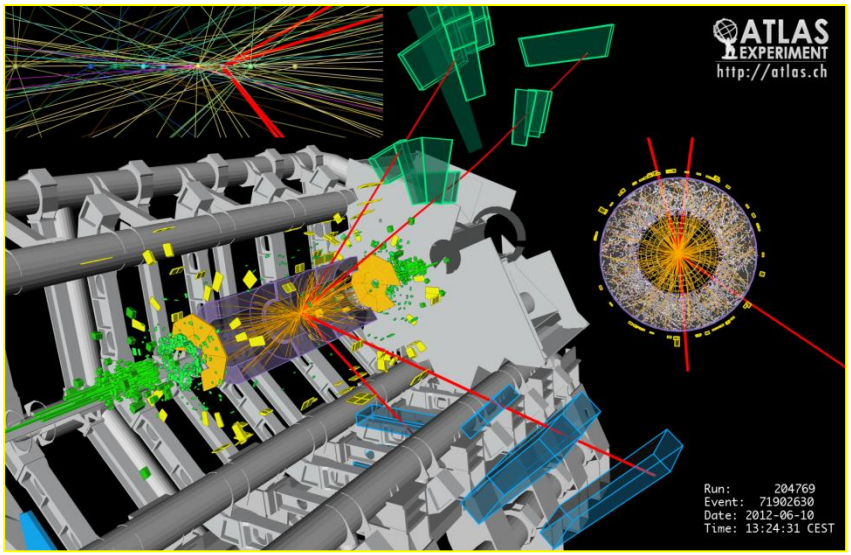
Higgs properties measurement through H→ZZ*→4l with the ATLAS Detector

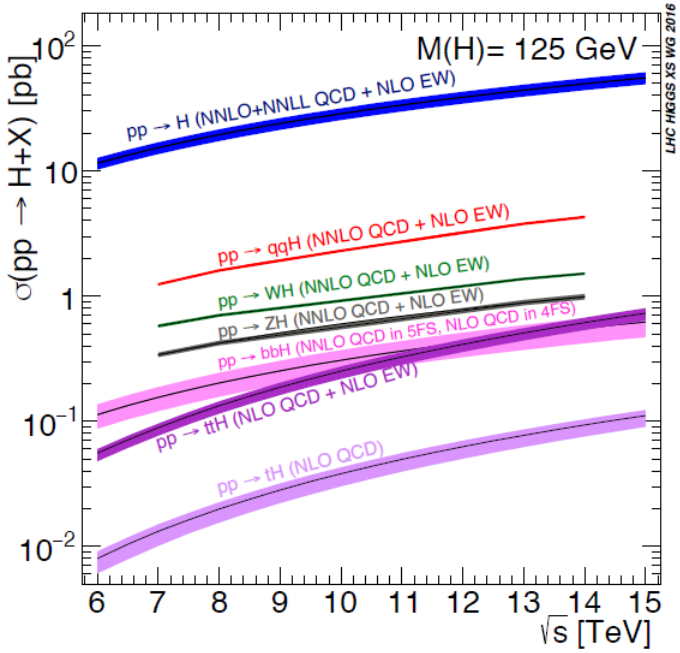


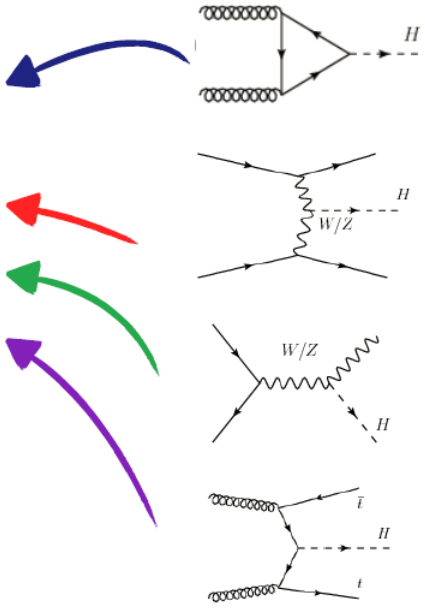
Haijun Yang (SJTU)

The 2nd China LHC Physics Workshop

Peking University, December 17-19, 2016

Higgs Productions and Decays





@13TeV ggH 87%
m_H=125 GeV

(N3LO QCD + NLO EW)

@13TeV VBF 7%
m_H=125 GeV

@13TeV VH 4%
m_H=125 GeV

(NNLO QCD + NLO EW)

@13TeV ttH/bbH 2%
m_H=125 GeV

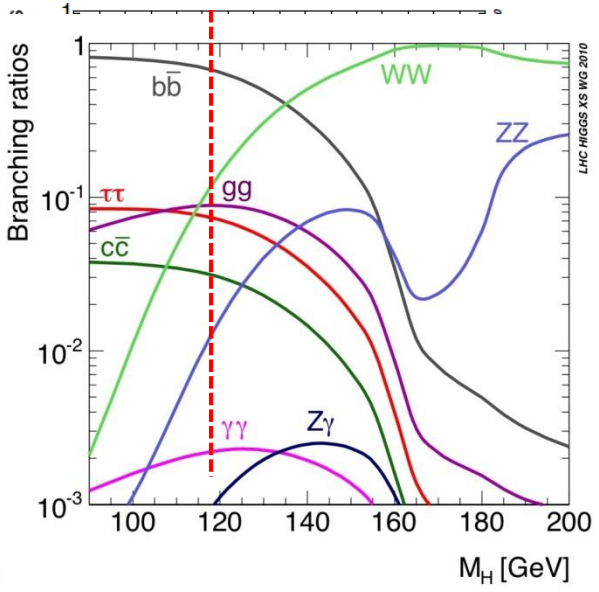
(NLO QCD + NLO EW)

➔ **ggH, ttH, bbH – Yukawa coupling**

➔ **VBF, VH – Gauge coupling**

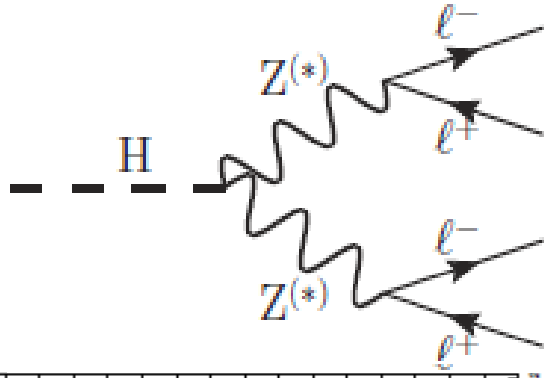
Higgs Production (NNLO QCD and NLO EW) (for M_H = 125 GeV)	Cross section (pb) $\sqrt{s}$ = 8 TeV	Cross section (pb) $\sqrt{s}$ = 13 TeV
ggF	19.27	48.5
VBF	1.58	3.78
WH	0.70	1.37
ZH	0.42	0.88
ttH	0.13	0.51
bbH	0.20	0.49
Total	22.30	55.53

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

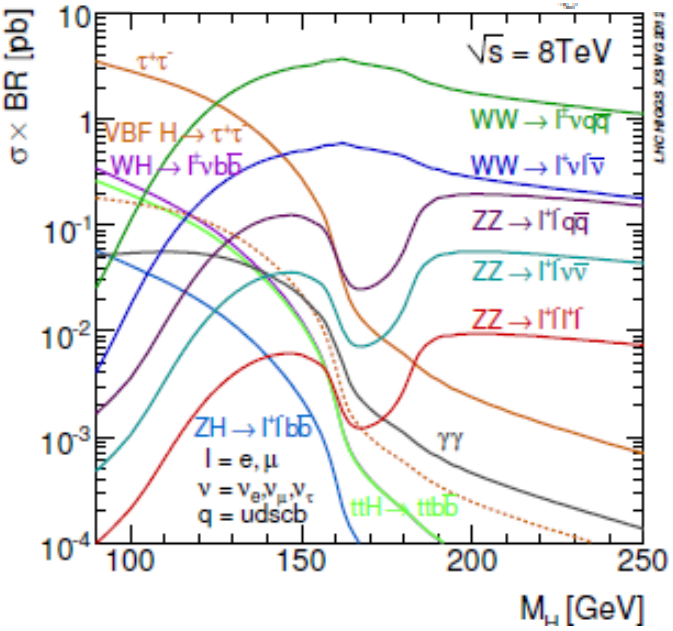


Higgs → ZZ* → 4ℓ Analysis

- Extremely clean – "Gold-plated" channel
  - Fully reconstructed final states
  - Good mass resolution (~ 1.6-2.4 GeV)
  - High S/B ratio (~ 2.2-2.4)
  - Low decay branching fraction (2.67%)



- Properties measurement
  - Higgs mass, width, spin, parity
  - Total and differential cross section
  - Couplings



Higgs → ZZ* → 4ℓ Selections

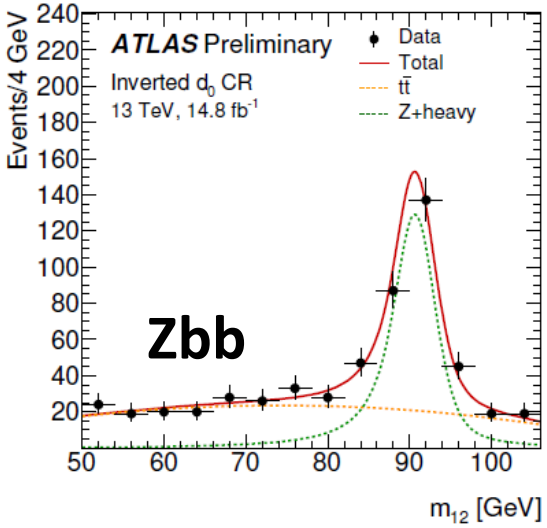
- Trigger match with single and/or di-lepton trigger
- **Four sub-channels: 4e, 2e2μ, 2μ2e, 4μ**

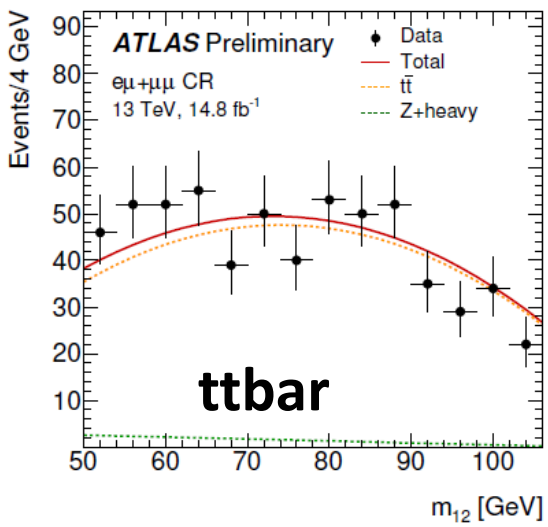
Leptons and Jets requirements	
Electrons	
Loose Likelihood quality electrons with hit in innermost layer, $E_{\mathrm{T}} > 7GeV$ and $\lvert\eta\rvert < 2.47$	
Muons	
Loose identification $\lvert\eta\rvert < 2.7$	
Calo-tagged muons with $p_{\mathrm{T}} > 15\,GeV$ and $\lvert\eta\rvert < 0.1$	
Combined, stand-alone (with ID hits if available) and segment tagged muons with $p_{\mathrm{T}} > 5\,GeV$	
Jets	
anti-k_t jets with $p_{\mathrm{T}} > 30GeV$, $\lvert\eta\rvert < 4.5$ and passing pile-up jet rejection requirements	
Event Selection	
Quadruplet Selection	Require at least one quadruplet of leptons consisting of two pairs of same flavour opposite-charge leptons fulfilling the following requirements: p_{T} thresholds for three leading leptons in the quadruplet - $20, 15$ and $10GeV$ Maximum of one calo-tagged or standalone muon per quadruplet Select best quadruplet to be the one with the (sub)leading dilepton mass (second) closest the Z mass Leading dilepton mass requirement: $50\,GeV < m_{12} < 106\,GeV$ Sub-leading dilepton mass requirement: $12 < m_{34} < 115GeV$ Remove quadruplet if alternative same-flavour opposite-charge dilepton gives $m_{\ell\ell} < 5\,GeV$ $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same(different)-flavour leptons in the quadruplet
Isolation	Contribution from the other leptons of the quadruplet is subtracted Muon track isolation ($\Delta R \leq 0.30$): $\Sigma p_{\mathrm{T}}/p_{\mathrm{T}} < 0.15$ Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_{\mathrm{T}}/p_{\mathrm{T}} < 0.30$ Electron track isolation ($\Delta R \leq 0.20$) : $\Sigma E_{\mathrm{T}}/E_{\mathrm{T}} < 0.15$ Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_{\mathrm{T}}/E_{\mathrm{T}} < 0.20$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $\lvert d_0/\sigma_{d_0}\rvert < 5$ For muons : $\lvert d_0/\sigma_{d_0}\rvert < 3$
Vertex Selection	Require a common vertex for the leptons $\chi^2/\mathrm{ndof} < 6$ for 4μ and < 9 for others.

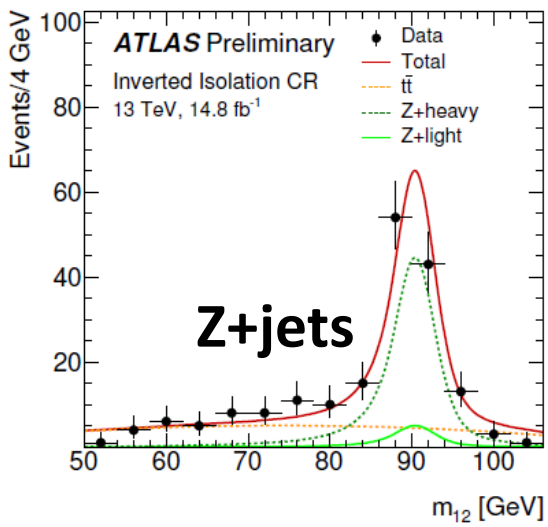
Estimated Backgrounds in Control Regions

➔ **Main background is ZZ: estimated from MC simulation, scaled to theoretical xsection**

➔ **Reducible backgrounds: Zbb, Z+light jets, ttbar, using data-driven method**



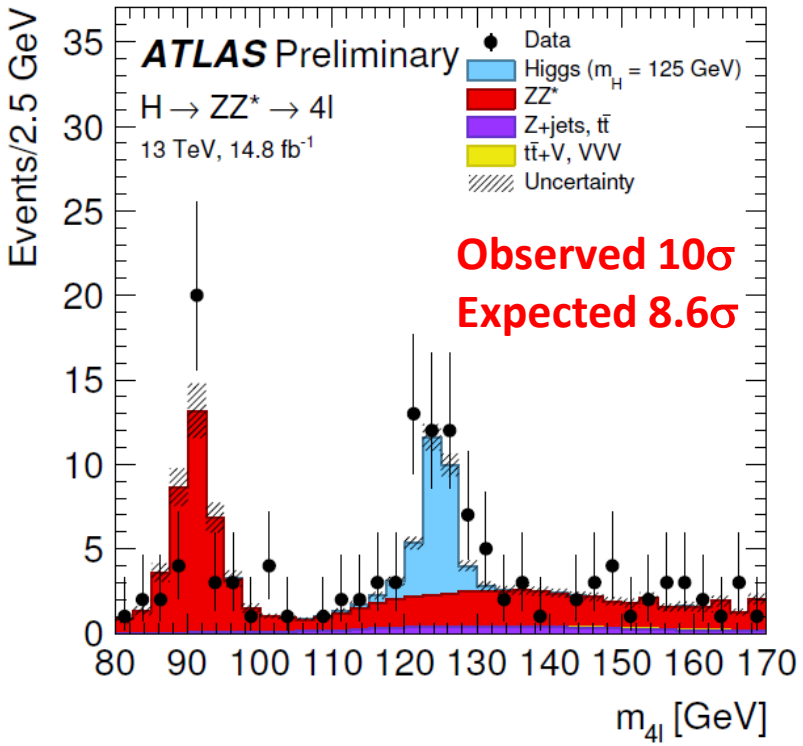


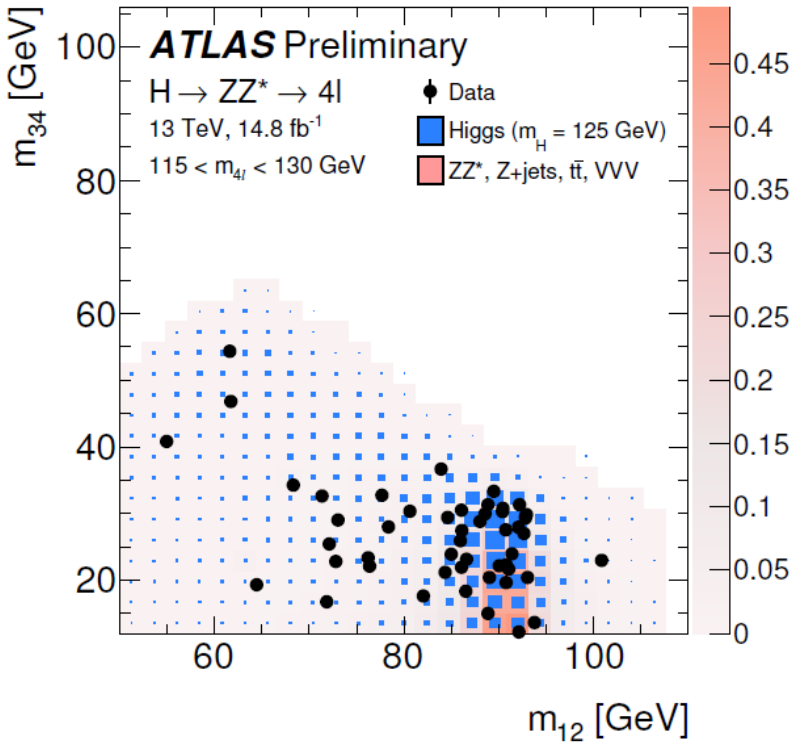


➔ **Estimates agree with data in control regions where isolated & d0 requirements are removed for subleading pairs. Estimated background using data-driven methods by extrapolating to signal region using extrapolation factors.**

Background	Fit yield in CR	Extrapolation factor [%]	Yield in SR
Z+heavy-flavour jets	348 ± 29	(0.60 ± 0.04)	$2.10 \pm 0.17 \pm 0.13$
$t\bar{t}$	351 ± 14	(0.21 ± 0.03)	$0.74 \pm 0.03 \pm 0.00$
Z+light-flavour jets	10 ± 15	(2.3 ± 0.3)	$0.24 \pm 0.35 \pm 0.03$
WZ		(MC-based estimation)	0.63 ± 0.31

H →ZZ* → 4ℓ Events





Final State	Signal full mass range	Signal	ZZ^*	$Z+$jets, $t\bar{t}$ ttV, VVV, WZ	S/B	Expected	Observed
4μ	8.8 ± 0.6	8.2 ± 0.6	3.11 ± 0.30	0.31 ± 0.04	2.4	11.6 ± 0.7	16
$2e2\mu$	6.1 ± 0.4	5.5 ± 0.4	2.19 ± 0.21	0.30 ± 0.04	2.2	8.0 ± 0.4	12
$2\mu 2e$	4.8 ± 0.4	4.4 ± 0.4	1.39 ± 0.16	0.47 ± 0.05	2.3	6.2 ± 0.4	10
$4e$	4.8 ± 0.5	4.2 ± 0.4	1.46 ± 0.18	0.46 ± 0.05	2.2	6.1 ± 0.4	6
Total	24.5 ± 1.8	22.3 ± 1.6	8.2 ± 0.8	1.54 ± 0.18	2.3	32.0 ± 1.8	44

Analysis Strategy

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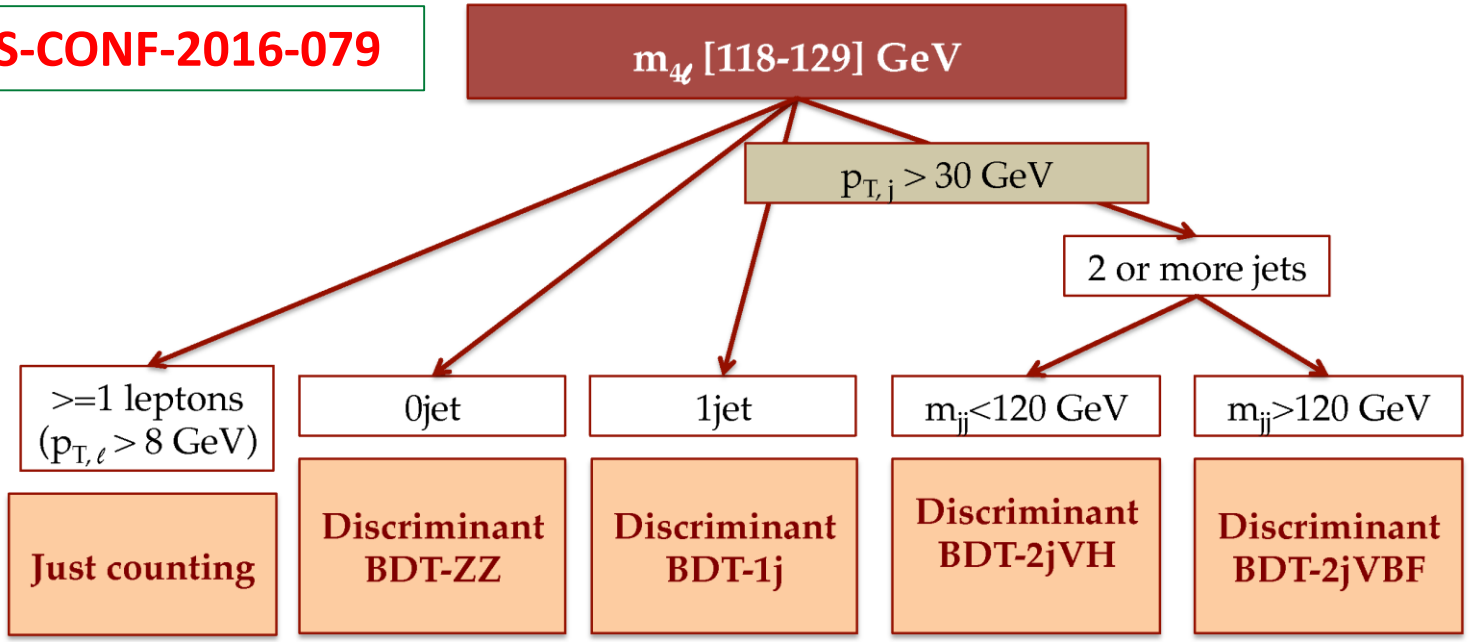


BDT_ZZ:
- $p_{T4\ell}$
- $\eta_{4\ell}$
- KD = $\log(ME_{HZZ}/ME_{ZZ})$

BDT_1jet:
- $p_{T,j}$
- η_j
- $\Delta R_{4\ell j}$

BDT_2jet_VH:
- $p_{T,j1}$
- $p_{T,j2}$
- η_{j1}
- $\Delta\eta_{jj}$
- $\Delta\eta_{4\ell jj}$
- m_{jj}
- $\min(\Delta R_{Zj})$

BDT_2jet_VBF:
- $p_{T,j1}$
- $p_{T,j2}$
- $p_{T,4\ell jj}$
- $\Delta\eta_{jj}$
- $\Delta\eta_{4\ell jj}$
- m_{jj}
- $\min(\Delta R_{Zj})$

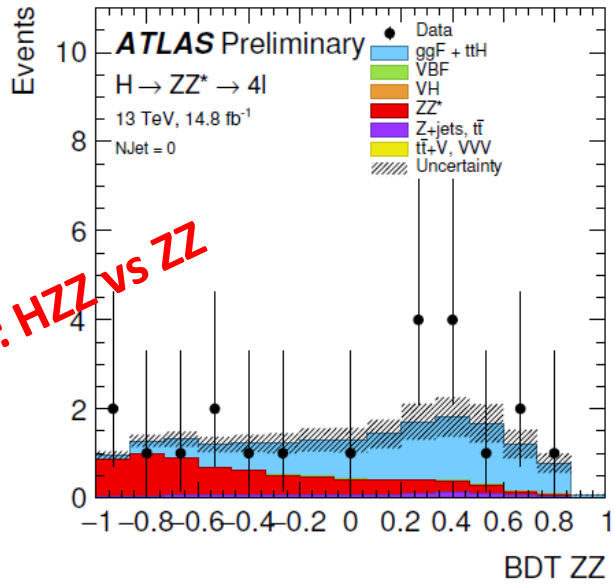
BDT-ZZ: HZZ vs ZZ

BDT-1j: ggF vs VBF

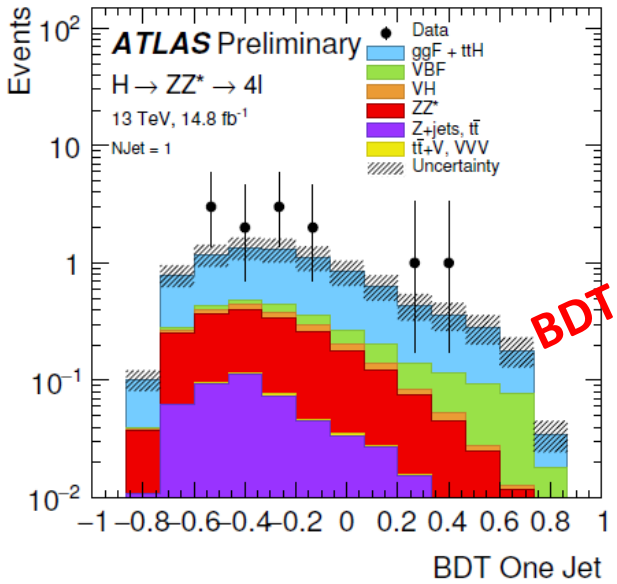
BDT-2jVH: ggF vs VH

BDT-2jVBF: ggF vs VBF

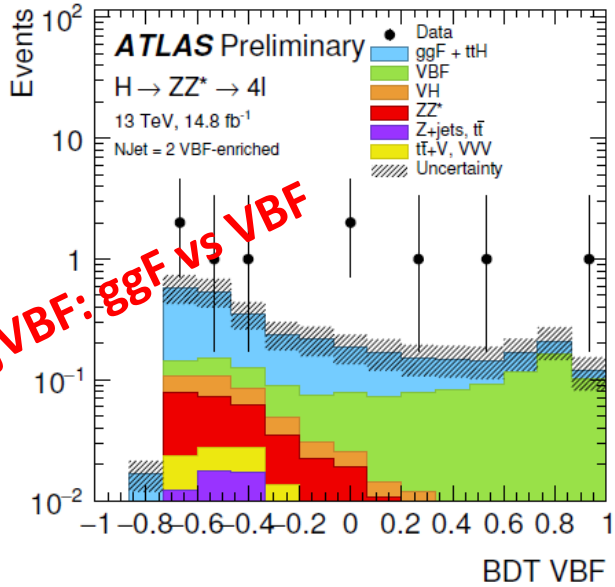
Higgs → ZZ* → 4ℓ BDT Outputs



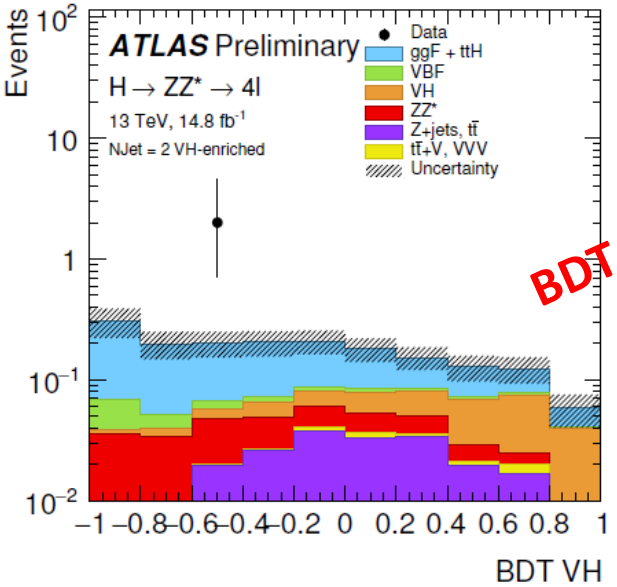
BDT-ZZ: HZZ vs ZZ



BDT-1j: ggF vs VBF



BDT-2jVBF: ggF vs VBF



BDT-2jVH: ggF vs VH

Higgs→ZZ*→4ℓ Cross Section

Total and fiducial cross section measurement.

$$\sigma^{\text{tot}} = \frac{N_s}{\mathcal{A} \cdot C \cdot \mathcal{B} \cdot \mathcal{L}_{\text{int}}}$$

$$\sigma^{\text{fid}}_{4\ell} = \frac{N_s}{C \cdot \mathcal{L}_{\text{int}}}$$

Lepton definition	
Muons: $p_T > 6$ GeV, $\lvert\eta\rvert < 2.7$	Electrons: $p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection	
Lepton kinematics:	Leading lepton $p_T > 20, 15, 10$ 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 (opposite) 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

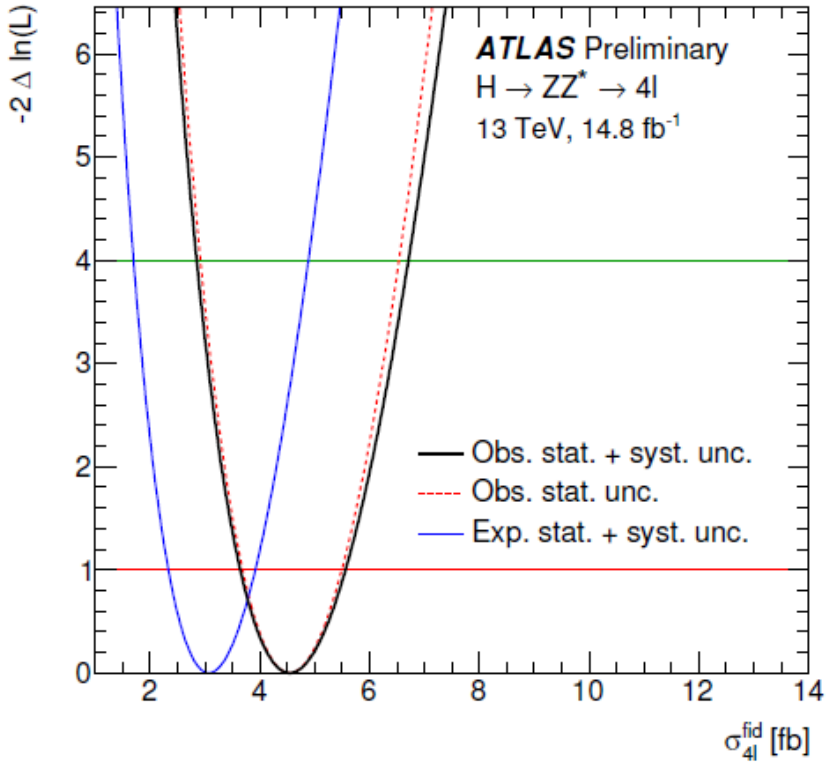
Final state	measured σ_{fid} [fb]	$\sigma_{\text{fid,SM}}$ [fb]
4μ	$1.28^{+0.48}_{-0.40}$	$0.93^{+0.06}_{-0.08}$
$4e$	$0.81^{+0.51}_{-0.38}$	$0.73^{+0.05}_{-0.06}$
$2\mu 2e$	$1.29^{+0.58}_{-0.46}$	$0.67^{+0.04}_{-0.04}$
$2e2\mu$	$1.10^{+0.49}_{-0.40}$	$0.76^{+0.05}_{-0.06}$

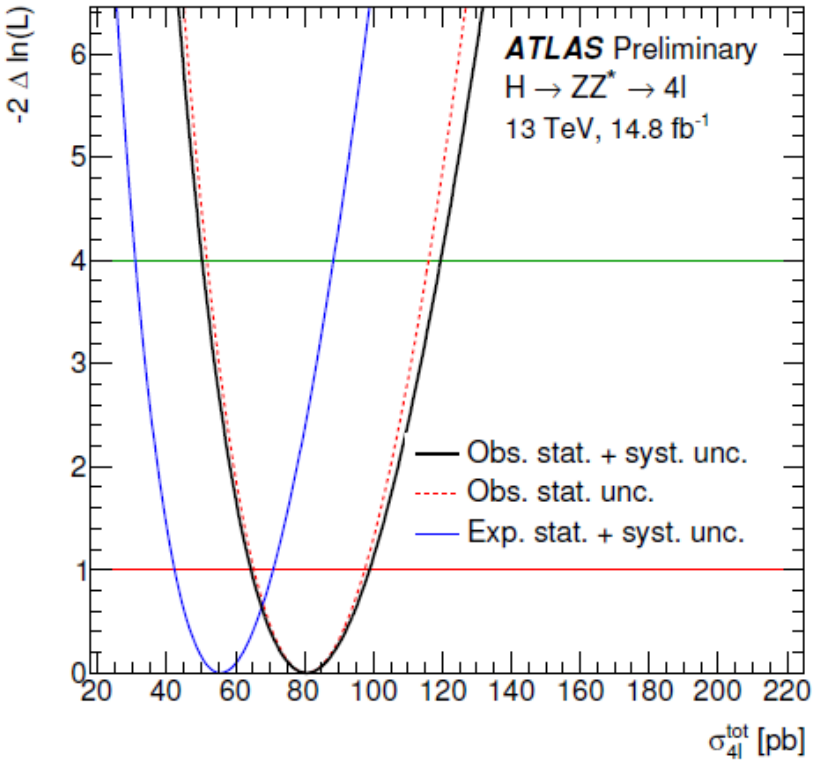
$$\sigma^{4\ell}_{\text{fid,sum}} = 4.48^{+1.01}_{-0.89} \text{ fb}$$

$$\sigma^{4\ell}_{\text{fid,comb}} = 4.54^{+1.02}_{-0.90} \text{ fb}$$

Higgs Fiducial and Total Cross Section

- Total and fiducial cross section measurement at 13 TeV.





$$\sigma^{4\ell}_{\text{fid,comb}} = 4.54^{+1.02}_{-0.90}\ \text{fb}$$

$$\sigma^{4\ell}_{\text{fid,SM}} = 3.07^{+0.21}_{-0.25}\ \text{fb}$$

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

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

Higgs → ZZ* → 4ℓ Couplings

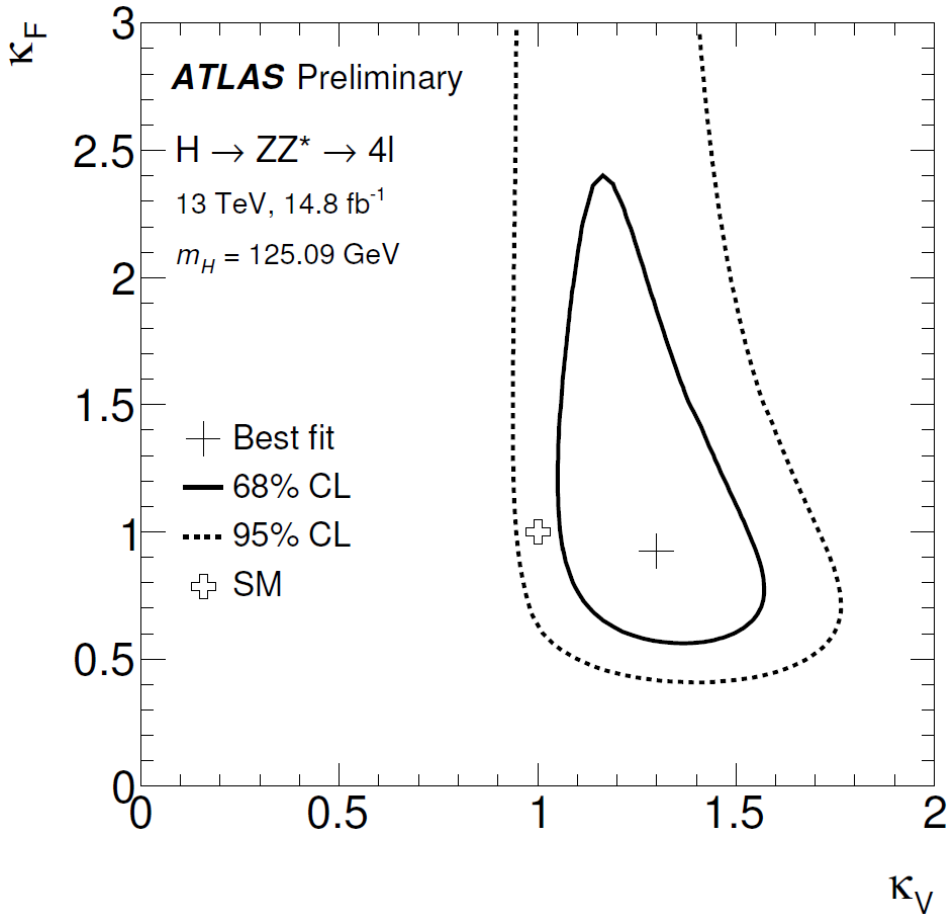
- The universal coupling strength scale factors
  - K_F for all fermions
  - K_V for all vector bosons.

$$\kappa_V = \kappa_W = \kappa_Z$$

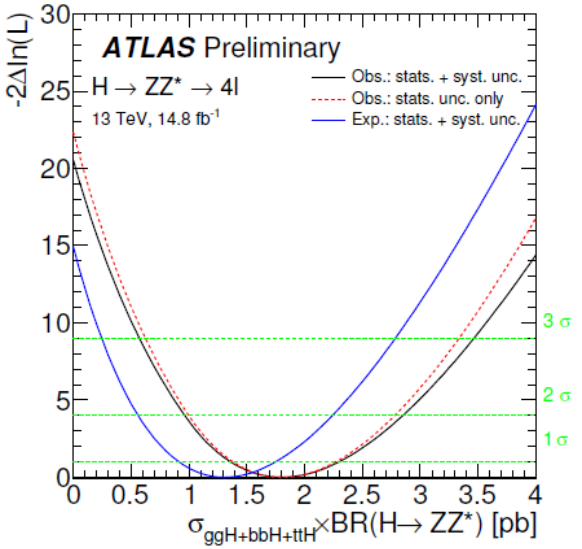
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g = \kappa_\mu$$

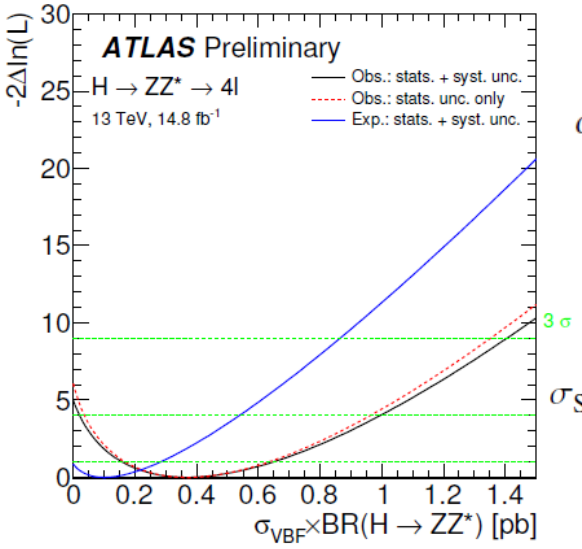
- The H→ZZ*→4l channel is not sensitive to the K_F and relative sign of the two couplings, only a quadrant is shown in K_V-K_F plane.

- Assume SM Higgs with mass of 125GeV, the fitted coupling scale factors are compatible with the SM predictions.



Higgs → ZZ* → 4ℓ Production Modes





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

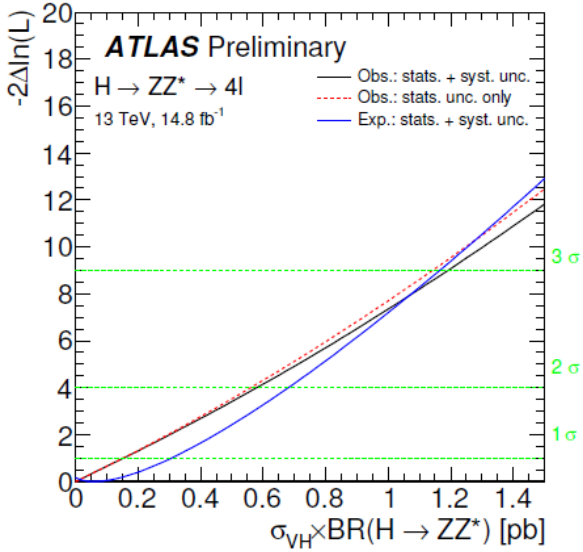
$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \mathrm{pb}$$

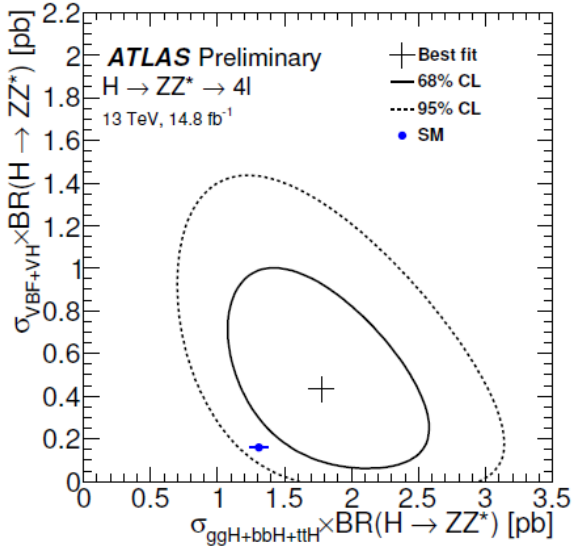
$$\sigma_{\mathrm{VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \mathrm{pb}$$

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

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

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





Compatibility between measured cross section and SM prediction is:

- **1.1σ for ggF+bbH+ttH**
- **1.4σ for VBF+VH**

Higgs Production Cross Sections

➔ Combining γγ and ZZ final states

➔ The compatibility between measurement and SM prediction corresponds to a p-value of 21%.

	Best fit value (pb)	SM prediction (pb)
σ_{ggF}	$47.8^{+9.8}_{-9.4}$	44.5 ± 2.3
σ_{VBF}	$7.9^{+2.8}_{-2.4}$	3.52 ± 0.07
σ_{VHhad}	$-2.5^{+2.9}_{-2.6}$	1.36 ± 0.03
σ_{VHlep}	$0.32^{+1.07}_{-0.79}$	0.64 ± 0.02
σ_{top}	$-0.11^{+0.67}_{-0.54}$	0.60 ± 0.06

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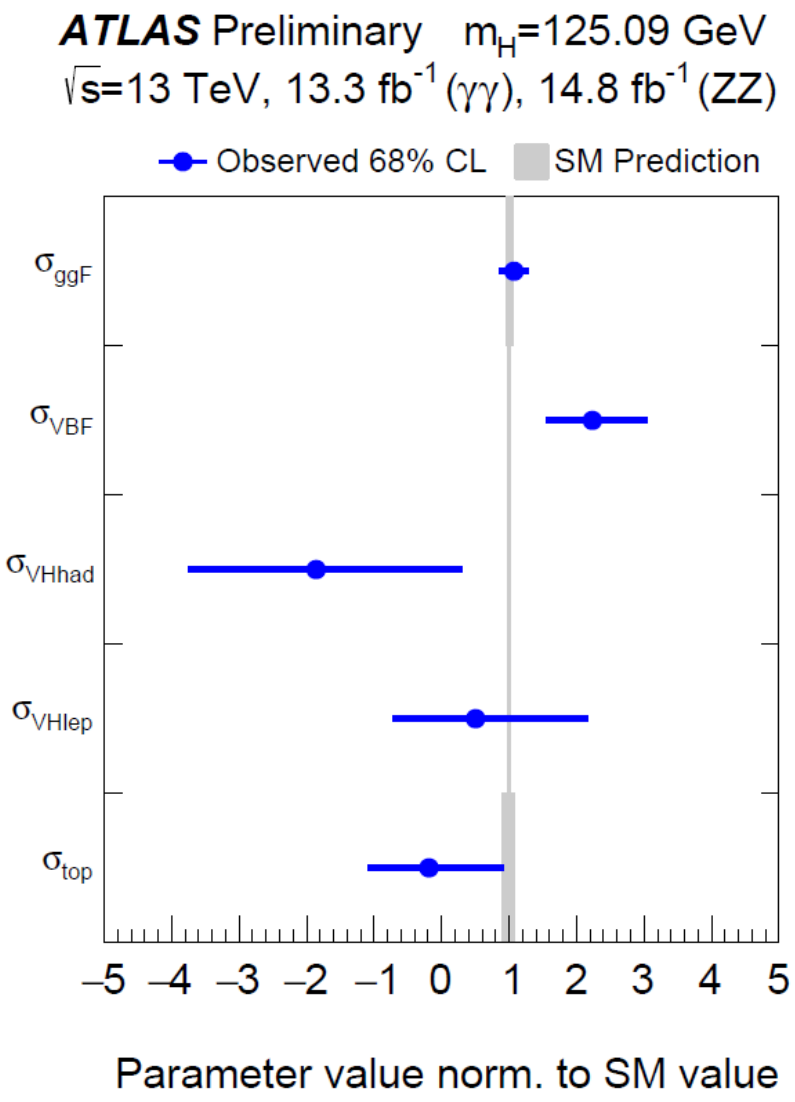
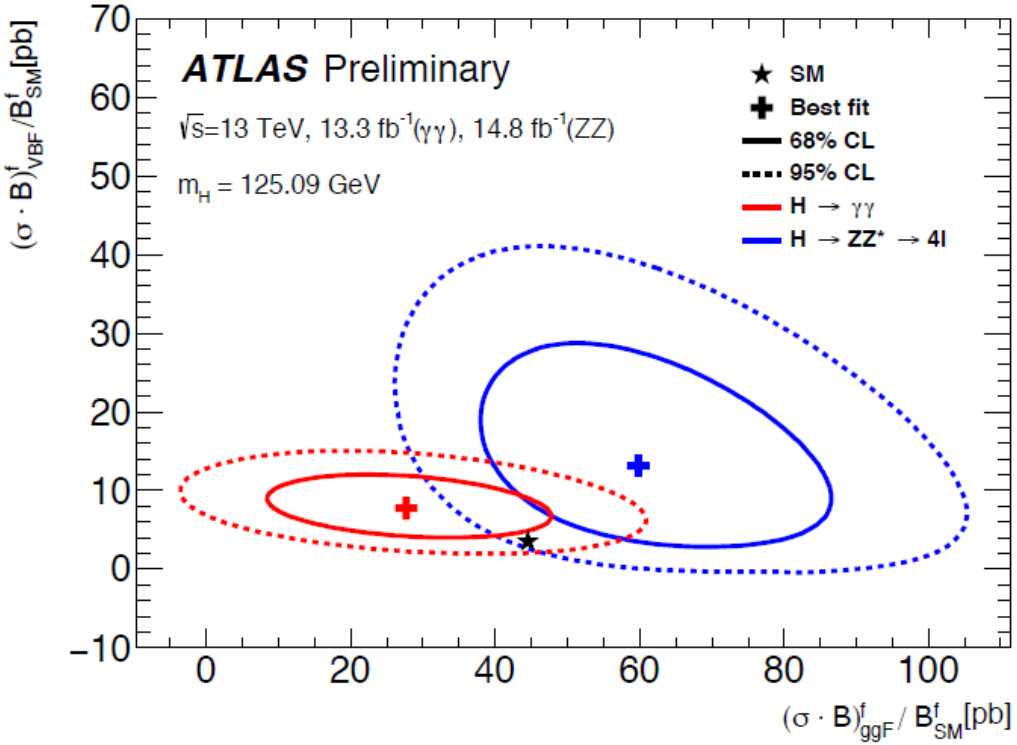
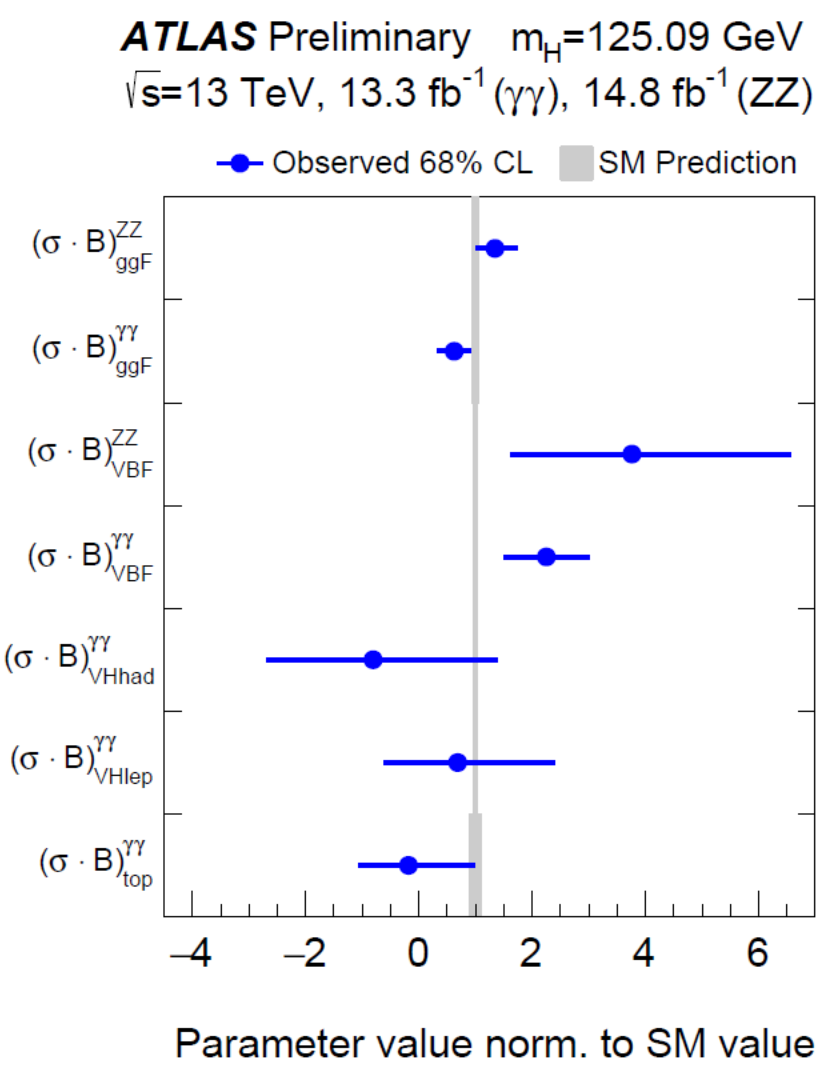


Higgs Cross Sections x Br

➔ **The compatibility between the measurement and SM prediction corresponds to a p-value of 11%.**





Higgs Production Cross Sections

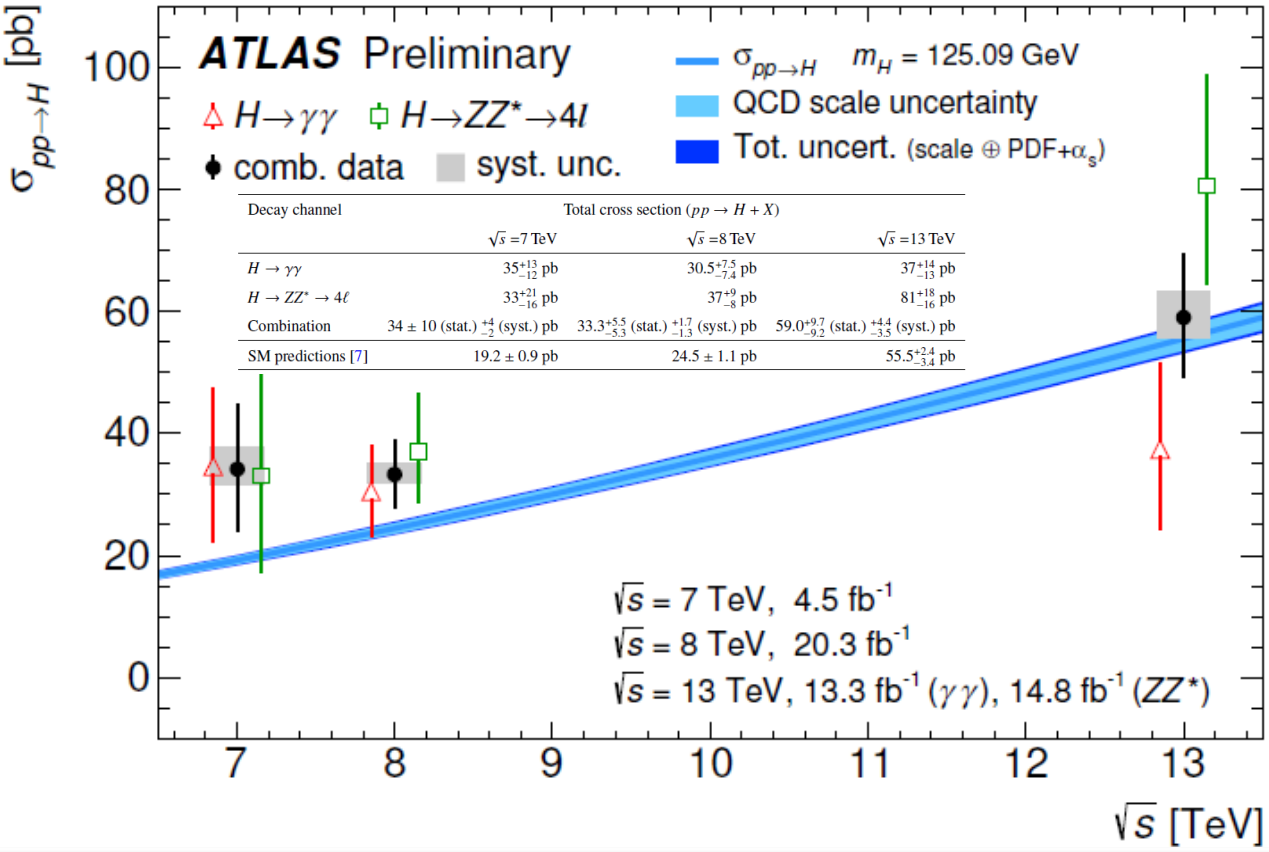
➔ The compatibility between measurement and SM prediction corresponds to a p-value of 43%.

➔ The global signal strength is measured to be:

$$\mu = \frac{\sigma \times \mathrm{B}}{(\sigma \times \mathrm{B})^{\mathrm{SM}}}$$

$$\mu = 1.13\ ^{+0.18}_{-0.17}$$

➔ The local significance of Higgs boson is 10σ (exp: 8.6σ)

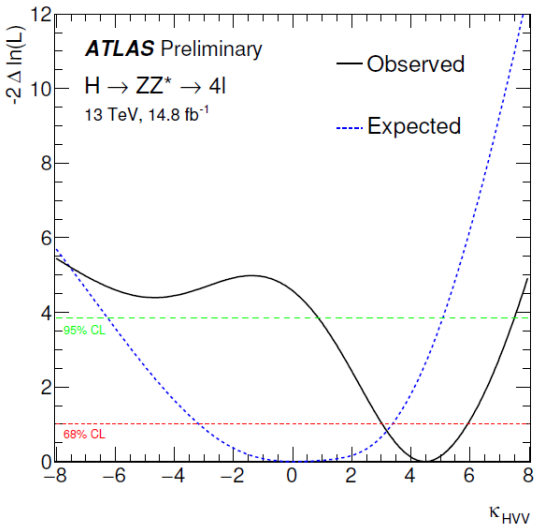


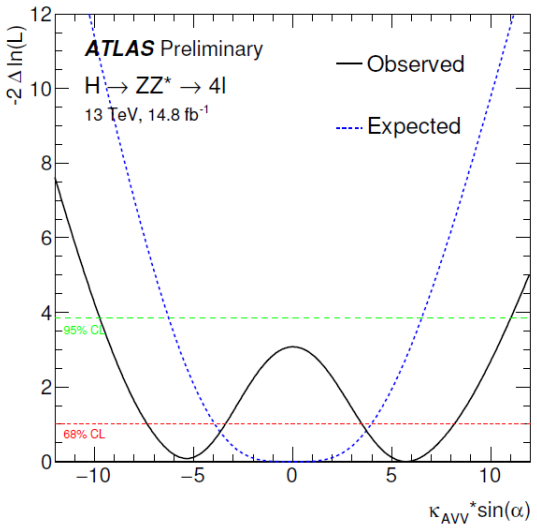
Decay channel	Total cross section ($pp \to H + X$)		
	$\sqrt{s}$ =7 TeV	$\sqrt{s}$ =8 TeV	$\sqrt{s}$ =13 TeV
$H \to \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16} pb	37^{+9}_{-8} pb	81^{+18}_{-16} pb
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb	$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb
SM predictions [7]	19.2 ± 0.9 pb	24.5 ± 1.1 pb	$55.5^{+2.4}_{-3.4}$ pb

Search for BSM Higgs

- Limits on the BSM parameters K_{HVV}, K_{AVV} sinα are derived with a fit of yields in different categories.
- K_{SM} which scales SM interactions is fixed to unity. ggF production is fixed to SM value, but Br(H→ZZ*) and BSM couplings are free parameters.

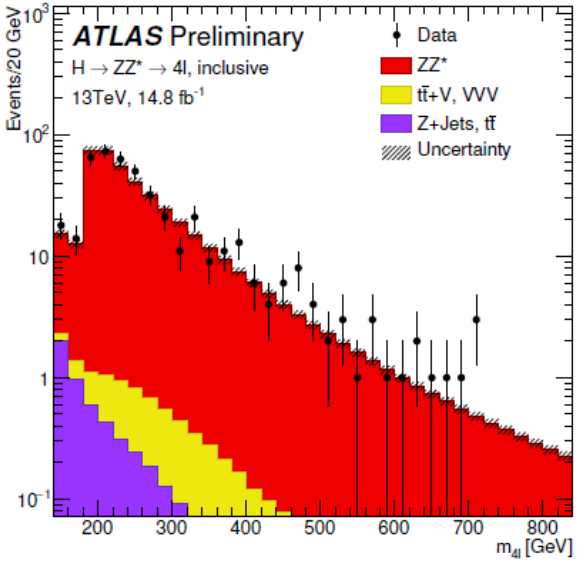
Not excluded range at 95% CL	κ_{HVV}		$\kappa_{AVV} \cdot \sin\alpha$	
	expected	observed	expected	observed
	[−6.3, 5.1]	[0.9, 7.5]	[−6.3, 6.5]	[−9.7, 11.0]

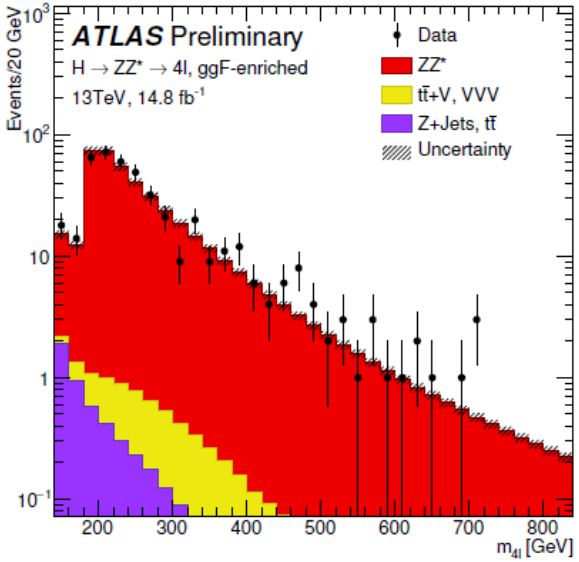


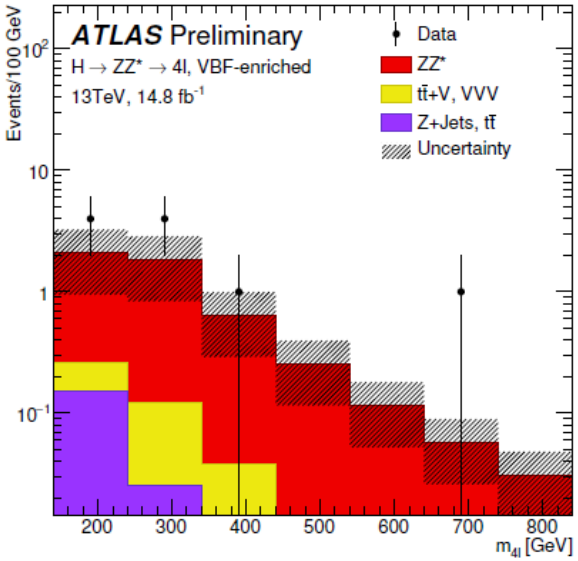


Analysis category	Signal ggF + $b\bar{b}H$ + $t\bar{t}H$	VBF	WH	ZH	Background ZZ^*	Z + jets, $t\bar{t}$	Total expected	Observed
0-jet	11.2 ± 1.4	0.120 ± 0.019	0.047 ± 0.007	0.060 ± 0.006	6.2 ± 0.6	0.84 ± 0.12	18.4 ± 1.6	21
1-jet	5.7 ± 2.4	0.59 ± 0.05	0.137 ± 0.012	0.091 ± 0.008	1.62 ± 0.21	0.44 ± 0.07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

Search for Heavy Higgs







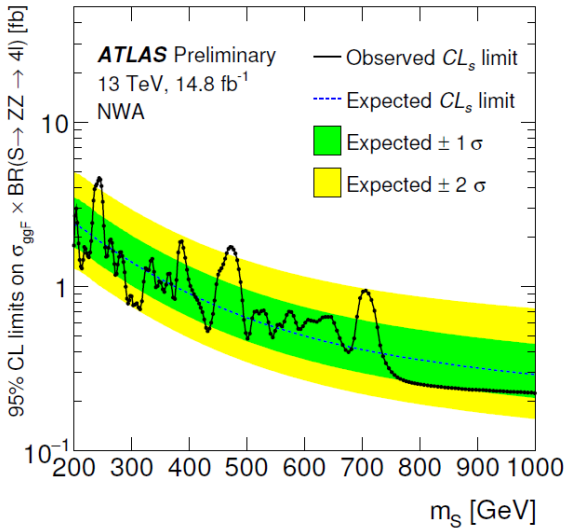
Final state	ZZ^*	Z + jets, $t\bar{t}$, WZ	$t\bar{t}V$,VVV	Expected	Observed
4μ ggF-enriched	125 ± 10	0.95 ± 0.14	1.57 ± 0.09	127 ± 10	128
$2e2\mu$ ggF-enriched	205 ± 17	2.5 ± 0.4	2.75 ± 0.17	211 ± 17	199
$4e$ ggF-enriched	83 ± 7	1.47 ± 0.22	1.28 ± 0.08	86 ± 7	111
VBF-enriched	4.6 ± 2.8	0.18 ± 0.05	0.268 ± 0.016	5.1 ± 2.8	10
Total	418 ± 35	5.1 ± 0.7	5.87 ± 0.35	429 ± 35	448

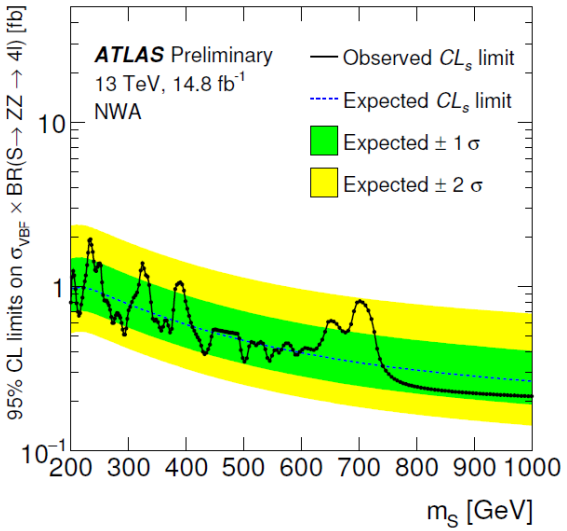
Search for Heavy Higgs

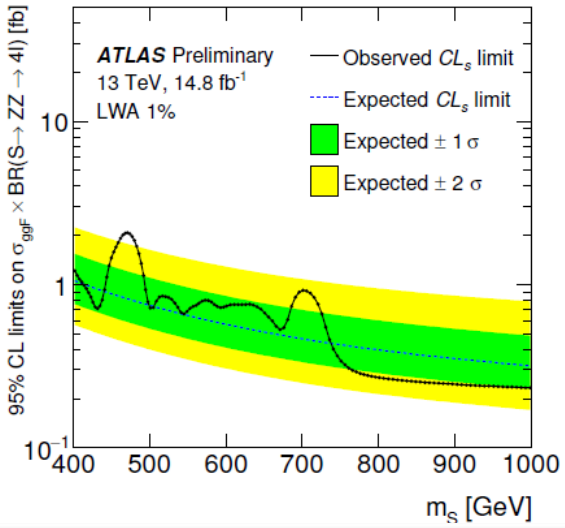
➔**BSM: two Higgs doublet model (2HDM); Electroweak singlet model (EWS)**

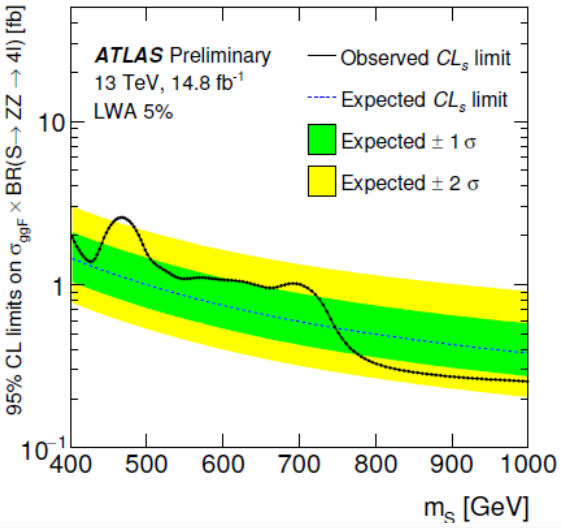
➔**The maximum deviation from SM bkgd is found at a mass ~705 GeV with NWA the global p-value is ~1.9σ.**

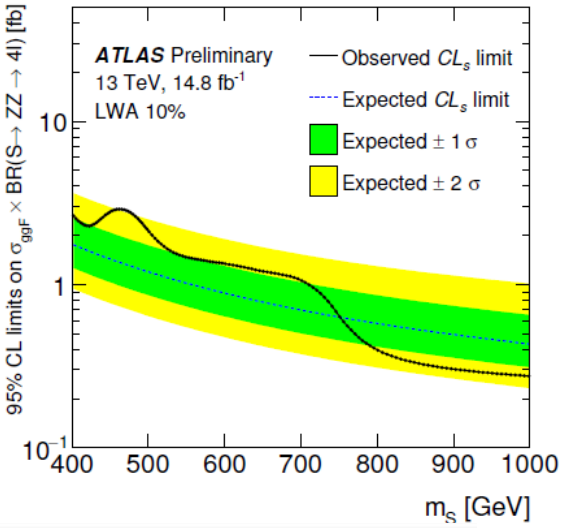
➔**No significant excess has been observed.**









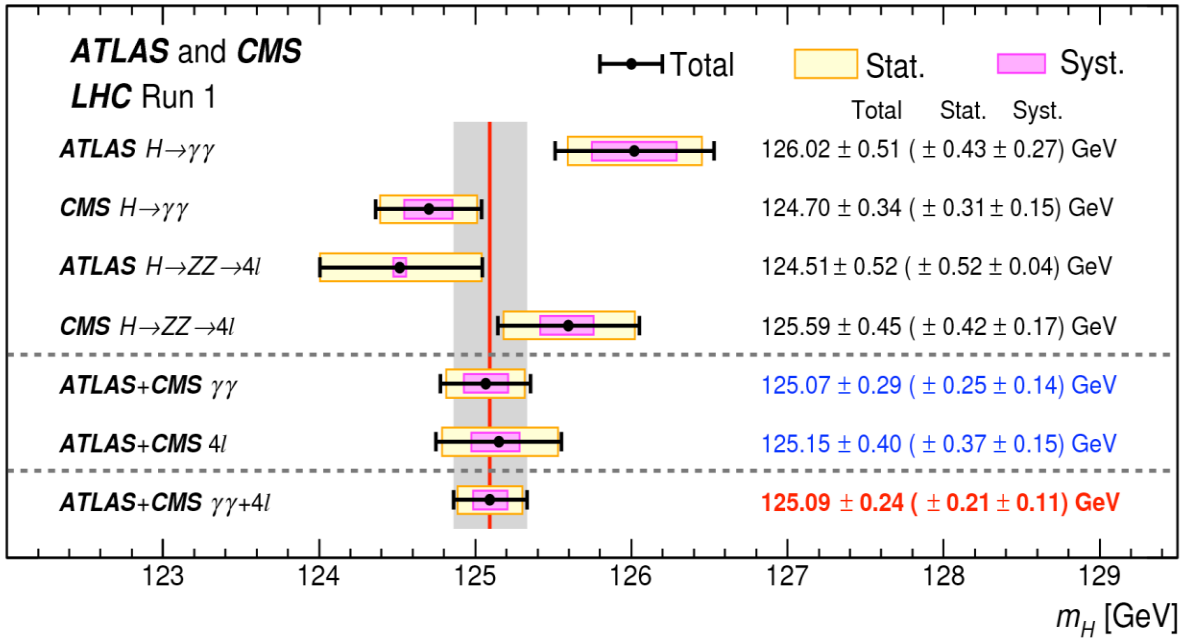


Analysis using full datasets is still ongoing, please stay tuned !

Thank you !

Combined Higgs Mass

ATLAS + CMS: PRL114 (2015) 191803



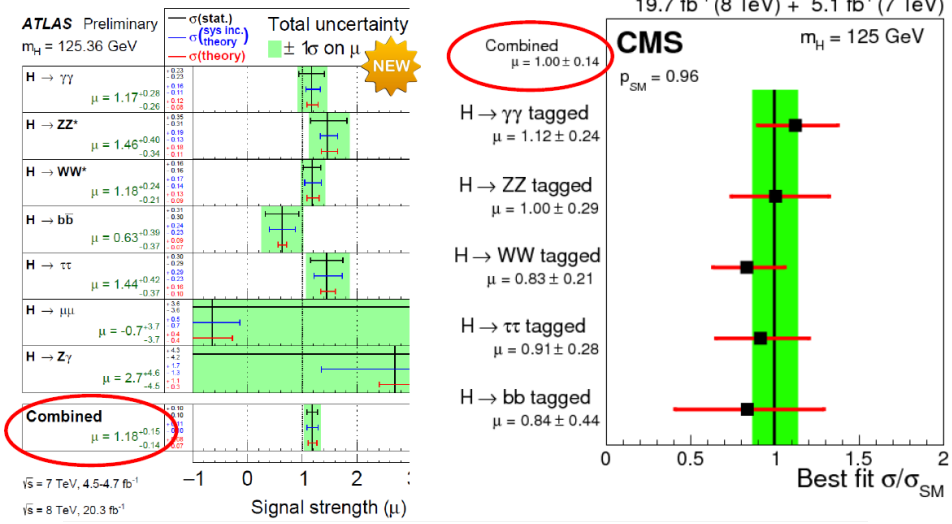
➔ **Higgs mass precision is better than 0.2%.**

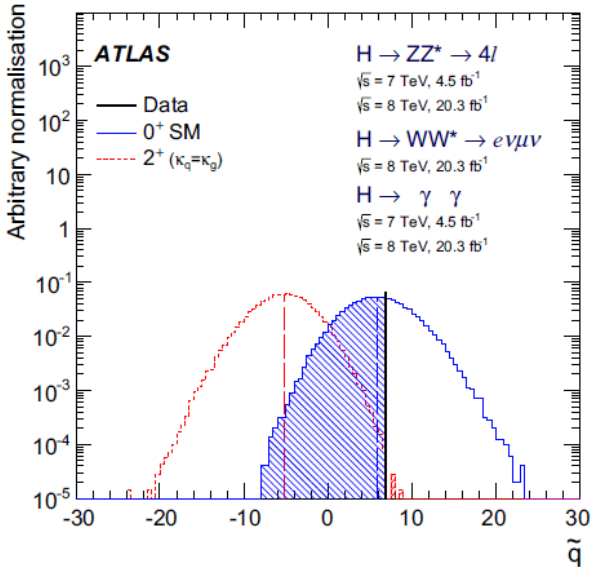
➔ **PRL Editor Suggestion**

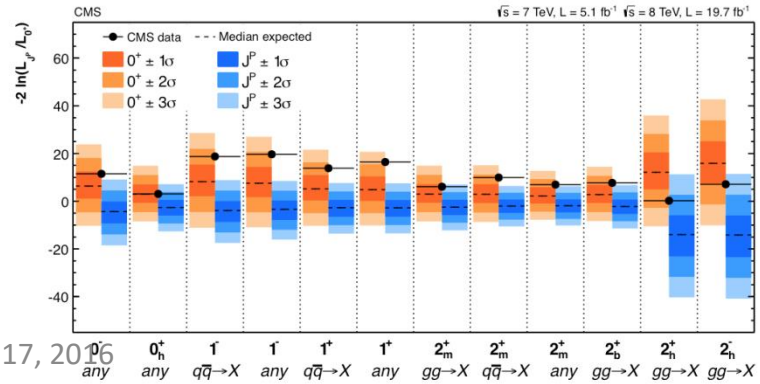
Higgs Properties Measurement

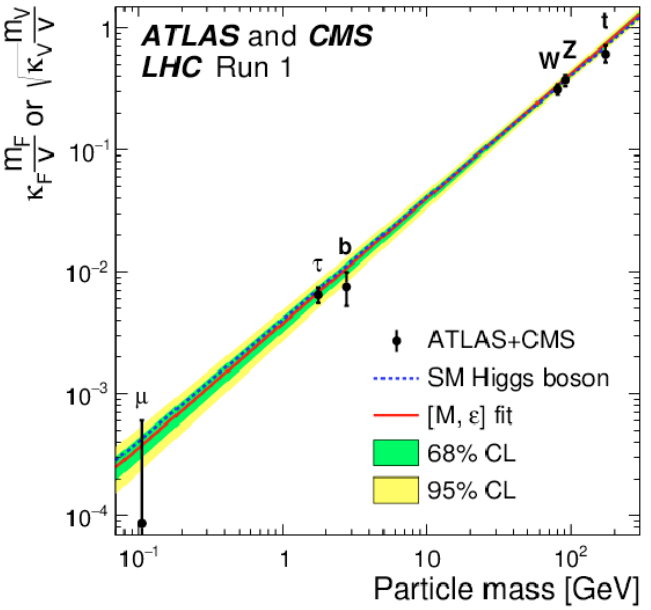
- **Higgs Strength μ = 1.09 ± 0.14**
- **Spin/Parity: 0^+**
- **Couplings: agree with SM predictions**

- **Results are consistent with the SM !**









Z*->4l Prope
ement

Higgs Properties Measurement

Coupling scale factors

2-parameter benchmark model:

$\kappa_V = \kappa_W = \kappa_Z$

$\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g$

(Gluon coupling are related to top, b, and their interference in tree level loop diagrams)

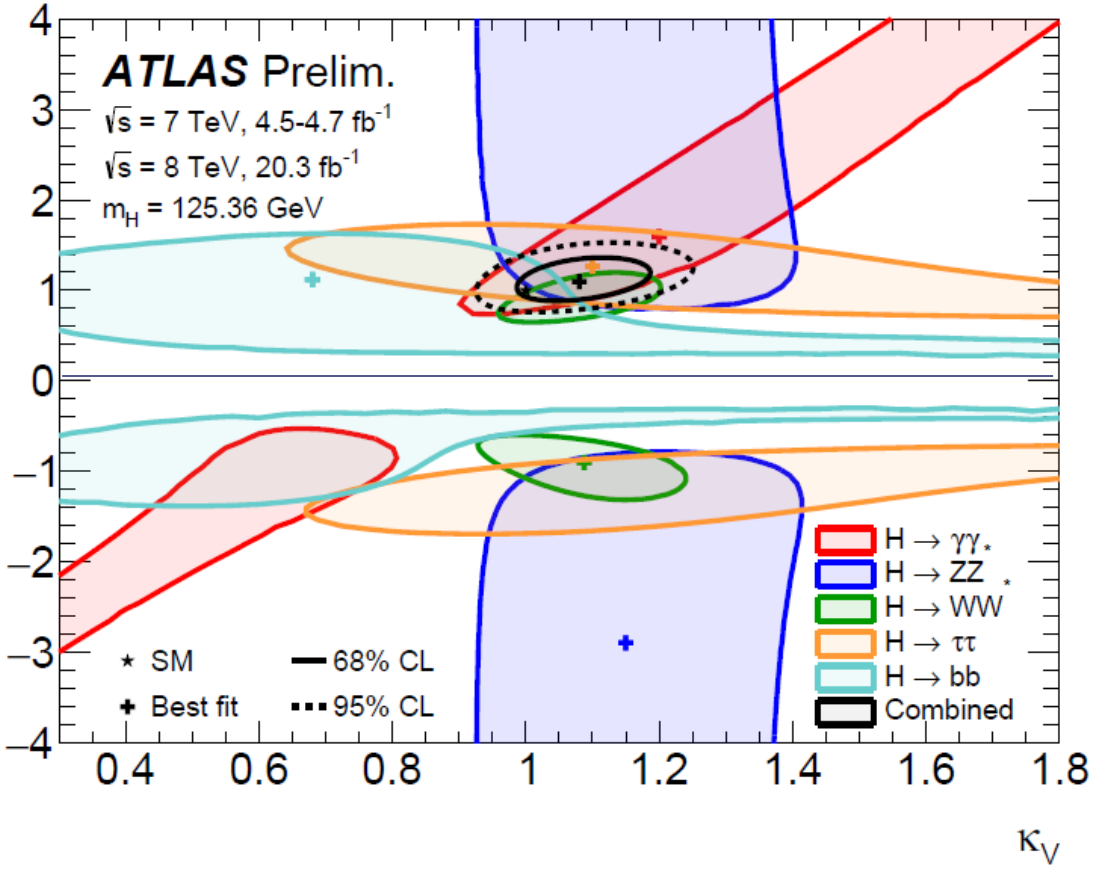
$$\frac{\sigma \cdot B\,(gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot B_{SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Assume no BSM contributions to loops: gg→ H and no BSM decays (no invisible decays)

$$\kappa_V = 1.09^{+0.07}_{-0.07}$$

$$\kappa_F = 1.11^{+0.17}_{-0.15}$$

➔ **$\kappa_F = 0$ is excluded (>5σ)**



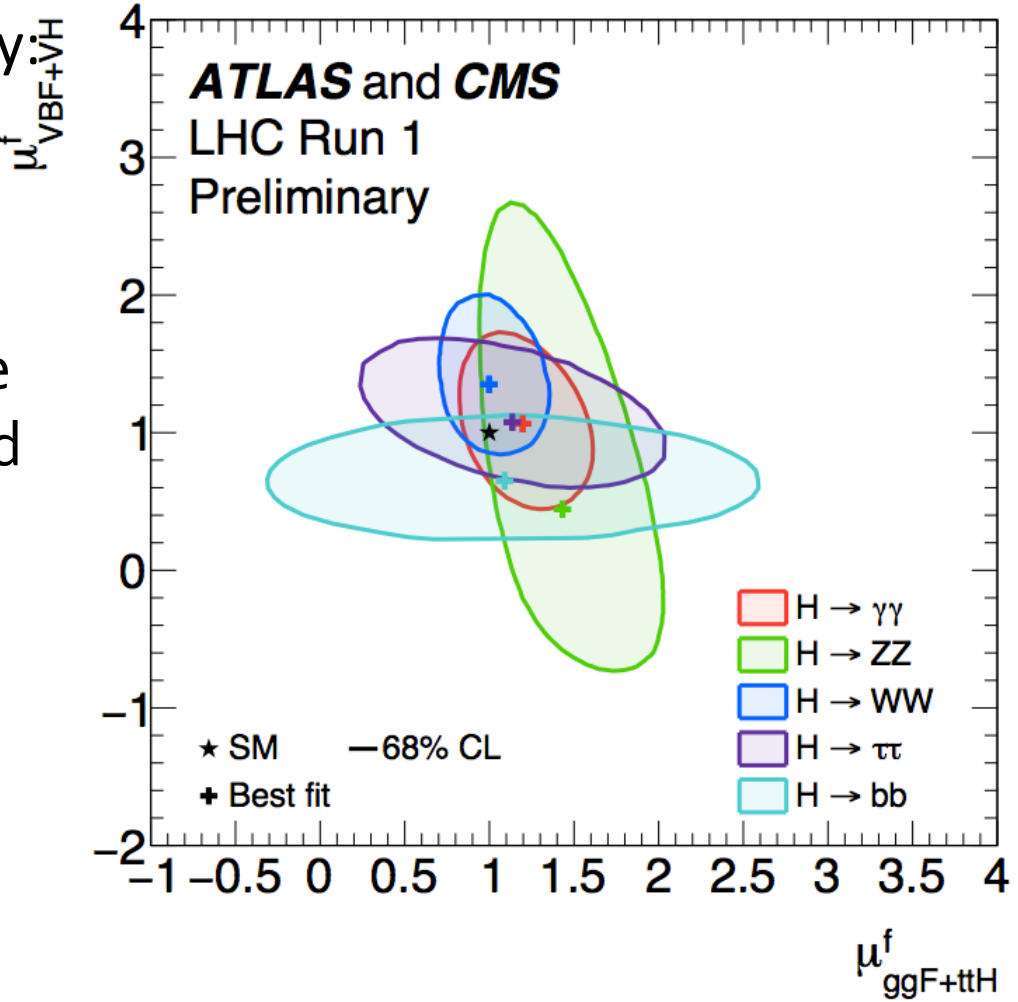
Fermionic & Bosonic production

- Can also fit μ_V^f vs μ_F^f per decay:
  - $\mu_V^f = \mu^f_{VBF+VH}$
  - $\mu_F^f = \mu^f_{ggF+ttH}$

- μ_V/μ_f can be measured in the different decay channels and combined:

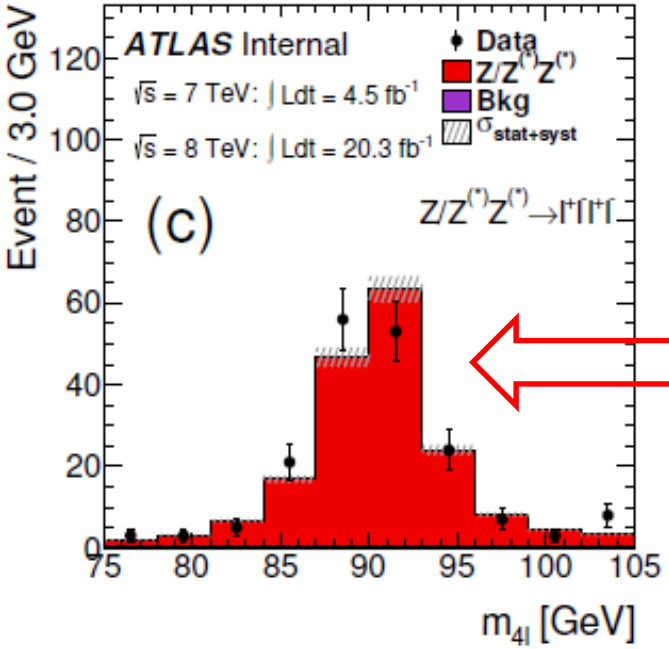
$$\mu_V/\mu_f = 1.06^{+0.35}_{-0.27}$$

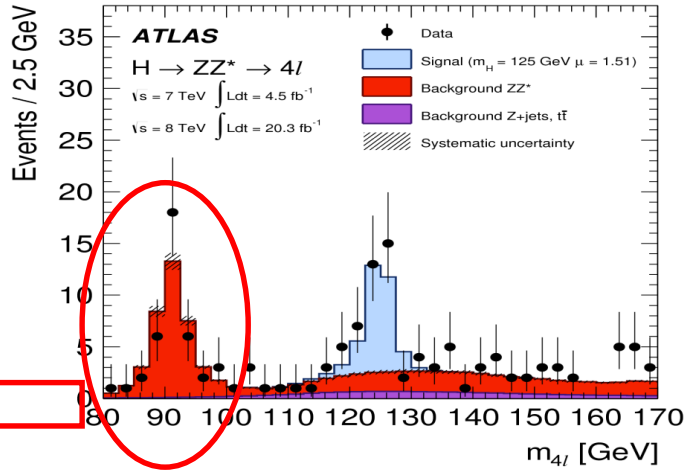
in agree with SM

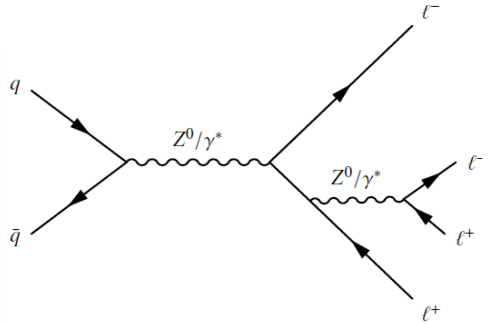


Analysis of Single Resonance Z→4ℓ

- The Z →4l production was first observed at the LHC by ATLAS and CMS. It serves as a standard candle for 4l decay channel along the Higgs discovery.
- Cross section and BR measurement of the Z → 4l production provides
  - A SM test for a rare decay process, measurements of σ(4l) and BR(Z→4l)
  - A complementary test of the detector response for H → 4l detection







$$BR = \frac{\sigma_{4l}^{PS} \cdot (1 - f_t)}{\sigma_{pp \to Z}}$$

$$BR(\text{meas.}) = 3.20 \pm 0.25 \pm 0.13 \times 10^{-6}$$

$$BR(\text{SM NLO}) = 3.33 \pm 0.01 \times 10^{-6}$$

Phys. Rev. Lett. 112, 231806 (2014)

Z/ZZ →4l Productions

arXiv: 1509.07844

- Very rich physics: resonant Z→4l, H→ZZ*→4l, SM ZZ→4l
- Differential cross section measurements in m_{4l} and P_T for inclusive 4l ($80<m_{4l}<1000$ GeV)
- First try to constraint gg→4l contribution from data
- Theoretical predictions available at different level of corrections

Theoretical Predictions:
qq → ZZ: Powheg (NLO)
on-shell H: Powheg (NLO)
gg → ZZ : MCFM (LO)
H → 4l & on-shell qq → ZZ:
NNLO QCD + NLO EWK