Standard Model H→ττ searches with ATLAS

Higgs Hunting 2016

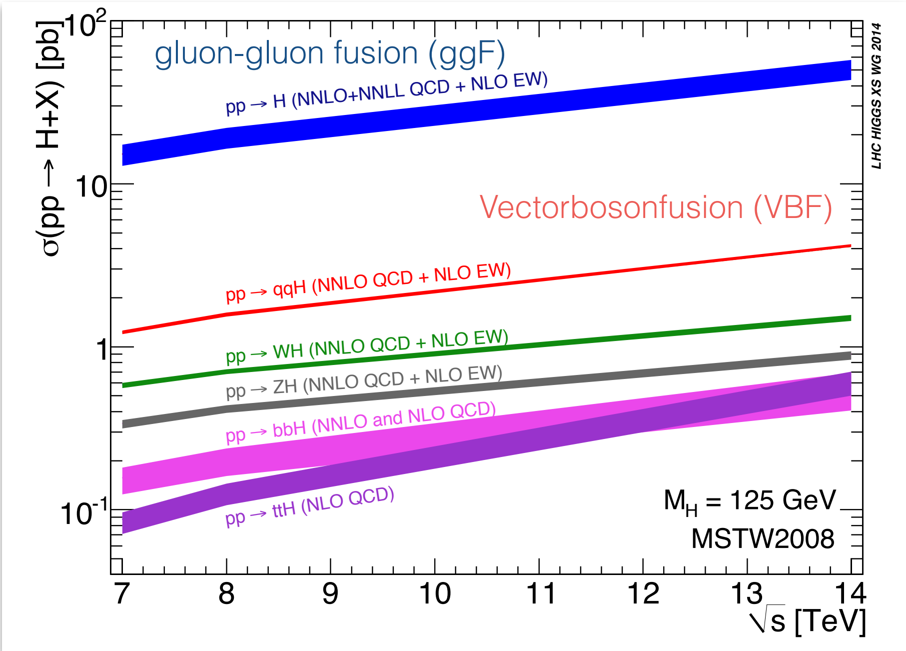
Eric Drechsler
on behalf of the ATLAS Collaboration

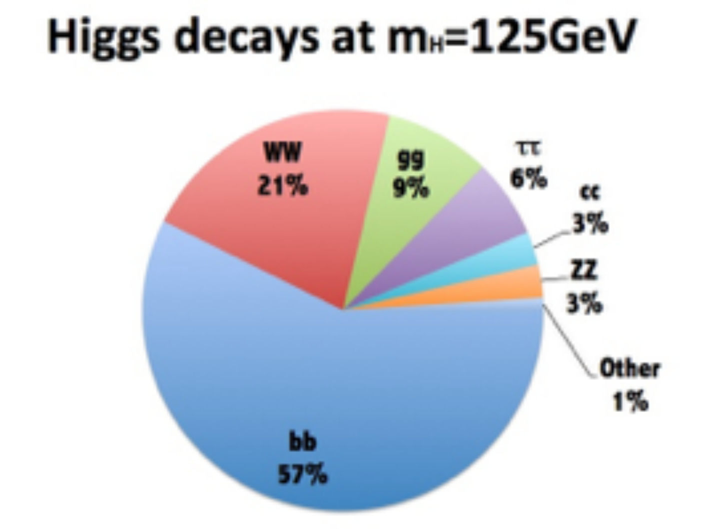
University of Göttingen
Group A. Quadt

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

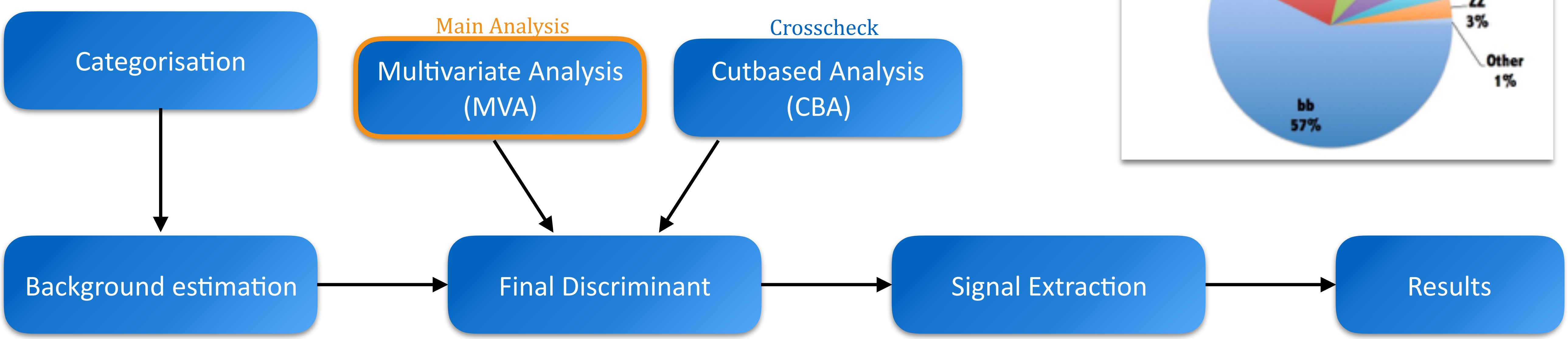
Introduction

- establishing SM **mass generation** mechanism for **fermions** at LHC
  - measure direct coupling
  - $H\to\tau\tau$ most promising candidate (signal to background ratio S/B)
  - direct access to Higgs-fermion vertex: Higgs CP measurements
- ATLAS Run I analysis: JHEP 04 (2015) 117
  - search in 7+8TeV datasets (4.5+20.3 fb^{-1})
  - **evidence** for direct $H\to\tau\tau$ coupling
  - first significant signature for H to fermion coupling
- in this talk: summary of Run I analyses





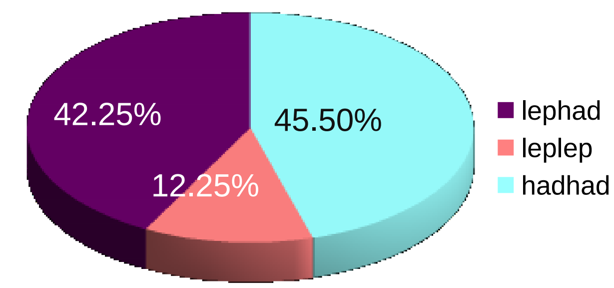
ATLAS Run I $H\to\tau\tau$ Analysis Strategy

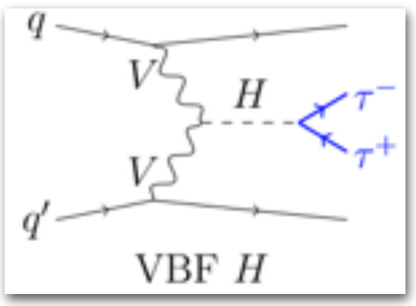


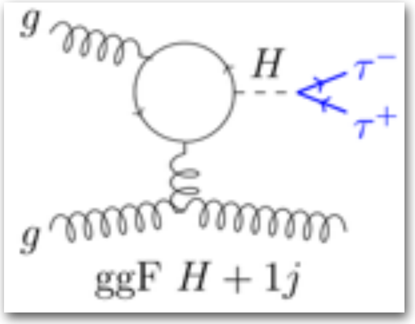
Event Categorisation

(1) split per **final state**: dileptonic (**leplep**), leptonic-hadronic (**lephad**), dihadronic (**hadhad**)

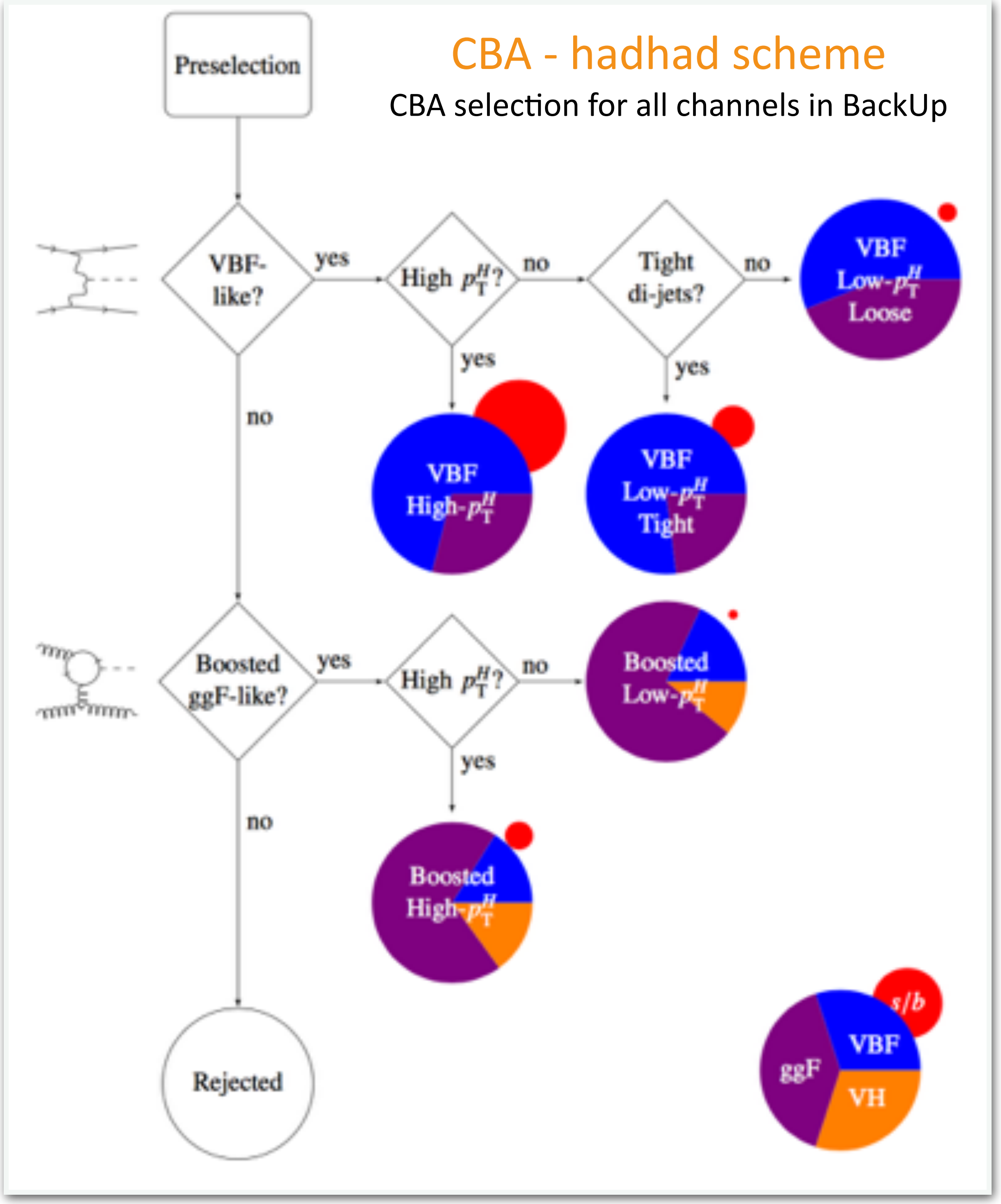
(2) divide in **categories** - production mode and S/B
- number of jets (at least one jet)
- rapidity gap between jets
- momentum of Higgs candidate





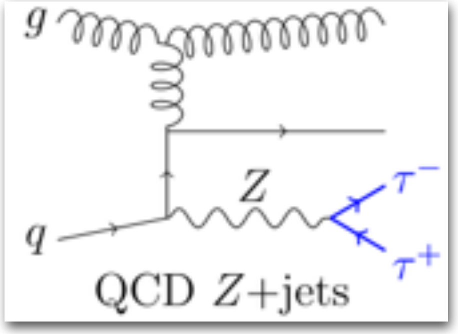


MVA	VBF	Boost	Rest
lep-lep	$p_T^{j} > 40, 30$ GeV $\Delta\eta_{jj} > 2.2$	Fail VBF $p_T^{H} > 100$ GeV	
lep-had	$p_T^{j} > 50, 30$ GeV $\Delta\eta_{jj} > 3$		
had-had	$p_T^{j} > 50, 30$ GeV $\Delta\eta_{jj} > 2$		Fail VBF, Boost

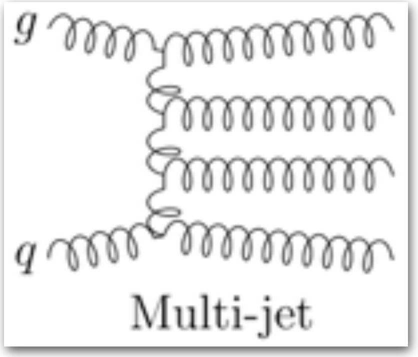


Background Estimation

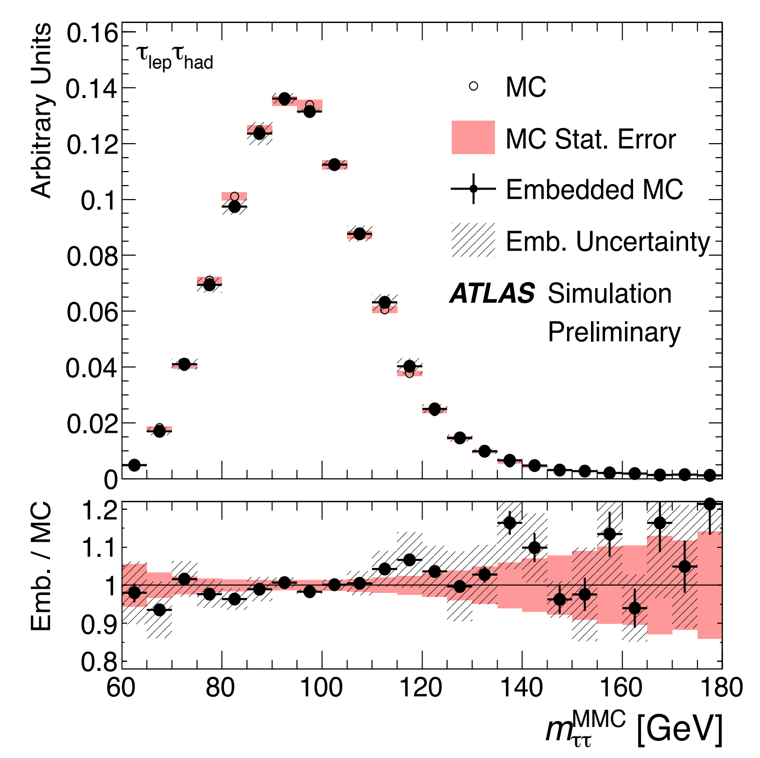
- irreducible **Z→ττ** background:
  - **embedding** technique: replace μ in pure Z→μμ data sample with simulated τ
  - corrections for μ/τ efficiencies , mass difference and polarisation effects

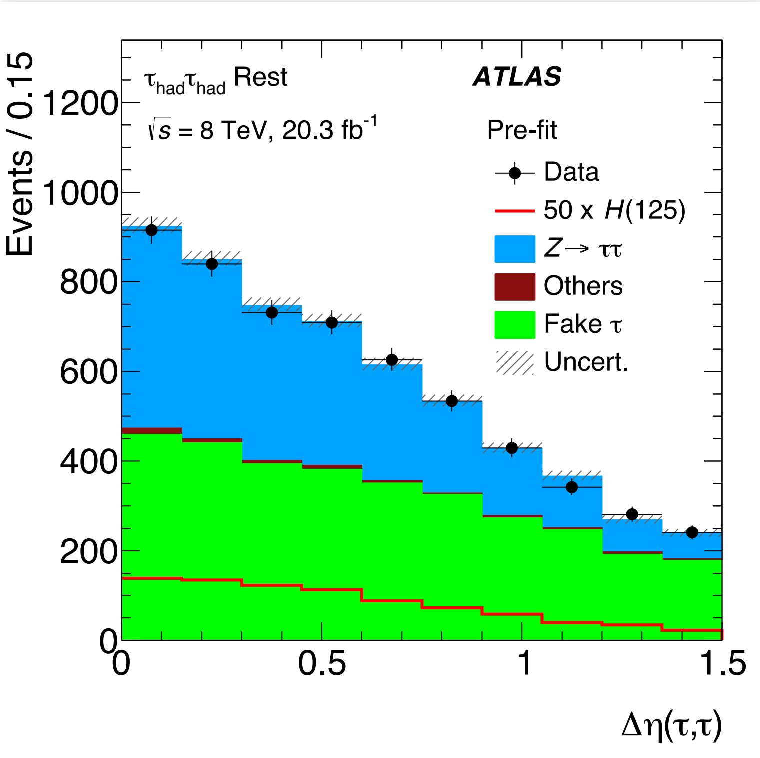


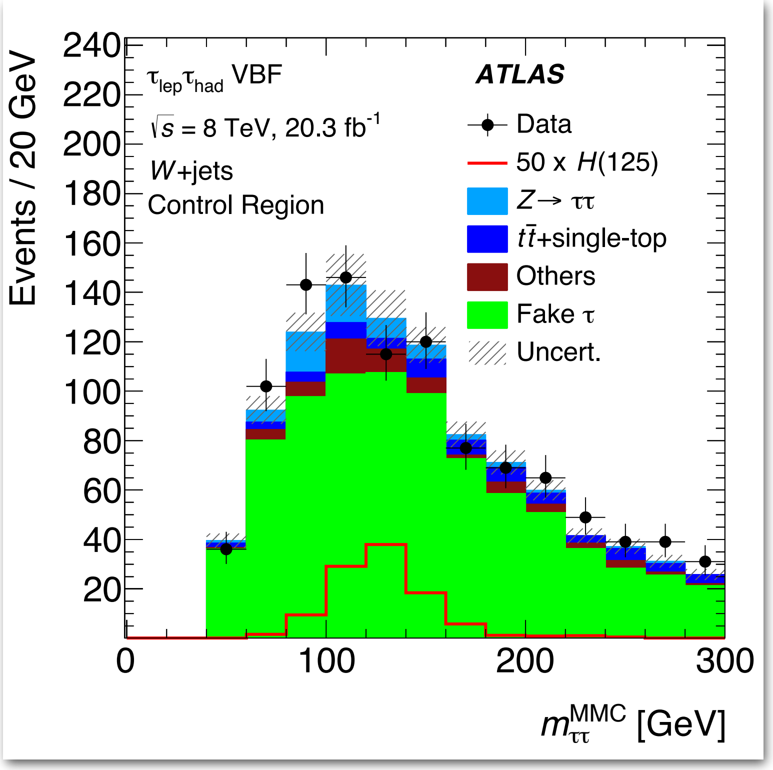
- background from **τ fakes**:
  - **data-driven** estimates
  - fits of fake templates (hadhad and leplep)
  - fake factor method (lephad)



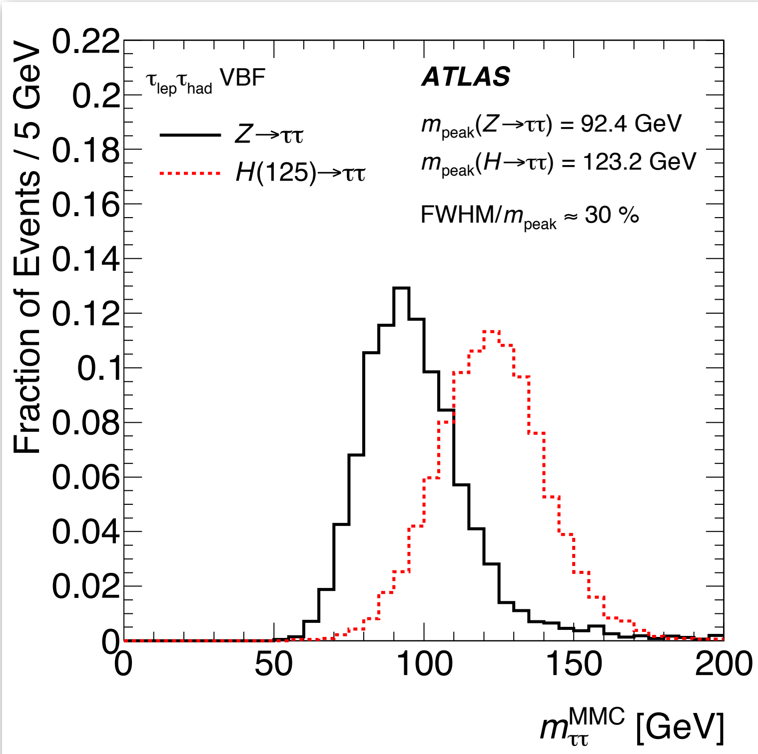
- **Other BG**: simulation and normalisation in dedicated control regions
- **Signal**: ggF/VBF H→ττ (@NLO accuracy) using POWHEG+ Pythia



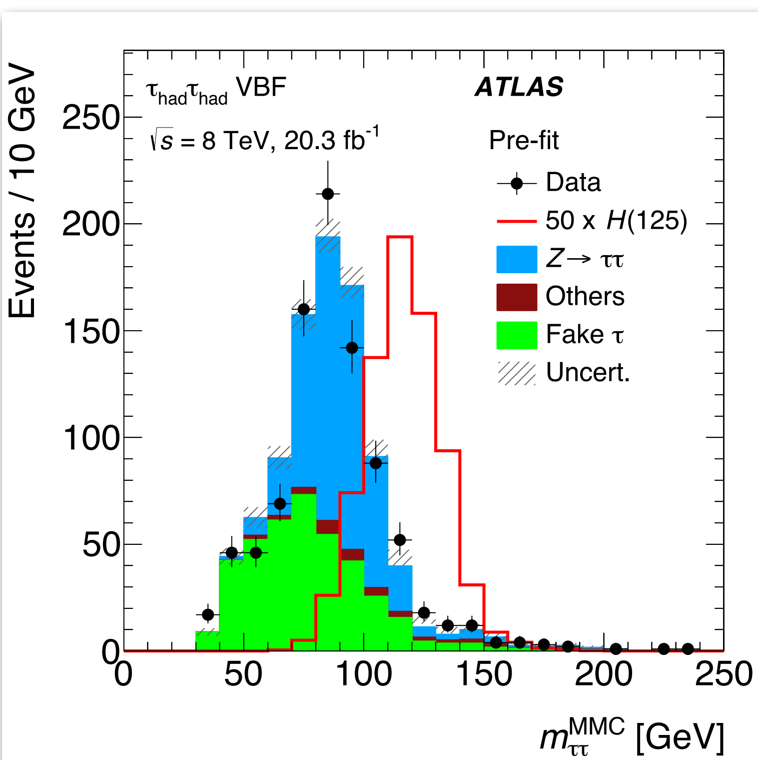


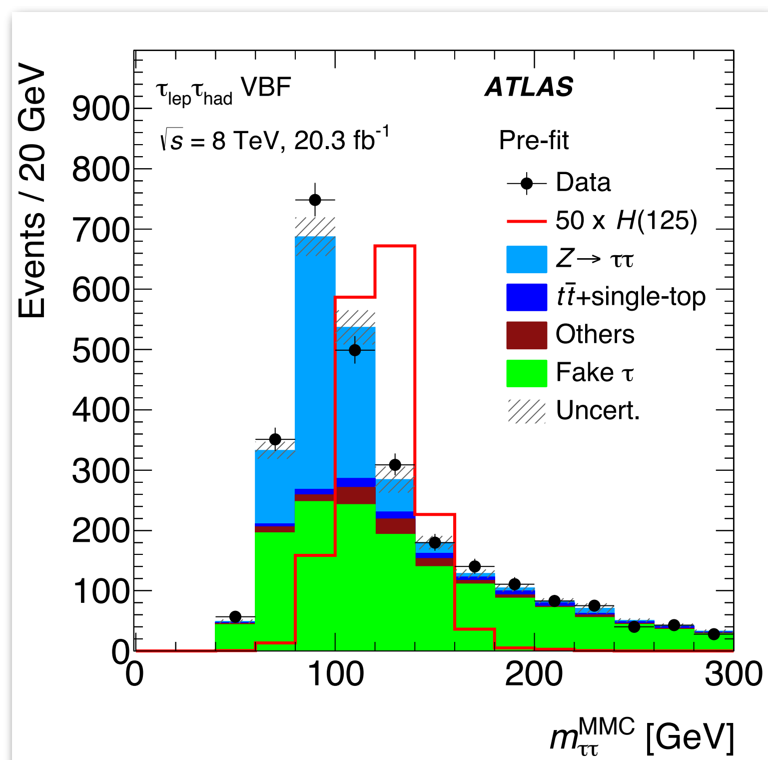


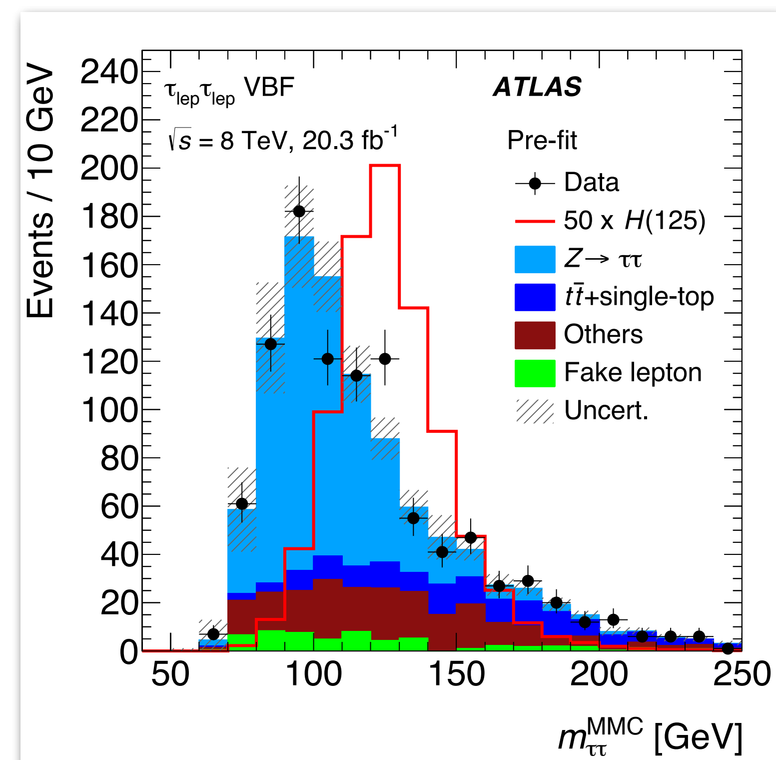
CBA - Final Discriminant: MMC mass



- CBA discriminant: **invariant mass of ττ-system** used for signal extraction
- **missing mass calculator** (MMC):
  - solving (underconstrained) system of equations
- uses $MET_{x/y}$, visible masses of τ candidates
  - most probable value for $m_{\tau\tau}$ estimated from MET resolution and τ decay topologies
  - losses due to large fluctuations of the MET
- **mass resolution ~15%**
  - ratio of full width at half max. and peak value of mass distribution = 30%



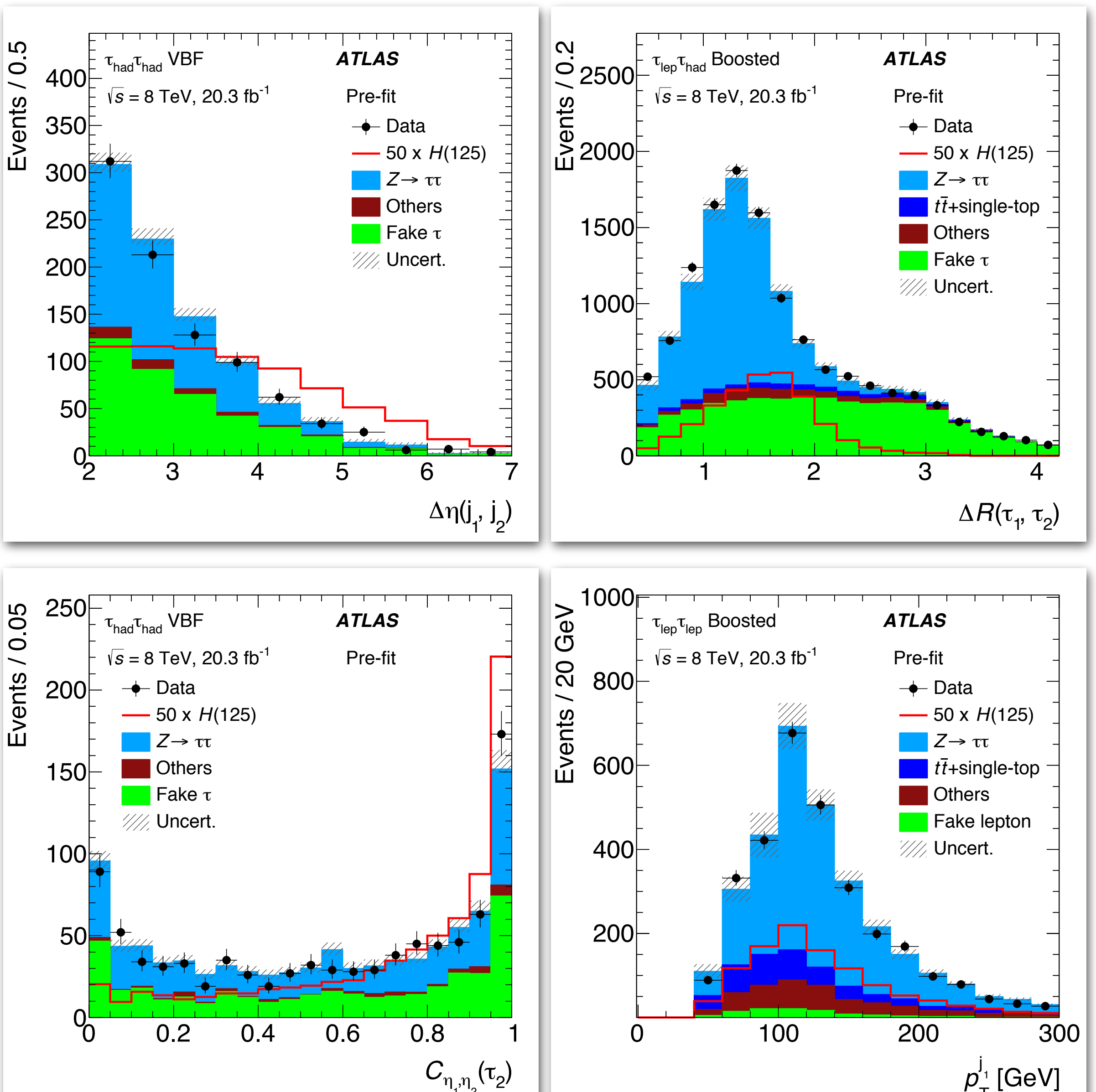




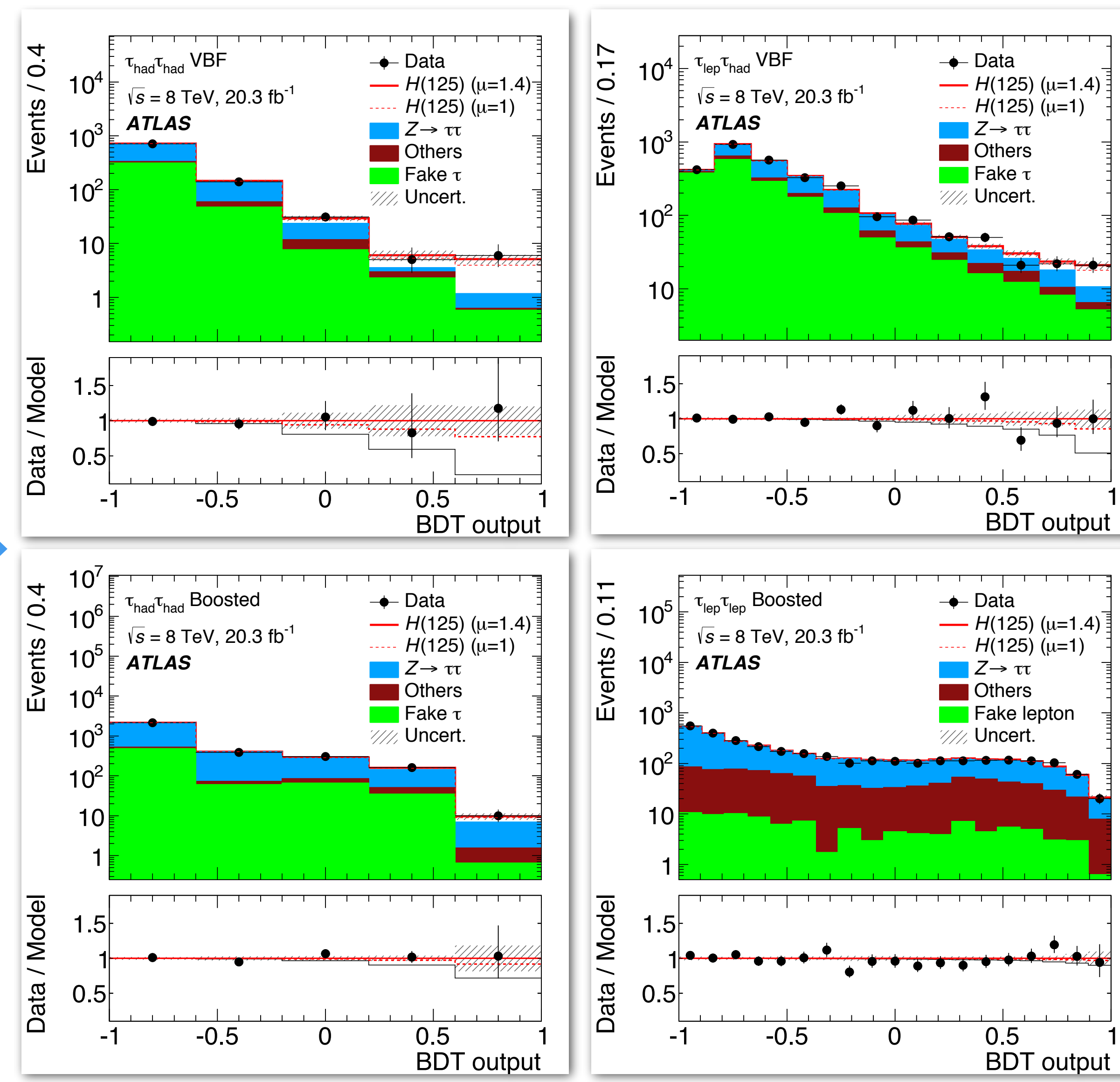
MVA - Final Discriminant: BDT output

- MVA discriminant: **Boosted Decision Tree (BDT)**
  - recursively partition multi variate parameter space - enhance S or B purities
  - variables channel-dependent: kinematic properties & event topology
- combination of trees in single discriminant - **BDT output**

Highest Ranked BDT Input Variables
$m_{\tau\tau}^{MMC}$
$\Delta R(\tau_1, \tau_2)$
$\Delta\eta(j_1, j_2)$
m_{j_1,j_2}
...



BDT

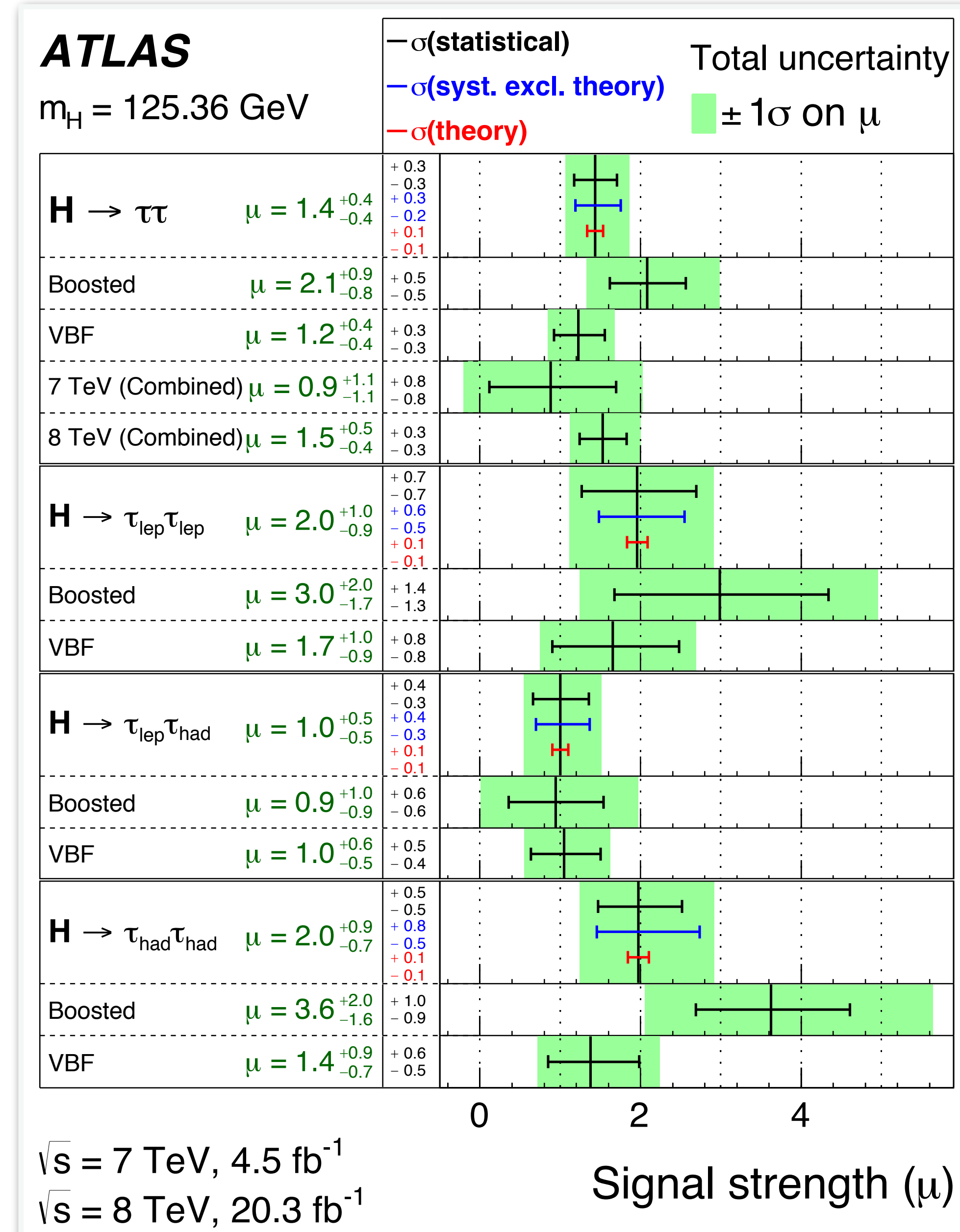


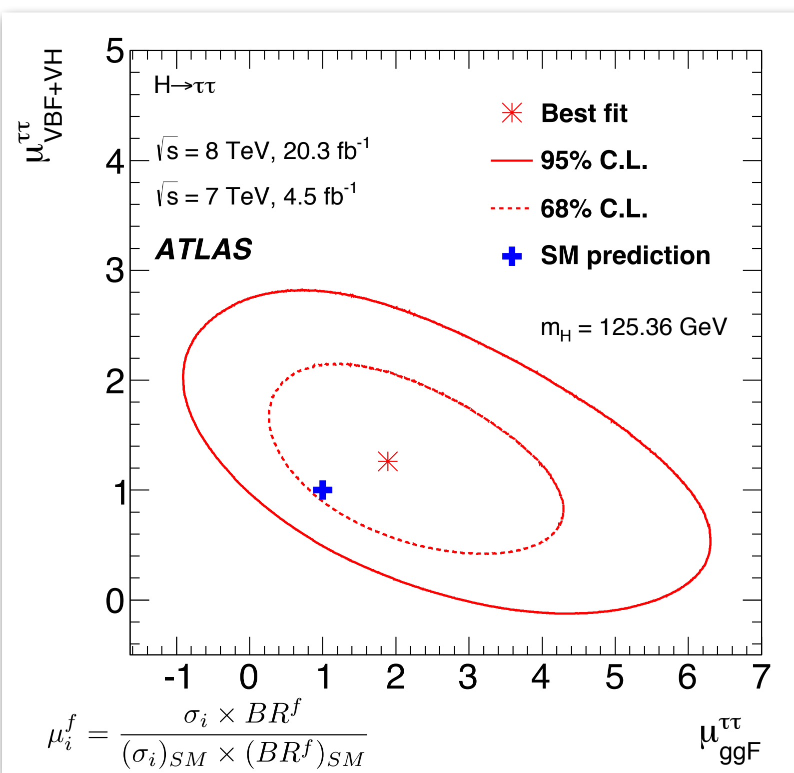
- combined, binned maximum-**Likelihood fit**
  - using BDT output in 6 signal categories (separate 7/8TeV)
  - Zll, top & Rest control region to constrain backgrounds
- extracting signal strength **μ**
  - ratio of observed/expected SM signal for cross section times branching ratio
- MVA result for Higgs mass **m_H=125.36 GeV**:

$$\text{observed (expected): } \sigma = 4.5(3.4)$$

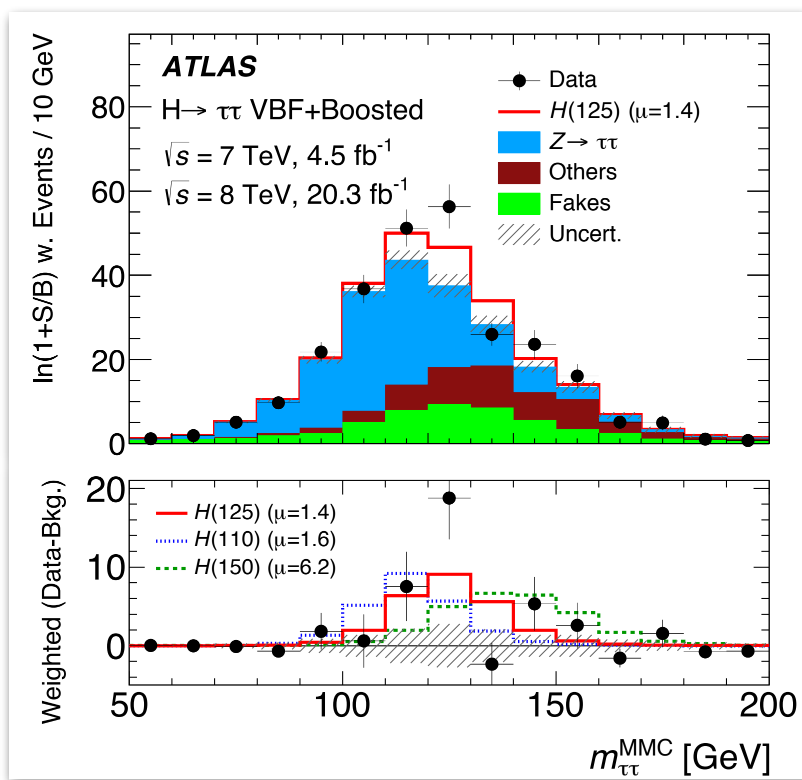
$$\mu = 1.43^{+0.27}_{-0.26}\ (\text{stat})\ ^{+0.32}_{-0.25}\ (\text{syst})\ \pm 0.09(\text{theory})$$

$$\mu = \frac{(\sigma \times BR)_{obs}}{(\sigma \times BR)_{SM}}$$





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



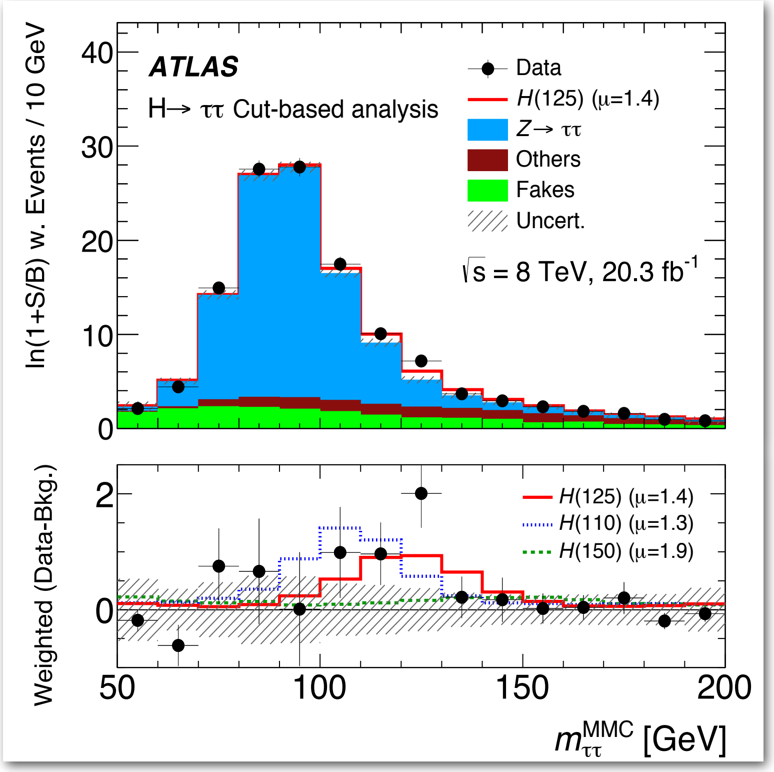
CBA - Results

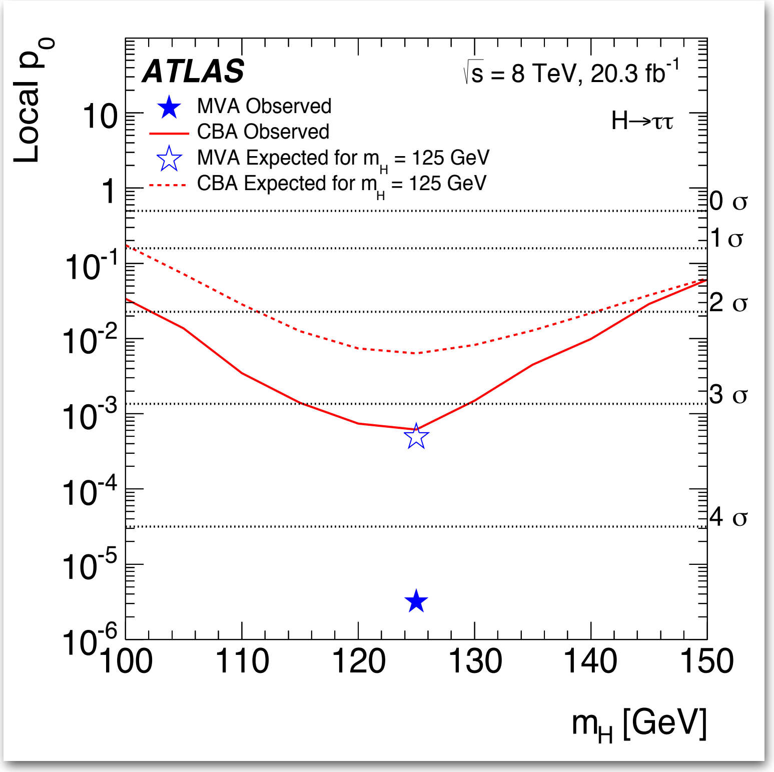
- same fit model but **MMC** as final discriminant
- CBA result @ m_H=125.36 GeV for **8 TeV only**

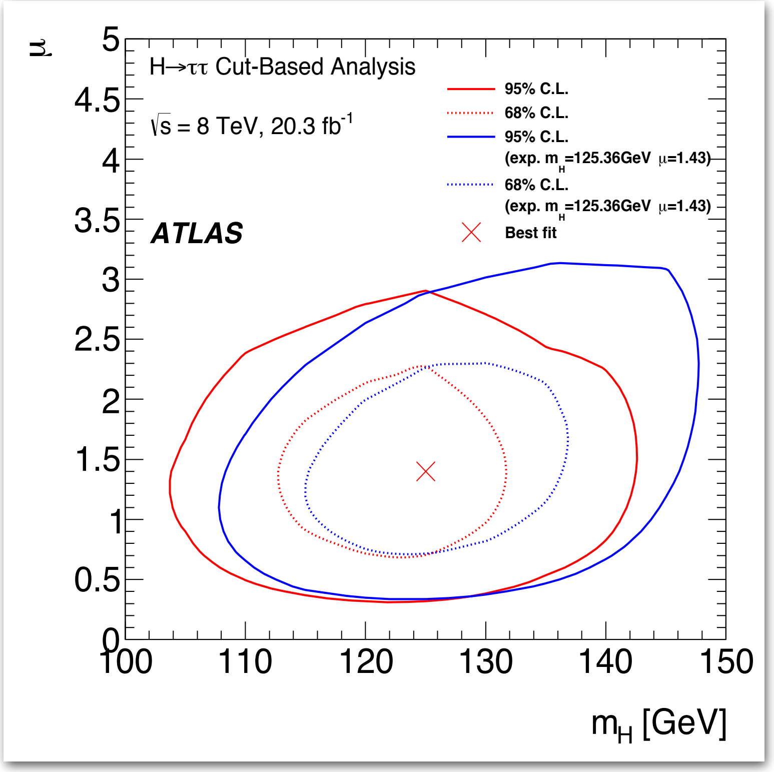
$$\text{observed (expected): } \sigma = 3.2(2.5)$$
$$\mu = 1.43^{+0.55}_{-0.49} \text{ (total)}$$

	Fitted μ values		
	$\sqrt{s}$	Multivariate analysis	Cut-based analysis
$\tau_{lep}\tau_{lep}$	8 TeV	$1.9^{+1.0}_{-0.9}$	$3.2^{+1.4}_{-1.3}$
$\tau_{lep}\tau_{had}$	8 TeV	$1.1^{+0.6}_{-0.5}$	$0.7^{+0.7}_{-0.6}$
$\tau_{had}\tau_{had}$	8 TeV	$1.8^{+0.9}_{-0.7}$	$1.6^{+0.9}_{-0.7}$
All channels	8 TeV	$1.53^{+0.47}_{-0.41}$	$1.43^{+0.55}_{-0.49}$

- **good agreement** between MVA and CBA- tested with jackknife technique
  - correlation of μ: 0.55-0.75 for all channels
  - results fully compatible







Summary & Outlook

- H→ττ important channel to validate SM
  - ATLAS Run I search strategies and results presented

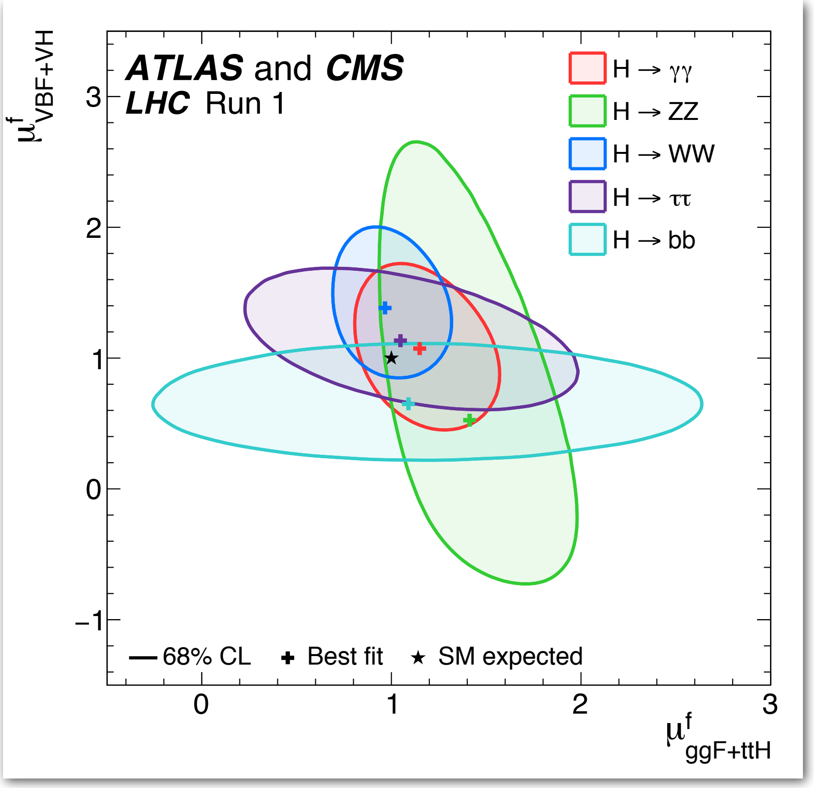
$$\text{observed (expected): } \sigma = 4.5(3.4)$$
$$\mu = 1.43^{+0.27}_{-0.26}\text{ (stat) }^{+0.32}_{-0.25}\text{ (syst) } \pm 0.09\text{(theory)}$$

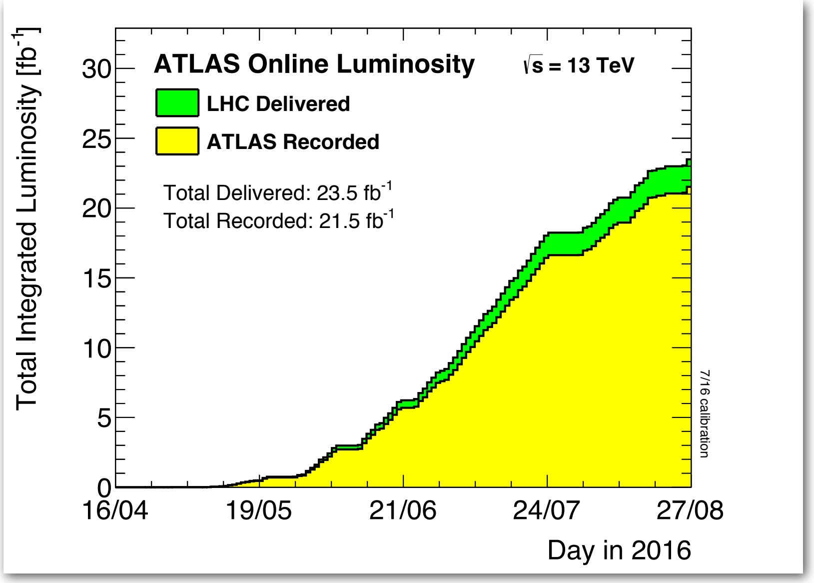
  - compatible results between different analyses approaches (MVA/CBA)

- not covered: **VH→ττ** searches (Phys. Rev. D 93, 092005)
  - limit on signal strength μ < 5.6 (3.7)

- **ATLAS + CMS combination** (ATLAS-CONF-2015-044/CMS-PAS-HIG-15-002)
  - establishes discovery of H→ττ with 5.5σ
  - VBF production mode discovered with 5.4σ significance
    - H→ττ major contribution

- **new results** with Run II dataset **expected soon**
  - higher center of mass energy **13 TeV**
    - signal cross sections increase factor > 2
    - changes in event topology (e.g. boost)
  - increase in multiple pp interactions per crossing (factor 2)
  - optimised reconstruction methods - better resolutions
  - new detector IBL in ATLAS
  - ★ excitement!

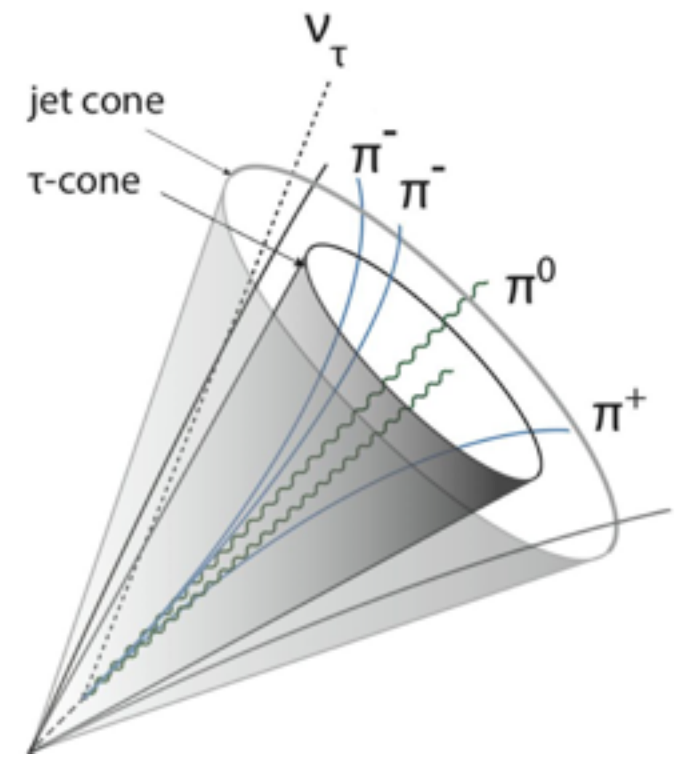


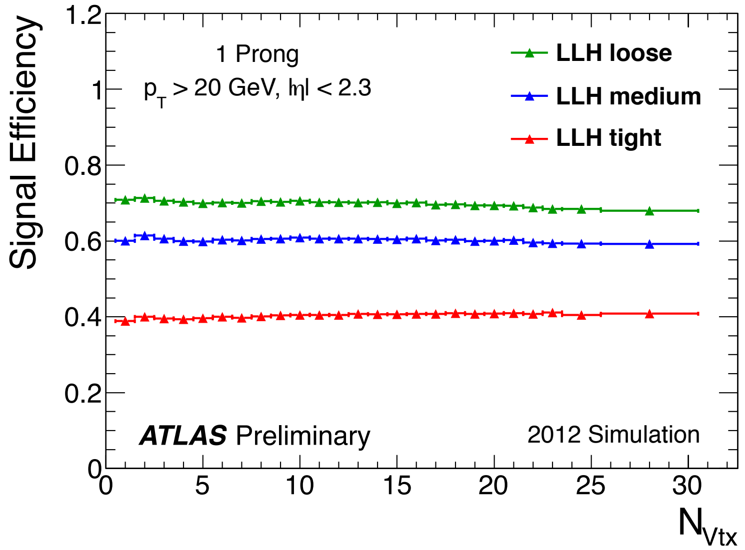


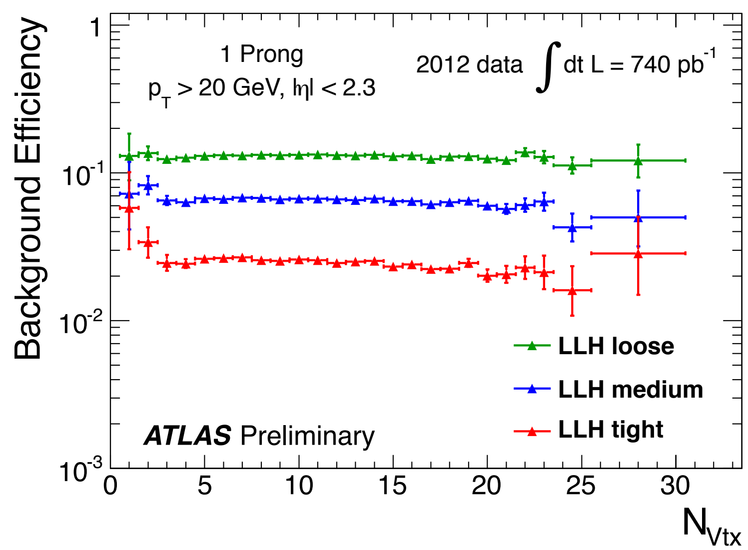
BACKUP

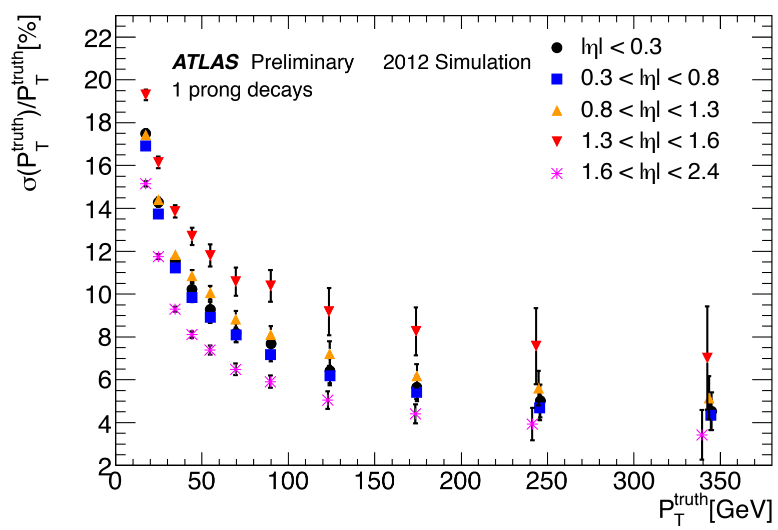
Backup

1. Reconstruction
2. Identification - discrimination against:
   a. Jets (multivariate BDT technique)
   b. Electrons
3. Calibration
4. Scaling
   a. scale factors from efficiency measurements



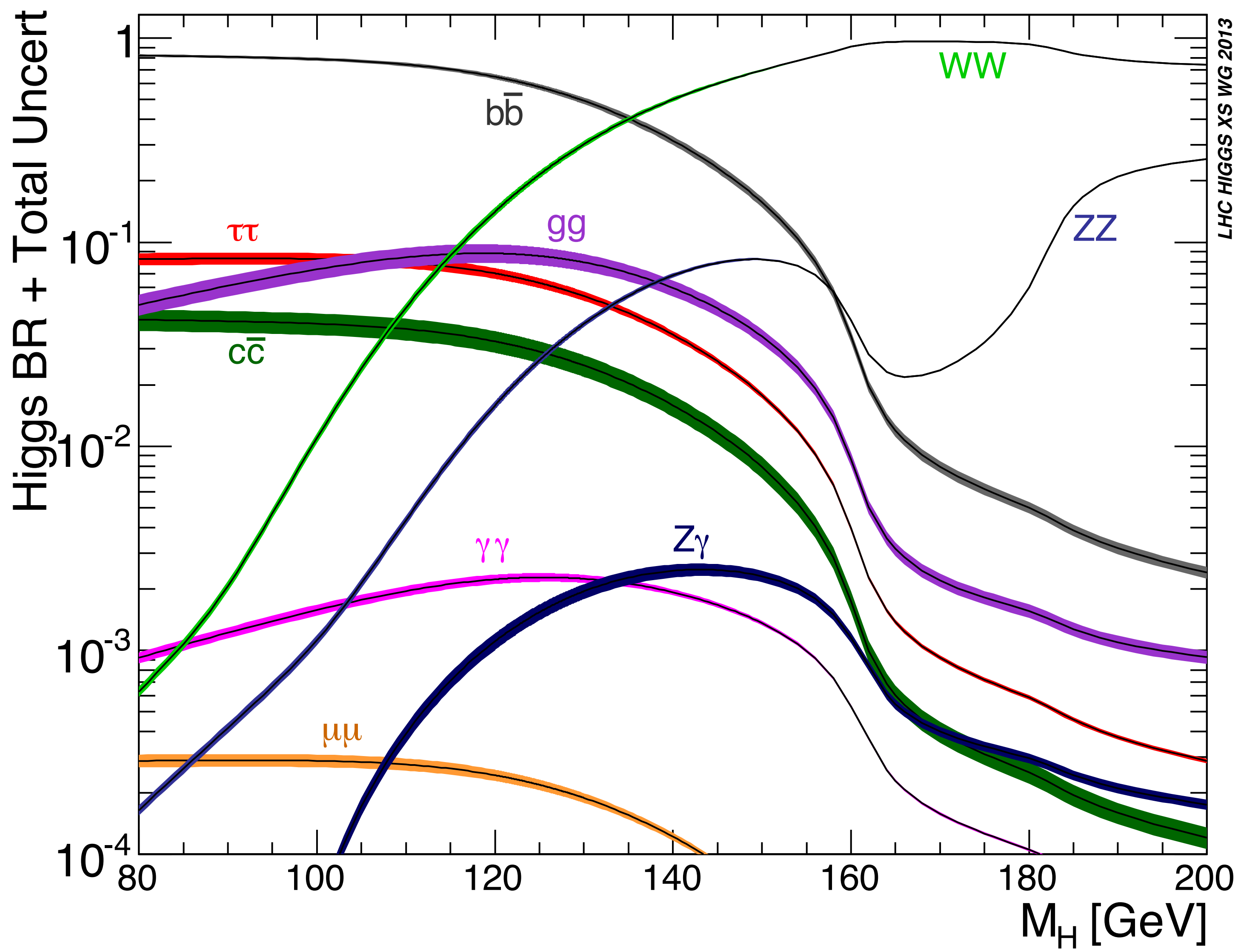






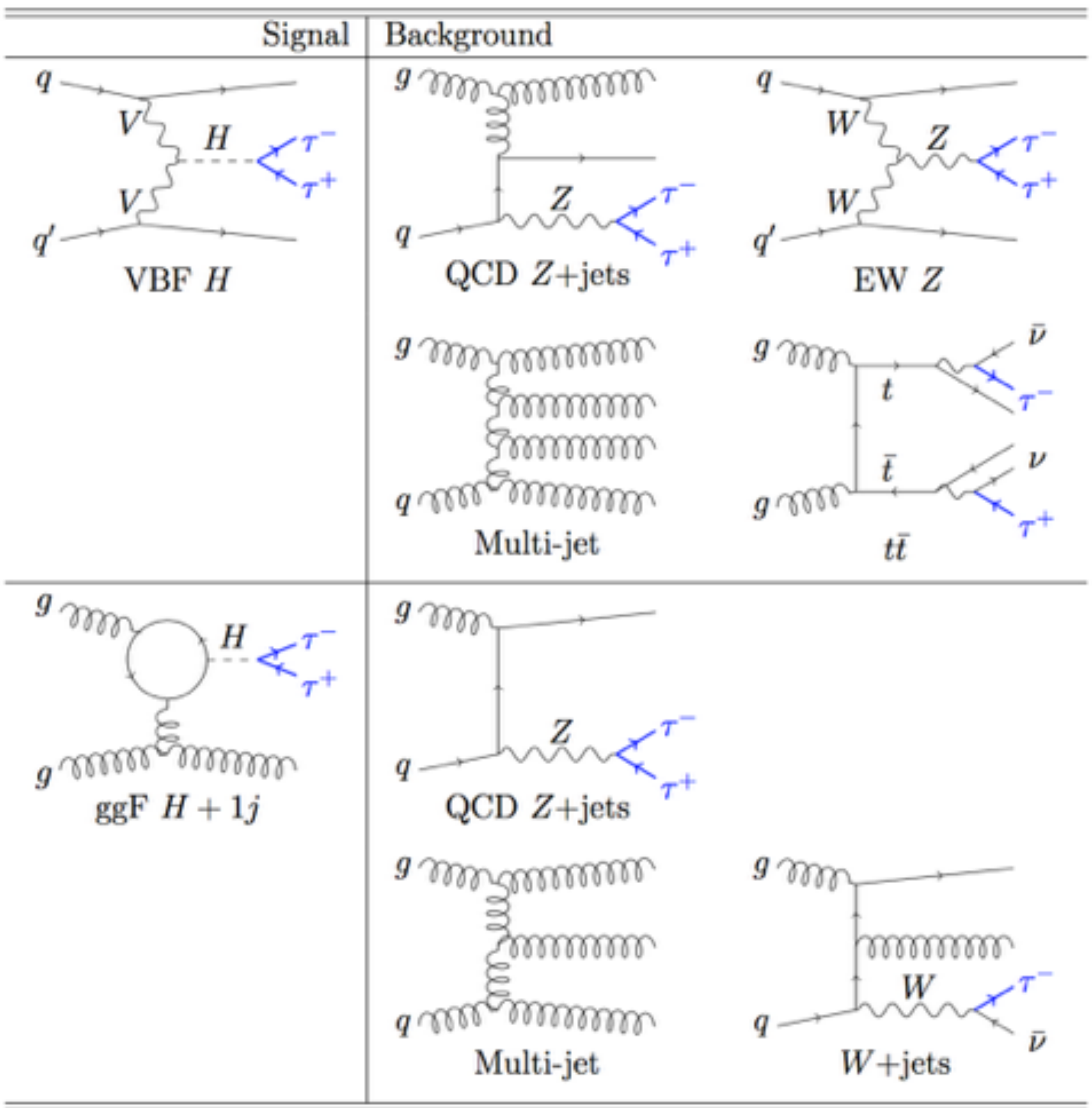
Backup

- Higgs Branching Ratios for different mass scenarios



• typical tree level diagrams for targeted signal production modes and corresponding backgrounds

Table 4.1: Typical tree-level Feynman diagrams for the two signal processes targeted by the event selection, together with the corresponding main background processes. The final states are characterised by hadronically decaying τ leptons (blue) and quark- or gluon-initiated jets.



Backup

ggF

$\sqrt{s}$ (TeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
7	15.11	+7.1	-7.8	+7.6	-7.1
8	19.24	+7.2	-7.8	+7.5	-6.9
13	43.87	+7.4	-7.9	+7.1	-6.0

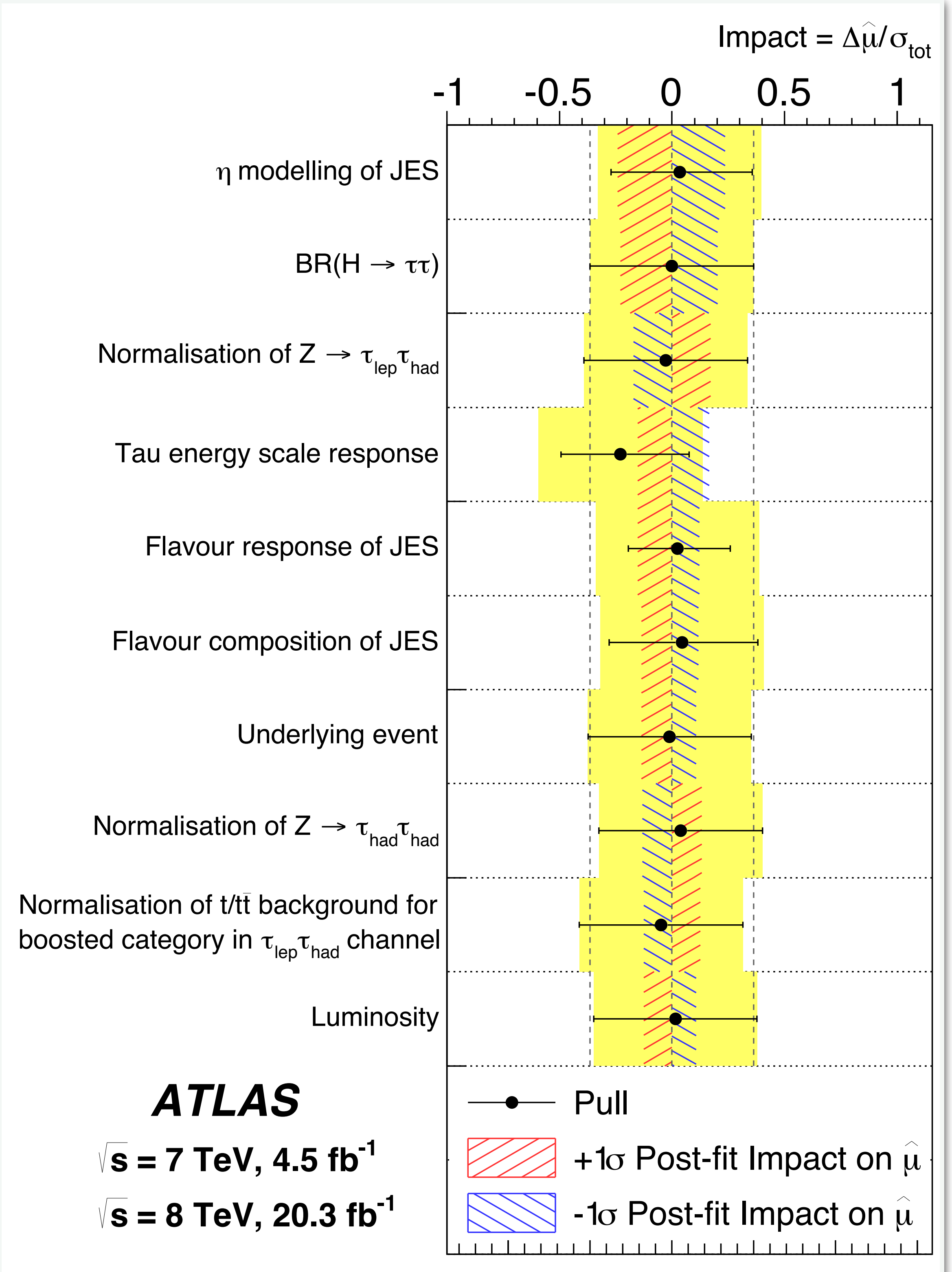
VBF

$\sqrt{s}$ (TeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
7	1.222	+0.3	-0.3	+2.5	-2.1
8	1.579	+0.2	-0.2	+2.6	-2.8
13	3.744	+0.7	-0.7	+3.2	-3.2

Systematic Uncertainties

- systematic uncertainty sources:
  - experimental: e.g. JES uncertainty
    - detector response
    - pile-up
    - η intercalibration
    - modelling of in situ jet calibration
  - theory: e.g. BR(H→ττ):
    - ~6% uncertainty direct effect on signal rates
  - background model: e.g. Zlh normalisation
    - fake factors: stat uncertainty & fake background composition

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.13
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR $(H \to \tau\tau)$	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03
Total sys.	$^{+0.33}_{-0.26}$
Total	$^{+0.43}_{-0.37}$



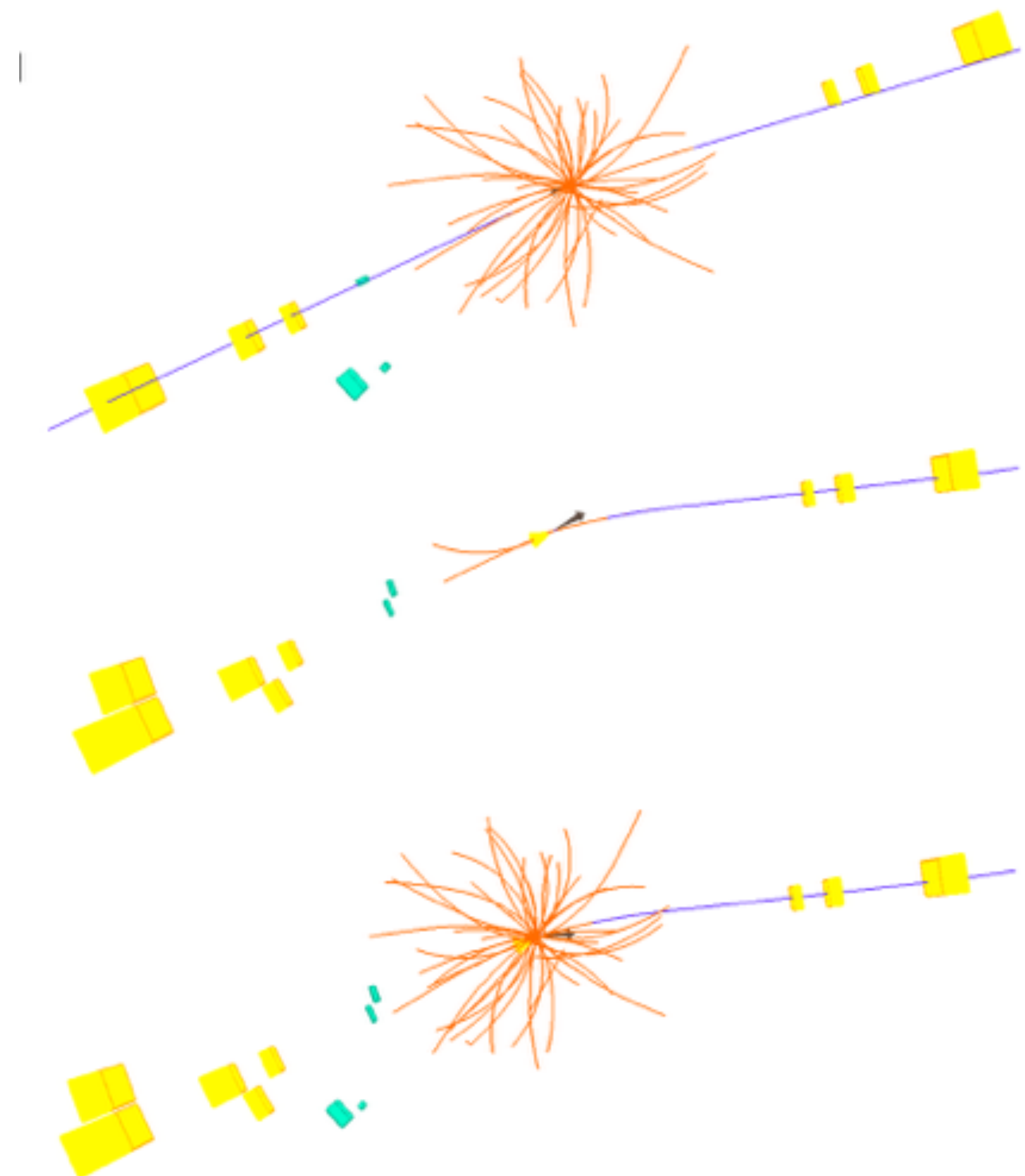
$$\mu = \frac{(\sigma \times BR)_{obs.}}{(\sigma \times BR)_{SM}}$$

Htt Analysis Strategy

- small branching ratio and high background contributions
  - event categorisation: improved BG rejection
- poor $\tau+\tau-$ mass resolution (at least two neutrinos from the τ lepton decays)
  - dedicated mass reconstruction algorithms (MMC)
- fully leptonic channel:
  - lowest sensitivity & worst mass resolution (4 neutrinos)
  - smallest branching ratio 12.4%
- semi-leptonic channel:
  - most sensitive final state - largest branching ratio of 45.6%
- dihadronic channel
  - second most sensitive final state - branching ratio of 42%
- final discriminant —> combined fit
  - MVA: construct BDT
  - CBA: MMC-mass

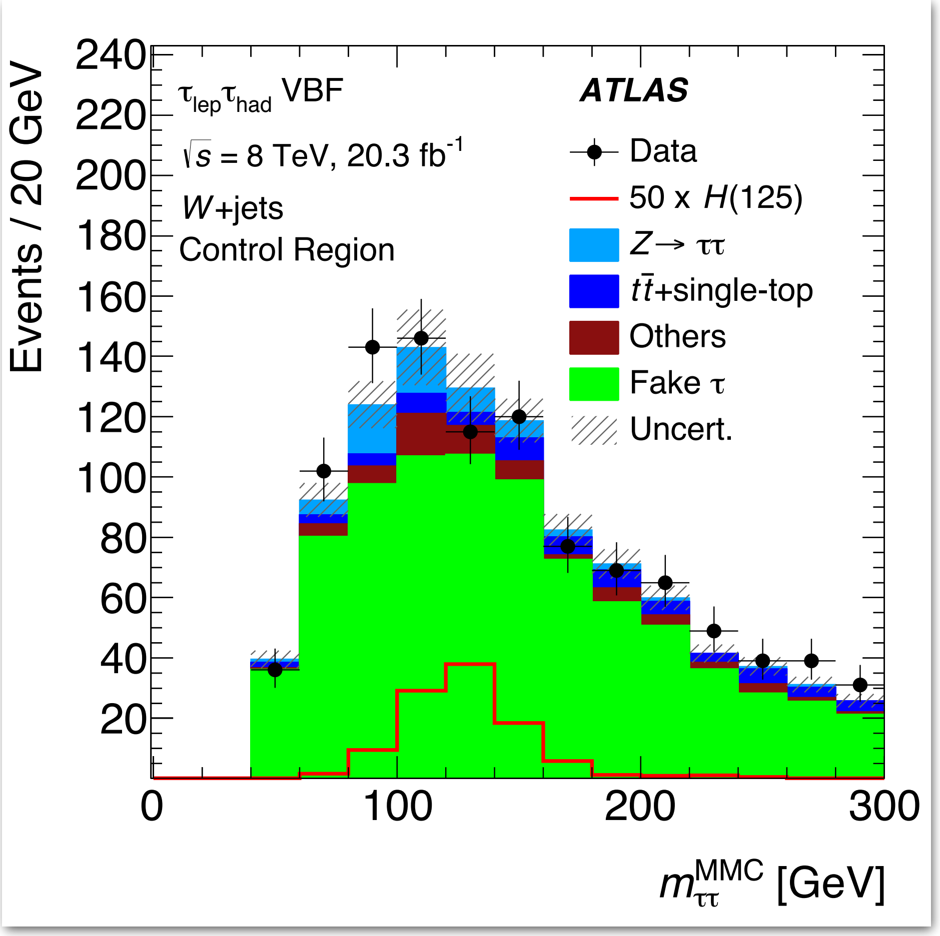
Embedding

- Take Z→μμ from data
- Remove the μ tracks and energy deposition in the calorimeter (using standalone μ simulation)
- Correct the particle 4-vectors for the μ-τ mass difference
- Simulate the ττ decay in Tauola for these initial 4-vectors
- Insert this simulated decay back into the data events
- Re-reconstruct objects and MET



Fake Factor Method

- $\tau_{lep}\tau_{had}$ channel: the fake-factor method to estimate contributions from misidentified τ_{had} candidate
- arising from multijet, W+jets, Z+jets, and semileptonic top background events
- fake factor: ratio of #jets identified as medium τ_{had} to #jets satisfying loose, but not medium tau ID
- depending on jet parton type, jet-p_T, track multiplicity
- W+jets, $t\bar{t}$ and Z+jets background components:
  - high-m_T region (m_T > 70 GeV)
  - inverting the b-jet veto
  - two leptons with 80 GeV < m_{ll} < 100 GeV
- multijet:
  - relaxing the lepton identification and requiring jet to satisfy the loose identification criteria
- template from SR but requiring loose not medium
  - apply SF according to expected relative contributions



Backup

- MC generators

Signal (m_H = 125 GeV)	MC generator	$\sigma \times$BR [pb] $\sqrt{s} = 8$ TeV		
ggF, $H \to \tau\tau$	POWHEG [36–39] + PYTHIA8 [40]	1.22	NNLO+NNLL	[42–47, 78]
VBF, $H \to \tau\tau$	POWHEG + PYTHIA8	0.100	(N)NLO	[51–53, 78]
WH, $H \to \tau\tau$	PYTHIA8	0.0445	NNLO	[56, 78]
ZH, $H \to \tau\tau$	PYTHIA8	0.0262	NNLO	[56, 78]
Background	**MC generator**	**$\sigma \times$BR [pb] $\sqrt{s} = 8$ TeV**		
$W(\to \ell\nu)$, $(\ell = e, \mu, \tau)$	ALPGEN [71]+PYTHIA8	36800	NNLO	[79, 80]
$Z/\gamma^*(\to \ell\ell)$, 60 GeV< $m_{\ell\ell}$ < 2 TeV	ALPGEN+PYTHIA8	3910	NNLO	[79, 80]
$Z/\gamma^*(\to \ell\ell)$, 10 GeV< $m_{\ell\ell}$ < 60 GeV	ALPGEN+HERWIG [81]	13000	NNLO	[79, 80]
VBF $Z/\gamma^*(\to \ell\ell)$	SHERPA [82]	1.1	LO	[82]
$t\bar{t}$	POWHEG + PYTHIA8	$253^{\dagger}$	NNLO+NNLL	[83–88]
Single top : Wt	POWHEG + PYTHIA8	$22^{\dagger}$	NNLO	[89]
Single top : s-channel	POWHEG + PYTHIA8	$5.6^{\dagger}$	NNLO	[90]
Single top : t-channel	AcerMC [74]+PYTHIA6 [67]	$87.8^{\dagger}$	NNLO	[91]
$q\bar{q} \to WW$	ALPGEN+HERWIG	$54^{\dagger}$	NLO	[92]
$gg \to WW$	GG2WW [73]+HERWIG	$1.4^{\dagger}$	NLO	[73]
WZ, ZZ	HERWIG	$30^{\dagger}$	NLO	[92]
$H \to WW$	same as for $H \to \tau\tau$ signal	$4.7^{\dagger}$		

Backup

- Trigger thresholds

$\sqrt{s} = 7$ TeV				
Trigger	Trigger level thresholds, p_T [GeV]	Analysis level thresholds [GeV] $\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Single electron	20–22	$e\mu$: $p_T^e > 22-24$, $p_T^\mu > 10$	$e\tau$: $p_T^e > 25$, $p_T^\tau > 20$	–
Single muon	18	$\mu\mu$: $p_T^{\mu 1} > 20$, $p_T^{\mu 2} > 10$; $e\mu$: $p_T^\mu > 20$, $p_T^e > 15$	$\mu\tau$: $p_T^\mu > 22$, $p_T^\tau > 20$	–
Di-electron	12/12	ee: $p_T^{e1} > 15$, $p_T^{e2} > 15$	–	–
Di-τ_{had}	29/20	–	–	$\tau\tau$: $p_T^{\tau 1} > 35$, $p_T^{\tau 2} > 25$

$\sqrt{s} = 8$ TeV				
Trigger	Trigger level thresholds, p_T [GeV]	Analysis level thresholds [GeV] $\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Single electron	24	$e\mu$: $p_T^e > 26$, $p_T^\mu > 10$; ee: $p_T^{e1} > 26$, $p_T^{e2} > 15$	$e\tau$: $p_T^e > 26$, $p_T^\tau > 20$	–
Single muon	24	–	$\mu\tau$: $p_T^\mu > 26$, $p_T^\tau > 20$	–
Di-electron	12/12	ee: $p_T^{e1} > 15$, $p_T^{e2} > 15$	–	–
Di-muon	18/8	$\mu\mu$: $p_T^{\mu 1} > 20$, $p_T^{\mu 2} > 10$	–	–
Electron+muon	12/8	$e\mu$: $p_T^e > 15$, $p_T^\mu > 10$	–	–
Di-τ_{had}	29/20	–	–	$\tau\tau$: $p_T^{\tau 1} > 35$, $p_T^{\tau 2} > 25$

Backup

- MVA selection

Channel	Preselection cuts
$\tau_{lep}\tau_{lep}$	Exactly two isolated opposite-sign leptons Events with τ_{had} candidates are rejected 30 GeV$< m_{\tau\tau}^{vis} <$ 100 (75) GeV for DF (SF) events $\Delta\phi_{\ell\ell} < 2.5$ $E_T^{miss} > 20$ (40) GeV for DF (SF) events $E_T^{miss,HPTO} > 40$ GeV for SF events $p_T^{\ell_1} + p_T^{\ell_2} > 35$ GeV Events with a b-tagged jet with $p_T > 25$ GeV are rejected $0.1 < x_{\tau_1}, x_{\tau_2} < 1$ $m_{\tau\tau}^{coll} > m_Z - 25$ GeV
$\tau_{lep}\tau_{had}$	Exactly one isolated lepton and one medium τ_{had} candidate with opposite charges $m_T < 70$ GeV Events with a b-tagged jet with $p_T > 30$ GeV are rejected
$\tau_{had}\tau_{had}$	One isolated medium and one isolated tight opposite-sign τ_{had}-candidate Events with leptons are vetoed $E_T^{miss} > 20$ GeV E_T^{miss} points between the two visible taus in ϕ, or $\min[\Delta\phi(\tau, E_T^{miss})] < \pi/4$ $0.8 < \Delta R(\tau_{had_1}, \tau_{had_2}) < 2.4$ $\Delta\eta(\tau_{had_1}, \tau_{had_2}) < 1.5$
Channel	**VBF category selection cuts**
$\tau_{lep}\tau_{lep}$	At least two jets with $p_T^{j_1} > 40$ GeV and $p_T^{j_2} > 30$ GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{lep}\tau_{had}$	At least two jets with $p_T^{j_1} > 50$ GeV and $p_T^{j_2} > 30$ GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{vis} > 40$ GeV
$\tau_{had}\tau_{had}$	At least two jets with $p_T^{j_1} > 50$ GeV and $p_T^{j_2} > 30$ GeV $p_T^{j_2} > 35$ GeV for jets with $\|\eta\| > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$
Channel	**Boosted category selection cuts**
$\tau_{lep}\tau_{lep}$	At least one jet with $p_T > 40$ GeV
All	Failing the VBF selection $p_T^H > 100$ GeV

- MVA CR

Process	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
$Z \to \ell\ell$-enriched	$80 < m_{\tau\tau}^{vis} < 100$ GeV (same-flavour)		
Top control region	Invert b-jet veto	Invert b-jet veto and $m_T > 40$ GeV	
Rest category			Pass preselection, Fail VBF and Boosted selections
$Z \to \tau\tau$-enriched	$m_{\tau\tau}^{HPTO} < 100$ GeV	$m_T < 40$ GeV and $m_{\tau\tau}^{MMC} < 110$ GeV	
Fake-enriched	Same sign τ decay products	Same sign τ decay products	
W-enriched		$m_T > 70$ GeV	
Mass sideband			$m_{\tau\tau}^{MMC} < 110$ GeV or $m_{\tau\tau}^{MMC} > 150$ GeV

Backup

postfit event yields

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	1680 ± 50	8.2 ± 0.9	5.2 ± 0.7	5640 ± 160	51.0 ± 2.5	22.3 ± 1.8
$Z \to \tau\tau$	877 ± 29	7.6 ± 0.9	4.2 ± 0.7	6210 ± 170	57.5 ± 2.8	41.1 ± 3.2
Top	82 ± 15	0.3 ± 0.4	0.5 ± 0.4	380 ± 50	12 ± 4	4.8 ± 1.5
$Z \to \ell\ell(\ell \to \tau_{\rm had})$	54 ± 26	1.0 ± 0.7	0.30 ± 0.28	200 ± 50	13 ± 4	8.6 ± 3.5
Diboson	63 ± 11	1.0 ± 0.4	0.48 ± 0.20	430 ± 40	9.7 ± 2.2	4.7 ± 1.6
ggF: $H \to \tau\tau$ ($m_H = 125 GeV$)	16 ± 6	1.0 ± 0.4	1.2 ± 0.6	60 ± 20	9.2 ± 3.2	10.1 ± 3.4
VBF: $H \to \tau\tau$	31 ± 8	4.5 ± 1.1	9.1 ± 2.2	16 ± 4	2.5 ± 0.6	2.9 ± 0.7
$WH: H \to \tau\tau$	0.6 ± 0.4	< 0.1	< 0.1	9.1 ± 2.3	1.3 ± 0.4	1.9 ± 0.5
$ZH: H \to \tau\tau$	0.16 ± 0.07	< 0.1	< 0.1	4.6 ± 1.2	0.77 ± 0.20	0.93 ± 0.24
Total background	2760 ± 40	18.1 ± 2.3	10.7 ± 2.7	12860 ± 110	143 ± 6	82 ± 6
Total signal	48 ± 12	5.5 ± 1.3	10.3 ± 2.5	89 ± 26	14 ± 4	16 ± 4
Data	2830	22	21	12952	170	92

lephad

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
$Z \to \tau\tau$	589 ± 24	9.7 ± 1.0	1.99 ± 0.34	2190 ± 80	33.7 ± 2.3	11.3 ± 1.3
Fake background	57 ± 12	1.2 ± 0.6	0.55 ± 0.35	100 ± 40	2.9 ± 1.3	0.6 ± 0.4
Top	131 ± 19	0.9 ± 0.4	0.89 ± 0.33	380 ± 50	9.8 ± 2.1	4.3 ± 1.0
Others	196 ± 17	3.0 ± 0.4	1.7 ± 0.6	400 ± 40	8.3 ± 1.6	2.6 ± 0.7
ggF: $H \to WW$ ($m_H = 125$ GeV)	2.9 ± 0.8	0.12 ± 0.04	0.11 ± 0.04	7.7 ± 2.3	0.43 ± 0.13	0.24 ± 0.08
VBF: $H \to WW$	3.4 ± 0.4	0.40 ± 0.06	0.38 ± 0.08	1.65 ± 0.18	0.102 ± 0.017	< 0.1
$WH: H \to WW$	< 0.1	< 0.1	< 0.1	0.90 ± 0.10	< 0.1	< 0.1
$ZH: H \to WW$	< 0.1	< 0.1	< 0.1	0.59 ± 0.07	< 0.1	< 0.1
ggF: $H \to \tau\tau$ ($m_H = 125 GeV$)	9.8 ± 3.4	0.73 ± 0.26	0.35 ± 0.14	21 ± 8	2.4 ± 0.9	1.3 ± 0.5
VBF: $H \to \tau\tau$	13.3 ± 4.0	2.7 ± 0.7	3.3 ± 0.9	5.5 ± 1.5	0.95 ± 0.26	0.49 ± 0.13
$WH: H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	3.8 ± 1.0	0.44 ± 0.12	0.22 ± 0.06
$ZH: H \to \tau\tau$	0.14 ± 0.04	< 0.1	< 0.1	2.0 ± 0.5	0.21 ± 0.06	0.113 ± 0.031
Total background	980 ± 22	15.4 ± 1.8	5.6 ± 1.4	3080 ± 50	55 ± 4	19.2 ± 2.1
Total signal	24 ± 6	3.5 ± 0.9	3.6 ± 1.0	33 ± 10	4.0 ± 1.2	2.1 ± 0.6
Data	1014	16	11	3095	61	20

leplep

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	370 ± 18	2.3 ± 0.9	0.57 ± 0.29	645 ± 26	35 ± 4	0.65 ± 0.33
Others	37 ± 5	0.67 ± 0.22	< 0.1	89 ± 11	15.9 ± 2.0	0.92 ± 0.22
$Z \to \tau\tau$	475 ± 16	0.6 ± 0.7	0.6 ± 0.4	2230 ± 70	93 ± 4	5.4 ± 1.6
ggF: $H \to \tau\tau$ ($m_H = 125 GeV$)	8.0 ± 2.7	0.67 ± 0.23	0.53 ± 0.20	21 ± 8	9.1 ± 3.3	1.6 ± 0.6
VBF: $H \to \tau\tau$	12.0 ± 3.1	1.8 ± 0.5	3.4 ± 0.9	6.3 ± 1.6	2.8 ± 0.7	0.52 ± 0.13
$WH: H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	4.0 ± 1.1	1.9 ± 0.5	0.41 ± 0.11
$ZH: H \to \tau\tau$	0.16 ± 0.04	< 0.1	< 0.1	2.4 ± 0.6	1.13 ± 0.30	0.23 ± 0.06
Total background	883 ± 18	3.6 ± 1.3	1.2 ± 1.0	2960 ± 50	143 ± 6	7.0 ± 1.8
Total signal	20 ± 5	2.5 ± 0.6	3.9 ± 1.0	34 ± 10	15 ± 4	2.7 ± 0.8
Data	892	5	6	3020	161	10

hadhad

CBA selection criteria

Channel	VBF category selection criteria
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_{\rm T}^{j1} > 40$ GeV and $p_{\rm T}^{j2} > 30$ GeV $\|\Delta\eta_{j_1,j_2}\| > 3.0$ $m_{j_1,j_2} > 400$ GeV b-jet veto for jets with $p_{\rm T} > 25$ GeV Jet veto: no additional jet with $p_{\rm T} > 25$ GeV within $\|\eta\| < 2.4$
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j1} > 40$ GeV and $p_{\rm T}^{j2} > 30$ GeV $E_{\rm T}^{\rm miss} >$ 20 GeV $\|\Delta\eta_{j_1,j_2}\| > 3.0$ and $\eta(j_1)\cdot\eta(j_2) < 0$, $m_{j_1,j_2} > 300$ GeV $p_{\rm T}^{\rm Total} = \|\vec{p}_{\rm T}^{\ell} + \vec{p}_{\rm T}^{\tau_{\rm had}} + \vec{p}_{\rm T}^{j1} + \vec{p}_{\rm T}^{j2} + \vec{E}_{\rm T}^{\rm miss}\| < 30$GeV b-jet veto for jets with $p_{\rm T} > 30$ GeV $\min(\eta_{(j_1)},\eta_{(j_2)}) < \eta_{(\ell)},\eta_{(\tau_{\rm had})} < \max(\eta_{(j_1)},\eta_{(j_2)})$ **VBF tight**: $m_{j_1,j_2} > 500$ GeV; $p_{\rm T}^{H} > 100$ GeV; $p_{\rm T}^{\tau_{\rm had}} > 30$ GeV; $m_{\rm vis} > 40$ GeV **VBF loose**: Non tight VBF
$\tau_{\rm had}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j1} > 50$ GeV and $p_{\rm T}^{j2} > 30$ GeV $\|\Delta\eta(\tau_1,\tau_2)\| < 1.5$ $\|\Delta\eta_{j_1,j_2}\| > 2.6$ and $m_{j_1,j_2} > 250$ GeV $\min(\eta_{(j_1)},\eta_{(j_2)}) < \eta_{(\tau_1)},\eta_{(\tau_2)} < \max(\eta_{(j_1)},\eta_{(j_2)})$ **VBF high $p_{\rm T}^{H}$**: $\Delta R(\tau_1,\tau_2) < 1.5$ and $p_{\rm T}^{H} > 140$ GeV **VBF low $p_{\rm T}^{H}$, tight**: $\Delta R(\tau_1,\tau_2) > 1.5$ or $p_{\rm T}^{H} < 140$ GeV; $m_{j_1,j_2}[{\rm GeV}] > (-250\cdot\|\Delta\eta_{j_1,j_2}\| + 1550)$ **VBF low $p_{\rm T}^{H}$, loose**: $\Delta R(\tau_1,\tau_2) > 1.5$ or $p_{\rm T}^{H} < 140$ GeV; $m_{j_1,j_2}[{\rm GeV}] < (-250\cdot\|\Delta\eta_{j_1,j_2}\| + 1550)$

Channel	Boosted category selection criteria
$\tau_{\rm lep}\tau_{\rm lep}$	Exclude events passing the VBF selection $p_{\rm T}^{H} > 100$ GeV b-jet veto for jets with $p_{\rm T} > 25$ GeV
$\tau_{\rm lep}\tau_{\rm had}$	Exclude events passing the VBF selection $E_{\rm T}^{\rm miss} > 20$ GeV $p_{\rm T}^{H} > 100$ GeV $p_{\rm T}(\tau_{\rm had}) > 30$ GeV b-jet veto for jets with $p_{\rm T} > 30$ GeV
$\tau_{\rm had}\tau_{\rm had}$	Exclude events passing the VBF selection $\Delta\eta(\tau_1,\tau_2) < 1.5$ $p_{\rm T}^{H} > 100$ GeV **Boosted high $p_{\rm T}^{H}$**: $\Delta R(\tau_1,\tau_2) < 1.5$ and $p_{\rm T}^{H} > 140$ GeV **Boosted low $p_{\rm T}^{H}$**: $\Delta R(\tau_1,\tau_2) > 1.5$ or $p_{\rm T}^{H} < 140$ GeV

Backup

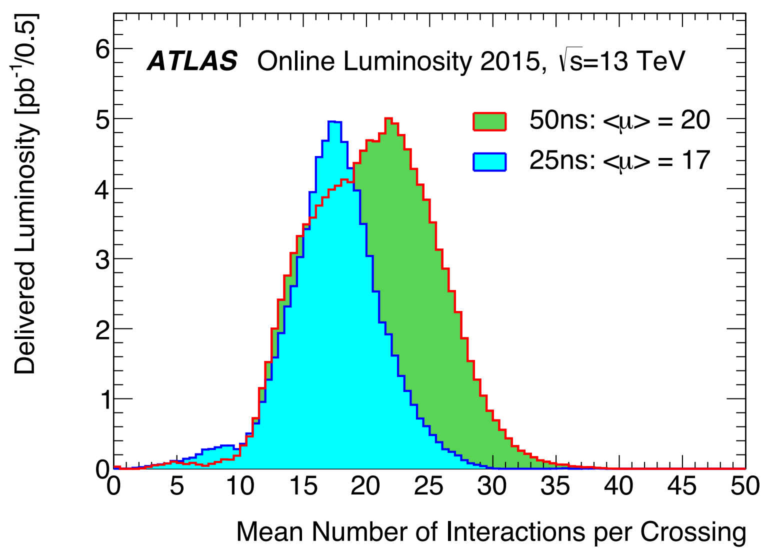
MMC variable ranking

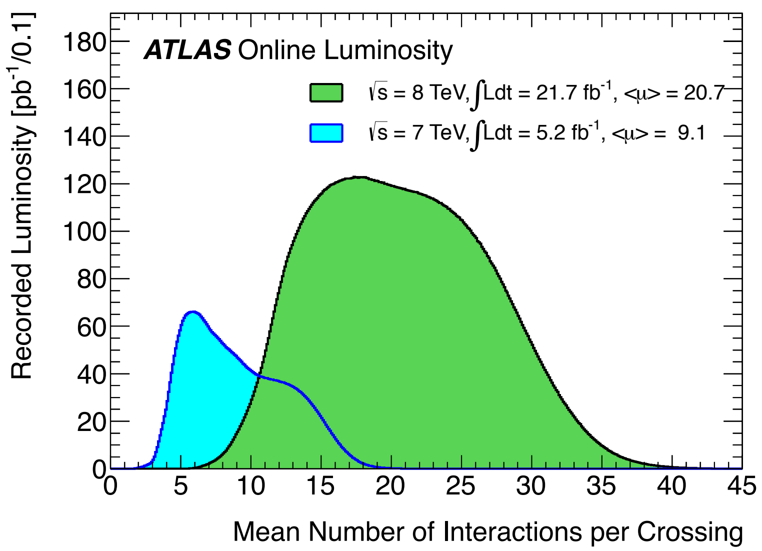
Variable	VBF			Boosted		
	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$
$m_{\tau\tau}^{\rm MMC}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1,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

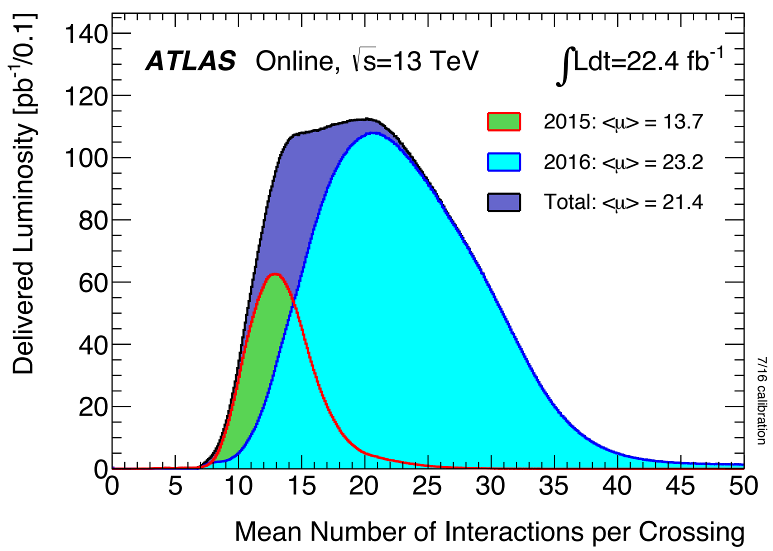
significances MVA per channel and category

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

Backup


ATLAS Online Luminosity 2015, √s=13 TeV
50ns: <μ> = 20
25ns: <μ> = 17
Delivered Luminosity [pb-1/0.5]
Mean Number of Interactions per Crossing


ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 21.7 fb-1, <μ> = 20.7
√s = 7 TeV, ∫Ldt = 5.2 fb-1, <μ> = 9.1
Recorded Luminosity [pb-1/0.1]
Mean Number of Interactions per Crossing


ATLAS Online, √s=13 TeV
∫Ldt=22.4 fb-1
2015: <μ> = 13.7
2016: <μ> = 23.2
Total: <μ> = 21.4
Delivered Luminosity [pb-1/0.1]
Mean Number of Interactions per Crossing
7/16 calibration

ATLAS+CMS combination

- ATLAS-CONF-2015-044 or CMS-PAS-HIG-15-002
- based on 7+8TeV datasets

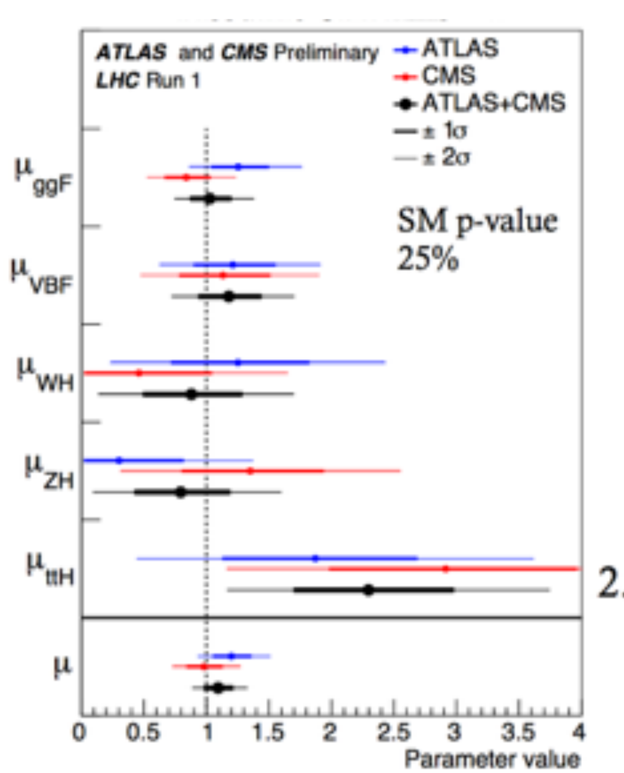
Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$ ($^{+0.26}_{-0.24}$)	$1.12^{+0.25}_{-0.23}$ ($^{+0.24}_{-0.22}$)	5.0 (4.6)	5.6 (5.1)
$H \to ZZ \to 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$ ($^{+0.33}_{-0.27}$)	$1.05^{+0.32}_{-0.27}$ ($^{+0.31}_{-0.26}$)	6.6 (5.5)	7.0 (6.8)
$H \to WW$	[55,56]	[57]	$1.23^{+0.23}_{-0.21}$ ($^{+0.21}_{-0.20}$)	$0.91^{+0.24}_{-0.21}$ ($^{+0.23}_{-0.20}$)	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$ ($^{+0.37}_{-0.33}$)	$0.89^{+0.31}_{-0.28}$ ($^{+0.31}_{-0.29}$)	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$ ($^{+0.39}_{-0.37}$)	$0.81^{+0.45}_{-0.42}$ ($^{+0.45}_{-0.43}$)	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[60]	[61]	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		
ttH production	[28,62,63]	[65]	$1.9^{+0.8}_{-0.7}$ ($^{+0.72}_{-0.66}$)	$2.9^{+1.0}_{-0.9}$ ($^{+0.88}_{-0.80}$)	2.7 (1.6)	3.6 (1.3)

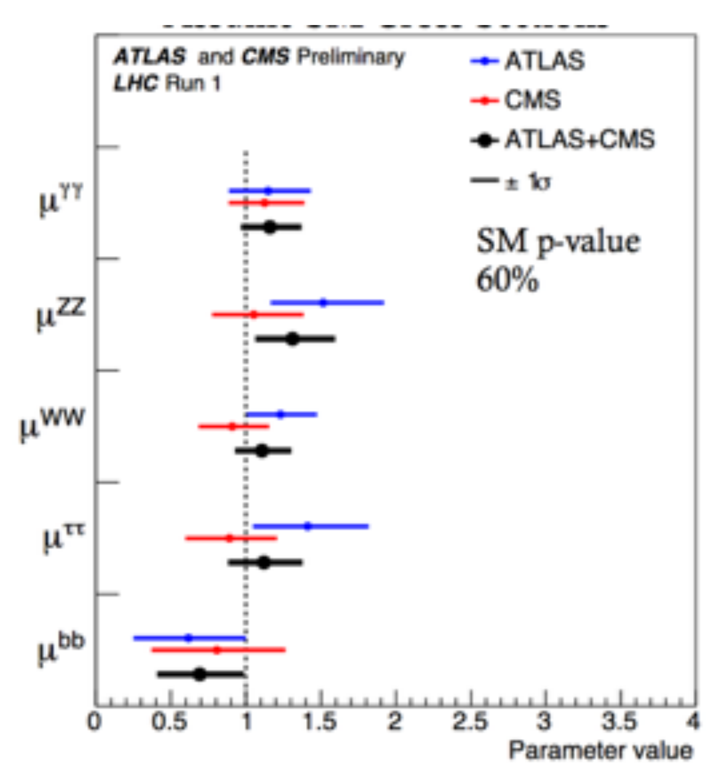
	Untagged	VBF	VH	ttH
$H \to \gamma\gamma$	✓	✓	✓	✓
H→ZZ→llll	✓	✓	✓	✓
H→WW	✓	✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
H→bb			✓	✓
$H \to \mu\mu$	*included in tree level fit for H-μ coupling*			

ATLAS+CMS combination

- The ATLAS+CMS coupling combination results include:
  1) Fits of signal strengths (global, by production, by decay) relative to the SM
  2) Fits in the κ-framework, measuring coupling modifiers
- 3) Generic parameterizations based on ratios of XS and BR and on coupling modifier ratios
- Common Assumptions:
- Assume there is only one Higgs boson with Spin Parity 0+ and with a narrow width such that production and decay are decoupled

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})^{+0.04}_{-0.04}\,(\text{expt})^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$





	Production process	Measured significance (σ)	Expected significance (σ)
> 5 σ →	VBF	5.4	4.7
	WH	2.4	2.7
	ZH	2.3	2.9
	VH	3.5	4.2
	ttH	4.4	2.0
	Decay channel		
> 5 σ →	$H \to \tau\tau$	5.5	5.0
	$H \to bb$	2.6	3.7