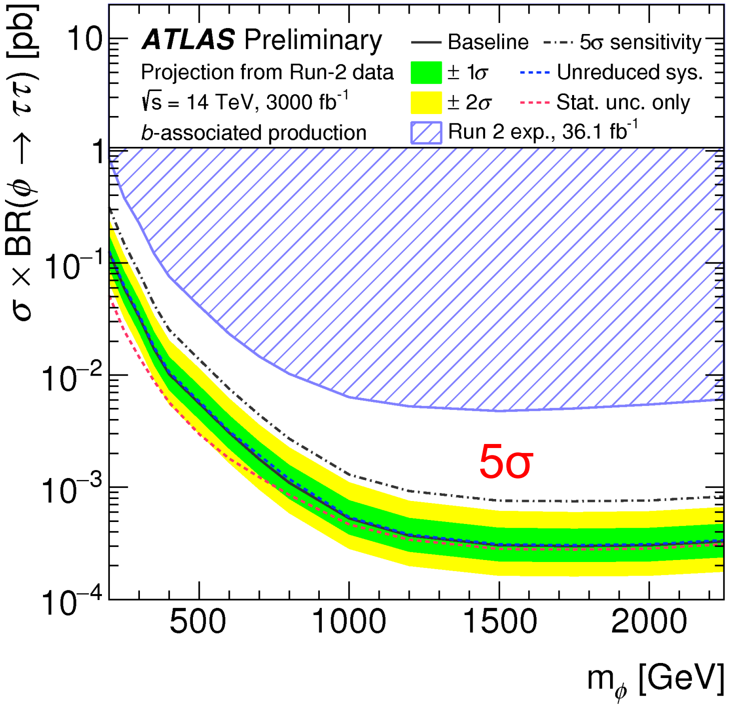
- Heavy Higgs Search ($\Phi \rightarrow \tau\tau$) extrapolated from Run2 ($36 fb^{-1}$)
- 4 signal region : (ggF, b-associated production) × ($\tau_{had}\tau_{had}$, $\tau_{had}\tau_{had}$)
- Much larger parameter space over Run2 exclusion has 5σ sensitivity



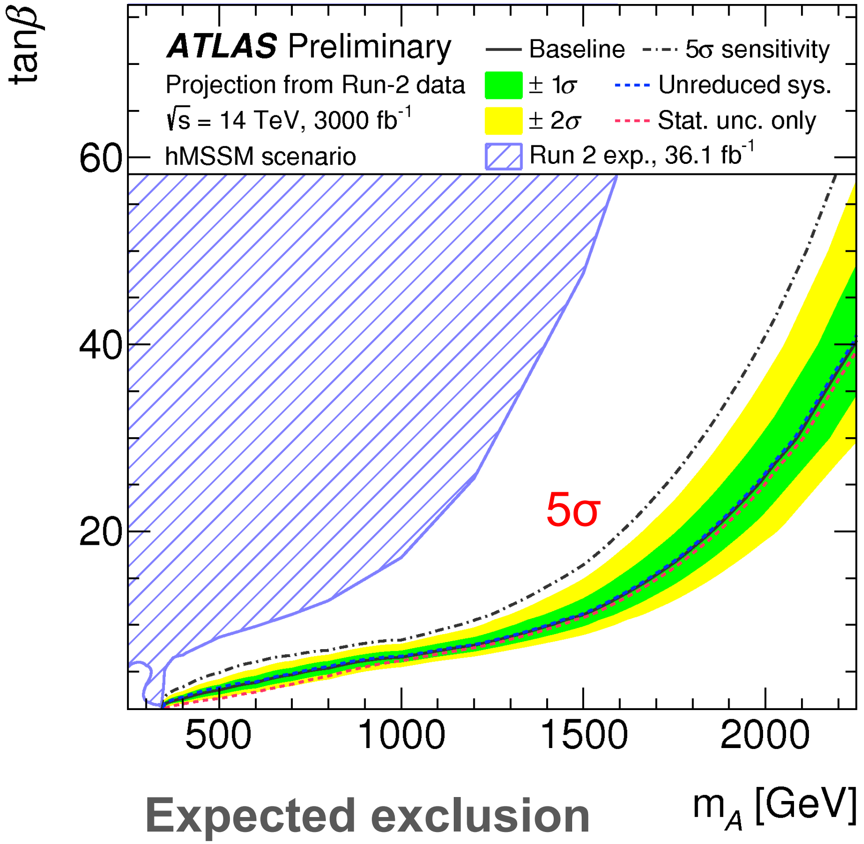




Exclusion limit **~0.4fb at 2.25TeV**



Exclusion limit **~0.3fb at 2.25TeV**



Expected exclusion

$\tan\beta > 10$ for m_A=1.5 TeV

Summary

- Run2 Higgs analysis already made great achievement in **$36fb^{-1}/80fb^{-1}$**
  - H→bb observation : **5.4σ (ATLAS), 5.4σ(CMS)**
  - ttH observation : **5.8σ (ATLAS), 5.2σ(CMS)**
  - VH observation : **5.3σ (ATLAS)**

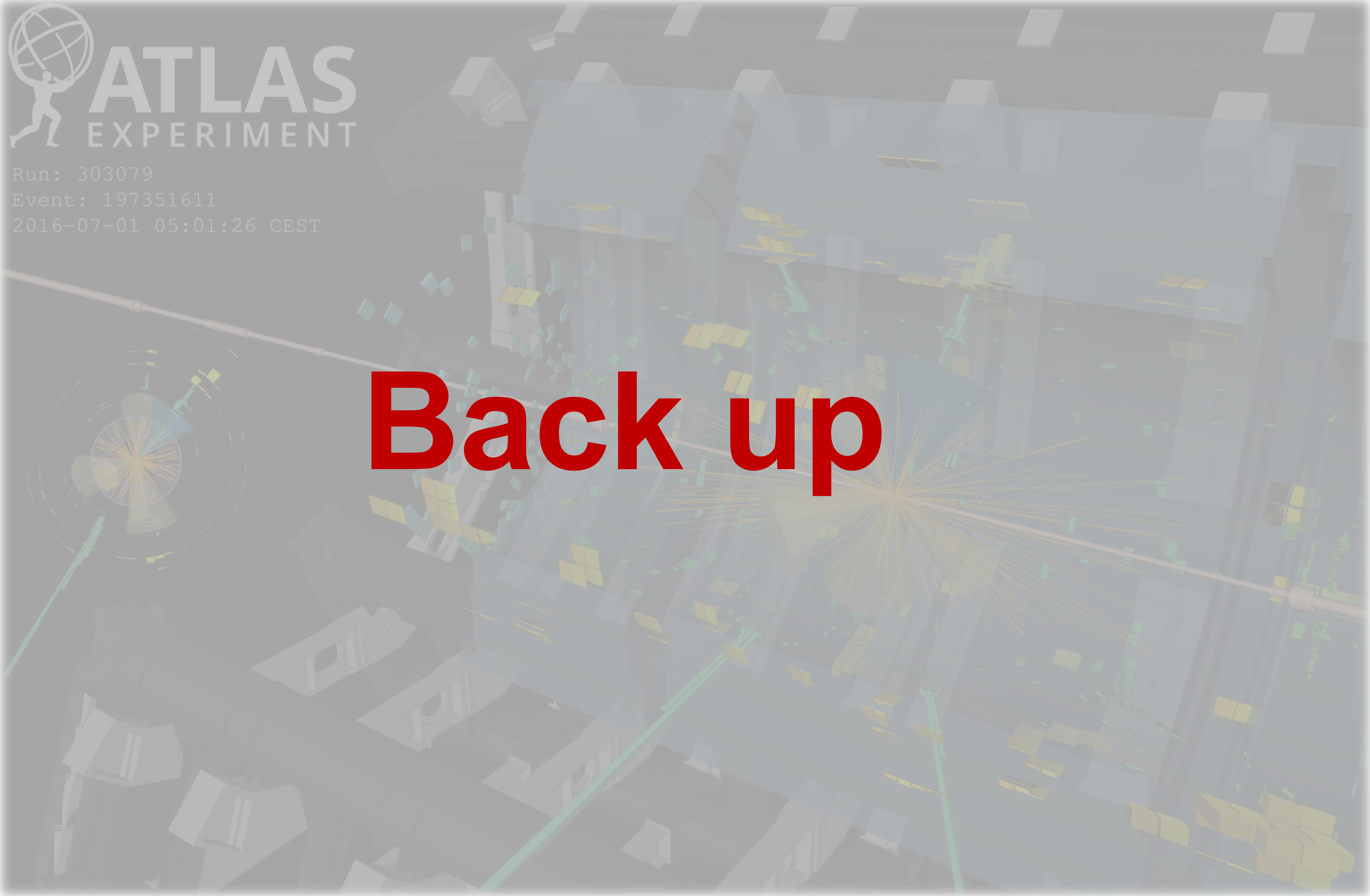
  ➔Earlier than expectation from Run2

- HL-LHC prospects show lot of promising Higgs results
  - Precision measurement of cross section/coupling : **2-5% level**
  - Significant increase of search sensitivity for rare production/decay : **Higgs pair production ~4σ (κ_λ=1)** in ATLAS+CMS combination

- We don’t analysis full Run2 data yet!! ☺
  - $36fb^{-1}/80fb^{-1}$ ➔ $140fb^{-1}$ (×4/×1.8 more data!!)
  - Still many improvements of analysis techniques (e.g. ML)

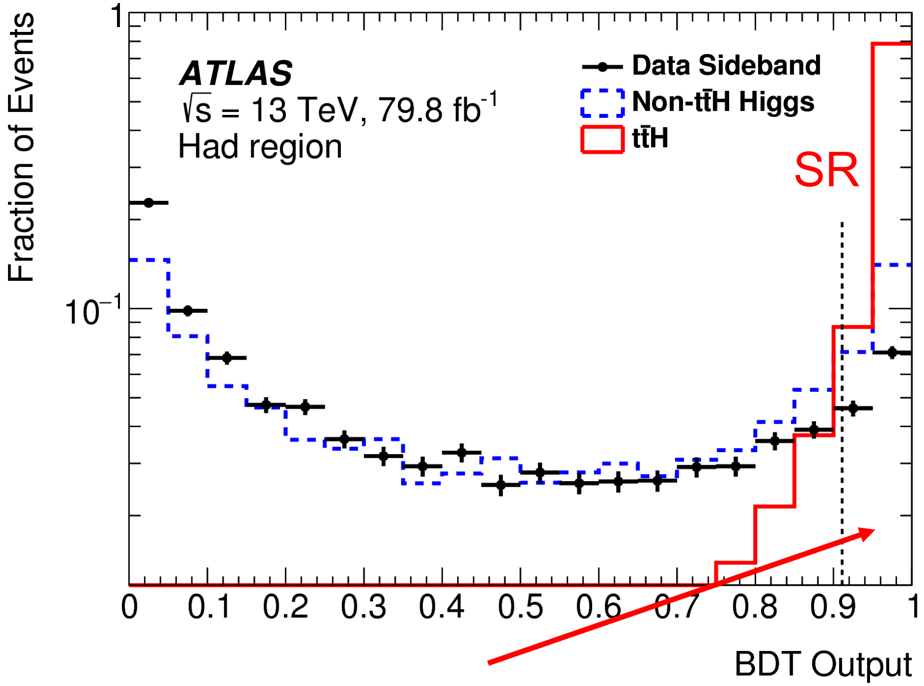
Many full Run2 results will come in 2019!!

Back up

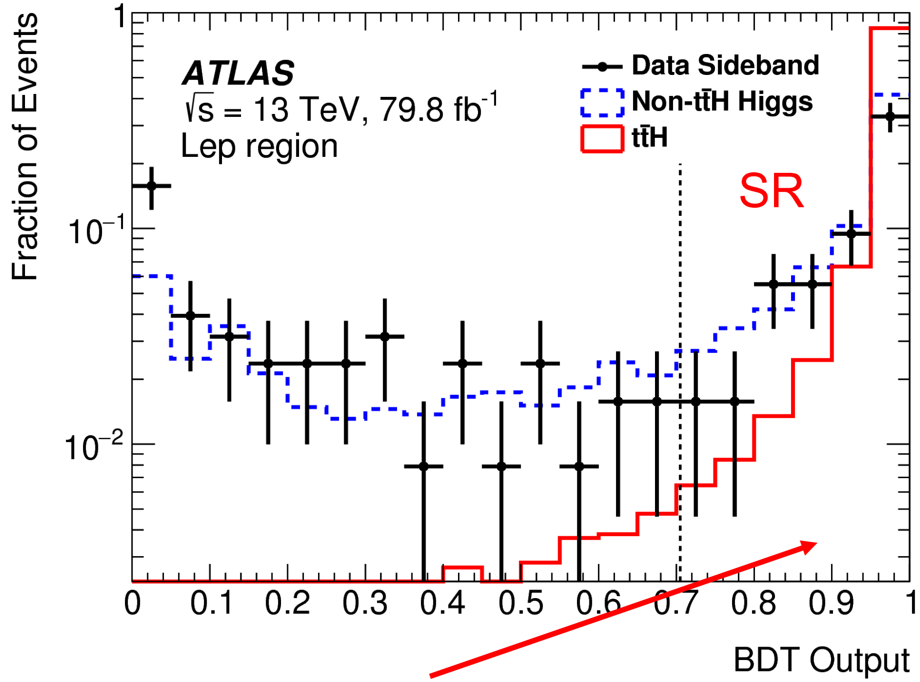

ATLAS
EXPERIMENT
Run: 303079
Event: 197351611
2016-07-01 05:01:26 CEST

ttH→γγ Categorization

- BDT input variables does not have correlation with $m_{\gamma\gamma}$
  - lep : jet and lepton 4 momentum, photon 4 momentum ($p_T/m_{\gamma\gamma}$ instead of p_T)
  - had : jet 4 momentum (up to 6jets), b-tagging information, photon 4 momentum
- Background modeling from $m_{\gamma\gamma}$ sideband (105 GeV < $m_{\gamma\gamma}$ < 120 GeV, 130 GeV < $m_{\gamma\gamma}$ < 160 GeV)
- Signal region keep 85%(97%) ttH signal, reject 89%(43%) non-resonant background

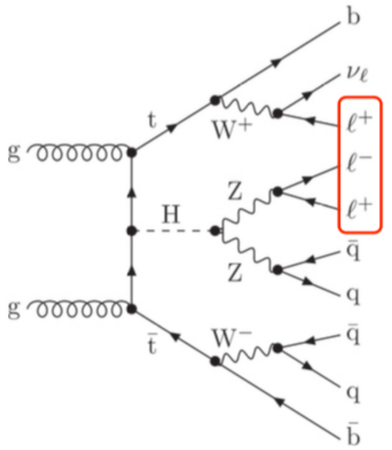


subdivided into three categories



subdivided into four categories

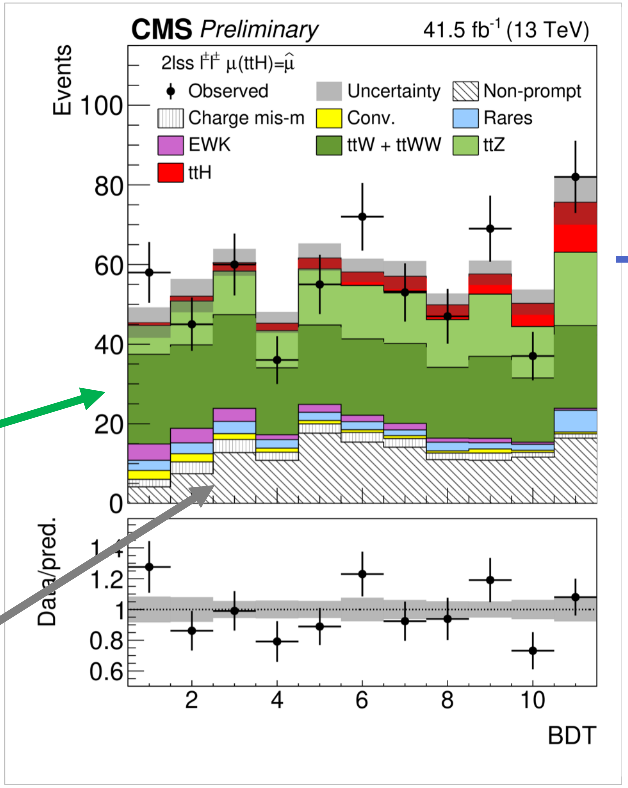
Search for ttH Production

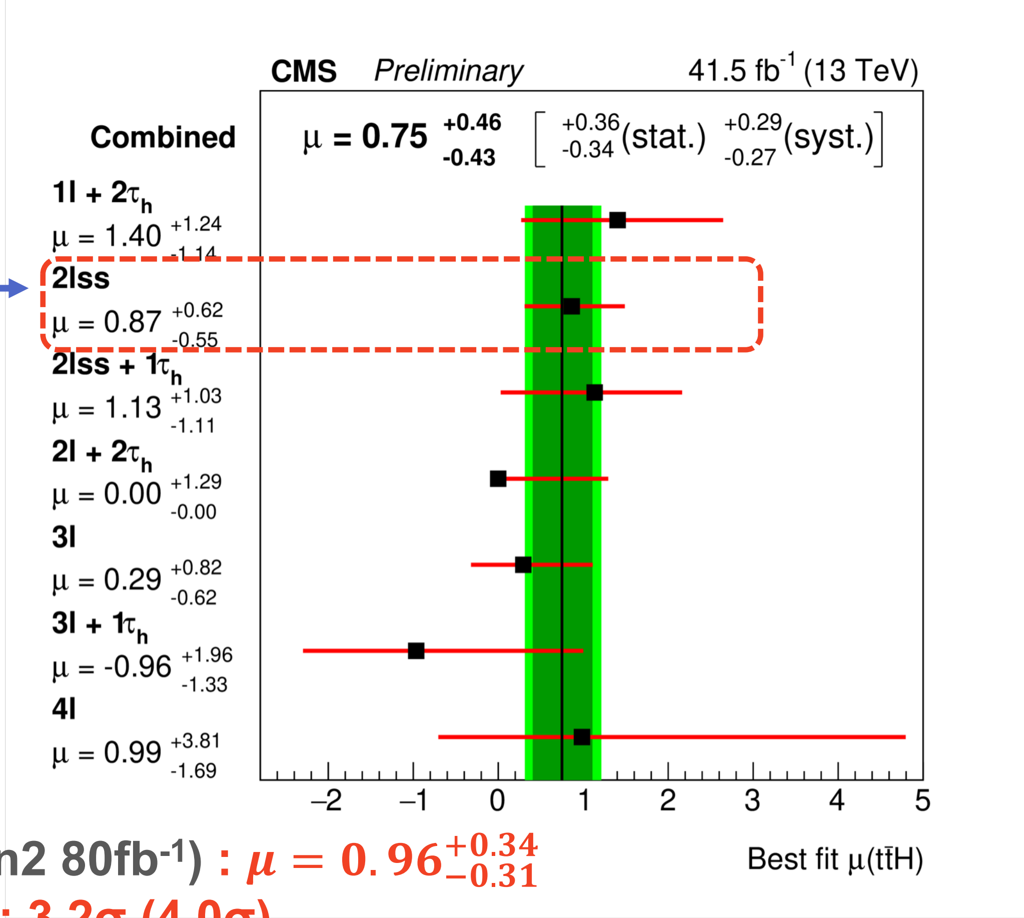


- **H→ multi-lepton : CMS update with 80^{-1}**
- Category with 2lep(same-sign), 3lep has best significance

BDT discriminant is used to extract signal

- lepton kinematics
- jet multiplicity
- ΔR(lep-jet)





ttV(V) background

➔ constrain with control region (low jet multiplicity, Z region)

Fake background

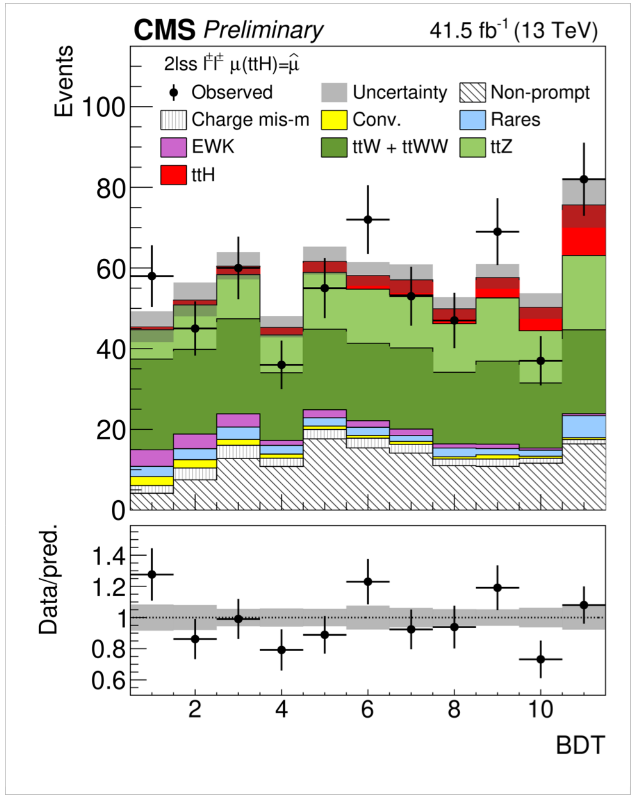
➔ dominant systematic source

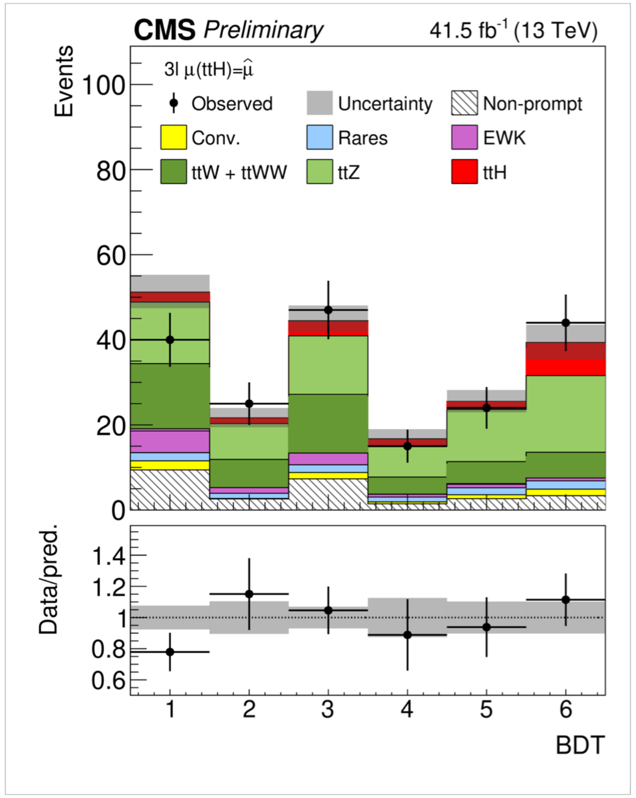
signal strength (combined Run2 80fb^{-1}) : $\mu = 0.96^{+0.34}_{-0.31}$

Obs(exp) significance (80fb^{-1}) : 3.2σ (4.0σ)

ttH Multi-Lepton

- BDTs have been trained separately for each channel including τ_h
- MVA with kinematic variables, hadronic top tagger (D_{thad}^{max}), jet tagger (D_{Hj}^{max}) is used in $2l_{ss}$
  - Two discriminant ttH vs ttV, ttH vs ttbar)





Category	$1\ell+2\tau_h$	$2\ell ss+1\tau_h$	$2\ell+2\tau_h$	$3\ell+1\tau_h$	$2\ell ss$		3ℓ	
					$t\bar{t}$	$t\bar{t}V$	$t\bar{t}$	$t\bar{t}V$
Leading ℓ cone p_T	X		X	X		X		X
Trailing ℓ cone p_T		X		X		X		X
Minimum of ΔR(leading ℓ, j)	X	X	X	X	X	X	X	X
Minimum of ΔR(trailing ℓ, j)		X			X	X	X	X
ΔR(leading ℓ, trailing ℓ		X		X				
Transverse Mass of leading ℓ	X	X			X	X	X	X
Transverse Mass of trailing ℓ		X						
Maximum $\lvert\eta\rvert$ of ℓ collection		X		X	X	X	X	X
Signal leading $\ell\times$ signal trailing ℓ			X					
Average of ΔR(jj)	X	X	X					
Number of jets ($p_T > 25$ GeV)		X		X	X	X	X	X
Number of loose b-jets	X		X					
Mass of leading medium b-jet pair		X						
Mass of leading loose b-jet pair				X				
E_T^{miss}	X	X		X				
res-hTT	X	X						
Hadronic t p_T	X	X						
$\mathcal{D}_{\mathrm{thad}}^{\mathrm{max}}$					X			
$\mathcal{D}_{\mathrm{Hj}}^{\mathrm{max}}$						X		
Leading τ_h p_T	X	X	X	X				
Trailing τ_h p_T	X		X					
Mass of leading τ_h + trailing τ_h	X		X					
ΔR(leading τ_h, trailing τ_h)	X		X					
$cos(\theta)^*$(leading τ_h, trailing τ_h)	X		X					
Minimum of ΔR(leading τ_h, j)	X	X		X				
Minimum of ΔR(trailing τ_h, j)	X							
Minimum of $\Delta R(\tau_h, j)$			X					
Mass of leading ℓ+ leading τ_h				X				
Mass of trailing ℓ+ leading τ_h		X		X				
ΔR(leading ℓ, leading τ_h)	X	X						
ΔR(trailing ℓ, leading τ_h)		X						
$\Delta R(\ell, \tau_h)$ for same-sign pair of (ℓ, τ_h)	X							
Average of $\Delta R(\ell, \tau_h)$			X					
MEM							X	X
Number of variables	17	18	13	12	6	8	6	8

VH Higgs Effective Lagrangian

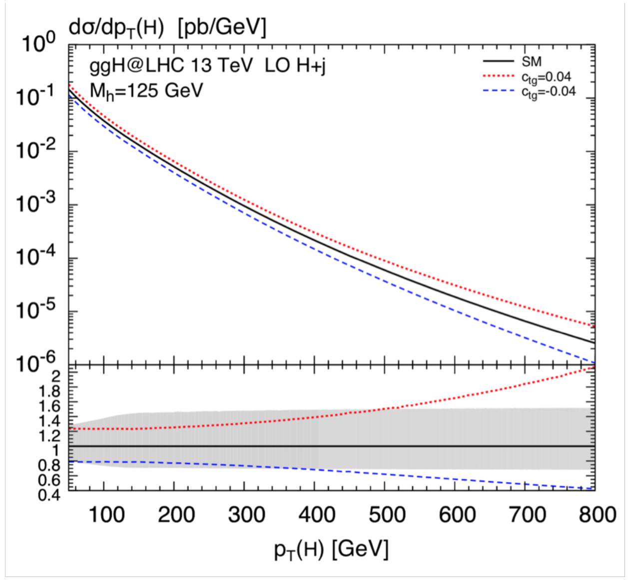
- Strongly Interacting Light Higgs basis

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2}$$

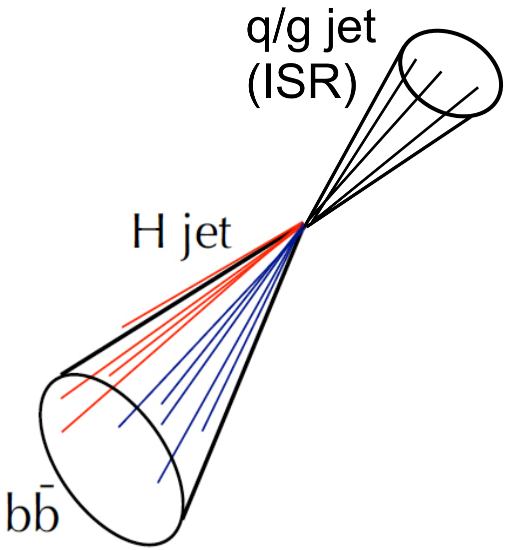
$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = {} & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R\right) + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\left(D^\mu H\right)^\dagger\left(D^\nu H\right) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,
\end{aligned}$$

Boosted H→bb analysis ATLAS

- High p_T Higgs (p_T^H) is sensitive to new physics
- H→γγ, H→ZZ→4l cross section is too small to access high p_T^H due to low statistics
  - 29fb with p_T^H>400 GeV
    - (pp→H+X)*BR(H→bb) : 17fb : 2000events
    - (pp→H+X)* BR(H→γγ) : 0.07fb ~10 events
    - (pp→H+X)* BR(H→ZZ→4l) : 0.0003fb ~0.01events



- Selection
  - at least two larger-R (Anti-k_t, R=1.0) jets, p_T>480(250) GeV ← trigger requirement
  - Signal Region : Require 2 b-tagging (WP : 77% eff)
  - Control Region : no b-tagging

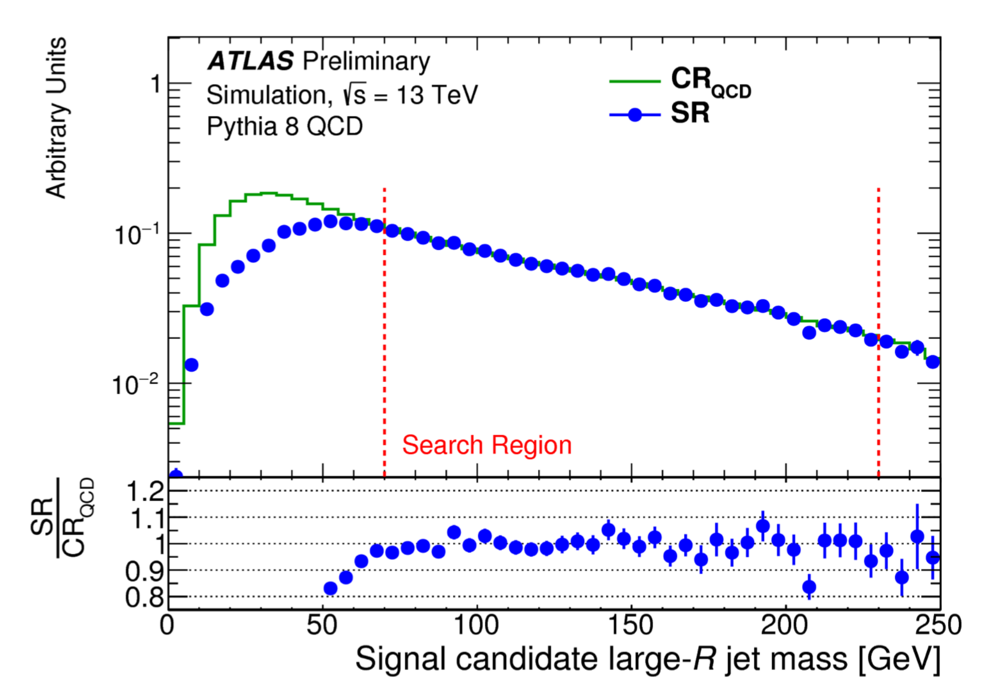


- Signal/Background component
  - ggF is dominant but VBF/VH is not negligible
  - Z(→bb) is dominant resonant background in SR

		CR_{QCD}	SR
V + jets	Z + jets	0.28	0.80
	W + jets	0.72	0.20
$t\bar{t}$	All hadronic	0.58	0.63
	Semi-leptonic	0.38	0.34
	Dileptonic	0.04	0.03
$H \to b\bar{b}$	ggF	0.49	0.53
	VBF	0.17	0.25
	WH	0.21	0.12
	ZH	0.12	0.10

Boosted H→bb analysis (ATLAS)

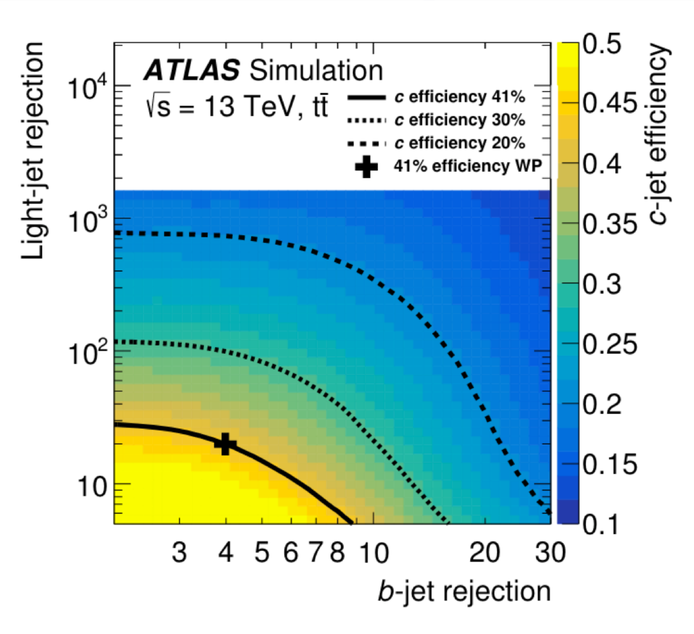
- Background estimation
  - Non resonant QCD background : parametric function ➔ function is validated in CR_{QCD} data
  - Z/W+jets : m_J shape from MC, normalization fitted to data
  - ttbar : MC with extra scale factor from CR_{ttbar}
    - CR_{ttbar} μ+jets events (90% pure ttbar events)
    - Estimated normalization factor 0.84
- Systematic uncertainty
  - Higgs theory uncertainty (p_T^V>400 GeV) ~30%
  - Experimental uncertainty : jet energy/mass scale and mass resolution, b-tagging

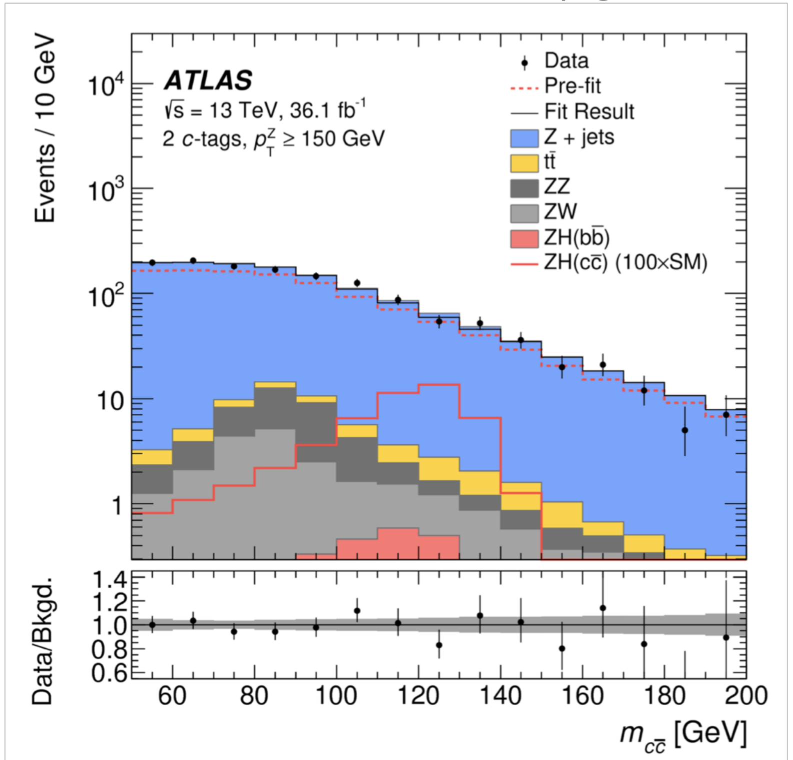


		Impact on Signals ($\sqrt{\Delta\sigma^2}/\mu$)			
Source	Type	V+jets	Higgs	Z' (100 GeV)	Z' (175 GeV)
Jet energy and mass scale	Norm. & Shape	15%	14%	23%	18%
Jet mass resolution	Norm. & Shape	20%	17%	30%	20%
V + jets modeling	Shape	9%	4%	4%	< 1%
$t\bar{t}$ modeling	Shape	< 1%	1%	< 1%	11%
b-tagging (b)	Normalisation	11%	12%	11%	15%
b-tagging (c)	Normalisation	3%	1%	3%	5%
b-tagging (l)	Normalisation	4%	1%	4%	7%
$t\bar{t}$ scale factor	Normalisation	2%	3%	2%	58%
Luminosity	Normalisation	2%	2%	2%	3%
Alternative QCD function	Norm. & Shape	4%	4%	3%	17%
W/Z and QCD (Theory)	Normalisation	14%	–	–	–
Higgs (Theory)	Normalisation	–	30%	–	–

Search for H→cc (and Prospect)

- Direct search for the interaction of Higgs with 2nd generation fermion
  - BR(H→cc) ~2.9%
- Analyzed only VH→llcc channel
  - Dedicated c-tagging algorithm : c-tag eff 41%, b-jet eff 25%, light eff 5%
  - Final discriminant : m_{cc} (tighter selection than VH→llbb analysis)





No significant excess in 36fb^{-1}

95% CL upper limit on σ(pp→ZH)*BR(H→bb)

2.7pb (still 100 × higher than SM)

HL-LHC prospect (3000fb^{-1})

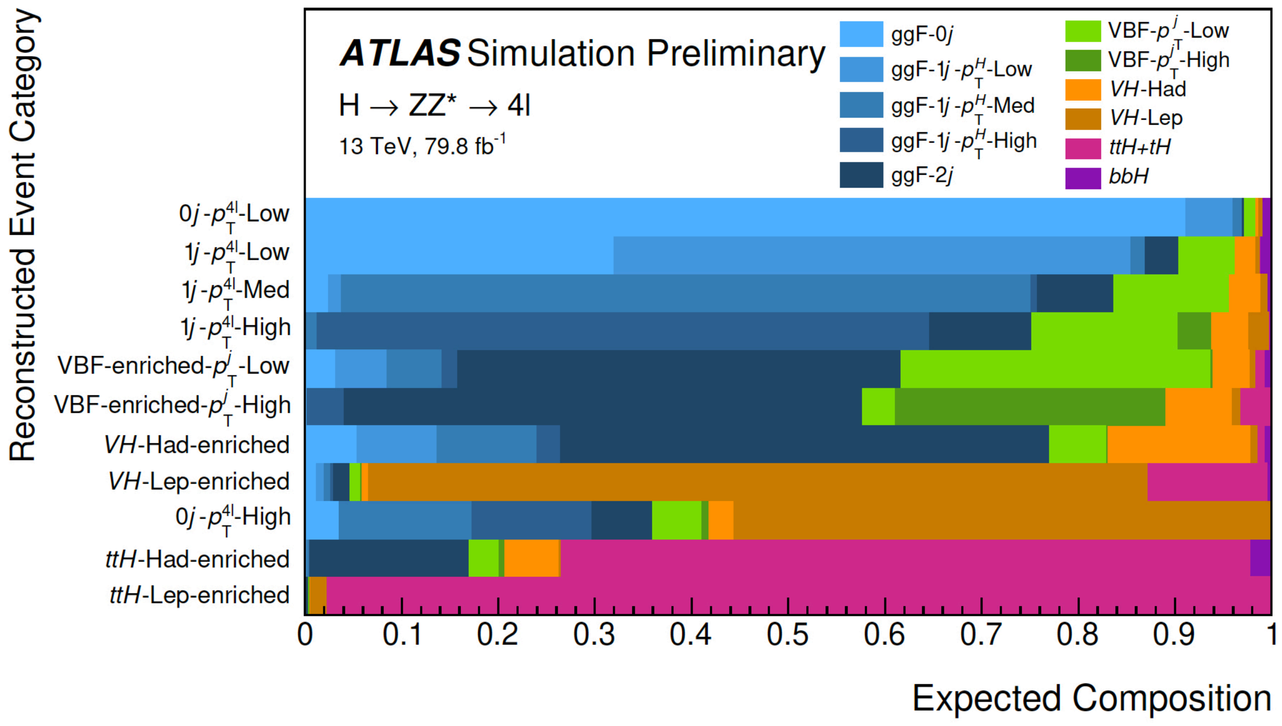
95% CL upper limit on signal strength

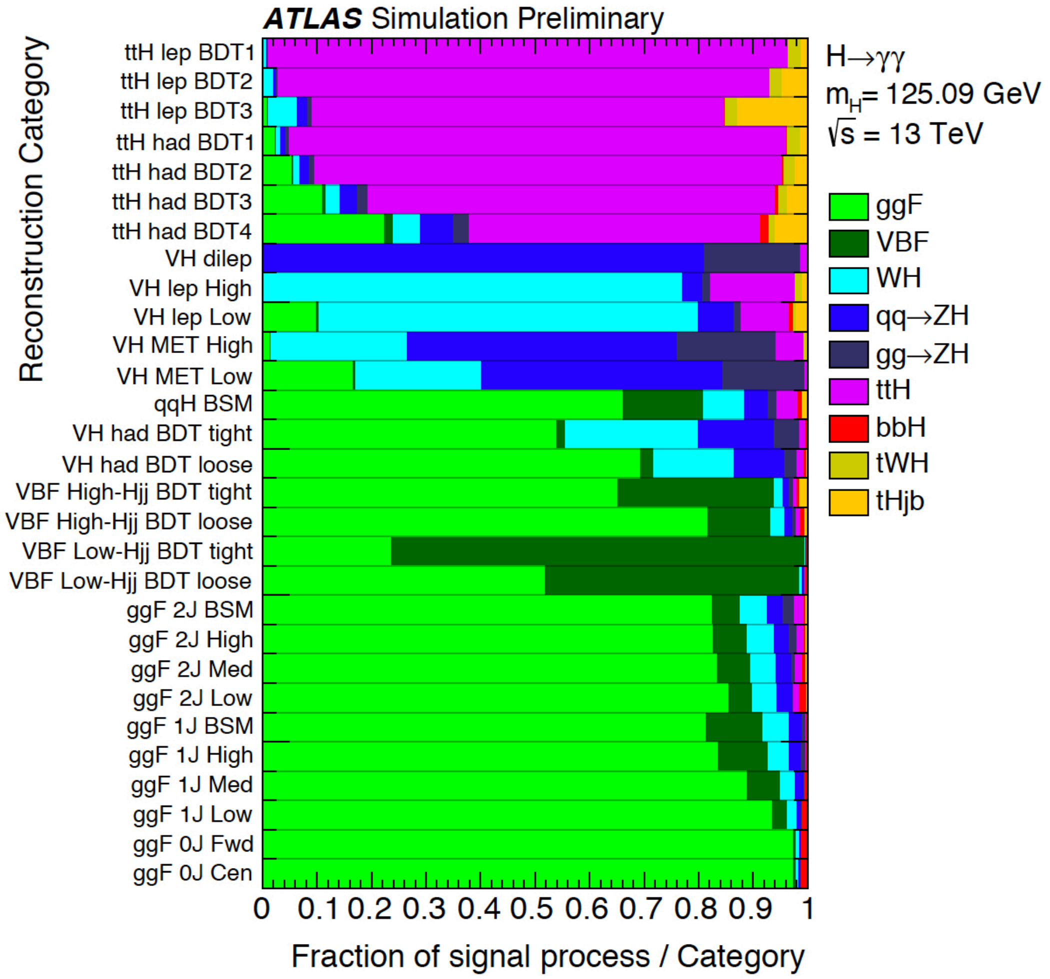
$\mu_{ZH(cc)}$<6.3

* Analysis improvement is required (c-tagging, MVA)

Property Measurement

- STXS measurement



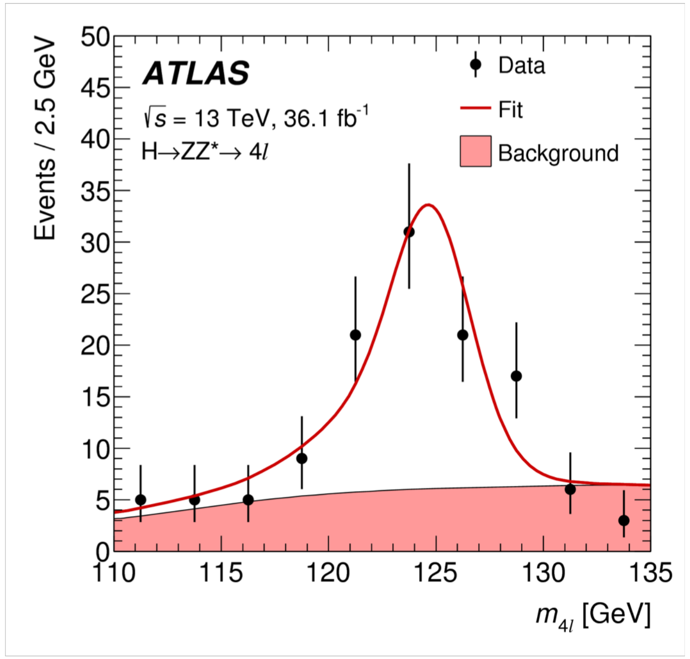


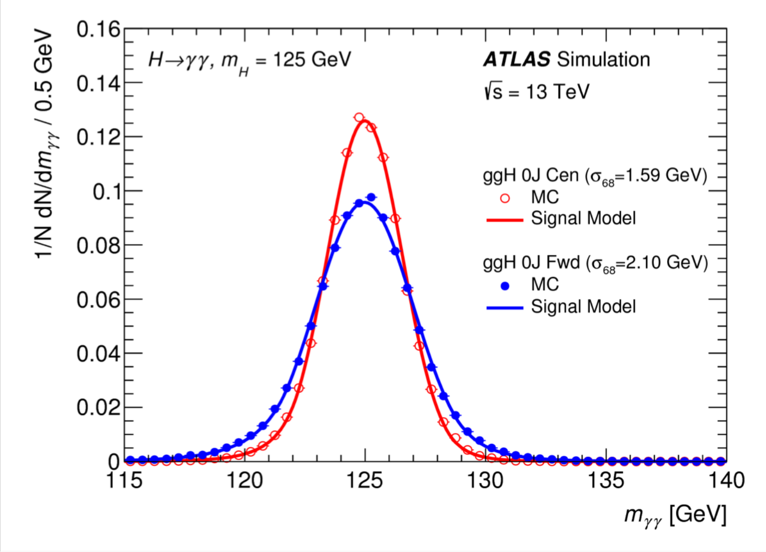
Nicely separate targetting signal process

0j-p_T^{4l}-High category : require N_{jet}=0 p_T^{4l}>100 GeV

➔ enhance VH→lν(missed lepton)4l and νν4l

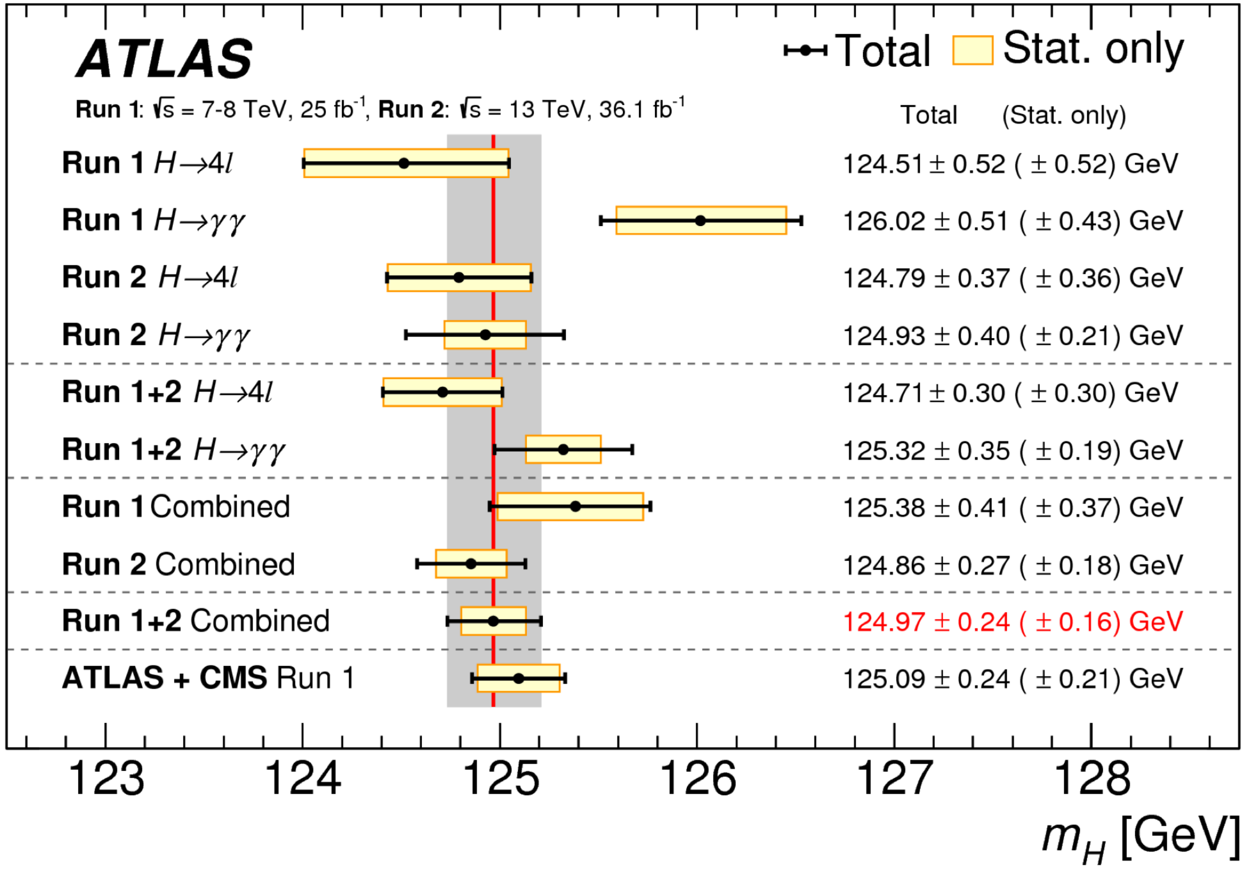
Mass Measurement (ATLAS)





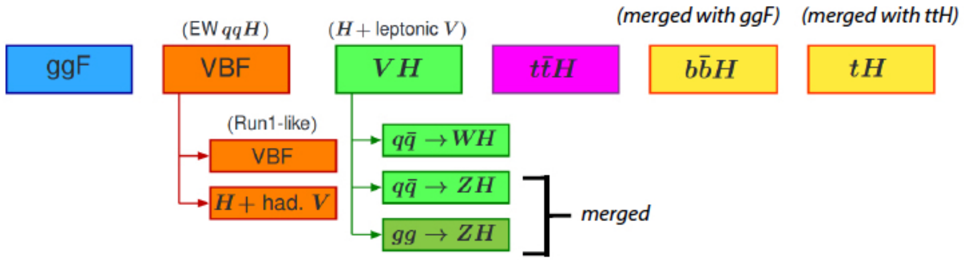
- Mass measurement in Run2 (H→γγ, H→ZZ→4l)
  - H→γγ : dominated by systematics (EM calorimeter response, material)
  - H→ZZ→4μ : dominated by statistics (μ resolution is excellent)

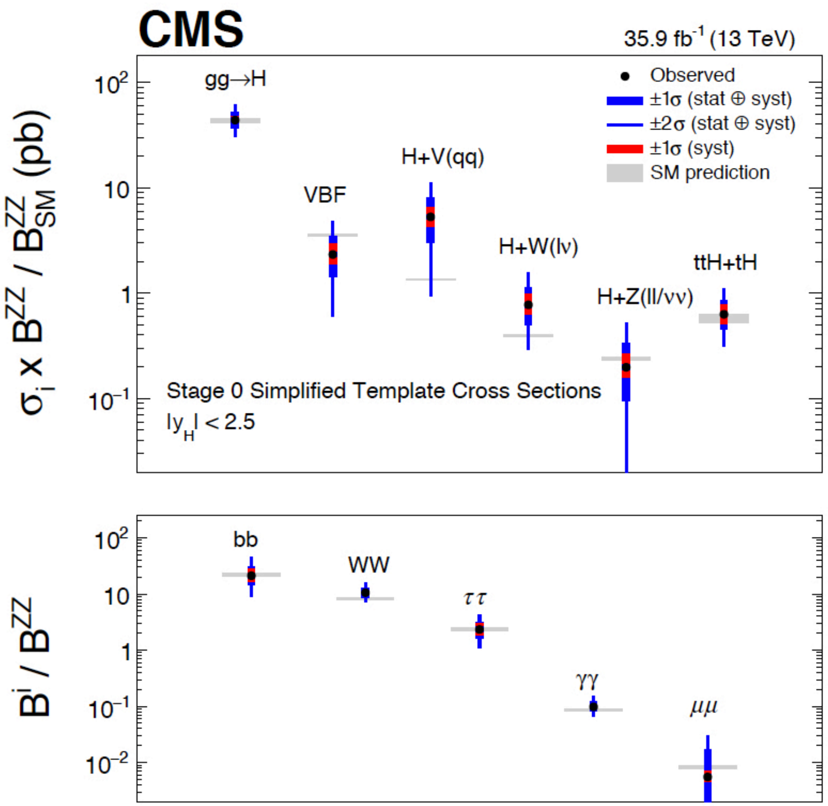
124.97±0.24 (0.19% accuracy!!)



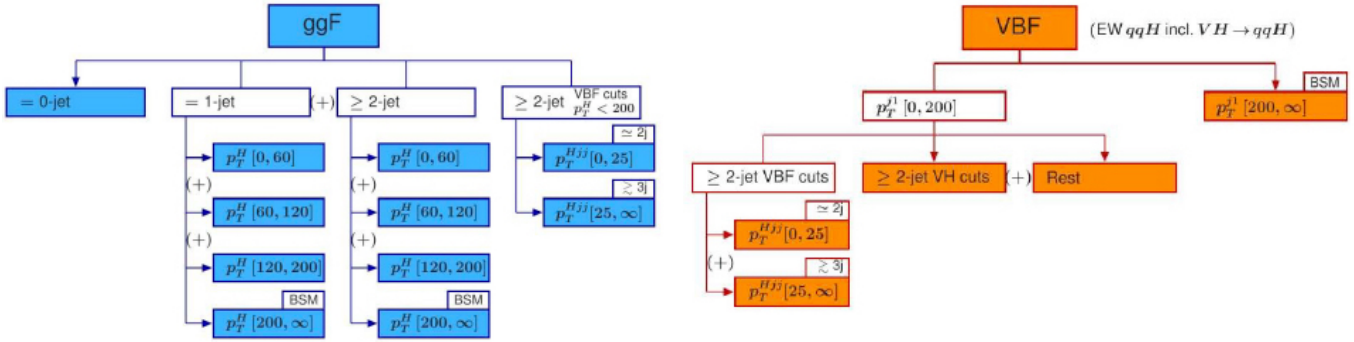
STXS Combined measurement

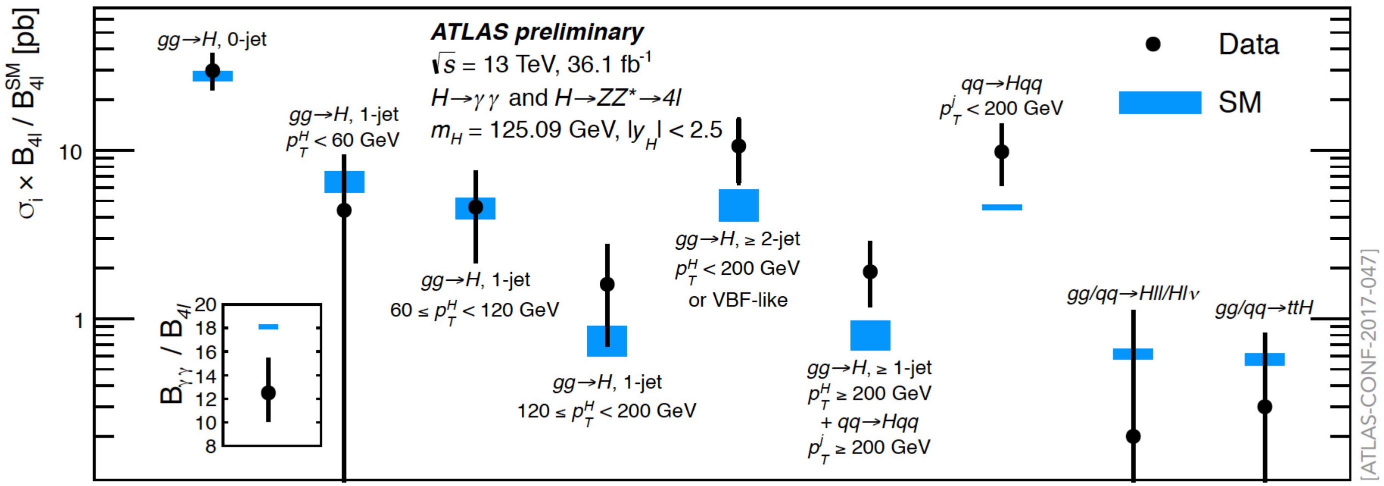
- Stage 0 STXS measurement (CMS)





- Stage 1 STXS measurement (CMS)
  - mainly for ggF and VBF (no sensitivity for VH and ttH yet)
  - Merged several blocks depending on the current sensitivty



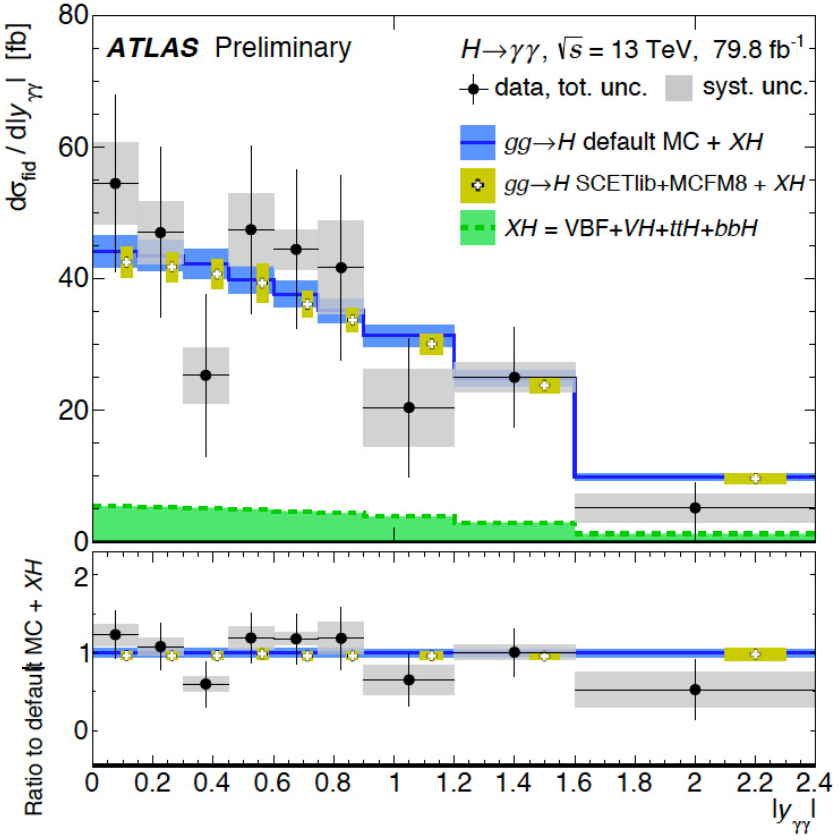


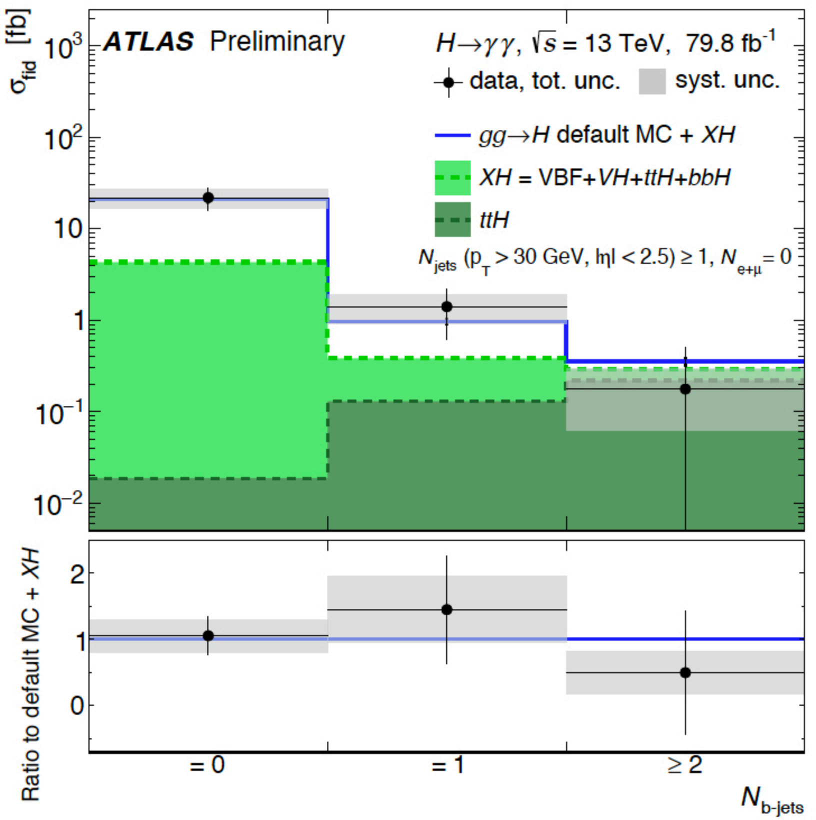
Differential Cross Section Measurement

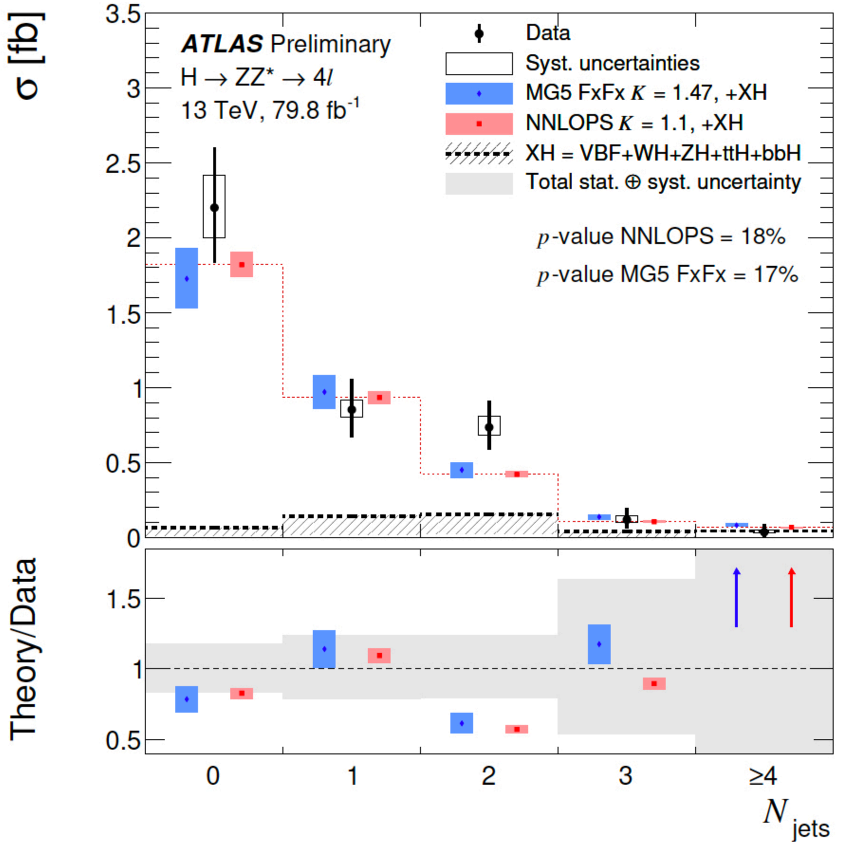
- ATLAS $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ\rightarrow 4l$ (80fb^{-1})
- Compare to state-of-art theory prediction

Sensitive to PDF

$N_{b\text{-jets}}$, N_{jets} : Sensitive to signal composition and PDF







<ins>No significant deviation from theory found</ins>

Combined Measurement (X-sec)

- ATLAS

Process ($\|y_H\| < 2.5$)	Value [pb]	Uncertainty [pb] Total	Stat.	Exp.	Sig. th.	Bkg. th.	SM pred. [pb]	Significance obs. (exp.)
ggF	47.8	± 4.0	± 3.1	$^{+2.7}_{-2.2}$	± 0.9	± 1.3	44.7 ± 2.2	-
VBF	4.25	$^{+0.77}_{-0.74}$	± 0.63	$^{+0.39}_{-0.35}$	$^{+0.25}_{-0.21}$	$^{+0.14}_{-0.11}$	3.515 ± 0.075	6.5 (5.3)
WH	1.89	$^{+0.63}_{-0.58}$	$^{+0.45}_{-0.42}$	$^{+0.29}_{-0.28}$	$^{+0.25}_{-0.16}$	$^{+0.23}_{-0.22}$	1.204 ± 0.024	4.1 (3.7) (WH and ZH combined)
ZH	0.59	$^{+0.33}_{-0.32}$	$^{+0.27}_{-0.25}$	± 0.14	$^{+0.08}_{-0.02}$	± 0.11	$0.794^{+0.033}_{-0.027}$	
$t\bar{t}H{+}tH$	0.71	± 0.15	± 0.10	± 0.07	$^{+0.05}_{-0.04}$	$^{+0.08}_{-0.07}$	$0.586^{+0.034}_{-0.050}$	5.8 (5.3)

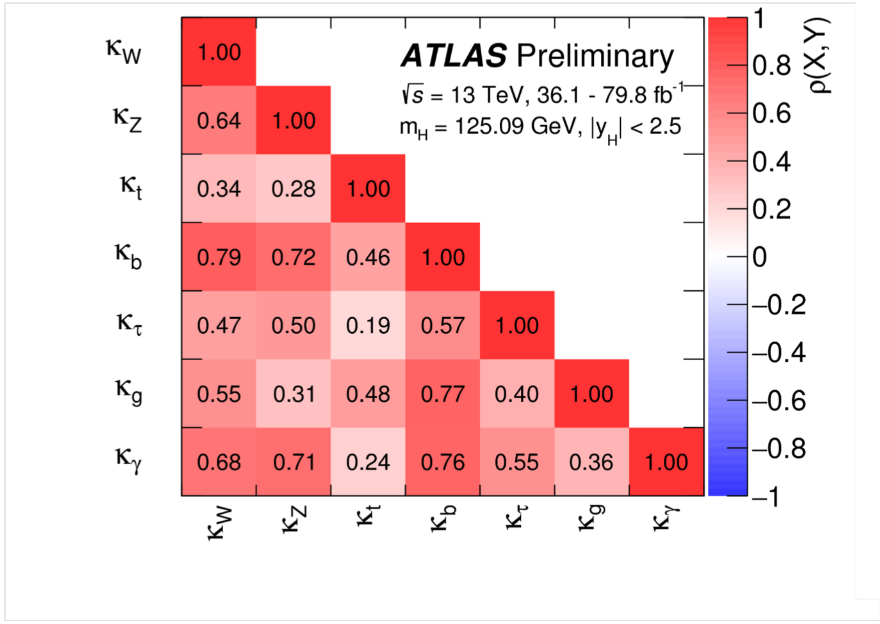
- CMS

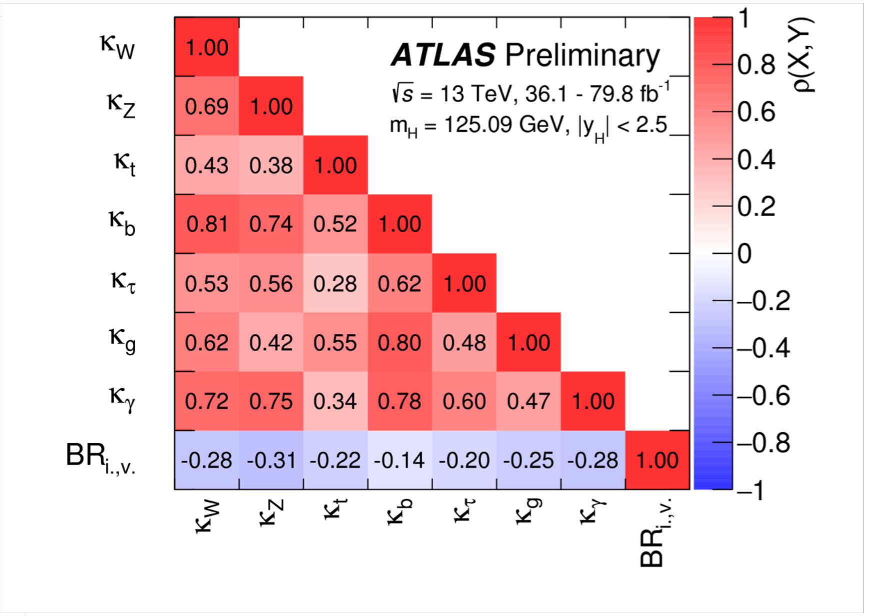
Production process	Best fit value	Uncertainty	stat.	syst.
ggH	1.22	$^{+0.14}_{-0.12}$	$^{+0.08}_{-0.08}$	$^{+0.12}_{-0.10}$
		$\left(^{+0.11}_{-0.11}\right)$	$\left(^{+0.07}_{-0.07}\right)$	$\left(^{+0.09}_{-0.08}\right)$
VBF	0.73	$^{+0.30}_{-0.27}$	$^{+0.24}_{-0.23}$	$^{+0.17}_{-0.15}$
		$\left(^{+0.29}_{-0.27}\right)$	$\left(^{+0.24}_{-0.23}\right)$	$\left(^{+0.16}_{-0.15}\right)$
WH	2.18	$^{+0.58}_{-0.55}$	$^{+0.46}_{-0.45}$	$^{+0.34}_{-0.32}$
		$\left(^{+0.53}_{-0.51}\right)$	$\left(^{+0.43}_{-0.42}\right)$	$\left(^{+0.30}_{-0.29}\right)$
ZH	0.87	$^{+0.44}_{-0.42}$	$^{+0.39}_{-0.38}$	$^{+0.20}_{-0.18}$
		$\left(^{+0.43}_{-0.41}\right)$	$\left(^{+0.38}_{-0.37}\right)$	$\left(^{+0.19}_{-0.17}\right)$
ttH	1.18	$^{+0.30}_{-0.27}$	$^{+0.16}_{-0.16}$	$^{+0.26}_{-0.21}$
		$\left(^{+0.28}_{-0.25}\right)$	$\left(^{+0.16}_{-0.15}\right)$	$\left(^{+0.23}_{-0.20}\right)$
Decay mode	**Best fit value**	**Uncertainty**	**stat.**	**syst.**
$H \to bb$	1.12	$^{+0.29}_{-0.29}$	$^{+0.19}_{-0.18}$	$^{+0.22}_{-0.22}$
		$\left(^{+0.28}_{-0.27}\right)$	$\left(^{+0.18}_{-0.18}\right)$	$\left(^{+0.21}_{-0.20}\right)$
$H \to \tau\tau$	1.02	$^{+0.26}_{-0.24}$	$^{+0.15}_{-0.15}$	$^{+0.21}_{-0.19}$
		$\left(^{+0.24}_{-0.22}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.19}_{-0.17}\right)$
$H \to WW$	1.28	$^{+0.17}_{-0.16}$	$^{+0.09}_{-0.09}$	$^{+0.14}_{-0.13}$
		$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.09}_{-0.09}\right)$	$\left(^{+0.11}_{-0.10}\right)$
$H \to ZZ$	1.06	$^{+0.19}_{-0.17}$	$^{+0.16}_{-0.15}$	$^{+0.11}_{-0.08}$
		$\left(^{+0.18}_{-0.16}\right)$	$\left(^{+0.15}_{-0.14}\right)$	$\left(^{+0.10}_{-0.08}\right)$
$H \to \gamma\gamma$	1.20	$^{+0.18}_{-0.14}$	$^{+0.13}_{-0.11}$	$^{+0.12}_{-0.09}$
		$\left(^{+0.14}_{-0.12}\right)$	$\left(^{+0.10}_{-0.10}\right)$	$\left(^{+0.09}_{-0.07}\right)$
$H \to \mu\mu$	0.68	$^{+1.25}_{-1.24}$	$^{+1.24}_{-1.24}$	$^{+0.13}_{-0.11}$
		$\left(^{+1.20}_{-1.17}\right)$	$\left(^{+1.18}_{-1.17}\right)$	$\left(^{+0.19}_{-0.03}\right)$

Combined Measurement (κ)

- ATLAS

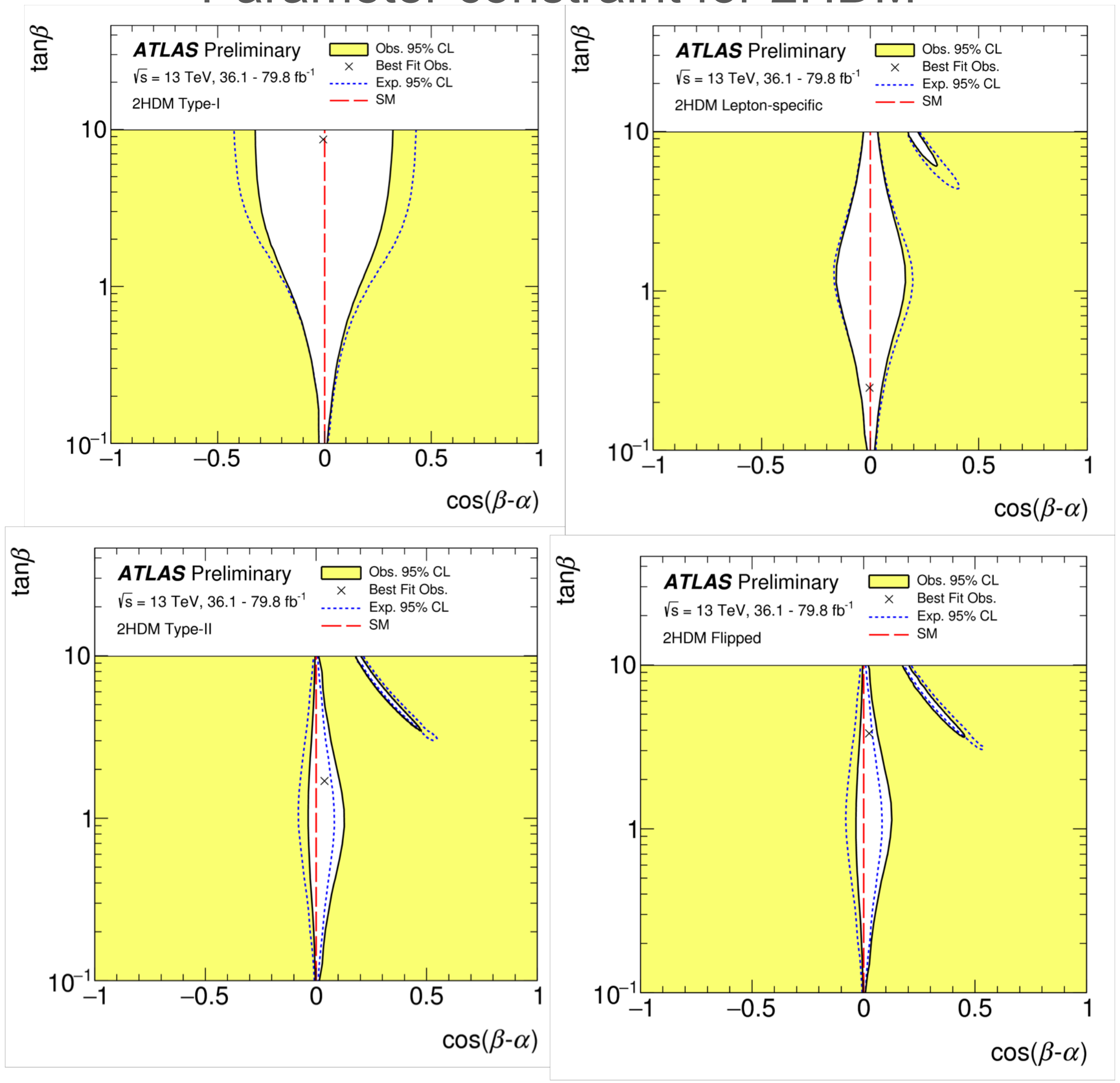
Parameter	(a) no BSM	(b) with BSM
κ_Z	1.07 ± 0.10	restricted to $\kappa_Z \leq 1$
κ_W	1.07 ± 0.11	restricted to $\kappa_W \leq 1$
κ_b	$0.97^{+0.24}_{-0.22}$	$0.85^{+0.13}_{-0.14}$
κ_t	$1.09^{+0.15}_{-0.14}$	$1.05^{+0.14}_{-0.13}$
κ_τ	$1.02^{+0.17}_{-0.16}$	0.95 ± 0.13
κ_γ	$1.02^{+0.09}_{-0.12}$	$0.98^{+0.05}_{-0.08}$
κ_g	$1.00^{+0.12}_{-0.11}$	$0.97^{+0.10}_{-0.09}$
B_{BSM}	-	< 0.26 at 95% CL





BSM combination

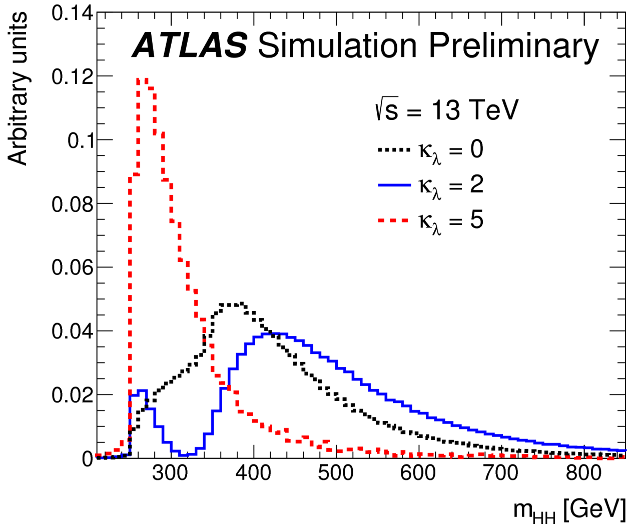
- Parameter constraint for 2HDM

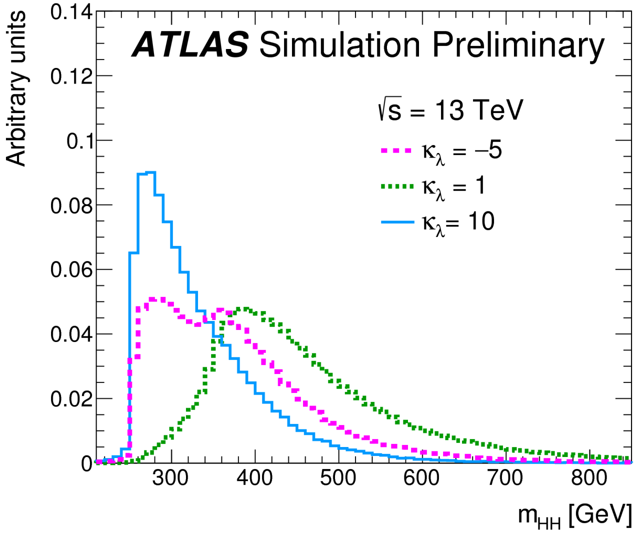


Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Higgs Pair Production

- Acceptance Dependence as a function of κ_λ

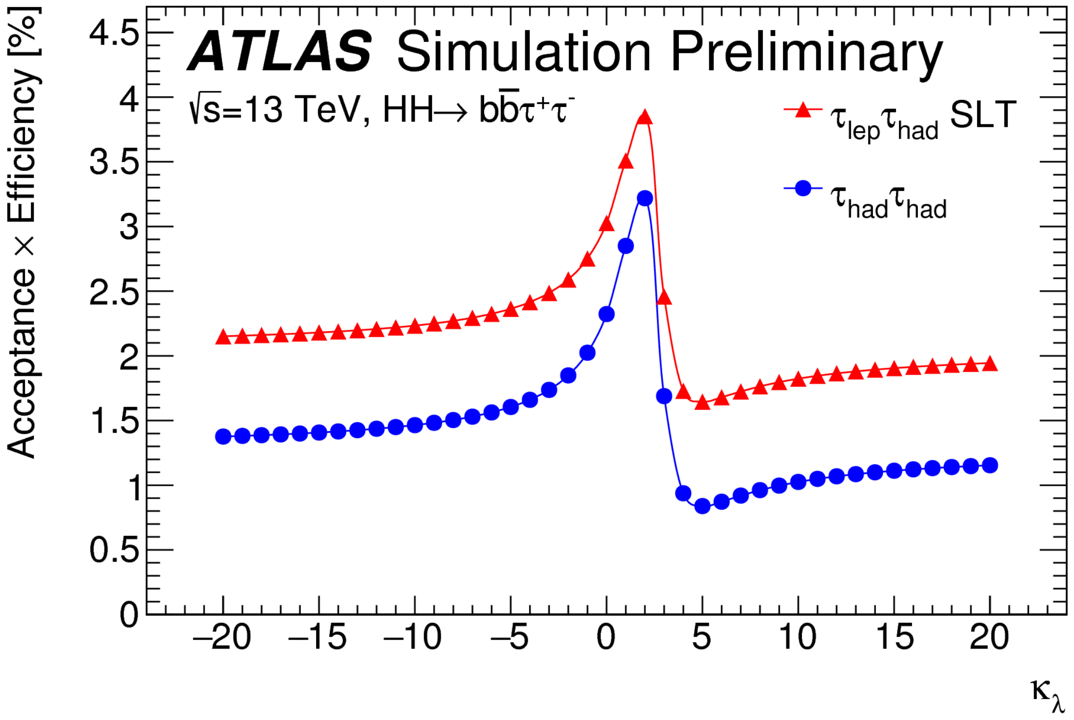




Depending on κ_λ, m_{HH} distribution varies

$\kappa_\lambda = 2$ ➔ hardest m_{HH} (higher acceptance)

$\kappa_\lambda = 5$ ➔ softest m_{HH} (lower acceptance)

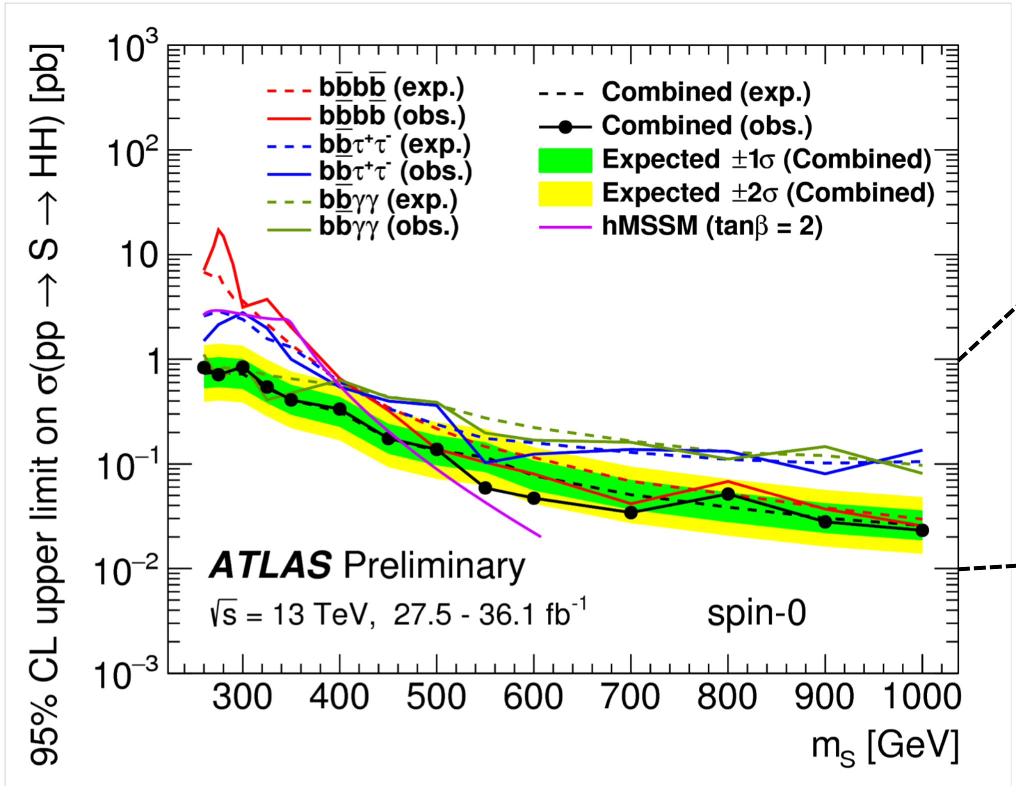


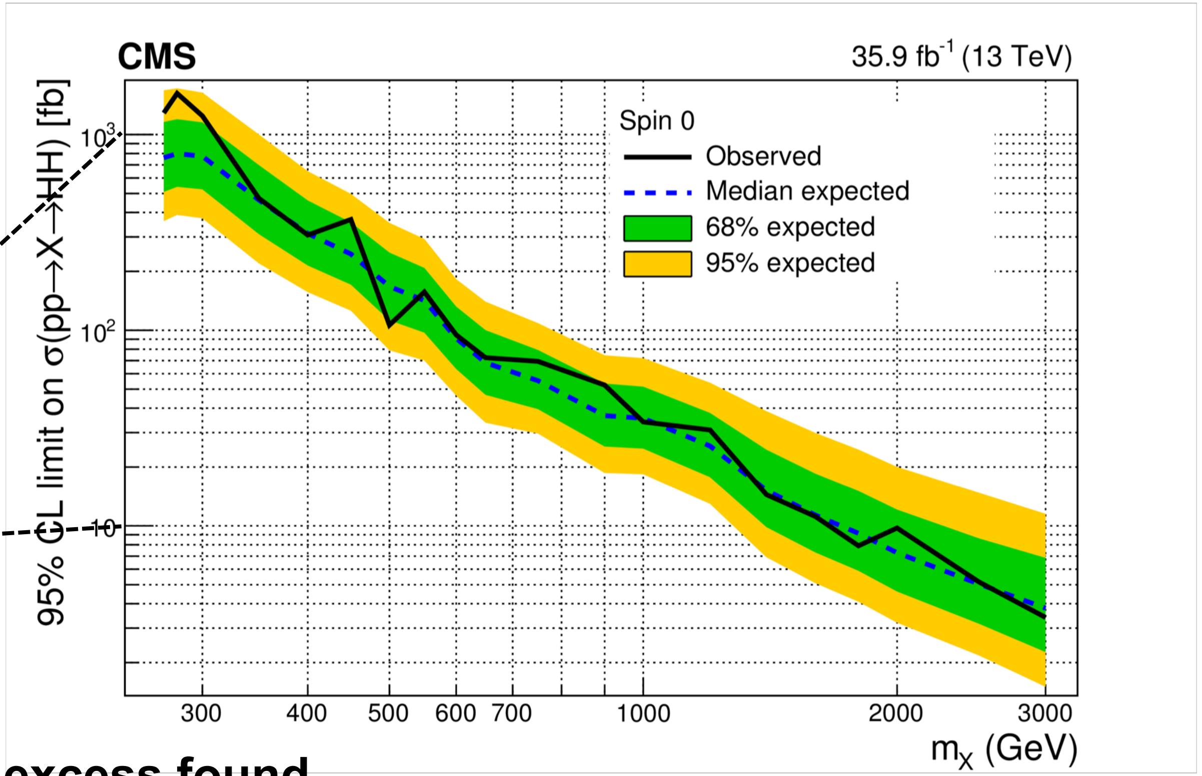
bbττ acceptancechanges from
1% to 3% ($\tau_{had}\tau_{had}$)
1.5% to 4% ($\tau_{lep}\tau_{had}$)

bbbb changes by ~factor 2
bbγγ change by ~30%

Search for DiHiggs Resonance

- Dihiggs resonance combined results





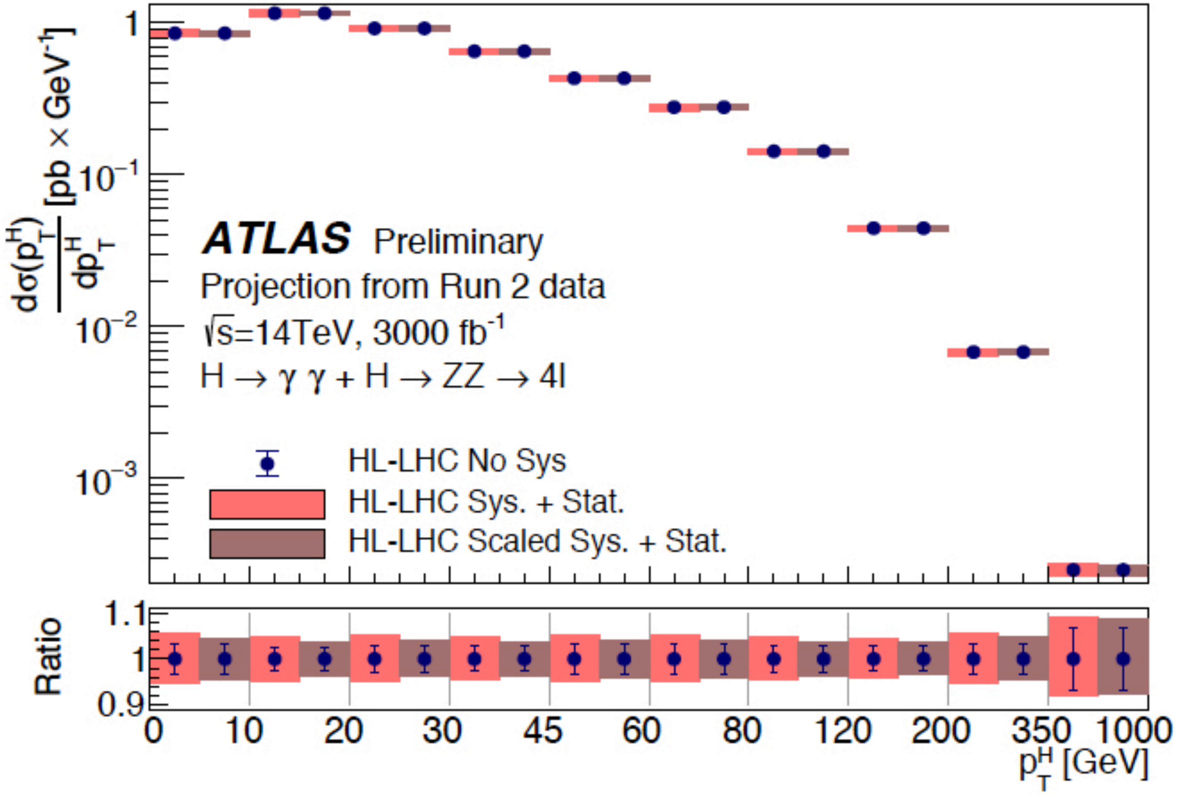
No significance excess found

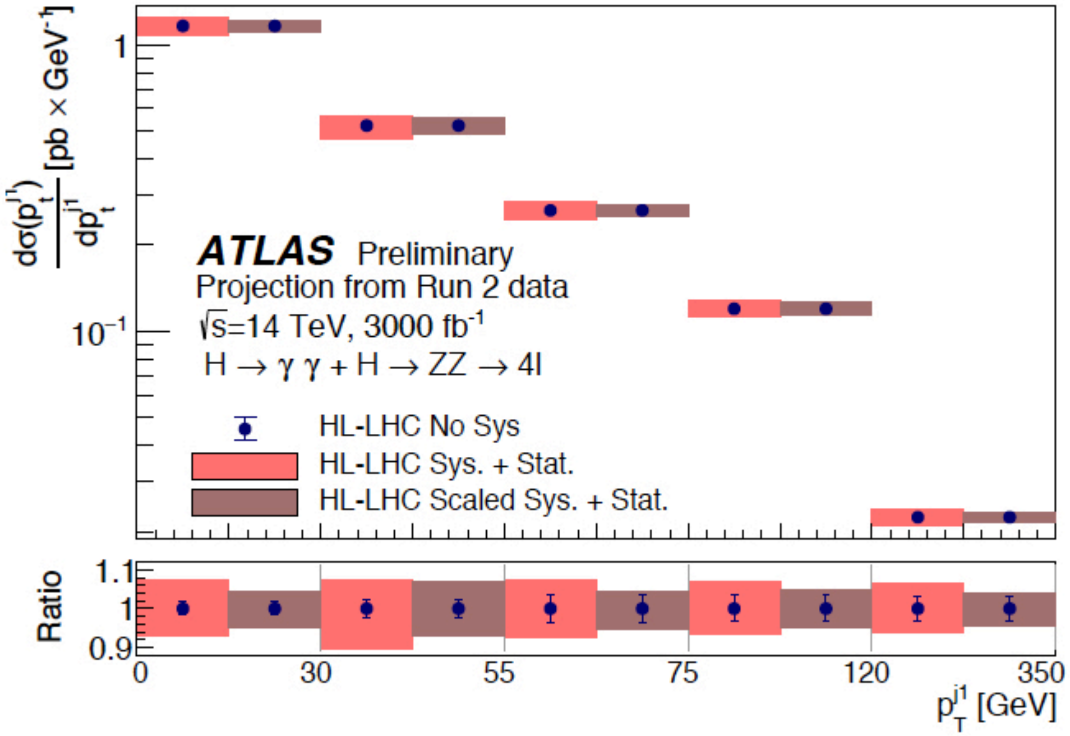
Cross section limit (95% CL)
0.83pb at 260 GeV
0.02pb at 1TeV

Cross section limit (95% CL)
0.83pb at 260 GeV
0.02pb at 1TeV

LH-LHC Differential Cross Section

- Combined H→γγ, H→ZZ
- Highest p_T^H bin (p_T^H>350 GeV)



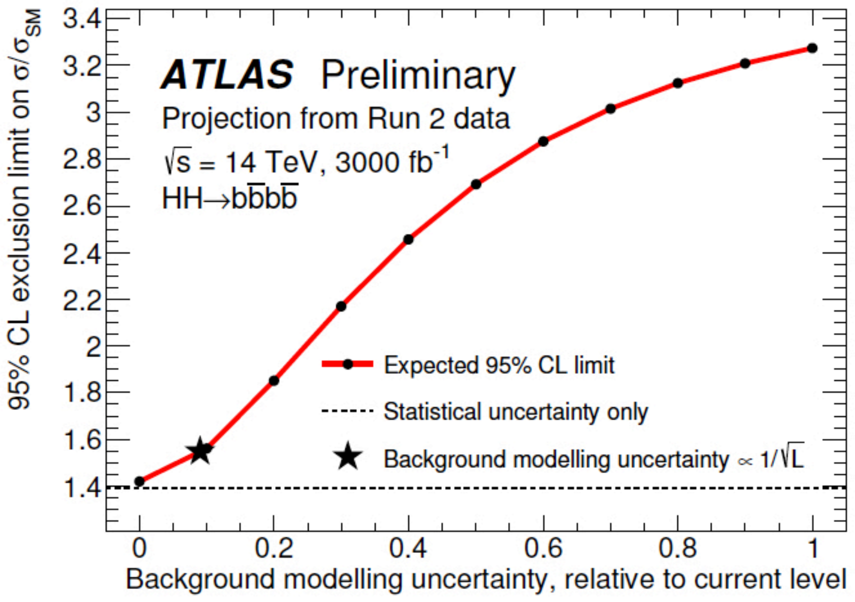


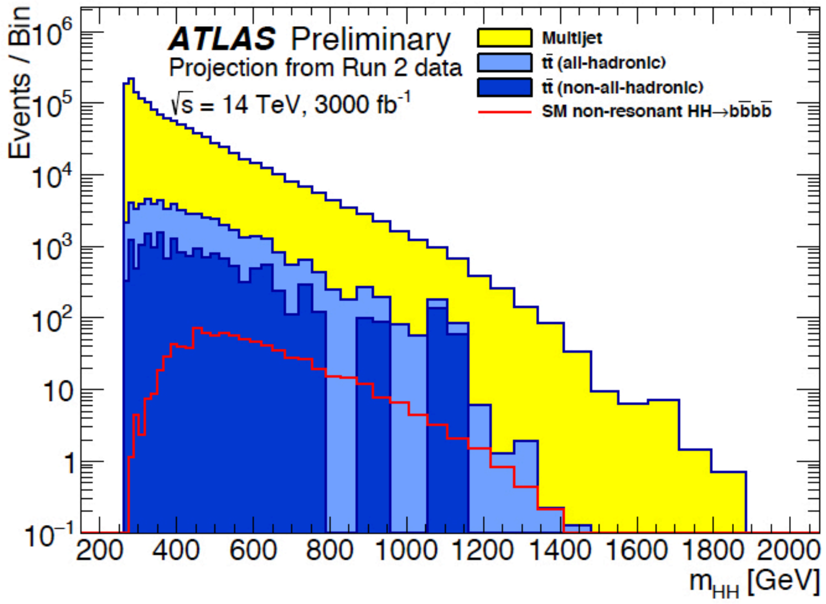
8 % accuracy (still stat limited) in p_T^H>350 GeV
Boosted H→bb channel will improve high-p_T stat

DiHiggs Extrapolation from Run2

- HH→4b channel (ATLAS)
  - Extrapolating from Run2 analysis of 24.3fb^{-1}
  - 8% improvement of b-tagging eff is applied
  - QCD multi-jet background (95% of total)
    ➔ assessed using data-driven technique
    ➔ largest systematic source of this analysis

Trigger in HL-LHC is crucial
if jet threshold increase from 40 to 75 GeV, sensitivity down by 50%

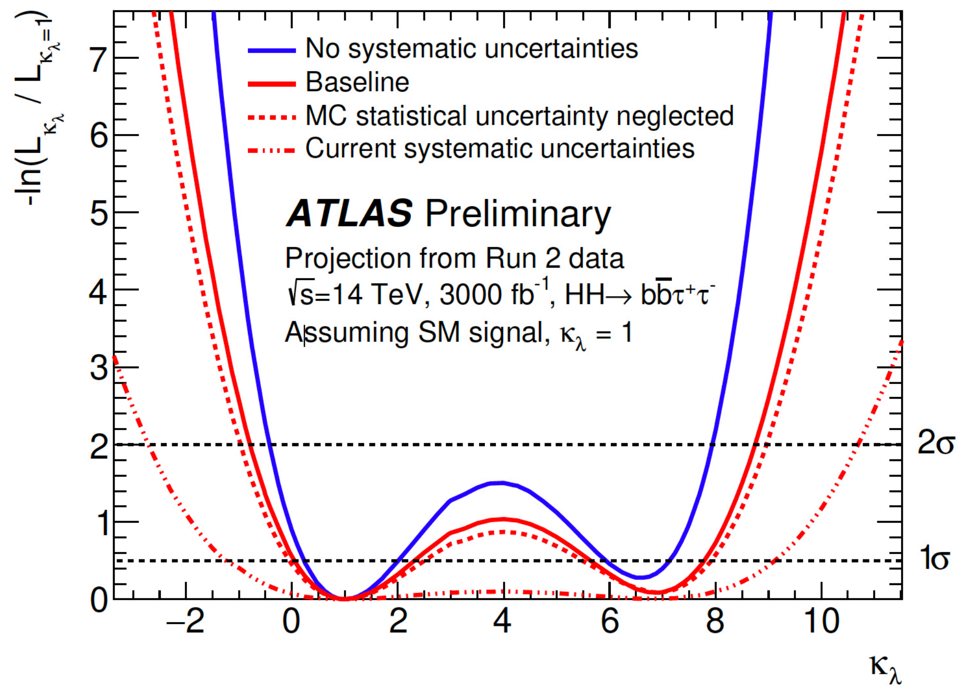




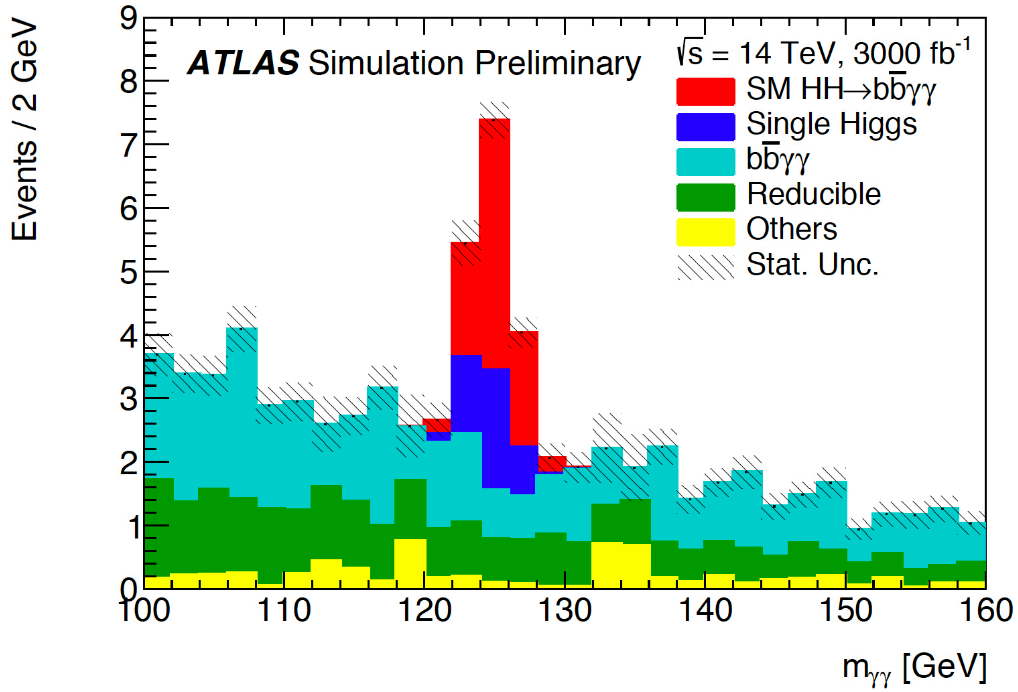
1.4σ (without systematic), 0.6σ (with Run2 sys)

DiHiggs at HL-LHC

- bbττ (most sensitive analysis in Run2)
  - $bb\tau_{lep}\tau_{had}$, $bb\tau_{had}\tau_{had}$ analyzed separately
  - BDT trained with κ_λ=20 (softer m_{HH} distribution) ➔ not fully optimal
  - MC stat uncertainty neglected
  - 2.1σ with baseline systematic scenario

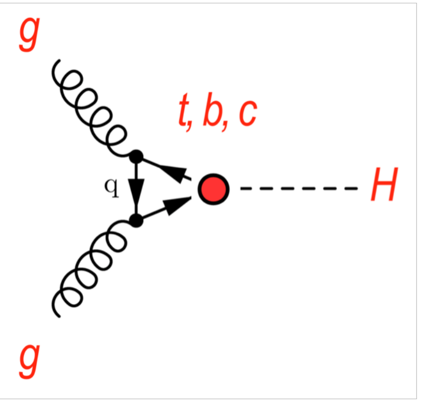


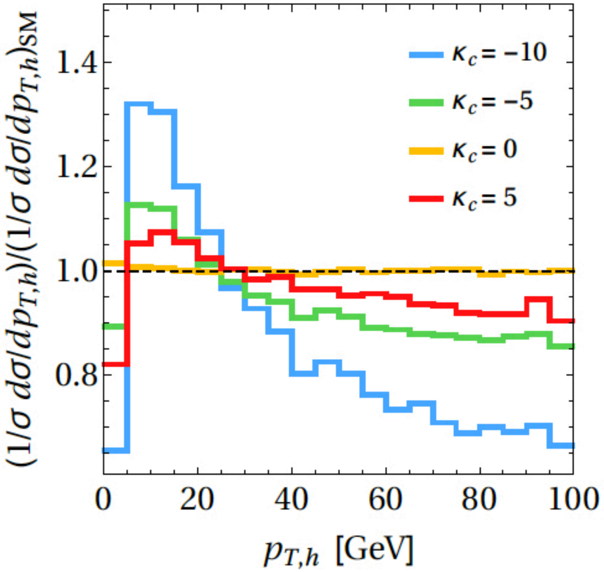
- bbττ (most sensitive analysis in Run2)
  - truth level particle studies convoluted with smearing
  - Higgs pair : single Higgs : bkg = 2:1:1
  - BDT trained with κ_λ=1
  - 2.0σ with systematic

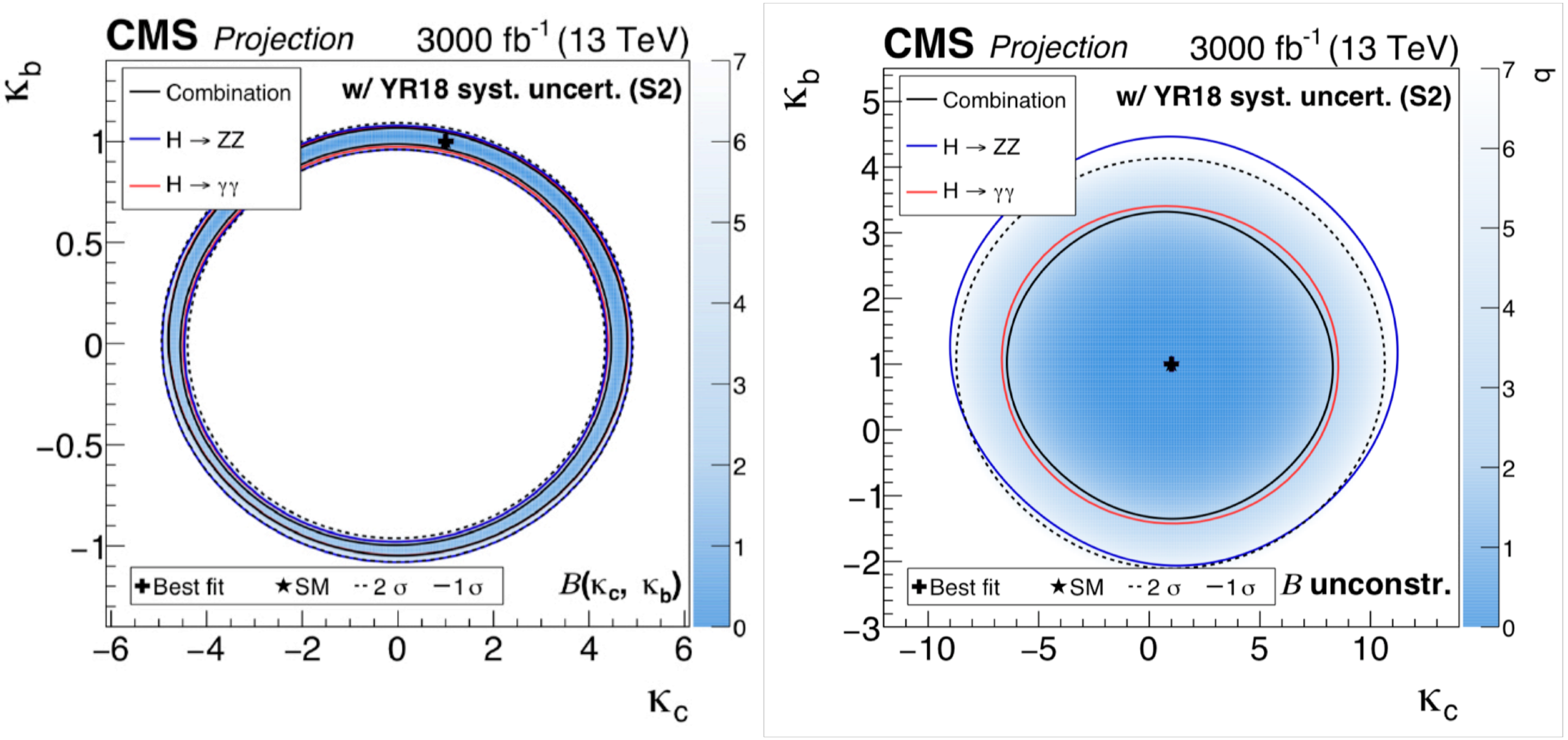


Measurement at HL-LHC

- Indirect κ_c measurement using ggF Higgs p_T differential measurement
  - if charm Yukawa coupling is enhanced, p_T^H spectrum would be softer
  - Differential cross section measurement of H→γγ and H→ZZ→4l can be used to constraint the charge Yukawa (κ_c)







- no BSM particle in the loop
- with/without coupling dependence on the branching fraction

DiHiggs (HE-LHC Projection)

- HE-LHC : 27 TeV, 15ab^{-1}
- Combination of bbγγ and bbττ
- Expected uncertainty on κ_λ ~10-20%