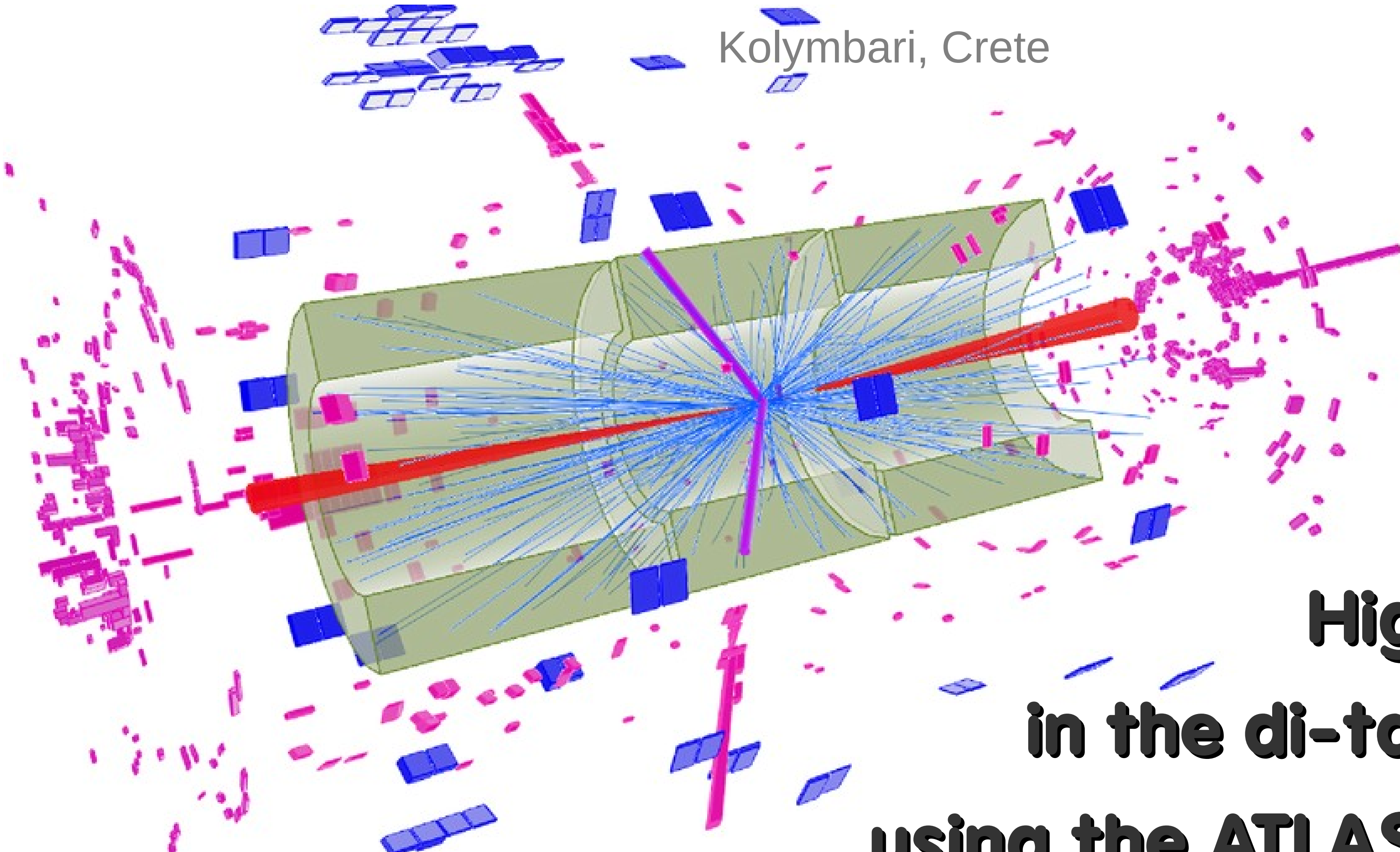
International Conference on New Frontiers in Physics 2013

Kolymbari, Crete



Search for the Higgs boson in the di-tau channel using the ATLAS detector

Z. Zinonos

ATLAS EXPERIMENT

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Overview

- Higgs production @ LHC
- Tau Lepton
- Missing ET
- Di-tau mass reconstruction
- Results
- Recent developments
- Conclusions & perspectives

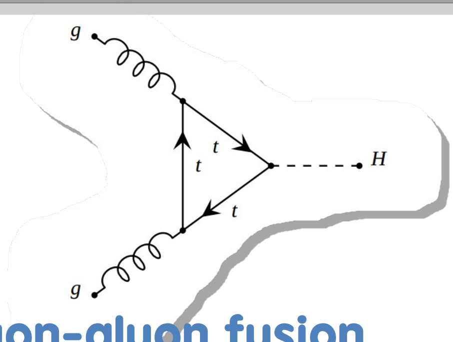
- Main Documentation
  - Publication @ 7 TeV JHEP09(2012)070
  - Conf. Note @ 7 & 8 TeV ATLAS-CONF-2012-160
- Analysis Summary

Analysis	Cut-based	Multivariate
7 TeV	4.7 fb^{-1}	4.7 fb^{-1}
8 TeV	13 fb^{-1}	21 fb^{-1}
Last update	13 / 11 / 2012	Ongoing

Presented today

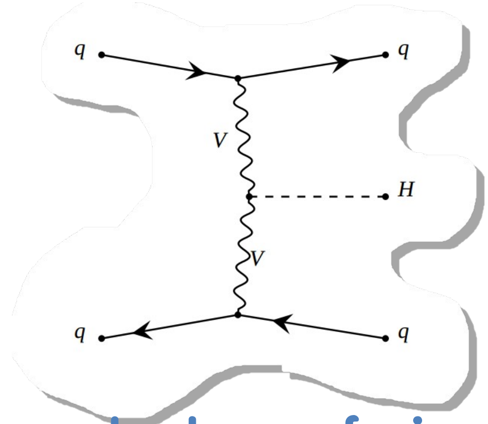
Higgs → $\tau^+\tau^-$ @ LHC

Production Mechanisms (8 TeV)



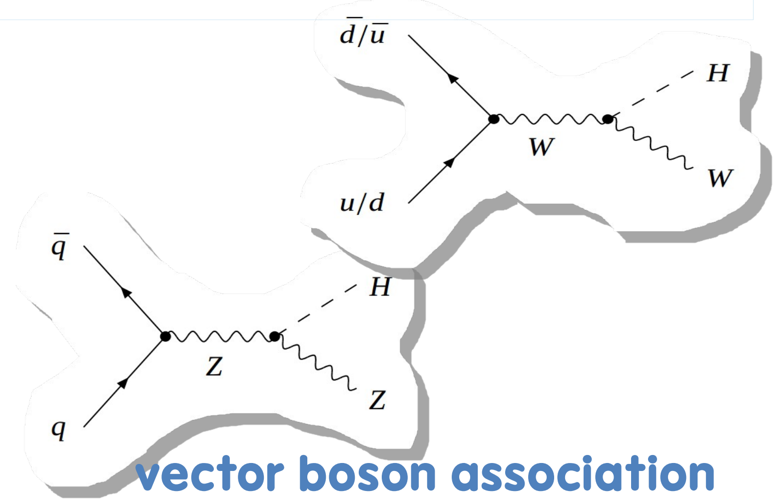
gluon-gluon fusion

σ (m_H=125 GeV) = 19.5 pb



vector boson fusion

σ (m_H=125 GeV) = 1.6 pb

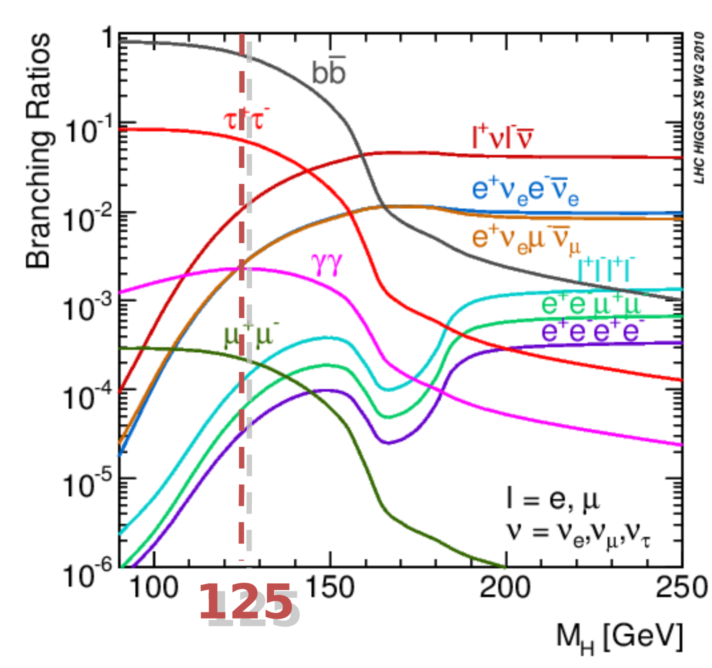


vector boson association

σ (m_H=125 GeV) = 1.1 pb

Importance

- Higgs→ττ is probably the only accessible fermionic channel with current data
    * powerful reco / ID of hadronic τ decays
    * distinctive VBF and ggH topological signatures
    * establishment of the SM Higgs boson discovery
- Provides the best chance to measure Higgs properties
    * fermionic couplings (lepton family)



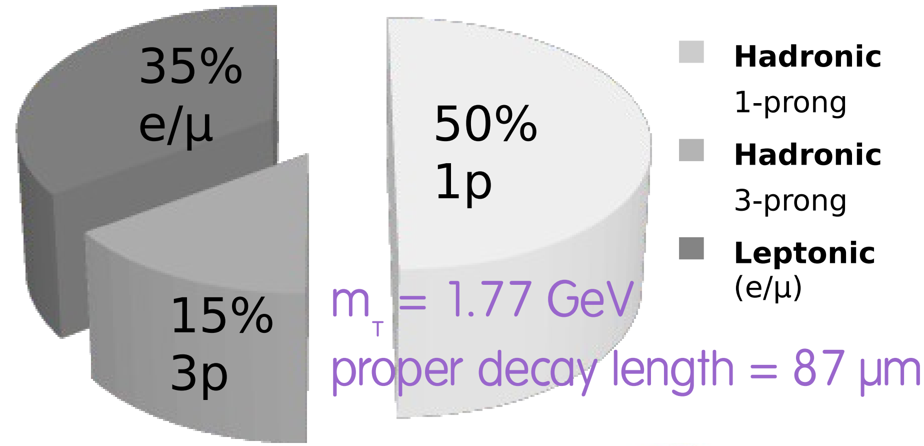
arXiv:1201.3084 ; CERN-2012-002

BR [Higgs(125GeV) → τ τ] = 6.2%

The τ-lepton in ATLAS

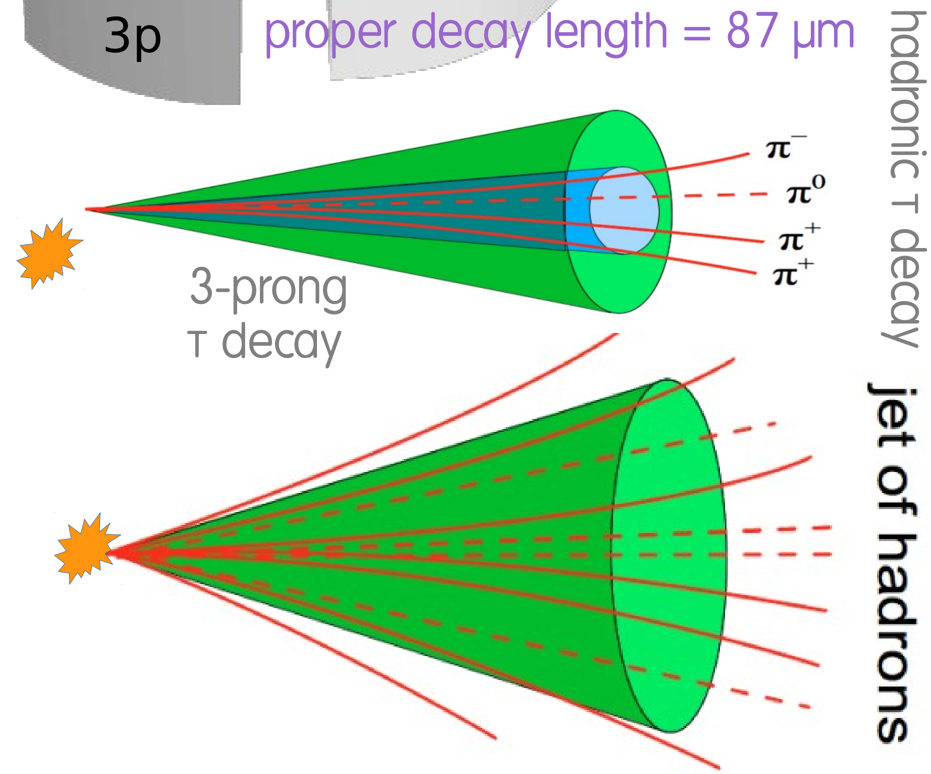
Reconstruction

- τ_{had} algorithm ; seeded from anti-k_t R=0.4 jets
  noise-suppressed calo-clusters
- track association; within a *core cone* δR< 0.2
- track-vertex association; robust against Pile-Up



Identification

- Boosted Decision Trees /Log-likelihood
  regression methods
- Identification variables:
  - * calorimetric (HAD and EM shower shapes)
  - * tracking (isolation, momentum, ...)
- Lepton (μ, e) veto

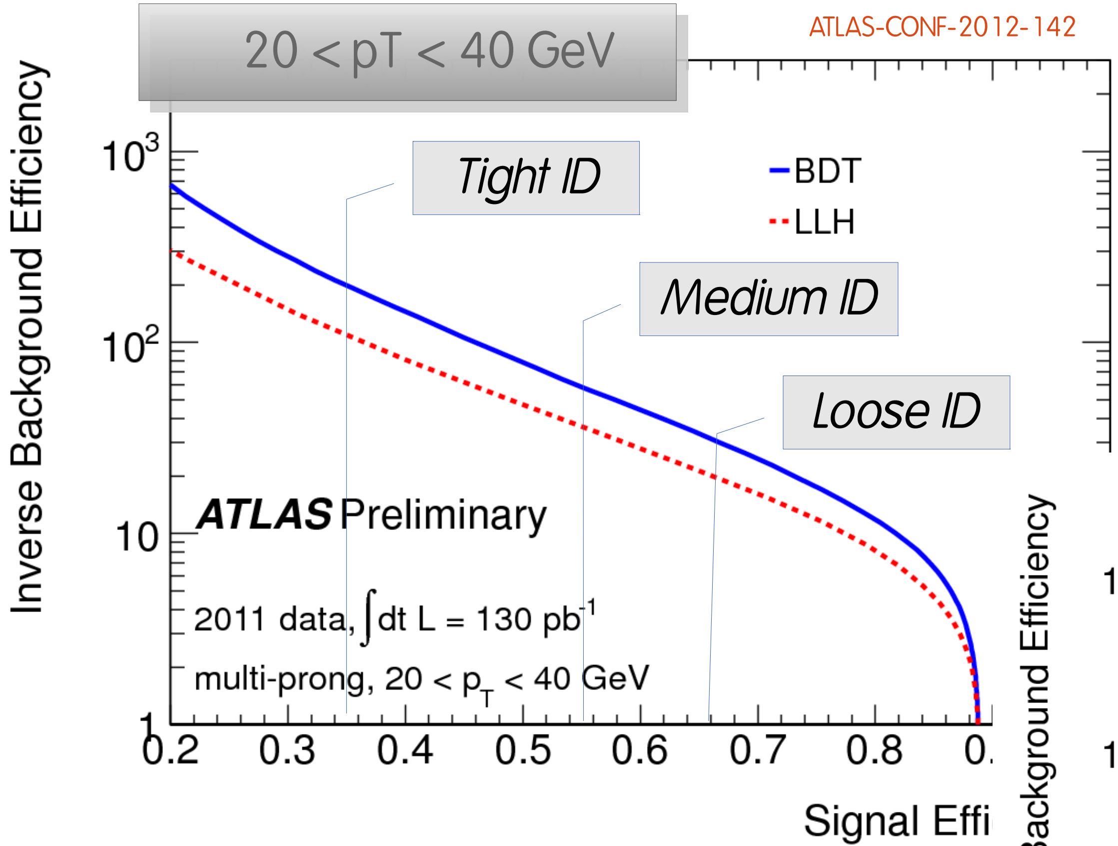


QCD jets typically have

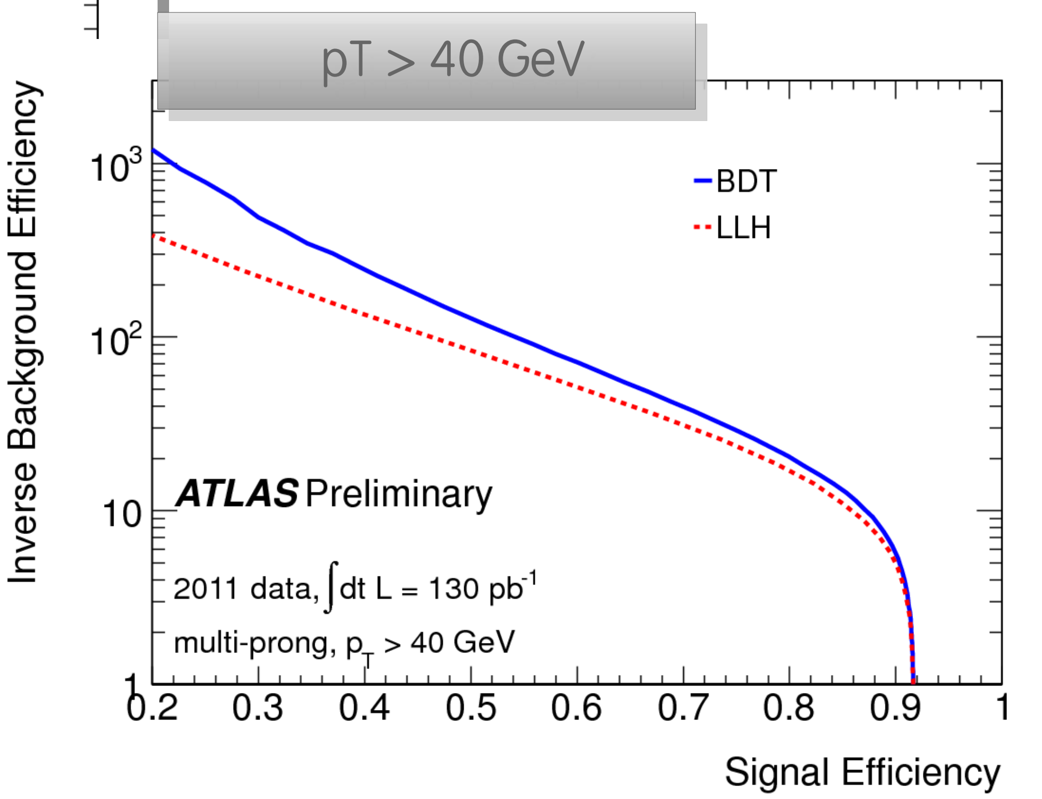
* more associated tracks
* more broadly spaced tracks
* no displaced secondary vertex
* wider calorimeter showers

Tau ID Performance

ATLAS-CONF-2012-142



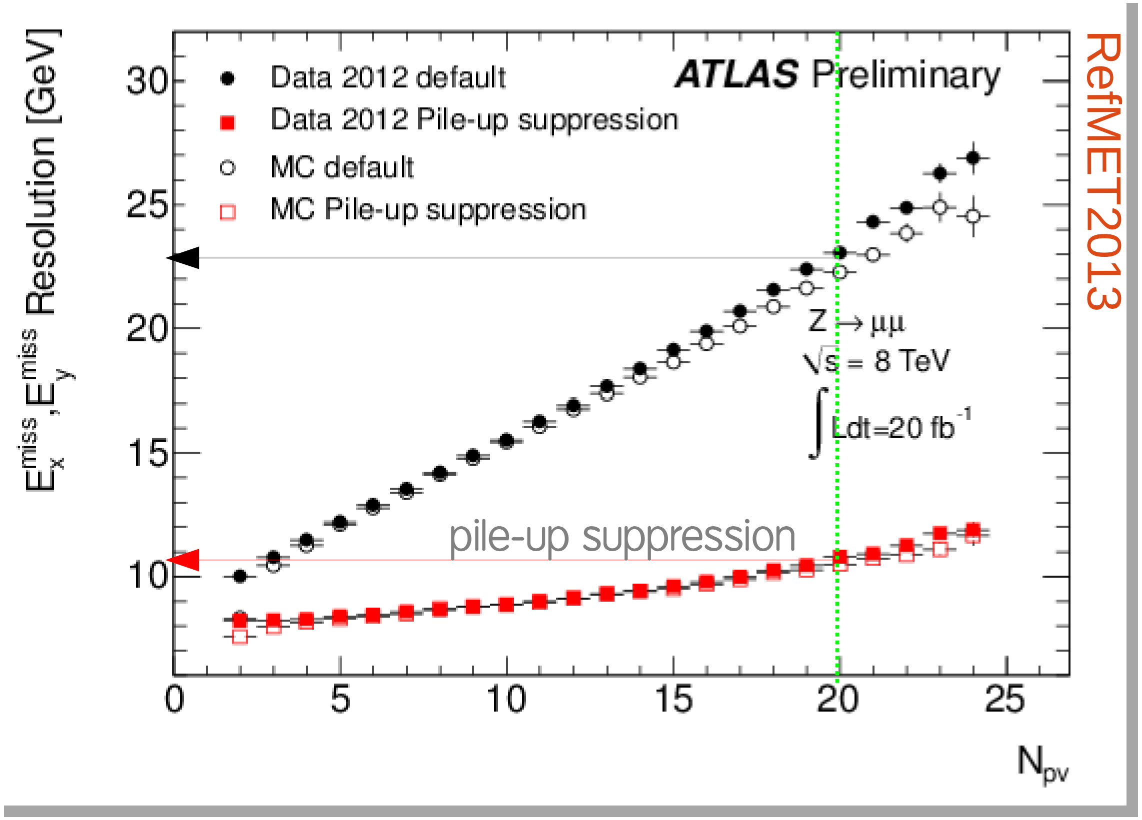
Multi-prong tau decays

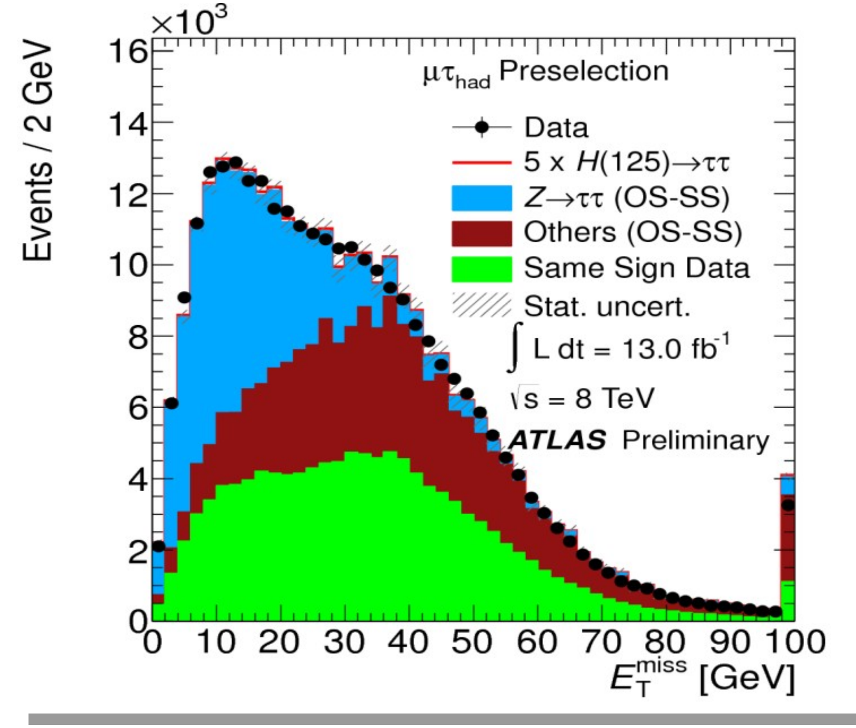


Tag-and-Probe method

Measured in Zττ, Z'ττ, Wτν MC events and QCD-enriched data

Missing ET





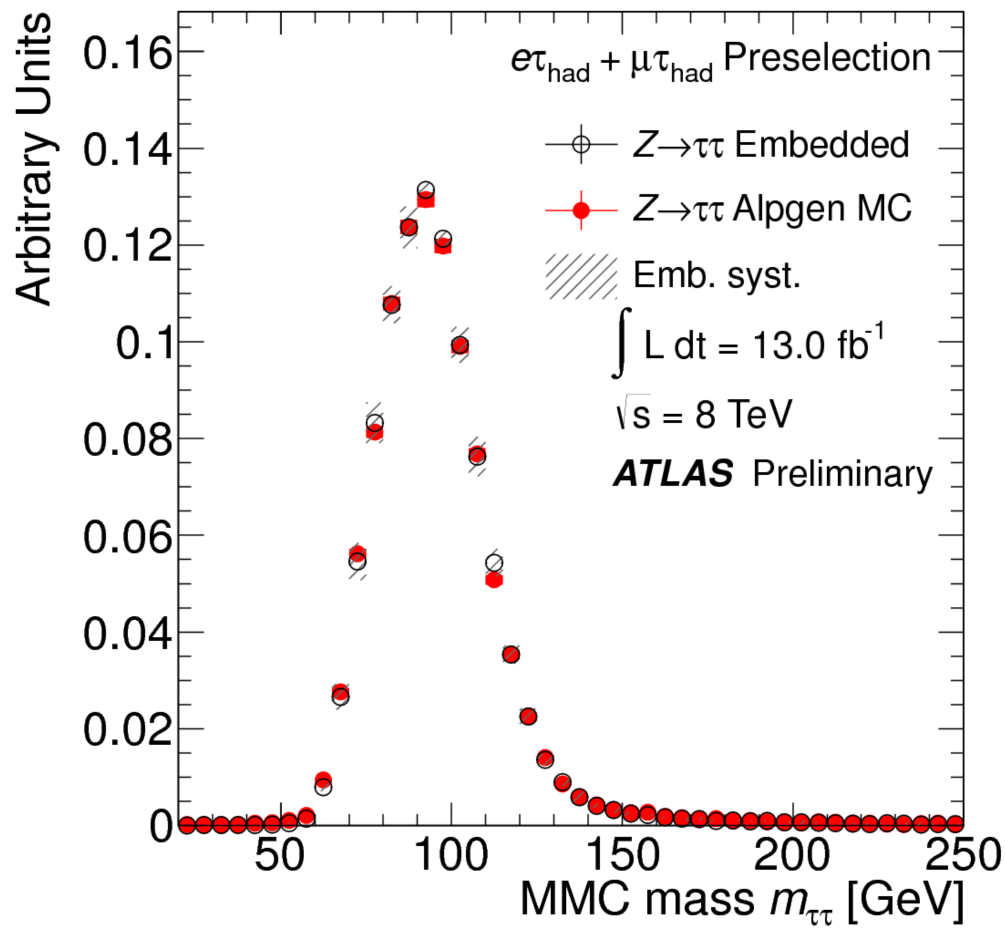
MET in μ-τ_{had} channel

- Built up with calorimeter cells associated to reconstructed / identified high-pT objects
- Resolution of x and y MET components as a function of the number of primary vertices for data and MC in Z->μμ candidates:
  * before pile-up suppression
  * after pile-up suppression (based on the ratio of the *sum pT* of the tracks associated to the primary vertex and all tracks in the event)

Di-tau Mass Reconstruction

- Invariant di-tau mass is the final discriminating variable
- Missing Mass Calculator
  Provides reconstruction of the ττ event kinematics with
  - * $\epsilon > 99\%$
  - * 13-20% $m_{\tau\tau}$ resolution

  depending on the topology



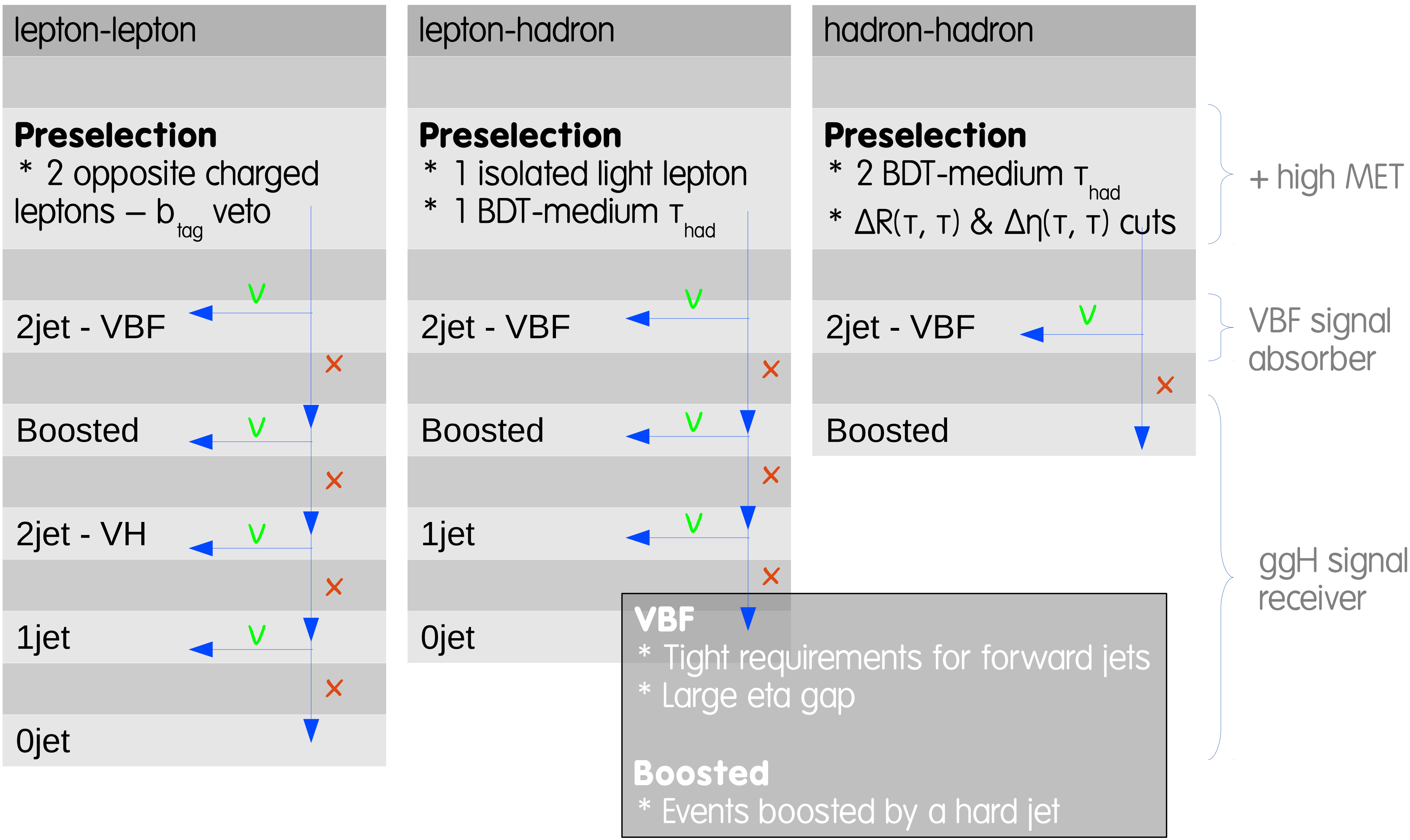
- Main improvement comes from requiring that relative orientations of the neutrinos and other decay products are consistent with the mass and kinematics of the τ decay (maximize probability in allowed phase-space)

Trigger

Channel	Trigger @ $\sqrt{s}$=8 TeV	Offline pT threshold
lep-lep	Single electron	25 GeV (e) 10 GeV (μ)
	Di-electron	15, 15 GeV
	Di-muon	20, 10 GeV
	Combined e + μ	15 GeV (e) 10 GeV (μ)
lep-had	Single electron	26 GeV (e) 20 GeV (μ)
	Single muon	26, 20 GeV
	Combined $e + \tau_{had}$	20-26 GeV (e) 25 GeV (τ)
	Combined $\mu + \tau_{had}$	40 GeV (μ) 25 GeV (τ)
had-had	Combined $\tau_{had} + \tau_{had}$	40, 25 GeV

Event Filter pT thresholds 29, 20 GeV !

Analysis Strategy – Event Categorization



» Exclusively defined categories – optimized selection cuts to disentangle VBF from ggH

Background Estimation

lep-had

Z → ττ embedded / hybrid data

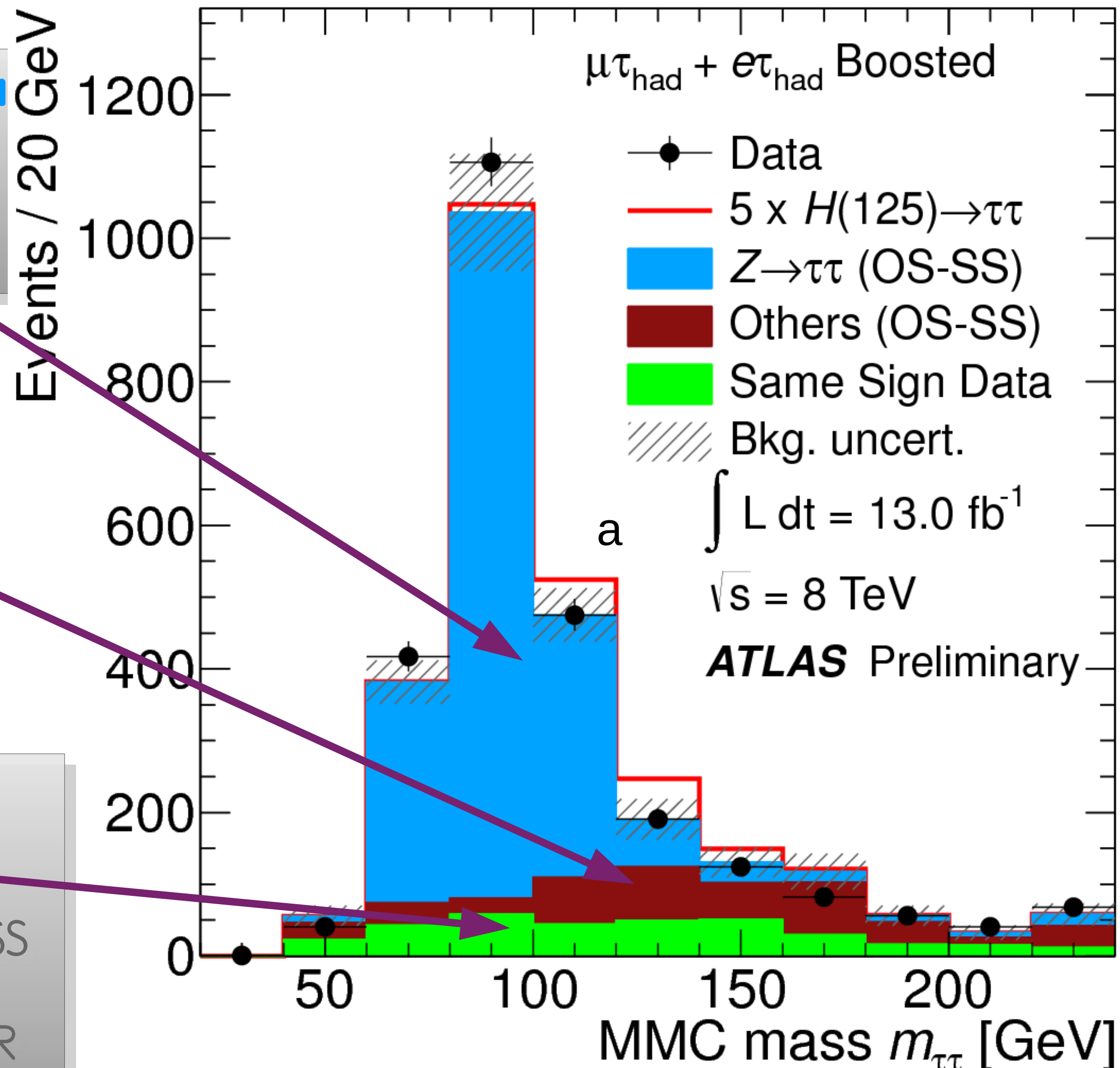
* μ in Z → μμ data is replaced by simulated τ hadronic decay + full event reprocessing

Other backgrounds

* ttbar, W+jets, dibosons
* Shape from simulation
* Normalization from control regions (CR)

SS data - QCD multijets

* jet faking e/μ or/and τ_{had}
* SS data model is corrected for OS-SS asymmetry (add-on terms)
* Normalization from QCD-enriched CR



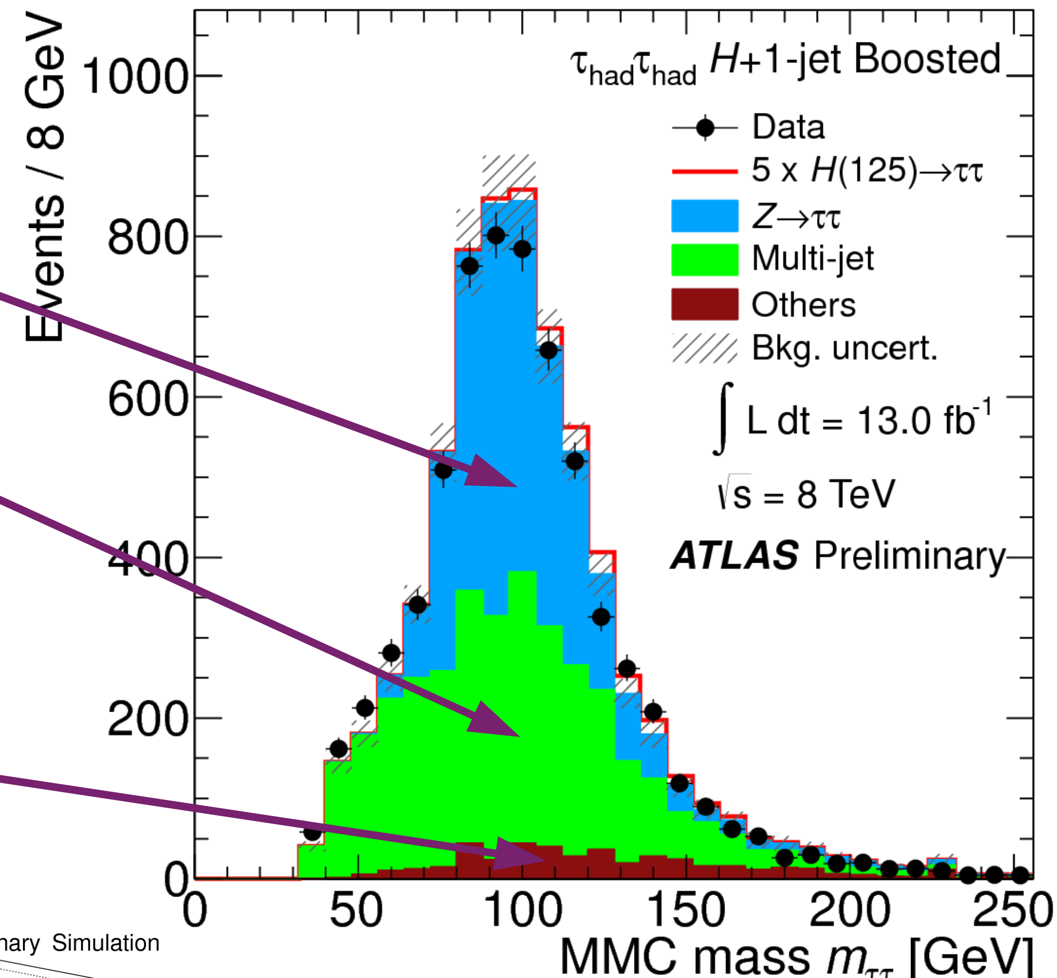
Background Estimation

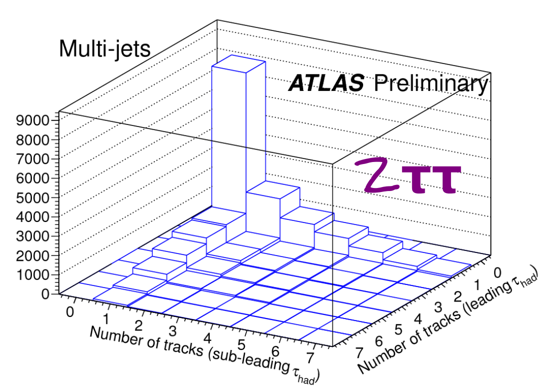
had–had

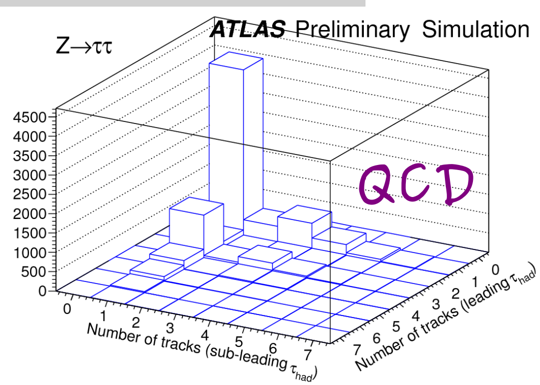
Z→ττ
* Shape: Z → ττ embedded data
* Normalization from TrackFit

QCD multijets
* 2 jets faking τ_{had} candidates
* Shape: OS(ID failed, ID failed) model
* Normalization from TrackFit

Other backgrounds
* ttbar, W+jets, dibosons
* Shape and normalization from simulation
* Tiny contribution







TrackFit: fit 2D tau track templates to Data

Important backgrounds
- Zττ and QCD jets -
are estimated using only data!

Systematic Uncertainties

Uncertainty	lep-lep	lep-had	had-had
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%
Normalization	5%	4%(non-VBF) 16% (VBF)	9-10%

Zττ dominant background

Uncertainty	lep-lep	lep-had	had-had
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	2-28%	18-23%	3-20%
Trigger Efficiency	small	small	5%

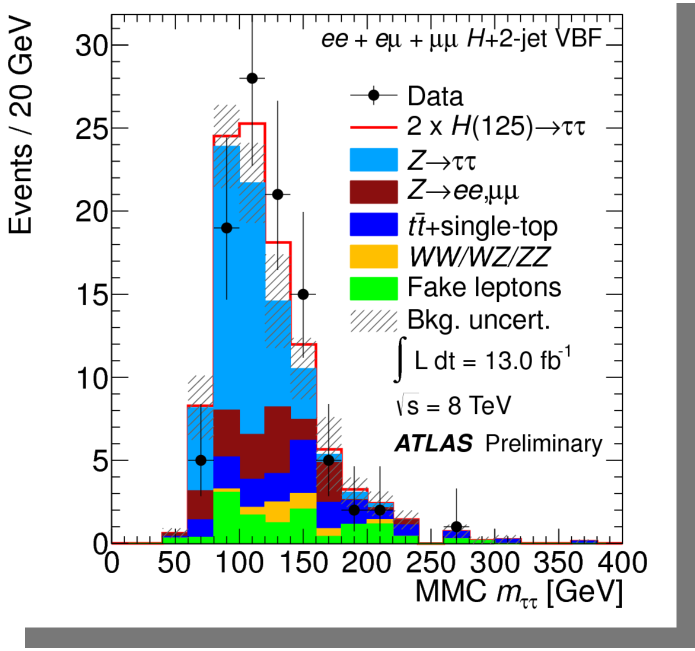
Jet Energy Scale 2-15%

Signal

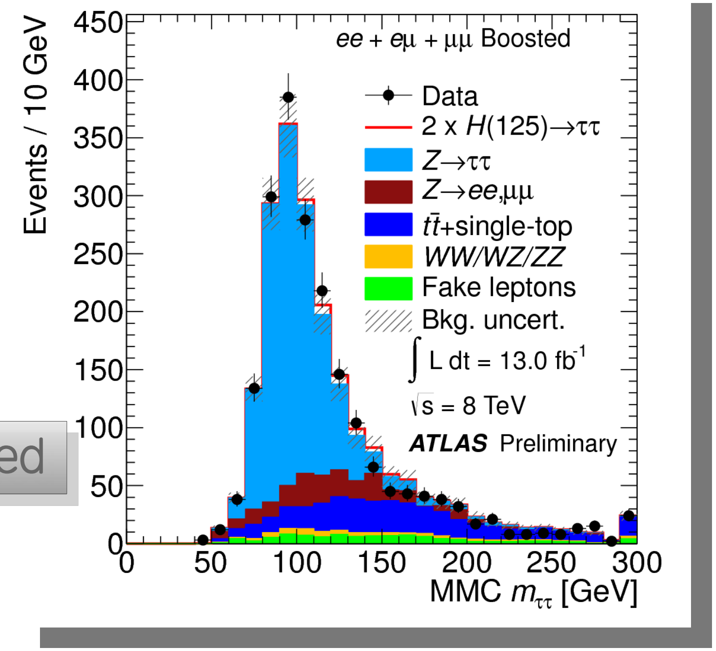
S: uncertainties applied bin-by-bin affecting the final shape

Results @ 8 TeV

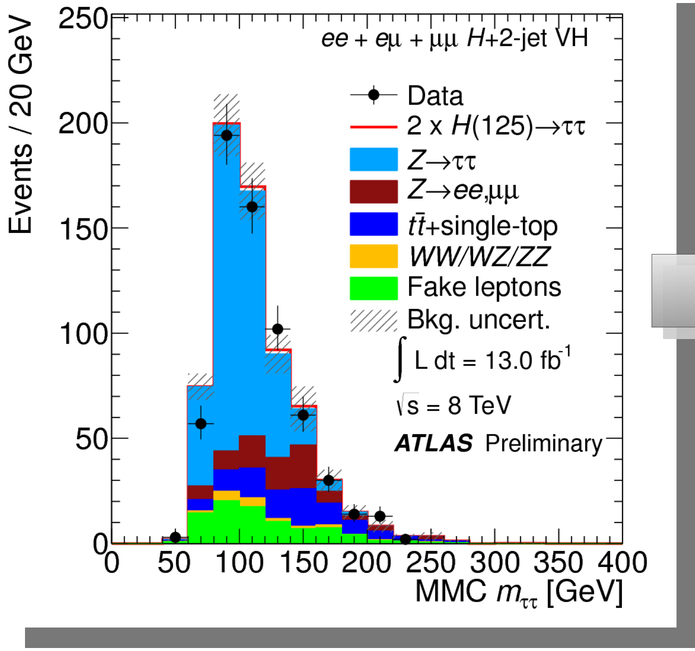
lep–lep



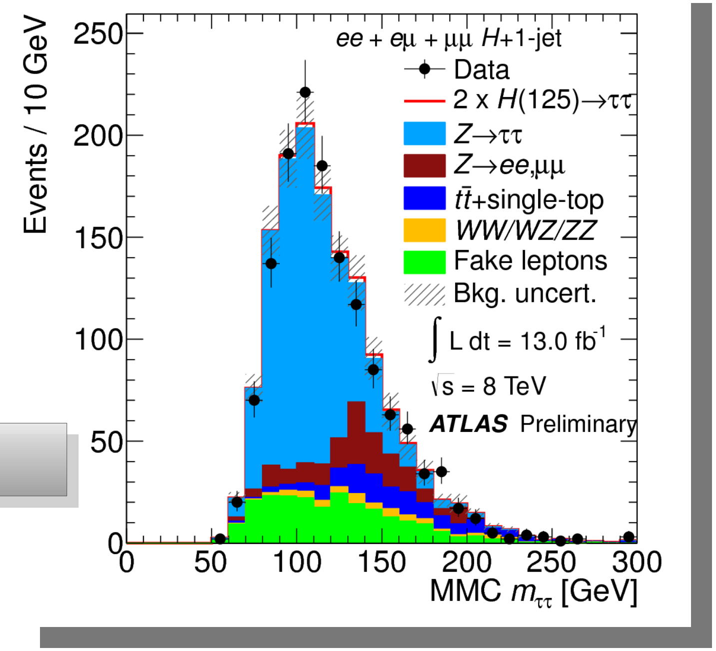
VBF



Boosted



2jet

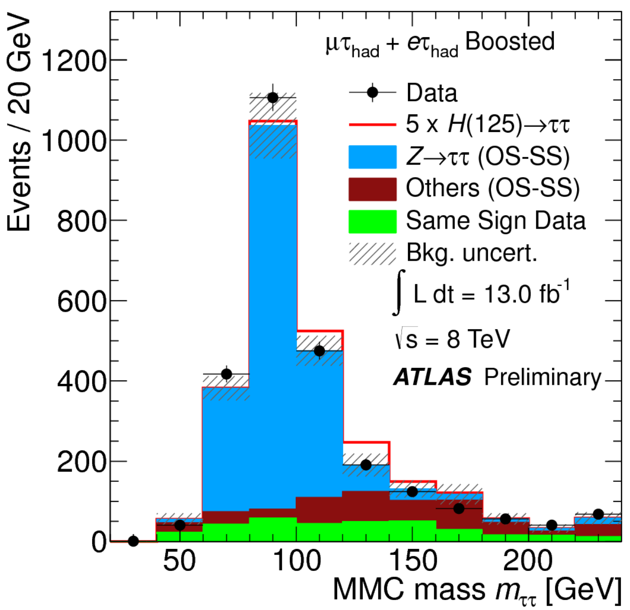


1jet

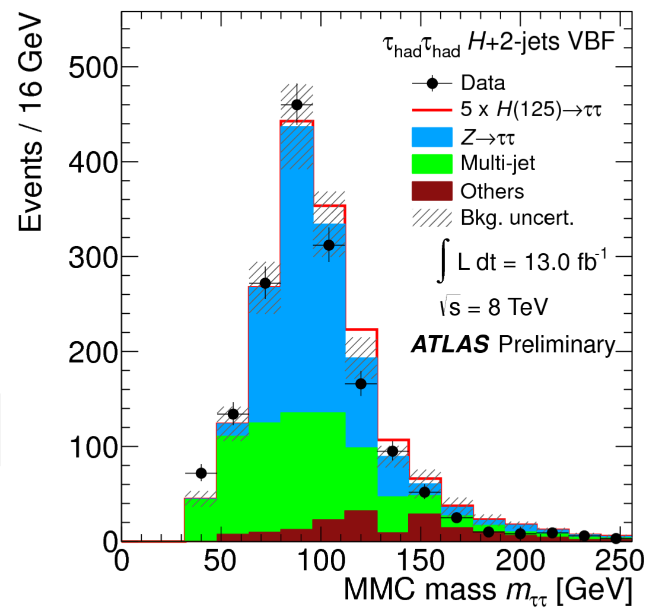
Results @ 8 TeV

lep−had

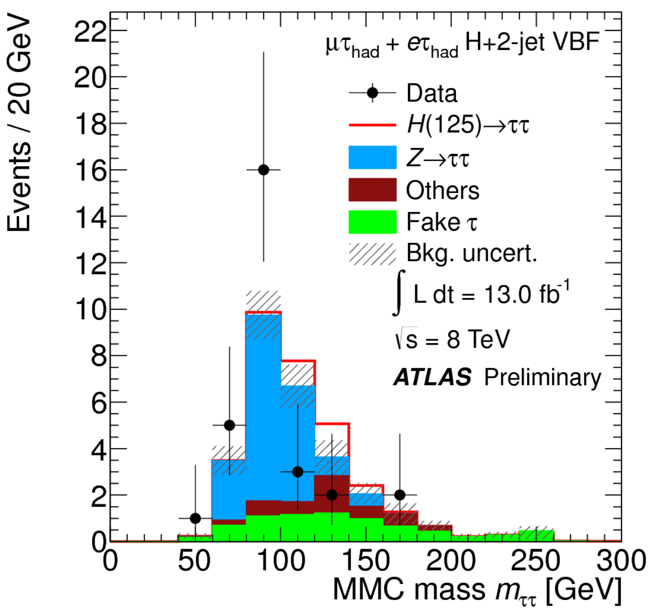
had−had



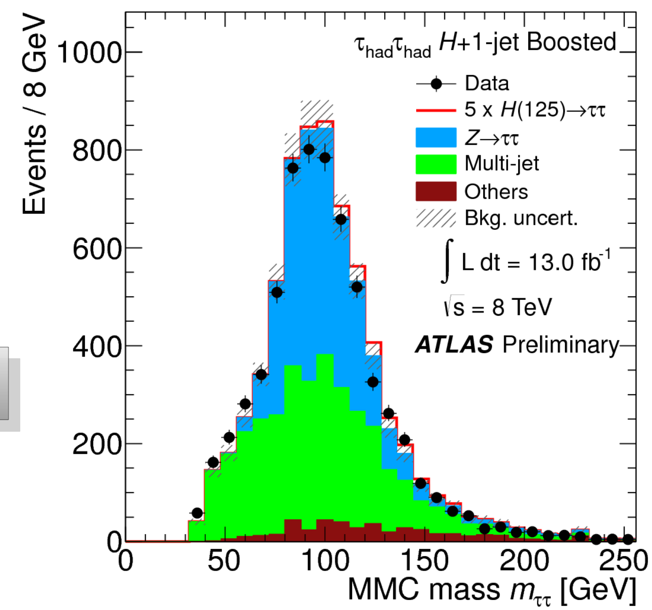
VBF



VBF

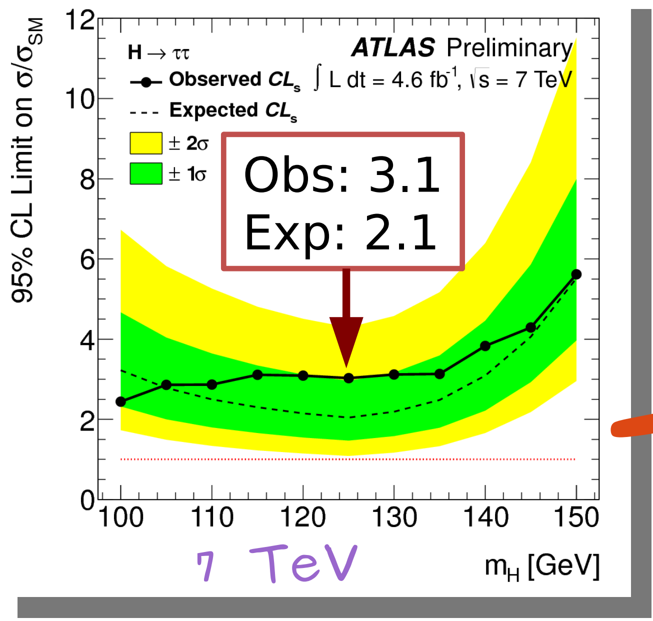


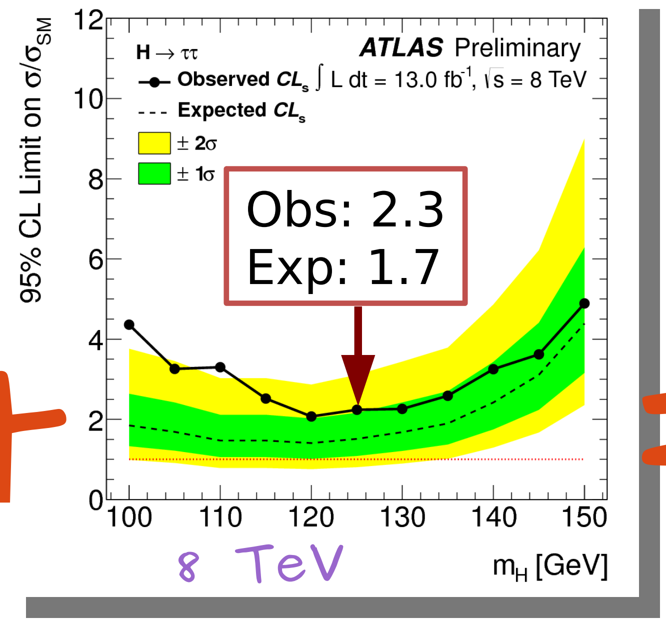
Boosted

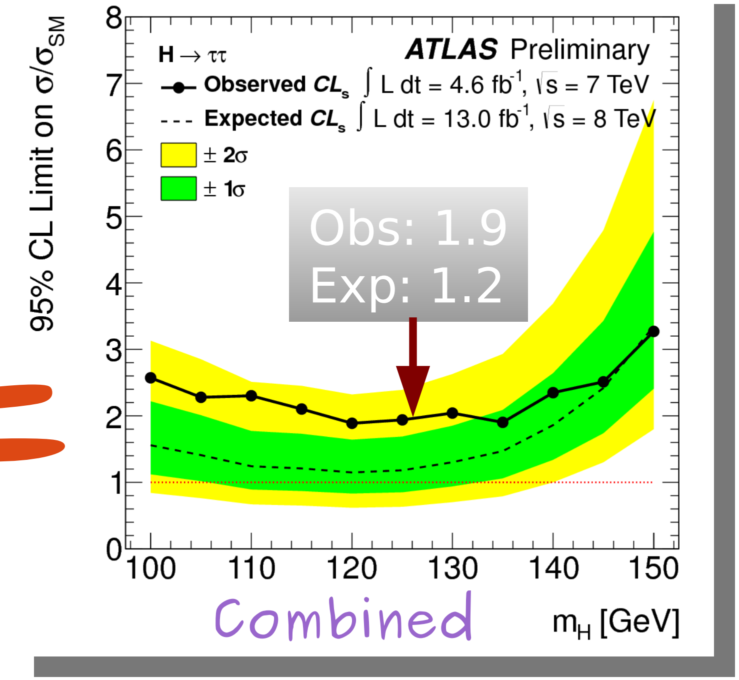


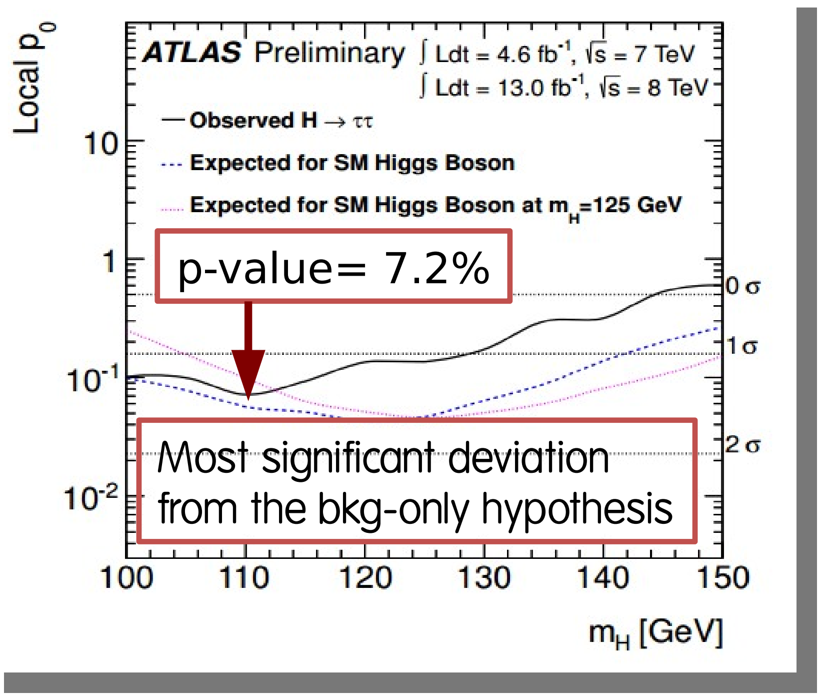
Boosted

Limits & Sensitivity









Observed / Expected 95% CLs upper limits on $\sigma_{Higgs}/\sigma_{SM}$ Vs m_{Higgs} in the mass range 100-150 GeV

Observed and expected p0-values, as a function of m_H corresponding to SM Higgs boson signal introduced with signal strength μ=1 at the mass in question

Synopsis & Perspectives

- ATLAS has performed searches for the SM Higgs boson decaying into tau-lepton pairs

  * cut-based analyses performed for all di-tau final states
  * exploits 4.7 fb^{-1} @ 7 TeV & 13 fb^{-1} @ 8 TeV datasets
  * expected limit = 1.18xSM & sensitivity p0 = 1.7σ @ m_H = 125 GeV

- Presently, multivariate analyses are being pursued across all 3 channels aiming for higher sensitivities using the complete LHC pp dataset

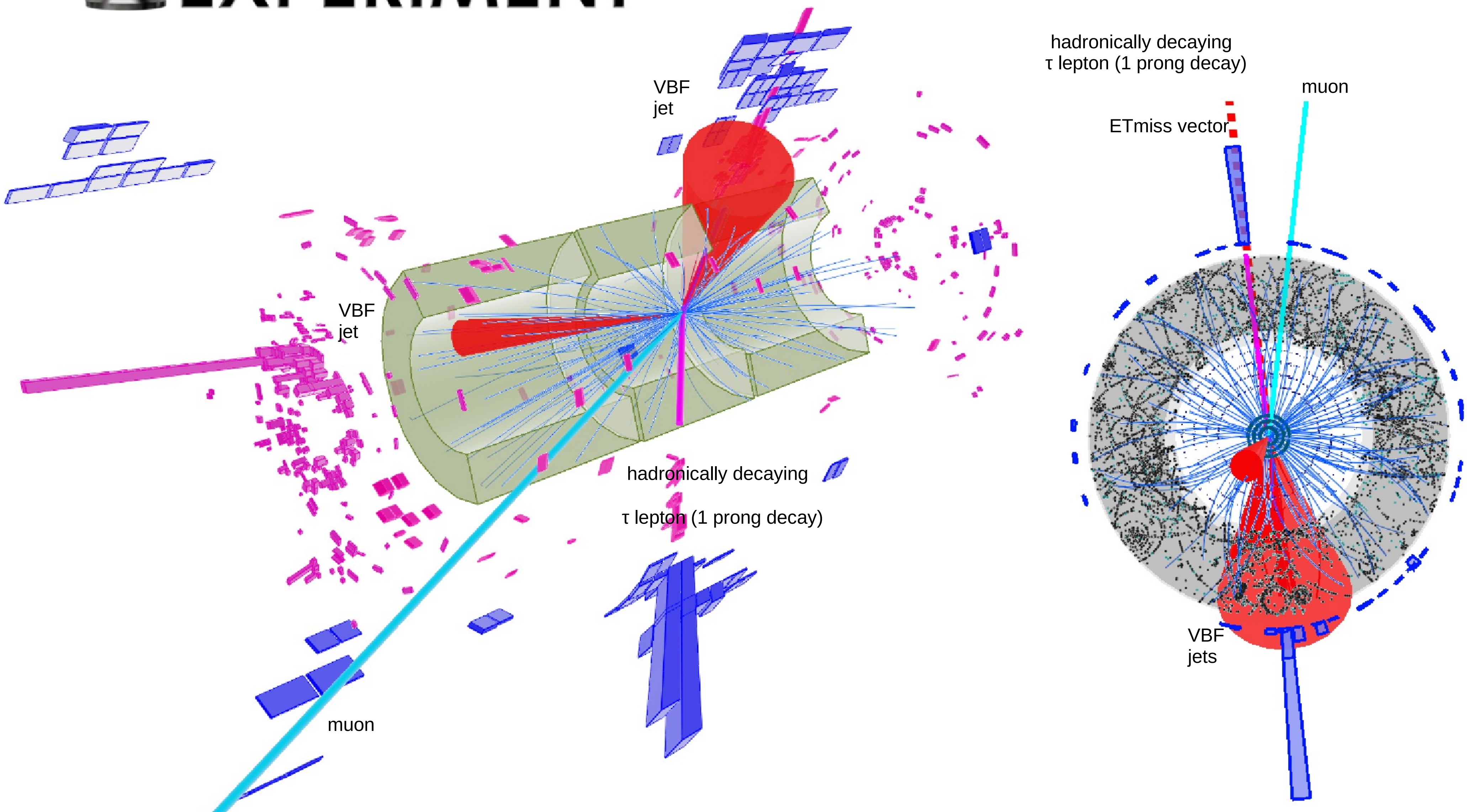
- Also, now using new tau ID, new Z embedding samples, categorization schemes, new lower pT-threshold triggers and reduced systematic uncertainties

Auxiliary Material

ATLAS EXPERIMENT

Run Number: 204265, Event Number: 178165311

Date: 2012-06-02 19:53:30 CEST



Display of an event selected by the **H→ τlep τhad** analysis in the VBF category, where one τ decays to a muon. The muon has **pT = 63 GeV**, the τhad candidate has **pT = 96 GeV, ETmiss=119 GeV**, **mjj=625 GeV** and **mMMC=129 GeV**.

Lep-Lep Selection Criteria

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

$$x_{1,2} = \frac{|p_{\text{vis}1,2}|}{|(p_{\text{vis}1,2} + p_{\text{mis}1,2})|} .$$

$$p_{T,\tau\tau} = |\vec{p}_{\text{T}}^{\,\ell,1} + \vec{p}_{\text{T}}^{\,\ell,2} + \vec{E}_{\text{T}}^{\text{miss}}|.$$

Lep-Had Selection Criteria

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

$$m_T = \sqrt{2 p_T^{\ell} E_T^{\text{miss}} (1 - \cos\Delta\phi)}$$

$$p_T{}^{H} = |\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\tau_{\text{had-vis}}} + \vec{E}_T^{\text{miss}}|$$

$$p_T{}^{\text{Total}} = |\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\tau_{\text{had-vis}}} + \vec{p}_T^{\,j1} + \vec{p}_T^{\,j2} + \vec{E}_T^{\text{miss}}|$$

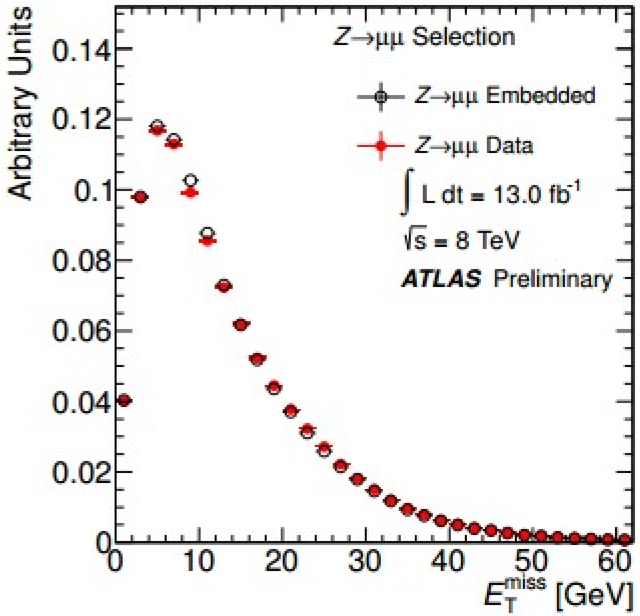
$$\sum \Delta\phi = |\phi_\ell - \phi_{E_T^{\text{miss}}}| + |\phi_\tau - \phi_{E_T^{\text{miss}}}|$$

Suppress W+jets background

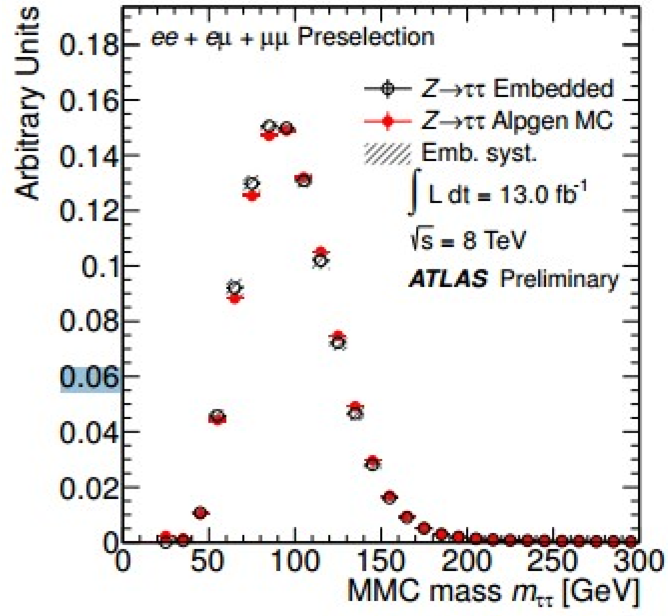
Had-Had Selection Criteria

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, $\|\eta\| < 2.5$
	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, $\min\left\{\Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_1), \Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_2)\right\} < 0.1\pi$.

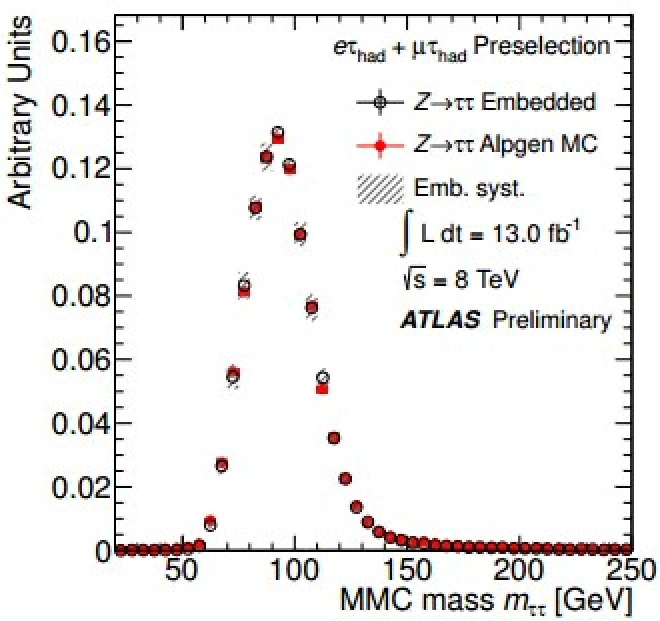
Zττ



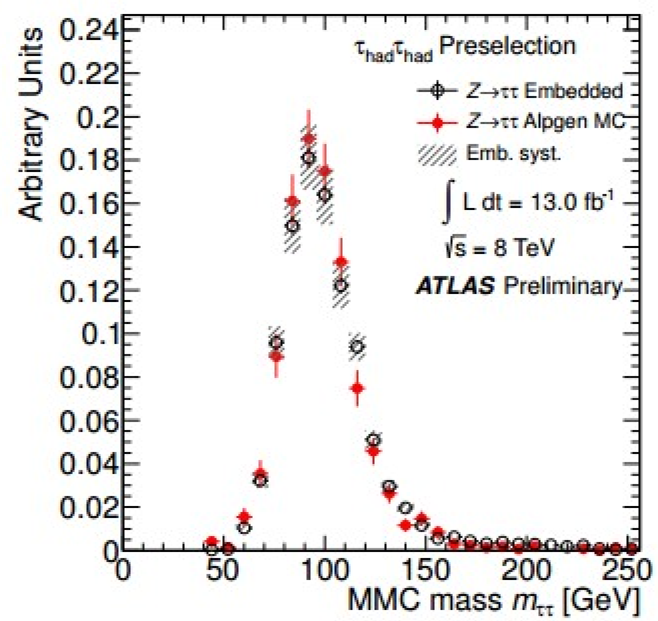
(a) E_T^{miss} in $Z/\gamma^* \to \mu\mu$ data



(b) Invariant mass $m_{\tau\tau}$ in $\tau_{lep}\tau_{lep}$ channel



(c) Invariant mass $m_{\tau\tau}$ in $\tau_{lep}\tau_{had}$ channel

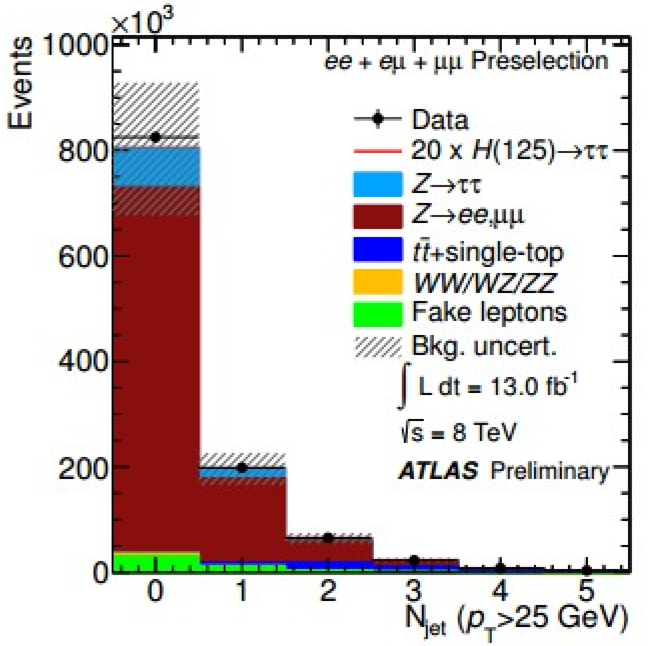


(d) Invariant mass $m_{\tau\tau}$ in $\tau_{had}\tau_{had}$ channel

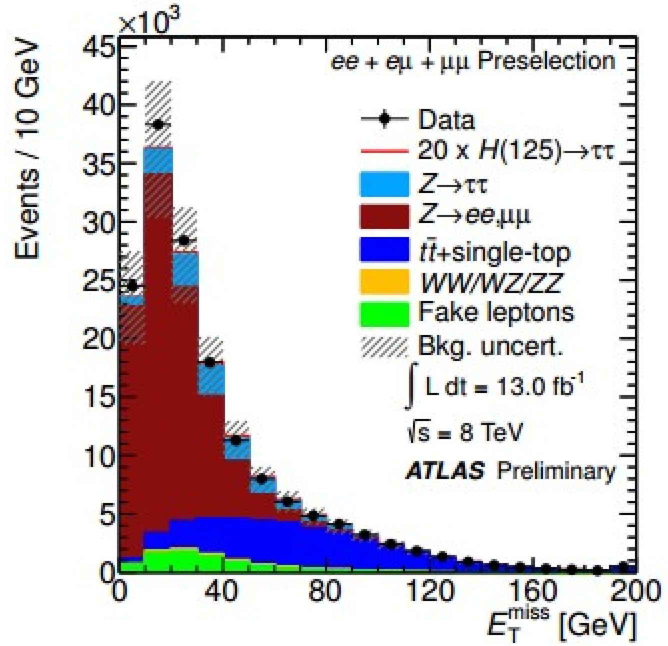
Embedded data

Alpgen MC

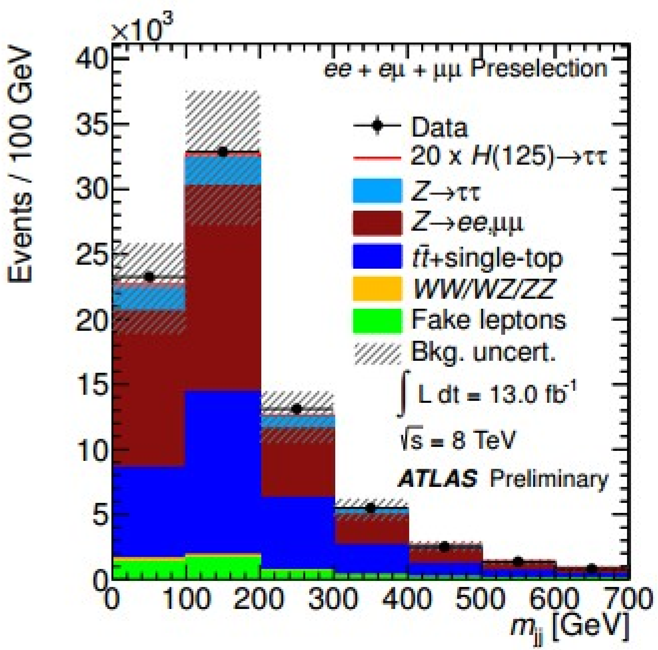
Lep-Lep



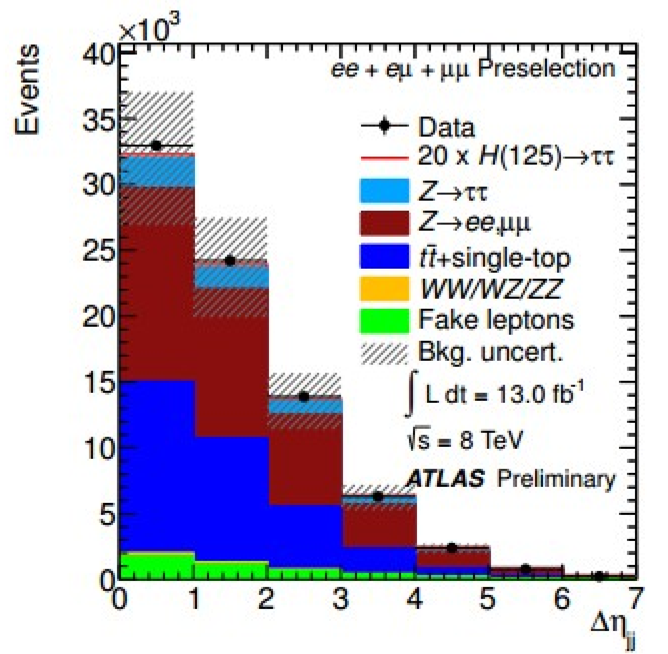
(a) Jet multiplicity ($p_T > 25$ GeV)



(b) E_T^{miss}



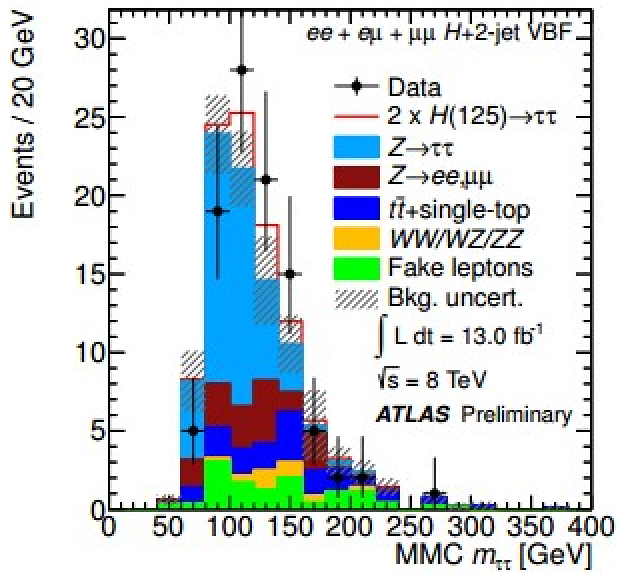
(c) Invariant mass of the two leading jets



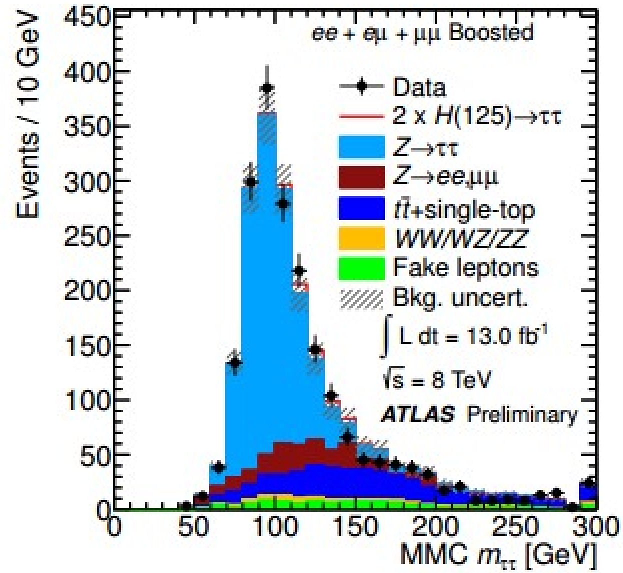
(d) η difference of the two leading jets

Distributions
At preselection

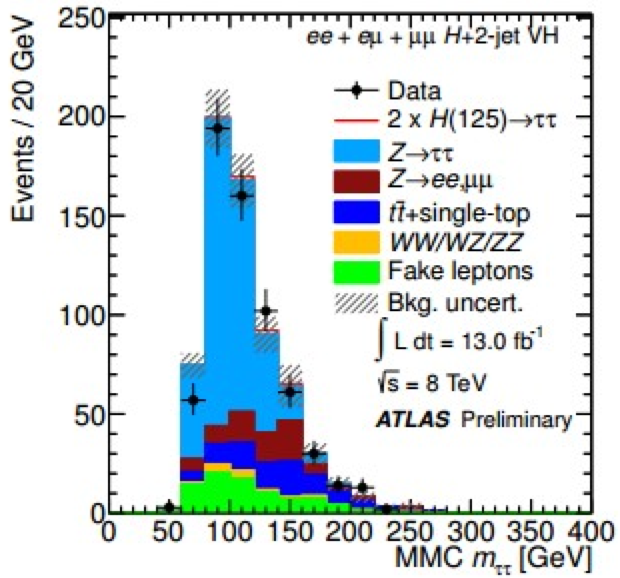
Lep-Lep



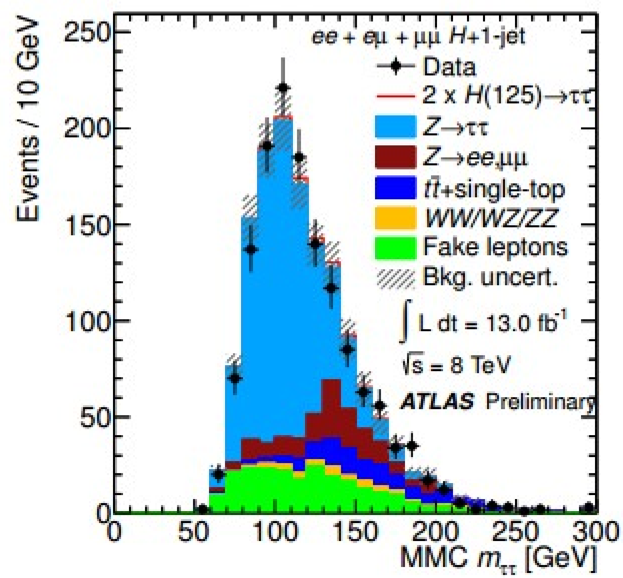
(a) H+2-jet VBF



(b) H+1-jet Boosted



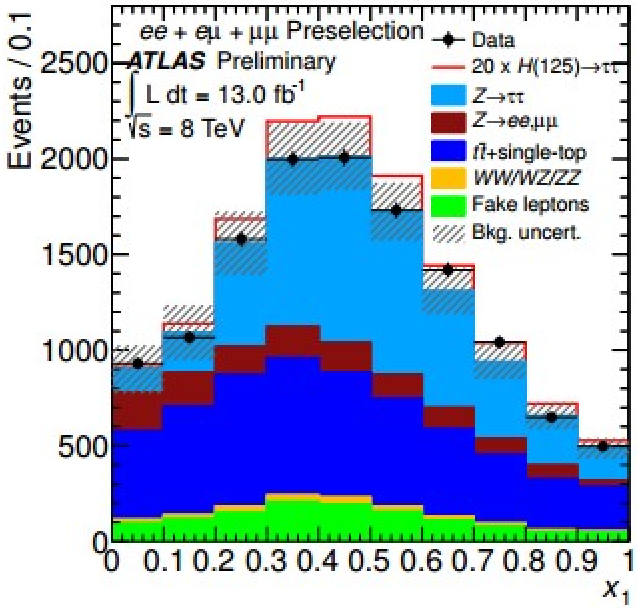
(c) H+2-jet VH



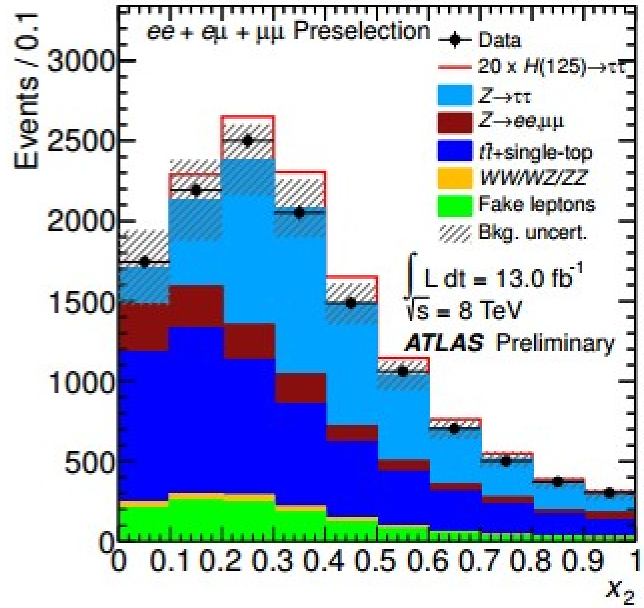
(d) H+1-jet

Reconstructed
Di-tau mass

Lep-Lep distributions



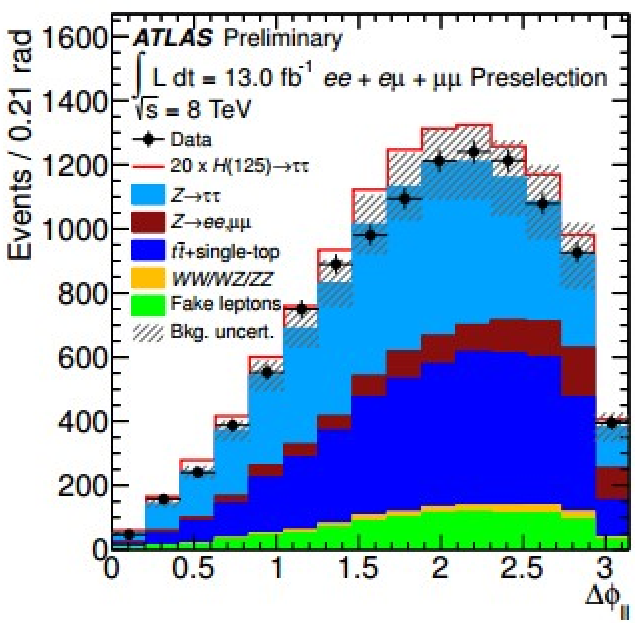
(a) x_1 after the E_T^{miss} cut

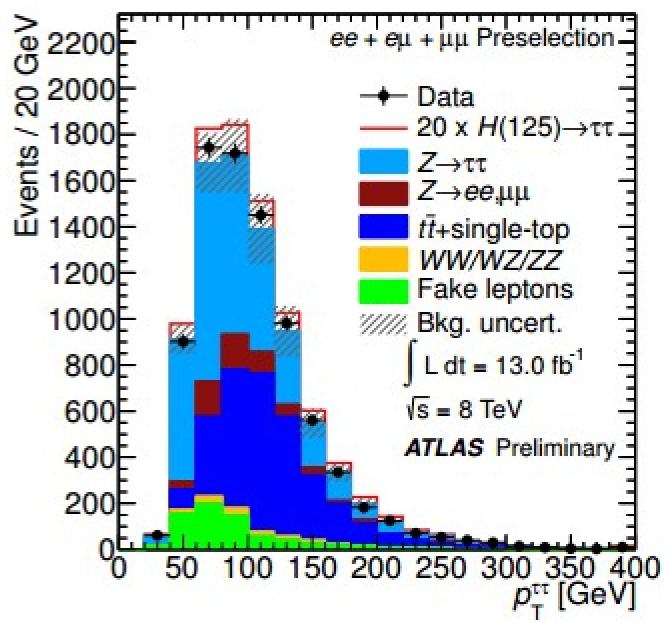


(b) x_1 after the E_T^{miss} cut

Preselection

8 TeV





Lep-Had Events @ 7 TeV

Process	Events	
	Boosted	VBF
$gg \rightarrow H$ (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
$Z/\gamma^* \rightarrow \tau\tau^\dagger$	$(0.70 \pm 0.02 \pm 0.10)\times 10^3$	$6.5 \pm 0.6 \pm 1.5$
Diboson †	$8.4 \pm 0.7 \pm 0.8$	$0.12 \pm 0.06 \pm 0.03$
$Z/\gamma^* \rightarrow \ell\ell^\dagger$	$3.7 \pm 1.3 \pm 1.0$	$0.8 \pm 0.3 \pm 1.0$
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	$(0.90 \pm 0.02 \pm 0.10)\times 10^3$	$9.5 \pm 0.8 \pm 1.9$
Observed data	834	10

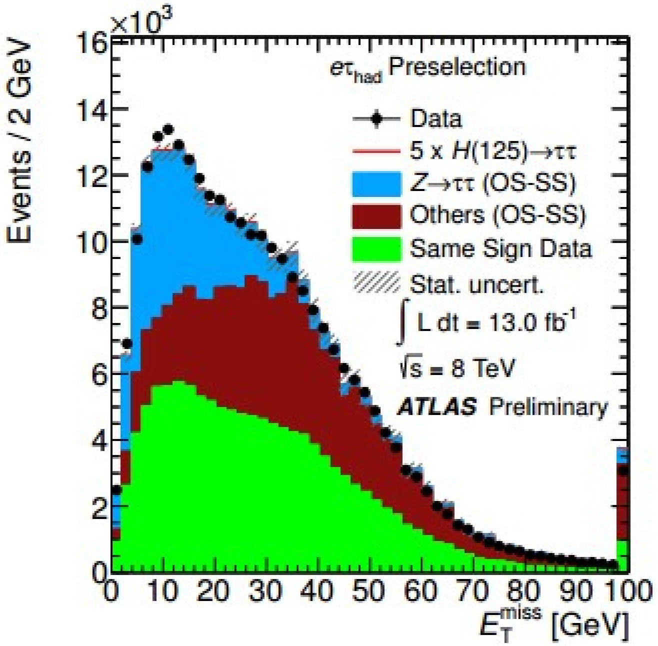
Number of events in the Boosted and VBF categories for the eτhad and μhad channels combined, for the 7 TeV analysis. The uncertainties are statistical and systematic, in this order. For the backgrounds marked with a dagger, the values in the Boosted column indicate the (OS-SS) component.

Lep-Had Events @ 8 TeV

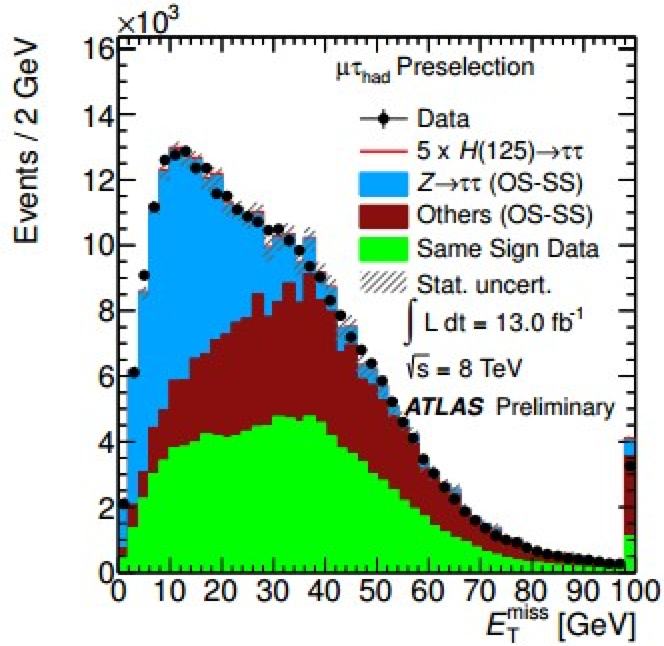
Process	Events	
	Boosted	VBF
$gg \to H$ (125 GeV)	20.3 ± 0.7 ± 5.1	0.5 ± 0.1 ± 0.3
VBF H (125 GeV)	5.3 ± 0.2 ± 0.3	2.5 ± 0.2 ± 0.4
VH (125 GeV)	2.7 ± 0.2 ± 0.2	<0.001
$Z/\gamma^* \to \tau\tau$ †	(1.78 ± 0.03 ± 0.11)×10³	17 ± 2 ± 6
Diboson †	12.2 ± 0.9 ± 1.0	0.6 ± 0.3 ± 0.4
$Z/\gamma^* \to \ell\ell$ †	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 ± 0.06 ± 0.04)×10³	–
Same sign data	(0.34 ± 0.02 ± 0.01)×10³	–
Fake-$\tau_{\text{had-vis}}$ backgrounds	–	7.6 ± 0.7 ± 3.8
Total background	(2.53 ± 0.07 ± 0.13)×10³	29 ± 2 ± 7
Observed data	2602	29

Number of events in the Boosted and VBF categories for the eτhad and μhad channels combined, for the 8 TeV analysis. The uncertainties are statistical and systematic, in this order. For the backgrounds marked with a dagger, the values in the Boosted column indicate the (OS-SS) component.

Lep-Had

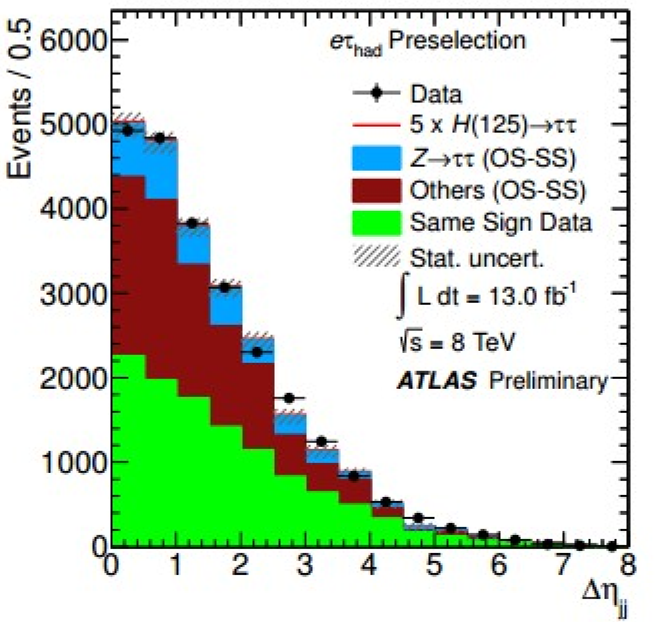


(a) $\tau_e\,\tau_{\rm had}$ Preselection

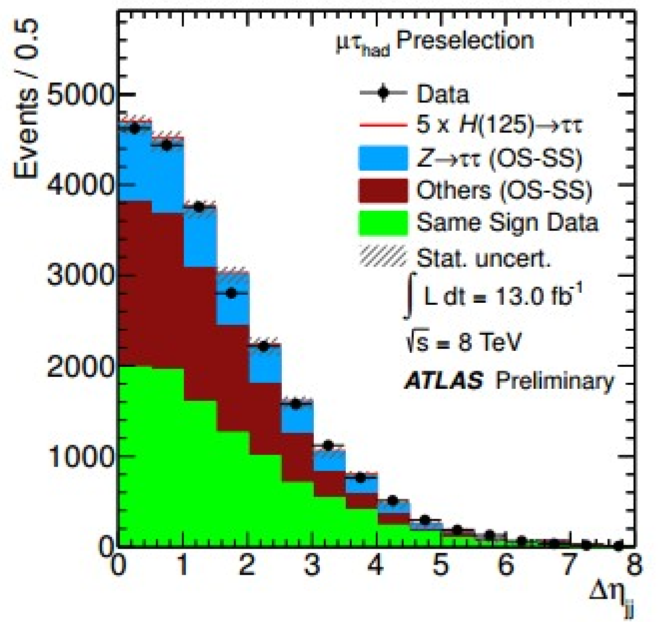


(b) $\tau_\mu\,\tau_{\rm had}$ Preselection

Preselection
8 TeV

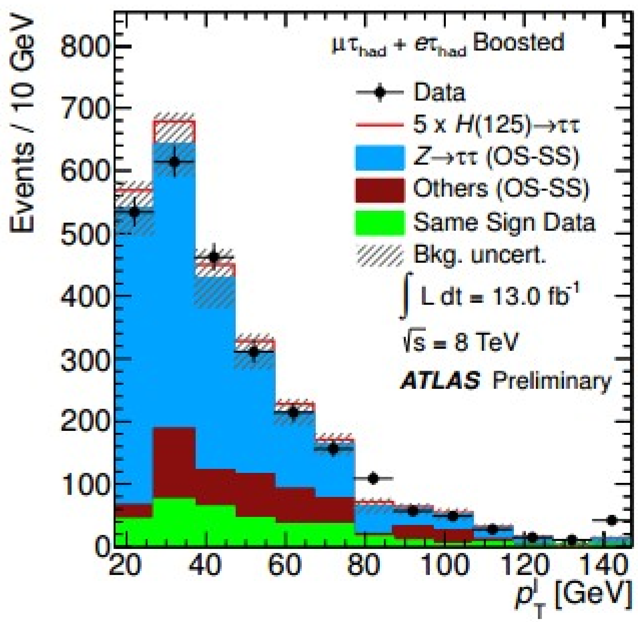


(c) $\tau_e\,\tau_{\rm had}$ Preselection

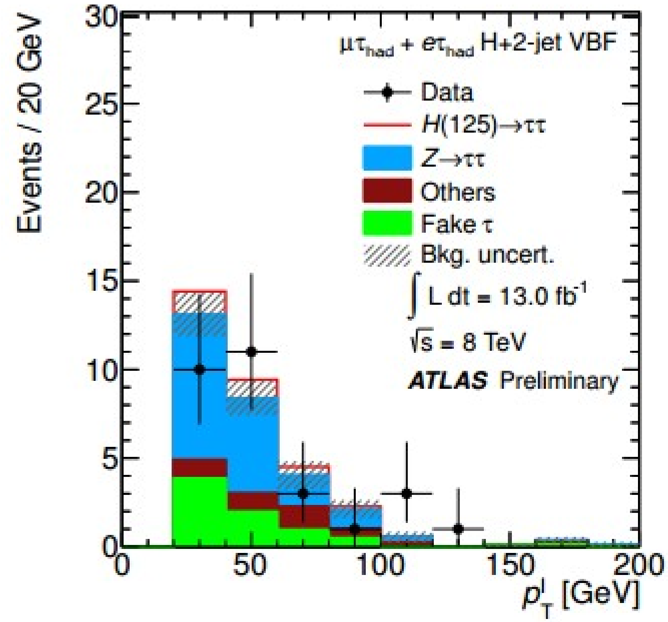


(d) $\tau_\mu\,\tau_{\rm had}$ Preselection

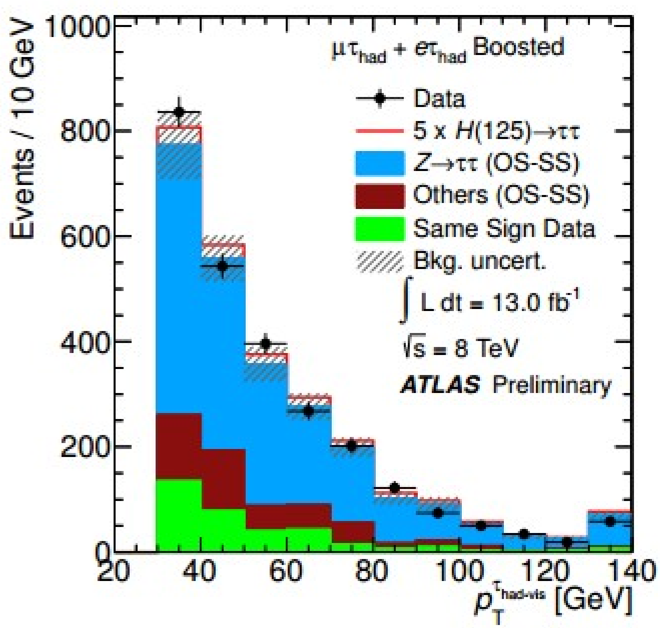
Lep-Had



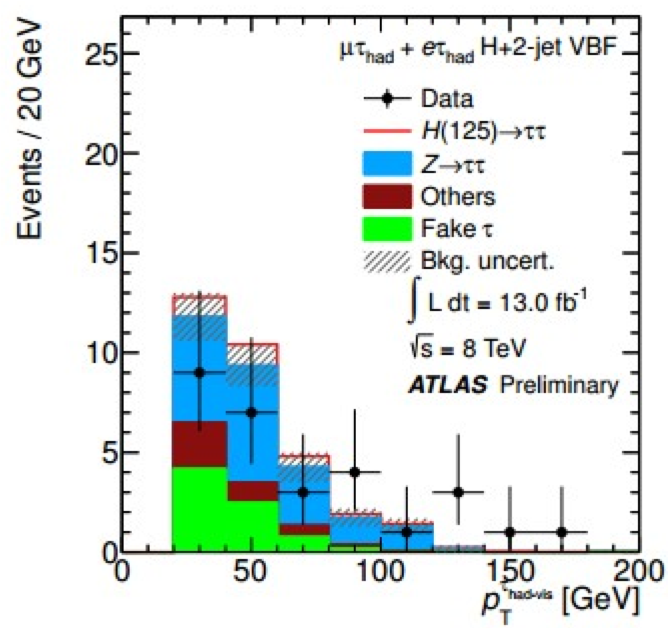
(a) Boosted category



(b) VBF category



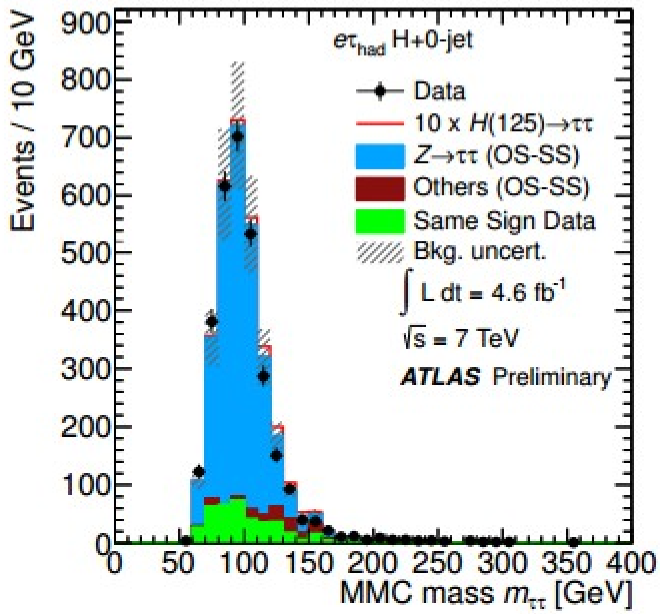
(c) Boosted category



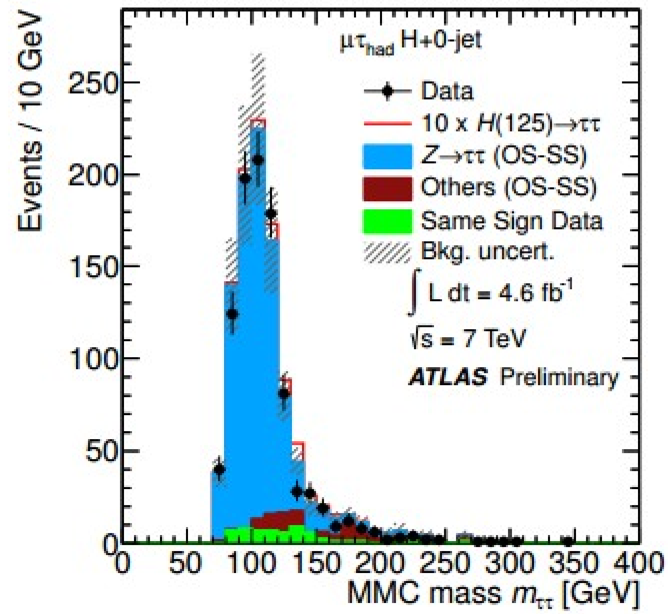
(d) VBF category

Tau pT distributions
8 TeV

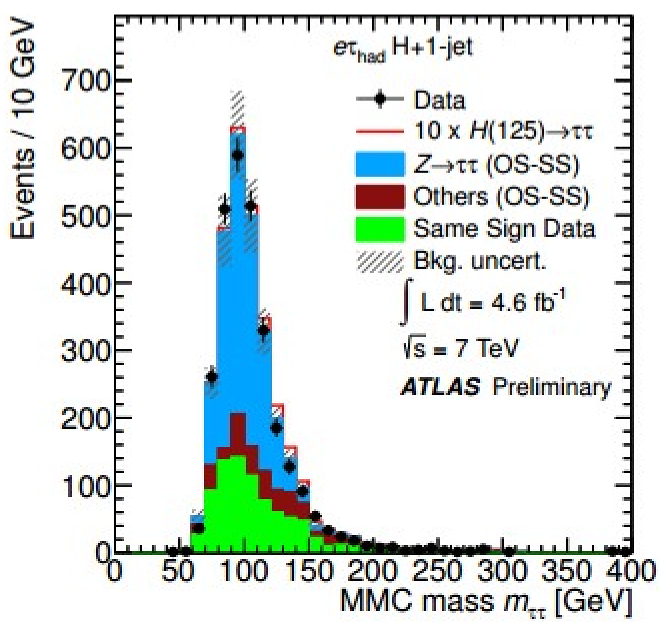
Lep-Had



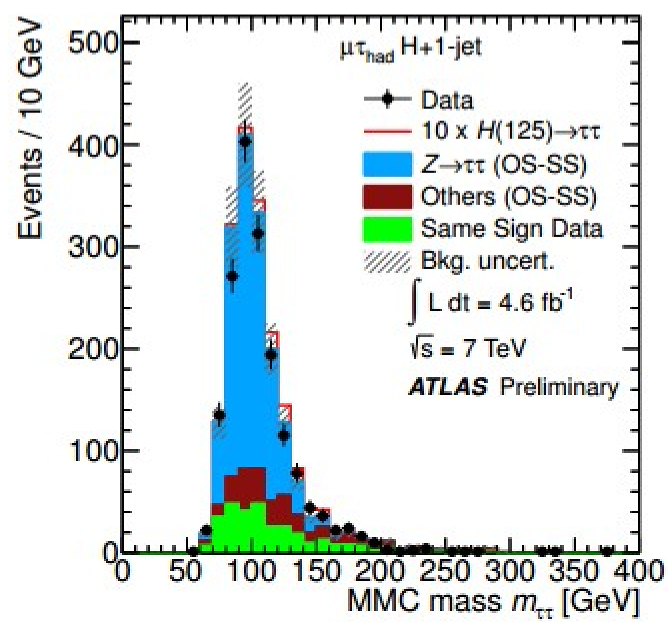
(a) H +0-jet ($\tau_e\ \tau_{\rm had}$)



(b) H +0-jet ($\tau_\mu\ \tau_{\rm had}$)



(c) H +1-jet ($\tau_e\ \tau_{\rm had}$)

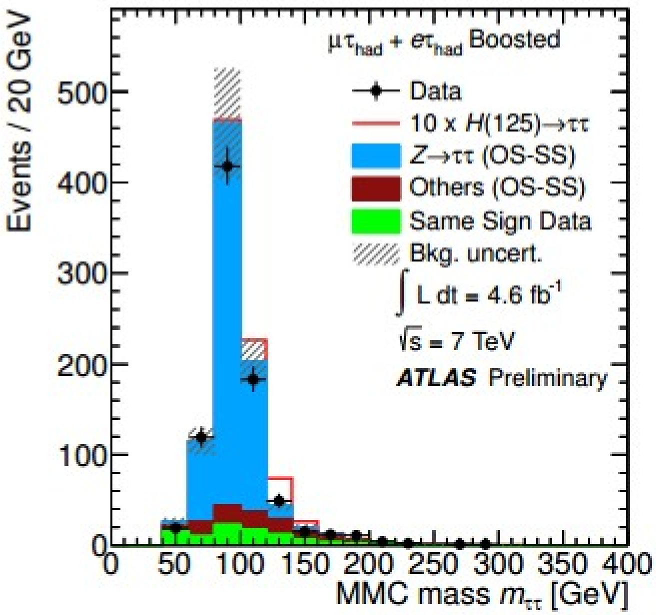


(d) H +1-jet ($\tau_\mu\ \tau_{\rm had}$)

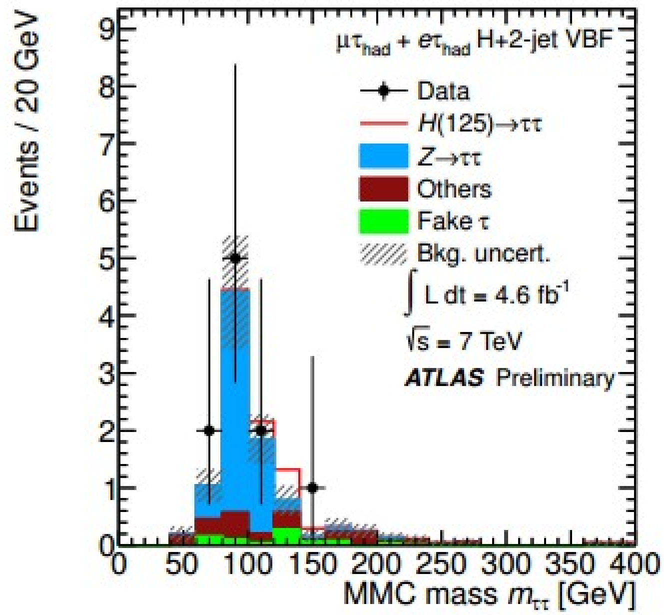
MMC di-tau mass distributions

7 TeV

Lep-Had MMC



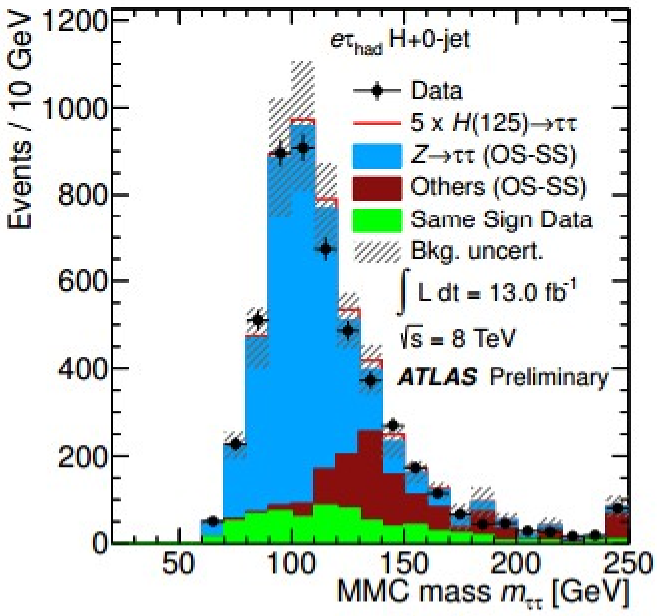
(a) Boosted category



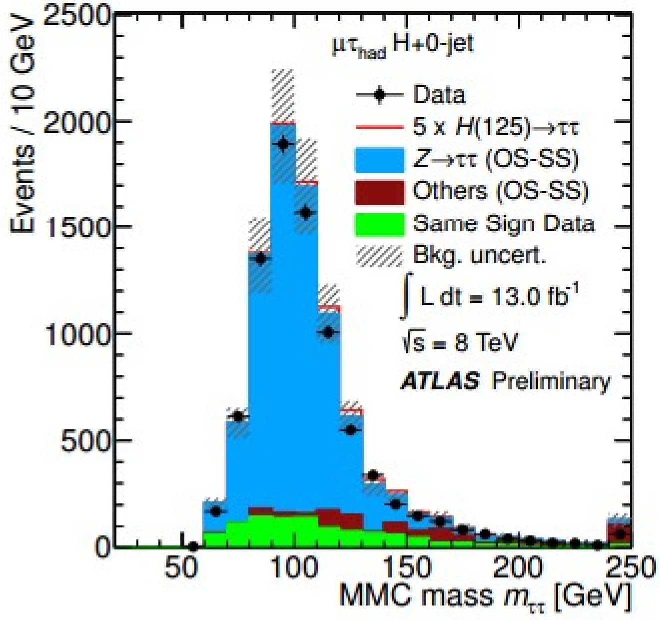
(b) VBF category

MMC mass distributions of the selected events in the Boosted and VBF categories of the Higgs tautau lephad channel for the 7 TeV analysis

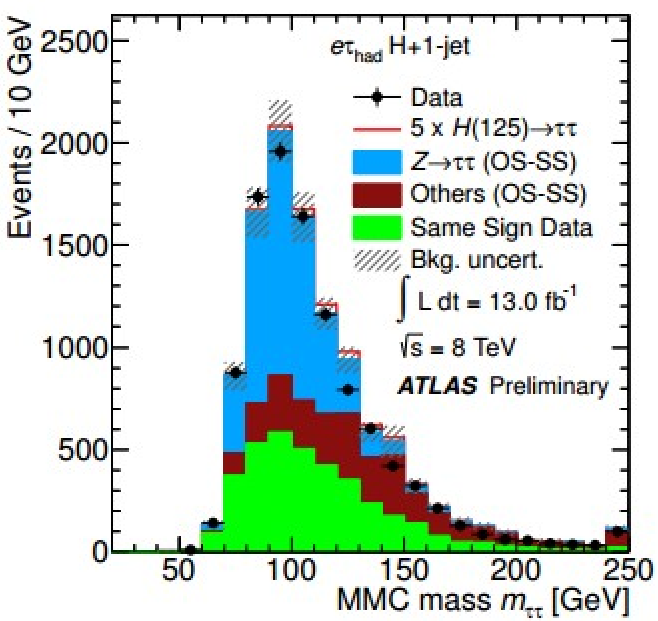
Lep-Had



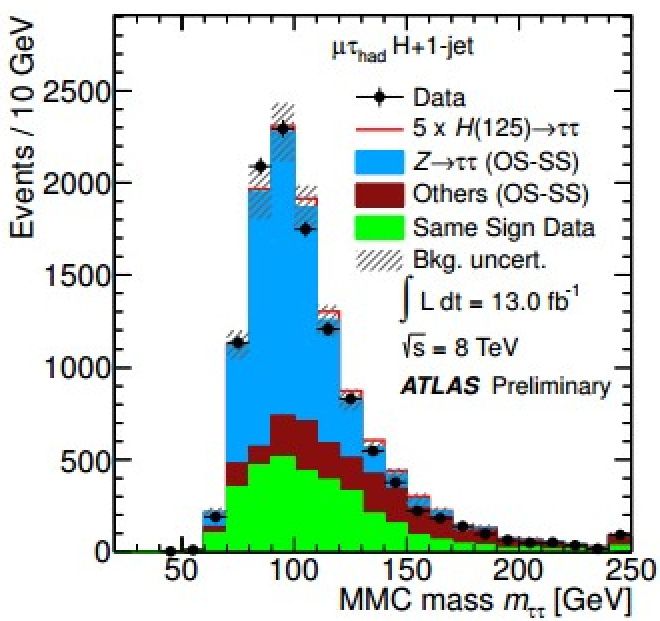
(a) H +0-jet ($\tau_e\ \tau_{had}$)



(b) H +0-jet ($\tau_\mu\ \tau_{had}$)



(c) H +1-jet ($\tau_e\ \tau_{had}$)

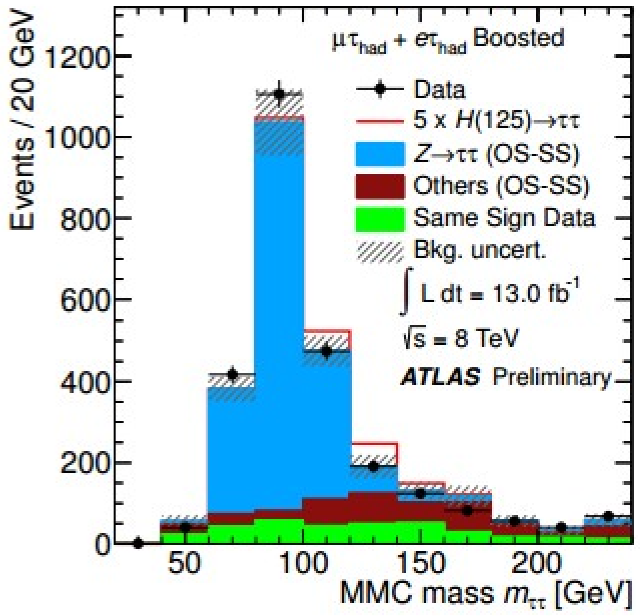


(d) H +1-jet ($\tau_\mu\ \tau_{had}$)

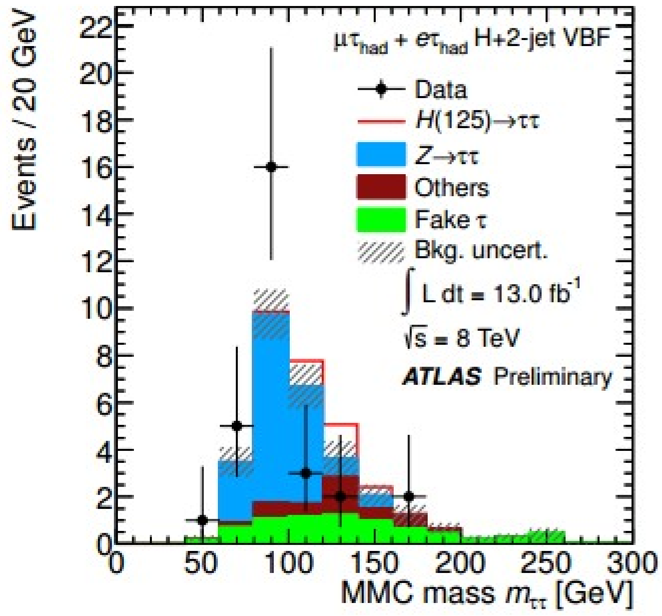
MMC di-tau mass distributions

8 TeV

Lep-Had MMC



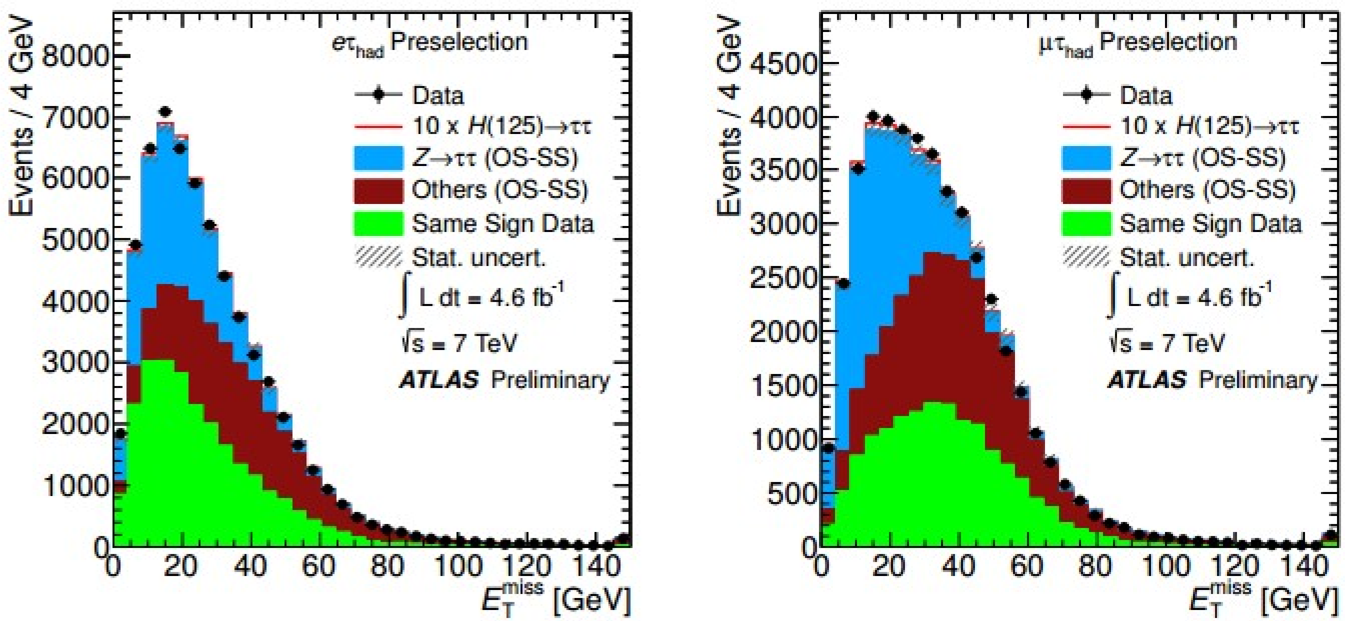
(a) Boosted category



(b) VBF category

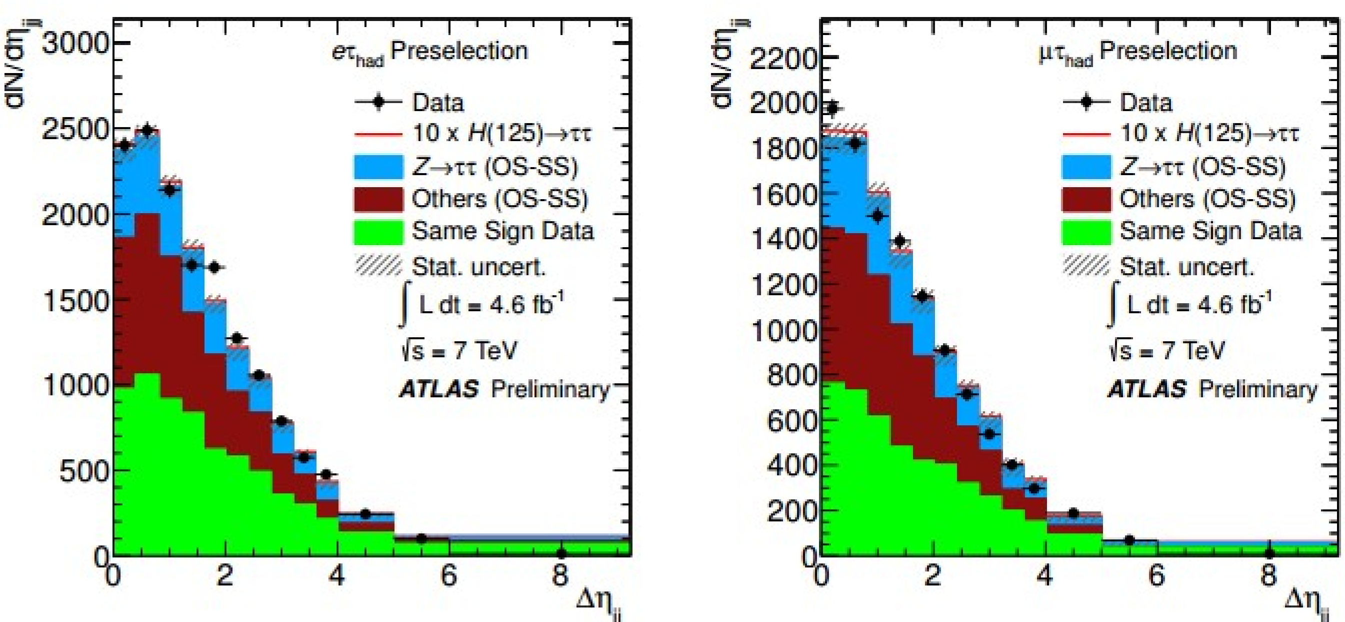
MMC mass distributions of the selected events in the Boosted and VBF categories of the Higgs tautau lephad channel for the 8 TeV analysis

Lep-Had distributions



(a) $\tau_e\ \tau_{had}$ Preselection

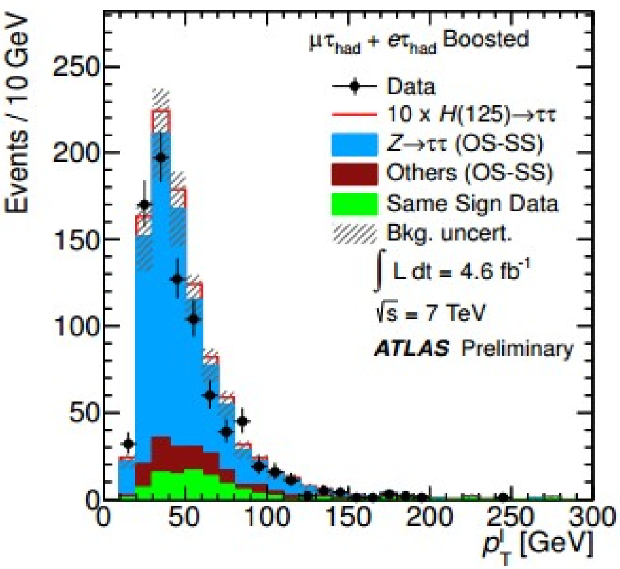
(b) $\tau_\mu\ \tau_{had}$ Preselection



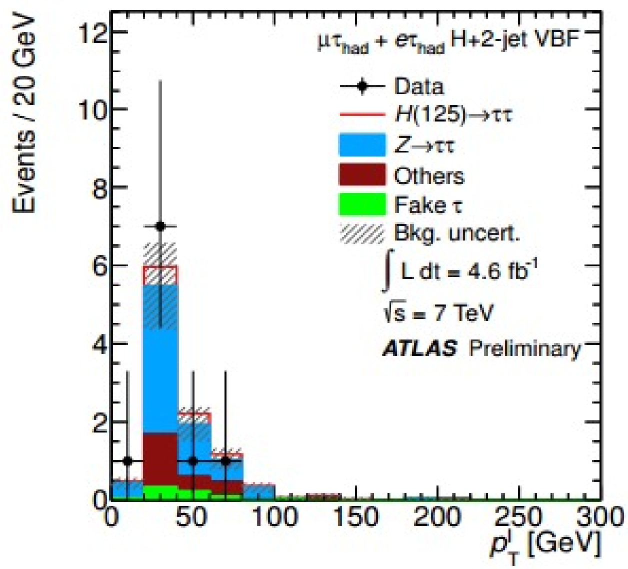
Preselection

7 TeV

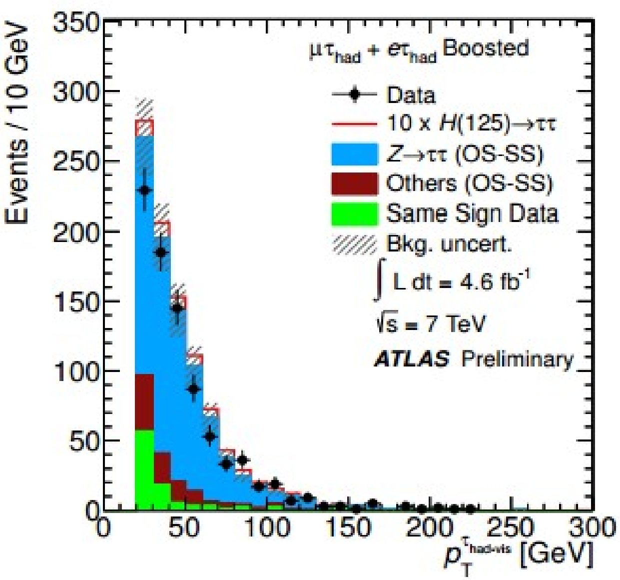
Lep-Had tau pT distributions



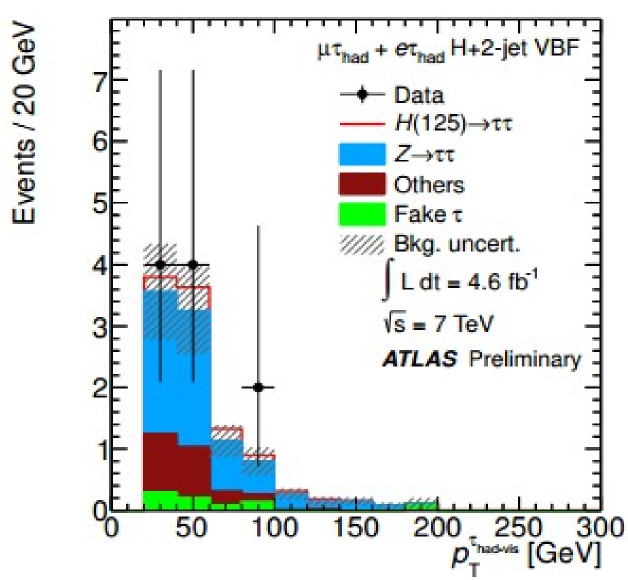
(a) Lepton p_T in the Boosted category



(b) Lepton p_T in the VBF category



(c) τ_{had} candidate p_T in the Boosted category

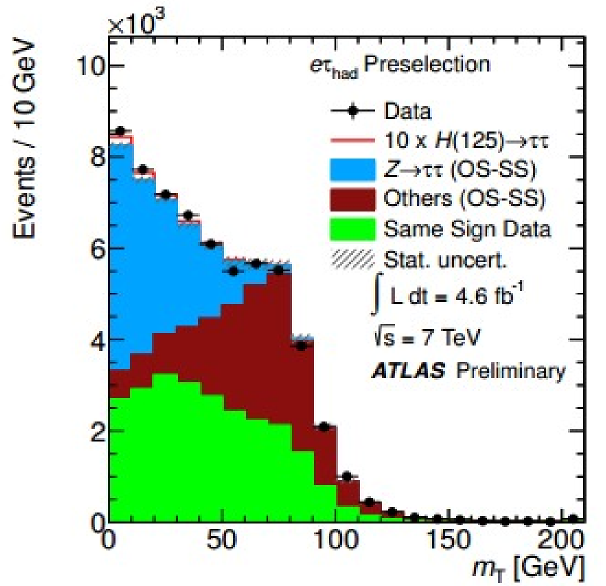


(d) τ_{had} candidate p_T in the VBF category

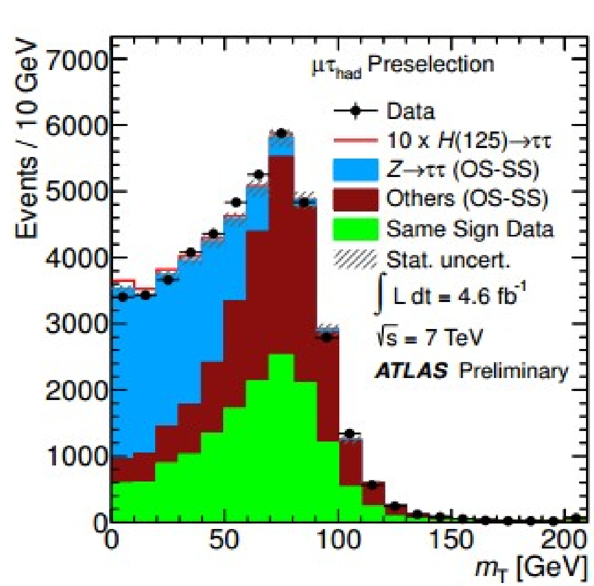
Preselection

7 TeV

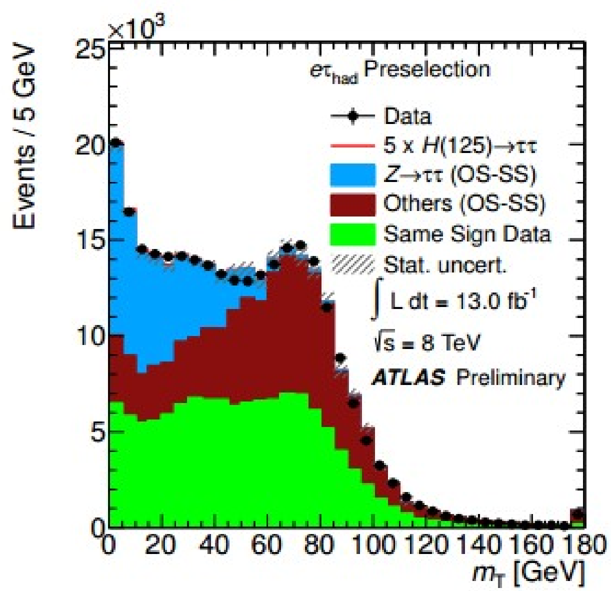
Lep-Had distributions



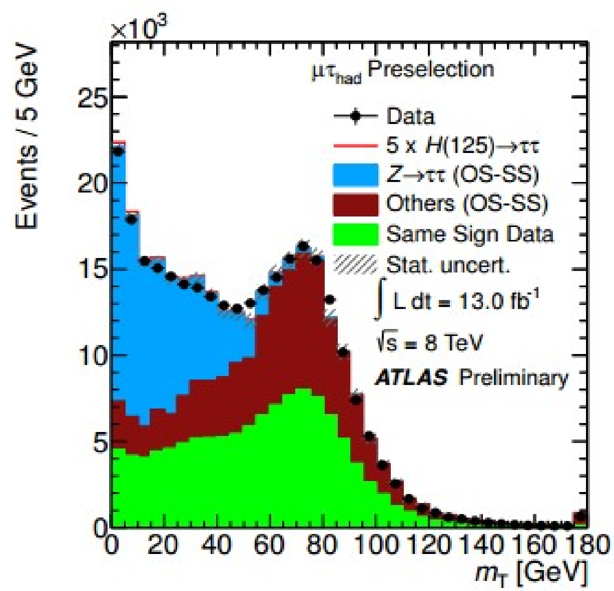
(a) $\tau_e \tau_{had}$ Preselection



(b) $\tau_\mu \tau_{had}$ Preselection



(c) $\tau_e \tau_{had}$ Preselection

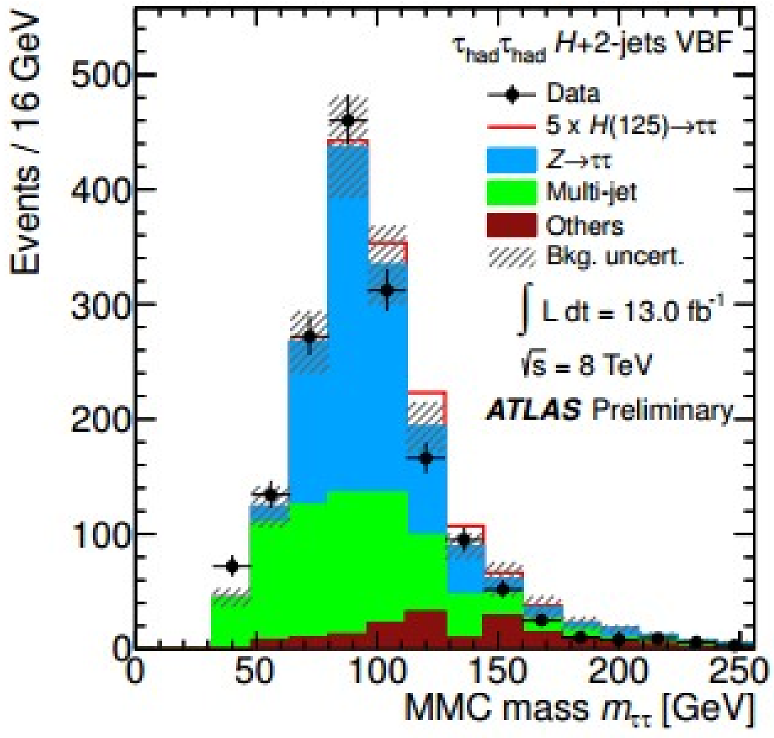


(d) $\tau_\mu \tau_{had}$ Preselection

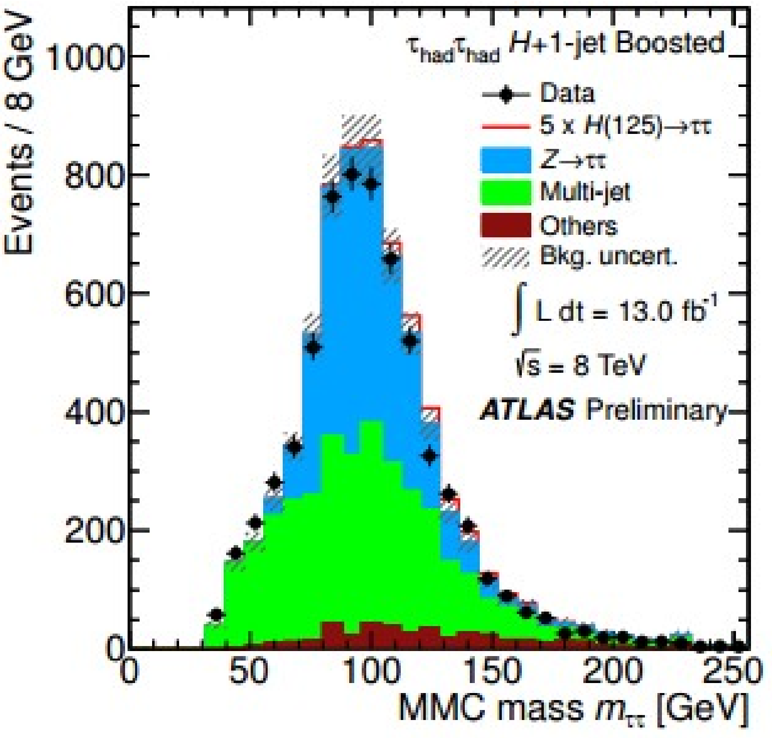
Preselection

7 TeV

Had-Had MMC



(a) 2-jet preselection



(b) 1-jet preselection

Reconstructed mass of the two selected had candidates in the VBF (a) and Boosted (b) preselected regions for 8 TeV collision data.

The selected events in data are shown together with the predicted Higgs boson signal (mH=125 GeV) stacked above the background contributions.

Ssignal contributions have been scaled by a factor of five.

The hatched band indicates the total background uncertainty.

Had-Had Events

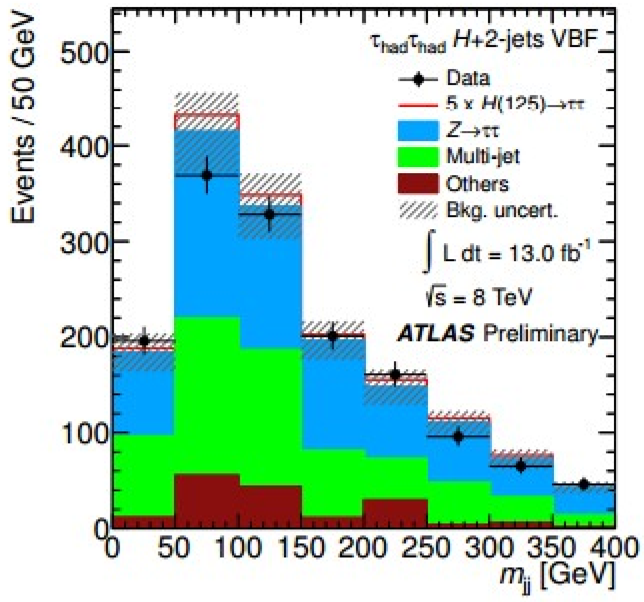
$H \to \tau_{had}\tau_{had}$	7 TeV analysis (4.6 fb^{-1})		8 TeV analysis (13.0 fb^{-1})	
	VBF category	Boosted category	VBF category	Boosted category
$gg \to H$ (125 GeV)	0.36 ± 0.06 ± 0.12	2.4 ± 0.2 ± 0.7	1.0 ± 0.1 ± 0.3	8.2 ± 0.4 ± 1.8
VBF H (125 GeV)	1.12 ± 0.04 ± 0.18	0.68 ± 0.03 ± 0.07	3.01 ± 0.09 ± 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

Number of events after the Higgs → hadhad selection in data and predicted number of background events, for an integrated luminosity of 4.6/fb and 13.0/fb at √s = 7 TeV and 8 TeV, respectively.

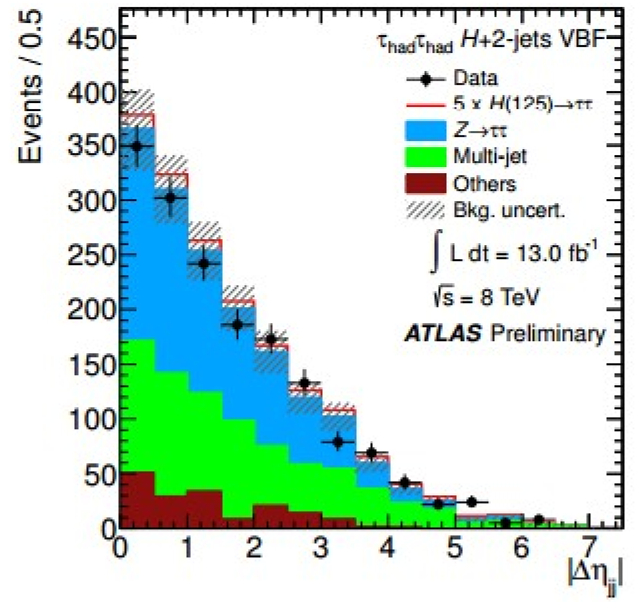
Predictions for the Higgs boson signal (mH = 125 GeV) are also given.

The statistical and systematic uncertainties are quoted, in that order.

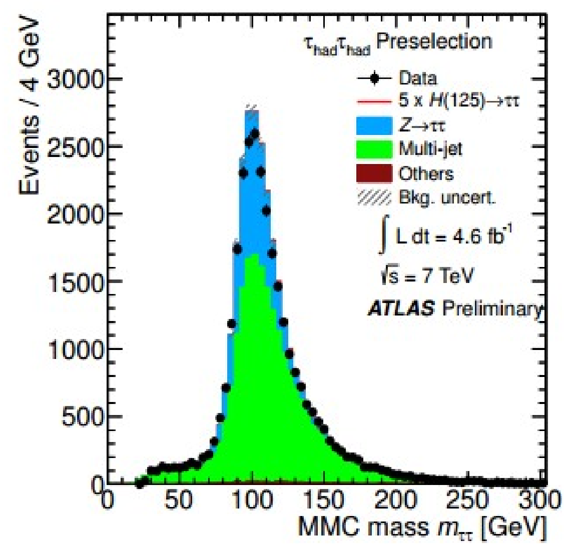
Had-Had

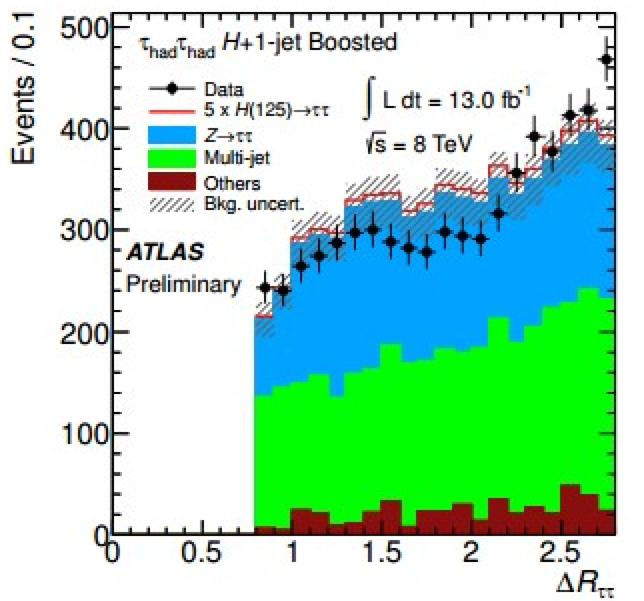


(a) 2-jet preselection

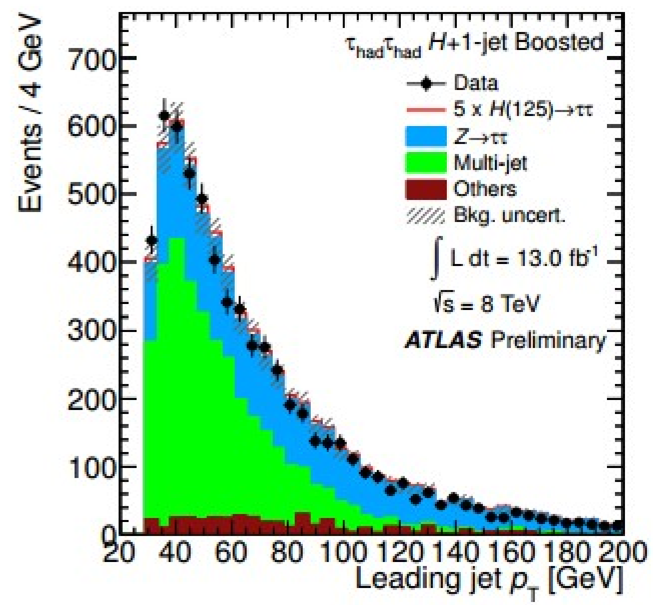


(b) 2-jet preselection



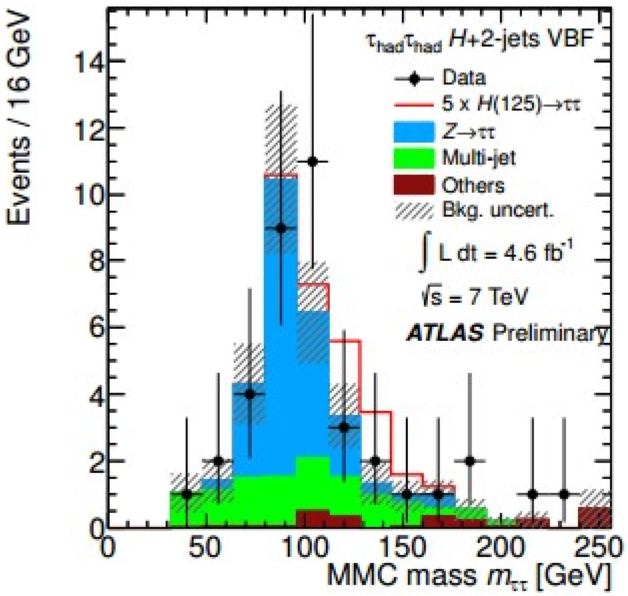


(c) 1-jet preselection

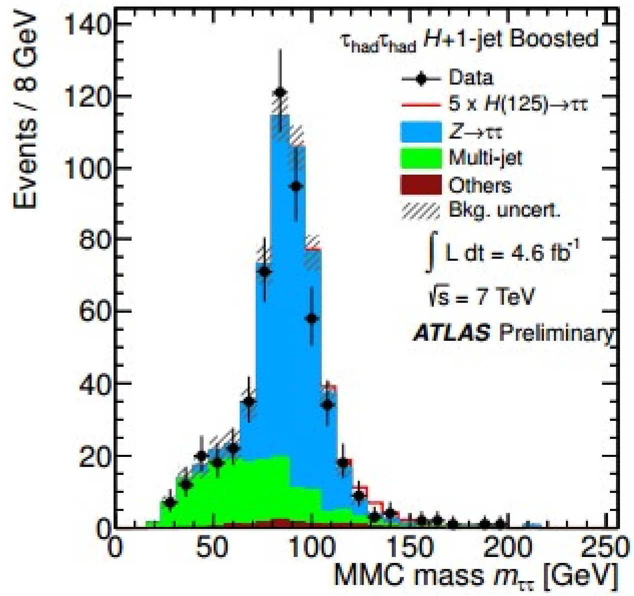


(d) 1-jet preselection

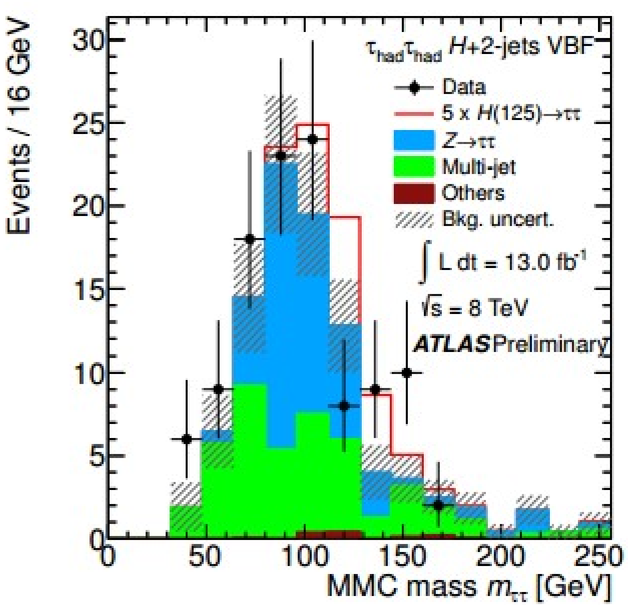
Had-Had



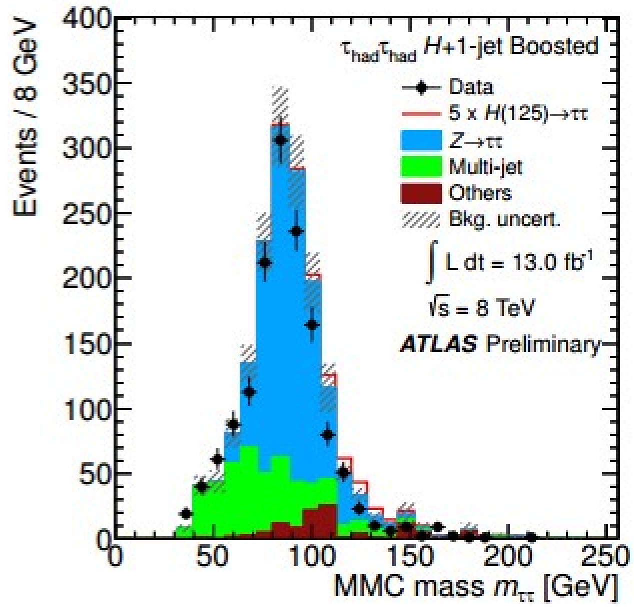
(a) VBF category



(b) Boosted category



(c) VBF category



(d) Boosted category

Reconstructed
Di-tau mass

Statistical Analysis

The statistical analysis of the data employs a binned likelihood function constructed as a product of the likelihood terms for each category.

In each bin of the mass distributions, the likelihood function L(μ, θ) for the observed number of events (N) is modelled according to a Poisson distribution based upon the expected signal and background contributions

The “signal strength” parameter (μ) multiplying the expected signal yield in each bin the parameter of interest in the fit procedure

The value μ = 0 (μ = 1) corresponds to the absence (presence) of a Higgs boson signal with the SM production cross-section.

Signal and background predictions (sj and bj) depend on systematic uncertainties that are parametrized by nuisance parameters, which in turn are constrained using Gaussian functions

The correlations of the systematic uncertainties across categories are taken into account. The likelihood function is given by

$$\mathcal{L}(\mu, \theta) = \prod_{\text{category}} \left[\prod_{\text{bin } j} \text{Poisson}(N_j | \mu \cdot s_j + b_j) \prod_{\theta} \text{Gaussian}(t | \theta, 1) \right]$$

t represents the auxiliary measurements, such as control regions and dedicated calibration measurements

Statistical Analysis

The parametrisation is chosen such that the rates in each channel are log-normally distributed for a normally distributed θ

The expected signal and background event counts in each bin j are multiplied by

$(1 + \sigma_{\theta N}\text{Gaussian}(t_N|\theta_N,1))\ .\ \sigma_{\theta S}\ \text{Gaussian}(t_S\ |\ \theta_S\ , 1)$,

where $\sigma_{\theta N}$ and $\sigma_{\theta S}$ are the normalization and shape uncertainties associated to the θ nuisance πarameter with their nominal values t_N and t_S, respectively

The signal and background yields are adjusted to take into account the auxiliary measurements, which are obtained from their best fitted values in the observed dataset

The test statistic q_μ is defined as:

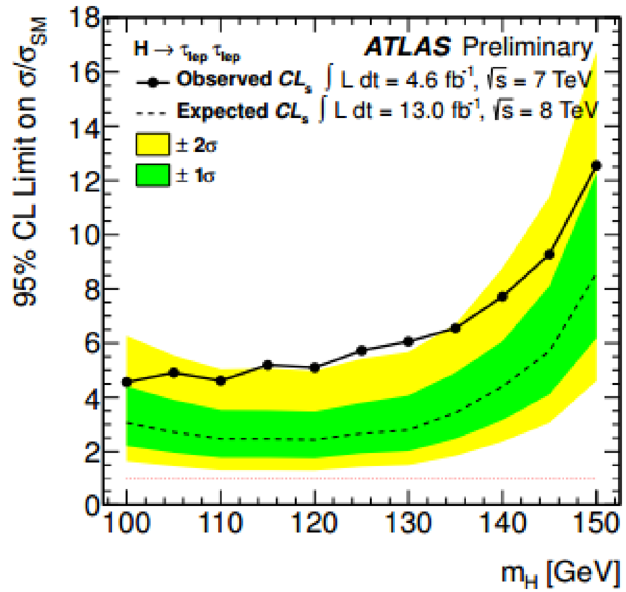
$$q_\mu = -2\ln\left(\mathcal{L}(\mu, \hat{\theta}_\mu)/\mathcal{L}(\hat{\mu}, \hat{\theta})\right)$$

This test statistic is used to compute exclusion limits following the modified frequentist method known as CL

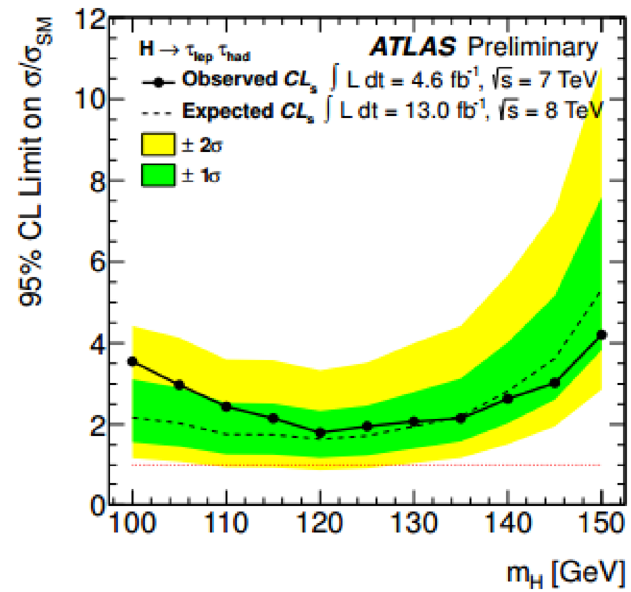
corresponds to the conditional maximum likelihood of θ for a given μ

refer to the global maximum of the likelihood

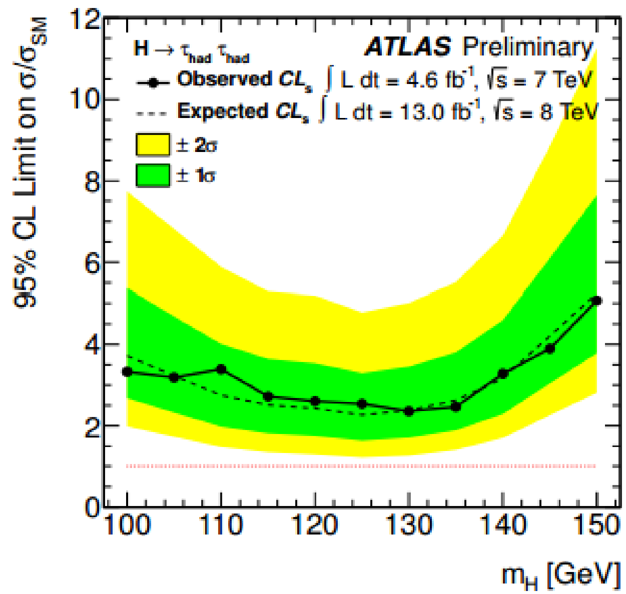
Limits per channel



(a) Combined $H \to \tau_{\rm lep}\tau_{\rm lep}$



(b) Combined $H \to \tau_{\rm lep}\tau_{\rm had}$



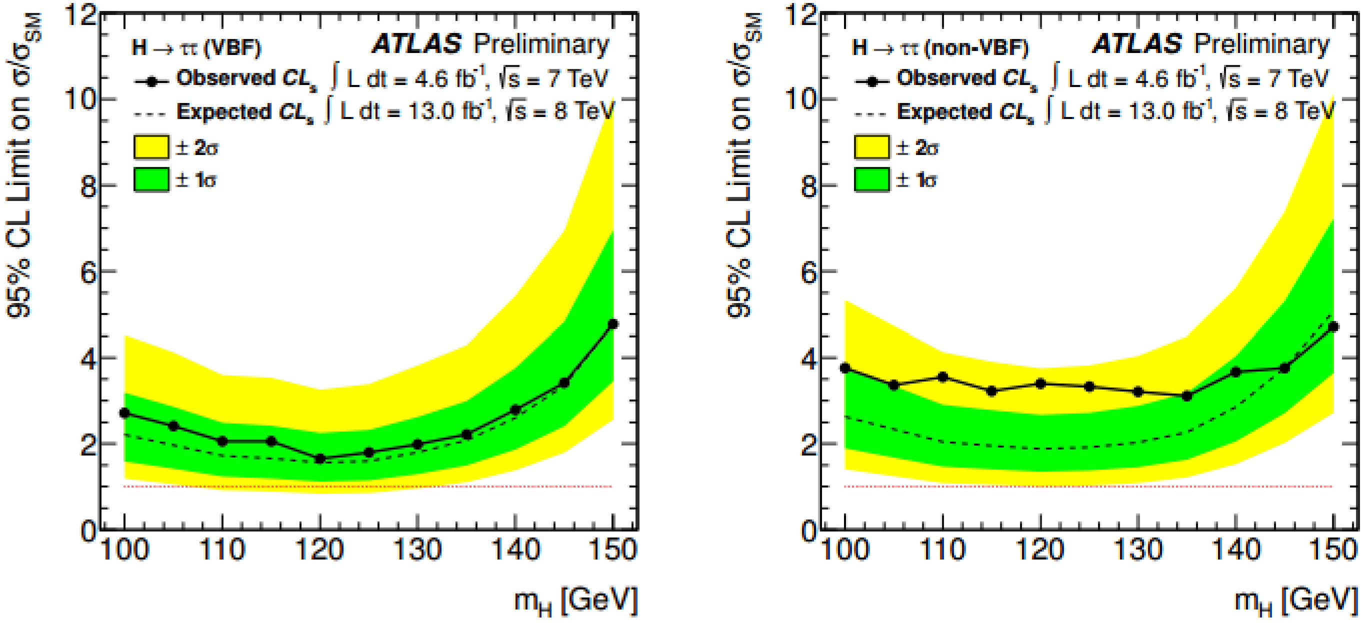
(c) Combined $H \to \tau_{\rm had}\tau_{\rm had}$

Observed (solid) and expected (dashed) 95% confidence level upper limits on the Higgs boson cross-section times branching ratio, normalised to the SM expectation, as a function of the Higgs boson mass.

Expected limits are given for the scenario with no signal.

The bands around the dashed line indicate the +- 1σ and 2σ uncertainties of the expected limit

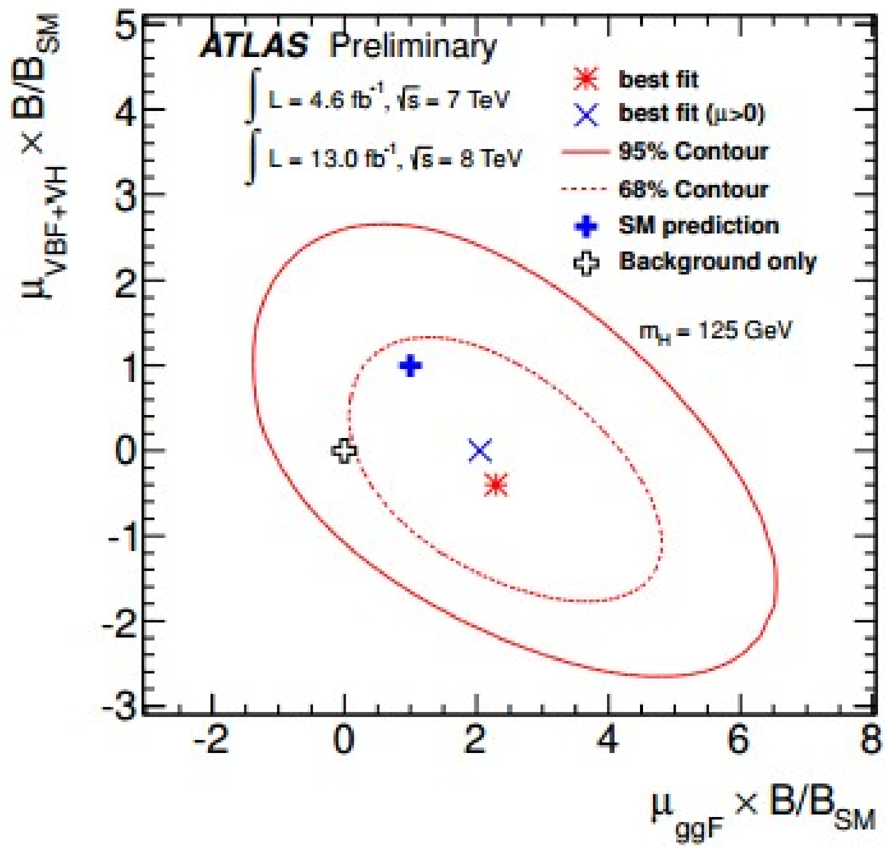
Limits per category



(a) VBF categories

(b) Non-VBF categories

Contours



Likelihood contours for the $H \rightarrow \tau\tau$ channel in the (μ_{ggF} x B/B_{SM}, μ_{VBF+VH} x B/B_{SM}) plane are shown for the 68% and 95% CL by dashed and solid lines, respectively. The SM expectation and the one corresponding to background-only hypothesis are shown by a filled plus and an open plus symbol, respectively. The best fit to the data are shown for the case when both the μ_{ggF} and μ_{VBF+VH} have been constrained to be non-negative, as well as for the unconstrained case. Likelihood contours are obtained from the unconstrained fits for the μ_{ggF} and μ_{VBF+VH} parameters.

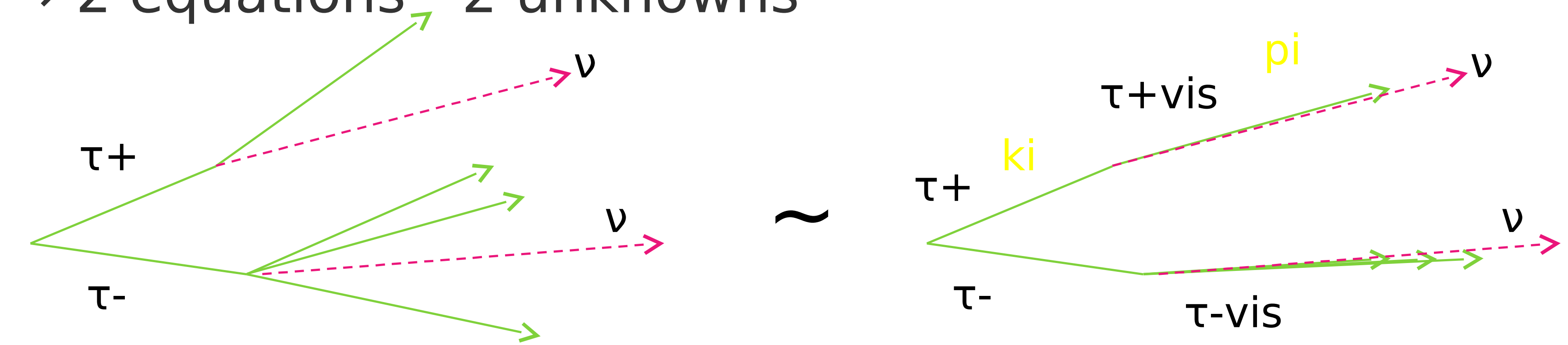
Channel	Trigger	Trigger p_{T} Threshold (GeV)	Offline p_{T} Threshold (GeV)
		7 TeV	
$H \to \tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	single electron	${p_{\mathrm{T}}}^{e} > 20 - 22$	electron p_T 2 GeV above trigger threshold ${p_{\mathrm{T}}}^{\mu} > 10$
	single muon	${p_{\mathrm{T}}}^{\mu} > 18$	${p_{\mathrm{T}}}^{\mu}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

Di-tau mass reconstruction

Collinear Approximation

Assumption: τ collinear visible decay products (P) and ETmiss (M) can be projected onto the x-y plane:

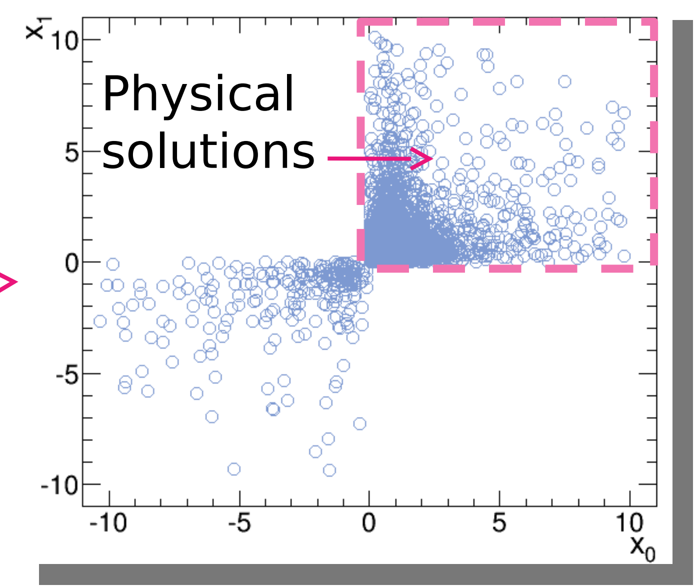
→ 2 equations - 2 unknowns



$$P = \begin{bmatrix} p_x^{(1)} & p_x^{(2)} \\ p_y^{(1)} & p_y^{(2)} \end{bmatrix}, \quad M = \begin{bmatrix} etx \\ ety \end{bmatrix}, \quad X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \quad \boxed{PX - M = 0,}$$

Visible MET e-fraction

xi = visible energy fraction of the τ parent



$$M^2 = (\mathbf{k}_1 + \mathbf{k}_2)^2 \quad \text{where} \quad \mathbf{p}_i = x_i \mathbf{k}_i$$

C.A. gives always a solution but σ(M) is not the best

Di-tau mass reconstruction

Missing Mass Calculator – MMC

Algorithm logic: Solve equations for 6 unknowns: x,y,z of the 2 ν's momenta

But only 4 equations available:

Ex,ymis(pmis, θ, φ) & M1,2(m1,2, pvis, Δθmis-vis)

Additional information:

3-D angle of visible and invisible τ decay products

Δθ3D(pvis, pmis)

parametrized to build probability functions

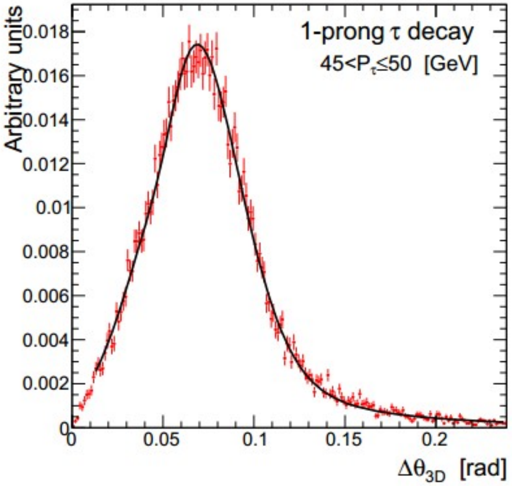
P(Δθ)

and assign probability to the events

P(event) = P(τ1) x P(τ1)

Perform scans in the (φmis1, φmis2) parameter space to detect the maximum of the Mττ distribution

Achieves better mττ resolution (δm~12-15 GeV @ mH = 125 GeV)



Probability distribution function P(τ) fitted in Zττ events

MMC

$$E_x^{miss} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$

$$E_y^{miss} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$

$$M_{\tau_1}^2 = m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2} - 2 p_{\text{vis}_1} p_{\text{mis}_1} \cos\Delta\theta_{vm_1}$$

$$M_{\tau_2}^2 = m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2} - 2 p_{\text{vis}_2} p_{\text{mis}_2} \cos\Delta\theta_{vm_2},$$

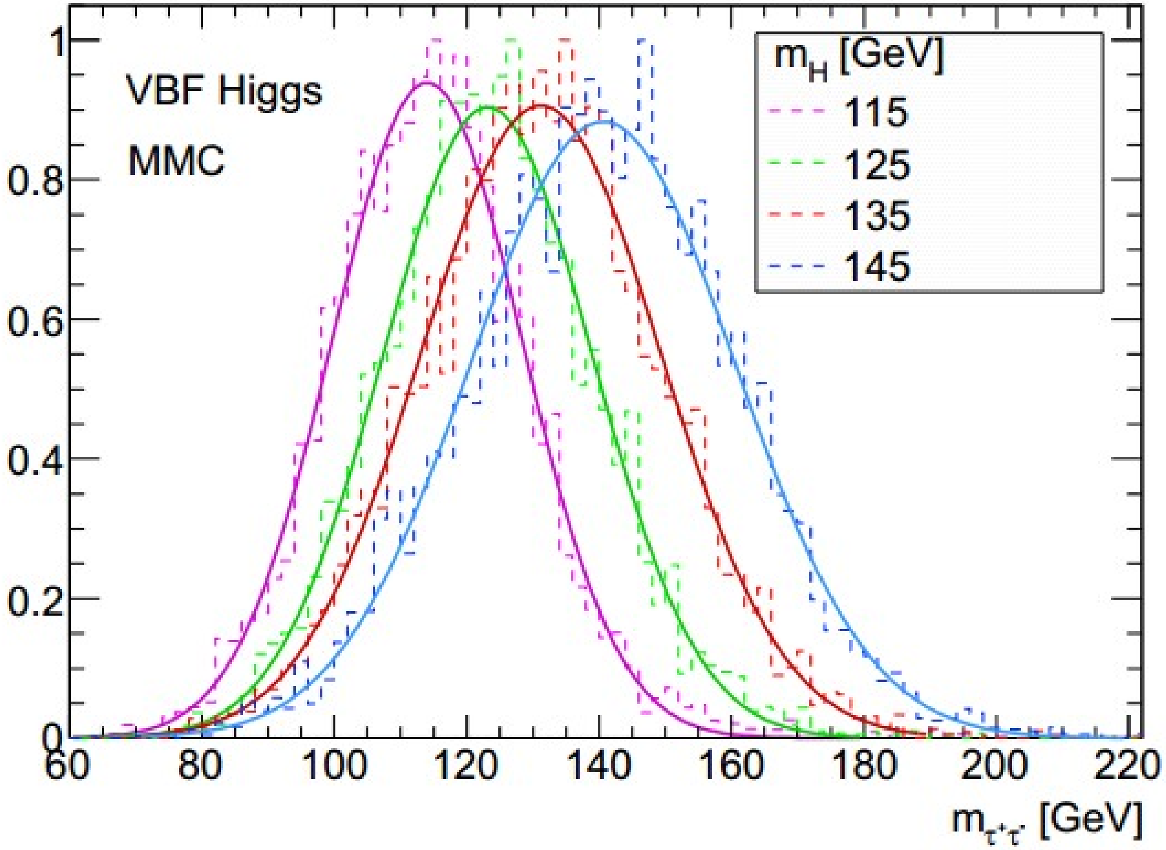
$$\mathcal{P}_{event} = \mathcal{P}(\Delta\theta_1, p_{\tau 1}) \times \mathcal{P}(\Delta\theta_2, p_{\tau 2}) \times \mathcal{P}(\Delta E_x^{miss}) \times \mathcal{P}(\Delta E_y^{miss}),$$

$$\mathcal{P}_{event} = \mathcal{P}(\Delta\theta_1, p_{\tau 1}) \times \mathcal{P}(\Delta\theta_2, p_{\tau 2}),$$

Probability functions accounting for the MET resolution

$$\mathcal{P}(E_{x,y}^{miss}) = \exp\left(-\frac{(\Delta E_{x,y}^{miss})^2}{2\sigma^2}\right),$$

MMC Resolution (2011)

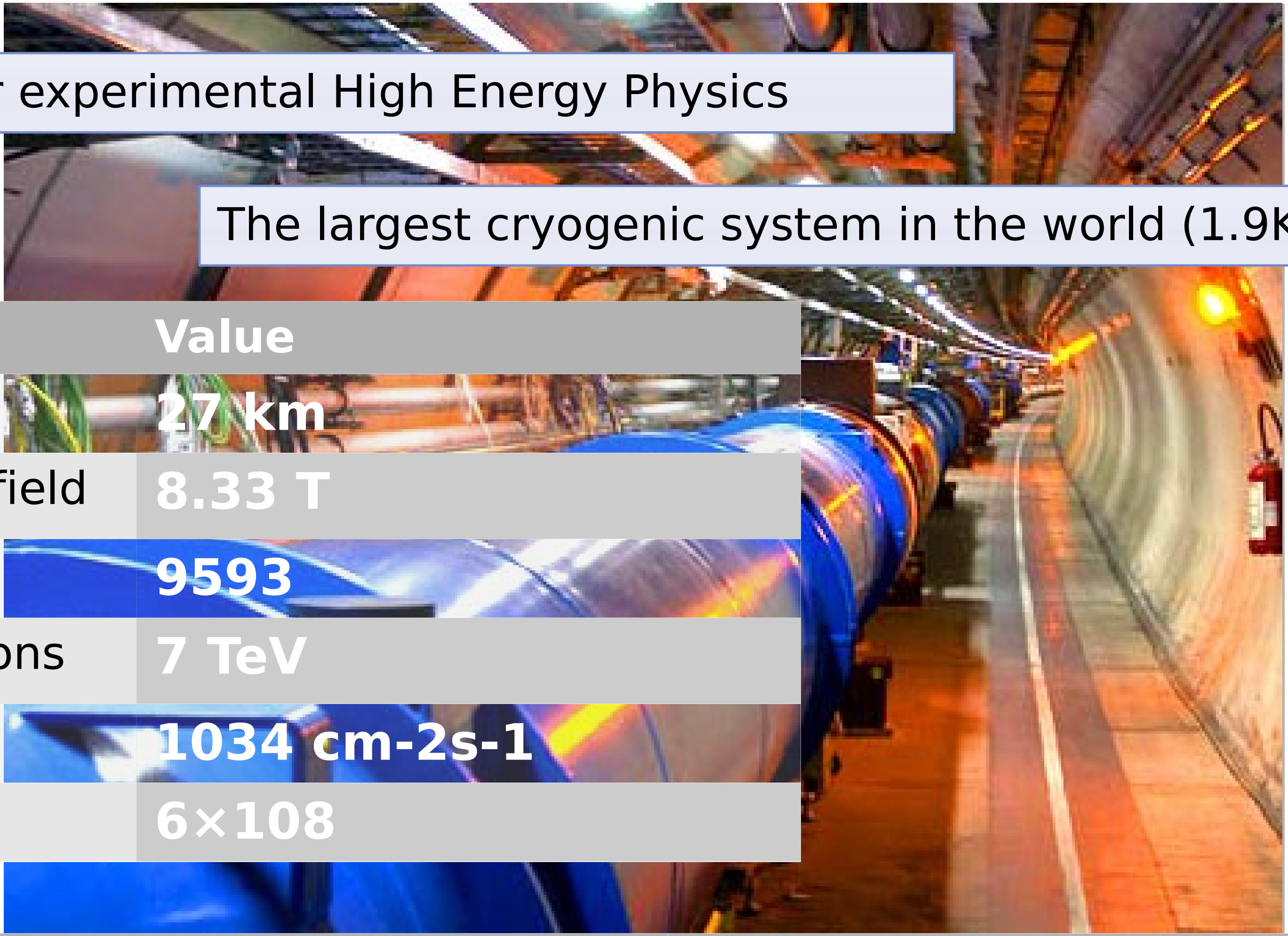


Mass [GeV]	Mean [GeV]	Sigma [GeV]
115	114 ± 3	14 ± 3
125	123 ± 4	16 ± 3
135	131 ± 4	18 ± 3
145	140 ± 4	20 ± 3

The Large Hadron Collider

The most powerful tool for experimental High Energy Physics

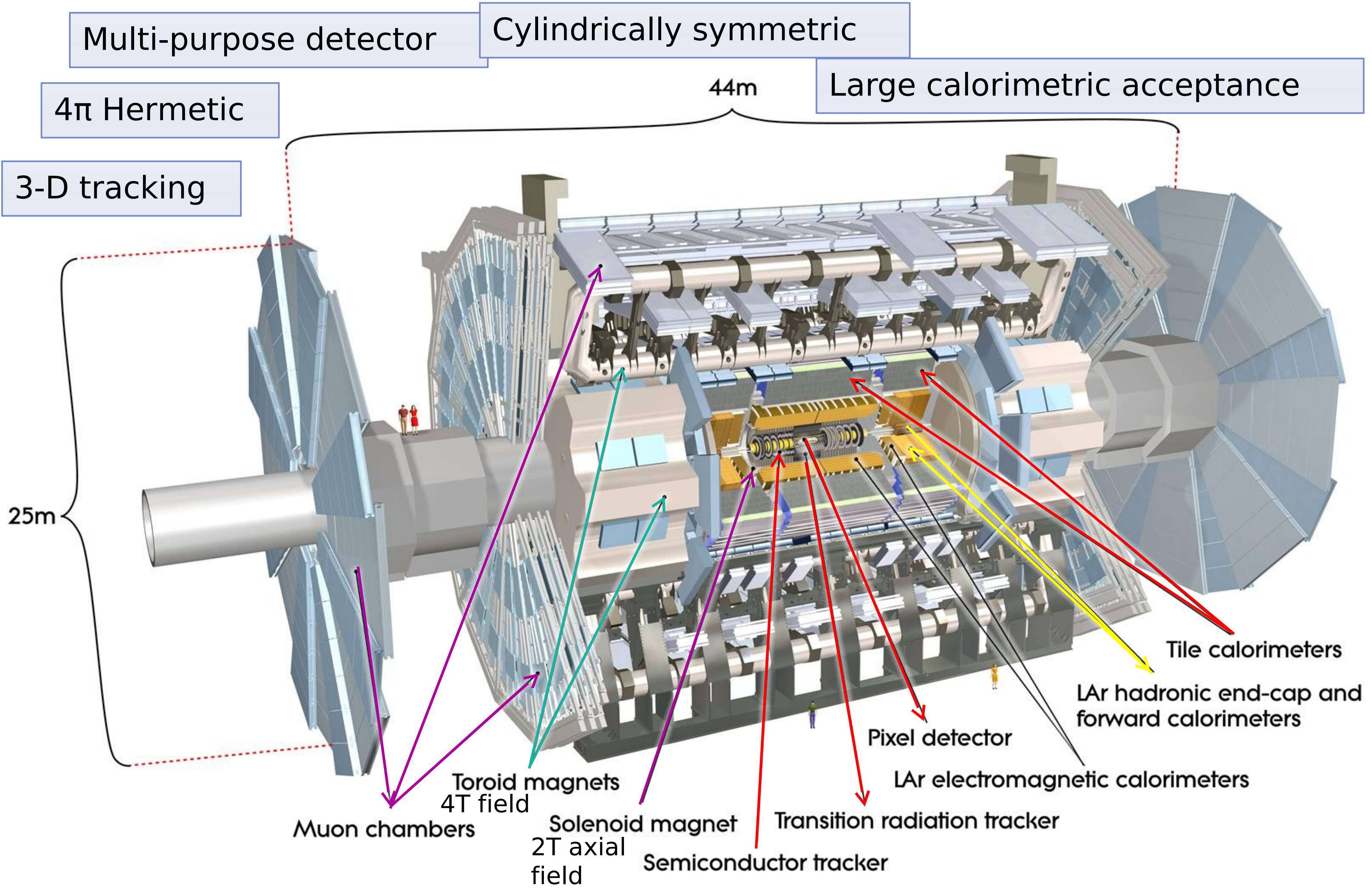
The largest cryogenic system in the world (1.9K)



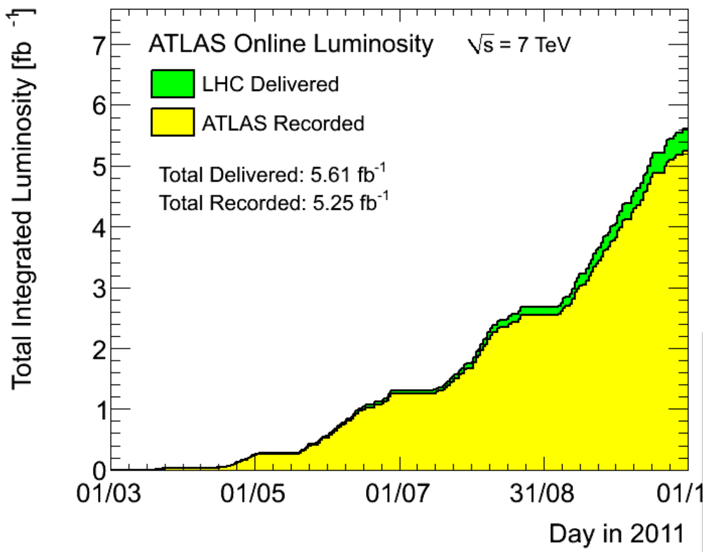
Quantity	Value
Circumference	27 km
Peak magnetic dipole field	8.33 T
Number of magnets	9593
Nominal energy - protons	7 TeV
Design luminosity	1034 cm-2s-1
Collisions per second	6×108

pp collisions	2010 @ 7 TeV	2011@ 7 TeV	2012 @ 8 TeV
Peak stable instantaneous luminosity cm-2s-1	2.07×1032	3.65×1033	7.73×1033
Recorded integrated luminosity in ATLAS	46.72 pb-1	5.25 fb-1	21.74 fb-1

The ATLAS Detector



Data 2011-12 @ √s = 7,8 TeV

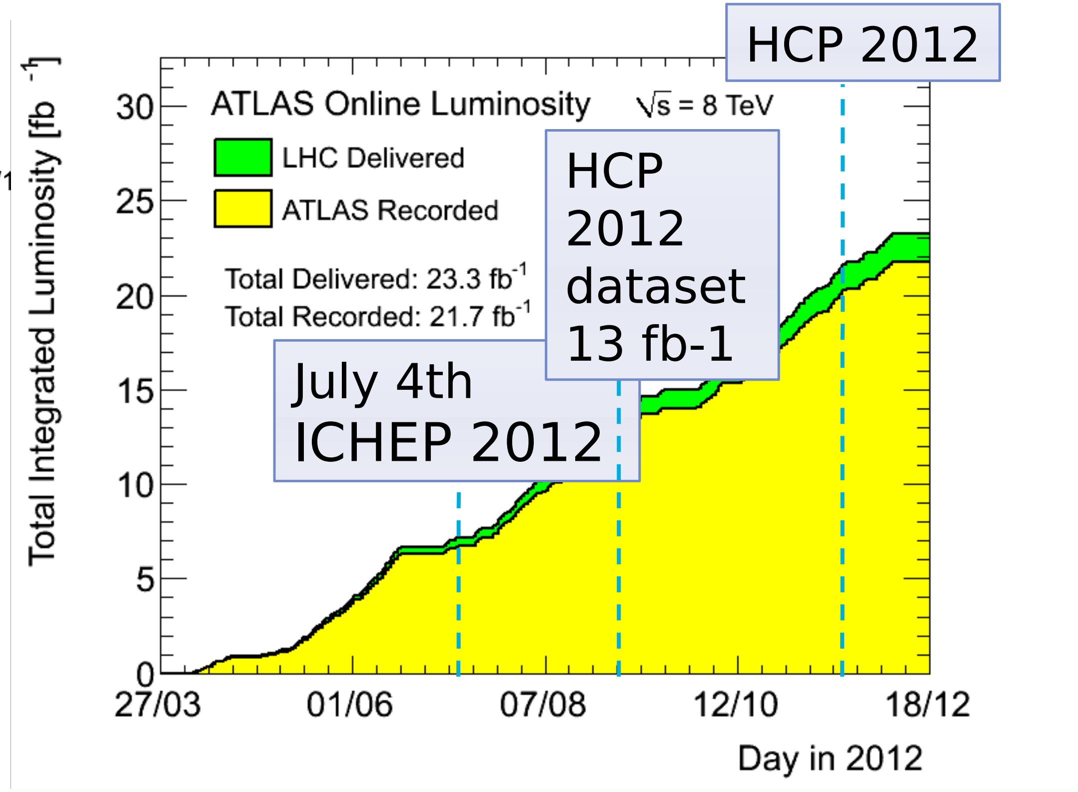


Delivered
5.61 fb-1

Data Quality
4.7 fb-1

On the tapes
5.25 fb-1

Analyzed
4.7 fb-1



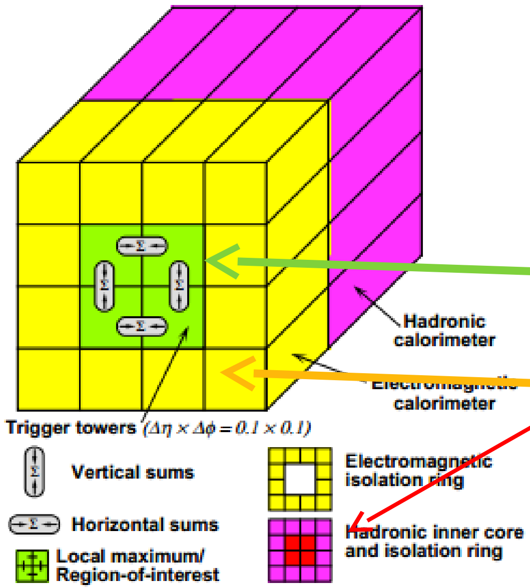
Delivered
23.3 fb-1

Data Quality
21.1 fb-1

On the tapes
21.7 fb-1

Analyzed
20.3 fb-1

Tau triggers in ATLAS



Level 1 (L1):

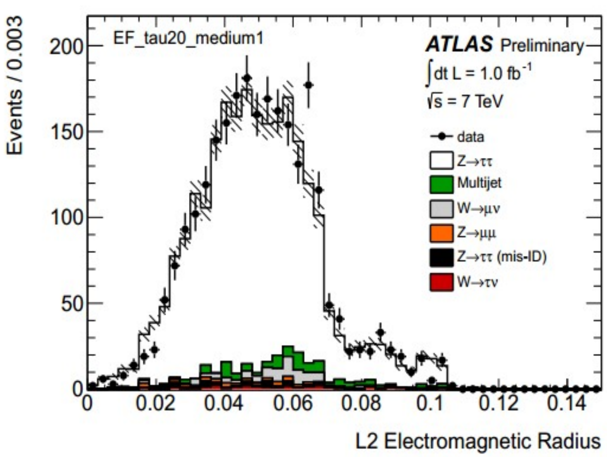
Hardware based system

Calo towers of granularity $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

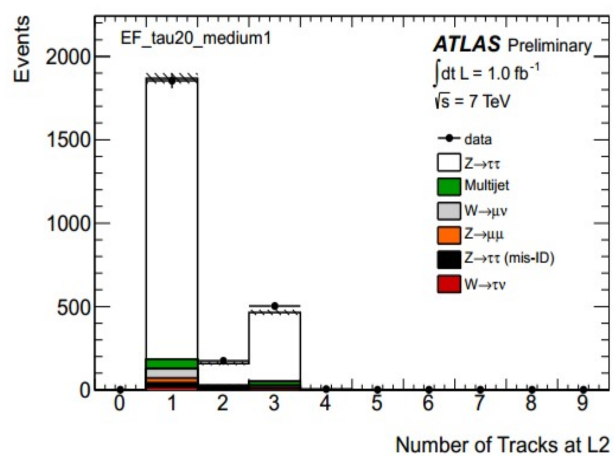
Signatures:

- EM: Sum of energy in 2 × 1 pairs of towers
- HAD: Energy in 2 × 2 towers behind the EM cluster
- Isolation ring: Energy in 4 × 4 around the 2 × 2 core

Region-of-Interest



Energy weighted radius of tau decay products



Number of reconstructed tracks in $\delta R < 0.2$

Level 2 (L2)

Full calo and track granularity within RoI

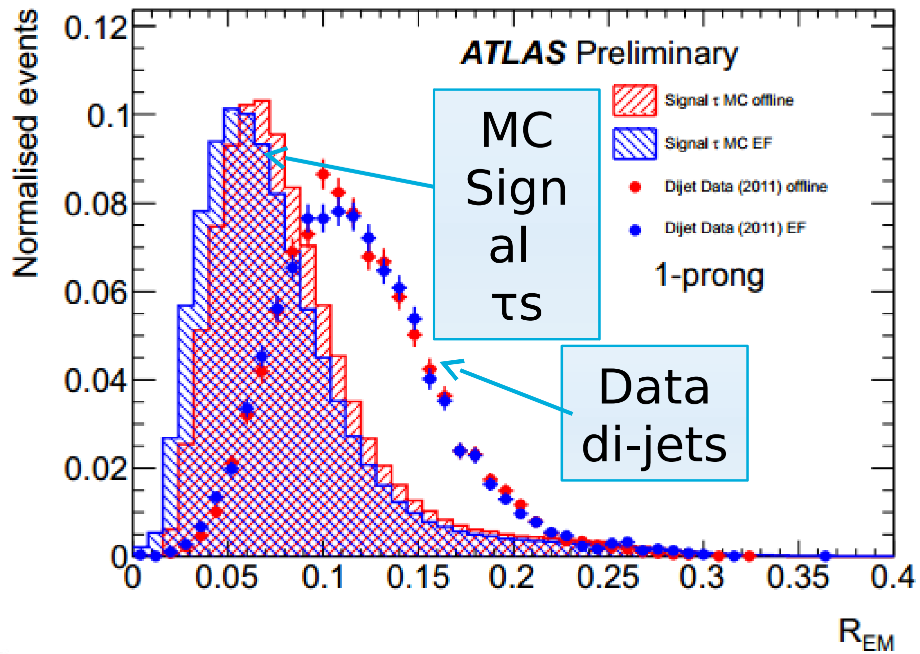
Track and calo information used to calculate τhad ID dicriminant

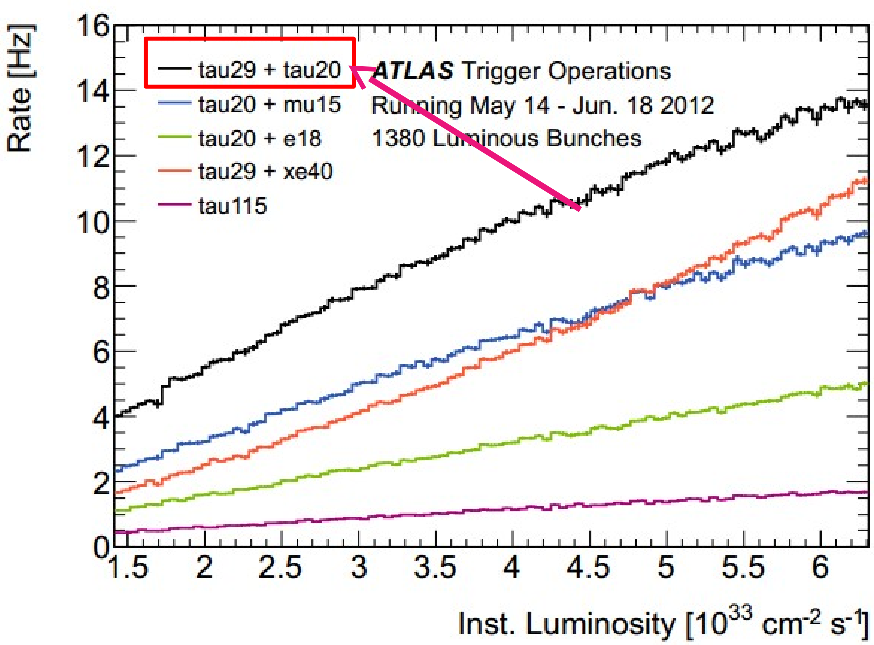
Tau triggers in ATLAS

Event Filter (EF)

Uses algorithms similar to the offline tau reconstruction

Energy weighted radius REM
Probe energy calibration at Event Filter and Offline reconstruction → similar performances

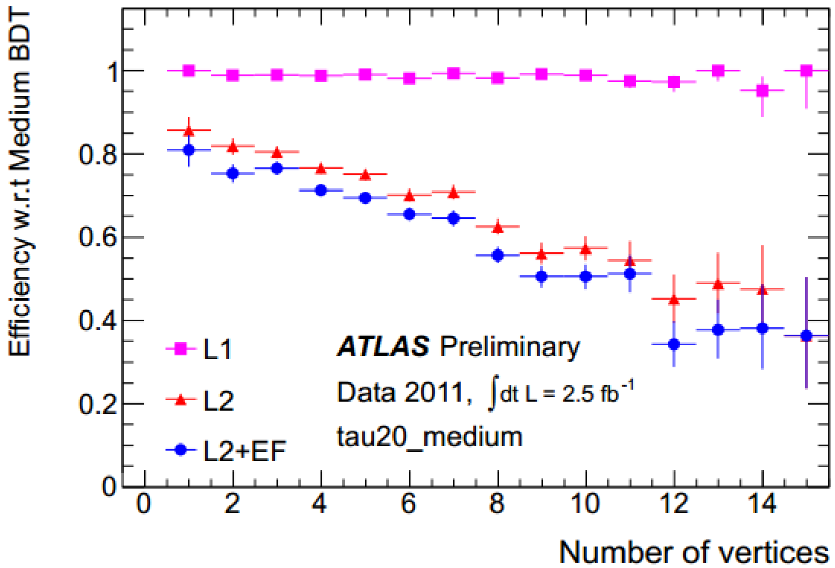


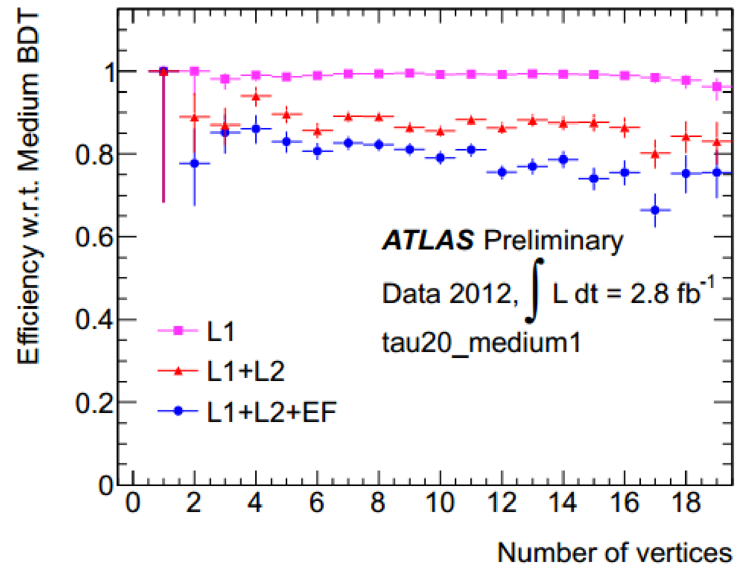


Rates

Bunch crossing: 40-50 MHz
L1 : 75-100 kHz
L2 : 5 kHz
EF : 200-400 Hz
EF tau : ~20 Hz (L~7e33 cm-2s-1)

Tau triggers in ATLAS





2011 → 2012

High Pile-Up Robustness

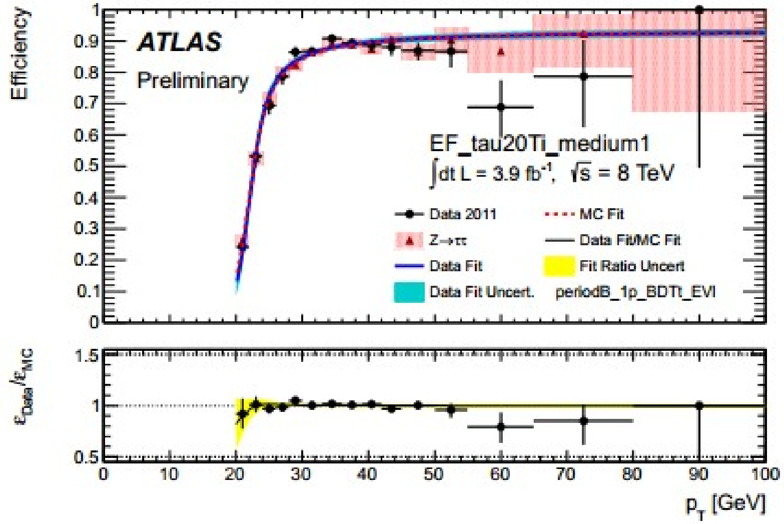
2011: triggers showed a degradation of the efficiency with increasing pile-up

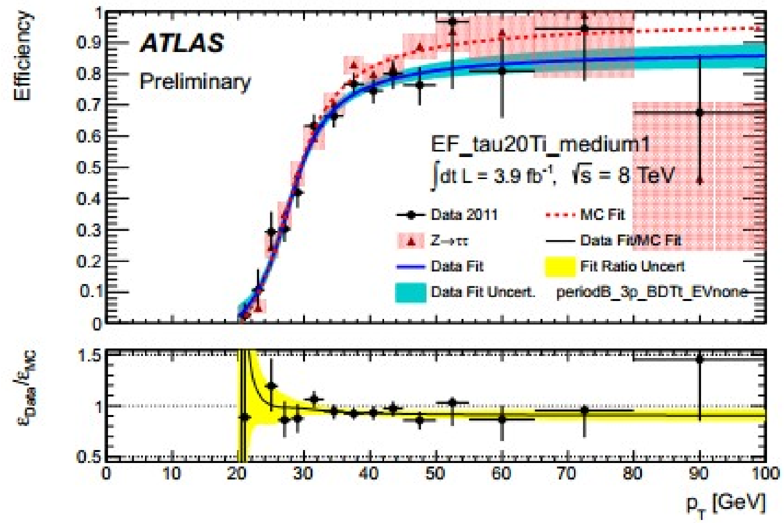
2012: new selection criteria provide robustness against high pile-up conditions

- decrease the calorimetric cone size δR from 0.4 (2011) to 0.2 (2012)
- |ΔZ| < 0.2 mm cut on the tau leading track with respect to Primary Vertex

Tau triggers in ATLAS

tau_20_medium





1-prong multi-prong

Trigger Efficiency and Data/MC Scale Factors

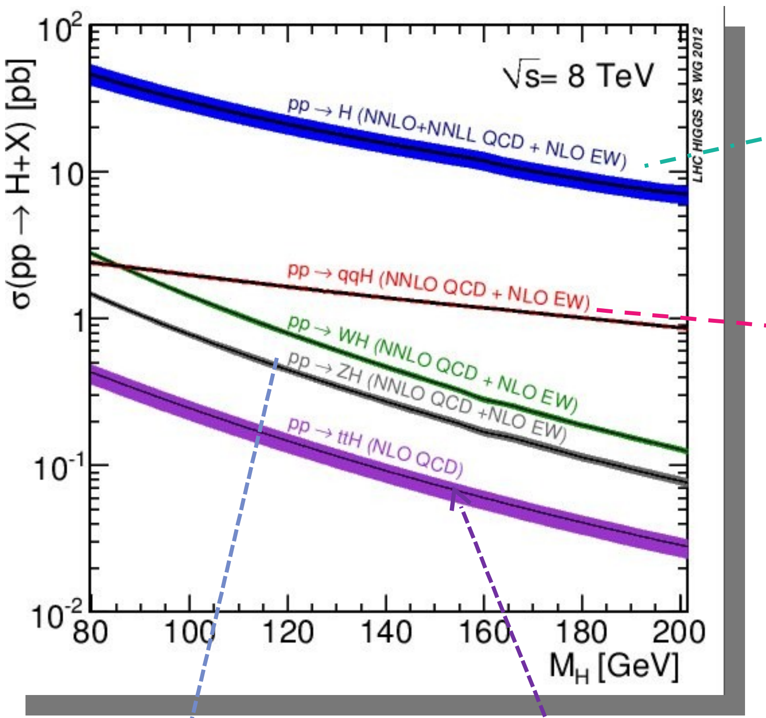
Physics analysis involving tau triggers must know the trigger performance in data and MC

Z → τ τ →μ τhad tag (μ)-and-probe(τhad) technique applied in data and MC

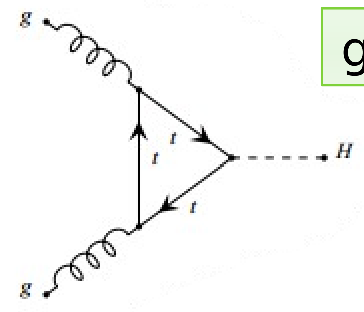
- Measure efficiency with respect to offline taus identified by the BDT algorithm

Extract scale factors and apply them in modeled events

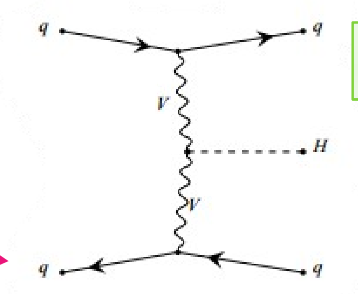
Higgs Production Mechanisms



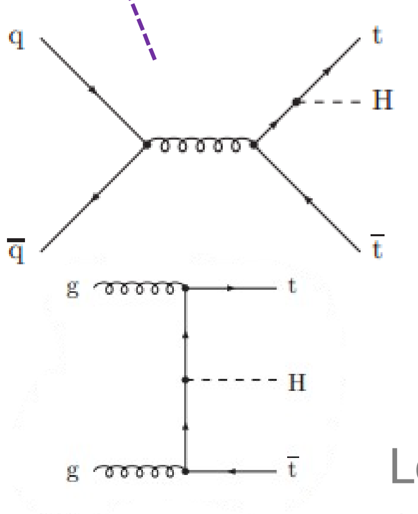
ggF

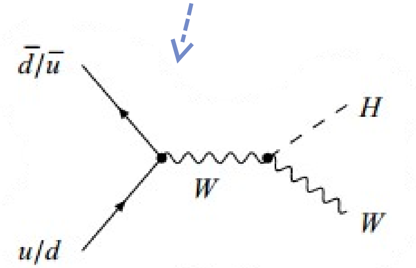


VBF

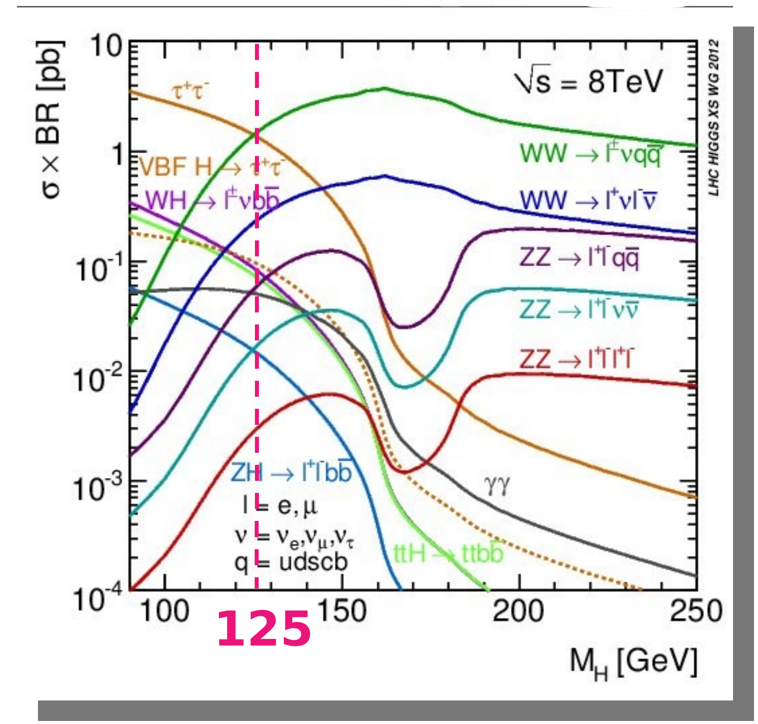


ttH





VH



Low-mass region: **VBF Higgs** is the dominant and most prominent production mechanism

Extended Track Counting

- **QCD jets:** tracks are *pT*-correlated and uniformly spread inside the cone
- **Real hadronic taus:** tracks are collimated in a narrow cone δR<0.2 (default counting)
- Perform track counting in a wider cone 0.2 < δR < 0.6:

  → increase probability to find more tracks associated to misidentified τ-jets

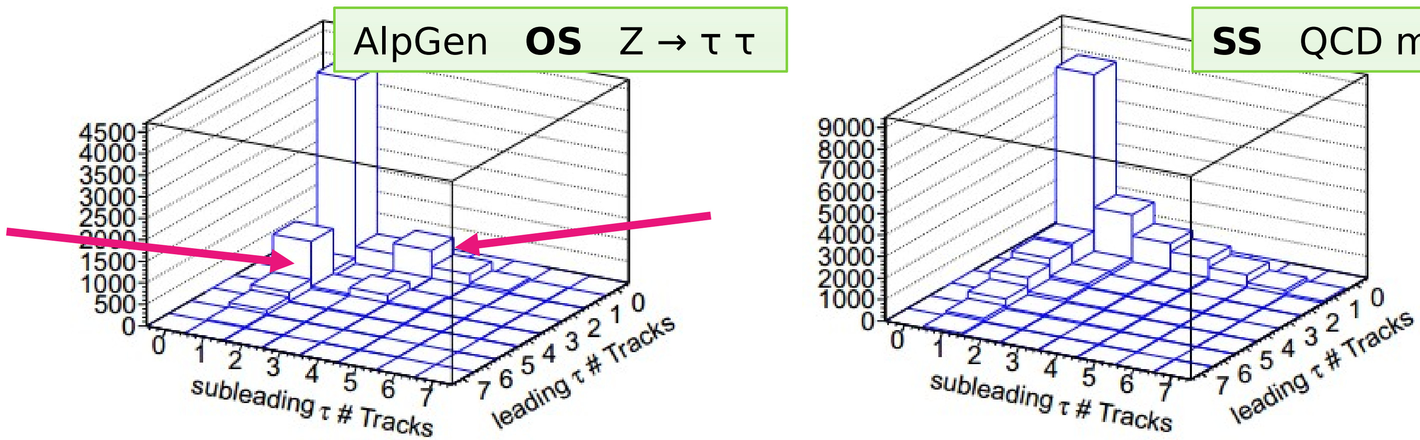
  - Define a new counting metric for outer tracks 0.2 < δR < 0.6 passing

$$D = \max\left\{\frac{p_T^{\text{core}}\,\Delta R(\text{core},\text{outer})}{p_T^{\text{outer}}}\right\} \leq 4$$

$p_T > 500$ MeV in $0.2 < \Delta R \leq 0.6$

$500 < p_T < 1000$ MeV in $\Delta R \leq 0.2$

– Threshold D is a tuning parameter to be less sensitive to UE and PU



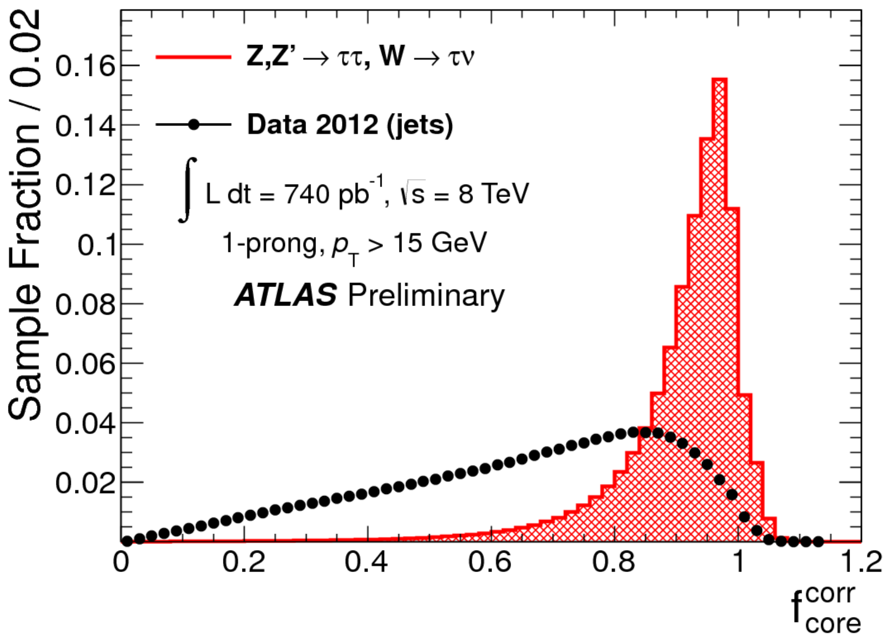
2-dimensional track multiplicity templates

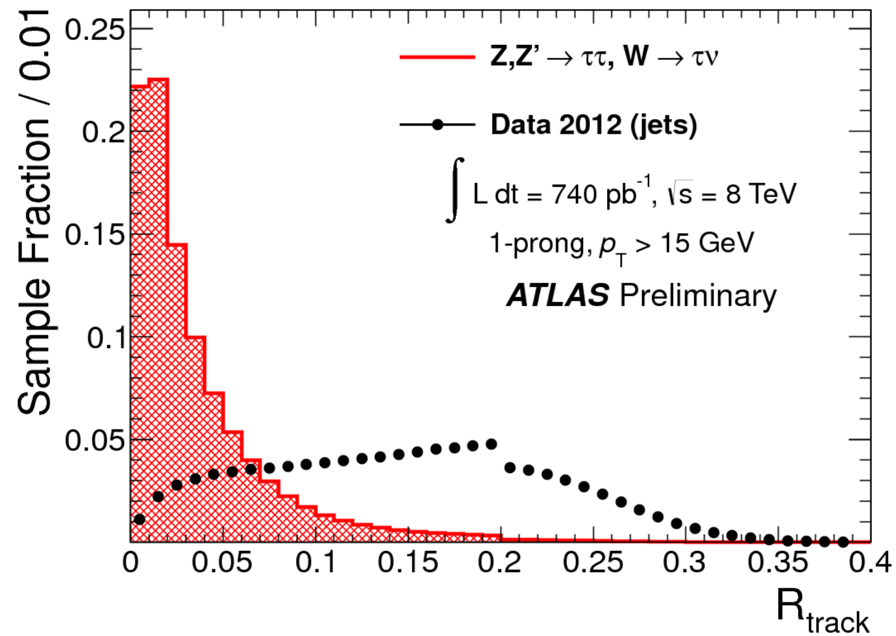
Tau Identification

The discriminating variables used to separate hadronically decaying tau leptons from jets, electrons and muons are defined in ATLAS-CONF-2013-064 Appendix A, page 39

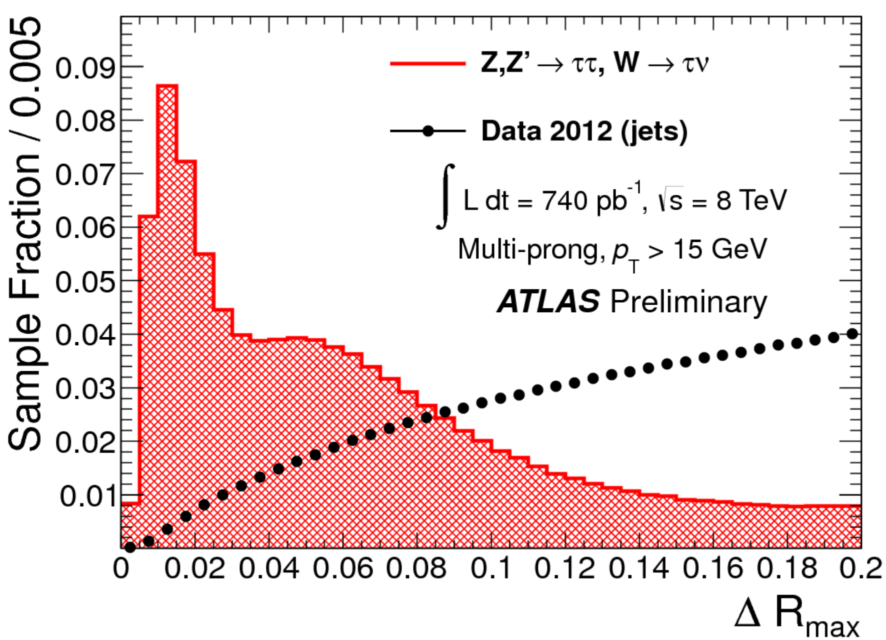
Tau Identification

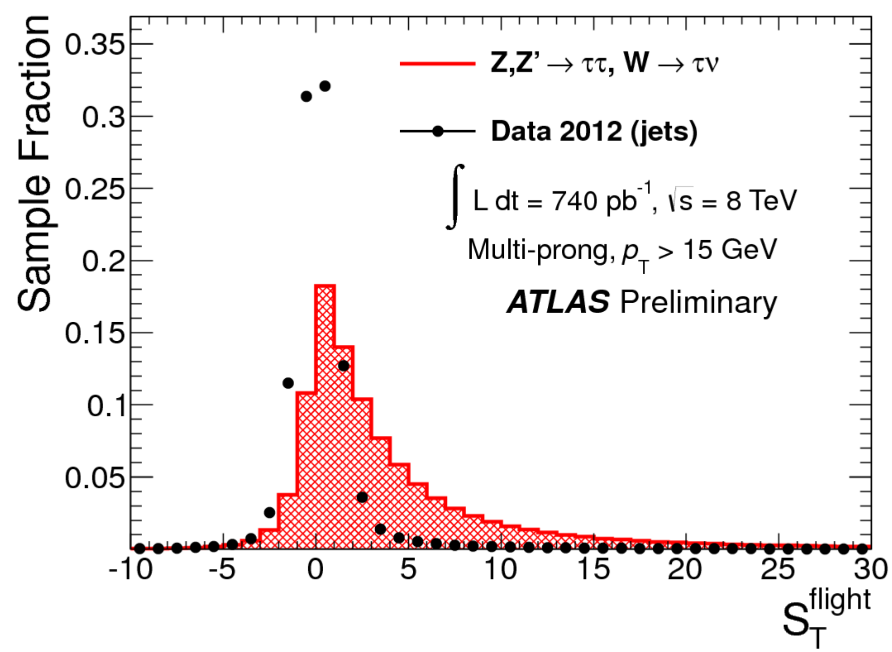
ATLAS CONF Note





Distributions of a selection of jet discriminating variables for simulated Z, Z′→ττ and W→τν signal samples and a jet background sample selected from 2012 data. The distributions are normalized to unity.



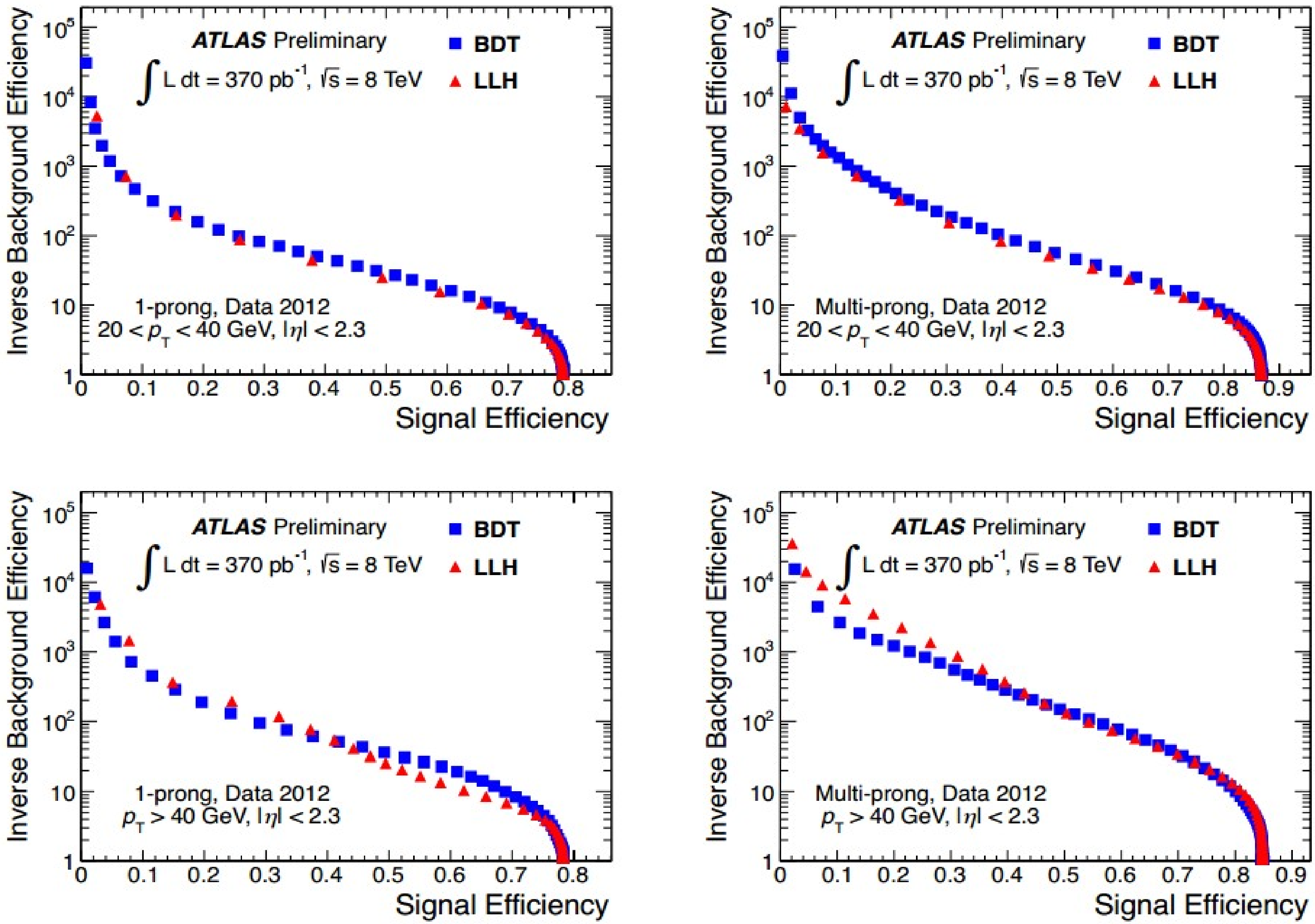


Tau Identification

Variable	LLH tau ID		BDT tau ID		e-veto	muon veto
	1-prong	3-prong	1-prong	3-prong	1-prong	1-prong
$f_{\mathrm{core}}^{\mathrm{corr}}$	•	•	•	•	•	
$f_{\mathrm{track}}^{\mathrm{corr}}$	•	•	•	•	•	
f_{track}					•	•
R_{track}	•	•	•	•	•	
$S_{\mathrm{lead\ track}}$	•		•			
$N_{\mathrm{track}}^{\mathrm{iso}}$	•		•			
ΔR_{max}		•		•		
$S_{\mathrm{T}}^{\mathrm{flight}}$		•		•		
m_{tracks}		•		•		
f_{EM}					•	•
f_{HT}					•	
$E_{\mathrm{T,max}}^{\mathrm{strip}}$					•	
$f_{\mathrm{HCAL}}^{\mathrm{leadtrk}}$					•	
$f_{\mathrm{ECAL}}^{\mathrm{leadtrk}}$					•	
f_{PS}					•	
$f_{\mathrm{EM}}^{\pi^{\pm}}$					•	
f_{iso}					•	
[illegible]					•	

Comparison of variables used by the $\tau_{\text{had-vis}}$ identification algorithms: projective likelihood identification (LLH tau ID), boosted decision tree identification (BDT tau ID), boosted decision tree based electron veto (e-veto) and cut based muon veto (muon veto).

Tau Identification – 8 TeV



Inverse background efficiencies as a function of signal efficiency for 1-prong (left) and multiprong (right) candidates, in low (top) and high (bottom) pT ranges, for the two tau ID methods BDT and LLH. The signal efficiencies were obtained using $Z \rightarrow \tau\tau$, $Z' \rightarrow \tau\tau$ and $W \rightarrow \tau\nu$ simulated samples and the inverse background efficiencies from data multi-jet events.