Higgs searches at CMS

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on behalf of CMS collaboration

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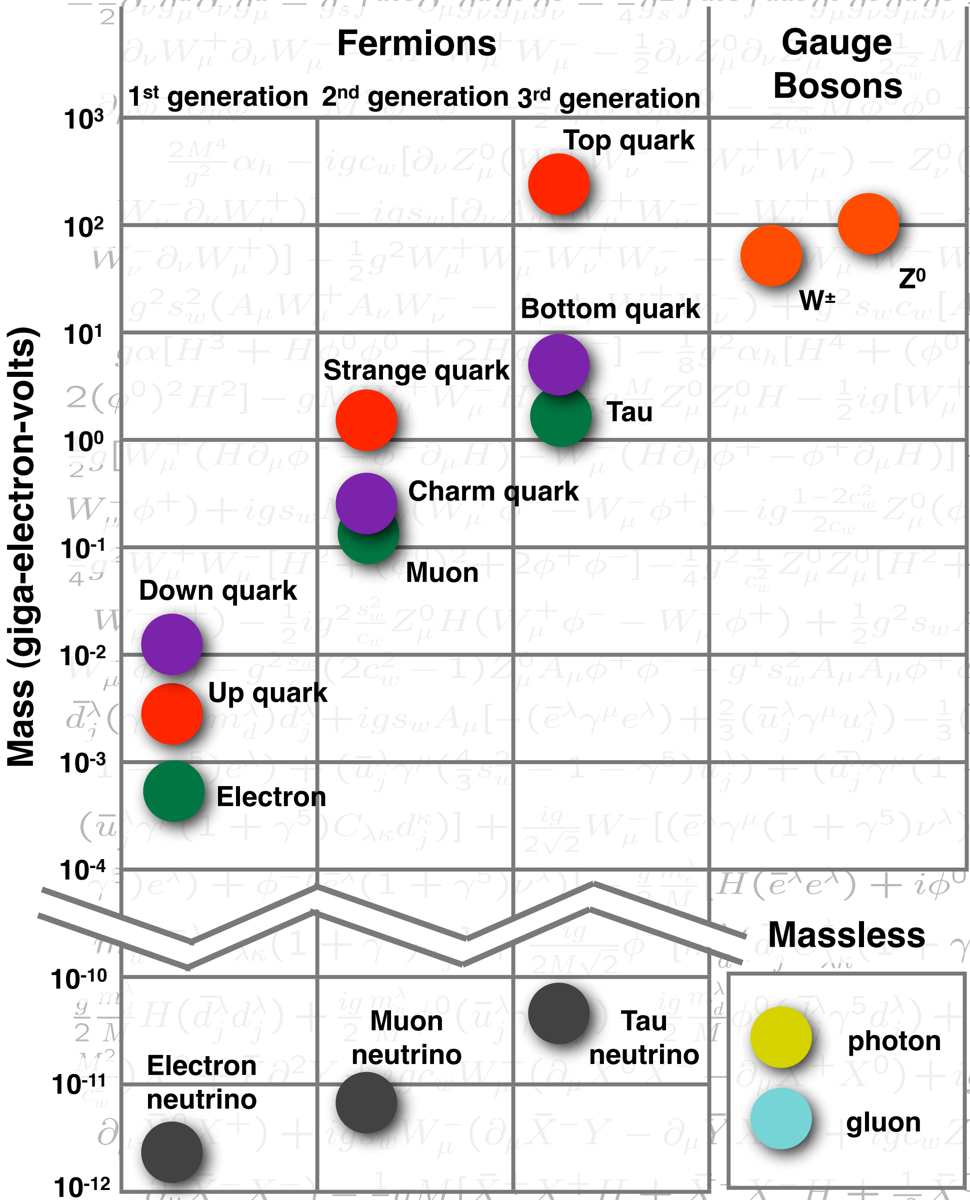
The Standard Model of particle physics

$$
\begin{aligned}
&-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \\
&\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \frac{1}{2}m_h^2 H^2 - \\
&\partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \\
&\frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
&W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
&W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - \\
&g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + \\
&2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \\
&\frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\frac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
&\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - \\
&1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
&(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \\
&\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
&m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
&\frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
&\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \\
&\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
&\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \\
&\frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{aligned}
$$

Standard Model Lagrangian Density

The Standard Model of particle physics

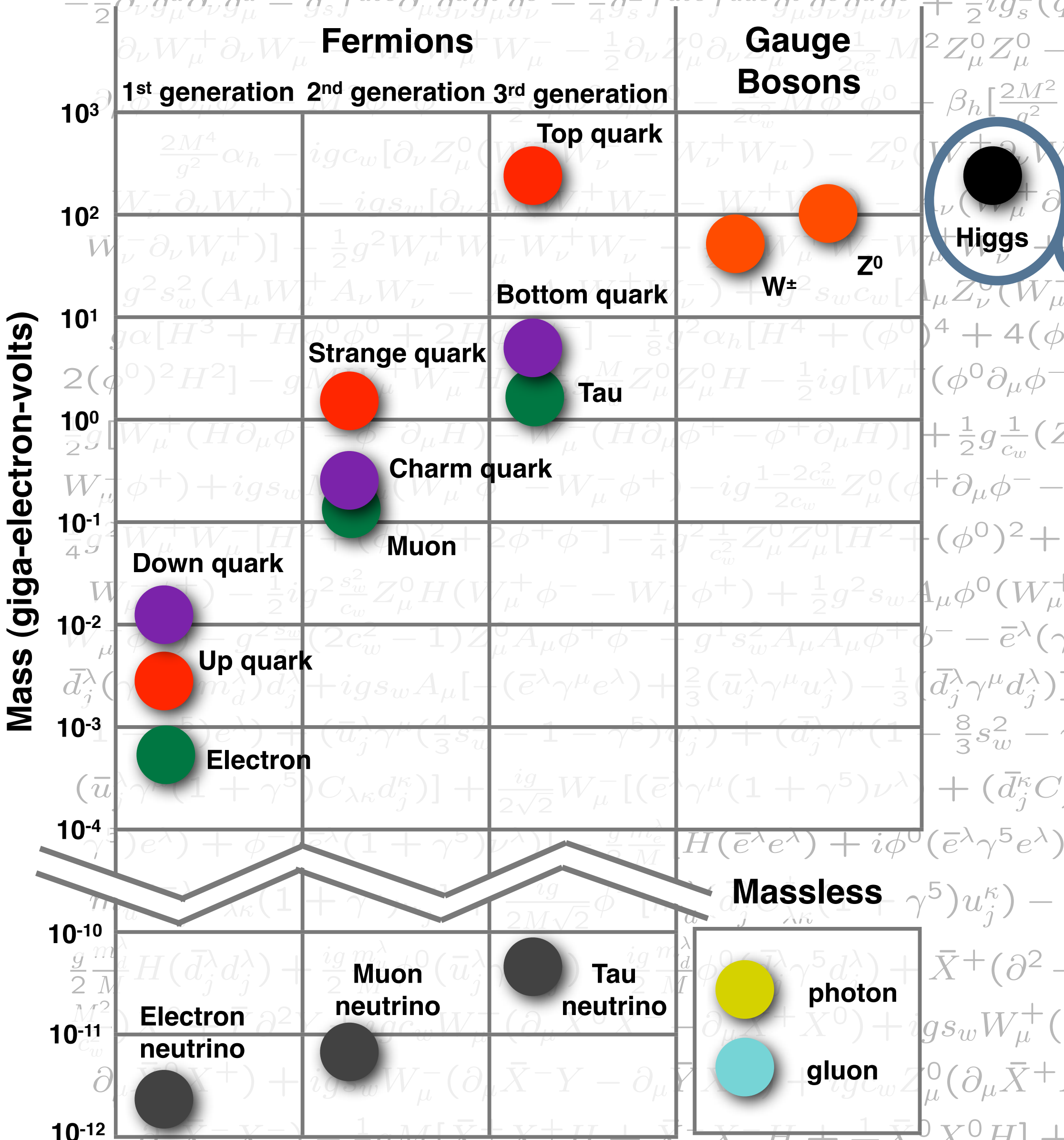


Confirmed to better than 1% uncertainty by 100's of precision measurements

But one thing "was" still missing!

Standard Model Lagrangian Density

The Standard Model of particle physics



The Higgs boson

40+ years of collective obsession

Confirmed to better than 1% uncertainty by 100's of precision measurements

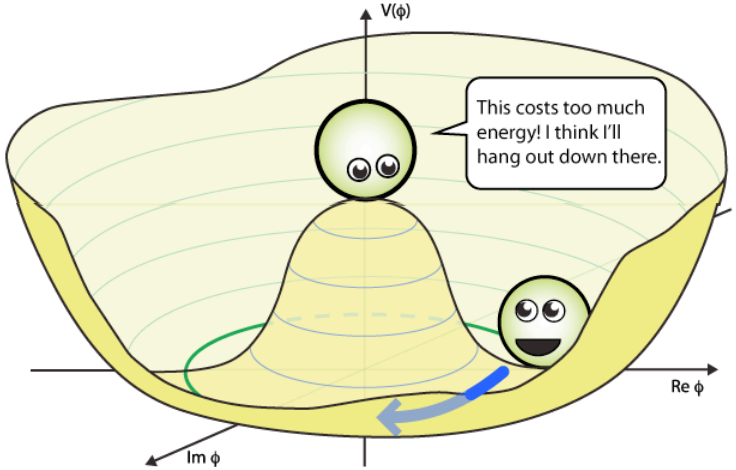
But one thing "was" still missing!

Standard Model Lagrangian Density

Higgs mechanism

The economical way to endow fundamental particles with mass while keeping the theory gauge invariant and predictive

The field is responsible for the spontaneous breaking of electroweak symmetry



PRL 13, 321-323 (1964) Englert and Brout
PRL 13, 508-509 (1964) Higgs
PRL 13, 585-587 (1964) Guralnik, Hagen, Kibl

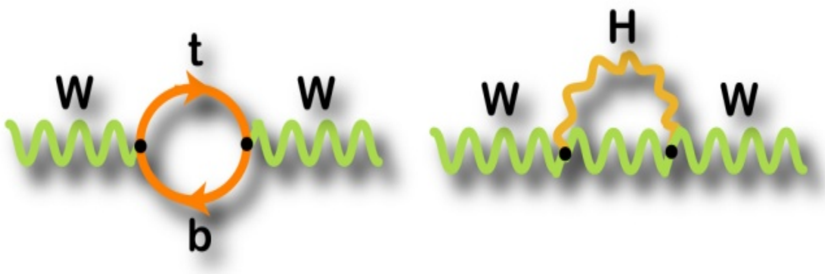
"Only" requires one new particle: spin 0 boson
"Only" one unknown: the mass

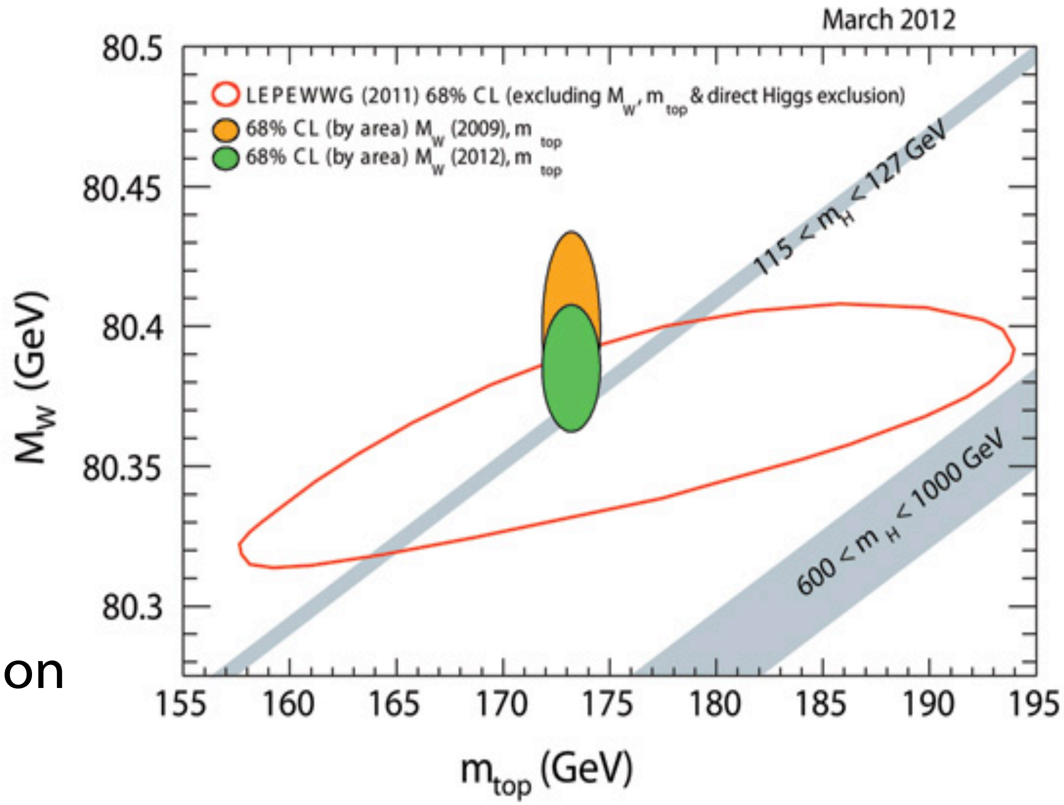
Less economical (Higgs doublets, families of Higgses, ...) or more complicated (Higgs-less solutions, Technicolor, ...) routes exist

Constraints on SM Higgs boson

Before of the 4th July

SM parameters (M_W , M_t ,
Z pole measurements , etc.)
constrain the Higgs boson mass

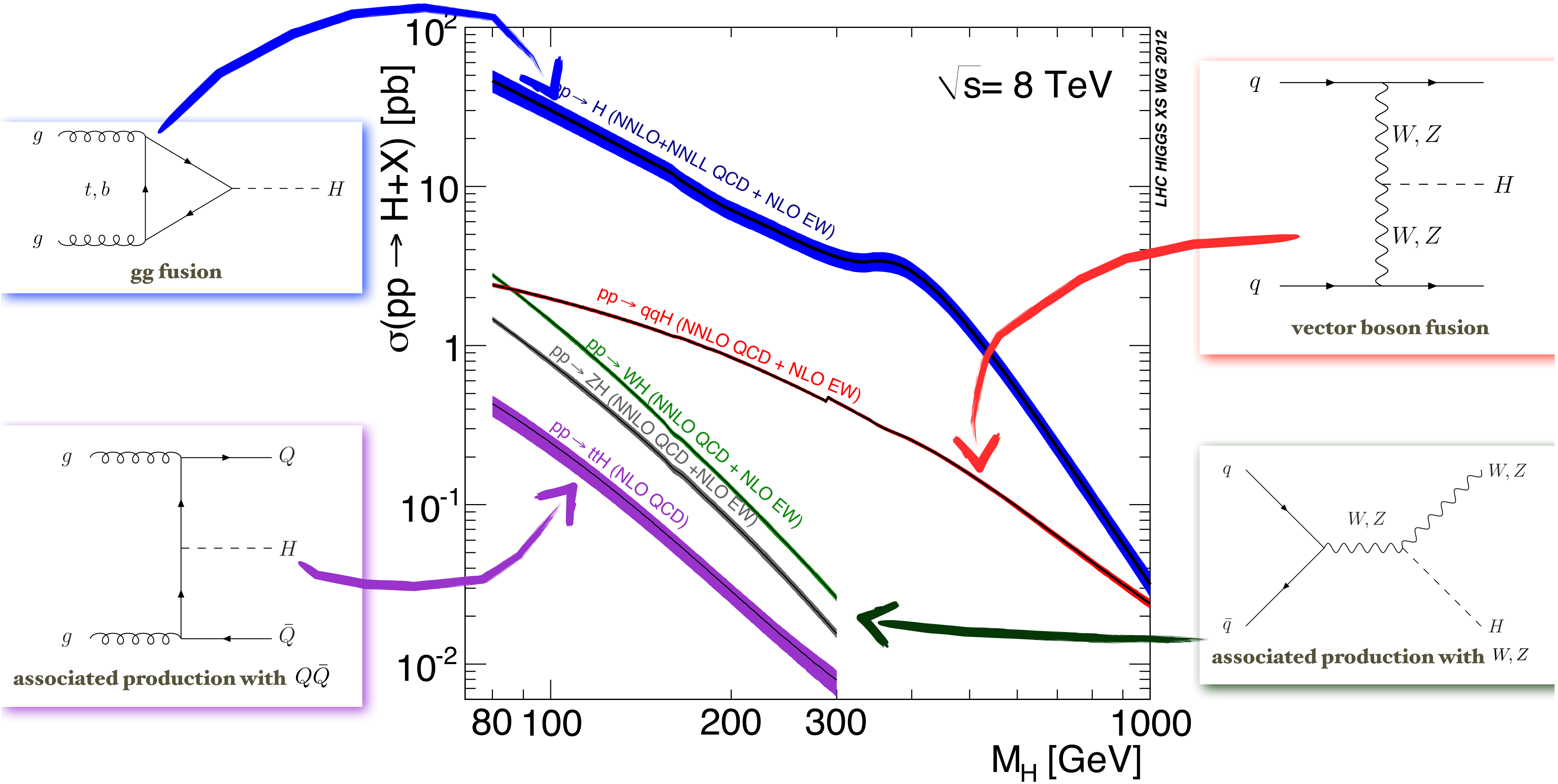




Tevatron new M_W measurements
shifts SM Higgs boson mass expectation
$M_W = 80.385 \pm 0.015$ GeV (March 2012)

Hadron Colliders have significantly constrained the Higgs boson mass
excluded at 95% CL $M_H < 122.1$ GeV (except 116.6-119.4) and $127 < M_H < 600$ GeV

SM Higgs boson production @ LHC



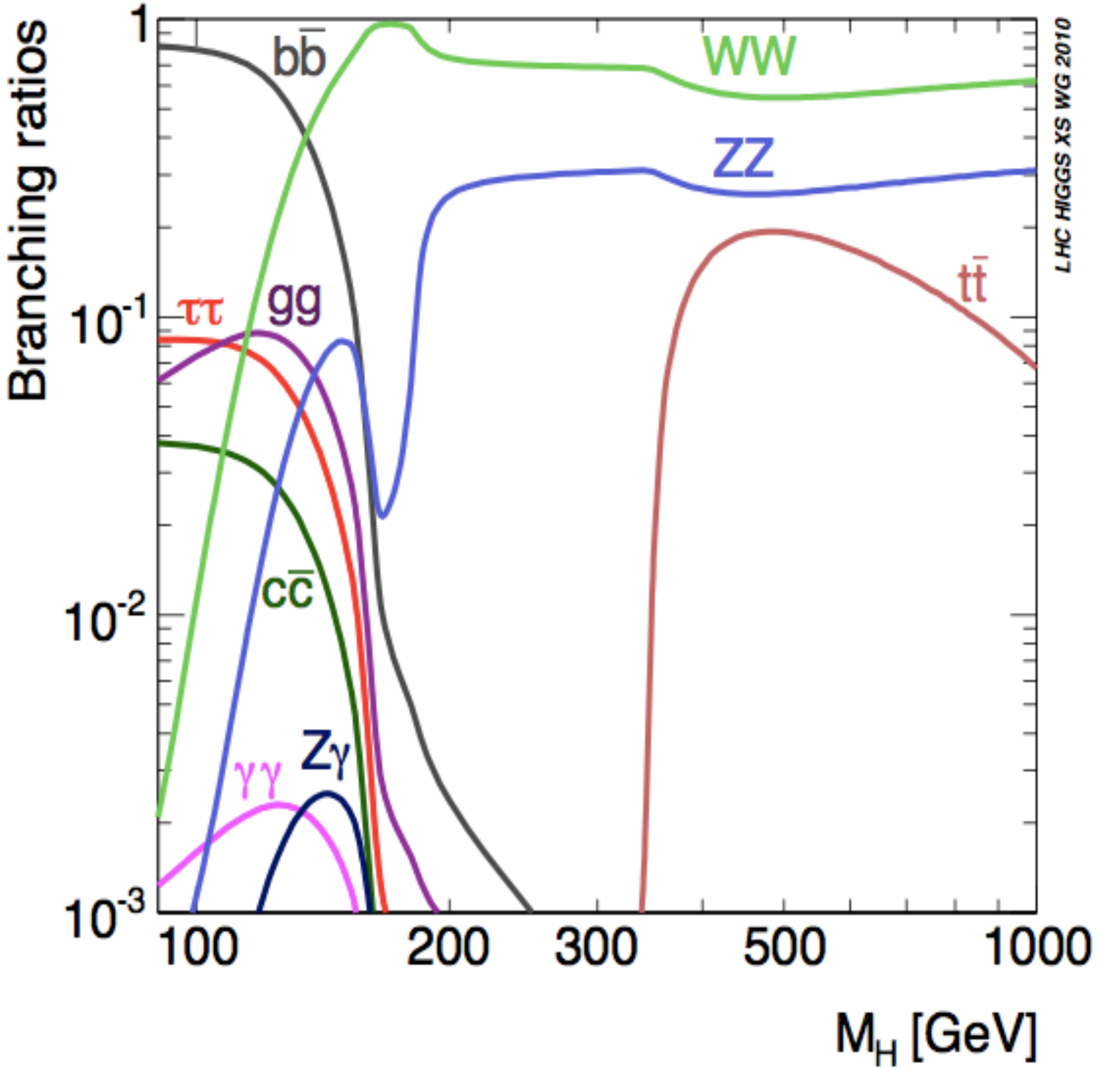
SM Higgs boson decay modes

Low mass region is very rich but also very challenging:

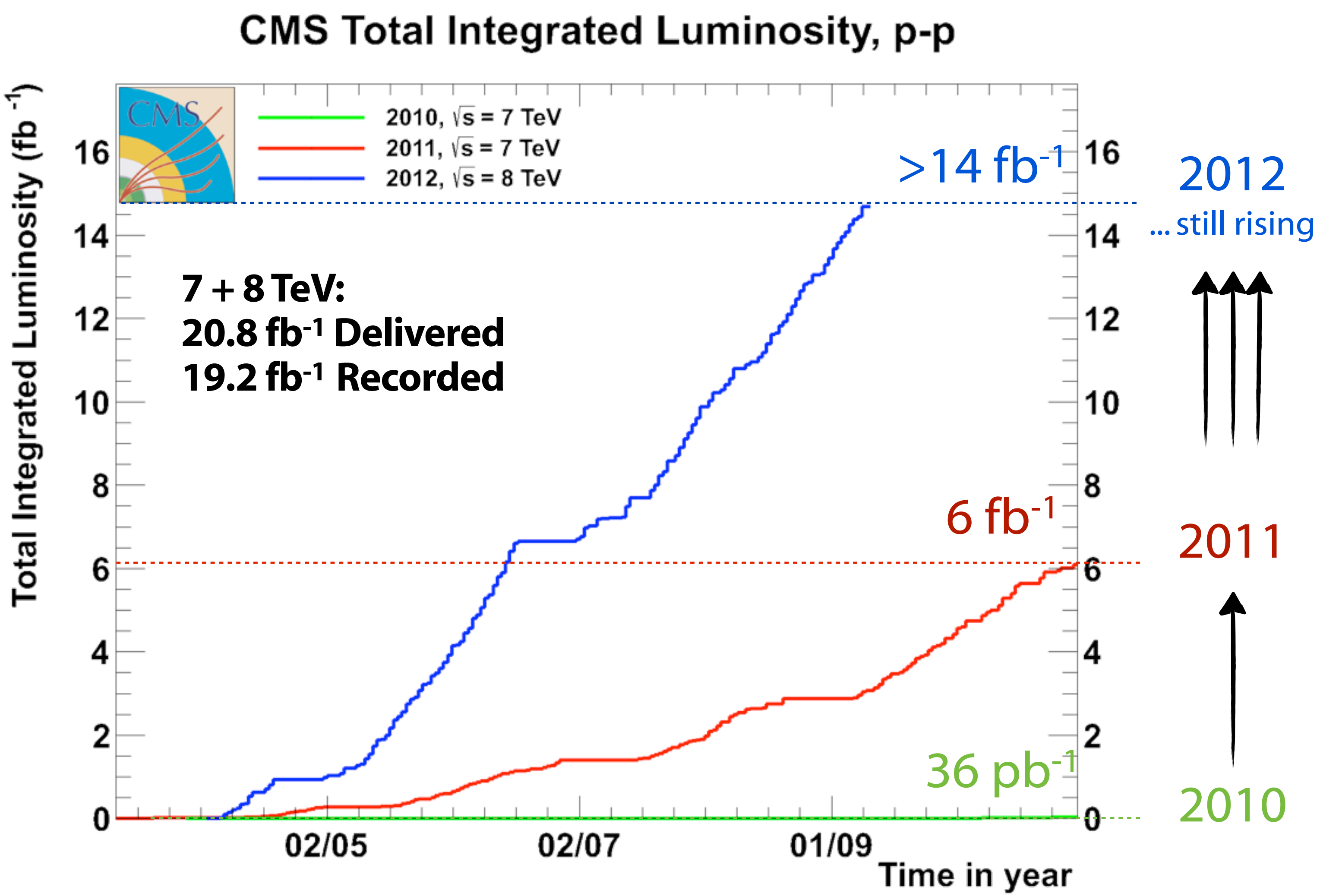
- **$H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^{(*)}\rightarrow 4l$ have excellent mass resolution ($\approx$1%) but low BR**
- **$H\rightarrow bb$ and $H\rightarrow\tau\tau$ have high BR but huge background**

Decay branching ratio (M_H = 125 GeV)

Process	Branching ratio	
$H\rightarrow bb$	5.77×10^{-1}	fermions
$H\rightarrow cc$	2.91×10^{-2}	fermions
$H\rightarrow\tau\tau$	6.32×10^{-2}	fermions
$H\rightarrow\mu\mu$	2.20×10^{-4}	fermions
$H\rightarrow gg$	8.57×10^{-2}	gauge bosons
$H\rightarrow\gamma\gamma$	2.28×10^{-3}	gauge bosons
$H\rightarrow Z\gamma$	1.54×10^{-3}	gauge bosons
$H\rightarrow WW$	2.15×10^{-1}	gauge bosons
$H\rightarrow ZZ$	2.64×10^{-2}	gauge bosons
Γ_H [GeV]	4.07×10^{-3}	

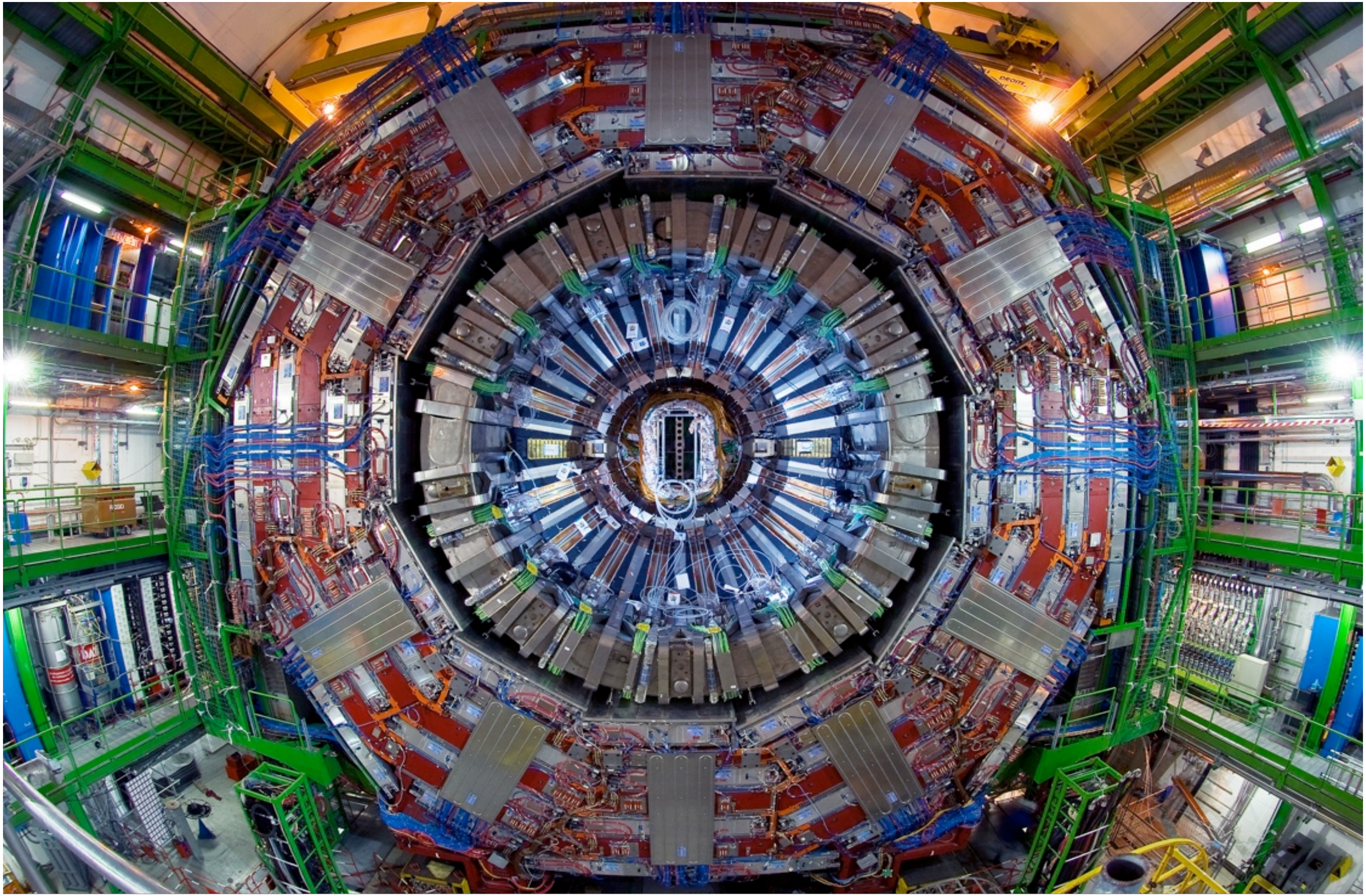


LHC and its outstanding performance

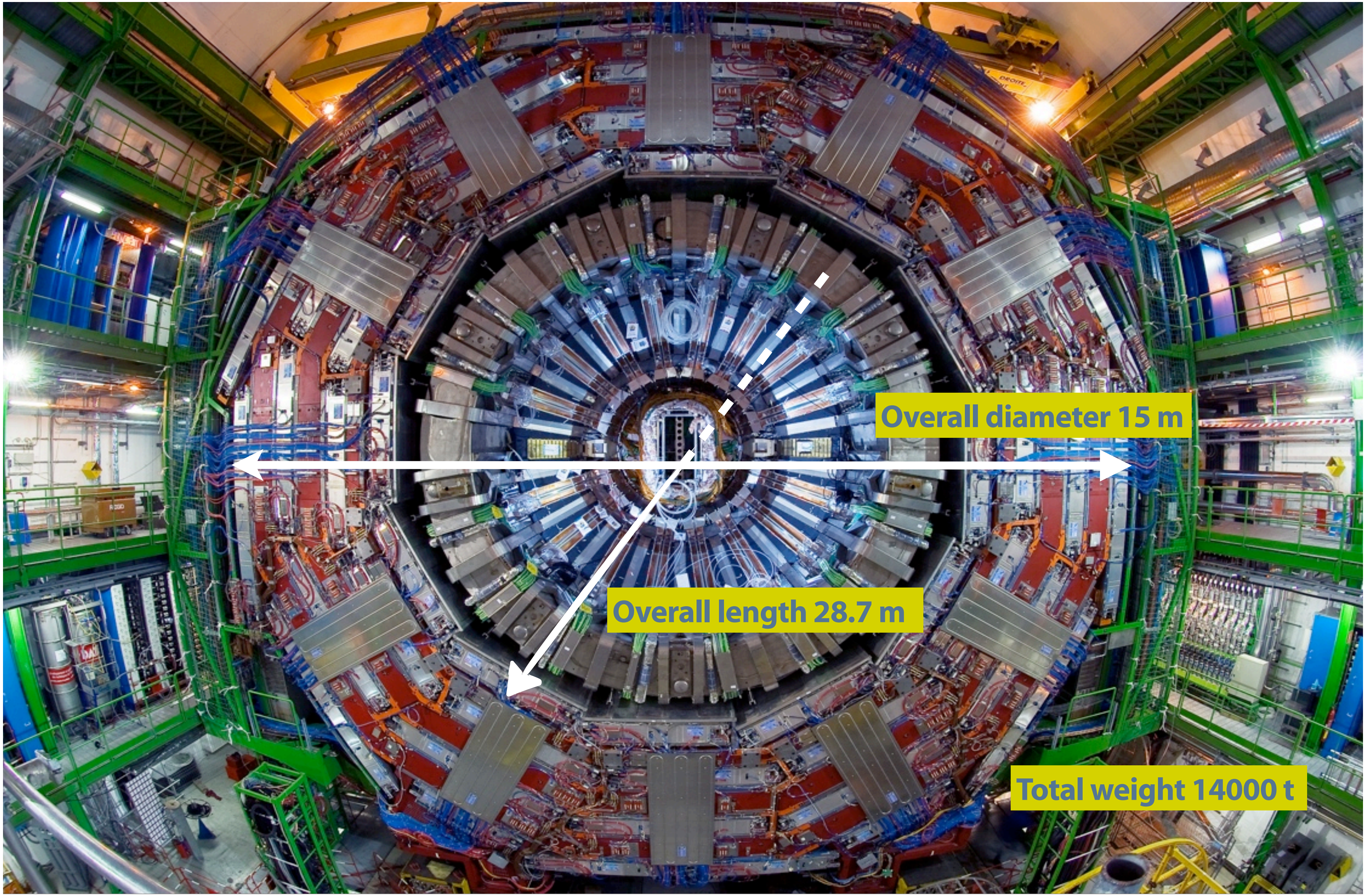


Excellent performance over the three years
Data taking efficiency always higher than 91%

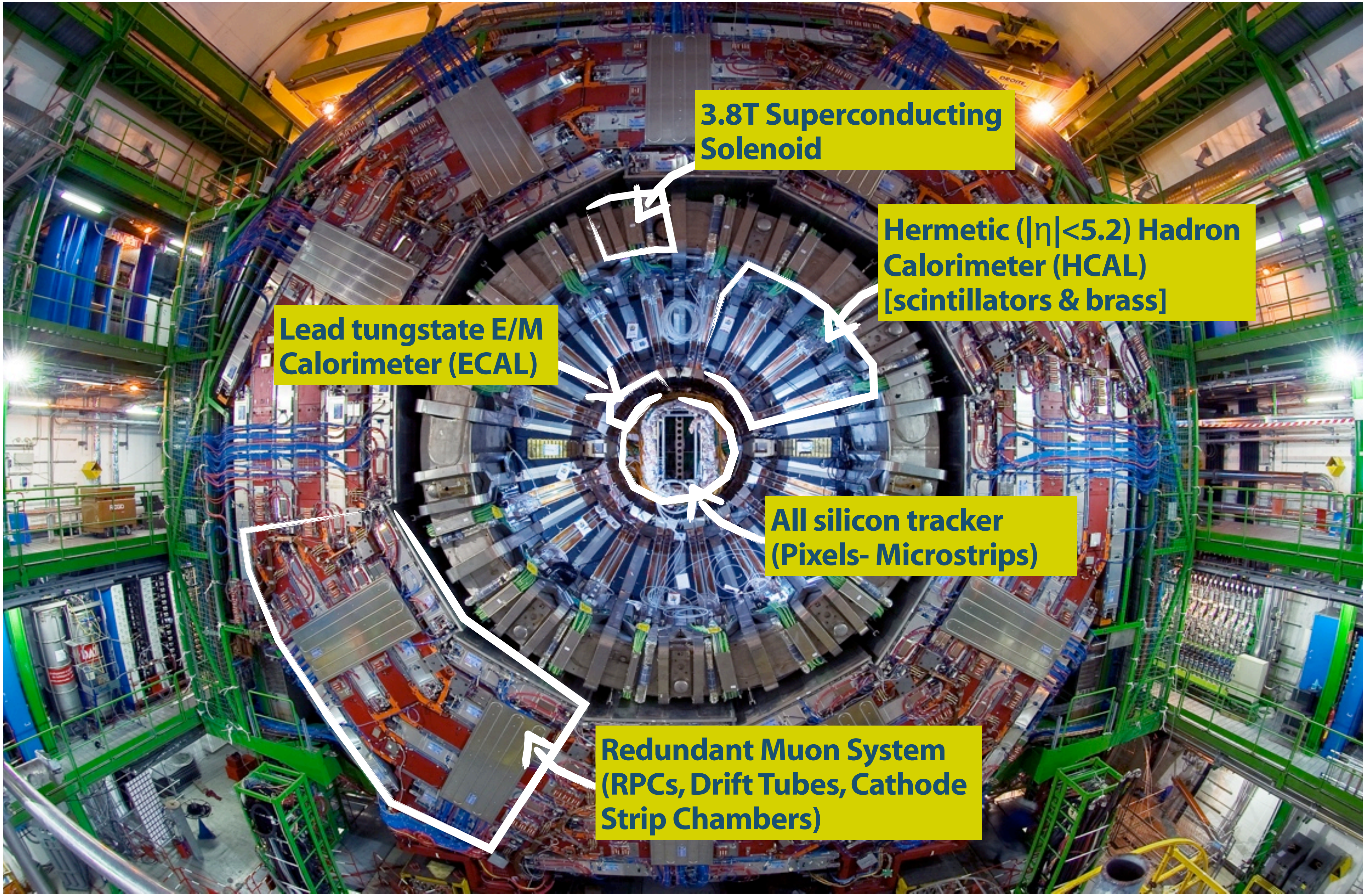
The CMS detector



The CMS detector



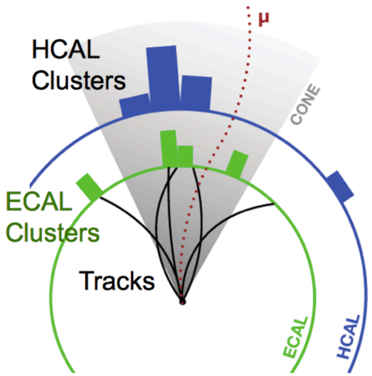
The CMS detector



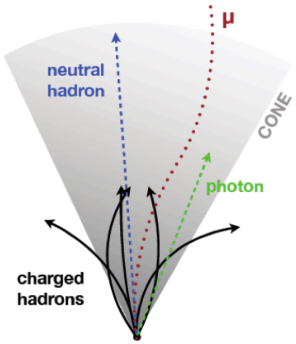
Global event description

Optimal use of information
from **high resolution, high granularity** sub-detectors

From
detector based
reconstruction



To
particle based
reconstruction



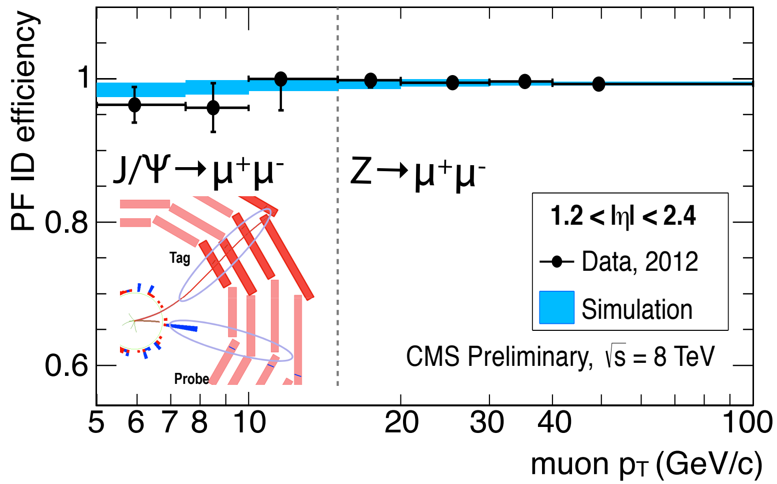
- Charged particles well separated in large tracker volume and 3.8 T magnetic field
- Excellent tracking, able to go to down to very low momenta (~100 MeV)
- Granular electromagnetic calorimeter with excellent energy resolution
- In multi-jet events, only 10% of the energy goes to neutral (stable) hadrons (~60% charged, ~30% neutral electromagnetic)

Use a global event description → Returns a list of reconstructed particles

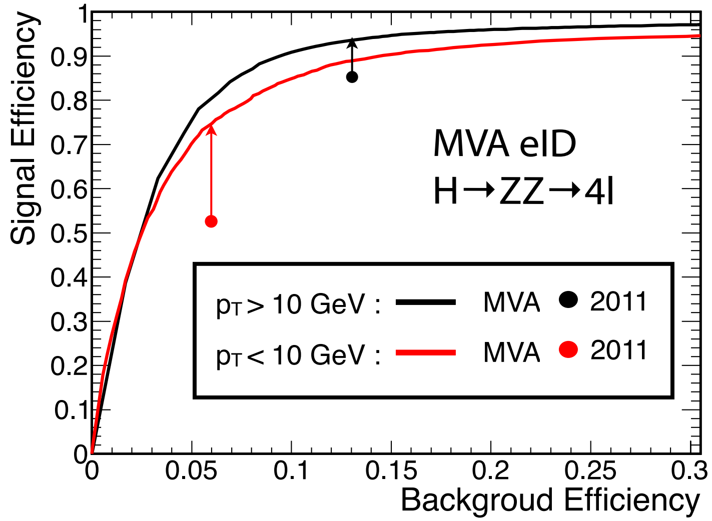
e,μ,γ, charged and neutral hadrons (specialized algorithm for e/γ)
Used as building blocks for jets, taus , missing transverse energy , isolation
PU particle identification

Objects: grand summary

Muons



Electrons

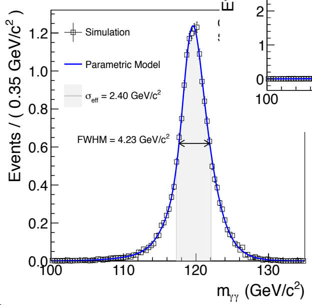


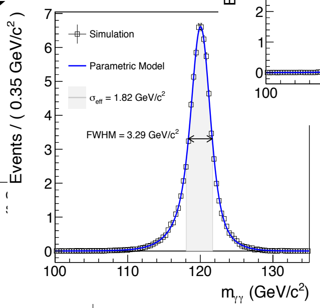
Photons

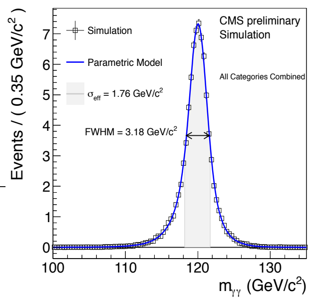
July 2012 (ICHEP)

March 2011 (Moriond)

July 2011 (EPS)

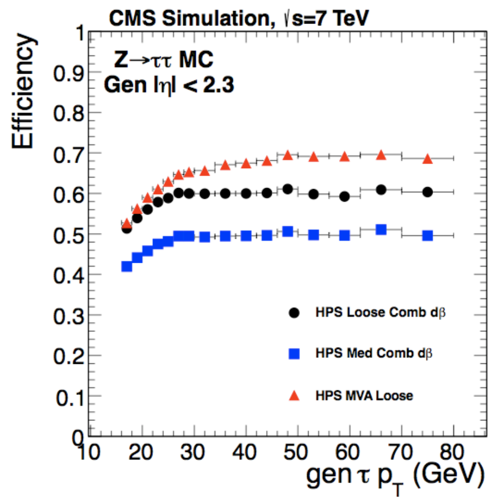






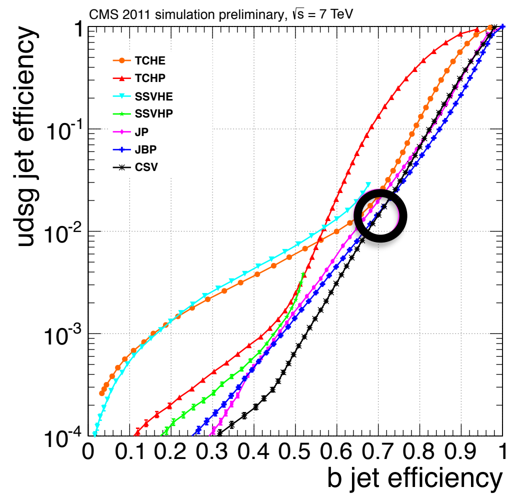
Progress in understanding ECAL

Taus



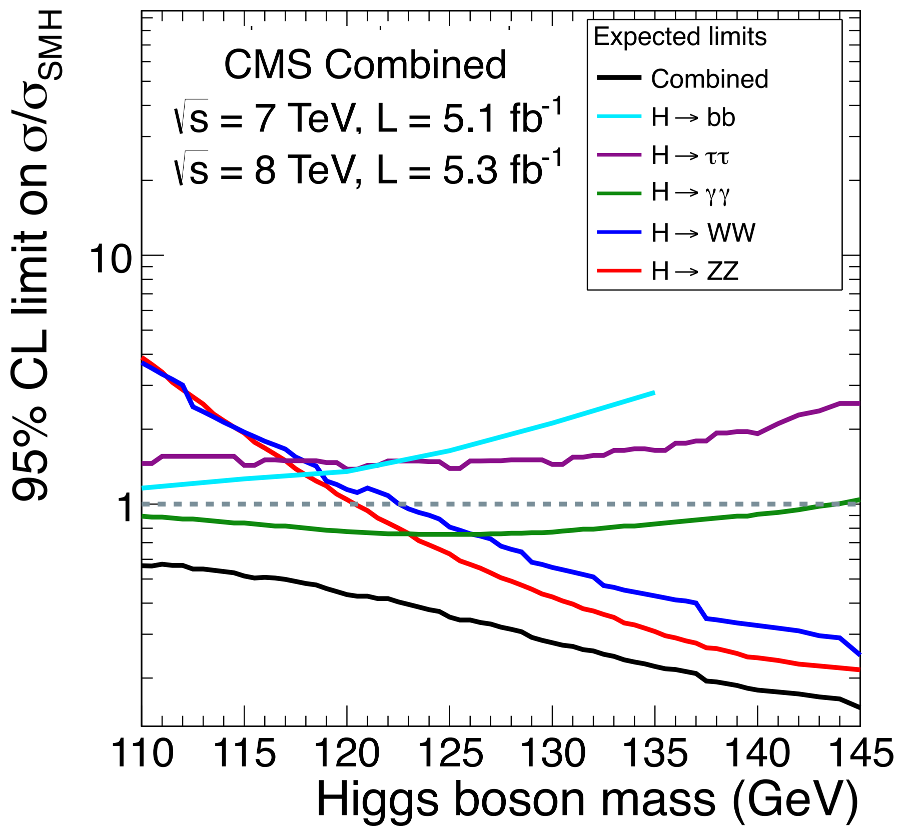
Reconstruct individual decay modes

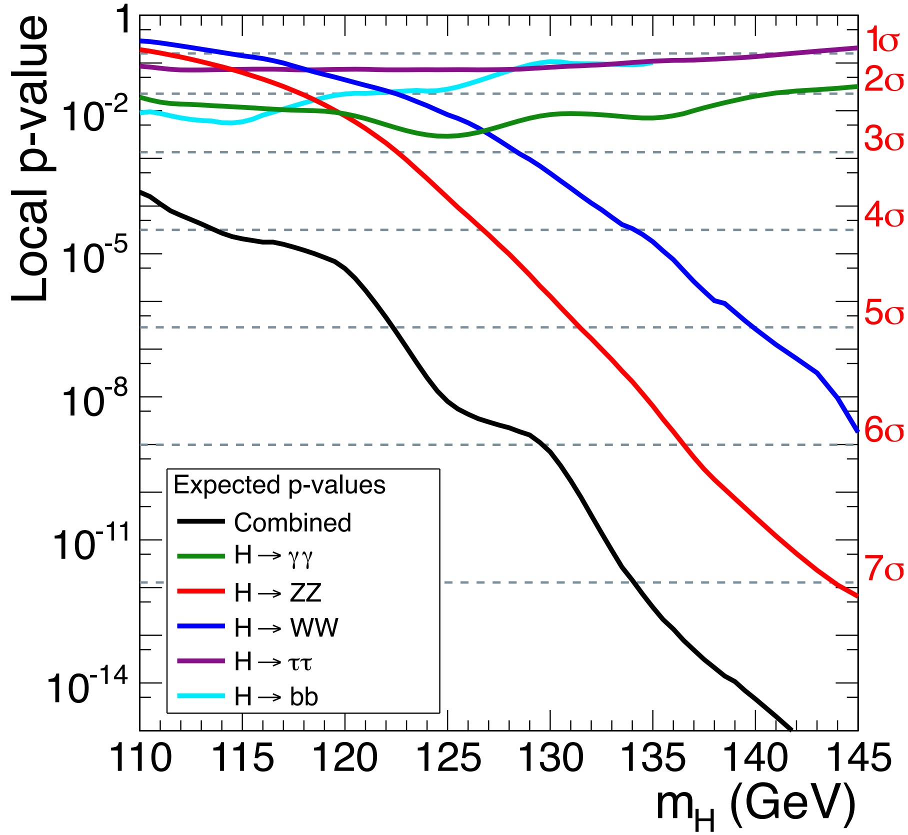
b-jets



Likelihood tagger using many jet properties

Expectation for exclusion and discovery





High mass resolution decay modes: **H →ZZ** / **H →γγ**

Lower mass resolution decay modes: **H →WW** / **H →bb** / **H→ττ**

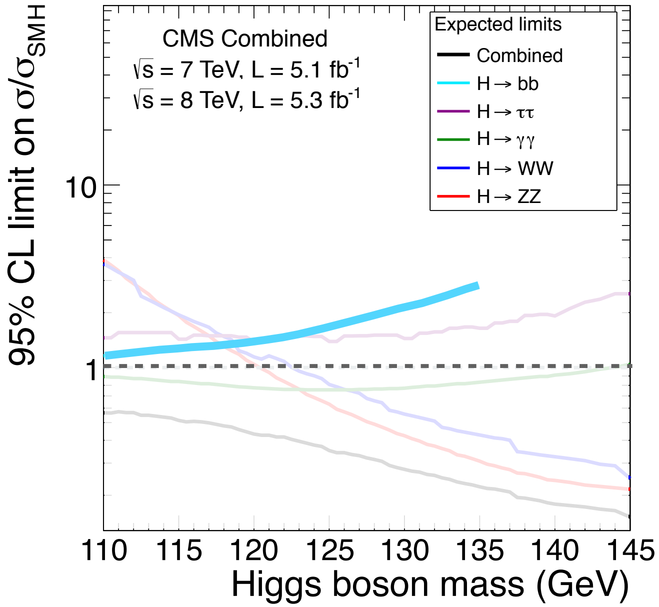
Most analyses have been re-optimized in 2012.

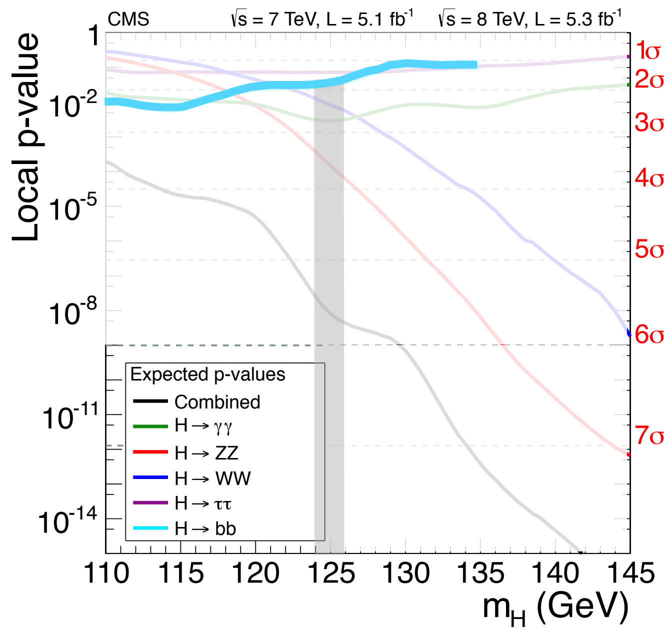
To avoid the possibility of unwanted biases the **data was blinded**

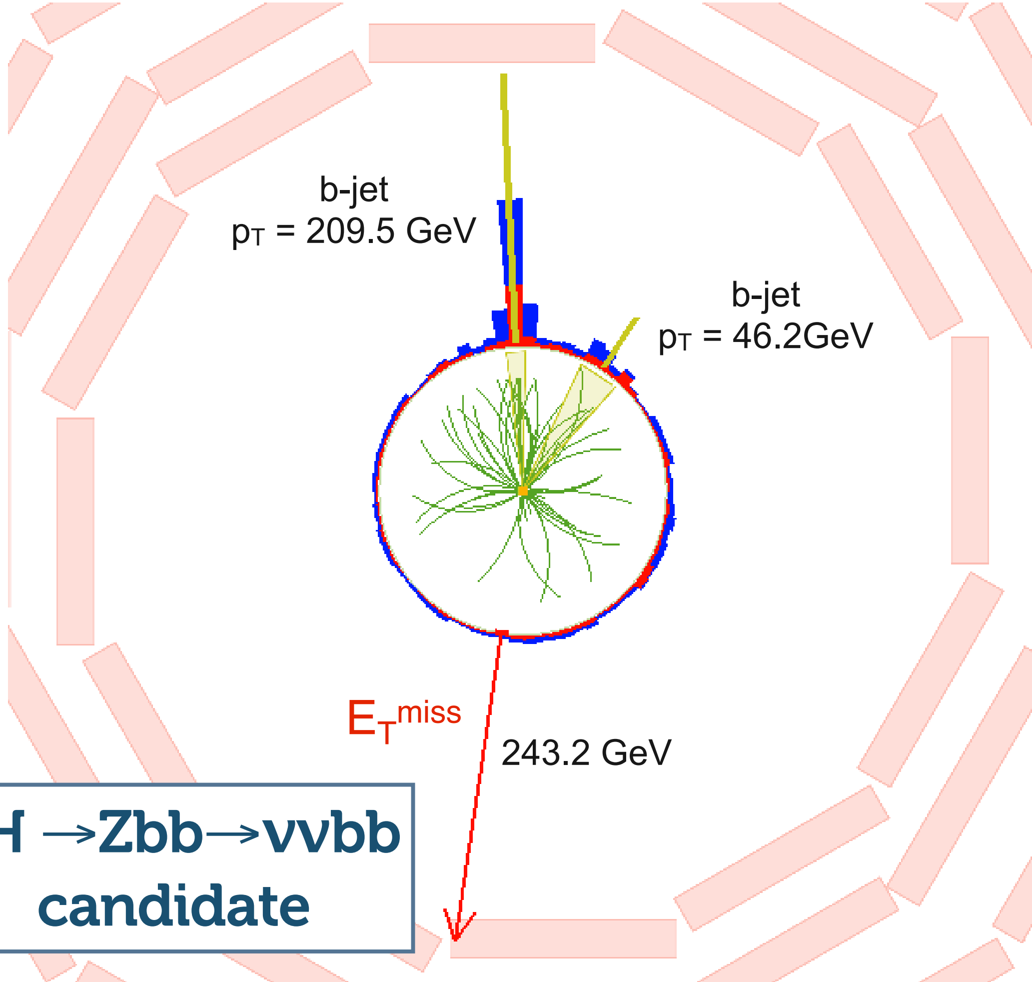
All selection criteria frozen on the basis of simulation and/or control regions without looking at signal region

Lots of **cross checks** and independent teams

$H \rightarrow bb$







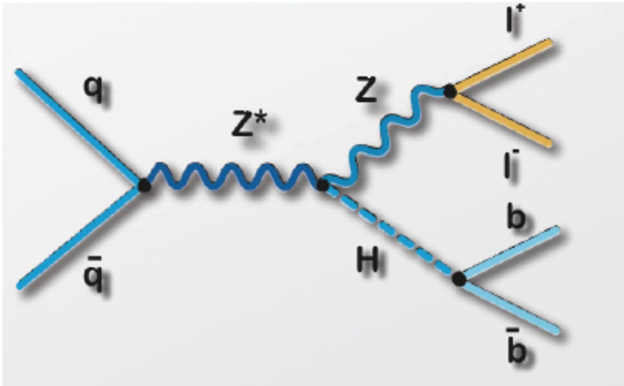
ZH → Zbb → ννbb candidate

5 fb-1 @ 7 TeV (2011) + 5 fb-1 @ 8 TeV (2012): HIG-12-019

VH →Vbb (V→lν,ll,νν)

The largest BR for m_H<130 GeV
but σ_{bb}(QCD) ~ 10^7 x σ_H x BR(H→bb)

⇒Search in associated production with W or Z
final states with leptons, MET, and b-jets

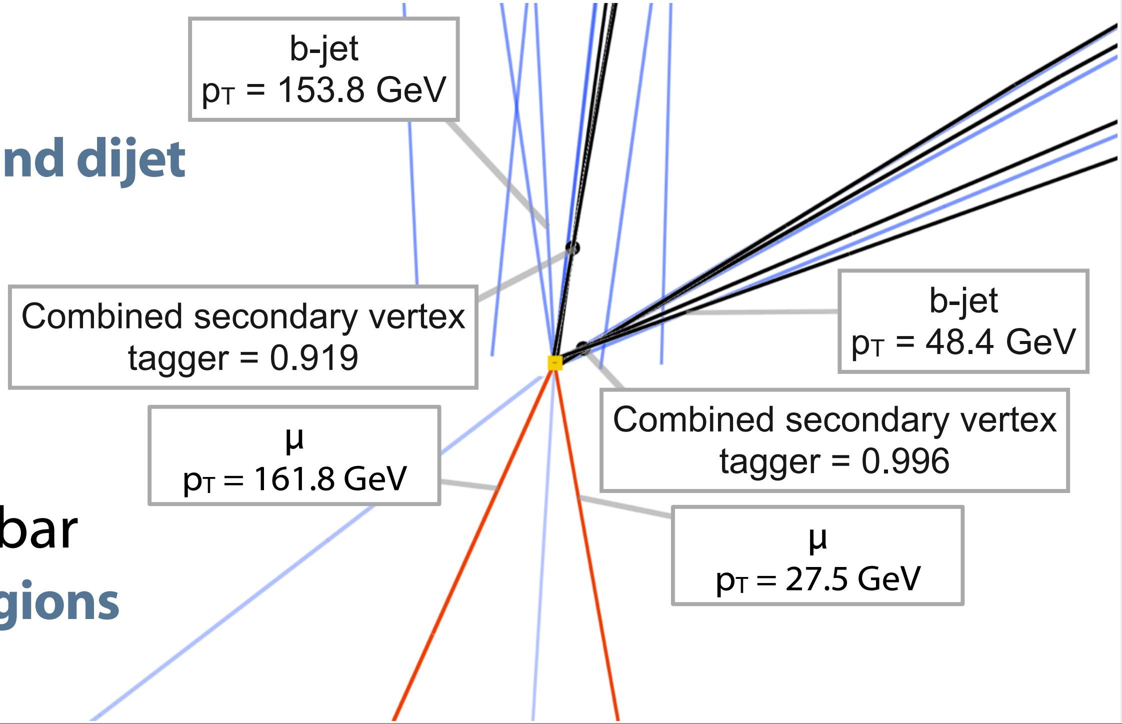


5 topologies
Z(ll)H(bb)
Z(νν)H(bb)
W(lν)H(bb)

General strategy:

- **High boosted vector boson and dijet**
- **2 b-tagged jets**
- **back-to-back V & H**
- **Reconstruct m_{bb}**

Main backgrounds → V+jets, ttbar
estimated from data in control regions

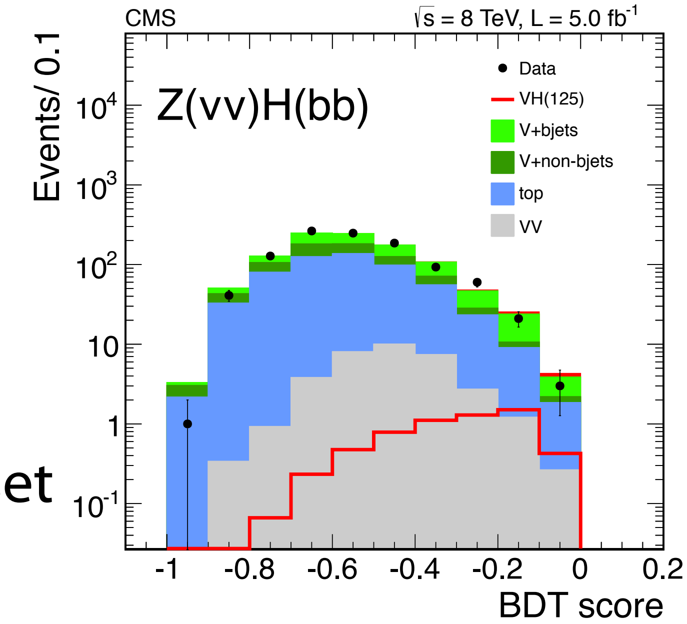


H→bb

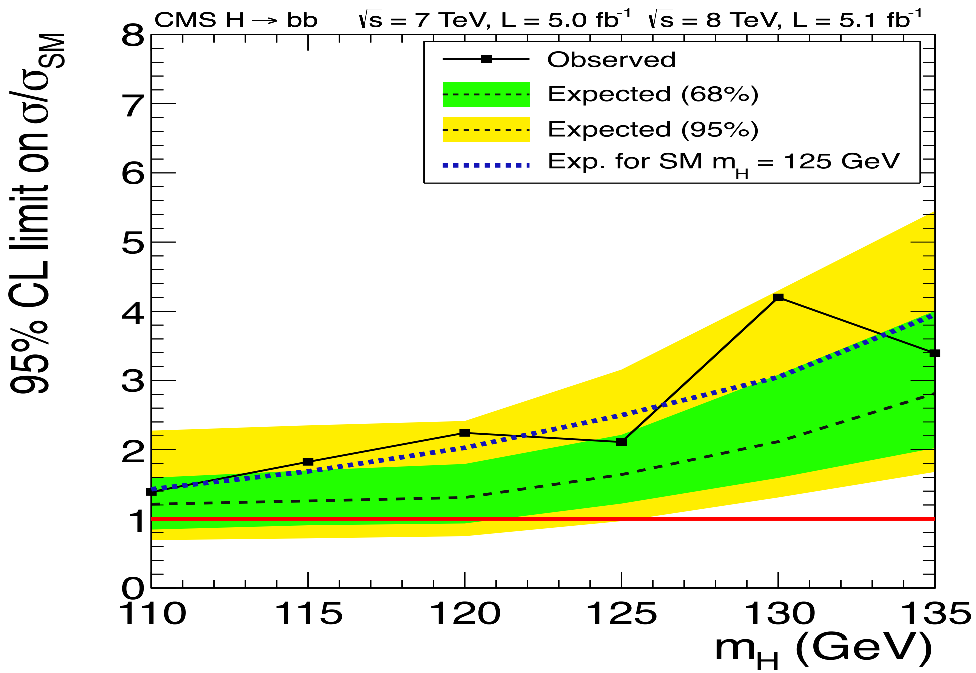
VH →Vbb (V→lν,ll,νν) - Results

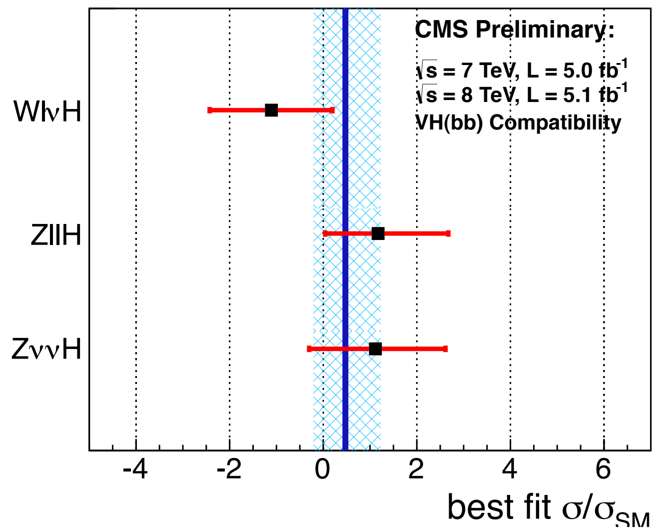
In 2012 many improvements w.r.t. 2011:

- **Jet energy reconstruction using BDT**
- **Categorize events in medium and high boost**
- **Use full shape of final MVA discriminator**



Gain in sensitivity ~50% already on 2011 dataset

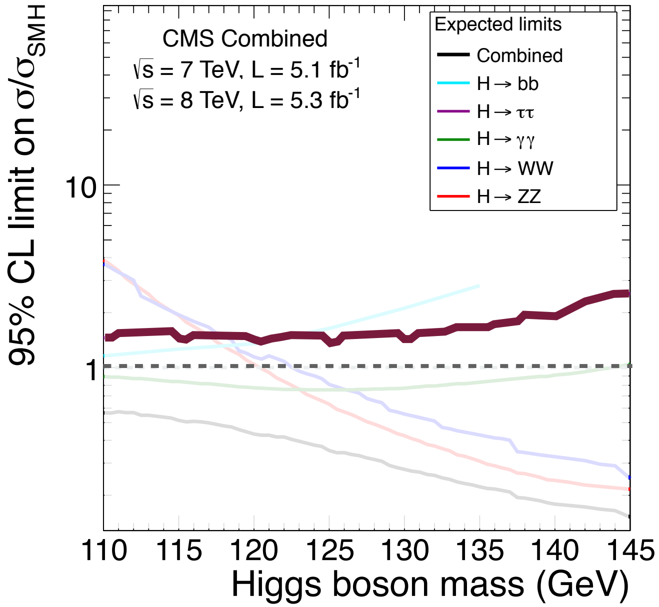


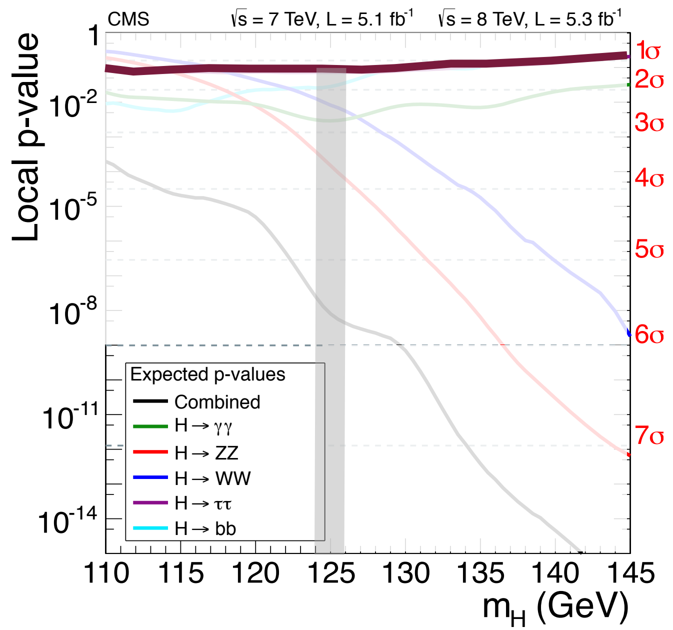


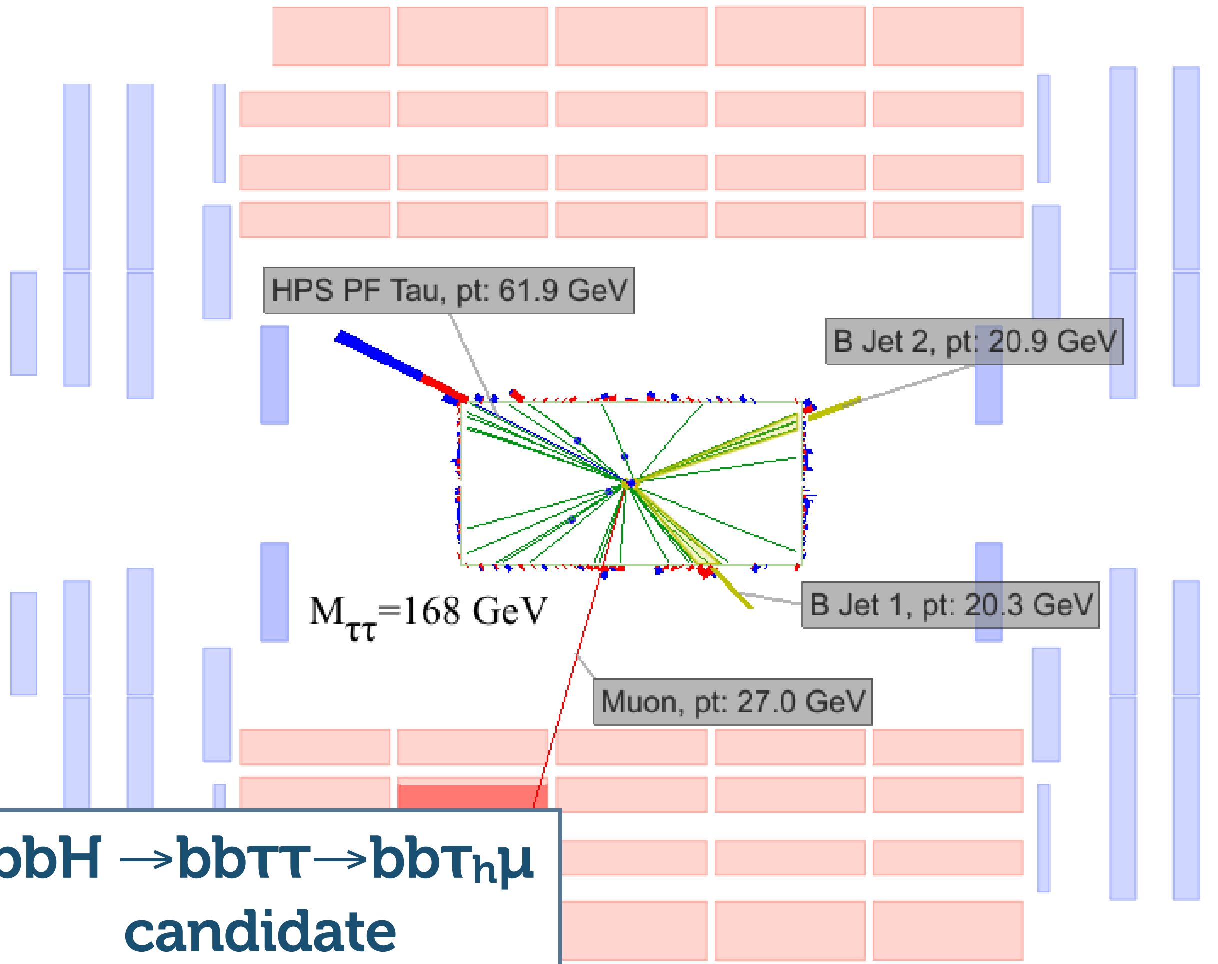
Compatible with both with a signal or a background-only

H→bb

$H \rightarrow \tau\tau$







$bbH \rightarrow bb\tau\tau \rightarrow bb\tau_h\mu$ candidate

5 fb^{-1} @ 7 TeV (2011) + 5 fb^{-1} @ 8 TeV (2012): HIG-12-018

$H \rightarrow \tau\tau \rightarrow \mu\tau_h, e\tau_h, e\mu, \mu\mu$

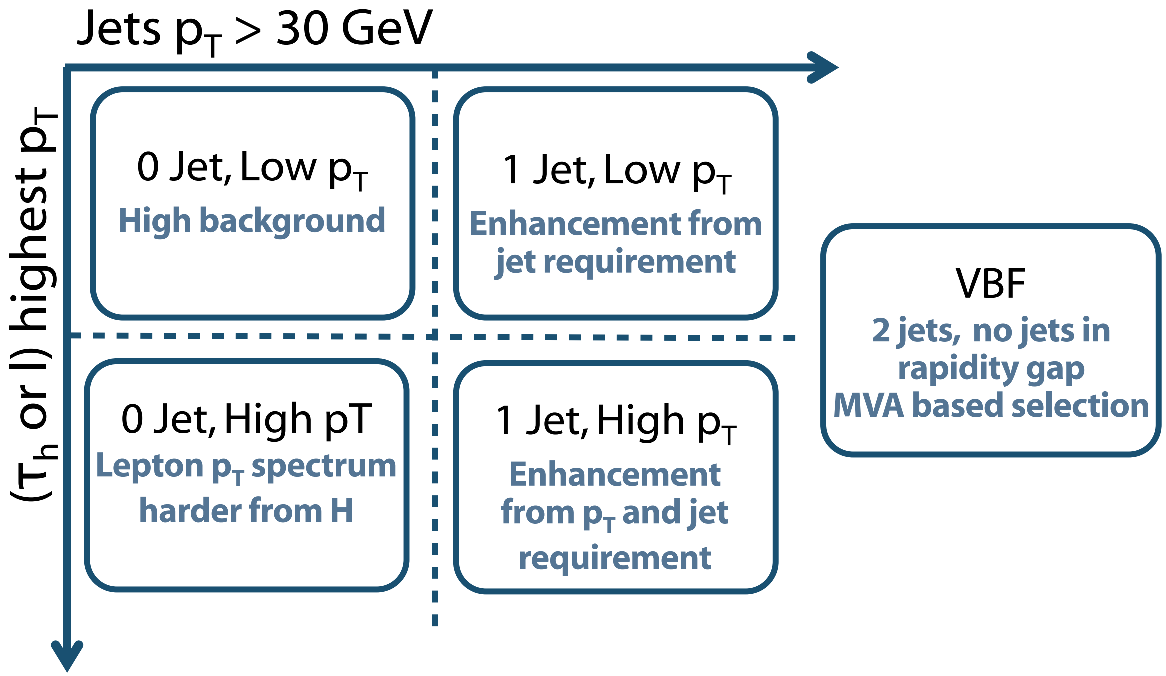
High σxBR at low mass
- **Sensitive to all production modes**
- **Probes coupling to leptons**
- **Enhanced σ x BR in MSSM**

Challenging large backgrounds
DY$\rightarrow\tau\tau$, W+Jets, QCD

Analysis Strategy

Analysis divided into 5 categories mass resolution, S/B

All categories are fit simultaneously

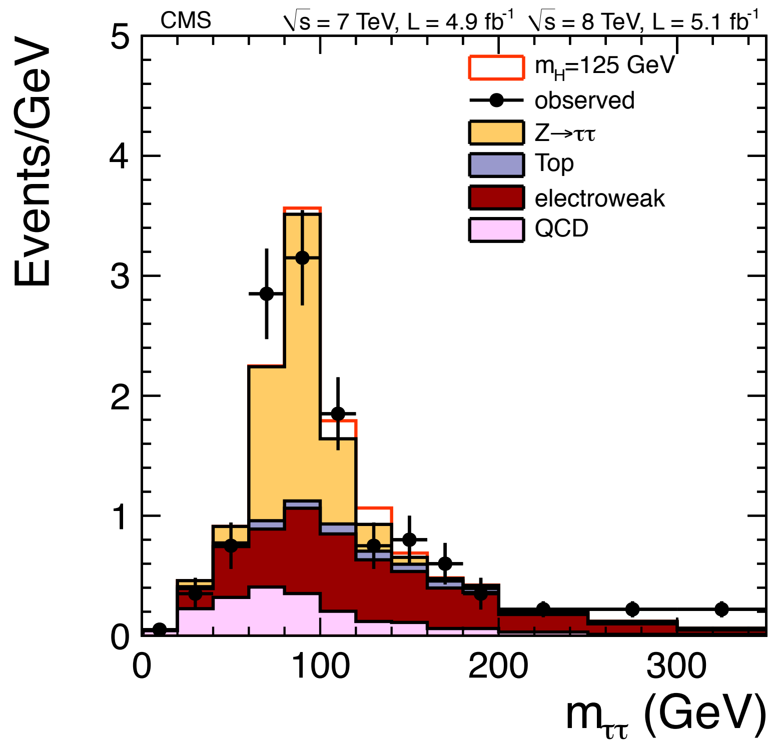


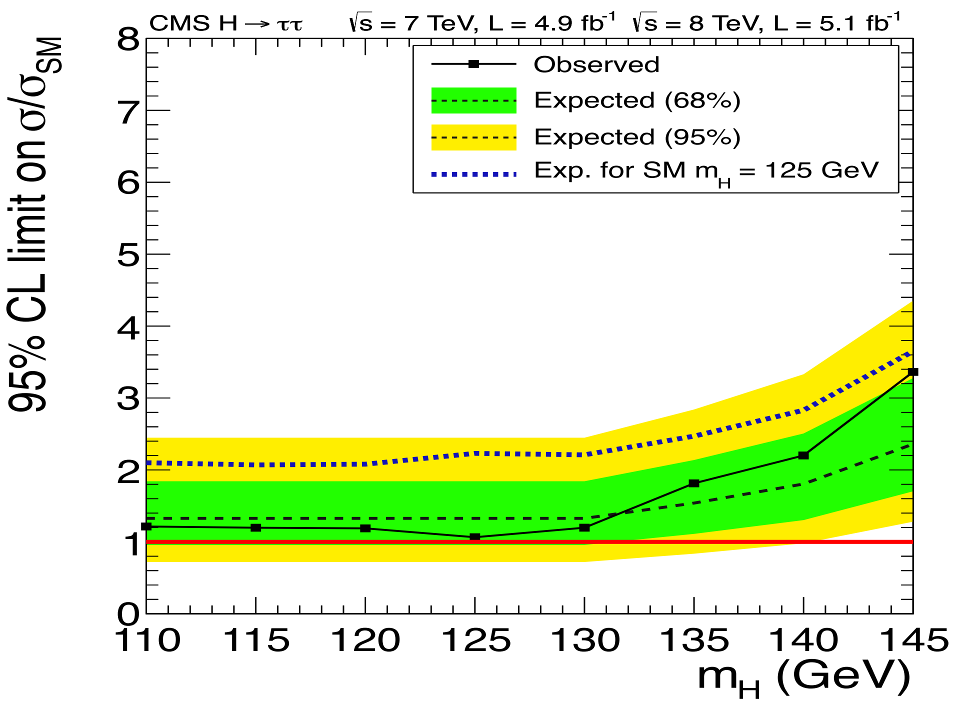
$H \rightarrow \tau\tau$

$H \to \tau\tau \to \mu\tau_h$, $e\tau_h$, $e\mu$, $\mu\mu$ - Results

In 2012 many improvements w.r.t. 2011:

- **new tau ID, improved mass reconstructions with 20% better resolution**
- **event categorization (0-jet and 1-jet): lower jet p_T thresholds, rely also on p_T of the tau**
- **MVA selection for VBF category**



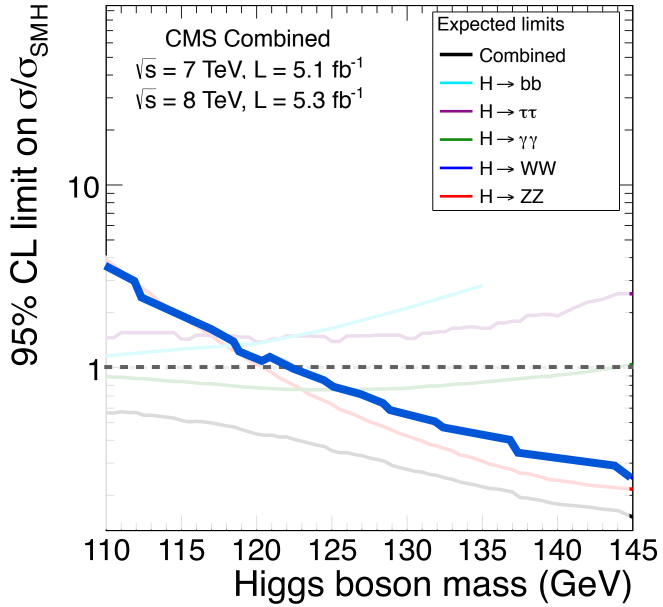


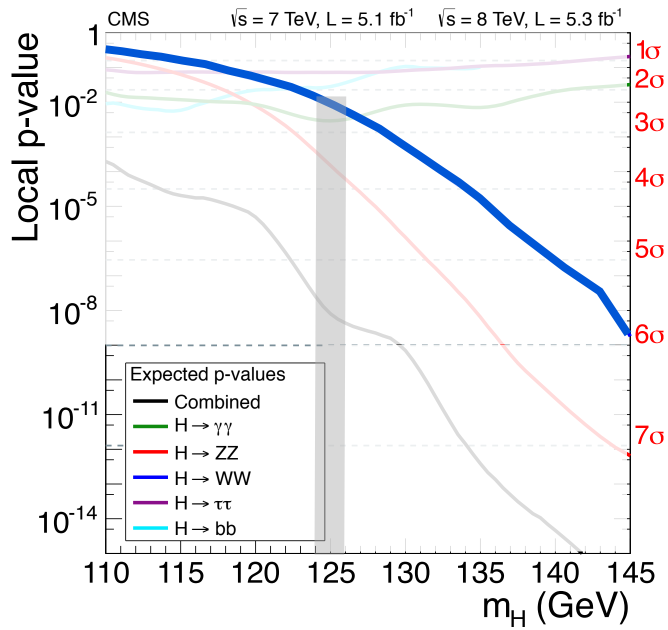
Observed limit of 1.06 x SM at m_H = 125 GeV

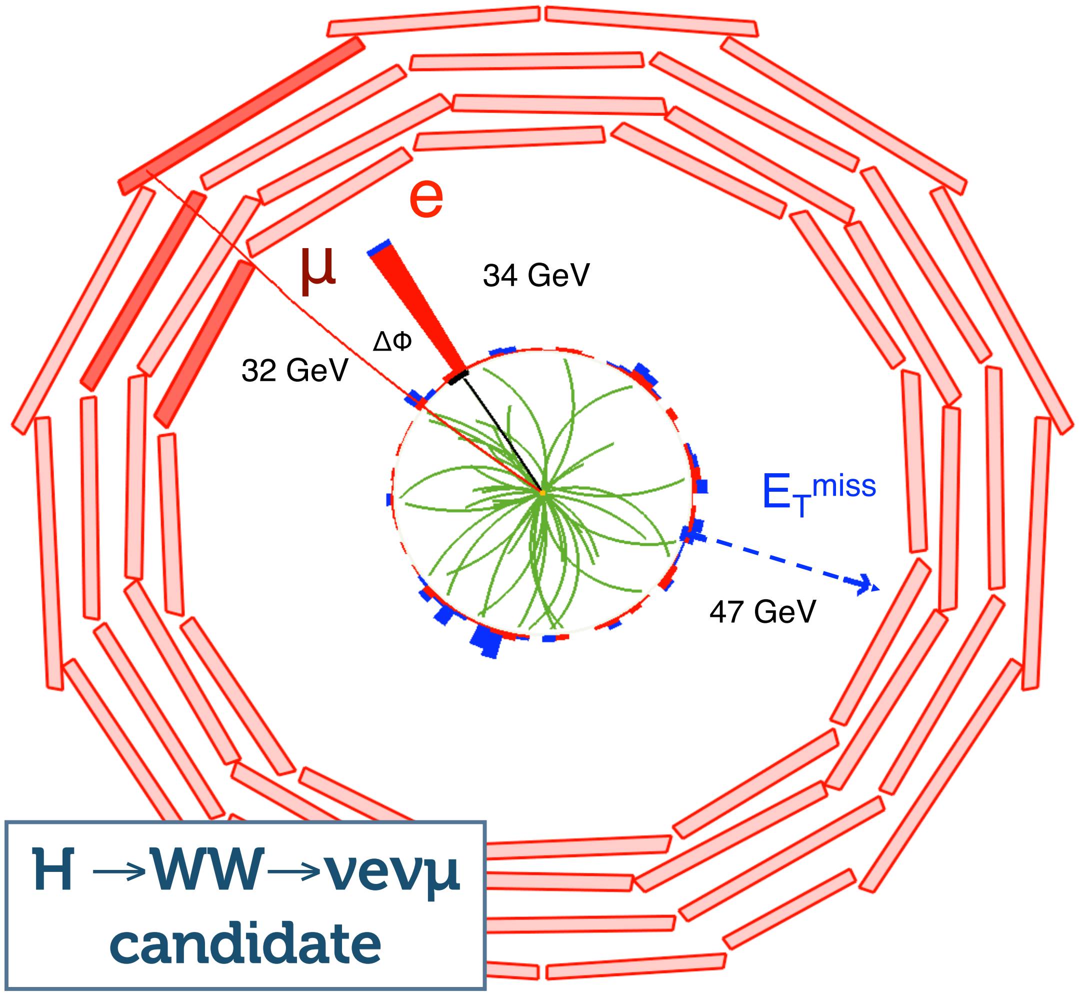
No significant departure from SM background-only expectation

$H \to \tau\tau$

H → WW







5 fb^{-1} @ 7 TeV (2011) + 5 fb^{-1} @ 8 TeV (2012): HIG-12-017

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

Excess of events with two leptons of opposite signs, and missing E_T

Irreducible background

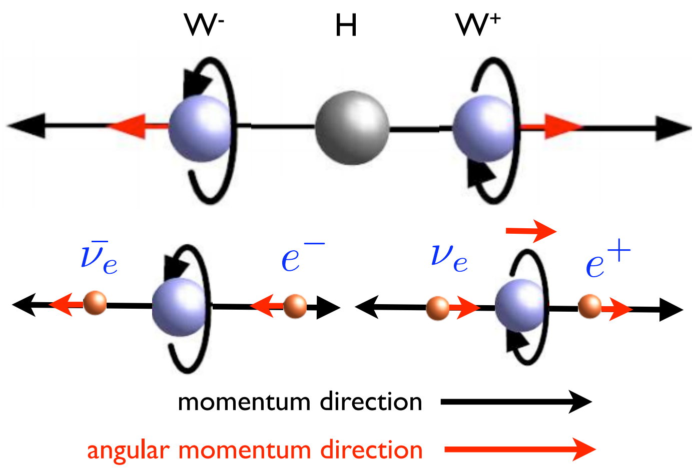
- $qq \to WW + gg \to WW$

Data driven estimates

- W+jets: Fake rate measured in QCD enriched data sample
- Z/γ^*: Normalized in Z mass
- Top: b-tagging efficiency from top control region in data

Split in categories with different S/B and B composition:

- 0/1 jet and VBF
- Final state lepton flavors (ee, μμ, eμ)

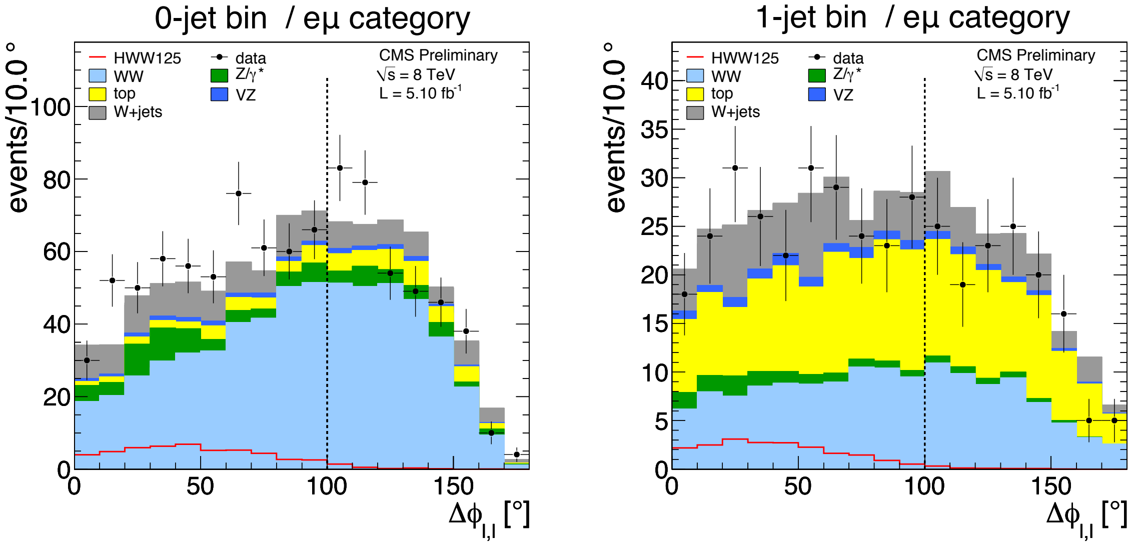


Spin correlation, scalar boson decay to vector bosons + V-A structure of EWK interaction

- Expect small di-lepton Δφ and invariant mass if SM Higgs boson

Kinematics at final selection

One step before
the final selection

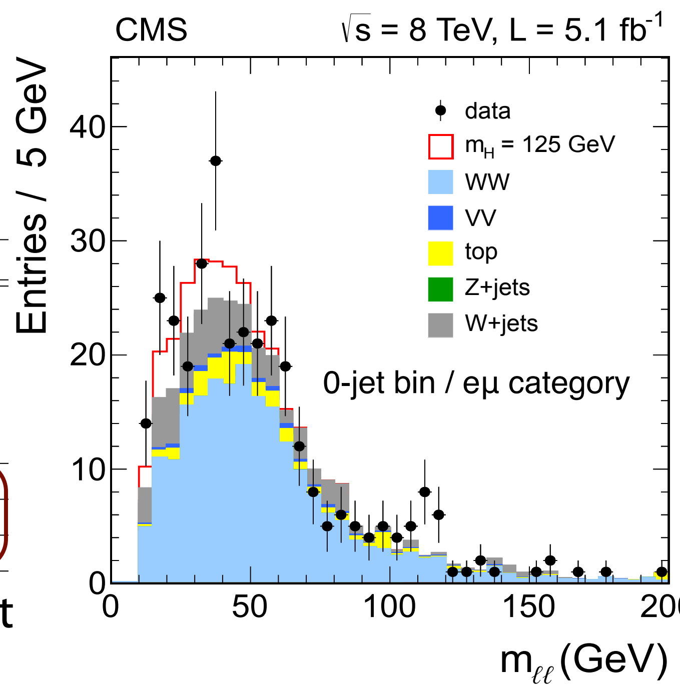


Final selection

Observed number of events, background estimates and signal predictions for m_H = 125 GeV in the different categories

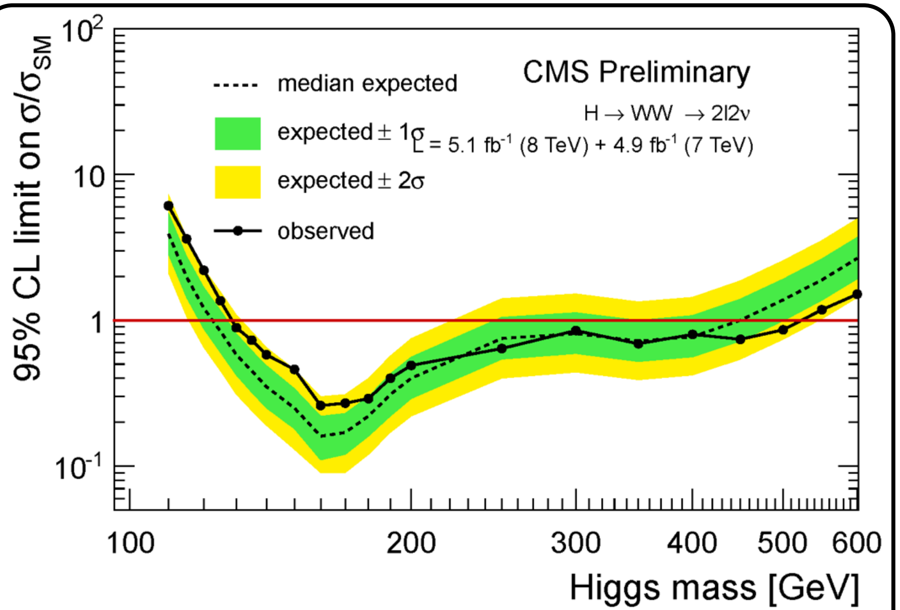
Category:	0-jet $e\mu$	0-jet $\ell\ell$	1-jet $e\mu$	1-jet $\ell\ell$	2-jet $e\mu$	2-jet $\ell\ell$
pp→ WW	87.6 ± 9.5	60.4 ± 6.7	19.5 ± 3.7	9.7 ± 1.9	0.4 ± 0.1	0.3 ± 0.1
$WZ + ZZ + Z\gamma$	2.2 ± 0.2	37.7 ± 12.5	2.4 ± 0.3	8.7 ± 4.9	0.1 ± 0.0	3.1 ± 1.8
Top	9.3 ± 2.7	1.9 ± 0.5	22.3 ± 2.0	9.5 ± 1.1	3.4 ± 1.9	2.0 ± 1.2
W + jets	19.1 ± 7.2	10.8 ± 4.3	11.7 ± 4.6	3.9 ± 1.7	0.3 ± 0.3	0.0 ± 0.0
$W\gamma^{(*)}$	6.0 ± 2.3	4.6 ± 2.5	5.9 ± 3.2	1.3 ± 1.2	0.0 ± 0.0	0.0 ± 0.0
All background	124.2 ± 12.4	115.5 ± 15.0	61.7 ± 7.0	33.1 ± 5.7	4.1 ± 1.9	5.4 ± 2.2
Signal (m_H = 125 GeV)	23.9 ± 5.2	14.9 ± 3.3	10.3 ± 3.0	4.4 ± 1.3	1.5 ± 0.2	0.8 ± 0.1
Data	158	123	54	43	6	7

8 TeV dataset



H → WW

H→WW^(*)→lνlν - Results

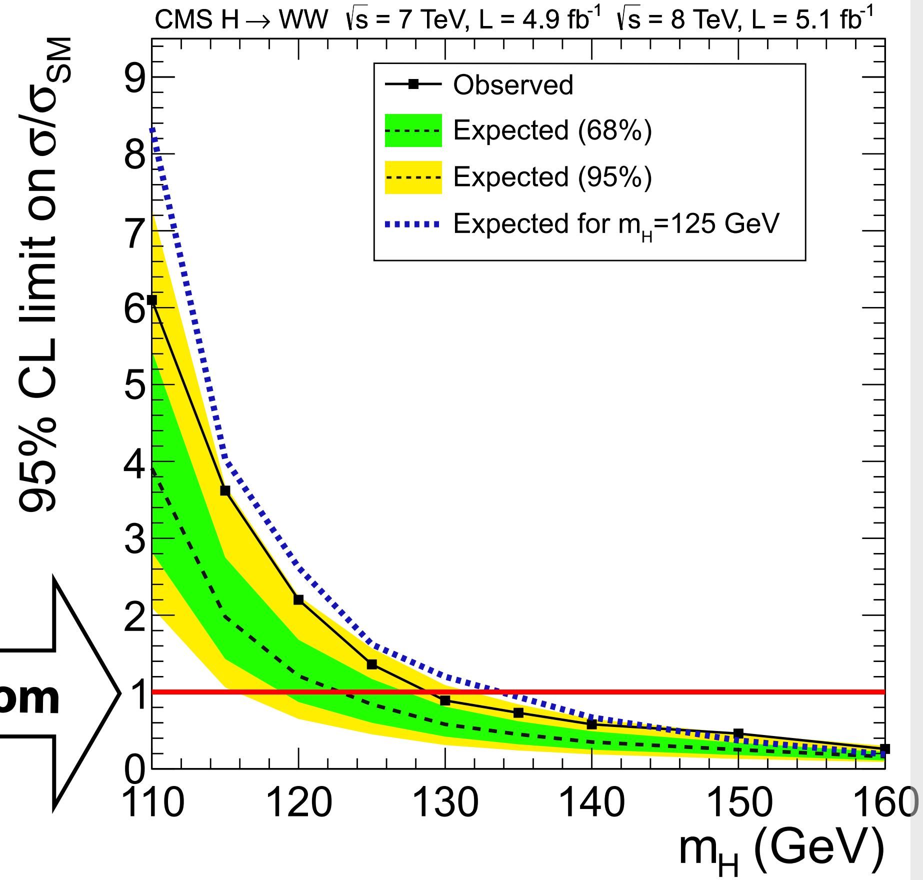


Exclusion Range

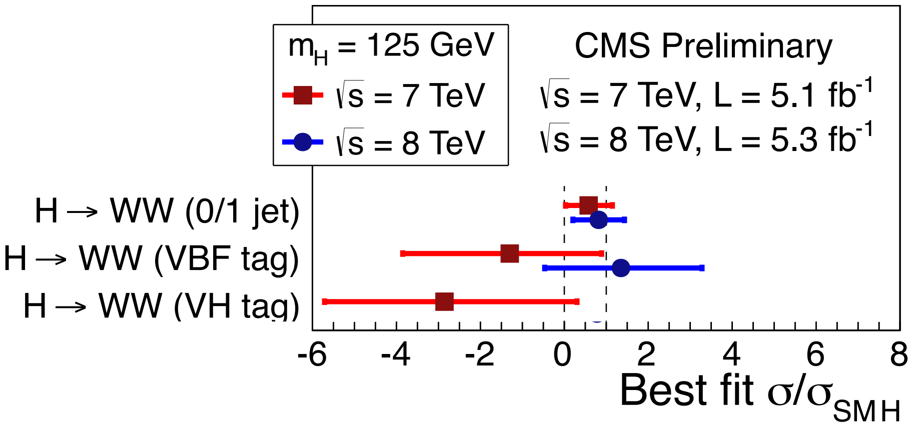
Observed: 129 - 520 GeV

Expected: 123 - 450 GeV

Zoom



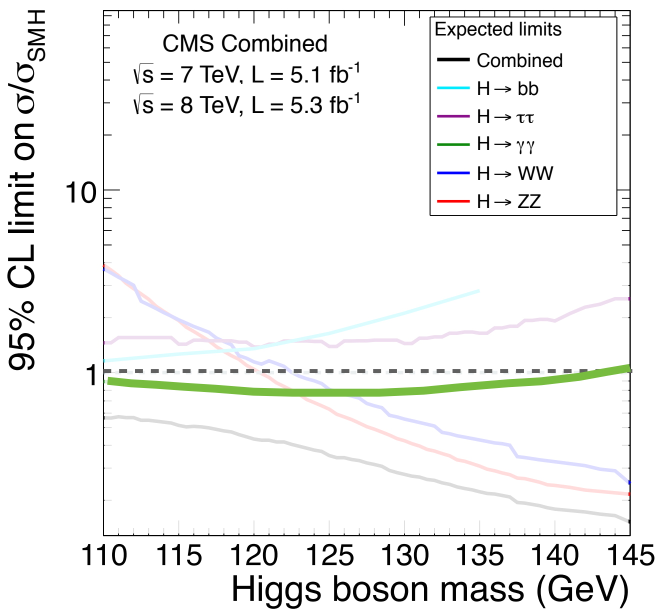
H→WW



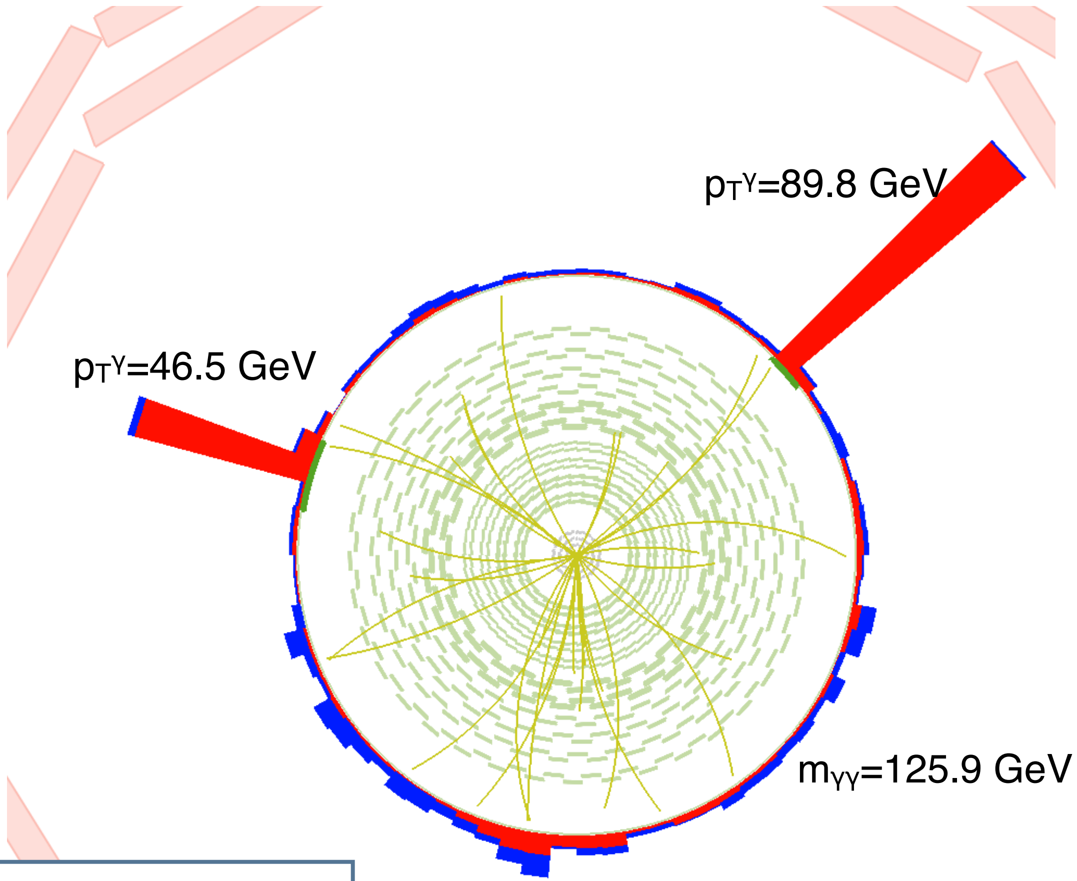
Results in WW topologies are compatible within uncertainties

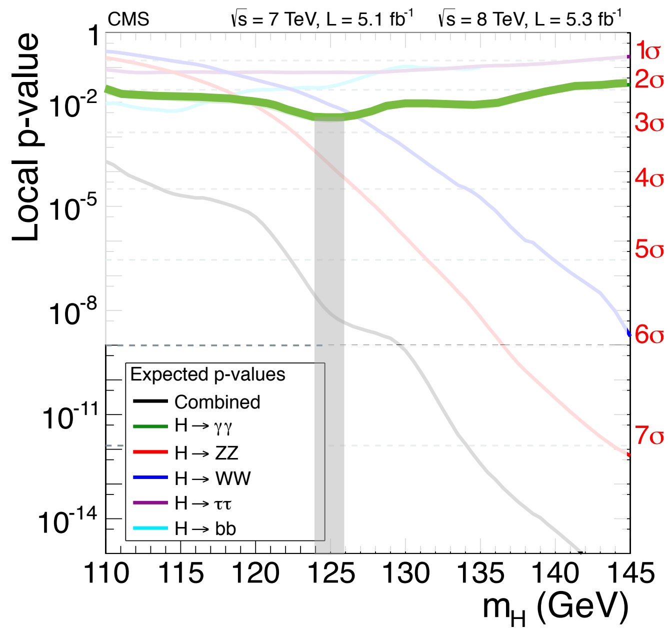
The excess in the low mass (2σ) is compatible with both with a signal or a background-only

High mass resolution decay mode



H → γγ





H → γγ candidate

5 fb^{-1} @ 7 TeV (2011) + 5 fb^{-1} @ 8 TeV (2012): HIG-12-015

H→ γγ

Search for a narrow mass peak with two isolated high E_T photons on a smoothly falling background

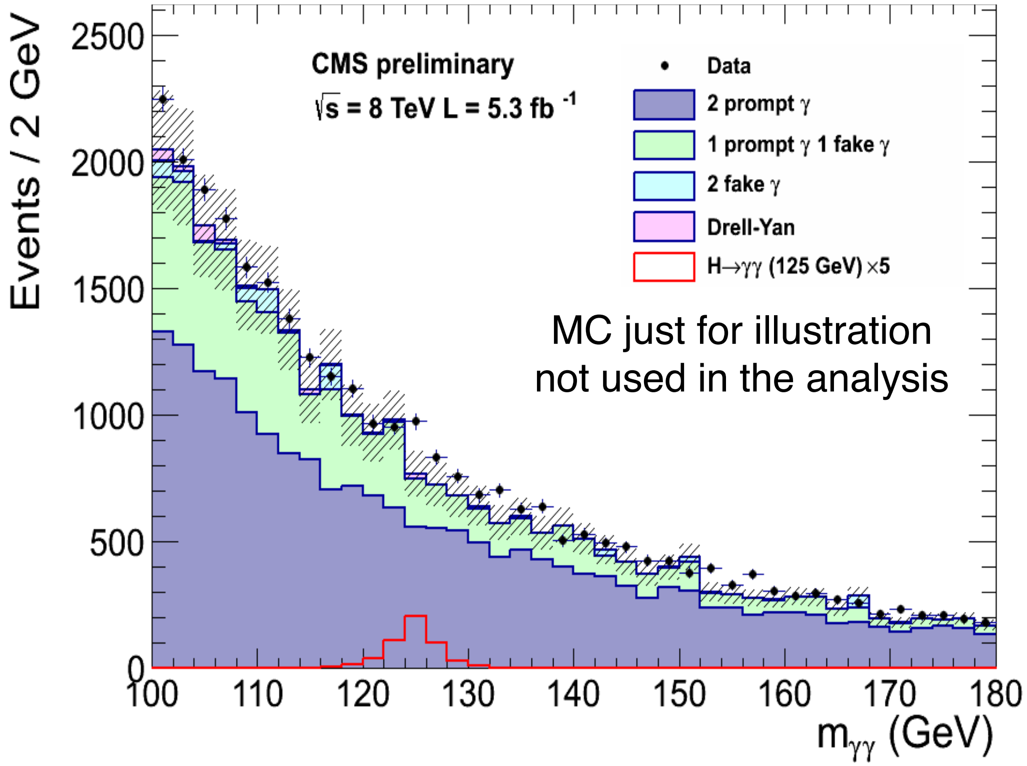
High Resolution: ~1% in barrel

Analysis optimized categorizing events according to purity and mass resolution

Specific di-jet tag categories targeting VBF production mode (Higher S/B)

Main analysis uses Multi-Variate Analysis (**MVA**) technique to **identify** and to **classify** events

Cross-checked with (independent) cut-based and mass sideband background MVA model



Background model derived from data

$H \rightarrow \gamma\gamma$ - Selection

Photon pre-selection

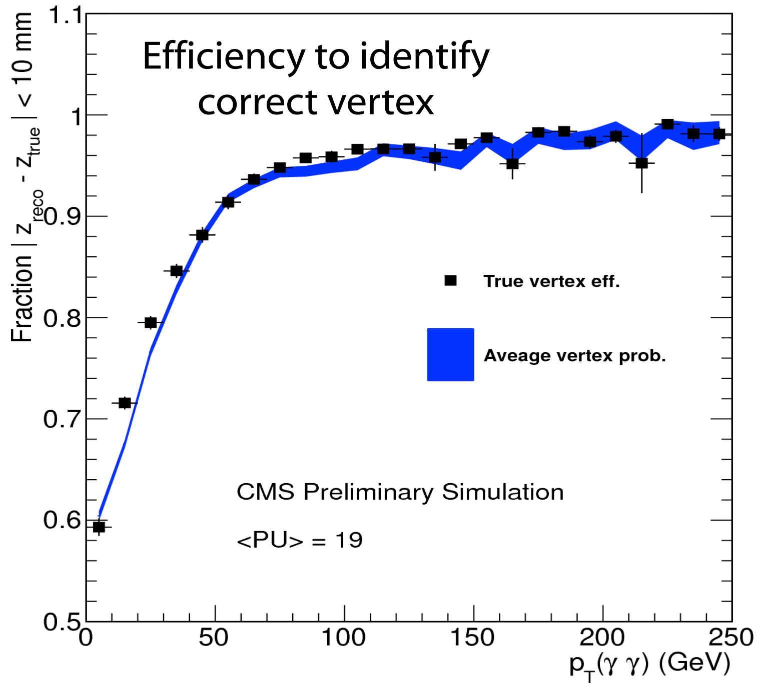
$E_{T\gamma1}/m_{\gamma\gamma} > 3$ and $E_{T\gamma2}/m_{\gamma\gamma} > 4$

Photon ID to separate prompt photons from π^0 emerged from jets → photon ID **MVA based**

Inputs variables: isolation, shower shape, pre- shower energy, per event energy density, and pseudorapidity

Vertex ID **MVA based**

Input variables: Σp_t^2, Σp_t projected onto the $\gamma\gamma$ transverse direction, p_t asymmetry, and conversions

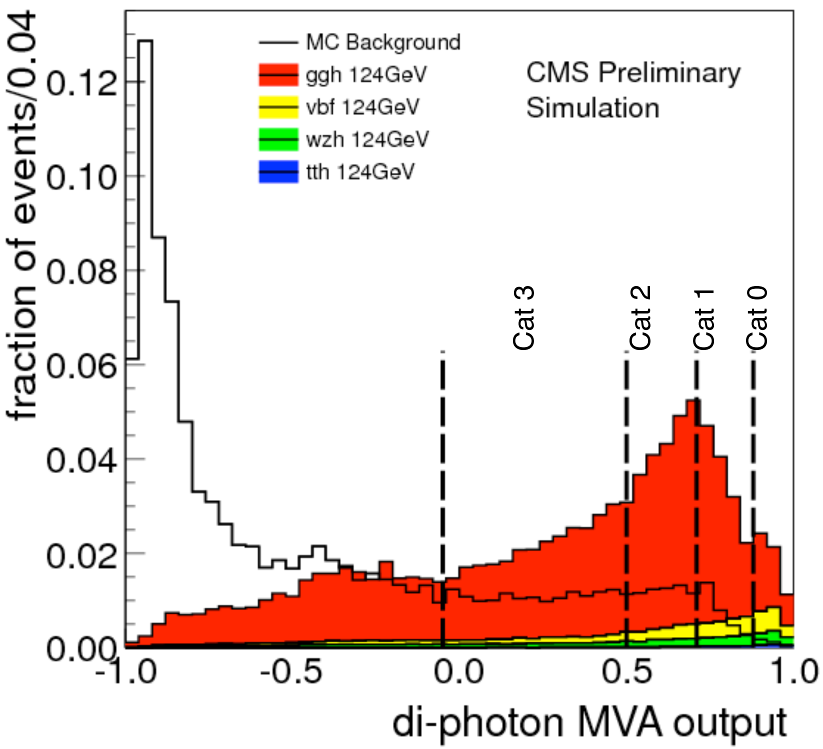


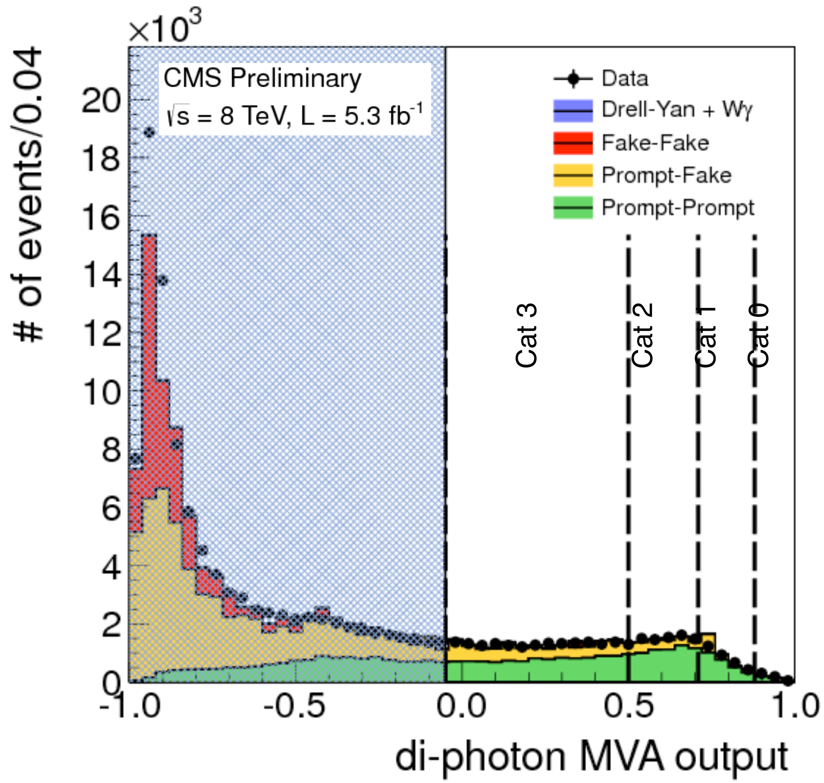
$H \rightarrow \gamma\gamma$

The γγ MVA - Event Classification

Trained on signal and background MC

- Kinematics variables(p_T and η of each photon, and cosΔφ between the 2 photons)
- Photon ID MVA output for each photon
- Per-event mass resolution
- Vertex probability





Residual data-MC disagreement

For BG only make analysis sub-optimal

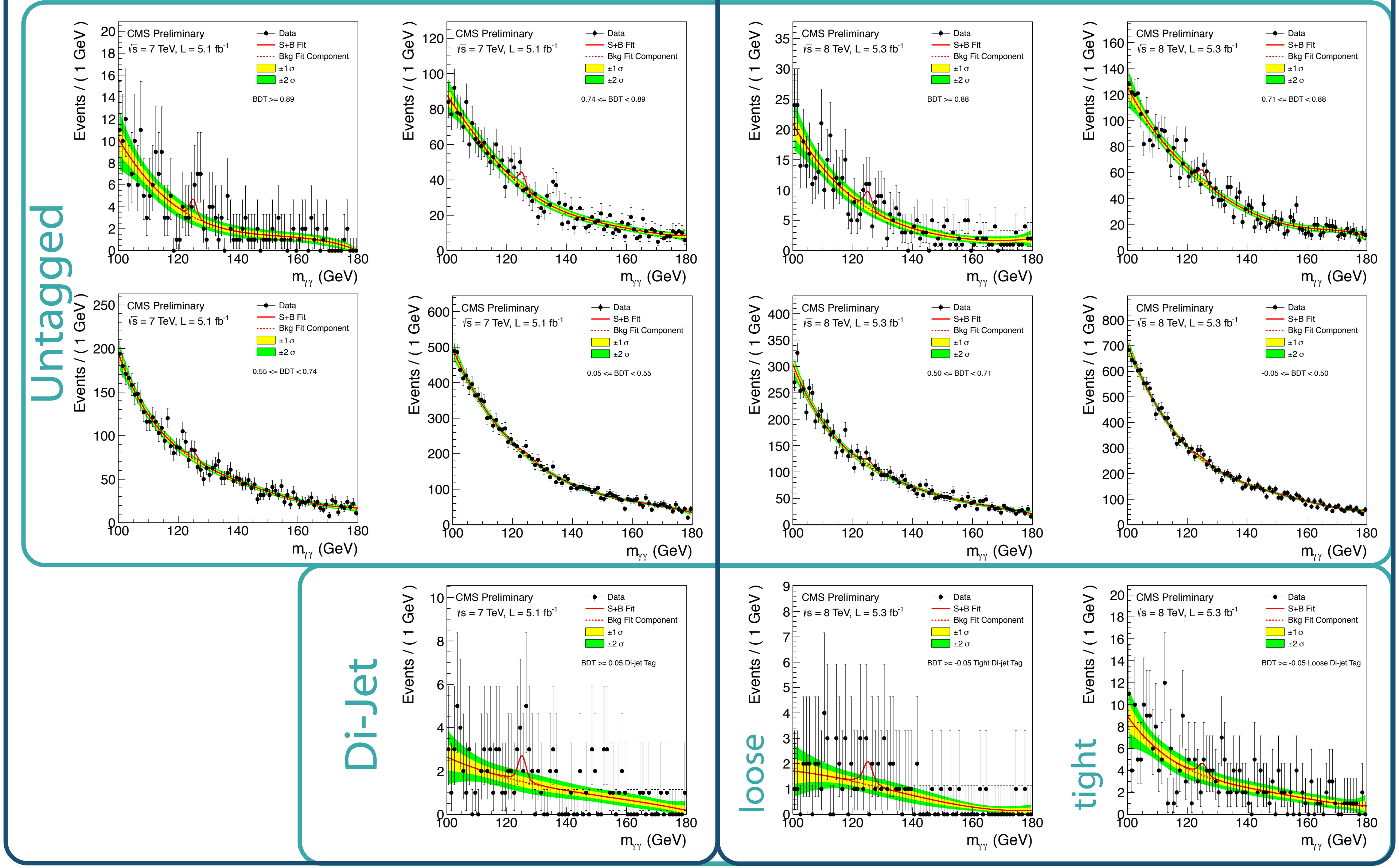
For signal would cause some category migration included in the systematic errors

H → γγ

Mass distributions in categories

7 TeV (5 categories)

8 TeV (6 categories)

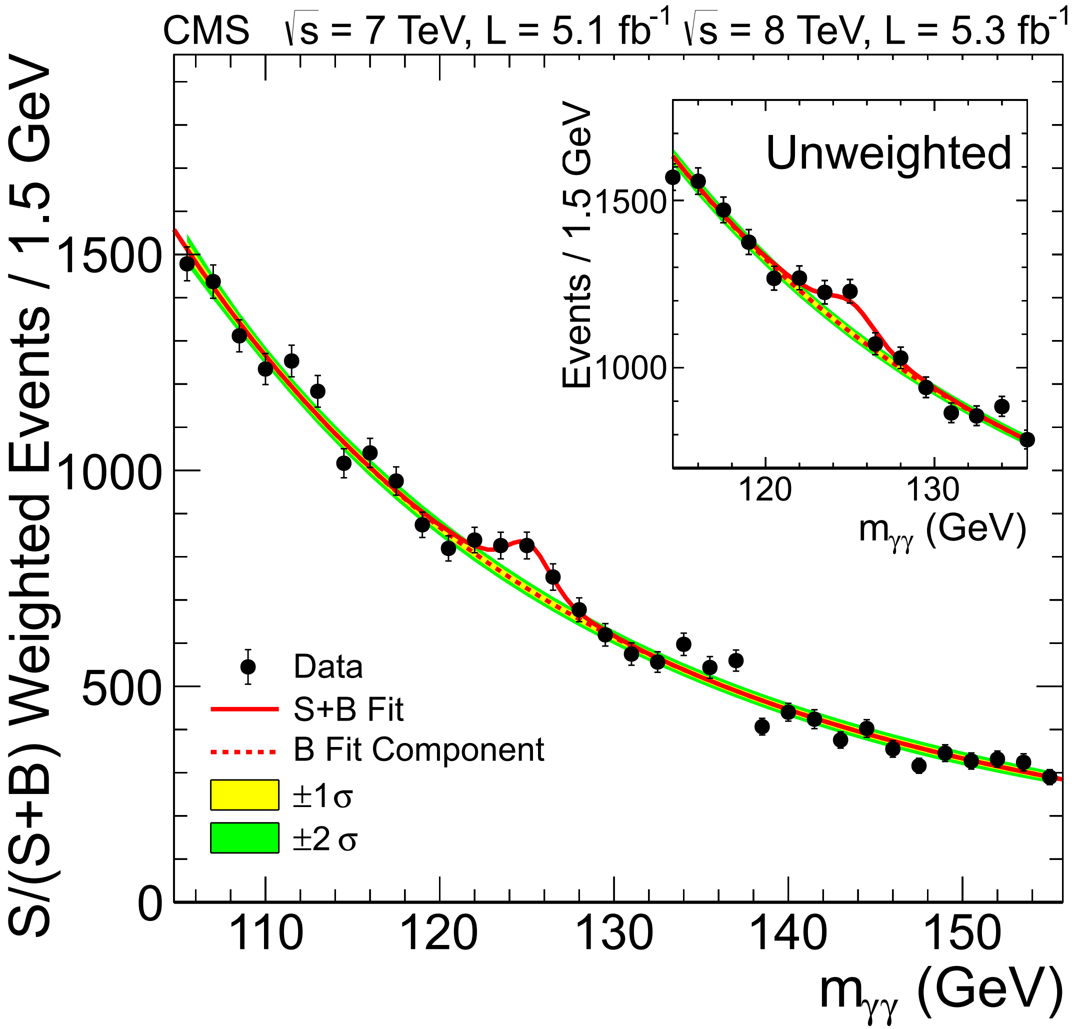


H → γγ

S/(S+B) weighted mass distribution

S and B are the number of signal and background events calculated from the simultaneous fit to all categories

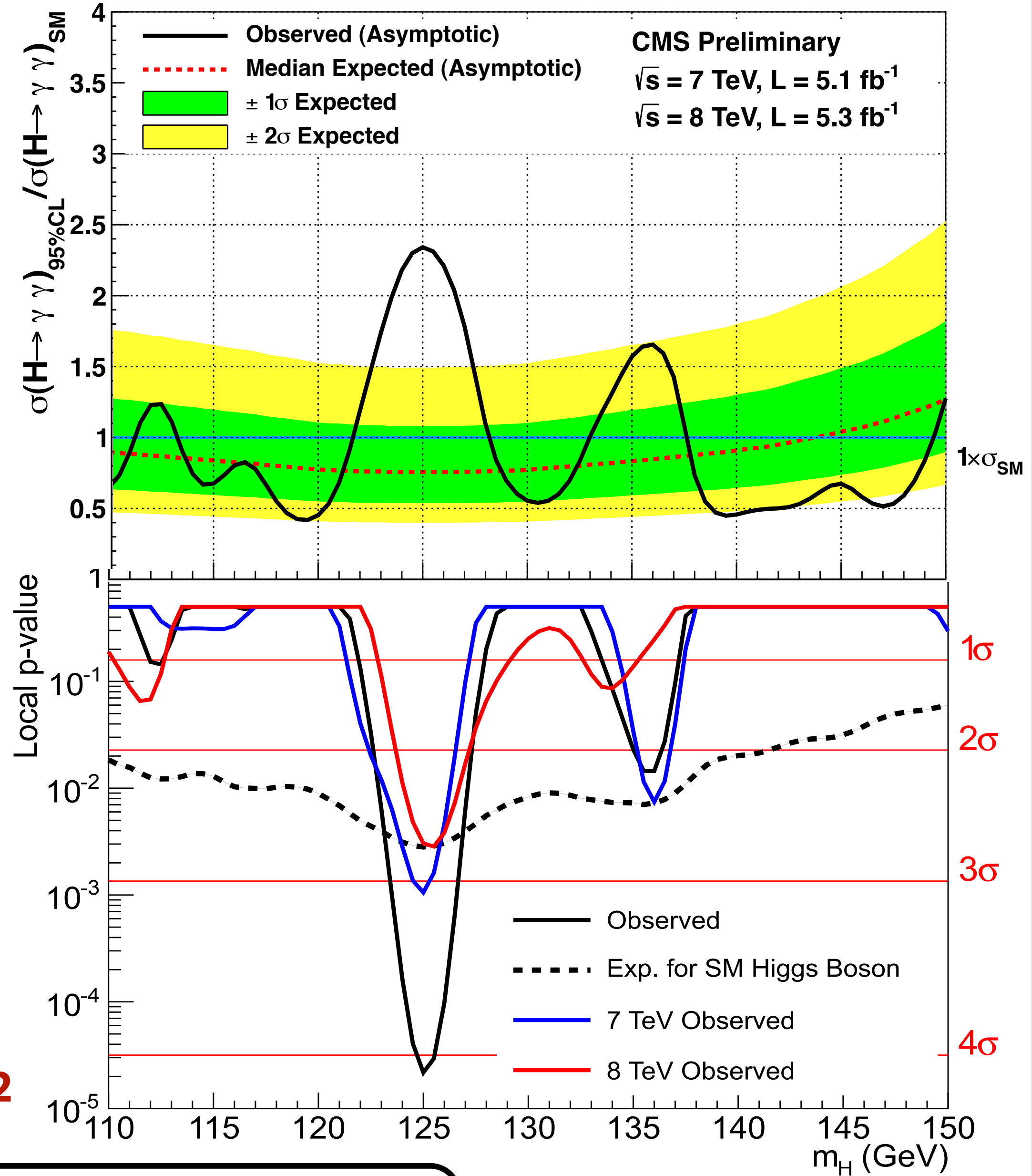
Summed plot for illustration, results obtained with simultaneous maximum-likelihood fit of all the categories



As suggested in:
R.J. Barlow, "Event Classification Using Weighting Methods",J. Comput. Phys. 72 (1987) 202

H → γγ

$H \rightarrow \gamma\gamma$ - Results



Largest excess at 125 GeV

Expected 95% CL exclusion 0.76 times SM at 125 GeV

Minimum p-value at 125 GeV with local significance **4.1 σ**

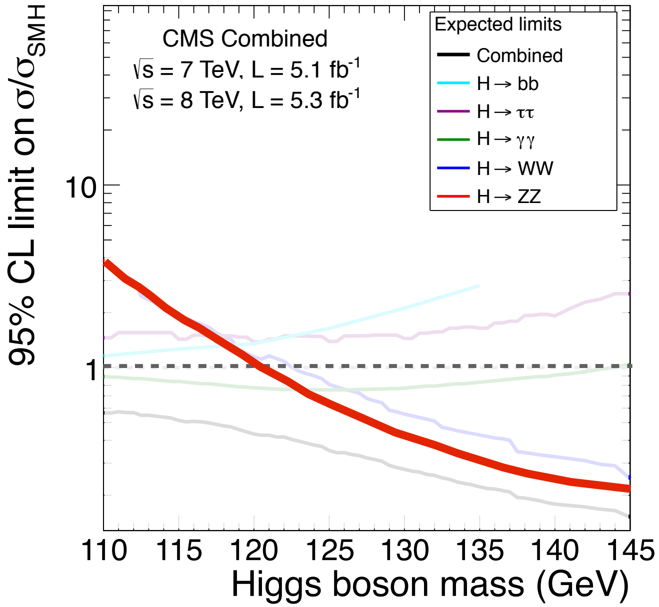
Global significance in full search range 110-150 GeV is 3.2 σ

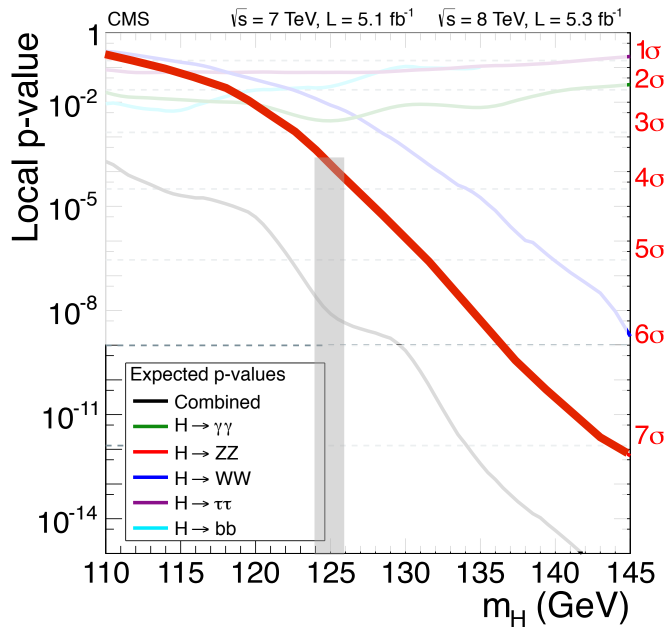
Similar excess in **2011** & **2012**

Evidence for a new state

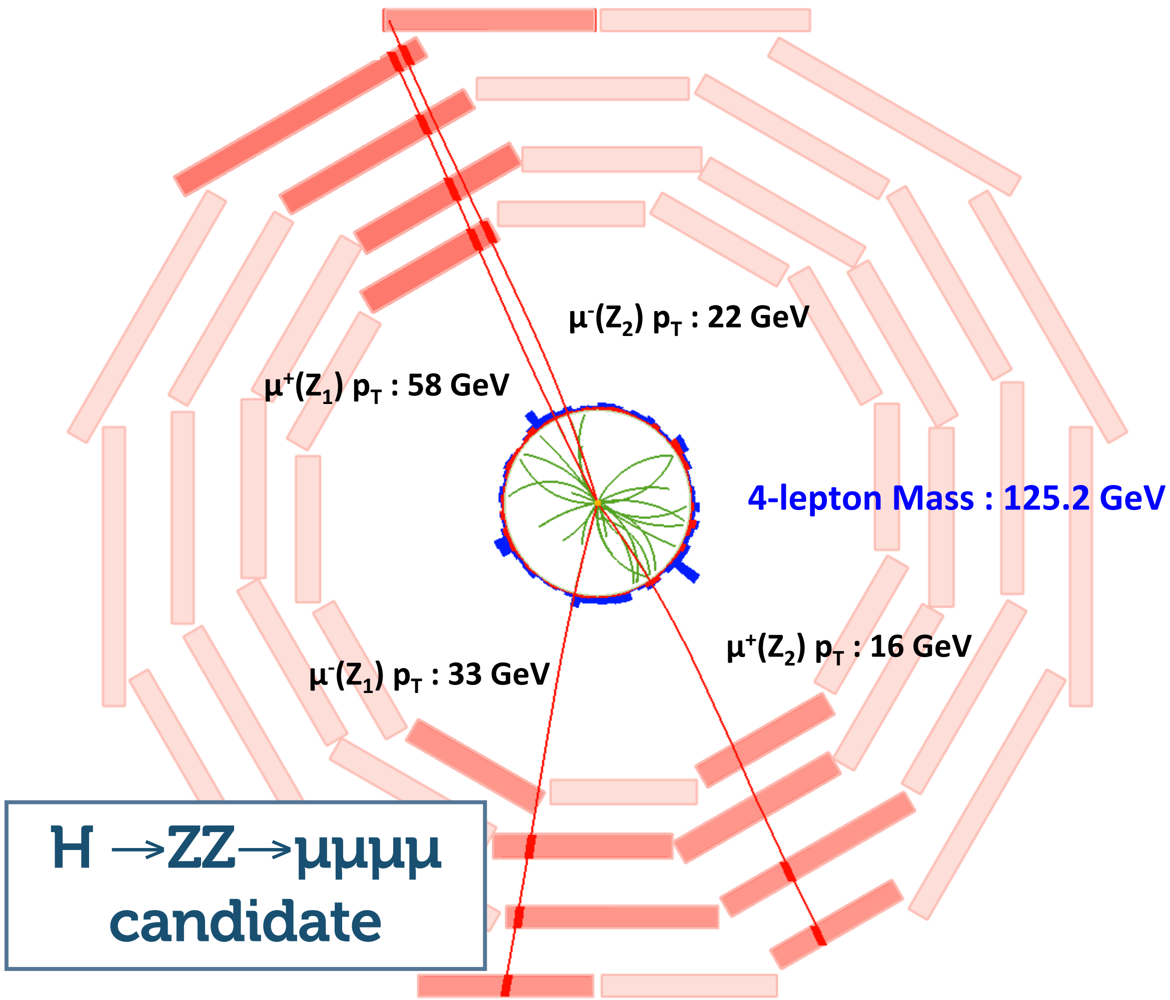
$H \rightarrow \gamma\gamma$

High mass resolution decay mode





H → ZZ



5 fb^{-1} @ 7 TeV (2011) + 5 fb^{-1} @ 8 TeV (2012): HIG-12-016

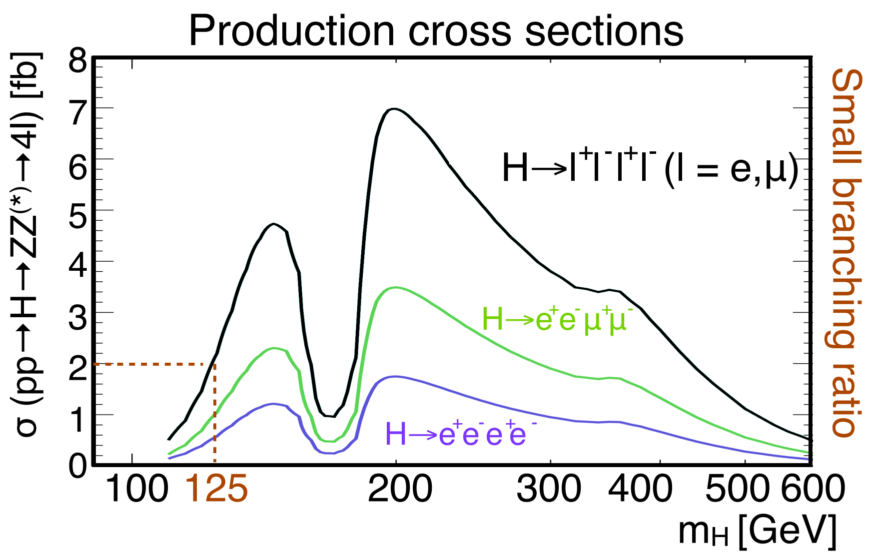
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (l = e,μ): the golden channel

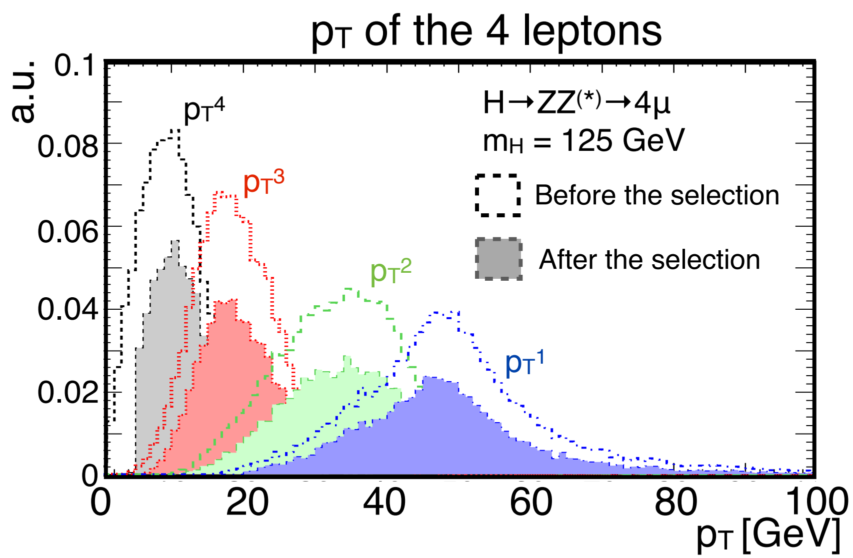
Clean experimental signature

Narrow resonance
Four primary and isolated leptons in the invariant mass spectrum
Background: irreducible $ZZ^{(*)}$, reducible (data driven estimate) Z+jets, ttbar, WZ

A great performing channel on the in mass range ...

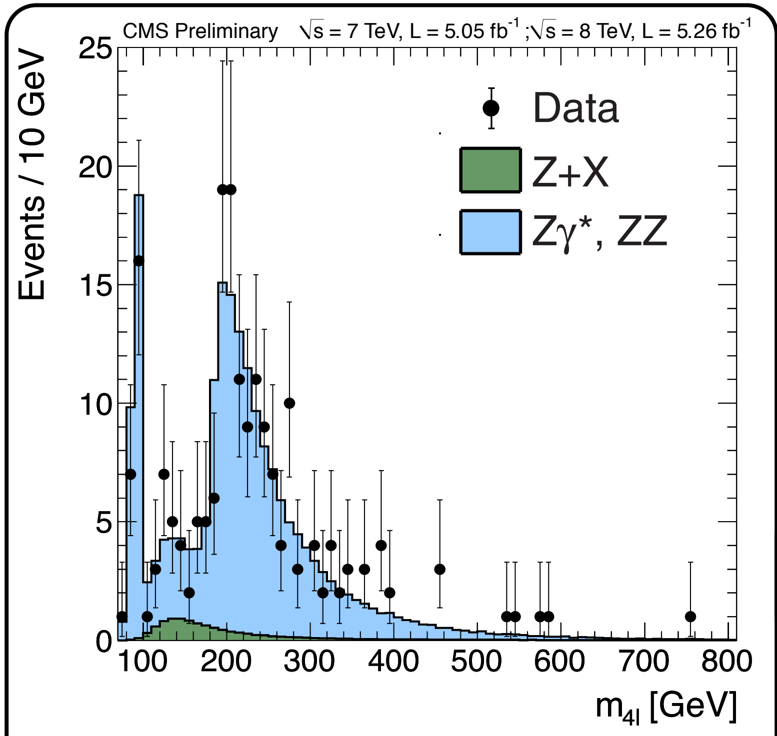
... but extremely demanding channel for selection (ε^4)





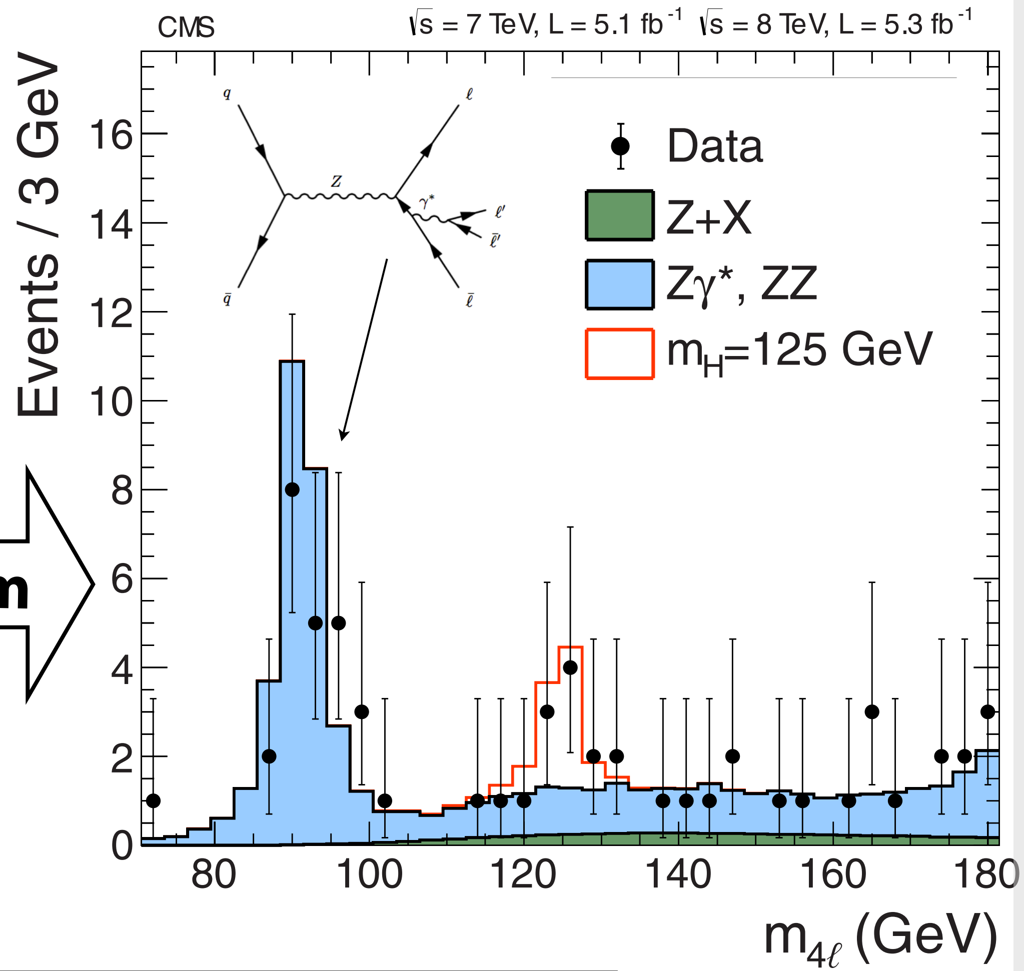
H→ZZ

Invariant mass



164 events expected in [100, 800] GeV
172 events observed in [100, 800] GeV

Zoom



ZZ→H

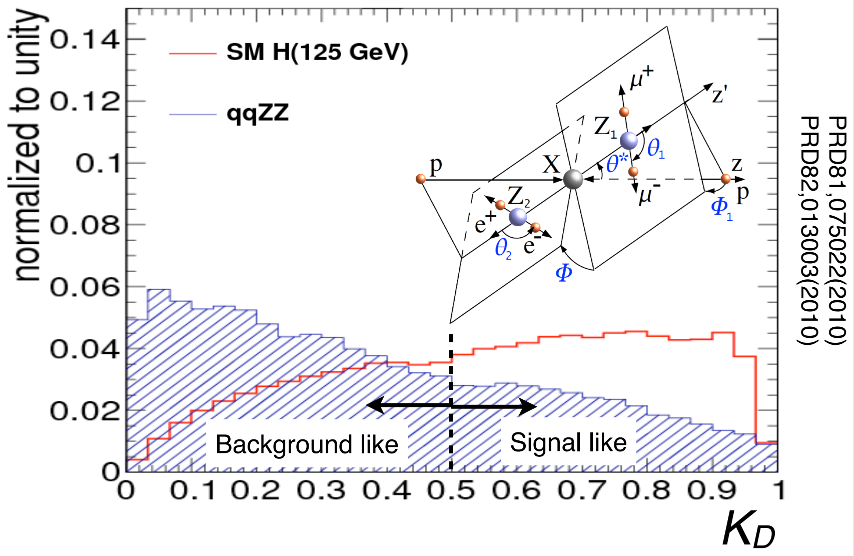
Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
Z + X	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160$ GeV)	4.0 ± 1.0	6.6 ± 0.9	9.7 ± 1.8	20 ± 3
Observed ($110 < m_{4\ell} < 160$ GeV)	6	6	9	21
Signal ($m_H = 125$ GeV)	1.36 ± 0.22	2.74 ± 0.32	3.44 ± 0.44	7.54 ± 0.78
All backgrounds (signal region)	0.7 ± 0.2	1.3 ± 0.1	1.9 ± 0.3	3.8 ± 0.5
Observed (signal region)	1	3	5	9

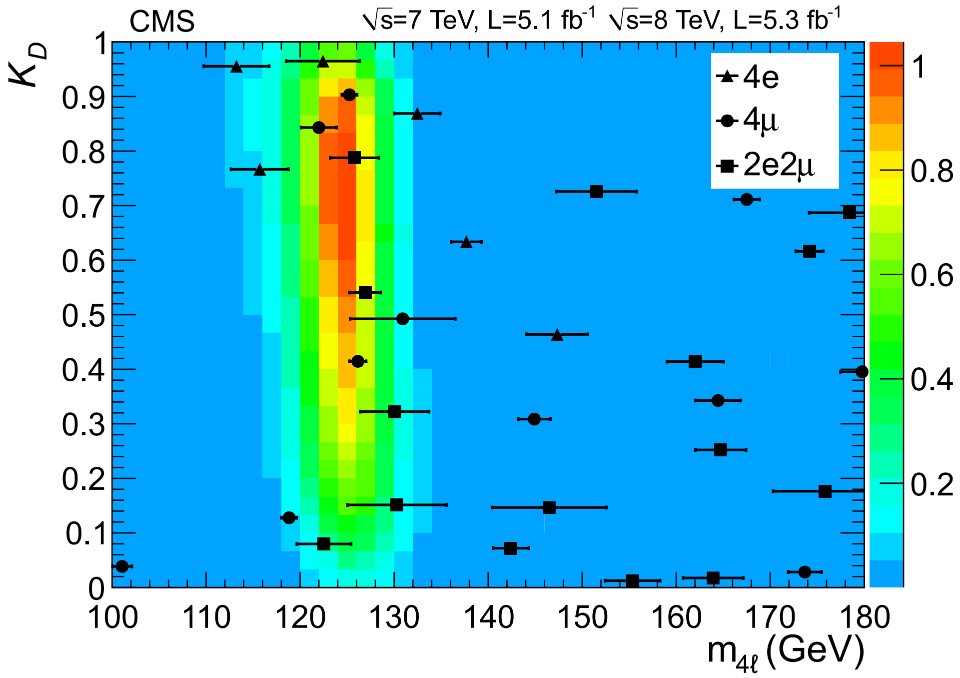
$121.5 < m_{4l} < 130.5$ GeV

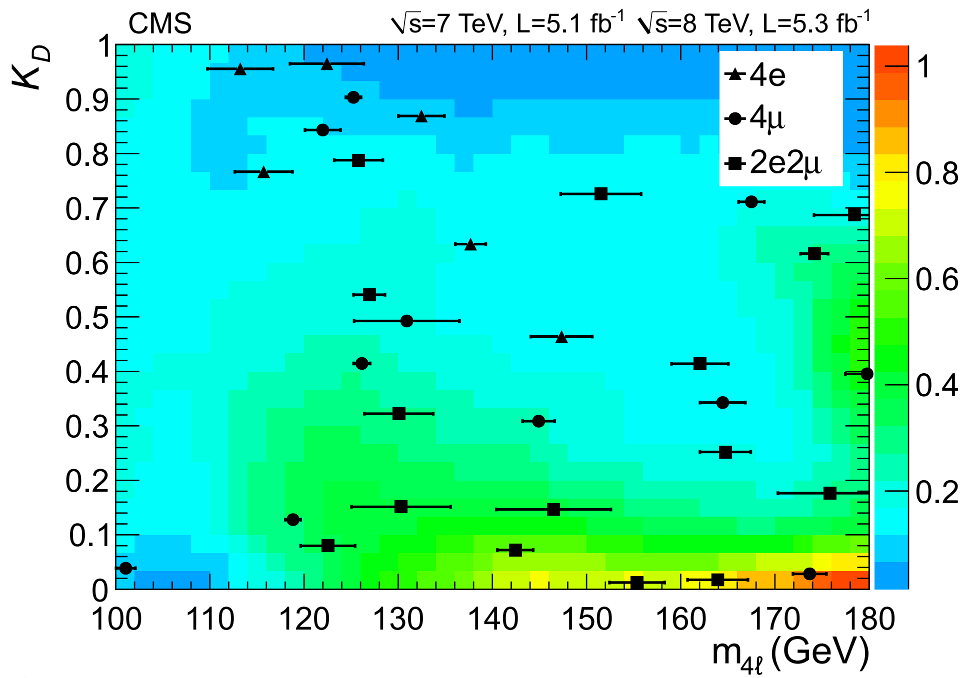
Matrix Element Likelihood Analysis

A kinematic discriminant (K_D) is constructed based on the probability ratio of the signal and background hypotheses

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







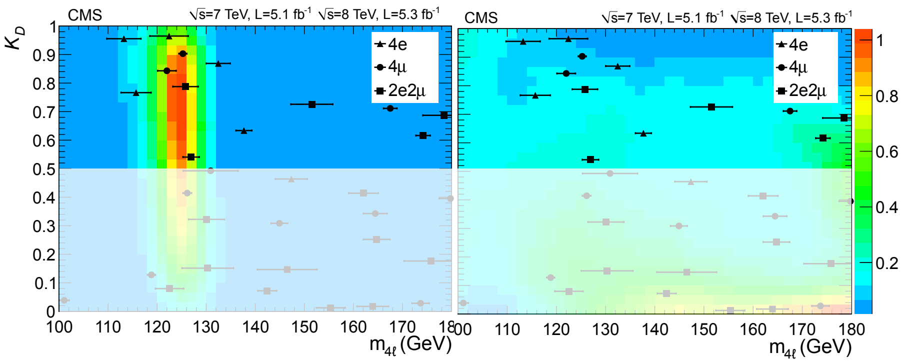
2D analysis using m_{4l} and K_D

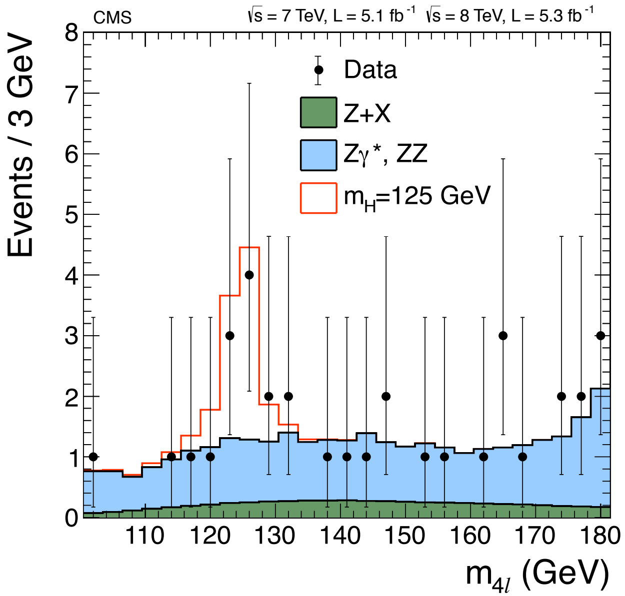
H → ZZ

Low mass region ($K_D > 0.5$)

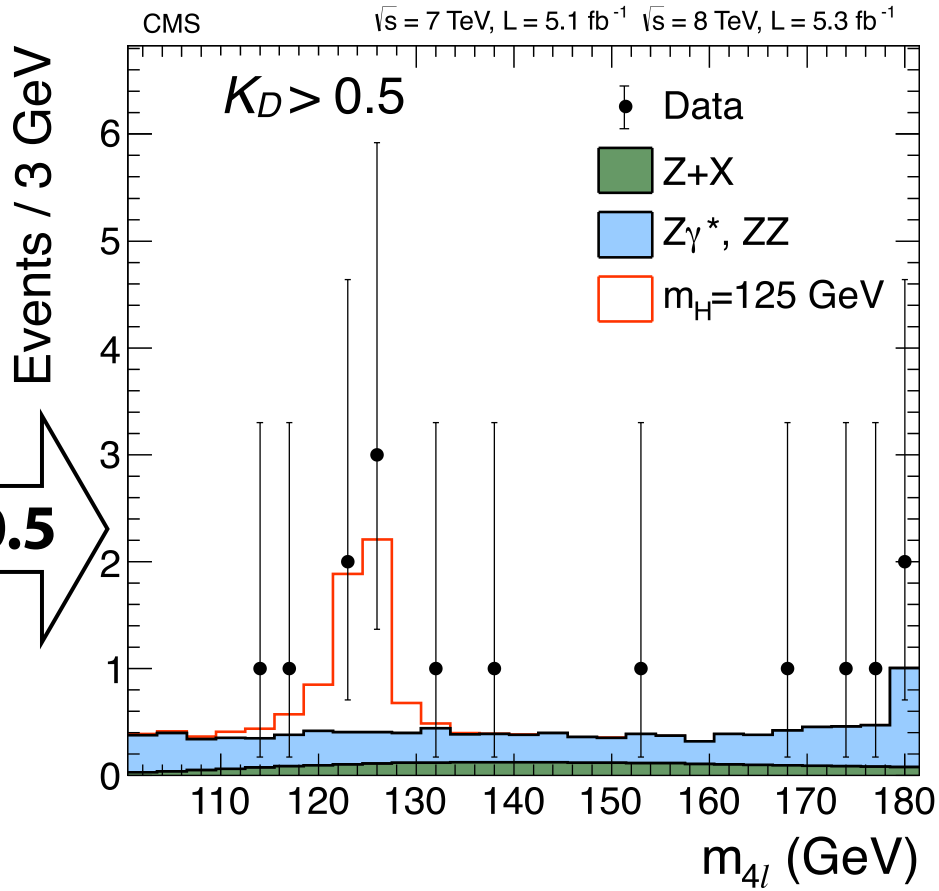
Enrich the signal content

Cut value (0.5) chosen such that signal probability > background probability





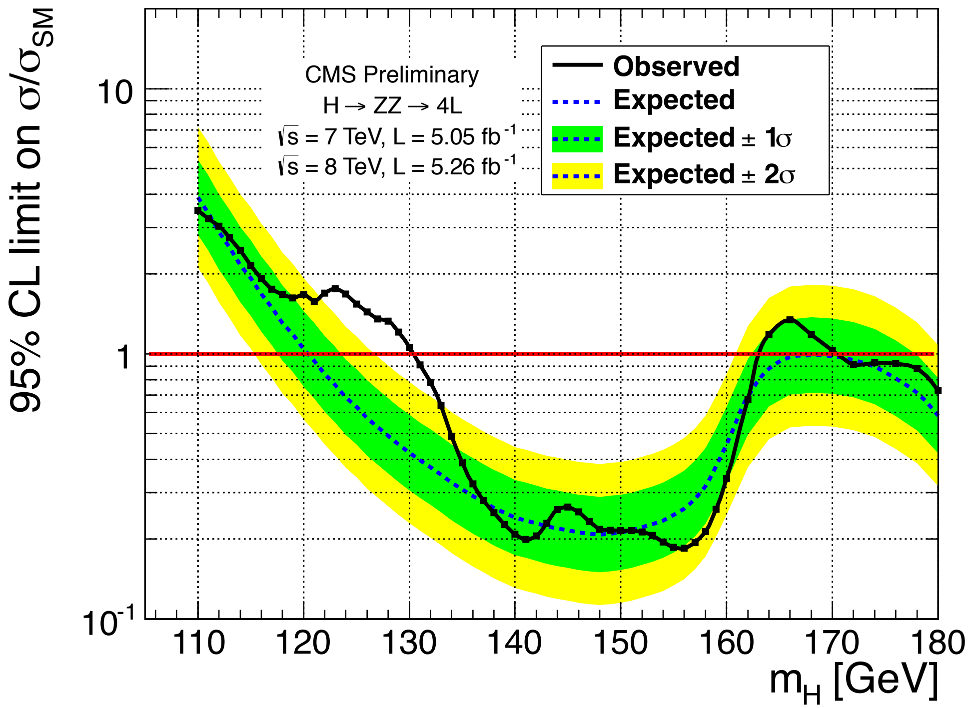
$K_D > 0.5$

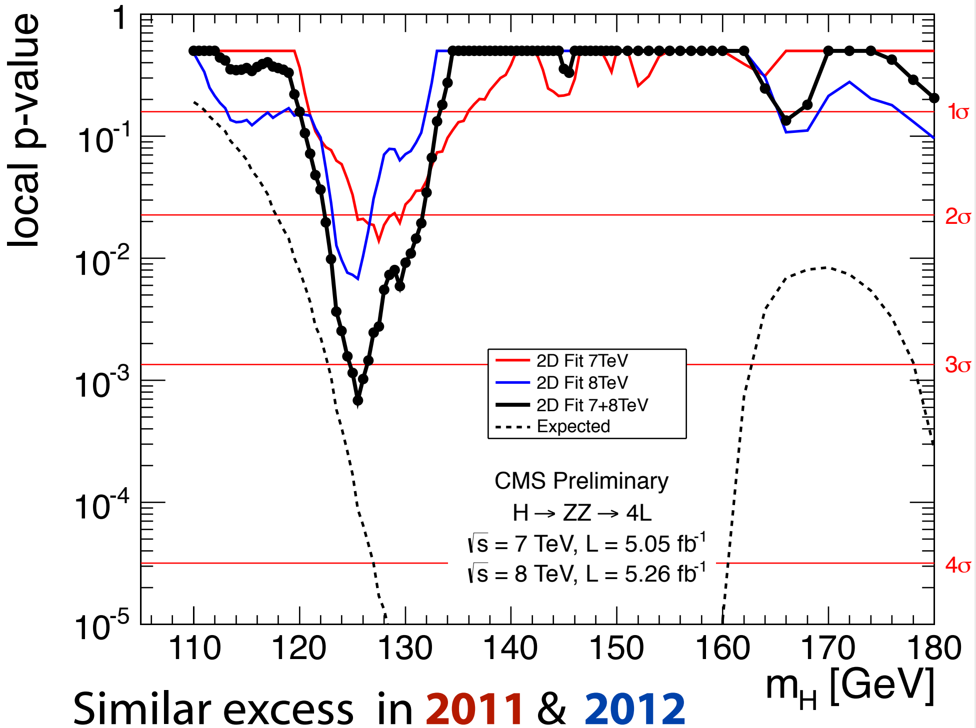


For illustration purposes only

$H \to ZZ$

H→ZZ(*)→4l - Results





Similar excess in **2011** & **2012**

Expected exclusion at 95% CL

121-550 GeV

Observed exclusion at 95% CL

131-162 GeV and 172-530 GeV

Expected significance at 125.5 GeV

3.8 σ

Observed significance at 125.5 GeV

3.2 σ

Evidence for a new state

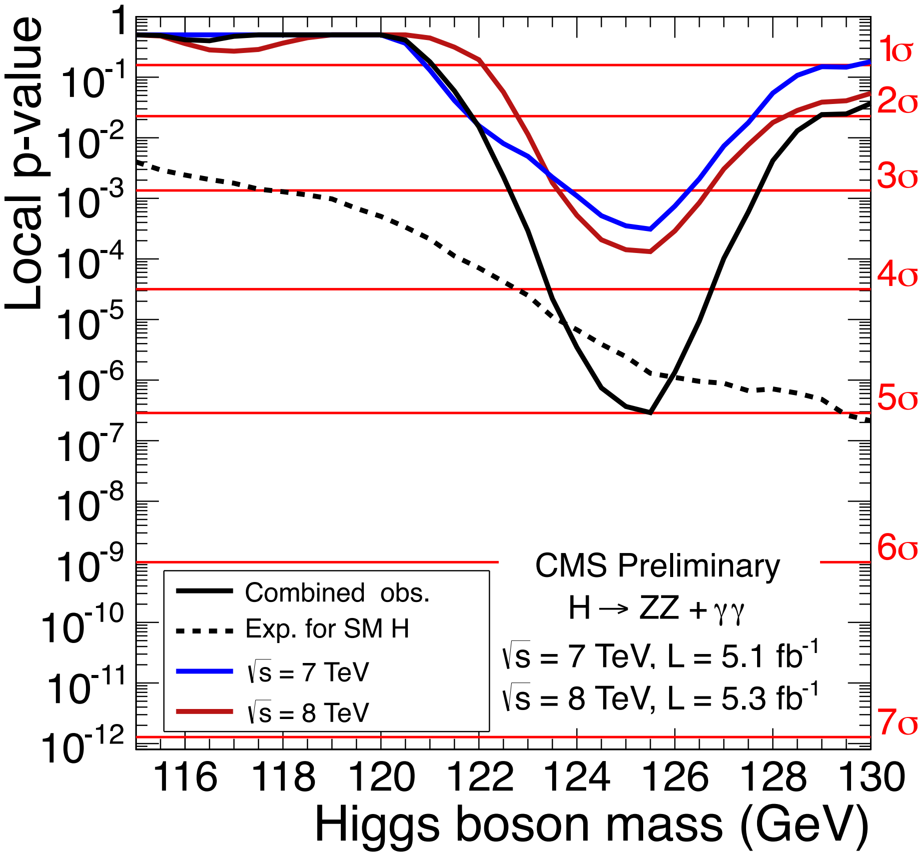
H → ZZ

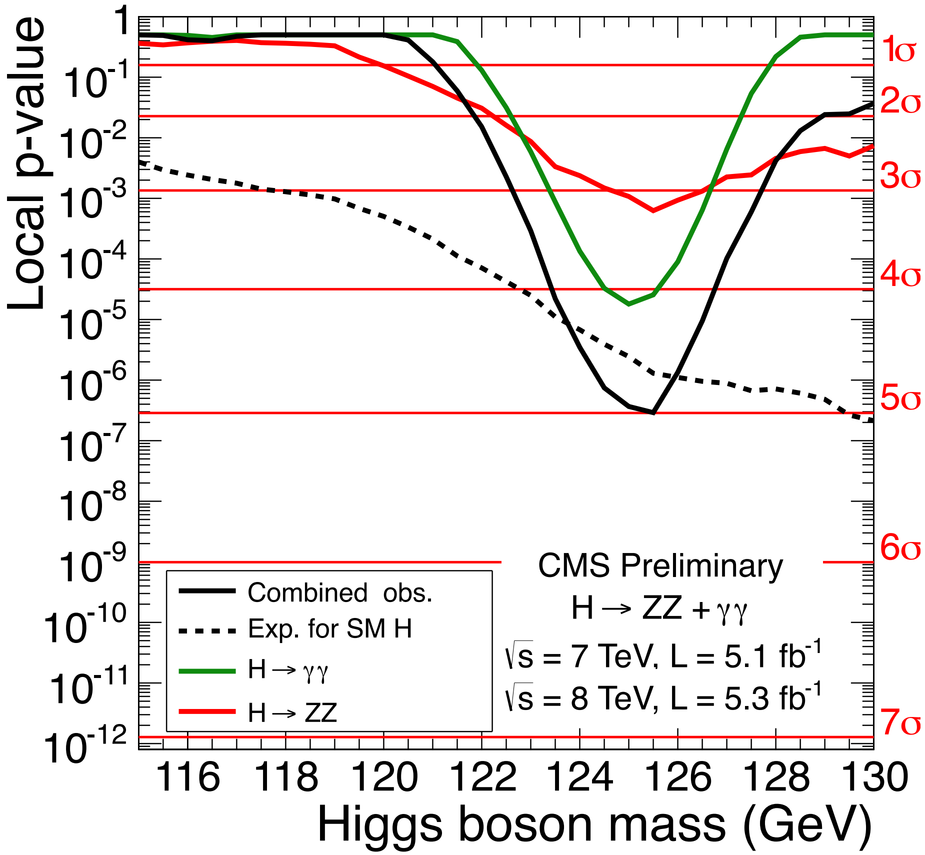
Combination

Combination: ZZ + γγ

Local significance of excess: 5.0σ

Expected for SM Higgs signal: 4.7σ



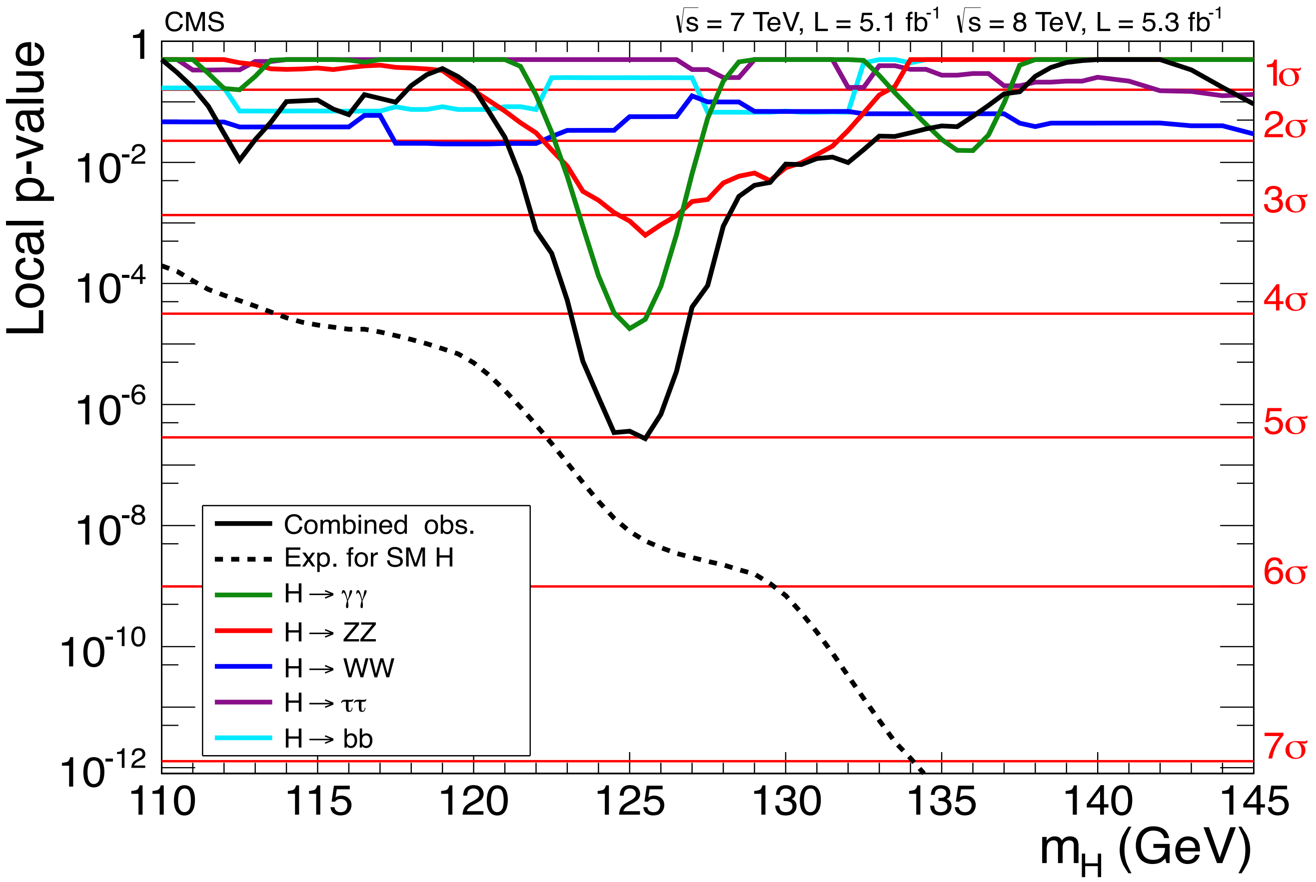


Discovery of a new state

Combination: all the channels

Local significance of excess: 5.0σ

Expected for SM Higgs signal: 6.0σ

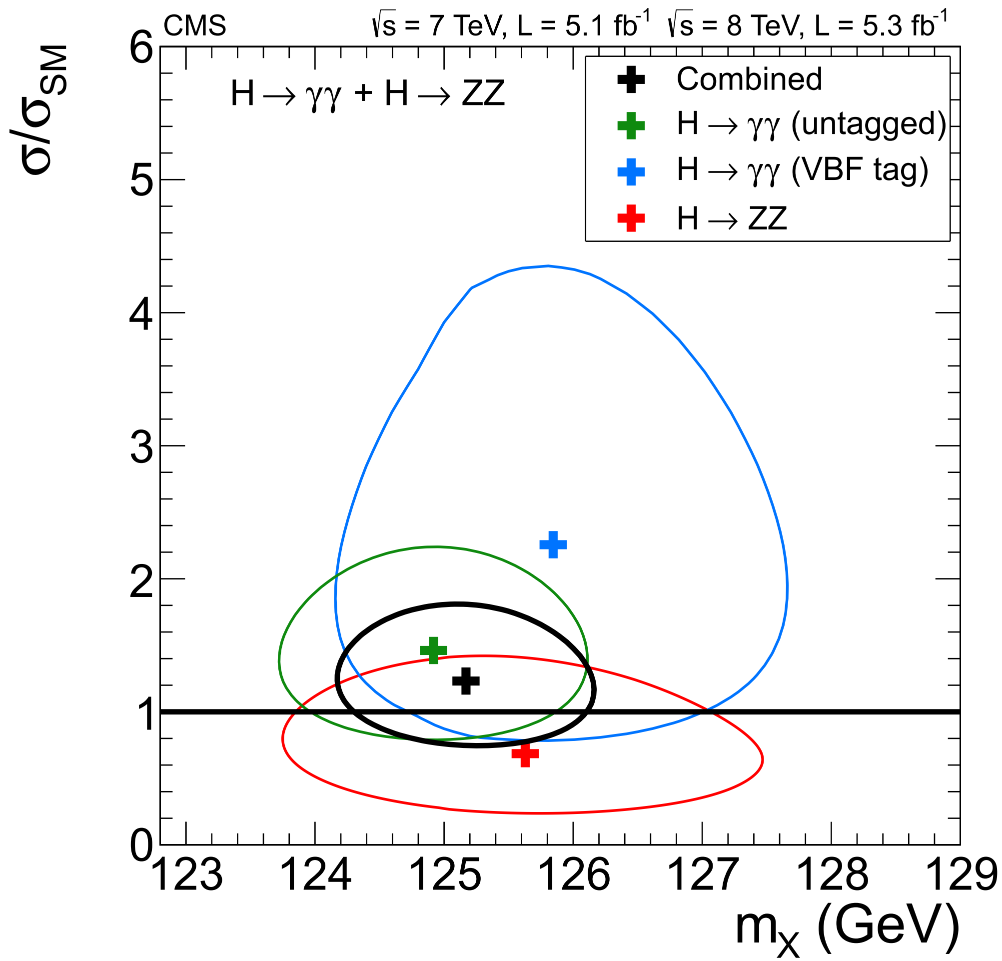


Discovery of a new state

Mass of the observed particle

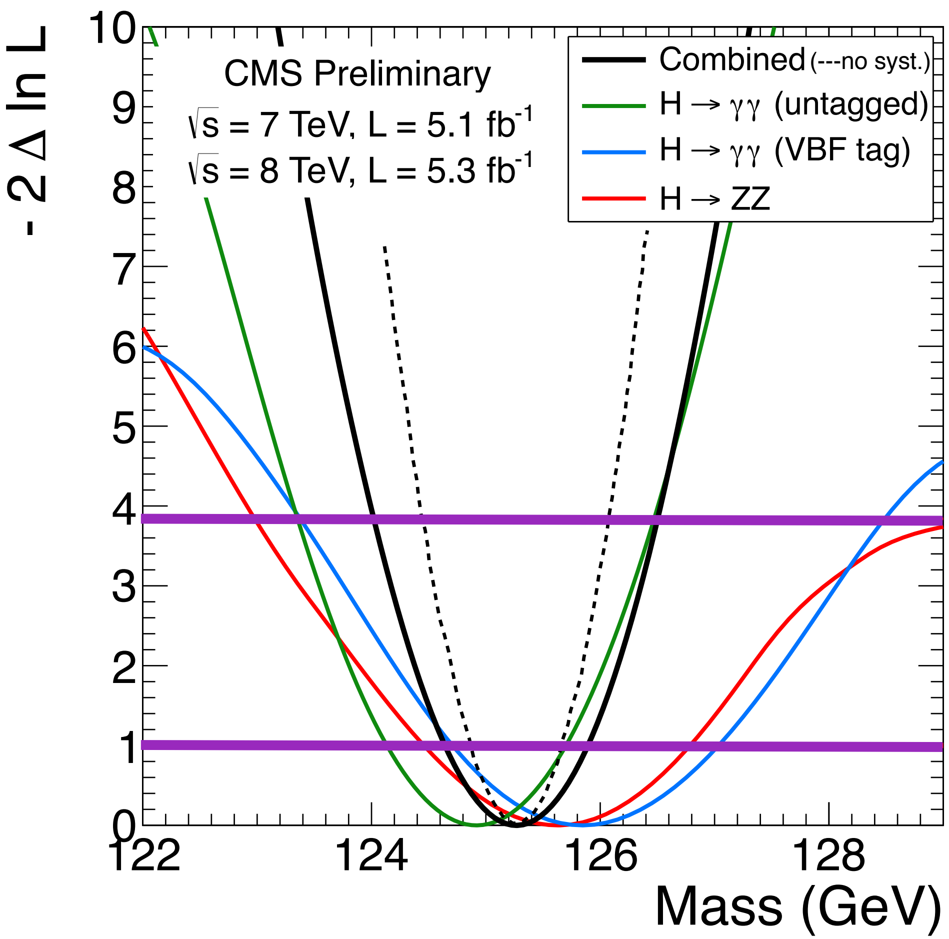
Likelihood scan for mass and signal strength in three high mass resolution channels:

- **ZZ→4l**
- **γγ untagged**
- **γγ with di-jet tag**



Results are compatible within the uncertainties and can be combined

Mass measurement



Perform a fit of the mass with freely floating signal strength for the three final states, to minimize model dependence

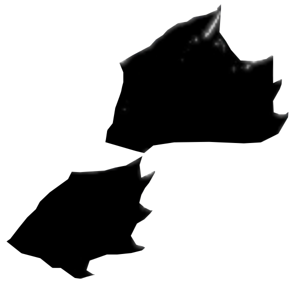
M_X = 125.3 ± 0.4 (stat.)
± 0.5 (syst.)
= 125.3 ± 0.6 GeV

Systematics driven by energy scale uncertainty ~0.5%
Will still improve

We interpret this excess as the observation of a new boson with mass around 125 GeV

Is it the SM Higgs boson?

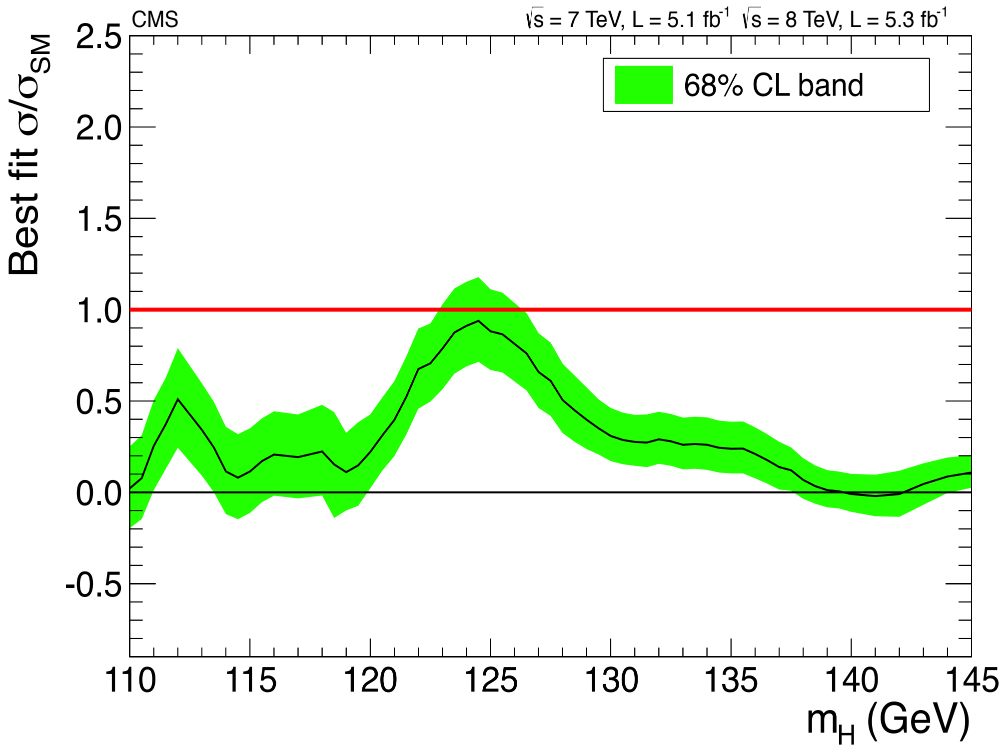
If it swims like a duck and quacks like a duck ...

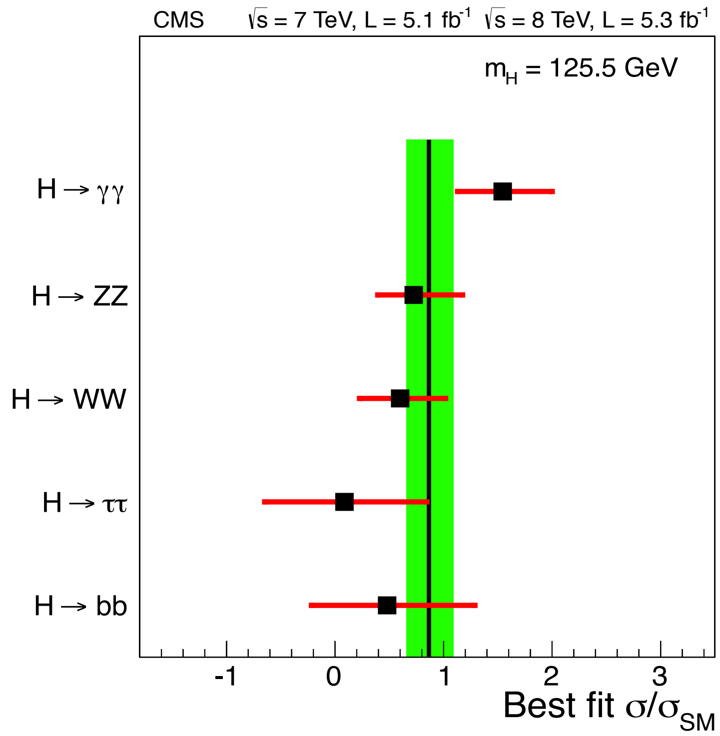


... then it probably is a duck ... but ...

...it could be a platypus

Compatibility with SM Higgs boson





Best fit signal strength combining all channels, observed value for an excess around 125 GeV

$\sigma/\sigma_{SM} = 0.85 \pm 0.22$

Signal strength σ/σ_{SM} combining channels by decay mode

Compatible with SM Higgs within uncertainties

Test of custodial symmetry

Compare WW and ZZ observed signal strength

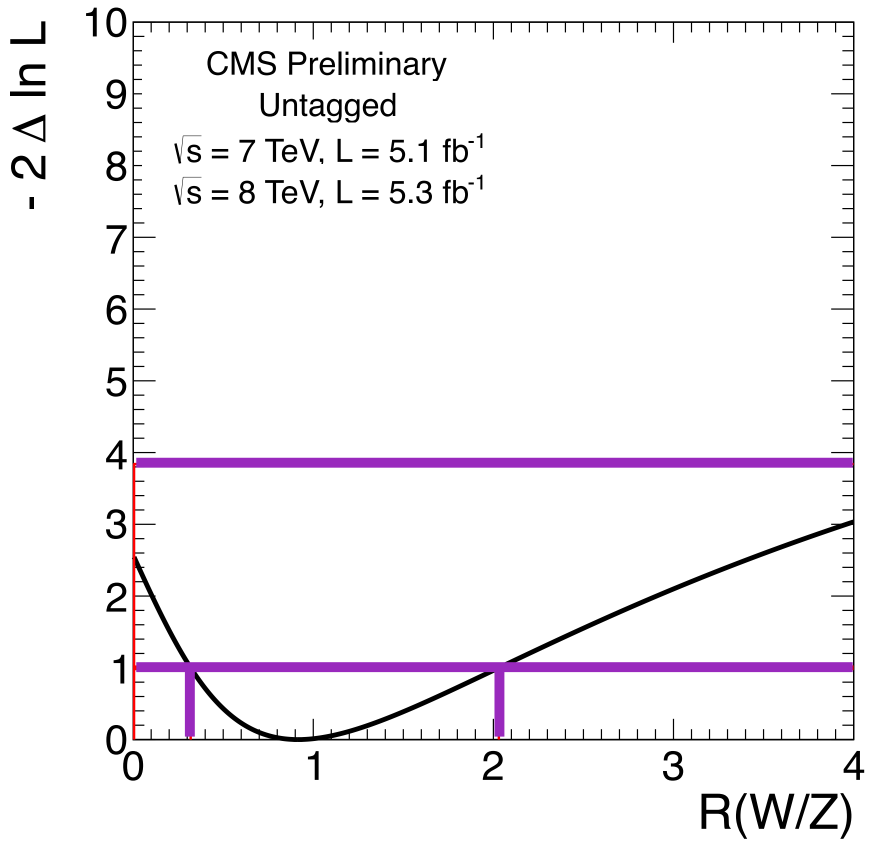
Fit the the ZZ and WW (0/1 jet) data assuming:

$\sigma \times BR(H \to ZZ) \quad = \qquad \mu_{ZZ} \times [\sigma \times BR(H \to ZZ)]_{\text{SM Higgs}}$

$\sigma \times BR(H \to WW) = R_{W/Z} \times \mu_{ZZ} \times [\sigma \times BR(H \to WW)]_{\text{SM Higgs}}$

$R_{W/Z} = 0.9^{+1.1}_{-0.6}$

Result compatible with SM within the large uncertainties



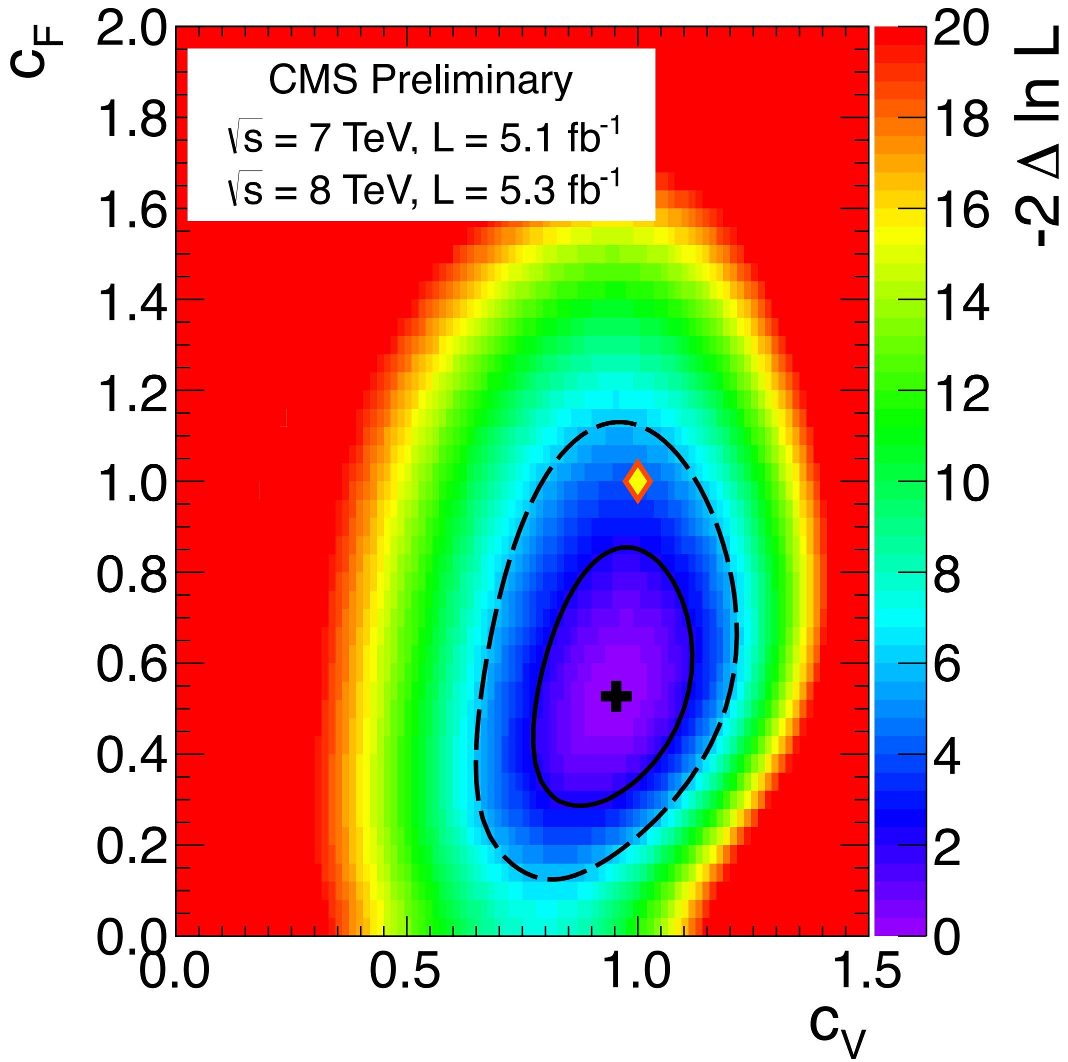
Couplings to bosons and fermions

Test compatibility by introducing two parameter (C_V, C_F)

C_V and C_F modify expected signal yields in each mode through simple LO expressions

CMS data compatible with SM prediction at 95% C.L.

Best fit C_F driven to low values by VBF γγ excess and ττ deficit
More data needed to draw any definite conclusion



solid contour: 68% CL
dashed contour: 95% CL

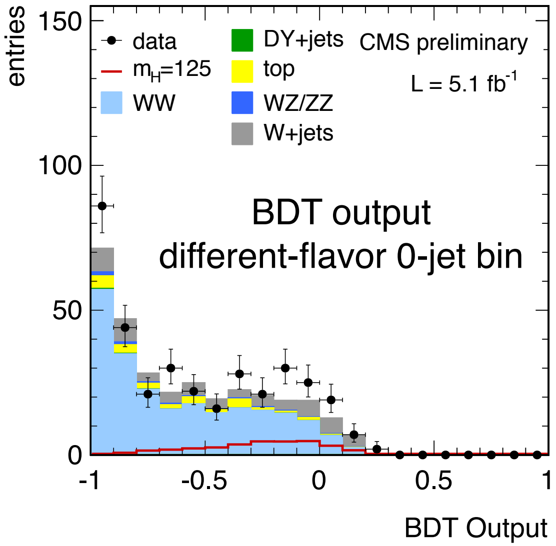
Is it the SM Higgs boson?

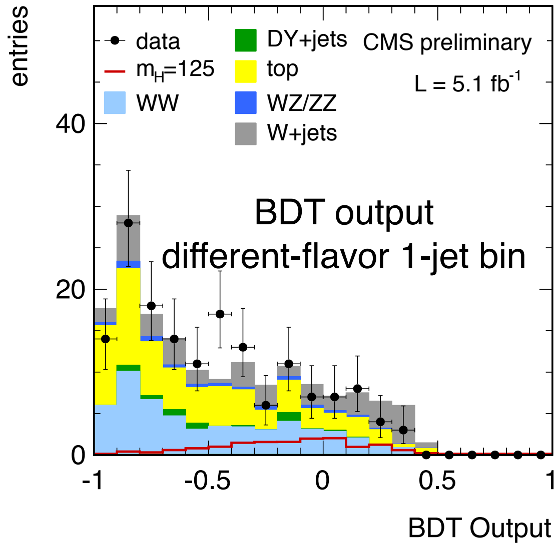
Within the **limited precision of the current data**, the results shown **are consistent**, within uncertainties, with expectations for a SM Higgs boson

After the discovery, what's next?

- **Collection of further 2012 data will provide > 5σ each in $\gamma\gamma$, $ZZ\to 4l$ channels ($\sigma/\sigma_{SM} = 1$?)**
- **Confirm observation or not in the other channels (3σ each in WW, bb, and $\tau\tau$ channels. Coupling to leptons?)**
- **Precision measurement of the properties of the new particle**

H→WW$^{(*)}$→lνlν: full shape analysis



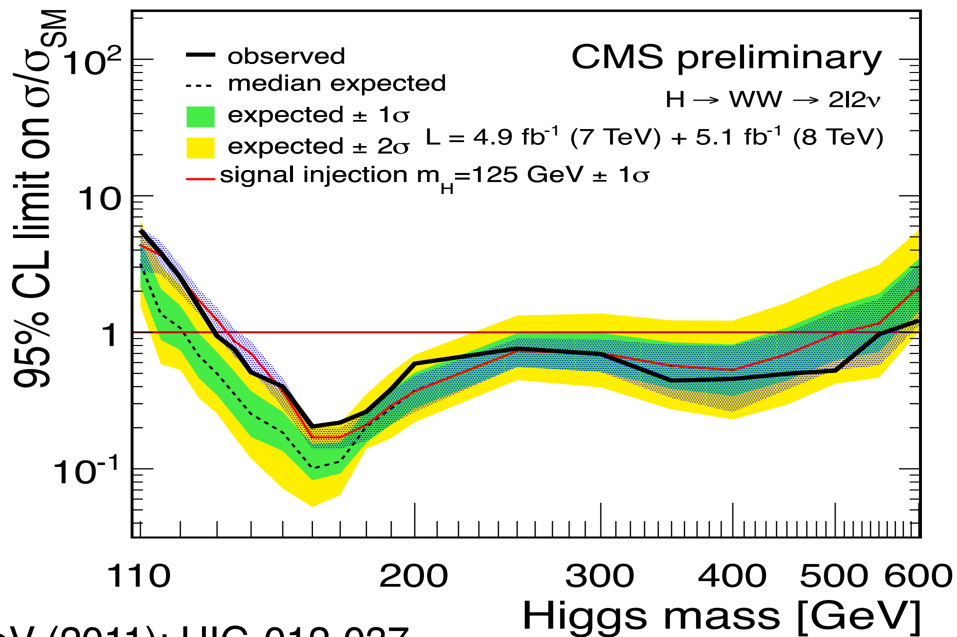


Inclusion of a multivariate analysis for the different-flavor final state in the 0-jet and 1-jet categories

@ m_H = 125 GeV

Obs. (Exp.) significance: **2.2 (2.5)σ**

Signal strength: **0.82 ± 0.38**



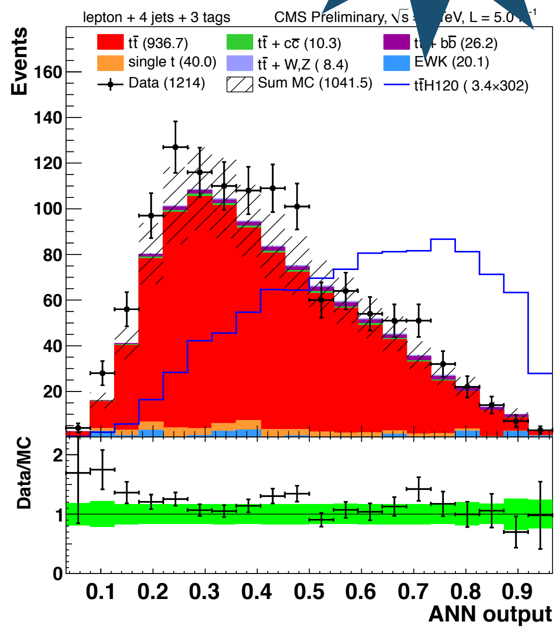
5 fb^{-1} @ 7 TeV (2011): HIG-012-037

H → WW

ttH, H→bb

NEW

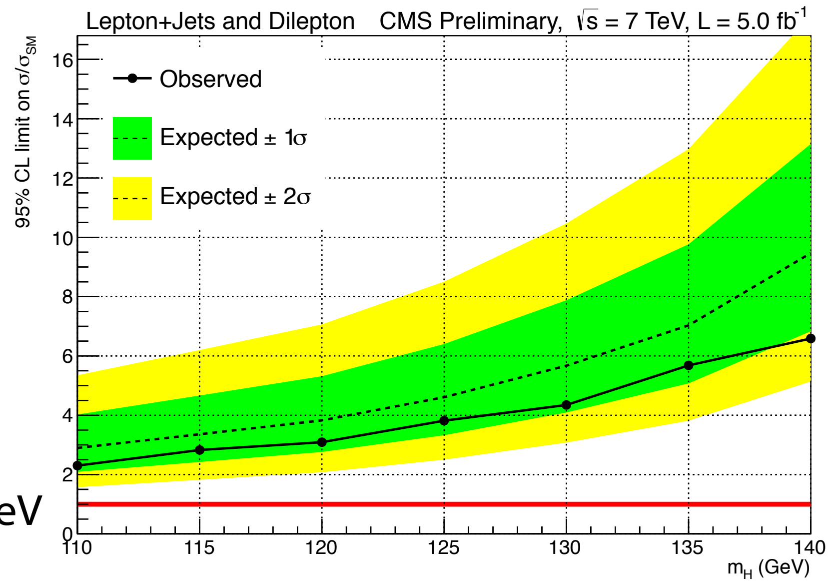
Important for a direct probe of the coupling
production cross section but at tree level
(no loopholes for BSM particles to contribute...)



Strategy:

- **Separate events by top decay mode (lep.+jets/dilep.) and by number of jets and b-tags**
- **MVA shape analysis in each event category**

No evidence of excess,
but not yet sensitive to a 1×σ_{SMH} signal
Only 2011 data analyzed at the moment



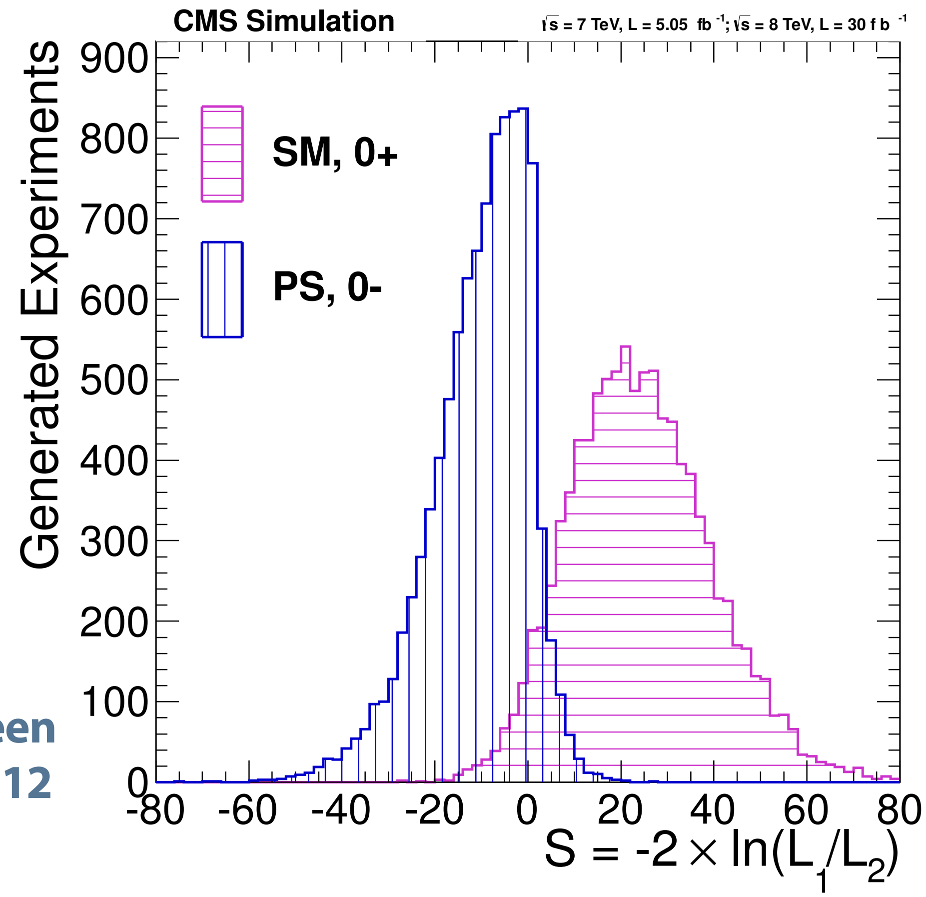
ttH cross section grows very quickly with √s
(x1.5 from 7 to 8 TeV, x5 from 8 to 14 TeV!)
We could have $\Delta\sigma/\sigma_{SMH}$ ~1 with L ~20 fb^{-1} at 8 TeV

5 fb^{-1} @ 7 TeV (2011): HIG-012-025

H→bb

Spin-Parity / Couplings

Measurement of spin and parity using angular distributions in ZZ, WW, and γγ



Expect ~3σ separation between scalar and pseudoscalar in 2012

Search for deviations from the SM in the couplings by progressively introducing new degrees of freedom in the fit to the data

Beyond SM Higgs

Beyond SM Higgs: Overview

Extensions to the SM

Fermiophobic Higgs sector

4th generation of heavy fermions

Supersymmetric

Minimal Supersymmetric Standard Model (**MSSM**) with two Higgs doublets

- $H^0 \rightarrow bb, \tau\tau, \mu\mu$
- $H^\pm \rightarrow \tau\nu$

Next-to-Minimal Supersymmetric Standard Model (**nMSSM**) with additional scalar field

- $a_1 \rightarrow \mu\mu$

Triple your fun

Minimal Type II Seesaw Model (relate to NP + ν mass)

Triplet scalar field → doubly charged Higgs

Fermiophobic Higgs: H→ γγ

NEW

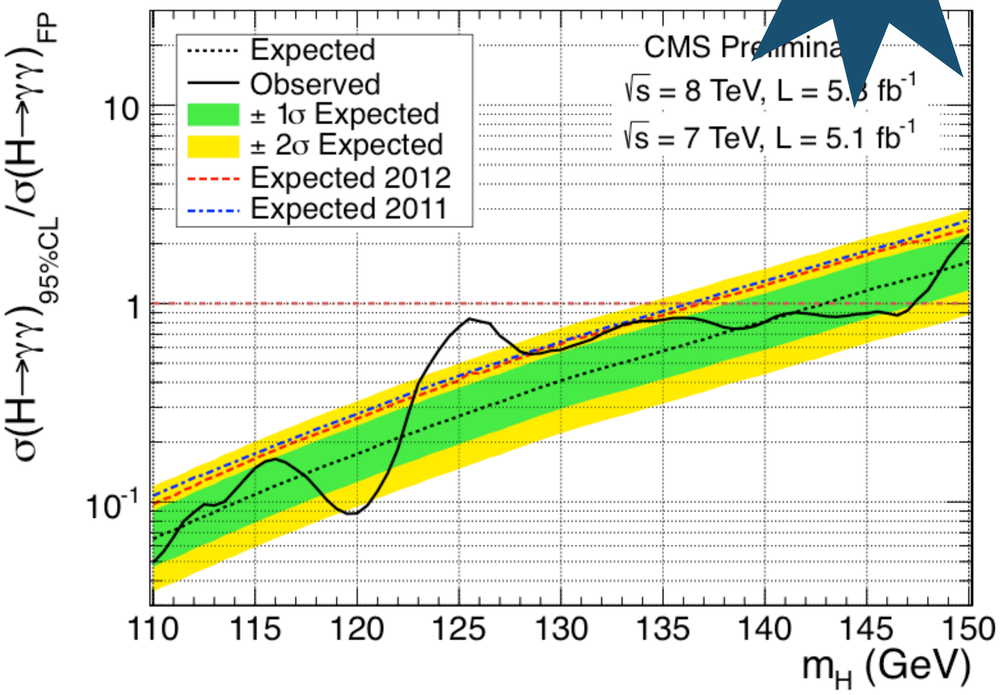
Beyond SM Higgs

No couplings to fermions

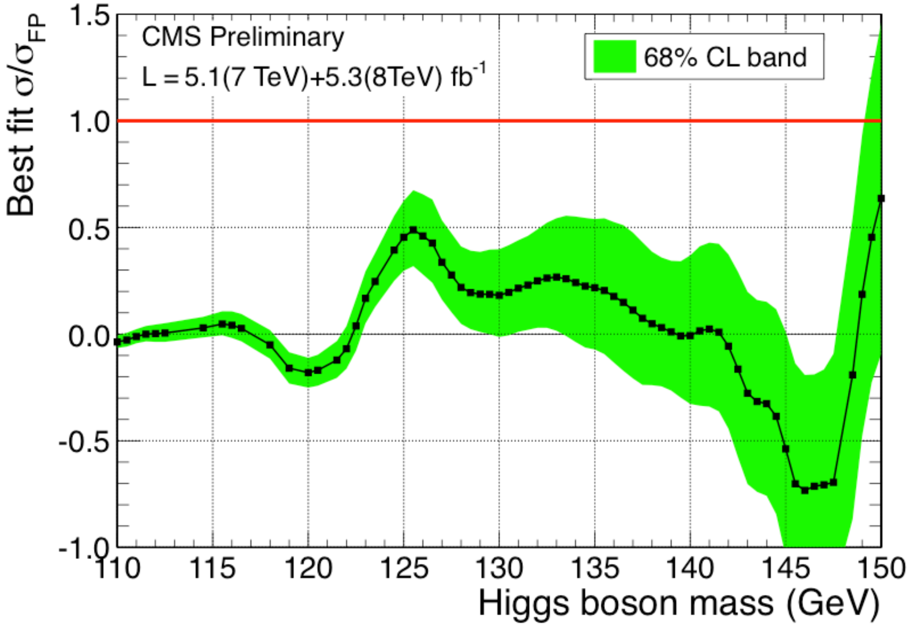
- **VBF or associated VH production only**

Low mass Higgs decays change dramatically

Higgs is boosted



Excludes at 95% CL 110-147 GeV
Excludes at 99% CL 110-134 GeV



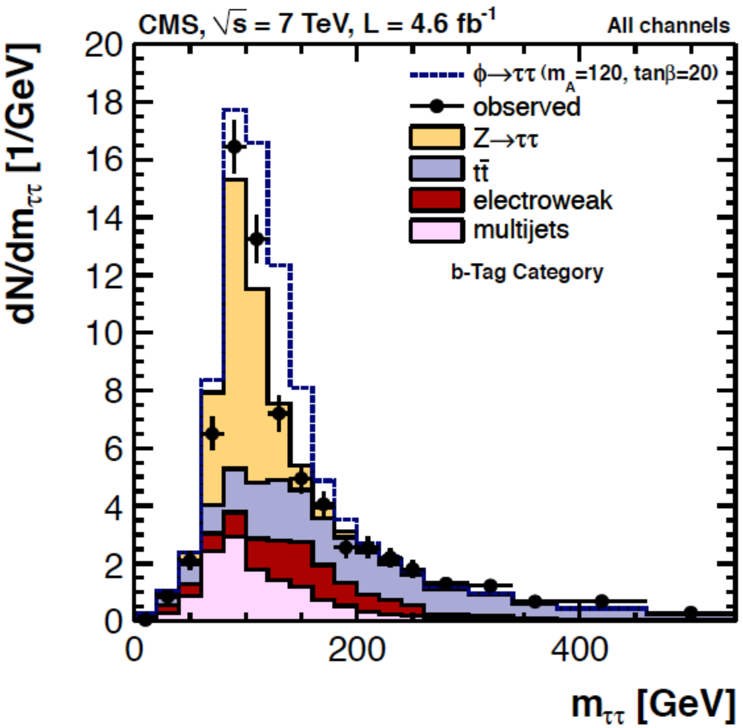
The observed state @ ~125 GeV is excluded at 99% CL under the fully-fermiophobic hypothesis.

The excess shows tension with FP signal: best fit signal rate 0.49±0.18

5 fb^{-1} @ 7 TeV (2011) + 5 fb^{-1} @ 8 TeV (2012): HIG-12-022

MSSM Higgs: $\Phi(h, H, A) \rightarrow \tau\tau$

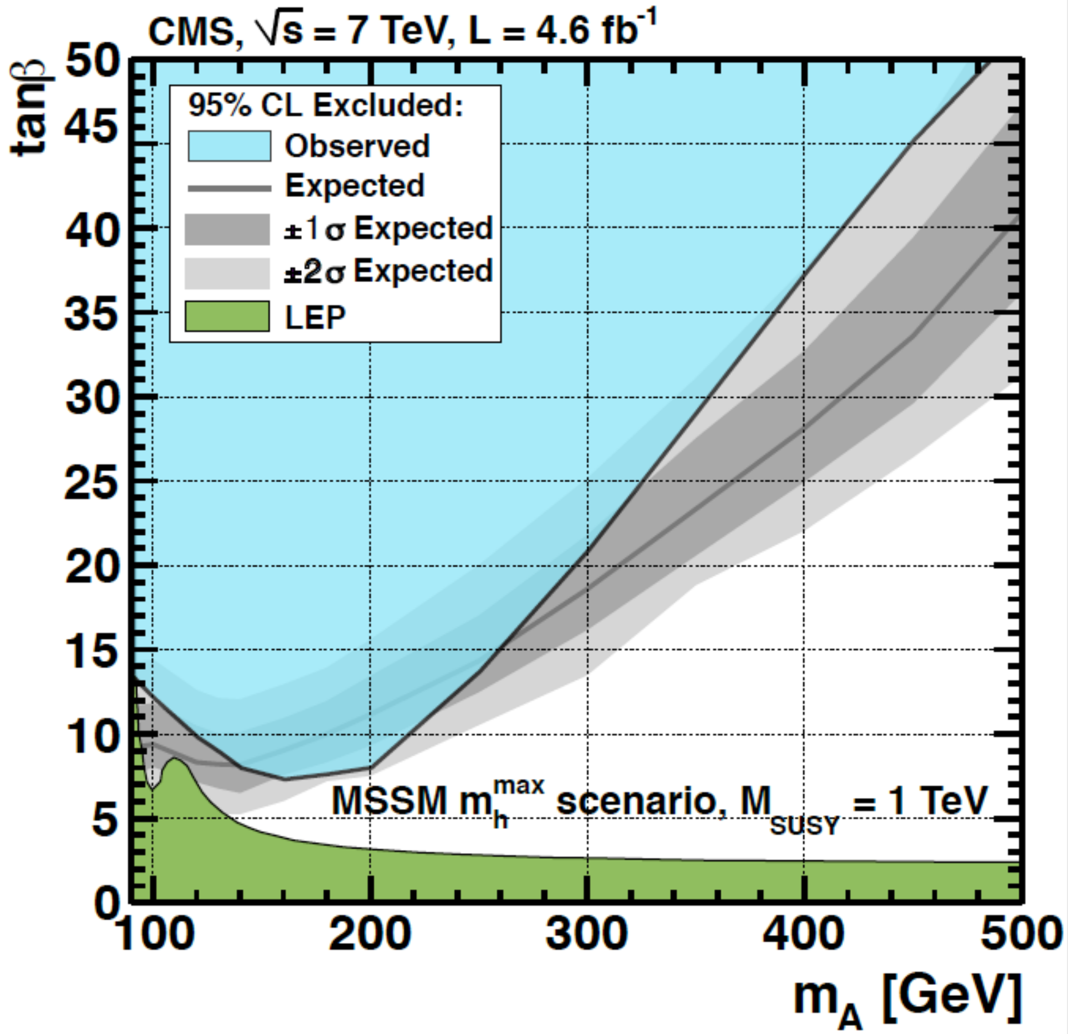
Beyond SM Higgs



Mass of ττ pair constructed via likelihood technique

- **τ decay kinematics**
- **Compatibility of E_T^{Miss} with neutrino hypothesis**

Resulting $M_{\tau\tau}$ resolution ~20%, almost Gaussian



Limit obtained by scanning tan(β) for each mass hypothesis M_A

5 fb^{-1} @ 7 TeV (2011): arXiv:1202.4083

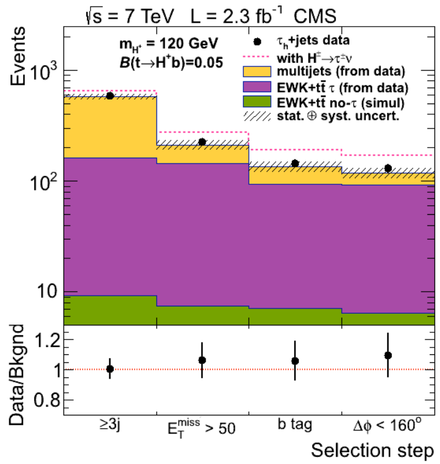
MSSM Higgs: $H^{\pm} \rightarrow \tau\nu$

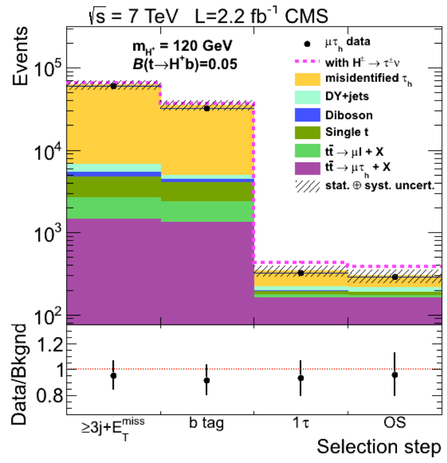
Look for tt → H^+W^-bb or H^+H^-bb with $H^+ \rightarrow \tau\nu$

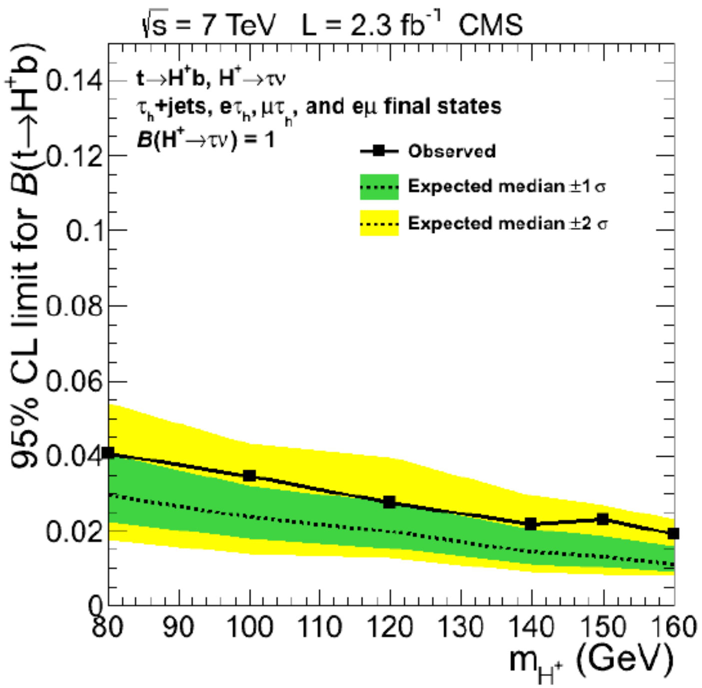
Three classes of events:

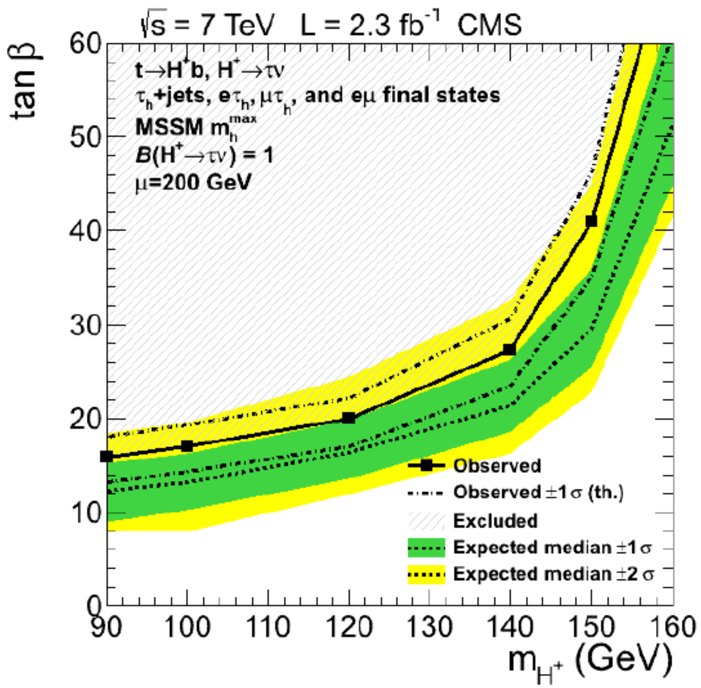
1. All hadronic with jets+τ→hadrons
2. Lepton+jets with τ→had
3. Di-lepton in the eμ channel

Excludes large tan β region









2 fb^{-1} @ 7 TeV (2011): arXiv:1205.5736

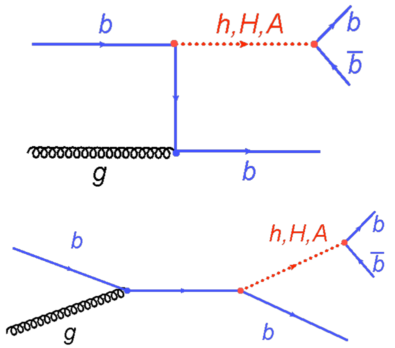
Beyond SM Higgs

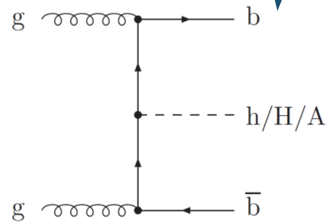
MSSM Higgs: neutral Higgs + b-quarks

NEW

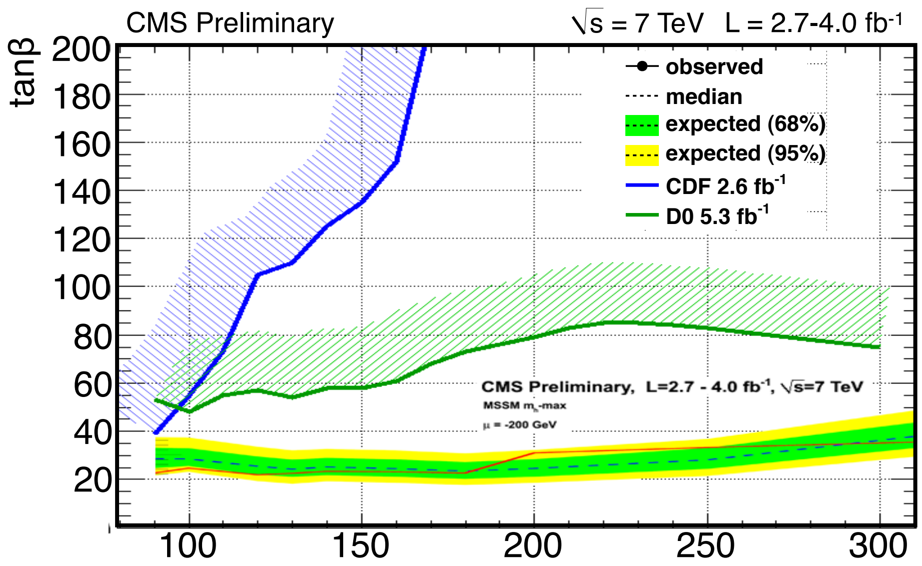
First Time at LHC

Search of neutral supersymmetric Higgs particles decaying into a pair of b quarks produced in association with at least one or two further b-quarks

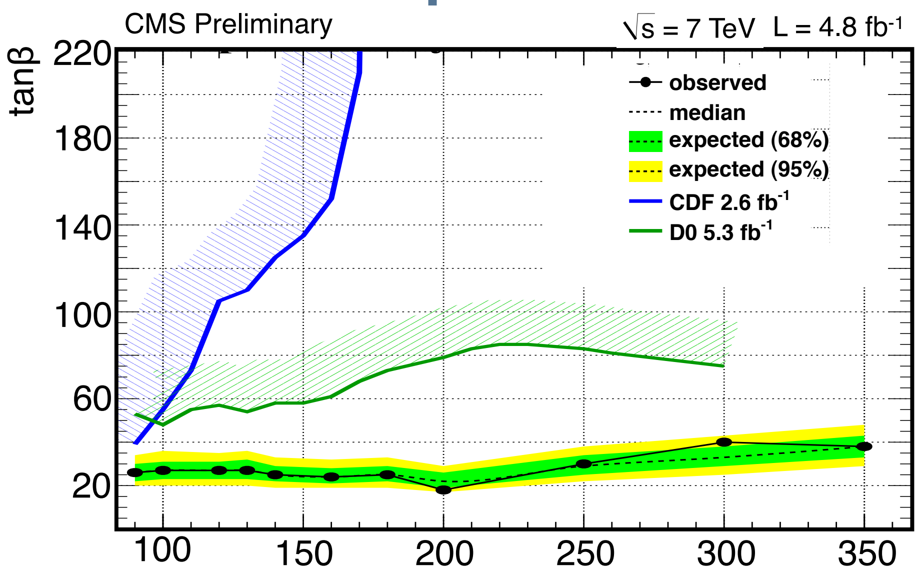




fully hadronic channel



semi leptonic channel



No significant excess with respect to the expected SM background
In the framework of MSSM in the m_h^{max} scenario is excluded a region phase space previously unexplored

2.7-4.0 / 4.8 fb^{-1} @ 7 TeV (2011): HIG-12-026 HIG-12-027

Beyond SM Higgs

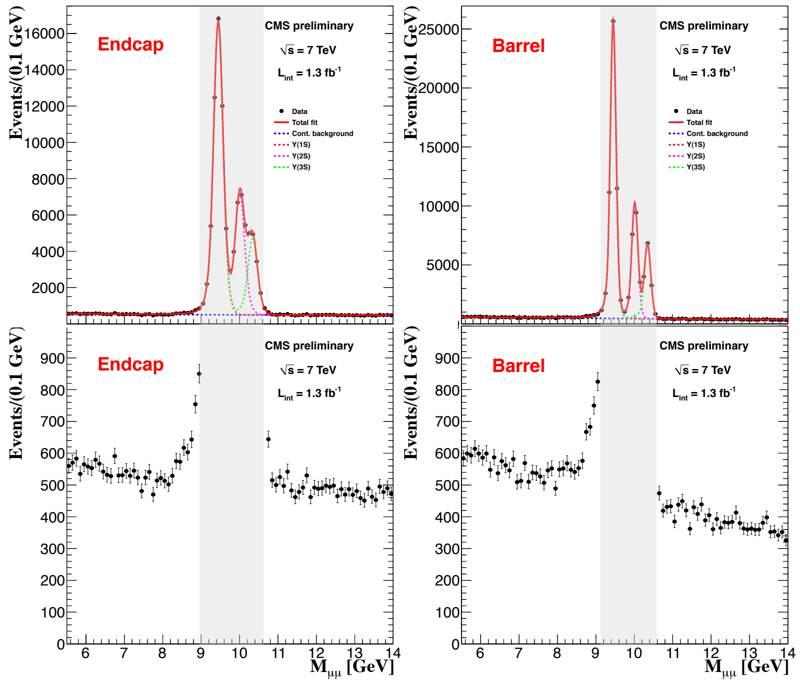
nMSSM: $a_1 \to \mu\mu$

Adds singlet scalar field
Expanding the Higgs sector to:

3 CP-even (h_1, h_2 and h_3),

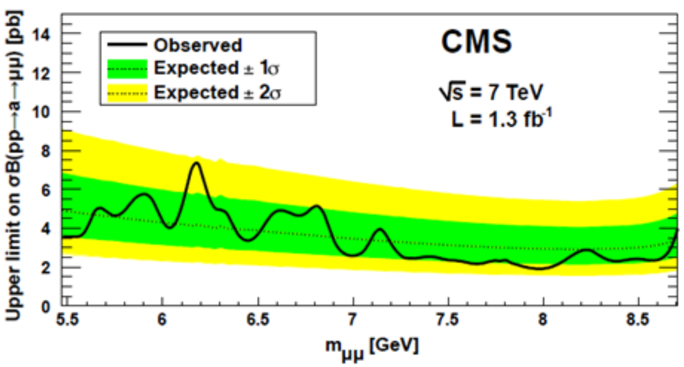
2 CP-odd (a_1, a_2)

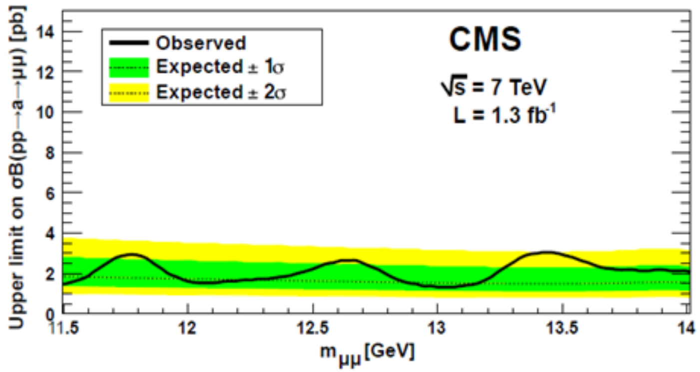
2 charged scalars (H^+, H^-)



A light (~10GeV) boson is produced

This model can survive also with a Higgs at 125 GeV!





No significant excess of events observed in 1.3 fb^{-1} @ 7 TeV
Exclusion limits set at the level of 2-6 pb for σ x Br

1.3 fb^{-1} @ 7 TeV (2011): HIG-012-004

Doubly charged Higgs

Triplet Higgs-field in Minimal Type II See-Saw Models
The triplet is responsible for neutrino masses, the couplings directly linked to the mass matrix

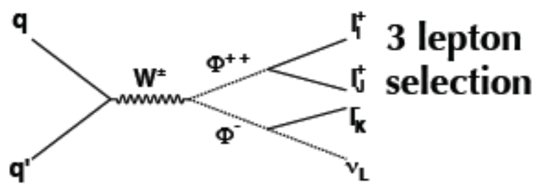
Prediction of additional scalar field

New Higgs-like particles: Φ^{++}, Φ^{+}, Φ^{0}

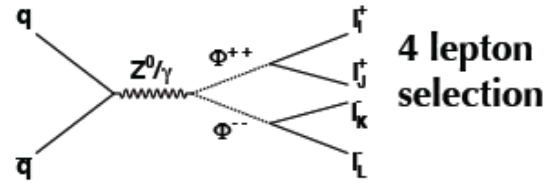
Unique experimental signature

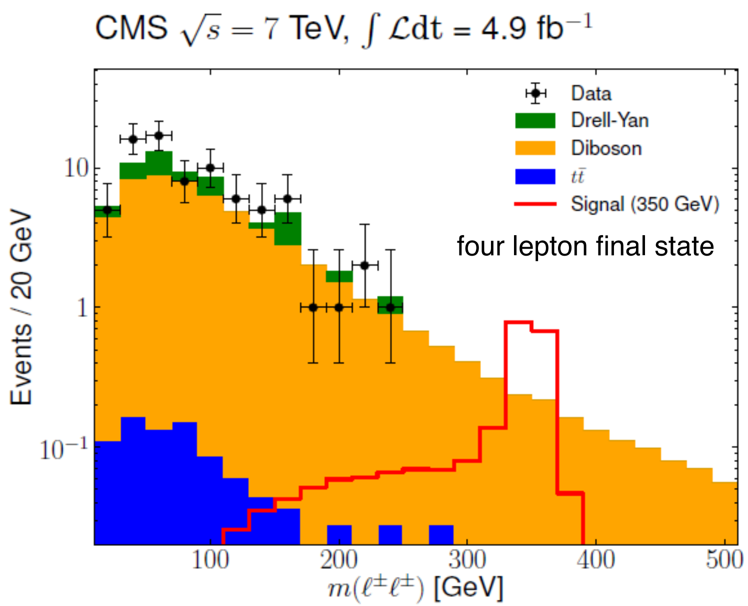
3 or 4 leptons in the final state

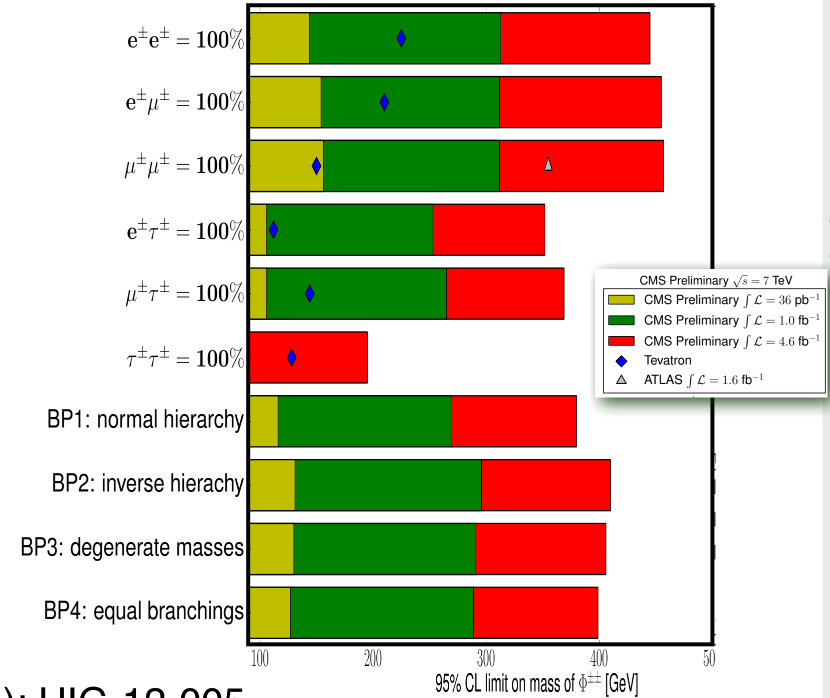
associated production



pair production







5 fb^{-1} @ 7 TeV (2011): HIG-12-005

Conclusion

Results are presented from searches for the SM Higgs boson in pp collisions at 7 and 8 TeV with the CMS detector

An excess of events is observed above the expected background, with a local significance of 5.0σ, we interpret this as the observation of a new boson .

The excess is most significant in the two decay modes with the best mass resolution, γγ and ZZ, and a fit to these signals gives a mass of 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV.

The results are consistent, within uncertainties, with expectations for a SM Higgs boson.

More data are needed to check whether the properties of this new state imply physics beyond SM.

Active CMS searches for beyond MSSM Higgs

No evidence for any excess above backgrounds

Strong constraints on Fermiophobic, SM4, light pseudoscalar (a_1), and doubly charged Higgs boson hypotheses

Additional material

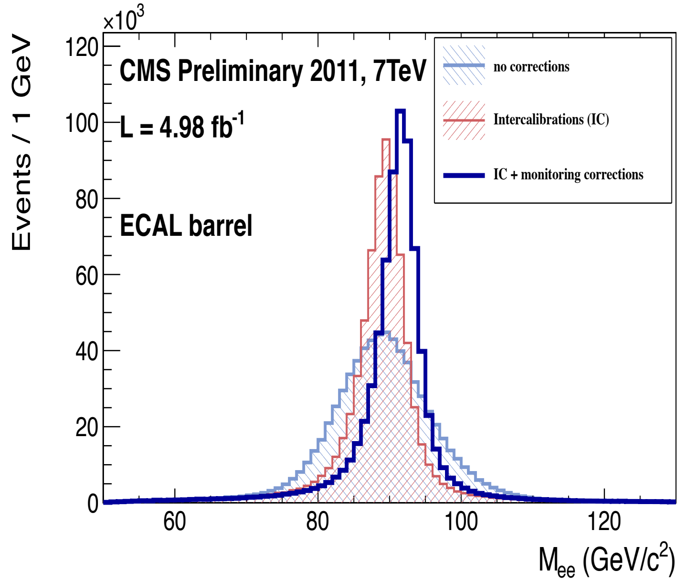
Photons

Energy reconstruction

Dynamic clustering to recover energy radiated upstream of ECAL via bremsstrahlung or conversions

- **Super-clusters of clusters along φ (bending direction)**
- **In the endcaps, add also preshower energy**

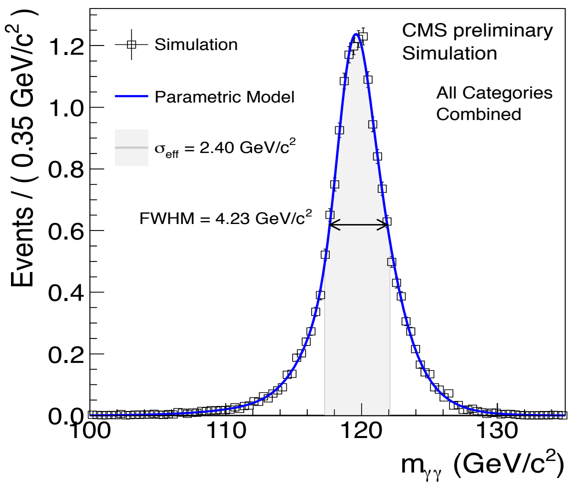
e/γ dependent algorithmic corrections based on MC



Progress in understanding ECAL

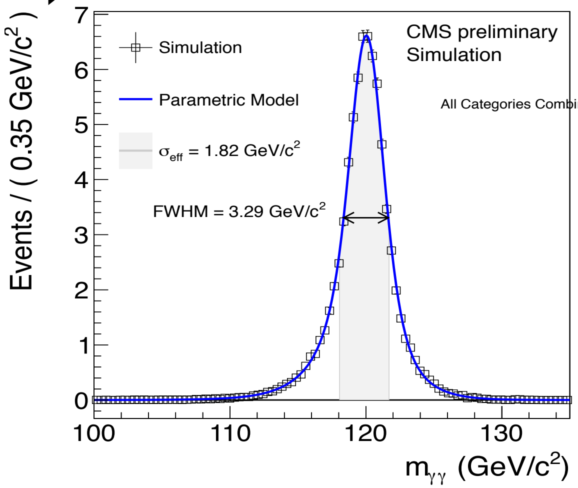
July 2011 (EPS):

FWHM = 4.23 GeV/c²



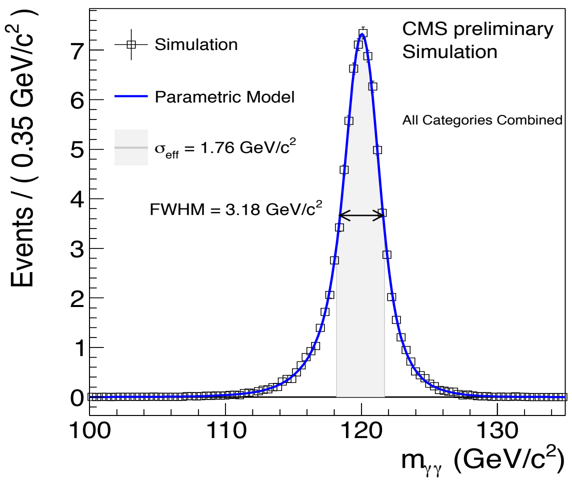
March 2011 (Moriond):

FWHM = 3.29 GeV/c²



July 2012 (ICHEP):

FWHM = 3.18 GeV/c²



Electrons

In analyses: $p_T > 7$ GeV/c $|\eta| < 2.5$

Superclusters in ECAL (E_T> 4 GeV)

collect energy spread in φ

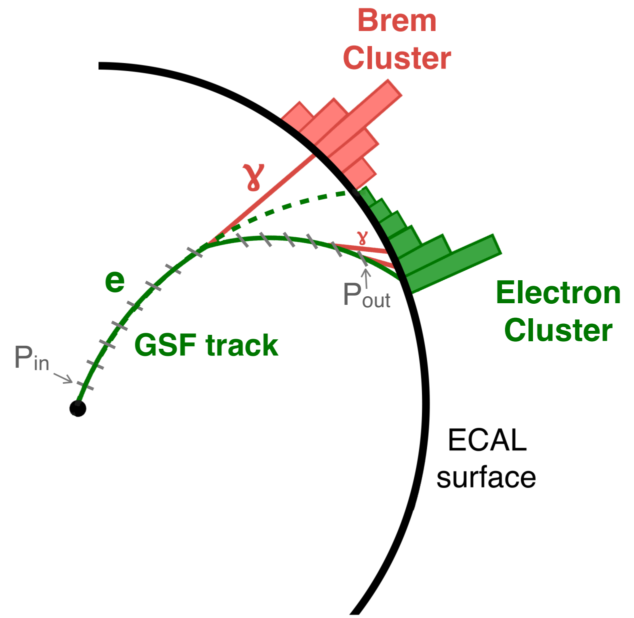
dedicated track finding and GSF fit

change of curvature and hit collection up to ECAL

ECAL-seed complemented by tracker-seed

Electron classes bremsstrahlung sensitive

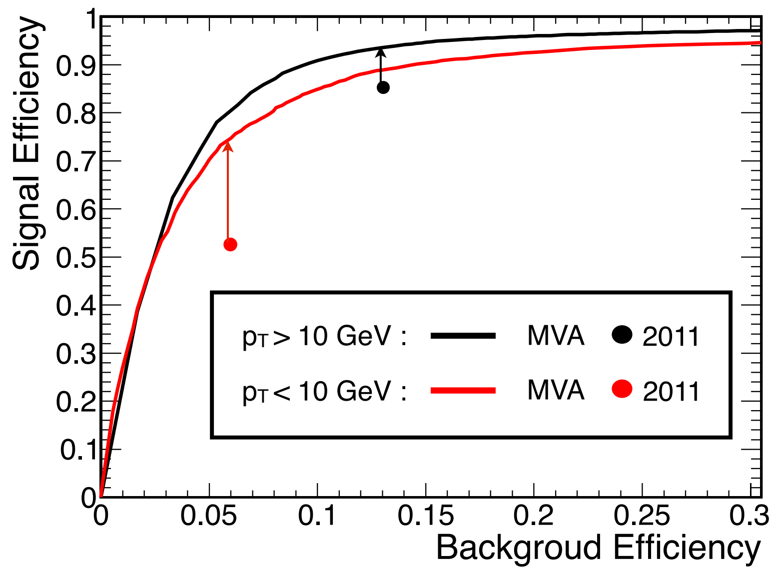
Momentum from E-p combination



Multivariate electron identification

Significative gain in the signal efficiency (↑)
for the same 2011 background rejection

HZZ4e efficiency gain: 30% @ m_H = 125 GeV



Efficiency measured via Z Tag&Probe

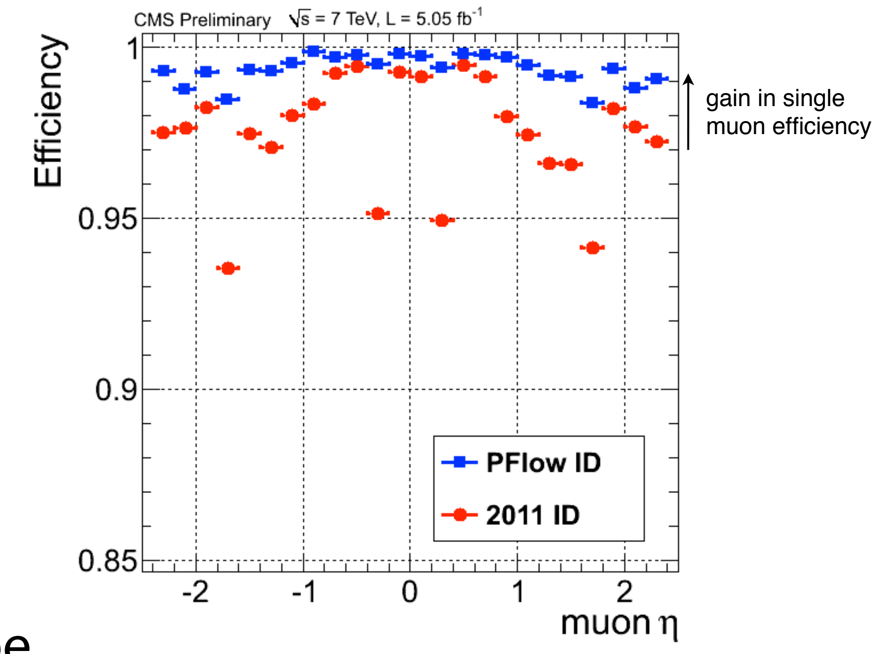
Muons

In analyses: $p_T > 5$ GeV/c $|\eta| < 2.4$

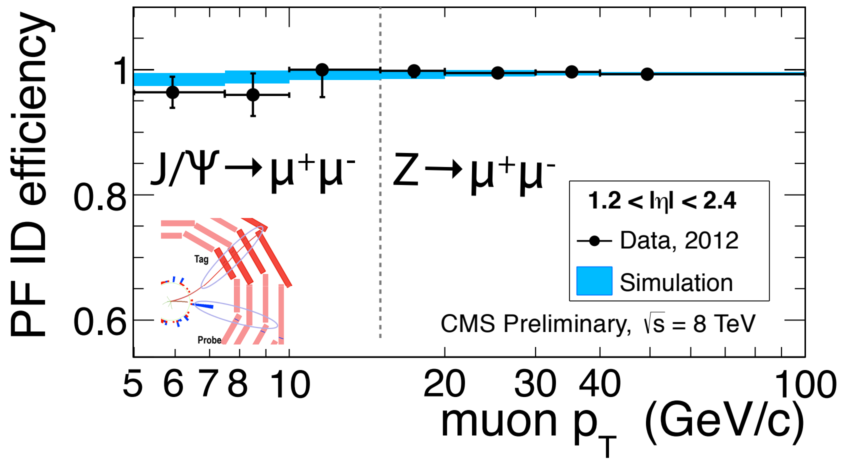
Combination of inner tracker tracks and muon system tracks

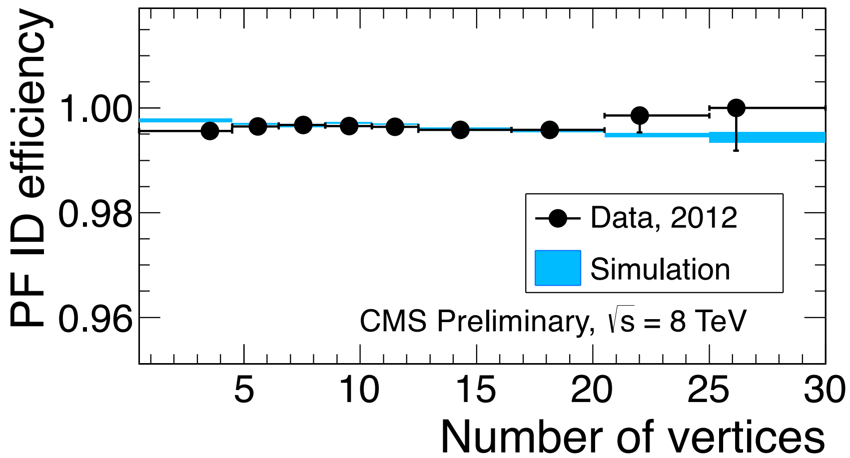
Particle Flow ID

inner and muon tracks quality and matching
99 % efficient for same fake rate as in 2011



Efficiency measured via Z and J/ψ Tag&Probe



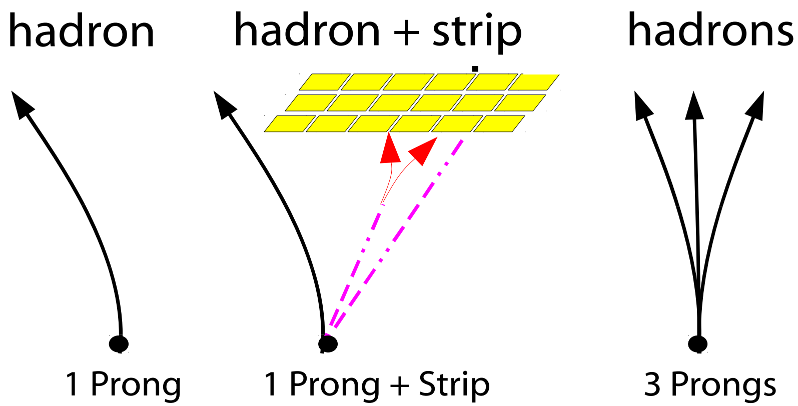


stable in high PU environment

Taus

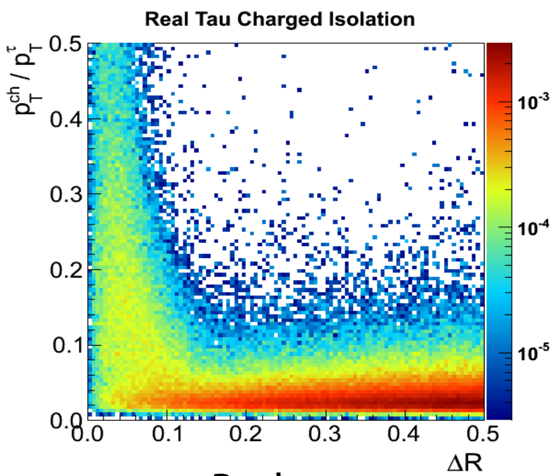
Tau identification

- **Reconstruct individual decay modes**
- **Charged hadrons + electromagnetic obj**
- EM strips account for material effects

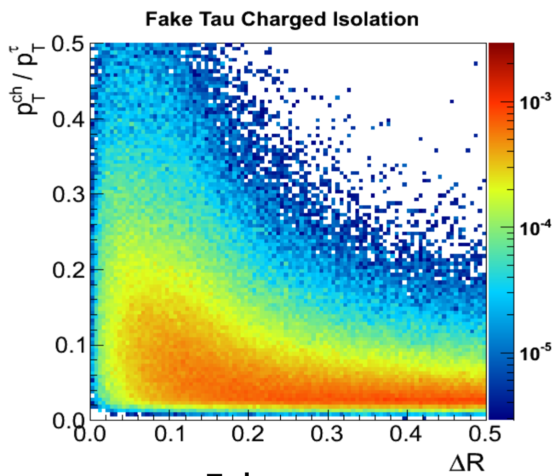


Tau isolation

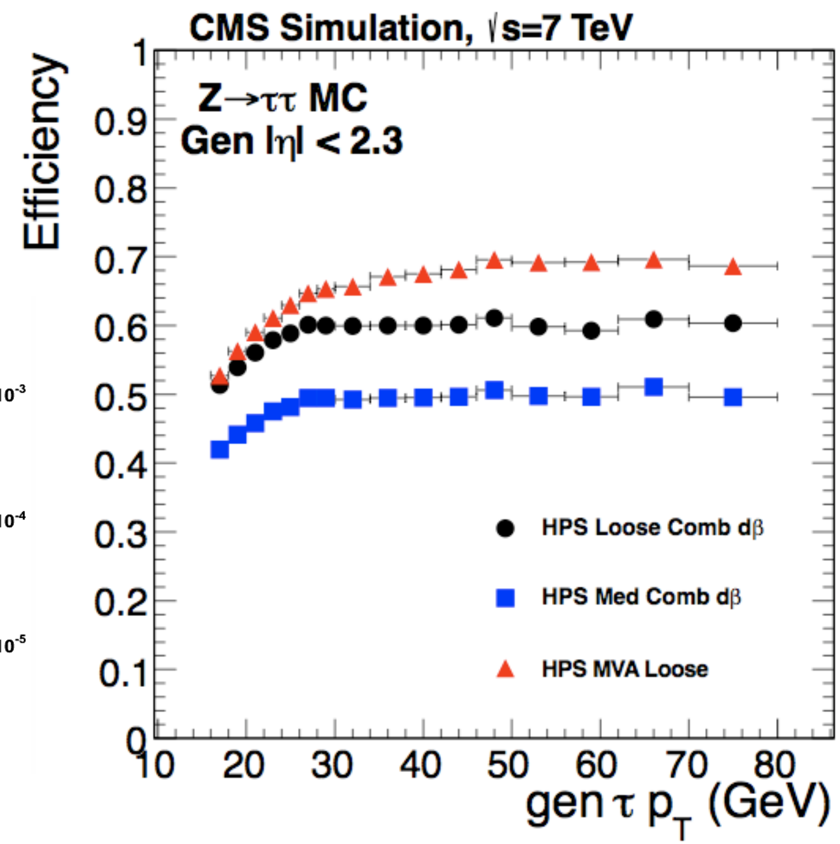
- **Multivariate discriminator using sum of energy deposits in dR rings around the tau**



Real taus



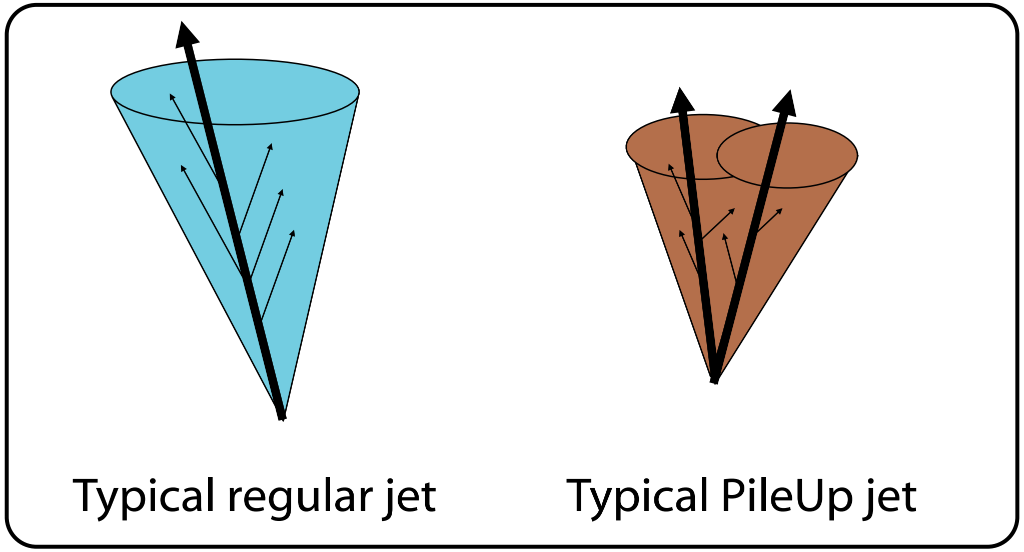
Fakes taus

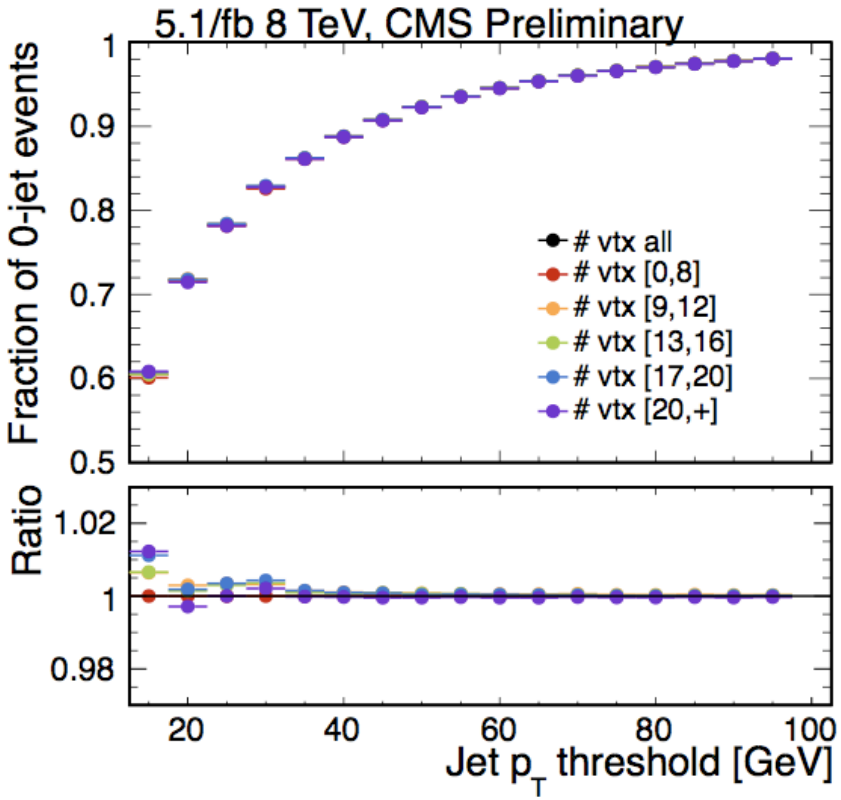


Jets

Jet reconstruction

Reconstruction with particle flow objects





Pileup jets structure differs w.r.t. regular jets:

- **Pileup jets originate from several overlapping jets which merge together**
- **Likelihood grows rapidly with high pileup**

Discriminant exploits shape and tracking variables

- **Discrimination both inside and outside tracker acceptance**

Photon Selection: MVA ID

Photon pre-selection

$E_{T\gamma 1}/m_{\gamma\gamma}>3$ and $E_{T\gamma 2}/m_{\gamma\gamma}>4$

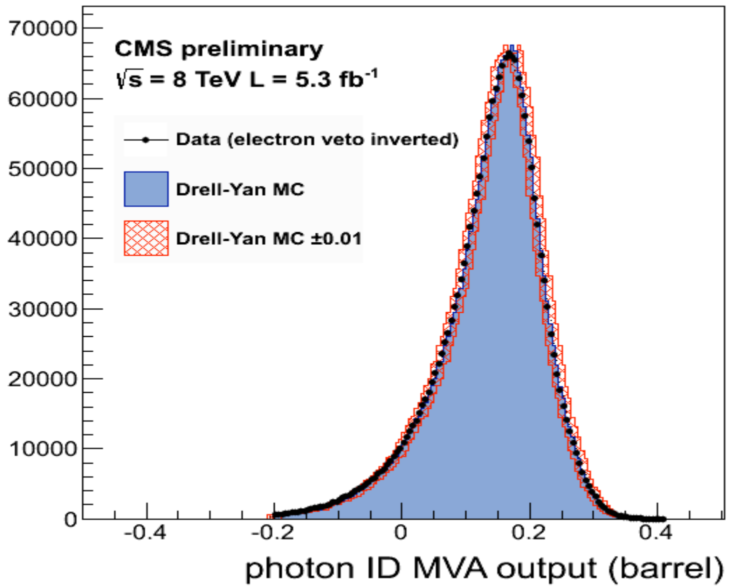
Photon ID to separate prompt photons from π^0 emerged from jets→photon ID **MVA based**

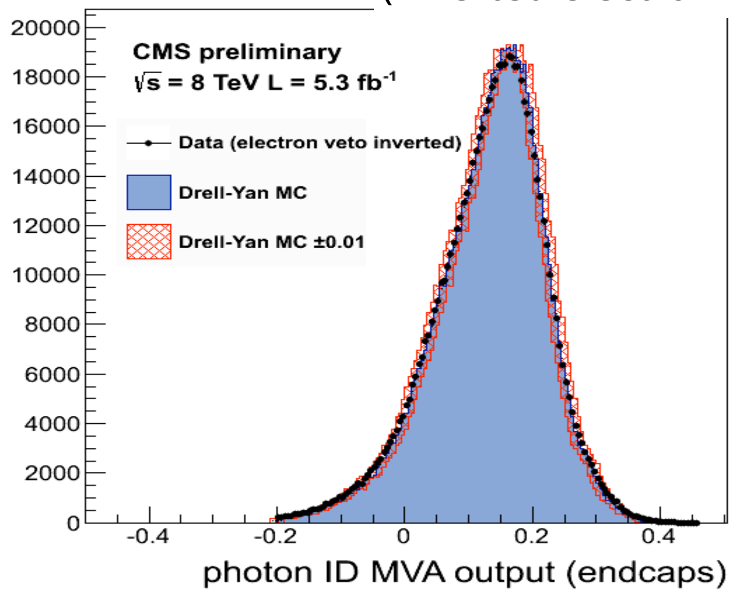
Inputs variables: isolation, shower shape, pre- shower energy, per event energy density, and pseudorapidity

Efficiency measured

using tag and probe with Z→ee
using tag and probe with Z→μμγ

Validation with Z→ee (inverted electron veto)





H → γγ

The γγ vertex choice

$m_{\gamma\gamma}$ depends on the correct position of the primary vertex

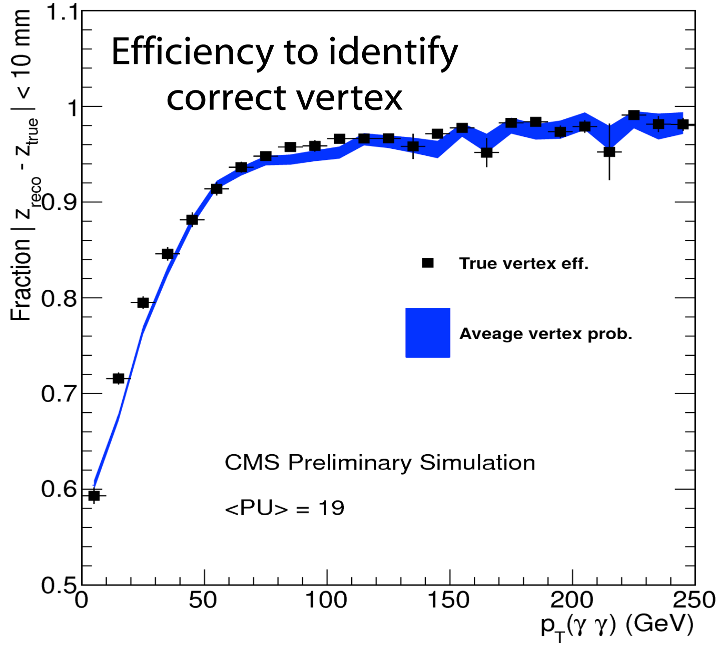
Interaction vertex is identified using tracks from recoiling jets and underlying event plus conversions

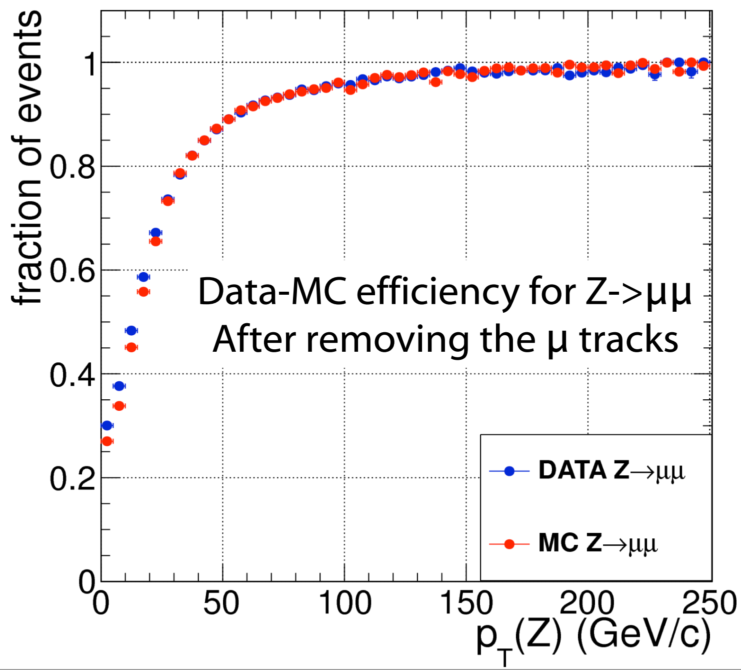
- **Correct in ~83% of cases for pileup in 2011 sample**
- **Correct in ~80% of cases for pileup in 2012 sample**

Vertex identification with a MVA Boosted Decision Tree

- **Input variables: Σp_t^2, Σp_t projected onto the γγ transverse direction, p_t asymmetry, and conversions**

Correct vertex finding probability also estimated using a BDT





H → γγ

Fermiophobic Higgs

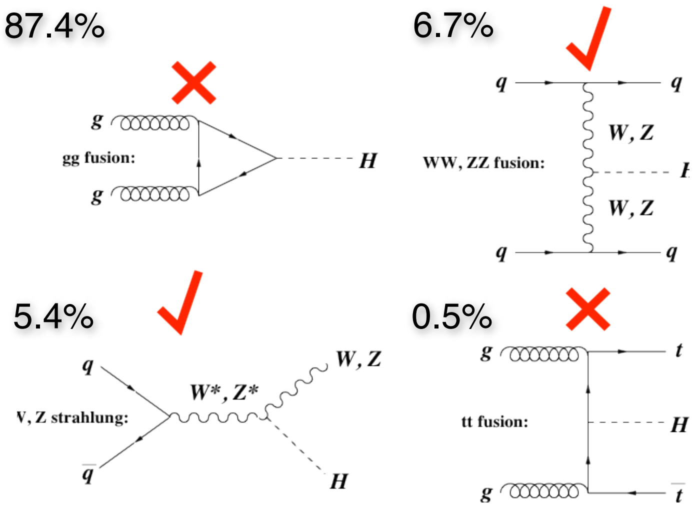
No couplings to fermions

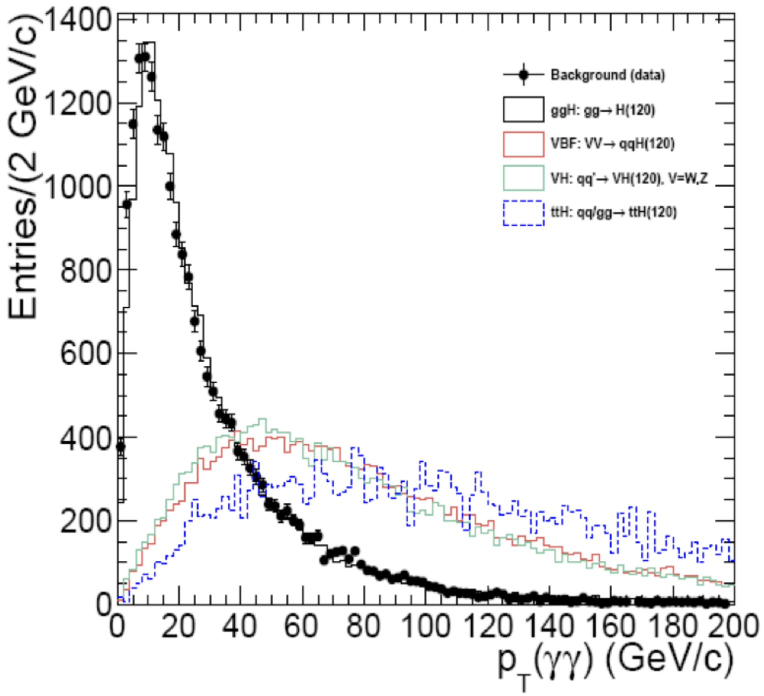
VBF or associated VH production only

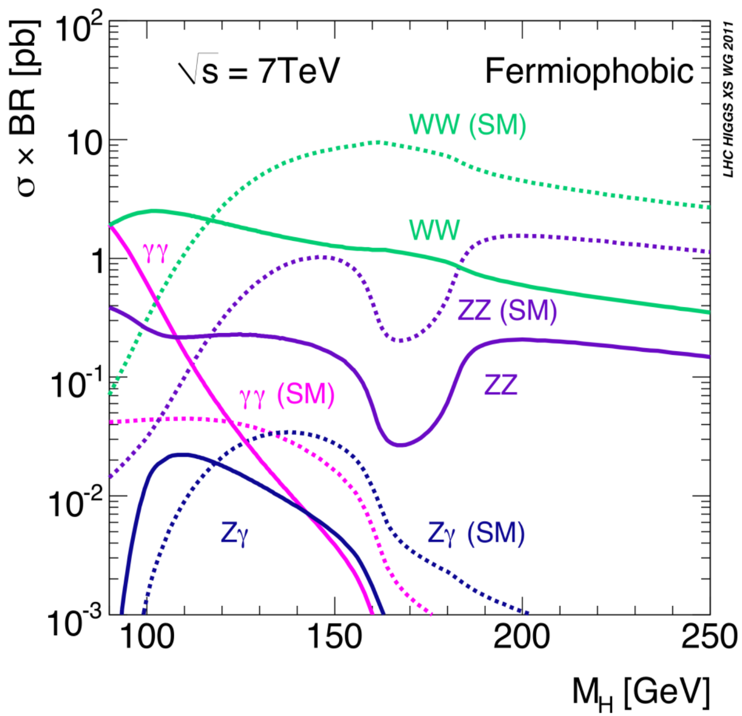
Low mass Higgs decays change dramatically

Higgs is boosted

presence of two tag jets in forward region or associate W and Z







Beyond SM Higgs

MSSM Higgs

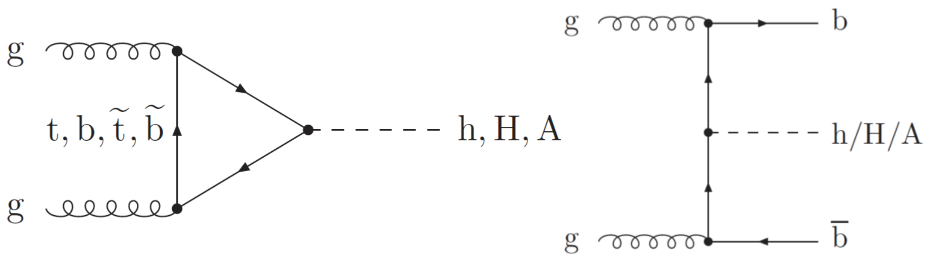
Two Higgs doublets 5 Higgs particles

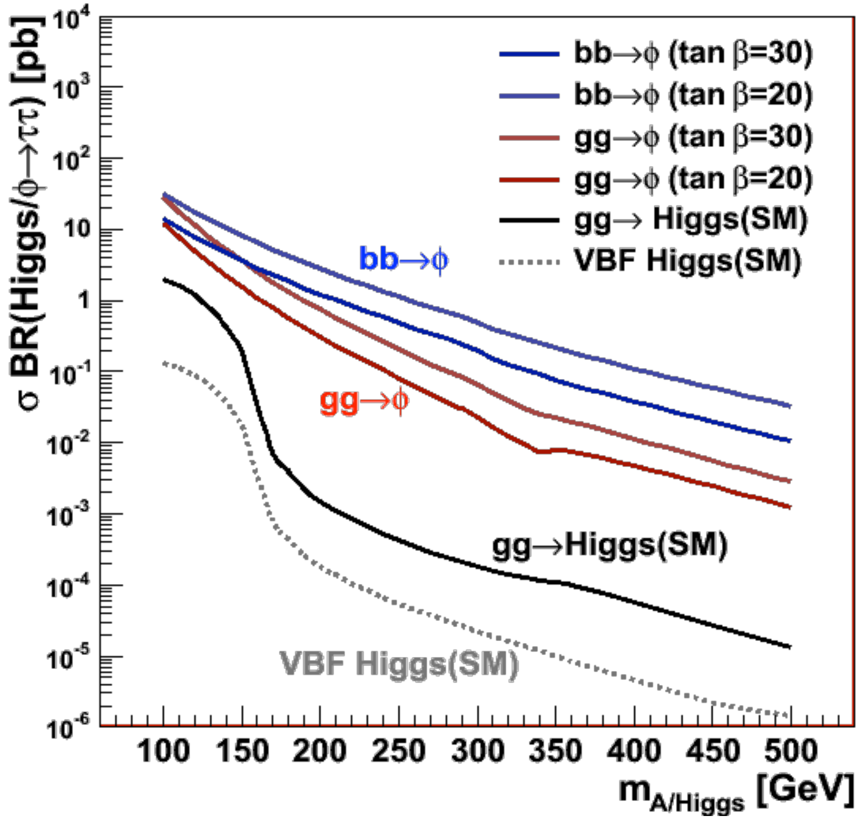
Three neutral (Φ = h, H, A)

Two charged ($H^{\pm}$)

Two free parameters

Search in m_A – tanβ plane





Production via gluon fusion (b, t loops) and associated b-quark annihilation

Enhanced coupling to b-quarks and τ-leptons (production rate enhanced × $\tan^2\beta$)

b-associated production becomes dominant

CMS searches in decays into b-bbar (90%), ττ (10%), μμ (0.04%)

Beyond SM Higgs

Projections: Significance, Signal strength