

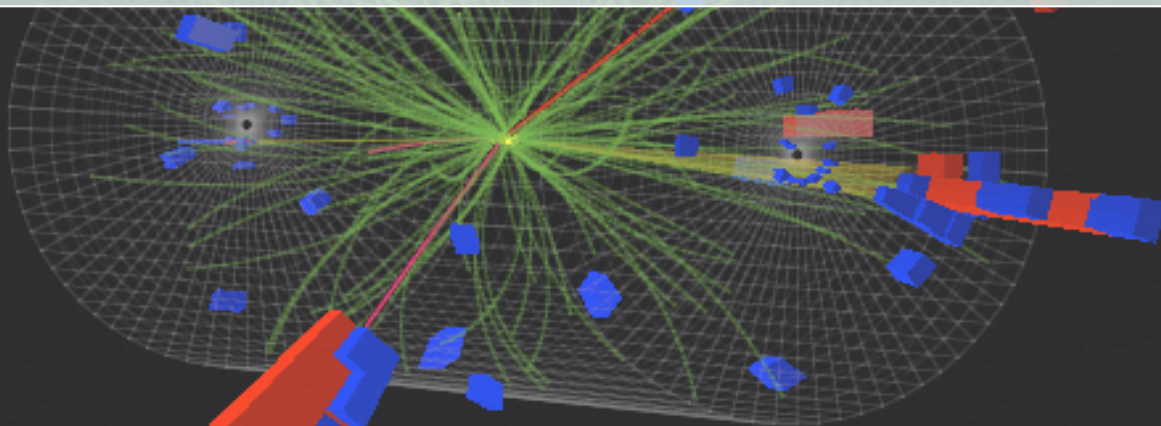
CMS Experiment at LHC, CERN  
Data recorded: Sun Nov 25 00:15:46 2012 CEST  
Run/Event: 207898 / 97057018



ULB

UNIVERSITÉ  
LIBRE  
DE BRUXELLE

# Search for SM Higgs boson in *fermionic* final state at CMS



**Abdollah Mohammadi**

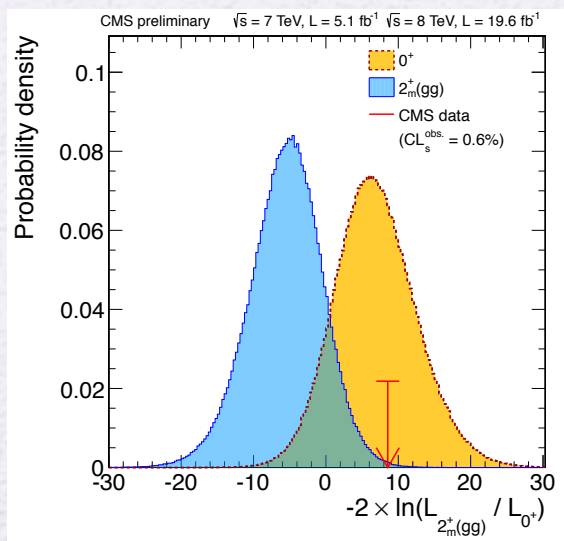
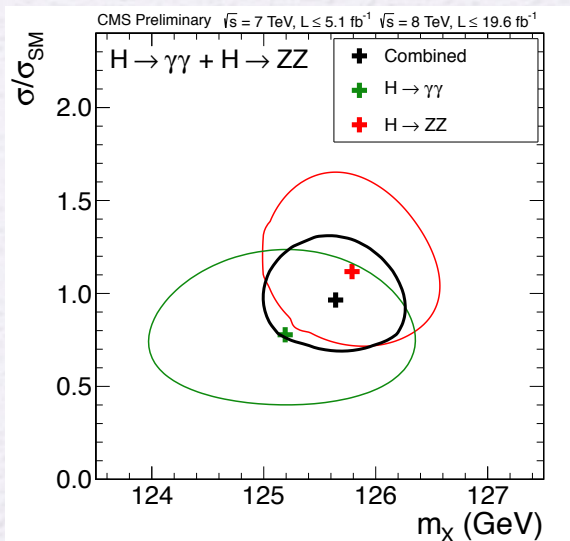
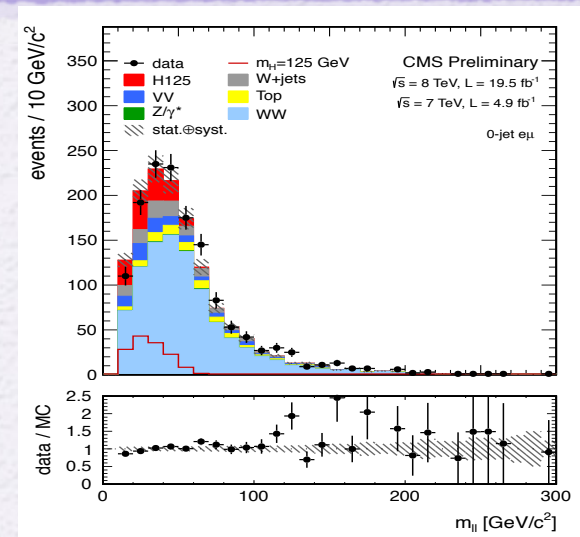
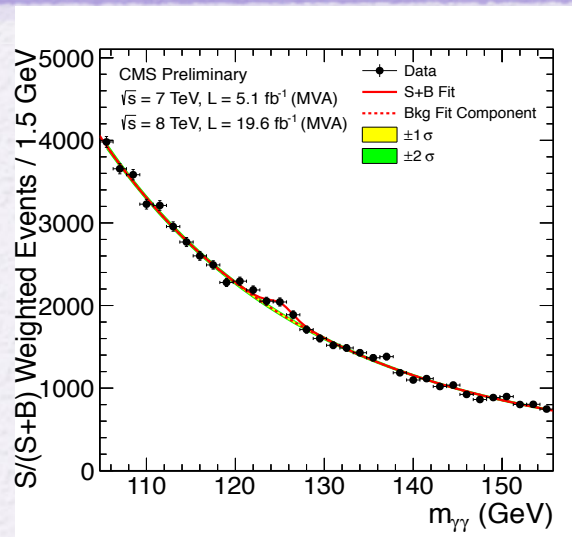
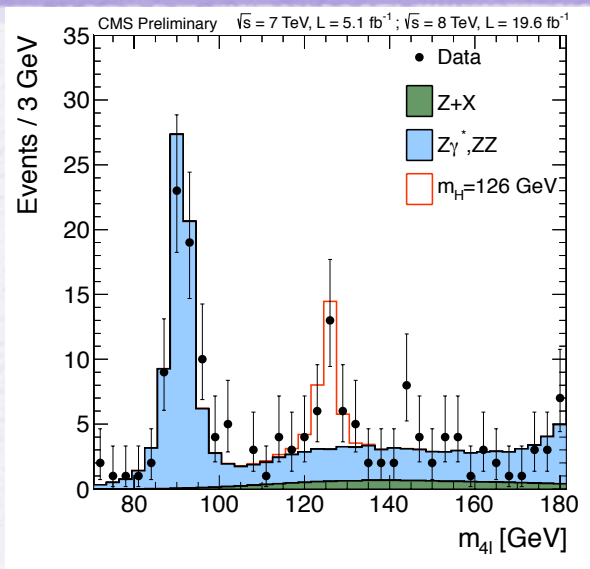
IIHE-ULB, Université Libre de Bruxelles

2<sup>nd</sup> LHC-IPM Meeting, Tehran, Iran

Oct. 2013



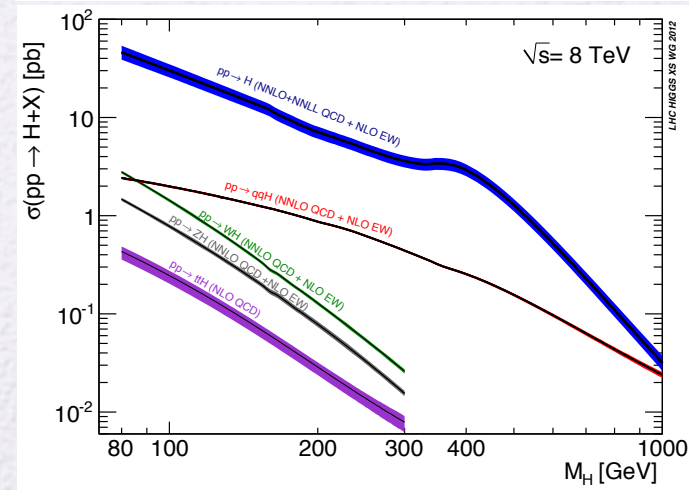
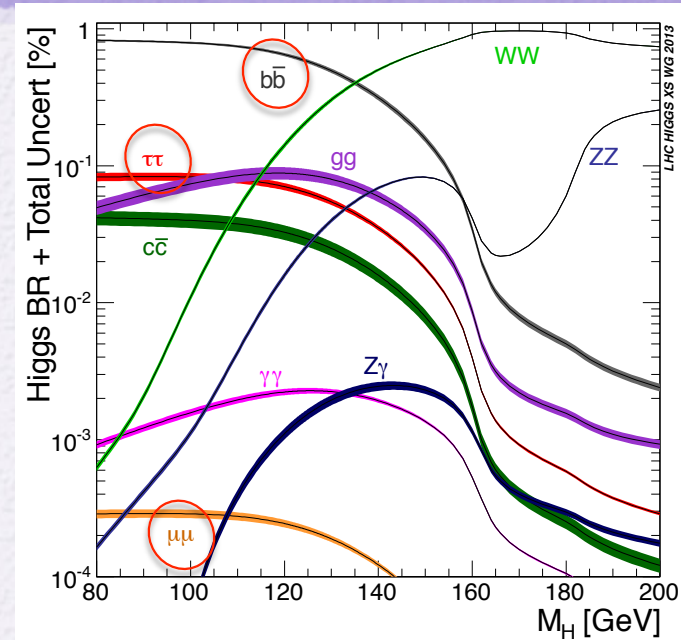
# Enough indications for a **new** particle (scalar boson) @ ~125 GeV



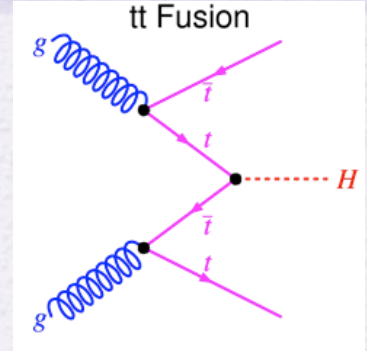
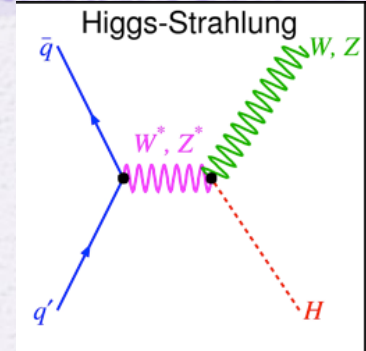
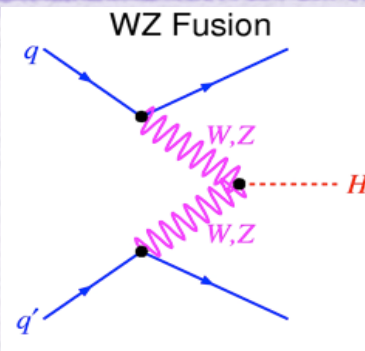
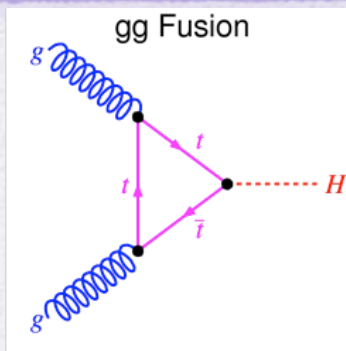
**Our friend** couples to bosons, what about coupling to fermions??

# Introduction

- Observation of the scalar boson in fermionic final states is a check to confirm the resonant at 125 GeV is **the** Higgs boson predicted by standard model.
- $H \rightarrow bb$ ,  $H \rightarrow \tau\tau$  and  $H \rightarrow \mu\mu$  are the possible fermionic decay channels (to check the Yukawa couplings between fermions and Higgs boson)
- The current results are based on full 2011 and 2012 CMS data and includes all main Higgs production modes.



# 5 Production & 3 Decay modes



	<b>GGF</b> Glu-Glu Fusion	<b>VBF</b> vector boson fusion	<b>(W/Z)H</b> WZ associated	<b>ttH</b> tt associated
$H \rightarrow bb$	X	✓	✓	✓
$H \rightarrow \tau\tau$	✓	✓	✓	✓
$H \rightarrow \mu\mu$	✓	✓	X	X

HIG-13-011

HIG-13-012

HIG-13-019

HIG-13-004

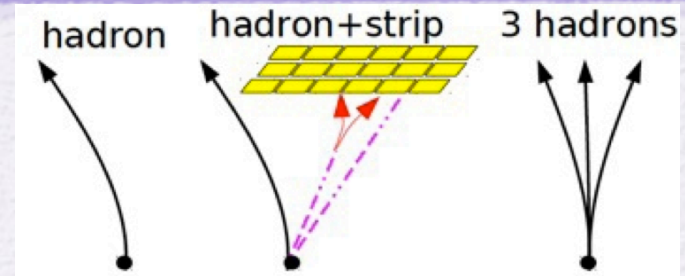
HIG-12-053

HIG-13-007

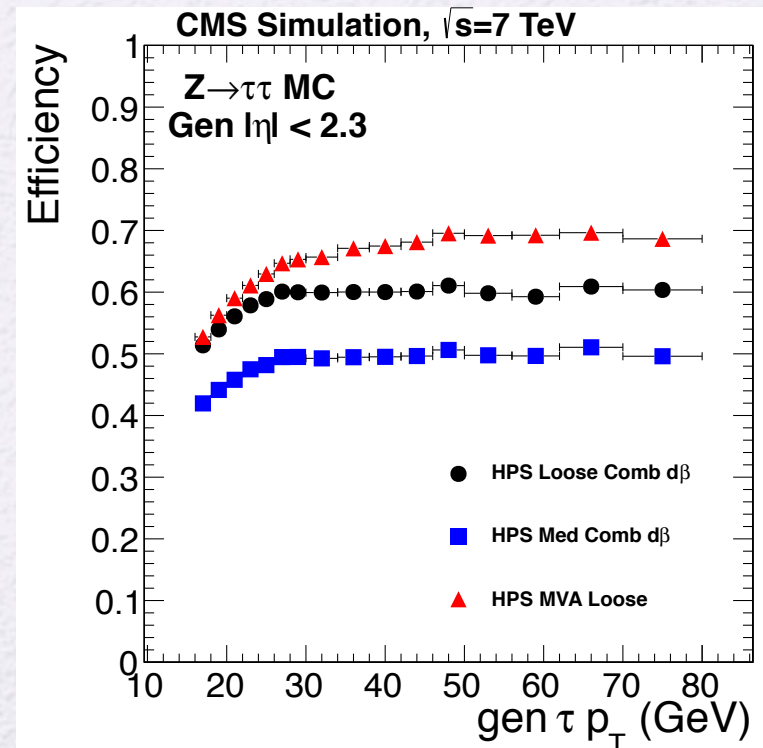
**H → ττ**

# Tau Reco & Id

Decay mode	Resonance	Mass (MeV/c <sup>2</sup> )	Branching fraction (%)
$\tau^- \rightarrow h^- \nu_\tau$			11.6%
$\tau^- \rightarrow h^- \pi^0 \nu_\tau$	$\rho^-$	770	26.0%
$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$	$a_1^-$	1200	9.5%
$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$	$a_1^-$	1200	9.8%
$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$			4.8%

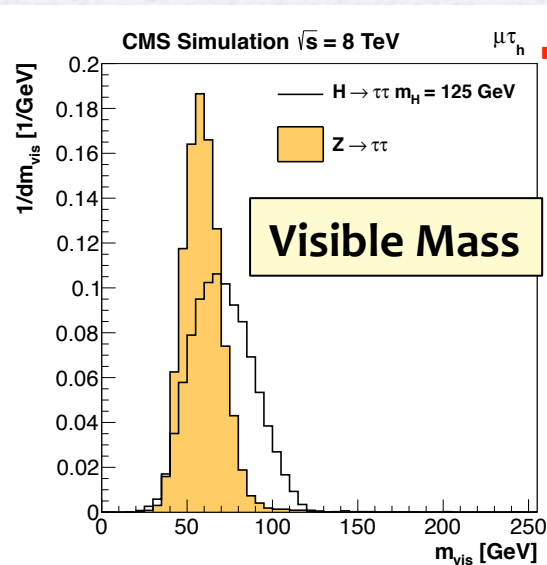
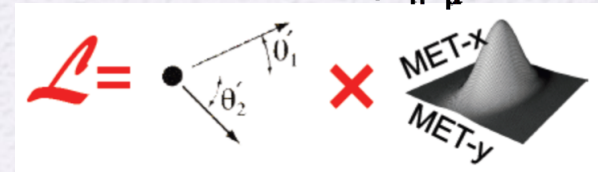
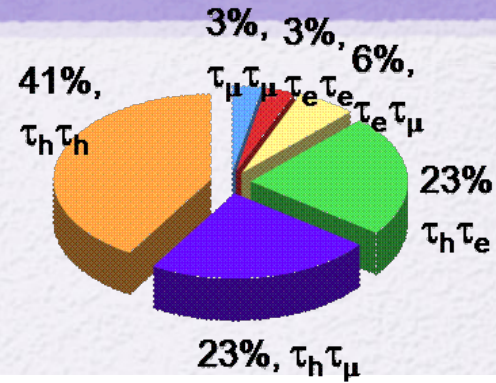


- Reconstruct the hadronic decays of tau based on the PFlow algorithm in 1-prong, 1-prong+ $\pi_0$ 's and 3-prongs.
- For isolation, use multivariate discriminant based on  $\Sigma p_T$  of particles in rings around  $\tau_h$
- $\epsilon_{\text{rec}} > 60\%$  (flat for  $p_T(\tau) > 30\text{GeV}$ ), Fakerate 1–3%.
- Efficiency and momentum resolution (nearly) independent from pileup

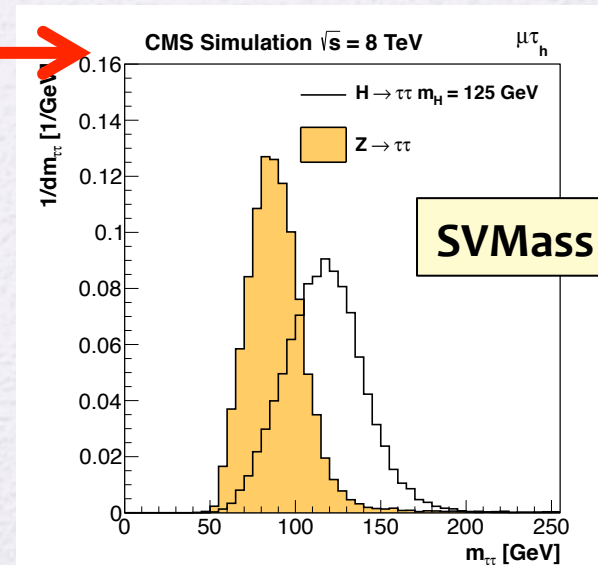


# di- $\tau$ Mass Reconstruction

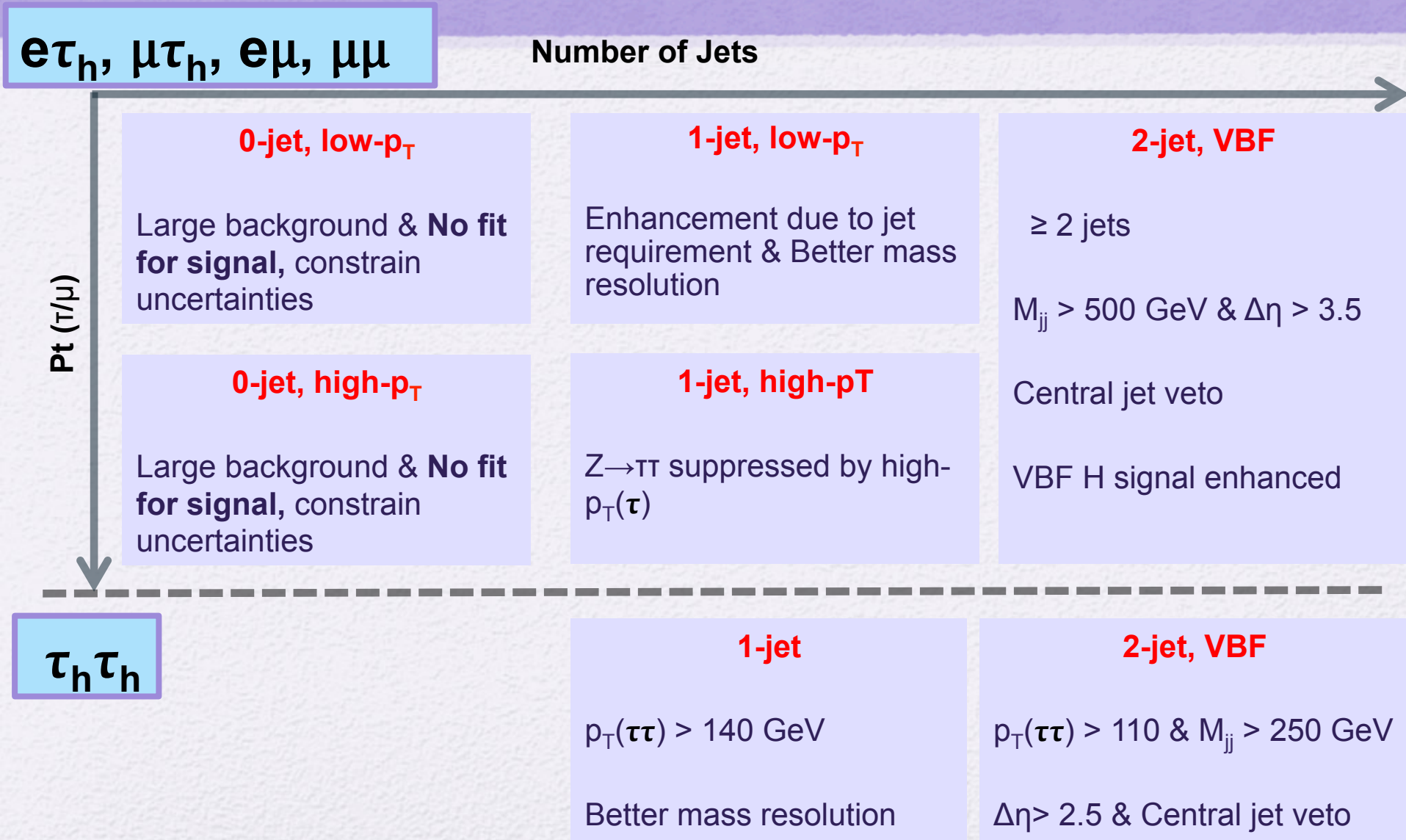
- Determine invariant mass of di- $\tau$  system with maximum likelihood method.
- marginalize the unobserved neutrinos d.o.f.
- Inputs: four-vector information of visible leptons, x- and y- component of MET and MET resolution



- Improve the Mass resolution (15-20%)
- Increase Z/H separation
- Impact on Limit/Sign.  $\sim 30\%$



# Event Categories





# Background Anatomy

## $Z \rightarrow \tau\tau$ :

- Irreducible BG
- Shape and norm from Embedded samples: Take the  $Z \rightarrow \mu\mu$ , replace  $\mu$  by sim.  $\tau$  decay.
- Norm is rescaled to observed  $Z \rightarrow \mu\mu$

## QCD:

- Suppressed by isolation
- Normalization & shape taken from SS from Data

## $T\bar{T}$ :

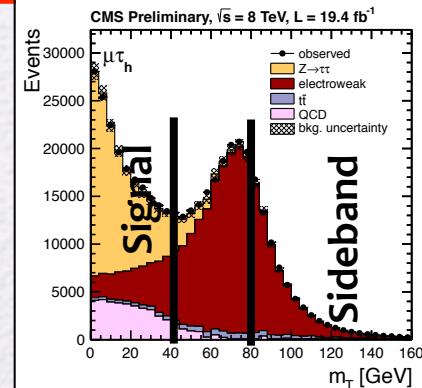
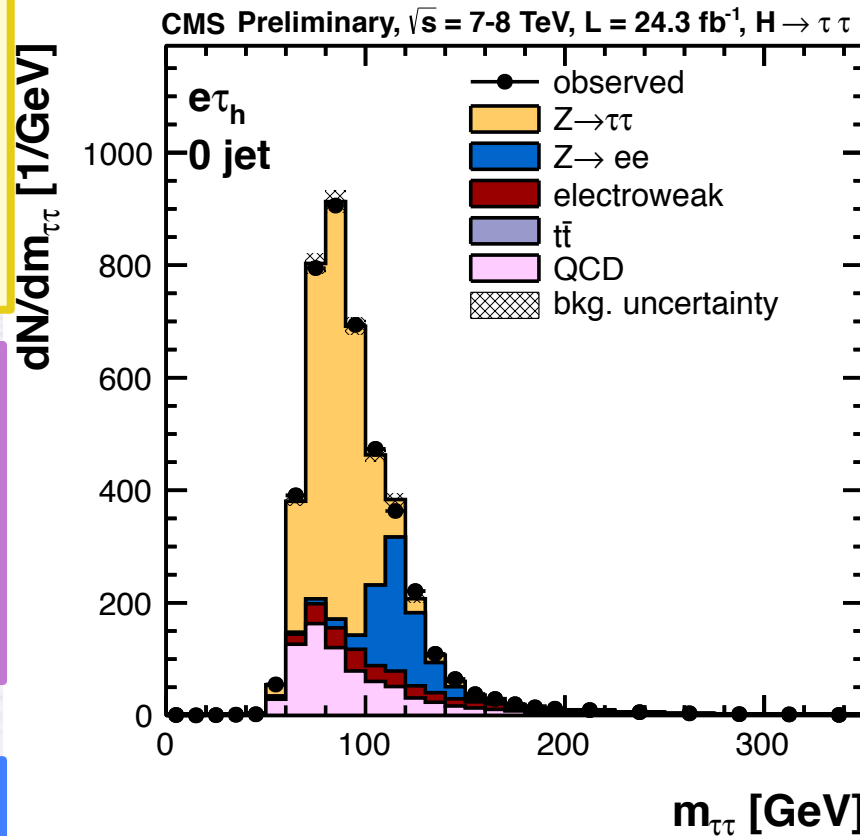
- Normalization & shape from MC from Sideband

## $Z \rightarrow ee(\mu\mu)$ :

- Suppressed by extra lep. veto and tau dis. against leptons
- Normalization and shape from MC
- Corrected for  $Z \rightarrow \mu\mu$  data over MC

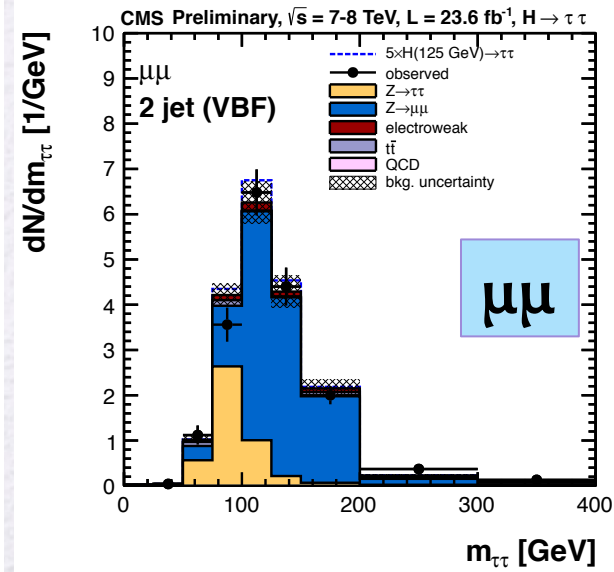
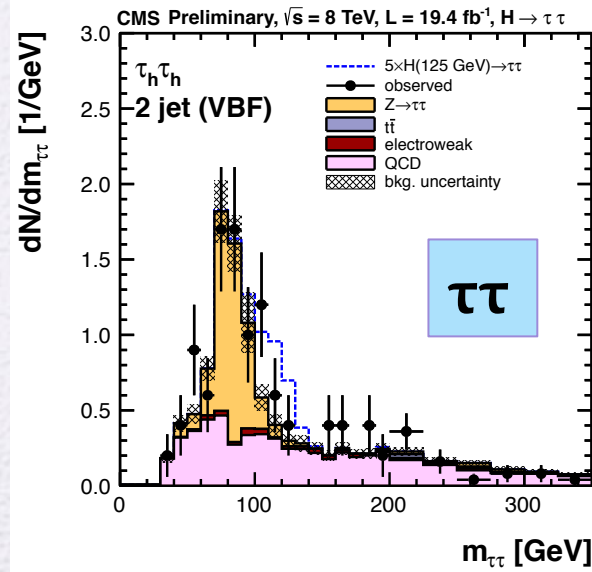
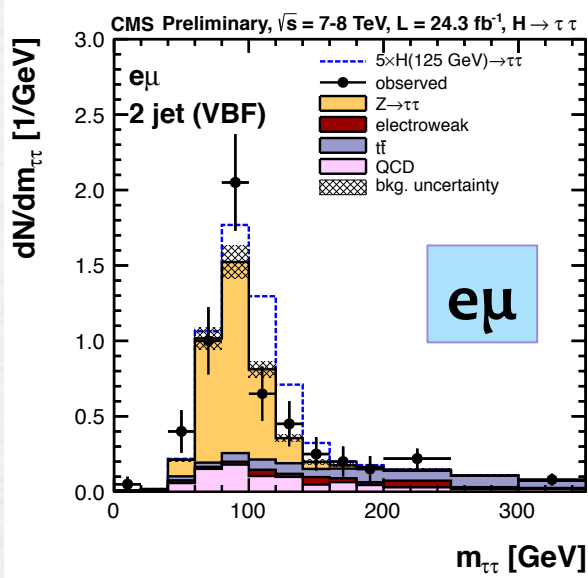
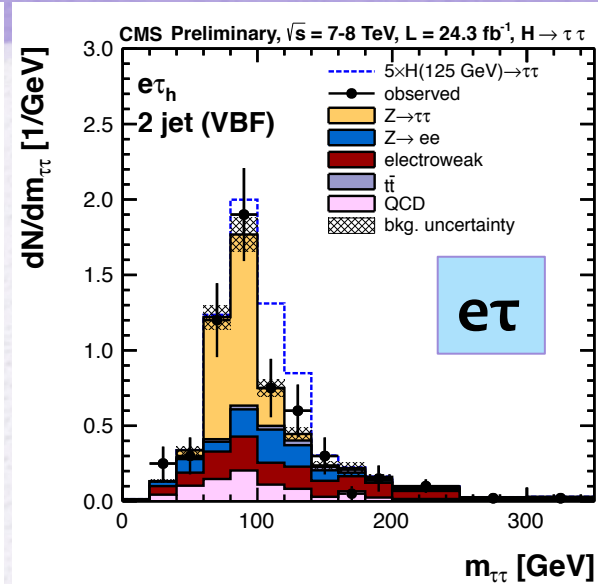
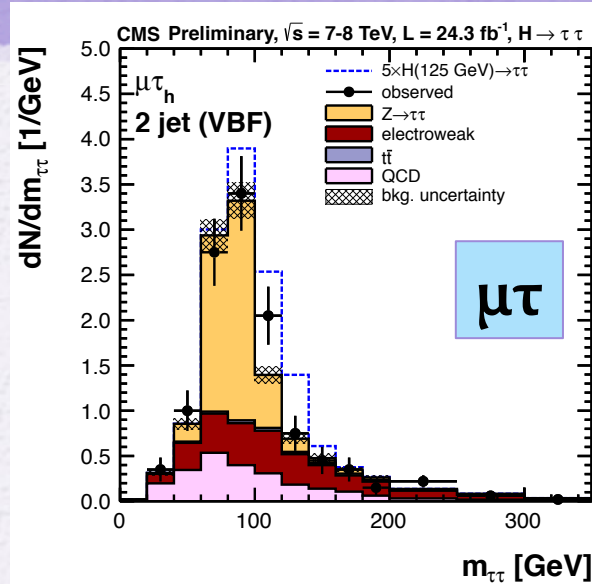
## Diboson/W+jets:

- Suppressed by topological cuts
- Normalization from sideband. (data/mc scale)
- Shape from MC



# 2-Jet VBF Category

- After template fit has been applied (S+B hypothesis)
- Shaded bands correspond to uncertainties after fit.

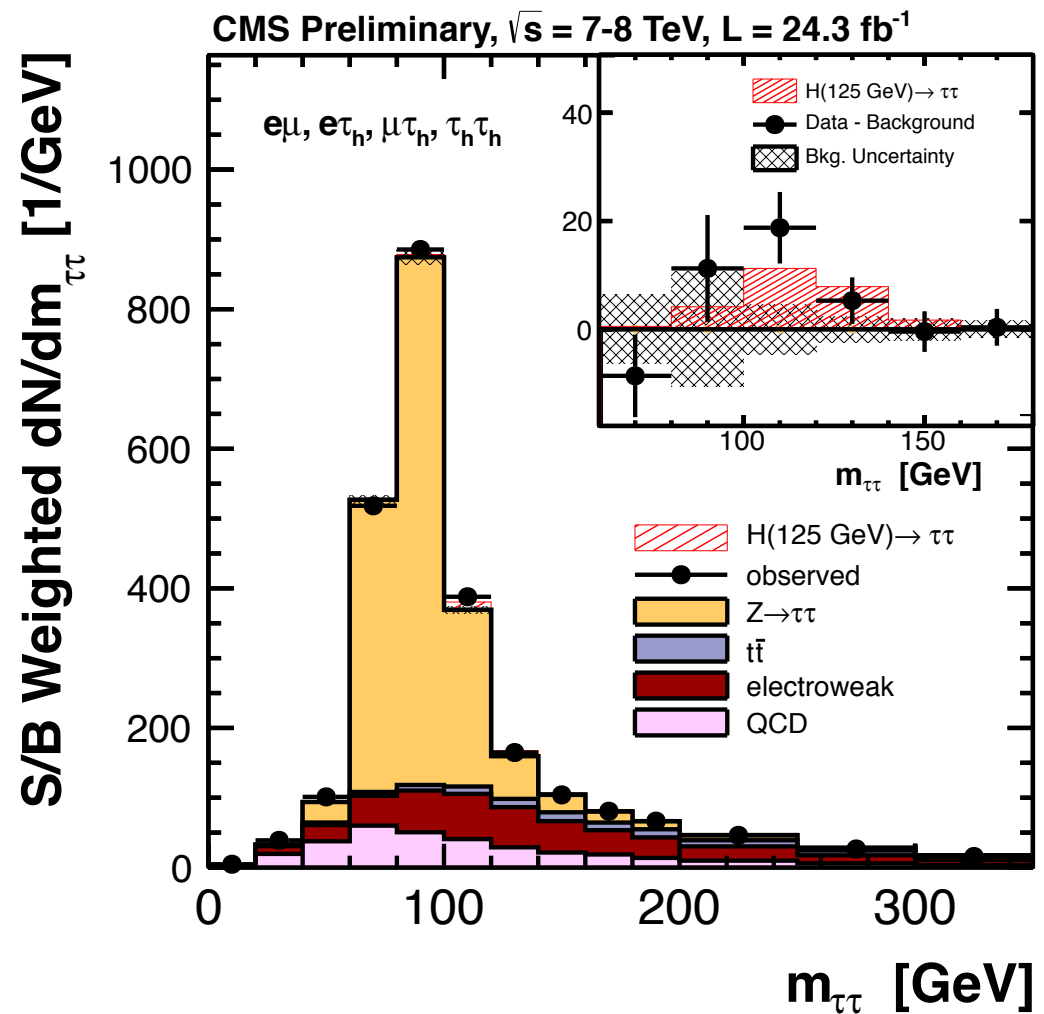


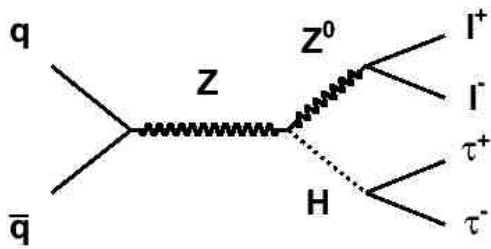
# Combined Weighted Mass

Combine channels and categories weighting each by **S/B** :

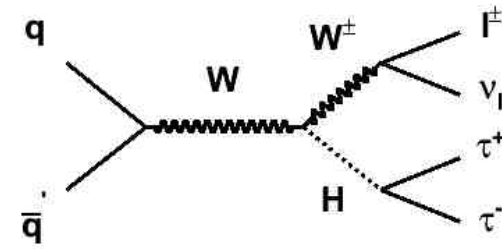
(**S** is expected signal and **B** is fitted background in  $m_{\tau\tau}$  interval containing 68% of signal around 125 GeV )

Excess of events between 100-140 GeV compatible with  $H \rightarrow \tau\tau$  from SM





$$VH \rightarrow V\tau\tau$$

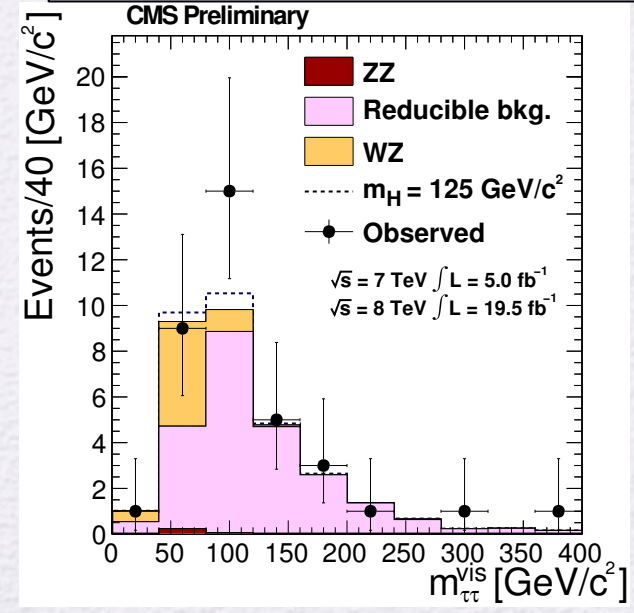
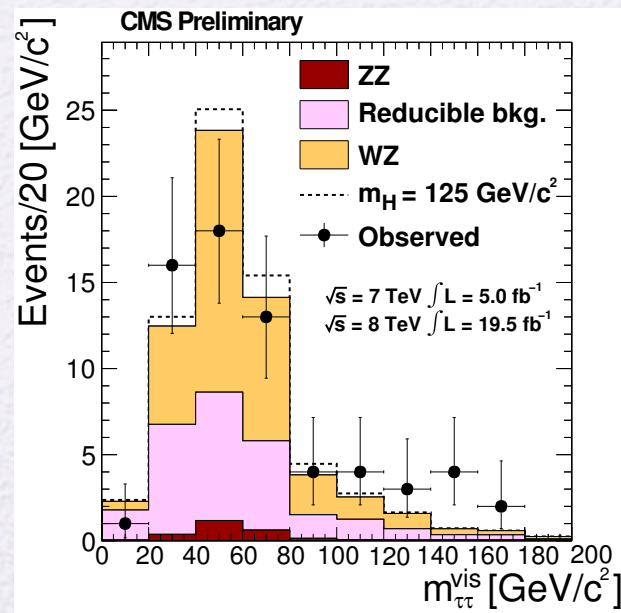
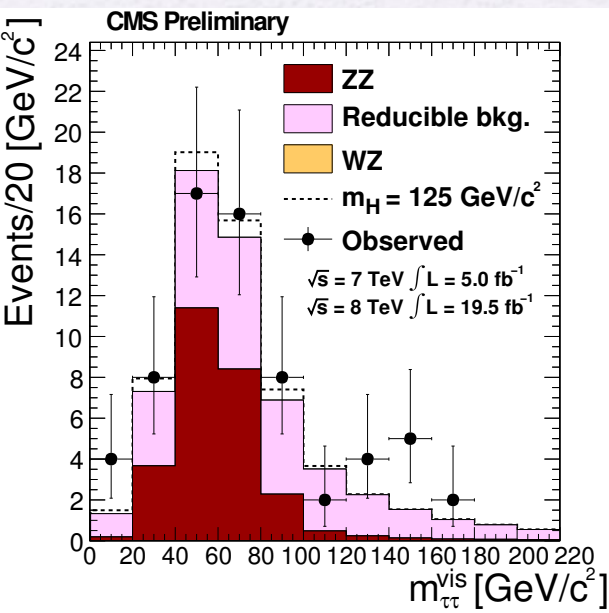


- Reducible BG: QCD, W/Z+jets, ttbar, ... : Estimated from data using fake rate method
- Irreducible BG: WZ for WH and ZZ for ZH: Estimated from MC
- Further topological cuts to suppress large backgrounds

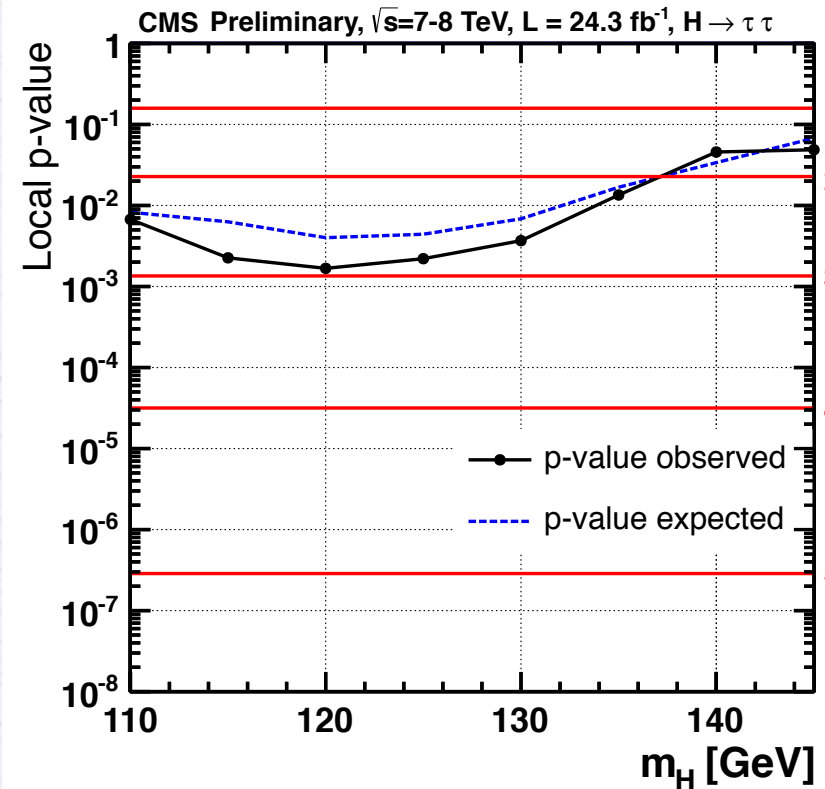
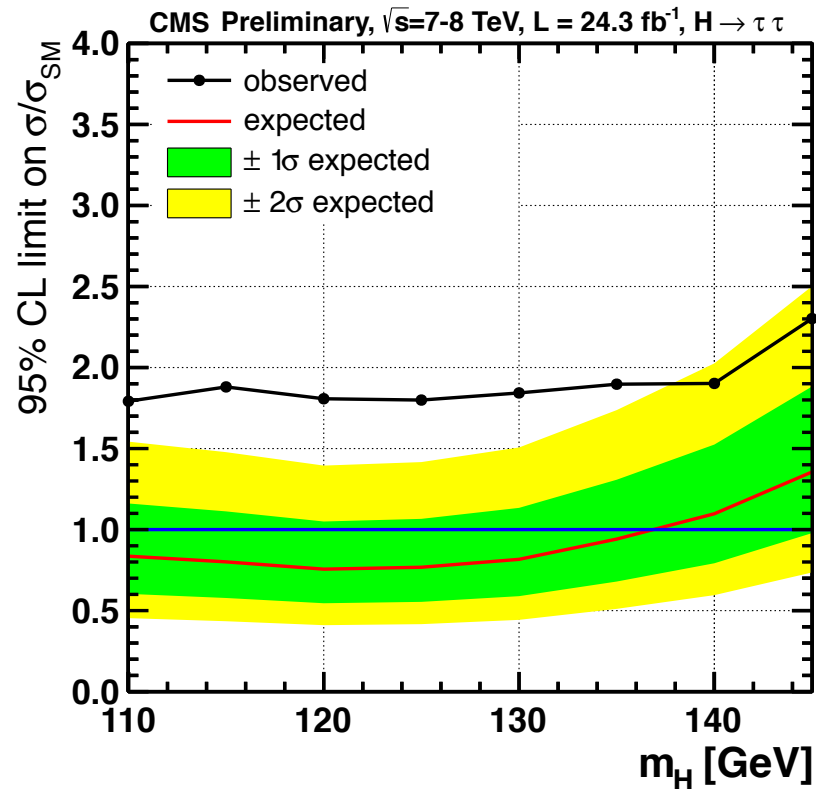
$$Z \rightarrow (\mu\mu, ee)H \rightarrow (\tau_h\tau_h, \tau_h\mu, \tau_h e, e\mu)$$

$$W \rightarrow (\mu\nu)H \rightarrow (\tau_h\mu, \tau_h e)$$

$$W \rightarrow (\mu\nu, e\nu)H \rightarrow (\tau_h\tau_h)$$



# Limit, p-value and Significance

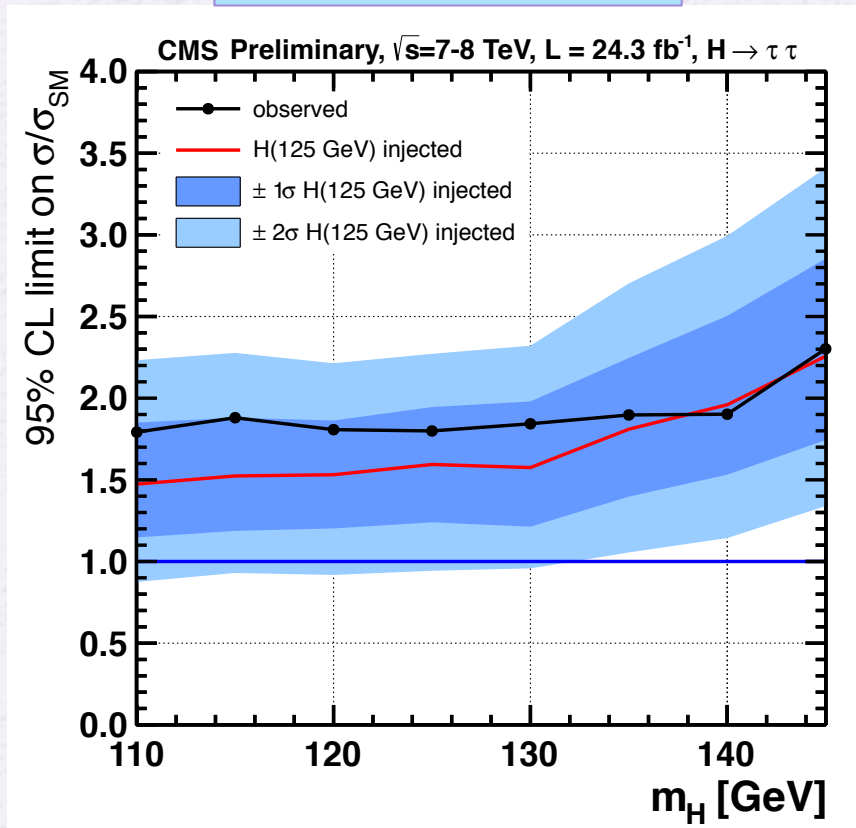


➤ Broad excess compatible with a presence of a SM Higgs boson at 125 GeV

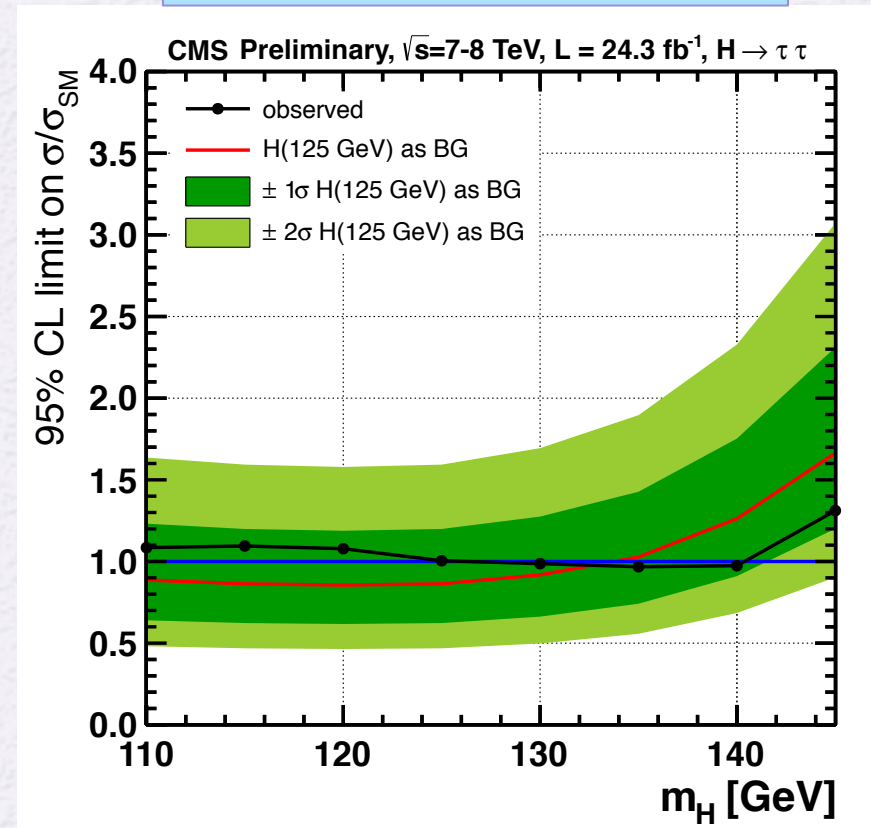
➤ Minimum p-value at 120 GeV corresponds to  $2.93\sigma$  → **Indicate that our friend couples to  $\tau$  lepton**

# Compatibility of Excess with SM Higgs boson

Signal Injection

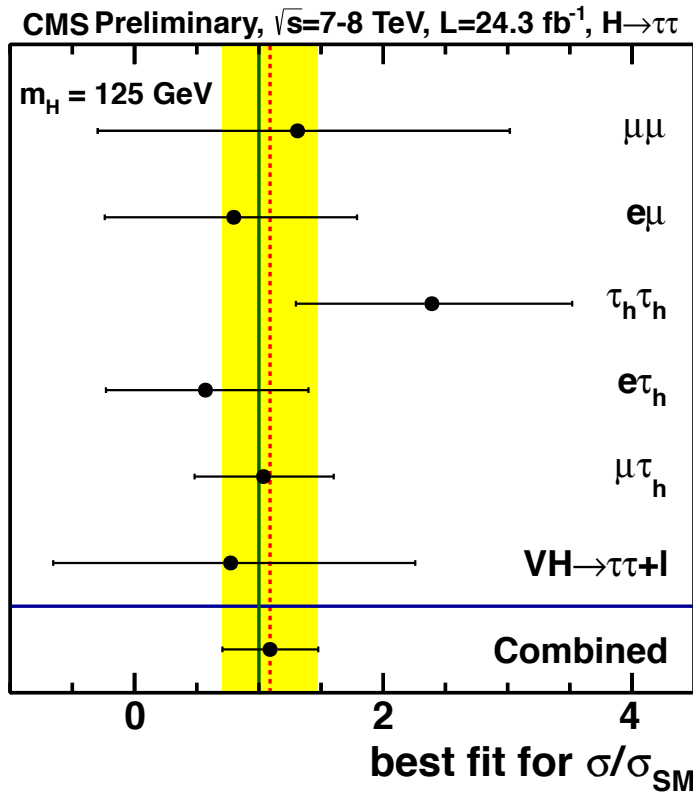


H125 as background



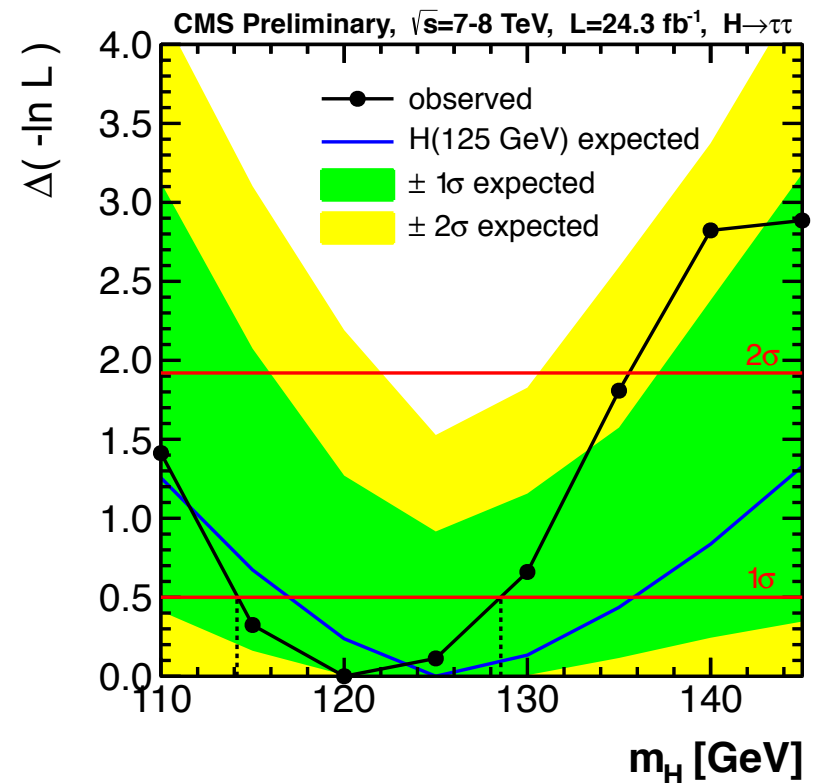
Both limit plots shows consistency of the excess with one and only one SM Higgs boson at 125 GeV.

# Best Fit Signal Strength & Mass



Best-fit signal strength values,  $\sigma/\sigma_{SM}$  for independent Channel

signal strength  $\mu=1.1 \pm 0.4$



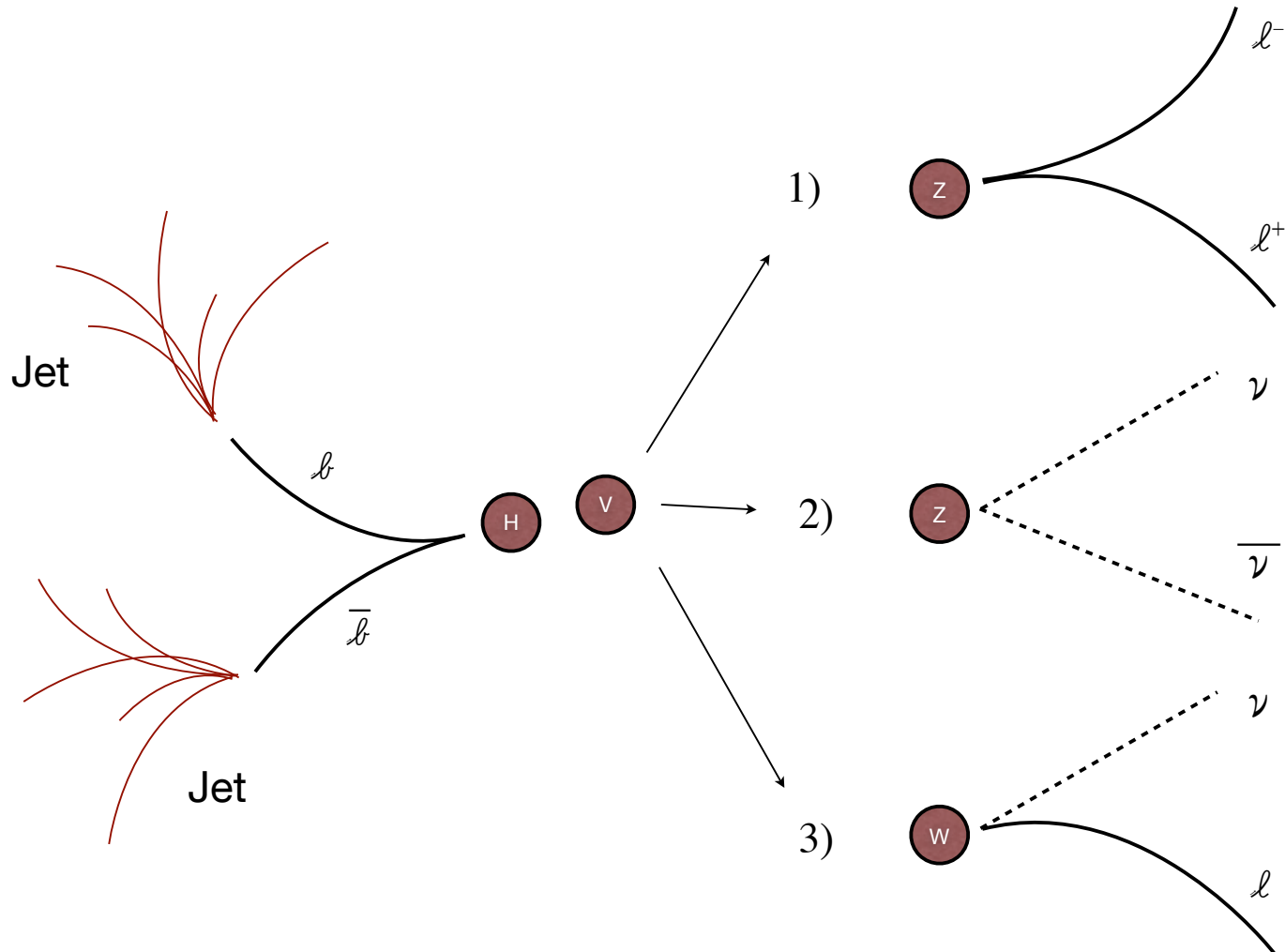
Log likelihood versus SM Higgs boson fit mass

$m_H = 120^{+9}_{-7}(\text{stat+syst})$  GeV

**H** → ***bb***



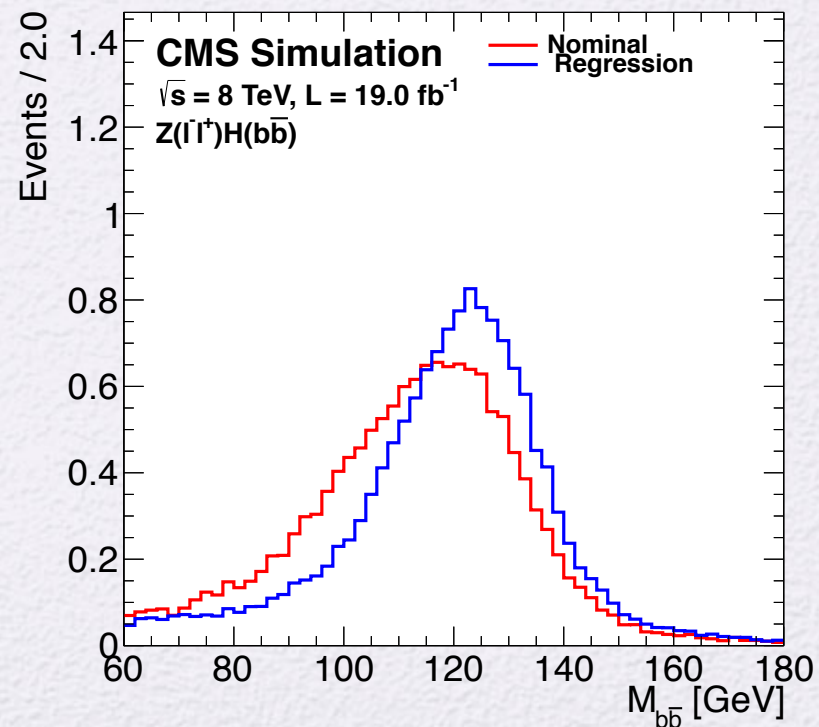
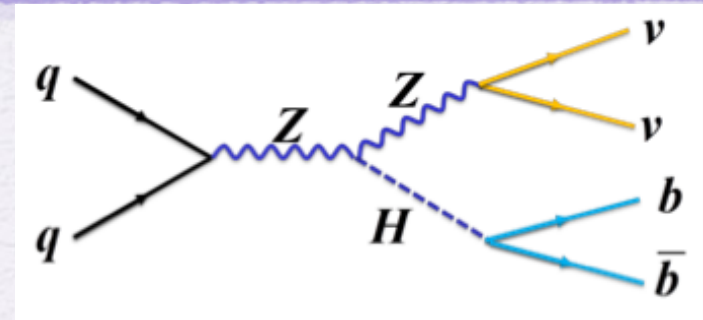
# $(V)H \rightarrow (W/Z)bb$



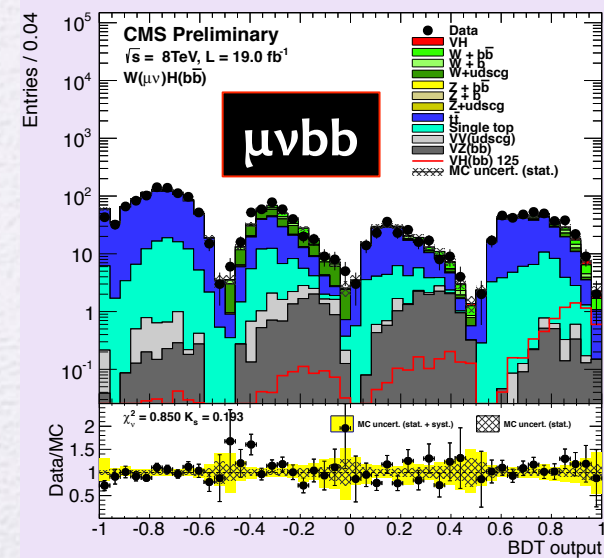
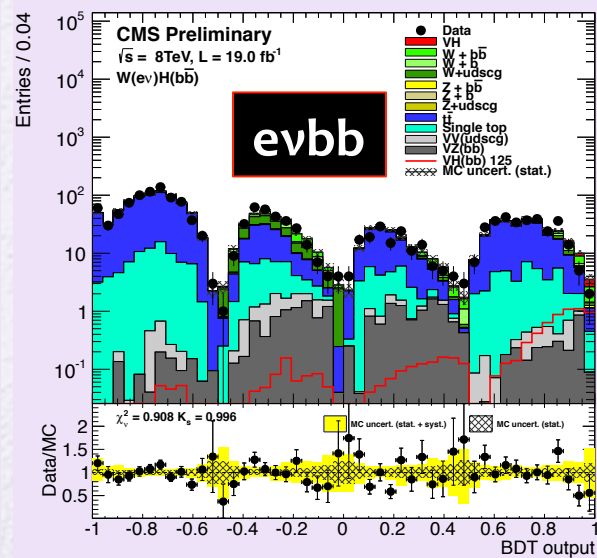
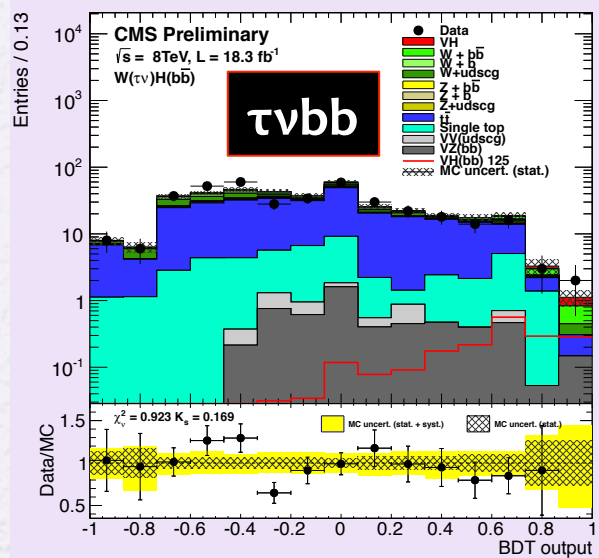
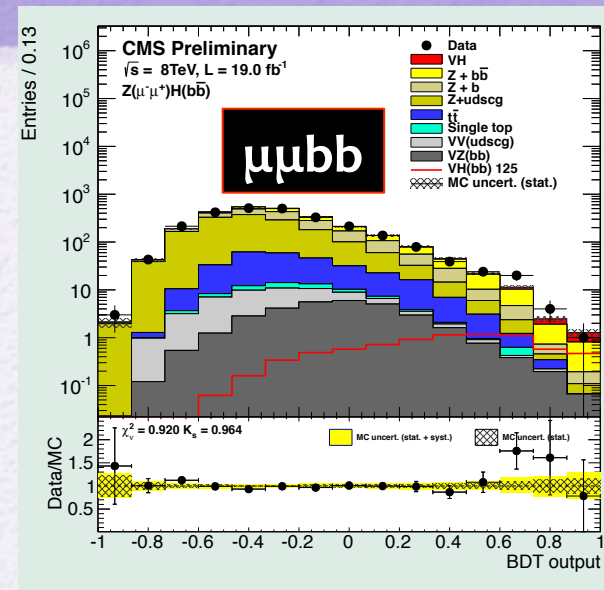
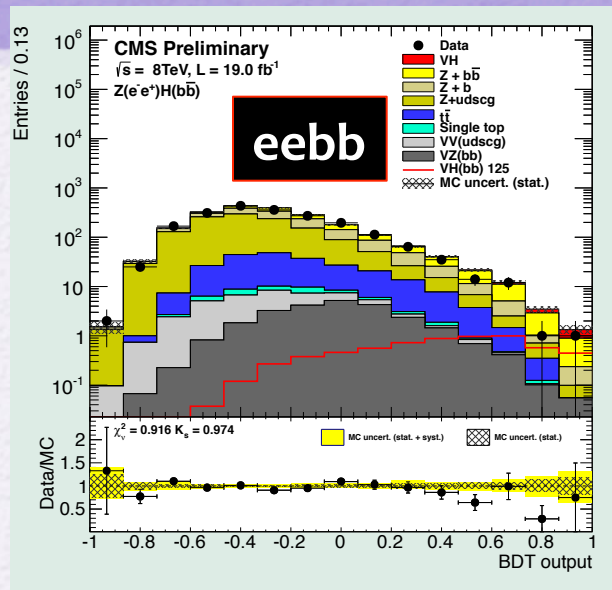
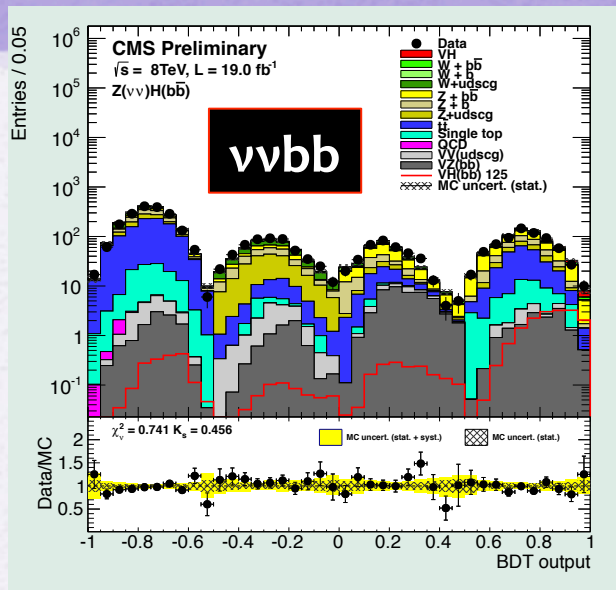
# VHbb Strategy

Di-jet selection in boosted regime:

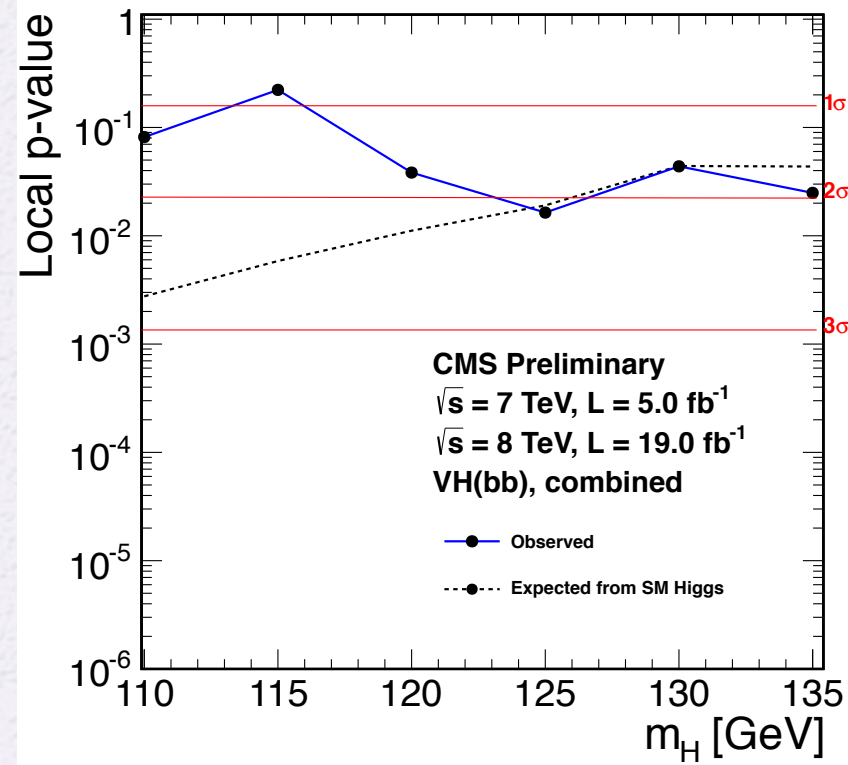
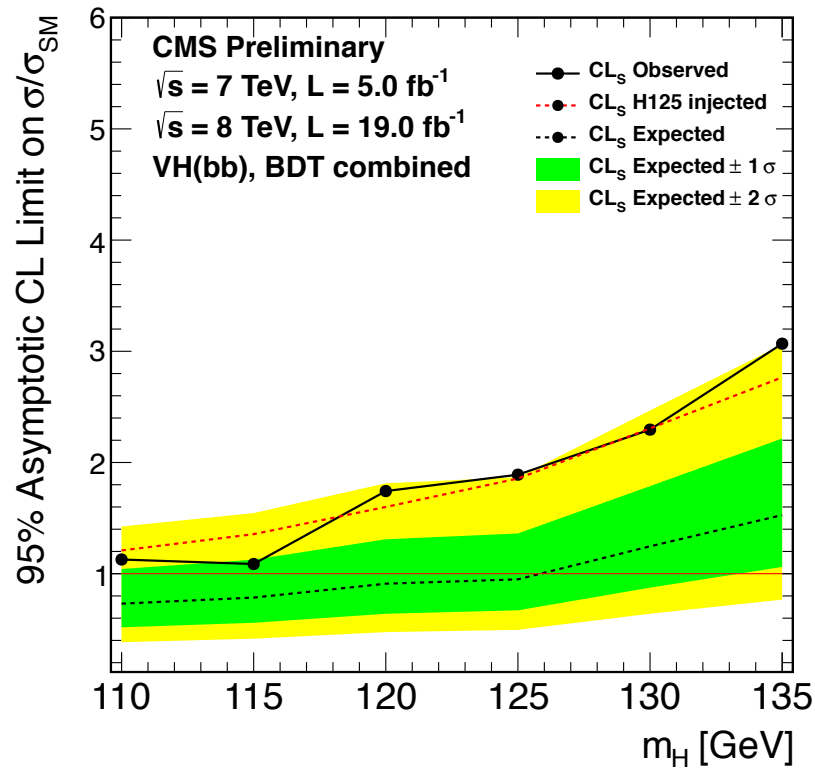
- 6 final states ( $W\mu\nu$ ,  $W\tau\nu$ ,  $W\tau\nu$ ,  $Z\nu\nu$ ,  $Z\mu\mu$ ,  $Zee$ )
- Final state with leptons (MET), b-tag
- binning in vector boson PT
- Normalization of dominant backgrounds V+jets and tt extracted from data
- Improve mass resolution using a BDT regression
- BDT (discriminate signal from background) used for fitting mc to data



# BDT Output for different final states



# Limit and Significance



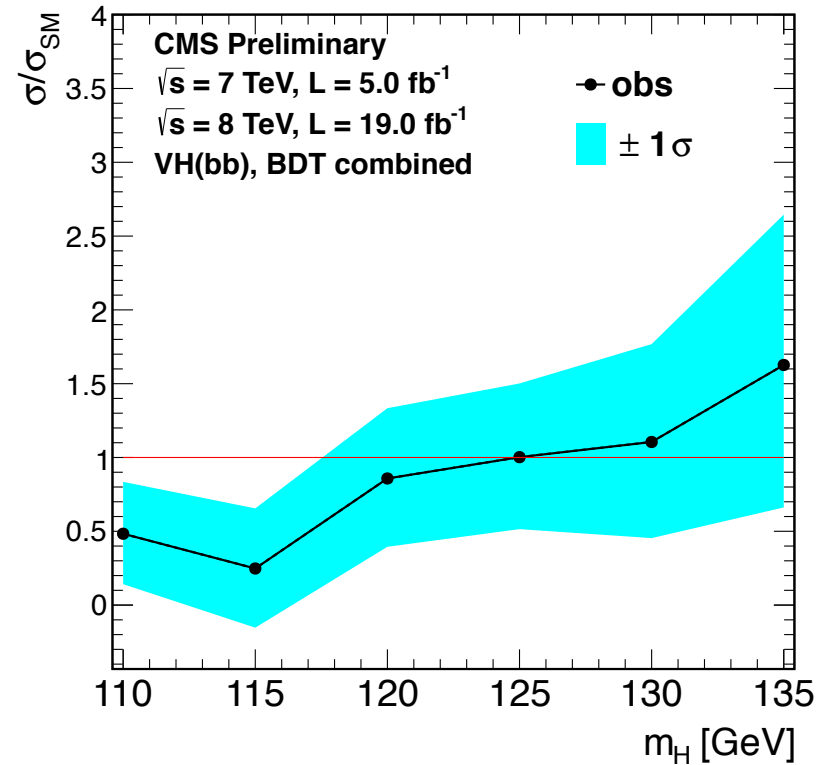
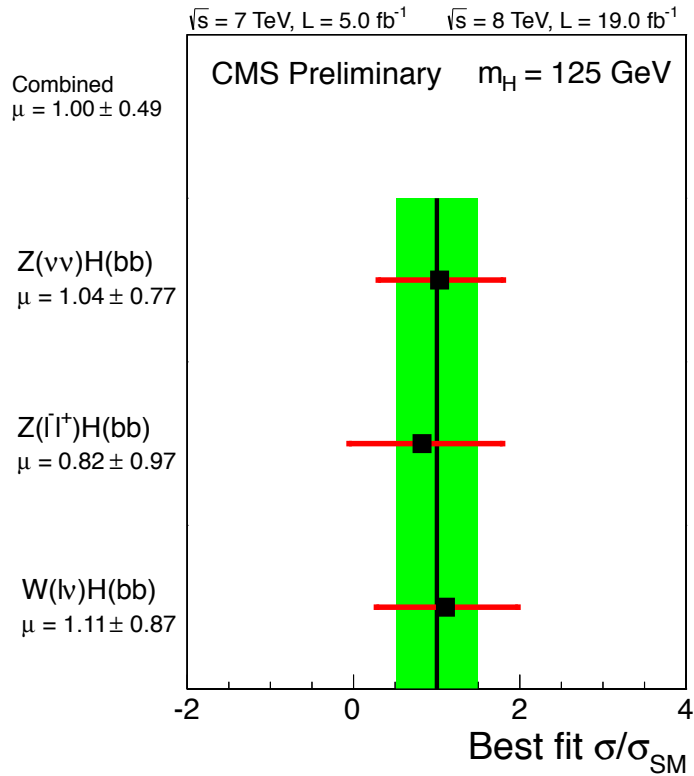
For  $m_H = 125 \text{ GeV}$

- Observed  $1.89 \times SM$
- Expected  $0.95 \times SM$

Significance  $2.1 \sigma$  ( $2.1\sigma$ )

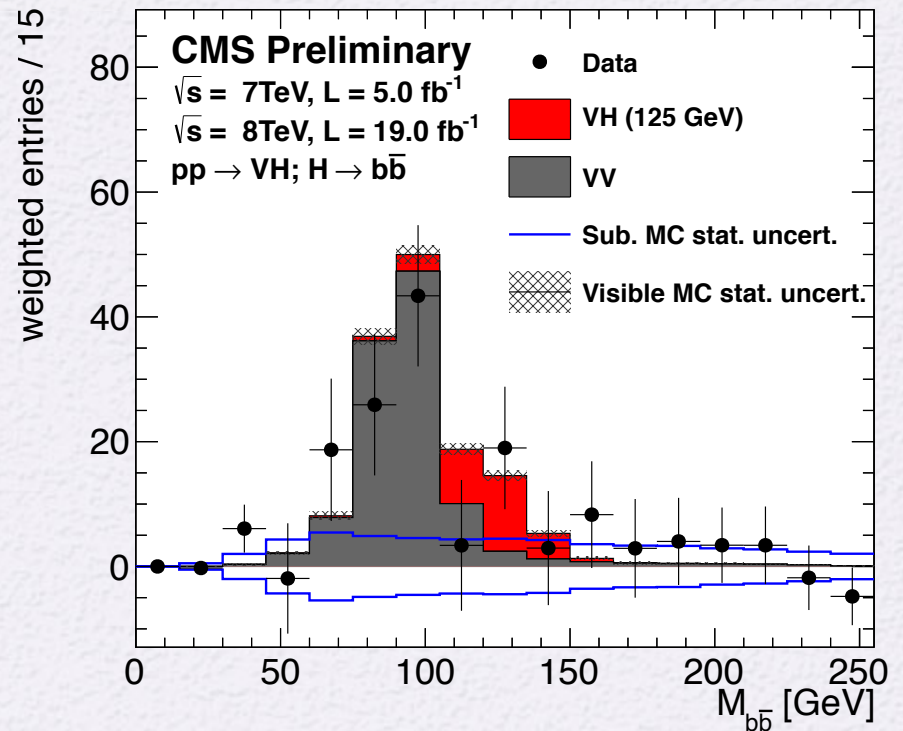
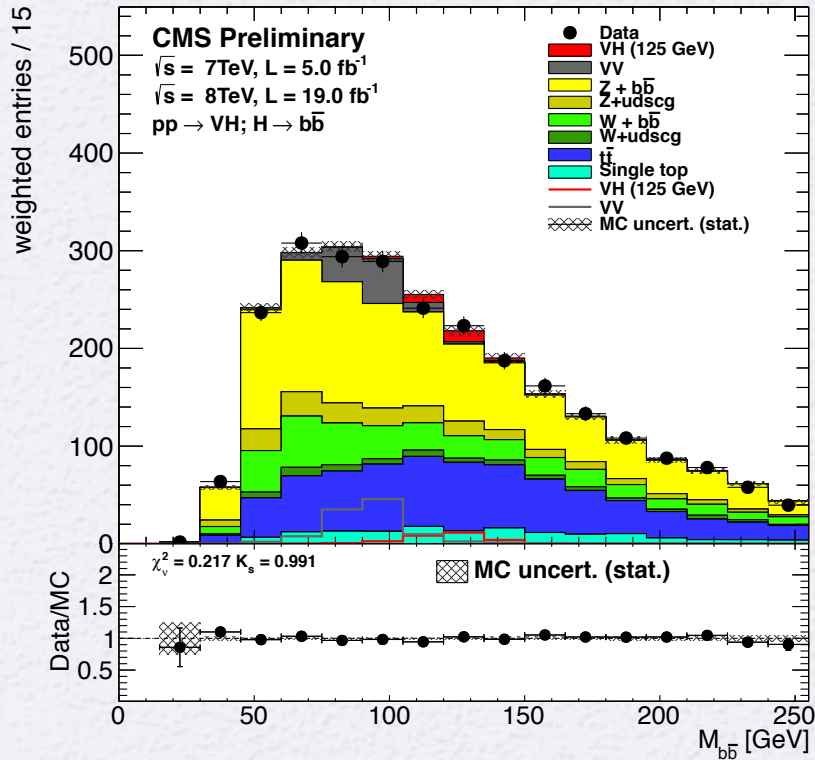
Observed agrees well with expectation from SM Higgs boson at 125 GeV

# Best Fit



$\mu = 1.0 \pm 0.5$   
All modes are compatible

# Combined Mass

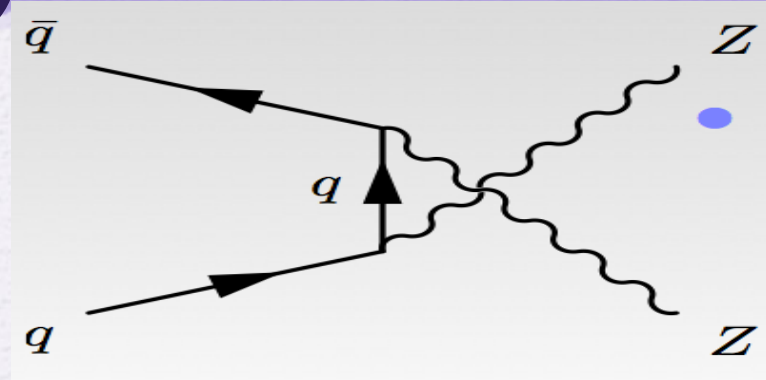


Weight each category by  $s/(s+b)$   
 in window 105-150 GeV

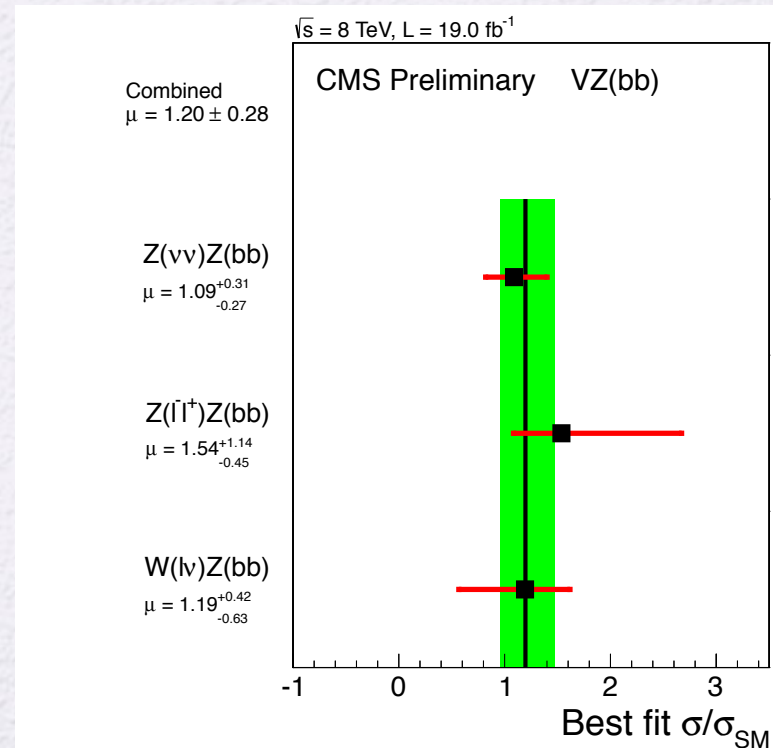
Subtract all BG, except VV,  
 from Data

# Validation of BDT using VZ(bb)

As Validation of MVA, BDT is trained using di-boson as signal and other processes (including VH) as BG.

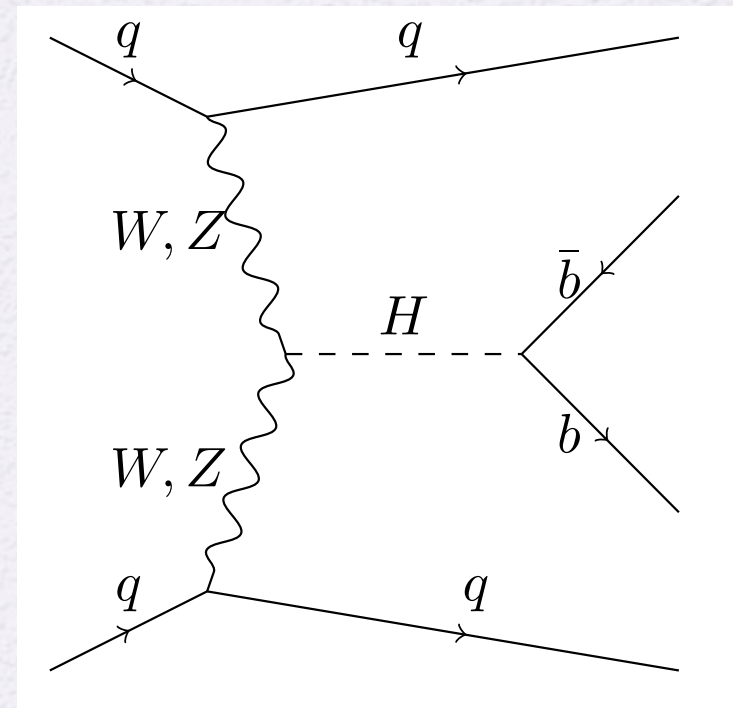


	BDT VZ(bb)
Exp. Sig	6.3 $\sigma$
Obs. Sig	7.5 $\sigma$
$\mu$	1.19 <sup>+0.27</sup> <sub>-0.23</sub>



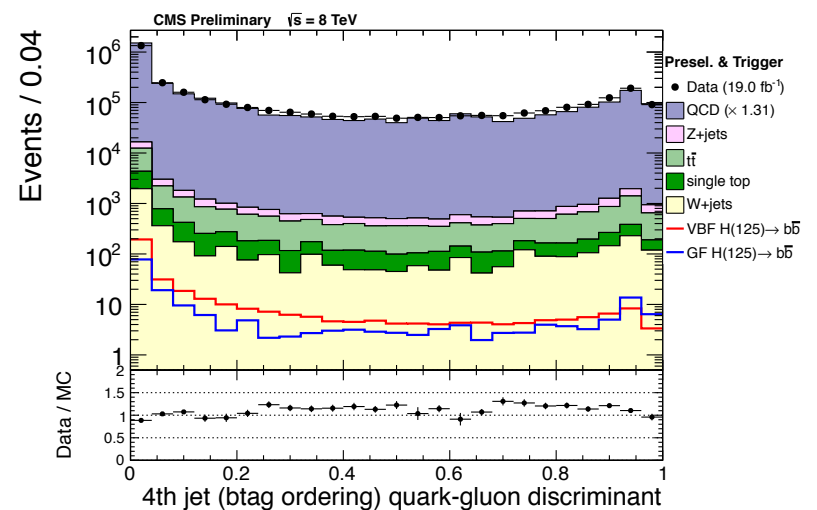
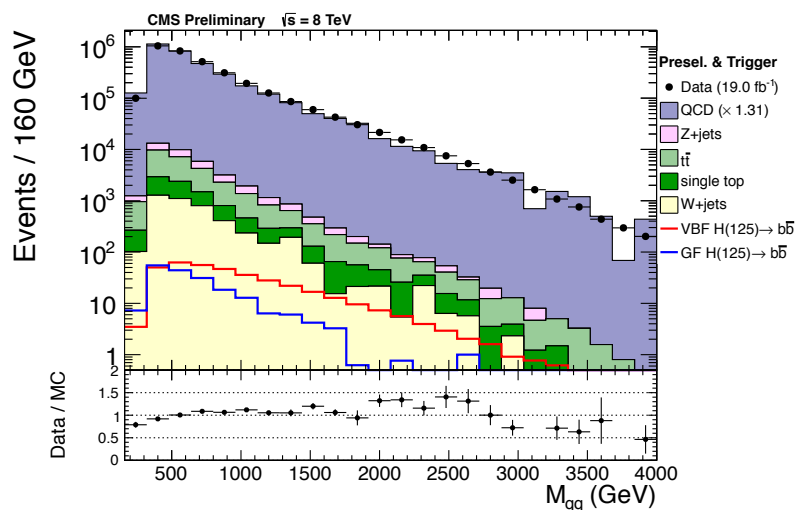
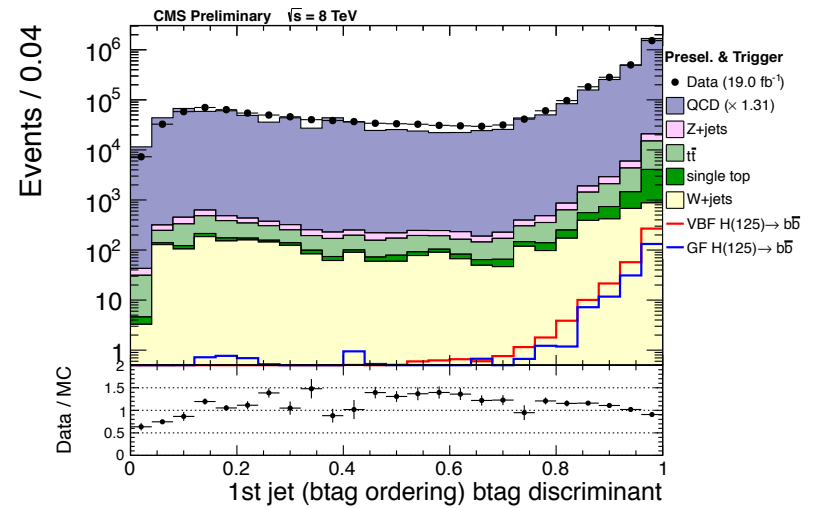
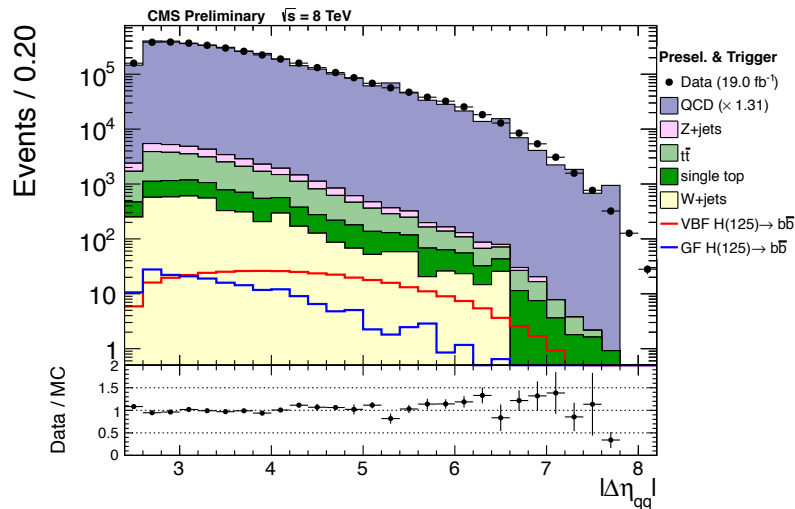
# VBF\_H $\rightarrow$ bb

- Using 4-jet Trigger (one is required to be btag)
- Key information to suppress large QCD and ttbar:
  - two b-jets (Non back to back)
  - two forward jets(light quarks)
  - Quark gluon tagger to separate quark jet (in signal) from gluon (in QCD)
  - Other topological variable to set up the neural network technique.





# Different variables as input of MVA

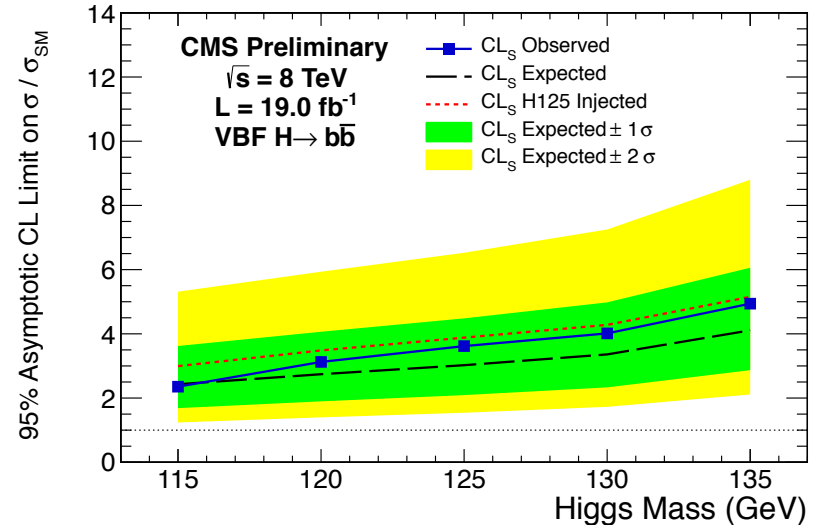
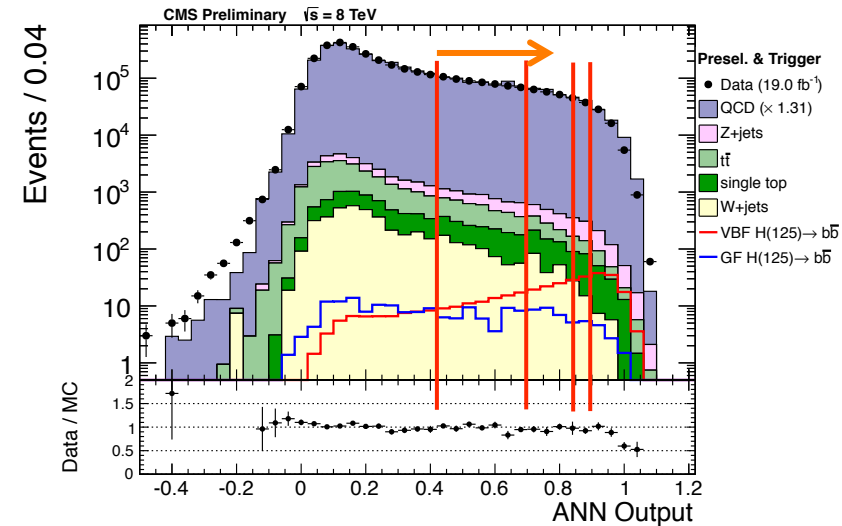


# ANN output and Limit

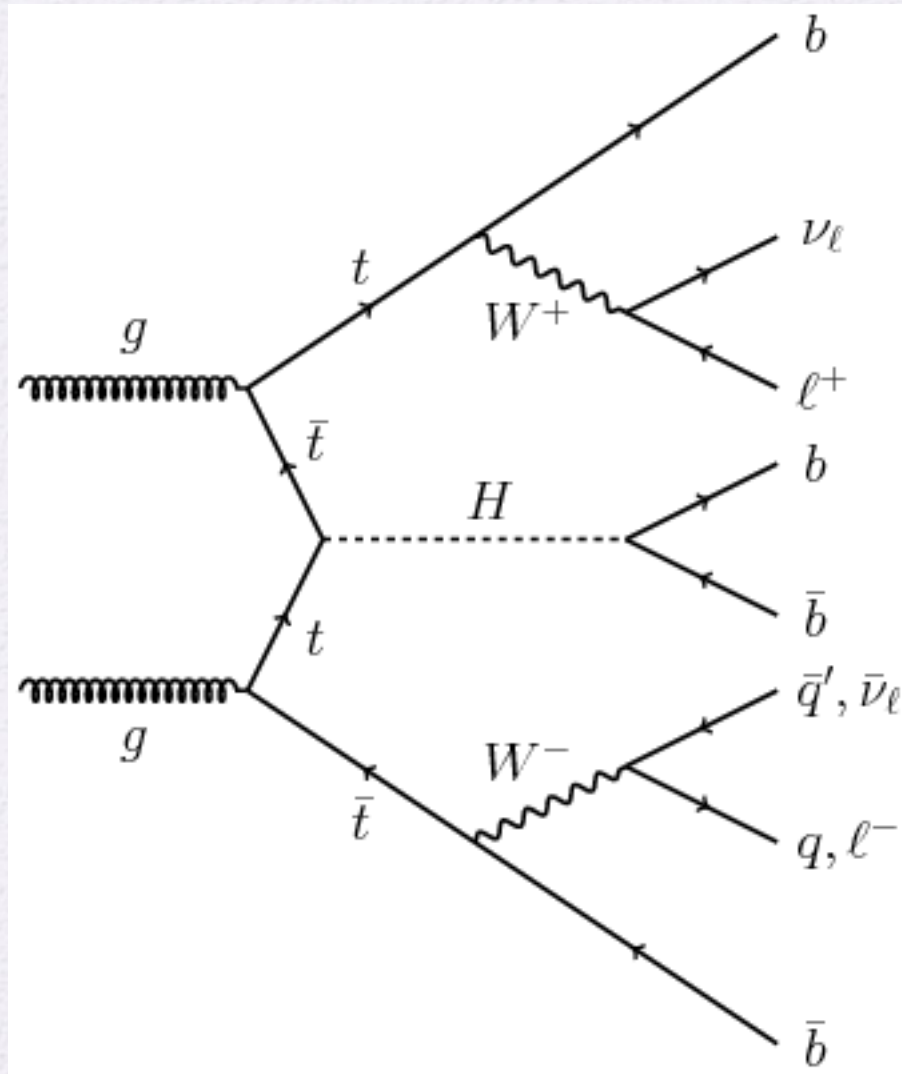
The ANN output splitted into 4 categories to increase sensitivity

@ 125 GeV

- obs. limit =  $3.6 \times SM$
- exp limit =  $3.0 \times SM$
- $\mu = \sigma/\sigma_{SM} = 0.7 \pm 1.4$



# $ttH \rightarrow tt(bb, \tau\tau)$



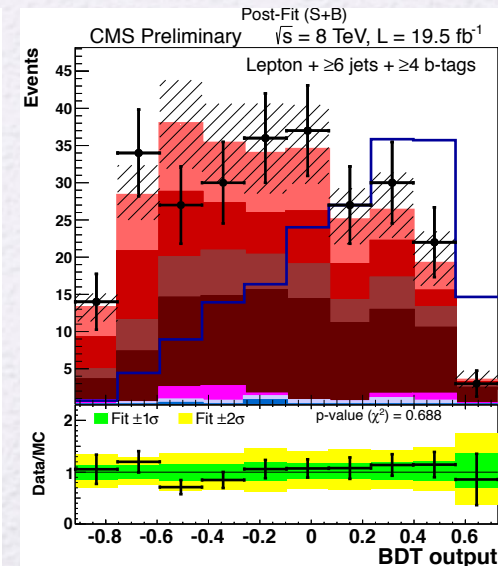
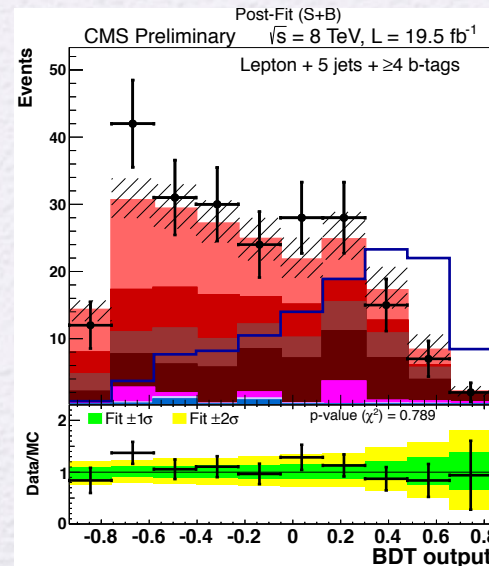
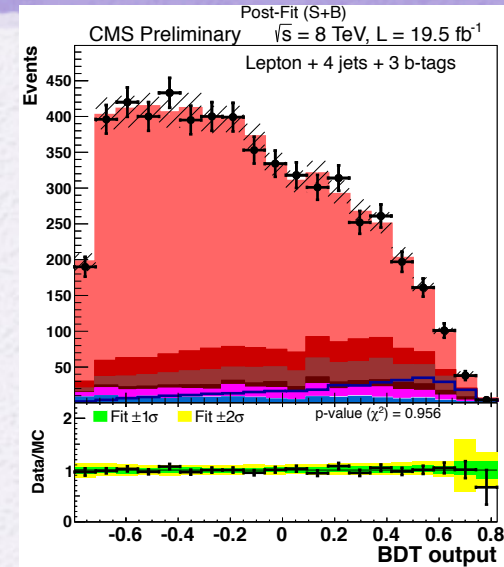
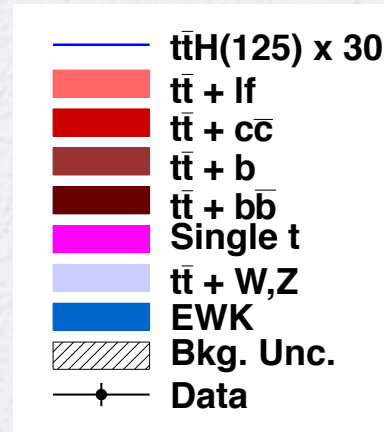
# Channels and Categories

3 different channels:

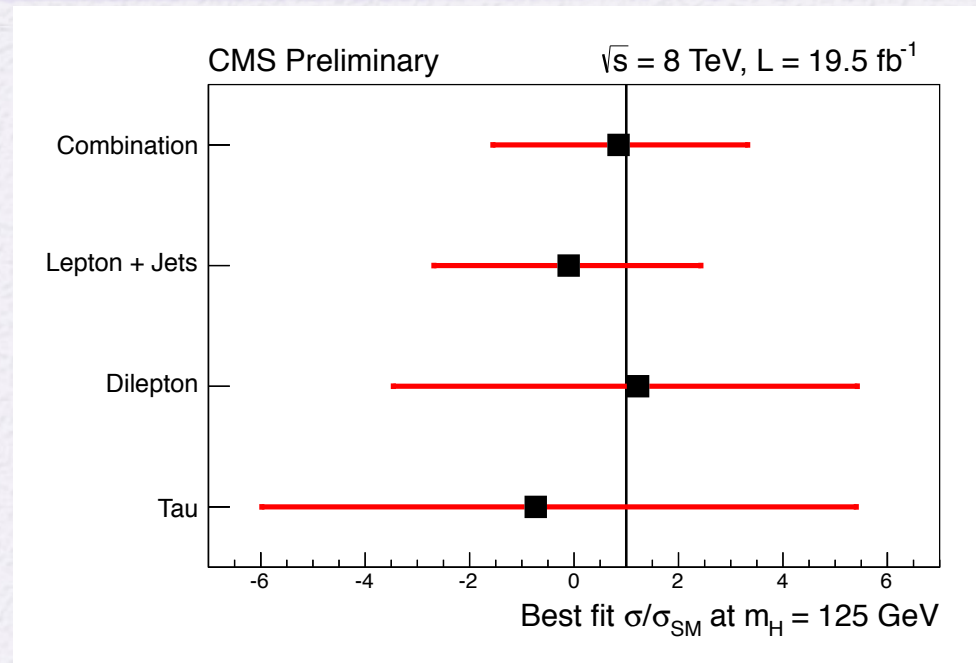
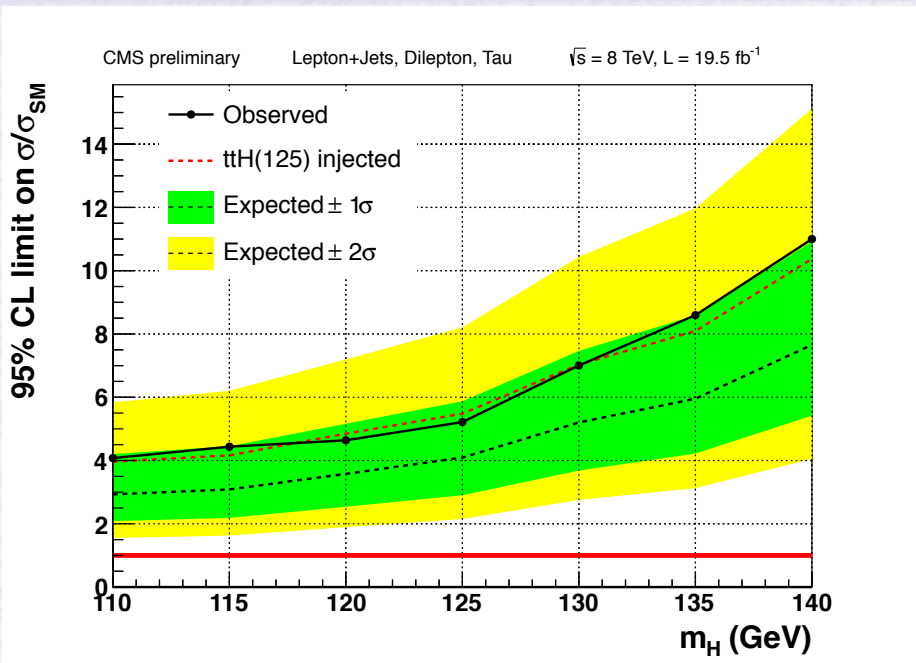
- lepton+jets ( $tt \rightarrow lvqq' bb, H \rightarrow bb$ )
  - 1 iso-lepton +  $\geq 4$  jets ( $\geq 2$  b-tagged)
- di-lepton+jets ( $tt \rightarrow l^+vl^-v bb, H \rightarrow bb$ )
  - 2 OS isolated lepton +  $\geq 3$  jets ( $\geq 2$  b-tagged)
- tau+jets ( $tt \rightarrow lvqq' bb, H \rightarrow \tau^+\tau^-$ )
  - 1 iso-lepton +  $\geq 4$  jets ( $2\tau_h + \geq 1$  b-tagged)
- Each channel divides to several sub channels based on the number of jets or bjet
- BDT is trained for each sub-channels separately.

# Lepton + Jets

- combination of different number of jets and b-jets (7 sub channels)
- reconstruct two top quarks based on the  $\chi^2$  calculation
- The “best Higgs boson mass” is mass of two highest  $p_T$  jets not assigned to top-quark



# Limit and Best Fit



@ 125 GeV: obs. limit =  $5.2 \times \text{SM}$  -  
exp limit =  $4.1 \times \text{SM}$

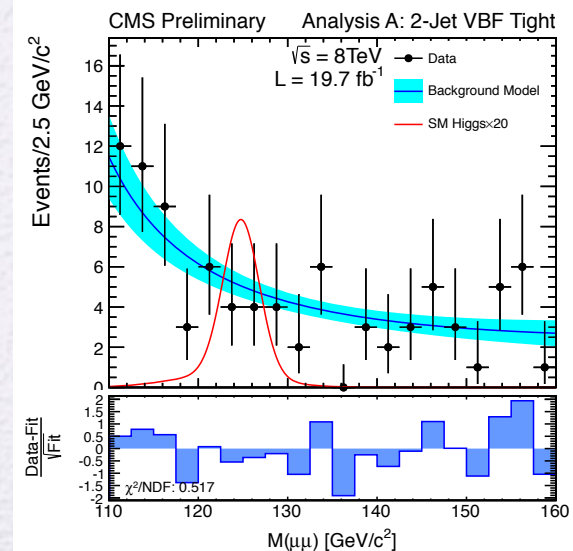
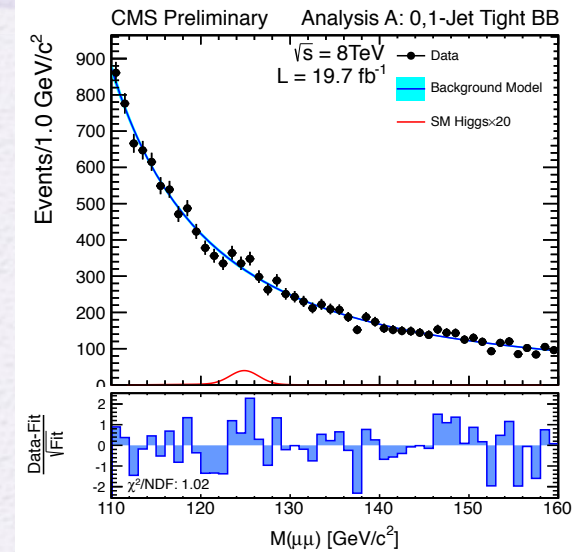
Observed agrees well with  
expectation from SM Higgs  
boson at 125 GeV

signal strength  $\mu = 0.85^{+2.47}_{-2.41}$

**H → μμ**

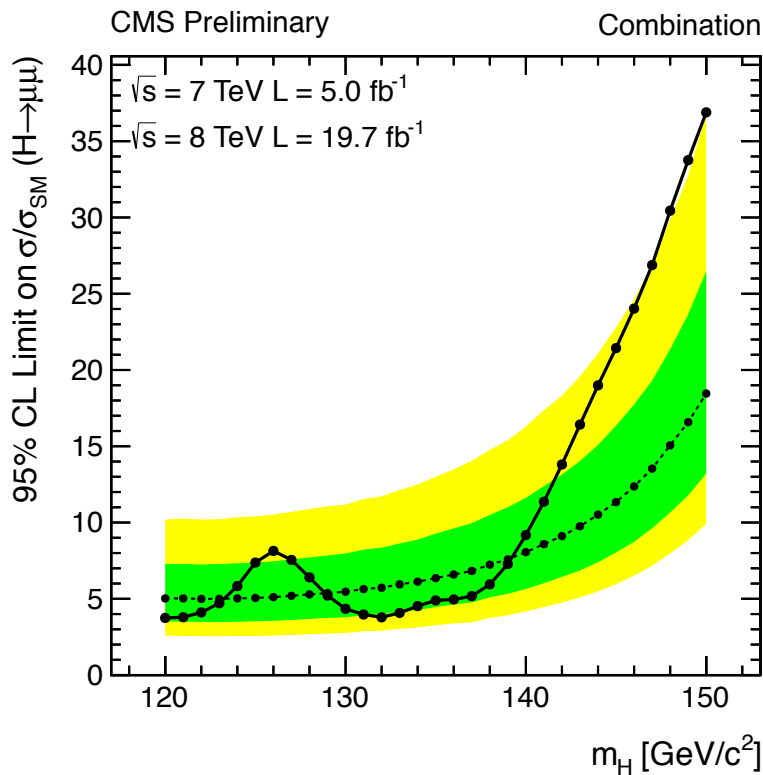
# Analysis Strategy

- Two isolated muon + further jets
- Categorization based on the jet multiplicity:
  - 2jets (VBF, GGF tight and GGF loose based on  $M_{jj}$  and  $\Delta\eta_{jj}$ )
  - 0-1Jet (loose and Tight based on  $p_T(\mu\mu)$ )
- More categorization based on  $\eta$  of each muon to optimize the  $M_{\mu\mu}$  resolution:  $|\eta|$  in  $[0,0.8]$ - $[0.8,1.6]$ - $[1.6,2.1]$
- $M_{\mu\mu}$  used to fit:
  - double Gaussian function for shape of the signal
  - polynomial and an exponential term for BG shape [dominated by the Drell-Yan]



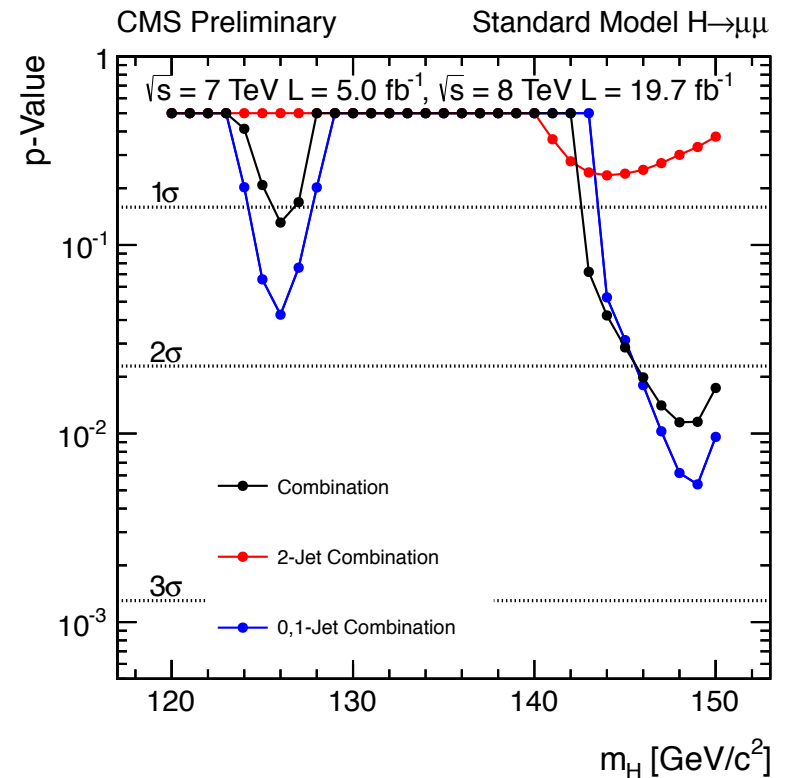


# Limit and Significance



@ 125 GeV

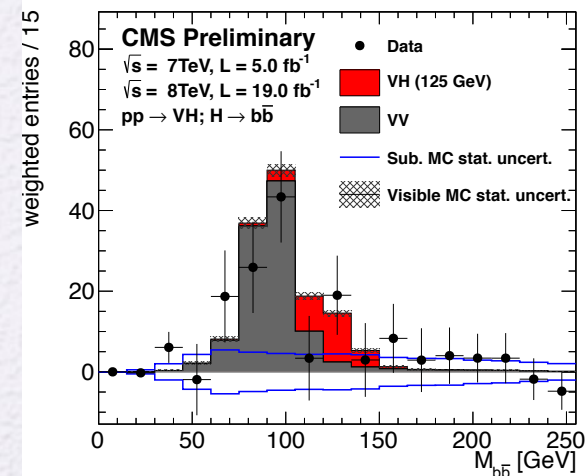
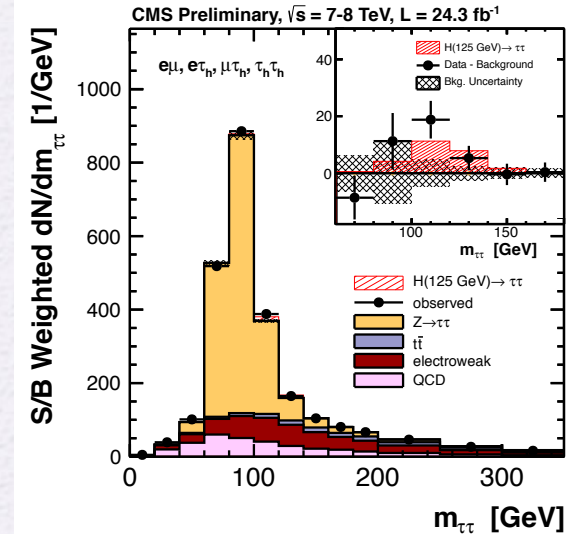
- obs. limit = 6.6 x SM
- exp limit = 4.9 x SM



A broad excess @ 149 GeV  
 ~ local significance of 2.8  $\sigma$   
 reduced to ~ 0.8  $\sigma$  after LEE

# Conclusions

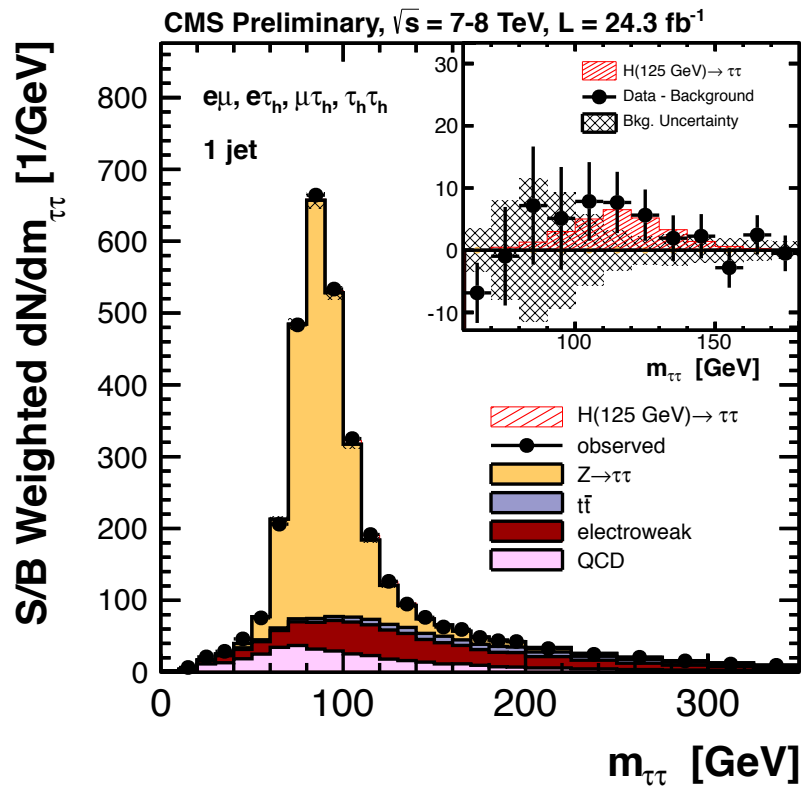
- Full search is done for fermionic decays of Higgs boson in 5 production and 3 decay modes with the full 2011+2012 dataset collected by CMS
- A wide excess compatible with SM Higgs is observed both in  $H \rightarrow \tau\tau$  and  $H \rightarrow b\bar{b}$ 
  - Observed significance of  $\sim 2.1\sigma$  for  $H \rightarrow b\bar{b}$  and  $\sim 2.9$  for  $H \rightarrow \tau\tau$
- All results are compatible with the presence of SM Higgs boson at the mass predicted by bosonic decays
- New updated and improved  $H \rightarrow \tau\tau$  results will appear soon, stay tuned ... 34



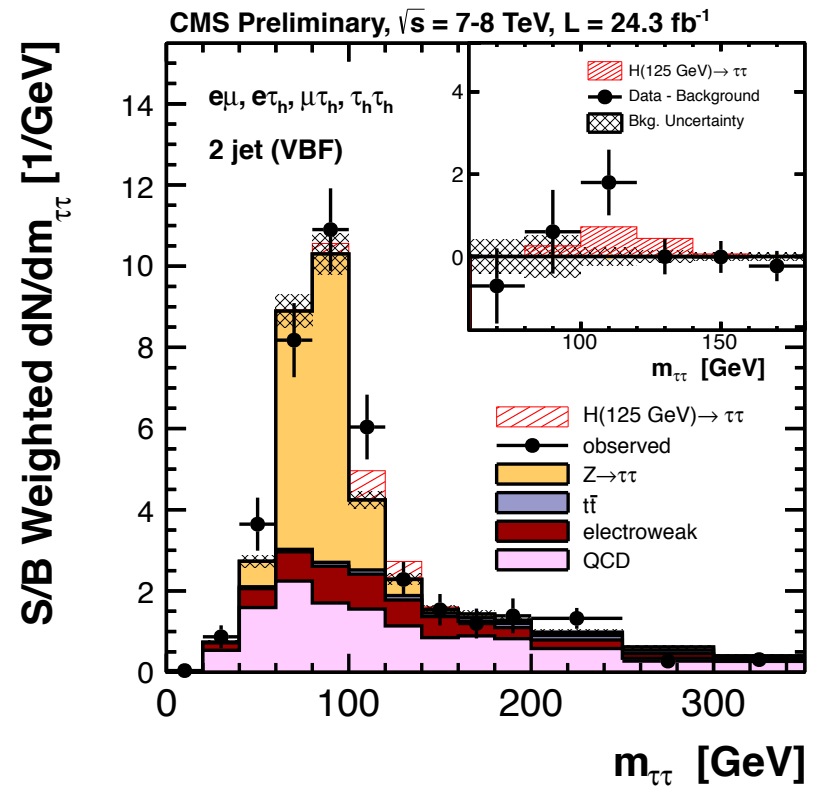
**Back Up**

# Weighted Mass

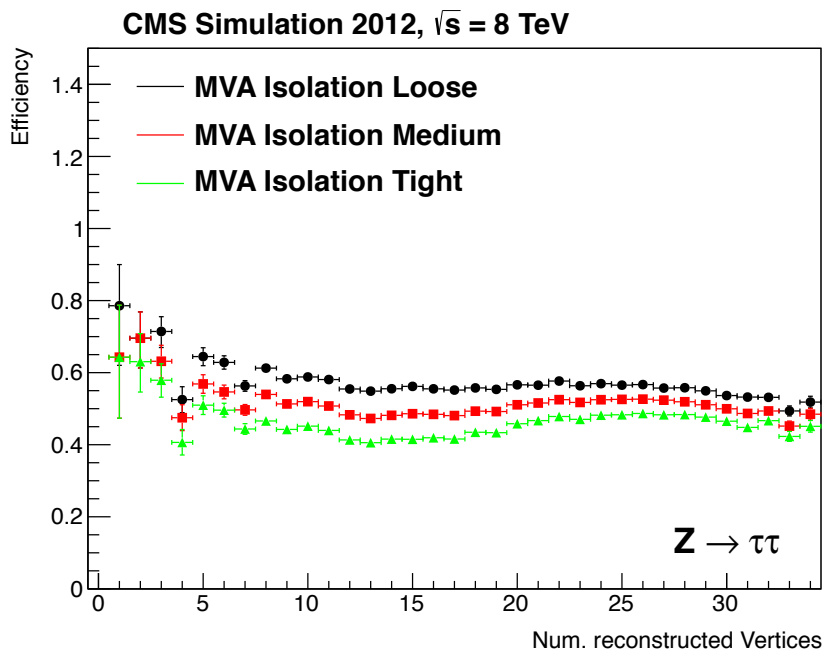
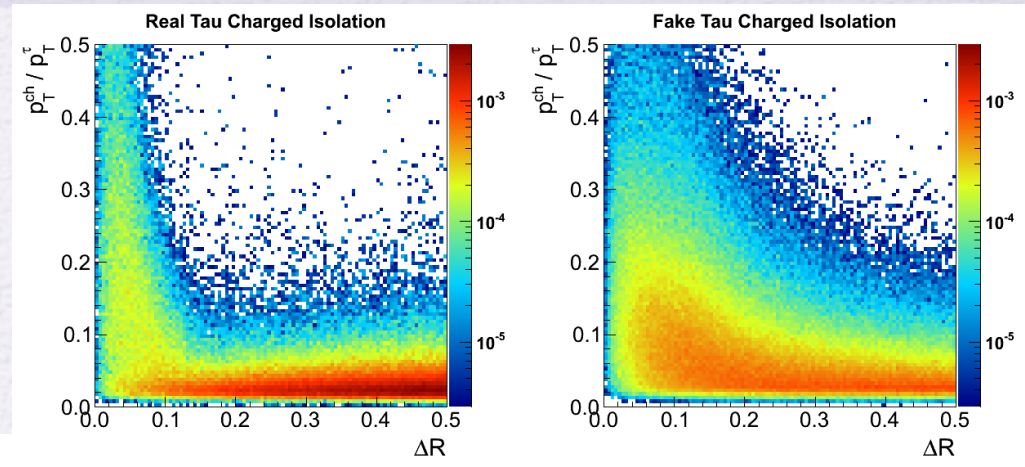
1 Jet Category



VBF Category

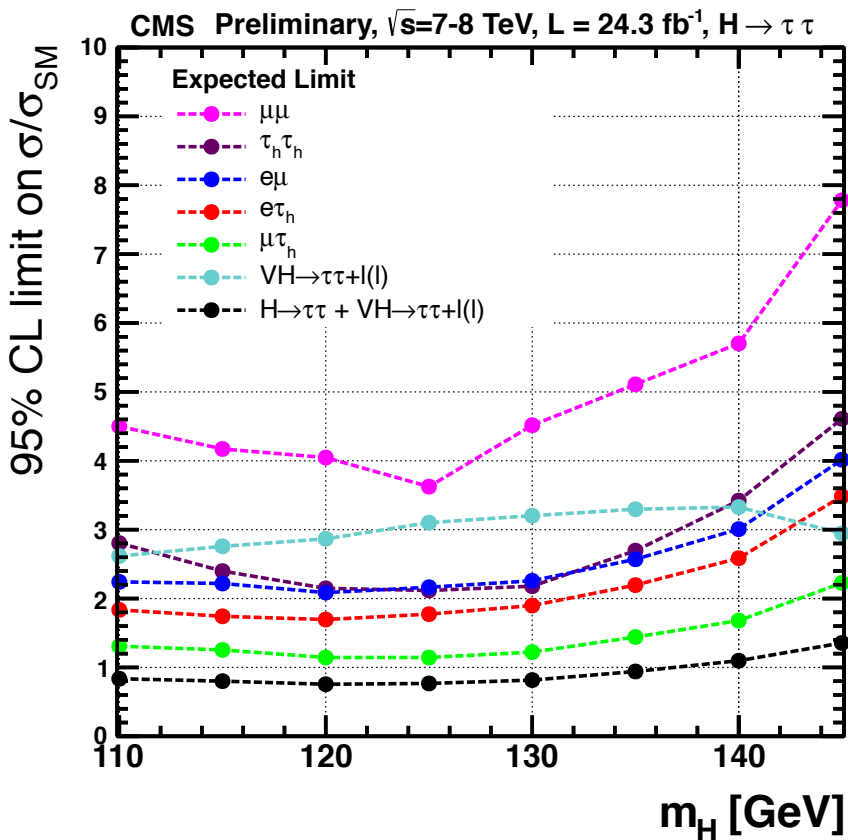


# More about Tau ID

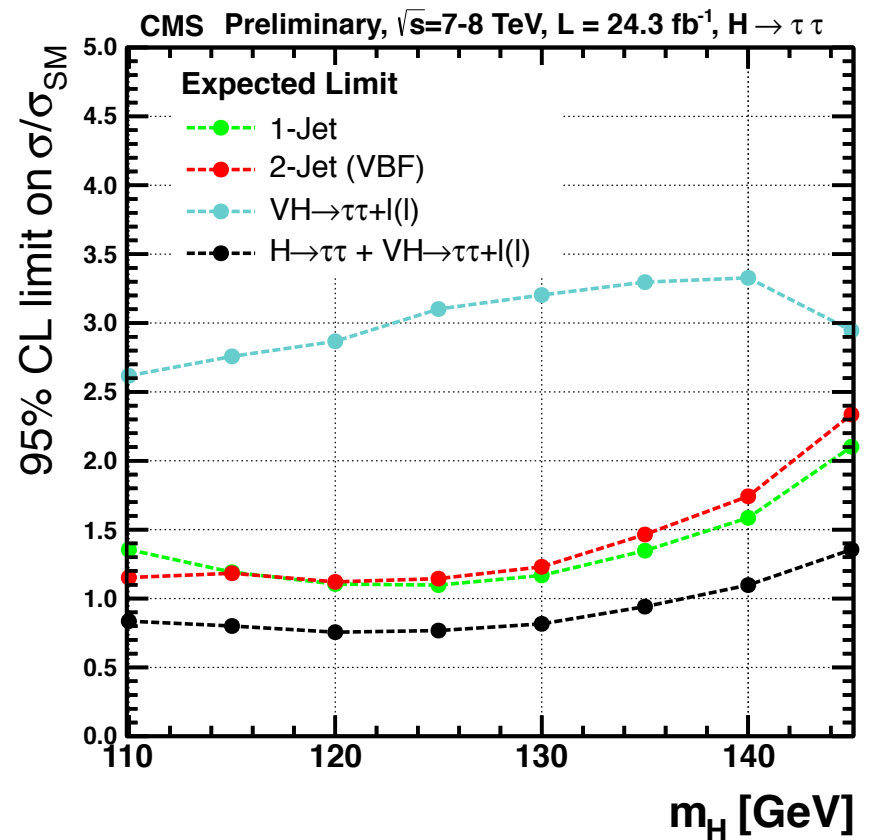


# Expected Limit

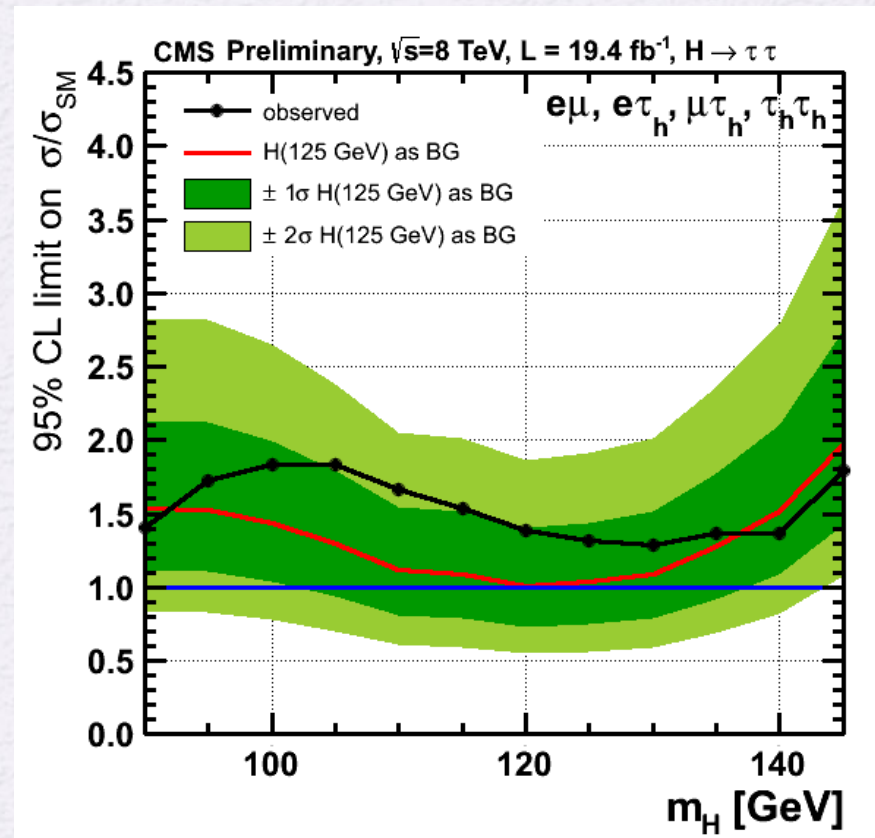
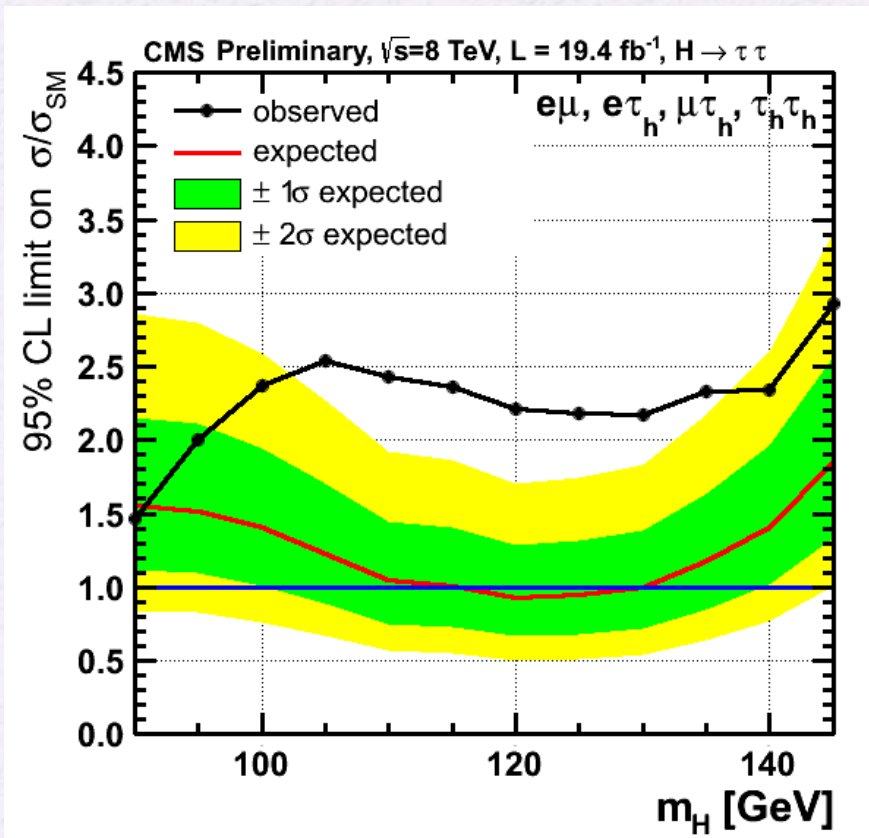
Per Channel



Per Category



# Extended Limit (Down to 90 GeV)

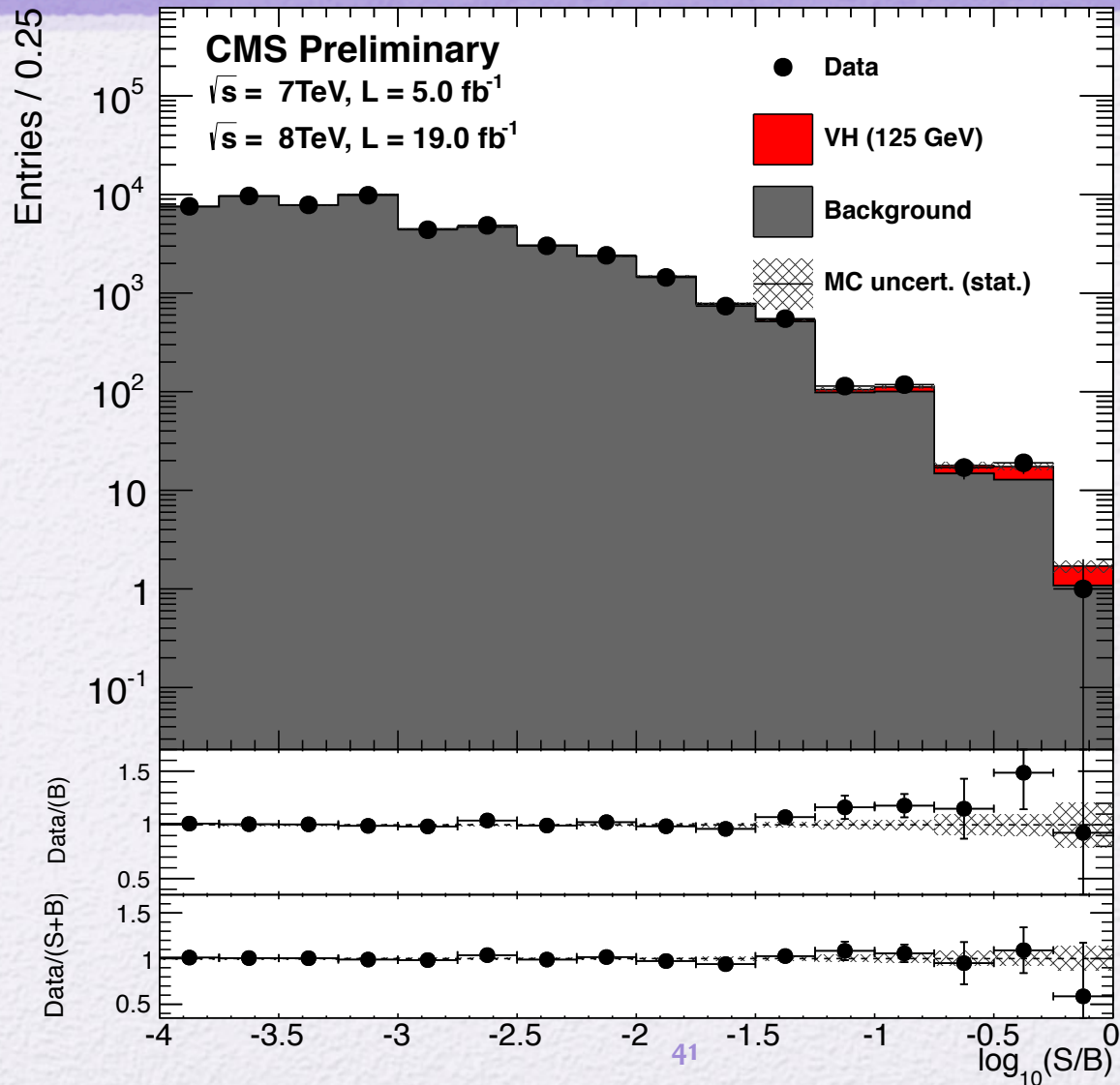


# Systematics

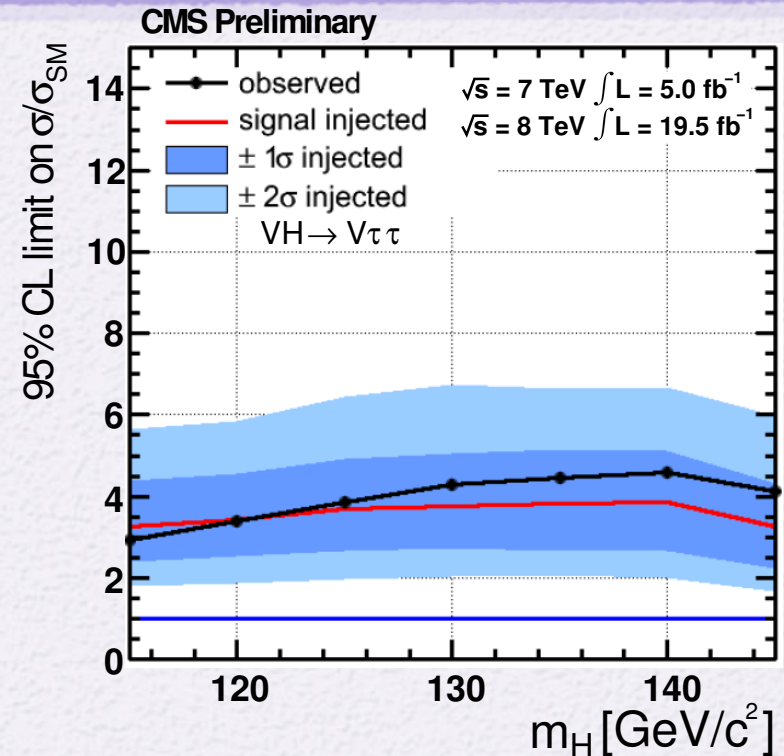
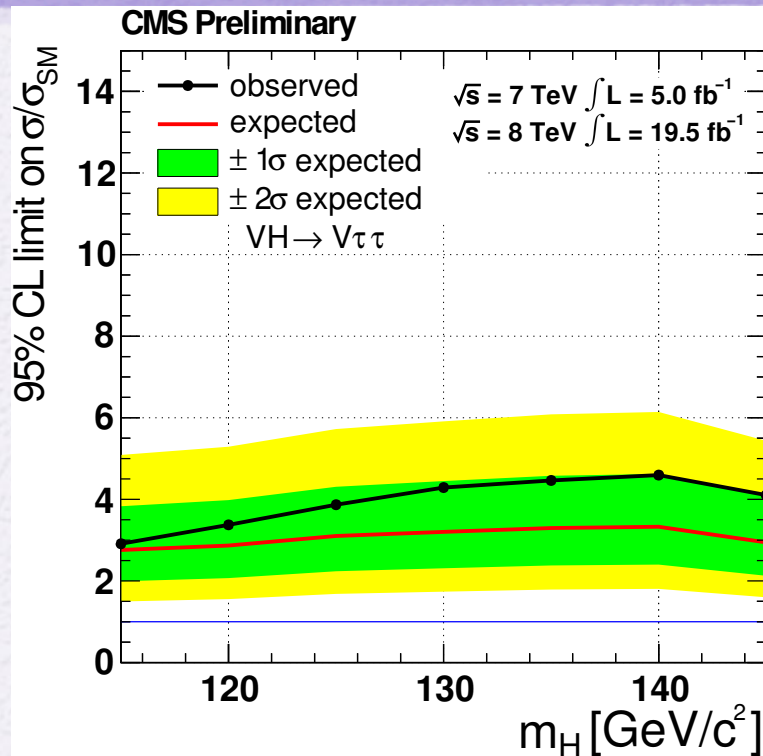
Uncertainty	Uncert.	Applied on ...
Electron Id & Trigger	2%	Normalization
Muon Id & Trigger	2%	Normalization
Tau Id & Trigger	8%	Normalization
Tau Energy Scale	3%	Shape
Electron Energy Scale	1%	Shape (emu channel)
JES	2.5-5%	Normalization
MET	5%	Normalization
b-tag efficiency	10%	Normalization
Luminosity 7 TeV (8TeV)	2.2% (4.2%)	Normalization
ttbar and Diboson	10-30%	Normalization
QCD multijet	6-32%	Normalization
Z→ll (e,mu,jet fake)	(20%,30%,20%)	Normalization
PDF	2-8 %	Normalization



# Combined BDT for VHbb



# Combined $VH\tau\tau$ Results

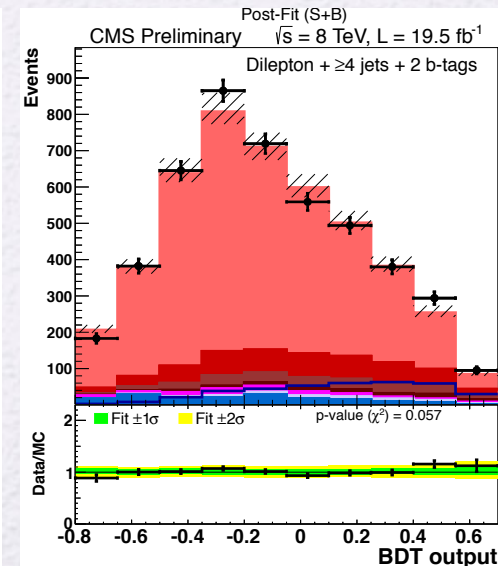
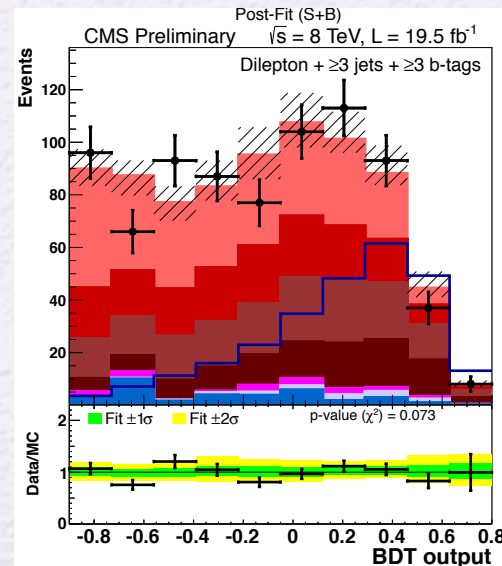
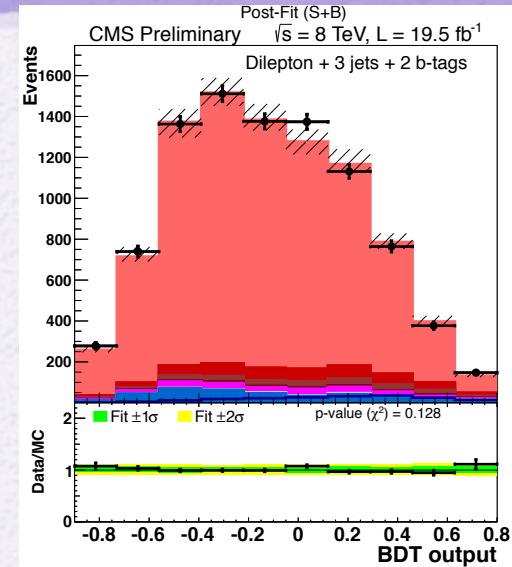
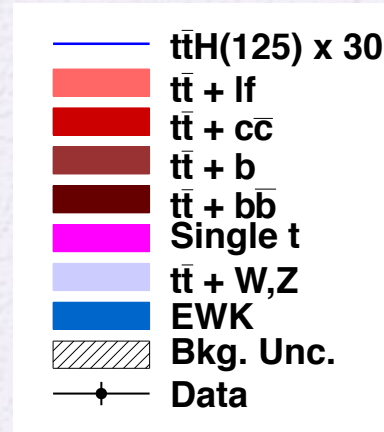


- Sensitivity of  $\sim 3 \times \text{SM}$
- Small excess

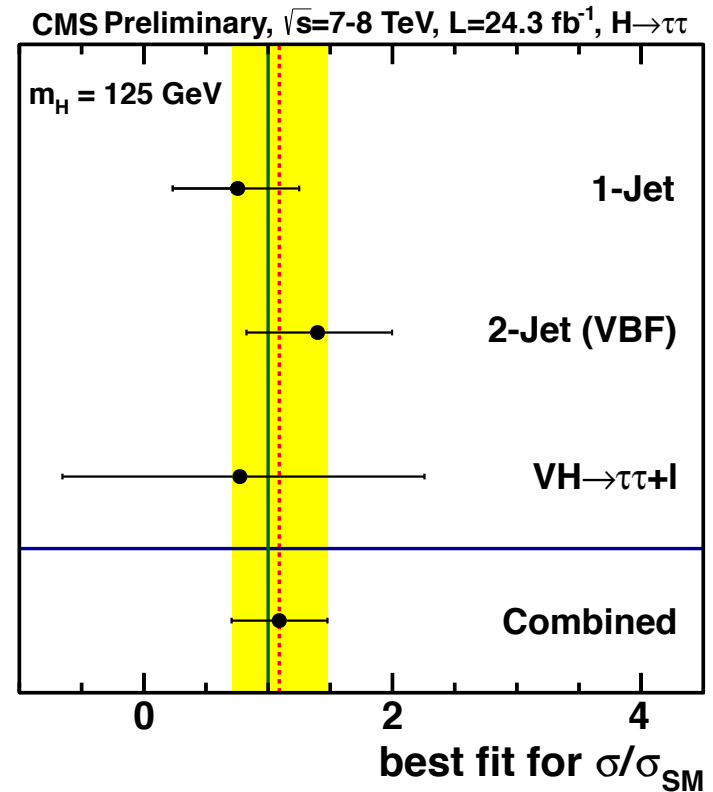
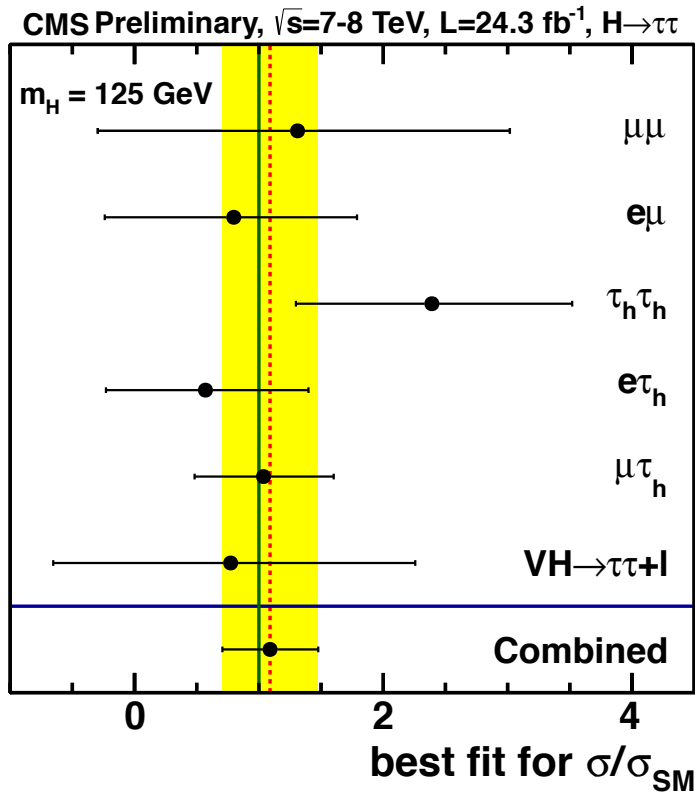
- consistent with both SM Higgs at 125 GeV and background

# Di-Lepton + Jets

- combination of different number of jets and b-jets (3 sub channels)



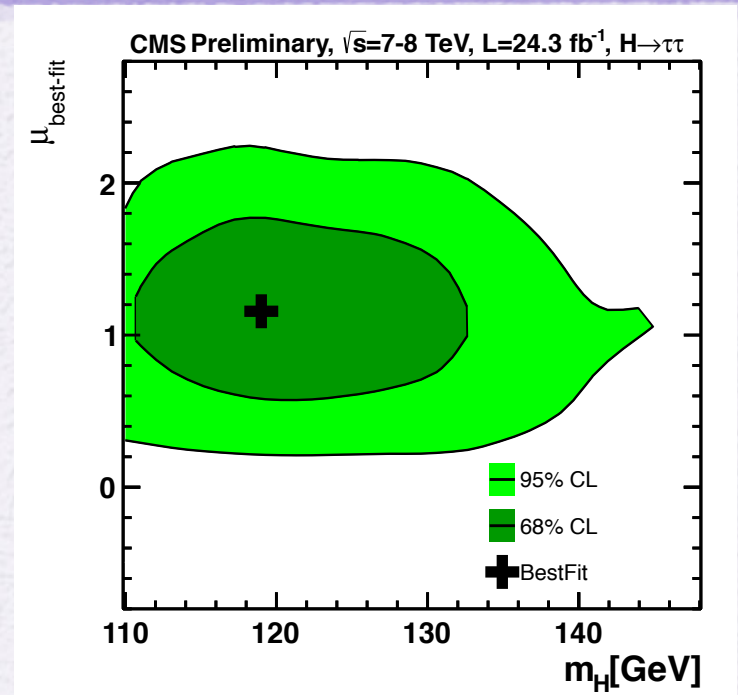
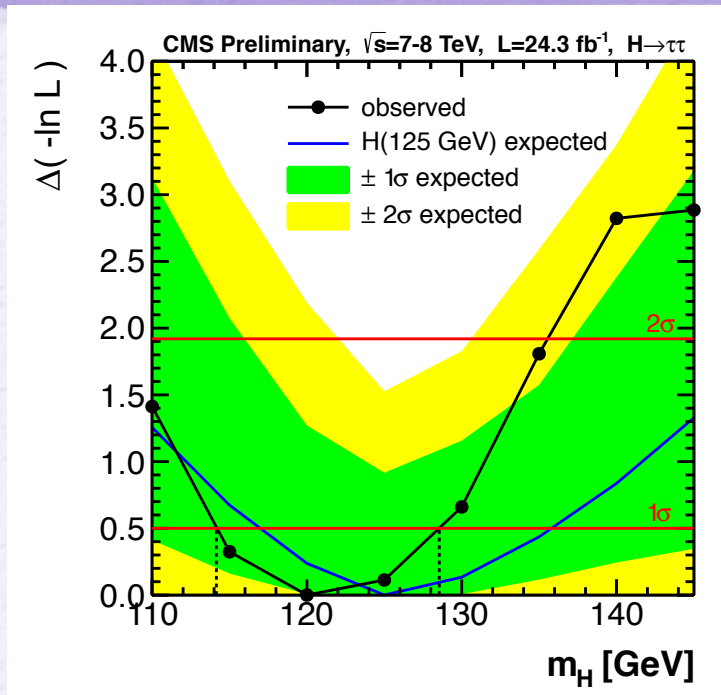
# Best Fit Signal Strength



Best-fit signal strength values,  $\sigma/\sigma_{SM}$  for independent Channel(categories) on left(right)

signal strength  $\mu=1.1 \pm 0.4$

# Mass and Best Fit v.s. Mass



Log likelihood versus SM Higgs boson fit mass

$$m_H = 120^{+9}_{-7}(\text{stat+syst}) \text{ GeV}$$

Best fit of signal strength compared to the SM expectation ( $\mu$ ) as a function of the Higgs mass

# Tau+ Jets

- combination of different number of jets and b-jets (6 sub channels)
- use  $t\bar{t}H$  ( $H \rightarrow \tau\tau$ ) as signal and  $t\bar{t}$ +jets as BG in training the BDT

