
CMS Results On Higgs Boson
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Higgs Production & Decay Processes Studied

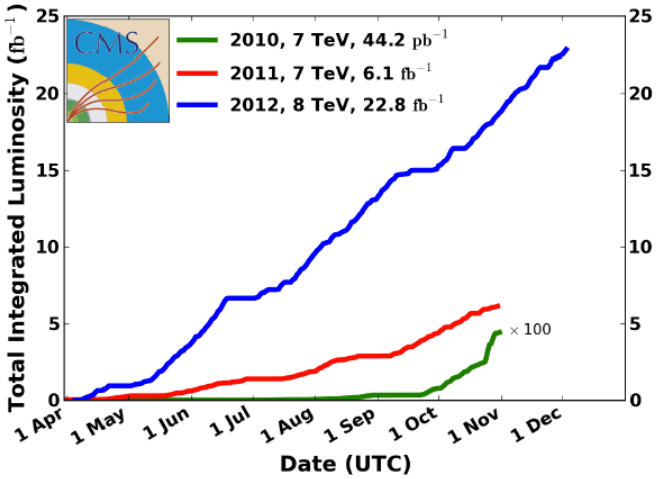
CMS

Results public In progress Forget it

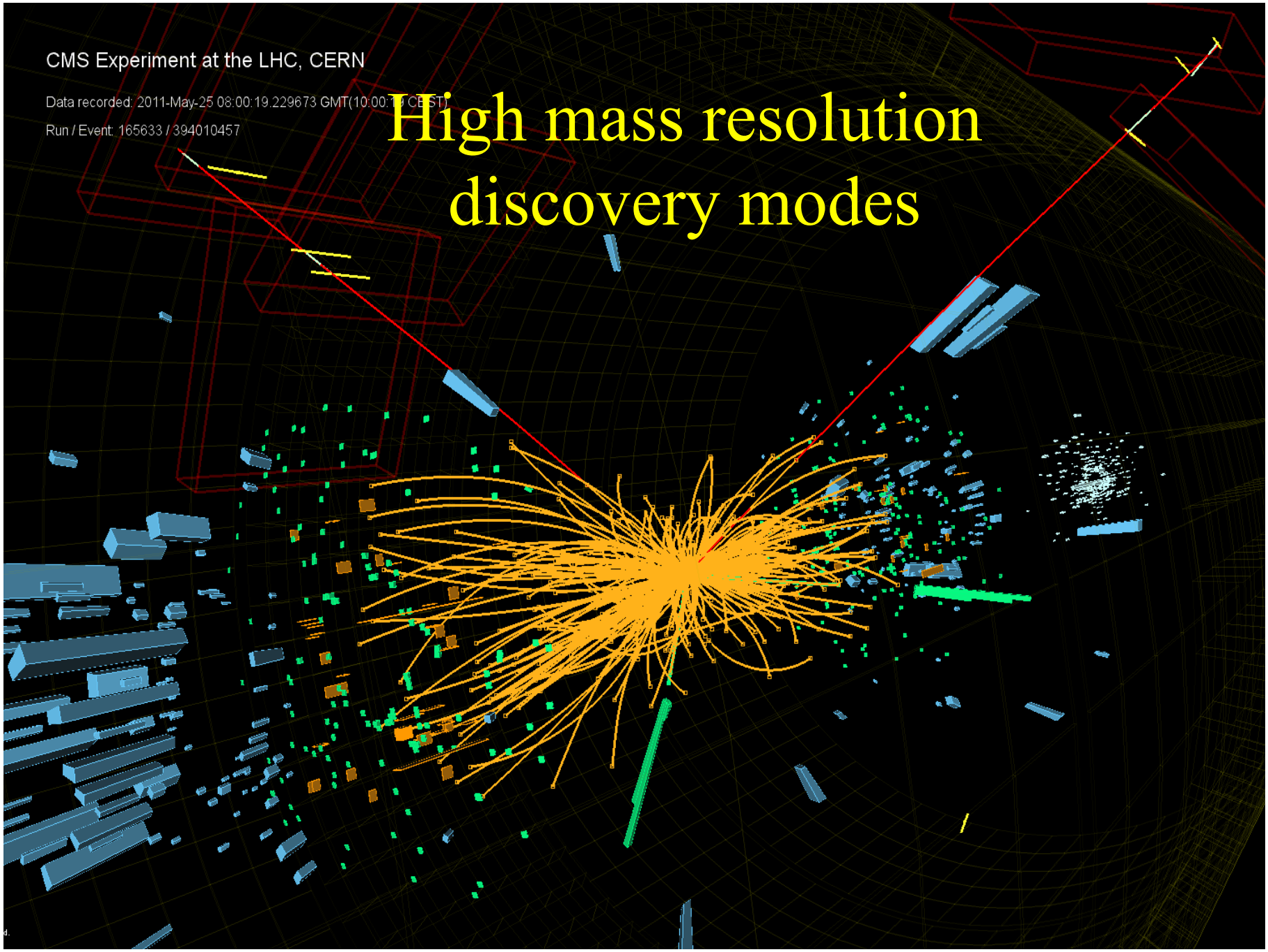
Mode	Untagged	VBF	VH	ttH
H → γγ				
H → ZZ				
H → WW				
H →bb				
H→ττ				
H → Z γ				
H → μμ				
H→ Invisible				

https://twiki.cern.ch/twiki/bin/view/CMSPublicPhysicsResultsHIG

Main Decay Channels At A Glance



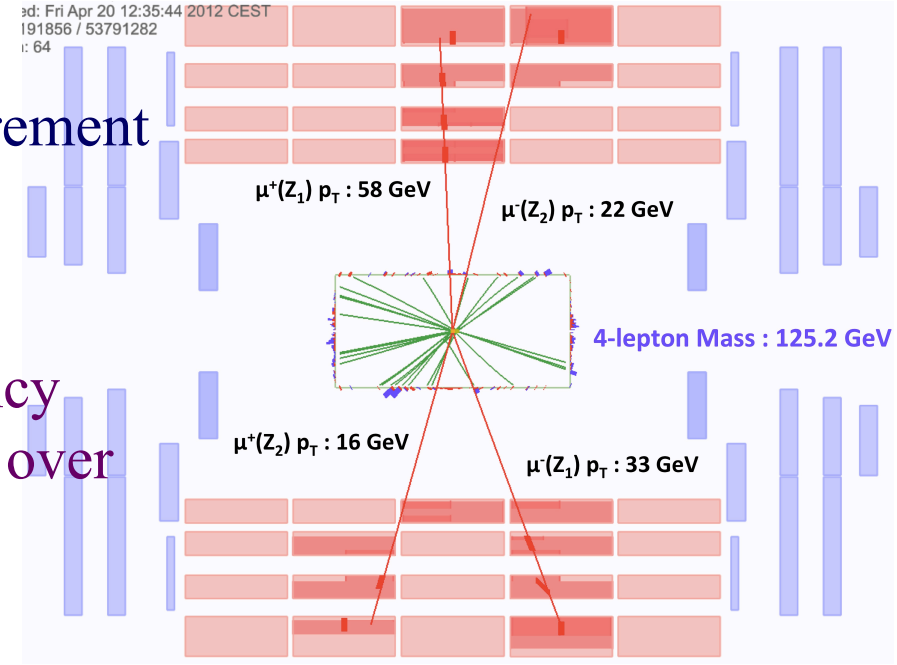
Channel	M_H Range (GeV)	Data Sample 7+8 TeV (fb^{-1})	M_H Resolution
H → ZZ→4l	110-1000	5.1 + 19.6	1-2%
H → γγ	110-150	5.1 + 19.6	1-2%
H → WW→ lυlυ	110-600	4.9 +19.5	20%
H→ττ	110-145	4.9+19.6	15%
H→bb	110-135	5.0+19.0	20%
H → Z γ	120-160	5.0+19.6	2 %

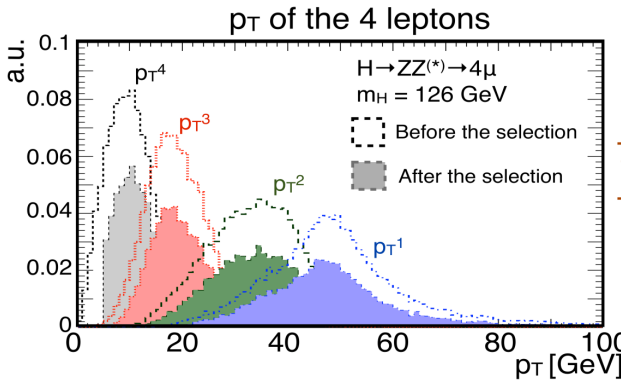


High mass resolution discovery modes

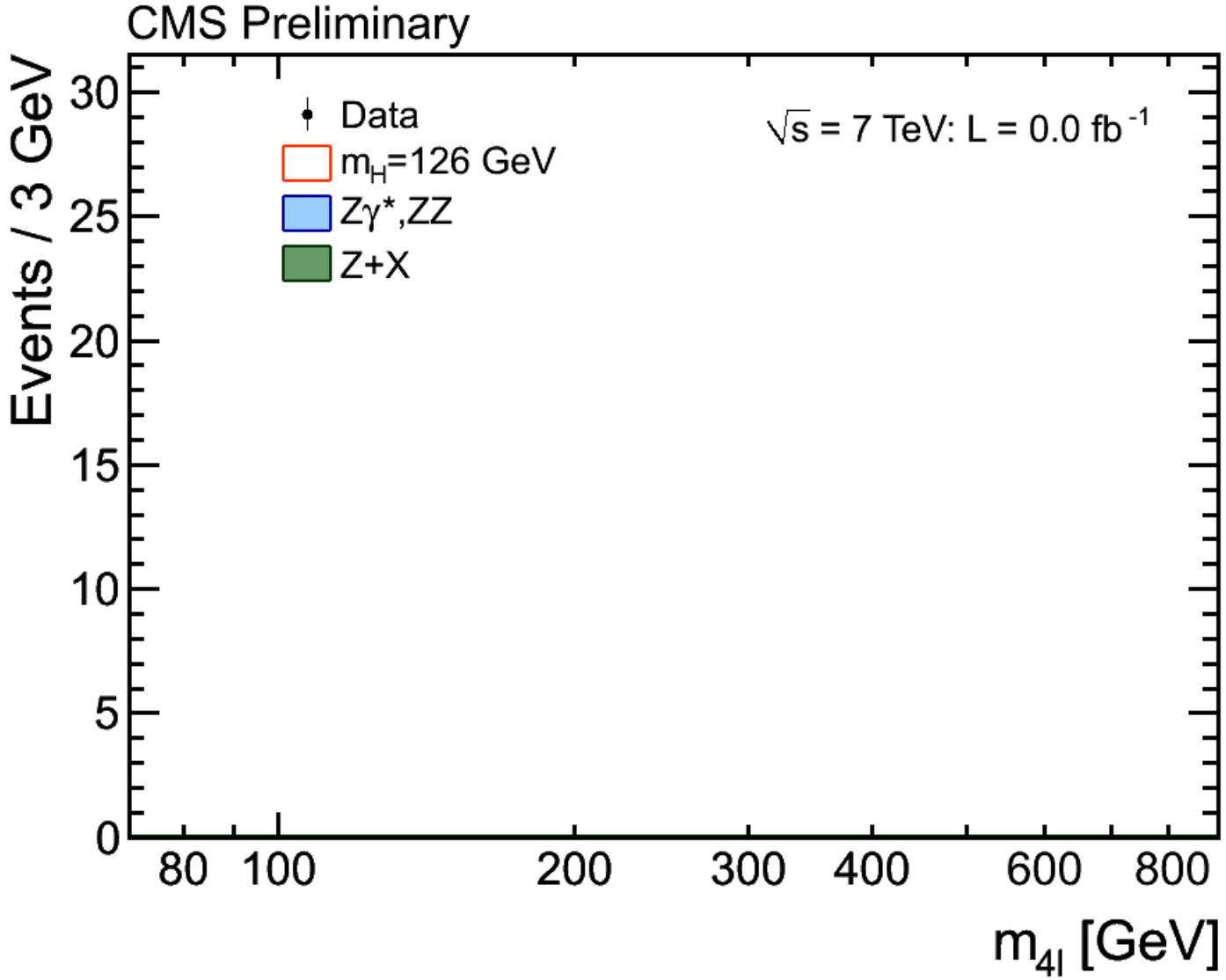
H → ZZ → 4*l*

- **Golden channel** : Four isolated leptons from one point in 3D space
- Benefits from excellent e/μ measurement
  - M_{4l} mass resolution ≈ 1-2 %
- σ×Br(H→ ZZ→ 4l) quite small
  - Needs highest selection efficiency possible → Efficient lepton ID over broad P_t range
- Backgrounds
  - Non-resonant pp→ ZZ→4l is largest and irreducible, has same topological signature as H → 4l
    - **But no narrow peak as in H → ZZ**
  - Z+jets,ttbar, WZ…all reducible and important at low M_{4l}

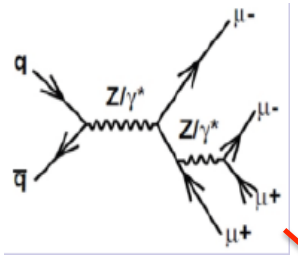


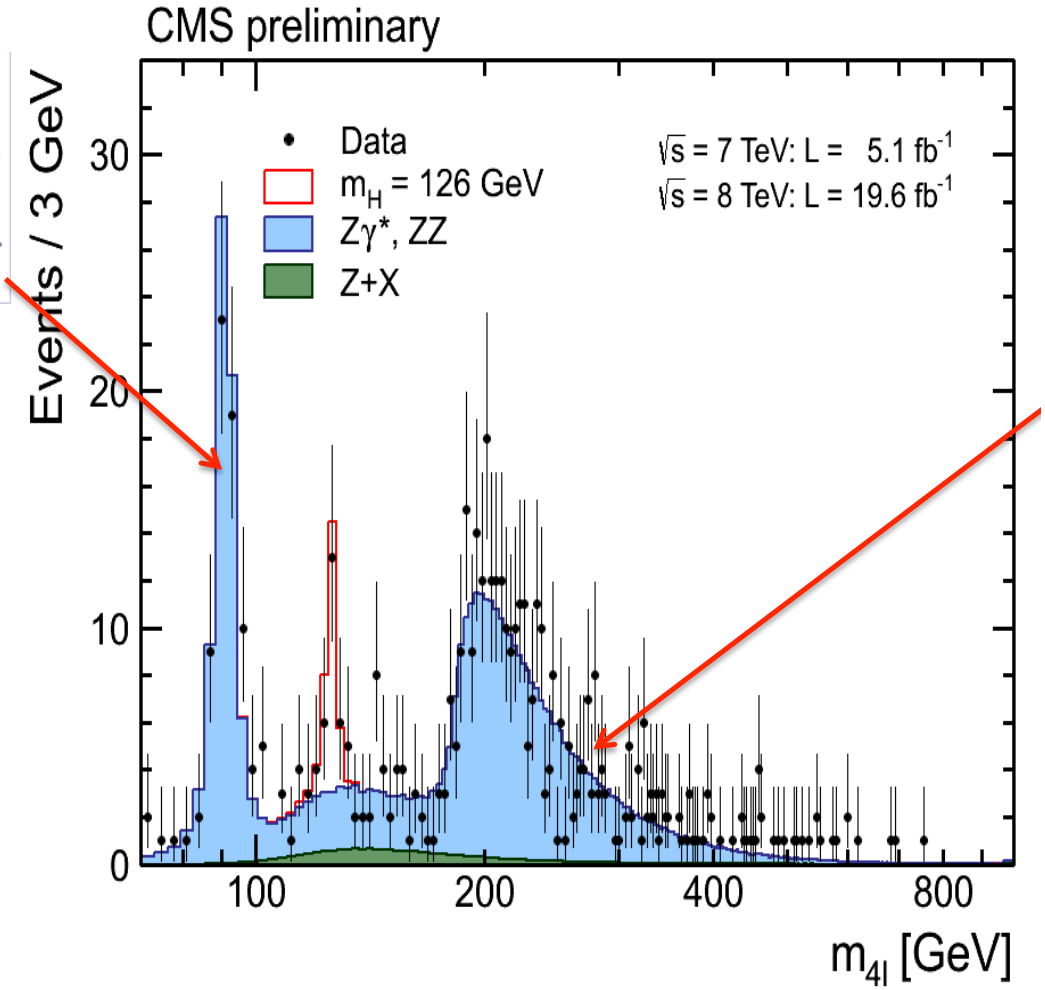


Discovery of A New Boson



H → ZZ → 4*l*





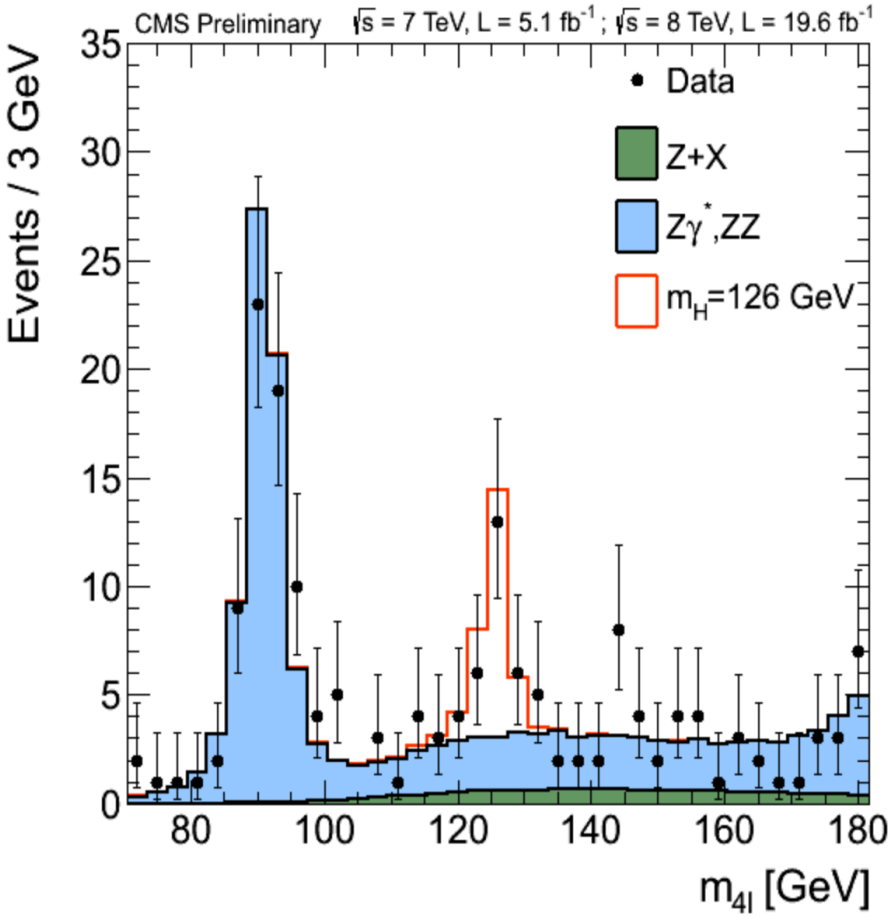
Good control of the dominant ZZ background

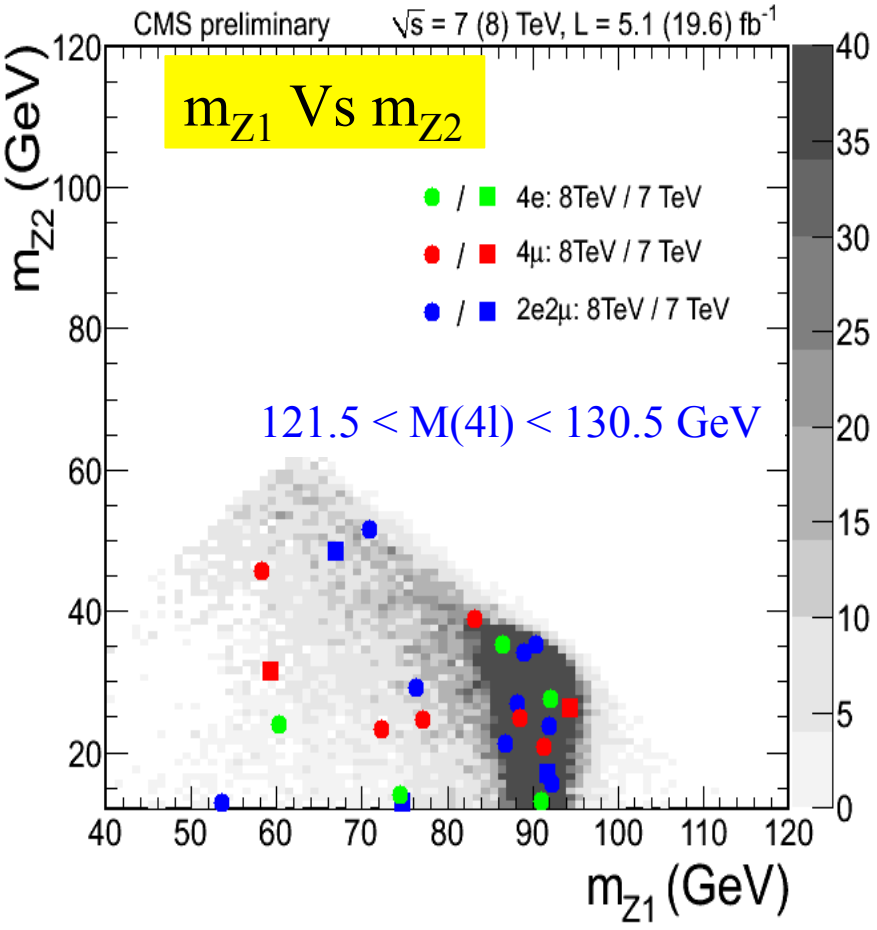
M(4l)>160 GeV
Data 380 evts
MC 364.5 evts

$\sigma(pp \rightarrow ZZ, 8TeV) = 8.4 \pm 1.0\ (stat.) \pm 0.7\ (syst.) \pm 0.4(lum.)$ pb

$\sigma_{SM}(th) = 7.8 \pm 0.6$ pb

H → ZZ → 4*l*

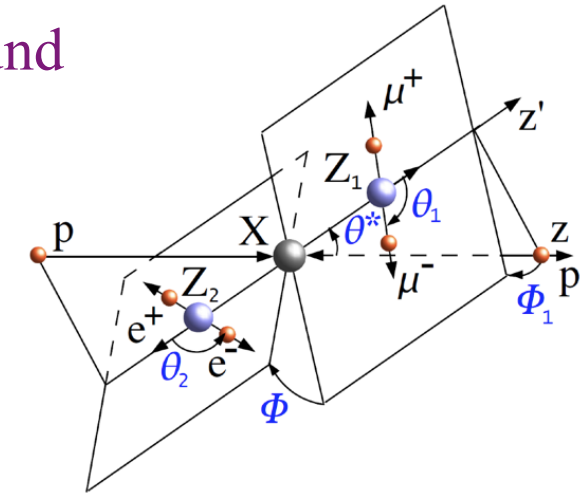

CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1 ; √s = 8 TeV, L = 19.6 fb-1
Data
Z+X
Zγ*,ZZ
mH=126 GeV
Events / 3 GeV
m4l [GeV]


CMS preliminary
√s = 7 (8) TeV, L = 5.1 (19.6) fb-1
mZ1 Vs mZ2
4e: 8TeV / 7 TeV
4μ: 8TeV / 7 TeV
2e2μ: 8TeV / 7 TeV
121.5 < M(4l) < 130.5 GeV
mZ2 (GeV)
mZ1 (GeV)

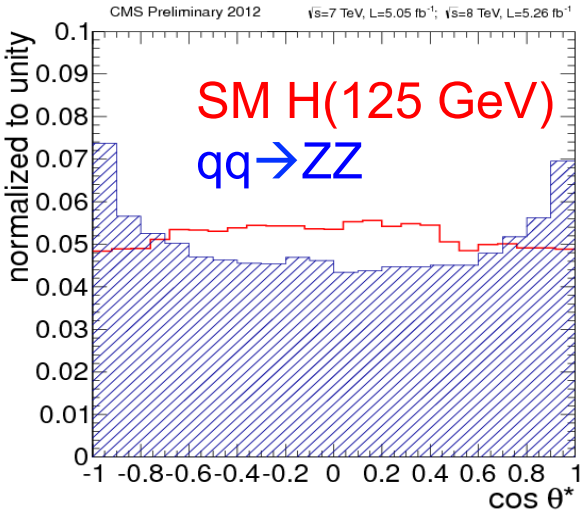
Angular Analysis In H → ZZ → 4l (CMS)

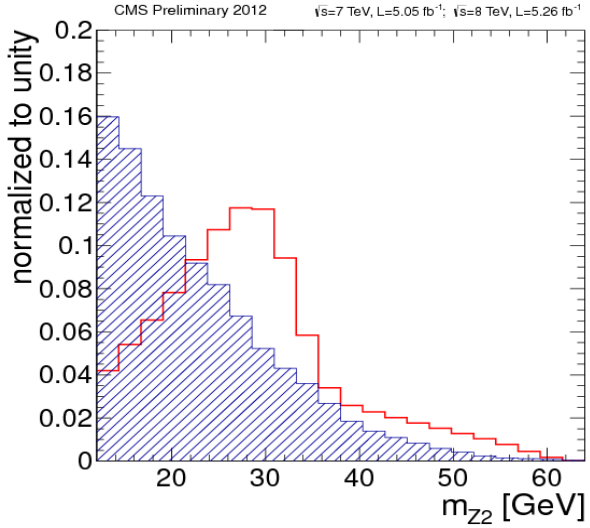
- H → ZZ → 4l Decay kinematic fully described by 5 angles and the 2 Z masses
  - discriminates spin 0 particle from background
  - MELA: matrix element likelihood analysis

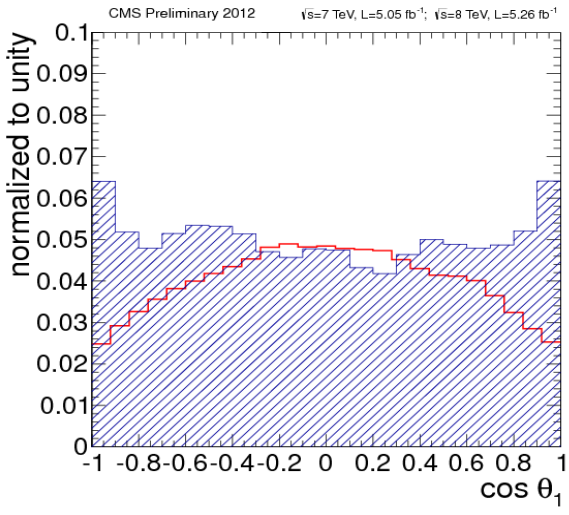
PR(D) 81, 075022(2010)



Some discriminating variables

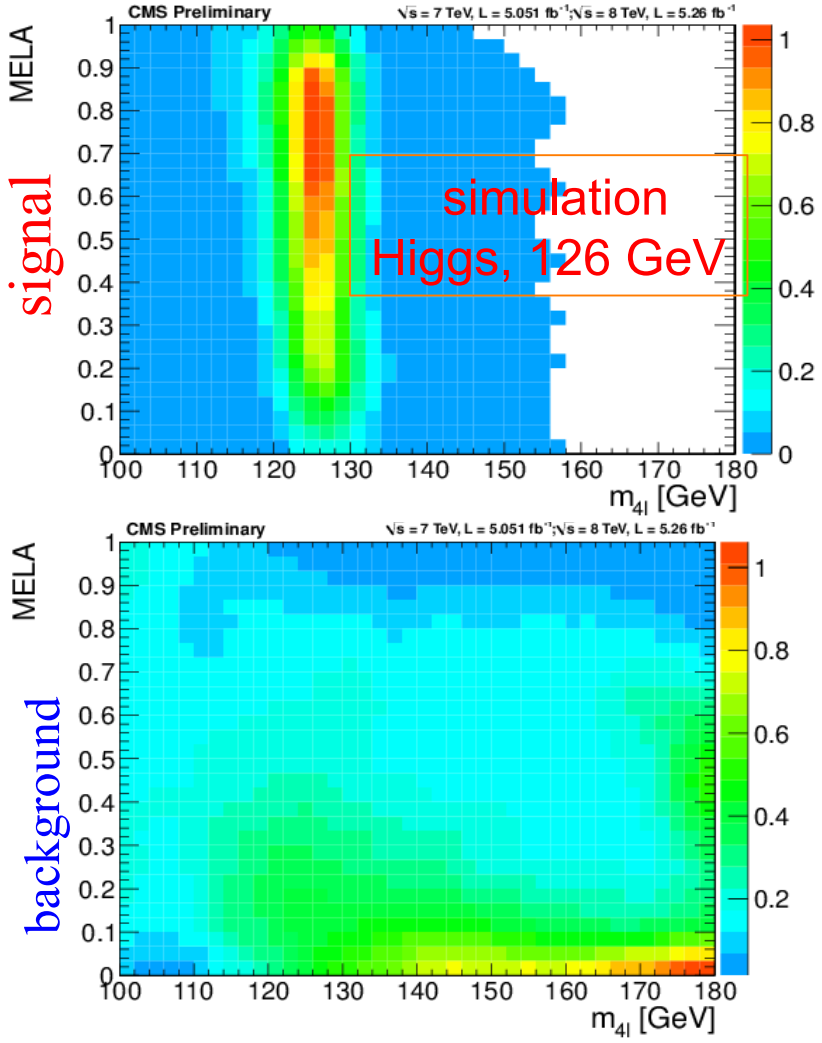


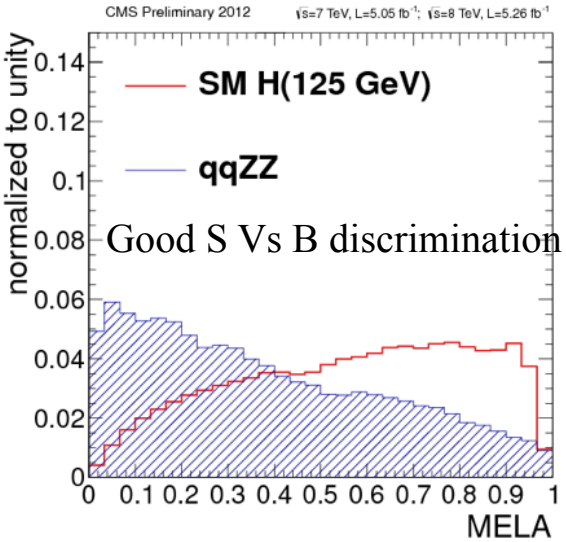


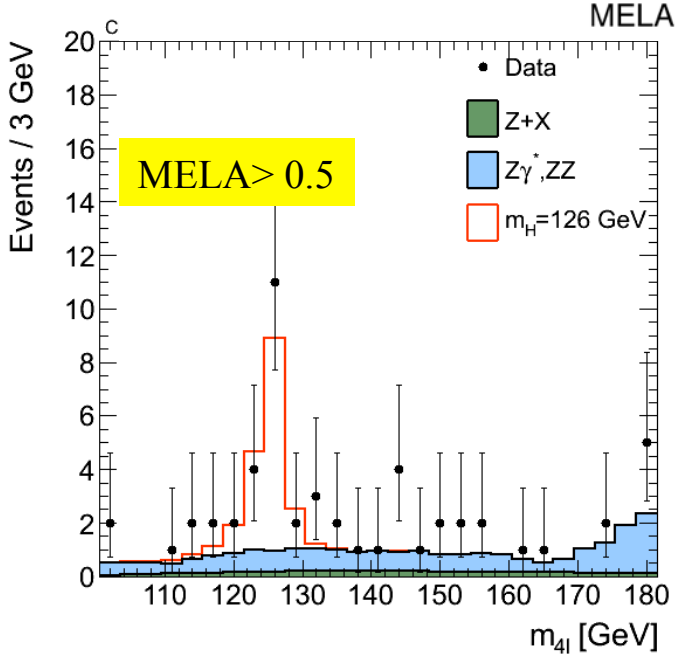


MELA Vs 4*l* Mass

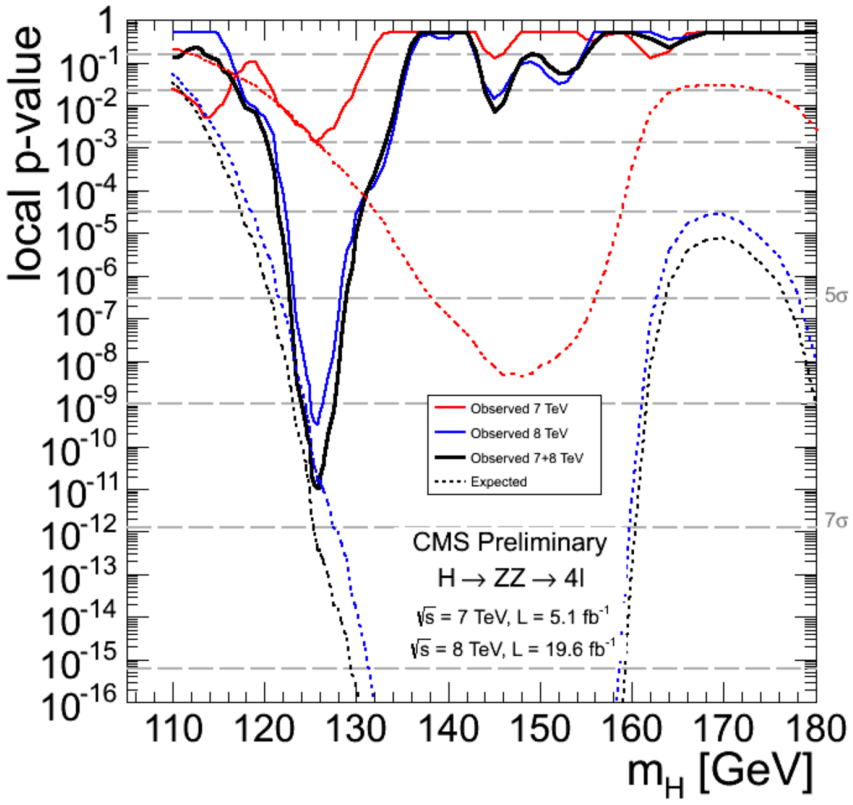
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

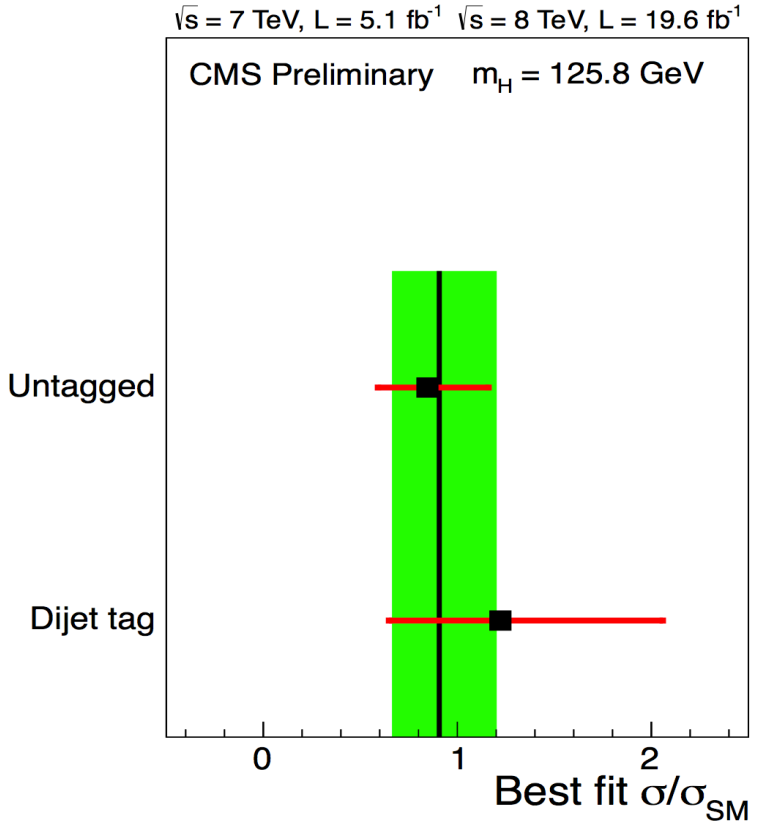






H → ZZ → 4*l*

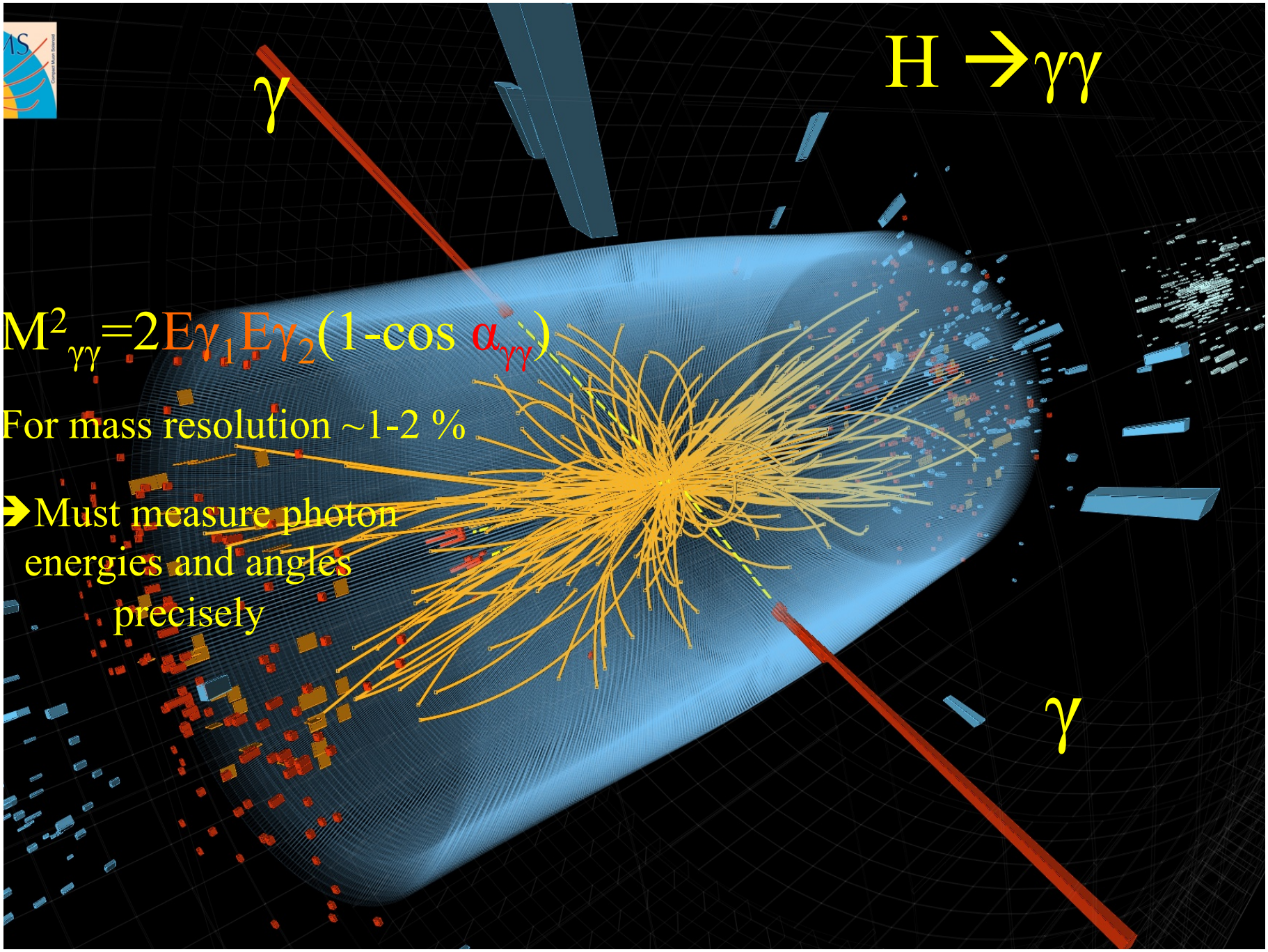




p-value: Expected: 7.1σ
Observed: 6.7σ

σ/σ_{SM} at 125.7 GeV = 0.92 ± 0.28

Signal significance > 6 standard deviations in this channel alone


γ
H →γγ
$M^2_{\gamma\gamma}=2E\gamma_1 E\gamma_2(1-\cos\alpha_{\gamma\gamma})$
For mass resolution ~1-2 %
→Must measure photon energies and angles precisely
γ

H → γγ

- Two inclusive analysis methods:

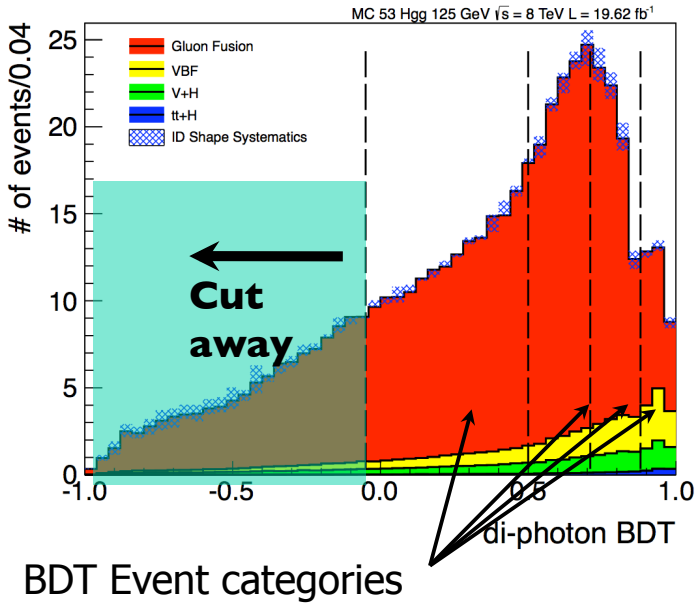
PRIMARY

- MVA: photons selected with a BDT. Variable in the BDT: photon kinematics, photon ID BDT score (shower shape, isolation), di-photon mass resolution. 4 BDT categories with different S/B

CROSS-CHECK

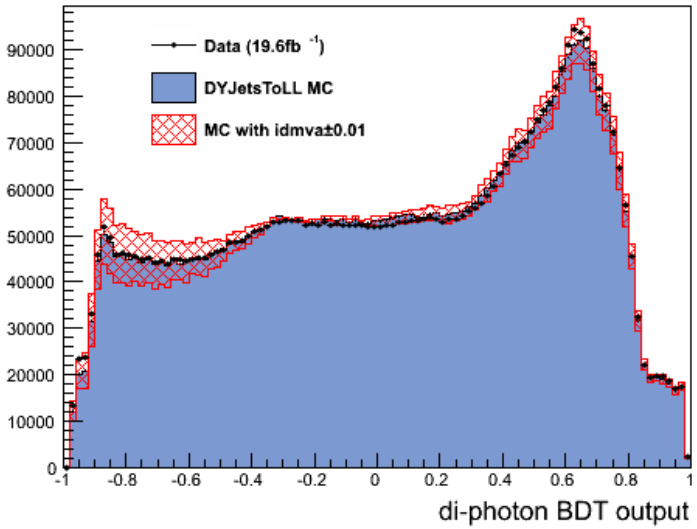
- Cut-based: photons selected with cuts. 4 categories based on: γ in Barrel/ Endcap, (un)converted γ. Each category has diff. mass resolution and S/B

- 3 VH channels (e, μ and MET tag) + VBF (2 dijet categories)



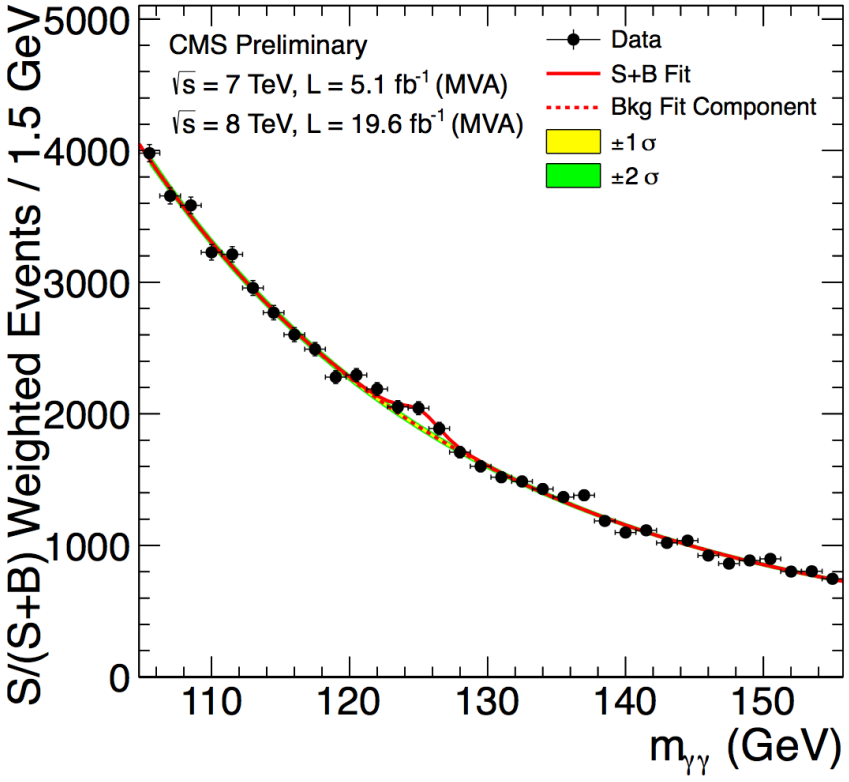
BDT Event categories

Output of BDT validated using Z→ee (where e are reconstructed as γ)

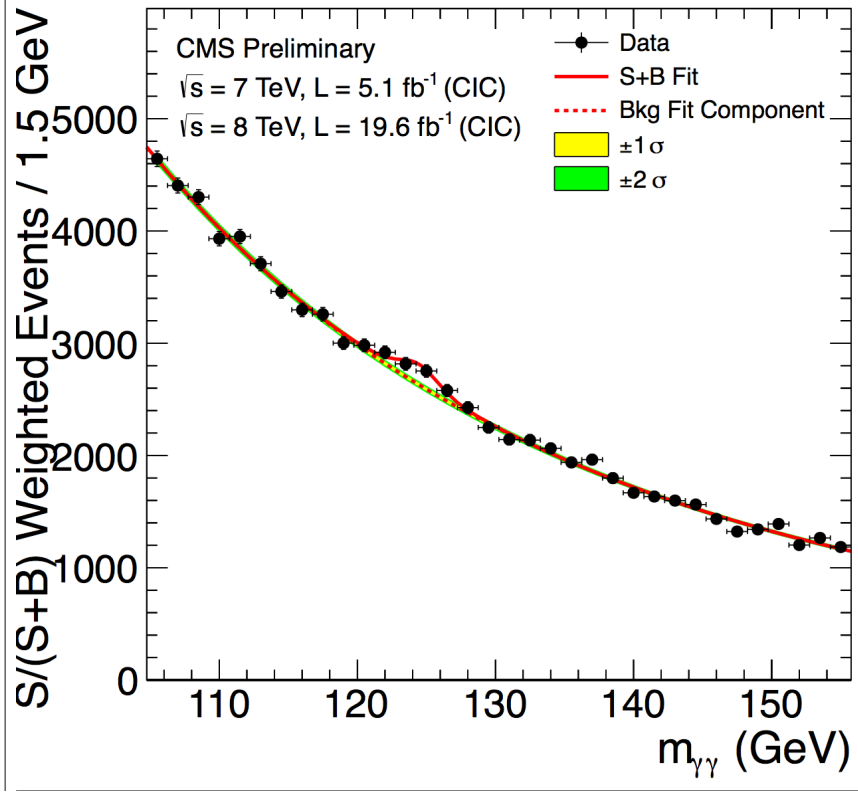


H → γγ

BDT Analysis



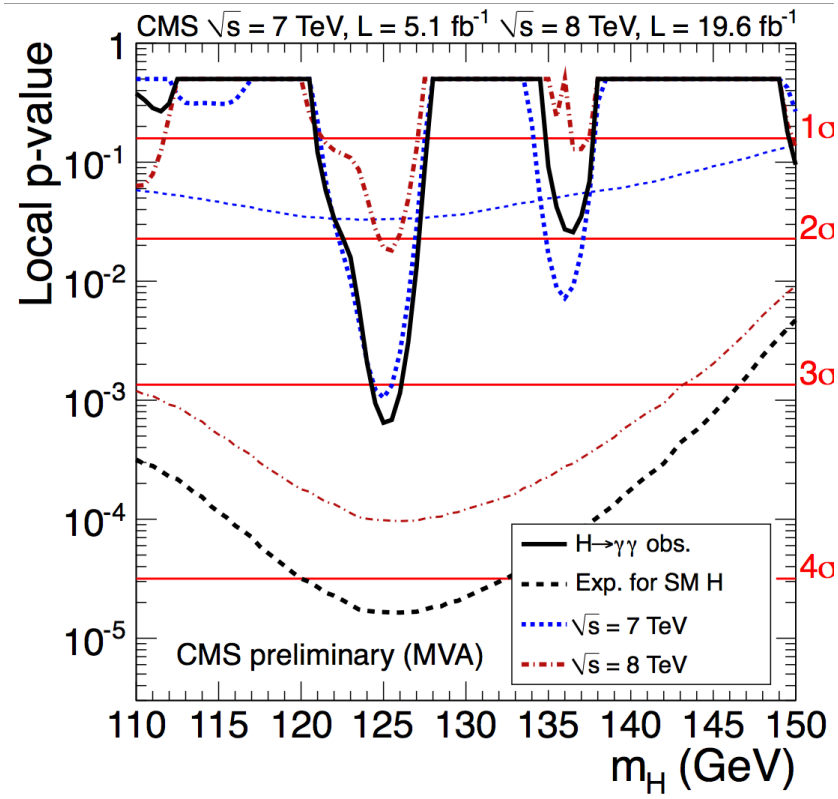
Cut-based



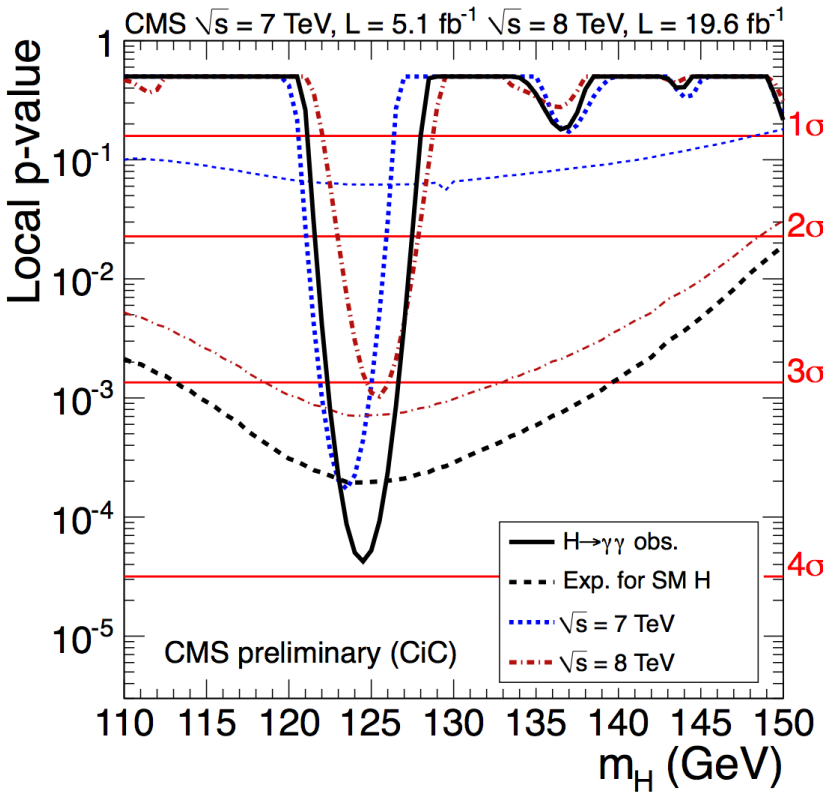
Above: Each event category is weighted by its S/(S+B) only for visualization purposes

H → γγ : Significance Of Observation

BDT Analysis

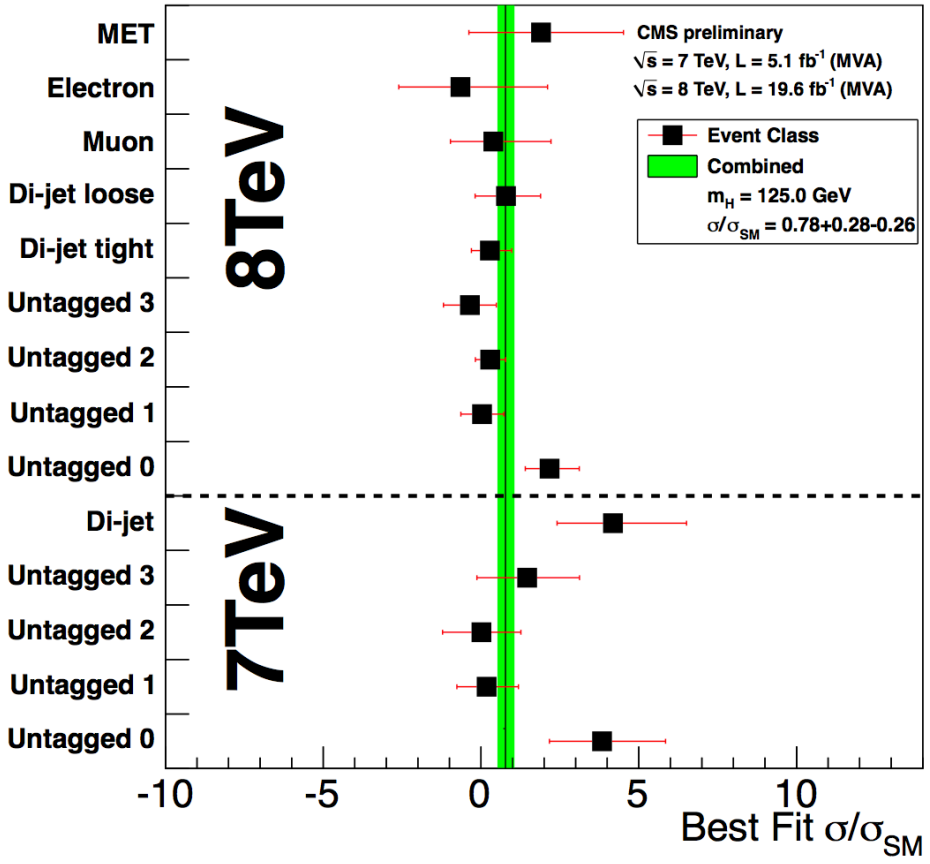


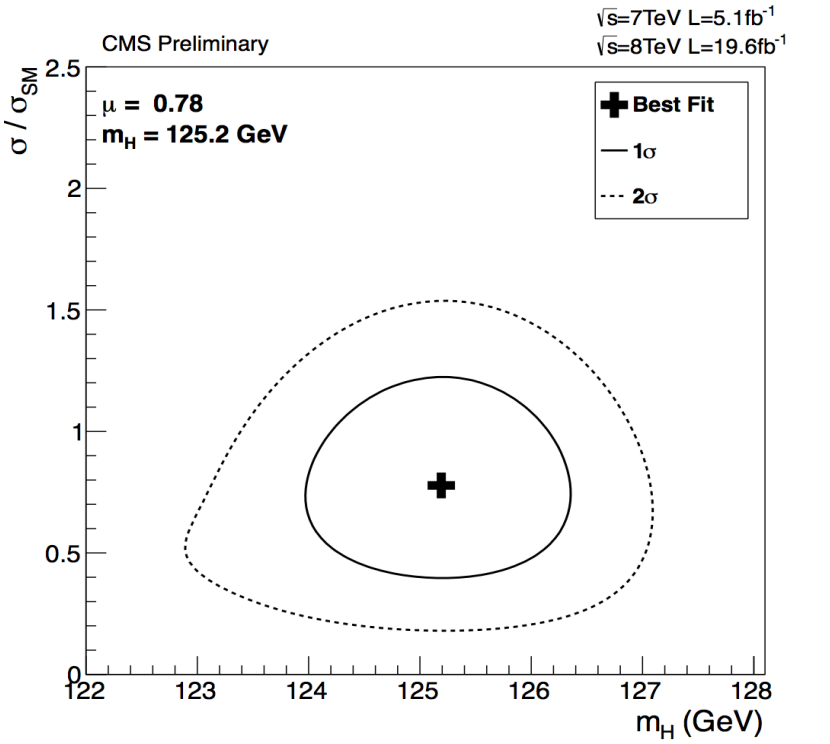
Cut-based



MVA analysis is the principal result

H → γγ : MVA Result

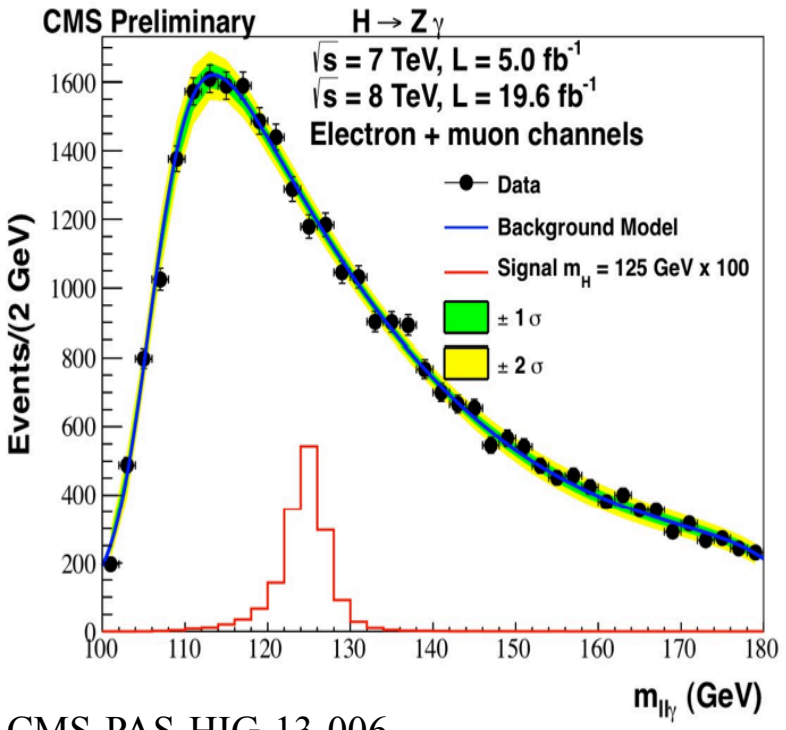


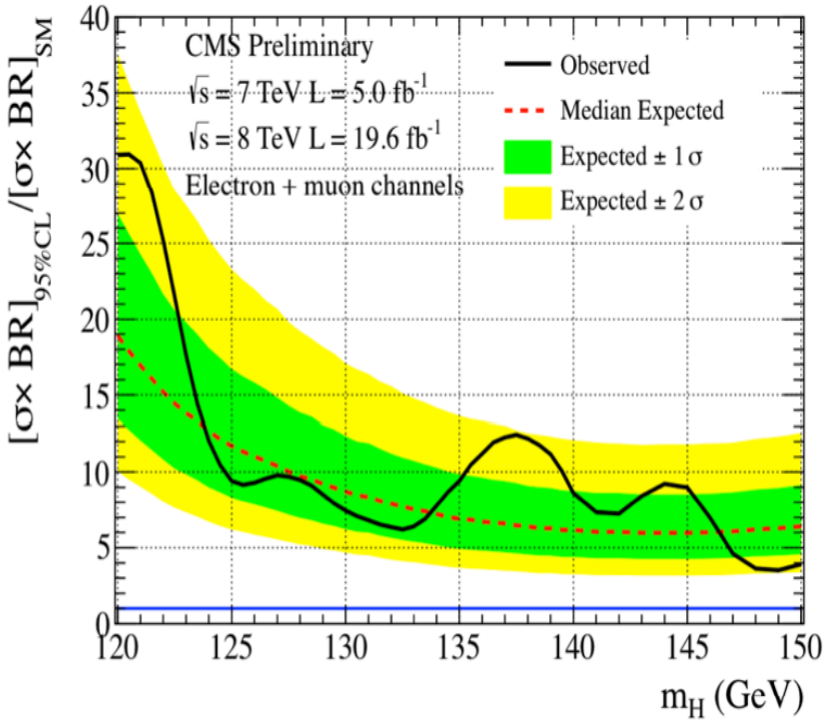


$M_H = 125.4 \pm 0.5(\text{stat}) \pm 0.6(\text{syst})$

7+8 TeV: σ/σ_{SM} for a mass of 125.0 GeV = $0.78\ ^{+0.28}_{-0.26}$

An Aside : H → Zγ





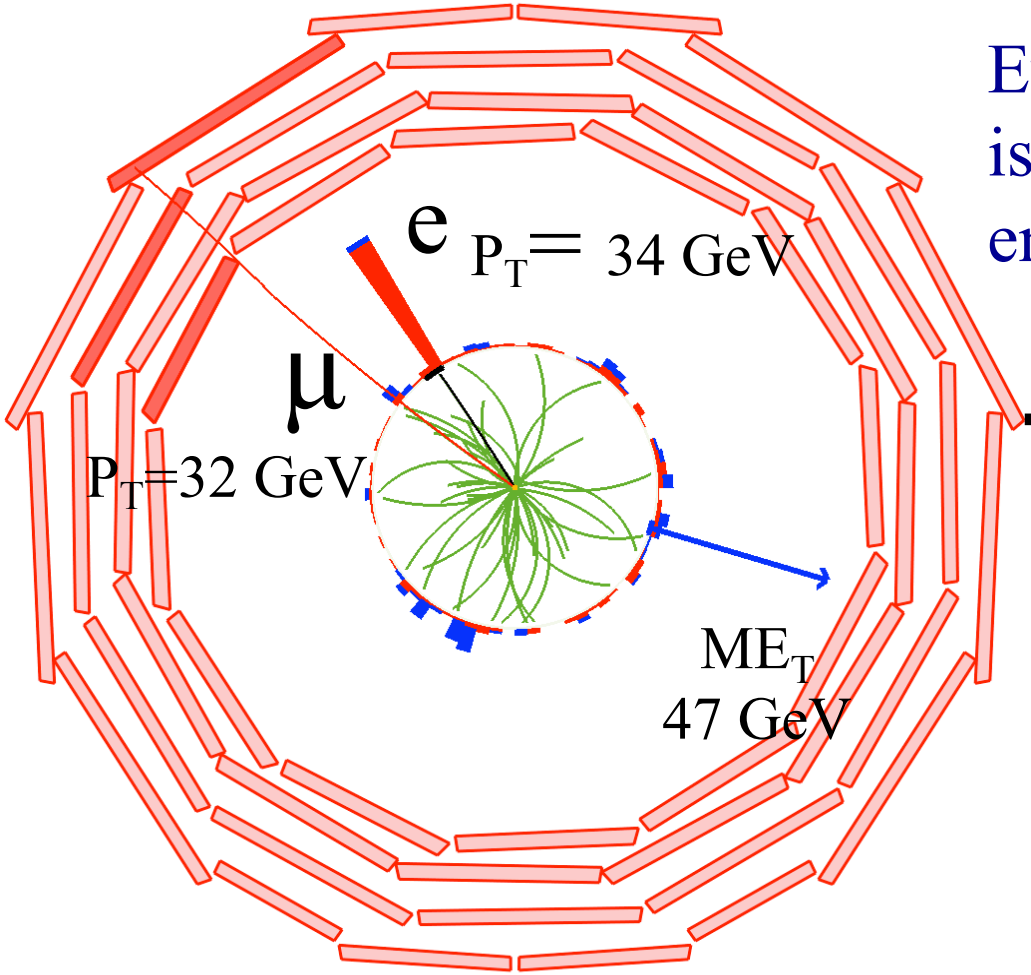
CMS-PAS-HIG-13-006

- Z decays into 2 charged leptons. The BR (H → Z γ) is comparable to BR(H → γγ) , but BR (Z → ll) reduces sensitivity (by factor of 16)
- Search for a narrow **llγ** peak on top of a falling background
- Data ➔No significant excess seen over the entire search region
- **Will need ~ x100 more data** for an observation at SM rate

In some BSM models, decay rates in this channel could be enhanced

Modes With Poor Mass Resolution

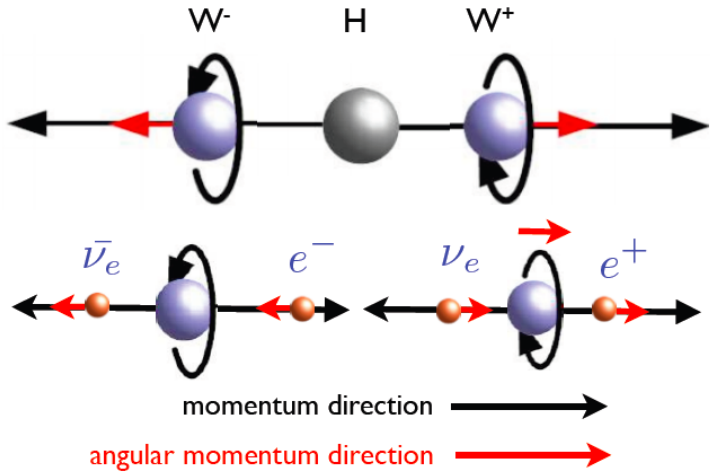
$H \rightarrow WW^{(*)} \rightarrow (l\,\nu)\,(l\,\nu)$



Events with two energetic & isolated leptons and missing energy (due to neutrinos)

Higgs boson has spin = 0

➔ Leptons spatially aligned

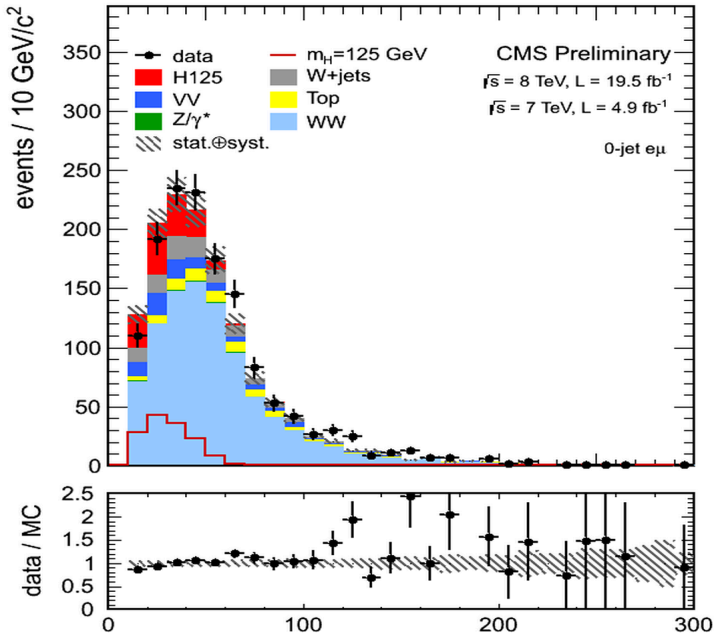


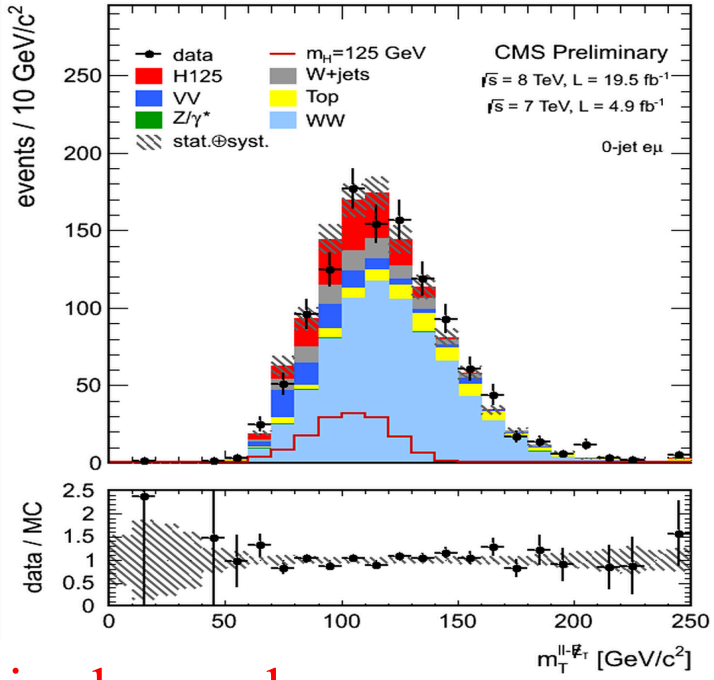
Poor mass resolution (~20%) due to escaping neutrinos

$H \rightarrow WW^{(*)} \rightarrow (l\,\nu)\,(l\,\nu)$

- Analysis of WW+0 jets and 1 jets categories in full 7/8 TeV data (W+2jets (VBF) channel is in progress)
- Cut based analysis for same flavour lepton events and 2-dimensional M_T - M_{ll} analysis for different flavour events $M_T = \sqrt{2p_T^{\ell\ell} E_T^{miss} \cos(\Delta\phi_{\ell\ell} - E_T^{miss})}$

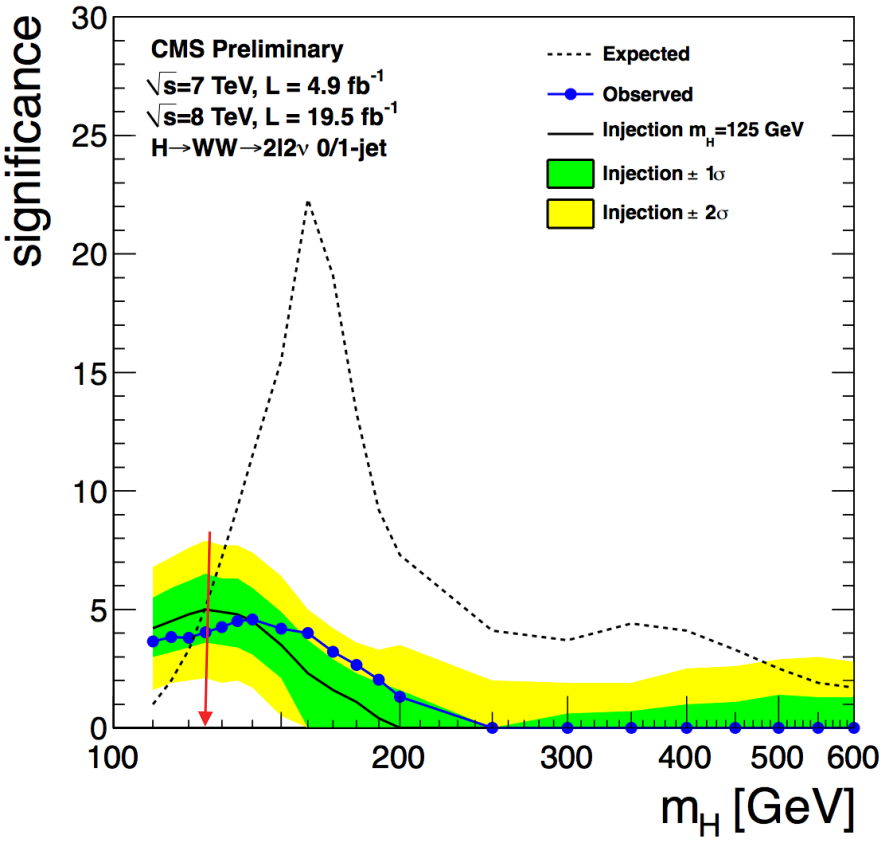
Events with 0 jets and different flavour leptons (7+8 TeV Data)

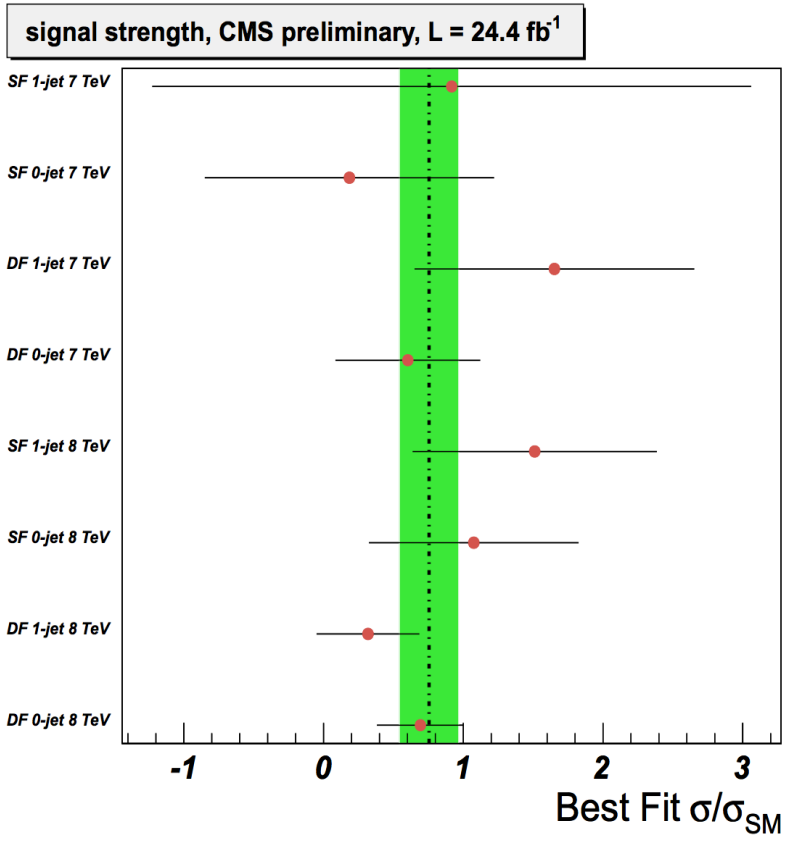




A significant excess is observed

H → WW(*) → (l ν) (l ν) : Significance Of Result





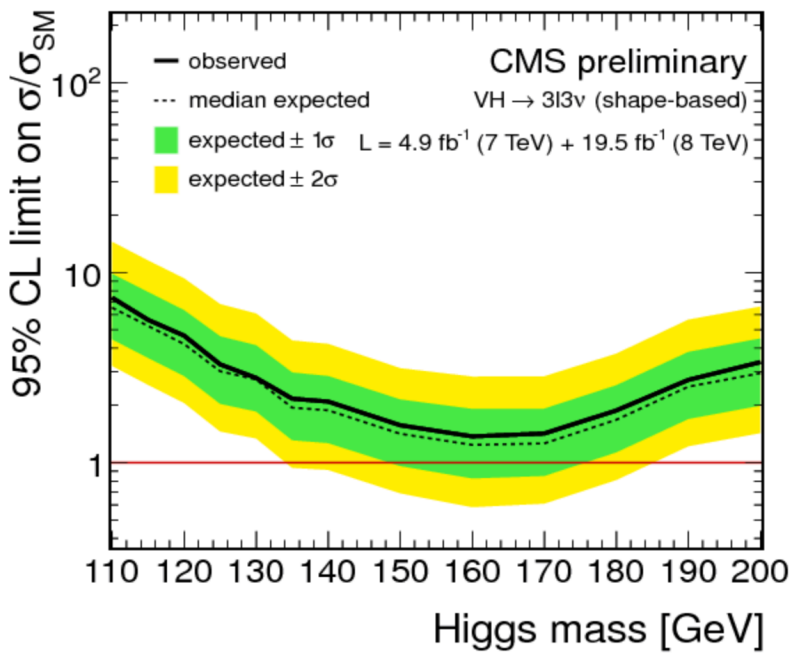
4.0σ (5.1σ) observed (expected) significance at $m_H \sim 125$ GeV

signal strength $\sigma/\sigma_{SM} = 0.76 \pm 0.21$

Aside: VH With H →WW(*)

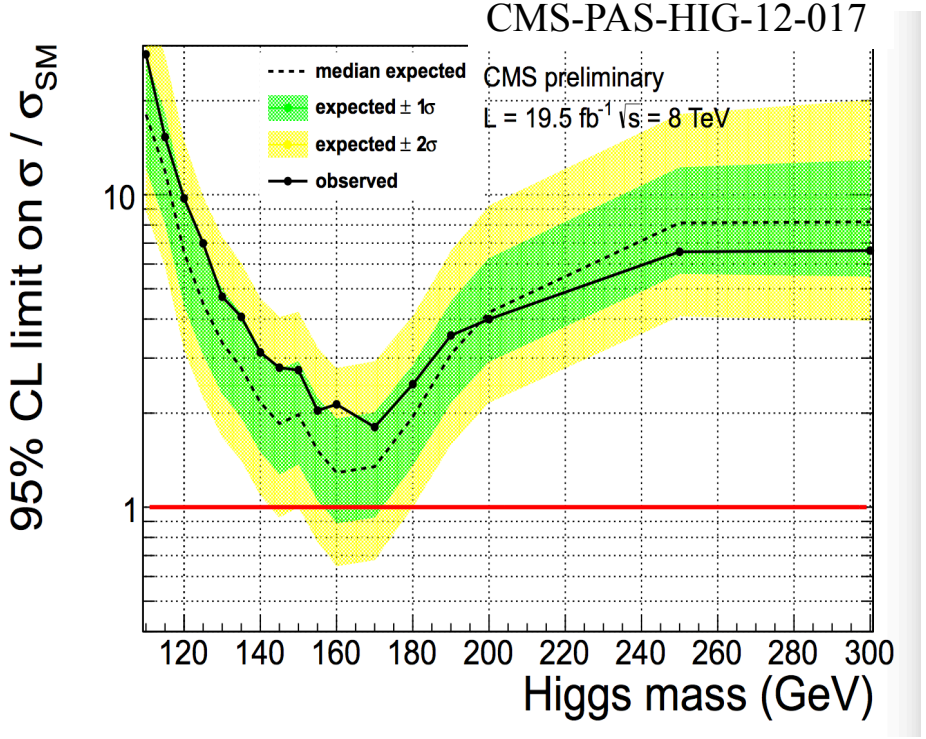
WH → WWW → 3l 3ν

CMS-PAS-HIG-13-009



VH → V+WW→2l 2ν + V→jj

CMS-PAS-HIG-12-017



Three high p_T leptons with moderate missing transverse momentum

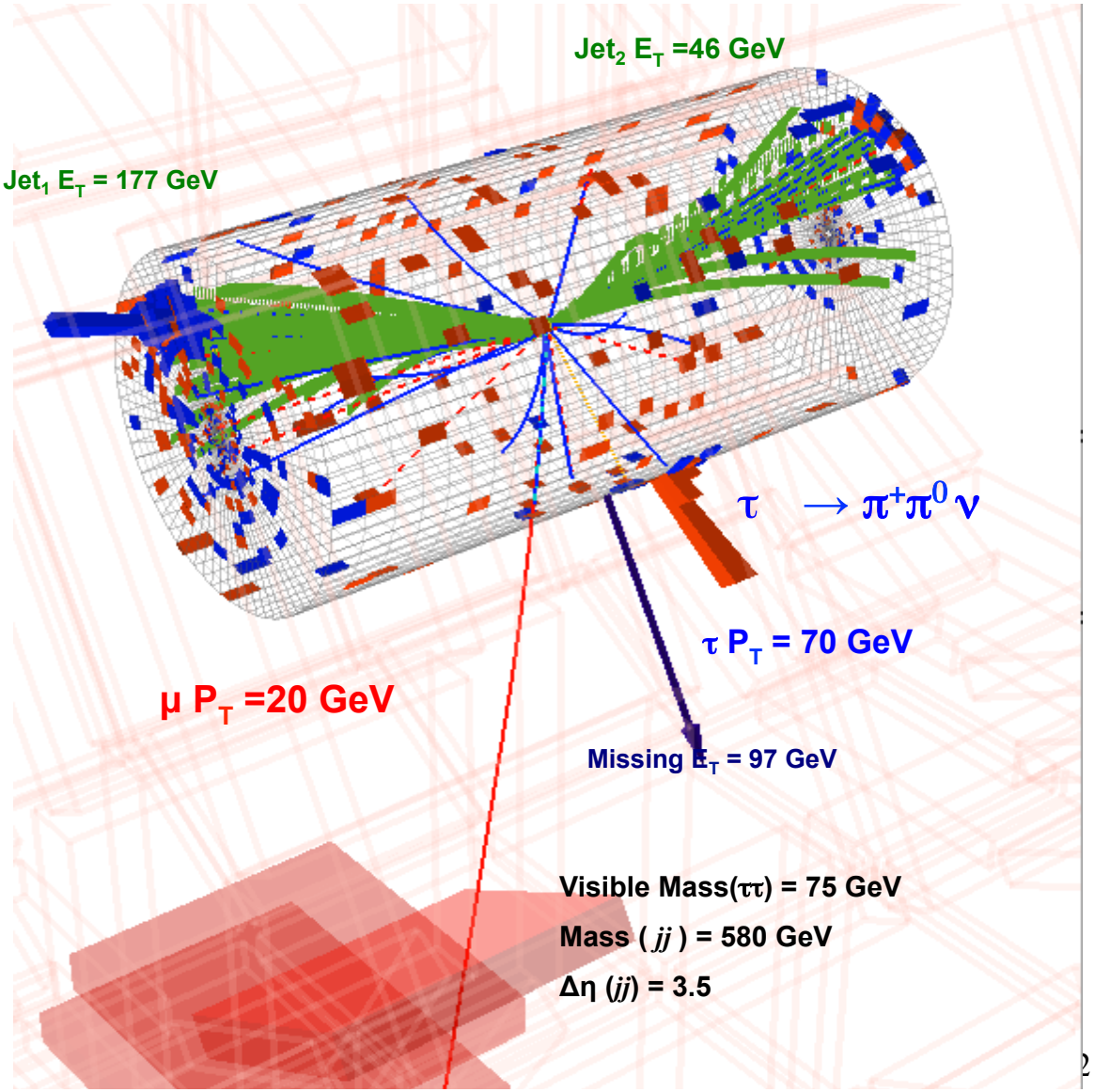
WW analysis requiring two central jets

Limited Standard Model Higgs sensitivity (~ 3.5-4 ×SM at 125 GeV)

Higgs Decays To Leptons

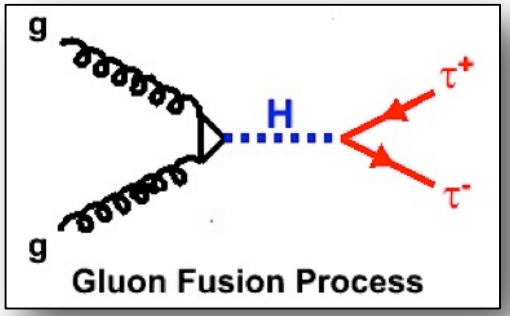
$H \rightarrow \tau\tau$

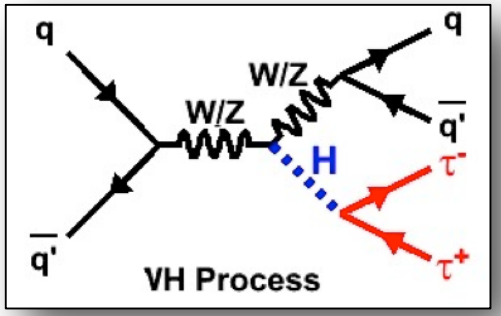
VBF candidate shown here

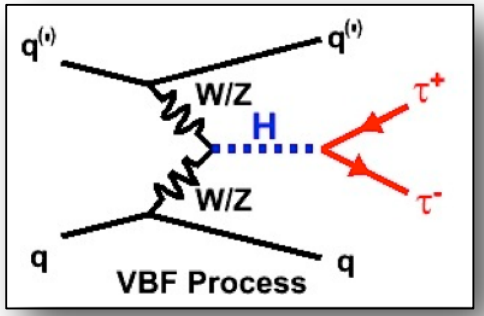


H → ττ

- Most promising mode for measuring Higgs coupling to leptons
- Searched for in three Higgs production modes







- And subsequent decay of τ lepton
  - τ →eνν , τ →μνν, τ→ hadrons
- Four signatures considered : eμ, μμ, $e\tau_h$, **$\mu\tau_h$**
- Search divided in 5 categories based on H→ττ mass resolution & S/B
  - **0,1 Jets with high/low P_T τ**
- Due to missing neutrinos, Higgs signal appears as a broad excess in reconstructed τ-pair mass (Mass resolution ≈ 20%)
- Major backgrounds arise from ttbar ; W & Z (+jets), dibosons

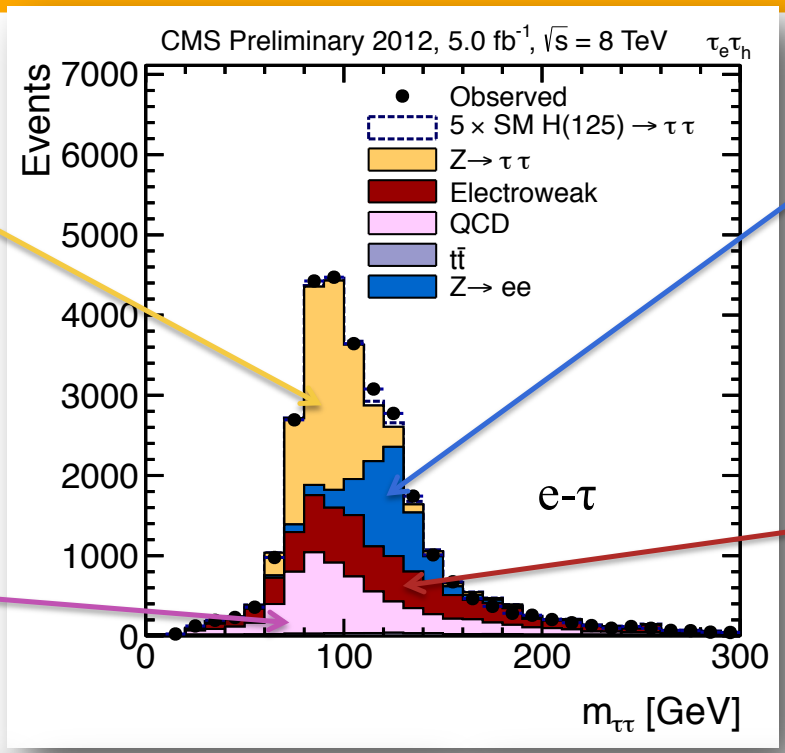
Anatomy of H→ ττ Analysis

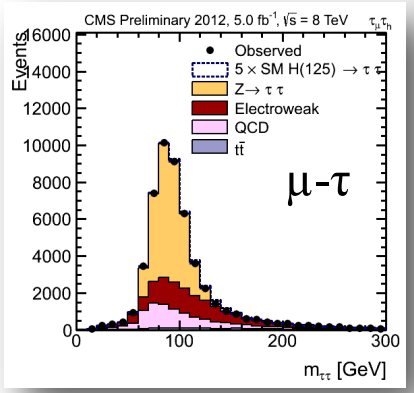
Z→ττ – Efficiency measured using τ embedded in Z→ μμ events

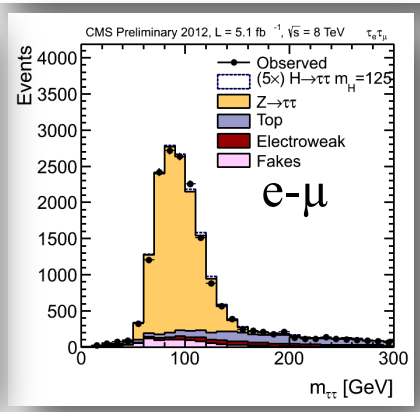
QCD – Estimated from same sign data

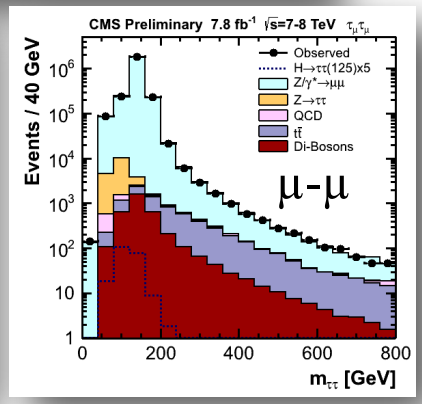
Z→ll – Taken from MC corrected for measured l→τ fake rates

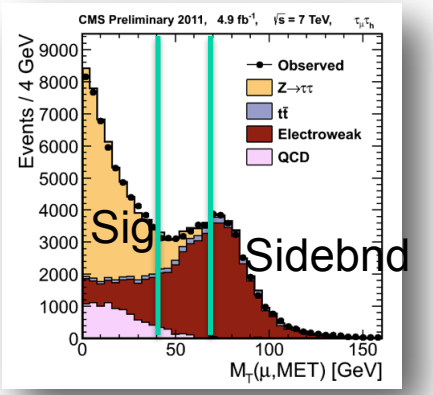
EWK – Mostly W+Jets, measured from high M_T sideband





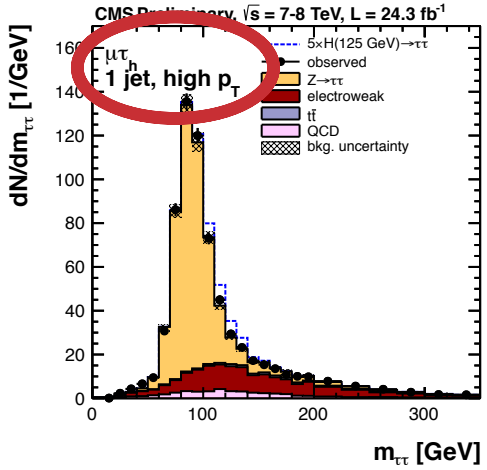


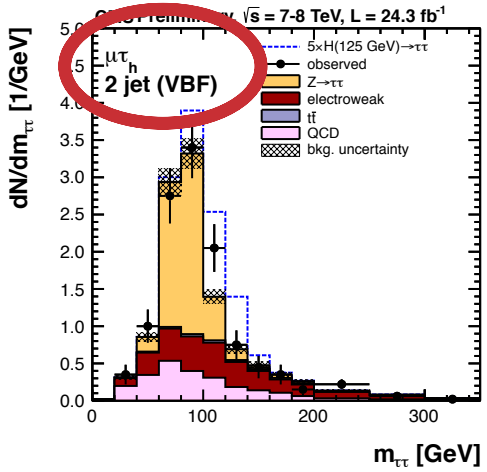




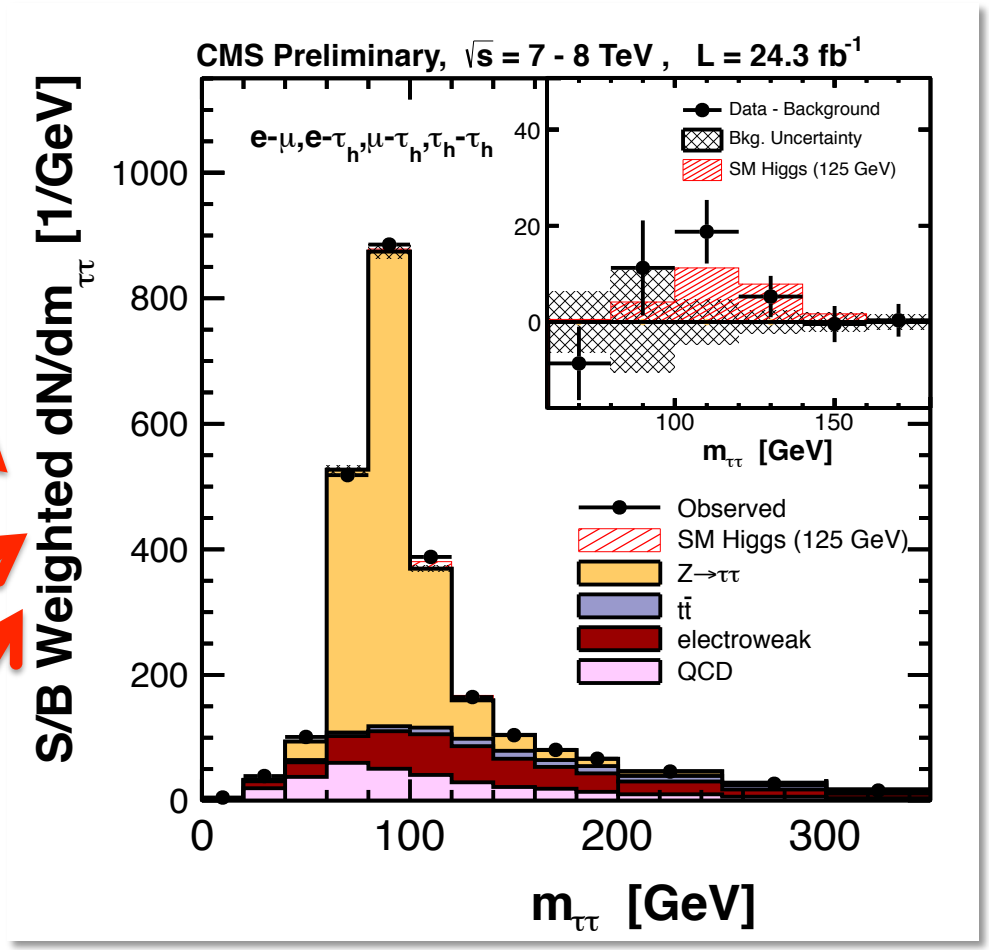
Plots are pre-fit

$H \rightarrow \tau\tau$





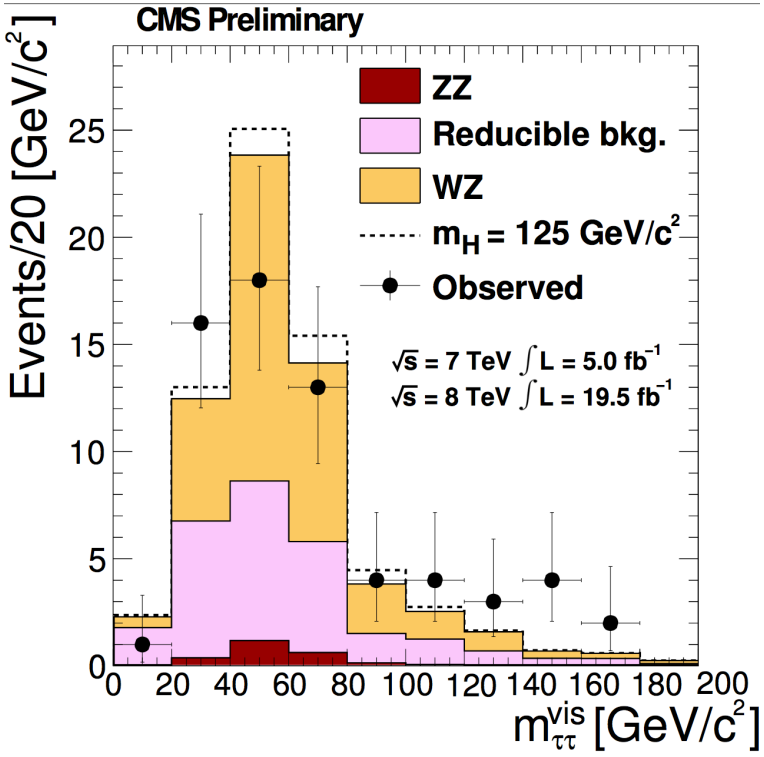
…plus all other tau decay modes: $e\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$



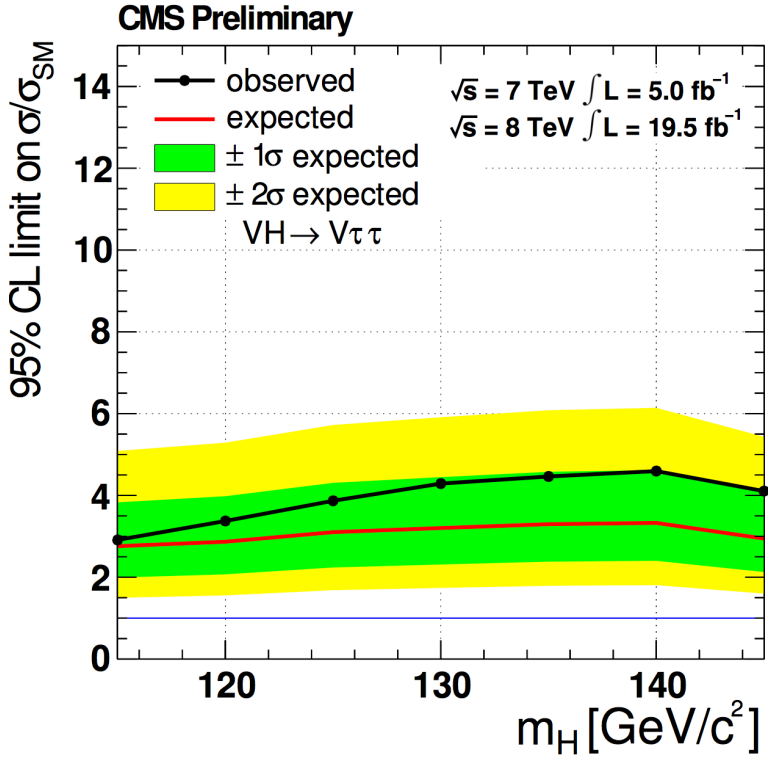
Combine the sensitive categories of all channels with a S/B weight

In addition : VH With H →ττ

Study topologies of **3 and 4 lepton** final states
Use τ decay into e, μ and hadronic final states

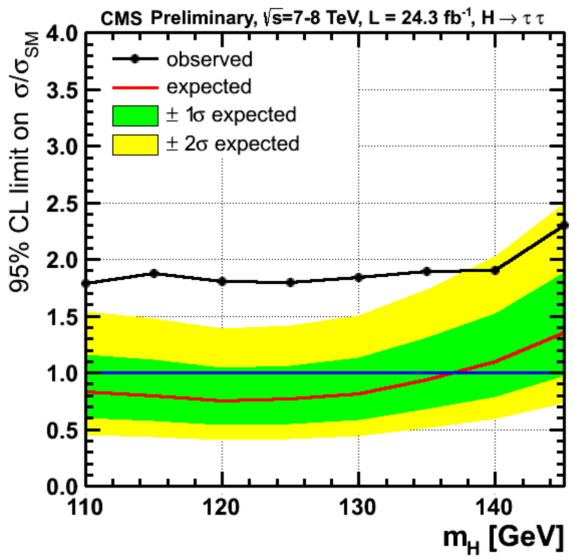


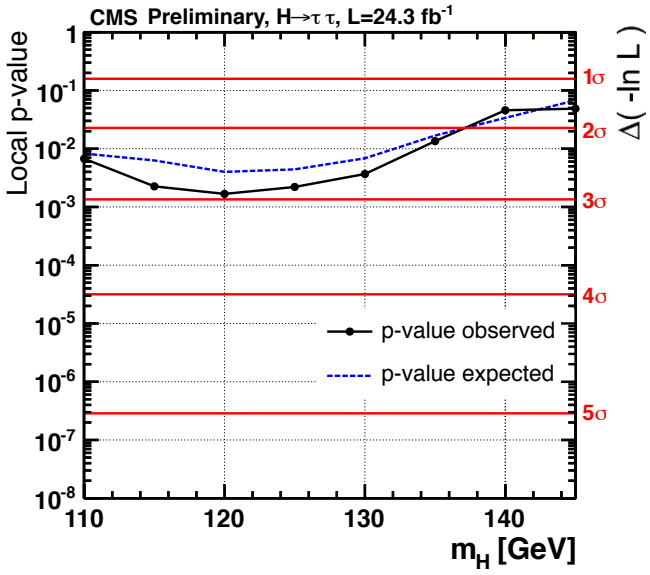
CMS-PAS-HIG-12-053

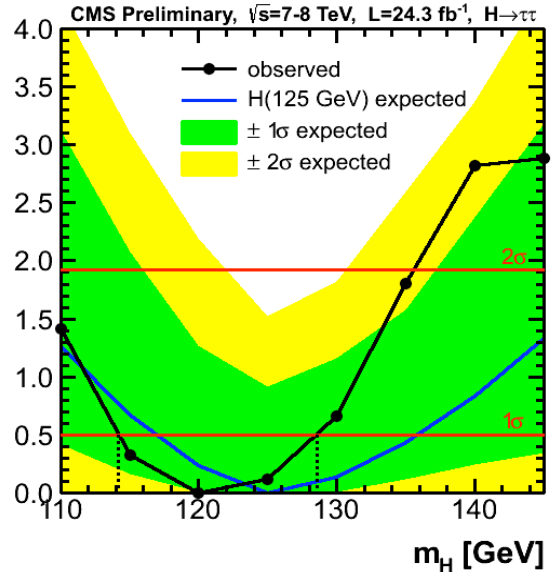


95% CL Upper limits on σ × BR of 2.9 to 4.6 x SM value

Adding It All Up : H →ττ







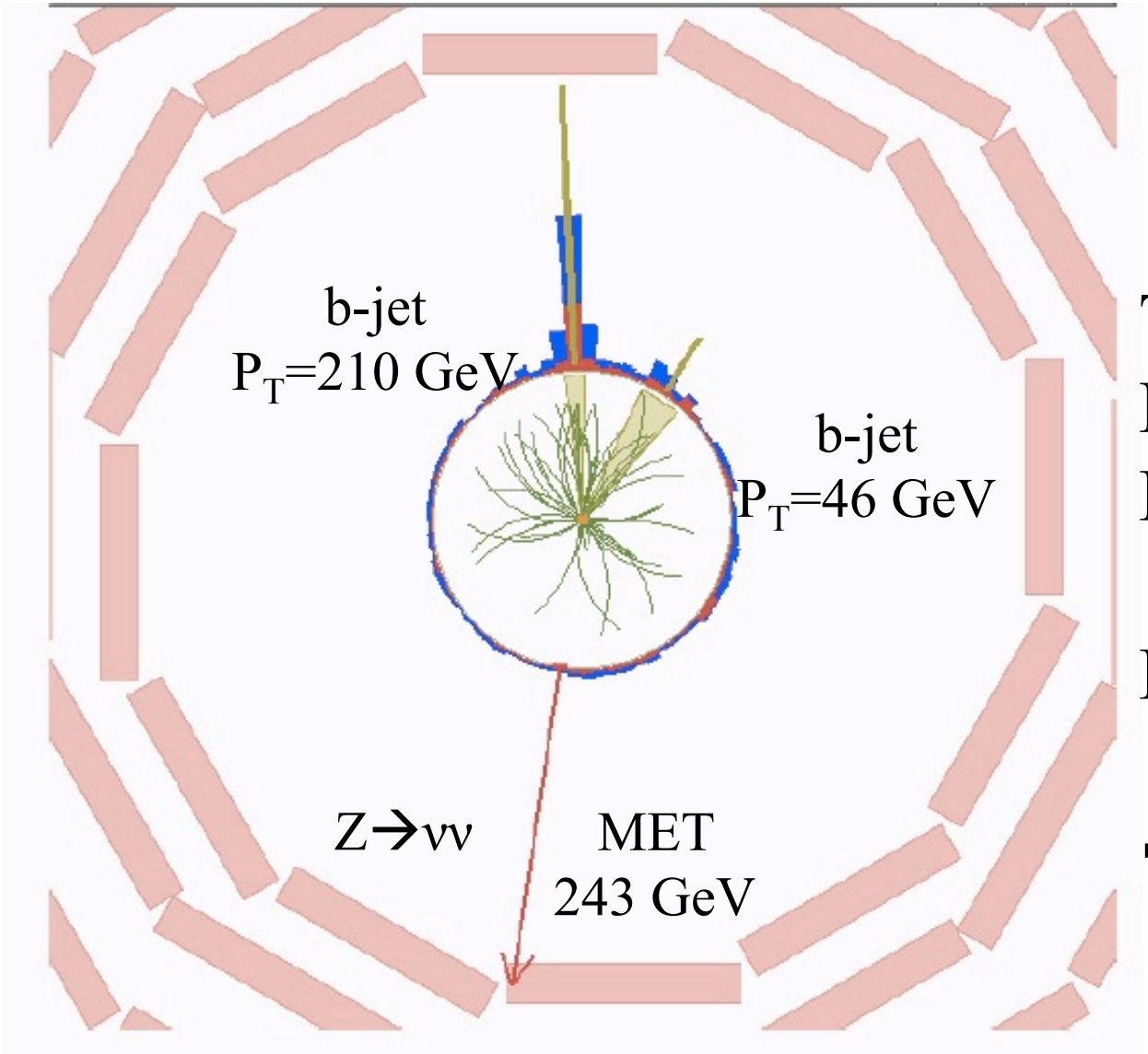
Significance: 2.85σ for m_H = 125 GeV

Signal strength $\mu = 1.1 \pm 0.4$

Mass
all ττ channels combined
$m_H = 120^{+9}_{-7}$ (stat+syst) GeV

Excess building up in the region of 120-130 GeV

Higgs Decay To Quarks



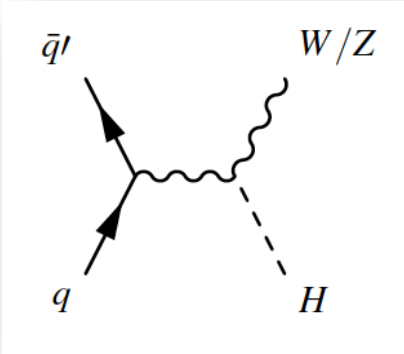
VH; H → bb
V = W, Z

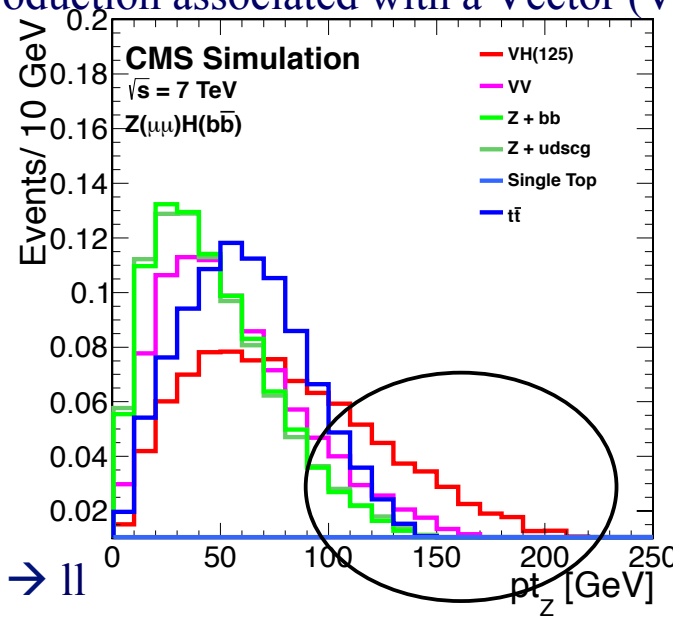
Two clean b-jets
M_{bb} = 120 GeV
$P_{T,bb}$ = 248 GeV

Recoiling against
Z→νν
➔ Large MET

CMS H→ bb Search In a Nutshell

- H → bb production via gluon fusion and VBF are quite large but are buried (10^7) under QCD production of b bbar pairs
- Most promising channel is H → bb production associated with a Vector (V=W or Z) boson

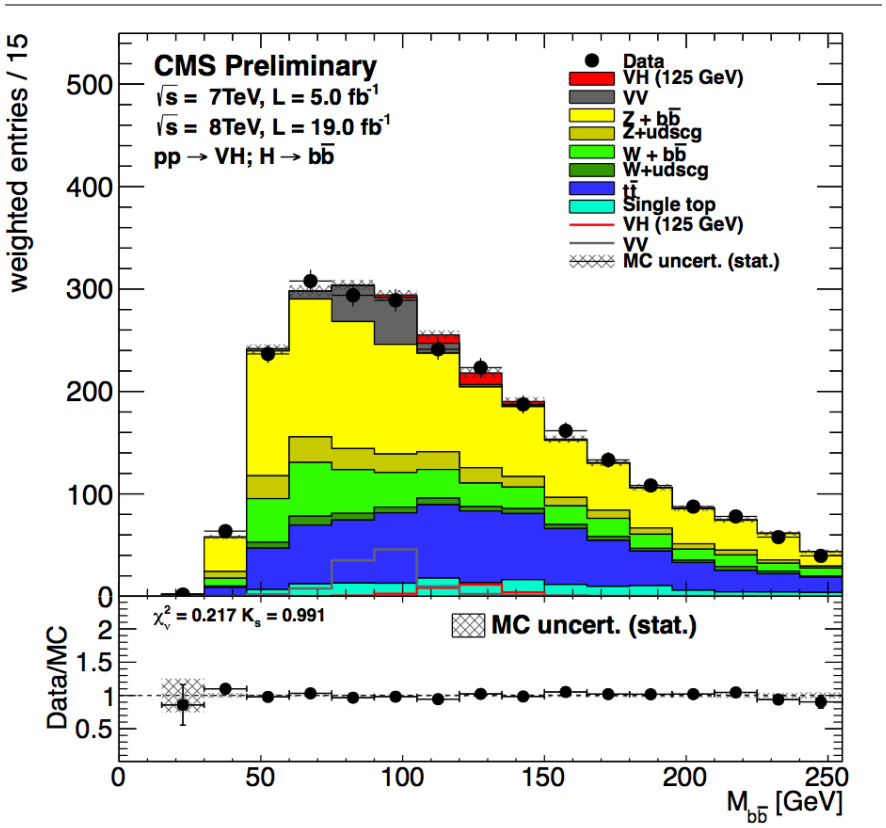


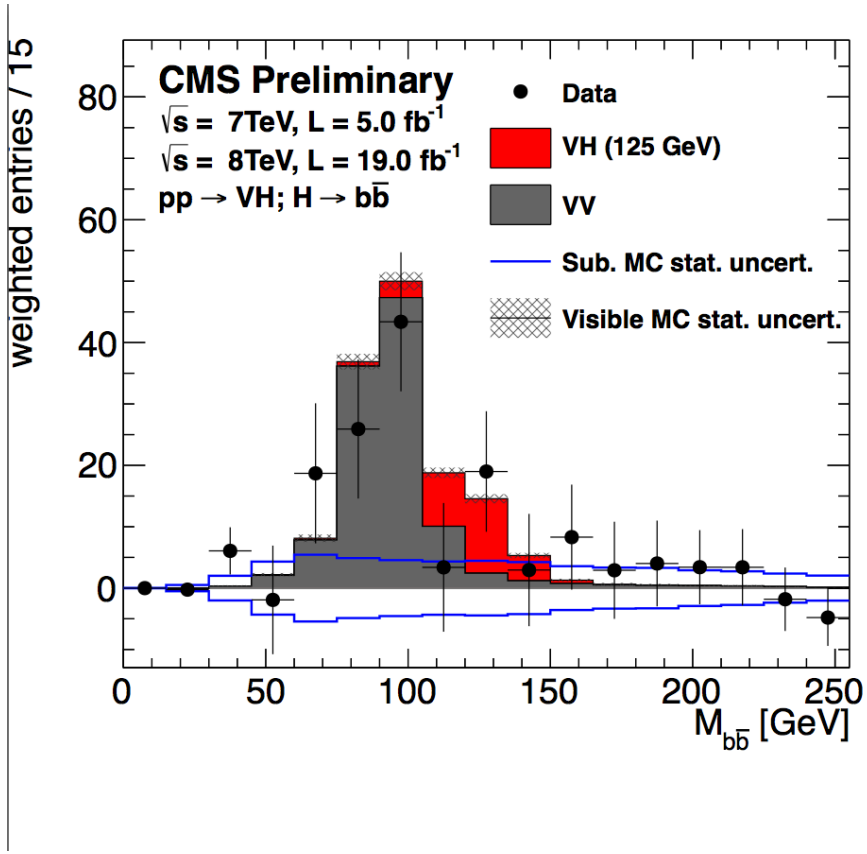


- V reconstruction: W → l ν, Z→ νν, Z → ll
- H→ bb reconstructed as two b-tagged jets recoiling against a high P_T W/Z boson
  - Large W/Z P_T ➔ smaller background & better di-jet mass resolution
  - Use b-jet energy regression ➔ improved H → bb mass resolution
- Events separated into categories , based on S/N (5 channels x 2 P_T(V) bins = 10)
- Use **data control regions** to constrain major backgrounds (V + jets, ttbar etc)
- Use MVA methods to discriminate between signal & background.

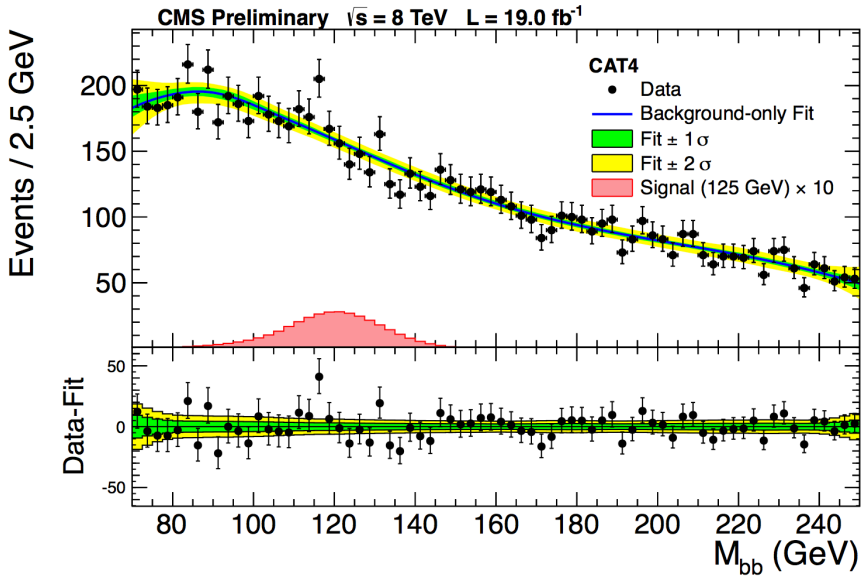
VH; H→ bb

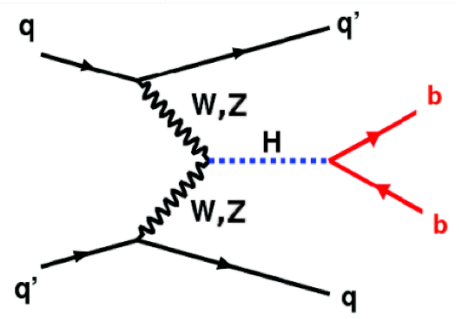
M_{bb} for all categories and 7+8 TeV



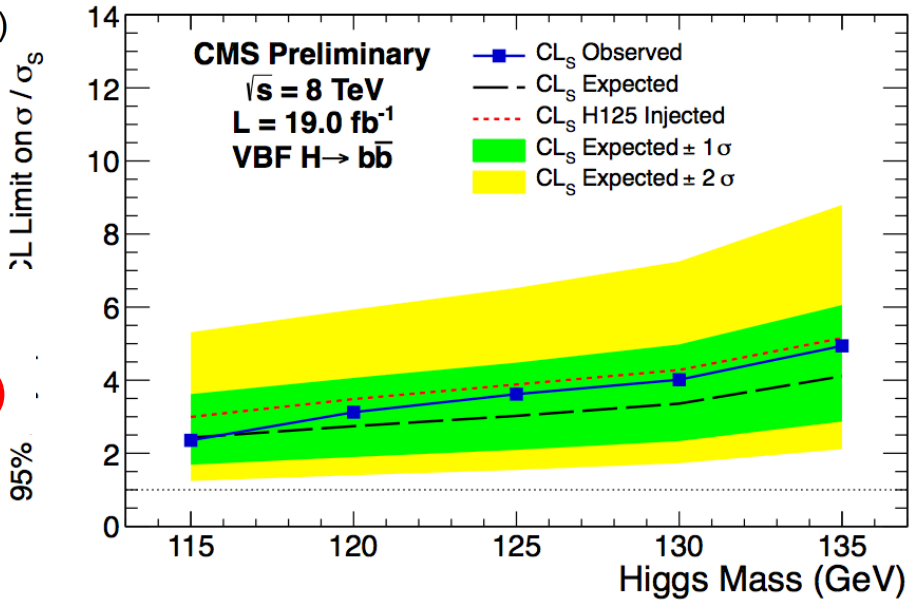


VBF; H → bb





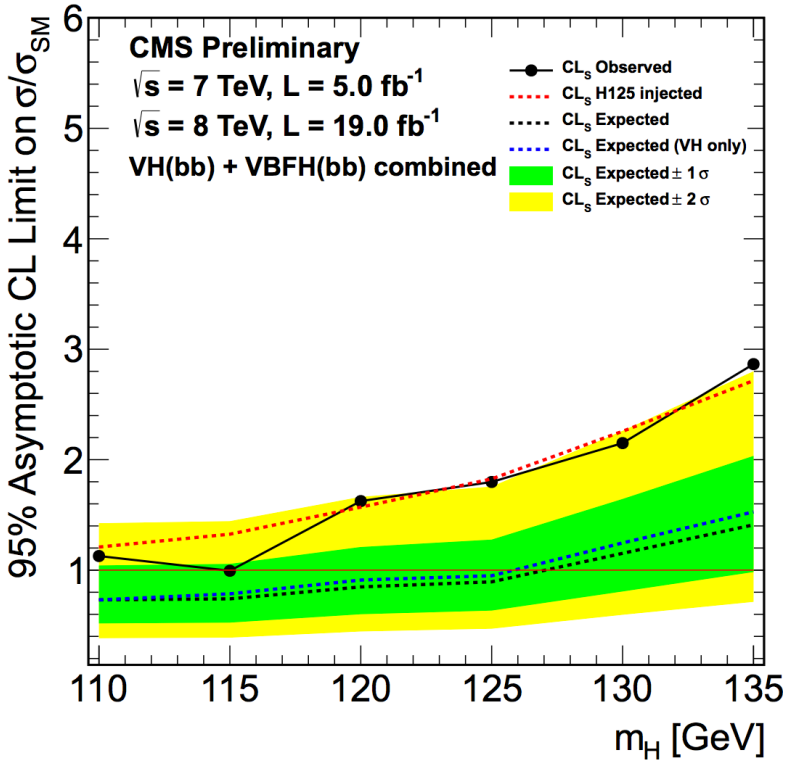
bb event + ≥ 2 non-b jets at large Δη

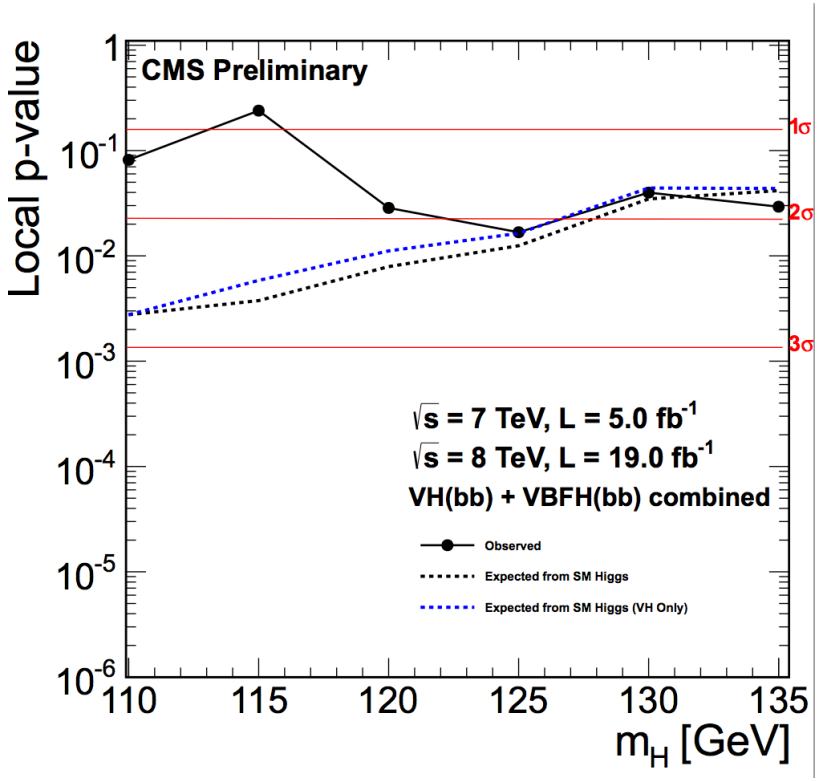


At 125 GeV the upper limit
on σ × BR = 3.6 × SM (3.0 exp.)

All H → bb Modes Combined

Combine the results of the VBF and VH processes for H→bb



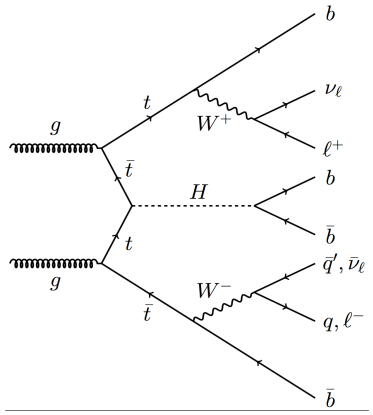


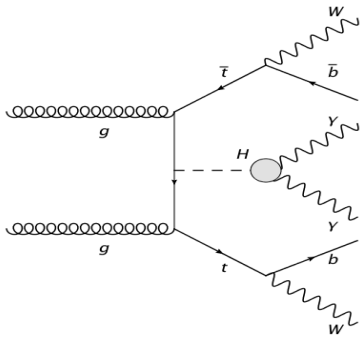
95% CL limit observed (expected) at 125 GeV: 1.79 (0.89)

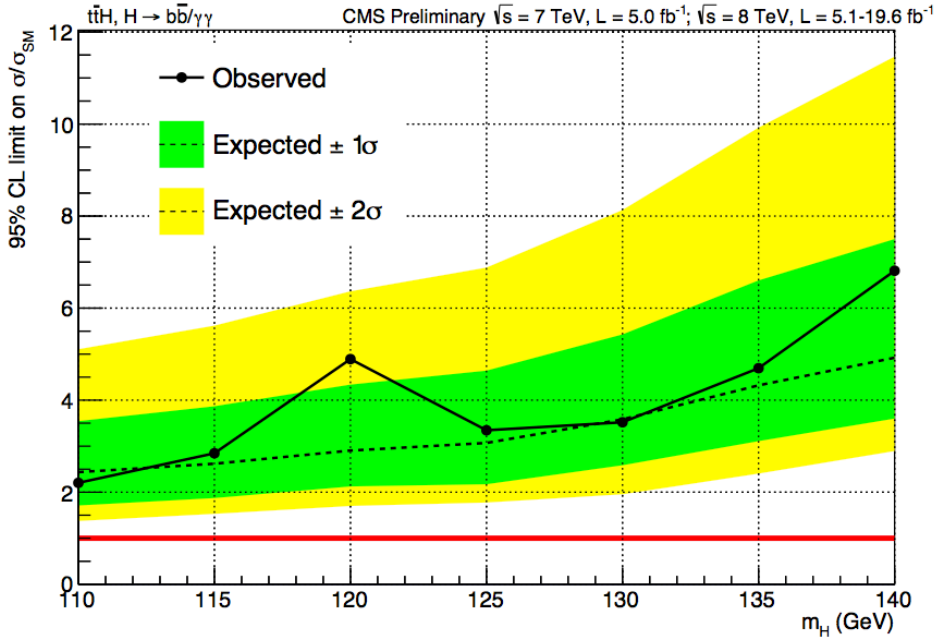
Significance observed (expected) at 125 GeV : 2.1σ (2.2σ)

Signal strength at 125 GeV: μ= 0.97± 0.48

Searches For tt+H →γγ & tt+H→bb Combined





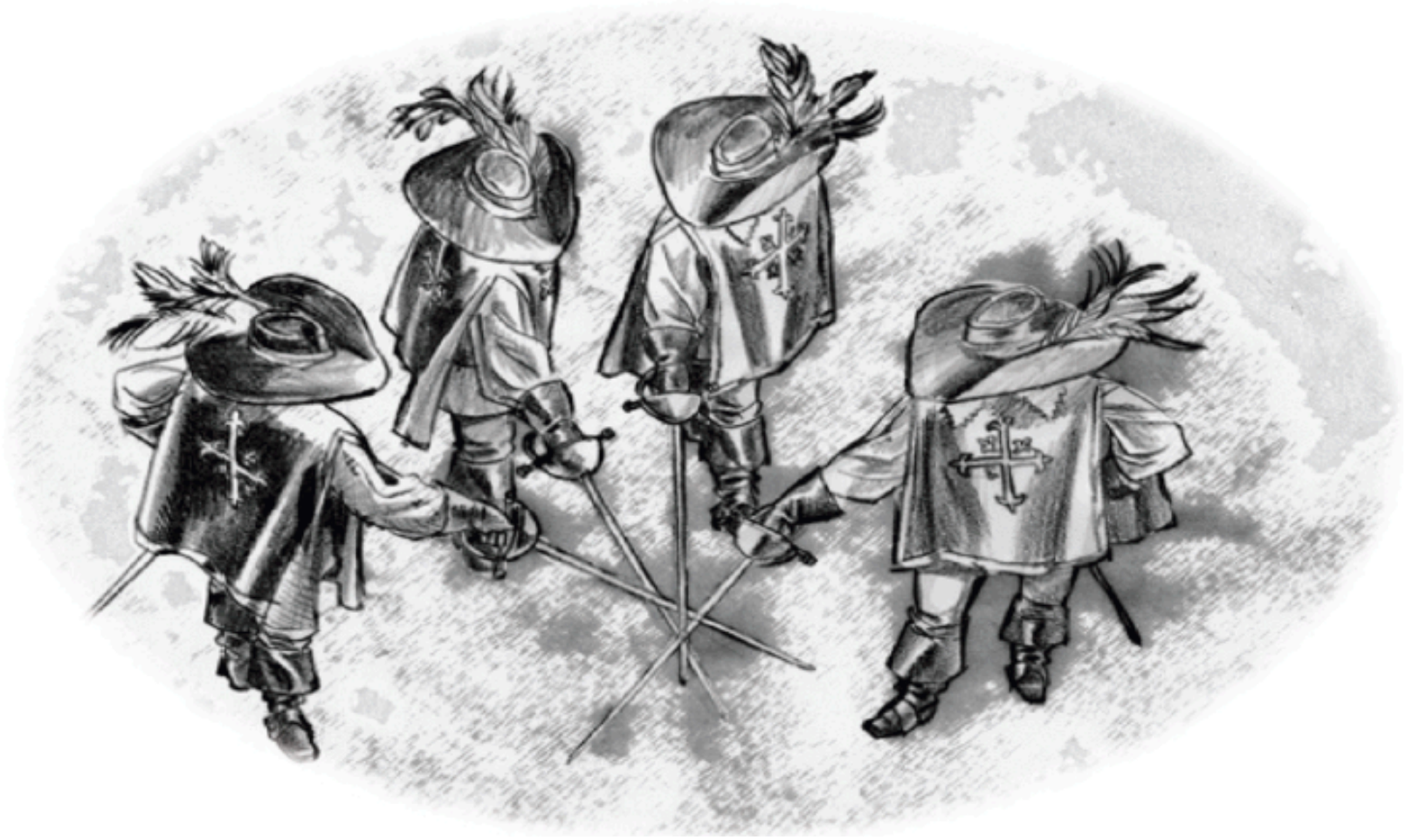


Observed 95% CL limit on σ/σ_{SM} at 125 GeV: 3.3

Expected 95% CL limit on σ/σ_{SM} at 125 GeV: 3.1

Sensitivity to 1-2 × SM within reach with full data set/all channels!

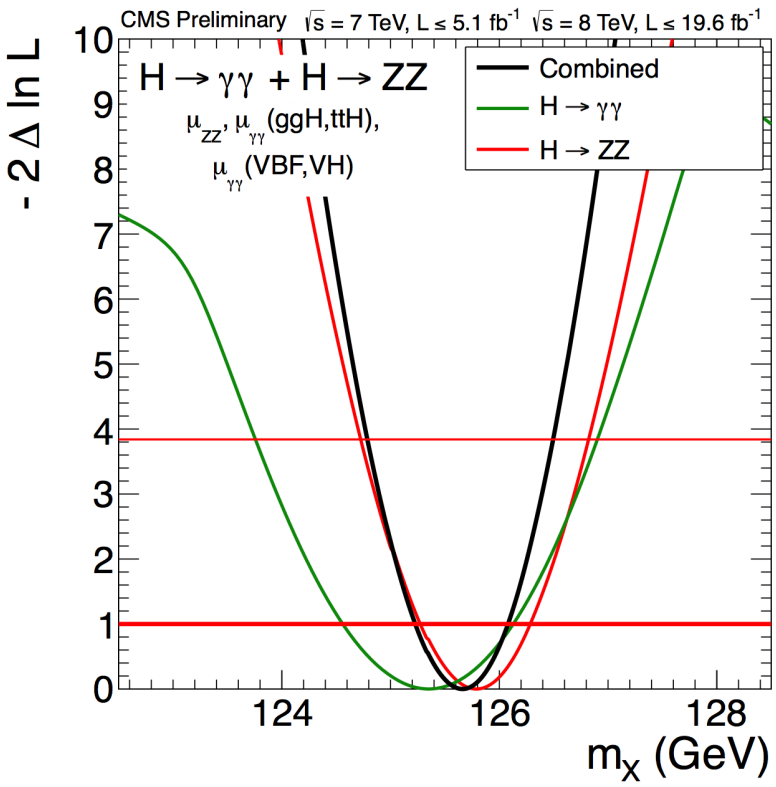
Combination Of All Higgs Measurements

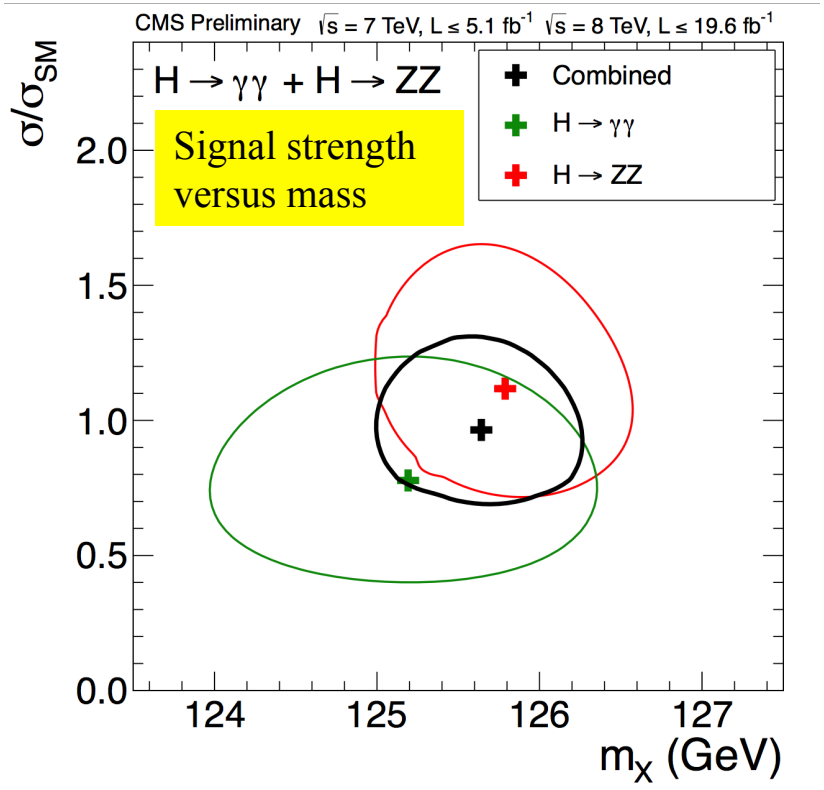


Higgs Boson Mass : Likelihood Scan

H →ZZ→4l: m_H = 125.8 ± 0.5 (stat.) ±0.2 (syst.) GeV

H →γγ: m_H = 125.4 ± 0.5 (stat.) ±0.6 (syst.) GeV





m_H = 125.7 ± 0.3$^{(stat)}$ ± 0.3$^{(syst)}$ GeV

= 125.7 ± 0.4 GeV

Low Mass Modes

CMS-PAS-HIG-13-005

For a mass of m_H = 125.7 GeV

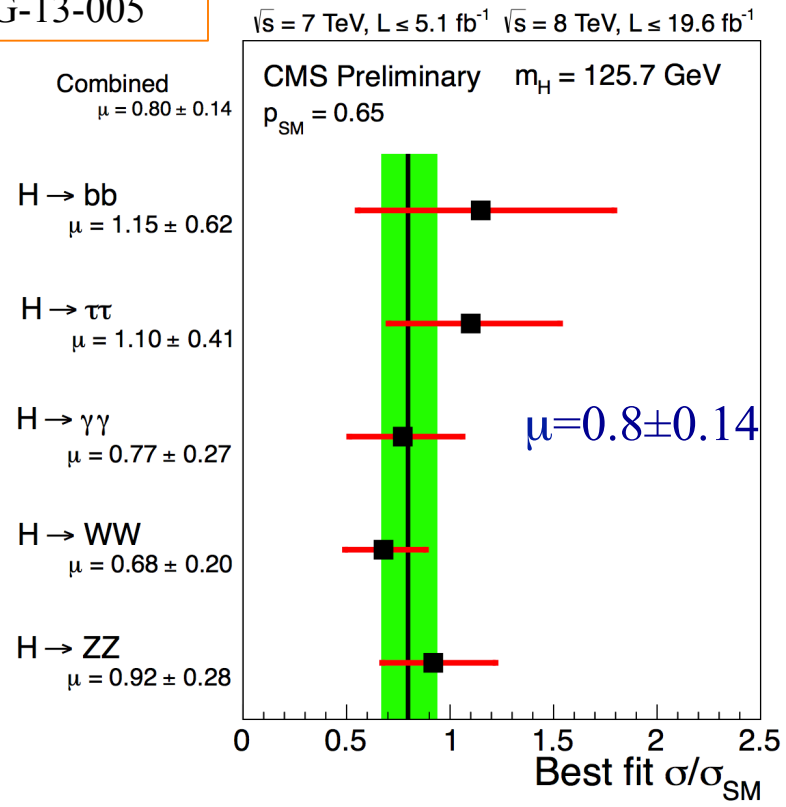
Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.1 σ
ττ	2.6 σ	2.8 σ

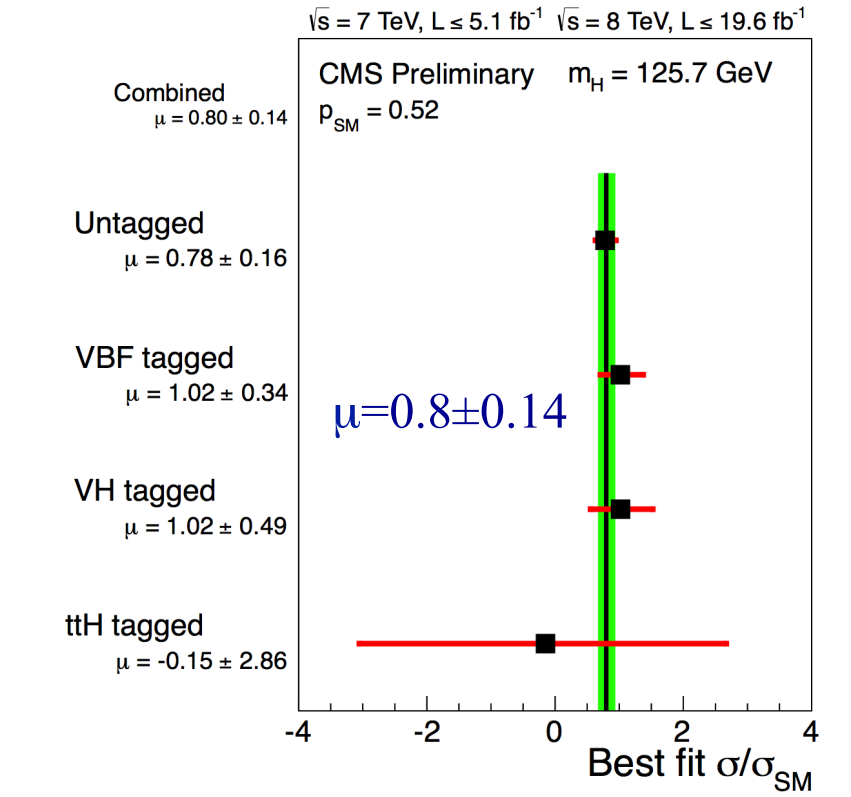
bb: includes VH and VBF
WW: includes ggF, VH, VBF

Measured Cross Sections Compared With SM

CMS-PAS-HIG-13-005

Here and onwards: bb results based on 12 fb^{-1} at 8 TeV and 5 fb^{-1} at 7 TeV





p-value= 0.65 w.r.t. μ=1

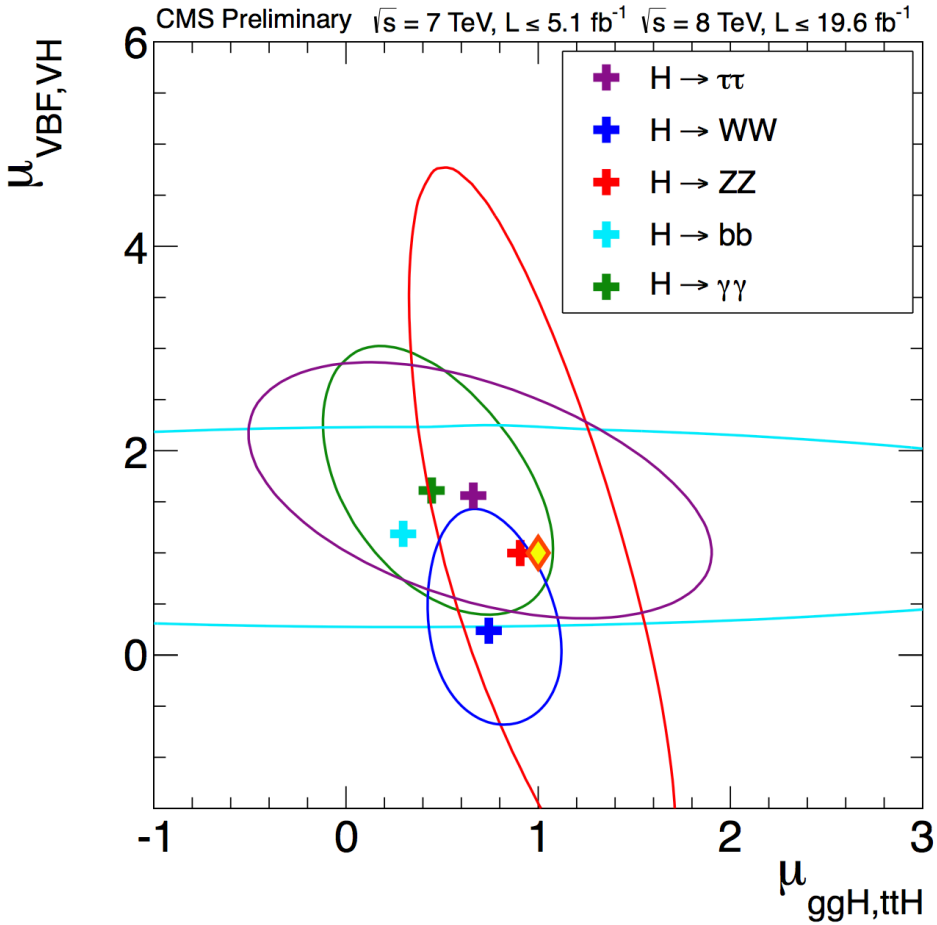
p-value= 0.52 w.r.t. μ=1

Combined signal strength: μ=0.80±0.14

Vector Boson Vs Fermion Coupling

2-dimensional view: test production modes in various decay channels

Vector Boson Couplings



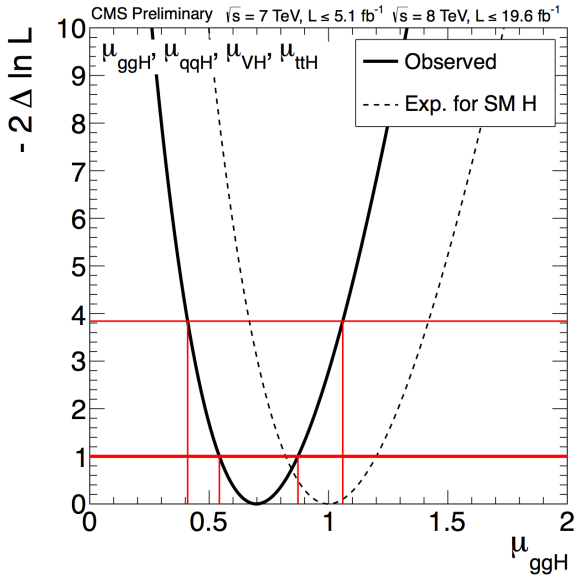
Fermion Couplings

Many more statistically limited tests described in CMS-PAS-HIG-13-005

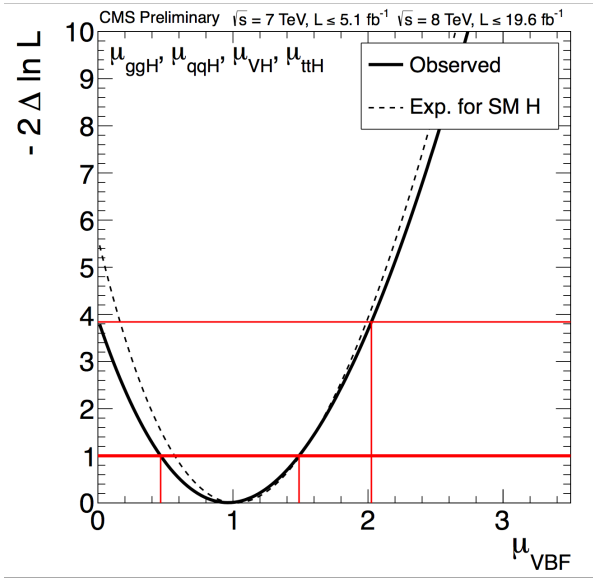
Signal Strength for Different Production Modes

Likelihood scans of $\mu=\sigma/\sigma_{SM}$, using all decay channels

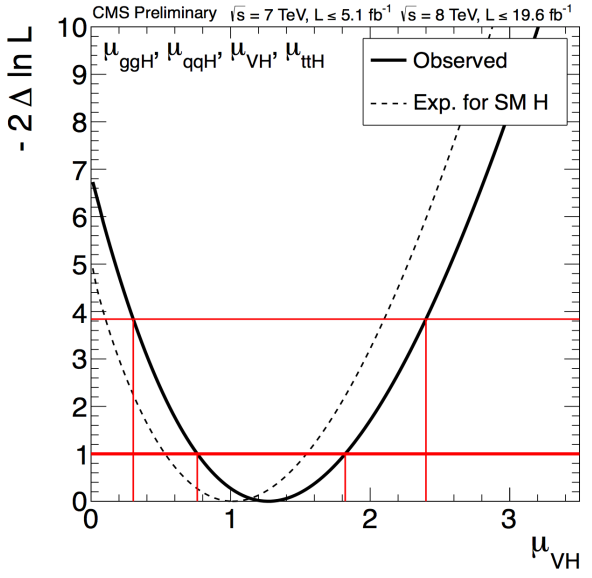
gg Fusion



VBF



VH

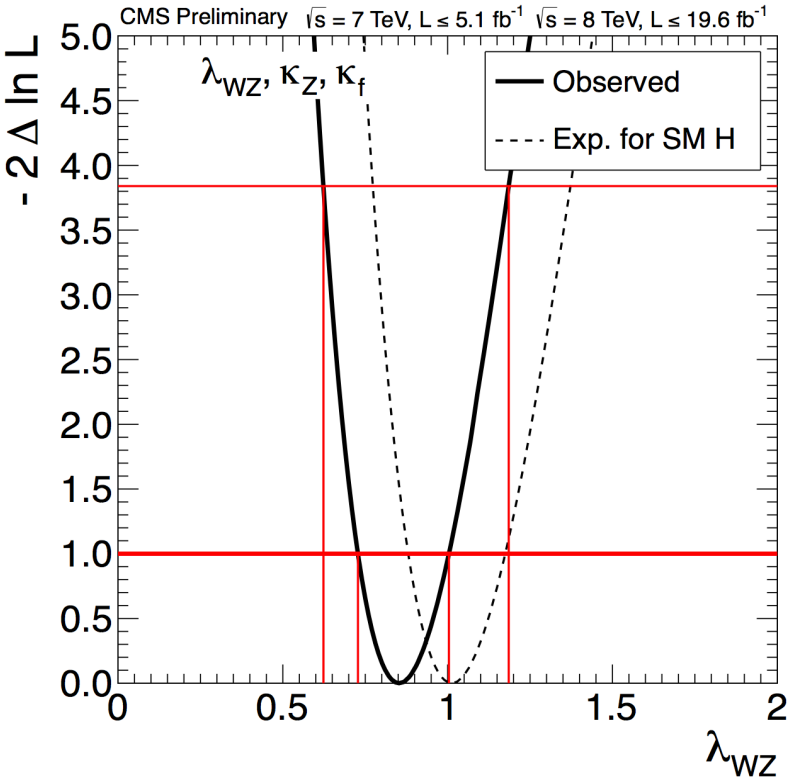


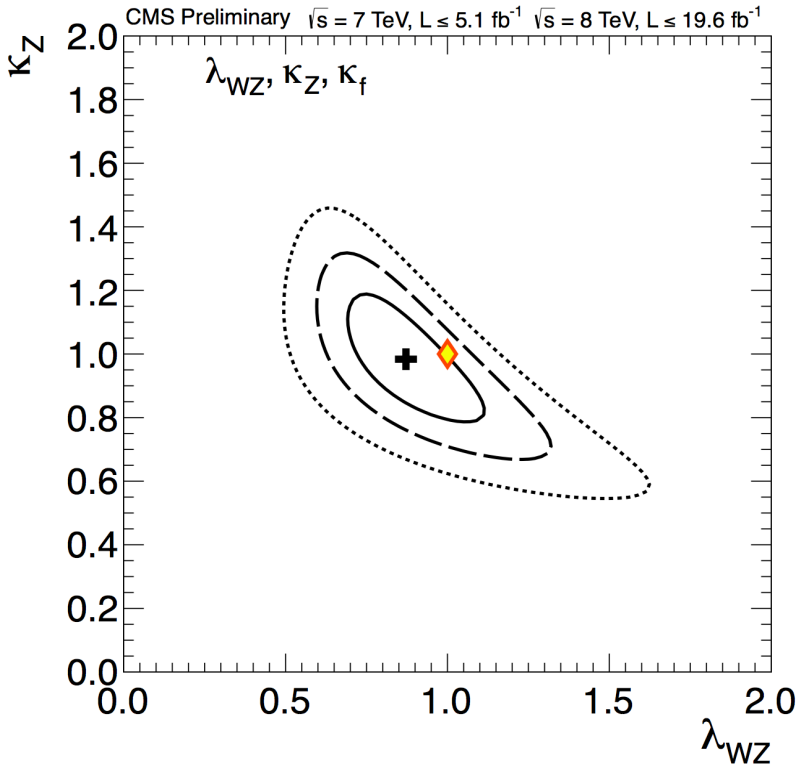
Data in good agreement with expectation

About 2σ significance for the VBF channel

Custodial Symmetry Test

Modify the SM Higgs boson couplings to the W and Z bosons by introducing two scaling factors κ_W and κ_Z and perform combinations to assess if $\lambda_{WZ} = \kappa_W/\kappa_Z = 1$ for $m_H = 125.7$ GeV



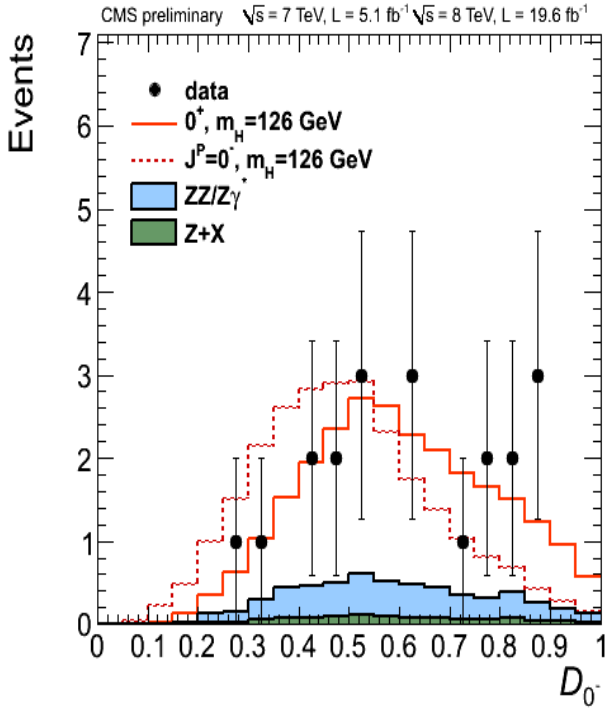


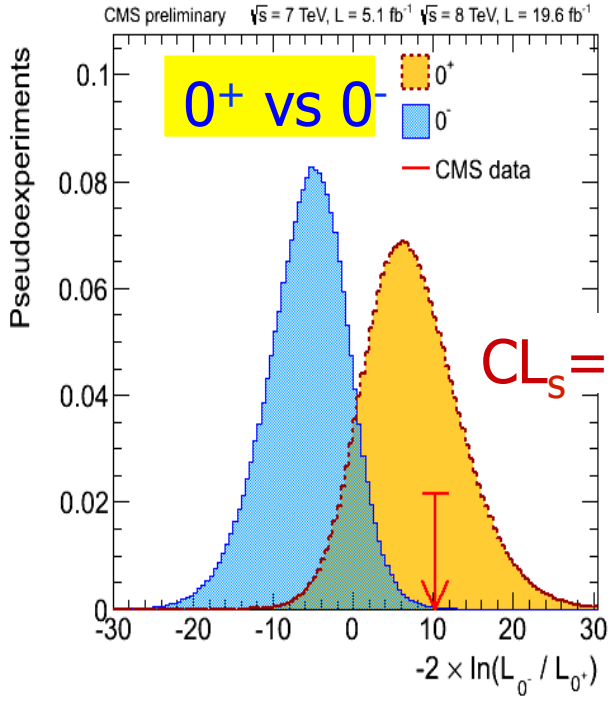
95% CL interval for λ_{WZ} : [0.62,1.19]

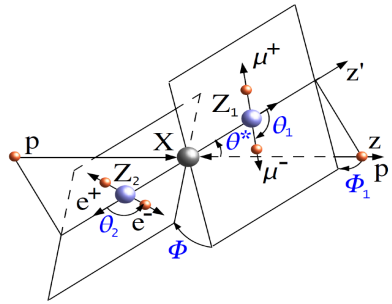
Spin/Parity Hypothesis Tests

Spin/parity hypothesis tests: $H \rightarrow ZZ \rightarrow 4l$ channel

Kinematic discriminant built to describe the kinematics of production and decay of different J^P state of a Higgs-like resonance







$CL_s = 0.16\%$

More J^P hypotheses have been tested in a similar way →

J^P	CL_s
0^-	0.16%
0_h^+	8.1%
2^+_{mgg}	1.5%
$2^+_{mq\bar{q}}$	<0.1%
1^-	<0.1%
1^+	<0.1%

Combination For Spin 0^+ Vs 2^+_{mgg} Test

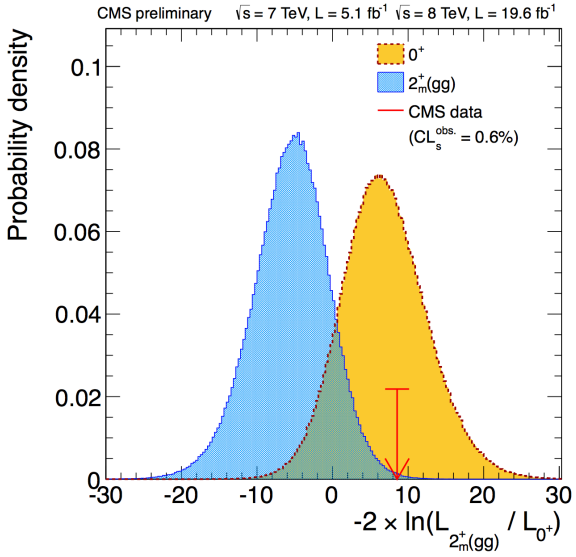
Combined results from WW and ZZ channel testing 2^+_{mgg}

- Expected results with μ=1

ZZ	WW	Comb
6.8%	1.4%	0.2%

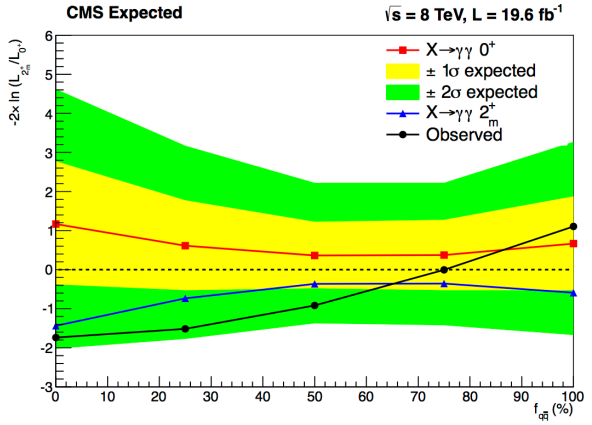
- Observed results at measured μ

ZZ	WW	Comb
1.4%	14%	0.6%



The observation is compatible with the SM Higgs expectations of 0^+. The data disfavours the $2^+_m(gg)$ hypothesis with a CLs value of 0.6%

CMS-PAS-HIG-12-016



Can use the γγ events to distinguish $0^+/2^+_{mgg}$

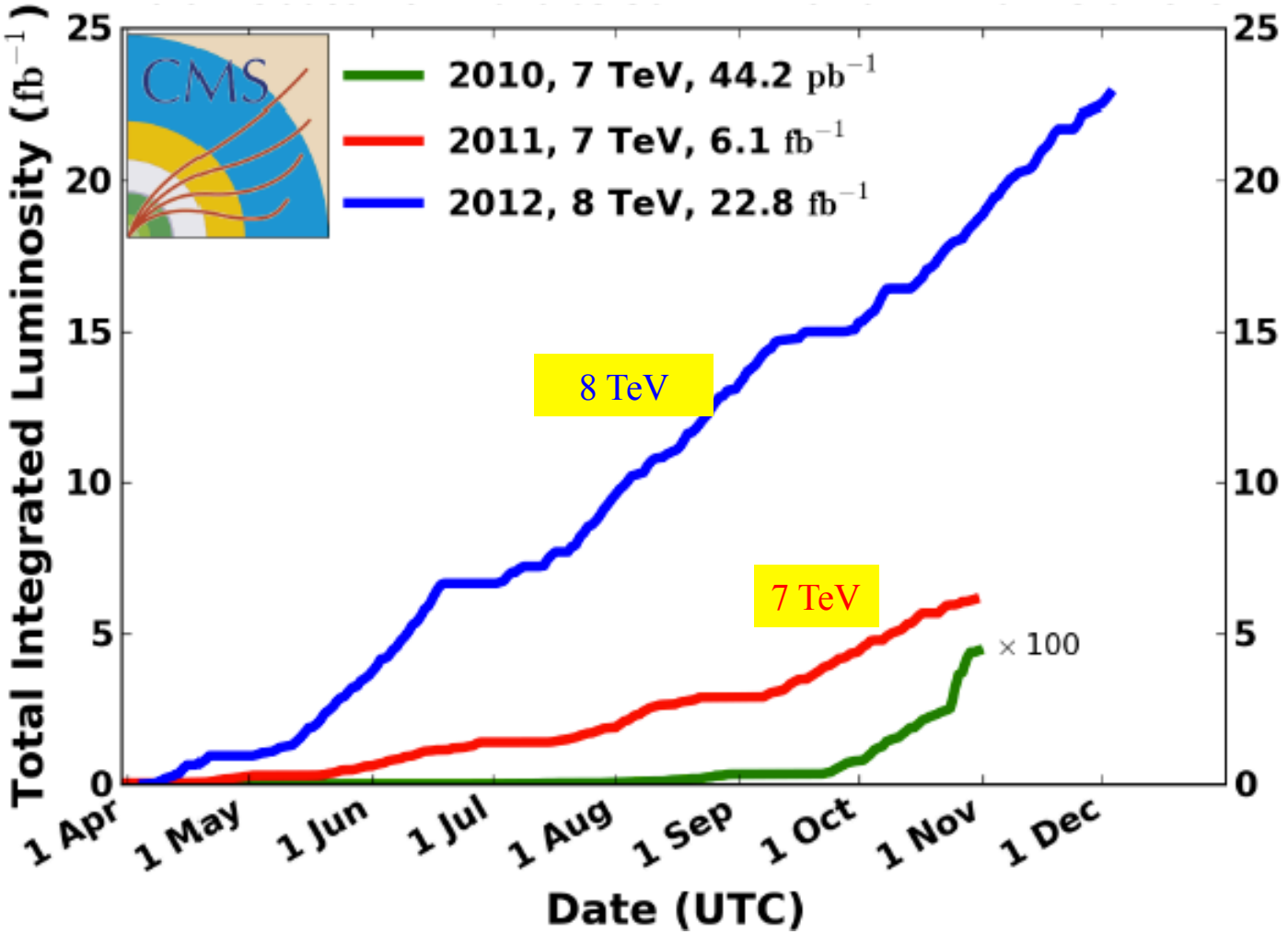
The present γγ data does not have the power for a significant hypothesis test

Summary

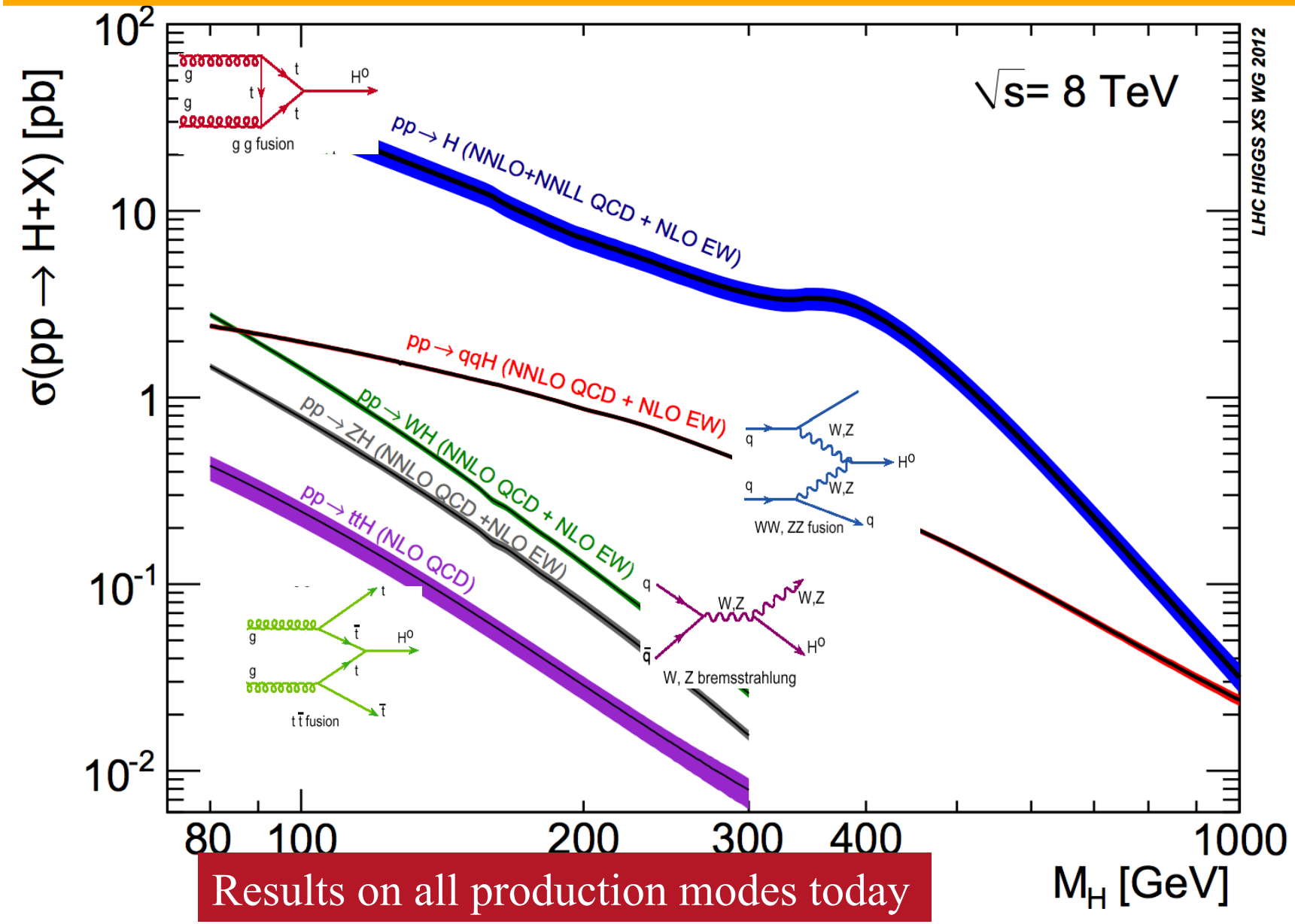
- New Resonance observed with $M = 125.7 \pm 0.4$ GeV
- Its spin/parity is compatible with a 0^+ state and not with (simple) 0^- or spin 2 states
- The couplings to bosons and fermions are consistent with SM predictions, but these are tested so far up to ~20-30% precision only
- From all properties investigated, within the limited statistics, the resonance looks consistent with the SM Higgs boson
- Additional statistics forthcoming in the 2015 run will provide a sharper portrait.

Spares

Most Results With Full 7 & 8 TeV Data

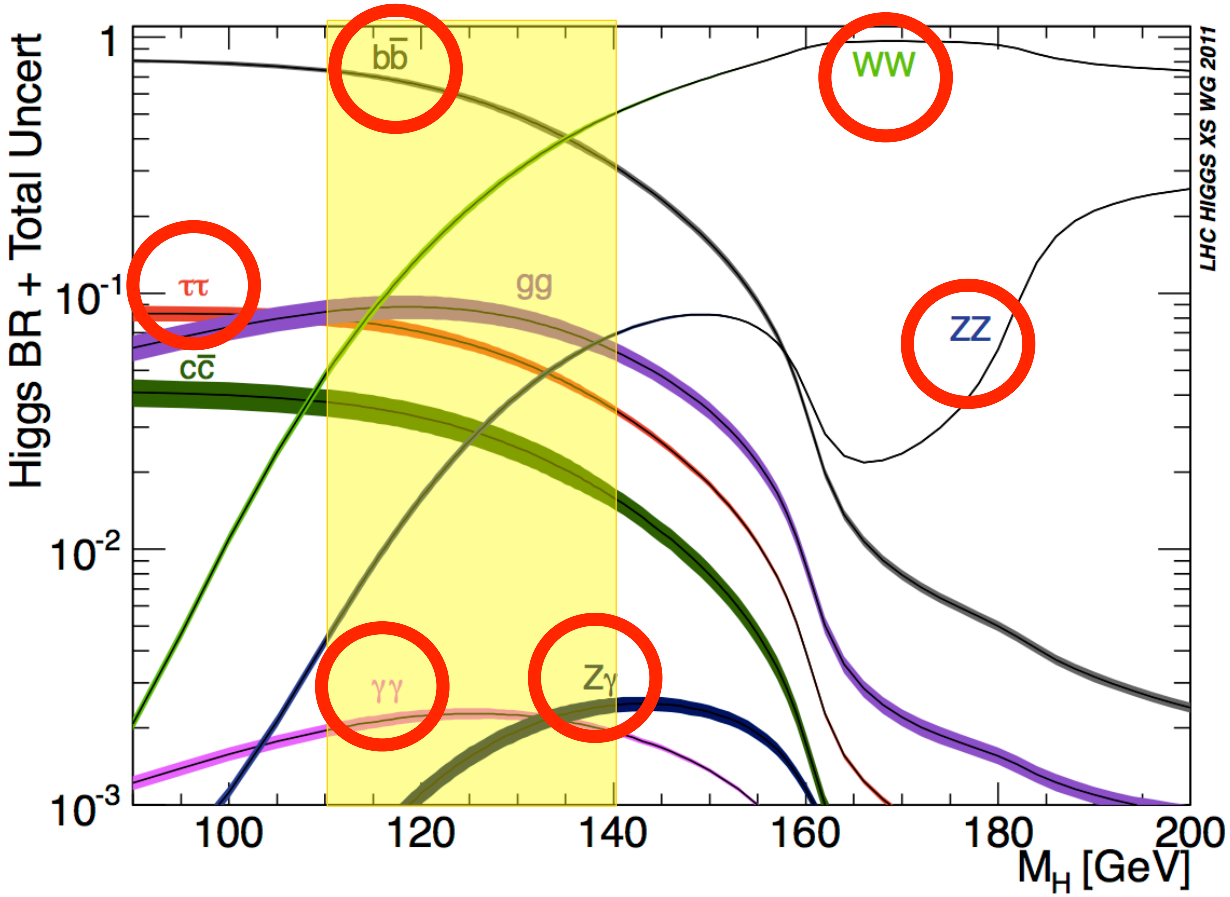


Higgs Production & Decay



Results on all production modes today

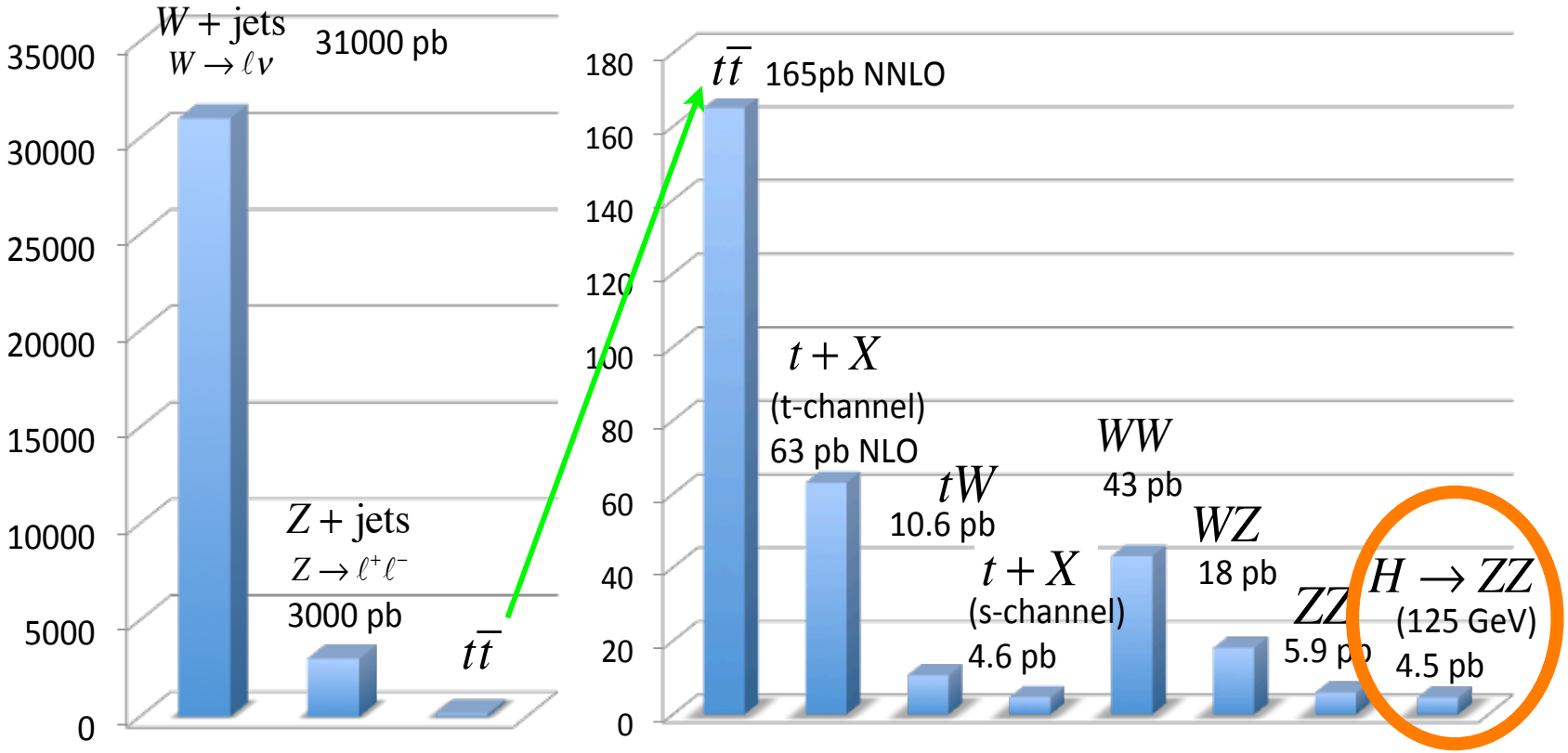
Low Mass Higgs Decay



At M_H = 125 GeV, only ~11 % of decay (H → gg, cc) undetectable

Cross Sections for Key SM Background Processes

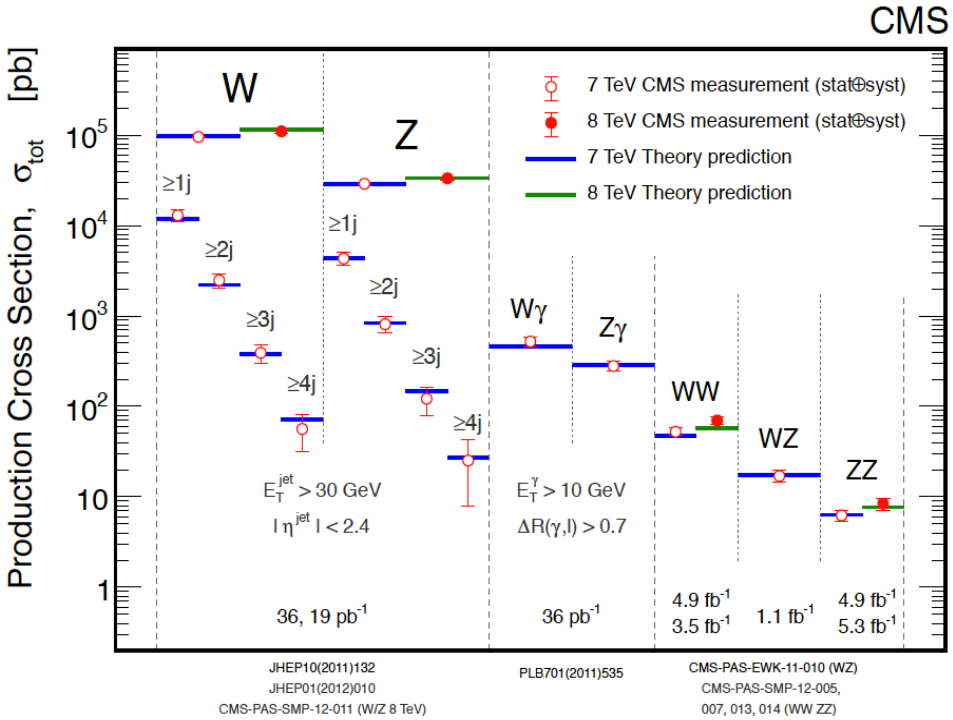
Backgrounds up to 5 orders of magnitude larger than signal !



Need to measure these cross sections & properties

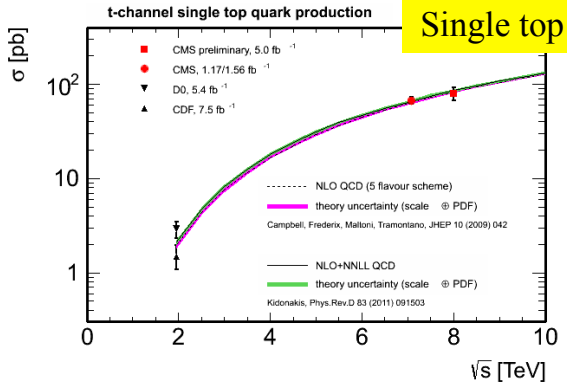
Key Standard Model Processes

Electroweak Measurements

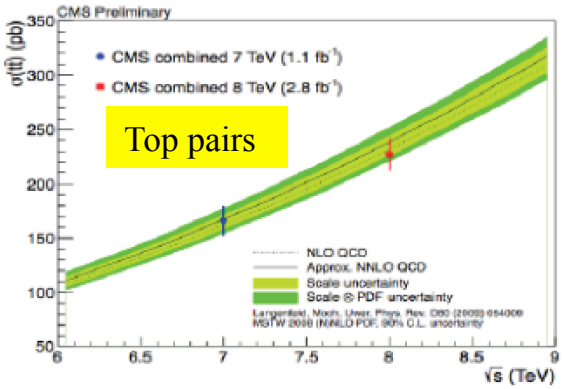


Top Quark Cross Sections

Single top



Top pairs



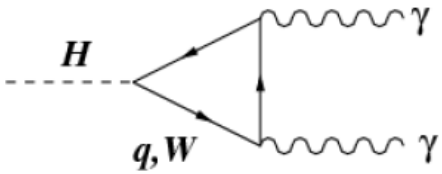
Good understanding of detector, simulation + accurate theory predictions

→Good knowledge of the backgrounds to the Higgs analyses

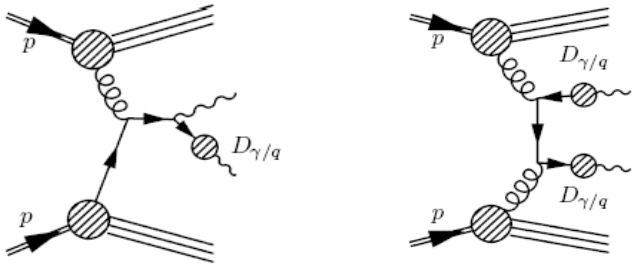
→Whenever possible, measure backgrounds from data control regions

H → γγ

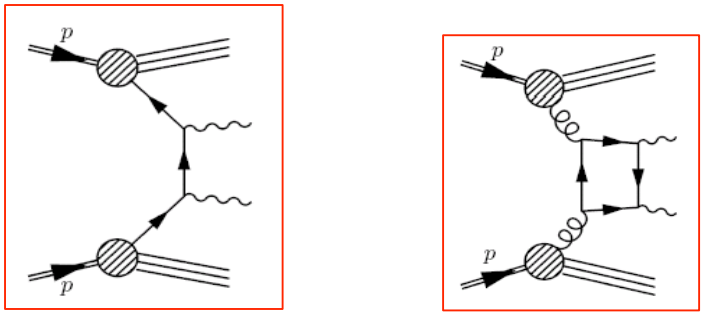
- Even though Br (H→ γγ) ≈ 10^{-3}
  - its a discovery channel in 110 < M_H < 150 GeV



- Search for a narrow peak with two isolated high E_T photons over a continuous di-photon background spectrum
- Background is large and composed of
  - Reducible: One or more misidentified (fake) photon (e.g. γ+jets)



- Irreducible: both photons are real



4^{th} July Results

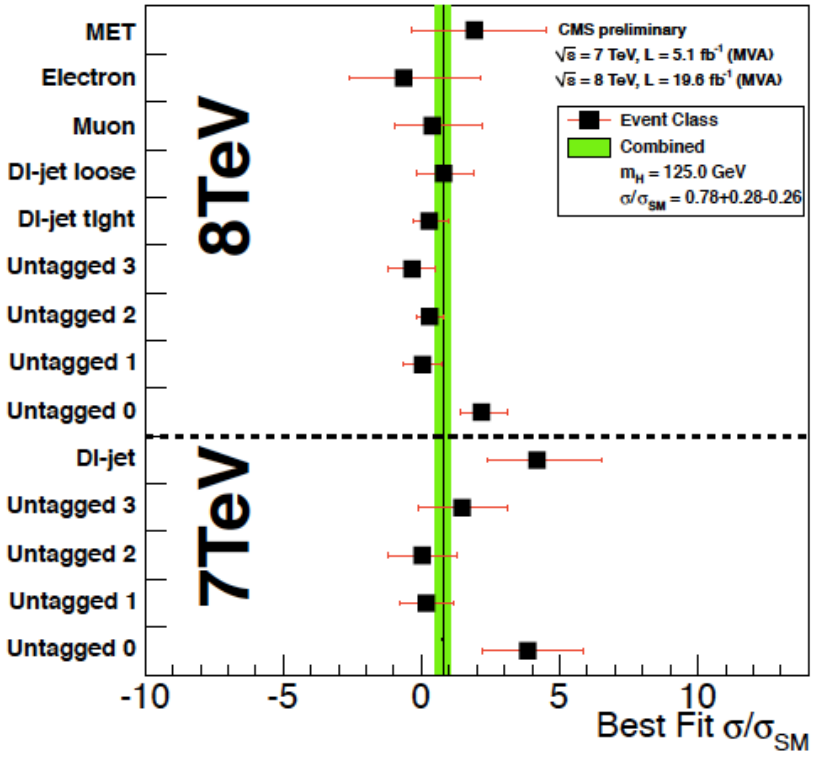
Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.8	3.2
$\tau\tau$ + bb	2.4	0.5
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

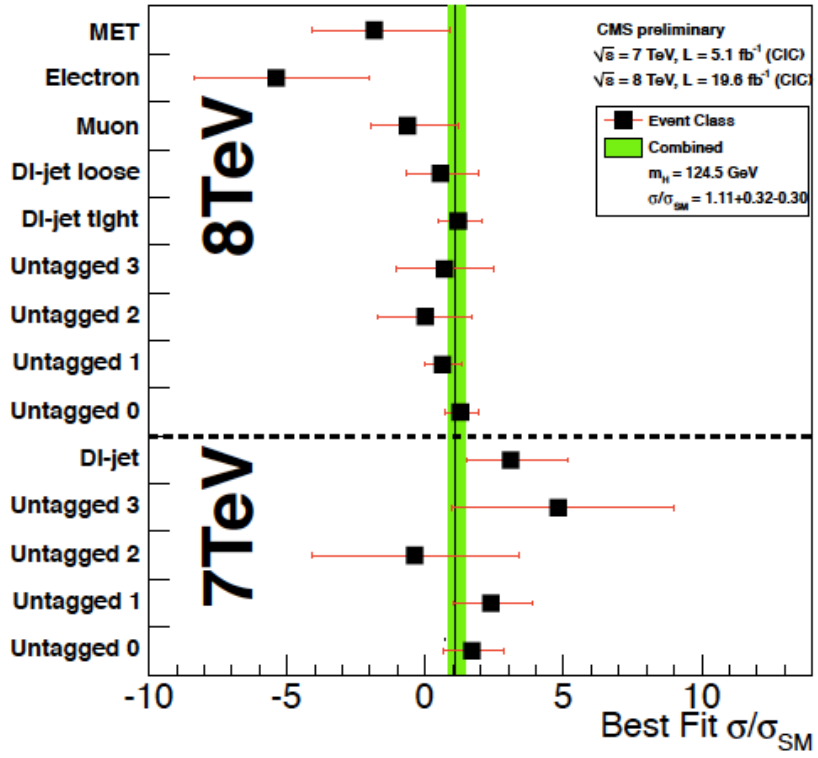
Yields By Data Set

	mass-fit-MVA (at $m_H = 125\,\text{GeV}$)	cut-based (at $m_H = 124.5\,\text{GeV}$)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.30}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

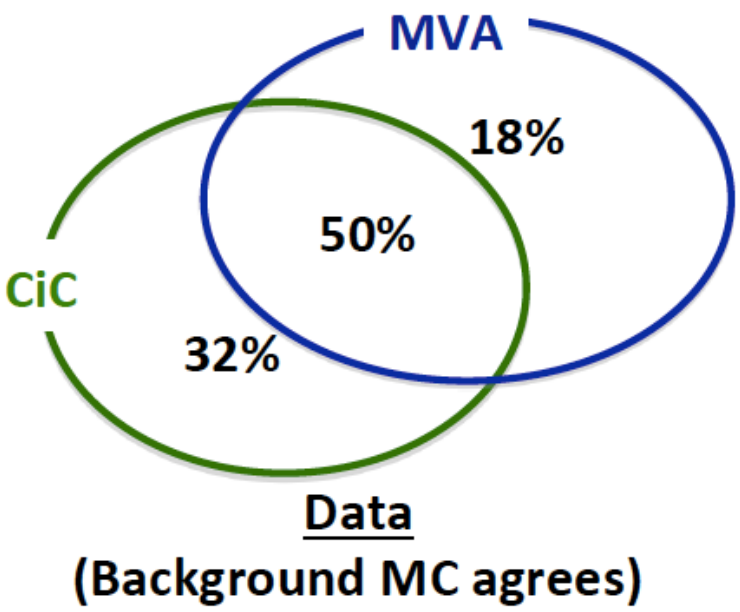
1.5 sigma

Table 4: The values of the best fit signal strength for the different datasets and analyses.

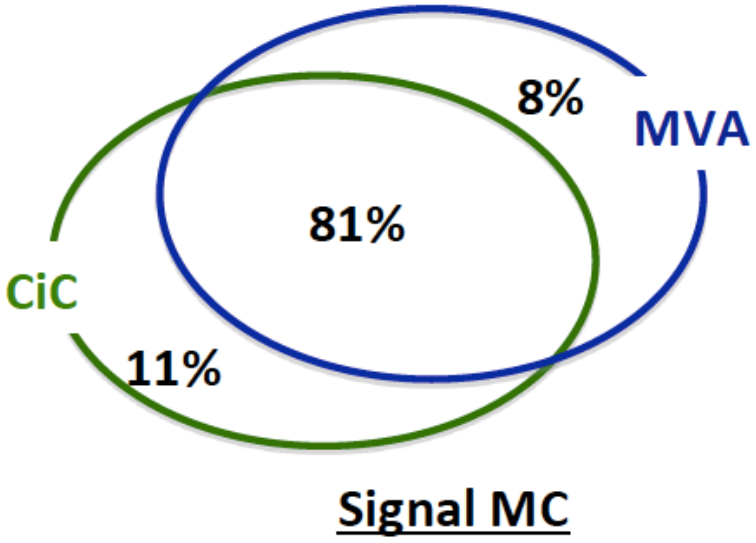




Overlap Between Cut Based & BDT Event Samples



Data
(Background MC agrees)



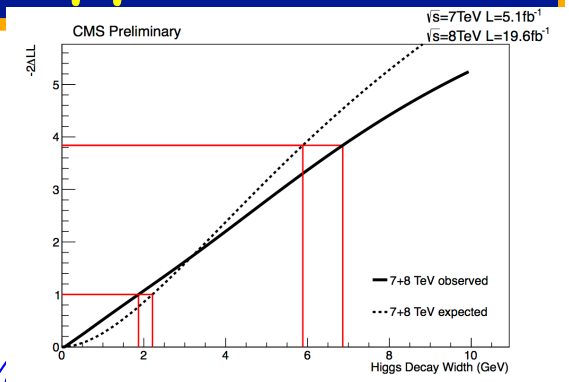
Signal MC

Higgs Properties from H→γγ

CMS-PAS-HIG-13-016

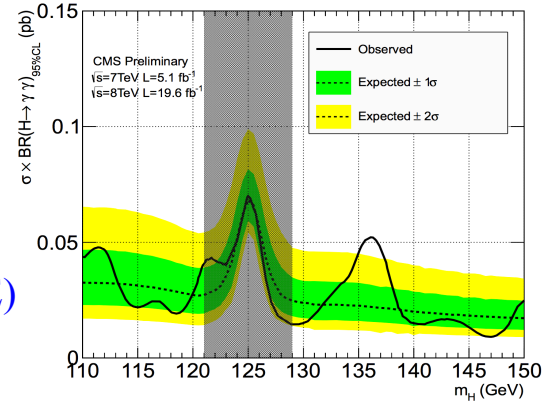
Upper limit on the Higgs width

- Dominated by experimental resolution
- Breit-Wigner + Gaussian fit
- Observed (exp) upper limit = 6.9 (5.9) GeV 95%



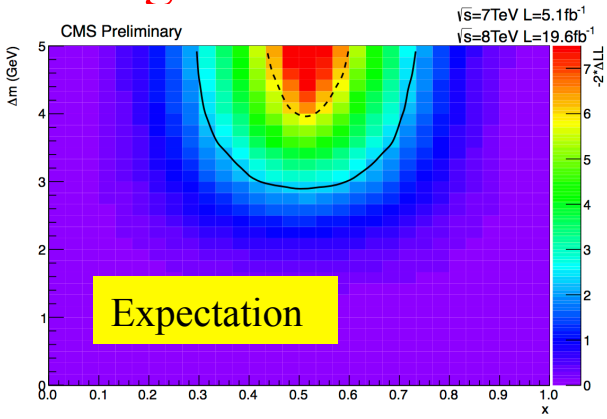
Additional Higgs-like states:

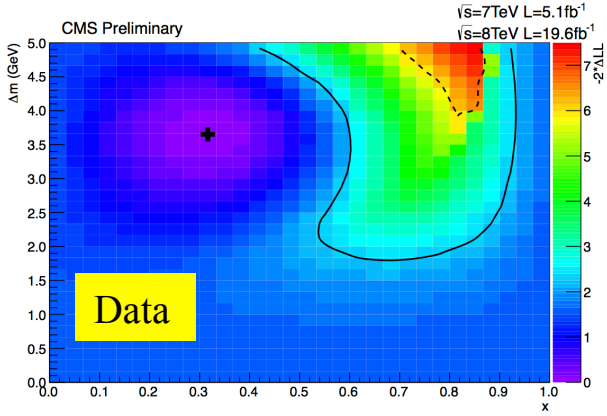
- Take SM 125 GeV as part of the background
- Search for additional Higgses
- Largest excess: 136.5 GeV with 2.9σ (<2σ after LEE)



Search for near mass degenerate states

- Two signals with relative strength x mass difference Δm
- Perform a 2D scan
- No signal at 95% C for Δm> 4 GeV

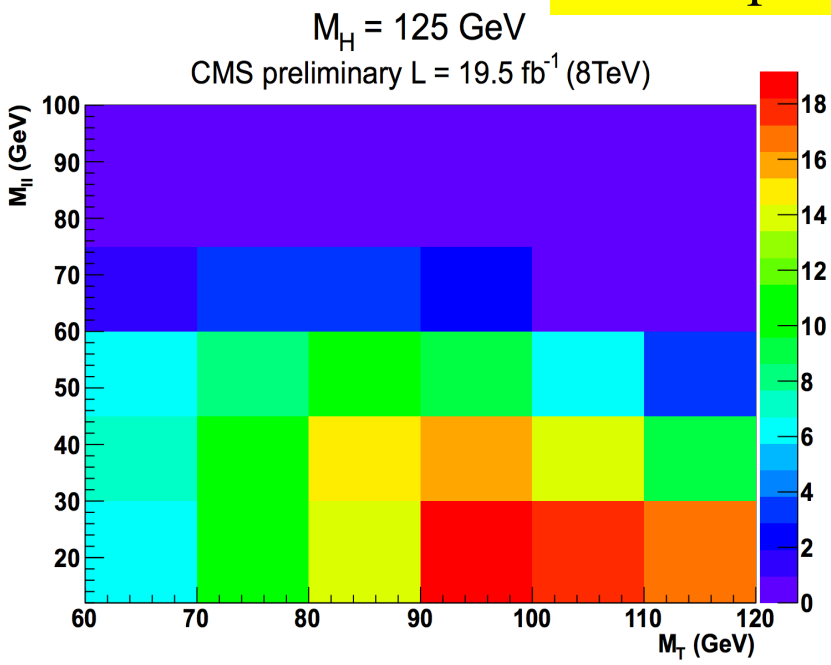


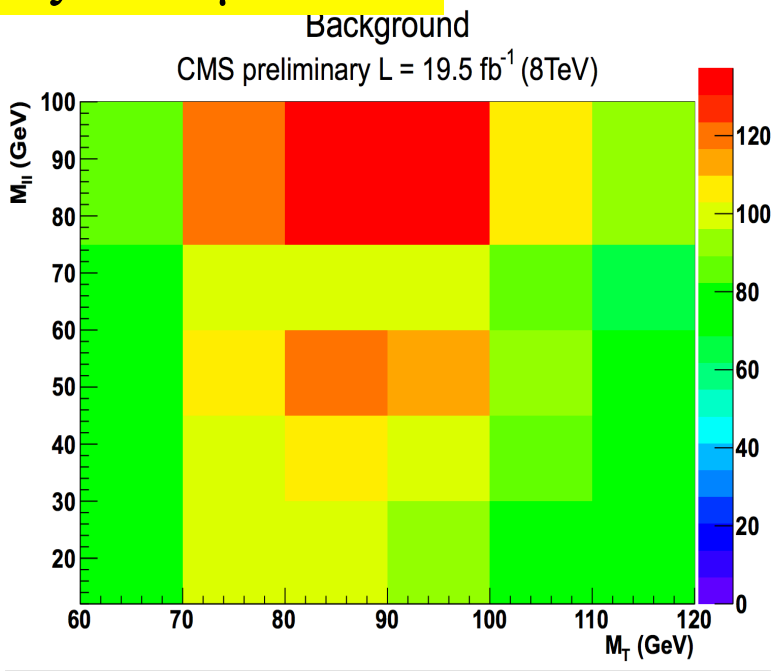


H → WW(*) → (l ν) (l ν)

- Analysis of WW+0 jets and 1 jets categories
  (W+2jets (VBF) channel is in progress)
- Cut based analysis for same flavour lepton events and 2-dimensional M_T - M_{ll} analysis for different flavour events $M_T = \sqrt{2p_T^{\ell\ell} E_T^{miss} \cos(\Delta\phi_{\ell\ell} - E_T^{miss})}$

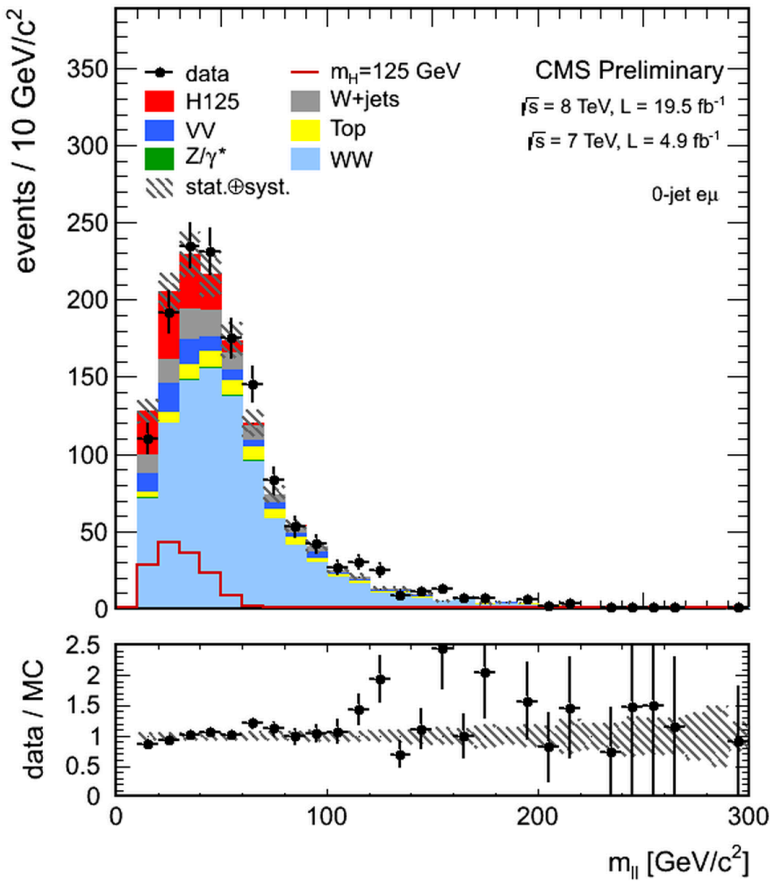
2D Shape analysis : eμ events

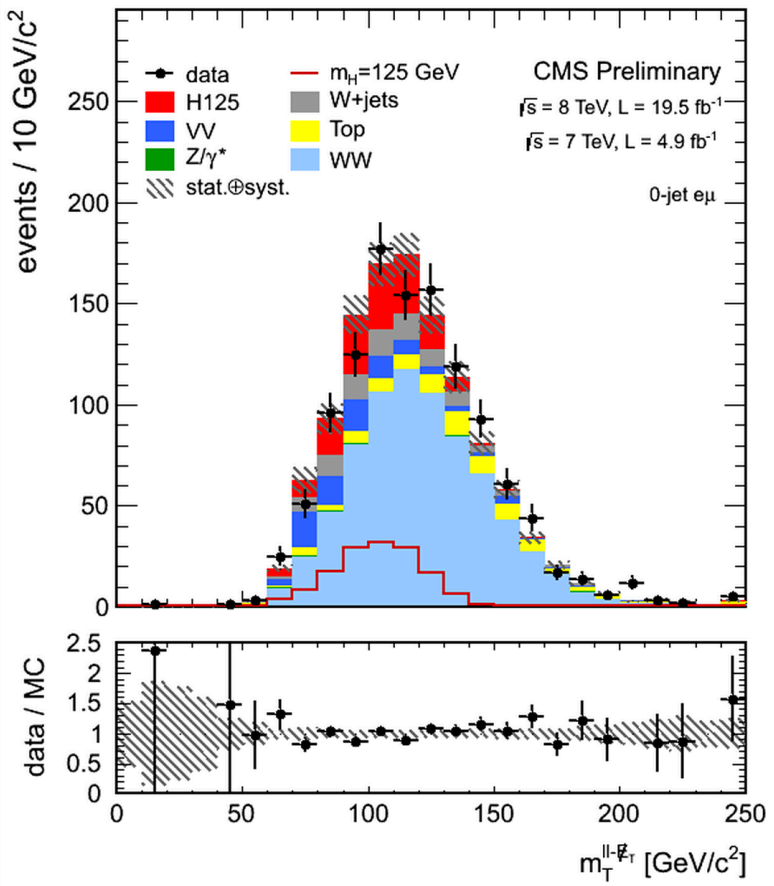




H → WW(*) → (e ν) (μ ν) Shape Analysis

Events with 0 jets and different flavour leptons (7+8 TeV Data)

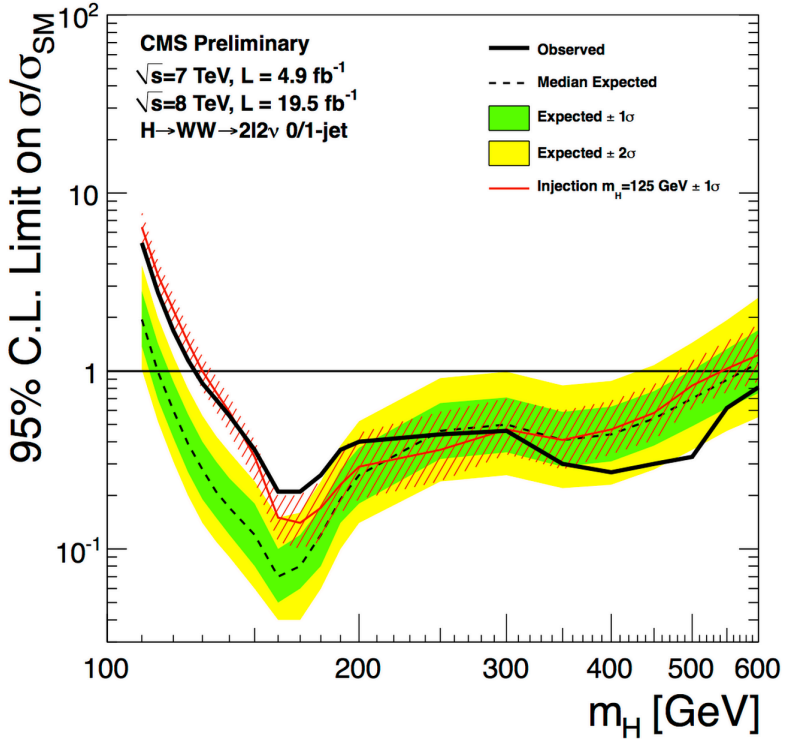




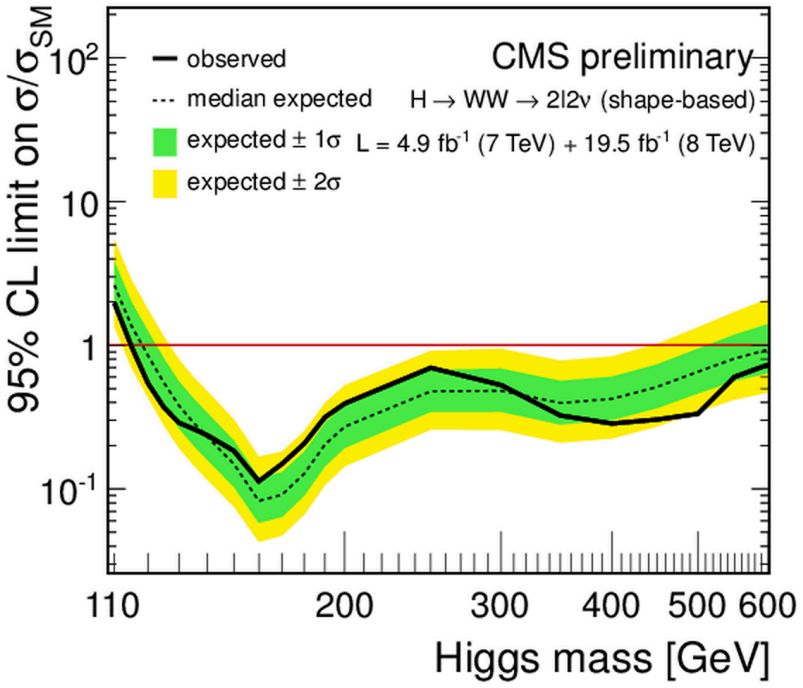
A significant excess is observed

H → WW(*) → (l ν) (l ν) Shape Analysis

Higgs Search Analysis



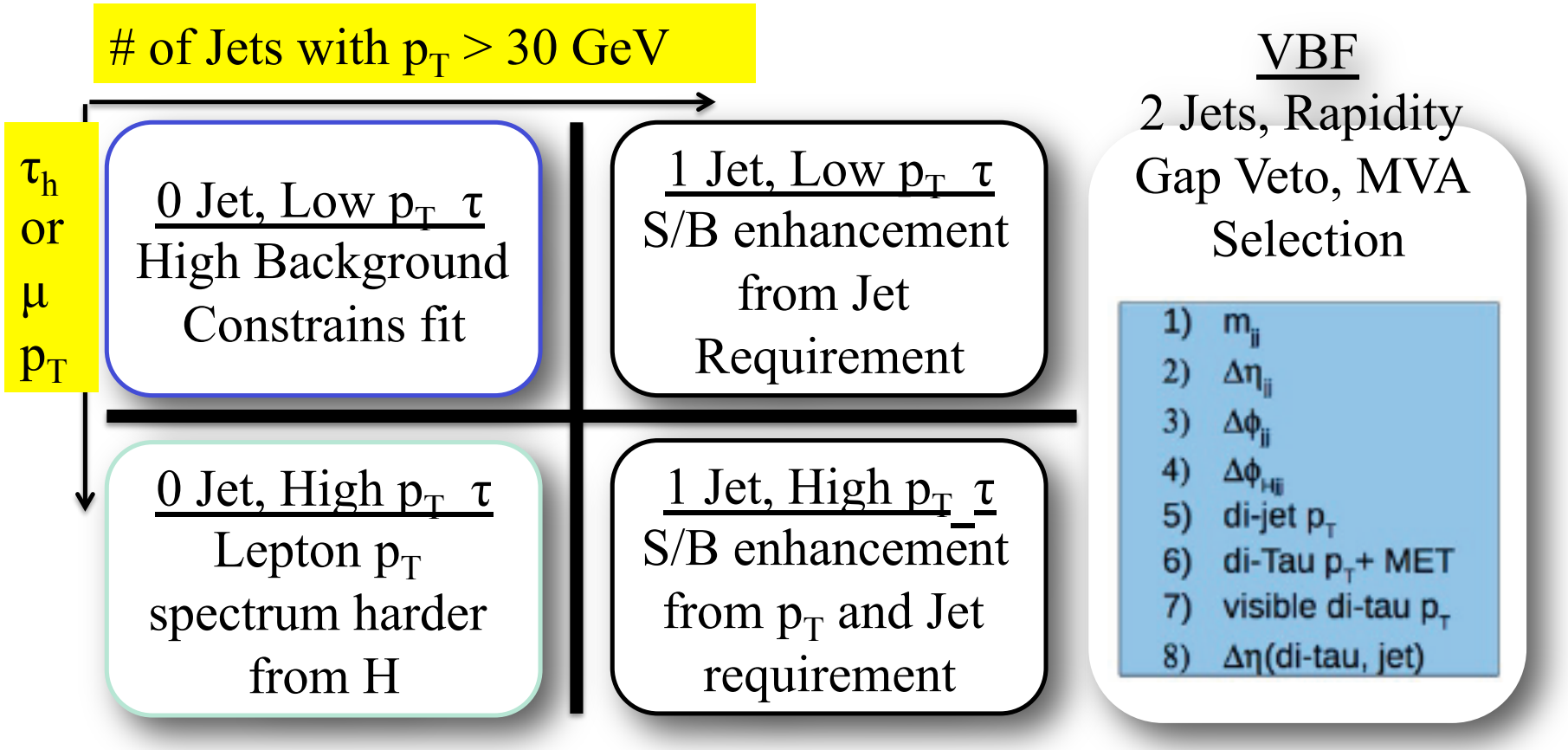
Using m_H = 125 GeV as a "Background"



- Exclusion at 95% CL in the mass range 128-600 GeV
- Large excess in the low mass region
- When including M_H=125 GeV as part of the background, no significant excess is seen over the entire mass range

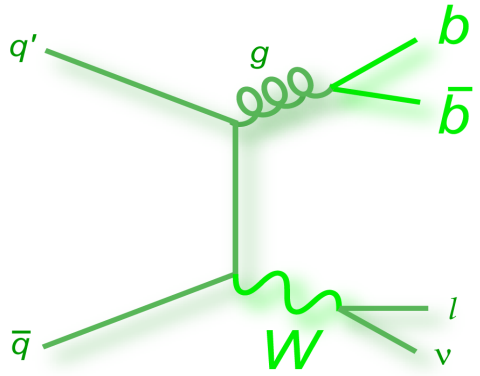
H → ττ Search Strategy

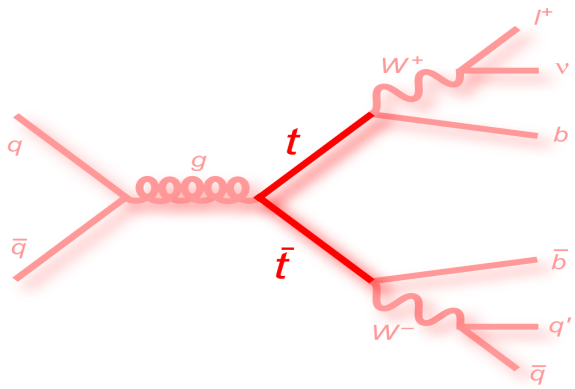
- Search divided in 5 categories based on H→ττ mass resolution & S/B



- All categories are fit simultaneously

Backgrounds in H→ bb Search





Reducible backgrounds:

- QCD (strongly suppressed by lepton isolation and Pt)
- V+udscg,V+bb @ low p_T and mass
- W(→lν)W(→jj)
- ttbar and single top (→Wb)

Irreducible backgrounds:

- V+bb @ high p_T and mass
- ZZ(→bb), W(lν)Z(→bb)

Important discriminating variables

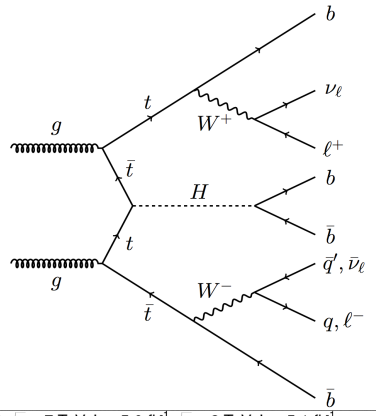
- Mass resolution (separation of VH from VV)
- b-tagging ➔ suppression of V+light quarks
- Back-to-back topology
- Additional jet activity in the event (ttbar)

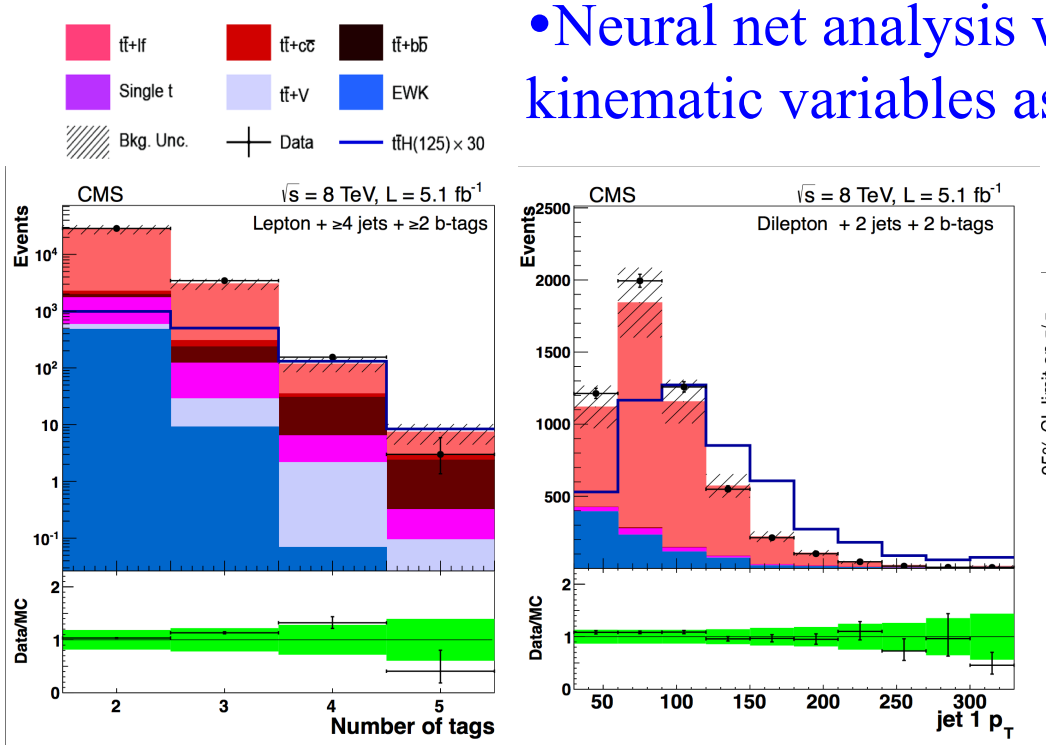
ttH; H → bb

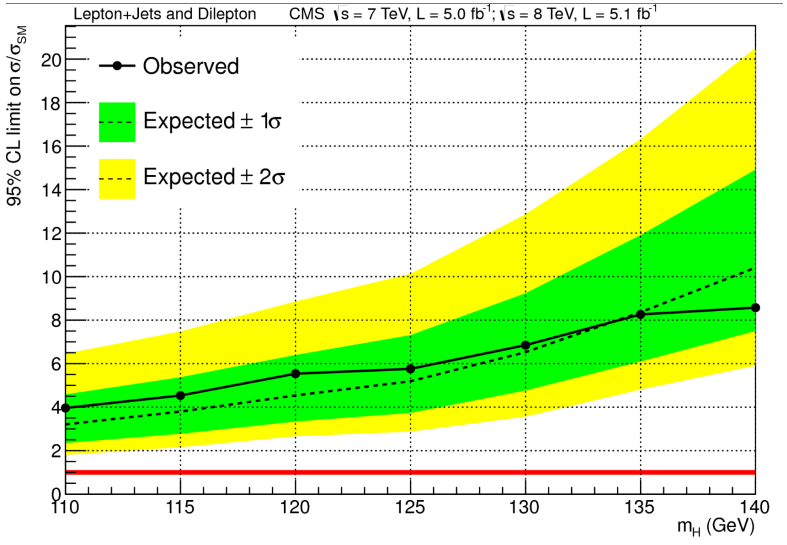
5/fb at 7 TeV +
5/fb at 8 TeV

- Identify ttbar decays into di-lepton and lepton+jets states
- Search for H → bb in them
- Neural net analysis with kinematic variables as input

CMS-PAS-HIG-12-035
Publ. JHEP05 145 (2013)



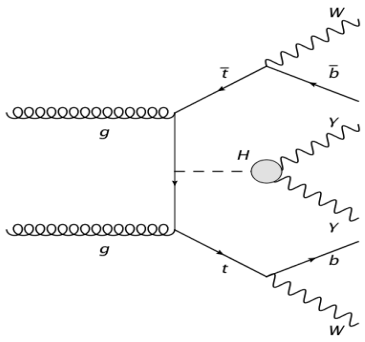




Data compatible with background expectations

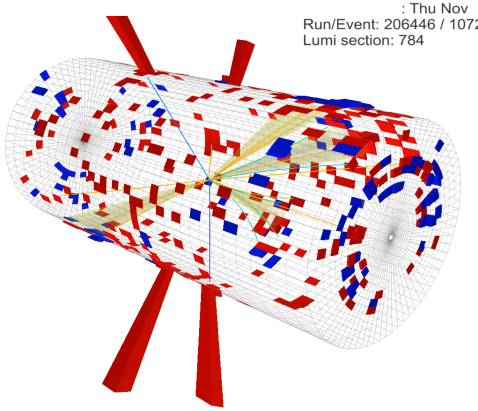
Limit on σ × BR: Exp:5.2 Obs:5.8 for m_H=125 GeV

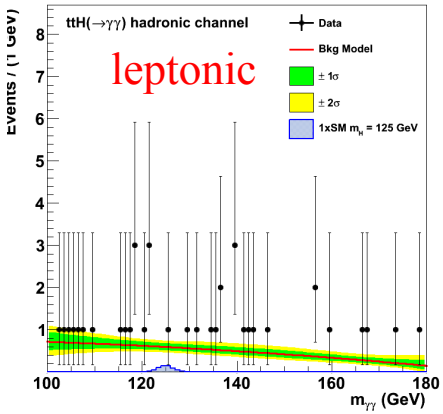
ttH; H → γγ

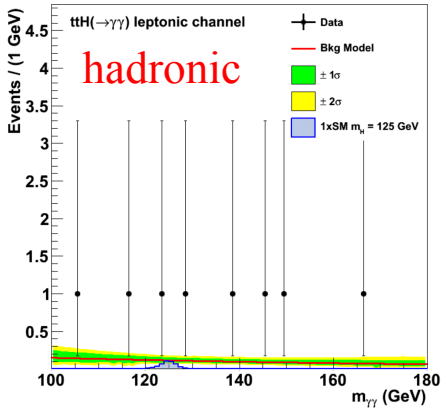


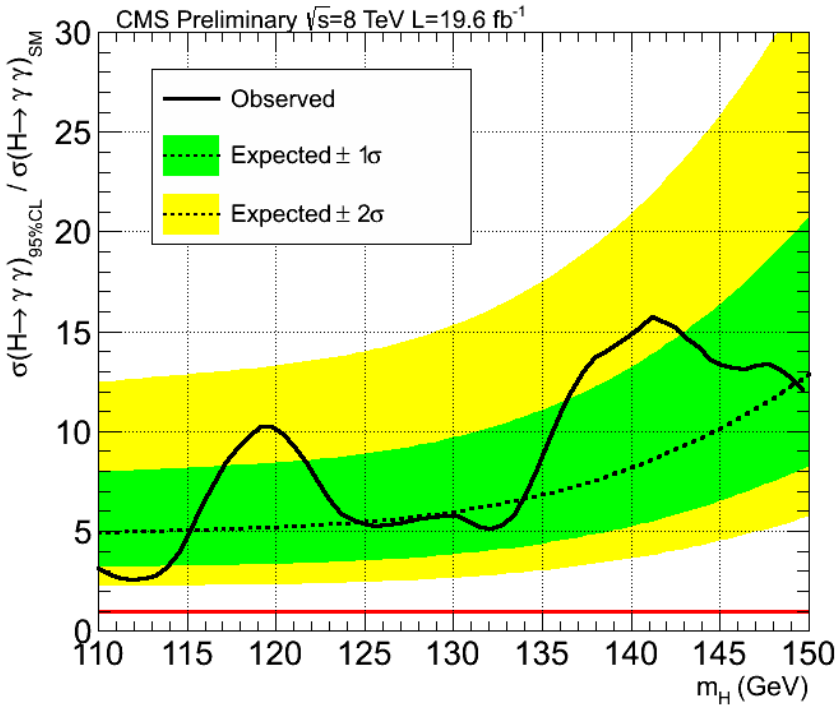
- In ttbar → dileptons, hadronic final states
- Search for H → γγ in it
- Sensitivity σ.BR ~ 5.3.SM for 125 GeV

CMS-HIG-13-015

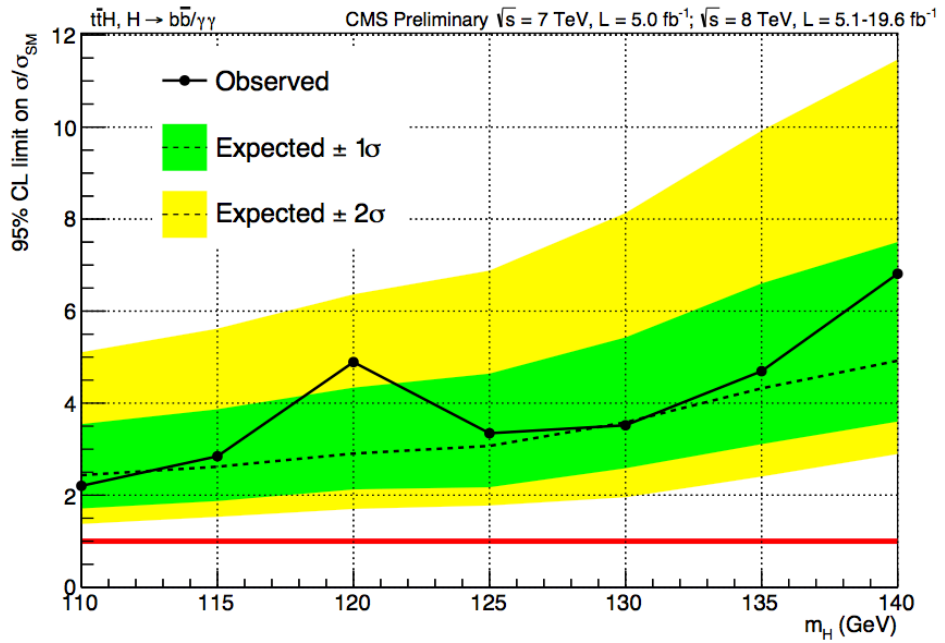








Combination of the ttH →γγ with ttH→bb

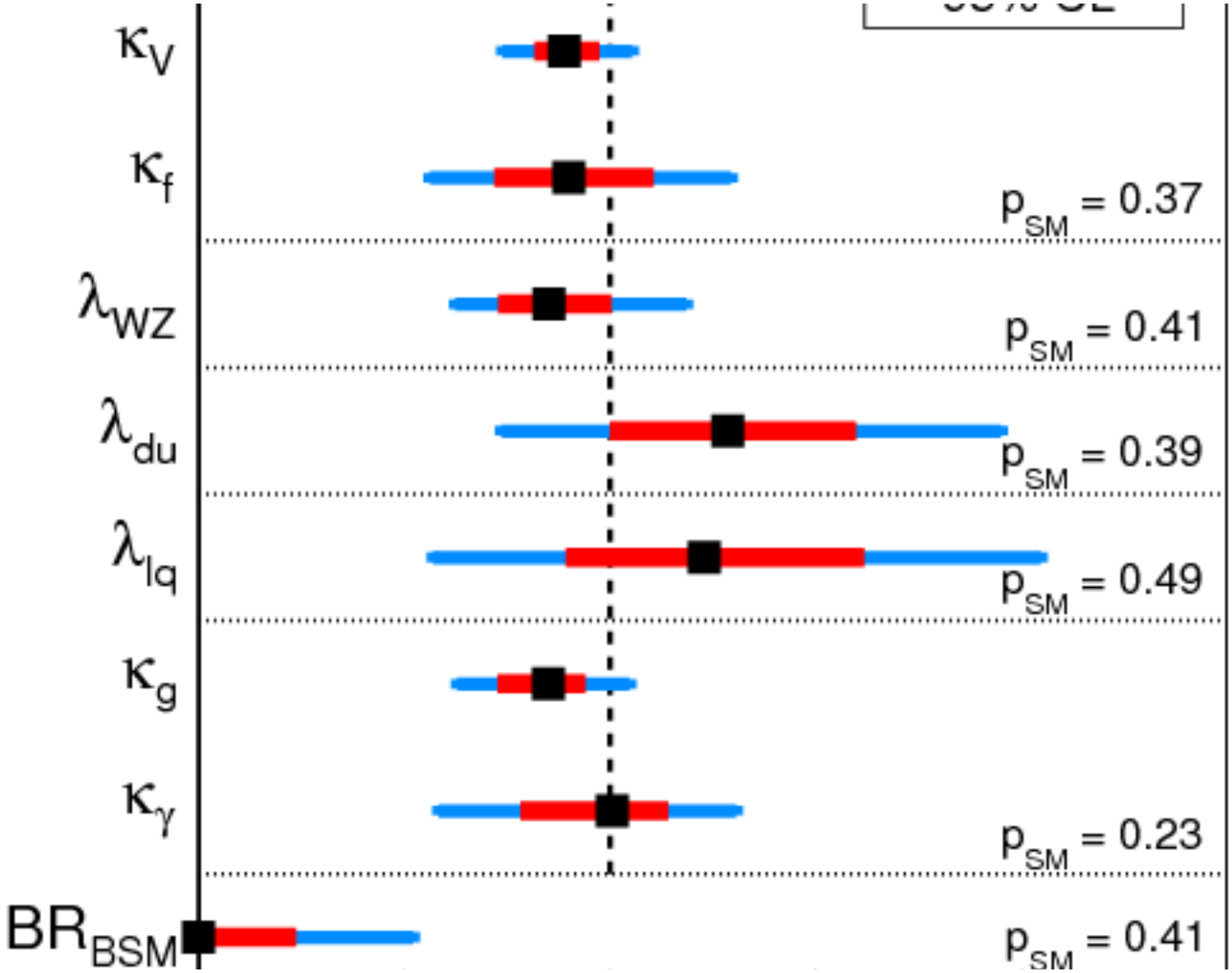


Observed 95% CL limit on σ/σ_{SM} at 125 GeV: 3.3

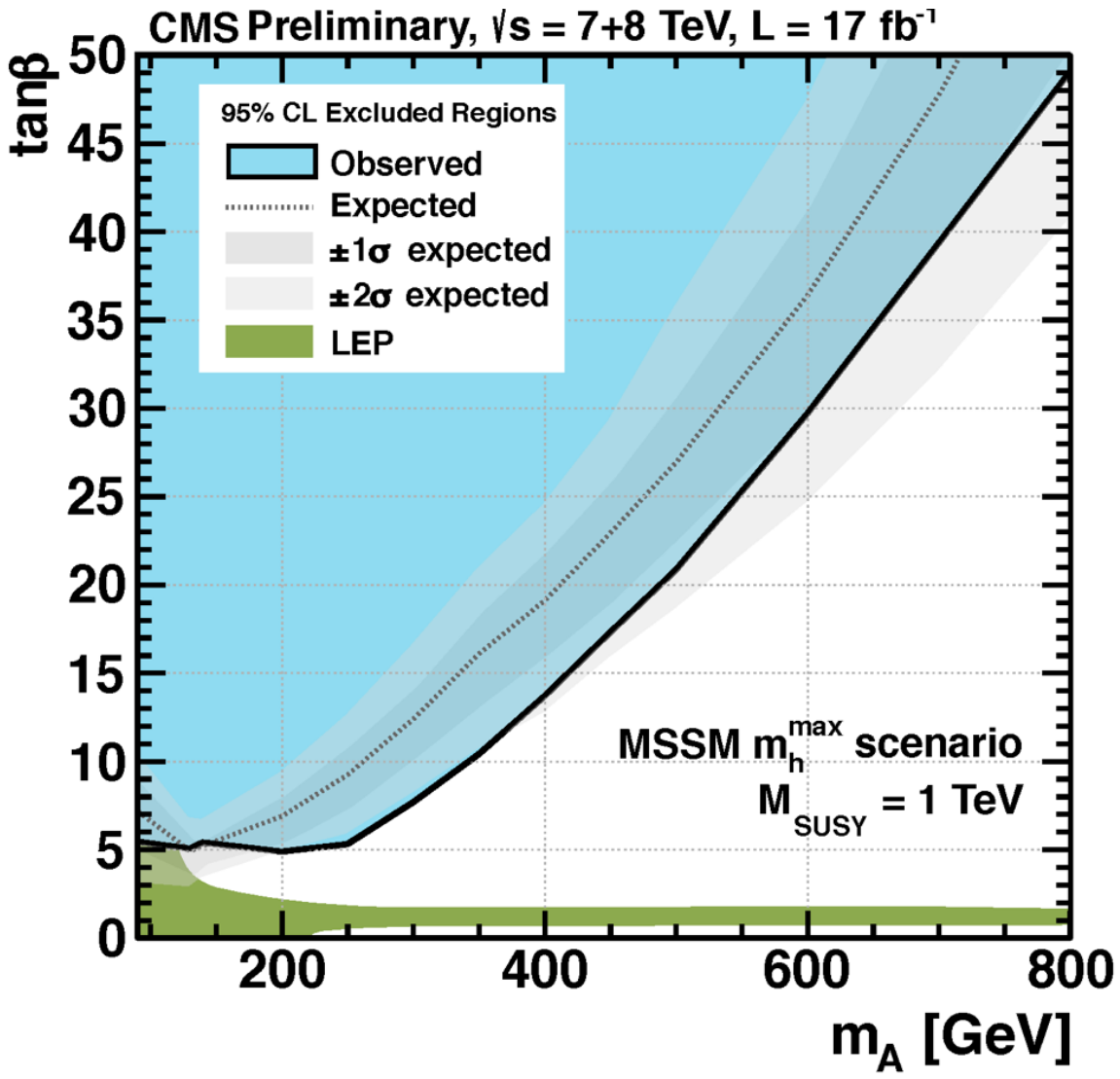
Expected 95% CL limit on σ/σ_{SM} at 125 GeV: 3.1

Sensitivity to 1-2 × SM within reach with full data set/all channels!

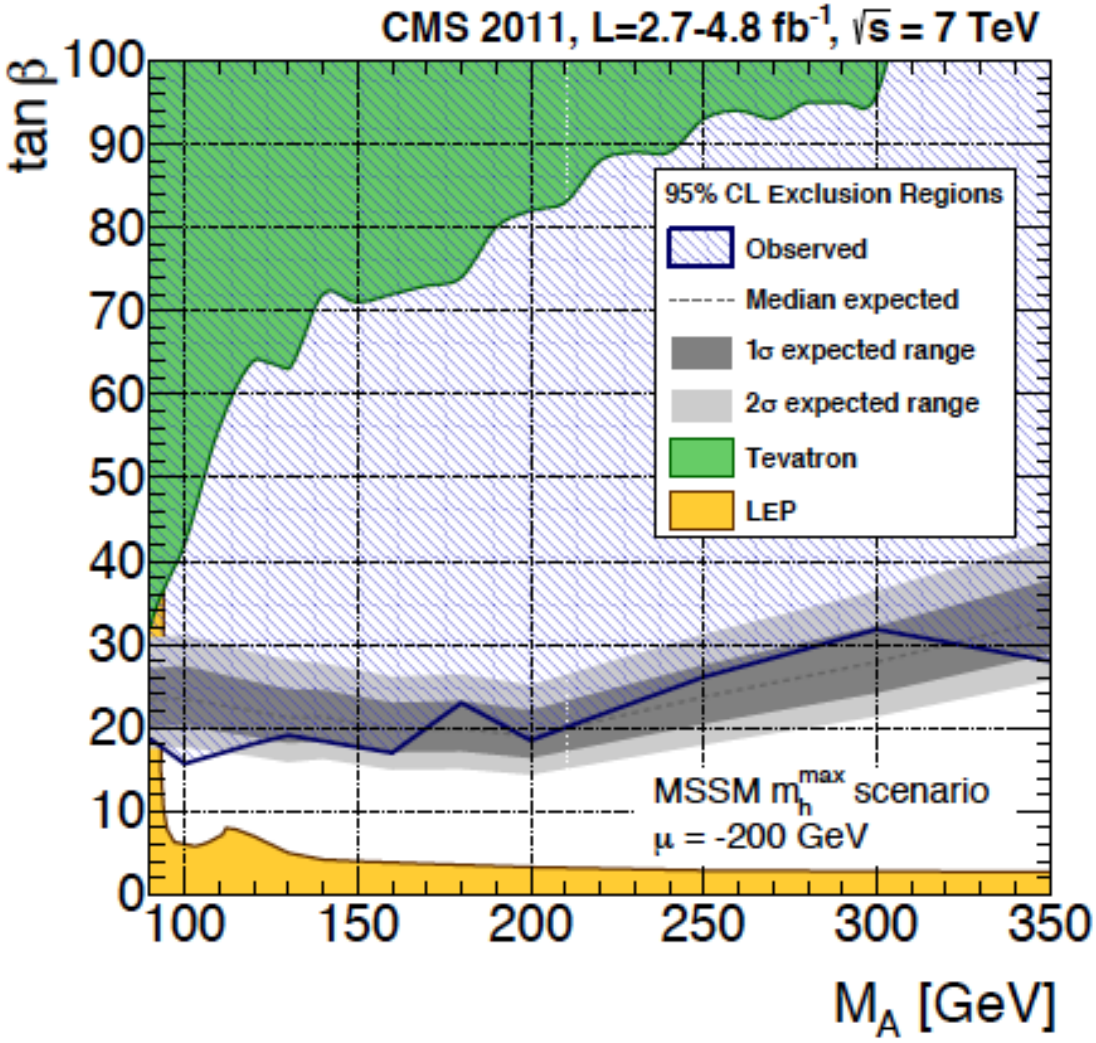
Summary of scalar couplings tests



$\phi \rightarrow \tau\tau$

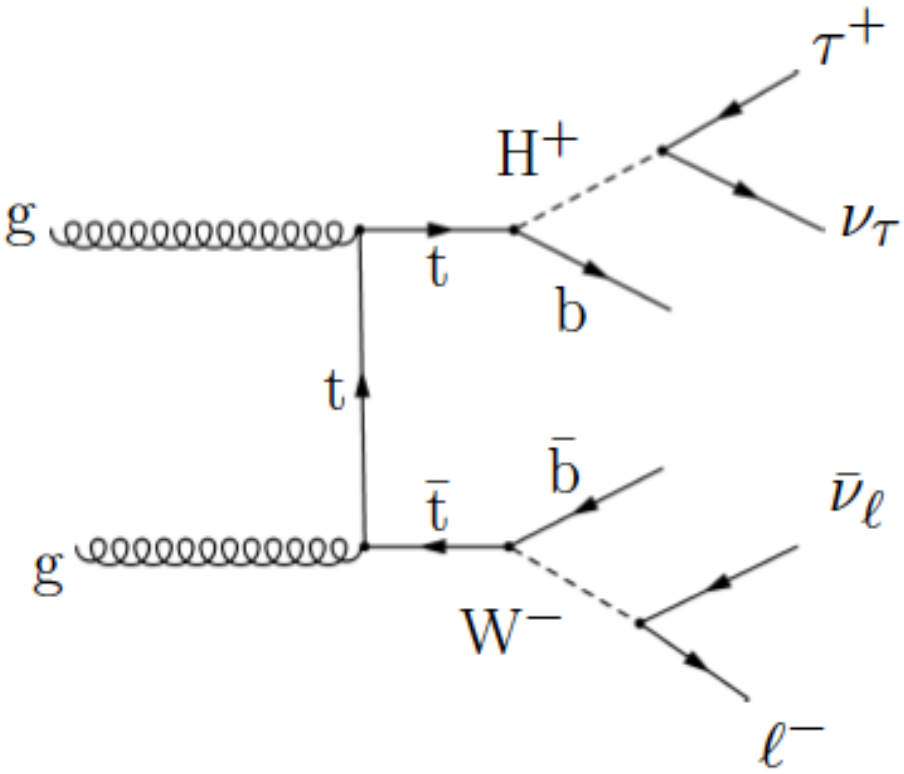


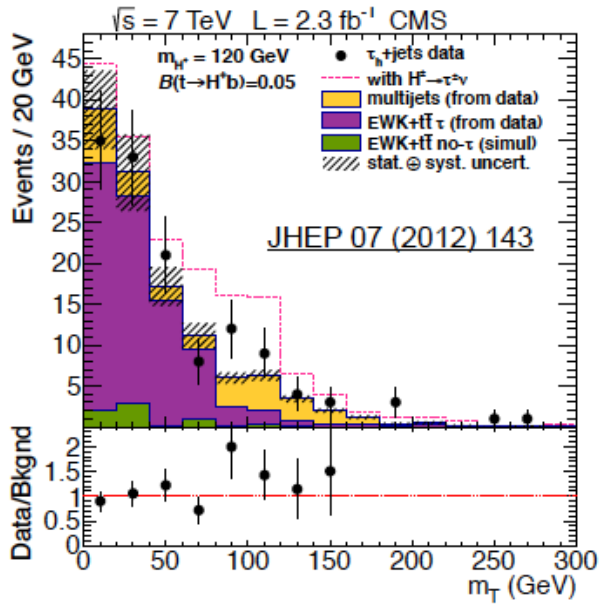
$\phi \rightarrow bb$

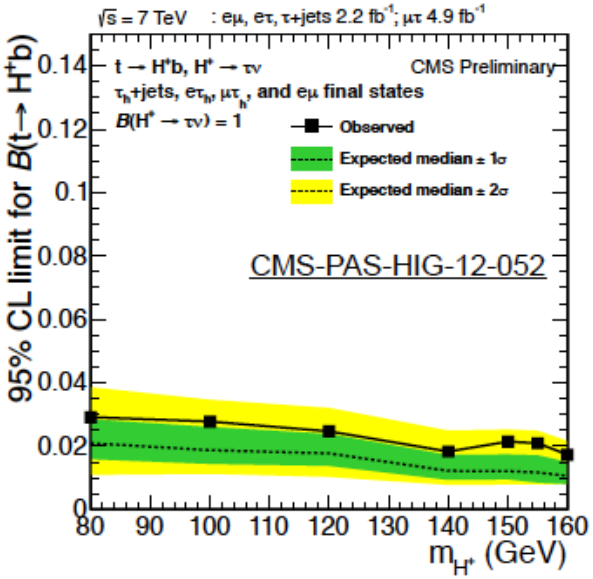


No significant excess seen - analysis excludes region of MSSM parameter space consistent with Tevatron excess.

Charged Higgs In Top Decays







High Mass Higgs Search

High mass Higgs searches with SM channels WW, ZZ updated with 2012 Statistics

Sensitivity reaches now up to ~ 1 TeV

Interpretation of the data in e.g EW-singlet models; Benchmark models proposed by the LHC XS WG:

See CMS-PAS-13-008
CMS-PAS-13-014