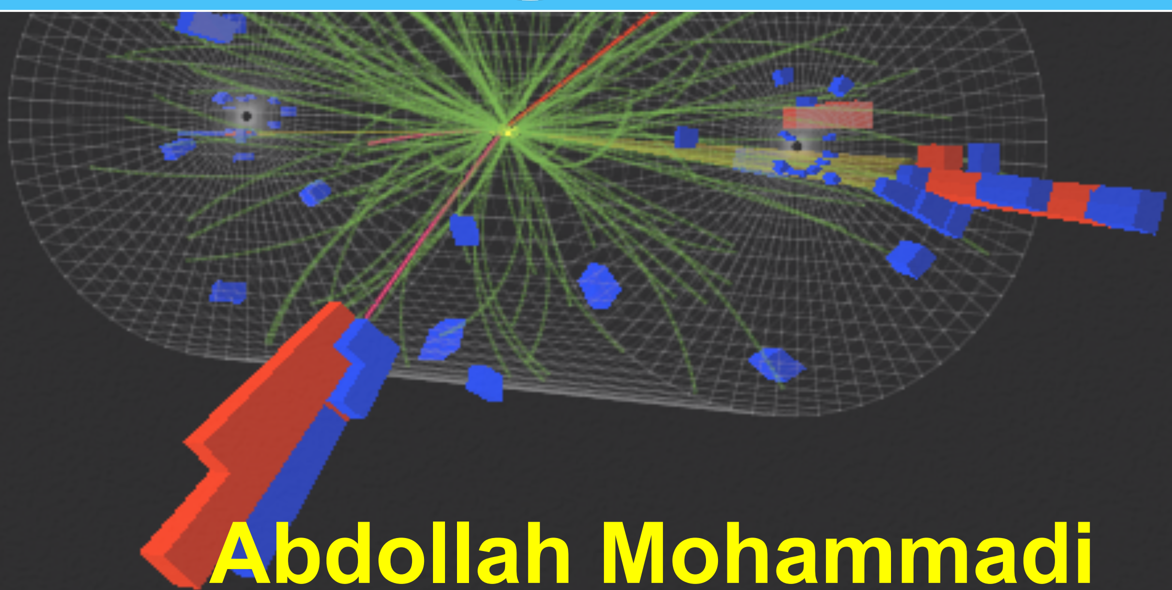
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 25 00:15:46 2012 CEST
Run/Event: 207898 / 97057018

LHC results on the 125 GeV boson decaying to fermions

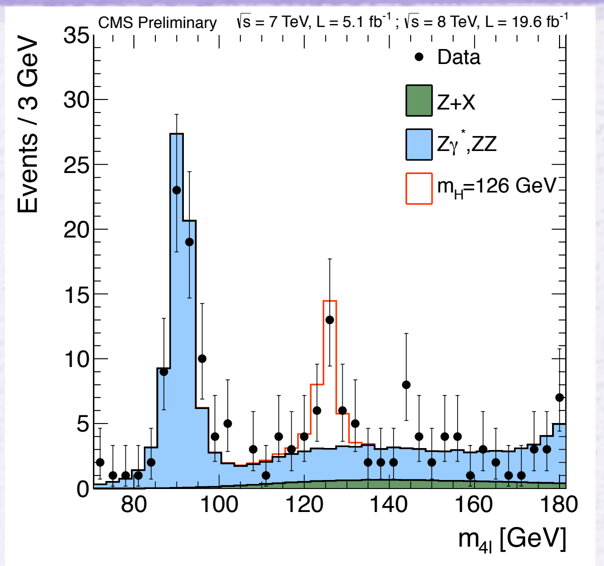


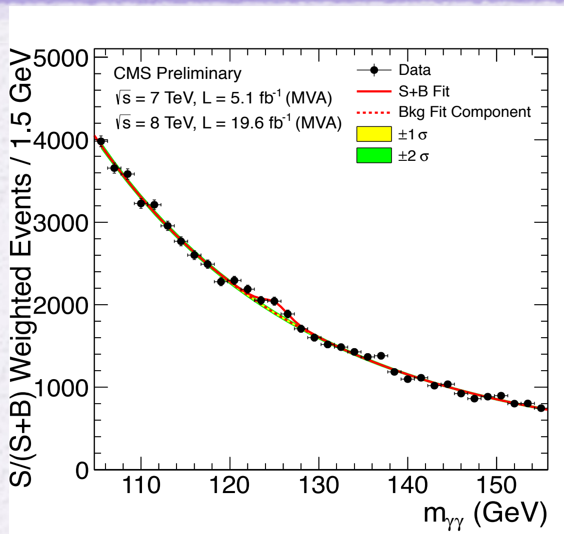
Abdollah Mohammadi

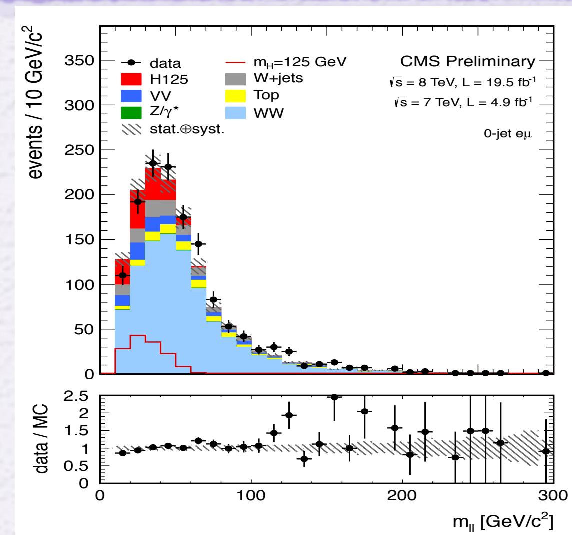
IIHE-ULB, Université Libre de Bruxelles

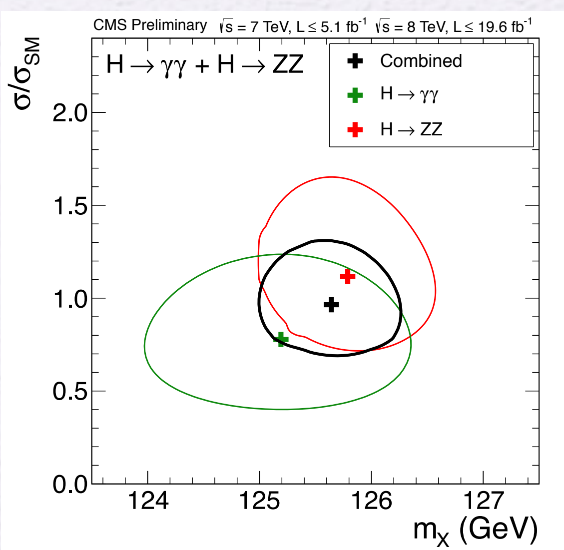
IAP Belgian Meeting, Dec. 2013

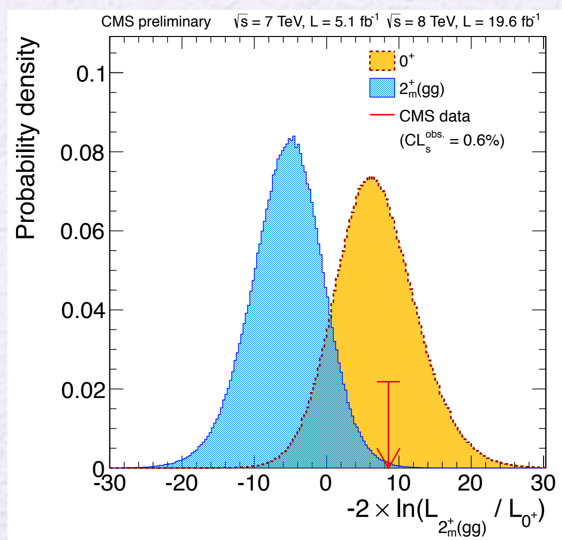
Enough indications for a **new** particle (scalar boson) @ ~125 GeV







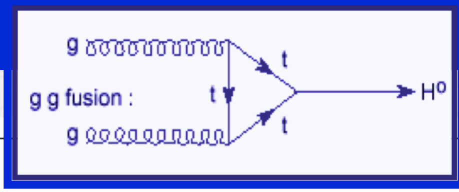


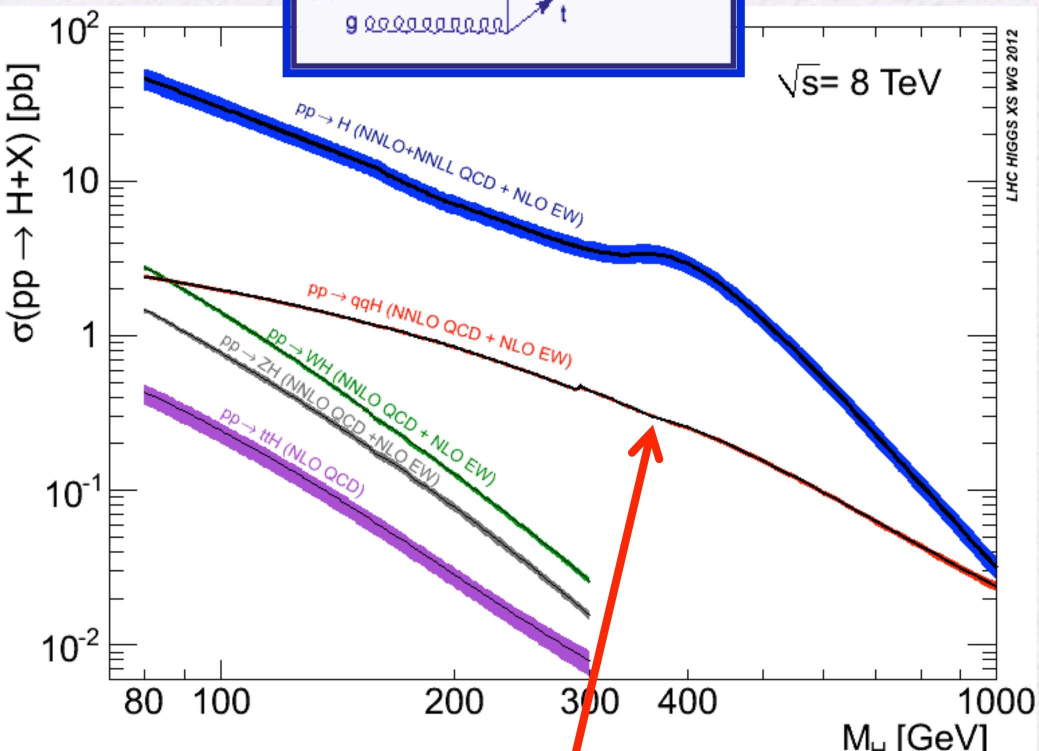


New particle couples to bosons, what about coupling to fermions??

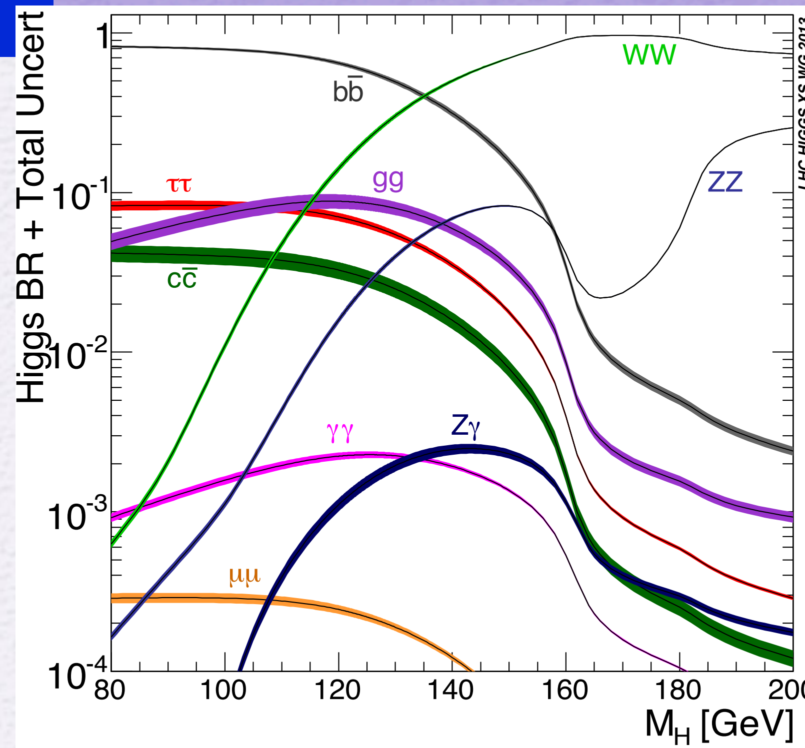
Standard Model Higgs Production @LHC

gluon-gluon fusion dominant production





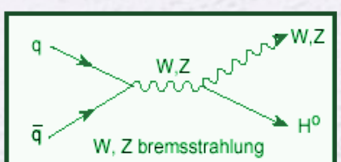
Branching Ratio



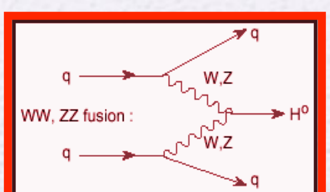
Fermionic decay modes:

- bb
- *ττ*
- μμ, ee

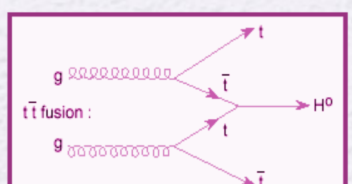
ttH



Higgs Strahlung



Vector boson fusion



ttH

Content

Most recent LHC Higgs fermionic searches

- will be presented in this talk:
  - **CMS VH($\rightarrow$bb)**
  - **ATLAS VH($\rightarrow$bb)**
  - **CMS (H$\rightarrow\tau\tau$)**
  - **ATLAS (H$\rightarrow\tau\tau$)**
  - **CMS combined VH($\rightarrow$bb) + (H$\rightarrow\tau\tau$)**
- will NOT be presented in this talk (see backup):
  - H$\rightarrow\mu\mu$ & H$\rightarrow$ee
  - ttH($\rightarrow$gg, bb, tt, multi-leptons)

$H \to bb$ associated production

H→bb associated production

Largest Branching Ratio at low mass

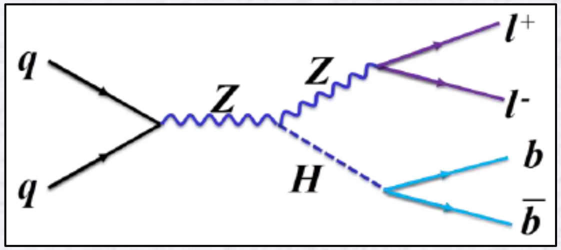
Challenges:

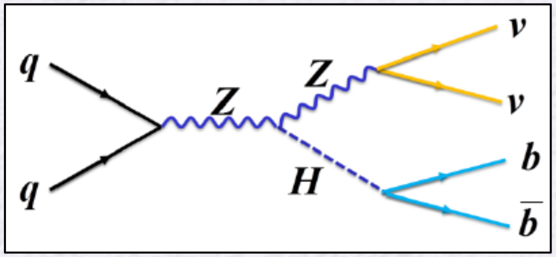
- Control of large SM background
- B-tagging

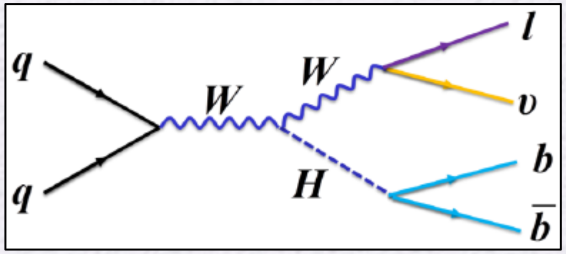
Improve sensitivity:

- b-jet energy regression
- boosted analysis: different regions of $p_t(V)$
- BDT shape analysis for signal extraction

6 topologies considered: Z(ll)H(bb), Z(νν) H(bb), W(lν) H(bb) W(τν) included

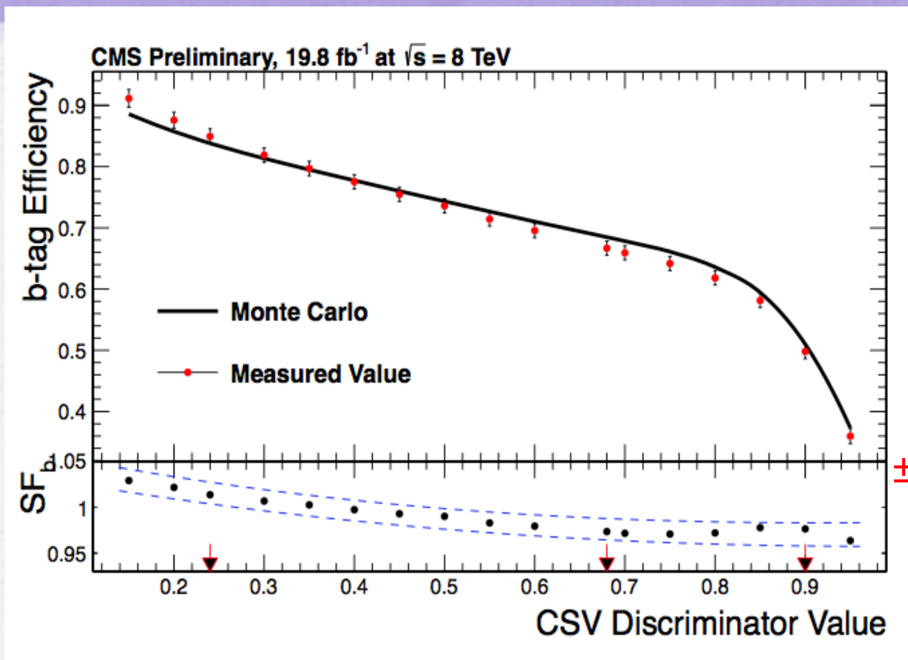






Main backgrounds: V+jets and ttbar

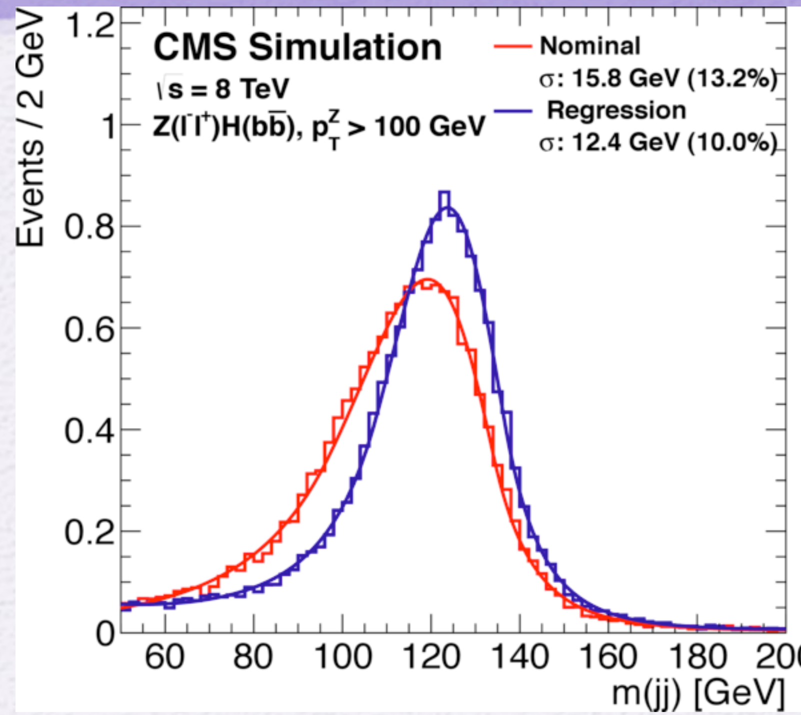
b-tagging & b-jet energy calibration



Combined Secondary Vertex discriminator (track impact parameters and secondary vertices within jets information used)

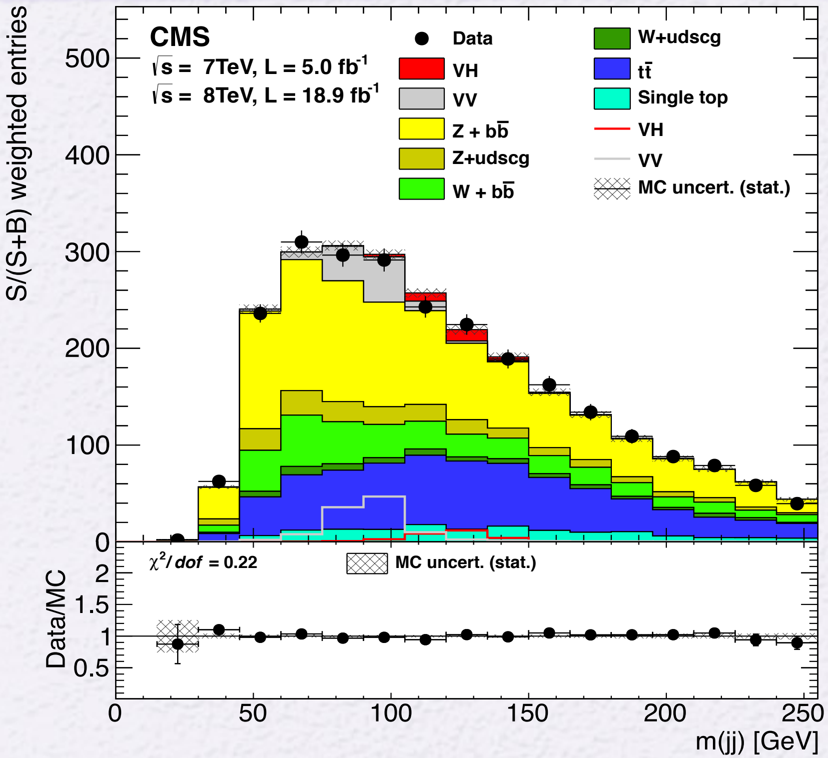
Tagging efficiency working points used

- b-tag: 50-75 %
- c-quark: 5-25%
- Light quark & gluons: 0.15-3%

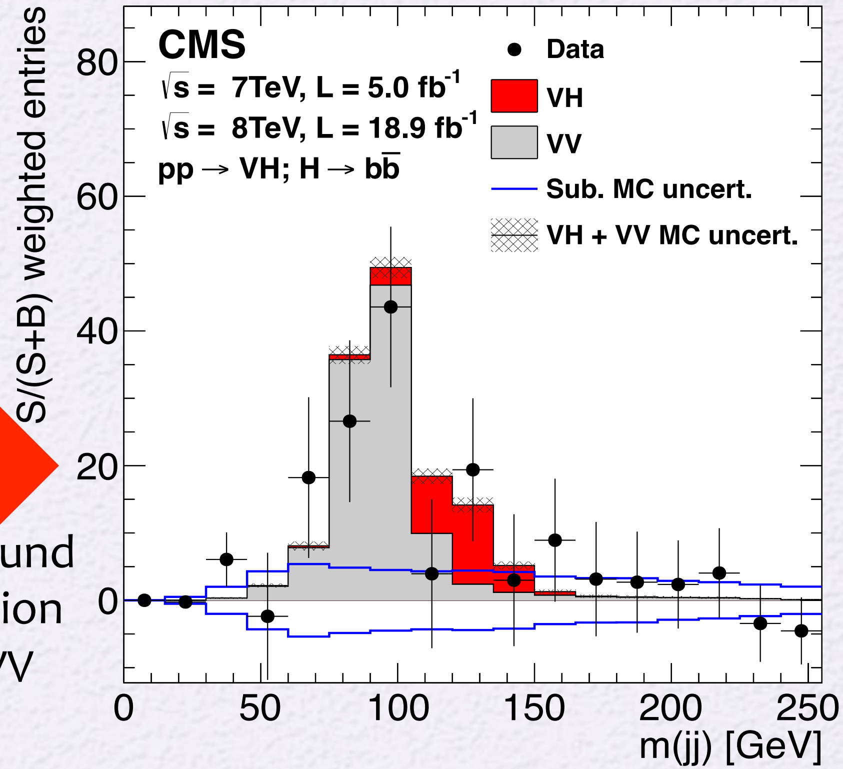


- BDT regression trained on VH signal using jet and soft-lepton variables
- Improves mass resolution by 15% and sensitivity by 10-20%
- Validated in data control regions (bbZ→ll, ttbar, single top, …)

Di-jet mass cross check analysis



Background subtraction except VV



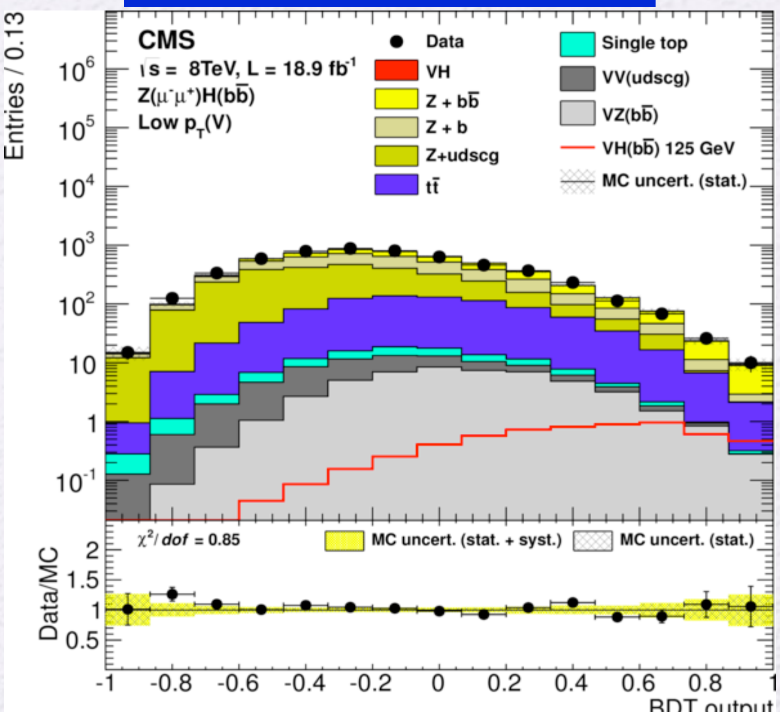
Fit to the dijet invariant mass M_{jj} gives:
small excess consistent with the production of SM Higgs at 125 GeV

H→bb associated production

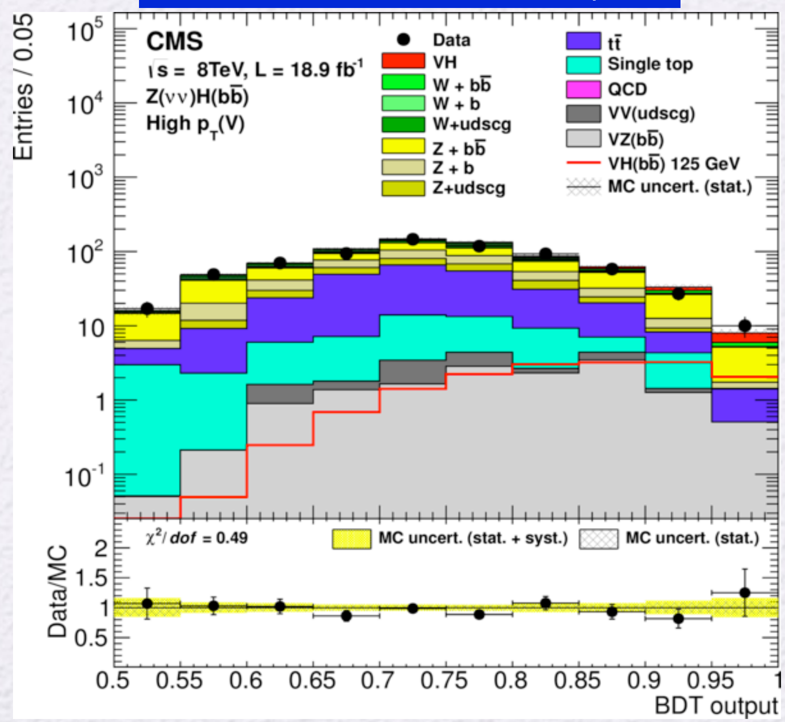
A fit to the BDT shape gives 20% improvement over cut-and-count

- Inputs include kinematics, b-tag information, angles
- Categorize in different $p_T(V)$ and b-tag categories
- BDT is studied in background control regions

Z(→μμ)H(→bb), low $p_T(Z)$

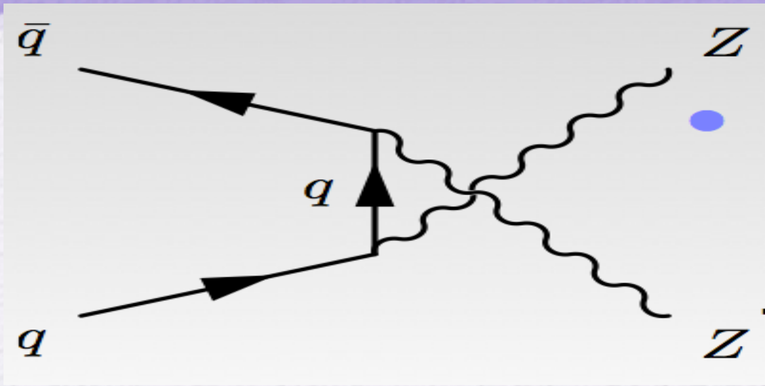


Z(→νν)H(→bb), high $p_T(Z)$

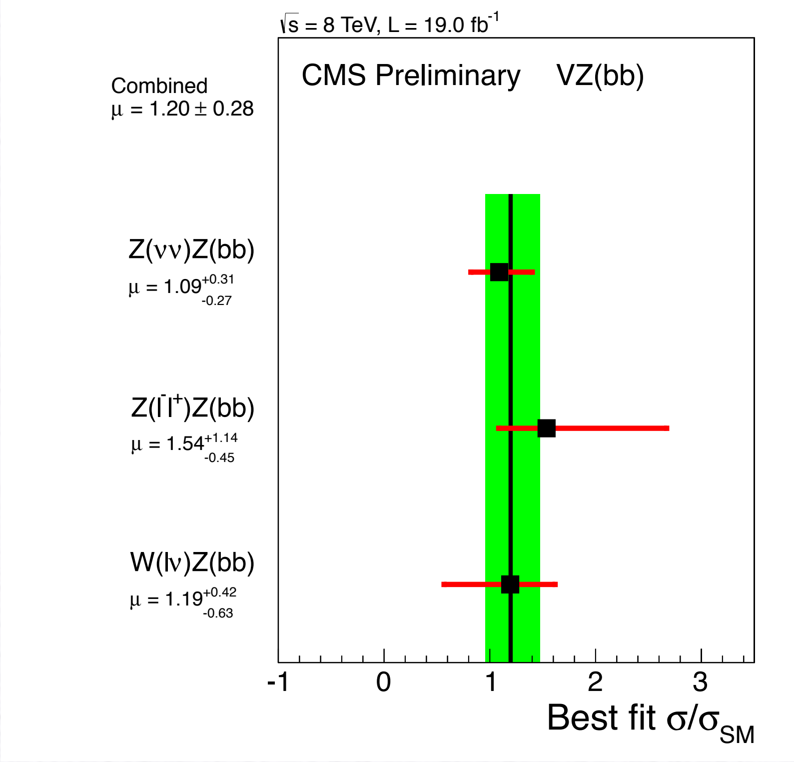


Validation of BDT using VZ(bb)

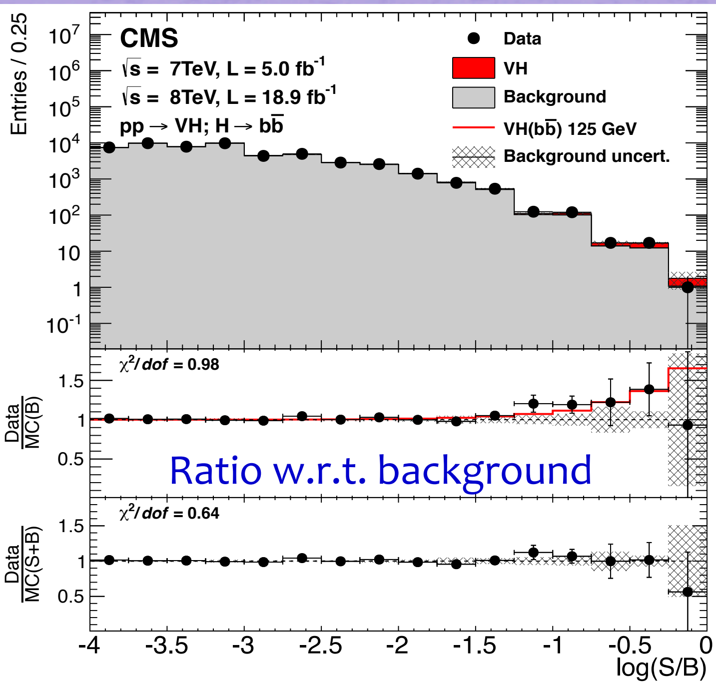
As Validation of MVA, BDT is trained using di-boson as signal and other processes (including VH) as BG.



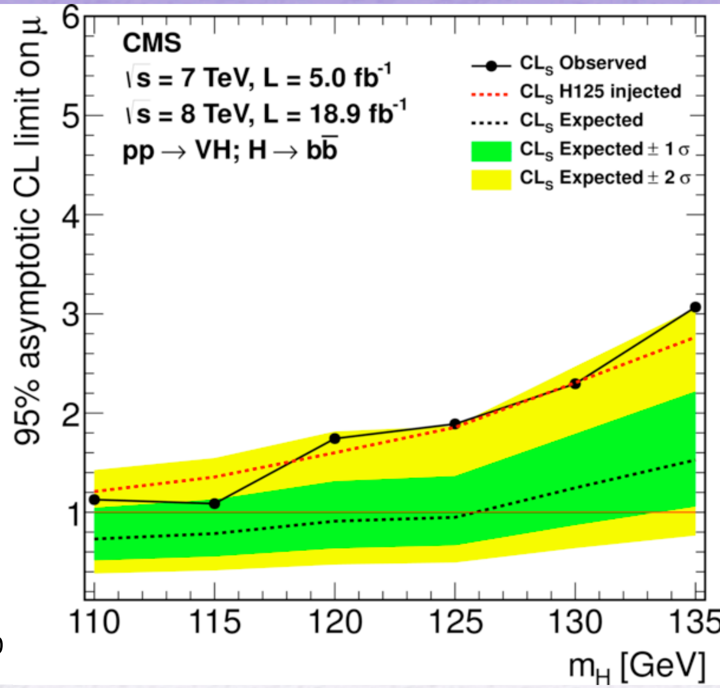
	BDT VZ(bb)
Exp. Sig	**6.3 σ**
Obs. Sig	**7.5 σ**
μ	**$1.19^{+0.27}_{-0.23}$**

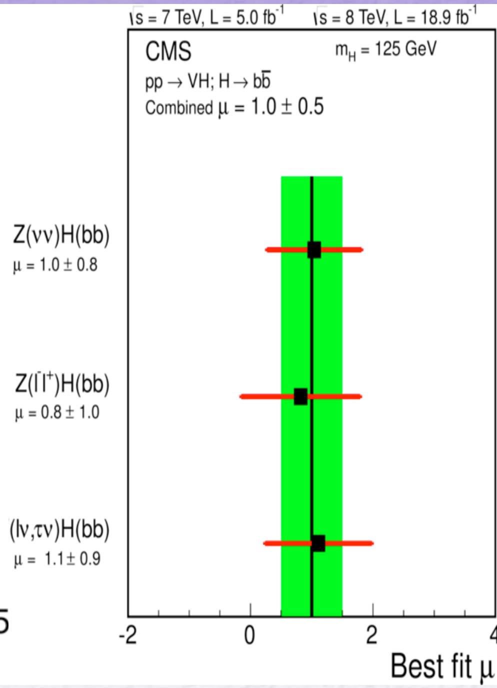


CMS H→bb Final results



Ratio w.r.t. (signal+background)





All channels combined

Events sorted in bins of similar S/B as given by the output of the BDT

2.1s observed excess!

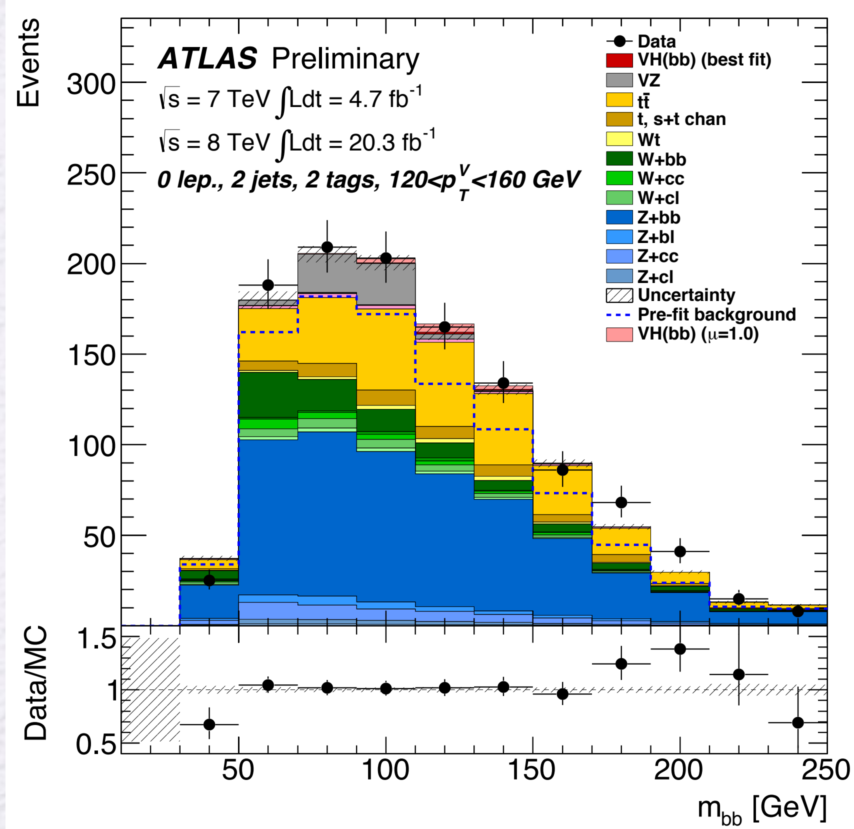
2.1s expected

Signal strength of excess: $\mu=1.0\pm0.5$

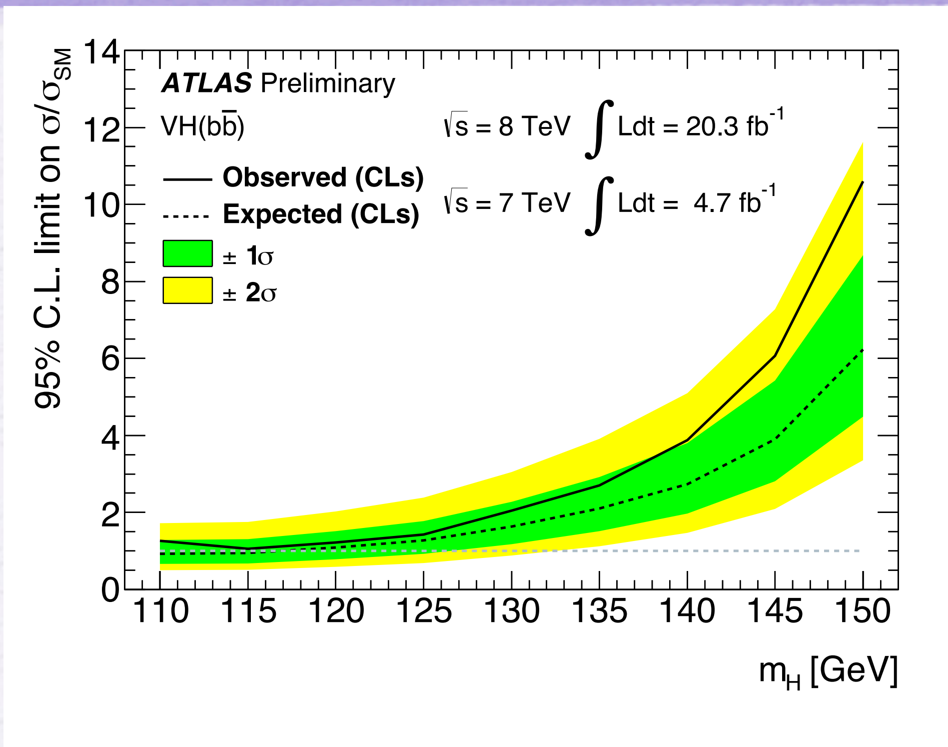
ATLAS VH→bb

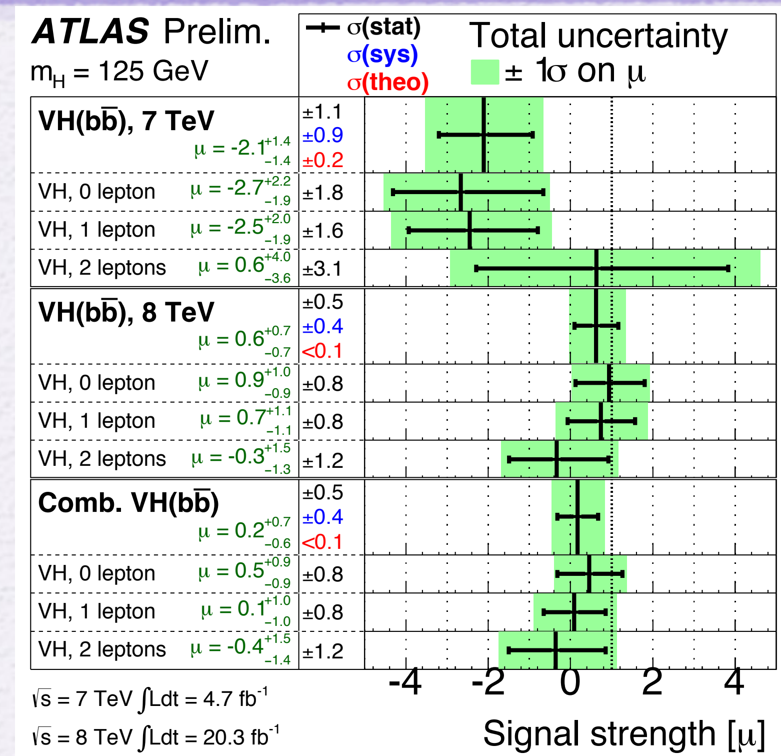
		2 jets 1 b-tag	3 jets 1 b-tag	2 jets 2 b-tags	3 jets 2 b-tags	Top CR eμ events
3 $p_T(V)$ bins	0-leptons	CR	CR	SR	SR	
5 $p_T(V)$ bins	1-lepton	CR	CR	SR	SR	
5 $p_T(V)$ bins	2-leptons	CR	CR	SR	SR	CR

- **Simultaneous fit in 26 2b---tag signal regions, 26 1b---tag control regions and 5 top control regions**
- – CR=control region; **normalization of backgrounds (1---bin only)**
- – SR=signal region; **shape and normalization to m_{bb} distribution**
- – Common nuisance parameters (NP) across SR's and CR's and channels



ATLAS VH→bb





@ 125 GeV
- Expected: 1.3×SM
- Observed: 1.4×SM

Results consistent with SM H→bb and background-only hypotheses

Fitted signal strength 7+8 TeV: $\mu=0.2^{+0.7}_{-0.6}$ 95% CLs @125 GeV

SM $H \to \tau\tau$ search

H→ττ

Significant Branching Ratio (~ 6%) at low mass

Challenges:

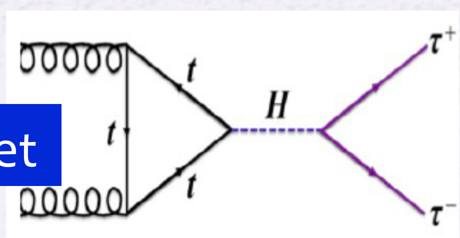
- Reconstruction of different tau decay modes: Hadronic tau (τ_h) reconstruction
- Reconstruction of di-t mass (presence of ν's)

Improve sensitivity:

- Different categories based on jet multiplicity and τ p_t
- Optimized τ_{had}-isolation and e, $\mu \rightarrow \tau_{had}$ fake rejection

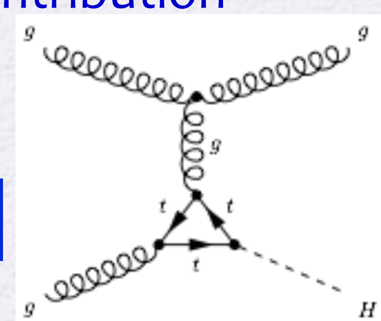
Background dominated

0-jet



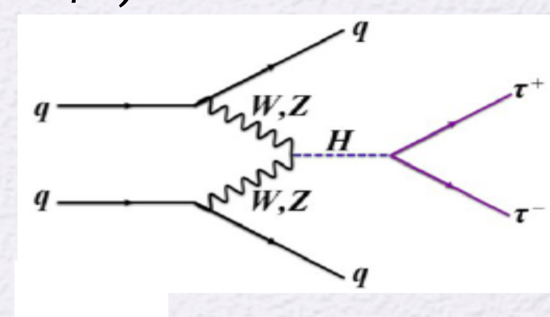
Enhanced gluon-fusion contribution

1-jet



Vector Boson Fusion (VBF) (best S/B)

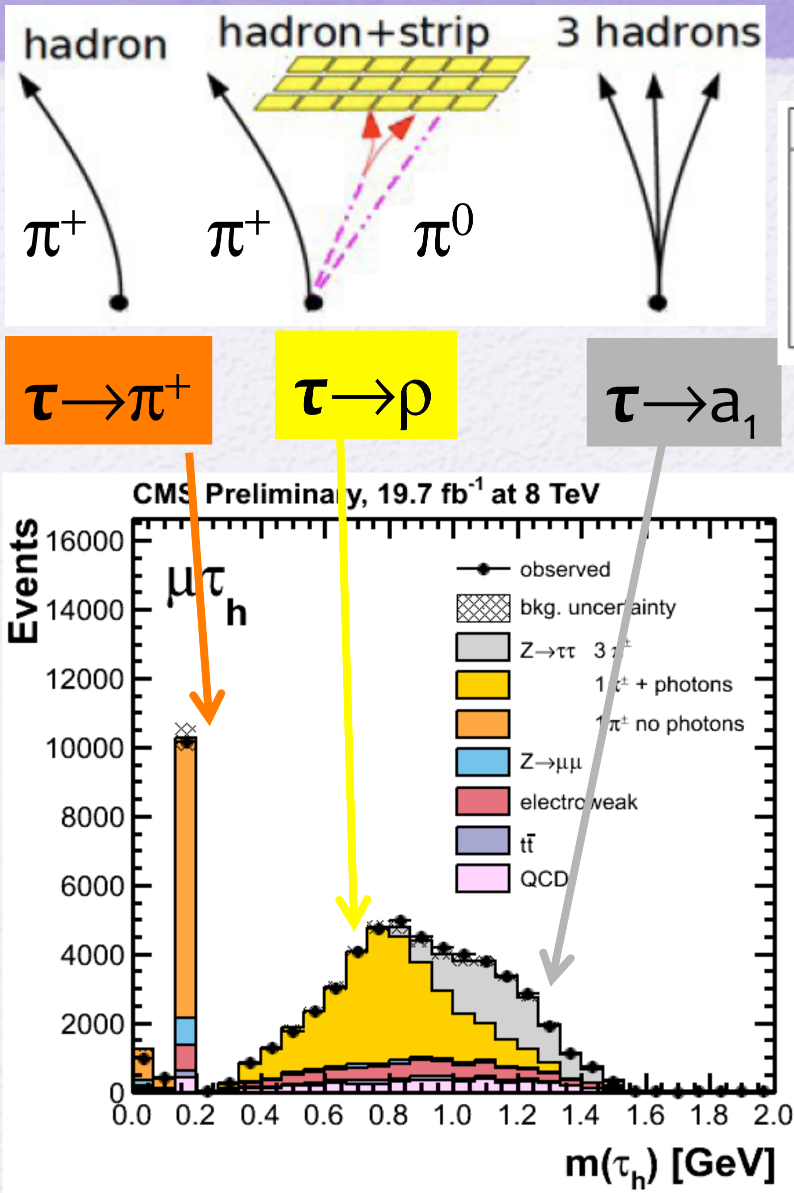
2-jet



0-jet category: allows to control systematics uncertainties (nuisances in fit)

Fit for Higgs signal is performed in all categories

Hadronic τ Reconstruction



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

Tau reconstruction: hadron+strip

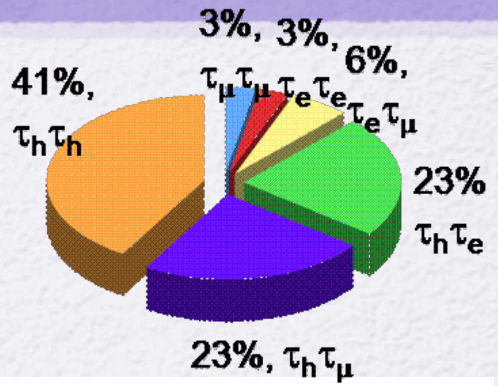
Particle-flow based algorithm to reconstruct different hadronic tau decay modes

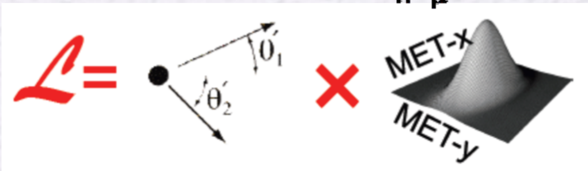
τ_h identification:

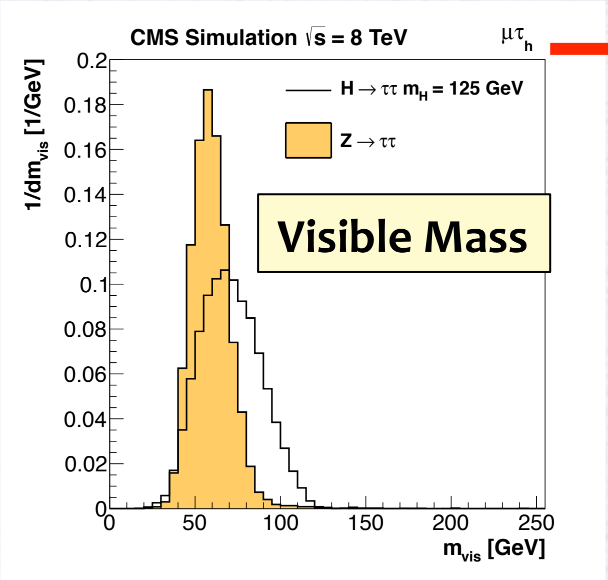
- efficiency ~ 60%
- fake rate ~ 1%

di-τ Mass Reconstruction

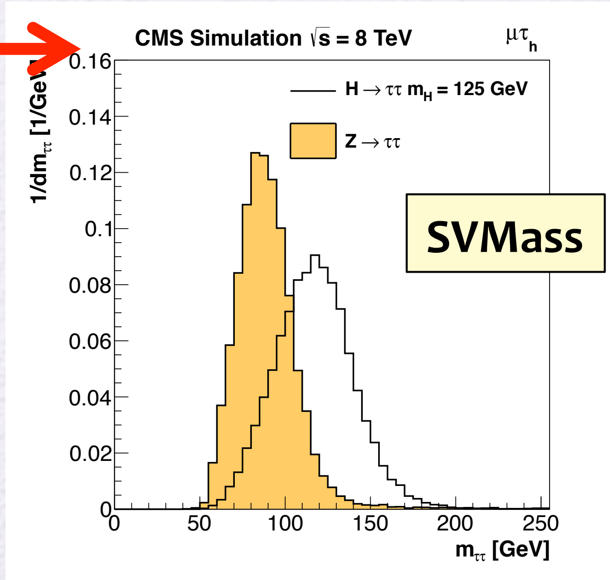
- Determine invariant mass of di-**τ** system with maximum likelihood method.
- marginalize the unobserved neutrinos d.o.f.
- Inputs: four-vector information of visible leptons, x- and y- component of MET and MET resolution



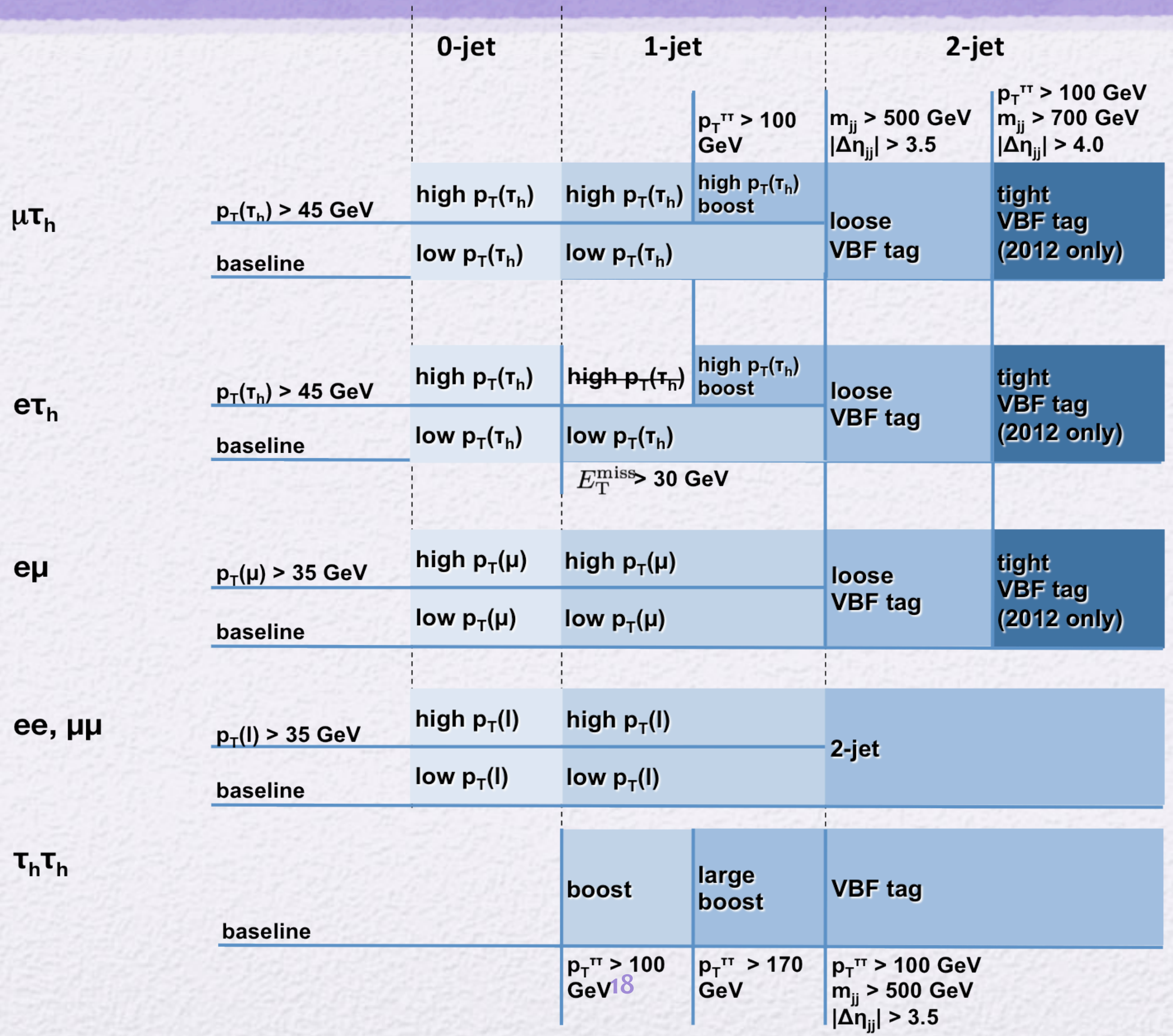




- Improve the Mass resolution (15-20%)
- Increase Z/H separation
- Impact on Limit/Sign. ~ 30%

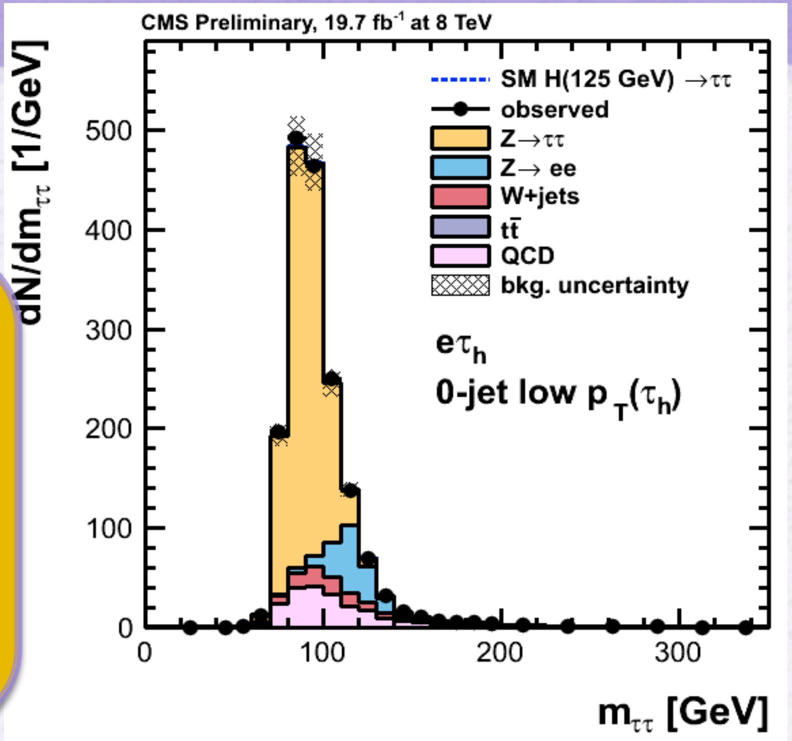


H→ττ categories



H→ττ: background estimation

All normalizations are data-driven



Z→ττ:
embedded samples
No MET/JES scale uncertainties
Shape estimation and correction for selection efficiencies

W+jets:
- Normalization from high m_T control region
- Shape from MC

ttbar:
- Normalization from em b-tag control region
- Shape from MC

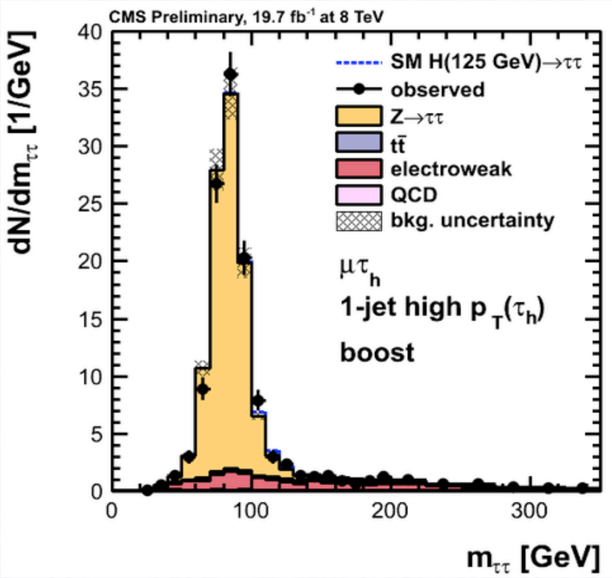
Z→ee/μμ
- Normalization scale factor from tag-and-probe in data
- Shape from MC

QCD:
- Normalization from ratio of same-sign(SS) to opposite-sign (OS) data events
- Shape from SS data events

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

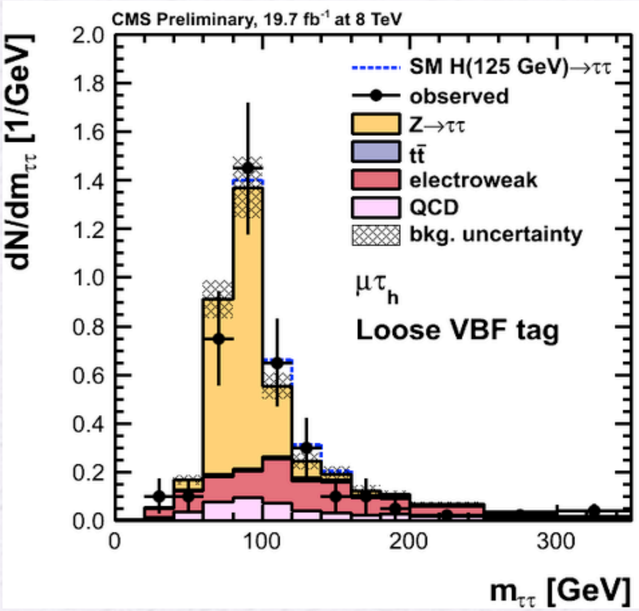
$\mu\tau_h$: most sensitive channel

1-jet
high $p_t(\tau_h)$ boost



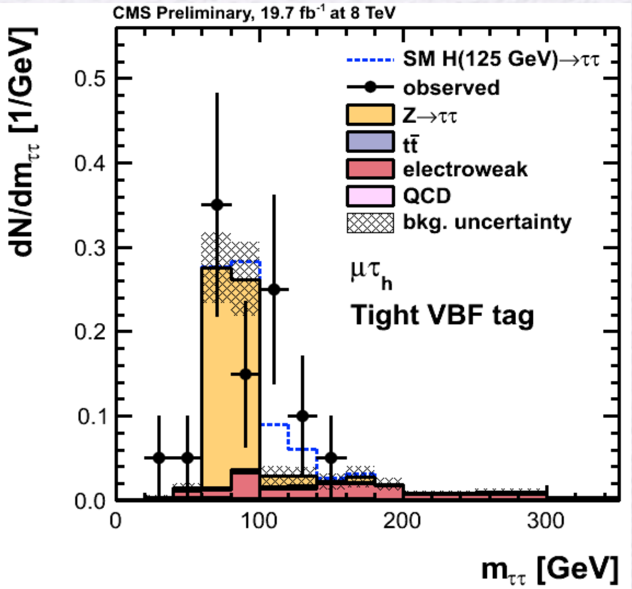
$p_t(\tau_h) > 45$ GeV
$p_t^{\tau\tau} > 100$ GeV

2-jet:
loose VBF tag



$M_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 3.5$

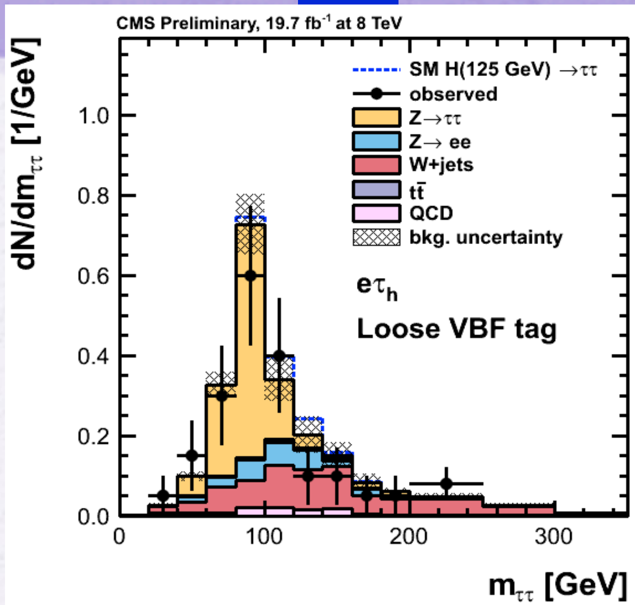
2-jet
tight VBF tag

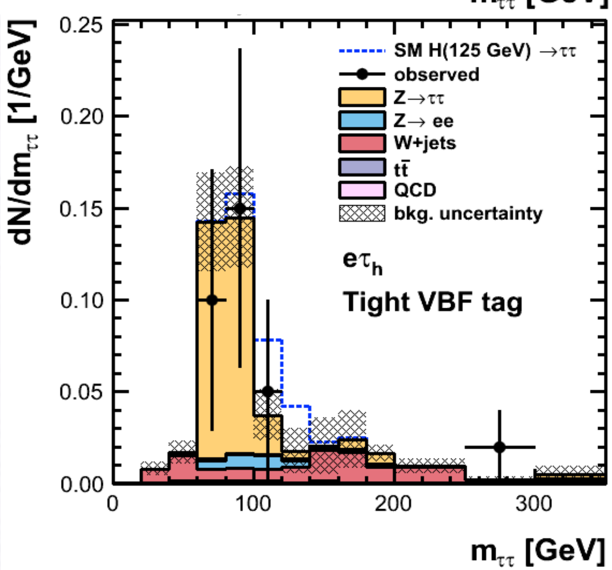


$M_{jj} > 700$ GeV, $|Dh_{jj}| > 4$
$p_t^{\tau\tau} > 100$ GeV

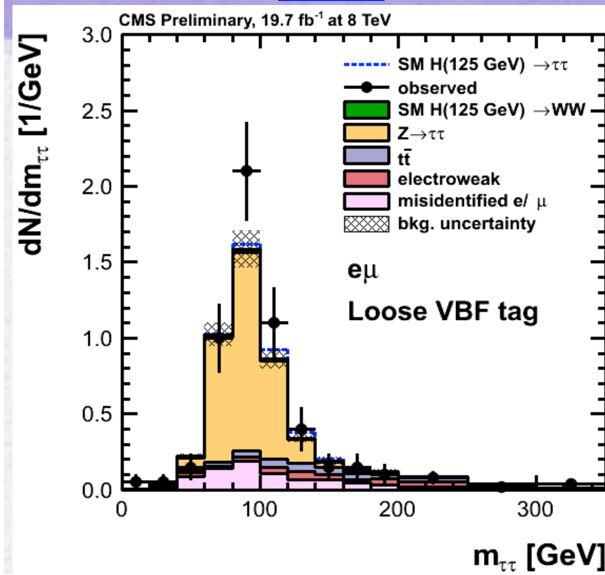
H→ττ: VBF tag

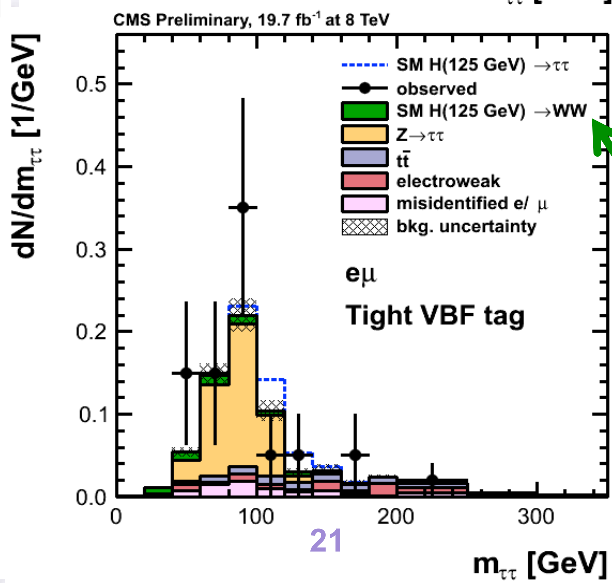
eτ



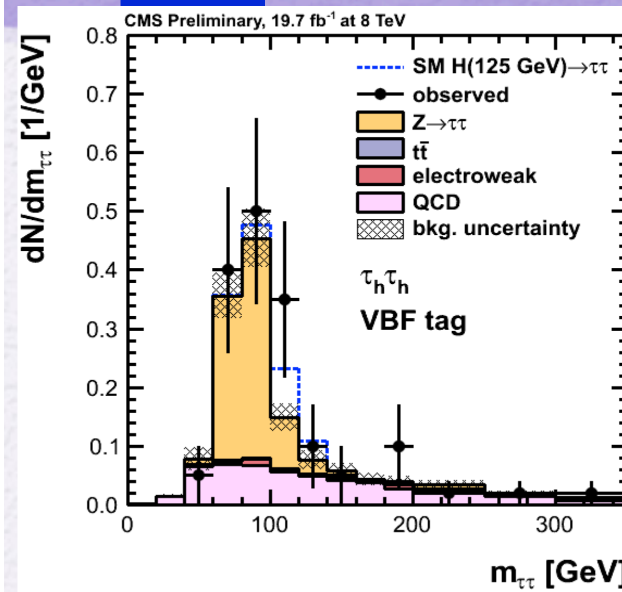


eμ





$\tau_h\tau_h$

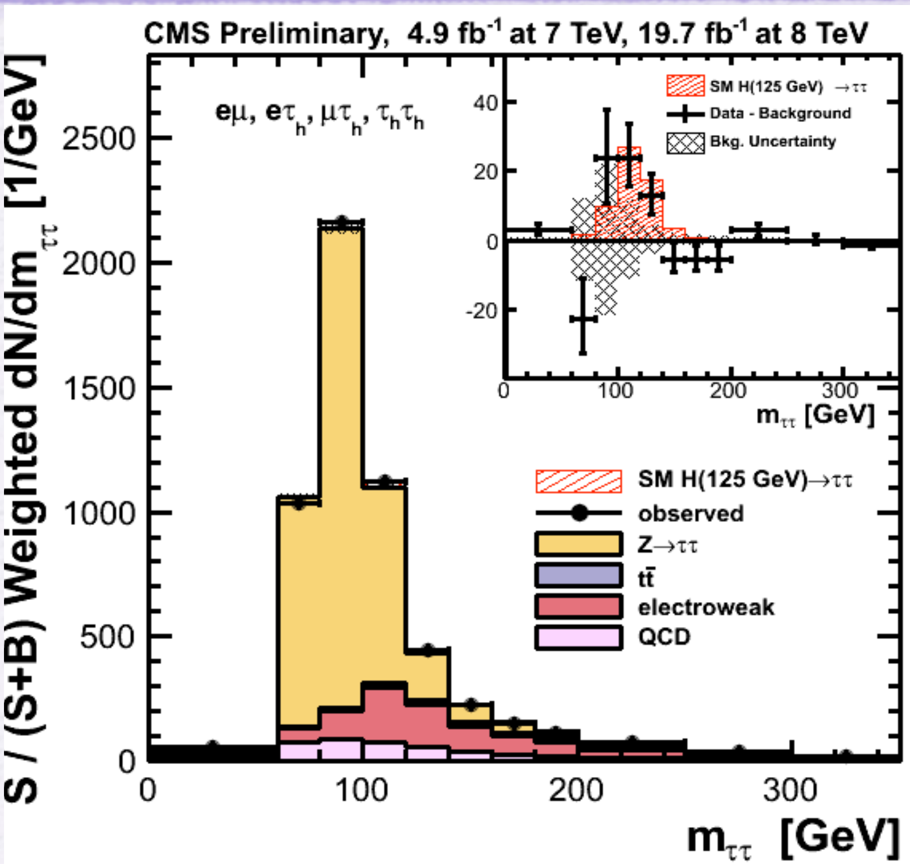


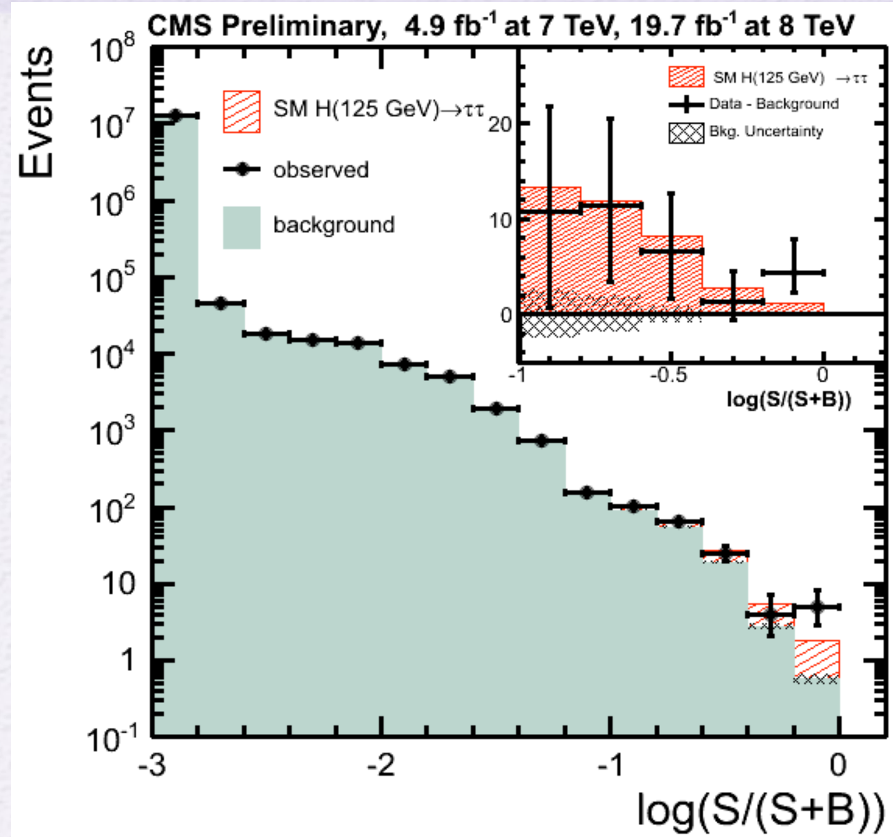
$\tau_h\tau_h$: no tight-VBF

eμ:
H→WW contribution!

H→WW is treated as background to probe fermionic decay contribution

H→ττ: Combined Mass

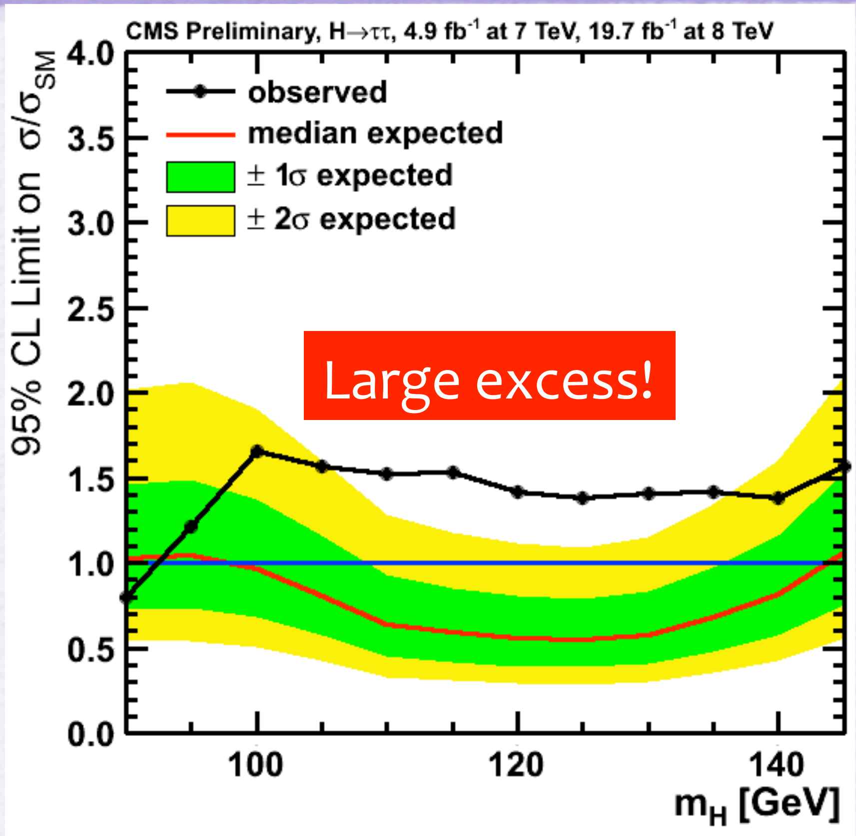


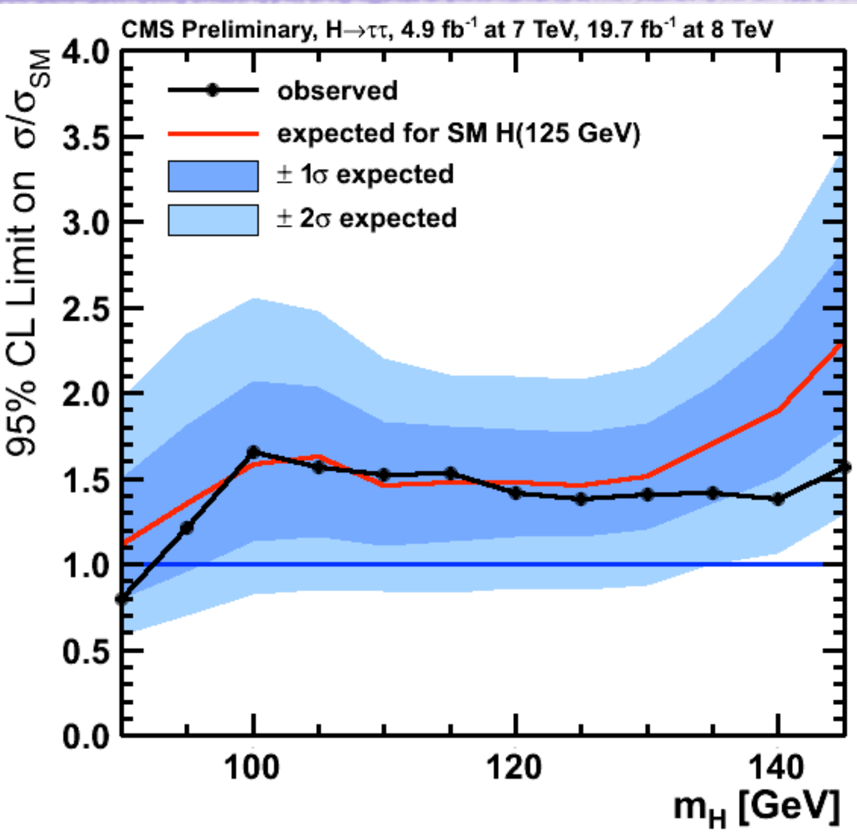


Weighted by S/(S+B) using 68% region around the $m_{\tau\tau}$ peak

Calculate S/(S+B) in every bin of the mass distributions of every event category and channel

H→ττ: 95% CL Upper Limits

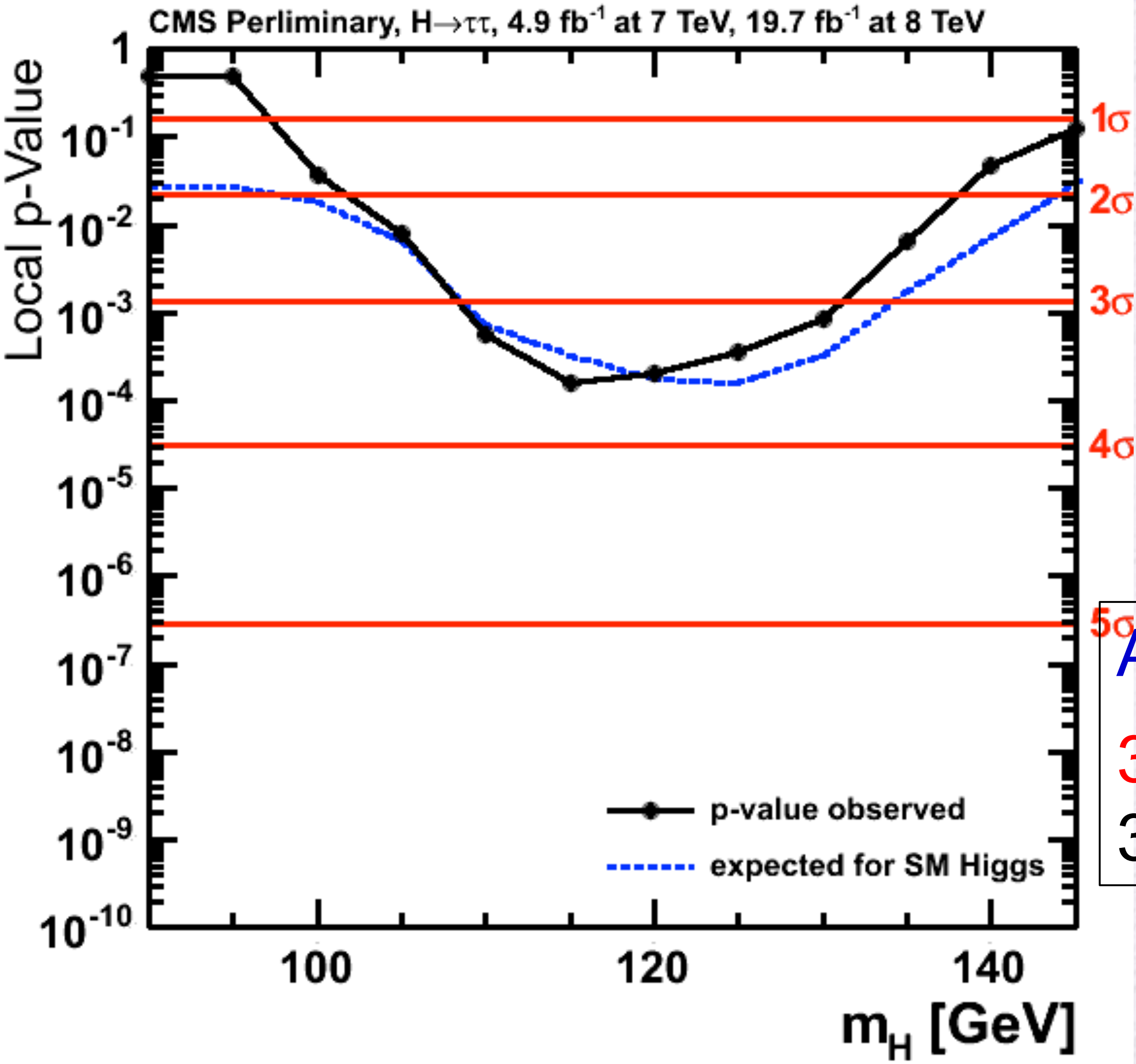




H→WW@125 is treated as background, motivated by the bosonic discovery

Compatible with a Standard Model Higgs boson signal @ 125 GeV

Evidence for a H→ττ signal!



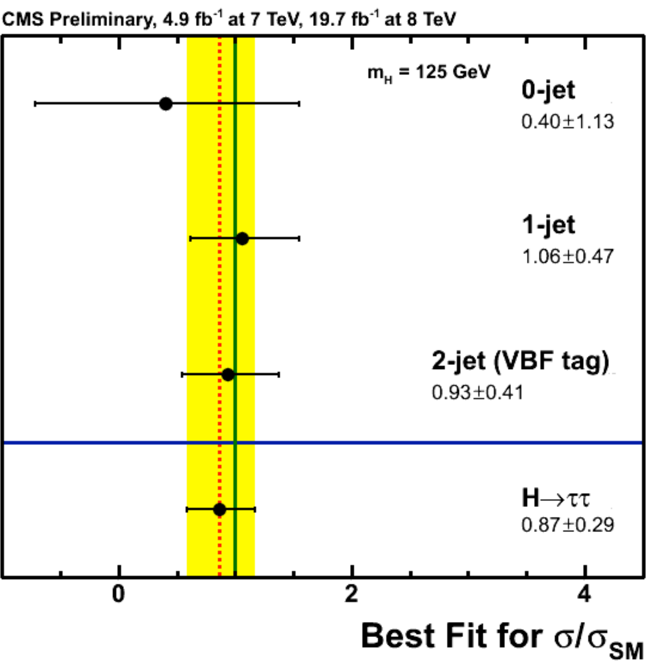
>3σ of H→ττ decays for M_H between 110 and 130 GeV

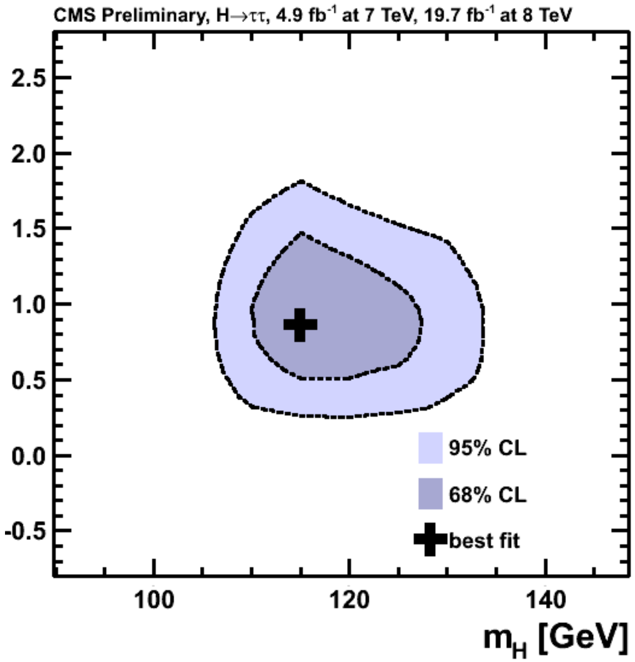
At m_H = 125 GeV:

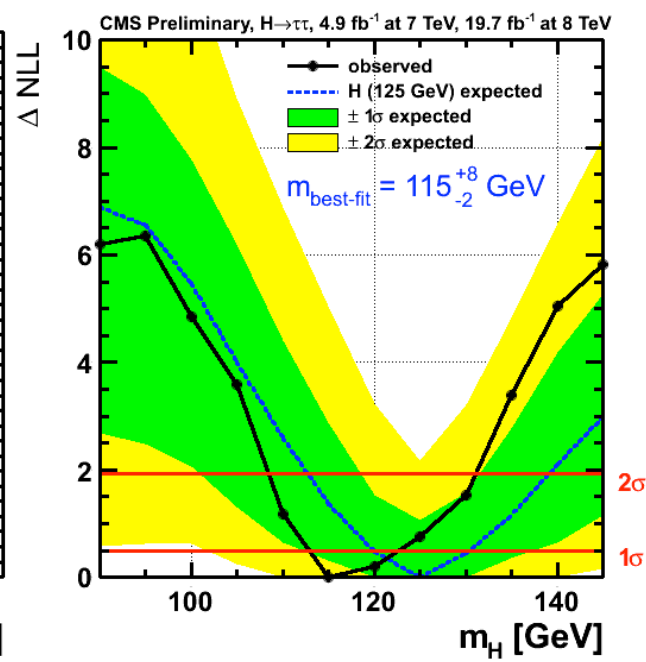
3.4s observed excess!

3.6s expected

H→ττ







$$m_{\text{best-fit}} = 115 + 8 - 2\,\text{GeV}$$

μ = 0.87 ± 0.29

$M_{\tau\tau}$ used for statistical interpretation

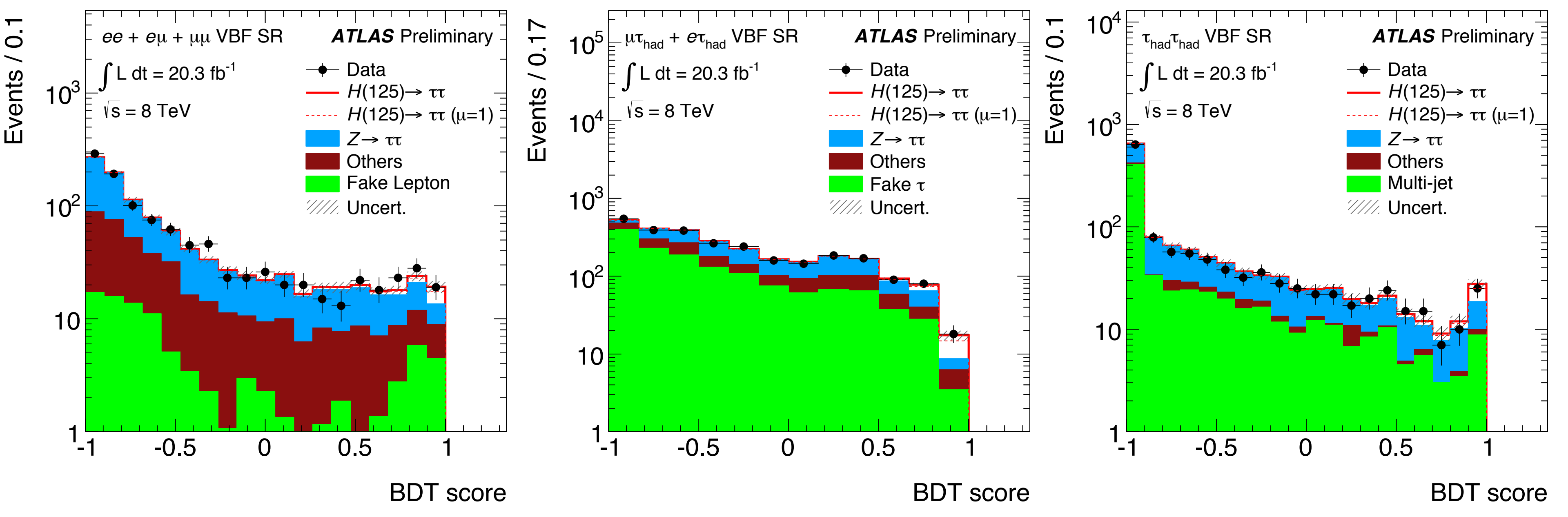
Mass scale systematic:

Lepton energy scale & MET: < 1%

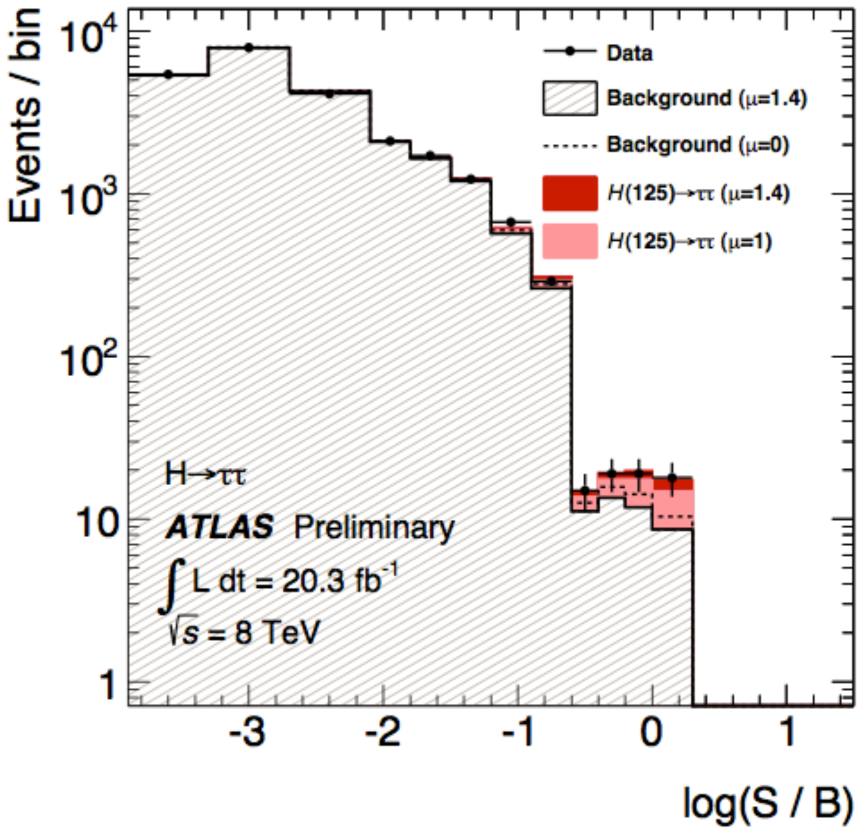
Tau energy scale < 2%

ATLAS H→ττ

- Design and perform multivariate analysis (based on BDT technique)
- Two main categories:VBF & Boosted
- Resonance and event topology as well as event activities as BDT input
- Fit BDT shape with signal+background templates
  - Simultaneous fit in 6 SR and 5 CR with common systematics NP's



BDT

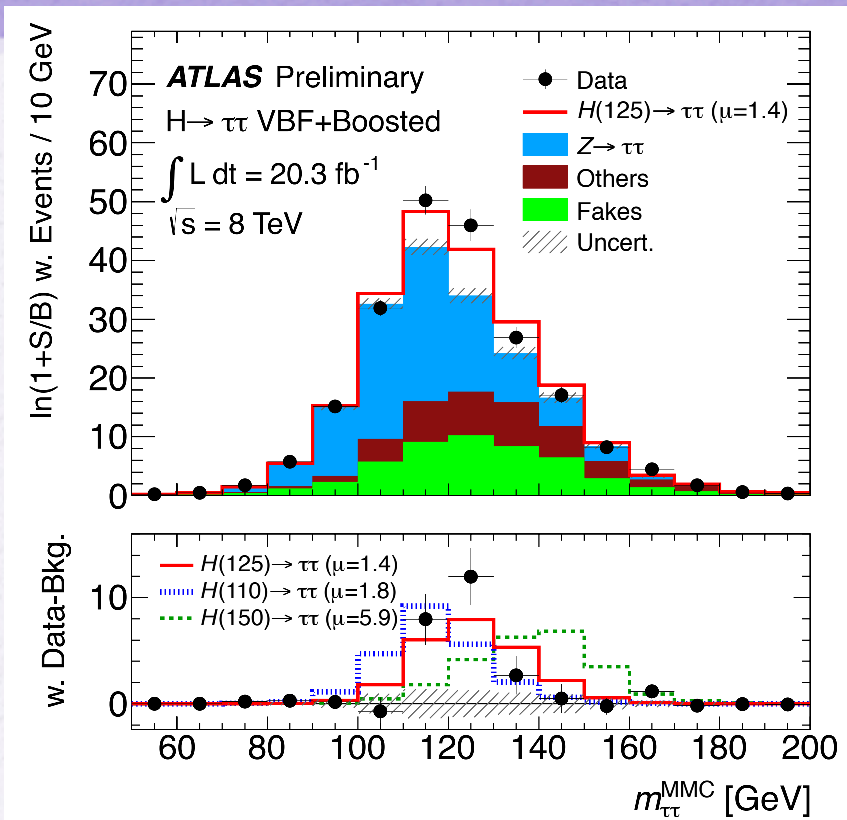


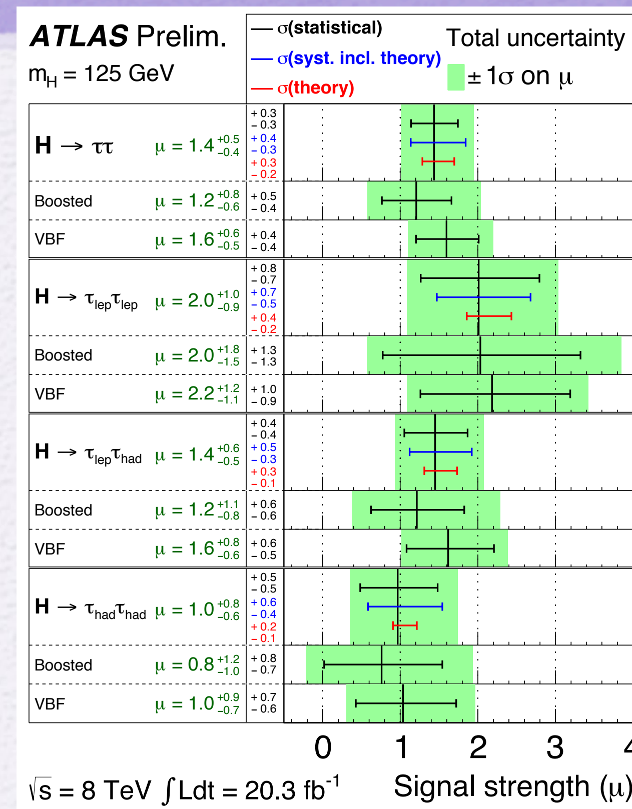
Numbers of events in highest BDT-score bin

		Lep-lep	Lep-had	Had-had
VBF	Signal	5.7±1.7	8.7±2.5	8.8±2.2
	Bckg	13.5±2.4	8.7±2.4	11.8±2.6
	Data	**19**	**18**	**19**
Boosted	Signal	2.6±0.8	8.0±2.5	3.6±1.1
	Bckg	20.2±1.8	32±4	11.2±1.9
	Data	20	34	15

- **ATLAS observes significant excess of data events in high S/B region**
  - Excess is observed in all three channels
  - **Expected** significance at M_H=125 GeV corresponds to **3.2 sigma**
  - **Observed** significance at M_H=125 GeV corresponds to **4.1 sigma**

ATLAS H→ττ results





- Each event is weighted by ln(1+S/B) for corresponding bin in BDT-score

  Excess of data events is consistent with presence of Higgs at 125 GeV

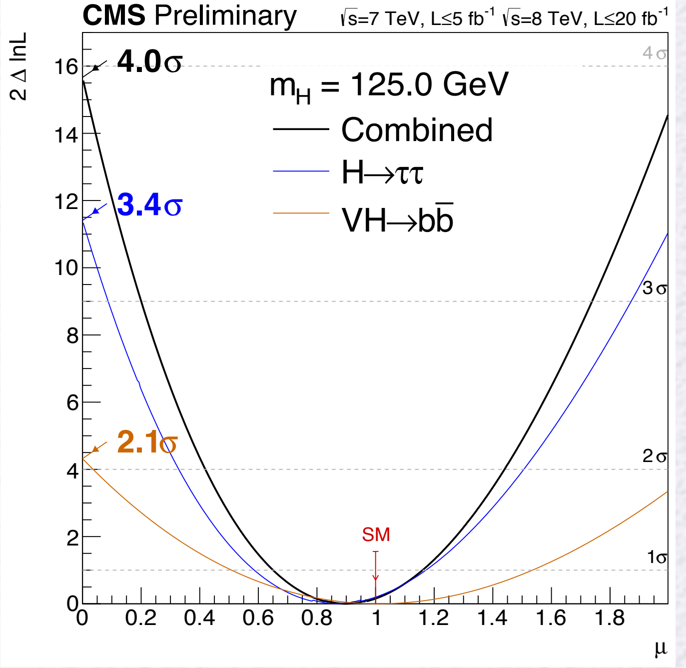
- Signals at MH=110, 125 and 150 GeV are shown at best fit μ; post--- fit background normalizations

Combination of SM $H \rightarrow \tau\tau$ and $H \rightarrow bb$ in CMS

H⟶ττ & H⟶bb: Combination @ 125 GeV

Preliminary

Channel M_H= 125 GeV	Significance		m
	Expected	Observed	
VH⟶bb	2.1 s	2.1s	1.0±0.5
H⟶ττ	3.6s	3.4s	0.87±0.29
Combination	4.2s	4.0s	0.90±0.26



4 σ: strong evidence of fermionic Higgs decays!

Summary

Latest LHC (CMS & ATLAS) results on fermionic Higgs properties have been presented

Direct evidence for Higgs couplings to the third-generation bottom-type fermions established

- ATLAS:
  - $H \rightarrow bb$: No sensitive yet
  - $H \rightarrow \tau\tau$: 4.1s (observed), 3.2s (expected)

- CMS:
  - $H \rightarrow \tau\tau$: 3.4s (observed), 3.6s (expected)
  - $H \rightarrow bb$: 2.1s (observed), 2.2s (expected)
  - $H \rightarrow \tau\tau + H \rightarrow bb$ combination: 4.0s (observed) 4.2s (expected)

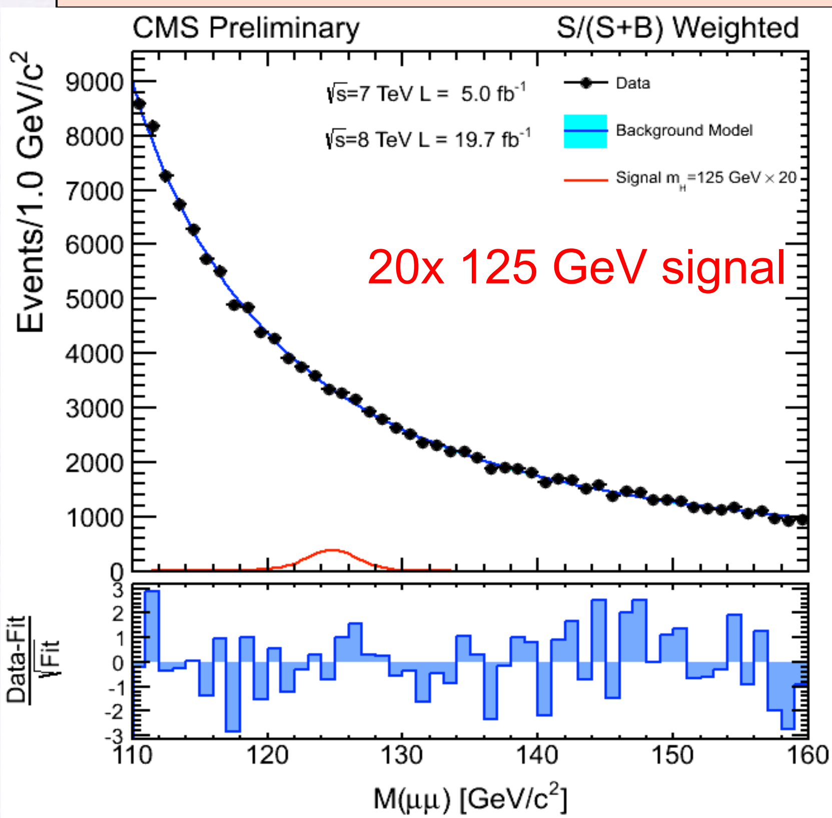
BACKUP

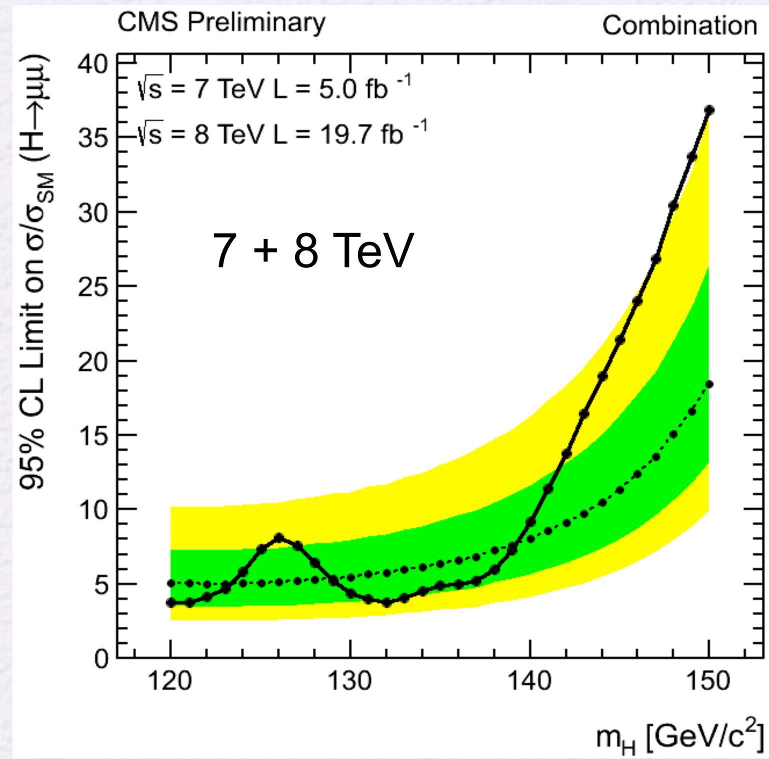
$H \rightarrow \mu\mu$ & $H \rightarrow ee$ search (test flavour non-universality)

H→mm search

Very small branching fraction: BR(H →μμ) = 2.2 x 10^{-4} at m_H = 125 GeV, but expected narrow peak on top of steep falling background from Z/g*→mm

Improve sensitivity: Different categories based on h^m, p_t(mm), jet multiplicity





s($M_{\mu\mu}$): 1.6 GeV (both m: h^m <0.8)
2.5 GeV (both m: 1.6< h^m <2.1)

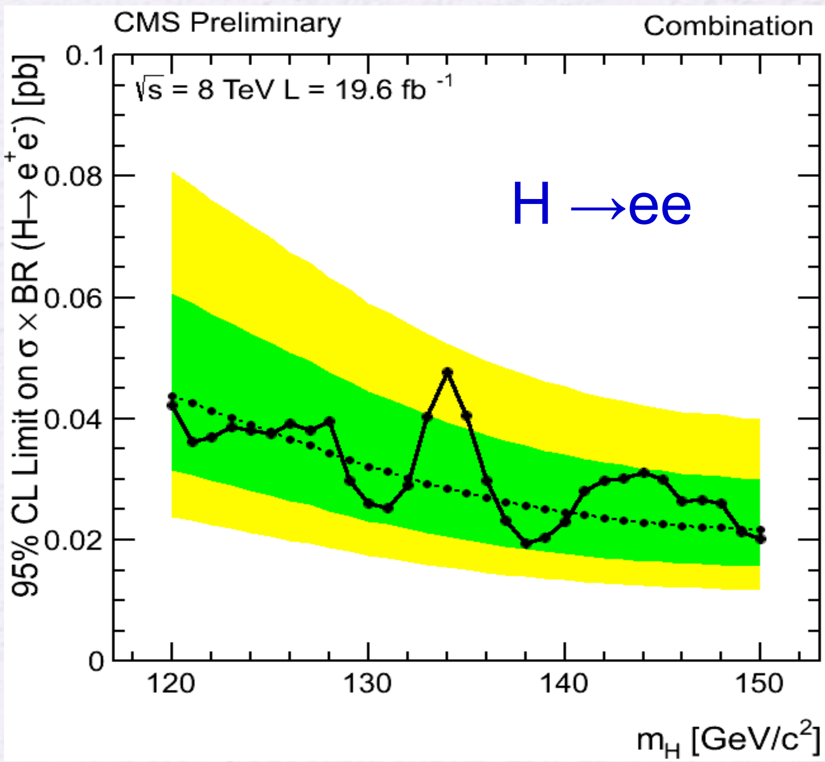
95% CL exclusion at m_H= 125 GeV:

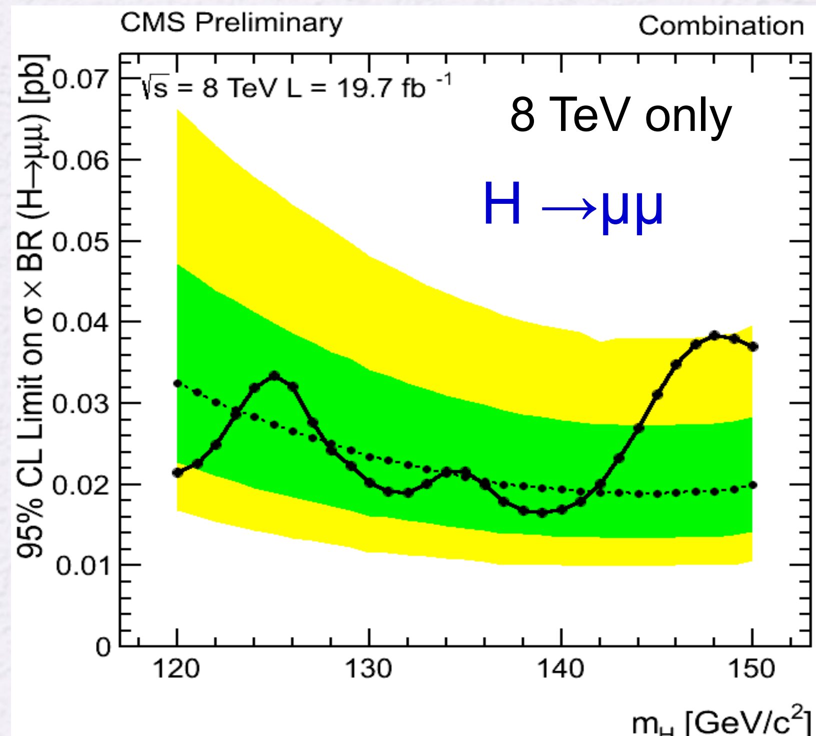
Observed limit: 7.4
Expected limit: 5.1

H→ee search

Very rare process: BR(H →ee) ~ $2x10^{-5}$ *BR(H →μμ)

Improve sensitivity: Different categories based on h^e and di-jet tag





95% CL observed upper limit s*BR at m_H= 125 GeV:

H→ee: 0.038 pb
H→mm: 0.034 pb

BR(H→ee) <0.0017

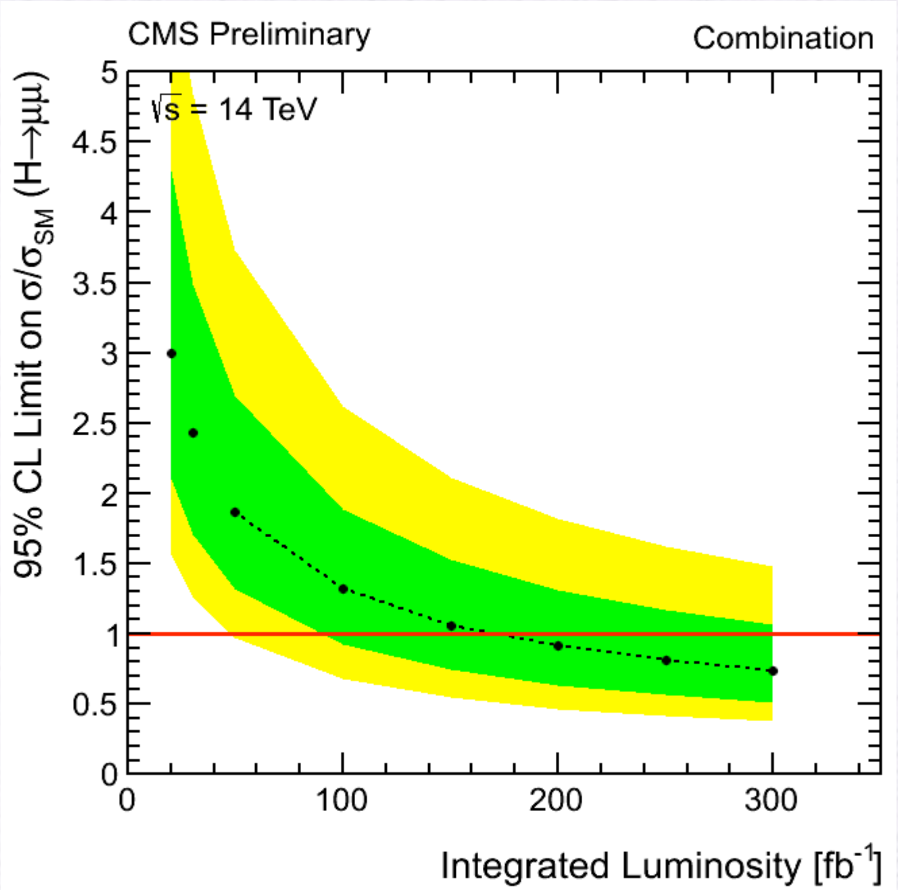
Evidence for flavour non-universality

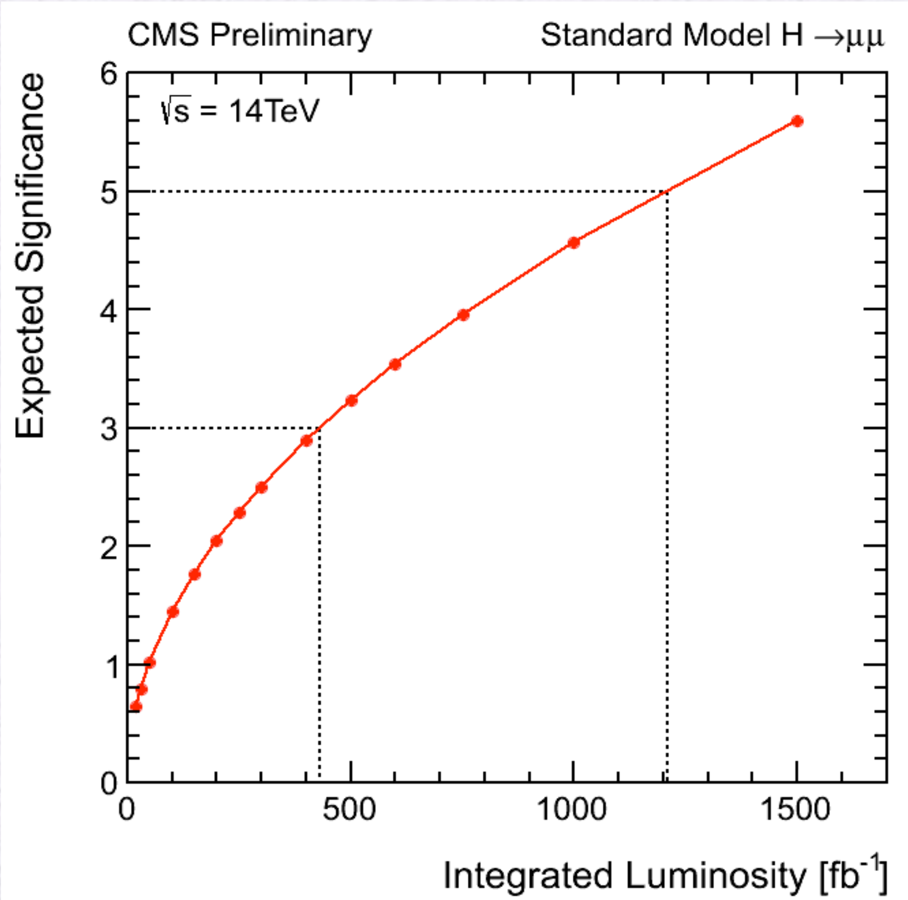
H→μμ search: projections @14 TeV

Looking ahead …

5 s discovery with ~ 1200 fb^{-1} @ 14 TeV

Measure muon coupling with 8% precision with ~3 ab^{-1} @14 TeV





ttH search

(search for direct evidence to top quark coupling)

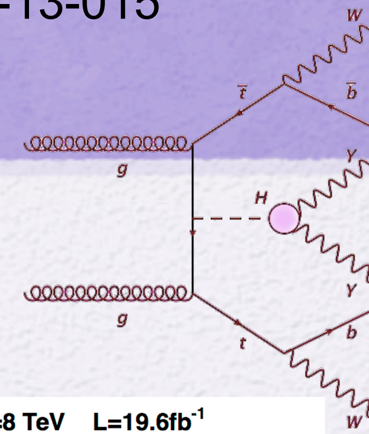
ttH, H→gg

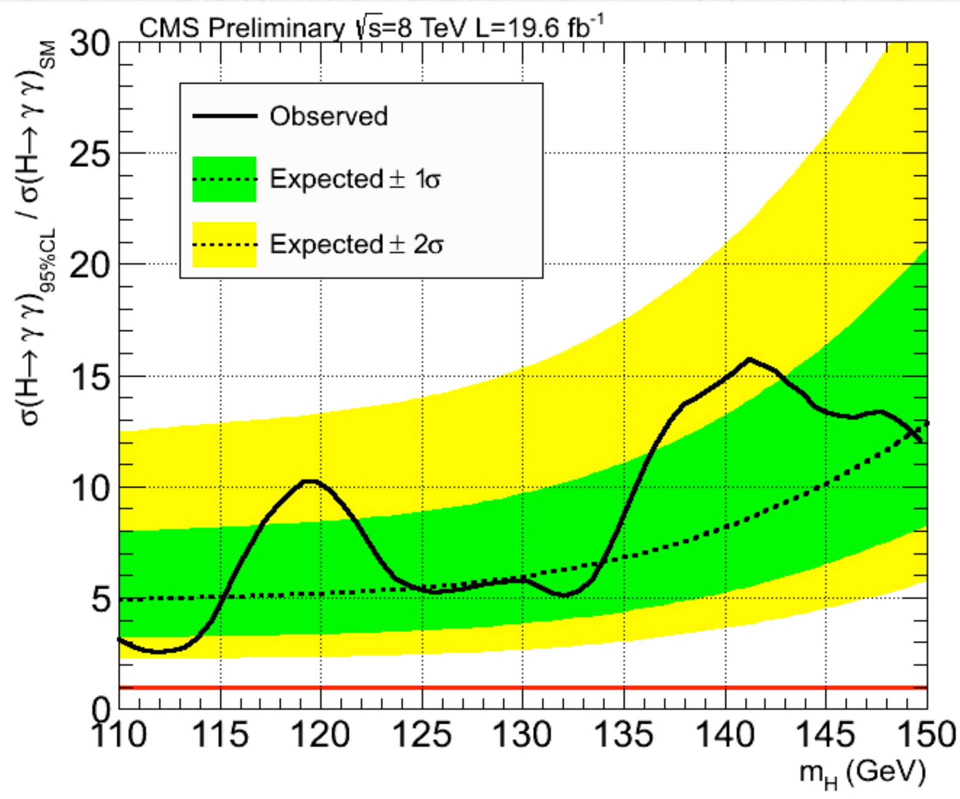
HIG-13-015

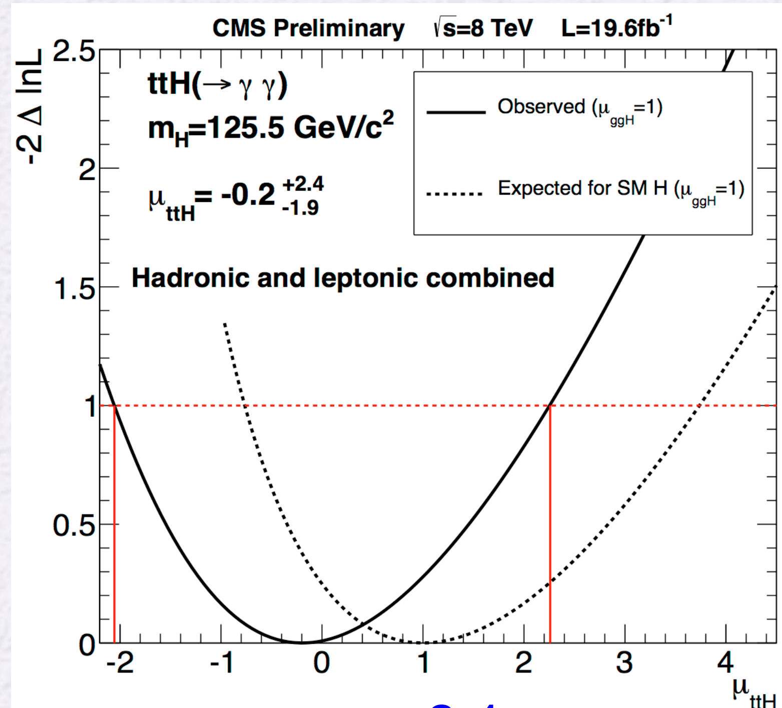
Select events with two photons, large number of jets and at least one b-tag

Search for mass peak in di-photon spectrum as standard H→gg analysis

Two channels: fully hadronic and leptonic







$\mu_{ttH} = -0.2^{+2.4}_{-1.9}$

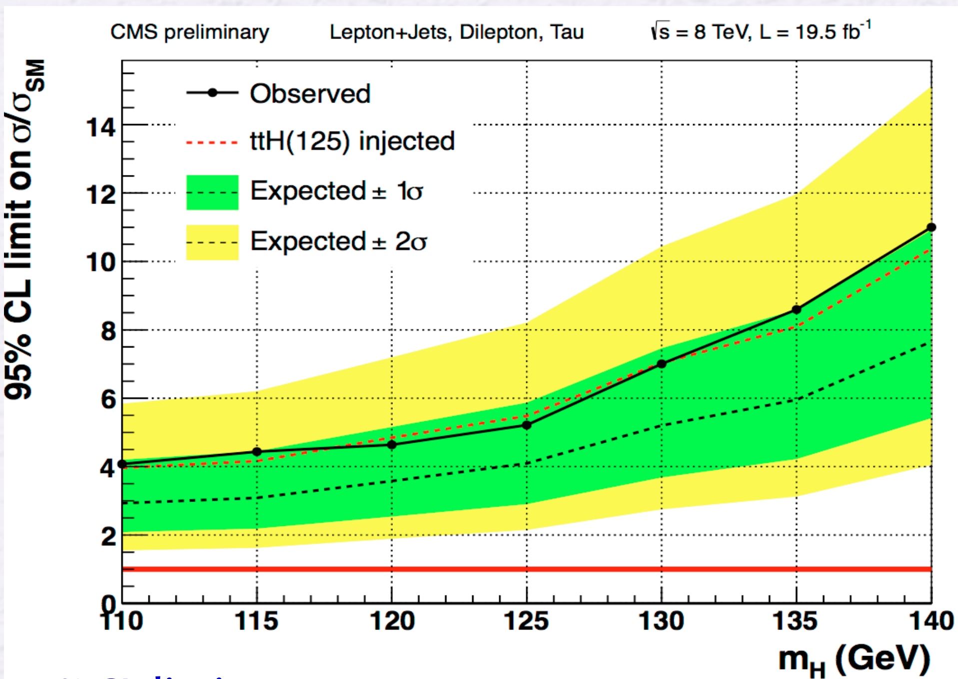
ttH, H→bb and H→ττ

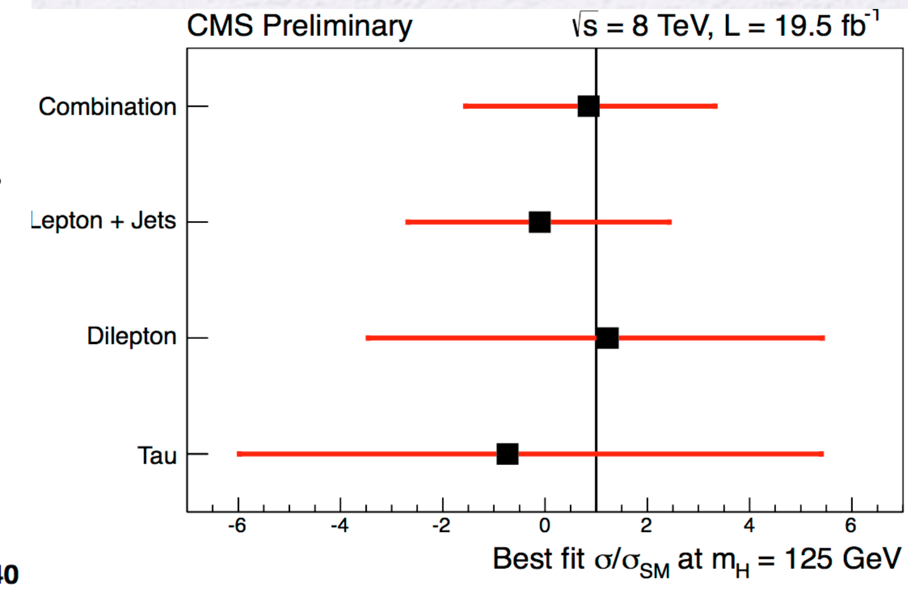
HIG-13-019

Semileptonic and dilepton tt decays with H→bb

- ttH→lνjjbb and ttH→lνlνbb
- H→ττ

Shape analysis using MVA with simultaneous fit of different jet and b-tag multiplicities





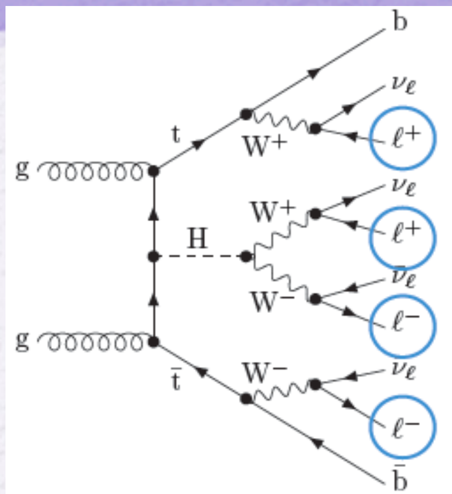
95% CL limit on m at m_H= 125 GeV

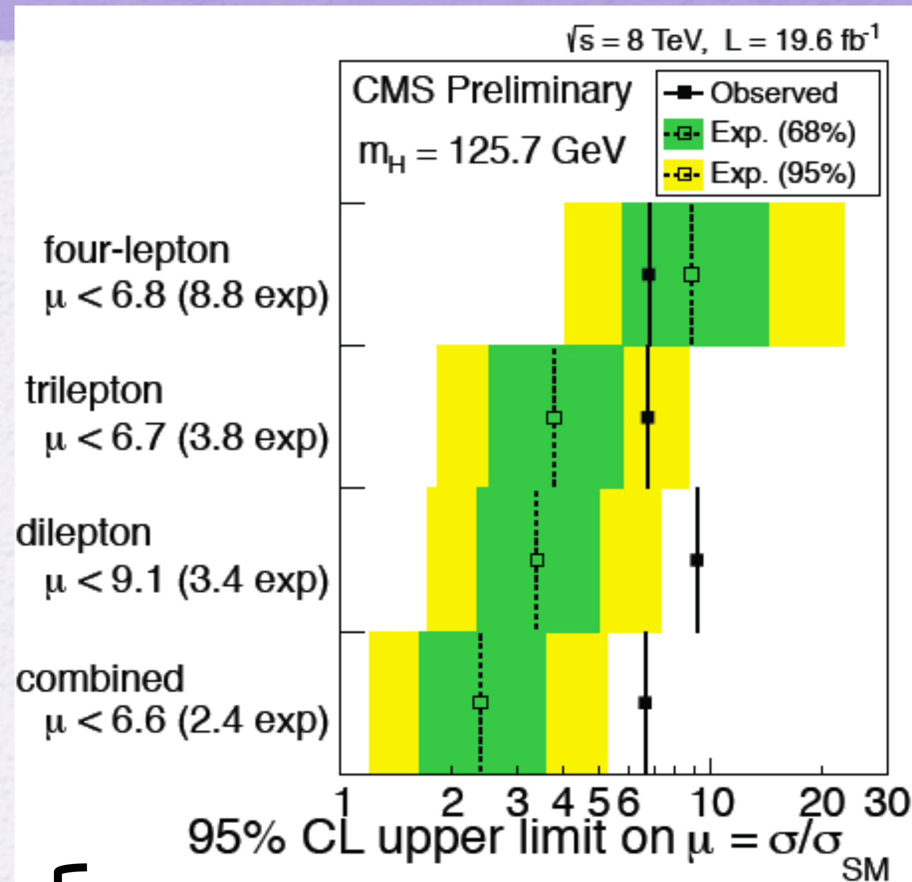
Observed: 5.2 Expected: 4.1

ttH: multi-lepton search

HIG-13-020

Target ttH production in leptonic (e, m) final states from H→tt, ZZ^*, WW^*





4 leptons + b-jets (other than H→ZZ→4l, no resonant Z→ll)

3 leptons + b-jets (no resonant Z→ll)

2 same-sign leptons (ee, em, mm) + b-jets

95% CL limit on m at m_H= 125 GeV

observed: 6.6

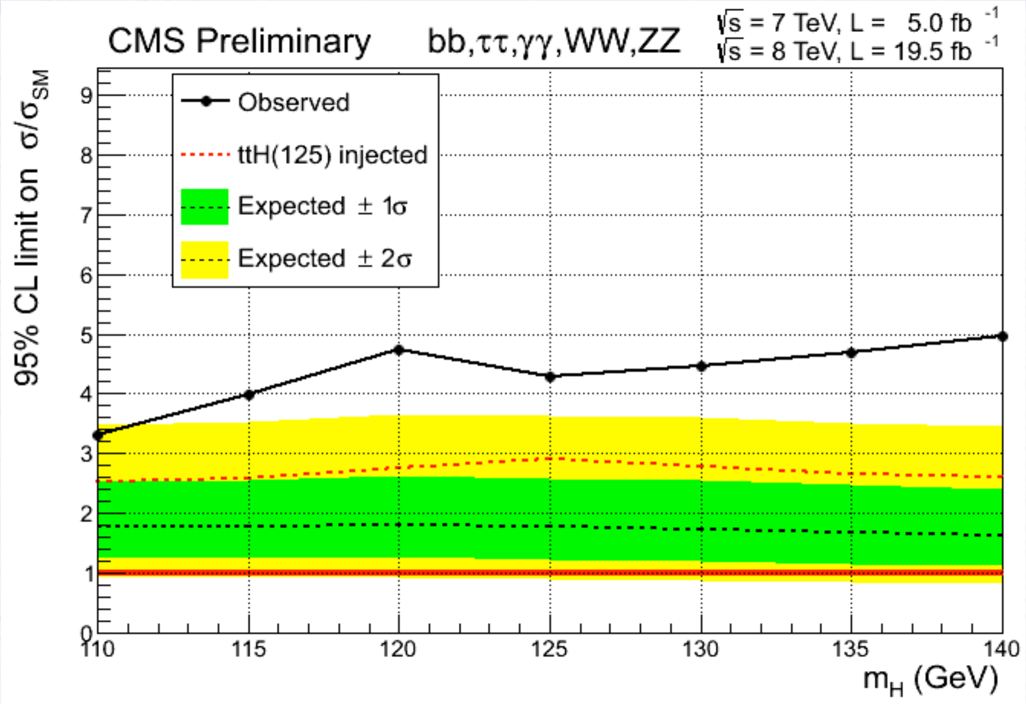
expected: 2.4 (in absence of ttH signal)
3.5 (with SM ttH production)

Excess mainly comes from SS di-muon channel

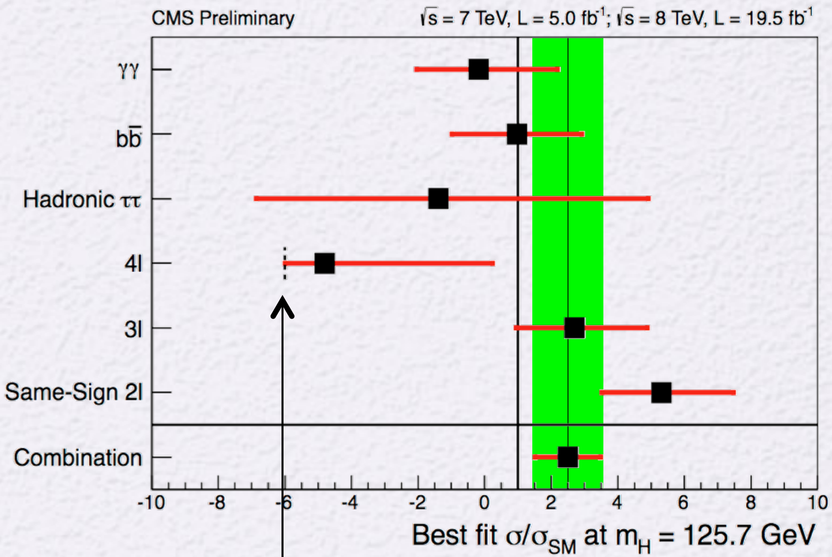
ttH search: combination

gg, bb, tt, multi-lepton channels combined

ttHCombinationTWiki



Best fit of signal strength



Expected signal-plus-background event yield must not be negative

95% CL limit on m
at m_H= 125 GeV

Observed limit: 4.3
Expected limit: 2.9

$$\mu = \frac{\sigma}{\sigma_{SM}} = 2.5^{+1.1}_{-1.0}$$

Direct hint of the Higgs coupling to top quarks

H→tt: systematic uncertainties

Experimental uncertainties

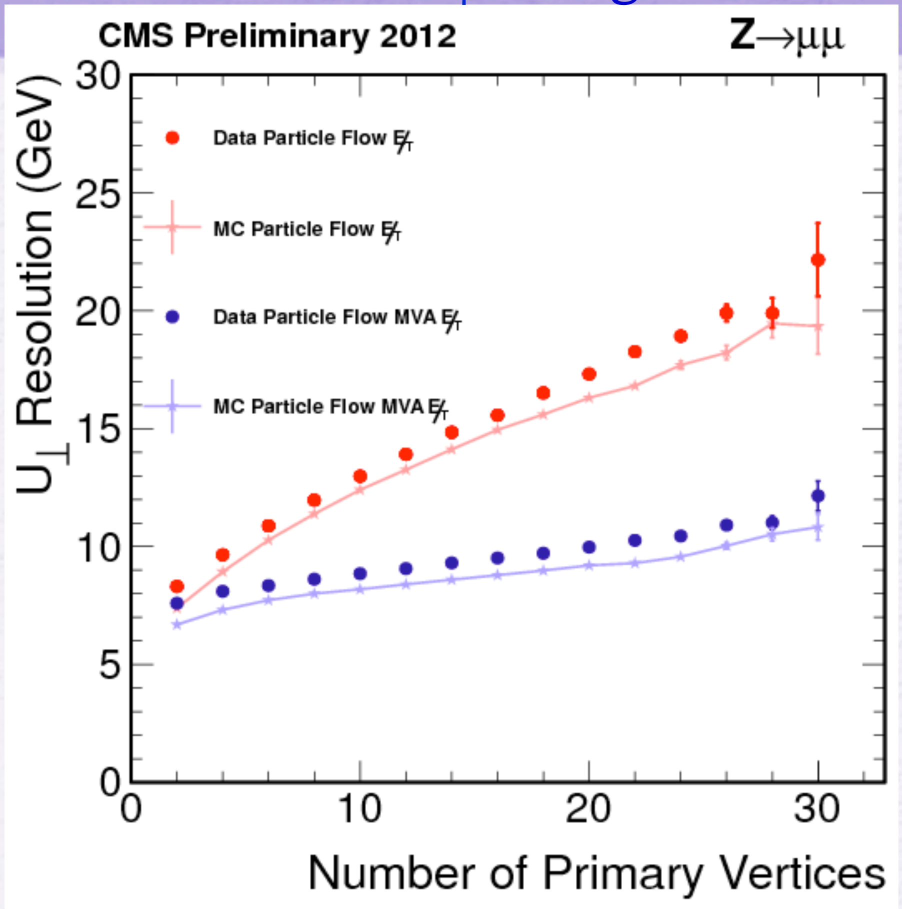
Uncertainty	Affected samples	Change in acceptance
Tau energy scale	signal & sim. backgrounds	shape
Tau ID & trigger	signal & sim. backgrounds	8–19%
e misidentified as τ_h	$Z \to ee$	20–74%
μ misidentified as τ_h	$Z \to \mu\mu$	30%
Jet misidentified as τ_h	Z boson plus jets	20–80%
Electron ID & trigger	signal & sim. backgrounds	2–6%
Muon ID & trigger	signal & sim. backgrounds	2–4%
Electron energy scale	signal & sim. backgrounds	shape
Jet energy scale	signal & sim. backgrounds	0–20%
E_T^{miss} scale	signal & sim. backgrounds	1–12%
$\varepsilon_{b\text{-tag}}$ b jets	signal & sim. backgrounds	0–8%
$\varepsilon_{b\text{-tag}}$ light-flavoured jets	signal & sim. backgrounds	1–3%
Norm. Z production	Z	3%
$Z \to \tau\tau$ category	$Z \to \tau\tau$	2–14%
Norm. W+jets	W+jets	10–100%
Norm. $t\bar{t}$	$t\bar{t}$	8–35%
Norm. diboson	diboson	15–45%
Norm. QCD multijet	QCD multijet	6–70%
Shape QCD multijet	QCD multijet	shape
Luminosity 7 TeV (8 TeV)	signal & sim. backgrounds	2.2% (2.6%)

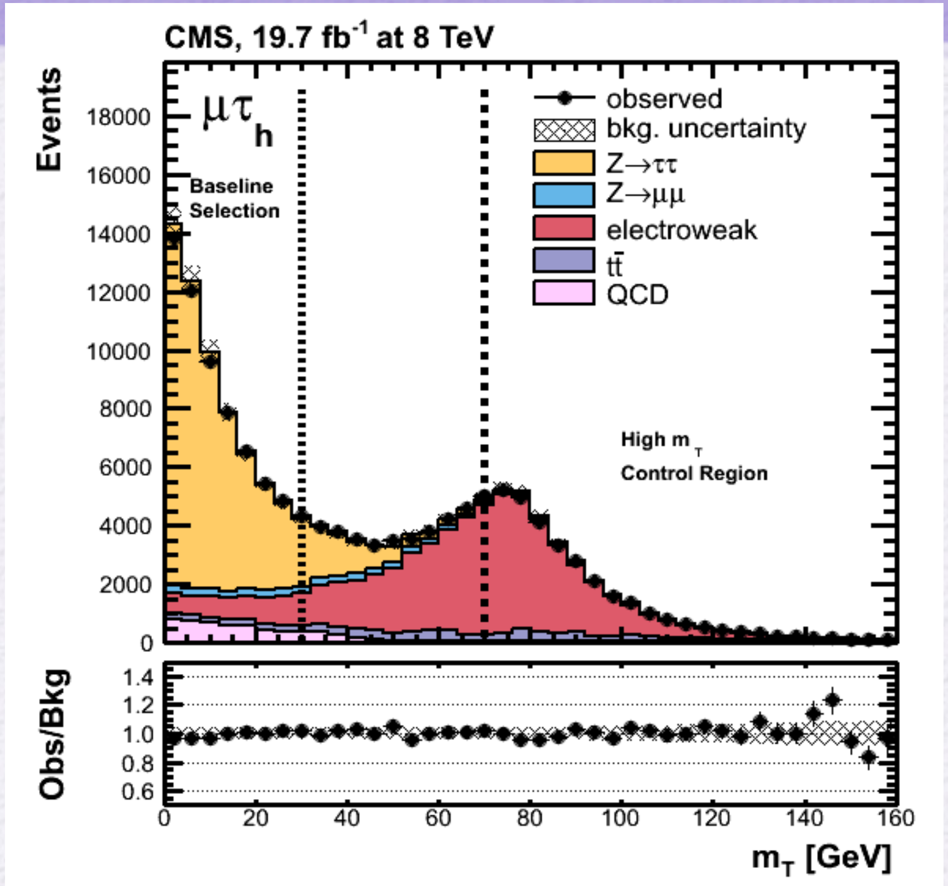
Background estimation

- t energy scale uncertainty: changes expected m value by less than 4%
  Ignoring t energy scale uncertainty has an effect of ~ 40% in the m uncertaint
- 0-jet category allows to constrain backgrounds (eg. peaking Z→ee, Z→mm)

H⟶tt: control of W+jet background

Multivariate E_T^{miss} regression





E_T^{miss}: significant improvement in resolution and dependence on pileup

Crucial for H→ττ analysis: $m_{\tau\tau}$ reconstruction and separation of signal from W+jets background using $m_T(m, E_T^{miss})$ selections

Miscellanea

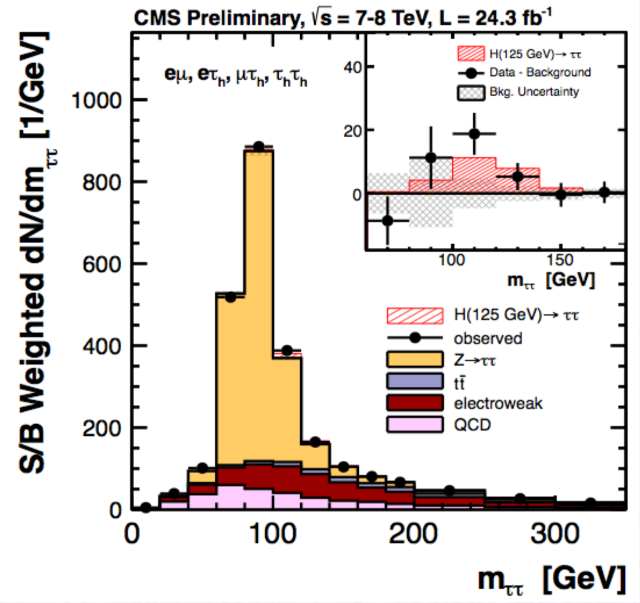
H→tt: Moriond 2013

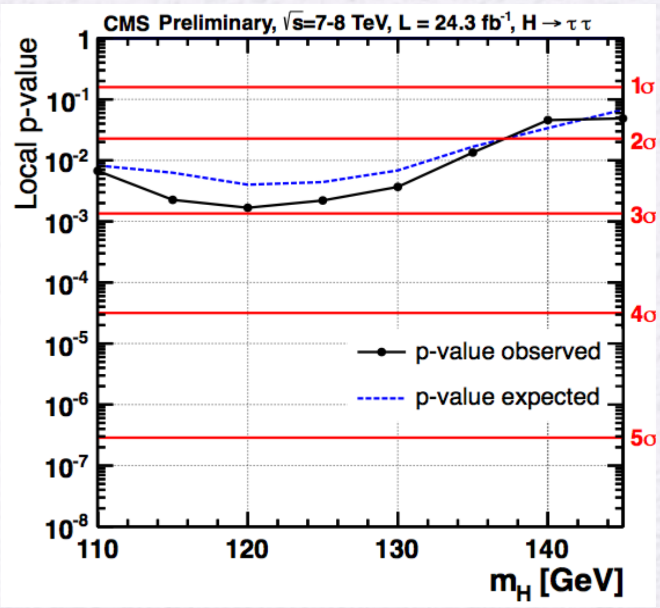
Analysis of 5 channels: $mt_{h,}$ et_h, t_ht_h, em, mm

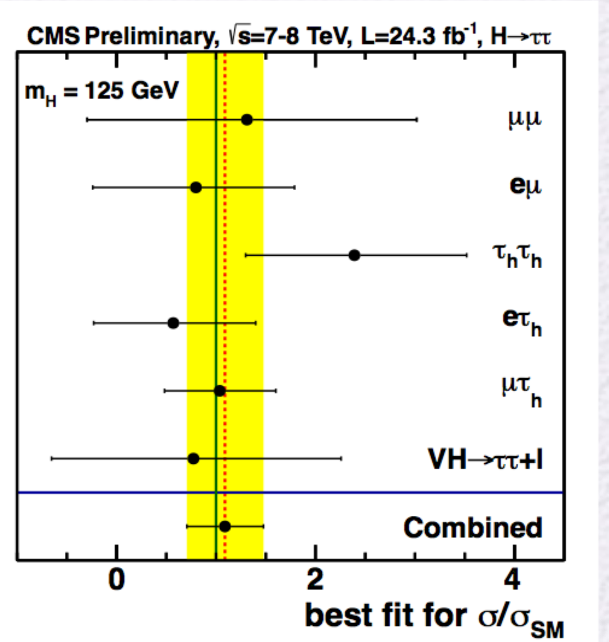
Maximum excess 2.93σ at m_H = 120 GeV

- 2.85σ at m_H = 125 GeV (expected 2.63σ)

Signal strength: $\mu = s/s_{SM} = 1.1 \pm 0.4$





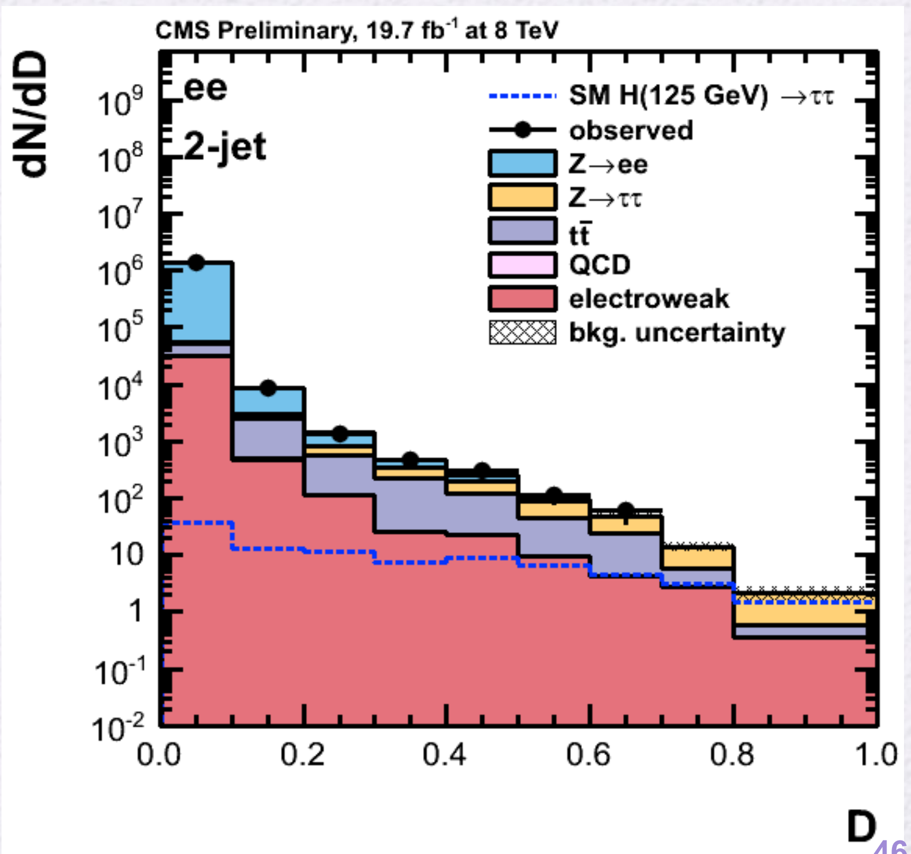


H→tt VBF tag: ee, mm

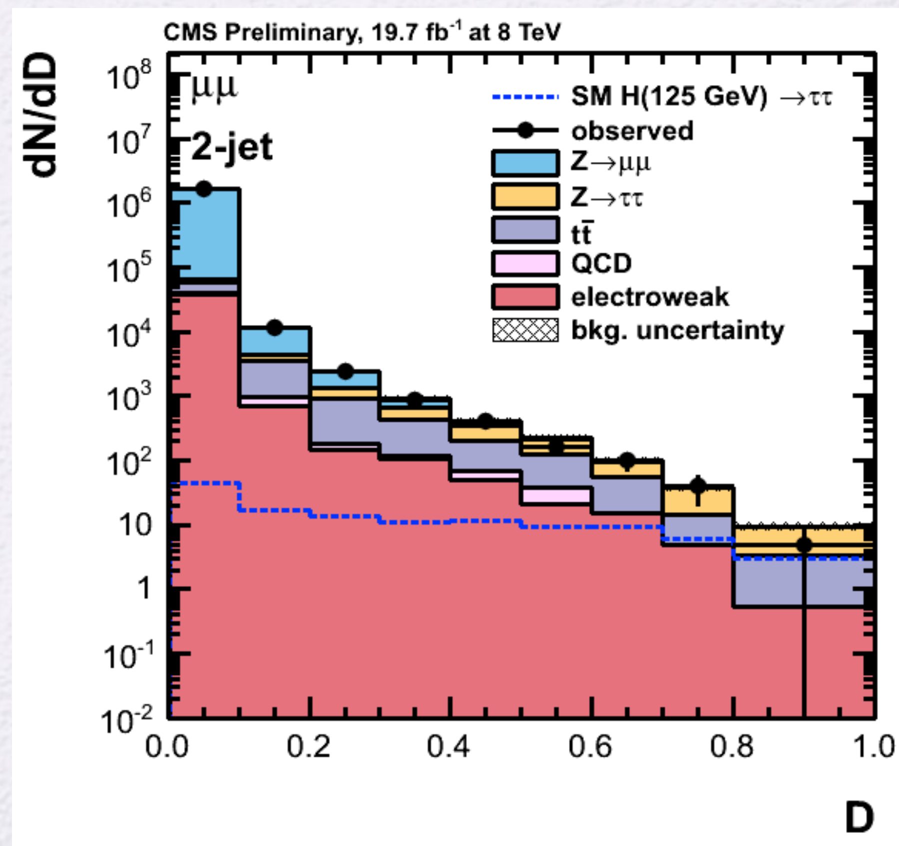
Final discriminant D used for statistical analysis derived from two BDTs

- BDT1 trained to separate di-tau events from dominant Z→ee/μμ decays
- BDT2 trained to separate H→ττ from Z→ττ
  - Two separate training for 0/1-jet and VBF categories
  - Trained with all Higgs signals at different masses assuming SM cross sections

H→tt→ee+4n



H→tt→mm+4n



H→tt: Theoretical uncertainties

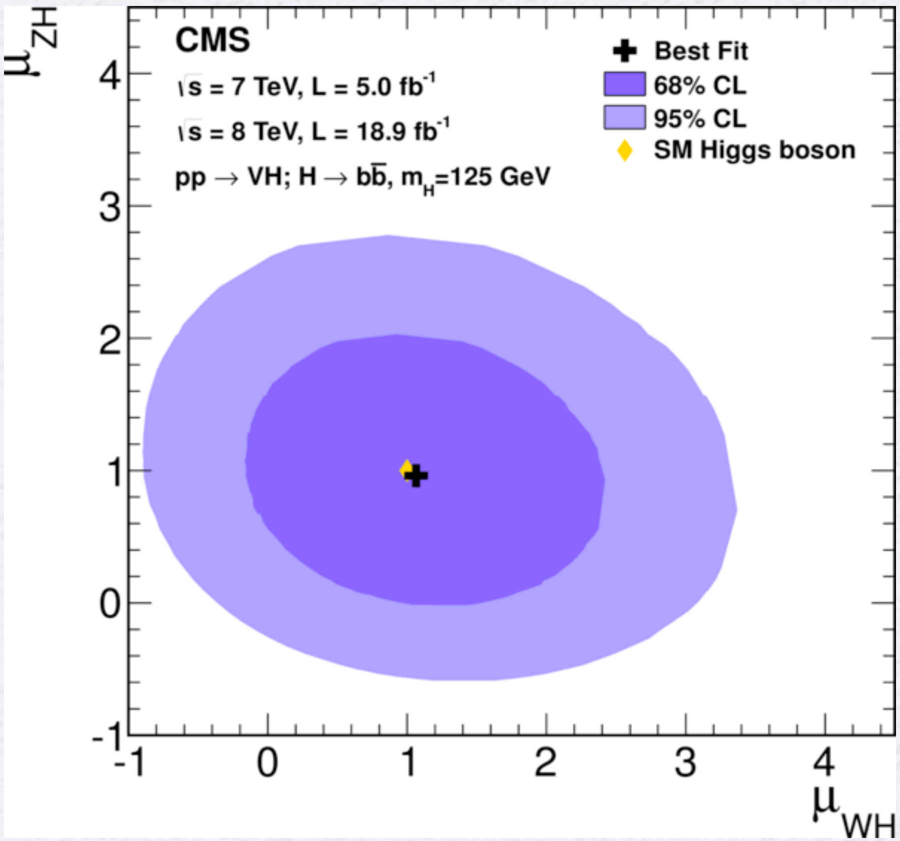
Uncertainty	Affected samples	Change in acceptance
PDF (qq)	signal & sim. backgrounds	4%
PDF (gg)	signal & sim. backgrounds	10%
Scale variation	signal	3–41%
Underlying event & parton shower	signal	2–10%
Limited number of events	all	bin-by-bin

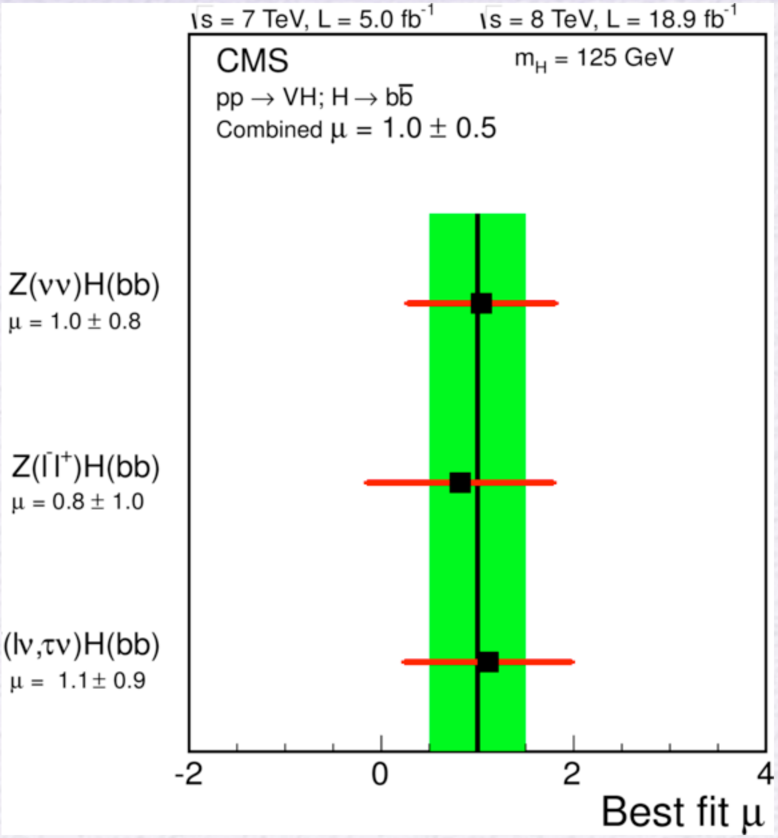
Uncertainty on signal acceptance in each category due to:

- PDF: take envelope of variation from CT10, MSTW and NNPDF sets
- Scale μ_F and μ_R: applied on total cross section and as a modified p_t spectrum
- Parton shower modeling: difference in acceptance between CMS (Z2*) and ATLAS (AUET2) tunes
- p_T Matching: vary Powheg threshold for the additional NLO jet
- ggH MC Comparison: compare default Powheg NLO to Madgraph, Powheg+MINLO and aMC@NLO

Re-weight Higgs p_T to NNLO Hres distribution in gluon-fusion samples
→Uncertainty covered by shape systematic on signal templates

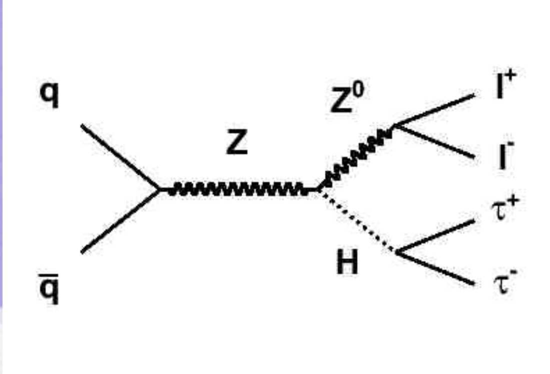
H→bb associated production: signal strength



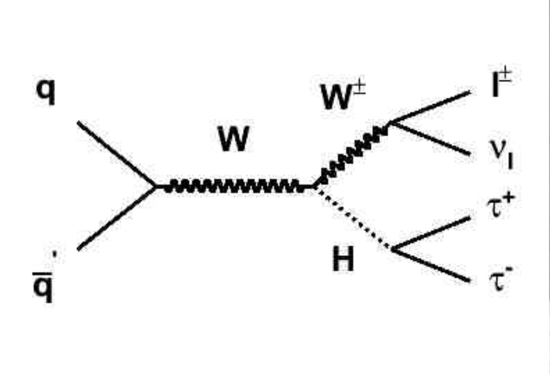


Signal strength and couplings consistent with SM expectations

Signal strength of excess: m=1.0±0.5

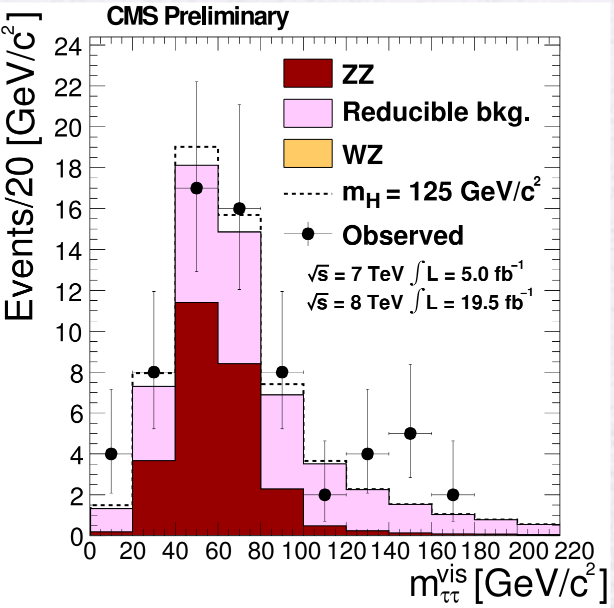


$VH \rightarrow V\tau\tau$ (Moriond)

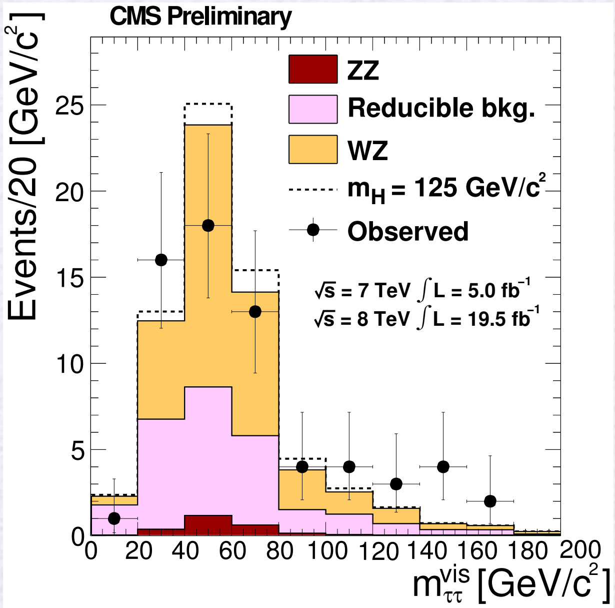


- Reducible BG: QCD,W/Z+jets, ttbar, … : Estimated from data using fake rate method
- Irreducible BG: WZ for WH and ZZ for ZH: Estimated from MC
- Further topological cuts to suppress large backgrounds

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



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



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