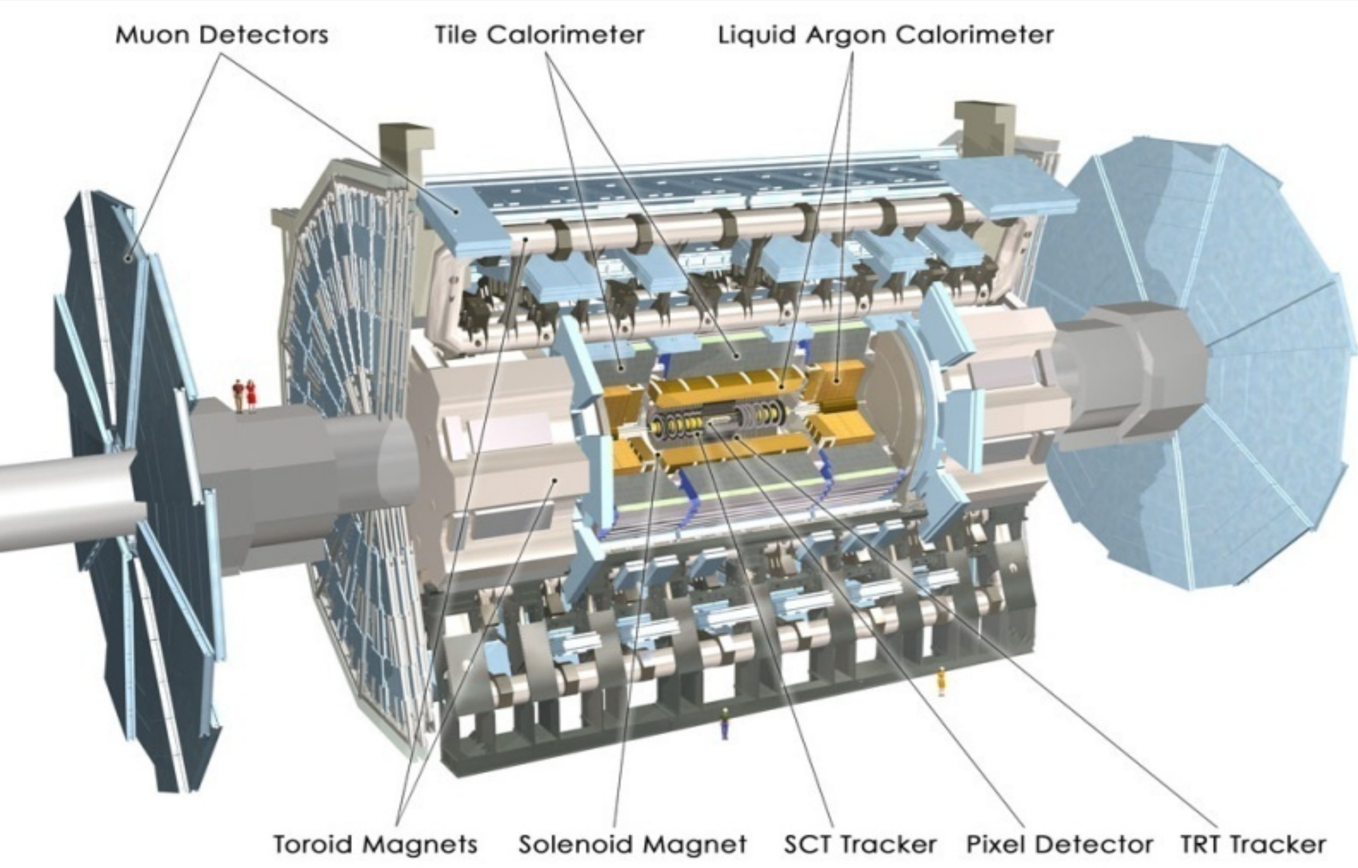
125 GeV Higgs at the LHC: $h \rightarrow \tau\tau, \mu\mu$

Harald Fox, Lancaster University
On behalf of the ATLAS and CMS collaborations

Higgs and Beyond
Tohoku Workshop on Higgs and Beyond

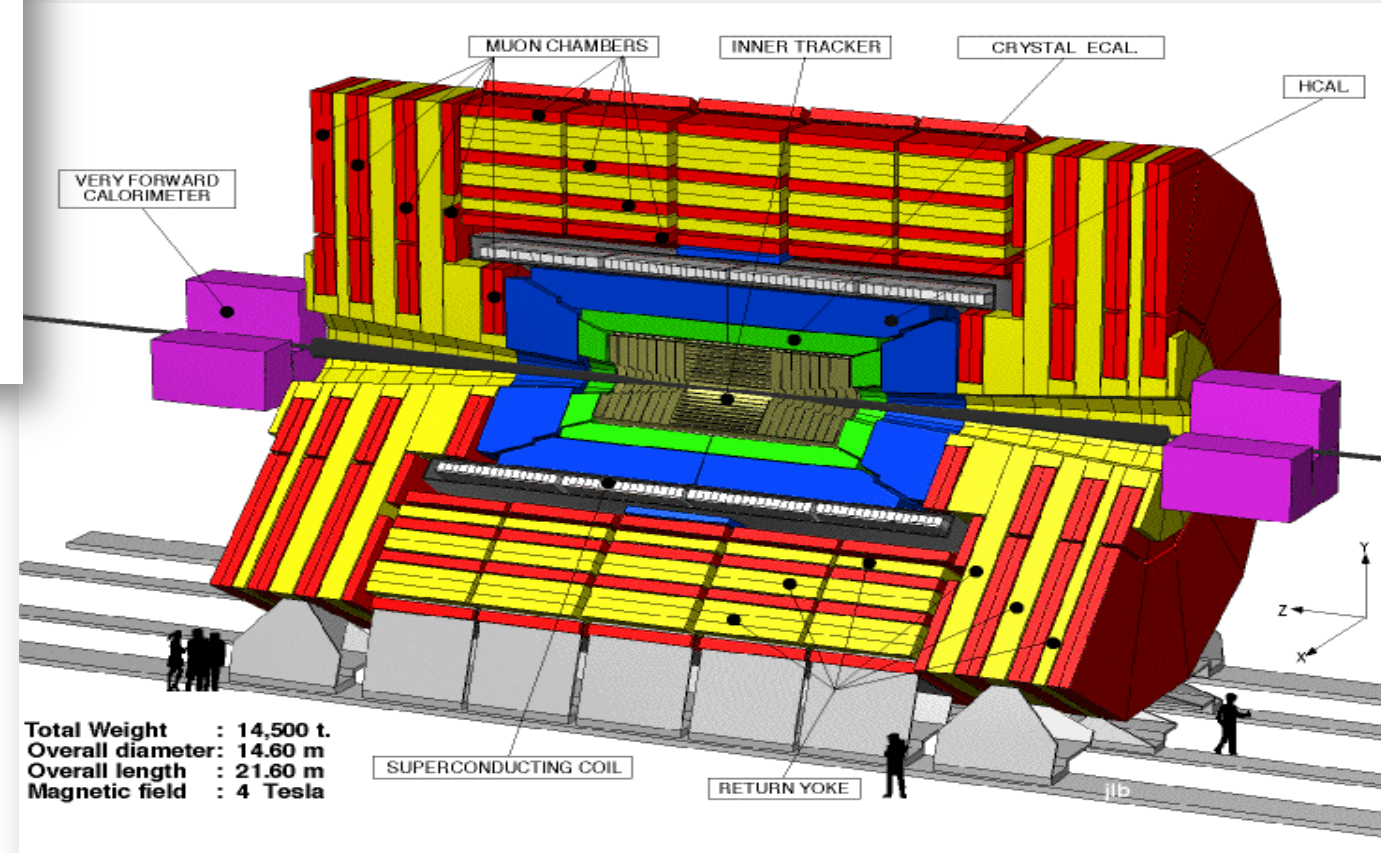
Detectors & Luminosity

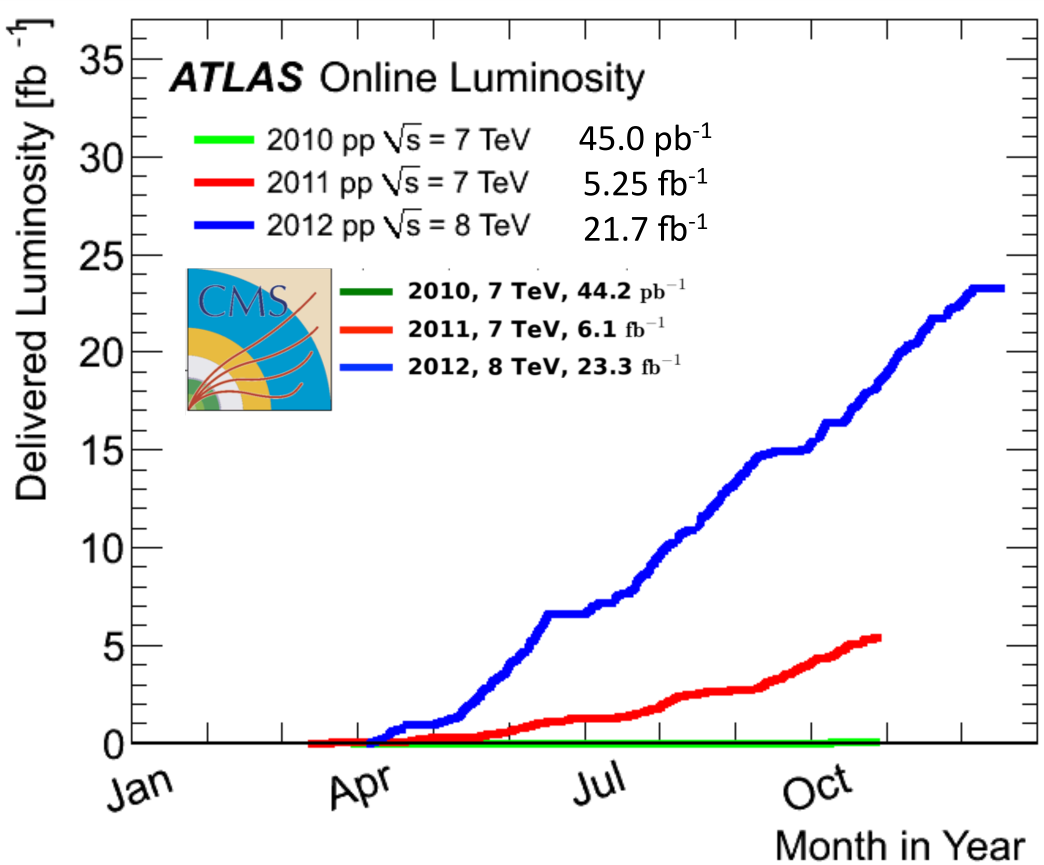


Good operational status: > 95% of channels working!

Overall data taking efficiency > 90 %

~90% of data taken with all sub-detectors fully operational





ATLAS $H\to\tau\tau$ 4.6+13fb^{-1}

CMS $H\to\tau\tau$ 4.9+19.4fb^{-1}

ATLAS $H\to\mu\mu$ 20.7fb^{-1}

Higgs Production & Decay Modes

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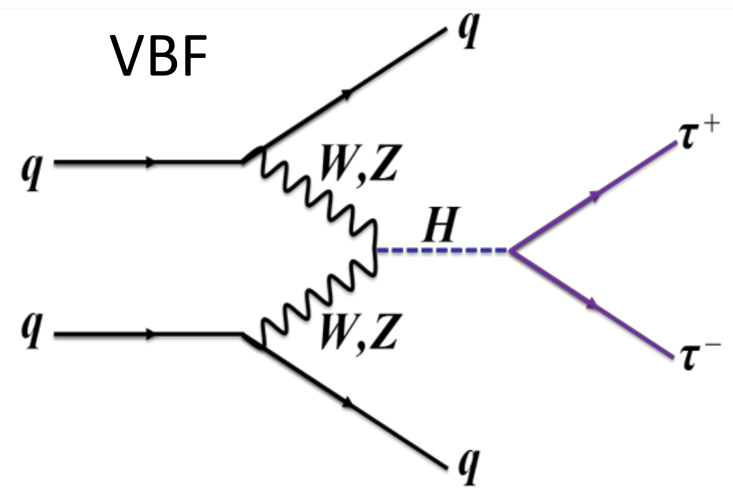
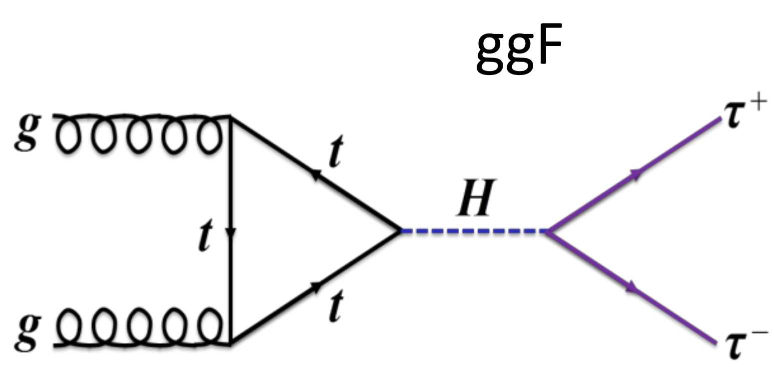
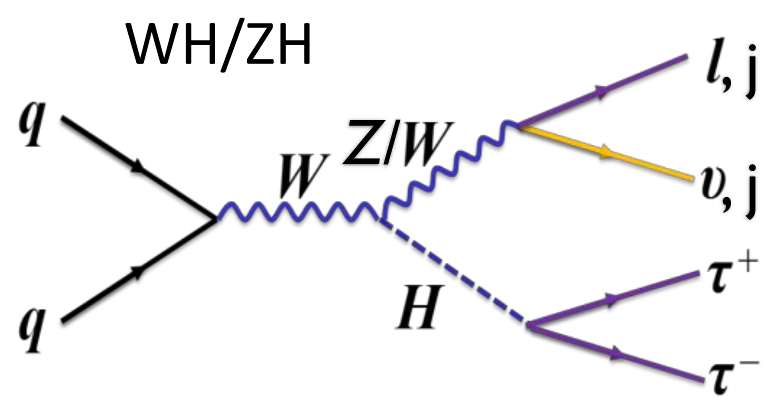
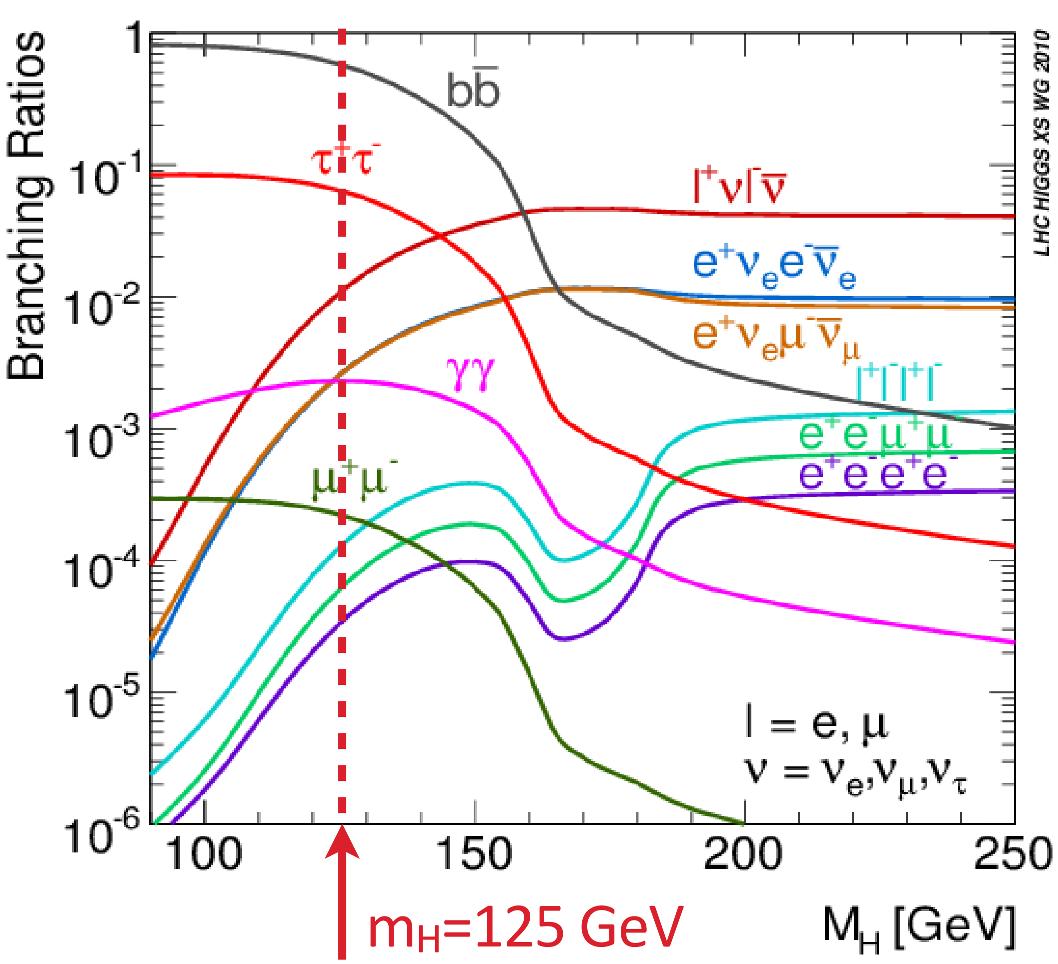
$H \rightarrow \tau\tau$ most sensitive channel for Vector Boson Fusion production (VBF)









- Most sensitive channel with fermions in the final state
  - Measuring the Yukawa couplings determines the true nature of the Higgs like boson
  - $BR(H \rightarrow \tau\tau) = (6.3 \pm 0.4)\%$ m_H=125 GeV
  - $BR(H \rightarrow \mu\mu) = (0.022 \pm 0.001)\%$ m_H=125 GeV

H → ττ Backgrounds

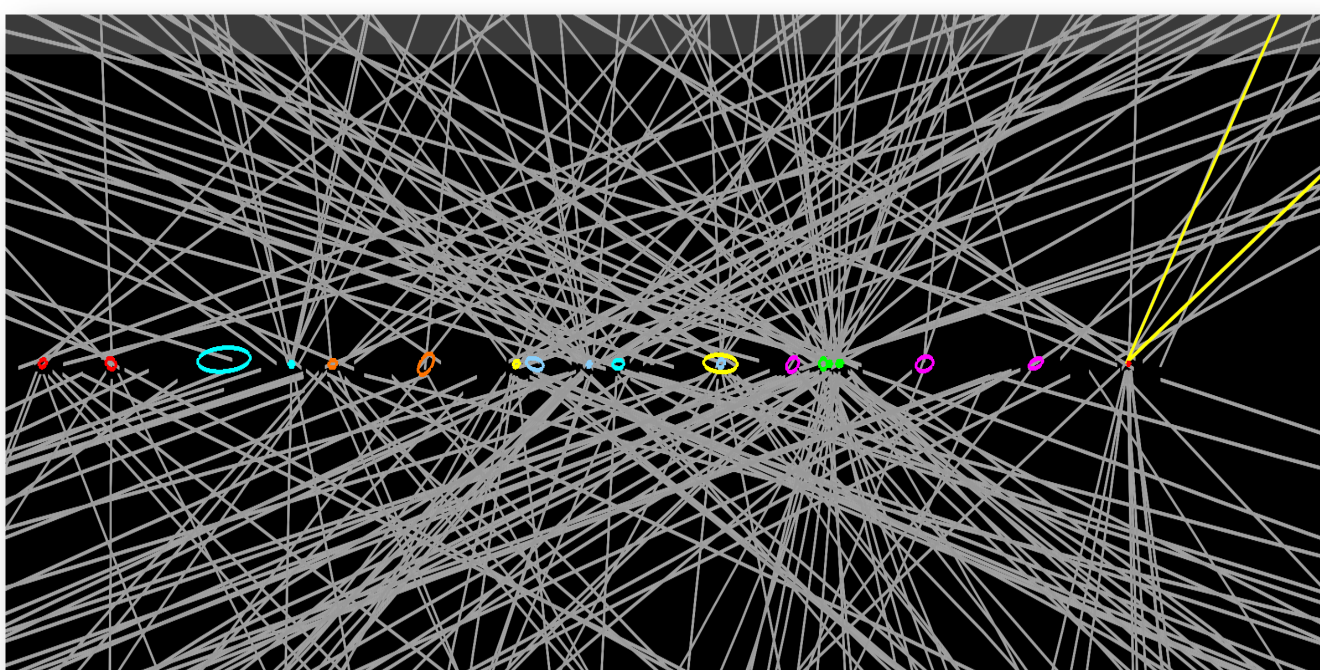
Most important background is from Z→ττ

- factor ×1000 higher cross section

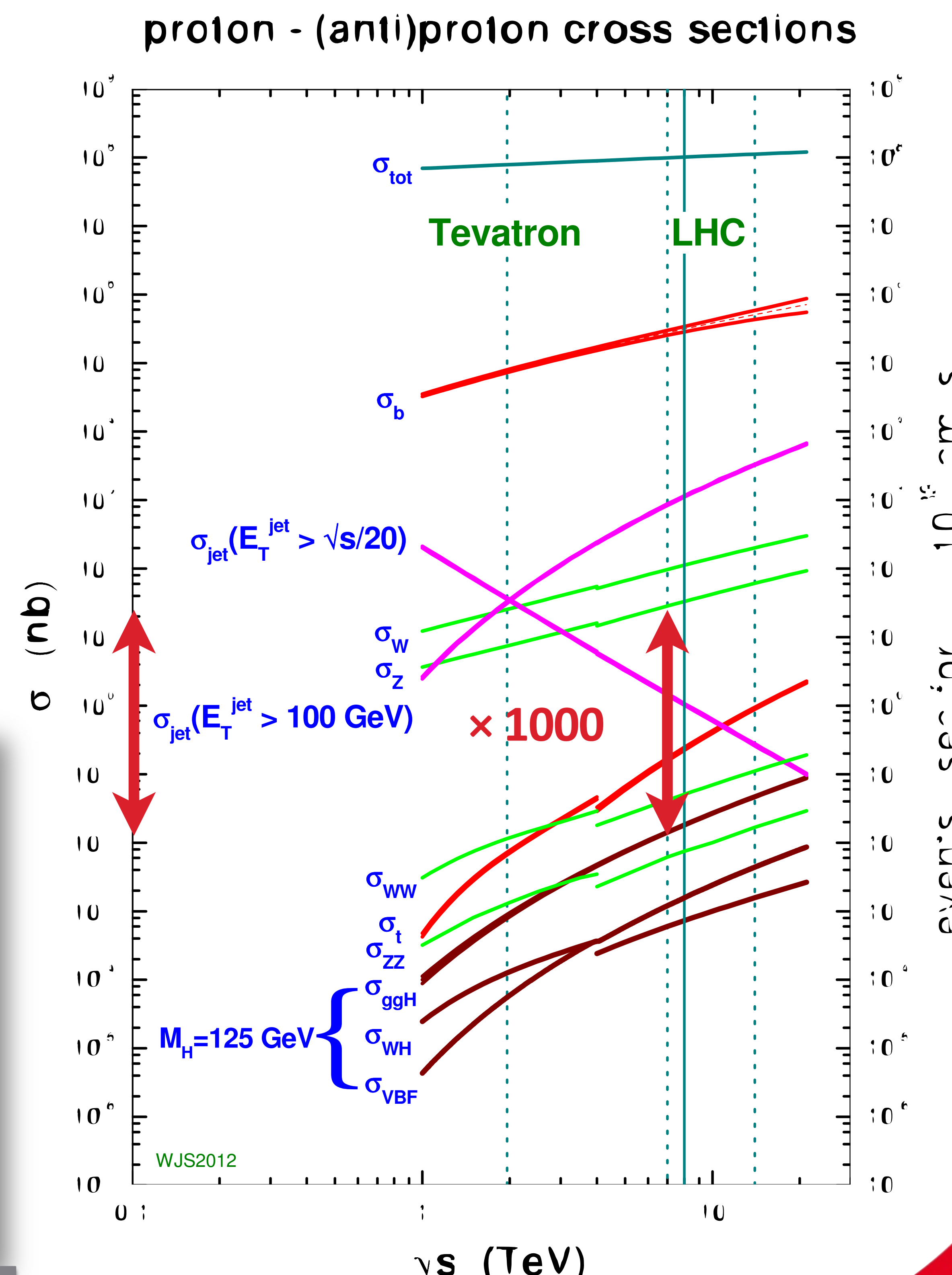
QCD jet production faking hadronic taus.

Top and di-boson production

Background from pileup

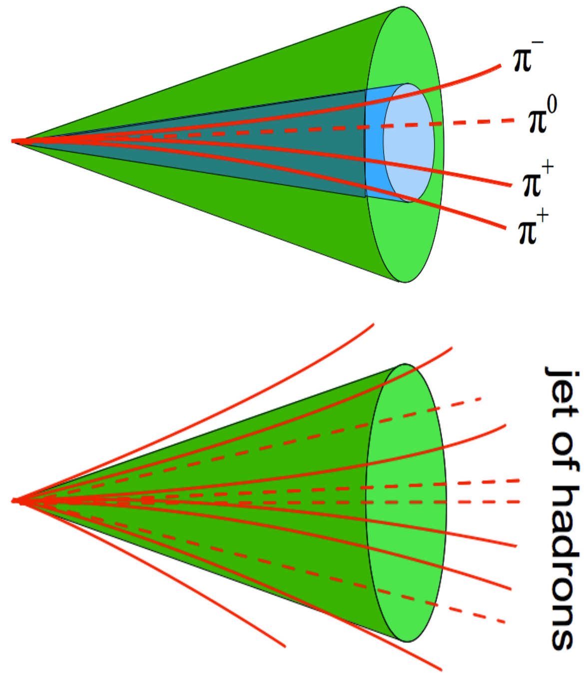


Example of Z → μμ decay with 20 reconstructed vertices (shown ± 15 cm, p_T (track) > 0.4 GeV



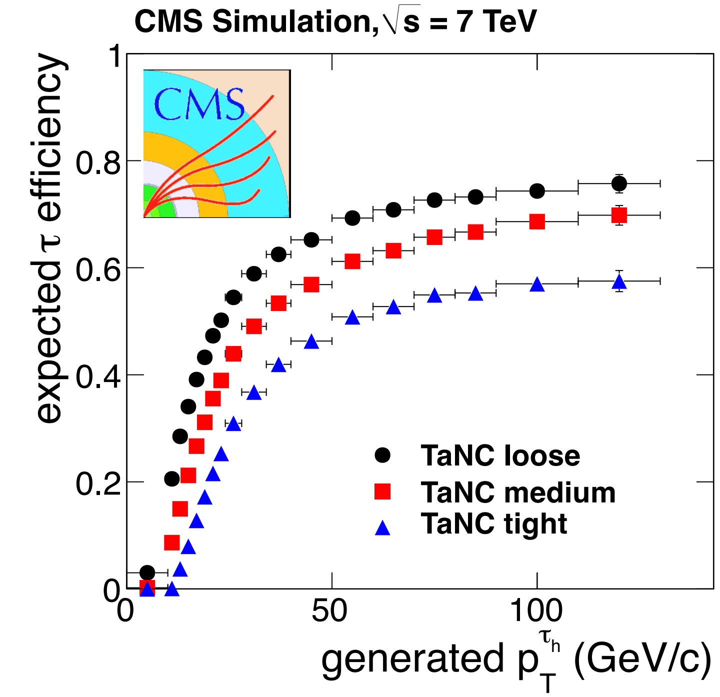
Tau Identification

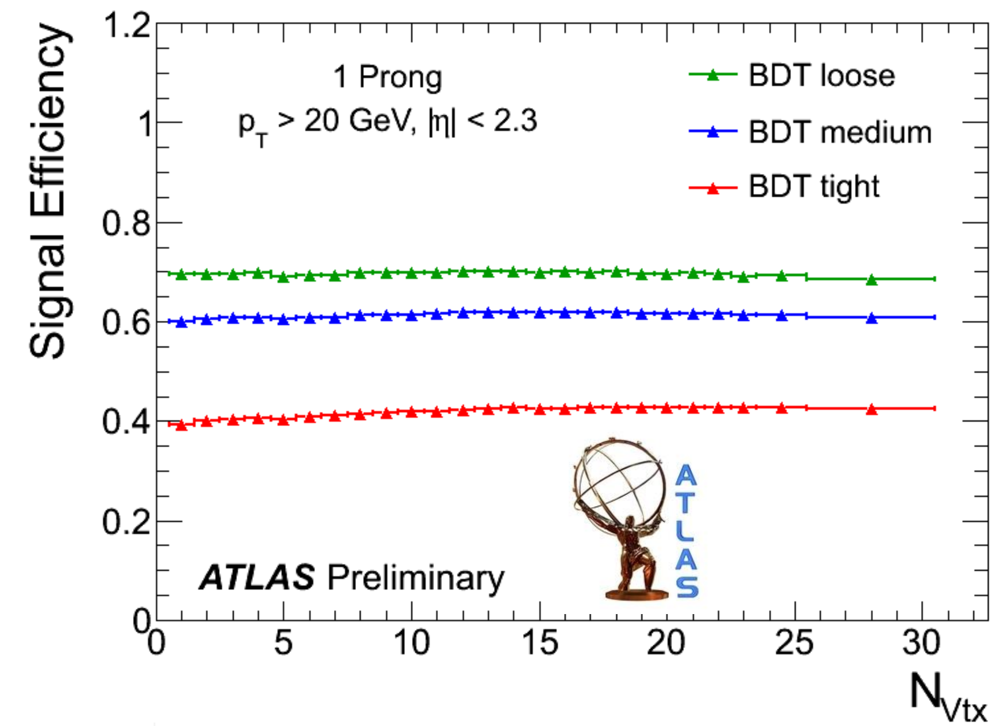
- Tau decay modes:
  - Leptons (e, μ): 35%
  - Hadrons ($\pi^{\pm}$, π^{0}):
    - 50% 1-prong
    - 15% 3-prong



- ID "Cut"-based and MVA
- Working points:
  - $\mathcal{E}(\tau)$ = 60-65% (medium)
    ~ 40% (tight)
  - $\mathcal{E}$(jet) = 2-3% (medium)
    ~0.5% (tight)

- Analyses in three final states
  - $H \rightarrow \tau_{lep}\,\tau_{lep}$
  - $H \rightarrow \tau_{lep}\,\tau_{had}$ (medium)
  - $H \rightarrow \tau_{had}\,\tau_{had}$ (medium, 1 tight for ATLAS)





ATLAS-CONF-2011-152
ATLAS-CONF-2013-044
ATLAS-CONF-2012-054
CMS: 2012 JINST 7 P01001

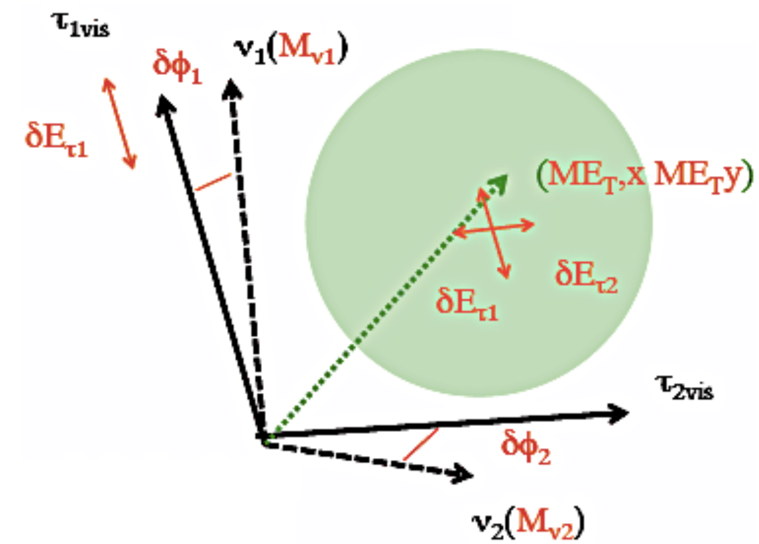
Mass Reconstruction

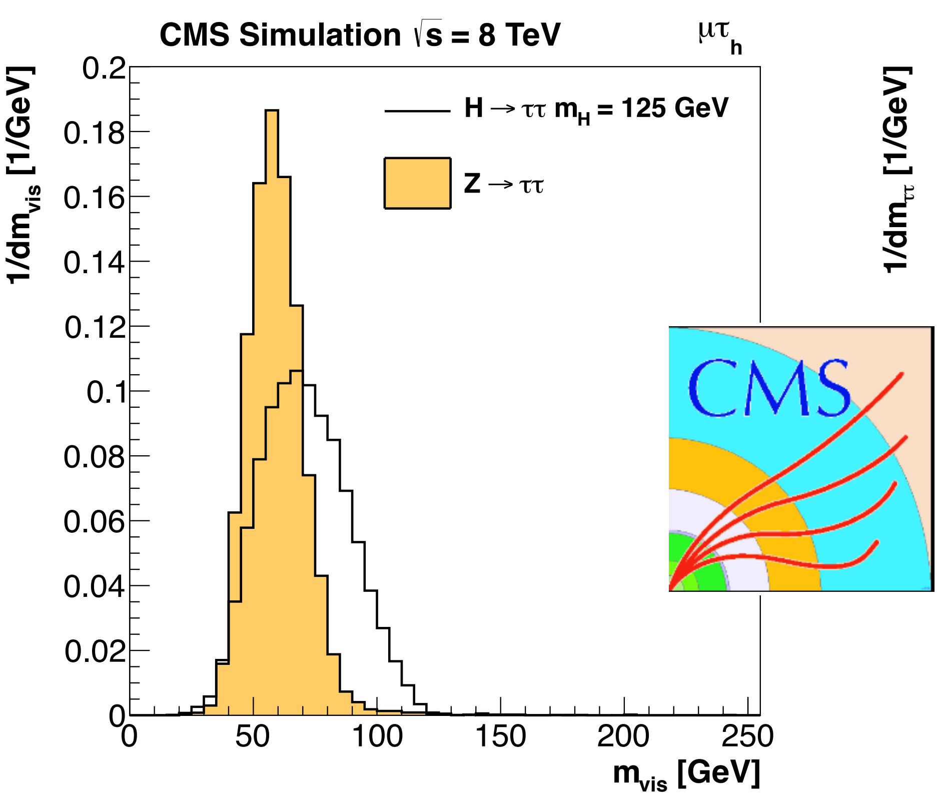
Improvement over collinear mass

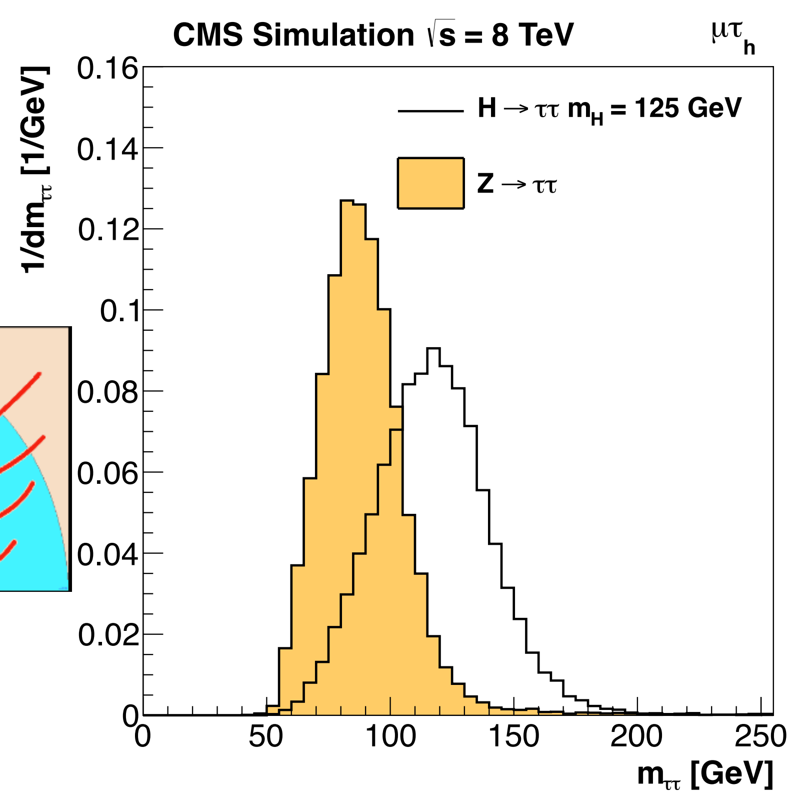
Maximising likelihood function that take the tau decay kinematics into account

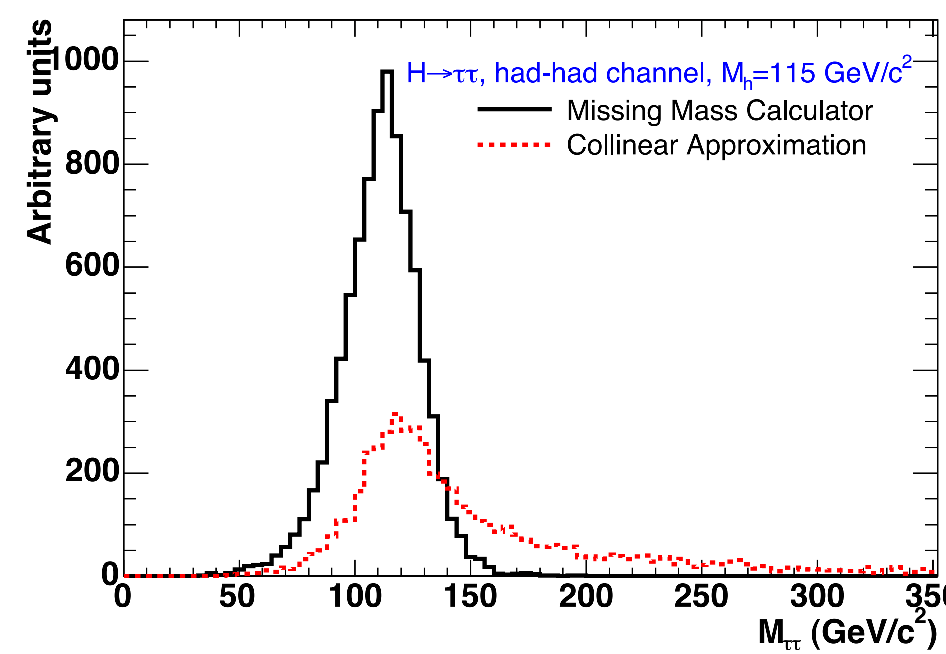
- Different for leptonic and hadronic decays
- Mass resolution 13-20% depending on topology
  - Resolution improves for boosted ττ-system
- E_T^{miss} resolution is an important factor

MMC: Nucl. Inst. Meth. A 654 (2011) 481

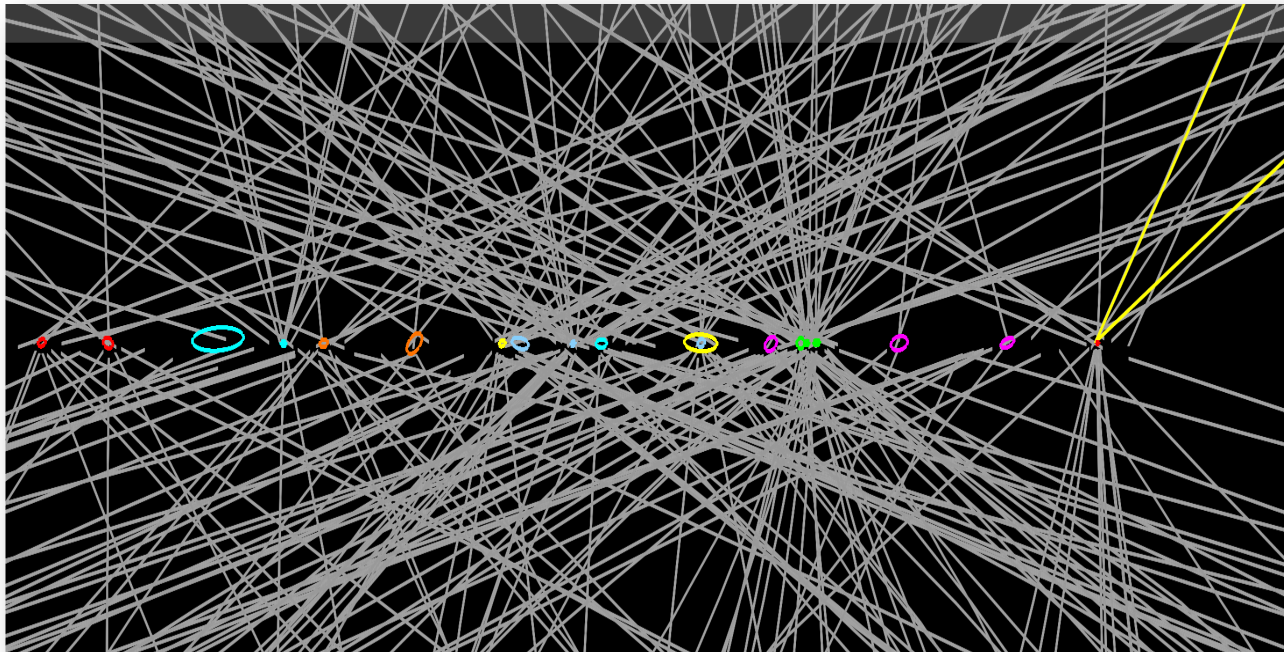




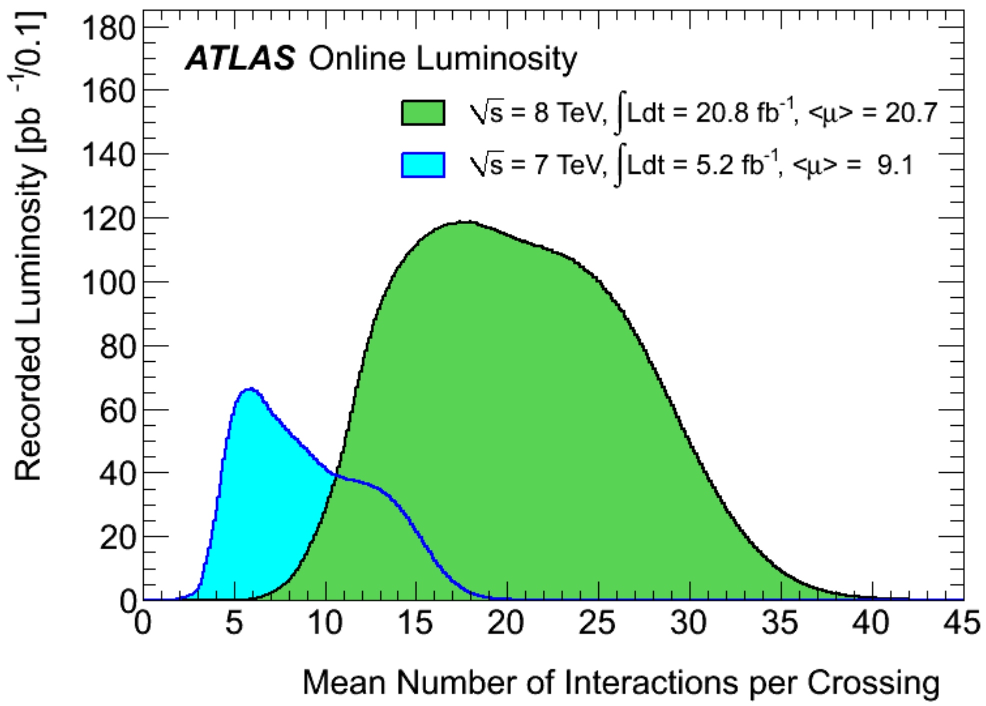




E_T^{miss} Reconstruction



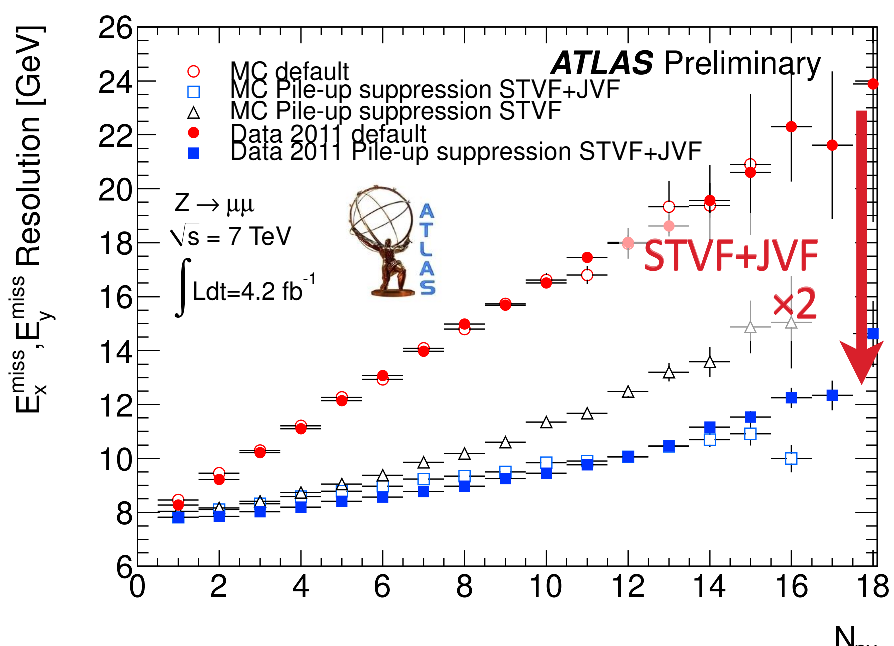
Example of Z → μμ decay with 20 reconstructed vertices (shown ± 15 cm, p_T (track) > 0.4 GeV



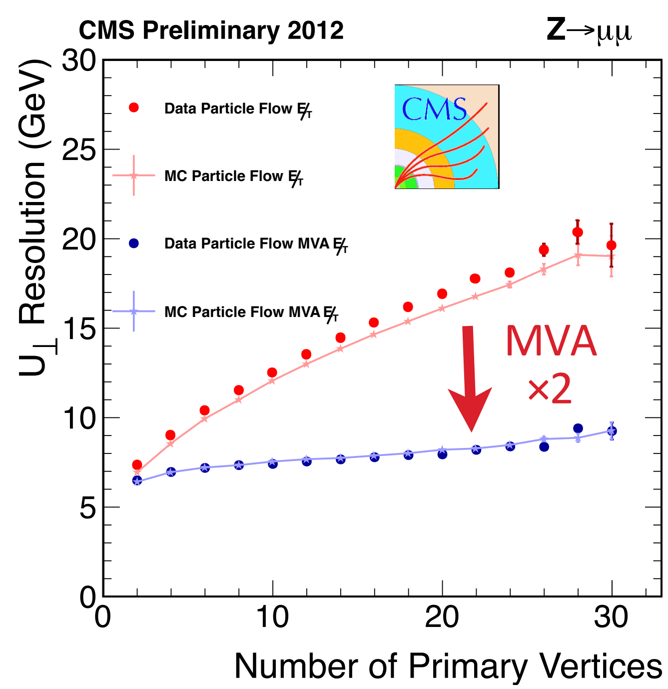
Pileup is a challenge for E_T^{miss} resolution.

Dedicated pile-up correction taking the hard scatter vertex into account.

- ATLAS uses Jet and Soft Term Vertex Fractions.
- CMS uses a BDT trained on different E_T^{miss} variables



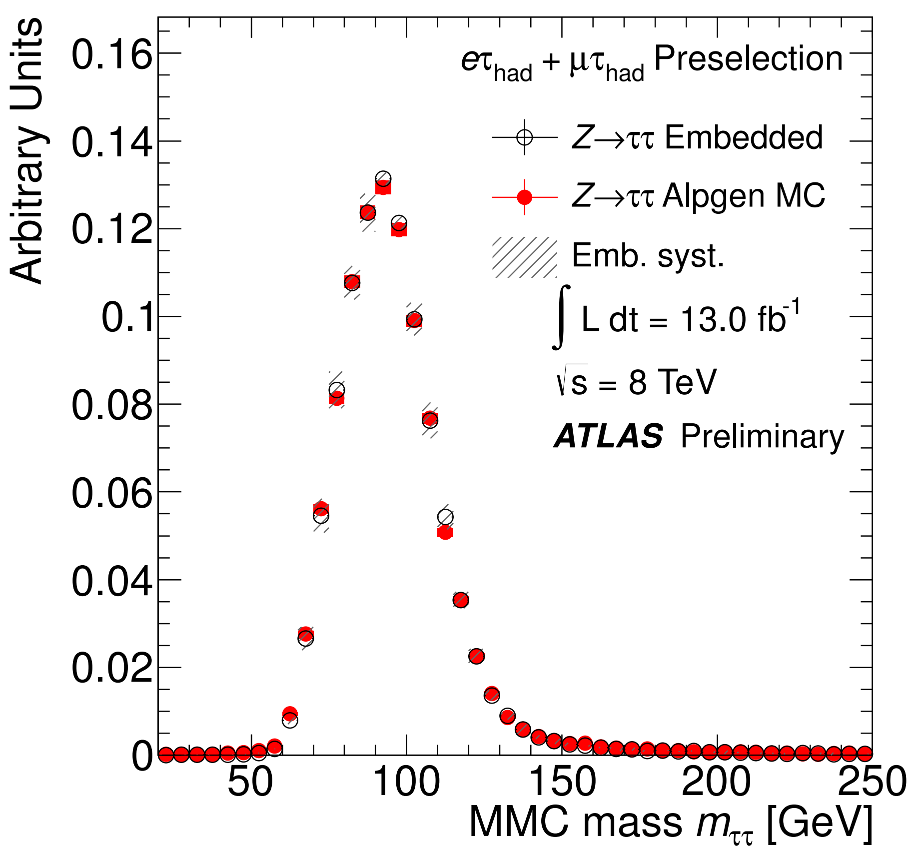
ATLAS-CONF-2012-101

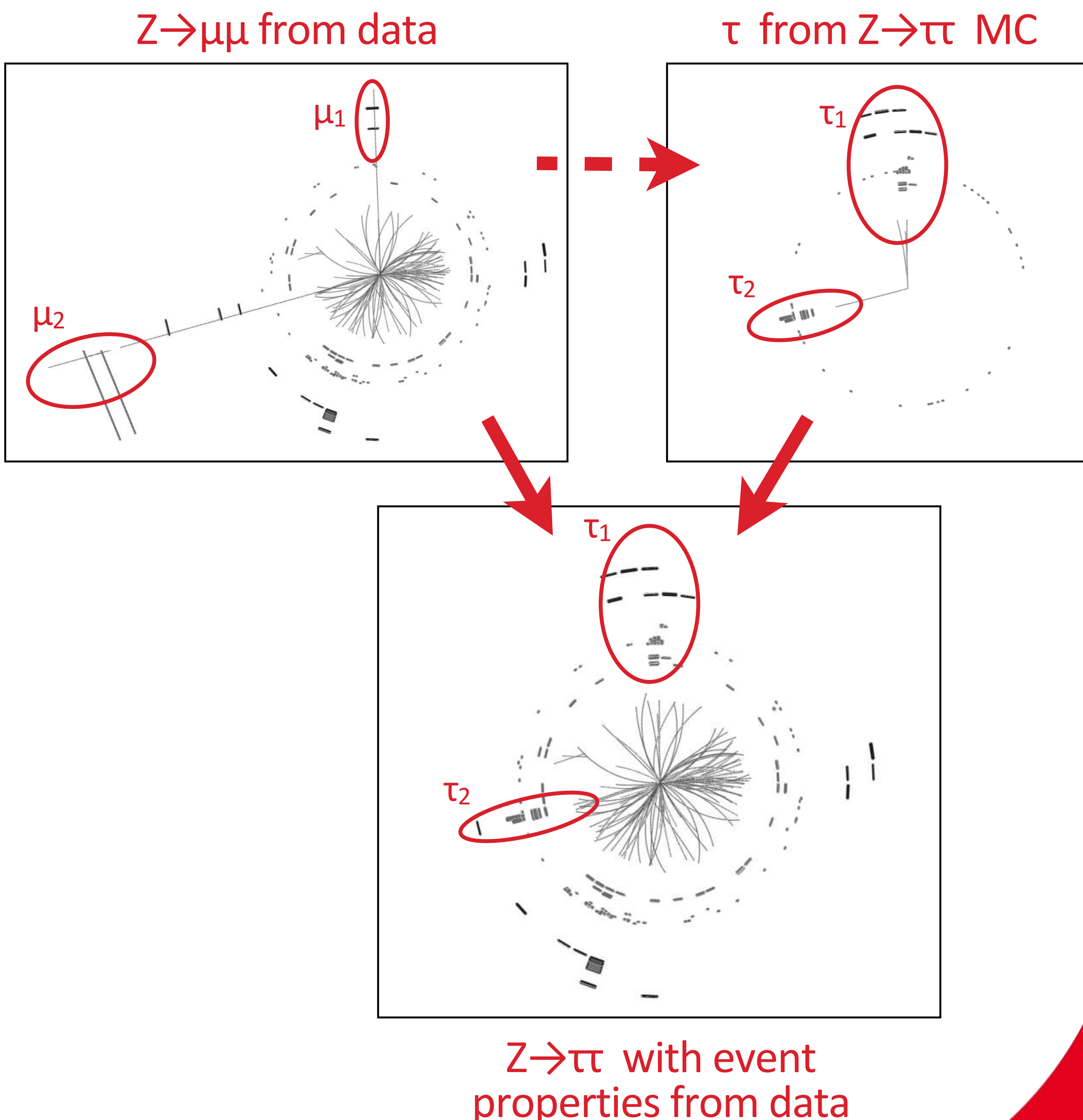


Z→ττ Simulation: Embedding

Z→μμ data is being used

- Remove μ from data
- Simulate τ including spin
- Add τ in place of the μ





Analysis Categories

The analysis categories are optimised for

- the three τ decay modes,
- the production modes,
- sensitivity.

H	lep-lep	lep-had	had-had
2-jet VBF	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS
Boosted	ATLAS	ATLAS	ATLAS
2-jet VH	ATLAS		
1-jet	ATLAS, CMS	ATLAS, CMS	CMS
0-jet	ATLAS, CMS	ATLAS, CMS	
ττ-l VH	CMS	CMS	CMS

Advantages of jets:

- Improved mass resolution
- Reduced background from V+jet(s)

Selection for VBF

- 2 forward jets in opposite hemispheres:
  - Cuts on $p_T(j)$, η, Δη, m_{jj}, ΔR, central jet veto
  - Lepton centrality
  - b-jet veto against $t\bar{t}$-background

Selection for Boosted / 1-jet high p_T

- $p_T(j)$, $p_T(H)$, $\Delta R(\tau\tau)$

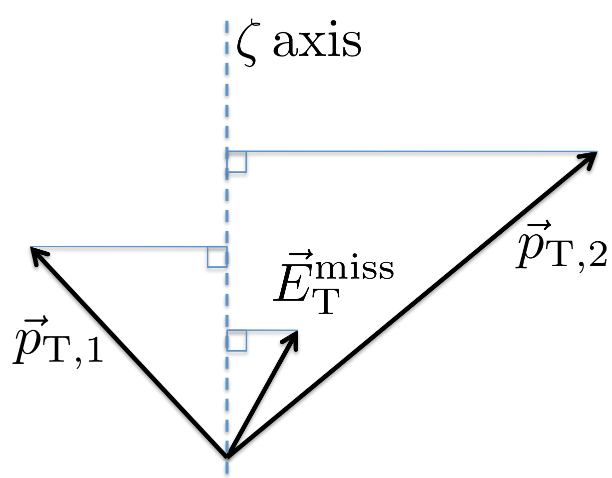
Event Selection

Event selection

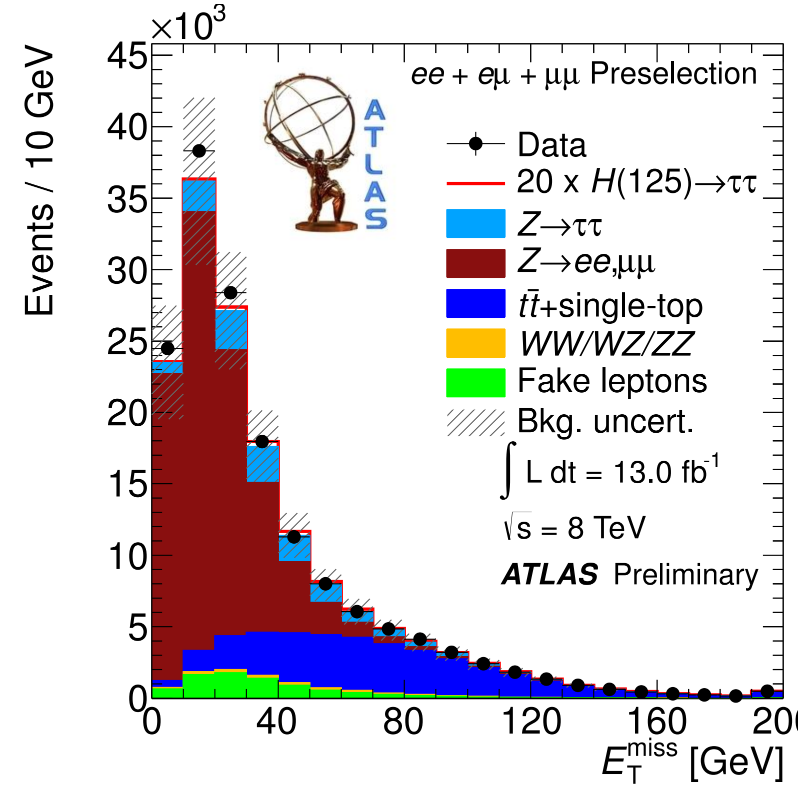
- General criteria
  - Opposite sign high p_T $e/\mu/\tau_h$ (trigger)
  - E_T^{miss}
- Event topology
  - MET consistent with ν from τ decays
    - ATLAS x_1, x_2

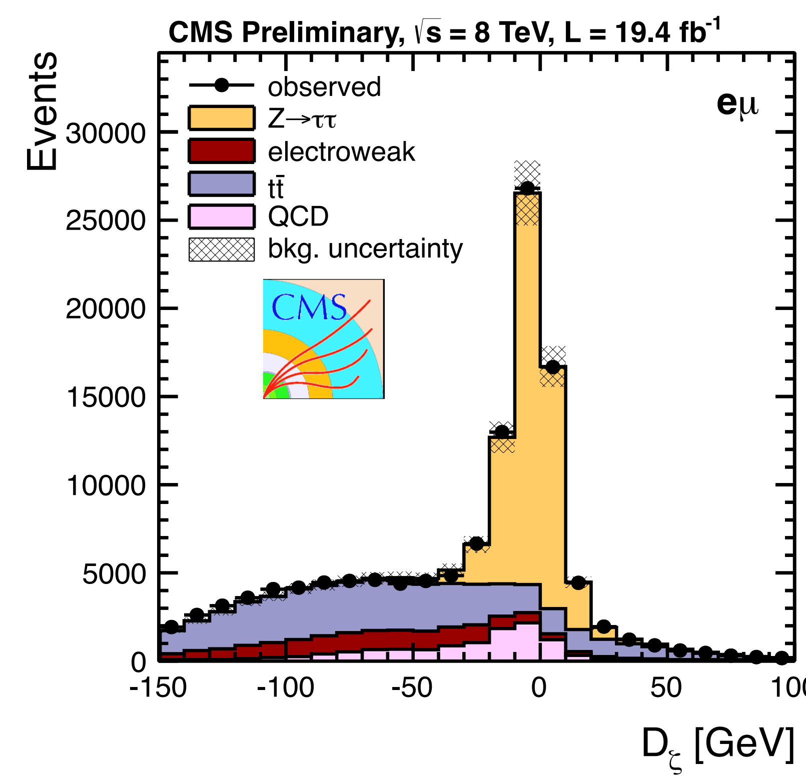
$$x_{1,2} = \frac{|p_{\mathrm{vis}1,2}|}{|(p_{\mathrm{vis}1,2} + p_{\mathrm{mis}1,2})|}$$

    - CMS Dζ



    - ΔΦ(τ, MET)





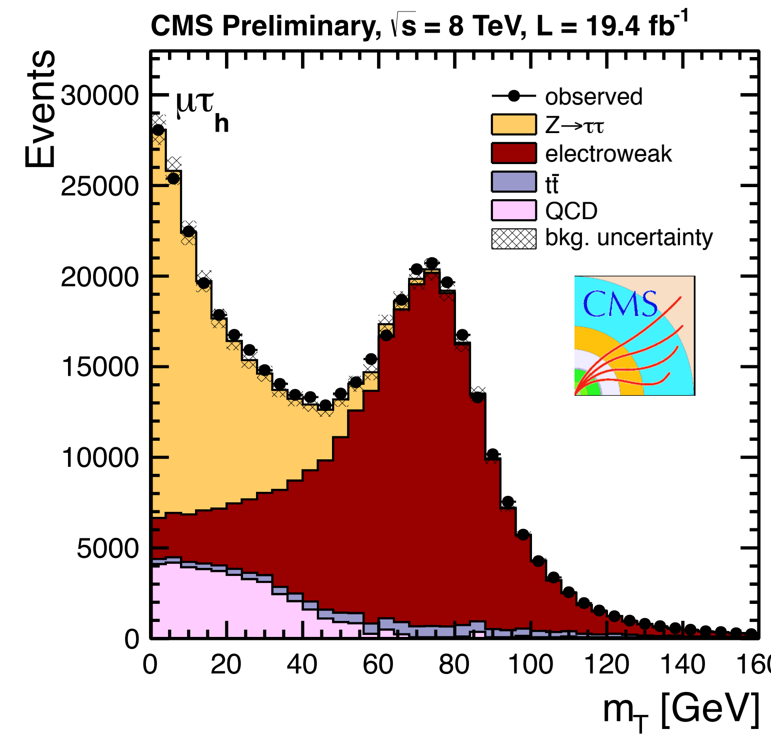
Event Selection

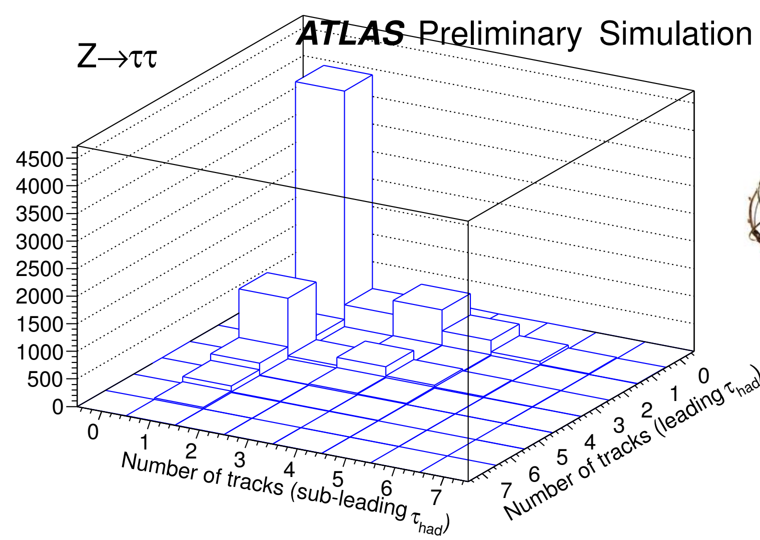
Event selection for background suppression

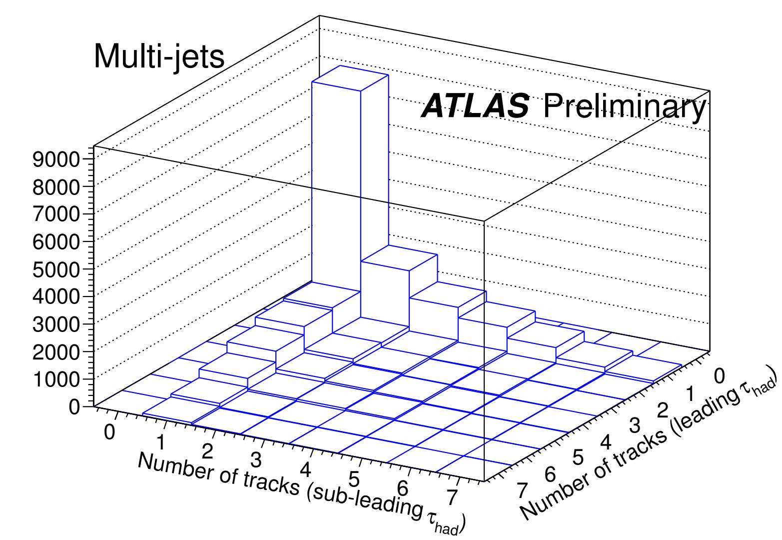
- b-veto against $t\bar{t}$ background
- E_T^{miss} and $\Delta\Phi(\tau\tau)$ against Z background
- m_T against W+jet background

Background modelling

- Z→ττ via embedding
- Z→ll from simulation with scaling from Z→μμ
- Fake τ (QCD, W+jet, $t\bar{t}$)
  - same sign
  - template fitting
- Di-boson (small) from MC







Results: VBF 2-jet

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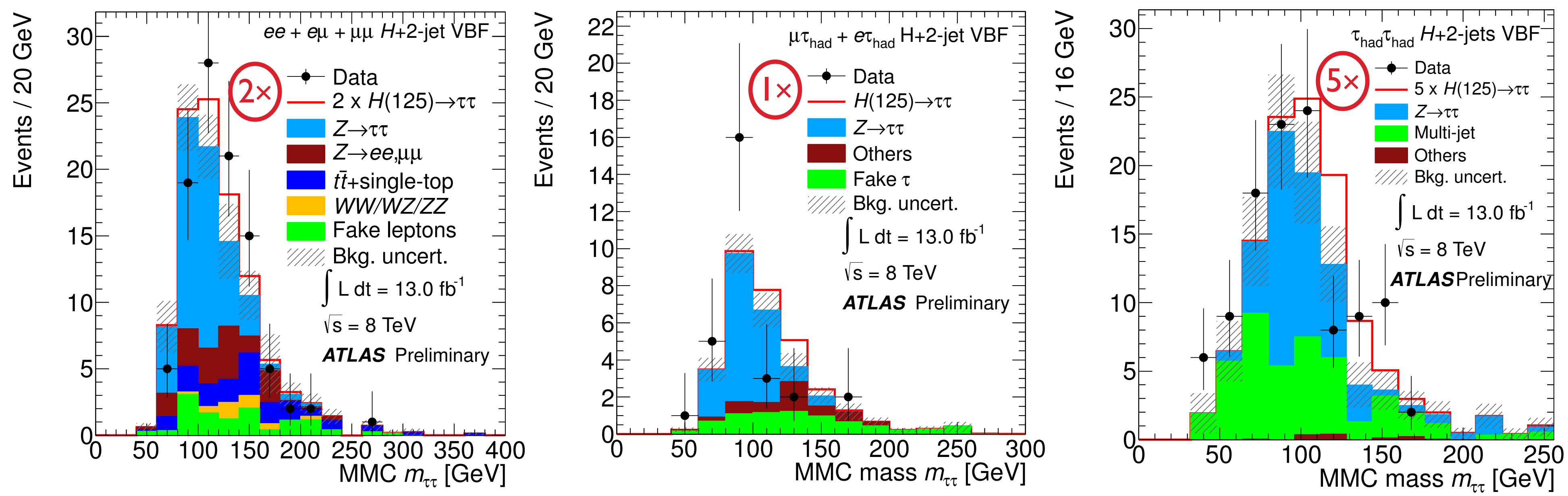
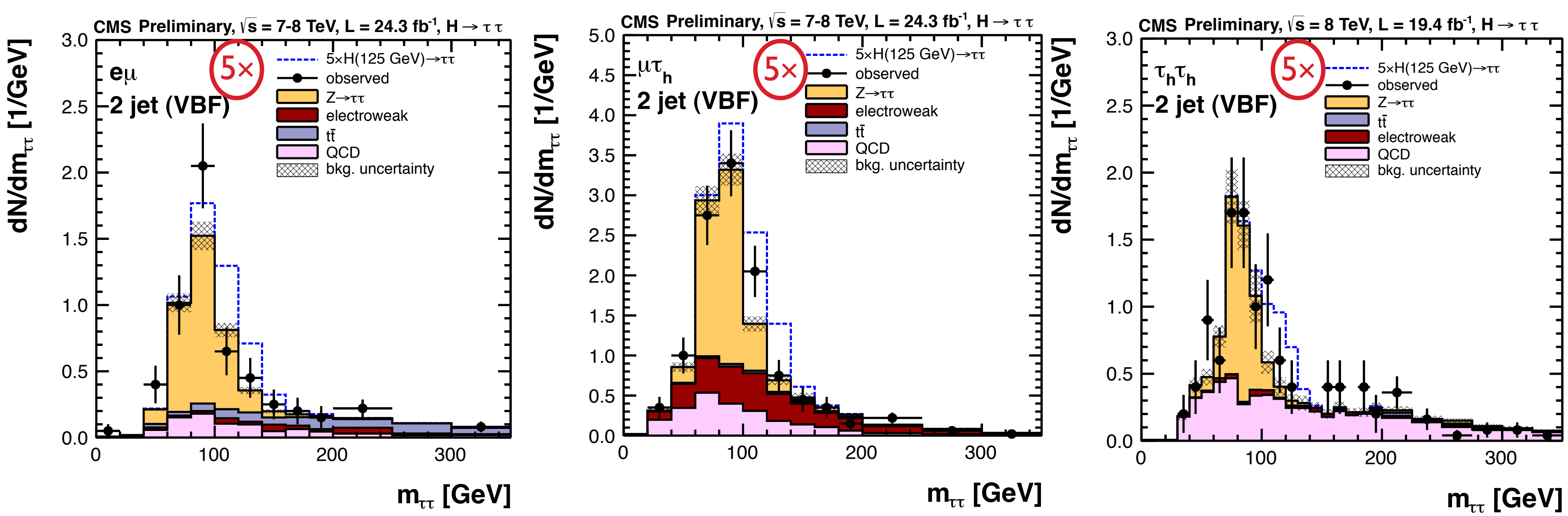
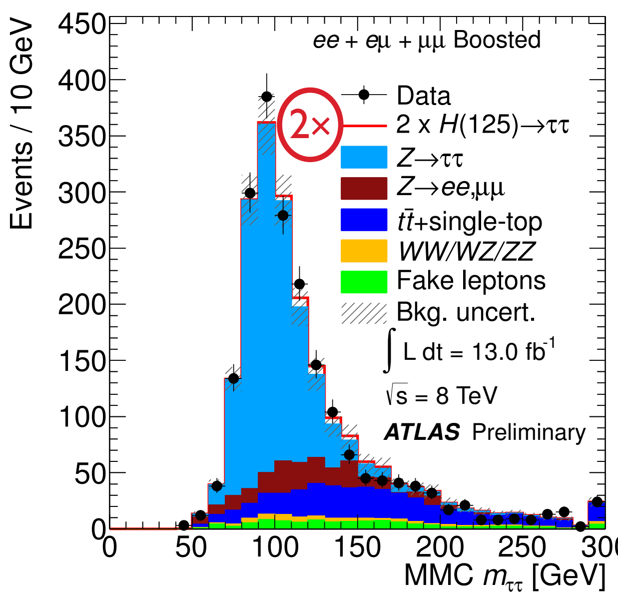
lep-lep | lep-had | had-had

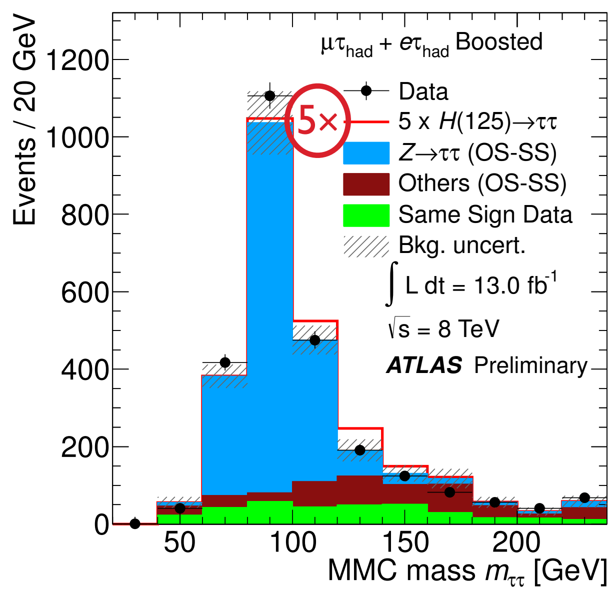


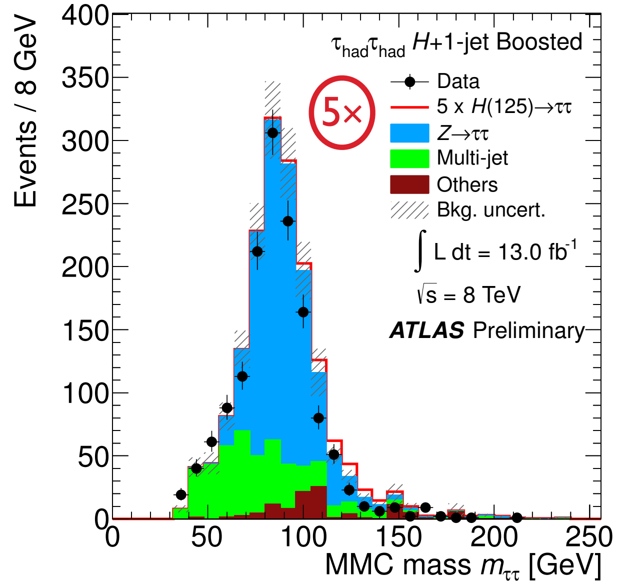


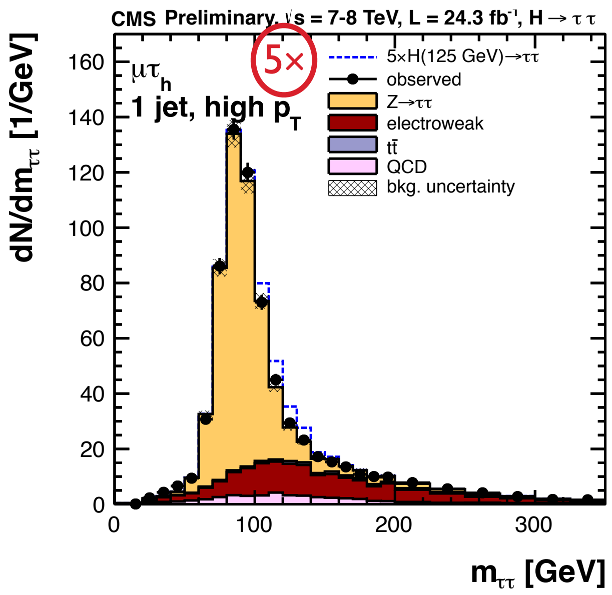
Results: Boosted / 1-jet high p_T

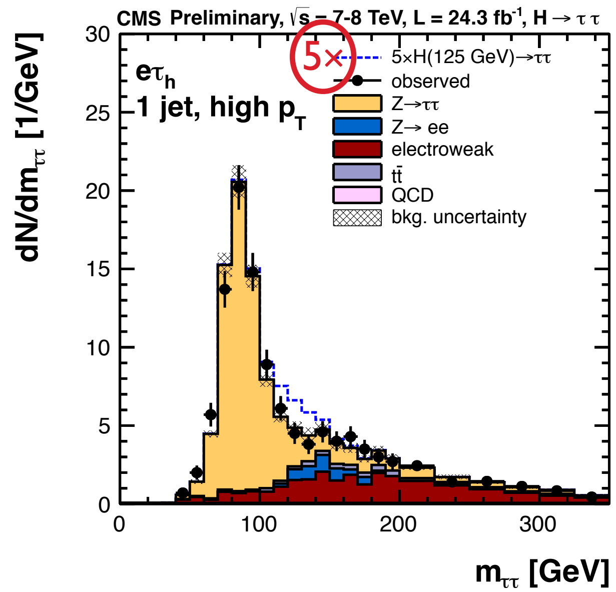
lep-lep | lep-had | had-had

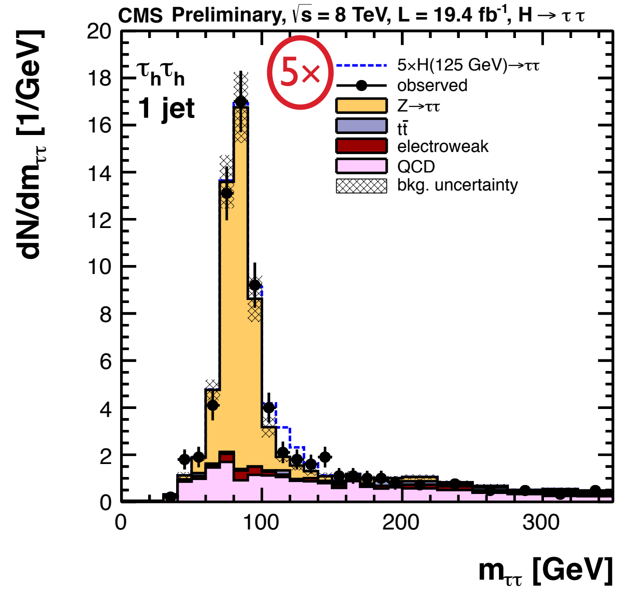








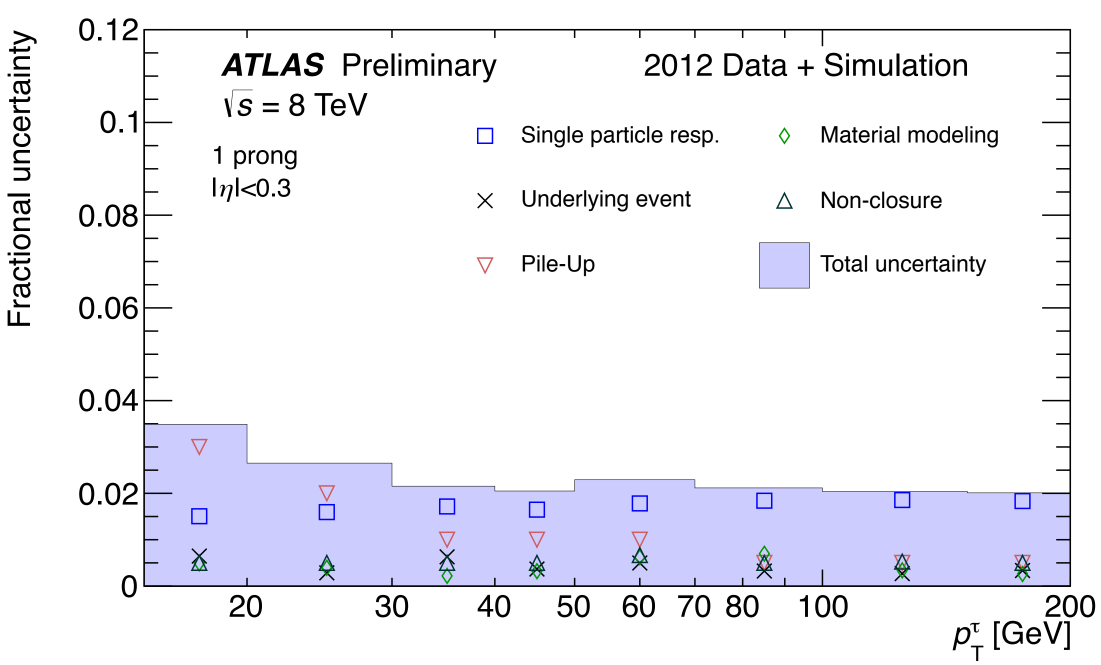




Systematics

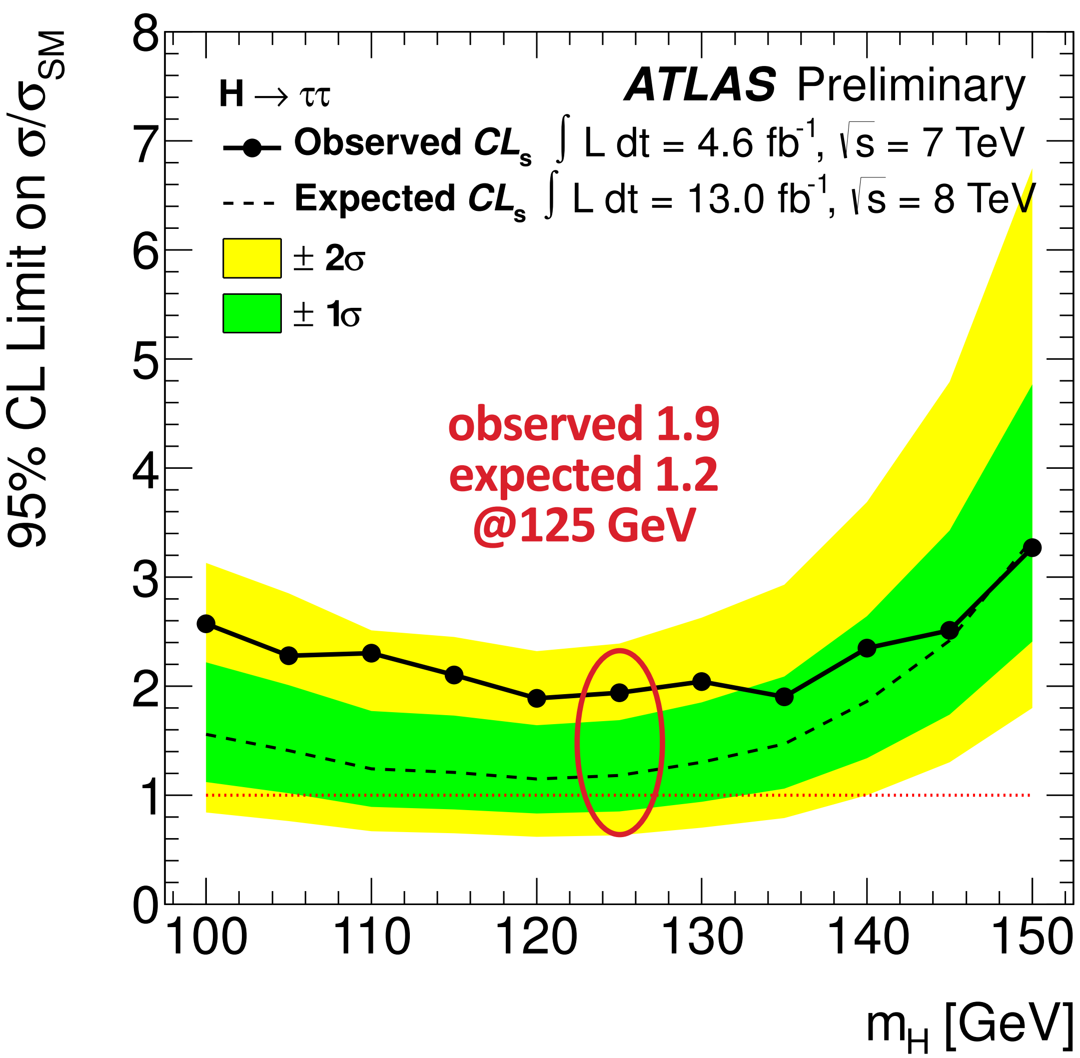
- Theory uncertainties dominate
  - 8-30% gg→H depending on jet multiplicity
  - total uncertainty 10-30% for VBF channel

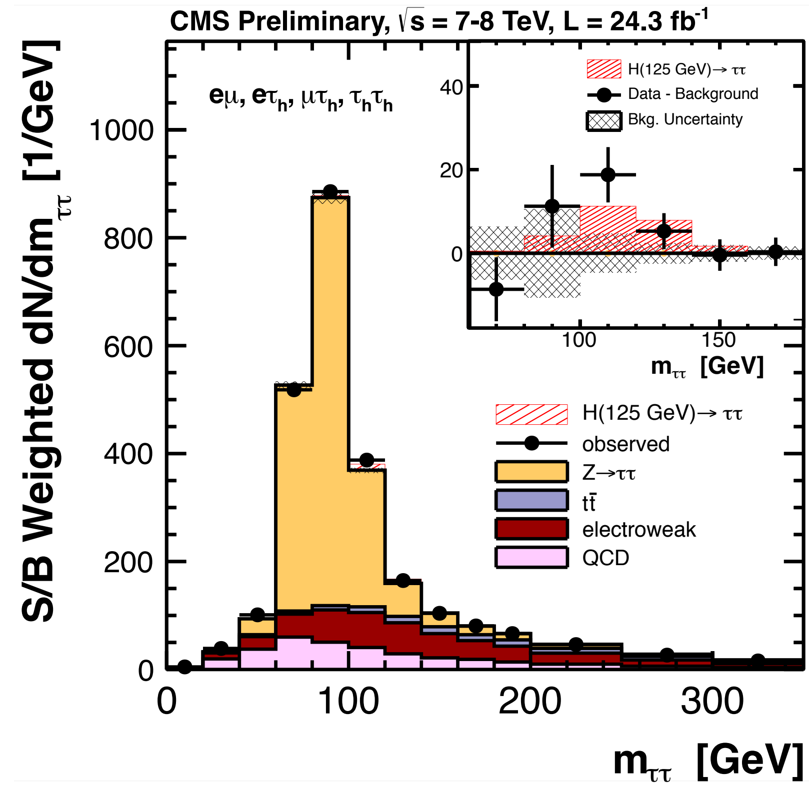
- Dominant detector uncertainty
  - jet energy scale 2-12%
  - τ-energy scale 2-15%
  - 8% τ_h ID
  - E_T^{mis} scale 5%

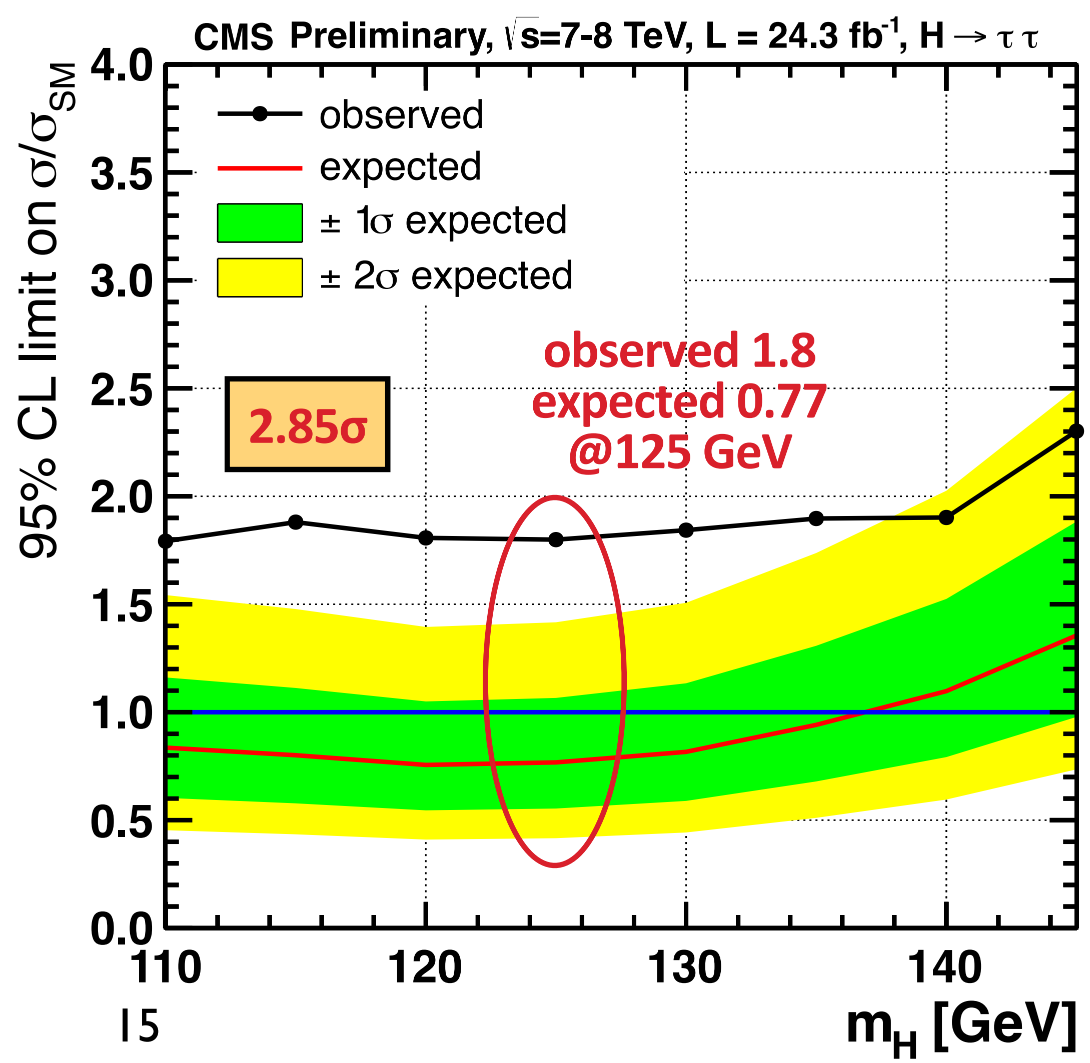


- Constraint fit:
  - Tau ID & Trigger: 0.0 ± 8.0% → −5.5 ± 1.9%
  - Tau Energy Scale ($\mu\tau_h$ channel): 0.0 ± 3.0% → −0.8 ± 0.2%
  - Tau Energy Scale ($e\tau_h$ channel): 0.0 ± 3.0% → −1.3 ± 0.5%

Results I


ATLAS Preliminary
H → ττ
Observed CLs ∫ L dt = 4.6 fb-1, √s = 7 TeV
Expected CLs ∫ L dt = 13.0 fb-1, √s = 8 TeV
± 2σ
± 1σ
observed 1.9
expected 1.2
@125 GeV
95% CL Limit on σ/σSM
mH [GeV]


CMS Preliminary, √s = 7-8 TeV, L = 24.3 fb-1
eμ, eτh, μτh, τhτh
H(125 GeV)→ ττ
Data - Background
Bkg. Uncertainty
H(125 GeV)→ ττ
observed
Z→ττ
tt̄
electroweak
QCD
S/B Weighted dN/dmττ [1/GeV]
mττ [GeV]


CMS Preliminary, √s=7-8 TeV, L = 24.3 fb-1, H → τ τ
observed
expected
± 1σ expected
± 2σ expected
2.85σ
observed 1.8
expected 0.77
@125 GeV
95% CL limit on σ/σSM
mH [GeV]

H→μμ

ATLAS-CONF-2013-010

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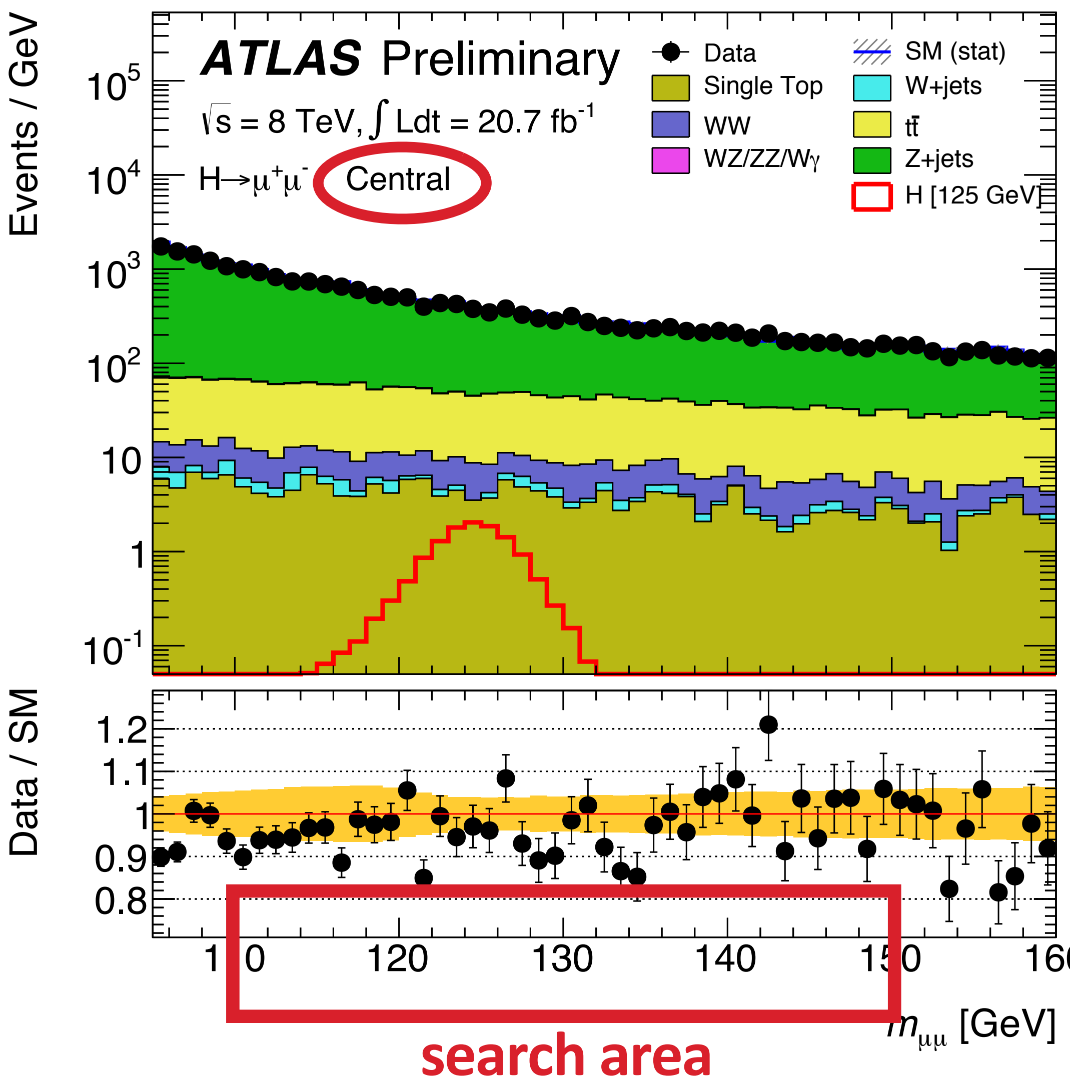
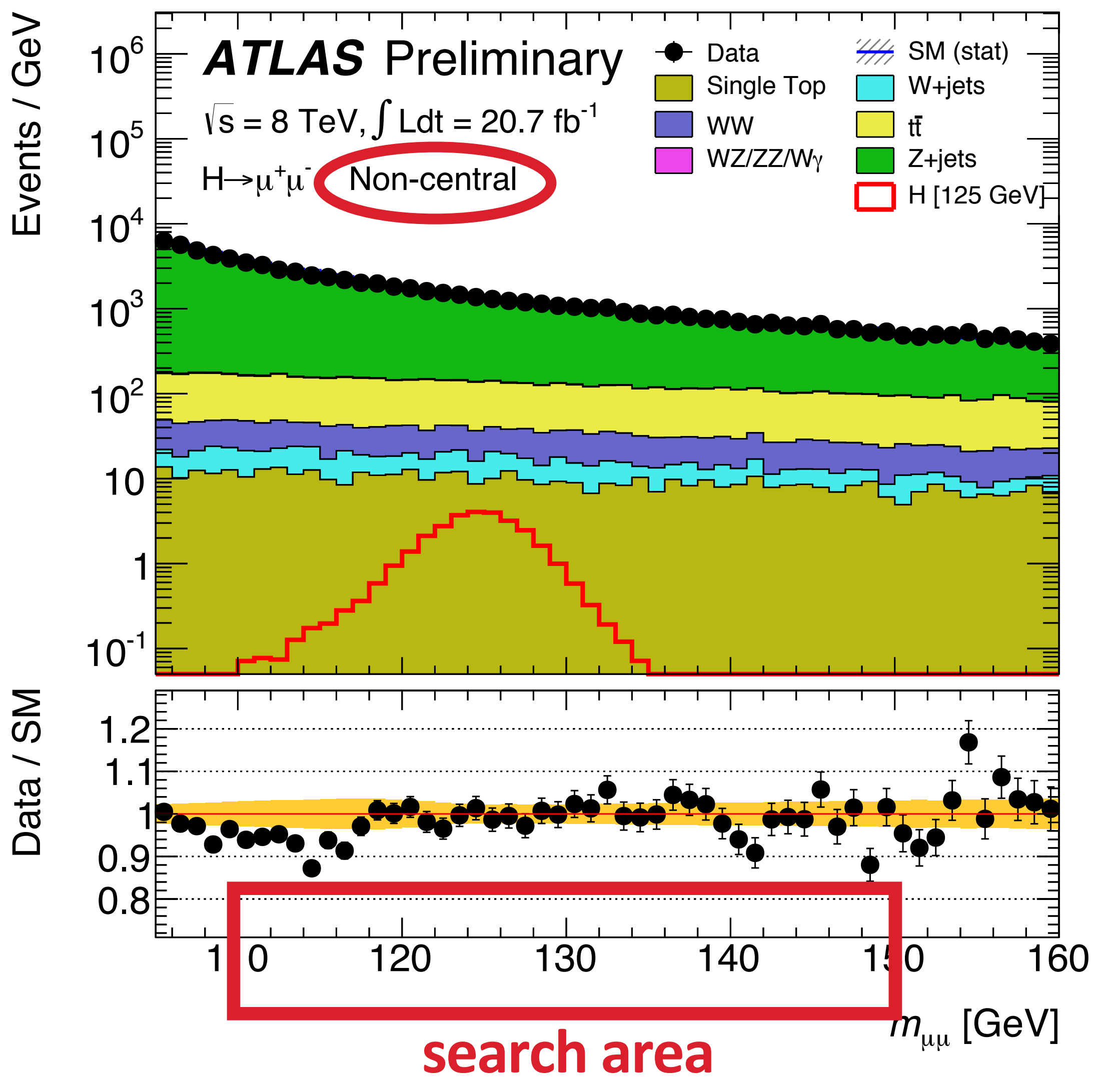
Event selection:

- 2 Isolated muons
- $p_T(\mu) > 25/15$ GeV
- $\mathcal{E}_{sig}$ is 50-60%
- $p_T(\mu^+\mu^-) > 15$GeV: $\mathcal{E}_{sig}$=80%, $\mathcal{E}_{bg}$=40%
- Central category for improved mass resolution

	$\lvert m_H - m_{\mu\mu}\rvert \leq 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
$WZ/ZZ/W\gamma$	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15810 ± 130
W+jets	88 ± 6
Total Bkg.	17700 ± 130
Observed	17442

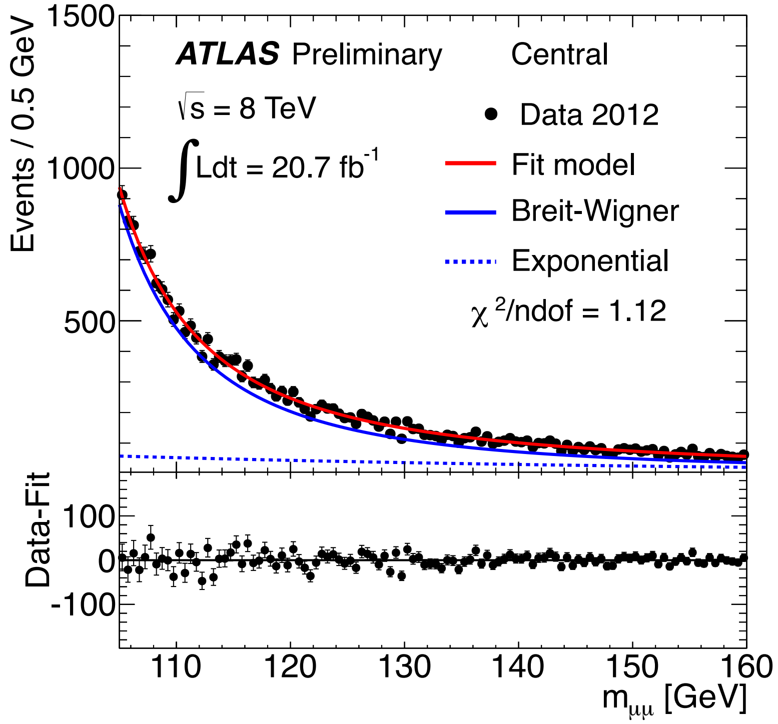
$|\eta(\mu_{1,2})| < 1$

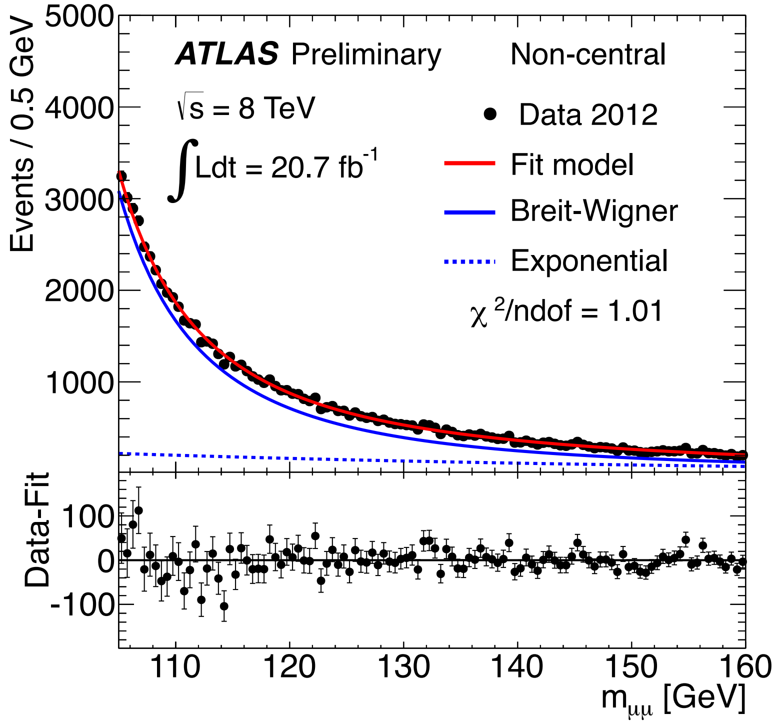


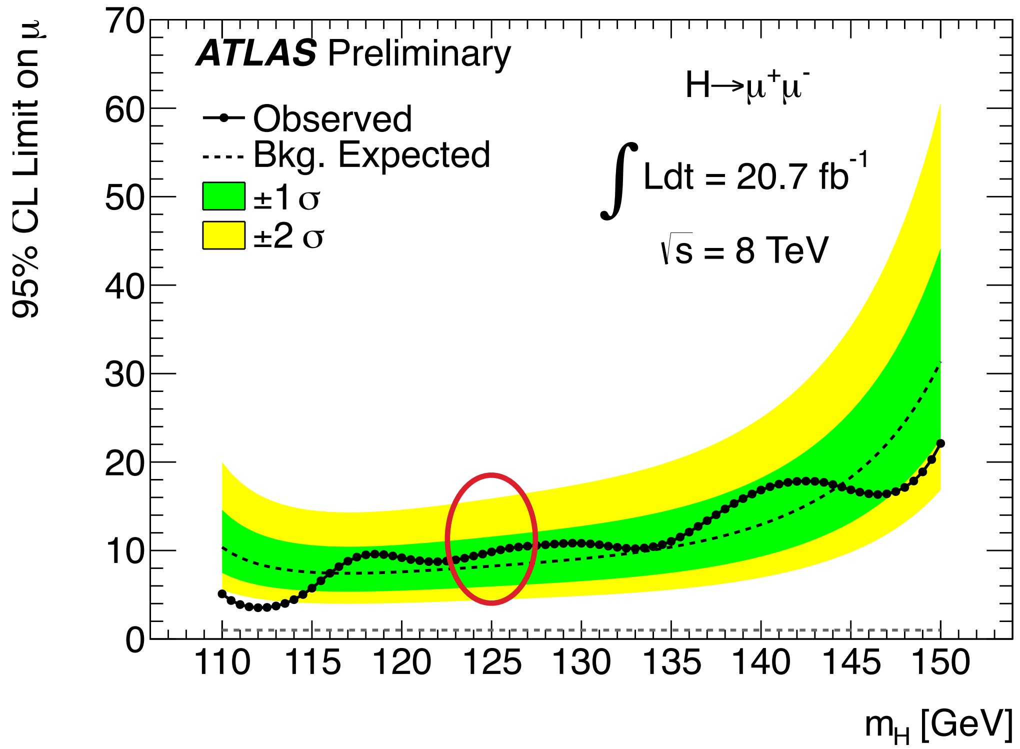


H→μμ

- Background fit of Breit-Wigner and exponential
- Signal fit of Crystal Ball + Gaussian

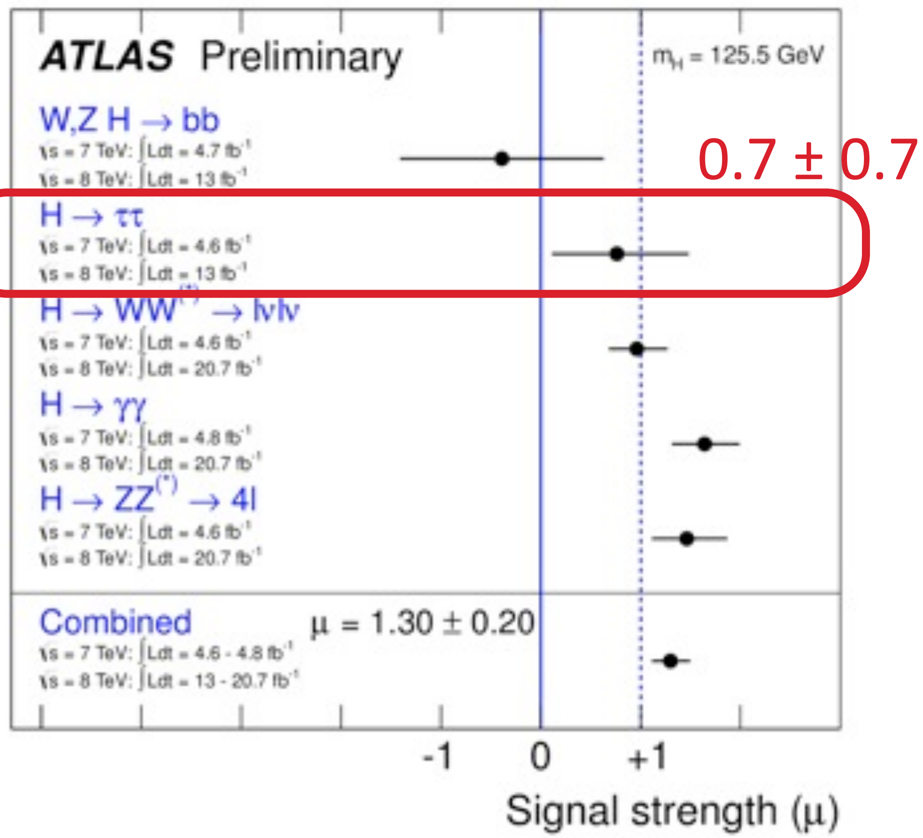


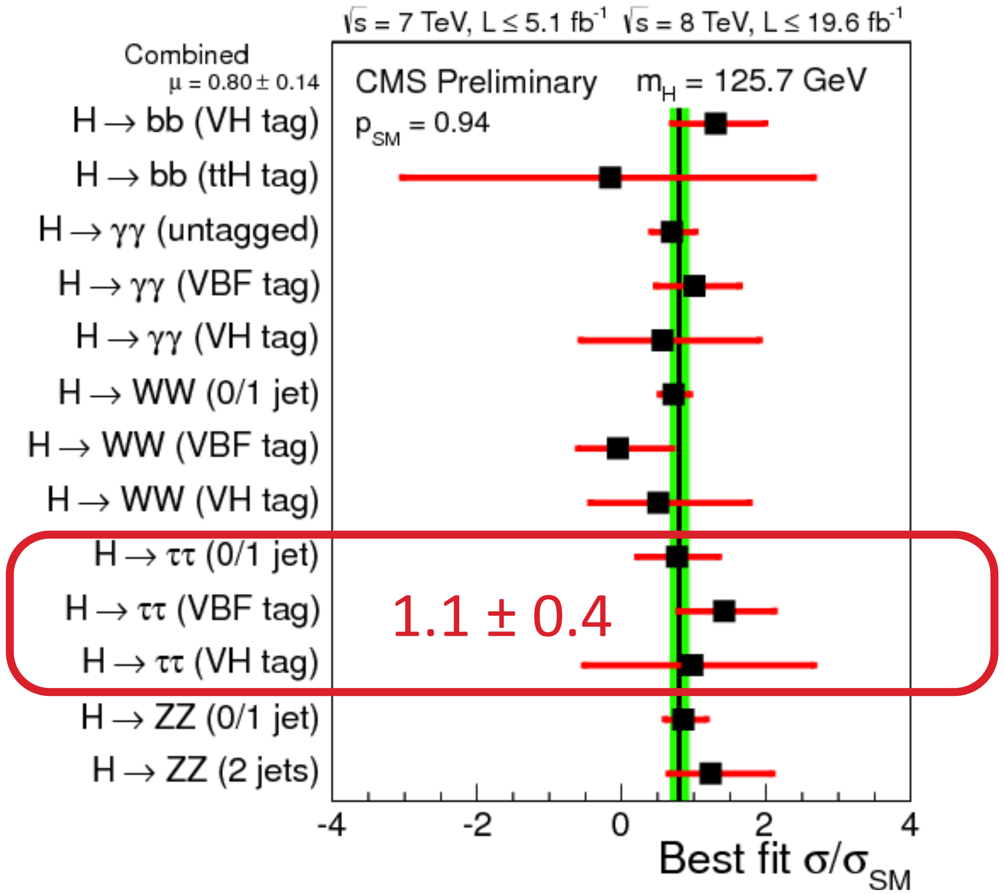


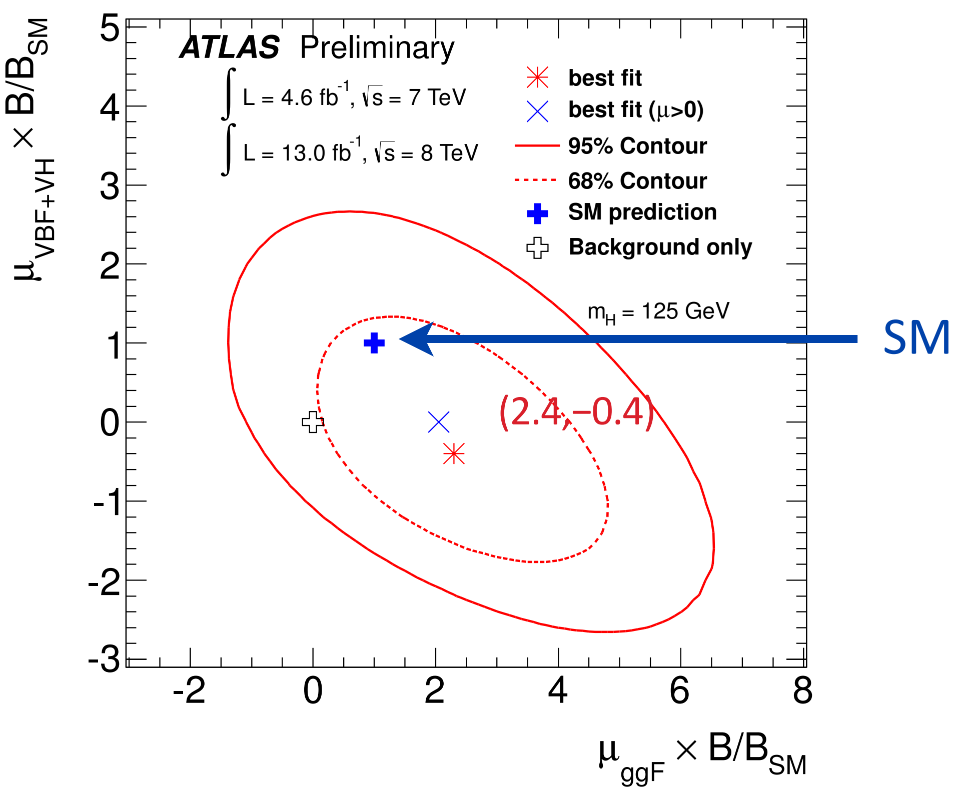


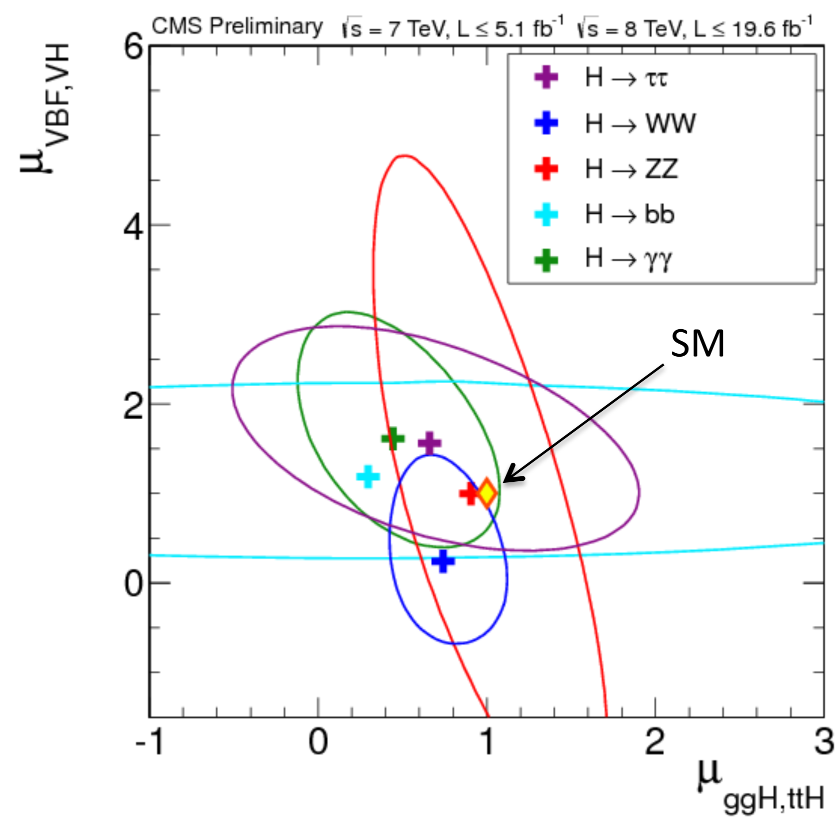
95% C.L. on σ/σ_{SM} at 125 GeV
observed 9.8
expected 8.2

Results II


ATLAS Preliminary
m_H = 125.5 GeV
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 fb⁻¹
H → ττ
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 fb⁻¹
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
H → γγ
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
Combined
μ = 1.30 ± 0.20
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 - 20.7 fb⁻¹
-1
0
+1
Signal strength (μ)
0.7 ± 0.7


√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
Combined
μ = 0.80 ± 0.14
CMS Preliminary
m_H = 125.7 GeV
p_{SM} = 0.94
H → bb (VH tag)
H → bb (ttH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → γγ (VH tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → ττ (0/1 jet)
H → ττ (VBF tag)
H → ττ (VH tag)
H → ZZ (0/1 jet)
H → ZZ (2 jets)
-4
-2
0
2
4
Best fit σ/σ_{SM}
1.1 ± 0.4


ATLAS Preliminary
∫L = 4.6 fb⁻¹, √s = 7 TeV
∫L = 13.0 fb⁻¹, √s = 8 TeV
best fit
best fit (μ>0)
95% Contour
68% Contour
SM prediction
Background only
m_H = 125 GeV
SM
(2.4,-0.4)
$\mu_{VBF+VH} \times B/B_{SM}$
$\mu_{ggF} \times B/B_{SM}$
5
4
3
2
1
0
-1
-2
-3
-2
0
2
4
6
8


CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
H → ττ
H → WW
H → ZZ
H → bb
H → γγ
SM
$\mu_{VBF,VH}$
$\mu_{ggH,ttH}$
6
4
2
0
-1
0
1
2
3

Conclusion

ATLAS and CMS have performed searches for $H \rightarrow \tau\tau$ decays in 17.6 and 25.3fb^{-1} and for $H \rightarrow \mu\mu$ in 20.7fb^{-1}.

- VBF and ggF couplings consistent with SM
- First hint of $H \rightarrow \tau\tau$
- Promising $H \rightarrow \mu\mu$ analysis for the future

The sensitivities are

	ATLAS	CMS	ATLAS
	$H \rightarrow \tau\tau$	$H \rightarrow \tau\tau$	$H \rightarrow \mu\mu$
expected	1.2	0.77	8.2
observed	1.9	1.8	9.8
σ/σ_{SM}	0.7±0.7	1.1±0.4	

Backup

Event Selection: ATLAS

Table 2: The categorization of the $H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$ analysis. The JVF cut is $|JVF| > 0.75$ for 7 TeV data, the lepton centrality is not applied for 7 TeV analysis, and the 0-jet category is not used for 8 TeV data analysis.

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

Event Selection: ATLAS

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Table 3: Event requirements applied in the different categories of the $H \to \tau_{lep}\tau_{had}$ analysis. Requirements marked with a triangle (▹) are categorization requirements, meaning that if an event fails that requirement it is still considered for the remaining categories. Requirements marked with a bullet (•) are only applied to events passing all categorization requirements in a category; events failing such requirements are discarded.

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

7 TeV		8 TeV	
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
• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$	• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$
–	• $p_T^{\ell} - p_T^{\tau} < 0$	–	• $p_T^{\ell} - p_T^{\tau} < 0$

Event Selection: ATLAS

Table 4: Summary of the event selection and categories for the $H \rightarrow \tau_{had}\tau_{had}$ channel.

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 $\tau_{had\text{-}vis}$ $p_T > 40$ GeV and sub-leading $\tau_{had\text{-}vis}$ $p_T > 25$ 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_T^{miss} vector is not pointing in between the two taus, min $\left\{\Delta\phi(E_T^{miss}, \tau_1), \Delta\phi(E_T^{miss}, \tau_2)\right\} < 0.2\pi$
VBF	At least two tagging jets, j_1, j_2, leading tagging jet with $p_T > 50$ GeV
	$\eta_{j1} \times \eta_{j2} < 0$, $\Delta\eta_{jj} > 2.6$ and invariant mass $m_{jj} > 350$ GeV
	$\min(\eta_{j1}, \eta_{j2}) < \eta_{\tau 1}, \eta_{\tau 2} < \max(\eta_{j1}, \eta_{j2})$
	$E_T^{miss} > 20$ GeV
Boosted	Fails VBF
	At least one tagging jet with $p_T > 70(50)$ GeV in the 8(7) TeV dataset
	$\Delta R(\tau_1, \tau_2) < 1.9$
	$E_T^{miss} > 20$ GeV
	if E_T^{miss} vector is not pointing in between the two taus, min $\left\{\Delta\phi(E_T^{miss}, \tau_1), \Delta\phi(E_T^{miss}, \tau_2)\right\} < 0.1\pi$.

Event Yields: ATLAS

Table 5: Number of events after the $H \to \tau_{\text{lep}}\tau_{\text{lep}}$ selection for the five categories in data and predicted number of background events, for an integrated luminosity of 4.6 fb^{-1} collected at 7 TeV. Expectations for the Higgs boson signal ($m_H = 125$ GeV) are also given. Statistical and systematic uncertainties are quoted, in that order.

			$ee + \mu\mu + e\mu$		
	VBF category	Boosted category	VH category	1-jet category	0-jet category
$gg \to H$ (125 GeV)	0.20 ± 0.04 ± 0.07	3.5 ± 0.2 ± 0.4	0.4 ± 0.1 ± 0.1	2.0 ± 0.1 ± 0.8	25±1±4
VBF H (125 GeV)	1.05 ± 0.03 ± 0.10	0.90 ± 0.03 ± 0.05	0.05 ± 0.01 ± 0.01	0.56 ± 0.02 ± 0.01	0.97±0.03±0.06
VH (125 GeV)	0.0	0.71 ± 0.03 ± 0.09	0.20 ± 0.01 ± 0.02	0.14 ± 0.01 ± 0.02	0.63±0.02±0.04
$Z/\gamma^* \to \tau\tau$ embedded	20 ± 2 ± 2	(0.41 ± 0.01 ± 0.02)×10^3	113 ± 5 ± 8	272 ± 8 ± 41	(10.71±0.05±0.07)×10^3
$Z/\gamma^* \to \ell\ell$	1.5 ± 0.6 ± 0.6	77 ± 7 ± 6	27 ± 4 ± 9	45 ± 5 ± 24	(0.17±0.01±0.01)×10^3
Top	4.8 ± 0.5 ± 0.6	132 ± 3 ± 6	27 ± 1 ± 6	31 ± 2 ± 10	284±4±15
Diboson	0.8 ± 0.1 ± 0.2	17.4 ± 0.7 ± 0.6	4.3 ± 0.4 ± 1.0	12 ± 1 ± 3	347±3±20
Backgrounds with fake leptons	2.7 ± 0.3 ± 0.9	22 ± 3 ± 4	19 ± 3 ± 6	24 ± 3 ± 10	(1.56±0.02±0.40)×10^3
Total background	29 ± 3 ± 2	(0.66 ± 0.01 ± 0.02)×10^3	190± 7 ± 15	(0.38±0.01 ± 0.05)×10^3	(13.07±0.06±0.41)×10^3
Observed data	28	673	176	371	13214

Table 6: Number of events after the $H \to \tau_{\text{lep}}\tau_{\text{lep}}$ selection for the four categories of the 8 TeV analysis in data and predicted number of background events, for an integrated luminosity of 13.0 fb^{-1}. Expectations for the Higgs boson signal ($m_H = 125$ GeV) are also given. Statistical and systematic uncertainties are quoted, in that order.

		$ee + \mu\mu + e\mu$		
	VBF category	Boosted category	VH category	1-jet category
$gg \to H$ (125 GeV)	1.3 ± 0.2 ± 0.4	12.4 ± 0.6 ± 2.9	2.5 ± 0.3 ± 0.6	7.0 ± 0.5 ± 1.6
VBF H (125 GeV)	3.63 ± 0.10 ± 0.02	3.36 ± 0.09 ± 0.30	0.21 ± 0.03 ± 0.02	1.82 ± 0.07 ± 0.18
VH (125 GeV)	0.01 ± 0.01 ± 0.01	2.20 ± 0.05 ± 0.22	0.64 ± 0.03 ± 0.09	0.44 ± 0.02 ± 0.05
$Z/\gamma^* \to \tau\tau$ embedded	47 ± 2 ± 1	(1.24 ± 0.01 ± 0.08)×10^3	393 ± 7 ± 26	(0.86 ± 0.01 ± 0.06)×10^3
$Z/\gamma^* \to \ell\ell$	14 ± 3 ± 2	(0.21 ± 0.02 ± 0.04)×10^3	(0.08 ± 0.01 ± 0.02)×10^3	(0.16 ± 0.01 ± 0.03)×10^3
Top	15 ± 2 ± 3	(0.39 ± 0.01 ± 0.07)×10^3	87 ± 4 ± 23	117 ± 5 ± 18
Diboson	3.6 ± 0.8 ± 0.6	55 ± 3 ± 10	15 ± 1 ± 4	40 ± 3 ± 7
Backgrounds with fake leptons	12 ± 2 ± 3	102 ± 7 ± 23	86 ± 4 ± 16	230 ± 8 ± 52
Total background	91 ± 5 ± 5	(2.01 ± 0.03 ± 0.12)×10^3	(0.66 ± 0.02 ± 0.05)×10^3	(1.40 ± 0.02 ± 0.08)×10^3
Observed data	98	2014	636	1405

Event Yields: ATLAS

Table 12: Number of events in the Boosted and VBF categories for the $e\tau_h$ and $\mu\tau_h$ 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.

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

Table 13: Number of events after the $H \to \tau_{\text{had}}\tau_{\text{had}}$ selection in data and predicted number of background events, for an integrated luminosity of 4.6 fb^{-1} and 13.0 fb^{-1} at $\sqrt{s}$ = 7 TeV and 8 TeV, respectively. Predictions for the Higgs boson signal (m_H = 125 GeV) are also given. The statistical and systematic uncertainties are quoted, in that order.

$H \to \tau_{\text{had}}\tau_{\text{had}}$	7 TeV analysis (4.6 fb^{-1})		8 TeV analysis (13.0 fb^{-1})	
	VBF category	Boosted category	VBF category	Boosted category
$gg \to H$ (125 GeV)	0.36 ± 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

Event Yields: CMS

Table 3: Observed and expected event yields, and expected signal efficiency in the $\mu\tau_h$ channel.

Process	*0-Jet*	*1-Jet high* p_T	*VBF*
Z→ $\tau\tau$	84833 ± 1927	4686 ± 232	109 ± 11
QCD	18313 ± 478	481 ± 38	48 ± 7
EWK	8841 ± 653	1585 ± 153	63 ± 9
$t\bar{t}$	11 ± 1	155 ± 11	5 ± 1
Total Background	111998 ± 2090	6908 ± 281	225 ± 16
H→ $\tau\tau$	- ± -	73 ± 13	11 ± 2
Observed	112279	7011	240

Signal Eff.

gg→ H	-	$1.99 \cdot 10^{-3}$	$8.51 \cdot 10^{-5}$
qq→ H	-	$4.09 \cdot 10^{-3}$	$3.46 \cdot 10^{-3}$
qq→ H$t\bar{t}$ or VH	-	$3.00 \cdot 10^{-3}$	$1.60 \cdot 10^{-5}$

Table 4: Observed and expected event yields, and expected signal efficiency in the $e\tau_h$ channel.

Process	*0-Jet*	*1-Jet high* p_T	*VBF*
Z→ $\tau\tau$	25161 ± 708	792 ± 62	47 ± 6
QCD	7706 ± 307	3 ± 0.3	17 ± 4
EWK	9571 ± 510	365 ± 53	44 ± 6
$t\bar{t}$	4 ± 0.5	47 ± 4	4 ± 1
Total Background	42443 ± 924	1207 ± 82	113 ± 9
H→ $\tau\tau$	- ± -	15 ± 3	5 ± 1
Observed	42481	1217	117

Signal Eff.

gg→ H	-	$3.94 \cdot 10^{-4}$	$3.33 \cdot 10^{-5}$
qq→ H	-	$1.10 \cdot 10^{-3}$	$1.78 \cdot 10^{-3}$
qq→ H$t\bar{t}$ or VH	-	$8.30 \cdot 10^{-4}$	$1.46 \cdot 10^{-6}$

Event Yields: CMS

Table 5: Observed and expected event yields, and expected signal efficiency in the $e\mu$ channel.

Process	*0-Jet*	*1-Jet high p_T*	*VBF*
$Z \rightarrow \tau\tau$	48882 ± 1282	1830 ± 105	61 ± 6
QCD	4374 ± 249	395 ± 36	19 ± 2
EWK	1185 ± 89	461 ± 44	7 ± 1
$t\bar{t}$	74 ± 5	1100 ± 66	19 ± 2
Total Background	54514 ± 1309	3785 ± 137	105 ± 7
$H \rightarrow \tau\tau$	- $\pm$ -	23 ± 4	5 ± 0.6
Observed	54694	3774	118
Signal Eff.			
$gg \rightarrow H$	-	$6.04 \cdot 10^{-4}$	$3.27 \cdot 10^{-5}$
$qq \rightarrow H$	-	$1.37 \cdot 10^{-3}$	$1.80 \cdot 10^{-3}$
$qq \rightarrow Ht\bar{t}$ or VH	-	$1.38 \cdot 10^{-3}$	$1.32 \cdot 10^{-5}$

Table 6: Observed and expected event yields, and expected signal efficiency in the $\mu\mu$ channe

Process	*0-Jet*	*1-Jet high p_T*	*VBF*
$Z \rightarrow \mu\mu$	1925174 ± 52051	685272 ± 27303	380 ± 38
$Z \rightarrow \tau\tau$	20669 ± 470	3888 ± 157	116 ± 9
QCD	1299 ± 226	561 ± 161	6 ± 11
EWK	4732 ± 1594	7827 ± 1297	22 ± 9
$t\bar{t}$	4708 ± 2110	2168 ± 522	15 ± 5
Total Background	1956582 ± 52120	699717 ± 27418	539 ± 42
$H \rightarrow \tau\tau$	- $\pm$ -	37 ± 5	5 ± 1
Observed	1956931	700020	548
Signal Eff.			
$gg \rightarrow H$	-	$9.50 \cdot 10^{-4}$	$7.23 \cdot 10^{-5}$
$qq \rightarrow H$	-	$1.85 \cdot 10^{-3}$	$1.03 \cdot 10^{-3}$
$qq \rightarrow Ht\bar{t}$ or VH	-	$2.95 \cdot 10^{-3}$	$1.39 \cdot 10^{-4}$

Event Yields: CMS

Table 7: Observed and expected event yields, and expected signal efficiency in the $\tau_h \tau_h$ channel.

Process	*1-Jet*	*VBF*
Z→ $\tau\tau$	428 ± 90	47 ± 28
QCD	210 ± 31	61 ± 10
EWK	41 ± 9	4 ± 1
$t\bar{t}$	29 ± 6	2 ± 2
Total Background	709 ± 95	114 ± 30
H→ $\tau\tau$	9 ± 4	4 ± 2
Observed	718	120

Signal Eff.

gg→ H	$2.52 \cdot 10^{-4}$	$4.99 \cdot 10^{-5}$
qq→ H	$5.93 \cdot 10^{-4}$	$1.20 \cdot 10^{-3}$
qq→ H$t\bar{t}$ or VH	$9.13 \cdot 10^{-4}$	$3.59 \cdot 10^{-5}$

Systematics

ATLAS

- Theory uncertainties
  - 8-25% gg→H depending on jet multiplicity
  - 24% per jet for W, Z, di-boson background
  - 3-6% QCD scale for top backgrounds
  - PDF 8% for gluon, 4% for quark
  - total uncertainty 10-30% for VBF channel
- Dominant detector uncertainty
  - jet energy scale 2-12%
  - τ-energy scale 2-15%
- Uncertainty on backgrounds due to mis-identification of lep or had can be up to 50% in lep-had VBF

CMS

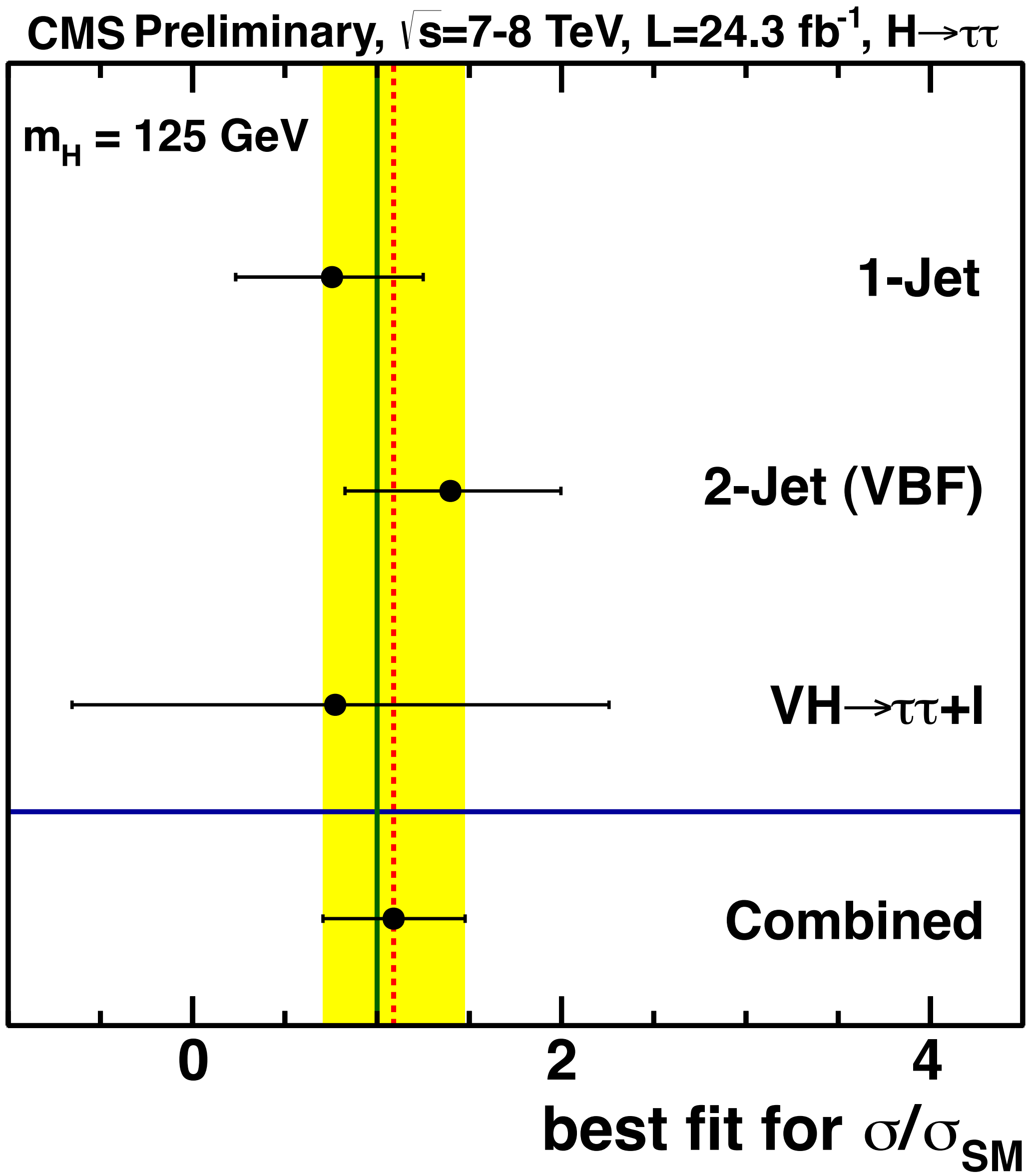
- Theory (PDF & scales)
  - VBF production 4%
  - up to 30% in ggF in VBF category
- Background:
  - l→had misid of 20-30%
  - jet to had misid of 20% propagates to 40%
  - 30% on W+jets
  - QCD 6-35%
- Experimental:
  - 8% τ_h id
  - MET scale 5%
- Constraint fit:
  - Tau ID & Trigger: 0.0 ± 8.0% → −5.5 ± 1.9%
  - Tau Energy Scale ($\mu\tau_h$ channel): 0.0 ± 3.0% → −0.8 ± 0.2%
  - Tau Energy Scale ($e\tau_h$ channel): 0.0 ± 3.0% → −1.3 ± 0.5%

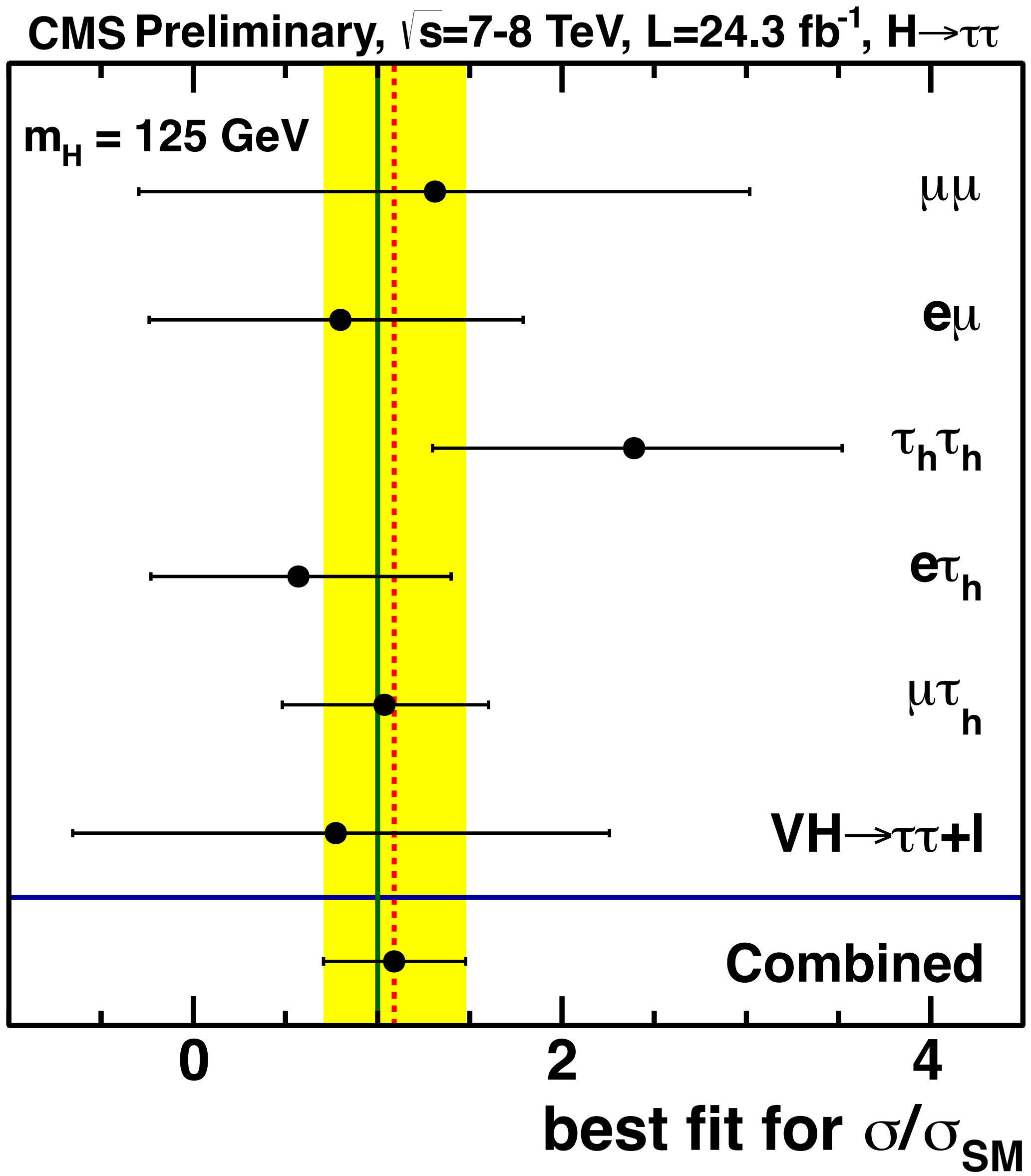
Systematics: CMS

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	$\pm 20\%$	$\pm 20\%$	$\pm 20\%$	$\pm 40\%$

Theory Uncertainties (SM)		Propagation into Limit Calculation		
Uncertainty	Uncert.	*0-Jet*	*1-Jet*	*VBF*
PDF (†*)	-	-	$\pm 2 - 8\%$	$\pm 2 - 8\%$
$\mu_r/\mu_f(gg \to H)$ (†*)	-	-	$\pm 10\%$	$\pm 30\%$
$\mu_r/\mu_f(qq \to H)$ (†*)	-	-	$\pm 4\%$	$\pm 4\%$
$\mu_r/\mu_f(qq \to VH)$ (†*)	-	-	$\pm 4\%$	$\pm 4\%$
UE & PS (†*)	-	-	$\pm 4\%$	$\pm 4\%$

Signal Strength: CMS





Signal Probability