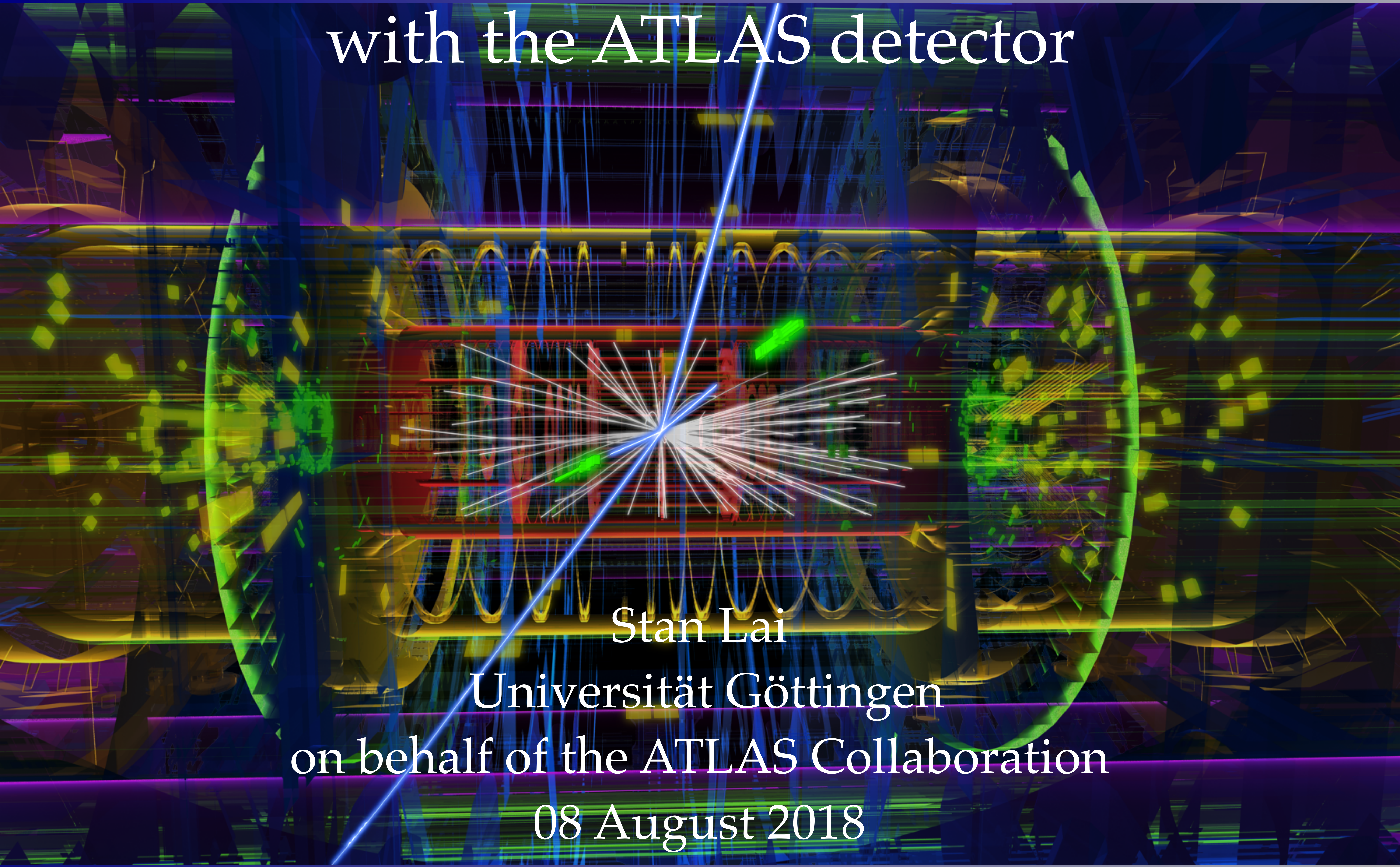
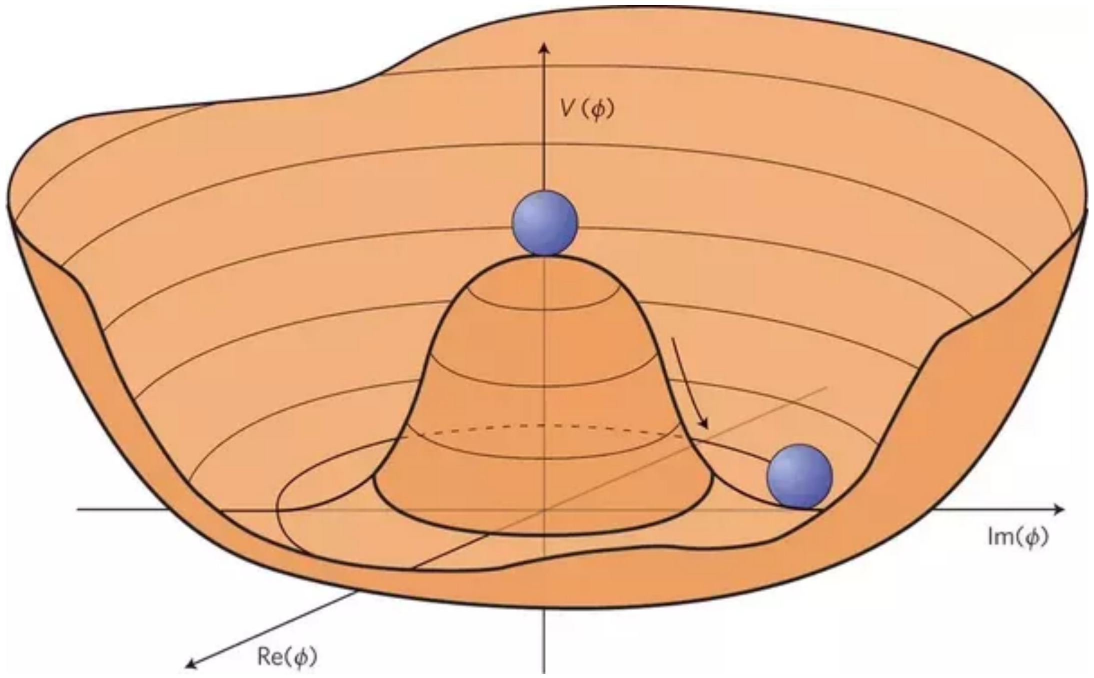
Higgs boson decays to fermions with the ATLAS detector



Stan Lai
Universität Göttingen
on behalf of the ATLAS Collaboration

08 August 2018

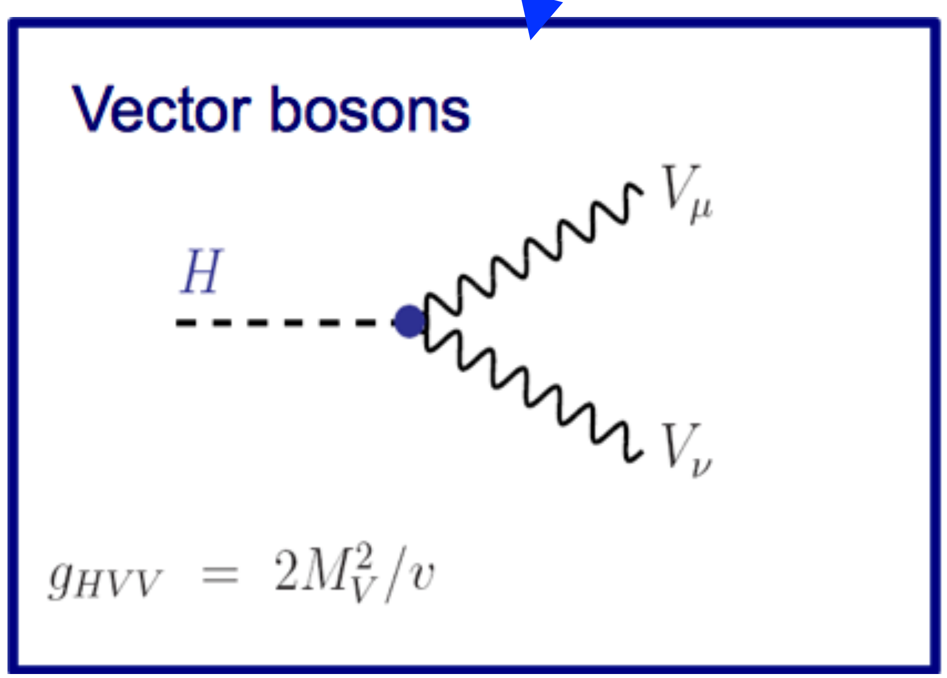
The Higgs Mechanism

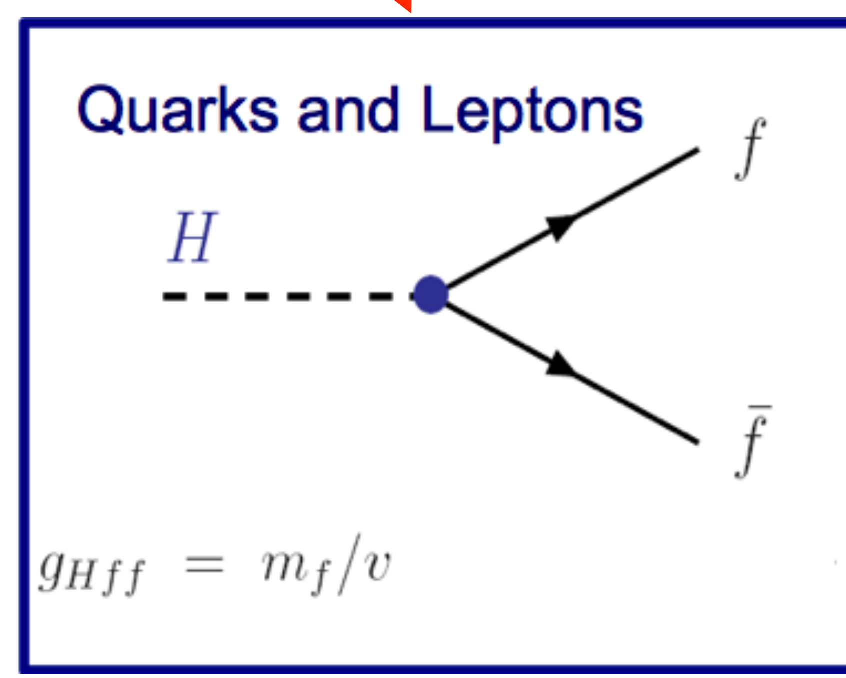


$$\mathscr{L}_{Higgs} = |D_\mu \varphi|^2 - V(\varphi)$$
$$- (g_f \bar{\Psi}_L \varphi \psi_R + h.c.)$$
$$- (g_f \bar{\Psi}_L \varphi_c \psi_R + h.c.)$$

Higgs discovery in 2012 based upon bosonic decays

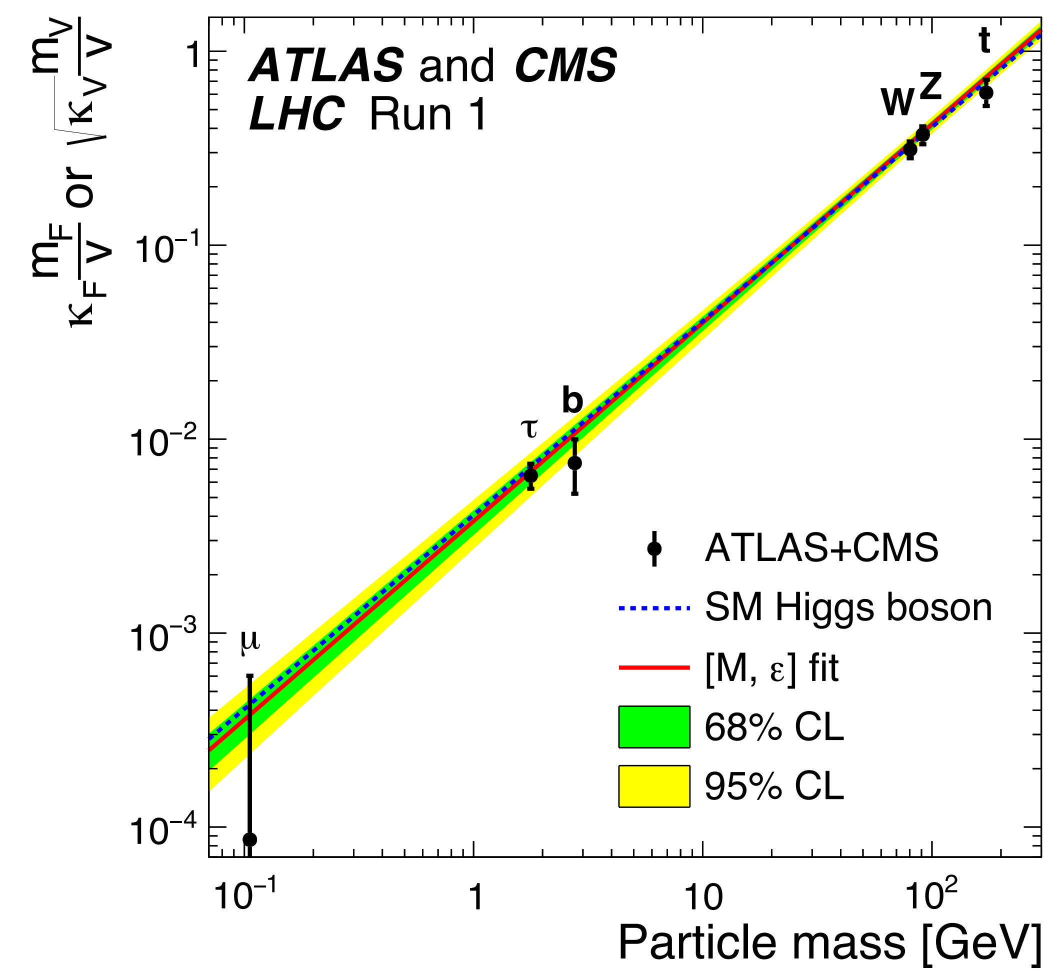
Fermionic couplings based upon different terms in Lagrangian

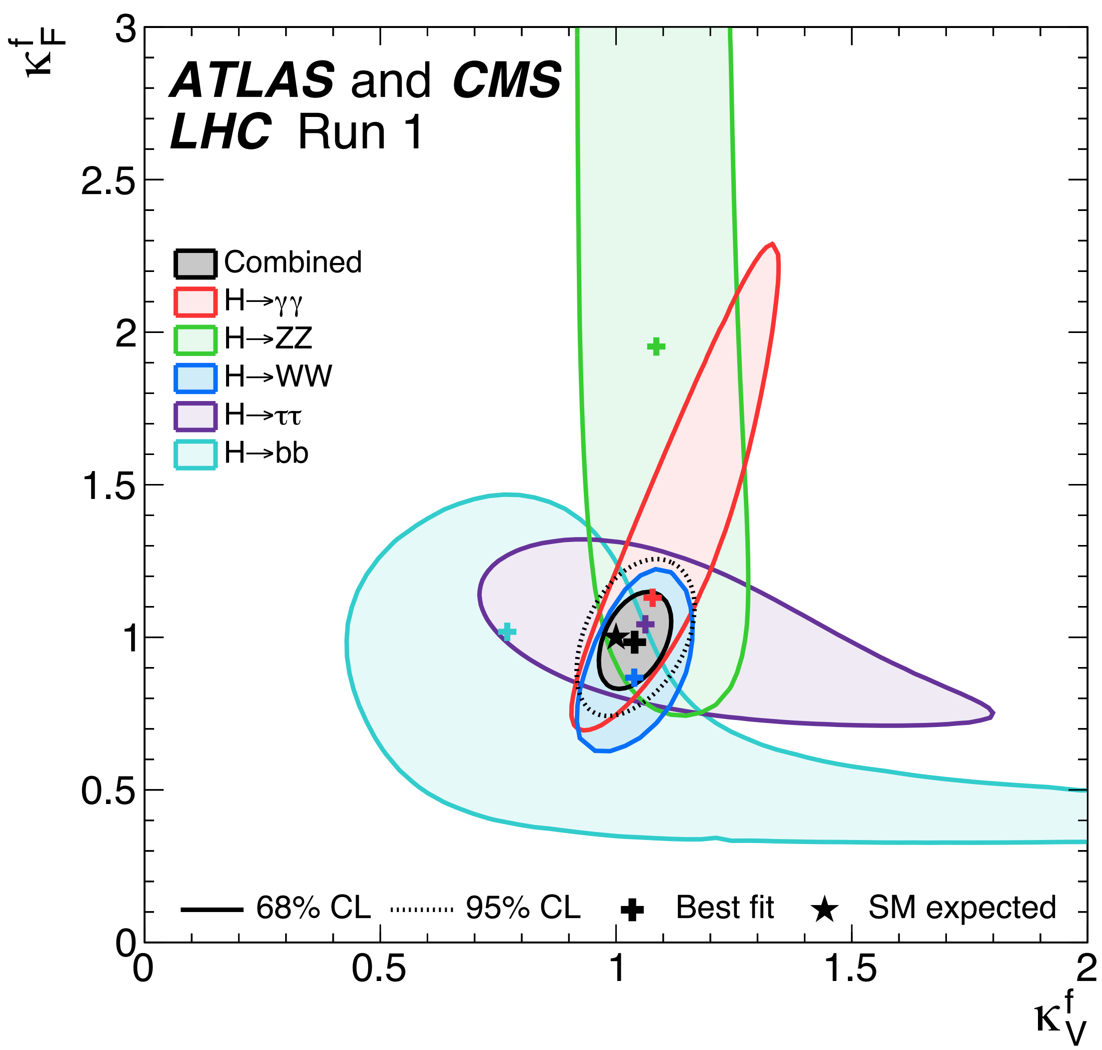




Run-1 Legacy for H→ff

Significance [σ] obs. (exp.)	ATLAS	CMS	Combination
H→ττ	4.5 (3.4)	3.4 (3.7)	5.5 (5.0)
H→bb	1.7 (2.7)	2.0 (2.5)	2.6 (3.7)





Upper Limit 95% CL signal strength	ATLAS	CMS
H→μμ	7.0 (7.2)	7.4 (6.5)

JHEP 08 (2016) 085

Updated Run-2 Analyses ($H \to ff$)

$H \to \tau\tau$

- **verify Higgs-lepton couplings**

36 fb^{-1} @ 13 TeV ATLAS-CONF-2018-021

$H \to bb$

- verify Higgs-quark couplings

80 fb^{-1} @ 13 TeV ATLAS-CONF-2018-036

$H \to \mu\mu$

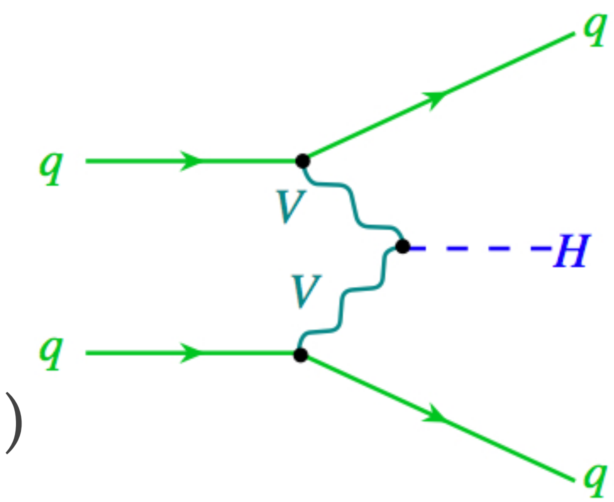
- verify Higgs couplings to 2nd generation fermions

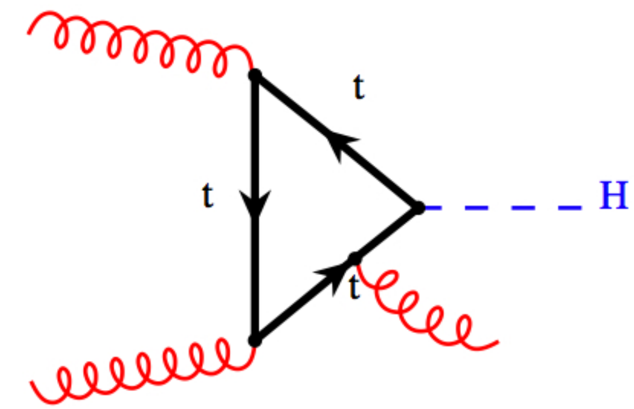
80 fb^{-1} @ 13 TeV ATLAS-CONF-2018-026

The H→ττ Channel

Exploit:

- Higgs production properties
  i.e. VBF and boosted kinematics
- All tau decay combinations
  $\tau_{lep}\tau_{lep}$ (12%), $\tau_{lep}\tau_{had}$ (46%), $\tau_{had}\tau_{had}$ (42%)

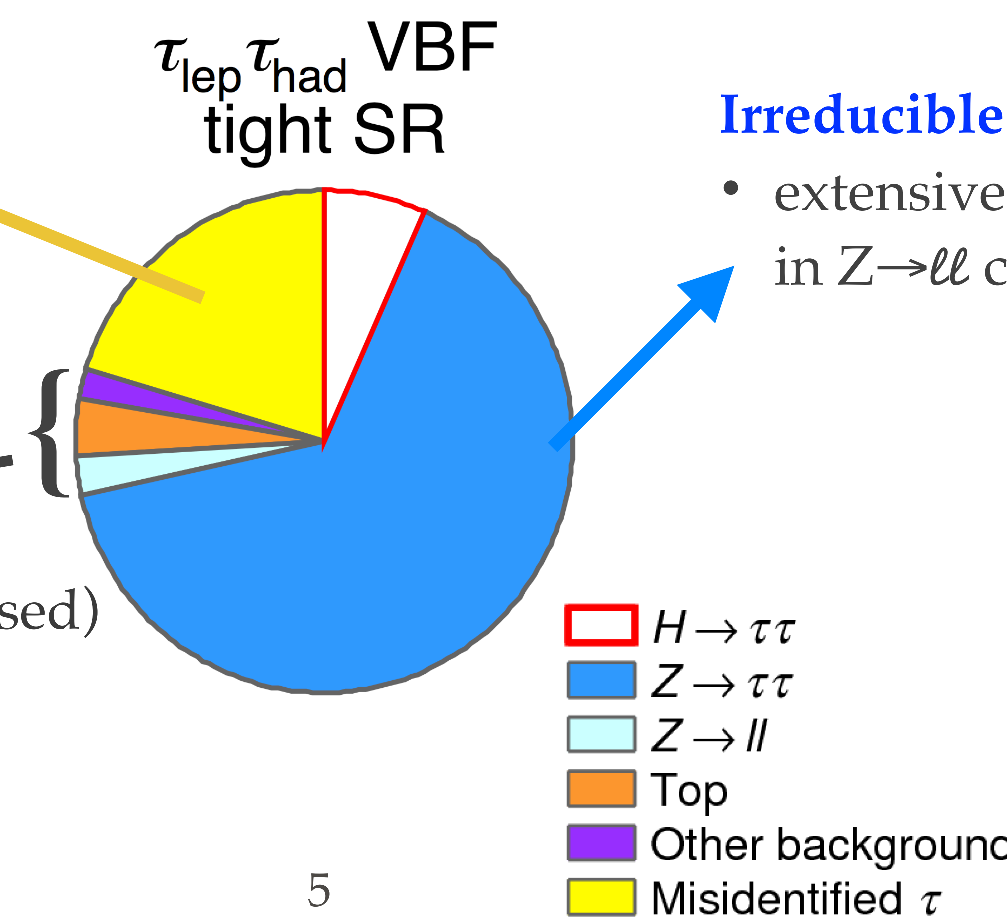




Cut-based analysis with 13 signal regions using $m_{\tau\tau}^{MMC}$ as final discriminating variable
($m_{\tau\tau}^{MMC}$ based on likelihood technique from visible products and E_T^{miss})

Fake τ backgrounds (data-driven)

- measurements of tau misidentification probability
- templates from inverted charge/track requirements



Irreducible Z→ττ (MC-based)

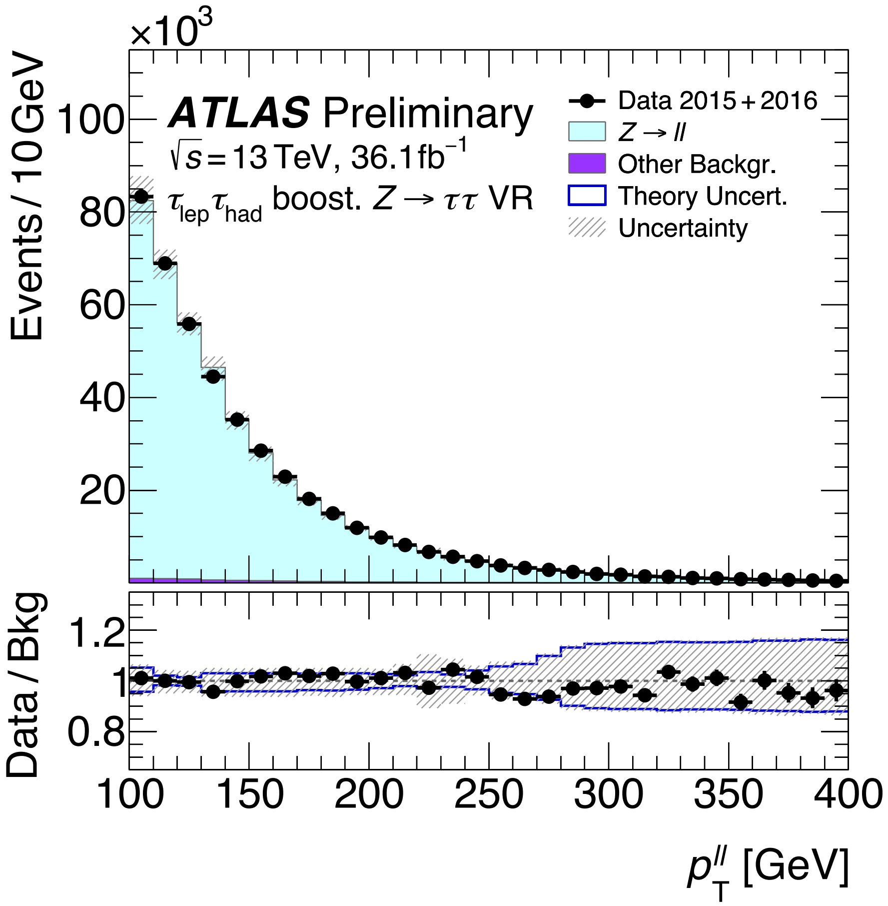
- extensive validation of Z modelling in Z→ℓℓ control region

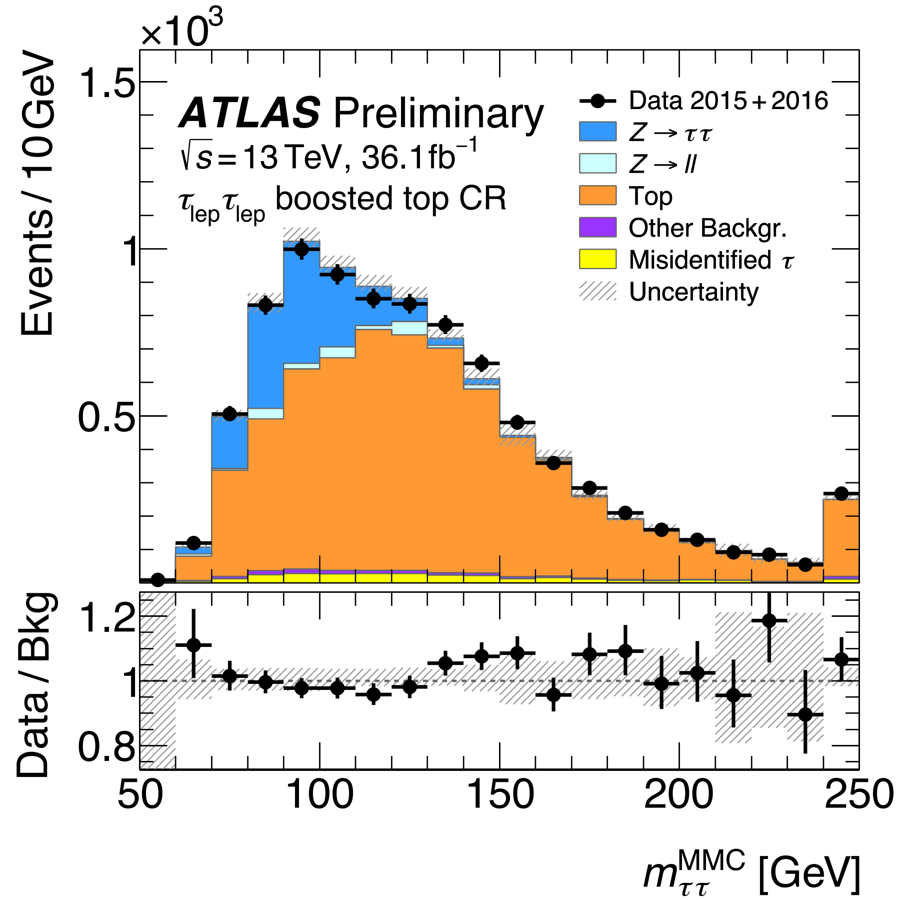
Top, Z→ll, other backgrounds (MC-based)

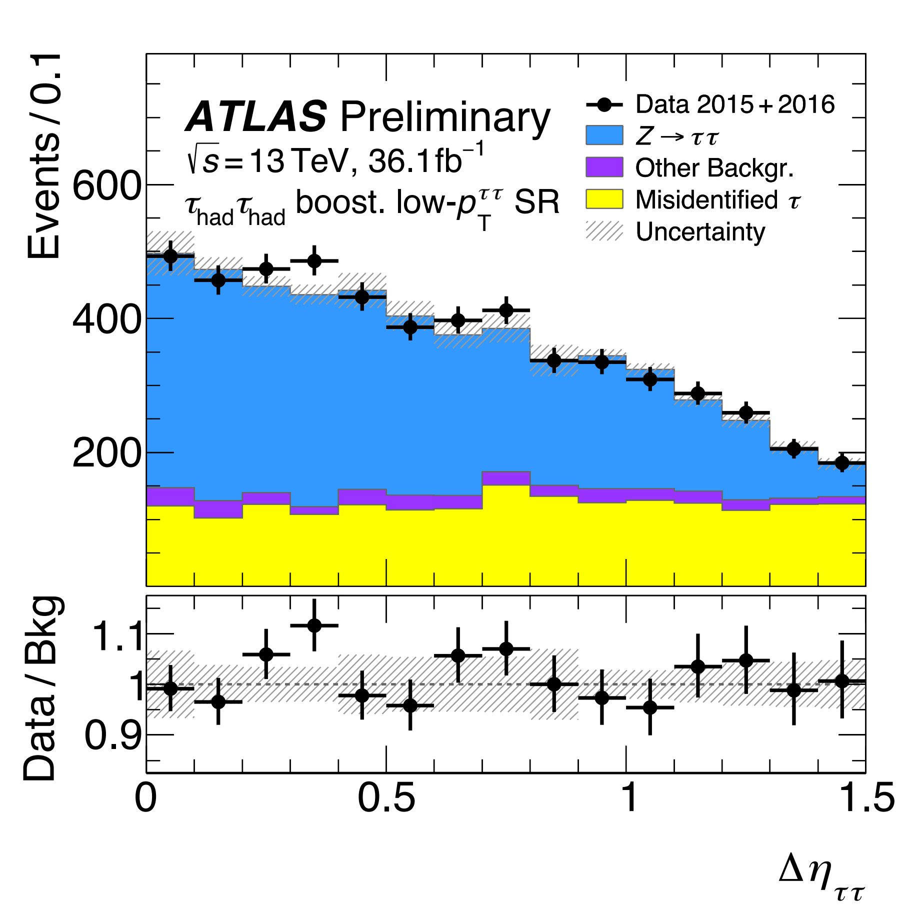
- dedicated control regions to normalize MC

ATLAS-CONF-2018-021

H→ττ: Background Estimation







Validation of $Z\to\ell\ell$ kinematics ensures reliable MC prediction of $Z\to\tau\tau$ background

- Sherpa NLO (Z+jets) used
- m_{jj}, $\Delta\eta_{jj}$, $\Delta R_{\ell\ell}$ distributions also checked

$Z\to\ell\ell$ backgrounds ($\tau_{lep}\tau_{lep}$) and top backgrounds ($\tau_{lep}\tau_{lep}$ / $\tau_{lep}\tau_{had}$) normalized in dedicated CRs

- $Z\to\ell\ell$ CRs defined through $80 < m_{\ell\ell} < 100$ GeV
- Top CRs defined through requiring a b-tag

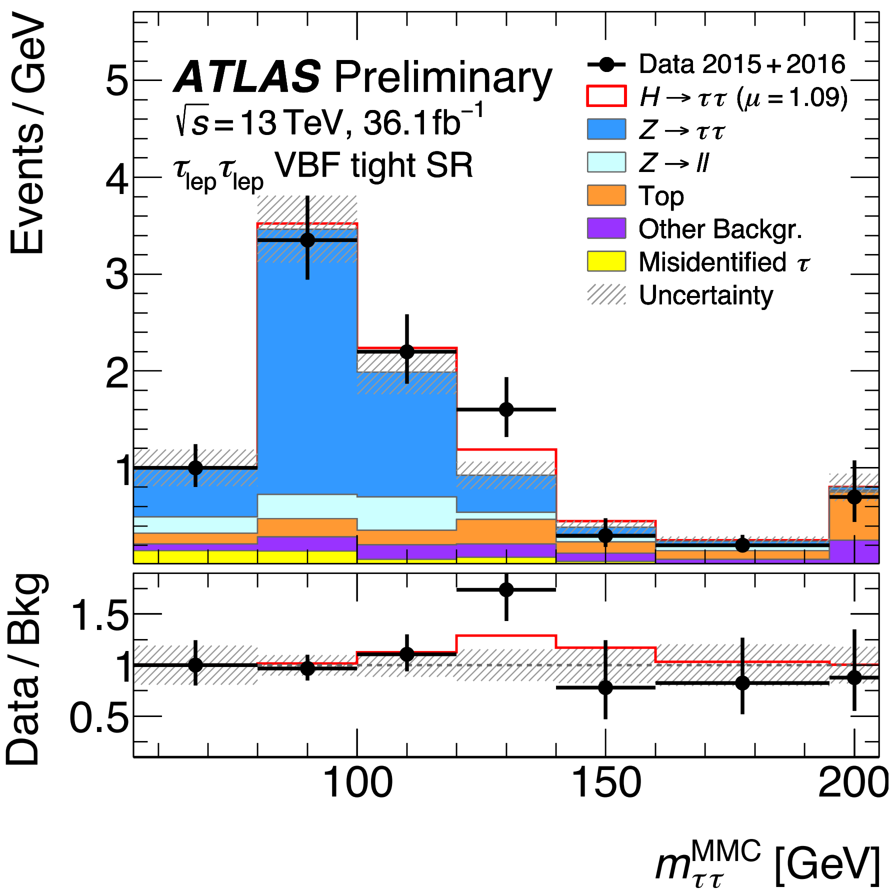
Fake tau backgrounds have data-driven estimates

- measurement of misid prob. ($\tau_{lep}\tau_{had}$)
- fit normalization of fake templates from CR with inverted charge / track criteria ($\tau_{had}\tau_{had}$)

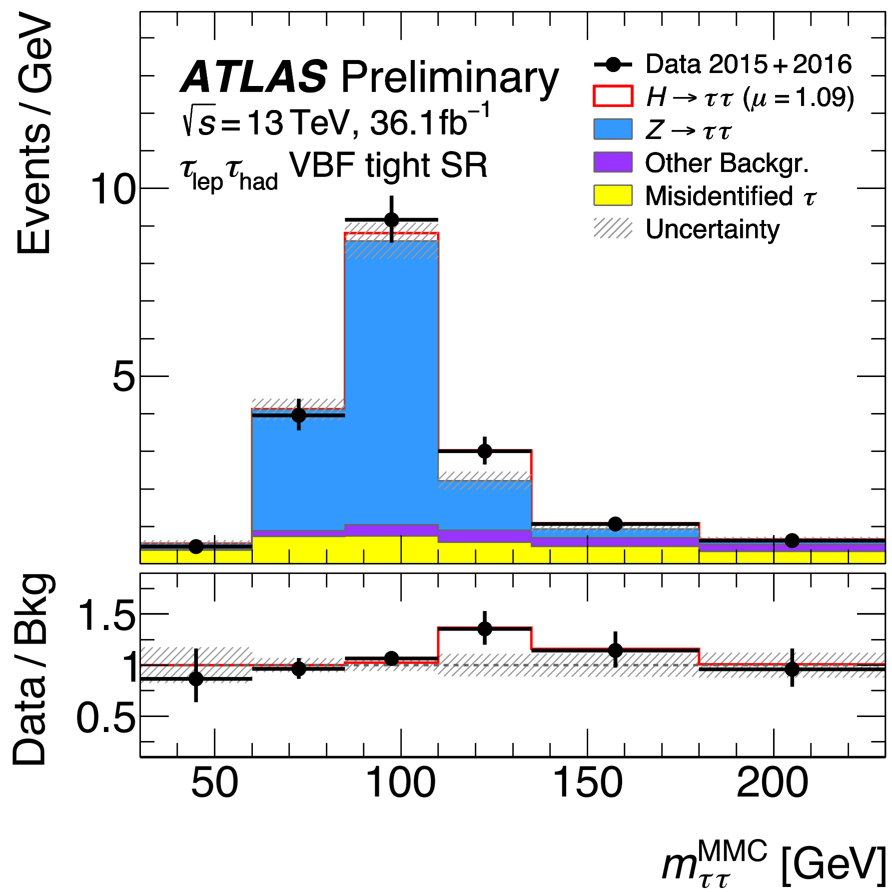
ATLAS-CONF-2018-021

H→ττ: Mass Distributions

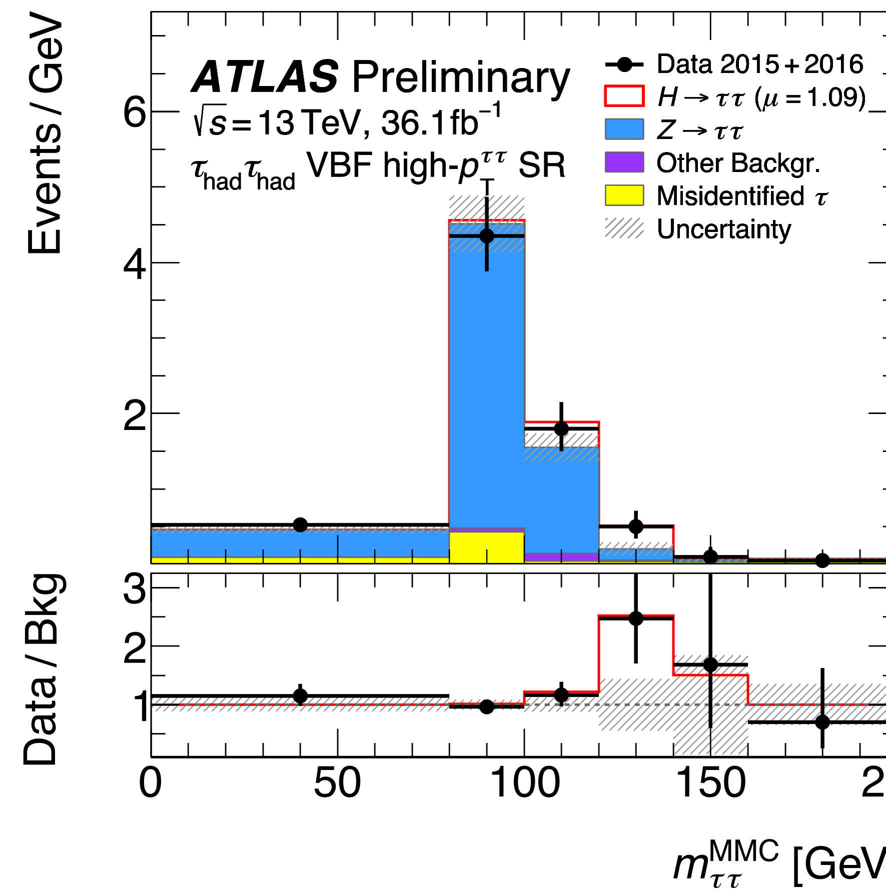
$\tau_{lep}\tau_{lep}$



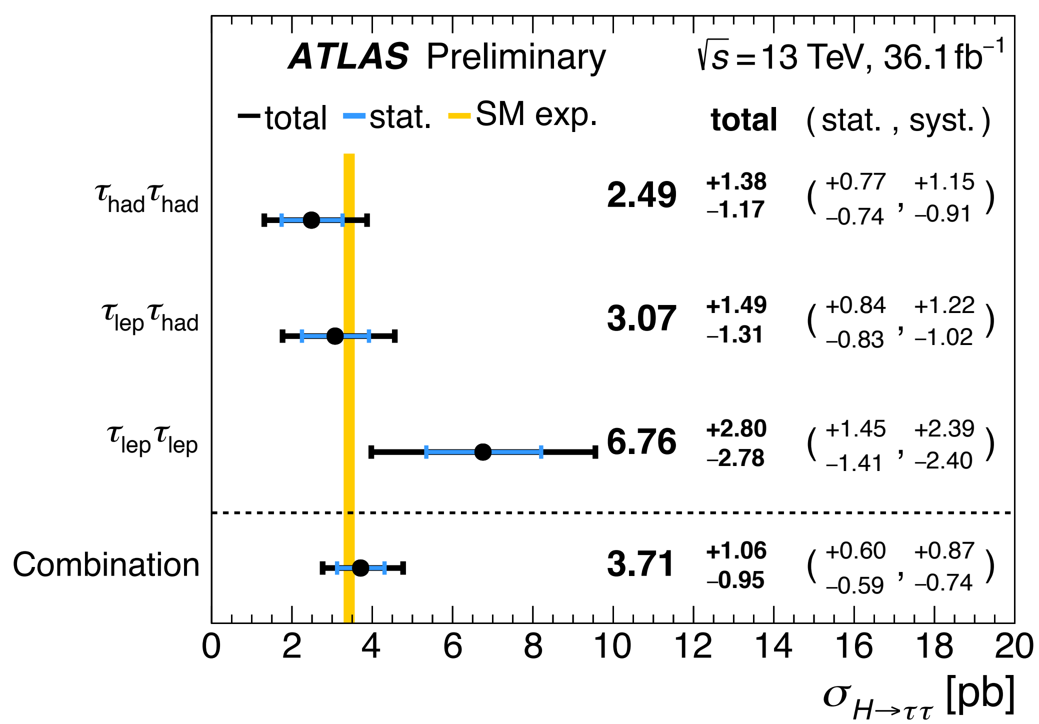
$\tau_{lep}\tau_{had}$

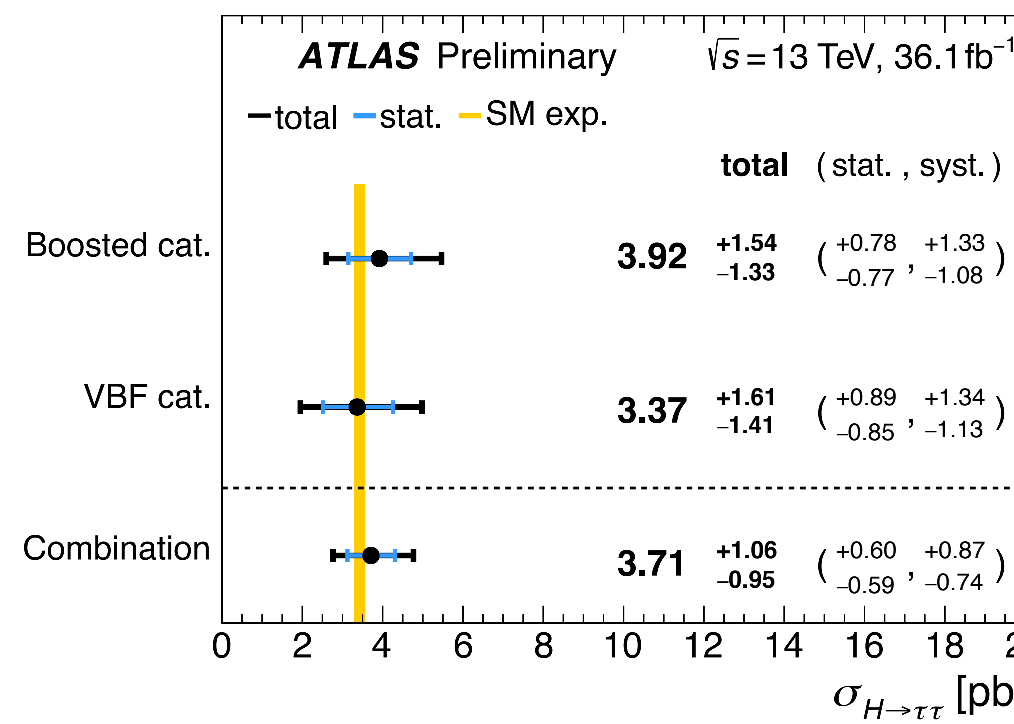


$\tau_{had}\tau_{had}$



Signal extraction via profile likelihood on $\mathbf{m_{\tau\tau}^{MMC}}$ distribution in 13 signal regions





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$H\to\tau\tau$: Summary of Results

For pp collisions at 13 TeV, measure $\sigma_{H\to\tau\tau} = \sigma_H \times BR(H\to\tau\tau)$

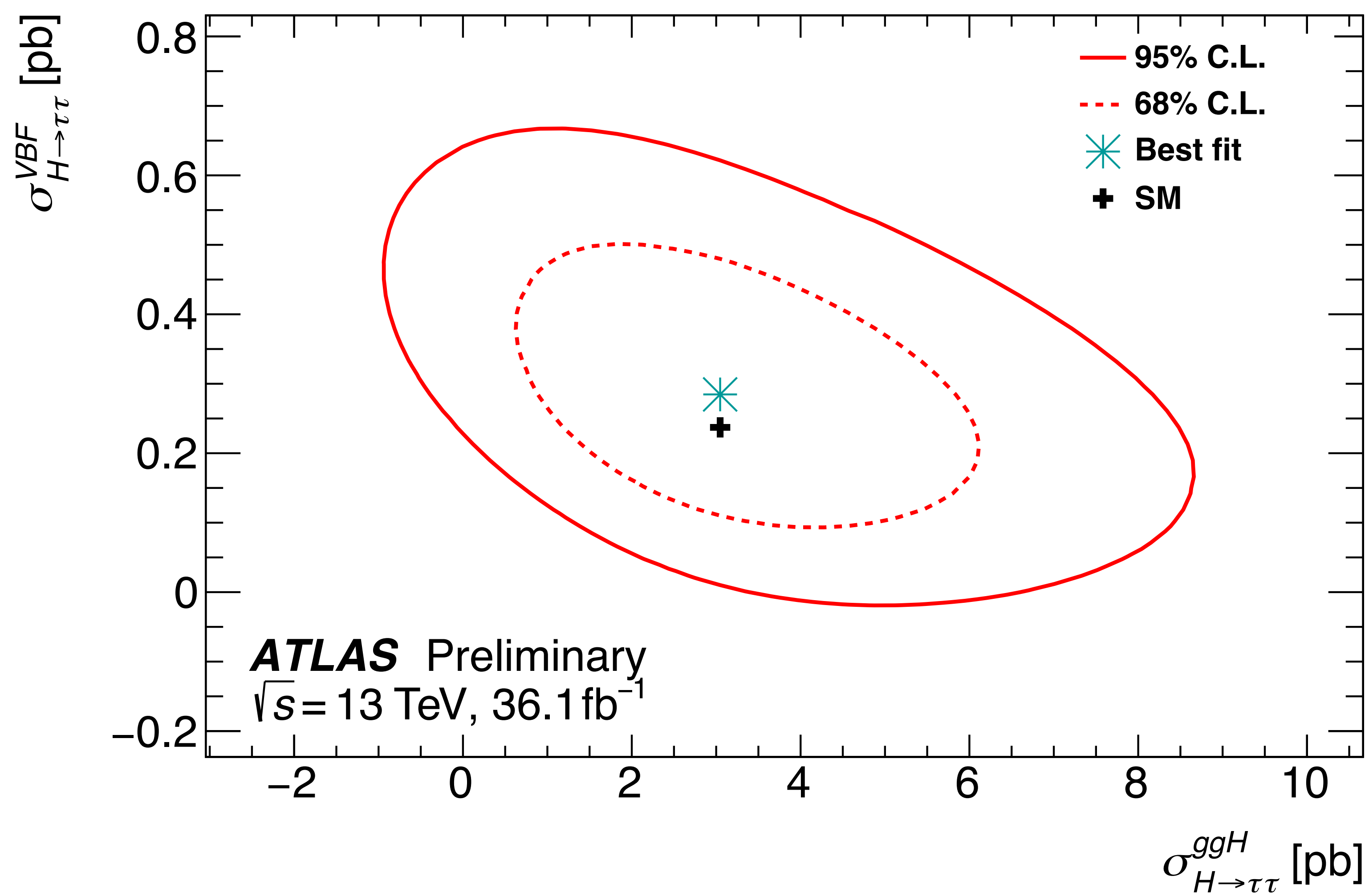
$$\sigma_{H\to\tau\tau} = 3.71 \pm 0.59\,(\text{stat.})\,^{+0.87}_{-0.74}\,(\text{syst.})\,\text{pb} \quad \text{vs.} \quad \sigma^{SM}_{H\to\tau\tau} = 3.43 \pm 0.13\,\text{pb}$$

corresponding to signal strength $\sigma/\sigma_{SM} = 1.09\,^{+0.18}_{-0.17}\,(\text{stat.})\,^{+0.27}_{-0.22}\,(\text{syst.})\,^{+0.16}_{-0.11}\,(\text{theory syst.})$

Signal significances (σ):

E_{CM}	7,8 TeV	13 TeV	Comb.
Observed	4.5	4.4	6.4
Expected	3.4	4.1	5.4

Precision era for H→ττ now beginning!



Two parameter fit (ϱ = -0.52)

ATLAS-CONF-2018-021

Updated Run-2 Analyses ($H \to ff$)

$H \to \tau\tau$

- verify Higgs-lepton couplings

36 fb^{-1} @ 13 TeV ATLAS-CONF-2018-021

$H \to bb$

- **verify Higgs-quark couplings**

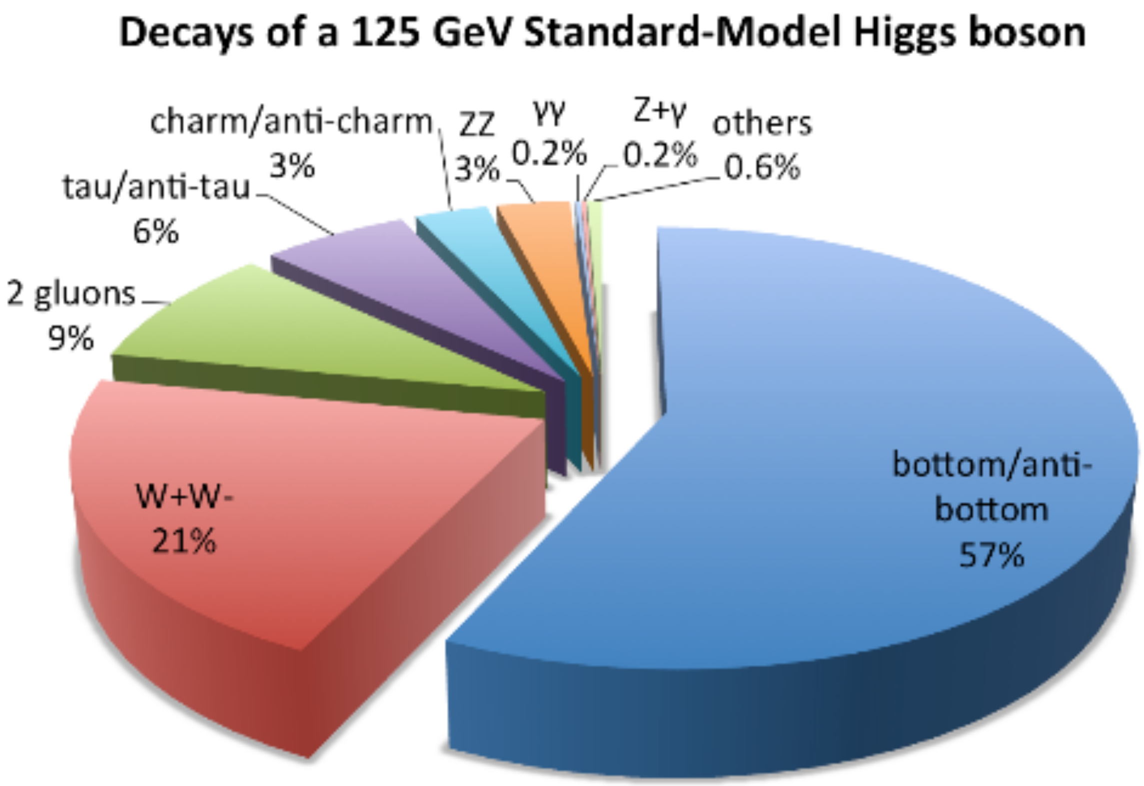
80 fb^{-1} @ 13 TeV ATLAS-CONF-2018-036

$H \to \mu\mu$

- verify Higgs couplings to 2nd generation fermions

80 fb^{-1} @ 13 TeV ATLAS-CONF-2018-026

The H→bb Channel



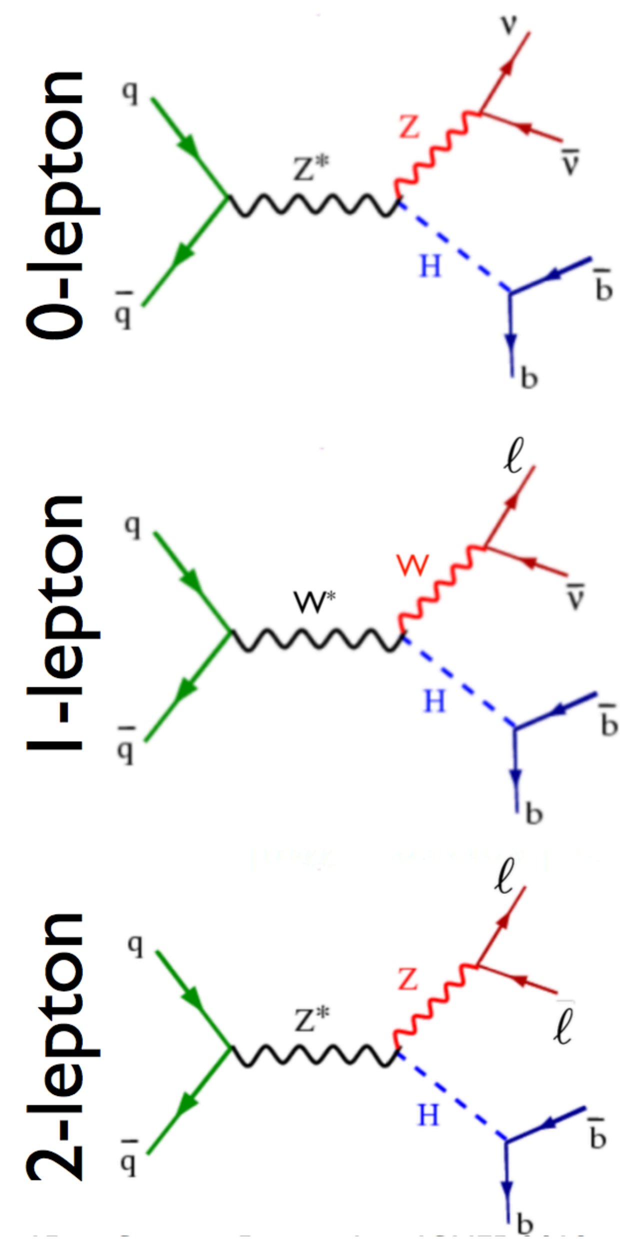
Important for:

- establishing most copious Higgs decay channel
- constraining Higgs decay width
- limits on invisible Higgs width

Evidence for H→bb decays from

- CDF/D∅ in 2012 (2.8σ)
- ATLAS/CMS with data up to 2016 (4.0σ/3.8σ)
- now: update with data taken in 2017

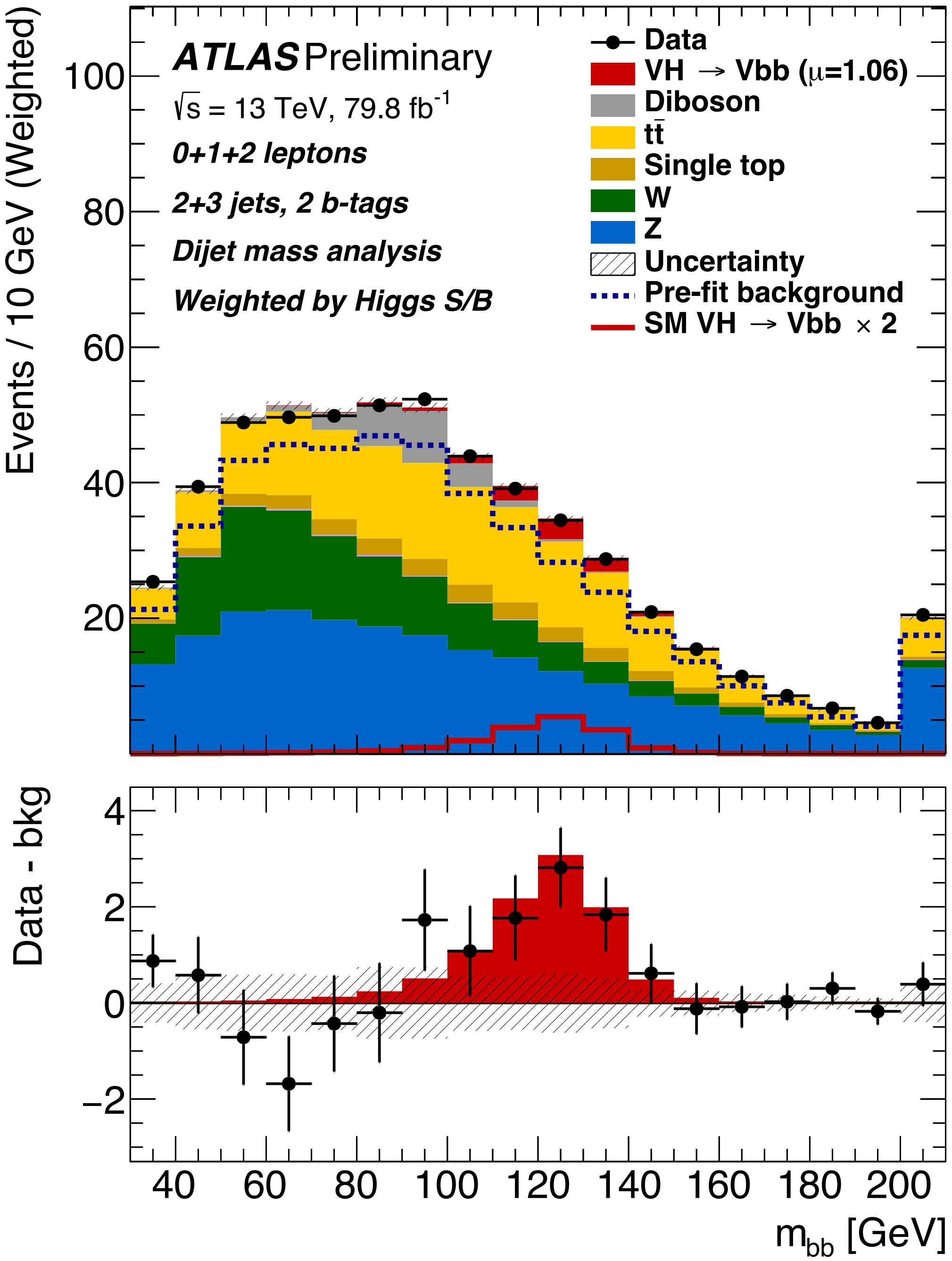
Focus on associated W/Z production (suppresses backgrounds)



Require 2 b-tags, $p_T(V) > 75$ or 150 GeV

ATLAS-CONF-2018-036

H→bb: Analysis Strategy

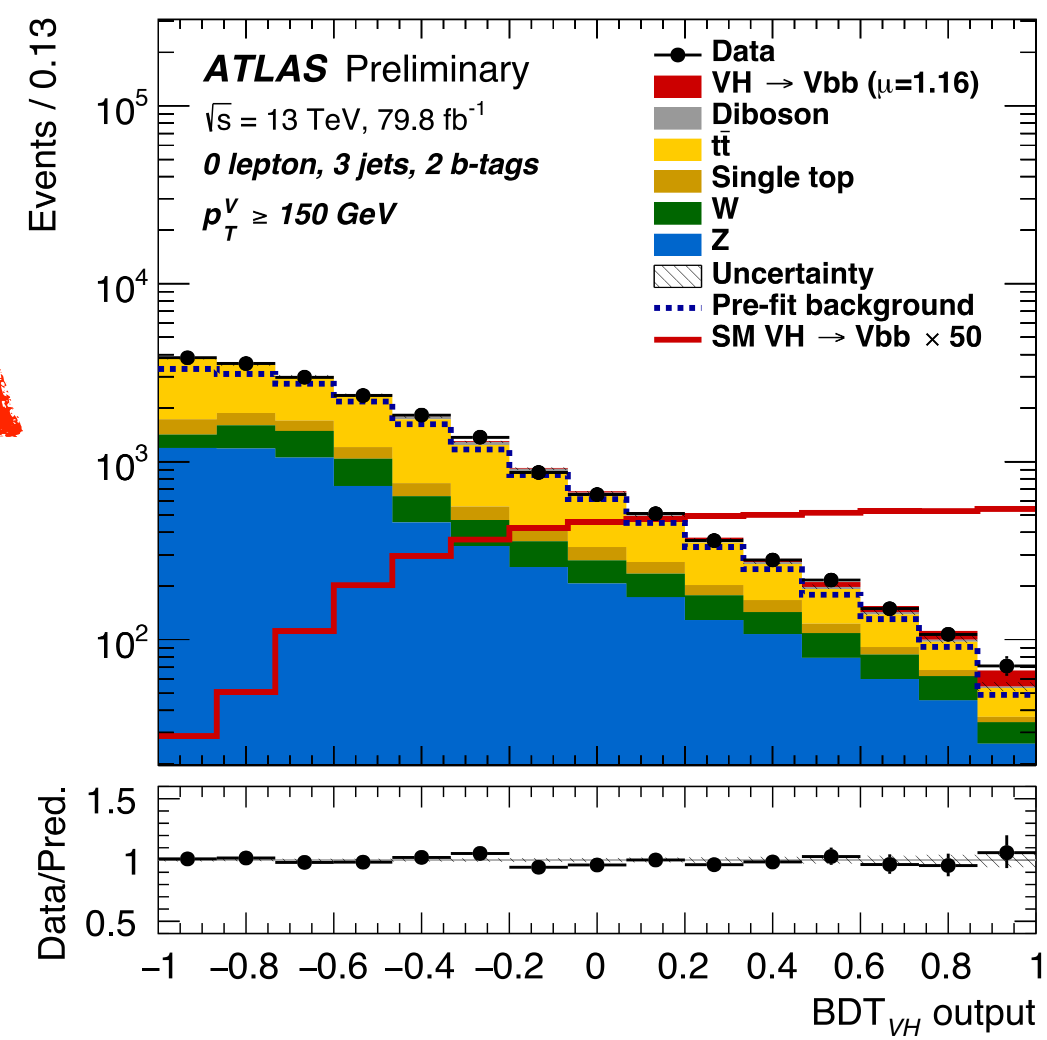


Corrections to m_{bb}:

- taking into account $p_T(\mu)$ in semi-leptonic b-jets
- for ν's and out-of-cone energy in decay chain
- kinematic fit in 2-lepton channel ($p_T(\ell\ell) \Leftrightarrow p_T(bb)$)

Background estimation (W/Z/top)

- shapes from MC
- normalization via inclusion of CRs in fit

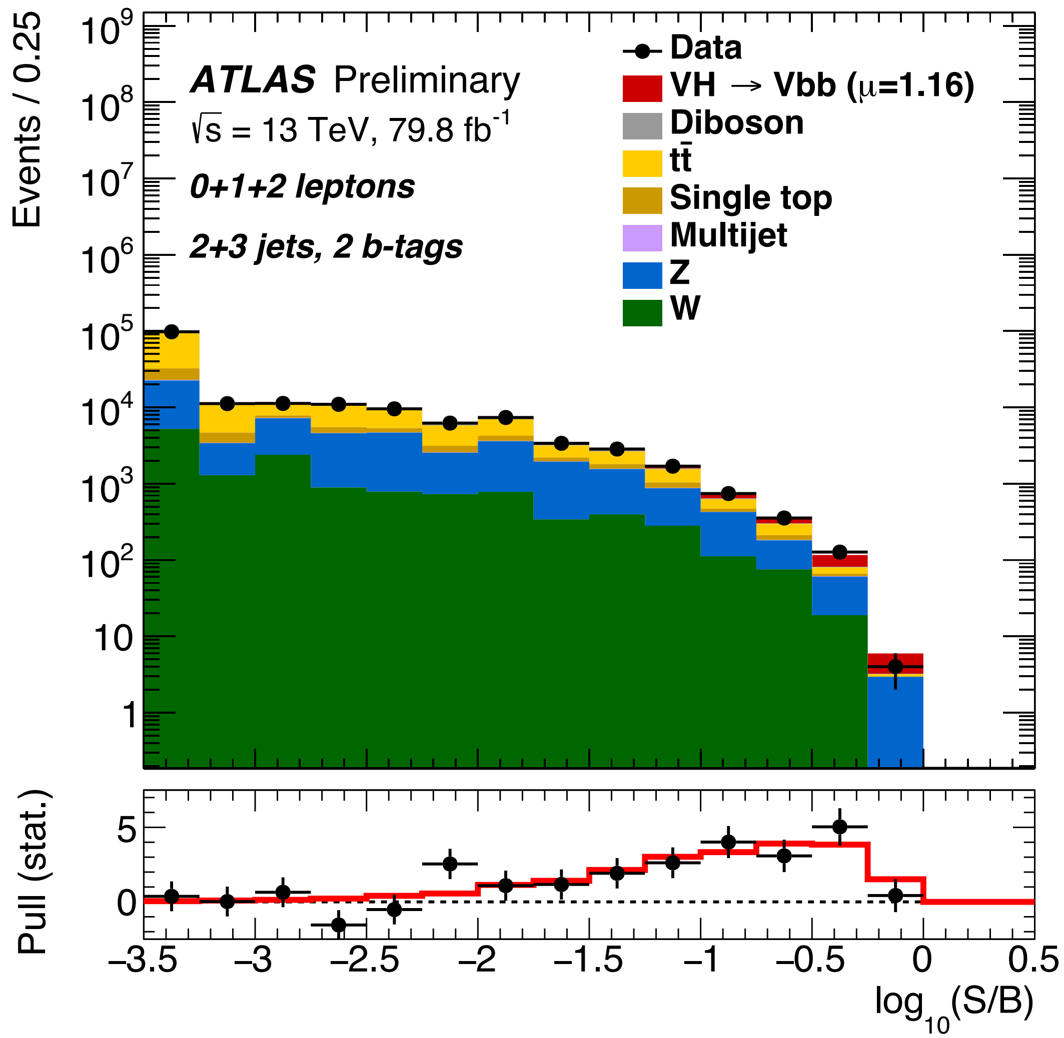


Final discriminant: BDT
based upon kinematic variables
(m_{bb}, ΔR_{bb}, $p_T(V)$, etc.)

ATLAS-CONF-2018-036

VH (H→bb): 13 TeV Results

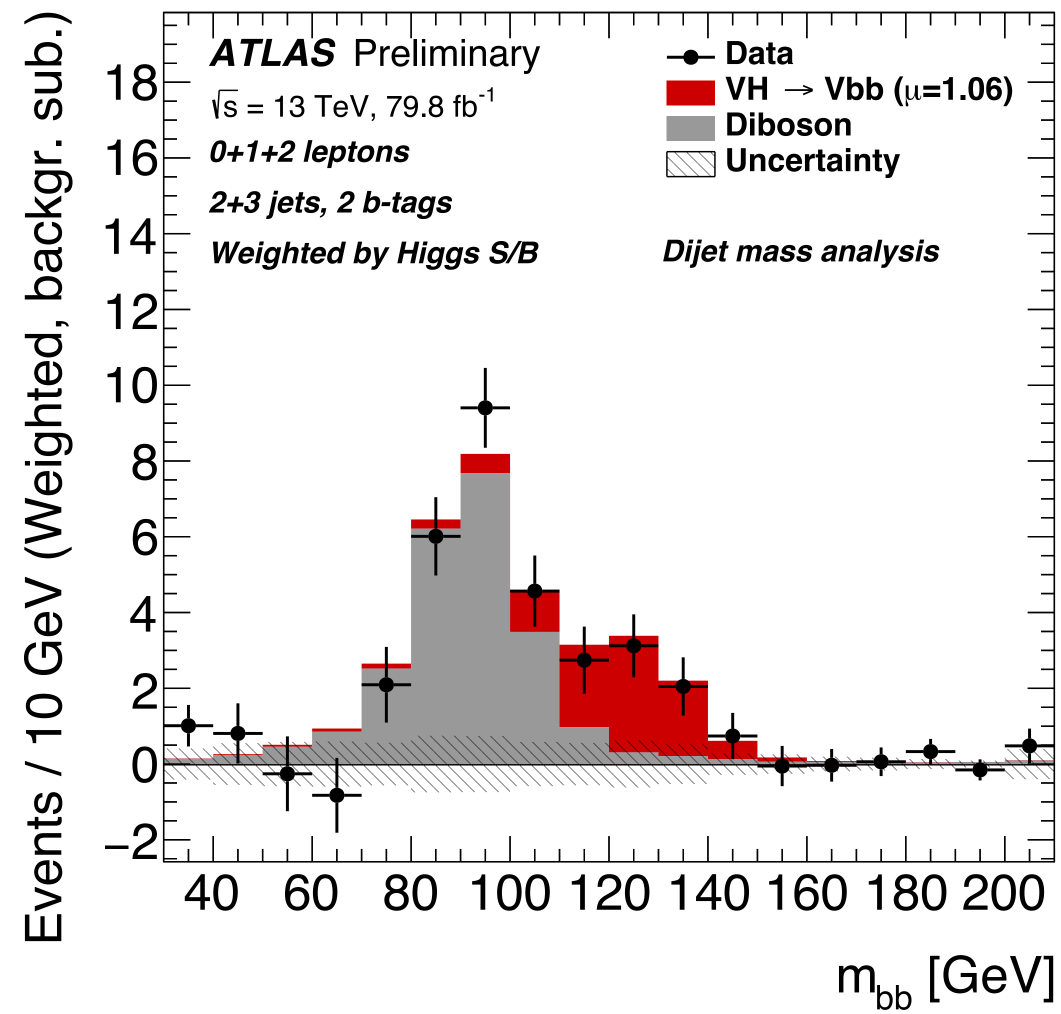
Fit to BDT distributions (8 SRs)



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

corresponding to **4.9σ** (4.3σ exp.)

Fit to m_{bb} distributions (14 SRs)



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

corresponding to **3.6σ** (3.5σ exp.)

ATLAS-CONF-2018-036

VH and H→bb Combination

H→bb Combination (VBF, VH, ttH for Run-1 and Run-2)

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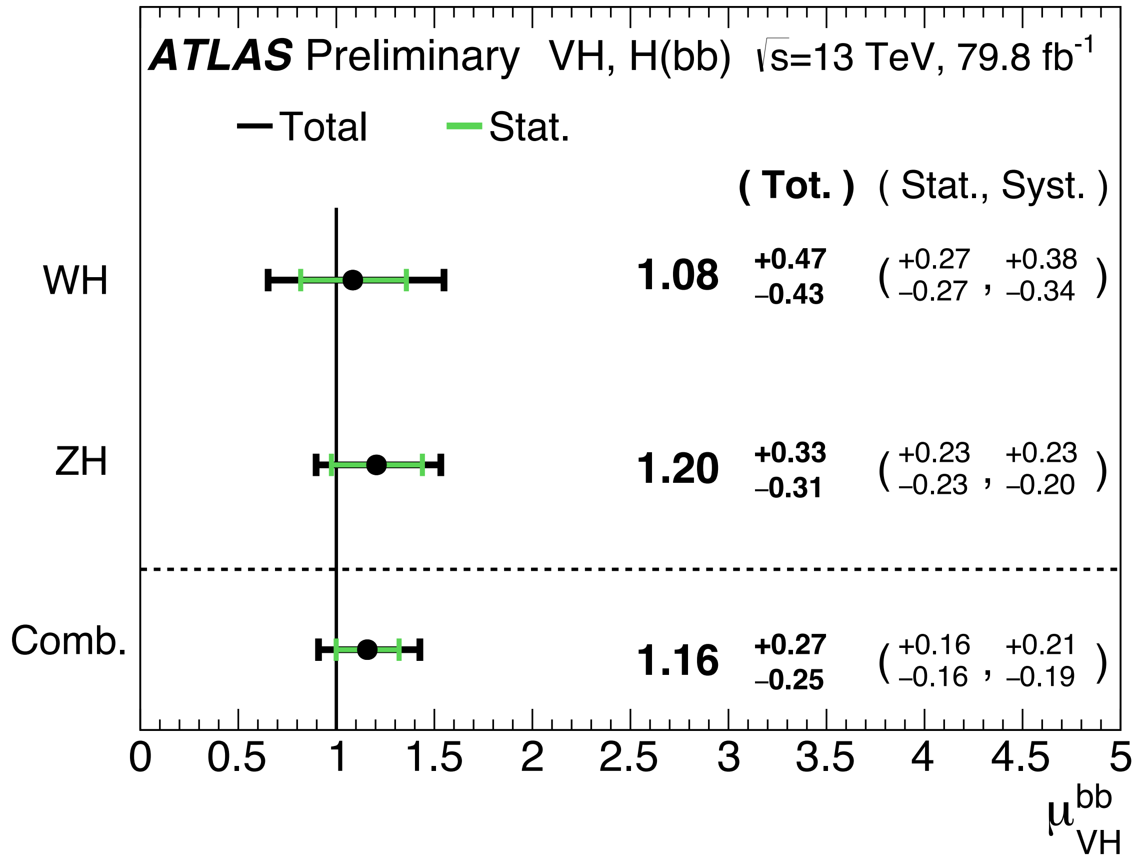
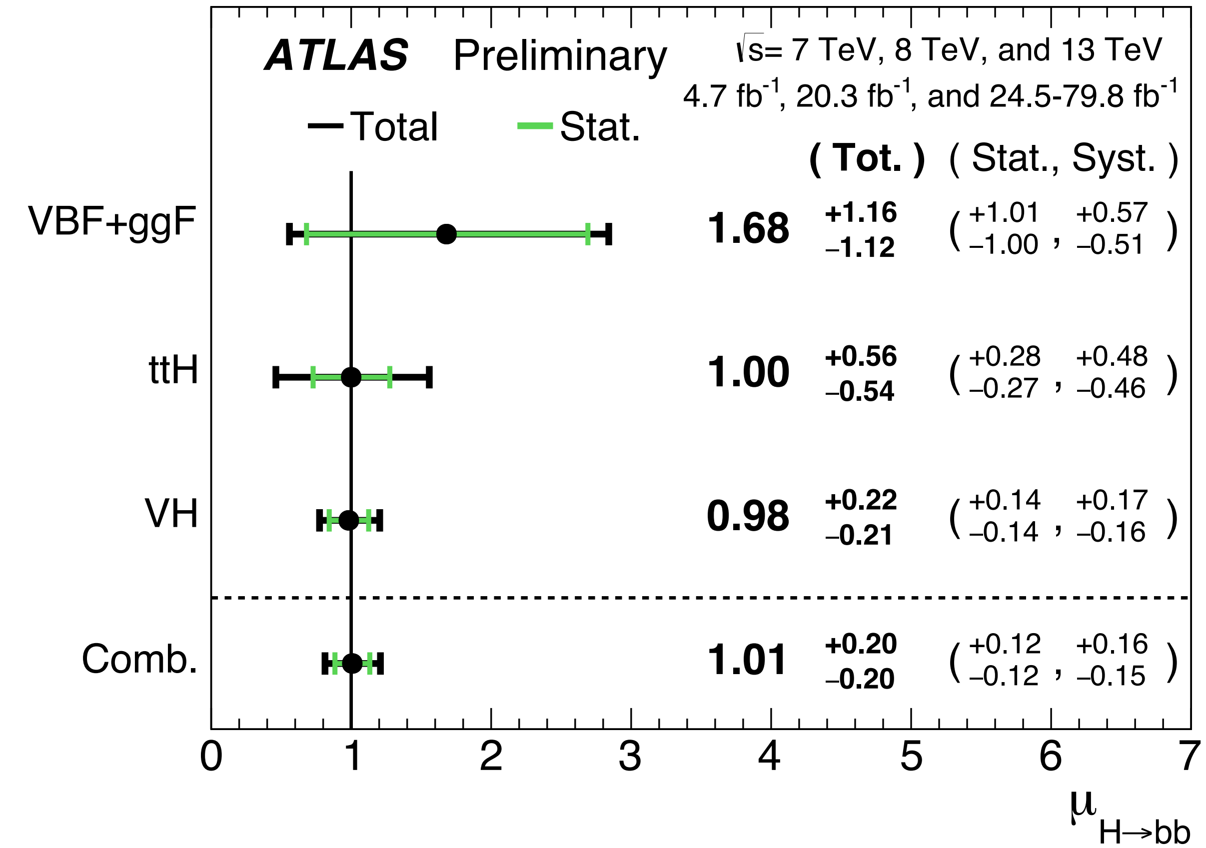




corresponding to **5.4σ** (5.5σ exp.)

VH Combination (H→bb, H→γγ, H→ZZ*) yields **5.3σ** (4.8σ exp.)

$$\mu_{VH}^{bb} = 0.98^{+0.22}_{-0.21} = 0.98 \pm 0.14(\text{stat.})^{+0.17}_{-0.16}(\text{syst.})$$

$$\mu_{H\to bb} = 1.01 \pm 0.20 = 1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$$

Measurements of Higgs properties with H→bb to come!

Updated Run-2 Analyses ($H \to ff$)

$H \to \tau\tau$

- verify Higgs-lepton couplings

36 fb^{-1} @ 13 TeV ATLAS-CONF-2018-021

$H \to bb$

- verify Higgs-quark couplings

80 fb^{-1} @ 13 TeV ATLAS-CONF-2018-036

$H \to \mu\mu$

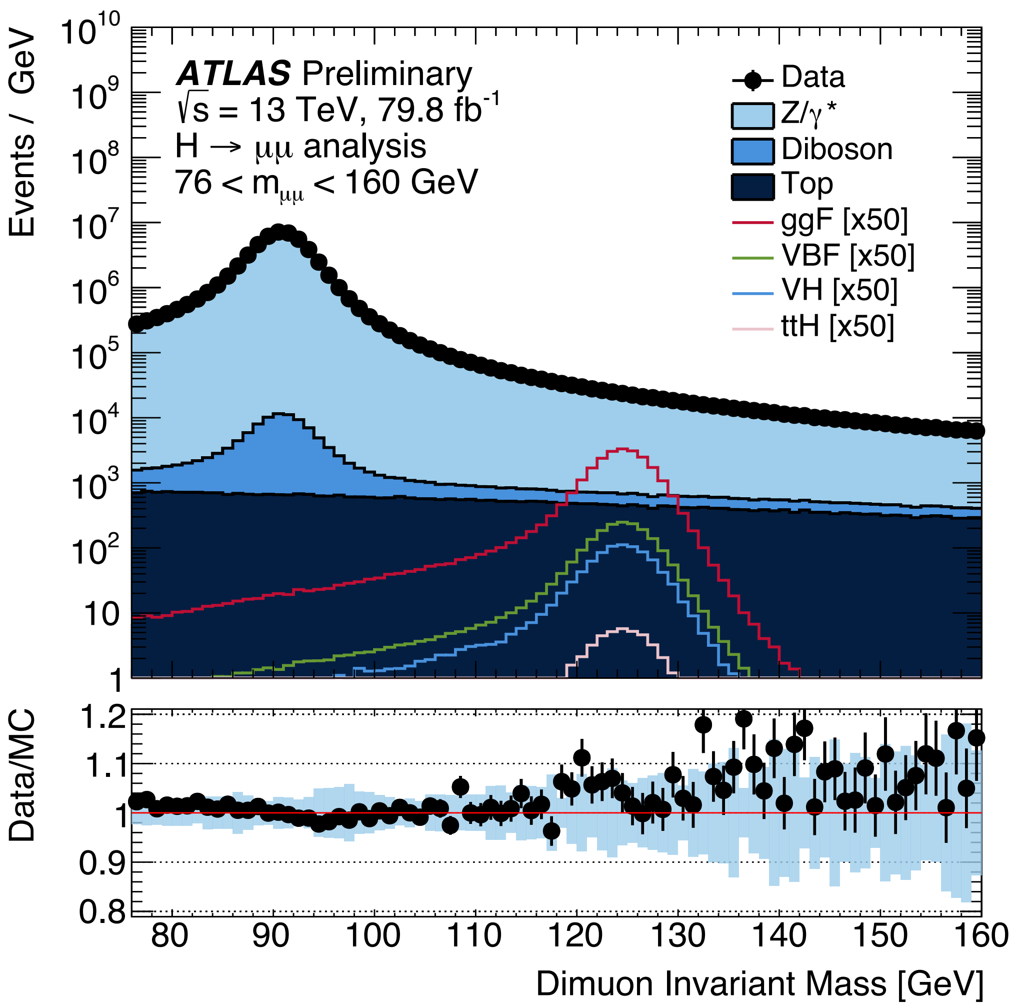
- **verify Higgs couplings to 2nd generation fermions**

80 fb^{-1} @ 13 TeV ATLAS-CONF-2018-026

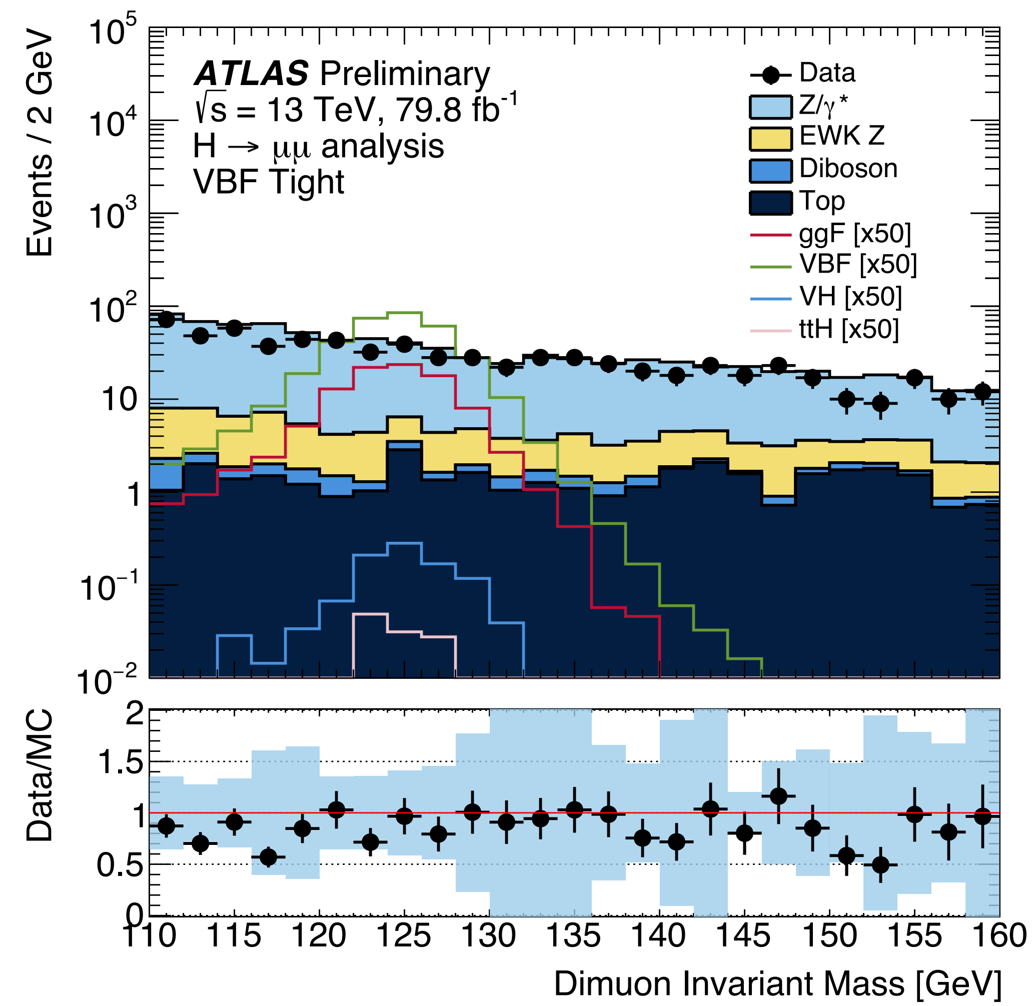
The H→μμ Channel

Important channel to establish Higgs Yukawa coupling to 2nd generation fermions

Huge challenge: tiny S/B ratio



VBF categorization and BDT selection

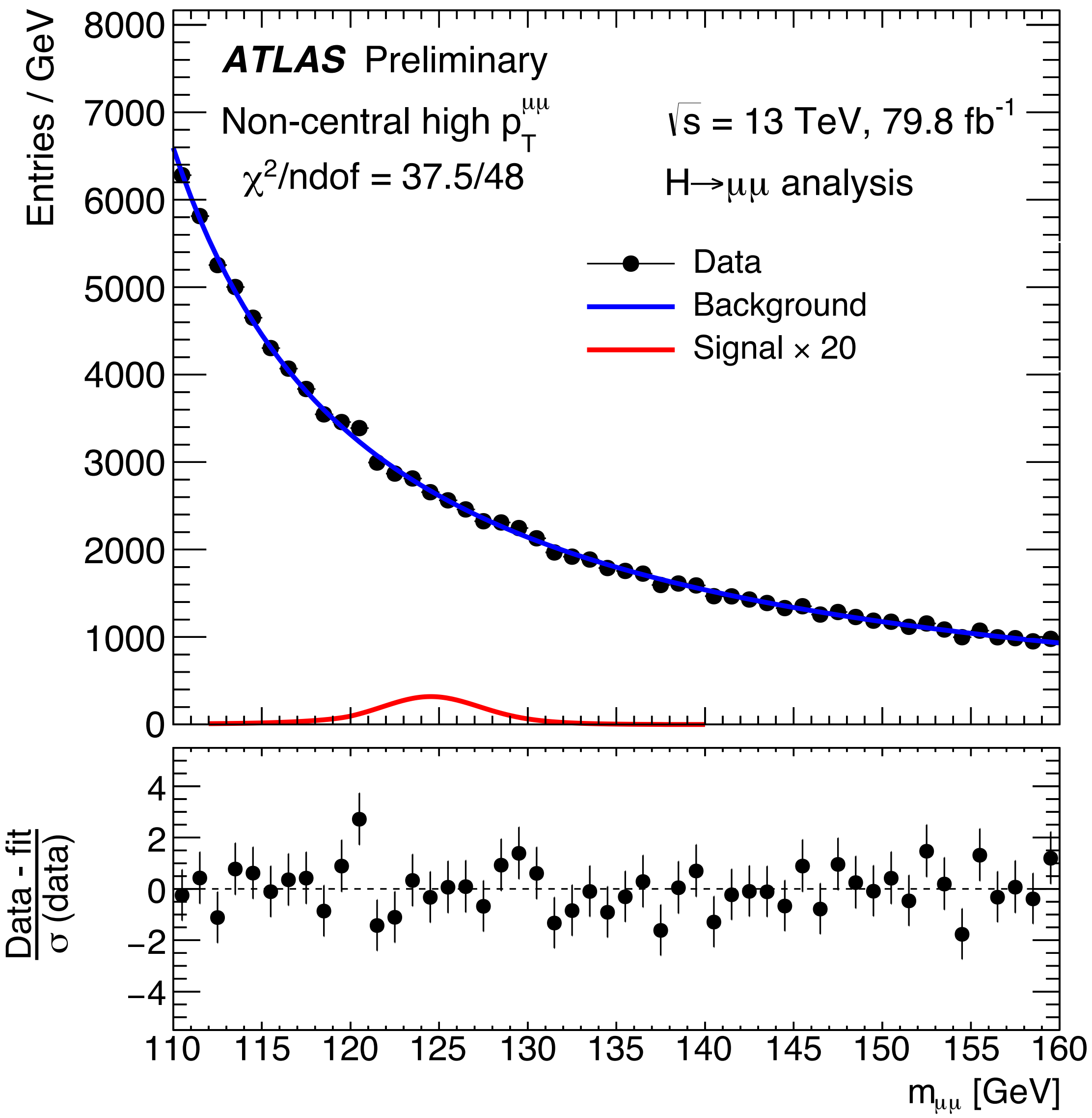


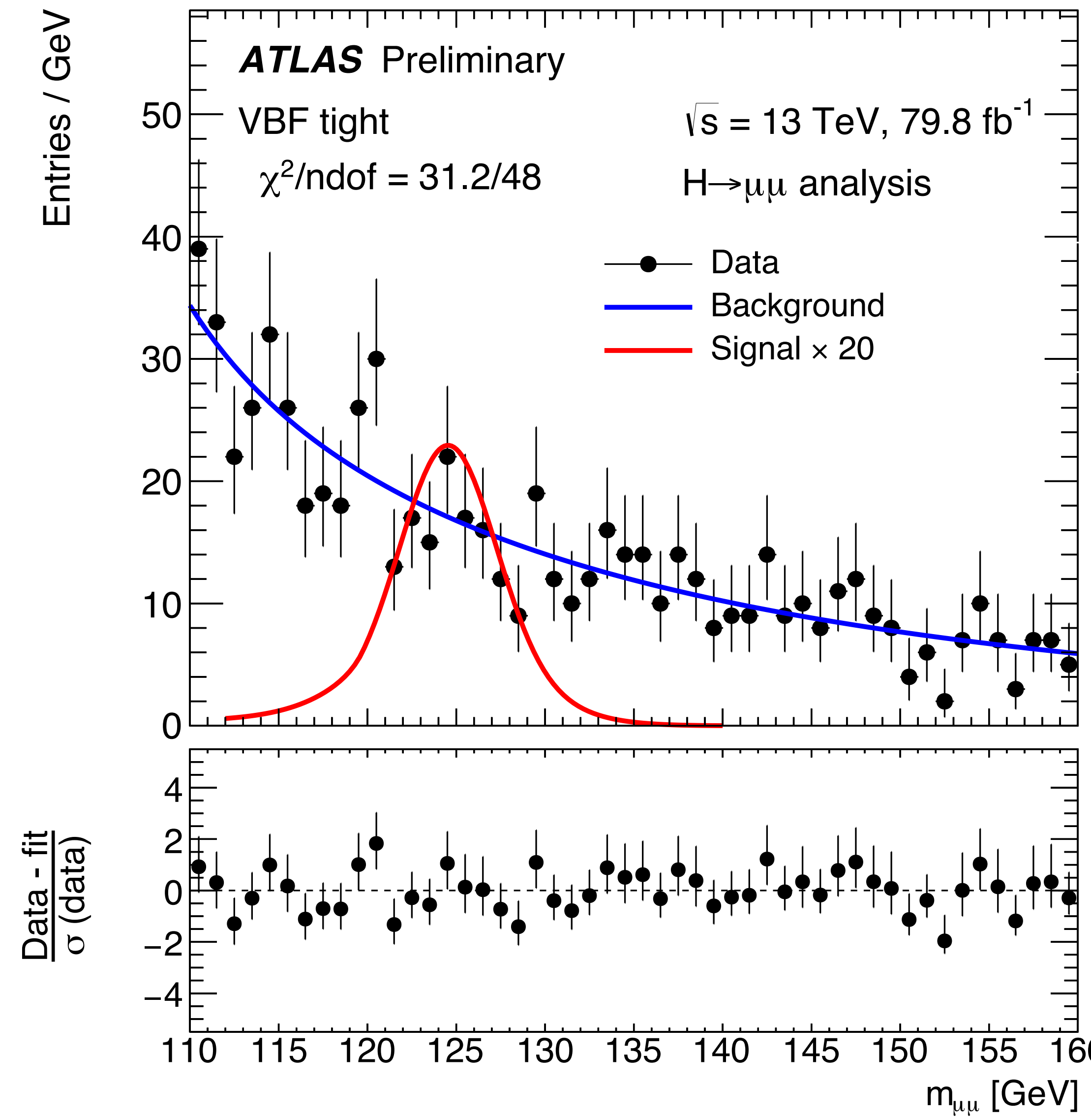
Categorization into VBF SRs (BDTs) and ggF SRs (based on $p_T^{\mu\mu}$)

Analytical fit to $m_{\mu\mu}$ mass spectrum (backgrounds based only on data sidebands)

ATLAS-CONF-2018-026

H→μμ: Results





$$\mu = 0.1^{+1.0}_{-1.1}$$

$$\mu < 2.1\ (2.0)\ \text{at}\ 95\%\ \text{CL}$$

Starting to approach SM sensitivity!

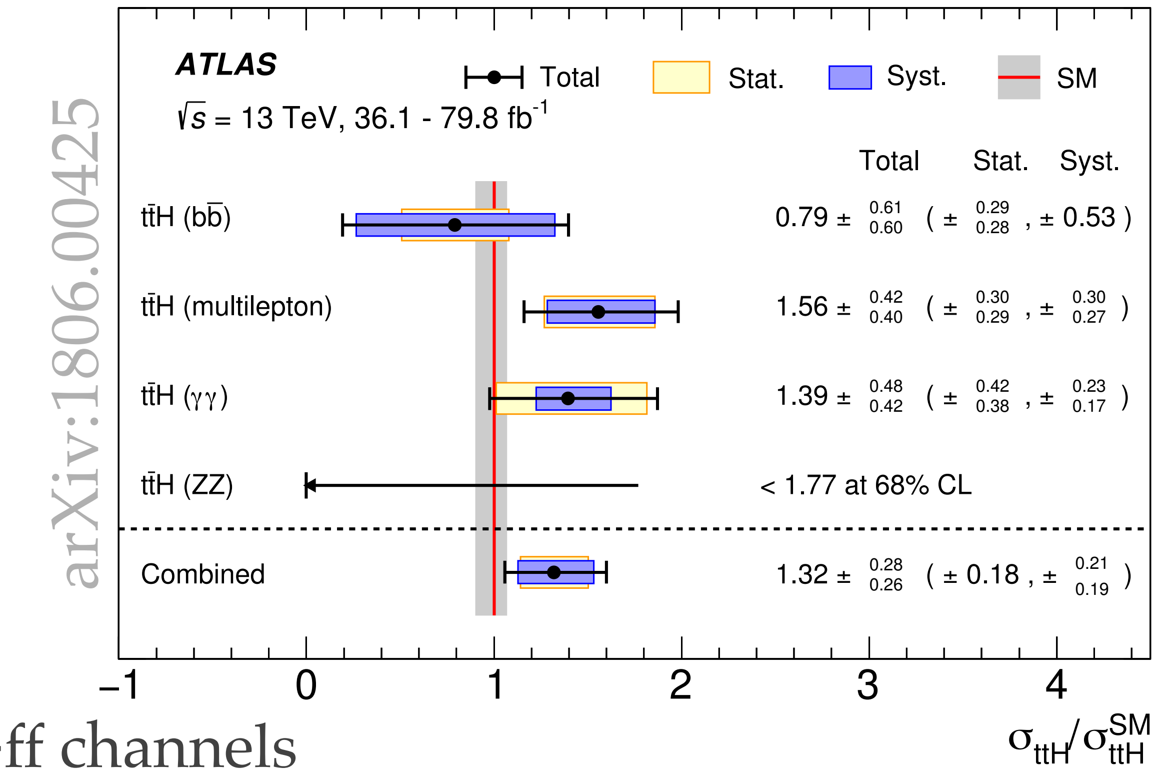
ATLAS-CONF-2018-026

Summary and Outlook

Precision era of H→ff has begun!

Channel	Precision on x-section
H→ττ	~30% @ 36 fb^{-1}
H→bb	~25% @ 80 fb^{-1}
H→μμ	~100% @ 80 fb^{-1}

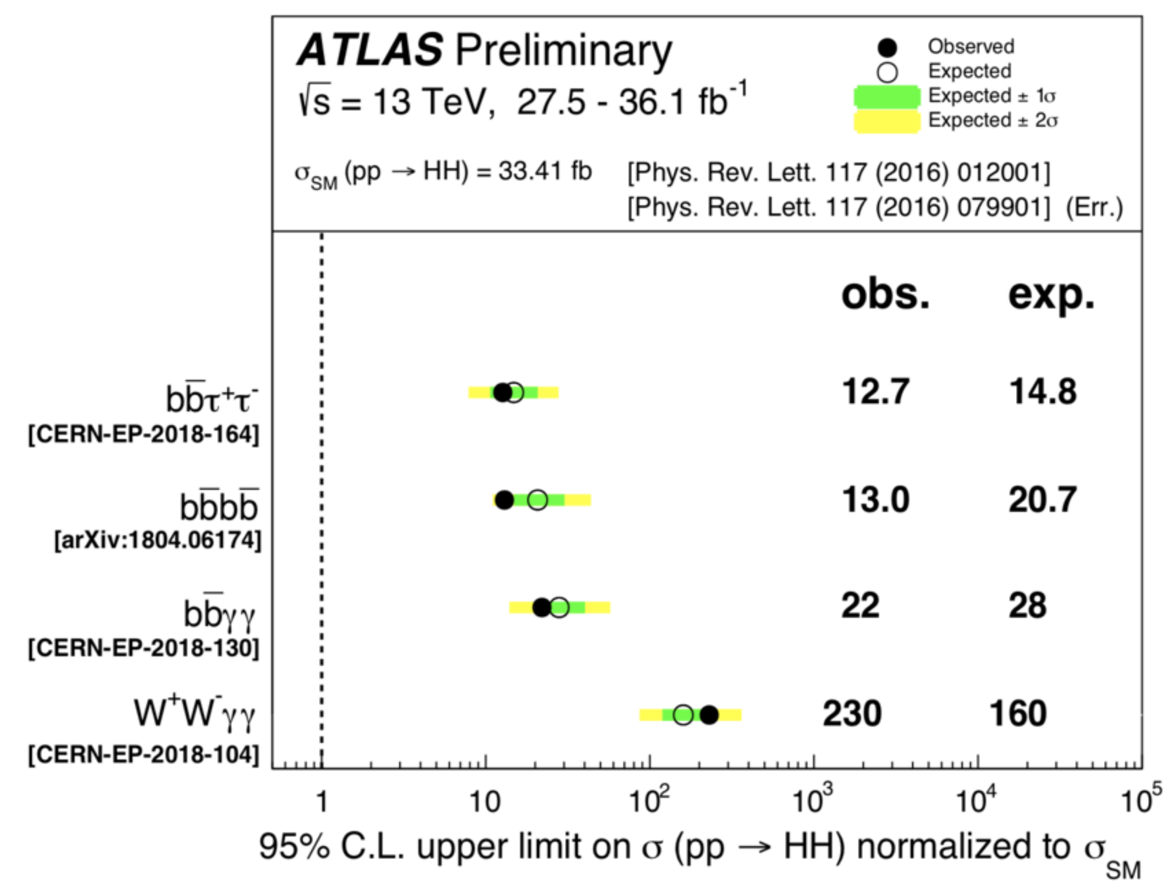
Complemented now by ttH (F. Blekman / J. Raine)



Allows interesting properties measurements in H→ff channels

With full Run-2 dataset and beyond:

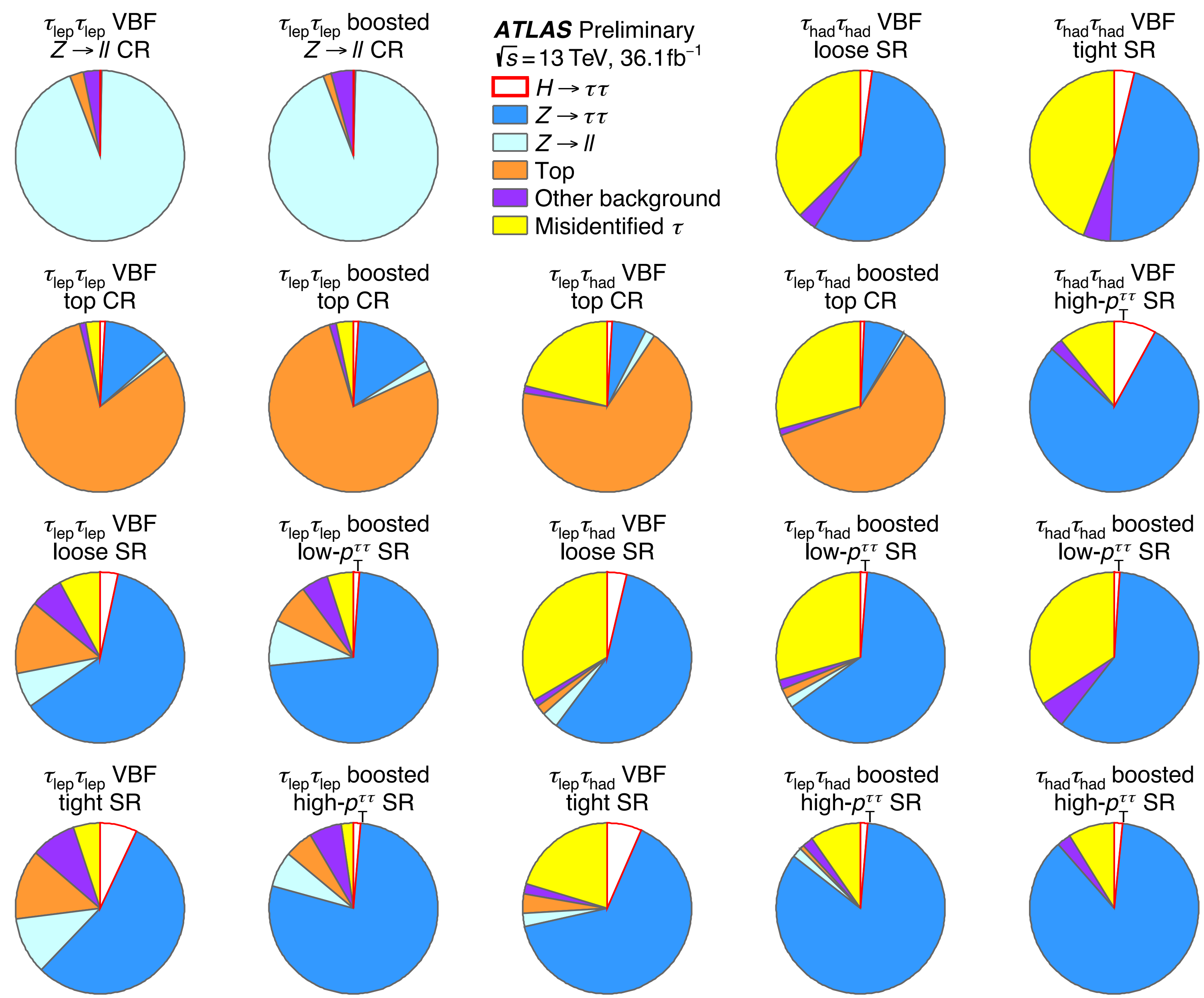
- characterization of CP nature of Higgs boson
- constraints on anomalous Higgs-fermion couplings
- differential cross-section measurements
- access to 2nd generation H→ff decays
- di-Higgs sensitivity dominated by fermionic channels (one or both legs)



cảm ơn bạn

H→ττ: Categorization

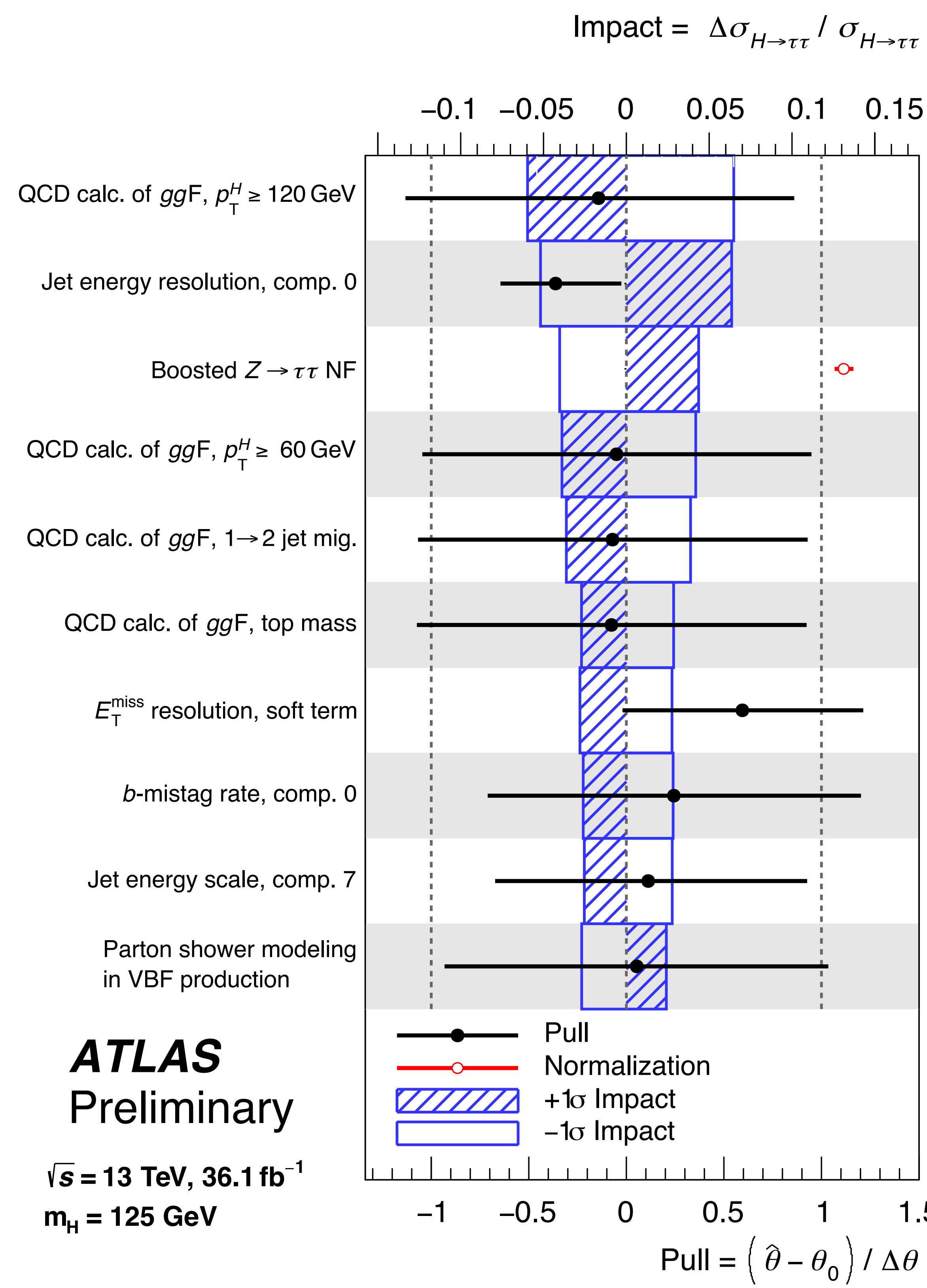
Signal Region		Inclusive	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
VBF	High-$p_T^{\tau\tau}$	$p_T^{j_2} > 30$ GeV $\lvert\Delta\eta_{jj}\rvert > 3$ $m_{jj} > 400$ GeV $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central leptons	—	—	$p_T^{\tau\tau} > 140$ GeV $\Delta R_{\tau\tau} < 1.5$
	Tight		$m_{jj} > 800$ GeV	$m_{jj} > 500$ GeV $p_T^{\tau\tau} > 100$ GeV	Not VBF high-p_T $m_{jj} > (1550 - 250 \cdot \Delta\eta_{jj})$ GeV
	Loose		Otherwise		
Boosted	High-$p_T^{\tau\tau}$	Not VBF $p_T^{\tau\tau} > 100$ GeV	$p_T^{\tau\tau} > 140$ GeV $\Delta R_{\tau\tau} < 1.5$		
	Low-$p_T^{\tau\tau}$		Otherwise		



ATLAS-CONF-2018-021

H→ττ: Measurement Uncertainties

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ (%) Observed	Expected
Theoretical uncert. on signal	+13.5 / −8.7	+11.9 / −7.7
Background statistics	+11 / −10	+10.2 / −9.8
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	+11.5 / −9.3	+10.5 / −8.6
Background normalization	+6.8 / −4.8	+6.6 / −4.6
Misidentified τ	+4.5 / −4.2	+3.7 / −3.4
Theoretical uncert. on background	+4.6 / −3.6	+5.1 / −4.2
Hadronic taus	+4.7 / −3.0	+5.8 / −4.2
Flavour tagging	+3.3 / −2.4	+2.9 / −2.2
Luminosity	+3.3 / −2.3	+3.1 / −2.2
Electrons and muons	+1.2 / −1.0	+1.1 / −0.9
Total systematic uncert.	+24 / −20	+22 / −19
Data statistics	±16	±15
Total	+28 / −26	+27 / −25



ATLAS-CONF-2018-021

H→bb: Selection Criteria

Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV	1 *tight* electron $p_{\mathrm{T}} > 27$ GeV	1 *tight* muon $p_{\mathrm{T}} > 25$ GeV	2 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_{T}	> 20 GeV for $\lvert\eta\rvert < 2.5$ and > 30 GeV for $2.5 < \lvert\eta\rvert < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^{\circ}$ (2 jets), $> 30^{\circ}$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^{\circ}$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^{\circ}$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T,trk}}^{\mathrm{miss}})$	$< 90^{\circ}$	–		–
p_{T}^{V} regions	> 150 GeV			75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV, > 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons Opposite-sign charges

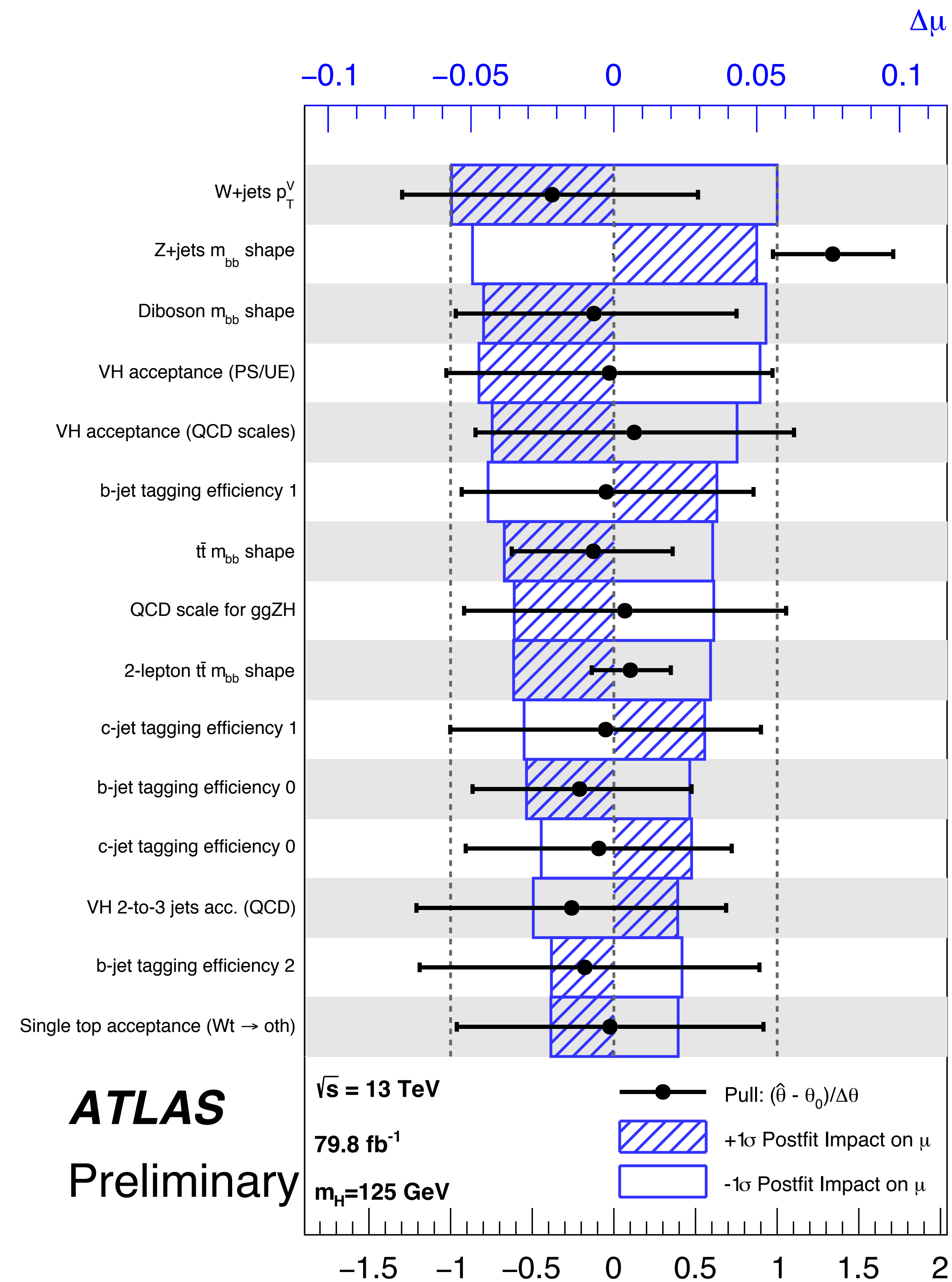
ATLAS-CONF-2018-036

H→bb: BDT Variables

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss} / $\sqrt{S_T}$	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\vec{b}_1, \vec{b}_2)$	×	×	×
$\|\Delta\eta(\vec{b}_1, \vec{b}_2)\|$	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\|\Delta\eta(\vec{V}, \vec{bb})\|$			×
m_{eff}	×		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
m_{top}		×	
$\|\Delta Y(\vec{V}, \vec{bb})\|$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

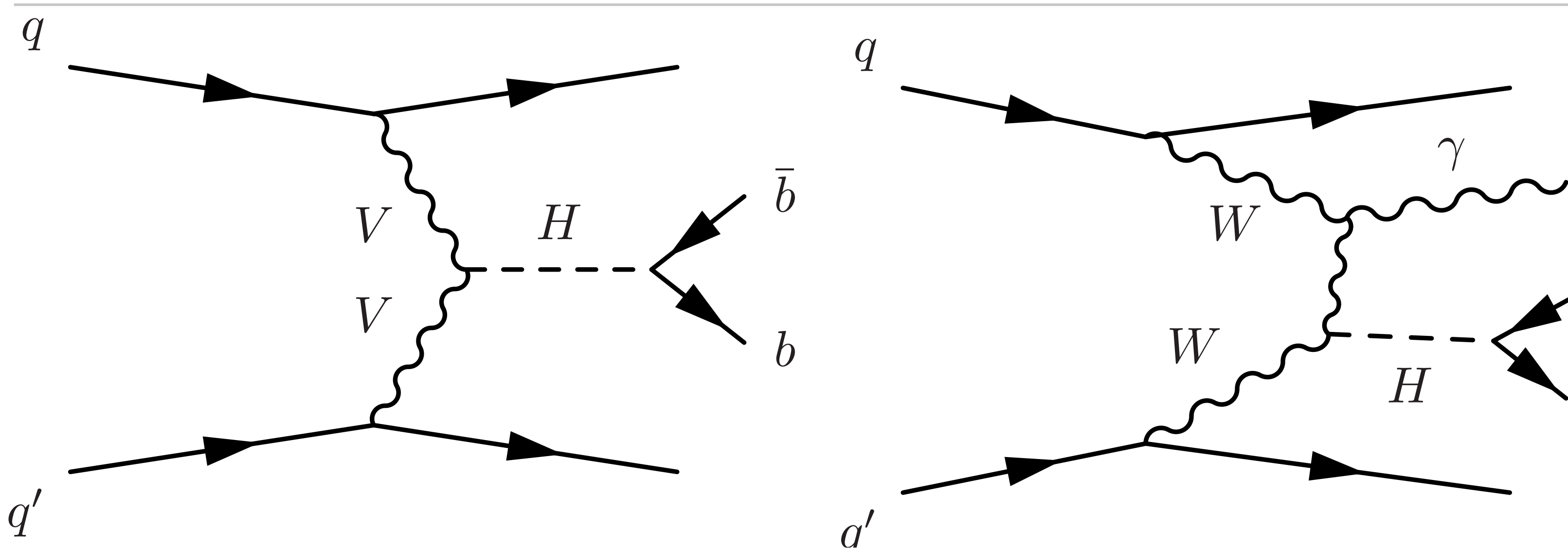
H→bb: Measurement Uncertainties

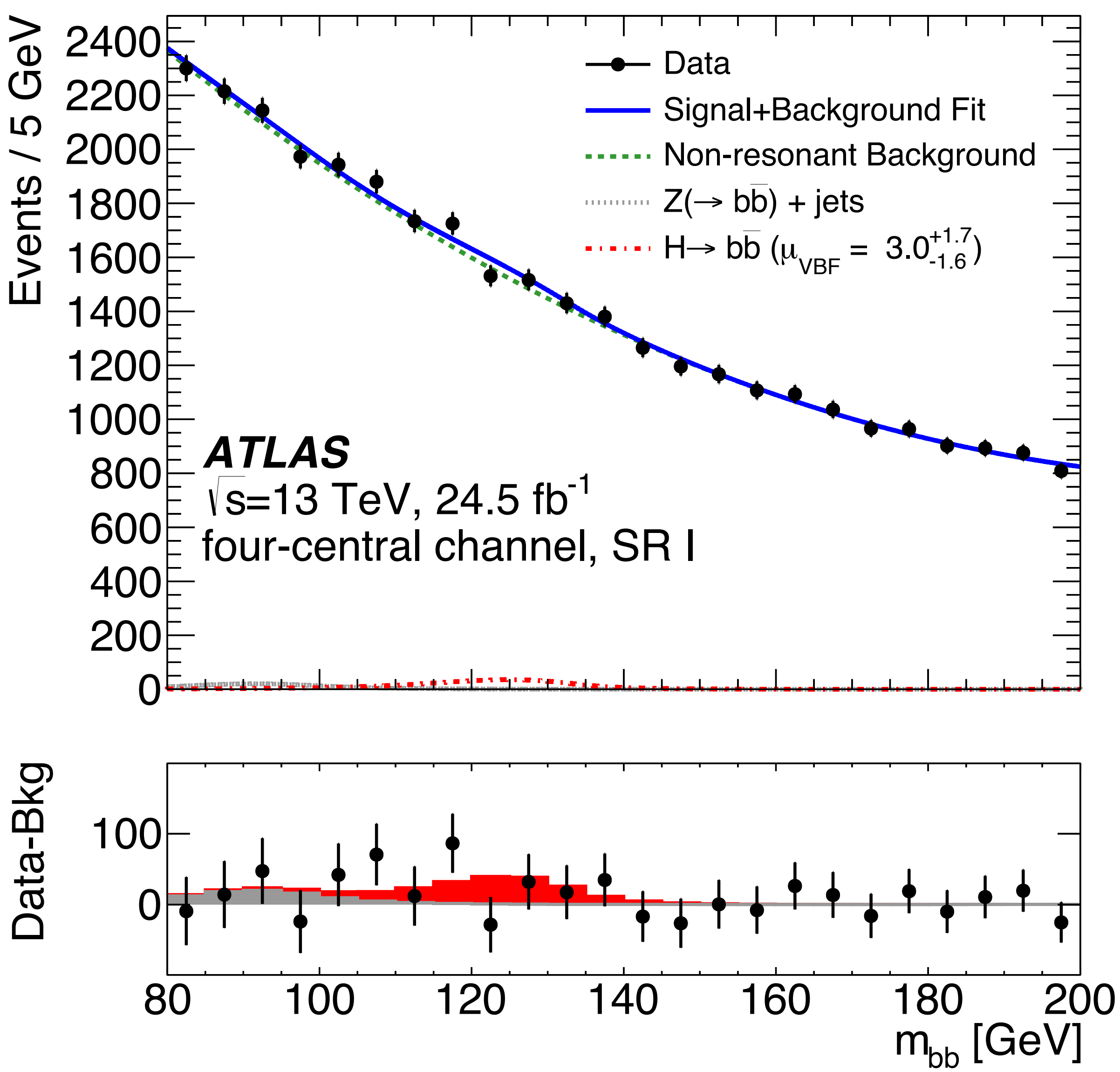
Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multijet		0.005
MC statistical		0.070

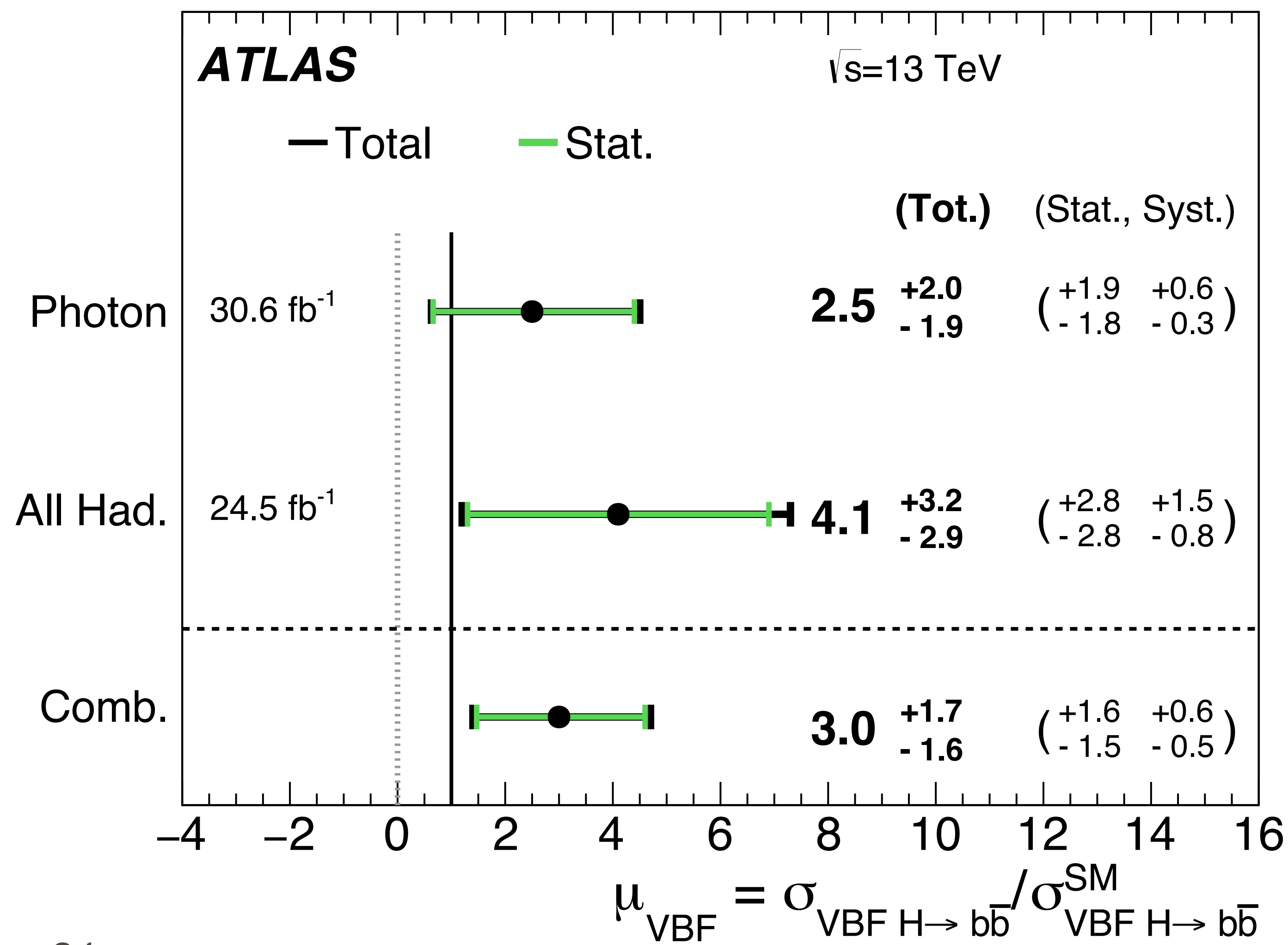


VBF H→bb

arXiv:1807.08639







H→μμ: More Details

	Z control region	$Z+\geq 2$ jets control region	VBF signal regions	ggF signal regions
Common	Primary vertex Two opposite-charge muons Muon: $\lvert\eta\rvert < 2.5$, $p_T^{\text{lead}} > 27\,\text{GeV}$, $p_T^{\text{sublead}} > 15\,\text{GeV}$ No b-tagged jets $E_T^{\text{miss}} < 80\,\text{GeV}$			
Dimuon mass	$76 < m_{\mu\mu} < 106\,\text{GeV}$		$110 < m_{\mu\mu} < 160\,\text{GeV}$	
Jets	—	≥ 2 jets, each with $p_T > 25\,\text{GeV}$ and $\lvert\eta\rvert < 2.5$ or with $p_T > 30\,\text{GeV}$ and $2.5 < \lvert\eta\rvert < 4.5$		fail VBF selection

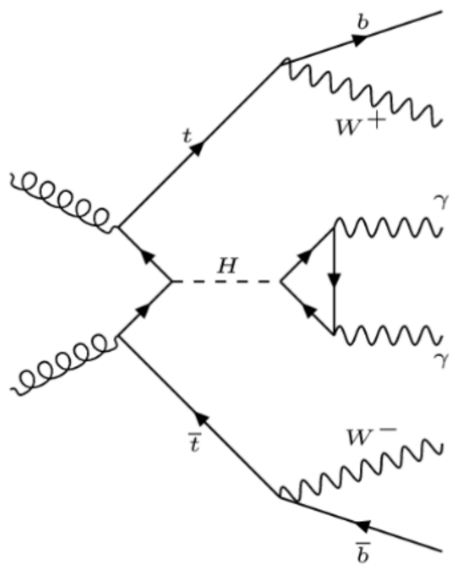
	Expected significance	Observed significance
Central low $p_T^{\mu\mu}$	0.10	−0.49
Non-central low $p_T^{\mu\mu}$	0.03	0.44
Central medium $p_T^{\mu\mu}$	0.31	1.55
Non-central medium $p_T^{\mu\mu}$	0.30	−1.16
Central high $p_T^{\mu\mu}$	0.38	0.48
Non-central high $p_T^{\mu\mu}$	0.43	0.15
VBF Loose	0.24	−0.88
VBF Tight	0.42	−0.26
Combined	0.88	0.04

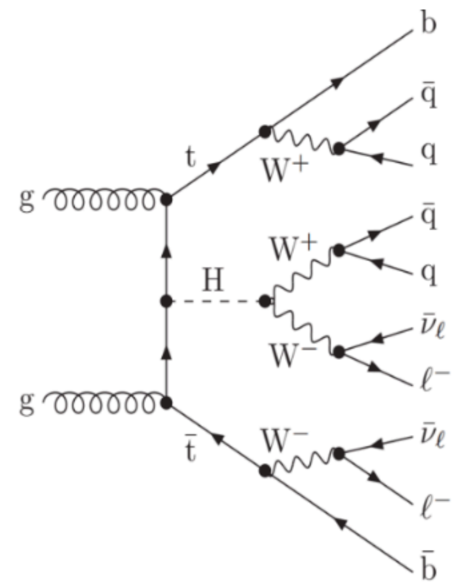
ATLAS-CONF-2018-026

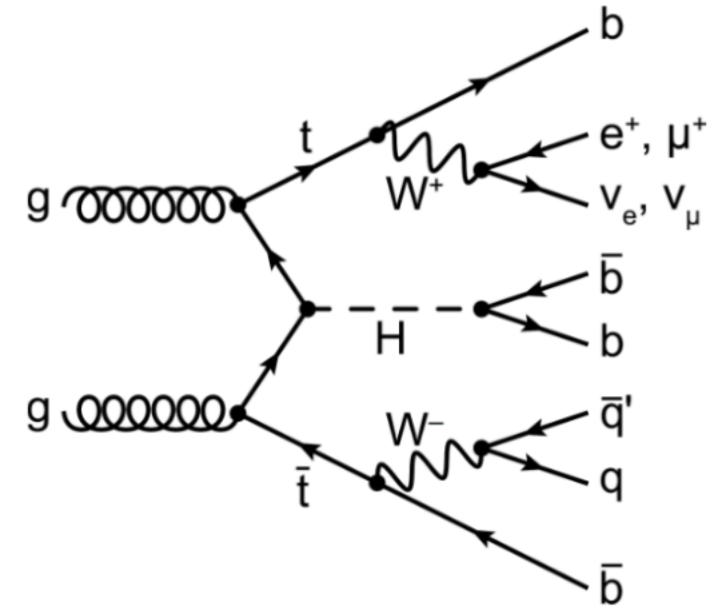
$$P_S(m_{\mu\mu}) = f_{CB} \times CB(m_{\mu\mu}, m_{CB}, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \times GS\left(m_{\mu\mu}, m_{GS}, \sigma_{GS}^{S}\right)$$

$$P_B(m_{\mu\mu}) = f \times [BW(m_{BW}, \Gamma_{BW}) \otimes GS(\sigma_{GS}^{B})](m_{\mu\mu}) + (1 - f) \times e^{A \cdot m_{\mu\mu}} / m_{\mu\mu}^3$$

ATLAS ttH Searches



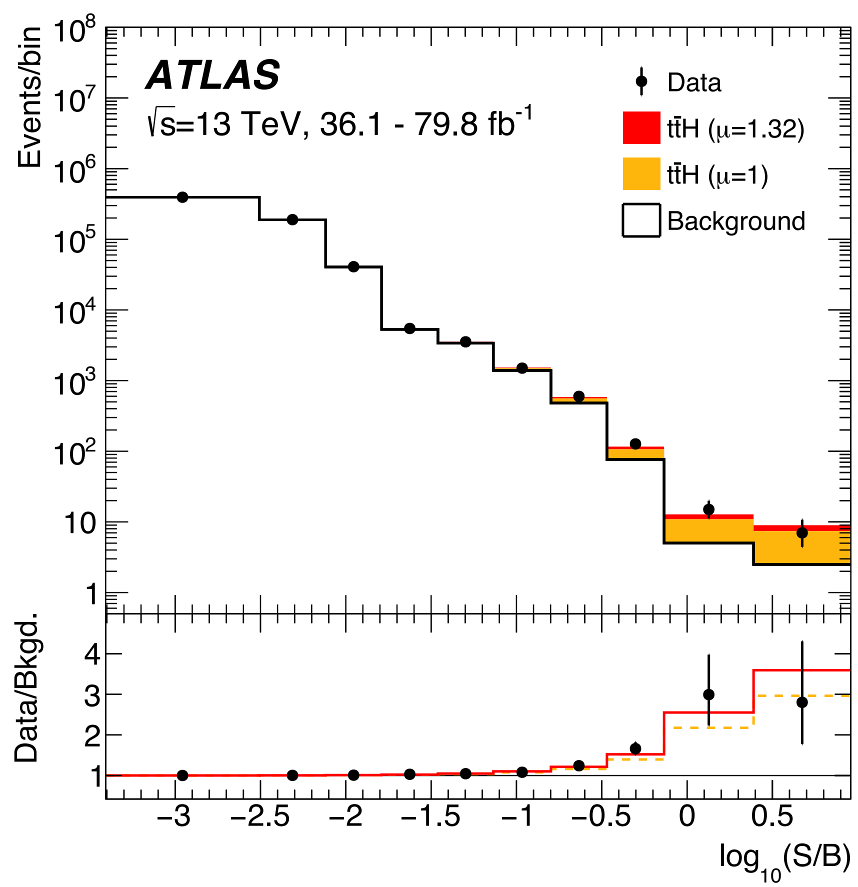


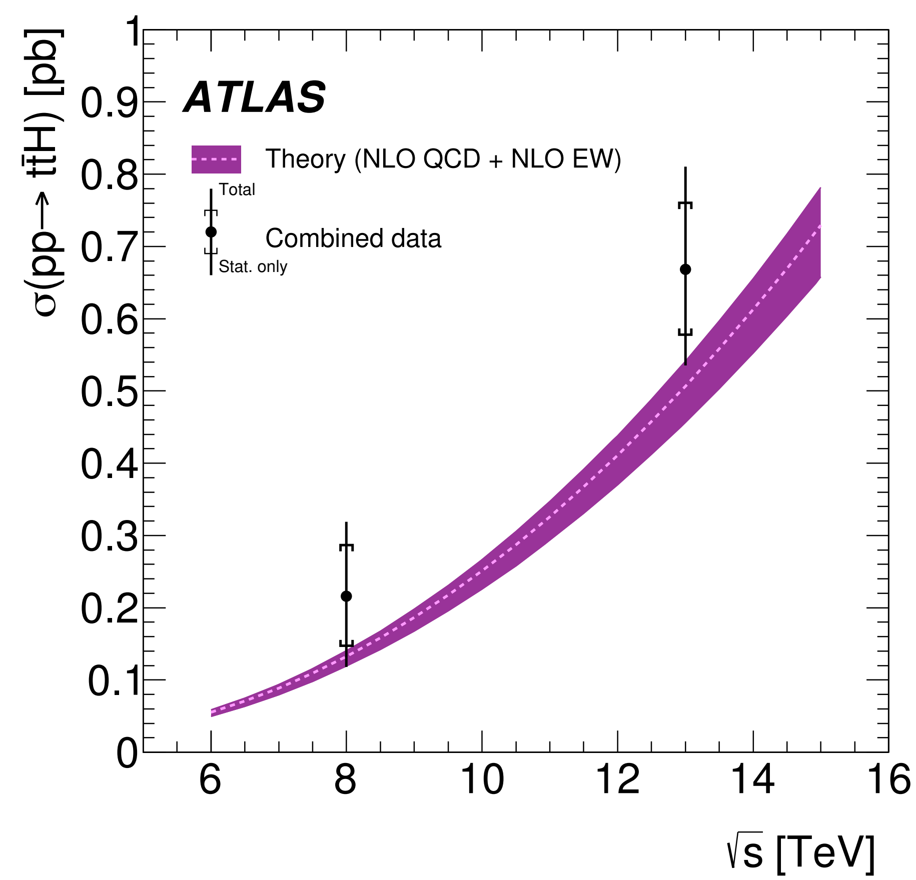


$$H \to ZZ^* \to 4\ell$$
$$H \to \gamma\gamma$$

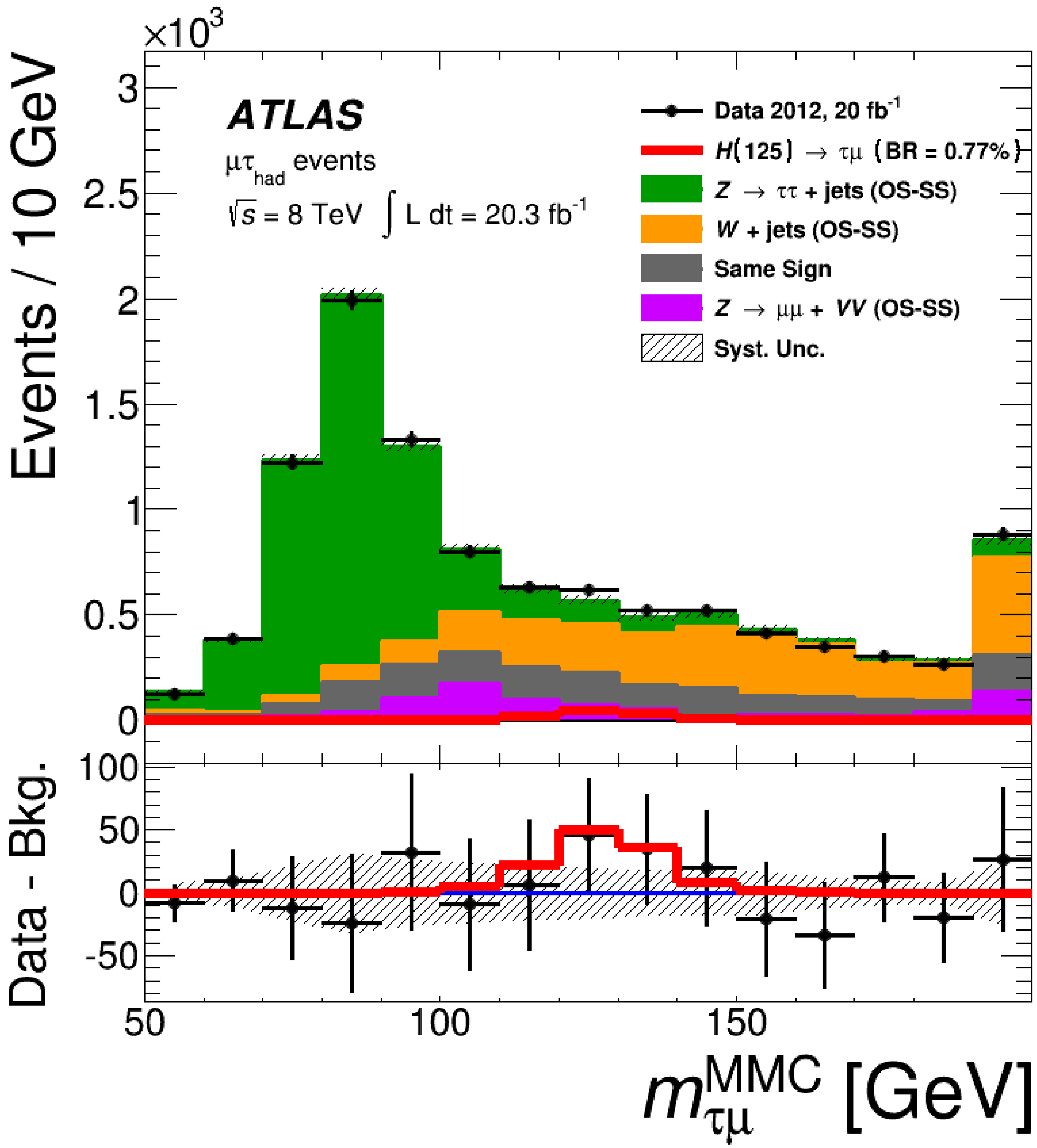
$$H \to WW^* \to \ell\nu\ell\nu$$
$$H \to \tau\tau$$
(multi-leptons)

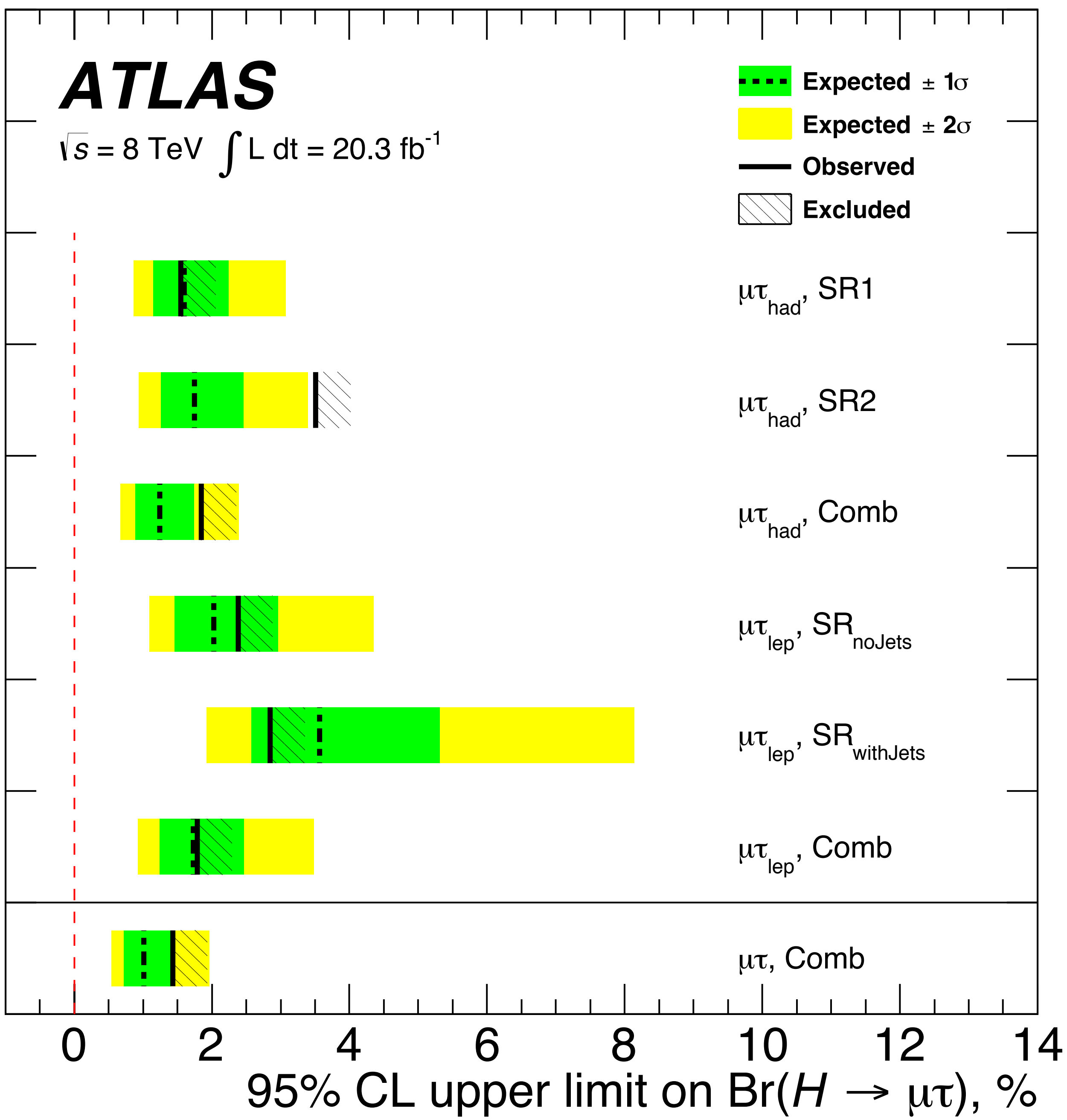
$$H \to b\bar{b}$$





LFV Searches





JHEP11(2015):211
EPJC 77 (2017) 70