ATLAS H(125) difermion results

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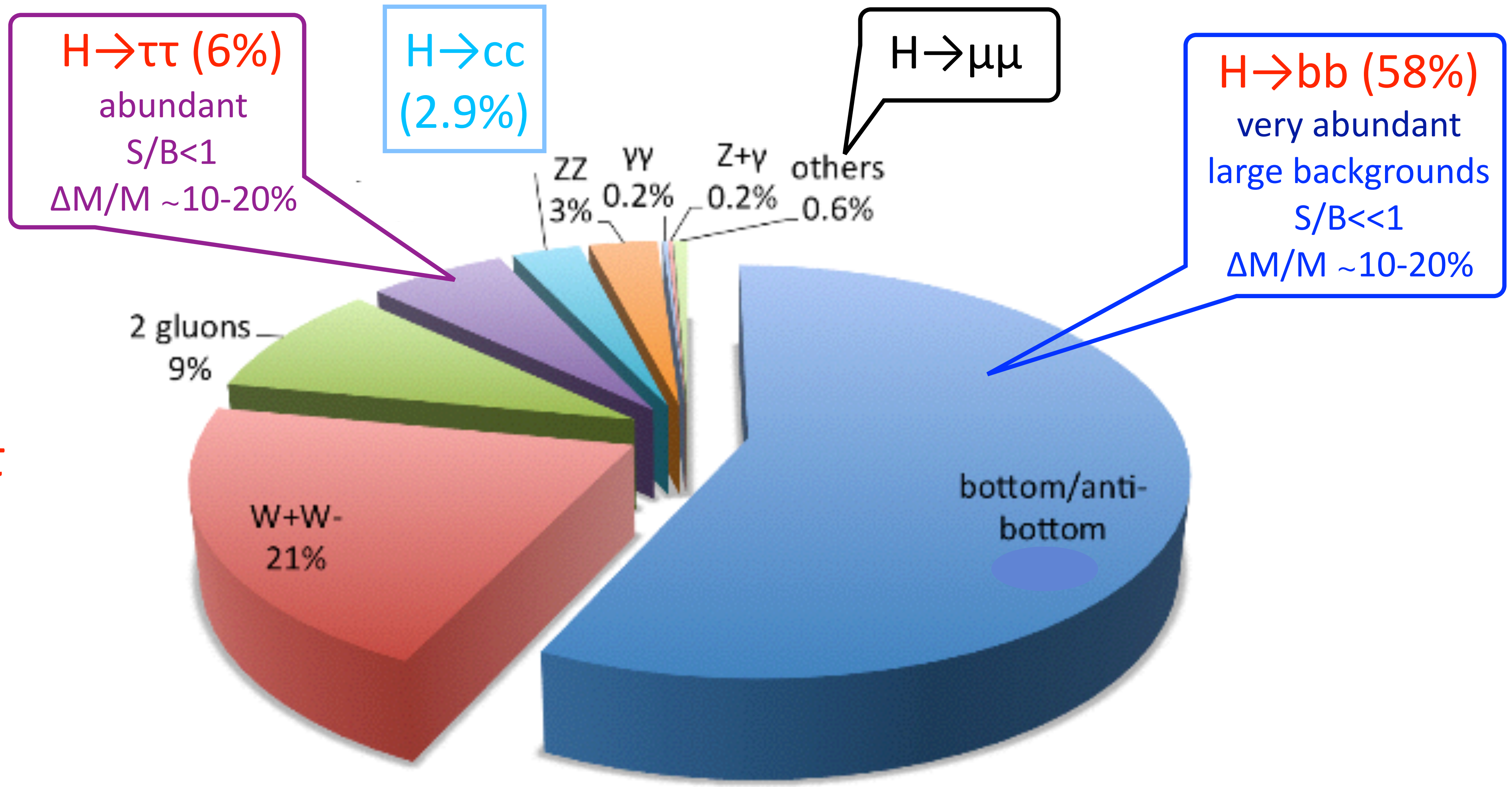
on behalf of the ATLAS collaboration

Introduction - I

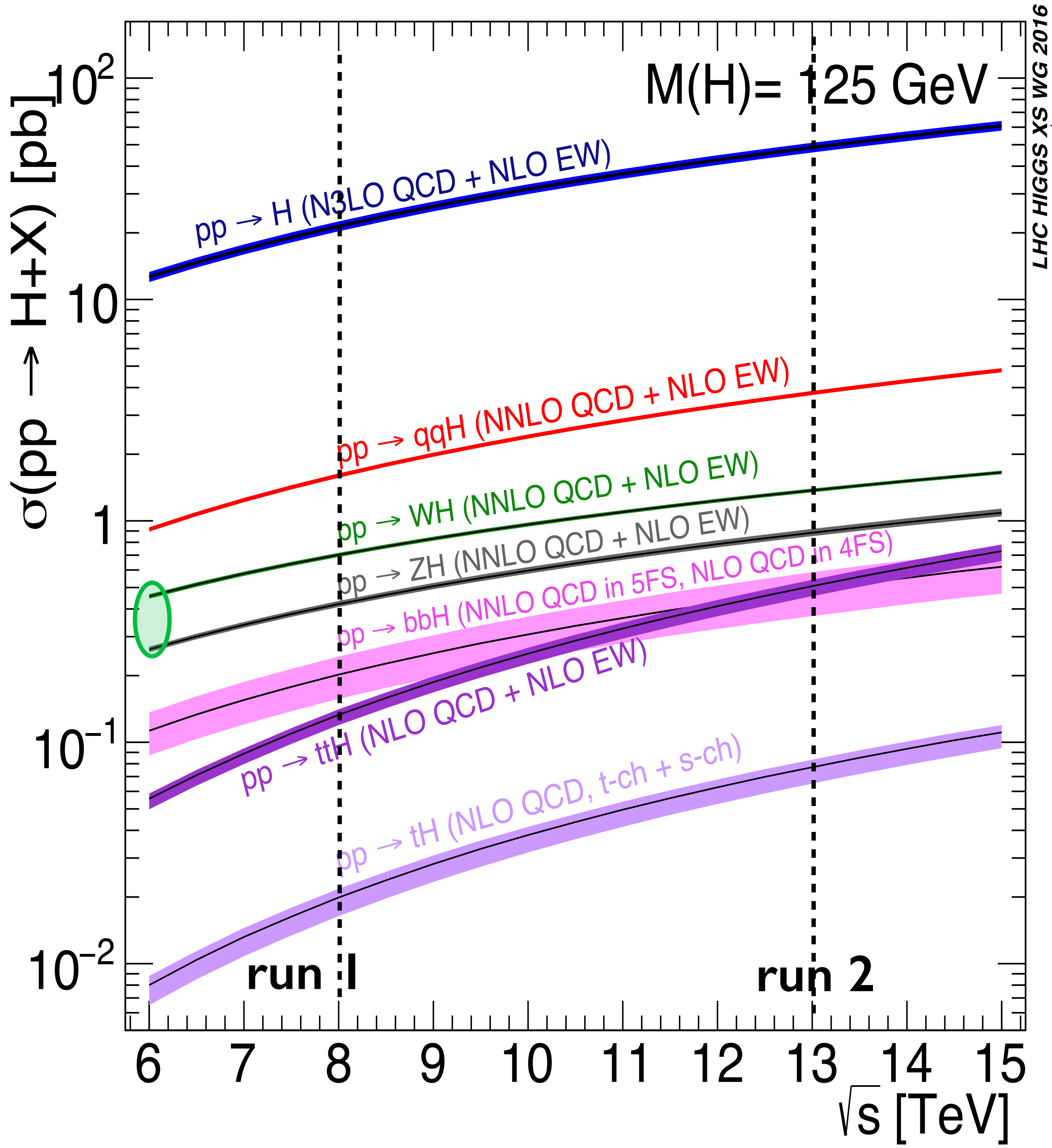
- Higgs discovery and measurements of its properties rely on bosonic Higgs decays
  - measurements confirm SM nature of Higgs
- Establish mass generation mechanism for fermions
  - demonstrate direct coupling of Higgs to fermions
  - proportionality of coupling to mass
- Larger Higgs boson sample in run 2 will allow for increased precision and probing new fermionic channels

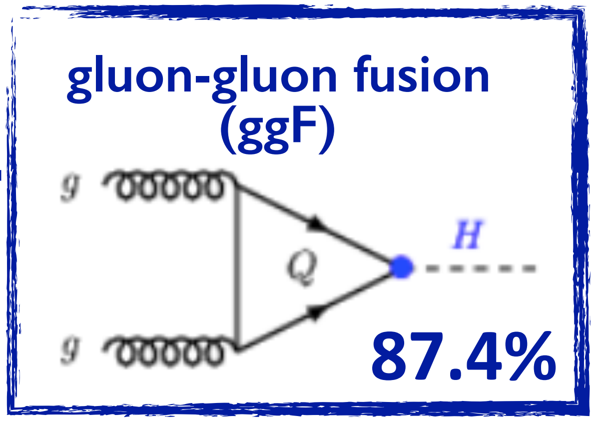
- Observed: H→ττ
- Yet to come:
  - H→bb
  - H→cc
  - H→μμ



Introduction - II

- Higgs discovery and precision measurements are driven by the ggF production mode

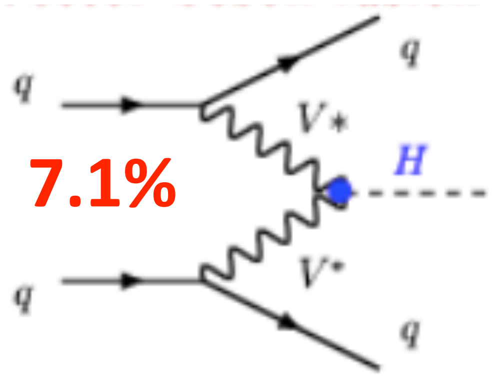




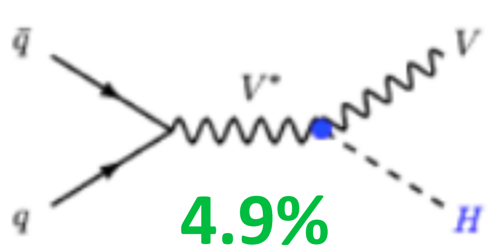
Introduction - II

H→μμ
H→ττ
H→bb

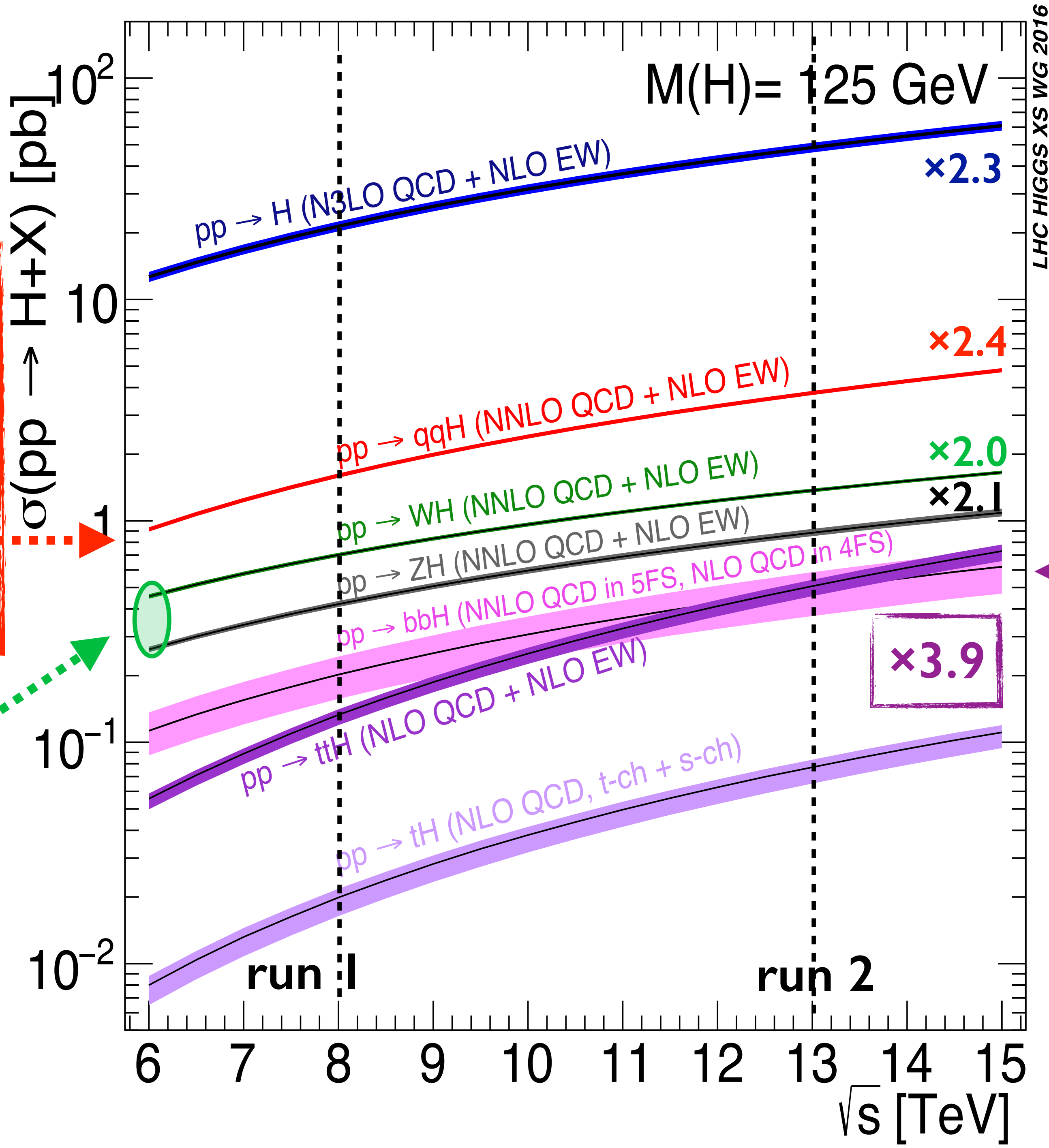
Vector boson fusion (VBF)



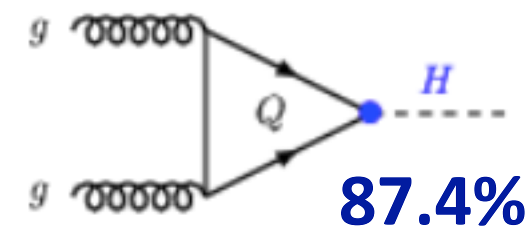
Higgs-strahlung (VH)



H→bb

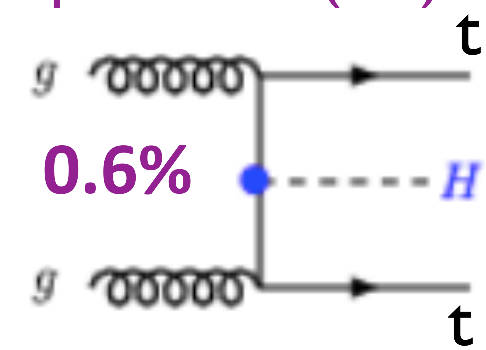


gluon-gluon fusion (ggF)



H→μμ
H→ττ (boosted)

Associated production (ttH)



H→bb

- VH and ttH production mechanisms haven't been observed yet
- These are the most promising channels to observe Higgs to bottom coupling

H→ττ

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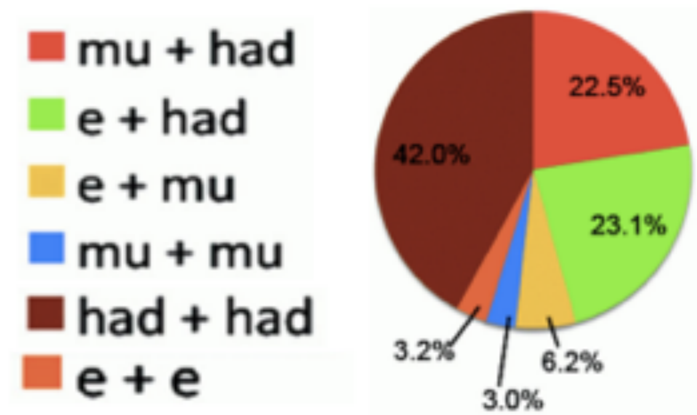
Run I recap

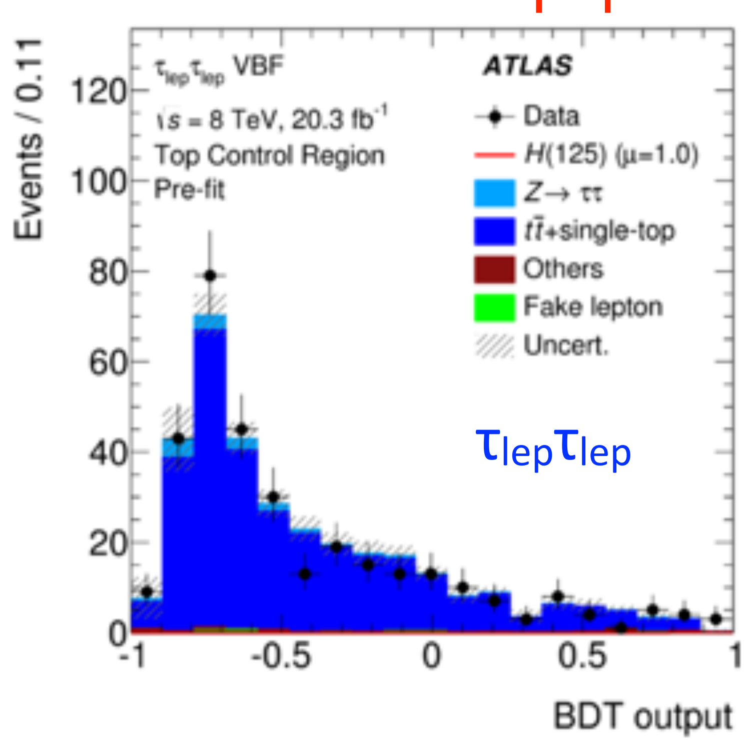
- Favourable S/B conditions
- Designed to be sensitive to ggF, VBF, VH
  - VBF category: require 2 jets with large η separation
  - boosted category (ggF dominated): Higgs candidate with large p_T
- Main backgrounds:
  - Z→ττ: determined from MC and data (τ embedding technique)
  - τ_{had} fakes determined from data
- Multiple control regions to validate background modelling for different categories and τ decays

- All τ decay modes

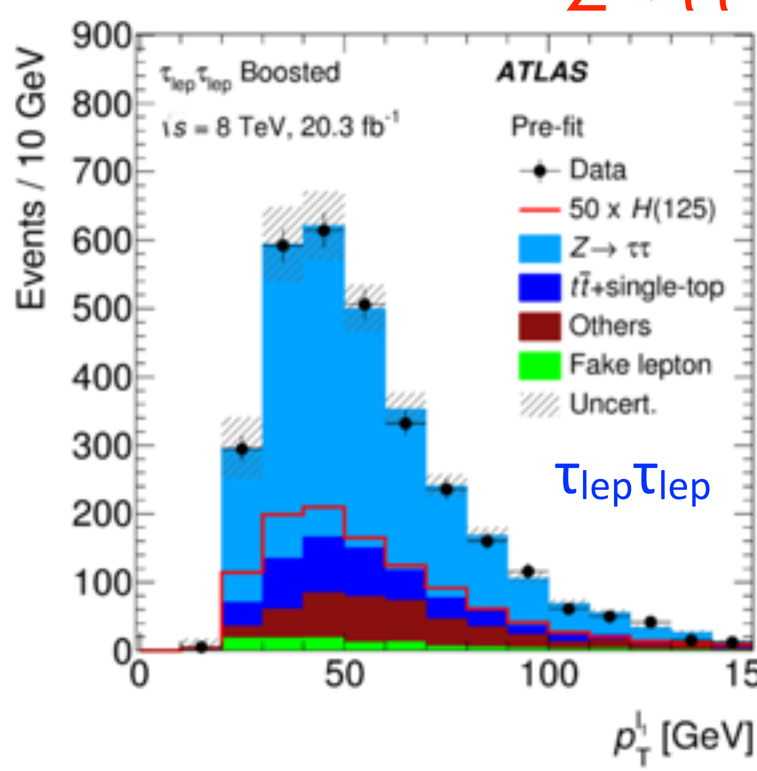


3 analysis channels: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$

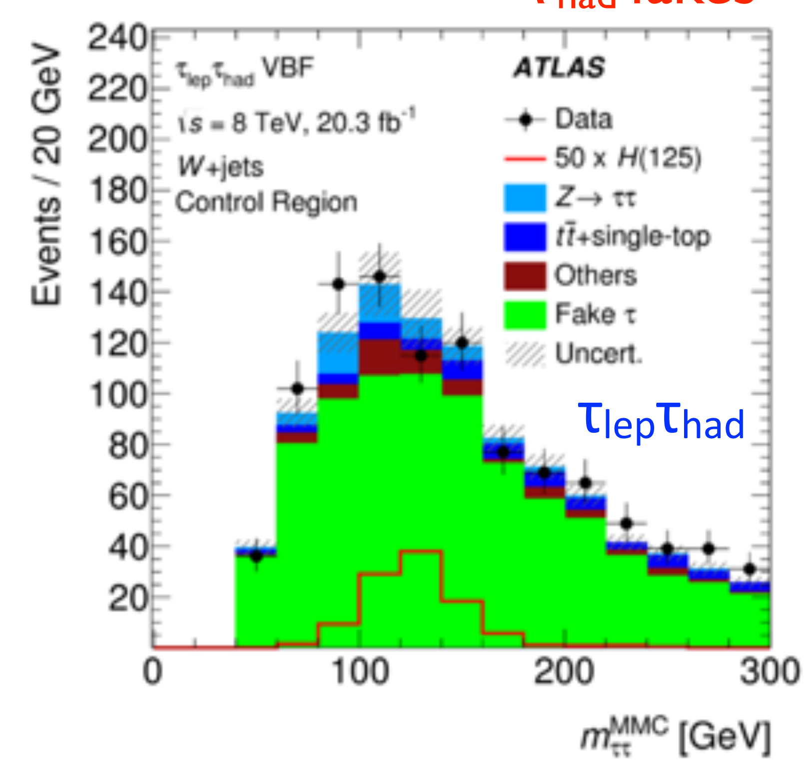
top quark



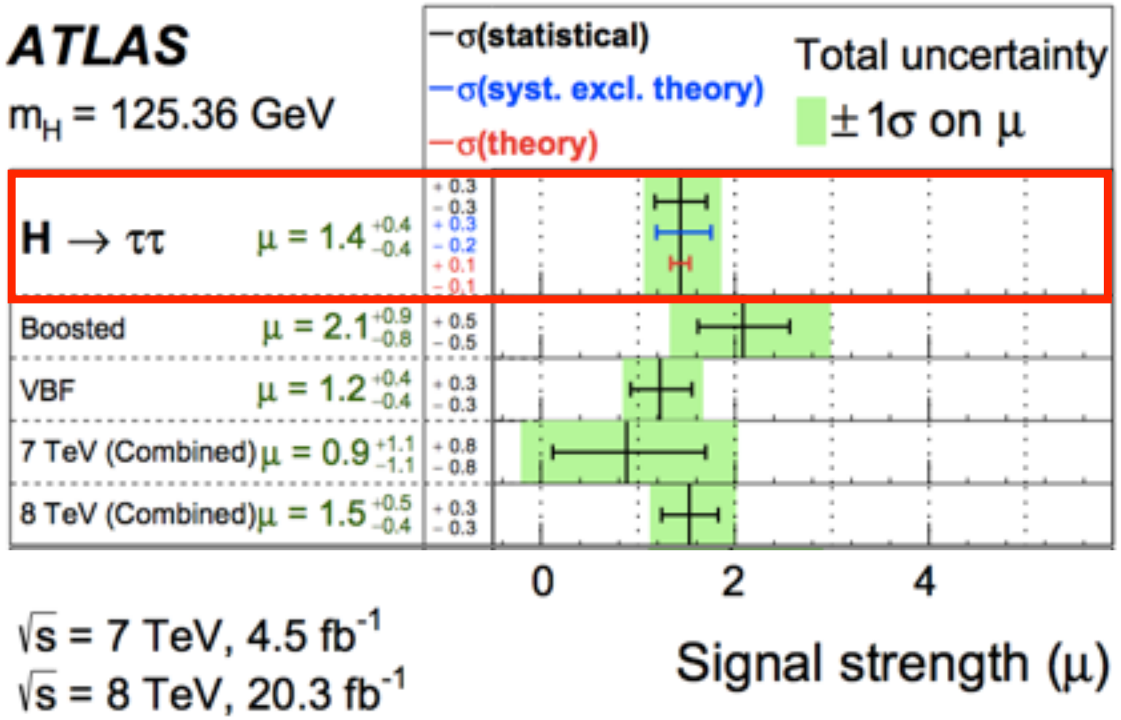
Z→ττ

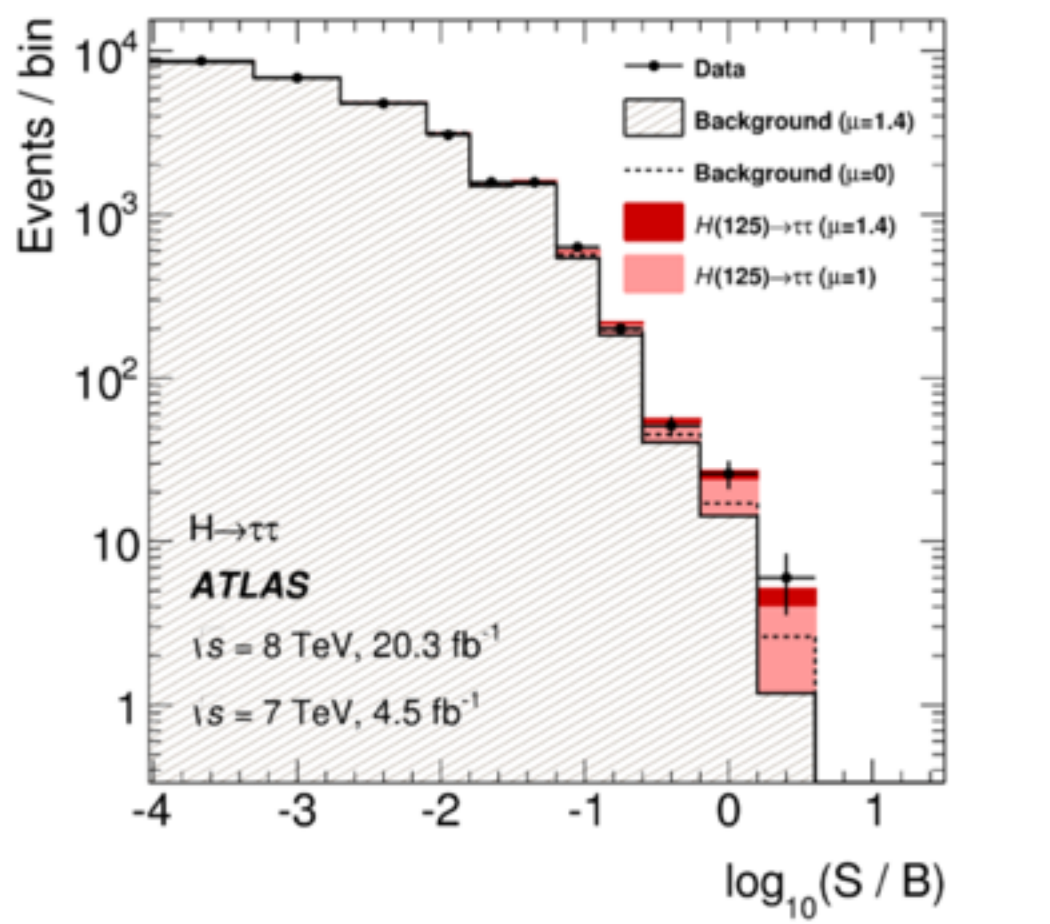


τ_{had} fakes



- BDT to extract signal: simultaneous fit to data in all 6 analysis regions





Yields in discriminant bins ordered by log(S/B)

Evidence for the Yukawa-coupling to τ leptons
Significance obs (exp) [σ]: 4.4 (3.3)
Combination with CMS provided observation
Significance obs (exp) [σ]: 5.5 (5.0)

VH(H→ττ) run 1 search:
Phys.Rev.D93, 092005

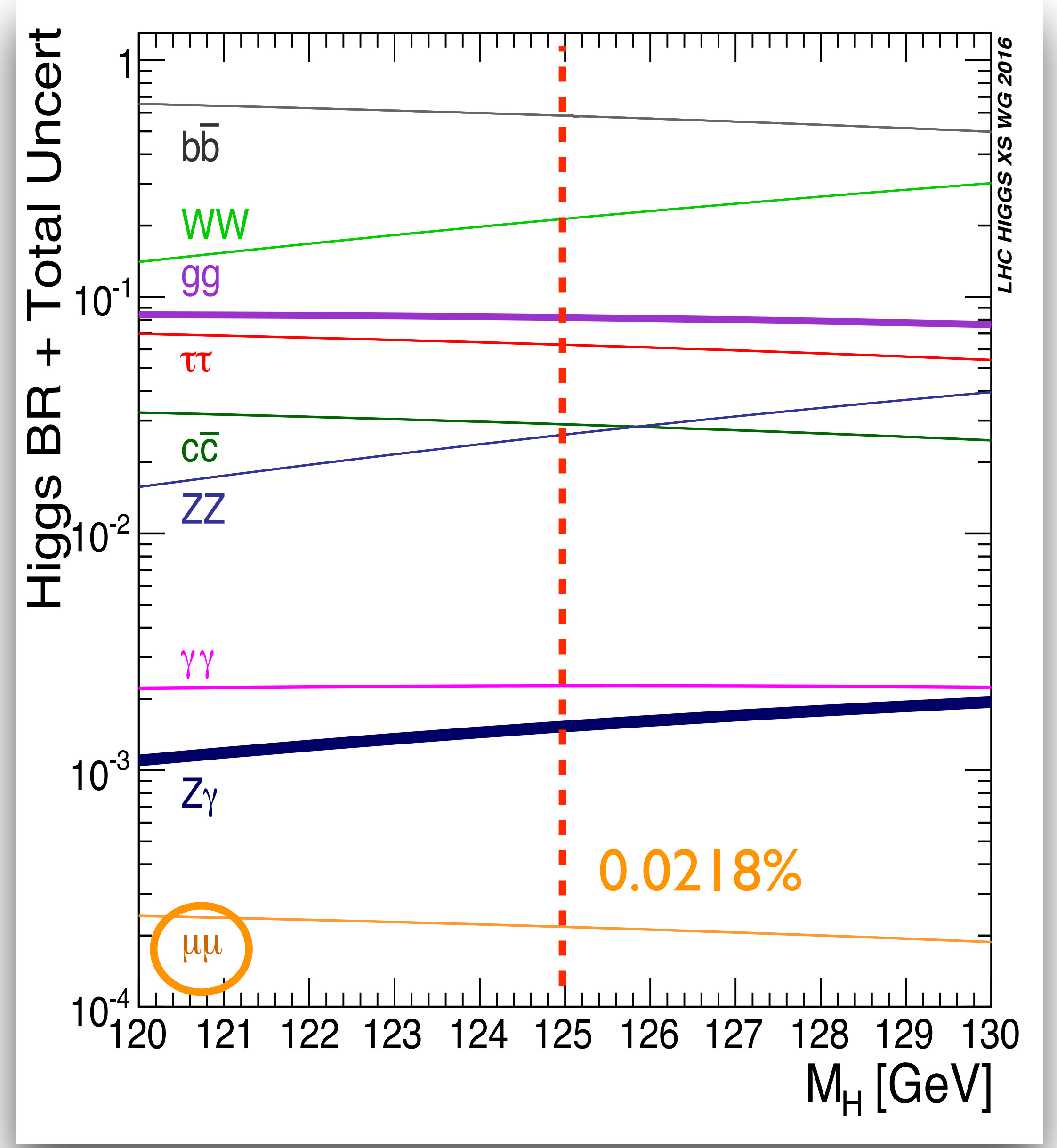
Dedicated YSF talk by Eric Drechsler later today:
"Standard model H→ττ searches with ATLAS"

Run 2 results

$H \rightarrow \mu\mu$

ATLAS-CONF-2016-041

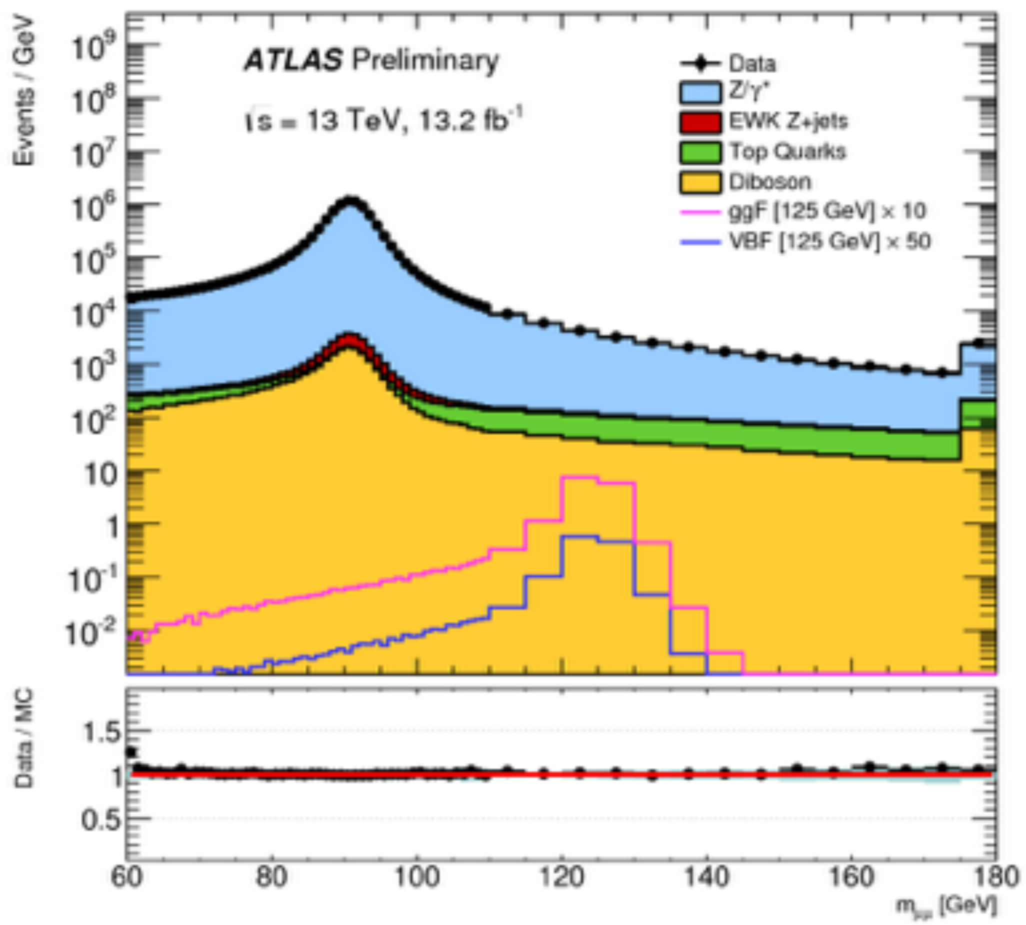
- Very small branching fraction in SM
  - Yukawa-coupling to 2nd generation fermions
  - mass dependence
  - coupling to leptons



$H \to \mu\mu$

ATLAS-CONF-2016-041

- Very small branching fraction in SM
  - Yukawa-coupling to 2nd generation fermions
  - mass dependence
  - coupling to leptons
- Clean signature: narrow resonance in dimuon invariant mass spectra
  - two opposite charge muons (p_T>25 (15) GeV)
  - b-veto and low MET requirement to suppress ttbar
  - examine (110-160) GeV mass range
- Dominant irreducible background
  - $Z/\gamma^* \to \mu\mu$: shape and normalisation from data (fit to dimuon mass spectra using parametrised function)
    - BreitWigner + Gauss (for Z->mumu)
    - e^{Ax}/x^3 (for the continuum)
    - all parameters are free in the fit



$m_{\mu\mu}$

$H \to \mu\mu$

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  - mass dependence
  - coupling to leptons
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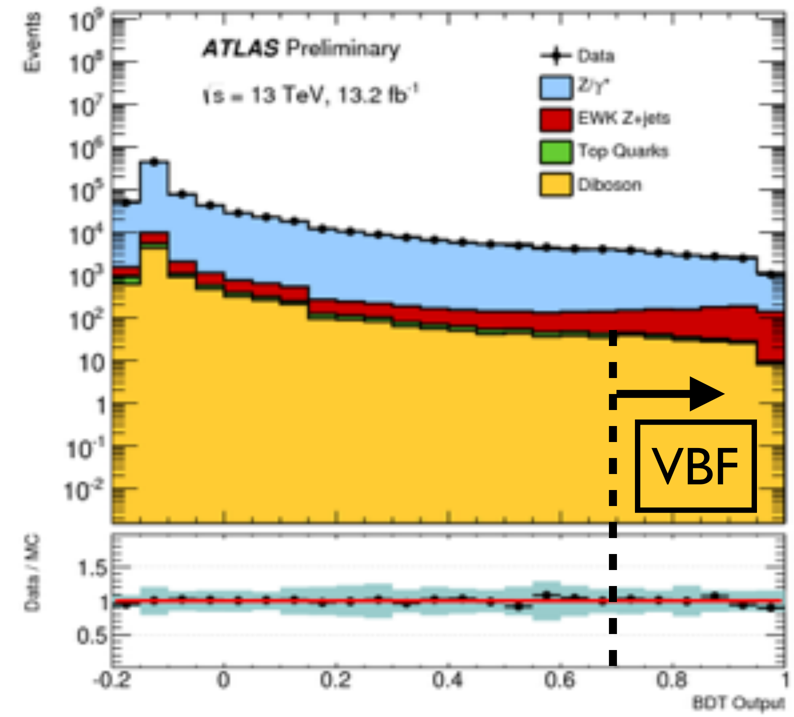
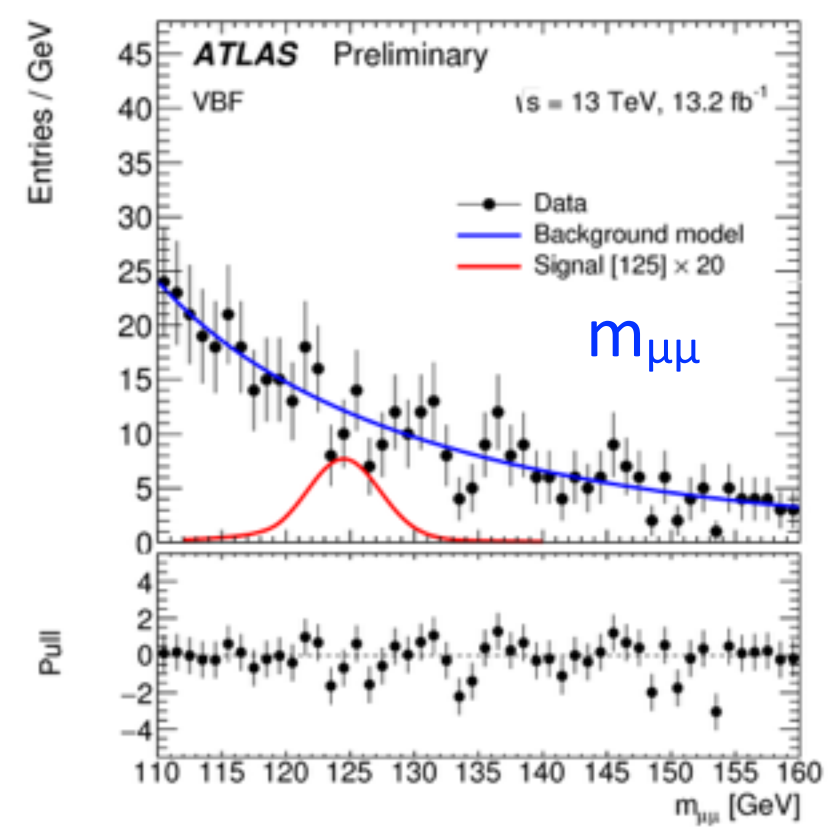
- Dominant irreducible background
  - $Z/\gamma^* \to \mu\mu$: shape and normalisation from data (fit to dimuon mass spectra using parametrised function)
- Analysis strategy
  - split in categories with different S/B
  - VBF category defined first using MVA discriminant
    - new in run 2: ~10% improvement of sensitivity
  - the rest is split into 6 categories in muon η and $p_T(\mu\mu)$ to take advantage of different dimuon mass resolution
- Signal extracted from simultaneous fit to $m_{\mu\mu}$ distribution in 7 categories



51.3% (2.4%) eff for VBF signal (total bckg)



H→μμ

- Very small branching fraction in SM
  - Yukawa-coupling to 2nd generation fermions
  - mass dependence
  - coupling to leptons
- Clean signature: narrow resonance in dimuon invariant mass spectra
  - two opposite charge muons (pT>25 (15) GeV)
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- Dominant irreducible background
  - Z/γ*→μμ : shape and normalisation from fit to dimuon mass spectra using parametrised function
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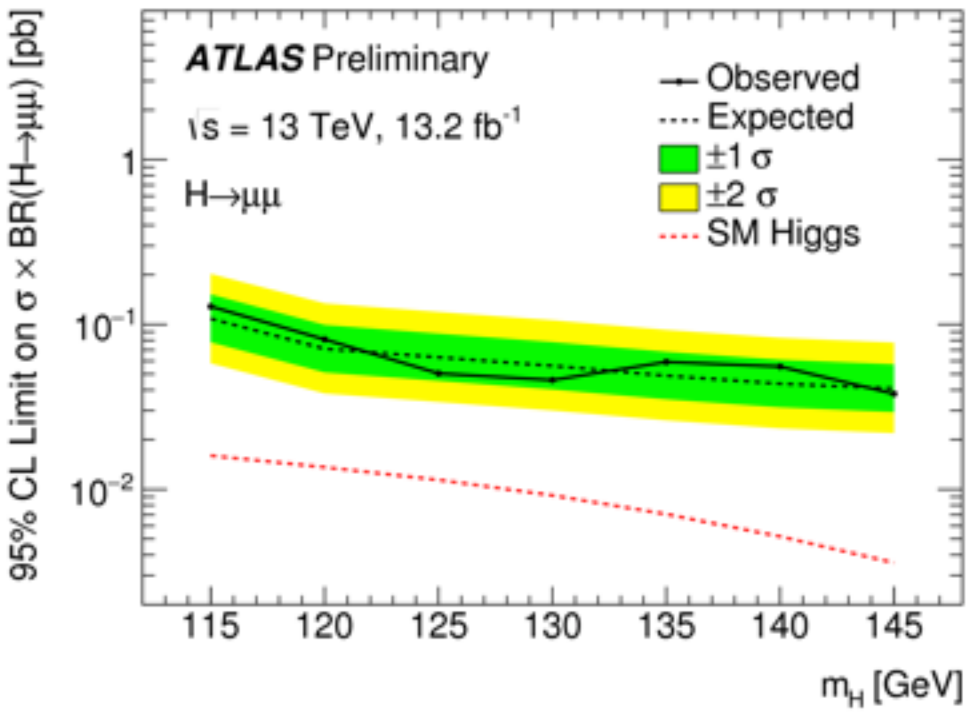
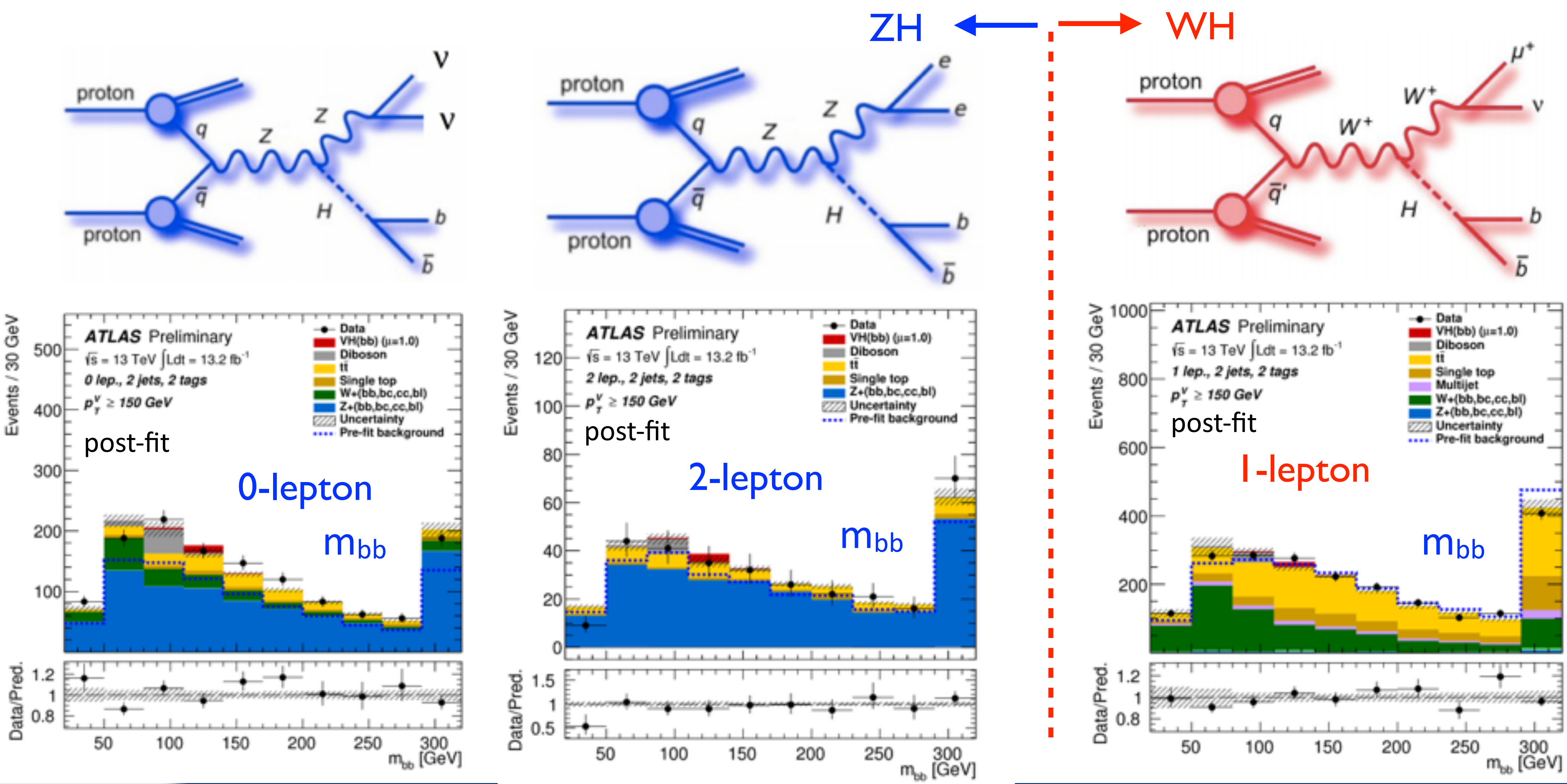


upper limit @95% CL	obs (exp)
ATLAS run 1+run 2	3.5 (4.5)
ATLAS run 2	4.4 (5.5)
ATLAS run 1	7.1 (7.2)
CMS run 1	7.4 (6.5)

VH (H→bb)

ATLAS-CONF-2016-091

- Final states with 0, 1 and 2 leptons and at least 2 jets, of which 2 b-tagged
- Higgs candidate built of 2 b-tagged jets
  - additional corrections for b-jets to improve m_{bb} resolution: *muon-in-jet*
  - *PtReco* (0- and 1-lepton), *kinematic LH fit* in 2-lepton channel
- Further categorisation based on p_T^V and nJets (2,3 or ≥3)
  - p_T^V defined as MET in 0-lepton channel; MET+$p_T(\ell)$ in 1-lepton channel; p_T of 2-lepton system
  - p_T^V >150 GeV in 0,1 lepton; p_T^V <150 GeV and p_T^V >150 GeV in 2-lepton

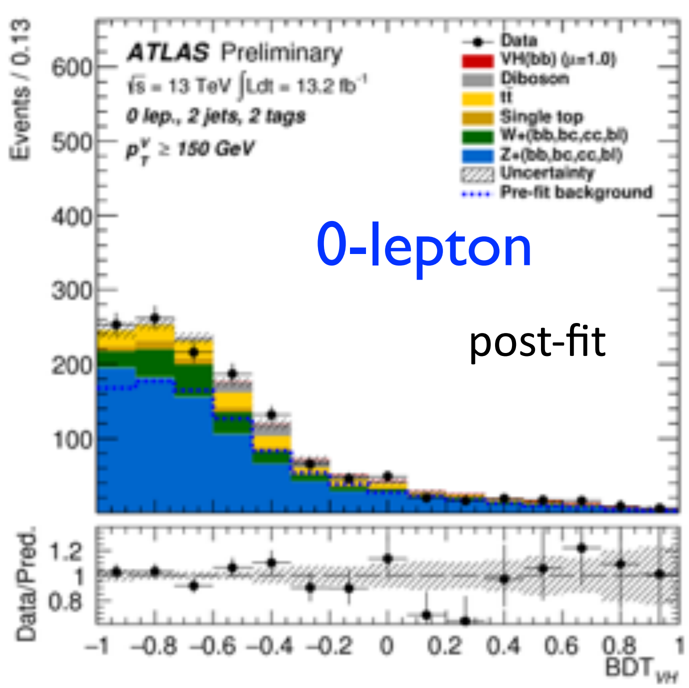


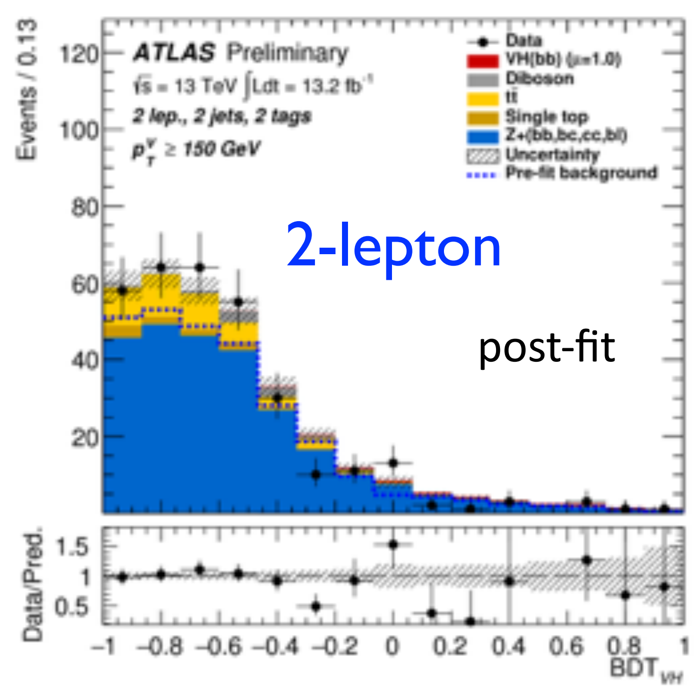
Signal extraction

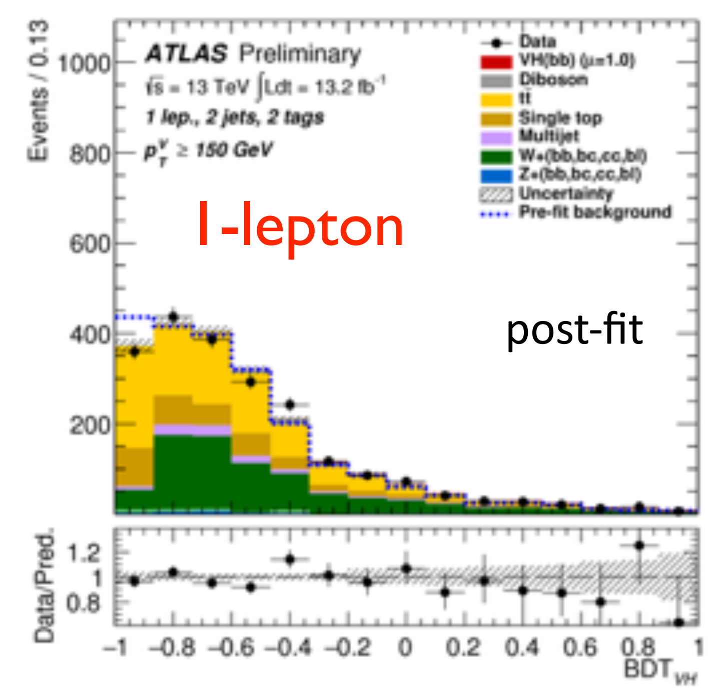
	p_T^V<150 GeV		p_T^V>150 GeV		
	2 jets	≥3 jets	2 jets	3 jets	≥3 jets
0-lepton	-	-	BDT	BDT	-
1-lepton	-	-	BDT	BDT	-
2-lepton	BDT	BDT	BDT	-	BDT

- Two types of BDTs: BDT_{VH} and BDT_{VZ}
  - m_{bb}, MET, p_T(b1), p_T(b2), ΔR(b1,b2) used in all channels
  - 1-lepton channel: m(top) and |ΔY(W,H)| to reject top pair background

ZH ← → WH







Signal extraction

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	2 jets	≥3 jets	2 jets	3 jets	≥3 jets
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1-lepton	-	-	BDT	BDT	-
2-lepton	BDT	BDT	BDT	-	BDT

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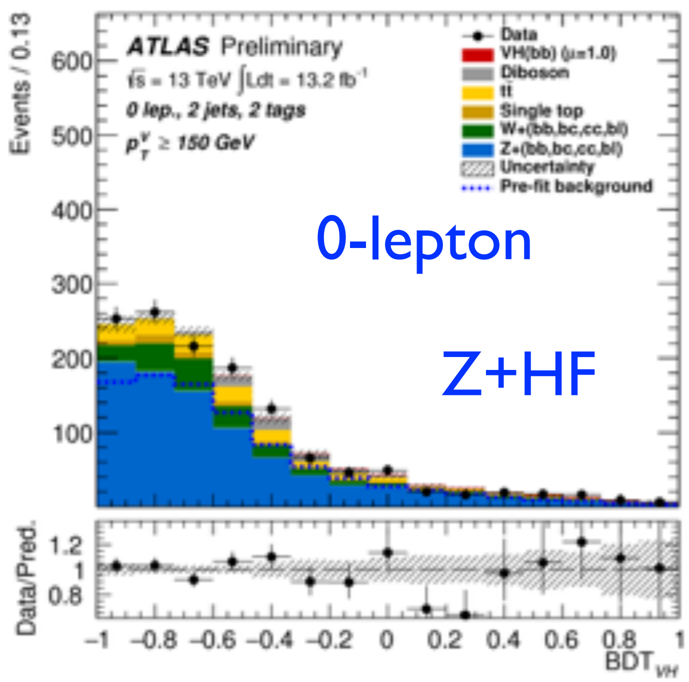
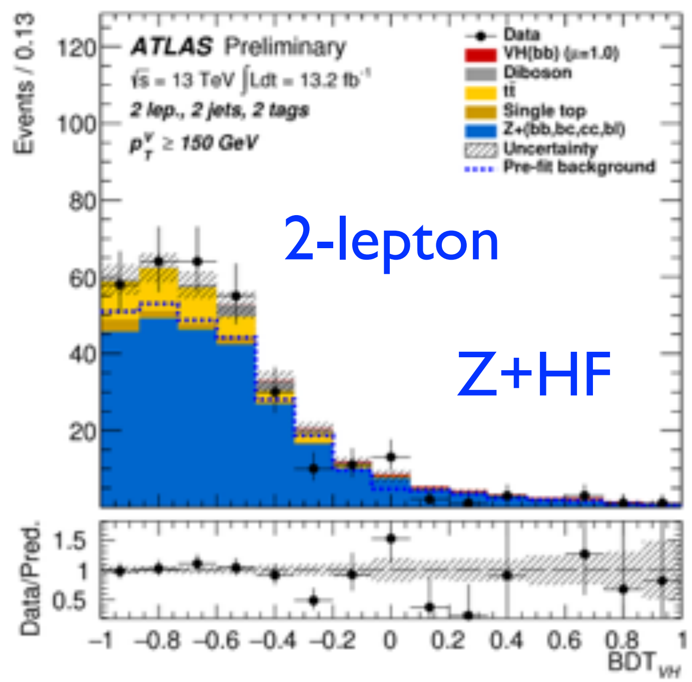
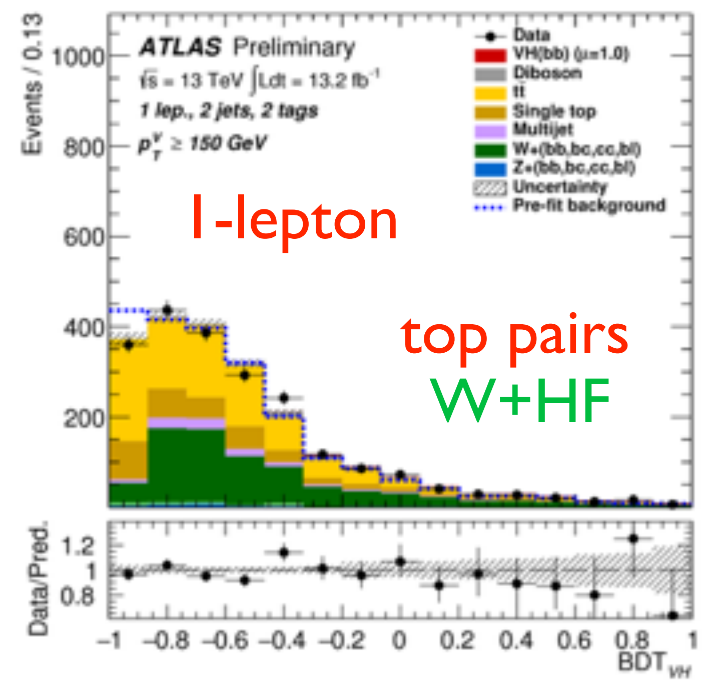




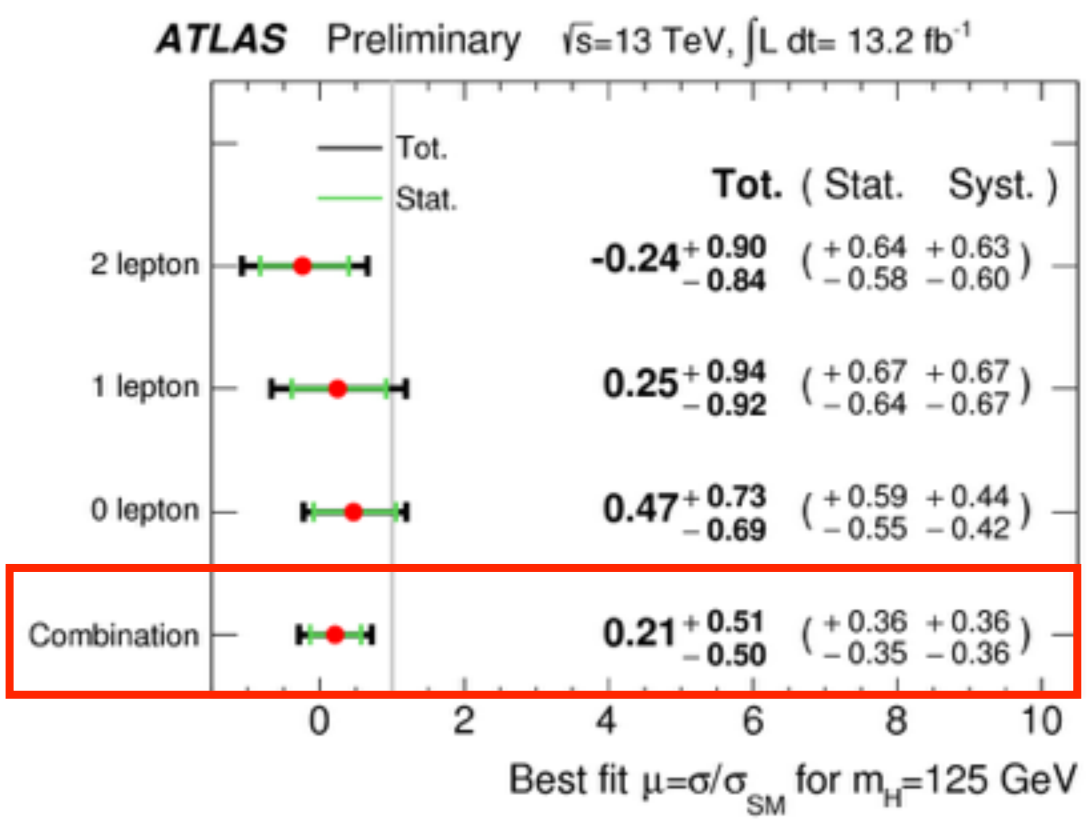


Background	V+jets	top pairs
baseline	Sherpa 2.2 (≤2p@NLO, 4p@LO)	Powheg+Py6
systematics	Fact, Renorm, CKKW, Resum scale, MG5_aMC+P8	Powheg+Hpp, MG5_aMC+Hpp, RadHi/RadLo
treatment	free: Z/W+HF (bb, bc, cc, bℓ) normalisation ; 2j/3j, 1ℓ/2ℓ(W); 2j/3j, 0ℓ/2ℓ(Z); bb/bc/bl/cc relative	free: 0+1-ℓ and 2-ℓ normalisations; 2j/3j ratio uncertainty

VH (H→bb) results

- Simultaneous fit to BDT distributions in 8 regions
  - uncertainties cover normalisation (overall and relative between analysis regions) and shape
    - derived for m_{bb} and p_T^V
  - free parameters have a large effect on signal strength
  - also important: b/c-tagging, Z+jets m_{bb} shape, ttbar model, MC statistics for background

Sample	Scale factor
$t\bar{t}$ 0+1-lepton	0.86 ± 0.13
$t\bar{t}$ 2-lepton	0.94 ± 0.09
W + HF	1.59 ± 0.39
Z + HF	1.04 ± 0.11



VZ fit result

$$\mu_{VZ} = 0.91 \pm 0.17(\mathrm{stat})^{+0.32}_{-0.27}(\mathrm{syst})$$

significance obs (exp) 3.0 (3.2) SD

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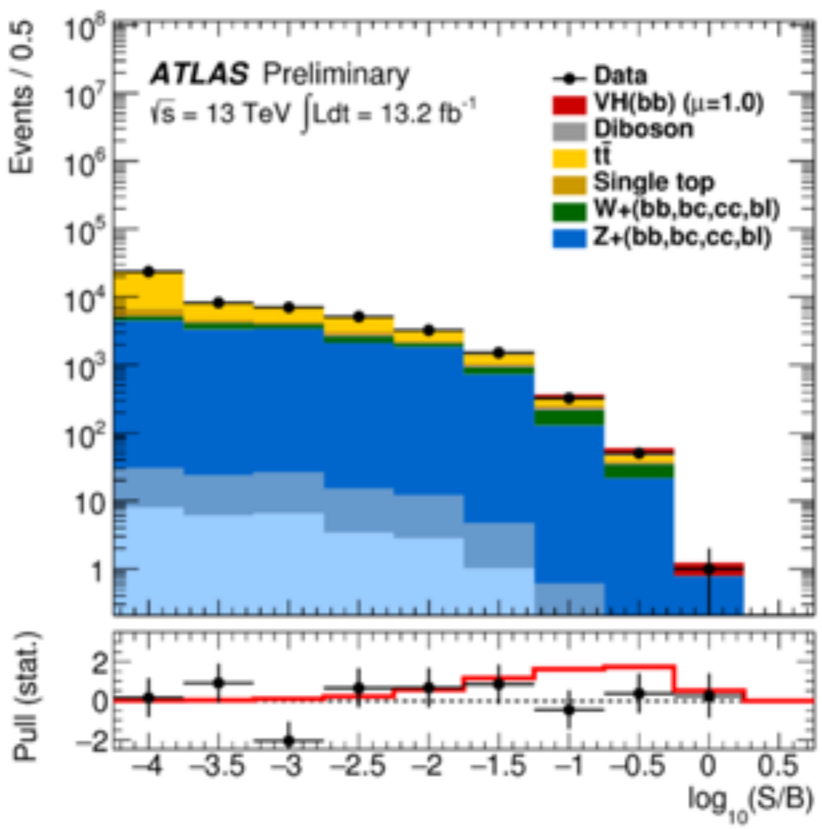
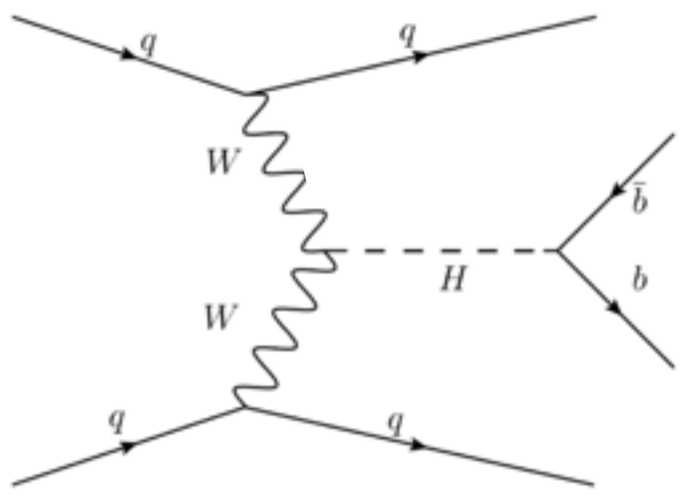


Data consistent with background only post-fit and also consistent with SM (μ=1)

	significance obs (exp) [σ]	μ
ATLAS run I	1.4 (2.6)	$0.51^{+0.40}_{-0.37}$
ATLAS run 2	0.42 (1.94)	$0.21^{+0.51}_{-0.50}$
CMS run I	2.1 (2.5)	0.89 ± 0.43
ATLAS+CMS run I	**2.6 (3.7)**	$\mathbf{0.70^{+0.29}_{-0.27}}$

More details in YSF talk by Jeff Hetherly: "Recent Vh, h→$b\bar{b}$ Analysis Results" on Friday

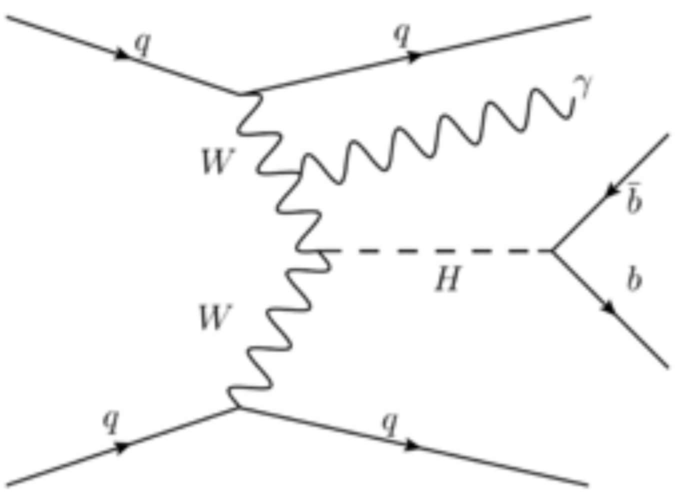
VBF H→bb



- VBF H→bb search suffers from large non-resonant *bbjj* background

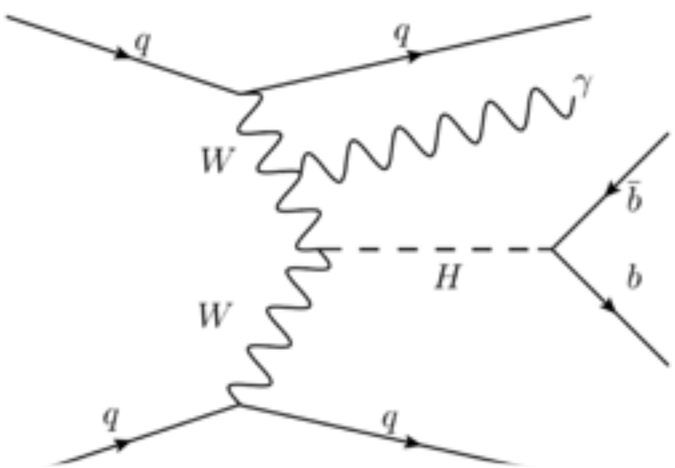
VBF $H \to bb$ with γ

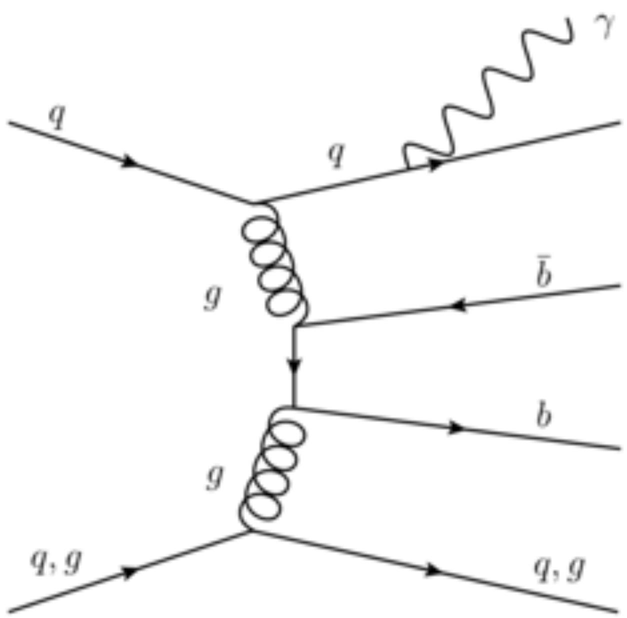
ATLAS-CONF-2016-063



- Require high p_T photon in the final state
  - provides a clean signature for efficient triggering
  - gluon-induced component of non-resonant bbjjγ is suppressed
  - destructive interference further suppresses central photon emissions
- Dramatically increases S/B in VBF mode

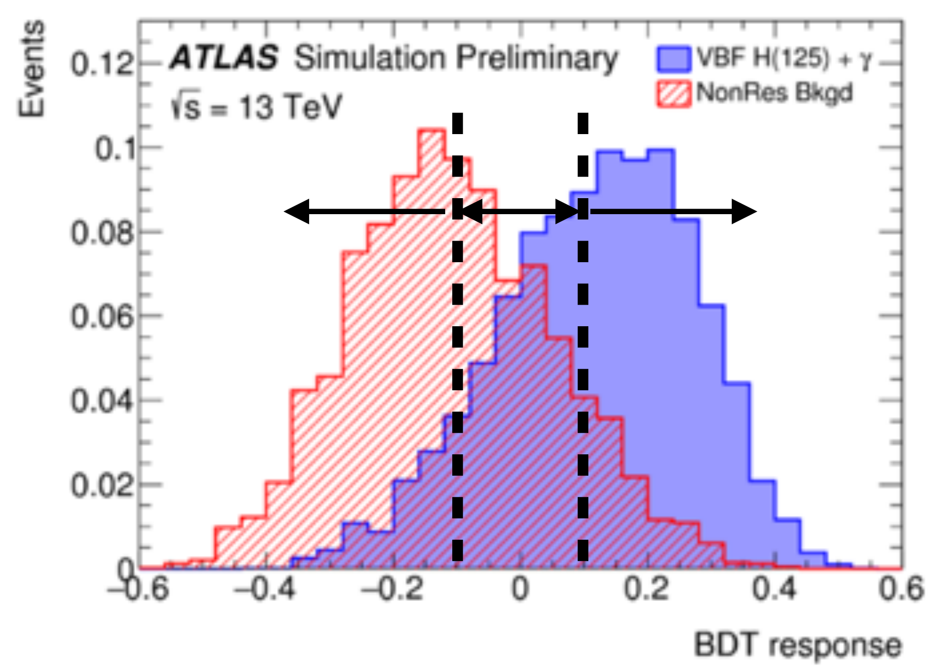
VBF $H \to bb$ with γ





- main background - non-resonant $bbjj\gamma$ production - determined from data
- smaller contribution from $Z\gamma$ + jets used for control measurement

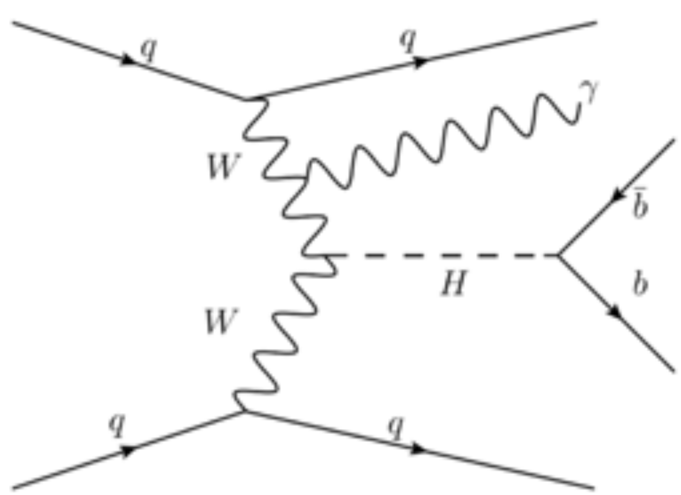
- Require high p_T photon in the final state
  - provides a clean signature for efficient triggering
  - gluon-induced component of non-resonant $bbjj\gamma$ is suppressed
  - destructive interference further suppresses central photon emissions
- Dramatically increases S/B in VBF mode
- Selection
  - one photon with p_T> 30 GeV
  - 4 jets two of which are central and b-tagged
  - $p_T(bb)$>80 GeV, VBF pair $m(jj)$>800 GeV



Variables:
angular separation $\Delta R(jet,\gamma)$
invariant mass of VBF par $m(jj)$
$\Delta\eta(jj)$
jet width

- Split events in 3 regions according to BDT
- Simultaneous fit to m_{bb} distributions in 3 regions

VBF $H \to bb$: results



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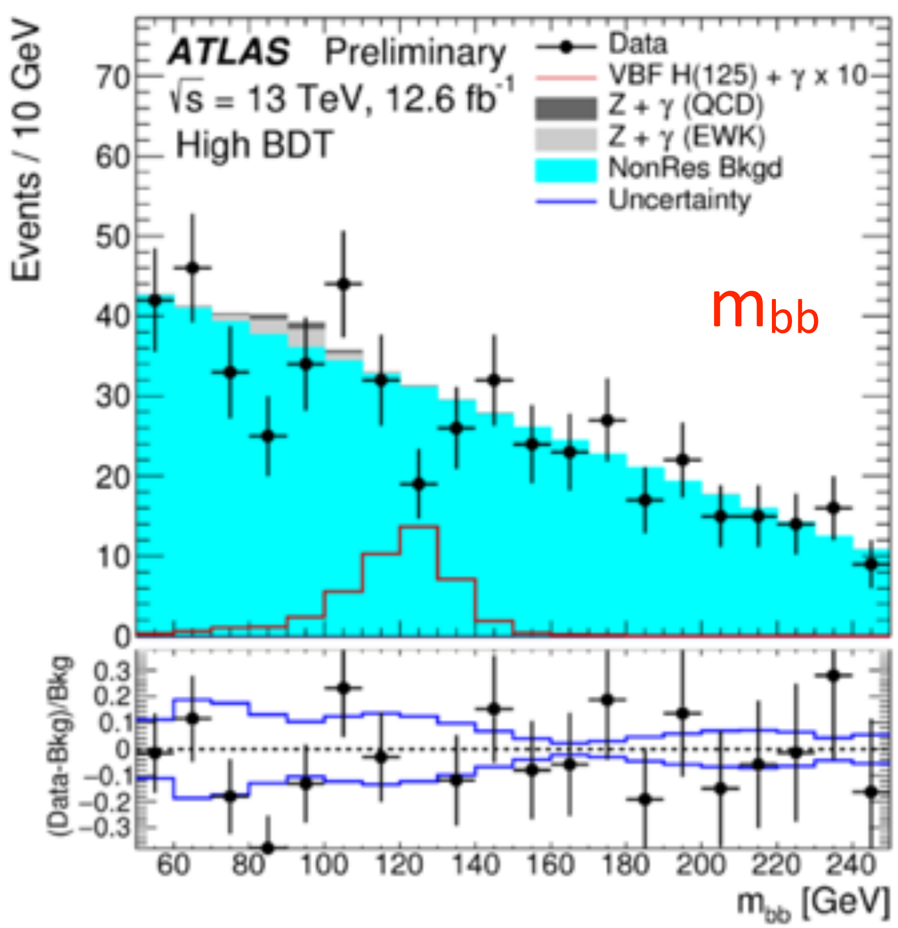


deficit of events near 125 GeV in high BDT region

upper limit @95% CL	obs (exp)	μ
ATLAS run I	4.4 (5.4)	-0.8 ± 2.3
ATLAS (VBF with γ) run 2	**4.0 (6.0)**	$-3.9^{+2.8}_{-2.7}$
CMS run I	5.5 (2.5)	$2.8^{+1.6}_{-1.4}$
CMS run 2	3.0 (5.0)	$-3.7^{+2.4}_{-2.5}$
CMS run I+run 2	3.4 (2.2)	$1.3^{+1.2}_{-1.1}$

Z+γ measurement with the same signature
obs (exp) limit: 2.0 (1.8), μ = 0.3±0.8

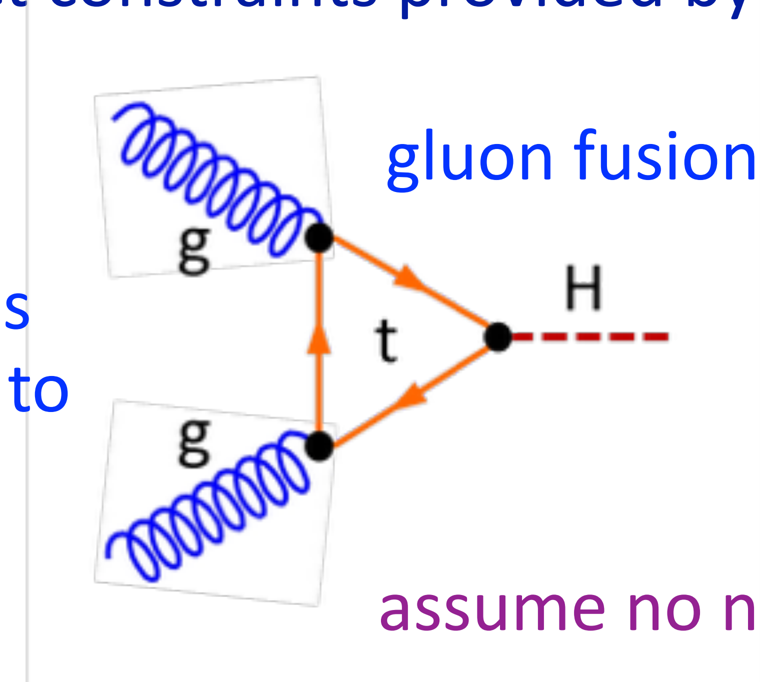
ttH production

- Top quark is the most strongly-coupled to Higgs SM particle (Y_t ~ 1)
- Precise measurement of top-Higgs Yukawa-coupling is critical to establish SM nature of Higgs boson and look for deviation from SM behaviour
  - most extensions of the SM predict the largest deviations from the SM couplings in ttH

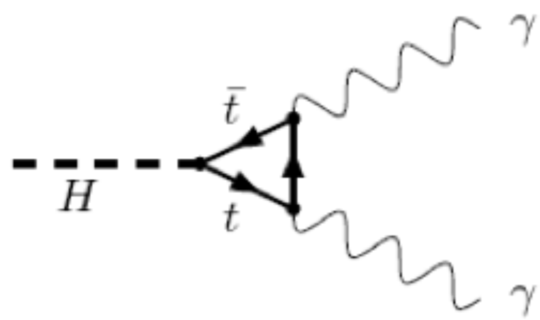
- Indirect constraints provided by the gluon fusion and via H→γγ decays

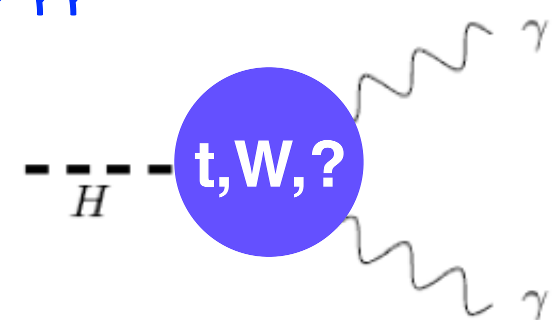
top-Higgs interactions contribute to the loops

gluon fusion



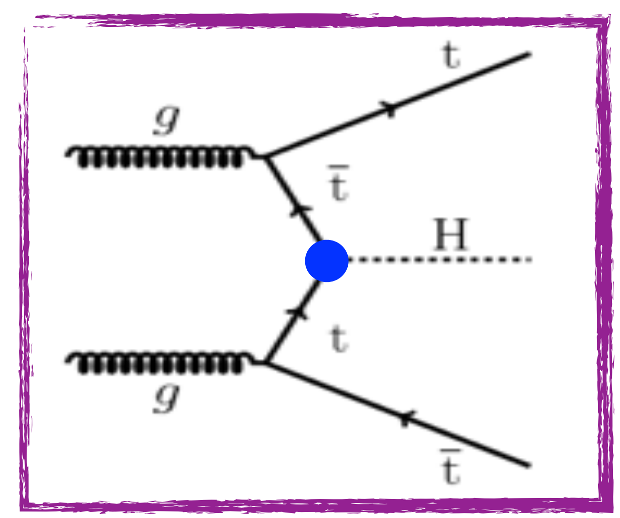
H→γγ





assume no new particles

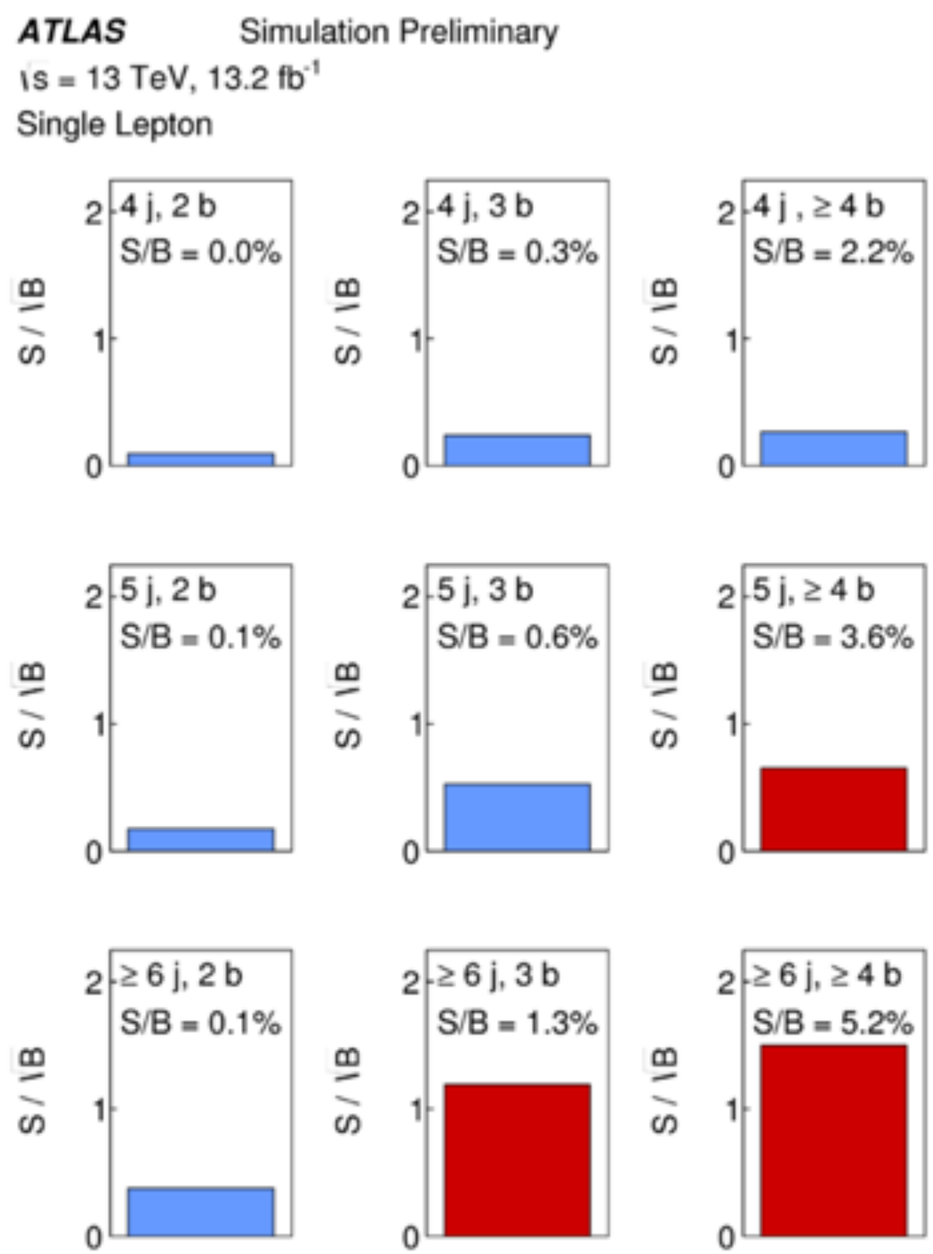
- Associated production probes directly Y_t at tree level

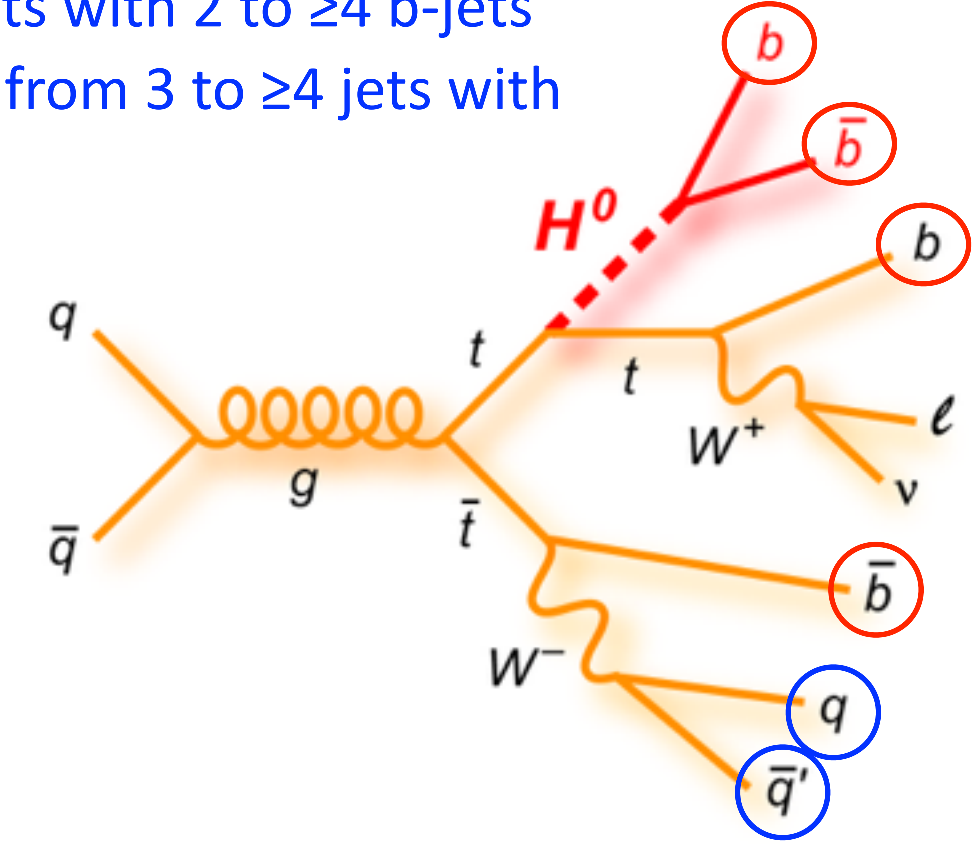


ttH (H→bb)

ATLAS-CONF-2016-080

- Event selection
  - Single lepton channel: 1 lepton (e or μ), from 4 to ≥6 jets with 2 to ≥4 b-jets
  - Dilepton channel: 2 opposite-sign leptons (ee, μμ, eμ), from 3 to ≥4 jets with 2 to ≥4 b-jets





- Categorise events by jet and b-jet multiplicity
  - take advantage of low S/B regions to constrain systematic uncertainties
  - maximise sensitivity by separating regions with different S/√B
- Build MVA discriminant to separate signal from background in signal-rich regions

Analysis strategy

single lepton channel

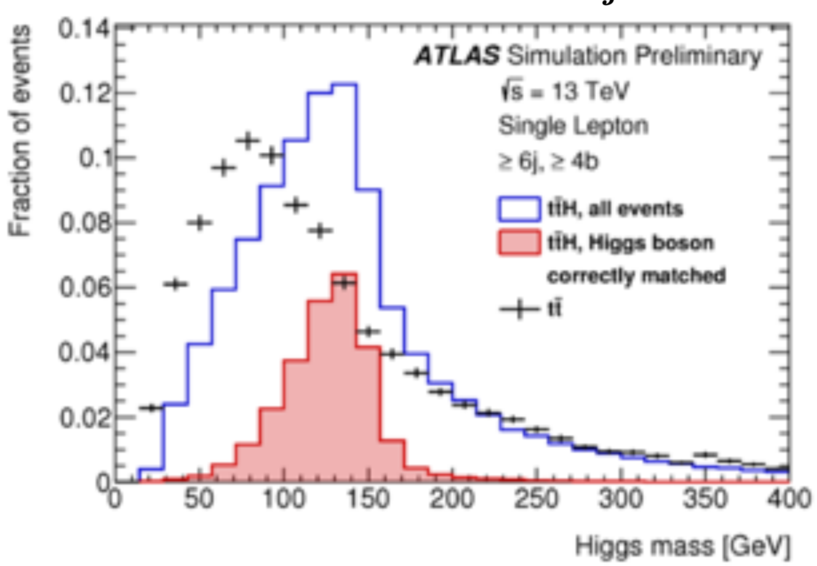
	2 b-tags	*3 b-tags*	*≥4 b-tags*
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	H_T^{had}	**BDT**
≥6 jets	H_T^{had}	**BDT**	**BDT**

$$H_T^{had} = \sum_{jets} p_T$$

dilepton channel

	2 b-tags	*3 b-tags*	*≥4 b-tags*
3 jets	H_T	**NN**	
≥4 jets	H_T	**BDT**	**BDT**

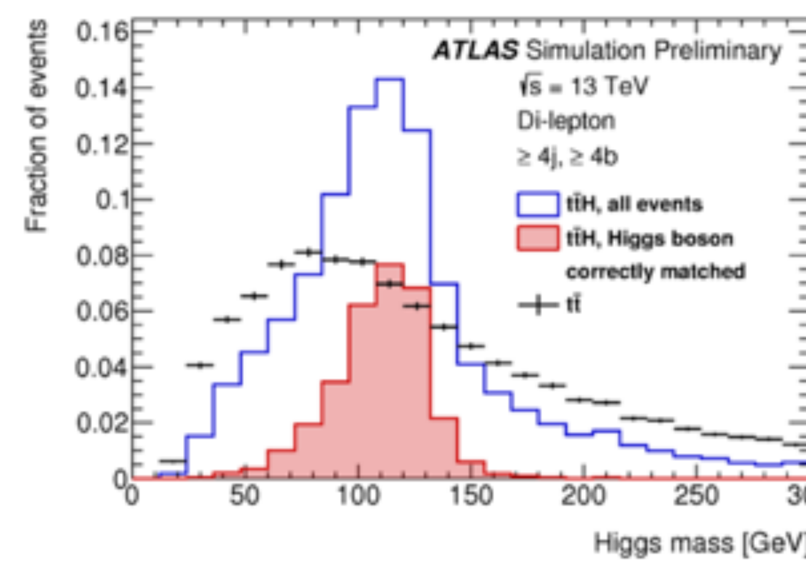
$$H_T = \sum_{jets} p_T + \sum_{lep} p_T$$



~12% (8%) efficiency to match all jets correctly in ≥6j, ≥4b region with (without) Higgs-related variables (max = 38%)

Reconstruction BDT

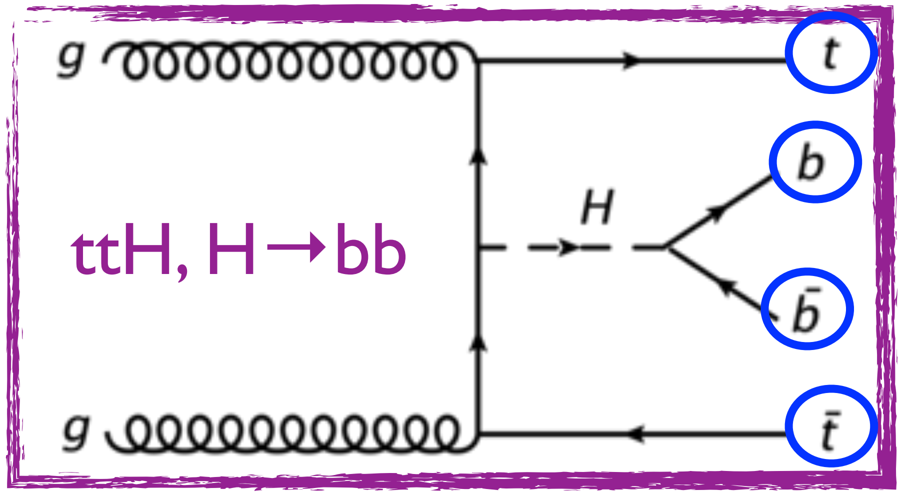
- trained to match reconstructed jets to partons
- with and without Higgs-related variables
- variables:
  - masses: $m_t(lep)$, $m_t(had)$, m_H
  - angular separation: $\Delta R(b_1, b_2)$, $\Delta R(b_1, \ell)$, $\Delta R(b \text{ from } t_{lep}, \ell)$

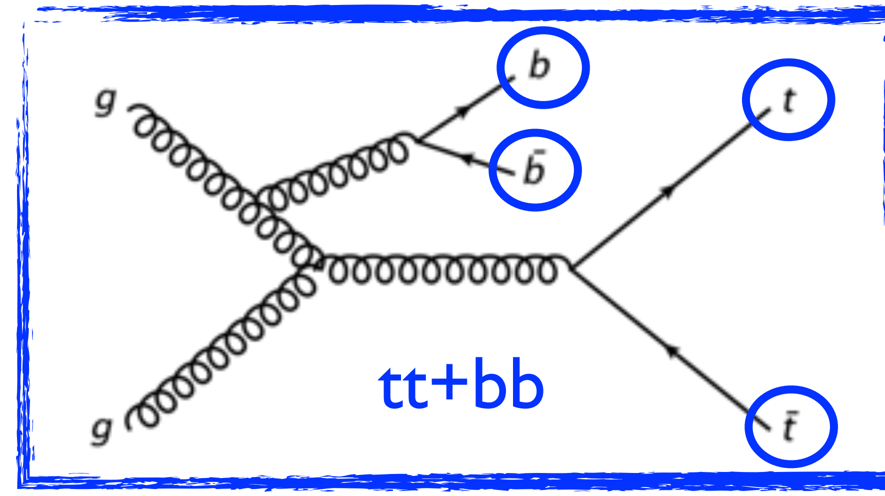


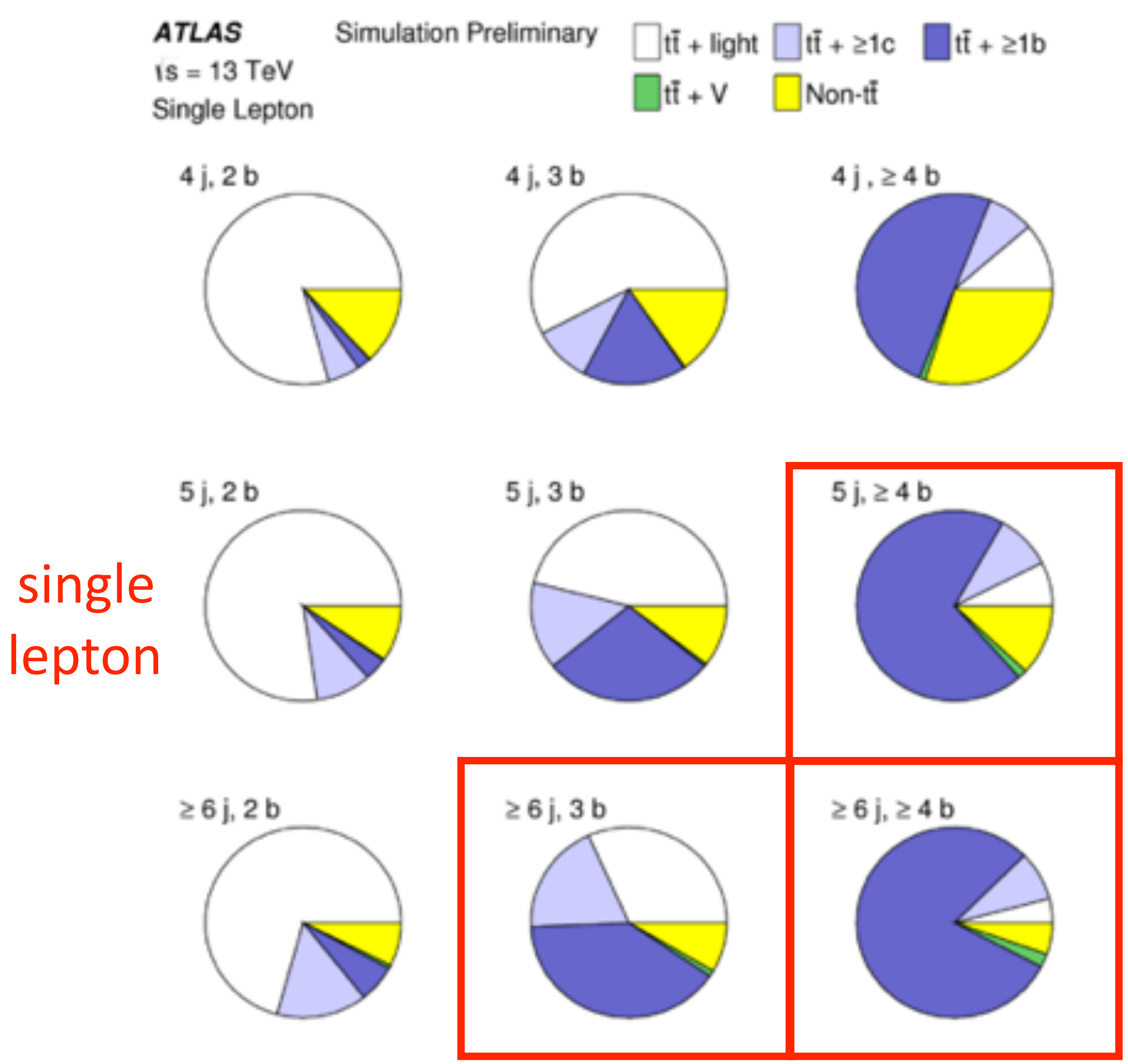
~42% (29%) efficiency to match all jets correctly in ≥4j, ≥4b region with (without) Higgs-related variables (max = 93%)

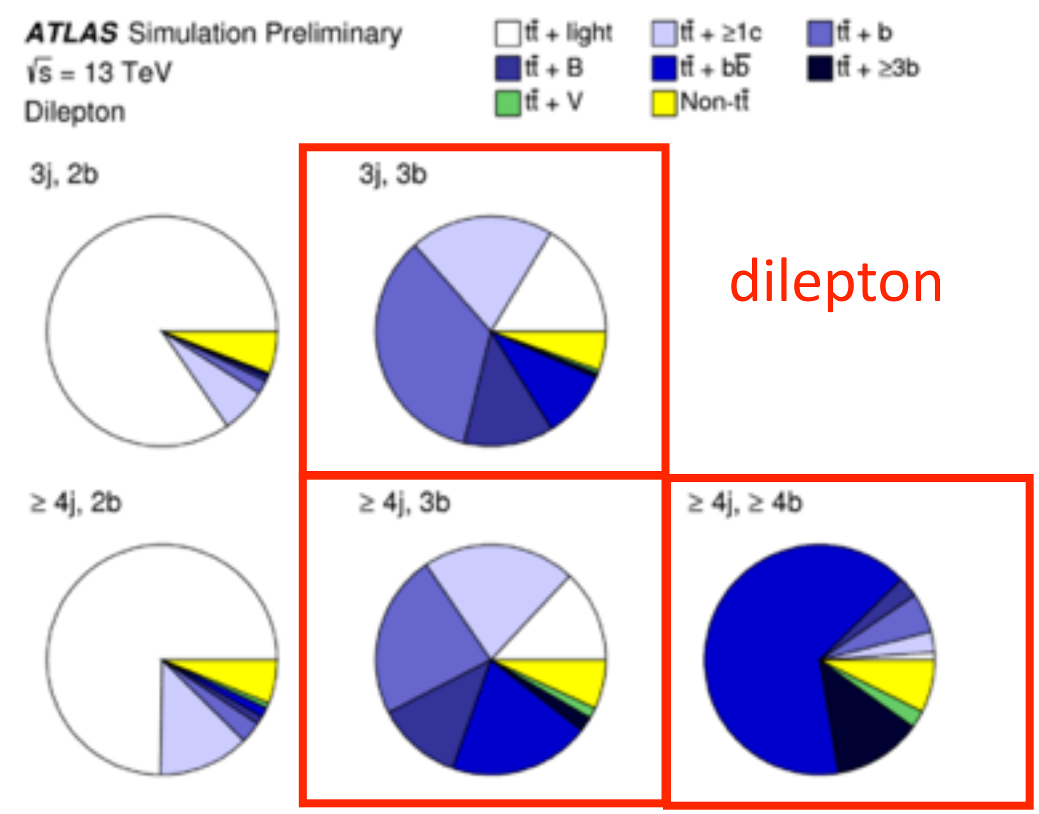
- Classification BDT
  - combines output of recoBDT with other variables to discriminate signal from background
  - distributions are used in the fit to data
- NN in 3j 3b region without reconstruction

Background composition







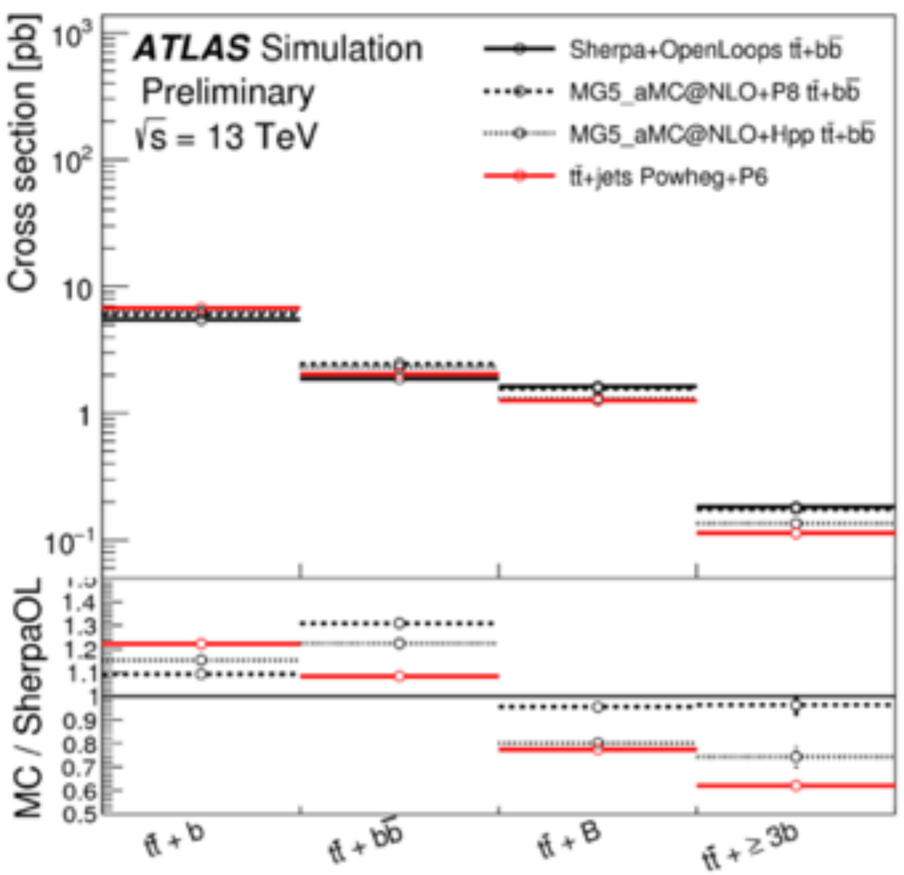


- Detailed classification
  - tt+≥1b: tt+b, tt+B, tt+bb, tt+≥3b
  - used to apply corrections and estimate uncertainties

Background model

- tt+jets
  - tt+light/tt+≥1c nominal (Powheg+Py6) and alternative ttbar samples are reweighted to NNLO theory prediction (sequential p_T(ttbar) and p_T(top) reweighting)
  - tt+≥1b nominal and alternative are reweighted to Sherpa OpenLoops

- tt+jets systematics
  - decorrelated between tt+light, tt+≥1c and tt+≥1b
  - for all three components:
    - ISR/FSR radiation
    - parton shower and hadronisation
    - NLO MC generator
  - tt+light, tt+≥1c: uncertainty on p_T(top) and p_T(ttbar)
  - tt+≥1b
    - variations of SherpaOL 4F settings
    - alternative generator MG5_aMC@NLO (4F)
    - alternative PS: MG5_aMC@NLO (4F)+P8 or H++



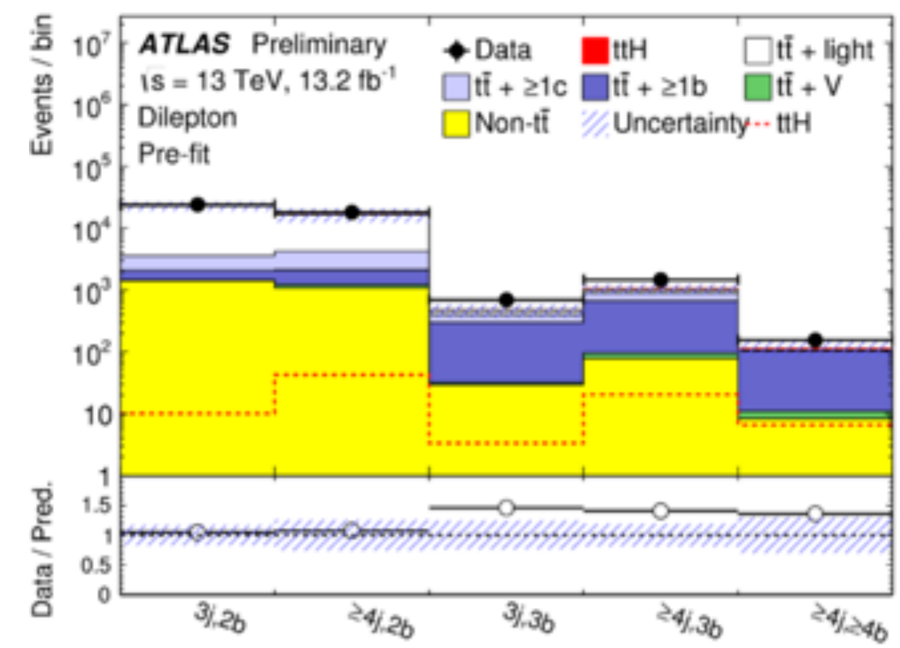
tt+≥1c and tt+≥1b normalisations are free parameters of the fit

Signal extraction

- Simultaneous fit to discriminants in 6 signal and 8 control regions
- Significant reduction of uncertainties post-fit

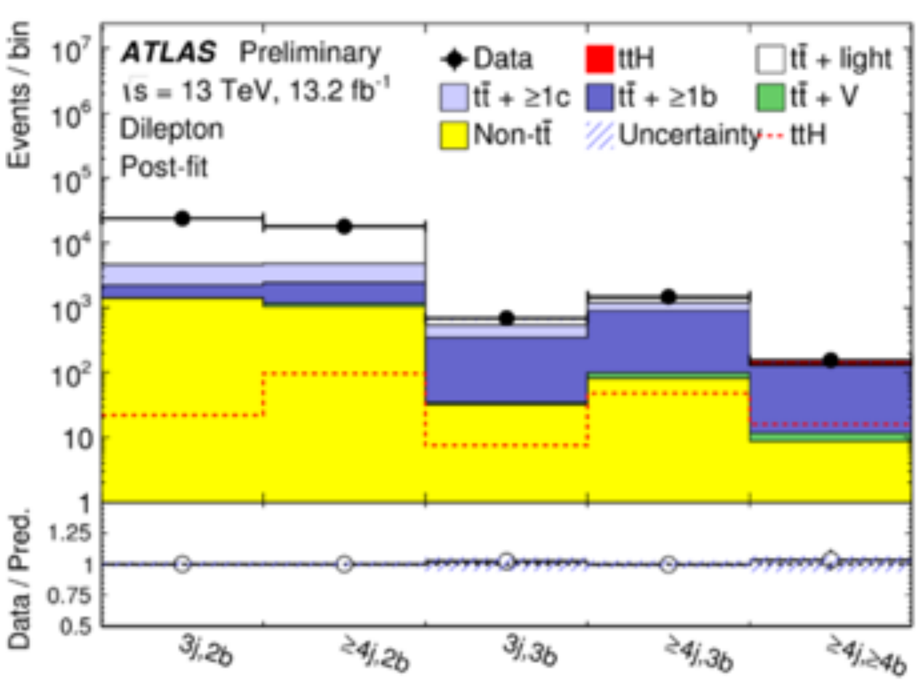
dilepton channel BDT

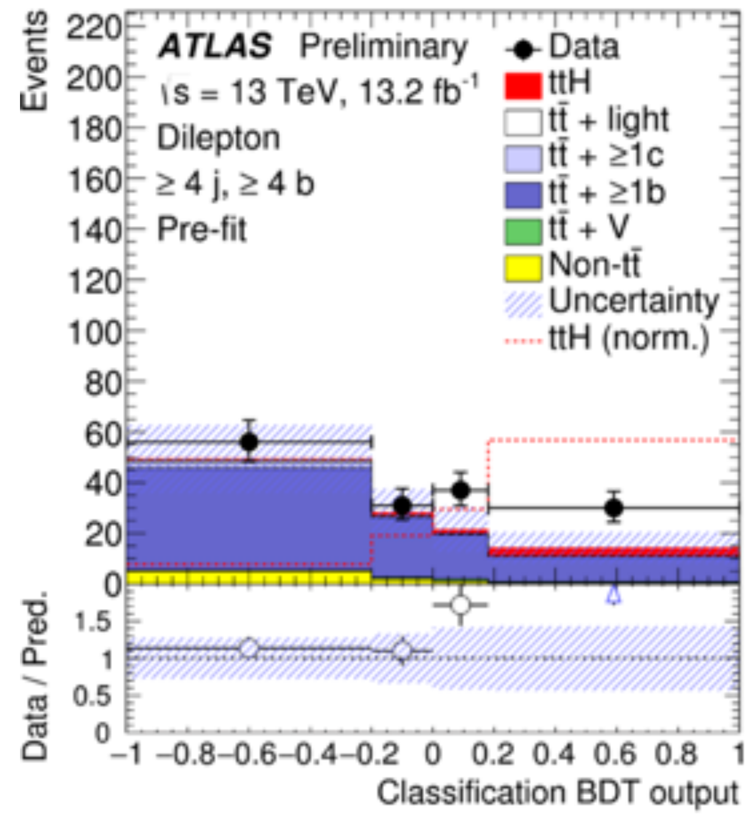
single lepton channel BDT

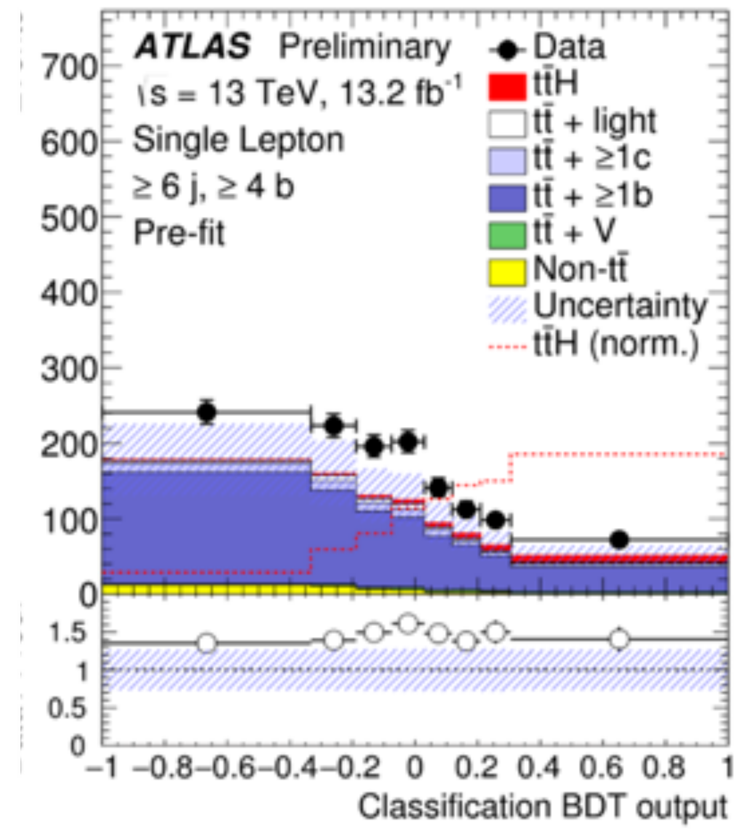


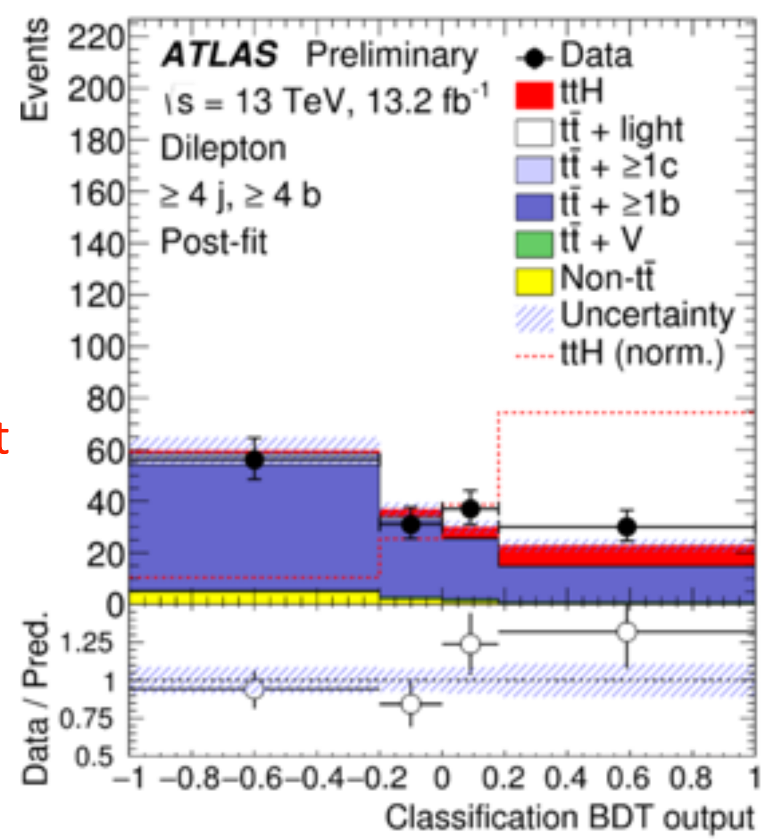
before the fit

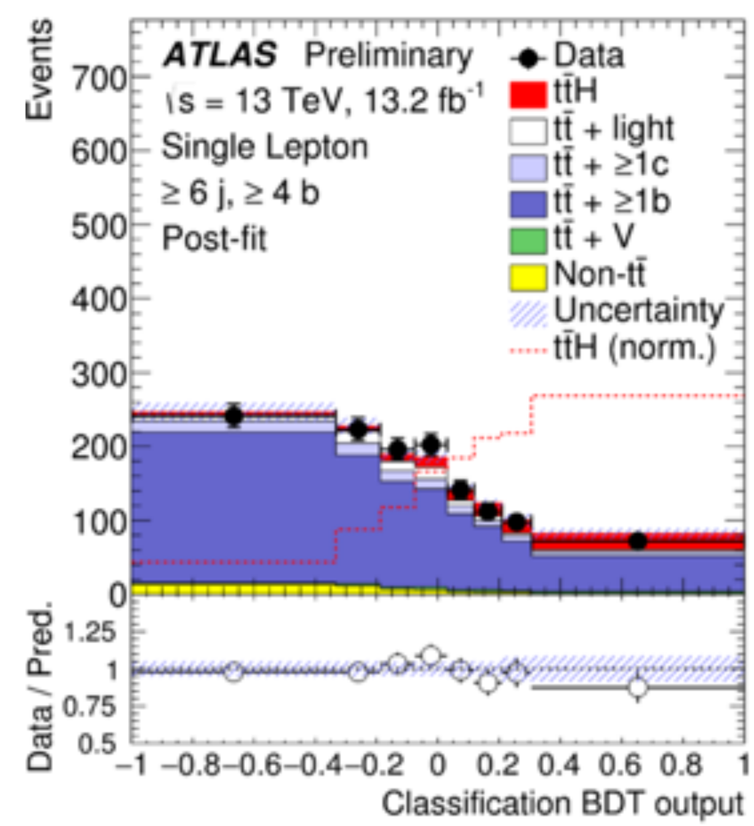
after the fit



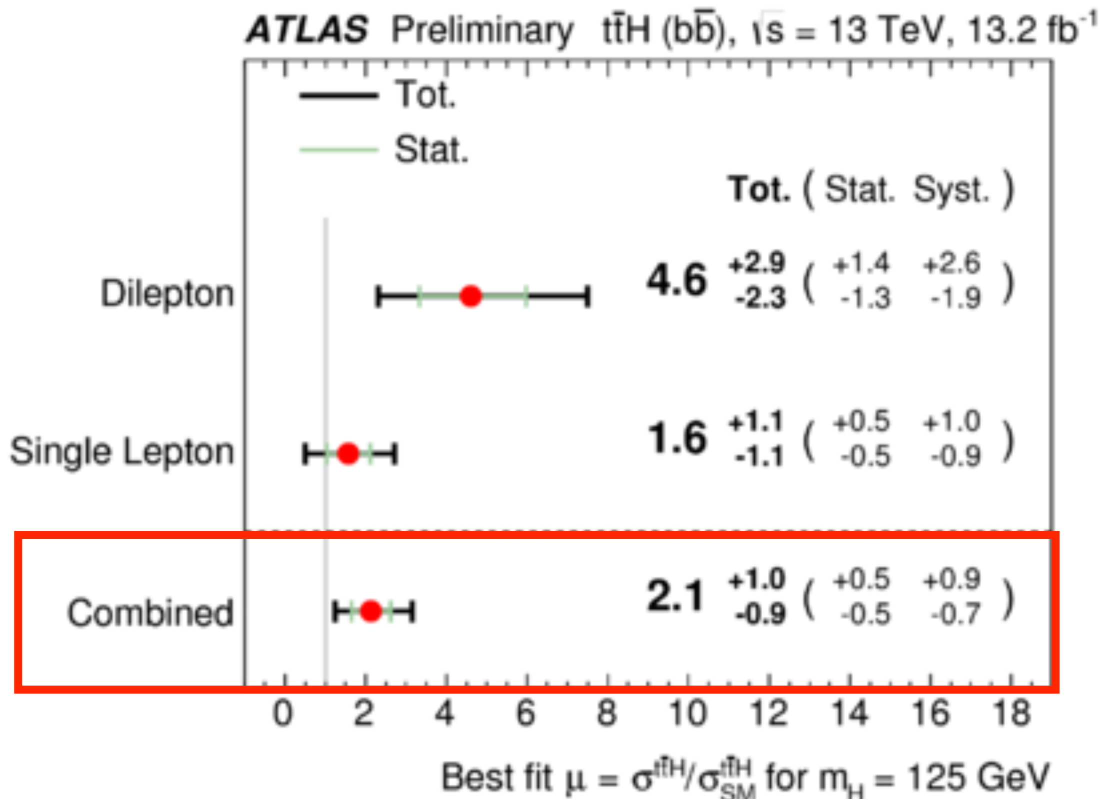


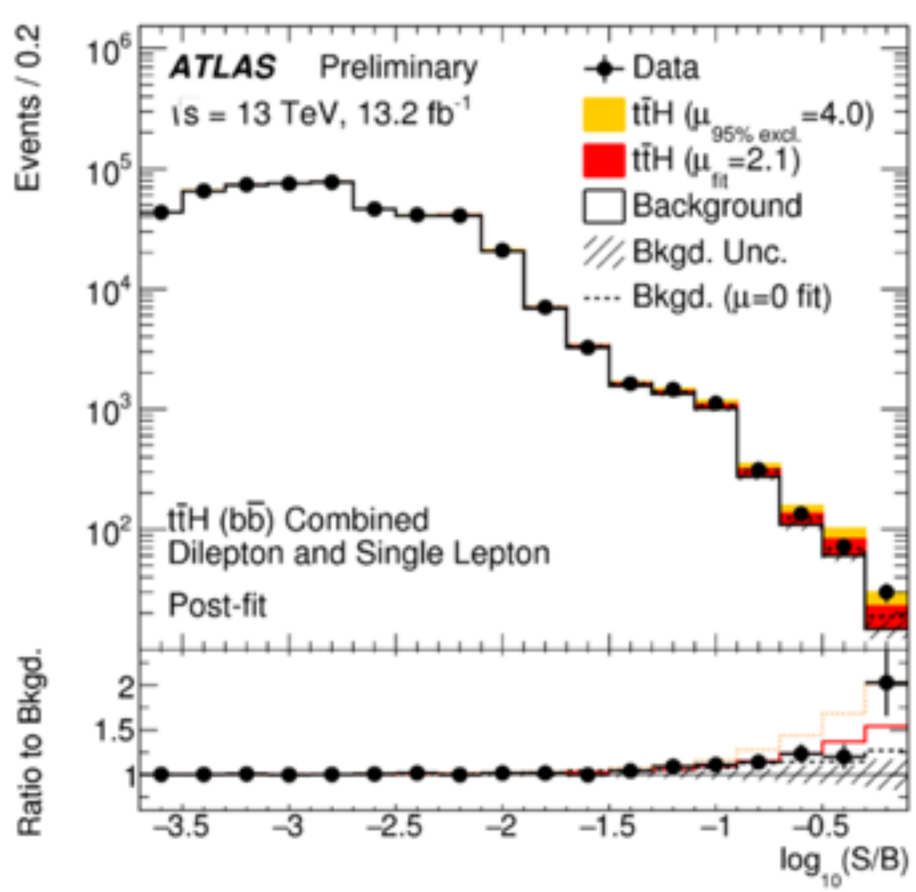






Results



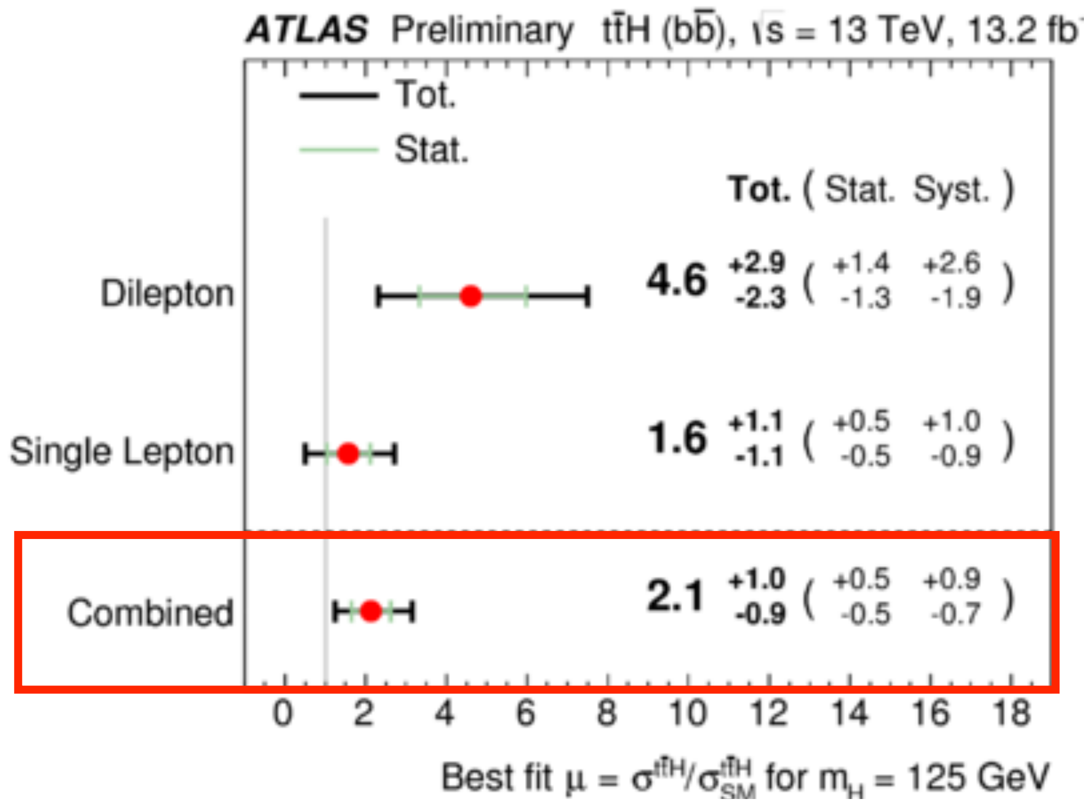


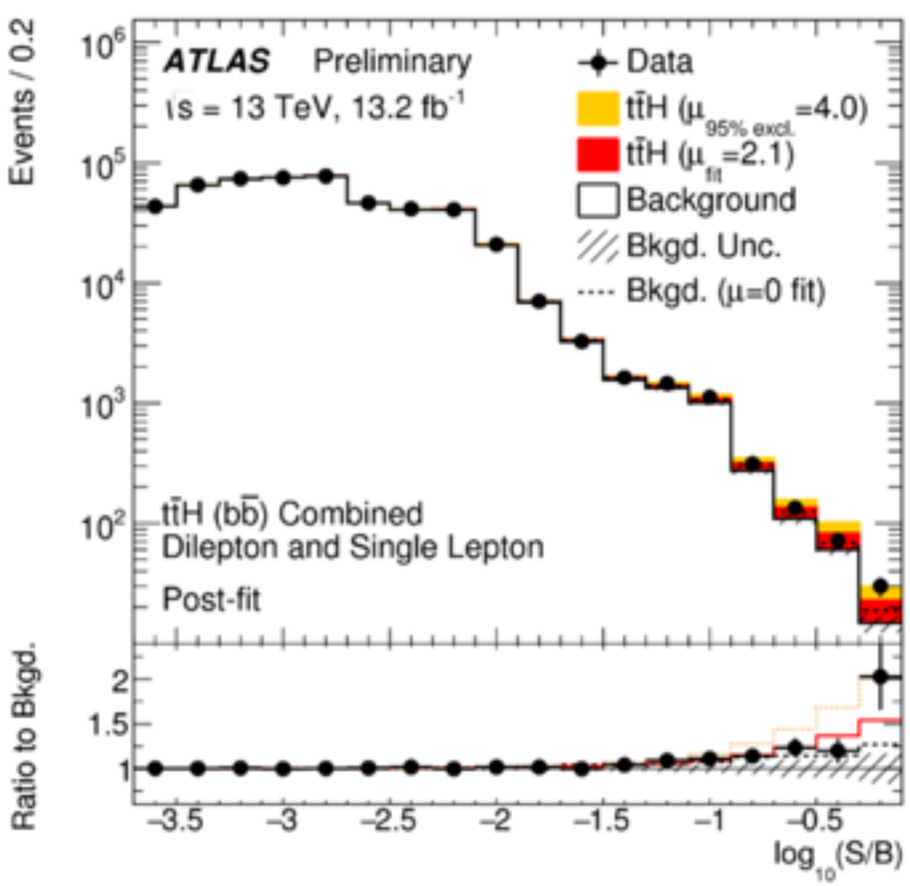
tt+≥1c and tt+≥1b normalisations post-fit

$$k_{t\bar{t}+\geq 1b} = 1.33^{+0.18}_{-0.17}$$

$$k_{t\bar{t}+\geq 1c} = 1.31^{+0.53}_{-0.40}$$

Results



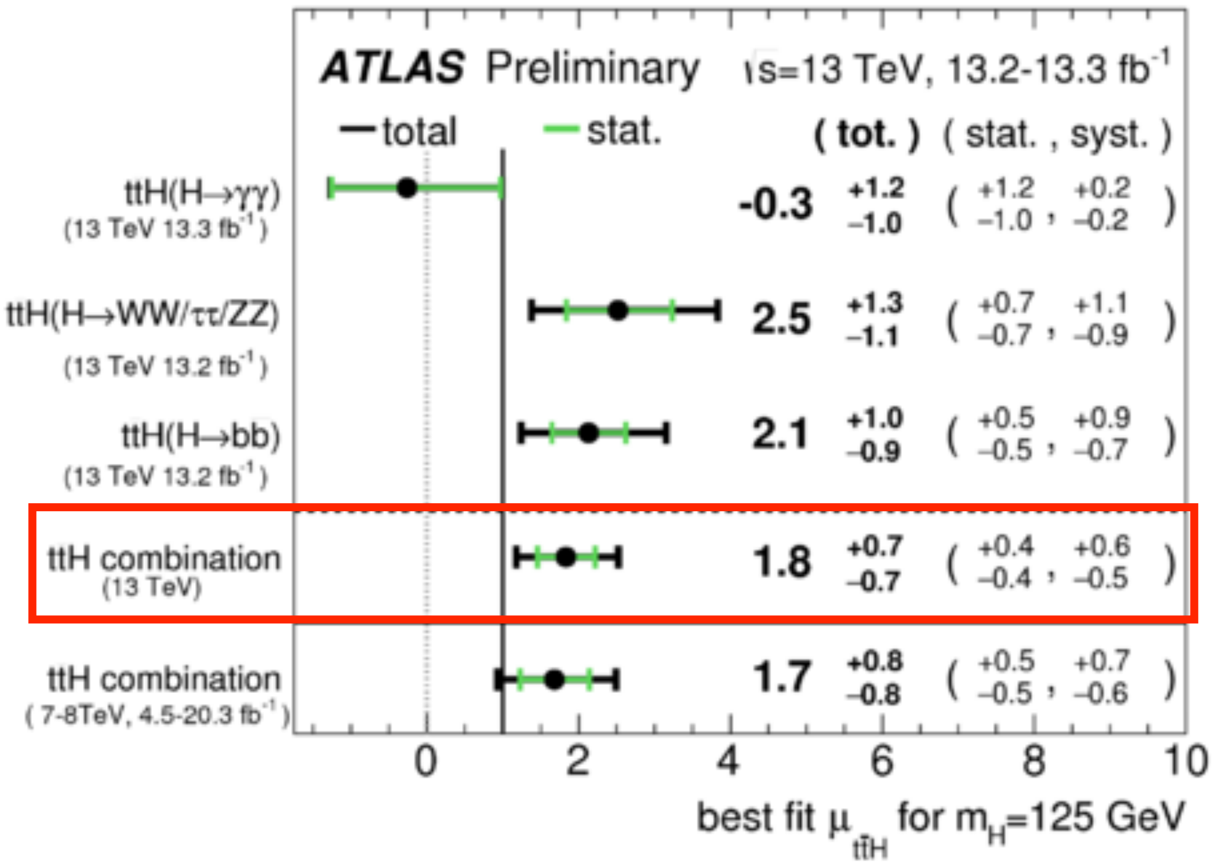


Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

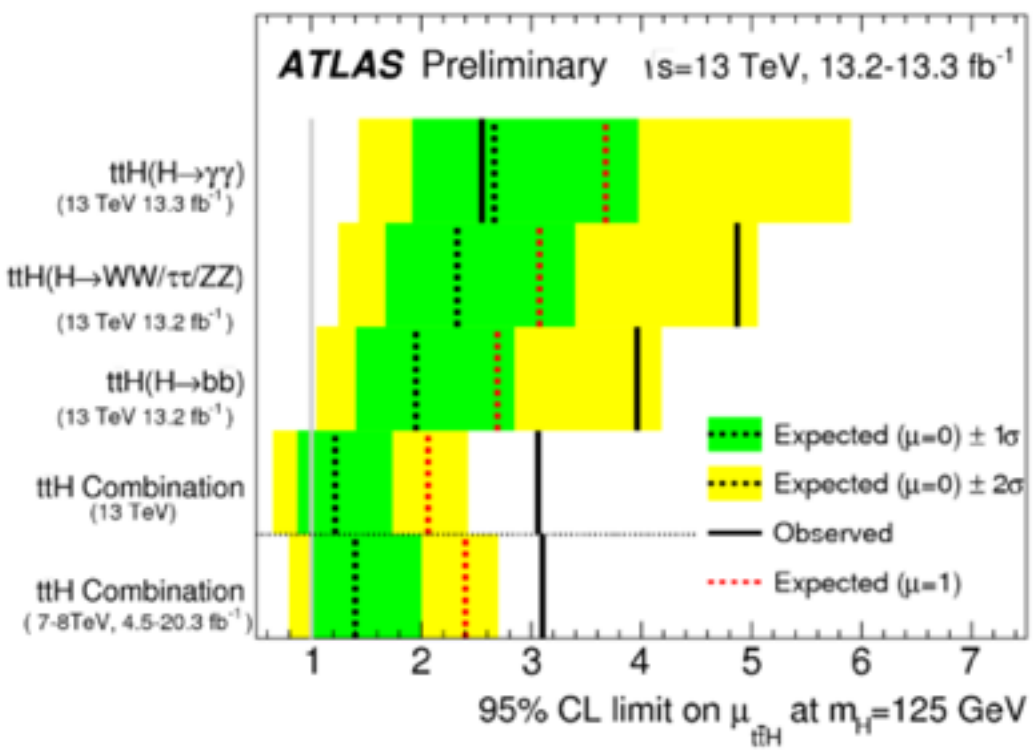
	significance obs (exp) [σ]	μ
ATLAS run 1	1.4 (1.1)	1.5 ± 1.1
ATLAS run 2	2.4 (1.2)	$2.1^{+1.0}_{-0.9}$
CMS run 2 (2.7 fb⁻¹)		-2.0 ± 1.8

ttH combination

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

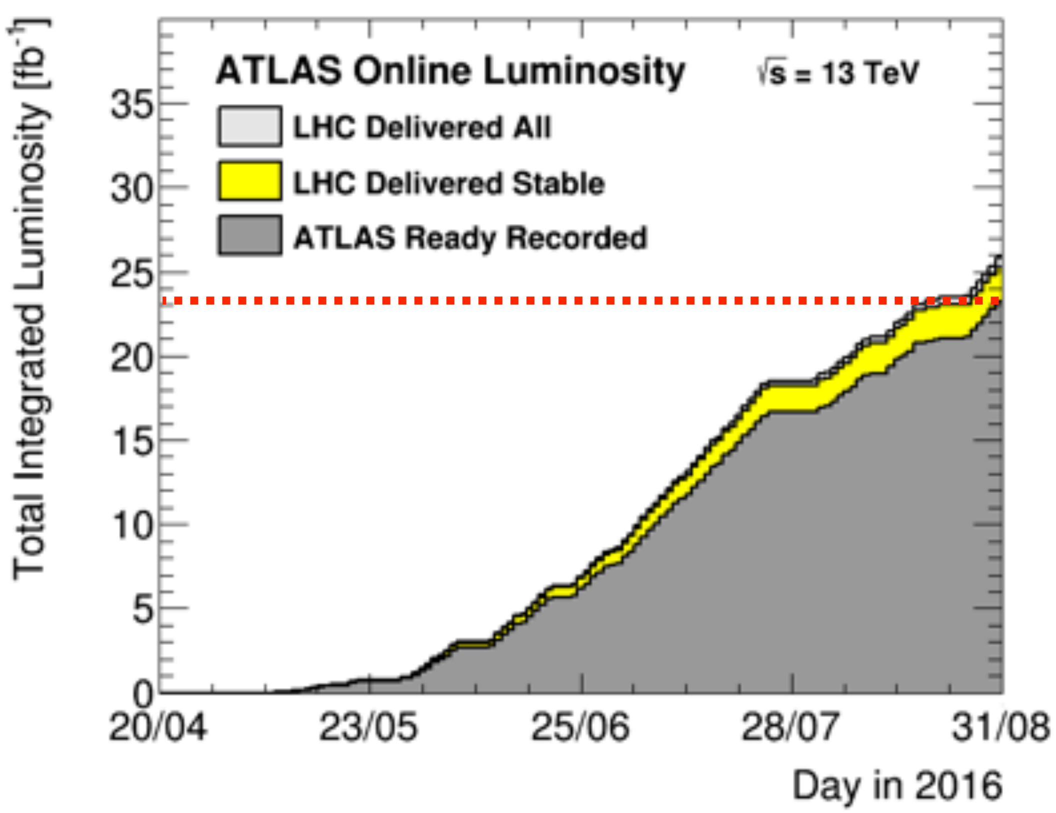


	significance obs (exp) [σ]	μ
ATLAS run I	2.33 (1.53)	1.7 ± 0.8
ATLAS run 2	2.8 (1.8)	1.8 ± 0.7
CMS run I	3.4 (1.2)	$2.8^{+1.0}_{-0.9}$
ATLAS+CMS run I	4.4 (2.0)	$2.3^{+0.7}_{-0.6}$

Conclusion and outlook

- ATLAS performed searches for Higgs boson decaying in two fermions with up to 13.2 fb^{-1} of data at 13 TeV
- New results are available for $H\rightarrow bb$ and $H\rightarrow\mu\mu$ decay channels
- Sensitivity of $H\rightarrow\mu\mu$ search is greatly improved with respect to run 1
- Combination of ttH searches in various final states was performed and it surpassed sensitivity of run 1 ttH search

Much more data is already available!



23 fb^{-1}

Backup

ttH: complete systematics

Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	$\pm 6\%$	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_R, μ_F, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_T	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC + Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

MC simulation details

tt inclusive MC model (5F)

ME gen.	Powheg-Box	Powheg-Box	MG5_aMC	Powheg-Box	Powheg-Box
PS/UE gen.	Pythia 6.428	Herwig++ 2.7.1	Herwig++ 2.7.1	Pythia 6.428	Pythia 6.428
Ren. scale	$\sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T},t}^2 + p_{\mathrm{T},\bar{t}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T},t}^2}$
Fact. scale	$\sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T},t}^2 + p_{\mathrm{T},\bar{t}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T},t}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T},t}^2}$
hdamp	m_t	m_t	–	$2 \cdot m_t$	m_t
ME PDF	CT10	CT10	CT10	CT10	CT10
PS/UE PDF	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1
Tune	P2012	UE-EE5	UE-EE5	P2012 radHi	P2012 radLo

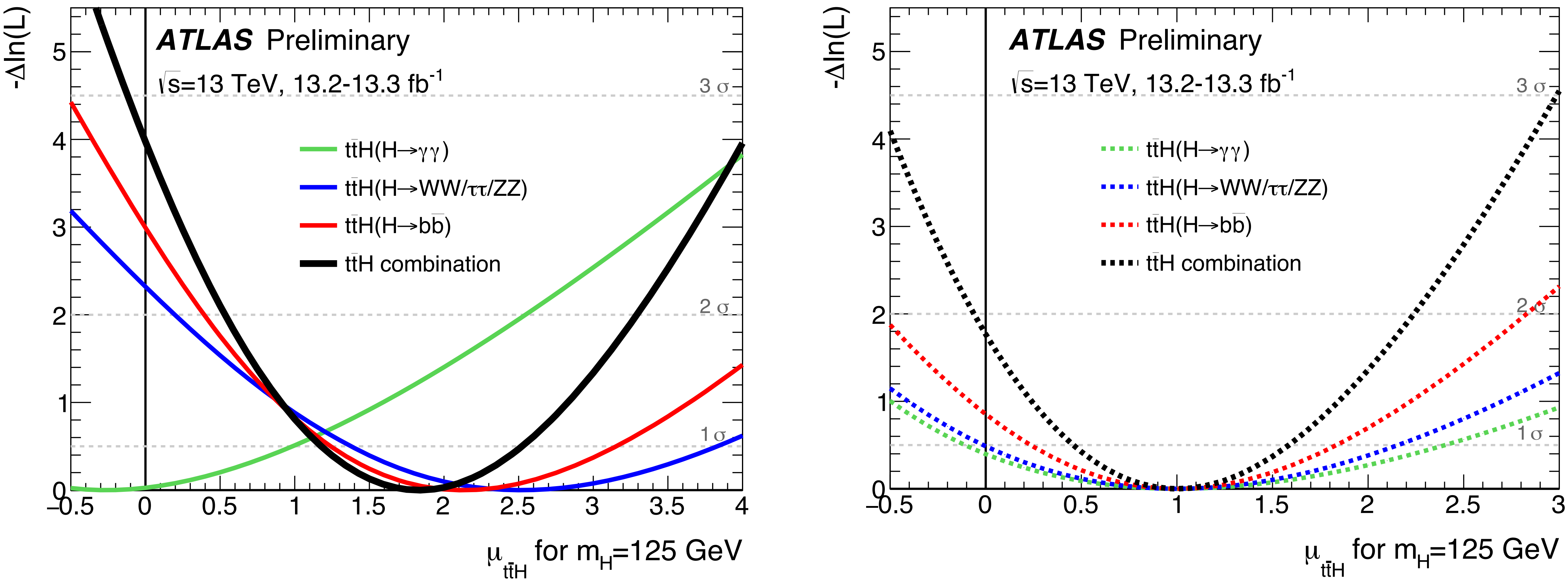
tt+bb MC model (4F)

ME gen.	MG5_aMC	MG5_aMC	SherpaOL
PS/UE gen.	Herwig++ 2.7.1	Pythia 8.210	Sherpa
Renorm. scale	μ_{CMMPS}	μ_{CMMPS}	μ_{CMMPS}
Fact. scale	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$
Resumm. scale	$f_Q\sqrt{\hat{s}}$	$f_Q\sqrt{\hat{s}}$	$H_{\mathrm{T}}/2$
ME PDF	NNPDF3.0 4F	NNPDF3.0 4F	CT10 4F
PS/UE PDF	CTEQ6L1	NNPDF2.3	
Tune	UE-EE-5	A14	Author's tune

ttH combination systematics

Uncertainty Source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	$+0.34$	-0.33
Jet flavour tagging	$+0.19$	-0.19
Background model statistics	$+0.18$	-0.18
$t\bar{t}+\geq 1c$ modelling	$+0.17$	-0.17
Jet energy scale and resolution	$+0.18$	-0.18
$t\bar{t}H$ modelling	$+0.20$	-0.13
$t\bar{t}$+light modelling	$+0.14$	-0.14
Other background modelling	$+0.16$	-0.15
Fake lepton uncertainties	$+0.11$	-0.12
Jet-vertex association, pileup modelling	$+0.09$	-0.09
Luminosity	$+0.09$	-0.09
$t\bar{t}Z$ modelling	$+0.08$	-0.07
Light lepton (e, μ), photon, and τ ID, isolation, trigger	$+0.04$	-0.04
Total systematic uncertainty	$+0.57$	-0.54
$t\bar{t}+\geq 1b$ normalisation	$+0.24$	-0.24
$t\bar{t}+\geq 1c$ normalisation	$+0.11$	-0.11
Statistical uncertainty	$+0.38$	-0.38
Total uncertainty	$+0.69$	-0.66

ttH combination LH curves

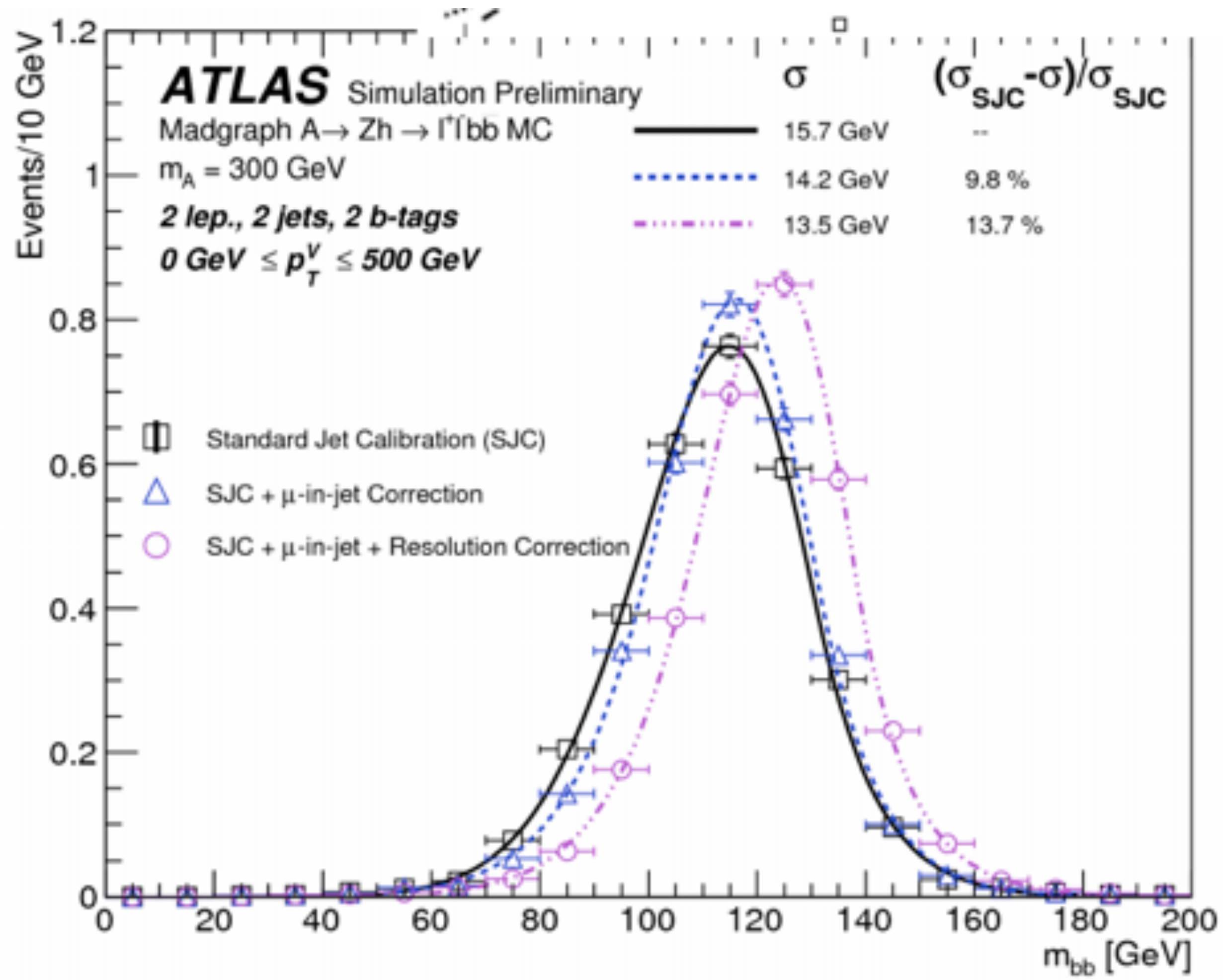


VH selection details

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		
$\min\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})$	$> 20^{\circ}$	-	-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, h)$	$> 120^{\circ}$	-	-
$\Delta\phi(\mathrm{jet1,jet2})$	$< 140^{\circ}$	-	-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, E_{\mathrm{T},trk}^{\mathrm{miss}})$	$< 90^{\circ}$	-	-
p_{T}^{V} regions	[0, 150] GeV (2-lepton), [150, ∞] GeV		

Improving m(bb)

- Additional corrections on top of standard JES
  - For jets that contain a reconstructed muon with pT>4 GeV, dR(μ,jet)<0.4 from semileptonic decays (about 12% of b-tagged jets):
    - muon 4-vector added
    - energy deposited in calorimeter removed
  - In 0 and 1-lepton channels for all jets PtReco correction
    - scaling of jet 4-vector as a function of jet pT derived from signal ZH MC by comparing calibrated jet energy to that of matched truth jet
    - 12% (24%) at low pT, 1% (6%) at high pT for hadronic (semi-leptonic) b-jets
  - In 2-lepton channel resolution is improved through kinematic likelihood fit

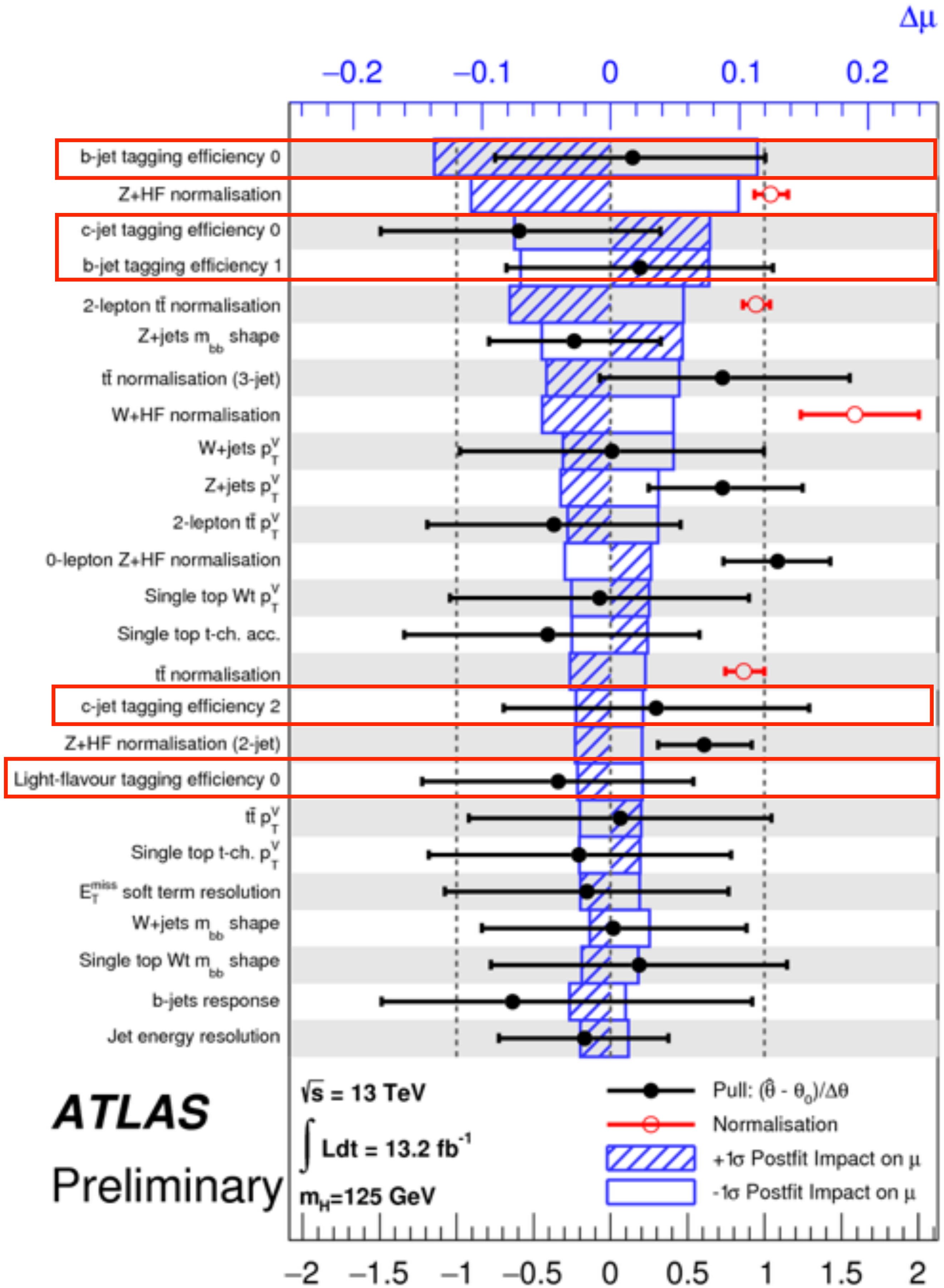


VH background systematics

Z+jets	
Zl normalisation	18%
Zcl normalisation	23%
Zbb normalisation	Floating
Zbc-to-Zbb ratio	14-27%
Zcc-to-Zbb ratio	7-31%
Zbl-to-Zbb ratio	15-38%
0-to-2 lepton ratio	26%
2-to-3 jet ratio	28% (0-lepton) and 25% (2-lepton)
p_T^V, m_{bb}	S
W+jets	
Wl normalisation	32%
Wcl normalisation	37%
Wbb normalisation	Floating
Wbl-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
Wbc-to-Wbb ratio	42% (0-lepton) and 21% (1-lepton)
Wcc-to-Wbb ratio	17% (0-lepton) and 31% (1-lepton)
2-to-3 jet ratio	23%
0-to-1 lepton ratio	17%
p_T^V, m_{bb}	S
$t\bar{t}$ (all are decorrelated between the 0−1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating
2-to-3-jet ratio	9% (0+1-lepton) and 24% (2-lepton)
p_T^V, m_{bb}	S

Single top	
Cross section	4.4% (s-channel), 4.6% (t-channel), 6% (Wt)
Acceptance 2-jet	16% (t-channel), 25% (Wt)
Acceptance 3-jet	19% (t-channel), 32% (Wt)
m_{bb}, p_T^V	S (p_T^V uncorrelated between 2 and 3-jet channels Wt)
ZZ	
Normalisation	20%
0-to-2 lepton ratio	30%
2-to-3 jet ratio	19 %
m_{bb}, p_T^V	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
2-to-3 jet ratio	14% (0-lepton) and 11% (1-lepton)
0-to-1 lepton ratio	12%
m_{bb}, p_T^V	S (correlated with ZZ uncertainties)
WW	
Normalisation	25%
Multi-jet (1-lepton)	
Normalisation	14-81% (electron), 5-50%(muon)
Template variations	S

VH: ranking



Signal systematics

	Signal
Cross section (scale)	0.7% ($q\bar{q}$), 27% (gg)
Cross section (PDF)	1.9% ($q\bar{q}\to WH$), 1.6% ($q\bar{q}\to ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance (scale)	1.4%–5%
3-jet acceptance (scale)	1.4%–4.7%
p_T^V shape (scale)	S
Acceptance (PDF)	0.3%–0.7%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	4%–7.5%

VZ fit

$$\mu_{VZ} = 0.91 \pm 0.17(\text{stat})^{+0.32}_{-0.27}(\text{syst})$$

significance obs (exp) 3.0 (3.2) SD

Signal model

- VH
  - qq→VH: Pythia8 with NNPDF23LO and A14
  - gg→ZH: Powheg+Pythia8 with CT10nlo and AZNLO
  - inclusive xs: NNLO (QCD) and NLO (EW)
  - gluon-induced ZH xs: NLO+NLL (QCD)
  - additional NLO (EW) SF(pT(V)) is applied based on Hawk
- VBF H→bb
  - Madgraph5_aMC@NLO+Pythia8; ME at LO with PDF4LHC_nlo_mc 5F (massless b)
- H→ττ, H→μμ
  - ggF and VBF: Powheg+Pythia8 with CT10;
  - ggF normalised to NNLO+NNLL (QCD) with NLO(EW)
  - VBF normalised to NLO (QCD and EW) with approximate NNLO QCD correction applied
  - ggF: Higgs pT distribution corrected to match HRes2.1
  - for events with 2 particle jets Higgs pT reweighed to MinLo HJJ