VI Workshop Italiano sulla Fisica pp a LHC
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SM Higgs $\rightarrow \tau\,\tau$

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Overview

Contents

- Higgs at LHC & tau lepton in detectors
- Physics objects definition, trigger & event categorization
- Results
- Conclusions and perspectives

Main Documentation

ATLAS-CONF-2012-160
CMS PAS HIG-13-004

Analyses Summary

	ATLAS	CMS
Analysis type	Cut-based	Cut-based
7 TeV	4.6 fb^{-1}	4.9 fb^{-1}
8 TeV	13 fb^{-1}	19.4 fb^{-1}
Last update	13 November 2012	15 March 2013

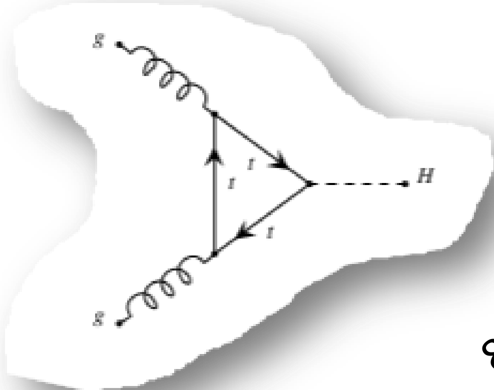
17.6 fb^{-1}

24.3 fb^{-1}

Final state	ee	eμ	μμ	$e\tau_{had}$	$\mu\tau_{had}$	$\tau_{had}\tau_{had}$
CMS		•	•	•	•	•
ATLAS	•	•	•	•	•	•

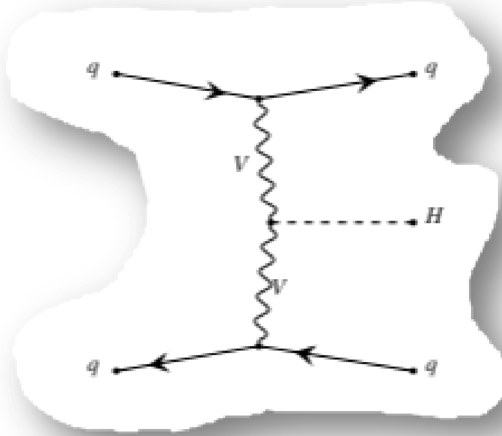
Higgs → τ τ @ LHC

Production

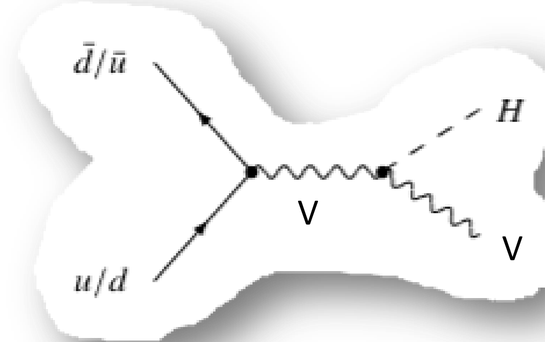


8 TeV

gluon-gluon fusion
19.5 pb (m_H = 125 GeV)



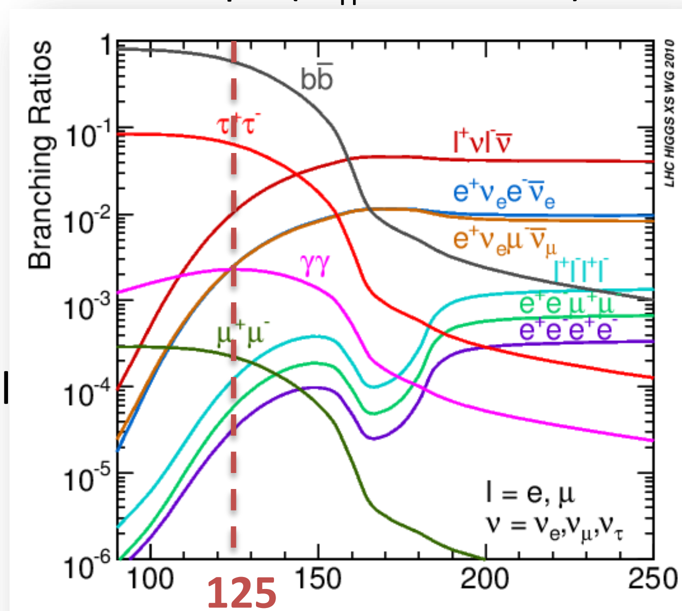
vector boson fusion
1.6 pb (m_H = 125 GeV)



vector boson association
1.1 pb (m_H = 125 GeV)

Importance

- **H → τ τ** is probably the only accessible fermionic channel
  → establishment of the SM Higgs
- Provides the best chance to measure the Higgs couplings to fermions (lepton family)

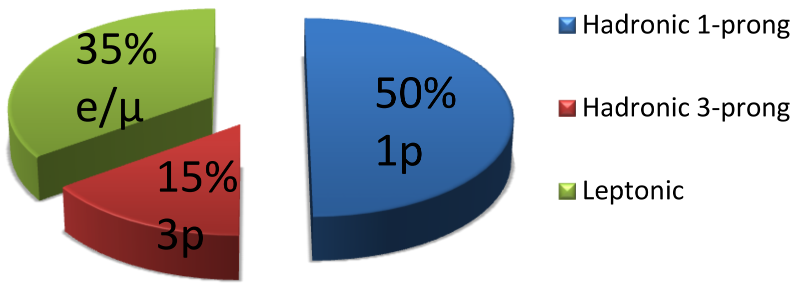


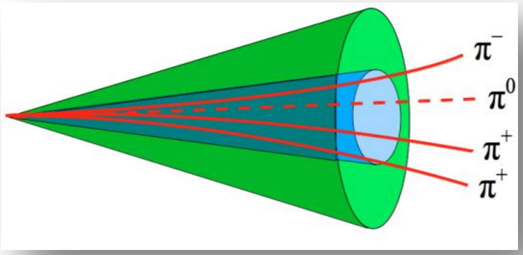
arXiv:1201.3084, CERN-2012-02

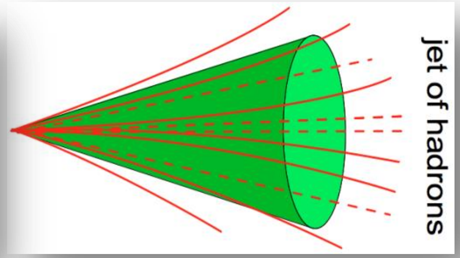
BR (Higgs(125GeV) → τ τ) = 6.2%

Tau Lepton

Tau Properties







QCD jets tend to have

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

Hadronic tau detection

ATLAS	CMS

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 methods
- Identification variables:
  - calorimetric (HAD and EM shower shapes)
  - tracking (isolation, momentum, …)
- Lepton (μ, e) veto

CMS

Reconstruction

- τ_{had}algorithm; seeded from PFJets
  - Only used to collect PFCandidates
- track-vertex association; robust against Pile-Up

Identification

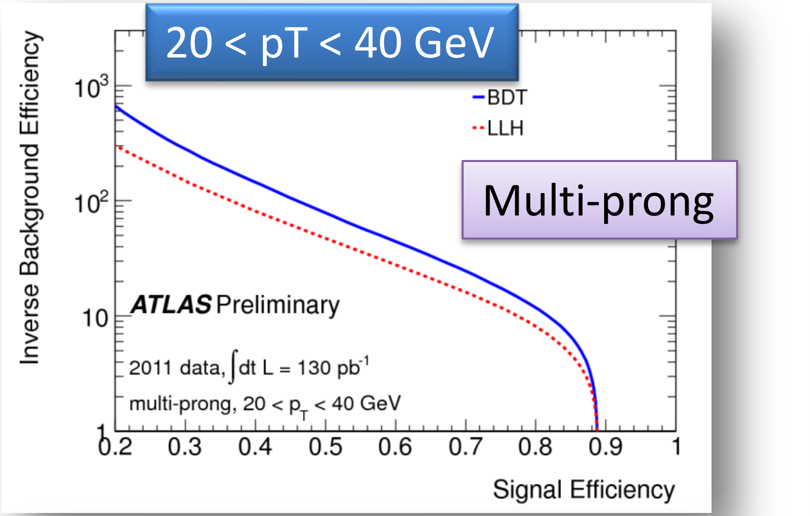
- rho/a1 mass reconstruction
- Separation between 1 (w/ and w/o pi0s) and 3 prongs
- isolation with MVA based variable

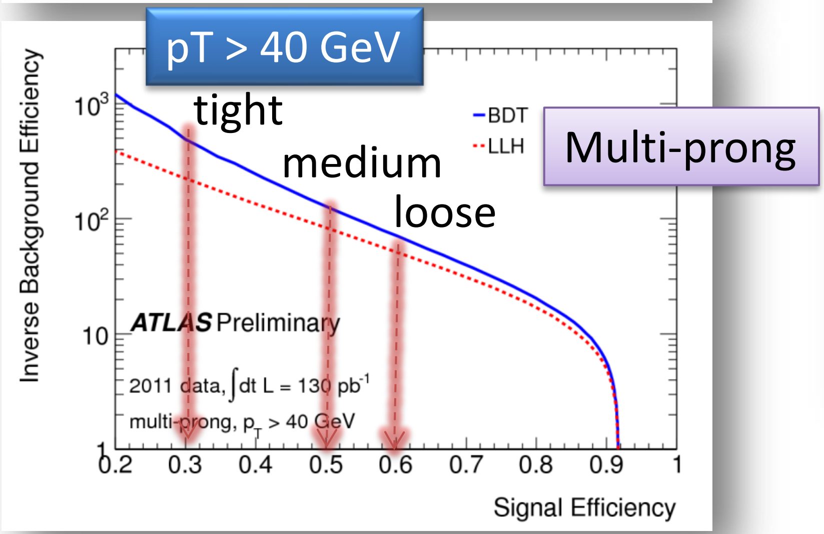
Tau ID Performance

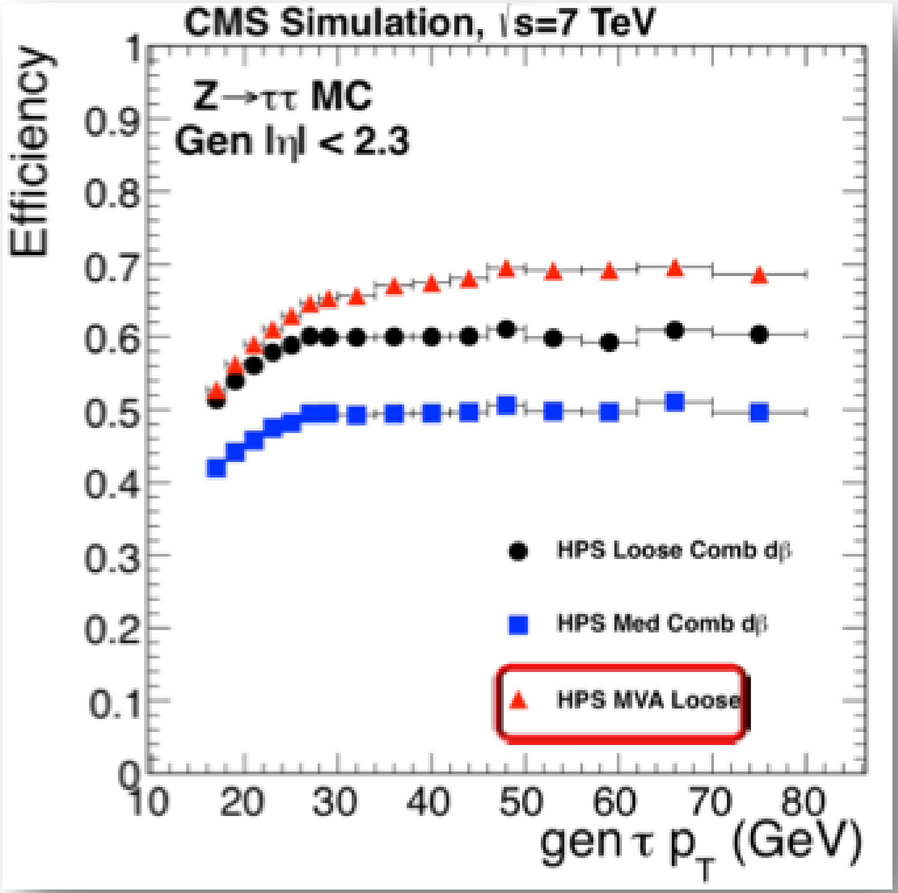
ATLAS

CMS

ATLAS-CONF-2012-142







Tag-and-Probe method

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

* Efficiency evaluated on the MC

* Data/MC SF computed in data with a global fit to the mass distribution

* Fake rate @ 30 GeV is around 1%

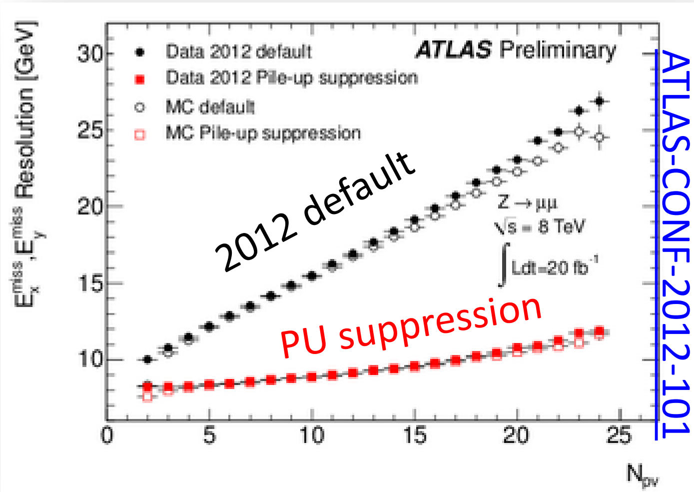
Missing E_T

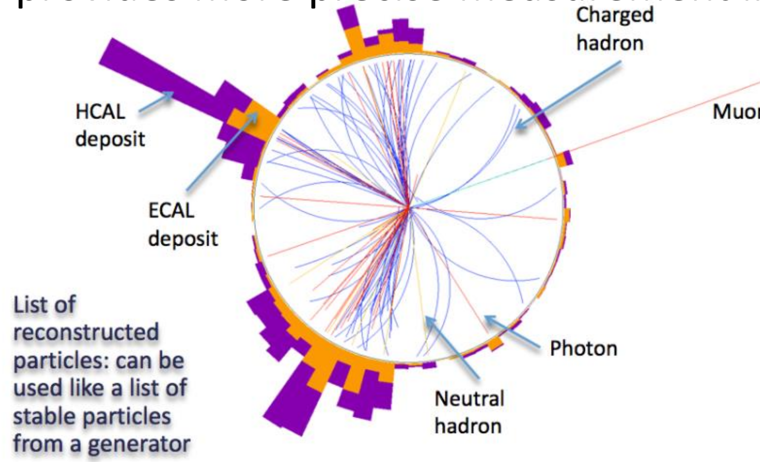
ATLAS

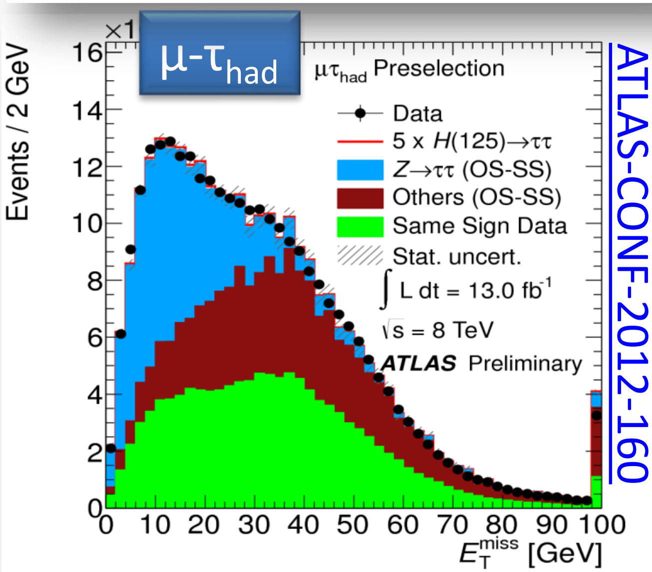
Calorimeter cells associated with reconstructed and identified high-pT objects

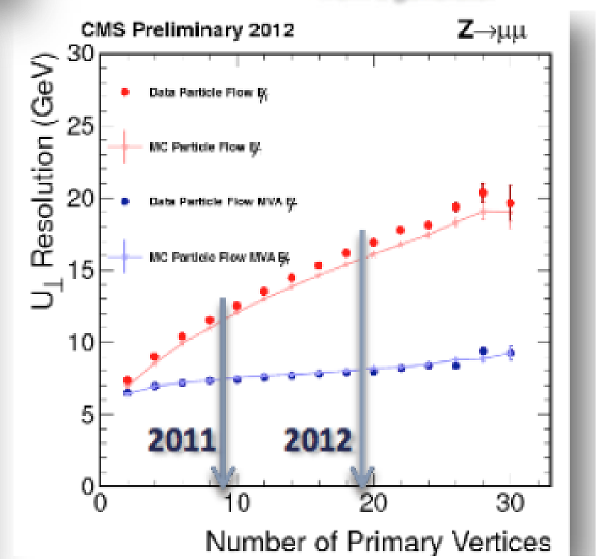
CMS

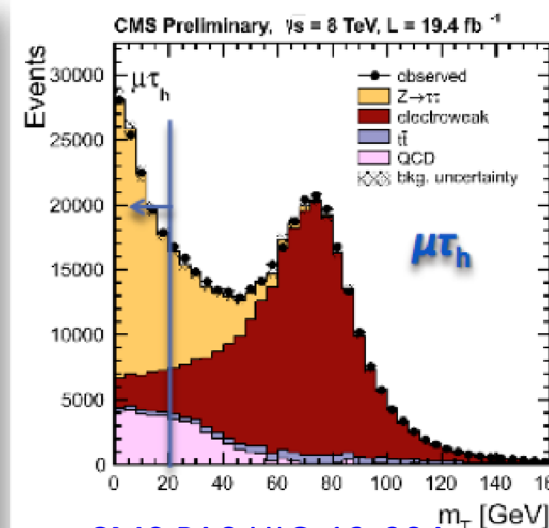
MVA MET regression from Pflow inputs
-> provides more precise measurement in PU











CMS PAS HIG-13-004

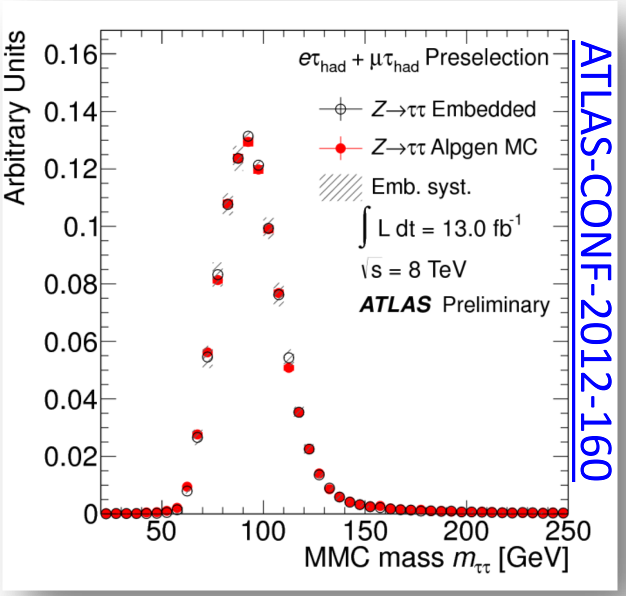
Di-tau Mass Reconstruction

ATLAS

Missing Mass Calculator

• Provide reconstruction of the ττ event kinematics: ε >99%, 13-20% m_τ resolution

- Extension of the Collinear Approximation technique
- Ongoing efforts: correct neutrino kinematics considering the secondary vertex



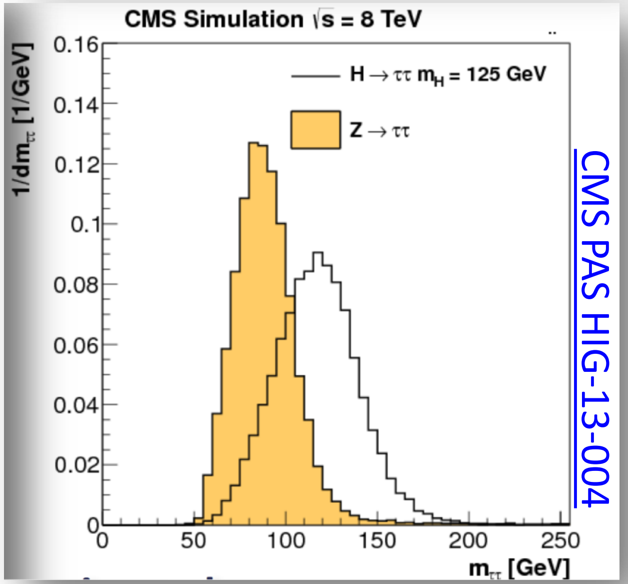
CMS

Secondary Vertex Fit

• Similar technique as MMC with the same resolution

in the future a secondary vertex fit may be introduced

• Gives about 20% improvement wrt visible mass



Trigger

Channel	√s=8 TeV	ATLAS	CMS
	Trigger	Offline pT threshold	
lep-lep	Single electron	25 GeV 10 GeV (μ)	-
	Di-electron	15, 15 GeV	-
	Di-muon	20, 10 GeV	20, 10 GeV
	Combined e+μ	15, 10 GeV	20, 10 GeV
lep-had	Single electron	20 GeV, 26 GeV (μ)	-
	Single muon	26 GeV (μ), 20 GeV	-
	Combined $e+\tau_{had}$	20-26 GeV (electron) 25 GeV	24GeV (electron), 20 GeV
	Combined $\mu+\tau_{had}$	17-26 GeV (muon) 25 GeV	20 GeV, 20 GeV
had-had	Combined $\tau_{had}+\tau_{had}$	40, 25 GeV	45, 45, 50 GeV (extra jet req. at HLT)

Analysis Categories - ATLAS

lep-lep

Preselection

- Exactly two isolated leptons- opposite charges
- Jet pT > 40 GeV
- High E_T^{miss} requirement
- b-tagged jet veto

2-jet VBF
$\Delta\eta_{jj} > 3.0$, $m_{jj} > 400$ GeV

Boosted
pT(Higgs) > 100 GeV

2-jet VH
Second jet with pT > 25 GeV

1-jet
$M_{\tau\tau\ jet} > 225$ GeV

0-jet (7 TeV only)
Only eμ final states

lep-had

Preselection

- Exactly one isolated light lepton
- τ_{had} candidate BDT-medium
- Large E_T^{miss}

VBF
Forward-backward di-jet
$\Delta\eta_{jj} > 3.0$, $m_{jj} > 500$ GeV
di-τ η-centrality

Boosted
pT(Higgs) > 100 GeV

1-jet
$M_{\tau\tau\ jet} > 225$ GeV

0-jet
No jets pT > 30 GeV
Separate $e\text{-}\tau_{had}$ / $\mu\text{-}\tau_{had}$

had-had

Preselection

- Two τ_{had} candidates BDT-medium
- Large E_t^{miss}
- ΔR(τ, τ) & Δη(τ, τ) cuts

VBF
Two tagging forward jets
$\Delta\eta_{jj} > 2.6$, $m_{jj} > 350$ GeV
di-τ η-centrality

Boosted
One high-pT jet

Tighter ΔR(τ, τ) cut

MET – ττ azimuthal correlation

Analysis Categories - CMS

number of jets → ($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$)

τ p_T ↓

Tau pT cut
Low @ 20 GeV
High @ 40 GeV

0-jet, low p_T
- High background, constrains nuisance parameters
- No fit for signal

1-jet, low p_T
- Enhancement from jet requirement

2-jet (VBF)
- ≥2 jets, no jet in rapidity gap
- m(jj) > 500 GeV, |$\Delta\eta$(jj)| > 3.5

0-jet, high p_T
- High background, constrains nuisance parameters
- No fit for signal

1-jet, high p_T
- Enhancement from jet and p_T requirement

Constrain background normalization, ID efficiencies & energy scales

$\tau_h\tau_h$ 1-jet
1 jet, high p_T(H) requirement

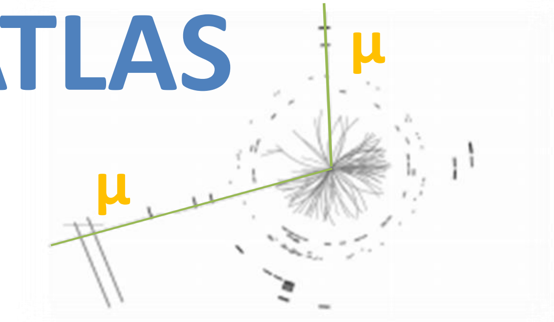
$\tau_h\tau_h$ 2-jet (VBF)
2 jets, high p_T(H) requirement, m(jj) > 250 GeV, |$\Delta\eta$(jj)| > 2.5

ggF, VH receivers

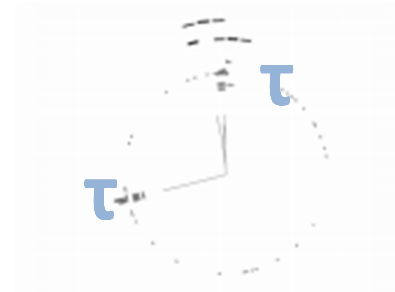
VBF selection

Mutually exclusive categories based on **Jet multiplicity** & **tau pT**

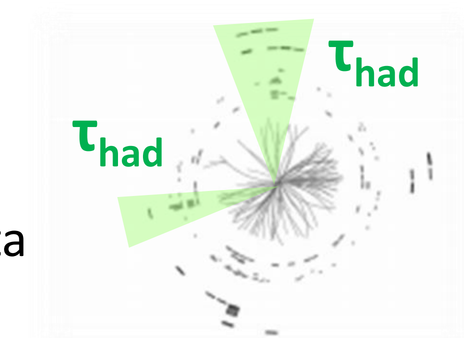
Background Estimation - ATLAS



Zμμ data event



τ τ MC simulation



Merge and perform full event reconstruction

Ztautau: embedding hybrid data-driven estimation

- Select $Z \rightarrow \mu\mu$ events in data → replace μ's by truth τ's
- Simulate τ decays in MC, merge data + simulated info
- Full *re*-reconstruction of the embedded $Z \rightarrow \tau\tau$

QCD: data-driven estimation

- **lep-had:** SS model using corrections from QCD-enriched OS control regions
- **had-had: OS** model with reverted τ-ID criteria
  - perform an extended track counting in the τ-cone
  - normalization: fit 2-D track templates

Z*ll*: from Monte Carlo with scaled yields obtained by comparing data/simulation in Zll-enriched samples

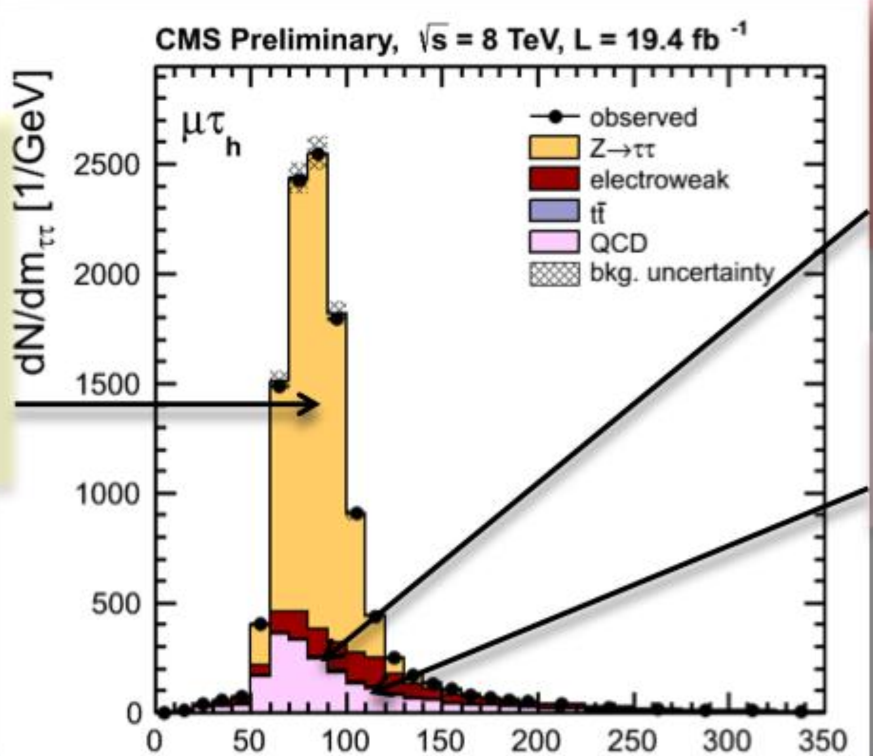
Wτν+jets: estimated from Monte Carlo

Fake lepton background: normalization and shape from data with templates of inverted lepton isolation criteria

Top &Dibosons: estimated from Monte Carlo

Background Estimation - CMS

Z→ττ
Embedding: Z→$\mu\mu$ data, replace μ with simulated τ decay
Normalization from Z→$\mu\mu$ data



[CMS PAS HIG-13-004]

W+jets
Shape from simulation
Normalization from control region
(high mT CR)

QCD
SS data, corrected for SS/OS ratio

Strategy:

- Select isolated, well-identified **leptons, τ_h**
- Topological cuts (e.g. m_T in $l\tau_h$, p_T(H) in $\tau_h\tau_h$) to suppress backgrounds
- Categorize events based on number of jets, τ p_T
- Template fit to $m_{\tau\tau}$ shape

Systematic Uncertainties - ATLAS

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%

Jet Energy Scale 2-15%

Zττ (dominant) background ↑ and signal ↓ systematic uncertainties (8TeV)

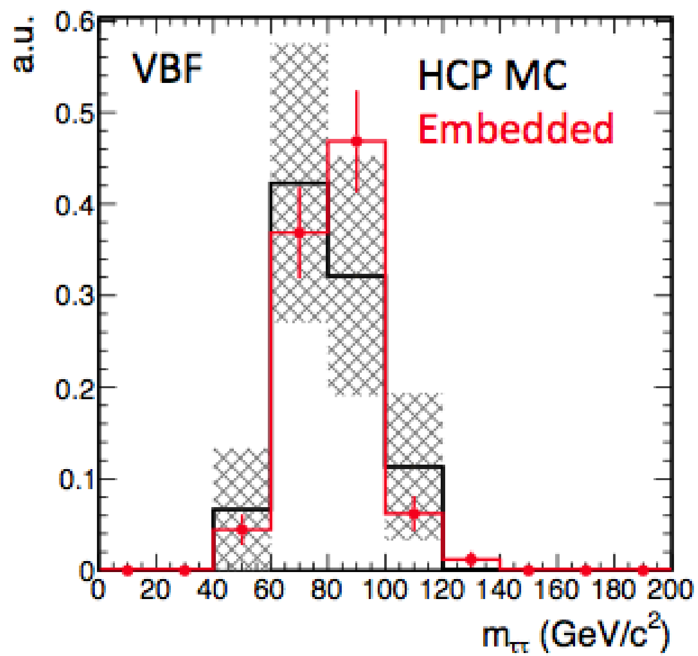
S: uncertainties applied bin-by-bin affecting the final shape

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%

Systematic Uncertainties - CMS

Uncertainty	mu-mu,e-mu, l-tau	tau-tau
Tau ID and Trigger	8%	19%
LeptonID	2(4%)	-
Tau ES	3%	6%
Jet ES	1-20% (depending on cat.)	1-20% (depending on cat.)
Z->tautau normalization	3-33% (depending on cat.)	10-30% Plus bin-by-bin

- Tau, lepton, MET ES uncertainties could modify the mass shape as well.
- Shifted templates are produced with morphing techniques to take into account shape uncertainties.
- For some backgrounds (depending on the categories and channels) bin-by-bin uncertainties are also being used.

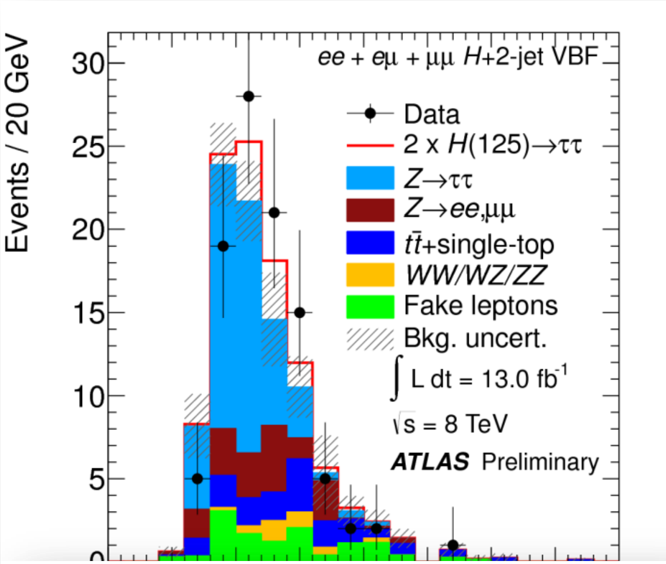


Results

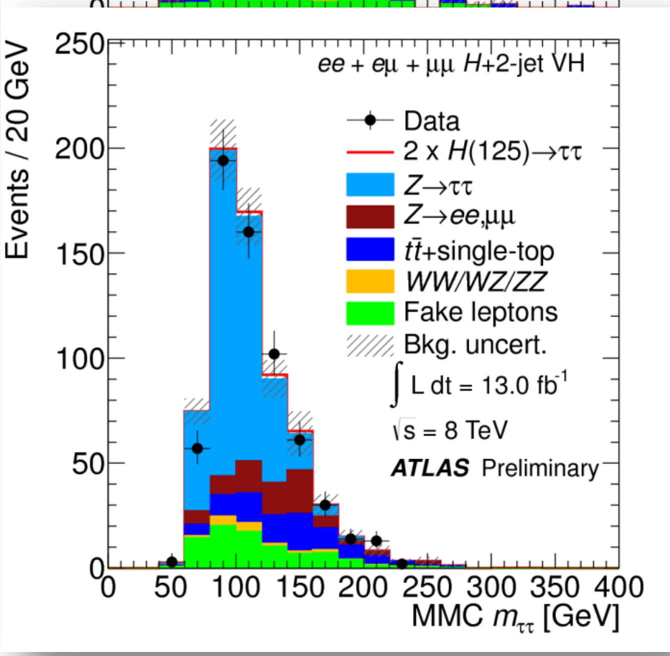
ATLAS

lep-lep

ATLAS-CONF-2012-160

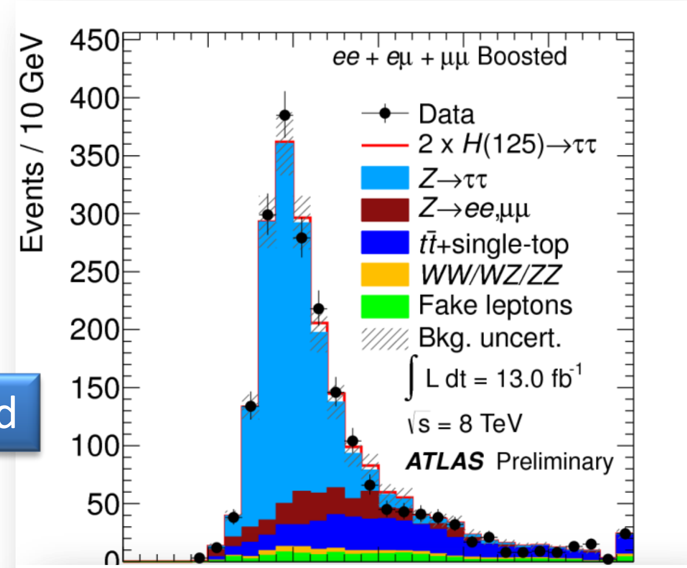


VBF
2-jet

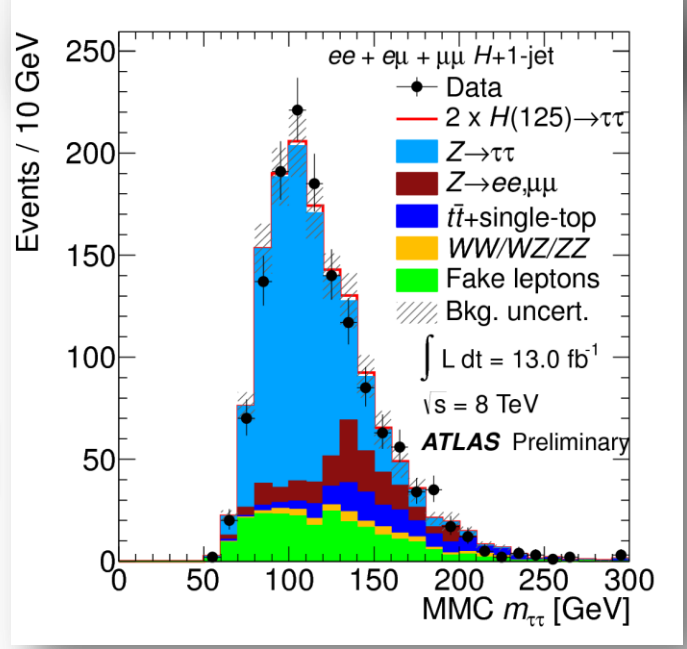


VH
2-jet

Boosted



1-jet



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Results

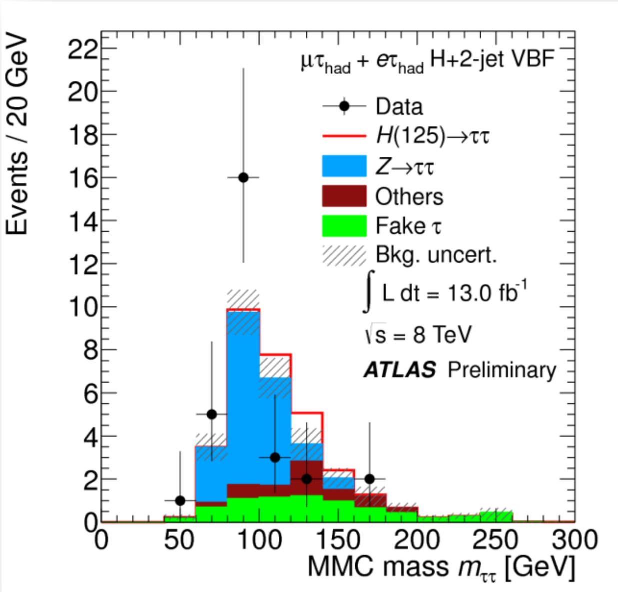
ATLAS

lep-had

had-had

ATLAS-CONF-2012-160

VBF



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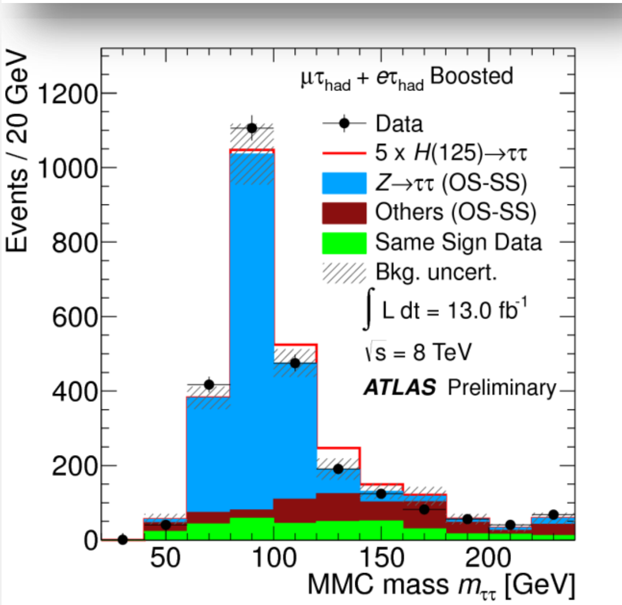
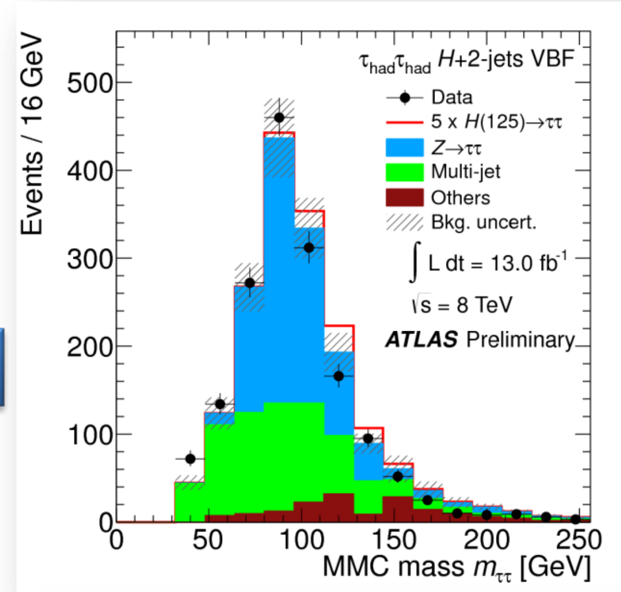
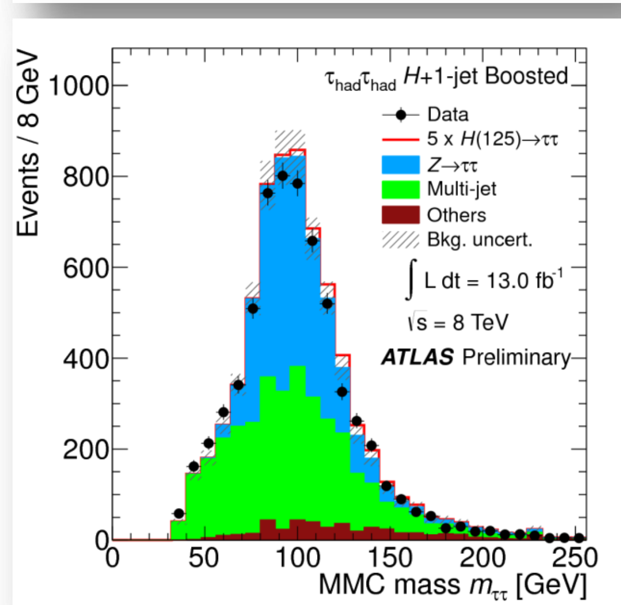


VBF



Boosted

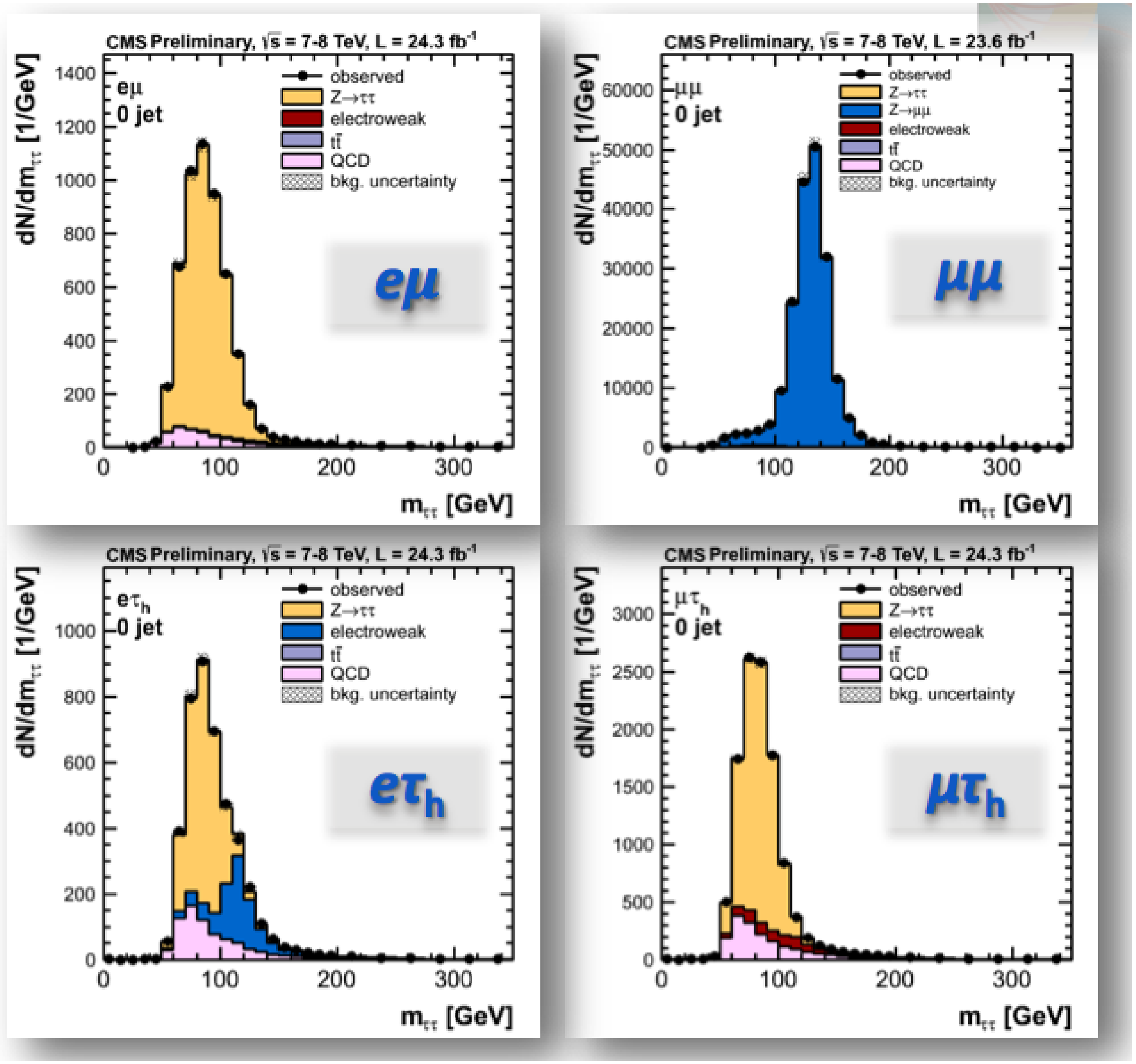


ATLAS-CONF-2012-160

Results CMS

0-jet

- Constrains backgrounds in sensitive categories in simultaneous fit



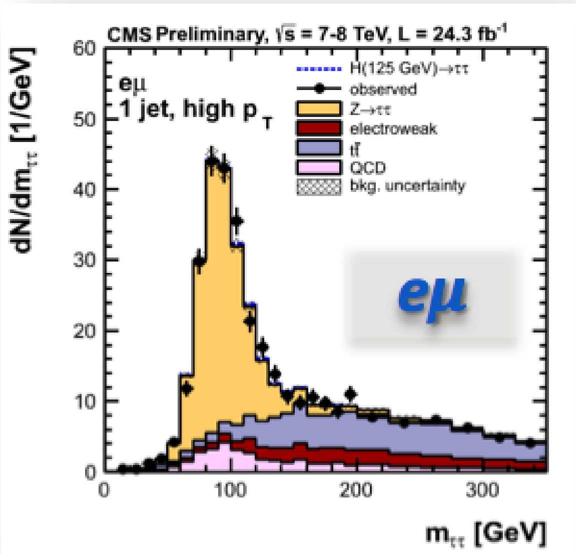
Expected and observed $m_{\tau\tau}$ distributions for the 0-jet category

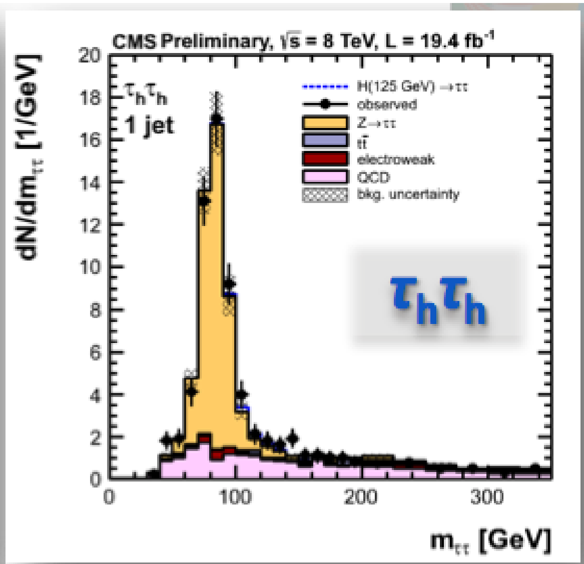
CMS PAS HIG-13-004

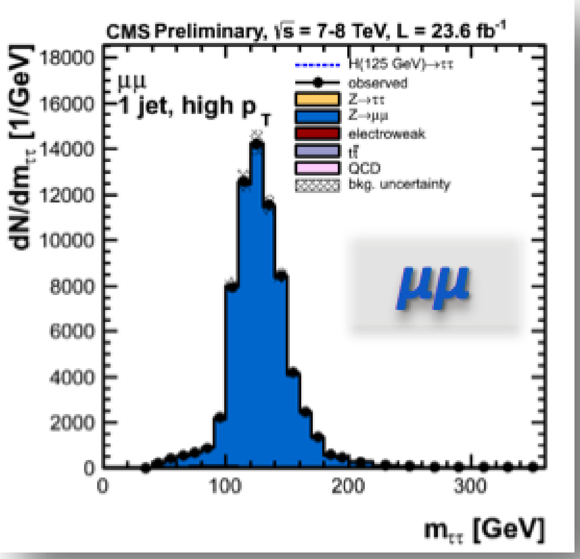
Results CMS

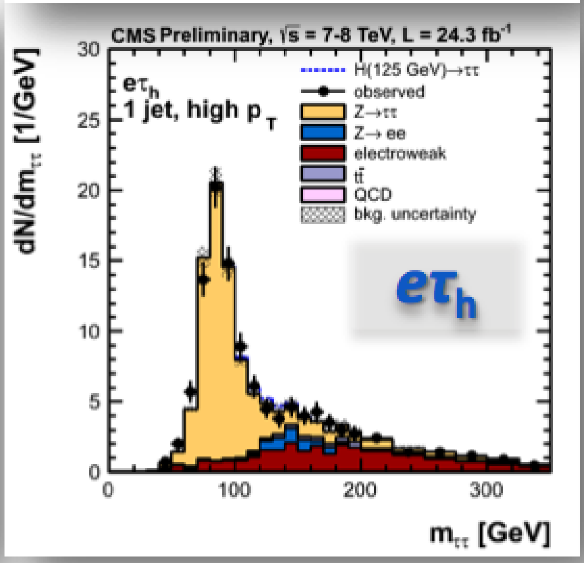
1-jet, high p_T

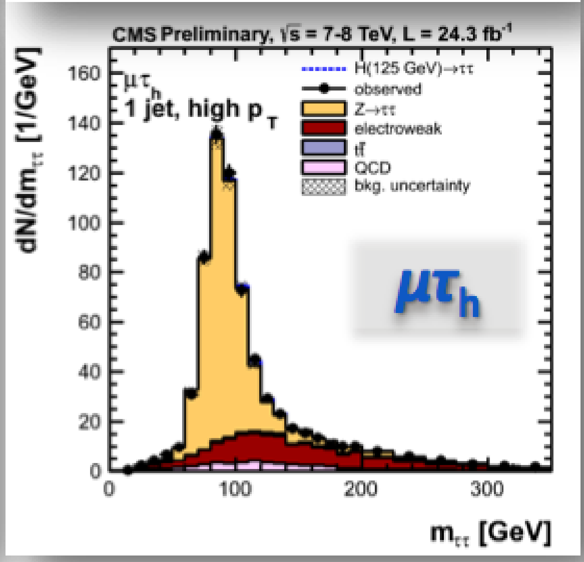
- Enhancement for gluon fusion signal
- Improved mass resolution
- High p_T requirement improves S/B







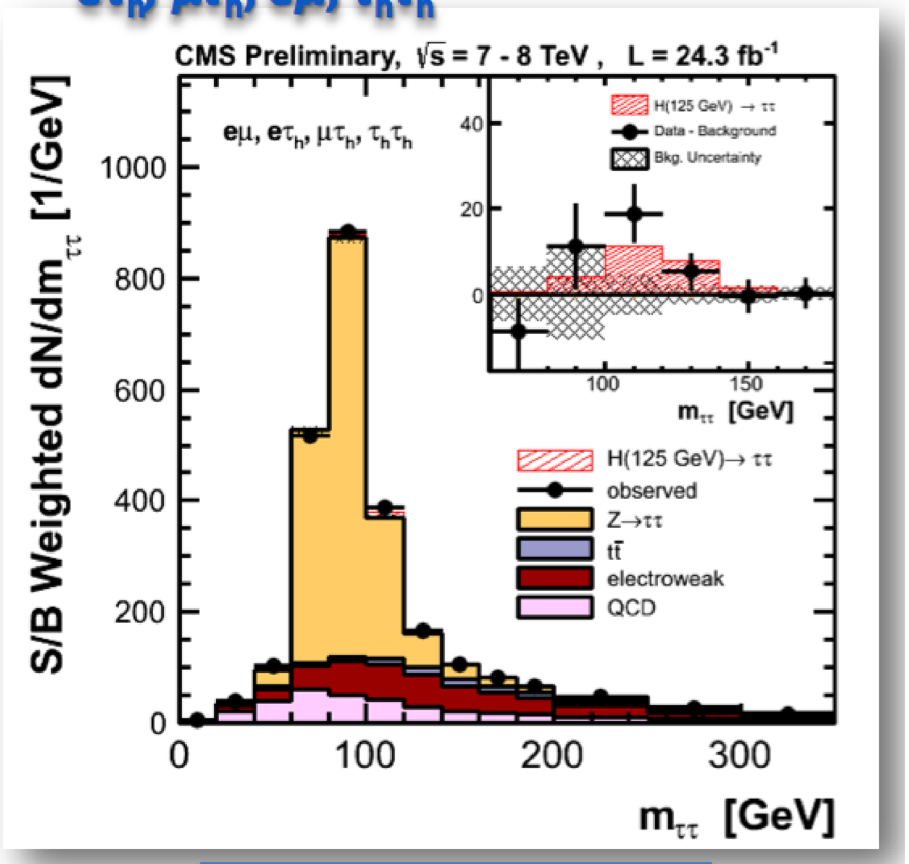




CMS PAS HIG-13-004

Results

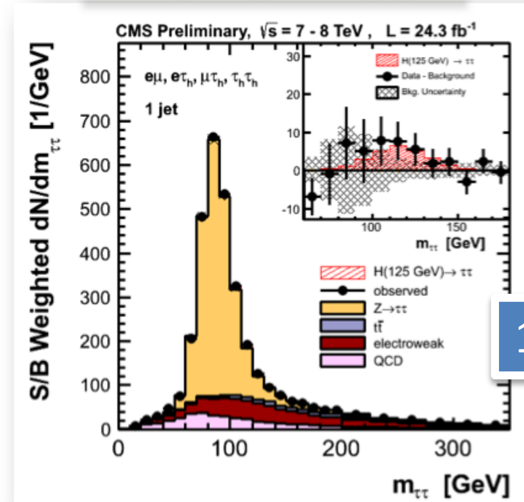
$e\tau_h$, $\mu\tau_h$, $e\mu$, $\tau_h\tau_h$



Combined all categories

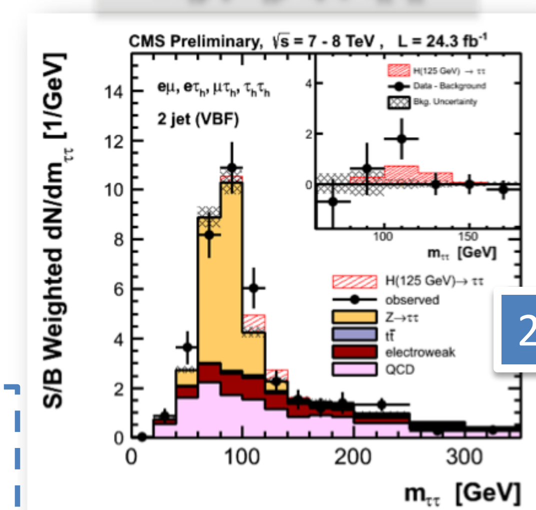
CMS PAS HIG-13-004

$e\tau_h$, $\mu\tau_h$, $e\mu$, $\tau_h\tau_h$



1jet

$e\tau_h$, $\mu\tau_h$, $e\mu$, $\tau_h\tau_h$



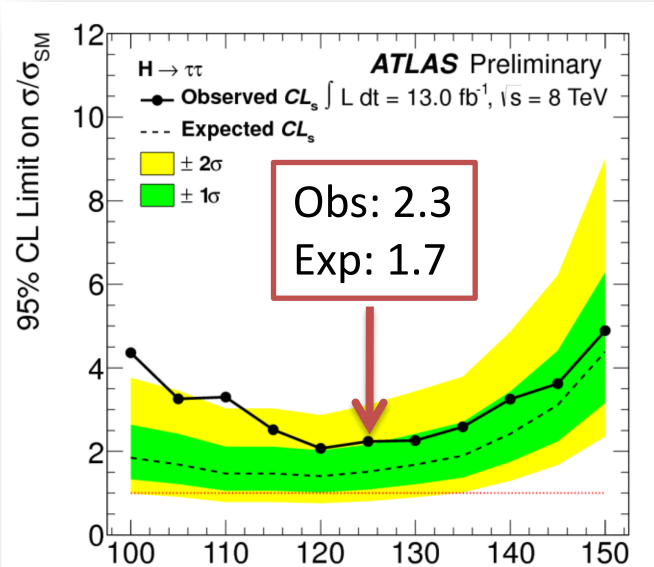
2jet

Distributions in each channel of each category are weighted by the ratio: expected signal/background yields

Limits

ATLAS

- Observed/Expected 95% CLs upper limits on the signal strength $\mu = \sigma_{Higgs}/\sigma_{SM}$ Vs m_{Higgs} in the mass range 100-150 GeV
- Channels: Lep-Lep, Lep-Had, Had-Had
- Combined 2011 & 2012 data
- Expected limits are given for the scenario with no signal



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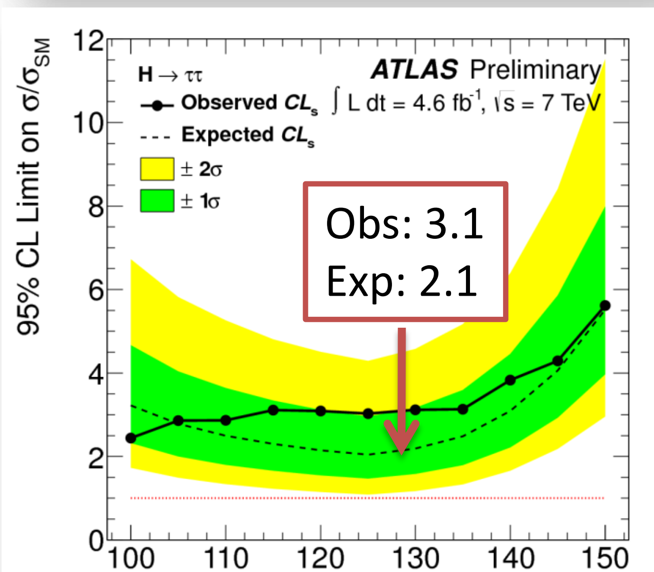

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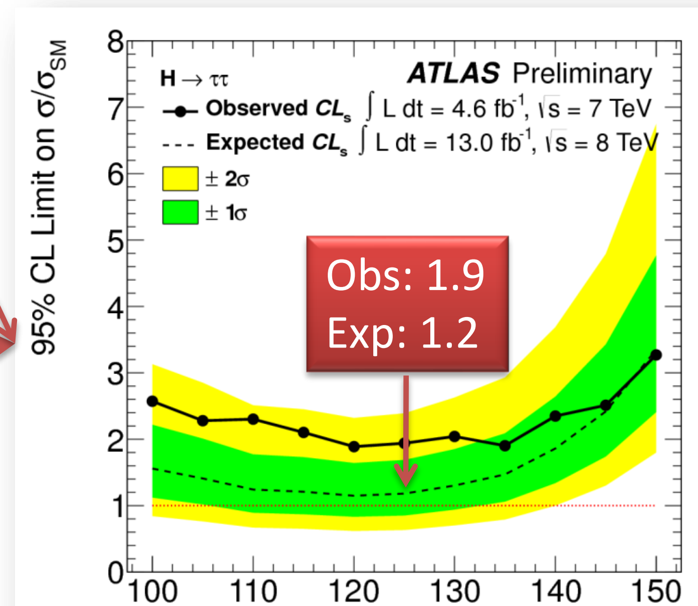

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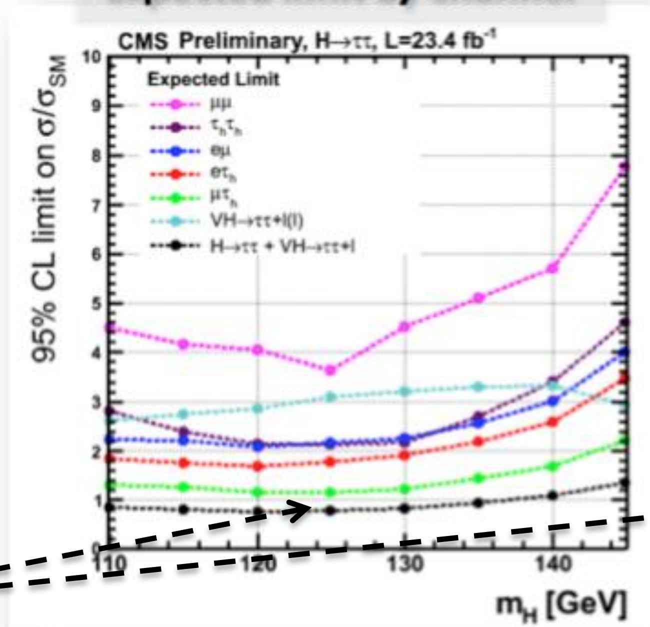
Limits

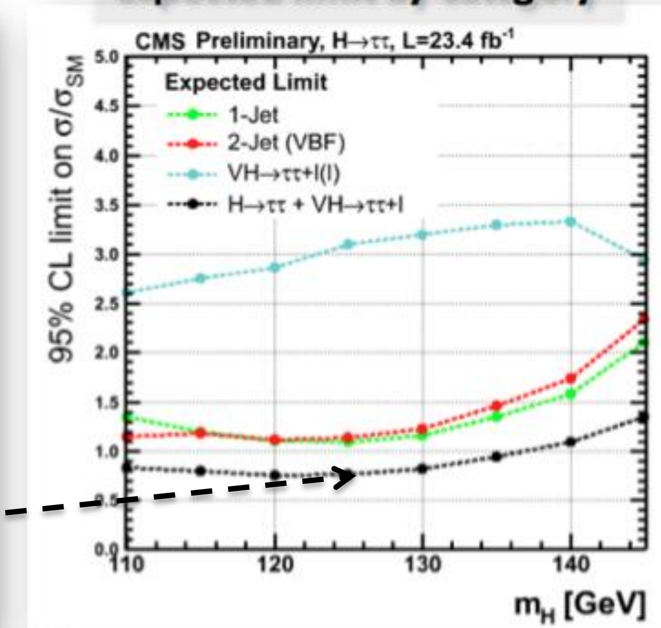
CMS

Background hypothesis

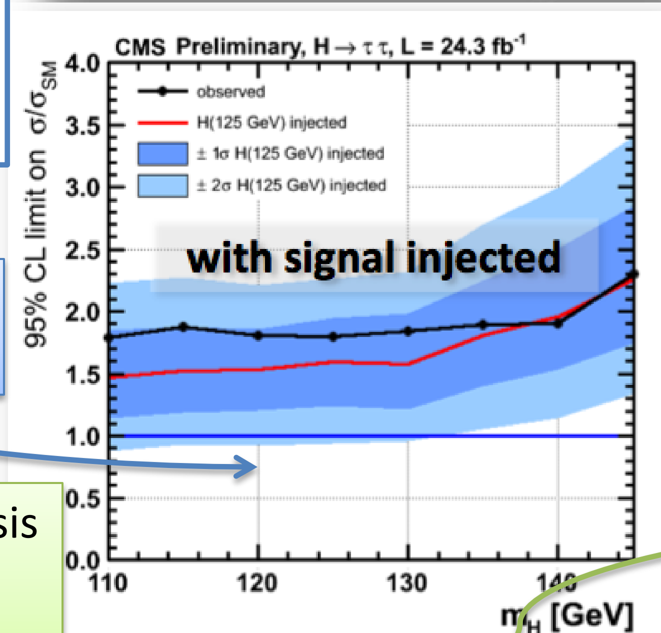
expected limit by channel

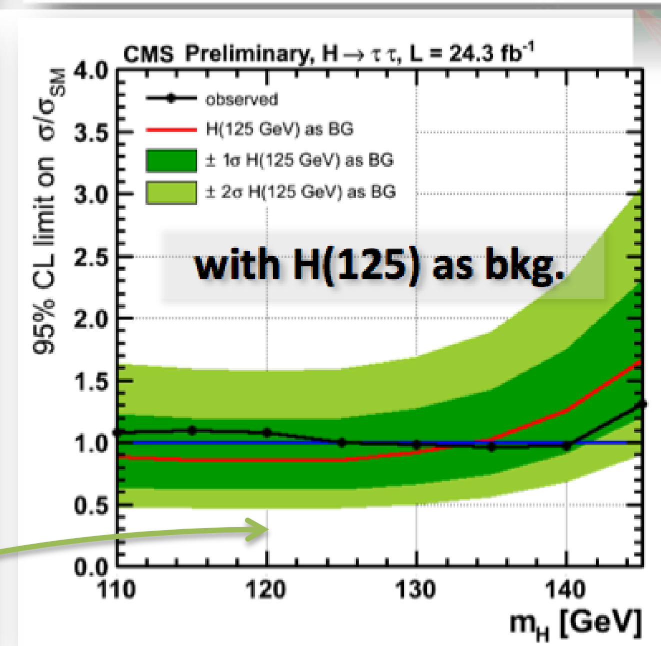


expected limit by category



Combined
Hττ + V(Z,W) Hττl
expected limits





Signal + Background hypothesis

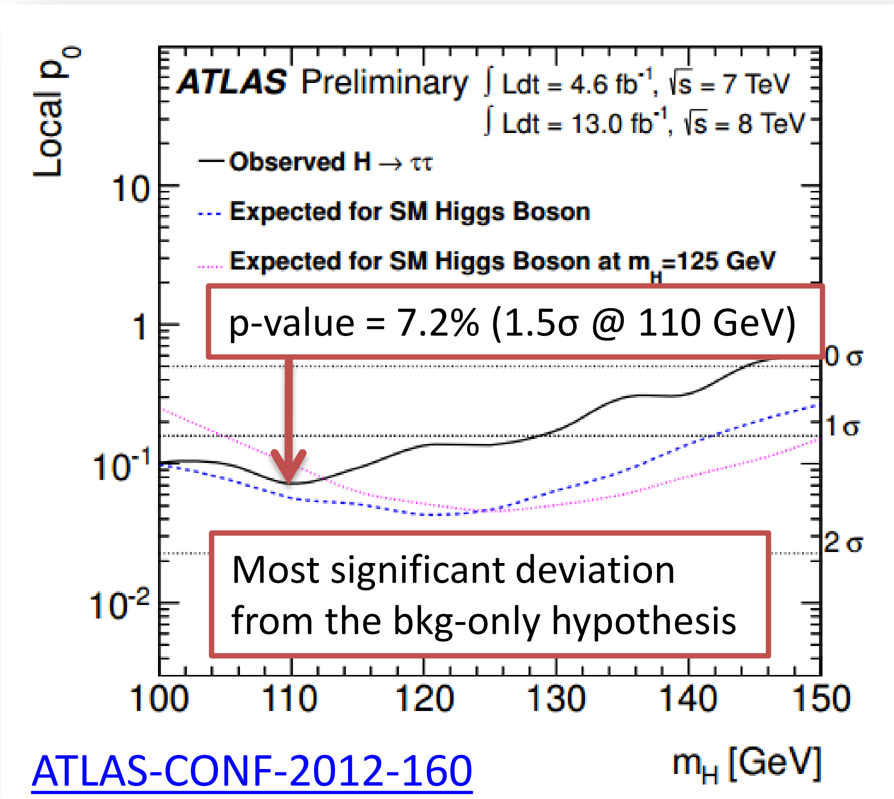
Background hypothesis including SM Higgs signal as bkg

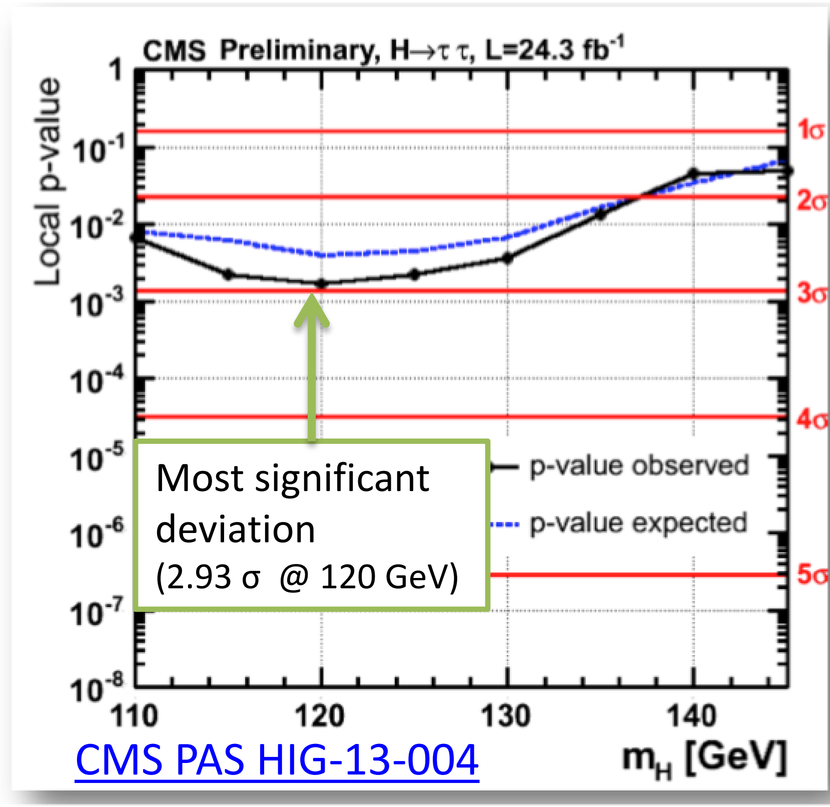
CMS PAS HIG-13-004

p-value

ATLAS

CMS



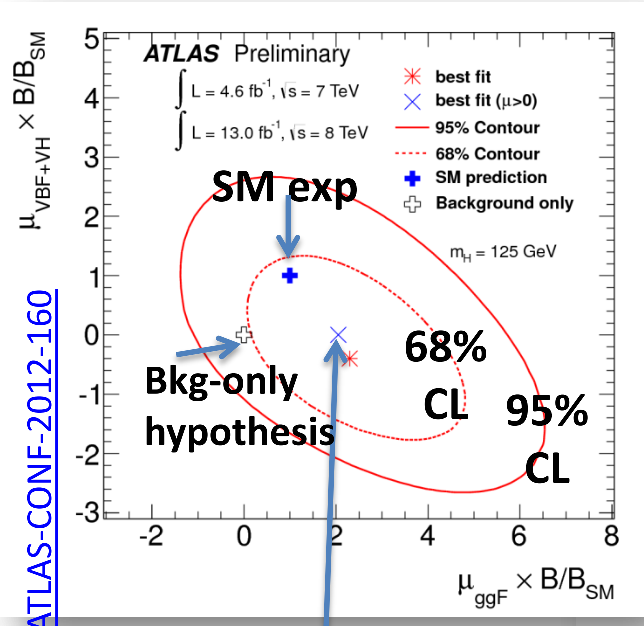


Observed and expected *p-values* and corresponding significance in std deviations as a function of m_H

Best-fit signal strength values (σ/σ_{SM})

ATLAS

CMS

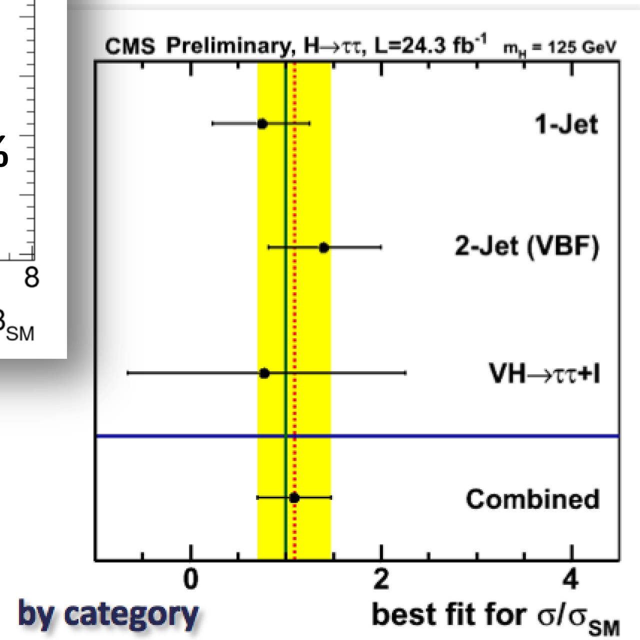


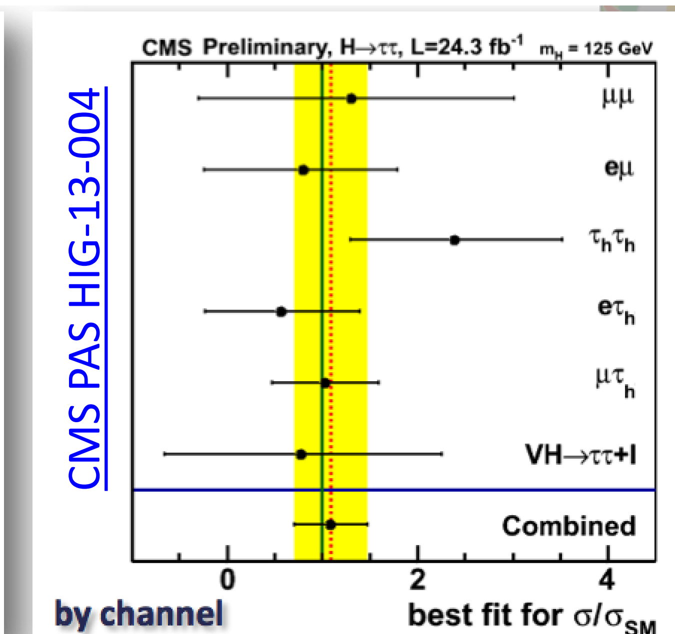
x Best fit to SM μ > 0

Likelihood contours in the plane
μ_{VBF+VH} x BR/BR_{SM}
vs
μ_{ggF} x BR/BR_{SM}

Best-fit value of the signal strength $\mu=\sigma/\sigma_{SM}$ obtained in the global fit

— = SM Higgs expectation





- Consistent picture across channels and categories
- Combined best-fit $\hat{\mu}$ of **1.1±0.4**

Conclusions & Perspectives

- ATLAS and CMS have reported searches for the SM Higgs boson decaying into tau-lepton pairs
- Both experiments exploit all di-tau final states

- ATLAS @ 4.6 + 13 fb^{-1} : expected limit = 1.18×SM & p0 = 1.7σ
  - Projections for 24.6 fb^{-1} : expected limit = 1.01×SM & p0 ≈2σ
- CMS @ 24.3 fb^{-1} : expected limit = 0.77×SM & p0 = 2.62σ
  - CMS result includes VH category and contribution from WW*
  - indication that the boson discovered on July 4, 2012 couples to tau leptons with a strength compatible to the SM prediction

- ATLAS is now pursuing a multivariate analysis aiming for higher sensitivities using the whole LHC dataset. Also, now using new tau ID, new lower-threshold triggers and reduced systematic uncertainties
- CMS is finalizing the analysis for a paper in summer. The MSSM analysis is carried out in parallel

Auxiliary Material

Systematic Uncertainties CMS

Table 2: Main systematic uncertainties entering the analysis. The $\mp$ symbol indicates that the uncertainty is anti-correlated with respect to other categories. The (*) symbol indicates correlation between separate channels. The (†) symbol indicates correlation between separate categories. In the instance where "ex. vbf" is indicated, an additional uncorrelated nuisance is added to account for statistical uncertainties.

Experimental Uncertainties		Propagation into Event Categories		
Uncertainty	Uncert.	*0-Jet*	*1-Jet*	*VBF*
Electron ID & Trigger (†*)	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
Muon ID & Trigger (†*)	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
Tau ID & Trigger (†)	$\pm 8\%$	$\pm 8\%$	$\pm 8\%$	$\pm 8\%$
Tau Energy Scale (†)	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$
Electron Energy Scale (†)	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$
JES (Norm.) (†*)	$\pm 2.5 - 5\%$	$\mp 3 - 15\%$	$\pm 1 - 6\%$	$\pm 5 - 20\%$
MET (Norm.) (†*)	$\pm 5\%$	$\pm 5 - 7\%$	$\pm 2 - 7\%$	$\pm 5 - 8\%$
b-Tag Efficiency (†*)	$\pm 10\%$	$\mp 2\%$	$\mp 2 - 3\%$	$\mp 3\%$
Mis-Tagging (†*)	$\pm 30\%$	$\mp 2\%$	$\mp 2\%$	$\mp 2 - 3\%$
Norm. Z production (†*)	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$
$Z \to \tau\tau$ Category	$\pm 3\%$	$\pm 0 - 5\%$	$\pm 3 - 5\%$	$\pm 10 - 13\%$
Norm. $t\bar{t}$ (†* ex.vbf)	$\pm 10\%$	$\pm 10\%$	$\pm 10\%$	$\pm 12 - 33\%$
Norm. Diboson (†* ex. vbf)	$\pm 15 - 30\%$	$\pm 15 - 30\%$	$\pm 15 - 30\%$	$\pm 15 - 100\%$
Norm. QCD Multijet	$\pm 6 - 32\%$	$\pm 6 - 32\%$	$\pm 9 - 30\%$	$\pm 19 - 35\%$
Lumi 7 TeV (8 TeV)	$\pm 2.2(4.2)\%$	$\pm 2.2(4.2)\%$	$\pm 2.2(4.2)\%$	$\pm 2.2(4.2)\%$
Norm. W+jets	$\pm 10 - 30\%$	$\pm 20 - 27\%$	$\pm 10 - 33\%$	$\pm 12.4\% - 30\%$
Norm. $Z \to \ell\ell$: e fakes τ_h (†)	$\pm 20\%$	$\pm 20\%$	$\pm 36\%$	$\pm 22\%$
Norm. $Z \to \ell\ell$: μ fakes τ_h (†)	$\pm 30\%$	$\pm 30\%$	$\pm 30\%$	$\pm 30\%$
Norm. $Z \to \ell\ell$: jet fakes τ_h	$\pm 20\%$	$\pm 20\%$	$\pm 20\%$	$\pm 40\%$

Trigger

ATLAS (8 TeV) CMS

	Trigger	Trigger pT Threshold	OfflinepT threshold	Trigger pT Threshold	OfflinepT threshold
lep-lep	Single electron	24 GeV	25 GeV 10 GeV (μ)	24 GeV	25 GeV 10 GeV (μ)
	Di-electron	12, 12 GeV	15, 15 GeV	12, 12 GeV	15, 15 GeV
	Di-muon	18, 8 GeV	20, 10 GeV	18, 8 GeV	20, 10 GeV
	Combinede+μ	12, 8 GeV	15, 10 GeV	12, 8 GeV	15, 10 GeV
lep-had	Single electron	24GeV	26 GeV 20 GeV (μ)		
	Single muon	24GeV	26, 20 GeV		
	Combined $e+\tau_{had}$	18, 20 GeV	20-26 GeV, 25 GeV	20, 20 GeV	24GeV, 20 GeV
	Combined $\mu+\tau_{had}$	15, 20 GeV	40 GeV, 25 GeV	17, 20 GeV	20 GeV, 20 GeV
had-had	Combined $\tau_{had}+\tau_{had}$	29, 20 GeV	40, 25 GeV	30,30,30 GeV (extra jet req.)	45, 45, 50 GeV

Physics Objects Definition

	ATLAS	CMS
electron	EM deposits associated to ID tracks; E_T>15 GeV, $\lvert\eta\rvert$<2.47; shower shape quality and isolation requirements	Se hai voglia di riempire, altrimenti cancelliamo la colonna
muon	ID tracks linked to μ-spectrometer tracks; Δz(track, PV)<1cm; quality &isolation criteria	
jet	anti-kt R=0.4; 3dcalo noise-suppressed clusters; pT>25 GeV; $\lvert\eta\rvert$<4.5; Jet-Vertex-Fraction to reduce PU activity	
b-jet	Impact parameter & displaced secondary vertex tagging algorithm; pT>15 GeV; $\lvert\eta\rvert$<2.5;	
tau	BDT-medium (ε=50%) τ-jet identif.;pT>20 GeV; $\lvert\eta\rvert$<2.5; 1/3-prong;	
MET	object-based definition; muon and calorimetric contributions	

Analysis Categories - lep-lep

ATLAS (8 TeV)

Preselection	Exactly two opposite sign charged leptons Jet pT> 40 GeV E_T^{miss}, H_T^{miss} cuts m_{ll}, $\Delta\phi_{ll}$, x1, x2 cuts
2-jet VBF	Jet pT> 25GeV (JVF) $\Delta\eta_{jj}$> 3.0, m_{jj}> 400 GeV b-tagged jet veto Lepton centrality, CJV
Boosted	Di-τ pT> 100 GeV b-tagged jet veto
2-jet VH	Jet pT> 25GeV (JVF) $\Delta\eta_{jj}$> 2, 160 >m_{jj}> 30 GeV b-tagged jet veto
1-jet	Mττ> 225 GeV b-tagged jet veto

Exclusively defined
Search regions

Analysis Categories - lep-had

ATLAS (8 TeV)

VBF	Boosted
Tau pT> 30 GeV, Lepton pT> 26 GeV Jets pT> 40, 30 GeV $\Delta\eta_{jj}$> 3, m_{jj}> 500 GeV ηj1 x ηj2 < 0 MET > 20 GeV ΣpT (τ1,τ2,j1,j2,MET)< 30 GeV	Tau pT> 30 GeV MET > 20 GeV pT(H) > 100 GeV x1, x2 cuts
mT< 50 GeV $\lvert\Delta R^{l\tau} - \Delta R^{l\tau}_{pred}\rvert$< 0.88 $\lvert\phi_l - \phi_{MET}\rvert + \lvert\phi_\tau - \phi_{MET}\rvert$<2.8 b-tagged jet veto	mT< 50 GeV Δ(ΔR) < 0.8 - b-tagged jet veto
1-jet	**0-jet**
No jetspT> 30 GeV, MET > 20 GeV	Jet pT> 30 GeV MET > 20 GeV
mT< 50 GeV Δ(ΔR) < 0.5 ΣΔϕ< 3.5 $pT^{lep} - pT^{\tau} < 0$	mT< 50 GeV Δ(ΔR) < 0.6 ΣΔϕ< 3.5

= if failed ,discard the event

Analysis regions are exclusively receiving events

Analysis Categories - had-had

ATLAS (8 TeV)

Preselection
No muons/electrons in the event 2 BDT-medium hadronicτs, 1 BDT-tight Both τs point to the same vertex TauspT> 40, 25 GeV, $\lvert\eta\rvert < 2.5$, 1/3-prong $0.8 < \Delta R_{\tau\tau} < 2.8$, $\Delta\eta_{\tau\tau} < 1.5$ Min { $\Delta\phi$(MET, τ1), $\Delta\phi$(MET, τ1) } < 0.2 π
VBF
Two tagging jets pT> 50 GeV $\Delta\eta_{jj} > 2.6$, $m_{jj} > 350$ GeV, $\eta j1 \times \eta j2 < 0$ Tau η-centrality MET > 20 GeV
Boosted
One tagging jet pT> 70 GeV $\Delta R_{\tau\tau} < 1.9$ MET > 20 GeV Min { $\Delta\phi$(MET, τ1), $\Delta\phi$(MET, τ1) } < 0.1 π