Updated Higgs Results from CMS

Rainer Mankel, Alexei Raspereza
DESY

LHC Physics Discussions
DESY, 17-Dec-2012

HELMHOLTZ ASSOCIATION

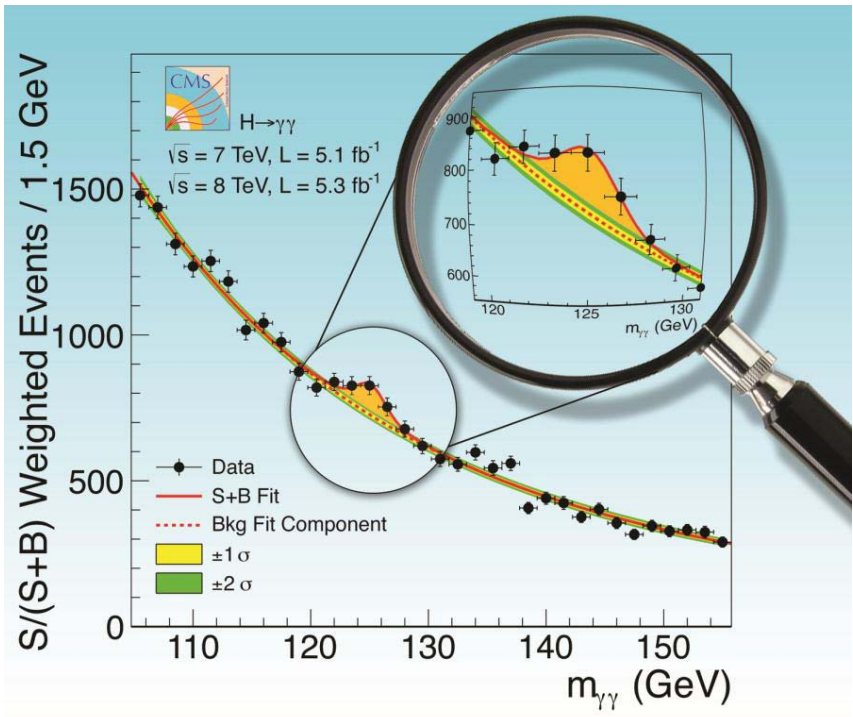
DESY

After the Discovery !

Main points of interest after the initial observation of a new boson has been made:

- Confirmation of the 126 GeV signal with more statistics → ZZ*, [WW]
- Do we see the decay to fermions ?
  - → ττ, bb
- Measurement of the couplings & comparison with SM
- Is the 126 GeV signal just one state in a more complex Higgs sector?
  - e.g. MSSM (five Higgs states)
  - → ττ, bb

Focus on new results as they were prepared for HCP 2012!



AP photo

"As a layman, I think we have it. But as a scientist, I have to say, 'What do we have?'" – R. Heuer

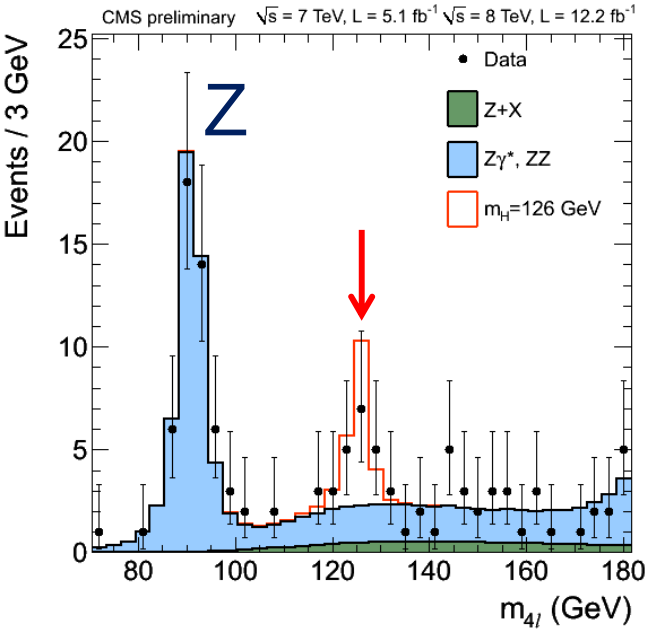
Confirmation of the 126 GeV Signal

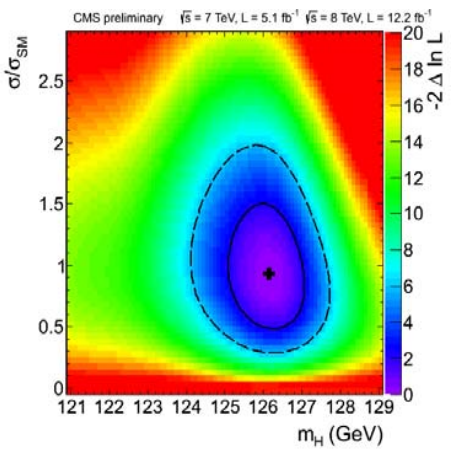
Update for H→ZZ*→ 4 ℓ

- Clean signature: 4 isolated leptons
- Excellent mass resolution
- Backgrounds: ZZ*, Z+jets/ttbar/WZ
- Matrix Element Likelihood Analysis (MELA)
  - kinematic discriminant separating signal + background
  - based on the 2 masses + 5 angles describing the decay

- Fitted mass value of the excess:
  $M_X = 126.2 \pm 0.6(\text{stat}) \pm 0.2(\text{sys})$ GeV
- ➔ Observed local significance: 4.5 σ
- ➔ Expected local significance: 5.1
- For comparison the July result (ICHEP) was:
  3.2 σ (observed), 3.8 σ (expected)

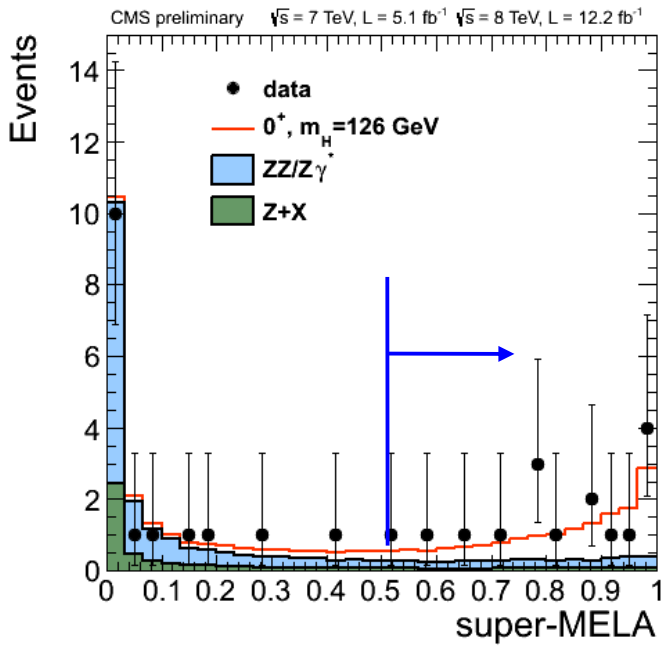
→ With 1.7x more data, the excess has grown as expected!

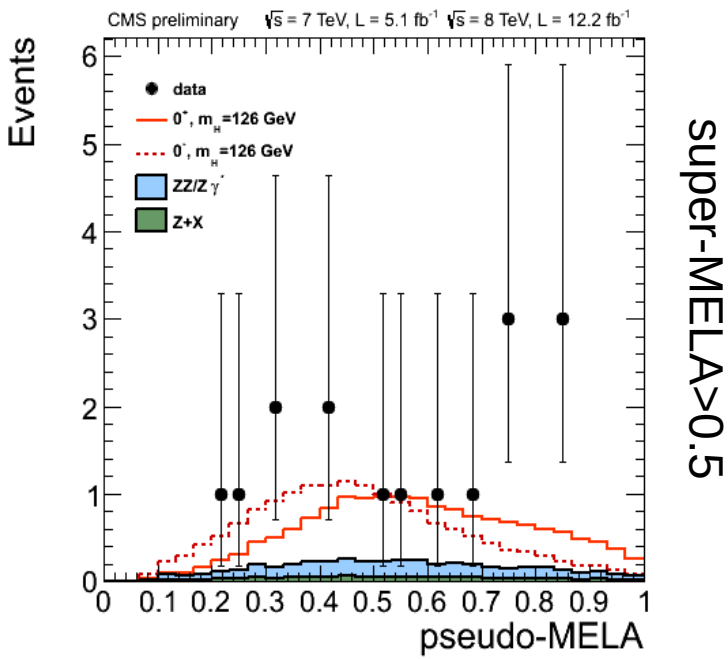




Determination of Parity (0^+ = SM, vs. 0^- Hypothesis)

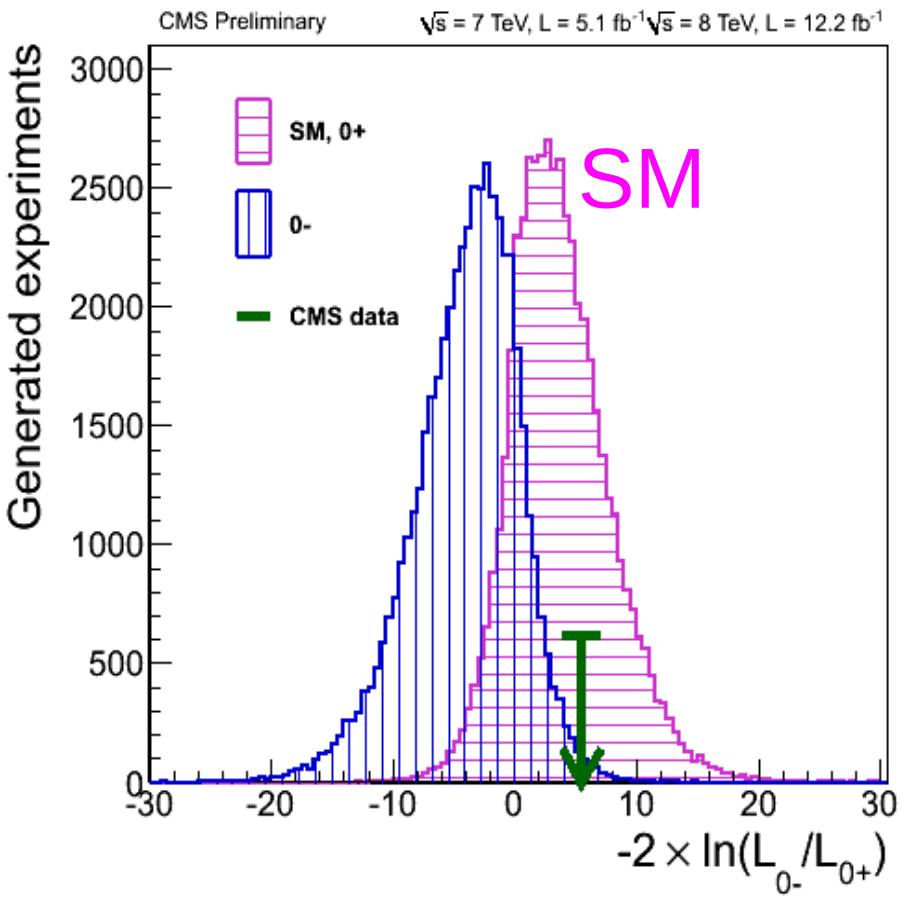
- Kinematic distributions of decay observables are sensitive to the parity
- ➔ Construct extended MELA-based likelihoods for both scalar and pseudoscalar hypotheses, taking also the mass into account





BG ⟷ Signal 0^- ⟷ 0^+

Scalar (0^+ = SM) vs. Pseudoscalar (0^-) Hypothesis



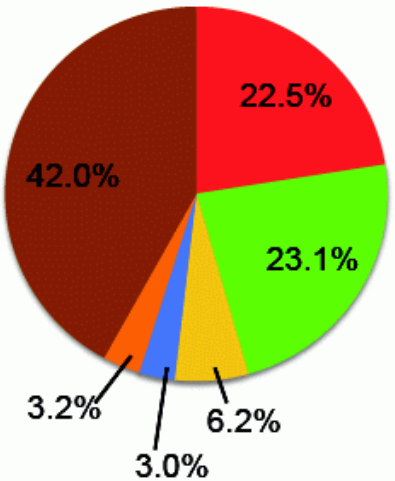
- Expected separation of the two hypotheses: ~1.9 σ
- ➔ Observation is consistent
  - with 0^+ at the level of 0.53 σ
  - with 0^- at the level of 2.45 σ

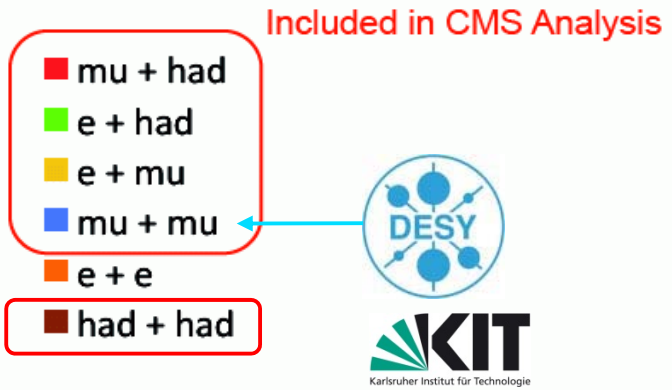
➔ With our current data, the pseudoscalar hypothesis is clearly disfavored (CL~2.4%)

Search for Fermionic Higgs Decays

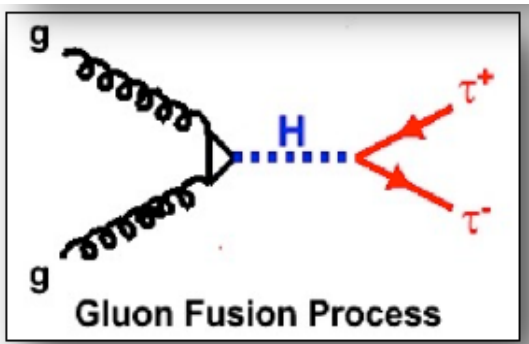
H → ττ

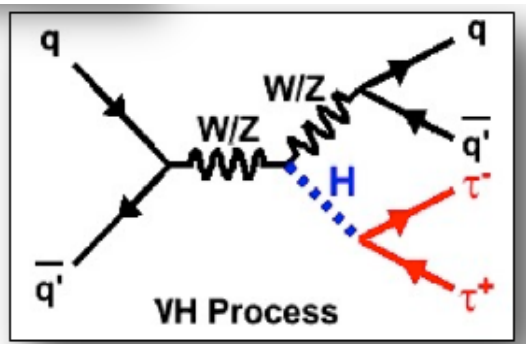
- Large σ * BR at low Higgs masses
- Sensitive to all production mechanisms
- Direct probe of Higgs coupling to leptons
- Full reconstruction of di-tau invariant mass from ττ decay kinematics / matrix element and missing E_T

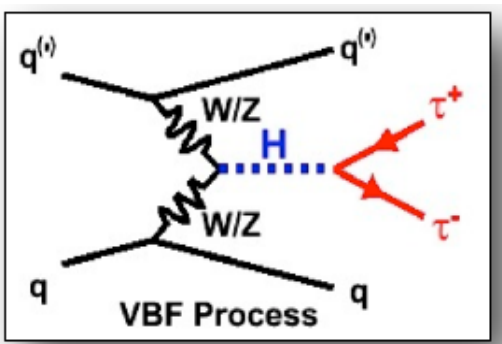




→ *almost full coverage of decay spectrum*

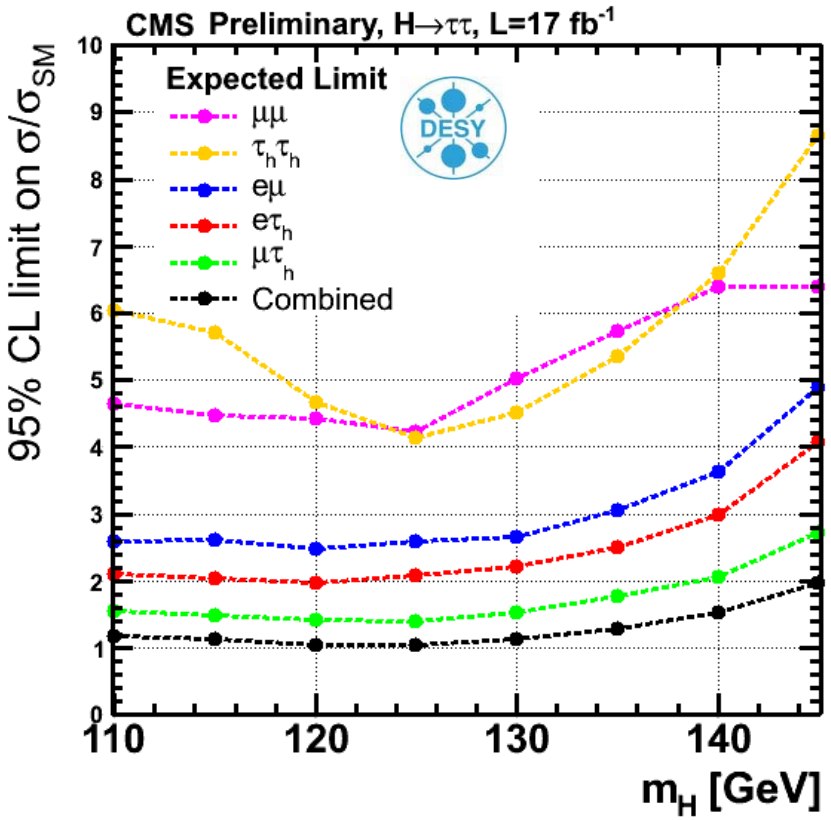




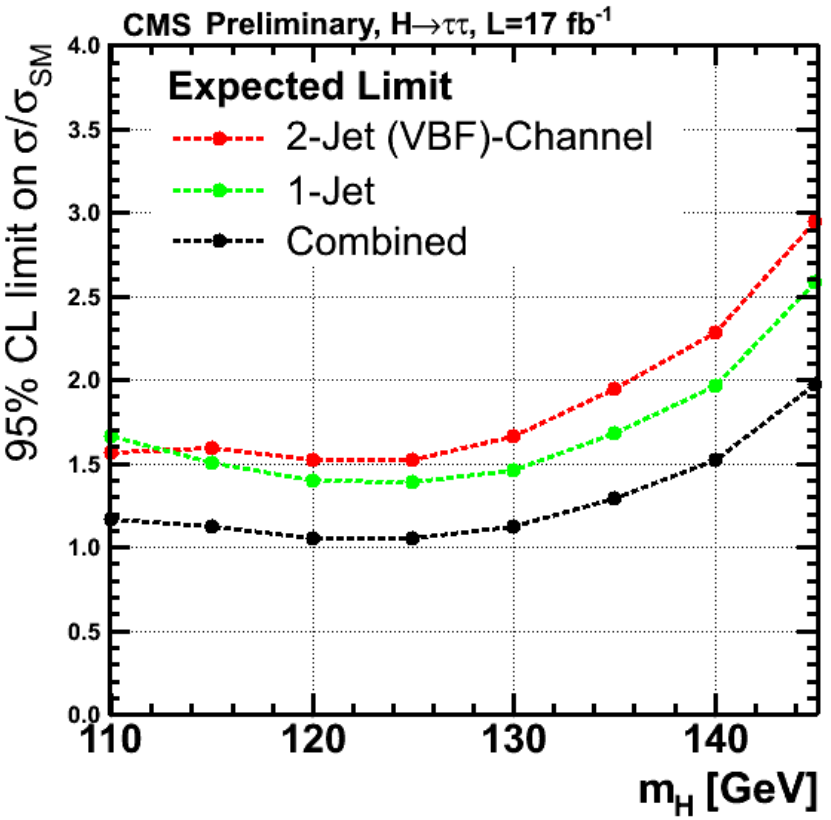


H → ττ Search Sensitivity

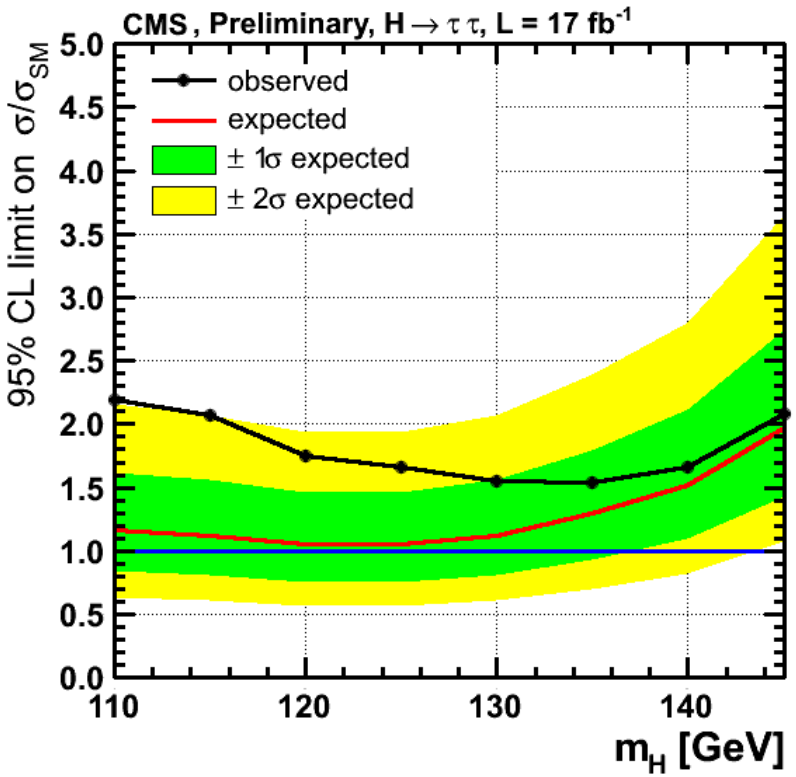
sensitivity / channel

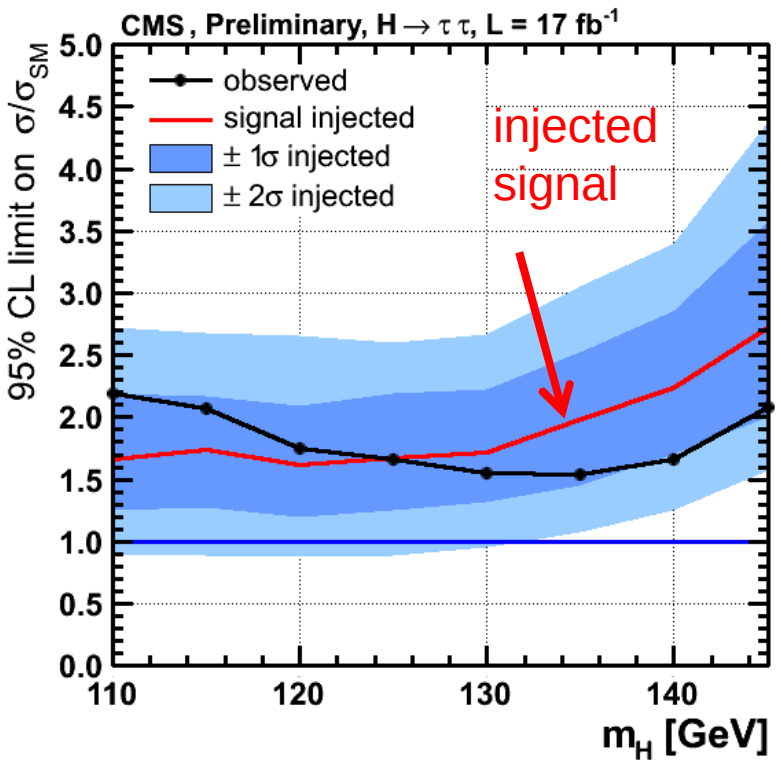


sensitivity / category



H → ττ Search Results

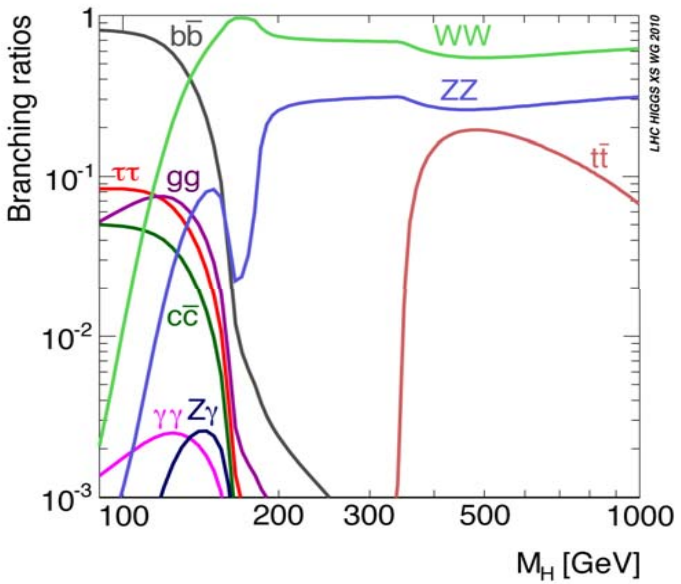


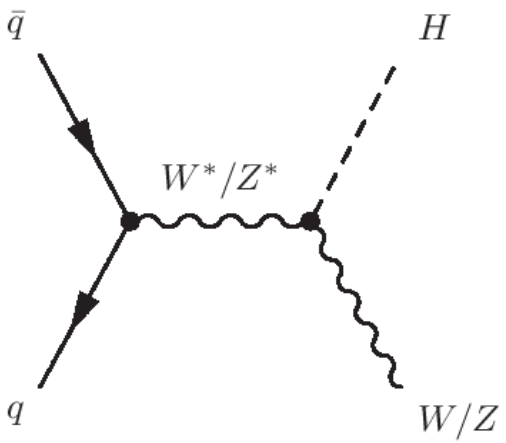


- While analysis approaches exclusion sensitivity for SM model Higgs, an excess develops which is compatible with SM Higgs σ * BR

→ *Compatible with the "gradual appearance" of a signal*

VH, H → bb

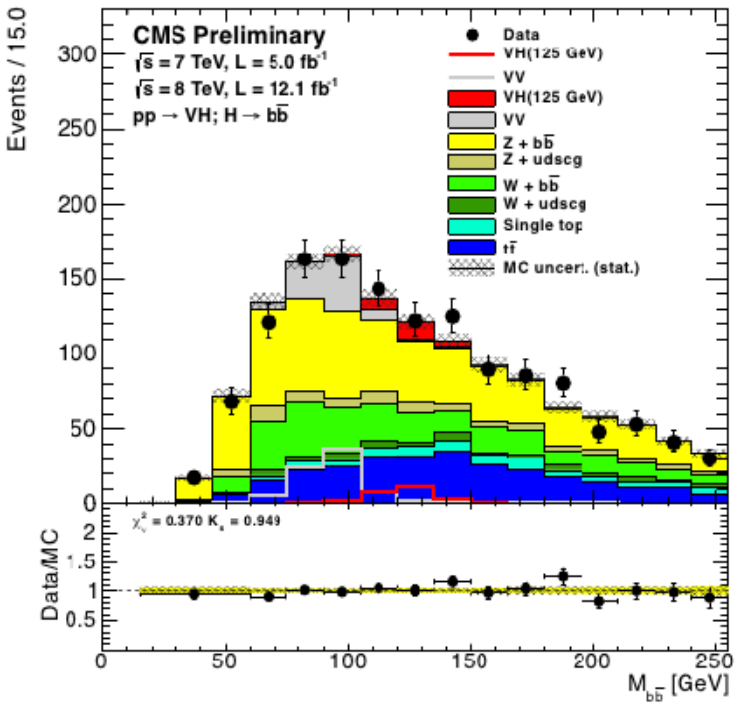


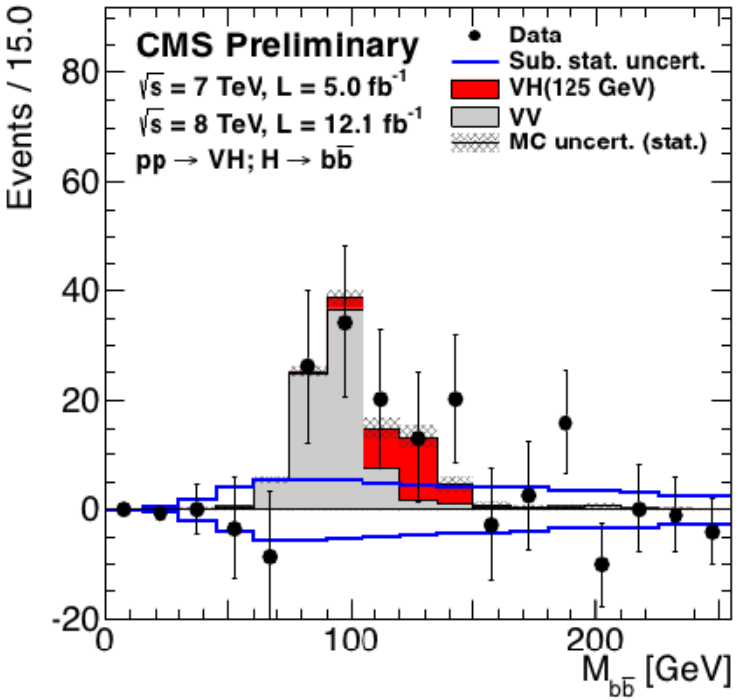


- H → bb decay has the largest branching ratio for $m_H \leq 130$ GeV
- Inclusive search is impossible due to the overwhelming QCD background (S/B~10^{-9})
- ➔ Study Higgs production in association with an additional vector boson (V = W or Z)
- Five subchannels included:
  - W→ eν, W → μν
  - Z → ee, Z → μμ, Z → νν (invisible)
- Strategy:
  - boosted Higgs candidate recoiling against V
  - ≥ 2 b-tagged jets
  - b-jet energy regression
  - BDT shape analysis

VH, H → bb (cont'd)

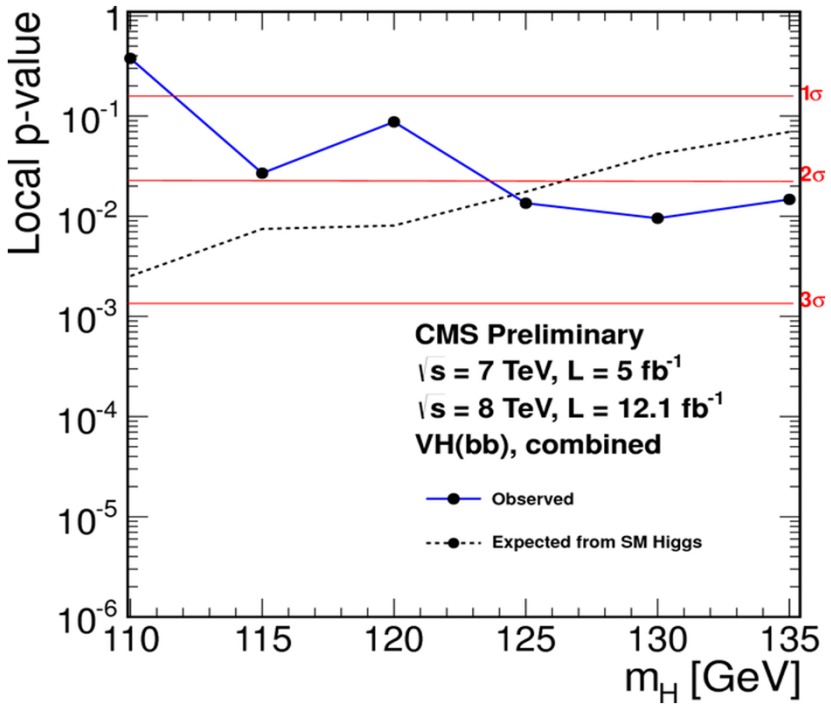
M(bb) after tight cuts on BDT discriminants:

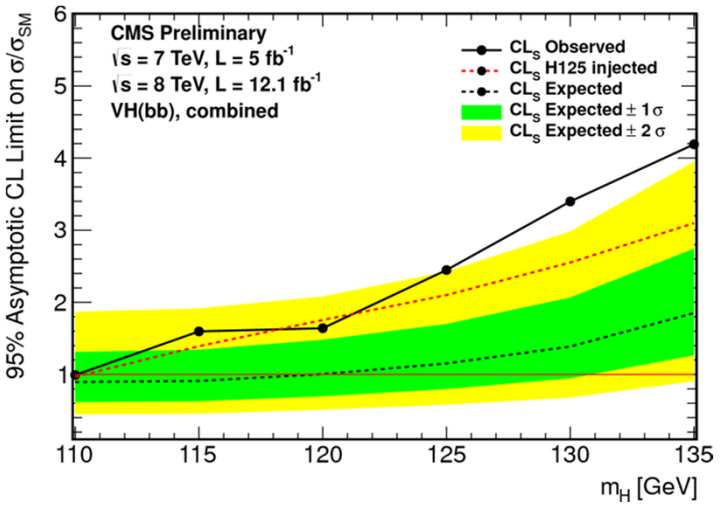


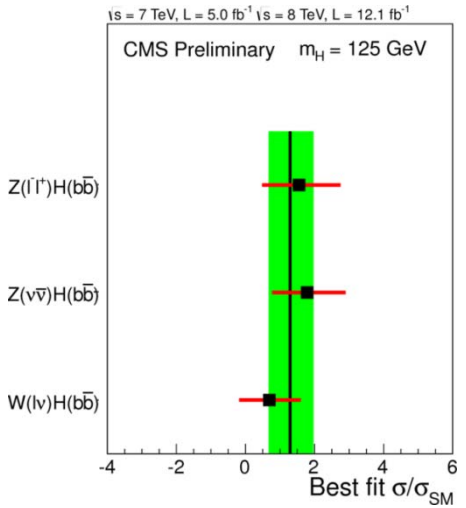


- VV production (an expected background) appears & is well described
  - important "standard candle"
- Additional excess attributed to VH production (not yet significant)

VH, H → bb Results







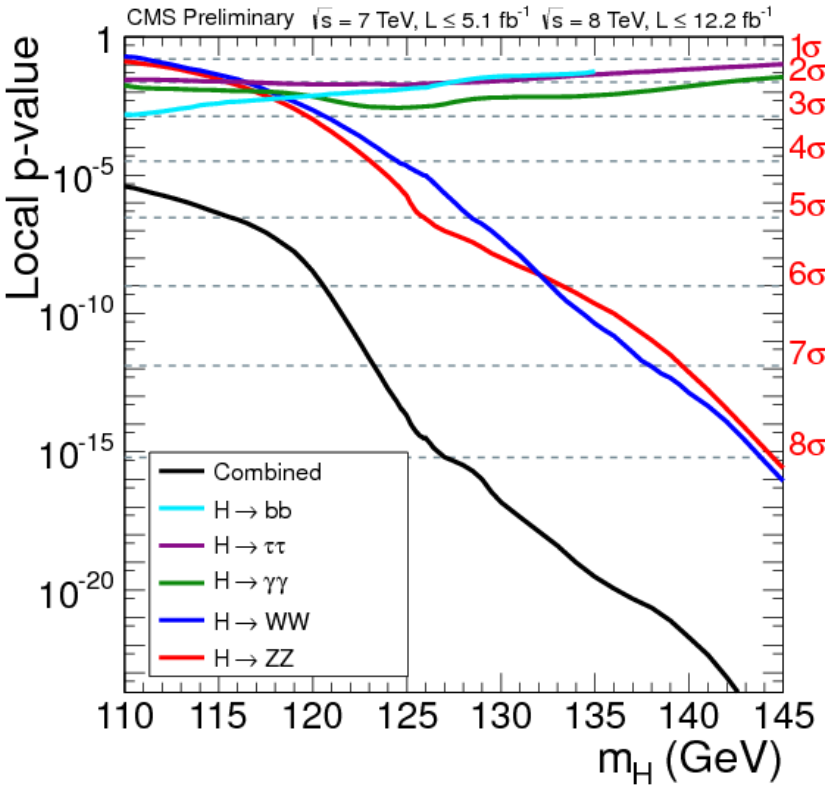
- At m_H=125 GeV:
  - observed excess = 2.2 σ
  - expected excess = 2.1 σ (with injected SM Higgs signal)

→ Best-fit signal strength is positive, consistent across channels & compatible with SM cross section

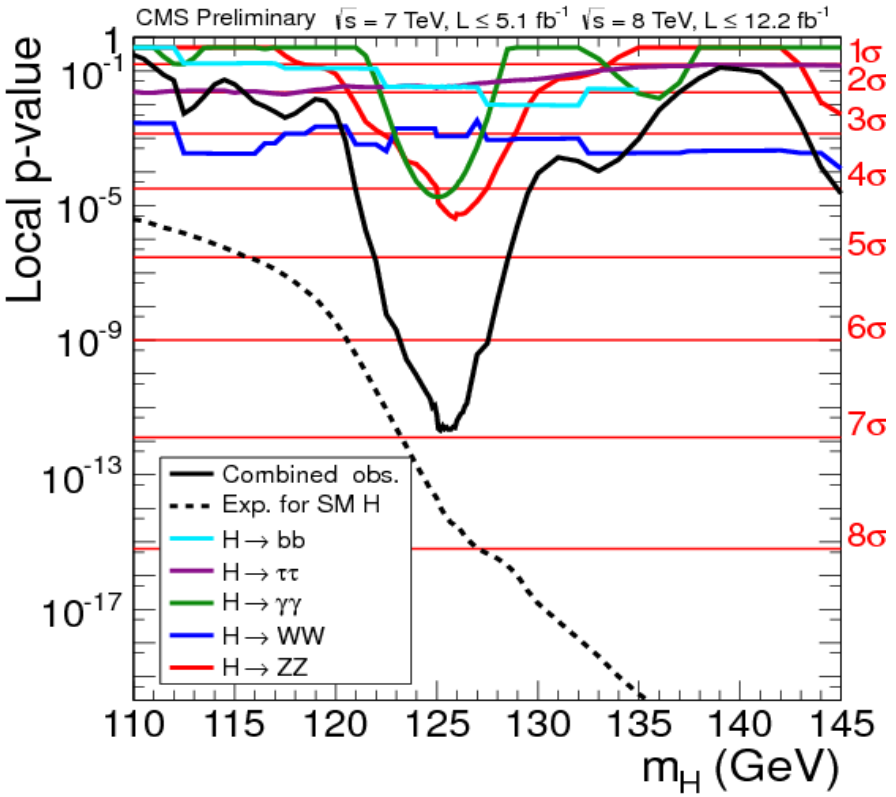
SM Higgs Combination

Combined Sensitivity & Observation

sensitivity / channel

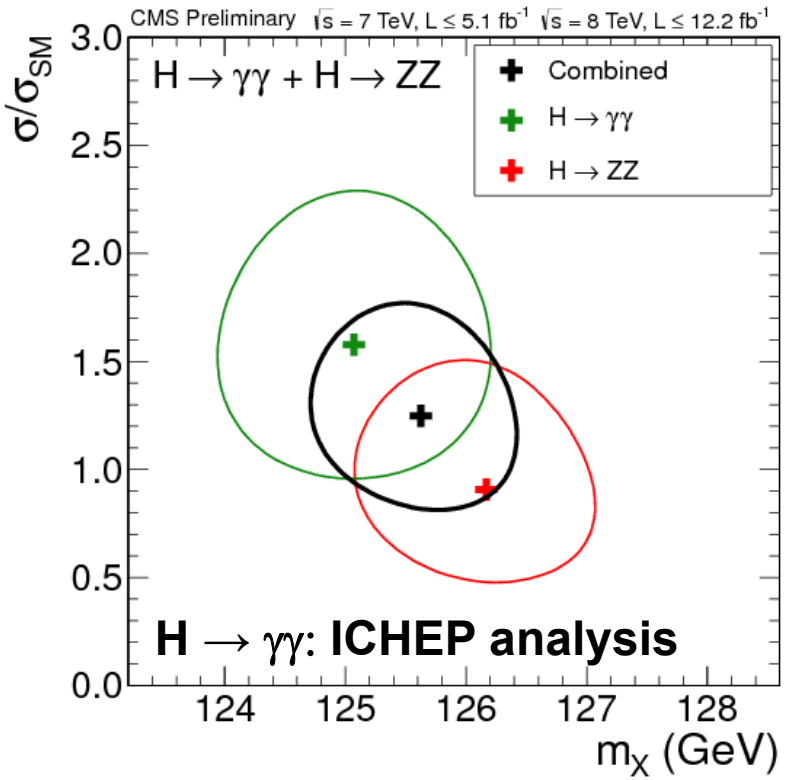


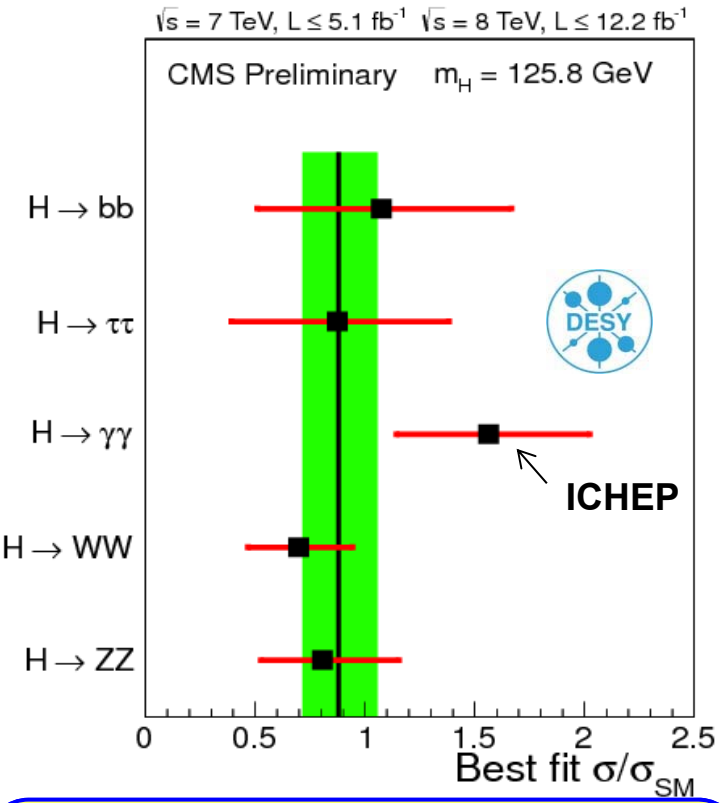
observed significance



- Combination of the five main channels (H→γγ at the level of ICHEP)
- Good consistency between expectation & observation at m_H ~ 126 GeV

Mass & Signal Strength



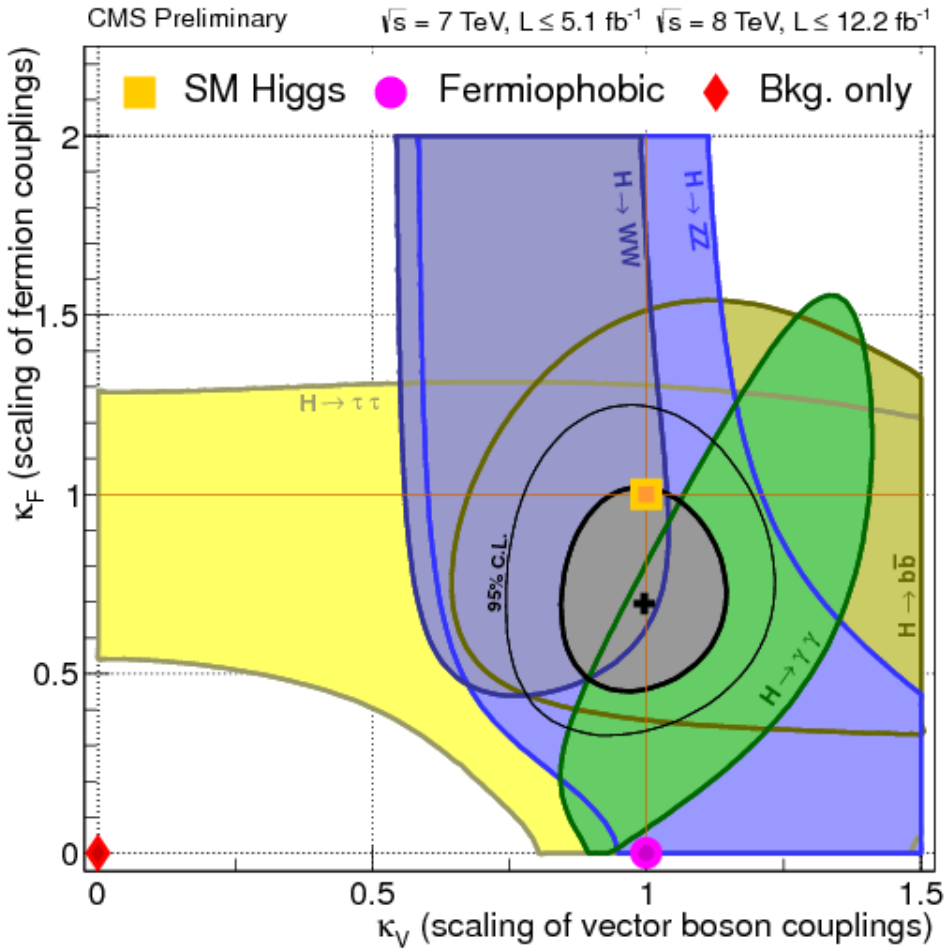


fitted mass

M_X = 125.8 ± 0.4(stat) ± 0.4(sys) GeV

Best fit of signal strength in combination
σ/σ_{SM} = 0.88 ± 0.21

Higgs Couplings



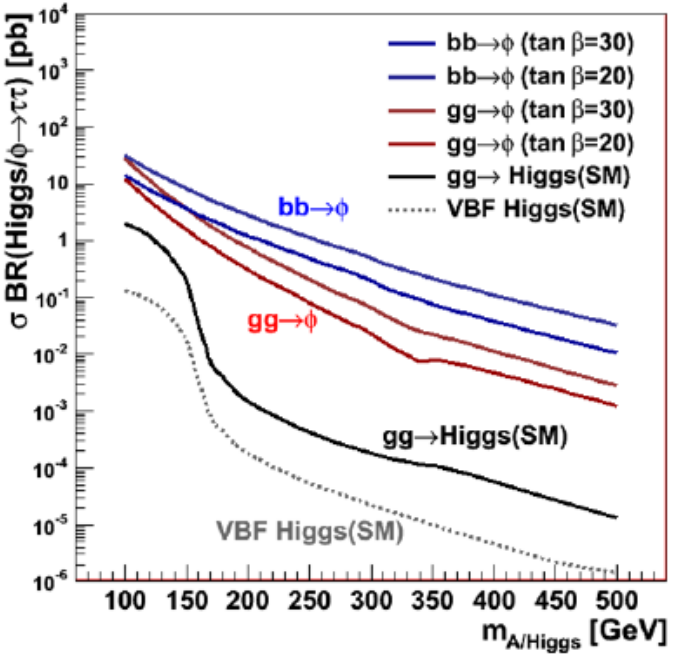
- K_F: uniform scaling factor applied to SM coupling of H to fermions (τ, b, t, …)
- K_V: uniform scaling factor applied to SM coupling of H to vector bosons (γ, W, Z)
- Combination of production and decay mechanism introduces correlations
- ➔ Couplings are consistent with standard model Higgs
  - ➔ fermiophobic Higgs is excluded

➔ *Everything is consistent with SM !*

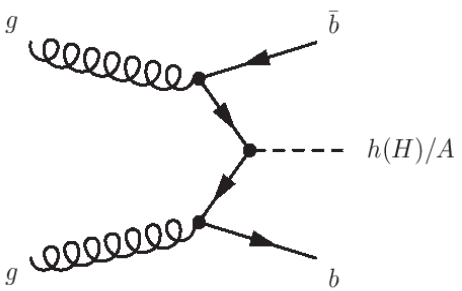
Searches for Neutral MSSM Higgs Bosons

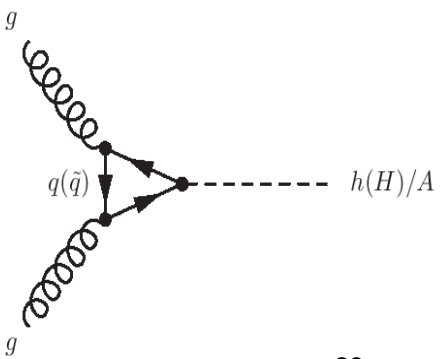
MSSM Higgs Bosons

- MSSM features two complex Higgs doublets
- Five Higgs particles
  - three neutral (h, H, A) → denoted Φ
  - two charged ($H^{\pm}$)
  - the observed 126 GeV state is often attributed to the lightest Higgs (h)
- Two free parameters:
  - m_A
  - tan β (ratio of vacuum expectation values of the two Higgs doublets)

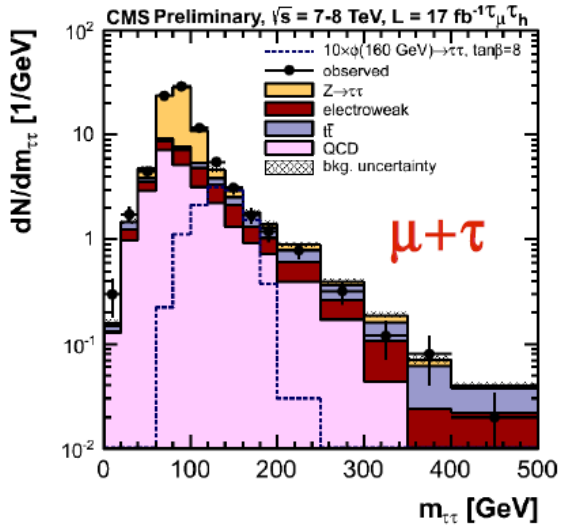


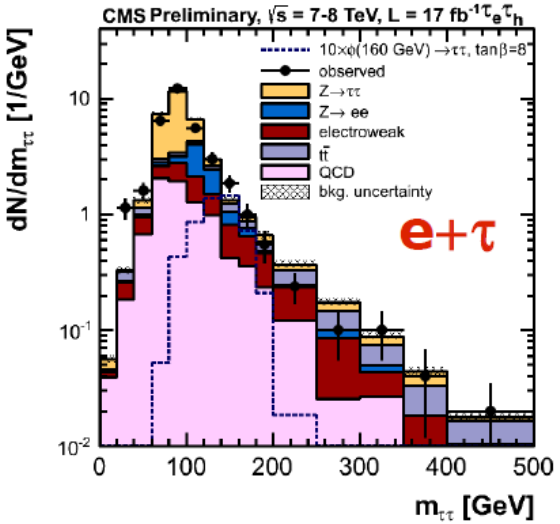
- MSSM search in ττ channel uses two event classes:
  - B-jet category
  - Non-B category

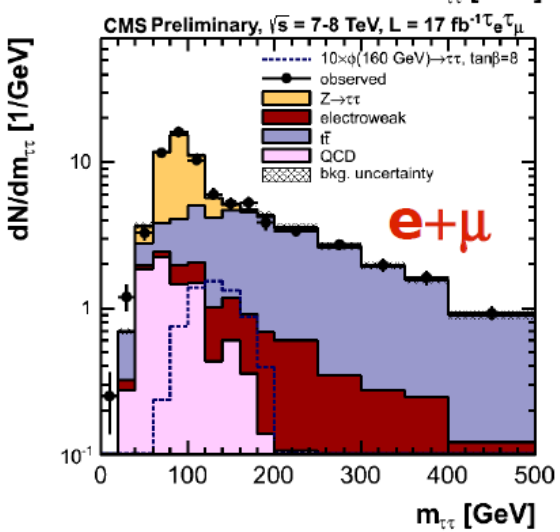


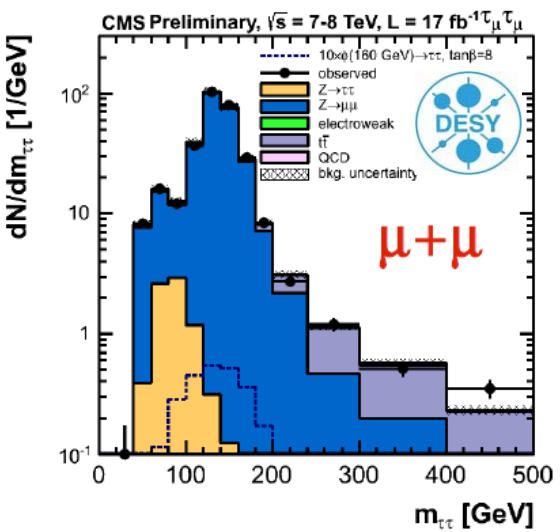


MSSM Φ → ττ: Mass Distribution in B-Category





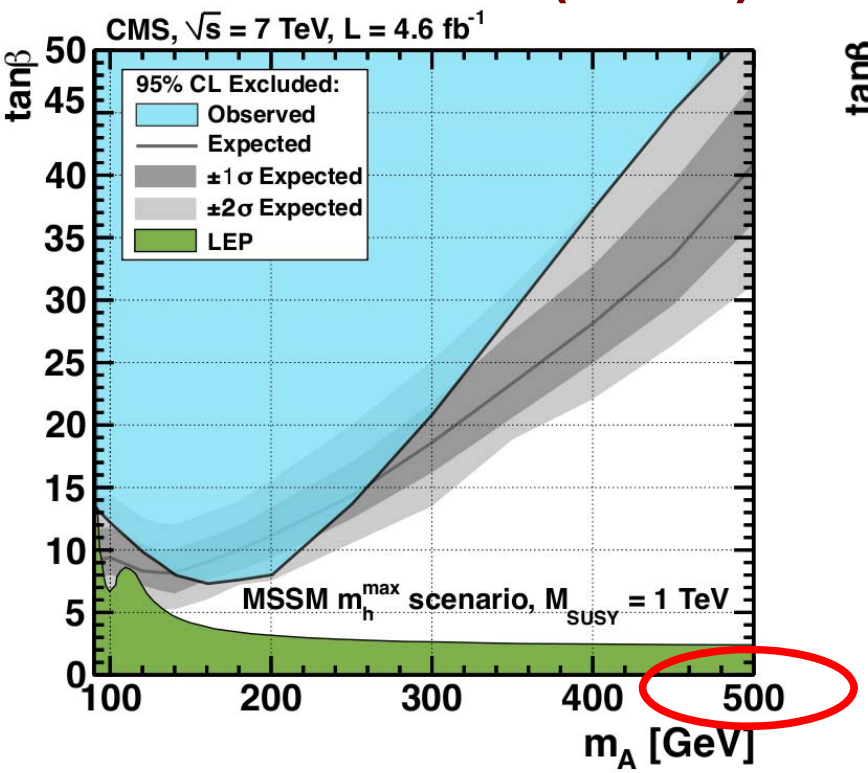




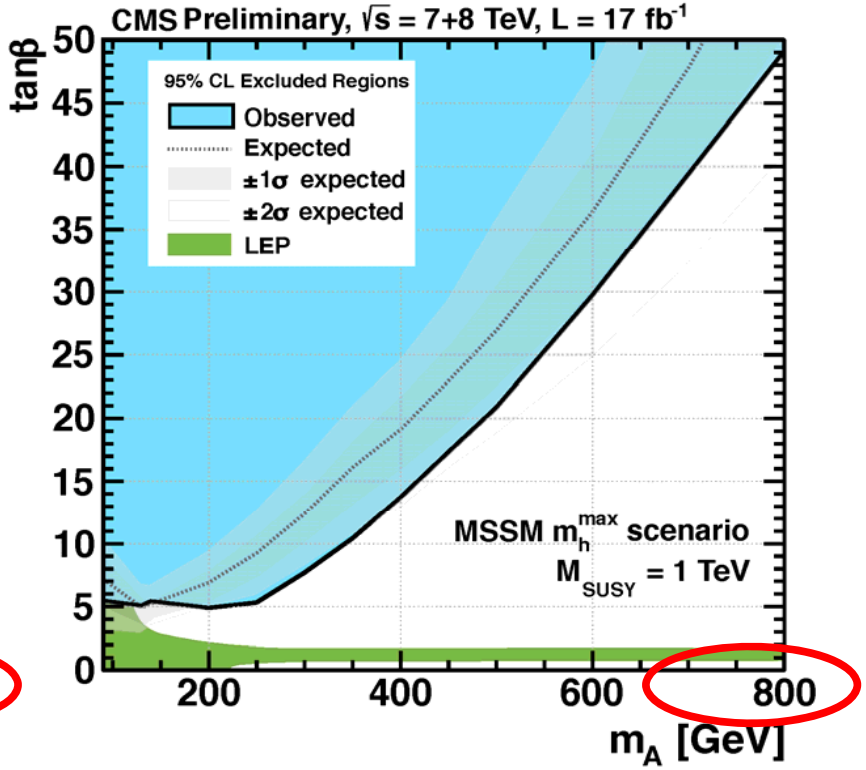
- Background compositions differ significantly across the various decay channels
- All distributions well described by background hypothesis

Results of MSSM Search ($\tau\tau$)

Previous result (7 TeV):



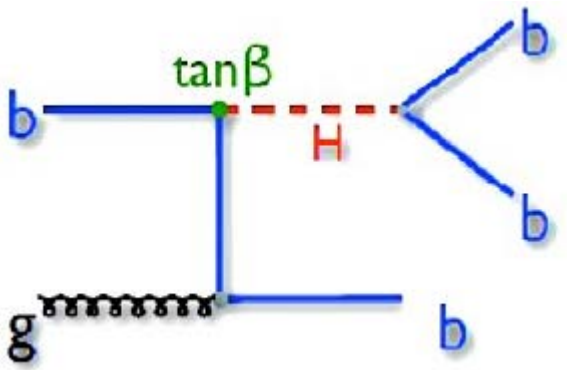
New result:



- ➔ Substantial improvement of tan β upper limits (tan β < 5 for m_A<250 GeV !)
  - touching the LEP constraint at low m_A
- ➔ Extension of mass scale up to 800 GeV

bΦ → 3b Search

- Search for MSSM Higgs boson decaying to b quarks, and produced with at least one additional b quark
  - → enhancement if tan β > 1
- Two analyses:
  - all-hadronic (CMS-PAS-12-026)
  - semileptonic (CMS-PAS-12-027)
  - new: combination (CMS-PAS-12-033)



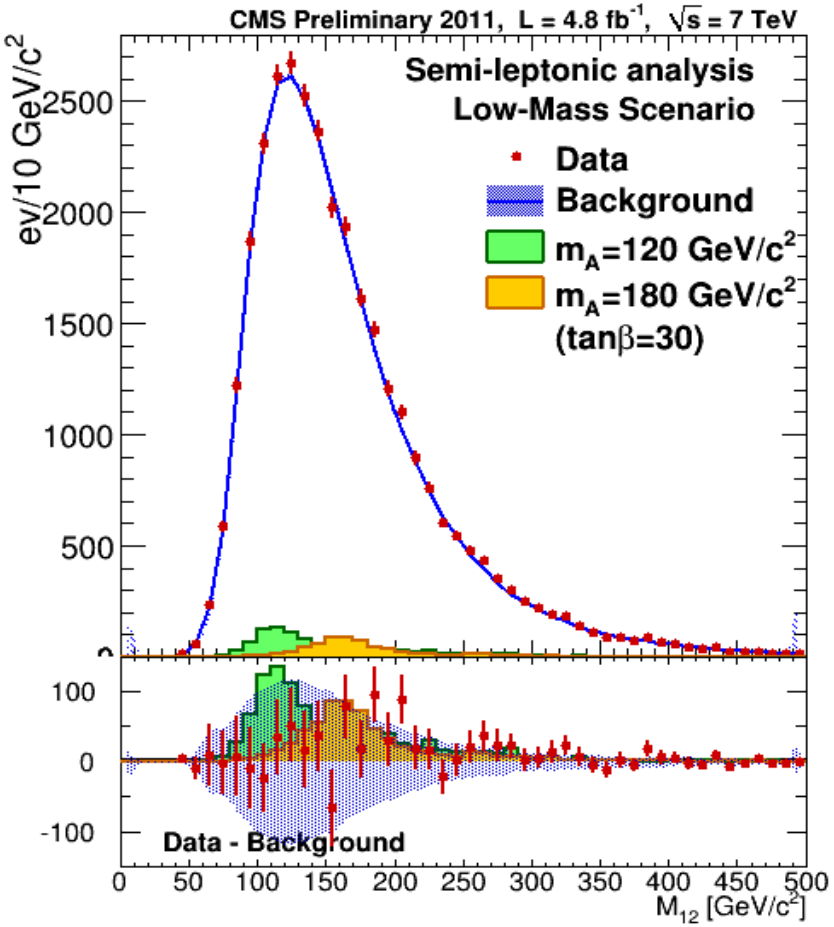
- Only accessible with sophisticated triggering
  - → dedicated triggers: jets + b-tagging (+ muon)

Pushing the CMS trigger to its limits!

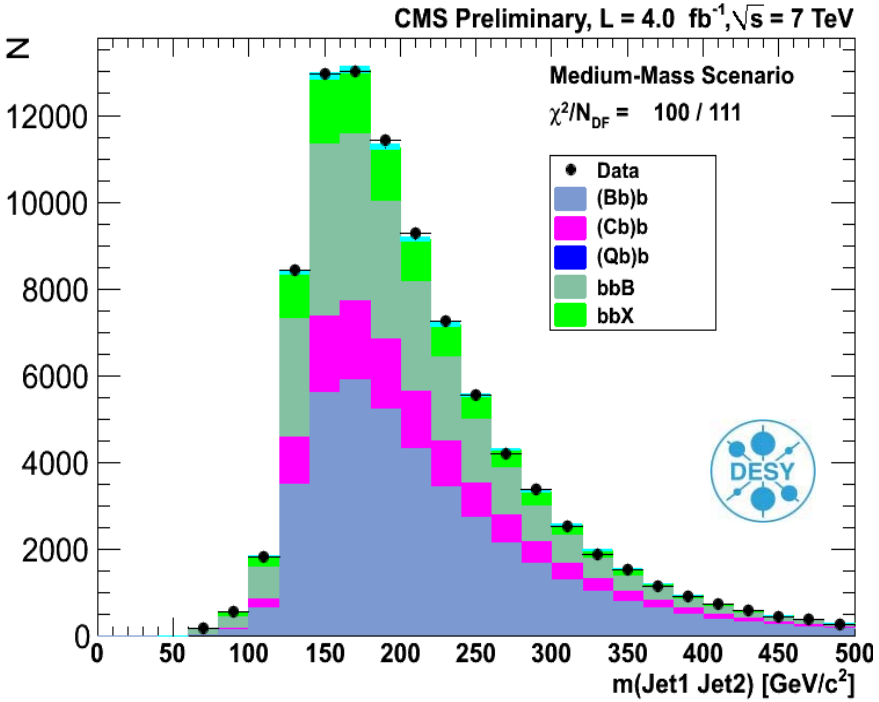
- Event selection: three leading b-tagged jets (+ non-isolated muon)
- Data: 2.7 – 4.8 fb^{-1} at 7 TeV
- Main background: multi-jet QCD
  - derived from data

Results from MSSM Higgs Search (bΦ → 3b)

semi-leptonic



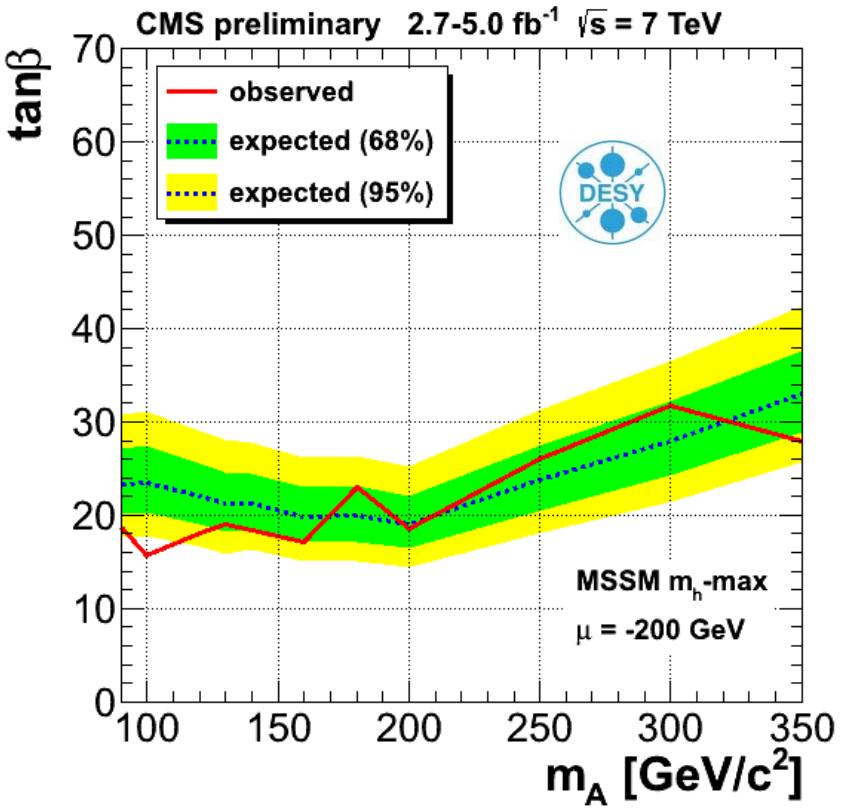
all-hadronic

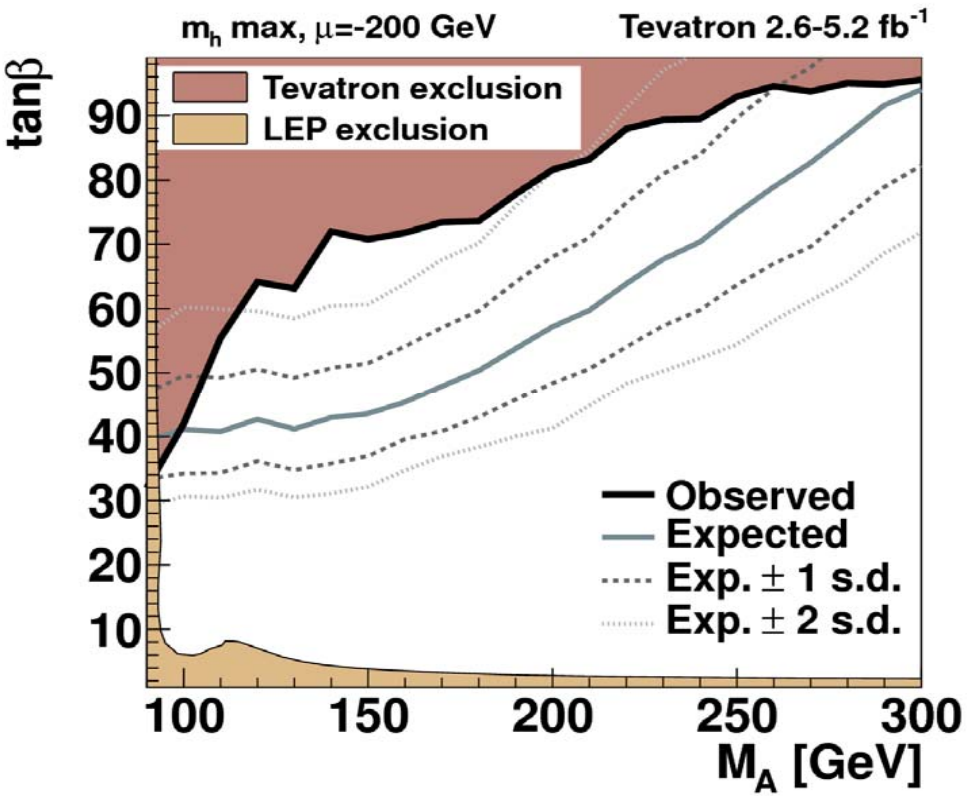


- No signal observed in either analysis
- Nearly orthogonal selection

➔ Analyses have been combined

bΦ → 3b Search: Combination & Comparison with Tevatron





- Not confirming ~2σ-plus excesses seen by CDF + DZero

→ *First time this is done at LHC! CMS has much better sensitivity already with 2011 data (2012 under analysis)*

Summary

- Significance of Higgs candidate at 126 GeV is growing as expected
  - Spin/parity: 0^+ is preferred over 0^-
- Observation of decays into fermions may be around the corner
  - SM-compliant excesses seen in $H \rightarrow \tau\tau$ and $H \rightarrow bb$
- Combination reaches a significance of 7 σ
  - signal strengths in various channels compatible with SM
  - coupling constants (F vs. V) consistent with SM
- Growing sensitivity for MSSM Higgs sector
  - very stringent exclusion limits from $\tau\tau$ at low m_A
  - new combination results from bb channel (for the first time at LHC) supersede those from the Tevatron

CMS Higgs Results for HCP

Document	Analysis
PAS HIG-12-041	$H \rightarrow ZZ \rightarrow 4\ell$ Search
PAS HIG-12-042	$H \rightarrow WW \rightarrow 2\ell 2\nu$ Search
PAS HIG-12-043	(SM) $H \rightarrow \tau\tau$ Search
PAS HIG-12-044	VH, $H \rightarrow bb$ Search
PAS HIG-12-045	CMS Combined Search for Higgs
PAS HIG-12-046	$H \rightarrow WW \rightarrow \ell\nu jj$
PAS HIG-12-050	MSSM $H \rightarrow \tau\tau$
PAS HIG-12-051	(SM) VH, $H \rightarrow \tau\tau$ Search
PAS HIG-12-033	$b\Phi \rightarrow 3b$ (combination)

CMS Higgs Results for HCP

Document | Analysis

Higgs @ CMS:

Very Successful Data Analysis

… and we @ DESY are part of it!

PAS HIG-12-033 | $b\Phi \rightarrow 3b$ (combination)

Backup

$H \rightarrow ZZ^* \rightarrow 4\ell$ Search Channel : Overview

- **Golden channel**
  - clean signature : 4 isolated leptons
  - excellent momentum resolution of leptons
  - Narrow mass peak m_{4l}
- **Backgrounds :**
  - irreducible : ZZ*
  - reducible : Z+jets/ttbar/WZ

Channels studied : 4μ, $2\mu 2e$, $4e$

Lepton selection

minimal lepton p_T = 5 GeV (μ), 7 GeV (e)

at least one lepton with p_T > 20 GeV

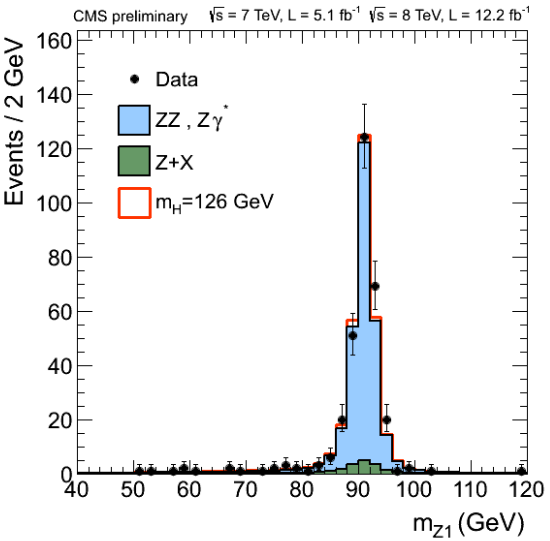
at least two leptons with p_T > 10 GeV

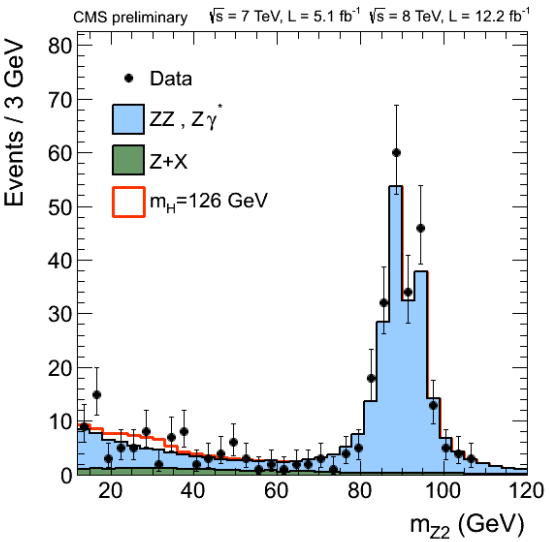
Z1 candidate : pair with mass closest to m(Z)

Z2 candidate : built from remaining leptons

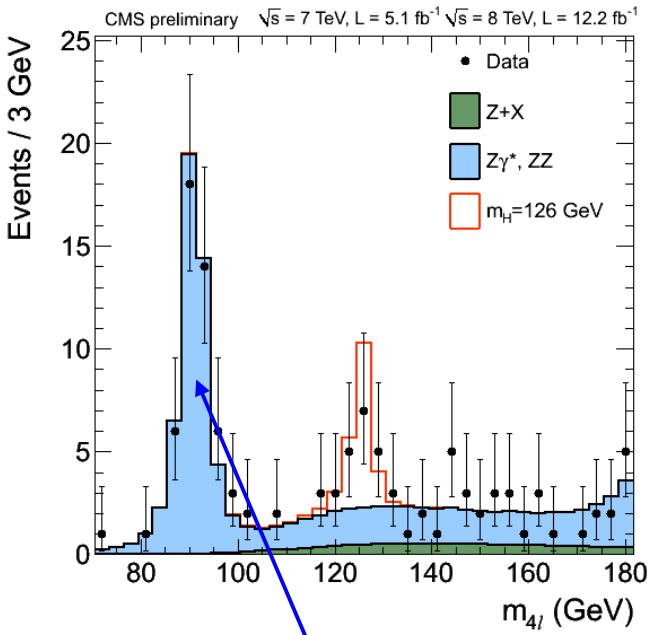
p_T

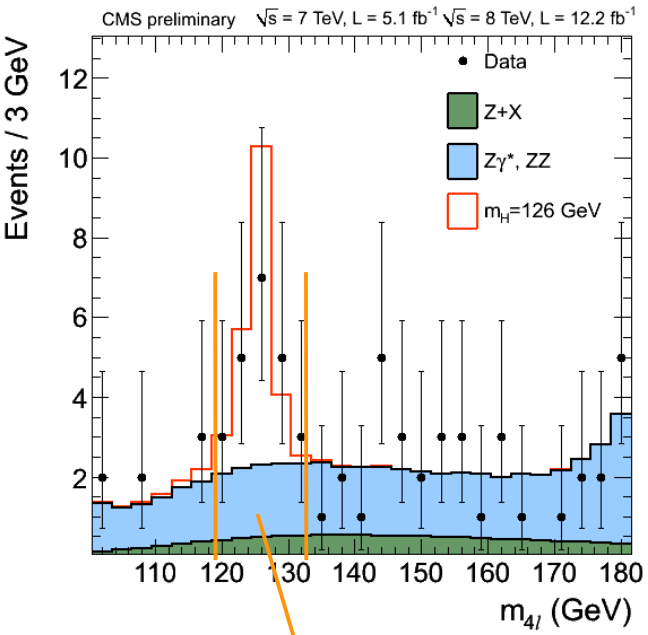
40 GeV < m(Z1) < 120 GeV 4 GeV < m(Z2) < 120 GeV

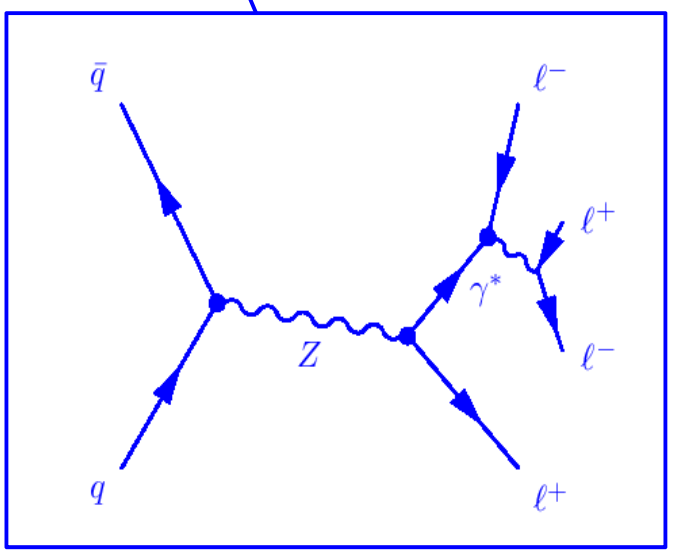


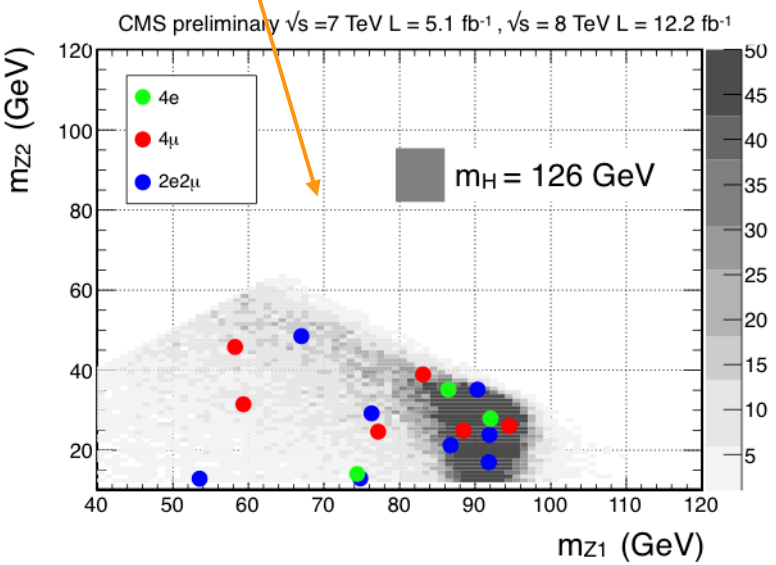


$M_{4\ell}$ after Dedicated Selection









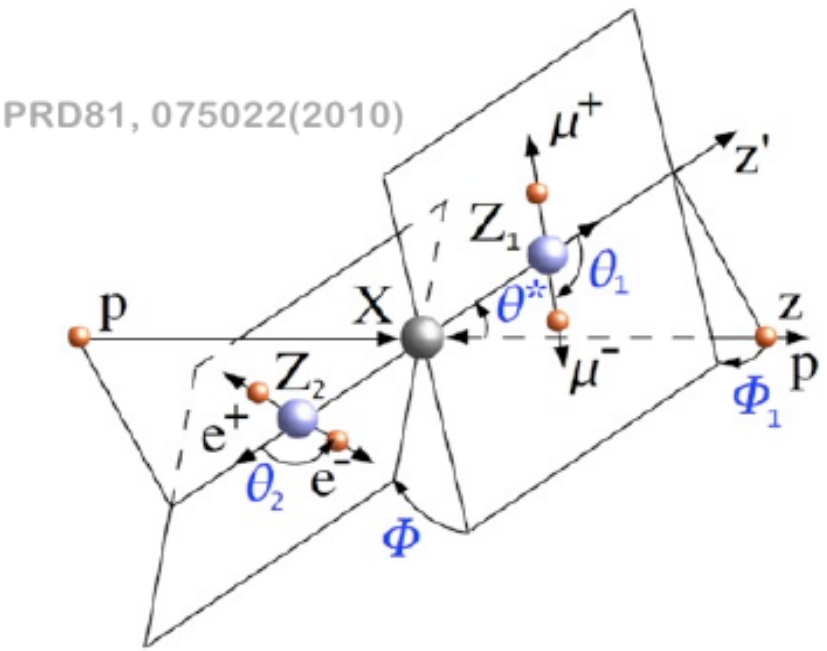
Matrix Element Likelihood Analysis

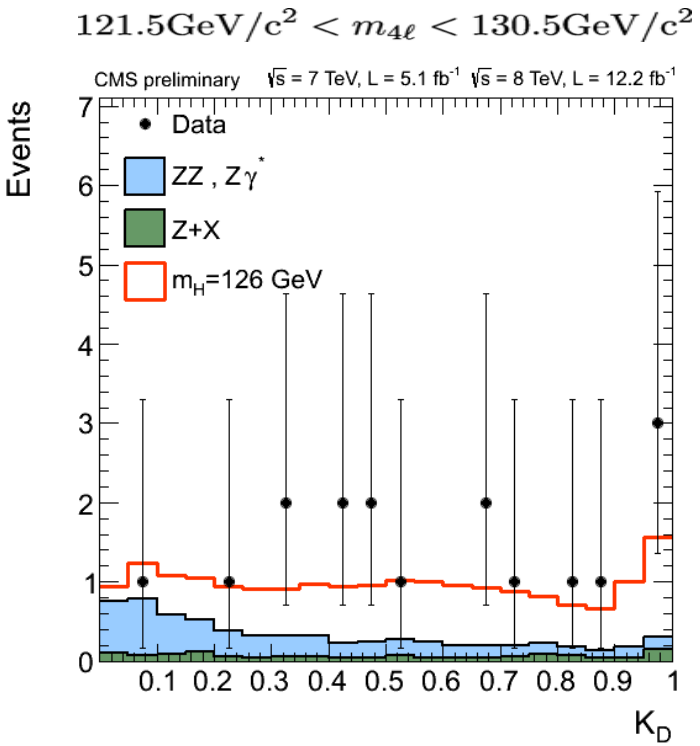
dynamics of decay described fully by 2 masses and 5 angles

Matrix Element Likelihood Analysis

discriminates $J^P = 0^+$ state from background

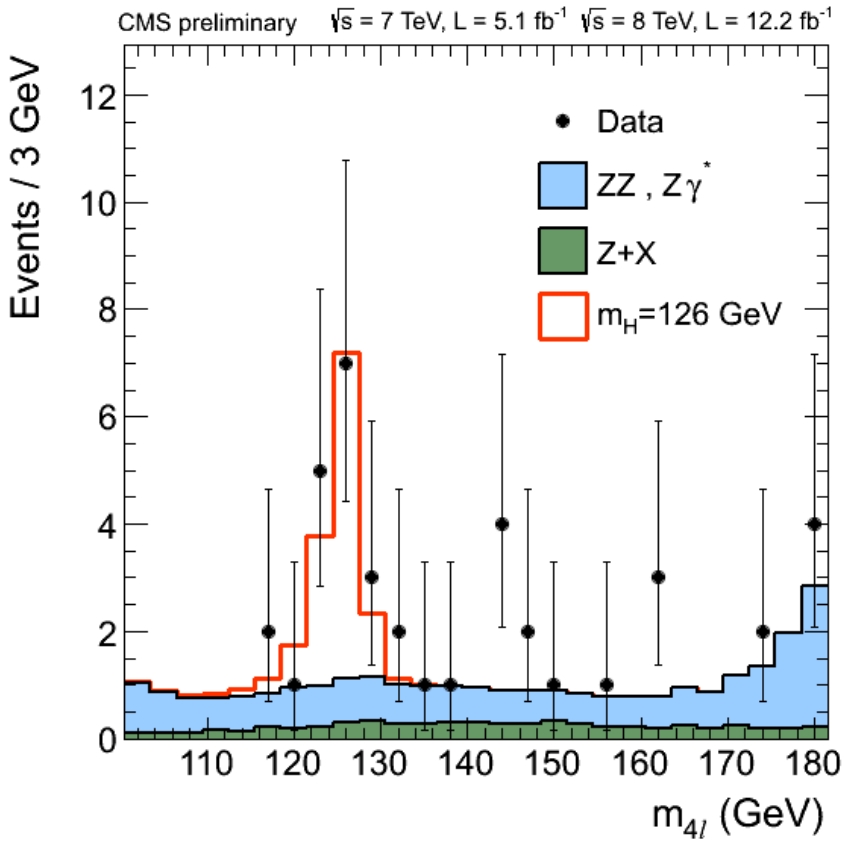
$$K_D = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\rm sig}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



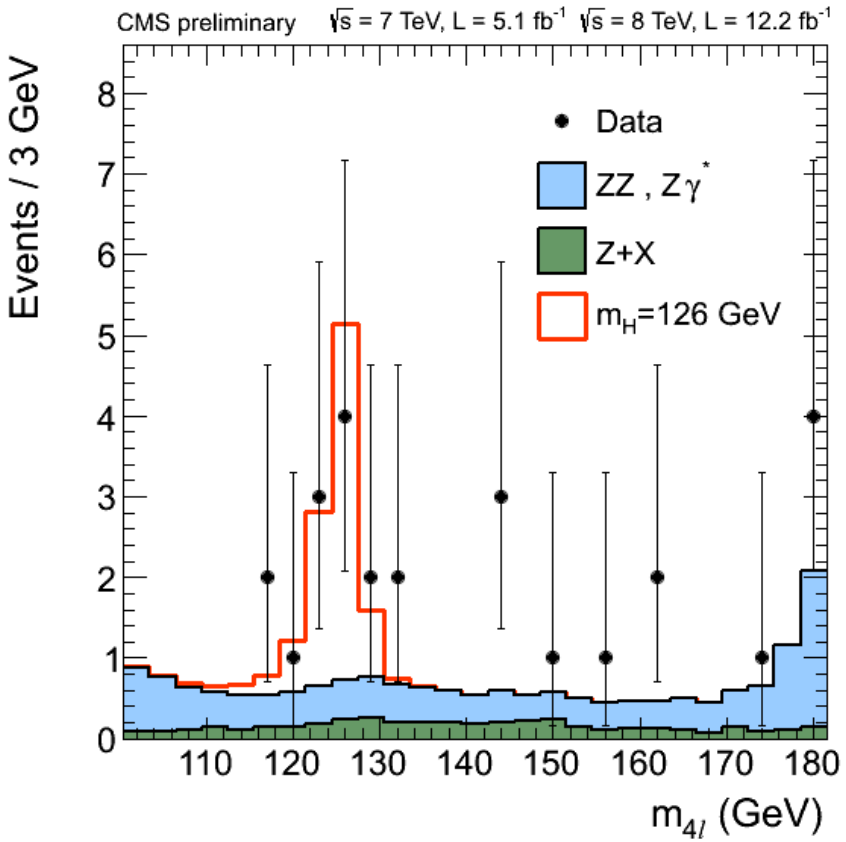


Statistical Analysis in H → ZZ* → 4ℓ Channel

$K_D > 0.3$

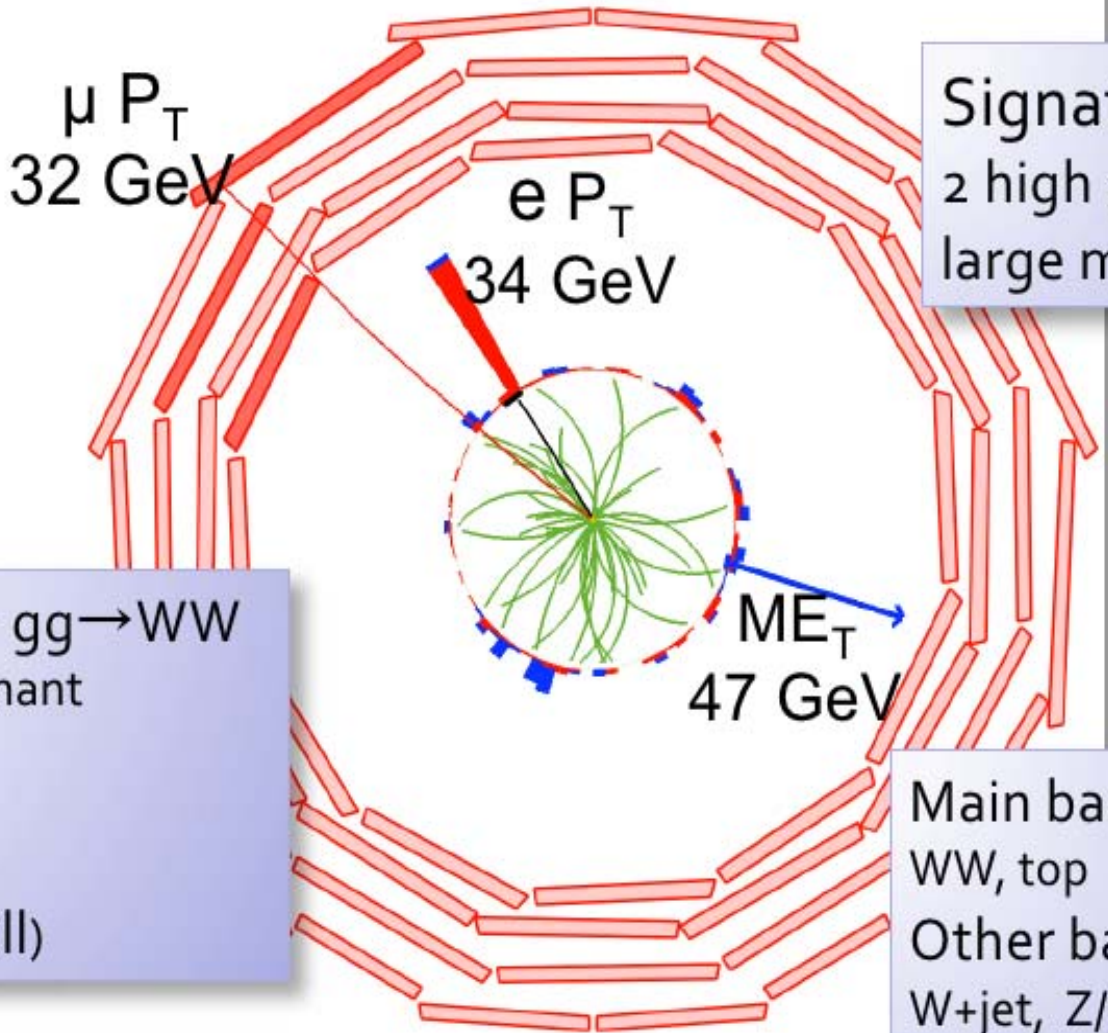


$K_D > 0.5$



statistical analysis performed with 2D distribution [K_D , m_{4l}]

$H \rightarrow WW^* \rightarrow 2\ell + 2\nu$



Signature:
2 high p_T leptons
large missing E_T

qq→WW + gg→WW
- Non-resonant

H→WW
- Large BR
- Small Δϕ(ll)

Main backgrounds:
WW, top
Other backgrounds:
W+jet, Z/γ*, WZ, ZZ, Wγ

Signatures

→ 2 hight p_T isolated leptons ($\mu\mu$, ee, $e\mu$)

→ large missing E_T

→ small $\Delta\varphi(\ell\ell)$ (SM Higgs scalarity)

Main backgrounds

WW, top, W+jets, Z+jets, WZ

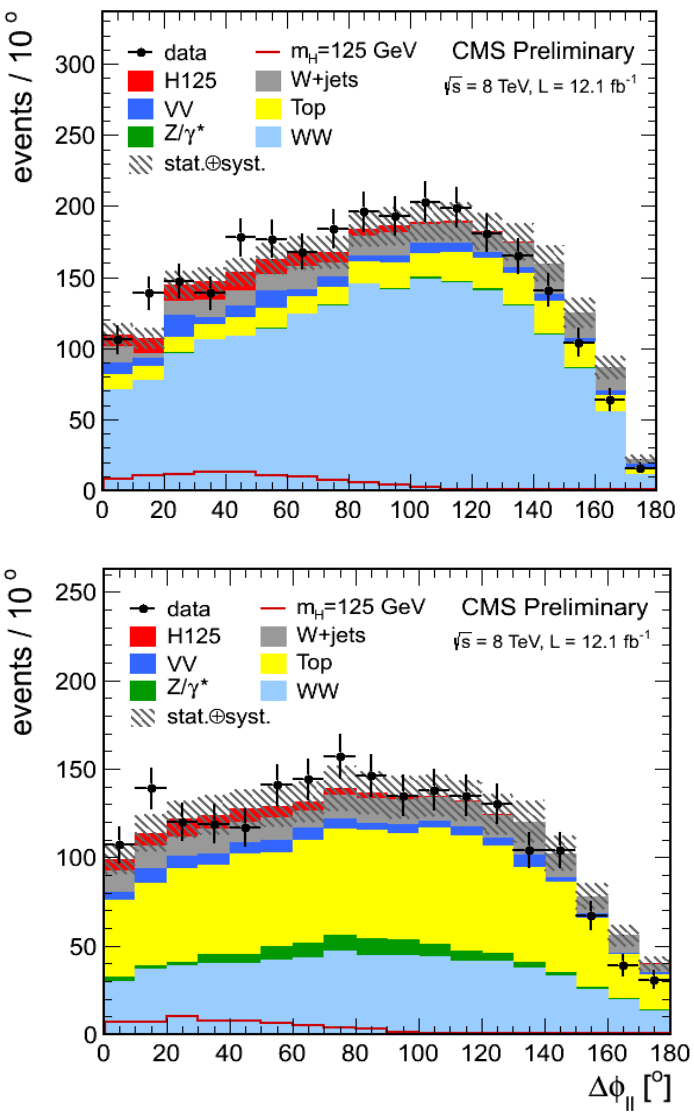
Search strategy

cut based selection
lepton kinematics;

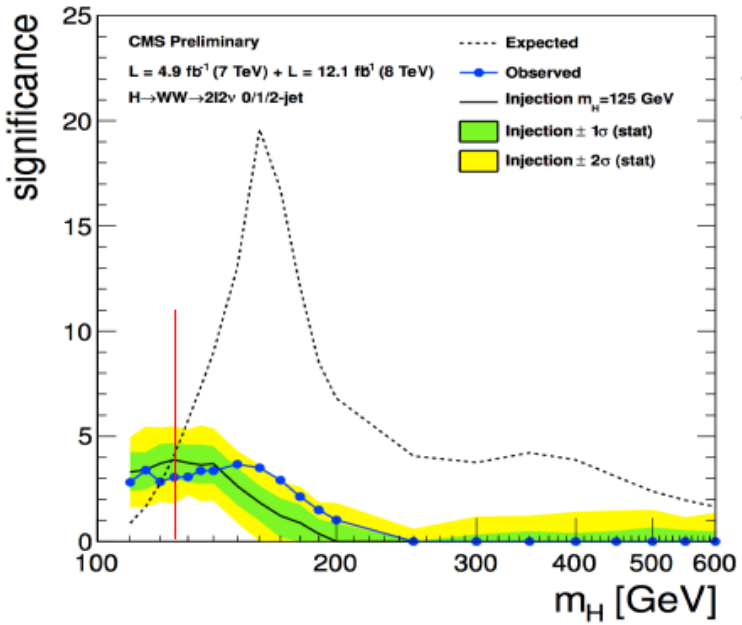
event categorization based on multiplicity

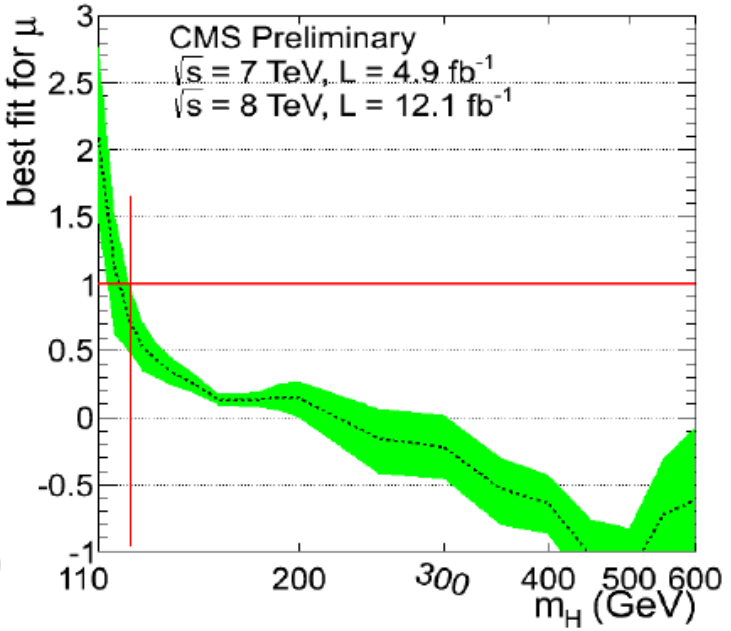
- $N_{jets} = 0$
- $N_{jets} \geq 1$

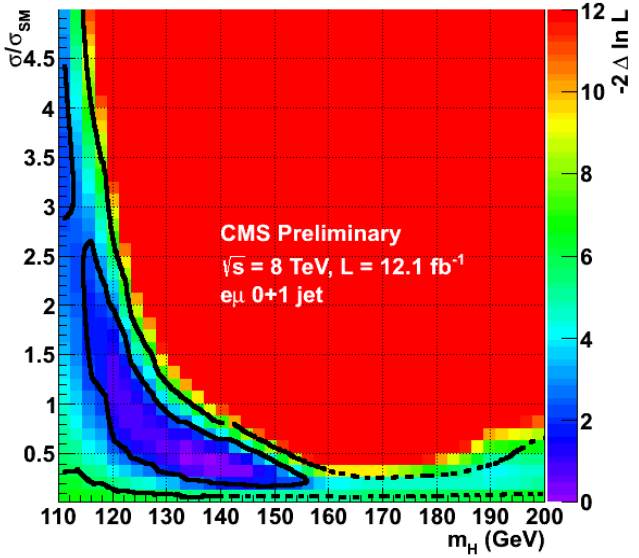
final 2D discriminant : [$M_{\ell\ell}$, M_T]



$H \rightarrow WW^* \rightarrow 2\ell + 2\nu$

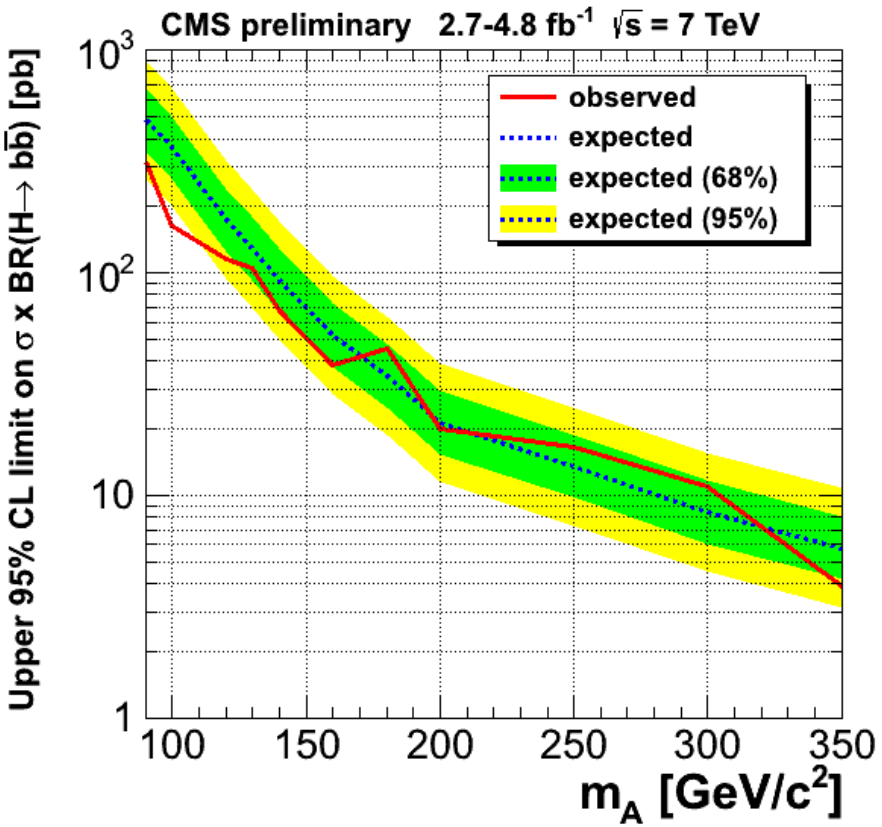


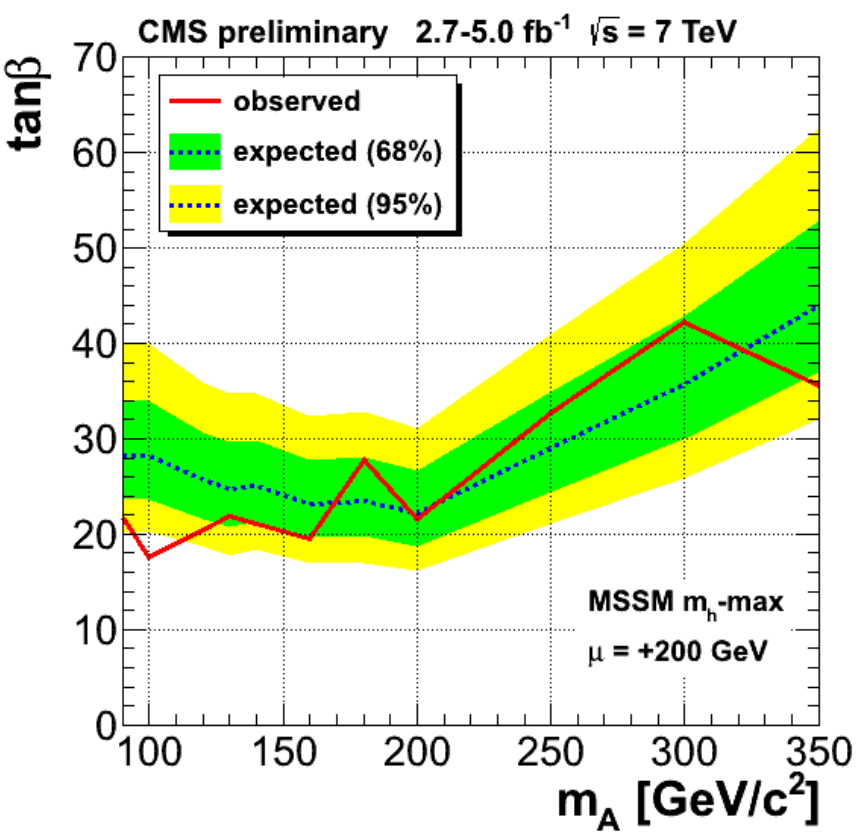




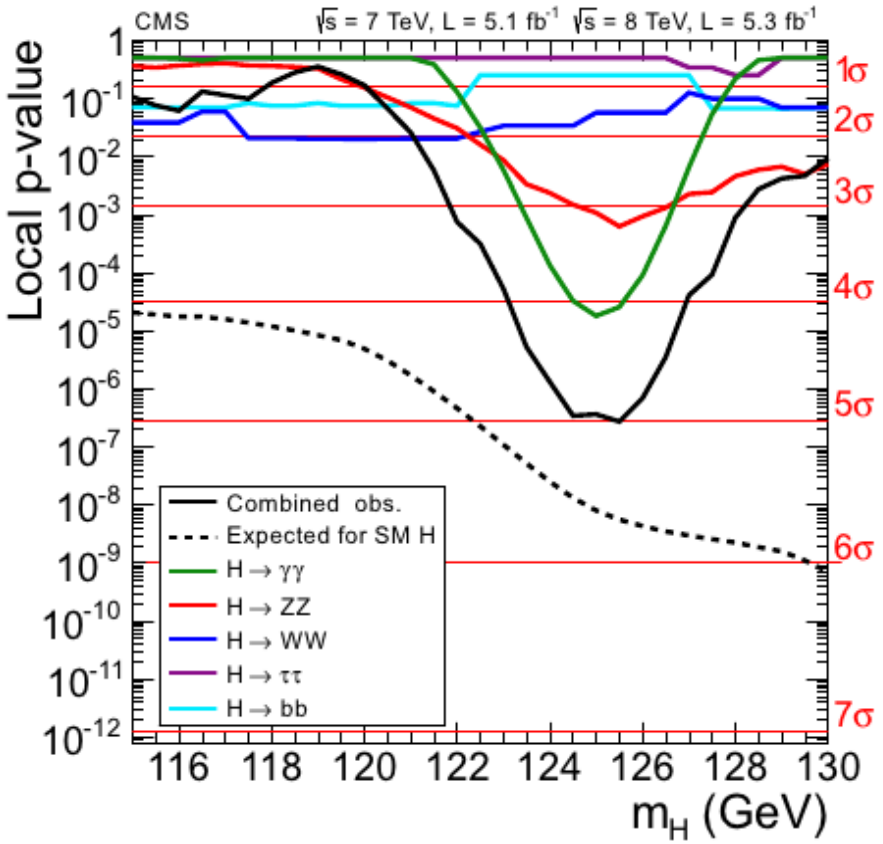
For M_H = 125 GeV:	7+8 TeV
Expected/observed signif.	4.1/**3.1**
Best fit $\mu=\sigma/\sigma_{SM}$	**0.74 ± 0.25**

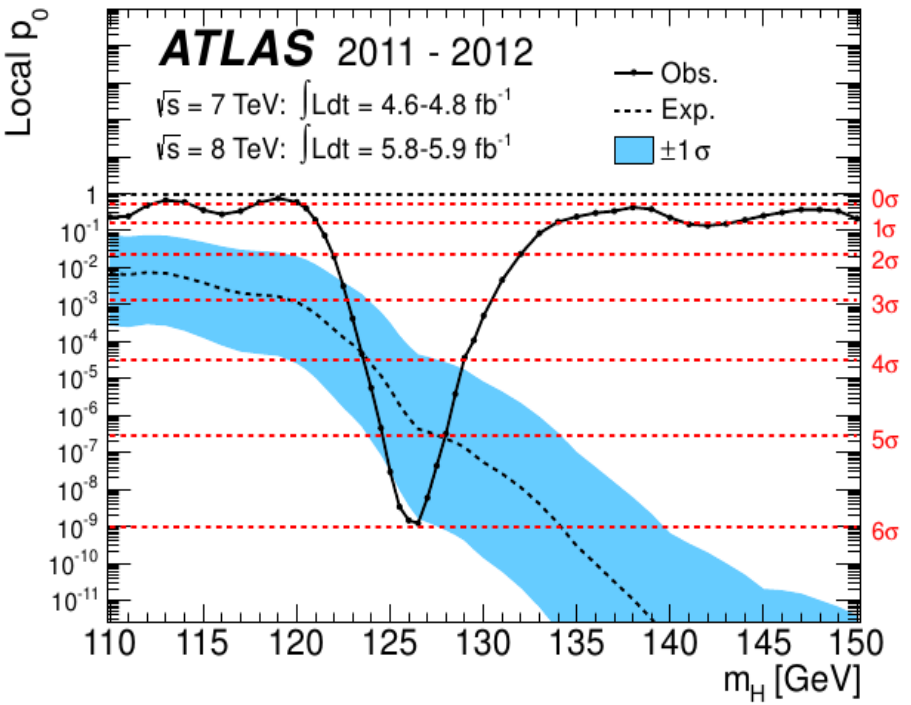
bΦ → bbb Combination





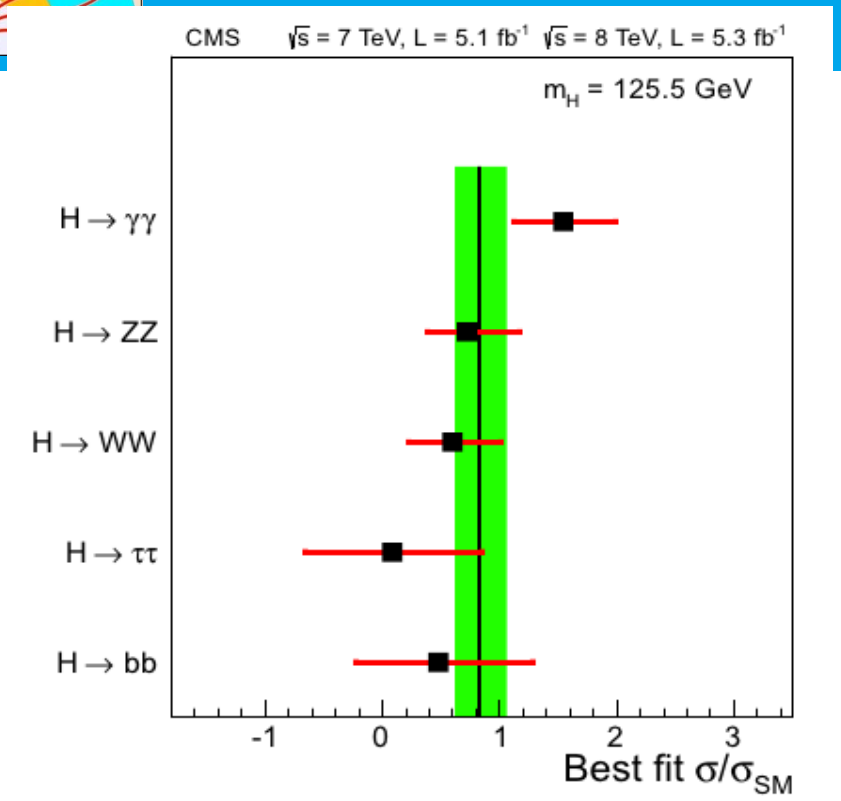
Published Results (July 2012)

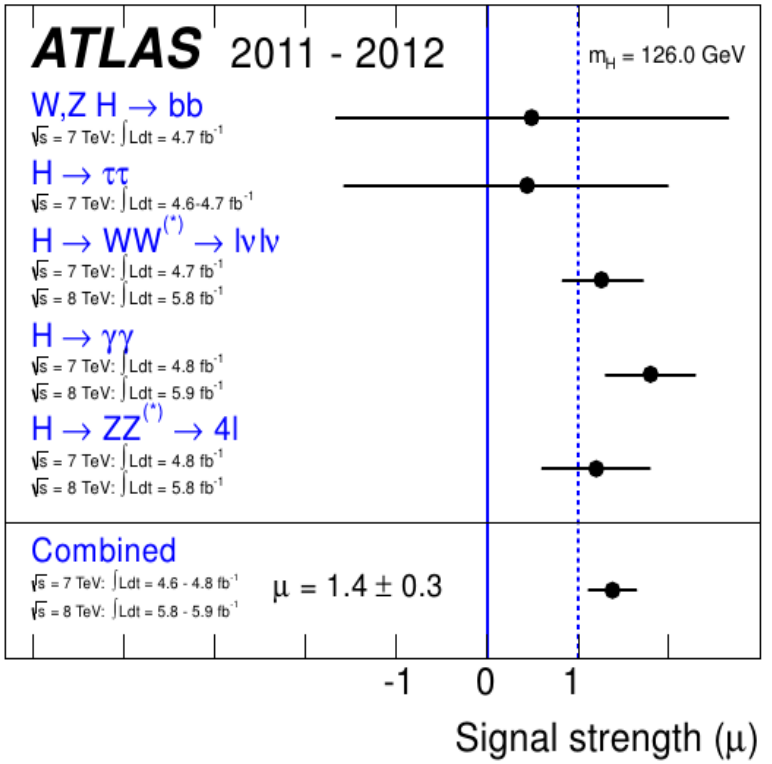




CMS and ATLAS experiments have observed a new boson consistent with expectations for the SM Higgs boson

Published Results (July 2012)





CMS

m_X = 125.3 ± 0.4(st.) ± 0.5(sys.) GeV

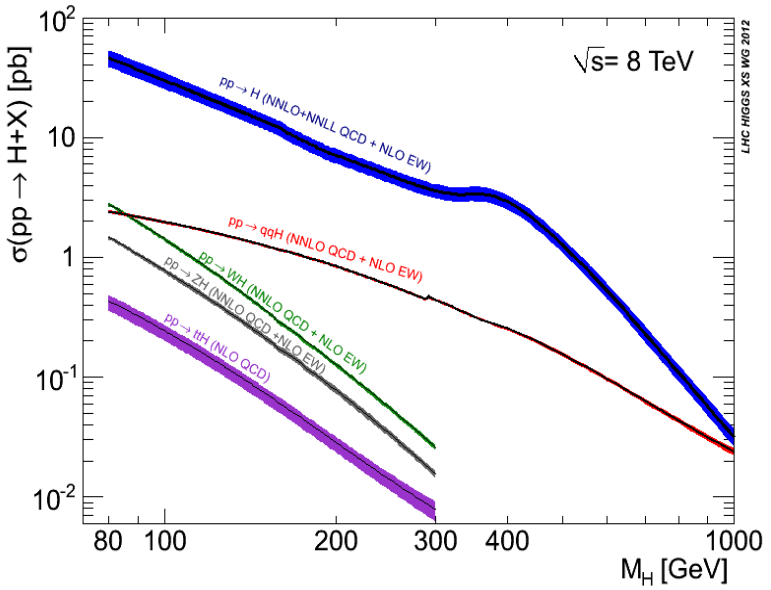
= 0.87 ± 0.23

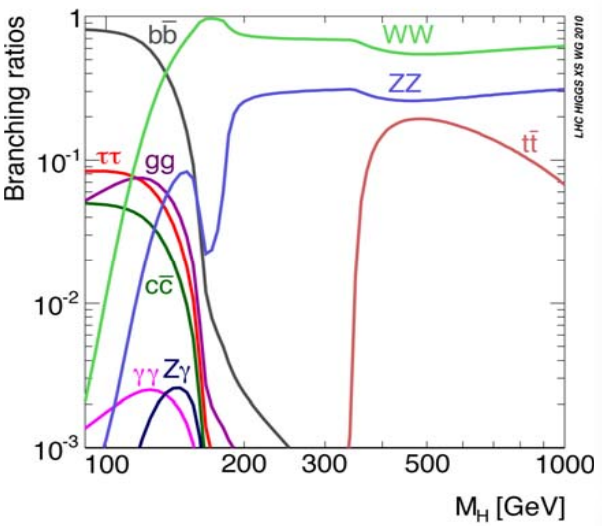
ATLAS

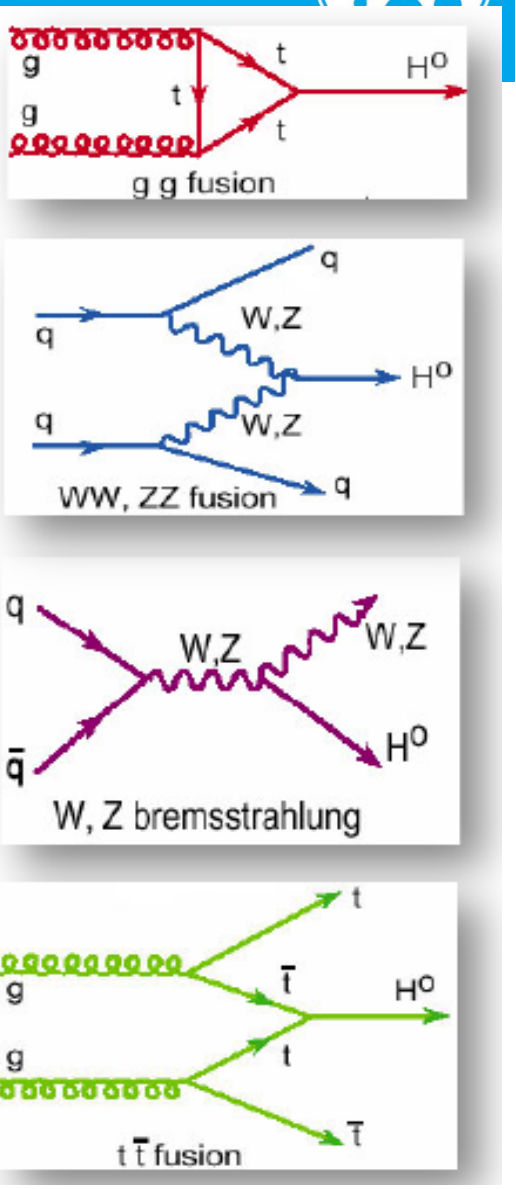
M_X = 126.0 ± 0.4(st.) ± 0.4(sys.) GeV

μ = 1.4 ± 0.3

Standard Model Higgs Boson at LHC







Main search channels ($m_H \leq 150$ GeV)	
qqH / gg→H	*H→γγ*
qqH / gg→H	*H→WW→2ℓ2ν*
gg→H	*H→ZZ→4ℓ*
qq→VH	*Z→ℓℓ,νν / W→ℓν / H→bb*
ttH	*H → bb*
qqH / VH / gg→H	*H→ττ*

SM Higgs: Data Samples

Channel	m_H range [GeV/c^2]	data set [fb^{-1}]	Data used CMS [fb^{-1}]	m_H resolution
1) $H \to \gamma\gamma$	110-150	5+5/fb	2011+12	1-2%
2) $H \to$ tau tau	110-145	5+12/fb	2011+12	15%
3) $H \to bb$	110-135	5+12/fb	2011+12	~~10%~~ 8-9%
4) $H \to WW \to l\nu l\nu$	110-600	5+12/fb	2011+12	20%
5) $H \to ZZ \to 4l$	110-1000	5+12/fb	2011+12	1-2%