

# Search for the Standard Model Scalar Boson Decaying to Fermions at CMS

Moriond EW, March 2-9, 2013

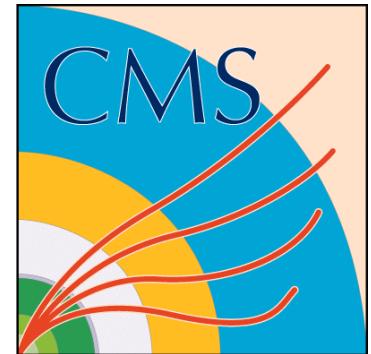
Valentina Dutta

*on behalf of the CMS Collaboration*



**Massachusetts  
Institute of  
Technology**

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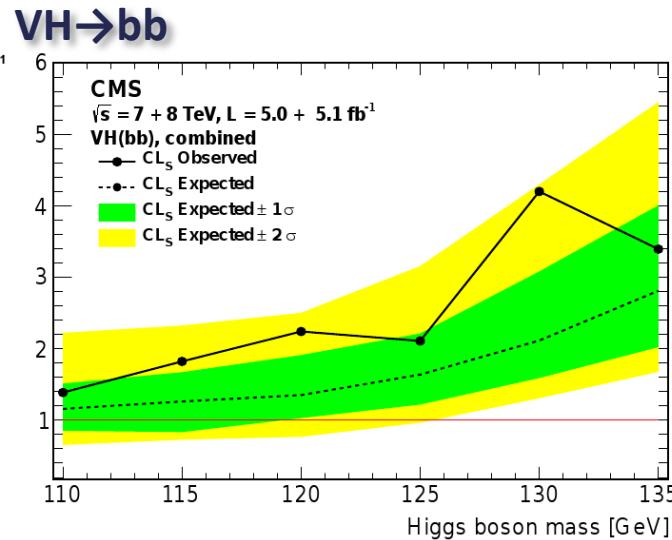
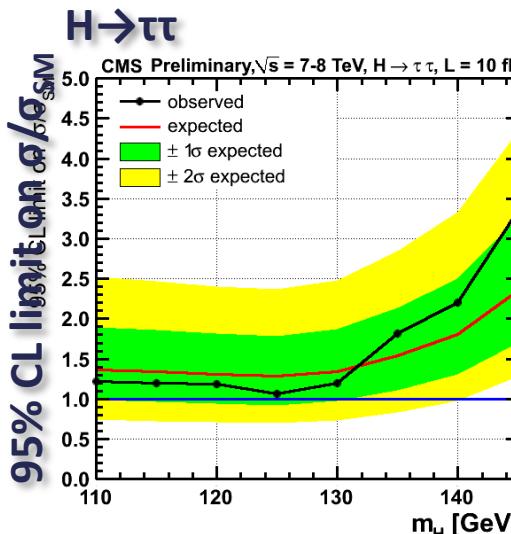
# Introduction

July 2012: **observation of a new boson** with mass around 125 GeV consistent with the Standard Model scalar boson by CMS, ATLAS

Driven by the bosonic decay channels:  $H \rightarrow ZZ \rightarrow 4l$ ,  $H \rightarrow \gamma\gamma$ , supported by  $H \rightarrow WW \rightarrow l\nu l\nu$

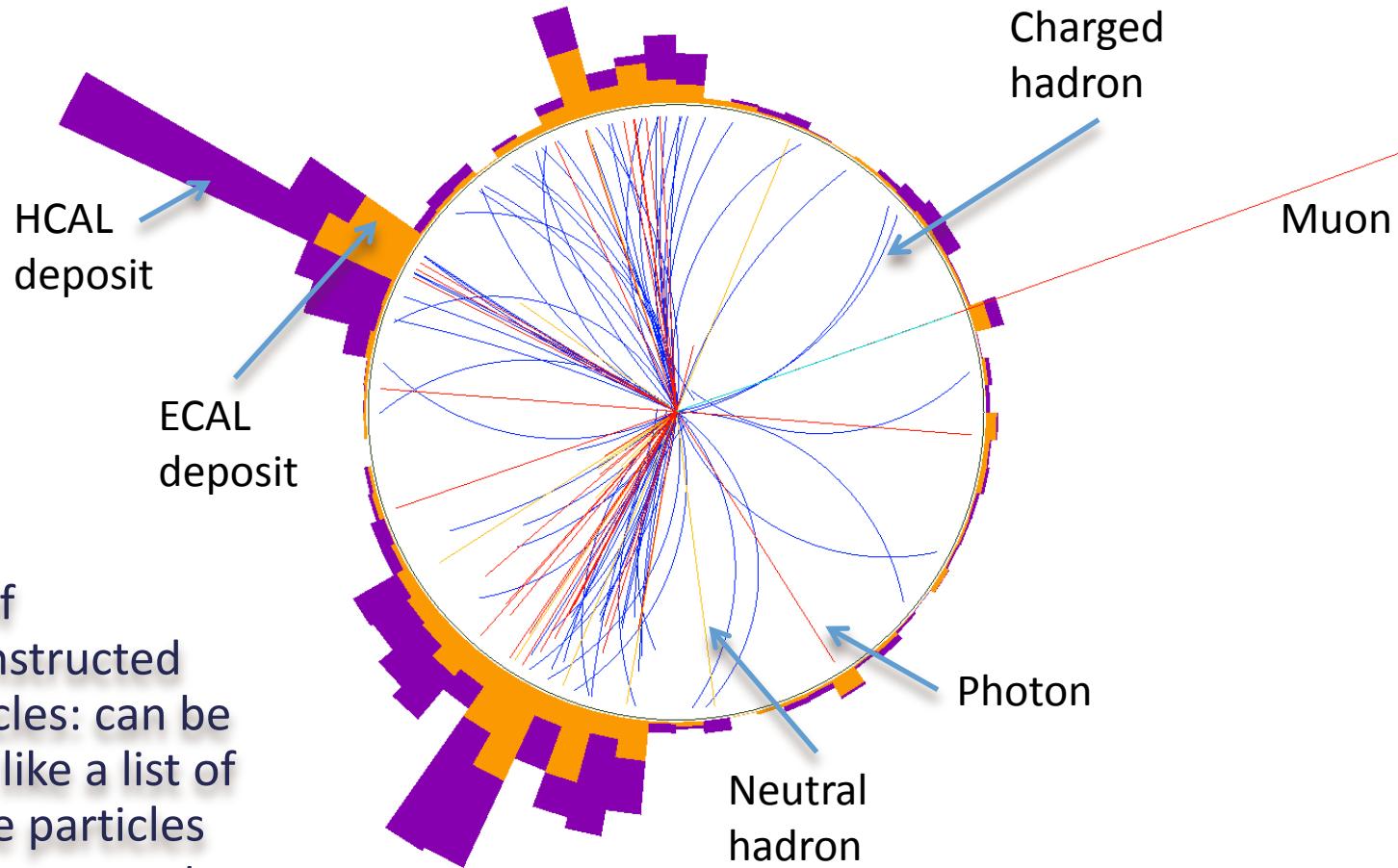
But does it decay to fermions?

## *Results shown at ICHEP 2012:*



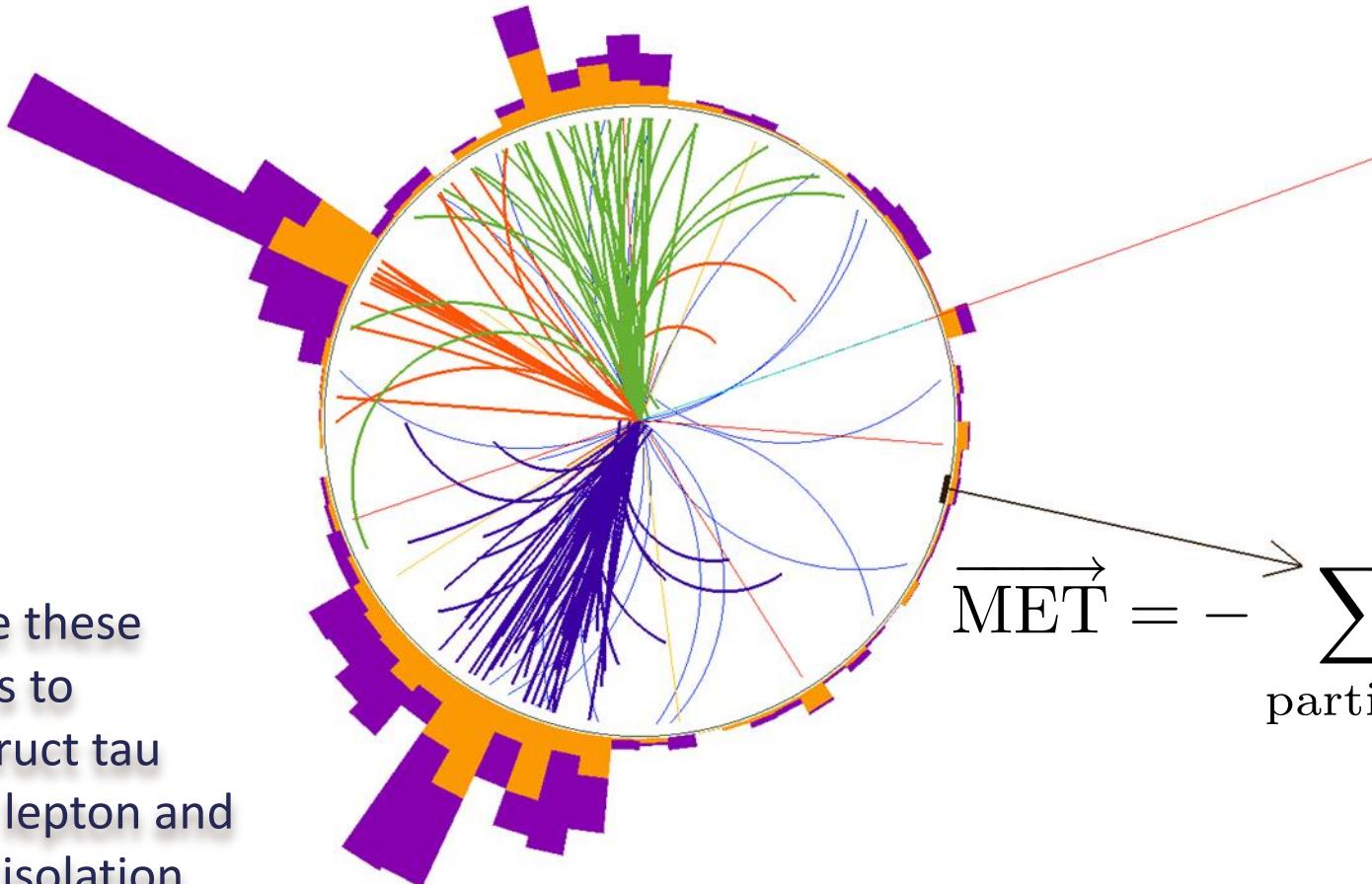
- Sensitivity was not yet at the level of the SM
- Results were consistent with either the presence or absence of a signal
- Analyses have since been updated with more data, improved techniques

# Particle flow reconstruction



# Jets and $E_T^{\text{miss}}$

Also use these particles to reconstruct tau decays, lepton and photon isolation



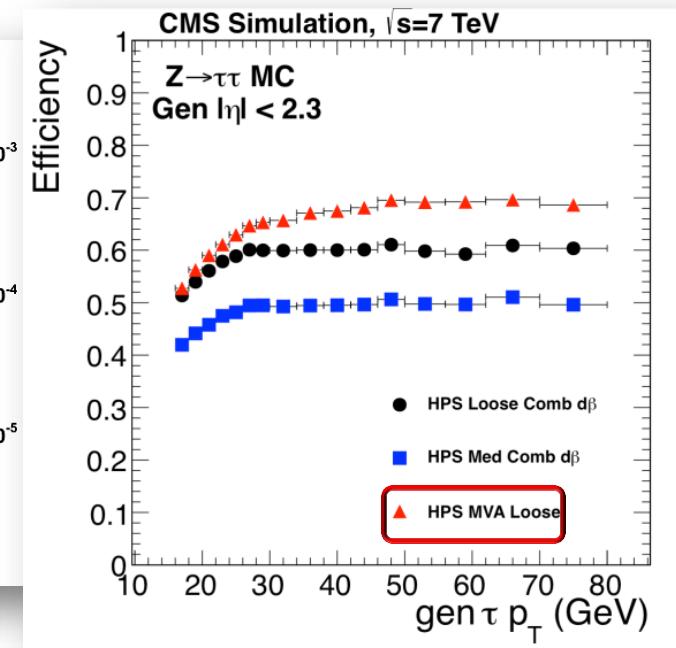
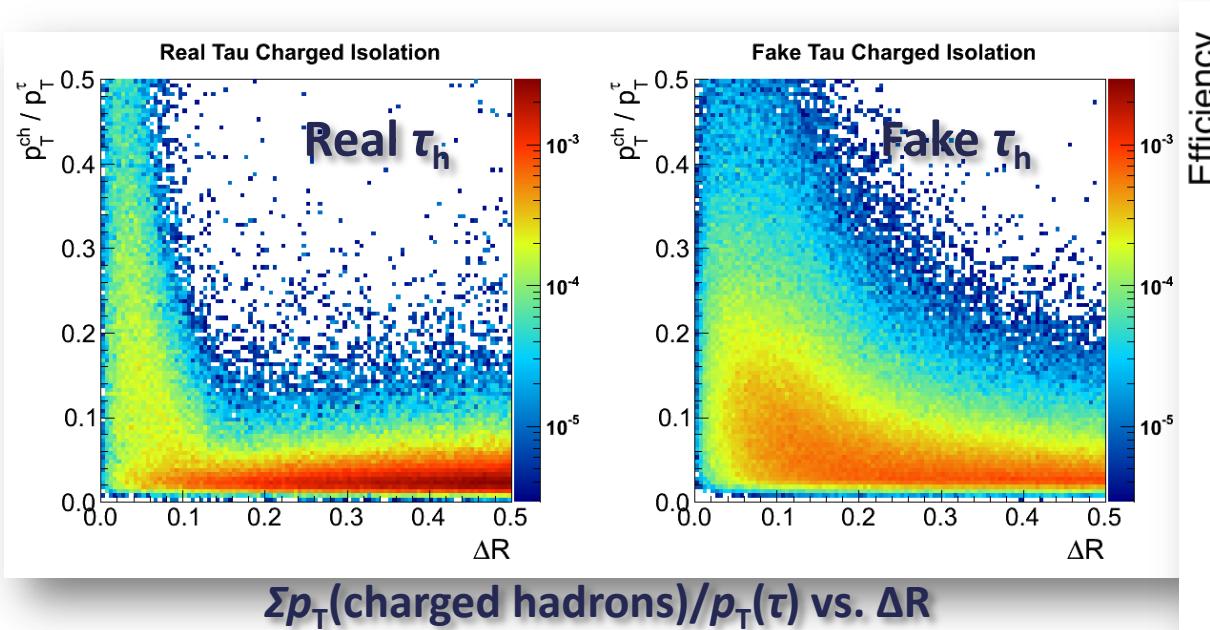
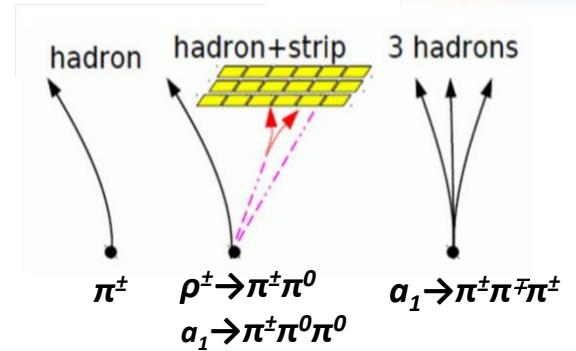
# $\tau_h$ identification

## Identification:

- Reconstructed based on decay modes: charged hadrons + ECAL deposits

## Isolation: New in 2012

- Multivariate isolation using relative  $\Sigma p_T$  of particle-flow candidates in concentric rings around  $\tau$



# More about jets

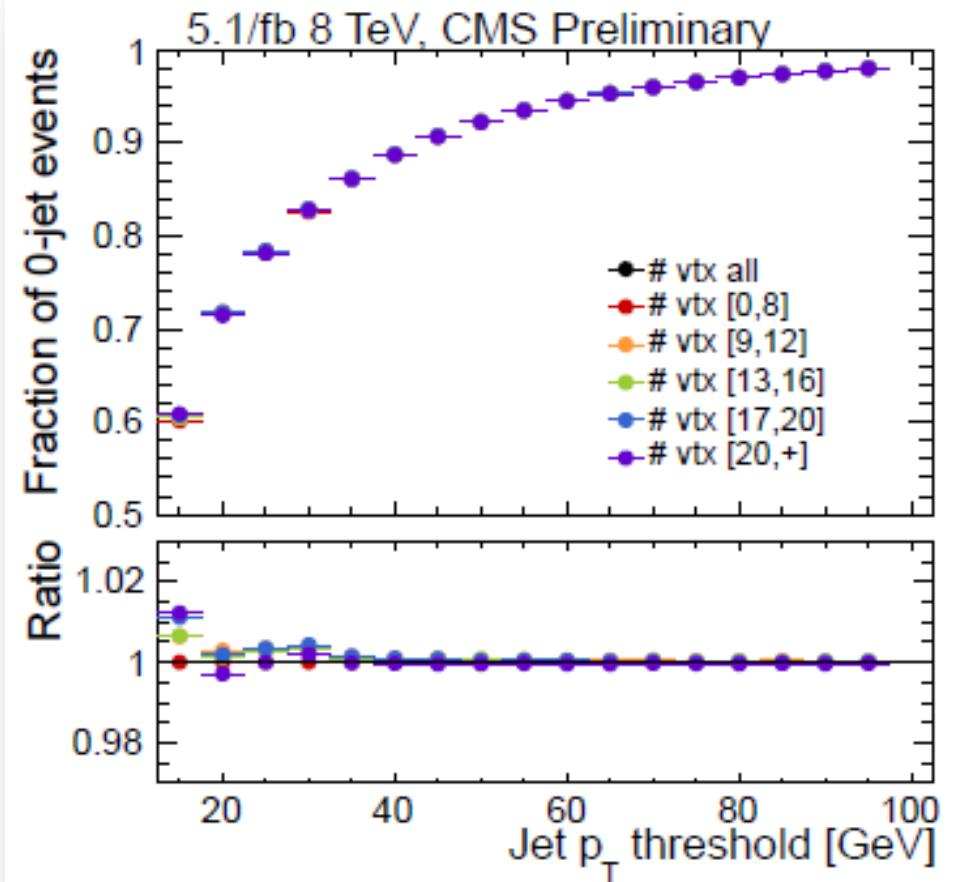
## Pileup-jet discrimination:

New in 2012

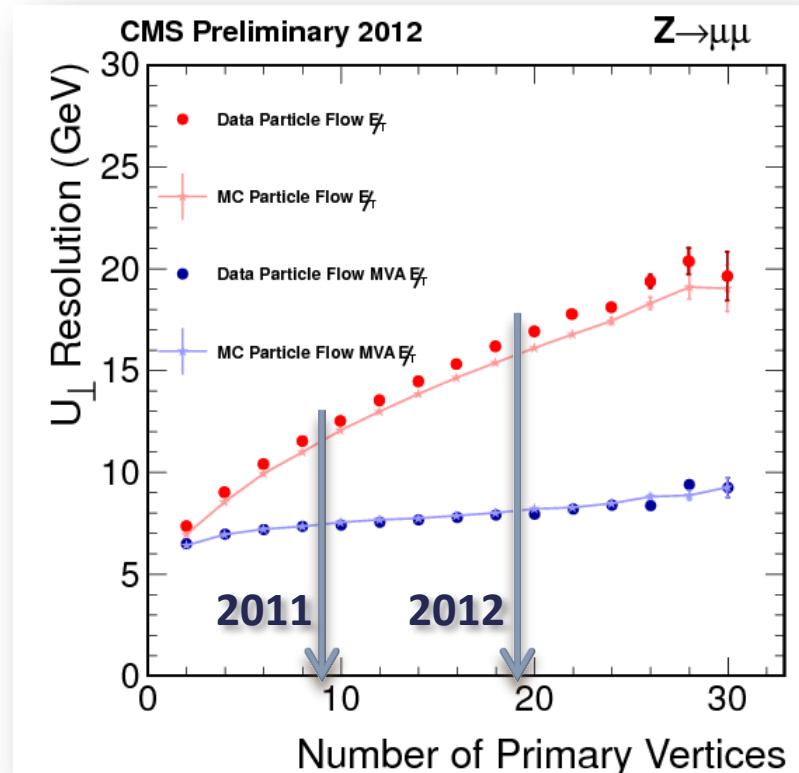
- Multivariate anti-pileup discriminant exploits shape and tracking variables

## B-tagging:

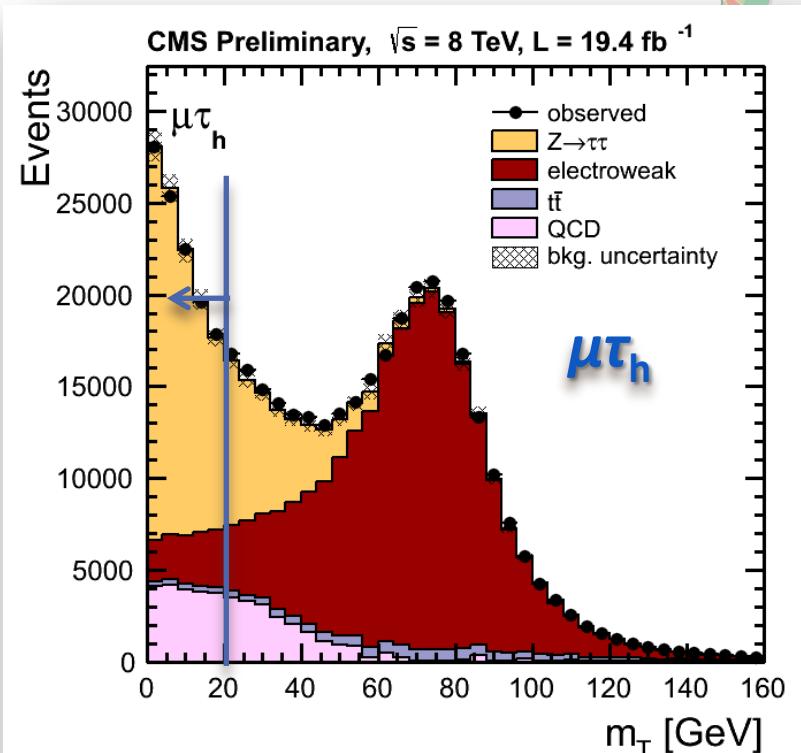
- Lifetime-based, use information about track impact parameters, secondary vertices



# Multivariate $E_T^{\text{miss}}$ regression

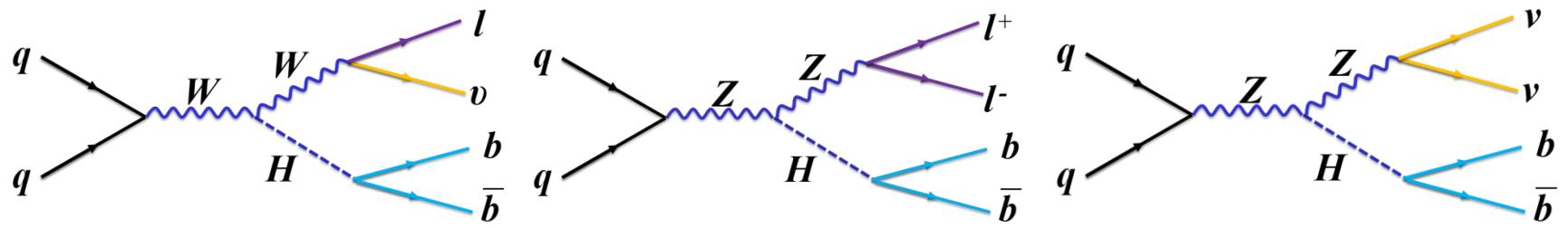


New in 2012

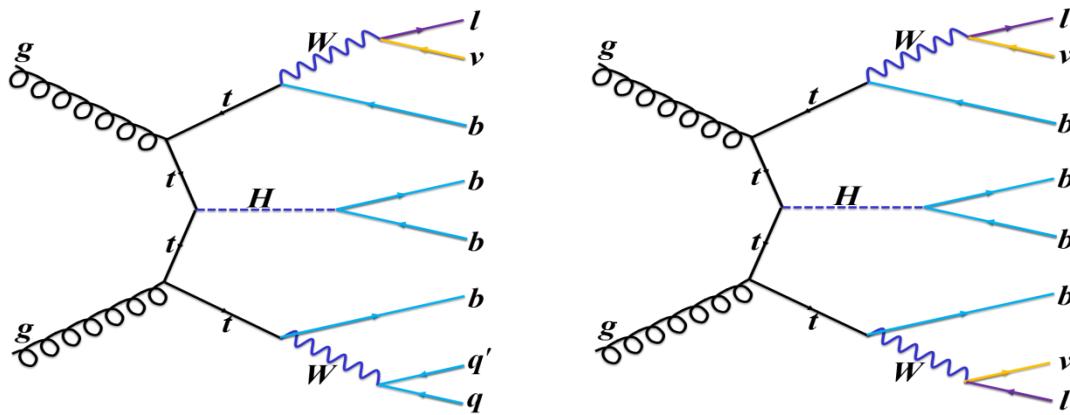


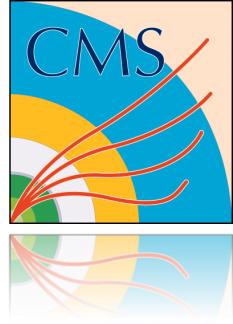
$$m_T = \sqrt{2 p_T E_T^{\text{miss}} (1 - \cos(\Delta\phi))}$$

- Significant improvement in resolution and dependence on pileup
- Crucial for  $H \rightarrow \tau\tau$  analysis:  $m_{\tau\tau}$  reconstruction, separation of signal from W+jets background using  $m_T$



# $H \rightarrow bb$





# VH analysis overview

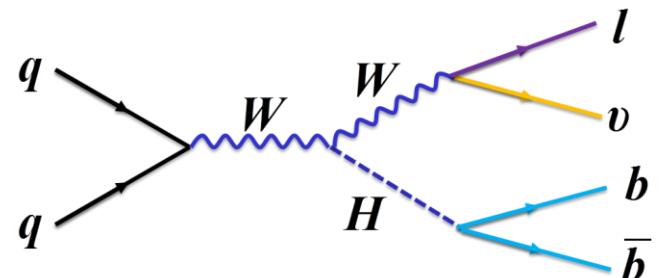
$H \rightarrow bb$  has largest BR at low mass but very high background

Search for associated production with W or Z ( $W \rightarrow l\nu$ ,  $Z \rightarrow ll$ ,  $Z \rightarrow vv$ )

- final states with **leptons**,  $E_T^{\text{miss}}$  and **b-jets**

Main backgrounds: W/Z + jets, top

- normalized from control regions in data



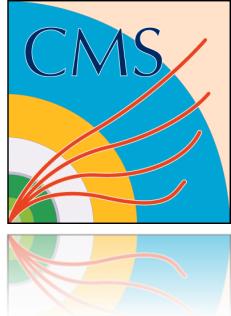
## Strategy:

- Require boosted V and H, 2 b-tagged jets
- b-jet energy regression to improve resolution
- Discriminate signal from background using Boosted Decision Tree (BDT)

no update since HCP 2012

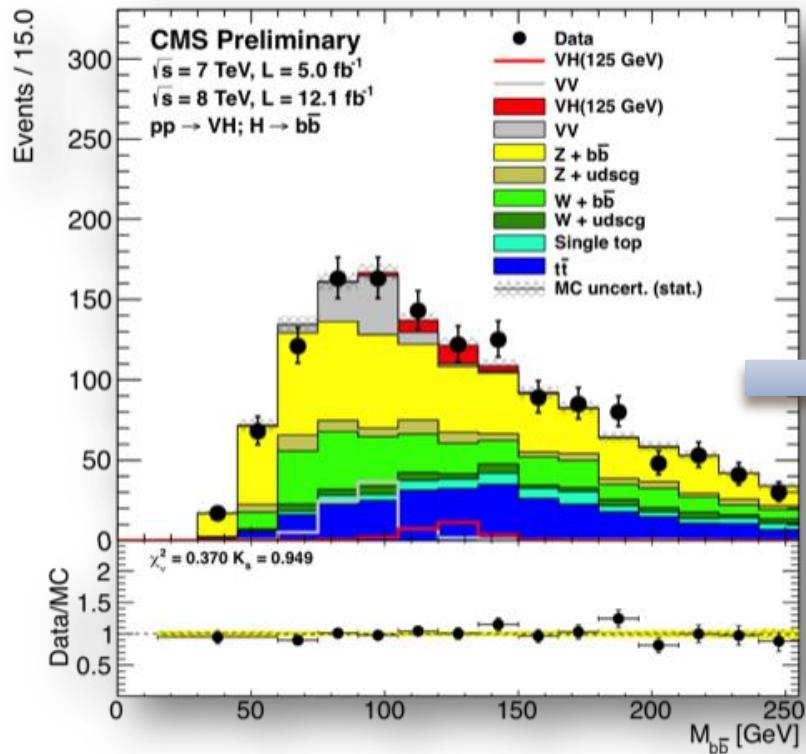
7TeV (2011)	8TeV (2012)
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5 $\text{fb}^{-1}$	12 $\text{fb}^{-1}$
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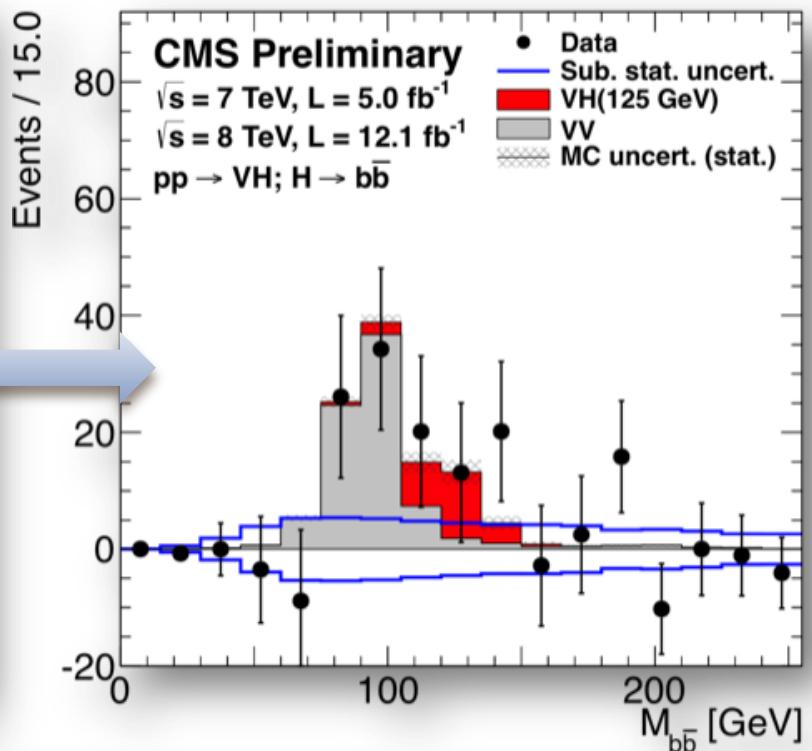


# $m_{b\bar{b}}$ distribution

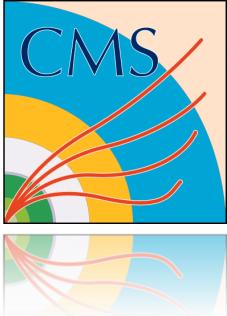
all channels



bkg. except VV subtracted



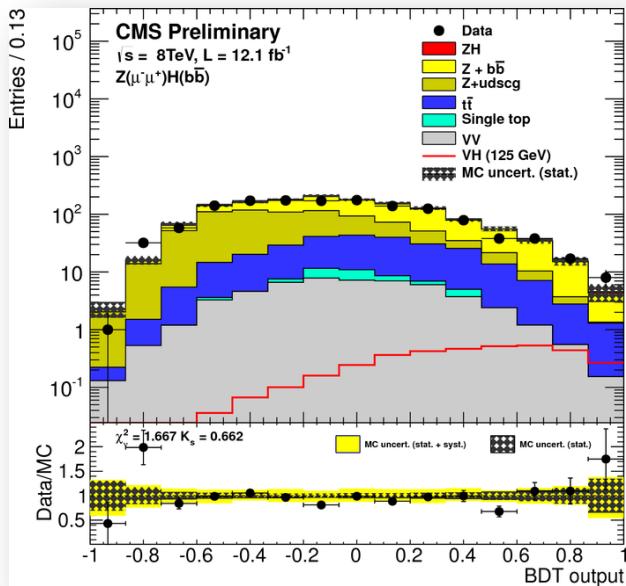
- Tighter selection than used in BDT analysis (for cut-and-count)
- Consistent with diboson expectation+ small excess in signal region



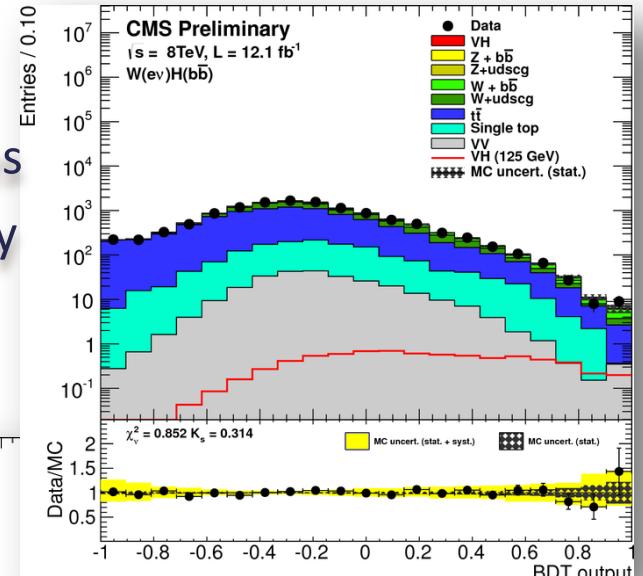
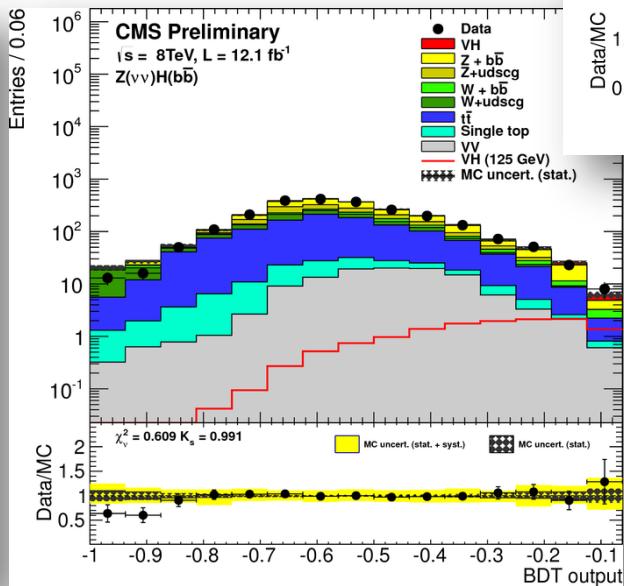
# Signal extraction

- Fit to BDT shape gives 20% improvement over cut-and-count
- Inputs include kinematics, b-tag information, angles
- Categorize into low/high- $p_T(V)$  + high  $p_T(V)$  category with looser b-tag requirement for some channels

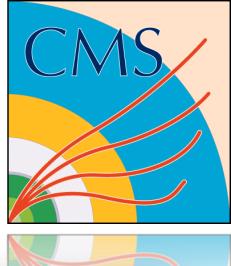
$Z(\mu\mu)H(bb)$ , low  $p_T(V)$



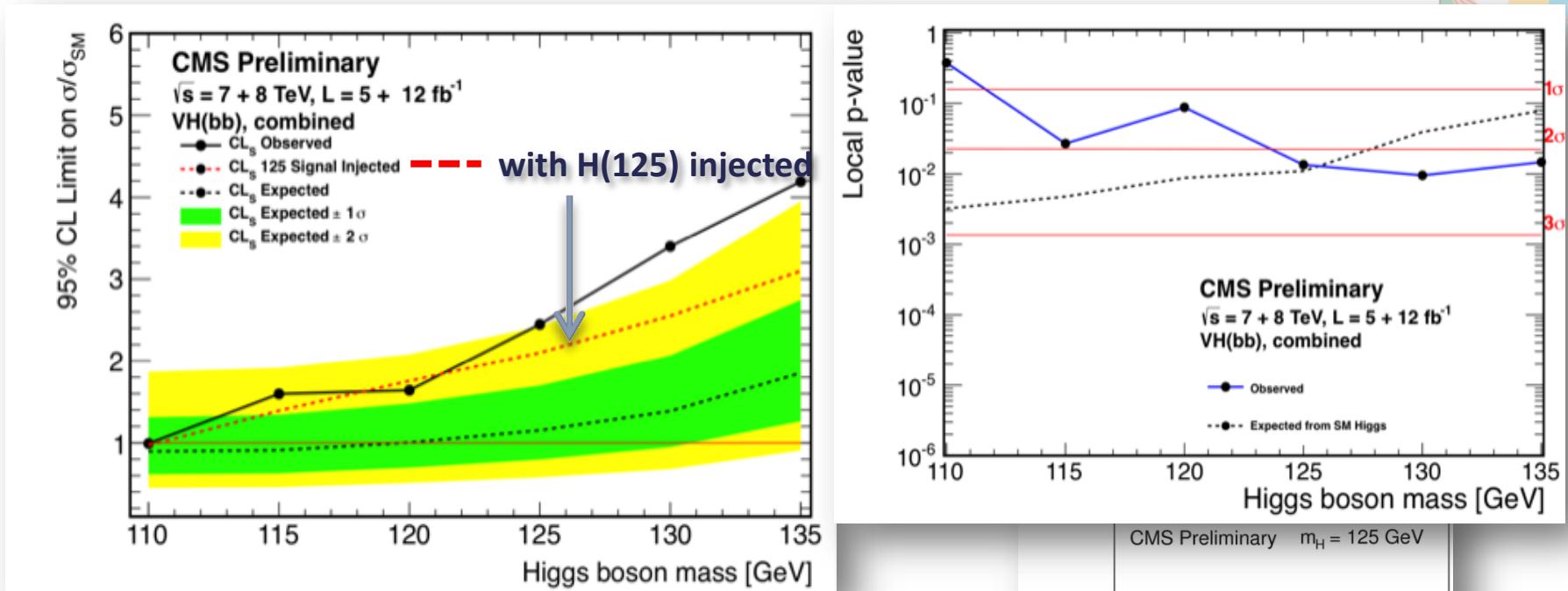
$Z(vv)H(bb)$ , high  $p_T(V)$



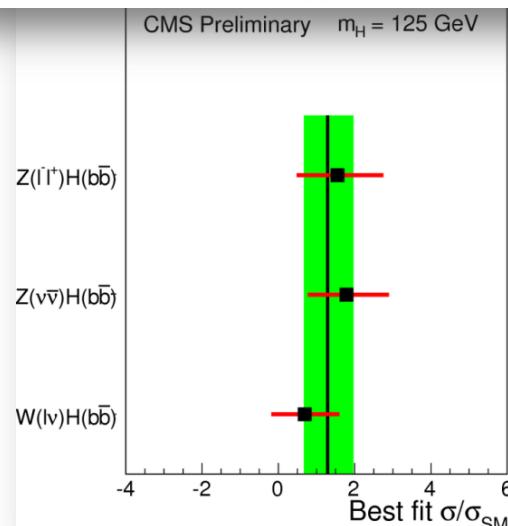
$W(ev)H(bb)$ , high  $p_T(V)$ , loose b-tag

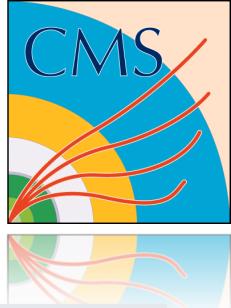


# Results



- Observed (expected) limit of **2.5 (1.2)  $\times$  SM** at 125 GeV
- Observed (expected) local significance of  **$2.2\sigma$  ( $2.1\sigma$ )** for  $m_H = 125 \text{ GeV}$
- Combined best-fit  $\hat{\mu}$  of  **$1.3^{+0.7}_{-0.6}$**





# $t\bar{t}H$ analysis and results

Directly probe  $t\bar{t}H$  vertex

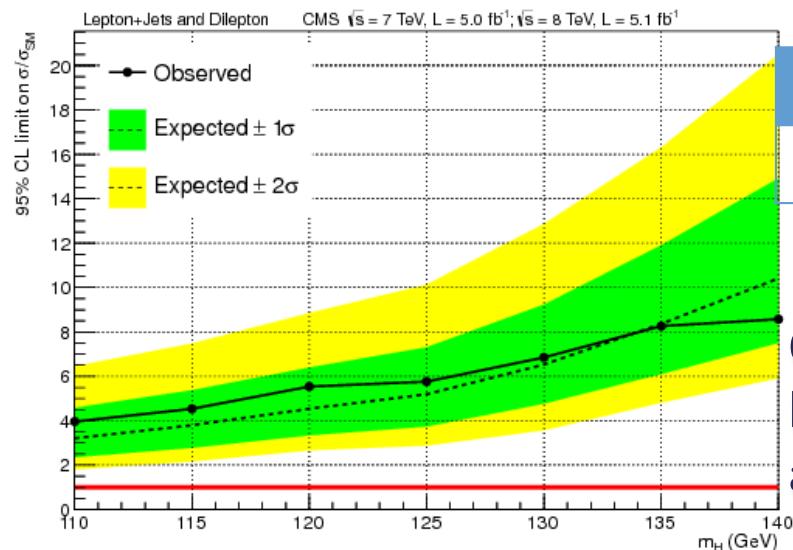
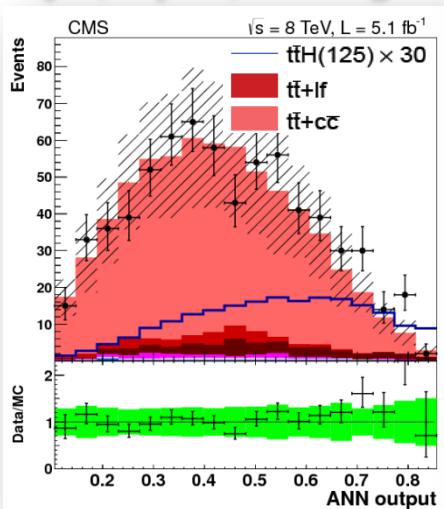
Dominant background:  $t\bar{t}$ +jets

Search done for lepton+jets  
and dilepton final states

## Strategy:

- 1-2 leptons +  $\geq 2$  jets +  $\geq 2$  b-tagged jets
- Categorize based on number of jets and number of b-tags
- Fit to output of neural network (ANN), inputs are b-tag information, kinematics and angular correlations

### 1+jet, 6 jets, 3 b-tags

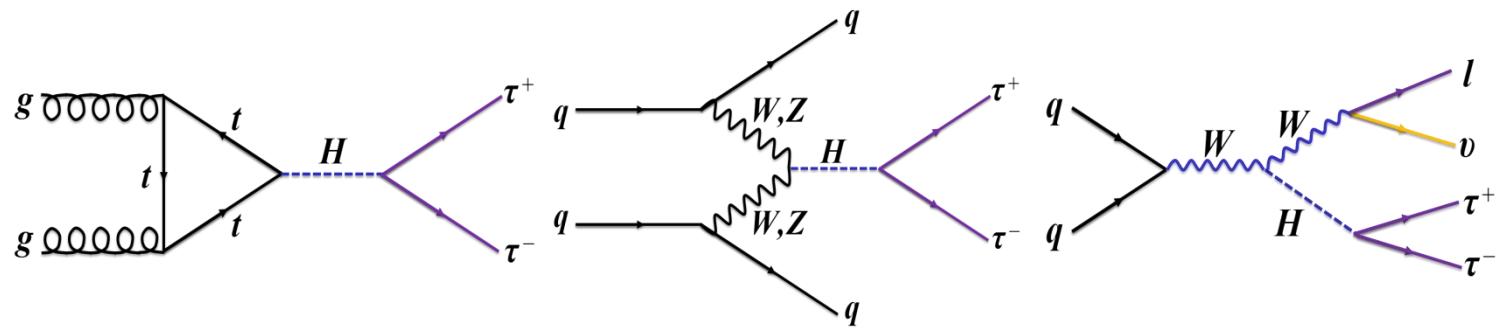


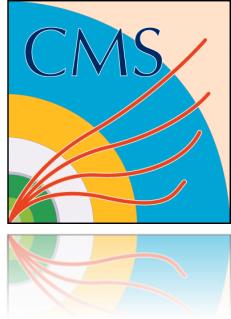
7TeV (2011)    8TeV (2012)

5  $\text{fb}^{-1}$     5  $\text{fb}^{-1}$

Observed (expected)  
limit of **5.8 (5.2)**  $\times \text{SM}$   
at 125 GeV

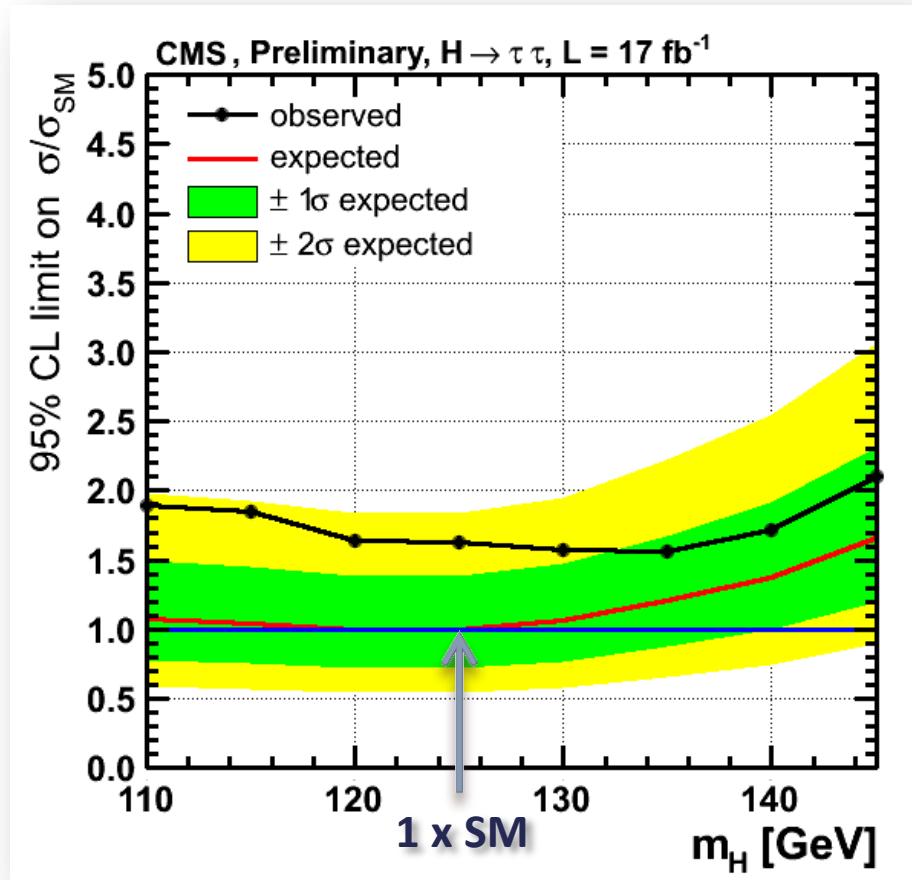
# $H \rightarrow \tau\tau$



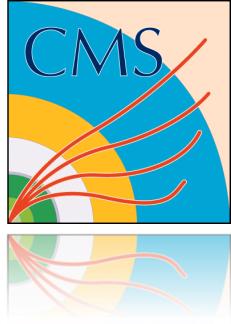


# Last public result

*Result shown at HCP 2012:*

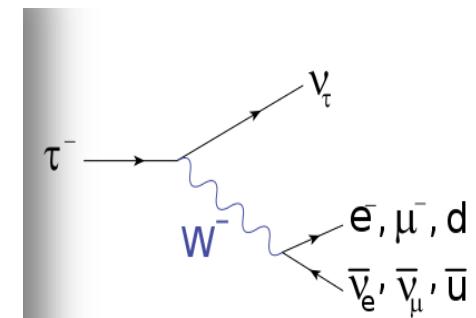
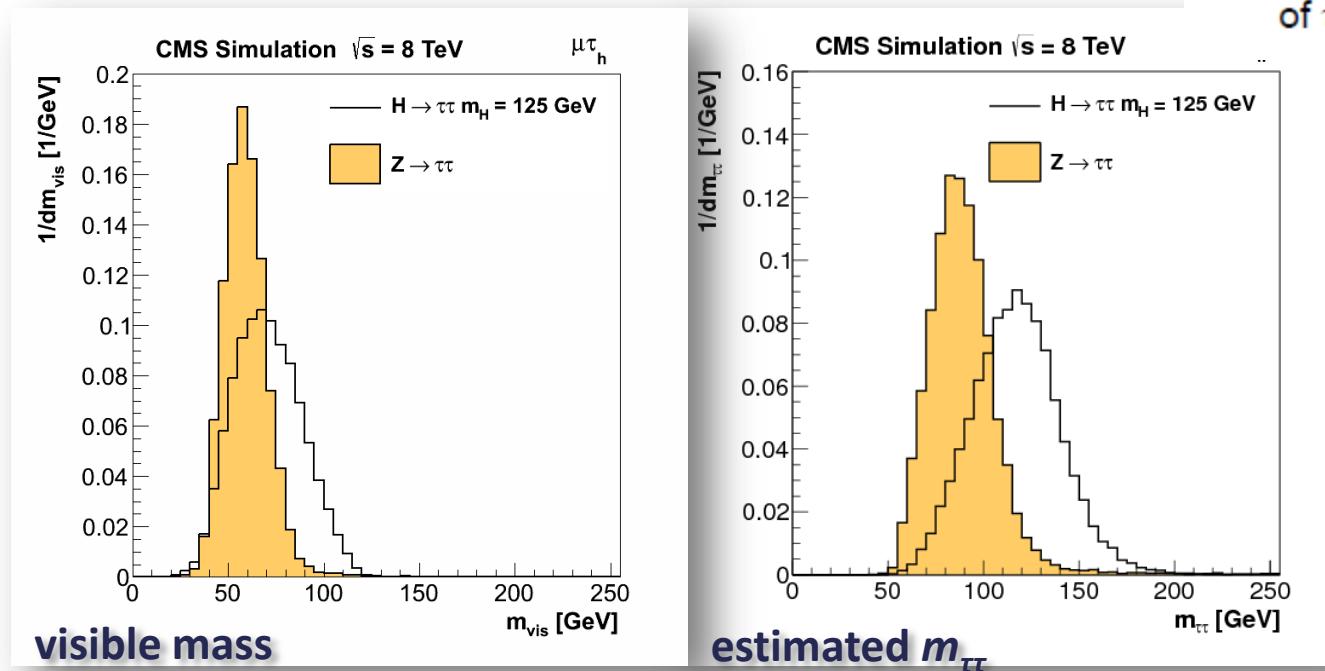
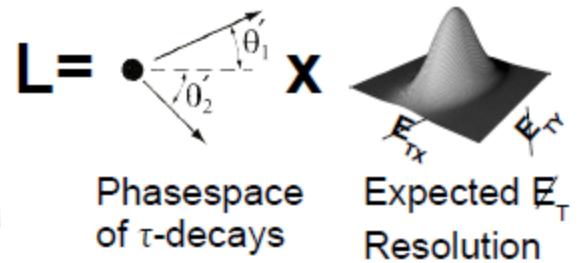


- Results for all  $H \rightarrow \tau\tau$  channels combined ( $\mu\tau_h$ ,  $e\tau_h$ ,  $e\mu$ ,  $\mu\mu$ ,  $\tau_h\tau_h$ ), + WH/ZH  $\rightarrow \tau\tau$  analysis
- Best-fit  $\hat{\mu}$  of  **$0.7 \pm 0.5$**



# $m_{\tau\tau}$ estimation

- Maximum likelihood method used
- Estimated on event-by-event basis using four-momenta of visible decay products,  $E_x^{\text{miss}}$ ,  $E_y^{\text{miss}}$ , expected  $E_T^{\text{miss}}$  resolution
- Nuisance parameters integrated out
- 15-20% resolution on reconstructed  $m_{\tau\tau}$

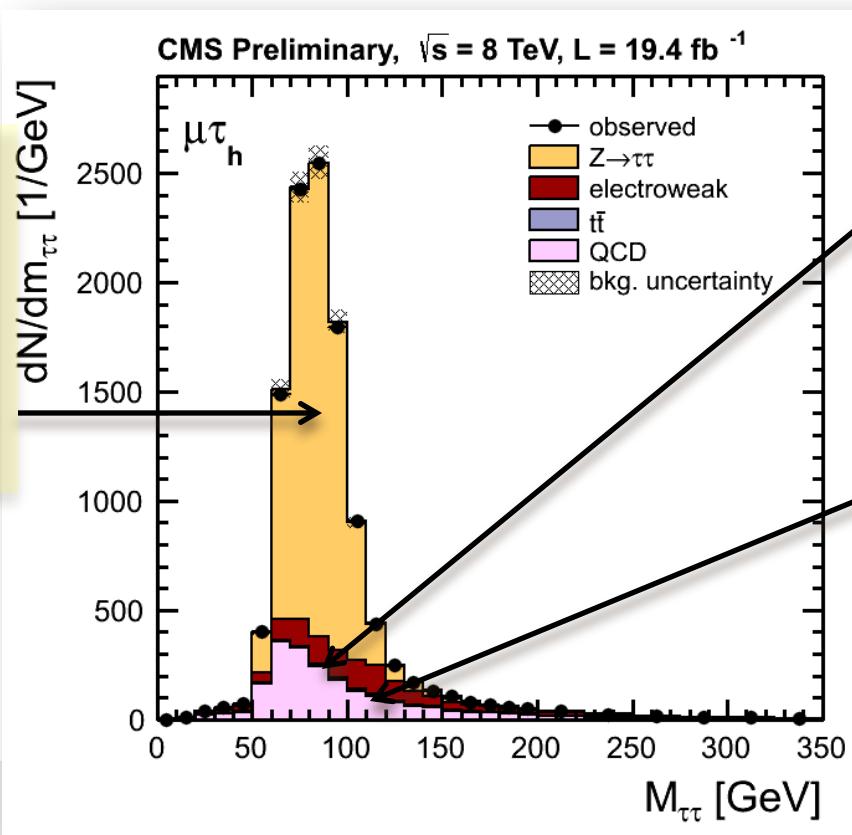




# Anatomy of the analysis

$Z \rightarrow \tau\tau$

**Embedding:**  $Z \rightarrow \mu\mu$  data, replace  $\mu$  with simulated  $\tau$  decay  
Normalization from  $Z \rightarrow \mu\mu$  data



**W+jets**

Shape from simulation  
Normalization from control region

**QCD**

SS data, corrected for SS/OS ratio

## Strategy:

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



# Event categories

number of jets

 $\tau p_T$ **0-jet, low  $p_T$** 

- High background, constrains nuisance parameters
- No fit for signal

**1-jet, low  $p_T$** 

- Enhancement from jet requirement

 $e\tau_h, \mu\tau_h, e\mu, \mu\mu$ **2-jet (VBF)**

- $\geq 2$  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  $p_T$** 

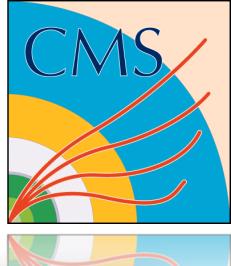
- Enhancement from jet and  $p_T$  requirement

 $\tau_h \tau_h$ **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,  $|\Delta\eta(jj)| > 2.5$



# $m_{\tau\tau}$ distributions

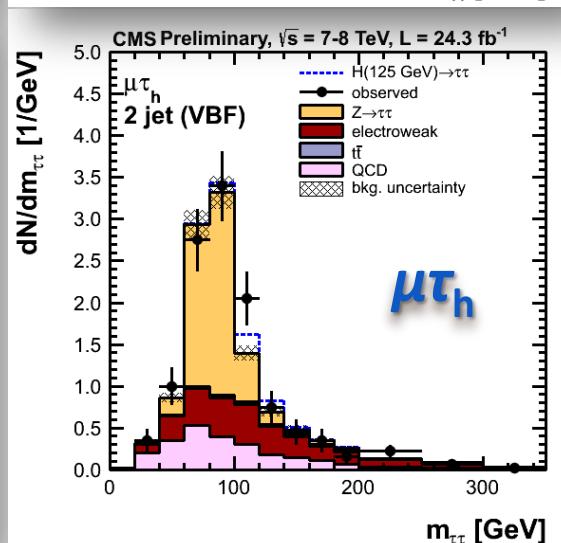
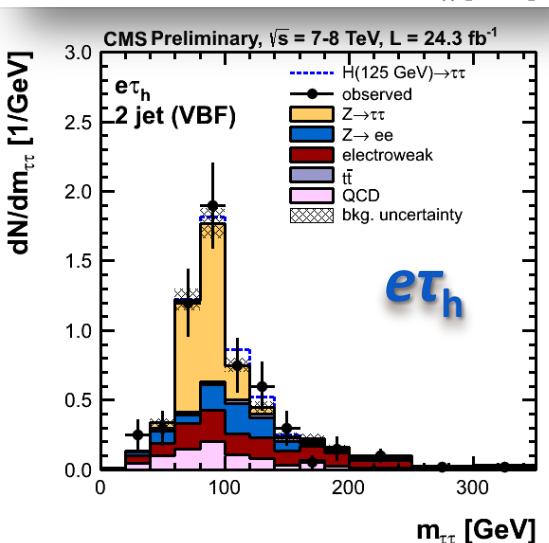
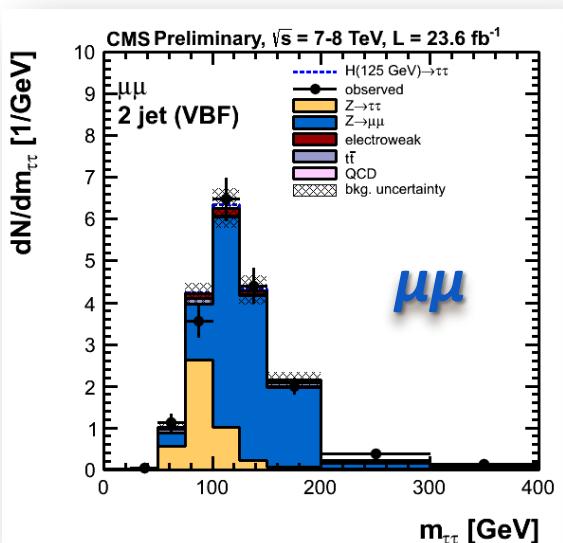
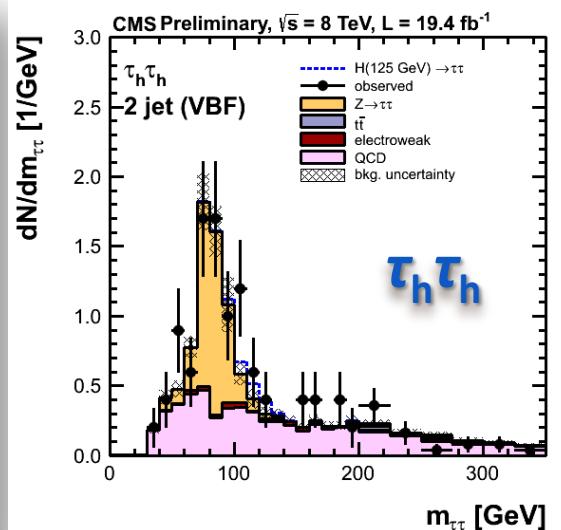
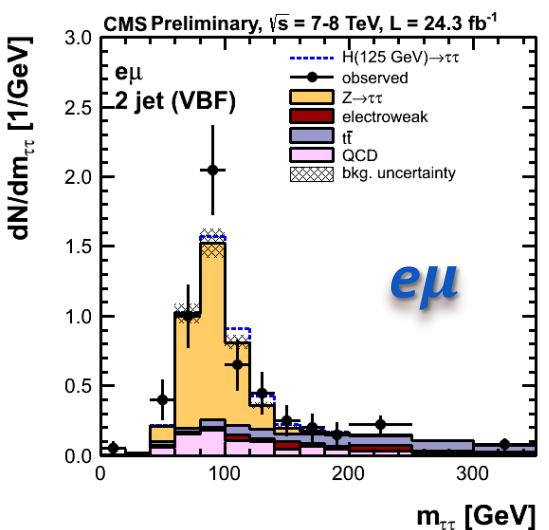
7TeV (2011)    8TeV (2012)

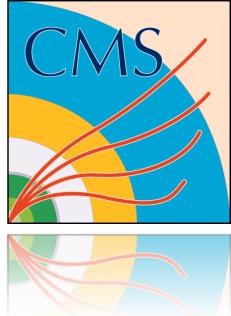
$5 \text{ fb}^{-1}$

$19 \text{ fb}^{-1}$

## 2-jet (VBF)

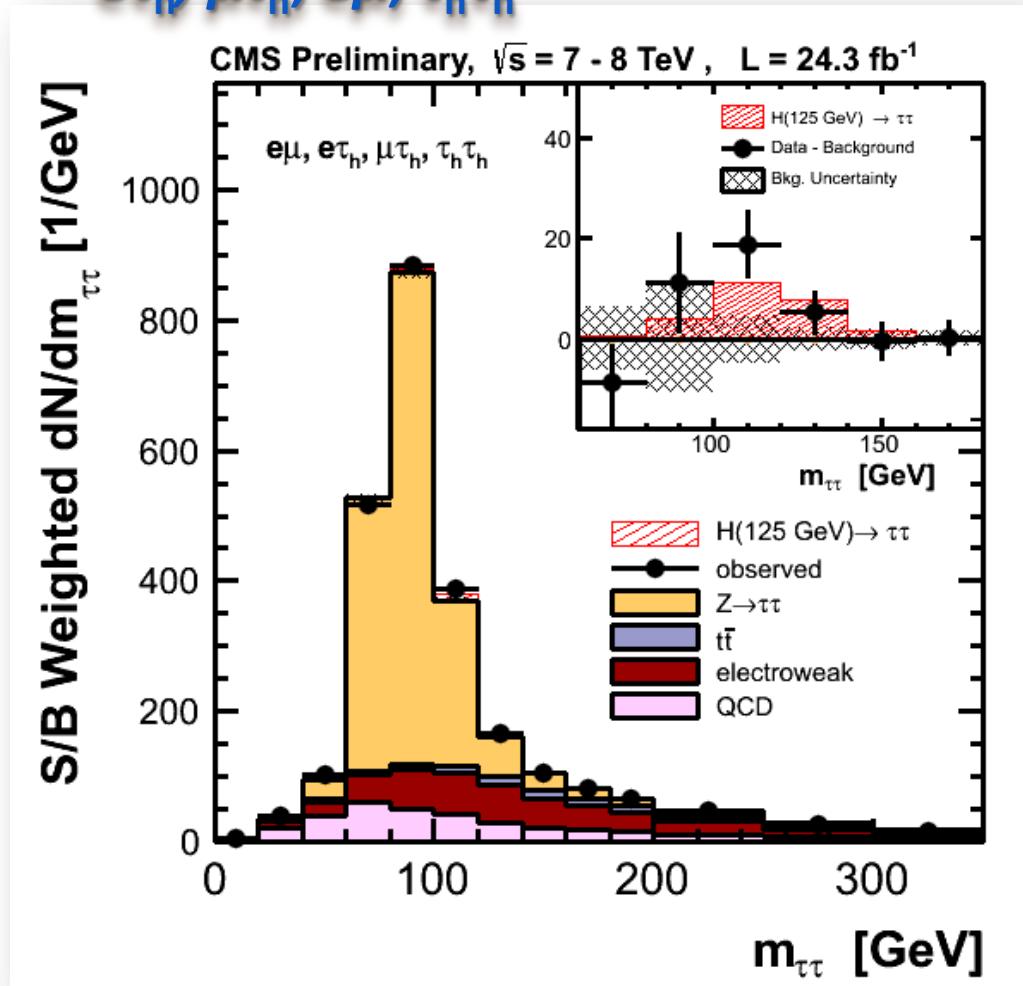
- Enhancement for VBF signal
- Category with best S/B



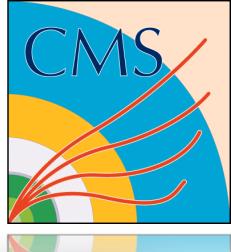


# Combined 1-jet and VBF

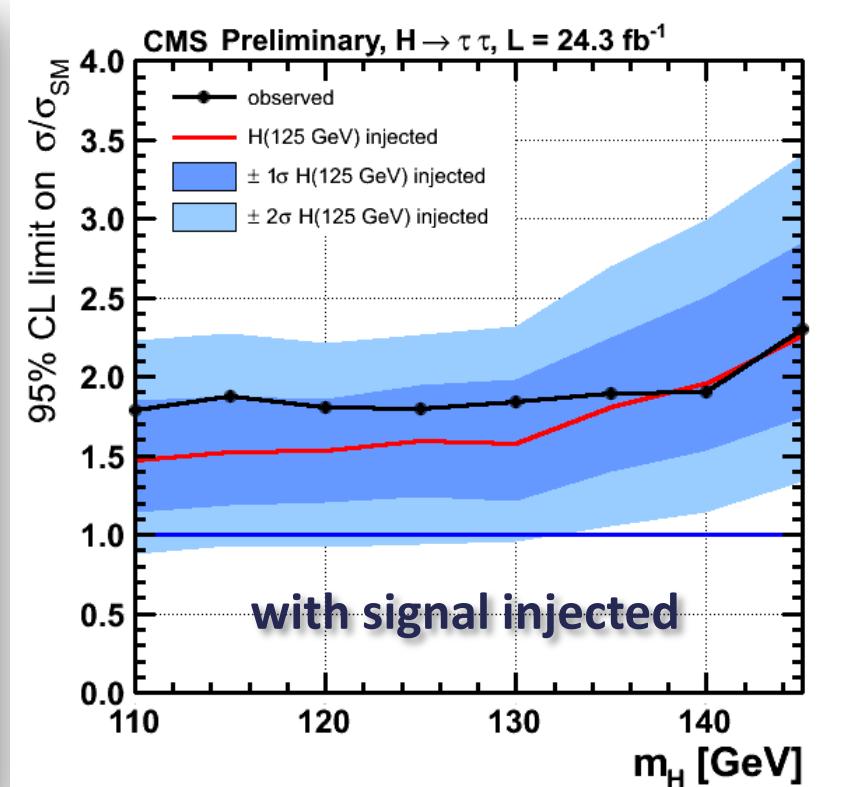
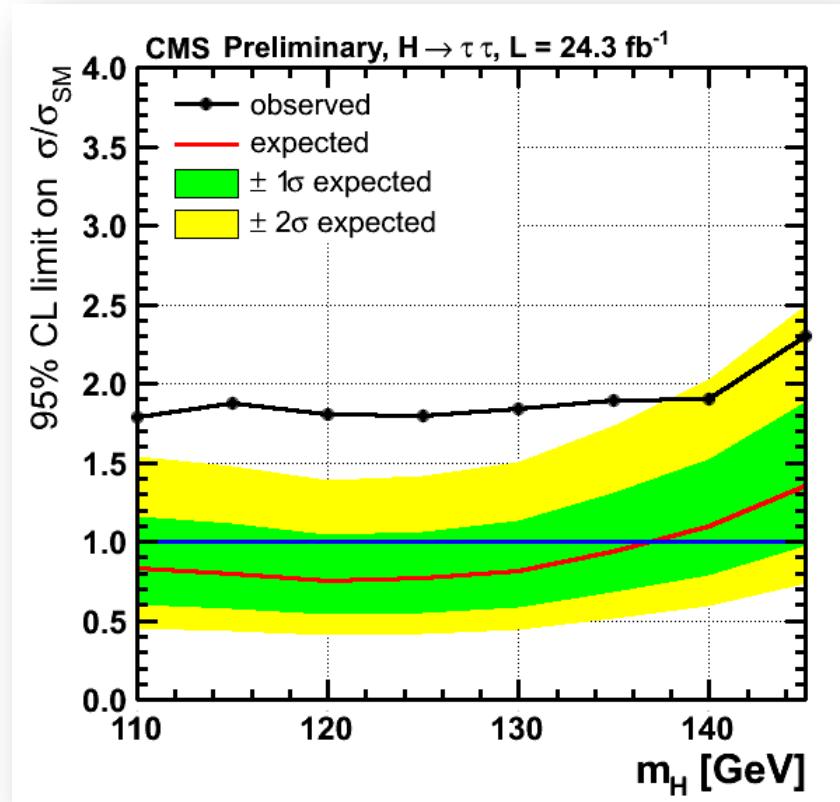
$e\tau_h, \mu\tau_h, e\mu, \tau_h\tau_h$



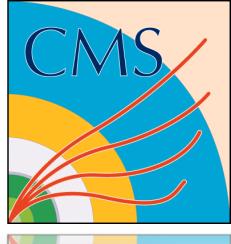
Combined channels and categories, each category in each channel weighted by its S/B



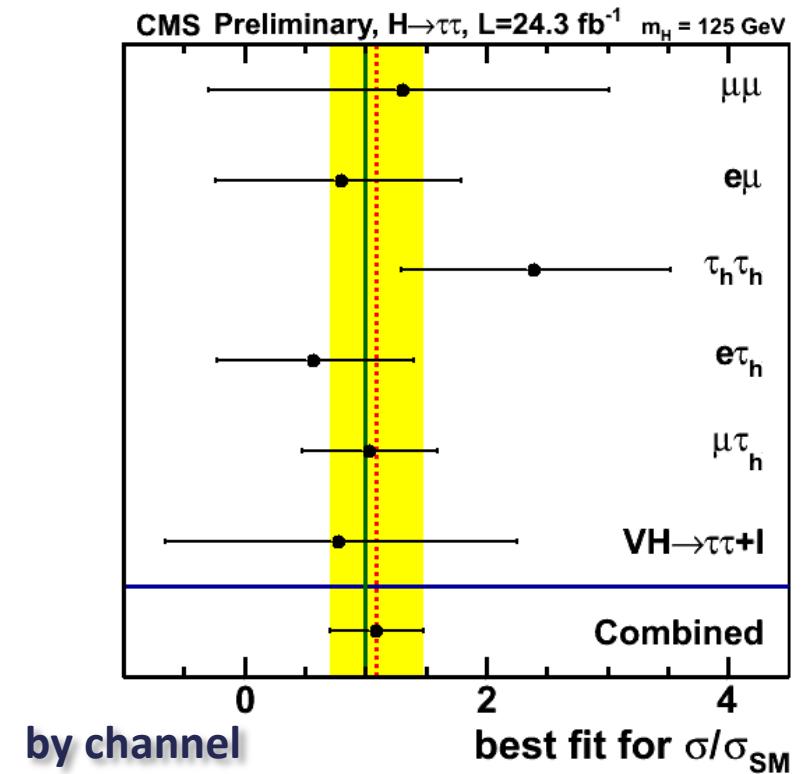
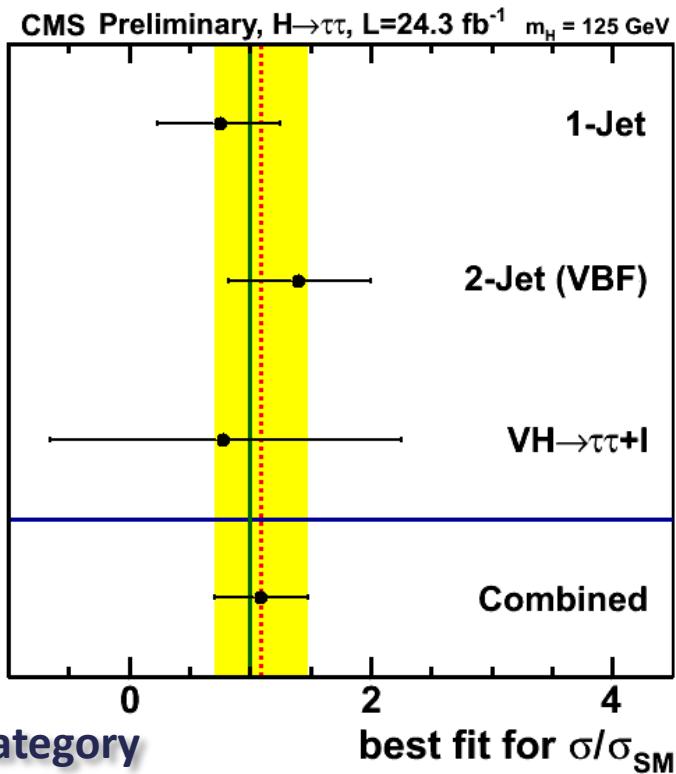
# Limits



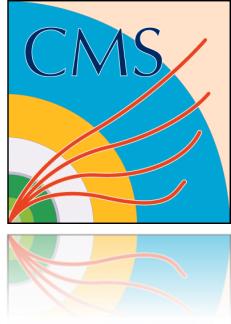
Results consistent with expectation for background + SM scalar at 125 GeV



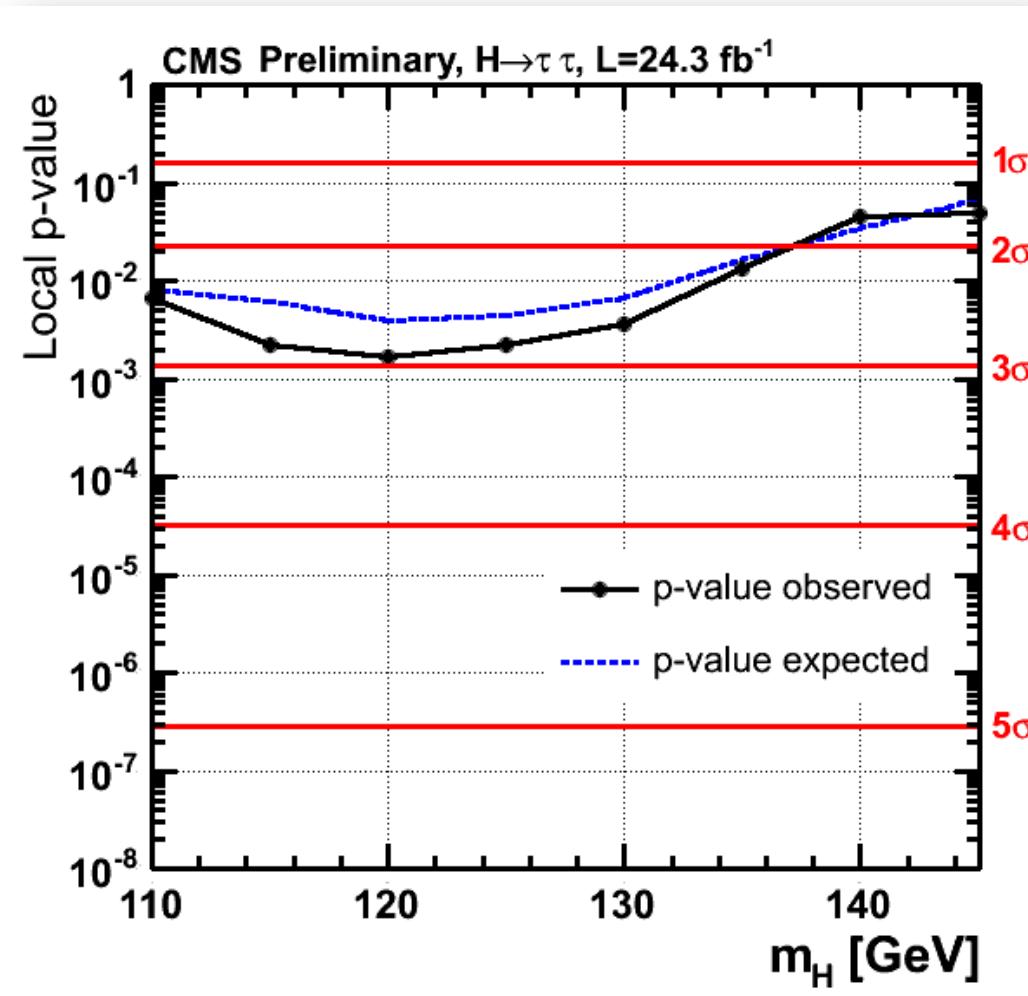
# Signal strength



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

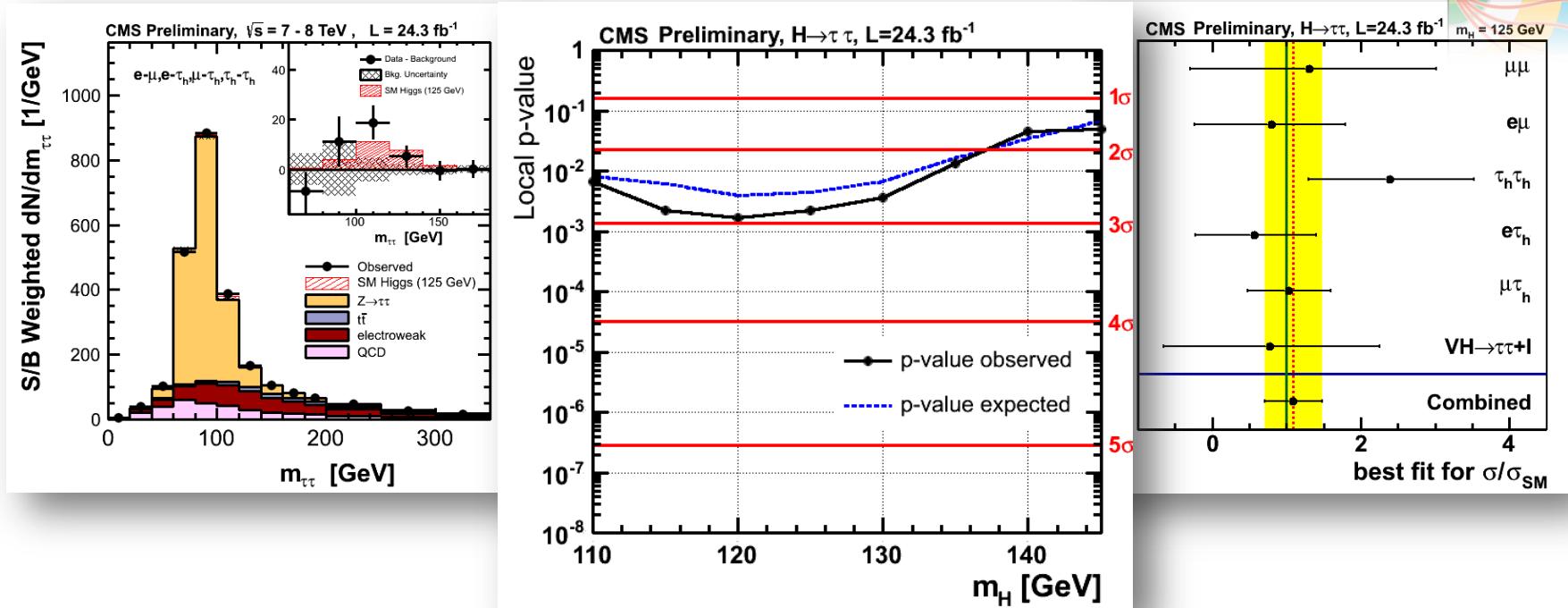


# Significance



- Broad excess observed over range of  $m_H$
- Maximum local significance of  $2.93\sigma$  at 120 GeV, compatible with presence of 125 GeV SM scalar boson
- Observed (expected) significance of  $2.85\sigma$  ( $2.62\sigma$ ) for  $m_H = 125$  GeV

# Conclusion



Strong indication that the new particle couples directly to taus!

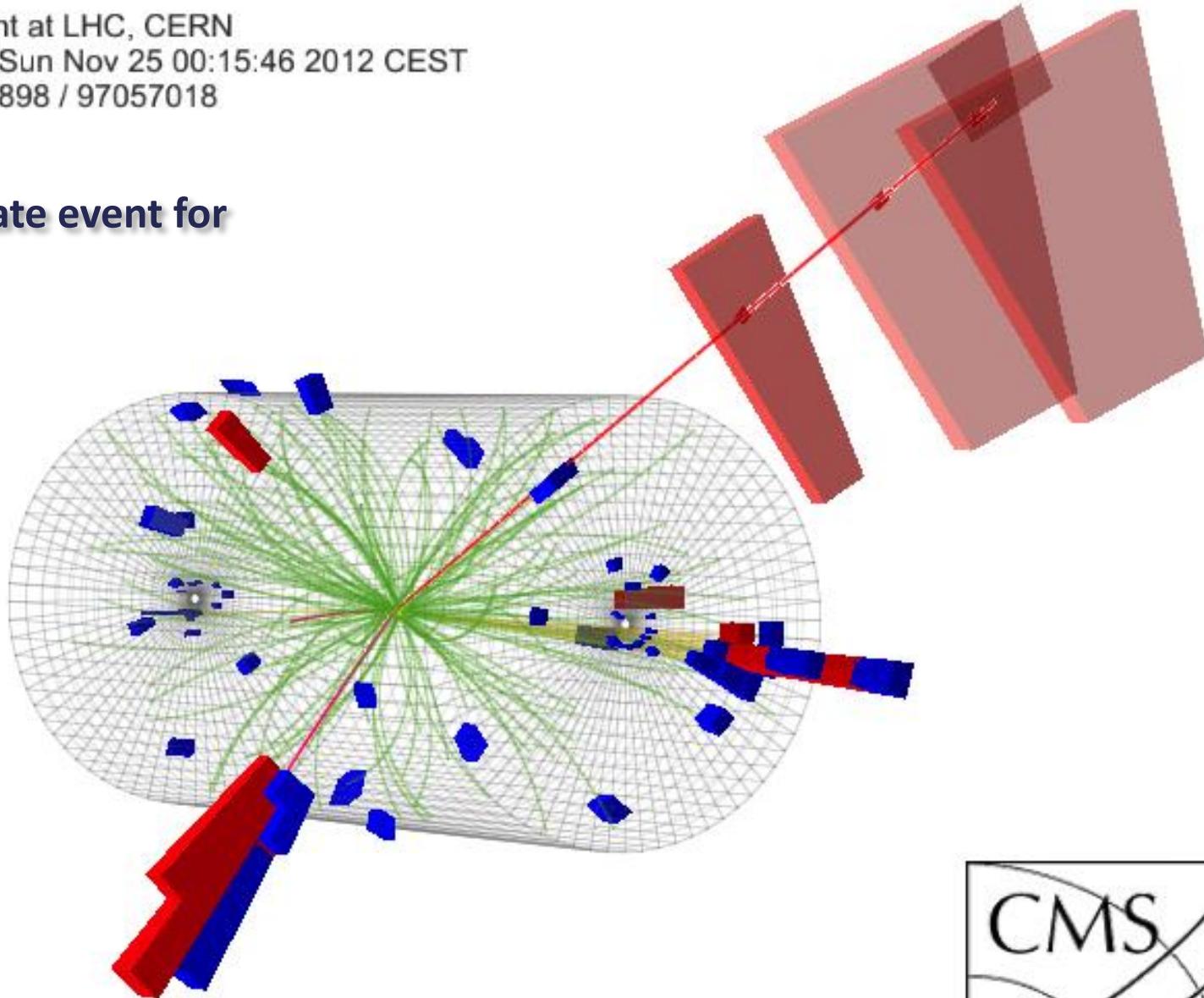
CMS Experiment at LHC, CERN

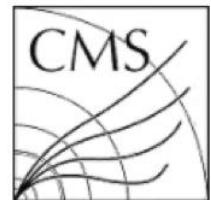
Data recorded: Sun Nov 25 00:15:46 2012 CEST

Run/Event: 207898 / 97057018

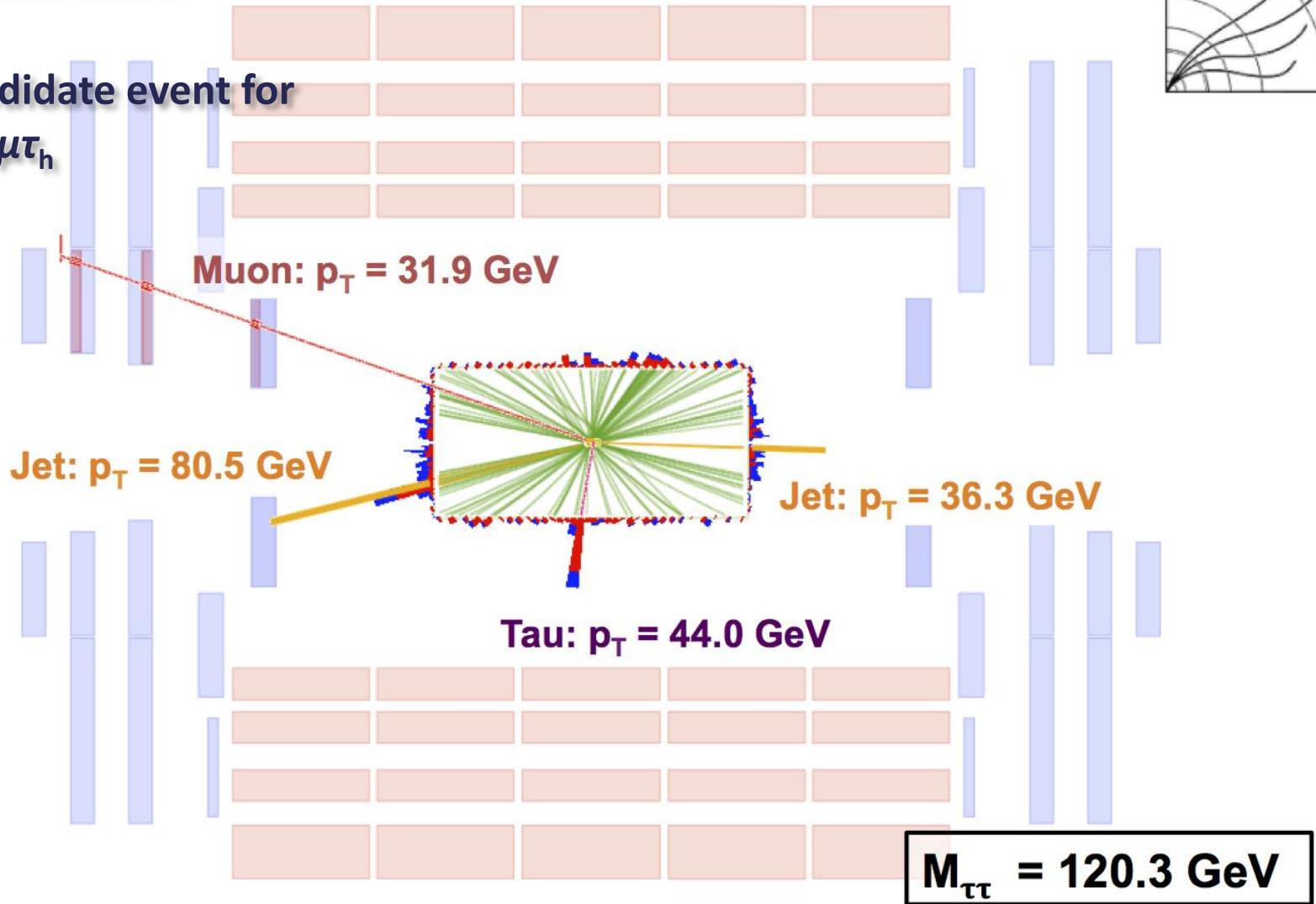
## VBF candidate event for

$H \rightarrow \tau\tau \rightarrow \mu\tau_h$

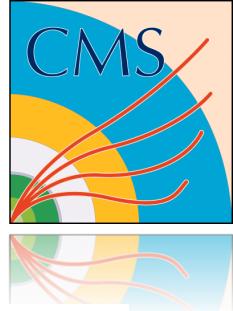




## VBF candidate event for $H \rightarrow \tau\tau \rightarrow \mu\tau_h$



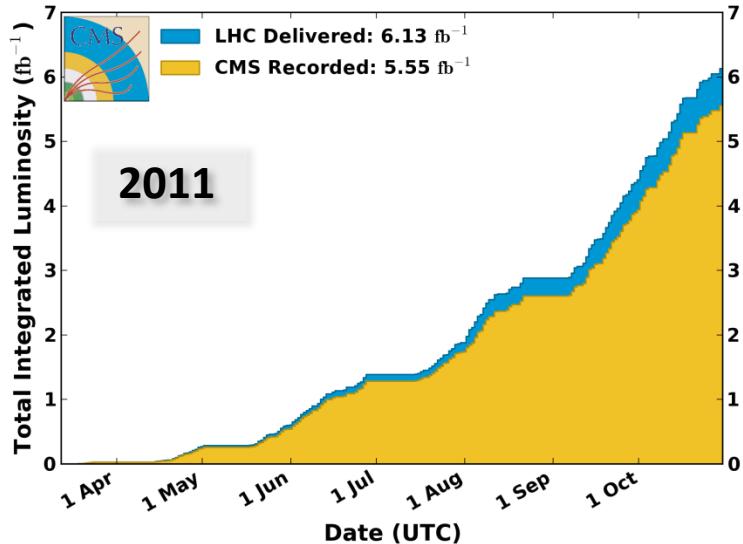
# **Additional material**



# Recorded luminosity

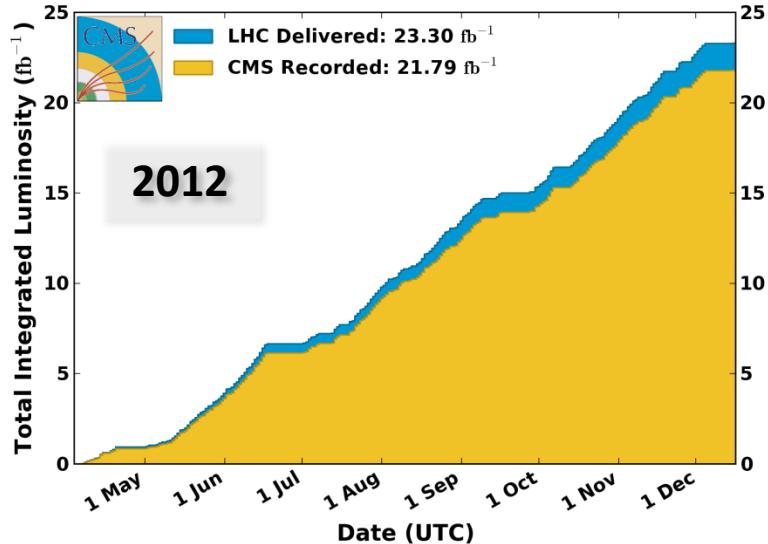
CMS Integrated Luminosity, pp, 2011,  $\sqrt{s} = 7 \text{ TeV}$

Data included from 2011-03-13 17:00 to 2011-10-30 16:09 UTC



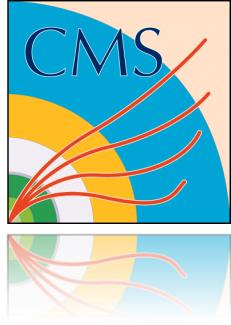
CMS Integrated Luminosity, pp, 2012,  $\sqrt{s} = 8 \text{ TeV}$

Data included from 2012-04-04 22:37 to 2012-12-16 20:49 UTC



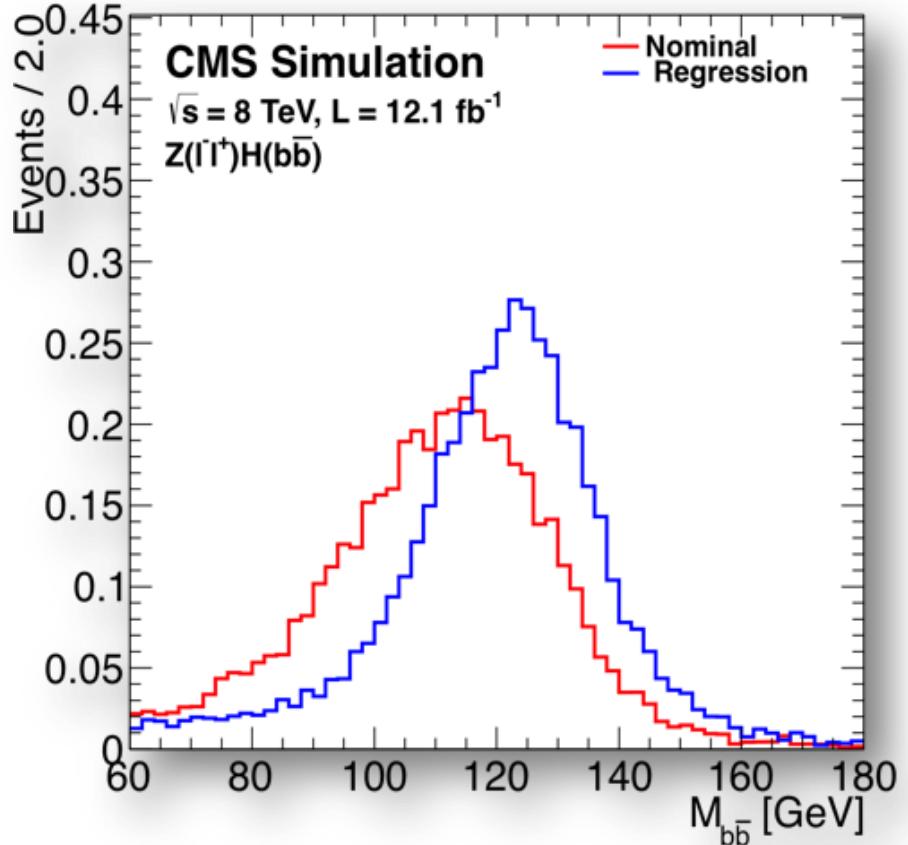
## After good runs selection

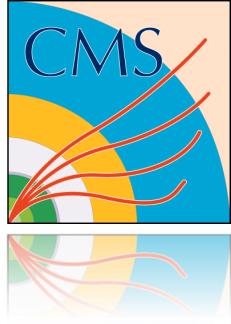
- $5 \text{ fb}^{-1}$  at  $7\text{TeV}$
- $19.4 \text{ fb}^{-1}$  at  $8\text{TeV}$



# b-jet energy regression

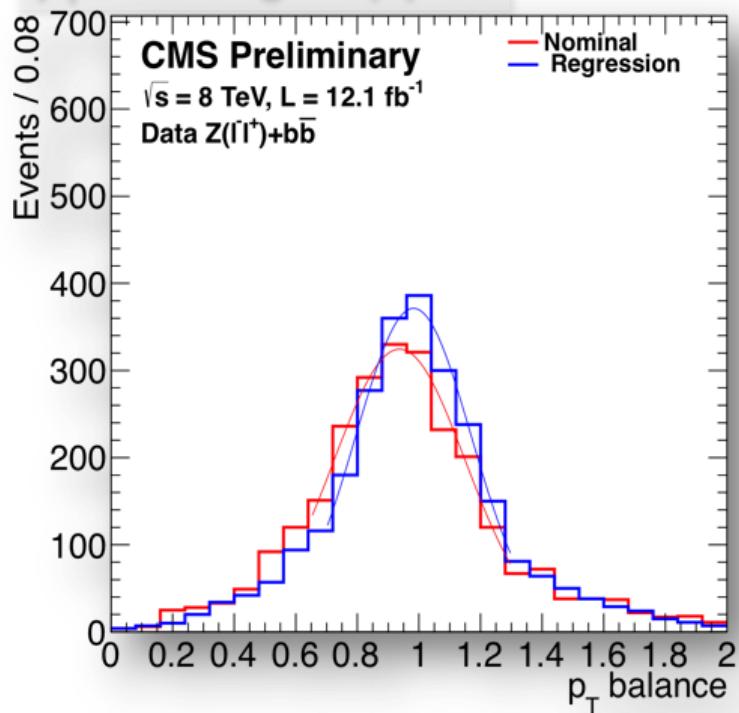
- Multivariate regression trained on VH signal events using jet and soft lepton variables
- ~15% better mass resolution  $\Rightarrow$  10-20% improvement in sensitivity
- Extensive validation on data and simulation
  - $p_T$  balancing in  $Z(l\bar{l})+bb$
  - reconstructed top mass



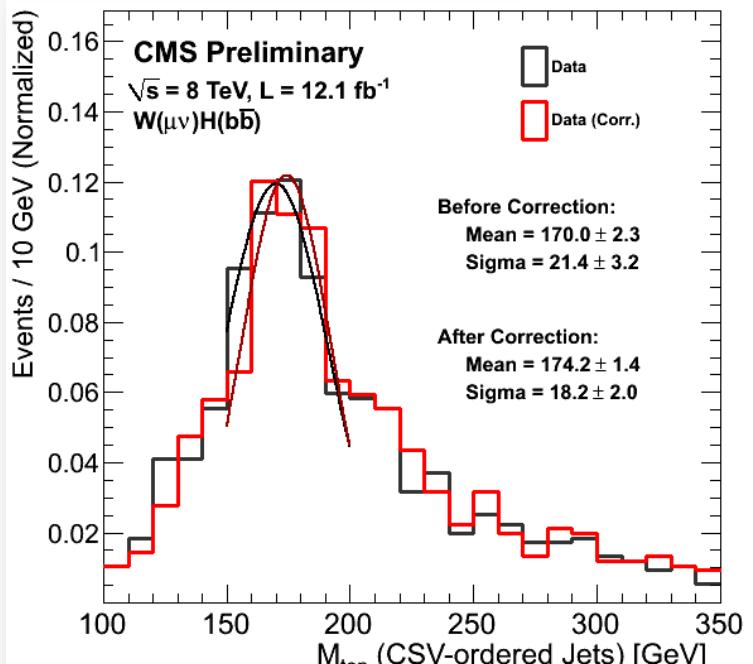


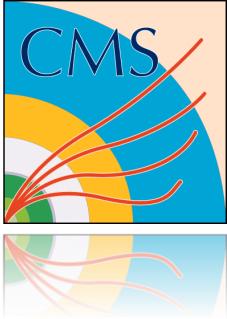
# $b$ -jet regression validation

$p_T$  balancing in  $Z(l\bar{l})+bb$

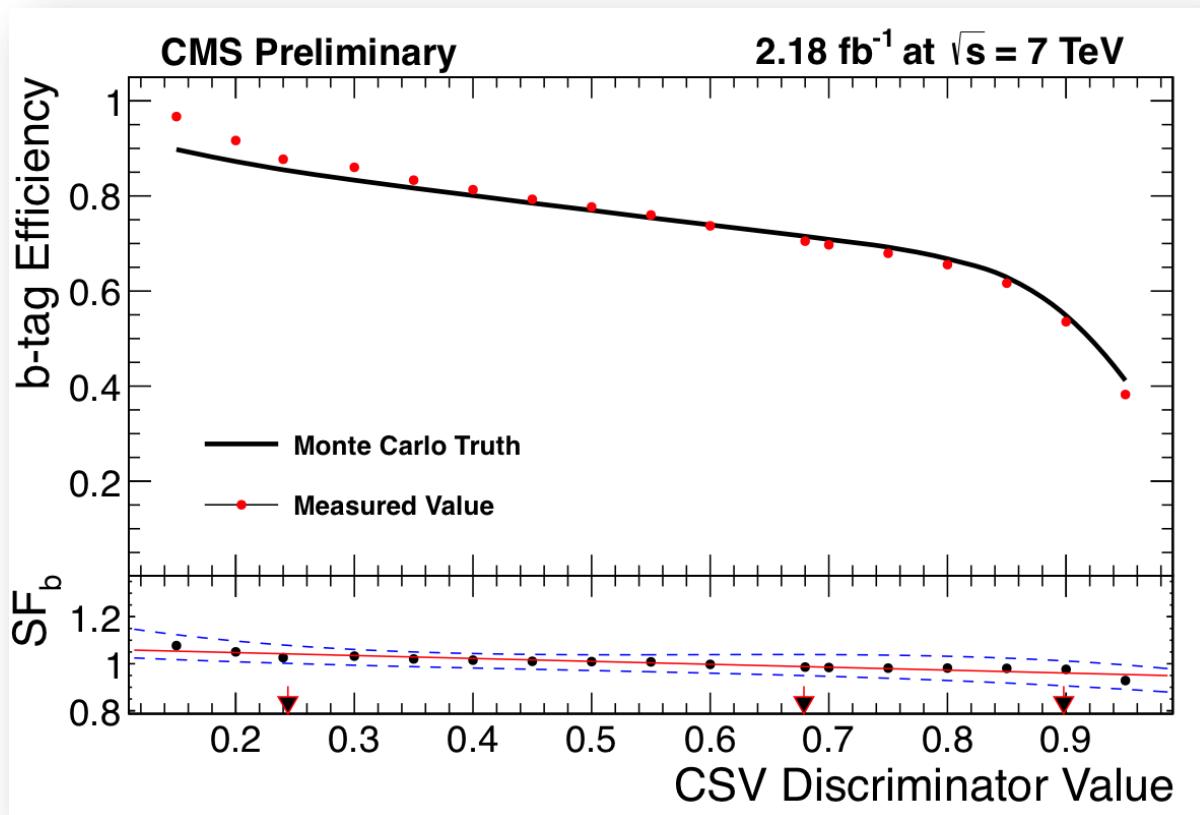


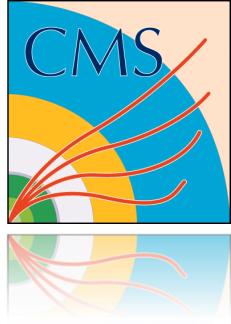
reconstructed top mass





# $b$ -tagging efficiency

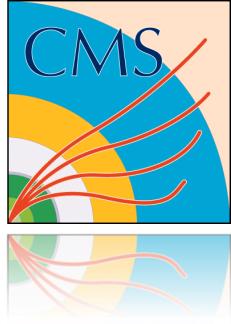




# BDT inputs

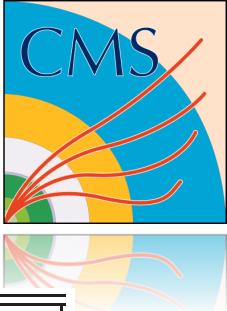
## BDT input variables

$p_{Tj}$	transverse momentum of each Higgs daughter
$m(jj)$	dijet invariant mass
$p_T(jj)$	dijet transverse momentum
$p_T(V)$	vector boson transverse momentum (or $E_T^{\text{miss}}$ )
$\text{CSV}_{\max}$	b-tag disc. value for Higgs daughter with largest value
$\text{CSV}_{\min}$	b-tag disc. value for Higgs daughter with second largest value
$\Delta\phi(V, H)$	azimuthal angle between V (or $E_T^{\text{miss}}$ ) and dijet
$ \Delta\eta(jj) $	difference in $\eta$ between Higgs daughters
$\Delta R(jj)$	difference in $\eta$ - $\phi$ between Higgs daughters
$N_{aj}$	number of additional jets
$\Delta\phi(E_T^{\text{miss}}, \text{jet})$	azimuthal angle between $E_T^{\text{miss}}$ and closest jet (only for Z(vv)H)
$\Delta\theta_{\text{pull}}$	color pull angle



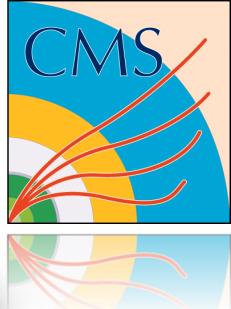
# Systematic uncertainties

Source	Range
Luminosity	2.2–4.4%
Lepton efficiency and trigger (per lepton)	3%
$Z(\nu\nu)H$ triggers	3%
Jet energy scale	2–3%
Jet energy resolution	3–6%
Missing transverse energy	3%
b-tagging	3–15%
Signal cross section (scale and PDF)	4%
Signal cross section ( $p_T$ boost, EWK/QCD)	5–10% / 10%
Signal Monte Carlo statistics	1–5%
Backgrounds (data estimate)	$\approx 10\%$
Single-top (simulation estimate)	15–30%
Dibosons (simulation estimate)	30%

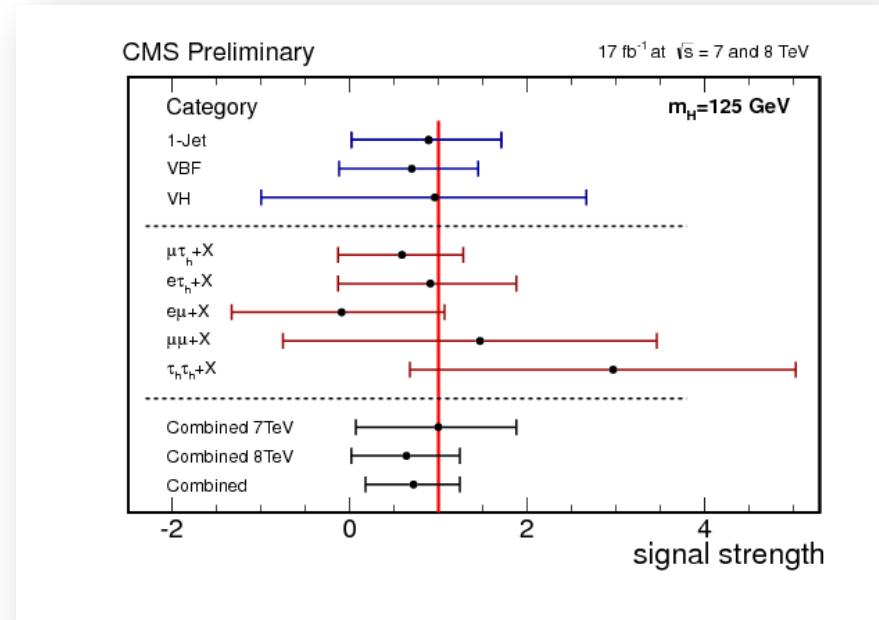
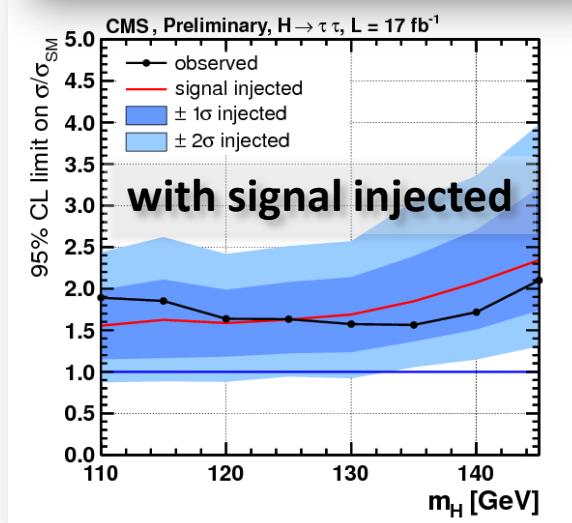
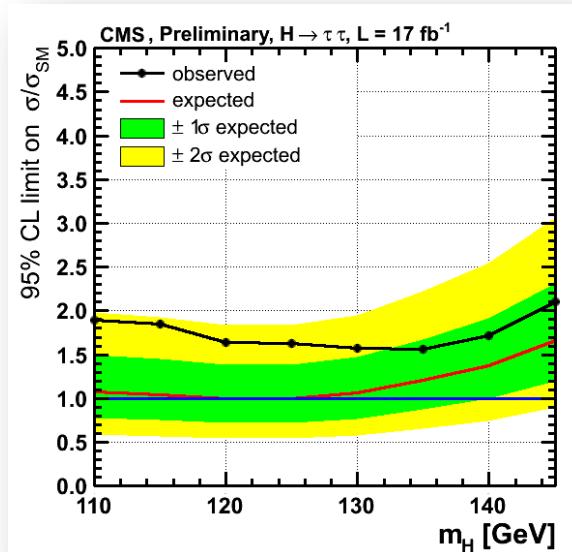


# Systematic uncertainties

Source	Rate Uncertainty	Shape	Remarks
Luminosity (7 TeV)	2.2%	No	All signal and backgrounds
Luminosity (8 TeV)	4.4%	No	All signal and backgrounds
Lepton ID/Trig	4%	No	All signal and backgrounds
Pileup	1%	No	All signal and backgrounds
Additional Pileup Corr.	—	Yes	All signal and backgrounds
Jet Energy Resolution	1.5%	No	All signal and backgrounds
Jet Energy Scale	0-60%	Yes	All signal and backgrounds
b-Tag SF (b / c)	0-33.6%	Yes	All signal and backgrounds
b-Tag SF (mistag)	0-23.5%	Yes	All signal and backgrounds
MC Statistics	—	Yes	All backgrounds
PDF (gg)	9%	No	For gg initiated processes ( $t\bar{t}$ , $t\bar{t}Z$ , $t\bar{t}H$ )
PDF (q $\bar{q}$ )	4.2-7%	No	For q $\bar{q}$ initiated processes ( $t\bar{t}W$ , W, Z).
PDF (qg)	4.6%	No	For qg initiated processes (single top)
QCD Scale ( $t\bar{t}H$ )	15%	No	For NLO $t\bar{t}H$ prediction
QCD Scale ( $t\bar{t}$ )	2-12%	No	For NLO $t\bar{t}$ and single top predictions
QCD Scale (V)	1.2-1.3%	No	For NNLO W and Z prediction
QCD Scale (VV)	3.5%	No	For NLO diboson prediction
Madgraph Scale ( $t\bar{t}$ )	0-20%	Yes	$t\bar{t}$ +jets/bb/c $\bar{c}$ uncorrelated. Varies by jet bin.
Madgraph Scale (V)	20-60%	No	Varies by jet bin.
$t\bar{t} + bb$	50%	No	Only $t\bar{t} + bb$ .



# Last public result (HCP)

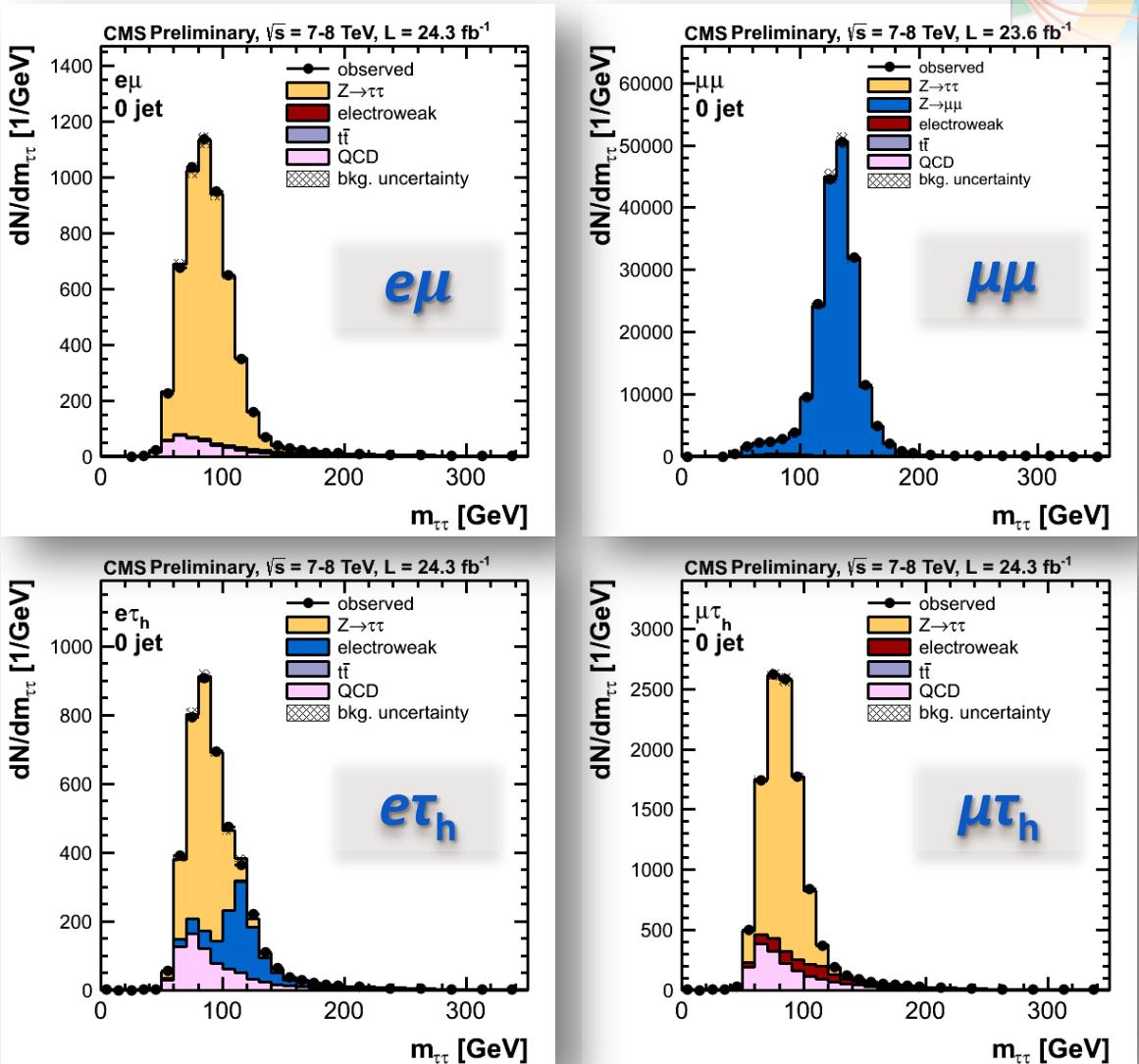


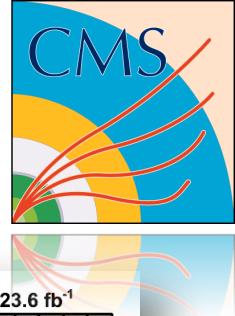
- Expected limit of **1.0  $\times$  SM** at 125 GeV
- Observed (expected) significance of  **$1.5\sigma$  ( $2.45\sigma$ )** for  $m_H = 125 \text{ GeV}$
- Combined best-fit  $\hat{\mu}$  of  **$0.7 \pm 0.5$**

# $m_{\tau\tau}$ distributions

## 0-jet

- Constrains backgrounds in sensitive categories in simultaneous fit

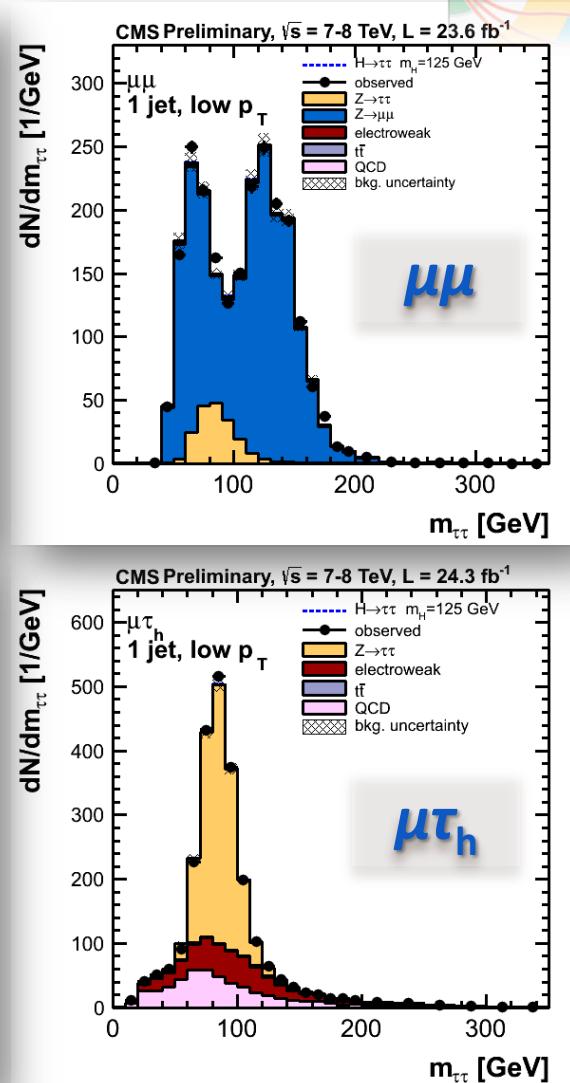
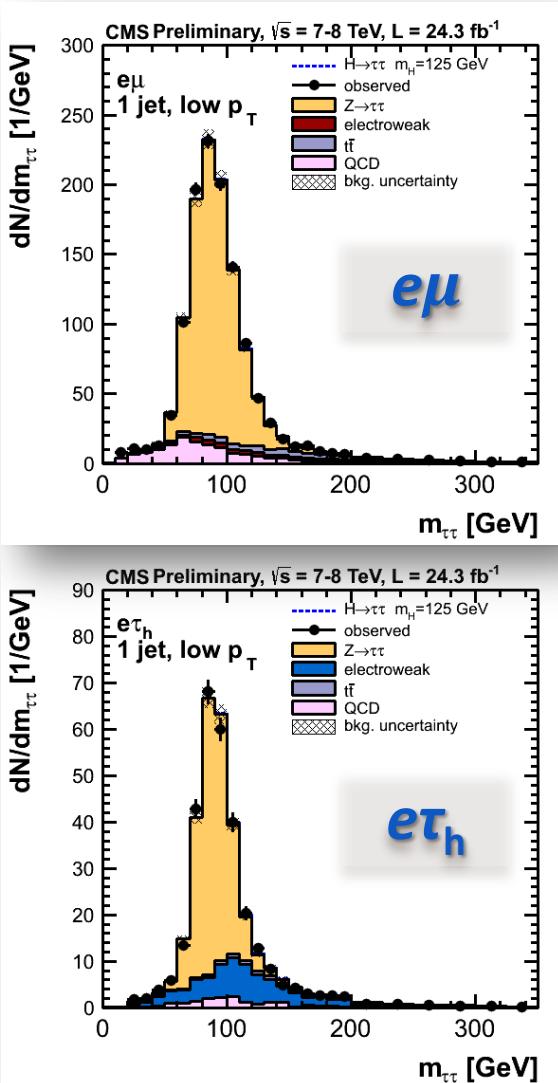


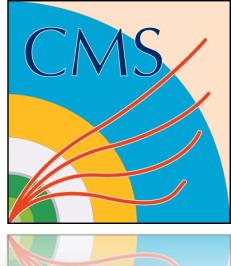


# $m_{\tau\tau}$ distributions

## 1-jet, low $p_T$

- Enhancement for gluon fusion signal

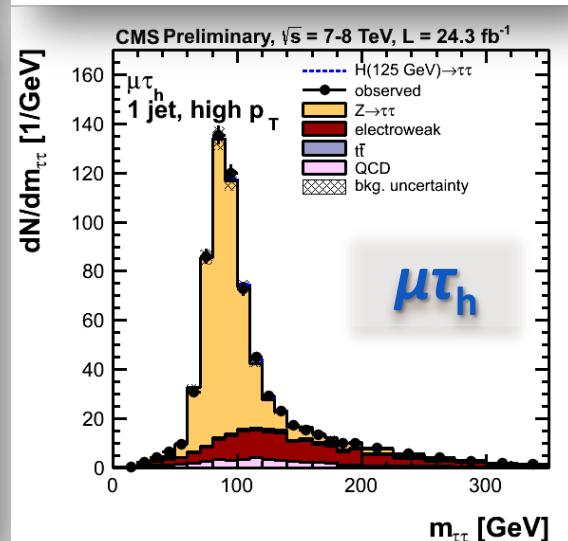
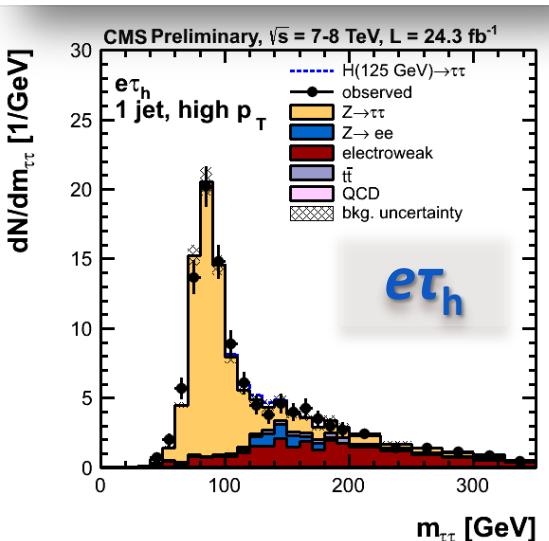
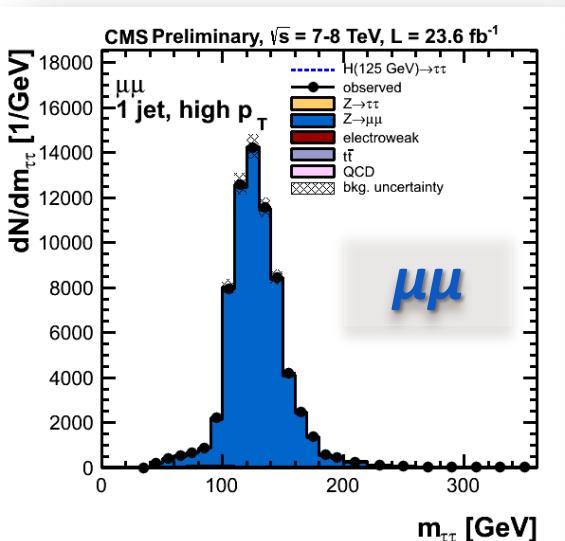
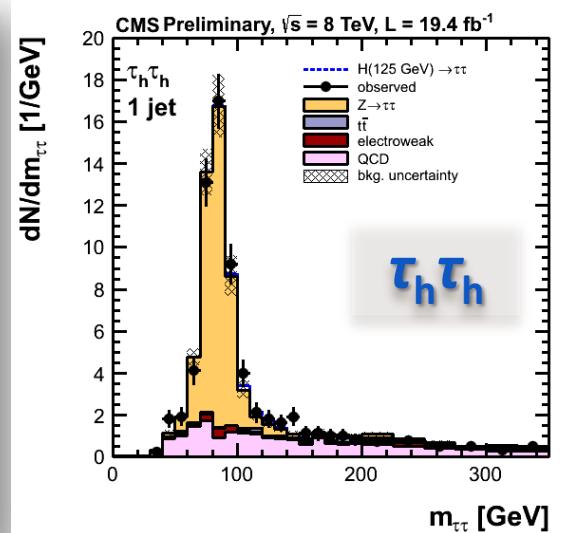
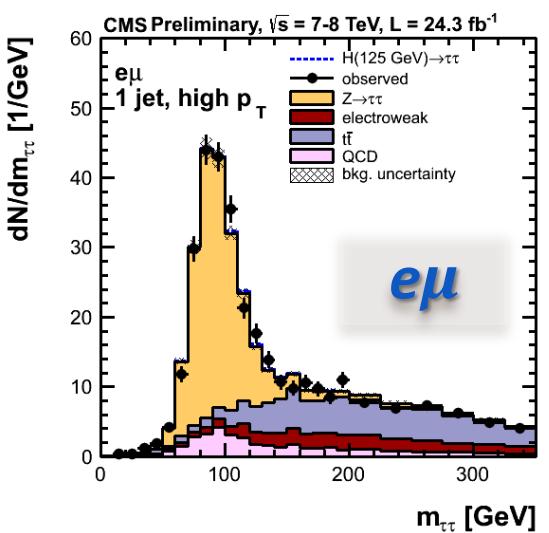


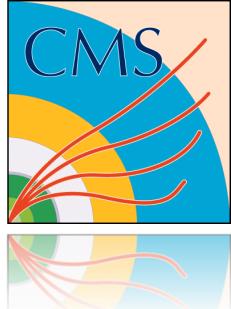


# $m_{\tau\tau}$ distributions

## 1-jet, high $p_T$

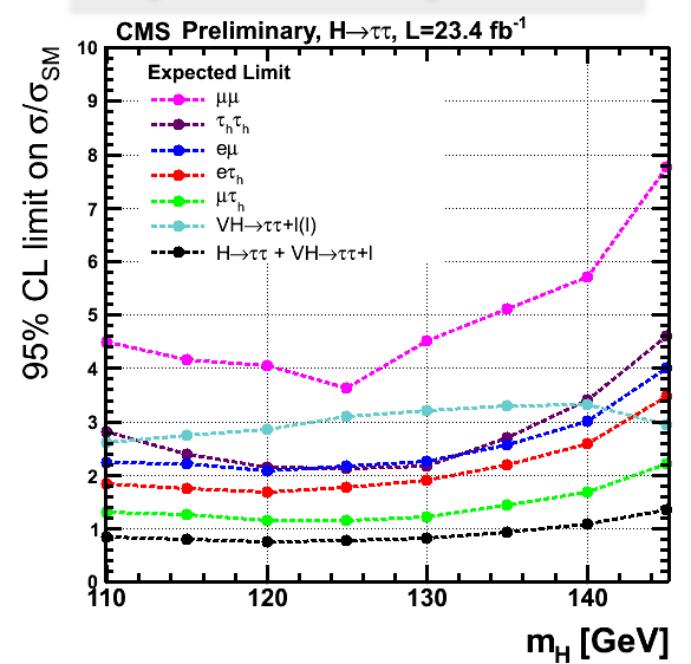
- Enhancement for gluon fusion signal
- Improved mass resolution
- High  $p_T$  requirement improves S/B



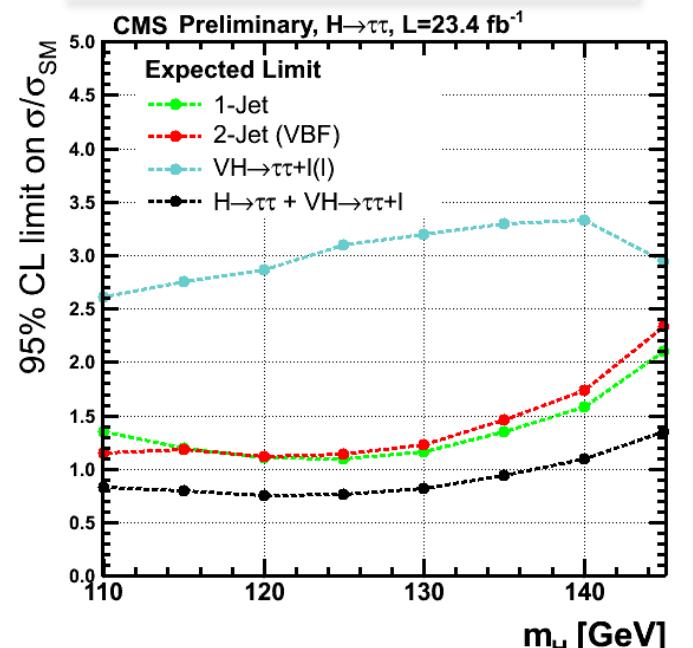


# Sensitivity break-down

expected limit by channel



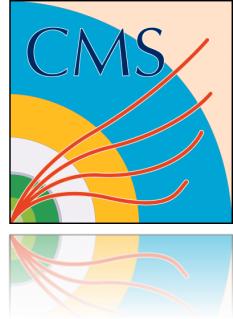
expected limit by category



- Results updated with full 2011+2012 dataset
- Sensitivity of **0.77**  $\times$  SM at 125 GeV

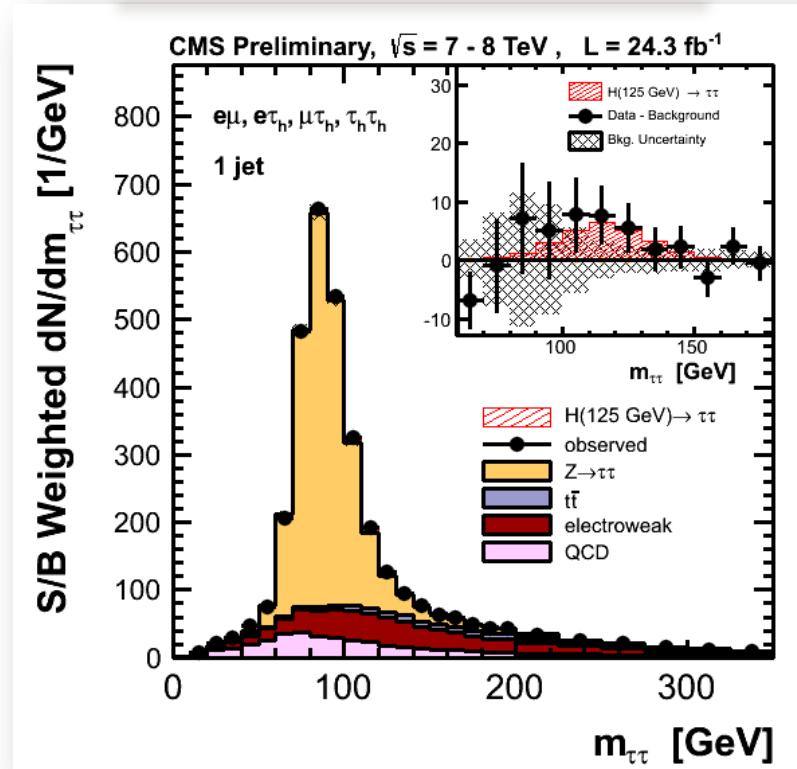
7TeV (2011)    8TeV (2012)

**5  $\text{fb}^{-1}$**     **19  $\text{fb}^{-1}$**

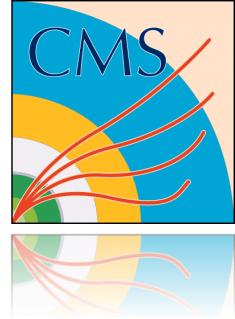


# Combined 1-jet

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

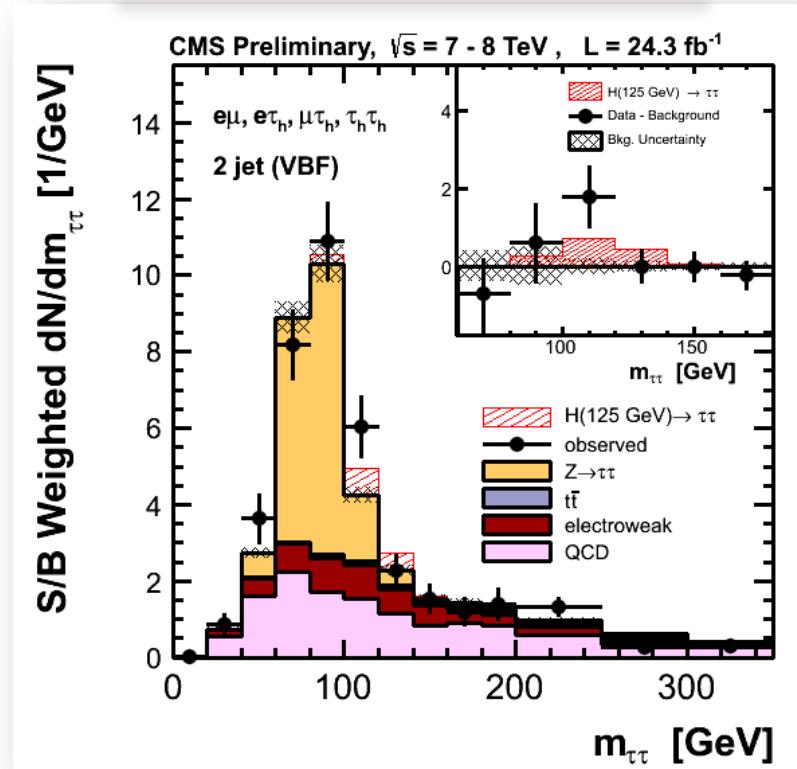


Combined channels, each channel weighted by expected S/B



# Combined VBF

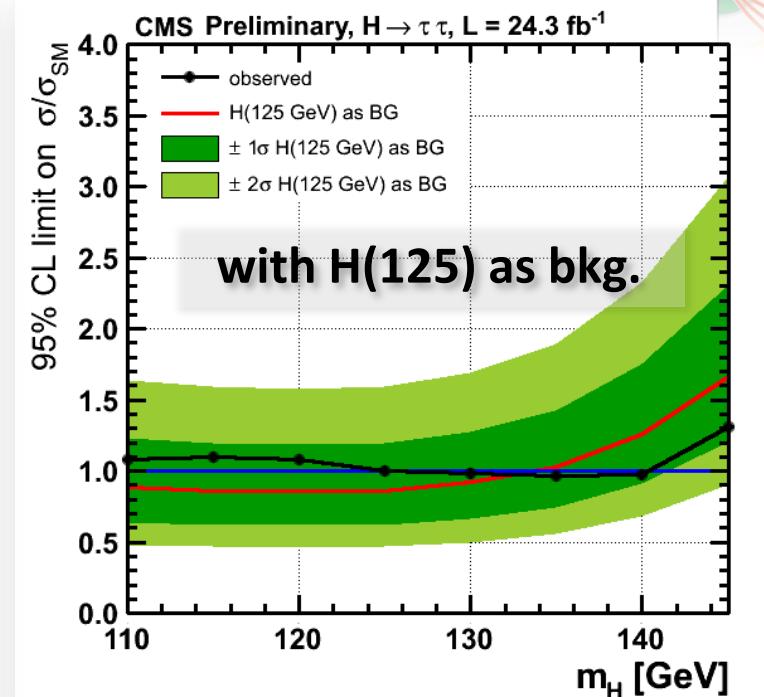
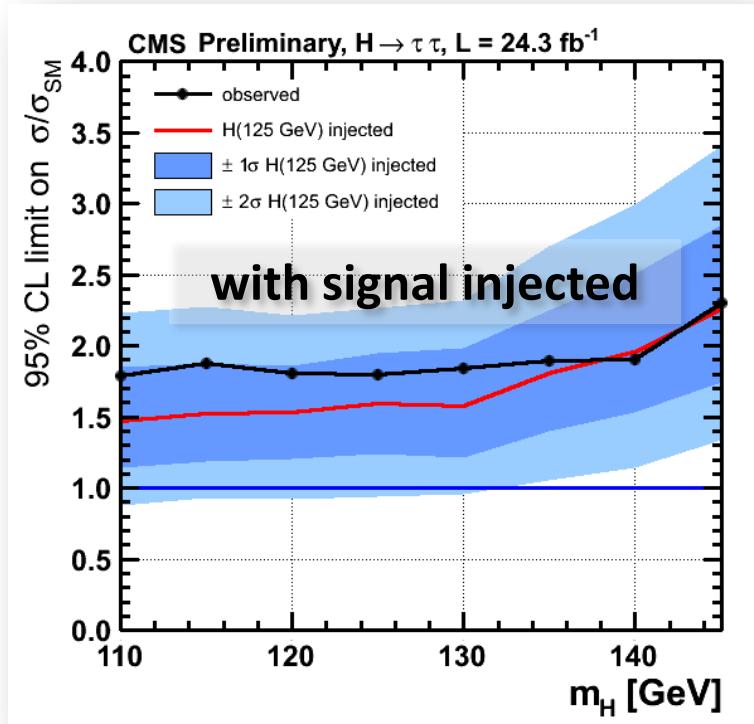
$e\tau_h, \mu\tau_h, e\mu, \tau_h\tau_h$



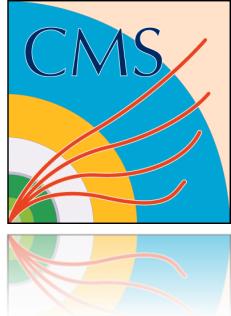
Combined channels, each channel weighted by expected S/B



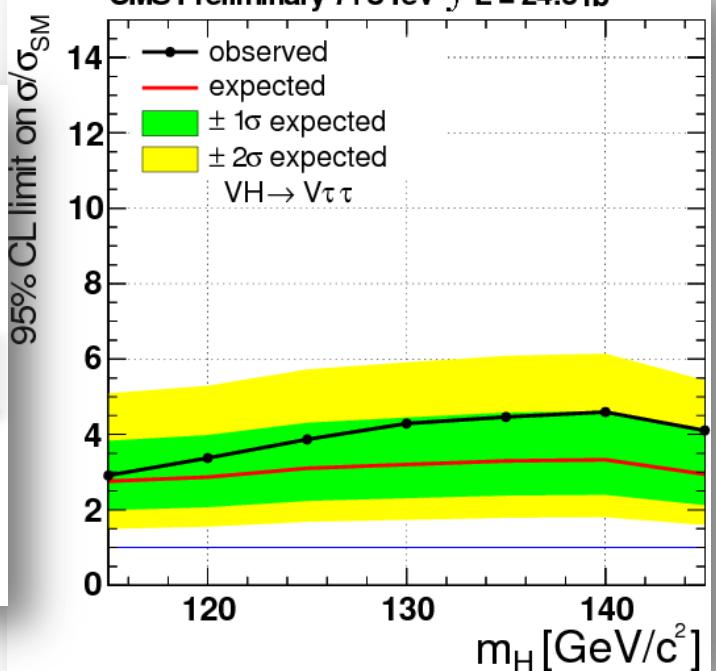
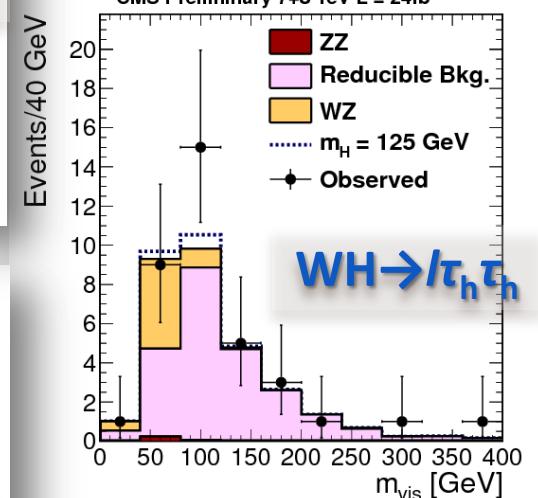
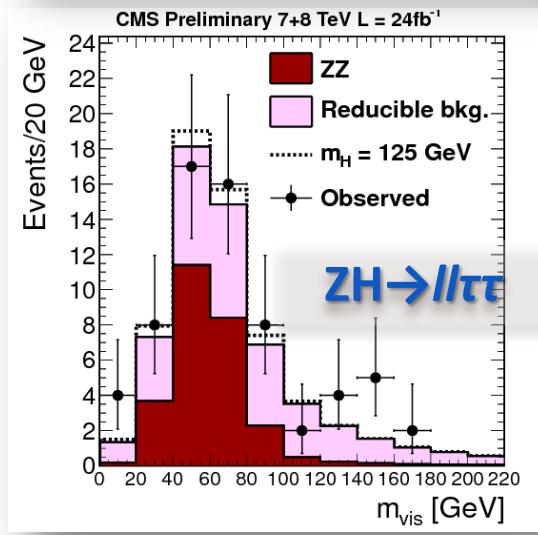
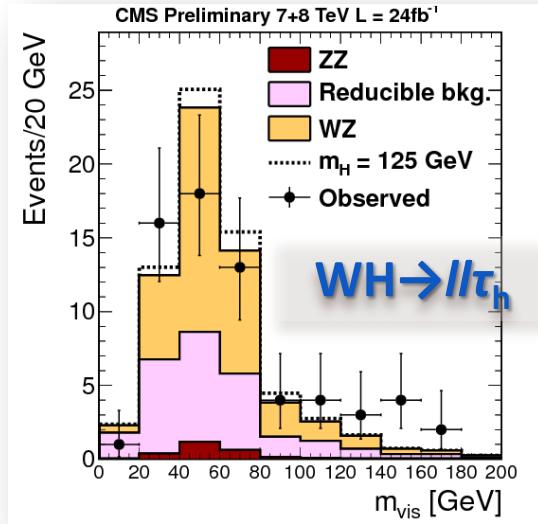
# Consistency with signal

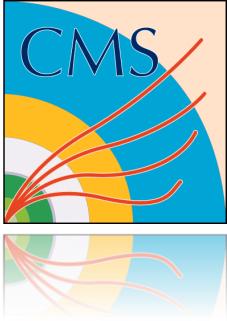


Results consistent with expectation for background + SM scalar at 125 GeV



# VH results

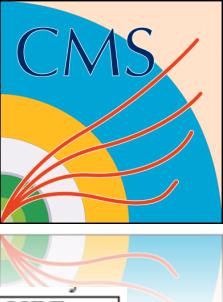




# Systematic uncertainties

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  $(\dagger)$  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 ( $\dagger^*$ )	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
Muon ID & Trigger ( $\dagger^*$ )	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
Tau ID & Trigger ( $\dagger$ )	$\pm 8\%$	$\pm 8\%$	$\pm 8\%$	$\pm 8\%$
Tau Energy Scale ( $\dagger$ )	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$
Electron Energy Scale ( $\dagger$ )	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$
JES (Norm.) ( $\dagger^*$ )	$\pm 2.5 - 5\%$	$\mp 3 - 15\%$	$\pm 1 - 6\%$	$\pm 5 - 20\%$
MET (Norm.) ( $\dagger^*$ )	$\pm 5\%$	$\pm 5 - 7\%$	$\pm 2 - 7\%$	$\pm 5 - 8\%$
$b$ -Tag Efficiency ( $\dagger^*$ )	$\pm 10\%$	$\mp 2\%$	$\mp 2 - 3\%$	$\mp 3\%$
Mis-Tagging ( $\dagger^*$ )	$\pm 30\%$	$\mp 2\%$	$\mp 2\%$	$\mp 2 - 3\%$
Norm. Z production ( $\dagger^*$ )	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$
$Z \rightarrow \tau\tau$ Category	$\pm 3\%$	$\pm 0 - 5\%$	$\pm 3 - 5\%$	$\pm 10 - 13\%$
Norm. $t\bar{t}$ ( $\dagger^*$ ex.vbf)	$\pm 10\%$	$\pm 10\%$	$\pm 10\%$	$\pm 12 - 33\%$
Norm. Diboson ( $\dagger^*$ 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. $W + \text{jets}$	$\pm 10 - 30\%$	$\pm 20 - 27\%$	$\pm 10 - 33\%$	$\pm 12.4\% - 30\%$
Norm. $Z \rightarrow \ell\ell$ : e fakes $\tau_h$ ( $\dagger$ )	$\pm 20\%$	$\pm 20\%$	$\pm 36\%$	$\pm 22\%$
Norm. $Z \rightarrow \ell\ell$ : $\mu$ fakes $\tau_h$ ( $\dagger$ )	$\pm 30\%$	$\pm 30\%$	$\pm 30\%$	$\pm 30\%$
Norm. $Z \rightarrow \ell\ell$ : jet fakes $\tau_h$	$\pm 20\%$	$\pm 20\%$	$\pm 20\%$	$\pm 40\%$



# Event yields

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

Signal Eff.

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

Process	$e\mu$	0-Jet	1-Jet high $p_T$	VBF
$Z \rightarrow \tau\tau$		$48882 \pm 1282$	$1830 \pm 105$	$61 \pm 6$
QCD		$4374 \pm 249$	$395 \pm 36$	$19 \pm 2$
EWK		$1185 \pm 89$	$461 \pm 44$	$7 \pm 1$
$t\bar{t}$		$74 \pm 5$	$1100 \pm 66$	$19 \pm 2$
Total Background		$54514 \pm 1309$	$3785 \pm 137$	$105 \pm 7$
$H \rightarrow \tau\tau$		- ± -	$23 \pm 4$	$5 \pm 0.6$
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	-	$1.38 \cdot 10^{-3}$	$1.32 \cdot 10^{-5}$

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

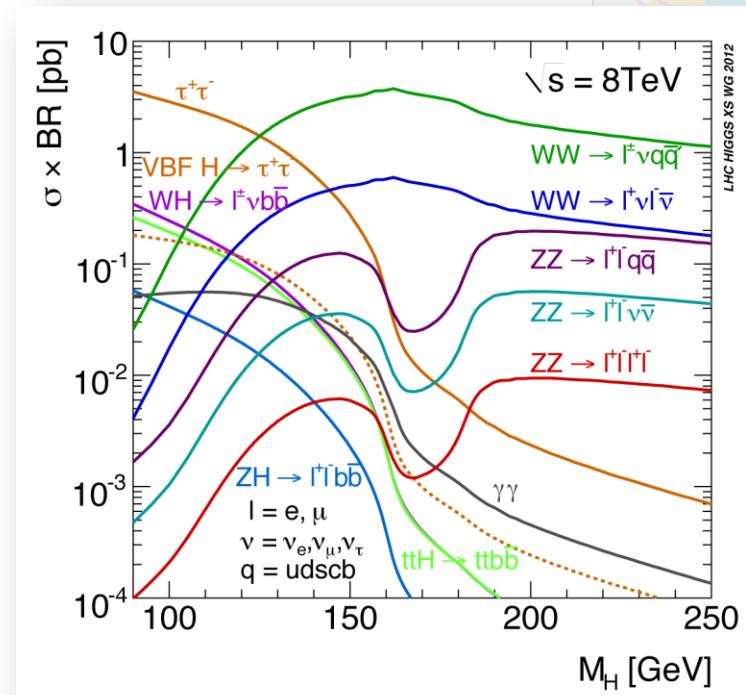
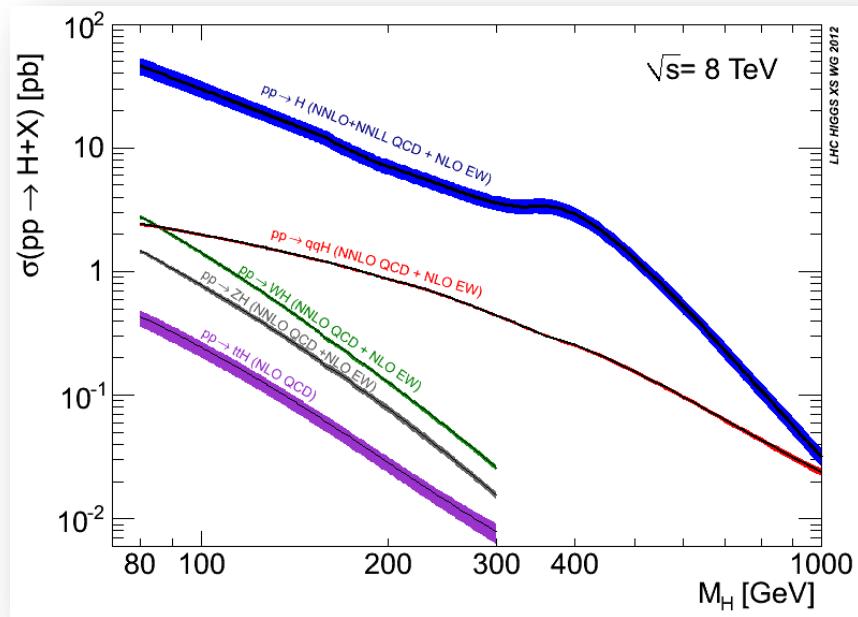
Process	$\tau_h\tau_h$	1-Jet	VBF
$Z \rightarrow \tau\tau$		$428 \pm 90$	$47 \pm 28$
QCD		$210 \pm 31$	$61 \pm 10$
EWK		$41 \pm 9$	$4 \pm 1$
$t\bar{t}$		$29 \pm 6$	$2 \pm 2$
Total Background		$709 \pm 95$	$114 \pm 30$
$H \rightarrow \tau\tau$		$9 \pm 4$	$4 \pm 2$
Observed		718	120

Signal Eff.

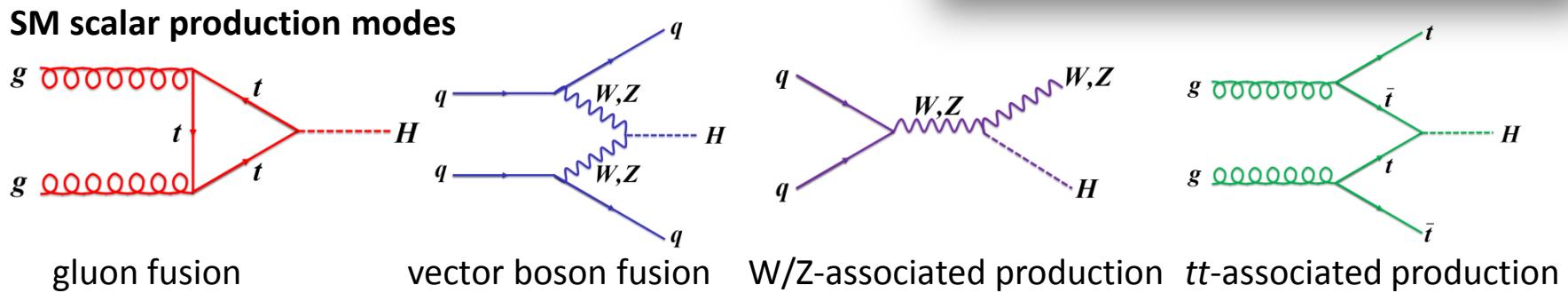
$gg \rightarrow H$	-	$3.94 \cdot 10^{-4}$	$3.33 \cdot 10^{-5}$
$qq \rightarrow H$	-	$1.10 \cdot 10^{-3}$	$1.78 \cdot 10^{-3}$
$qq \rightarrow Ht\bar{t}$ or VH	-	$8.30 \cdot 10^{-4}$	$1.46 \cdot 10^{-6}$

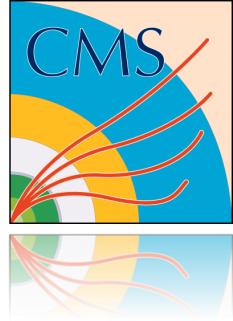
$gg \rightarrow H$	$2.52 \cdot 10^{-4}$	$4.99 \cdot 10^{-5}$
$qq \rightarrow H$	$5.93 \cdot 10^{-4}$	$1.20 \cdot 10^{-3}$
$qq \rightarrow Ht\bar{t}$ or VH	$9.13 \cdot 10^{-4}$	$3.59 \cdot 10^{-5}$

# Higgs production and decays



## SM scalar production modes





# MSSM search overview

Higgs sector: 2 Higgs doublets, 5 observable Higgs bosons

- 3 neutral: **H, h** (CP-even); **A** (CP-odd)
- 2 charged: **H $^\pm$**

Coupling to down-type fermions enhanced for large  $\tan\beta$

- current best sensitivity from  $\Phi \rightarrow \tau\tau$

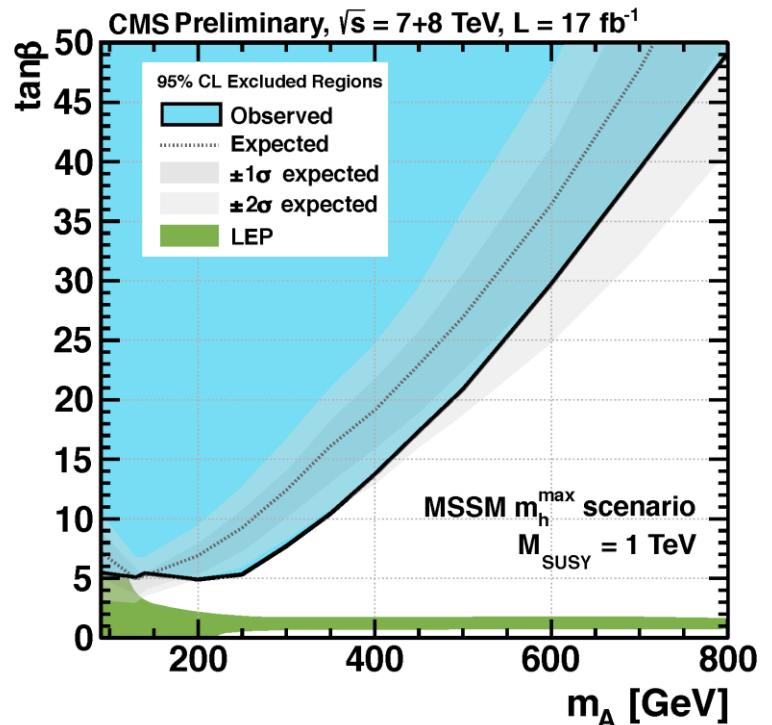
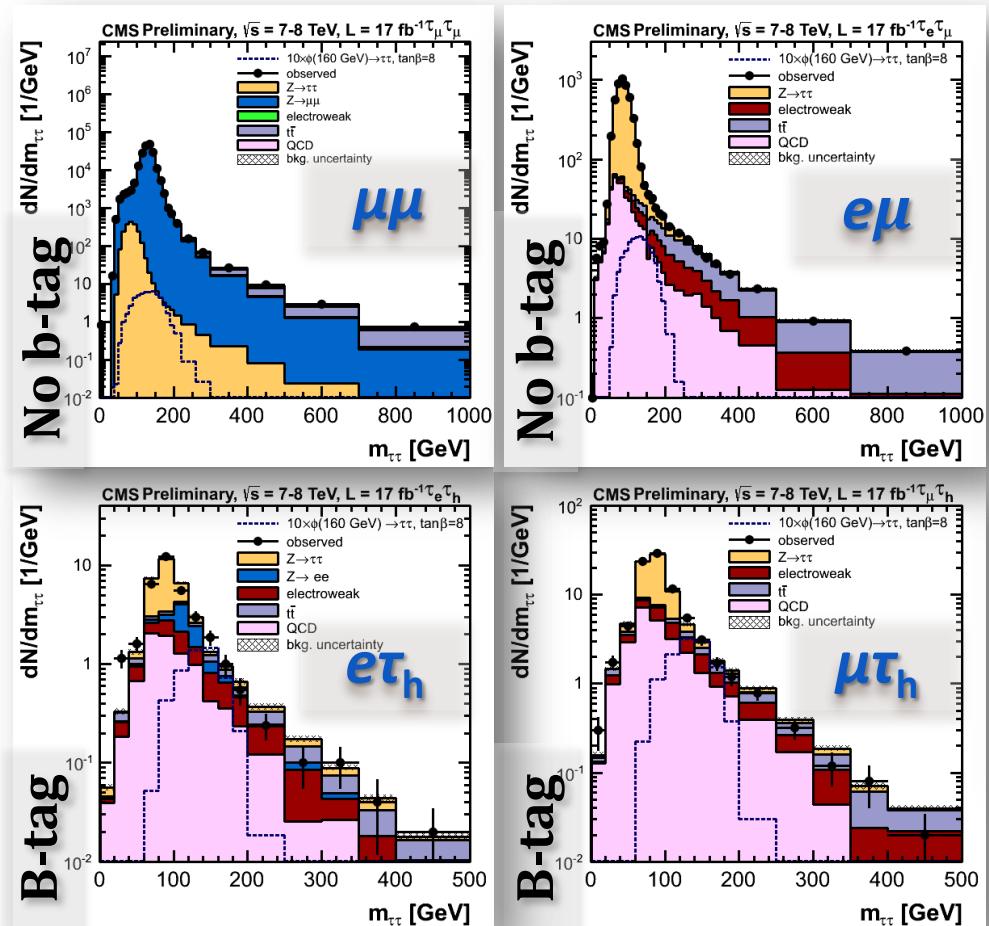
Production mechanisms: gluon fusion, associated production with  $b$ -quarks

## **Strategy:**

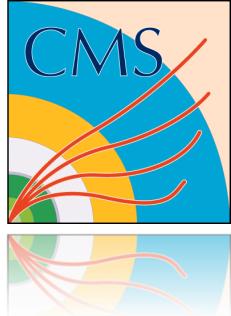
- Same object and topological selection as for SM search
- 2 event categories: b-tag ( $\geq 1$  b-tagged jet,  $p_T > 20$  GeV) and no b-tag
- Template fit to  $m_{\tau\tau}$  shape

7TeV (2011)	8TeV (2012)
<b>5 fb<math>^{-1}</math></b>	<b>12 fb<math>^{-1}</math></b>

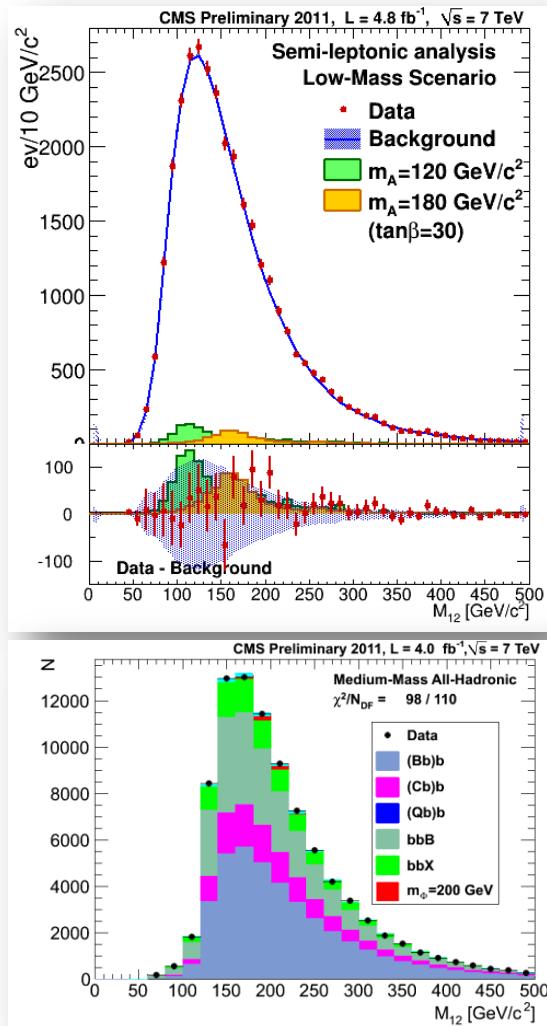
# Results



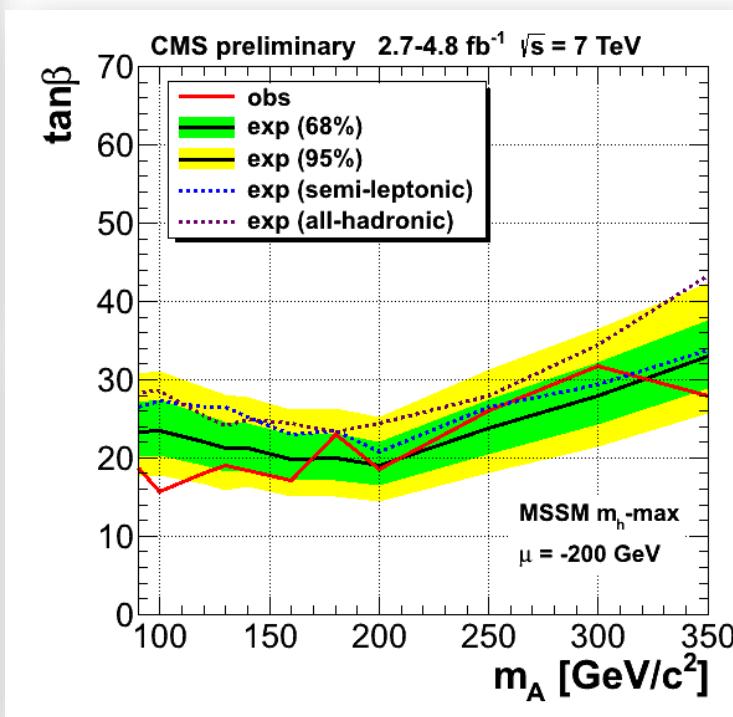
- Interpretation in  $m_h^{\max}$  benchmark scenario
- Exclusion limit in  $m_A$ - $\tan\beta$  parameter space



# MSSM $b(b)\Phi, \Phi \rightarrow bb$

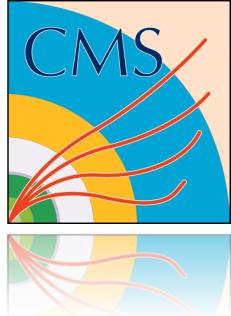


- Multijet final states with 3 b-tagged jets (one of which may include a non-isolated muon)
- Fit mass of 2 leading b-jets



7TeV (2011)

3-5  $\text{fb}^{-1}$



# MSSM $\Phi \rightarrow \mu\mu$

- Sensitive to gluon-fusion, associated production with b-quarks
- Fit  $m_{\mu\mu}$  in 3 categories: with a b-tagged jet, no b-tag but with additional muon from b decay, everything else

