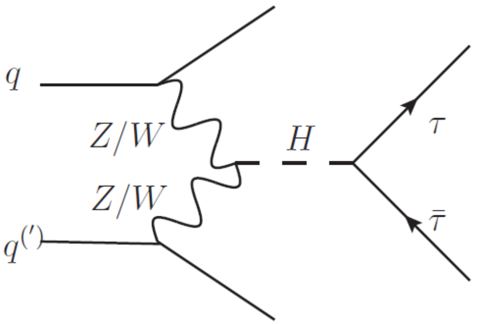


H → ττ Analyses at ATLAS and CMS

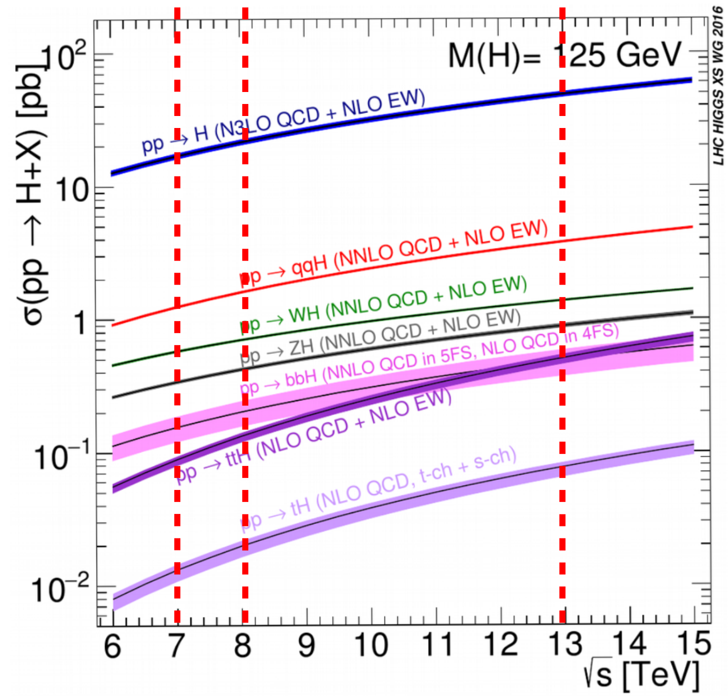
Peter Wagner
on behalf of the ATLAS and CMS Collaborations

QCD @ LHC, 29.8.2017

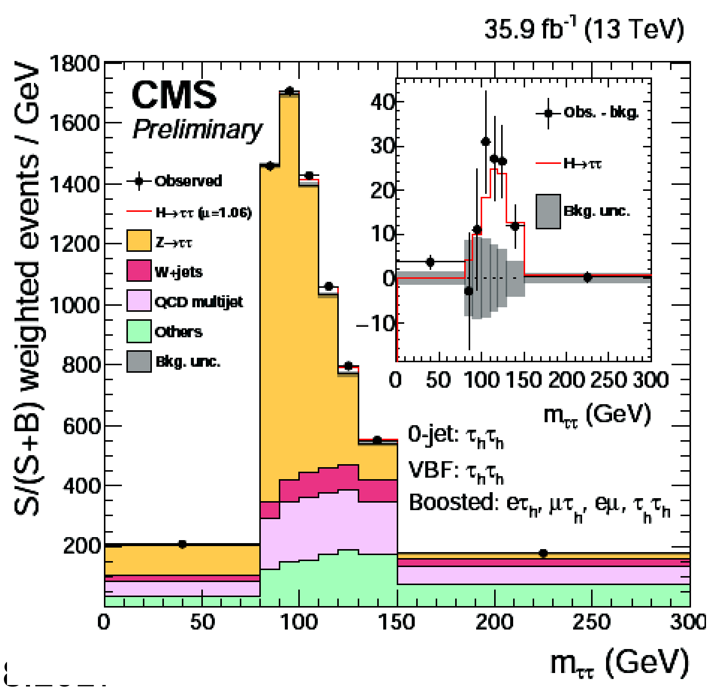
Overview

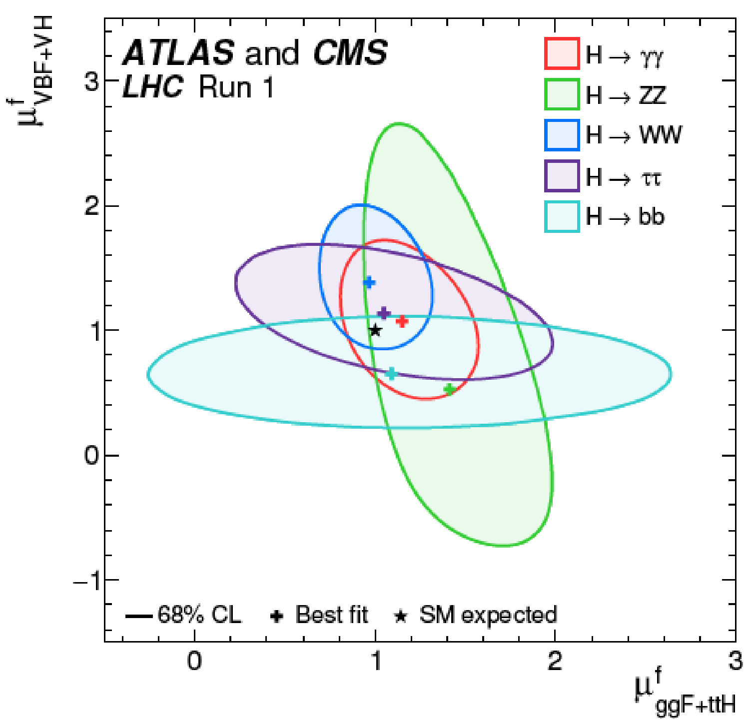
- Why $H \rightarrow \tau\tau$?
- ATLAS and CMS
- SM $H \rightarrow \tau\tau$ analysis overview
- Background estimates
- Conclusion

Why H→ττ ?



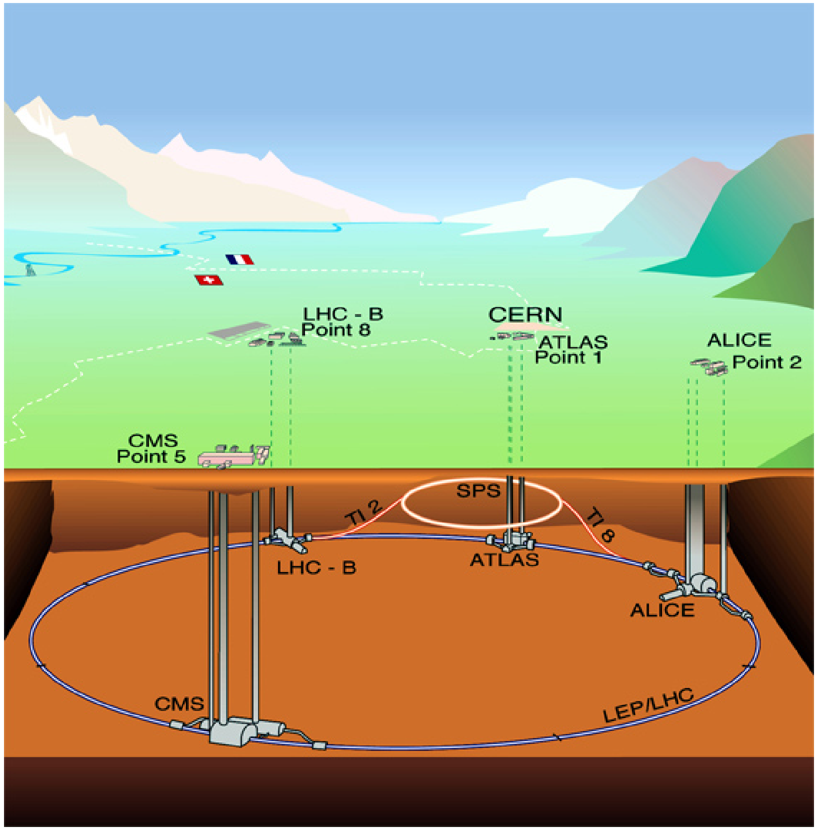
- SM Higgs-to-lepton coupling largest for τ (BR ~ 6%)
  - → only accessible leptonic decay channel so far
  - → first observation of Higgs Yukawa couplings
- Mainly ggF and VBF production – Strong constraints on VBF cross section
- Future: Possibility to measure CP phase in H→ττ coupling

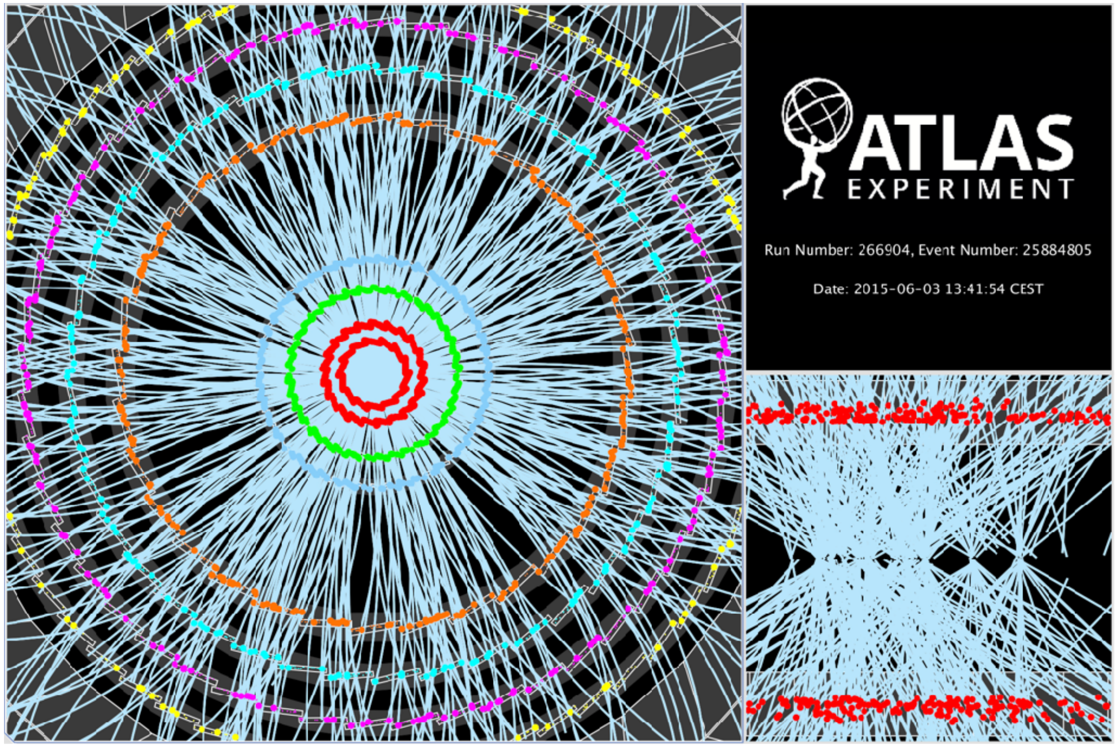




LHC Conditions

- Proton-proton collider
- Collision energy: 7 and 8 TeV up to Feb 2013, since then 13 TeV
- Up to ~45 pile-up collisions per event

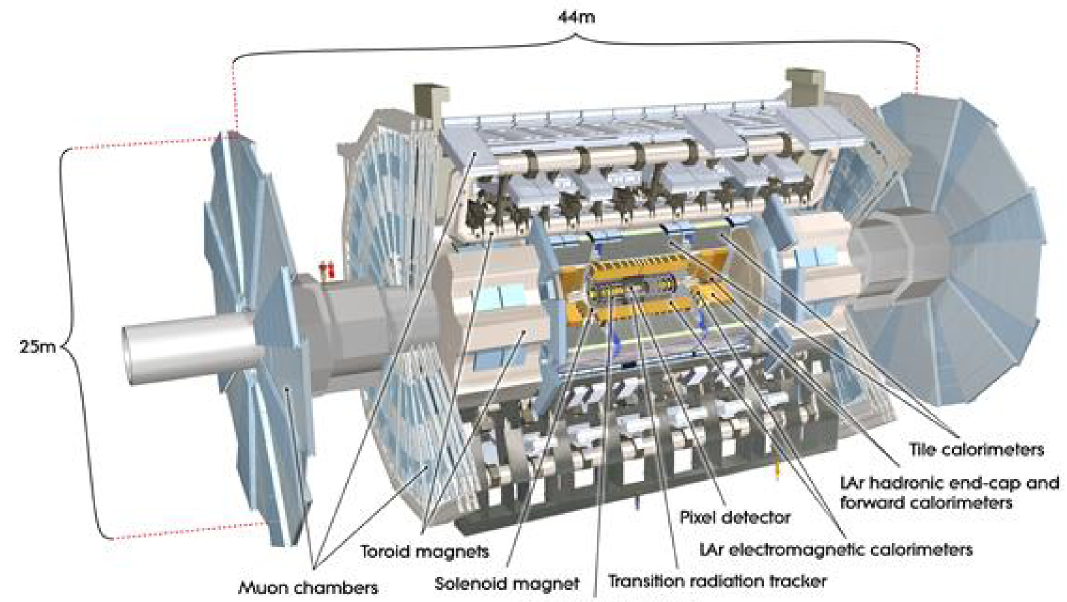


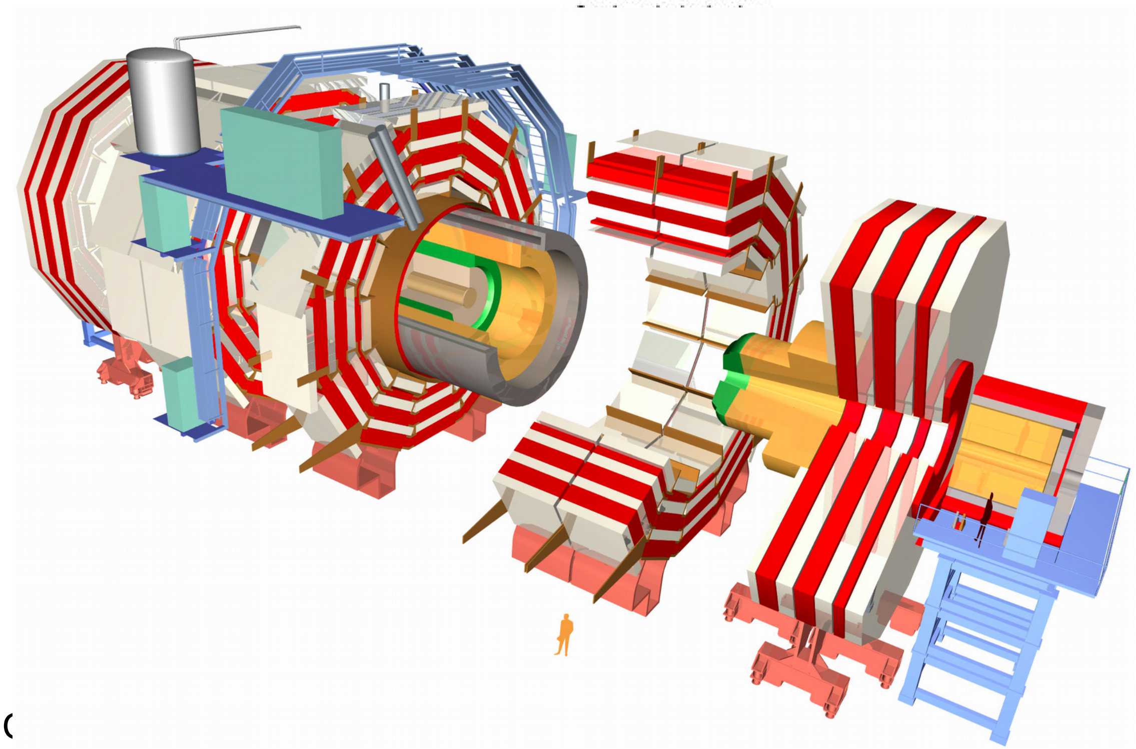


Detectors

- Proton-proton collider
- Collision energy: 7 and 8 TeV up to Feb 2013, since then 13 TeV
- Up to ~45 pile-up collisions per event

- ATLAS and CMS
  - cover similar kinematic phase space for τ's: $p_T > 20$ GeV, $|\eta| < \sim 2.3\text{-}2.5$
  - have similar MVA-based τ identification performance



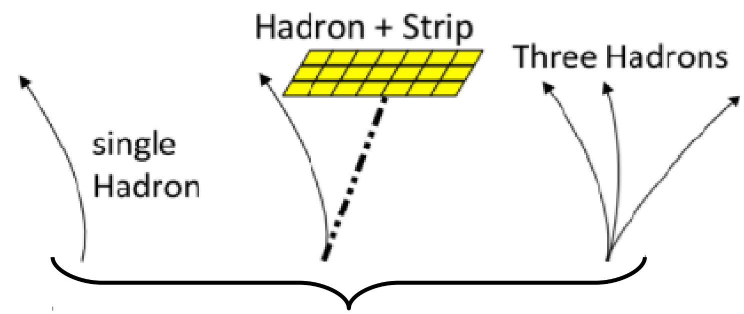


τ Reconstruction

- Proton-proton collider
- Collision energy: 7 and 8 TeV up to Feb 2013, since then 13 TeV
- Up to ~45 pile-up collisions per event

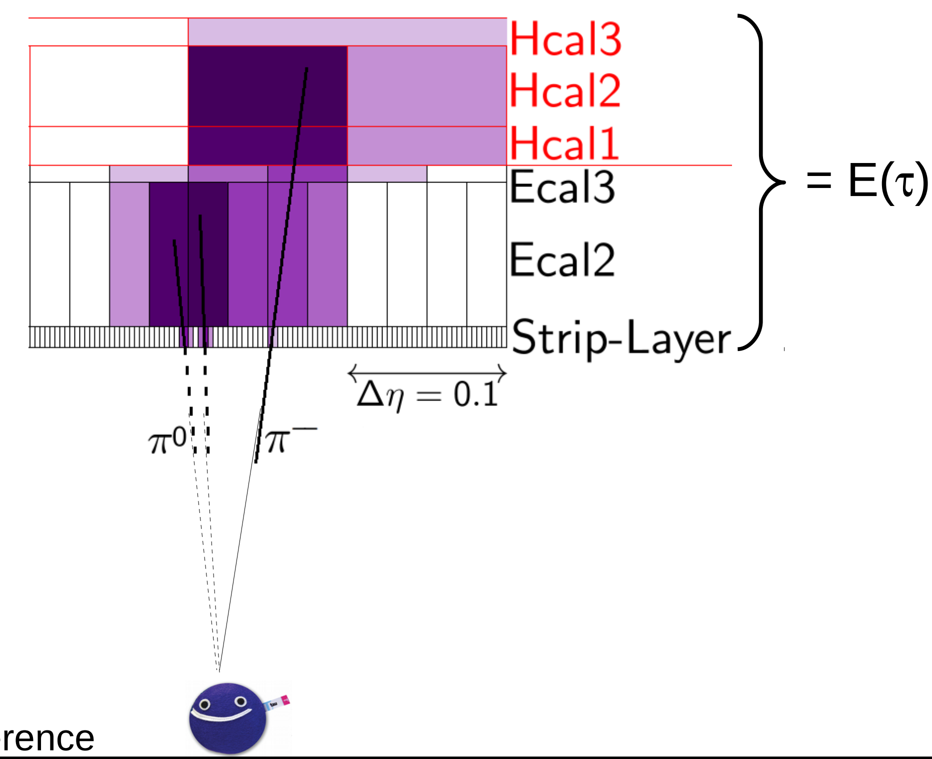
- ATLAS and CMS
  - cover similar kinematic phase space for τ's: p_T > 20 GeV, |η| < ~2.3-2.5
  - have similar MVA-based τ identification performance
  - have different τ reconstruction

CMS: particle flow



→ decay mode classification

ATLAS: calorimeter-based



τ Reconstruction

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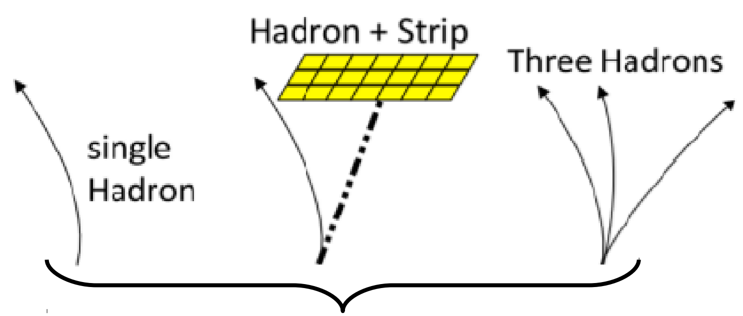
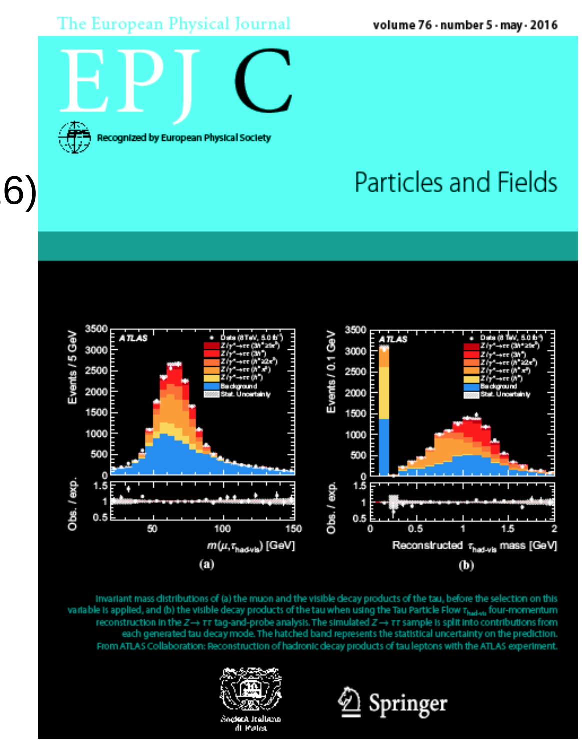


→ decay mode classification

ATLAS Prospects for Run 2:

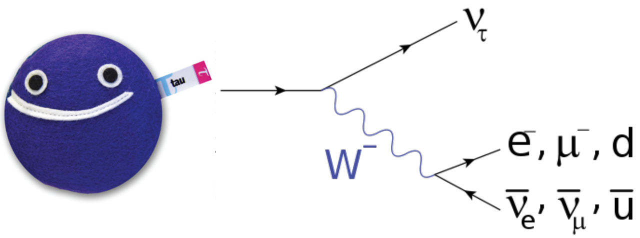
EPJ C76 (5) 1 (2016)

Particle flow



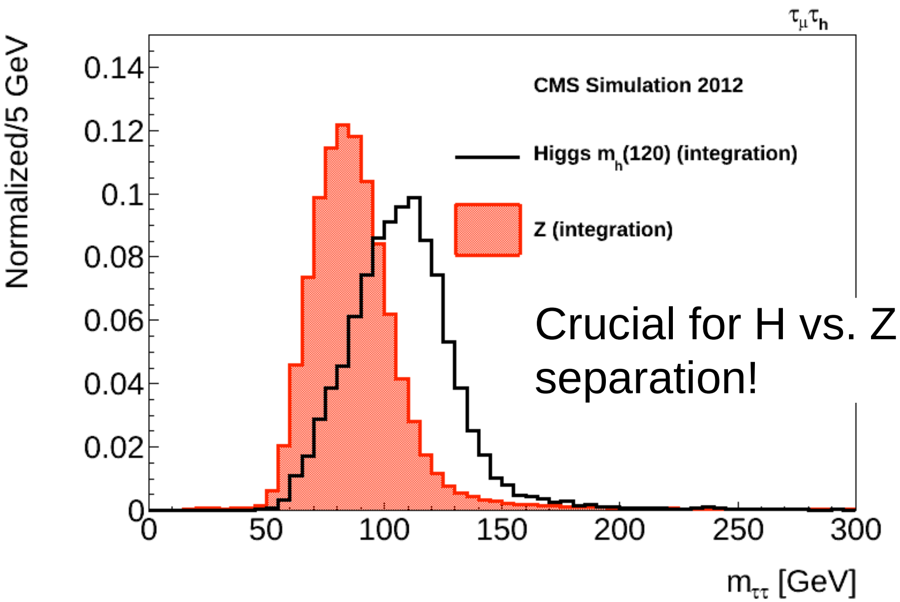
ττ Mass

- Proton-proton collider
- Collision energy: 7 and 8 TeV up to Feb 2013, since then 13 TeV
- Up to ~45 pile-up collisions per event



- ATLAS and CMS
  - cover similar kinematic phase space for τ's: p_T > 20 GeV, |η| < ~2.3-2.5
  - have similar MVA-based τ identification performance
  - have different τ reconstruction
  - ττ mass estimator

- τ decay contains invisible neutrinos
- Estimate ττ mass using likelihood fit to τ kinematics
- Z/H separation superior to m_{vis}, m_{coll} , ...



CMS method "SVFit": CMS-PAS-HIG-12-043

ATLAS method "MMC": ATLAS arXiv:1012.4686

$H\to\tau\tau$

Various SM $H\to\tau\tau$ analyses in both experiments:

ATLAS

- SM $H\to\tau\tau$ evidence — JHEP 04 (2015) 117
- CP Violation in VBF production using $H\to\tau\tau$ — EPJC 76 (2016) 658
- Search for LFV in $H\to\tau$+e/μ — EPJC 77 (2017) 70
- Search for VH production with $H\to\tau\tau$ — PRD 93 092005 (2016)

CMS

- SM Higgs observation — CMS-PAS-HIG-16-043
- Search for LFV in $H\to\tau$+e/μ — CMS-PAS-HIG-17-001

- CMS+ATLAS Combination of Run 1 SM $H\to\tau\tau$ analyses — JHEP 08 (2016) 045

In addition: searches for BSM Higgs and di-Higgs production with $\tau\tau$ in the final state

$H \rightarrow \tau\tau$

Various SM $H \rightarrow \tau\tau$ analyses in both experiments:

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CMS

- SM Higgs observation — CMS-PAS-HIG-16-043
- Search for LFV in $H \rightarrow \tau$+e/μ — CMS-PAS-HIG-17-001

Similar background estimation techniques

- CMS+ATLAS Combination of Run 1 SM $H \rightarrow \tau\tau$ analyses — JHEP 08 (2016) 045

In addition: searches for BSM Higgs and di-Higgs production with $\tau\tau$ in the final state

$H \rightarrow \tau\tau$

Various SM $H \rightarrow \tau\tau$ analyses in both experiments:

Topics of this talk

ATLAS

- SM $H \rightarrow \tau\tau$ evidence — JHEP 04 (2015) 117

CMS

- SM Higgs observation — CMS-PAS-HIG-16-043

Analyses cover different data:

Run 1

4.5 fb^{-1} at sqrt(s)=7 TeV

20 fb^{-1} at sqrt(s)=8 TeV

(Run 2 analysis in preparation)

Run 2

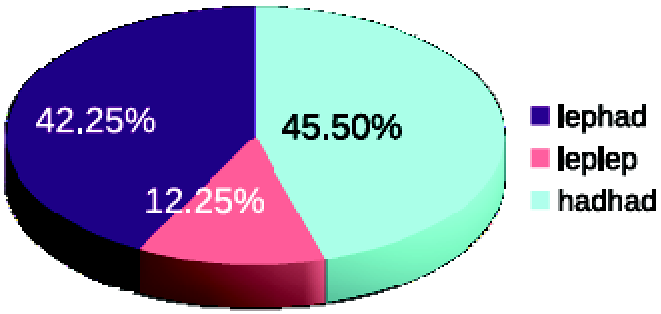
35 fb^{-1} at sqrt(s)=13 TeV

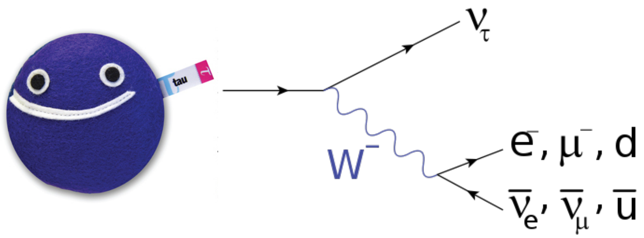
(Result also combined with Run 1)

Analysis Strategy

(1) Categorize into three di-τ decay channels

- dileptonic, leptonic-hadronic and di-hadronic
- different dominant backgrounds





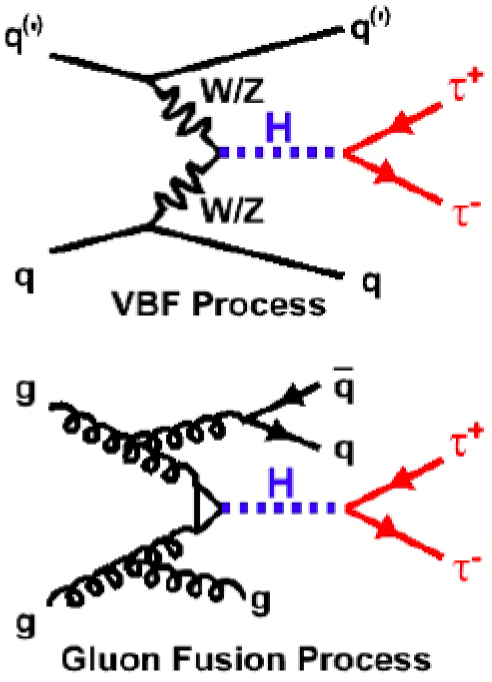
Analysis Strategy

(1) Categorize into three di-τ decay channels

(2) Require basic event selection to suppress backgrounds

- Isolated leptons & identified τ to suppress background from misidentified objects
- p_T cuts as low as trigger allows → configuration of di-hadronic trigger challenging!
- Kinematic requirements to suppress main backgrounds: Z/W+jets, $t\bar{t}$

Analysis Strategy



(1) Categorize into three di-τ decay channels

(2) Require basic event selection to suppress backgrounds

(3) Kinematically separate two production modes (VBF vs. ggF)

- VBF: require 2 jets at high-rapidity / high m_{jj}
- ggF: require high $p_T(\tau\tau)$ to improve signal sensitivity

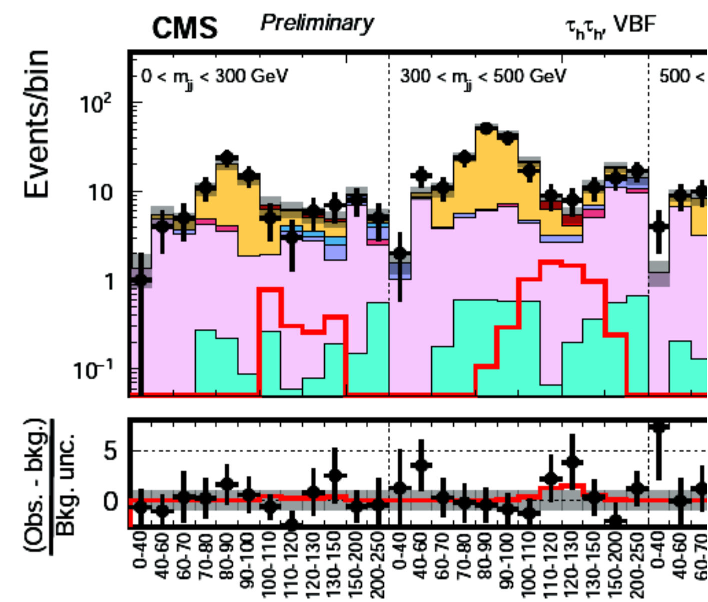
Analysis Strategy

(1) Categorize into three di-τ decay channels

(2) Require basic event selection to suppress backgrounds

(3) Kinematically separate two production modes (VBF vs. ggF)

(4) Further selection into regions of varying signal sensitivity



CMS:
Profile Likelihood fit to "unrolled" $\tau\tau$ mass in 12 signal regions

	In-situ bkg calibration / 0-jet	Boosted / 1-jet	VBF / 2-jet
lep-lep	$p_T(\mu)$ vs. m_{vis}	$p_T(\tau\tau)$	$m(jj)$
lep-had	Decay mode vs. m_{vis}	vs	vs
had-had	$m(\tau\tau)$ (1-dim)	$m(\tau\tau)$	$m(\tau\tau)$

0-jet:

- Choose fit variables to constrain backgrounds well, esp. simulated $Z \rightarrow \tau\tau$
- Better separation of $Z \rightarrow ll$ in m_{vis}

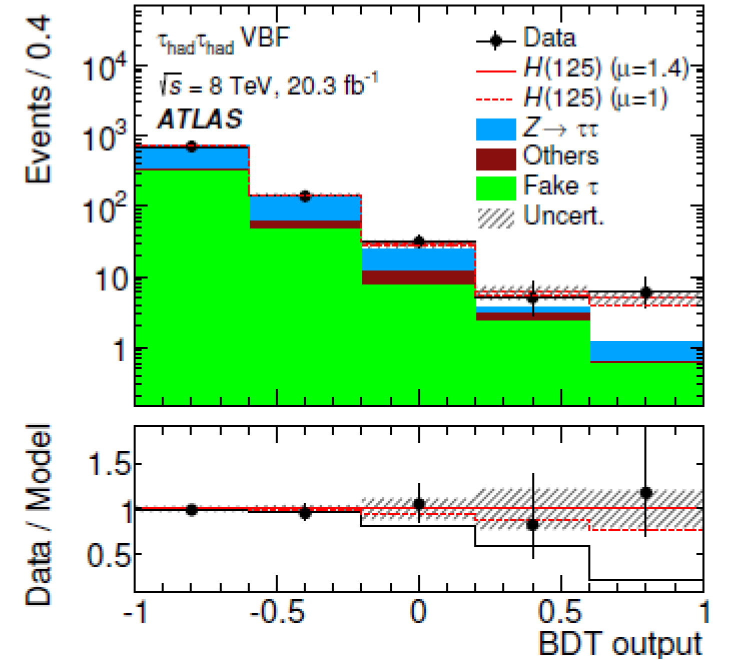
Analysis Strategy

(1) Categorize into three di-τ decay channels

(2) Require basic event selection to suppress backgrounds

(3) Kinematically separate two production modes (VBF vs. ggF)

(4) Further selection into regions of varying signal sensitivity



ATLAS:
Train 6 separate kinematic BDTs that include ττ mass
Profile Likelihood fit to each BDT distribution

	Rest: Not Boosted Not VBF	Boosted: Large $p_T(\tau\tau)$ to suppress $Z\rightarrow\tau\tau$	VBF: Large $\Delta\eta(jj)$
lep-lep Preselection		BDT	BDT
lep-had Preselection		BDT	BDT
had-had Preselection	Constrain $Z\rightarrow\tau\tau$ & multijets	BDT	BDT

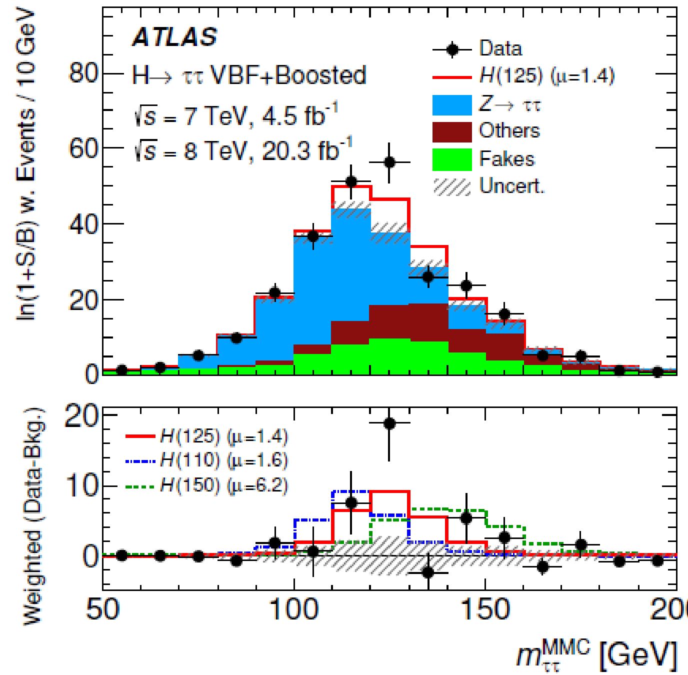
No 0-jet cat.

All major backgrounds estimated “data-driven”

Result & Backgrounds

Major backgrounds:

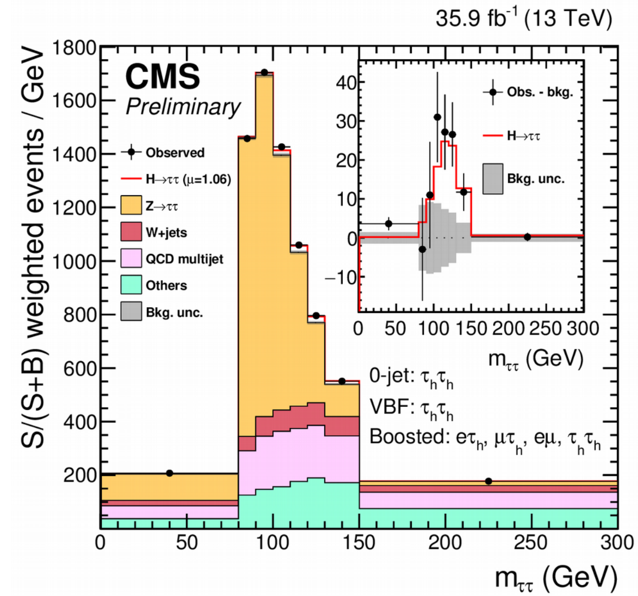
- $Z \to \tau\tau$
- Multijets
- W+jets
- $t\bar{t}$ (in eμ channel only)

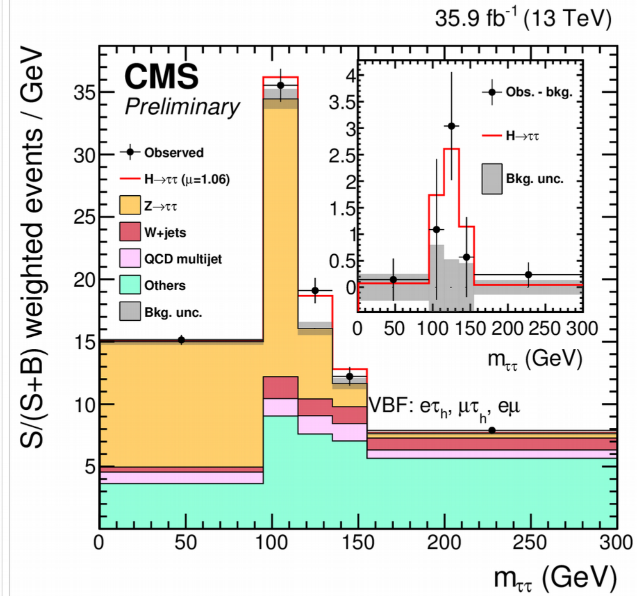


Different techniques in both experiments

→ Different resulting systematic uncertainties

(For ATLAS focus on MVA strategy, not cut-based)



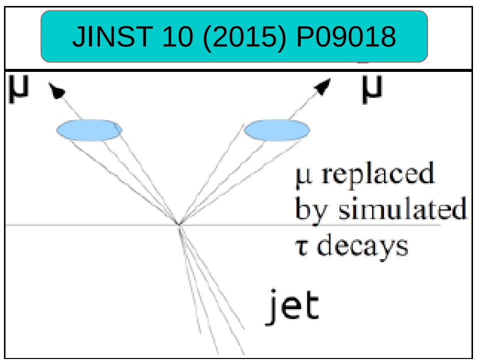


Z→ττ Background

Dominant in all regions/channels & irreducible

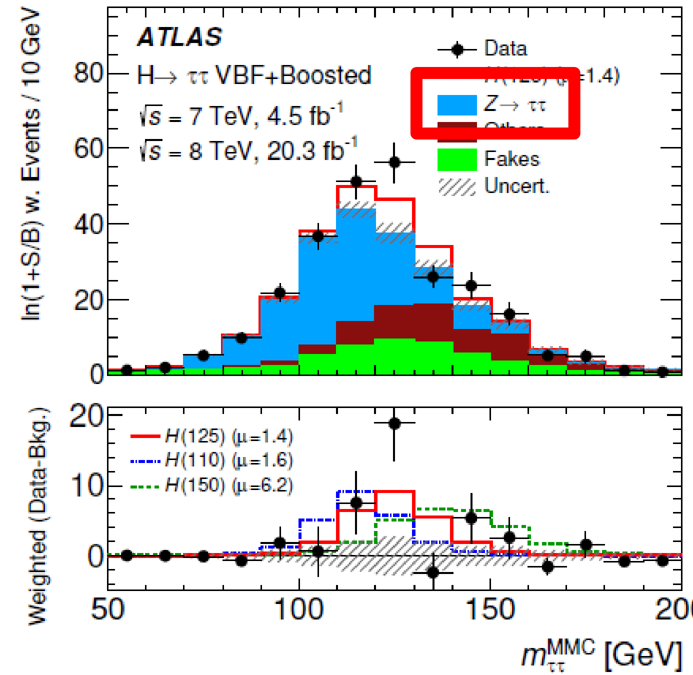
ATLAS

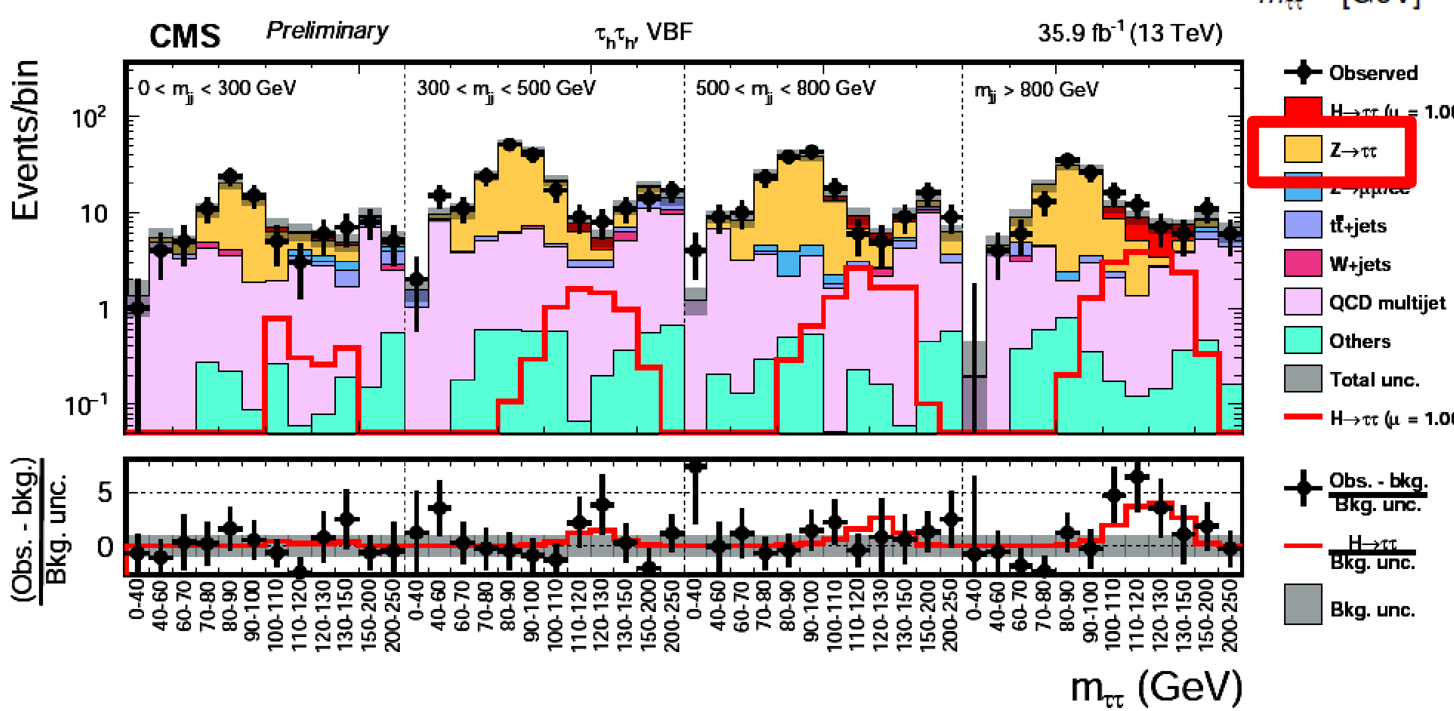
“Embedding” technique using Z→μμ data



CMS

Simulated Z→ττ corrected for Z-boson kinematics & jets using Z→μμ control region (Run 1 analysis also used “embedding”)





Backgrounds – Multijets

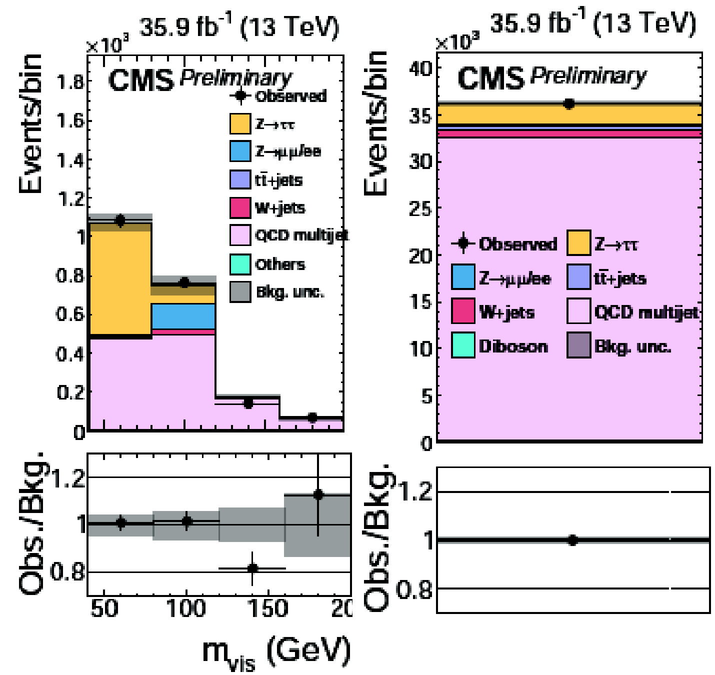
Major bkg in lep-had & had-had channels: jets misidentified as τ

lep-had

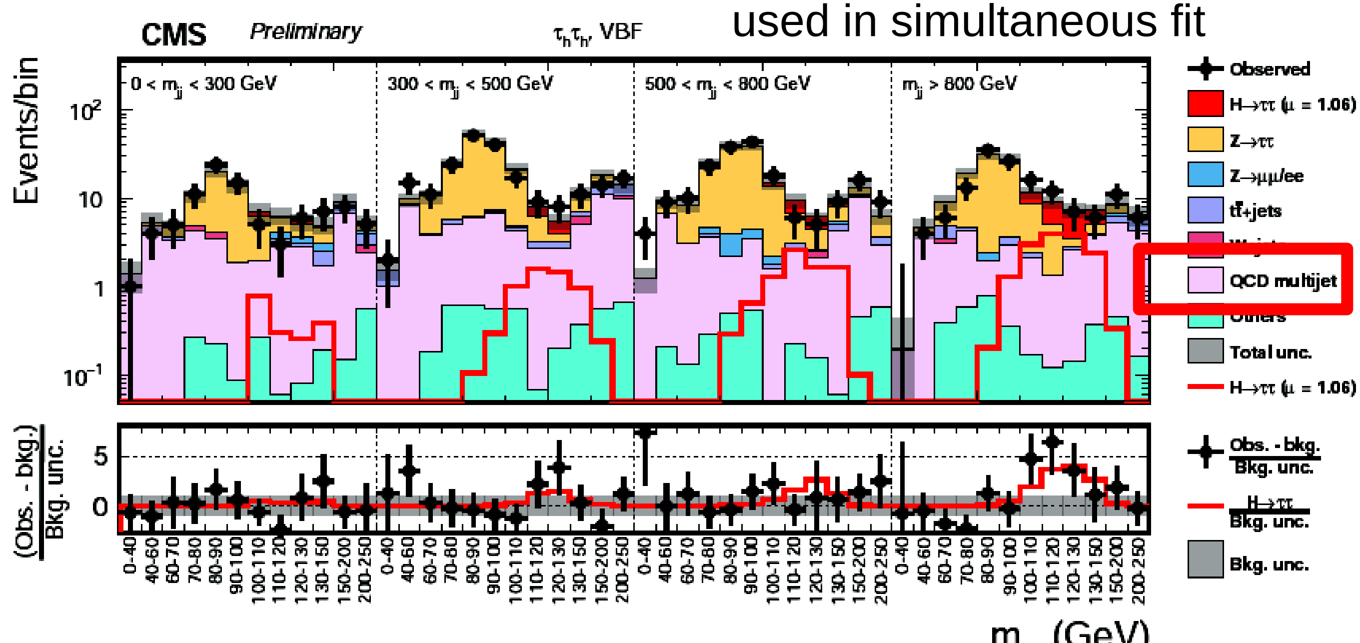
- Shape & normalization estimated from inverting opposite-sign requirement
- Scale factor to opposite-sign region from events in 0-jet and boosted categories with relaxed identification on l and τ

had-had

- Shape & normalization from events with relaxed identification on τ
- Scale factor to nominal identification from events with same-sign requirement in each category



CRs with relaxed identification used in simultaneous fit



W+jets, $t\bar{t}$ Backgrounds

$t\bar{t}$: dominant in lep-lep channel

W+jets & $t\bar{t}$: jet misidentified as τ, dominant in lep-had

W+jets in lep-had

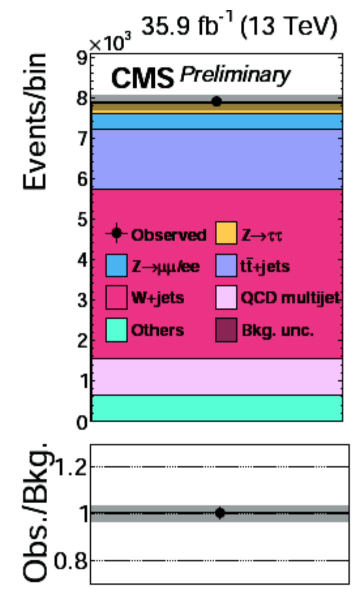
- Shape: simulation
- Normalization to data in high m_T sidebands in 0-jet and boosted

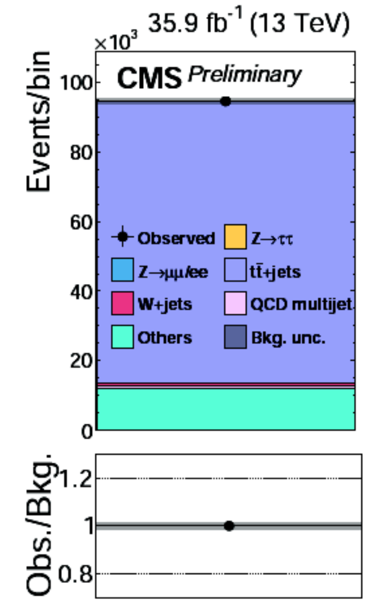
→ 4 CRs in final fit

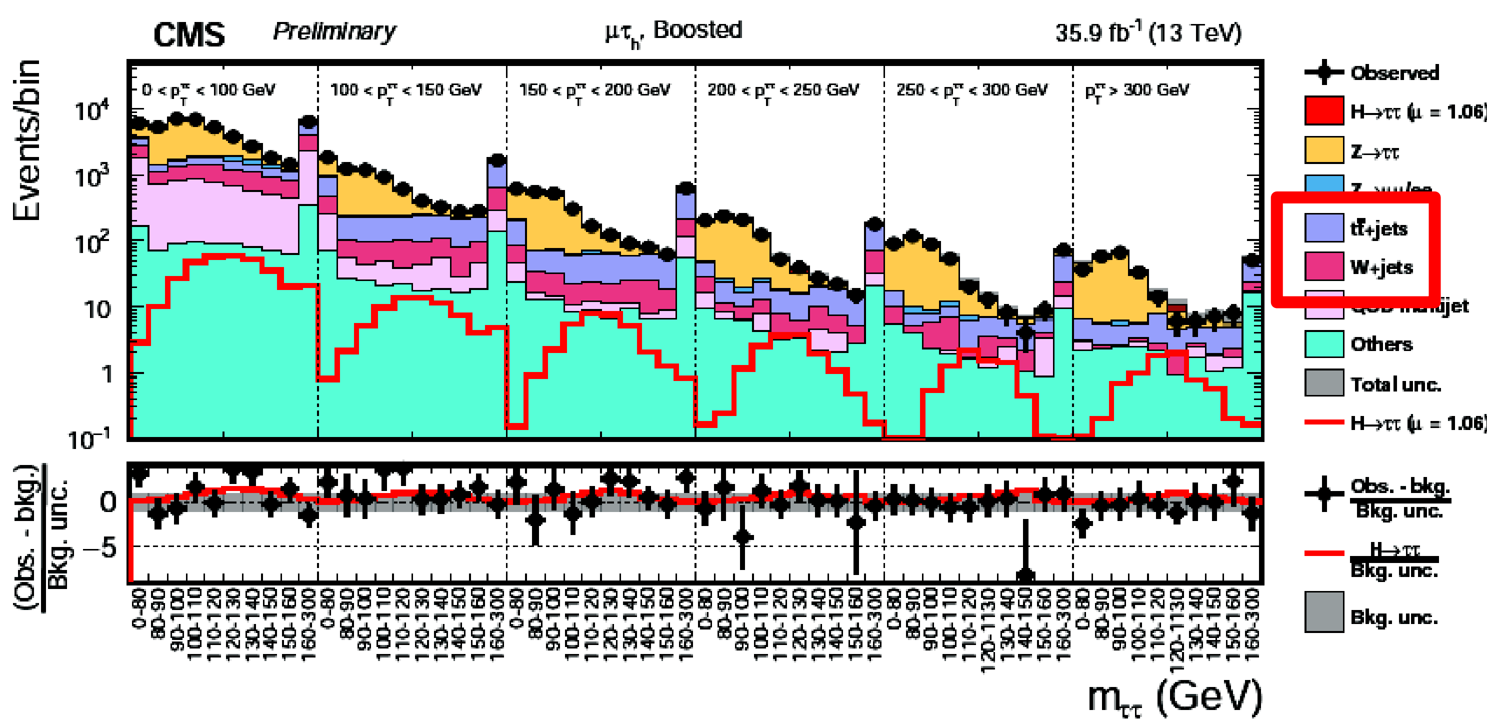
$t\bar{t}$ in lep-lep & lep-had

- Shape: simulation
- Normalization to data in kinematically selected CR in eμ channel

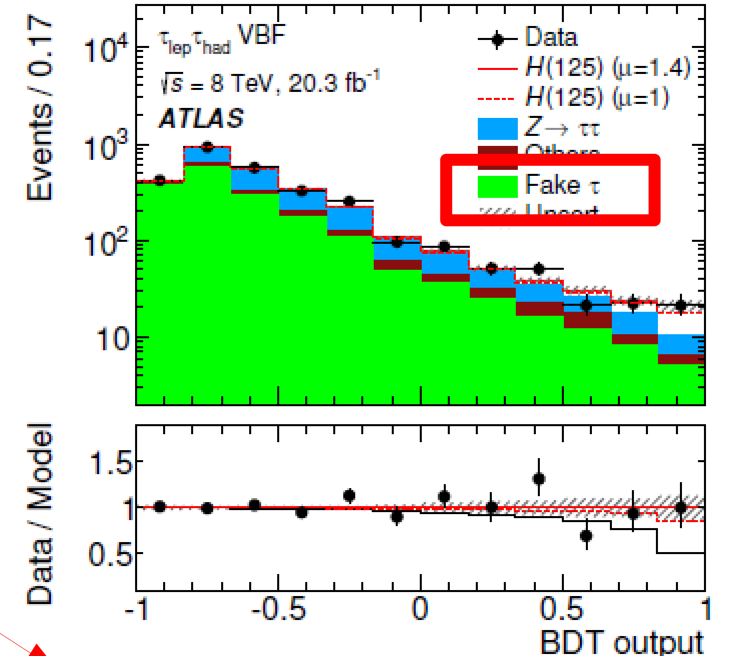
→ 1 CR in final fit







Backgrounds – Jets misidentified as τ



lep-had

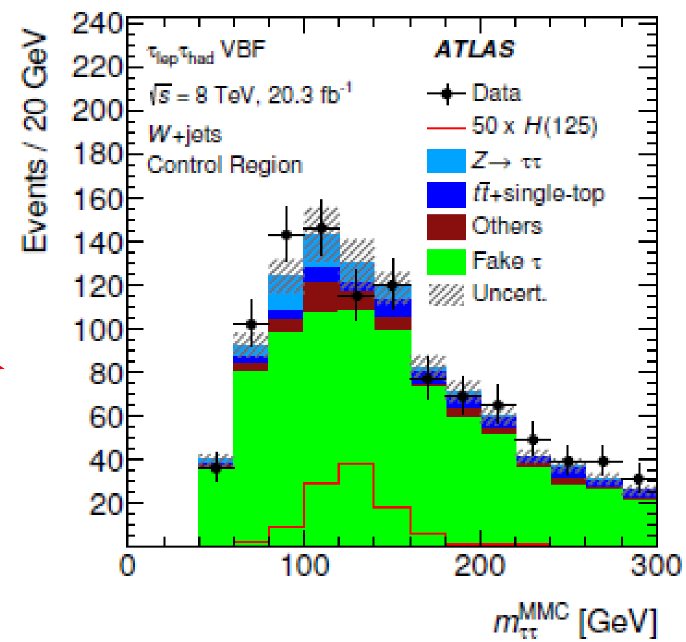
- "Fake Factor" method for all misidentified τ bkgs from multijet, Z/W+jets, $t\bar{t}$
- Extract ratio

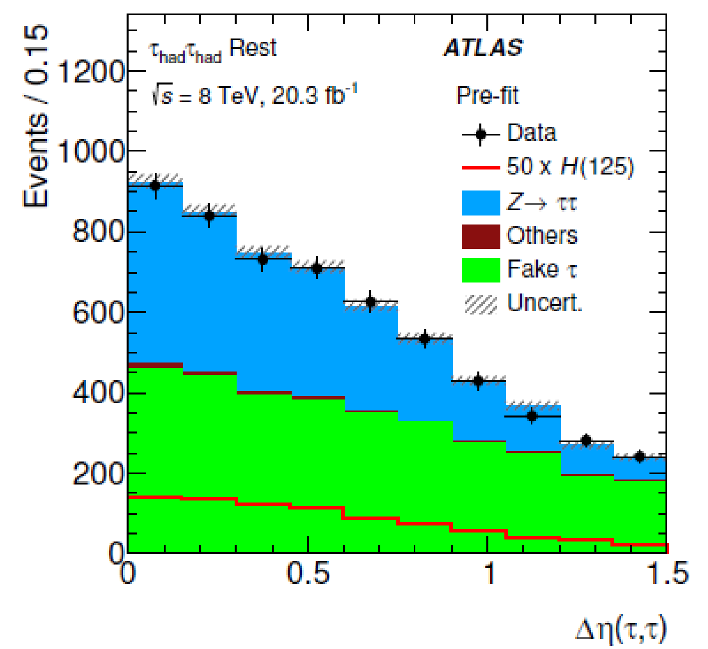
$$\frac{number\ of\ \ jets\ that\ \ pass\ \tau\ identification}{number\ of\ \ jets\ that\ fail}$$

dep. on τ kinematics in CRs enriched in each bkg source
- Apply factors in signal regions with reverted τ identification

had-had

- Shape: data with inverted τ identification & opposite-sign requirement
- Normalization: fit to Δη(τ,τ) in Rest category → included in final fit





Z+jets, $t\bar{t}$ Backgrounds with real τ

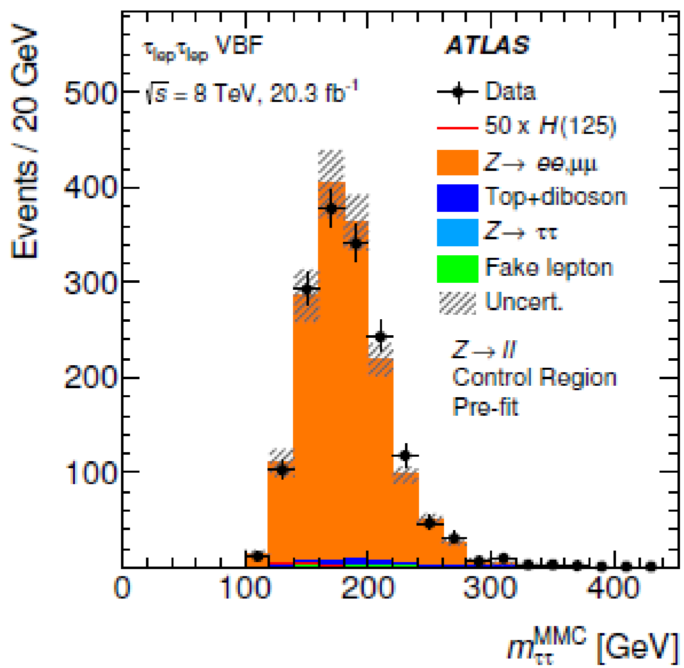
- Shape: simulation
- Normalization from high purity CRs:
  - m_{ll} consistent with Z mass
  - b-tagged jet requirement

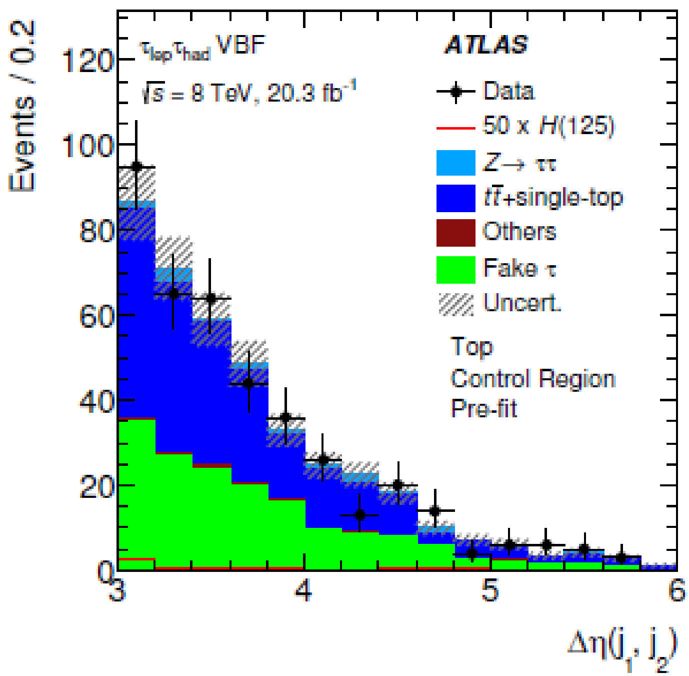
lep-lep

$t\bar{t}$ and Z+jets → real leptons from τ

lep-had

$t\bar{t}$ with real lepton + τ





Systematic Uncertainties

Source of uncertainty	Magnitude	
	Prefit	Postfit
τ_h energy scale	1.2% on energy scale	0.2-0.3%
e energy scale	1-2.5% on energy scale	0.2-0.5%
e misidentified as τ_h energy scale	3% on energy scale	0.6-0.8%
μ misidentified as τ_h energy scale	1.5% on energy scale	0.3-1.0%
Jet energy scale	27 sources, event-by-event	-
E_T^{miss} energy scale	Event-by-event	-
τ_h ID & isolation	5% per τ_h	3.5%
τ_h trigger	5% per τ_h	3%
τ_h reconstruction per decay mode	3% migration between decay modes	2%
e ID & isolation & trigger	2%	-
μ ID & isolation & trigger	2%	-
e misidentified as τ_h rate	12% per τ_h decay mode	5%
μ misidentified as τ_h rate	25% per τ_h decay mode	3-8%
Jet misidentified as τ_h rate	20% per 100 GeV τ_h p_T	15%
$Z \to \tau\tau/\ell\ell$ estimation	Normalization: 7-15%	3-15%
	Uncertainty on $m_{\ell\ell/\tau\tau}$, $p_T(\ell\ell/\tau\tau)$, and m_{jj} corrections	-
W + jets estimation	Normalization, eμ and $\tau_h\tau_h$: 4-20%	-
	Extrap. from high-m_T region, eτ_h and $\mu\tau_h$: 5-10%	-
	Unc. from CR, eτ_h and $\mu\tau_h$: $\simeq 5-15\%$	-
QCD multijet estimation	Normalization, eμ: 10-20%	5-20%
	Unc. from CR, eτ_h, $\tau_h\tau_h$, and $\mu\tau_h$: $\simeq 5-15\%$	-
	Extrap. from anti-iso. region, eτ_h and $\mu\tau_h$: 20%	7-10%
	Extrap. from anti-iso. region, $\tau_h\tau_h$: 3-15%	3-10%
Signal theoretical uncertainty	Up to 20%	-

Object uncertainties strongly constrained, esp. dominant identification & energy scale
→ in agreement with dedicated perf. studies

→ Benefit from
- large number of regions, esp. 0-jet region
- multiple decay channels

"-": not further constrained

Systematic Uncertainties

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	${}^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.13
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR ($H \to \tau\tau$)	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03
Total sys.	${}^{+0.33}_{-0.26}$
Total	${}^{+0.43}_{-0.37}$

Major uncertainties:

jet & tau energy scale

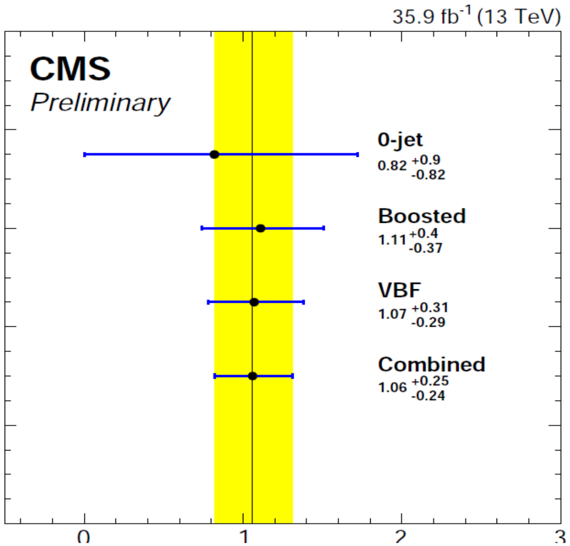
$Z \to \tau\tau$ and $t\bar{t}$ normalization

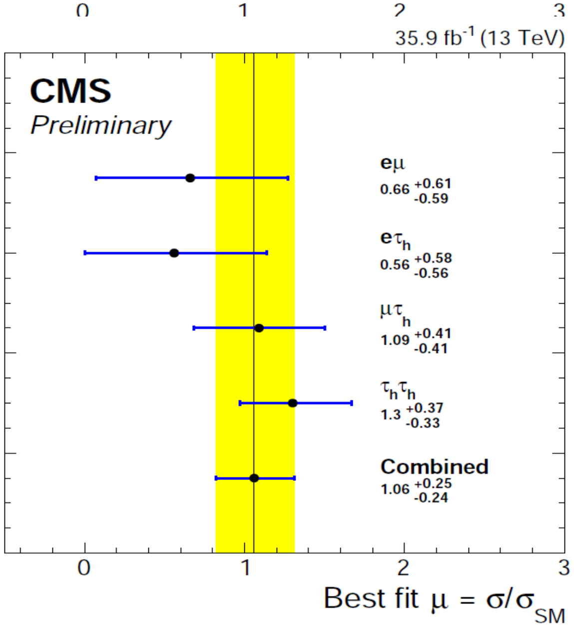
Results

CMS (Run 2): $\mu = \frac{\sigma_{meas}}{\sigma_{SM}} = 1.06 \pm 0.25$

Observed excess 4.9σ

Combined with Run 1: 5.9σ



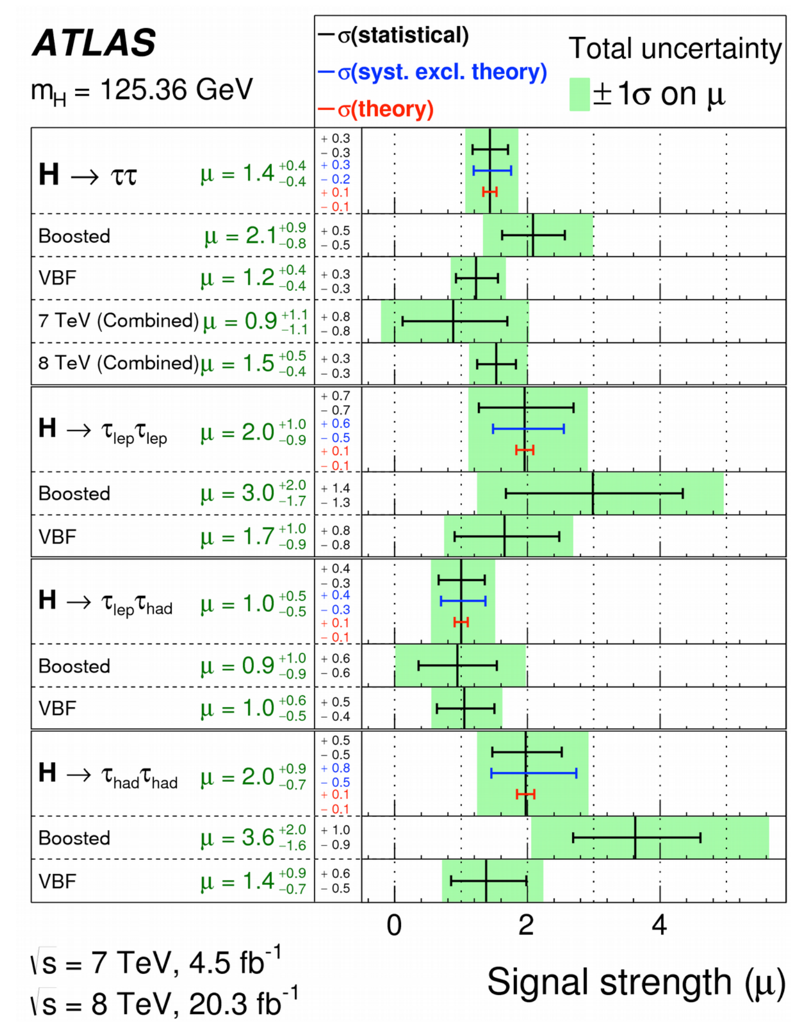


Most sensitive production mode: **VBF**

Most sensitive decay channel:
CMS: had-had
& comb. lep-had
ATLAS: lep-had

ATLAS (Run 1): $\mu = \frac{\sigma_{meas}}{\sigma_{SM}} = 1.4 \pm 0.4$

Observed excess 4.5σ

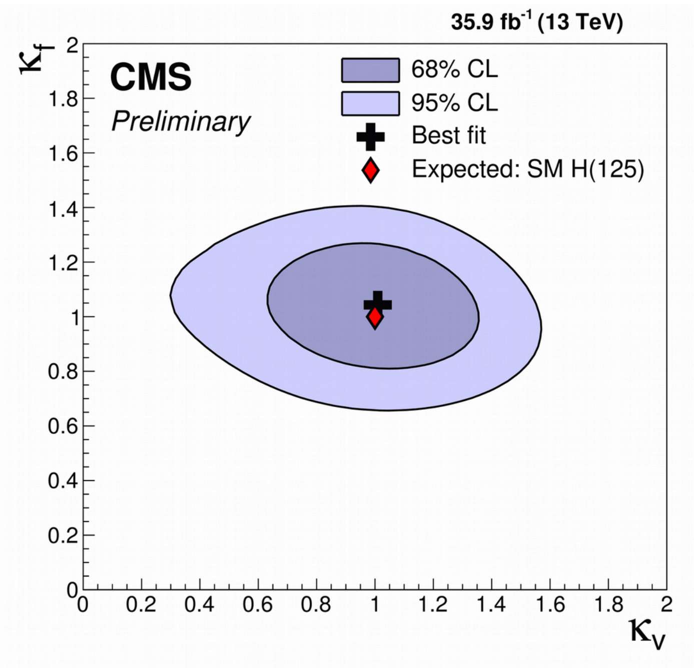


Results

Split in production mechanism:

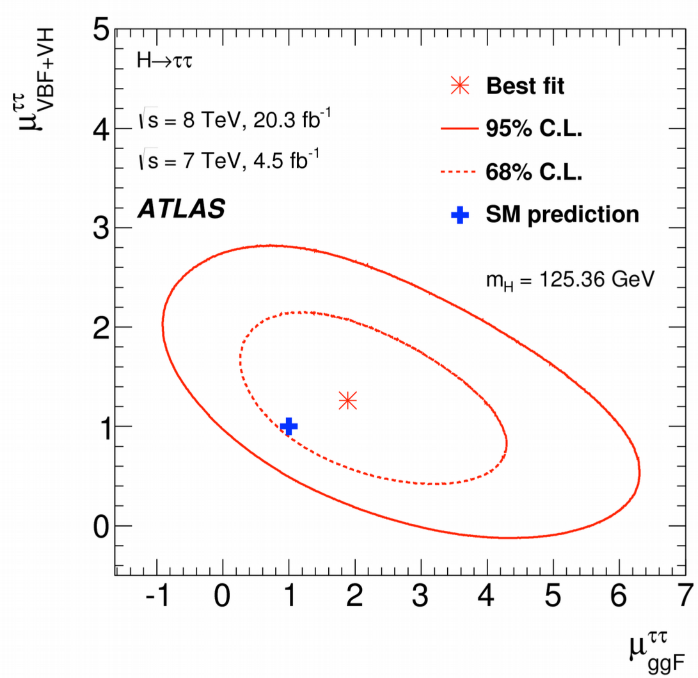
$$\kappa_f^2 \sim \mu_{ggF}^{\tau\tau}$$

$$\kappa_V^2 \sim \mu_{VBF+VH}^{\tau\tau}$$



Consistent with SM

(Note: Axes are flipped!)



Contribution from
VH production ...

… added but not
specifically targeted

… searched for in separate
analysis PRD 93 092005 (2016)

→ 95% upper limit on μ:
5.6 (exp. 3.7)

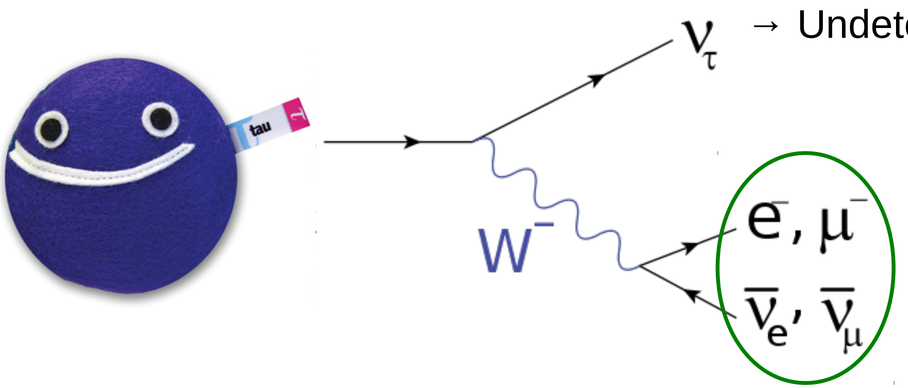
Conclusion & Outlook

- Presented SM $H \rightarrow \tau\tau$ analyses from CMS and ATLAS
- Different background estimation techniques with different impact on analysis result
- Status: CMS observed Yukawa couplings in $H \rightarrow \tau\tau$ (5.9σ combined with Run 1)
- ATLAS and CMS results consistent with SM expectations
- Looking forward to Run 2 results from ATLAS

Tau Lepton – Specifications

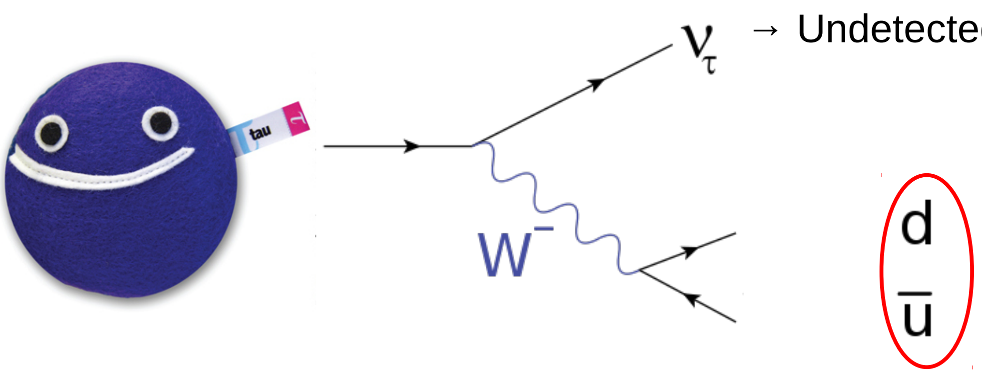
- Mass ~ 1.8 GeV: much heavier than μ(0.105 GeV) or e(0.00511 GeV)
- Proper decay length ~ 87 μm: similar to c-quark
- Weak decays:

Decay modes:



→ Undetected

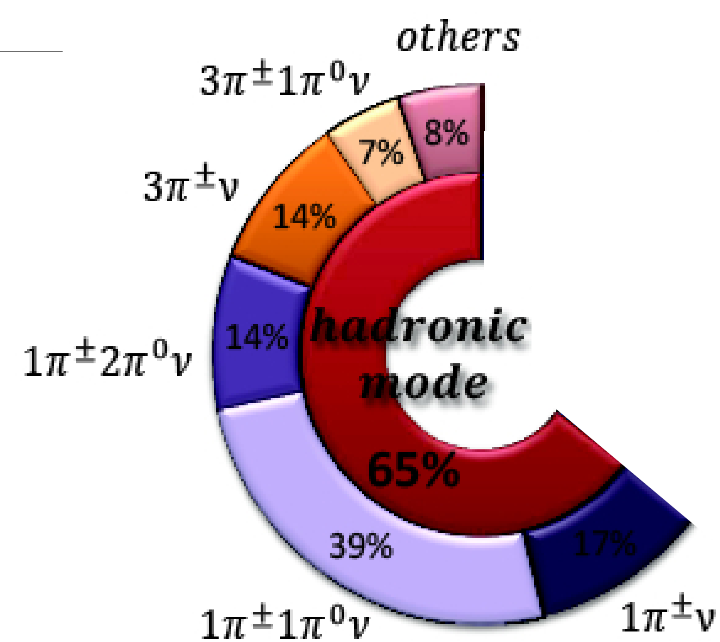
→ Leptonic modes



→ Undetected

→ Hadronic modes:

$\tau \to \pi\nu,\ \tau \to \pi\pi^0\nu,\ \dots$



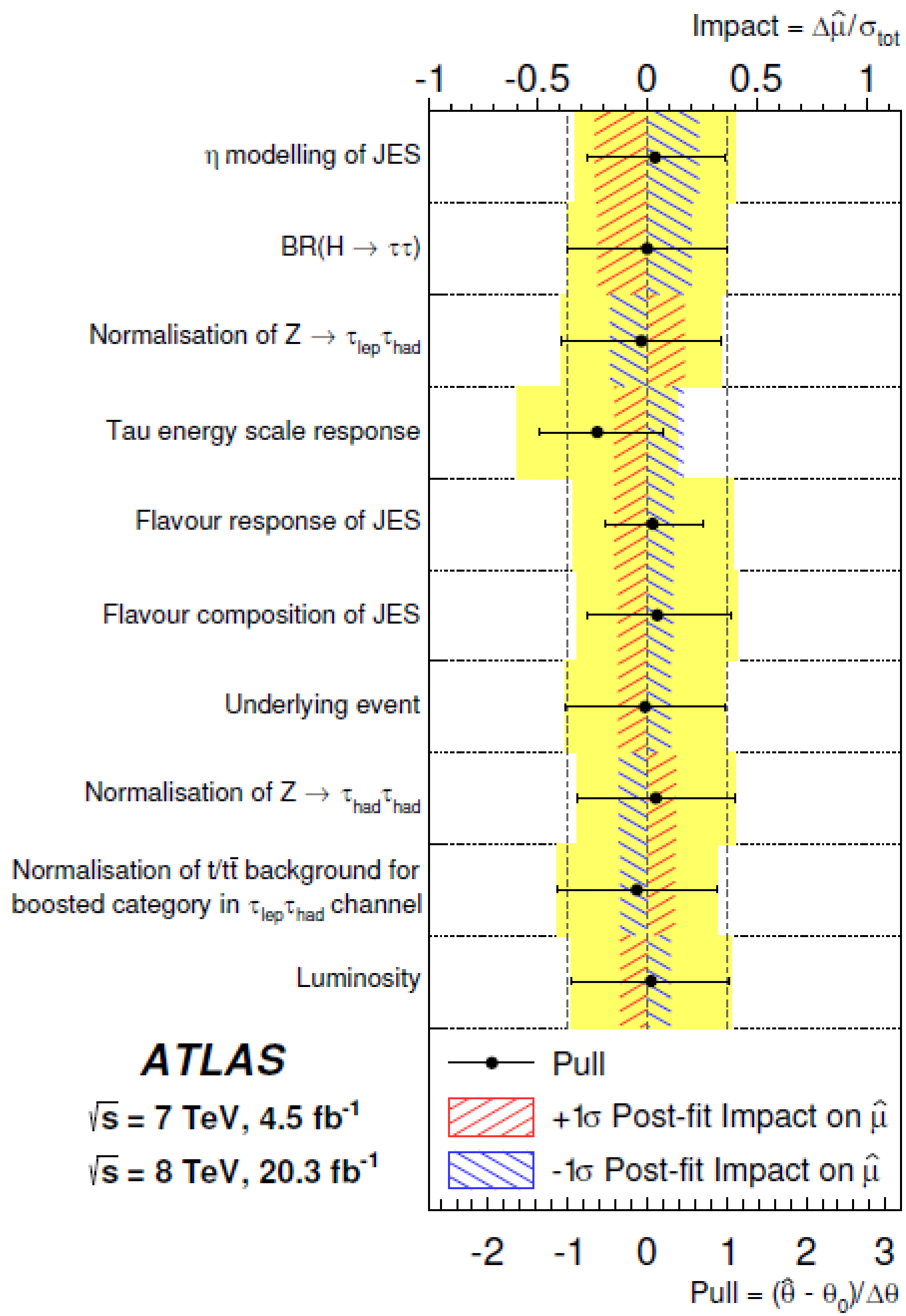
ATLAS Preselection

Channel	Preselection cuts
$\tau_{\text{lep}}\tau_{\text{lep}}$	Exactly two isolated opposite-sign leptons Events with τ_{had} candidates are rejected 30 GeV $< m_{\tau\tau}^{\text{vis}} <$ 100 (75) GeV for DF (SF) events $\Delta\phi_{\ell\ell} < 2.5$ $E_{\text{T}}^{\text{miss}} >$ 20 (40) GeV for DF (SF) events $E_{\text{T}}^{\text{miss,HPTO}} >$ 40 GeV for SF events $p_{\text{T}}^{\ell_1} + p_{\text{T}}^{\ell_2} >$ 35 GeV Events with a b-tagged jet with $p_{\text{T}} >$ 25 GeV are rejected $0.1 < x_{\tau_1}, x_{\tau_2} < 1$ $m_{\tau\tau}^{\text{coll}} > m_Z - 25$ GeV
$\tau_{\text{lep}}\tau_{\text{had}}$	Exactly one isolated lepton and one medium τ_{had} candidate with opposite charges $m_{\text{T}} <$ 70 GeV Events with a b-tagged jet with $p_{\text{T}} >$ 30 GeV are rejected
$\tau_{\text{had}}\tau_{\text{had}}$	One isolated medium and one isolated tight opposite-sign τ_{had}-candidate Events with leptons are vetoed $E_{\text{T}}^{\text{miss}} >$ 20 GeV $E_{\text{T}}^{\text{miss}}$ points between the two visible taus in ϕ, or $\min[\Delta\phi(\tau, E_{\text{T}}^{\text{miss}})] < \pi/4$ $0.8 < \Delta R(\tau_{\text{had}_1}, \tau_{\text{had}_2}) < 2.4$ $\Delta\eta(\tau_{\text{had}_1}, \tau_{\text{had}_2}) < 1.5$
Channel	VBF category selection cuts
$\tau_{\text{lep}}\tau_{\text{lep}}$	At least two jets with $p_{\text{T}}^{j_1} >$ 40 GeV and $p_{\text{T}}^{j_2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{\text{lep}}\tau_{\text{had}}$	At least two jets with $p_{\text{T}}^{j_1} >$ 50 GeV and $p_{\text{T}}^{j_2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\text{vis}} >$ 40 GeV
$\tau_{\text{had}}\tau_{\text{had}}$	At least two jets with $p_{\text{T}}^{j_1} >$ 50 GeV and $p_{\text{T}}^{j_2} >$ 30 GeV $p_{\text{T}}^{j_2} >$ 35 GeV for jets with $\|\eta\| > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$
Channel	Boosted category selection cuts
$\tau_{\text{lep}}\tau_{\text{lep}}$	At least one jet with $p_{\text{T}}>$ 40 GeV
All	Failing the VBF selection $p_{\text{T}}^{H} >$ 100 GeV

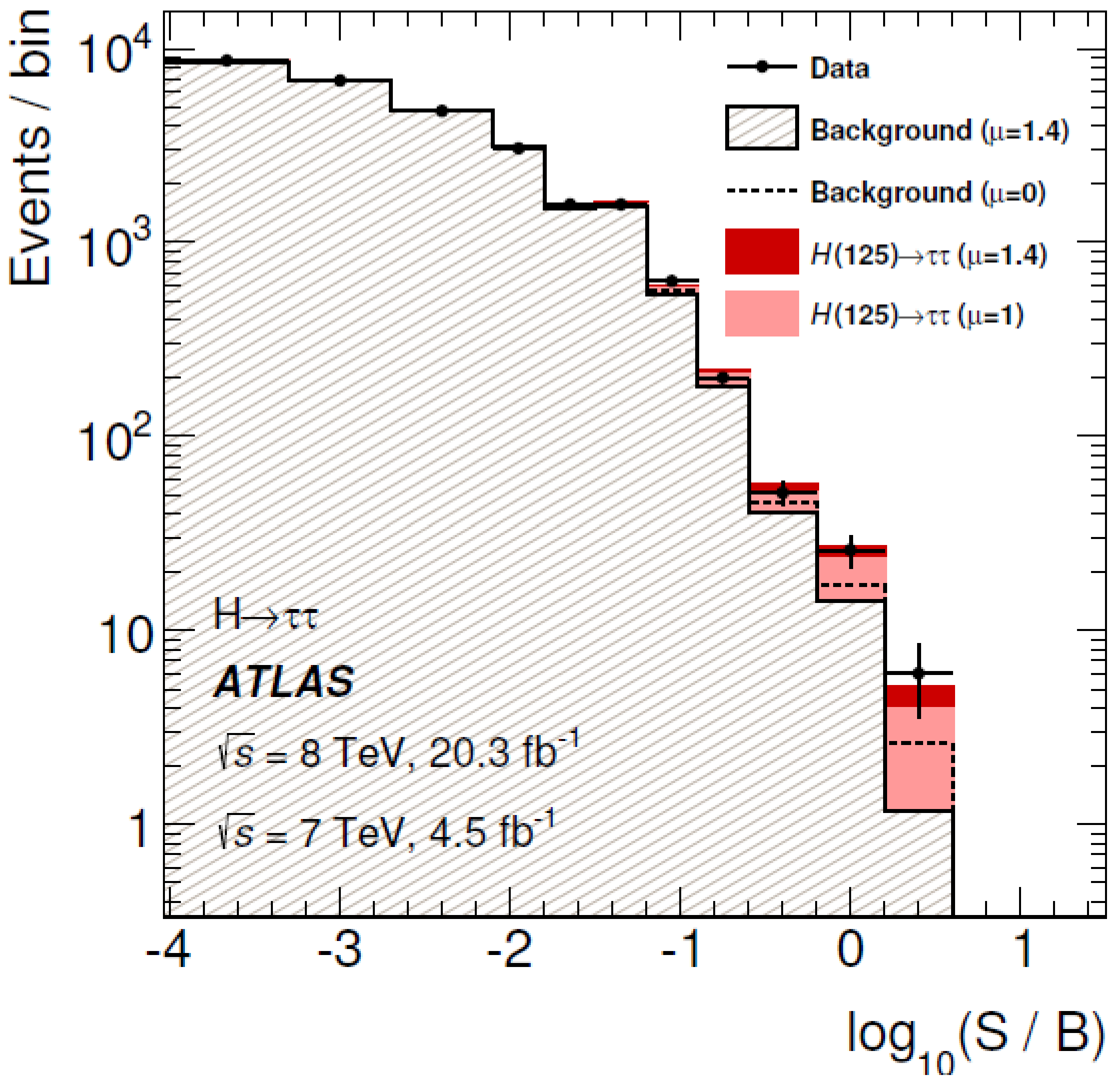
ATLAS BDT Variables

Variable	VBF			Boosted		
	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
$m_{\tau\tau}^{\mathrm{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\mathrm{T}}^{\mathrm{Total}}$		•	•			
Sum p_{T}					•	•
$p_{\mathrm{T}}^{\tau_1}/p_{\mathrm{T}}^{\tau_2}$					•	•
$E_{\mathrm{T}}^{\mathrm{miss}}\phi$ centrality		•	•	•	•	•
m_{ℓ,ℓ,j_1}				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi(\ell_1, \ell_2)$				•		
Sphericity				•		
$p_{\mathrm{T}}^{\ell_1}$				•		
$p_{\mathrm{T}}^{j_1}$				•		
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\mathrm{jets}})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	•					
$C_{\eta_1,\eta_2}(\eta_\ell)$		•				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	•					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			•			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			•			

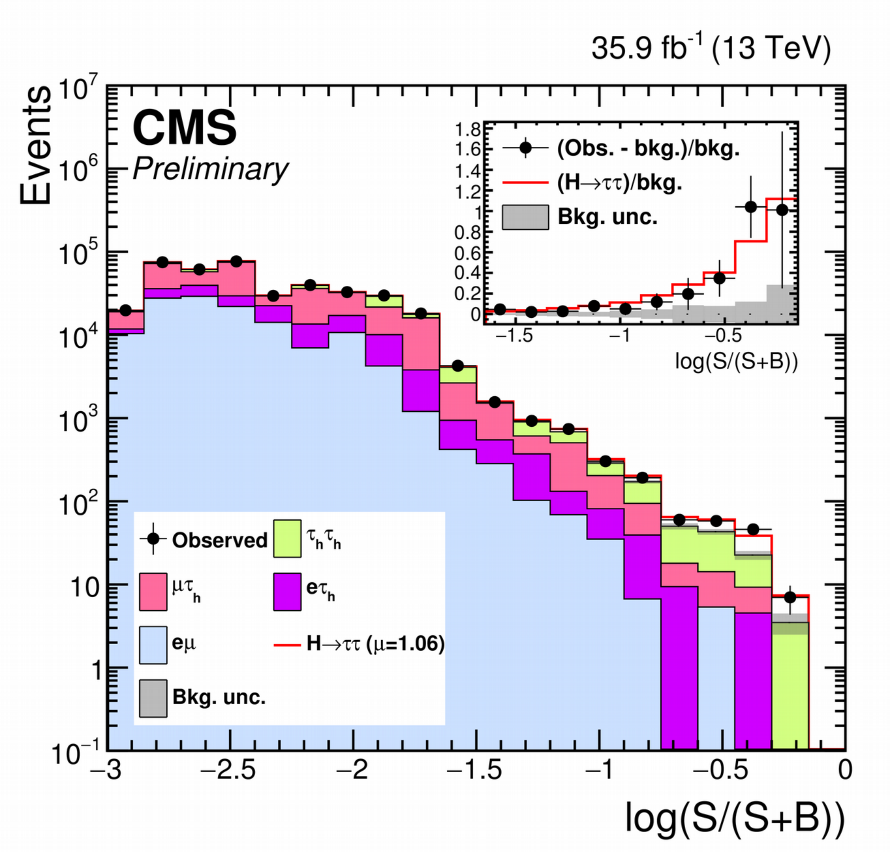
ATLAS Systematics

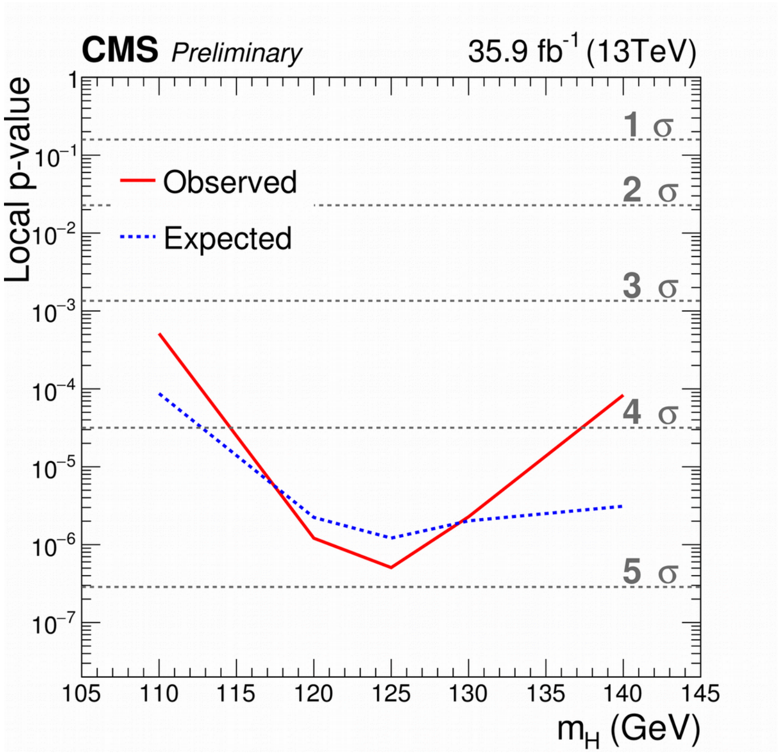


ATLAS Result (BDT)

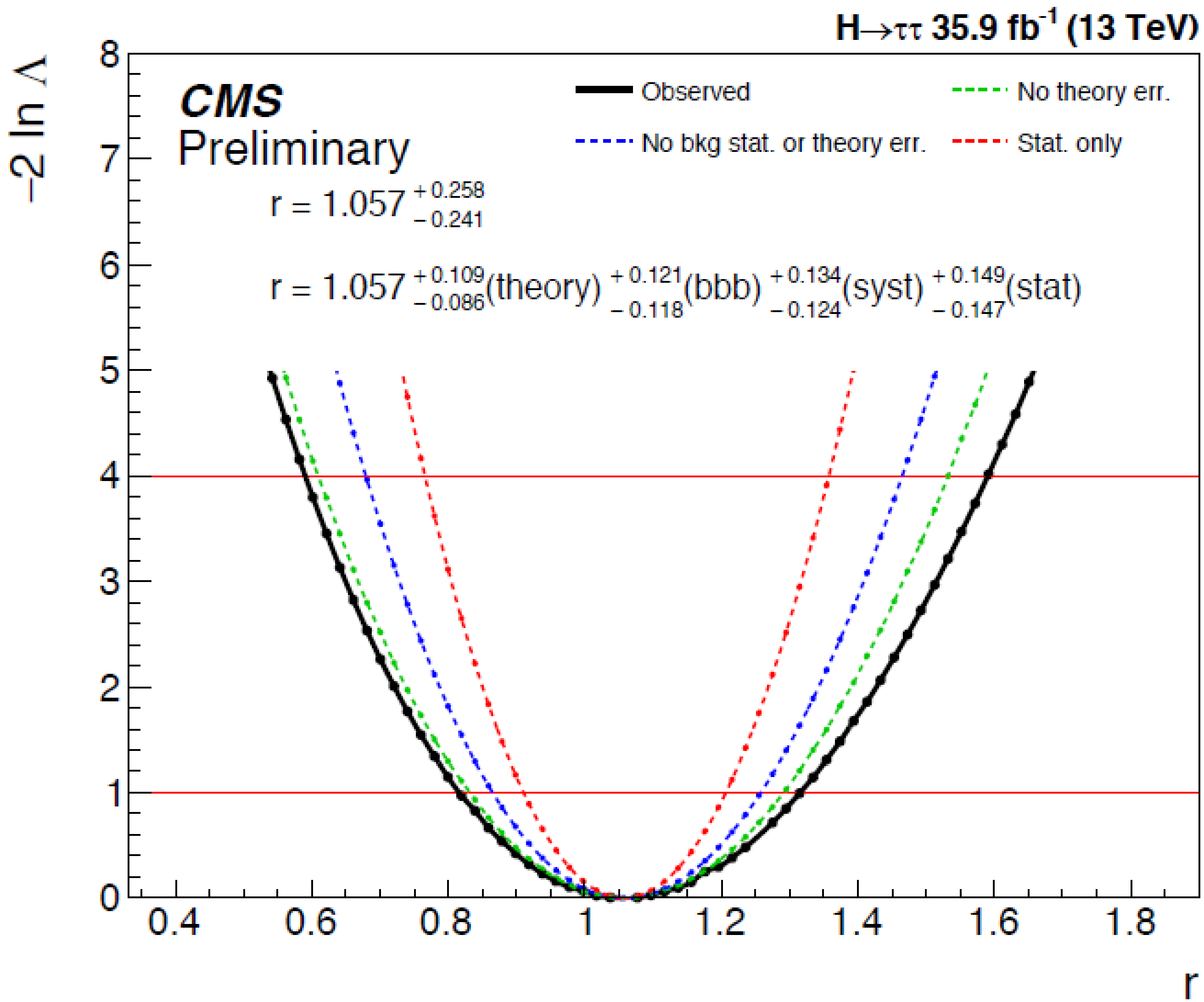


CMS Result


35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Events
(Obs. - bkg.)/bkg.
(H→ττ)/bkg.
Bkg. unc.
log(S/(S+B))
Observed
$\tau_h\tau_h$
$\mu\tau_h$
$e\tau_h$
eμ
H→ττ (μ=1.06)
Bkg. unc.
log(S/(S+B))

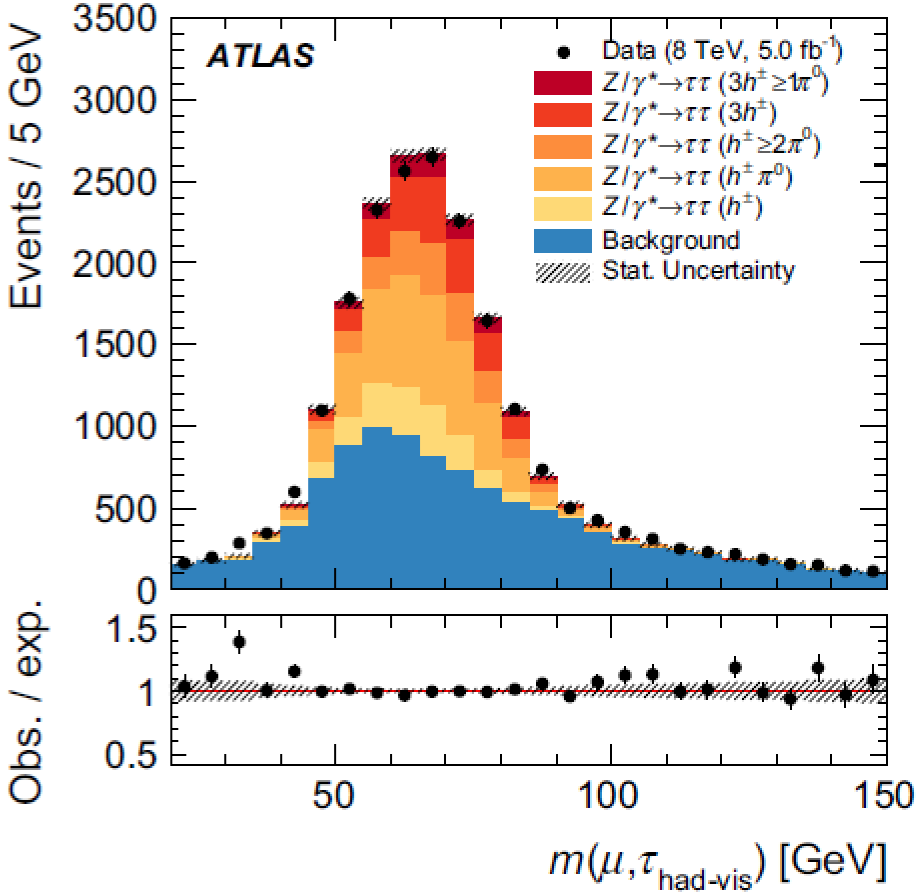

CMS Preliminary
35.9 fb^{-1} (13TeV)
Local p-value
Observed
Expected
1 σ
2 σ
3 σ
4 σ
5 σ
m_H (GeV)

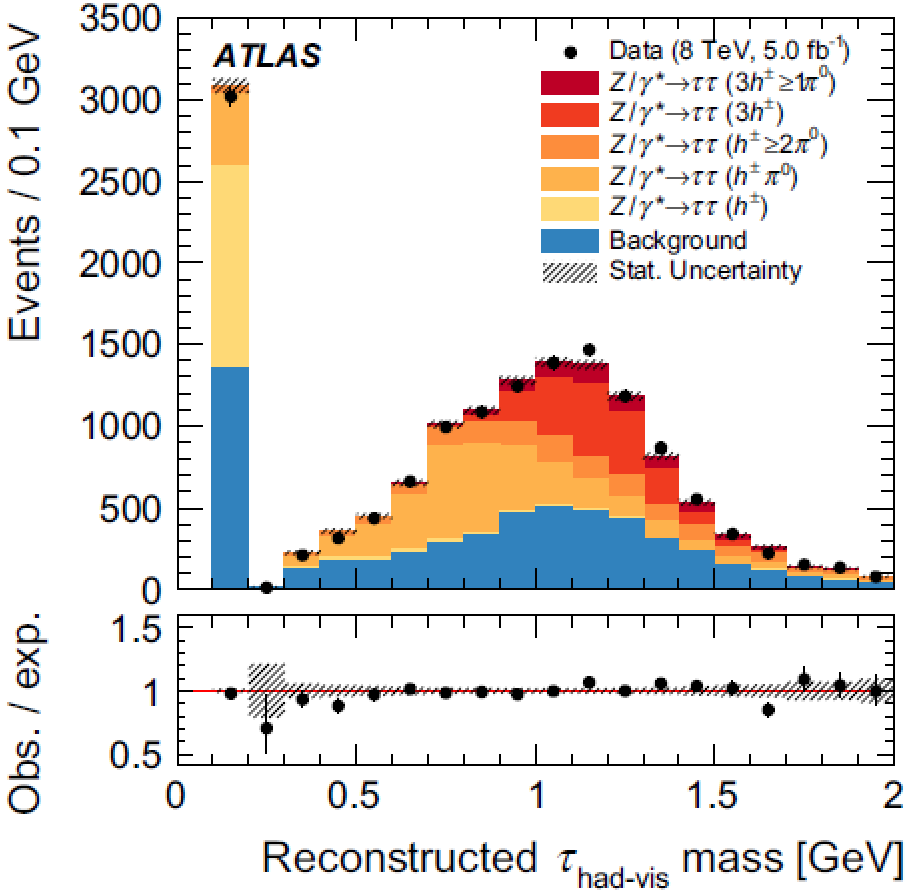
CMS Result



H→ττ 35.9 fb-1 (13 TeV)
CMS
Preliminary
r = 1.057 +0.258 −0.241
r = 1.057 +0.109 −0.086 (theory) +0.121 −0.118 (bbb) +0.134 −0.124 (syst) +0.149 −0.147 (stat)
Observed
No theory err.
No bkg stat. or theory err.
Stat. only
−2 ln Λ
r
0
1
2
3
4
5
6
7
8
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

ATLAS Particle Flow details





ATLAS Particle Flow details