Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector

arXiv:1501.04943

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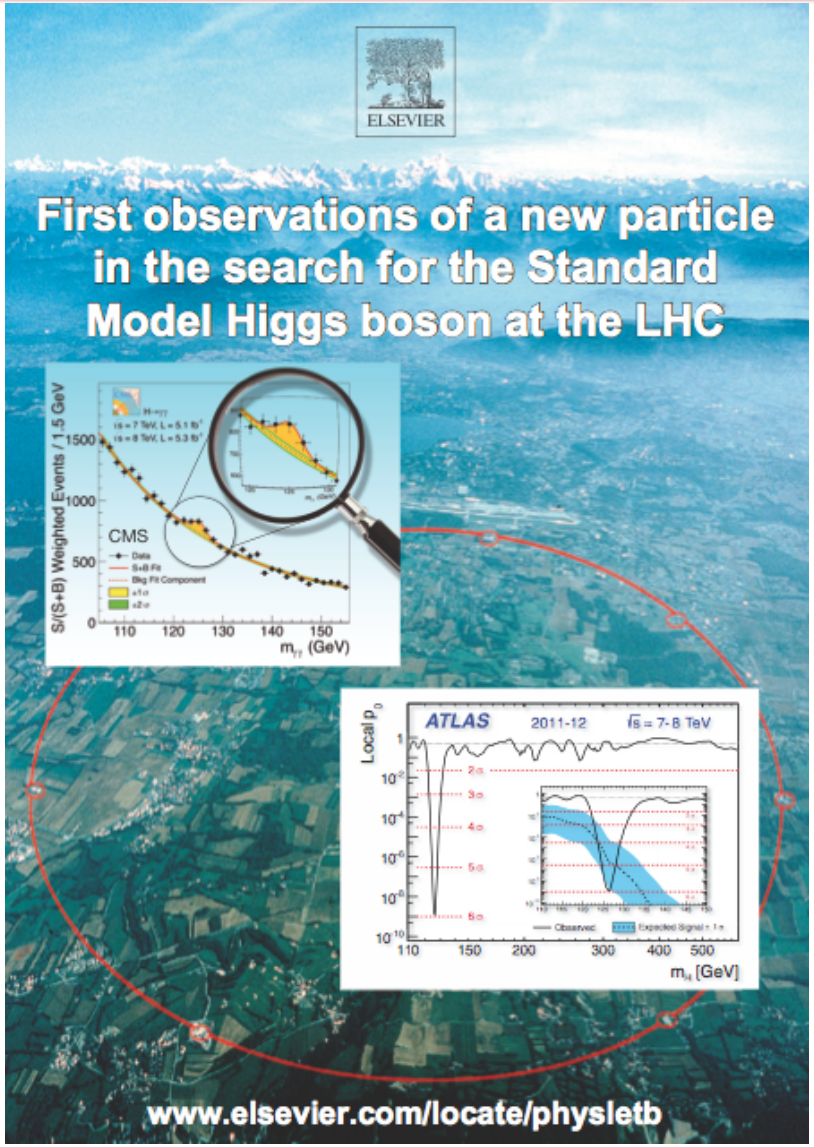
Higgs Boson Discovery



The Nobel Prize in Physics 2013

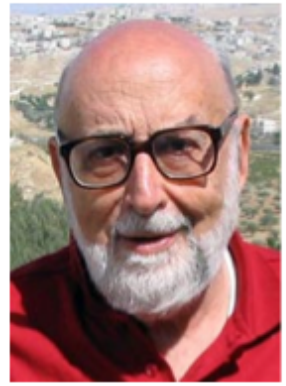


Photo: Pnicolet via Wikimedia Commons

François Englert

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Peter W. Higgs

Which Higgs Boson Did We Find?

- Higgs boson was discovered in ZZ*, $\gamma\gamma$, and WW* decays
- Higgs boson mass is ~125 GeV
  - measured in $H \rightarrow ZZ^* \rightarrow 4l$, and $H \rightarrow \gamma\gamma$
  - ATLAS: M_H=125.36 ± 0.37 (stat) ± 0.18 (syst) GeV
  - CMS: M_H=125.02 ± 0.27 (stat) ± 0.15 (syst) GeV
- ATLAS and CMS data strongly favor $J^P=0^+$ SM quantum numbers
  - All alternative J^P models tried are excluded at >95%CL
- Signal strength $\mu=\sigma/\sigma_{SM}$ and all couplings are consistent with 1
  - ATLAS: μ=1.30 ± 0.12 (stat)$^{+0.14}_{-0.11}$(syst)
  - CMS: μ=1.00 ± 0.09 (stat) ± 0.07 (syst)$^{+0.08}_{-0.07}$(theo)
  - Tevatron: μ=1.44±0.60
- >3σ evidence for V-boson mediated (VBF) production
- **All measured properties are compatible with SM Higgs hypothesis**

Higgs Boson: What is Next?

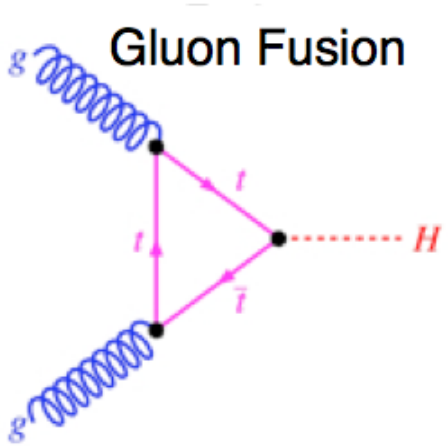
- **Evidence of coupling to fermions so far**
  - **Tevatron VH(→bb) combination:** 2.8σ excess @ M_H=125 GeV
  - **CMS VH(→bb):** 2.1σ excess @ M_H=125 GeV
  - **ATLAS VH(→bb)**: 1.4σ deviation @ M_H=125 GeV (2.6σ expected)
  - **CMS H→ττ:** 3.2σ excess @ M_H=125 GeV
- **Observation of direct H→fermions decays was one of the main goals for the Run-1 Higgs program**
  - In particular, does Higgs couple to leptons?
    - We already indirectly know that it couples to quarks
  - Are $\Gamma_{H\to ff}$ consistent with SM predictions?
  - Is it the same Higgs decaying to H→VV & H→ff?
    - Is mass the same? CP properties?

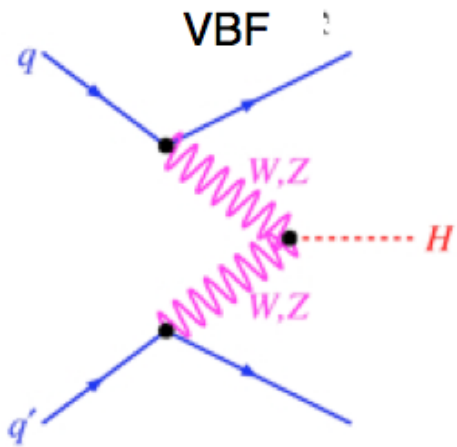
$$\Gamma_{H\to ff} = \frac{N_C M_H}{8\pi v^2} m_f^2 \beta_f^3, \quad \beta_f = \sqrt{1 - \frac{4m_f^2}{M_H^2}}$$

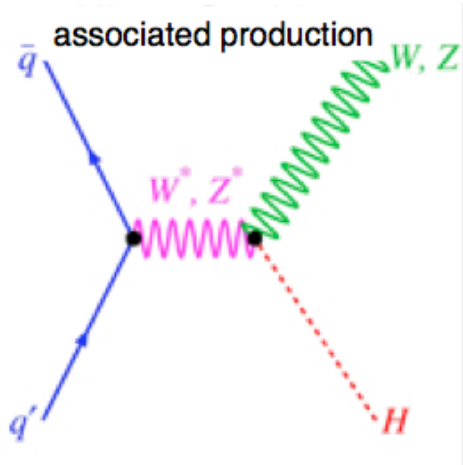
Talk Outline

- Challenges in $H \rightarrow \tau\tau$ search
- Highlights of ATLAS Performance
- ATLAS search for SM $H \rightarrow \tau\tau$
- Not covered in this talk
  - Results on BSM $A/H/h \rightarrow \tau\tau$ searches at ATLAS

SM Higgs Production (for M_H=125 GeV)







Largest production mode: ~88%

Unique signature of two jets with large M_{jj} & $|\Delta\eta_{jj}|$

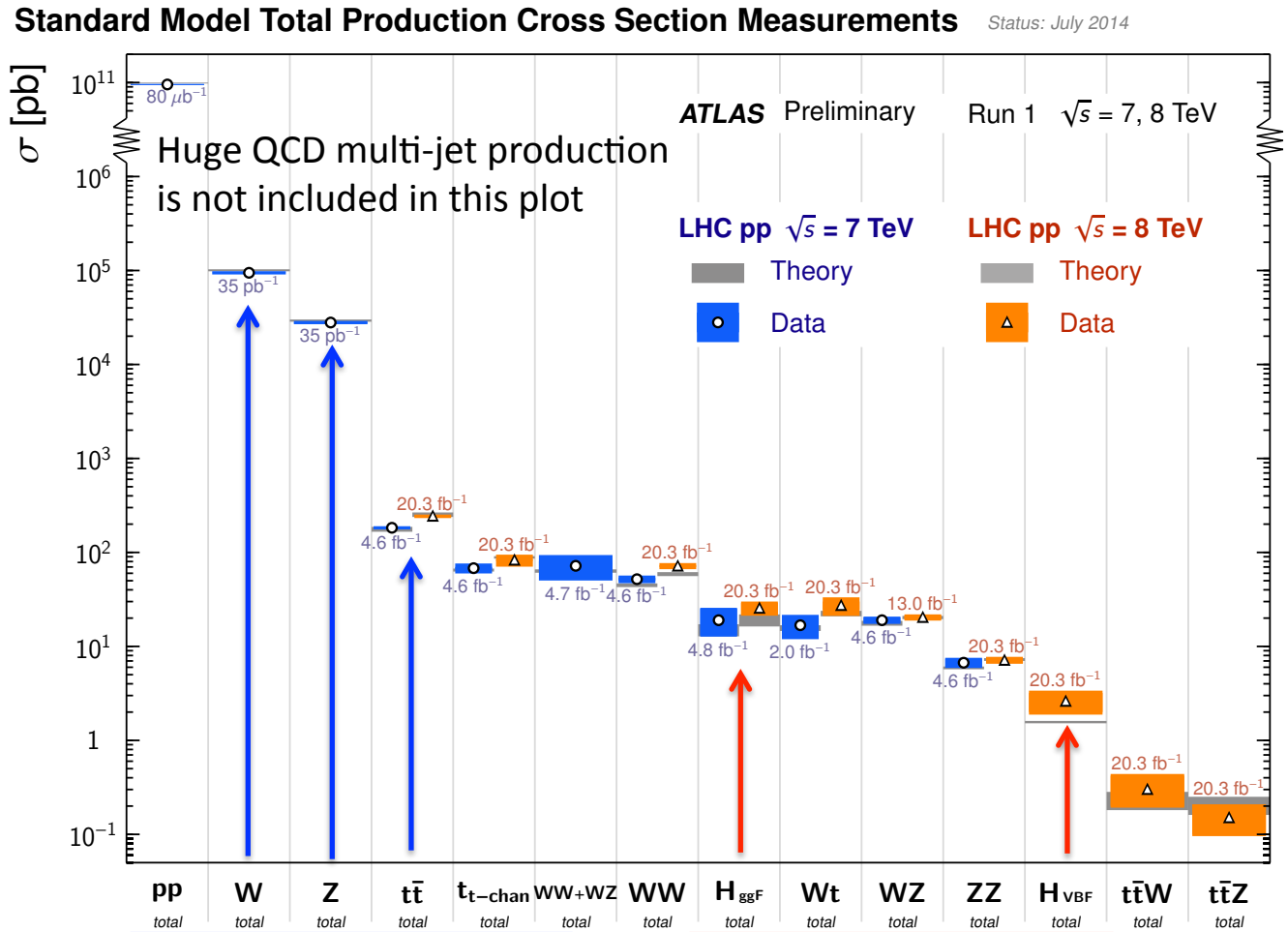
Unique signature with leptons & neutrinos

	gg→H	VBF	VH
LHC: 8 TeV	19.5 pb	1.57 pb	1.08 pb

	H→bb	H→WW*	**H→ττ**	H→ZZ*	H→γγ	H→Zγ	H→μμ
Br	57.7%	21.5%	**6.32%**	2.64%	0.228%	0.154%	$2.19*10^{-2}$ %

Challenges In The Search For H→ττ: S/B<10^{-3}

- Major backgrounds
  - Z→ττ (irreducible), Z(ee/μμ)+jets, W+jets, top, QCD multi-jets and di-bosons



$$\frac{H \to \tau\tau}{Z \to \tau\tau} = 0.001$$

$$\frac{H \to \tau\tau}{W(l\nu) + jets} \approx 0.00016$$

$$\frac{H \to \tau\tau}{t\bar{t} \to ll + X} \approx 0.053$$

Major backgrounds

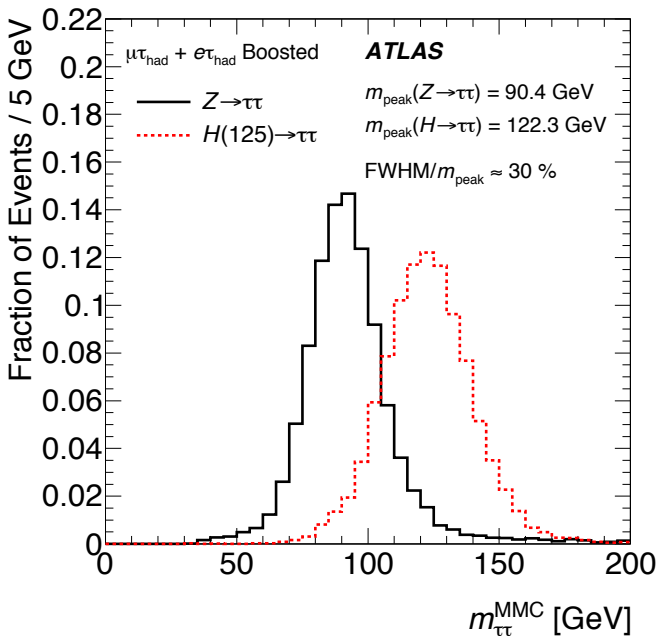
Higgs signal

Z→ττ: The Major Irreducible Background

- **Good m(ττ) resolution is single most effective tool against Z→ττ**
  - Mass reconstruction is complicated by presence of 2-4 neutrinos
- Exploit unique VBF signature: improves S/B by a factor O(100)
  - Two forward jets with large invariant mass separated by a large rapidity gap

$$\frac{H \to \tau\tau}{Z \to \tau\tau} = 0.001 \Rightarrow \frac{VBF\ H \to \tau\tau}{VBF\ Z \to \tau\tau} \approx 0.27$$

Robert N. Cahn et. al, PRD35 (1987) 1626



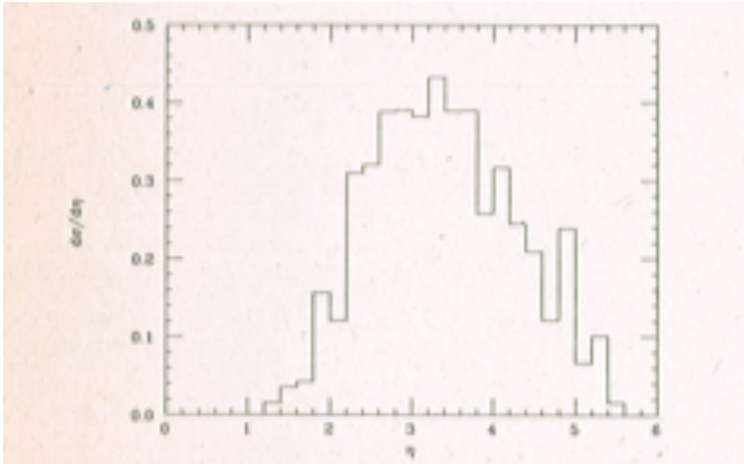


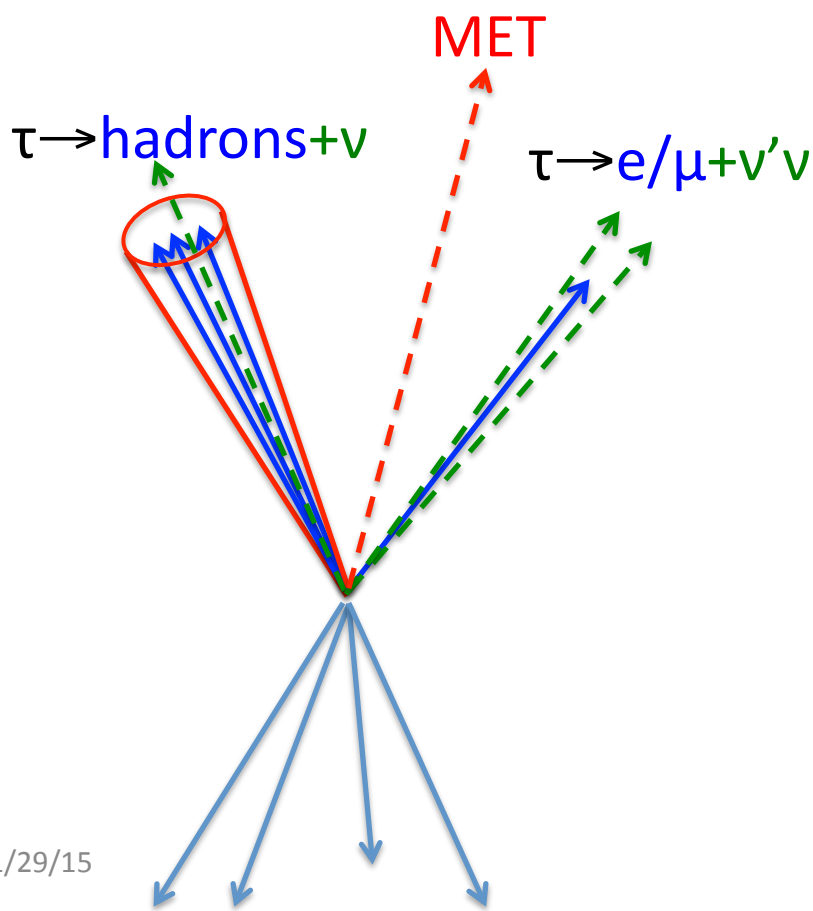
FIG. 7. The rapidity distribution for a quark jet used to tag a Higgs-boson production event. The jet is required to have longitudinal momentum greater than 500 GeV and transverse momentum greater than 60 GeV. The center-of-mass energy is 40 TeV and the Higgs-boson mass is 400 GeV.

W(→lν)+jets: The Major Reducible Background

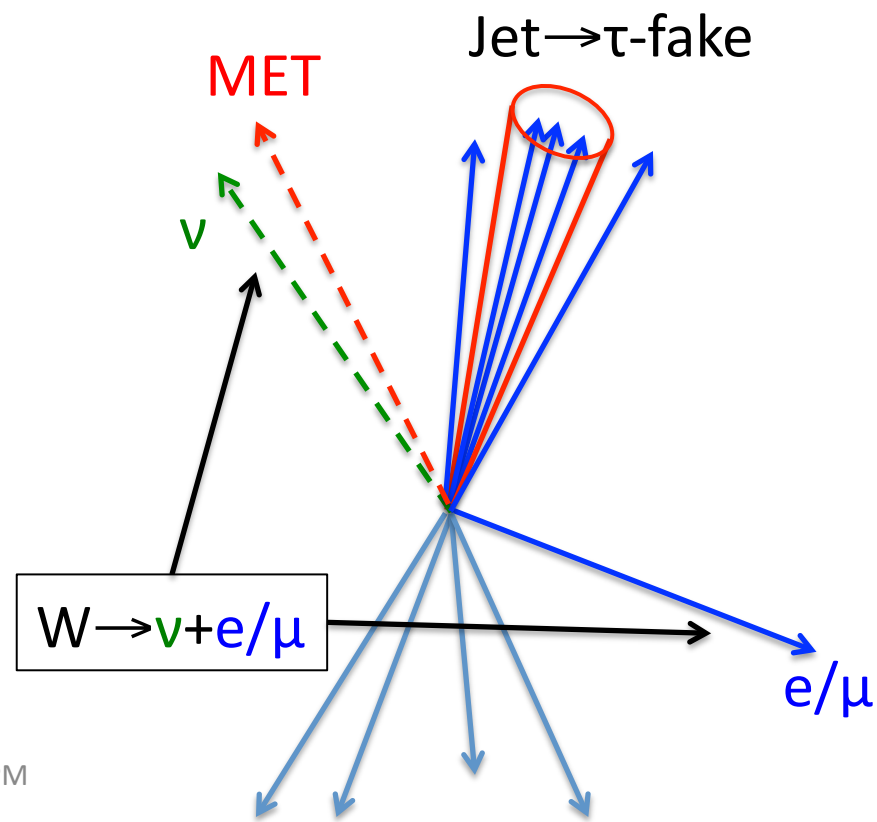
- Different event topology
- Presence of fake tau or fake lepton in W+jets

$$\frac{H \rightarrow \tau\tau}{W(l\nu) + jets} \approx 0.00016$$

Typical H→ττ event



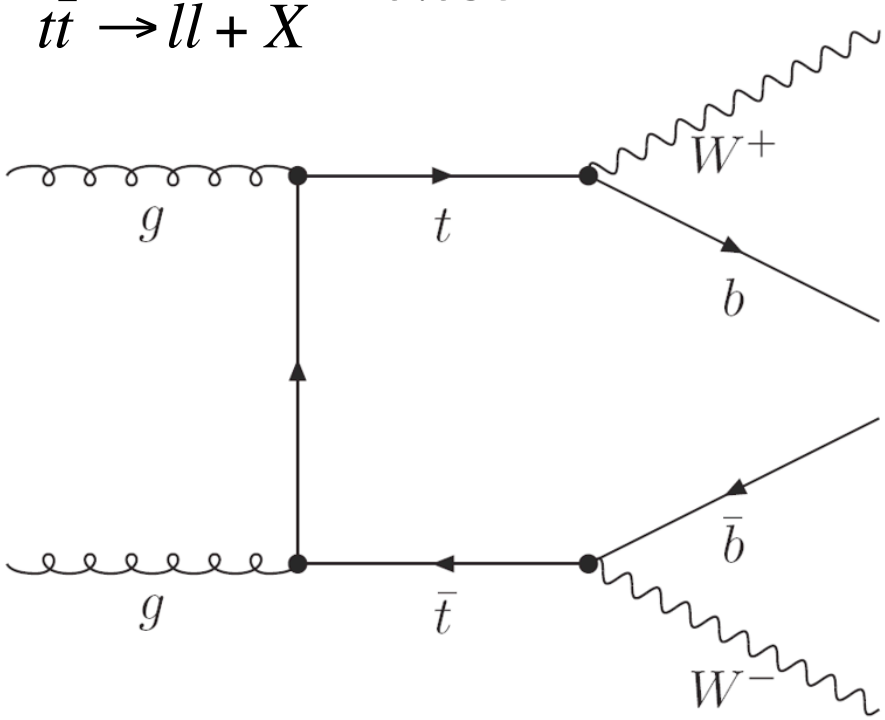
Typical W+jets event

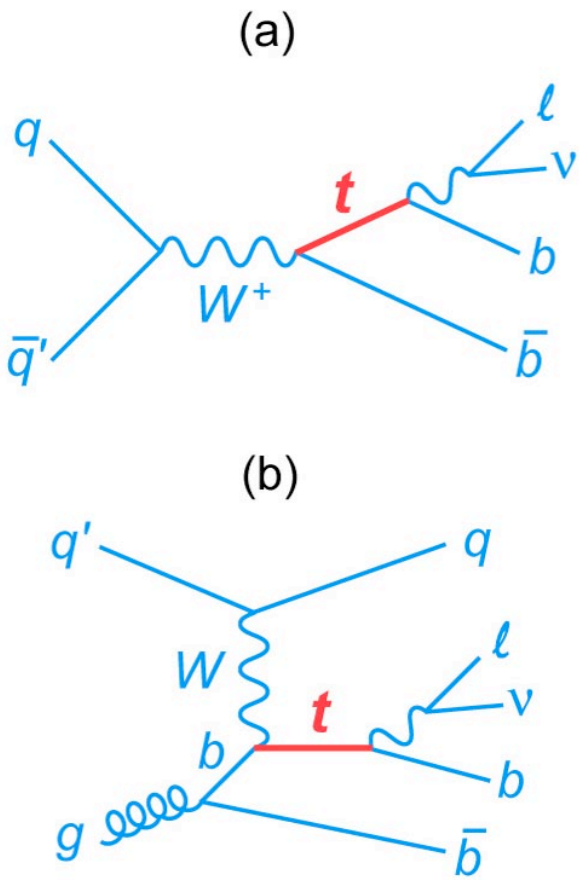


Events With Top Quarks: Large Reducible Background

- All ttbar and many single-top events have two b-jets
- Only ~0.3% of H→ττ events have b-jets
- **Reject events with b-jets to reduce backgrounds with top quarks**

$$\frac{H \to \tau\tau}{t\bar{t} \to ll + X} \approx 0.053$$





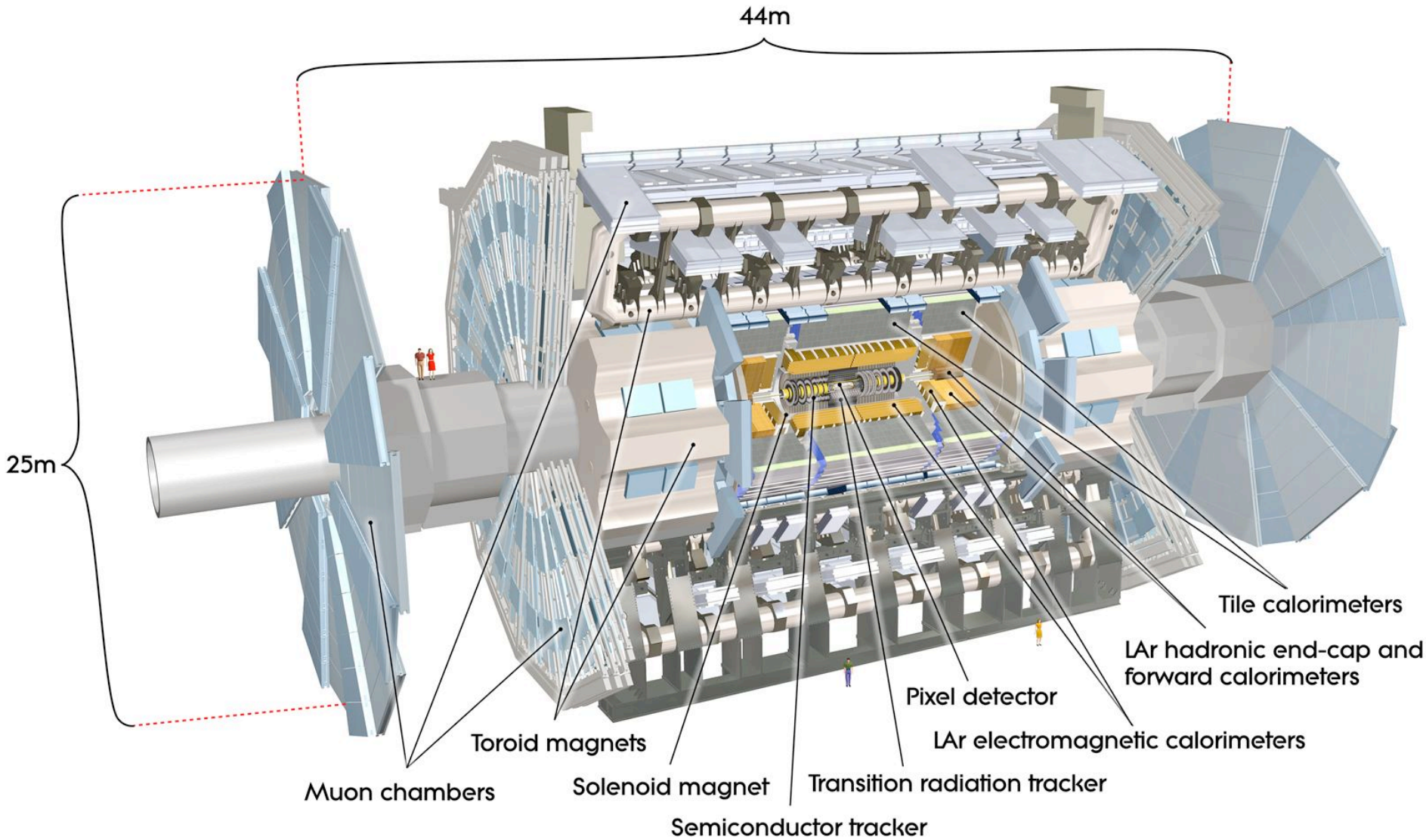
Analysis Concept

- Question that this analysis attempts to address
  - **Does the Higgs boson with $M_H \approx 125$ GeV decay to pair of τ-leptons?**
    - Is the $H \rightarrow \tau\tau$ decay rate consistent with SM predictions?

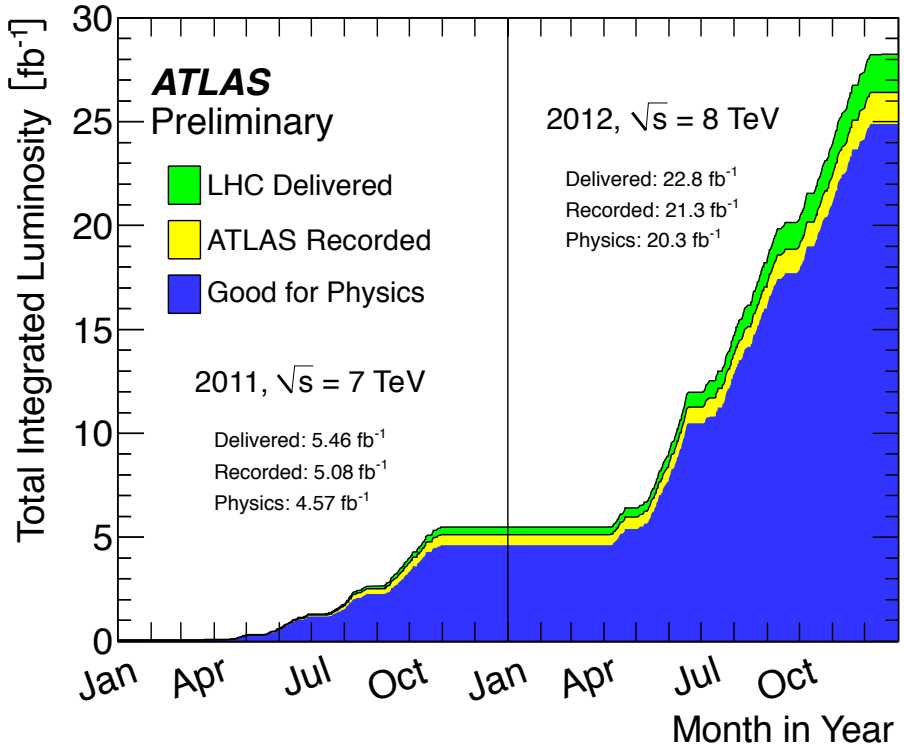
- Analysis strategy
  - Achieve maximum sensitivity for SM Higgs boson with $M_H \approx 125$ GeV
    - Design and perform multivariate analysis (based on BDT technique)
  - Perform "blind" analysis
  - Use entire Run-1 dataset: 4.5 fb^{-1} 7 TeV data and 20.3 fb^{-1} of 8 TeV data

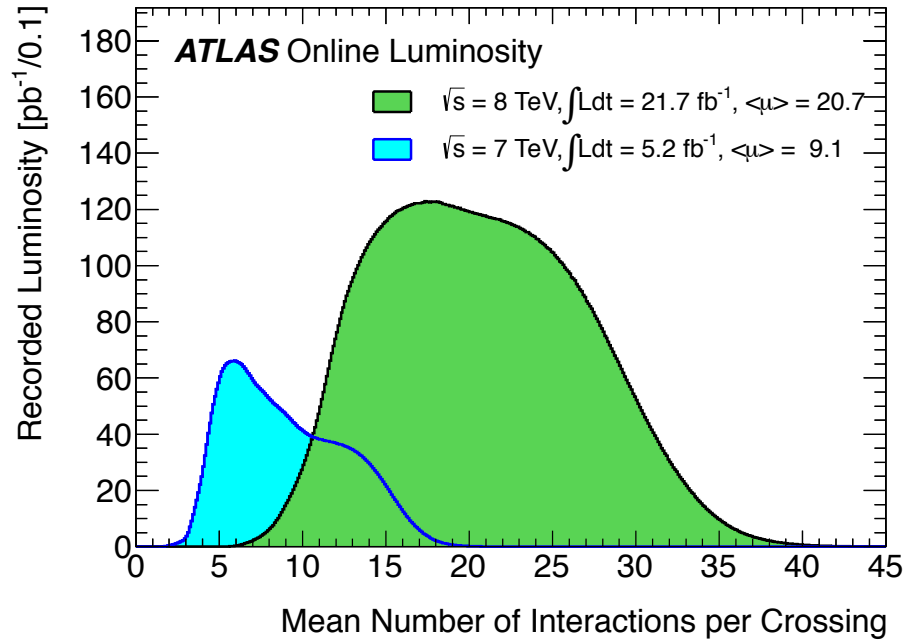
- Perform analysis in all final states of tau decays
  - Lep-lep channel: $H \rightarrow \tau\tau \rightarrow 2l+4\nu$, Br=12.4%
  - Lep-had channel: $H \rightarrow \tau\tau \rightarrow l+\tau_{had}+3\nu$, Br=45.6%
  - Had-had channel: $H \rightarrow \tau\tau \rightarrow 2\tau_{had}+2\nu$, Br=42%

ATLAS Detector



LHC & ATLAS Performance

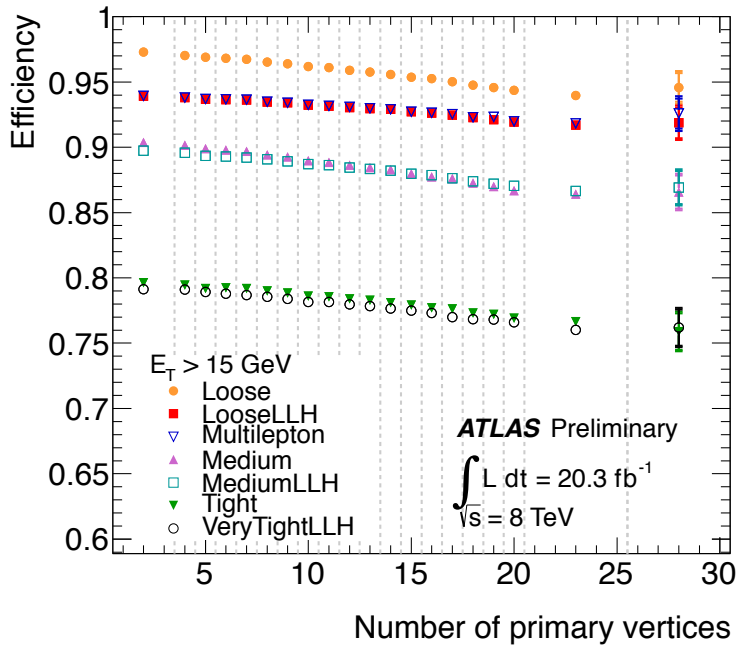




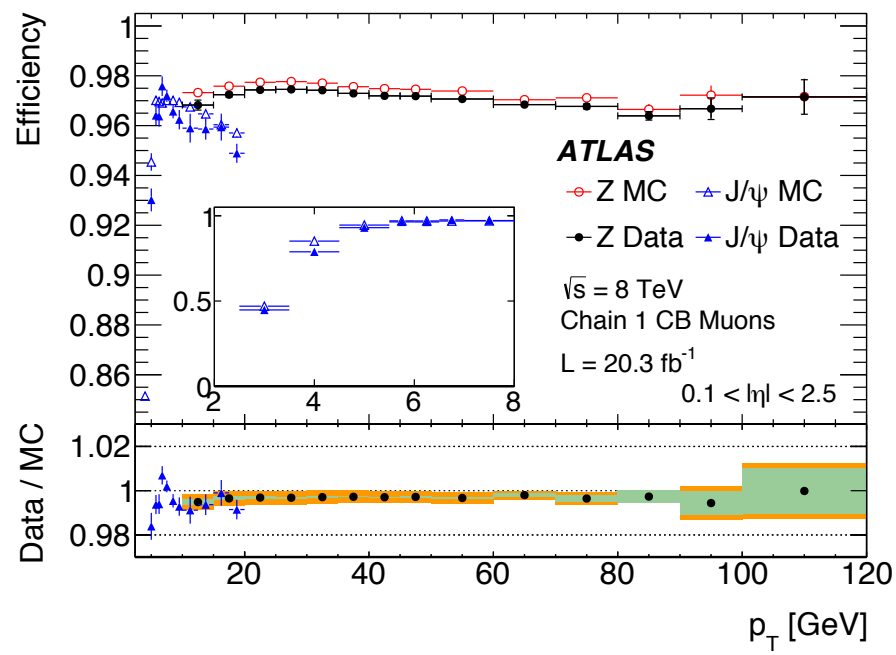
- Higgs boson discovery in 2012 would not be possible without outstanding performance of LHC
- Outstanding ATLAS detector performance in challenging high pile-up conditions with 90% efficiency for Physics

Electrons & Muons @ ATLAS

Electron efficiency

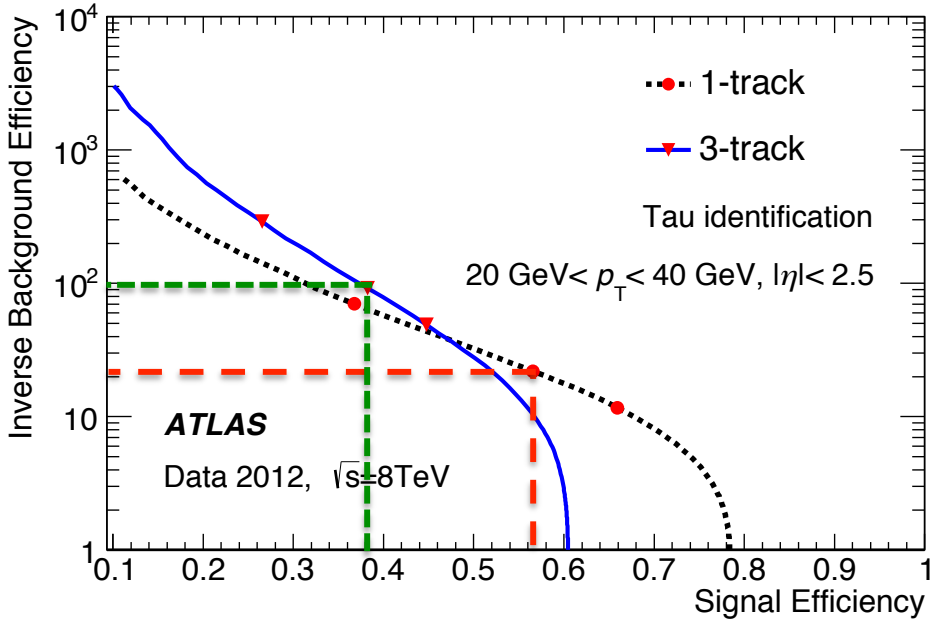


Muon efficiency

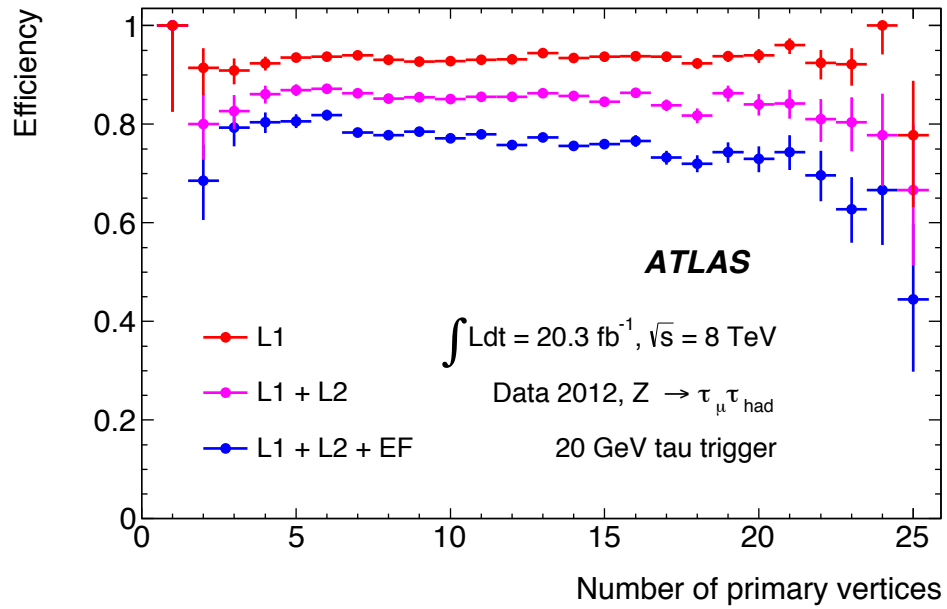


- Electrons
  - Stable (within a few %) identification efficiency as a function of N_{vertex}
  - Several working points; 80%-90% efficiency for eleID used in the analysis
- Muons
  - Stable >95% reconstruction efficiencies for P_T(muon)>10 GeV

Hadronic Tau's @ ATLAS



H→ττ search uses ~55% (1-prong) and ~38% (3-prong) signal efficiency operating points

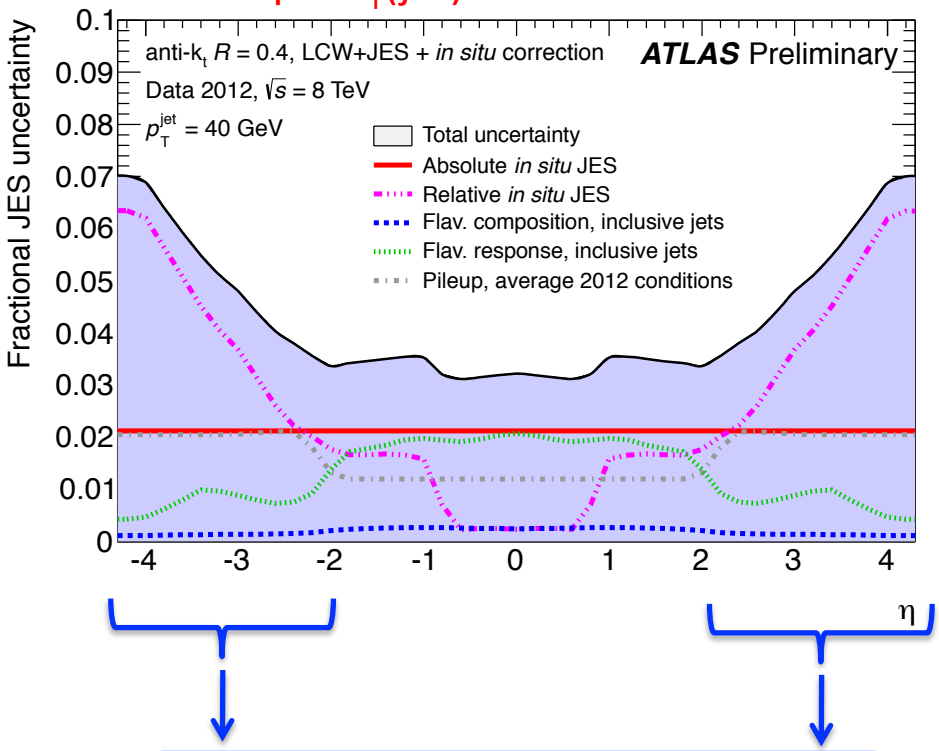


Stable hadronic tau trigger & ID efficiency as a function of N_{vertex}

- ATLAS employs multivariate hadronic tau identification techniques
  - Use information about shower shape in calorimeter and tracking detectors
  - TauID systematic uncertainties are 2-3% (3%-5%) for 1-prong (3-prong) taus
- Tau energy scale (TES) is derived with 2-4% precision using *in situ* calibration based on Z→ττ peak position

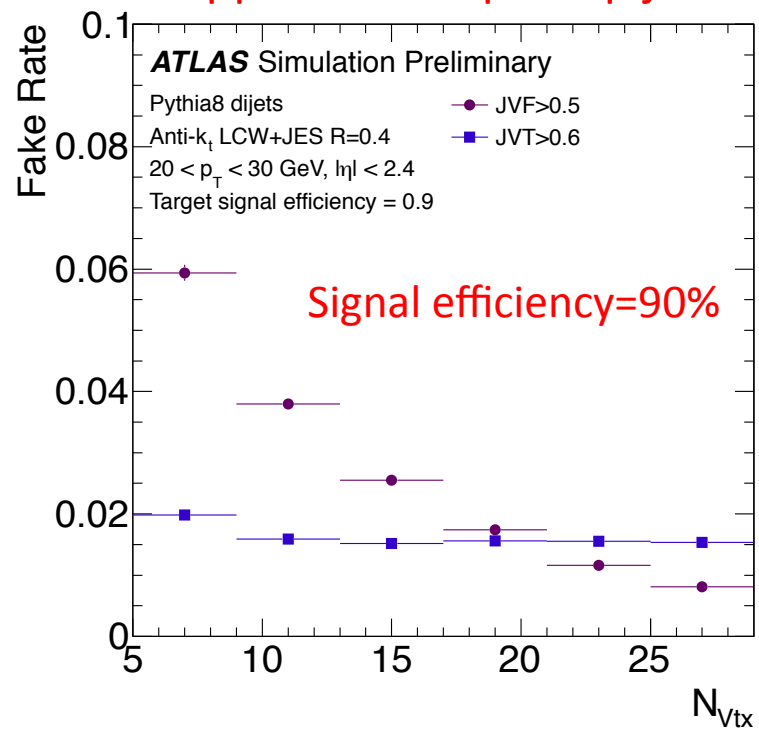
Jets @ ATLAS

JES vs η at P_T(jet)=40 GeV



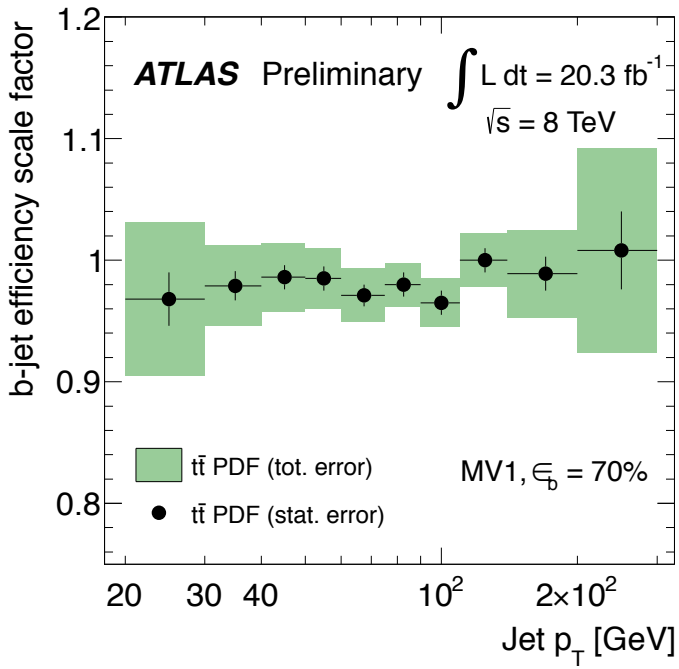
Important region for VBF signature

Suppression of pile-up jets



- H→ττ search relies on jets to select VBF-like events and benefits from reduced jet energy scale (JES) uncertainties
- Track-based jet-to-vertex tagging is used to suppress pile-up jets in |η|<2.4

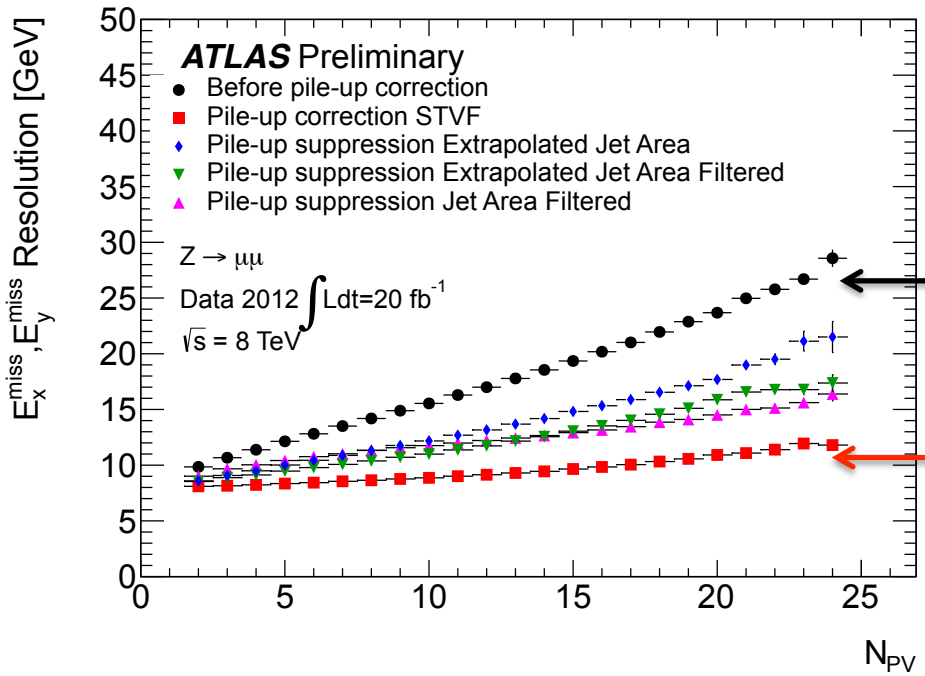
b-Tagging @ ATLAS



Data-to-MC scale factor vs P_T(jet)

- H→ττ search use NN *b*-tagging algorithm with working point corresponding to 70% *b*-tagging efficiency
  - Provides rejection factor of ~5 and ~150 against *c*-jets and light flavor jets
  - *b*-jet data-to-MC scale factors (SF) derived using *ttbar* di-lepton events
  - *b*-jet SF uncertainty in the range 2-10%
  - *c*-jet SF uncertainty in the range 8-15%

Missing Transverse Energy (MET) @ ATLAS



Before pile-up suppression

After pile-up suppression

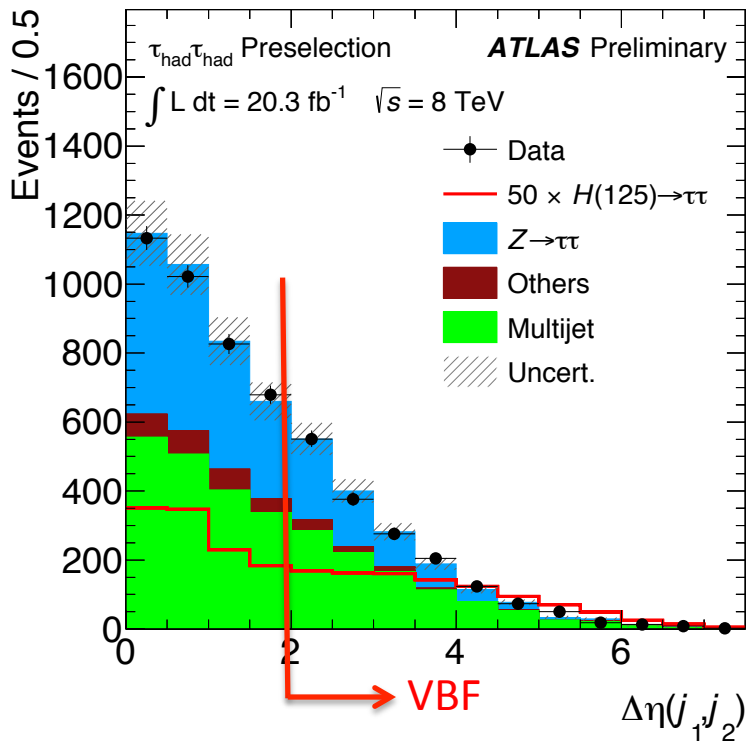
- Good MET resolution is very important for H→ττ search
  - MET is used in event selection and in $M_{\tau\tau}$ reconstruction
- Great improvement in MET resolution is achieved by using track-based pile-up suppression
  - Correction is based on the ratio of the Σp_T of the tracks associated to the primary vertex and all tracks

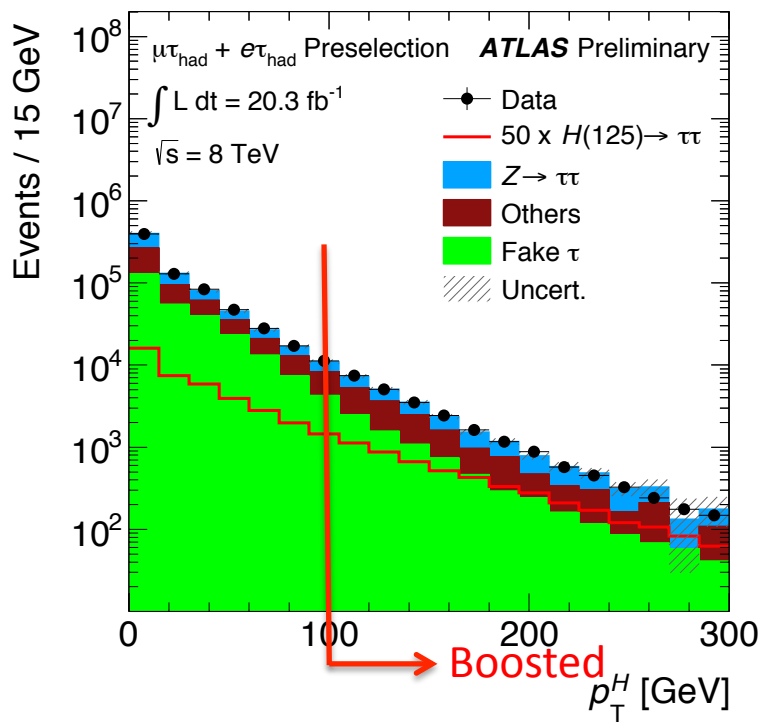
Event Selection

- Strategy
  - Keep simple common selection and let MVA separate signal and background
  - Use events after common selection to validate background modeling
- Triggers
  - **Lep-lep channel**: combination of single- and di-lepton triggers
  - **Lep-had channel**: single-lepton triggers
  - **Had-had channel:** di-tau triggers
- Common selection
  - **Lep-lep channel:** $N_{lepton}=2$
    - M_{ll} and MET cuts to suppress Drell-Yan and multijet backgrounds
  - **Lep-had channel:** $N_{lepton}=1$, $N_{\tau}=1$
    - $M_T<70$ GeV cut to suppress W+jets background
  - **Had-had channel:** $N_{\tau}=2$
    - MET>20 GeV, $\Delta R(\tau\tau)$ and $\Delta\eta(\tau\tau)$ cuts to suppress multijet background

Analysis Categories

- Analysis is performed in two simple categories
  - **VBF**: 2 jets with leading (sub-leading) P_T>40-50 (30-35) GeV; Δη(jj) cut
    - targeting VBF Higgs production (VBF/"total signal" fraction: 55%-65%)
  - **Boosted:** P_T(H)>100 GeV
    - dominated by gluon fusion (ggF/"total signal" fraction: 62%-67%)
  - **Lep-lep & Lep-had:** veto events with b-tags to suppress top background
- **"Rest" category in Had-had:** events failing Boosted & VBF selection used to constrain multijet and Z→ττ backgrounds

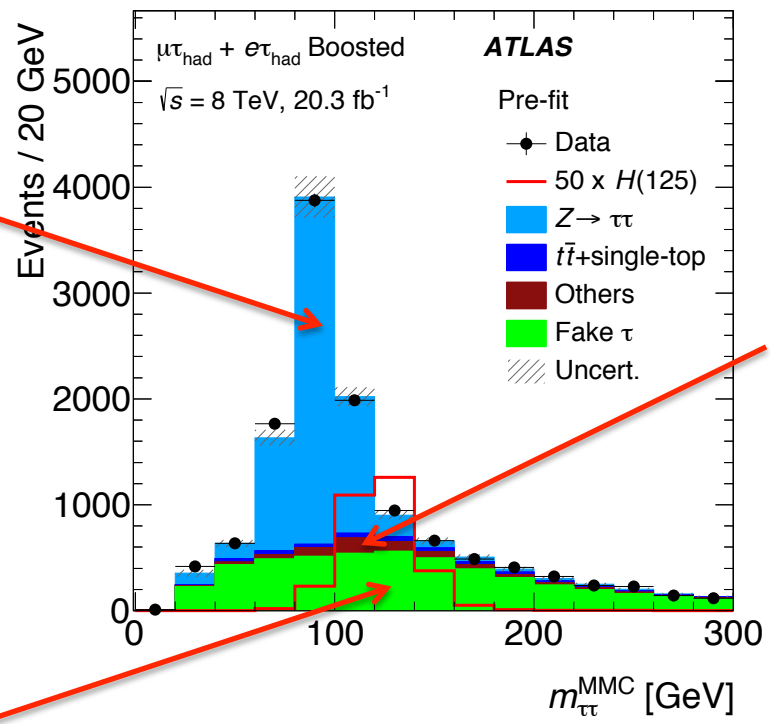




Background Estimation

- All major backgrounds are either directly estimated from data or normalized to data in dedicated control regions

Z→ττ: major background; modeled by data

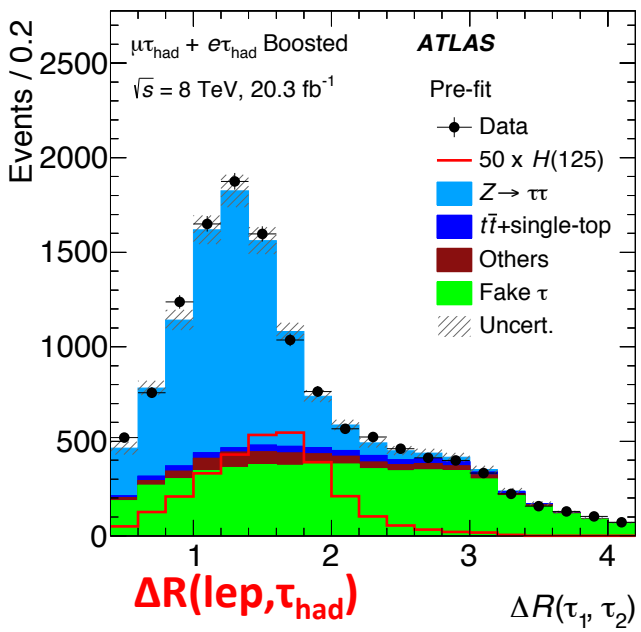


"Others" & Top – events with true leptons and taus: Dibosons & H→WW* modeled by MC; Z→ee/μμ & top modeled by MC and normalized to data

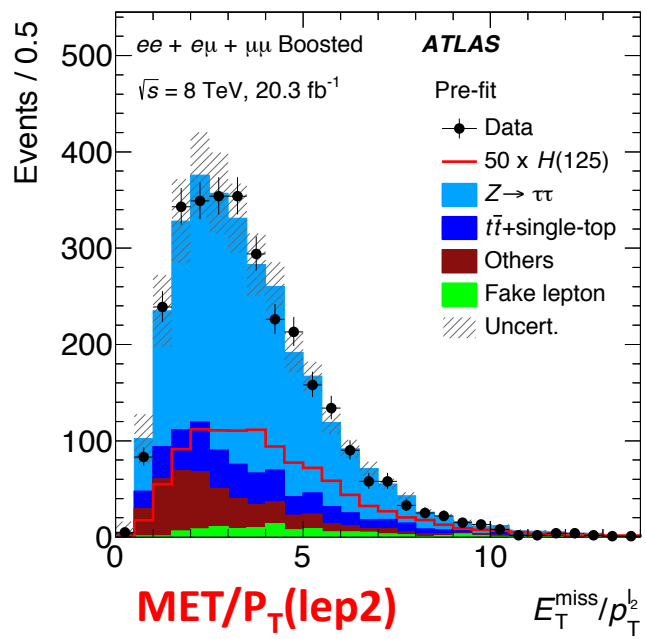
"Fakes"-- events with fake taus or leptons: multijet, Z/W+jets, top; modeled by data

Z→ττ Background

- **Z→ττ embedding: except for τ-decays, all properties of a Z→ττ event are modeled by actual Z→μμ data**
- **Major advantages of embedding:** Z-boson kinematics, jets, MET resolution, pile-up, and VBF/EWK production are directly modeled by data



ΔR(lep,τ_{had})

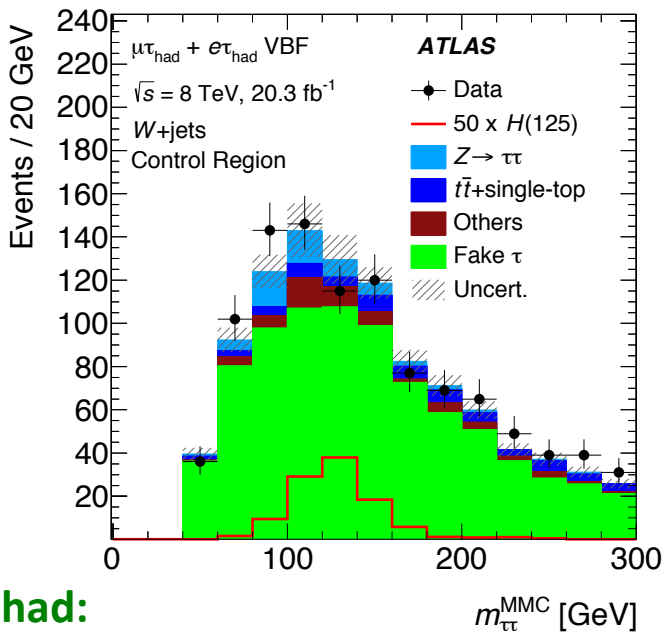


MET/P_T(lep2)

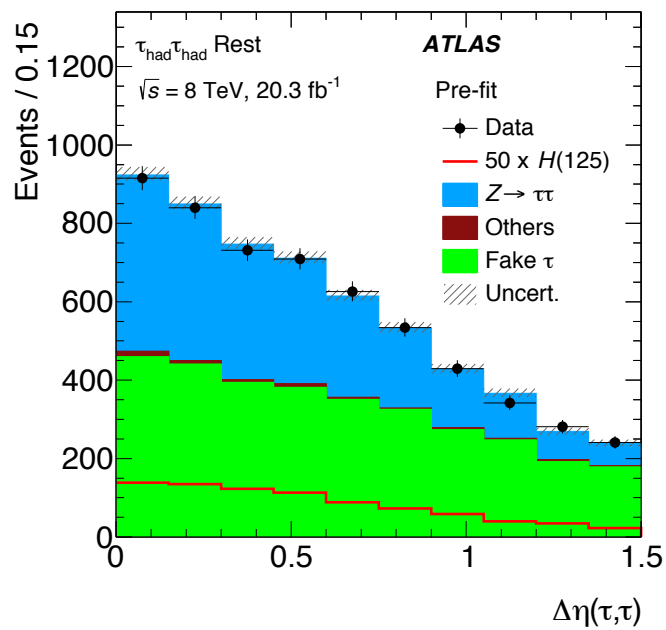
Data Z→μμ events
↓
Replace μμ→ττ
↓
τ-decays:
Tauola + Simulation
↓
Embed τ-decays back into Z event
↓
Hybrid Z→ττ event

Backgrounds With "Fakes"

- "Fakes" are estimated directly from data
  - **Lep-lep:** from sample of "anti-isolated" leptons (inverted isolation requirement)
  - **Lep-had:** from sample where hadronic tau fails ID requirements
  - **Had-had:** from non-isolated SS data events (where tau isolation not enforced)
  - Modeling of "Fakes" is checked in dedicated control regions (CR)
  - Uncertainties vary from ~3% to ~30% (depending on channel & category)



Lep-had:
W+jets CR with M_T>70 GeV



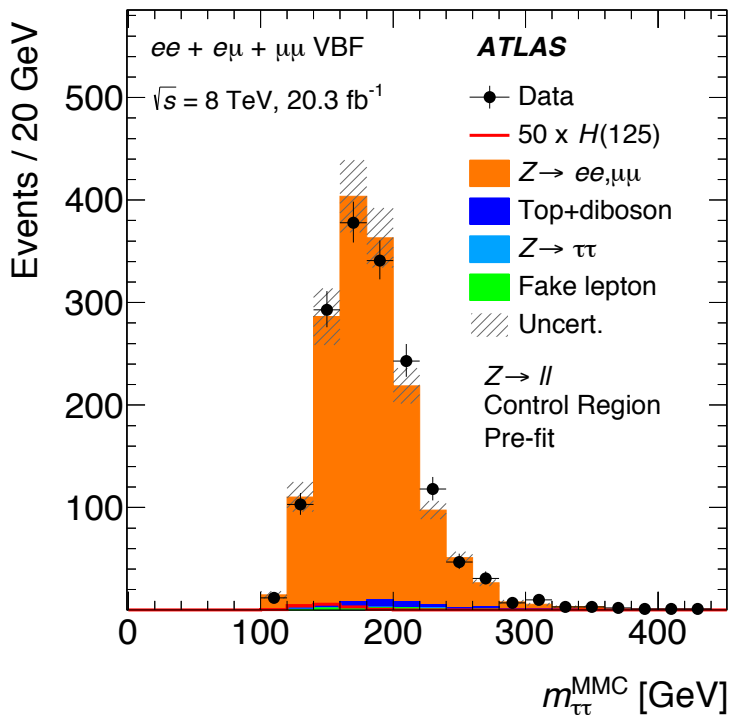
Had-had: "Rest" category

"Fakes" are shown by **green** histogram

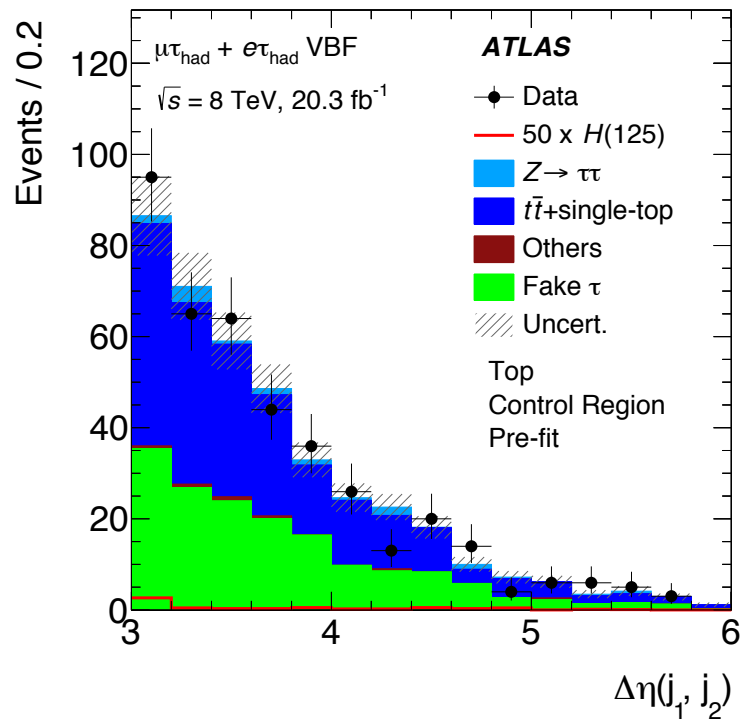
Z→ee/μμ And Top Backgrounds

- Z→ee/μμ and top backgrounds are modeled by MC (shape) and normalized in control regions to total integral of events
  - Z→ee/μμ CR (lep-lep only): $80<M_{ll}<100$ GeV
  - Top CR: invert b-veto (and require $M_T>40$ GeV in lep-had)
  - Separate normalization for Boosted & VBF categories

Z→ee/μμ CR for lep-lep

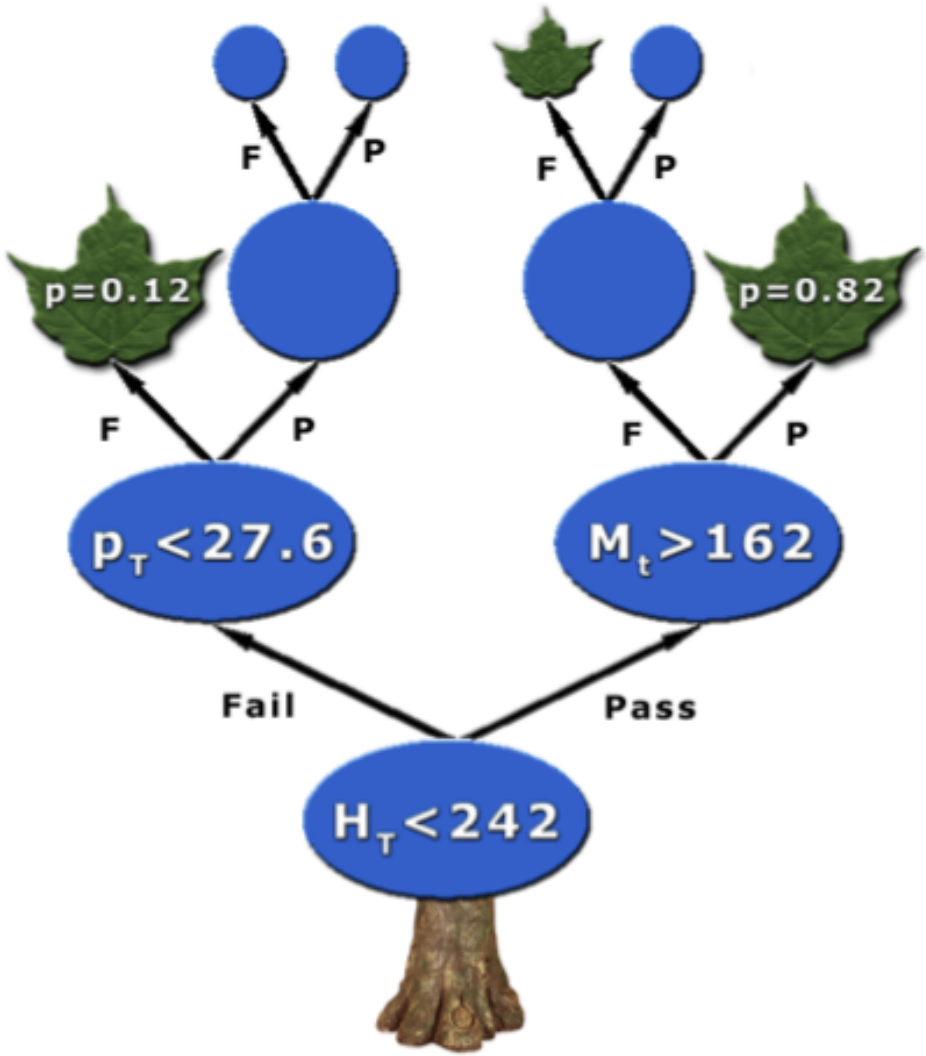


Top CR for lep-had

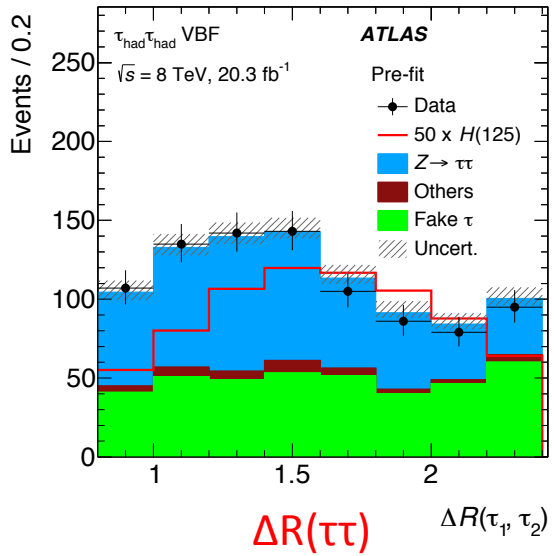


Boosted Decision Trees (BDT)

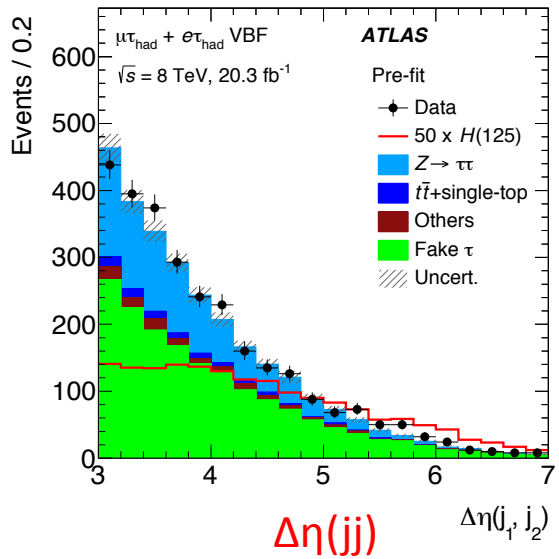
- BDT in a nutshell
  - Find best cut for each variable
  - Produce Fail and Pass branches
  - Repeat until some condition is met (tree depth, leaf size)
  - **Boosting:**
    - Modify original training sample by giving larger weight to mis-classified events
    - Re-train and repeat until condition is met (MAX number of trees)
- Training
  - Use very high statistics MC signal and background samples
  - Split each sample in two: train on sample-1 and check on sample-2 and vice versa



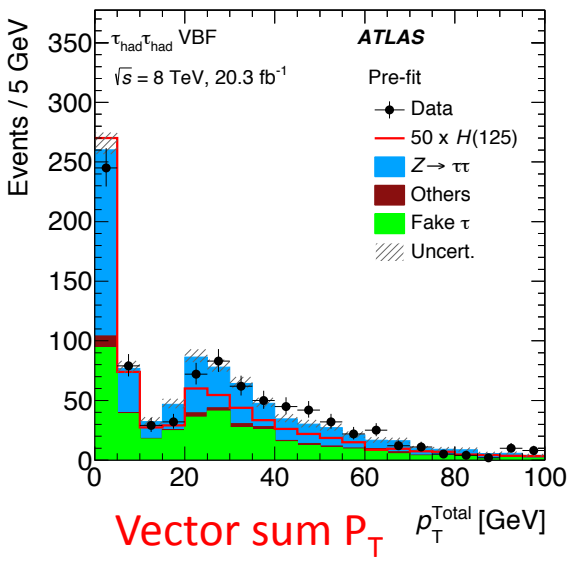
Input Variables to BDT



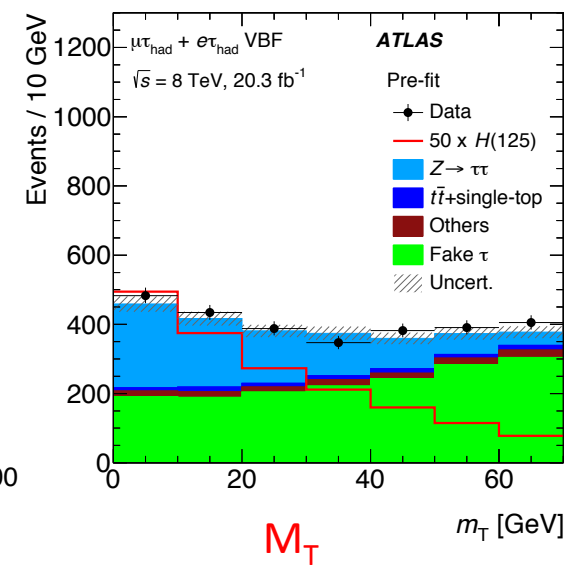
ΔR(ττ)



Δη(jj)



Vector sum P_T

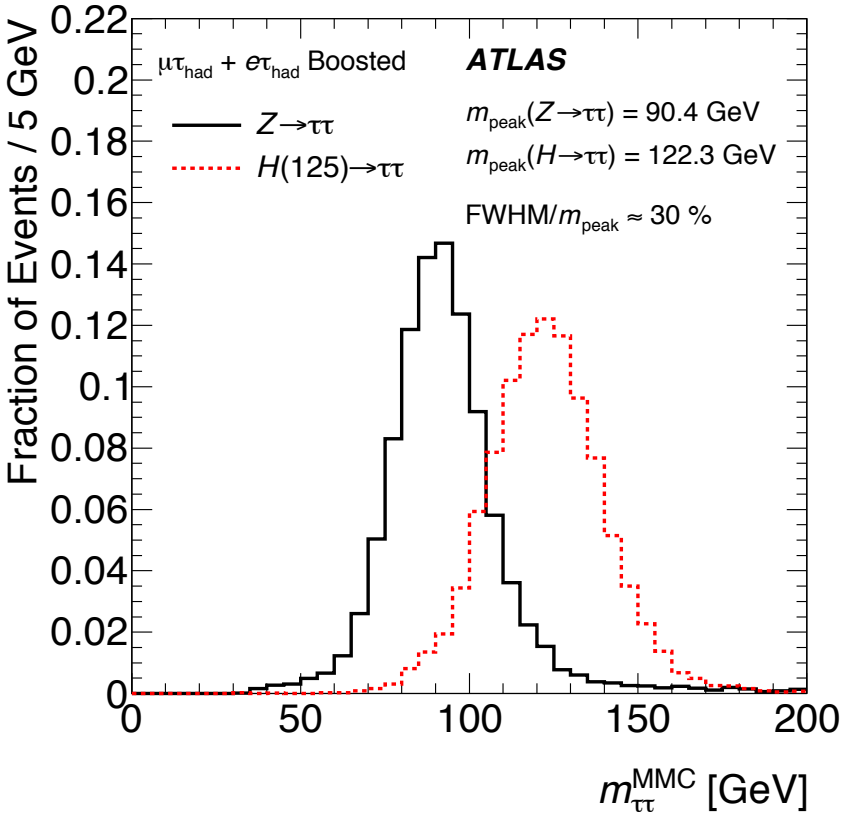


M_T

- Resonance properties
  - m(ττ), ΔR(ττ), etc
- VBF topology
  - m_{jj}, $\Delta\eta_{jj}$, etc
- Event activity
  - Scalar & vector P_T-sum
- Event topology
  - m_T, object centralities, $P_T(\tau_1)/P_T(\tau_2)$, etc
- Number of variables
  - VBF: 7-9
  - Boosted: 6-9

m(ττ) Reconstruction

- **m(ττ) is the highest ranked BDT input variable**
- m(ττ) reconstructed by Missing Mass Calculator (MMC)
  - MMC is sophisticated technique to reconstruct m(ττ) in presence of neutrinos from τ-decays (NIMA 654 (2011) 481)
  - Improves sensitivity by more than 20% compared to other methods



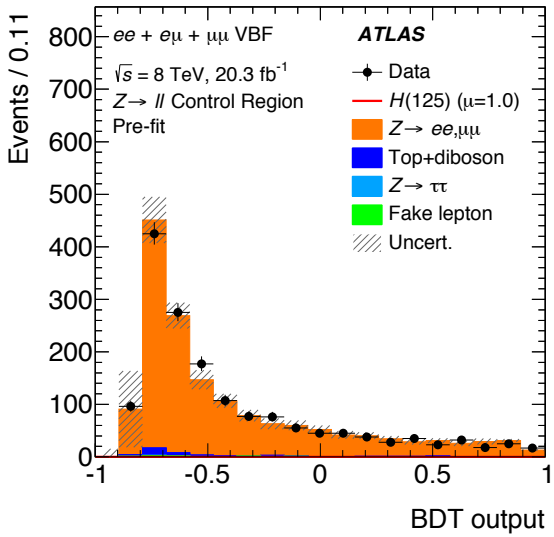
- MMC resolution:
  - Defined as FWHM/m_{peak}
  - The same ~30% core resolution in all categories and decay channels
  - Tails depend on channel and event topology

Cross-Checks

- Rigorous checks of background model and fitting technique
  - ✓ Check modeling of all input variables
  - ✓ Check modeling of correlations between each pair of input variables: $\langle V_i \rangle$ vs V_j
  - ✓ Dedicated control regions (CR) for all major backgrounds
    - **$Z \rightarrow ee/\mu\mu$ + jets CR** in lep-lep
    - **Top CR** in lep-lep & lep-had
    - **W+jets CR** in lep-had
    - **"Fakes"-enriched CR (same sign events)** in lep-lep and lep-had
    - **QCD-enriched CR** in had-had
  - ✓ Perform fit in mass sidebands (outside 100-150 GeV window)
    - Check of $Z \rightarrow \tau\tau$ background and overall background model
  - ✓ Study robustness of fits in signal extraction procedure

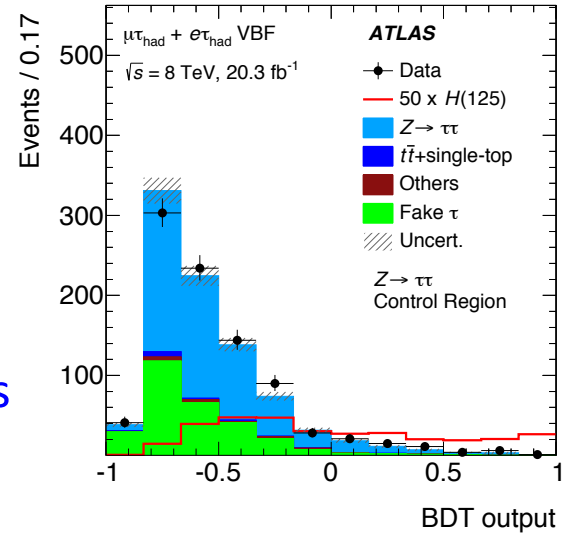
Building Confidence in Background Model

- Examples of BDT distributions in data CR's for major backgrounds

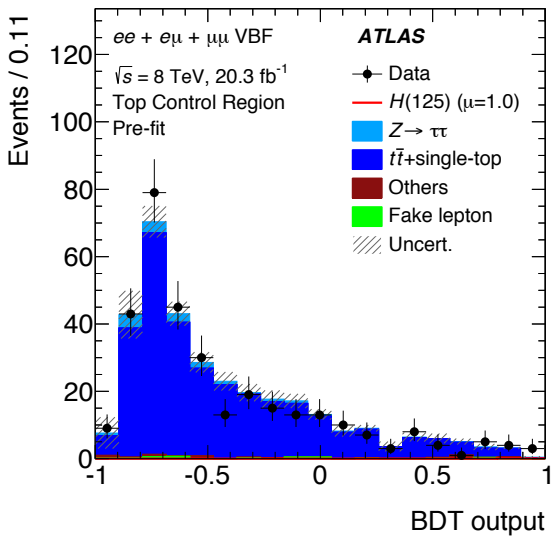


Lep-lep VBF:
Z→ee/μμ CR

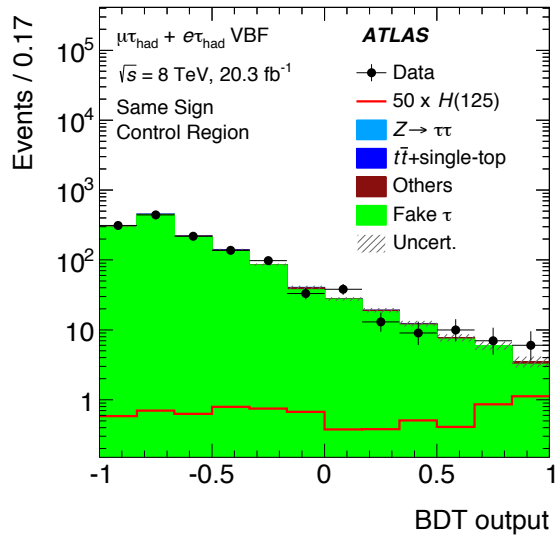
Good agreement in all BDT distributions with background normalizations before fit!



Lep-had VBF:
Z→ττ CR



Lep-lep VBF:
Top CR



Lep-had VBF:
same sign CR

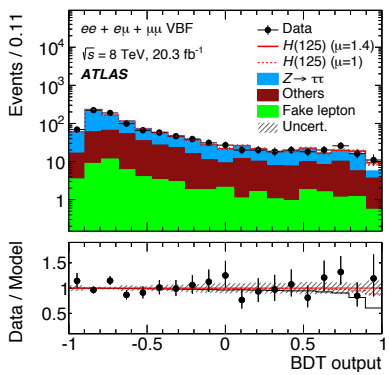
Signal Extraction

Lep-lep & Lep-had channels

Signal region (BDT shape)

Z→*ll* CR (1 bin)

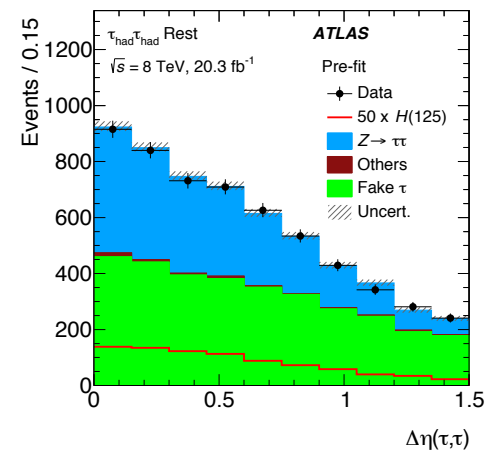
Top CR (1 bin)



Had-had channels

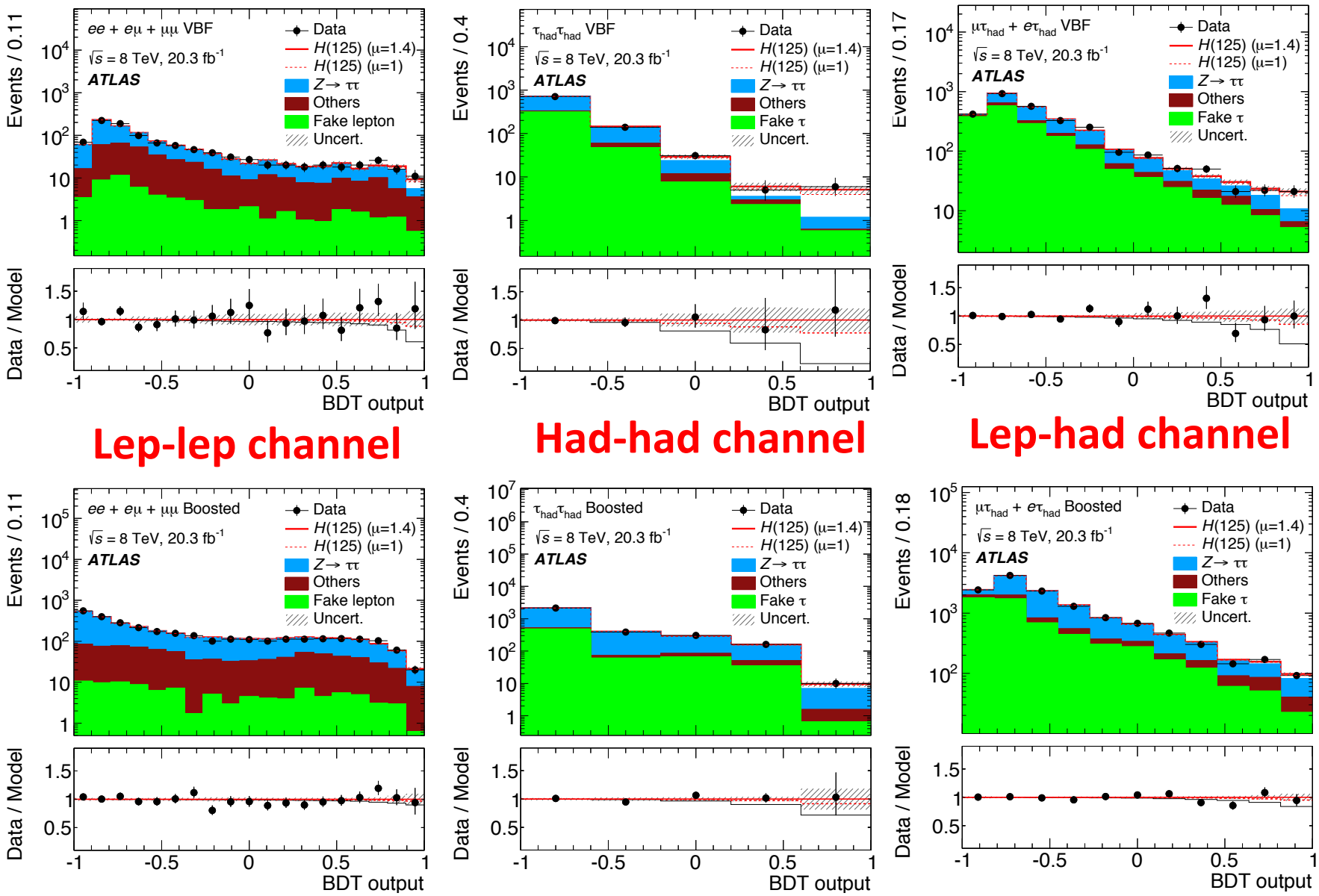
Signal region (BDT shape)

Rest category Δη(ττ) shape



- **Fit BDT shape with signal+background templates**
  - Simultaneous fit in 2×6 SR and 2×7 CR in 7 and 8 TeV data
    - with common systematics NP's
  - Z→ττ, Top, multijet (in had-had) & Z→ll (in lep-lep) normalizations are free in the fit
    - Control regions to constrain normalization of Top & Z→ll
    - **Had-had channel:** multijet & Z→ττ constrained in Rest category

BDT-score Distributions in 8 TeV Data After Fit



Lep-lep channel

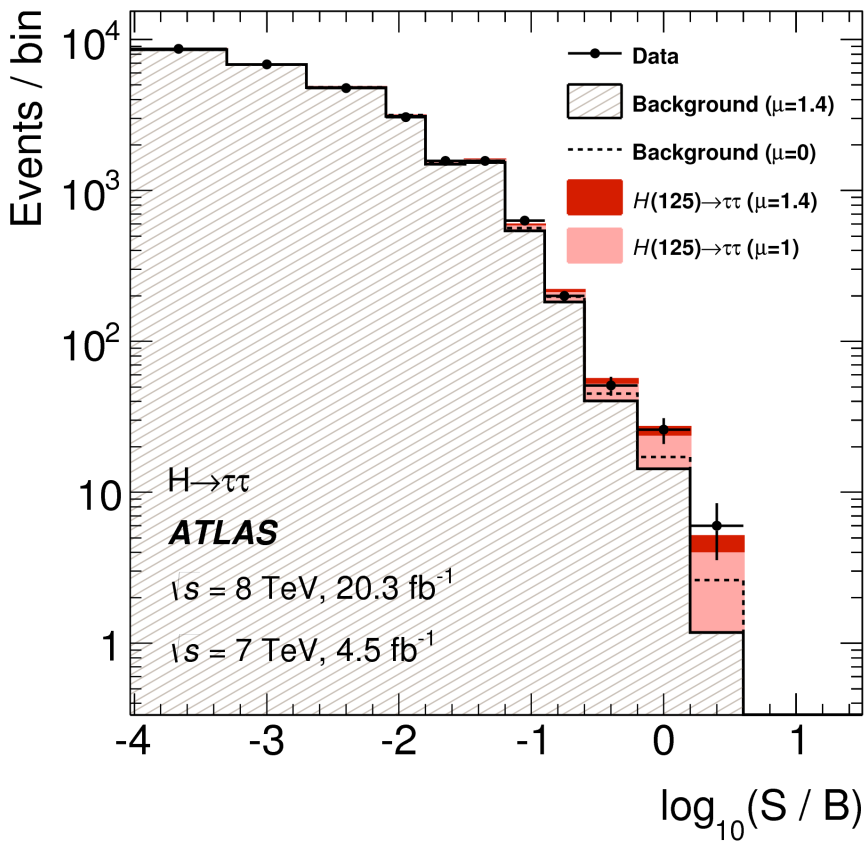
Had-had channel

Lep-had channel

VBF category

Boosted category

Results

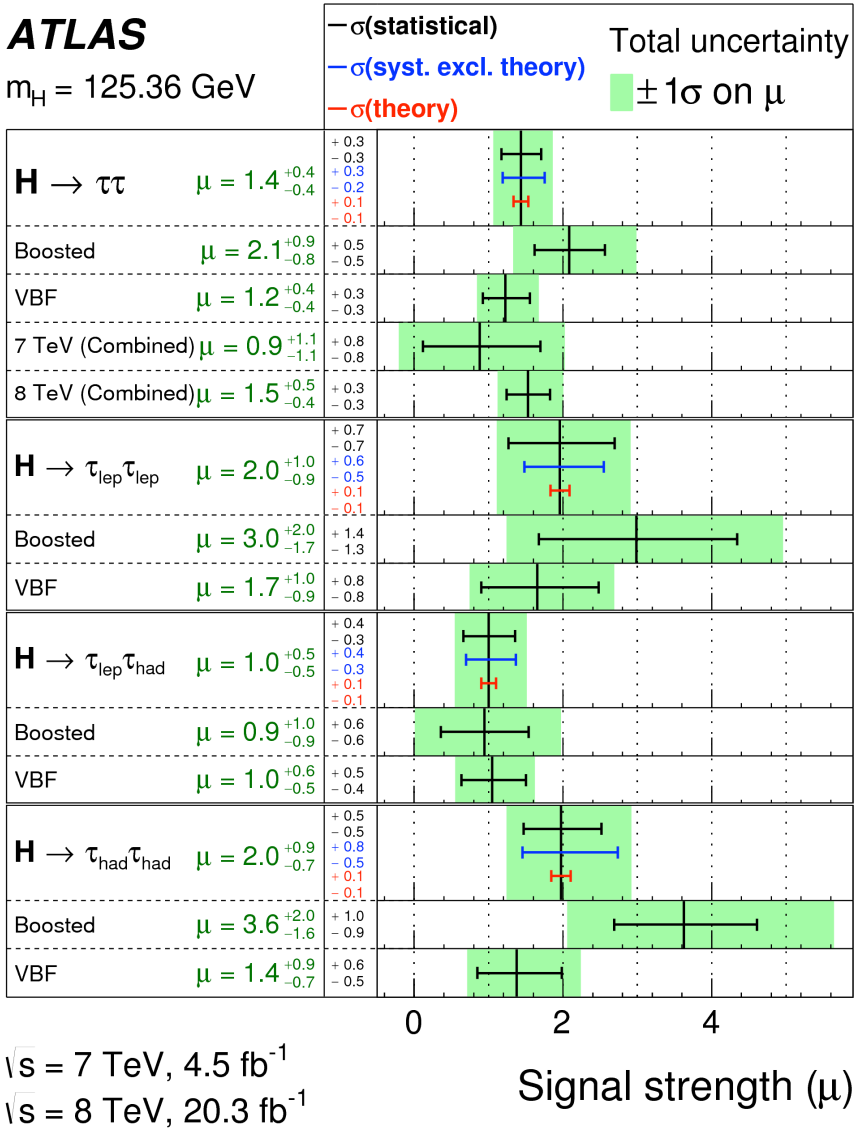


Numbers of events in highest BDT-score bin in √s=8 TeV data

		Lep-lep	Lep-had	Had-had
VBF	Signal	3.6±1.0	10.3±2.5	3.9±1.0
	Bckg	5.6±1.4	10.7±2.7	1.2±1.0
	Data	**11**	**21**	**6**
Boosted	Signal	2.1±0.6	16±4	2.7±0.8
	Bckg	19.2±2.1	82±6	7.0±1.8
	Data	**20**	**92**	**10**

- **ATLAS observes significant excess of data events in high S/B region**
  - Excess is observed in all three channels
  - **Expected** significance at M_H=125 GeV corresponds to **3.43 sigma**
  - **Observed** significance at M_H=125 GeV corresponds to **4.54 sigma**

Results Per Channel



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

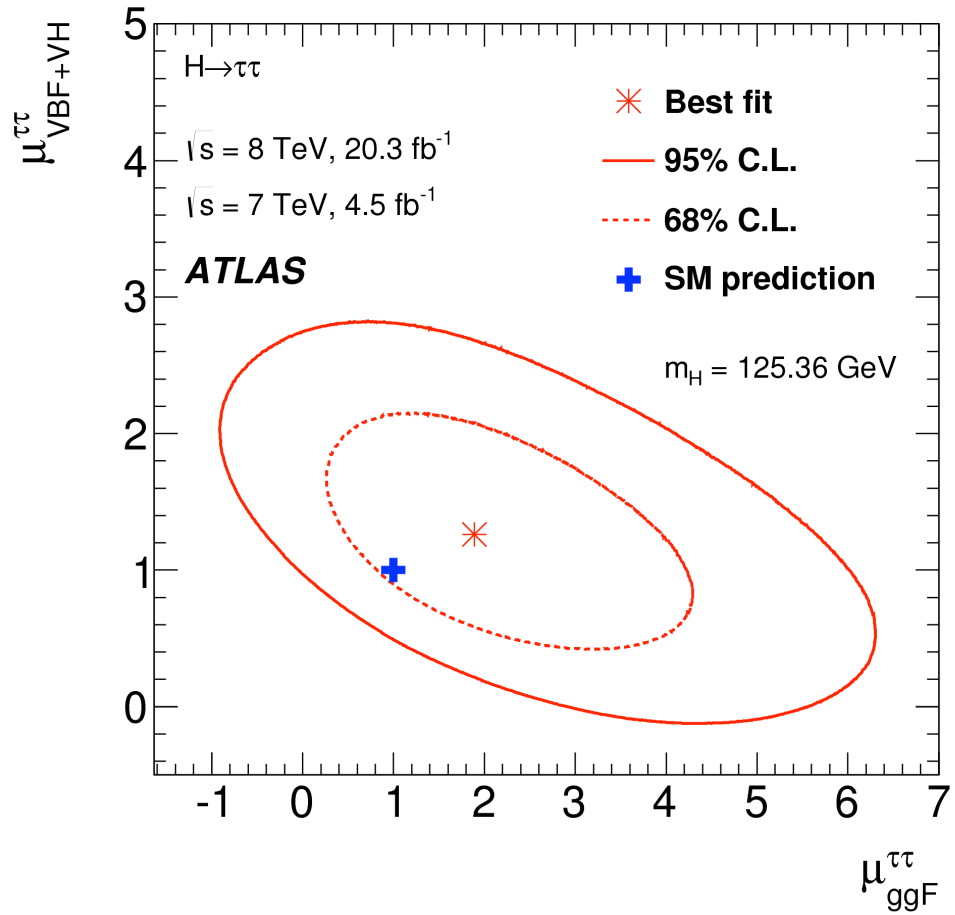
- Measured signal strength $\mu=\sigma_{mes}/\sigma_{SM}$
  - Boosted category: $\mu=2.1^{+0.9}_{-0.8}$
  - VBF category: $\mu=1.2\pm0.4$

Leading systematic uncertainties

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	$^{+0.43}_{-0.37}$

VBF+VH vs Gluon Fusion

- Results are consistent with SM predictions within 68% contour
- Observed (expected) signal significance:
  - ggF: 1.74σ (0.95σ)
  - VBF+VH: 2.25σ (1.72σ)

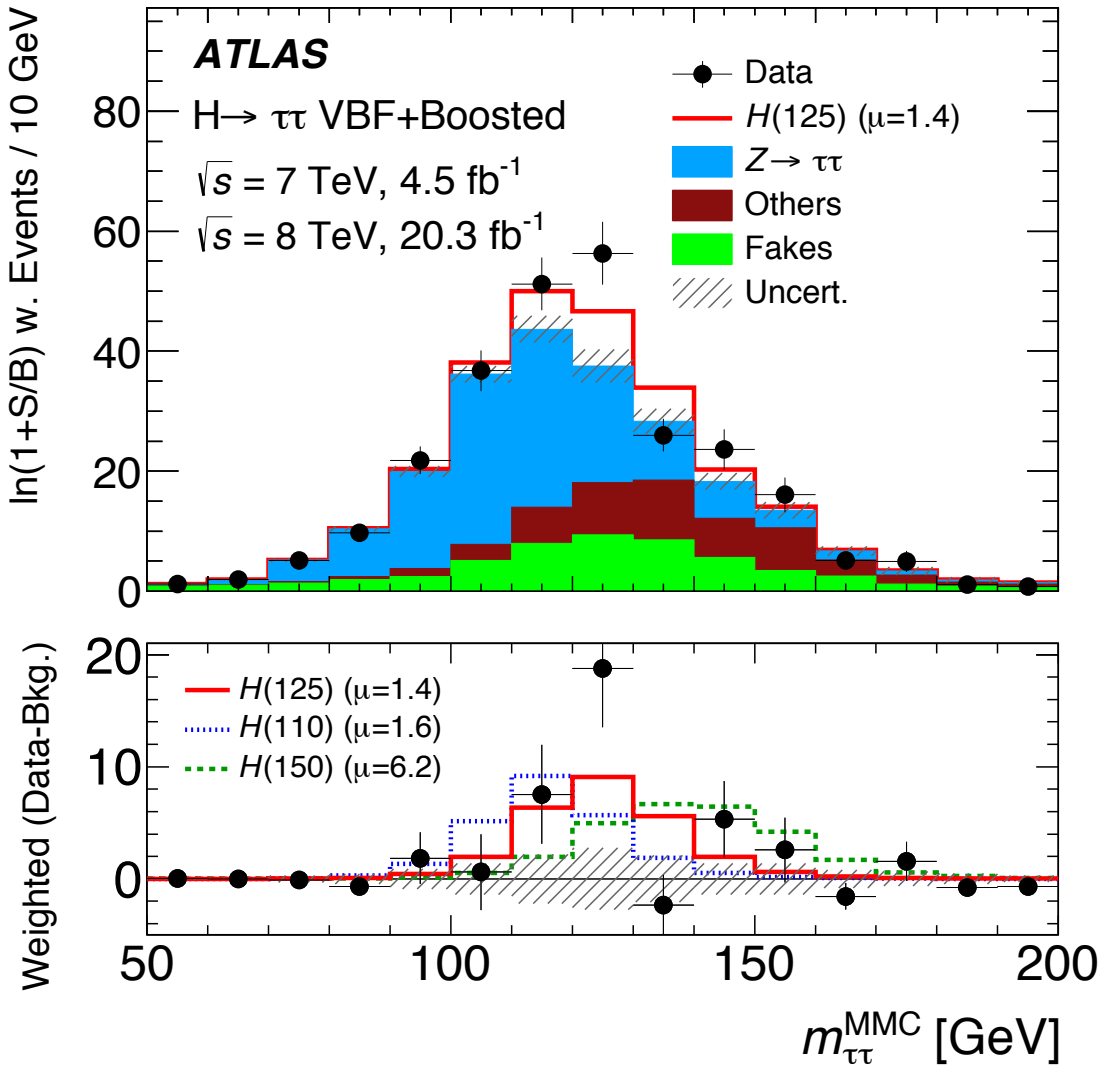


Best fit values

$$\mu^{\tau\tau}_{ggF} = 2.0 \pm 0.8(stat)\ ^{+1.2}_{-0.8}(syst) \pm 0.3(theory)$$

$$\mu^{\tau\tau}_{VBF+VH} = 1.24\ ^{+0.49}_{-0.45}(stat)\ ^{+0.31}_{-0.29}(syst) \pm 0.08(theory)$$

Compatibility With M_H=125 GeV



Each event is weighted by ln(1+S/B) for corresponding bin in BDT-score

Excess of data events is consistent with presence of Higgs at 125 GeV

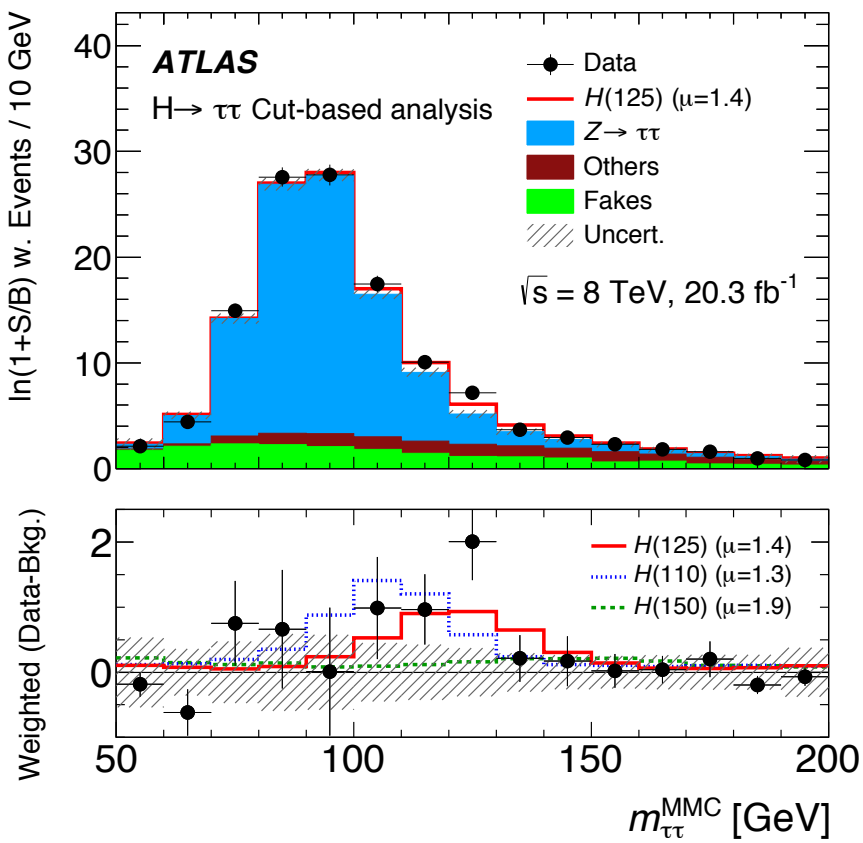
Signals at M_H=110, 125 and 150 GeV are shown at best fit μ; post-fit background normalizations

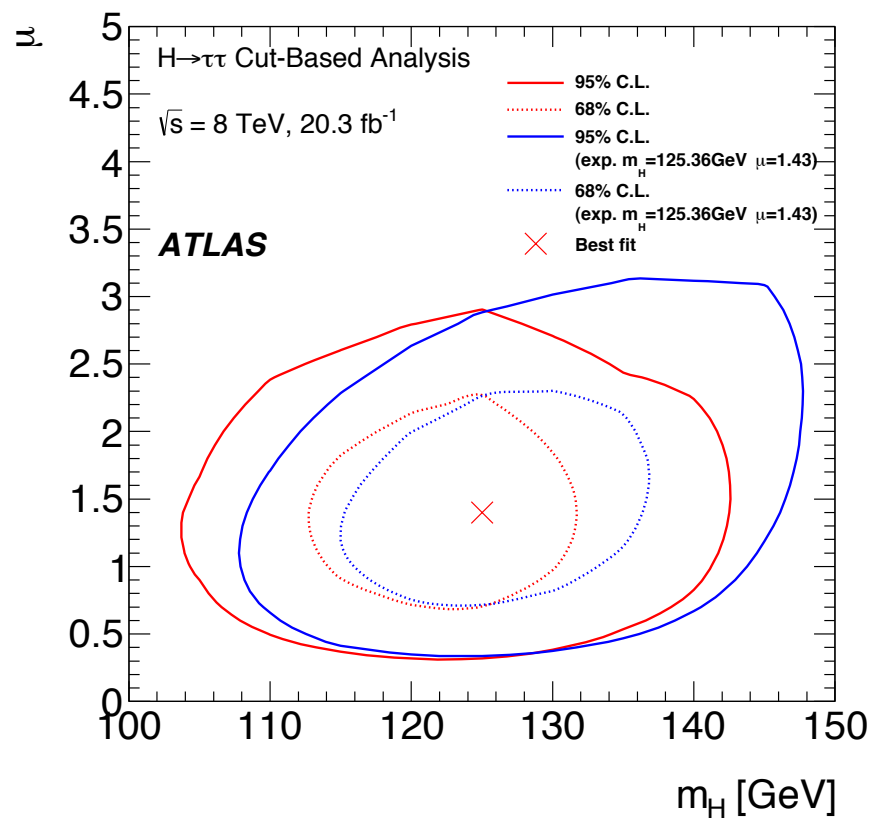
Cross check: Cut-based Analysis With 8 TeV Data

- Same channels and analysis categories as in MVA analysis
- Observed (expected) signal significance at 125 GeV: 3.2σ (2.5σ)

$$\mu = 1.43\ ^{+0.36}_{-0.35}(stat)\ ^{+0.41}_{-0.33}(syst) \pm 0.10(theory)$$

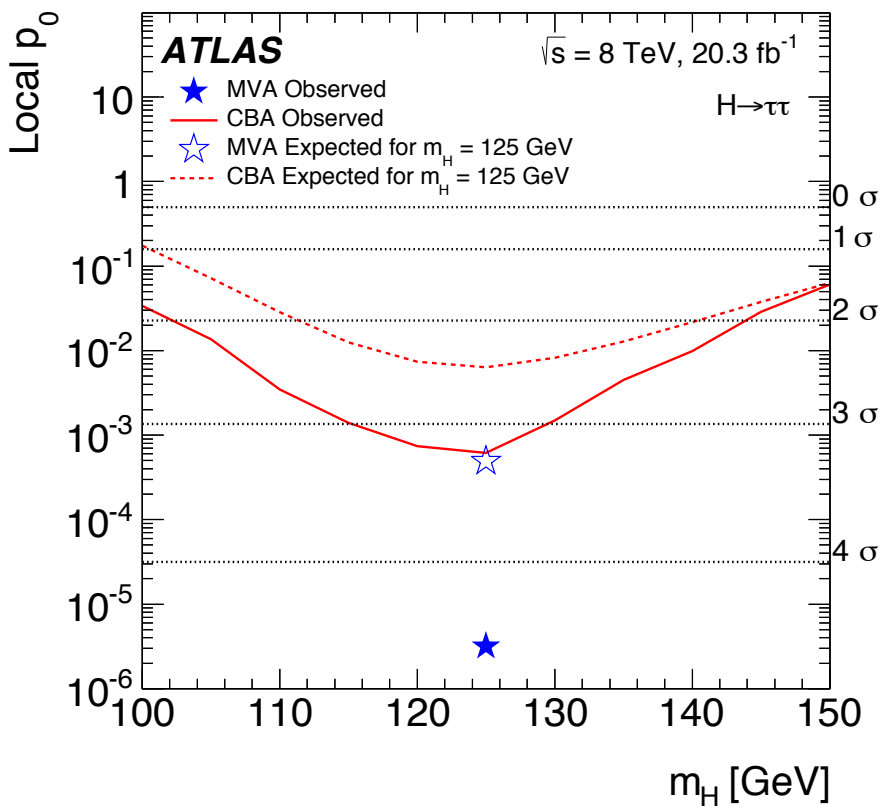
Results of cut-based analysis are consistent with results of MVA analysis





Summary

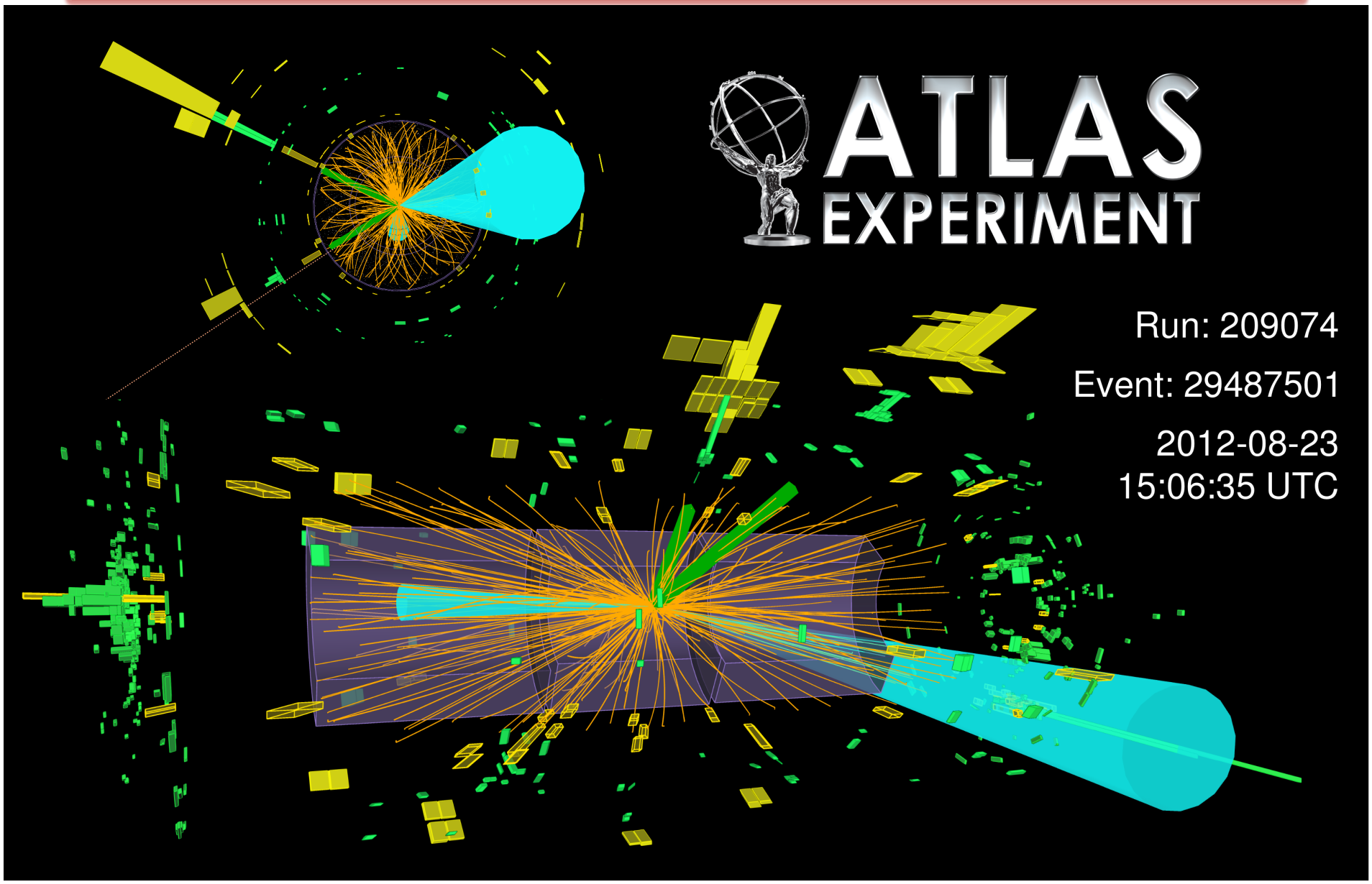
- **ATLAS observed 4.5σ evidence for H→ττ decays**
- **CMS and ATLAS results are consistent with SM predictions within ±1σ**
- **ATLAS results show that the Higgs boson does not universally couple to fermions (leptons)**
  - No excess over background observed in earlier H→μμ search
  - Possibility of Br(H→μμ)≈Br(H→ττ) is excluded at >95% CL



ATLAS result: $\mu = 1.43^{+0.43}_{-0.37}$

CMS result: $\mu = 0.78 \pm 0.27$

H→ττ Candidate Event In Had-Had Channel



Plans & Prospects For Run-2

- What else to expect from Run-1 data?
  - Public result for VH($\rightarrow\tau\tau$)
  - Public result for $h\rightarrow aa\rightarrow\mu\tau$
  - Public result for search of lepton flavor violating (LFV) $H\rightarrow\mu\tau$ decays
    - CMS observes 2.5σ excess corresponding to Br($H\rightarrow\mu\tau$)=0.9%
- Prospects for Run-2
  - Observation of $H\rightarrow\tau\tau$ and measurement of kinematic properties
    - Observation of $H\rightarrow\tau\tau$ decays in both ggF and VBF production
  - Search for CP violation in $H\rightarrow\tau\tau$ decays
    - Using $\Delta\phi(jj)$ distribution in VBF H production and in $gg\rightarrow H+2j$
    - **Using angular correlations between τ-lepton decay products**
  - Search for LFV $H\rightarrow\mu/e+\tau$ decays
  - Searches for BSM $A/H/h\rightarrow\tau\tau$, $H\rightarrow hh\rightarrow bb\tau\tau$, $A\rightarrow Zh(\rightarrow\tau\tau)$
    - Enhanced sensitivity for high mass due to larger cross section at 13 TeV

Backup Slides

Monte Carlo Samples

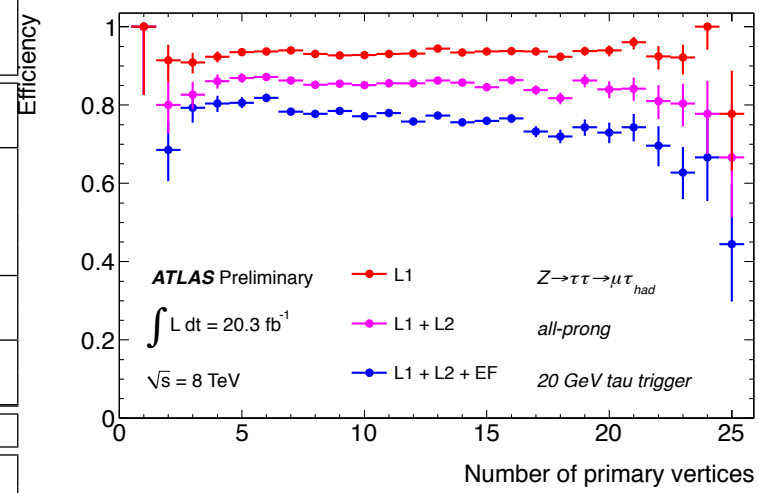
Signal ($m_H = 125$ GeV)	MC generator	$\sigma\times$BR [pb] $\sqrt{s} = 8$ TeV		
ggF, $H \to \tau\tau$	POWHEG [36–39] + PYTHIA8 [40]	1.22	NNLO+NNLL	[42–47, 78]
VBF, $H \to \tau\tau$	POWHEG + PYTHIA8	0.100	(N)NLO	[51–53, 78]
WH, $H \to \tau\tau$	PYTHIA8	0.0445	NNLO	[56, 78]
ZH, $H \to \tau\tau$	PYTHIA8	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	$4.7^\dagger$		

2012 Trigger for Fermionic Higgs Decays

$\sqrt{s} = 7$ 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: $p_T^{e_1} > 15$, $p_T^{e_2} > 15$	–	–
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: $p_T^{e_1} > 26$, $p_T^{e_2} > 15$	$e\tau$: $p_T^e > 26$, $p_T^\tau > 20$	–
Single muon	24	–	$\mu\tau$: $p_T^\mu > 26$, $p_T^\tau > 20$	–
Di-electron	12/12	ee: $p_T^{e_1} > 15$, $p_T^{e_2} > 15$	–	–
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	–	–	$\tau\tau$: $p_T^{\tau_1} > 35$, $p_T^{\tau_2} > 25$

tau trigger largely pileup independent



- Triggers used: single and di-lepton, di-tau
- Offline P_T thresholds are ~2 GeV higher than online thresholds

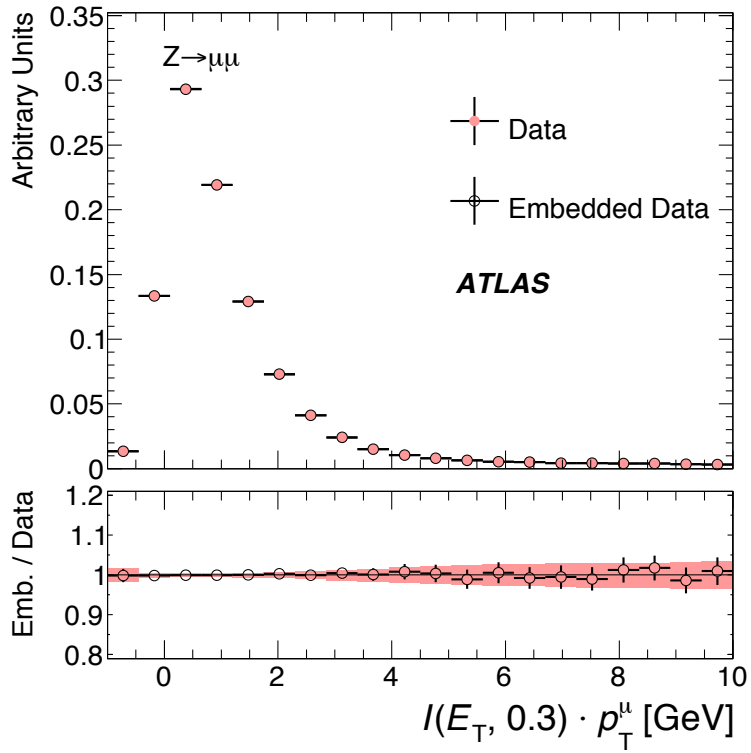
Event Selection

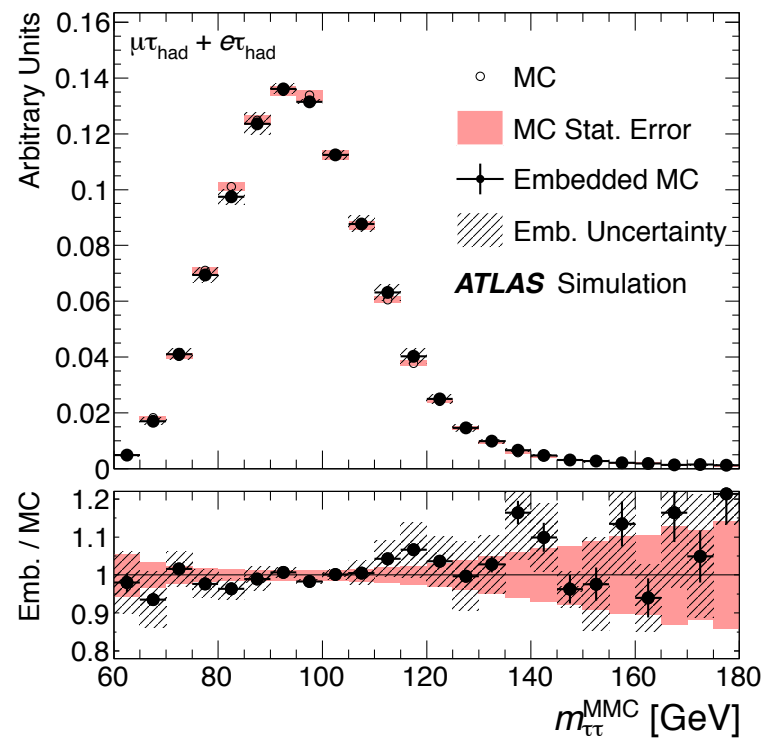
Channel	Preselection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	Exactly two isolated opposite-sign leptons Events with $\tau_{\rm had}$ candidates are rejected 30 GeV$< m_{\tau\tau}^{\rm vis} <$ 100 (75) GeV for DF (SF) events $\Delta\phi_{\ell\ell} < 2.5$ $E_{\rm T}^{\rm miss} >$ 20 (40) GeV for DF (SF) events $E_{\rm T}^{\rm miss,HPTO} >$ 40 GeV for SF events $p_{\rm T}^{\ell_1} + p_{\rm T}^{\ell_2} >$ 35 GeV Events with a b-tagged jet with $p_{\rm T} >$ 25 GeV are rejected $0.1 < x_{\tau_1}, x_{\tau_2} < 1$ $m_{\tau\tau}^{\rm coll} > m_Z -$ 25 GeV
$\tau_{\rm lep}\tau_{\rm had}$	Exactly one isolated lepton and one medium $\tau_{\rm had}$ candidate with opposite charges $m_{\rm T} <$ 70 GeV Events with a b-tagged jet with $p_{\rm T} >$ 30 GeV are rejected
$\tau_{\rm had}\tau_{\rm had}$	One isolated medium and one isolated tight opposite-sign $\tau_{\rm had}$-candidate Events with leptons are vetoed $E_{\rm T}^{\rm miss} >$ 20 GeV $E_{\rm T}^{\rm miss}$ points between the two visible taus in ϕ, or $\min[\Delta\phi(\tau, E_{\rm T}^{\rm miss})] < \pi/4$ $0.8 < \Delta R(\tau_{\rm had_1}, \tau_{\rm had_2}) < 2.4$ $\Delta\eta(\tau_{\rm had_1}, \tau_{\rm had_2}) < 1.5$

Analysis Categories

Channel	VBF category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_{\rm T}^{j_1} > 40$ GeV and $p_{\rm T}^{j_2} > 30$ GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} > 50$ GeV and $p_{\rm T}^{j_2} > 30$ GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\rm vis} > 40$ GeV
$\tau_{\rm had}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} > 50$ GeV and $p_{\rm T}^{j_2} > 30$ GeV $p_{\rm T}^{j_2} > 35$ GeV for jets with $\lvert\eta\rvert > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$
Channel	**Boosted category selection cuts**
$\tau_{\rm lep}\tau_{\rm lep}$	At least one jet with $p_{\rm T} > 40$ GeV
All	Failing the VBF selection $p_{\rm T}^{H} > 100$ GeV

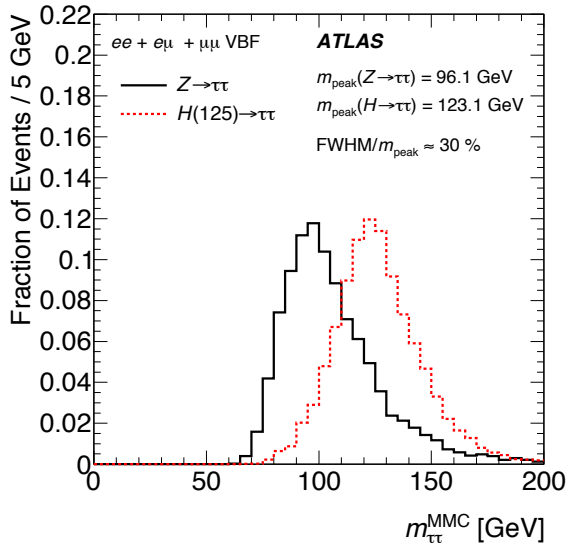
Validation of Z→ττ Embedding

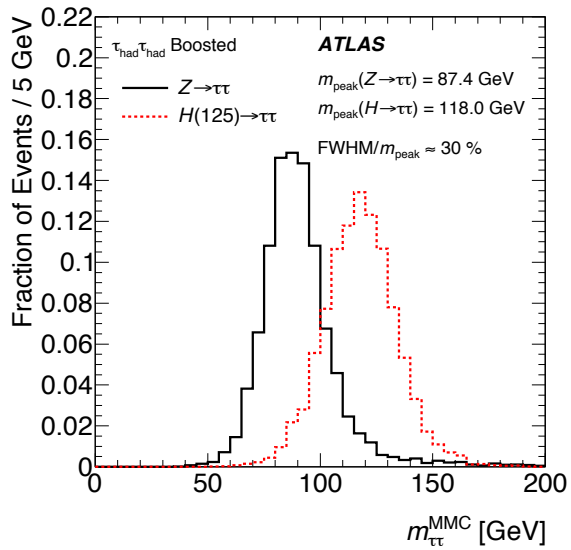


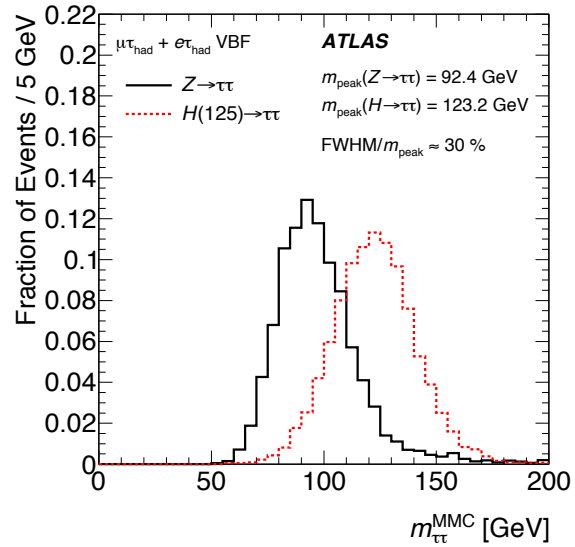


- Comparison of calorimeter isolation in Z→μμ events in data before and after embedding
- Comparison of m(ττ) distribution in MC Z→ττ and in embedded events using MC Z→μμ events

Missing Mass Calculator

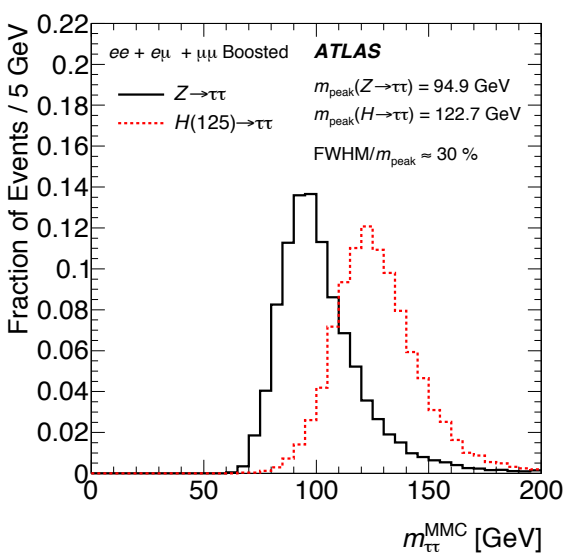


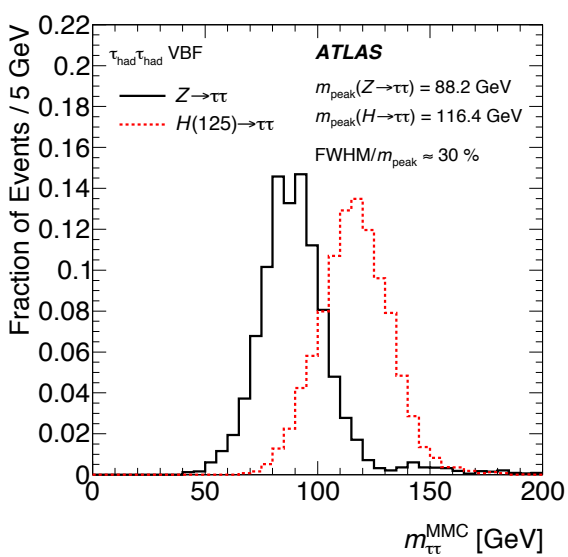


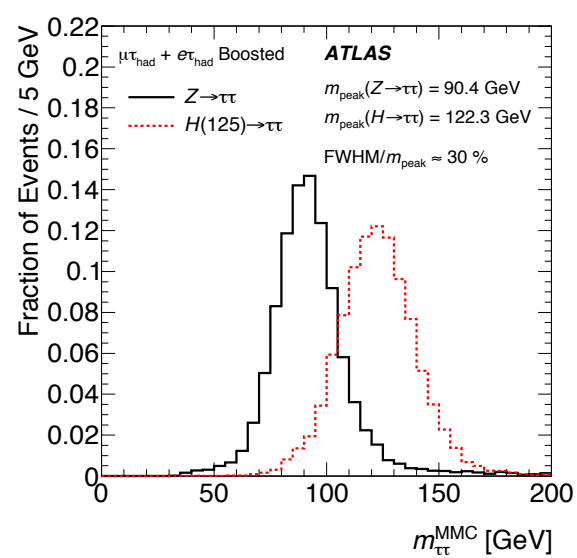


VBF category

Lep-lep channel **Had-had channel** **Lep-had channel**







Boosted category

Input Variables to BDT

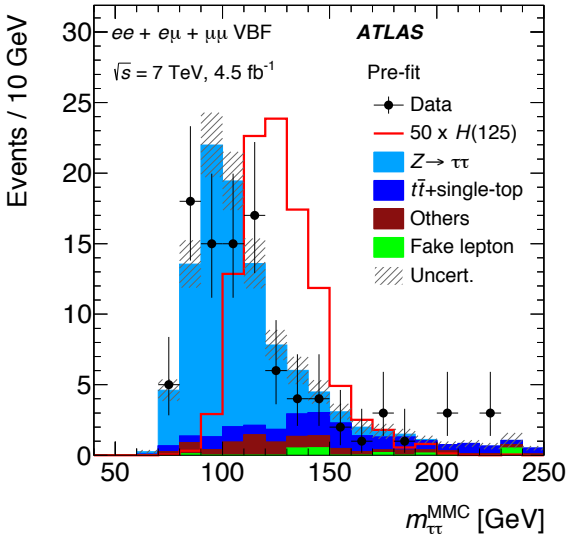
Variable	VBF			Boosted		
	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$
$m_{\tau\tau}^{\rm MMC}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1,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

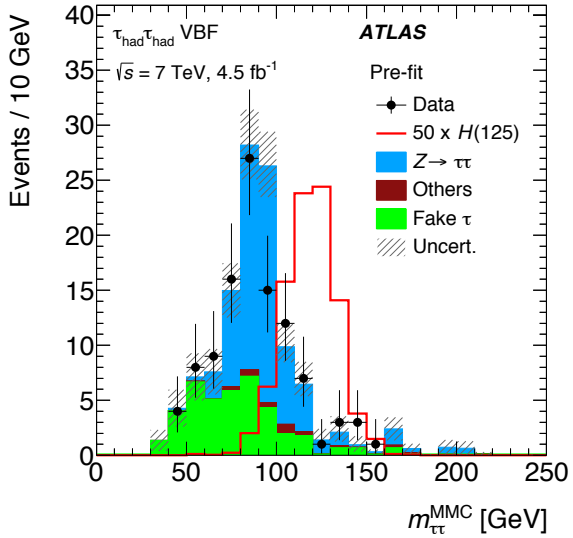
- Resonance properties
  - MMC, $\Delta R(\tau\tau)$, etc
- VBF topology
  - M_{jj}, $\Delta\eta_{jj}$, etc
- Event activity
  - Scalar & vector P_T-sum
- Event topology
  - M_T, object centralities, $P_T(\tau_1)/P_T(\tau_2)$, etc

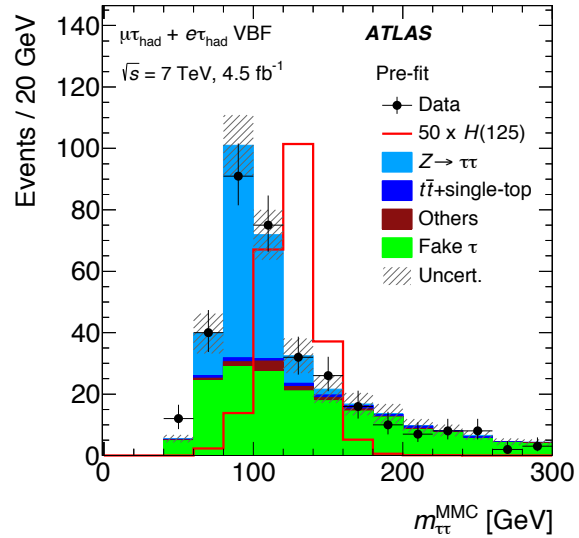
Control Regions

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

MMC Distribution In 7 TeV Data

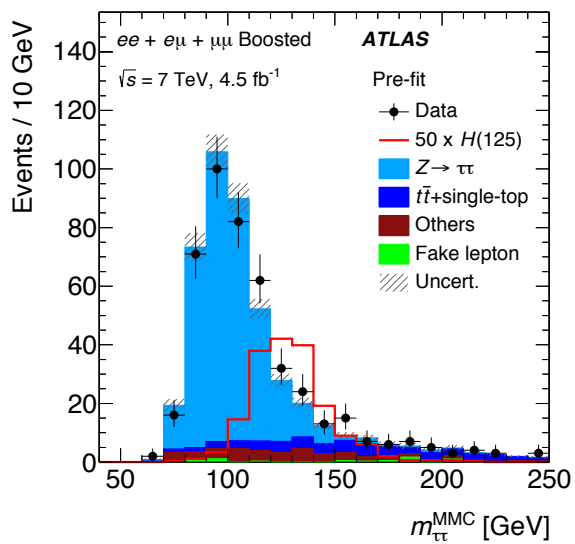


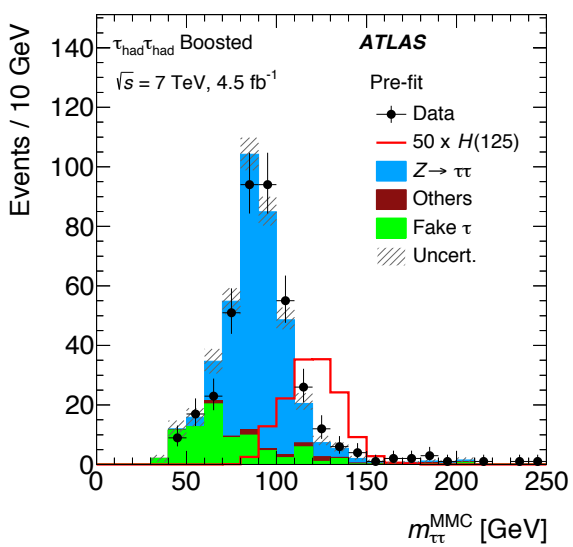


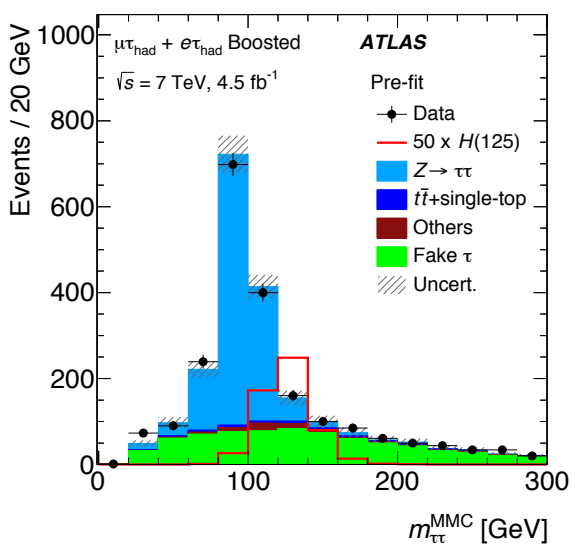


VBF category

Lep-lep channel **Had-had channel** **Lep-had channel**

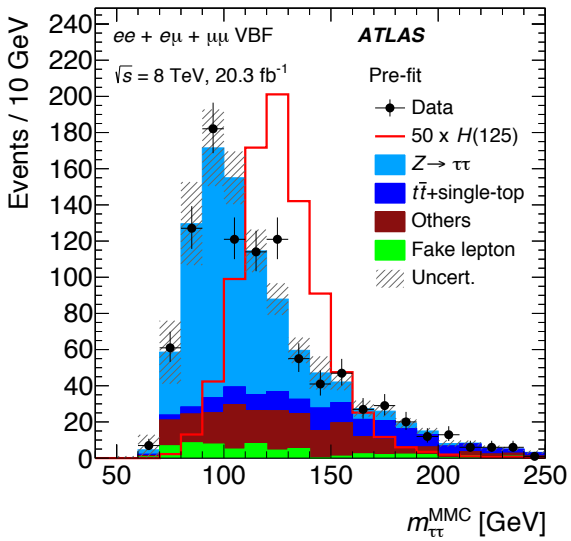




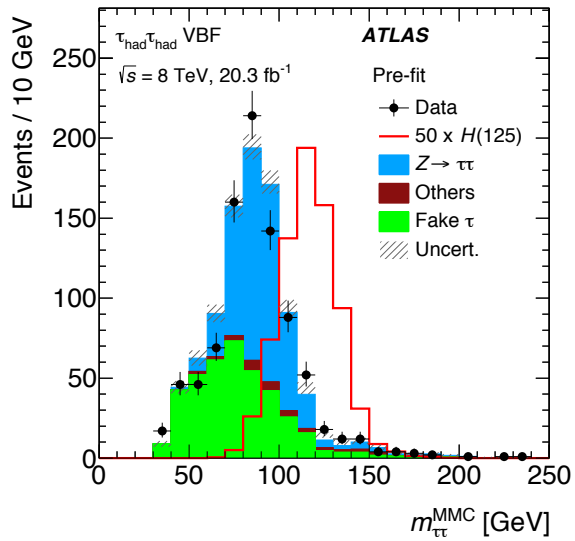


Boosted category

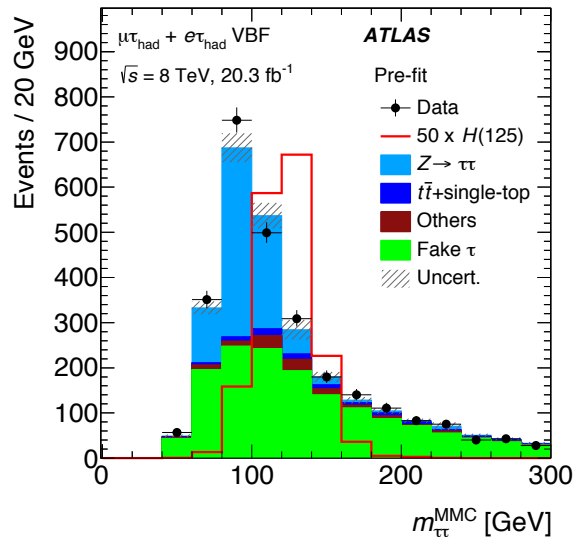
MMC Distribution In 8 TeV Data



Lep-lep channel

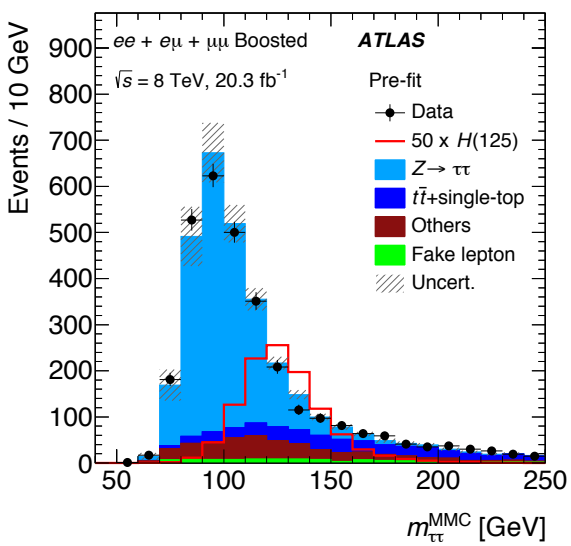


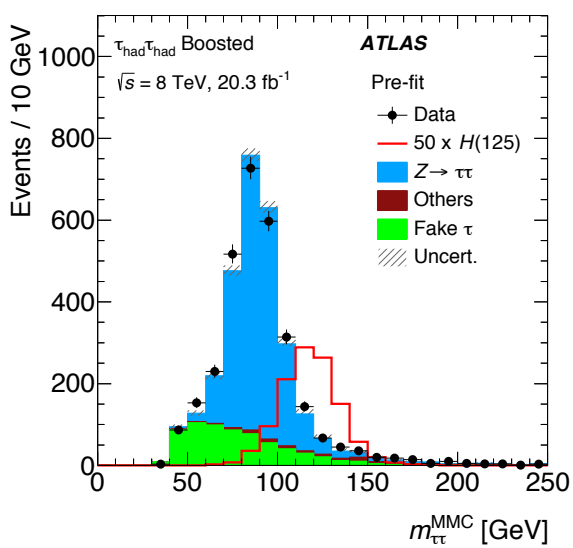
Had-had channel

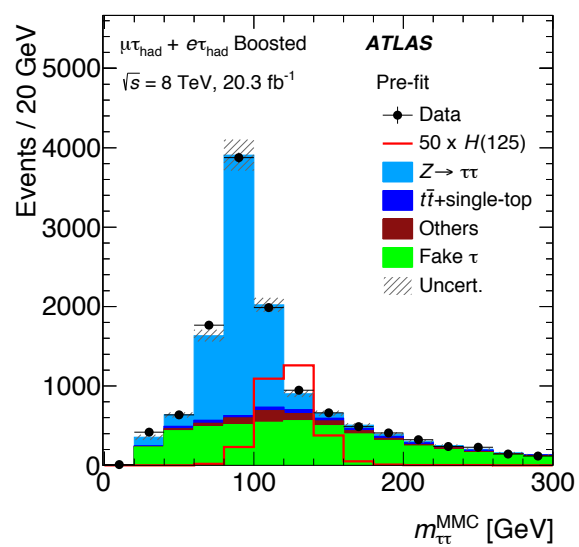


Lep-had channel

VBF category







Boosted category

Events in Highest S/B bins

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: $H \to WW \quad (m_H = 125\ GeV)$	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: $H \to \tau\tau \ (m_H = 125GeV)$	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

Lep-lep channel

Events in Highest S/B bins

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

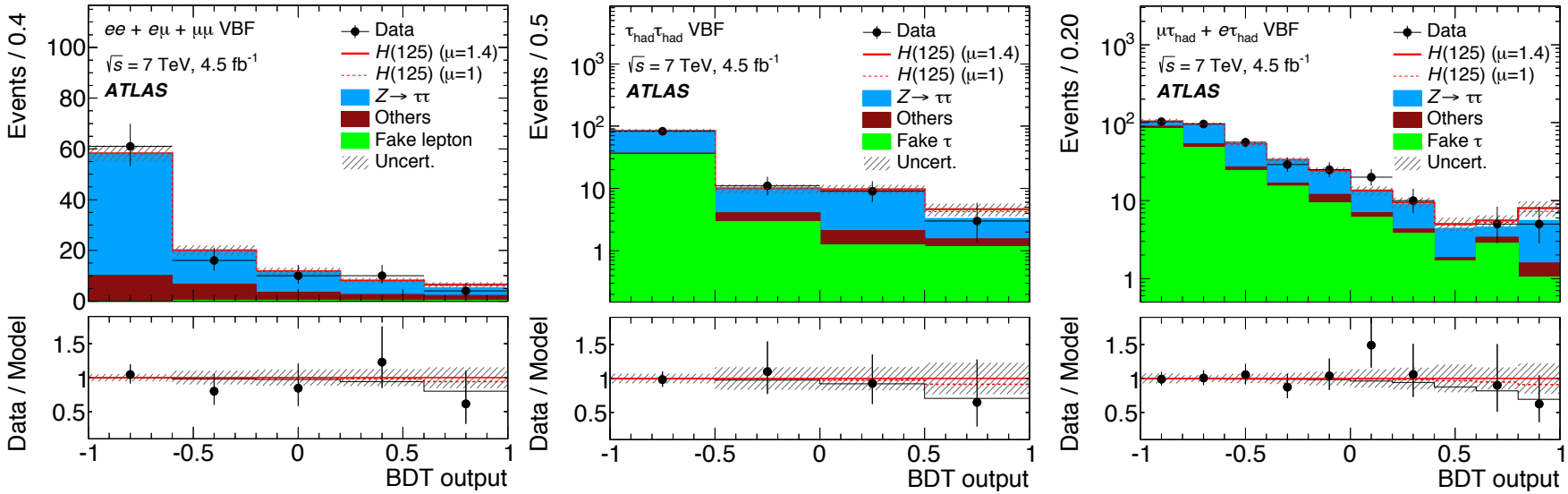
Lep-had channel

Events in Highest S/B bins

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: $H \to \tau\tau$ $(m_H = 125GeV)$	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

Had-had channel

BDT-score Distributions in 7 TeV Data After Fit

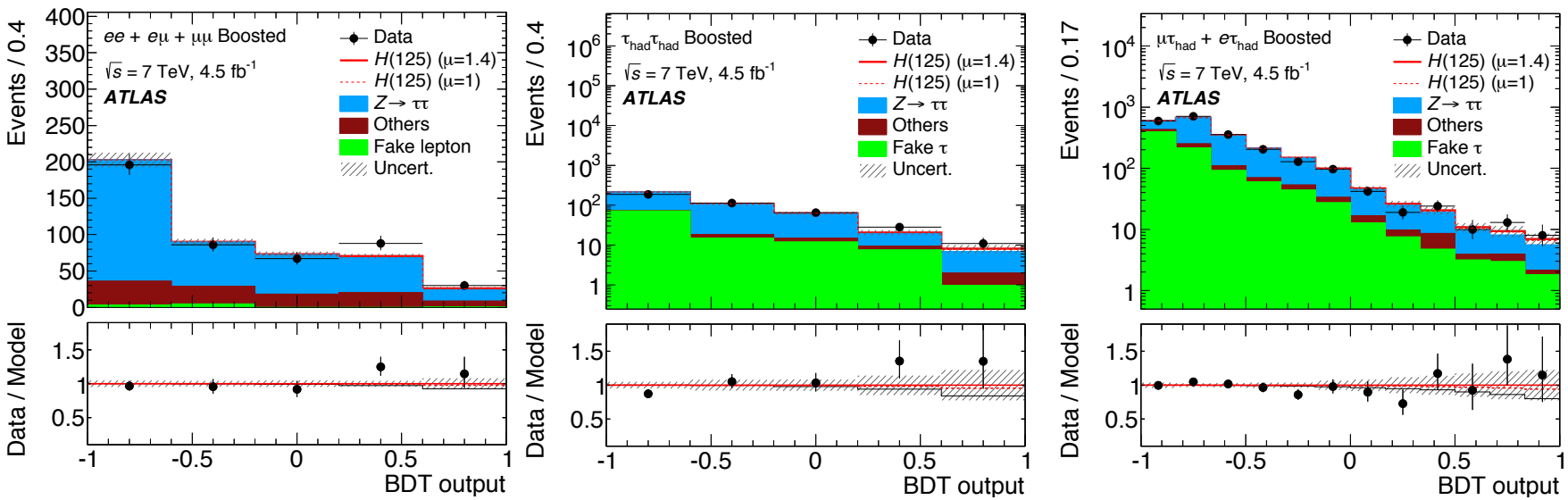


VBF category

Lep-lep channel

Had-had channel

Lep-had channel



Boosted category

Results For MVA Analysis

Signal significance

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

Measured cross section

	Measured $\sigma\times$BR [pb]	Predicted $\sigma\times$BR [pb]
7 TeV	$1.0\ ^{+0.9}_{-0.8}(\text{stat.})^{+0.9}_{-0.8}(\text{syst.})$	1.09 ± 0.11
8 TeV	$2.1 \pm 0.4(\text{stat.})^{+0.5}_{-0.4}(\text{syst.})$	1.39 ± 0.14
Gluon fusion, 8 TeV	$1.7 \pm 1.1(\text{stat.})^{+1.5}_{-1.1}(\text{syst.})$	1.22 ± 0.14
VBF+VH, 8 TeV	$0.26 \pm 0.09(\text{stat.})^{+0.06}_{-0.05}(\text{syst.})$	0.17 ± 0.01

Systematic Uncertainties For 8 TeV Analysis

Source	Relative signal and background variations [%]											
	$\tau_{\rm lep}\tau_{\rm lep}$ VBF		$\tau_{\rm lep}\tau_{\rm lep}$ Boosted		$\tau_{\rm lep}\tau_{\rm had}$ VBF		$\tau_{\rm lep}\tau_{\rm had}$ Boosted		$\tau_{\rm had}\tau_{\rm had}$ VBF		$\tau_{\rm had}\tau_{\rm had}$ Boosted	
	S	B	S	B	S	B	S	B	S	B	S	B
Experimental												
Luminosity	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1	± 2.8	± 0.1
Tau trigger*	–	–	–	–	–	–	–	–	$^{+7.7}_{-8.8}$	< 0.1	$^{+7.8}_{-8.9}$	< 0.1
Tau identification	–	–	–	–	± 3.3	± 1.2	± 3.3	± 1.8	± 6.6	± 3.8	± 6.6	± 5.1
Lepton ident. and trigger*	$^{+1.4}_{-2.1}$	$^{+1.3}_{-1.7}$	$^{+1.4}_{-2.1}$	$^{+1.1}_{-1.5}$	± 1.8	± 0.5	± 1.8	± 0.8	–	–	–	–
b-tagging	± 1.3	± 1.6	± 1.6	± 1.6	< 0.1	± 0.2	± 0.4	± 0.2	–	–	–	–
τ energy scale†	–	–	–	–	± 2.4	± 1.3	± 2.4	± 0.9	± 2.9	± 2.5	± 2.9	± 2.5
Jet energy scale and resolution†	$^{+8.5}_{-9.1}$	± 9.2	$^{+4.7}_{-4.9}$	$^{+3.7}_{-3.0}$	$^{+9.5}_{-8.7}$	± 1.0	± 3.9	± 0.4	$^{+10.1}_{-8.0}$	± 0.3	$^{+5.1}_{-6.2}$	± 0.2
$E_{\rm T}^{\rm miss}$ soft scale & resolution	$^{+0.0}_{-0.2}$	$^{+0.0}_{-1.2}$	$^{+0.0}_{-0.1}$	$^{+0.0}_{-1.2}$	$^{+0.8}_{-0.3}$	± 0.2	± 0.4	< 0.1	± 0.5	± 0.2	± 0.1	< 0.1
Background Model												
Modelling of fake backgrounds*†	–	± 1.2	–	± 1.2	–	± 2.6	–	± 2.6	–	± 5.2	–	± 0.6
Embedding†	–	$^{+3.8}_{-4.3}$	–	$^{+6.0}_{-6.5}$	–	± 1.5	–	± 1.2	–	± 2.2	–	± 3.3
$Z \to \ell\ell$ normalisation*	–	± 2.1	–	± 0.7	–	–	–	–	–	–	–	–
Theoretical												
Higher-order QCD corrections †	$^{+11.3}_{-9.1}$	± 0.2	$^{+19.8}_{-15.3}$	± 0.2	$^{+9.7}_{-7.6}$	± 0.2	$^{+19.3}_{-14.7}$	± 0.2	$^{+10.7}_{-8.2}$	< 0.1	$^{+20.3}_{-15.4}$	< 0.1
UE/PS	± 1.8	< 0.1	± 5.9	< 0.1	± 3.8	< 0.1	± 2.9	< 0.1	± 4.6	< 0.1	± 3.8	< 0.1
Generator modelling	± 2.3	< 0.1	± 1.2	< 0.1	± 2.7	< 0.1	± 1.3	< 0.1	± 2.4	< 0.1	± 1.2	< 0.1
EW corrections	± 1.1	< 0.1	± 0.4	< 0.1	± 1.3	< 0.1	± 0.4	< 0.1	± 1.1	< 0.1	± 0.4	< 0.1
PDF †	$^{+4.5}_{-5.8}$	± 0.3	$^{+6.2}_{-8.0}$	± 0.2	$^{+3.9}_{-3.6}$	± 0.2	$^{+6.6}_{-6.1}$	± 0.2	$^{+4.3}_{-4.0}$	± 0.2	$^{+6.3}_{-5.8}$	± 0.1
BR ($H \to \tau\tau$)	± 5.7	–	± 5.7	–	± 5.7	–	± 5.7	–	± 5.7	–	± 5.7	–

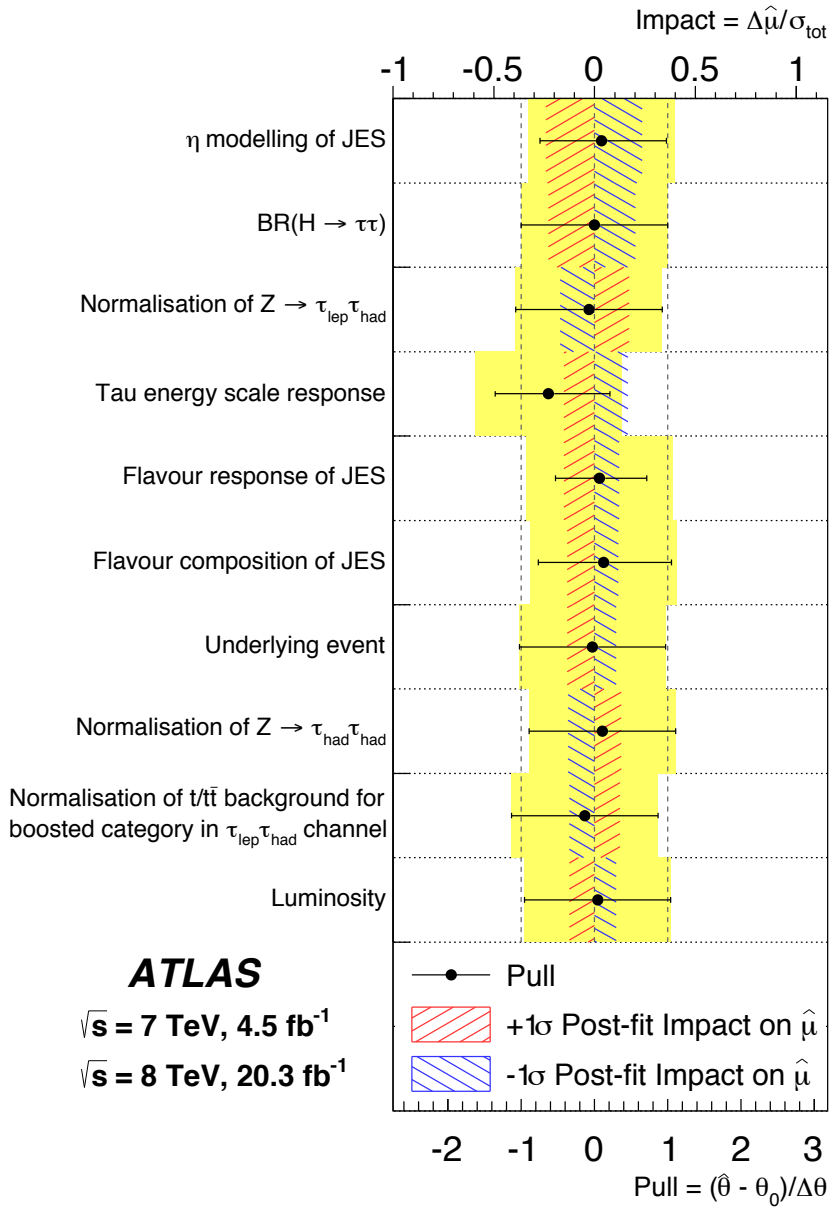
Leading Uncertainties

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	$^{+0.43}_{-0.37}$

$$Signal\ strength\ \mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$

- Leading theory uncertainty is due to BR(H→ττ): Δμ/μ~5.7%
- Leading experimental uncertainties are due to jet energy scale and background normalization: Δμ/μ~8.6-9.3%

Ranking Of Nuisance Parameters



Theory Systematic Uncertainties on Signal

- Uncertainty on NLO EWK corrections in VBF+VH: ±2%
- QCD scale uncertainty
  - VBF & VH: ±2% to ±4%, vary $\mu_R = \mu_F = M_W$ by factor of 2 up/down
  - ggF: ±24% (±23%) Boosted (VBF) category
    - vary $\mu_R = \mu_F = (M_H^2 + p_T^2)^{1/2}$ by factor of 2 up/down in NLO calculations of H+1j & H+2j
- Modeling of ggF H+3j events in VBF category
  - No explicit 3rd jet veto, but enough information to suppress ggF H+3j events
  - Scale variations in LO H+3j calculations by MCFM
  - About ±30% variation in highest BDT score bin for ggF contribution
- PDF choice:
  - CT10 uncertainties; compare CT10 to MSTW2008NLO and NNPDF
  - ±4.5% to ±6% for ggF; ±0.8% to ±1.0% for VBF
- Effects of underlying event and parton shower modeling
  - Compare Powheg+Herwig and Powheg+Pythia
  - VBF: ±1% to ±8% depending on channel and category
  - ggF: ±1% to ±9% depending on channel and category
- Choice of MC generator: ±2% (±4%) for ggF (VBF)
  - compare Powheg+Herwig to MC@NLO+Herwig (AMC@NLO+Herwig) for ggF (VBF)
- BR($H \to \tau\tau$): ±5.7%

Cut-Based Analysis: Event Selection

Channel	VBF category selection criteria		
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_{\rm T}^{j_1} > 40$ GeV and $p_{\rm T}^{j_2} > 30$ GeV $\lvert\Delta\eta_{j_1,j_2}\rvert > 3.0$ $m_{j_1,j_2} > 400$ GeV b-jet veto for jets with $p_{\rm T} > 25$ GeV Jet veto: no additional jet with $p_{\rm T} > 25$ GeV within $\lvert\eta\rvert < 2.4$		
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} > 40$ GeV and $p_{\rm T}^{j_2} > 30$ GeV $E_{\rm T}^{\rm miss} > 20$ GeV $\lvert\Delta\eta_{j_1,j_2}\rvert > 3.0$ and $\eta(j_1)\cdot\eta(j_2) < 0$, $m_{j_1,j_2} > 300$ GeV $p_{\rm T}^{\rm Total} = \lvert\vec{p}_{\rm T}^{\ell} + \vec{p}_{\rm T}^{\tau_{\rm had}} + \vec{p}_{\rm T}^{j_1} + \vec{p}_{\rm T}^{j_2} + \vec{E}_{\rm T}^{\rm miss}\rvert < 30$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 $p_{\rm T}^{j_1} > 50$ GeV and $p_{\rm T}^{j_2} > 30$ GeV $\lvert\Delta\eta(\tau_1,\tau_2)\rvert < 1.5$ $\lvert\Delta\eta_{j_1,j_2}\rvert > 2.6$ 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}[GeV] $> (-250 \cdot \lvert\Delta\eta_{\rm j_1,j_2}\rvert + 1550)$	**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}[GeV] $< (-250 \cdot \lvert\Delta\eta_{\rm j_1,j_2}\rvert + 1550)$

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

$\tau_{\rm lep}\tau_{\rm lep}$	VBF	Boosted
Total signal	11 ± 4	38 ± 13
Total background	130 ± 7	3400 ± 64
Data	152	3428

$\tau_{\rm lep}\tau_{\rm had}$	Tight VBF	Loose VBF	Boosted
Signal	8.8 ± 3	17 ± 6	52 ± 17
Background	52 ± 4	398 ± 17	4399 ± 73
Data	62	407	4435

$\tau_{\rm had}\tau_{\rm had}$	VBF high $p_{\rm T}^{H}$	VBF low $p_{\rm T}^{H}$		Boosted	
		tight	loose	high $p_{\rm T}^{H}$	low $p_{\rm T}^{H}$
Signal	5.7 ± 1.9	5.2 ± 1.9	3.7 ± 1.3	17 ± 6	20 ± 7
Background	59 ± 4	86 ± 5	156 ± 7	1155 ± 28	2130 ± 41
Data	65	94	157	1204	2121

Cut-Based Analysis: Results

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