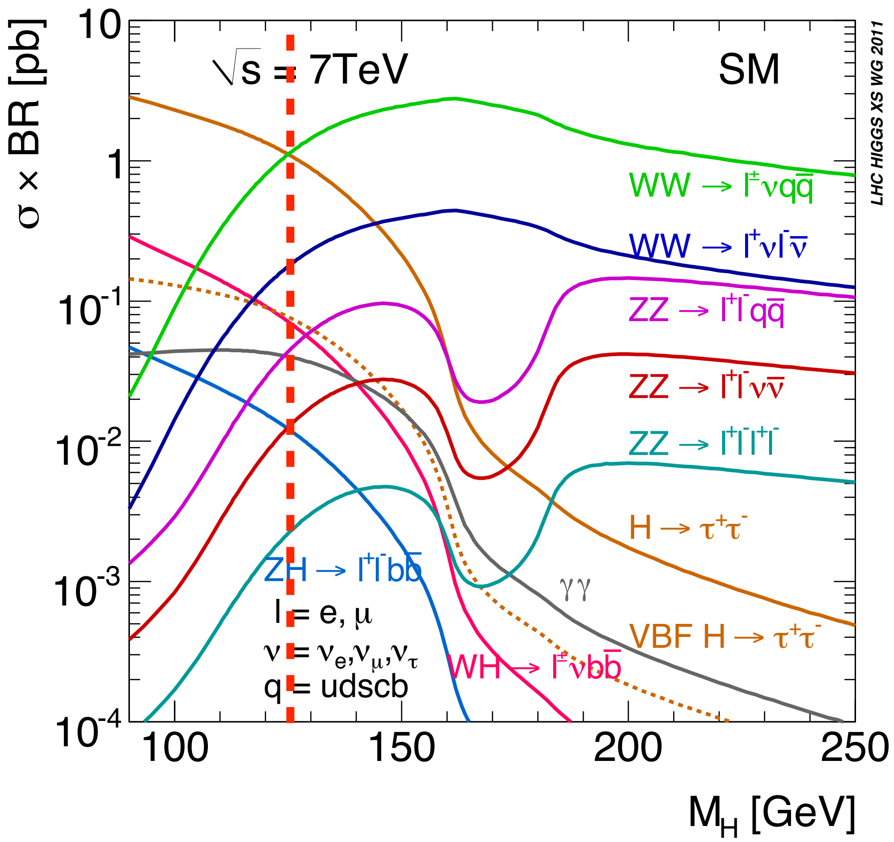
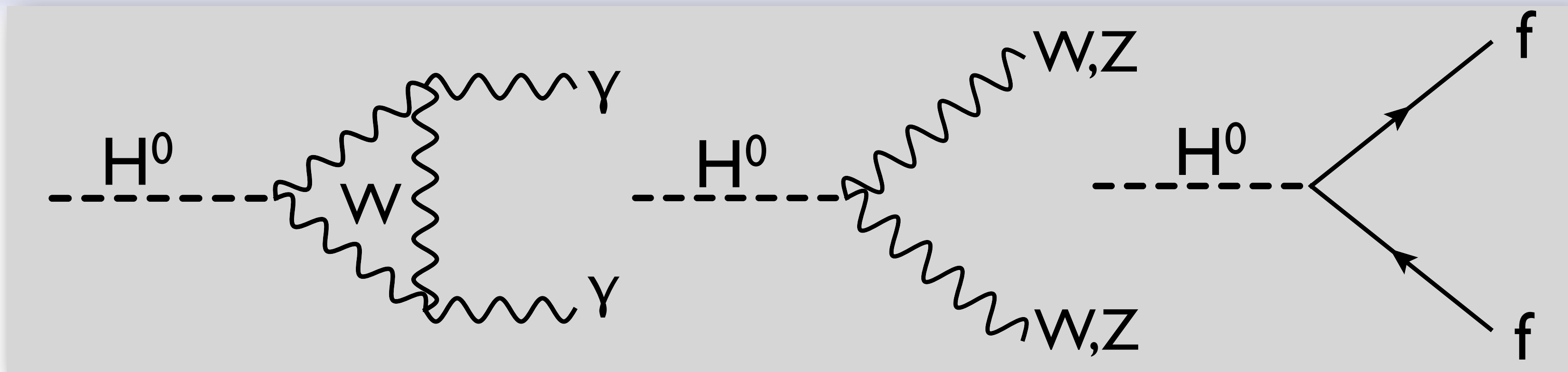
SM H→ττ search with ATLAS

Thomas Schwindt

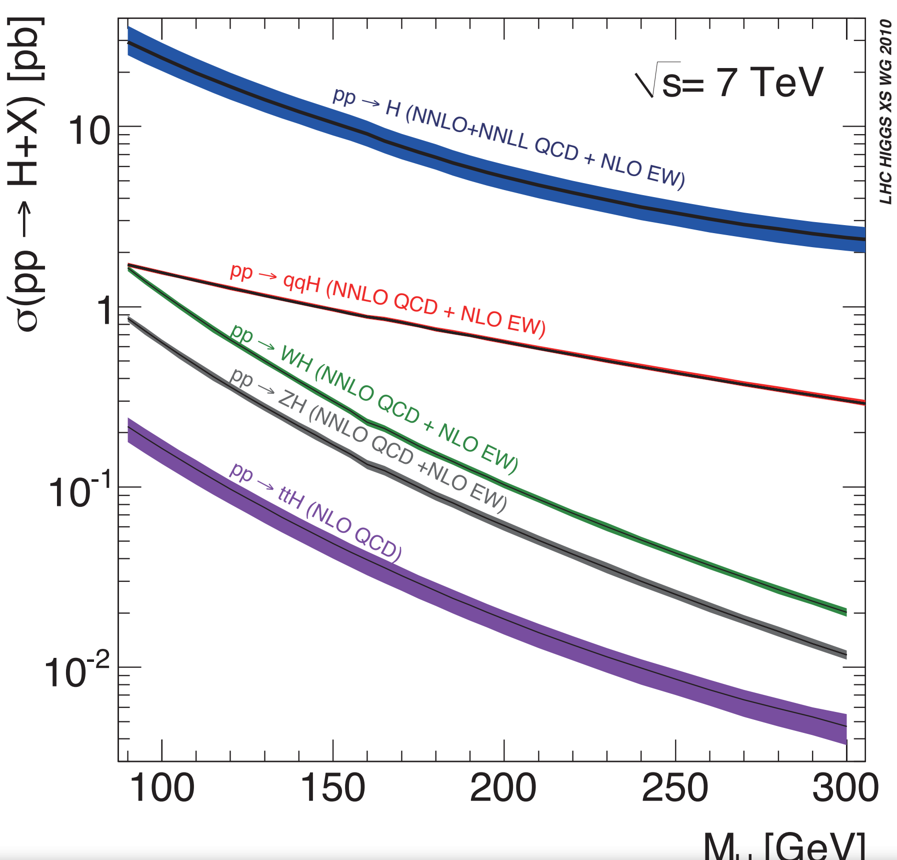
based on 4.6 + 13 fb^{-1} of data collected in 2011-2012, documented in ATLAS-CONF-2012-160

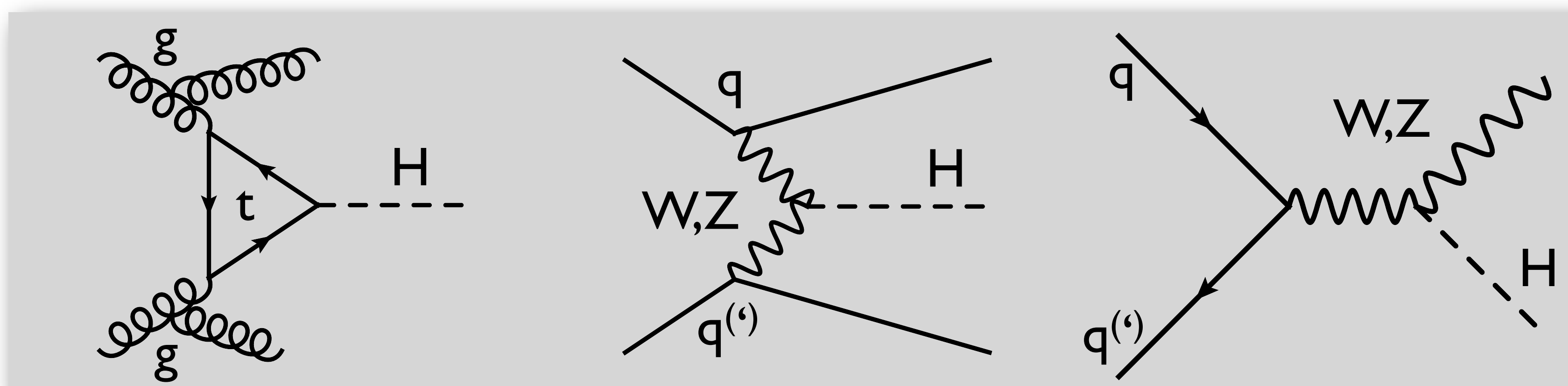
Motivation: H→ττ





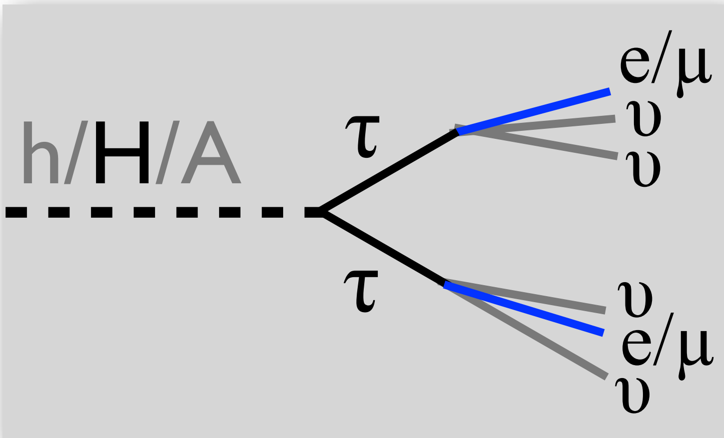
- H→ττ has one of the largest branching fractions for low masses, also for discovered Higgs-like resonance (m_H=126 GeV)
- However, still need to confirm its Yukawa couplings, giving masses to fermions (only indirectly via loops so far?)



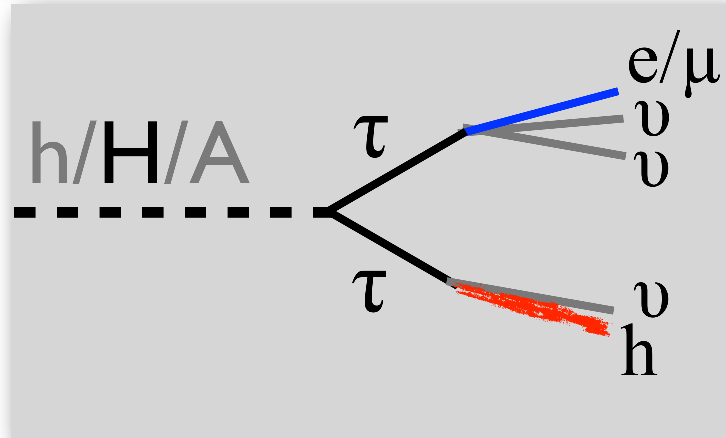


- In SM three main production channels:
  - gluon-fusion (ggH), qqH (VBF), associated (VH)
  - can exploit specific jet topologies in analysis

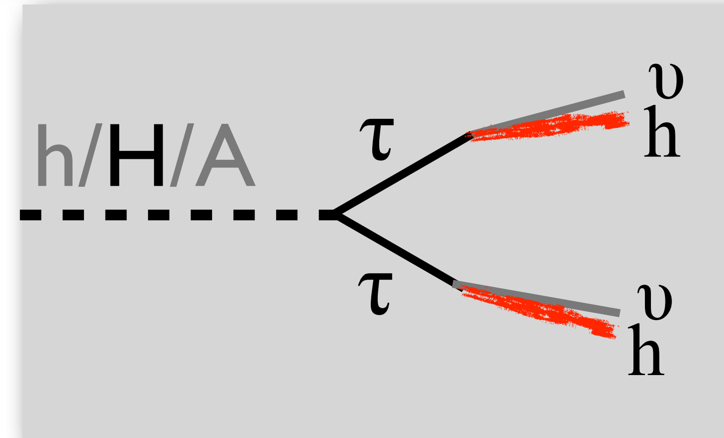
H→ττ final states



$H \rightarrow \tau_{lep}\tau_{lep} \rightarrow \ell\ell 4\nu$ (12.4%)

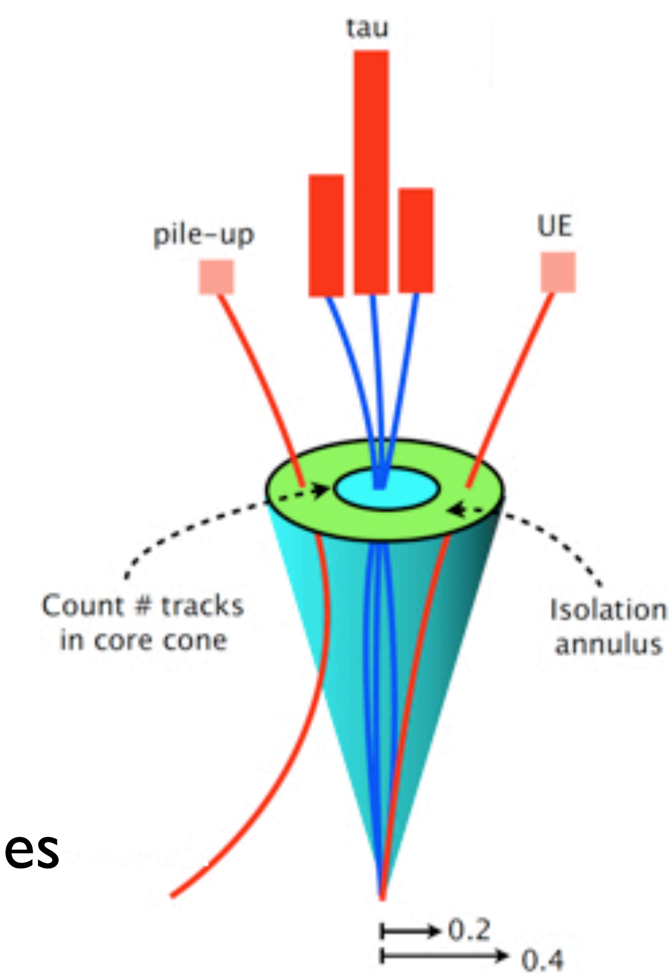


$H \rightarrow \tau_{lep}\tau_{had} \rightarrow \ell h 3\nu$ (45.6%)

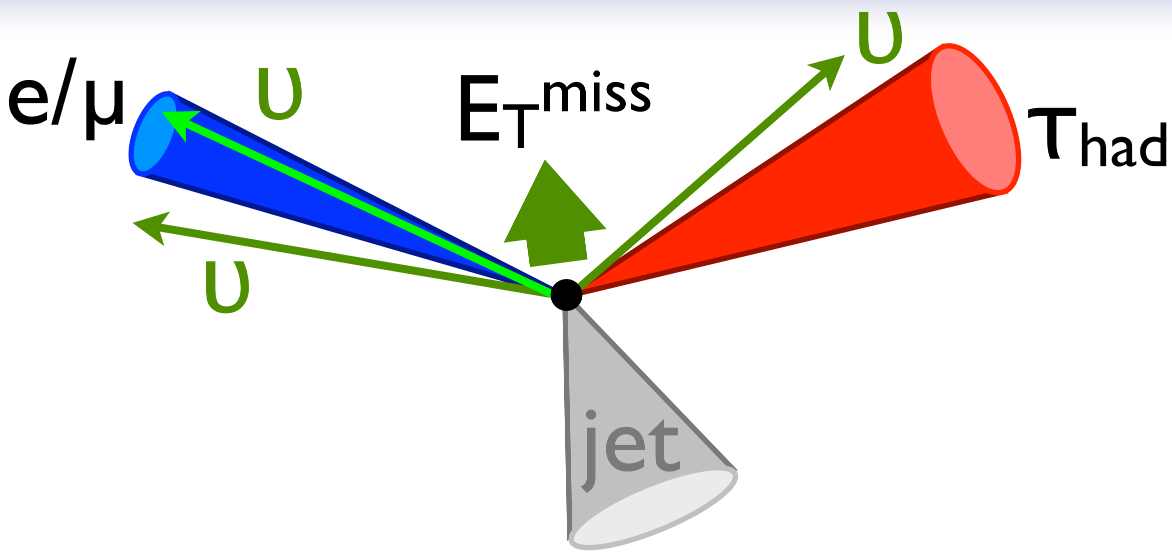


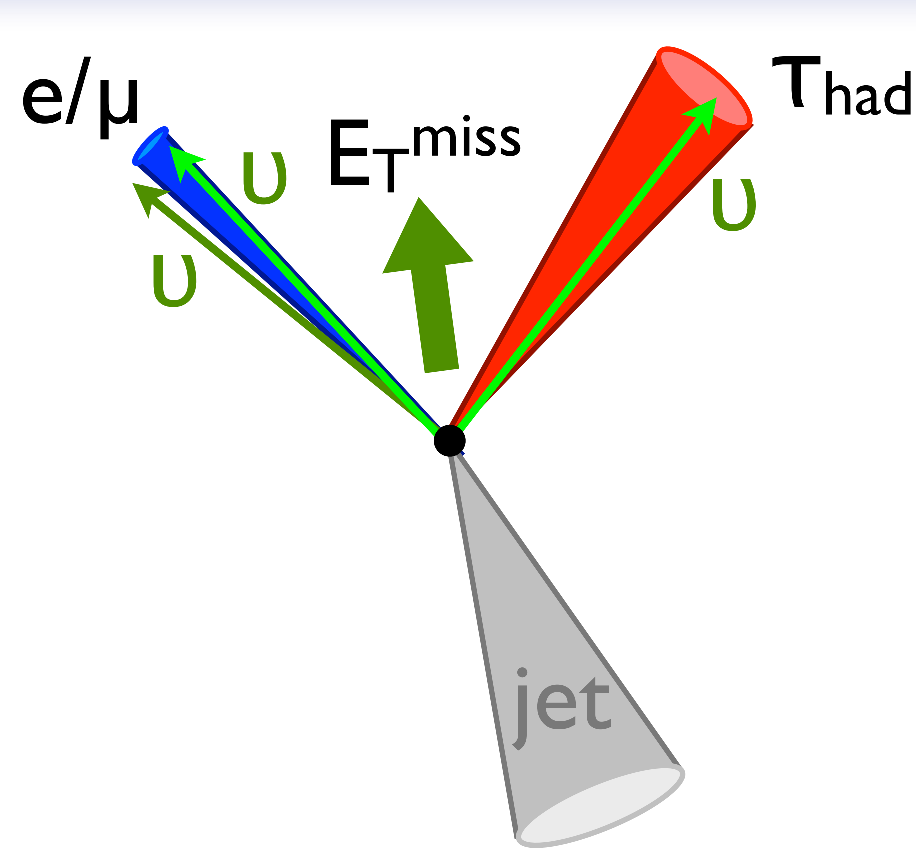
$H \rightarrow \tau_{had}\tau_{had} \rightarrow hh 2\nu$ (42.0%)

- τ-leptons subsequently decay into e/μ or τ_{had}
- mainly distinguish 3 final states: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
  - different background composition due to isolated leptons
  - important ingredient: separation of "τ-jets" from QCD-jets
- TauID efficiency ~50%, QCD-jet mis-identification < 1%
  - seeded with default anti-k_T (d=0.4) jets, tracks in dR≤0.2
  - separation with BDT based on several pile-up robust variables
    - shower shape, isolation, angular separation, track radius/mass

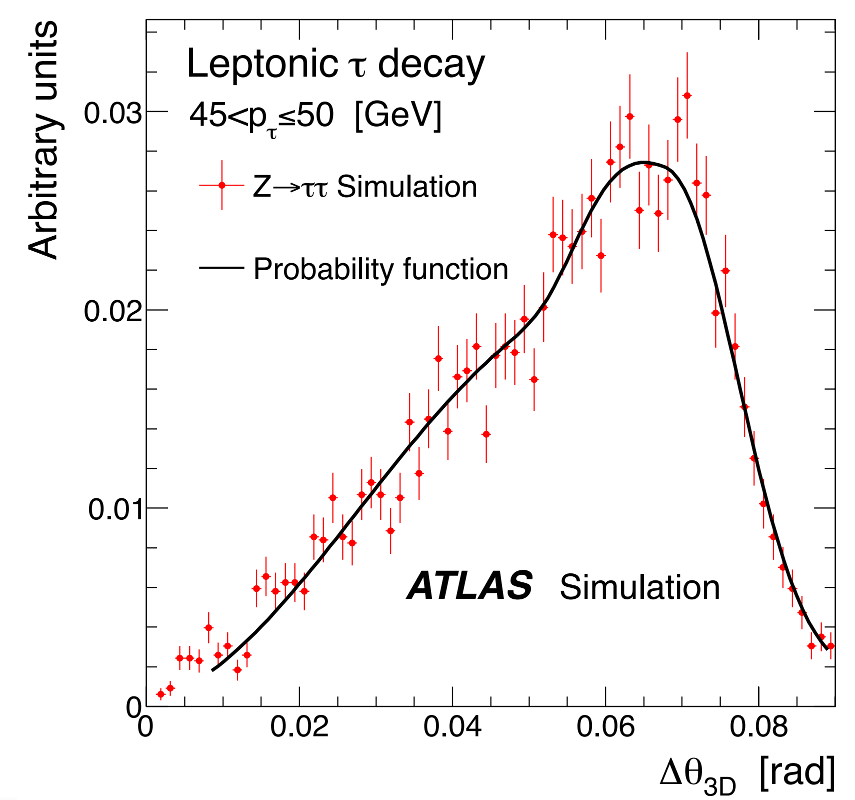


Mass reconstruction

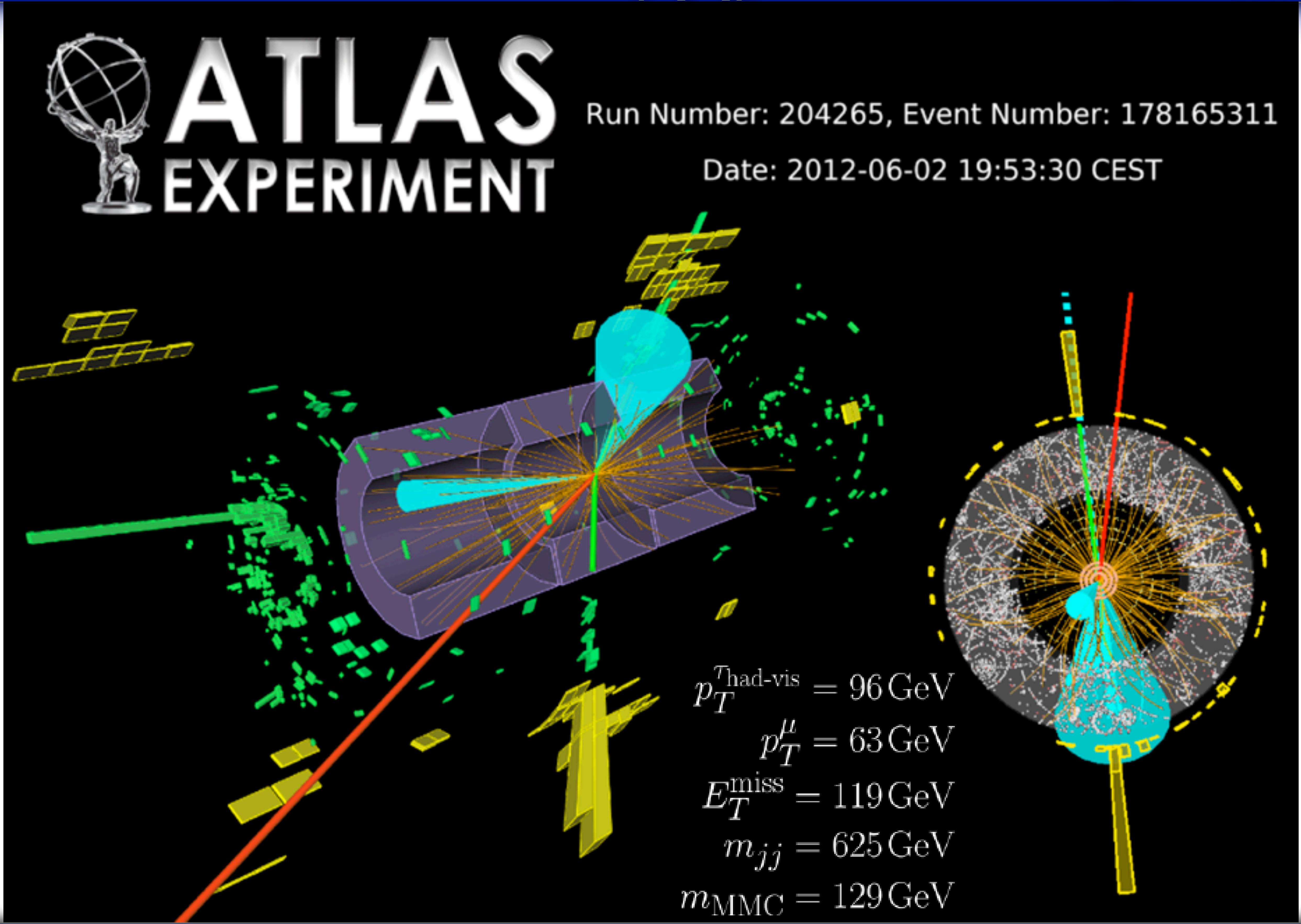




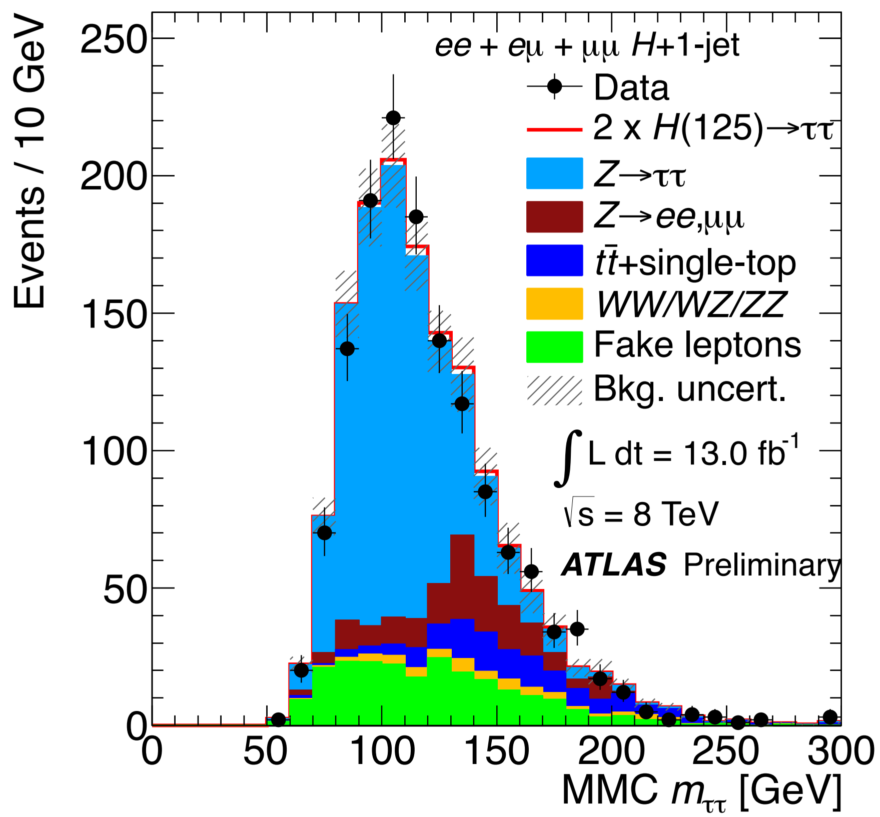
- Invariant mass to be reconstructed from E_T^{miss}
- ***MMC***: Missing Mass Calculator
  - $\Delta\theta_{3D}(\tau_{vis},\upsilon)$ from simulation ➔ weights in $\Delta\varphi(\tau_{vis},\upsilon)$
  - most probable value as the MMC mass estimator
  - A. Elagin et al., NIM A654 (2011), 481-489, arXiv:1012.4686
- Mass resolution dominated by resolution of E_T^{miss}
  - improves with boost of di-τ-resonance

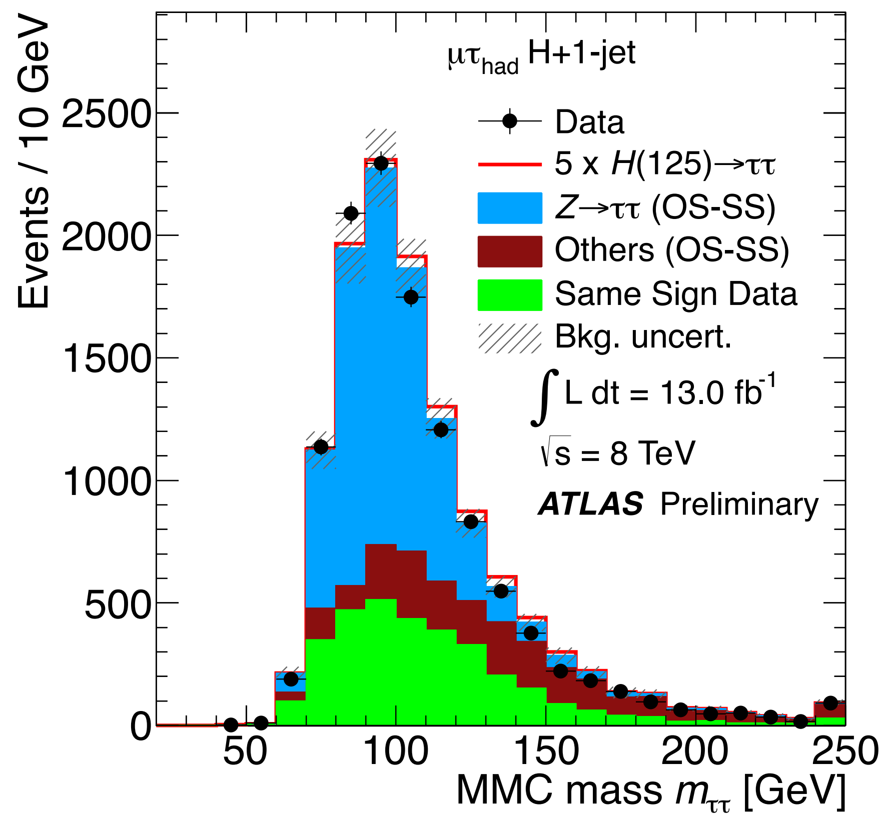


Candidate Event: (qq)H→ττ→μτ$_{had}$



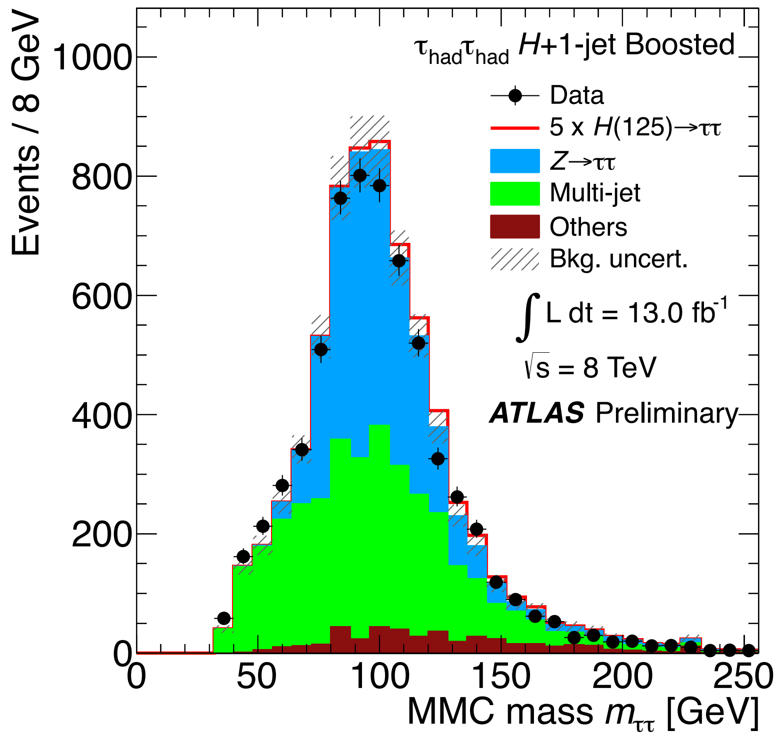
Background estimation (leptonic)



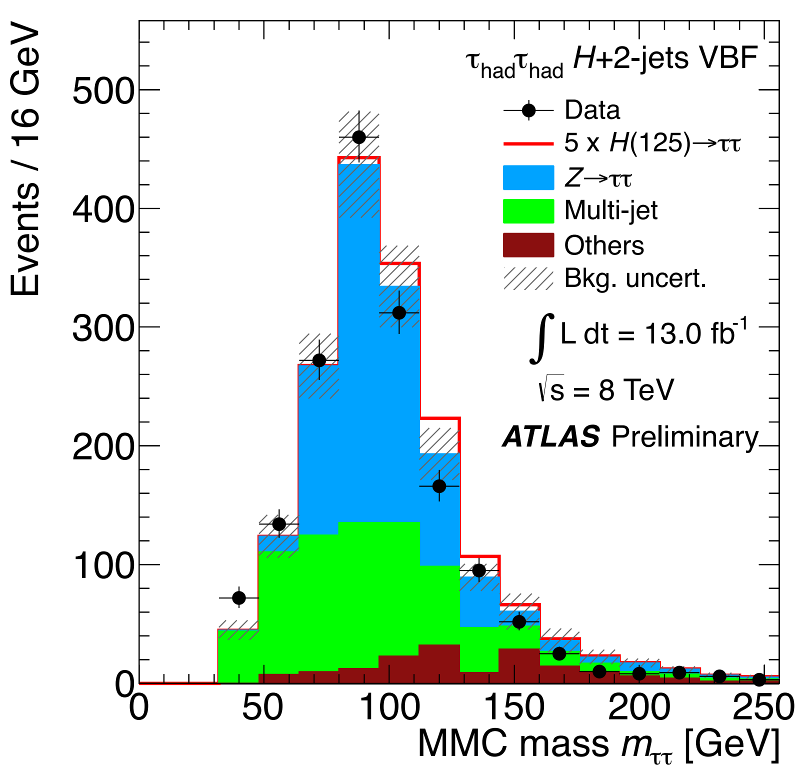


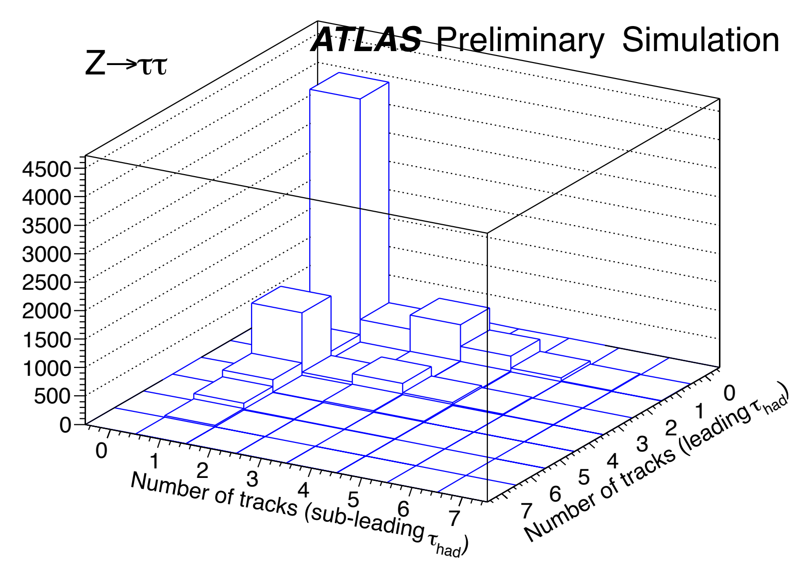
- Multi-jet and W+jets (with mis-identified objects)
  - Leptons (fakes) from jets estimated from template fit to non-isolated data
  - Hadronic τ-decays from data with same-sign charge (OS-SS from simulation)
- Z→ee/μμ (+jets), top, di-boson from simulation, corrections to data from dedicated control regions
- Z→ττ from Z→μμ data, where muons are replaced by τ-decays: "embedding"
  - cannot be estimated from signal-free data control region by construction
  - signal sitting on the right flank of the Z peak - important to be data driven

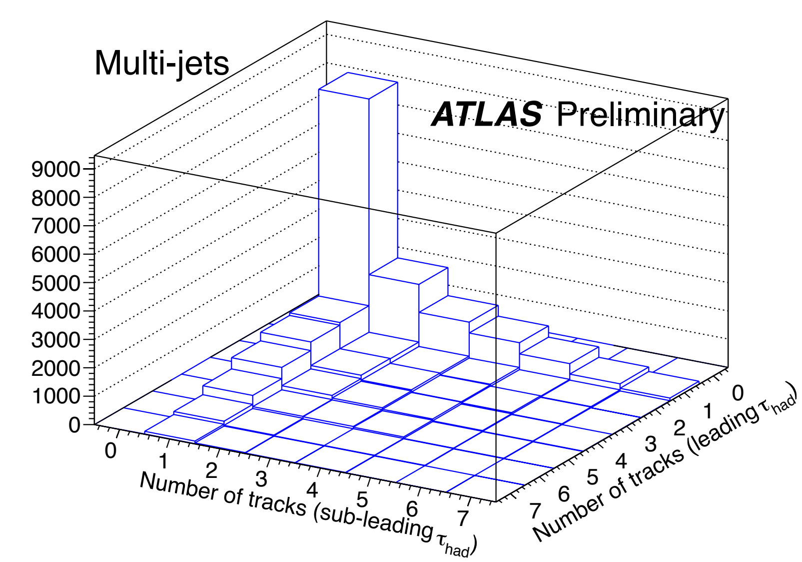
Background estimation (hadronic)



- $Z\rightarrow\tau\tau$ from embedding of $Z\rightarrow\mu\mu$ data
- Multi-jet from data with same-sign charge
- normalization from fit of 2-dimensional track template to data in control region



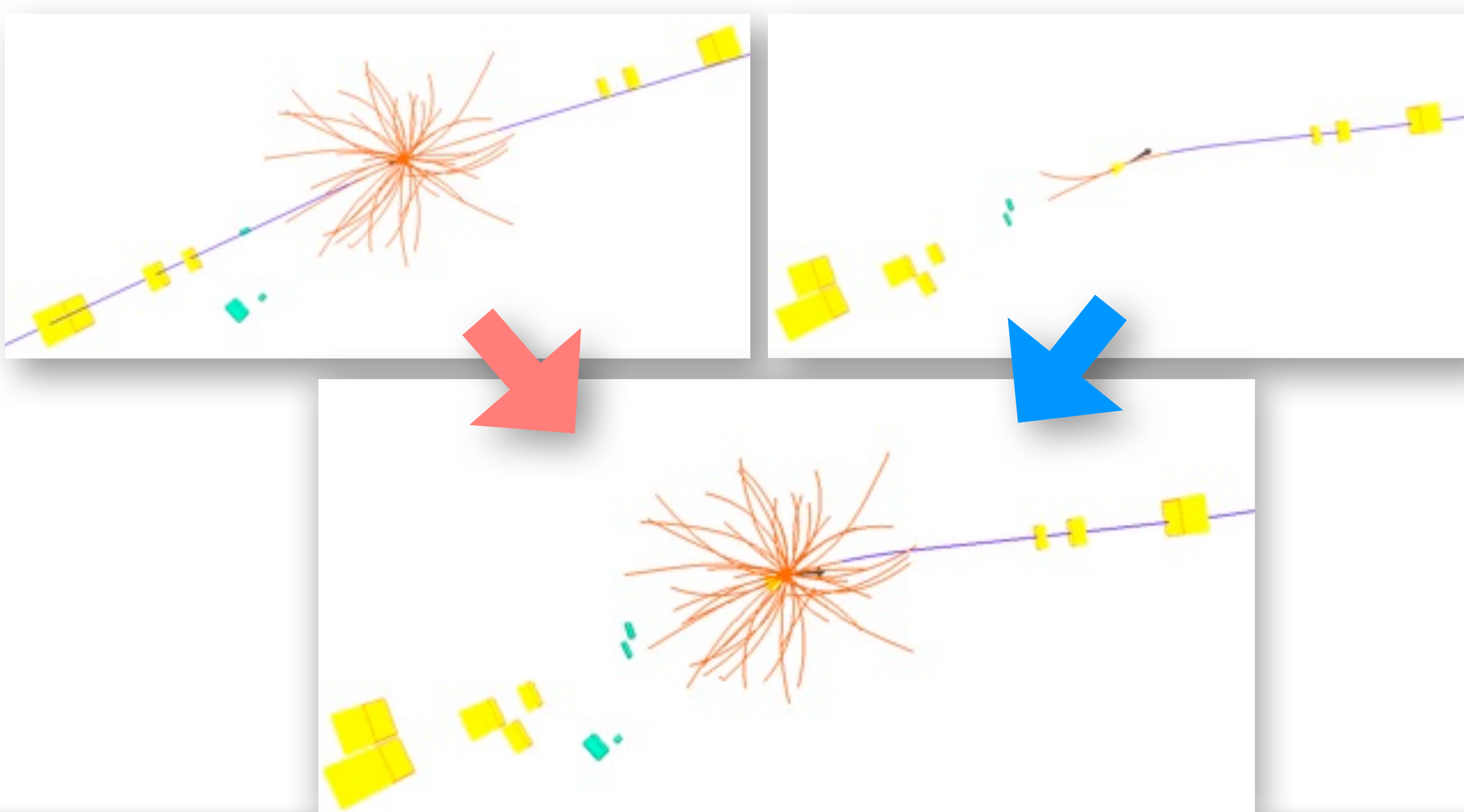


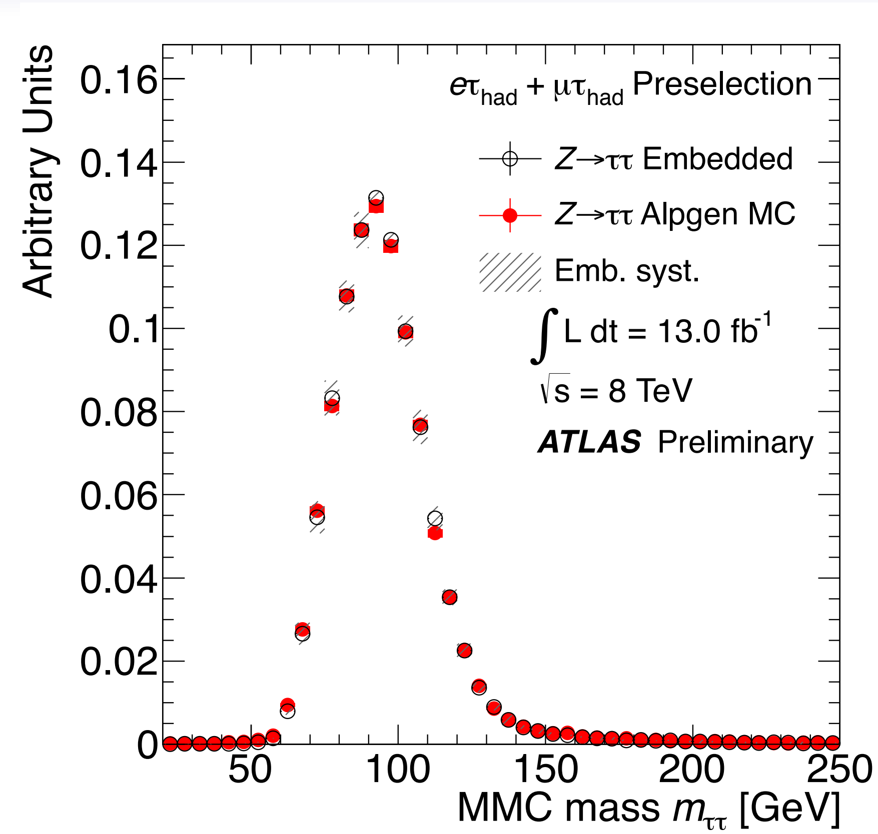


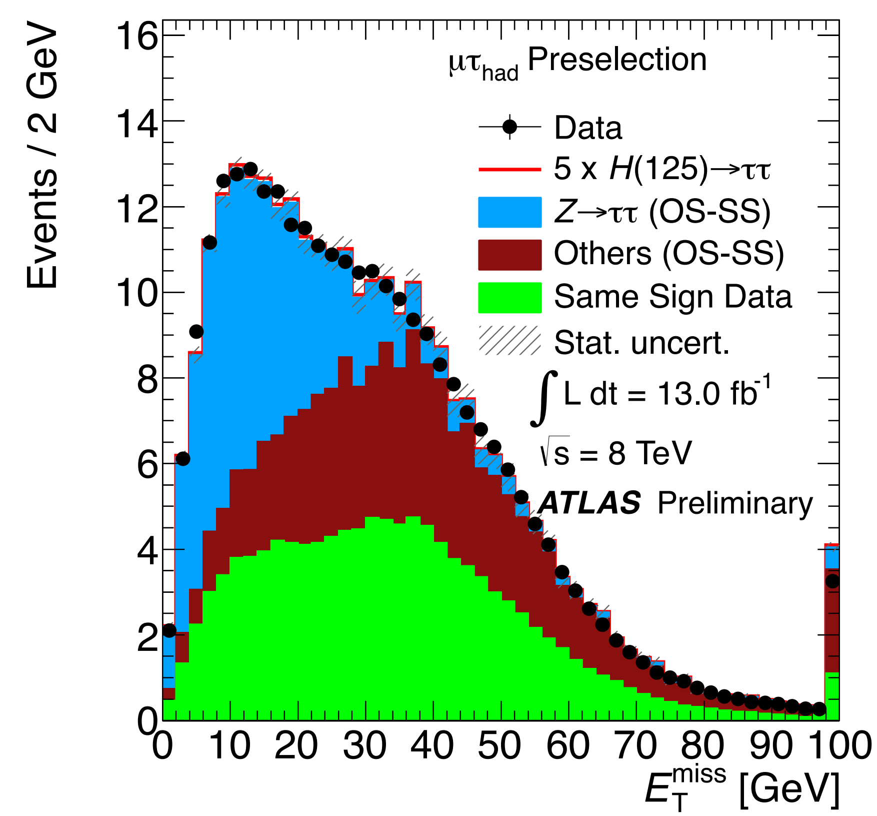
Estimation of $Z\rightarrow\tau\tau$ Background

Important shape of $Z\rightarrow\tau\tau$ from $Z\rightarrow\mu\mu$ data: "***Embedding***"

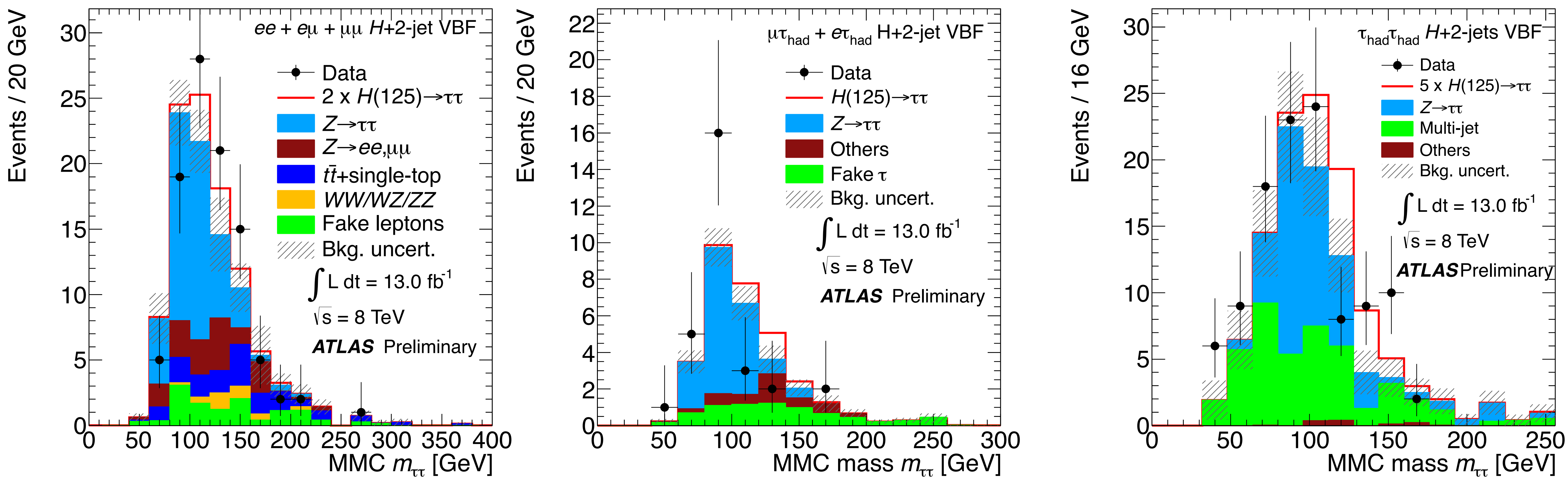
- remove muon tracks and simulated calorimeter energy from data
- replace by full-sim $Z\rightarrow\tau\tau$ decays, generated with Tauola
- re-run full event reconstruction: pile-up, jets and E_T^{miss} from data
- validation with $\mu\rightarrow\mu$ embedding (data to data) and Alpgen MC





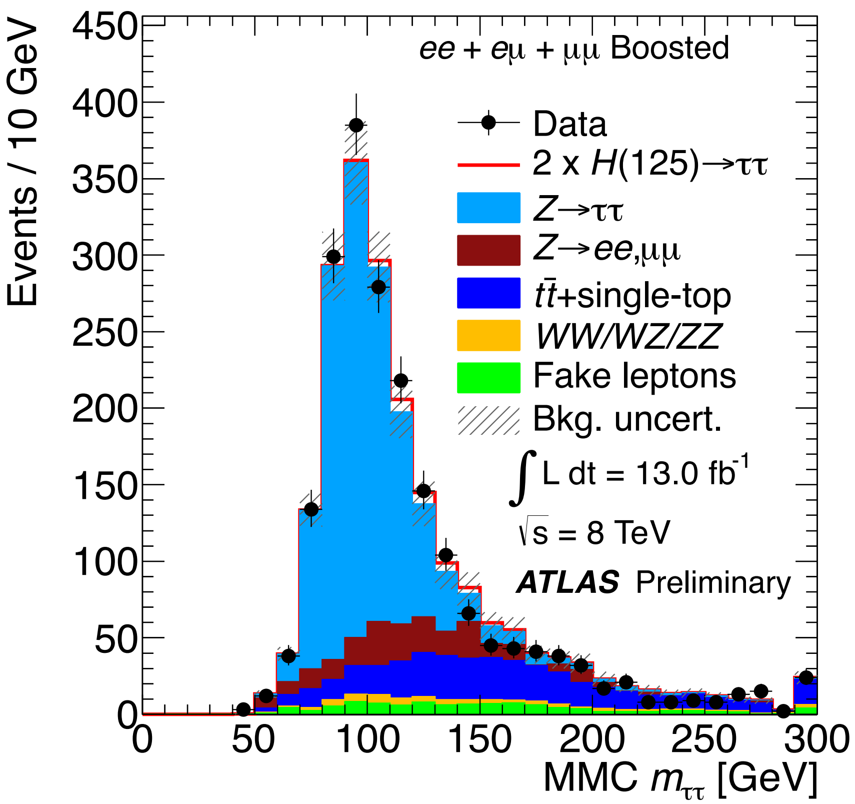


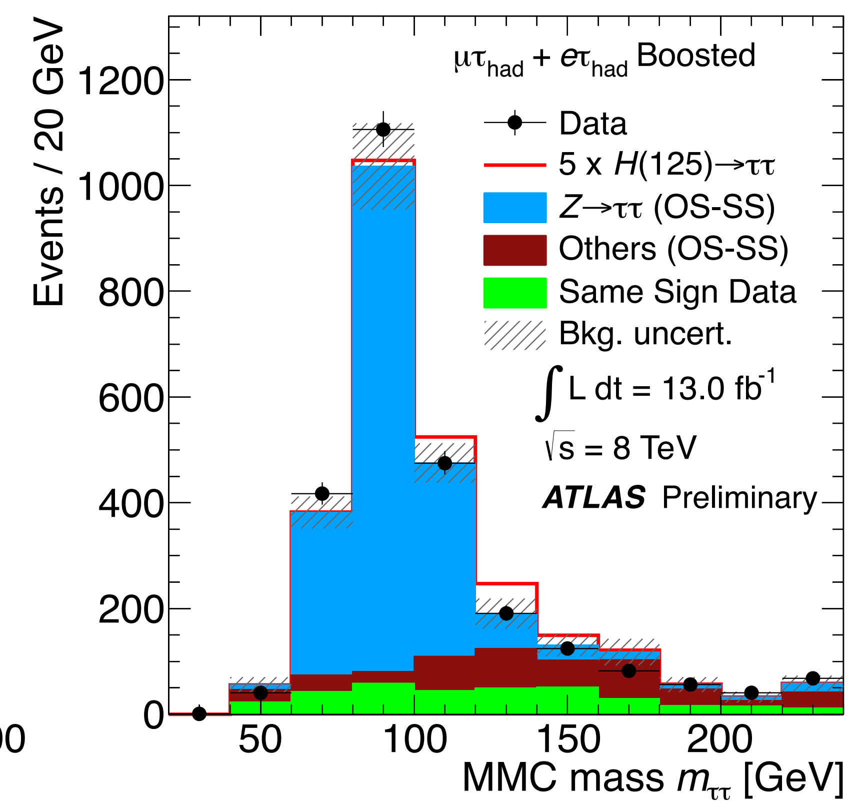
Results: VBF category

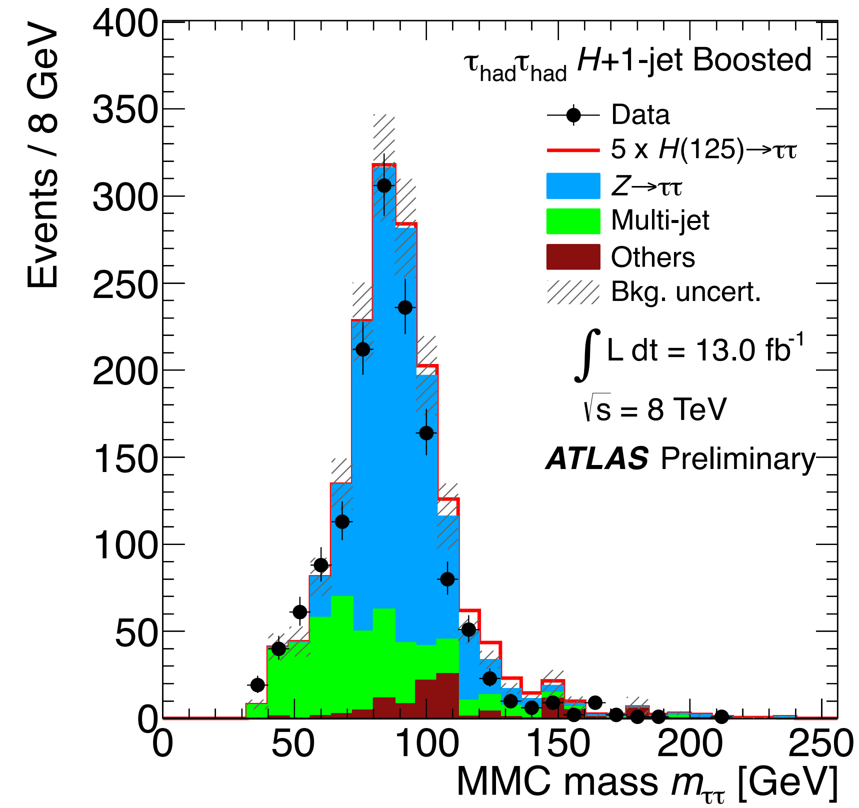


- Most sensitive category in all three channels - exploit production mechanism
  - limited statistics for background estimates, low signal expectation, but best S/B of all analysis categories
  - in lep-had, use VBF-filtered simulation for $Z\rightarrow\tau\tau$, with corrections derived from $Z\rightarrow\mu\mu$ data - systematics lower than from limited embedding statistics

Results: Boosted category (ggF)



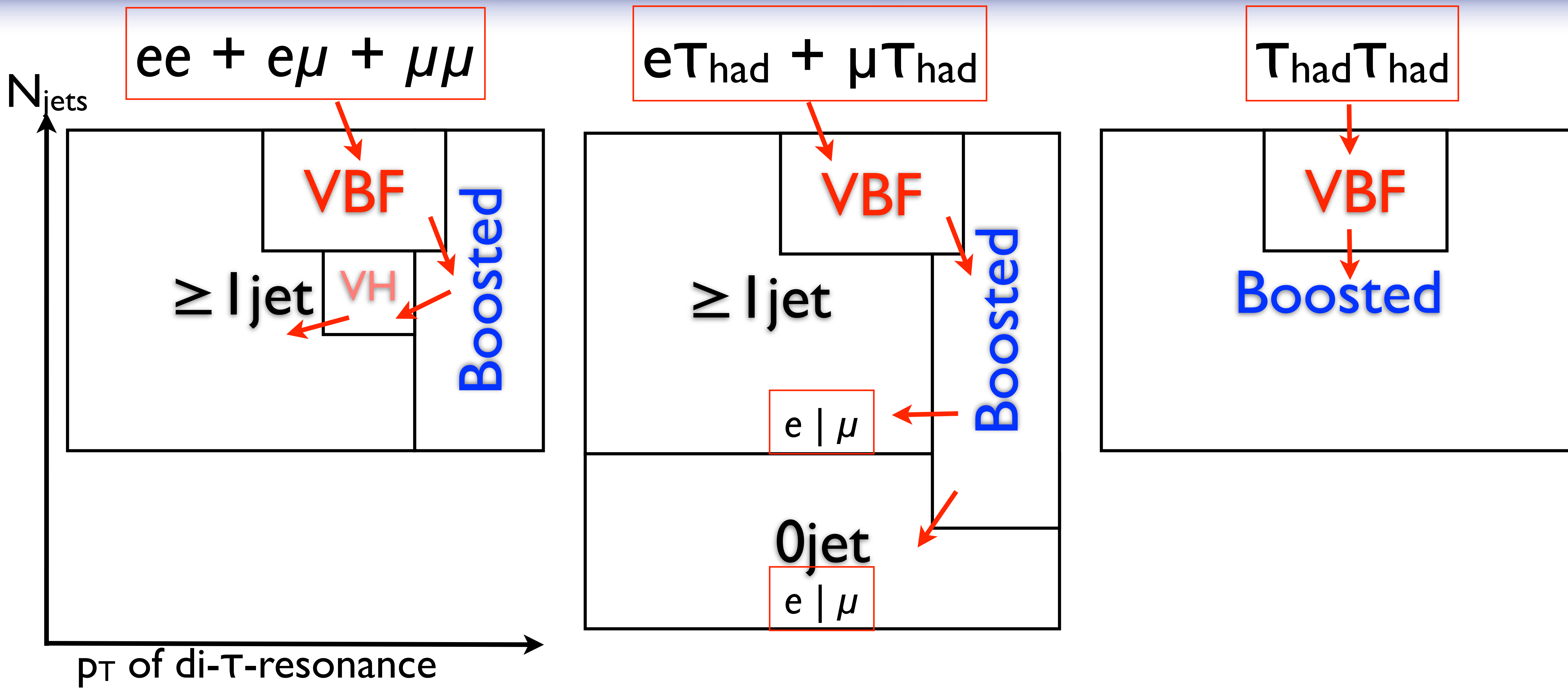




- In total 2nd most sensitive category in all three channels - best for ggH production
  - high p_T of Z/H (or additional jet as recoil) significantly improves mass resolution and S/B separation

- Additional categories (0/1jet) for lep-had and VH for lep-lep included in limit calculation, but overall sensitivity dominated by VBF and “Boosted”

Analysis Categorization



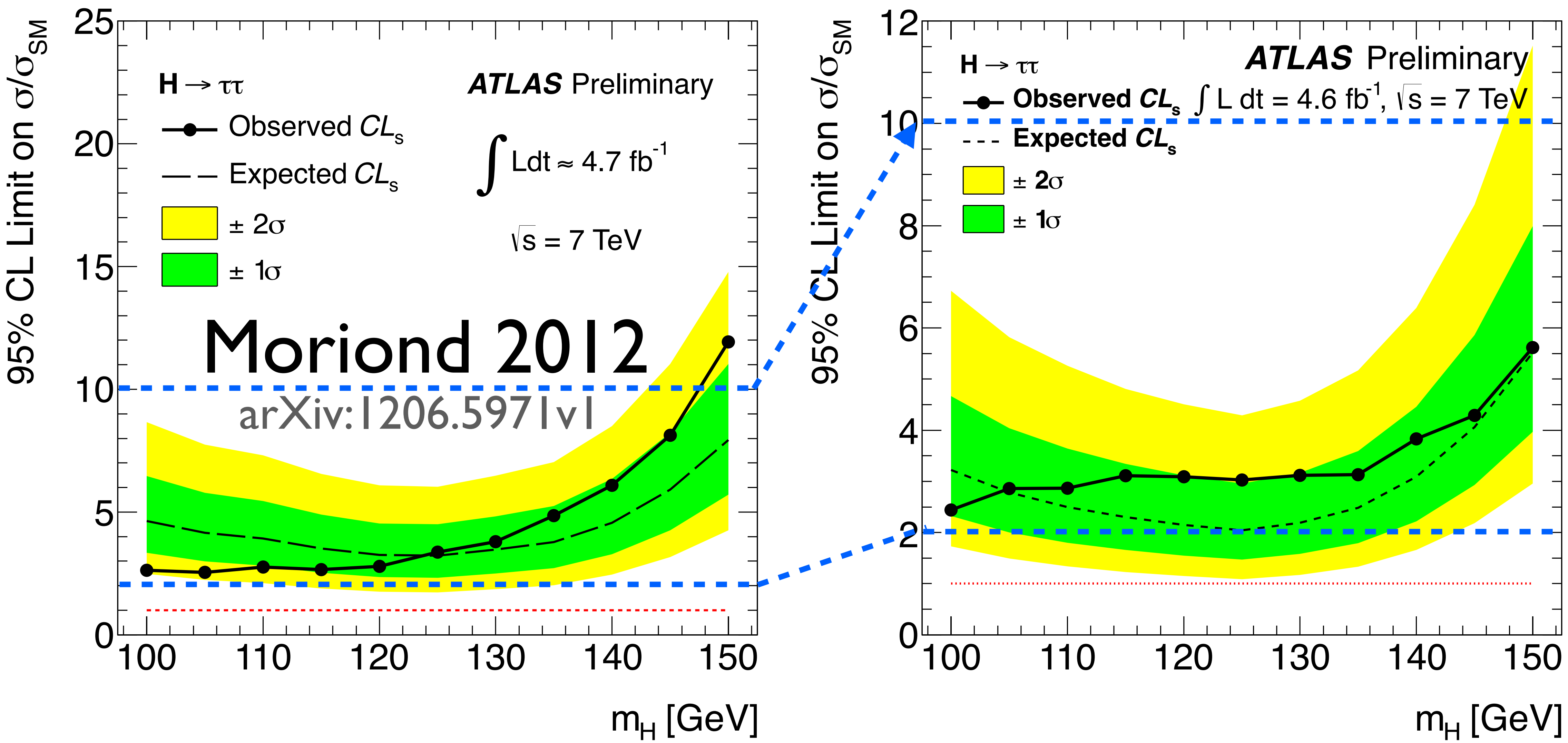
- VBF categories: large di-jet mass and separation in η
  - VH category: small di-jet mass and separation in η
- Boosted categories: high p_T of di-τ-resonance or recoiling jet
- Other categories: additional sensitivity from 0/1jet selection

Systematic uncertainties

- Dominant systematics from Jet/Tau Energy Scale, and embedding uncertainties
  - no JES and less MET systematics for embedding, but TES still from simulation, additional uncertainties from method variation (muon isolation, cell subtraction)
- Since these significantly affect the mass shapes, included as shape systematics

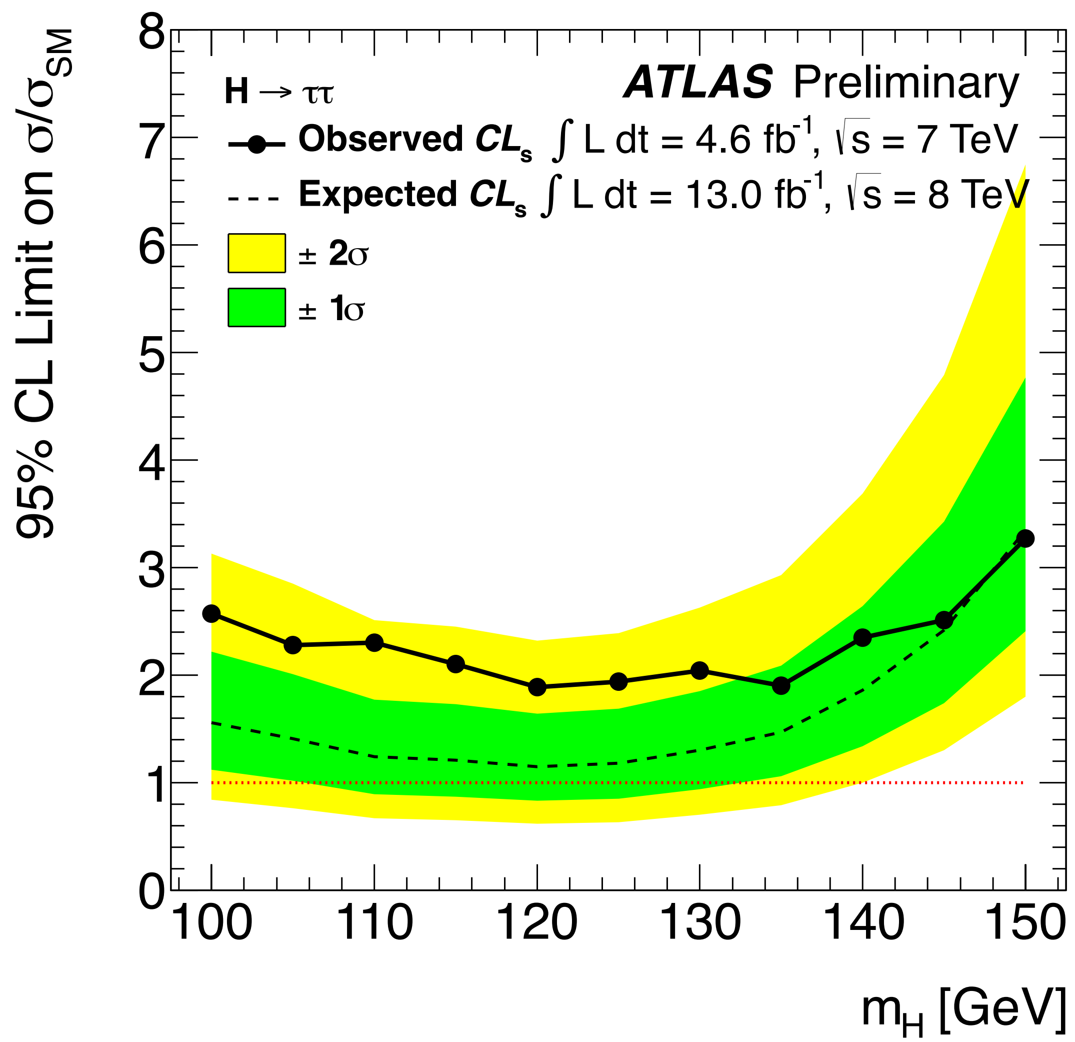
Uncertainty	$H \to \tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$H \to \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$
		$Z \to \tau^+\tau^-$	
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	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%

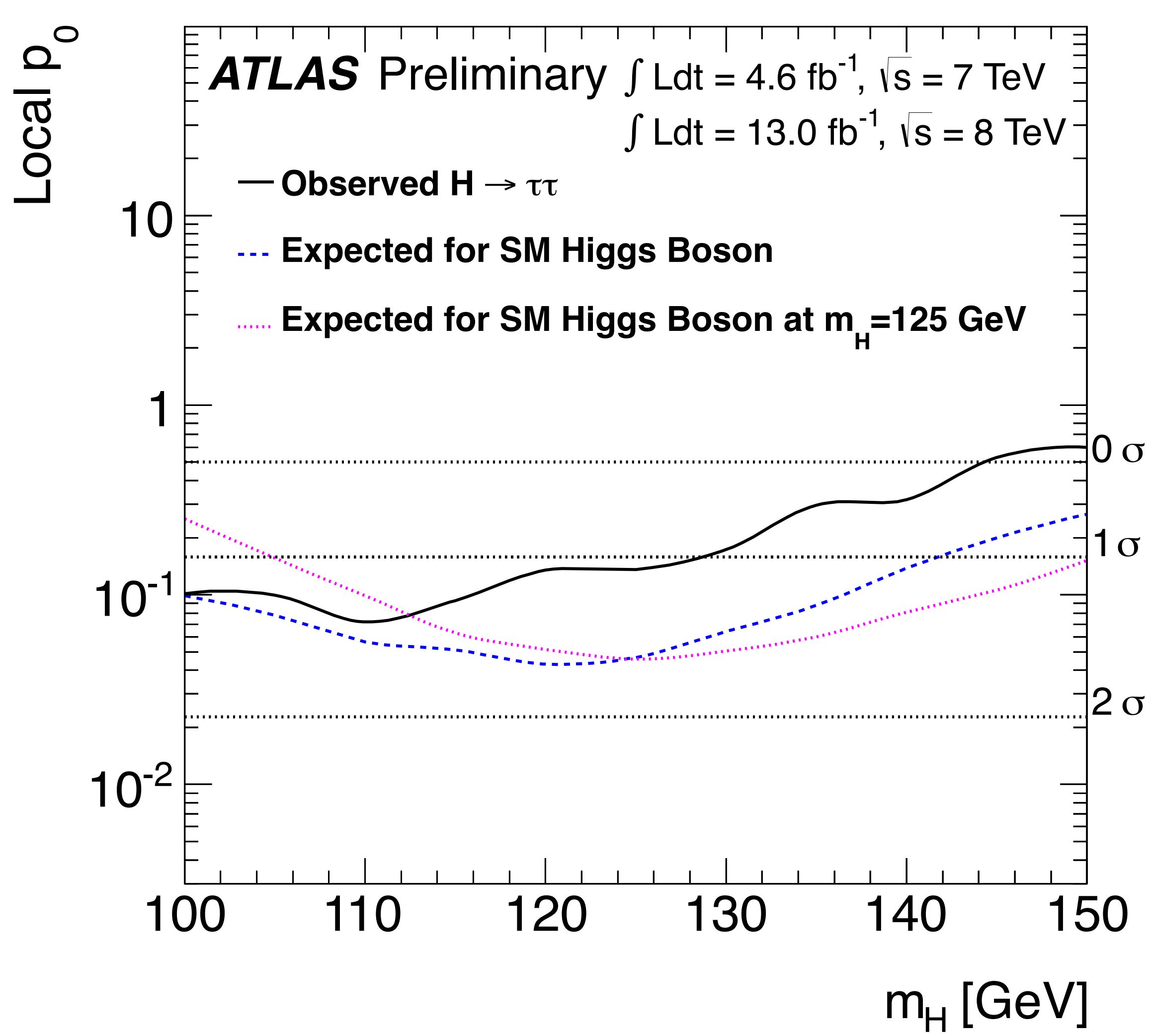
Limits - Improvements for 7 TeV



- Improvements in analysis shown for 7 TeV 2011 data only
  - mainly including boosted category, further optimizing VBF selection
- large improvement from 4xSM to 2xSM with the same dataset

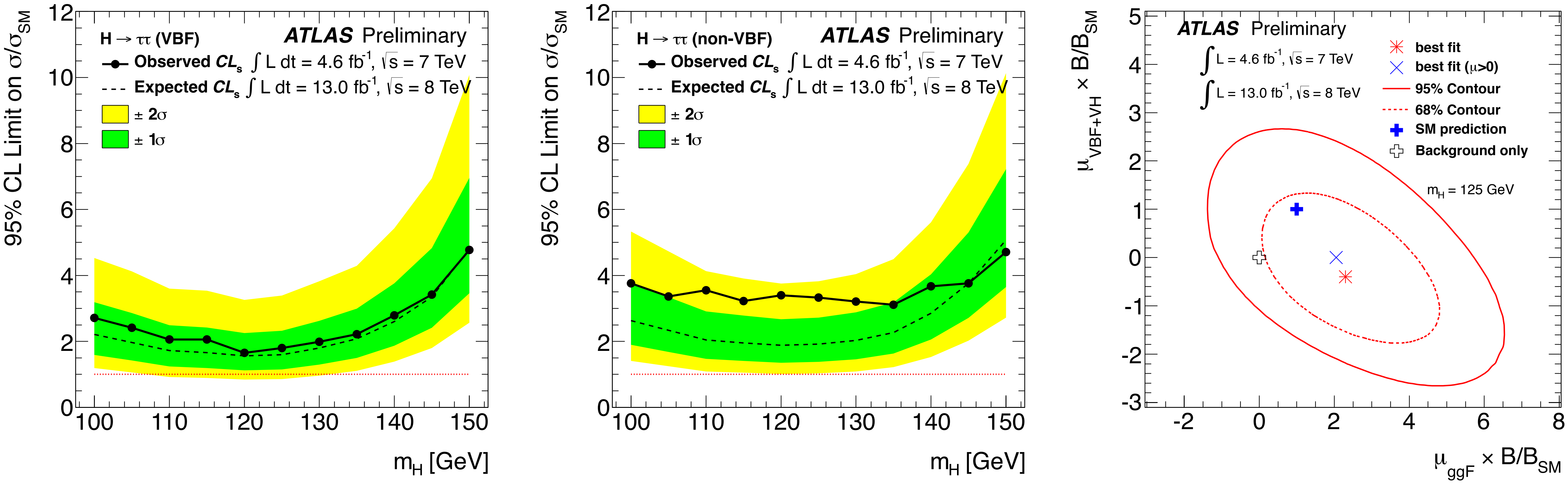
Combined Limits and p_0-Value





- Statistical analysis using profile likelihood from MMC distributions
  - expect exclusion limit (μ=0) of 1.2xSM, but observe only 1.9xSM
  - expect local significance (μ=1) of 1.7xSM, but observe only 1.1xSM
  - observed excess is smaller than expected from a SM Higgs (m_H=126 GeV)

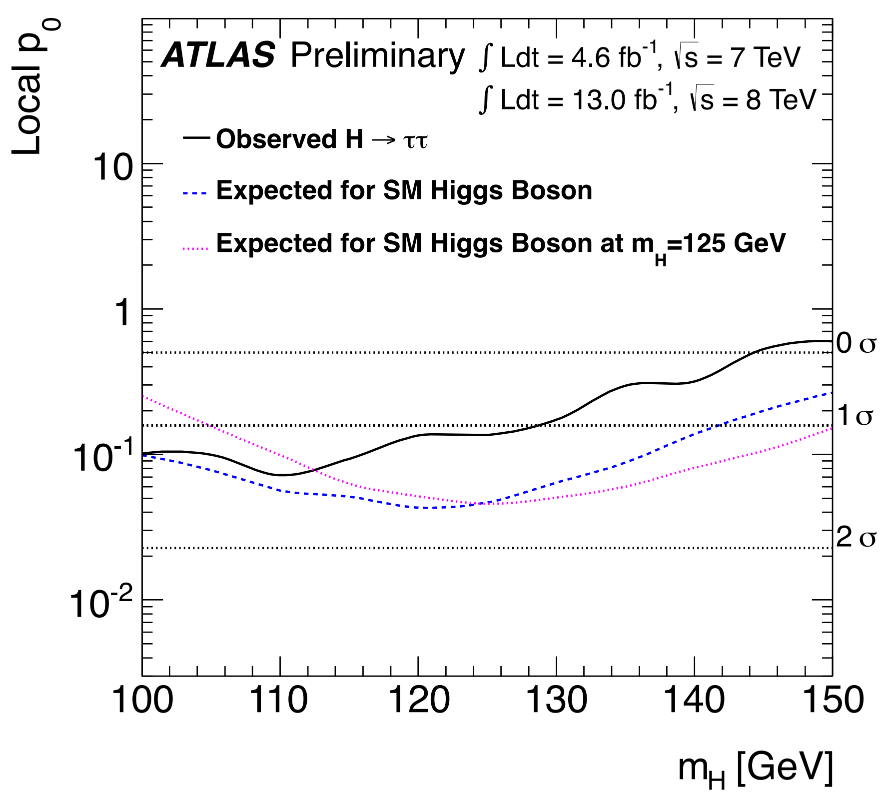
Production Processes?

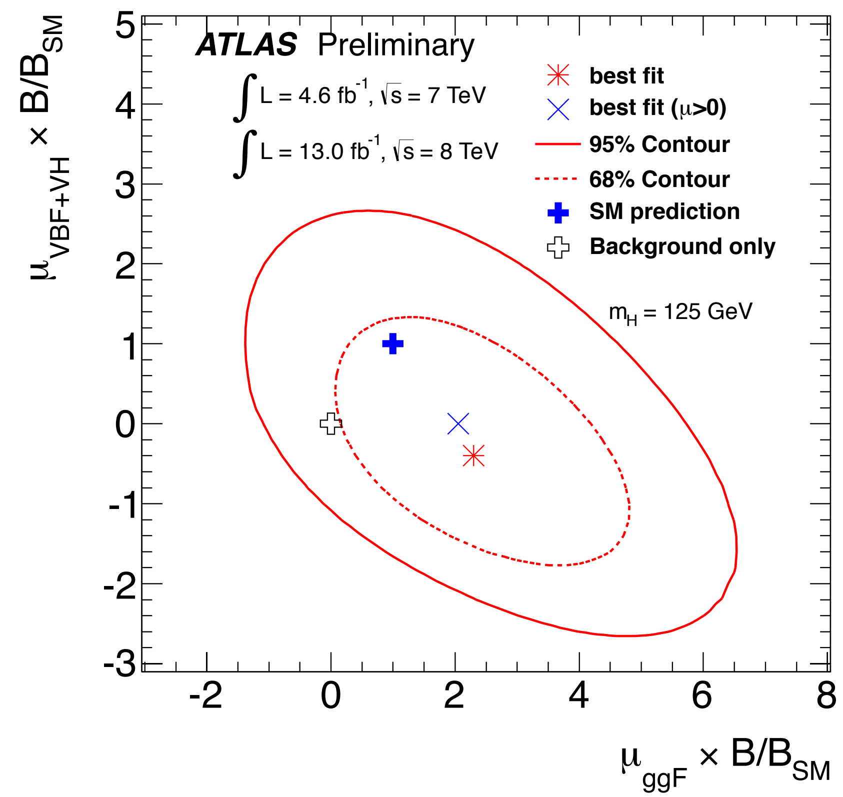


- Observed excess dominated by non-VBF categories
  - observe less data than expected from SM Higgs in VBF
  - best fitted signal strength favours ggF, but a lower contribution from VBF production than expected

Summary

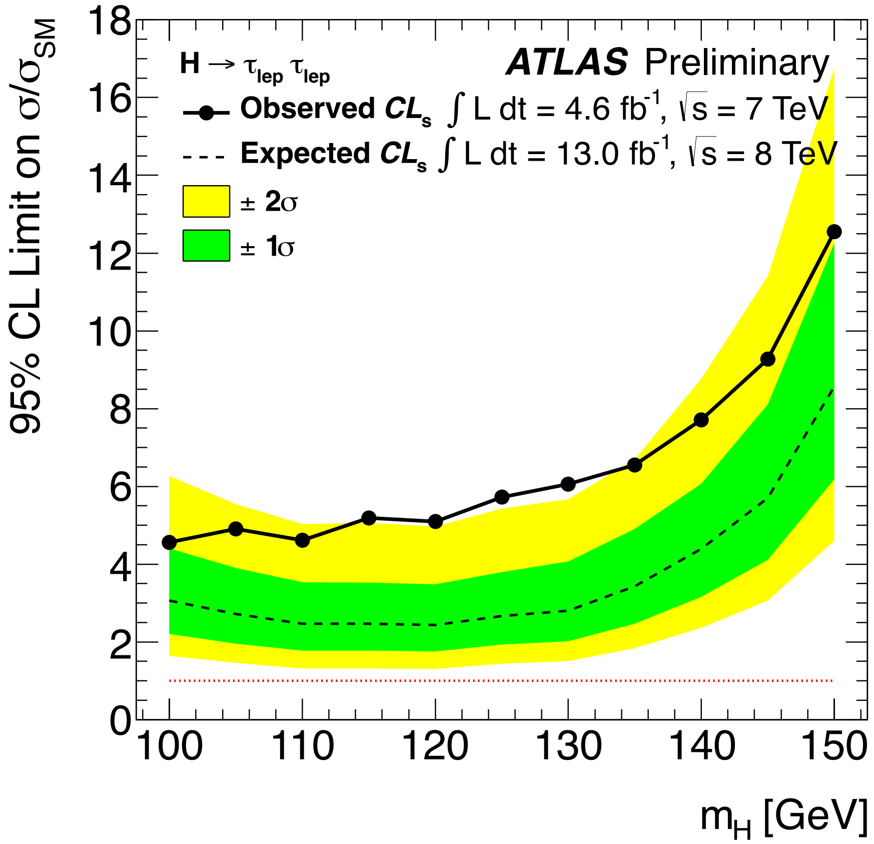
- Combined analysis of 4.6 fb^{-1} (@ 7 TeV) and 13 fb^{-1} (@ 8 TeV) data in three final states
  - Improvements in analysis yield ~50% better sensitivity compared to last result
- Only starting to become sensitive to a SM Higgs - confirmation of fermion couplings still needs more data
  - ***95% CL exclusion (μ=0): 1.2 (1.9) x SM exp. (obs.)***
  - ***local p_0 value (μ=1): 1.7 (1.1) x SM exp. (obs.)***
- Observed data still consistent with either background only or signal, couplings not yet conclusive:
  - ***signal strength (μ_{best}): 0.7 ± 0.7***
  - ***μ^{ggF}_{best} = 2.4, μ^{VBF+VH}_{best} = -0.4***

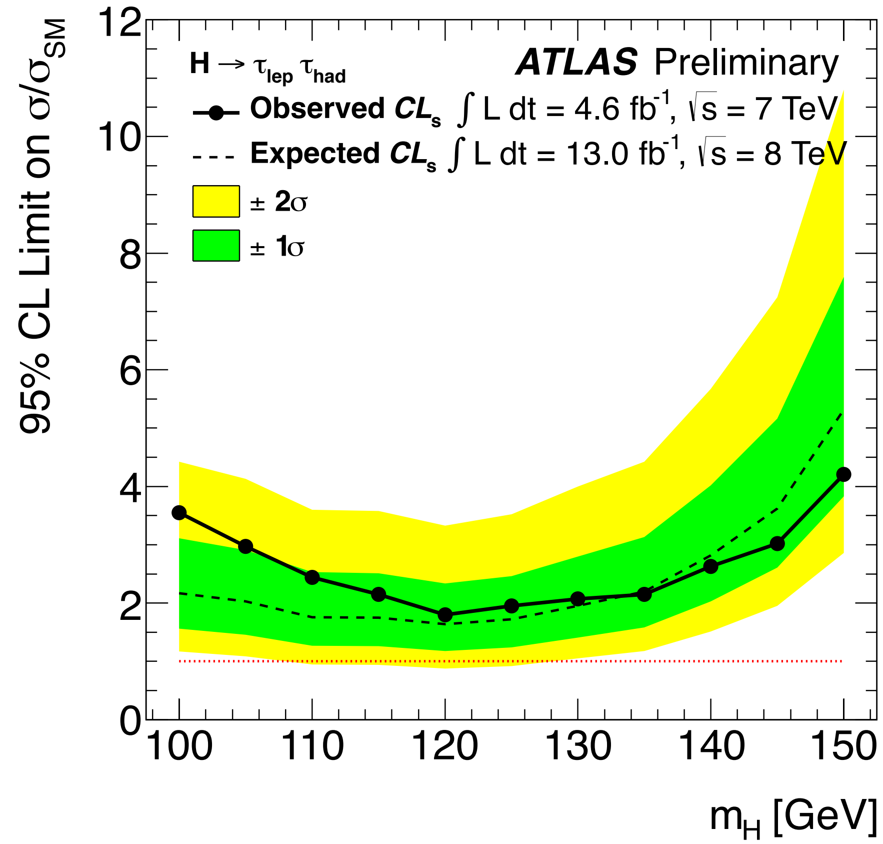


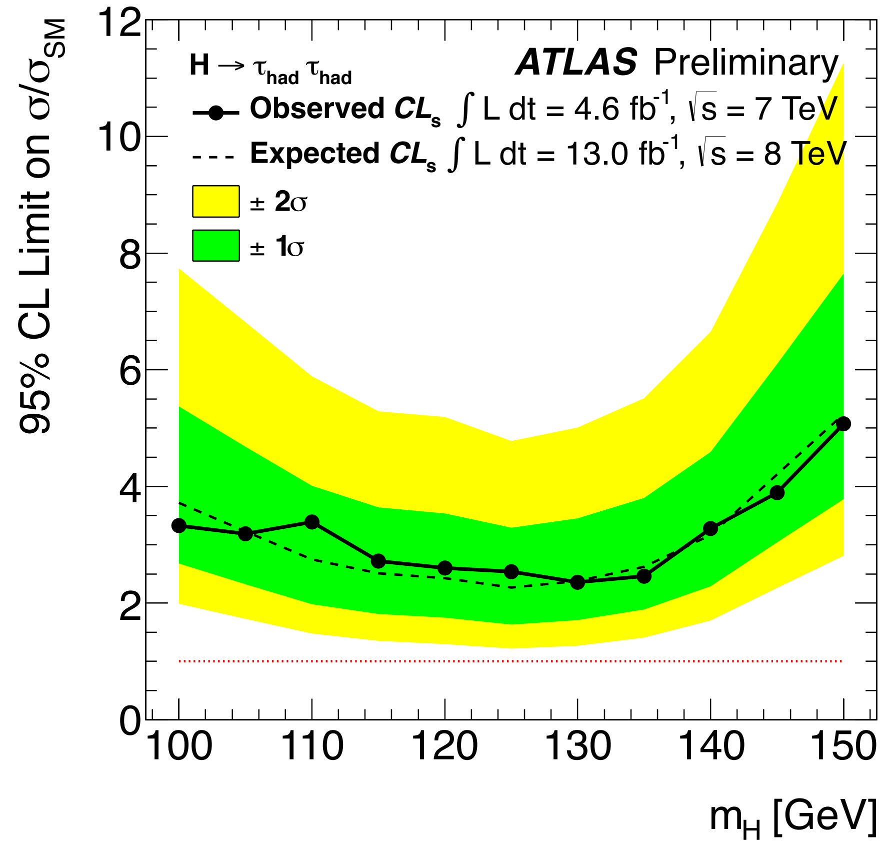


Backup

Limits per Channel

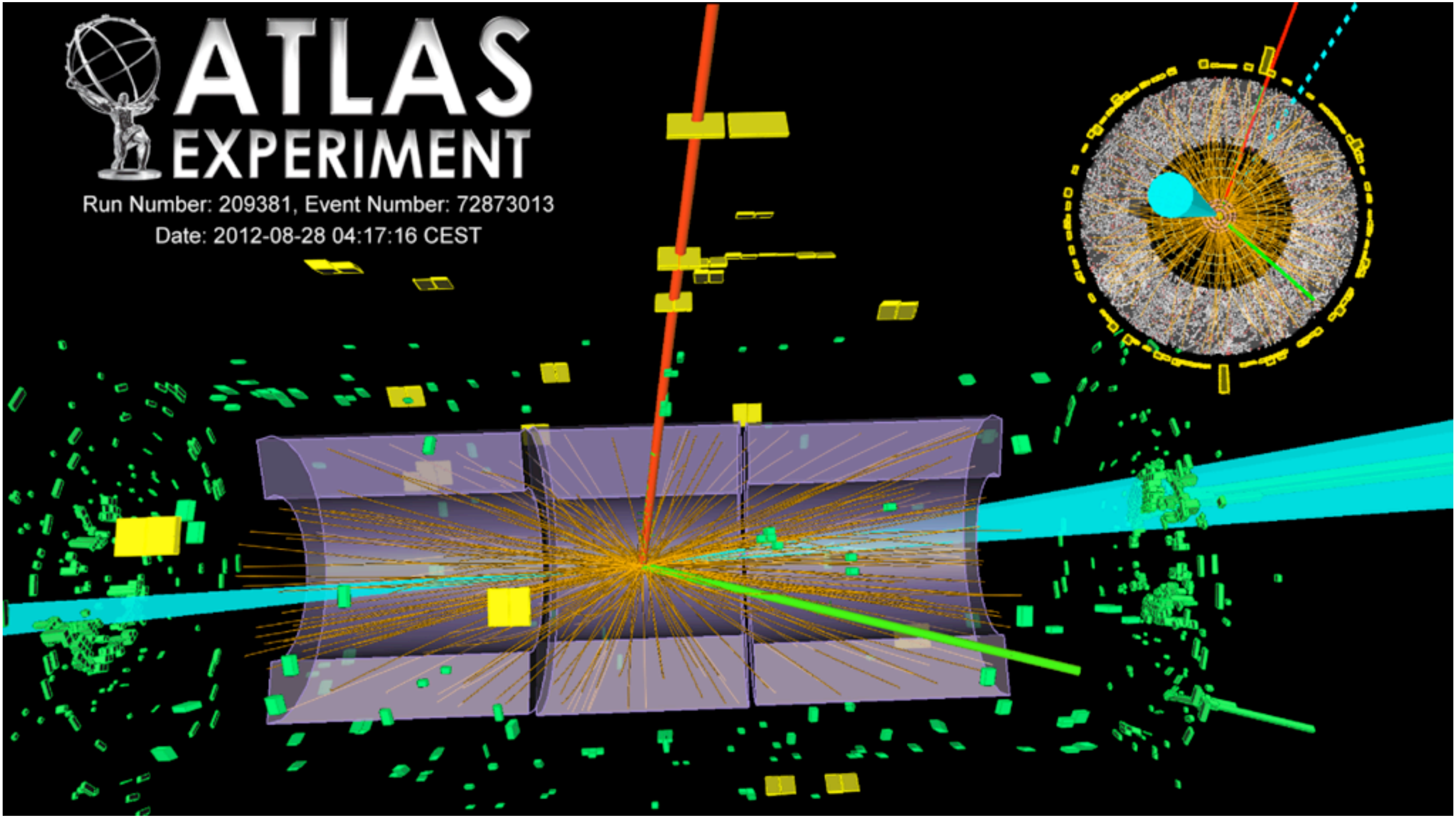




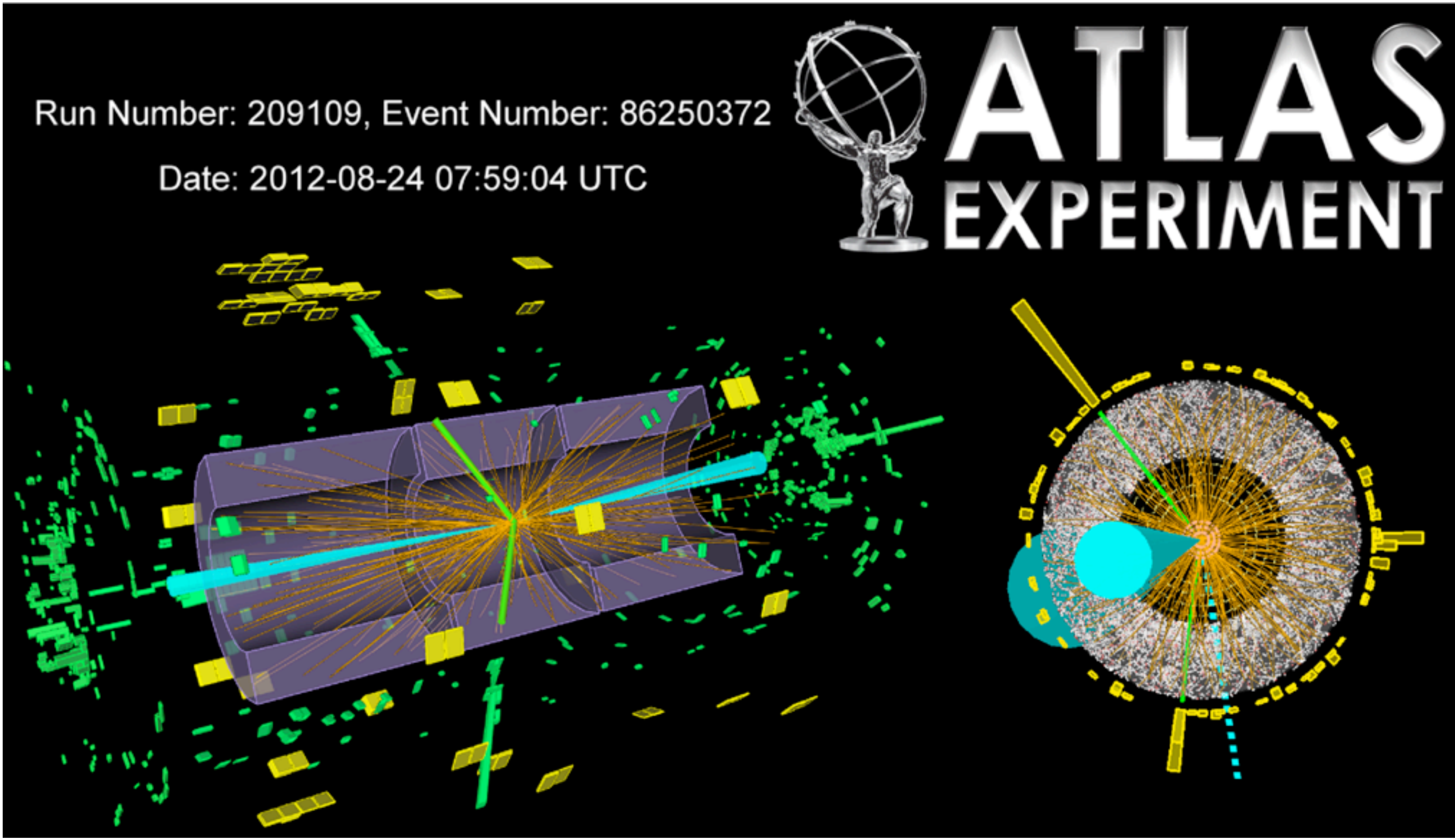


- Expected sensitivities comparable between channels
- Excess in observed limit dominated by lep-lep channel
    - (close to) no excess observed in lep-had and had-had

Candidate Event: (qq)H→ττ→eμ



Candidate Event: $(qq)H \to \tau\tau \to \tau_{had}\tau_{had}$



Trigger Thresholds in 7 | 8 TeV

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

- Few changes in trigger configuration due to higher luminosity
- offline p_T-thresholds for $e/\mu/\tau_{had}$ changed accordingly

Categorization (lep-lep)

<table>
<tr><th>2-jet VBF</th><th>Boosted</th><th>2-jet VH</th><th>1-jet</th></tr>
<tr><td colspan="4">Pre-selection: exactly two leptons with opposite charges</td></tr>
<tr><td colspan="4">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</td></tr>
<tr><td colspan="4">At least one jet with $p_T > 40$ GeV ($|JVF_{\mathrm{jet}}| > 0.5$ if $|\eta_{\mathrm{jet}}| < 2.4$)</td></tr>
<tr><td colspan="4">$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV ($E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV) for same-flavor (different-flavor) leptons</td></tr>
<tr><td colspan="4">$H_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV for same-flavor leptons</td></tr>
<tr><td colspan="4">$0.1 < x_{1,2} < 1$</td></tr>
<tr><td colspan="4">$0.5 < \Delta\phi_{\ell\ell} < 2.5$</td></tr>
<tr><td>$p_{T,j2} > 25$ GeV (JVF)</td><td>excluding 2-jet VBF</td><td>$p_{T,j2} > 25$ GeV (JVF)</td><td>excluding 2-jet VBF, Boosted and 2-jet VH</td></tr>
<tr><td>$\Delta\eta_{jj} > 3.0$</td><td>$p_{T,\tau\tau} > 100$ GeV</td><td>excluding Boosted</td><td>$m_{\tau\tau j} > 225$ GeV</td></tr>
<tr><td>$m_{jj} > 400$ GeV</td><td>b-tagged jet veto</td><td>$\Delta\eta_{jj} < 2.0$</td><td>b-tagged jet veto</td></tr>
<tr><td>b-tagged jet veto</td><td rowspan="2">–</td><td>30 GeV $< m_{jj} <$ 160 GeV</td><td rowspan="2">–</td></tr>
<tr><td>Lepton centrality and CJV</td><td>b-tagged jet veto</td></tr>
<tr><td colspan="4">0-jet (7 TeV only)</td></tr>
<tr><td colspan="4">Pre-selection: exactly two leptons with opposite charges</td></tr>
<tr><td colspan="4">Different-flavor leptons with 30 GeV $< m_{\ell\ell} <$ 100 GeV and $p_{T,\ell 1} + p_{T,\ell 2} > 35$ GeV</td></tr>
<tr><td colspan="4">$\Delta\phi_{\ell\ell} > 2.5$</td></tr>
<tr><td colspan="4">b-tagged jet veto</td></tr>
</table>

Event Yields (lep-lep)

7 TeV (4.6 fb^{-1})

	$ee + \mu\mu + e\mu$				
	VBF category	Boosted category	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

8TeV (13.0 fb^{-1})

	$ee + \mu\mu + e\mu$			
	VBF category	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

Event Yields (lep-had, 0/1 jet)

7 TeV (4.6 fb^{-1})

$e\tau_{had}$

Process	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

$\mu\tau_{had}$

Process	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

8 TeV (13.0 fb^{-1})

$e\tau_{had}$

Process	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

$\mu\tau_{had}$

Process	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

Event Yields (lep-had, had-had)

7 TeV (4.6 fb^{-1})

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

8TeV (13.0 fb^{-1})

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

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

Categorization (lep-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
• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$	• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$
–	• $p_T^{\ell} - p_T^{\tau} < 0$	–	• $p_T^{\ell} - p_T^{\tau} < 0$

Categorization (had-had)

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