Higgs to $\tau^+\tau^-$ in ATLAS (SM+BSM)

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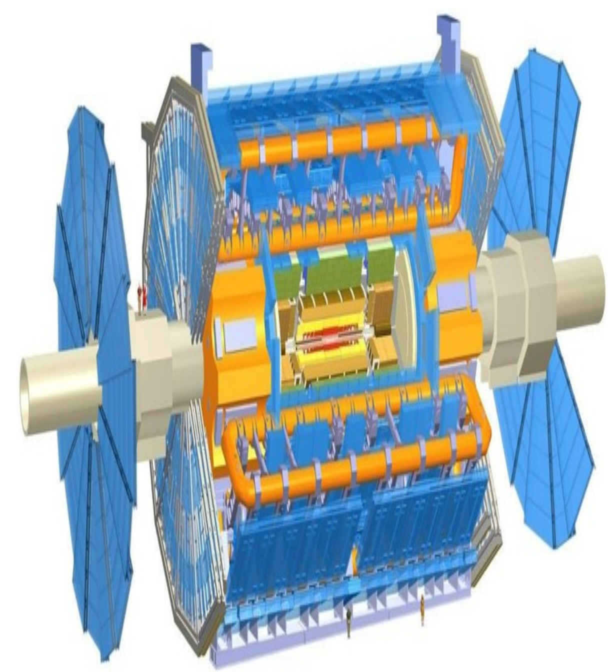
On behalf of the ATLAS Collaboration



Higgs Hunting 2013

July 25-27, Orsay-France

Outline

First of all:

in this talk BSM = MSSM

1) Common aspects to SM and MSSM Higgs $\rightarrow \tau\tau$ analyses

2) SM $H \rightarrow \tau\tau$ analysis

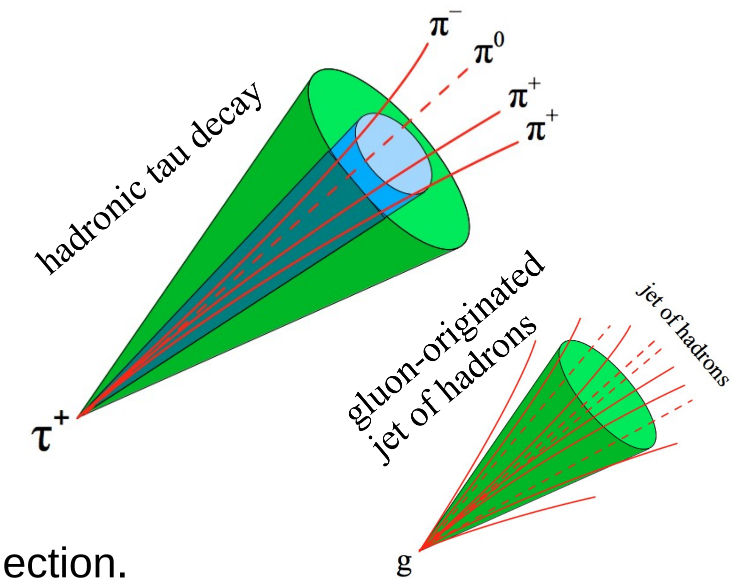
3) MSSM $h/A/H \rightarrow \tau\tau$ analysis

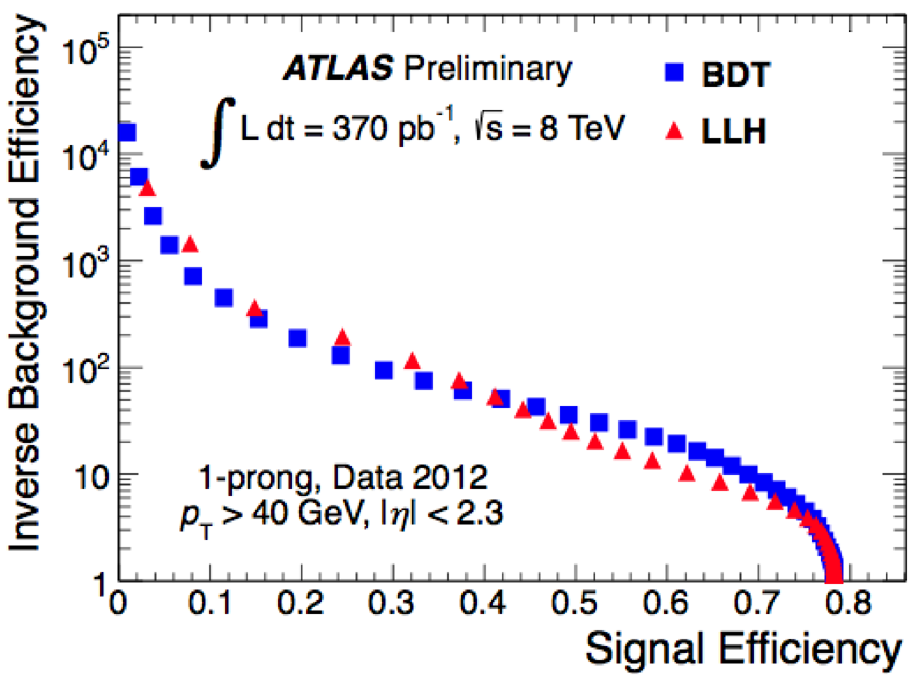
4) Summary

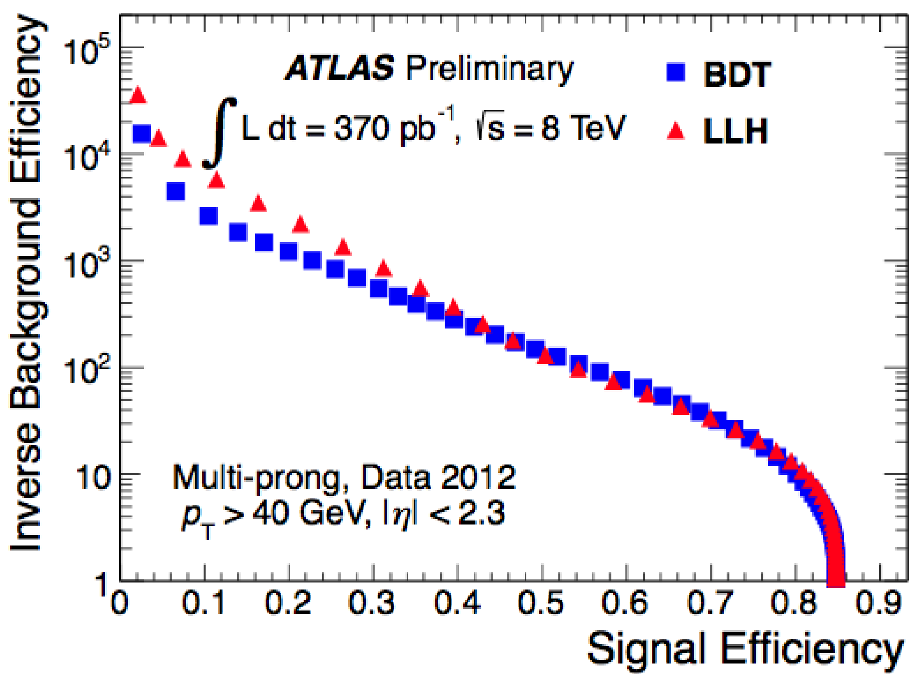
Reconstruction and identification of hadronic τ decays

- τ decay BR:
  - 35% leptonic ($\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$, ...) — "$\tau_{lep}$"
  - 50% hadronic 1-prong ($\tau^+ \to \pi^+ \pi^0 \bar{\nu}_\tau$, ...) — "$\tau_{had}$"
  - 15% hadronic 3-prong ($\tau^+ \to \pi^+ \pi^+ \pi^- \bar{\nu}_\tau$, ...) — "$\tau_{had}$"
- τ_{had} signature very similar to QCD jets (big background).
- τ_{had} characterization: low track multiplicity, narrowness, isolation.
- Dedicated τ_{had} triggers.
- Offline ID using Boosted Decision Trees and Log-LikeliHood:

  "Medium" working point: 50% signal efficiency, factor >30 in jet rejection.







Analysis strategy

Preselection

Channel-specific trigger + object selection + basic event selection. (Details in backup slides)

↓

Categorization

Channel-specific classification of events into mutually exclusive categories according to event topologies.

Each category targets one specific Higgs production process.

↓

(Farther) background suppression

Channel- and category-specific event selection to suppress the respective backgrounds.

↓

Discriminant distributions

Use $\tau\tau$ invariant mass as discriminant.

↓

Statistical analysis

Extract limit on Higgs cross section, probability of background fluctuation, model parameters, etc.

Reconstruction of the $\tau\tau$ invariant mass

- Invariant mass of $\tau\tau$ system can not be reconstructed directly due to presence of neutrinos.

Effective mass

- $m_{\tau\tau}^{eff} = \sqrt{(\vec{p}(l_1)+\vec{p}(l_2)+\vec{E}_T^{miss})^2}$

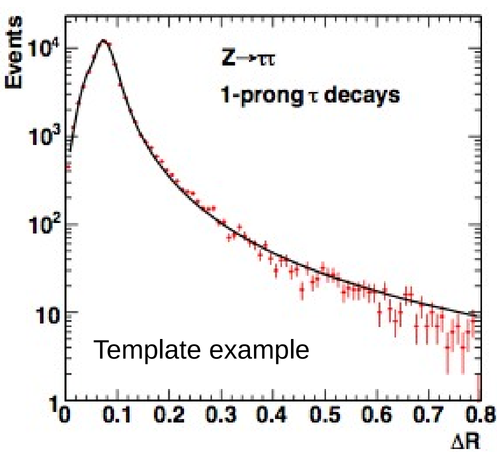
used in SM $\tau_{lep}\tau_{lep}$ channel for 7 TeV data

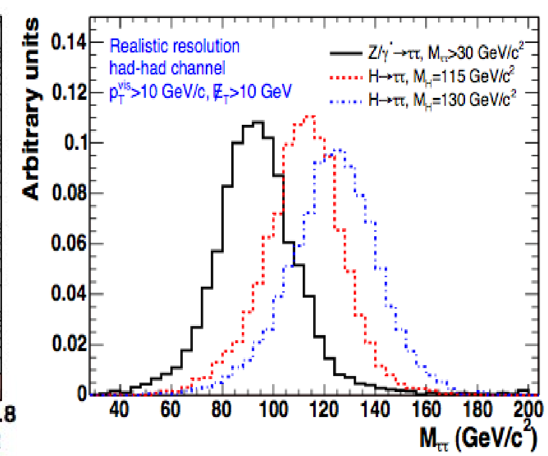
Collinear mass

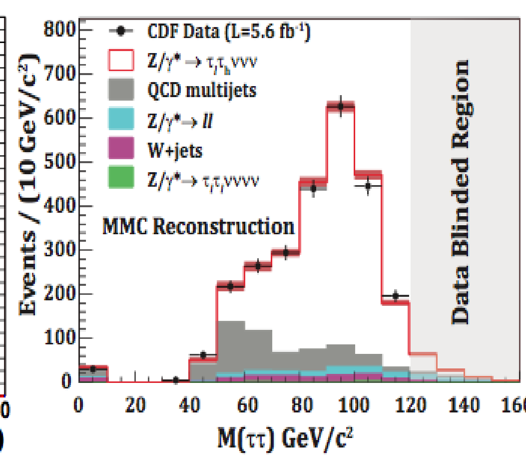
- Assumes momentum from neutrino(s) of a τ decay has same direction as visible momentum.

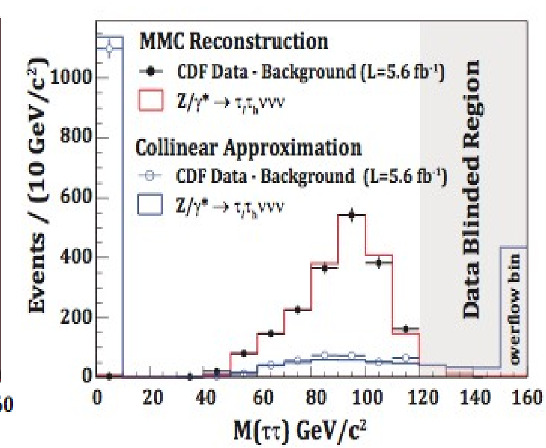
Missing Mass Calculator (MMC)

- Provides reconstruction of event kinematics in a $\tau\tau$ final state with ~99% efficiency.
- Reconstructs p^{miss} for each τ decay using all kinematic constraints and performing a scan over the undetermined variables (and on the E_T^{miss} resolution).
- Assigns a probability to each outcome based on pdf's from simulated τ decays.
- Takes the mass that maximizes the probability.
- Mass resolution 13-20% (better resolution for hadronic decays and for events with high-p_T jets).







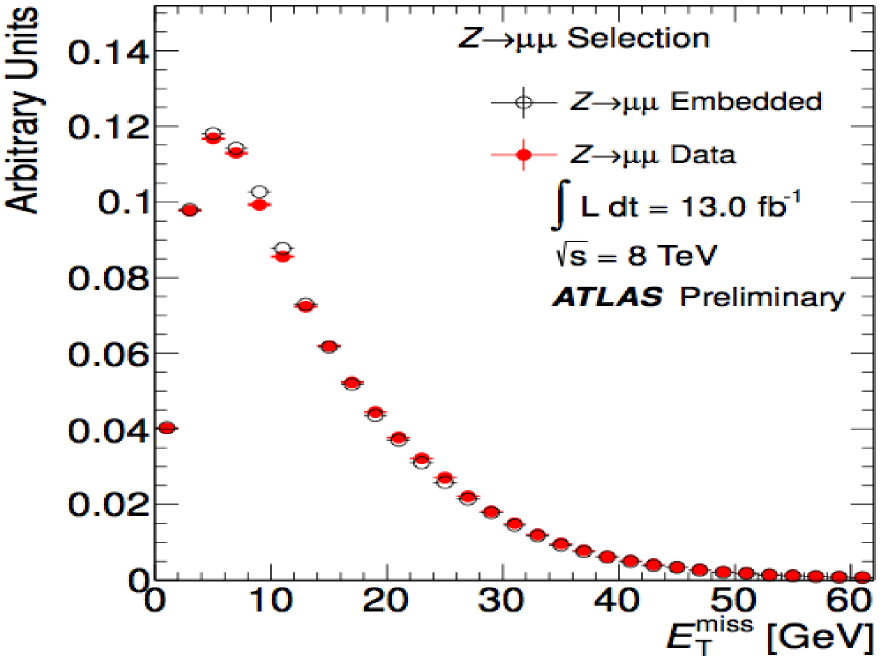


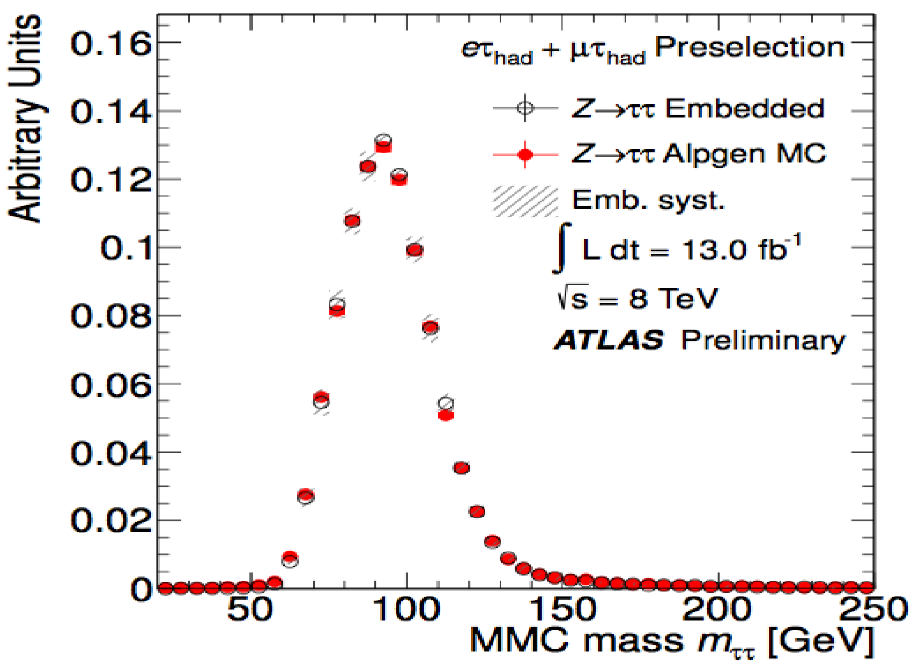
$Z/\gamma^* \to \tau\tau$ background modelling

Embedding technique

- Data-driven: consider a $Z/\gamma^* \to \mu\mu$ data sample. Same event kinematics as $Z/\gamma^* \to \tau\tau$, with negligible Higgs contamination.
- Remove μ from data; replace by τ from simulated $Z/\gamma^* \to \tau\tau$ decay with same kinematics. τ decays well understood (TAUOLA).
- Advantage: only τ decays from simulation, rest of event is just data.
  ⇨ Reduced systematic uncertainties.
- Systematic uncertainties from varying $Z/\gamma^* \to \mu\mu$ selection (isolation cuts) and μ energy subtraction procedure, and from μ acceptance effects (fiducial tracking range, trigger and reconstruction efficiencies).

- Embedding procedure validation: embedding muons instead of taus shows no bias (up-right).
- Comparison to $Z/\gamma^* \to \tau\tau$ Alpgen MC gives good agreement in all channels (down-right).





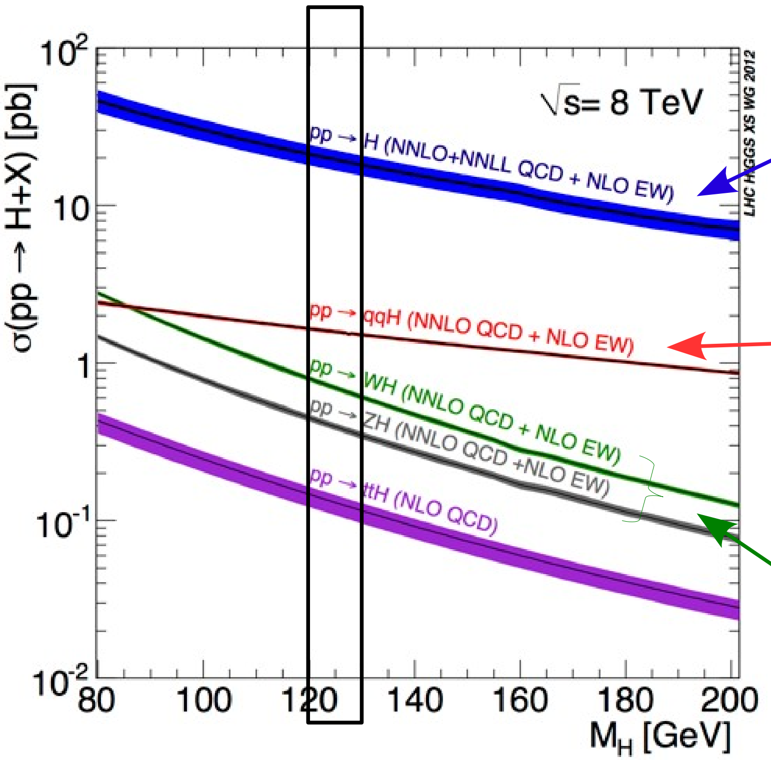
SM $H \rightarrow \tau\tau$

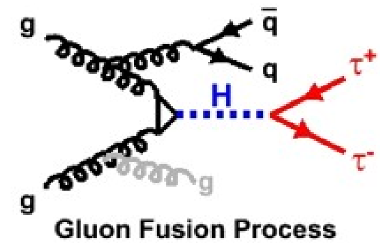
- Analysis based on:

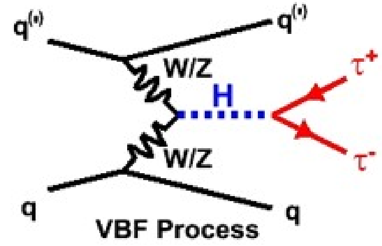
  4.6 fb^{-1} of ATLAS data at $\sqrt{s}$ = 7 TeV (full 7 TeV data set)

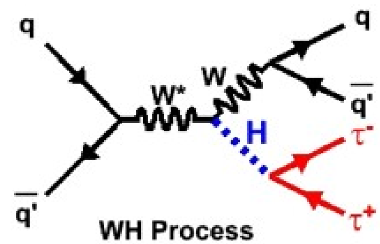
  13.0 fb^{-1} of ATLAS data at $\sqrt{s}$ = 8 TeV (>½ of the 8 TeV data set)

- All $\tau\tau$ decay modes included: $\tau_{lep}\tau_{lep}$ 12%, $\tau_{lep}\tau_{had}$ 46%, $\tau_{had}\tau_{had}$ 42%.
- Several different categories → 25 experimental sub-channels.









Gluon Fusion (~19pb)

Dominant process.

Can exploit high p_T Higgs,

or association with jets.

Vector Boson Fusion (~1.5pb)

Has the cleanest signature.

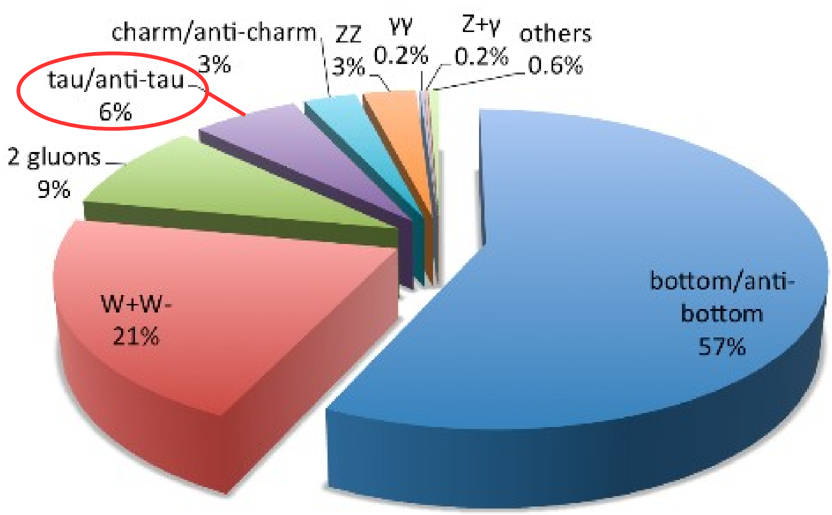
Associate with W/Z

Very important to study Higgs coupling to weak bosons.

Here only hadronic decays of W/Z are considered.

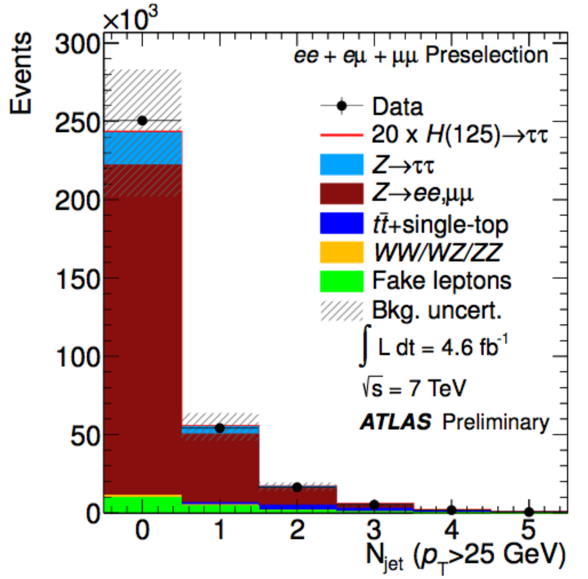
Associate with $t\bar{t}$: Neglected.

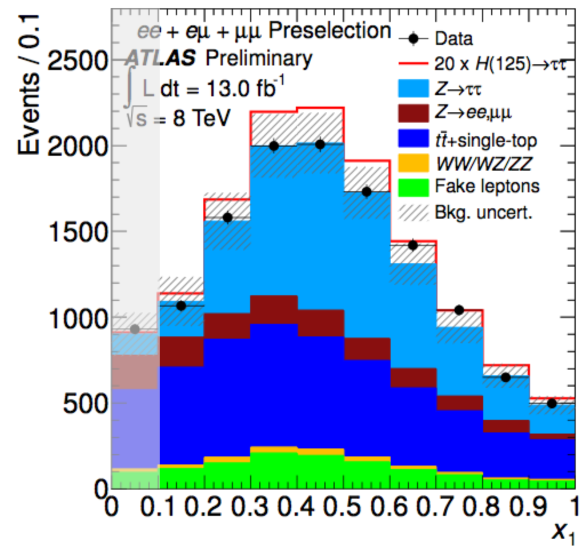
Decays of a 125 GeV Standard-Model Higgs boson

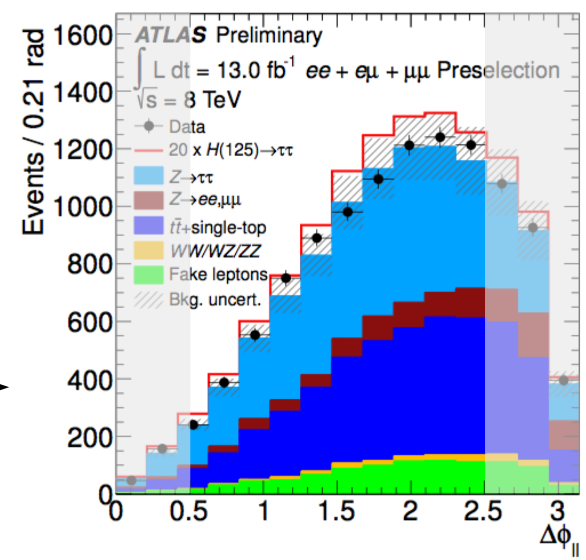


- $H \to \tau\tau$ important to probe Higgs coupling to fermions.
- $H \to \tau\tau$ only 6% BR, but can trigger on τ_{had}, so all τ decay modes can be used, in all H production modes.
- Sensitivity reduced because not a clean channel:
  - τ_{had} reconstruction challenging,
  - $Z/\gamma^* \to \tau\tau$ largely irreducible background.

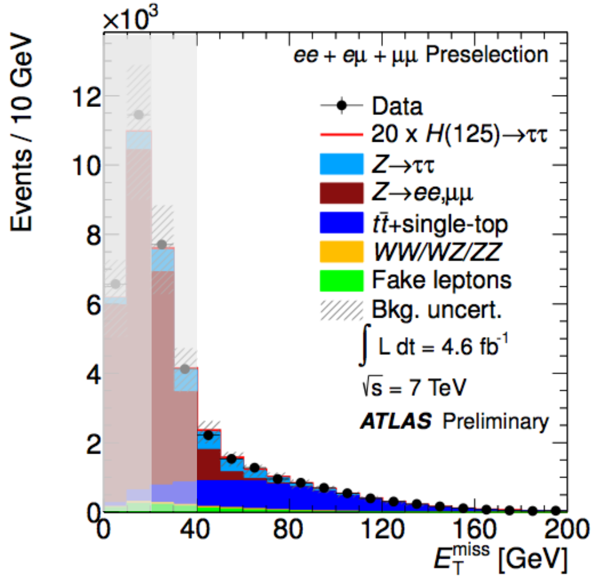
Event selection example in $H \rightarrow \tau_{lep}\tau_{lep}$

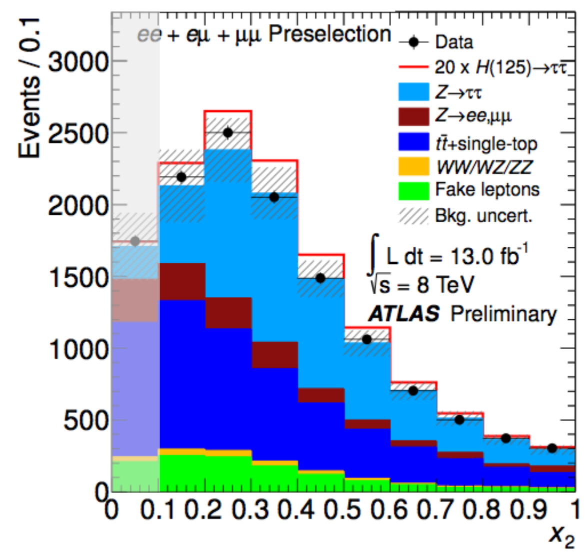


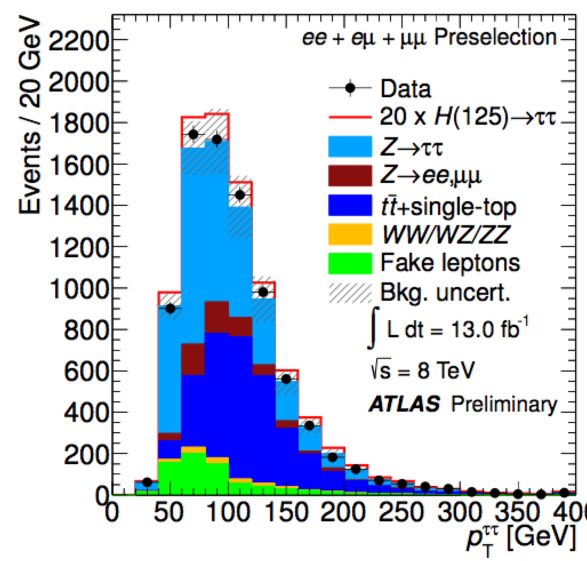




$0.5 < \Delta\phi_{ll} < 2.5$







$E_T^{miss} > 20\ (40)$ GeV

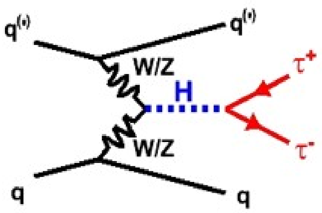
for $e\mu$ (ee and $\mu\mu$)

$0.1 < X_1, x_2 < 1.0$

x_i = visible momentum fraction of τ lepton

Categorization

VBF



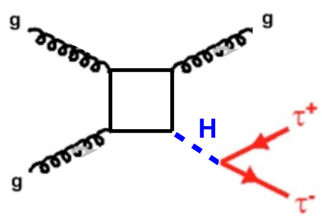
At least 2 jets (with minimum p_T cuts between 30 and 50 GeV)

Large gap in η between the two leading jets,

and large invariant mass m_{jj} (>350-500 GeV)

$e/\mu/\tau_{had}$ in between these two jets in η

boosted



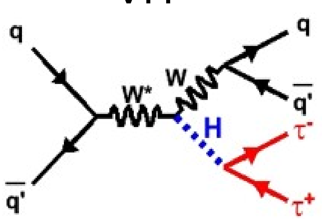
Boosted category takes advantage of better $\tau\tau$ mass resolution for high-p_T objects

Not in VBF

$p_T(H)$ > 100 GeV ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$), leading jet p_T > 50-70 GeV ($\tau_{had}\tau_{had}$)

At least 1 jet with p_T > 40 GeV ($\tau_{lep}\tau_{lep}$)

VH



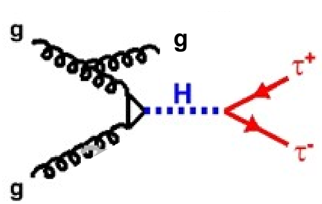
Only defined in $\tau_{lep}\tau_{lep}$

Not in VBF or boosted

At least 2 jets

Small gap in η between the two leading jets

1-jet



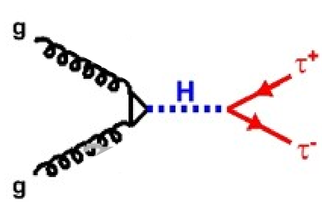
Not defined in $\tau_{had}\tau_{had}$

Not in VBF, boosted or VH

At least 1 jet

$p_T(j_1)$ > 25-40 GeV

0-jet



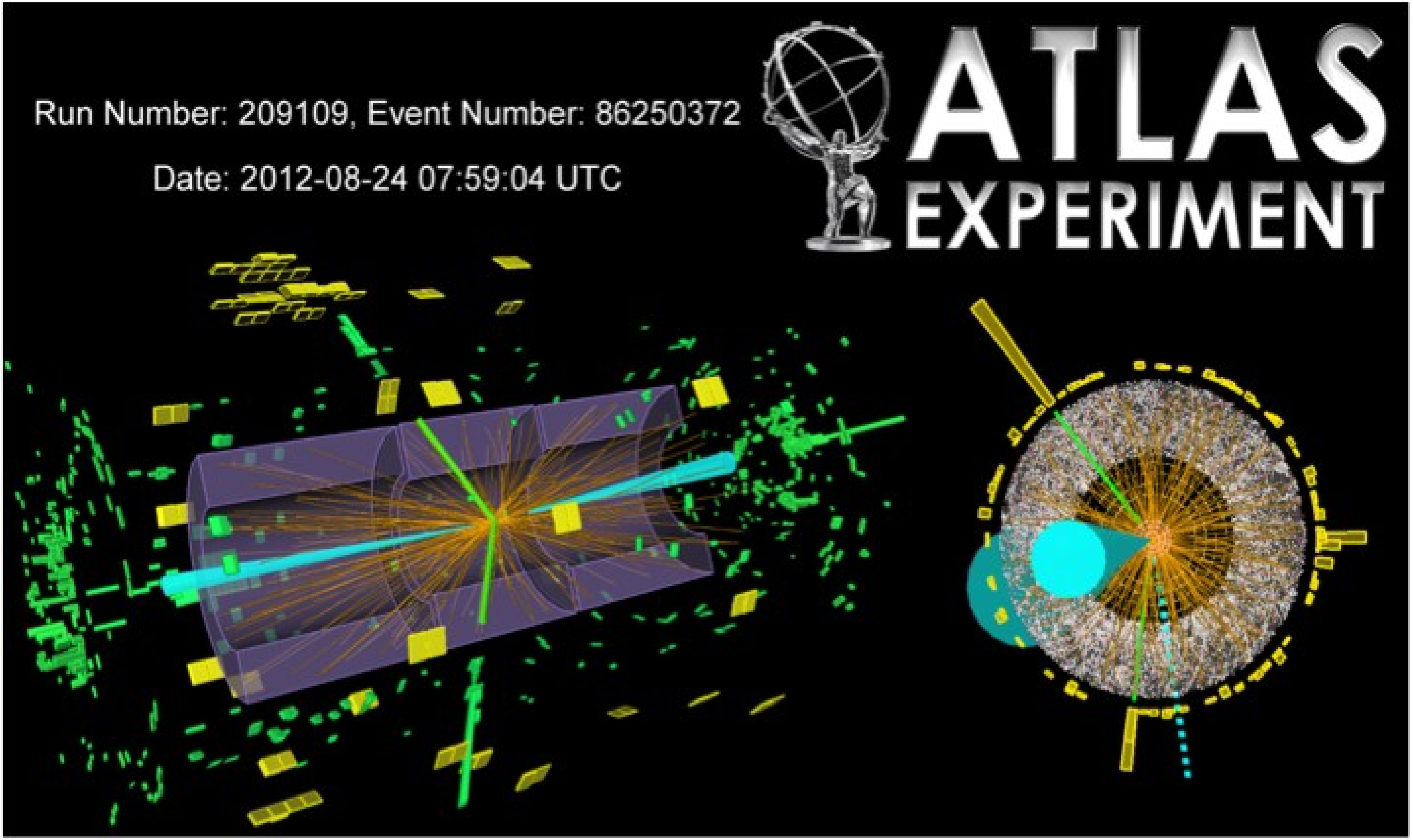
Not defined in $\tau_{had}\tau_{had}$

and in 7 TeV $\tau_{lep}\tau_{lep}$

Not in VBF, boosted, VH or 1-jet

0 jets with p_T > 25-30 GeV

VBF H $\to \tau_{had}\tau_{had}$ candidate event



Display of an event selected by the $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$ analysis in the VBF category. The τ_{had} candidates are indicated by green tracks. The dashed line represents the direction of the $E_{\mathrm{T}}^{\mathrm{miss}}$ vector, and there are two VBF jets marked with turquoise cones. The transverse momenta of the τ_{had} candidates are 56 GeVand 49 GeV, $E_{\mathrm{T}}^{\mathrm{miss}} = 26$ GeV, $m_{jj} = 408$ GeV and $m_{MMC} = 131$ GeV.

Main backgrounds

Each channel affected by different backgrounds !! ⇨ Cuts optimized separately.

Main backgrounds in each channel

	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
physics backgrounds			
$Z/\gamma^* \rightarrow \tau\tau$	●	●	●
$t\bar{t}$ (VBF, boosted)	●	●	
$Z/\gamma^* \rightarrow ee,\mu\mu$	●		
instrumental backgrounds			
multi-jets	●	●	●
$Z/\gamma^* \rightarrow ee$ ($e \rightarrow \tau_{had}$)		●	
$Z/\gamma^*(\rightarrow ee,\mu\mu)$+jet (jet$\rightarrow\tau_{had}$)		●	
$W(\rightarrow l\nu)$+jet (jet$\rightarrow\tau_{had}$)		●	
$W(\rightarrow l\nu)$+jet (jet$\rightarrow e,\mu$)	●		

Smaller backgrounds from single-top and di-bosons.

Suppression cuts (a few examples)

(Complete list of cuts in backup slides 34-36)

largely irreducible / rely on di-tau invariant mass

b-jet veto (not needed in 7 TeV $\tau_{lep}\tau_{had}$)

m_{ll} < 75 GeV

dedicated cuts on τ_{had} candidate (0-jet & 1-jet ctgs.)

m_T < 30-50 GeV

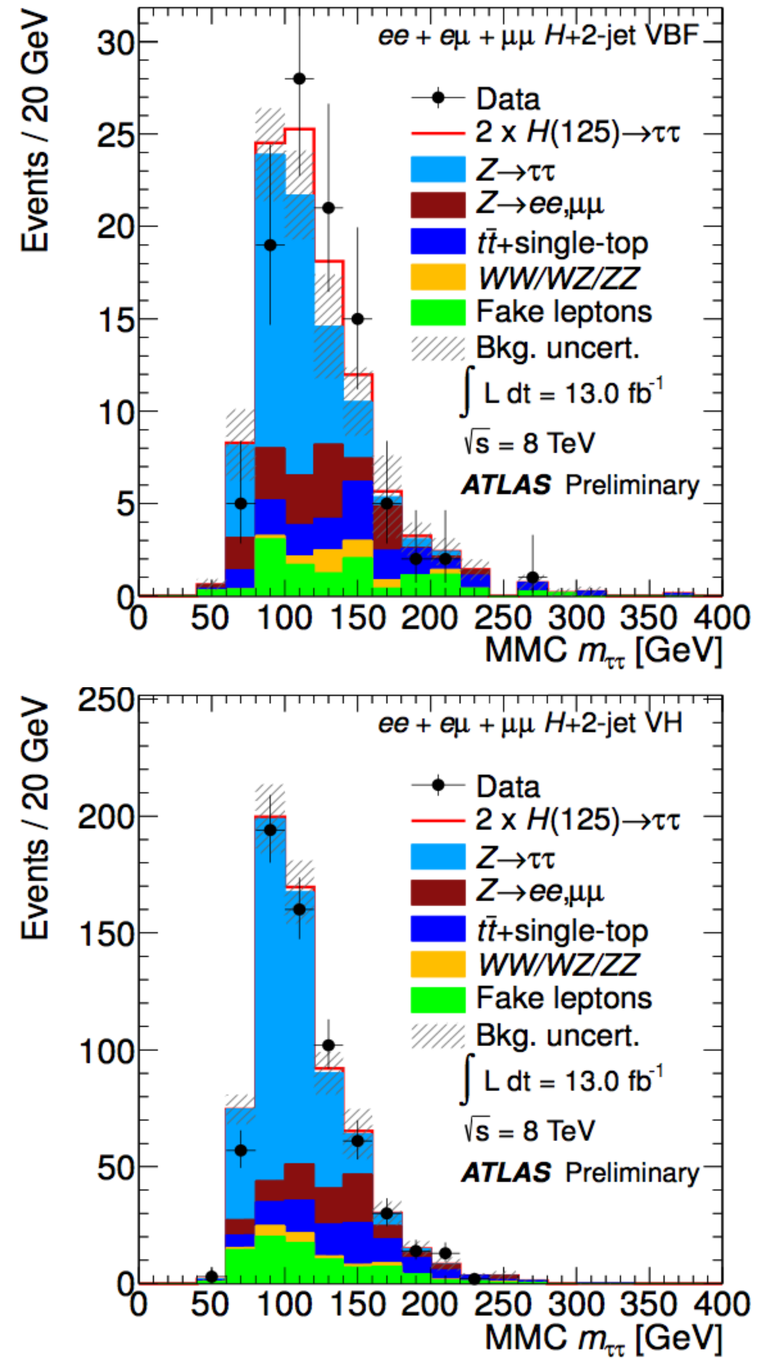
Signal acceptance×efficiencies (for 8 TeV)	1.6% ($\tau_{lep}\tau_{lep}$)	2.4% ($\tau_{lep}\tau_{had}$)	0.3% ($\tau_{had}\tau_{had}$)

(Event yield tables in backup slides 37-39)

Background modelling – MMC mass ($\tau_{lep}\tau_{lep}$)

- $Z/\gamma^* \to \tau\tau$: Embedding, normalized to MC (at preselection).
- Fake leptons (a reconstructed e/μ not from τ decay or leptonic decay from Z or W): Shape from data control sample with non-isolated e/μ. Normalized to data using template method in sub-leading lepton p_T distribution. Uncertainty 20-40%.
- Top and $Z/\gamma^*(\to ee,\mu\mu)$+jets: Shape from MC simulation. Normalized to data in CRs.
- Di-bosons: MC simulation.

For 8 TeV	VBF	boosted	VH	1-jet
ggH:VBF:VH [%]	26:74:0	69:19:12	75:6:19	76:20:4
Expected signal	~5	~18	~3	~9
Total background	91±5±5	2010±30±120	660±20±50	1400±20±80
Observed data	98	2014	636	1405



Background modelling – MMC mass ($\tau_{lep}\tau_{had}$, non-VBF)

Multi-jets: From data, inverting l-τ_{had} charge-product from opposite-sign (OS) to same-sign (SS). Correction factors to adjust fake rates. Contributions from other backgrounds in SS sample not subtracted. ⇒ Need OS minus SS add-on terms for the other backgrounds to account for possible OS–SS asymmetries.

$$N_{OS} = N_{SS} + \sum_{i = \text{other bkgs}} N_{i,OS\text{-}SS}$$

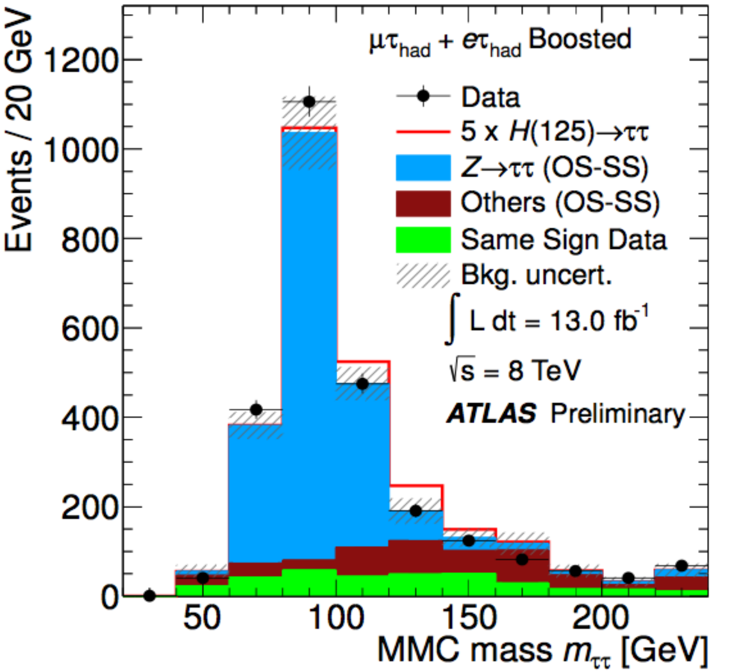
Uncertainties < 7%.

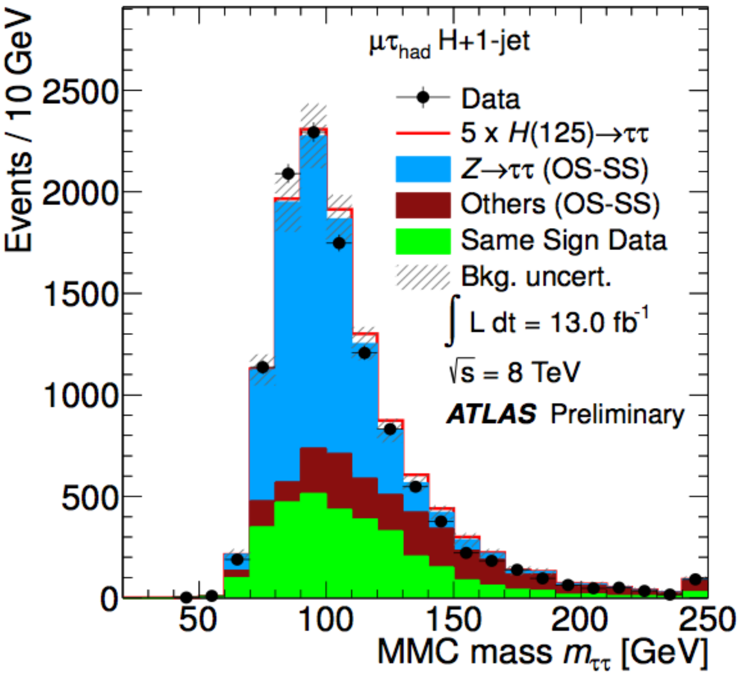
$Z/\gamma^* \to \tau\tau$: Embedding (OS-SS), normalized to data at preselection in m_{vis} window of 40-70 GeV.

Top and W+jets: Shape from MC simulation (OS–SS). Normalized to data in CRs.

$Z/\gamma^*(\to ee,\mu\mu)$+jets and di-bosons: MC simulation (OS–SS). For $Z/\gamma^* \to ee$, $e\to\tau_{had}$ fake rate from data (tag&probe study).

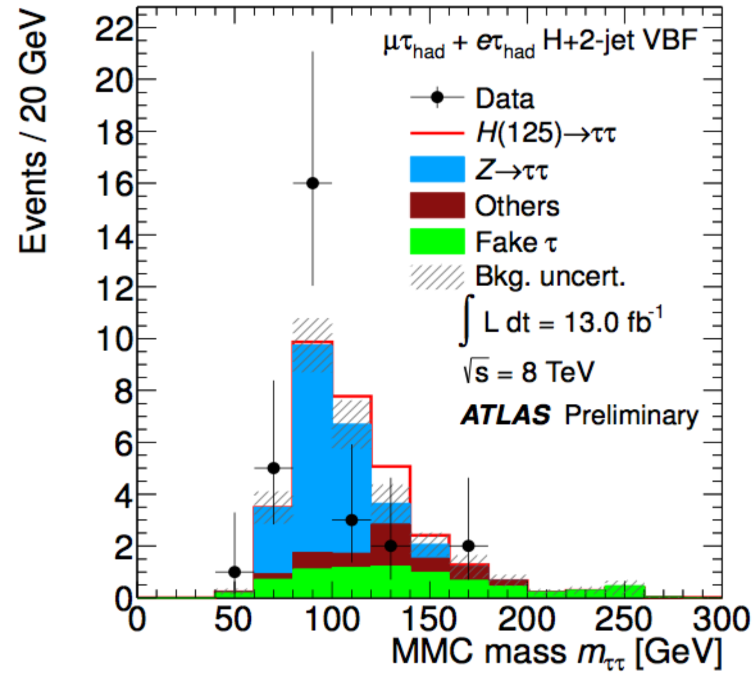
This method is not applied in VBF category, since it results in very large statistical uncertainties in the background estimates due to the tight selection.

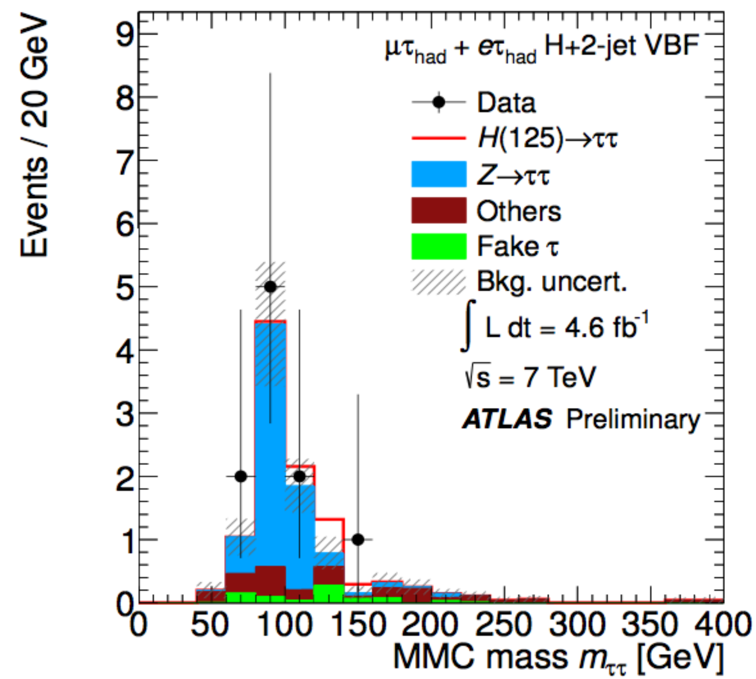




Background modelling – MMC mass ($\tau_{lep}\tau_{had}$, VBF)

- *Z*+jets: Filtered MC samples, applying VBF-type jet cuts at generator level. Normalized using $\Delta\eta_{jj}$-dependent factors derived from CRs.
- Multi-jets and *W*+jets: From data, inverting $\tau_{had\text{-}vis}$ ID.
  Subtract other expected backgrounds.
  Corrections using fake-factors: $ff = f_W * F_W + (1-f_W) * F_{MJ}$,
  Fake-factors ($=N_{ID}/N_{anti\text{-}ID}$) F_{MJ} and F_W obtained from CRs.
  Account for expected proportions f_W and $1-f_W$ in the sample.
  Uncertainty up to 50% from f_W.
  Other backgrounds: MC simulation.

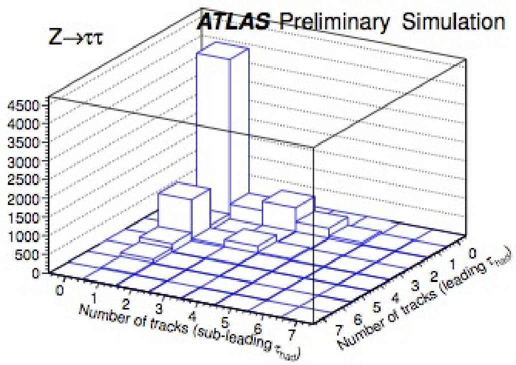


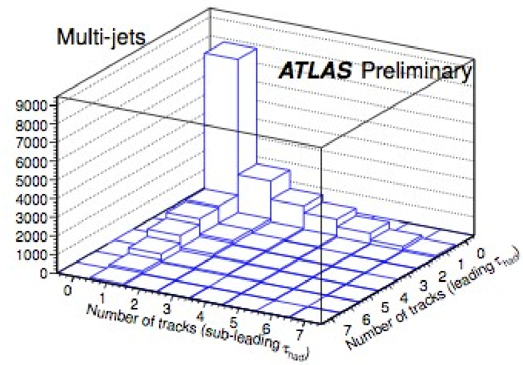


For 8 TeV	VBF	boosted	1-jet	0-jet
ggH:VBF:VH [%]	17:83:0	72:19:9	78:15:7	98:1:1
Expected signal	~3	~28	~107	~61
Total background	29±2±7	2530±70±130	22400±225±710	13960±135±590
Observed data	29	2602	21782	13312

Background modelling – MMC mass ($\tau_{had}\tau_{had}$)

- $Z/\gamma^* \to \tau\tau$: Shape from embedding. Normalization from 2D template fit to N_{tracks} distributions of the two τ_{had} (using as templates MC for $Z/\gamma^* \to \tau\tau$ and SS data for multi-jets).



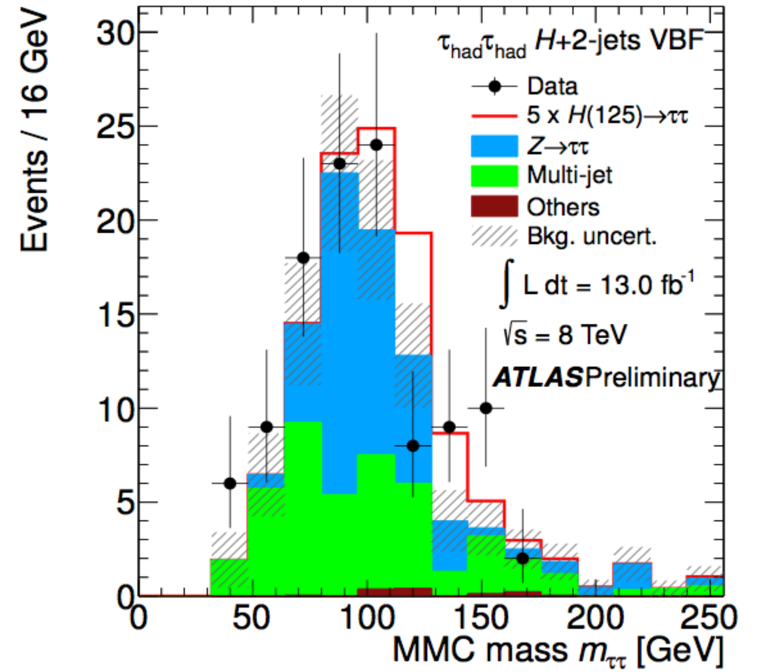


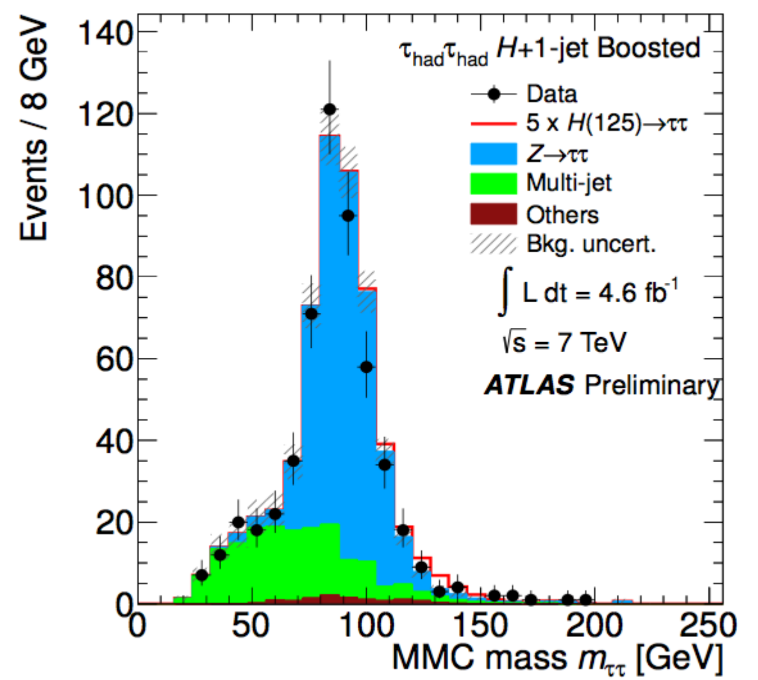
- Multi-jets: Shape from data CR, inverting OS to anti-OS (7 TeV), or with reversed τ_{had} ID (8 TeV). Normalization with same N_{tracks} 2D fit technique. Uncertainties < 11%.

For 8 TeV	VBF	boosted
ggH:VBF:VH [%]	25:74:1	71:17:12
Expected signal	~4	~12
Total background	96±6±9	1607±37±130
Observed data	110	1435

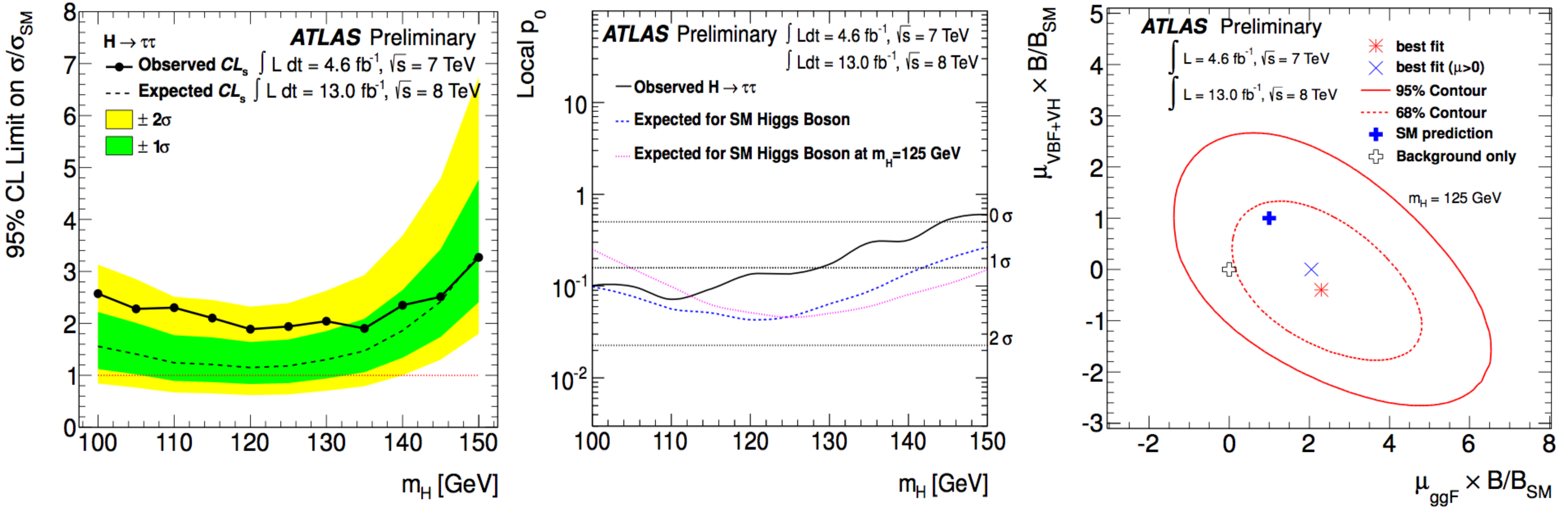
Other backgrounds:

MC simulation.





Results



- Observed (expected) 95% CL upper limit on the Higgs boson cross-section times branching ratio normalized to the SM prediction for m_H = 125 GeV: μ_{up} ($\equiv \sigma/\sigma_{SM}$) = 1.9 (1.2).
- Observed (expected) background fluctuation probability for m_H = 125 GeV: p_0 = 13.5% (4.7%) - 1.1σ (1.7σ). This corresponds to a best fit value: $\mu_{best} = 0.7 \pm 0.7$.
- Most significant deviation from background-only hypothesis observed for m_H = 110 GeV: 7.2% - 1.5σ.
- Considering ggF and VBF+VH contributions separately, best fit gives:

$\mu_{ggF} \times BR(H\to\tau\tau)/BR_{SM}(H\to\tau\tau)$ = 2.4 (2.1)

$\mu_{VBF+VH} \times BR(H\to\tau\tau)/BR_{SM}(H\to\tau\tau)$ = -0.4 (0)

values in () are constraining $\mu \geq 0$

Consistent with SM Higgs and background-only hypotheses within 95% CL contour.

MSSM $h/A/H \to \tau\tau$

- Analysis based on:

  4.7 fb^{-1} of ATLAS data at $\sqrt{s}$ = 7 TeV (full 7 TeV data set)

- 4 $\tau\tau$ decay modes included: $\tau_e\tau_\mu$ 6%, $\tau_e\tau_{had}$ 23%, $\tau_\mu\tau_{had}$ 23%, $\tau_{had}\tau_{had}$ 42%.
- 2 different categories → 8 experimental sub-channels.

MSSM Higgs sector

- 2 Higgs doublets to give mass to up- and down-type fermions.
  → 5 physical states: 3 neutral h/H (CP-even) A (CP-odd), 2 charged $H^{\pm}$.

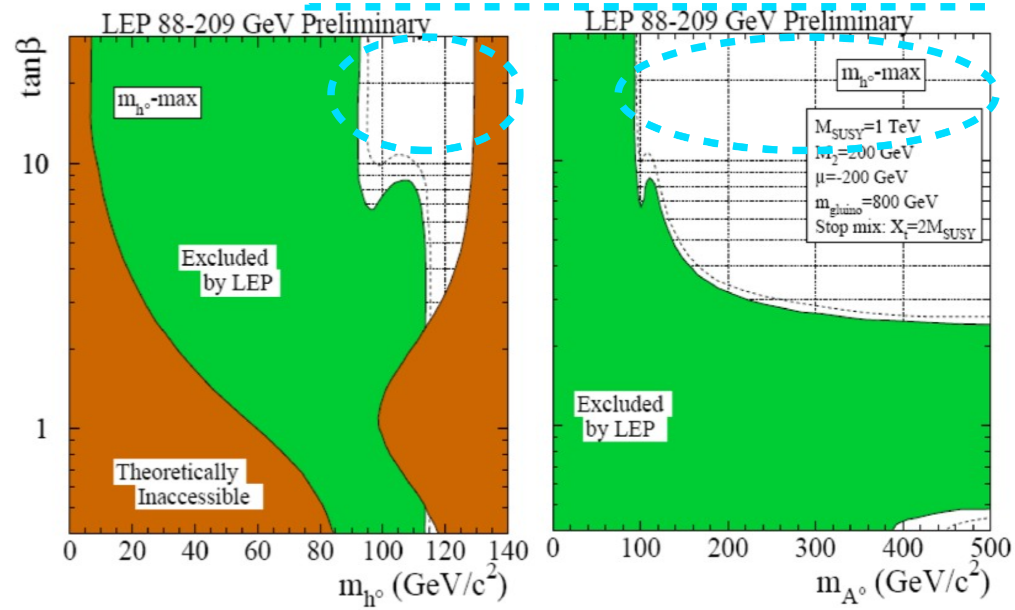
- 2 parameters at tree level: $\tan\beta = \upsilon_{up} / \upsilon_{down}$ and m_A.

- Large higher-order corrections involving many more SUSY parameters. ⇨ Use benchmark scenarios.
- Results interpreted in m_h^{max} scenario (m_h maximized in SUSY parameter space for each pair of ($\tan\beta$,m_A)). Consider Higgs sector bilinear coupling μ > 0.

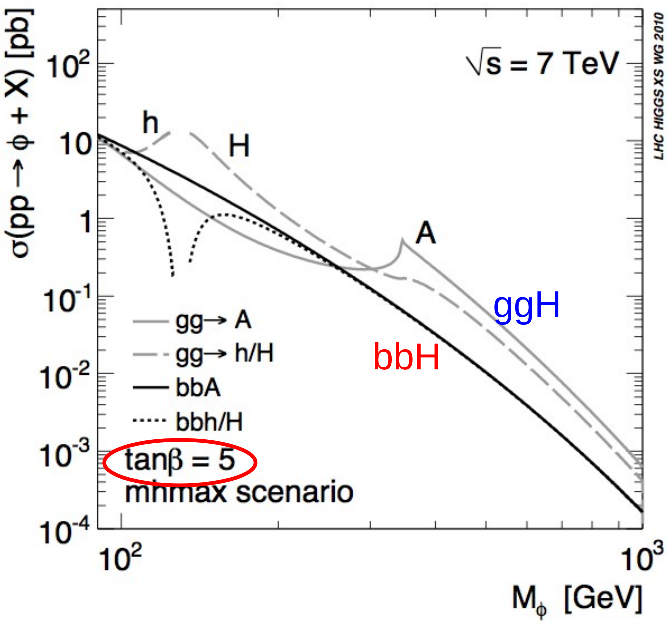
- Limits from LEP: $m_h, m_A \gtrsim m_Z$.

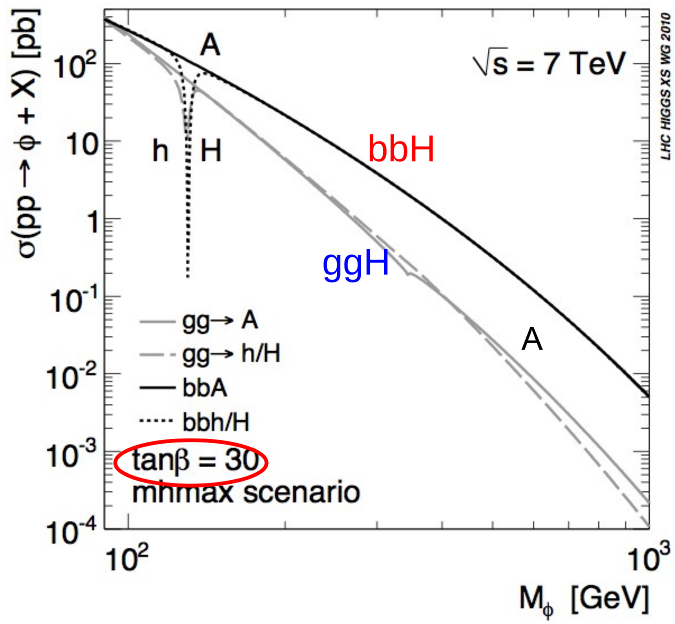
- In this scenario, and for large $\tan\beta$, two of the neutral Higgs bosons are closely degenerate in mass.
  For $m_A \lesssim 130$ GeV: $m_h \simeq m_A$ and $m_H \lesssim 130$ GeV.
  For $m_A \gtrsim 130$ GeV: $m_h \simeq 130$ GeV and $m_A \simeq m_H$.

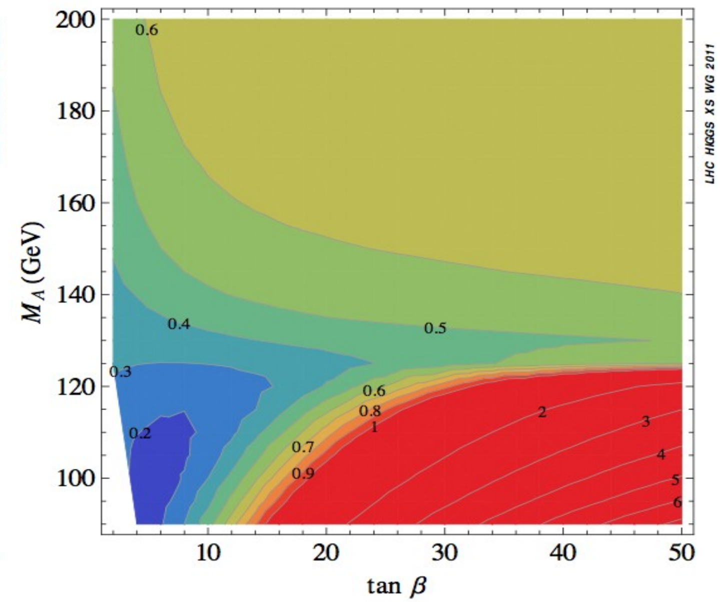
Region to be probed: large $\tan\beta$ in range 90 GeV < m_A < 500 GeV



MSSM neutral Higgs production (at the LHC) and decays





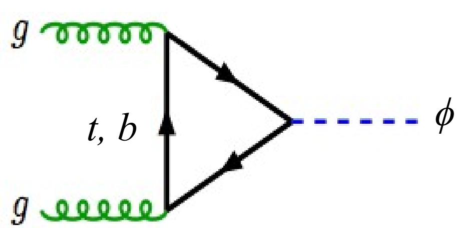


Ratio of total production cross section MSSM h / SM Higgs (with same mass).

- Coupling to *b* quark enhanced at large tanβ.

Gluon Fusion

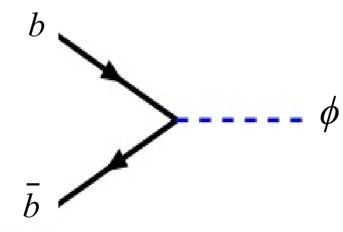
Dominates at small tanβ.

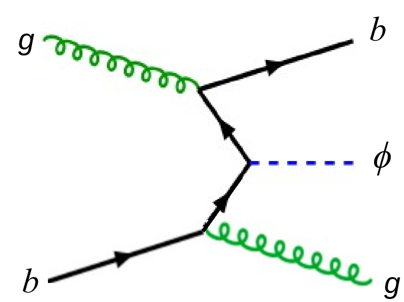


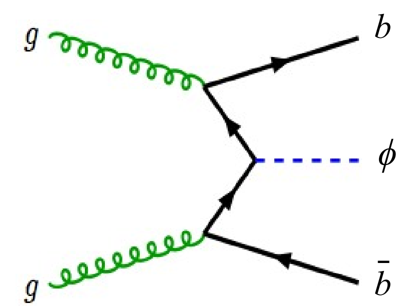
Associated with *b*-quarks

Dominates at large tanβ.

Large scale dependence: at least 3 diagrams contributing.





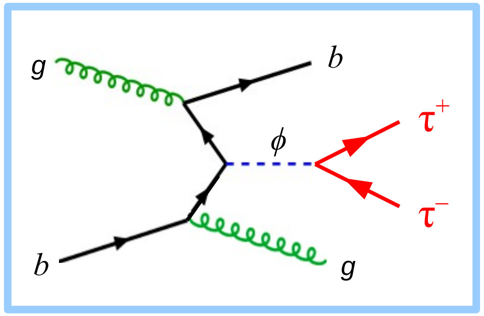


- Decay modes (typical values for interesting regions of parameter space): $b\bar{b}$ (~90%), $\tau\tau$ (~10%), $\mu\mu$ (~0.03%), SUSY particles(?).

Categorization, backgrounds, *b*-jet ID

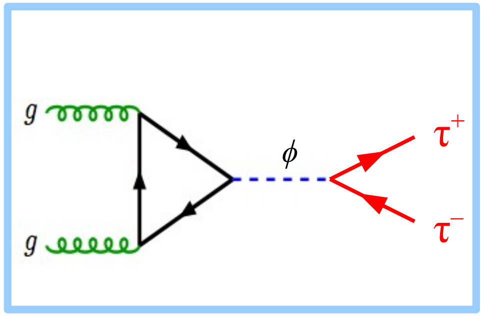
- 2 categories used, targeting the 2 MSSM h/A/H production modes:

b-tagged



Exactly 1 *b*-jet ($\tau_e\tau_\mu$).
Highest-E_T jet *b*-tagged ($\tau_\mathrm{lep}\tau_\mathrm{had}$, $\tau_\mathrm{had}\tau_\mathrm{had}$).

b-vetoed

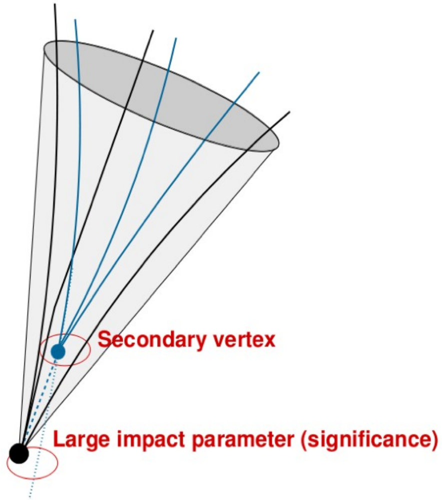


No *b*-jet ($\tau_e\tau_\mu$).
Highest-E_T jet not *b*-tagged ($\tau_\mathrm{lep}\tau_\mathrm{had}$, $\tau_\mathrm{had}\tau_\mathrm{had}$).

- Same backgrounds as in SM analysis ($Z/\gamma^* \rightarrow ll$ not a background in $\tau_\mathrm{lep}\tau_\mathrm{lep}$, since only using $\tau_e\tau_\mu$).

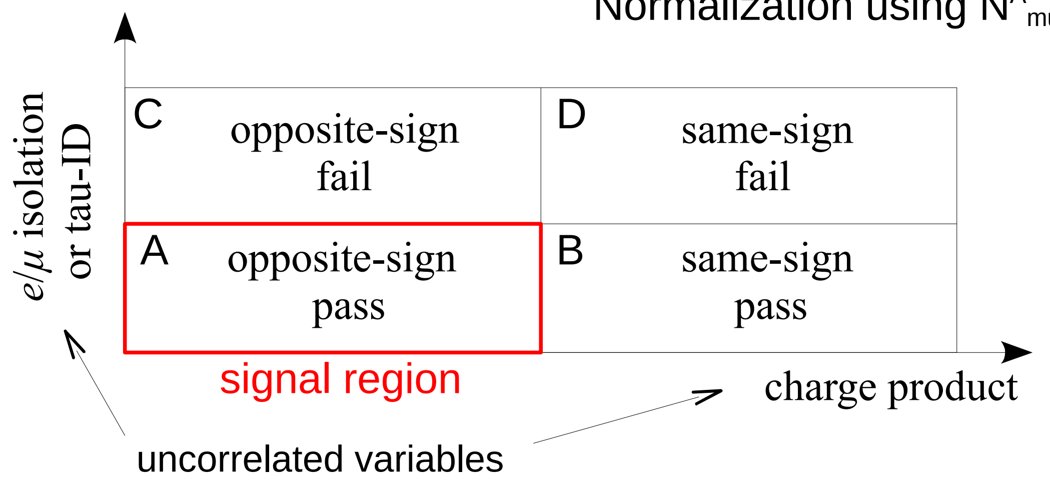
- *b*-jet ID important.
  Use multivariate algorithm based on a Neural Network,
  making use of following signatures:
  - large impact parameter (IP) and IP significance of tracks associated to the jet
  - displaced secondary vertex from *b*- and c-hadron decays.

  Efficiency ~70% (in $t\bar{t}$ events).
  Rejection factors ~130 for light jets, ~5 for *c*-jets.



Background modelling

- *$Z/\gamma^* \to \tau\tau$*: Embedding (normalized to MC), except in $\tau_{had}\tau_{had}$ channel where MC simulation is used (triggers not modelled in embedded sample; emulation hard for di-τ_{had} trigger).
- Multi-jets: **ABCD method** Shape from region B or C, subtracting other backgrounds using simulation.
  Normalization using $N^A_{multi\text{-}jets} / N^B_{multi\text{-}jets} = N^C_{multi\text{-}jets} / N^D_{multi\text{-}jets}$.



- All other backgrounds: MC simulation.
  $t\bar{t}$ normalized to data in CRs (except in $\tau_{had}\tau_{had}$).

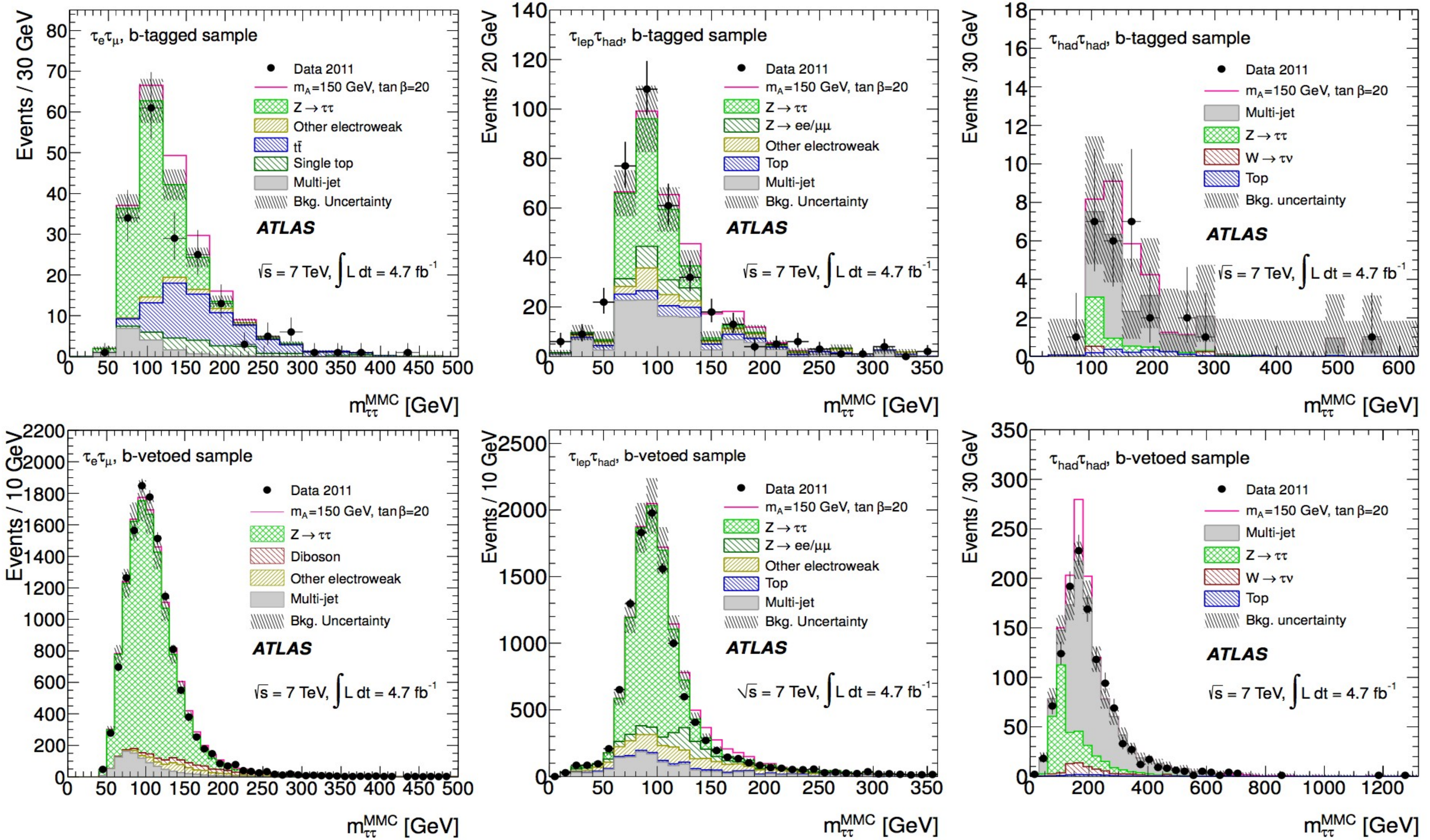
Corrections for instrumental effects

- *Z*+jets, *W*+jets and $t\bar{t}$ MC:
  Adjust for data-MC differences in jet $\to \tau_{had}$ fake rate: 0.54-0.88 (±5-15%)
- *Z*+jets and *W*+jets MC:
  Adjust for data-MC differences in *b*-jet fraction: 1.0-1.24 (± up to 30%)

(*) m_A = 150 GeV and $\tan\beta = 20$	$\tau_e\tau_\mu$		$\tau_{lep}\tau_{had}$		$\tau_{had}\tau_{had}$	
	b-tagged	*b*-vetoed	*b*-tagged	*b*-vetoed	*b*-tagged	*b*-vetoed
*bb*H:ggH [%]	89:11	65:35	93:7	59:41	94:6	61:39
Expected signal(*)	~20	~413	~37	~526	~8	~120
Total background	201±20	13000±1000	334±20	11800±1000	25±5	1200±80
Observed data	181	12947	377	11458	27	1223

(Complete event yield tables in backup slide 46.)

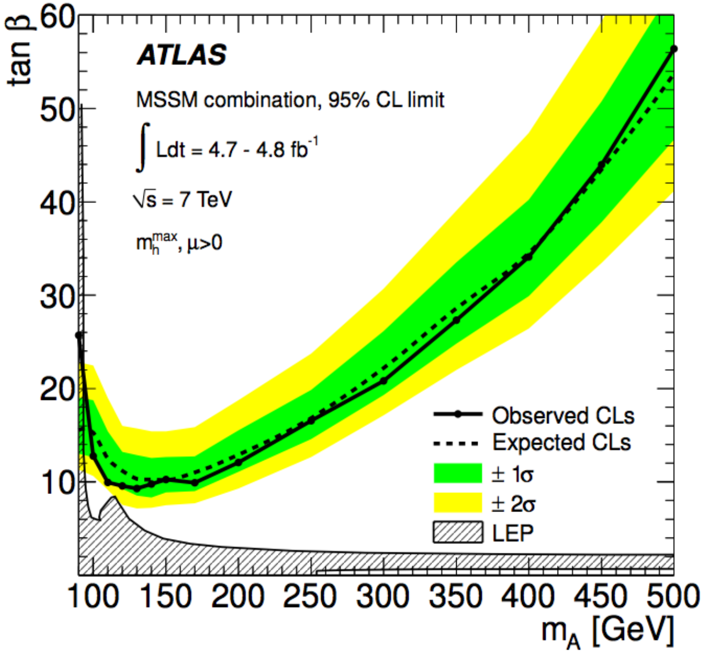
ττ invariant mass distributions

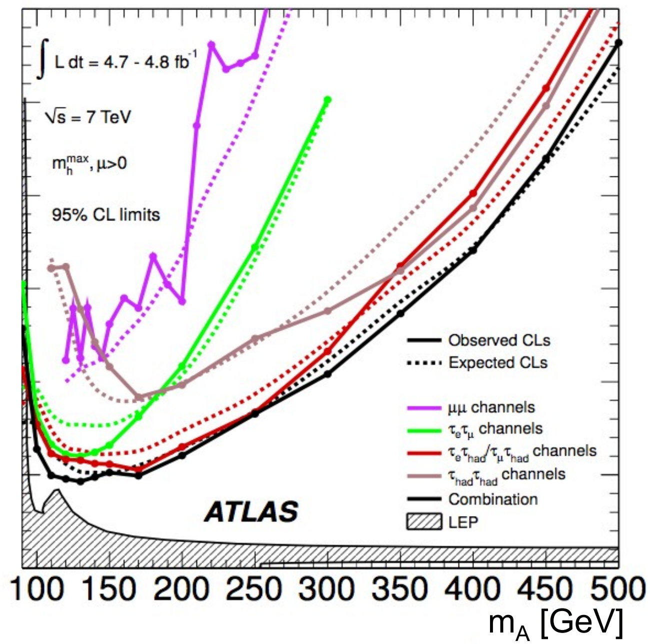


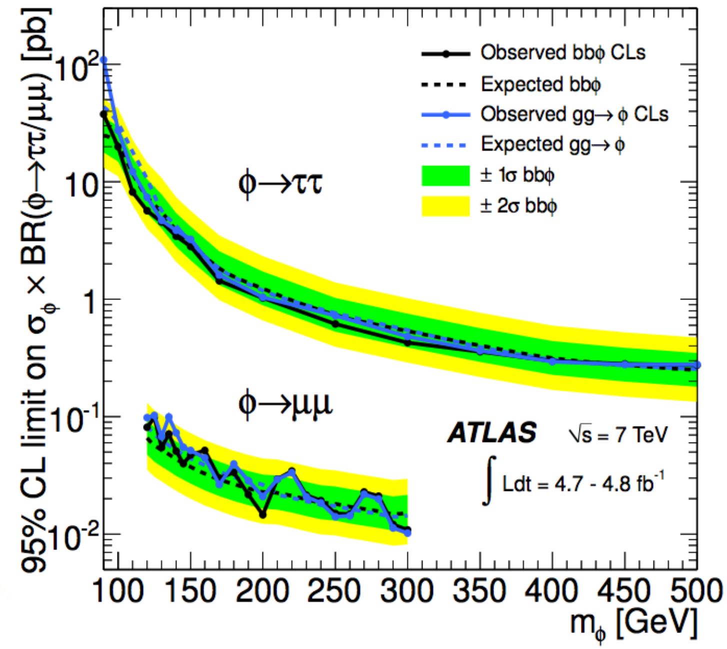
Good agreement between data and background model.

Systematic uncertainties

Source	Uncertainty on yield
Energy scale and resolution (on μ, e, τ_{had}, jets)	10-37% for signal
Cross section for signal ggH and bbH samples	10-20%
Acceptance modelling for simulated samples	2-20%
Data-driven background estimation	< 15%
τ_{had} ID and trigger efficiencies (more important in $\tau_{\text{had}}\tau_{\text{had}}$ channel)	< 11%
Cross section for Z and W background samples	5%
b-jet ID	5% in *b*-tagged sample
Luminosity (signals and backgrounds not normalized with data-driven methods)	3.9%







- Analysis combined with $H \to \mu\mu$ channel.
- 95% CL upper limits on tanβ (using Higgs boson cross sections in the m_h^{max} scenario with $\mu > 0$).

  Best limit occurs for m_A = 130 GeV: tanβ > 9.3 (expected 10.3).

- Further interpretation in terms of a single scalar boson ϕ.

  → 95% CL upper limits on $\sigma_\phi \times BR(\phi \to \tau\tau/\mu\mu)$ as function of m_ϕ for gluon-fusion and *b*-associated production modes.

Summary

SM $H \to \tau\tau$

- Search based on 4.6 fb^{-1} and 13.0 fb^{-1} of ATLAS data at $\sqrt{s}$ = 7 TeV and 8 TeV respectively.
- All $\tau\tau$ decay channels included.
- Observed (expected) 95% CL upper limits on σ/σ_{SM} are 1.9 (1.2) for m_H = 125 GeV.

  Observed (expected) background fluctuation probabilities are 1.1σ (1.7σ) for m_H = 125 GeV.
- No significant excess observed over predicted background.
- Results compatible with both background-only and SM Higgs.

MSSM $h/A/H \to \tau\tau$

- Search based on 4.7 fb^{-1} of ATLAS data at $\sqrt{s}$ = 7 TeV.
- Include 4 $\tau\tau$ decay channels: $\tau_e\tau_\mu$, $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_{had}\tau_{had}$. Combination with $H \to \mu\mu$ decay channel.
- 95% CL upper limits on tanβ in range 90 GeV < m_A < 500 GeV.

  Best limit at m_A = 130 GeV: tanβ > 9.3 (expected 10.3).
- No excess observed over predicted background.
- Results interpreted in the m_h^{max} scenario.
- Significant portion of non-excluded parameter space still compatible with last year discovered particle at LHC being one of the neutral CP-even MSSM Higgs bosons.

- Coming soon: updated analyses with all 2012 ATLAS data.

Backup slides

Preselection

- Summary of most generic preselection criteria (for both SM and MSSM analyses).
  - Triggers: single- and di-lepton ($\tau_{lep}\tau_{lep}$), single-lepton and lepton-tau ($\tau_{lep}\tau_{had}$), di-tau ($\tau_{had}\tau_{had}$)
  - Isolated μ's and e's with p_T cuts to be at trigger plateau (or $p_T^{\mu} > 10$ GeV, $E_T^{e} > 15$ GeV)
  - τ_{had} with 1 or 3 tracks, charge ±1, $p_T > 20\text{-}40$ GeV, $|\eta| < 2.5$
  - Jets with $p_T > 25$ (20) GeV (MSSM), $|\eta| < 4.5$ (suppress jets from pile-up)
  - Exactly 2 ($\tau_{lep}\tau_{lep}$), 1 ($\tau_{lep}\tau_{had}$), 0 ($\tau_{had}\tau_{had}$) e or μ } with opposite charge
  - 1 ($\tau_{lep}\tau_{had}$), 2 ($\tau_{had}\tau_{had}$) τ_{had} } with opposite charge
  - SM: Lower E_T^{miss} cut to account for ν's

- Additional cuts are applied at the preselection level to suppress backgrounds.

- Frequentist approach using a binned likelihood function:

$$\mathcal{L}(\mu,\boldsymbol{\theta}) = \prod_{\substack{j\,=\,\text{bin and}\\ \text{category}}} \underbrace{\mathcal{F}_{\mathrm{P}}\left(N_j \,|\, \mu\cdot s_j + b_j\right)}_{\text{Poisson}} \prod_{\theta_i} \underbrace{\mathcal{F}_{\mathrm{G}}\left(\theta_i \,|\, 0, 1\right)}_{\text{Gaussian}}$$

b_j: expected background yield, s_j: signal yield predicted by SM or MSSM for a given tanβ-m_A point, μ: "signal strength", N_j: n° events observed in data. b_j and s_j depend on systematic uncertainties parameterized by nuisance parameters, θ, constrained by Gaussians.

- For calculating upper limits use the following test statistic:

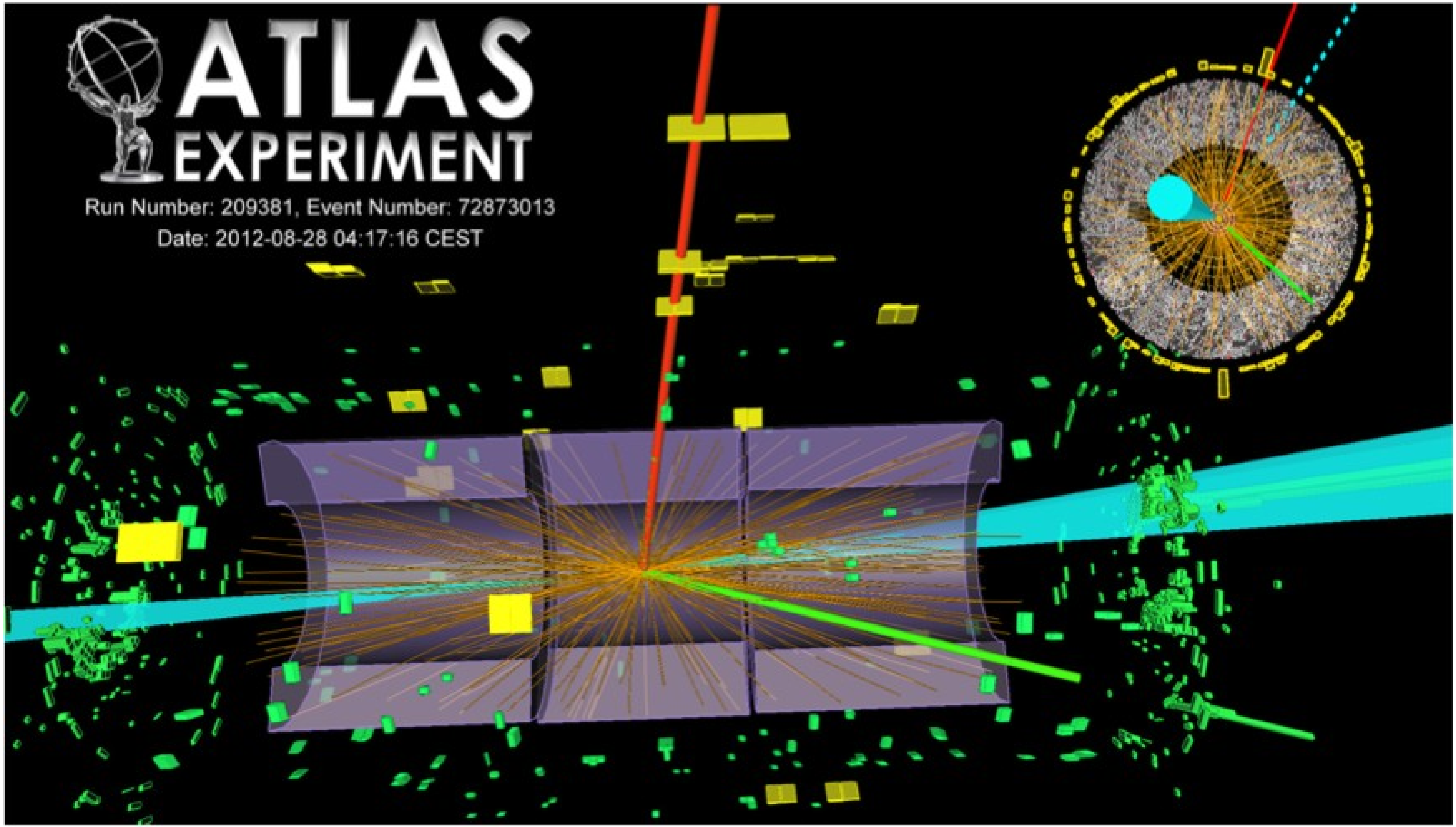
$$\tilde{q}_\mu = \begin{cases} -2\ln\left(\dfrac{\mathcal{L}(\mu,\hat{\boldsymbol{\theta}}_\mu)}{\mathcal{L}(0,\hat{\boldsymbol{\theta}}_0)}\right) & \text{if } \hat{\mu} < 0, \\ -2\ln\left(\dfrac{\mathcal{L}(\mu,\hat{\boldsymbol{\theta}}_\mu)}{\mathcal{L}(\hat{\mu},\hat{\boldsymbol{\theta}})}\right) & \text{if } 0 \le \hat{\mu} \le \mu, \\ 0 & \text{if } \hat{\mu} > \mu, \end{cases}$$

95% CLs upper limit on μ given by p($\tilde{q}_\mu|\mu s+b$) / p($\tilde{q}_\mu|b$) = 0.05.

- For calculating local p_0-values use the following test statistic:

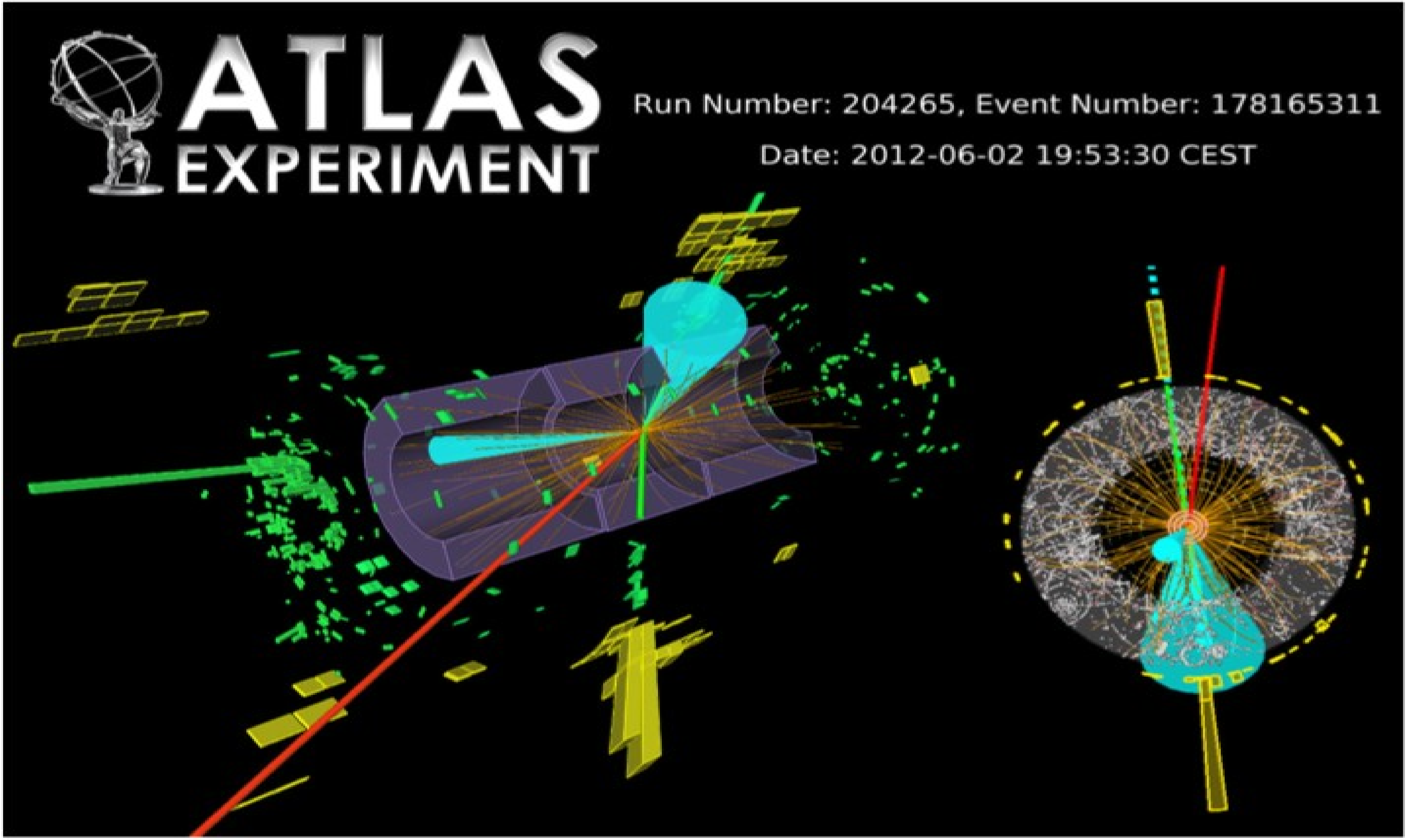
$$q_0 = \begin{cases} -2\ln\left(\dfrac{\mathcal{L}(0,\hat{\boldsymbol{\theta}}_0)}{\mathcal{L}(\hat{\mu},\hat{\boldsymbol{\theta}})}\right) & \text{if } \hat{\mu} \ge 0, \\ 0 & \text{if } \hat{\mu} < 0, \end{cases}$$

SM $H \rightarrow \tau\tau$



Display of an event selected by the $H \rightarrow \tau_{\rm lep}\tau_{\rm lep}$ analysis in the VBF category, where one τ decays to an electron and the other to a muon. The electron is indicated by a green track and the muon indicated by a red track. The dashed line represents the direction of the $E_{\rm T}^{\rm miss}$ vector, and there are two VBF jets marked with turquoise cones. The muon $p_{\rm T}$ is 20 GeV, the electron $p_{\rm T}$ is 17 GeV, $E_{\rm T}^{\rm miss}$ = 43 GeV, m_{jj} = 1610 GeV and m_{MMC} = 126 GeV.

VBF $H \to \tau_{lep}\tau_{had}$ candidate event



Display of an event selected by the $H \to \tau_{\rm lep}\tau_{\rm had}$ analysis in the VBF category, where one τ decays to a muon. The hadronically decaying τ lepton (1 prong decay) is indicated by a green track and the muon is indicated by a red track. The dashed line represents the direction of the $E_{\rm T}^{\rm miss}$ vector, and there are two VBF jets marked with turquoise cones. The muon $p_{\rm T}$ is 63 GeV, the $\tau_{\rm had}$ candidate $p_{\rm T}$ is 96 GeV, $E_{\rm T}^{\rm miss} = 119$ GeV, $m_{jj} = 625$ GeV and $m_{MMC} = 129$ GeV.

List of triggers

Channel	Trigger	Trigger p_T Threshold (GeV)	Offline p_T Threshold (GeV)
7 TeV			
$H \to \tau_{lep}\tau_{lep}$	single electron	$p_T{}^{e} > 20-22$	electron p_T 2 GeV above trigger threshold $p_T{}^{\mu} > 10$
	single muon	$p_T{}^{\mu} > 18$	$p_T{}^{\mu} > 20$ $p_T{}^{e} > 15$
	di-electron	$p_T{}^{e1} > 12$ $p_T{}^{e2} > 12$	$p_T{}^{e1} > 15$ $p_T{}^{e2} > 15$
	di-muon	$p_T{}^{\mu1} > 15$ $p_T{}^{\mu2} > 10$	$p_T{}^{\mu1} > 16$ $p_T{}^{\mu2} > 10$
	$e-\mu$ combined	$p_T{}^{e} > 10$ $p_T{}^{\mu} > 6$	$p_T{}^{e} > 15$ $p_T{}^{\mu} > 10$
$H \to \tau_{lep}\tau_{had}$	single electron	$p_T{}^{e} > 20-22$ –	$p_T{}^{e} > 25$ $p_T{}^{\tau_{had\text{-}vis}} > 20$
	single muon	$p_T{}^{\mu} > 18$ –	$p_T{}^{\mu} > 25$ $p_T{}^{\tau_{had\text{-}vis}} > 20$
	combined $e + \tau_{had\text{-}vis}$	$p_T{}^{e} > 15$ $p_T{}^{\tau_{had\text{-}vis}} > 16-20$	$17 < p_T{}^{e} < 25$ $p_T{}^{\tau_{had\text{-}vis}} > 25$
$H \to \tau_{had}\tau_{had}$	combined two τ_{had}	$p_T{}^{\tau_{had\text{-}vis}} > 29$ $p_T{}^{\tau_{had\text{-}vis}} > 20$	$p_T{}^{\tau_{had\text{-}vis}} > 40$ $p_T{}^{\tau_{had\text{-}vis}} > 25$
8 TeV			
$H \to \tau_{lep}\tau_{lep}$	single electron	$p_T{}^{e} > 24$	$p_T{}^{e} > 25$ $p_T{}^{\mu} > 10$
	di-electron	$p_T{}^{e1} > 12$ $p_T{}^{e2} > 12$	$p_T{}^{e1} > 15$ $p_T{}^{e2} > 15$
	di-muon	$p_T{}^{\mu1} > 18$ $p_T{}^{\mu2} > 8$	$p_T{}^{\mu1} > 20$ $p_T{}^{\mu2} > 10$
	$e-\mu$ combined	$p_T{}^{e} > 12$ $p_T{}^{\mu} > 8$	$p_T{}^{e} > 15$ $p_T{}^{\mu} > 10$
$H \to \tau_{lep}\tau_{had}$	single electron	$p_T{}^{e} > 24$ –	$p_T{}^{e} > 26$ $p_T{}^{\tau_{had\text{-}vis}} > 20$
	single muon	$p_T{}^{\mu} > 24$ –	$p_T{}^{\mu} > 26$ $p_T{}^{\tau_{had\text{-}vis}} > 20$
	combined $e + \tau_{had\text{-}vis}$	$p_T{}^{e} > 18$ $p_T{}^{\tau_{had\text{-}vis}} > 20$	$20 < p_T{}^{e} < 26$ $p_T{}^{\tau_{had\text{-}vis}} > 25$
	combined $\mu + \tau_{had\text{-}vis}$	$p_T{}^{\mu} > 15$ $p_T{}^{\tau_{had\text{-}vis}} > 20$	$17 < p_T{}^{\mu} < 26$ $p_T{}^{\tau_{had\text{-}vis}} > 25$
$H \to \tau_{had}\tau_{had}$	combined two τ_{had}	$p_T{}^{\tau_{had\text{-}vis}} > 29$ $p_T{}^{\tau_{had\text{-}vis}} > 20$	$p_T{}^{\tau_{had\text{-}vis}} > 40$ $p_T{}^{\tau_{had\text{-}vis}} > 25$

Event selection $(\tau_{lep}\tau_{lep})$

2-jet VBF	Boosted	2-jet VH	1-jet
Pre-selection: exactly two leptons with opposite charges			
30 GeV $< m_{\ell\ell} <$ 75 GeV (30 GeV $< m_{\ell\ell} <$ 100 GeV) for same-flavor (different-flavor) leptons, and $p_{T,\ell 1} + p_{T,\ell 2} >$ 35 GeV			
At least one jet with $p_T >$ 40 GeV ($\|JVF_{\text{jet}}\| > 0.5$ if $\|\eta_{\text{jet}}\| < 2.4$)			
$E_{\text{T}}^{\text{miss}} >$ 40 GeV ($E_{\text{T}}^{\text{miss}} >$ 20 GeV) for same-flavor (different-flavor) leptons			
$H_{\text{T}}^{\text{miss}} >$ 40 GeV for same-flavor leptons			
$0.1 < x_{1,2} < 1$			
$0.5 < \Delta\phi_{\ell\ell} < 2.5$			
$p_{T,j2} >$ 25 GeV (JVF)	excluding 2-jet VBF	$p_{T,j2} >$ 25 GeV (JVF)	excluding 2-jet VBF, Boosted and 2-jet VH
$\Delta\eta_{jj} > 3.0$	$p_{T,\tau\tau} >$ 100 GeV	excluding Boosted	$m_{\tau\tau j} >$ 225 GeV
$m_{jj} >$ 400 GeV	b-tagged jet veto	$\Delta\eta_{jj} < 2.0$	b-tagged jet veto
b-tagged jet veto	–	30 GeV $< m_{jj} <$ 160 GeV	–
Lepton centrality and CJV		b-tagged jet veto	
0-jet (7 TeV only)			
Pre-selection: exactly two leptons with opposite charges			
Different-flavor leptons with 30 GeV $< m_{\ell\ell} <$ 100 GeV and $p_{T,\ell 1} + p_{T,\ell 2} >$ 35 GeV			
$\Delta\phi_{\ell\ell} > 2.5$			
b-tagged jet veto			

Event selection ($\tau_{lep}\tau_{had}$)

7 TeV		8 TeV	
VBF Category	Boosted Category	VBF Category	Boosted Category
▹ $p_T{}^{\tau_{\text{had-vis}}}$ >30 GeV	–	▹ $p_T{}^{\tau_{\text{had-vis}}}$ >30 GeV	▹ $p_T{}^{\tau_{\text{had-vis}}}$ >30 GeV
▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV
▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV	▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV
▹ $p_T{}^{j1}, p_T{}^{j2} > 40$ GeV	▹ $0 < x_1 < 1$	▹ $p_T{}^{j1} > 40, p_T{}^{j2}$ >30 GeV	▹ $0 < x_1 < 1$
▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$	▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$
▹ $m_{jj} > 500$ GeV	▹ Fails VBF	▹ $m_{jj} > 500$ GeV	▹ Fails VBF
▹ centrality req.	–	▹ centrality req.	–
▹ $\eta_{j1} \times \eta_{j2} < 0$	–	▹ $\eta_{j1} \times \eta_{j2} < 0$	–
▹ $p_T{}^{\text{Total}} < 40$ GeV	–	▹ $p_T{}^{\text{Total}} < 30$ GeV	–
–	–	▹ $p_T{}^{\ell}$ >26 GeV	–
• m_T <50 GeV	• m_T <50 GeV	• m_T <50 GeV	• m_T <50 GeV
• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 1.6$	• $\sum \Delta\phi < 2.8$	–
–	–	• b-tagged jet veto	• b-tagged jet veto
1 Jet Category	0 Jet Category	1 Jet Category	0 Jet Category
▹ ≥ 1 jet, p_T >25 GeV	▹ 0 jets p_T >25 GeV	▹ ≥ 1 jet, p_T >30 GeV	▹ 0 jets p_T >30 GeV
▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV
▹ Fails VBF, Boosted	▹ Fails Boosted	▹ Fails VBF, Boosted	▹ Fails Boosted
• m_T <50 GeV	• m_T <30 GeV	• m_T <50 GeV	• m_T <30 GeV
• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$	• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$
–	• $p_T^{\ell} - p_T^{\tau} < 0$	–	• $p_T^{\ell} - p_T^{\tau} < 0$

Event selection ($\tau_{had}\tau_{had}$)

Cut	Description
Preselection	No muons or electrons in the event
	Exactly 2 medium $\tau_{\rm had}$ candidates matched with the trigger objects
	At least 1 of the $\tau_{\rm had}$ candidates identified as tight
	Both $\tau_{\rm had}$ candidates are from the same primary vertex
	Leading $\tau_{\text{had-vis}}$ $p_T > 40$ GeV and sub-leading $\tau_{\text{had-vis}}$ $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
	$\tau_{\rm had}$ candidates have opposite charge and 1- or 3-tracks
	$0.8 < \Delta R(\tau_1, \tau_2) < 2.8$
	$\Delta\eta(\tau, \tau) < 1.5$
	if $E_{\rm T}^{\rm miss}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\rm T}^{\rm miss}, \tau_1), \Delta\phi(E_{\rm T}^{\rm miss}, \tau_2)\right\} < 0.2\pi$
VBF	At least two tagging jets, j_1, j_2, leading tagging jet with $p_{\rm T} > 50$ GeV
	$\eta_{j1} \times \eta_{j2} < 0$, $\Delta\eta_{jj} > 2.6$ and invariant mass $m_{jj} > 350$ GeV
	$\min(\eta_{j1}, \eta_{j2}) < \eta_{\tau 1}, \eta_{\tau 2} < \max(\eta_{j1}, \eta_{j2})$
	$E_{\rm T}^{\rm miss} > 20$ GeV
Boosted	Fails VBF
	At least one tagging jet with $p_{\rm T} > 70(50)$ GeV in the 8(7) TeV dataset
	$\Delta R(\tau_1, \tau_2) < 1.9$
	$E_{\rm T}^{\rm miss} > 20$ GeV
	if $E_{\rm T}^{\rm miss}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\rm T}^{\rm miss}, \tau_1), \Delta\phi(E_{\rm T}^{\rm miss}, \tau_2)\right\} < 0.1\pi$.

Expected yields and observed number of events ($\tau_{lep}\tau_{lep}$)

7 TeV

	VBF category	Boosted category	$ee + \mu\mu + e\mu$ VH category	1-jet category	0-jet category
$gg \to H$ (125 GeV)	0.20 ± 0.04 ± 0.07	3.5 ± 0.2 ± 0.4	0.4 ± 0.1 ± 0.1	2.0 ± 0.1 ± 0.8	25±1±4
VBF H (125 GeV)	1.05 ± 0.03 ± 0.10	0.90 ± 0.03 ± 0.05	0.05 ± 0.01 ± 0.01	0.56 ± 0.02 ± 0.01	0.97±0.03±0.06
VH (125 GeV)	0.0	0.71 ± 0.03 ± 0.09	0.20 ± 0.01 ± 0.02	0.14 ± 0.01 ± 0.02	0.63±0.02±0.04
$Z/\gamma^* \to \tau\tau$ embedded	20 ± 2 ± 2	(0.41 ± 0.01 ± 0.02)×10^3	113 ± 5 ± 8	272 ± 8 ± 41	(10.71±0.05±0.07)×10^3
$Z/\gamma^* \to \ell\ell$	1.5 ± 0.6 ± 0.6	77 ± 7 ± 6	27 ± 4 ± 9	45 ± 5 ± 24	(0.17±0.01±0.01)×10^3
Top	4.8 ± 0.5 ± 0.6	132 ± 3 ± 6	27 ± 1 ± 6	31 ± 2 ± 10	284±4±15
Diboson	0.8 ± 0.1 ± 0.2	17.4 ± 0.7 ± 0.6	4.3 ± 0.4 ± 1.0	12 ± 1 ± 3	347±3±20
Backgrounds with fake leptons	2.7 ± 0.3 ± 0.9	22 ± 3 ± 4	19 ± 3 ± 6	24 ± 3 ± 10	(1.56±0.02±0.40)×10^3
Total background	29 ± 3 ± 2	(0.66 ± 0.01 ± 0.02)×10^3	190± 7 ± 15	(0.38±0.01 ± 0.05)×10^3	(13.07±0.06±0.41)×10^3
Observed data	28	673	176	371	13214

8 TeV

	VBF category	$ee + \mu\mu + e\mu$ Boosted category	VH category	1-jet category
$gg \to H$ (125 GeV)	1.3 ± 0.2 ± 0.4	12.4 ± 0.6 ± 2.9	2.5 ± 0.3 ± 0.6	7.0 ± 0.5 ± 1.6
VBF H (125 GeV)	3.63 ± 0.10 ± 0.02	3.36 ± 0.09 ± 0.30	0.21 ± 0.03 ± 0.02	1.82 ± 0.07 ± 0.18
VH (125 GeV)	0.01 ± 0.01 ± 0.01	2.20 ± 0.05 ± 0.22	0.64 ± 0.03 ± 0.09	0.44 ± 0.02 ± 0.05
$Z/\gamma^* \to \tau\tau$ embedded	47 ± 2 ± 1	(1.24 ± 0.01 ± 0.08)×10^3	393 ± 7 ± 26	(0.86 ± 0.01 ± 0.06)×10^3
$Z/\gamma^* \to \ell\ell$	14 ± 3 ± 2	(0.21 ± 0.02 ± 0.04)×10^3	(0.08 ± 0.01 ± 0.02)×10^3	(0.16 ± 0.01 ± 0.03)×10^3
Top	15 ± 2 ± 3	(0.39 ± 0.01 ± 0.07)×10^3	87 ± 4 ± 23	117 ± 5 ± 18
Diboson	3.6 ± 0.8 ± 0.6	55 ± 3 ± 10	15 ± 1 ± 4	40 ± 3 ± 7
Backgrounds with fake leptons	12 ± 2 ± 3	102 ± 7 ± 23	86 ± 4 ± 16	230 ± 8 ± 52
Total background	91 ± 5 ± 5	(2.01 ± 0.03 ± 0.12)×10^3	(0.66 ± 0.02 ± 0.05)×10^3	(1.40 ± 0.02 ± 0.08)×10^3
Observed data	98	2014	636	1405

Expected yields and observed number of events ($\tau_{lep}\tau_{had}$)

7 TeV

Process $\tau_e\tau_{had}$ channel	Events	
	0-Jet	1-Jet
$gg \to H$ (125 GeV)	9.4 ± 0.3 ± 2.3	8.7 ± 0.2 ± 1.8
VBF H (125 GeV)	0.09 ± 0.01 ± 0.01	1.68 ± 0.03 ± 0.15
VH (125 GeV)	0.05 ± 0.01 ± 0.01	0.73 ± 0.04 ± 0.07
$Z/\gamma^* \to \tau\tau$ embedded (OS-SS)	$(2.57 \pm 0.03 \pm 0.44)\times10^3$	$(1.63 \pm 0.02 \pm 0.24)\times10^3$
Diboson (OS-SS)	2.1 ± 0.6 ± 0.3	12.2 ± 1.3 ± 1.1
$Z/\gamma^* \to \ell\ell$ (OS-SS)	47 ± 5 ± 12	34 ± 5 ± 8
Top (OS-SS)	0.7 ± 0.2 ± 0.2	121 ± 3 ± 19
W boson + jets (OS-SS)	116 ± 15 ± 6	$(0.24 \pm 0.02 \pm 0.03)\times10^3$
Same sign data	$(0.40 \pm 0.02 \pm 0.06)\times10^3$	$(0.82 \pm 0.04 \pm 0.04)\times10^3$
Total background	$(3.13 \pm 0.04 \pm 0.44)\times10^3$	$(2.85 \pm 0.04 \pm 0.25)\times10^3$
Observed data	3064	2828

Process $\tau_\mu\tau_{had}$ channel	Events	
	0-Jet	1-Jet
$gg \to H$ (125 GeV)	4.6 ± 0.2 ± 1.2	6.4 ± 0.2 ± 1.3
VBF H (125 GeV)	0.04 ± 0.00 ± 0.01	1.35 ± 0.03 ± 0.12
VH (125 GeV)	0.03 ± 0.01 ± 0.00	0.67 ± 0.04 ± 0.06
$Z/\gamma^* \to \tau\tau$ embedded (OS-SS)	$(0.88 \pm 0.01 \pm 0.17)\times10^3$	$(1.20 \pm 0.02 \pm 0.17)\times10^3$
Diboson (OS-SS)	2.3 ± 0.3 ± 0.4	9.1 ± 1.2 ± 0.8
$Z/\gamma^* \to \ell\ell$ (OS-SS)	10 ± 3 ± 2	13 ± 3 ± 4
Top (OS-SS)	0.5 ± 0.2 ± 0.1	92 ± 3 ± 14
W boson + jets (OS-SS)	65 ± 11 ± 6	$(0.15 \pm 0.02 \pm 0.02)\times10^3$
Same sign data	60 ± 8 ± 3	$(0.31 \pm 0.02 \pm 0.02))\times10^3$
Total background	$(1.01 \pm 0.02 \pm 0.17)\times10^3$	$(1.78 \pm 0.03 \pm 0.18)\times10^3$
Observed data	958	1701

Process	Events	
	Boosted	VBF
$gg \to H$ (125 GeV)	4.1 ± 0.1 ± 1.0	0.17 ± 0.03 ± 0.06
VBF H (125 GeV)	1.52 ± 0.03 ± 0.13	0.87 ± 0.02 ± 0.15
VH (125 GeV)	0.86 ± 0.04 ± 0.08	<0.001
$Z/\gamma^* \to \tau\tau$ †	$(0.70 \pm 0.02 \pm 0.10)\times10^3$	6.5 ± 0.6 ± 1.5
Diboson †	8.4 ± 0.7 ± 0.8	0.12 ± 0.06 ± 0.03
$Z/\gamma^* \to \ell\ell$ †	3.7 ± 1.3 ± 1.0	0.8 ± 0.3 ± 1.0
Top †	52 ± 2 ± 9	1.2 ± 0.3 ± 0.1
W boson + jets (OS-SS)	41 ± 7 ± 8	–
Same sign data	90 ± 10 ± 5	–
Fake-$\tau_{had\text{-}vis}$ backgrounds	–	0.8 ± 0.2 ± 0.4
Total background	$(0.90 \pm 0.02 \pm 0.10)\times10^3$	9.5 ± 0.8 ± 1.9
Observed data	834	10

8 TeV

Process $\tau_e\tau_{had}$ channel	Events	
	0-Jet	1-Jet
$gg \to H$ (125 GeV)	25.9 ± 0.8 ± 6.1	37.3 ± 0.9 ± 8.4
VBF H (125 GeV)	0.30 ± 0.05 ± 0.04	7.8 ± 0.3 ± 0.5
VH (125 GeV)	0.27 ± 0.05 ± 0.03	3.5 ± 0.2 ± 0.2
$Z/\gamma^* \to \tau\tau$ (OS-SS)	$(3.59 \pm 0.03 \pm 0.278)\times10^3$	$(4.50 \pm 0.04 \pm 0.37)\times10^3$
Diboson (OS-SS)	9.9 ± 0.7 ± 0.9	27 ± 1 ± 2
$Z/\gamma^* \to \ell\ell$ (OS-SS)	$(0.41 \pm 0.04 \pm 0.13)\times10^3$	$(0.28 \pm 0.07 \pm 0.14)\times10^3$
Top (OS-SS)	8 ± 2 ± 1	$(1.00 \pm 0.02 \pm 0.03)\times10^3$
W boson + jets (OS-SS)	$(0.48 \pm 0.07 \pm 0.04)\times10^3$	$(1.32 \pm 0.12 \pm 0.12)\times10^3$
Same sign data	$(0.66 \pm 0.03 \pm 0.03)\times10^3$	$(3.68 \pm 0.06 \pm 0.18)\times10^3$
Total background	$(5.16 \pm 0.09 \pm 0.31)\times10^3$	$(10.8 \pm 0.2 \pm 0.5)\times10^3$
Observed data	5012	10409

Process $\tau_\mu\tau_{had}$ channel	Events	
	0-Jet	1-Jet
$gg \to H$ (125 GeV)	34.3 ± 0.9 ± 8.0	46 ± 1 ± 11
VBF H (125 GeV)	0.47 ± 0.06 ± 0.04	8.5 ± 0.3 ± 0.6
VH (125 GeV)	0.20 ± 0.05 ± 0.02	3.7 ± 0.2 ± 0.3
$Z/\gamma^* \to \tau\tau$ (OS-SS)	$(7.13 \pm 0.04 \pm 0.48)\times10^3$	$(6.14 \pm 0.04 \pm 0.45)\times10^3$
Diboson (OS-SS)	10.5 ± 0.7 ± 0.9	30 ± 1 ± 3
$Z/\gamma^* \to \ell\ell$ (OS-SS)	$(0.10 \pm 0.02 \pm 0.02)\times10^3$	$(0.12 \pm 0.02 \pm 0.03)\times10^3$
Top (OS-SS)	10.4 ± 2.3 ± 0.6	$(1.03 \pm 0.03 \pm 0.05)\times10^3$
W boson + jets (OS-SS)	$(0.51 \pm 0.09 \pm 0.04)\times10^3$	$(1.0 \pm 0.1 \pm 0.14)\times10^3$
Same sign data	$(1.03 \pm 0.03 \pm 0.07)\times10^3$	$(3.27 \pm 0.06 \pm 0.24)\times10^3$
Total background	$(8.8 \pm 0.1 \pm 0.5)\times10^3$	$(11.6 \pm 0.1 \pm 0.5)\times10^3$
Observed data	8300	11373

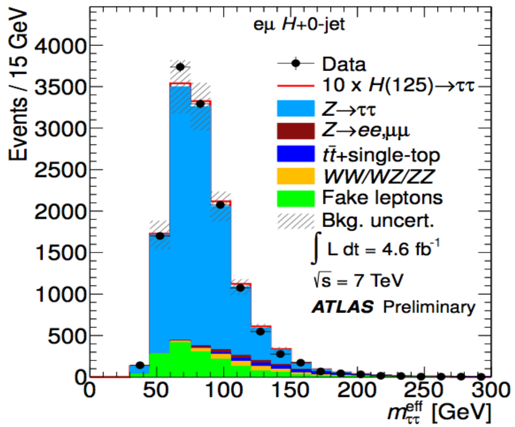
Process	Events	
	Boosted	VBF
$gg \to H$ (125 GeV)	20.3 ± 0.7 ± 5.1	0.5 ± 0.1 ± 0.3
VBF H (125 GeV)	5.3 ± 0.2 ± 0.3	2.5 ± 0.2 ± 0.4
VH (125 GeV)	2.7 ± 0.2 ± 0.2	<0.001
$Z/\gamma^* \to \tau\tau$ †	$(1.78 \pm 0.03 \pm 0.11)\times10^3$	17 ± 2 ± 6
Diboson †	12.2 ± 0.9 ± 1.0	0.6 ± 0.3 ± 0.4
$Z/\gamma^* \to \ell\ell$ †	18 ± 9 ± 4	1.7 ± 0.5 ± 1.2
Top †	111 ± 8 ± 33	2.0 ± 0.7 ± 1.0
W boson + jets (OS-SS)	$(0.27 \pm 0.06 \pm 0.04)\times10^3$	–
Same sign data	$(0.34 \pm 0.02 \pm 0.01)\times10^3$	–
Fake-$\tau_{had\text{-}vis}$ backgrounds	–	7.6 ± 0.7 ± 3.8
Total background	$(2.53 \pm 0.07 \pm 0.13)\times10^3$	29 ± 2 ± 7
Observed data	2602	29

Expected yields and observed number of events $(\tau_{had}\tau_{had})$

7 TeV | 8 TeV

$H \to \tau_{had}\tau_{had}$	7 TeV analysis (4.6 fb^{-1})		8 TeV analysis (13.0 fb^{-1})	
	VBF category	Boosted category	VBF category	Boosted category
$gg \to H$ (125 GeV)	0.36 ± 0.06 ± 0.12	2.4 ± 0.2 ± 0.7	1.0 ± 0.1 ± 0.3	8.2 ± 0.4 ± 1.8
VBF H (125 GeV)	1.12 ± 0.04 ± 0.18	0.68 ± 0.03 ± 0.07	3.01 ± 0.09 ± 0.48	1.98 ± 0.07 ± 0.30
VH (125 GeV)	<0.02	0.61 ± 0.05 ± 0.06	<0.05	1.4 ± 0.2 ± 0.2
$Z/\gamma^* \to \tau\tau$ embedded	20 ± 2 ± 3	392 ± 9 ± 12	50 ± 4 ± 6	1080 ± 20 ± 110
W/Z boson+jets	1.5 ± 0.7 ± 0.4	5 ± 1 ± 1	0.4 ± 0.4	90 ± 20 ± 30
Top	1.0 ± 0.2 ± 0.2	3.0 ± 0.3 ± 0.5	1.4 ± 1.0	21 ± 3 ± 5
Diboson	0.10 ± 0.07 ± 0.02	4.4 ± 0.6 ± 0.7	<0.01	<0.5
Multijet	10.2 ± 0.9 ± 5.0	156 ± 6 ± 30	44 ± 5 ± 7	420 ± 20 ± 60
Total background	32.5 ± 2.2 ± 5.9	561 ± 11 ± 32	96 ± 6 ± 9	1607 ± 37 ± 130
Observed data	38	535	110	1435

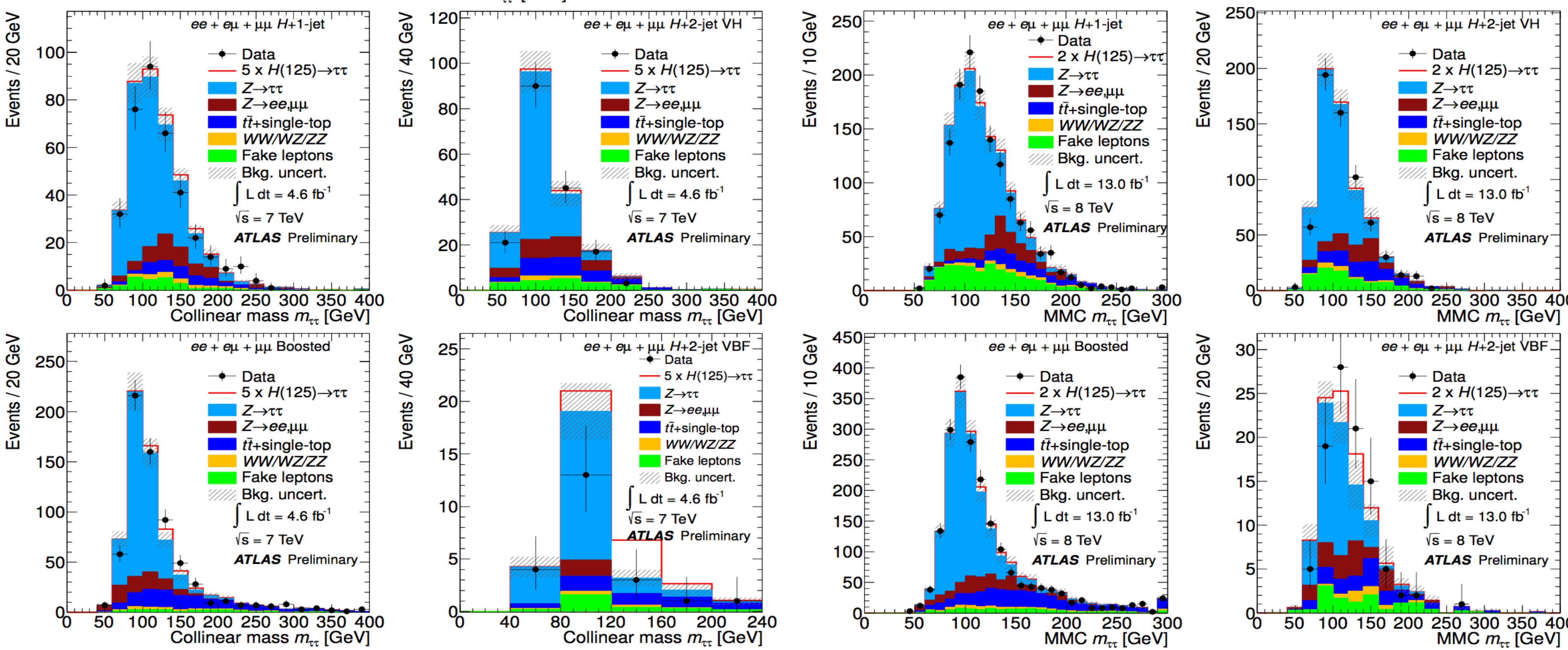
7 TeV



8 TeV

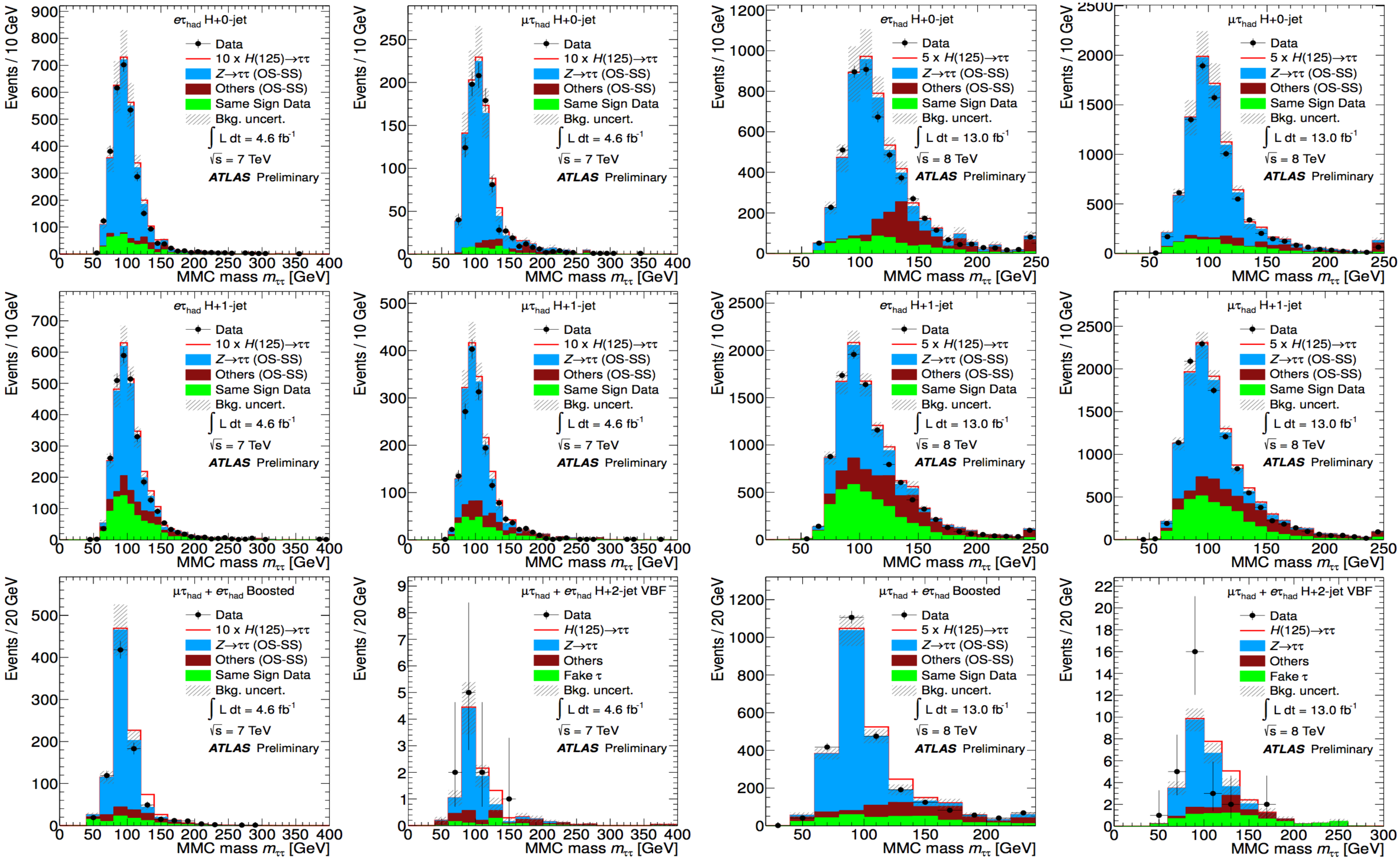
Use MMC in 8 TeV data.

Use collinear mass in 7 TeV data, except in 0-jet category where effective mass is used (collinear mass non-optimal in events where leptons are back-to-back in transverse plane).



7 TeV

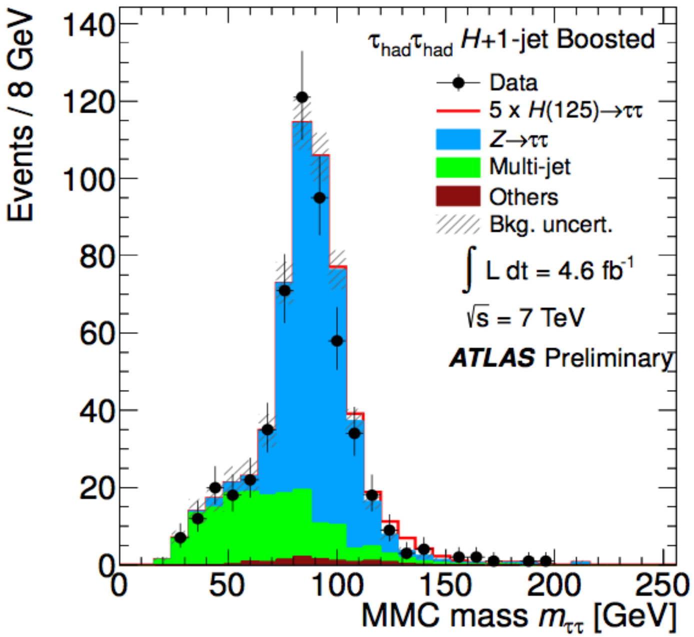
8 TeV

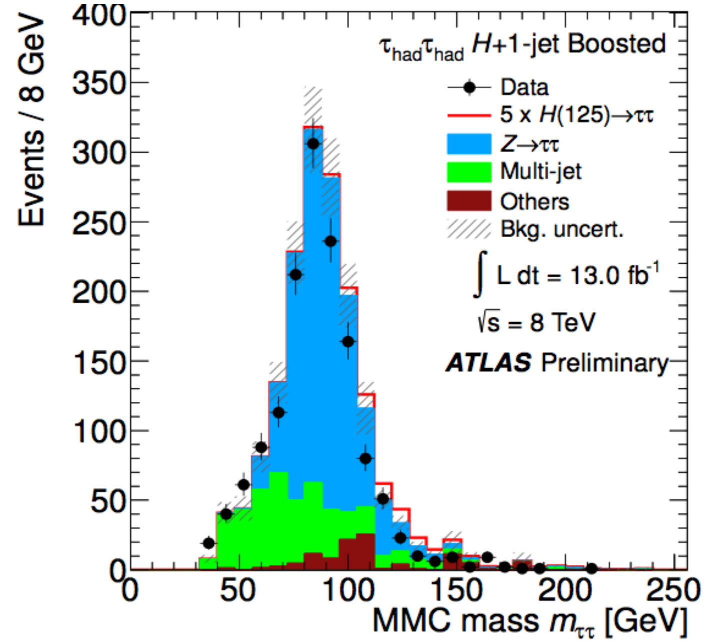


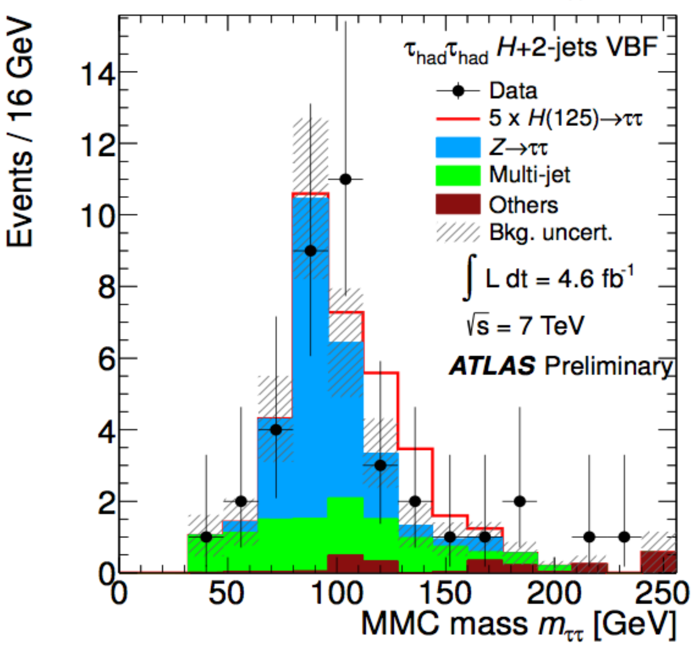
eτhad H+0-jet
μτhad H+0-jet
eτhad H+1-jet
μτhad H+1-jet
μτhad + eτhad Boosted
μτhad + eτhad H+2-jet VBF
Data
10 x H(125)→ττ
5 x H(125)→ττ
H(125)→ττ
Z→ττ (OS-SS)
Z→ττ
Others (OS-SS)
Others
Same Sign Data
Fake τ
Bkg. uncert.
∫ L dt = 4.6 fb-1
∫ L dt = 13.0 fb-1
√s = 7 TeV
√s = 8 TeV
ATLAS Preliminary
Events / 10 GeV
Events / 20 GeV
MMC mass mττ [GeV]

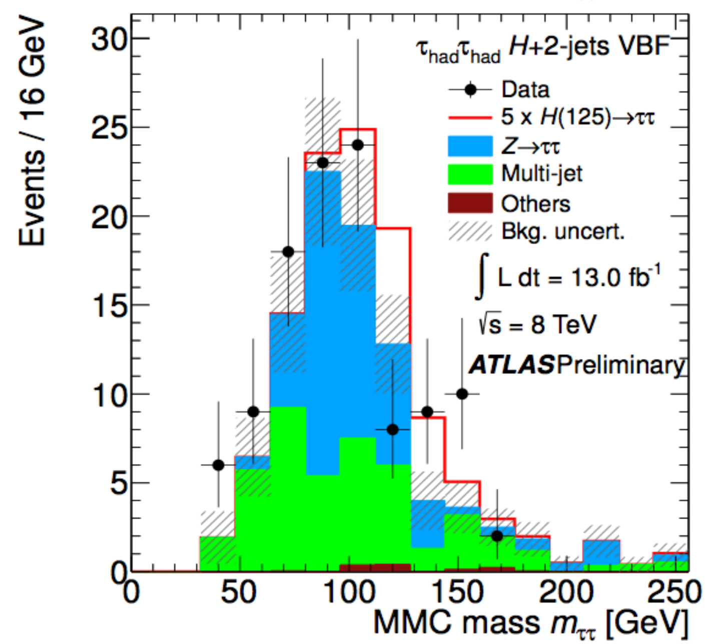
ττ invariant mass distributions ($\tau_{had}\tau_{had}$)

7 TeV	8 TeV









Systematic uncertainties

Uncertainty	$H \to \tau_{lep}\tau_{lep}$	$H \to \tau_{lep}\tau_{had}$	$H \to \tau_{had}\tau_{had}$
		$Z \to \tau^+\tau^-$	
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	2–4%	2–5%	2–4%
Normalisation	5%	4% (non-VBF), 16% (VBF)	9–10%
		Signal	
Jet Energy Scale	1–5% (S)	3–9% (S)	2–4% (S)
Tau Energy Scale	–	2–9% (S)	4–6% (S)
Tau Identification	–	4–5%	10%
Theory	8–28%	18–23%	3–20%
Trigger Efficiency	small	small	5%

(S) = also shape uncertainty

- Theory:

  QCD scale: ~1% for VBF and VH, 8-25% for ggH.

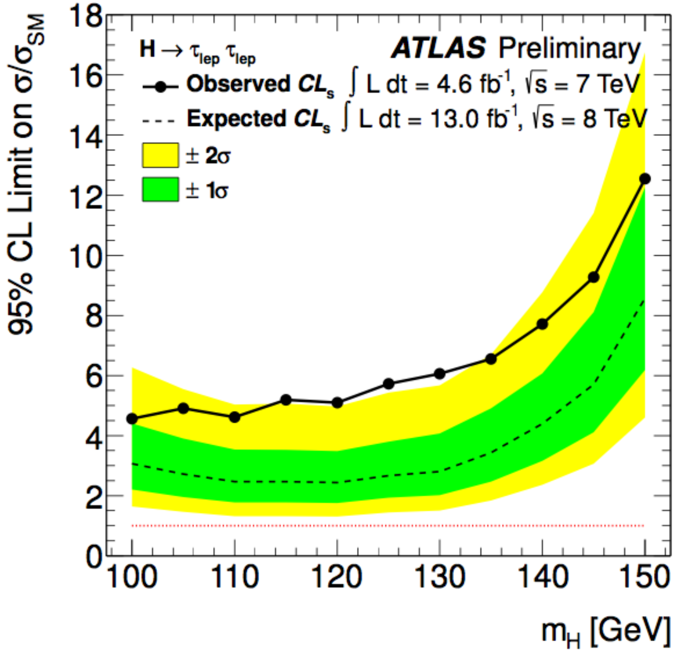
  PDF: ~ 8% (4%) for gluon-initiated (quark-initiated) processes.

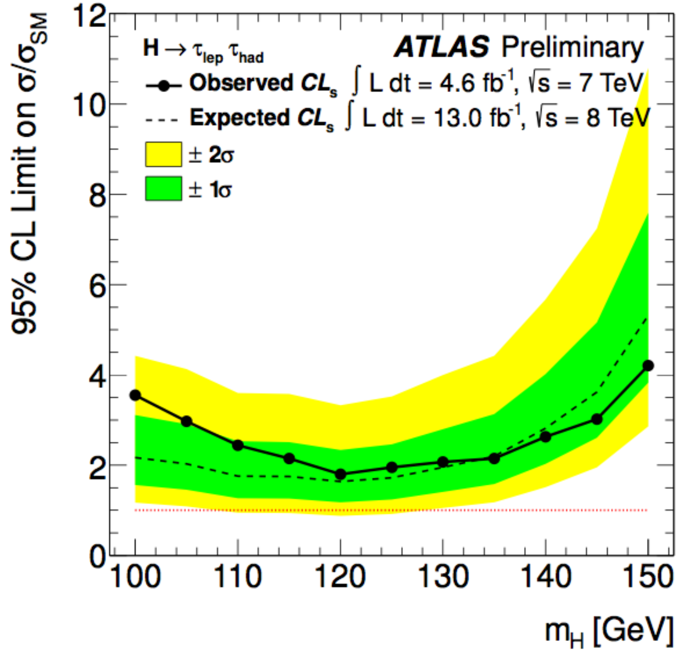
  Hadronization, parton shower, ISR/FSR, underlying event: 10-30% for VBF signal, smaller for others.

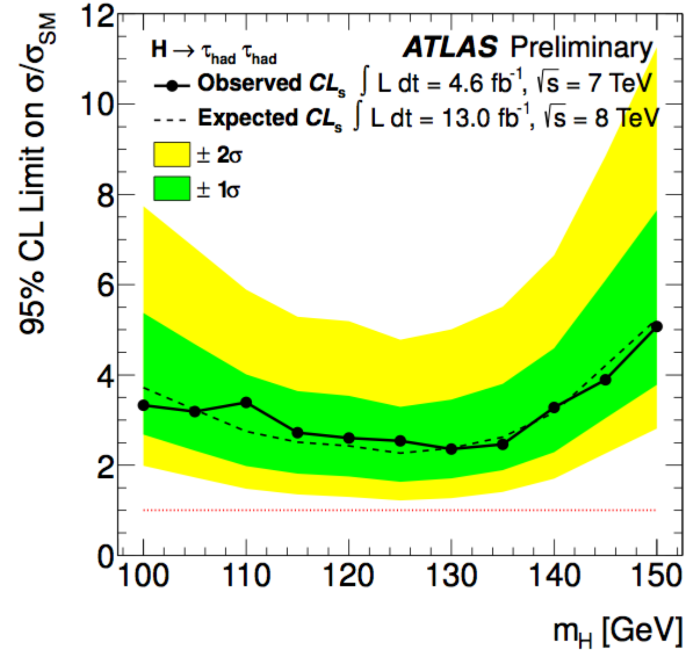
- Background modelling:

  Largest uncertainty is in W+jets fraction estimate in fake-factor method ($\tau_{lep}\tau_{had}$, VBF): ~50%.

Limits on Higgs cross section







- Most sensitive channel:

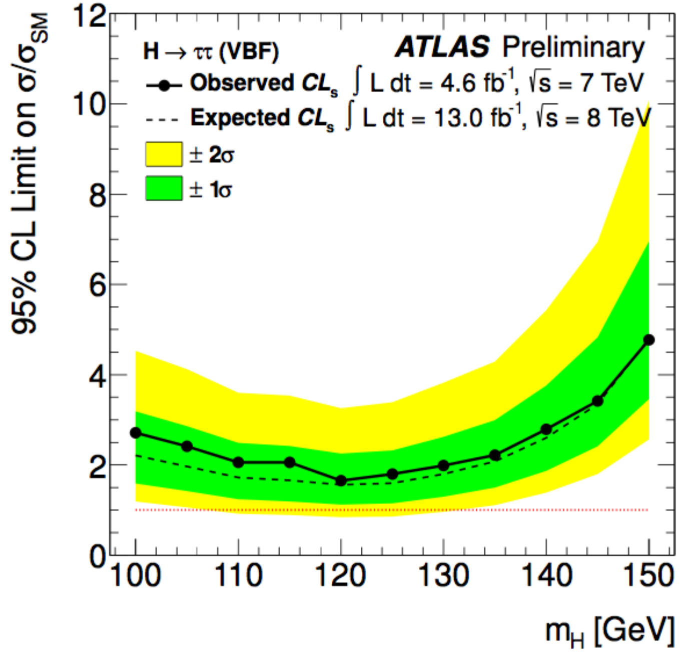
  $H \rightarrow \tau_{lep}\tau_{had}$

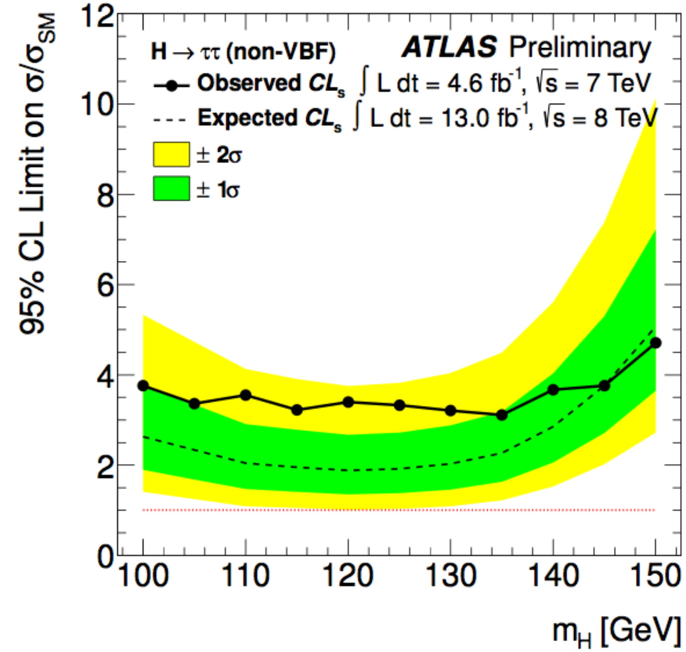
- Most sensitive categories:

  $H \rightarrow \tau_{lep}\tau_{lep}$ VBF

  $H \rightarrow \tau_{lep}\tau_{had}$ boosted, VBF, 1-jet

  $H \rightarrow \tau_{had}\tau_{had}$ VBF





MSSM $h/A/H \rightarrow \tau\tau$

Expected yields and observed number of events

	b-tagged sample		b-vetoed sample	
$Z/\gamma^* \to \tau^+\tau^-$	109	± 12	11000	± 1000
$W+$jets	1.2	$^{+1.1}_{-0.9}$	111	± 23
$Z/\gamma^* \to \ell^+\ell^-$	1.1	± 0.8	196	$^{+22}_{-23}$
$t\bar{t}$	56	$^{+11}_{-9}$	150	$^{+60}_{-50}$
Single top	16	$^{+3}_{-4}$	35	± 5
Diboson	3.9	± 0.7	470	± 50
Multi-jet	15	± 11	980	± 230
Total	201	$^{+20}_{-19}$	13000	± 1000
Signal $m_A = 150\,\text{GeV}, \tan\beta = 20$				
$b\bar{b}(h/A/H \to \tau\tau)$	18	$^{+4}_{-5}$	270	$^{+40}_{-50}$
$gg \to h/A/H \to \tau\tau$	2.3	± 0.8	143	$^{+23}_{-21}$
Data	181		12947	

	Muon Channel ($\tau_\mu\tau_{\text{had}}$)			
	b-tagged sample		b-vetoed sample	
$Z/\gamma^* \to \tau^+\tau^-$	86	± 15	4800	± 700
$W+$jets	19	$^{+6}_{-8}$	780	$^{+100}_{-140}$
$Z/\gamma^* \to \ell^+\ell^-$	8	$^{+5}_{-4}$	350	$^{+100}_{-90}$
Top	14.5	$^{+3.5}_{-2.7}$	105	$^{+20}_{-21}$
Diboson	0.8	± 0.4	38	$^{+6}_{-5}$
Multi-Jet	51	± 11	580	$^{+140}_{-130}$
Total	180	± 20	6600	± 800
Signal $m_A = 150\,\text{GeV}, \tan\beta = 20$				
$b\bar{b}(h/A/H \to \tau\tau)$	20	$^{+5}_{-6}$	174	$^{+27}_{-35}$
$gg \to h/A/H \to \tau\tau$	1.2	± 0.6	115	± 16
Data	202		6424	

	b-tagged sample		b-vetoed sample	
Multi-jet	19	± 5	870	± 50
$Z/\gamma^* \to \tau^+\tau^-$	4.0	± 3.0	300	$^{+80}_{-70}$
$W+$jets	0.5	$^{+0.5}_{-0.4}$	50	± 20
Top	1.7	± 0.6	11.2	± 2.2
Diboson	0.01	± 0.04	4.9	± 1.0
Total	25	± 5	1200	$^{+80}_{-70}$
Signal $m_A = 150\,\text{GeV}, \tan\beta = 20$				
$b\bar{b}(h/A/H \to \tau\tau)$	7.7	± 3.4	73	± 21
$gg \to h/A/H \to \tau\tau$	0.5	± 0.2	47	± 11
Data	27		1223	

	Electron Channel ($\tau_e\tau_{\text{had}}$)			
	b-tagged sample		b-vetoed sample	
$Z/\gamma^* \to \tau^+\tau^-$	42	± 20	2700	± 500
$W+$jets	18	$^{+9}_{-12}$	740	$^{+110}_{-160}$
$Z/\gamma^* \to \ell^+\ell^-$	19	± 10	700	$^{+350}_{-270}$
Top	15.1	± 3.0	106	$^{+20}_{-21}$
Diboson	1.0	$^{+0.4}_{-0.5}$	29	$^{+5}_{-4}$
Multi-Jet	60	± 15	920	$^{+230}_{-240}$
Total	154	± 30	5200	± 600
Signal $m_A = 150\,\text{GeV}, \tan\beta = 20$				
$b\bar{b}(h/A/H \to \tau\tau)$	15	$^{+3}_{-5}$	138	$^{+22}_{-29}$
$gg \to h/A/H \to \tau\tau$	1.2	$^{+0.6}_{-0.4}$	99	$^{+15}_{-14}$
Data	175		5034	