The study Higgs decaying into tau tau with CMS

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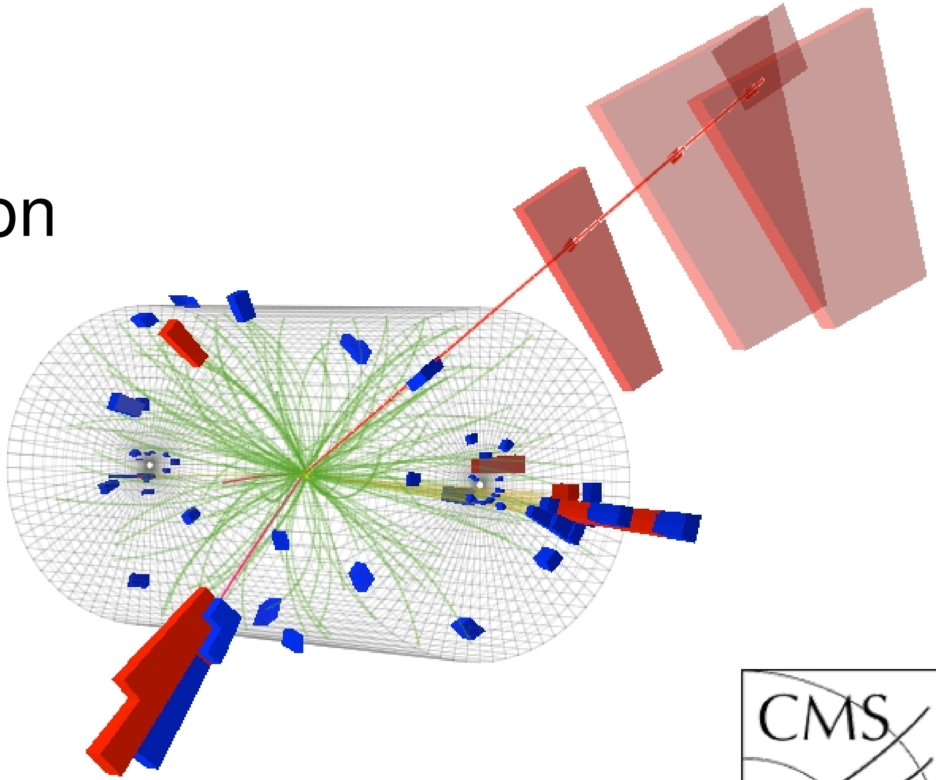
Michał Bluj
LLR/École Polytechnique – CNRS/IN2P3
on behalf of the CMS Collaboration

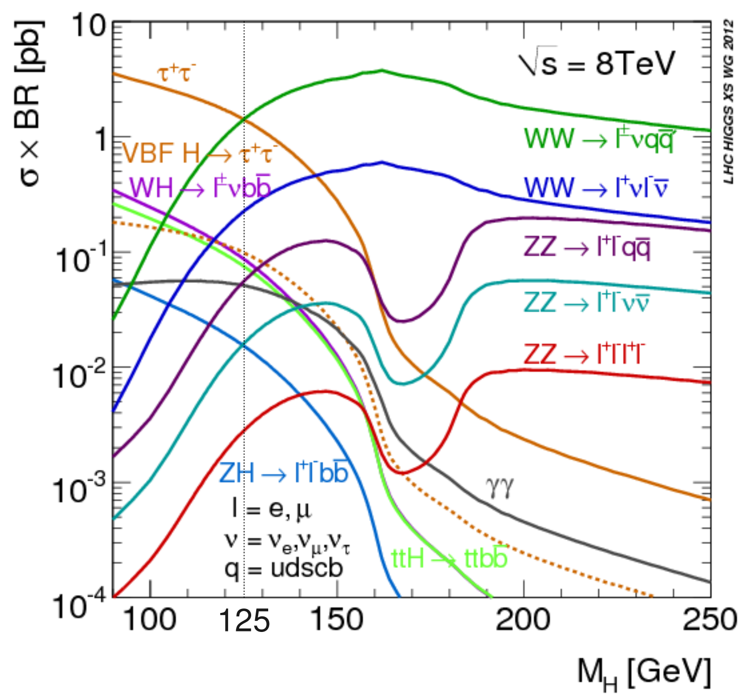


Documentation: CMS PAS HIG-13-004, CMS PAS HIG-12-053

Outline

- Observation of a new boson with mass around 125 GeV consistent with the standard model scalar driven by the bosonic decay modes: **H→ZZ→4l**, **H→γγ**
- **Observation of the new boson decaying into tau tau is an important test of compatibility with the standard model**
- Decays into tau leptons interesting also in frame of extended models (e.g. MSSM)*

- This talk: overview of the H→ττ search with CMS
  - Search strategy strategy
  - Analysis tools
  - Discussion of results



* Not discussed here, see A. Nayak's talk

Analysis overview

- 5 channels for ggH and VBF
  - $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$ $e\mu$, $\mu\mu$
- 3 channels for VH (l=e/μ, L=e/μ/τ_h)
  - W(l)H(lτ_h/$\tau_h\tau_h$), Z(ll)H(LL)

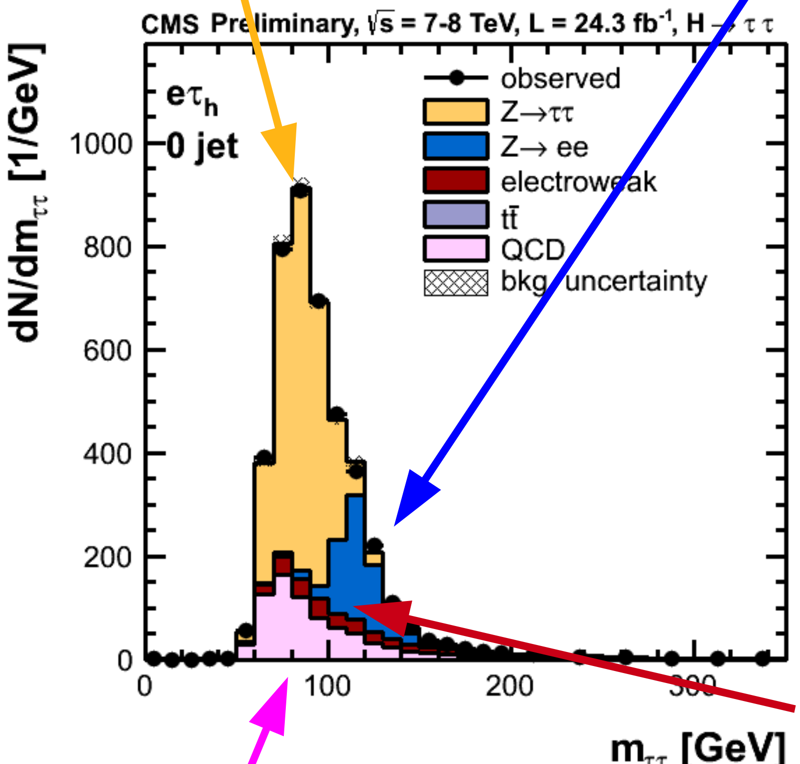
- Analysis strategy
  - Require well identified and isolated leptons, taus (τ_h)
  - Topological cut to suppress background (e.g. m_T against W+jets in $e\tau_h$/$\mu\tau_h$)
  - Categorisation based on jet multiplicity and p_T of τ_h/μ
  - Simultaneous max-likelihood fit of di-tau mass ($m_{\tau\tau}$) shape (binned) in all channels and categories

Z→ττ

Embedding: Z→μμ data with μ replaced by simulated τ

Z→ll

- l/jet→τ_h fakes
- Shape from simulation corrected for yield in visible mass region



W+jets

- Jet→τ_h fakes
- Suppressed by topological cuts (e.g. m_T)
- Simulation normalized to data in sideband

QCD

- Jet→l/τ_h fakes
- Suppressed by isolation
- Same-sign data (corrected for OS/SS ratio)

Event categories

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

No. of jets →

↓ $p_T(\tau_h/\mu)$

0-jet, low-p_T
- Large background
- **No fit for signal**, constrain uncertainties

1-jet, low-p_T
- Enhancement due to jet requirement
- Better mass resolution

2-jet, VBF
- $\geq$ 2 jets
- $M_{jj} > 500$ GeV
- $\Delta\eta_{jj} > 3.5$
- Central jet veto
- VBF H signal enhanced

0-jet, high-p_T
- Large background
- **No fit for signal**, constrain uncertainties

1-jet, high-p_T
- Enhancement due to jet requirement
- Better mass resolution
- $Z\rightarrow\tau\tau$ suppressed by high-p_T(tau)

$\tau_h\tau_h$

1-jet
- $p_T(\tau\tau) > 140$ GeV
- Better mass resolution
- QCD suppressed

2-jet, VBF
- $p_T(\tau\tau) > 110$ GeV
- $M_{jj} > 250$ GeV
- $\Delta\eta_{jj} > 2.5$
- Central jet veto

Event categories

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

No. of jets

$p_T(\tau_h/\mu)$

0-jet, low-p_T
- Large background
- **No fit for signal**, constrain uncertainties

0-jet, high-p_T
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- **No fit for signal**, constrain uncertainties

No fit for signal

1-jet, low-p_T
- Enhancement due to jet requirement
- Better mass resolution

1-jet, high-p_T
- Enhancement due to jet requirement
- Better mass resolution
- $Z \rightarrow \tau\tau$ suppressed by high-p_T(tau)

Constrain uncertainties

2-jet, VBF
- ≥ 2 jets
- M_{jj} > 500 GeV
- $\Delta\eta_{jj}$ > 3.5
- Central jet veto
- VBF H signal enhanced

$\tau_h\tau_h$

1-jet
- $p_T(\tau\tau)$ > 140 GeV
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2-jet, VBF
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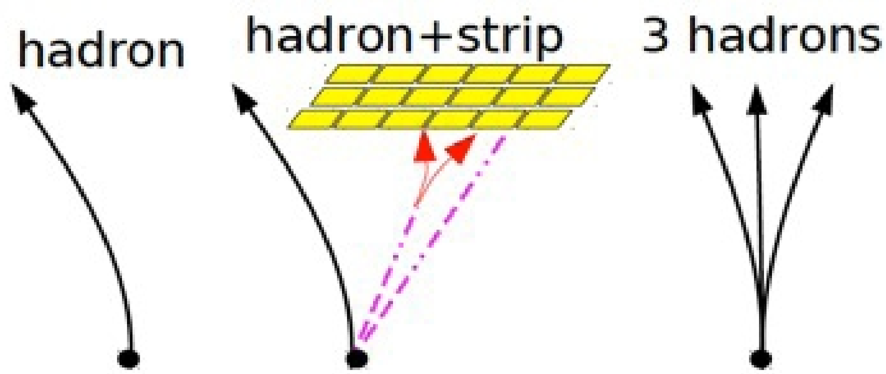
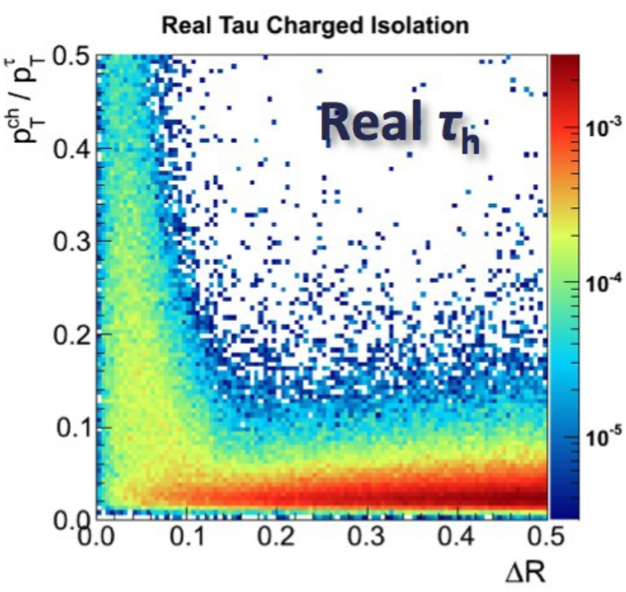
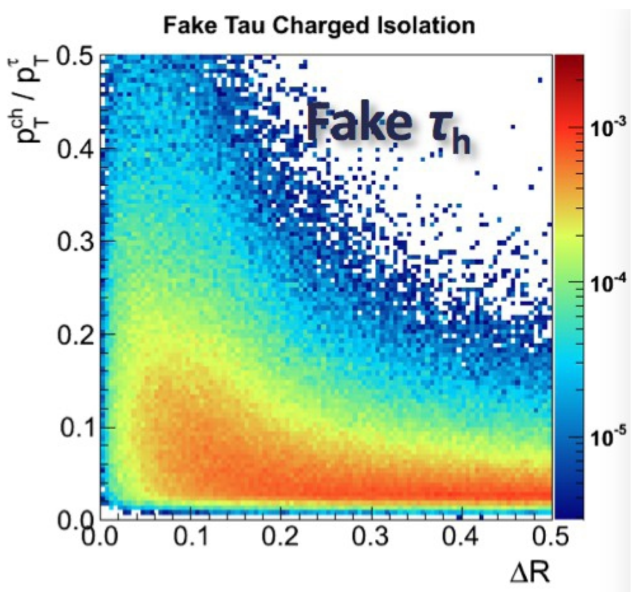
- M_{jj} > 250 GeV
- $\Delta\eta_{jj}$ > 2.5
- Central jet veto

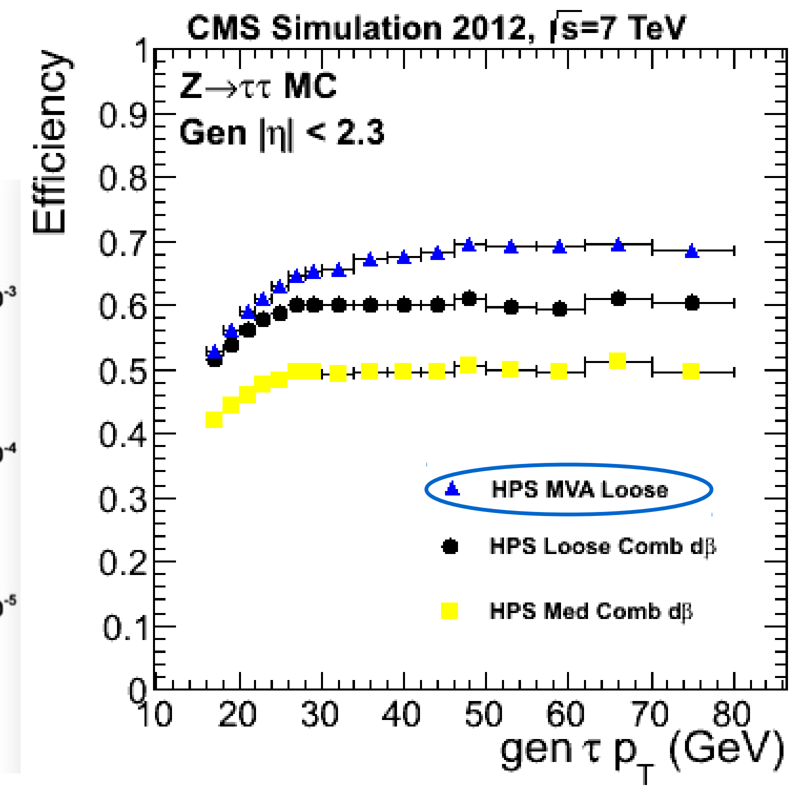
Identification of τ_h

- Reconstruction of individual decay modes (Hadron-plus-strip algorithm. HPS)
  - Particles by Particle Flow algorithm used
  - 1-prong, 1-prong+π^0's, 3-prongs
- Isolation
  - Multivariate discriminant based on Σp_T of particles in rings around τ_h
  - Pileup mitigated with FastJet rho used by isolation MVA
- Additional selection to reject leptons



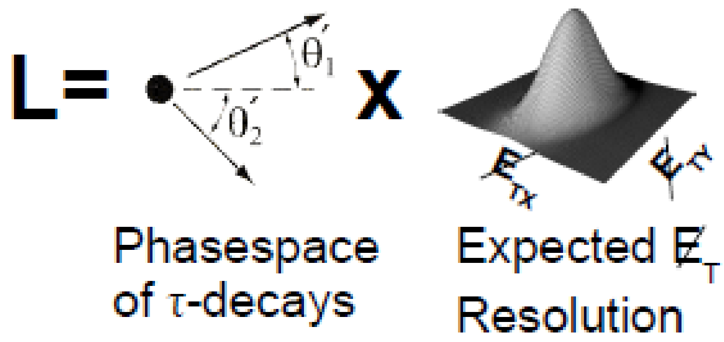




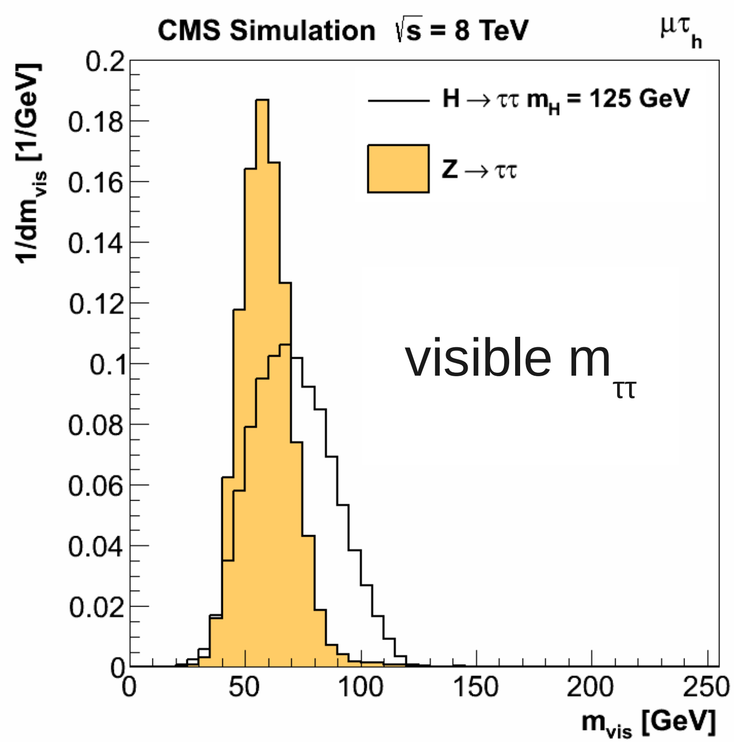


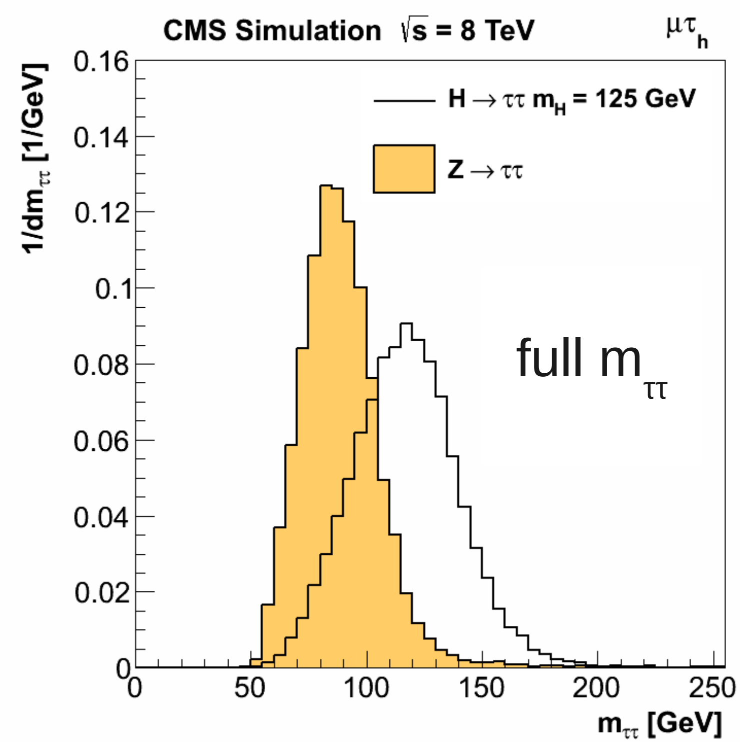
Di-tau mass estimation

- Neutrinos present in tau decays ⇒ invisible component
- Use maximum likelihood based full di-tau mass ($m_{\tau\tau}$) estimate
  - Computed on event-by-event basis using four-momenta of visible decay products, E_x^{miss}, E_y^{miss}, expected E_T^{miss} resolution



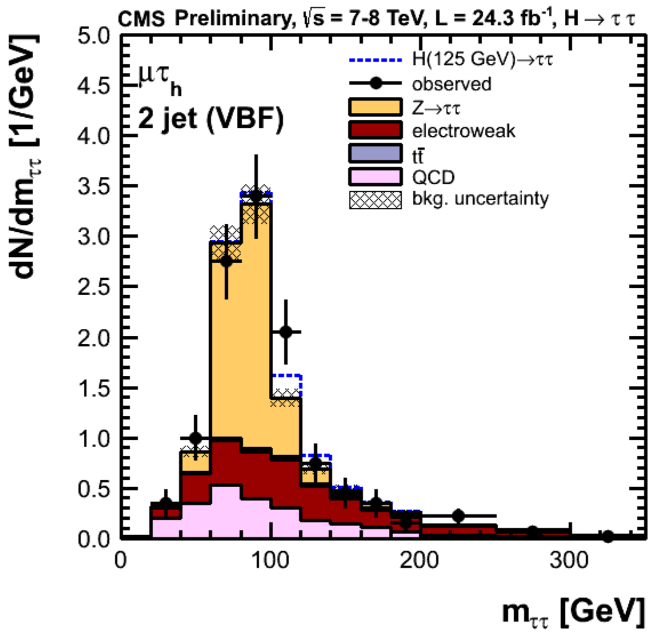
- 15-20% resolution on reconstructed $m_{\tau\tau}$
  - better Z/H separation than with the visible mass

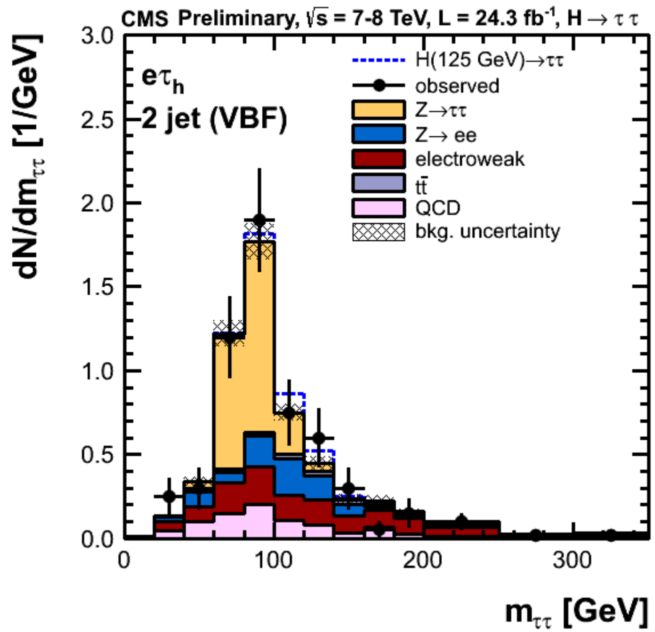


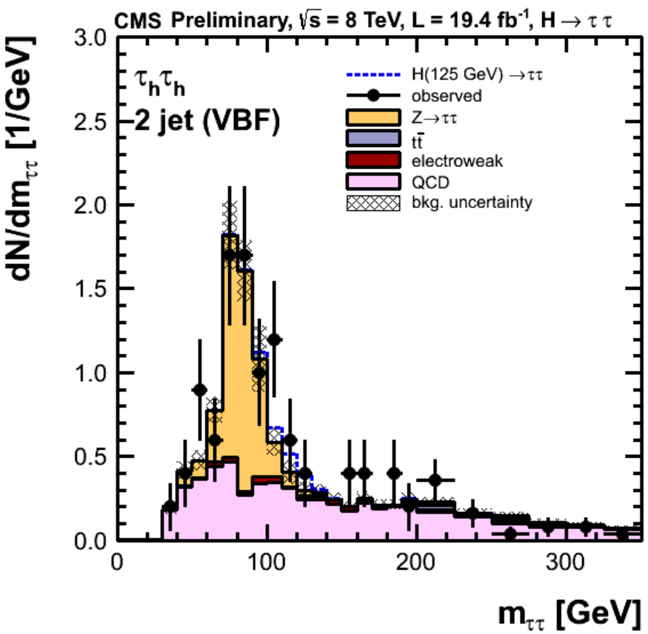


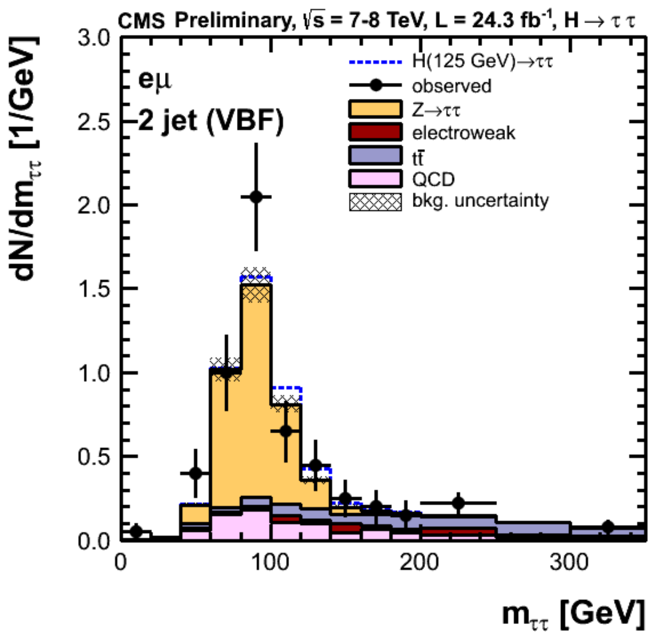
Mass distributions

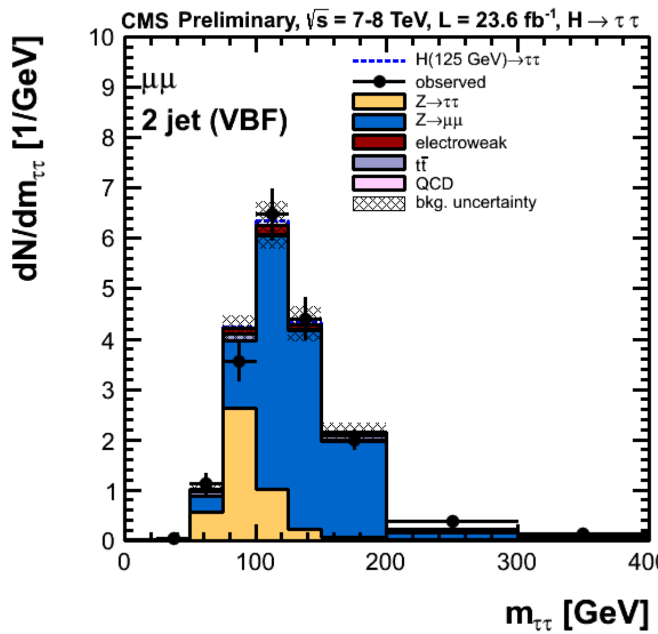
- **2-jet VBF**
  - Best S/B category
  - VBF H signal enhanced





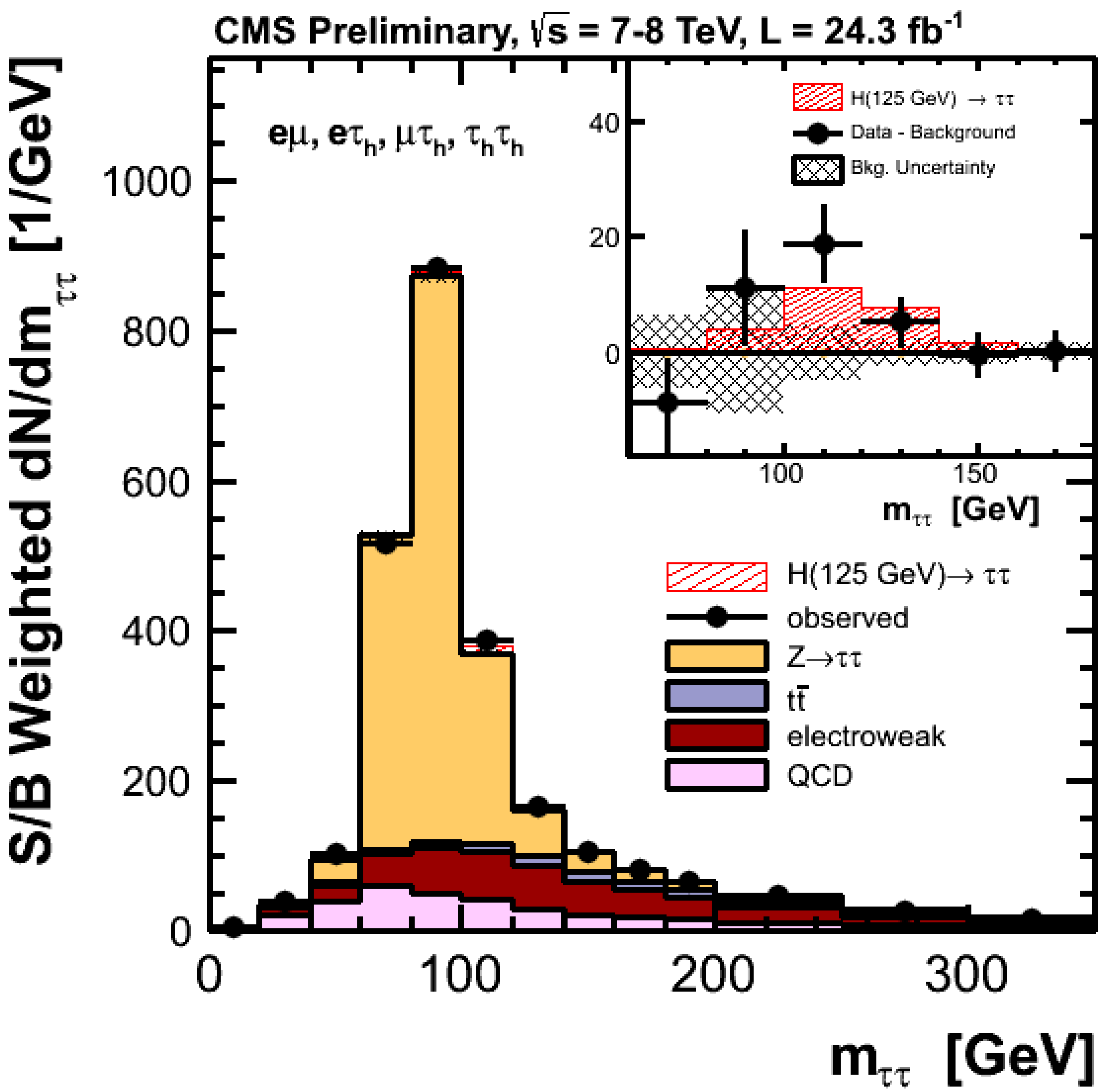






Combined mass distribution

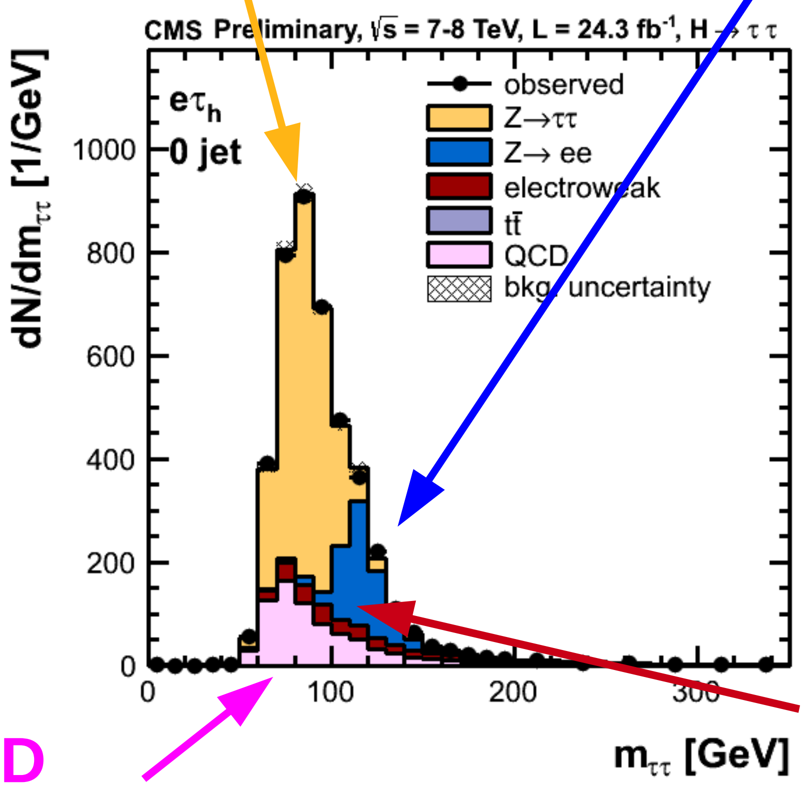
- Combine channels and categories weighting each by S/B
  - S – expected signal
  - B – fitted background
  - Both S and B in window around peak at 125 GeV Higgs



Main systematics

$Z \to \tau\tau$

- 8% tau-Id efficiency
- Category efficiency 0-8%
- Tau energy scale 3% (shape)



$Z \to ll$

- Normalization 20%/30% for ee/μμ

W+jets

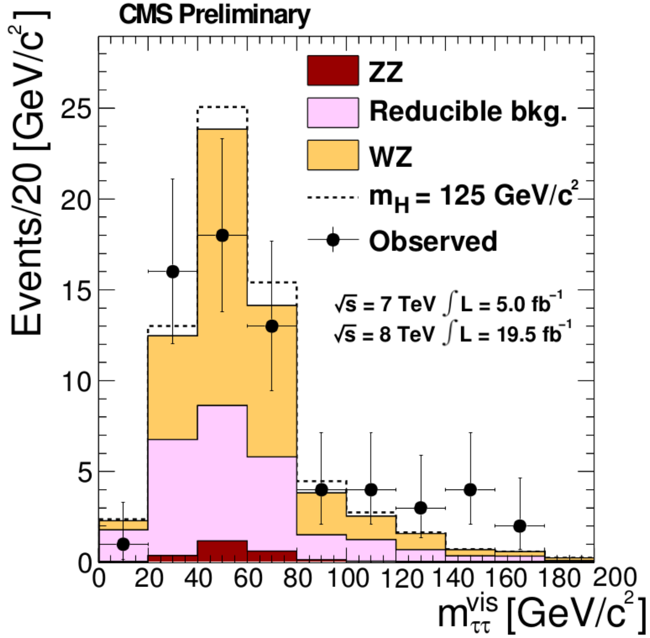
- Normalization 10-20%
- Includes
  - Statistical unc. In control region
  - Unc. of extrapolation factor
  - Unc. of MC bias of topological variable

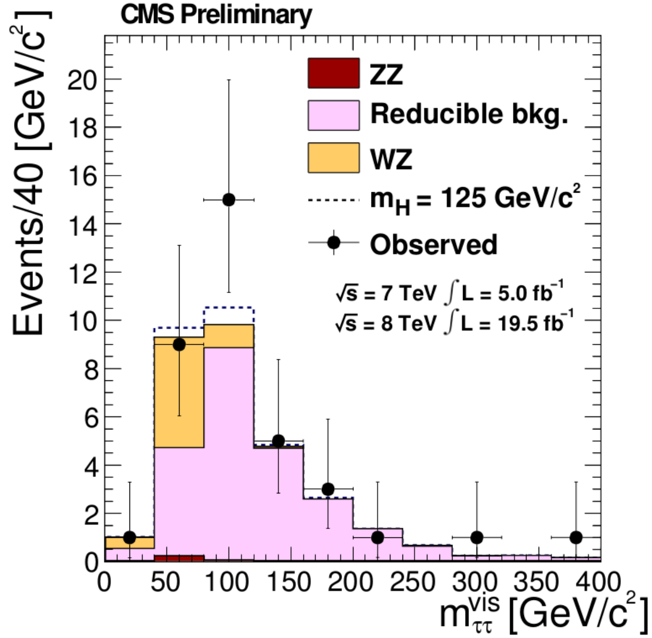
QCD

- Normalization 10%
- Shape (bin-by-bin) uncertainty in low stat categories

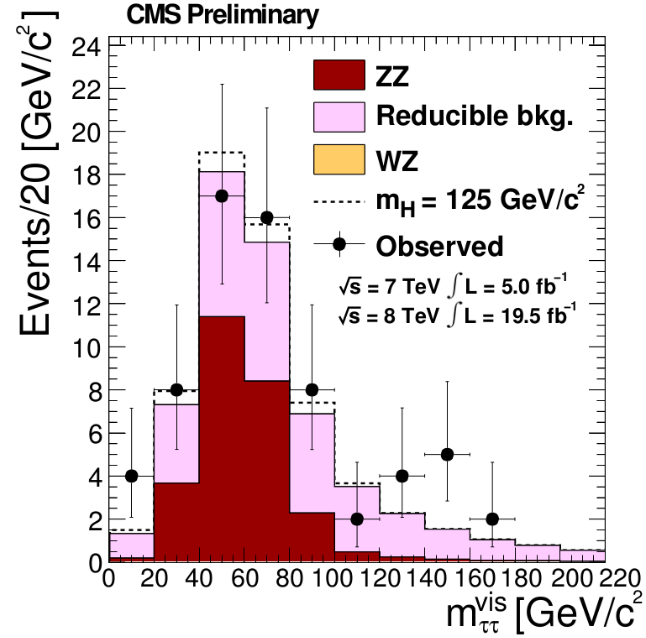
VH analysis

WH channel





ZH channel



W(l)H(lτ_h)

- Main background irreducible WZ
- Same-sign of two leptons to suppress $Z \rightarrow ll$+(jet$\rightarrow \tau_h$ fake)

W(l)H($\tau_h \tau_h$)

- Main when one or two fake τ_h (reducible)
- $Z \rightarrow ll$+2(jet$\rightarrow \tau_h$) fakes reduced by vetoing events with 2nd lepton

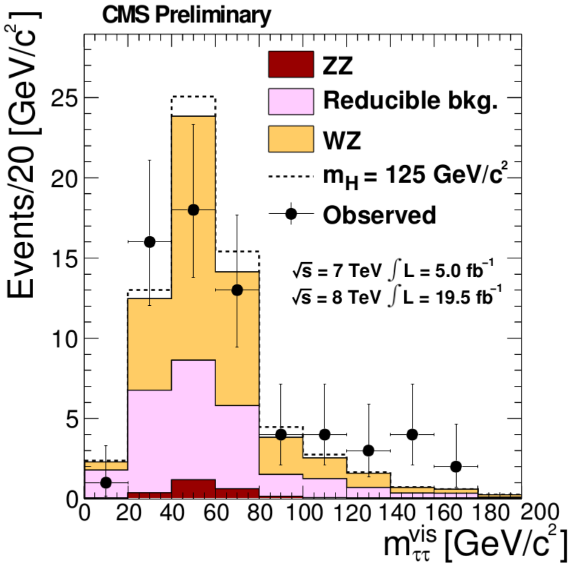
Z(ll)H(LL)

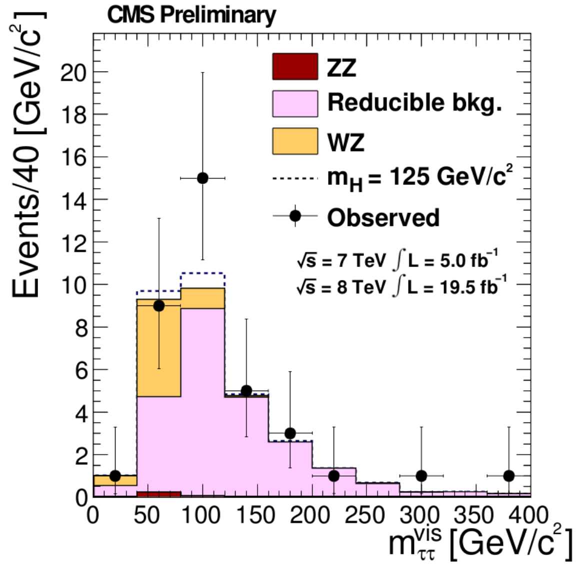
- Four final states
  - $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, $e\mu$
- Require $Z \rightarrow ll$ candidate
- Irreducible background from ZZ, reducible from $Z \rightarrow ll$+2jets

All VH channels: Reducible backgrounds with jet$\rightarrow$l/τ_h fakes measured from data using fake-rate method

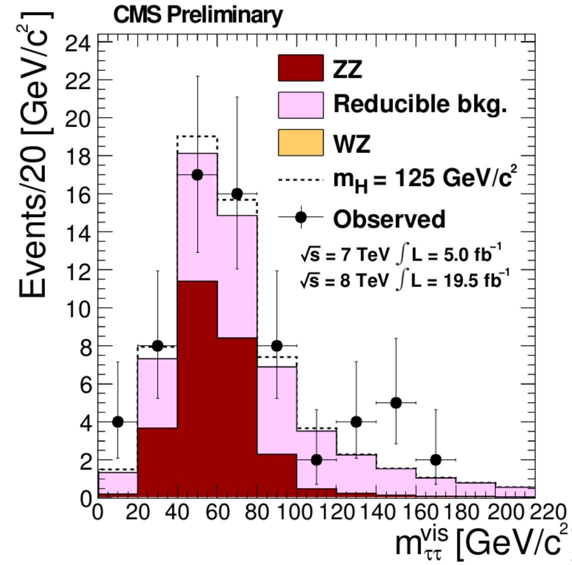
VH results

WH channel



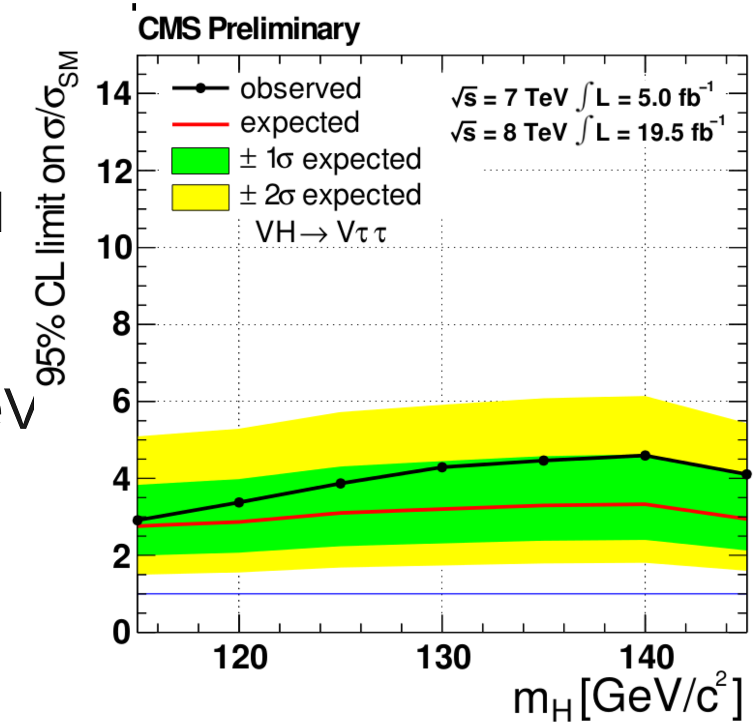


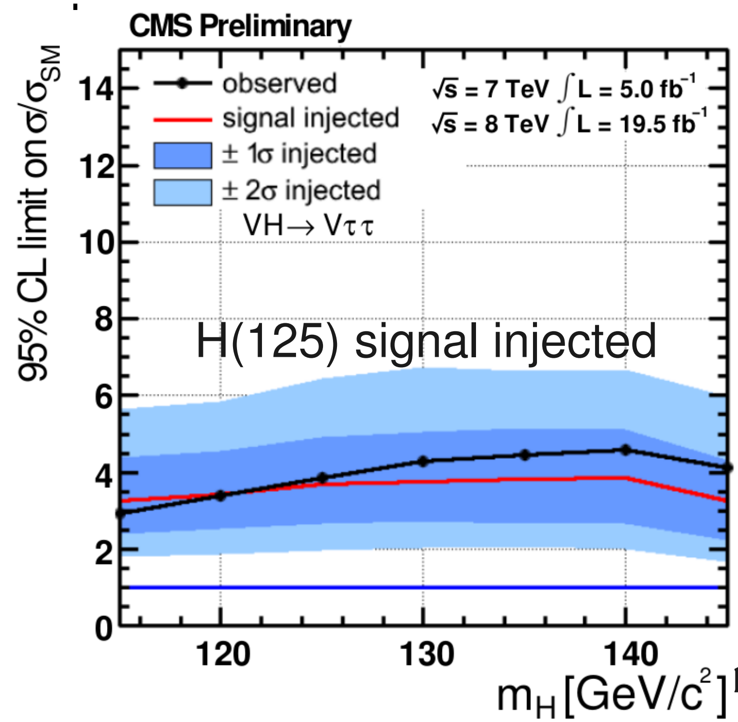
ZH channel



Combined VH limit

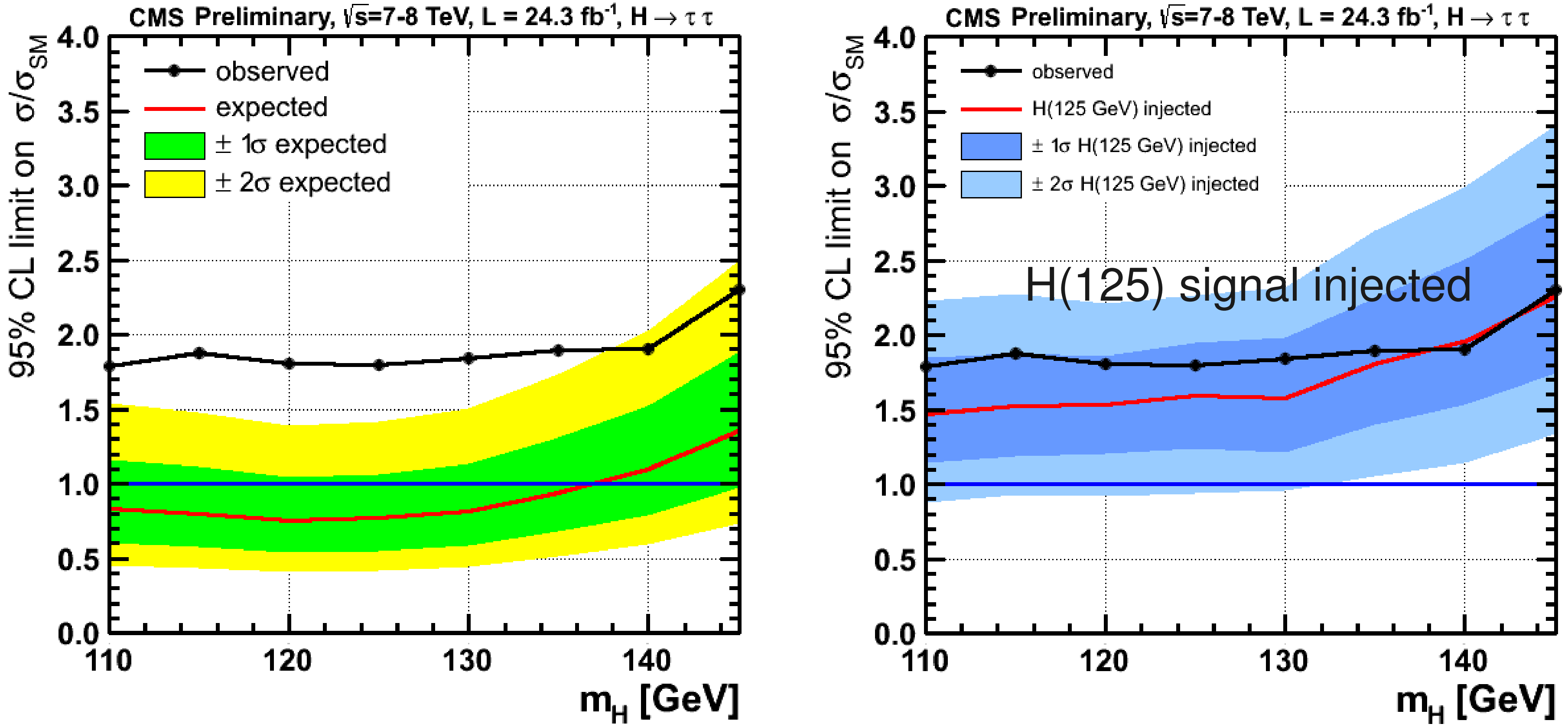
- Sensitivity of ~3xSM
- Small excess consistent with both SM Higgs at 125 GeV and background





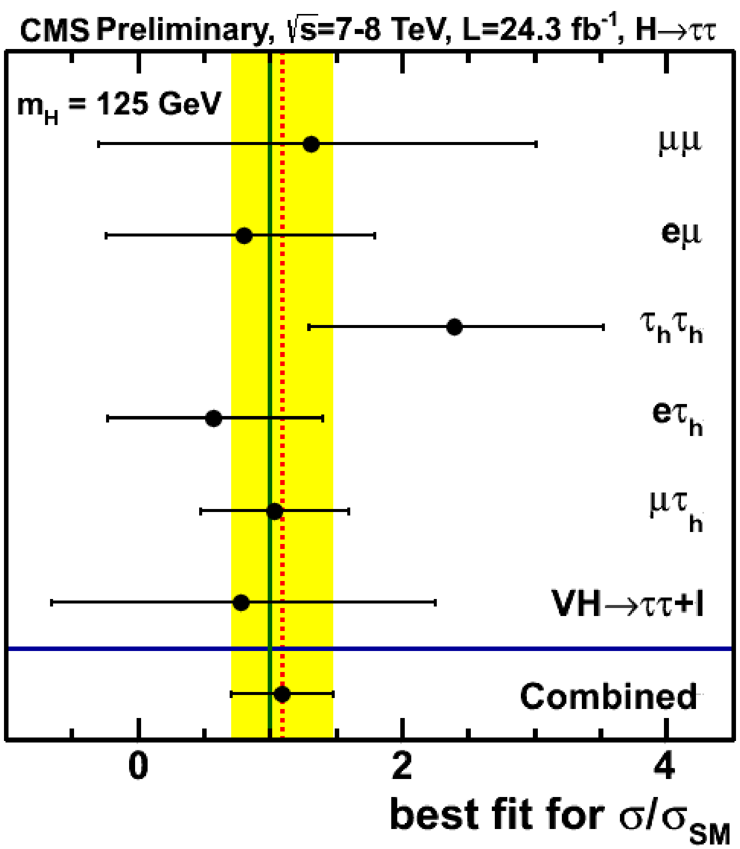
Limits

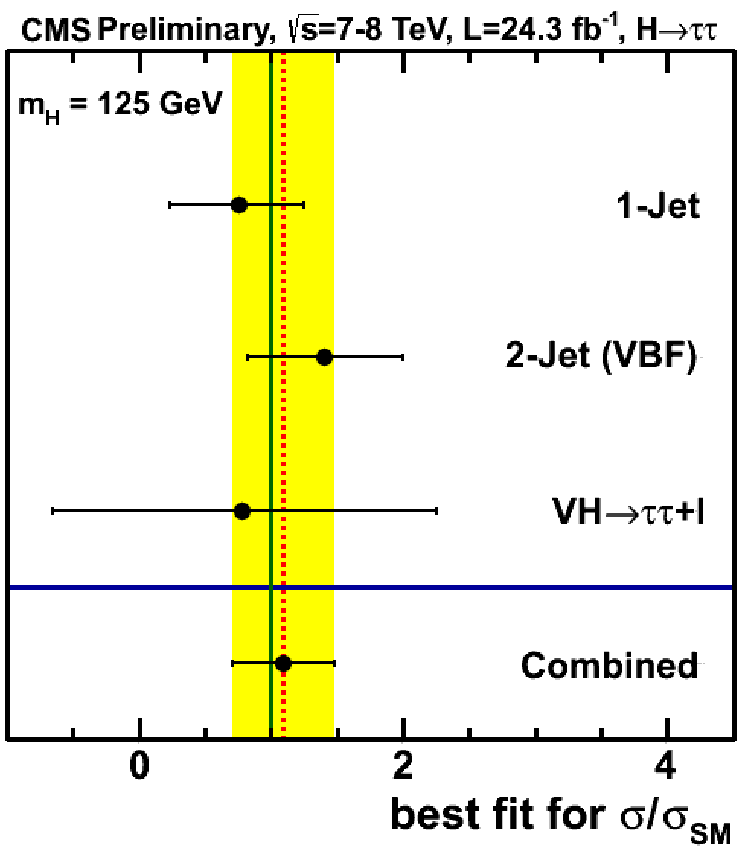
- Combining all channels (VH included)
- Observed exclusion limit of **1.81 x SM** at 125 GeV, while **0.76 x SM** expected
- Result consistent with SM Higgs expectation



Signal cross section

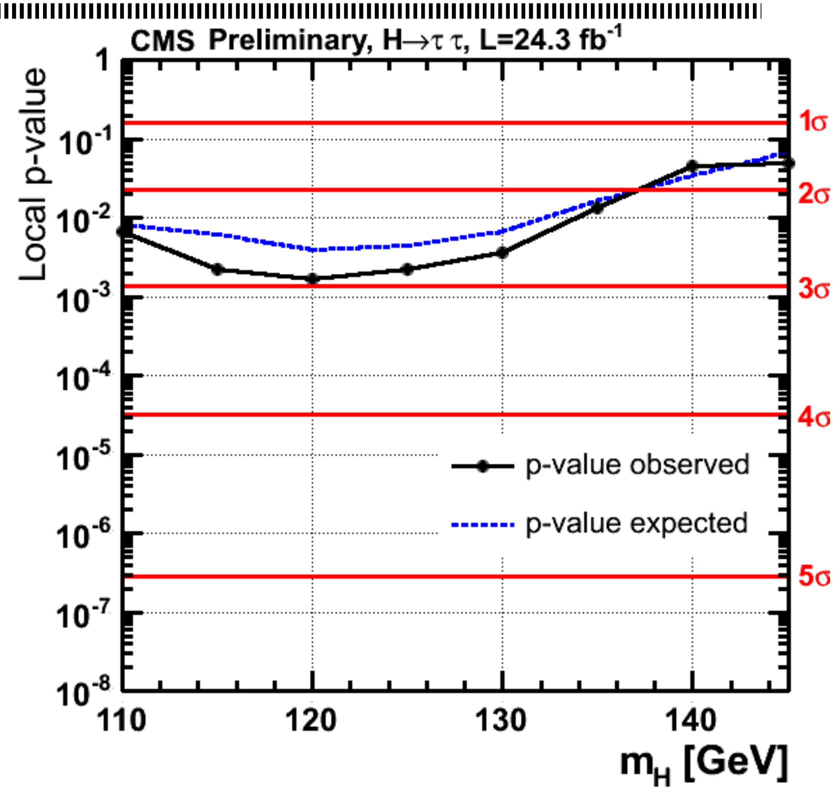
- Signal strength (σ/σ_{SM}) by channel (left) and by category (right) at 125 GeV
- Combined signal strength $\boldsymbol{\sigma/\sigma_{SM} = 1.1 \pm 0.4}$
- Consistent between channels and categories

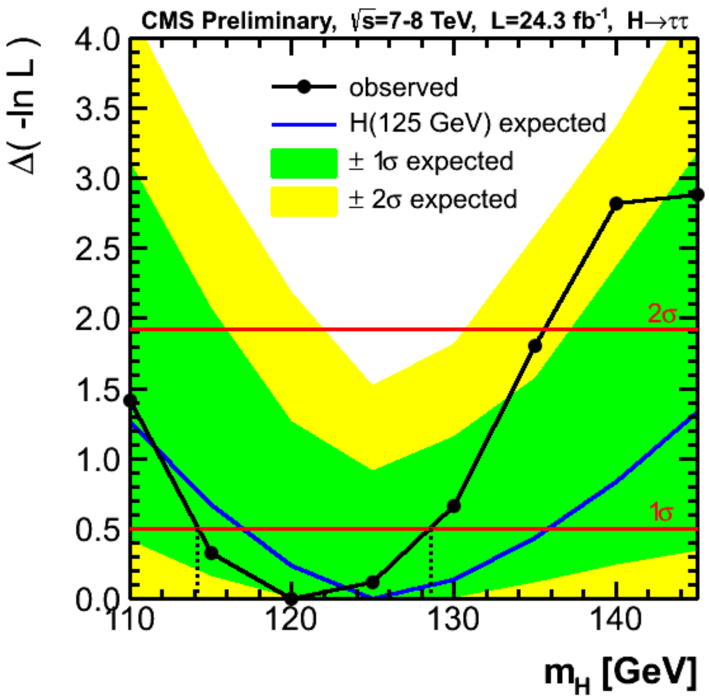




Significance & mass

- Observe broad excess over whole probed mass range
- Consistent with SM Higgs expectation
- **Max. significance of 2.93σ at 120 GeV**
- **2.85σ obs. (2.62σ exp.) at 125 GeV**

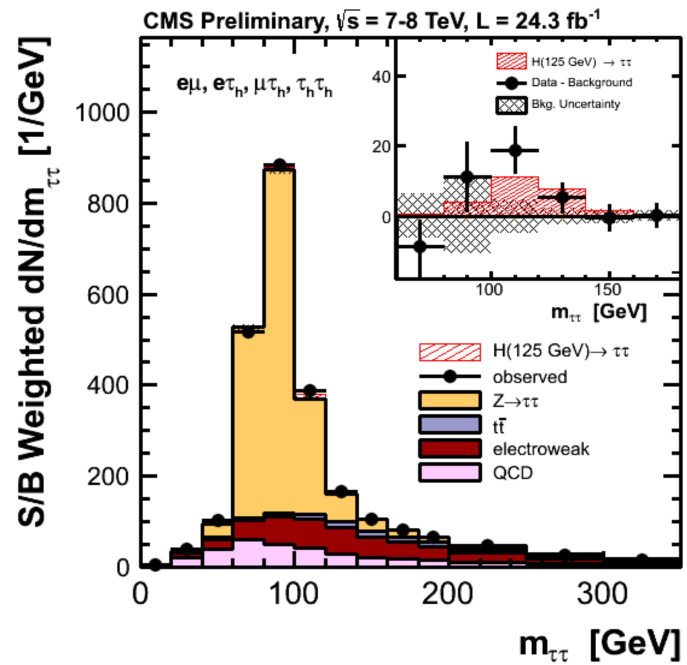


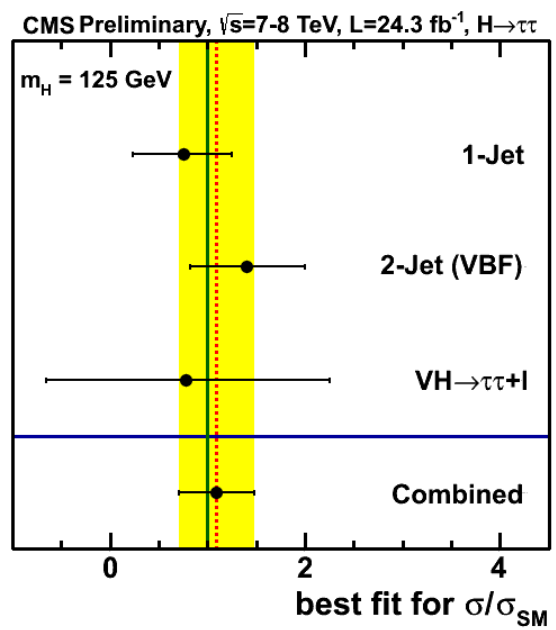


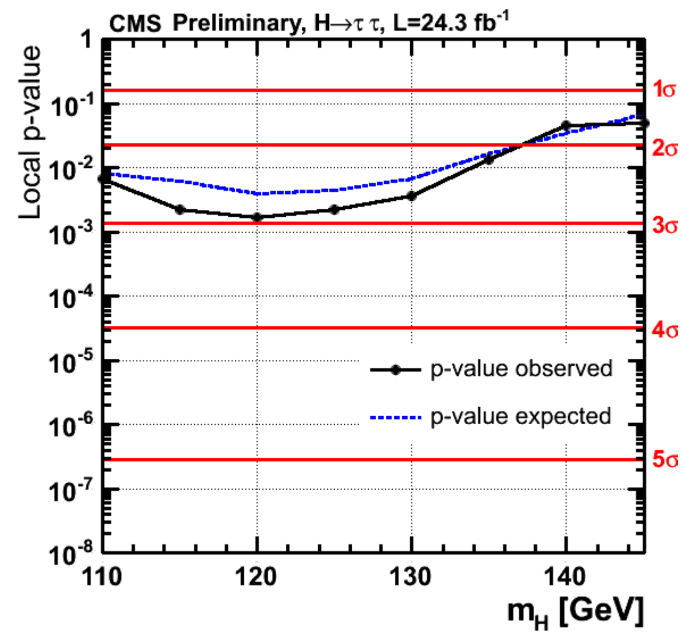
- Most favoured mass of the observed excess
  - From likelihood fit
- $m_H = 120^{+9}_{-7}$(stat+sys) GeV
  - Consistent with $m_H(4l) = 125.8 \pm 0.5$ GeV

Conclusions

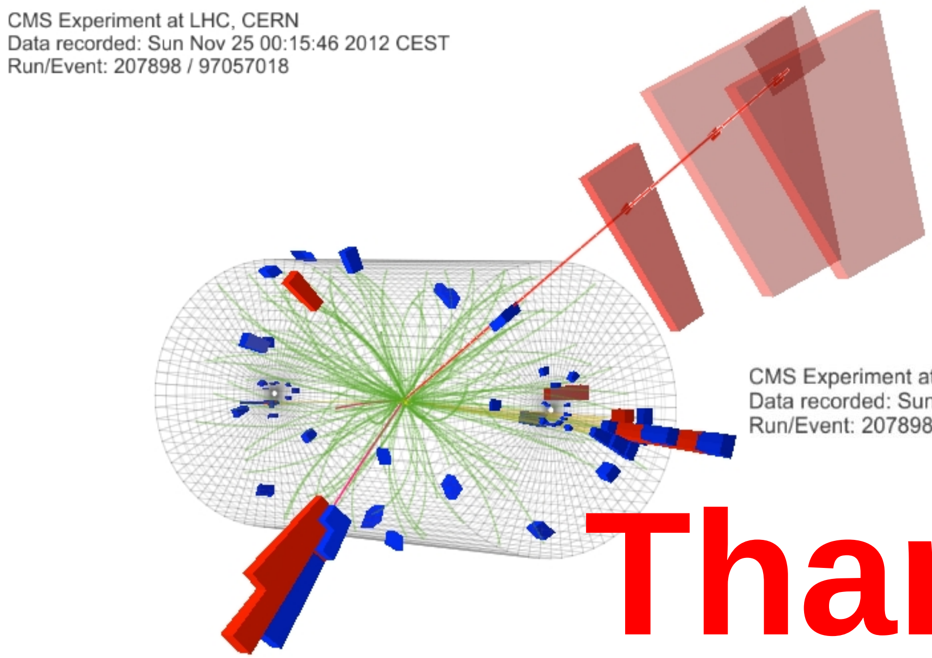
- Search for **H → ττ** with the full 2011+2012 dataset collected by CMS was shown
- A wide excess compatible with SM Higgs is observed
  - Obs. limit of 1.81xSM at 125 GeV, while 0.76xSM exp.
  - Signal strength of 1.1 ± 0.4
  - Significance of 2.85σ obs. (2.62 exp.) at 125 GeV
- **Strong indication that the new particle decays to taus!**



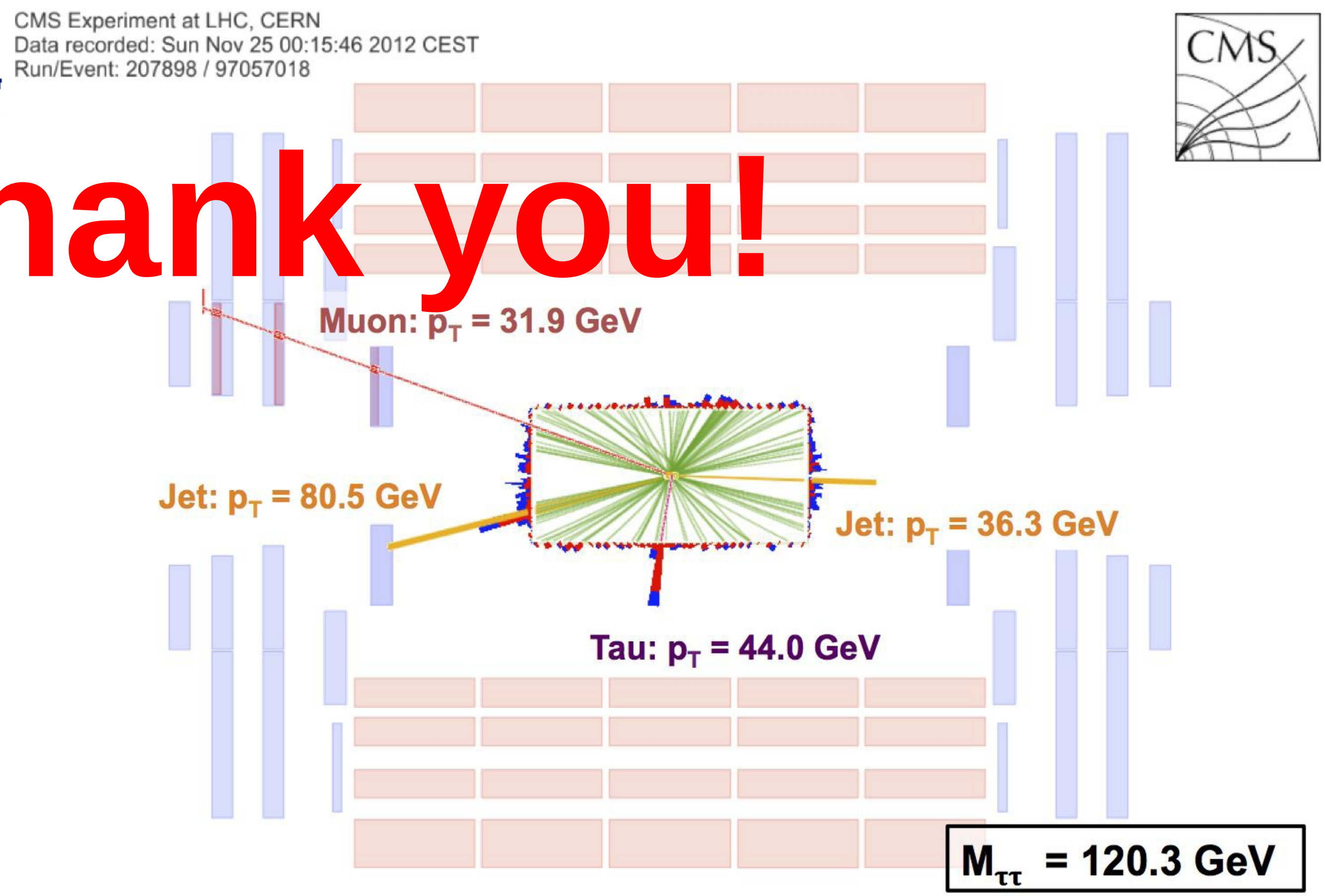




VBF H $\rightarrow \mu\tau_h$ event candidate

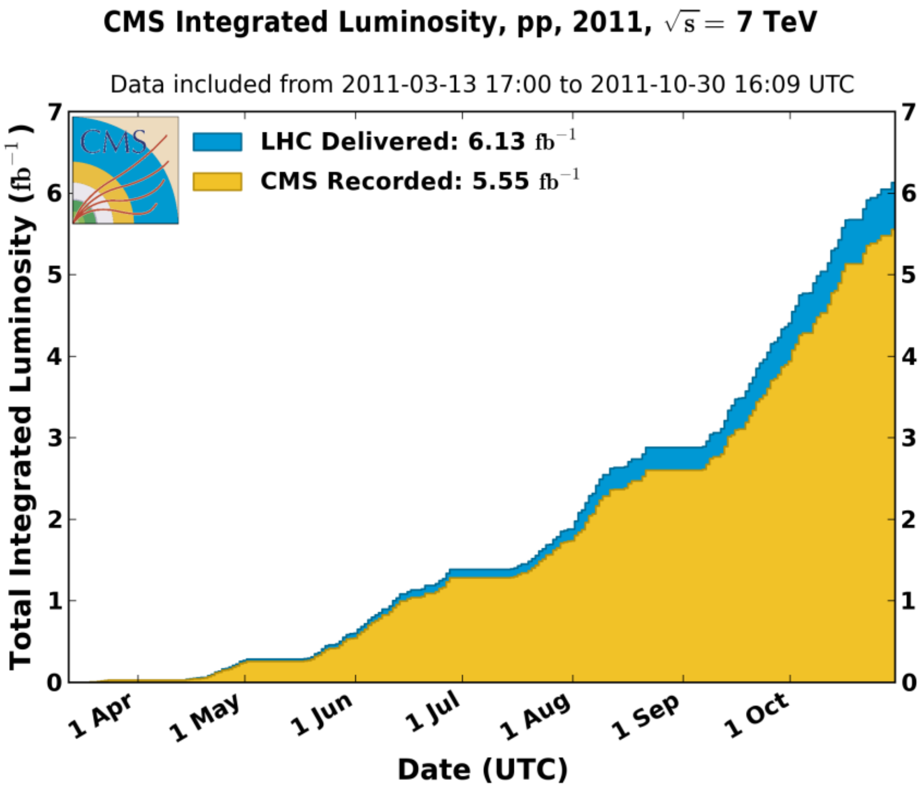


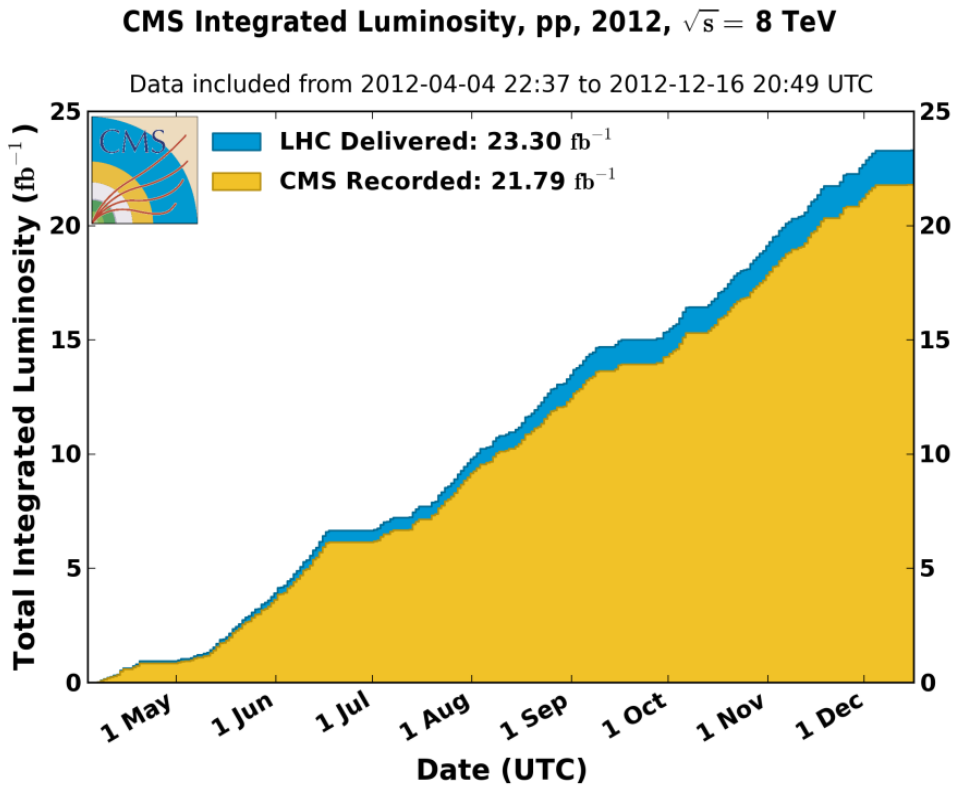
Thank you!



Additional material

Luminosity

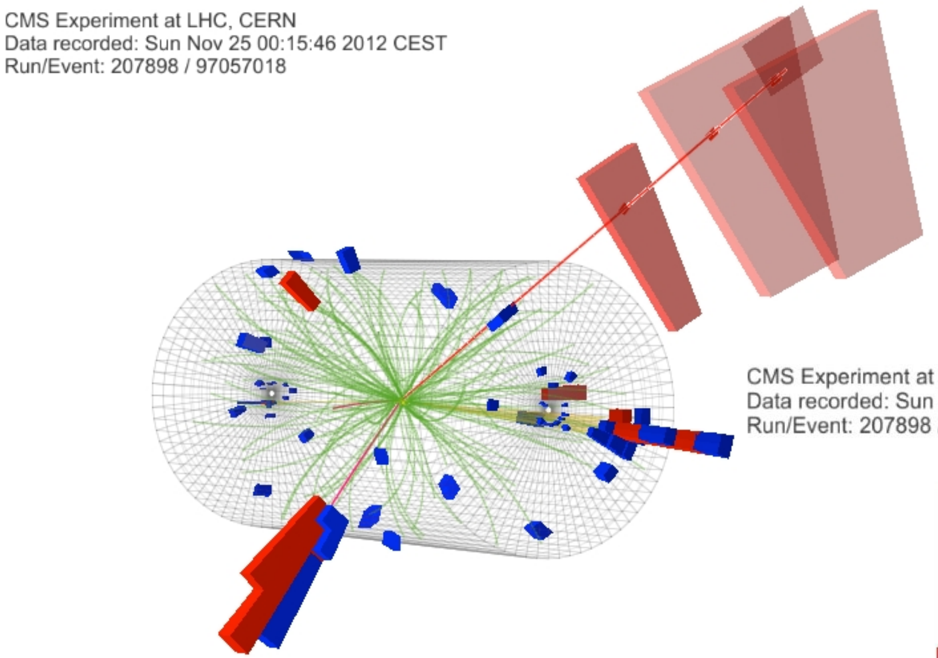


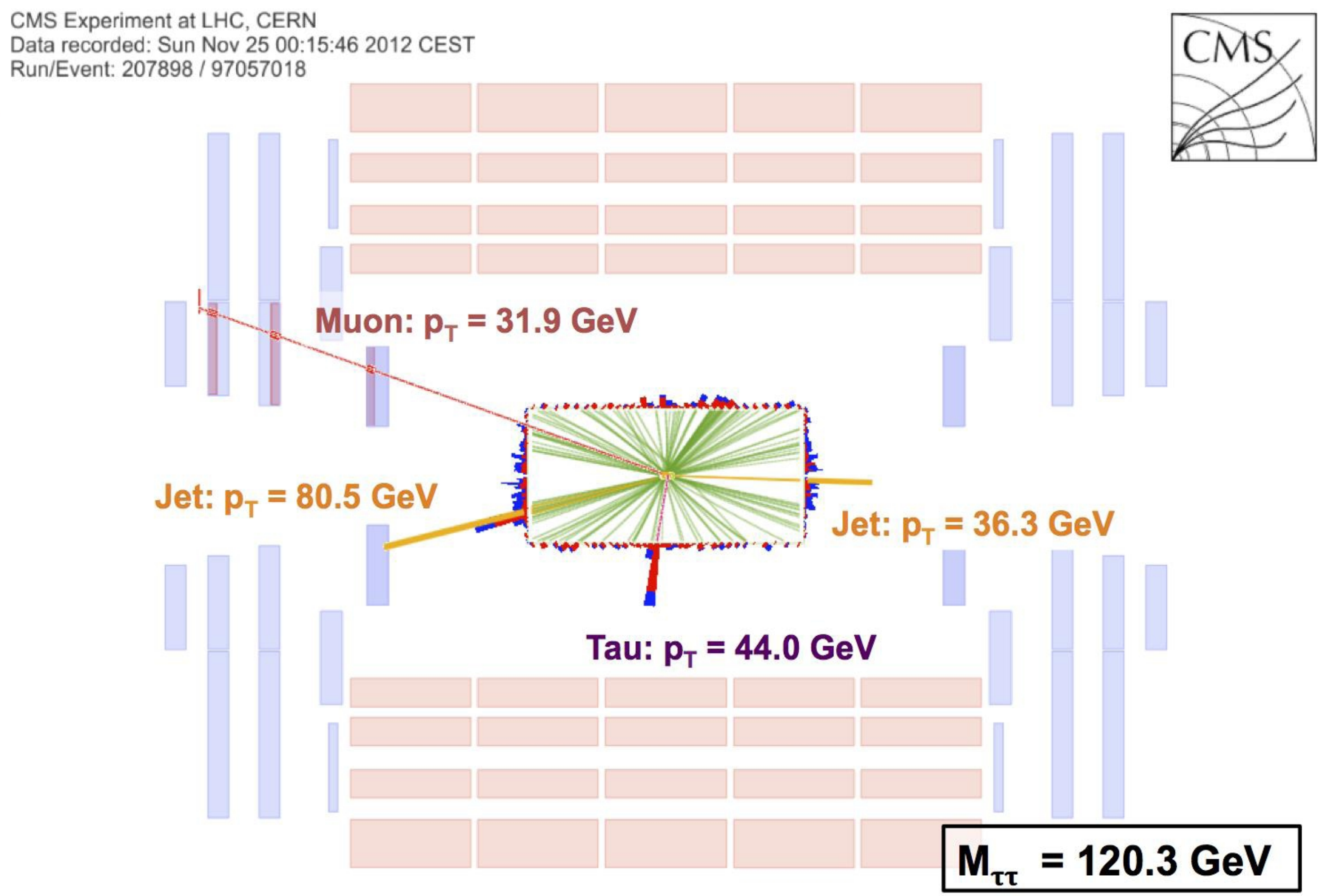


After high quality selection

- 4.9/fb at 7 TeV (2011)
- 19.4/fb at 8 TeV (2012)

VBF $H \rightarrow \mu\tau_h$ event candidate





Systematic uncertainties (exp)

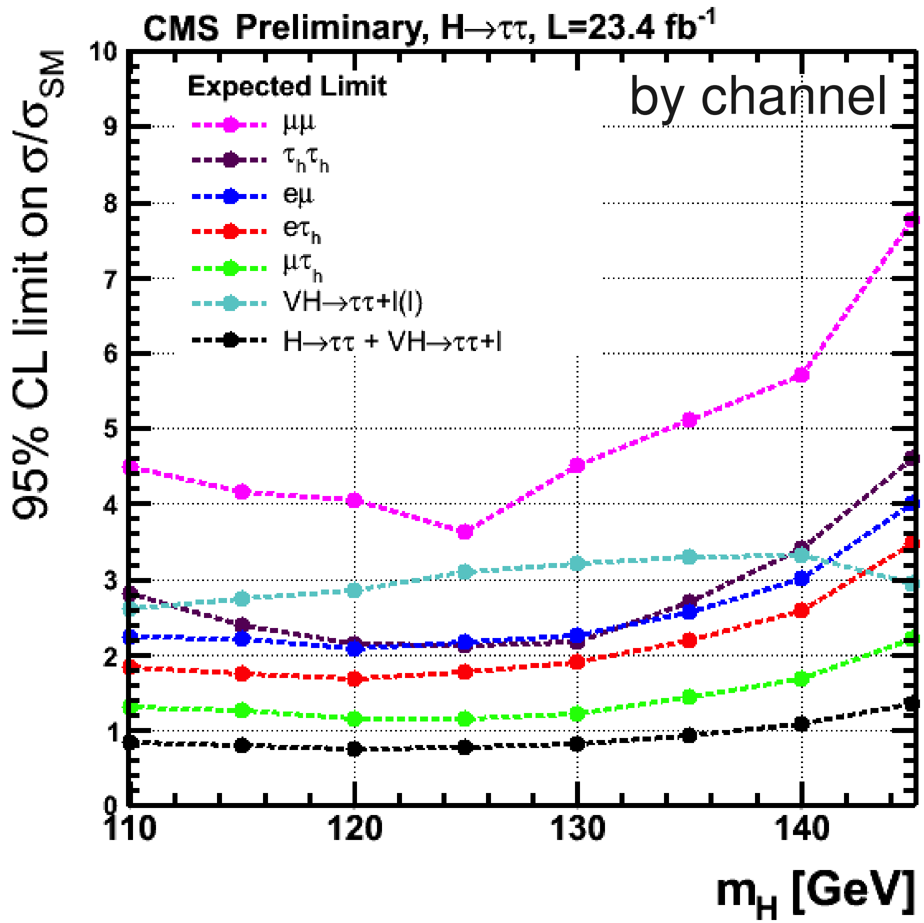
Table 2: Main systematic uncertainties entering the analysis. The ∓ symbol indicates that the uncertainty is anti-correlated with respect to other categories. The (*) symbol indicates correlation between separate channels. The (†) symbol indicates correlation between separate categories. In the instance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

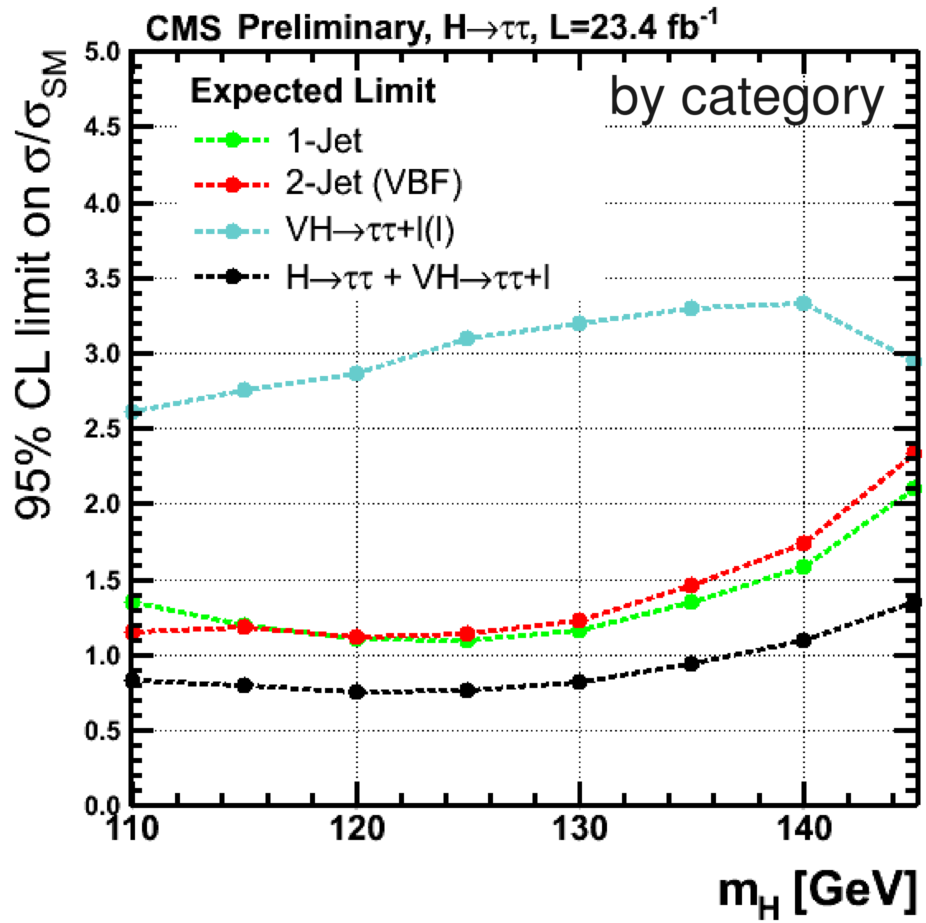
Experimental Uncertainties		Propagation into Event Categories		
Uncertainty	Uncert.	*0-Jet*	*1-Jet*	*VBF*
Electron ID & Trigger (†*)	±2%	±2%	±2%	±2%
Muon ID & Trigger (†*)	±2%	±2%	±2%	±2%
Tau ID & Trigger (†)	±8%	±8%	±8%	±8%
Tau Energy Scale (†)	±3%	±3%	±3%	±3%
Electron Energy Scale (†)	±1%	±1%	±1%	±1%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

Systematic uncertainties (th)

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 (†*)	-	-	$\pm 4\%$	$\pm 4\%$

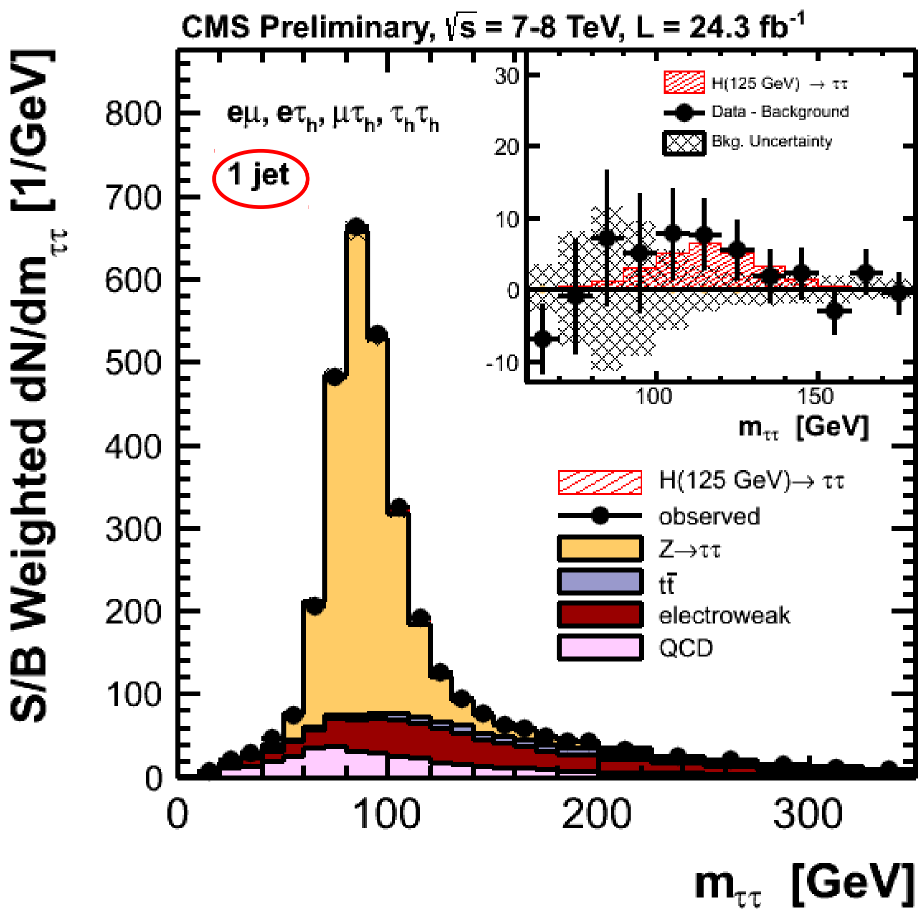
Sensitivity break-down

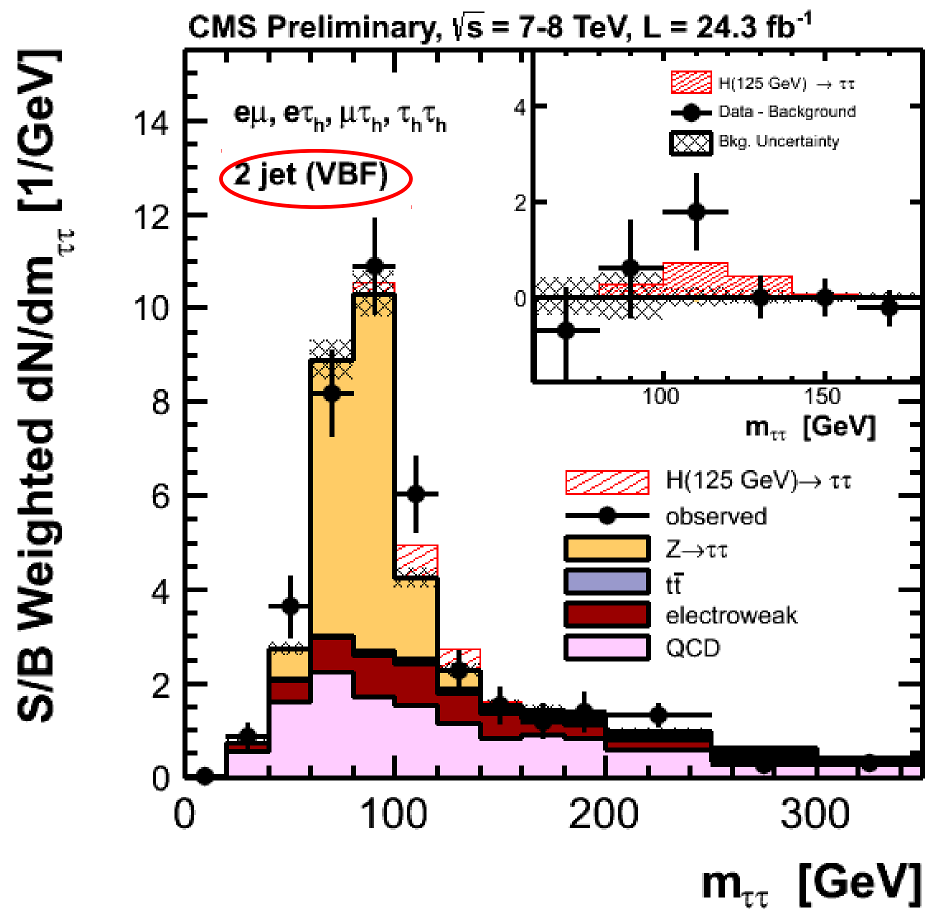




- Expected limits for full 2011+2012 dataset
- Sensitivity of 0.76 x SM at 125 GeV
- Sensitivity lead by the $\mu\tau_h$ channel

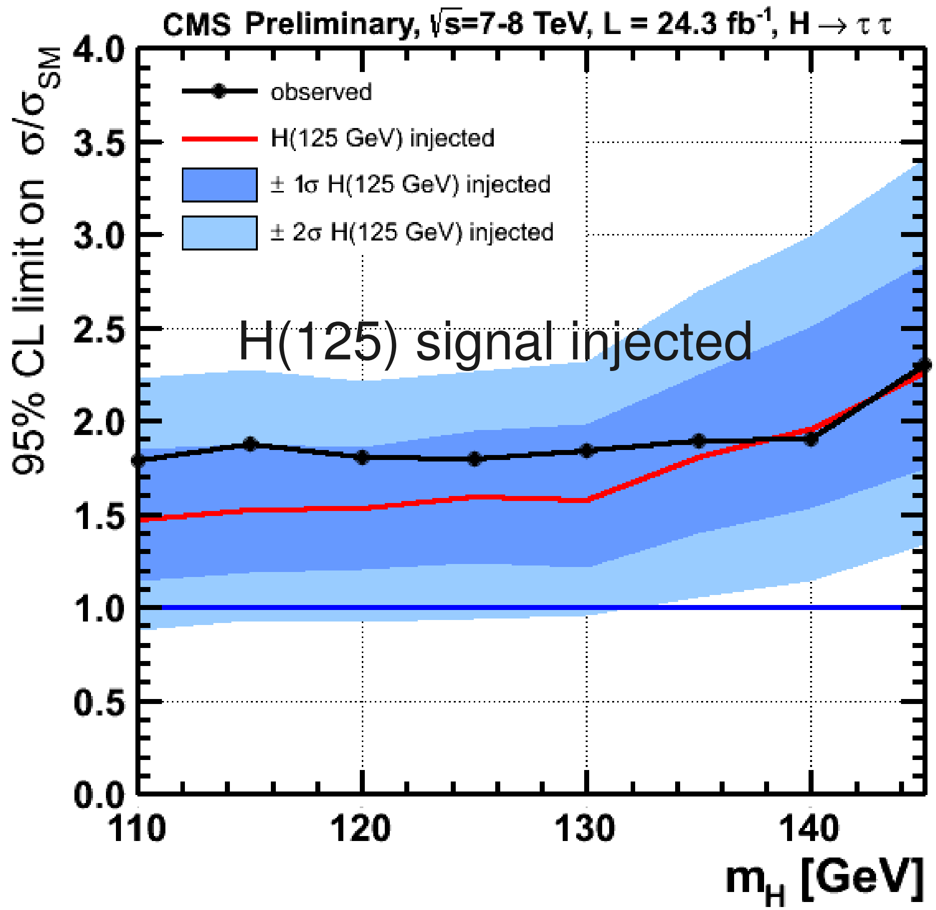
Combined mass distribution

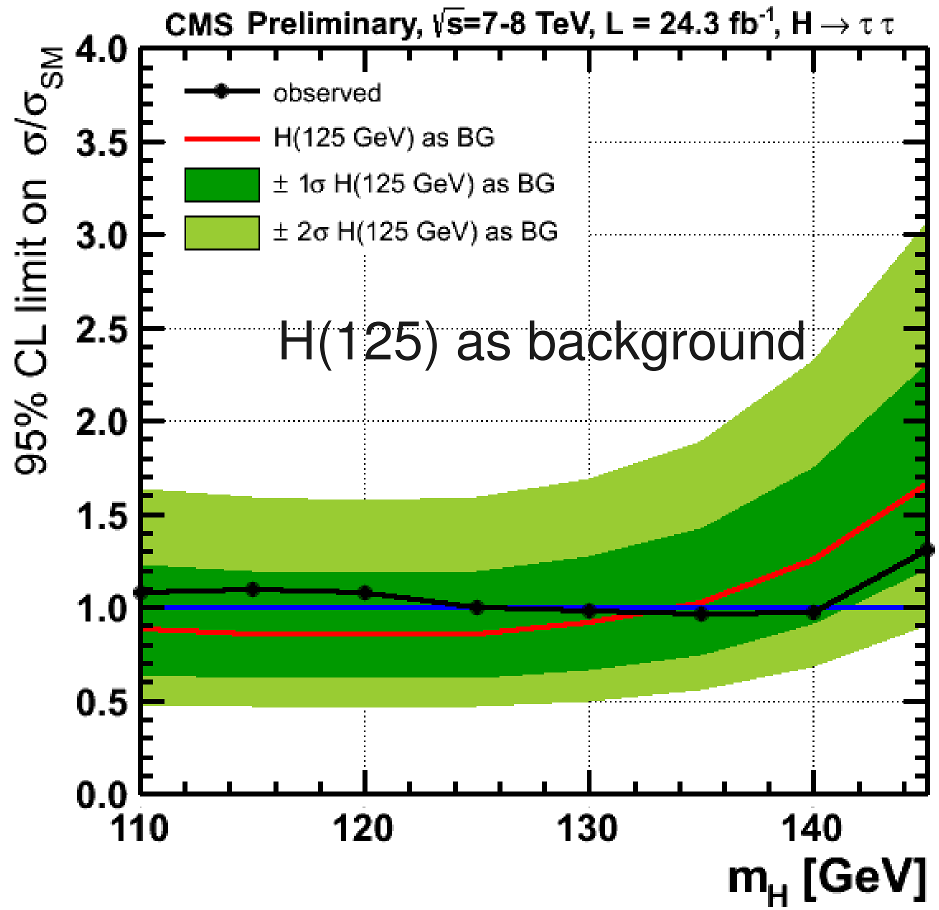




- Combine channels and categories weighting each by S/B
  - S – expected signal
  - B – fitted background
  - Both S and B in window around peak at 125 GeV Higgs

Consistency with SM H(125)





- Result consistent with background + SM Higgs $m_H = 125$ GeV

Event yields and efficiency

$\mu\tau_h$

Process	0-Jet	1-Jet high pT	VBF
Ztautau	84833 ± 1927	4686 ± 232	109 ± 11
QCD	18313 ± 478	481 ± 38	48 ± 7
EWK	8841 ± 653	1585 ± 153	63 ± 9
ttbar	11 ± 1	155 ± 11	5 ± 1
Total Background	111998 ± 2090	6908 ± 281	225 ± 16
Htautau		73 ± 13	11 ± 2
Observed	112279	7011	240

Signal Eff.		
	1-Jet high pT	VBF
ggH	1.99 10^-3	8.51 10^-5
qqH	4.09 10^-3	3.46 10^-3
qqHttbar or VH	3.00 10^-3	1.60 10^-5

$e\tau_h$

Process	0-Jet	1-Jet high pT	VBF
Ztautau	25161 ± 708	792 ± 62	47 ± 6
QCD	7706 ± 307	3 ± 0.3	17 ± 4
EWK	9571 ± 510	365 ± 53	44 ± 6
ttbar	4 ± 0.5	47 ± 4	4 ± 1
Total Background	42443 ± 924	1207 ± 82	113 ± 9
Htautau		15 ± 3	5 ± 1
Observed	42481	1217	117

Signal Eff.		
	1-Jet high pT	VBF
gg H	3.94 10^-4	3.33 10^5
qqH	1.10 10^-3	1.78 10^3
qqHttbar or VH	8.30 10^-4	1.46 10^-6

$\tau_h\tau_h$

Process	1-Jet	VBF
Ztautau	428 ± 90	47 ± 28
QCD	210 ± 31	61 ± 10
EWK	41 ± 9	4 ± 1
ttbar	29 ± 6	2 ± 2
Total Background	709 ± 95	114 ± 30
Htautau	9 ± 4	4 ± 2
Observed	718	120

Signal Eff.		
	1-Jet	VBF
ggH	2.52 10^-4	4.99 10^-5
qqH	5.93 10^-4	1.20 10^-3
qqHttbar or VH	9.13 10^-4	3.59 10^-5

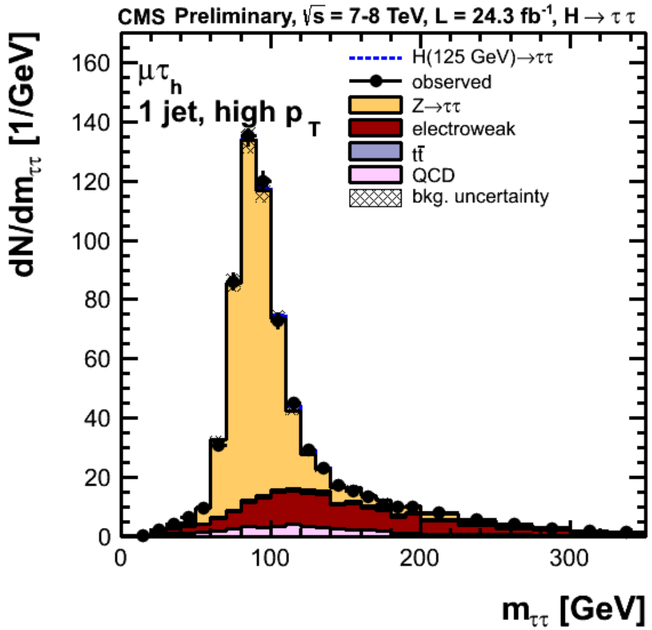
$e\mu$

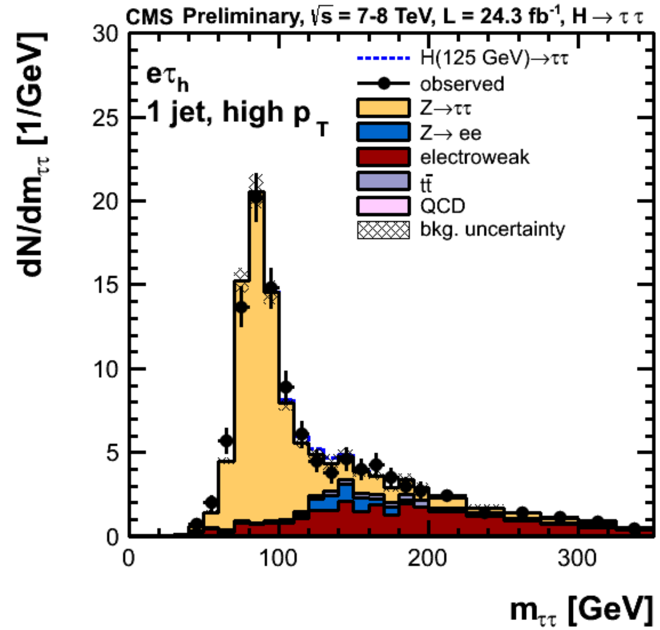
Process	0-Jet	1-Jet high pT	VBF
Ztautau	48882 ± 1282	1830 ± 105	61 ± 6
QCD	4374 ± 249	395 ± 36	19 ± 2
EWK	1185 ± 89	461 ± 44	7 ± 1
ttbar	74 ± 5	1100 ± 66	19 ± 2
Total Background	54514 ± 1309	3785 ± 137	105 ± 7
Htautau		23 ± 4	5 ± 0.6
Observed	54694	3774	118

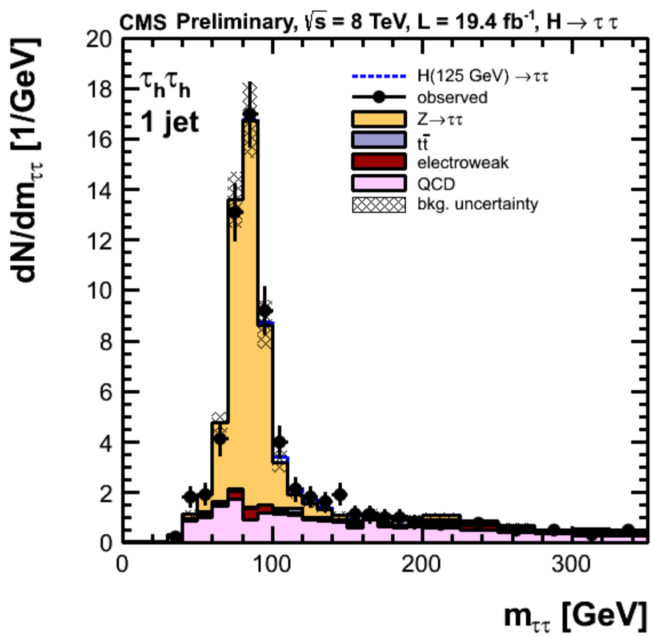
Signal Eff.		
	1-Jet high pT	VBF
ggH	6.04 10^-4	3.27 10^-5
qqH	1.37 10^-3	1.80 10^-3
qqHttbar or VH	1.38 10^-3	1.32 10^-5

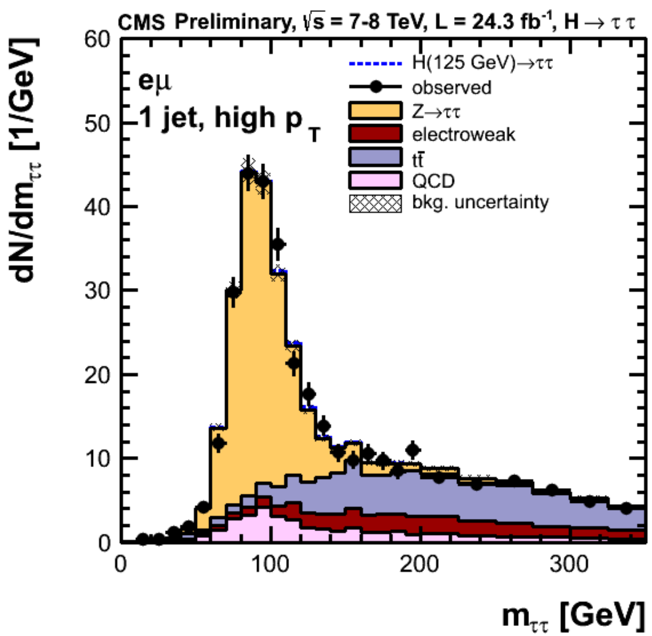
Mass distributions (1-jet)

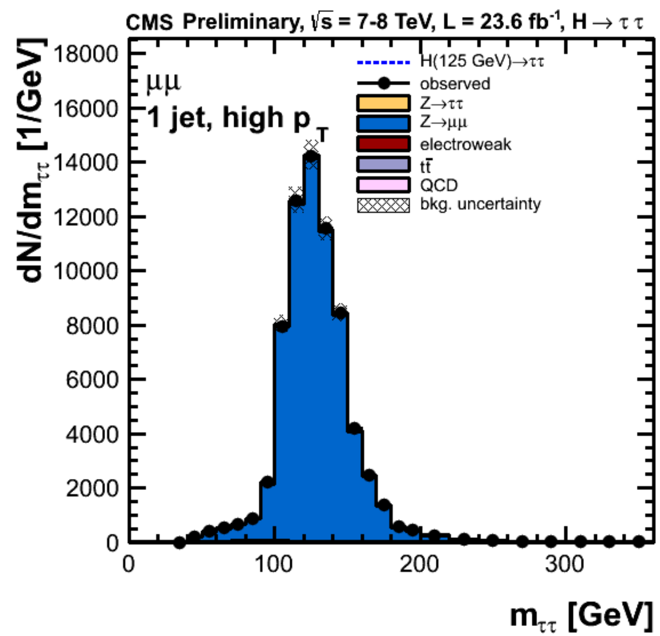
- **1-jet, high-p_T**: second most sensitive category
  - ggH dominated
  - Jet and high-p_T requirements improve resolution and S/B





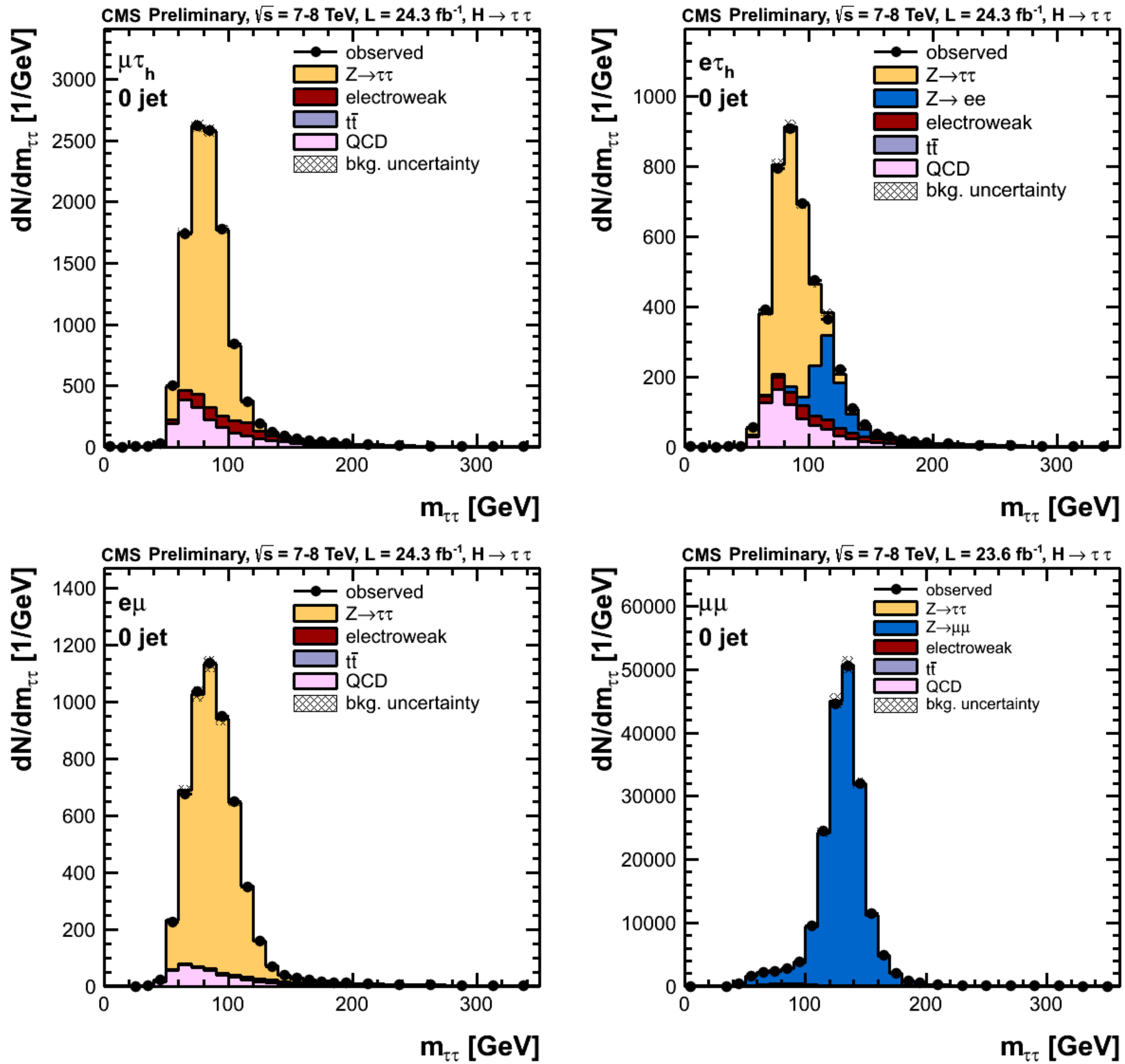






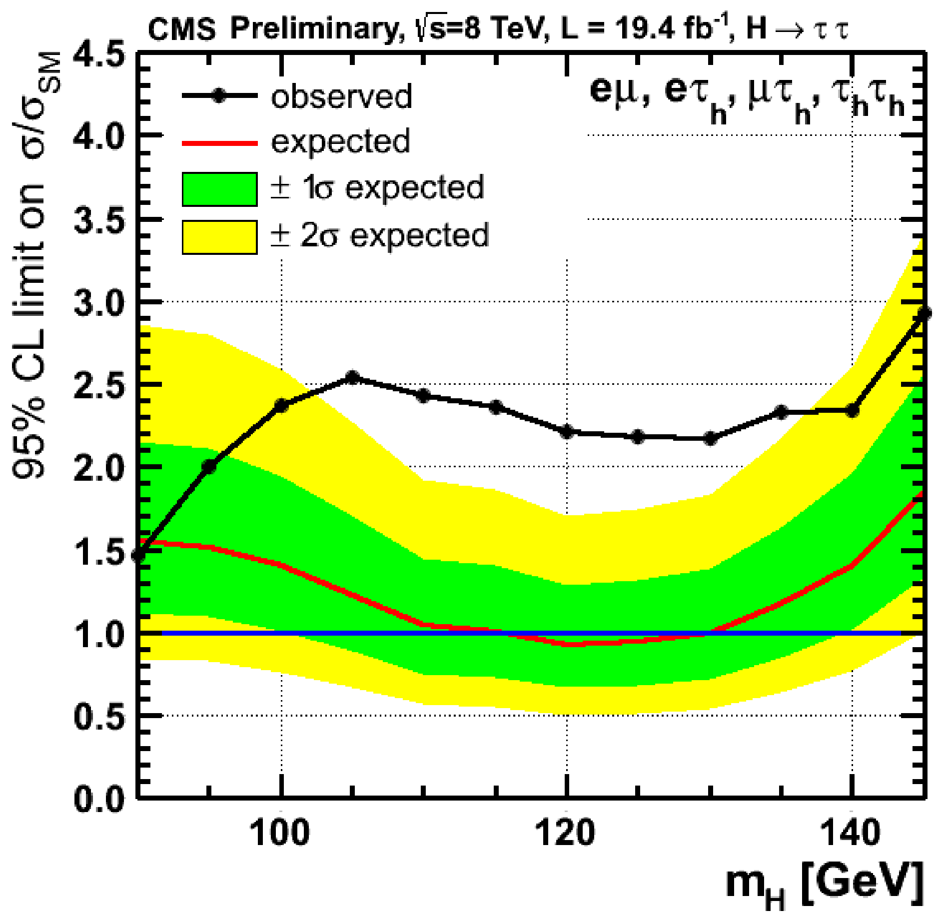
Mass distributions (0-jet)

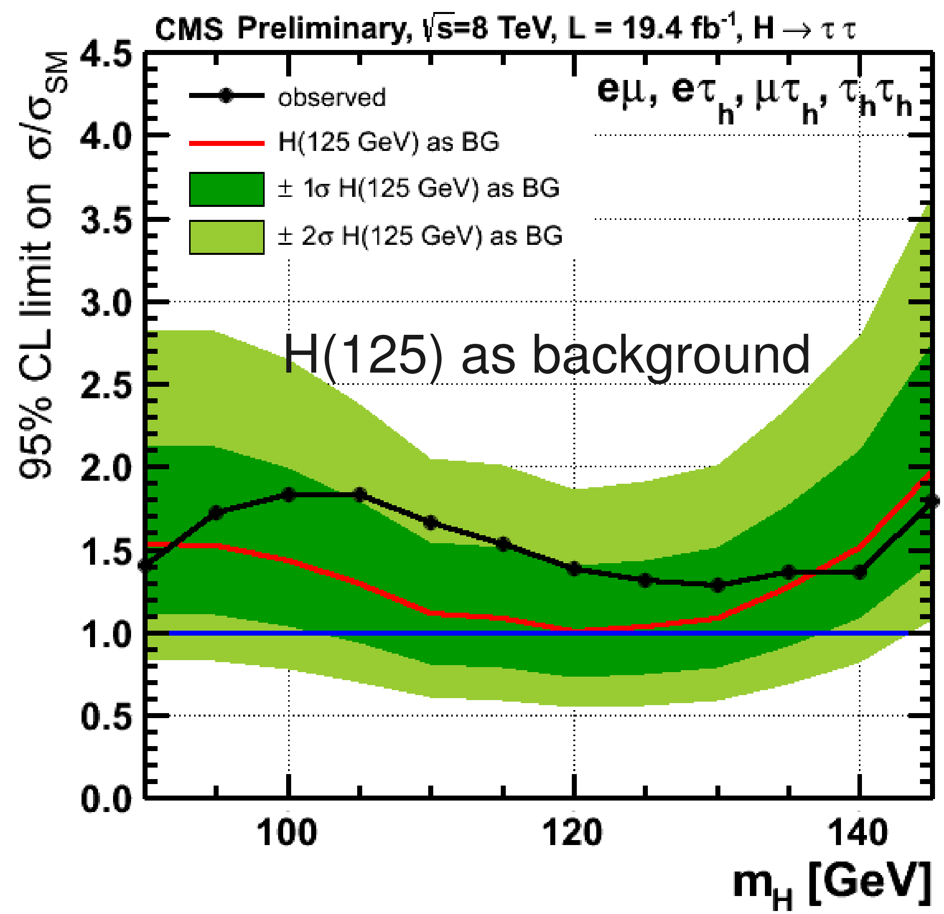
- **0-jet**:
  - Low S/B
  - Background fit only
  - To constrain uncertainties in signal sensitive categories



Extension to low mass

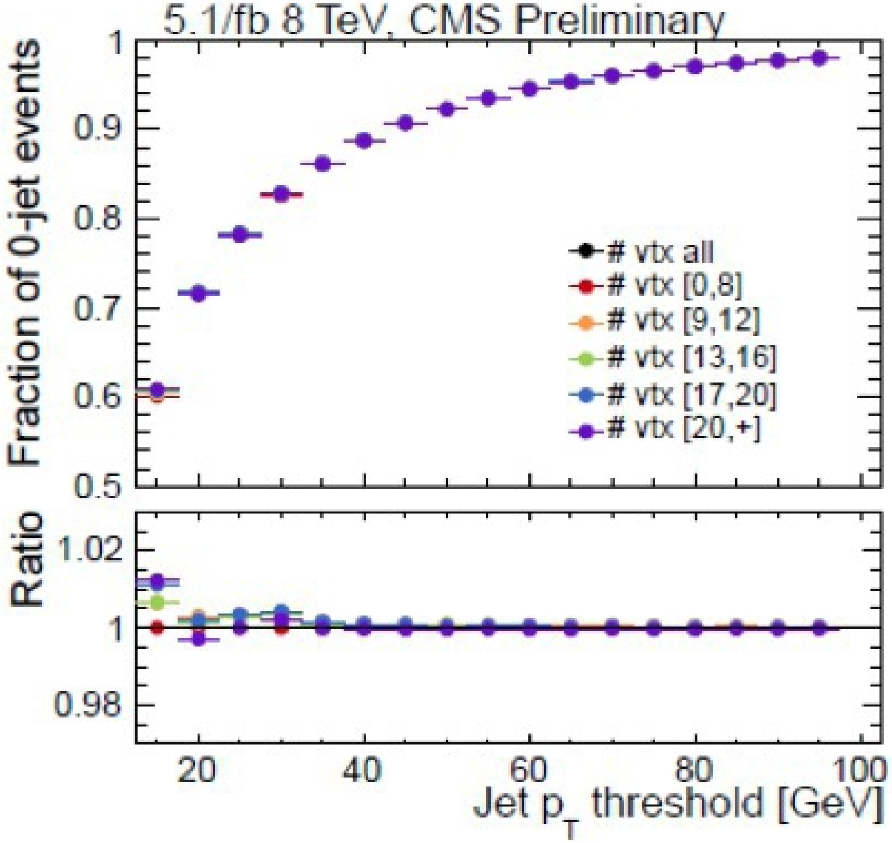
- **8 TeV (2012) only**:
  - Limit extended down to 90 GeV
  - Combining the $e\tau_h$, $\mu\tau_h$, $e\mu$ and $\tau_h\tau_h$ channels. The $\mu\mu$ and VH channels not included.

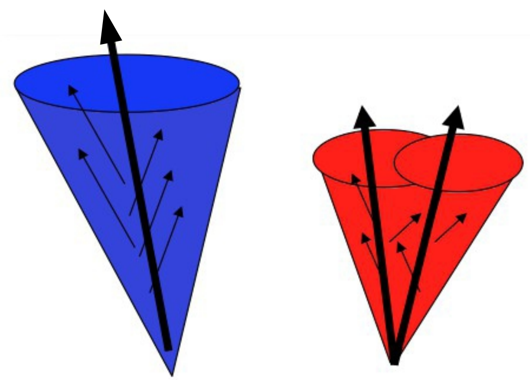




Jets

- Used for event categorisation
  - Specially important as tags of VBF H
- "Fake" jets from pileup
  - High-E_T jets from overlapping pileup jets
- Discriminate "fake" jets with MVA using
  - Track-vertex association
  - Jet shape
- Reduces background in VBF category by a factor of ~2





Typical jet   Pileup jet

Missing Transverse Energy

- Used to reject background and for full di-tau mass reconstruction
  - Specially important as tags of VBF H
- Resolution of ME_T degrades with pileup
  - <19> interactions in 2012
- Use MVA (BDT regression) using 5 different ME_T estimators as input
- Test: compare components of the recoil to the hard probe (e.g. in $Z \rightarrow \mu\mu$)
  - Standard ME_T (particle-flow) vs MVA ME_T
- Significant improvement in resolution, pileup dependence suppressed