Higgs Boson Production and Decays in ATLAS

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On behalf of the ATLAS Collaboration

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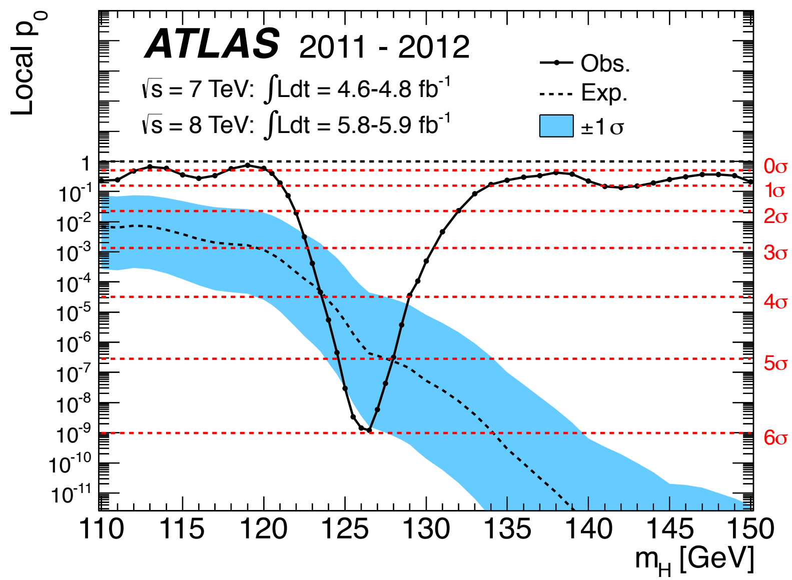
Introduction

- The Higgs boson, predicted by Brout-Englert-Higgs mechanism, was discovered at LHC by ATLAS and CMS in July 2012
- Nobel prize was awarded to François Englert and Peter Higgs in 2013
- With LHC Run 2 data at 13 TeV, need to re-discover the Higgs boson and measure Higgs couplings and other properties
- Use Higgs boson as a tool to probe new physics (not in this talk)

Phys. Lett. B 716 (2012) 1-29



Brout

Englert

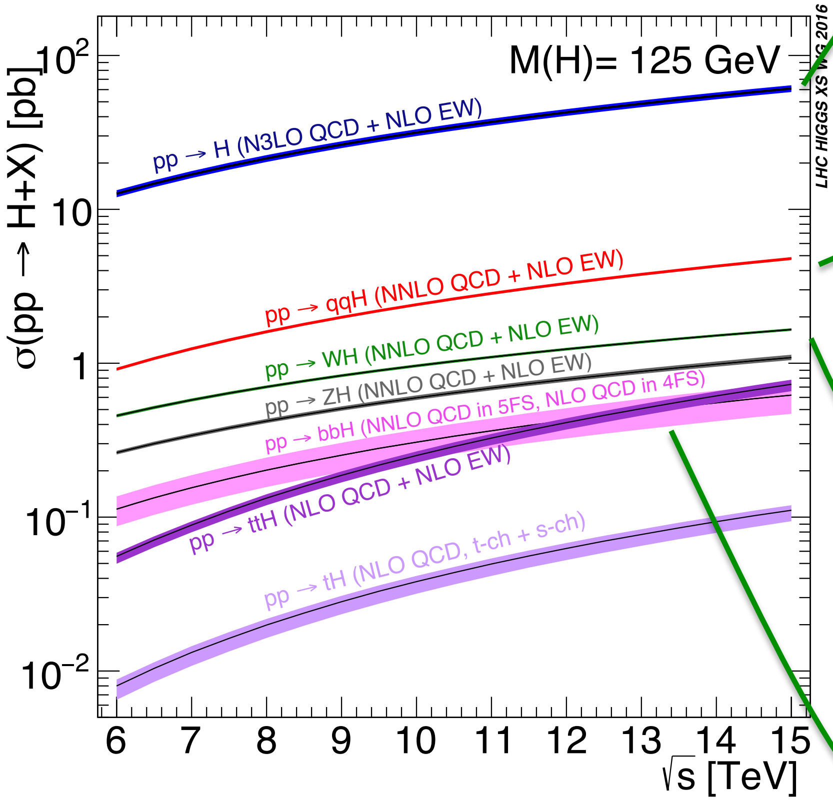
Photo: A. Mahmoud
François Englert
Prize share: 1/2

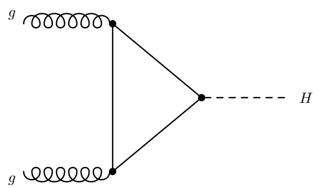
Higgs

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

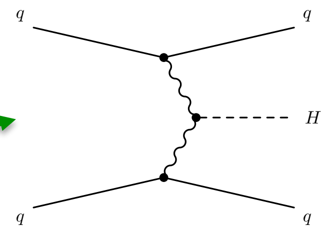
Higgs Boson Production at the LHC

LHC Higgs Cross Section Working Group

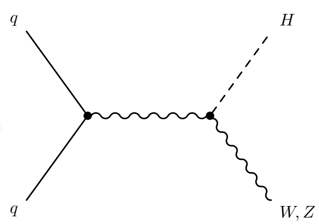




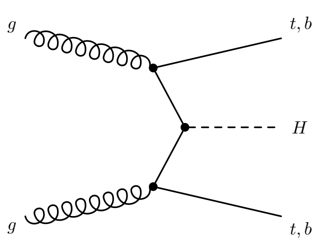
ggF: dominant, larger initial state radiation from gluons



VBF: two forward jets with high mass and large rapidity gap



VH: vector boson (lν, ll’, qq’)



ttH: many b-jets, leptons, E_T^{miss}

Higgs Boson Production at LHC

LHC Higgs Cross Section Working Group

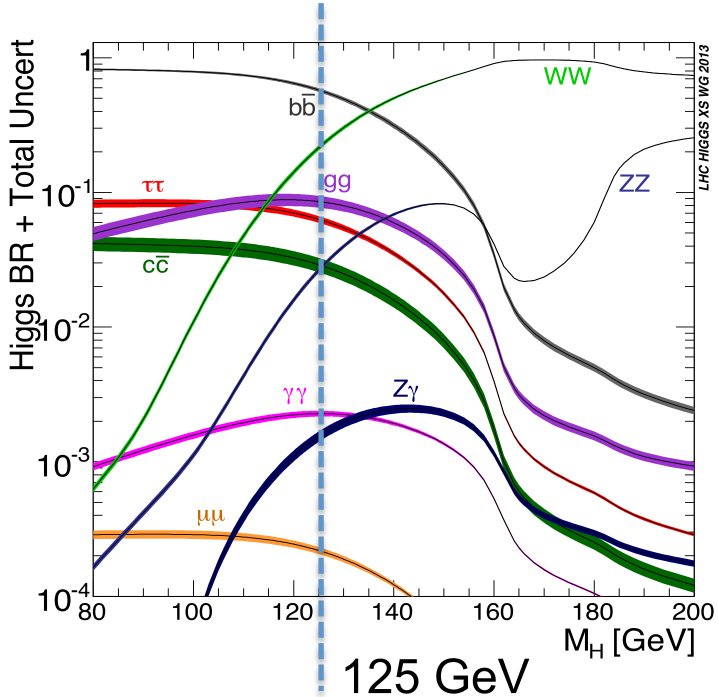
m_H=125 GeV [pb]	8 TeV (Run 1, CERN Report 3)	13 TeV (Run 2, CERN Report 4)	σ(13 TeV)/ σ(8 TeV)
ggF	19.27 NNLO QCD + NLO EW	48.58 N3LO QCD and NLO EW	2.52
VBF	1.58 NNLO QCD + NLO EW	3.78 NNLO QCD + NLO EW	2.40
WH	0.70 NNLO QCD + NLO EW	1.37 NNLO QCD + NLO EW	1.95
ZH	0.43 NNLO QCD + NLO EW	0.88 NNLO QCD + NLO EW	2.13
ttH	0.13 (NLO QCD)	0.51 NLO QCD + NLO EW	3.92

- From 8 TeV to 13 TeV, the cross sections increase by a factor of **2-4**.
- Uncertainties of ggF:
  - CERN Report 3: 8% (QCD scale), 7.5% (PDF)
  - CERN Report 4: 4% (QCD scale), 3.2% (PDF)

N3LO ggF: Anastasiou *et at.*, JHEP 1605 (2016) 058
PDF4LHC, Butterworth *et al.*, J.Phys. G43 (2016) 023001

Higgs Boson Decays

LHC Higgs Cross Section Working Group



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

- Low BR channels (ZZ→4l, γγ, Zγ and μμ) have better mass resolutions but small rate
- Channels with higher BRs (the rest) are challenging experimentally
- Note: BR (H→μμ) = 2.19E-4; BR(H→ZZ→4l) = 1.26E-4

Status of Individual Channels

LHC Run 1: data taking in 2011 and 2012 with $\sqrt{s}$ = 7 TeV (~4.5 fb^{-1}) and $\sqrt{s}$ = 8 TeV (~20 fb^{-1})

LHC Run 2: data taking in 2015 and 2016 with $\sqrt{s}$ = 13 TeV (~20.7 fb^{-1}).
13.2 fb^{-1} to 14.8 fb^{-1} are used for the results

Status	Run 1	Run 2
$H \to \gamma\gamma$	✔	✔
$H \to ZZ^* \to 4l$	✔	✔
$\gamma\gamma$ & ZZ combination	✔	✔
$H \to WW^* \to l\nu l\nu$	✔	
$H \to \tau\tau$	✔	
VH, $H \to bb$	✔	✔
VBF, H->bb + γ		✔
ttH, H->bb	✔	✔
ttH, H->multi-leptons	✔	✔

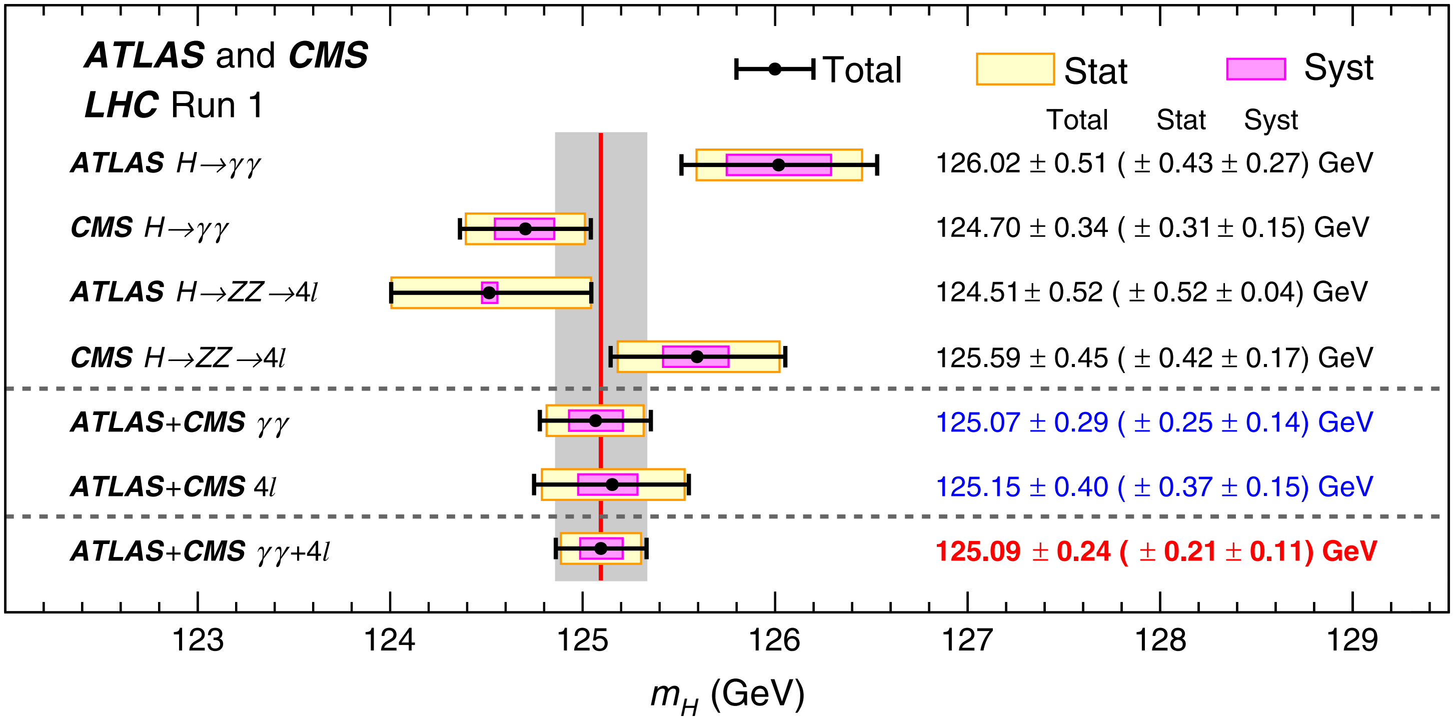
$H \to \mu\mu$ will be covered by Liang Li

Higgs Mass Measurement from ATLAS and CMS at Run 1

- Higgs mass is the only free parameter in BEH mechanism
- Mass combination using γγ and ZZ channels gives:

m_H=125.09 ± 0.24 GeV

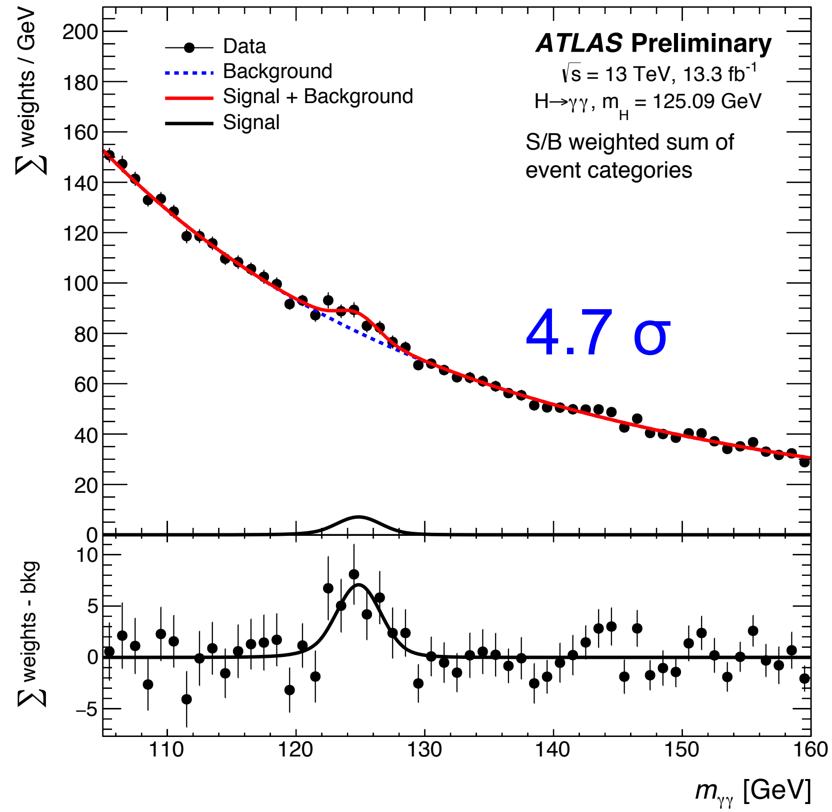
PRL 114, 191803 (2015)

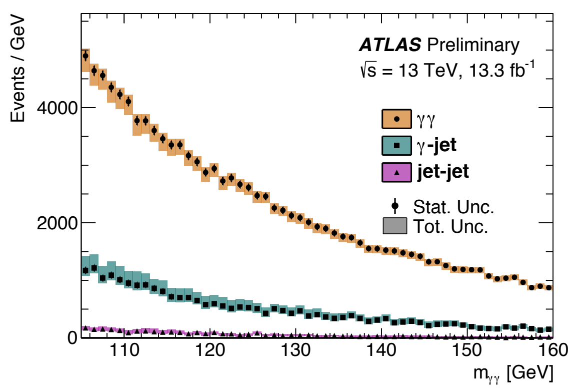


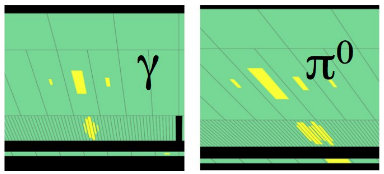
Uncertainty is at the level of 0.2%

H→γγ (Run 2) ATLAS-CONF-2016-067

- Signal: small BR, but good mass resolution
- Select 2 tight isolated photons with cut on $p_T/m_{\gamma\gamma} > 0.35$ (0.25)
- Background composition: continuum di-photon (about 79%), γ-jet and jet-jet fake (about 21%)
- Signal extraction by fitting the $m_{\gamma\gamma}$ distribution



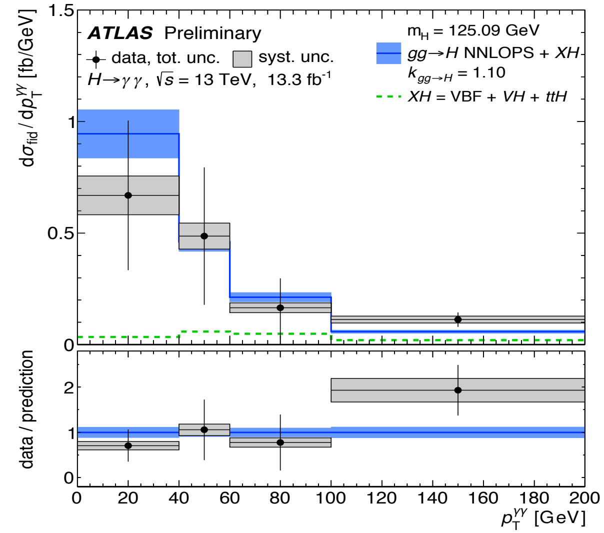




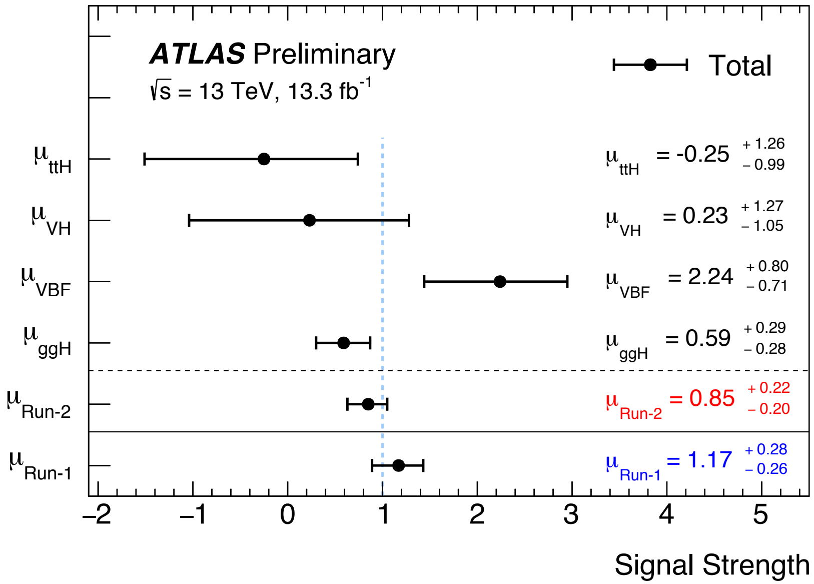
Fine η granularity of first layer can help reject π_0 background

H→γγ (Run 2) ATLAS-CONF-2016-067

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



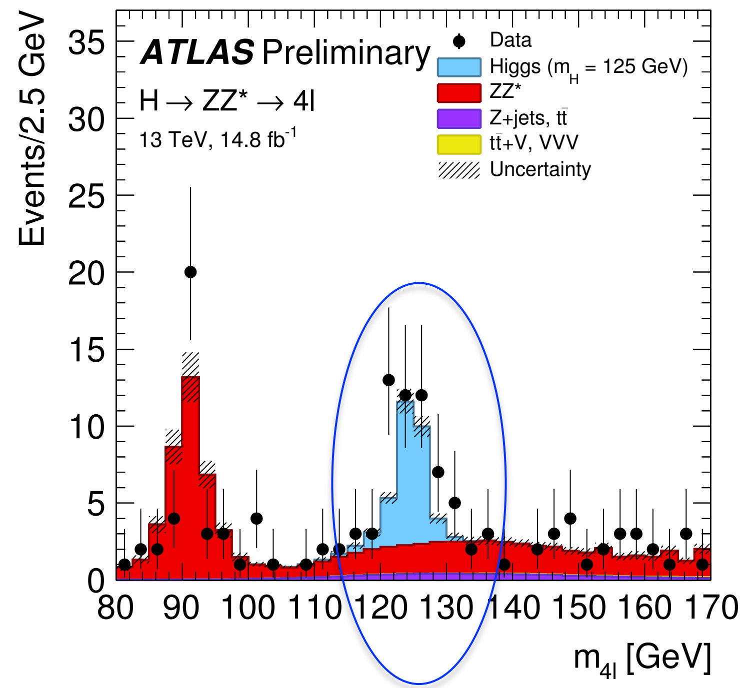
- Fiducial cross section measurement: reasonable agreement between data and theory



- Results consistent with SM expectations
- Run 2 signal strength measurement have smaller uncertainty compared with Run 1

H→ZZ*→4l (Run 2) ATLAS-CONF-2016-079

- Good signal mass resolution and S/B. Small rate.
- Lepton pT[1,2,3,4] > 20, 15, 10, (5)7 GeV (mu)e
- FSR correction and kinematic fit with Z mass constraint improve the signal mass resolution by 15%
- Background: continuum ZZ*: normalization and shape taken from MC simulation. Z+jets, ttbar (normalized from data control regions)

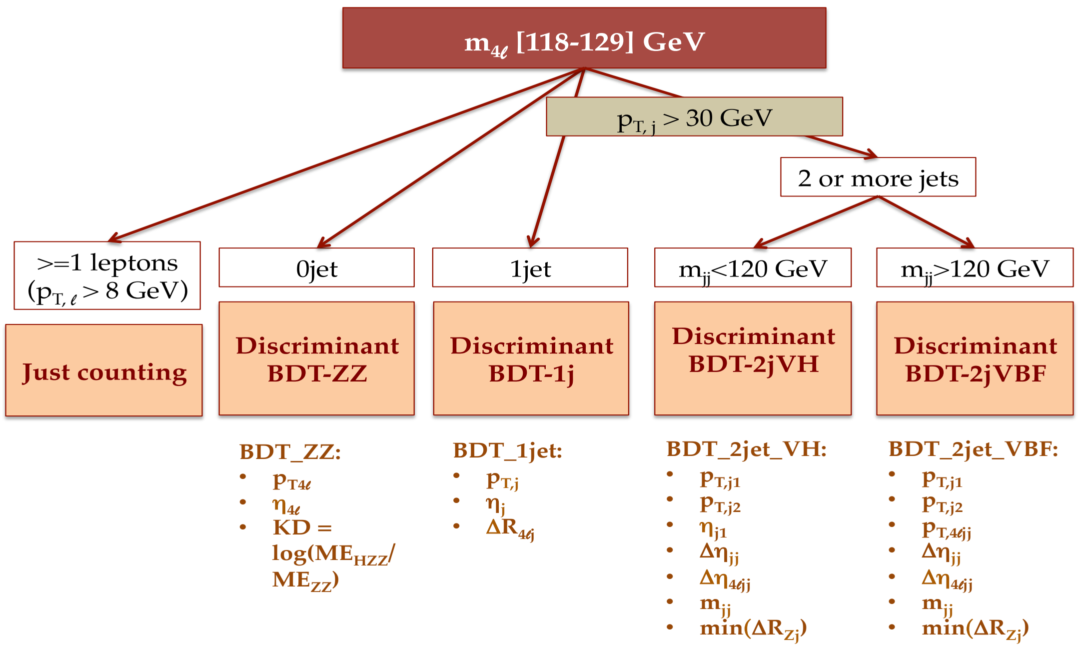


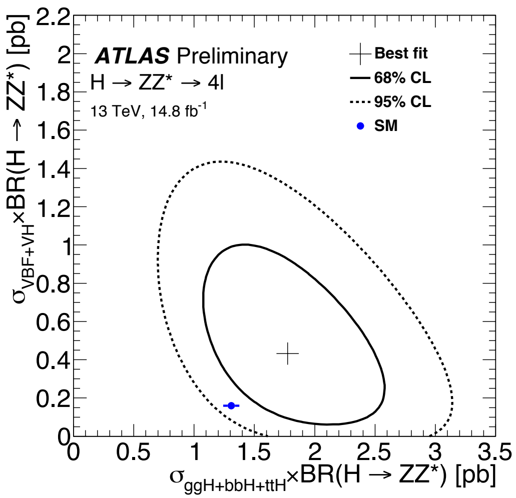
Final State	Signal full mass range	Signal	ZZ^*	$Z+$jets, $t\bar{t}$ ttV,VVV, WZ	S/B	Expected	Observed
4μ	8.8 ± 0.6	8.2 ± 0.6	3.11 ± 0.30	0.31 ± 0.04	2.4	11.6 ± 0.7	16
$2e2\mu$	6.1 ± 0.4	5.5 ± 0.4	2.19 ± 0.21	0.30 ± 0.04	2.2	8.0 ± 0.4	12
$2\mu 2e$	4.8 ± 0.4	4.4 ± 0.4	1.39 ± 0.16	0.47 ± 0.05	2.3	6.2 ± 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

118 <m4l<129 GeV

$H \to ZZ^* \to 4l$ (Run 2) ATLAS-CONF-2016-079

- Take the events between 118<m4l<129 GeV
- Boosted Decision Tree (BDT) method is used to improve the sensitivity
- Signal extraction by fitting the BDT output.
- Use m_H=125.09 GeV





Compatible to SM prediction

- 1.1 sigma for $\sigma_{ggF,bbH,ttH}$
- 1.4 sigma for $\sigma_{VBF,VH}$

Combined measurement with ZZ* and γγ (Run 2)

ATLAS-CONF-2016-081

Input: 13.3 fb^{-1} γγ & 14.8 fb^{-1} ZZ

$H \to ZZ^* \to 4\ell$ Category	Target	$H \to \gamma\gamma$ Category	Target
VH-leptonic	VHlep	$t\bar{t}H$ leptonic	top
0-jet	ggF	$t\bar{t}H$ hadronic	top
1-jet	ggF	VH dilepton	VHlep
2-jet VBF-like	VBF	VH one-lepton	VHlep
2-jet VH-like	VHhad	VH Emiss	VHlep
		VH hadronic loose	VHhad
		VH hadronic tight	VHhad
		VBF loose	VBF
		VBF tight	VBF
		ggH central low-$p_{\mathrm{T}t}$	ggF
		ggH central high-$p_{\mathrm{T}t}$	ggF
		ggH fwd low-$p_{\mathrm{T}t}$	ggF
		ggH fwd high-$p_{\mathrm{T}t}$	ggF

Build combined likelihood using the categories from individual analyses

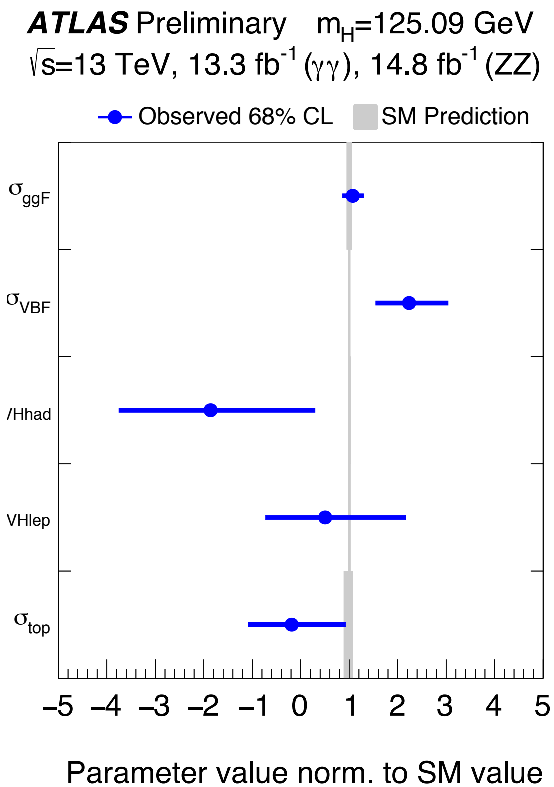
POI

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

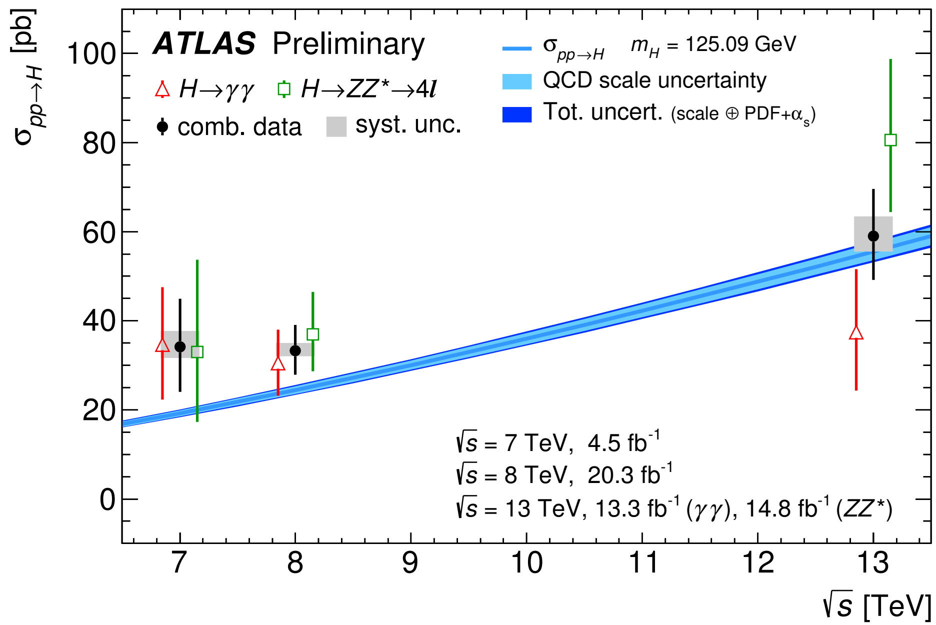
- All systematic uncertainties (nuisance) are varied to maximize the profile likelihood (profiled)
- Nuisance parameters: about 200
- Signal normalization uncertainties and experimental uncertainties between the two analyses are correlated

Combined measurement with ZZ* and γγ (Run 2)

ATLAS-CONF-2016-081



Combined signal strength: $\boxed{\mu = 1.13\,^{+0.18}_{-0.17}}$



- Higgs boson production is observed in the 13 TeV dataset with a local significance of about **10 σ** (8.6 σ expected)
- No significant deviation from the Standard Model predictions is observed

H→WW*→lνlν (Run 1)

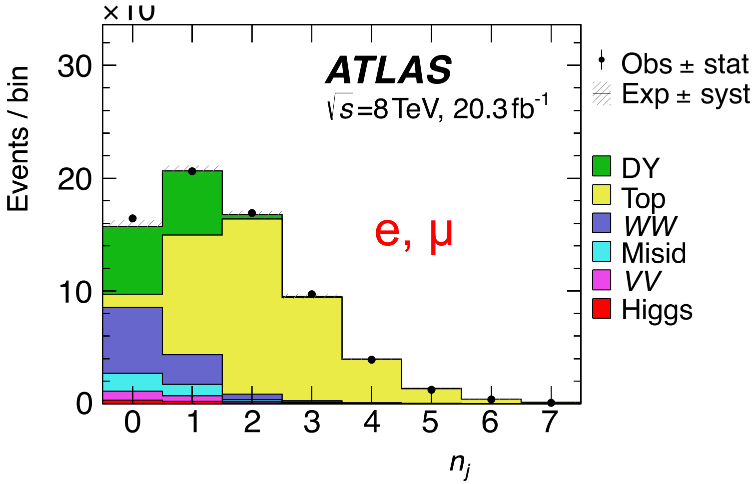
PRD 91, 012006 (2015)
JHEP08 (2015) 137

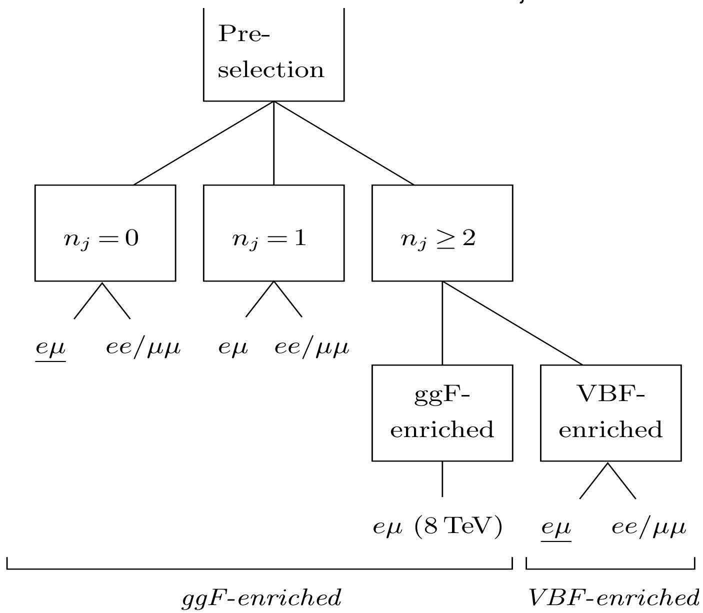
- Large rate but worse mass resolution due to the two missing neutrinos
- Categorization: split by lepton flavor and number of jets due to different background composition
- Use transverse mass (m_T) or BDT score as discriminants:

$$\text{where } E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + (m_{\ell\ell})^2},$$

$$m_T = \sqrt{(E_T^{\ell\ell} + p_T^{\nu\nu})^2 - |\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{p}_T^{\nu\nu}|^2},$$

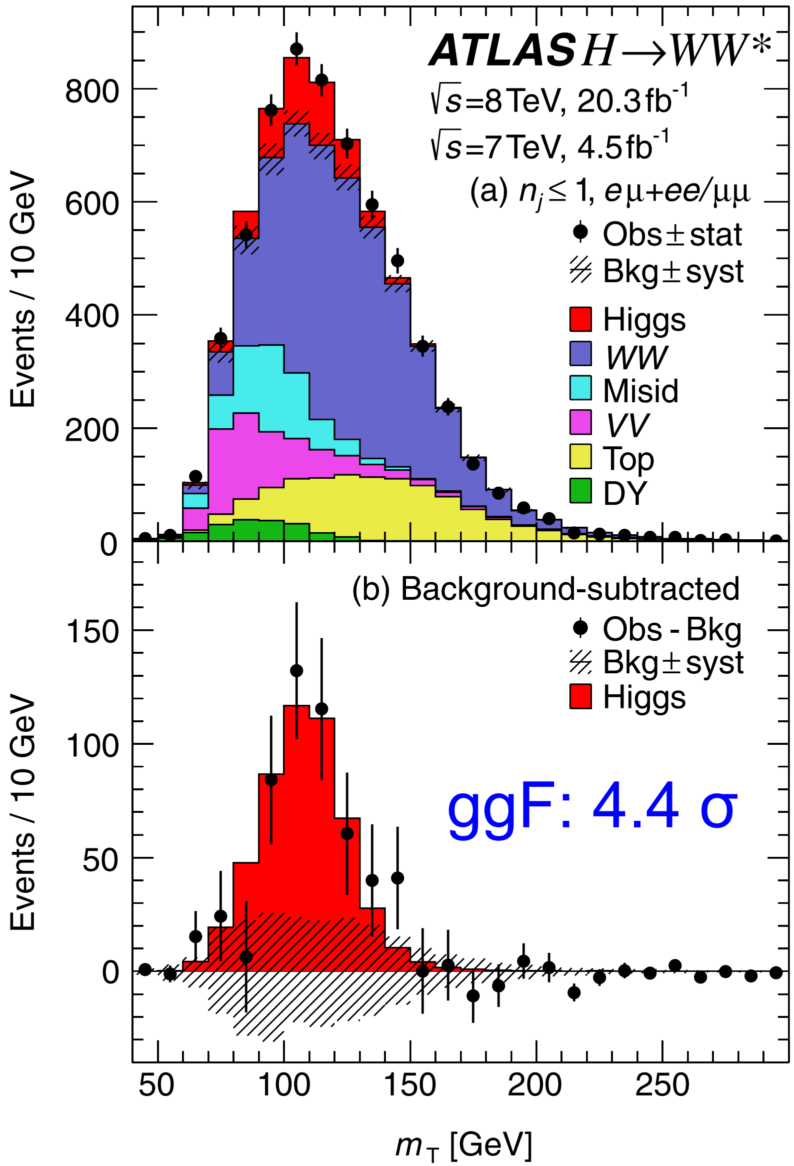
- Also have WH (3 leptons) and ZH (4 leptons) analyses



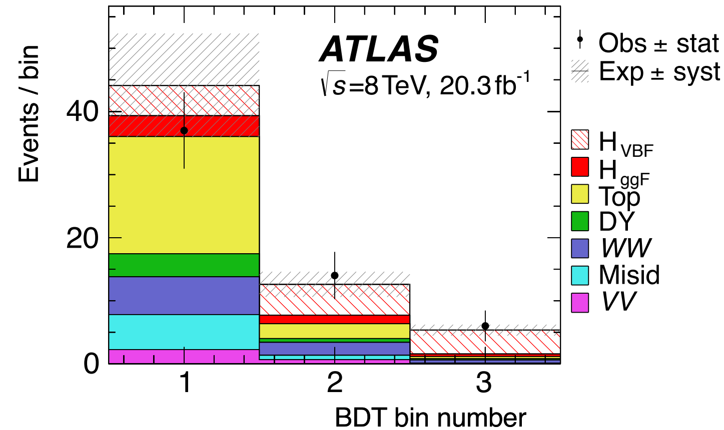


H→WW*→lvlv (Run 1)

PRD 91, 012006 (2015)
JHEP08 (2015) 137



VBF: 2.6 σ



Category	Exp. Z_0	Obs. Z_0	Obs. Z_0
ggF	4.4	4.2	
VBF	2.6	3.2	
VH	0.93	2.5	
WH only	0.77	1.4	
ZH only	0.30	2.0	
ggF+VBF+VH	5.9	6.5	

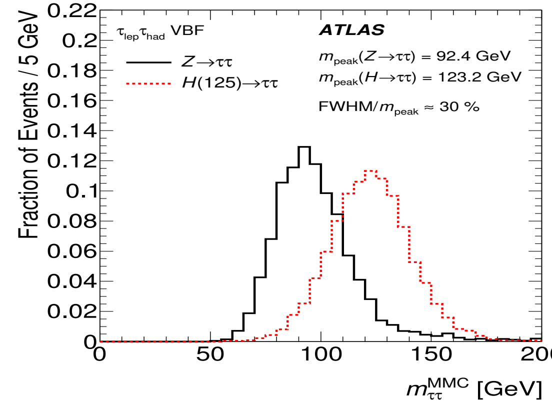
Signal significance Z_0

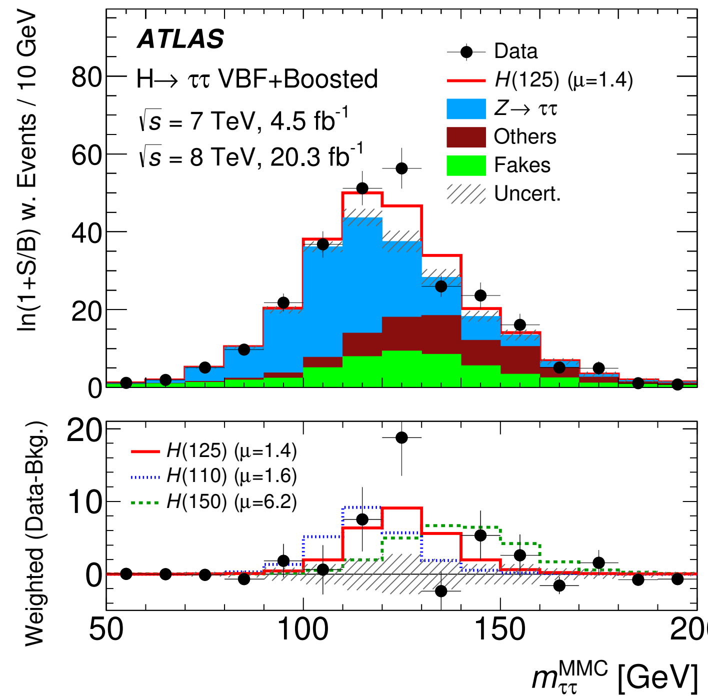
Combined: 6.5 σ

H→ττ (Run 1)

JHEP04 (2015) 117

- ττ has 3 final states:
  - Fully leptonic: 12.4%
  - Semi-leptonic: 45.6%
  - Hadronic: 42%
- Experimentally challenging
- Boosted ggF and VBF are most sensitive categories
- Z→ττ is estimated using Z→μμ data where μ is replace by simulated τ (2015 JINST 10 P09018)
- Data-driven method to estimate τ-fakes
- $m_{\tau\tau}$ is reconstructed with kinematic fit method (missing mass calculator)



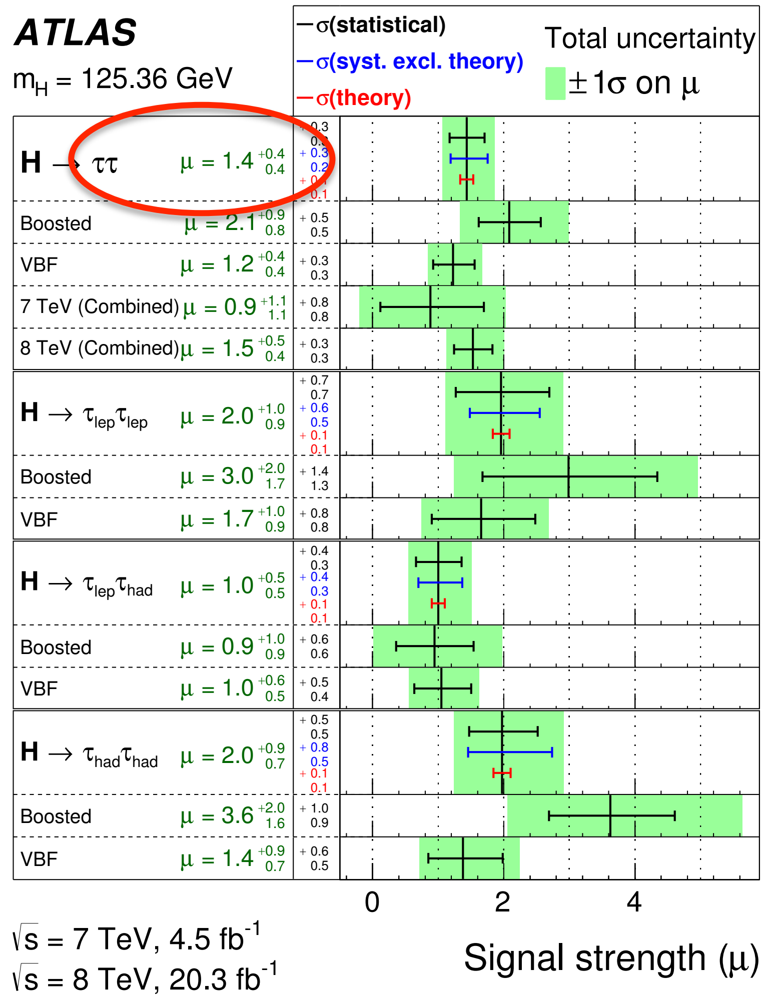


H→ττ (Run 1)

JHEP04 (2015) 117

- Use BDT method to improve sensitivity
- Signal extraction by fitting the BDT score

Channel and Category	Expected Significance (σ)	Observed Significance (σ)
$\tau_{lep}\tau_{lep}$ VBF	1.15	1.88
$\tau_{lep}\tau_{lep}$ Boosted	0.57	1.72
$\tau_{lep}\tau_{lep}$ Total	1.25	2.40
$\tau_{lep}\tau_{had}$ VBF	2.11	2.23
$\tau_{lep}\tau_{had}$ Boosted	1.11	1.01
$\tau_{lep}\tau_{had}$ Total	2.33	2.33
$\tau_{had}\tau_{had}$ VBF	1.70	2.23
$\tau_{had}\tau_{had}$ Boosted	0.82	2.56
$\tau_{had}\tau_{had}$ Total	1.99	3.25
Combined	3.43	4.54



4.54 σ

Lep, had channel is the most sensitive channel

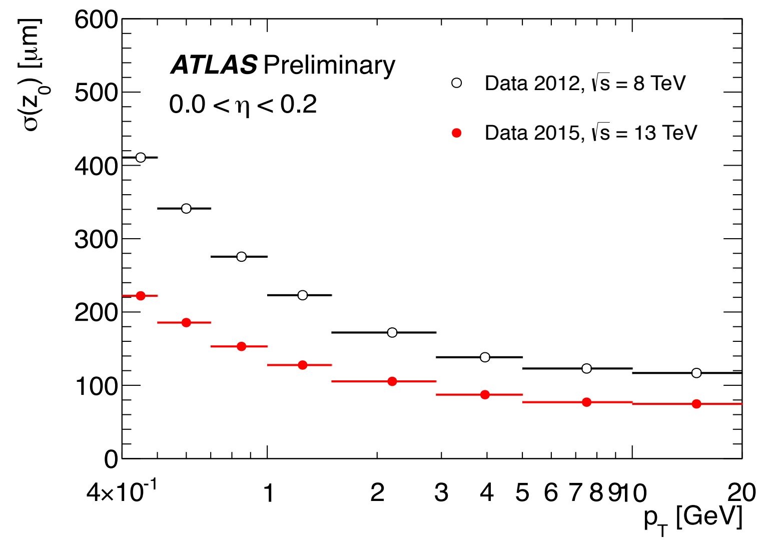
VH, H→bb (Run 2) ATLAS-CONF-2016-091

- Largest BR (~58%). ggF events can not trigger detector. Rely on VH production to trigger
- Signal mass resolution is worse.

It includes

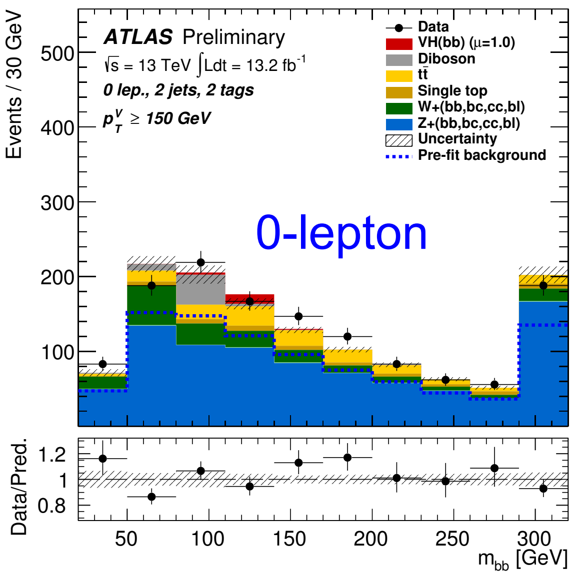
- **0-lepton (ZH, Z→vv),**
  - Missing ET > 150 GeV
- **1-lepton (WH, W→lv)**
  - Electron or muon, p_T > 25 GeV
  - Tight isolation
  - Missing ET > 30 GeV
  - p_T^V>150 GeV
- **2-lepton (ZH, Z→ll) channels**
  - Isolated di-electron or di-muon
  - Leading lepton p_T > 25 GeV, sub-leading lepton p_T > 7 GeV
  - 71 < m_{ll} < 121 GeV

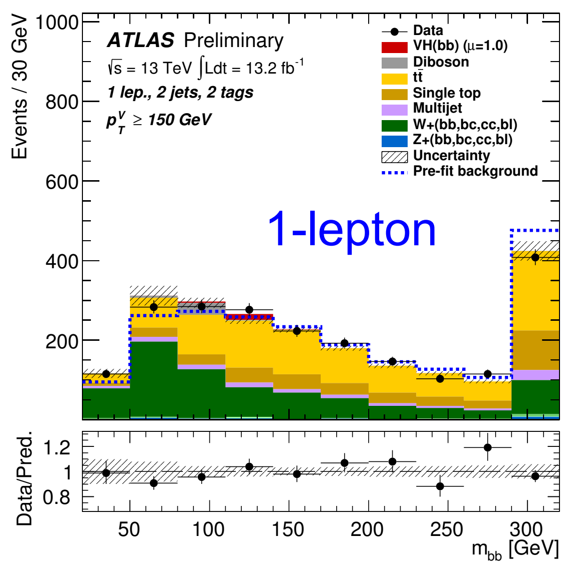
Significance of longitudinal impact parameter

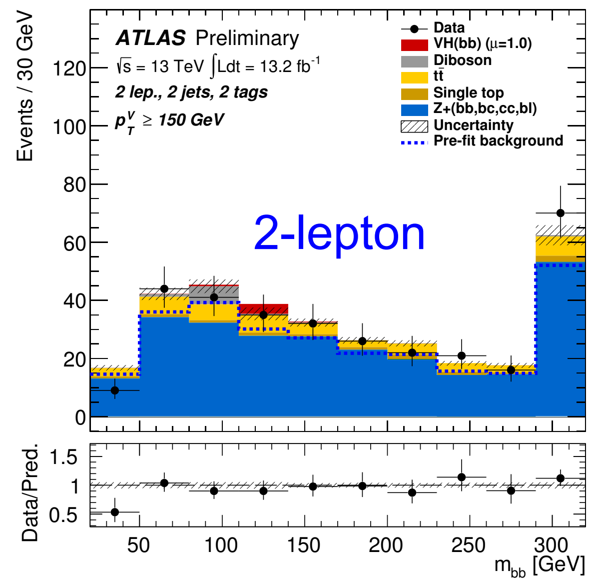


VH, H→bb (Run 2) ATLAS-CONF-2016-091

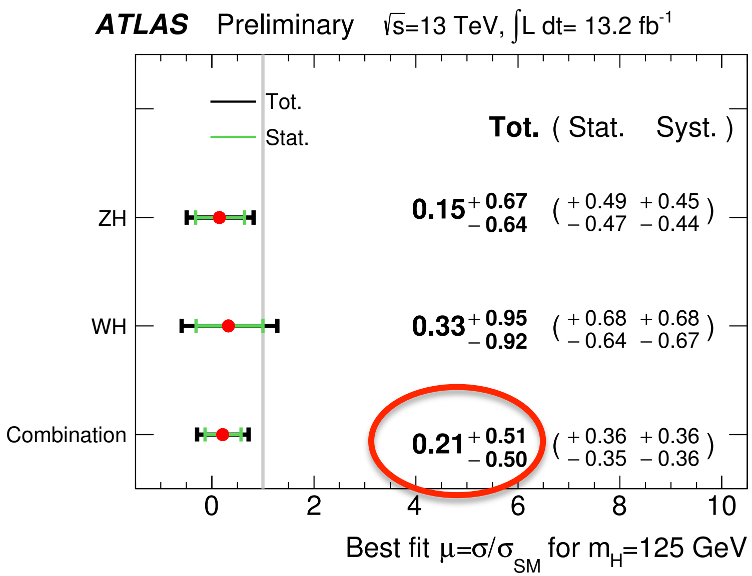
- For 0-lepton and 2-lepton channels, the main background is Z + heavy flavor production
- For 1-lepton channel, W and top are main backgrounds

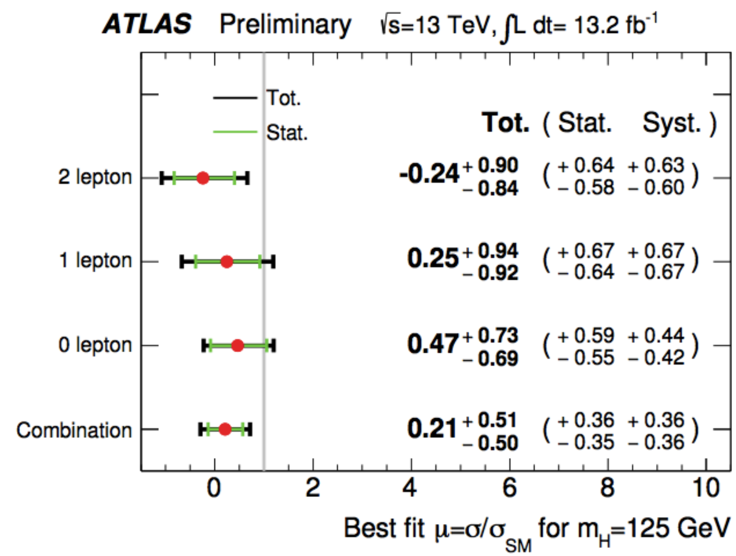






VH, H→bb (Run 2) ATLAS-CONF-2016-091





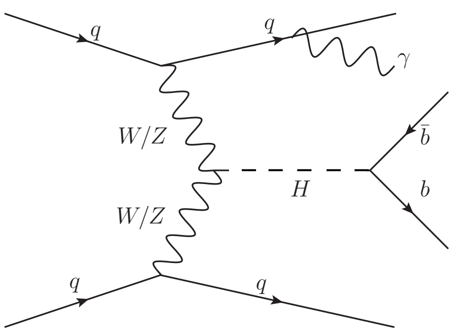
- Observed (expected) significance is 0.42 (1.94) σ

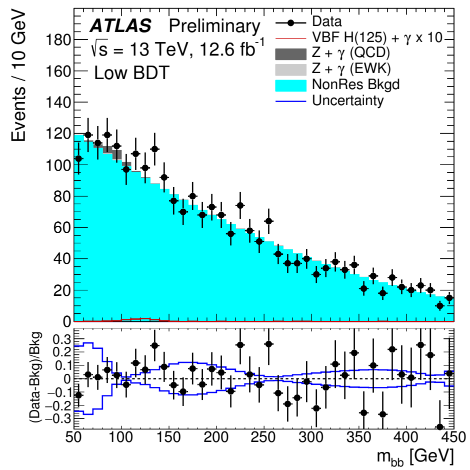
Dataset	Limit		p_0		Significance	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
0-lepton	$1.4^{+0.6}_{-0.4}$	2.0	0.07	0.15	1.45	1.02
1-lepton	$2.0^{+0.8}_{-0.6}$	2.1	0.15	0.46	1.04	0.10
2-lepton	$1.8^{+0.7}_{-0.5}$	1.7	0.13	0.57	1.14	−0.17
Combined	$1.0^{+0.4}_{-0.3}$	1.2	0.03	0.34	1.94	0.42

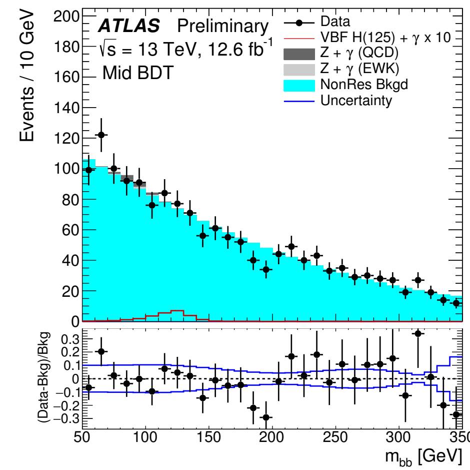
VBF, H→bb + γ (Run 2)

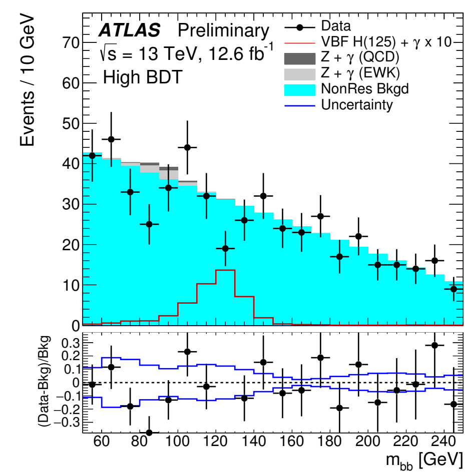
ATLAS-CONF-2016-063

- Single photon is used to trigger detector at the first level (L1)
- Use BDT method to separate the events into three categories





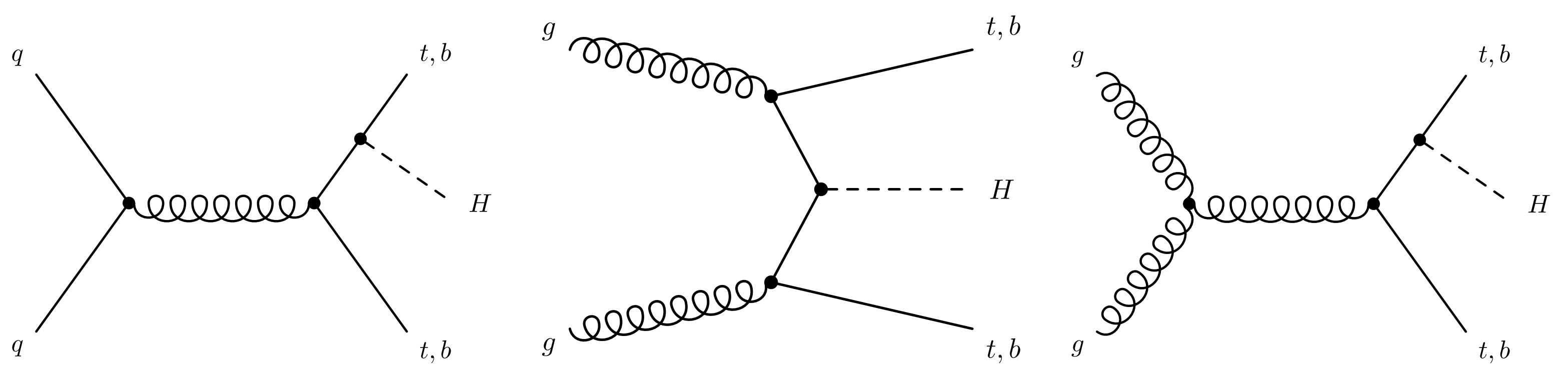




Expected limit	$6.0^{+2.3}_{-1.7}$
Observed limit	4.0
Observed signal strength μ	$-3.9^{+2.8}_{-2.7}$

ttH (Run 2)

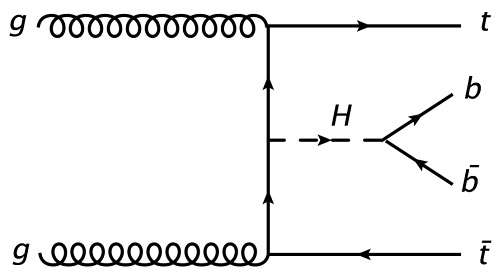
- Direct probe of top Yukawa coupling
- Search for the ttH production in
  - ttH, H->bb: largest branching ratio (58%)
  - ttH, H->multi-leptons (contributions from WW/ZZ/ττ decays, including τ leptonic and hadronic decays)
  - ttH, H→γγ



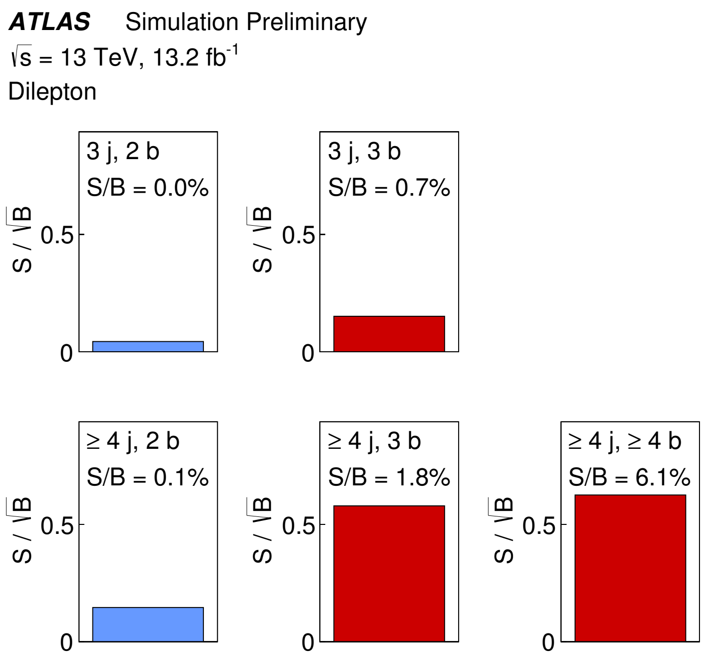
Representative LO diagrams

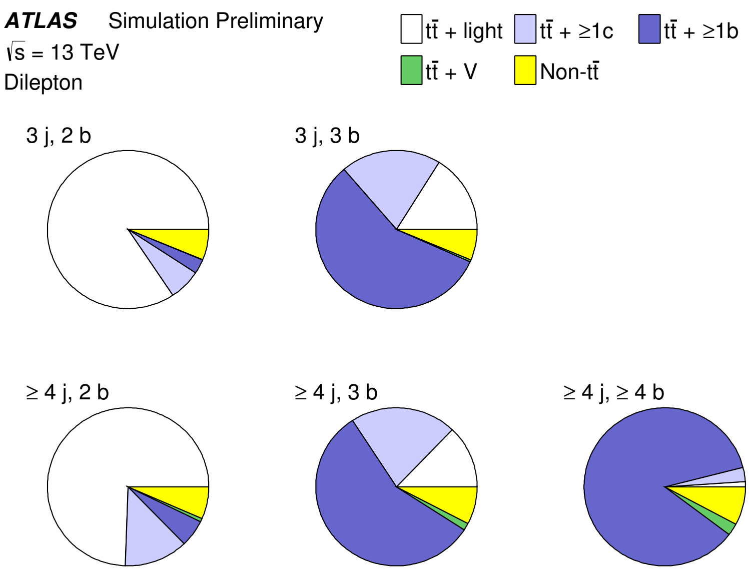
ttH, H->bb (Run 2)

ATLAS-CONF-2016-080



- Main background is ttbar + heavy flavor production
- Events are classified with BDT or Neural Network (NN) methods



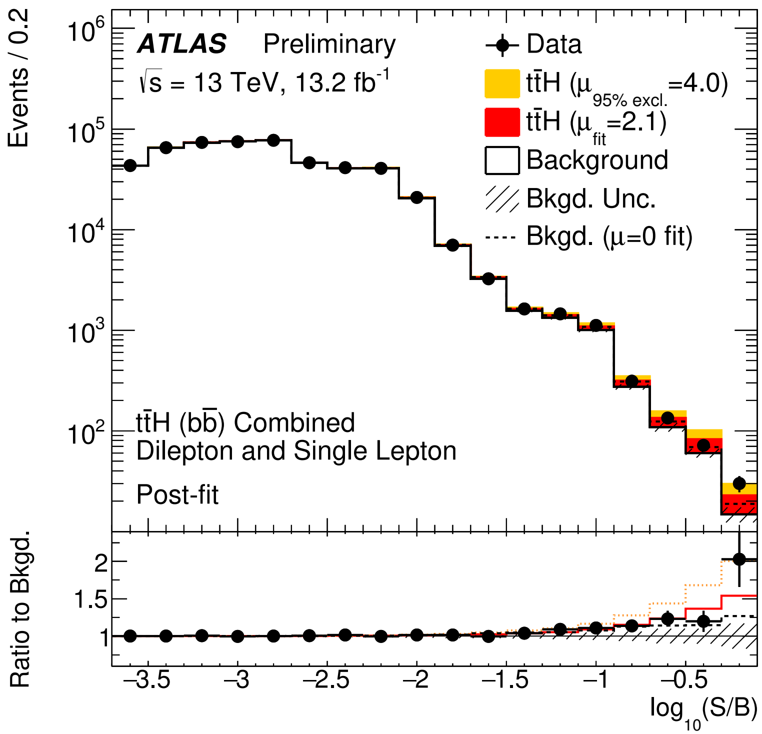


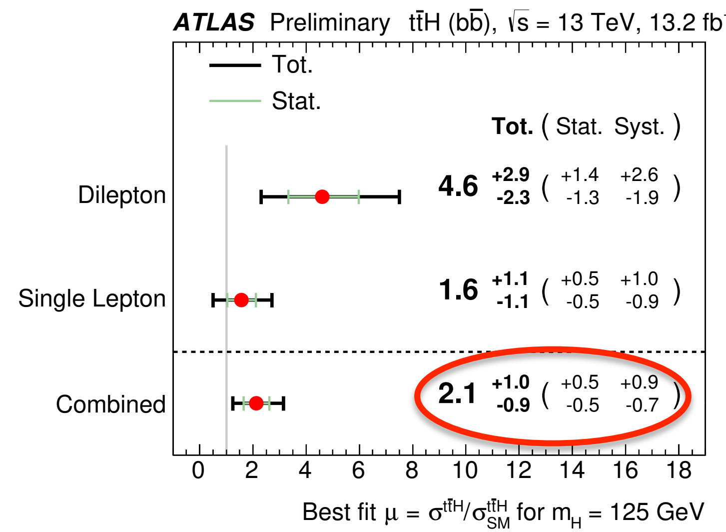
Signal regions are shaded in red, while the control regions are shown in blue

ttH, H->bb (Run 2)

ATLAS-CONF-2016-080

Events yields at different analysis bins ordered by $\log_{10}$(S/B)



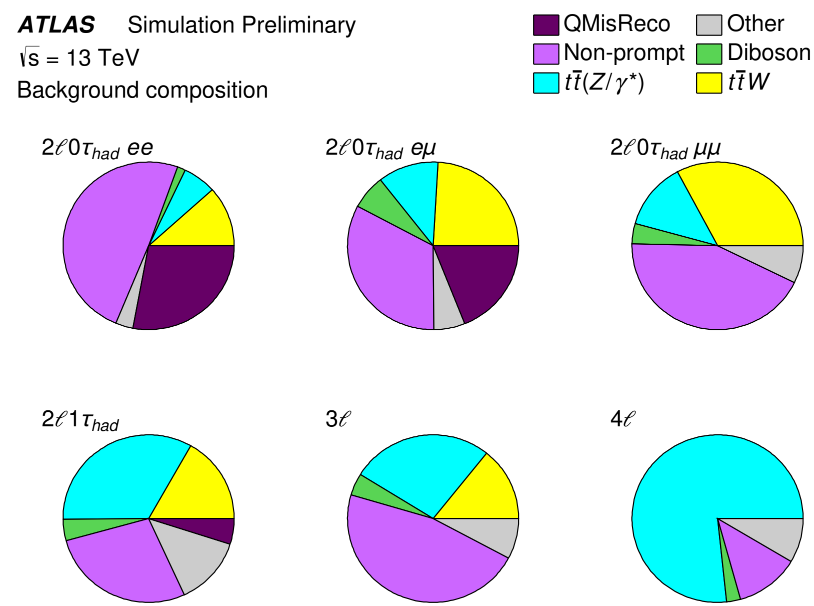


ttH, H->multi-leptons (Run 2)

ATLAS-CONF-2016-058

Signature: 2-4 leptons
Categories:

- Two same-charge light leptons + no τ_{had}
- Two same-charge light leptons + one τ_{had}
- Three light leptons
- Four light leptons

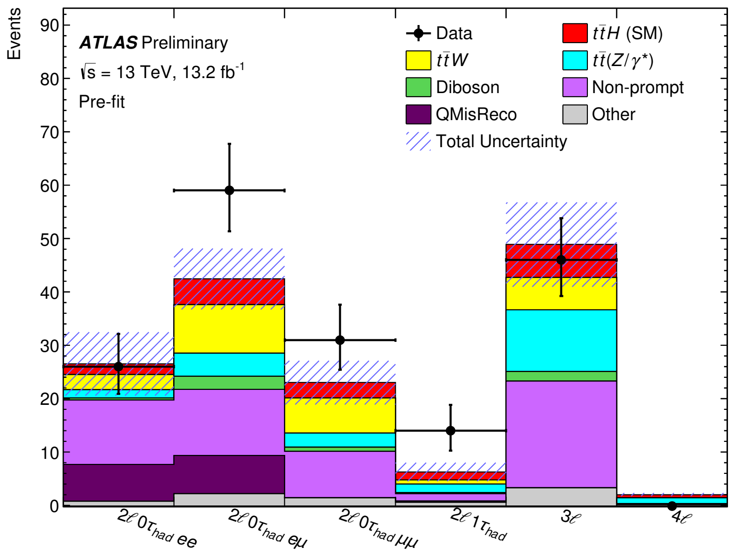


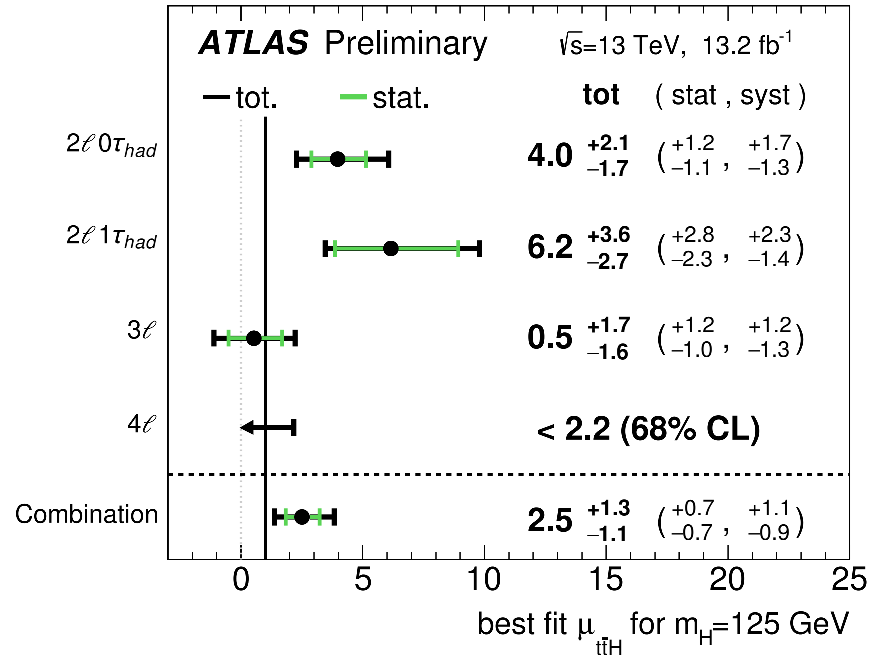
Main backgrounds:

- ttW, ttZ: estimated from simulation
- Di-boson: estimated from simulation
- Non-prompt light leptons: estimated from data control regions
- Electron charge mis-identification: estimated from data Z events
- Hadronic τ mis-reconstruction: estimated from simulation and normalized to data control region

ttH, H->multi-leptons (Run 2)

ATLAS-CONF-2016-058

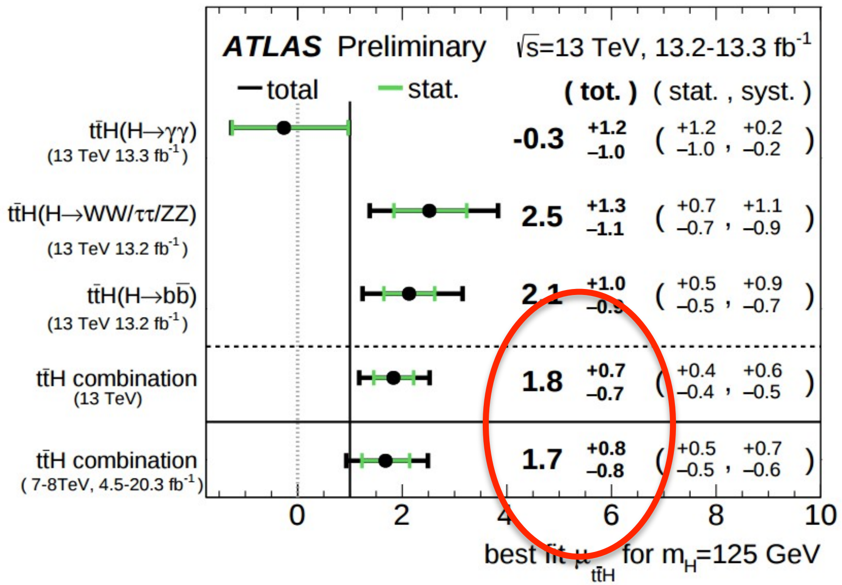




QMisReco: charge mis-ID

ttH combination (Run 2) ATLAS-CONF-2016-068

Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H,\, H \to \gamma\gamma$	-0.2	0.9
$t\bar{t}H,\, H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H,\, H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8



Signal strength measurement:

- Central value is compatible with Run 1 measurement
- Uncertainty is smaller compared with Run 1

Summary

- Most of Higgs results have been updated to use Run 2 data
- With 13 TeV data, Higgs boson is observed again (significance is ~10 σ)
- No significant deviation from the Standard Model expectations is observed.

Outlook for Run 2:

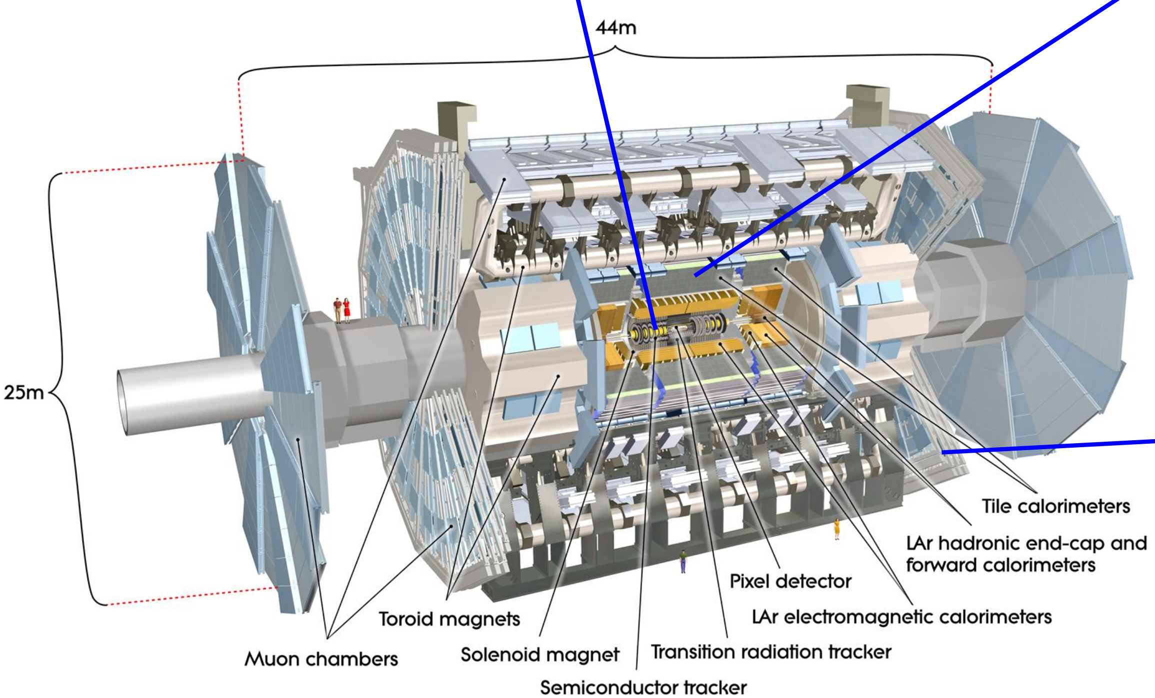
- It is expected to have 100 fb^{-1} for the whole LHC Run 2 (by 2018). We are going to measure the Higgs boson with higher precision using established channels and keep searching for the channels which are not observed yet

Thanks

ATLAS Detector

Inner Detector;
$|\eta| < 2.5$
Solenoid 2 T
Tracking and vertexing
$\sigma/p_T \sim 0.05\% \cdot p_T \oplus 1\%$

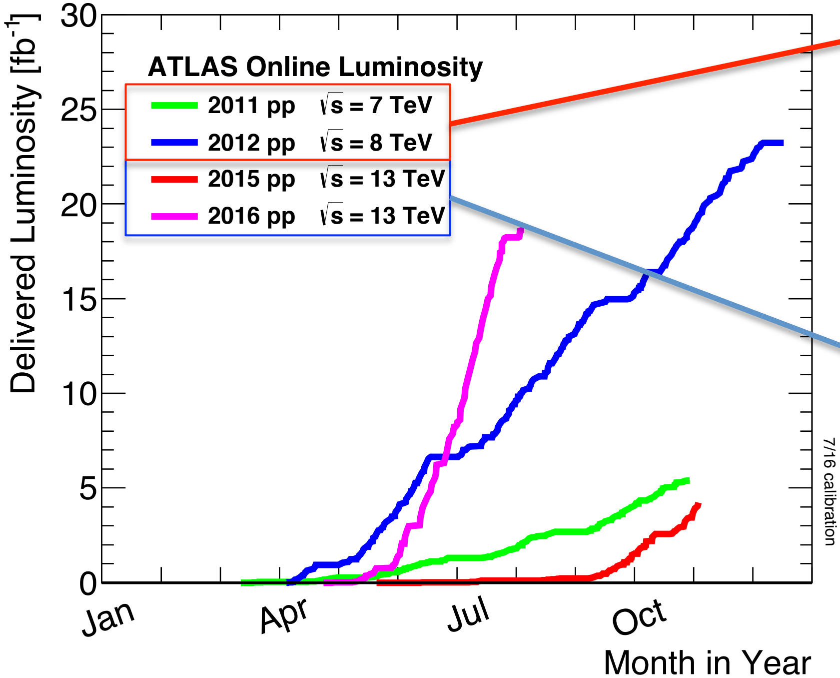
Calorimeter;
$|\eta| < 4.9$
EM : Pb-LAr; $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$
Had : Fe-Scint.; $\sigma/E \sim 50\%/\sqrt{E} \oplus 4\%$



Muon Spectrometer;
$|\eta| < 2.7$
Air-core toroidal & gas chambers
$\sigma/p_T \sim 2\%$ @ 50 GeV
$\sigma/p_T \sim 10\%$ @ 1 TeV

40 m long, 25 m high. 100 M read-out channels

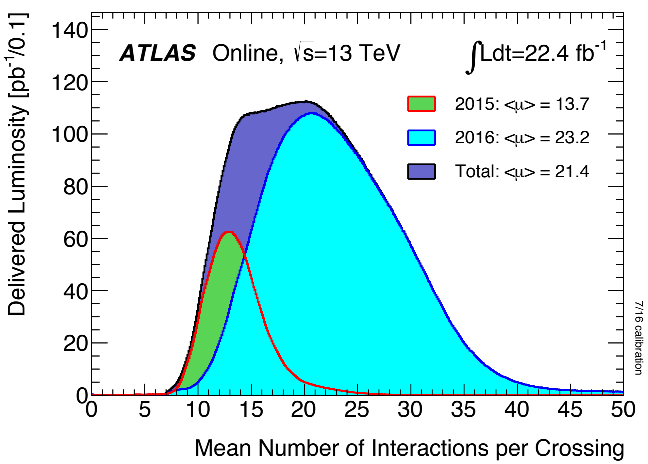
LHC Run 1 and Run 2



LHC Run 1: data taking in 2011 and 2012 with $\sqrt{s}$ = 7 TeV (~4.5 fb^{-1}) and $\sqrt{s}$ = 8 TeV (~20 fb^{-1})

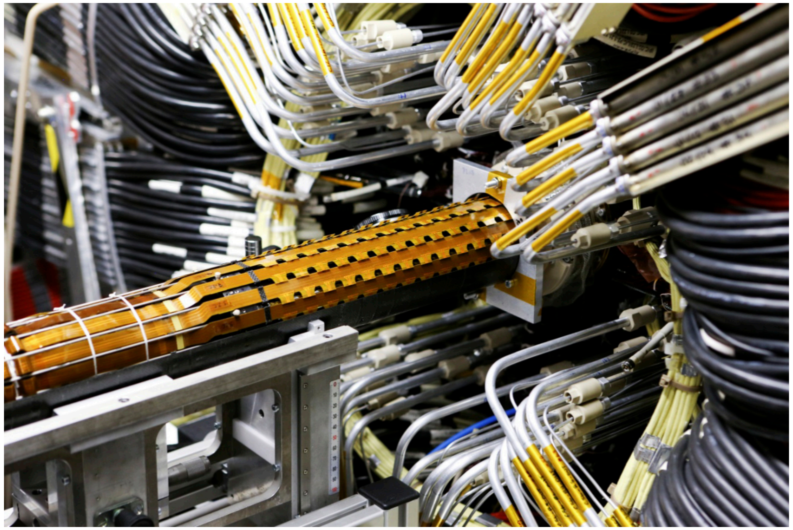
LHC Run 2: data taking in 2015 and 2016 with $\sqrt{s}$ = 13 TeV (~22.4 fb^{-1})

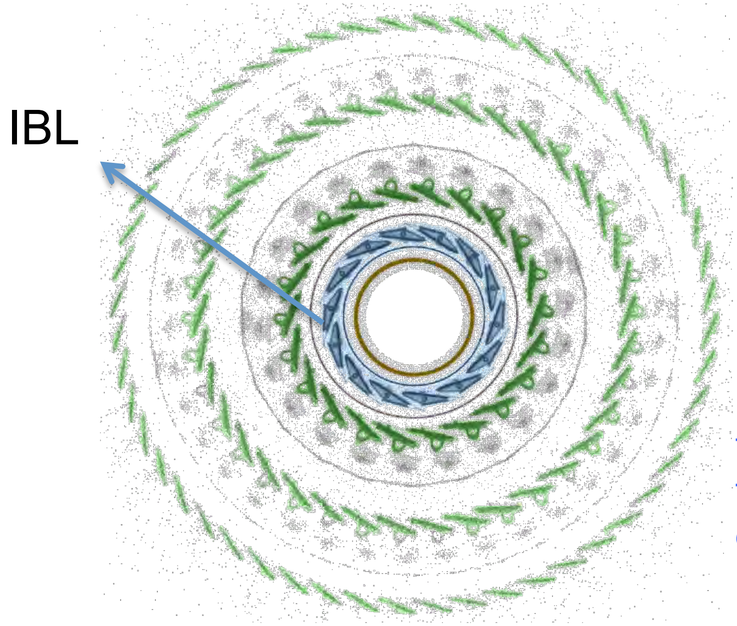
Run 2: 13.2 fb^{-1} to 14.8 fb^{-1} are used for the results



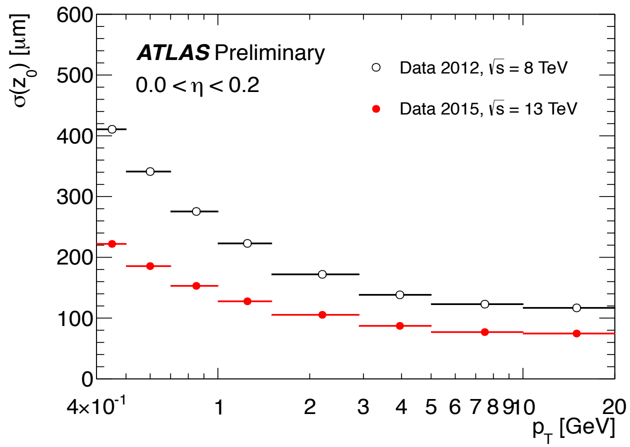
ATLAS Upgrade during Shutdown

- Innermost silicon pixel detector layer (IBL)
- 33 mm from beam
- Improve tracking and bjet tagging (~4 times better for light flavor jet rejection)





B hadron with pT=50 GeV will travel 3 mm in the transverse direction

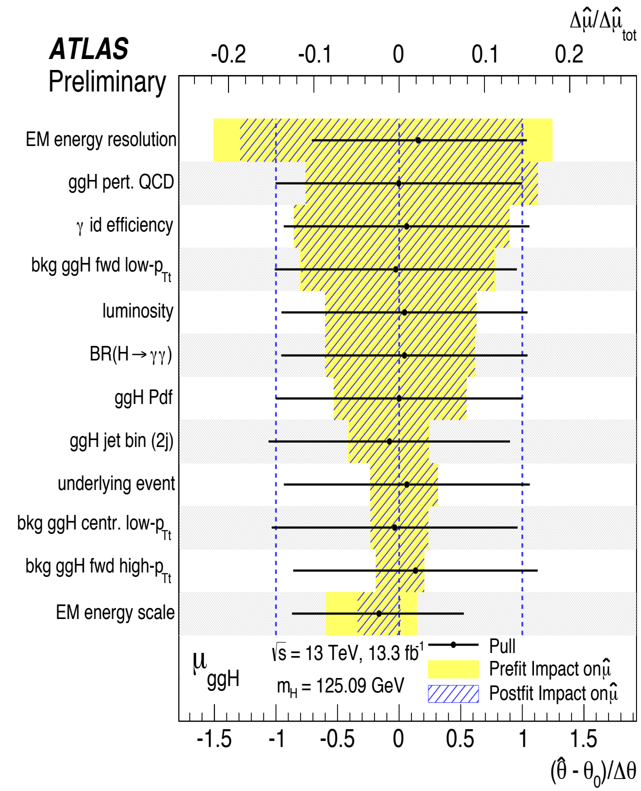


H→γγ

Definition of fiducial regions

Table 1: The summary of the selection criteria that define the fiducial regions.

	diphoton baseline	VBF enhanced	single lepton
Photons	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$ $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}$ and $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$		
Jets	- - -	$p_T > 30\,\mathrm{GeV}$, $\|y\| < 4.4$ $m_{jj} > 400\,\mathrm{GeV}$, $\|\Delta y_{jj}\| > 2.8$ $\|\Delta\phi_{\gamma\gamma,jj}\| > 2.6$	- - -
Leptons	-	-	$p_T > 15\,\mathrm{GeV}$ $\|\eta\| < 2.47$



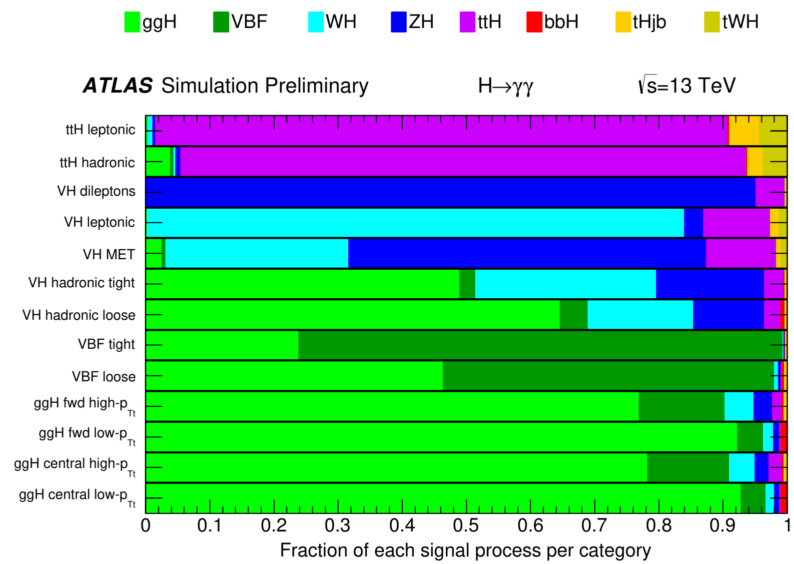
– Selection: two isolated photons with $p_{T,1} > 0.35\, m_{\gamma\gamma}$, $p_{T,2} > 0.25\, m_{\gamma\gamma}$ and $|\eta| < 2.37$ (excuding $1.37<|\eta|<1.52$)

– Signal model: double-sided Crystal Ball (parameters from simulation)

– Background model: exponential of polynomial, or Bernstein polynomial

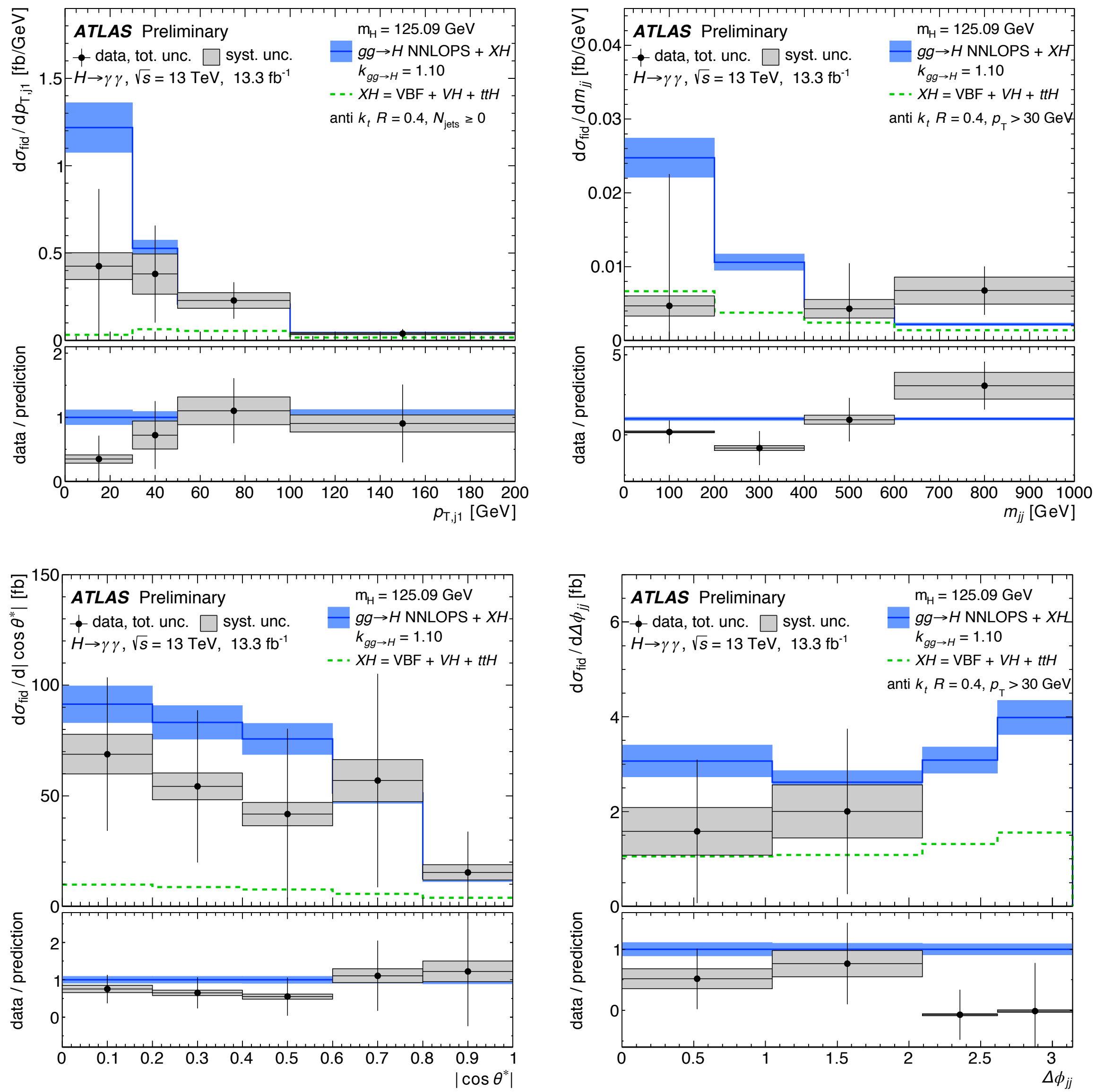
– Dominant systematic: photon energy resolution and background choice bias.

H→γγ



	ggH		VBF		*WH*		*ZH*		$t\bar{t}H$		$b\bar{b}H$		*tHjb*		*tWH*	
Category	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)
Central low-p_{Tt}	12.7	92.7	6.9	3.9	6.3	1.3	6.0	0.8	3.5	0.3	14.2	1.0	4.6	0.1	3.8	0.0
Central high-p_{Tt}	1.2	78.2	2.4	12.8	2.1	4.0	1.8	2.2	2.9	2.0	0.4	0.3	3.7	0.4	5.1	0.2
Forward low-p_{Tt}	22.0	92.1	12.5	4.1	13.0	1.5	12.7	1.0	5.1	0.2	24.9	1.0	9.5	0.1	4.8	0.0
Forward high-p_{Tt}	1.9	76.8	4.1	13.4	3.9	4.6	3.7	2.8	3.6	1.5	0.8	0.3	6.6	0.4	4.8	0.1
VBF loose	0.5	46.3	7.3	51.6	0.2	0.6	0.2	0.4	0.3	0.3	0.4	0.3	3.4	0.5	0.6	0.0
VBF tight	0.1	23.8	5.4	75.5	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	1.2	0.3	0.1	0.0
VH hadronic loose	0.4	64.6	0.4	4.3	3.9	16.5	4.1	11.0	1.7	2.6	0.5	0.6	1.0	0.2	2.2	0.2
VH hadronic tight	0.1	48.9	0.1	2.5	1.8	28.1	1.6	16.9	0.5	3.1	0.0	0.1	0.3	0.2	0.7	0.2
VH $E_{\mathrm{T}}^{\mathrm{miss}}$	0.0	2.4	0.0	0.6	0.6	28.5	1.9	55.8	0.6	10.9	0.0	0.0	0.3	0.7	1.2	1.0
VH one-lepton	0.0	0.2	0.0	0.0	1.3	83.7	0.1	3.0	0.4	10.4	0.0	0.0	0.4	1.3	1.1	1.3
VH dilepton	0.0	0.0	0.0	0.0	0.0	0.0	1.2	95.1	0.1	4.5	0.0	0.0	0.0	0.0	0.2	0.4
$t\bar{t}H$ hadronic	0.0	3.8	0.0	0.5	0.0	0.3	0.1	0.8	11.5	88.1	0.0	0.2	2.2	2.5	10.1	3.8
$t\bar{t}H$ leptonic	0.0	0.3	0.0	0.1	0.0	0.7	0.0	0.4	8.4	89.3	0.0	0.2	3.1	4.8	8.3	4.3
Total efficiency (%)	38.9	-	39.2	-	33.2	-	33.5	-	38.6	-	41.2	-	36.2	-	43.1	-
Events	568.8		44.6		13.7		8.9		5.9		5.6		0.8		0.3	

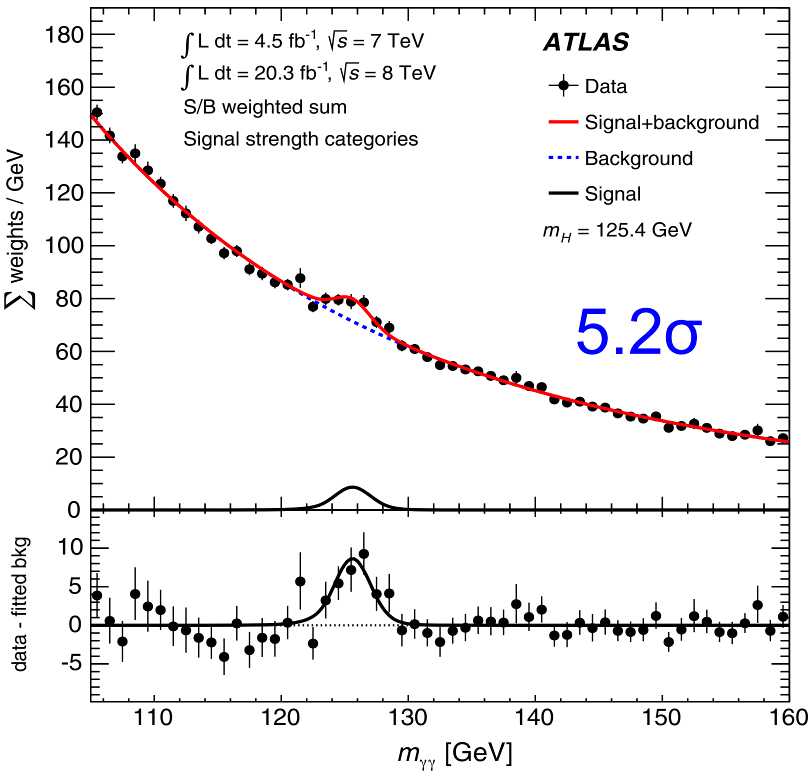
H→γγ

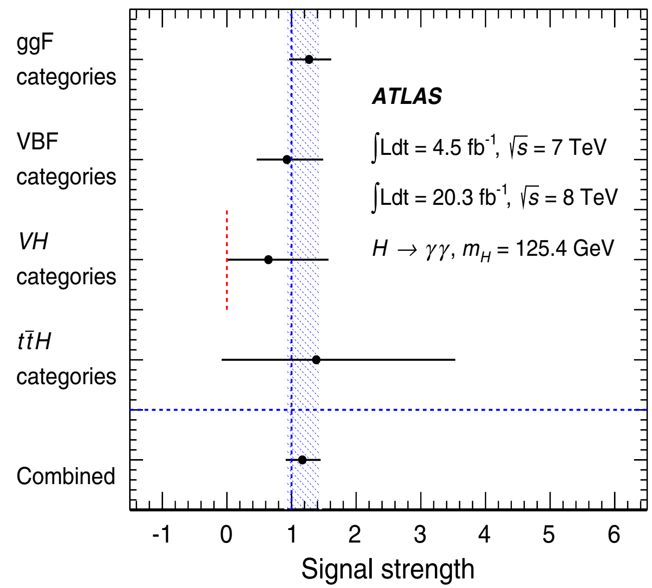


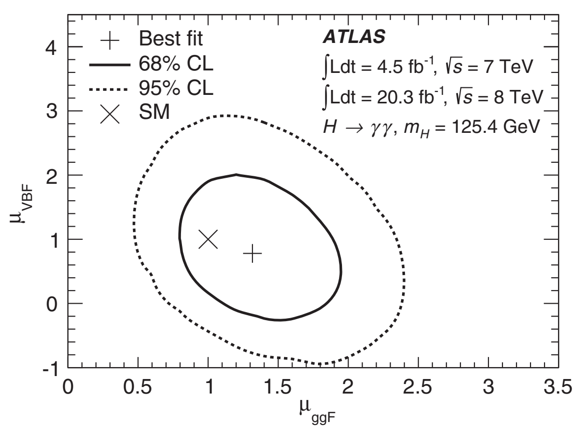
ATLAS Preliminary
data, tot. unc.
syst. unc.
H→γγ, √s = 13 TeV, 13.3 fb-1
mH = 125.09 GeV
gg→H NNLOPS + XH
kgg→H = 1.10
XH = VBF + VH + ttH
anti kt R = 0.4, Njets ≥ 0
anti kt R = 0.4, pT > 30 GeV
data / prediction
pT,j1 [GeV]
mjj [GeV]
|cos θ*|
Δφjj

Run 1 H→γγ

Phys. Rev. D 90, 112015 (2014)







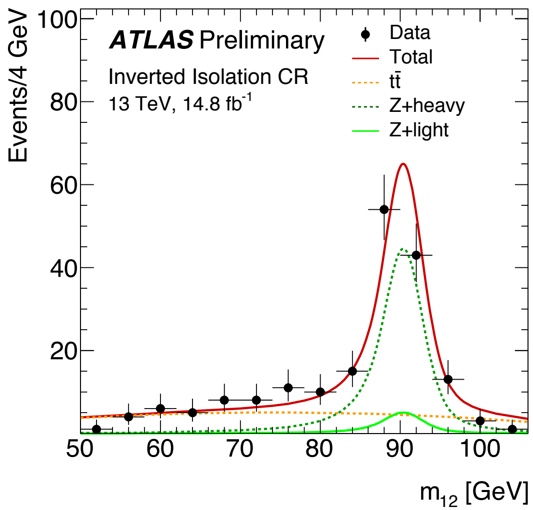
H→ZZ*→4l

Lepton definition	
Muons: $p_{\mathrm{T}} > 5$ GeV, $\|\eta\| < 2.7$	Electrons: $p_{\mathrm{T}} > 7$ GeV, $\|\eta\| < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection	
Lepton kinematics:	Leading leptons $p_{\mathrm{T}} > 20, 15, 10$ 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:	$115 < m_{4\ell} < 130$ GeV

Acceptance factors $\mathcal{A}[\%]$					
Decay	Production mode				
Channel	ggF	VBF	WH	ZH	$t\bar{t}H$
4μ	50.9	55.0	43.8	46.5	53.6
$4e$	39.6	43.9	34.4	36.0	44.6
$2\mu 2e$	40.0	42.9	34.0	35.5	42.4
$2e2\mu$	45.9	48.6	38.0	40.4	47.2

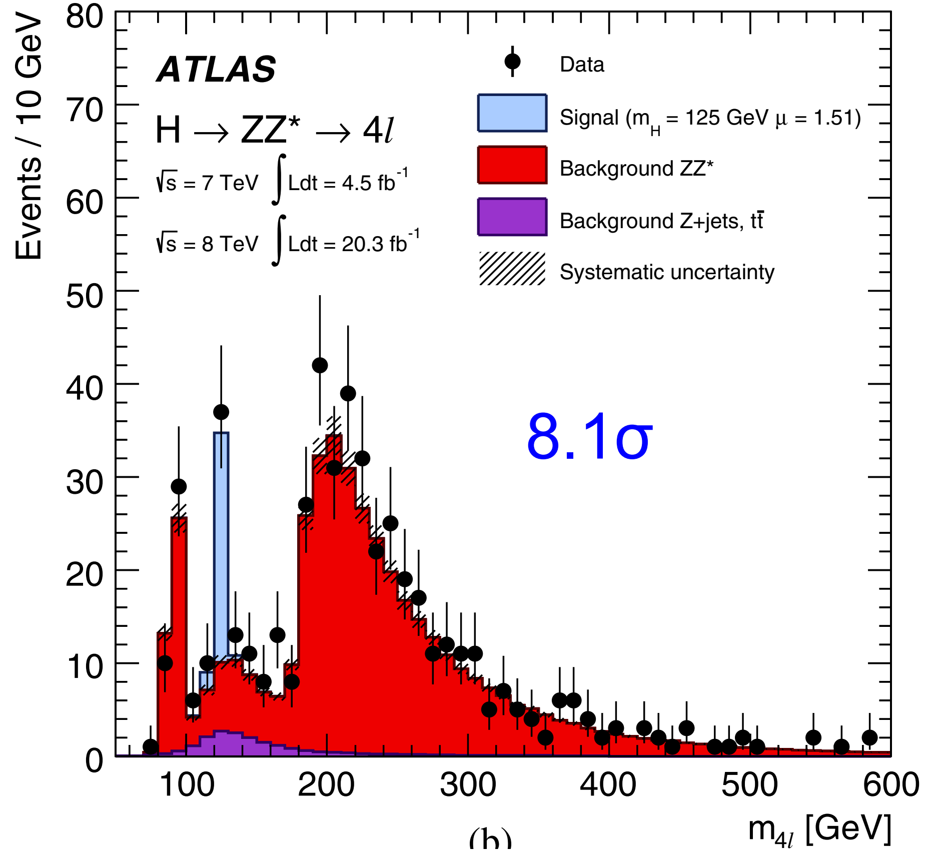
Narrow peak (1.6-2.3 GeV @125 GeV) on top of smooth background

Lowering muon pT cut from 6 to 5 GeV → ~8% increase on the signal acceptance



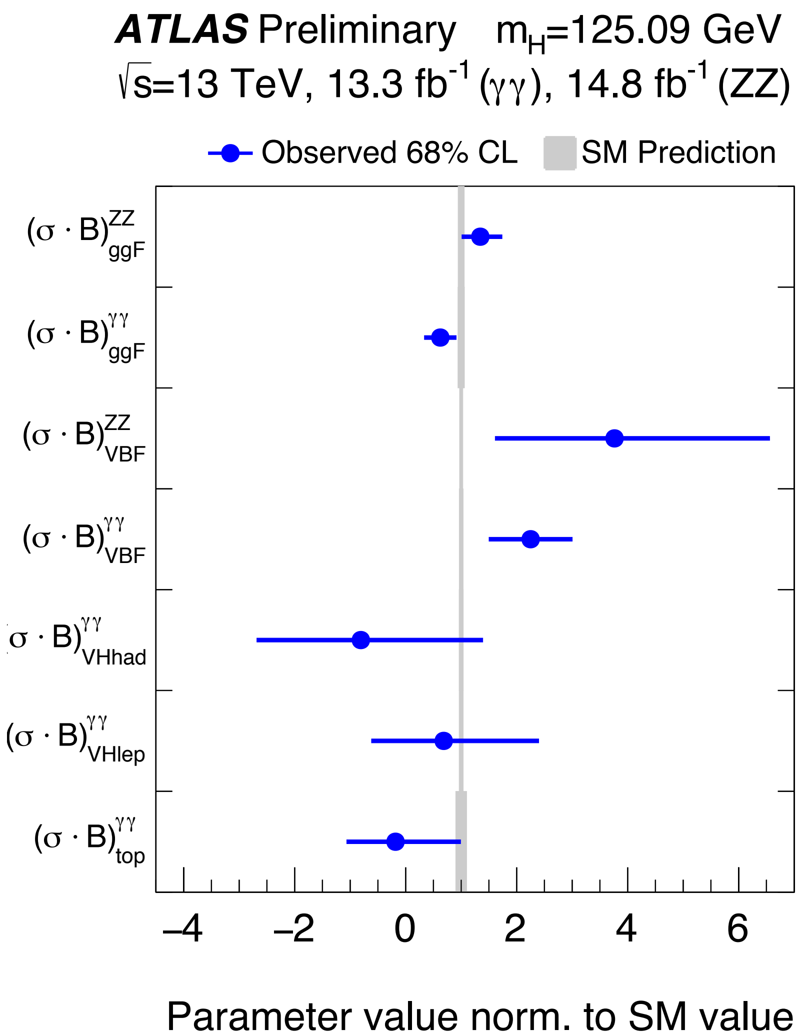
Run 1 H→ZZ*→4l

Phys. Rev. D 91, 012006 (2015)

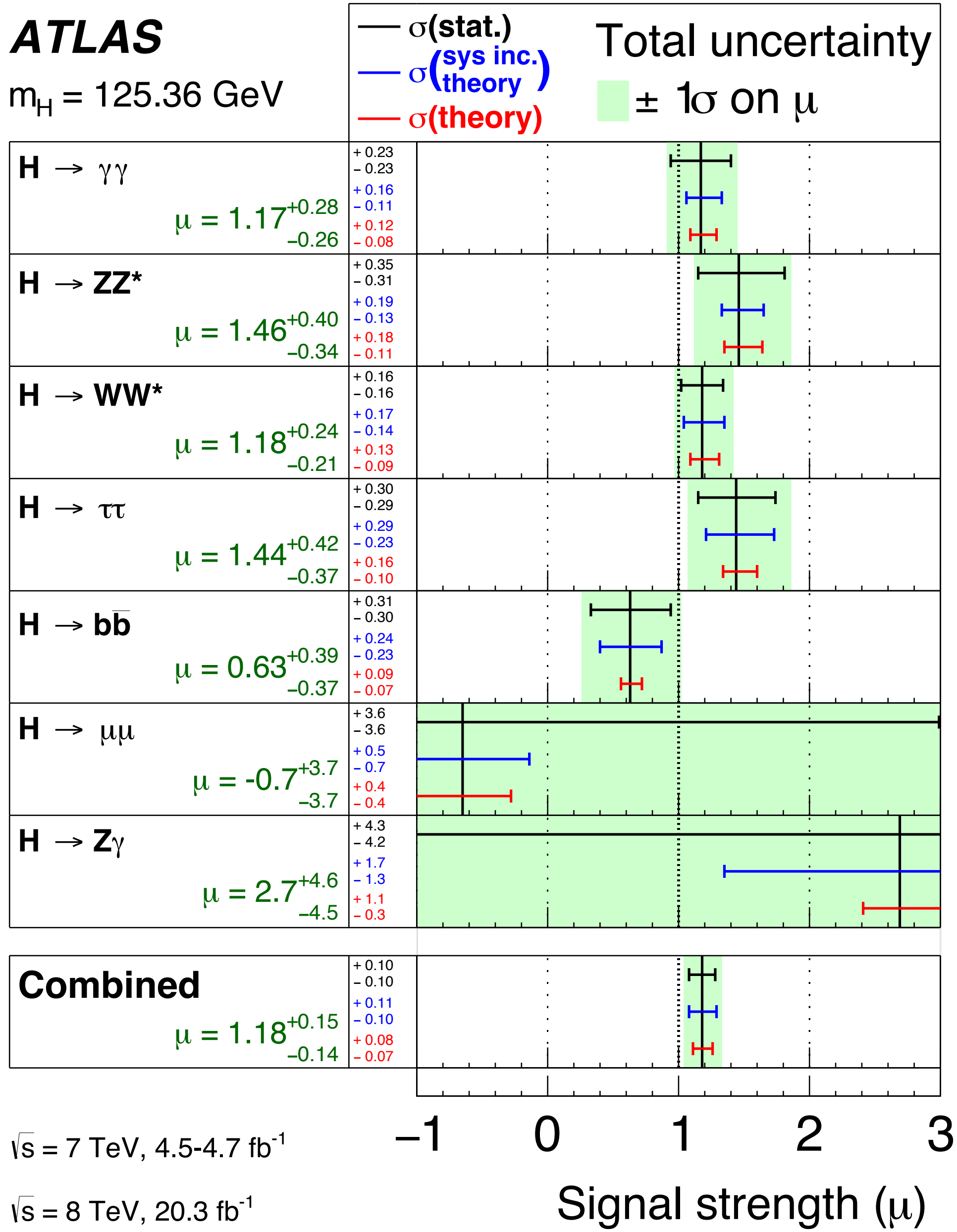


Signal	ZZ*	Z, ttbar	Expected	Observed
16.2±1.6	7.41±0.40	2.95±0.33	26.5±1.7	37

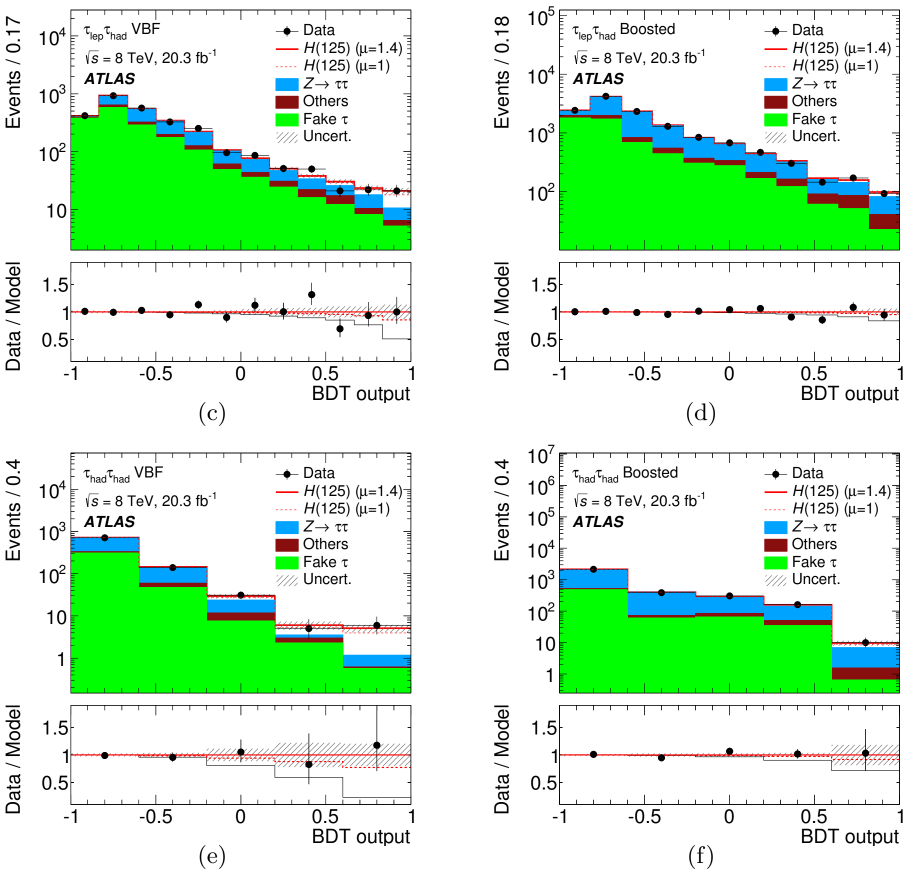
Combination with ZZ* and γγ



Run 1


ATLAS
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ μ = 1.17 +0.28 −0.26
+0.23 −0.23 +0.16 −0.11 +0.12 −0.08
H → ZZ* μ = 1.46 +0.40 −0.34
+0.35 −0.31 +0.19 −0.13 +0.18 −0.11
H → WW* μ = 1.18 +0.24 −0.21
+0.16 −0.16 +0.17 −0.14 +0.13 −0.09
H → ττ μ = 1.44 +0.42 −0.37
+0.30 −0.29 +0.29 −0.23 +0.16 −0.10
H → bb̄ μ = 0.63 +0.39 −0.37
+0.31 −0.30 +0.24 −0.23 +0.09 −0.07
H → μμ μ = -0.7 +3.7 −3.7
+3.6 −3.6 +0.5 −0.7 +0.4 −0.4
H → Zγ μ = 2.7 +4.6 −4.5
+4.3 −4.2 +1.7 −1.3 +1.1 −0.3
Combined μ = 1.18 +0.15 −0.14
+0.10 −0.10 +0.11 −0.10 +0.08 −0.07
√s = 7 TeV, 4.5-4.7 fb-1
√s = 8 TeV, 20.3 fb-1
−1 0 1 2 3
Signal strength (μ)

Run 1 H→ττ



Variable	VBF			Boosted		
	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
$m_{\tau\tau}^{\mathrm{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\mathrm{T}}^{\mathrm{Total}}$		•	•			
Sum p_{T}					•	•
$p_{\mathrm{T}}^{\tau_1}/p_{\mathrm{T}}^{\tau_2}$					•	•
$E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality		•	•	•	•	•
m_{ℓ,ℓ,j_1}				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi(\ell_1, \ell_2)$				•		
Sphericity				•		
$p_{\mathrm{T}}^{\ell_1}$				•		
$p_{\mathrm{T}}^{j_1}$				•		
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\mathrm{jets}})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell})$		•				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	•					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			•			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			•			

Table 5. Discriminating variables used in the training of the BDT for each channel and category at $\sqrt{s}$ = 8 TeV. The more complex variables are described in the text. The filled circles indicate which variables are used in each case.

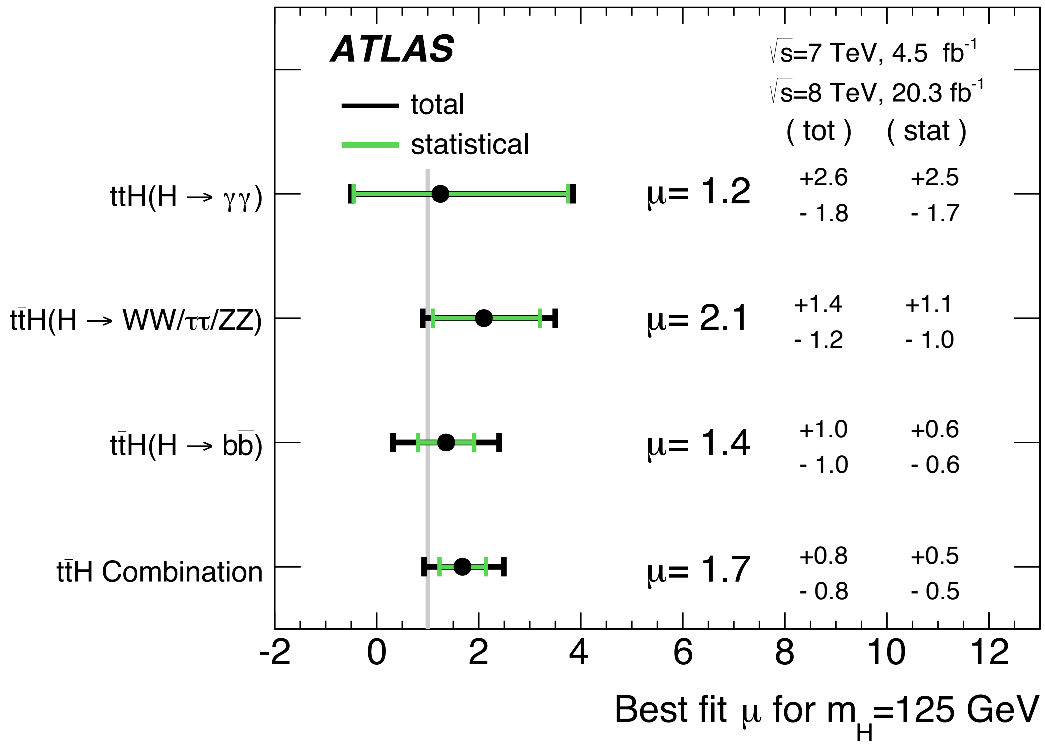
VH, H->bb

Selection	0-lepton	1-lepton	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$ (μ sub-channel)	
		Lowest unprescaled single lepton	
Leptons	0 loose lepton	1 tight lepton	2 loose leptons ($\geq$ 1 medium lepton)
Lepton pair	-	-	Same flavour opposite-charge for $\mu\mu$
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV (e sub-channel)	-
m_{ll}	-	-	$71 < m_{ll} < 121$ GeV
S_{T}	> 120 (2 jets), >150 GeV (3 jets)	-	-
Jets	Exactly 2 or 3 signal jets		Exactly 2 or $\geq$ 3 signal jets
b-jets	2 b-tagged signal jets		
Leading jet p_{T}	> 45 GeV		
$\min\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})$	$> 20^{\circ}$	-	-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, h)$	$> 120^{\circ}$	-	-
$\Delta\phi(\mathrm{jet1},\mathrm{jet2})$	$< 140^{\circ}$	-	-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, E_{\mathrm{T},trk}^{\mathrm{miss}})$	$< 90^{\circ}$	-	-
p_{T}^{V} regions	[0, 150] GeV (2-lepton), [150, ∞] GeV		

Table 1: Summary of the event selection in the 0-, 1- and 2-lepton channels.

Run 1 ttH

Multi leptons: Phys. Lett. B 749 (2015) 519–541
bb: arXiv:1604.03812



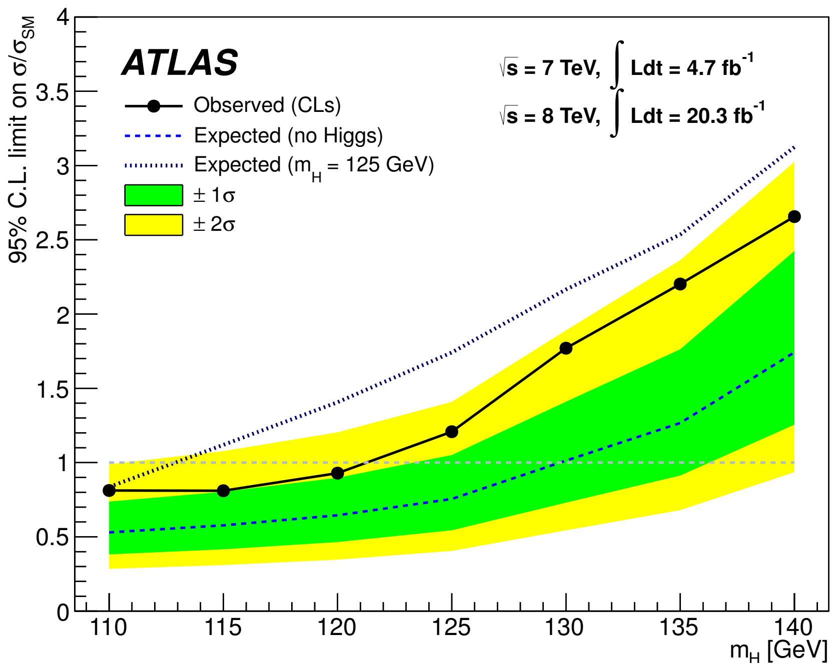
VH, H→bb

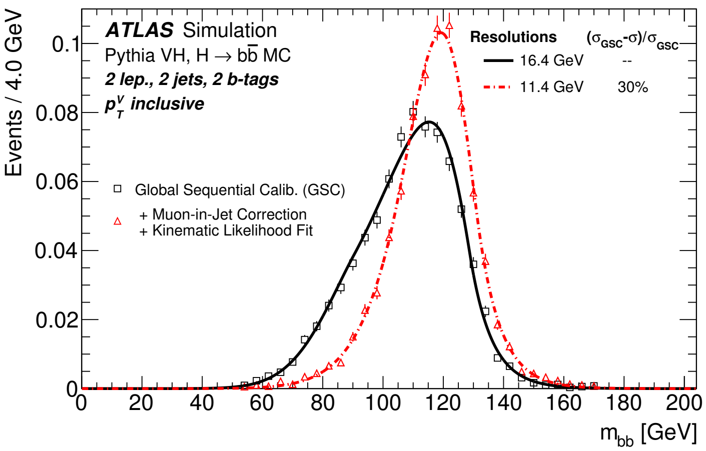
Variable	0-lepton	1-lepton	2-lepton
p_{T}^{V}		$\times$	$\times$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\times$	$\times$	$\times$
$p_{\mathrm{T}}^{b_1}$	$\times$	$\times$	$\times$
$p_{\mathrm{T}}^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(b_1, b_2)$	$\times$	$\times$	$\times$
$\|\Delta\eta(b_1, b_2)\|$	$\times$		$\times$
$\Delta\phi(V, bb)$	$\times$	$\times$	$\times$
$\|\Delta\eta(V, bb)\|$			$\times$
H_{T}	$\times$		
$\min[\Delta\phi(\ell, b)]$		$\times$	
m_{T}^{W}		$\times$	
m_{ll}			$\times$
m_{Top}		$\times$	
$\|\Delta Y(V, H)\|$		$\times$	
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	$\times$	$\times$	$\times$
m_{bbj}	$\times$	$\times$	$\times$

Variables used in the multivariate analysis for the 0-, 1- and 2-lepton channels.

Run 1 VH, H→bb

JHEP01 (2015) 069





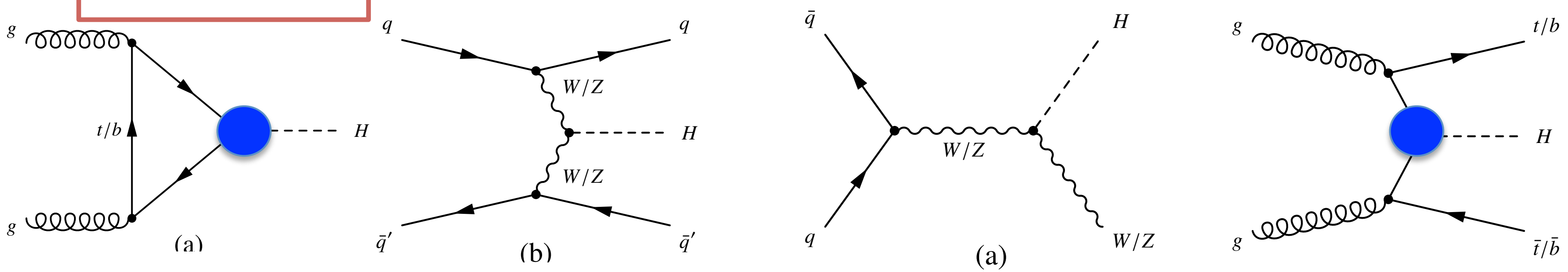
1.4σ for 125 GeV

Higgs Coupling Measurement

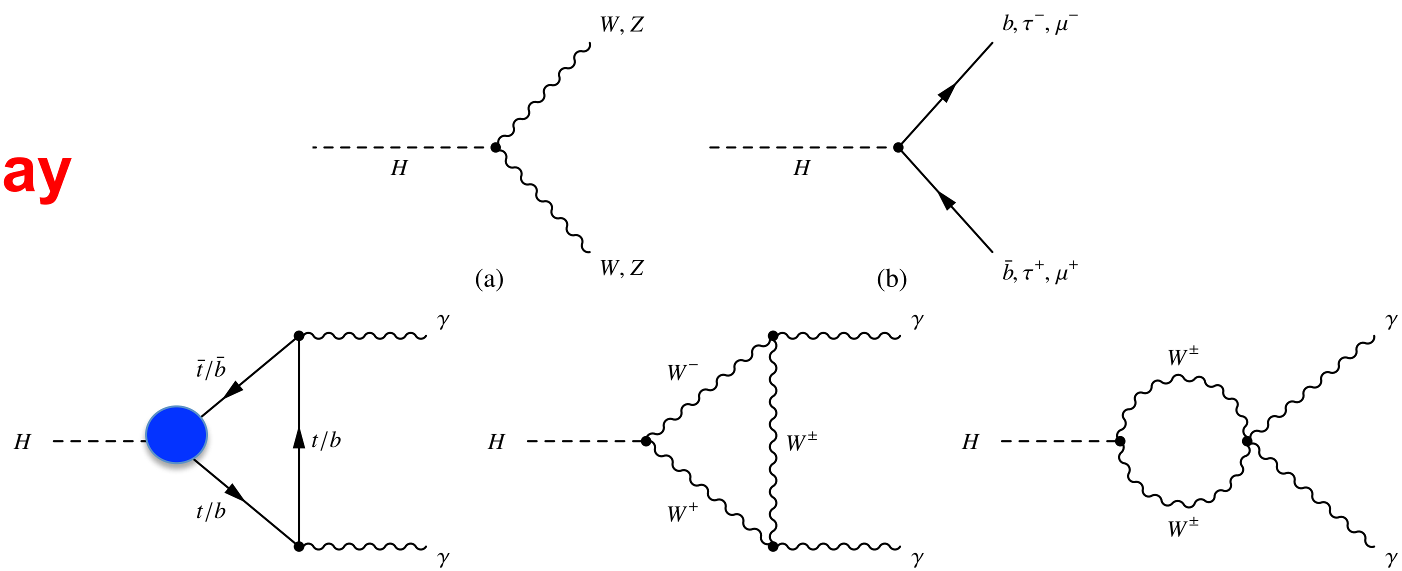
- Coupling information can be extracted from individual processes

ttH/bbH

production



decay

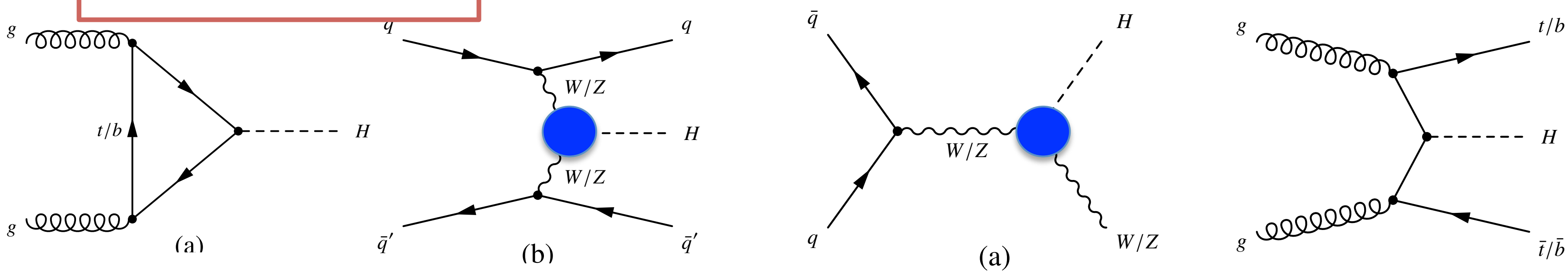


Higgs Coupling Measurement

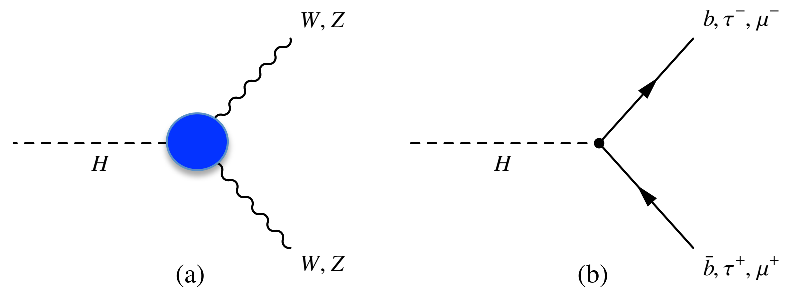
- Coupling information can be extracted from individual processes

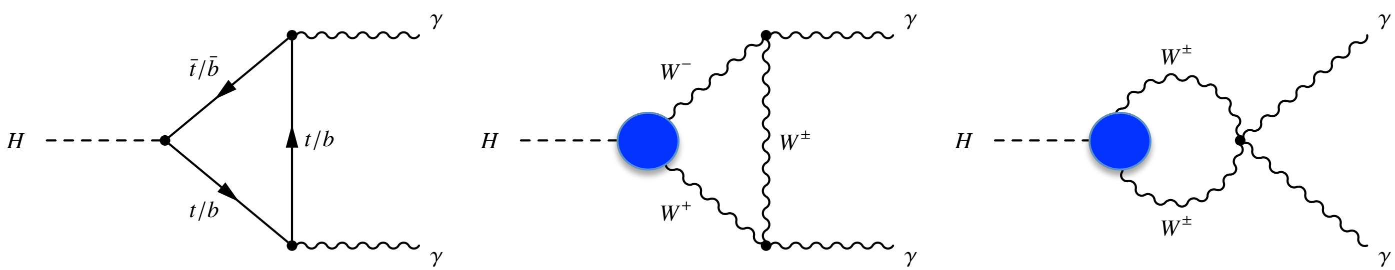
WWH/ZZH

production



decay

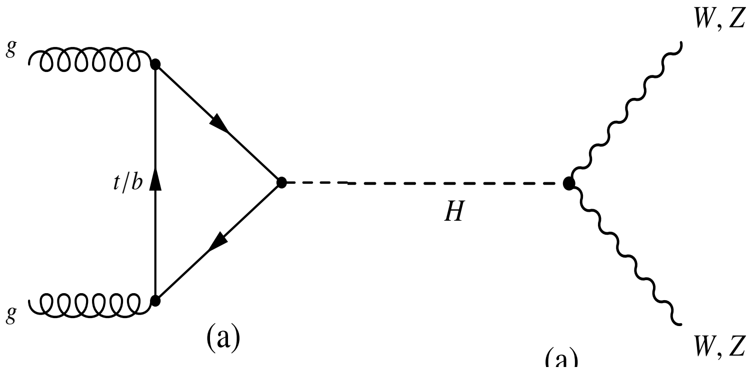




Signal strength and fitting framework

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

Leading-order motivated framework: κ-framework



$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}},$$

Definition of modifier: $\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}}$ or $\kappa_j^2 = \Gamma^j / \Gamma_{\mathrm{SM}}^j$.

Dictionary

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Profile likelihood and systematics

Nuisance parameters: about 4200 NPs (most of them are related to MC statistics uncertainties), one single fitting takes hours

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

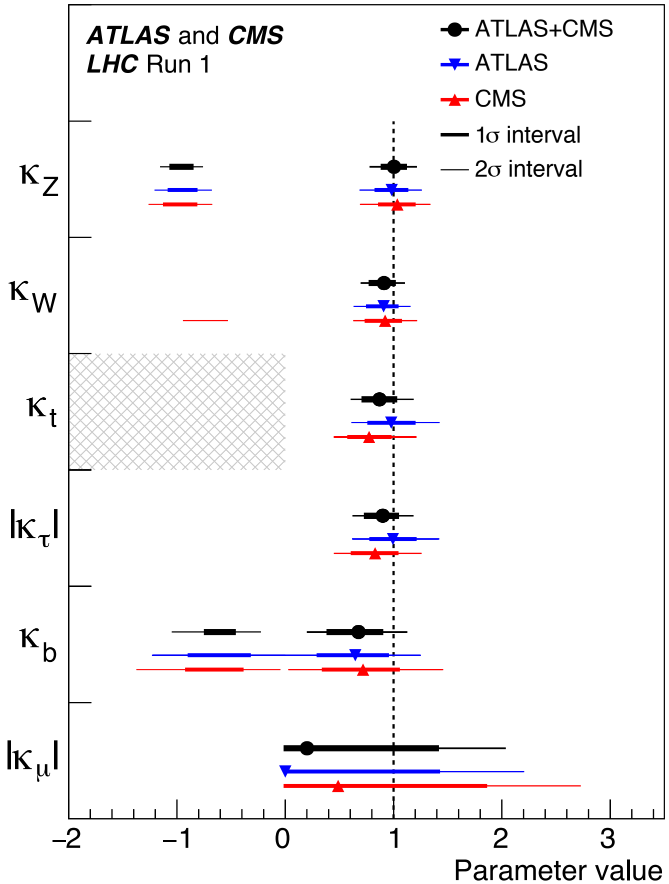
POI

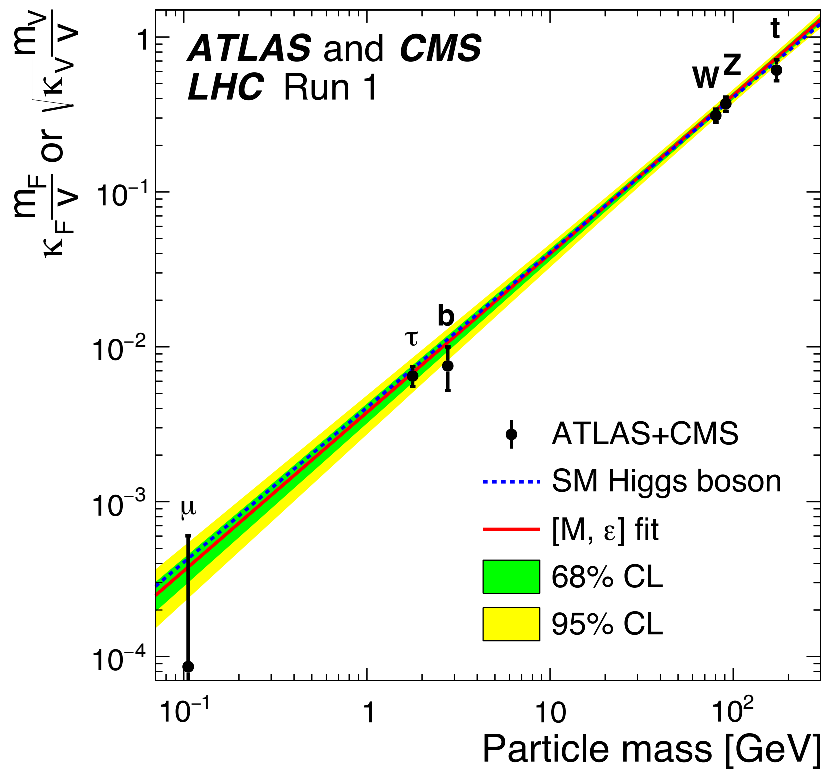
- RooFit development
- Asymptotic method

- Most of experimental systematics are assumed uncorrelated
- Main correlated systematics are the signal theoretical uncertainties

Higgs Coupling Measurement with ATLAS and CMS at Run 1

arXiv:1606.02266





$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v},$$

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}}.$$

$$y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v},$$