Evidence for $H \to \tau\tau$ in proton-proton collisions recorded by ATLAS

Romain Madar

Physikalisches Institut
Albert-Ludwigs-Universität, Freiburg – Germany

Laboratoire de Physique Nucléaire et des Hautes Énergies

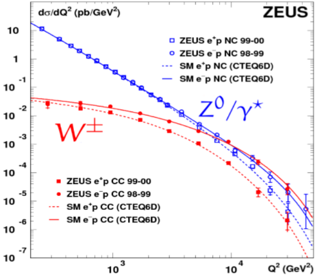
The 21st of February 2014 – Paris, France

Overview

Unified theory of interactions

$$SU(2)_L \times U(1)_Y \times SU(3)_c$$
+ Higgs mechanism

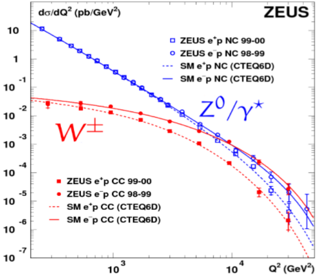
→ **Additional scalar excitation,**
relic of EW symmetry breaking

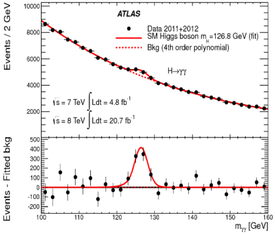


Unified theory of interactions

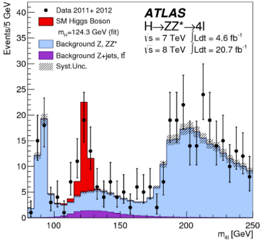
$$SU(2)_L \times U(1)_Y \times SU(3)_c$$
\+ Higgs mechanism

→ **Additional scalar excitation,**
relic of EW symmetry breaking

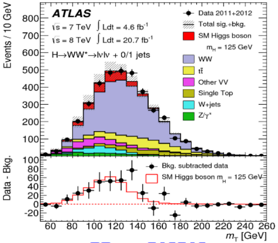




H→γγ

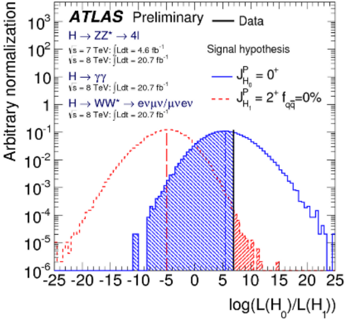


H→ZZ



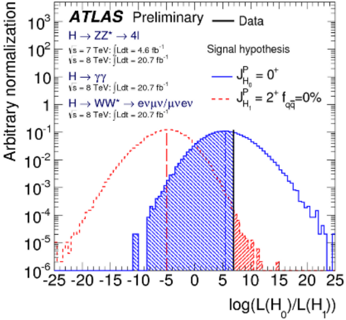
H→WW

The **discovered particle** has the right **couplings to gauge bosons** ...



... and is indeed **a scalar !**

The **discovered particle** has the right **couplings to gauge bosons** …



… and is indeed **a scalar** !

What's about **couplings to fermions** ? **Before 12/2013:**

TeV VH(→bb): 2.8σ

CMS VH(→bb): 2.1σ

CMS H→ττ: 2.85σ ← lepton

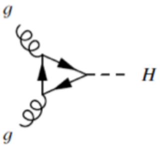
Not imposed by the gauge interaction!

– in opposition to EW bosons –

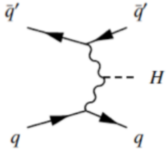
Overview

1. Production of $H(125)$

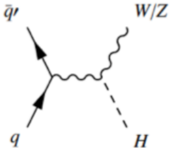
$\sigma_{\text{tot}}(H) = 22.1$ pb $\sigma_{\text{tot}}(Z) \sim 10^4$ pb



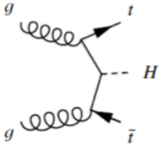
GGF (88%)
high rate but loops,
no specific topology



VBF (6.6%)
low rate but tree level,
specific jet topology



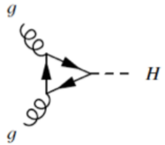
VH (5%)
low rate but **clean final state** (leptons)



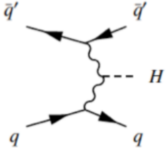
ttH (0.4%)
extremely low rate and
busy final state

1. Production of $H(125)$

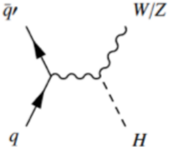
$\sigma_{\text{tot}}(H) = 22.1$ pb $\sigma_{\text{tot}}(Z) \sim 10^4$ pb



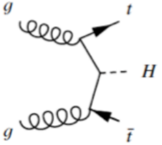
GGF (88%)
high rate but loops,
no specific topology



VBF (6.6%)
low rate but tree level,
specific jet topology

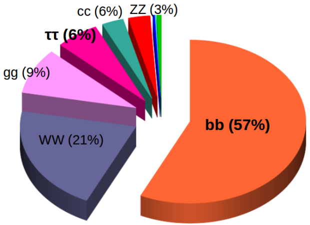


VH (5%)
low rate but **clean final state** (leptons)



ttH (0.4%)
extremely low rate and
busy final state

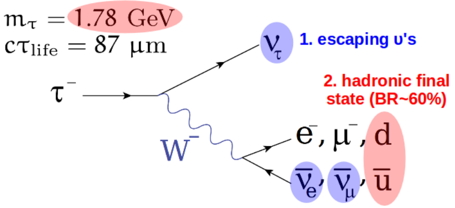
2. Decays of $H(125)$ (emphasis on fermionic decay)

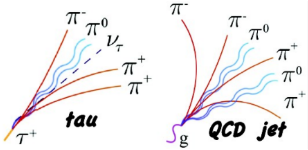


- ***bb* decay** : largest BR, benefits from additional lepton to reduce $pp \to b\bar{b} + X$.
- **$\tau\tau$ decay** : lower BR, cleaner signature
- ***cc* decay** : impossible in hadron collider
- **$\mu\mu$ decay :** extremely low BR (0.02%), good mass resolution

Overview

Experimentally challenging ! Jets contamination very frequent in hadrons collider !

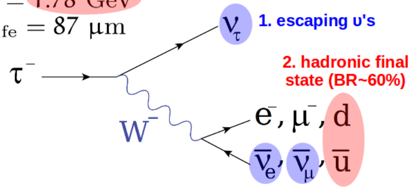


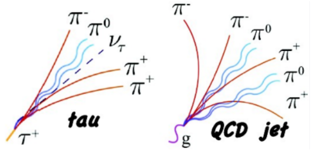


$\tau_{had} \approx$ narrower jet with lower track multiplicities

Experimentally challenging ! Jets contamination very frequent in hadrons collider !

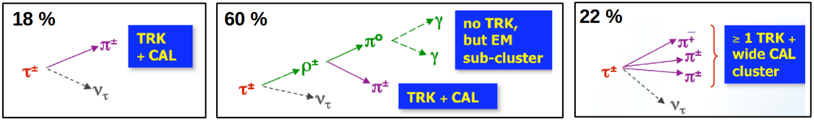
$m_\tau = 1.78$ GeV
$c\tau_{life} = 87$ µm





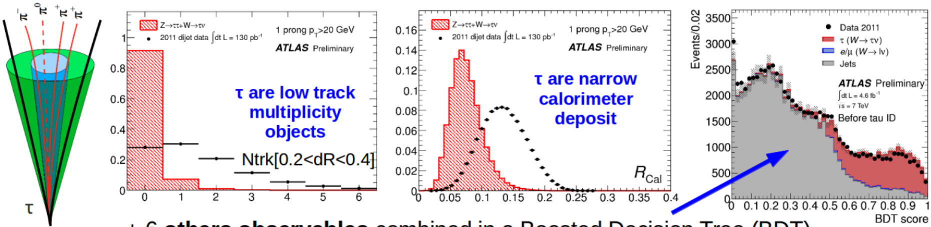
$\tau_{had} \approx$ narrower jet with lower track multiplicities

Typical signature of hadronic τ decay :



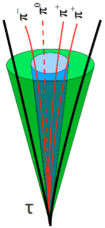
- 1 or 3 isolated tracks, with possible secondary vertex reconstruction.
- Collimated calorimeter energy deposit.

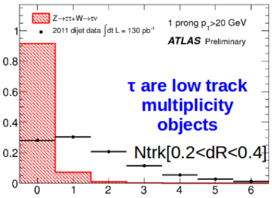
Final state with τ leptons : how ?

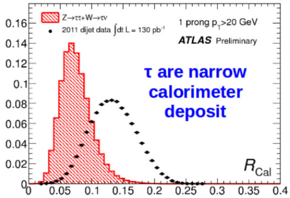


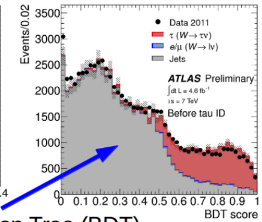
+ 6 **others observables** combined in a Boosted Decision Tree (BDT)

$\varepsilon_{sig} \sim 65\%$ – $\varepsilon_{bkg} \sim 2\%$





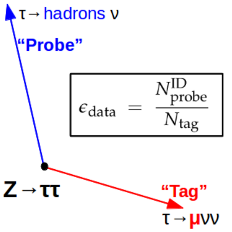




+ 6 **others observables** combined in a Boosted Decision Tree (BDT)

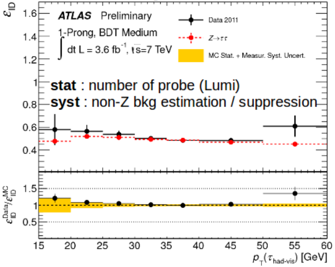
$\varepsilon_{sig} \sim 65\%$ – $\varepsilon_{bkg} \sim 2\%$

"Tag and probe" method



$$\epsilon_{\rm data} = \frac{N^{\rm ID}_{\rm probe}}{N_{\rm tag}}$$

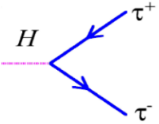
Efficiency measurement



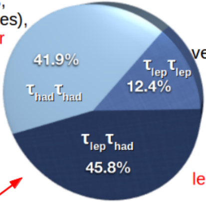
Overview

$H \to \tau\tau$: how ?

	H → ττ
GGF	YES
VBF	YES
VH	
ttH	



$\otimes$

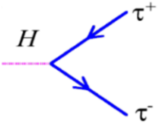


	H→ττ
GGF	YES
VBF	YES
VH	
ttH	

All H→ττ final states can be reconstructed and analyzed

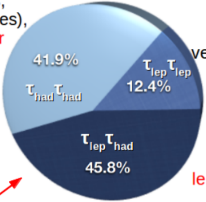
(in opposition with H→WW, with twice BR)

$H \to \tau\tau$: how ?



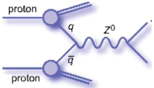
⊗

high BR, 2 ν's,
high MJ bkg (fakes),
τ-based trigger



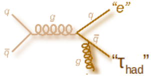
low BR, 4 ν's,
very clean signature,
lep-based trigger

high BR, 3 ν's,
~clean signature
(W+jets as bkg),
lep & τ-based trigger

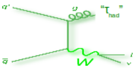


Z → ττ
irreducible, $m_Z < m_H$

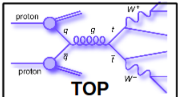
	H→ττ
GGF	YES
VBF	YES
VH	
ttH	



Multijets
fake lepton/taus

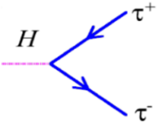


W (→ lν) + jets
real lepton, fake taus

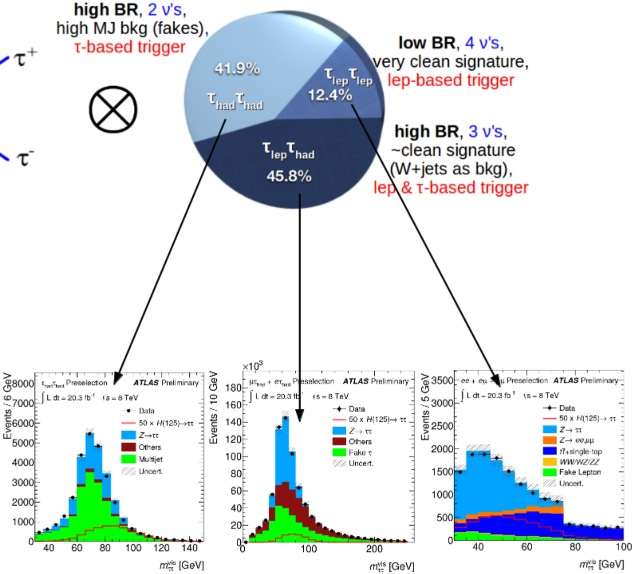


TOP
real/fake lepton/taus

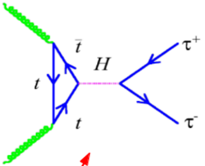
$H \to \tau\tau$: how ?

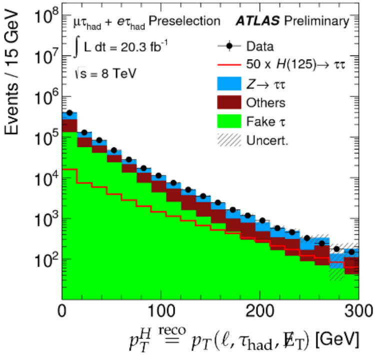


$\otimes$



	H→ττ
GGF	YES
VBF	YES
VH	
ttH	

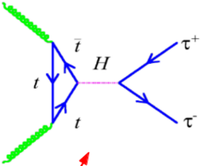


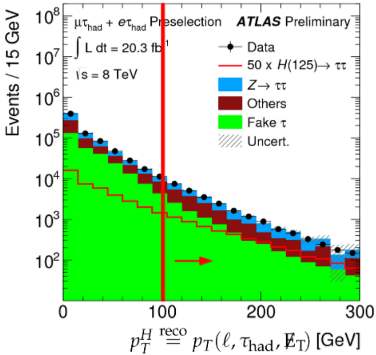


	$H \to \tau\tau$
GGF	YES
VBF	YES
VH	
ttH	

gg→H is particularly subject to **QCD radiations** (colored initial state, colored loop)

$p_T(\tau,\tau)$ spectrum is **harder** for signal





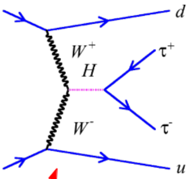
	$H \to \tau\tau$
GGF	YES
VBF	YES
VH	
ttH	

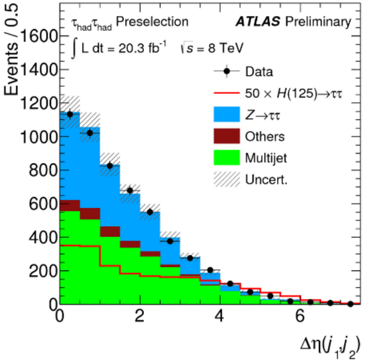
gg→H is particularly subject to **QCD radiations**
(colored initial state, colored loop)

$p_T(\tau,\tau)$ spectrum is **harder** for signal

We define a **"boosted category"** enriched in gg→H

70% GGF – 16% VBF – 14% VH

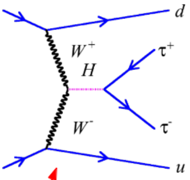


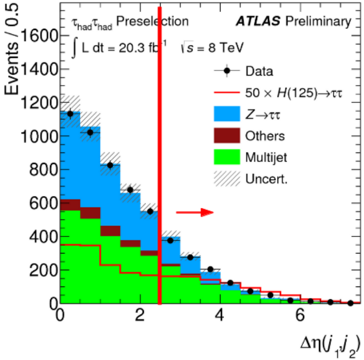


	H→ττ
GGF	YES
VBF	YES
VH	
ttH	

VBF has a particular jet topology:
2 forward high p_T jets

(process similar to a t-channel → $|\mathcal{M}_t|^2 \propto \dfrac{1}{(1-\cos\theta)^2}$ → forward objects)





	H→ττ
GGF	YES
VBF	YES
VH	
ttH	

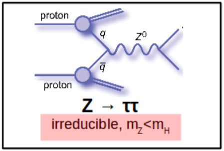
VBF has a particular jet topology:
2 forward high p_T jets

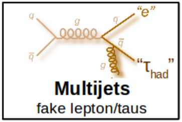
(process similar to a t-channel → $|\mathcal{M}_t|^2 \propto \dfrac{1}{(1-\cos\theta)^2}$ → forward objects)

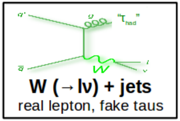
We define a **"VBF category"** enriched in VBF

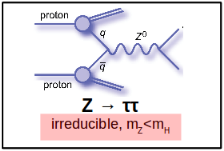
75% VBF – 25% GGF

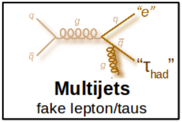
$H \to \tau\tau$: how ?

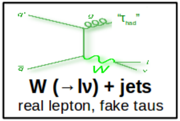








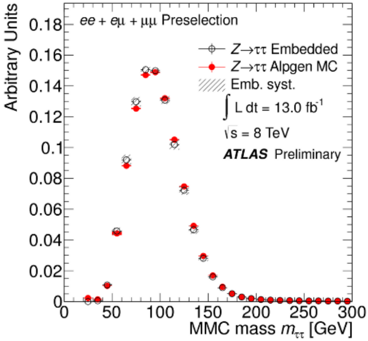




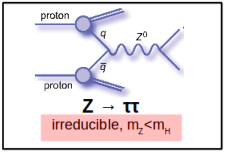
For all 3 channels

Data driven : τ "embedding" in $Z \to \mu\mu$ data events

- remove μ deposits and replace by a simulated τ.
- It's data (jets, pile-up, calo noise, soft radiations)
- limited by data statistics



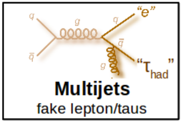
data-driven estimation!

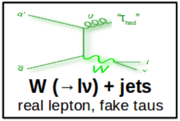


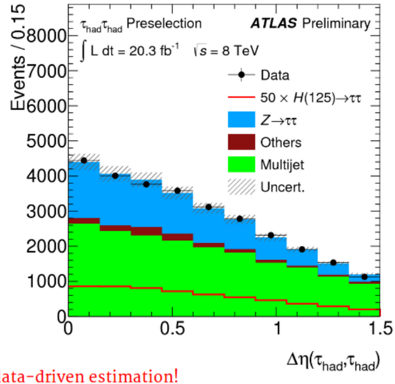
For hadhad channel

data-driven estimation

Normalization: template fit using $\Delta\eta(\tau_{had},\tau_{had})$
Template: events without opposite charge candidates





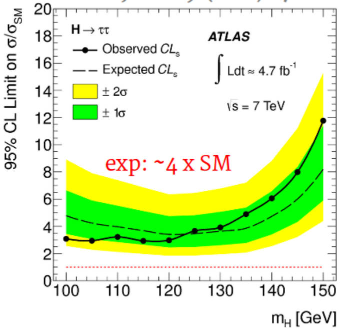


data-driven estimation!

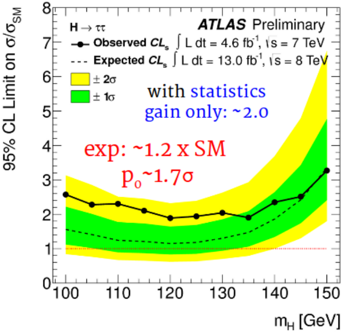
Signal extraction using the di-tau mass

Natural strategy : Use the reconstructed mass to test the presence of signal. It was done in the last two ATLAS public results.

2011 - JHEP 09 (2012) 070



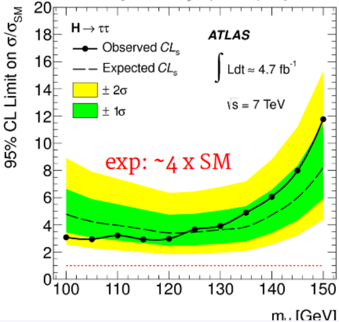
2012 - ATLAS-CONF-2012-160



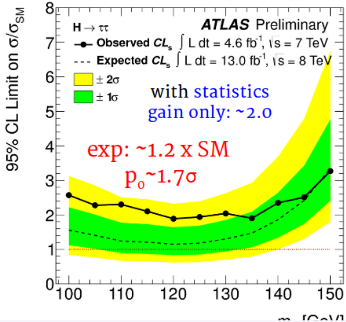
Signal extraction using the di-tau mass

Natural strategy : Use the reconstructed mass to test the presence of signal. It was done in the last two ATLAS public results.

2011 - JHEP 09 (2012) 070



2012 - ATLAS-CONF-2012-160



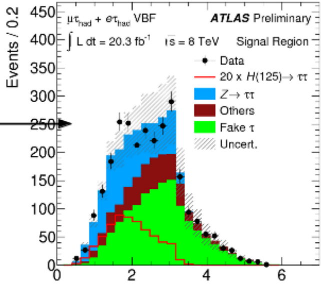
Naive projection with 25 fb^{-1} : limit $\sim$ 1.0 and $p_0 \sim 2.0\,\sigma$.

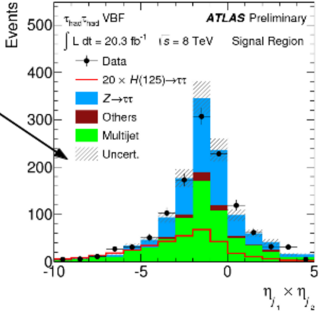
Not sensitive enough to unambiguously conclude on $H \to \tau\tau$

Switch to a more efficient approach : Multivariate analysis (**BDT**)

$H \to \tau\tau$: how ?

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



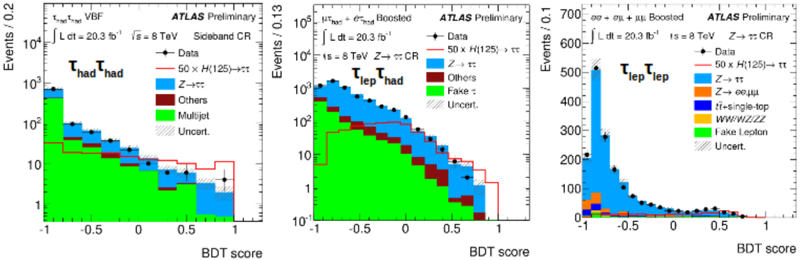


Validation of the MVA approach

Multivariate Analysis exploit correlations between variables.
Are they well modelled by the simulation?

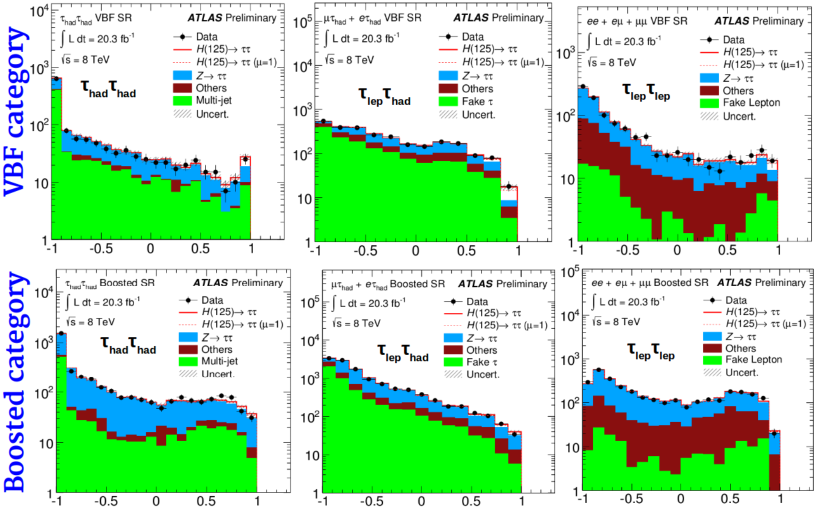
- Difficult to assess by only looking at 1D distributions
- Can be probed by looking at $<X_i>$ versus X_j in data and simulation
- Checking the final BDT output in **control regions**

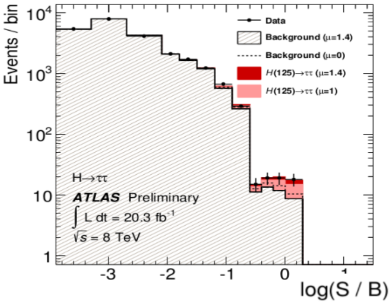
Validation of **$Z \to \tau\tau$** modelling in **control regions**



Overview

Final distribution in the 6 signal regions



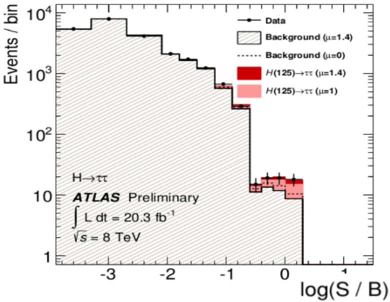


Event yield (VBF category)

	Lep-lep	Lep-had	Had-had
Signal	5.7±1.7	8.7±2.5	8.8±2.2
Bckg	13.5±2.4	8.7±2.4	11.8±2.6
Data	**19**	**18**	**19**

Observed (expected)
excess of 4.1σ (3.2σ)

$$\mu = 1.43^{+0.31}_{-0.29}(\text{stat.})^{+0.41}_{-0.30}(\text{syst.})$$

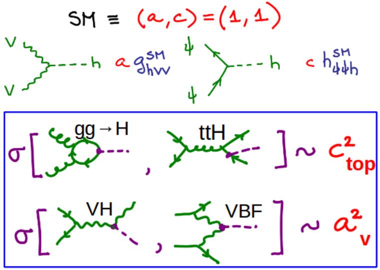


Event yield (VBF category)

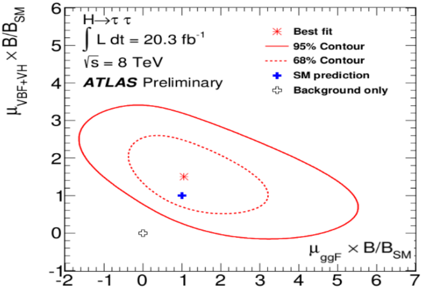
	Lep-lep	Lep-had	Had-had
Signal	5.7±1.7	8.7±2.5	8.8±2.2
Bckg	13.5±2.4	8.7±2.4	11.8±2.6
Data	**19**	**18**	**19**

Observed (expected)
excess of 4.1σ (3.2σ)

$$\mu = 1.43^{+0.31}_{-0.29}(\text{stat.})^{+0.41}_{-0.30}(\text{syst.})$$



arXiv :1209.0040, ATLAS-CONF-2012-127



Systematic uncertainties

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	0.30
$Z \to \ell\ell$ normalization ($\tau_{lep}\tau_{had}$ boosted)	0.13
ggF $d\sigma/dp_T^H$	0.12
JES η calibration	0.12
Top normalization ($\tau_{lep}\tau_{had}$ VBF)	0.12
Top normalization ($\tau_{lep}\tau_{had}$ boosted)	0.12
$Z \to \ell\ell$ normalization ($\tau_{lep}\tau_{had}$ VBF)	0.12
QCD scale	0.07
di-τ_{had} trigger efficiency	0.07
Fake backgrounds ($\tau_{lep}\tau_{lep}$)	0.07
τ_{had} identification efficiency	0.06
$Z \to \tau^+\tau^-$ normalization ($\tau_{lep}\tau_{had}$)	0.06
τ_{had} energy scale	0.06

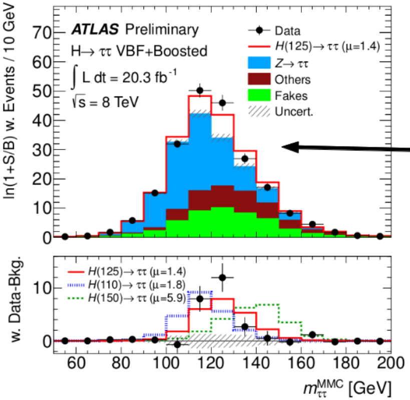
Total uncertainty ~ 0.5

Uncertainties related to **background estimation**

Uncertainties related to **trigger/reco/identification**

Uncertainties related to **theory predictions**

Mass spectrum of the excess



At which di-tau invariant mass the excess peaks ?

Mass distribution: events are weighted by the expected significance computed in each BDT bin

Observed excess compatible with a Higgs boson of 125 GeV (red line)

Overview

$H \to \tau\tau$ probes the Yukawa couplings between the Higgs boson and fermions, directly. Probe lepton-Higgs couplings. Constraint VBF production.

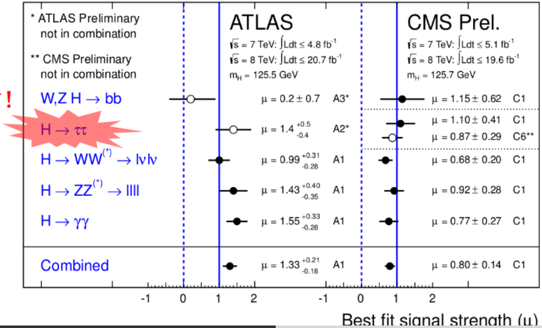
τ **lepton** needs sophisticated algorithms and a deep undersdanding of the experiment. Background modelling challenging.

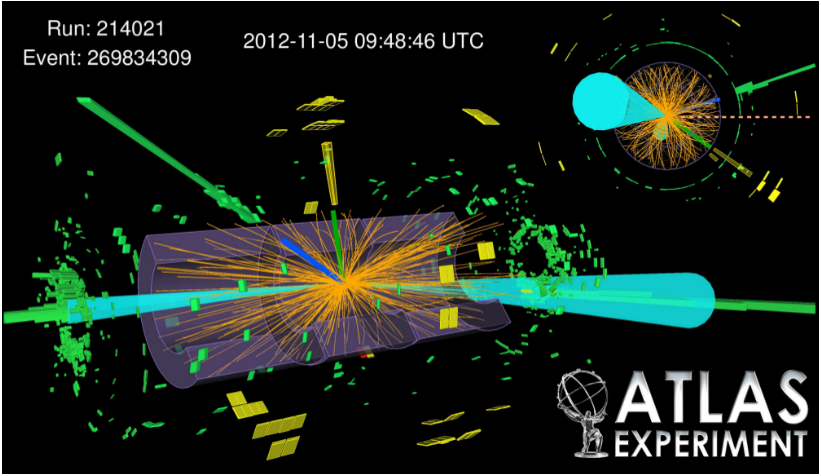
New ATLAS analysis (MVA)

Observed (expected) evidence for $H \to \tau\tau$ at 4.1 σ (3.2 σ).

Summary of the PDG

NEW !





$H \to \tau_\ell \tau_{\text{had}}$ candidate (data)

$m(\tau,\tau) = 129$ GeV, BDT$= 0.99$ $(S/B = 1.0)$, $m(j_1, j_2) = 1.53$ TeV

BACK UP

Gauge symmetry and fermion masses

Why the couplings to fermions are **crucial** to measure ?
(CMS $\tau\tau + bb$ combination submitted to *Nature Physics* - arXiv :1401.6527)

QED

$$m_\gamma A^\mu A_\mu$$

Boson mass:
NOT gauge invariant

$$m_f(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R)$$

Fermion mass:
gauge invariant

SM

$$\partial_\mu \Phi \to D_\mu \Phi$$

Interaction with $W^\pm, Z^0$

Higgs = charged under $SU(2)_L \times U(1)$
masses of gauge bosons

$$\bar{\psi}_L \psi_R$$

$\bar{\psi}_L$: $SU(2)_L \times U(1)_Y$; ψ_R: $U(1)_Y$

Fermion masses **are not $SU(2)_L \times U(1)$ invariant**

Introducing a new field charged under $SU(2)_L \times U(1)$, doesn't automatically generate fermion masses.

Need to **add a new term** – *Yukawa couplings* – to **generate fermion masses**

$$\lambda_f \, \bar{\psi}_L \, \Phi \, \psi_R$$

Not coming from gauge symmetry

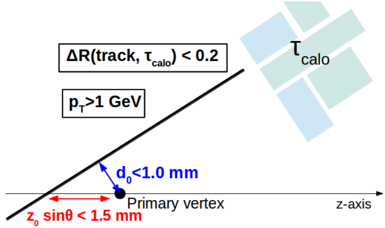
Reconstruction of τ lepton in ATLAS

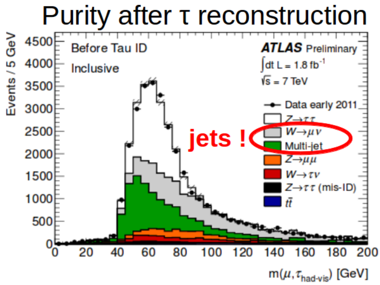
τ_{had} candidate is built from the calorimeter ($\pi^{\pm}$ and π^{0}) and the tracking system ($\pi^{\pm}$)

1. Calorimeter object :

1. calorimeter cells $\to$ 3D clusters (topological cluster)
2. τ_{calo} is defined as a jet of topo-clusters (anti-k_T algorithm with $\Delta R = 0.4$)

2. Tracks : a track is matched if

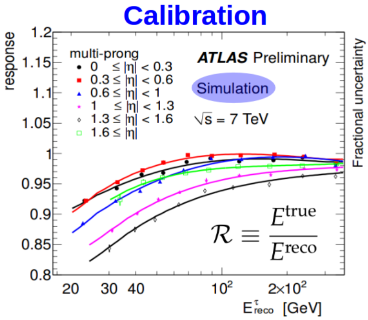


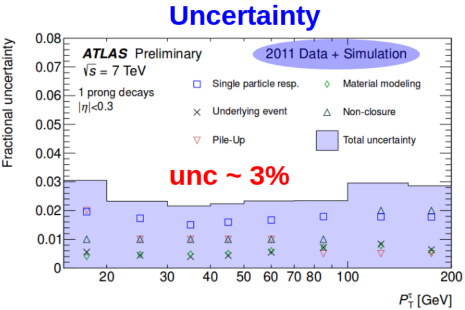


Energy calibration of τ lepton

Why and how ?

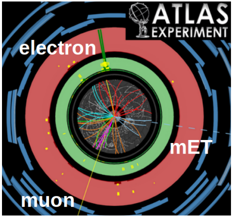
- $m_{\tau\tau} \propto \sqrt{E_{\tau_1} E_{\tau_2}}$: a wrong scale will lead to shifted mass peak.
- Use the simulation to measure the energy response
- Use data (and MC) to estimate the uncertainty - and a potential bias





Neutrinos momentum : $\not{E}_T$ reconstruction

Neutrinos don't interact with the detector : they are measured using the unbalance of the total transverse momentum.



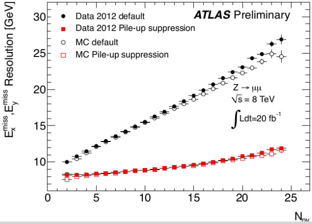
Calorimeter based :

- Raw : $\vec{\not{E}}_T \equiv -\sum_{\text{cell } i} \vec{E}_T^i$,
- Corrected for muons (only MIP),
- Corrected for energy scale of each type of object

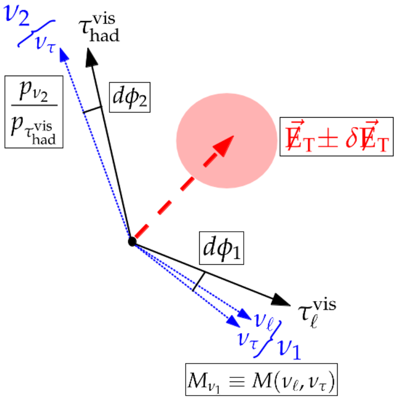
Keep in mind : $\vec{\not{E}}_T \overset{\text{reco}}{=} \left(\sum_i \vec{p}_{\nu_i}\right)_T$

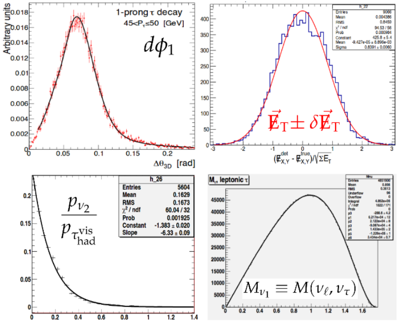
Comments : sensitive to all the activity in the event (pile up, detector noise, soft radiations, ...).

Some technics are elaborated to reduce pile-up effect on the $\not{E}_T$ resolution.



$m_{\tau\tau}$ reconstruction : Missing Mass Calculator





☐ = unknown value

(1) **Perform a scan** over the unknowns, ie choose a config : q = ($d\Phi_1$, $d\Phi_2$, $M_{\nu 1}$, mET, p_ν/p_τ)

(2) For each configuration q_i : compute the **full invariant mass** m_i

(3) Fill an histogram of m_i **weighted by w_i=PDF(q_i)** , as a product each above PDF

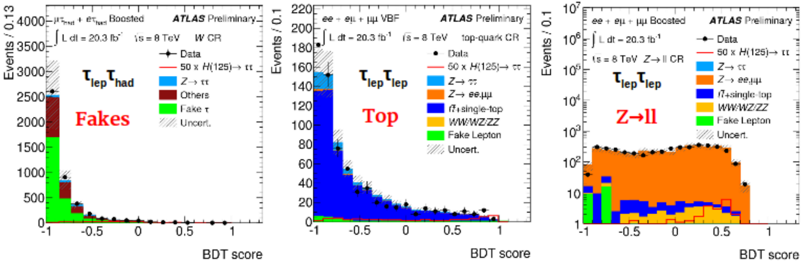
(4) Final reconstruced mass, **MMC**, is given by the **max of this histogram**

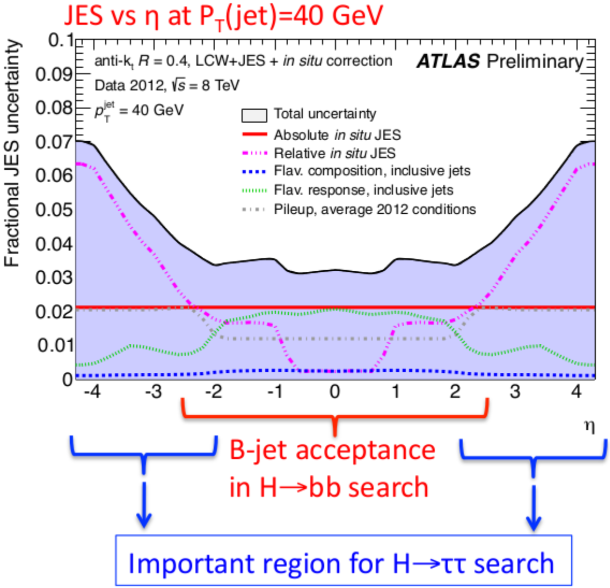
Validation of the MVA approach

Multivariate Analysis exploit correlations between variables.
Are they well modelled by the simulation?

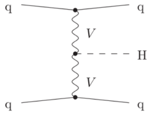
- Difficult to assess by only looking at 1D distributions
- Can be probed by looking at $\langle X_i \rangle$ versus X_j in data and simulation
- Checking the final BDT output in **control regions**

But also done for **other backgrounds** ...




JES vs η at P_T(jet)=40 GeV
anti-k_t R = 0.4, LCW+JES + in situ correction
ATLAS Preliminary
Data 2012, √s = 8 TeV
p_T^jet = 40 GeV
Total uncertainty
Absolute in situ JES
Relative in situ JES
Flav. composition, inclusive jets
Flav. response, inclusive jets
Pileup, average 2012 conditions
Fractional JES uncertainty
η
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-4
-3
-2
-1
0
1
2
3
4
B-jet acceptance
in H→bb search
Important region for H→ττ search

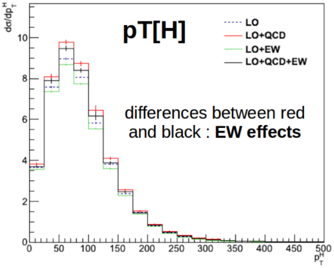
Signal modeling : EW corrections of $qq' \to qq'H$

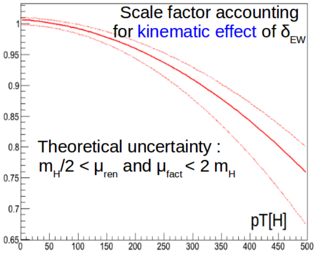


Motivations and goal :

- VBF@LO is EW : $\delta_{\mathrm{EW}} \sim \delta_{\mathrm{QCD}}$ (unlike $gg \to H$)
- σ_{tot} is already QCD+EW NLO : but shape effects of δ_{EW} ?

At generated level : most affected distribution is p_T^H - HAWK



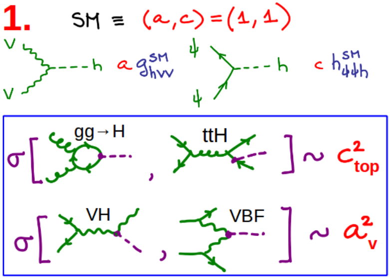


At reconstructed level :

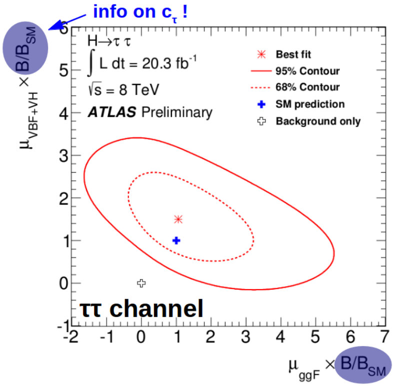
- negligeable impact, wrt to other exisiting systematics,
- This spectrum distortions should be kept in mind for the future.

3 types of property

1. Couplings to other SM particles : **observed event rates**
2. Mass : full **reconstruction**, energy resolution
3. Spin/CP : **polarization**, **angular** correlation/distributions

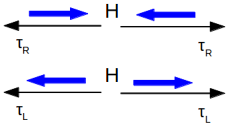


arXiv :1209.0040, ATLAS-CONF-2012-127



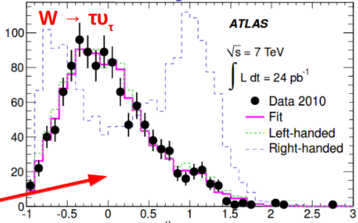
2.

Probe τ spin **correlations** :



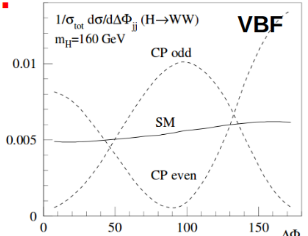
Be able to measure τ polarization ? **YES**

Eur.Phys.J. C72 (2012) 2062



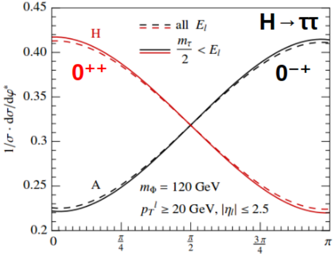
$$\frac{E_T^{\pi^-} - E_T^{\pi^0}}{p_T} \approx 2\frac{p_T^{\mathrm{trk}}}{p_T} - 1 = \Upsilon.$$

3. *Phys. Rev. Lett. 88 (2002) 051801*



tagging jets related angles

arXiv :1108.0670



φ^* (related τ angles)

Statistical procedure

$$q_{\mu=0} = -2\ln(\mathcal{L}(0,\hat{\hat{\vec{\theta}}})/\mathcal{L}(\hat{\mu},\hat{\vec{\theta}}))$$

Fit assuming no signal

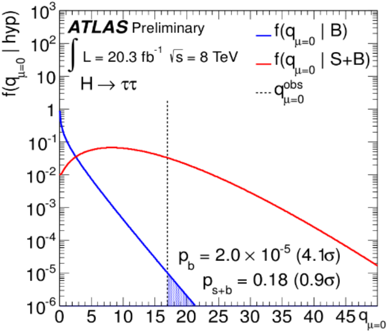
Best fitted signal

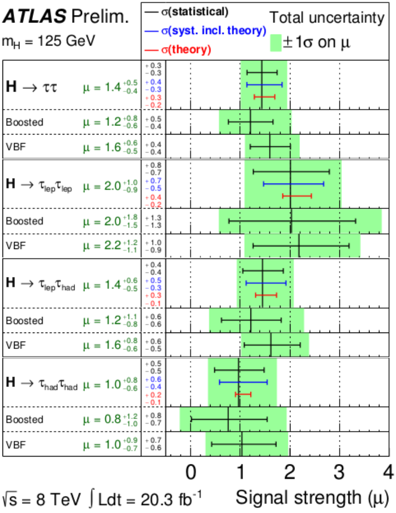
$$\mu \equiv \frac{\sigma_H^{obs}}{\sigma_H^{SM}}$$

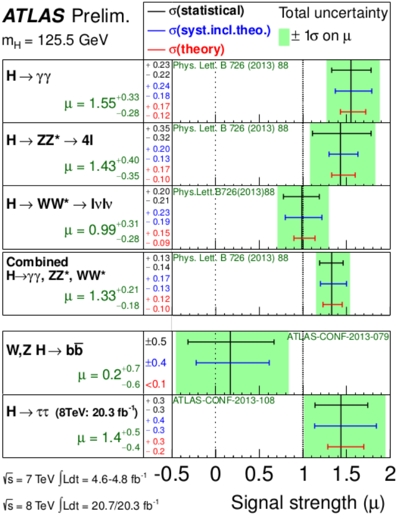
$\vec{\theta}$ = vector of nuisance parameters accounting for systematics

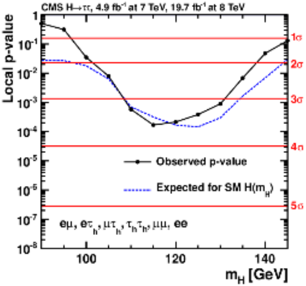
Excess of 4.1σ (3.2σ expected)

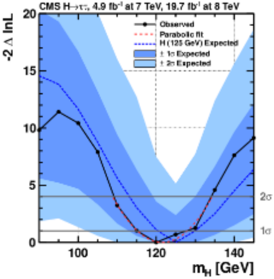
$$\mu = 1.43^{+0.31}_{-0.29}(\text{stat.})^{+0.41}_{-0.30}(\text{syst.})$$

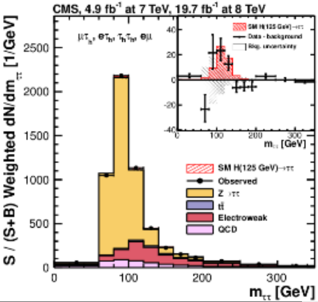


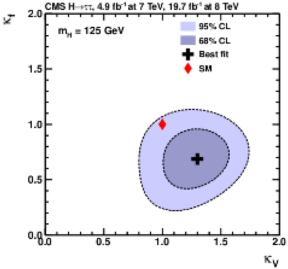

ATLAS Prelim.
m_H = 125 GeV
σ(statistical)
σ(syst. incl. theory)
σ(theory)
Total uncertainty
±1σ on μ
H → ττ μ = 1.4 +0.5 −0.4
Boosted μ = 1.2 +0.8 −0.6
VBF μ = 1.6 +0.6 −0.5
H → τlepτlep μ = 2.0 +1.0 −0.9
Boosted μ = 2.0 +1.8 −1.5
VBF μ = 2.2 +1.2 −1.1
H → τlepτhad μ = 1.4 +0.6 −0.5
Boosted μ = 1.2 +1.1 −0.8
VBF μ = 1.6 +0.8 −0.6
H → τhadτhad μ = 1.0 +0.8 −0.6
Boosted μ = 0.8 +1.2 −1.0
VBF μ = 1.0 +0.9 −0.7
0 1 2 3 4
√s = 8 TeV ∫Ldt = 20.3 fb-1
Signal strength (μ)


ATLAS Prelim.
m_H = 125.5 GeV
σ(statistical)
σ(syst.incl.theo.)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ μ = 1.55 +0.33 −0.28
Phys. Lett. B 726 (2013) 88
H → ZZ* → 4l μ = 1.43 +0.40 −0.35
Phys. Lett. B 726 (2013) 88
H → WW* → lνlν μ = 0.99 +0.31 −0.28
Phys.Lett.B726(2013)88
Combined H→γγ, ZZ*, WW* μ = 1.33 +0.21 −0.18
Phys. Lett. B 726 (2013) 88
W,Z H → bb̄ μ = 0.2 +0.7 −0.6
±0.5 ±0.4 <0.1
ATLAS-CONF-2013-079
H → ττ (8TeV: 20.3 fb-1) μ = 1.4 +0.5 −0.4
ATLAS-CONF-2013-108
-0.5 0 0.5 1 1.5 2
√s = 7 TeV ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV ∫Ldt = 20.7/20.3 fb-1
Signal strength (μ)


CMS H→ττ, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
Local p-value
Observed p-value
Expected for SM H(m_H)
eμ, eτ_h, μτ_h, τ_hτ_h, μμ, ee
m_H [GeV]


CMS H→ττ, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
-2 Δ lnL
Observed
Parabolic fit
H (125 GeV) Expected
± 1σ Expected
± 2σ Expected
m_H [GeV]


CMS, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
S / (S+B) Weighted dN/dm_ττ [1/GeV]
μτ_h, eτ_h, τ_hτ_h, eμ
SM H(125 GeV)→ττ
Observed
Z→ττ
tt̄
Electroweak
QCD
m_ττ [GeV]


CMS H→ττ, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
m_H = 125 GeV
95% CL
68% CL
Best fit
SM
κ_f
κ_V

Uncertainty	Affected processes	Change in acceptance
Tau energy scale	signal & sim. backgrounds	1–29%
Tau ID (& trigger)	signal & sim. backgrounds	6–19%
e misidentified as τ_h	$Z \to ee$	20–74%
μ misidentified as τ_h	$Z \to \mu\mu$	30%
Jet misidentified as τ_h	$Z + \text{jets}$	20–80%
Electron ID & trigger	signal & sim. backgrounds	2–6%
Muon ID & trigger	signal & sim. backgrounds	2–4%
Electron energy scale	signal & sim. backgrounds	up to 13%
Jet energy scale	signal & sim. backgrounds	up to 20%
E_T^{miss} scale	signal & sim. backgrounds	1–12%
$\varepsilon_{b\text{-tag}}$ b jets	signal & sim. backgrounds	up to 8%
$\varepsilon_{b\text{-tag}}$ light-flavoured jets	signal & sim. backgrounds	1–3%
Norm. Z production	Z	3%
$Z \to \tau\tau$ category	$Z \to \tau\tau$	2–14%
Norm. $W + \text{jets}$	$W + \text{jets}$	10–100%
Norm. $t\bar{t}$	$t\bar{t}$	8–35%
Norm. diboson	diboson	6–45%
Norm. QCD multijet	QCD multijet	6–70%
Shape QCD multijet	QCD multijet	shape only
Norm. reducible background	Reducible bkg.	15–30%
Shape reducible background	Reducible bkg.	shape only
Luminosity 7 TeV (8 TeV)	signal & sim. backgrounds	2.2% (2.6%)
PDF (qq)	signal & sim. backgrounds	4–5%
PDF (gg)	signal & sim. backgrounds	10%
Norm. ZZ/WZ	ZZ/WZ	4–8%
Norm. $t\bar{t} + Z$	$t\bar{t} + Z$	50%
Scale variation	signal	3–41%