中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

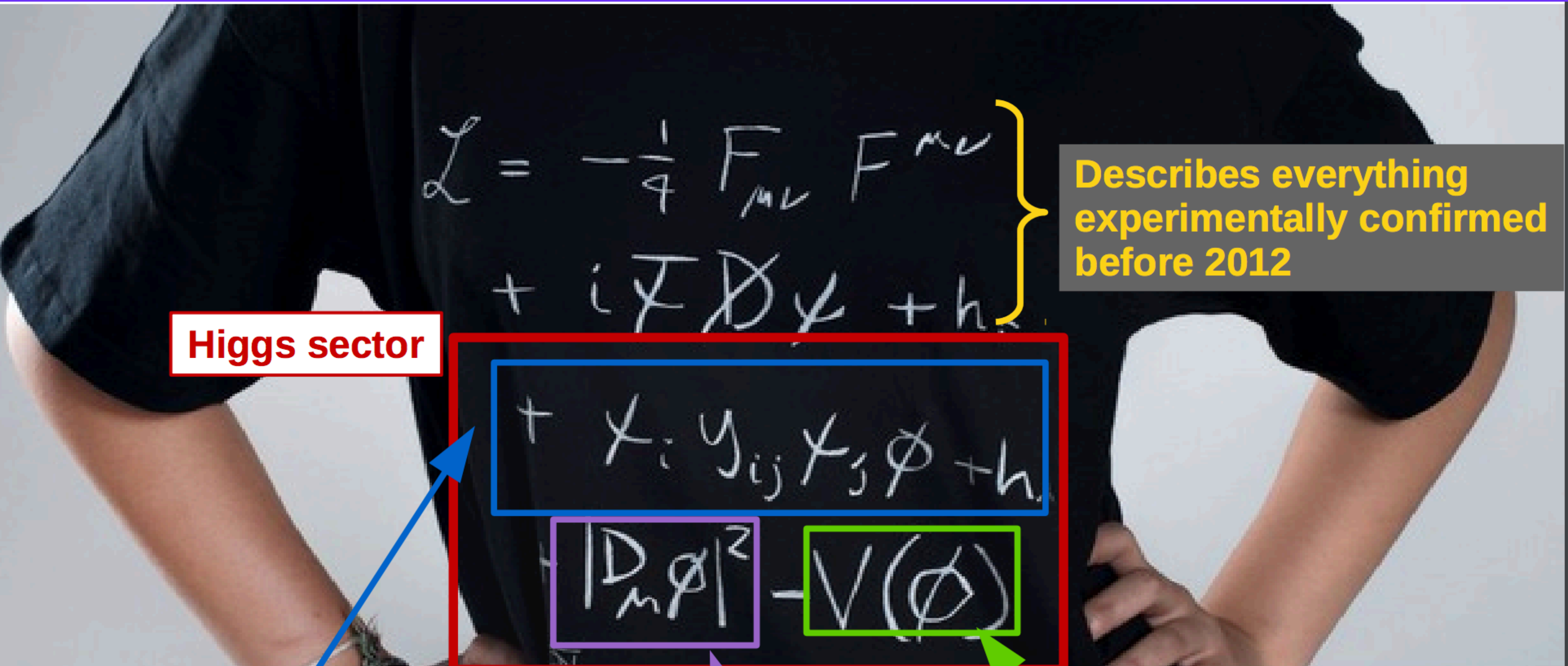
Higgs boson couplings to quarks at the ATLAS experiment

Zhijun Liang
on behalf of the ATLAS Collaboration

Institute of High Energy Physics ,
Chinese Academy of Science

The 27th International Workshop on Weak Interactions and Neutrinos

The Standard Model



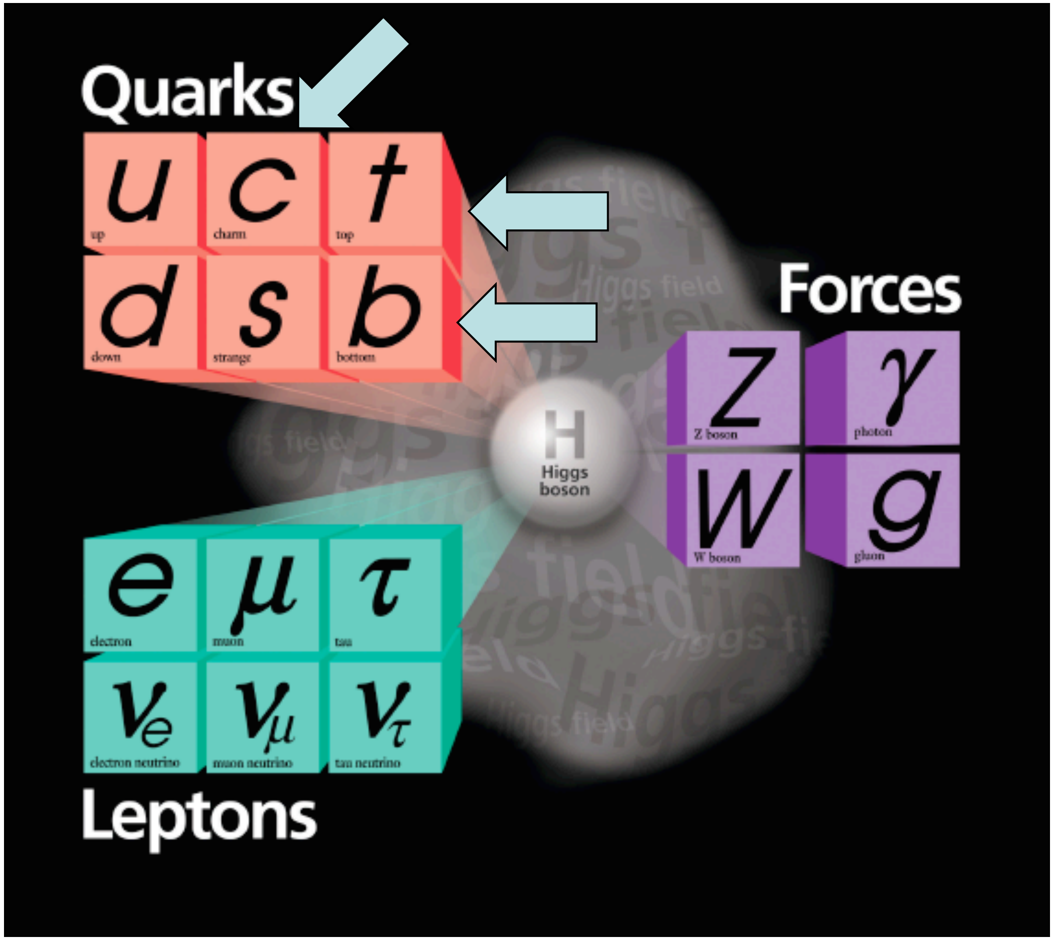
Yukawa coupling with new scalar
(completely new interaction type)
ttH, H→bb and H→ ττ are important !

Higgs potential ($\mu^2 \phi^2 + \lambda \phi^4$)
(to be explored by High Lumi-LHC)

Gauge boson interaction with new scalar
(new for scalar, but known for fermions)

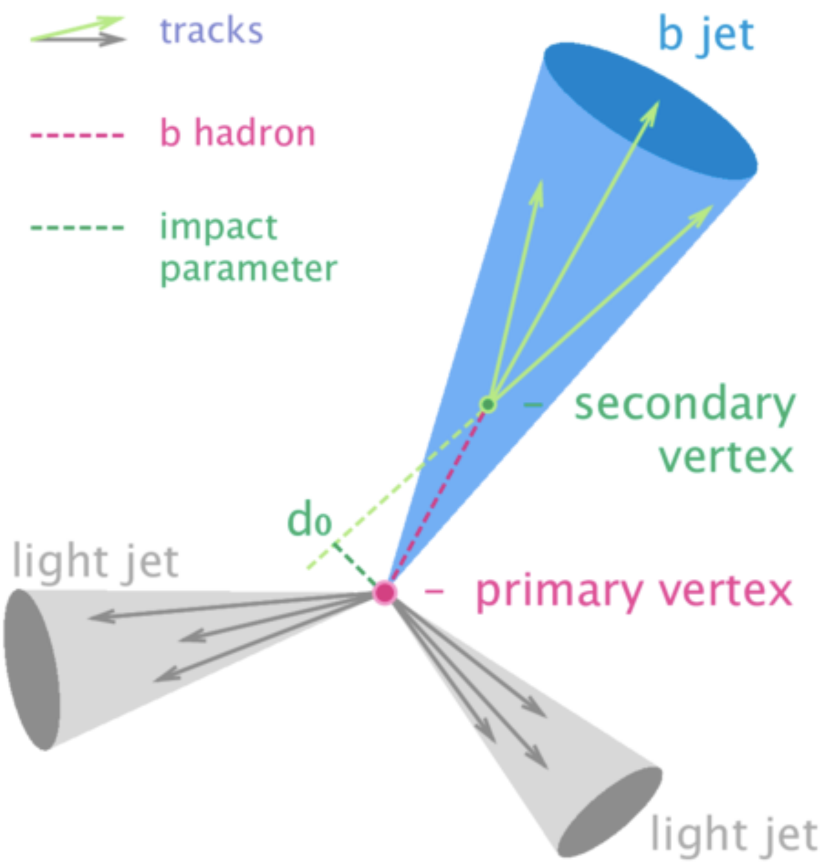
Outline

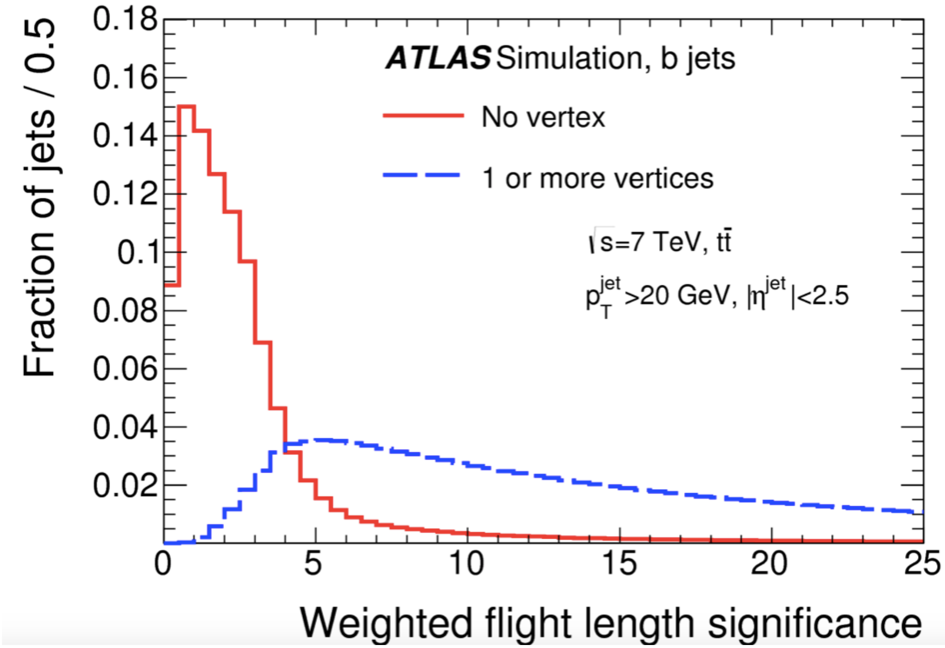
- Higgs coupling to top quarks
- Higgs coupling to bottom quarks
- Higgs coupling to charm quarks



How to Identify b quark jets in ATLAS

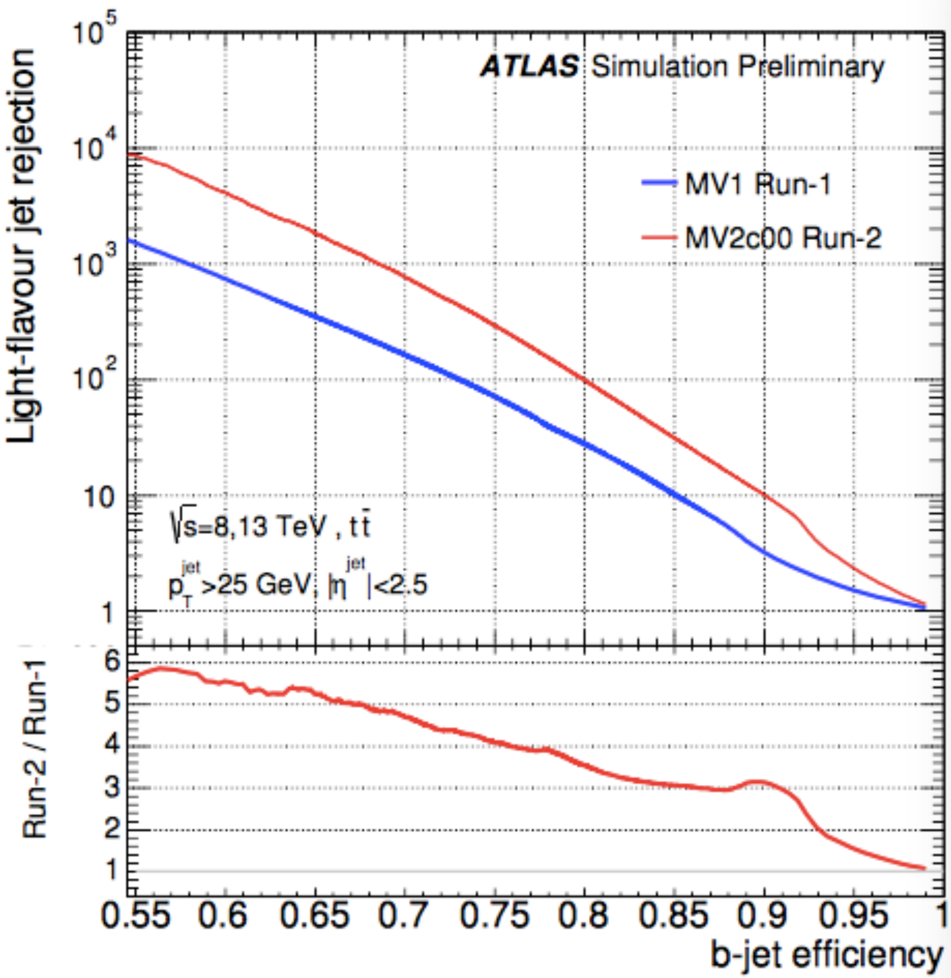
- Two major information to Identify b jets
  - Impact parameters
  - Secondary vertex from B decay

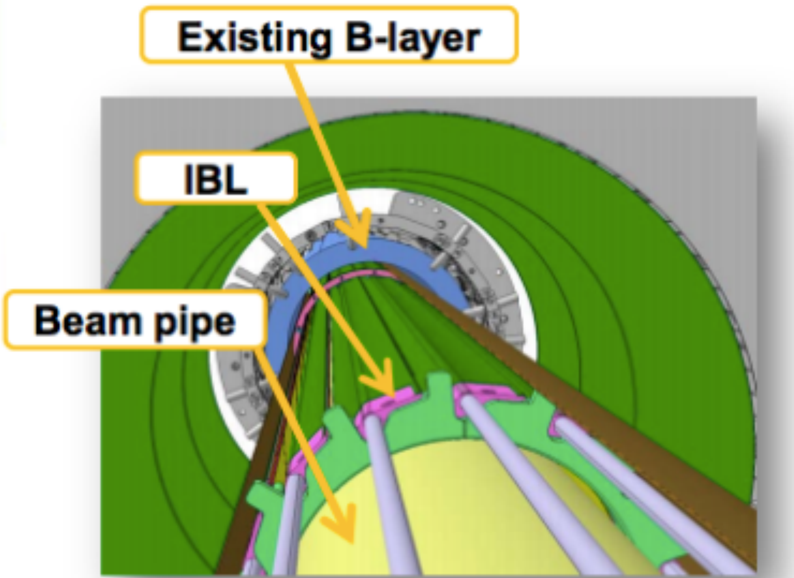




ATLAS Detector upgrade : Run 1 to Run 2

- 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



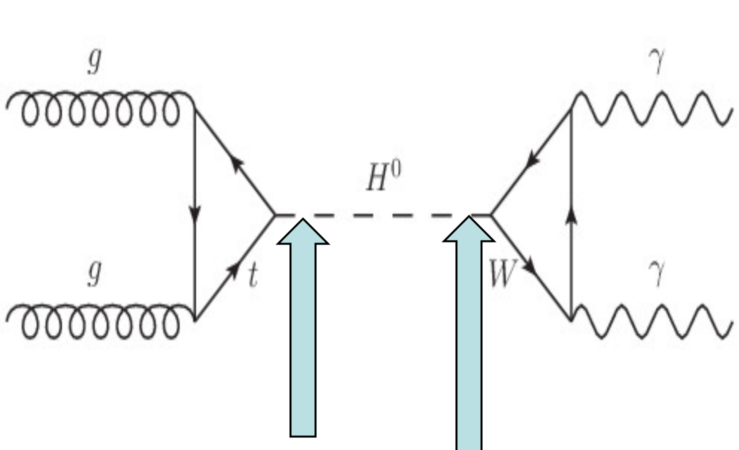


Higgs coupling to top quarks

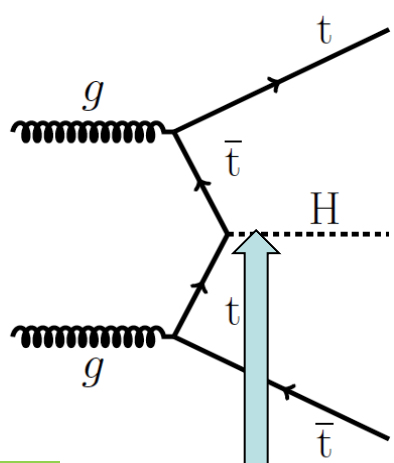
- Higgs coupling to top quarks
  - Associated production with a top quark pair (ttH)
- Higgs coupling to bottom quarks
  - V+H (→ bb) , (where V=W/Z)
  - Vector boson fusion (VBF) H → bb
  - Boosted H→ bb
  - H → bb combination
- Higgs coupling to charm quarks
  - Z+H (→ bb)

Why ttH?

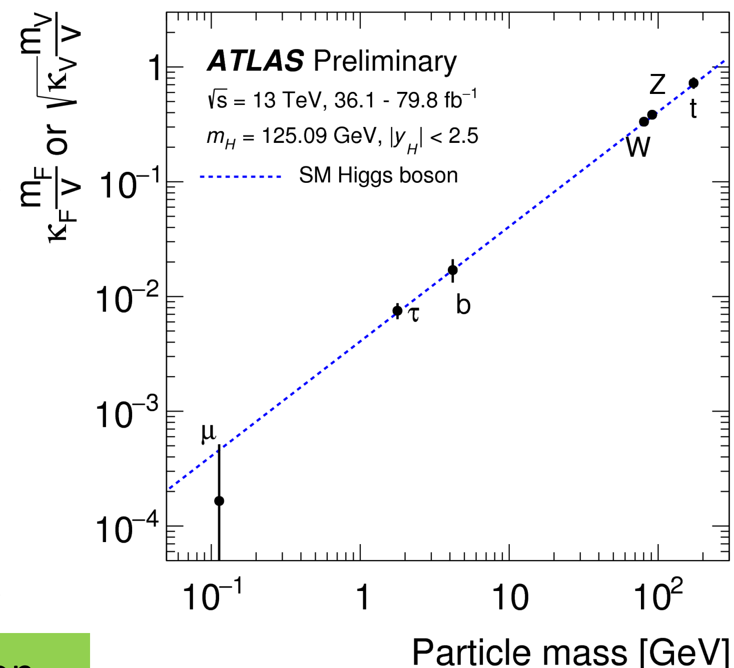
- Explore Higgs-Fermion interactions at LHC
  - The strength of Higgs-Fermion interactions
    - Higgs-Top coupling is the largest
  - At LHC: Model dependent vs independent



Indirect detection, model dependent



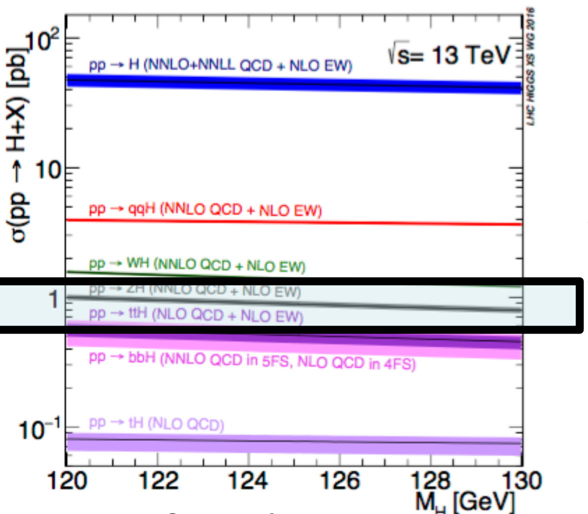
direct detection in production

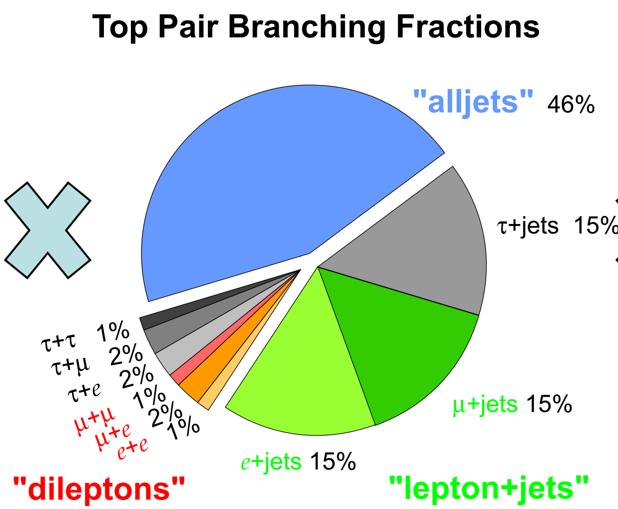


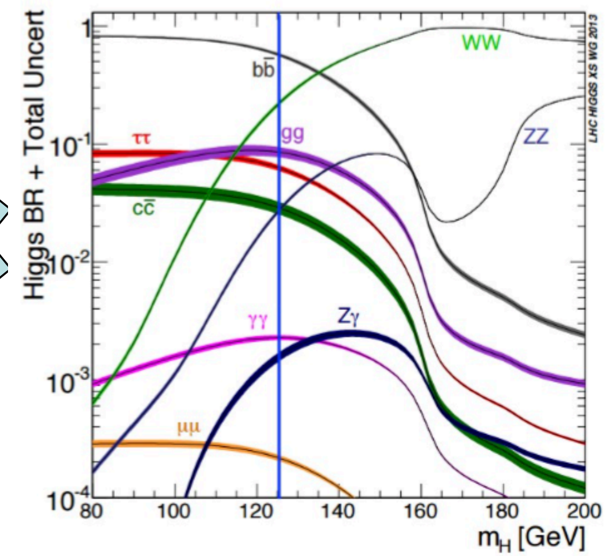
ttH: probably the only channel that can **directly** probe Higgs Yukawa coupling via production

How to study ttH?

- Production
- Decays





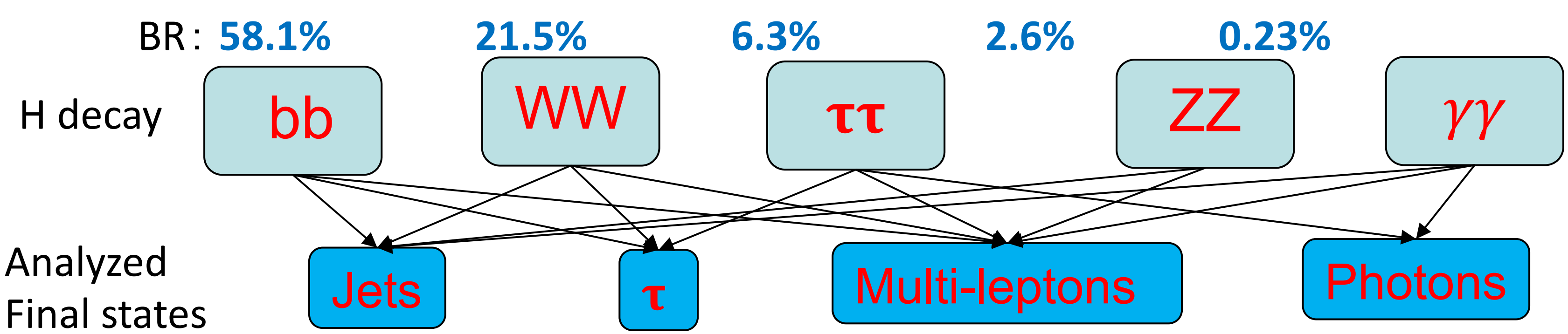


~1% of total Higgs

~0.06% of ttbar

~1/10[11] of total interaction

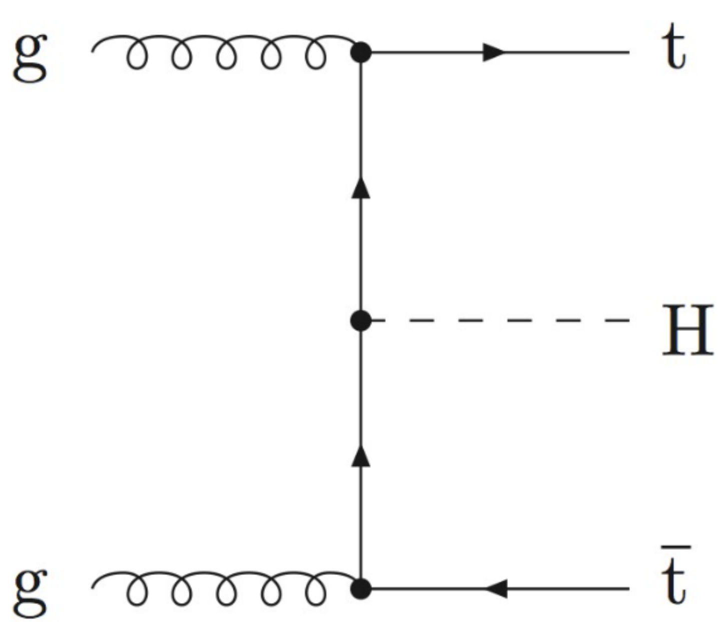
Hundreds of complex final states

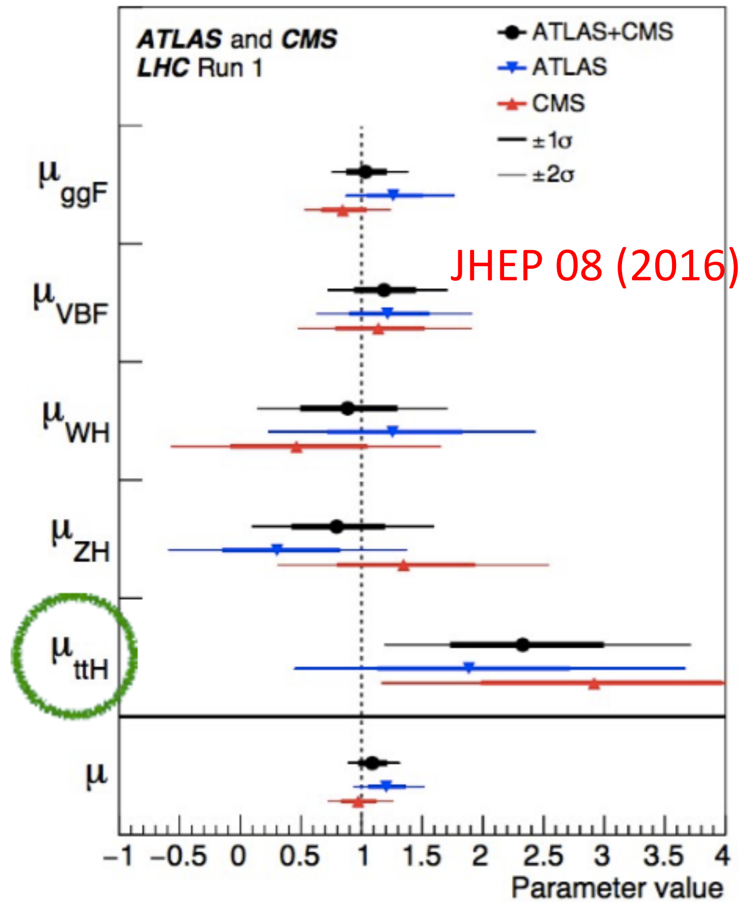


Higgs-top Yukawa coupling in run1

- 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

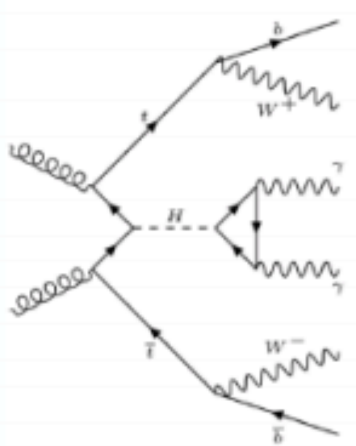
$$\mu = \sigma_{measured}/\sigma_{SM}$$

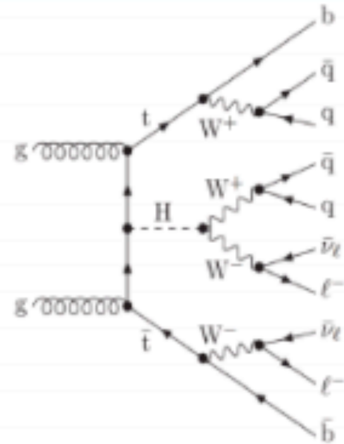


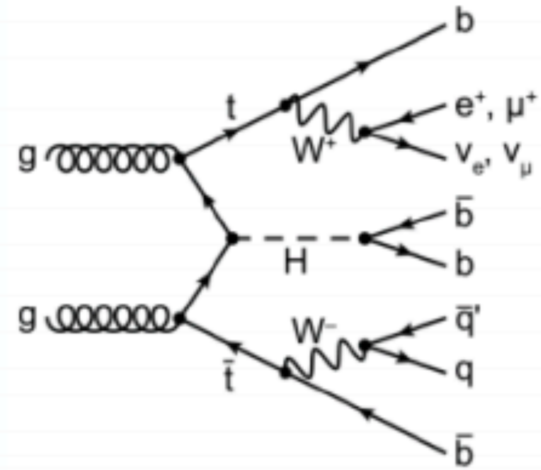


JHEP 08 (2016) 045

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 →

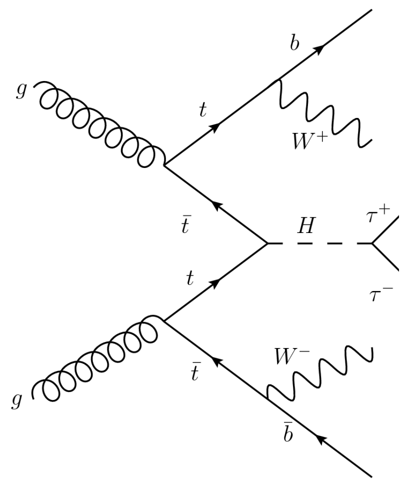
← Higher signal purity

ttH multilepton

Phys. Rev. D 97 (2018) 072003

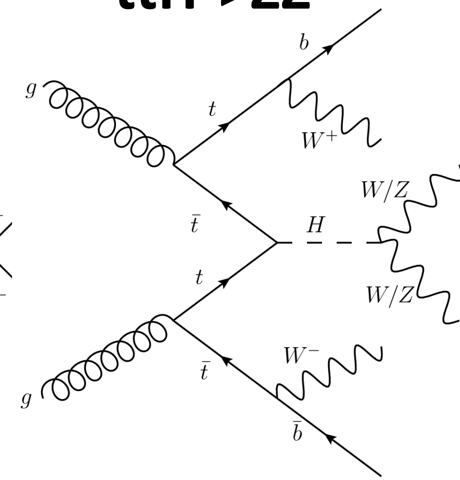
- **Obs. (exp.) significance at 4.1σ (2.8σ)**
  - **ttbar background suppressed at**
    - Same sign di-lepton channel
    - 3 and 4 leptons channel
  - **Major syst.**
    - ttH predicted cross section
    - Jet energy scale and resolution

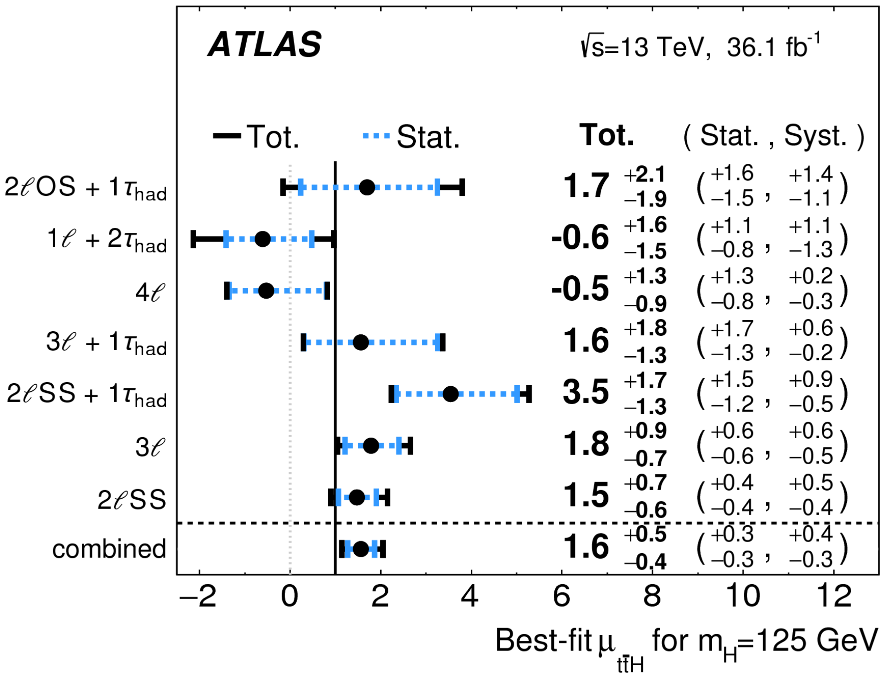
ttH->tautau

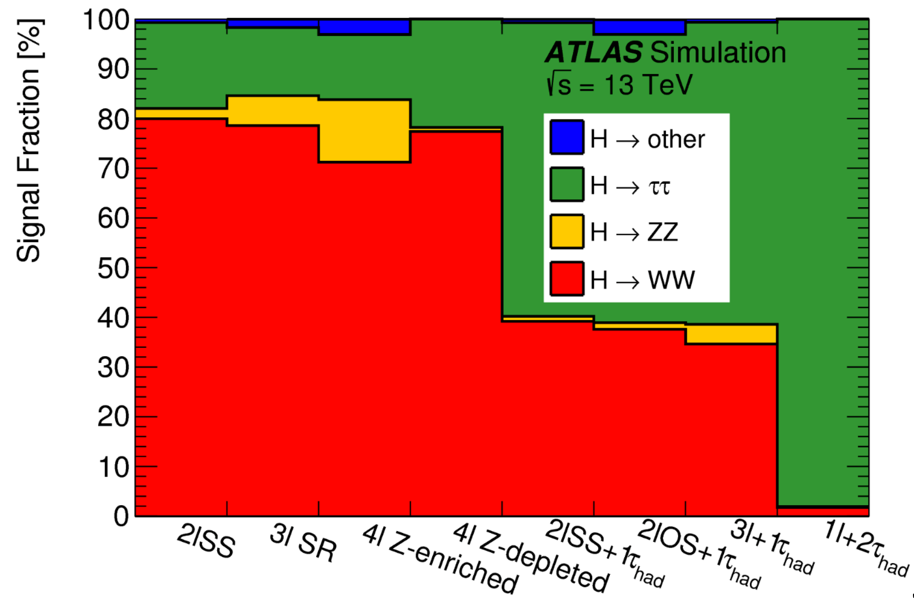


ttH->WW

ttH->ZZ



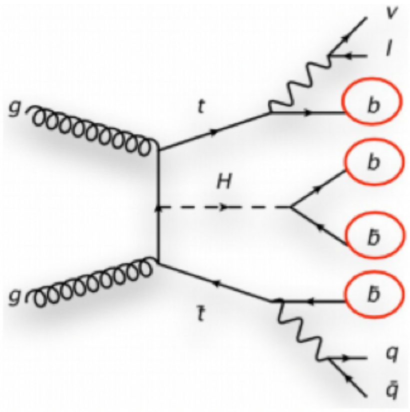


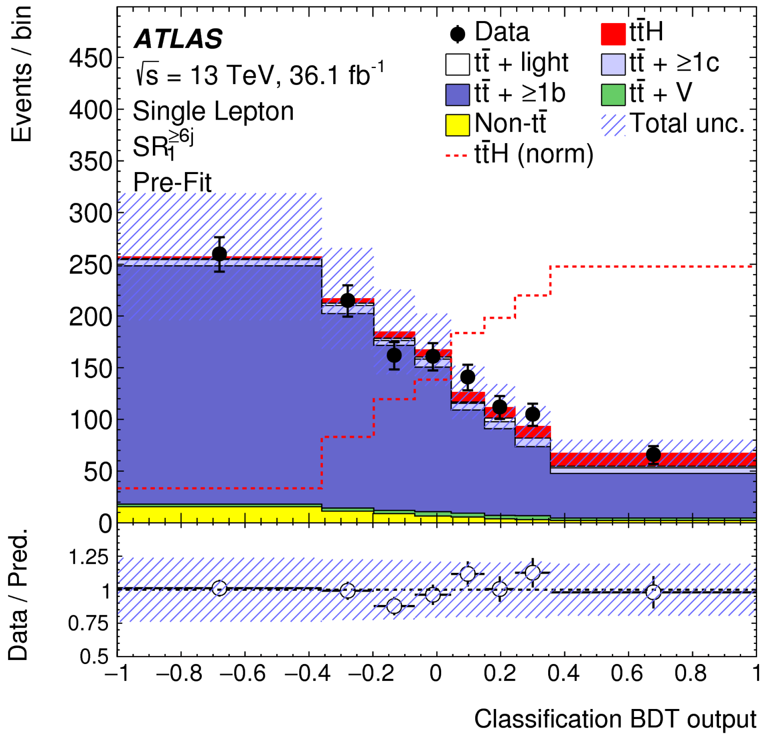


ttH→bb

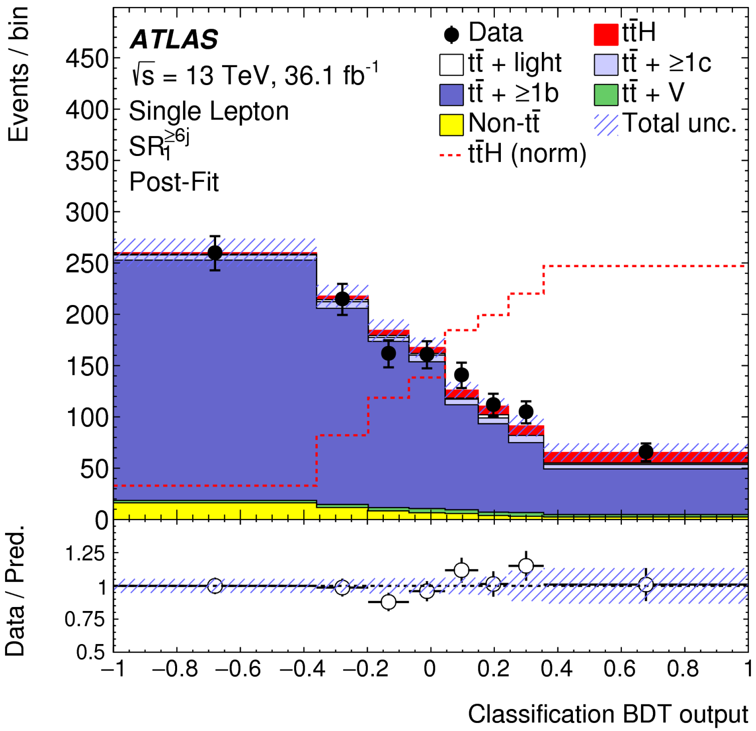
Phys. Rev. D 97 (2018) 072016

- **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)**

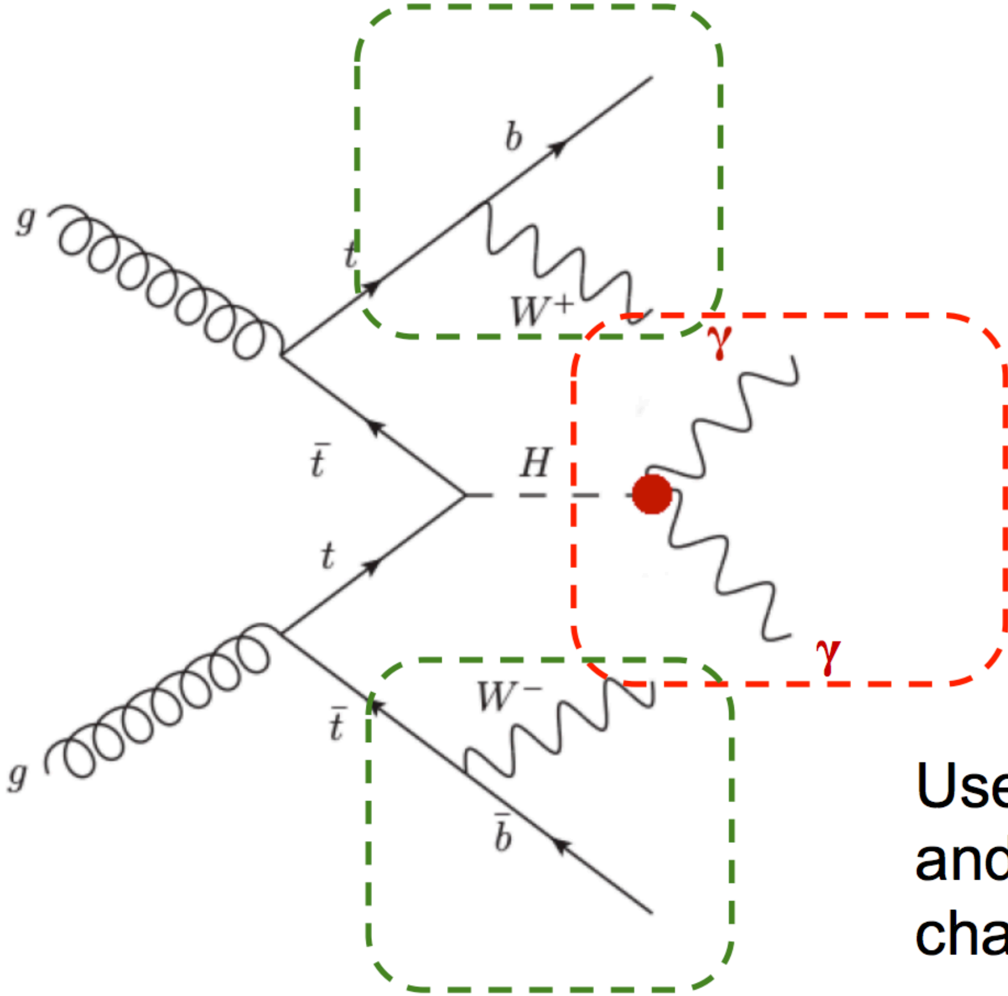




Simultaneous Fit with CR



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

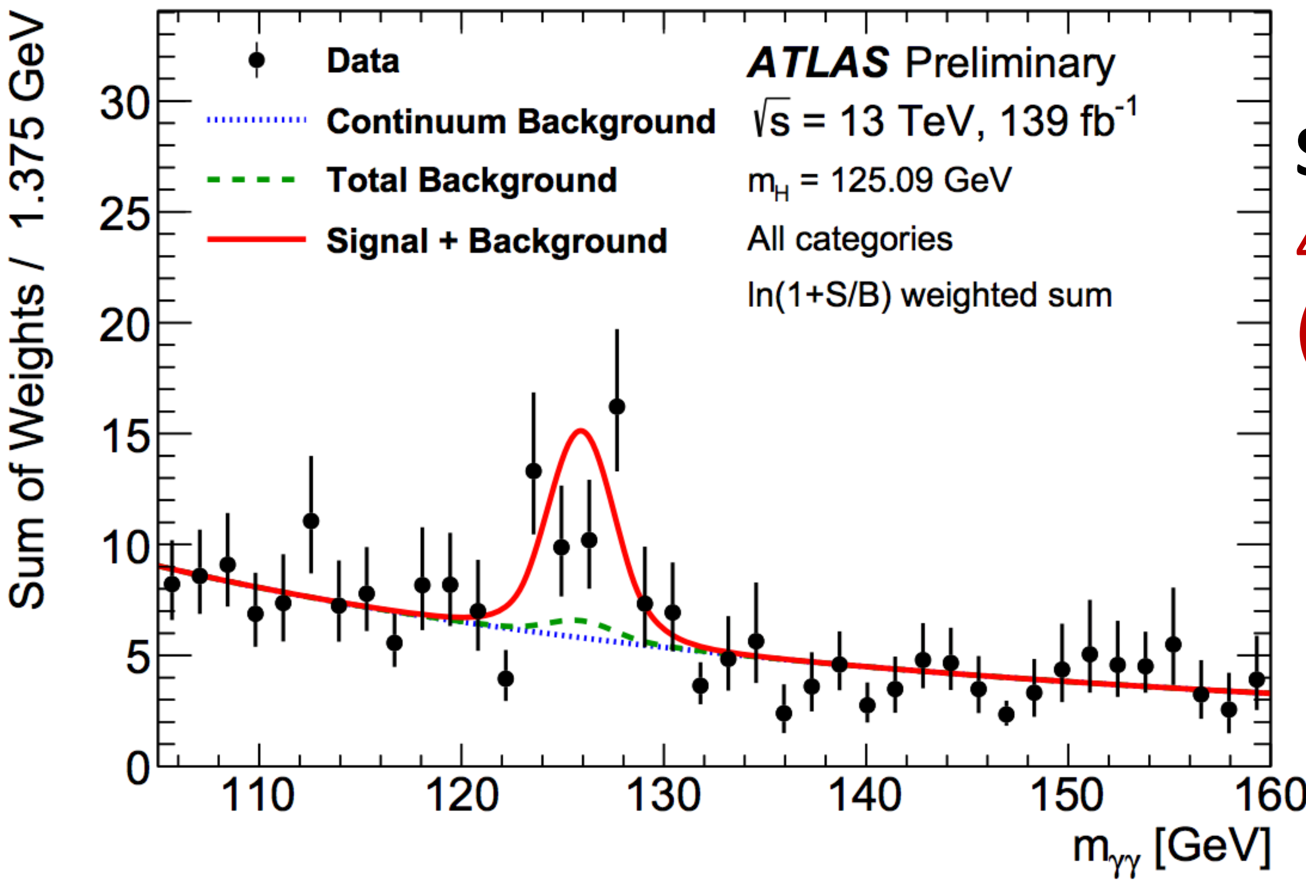
Directly use properties of the objects in the event to train a multivariate discriminant

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

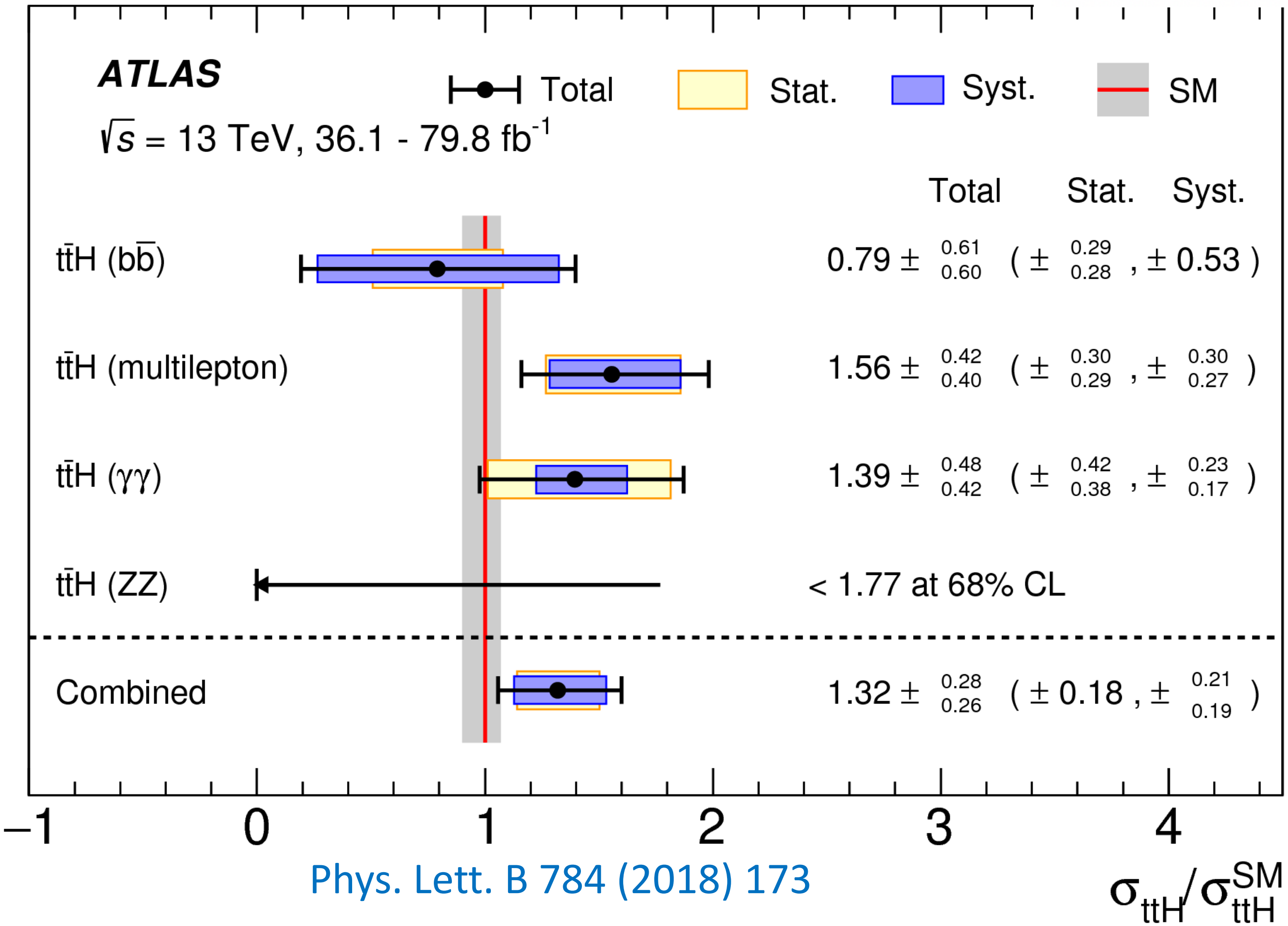
(4.2σ expected.)

ttH combination

Phys. Lett. B 784 (2018) 173

- 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.)



Phys. Lett. B 784 (2018) 173

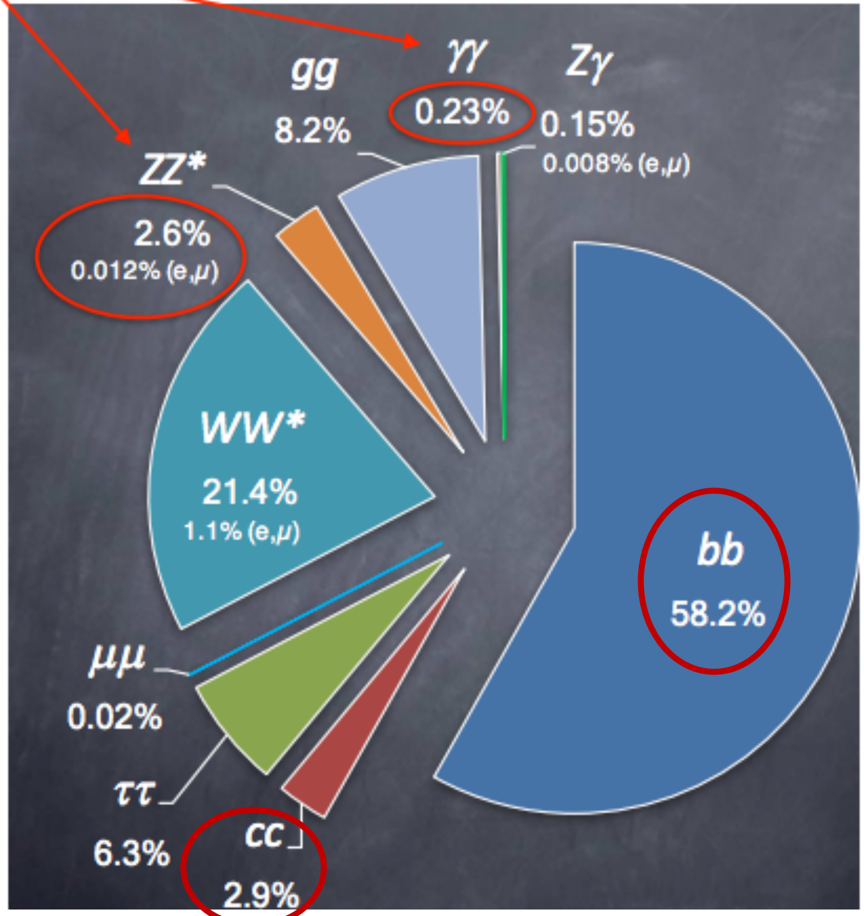
Higgs coupling to bottom quarks

- 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)

Higgs decay

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

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



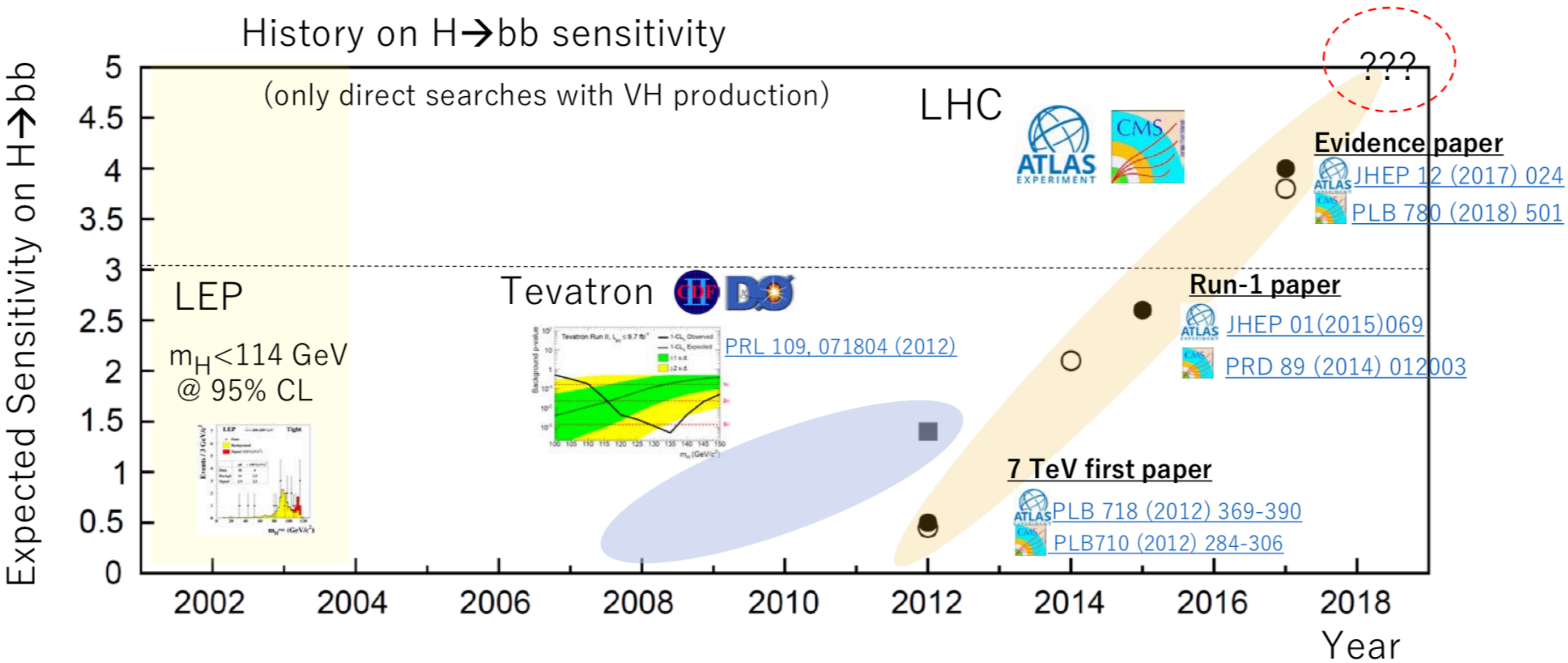
WW: High BR, Poor mass resolution

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

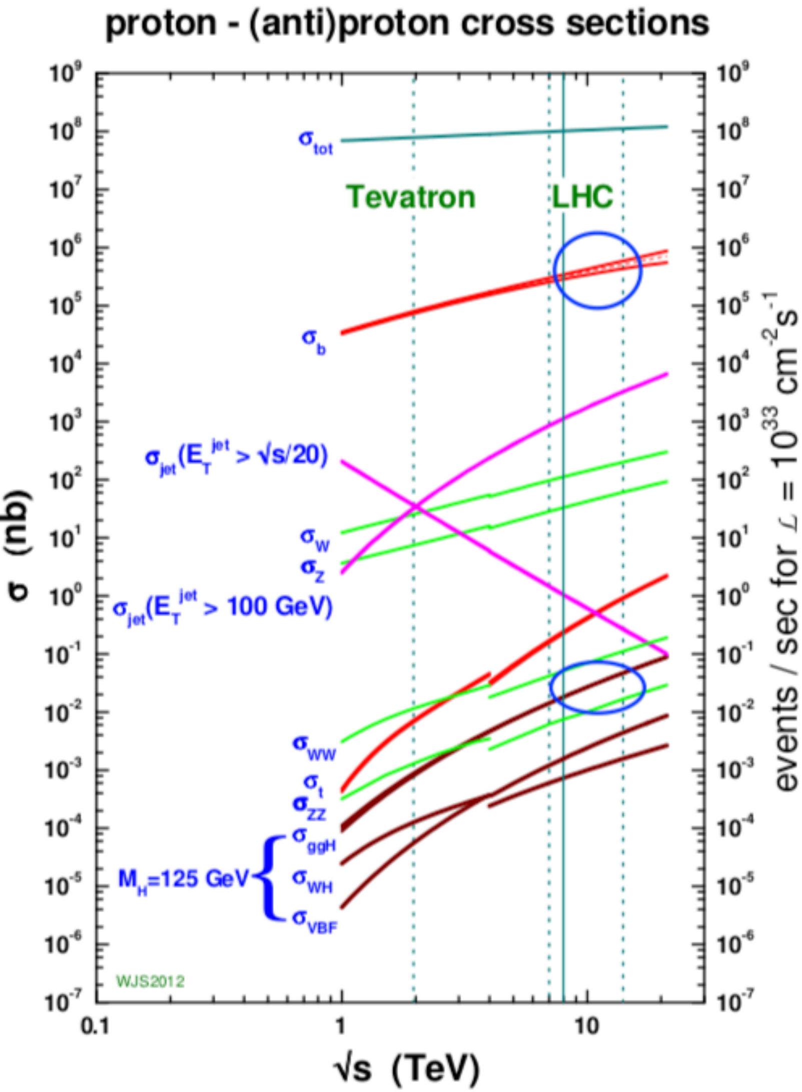
Road to discovery of H → bb

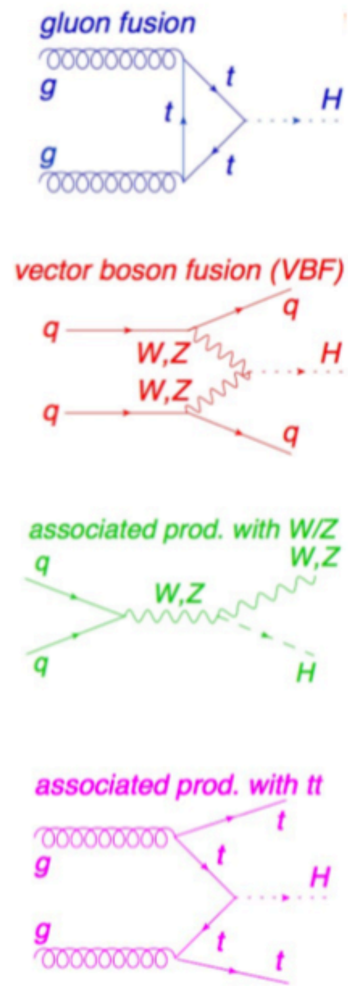
- Started in LEP era, developed in Tevatron, found at LHC
  - H->bb observation in middle of 2018 by ATLAS and CMS
  - Top 10 Physics highlight in 2018 by American Physics Society.



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

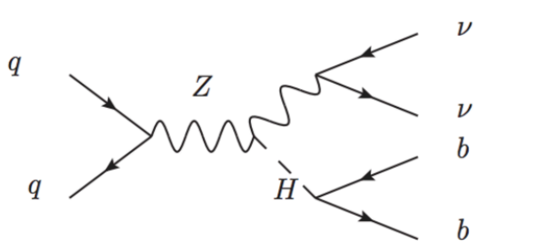
0-Lepton

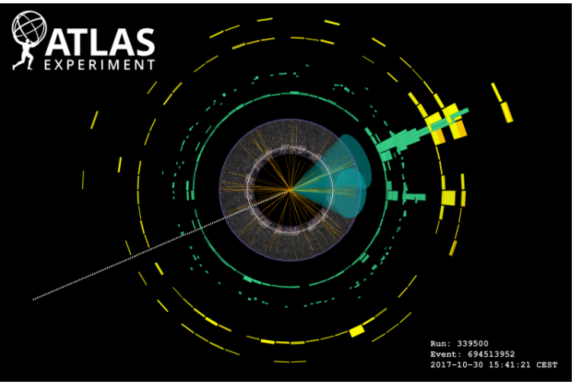
E_T^{miss} trigger

Veto leptons p_T>7 GeV

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

Angular cuts to remove MJ





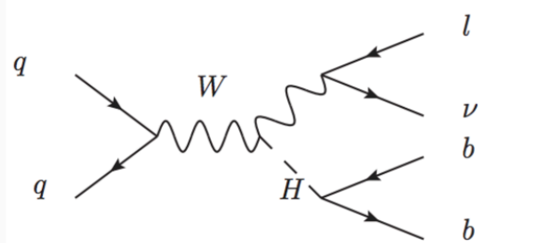
1-Lepton

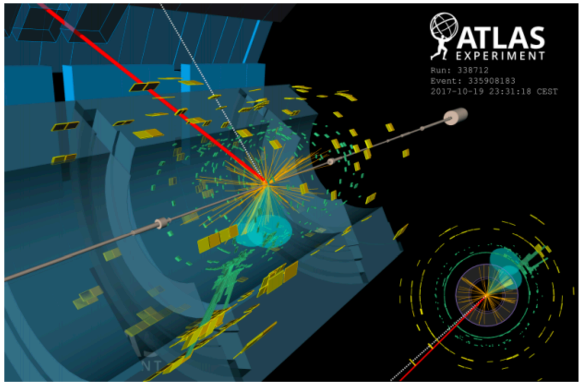
Single-electron or E_T^{miss} trigger

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





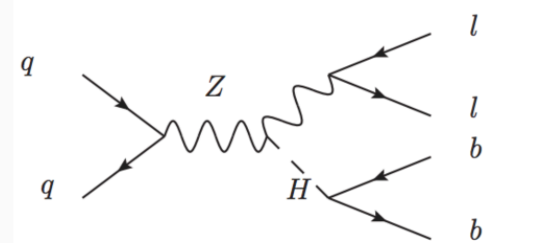
2-Lepton

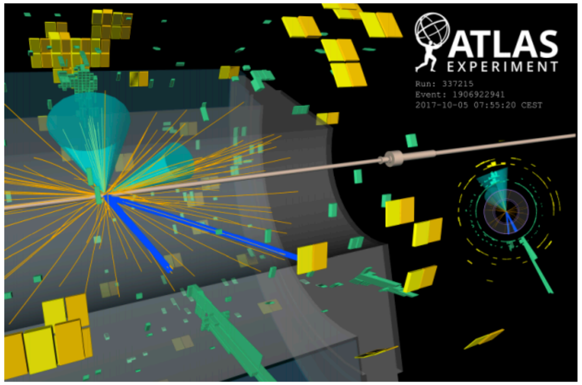
Single-lepton trigger

2 electrons or muons p_T>27 (7) GeV

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

$81 < m_{ll} < 101$ GeV

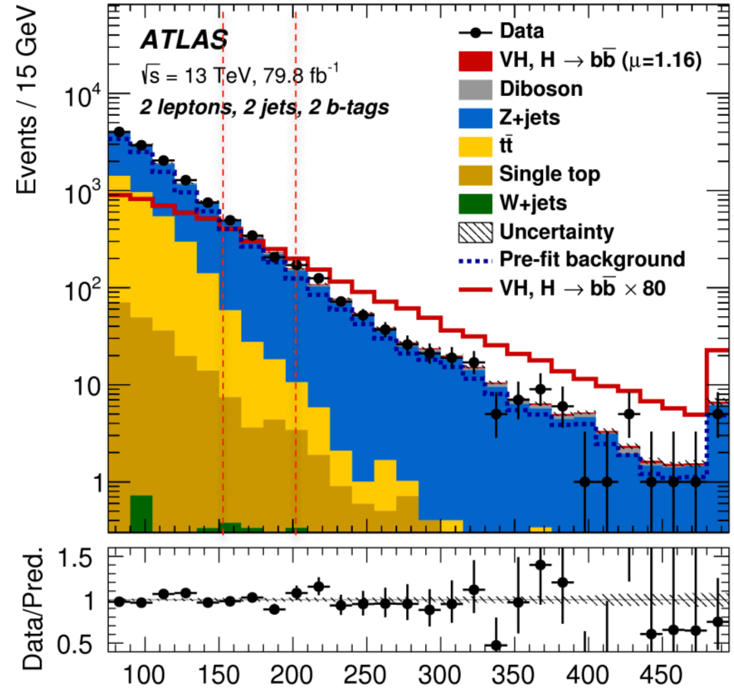


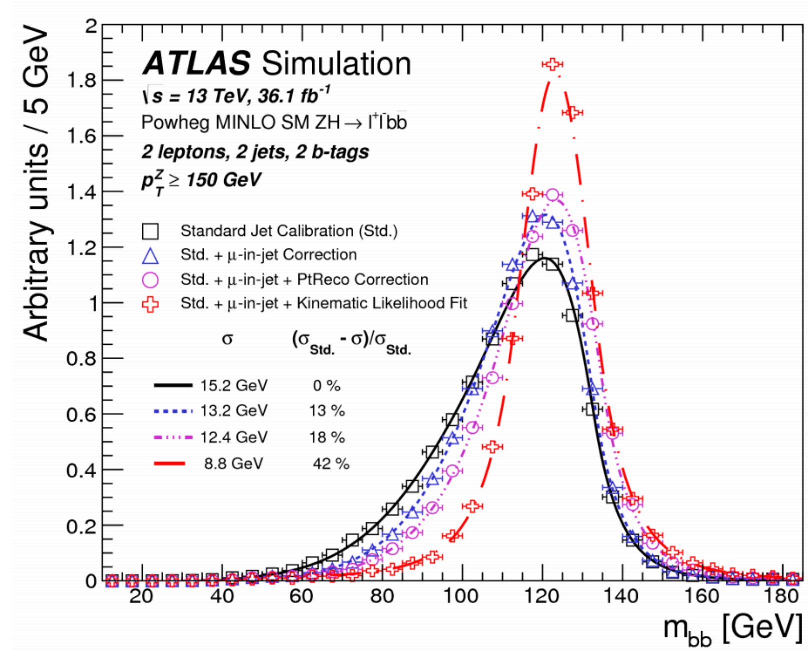


Phys. Lett. B 786 (2018) 59

VH → bb: strategy

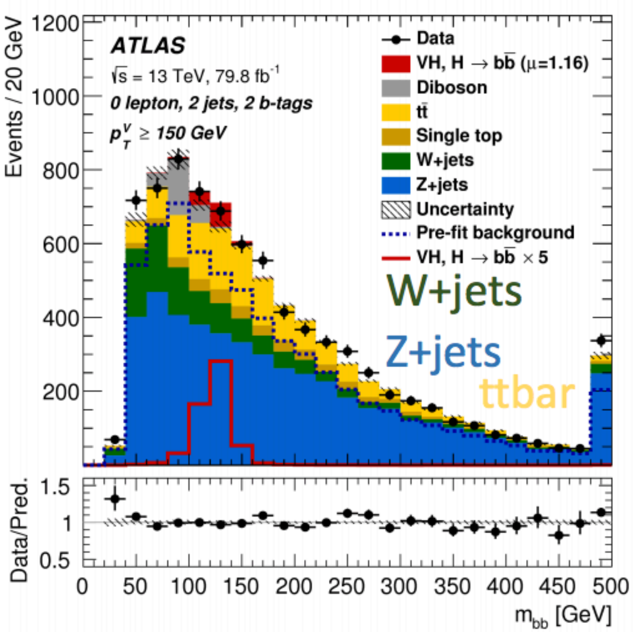
- Harder p_T^V spectrum for signal
  - V=W or Z
  - Higher S/B ratio in high p_T region
- 8 signal categories:
  - Number of lepton (0,1,2-lepton)
  - $75 < p_T^V < 150$ GeV (2-lepton), $p_T^V > 150$ GeV
  - Number of jets (2jet or 3 jets)
- Main discriminant variables
  - m_{bb}, p_T^V and ΔR_{bb}
  - 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



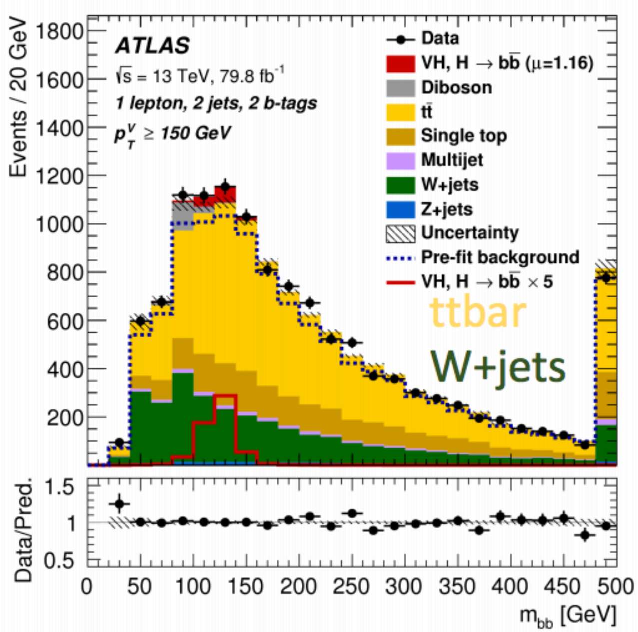


V+H (→ bb): background

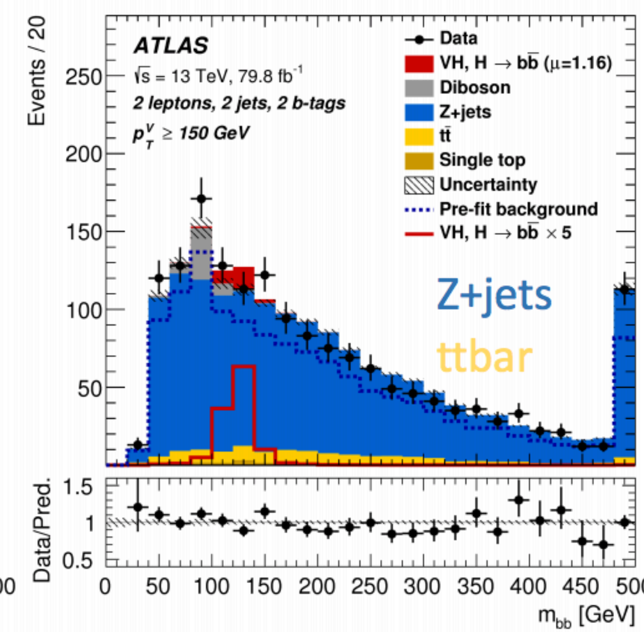
0-lepton



1-lepton



2-lepton

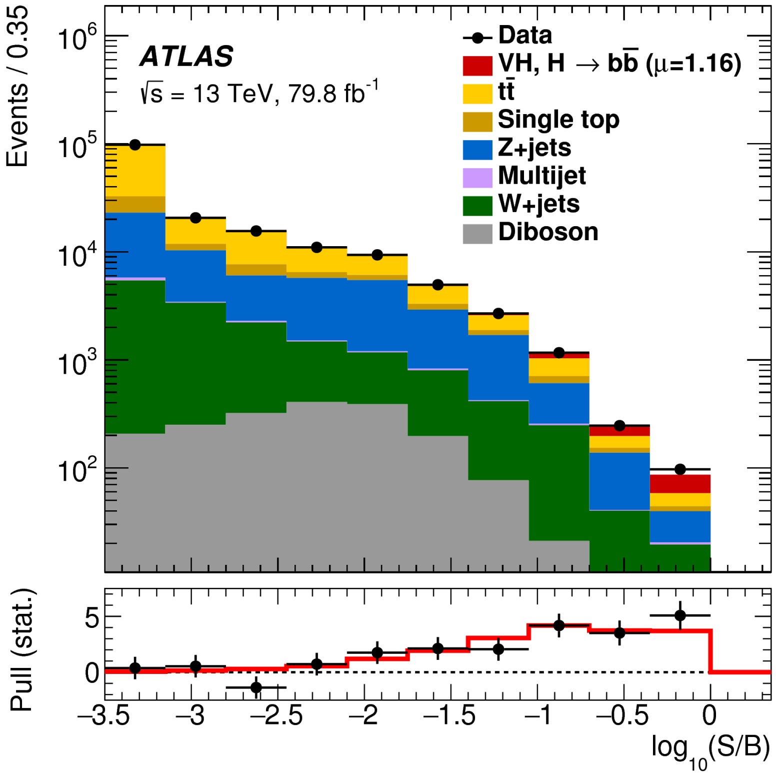


- Z+bjets dominates in 0, 2 lepton channels
- Top quark and W+jets in 1 lepton channel
- Multi-jet background
  - Negligible in 0/2 lepton channels after anti-QCD cuts
  - Data-driven estimate in 1 lepton channel

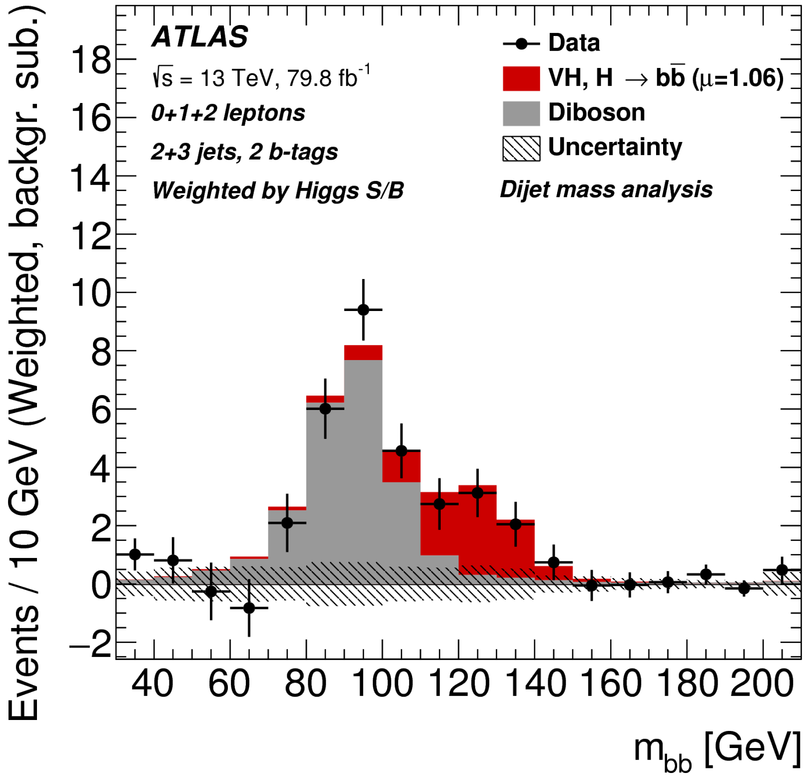
VH → bb: Result

Phys. Lett. B 786 (2018) 59

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.)

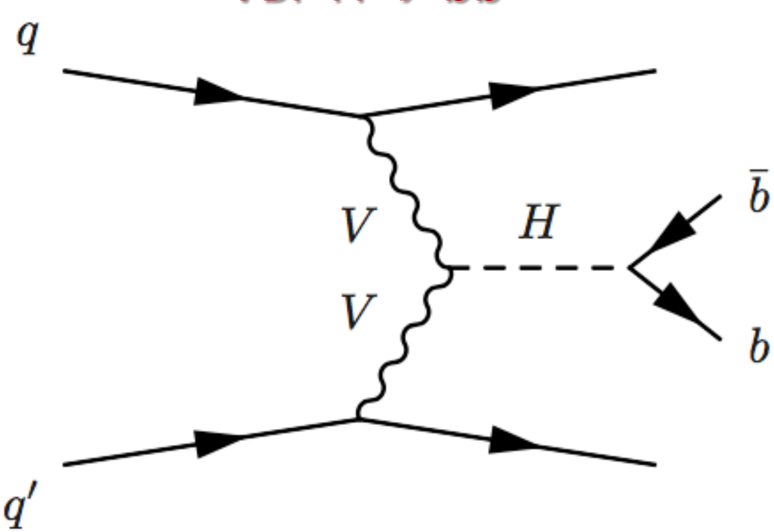
Higgs coupling to bottom quarks

- 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)

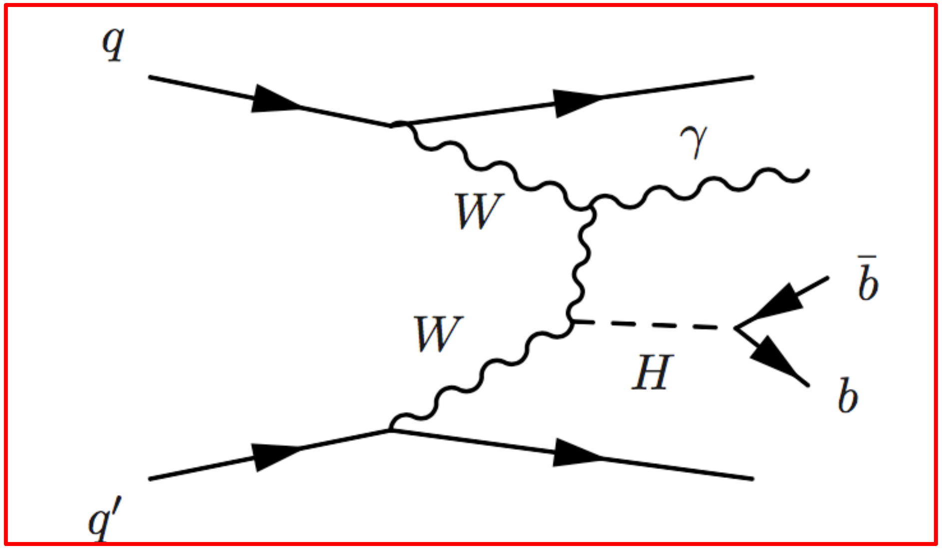
VBF H → bb analysis

- 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



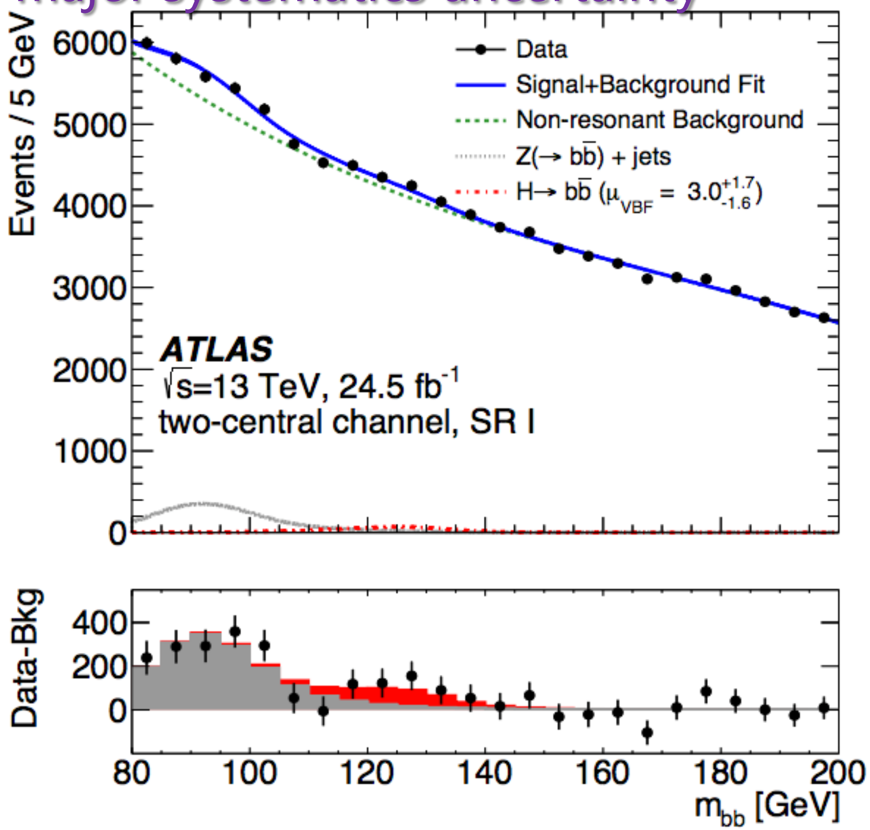
VBF H → bb result

Phys. Rev. D 98 (2018) 052003

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

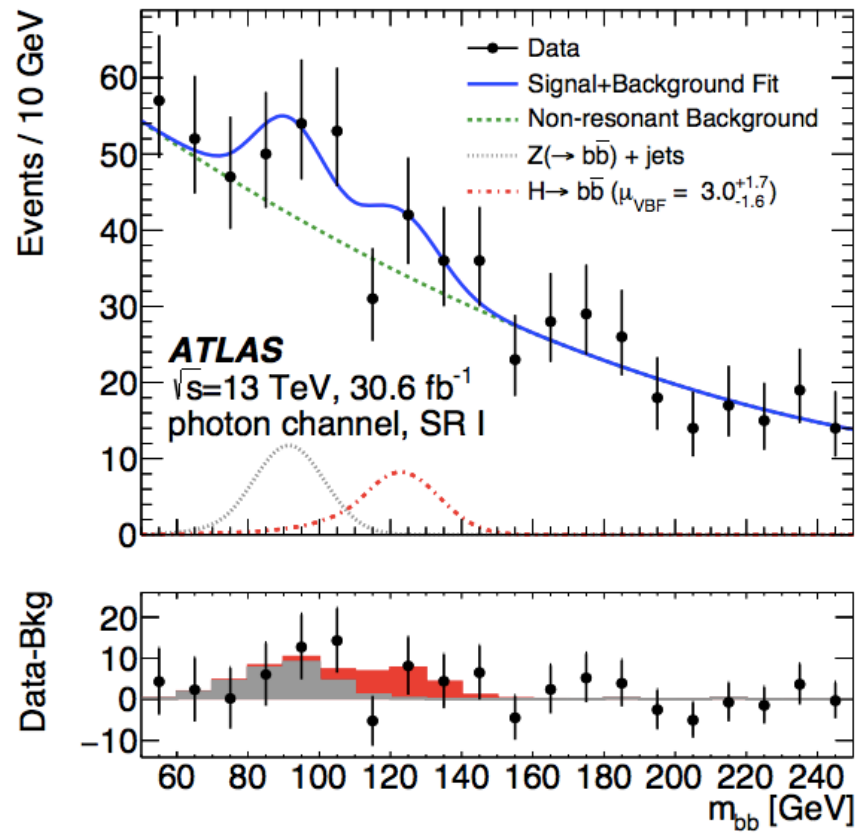
VBF H→ bb

Background uncertainty is the major systematics uncertainty



VBF H→ bb +γ

Statistics uncertainty dominated



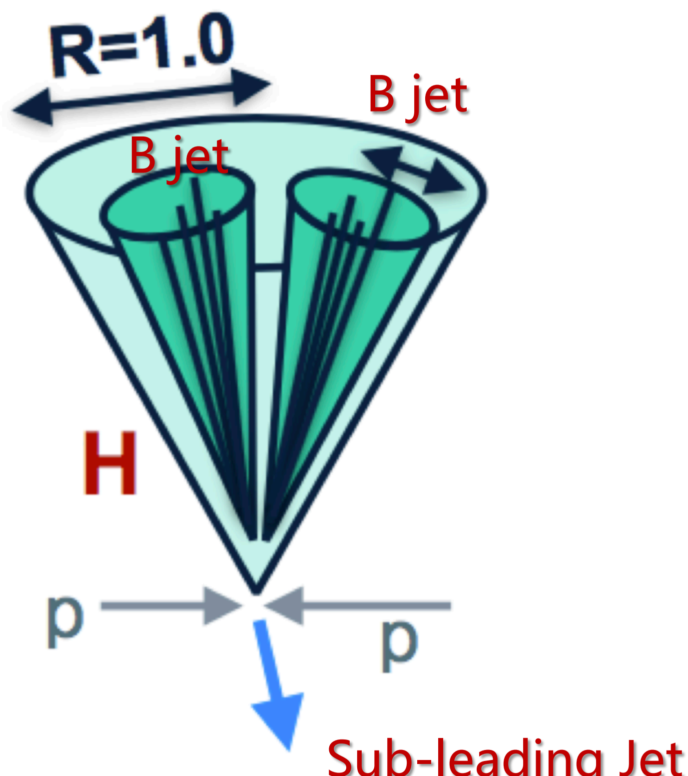
Higgs coupling to bottom quarks

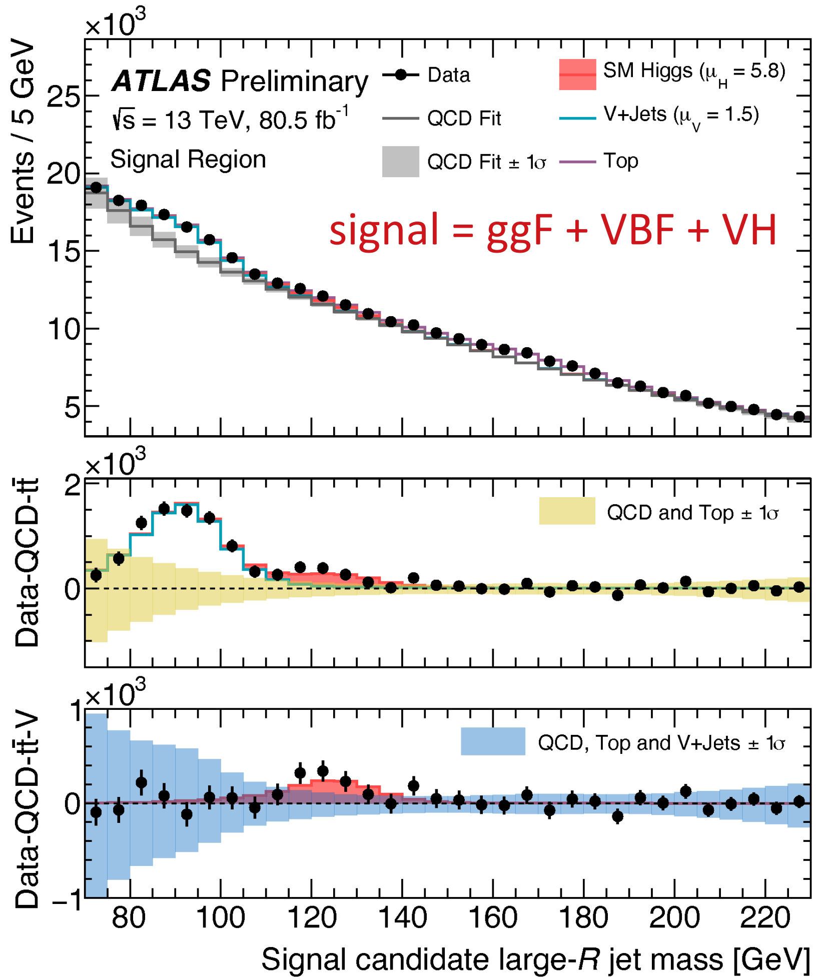
- Higgs coupling to top quarks
  - Associated production with a top quark pair (ttH)
- Higgs coupling to bottom quarks
  - V+H (→ bb) , (where V=W/Z)
  - Vector boson fusion (VBF) H → bb
  - Boosted H→ bb
  - H → bb combination
- Higgs coupling to charm quarks
  - Z+H (→ bb)

Boosted H → bb

ATLAS-CONF-2018-052

- 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**





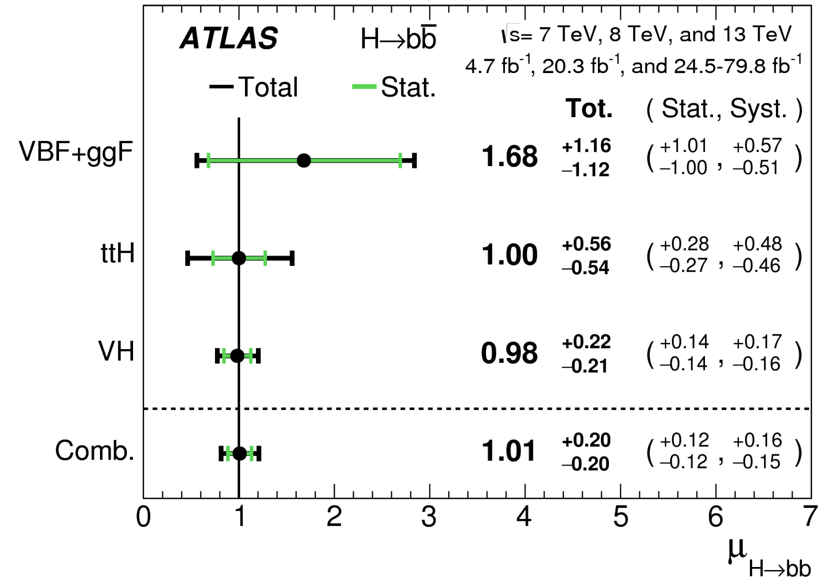
Higgs coupling to bottom quarks

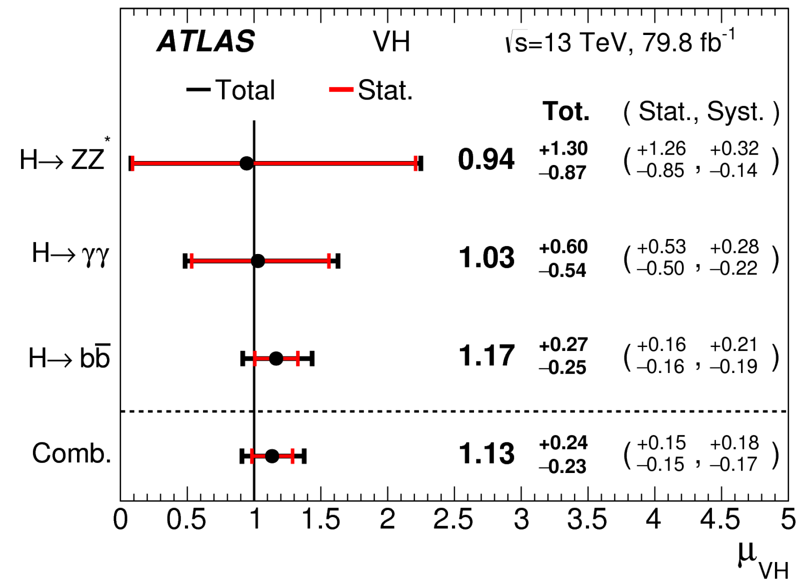
- Higgs coupling to top quarks
  - Associated production with a top quark pair (ttH)
- Higgs coupling to bottom quarks
  - V+H (→ bb) , (where V=W/Z)
  - Vector boson fusion (VBF) H → bb
  - Boosted H→ bb
  - H → bb combination
- Higgs coupling to charm quarks
  - Z+H (→ bb)

Observation of H → bb

Phys. Lett. B 786 (2018) 59

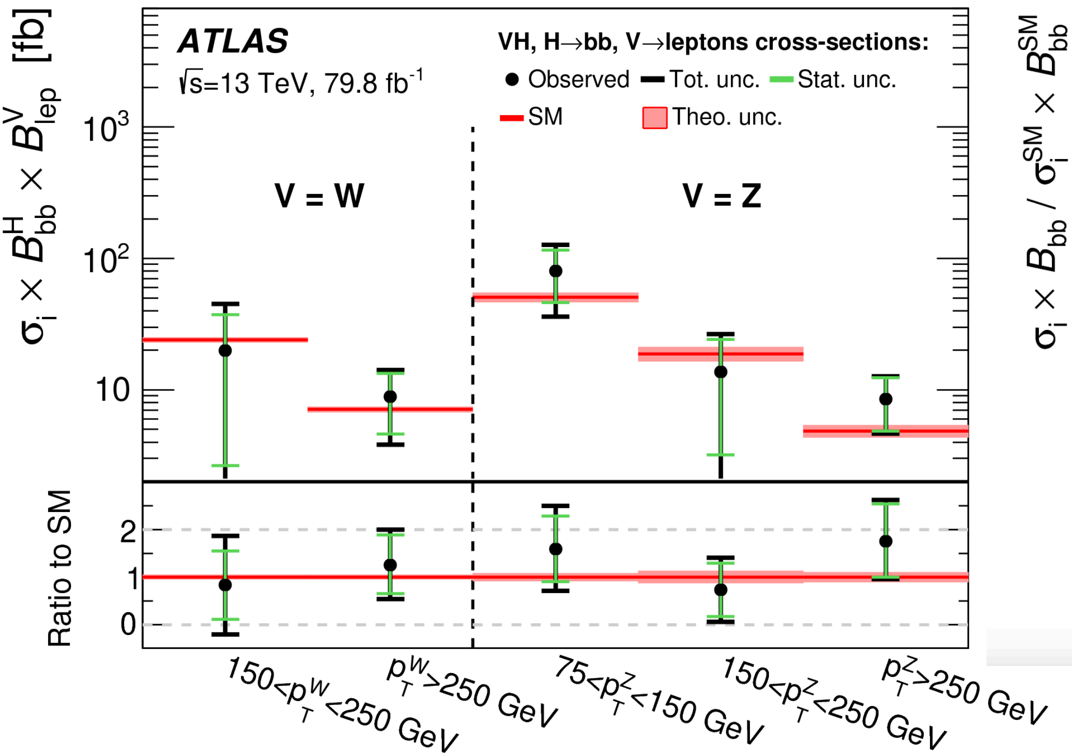
- VH → bb in Run 2:
  - Observed (expected) of 4.9σ (4.3 σ)
- Adding VH → bb in Run1
  - Observed (expected) of 4.9σ (5.1 σ)
- Adding VBF and ttH
  - Observed (expected) of 5.4σ (5.5 σ)
  - Observation of H → bb decay
- Adding H→ ZZ and H → γ γ:
  - Observed (expected) of 5.4σ (5.5 σ)
  - Observation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

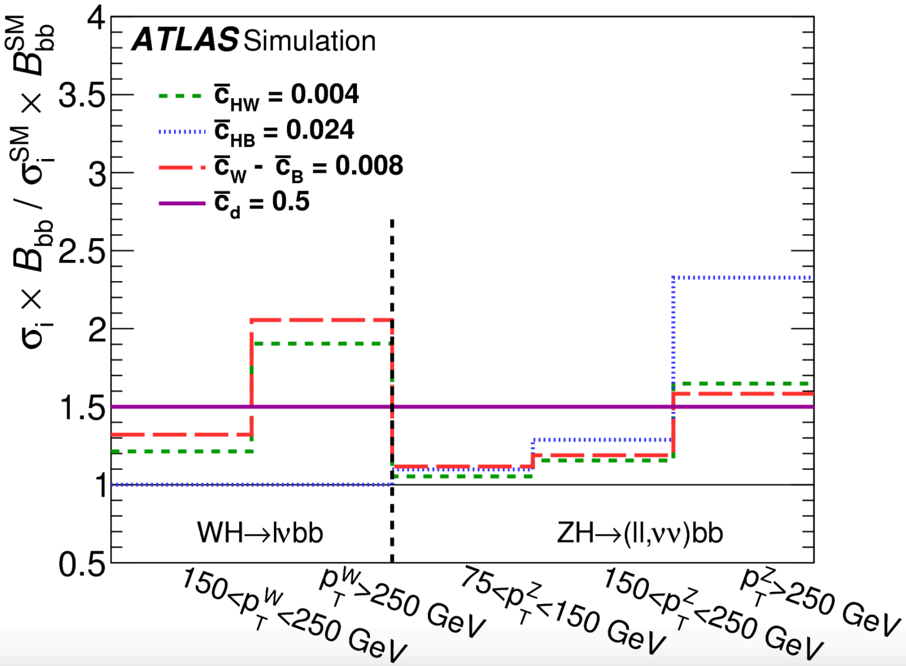




VH → bb: Differential cross section

- 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)





JHEP 05 (2019) 141

Higgs coupling to charm 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)

Search for H → cc

Phys. Rev. Lett. 120 (2018) 211802

- Charm jet tagging performance is the key.

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

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

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

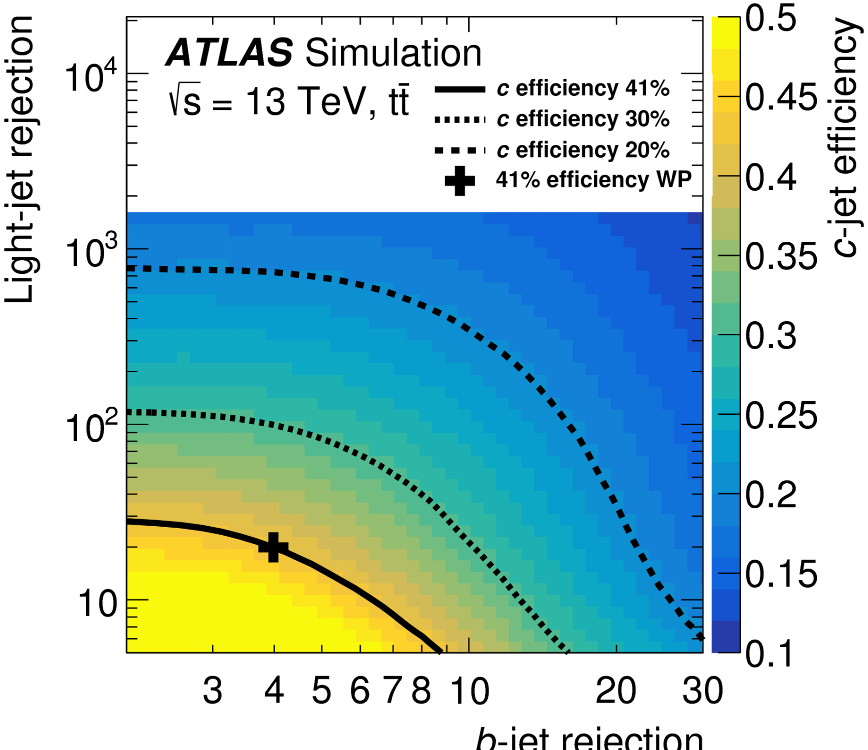
≥ 2 jets, with 1 or 2 c-tags
pT(c1) > 45 GeV

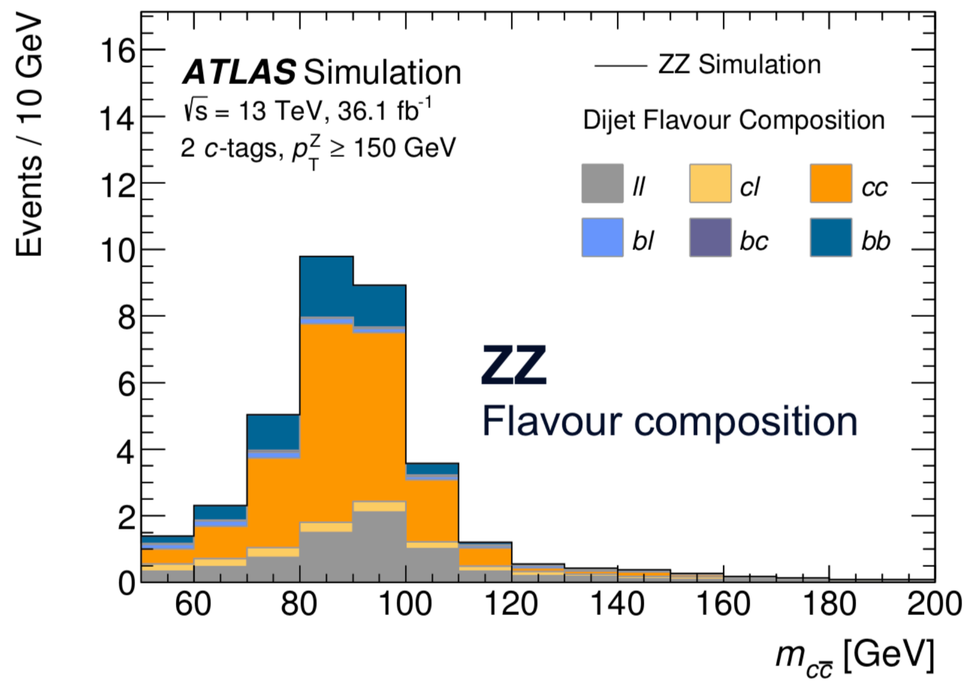
\+

$$75\ \mathrm{GeV} < p_T^Z < 150\ \mathrm{GeV} \rightarrow \Delta R < 2.2$$
$$150\ \mathrm{GeV} < p_T^Z < 200\ \mathrm{GeV} \rightarrow \Delta R < 1.5$$
$$p_T^Z > 200\ \mathrm{GeV} \rightarrow \Delta R < 1.3$$

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

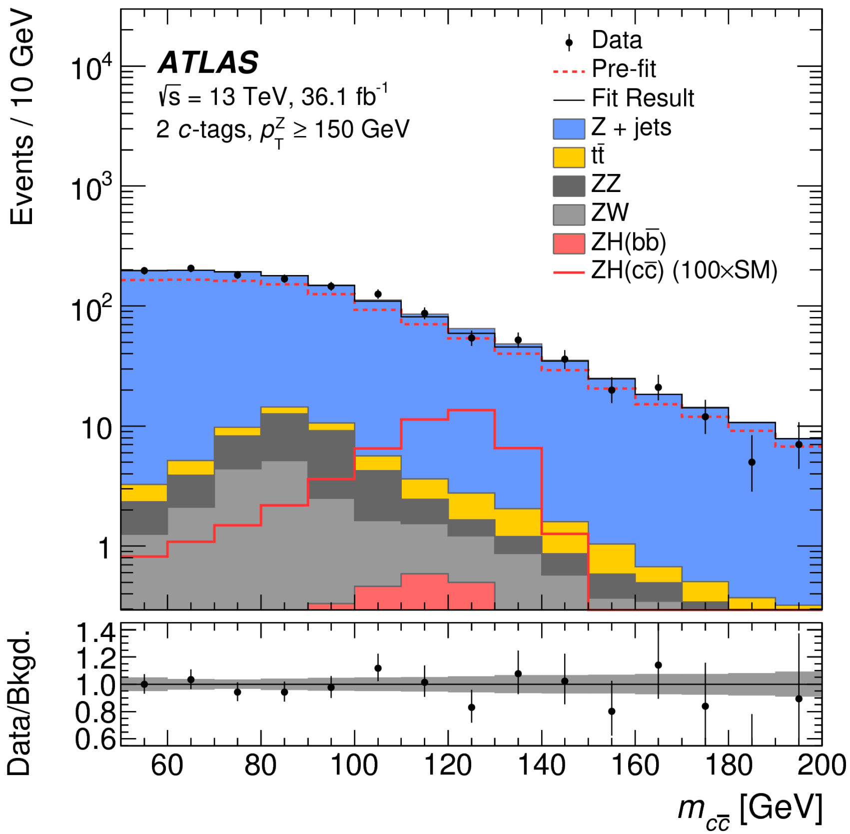




Search for H → cc: result

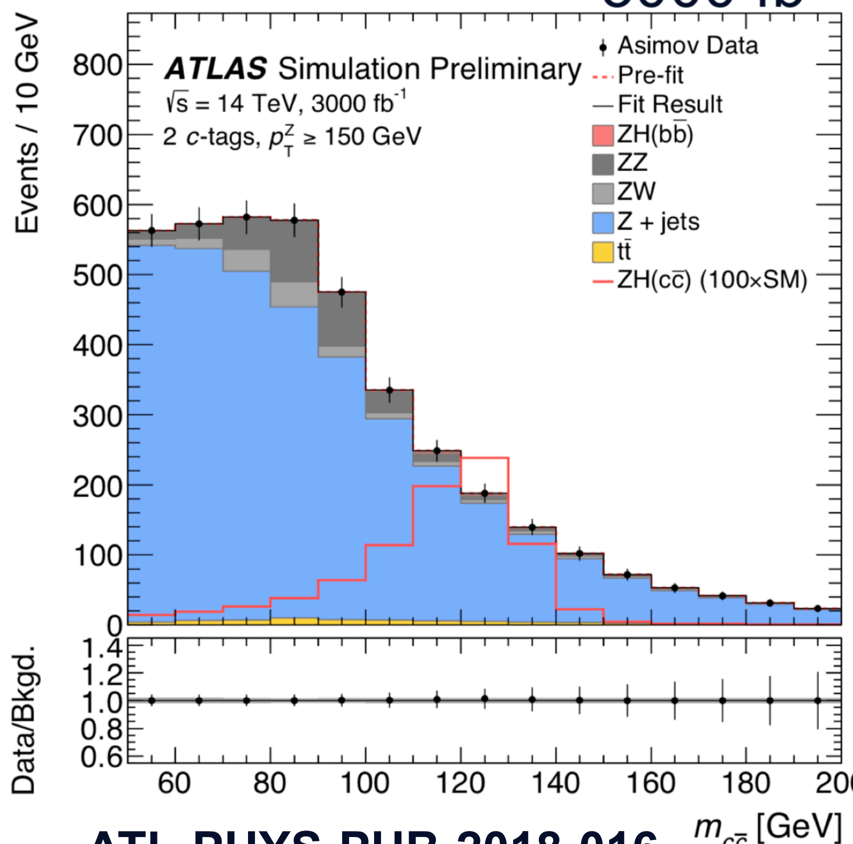
- Z(ll)H(->cc) has been studied in run2 with 36.1fb^{-1}.
  - H->J/ψγ search on ATLAS gives similar precision
- Also extrapolated to 3000 fb^{-1}

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



Phys. Rev. Lett. 120 (2018) 211802

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



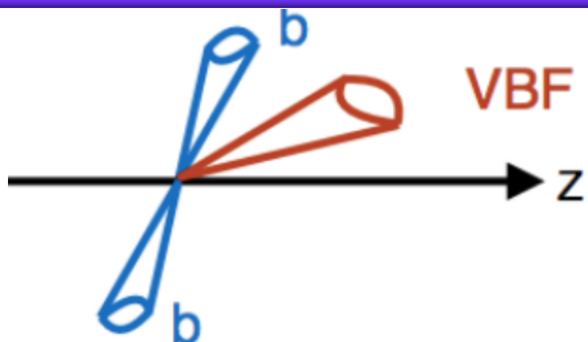
ATL-PHYS-PUB-2018-016

Summary

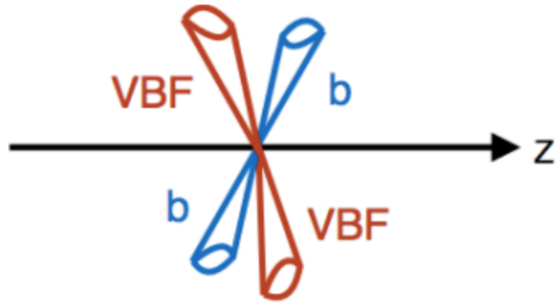
- With the large LHC Run 2 dataset,
  - the coupling of the Higgs boson to quarks can be determined with unprecedented precision
  - Confirmation of coupling to 3rd generation fermions
  - Recent observation bottom and top quark Higgs coupling were presented
  - Observation of VH and ttH production shown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

Backup

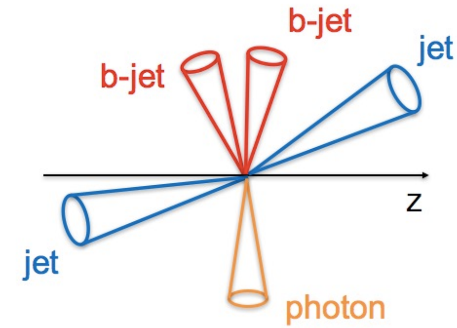
VBF H → bb: Event Selection



Two central jets
Channel (1fj+2b)



Four central
Channel (2b+2j)



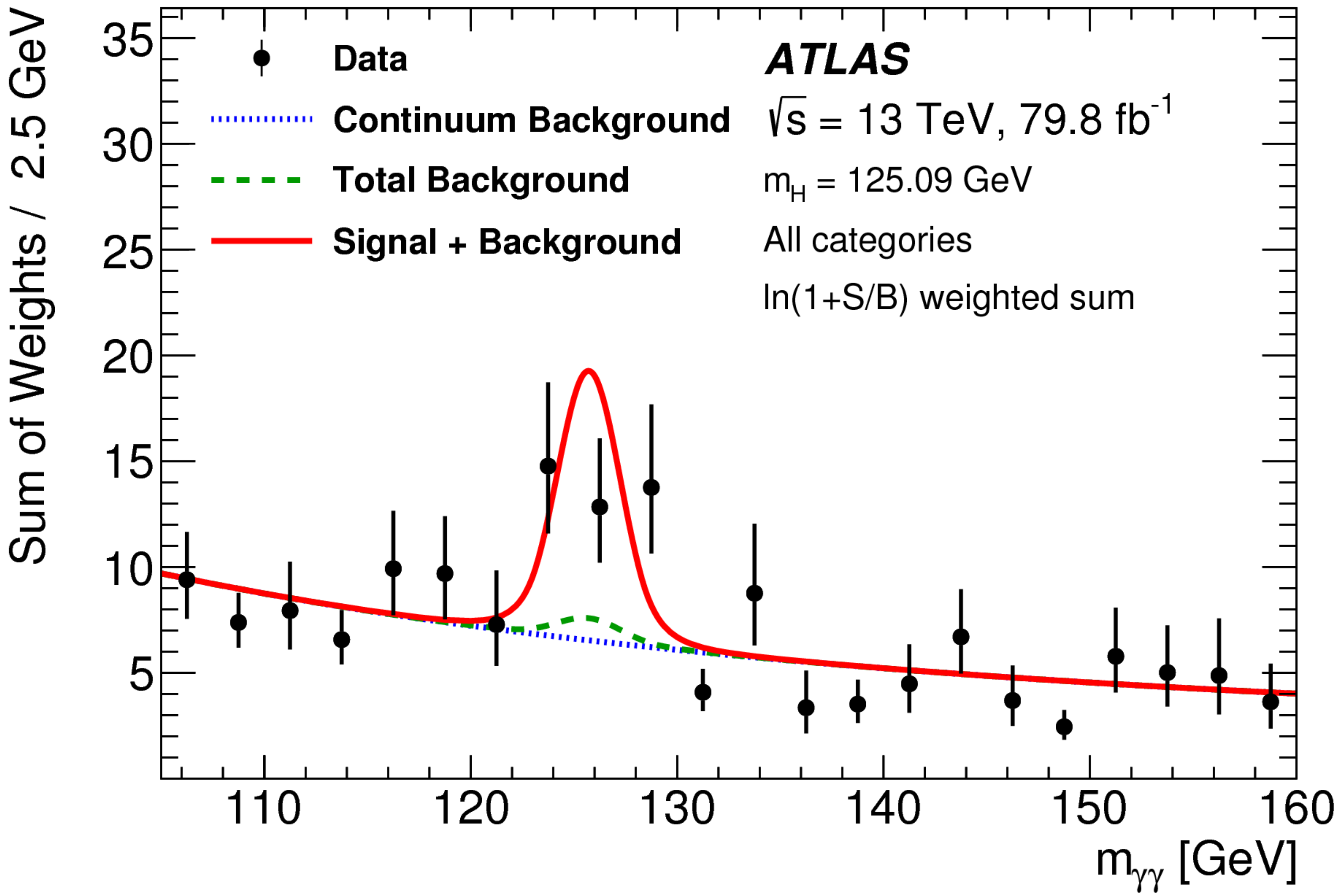
Photon channel
γ+2b+2fj

	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

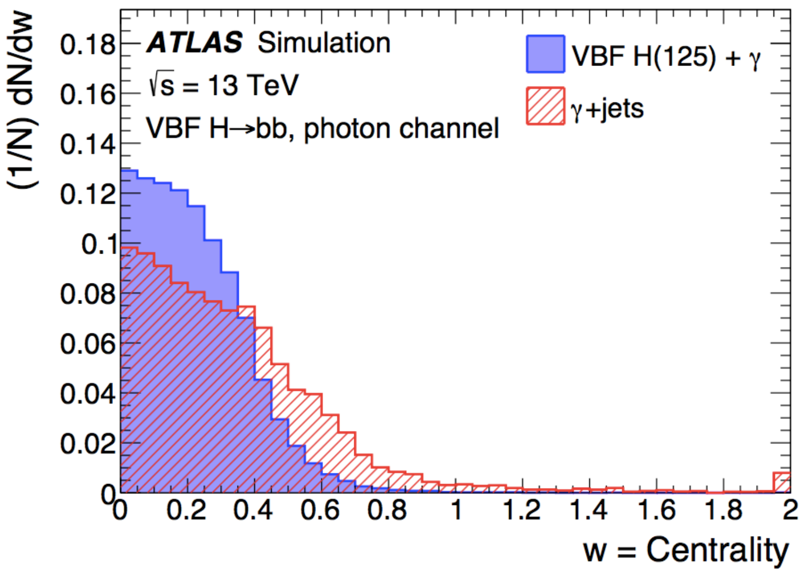
ttH→γ γ

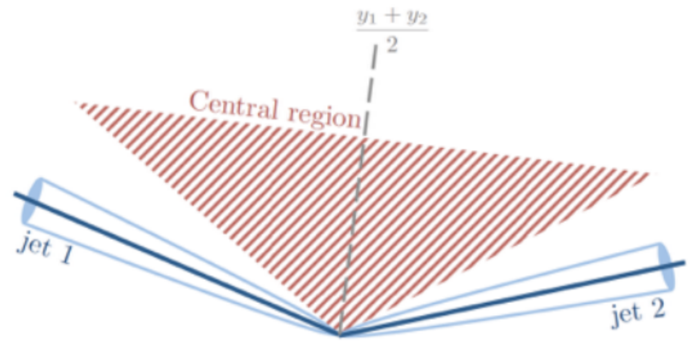
- Select events based on mγγ + b-jets
  - Significance: 4.1σ (3.7σ exp.)



Boosted Decision Tree (BDT) Analysis

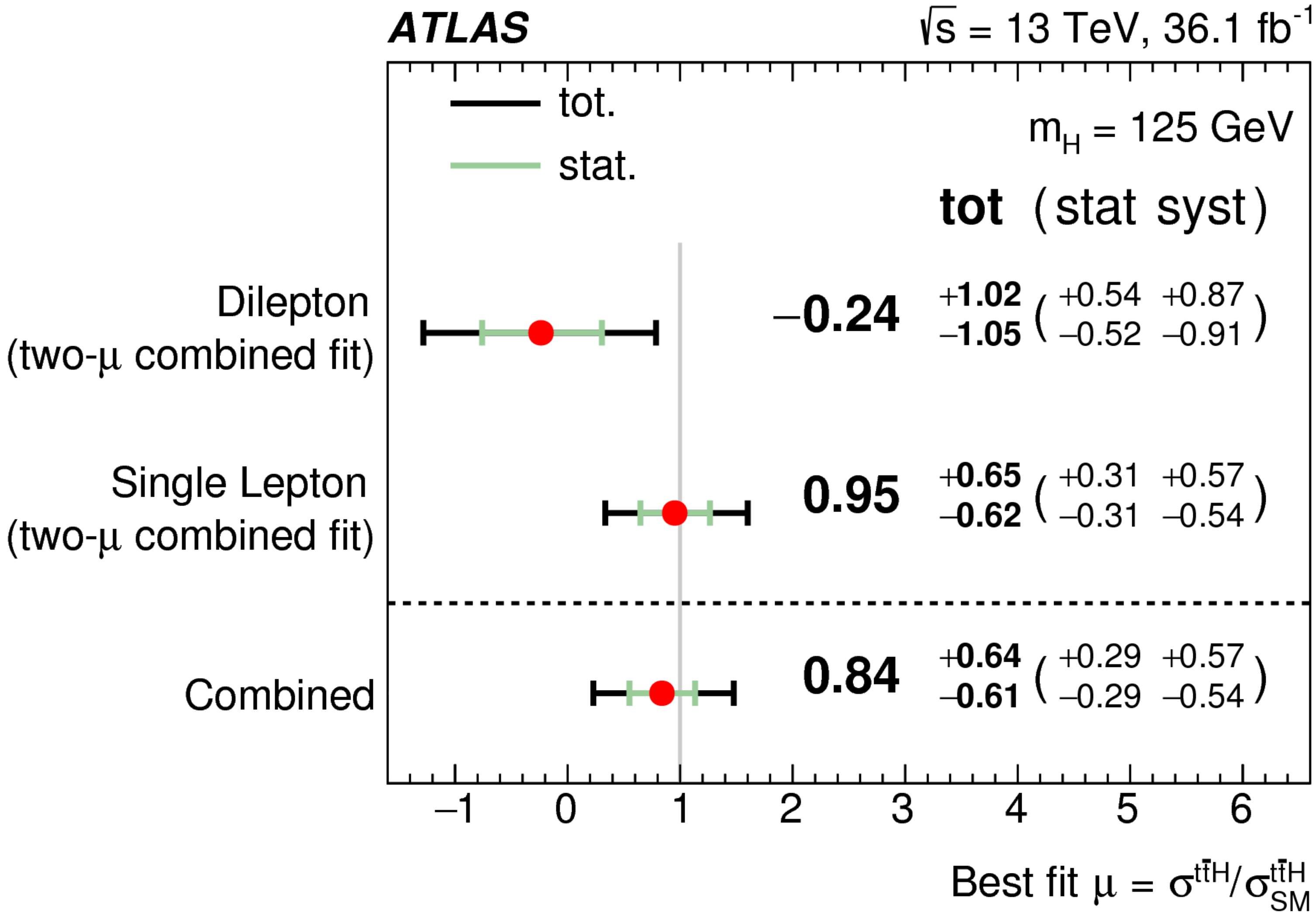
- 11 variables used in BDT analysis





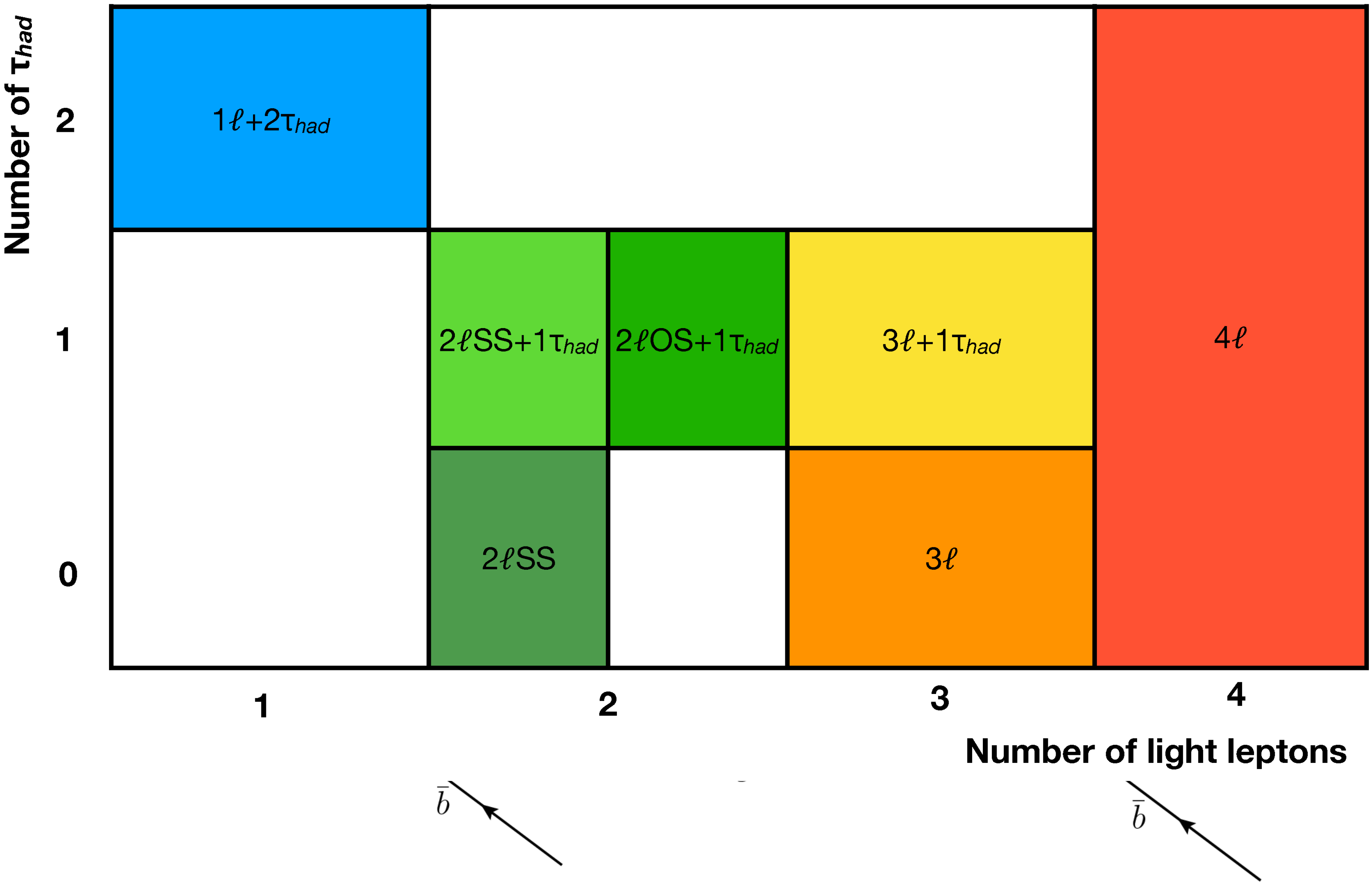
$$centrality(\gamma) = \left| \frac{y_\gamma - \frac{y_{j_1}+y_{j_2}}{2}}{y_{j_1} - y_{j_2}} \right|$$

	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), $\Delta\eta$(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),$\Delta\phi$(bb,jj),cos θ



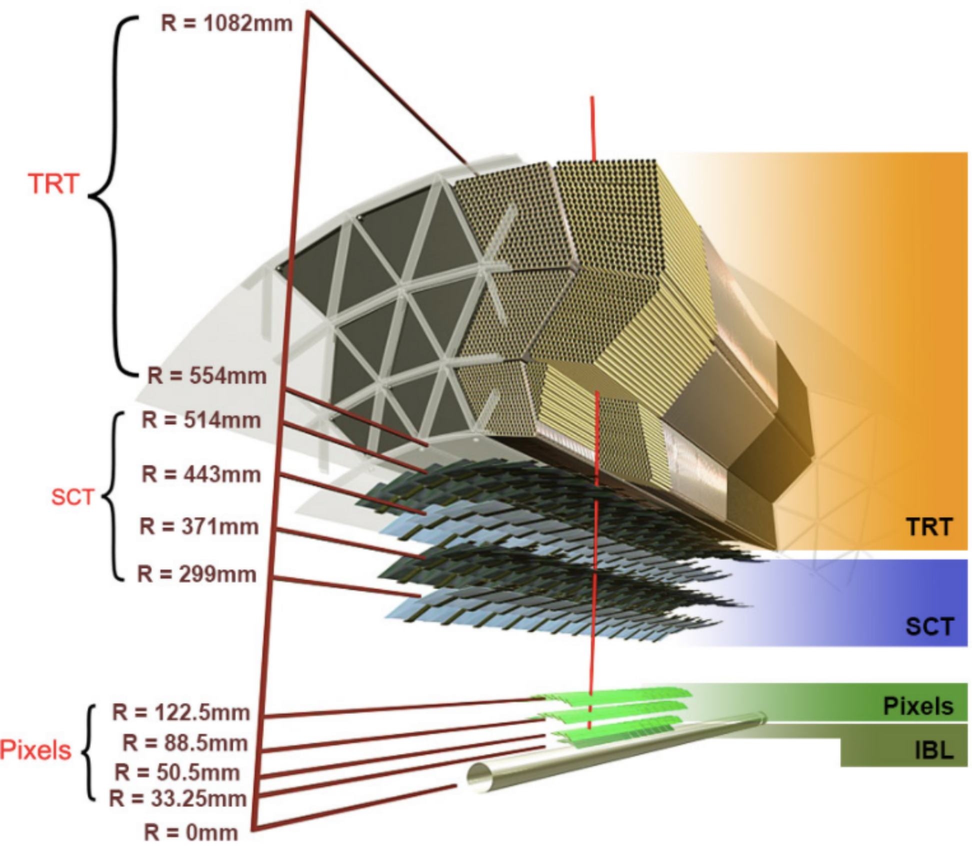
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
tot.
stat.
m_H = 125 GeV
tot (stat syst)
Dilepton
(two-μ combined fit)
−0.24 +1.02 −1.05 (+0.54 −0.52 +0.87 −0.91)
Single Lepton
(two-μ combined fit)
0.95 +0.65 −0.62 (+0.31 −0.31 +0.57 −0.54)
Combined
0.84 +0.64 −0.61 (+0.29 −0.29 +0.57 −0.54)
−1
0
1
2
3
4
5
6
Best fit μ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

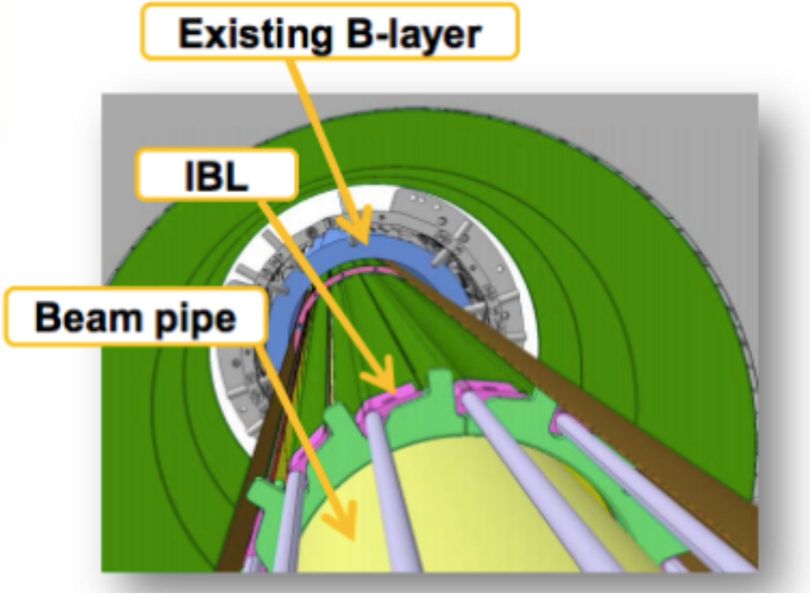
ttH multilepton



ATLAS Detector upgrade : Run 1 to Run 2

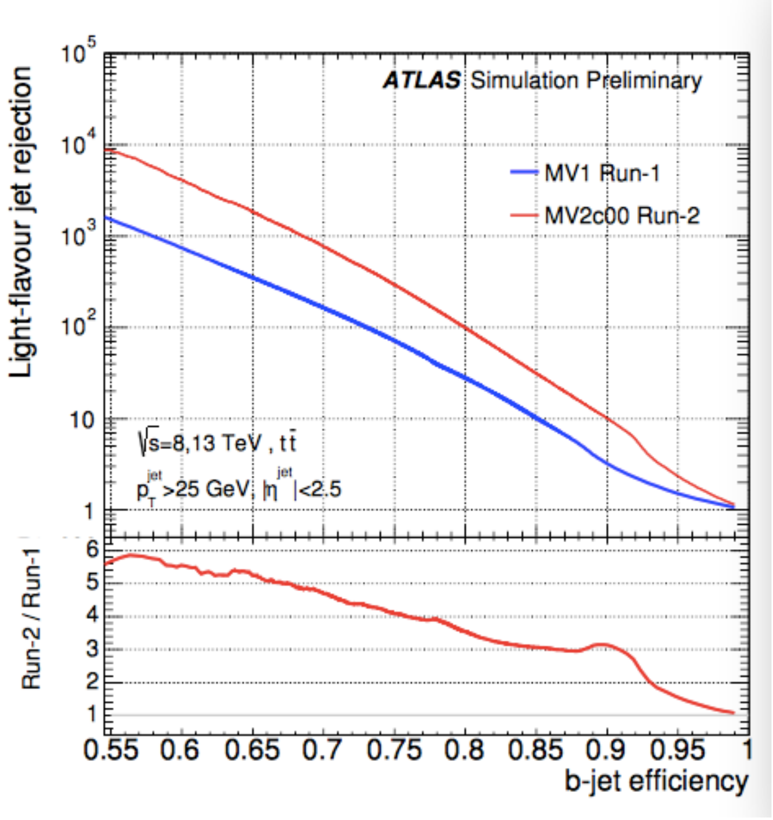
- Adding a new layer of pixel detector
- IBL = New Insertable pixel B-Layer at R=33 mm

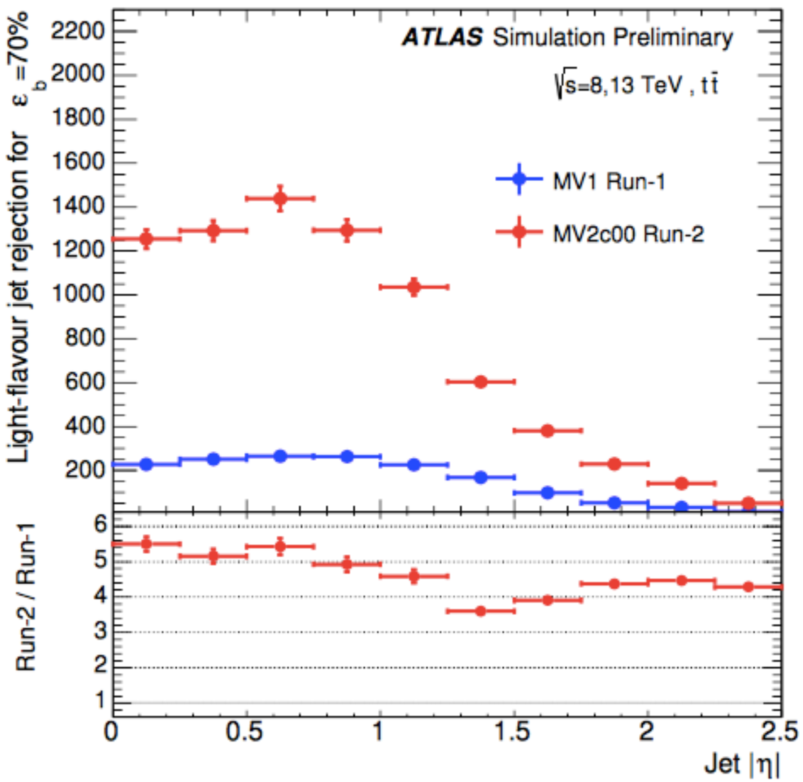




B tagging performance Improvement

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

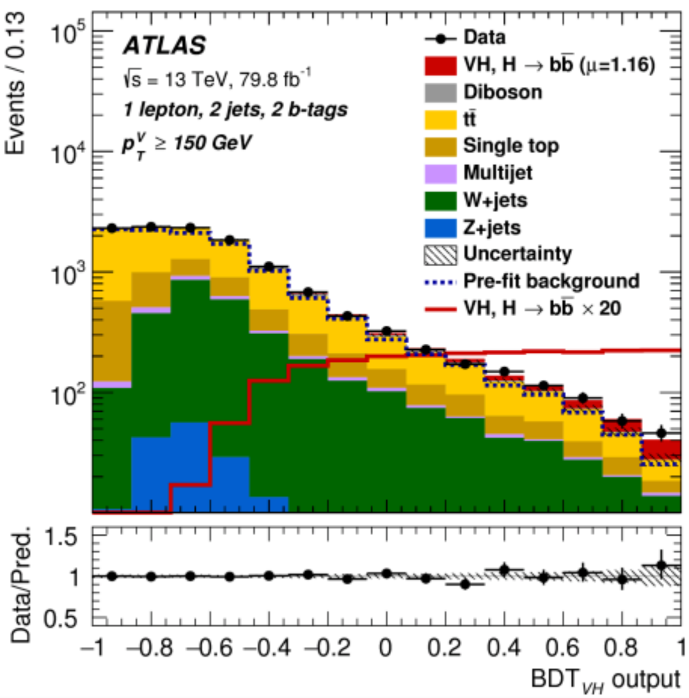


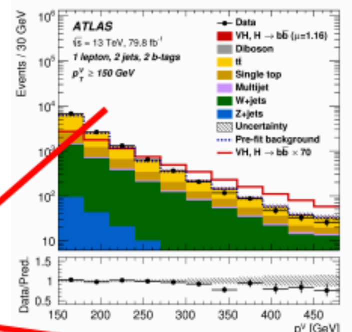


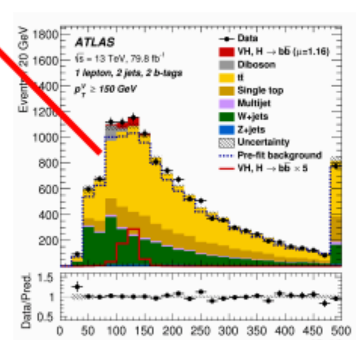
VH → bb: Multivariate Analysis (MVA)

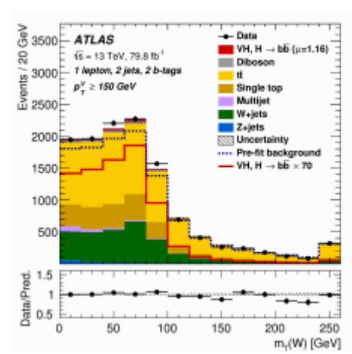
- MVA setup
  - Use simple and robust Boosted Decision Tree (BDT)
  - Input variables and training parameters tuned to yield best sensitivity
- Inputs Variables
  - Kinematic variables, some specific to 3-jet regions
  - m_{bb}, ΔR_{bb}, p_T^V most important ones

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss}	×	×	
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\|\Delta\eta(b_1, b_2)\|$	×		
$\Delta\phi(V, bb)$	×	×	×
$\|\Delta\eta(V, bb)\|$			×
m_{eff}	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$E_T^{miss}/\sqrt{S_T}$			×
m_{top}		×	
$\|\Delta Y(V, bb)\|$		×	
Only in 3-jet events			
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×



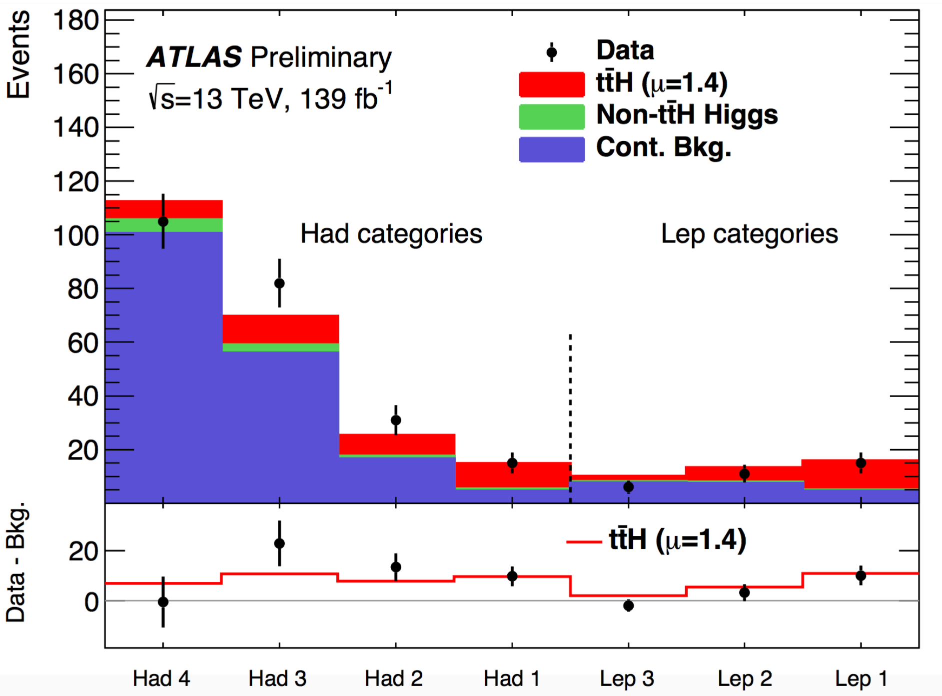


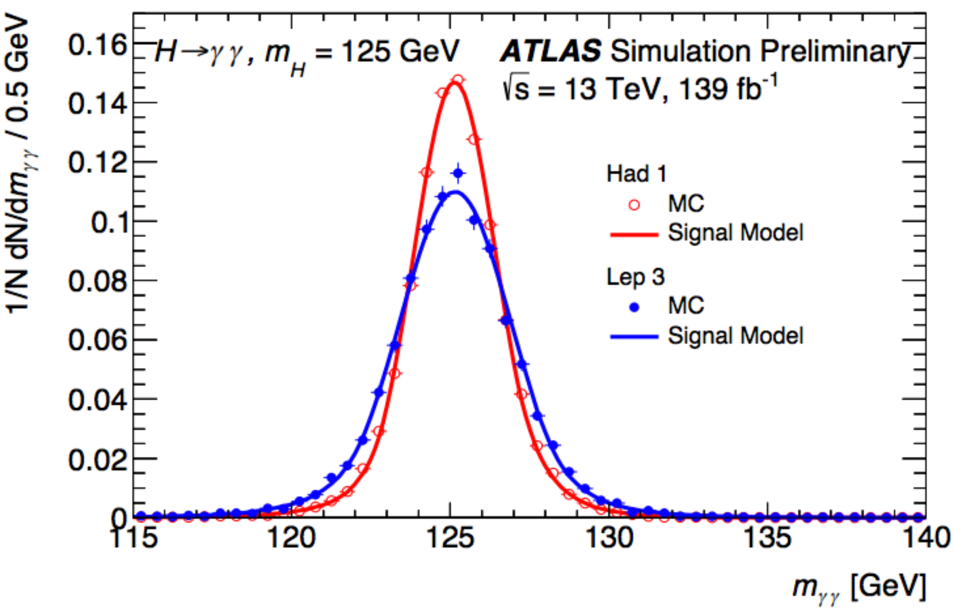




ttH→γ γ: signal regions

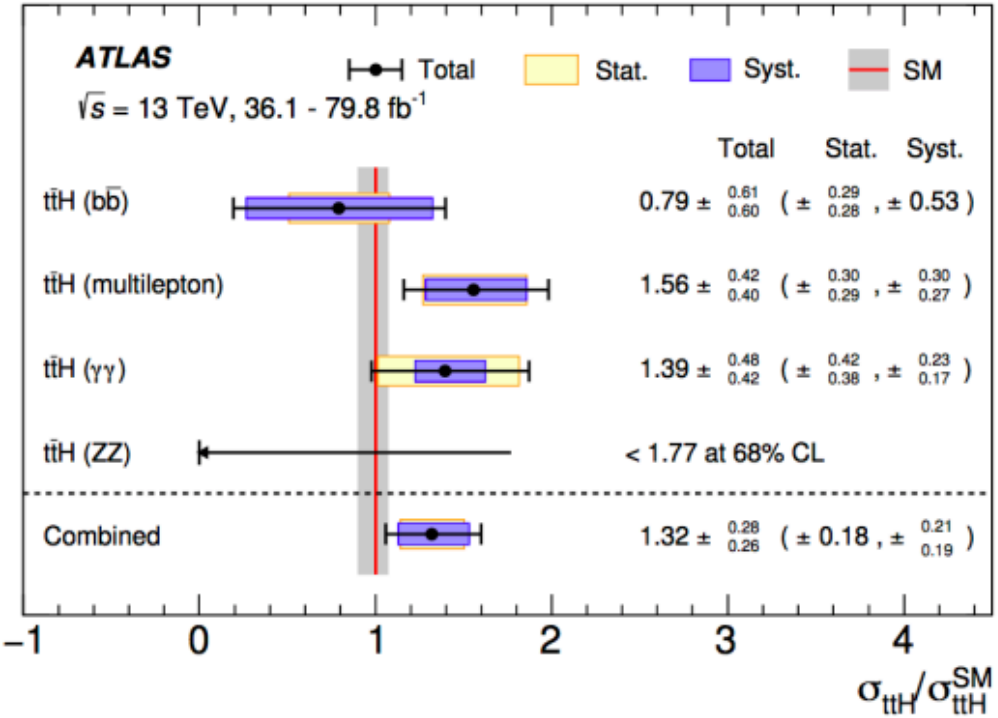
- 7 signal regions (categories) are used.
  - Di-photon mass resolution is slightly different in different categories





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_T^{miss}	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-leptons	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4