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Higgs boson couplings to quarks at the ATLAS experiment

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on behalf of the ATLAS Collaboration

Institute of High Energy Physics ,
Chinese Academy of Science

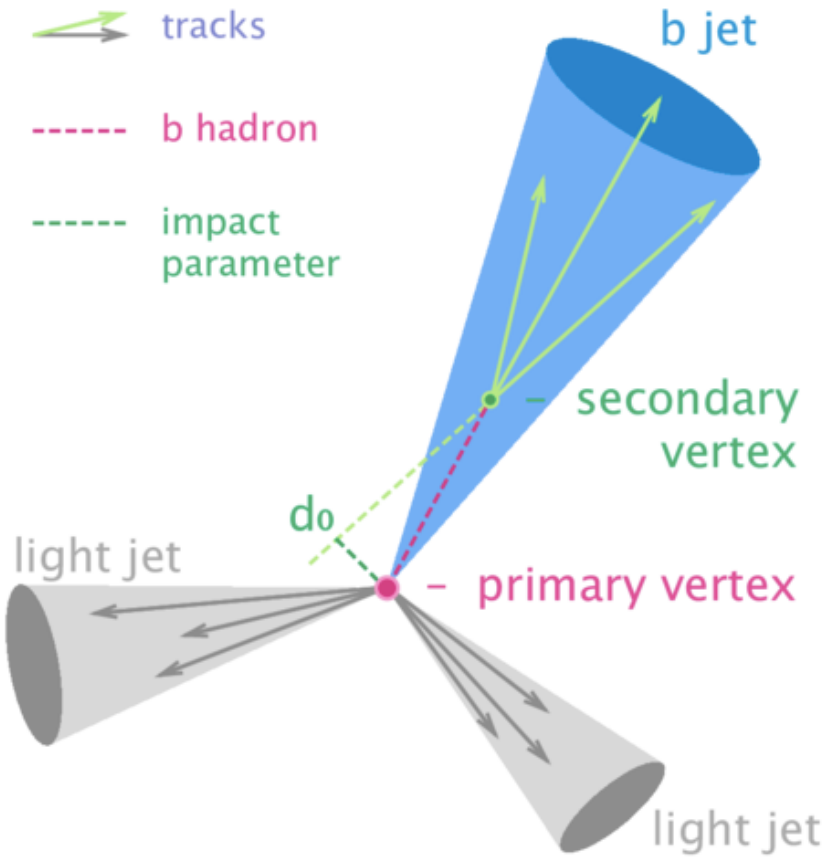
The 27th International Workshop on Weak Interactions and Neutrinos

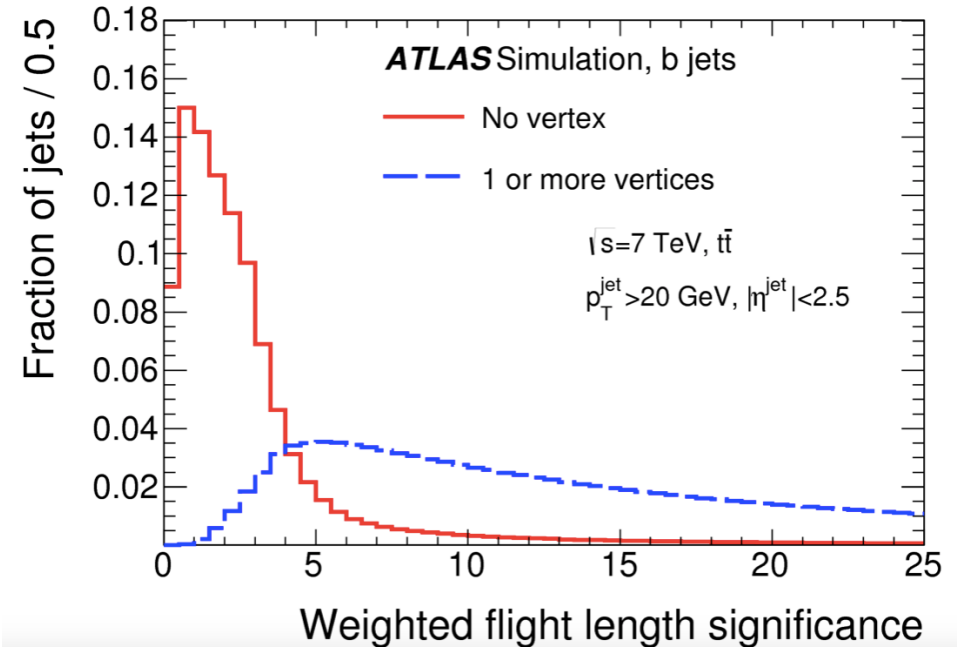
Outline

- Higgs coupling to bottom quarks
  - V+H (→ bb) , (where V=W/Z)
  - Vector boson fusion (VBF) H → bb
  - Boosted H→ bb
  - H → bb combination
- Higgs coupling to charm quarks
  - Z+H (→ bb)
- Higgs coupling to top quarks
  - Associated production with a top quark pair (ttH)

How to Identify b quark jets in ATLAS

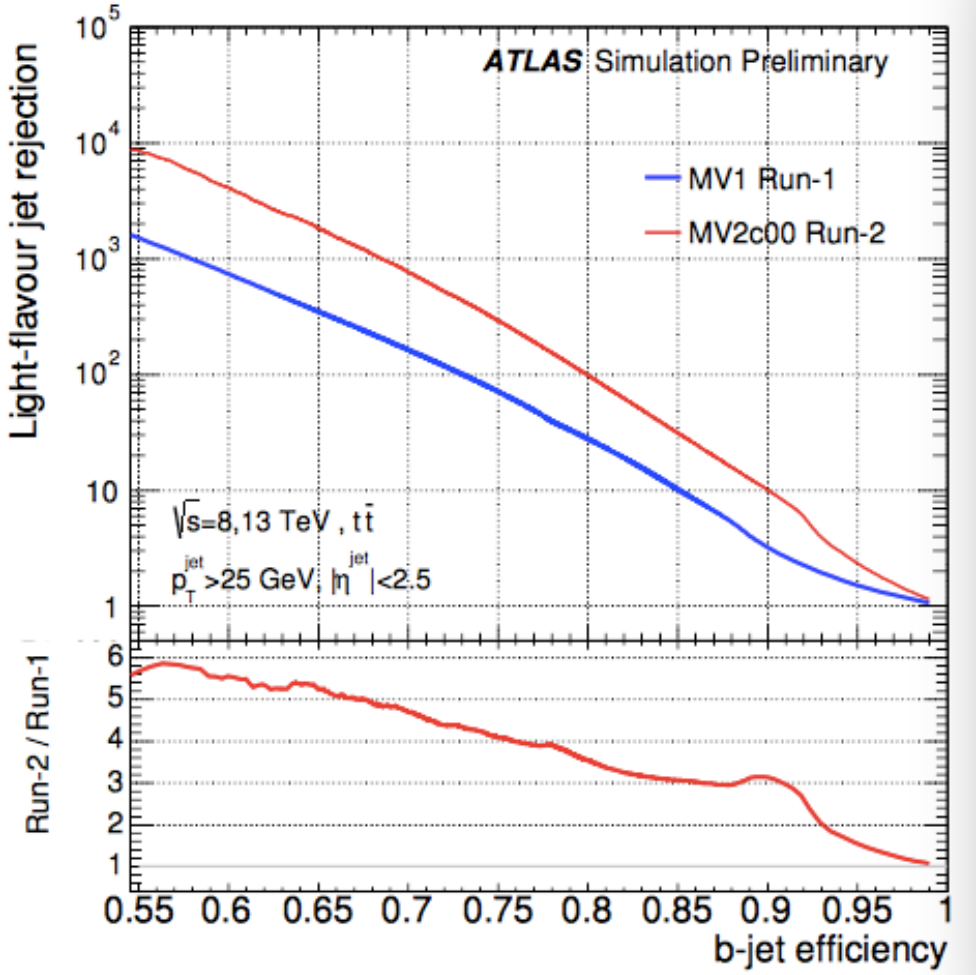
- Two major information to Identify b jets
  - Impact parameters
  - Secondary vertex from B decay

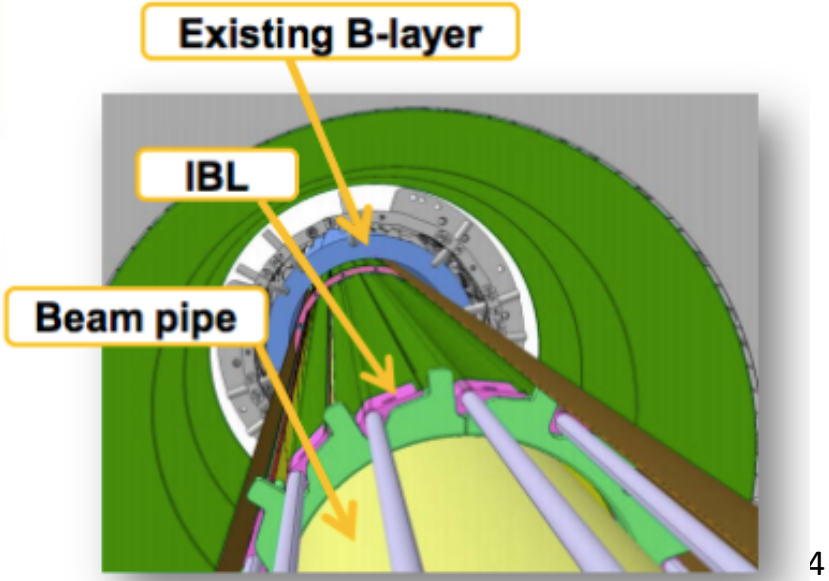




ATLAS Detector upgrade : Run 1 to Run 2

- Adding a new layer of pixel detector
  - IBL = New Insertable pixel B-Layer at R=33 mm
- Light jet rejection power with vertexing algorithm increased





Higgs coupling to top quarks

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- Higgs coupling to bottom quarks
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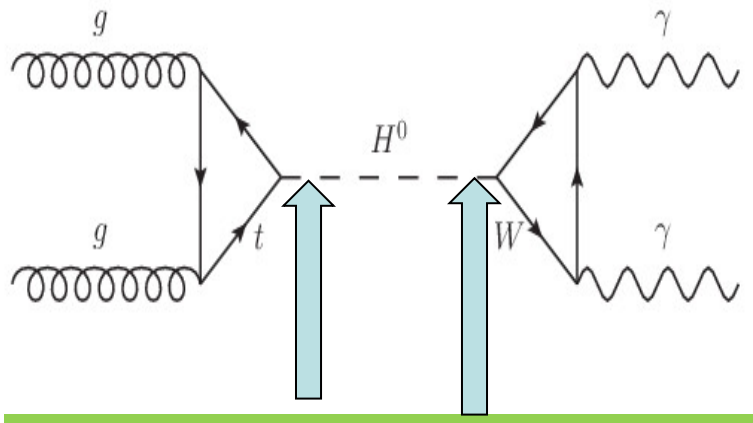
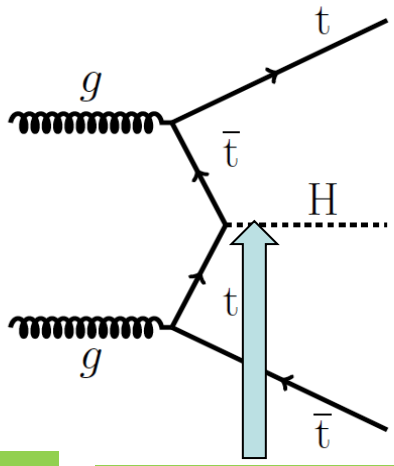
- Higgs coupling to charm quarks
  - Z+H (→ bb)

Why ttH?

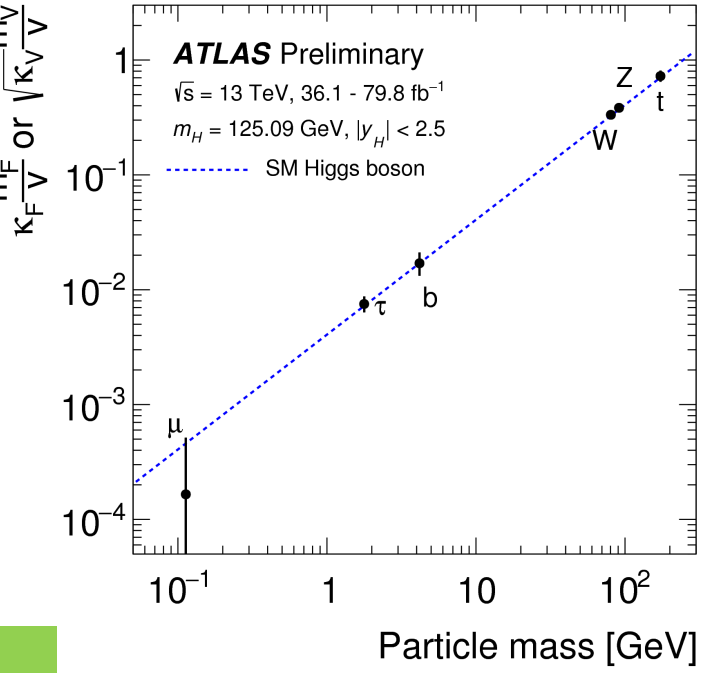
- Explore Higgs-Fermion interactions at LHC
  - The strength of Higgs-Fermion interactions
    - Higgs-Top coupling is the largest
  - At LHC: Model dependent vs independent



Indirect detection, model dependent



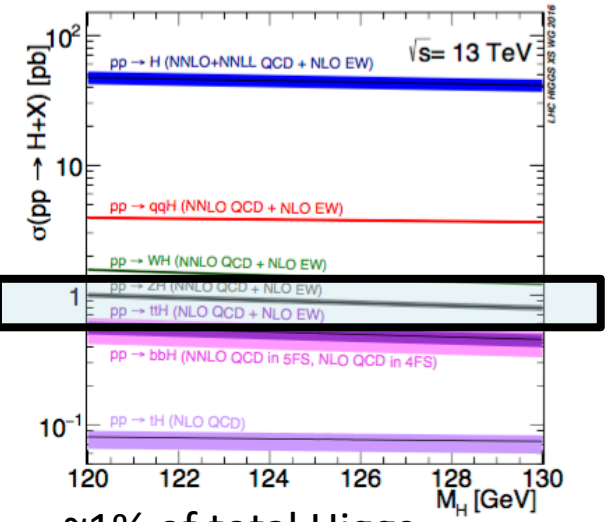
direct detection in production



ttH: probably the only channel that can **directly** probe Higgs Yukawa coupling via production

How to study ttH?

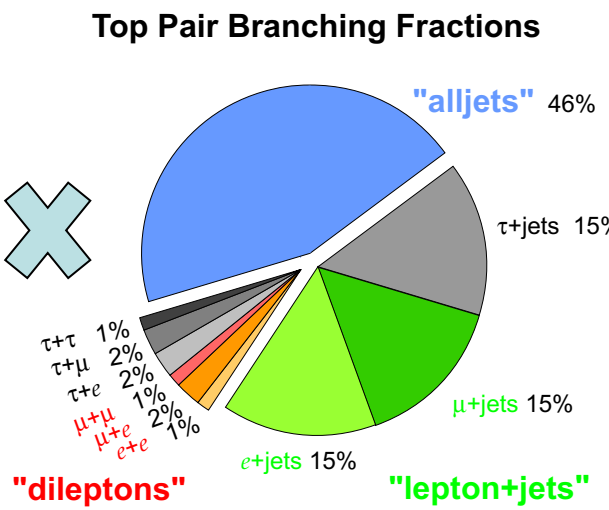
- Production
- Decays

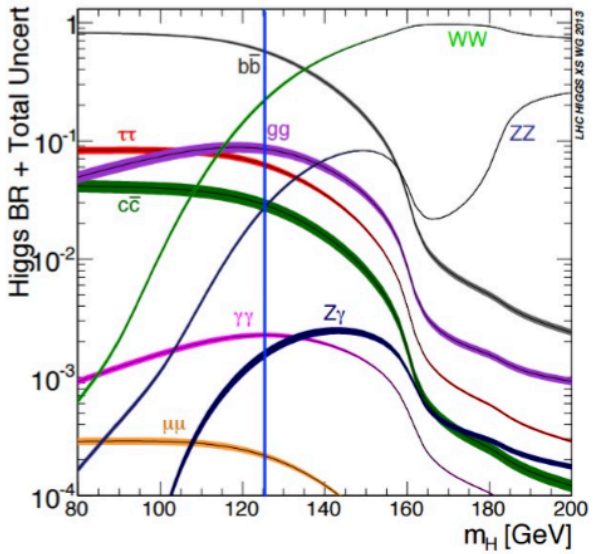


~1% of total Higgs

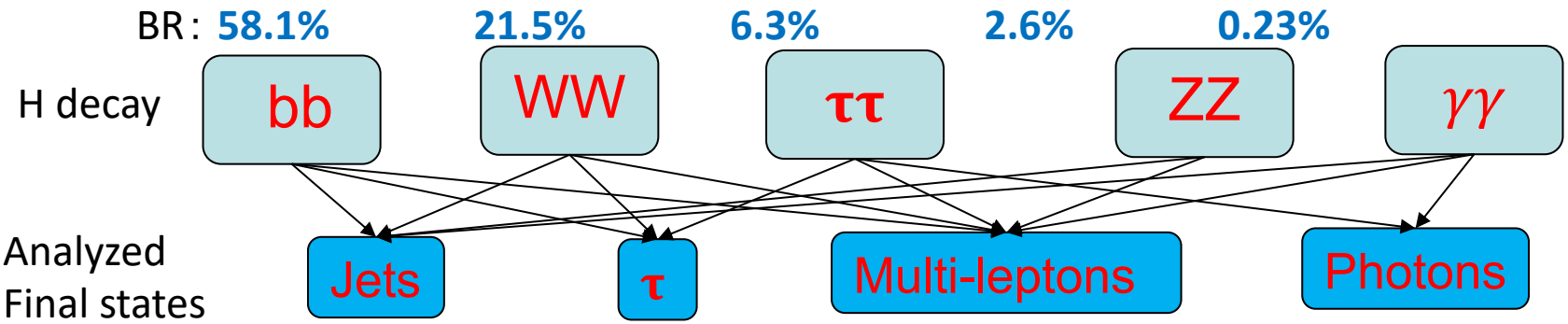
~0.06% of ttbar

~$1/10^{11}$ of total interaction





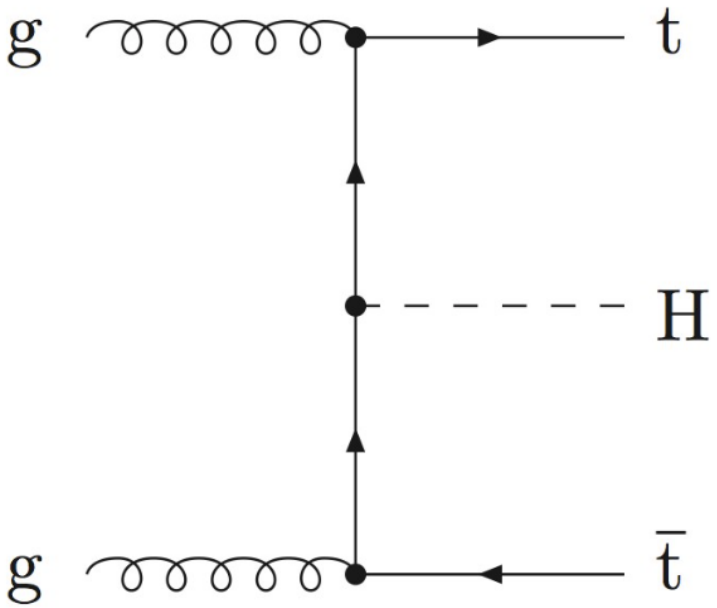
Hundreds of complex final states

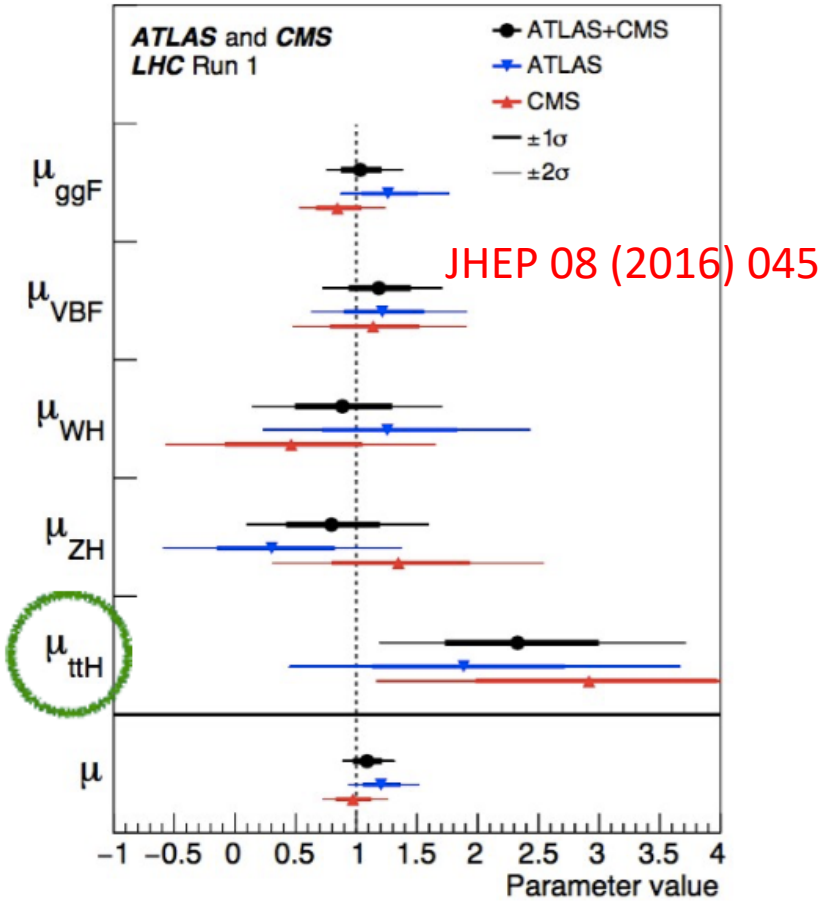


Higgs-top Yukawa coupling in run1

- Direct measurement of Higgs-Top coupling via ttH production.
- ttH signal strength (μ_{ttH}) measured in LHC Run 1
  - 4.4 sigma observed significance (ATLAS+CMS run1 combination)
  - 2.0 sigma expected significance

$$\mu = \sigma_{measured}/\sigma_{SM}$$





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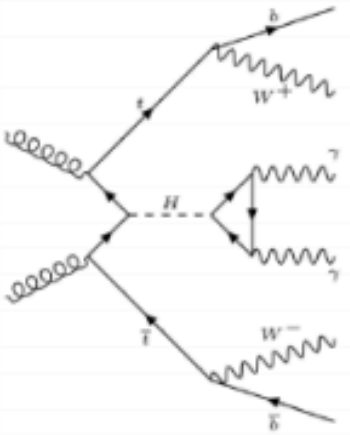
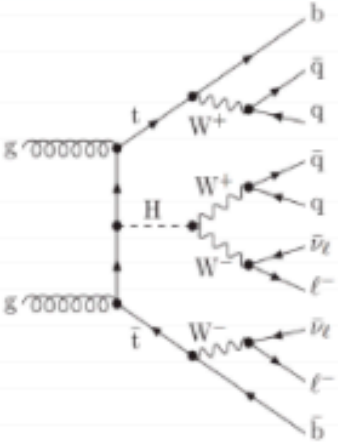
ttH channels



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

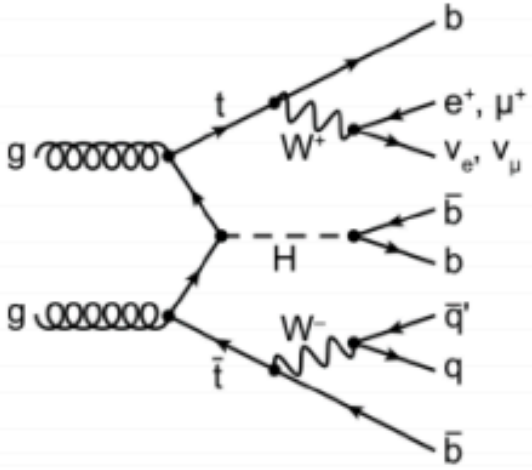
$H \to \gamma\gamma$



$H \to WW^* \to \ell\nu\ell\nu$

$H \to \tau\tau$

(multi-leptons)



$H \to b\bar{b}$

Higher cross section x branching ratio

Higher signal purity

ttH multilepton

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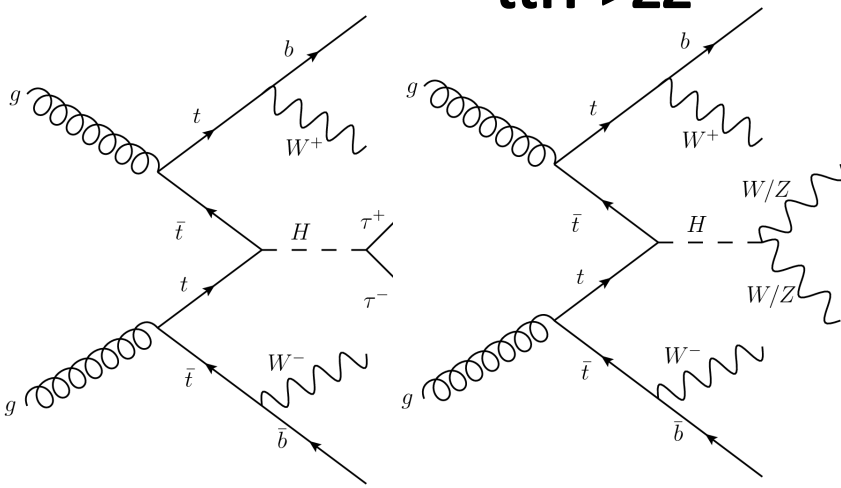
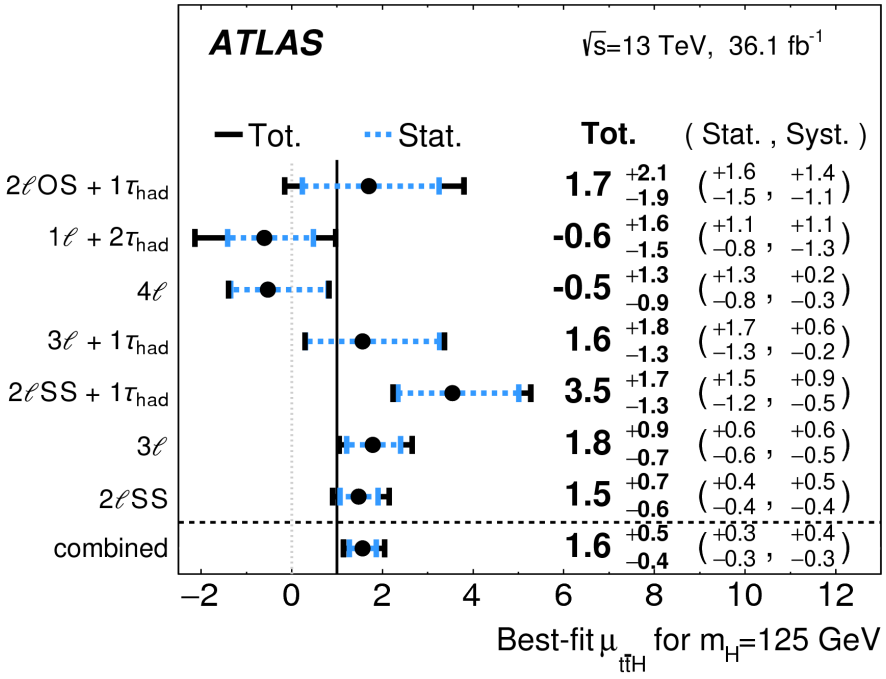
- **Obs. (exp.) significance at 4.1σ (2.8σ)**
  - **ttbar background suppressed at**
    - Same sign di-lepton channel
    - 3 and 4 leptons channel
  - **Major syst.**
    - ttH predicted cross section
    - Jet energy scale and resolution

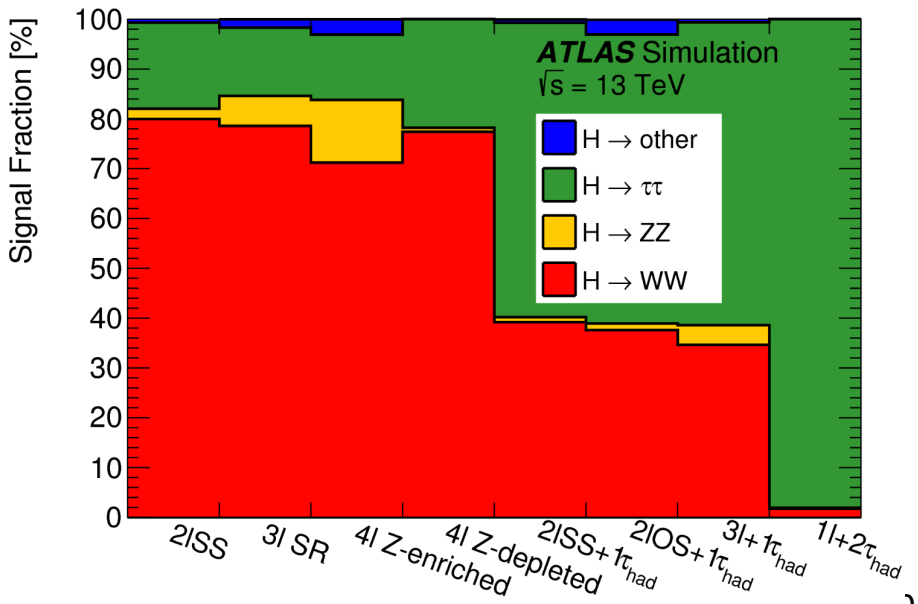
ttH->tautau

ttH->WW

ttH->ZZ







ttH→bb

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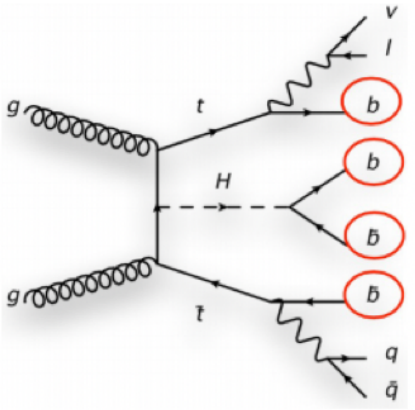
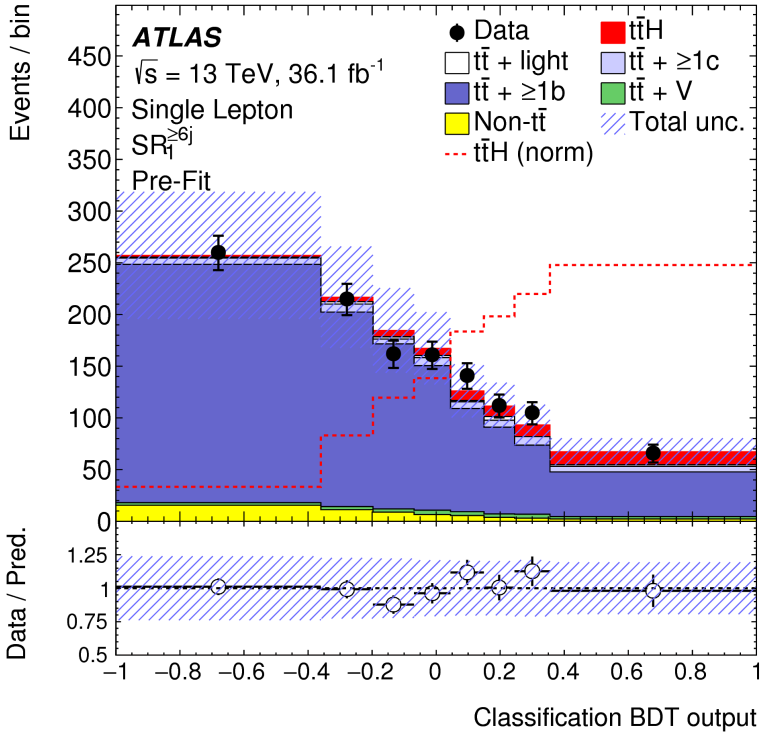
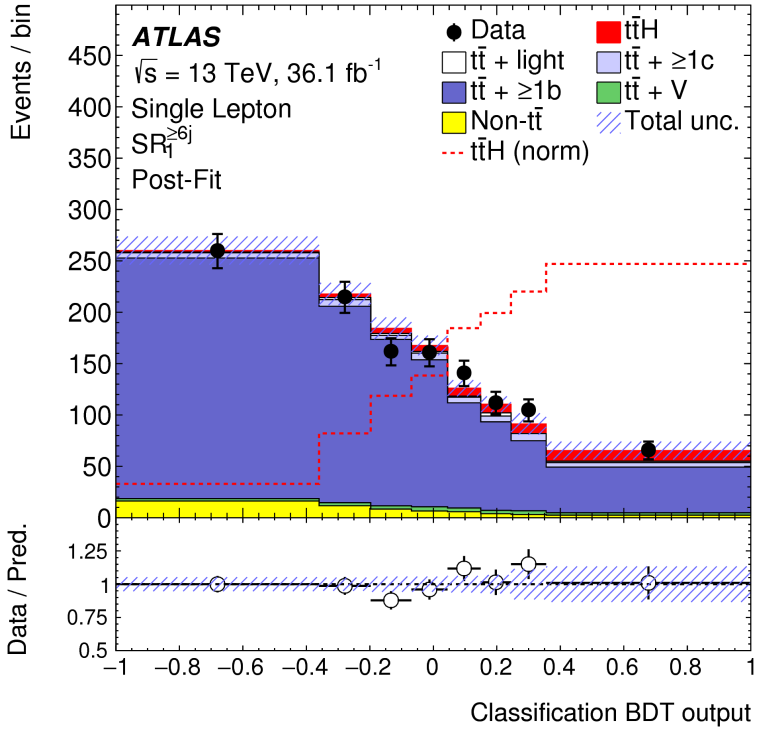
- Suffers from large QCD background from tt+bjets
- Combined fit to all 19 regions (with control region)
  - Reduce background systematics
  - Observed(expected) significance at 1.4σ (1.6σ)

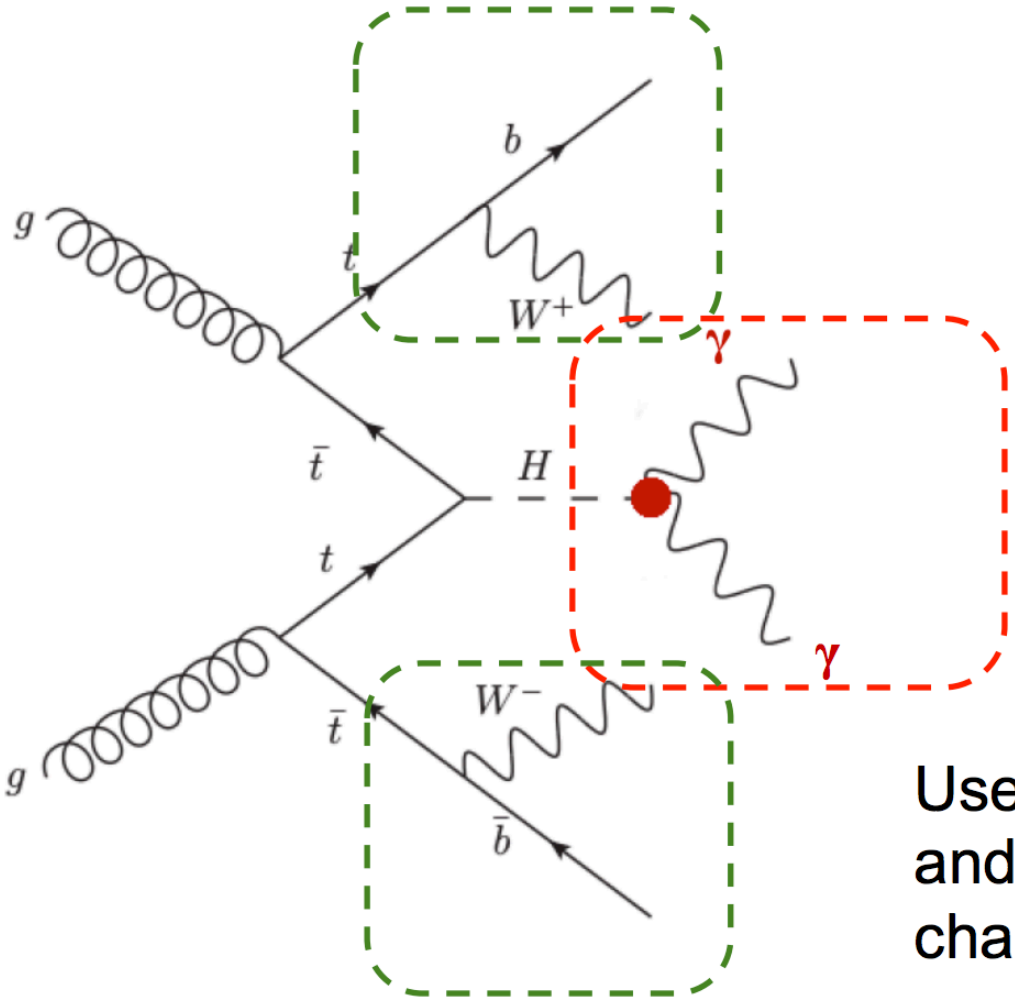




Simultaneous Fit with CR



ttH→γ γ



Use photons to tag the Higgs Boson

Use jets (b-jets), leptons, and E_T^{miss} to capture the characteristics of top quarks

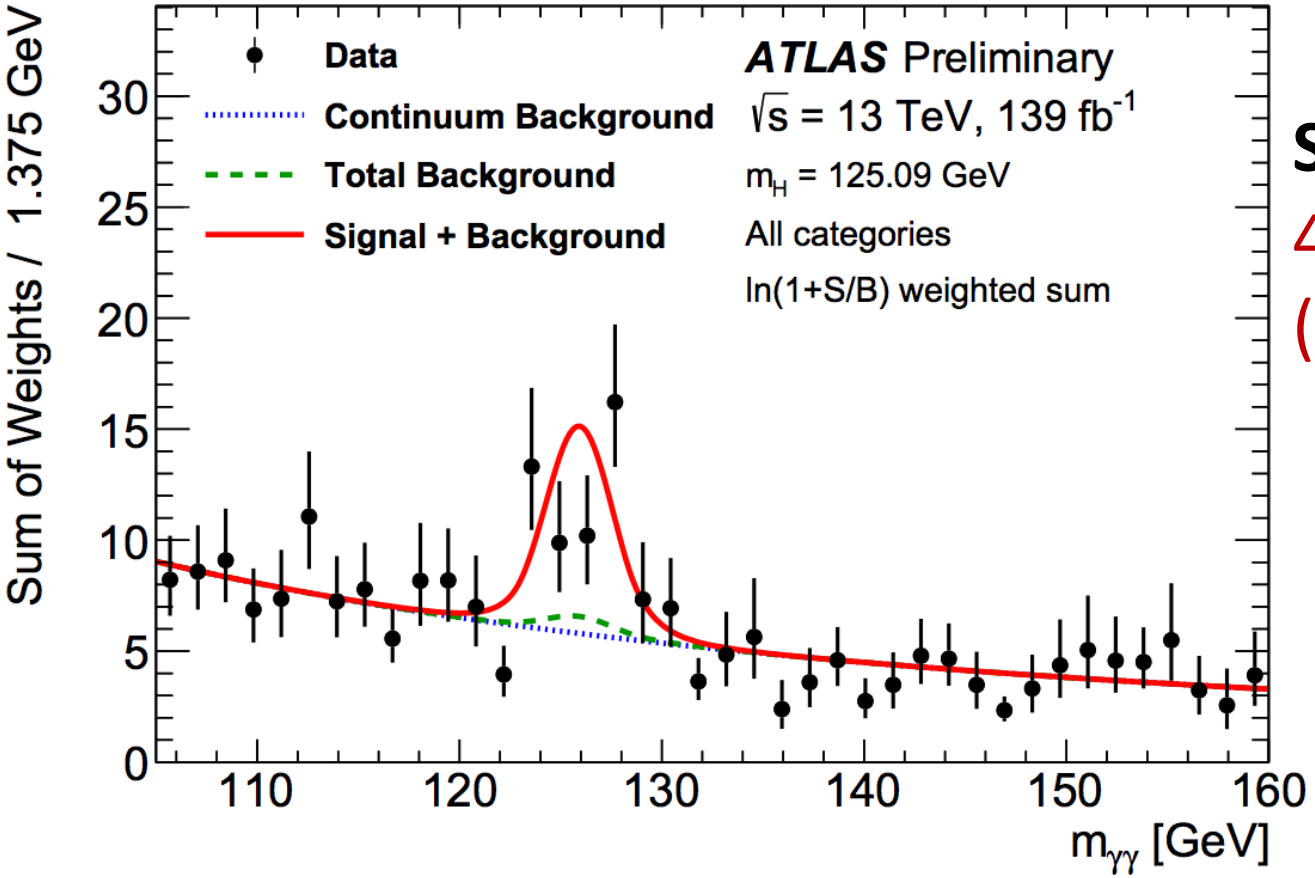
Directly use properties of the objects in the event to train a multivariate discriminant

ttH→γ γ

ATLAS-CONF-2019-004

- The signal strength (observed/predicted) is measured to be:

$$\mu_{t\bar{t}H} = 1.38\ ^{+0.41}_{-0.36} = 1.38\ ^{+0.33}_{-0.31}\ (\text{stat.})\ ^{+0.13}_{-0.11}\ (\text{exp.})\ ^{+0.22}_{-0.14}\ (\text{theo.})$$



Significance:

4.9σ observed

(4.2σ expected.)

ttH combination

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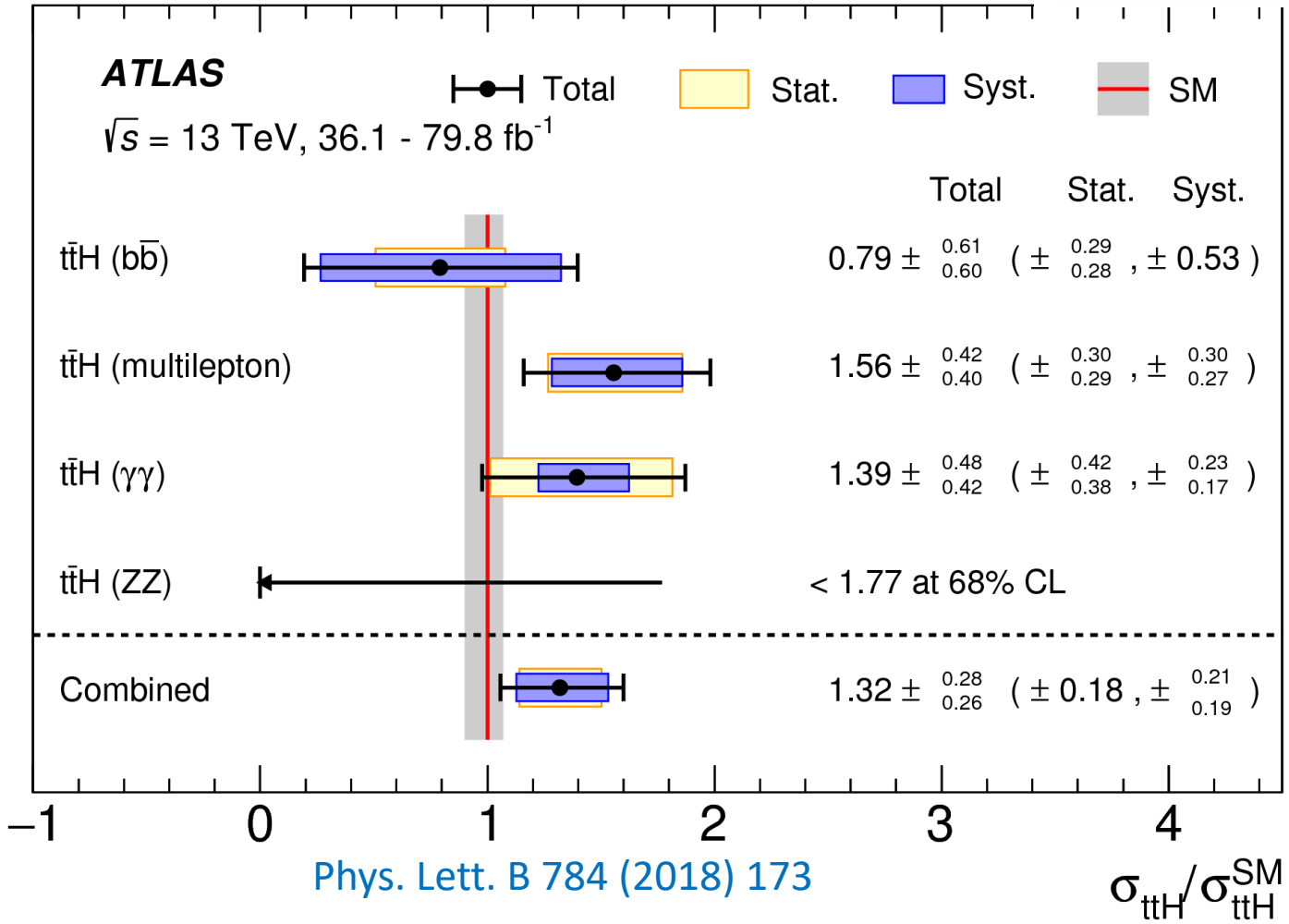
- Observation of ttH production!
  - ttH→γ γ is still dominated by statistics unc.

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



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Higgs coupling to bottom quarks

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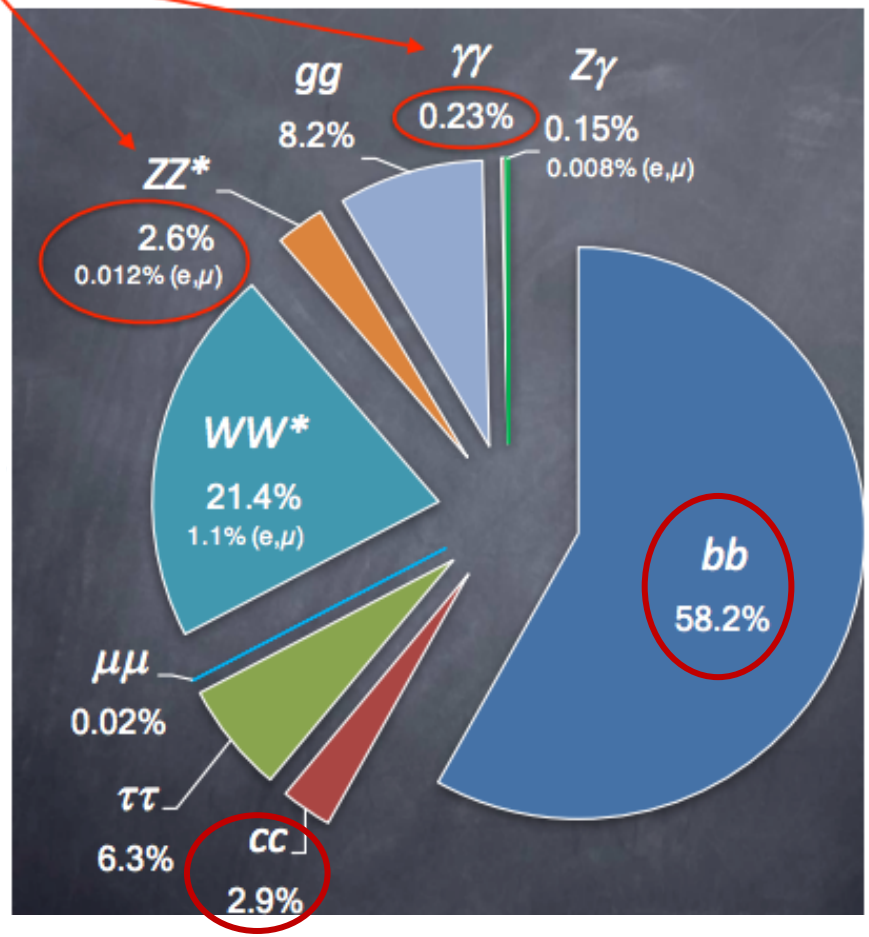
Higgs decay

- H→bb is the Dominant Decay mode of Higgs Boson(58%)
- Motivation: Search H→bb decay mode in VBF final state

ZZ, γγ: Good mass resolution channels mass and precise differential measurements



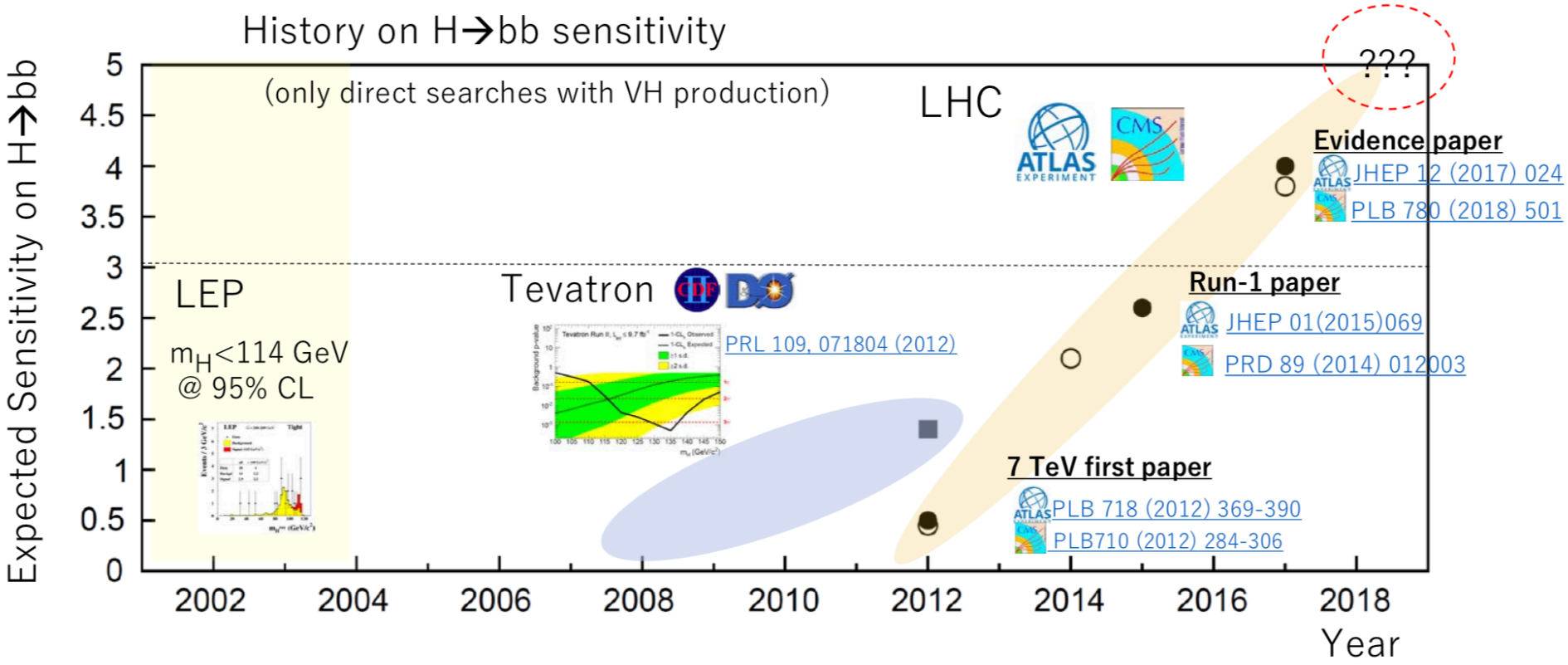
WW: High BR, Poor mass resolution

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

bb, ττ: high BR, but low S/B, important to directly probe Higgs boson coupling to fermions

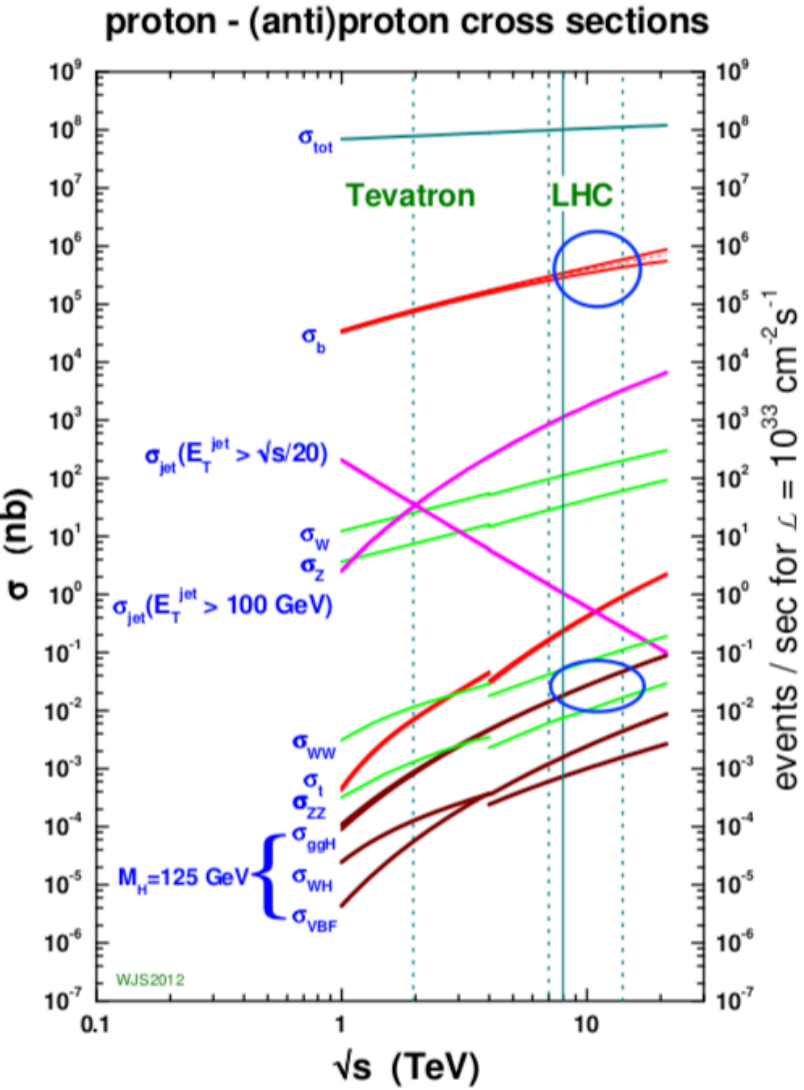
Road to discovery of H → bb

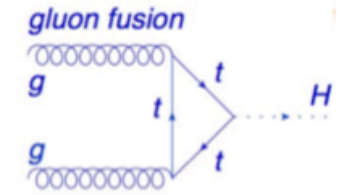
- Started in LEP era, developed in Tevatron, found at LHC
  - H->bb observation in middle of 2018 by ATLAS and CMS
  - Top 10 Physics highlight in 2018 by American Physics Society.



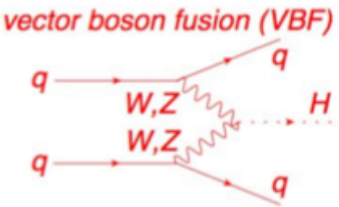
H → bb searches in different channels

- H->bb is hadronic final state
  - Need a clear signature for trigger in ATLAS

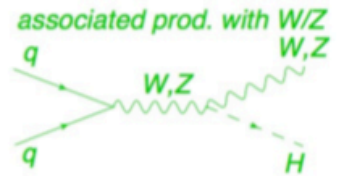




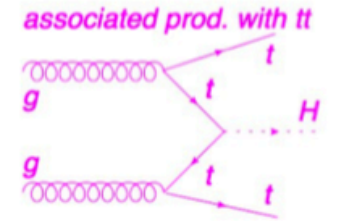
- Largest cross section
- Huge multi-jet (MJ) background



- Two forward jets
- Large MJ



- Leptonic signature
- Better triggering
- Better MJ suppression



- Leptonic signature
- Also top quark coupling

V+H(→ bb) : event selection

0-Lepton

E_T^{miss} trigger

Veto leptons p_T>7 GeV

$p_T^Z(E_T^{miss})$ > 150GeV

Angular cuts to remove MJ

1-Lepton

Single-electron or E_T^{miss} trigger

Exactly one isolated lepton
p_T>25 (27)GeV for muon (electron)

$p_T^W(l,\nu)$ > 150GeV

E_T^{miss} >30 GeV in electron channel

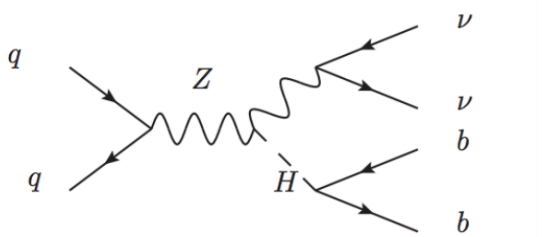
2-Lepton

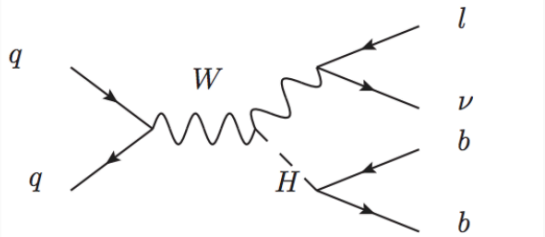
Single-lepton trigger

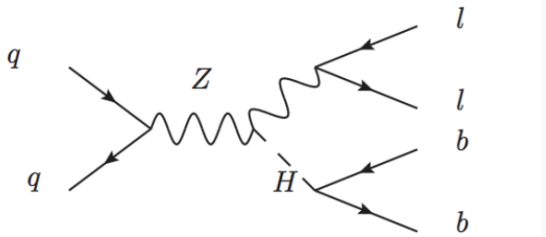
2 electrons or muons p_T>27 (7) GeV

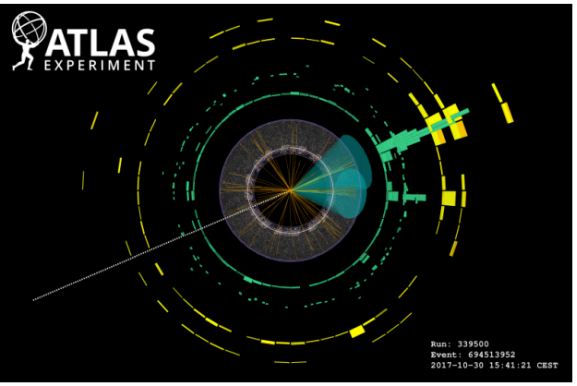
$p_T^Z(l,l)$ [75-150GeV] or >150GeV

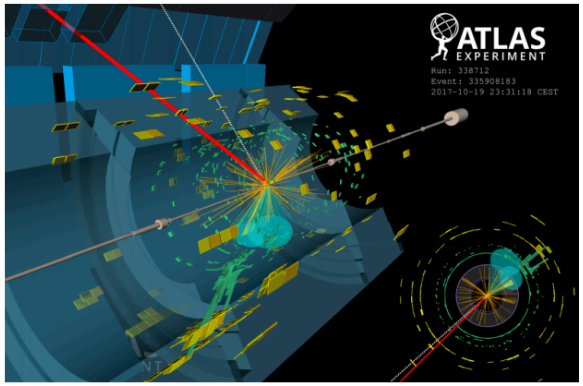
81 < m_{ll} < 101 GeV

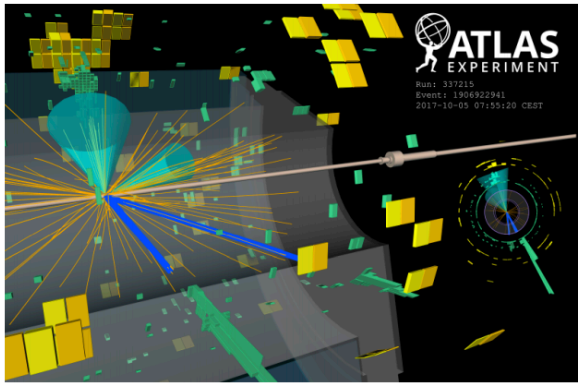












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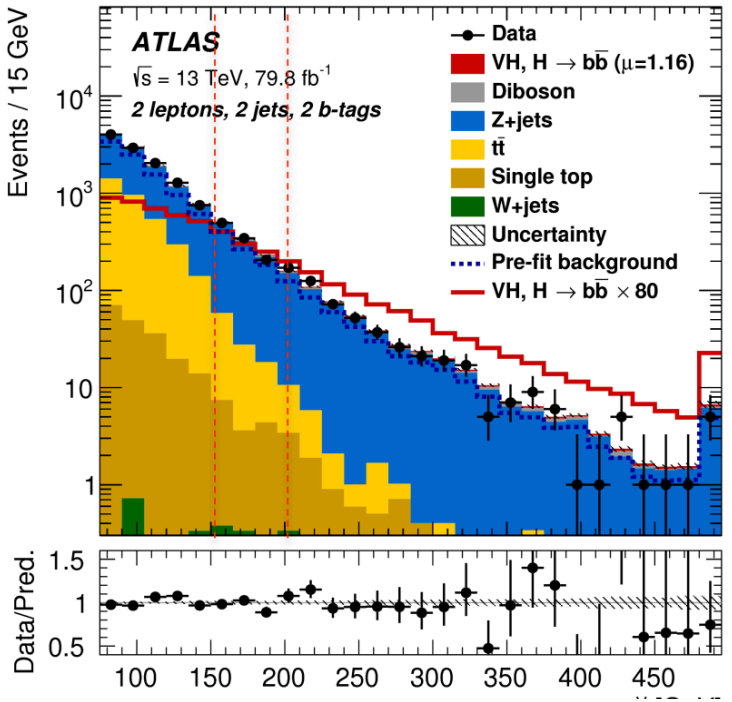
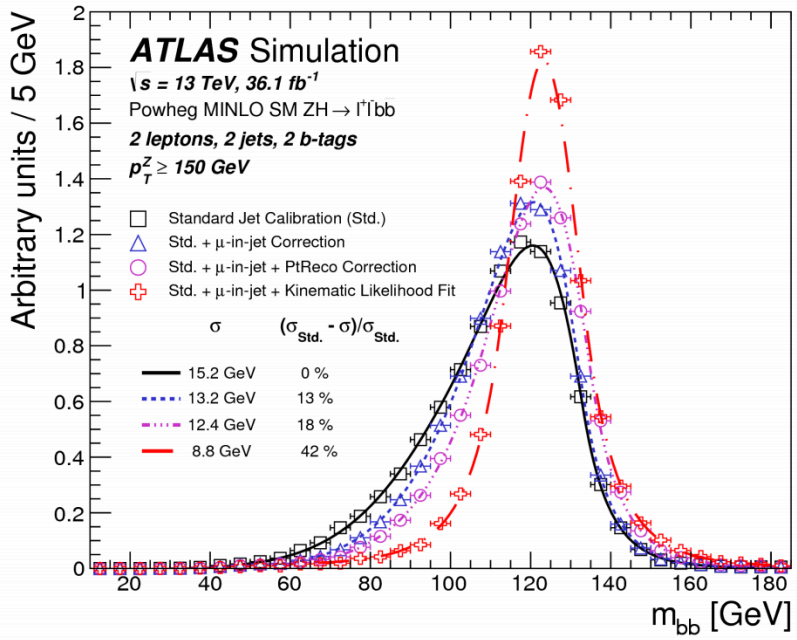
VH → bb: strategy

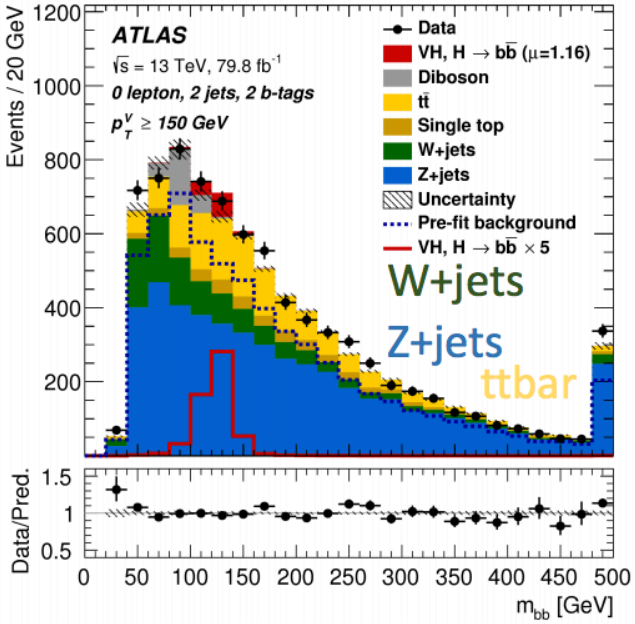
- Harder p_T^V spectrum for signal
  - V=W or Z
  - Higher S/B ratio in high p_T region
- 8 signal categories:
  - Number of lepton (0,1,2-lepton)
  - $75 < p_T^V < 150$ GeV (2-lepton), $p_T^V > 150$ GeV
  - Number of jets (2jet or 3 jets)
- Main discriminant variables
  - m_{bb}, p_T^V and ΔR_{bb}
  - m_{bb} resolution extremely important!
  - Correction to m_{bb}
    - taking into account pT(μ) in b-jets
    - for ν's and out-of-cone energy in decay
    - kinematic fit in 2-lepton channel



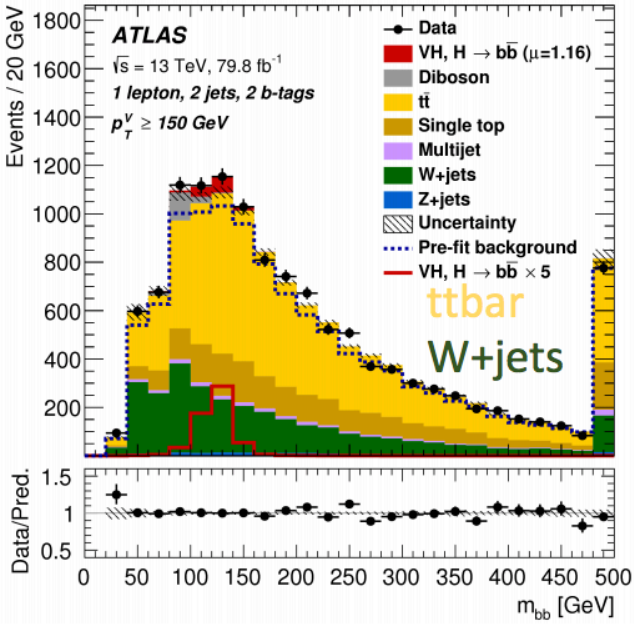


V+H (→ bb): background

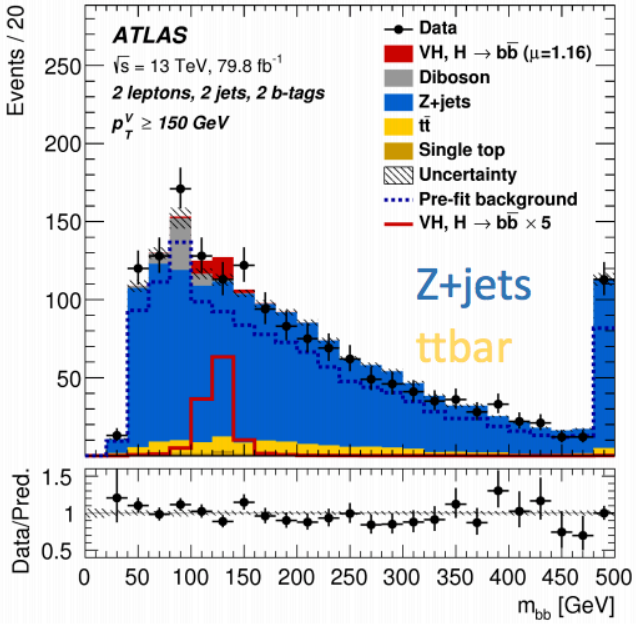
0-lepton



1-lepton



2-lepton



- Z+bjets dominates in 0, 2 lepton channels
- Top quark and W+jets in 1 lepton channel
- Multi-jet background
  - Negligible in 0/2 lepton channels after anti-QCD cuts
  - Data-driven estimate in 1 lepton channel

VH → bb: Result

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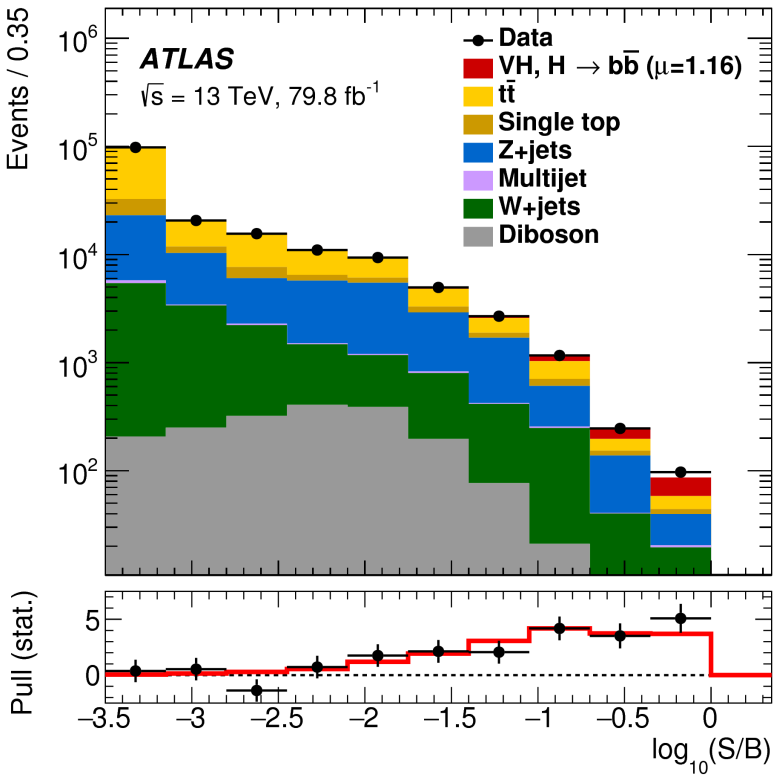
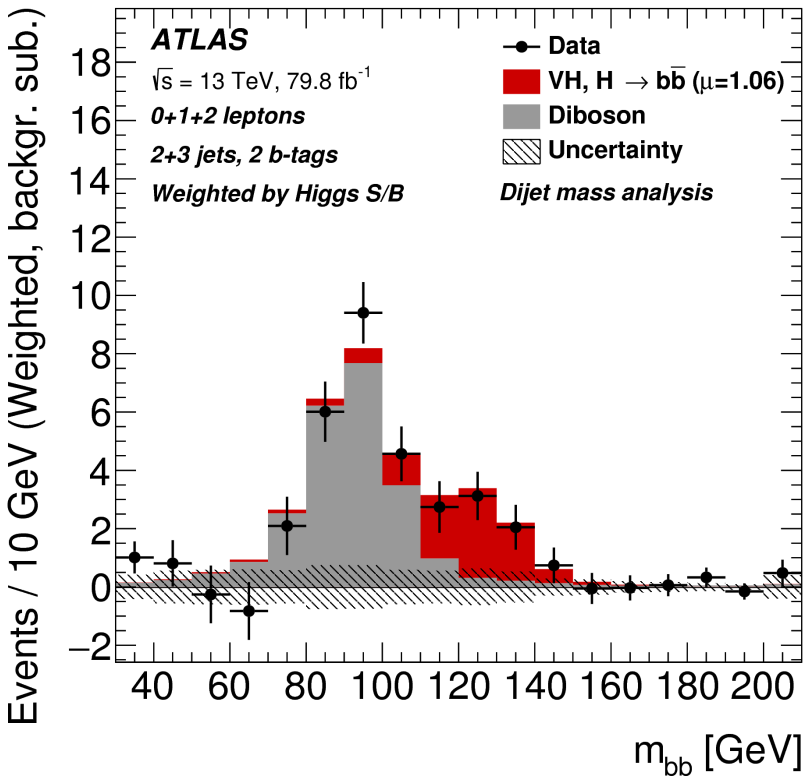
Fit to BDT distributions (8 SRs)



Fit to m_{bb} distributions (14 SRs)



μ=(observed signal yield) /(signal yield from theory)

$$\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$$

corresponding to **4.9σ** (4.3σ exp.)

$$\mu_{VH}^{bb} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.})$$

corresponding to **3.6σ** (3.5σ exp.)

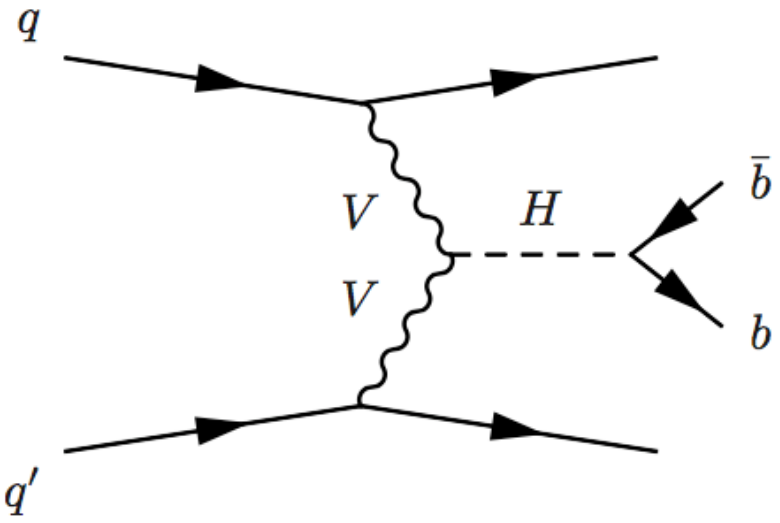
Higgs coupling to bottom quarks

- Higgs coupling to top quarks
  - Associated production with a top quark pair (ttH)
- Higgs coupling to bottom quarks
  - V+H (→ bb) , (where V=W/Z)
  - Vector boson fusion (VBF) H → bb
  - Boosted H→ bb
  - H → bb combination
- Higgs coupling to charm quarks
  - Z+H (→ bb)

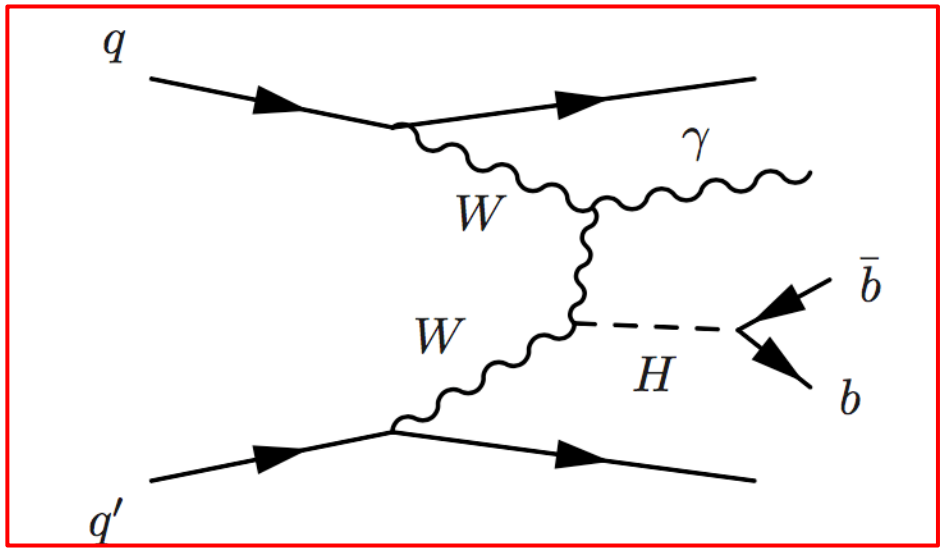
VBF H → bb analysis

- Search for H->bb in VBF events with/without photons
- Advantages of requiring a photon
  - extra handle for trigger
  - suppresses QCD background

VBF H → bb



VBF H → bb +γ

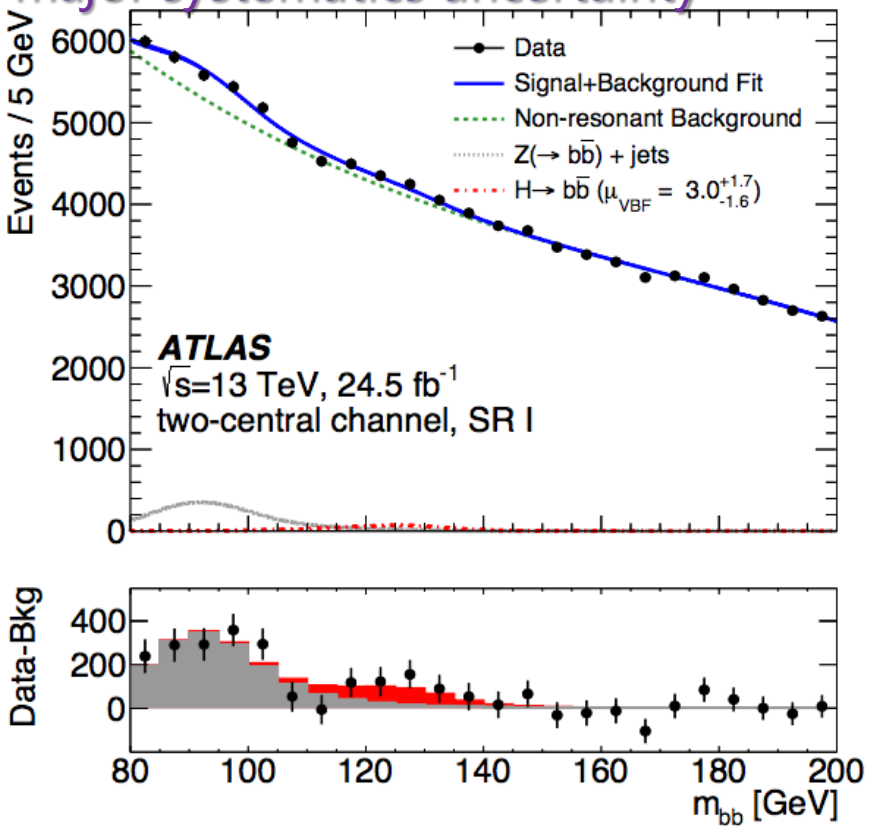


VBF H → bb result

- 1.9σ (0.7σ) Observed (Expected) significance
  - By combing all VBF H→ bb channels

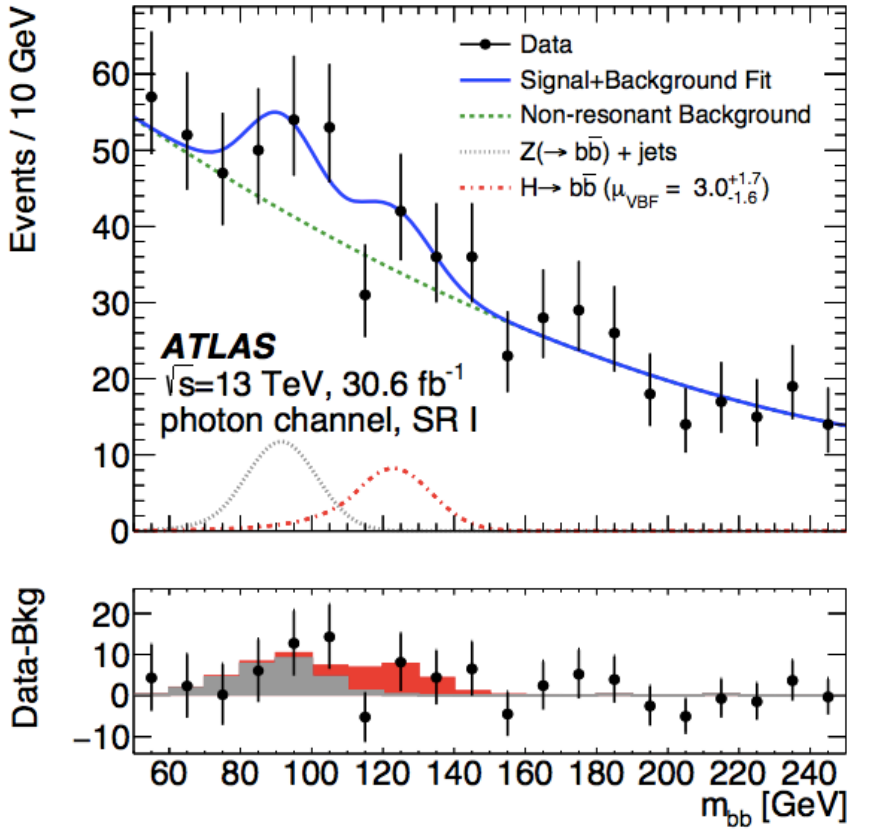
VBF H→ bb

Background uncertainty is the major systematics uncertainty



VBF H→ bb +γ

Statistics uncertainty dominated



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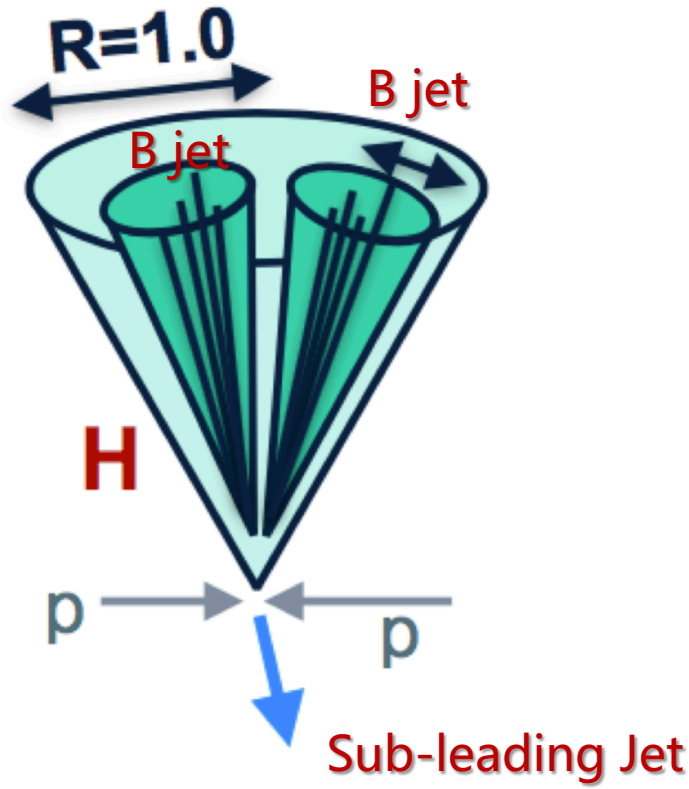
Higgs coupling to bottom quarks

- Higgs coupling to top quarks
  - Associated production with a top quark pair (ttH)
- Higgs coupling to bottom quarks
  - V+H (→ bb) , (where V=W/Z)
  - Vector boson fusion (VBF) H → bb
  - Boosted H→ bb
  - H → bb combination
- Higgs coupling to charm quarks
  - Z+H (→ bb)

Boosted H → bb

- Looking for a high p_T large radius jet with two b-tags
  - Leading jet (R=1.0) p_T>480GeV, sub-leading jet p_T>250GeV
  - Two b tagged track jets in leading jet
  - **μ_H=5.8±3.1(stat.)±1.9(syst.)±1.7(th.)**
  - **1.6 σ observed significance**



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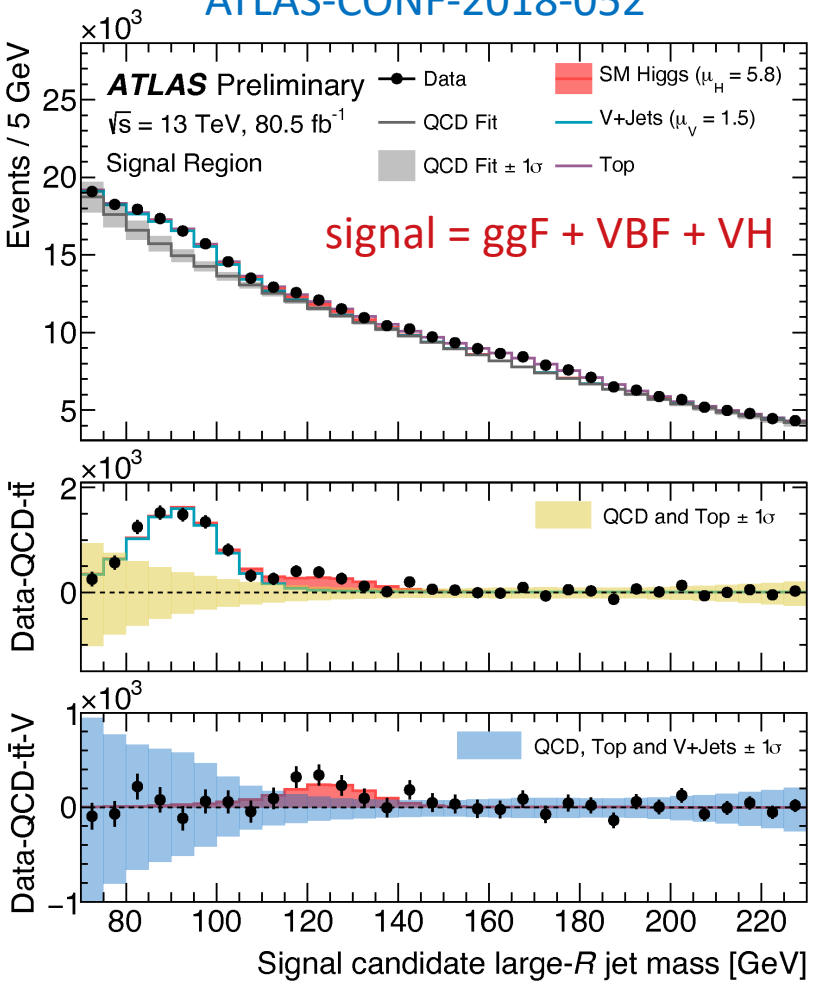

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  - Associated production with a top quark pair (ttH)
- Higgs coupling to bottom quarks
  - V+H (→ bb) , (where V=W/Z)
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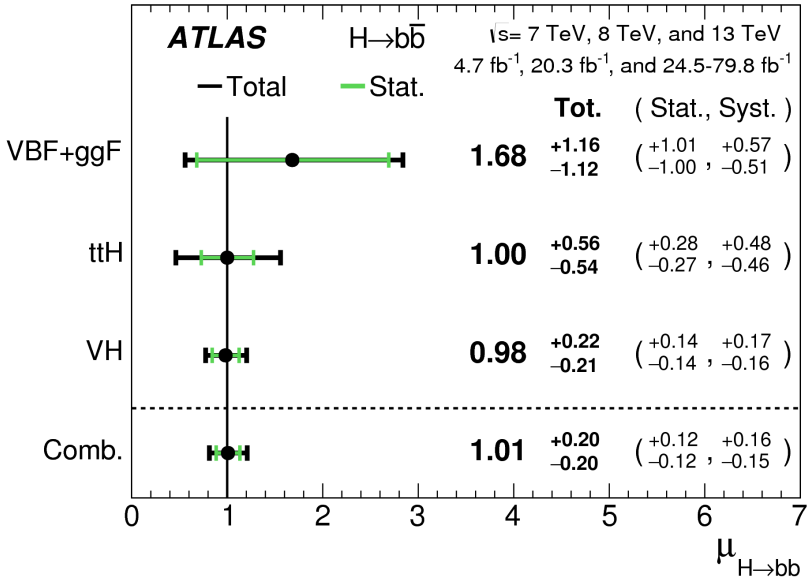
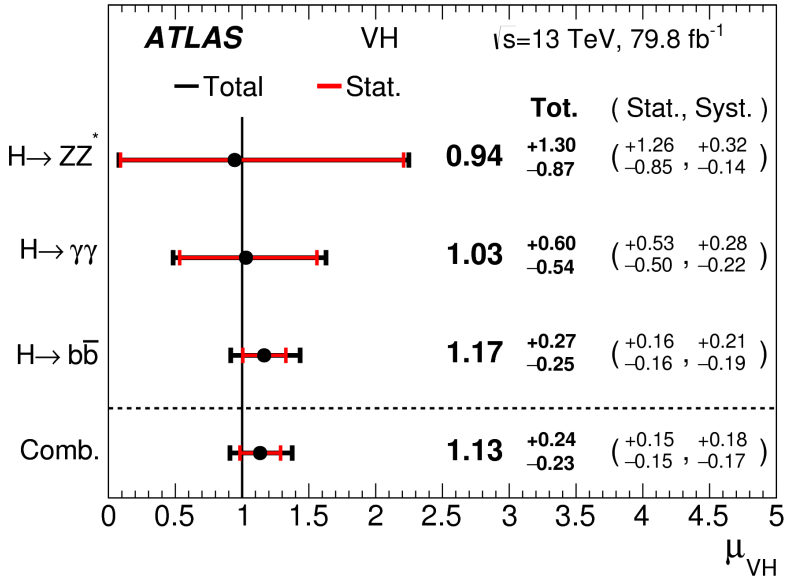
  - Boosted H→ bb
  - H → bb combination
- Higgs coupling to charm quarks
  - Z+H (→ bb)

Observation of H → bb

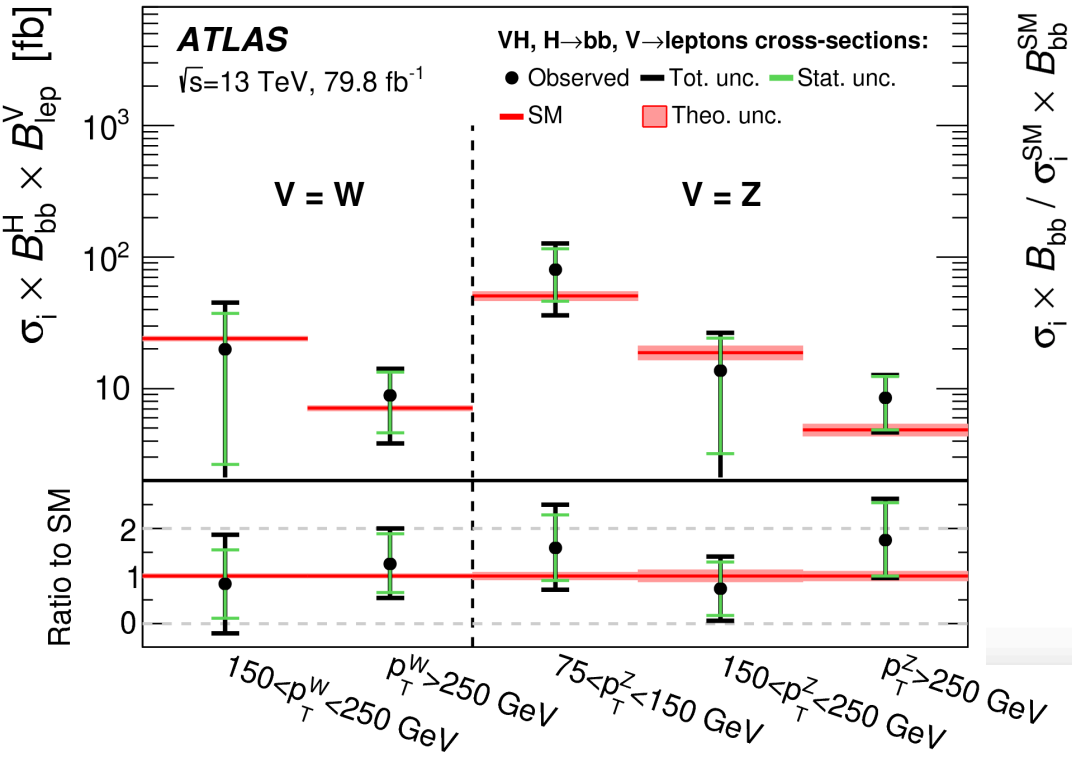
- VH → bb in Run 2:
  - Observed (expected) of 4.9σ (4.3 σ)
- Adding VH → bb in Run1
  - Observed (expected) of 4.9σ (5.1 σ)
- Adding VBF and ttH
  - Observed (expected) of 5.4σ (5.5 σ)
  - Observation of H → bb decay
- Adding H→ ZZ and H → γ γ:
  - Observed (expected) of 5.4σ (5.5 σ)
  - Observation of VH production

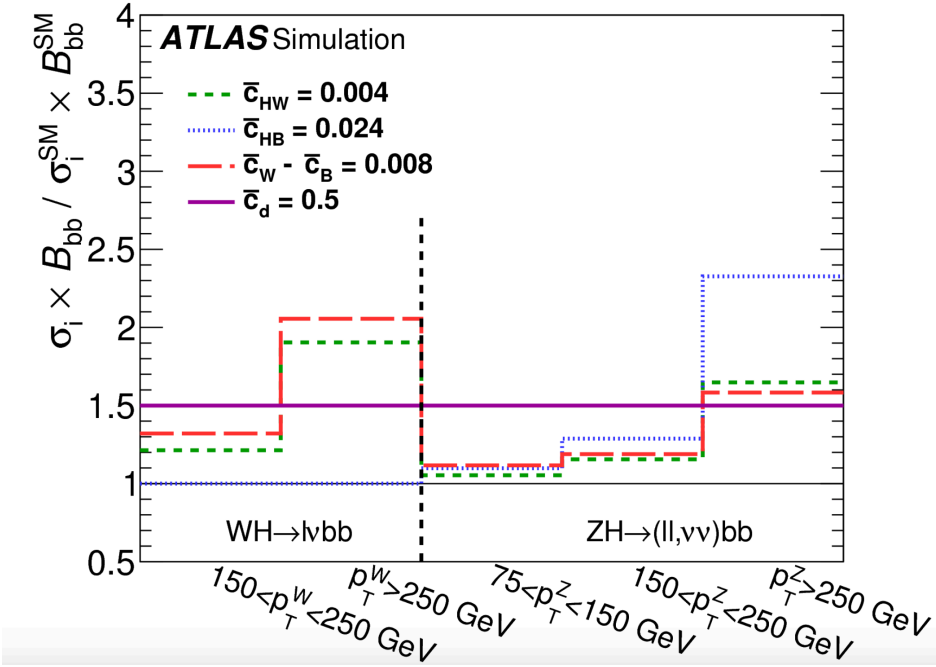




VH → bb: Differential cross section

- Differential cross section measurements for W/Z boson p_T
  - In the 'simplified template cross-section' framework.
  - Constraint to new physics in Higgs Effective Lagrangian (HEL)





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Higgs coupling to charm quarks

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  - Vector boson fusion (VBF) H → bb
  - Boosted H→ bb
  - H → bb combination
- Higgs coupling to charm quarks
  - Z+H (→ bb)

Search for H → cc

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- Charm jet tagging performance is the key.

~~0 Lepton: ZH → νν̄cc ...as VH, H→bb~~

~~1 Lepton: WH → lνcc ...as VH, H→bb~~

2 Leptons: ZH → llcc
- p_T^Z > 75 GeV
- 81 < m_{ll} < 101 GeV

≥ 2 jets, with 1 or 2 c-tags
pT(c1) > 45 GeV

+

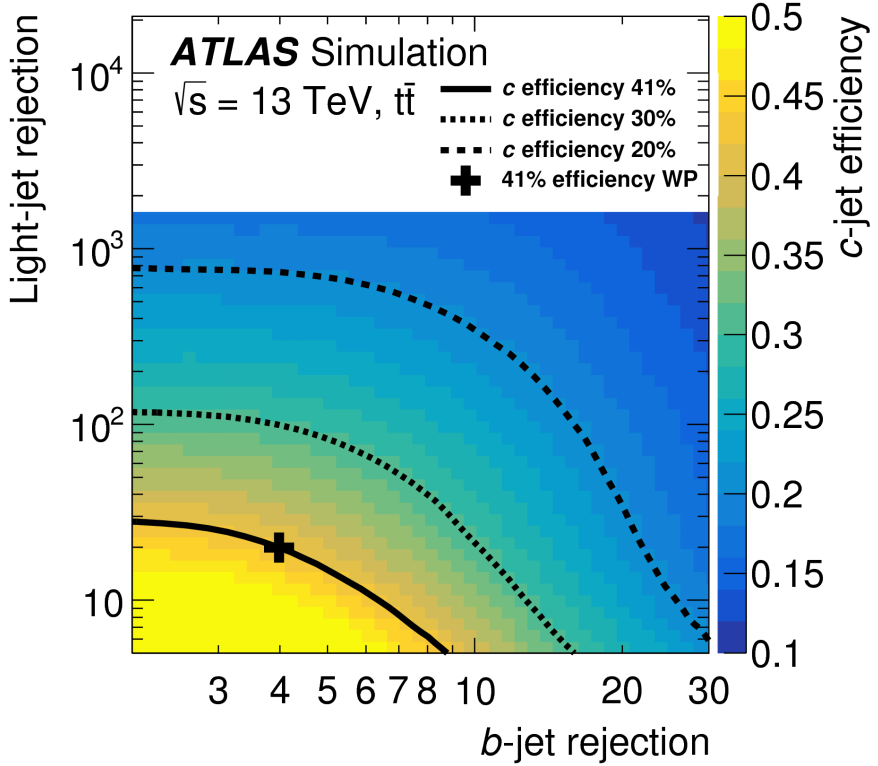
$$75\ \text{GeV} < p_{\text{T}}^{Z} < 150\ \text{GeV} \rightarrow \Delta R < 2.2$$
$$150\ \text{GeV} < p_{\text{T}}^{Z} < 200\ \text{GeV} \rightarrow \Delta R < 1.5$$
$$p_{\text{T}}^{Z} > 200\ \text{GeV} \rightarrow \Delta R < 1.3$$

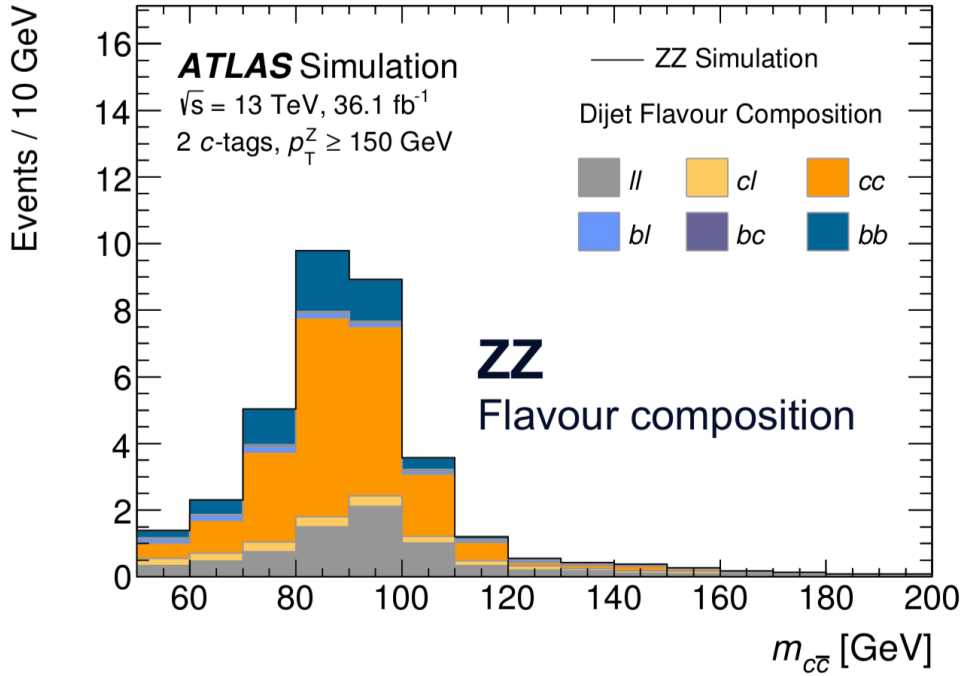
Cross check with diboson

✓ ZZ → llcc and WZ →(cs/cd)ll

✓ Run2 36.1 fb^{-1} result:

Obs.(exp.) significance: 1.4 (2.2) σ

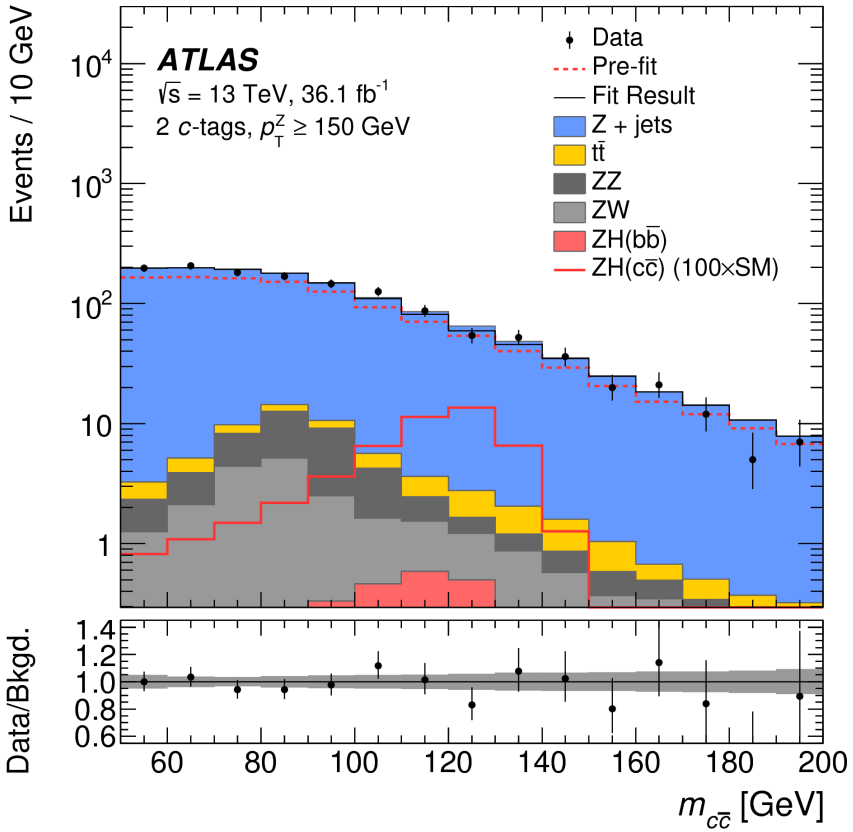




Search for H → cc: result

- Z(ll)H(->cc) has been studied in run2 with 36.1fb^{-1}.
  - H->J/ψγ search on ATLAS gives similar precision
- Also extrapolated to 3000 fb^{-1}

$\mu_{ZH(cc)} < 110$ 36.1 fb^{-1}



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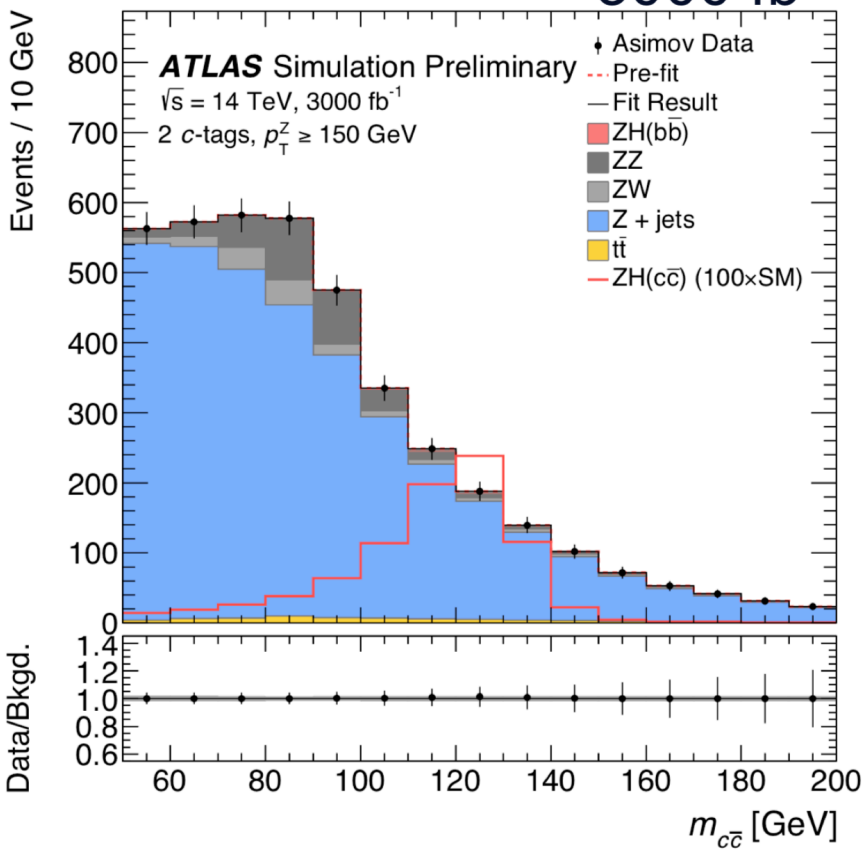
$\mu_{ZH(cc)} < 6.3^{+2.5}_{-1.8}$ 3000 fb^{-1}



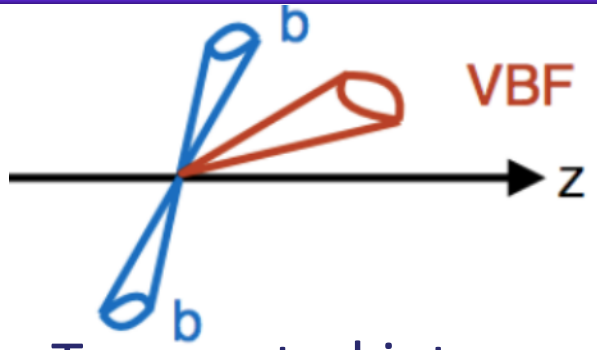
ATL-PHYS-PUB-2018-016

Summary

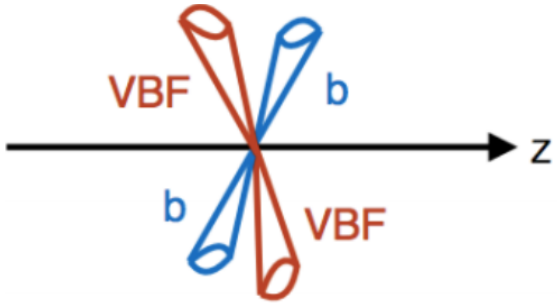
- With the large LHC Run 2 dataset,
  - the coupling of the Higgs boson to quarks can be determined with unprecedented precision
  - Confirmation of coupling to 3rd generation fermions
  - Recent observation bottom and top quark Higgs coupling were presented
  - Observation of VH and ttH production shown
- All measurements of the Higgs boson are compatible with the Standard Model

Backup

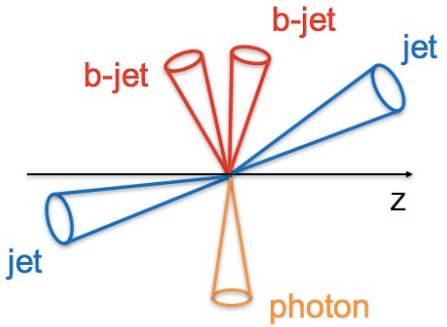
VBF H → bb: Event Selection



Two central jets Channel (1fj+2b)



Four central Channel (2b+2j)



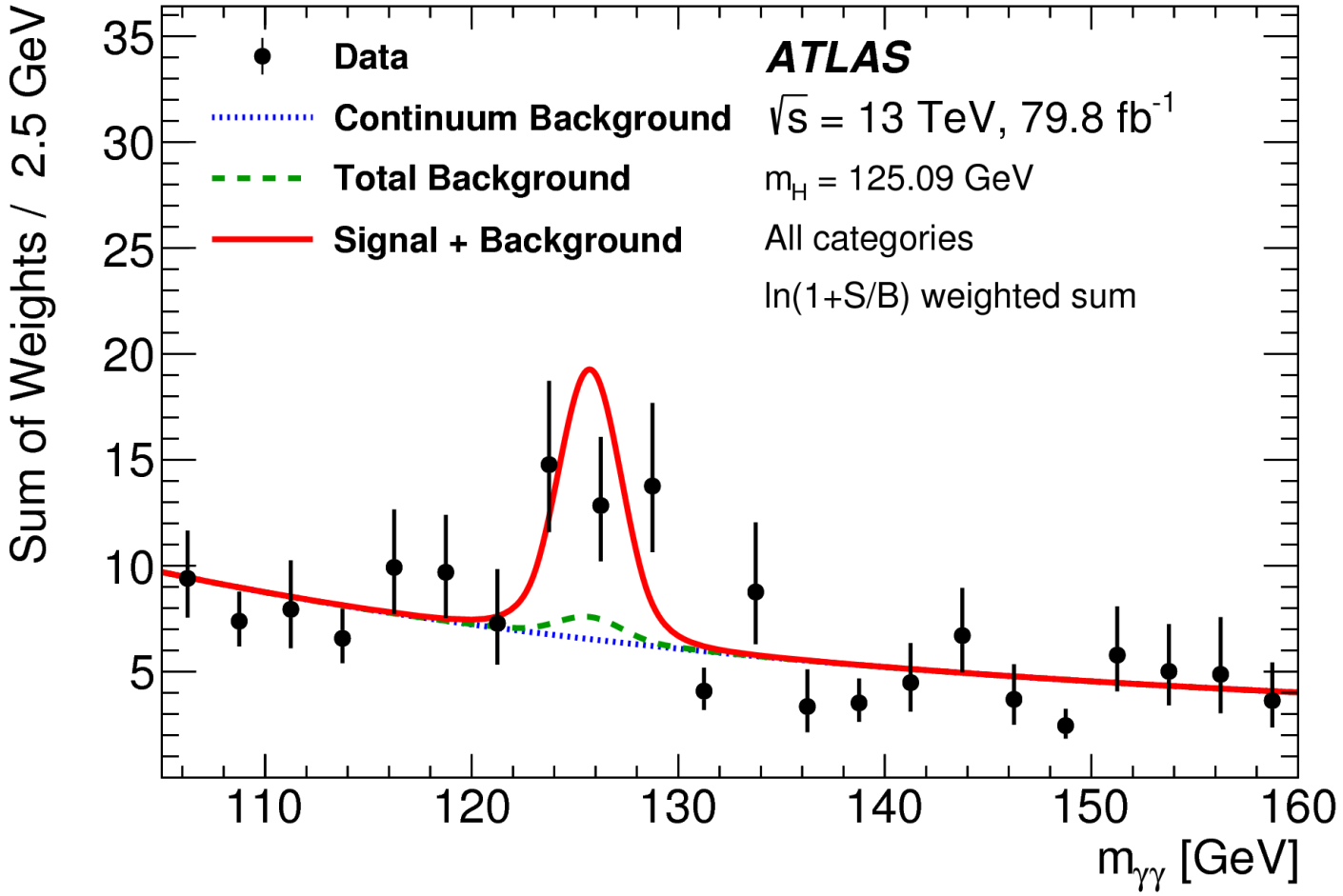
Photon channel γ+2b+2fj

	Two central	Four central	Photon
2 b-jet	p_T>95GeV p_T>70GeV	p_T>55GeV	p_T>40GeV
2 VBF jets	p_T>60GeV, 3.2<|η|<4.4 p_T>20GeV, |η|<4.4	p_T>55 GeV,|η|<4.4 Veto event with jet p_T >60GeV, 3.2<|η|<4.4	p_T>40GeV |η|< 4.4
Photon			E_T>30GeV
Event topology	p_T(bb)>160GeV	p_T(bb)>150GeV	p_T(bb)>80GeV M(jj) >800GeV

Inclusive analysis veto data events in photon channel orthogonality between different channels

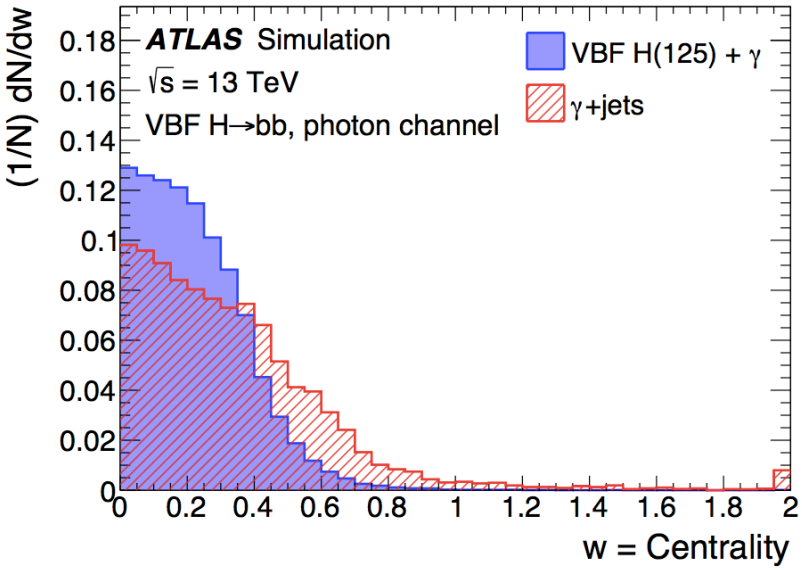
ttH→γ γ

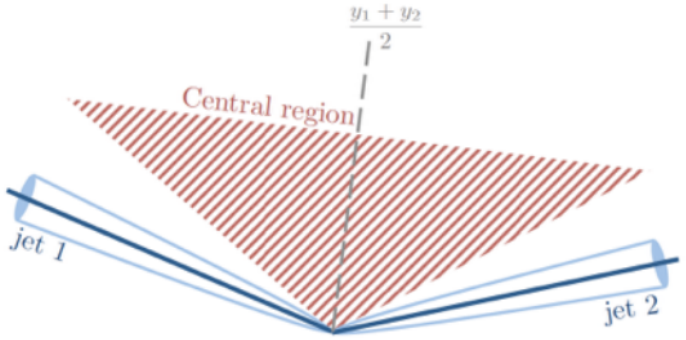
- Select events based on mγγ + b-jets
  - Significance: 4.1σ (3.7σ exp.)



Boosted Decision Tree (BDT) Analysis

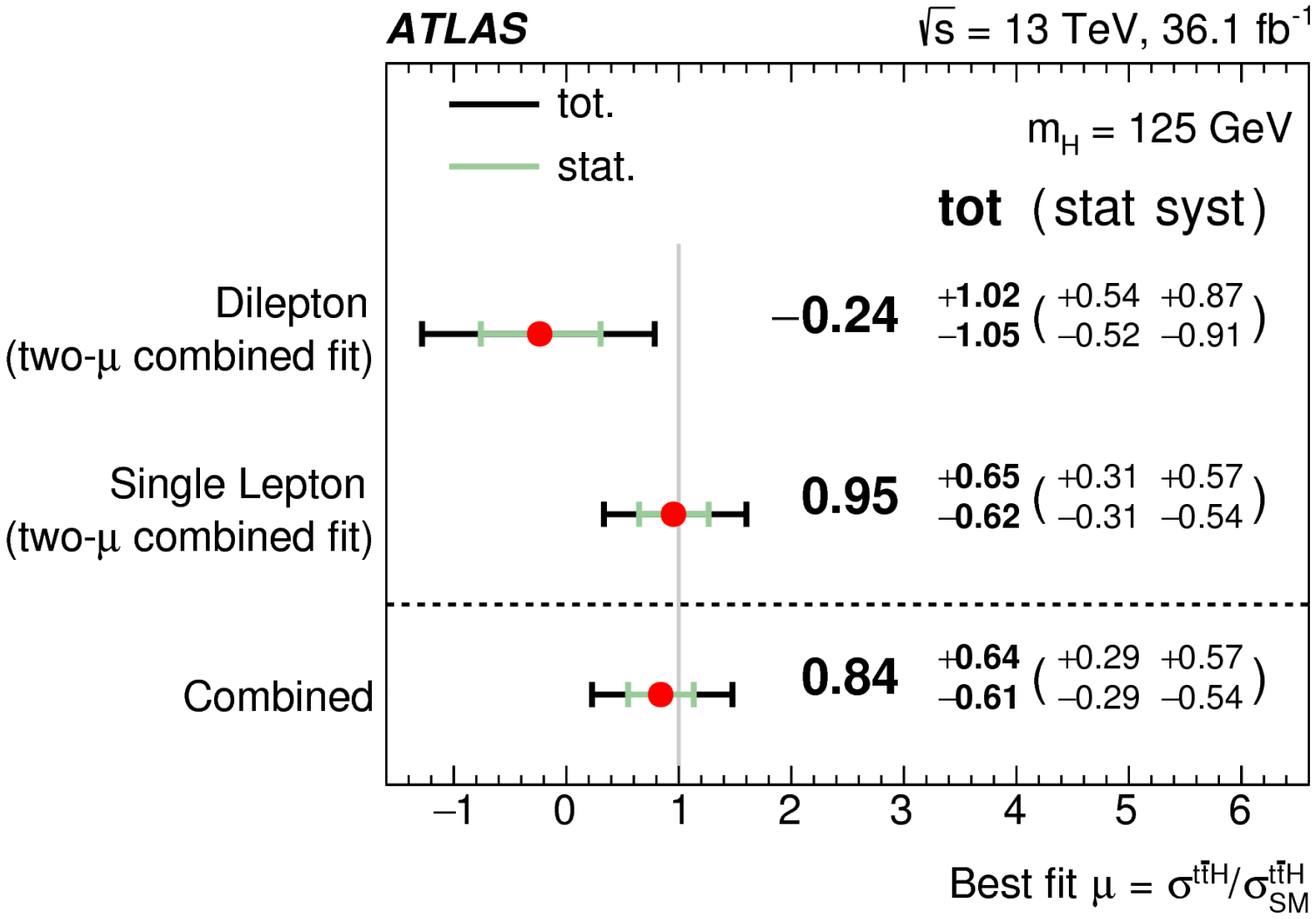
- 11 variables used in BDT analysis



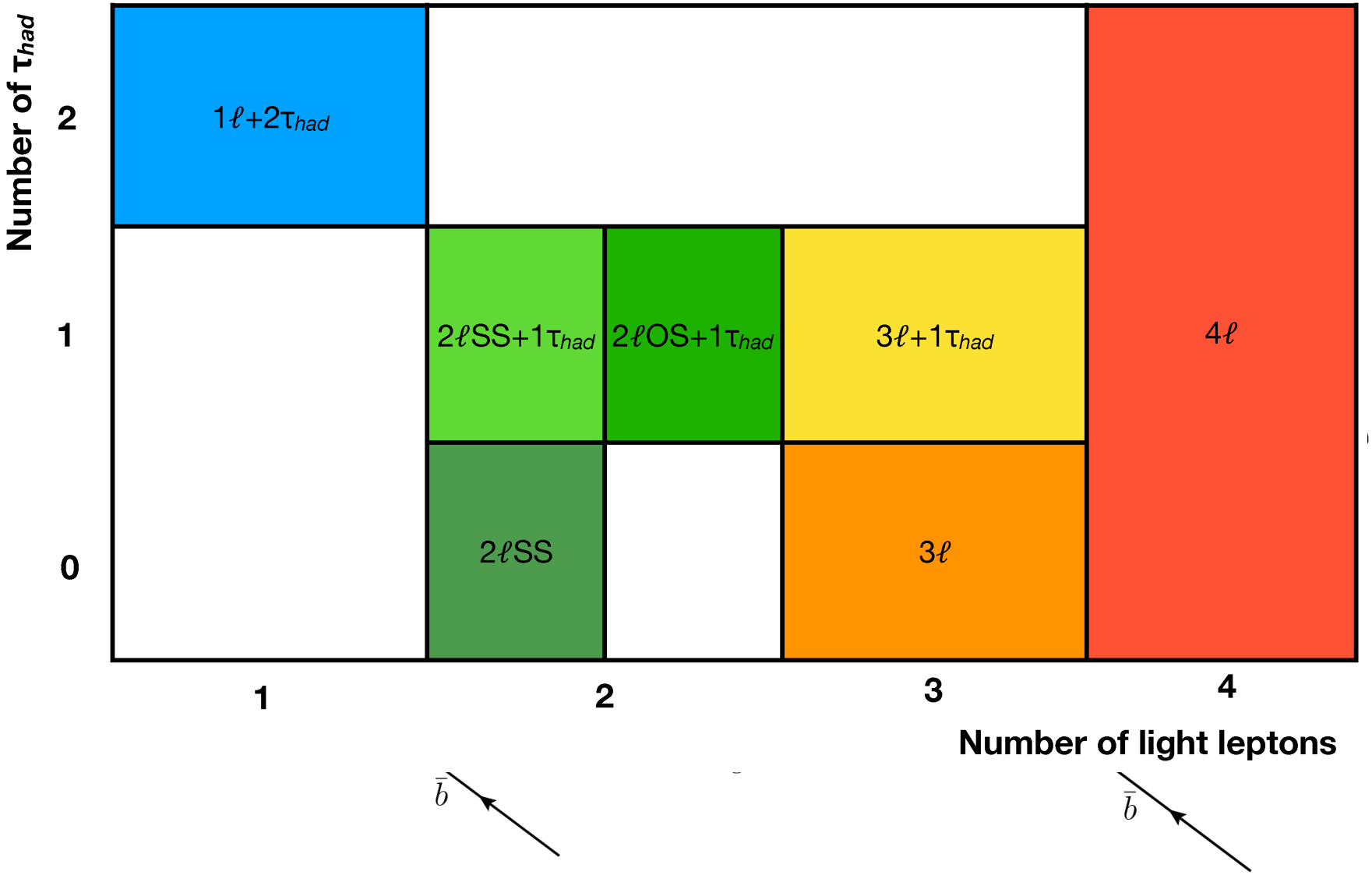


$$centrality(\gamma) = \left| \frac{y_\gamma - \frac{y_{j_1} + y_{j_2}}{2}}{y_{j_1} - y_{j_2}} \right|$$

	VBF H(bb) Inclusive	VBF H(bb)+Photon
g/q seperation	Ntrk(j1),Ntrk(j2) minΔR(J1),minΔR(J2)	Ntrk(j1),Ntrk(j2)
VBF jets	p_T(JJ), M(JJ),ΔM(JJ) Max(η(J1), η(J2))	p_T(JJ), M(JJ), Δη(JJ)
Color connection	p_T balance η^* (Higgs centrality)	p_T balance Photon Centrality
Angular	cos θ(bb,jj)	ΔR(b1,γ),ΔR(b2,γ),Δϕ(bb,jj),cos θ

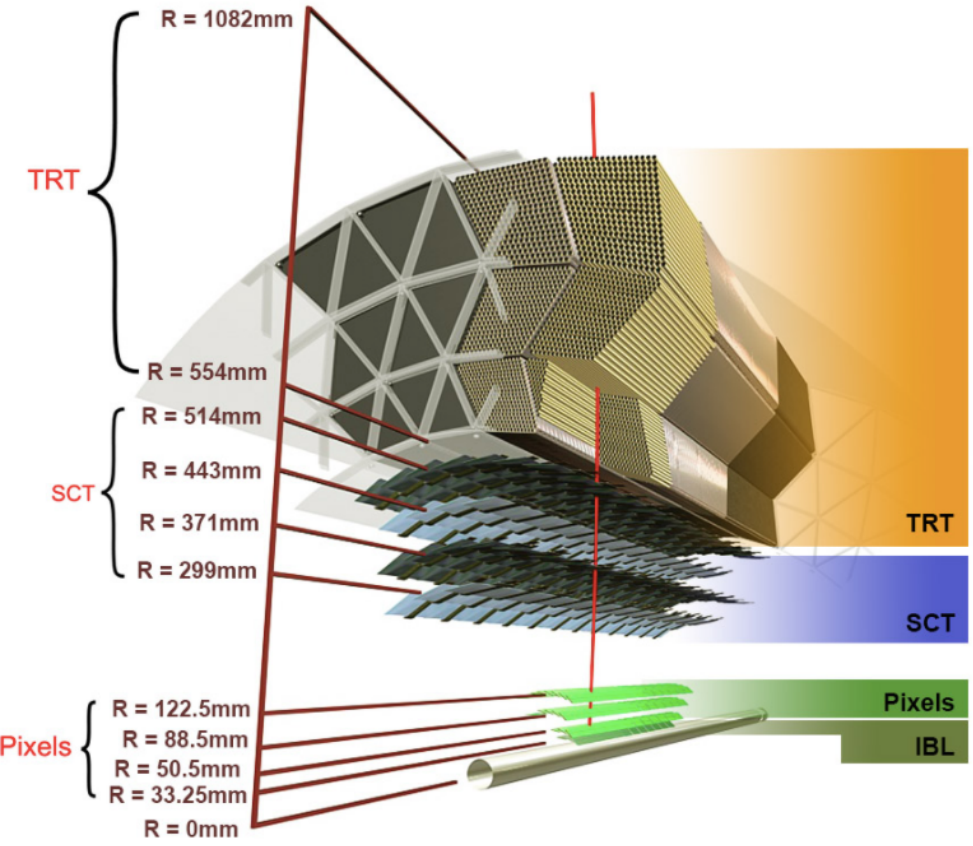

ATLAS
√s = 13 TeV, 36.1 fb-1
tot.
stat.
mH = 125 GeV
tot (stat syst)
Dilepton
(two-μ combined fit)
−0.24
+1.02 −1.05 (+0.54 +0.87 −0.52 −0.91)
Single Lepton
(two-μ combined fit)
0.95
+0.65 −0.62 (+0.31 +0.57 −0.31 −0.54)
Combined
0.84
+0.64 −0.61 (+0.29 +0.57 −0.29 −0.54)
−1
0
1
2
3
4
5
6
Best fit μ = σttH/σttHSM

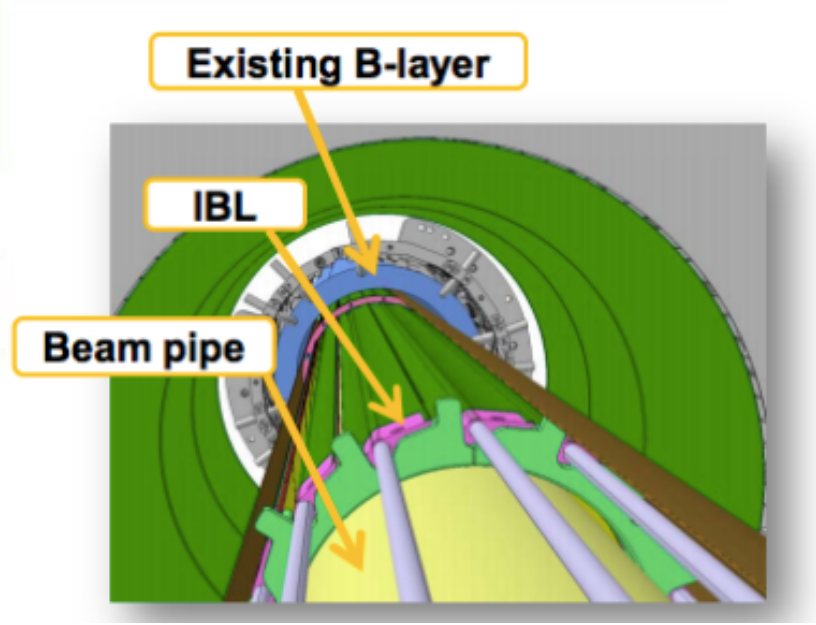
ttH multilepton



ATLAS Detector upgrade : Run 1 to Run 2

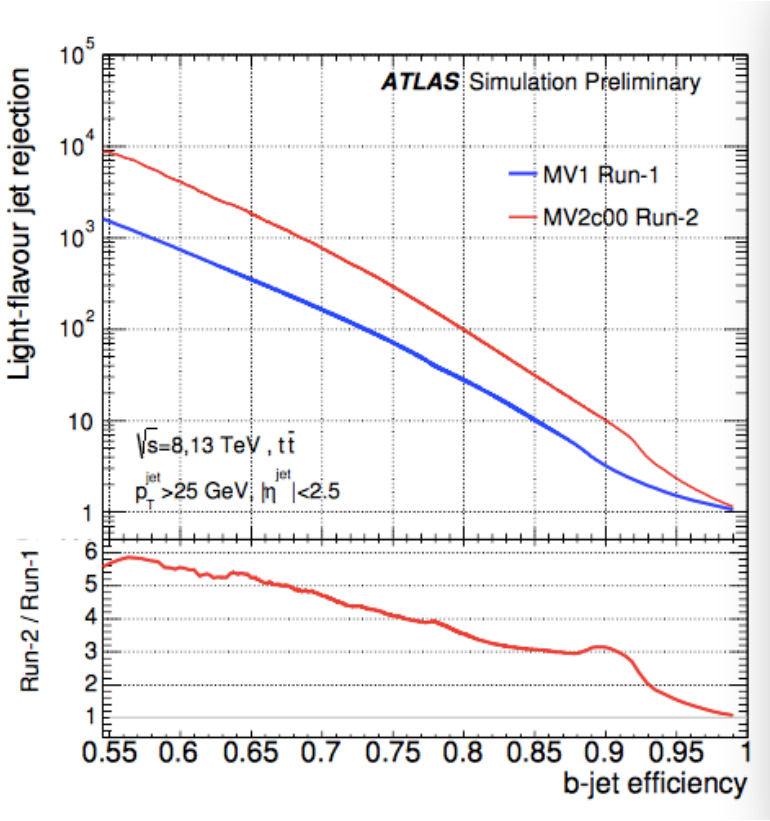
- Adding a new layer of pixel detector
- IBL = New Insertable pixel B-Layer at R=33 mm

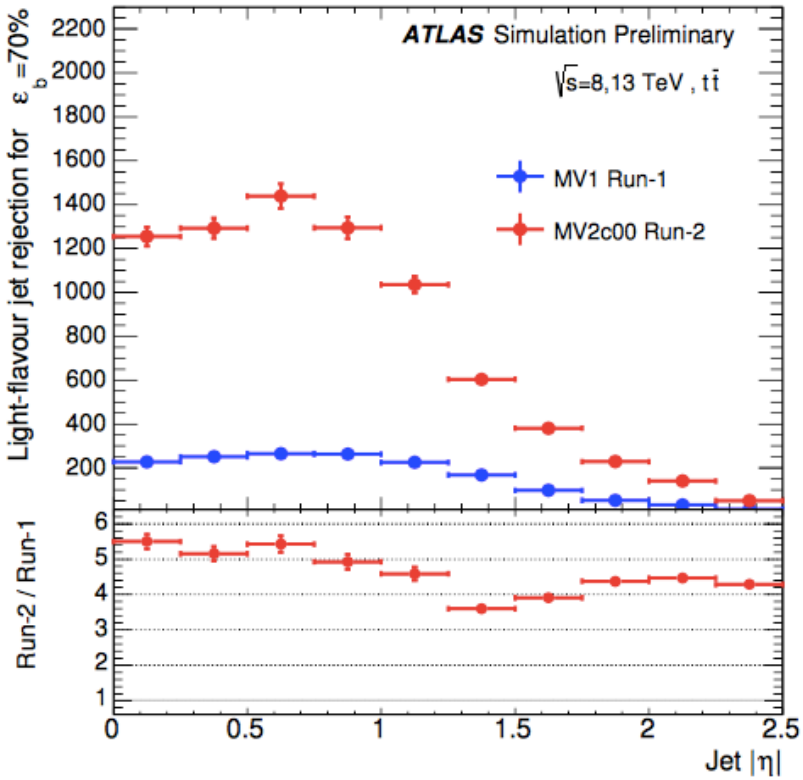




B tagging performance Improvement

- Light jet rejection power with vertexing algorithm increased
  - Benefitting from IBL detector

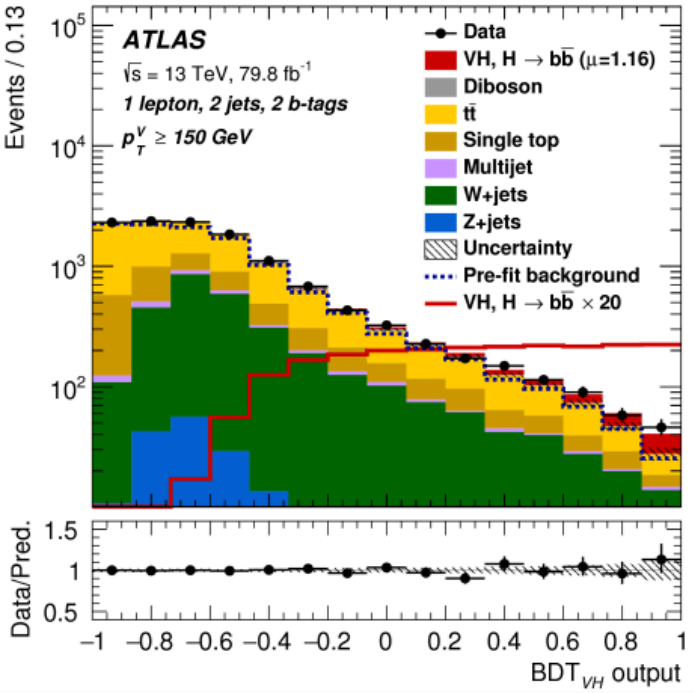


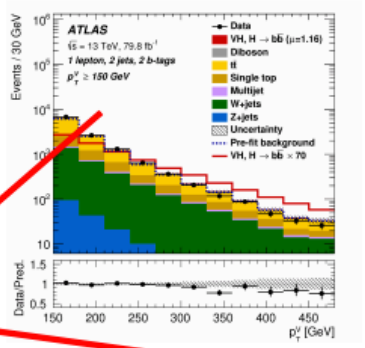


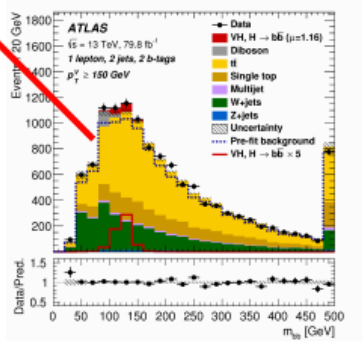
VH → bb: Multivariate Analysis (MVA)

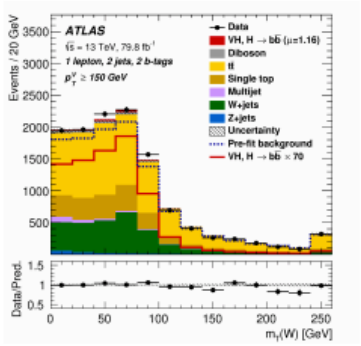
- MVA setup
  - Use simple and robust Boosted Decision Tree (BDT)
  - Input variables and training parameters tuned to yield best sensitivity
- Inputs Variables
  - Kinematic variables, some specific to 3-jet regions
  - m_{bb}, ΔR_{bb}, p_T^V most important ones

Variable	0-lepton	1-lepton	2-lepton
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	×	×
$E_{\mathrm{T}}^{\mathrm{miss}}$	×	×	
$p_{\mathrm{T}}^{b_1}$	×	×	×
$p_{\mathrm{T}}^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\boldsymbol{b}_1, \boldsymbol{b}_2)$	×	×	×
$\lvert\Delta\eta(\boldsymbol{b}_1, \boldsymbol{b}_2)\rvert$	×		
$\Delta\phi(\boldsymbol{V}, \boldsymbol{bb})$	×	×	×
$\lvert\Delta\eta(\boldsymbol{V}, \boldsymbol{bb})\rvert$			×
m_{eff}	×		
$\min[\Delta\phi(\boldsymbol{\ell}, \boldsymbol{b})]$		×	
m_{T}^{W}		×	
$m_{\ell\ell}$			×
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$			×
m_{top}		×	
$\lvert\Delta Y(\boldsymbol{V}, \boldsymbol{bb})\rvert$		×	
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	×	×	×
m_{bbj}	×	×	×



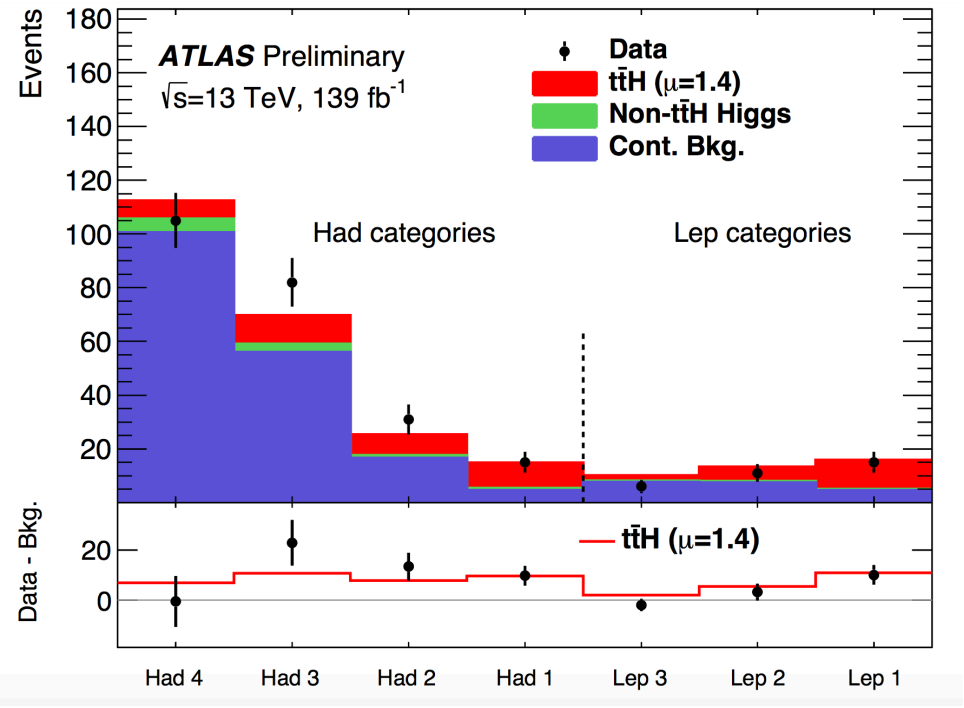


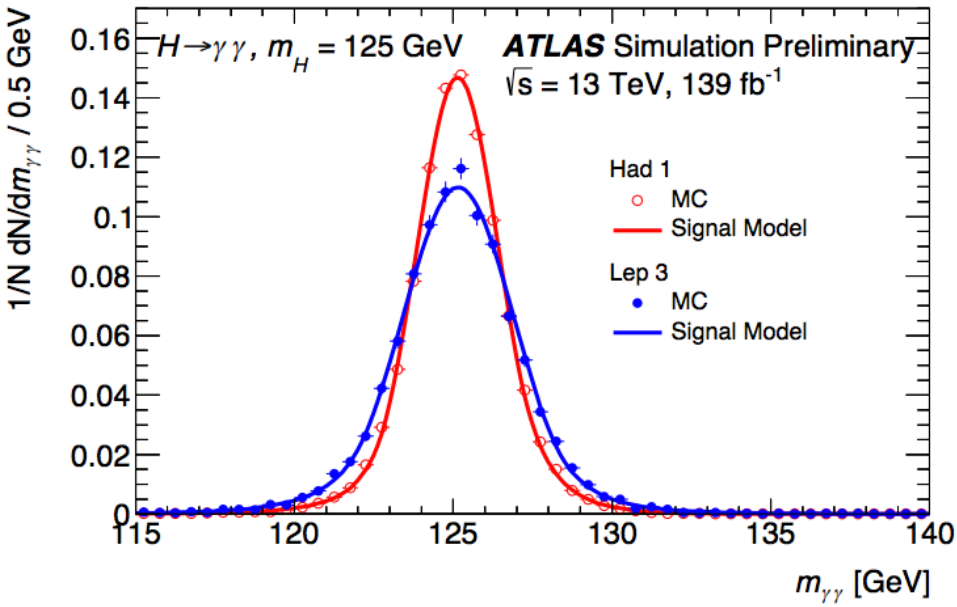




ttH→γ γ: signal regions

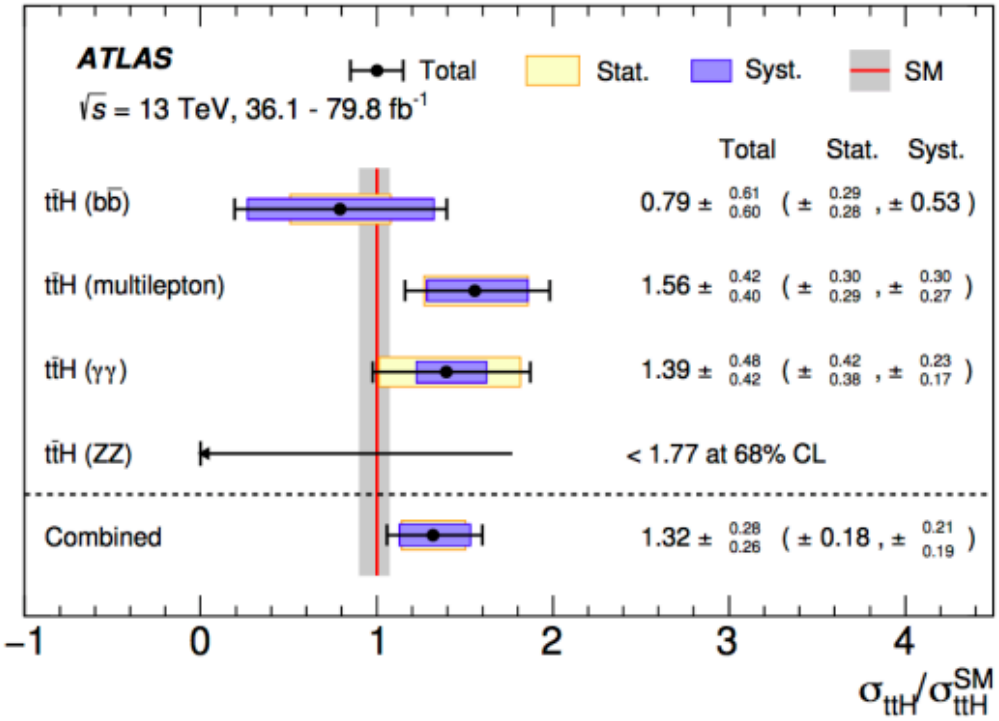
- 7 signal regions (categories) are used.
  - Di-photon mass resolution is slightly different in different categories





ttH combination

- Observation of ttH production !



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

Compute signal strength σ_{ttH}/σ_{SM} from profile likelihood fit over all channels. Correlate systematic uncertainties were appropriate.

Sensitivity limited by theory uncertainties on signal and background modelling.

ttH→γ γ is still dominated by statistics unc.

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-leptons	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4