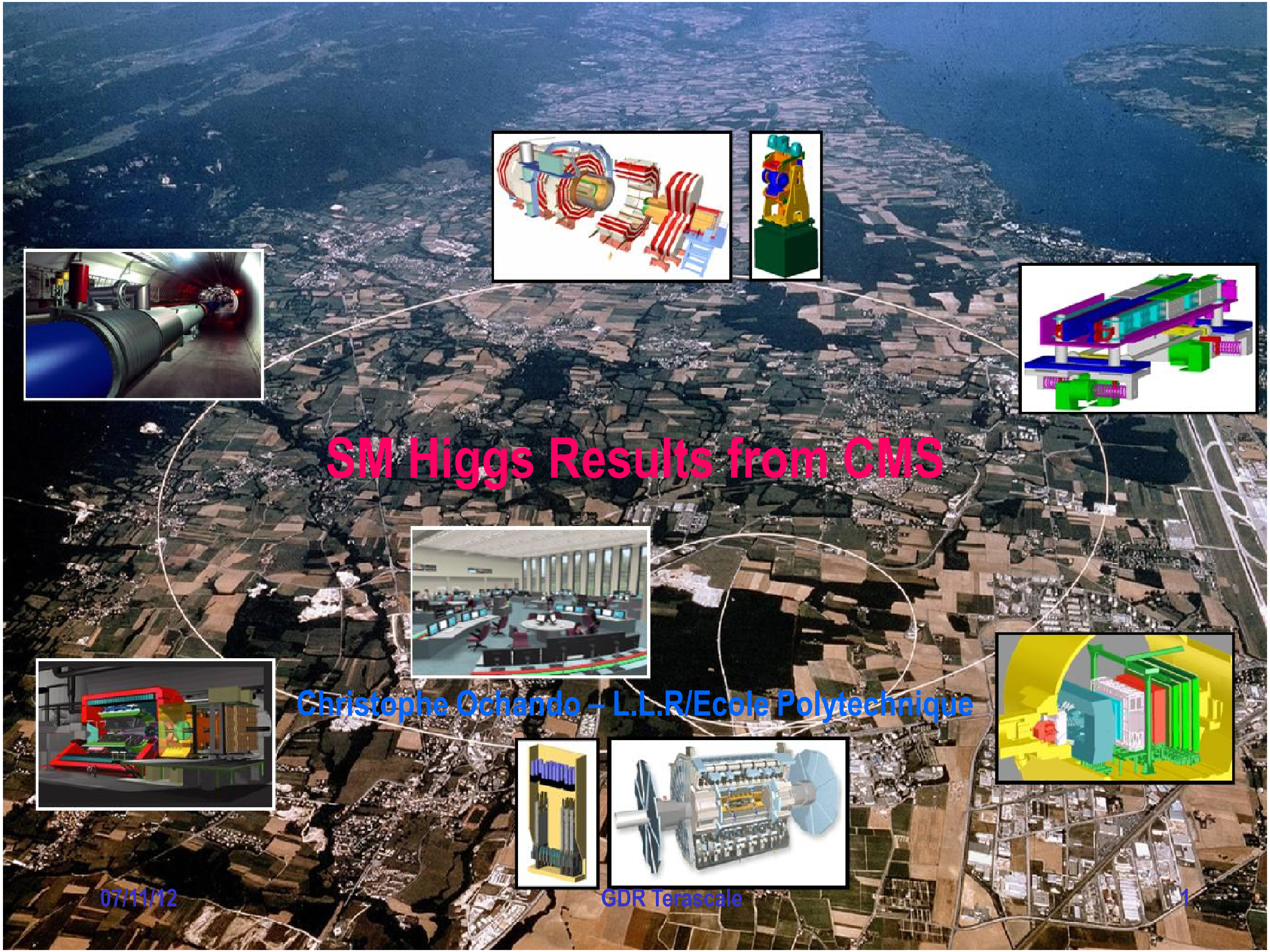
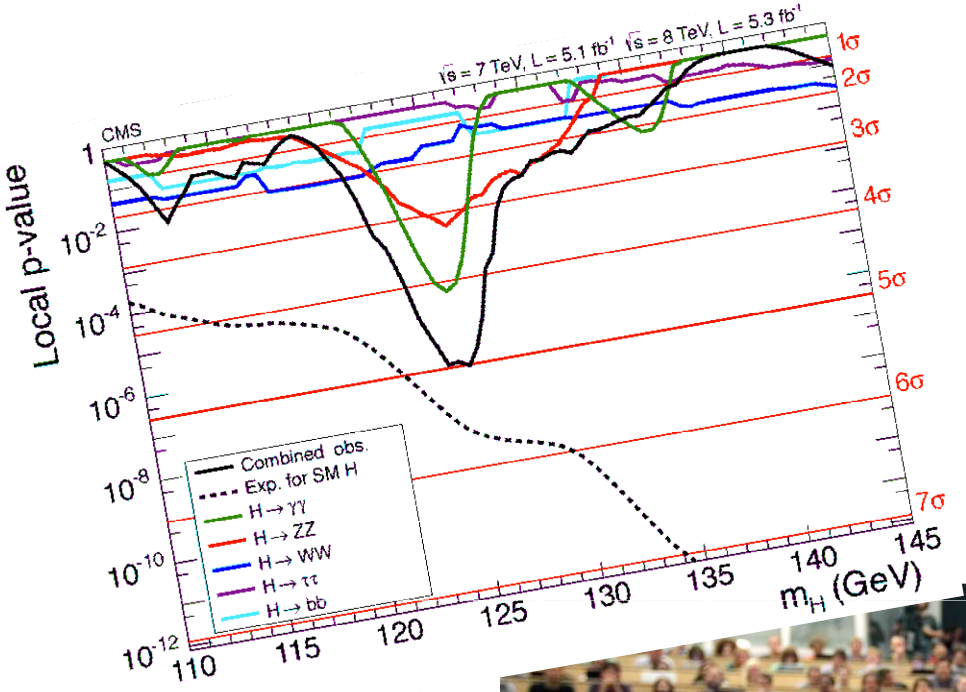
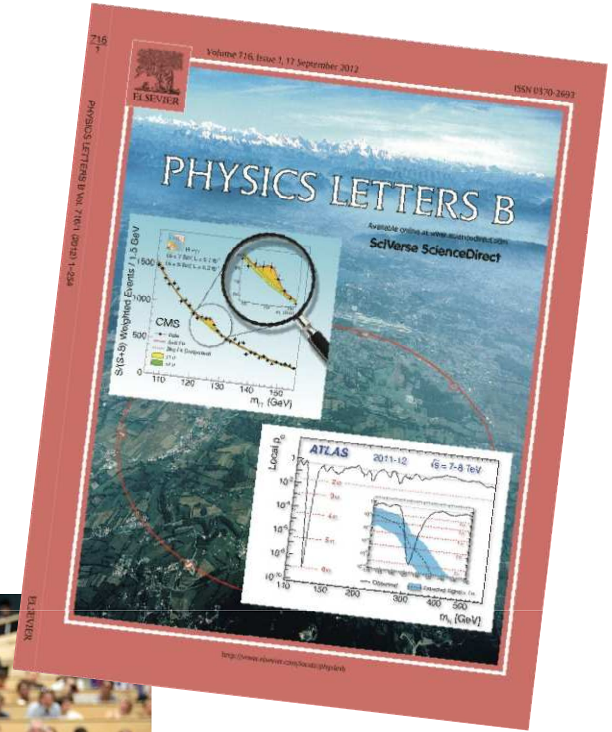


SM Higgs Results from CMS

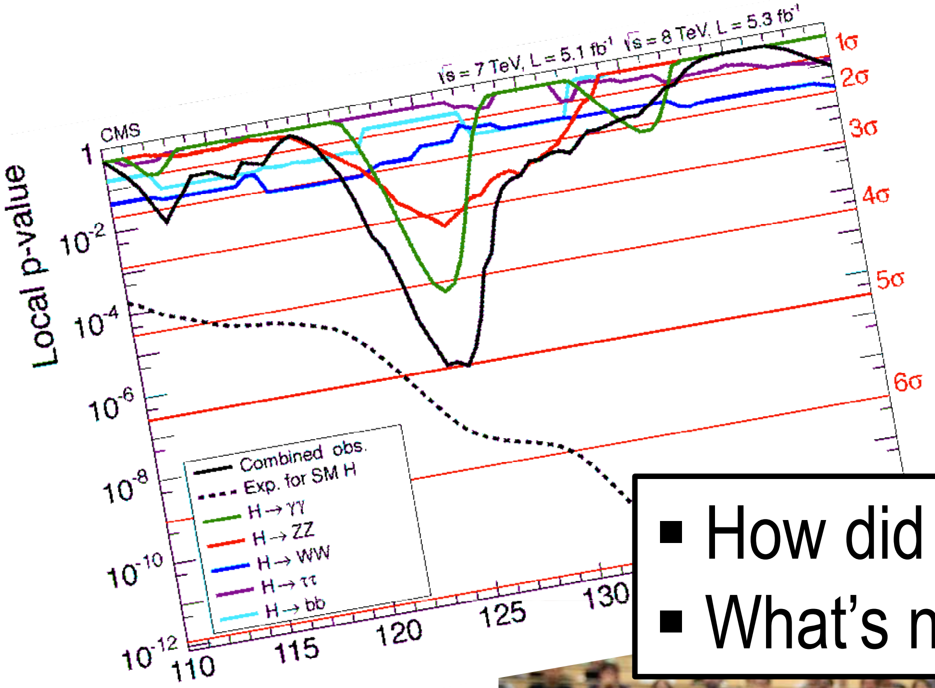
Christophe Ochando – L.L.R/Ecole Polytechnique

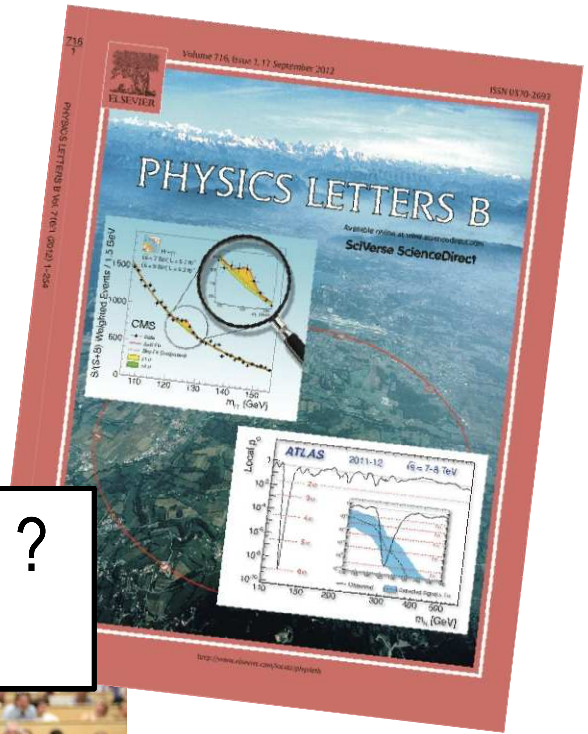
July 4th Discovery…





July 4th Discovery…

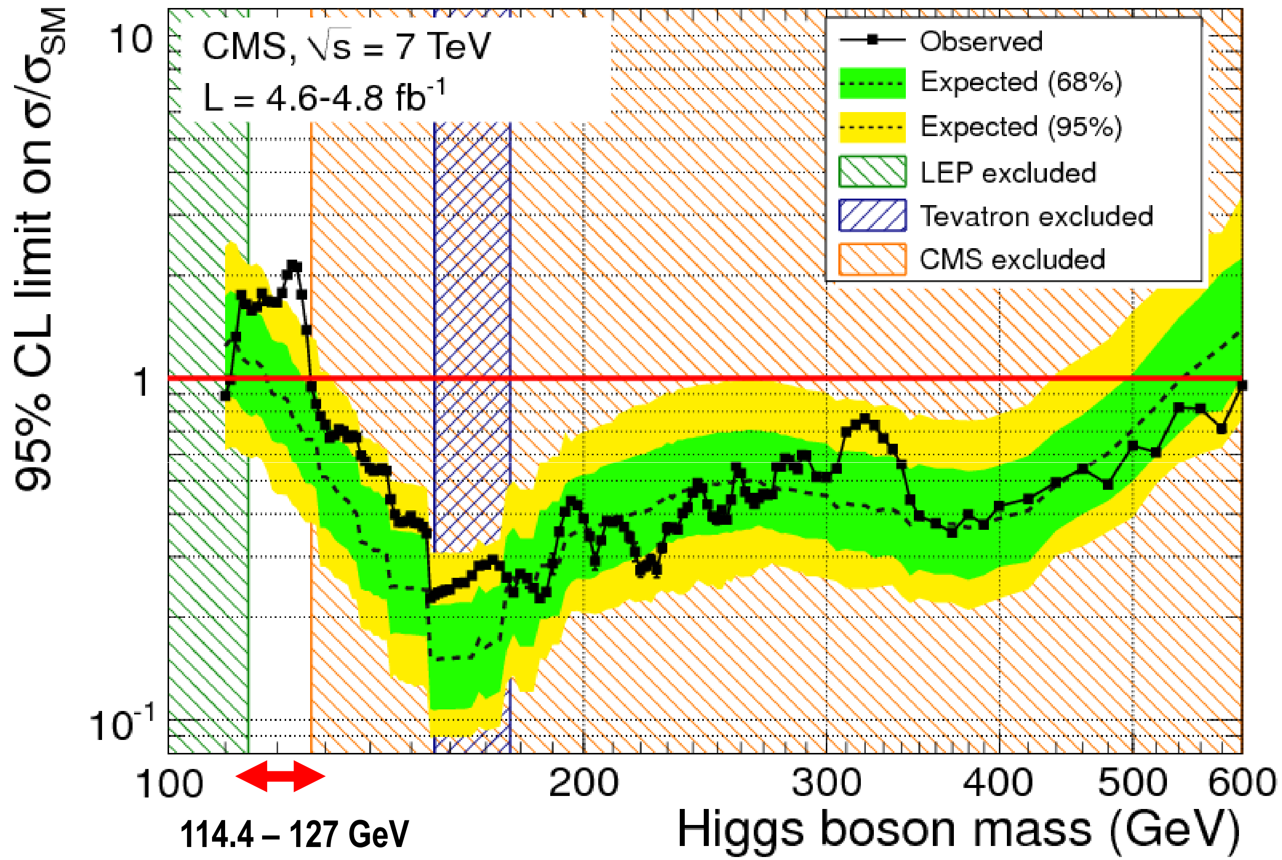




- How did we get there ?
- What's next ?

Let's go back in time…

- Full 2011 dataset (7 TeV)

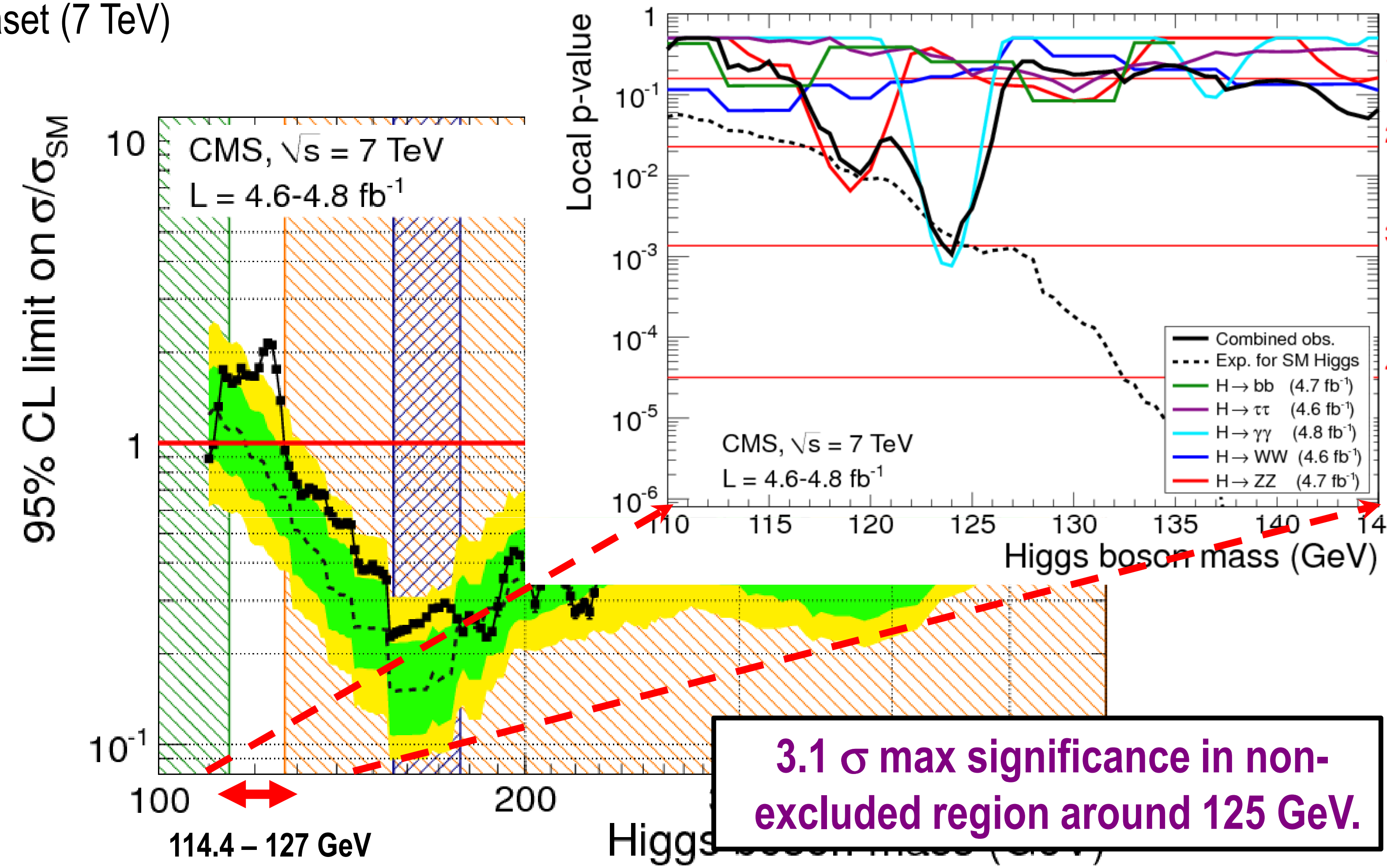


Allowed mH range for the SM Higgs boson

CMS HIG-11-032 (December 2011) … PLB710 (2012) 26-48.

Let's go back in time…

- Full 2011 dataset (7 TeV)



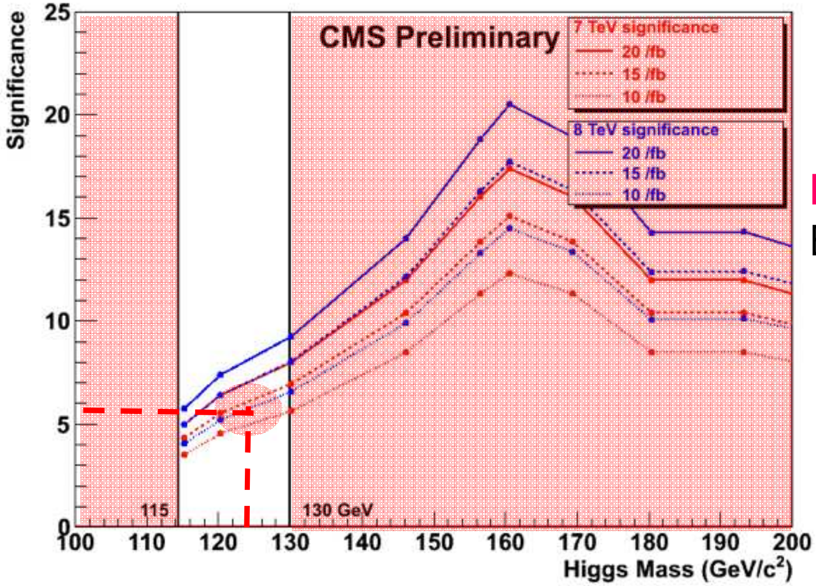
Allowed mH range for the SM Higgs boson

CMS HIG-11-032 (December 2011) … PLB710 (2012) 26-48.

From December'11 to July'12

- LHC conditions:
  - $\sqrt{s}$: 7 $\rightarrow$ 8 TeV,
  - <n PU>: 9 $\rightarrow$ 19.
- Re-optimize all analyses.
  - improvements from object reconstruction & selection performances, PU treatment, etc…
- Signal region fully **blind** (re-inforcement of existing procedure).

CMS Inputs to Chamonix Workshop (Winter 2011)

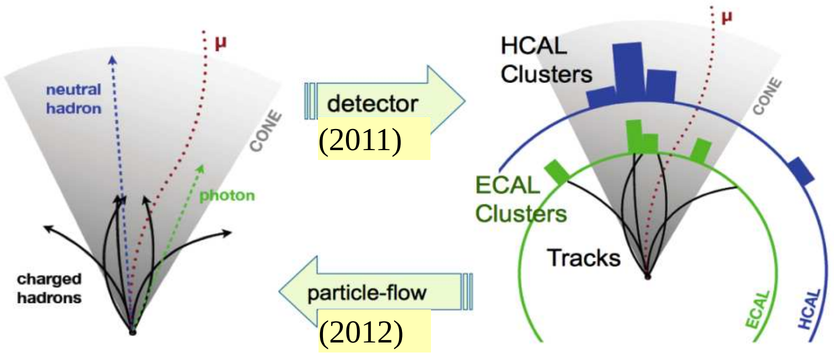


Possible discovery with an additional ~ 5 fb-1 of data !

Expect > 3σ in each the H $\rightarrow$ 2γ and H $\rightarrow$ 4 l !

Improvements: a few selected examples

Global Event Description, aka Particle Flow (PF).



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

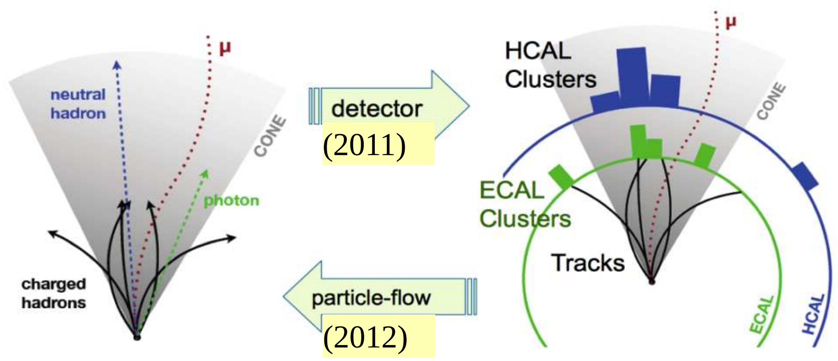
- Charged particles well separated in large tracker volume and 3.8 T magnetic field
- Excellent tracking, able to go to down to very low momenta (~100 MeV)
- Granular electromagnetic calorimeter with excellent energy resolution

Returns a list of reconstructed particles:

- e, μ, γ, charged & neutral hadrons (specialized algorithsm for e/γ)
- Inputs to build τ, jets, MET & lepton/photon isolation.

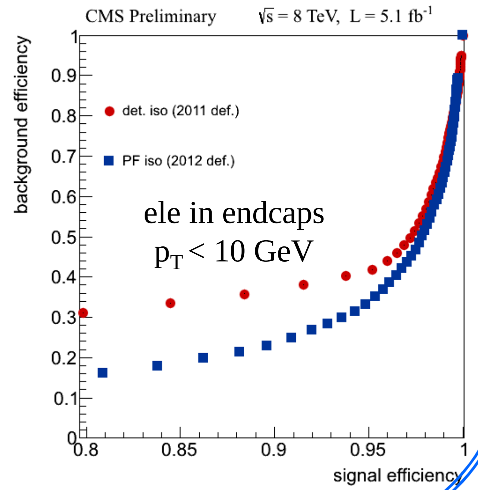
Improvements: a few selected examples

Global Event Description, aka Particle Flow (PF).



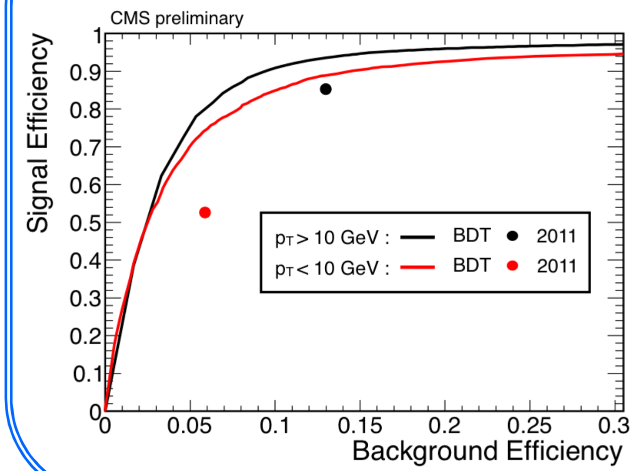
Lepton/Photon Particle-based Isolation

- Around ΔR cone of the considered particle: scalar Σ transverse momenta from other particles
- No double counting for the charges particles
- Automatic removal of overlapping leptons.



Improvements: a few selected examples

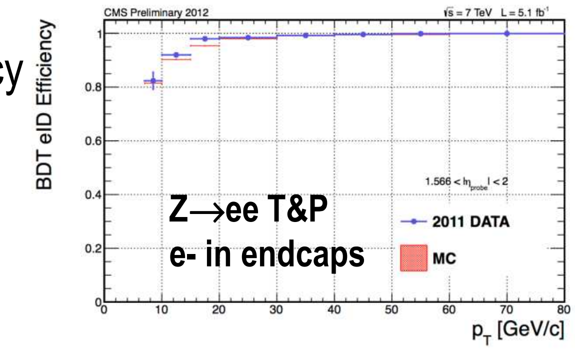
Electrons



- Cut-based eID → MVA eID(*)

(*)BDT using shower shape, track-cluster matching, brem-sensitive observables.

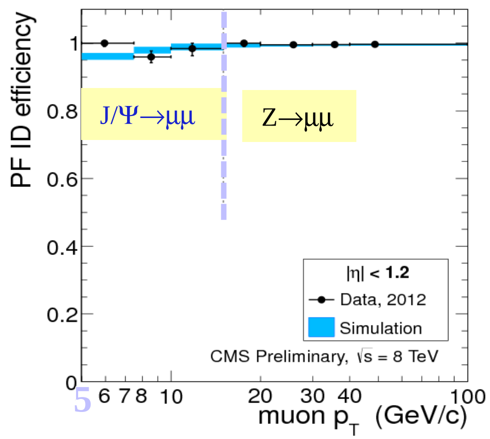
- 30% gain in H→ZZ→4l efficiency

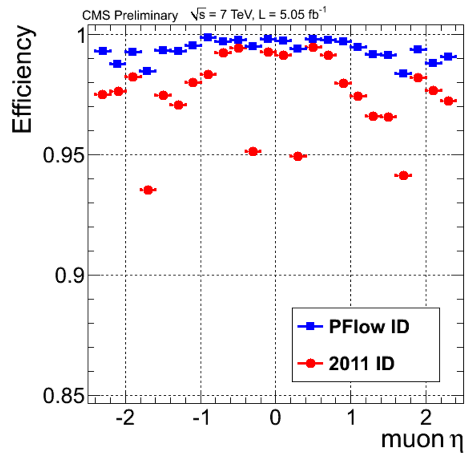


Muons

- Combinations of inner tracker tracks and muon system tracks…
- … with new Particle-Flow (PF) algorithm.

- 99% efficient.
    - 10% efficiency gain wrt 2011.

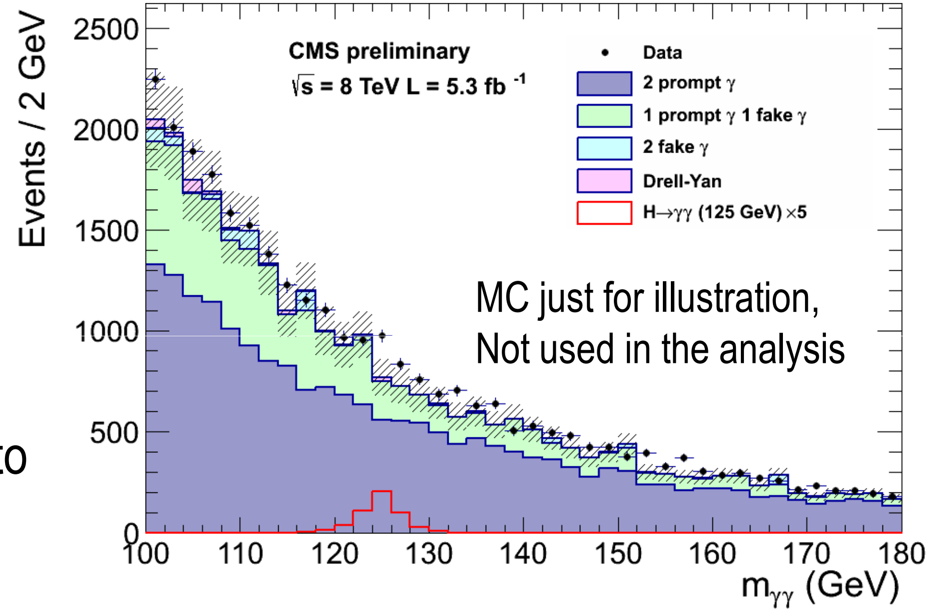




$H \to \gamma\gamma$: Overview

- **Search for a narrow mass peak from 2 isolated high E_T photons** on a smoothly falling background.

- **Analysis optimized categorizing events according to purity and mass resolution.**
  - 5 (7 TeV)/6 (8 TeV) categories, including di-jet tag targeting VBF production mode.

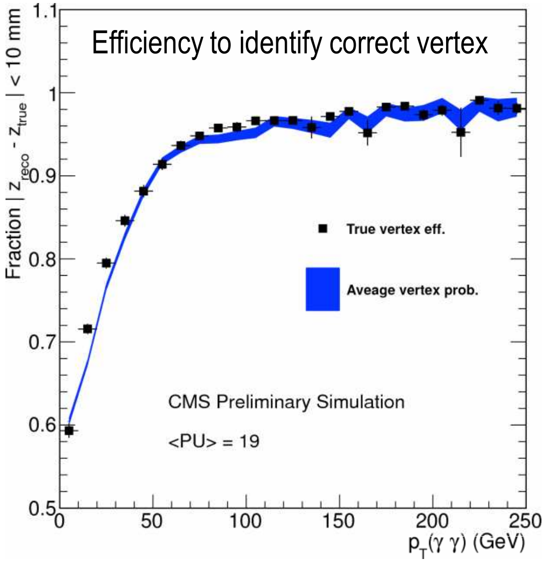


- Main Analysis makes use of **MVA technics** to identify photons, classify events and improve mass resolution.
  - Cross-check with independent cut-based analysis.

Background model derived from data.

H→γγ: Mass resolution as a key ingredient

Mass resolution: Depends on precision from ECAL energy and Photon direction

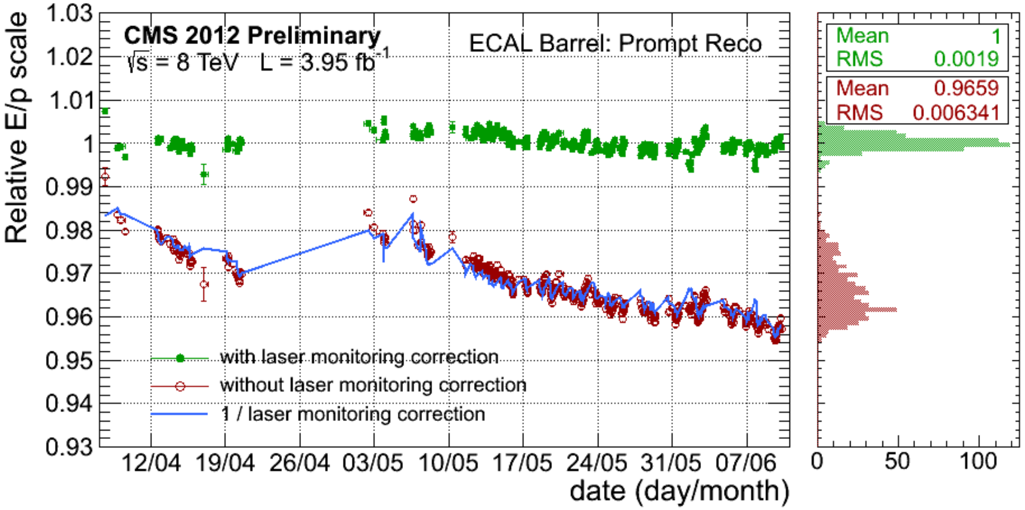


- **Vertex ID: MVA based**

Based on $\Sigma p_T^{2\,(tracks)}$, conversion information, pT balance vs di-photon system,

~80% vertex efficiency for mH=120 GeV

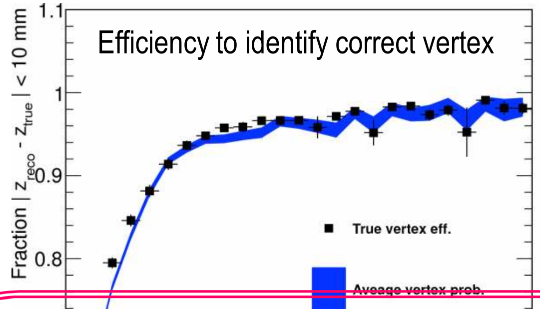
- **ECAL stability:**



- **Photon energy:**
  - Starting from raw SuperCluster Energy
  - Corrections computed from Multivariate Regression Technic
    - Inputs: shower shapes, local cluster coordinates, ….

H→γγ: Mass resolution as a key ingredient

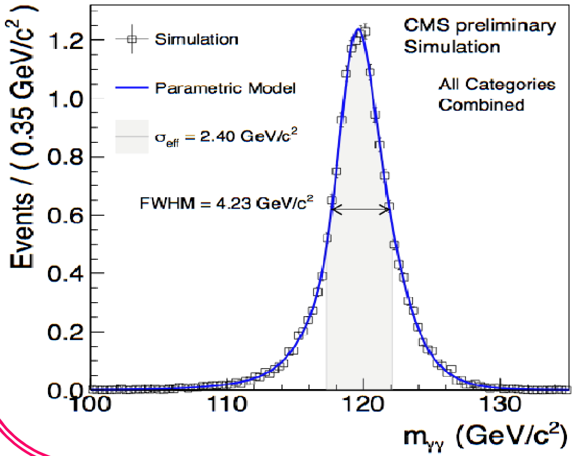
Mass resolution: Depends on precision from ECAL energy and Photon direction



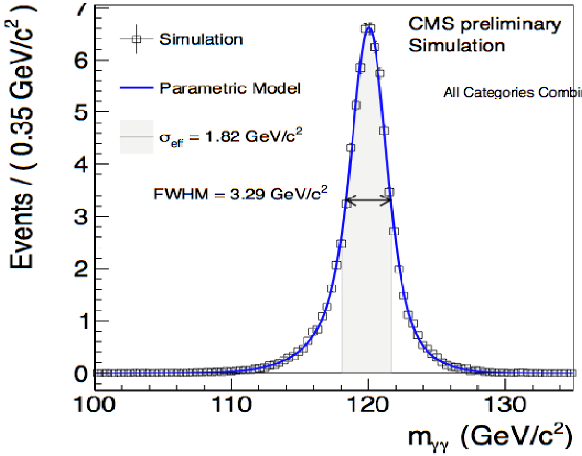
- **Vertex ID: MVA based**

Based on $\Sigma p_T^{2\ (tracks)}$, , conversion information, pT balance vs di-photon system,

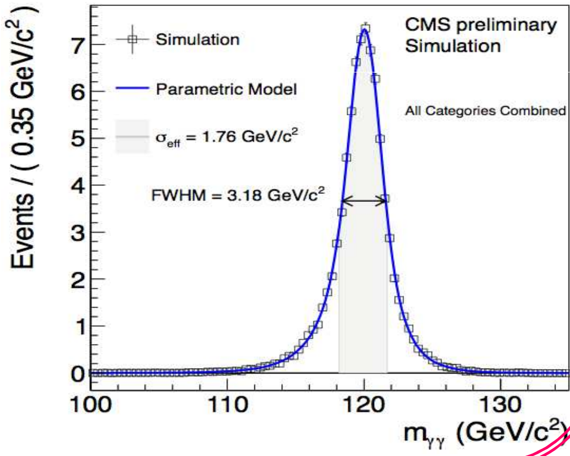
July 2011 (EPS):
FWHM = 4.23 GeV/c²

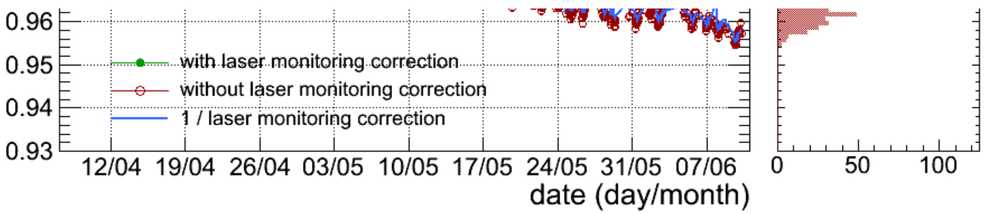


March 2011 (Moriond):
FWHM = 3.29 GeV/c²



July 2012 (ICHEP):
FWHM = 3.18 GeV/c²



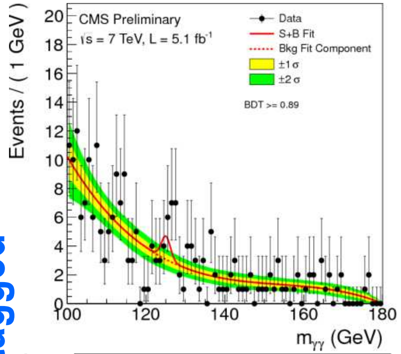


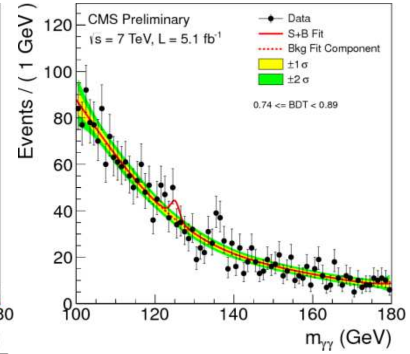
Mass spectrum in categories

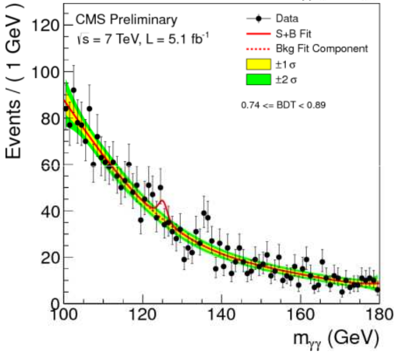
7 TeV

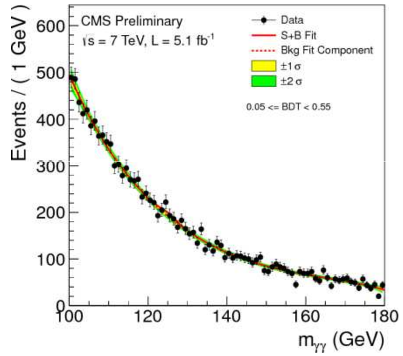
8 TeV

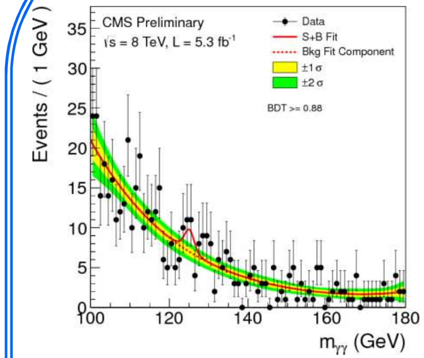
Un-tagged

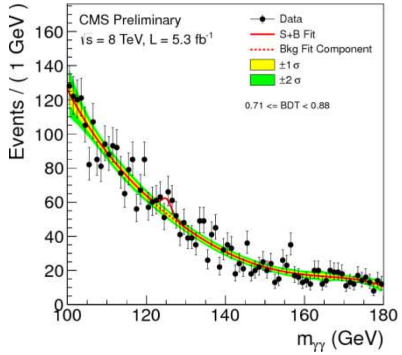


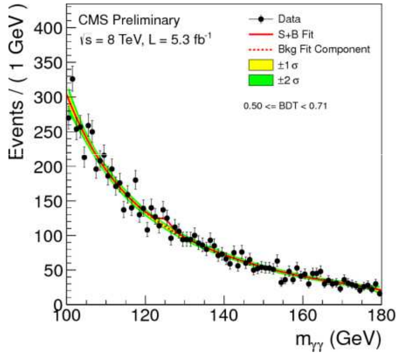


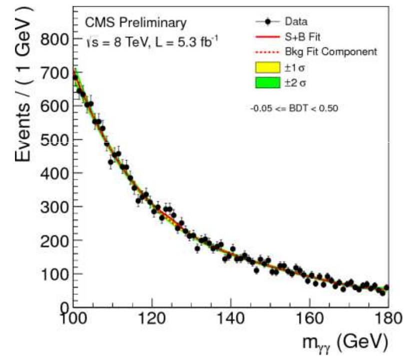




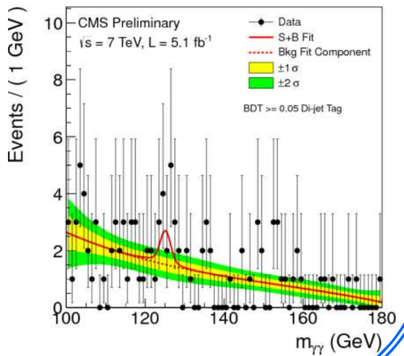


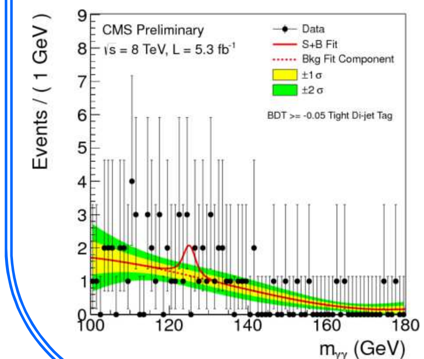


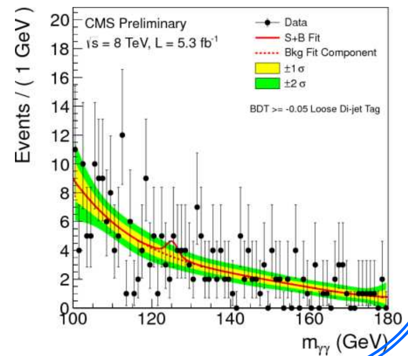




Di-jet Tagged

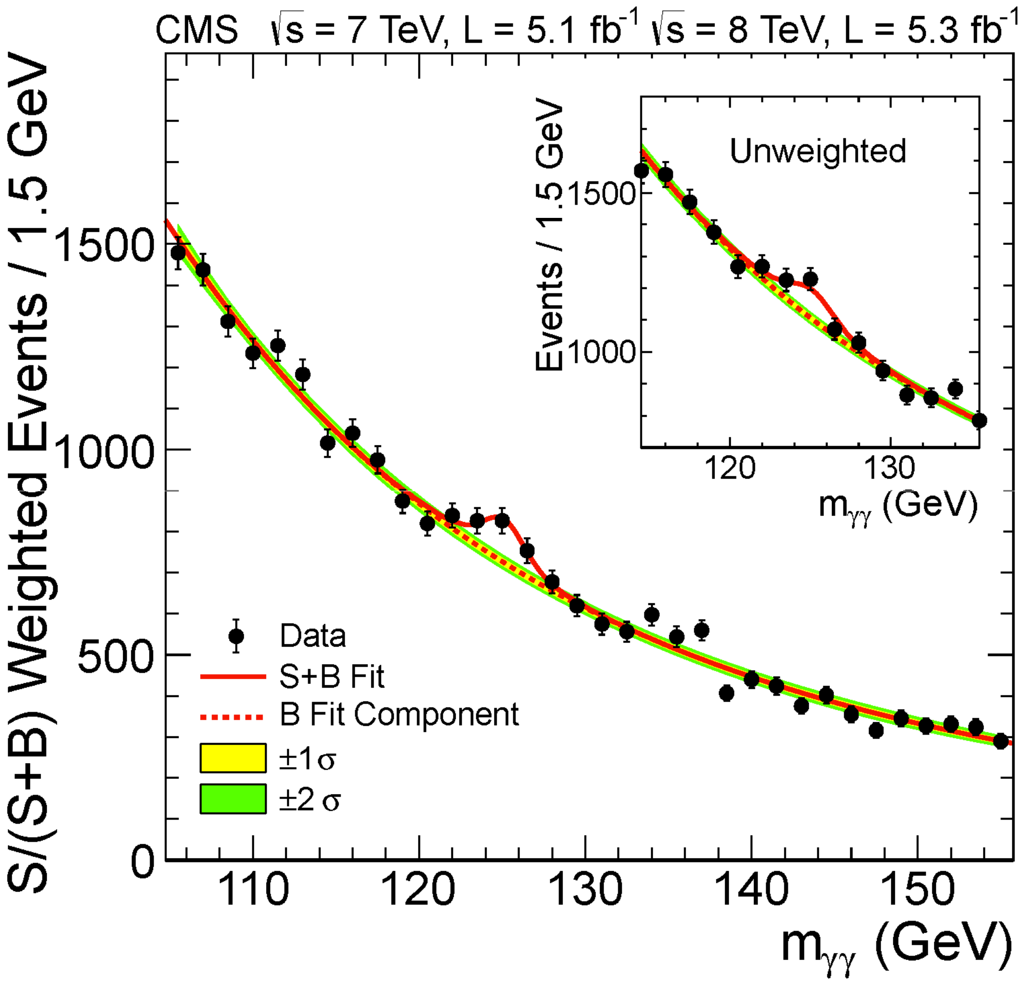






Weighted Mass distribution

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

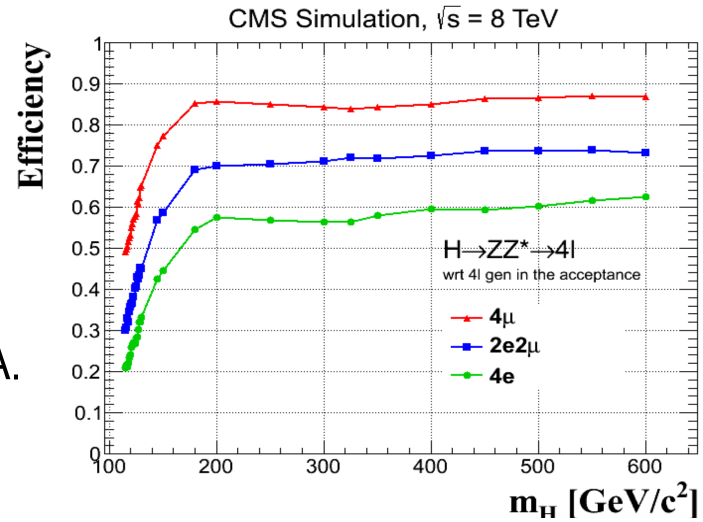


Summed plot for illustration, results obtained with simultaneous maximum-likelihood fit of all the categories

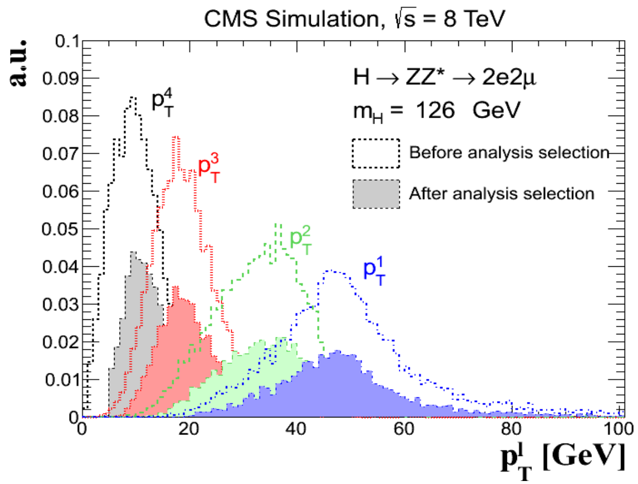
As suggested in:
R.J. Barlow, “Event Classification Using Weighting Methods”,J. Comput. Phys. 72 (1987) 202

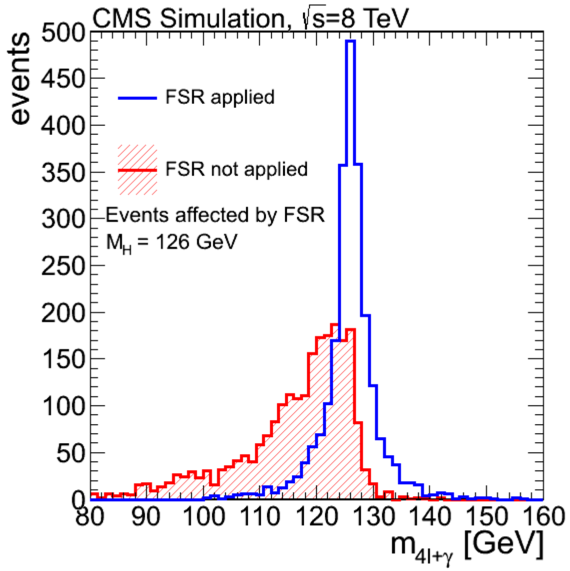
H→ZZ→4 leptons: Overview

- **Golden Channel: clean experimental signature,**
  - Narrow resonance
  - 4 primary & isolated leptons (e, mu)
  - Low background:
    - ZZ(*): from MC,
    - Reducible (Z+lf/hf jets, tt, WZ+jets): from DATA.



- **Extremly demanding channel for selection:**
  - Electrons (muons) down to 7 (5) GeV.
  - Open phase space 40: (12) <mZ1 (mZ2) <120 GeV





- **Final State Radiation (FSR) Recovery:**
  - PF photons near the leptons from Z's (down to 2 GeV, ΔR(l,γ) up to 0.5)
  - 6% of event affected, 50% efficiency, 80% purity

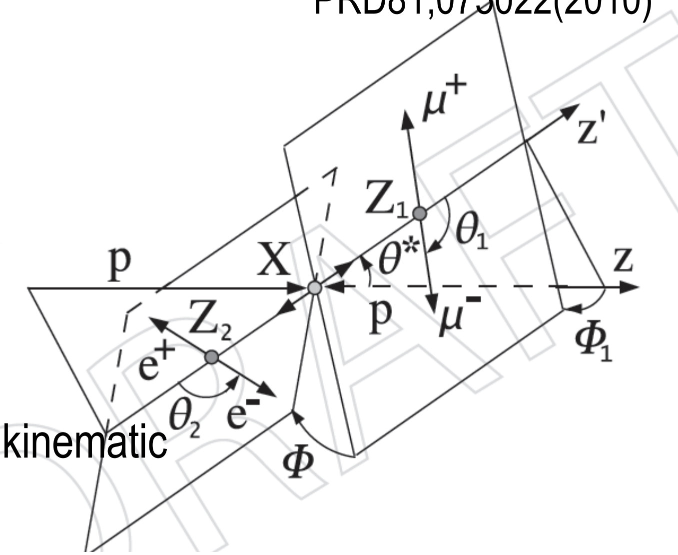
H→ZZ→4l: Kinematics

PRD81,075022(2010)

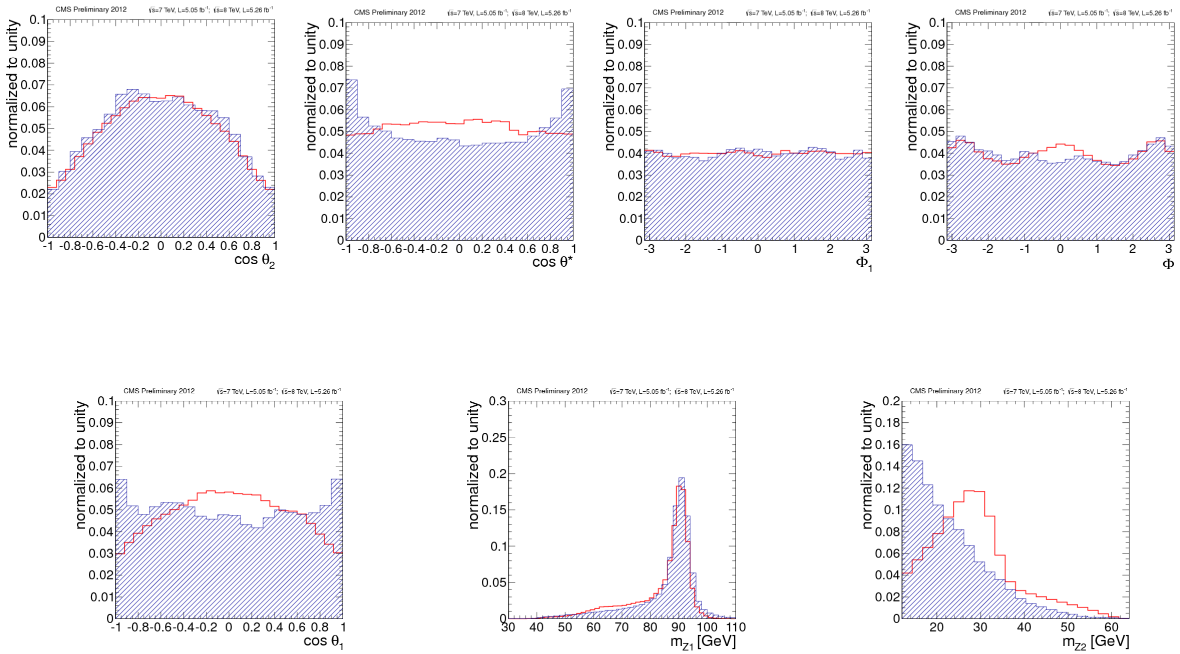
➢ Matrix Element Likelihood Approach (MELA):

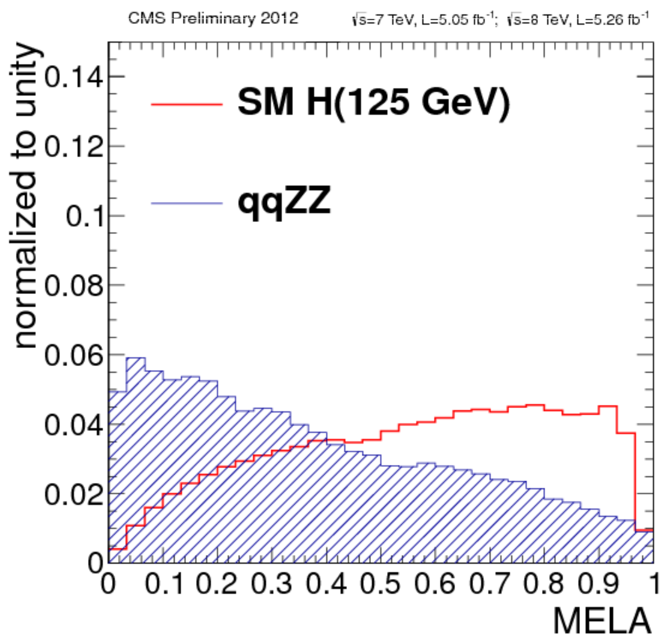
A kinematic discriminant (KD) is built based on the probability ratio of the signal and background hypothesis

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



- 5 angles and 2 masses (mZ1, mZ2) are sufficient to describe the kinematic

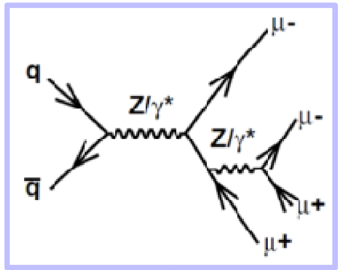


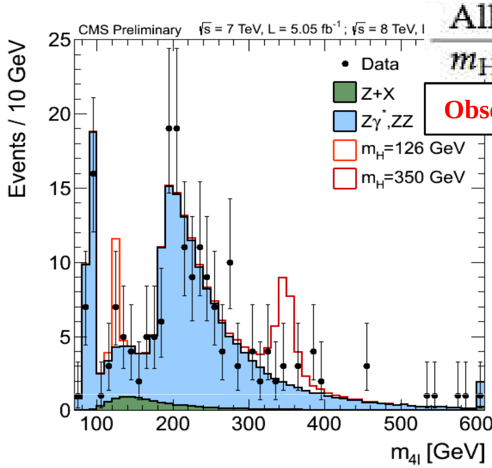


H→ZZ→4l: Mass Spectrum

Yields for m_{4l}= [110 - 160] GeV

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126\,\mathrm{GeV}$	1.51 ±0.48	2.99 ±0.60	3.81 ±0.89	8.31 ±1.18
Observed	**6**	**6**	**9**	**21**

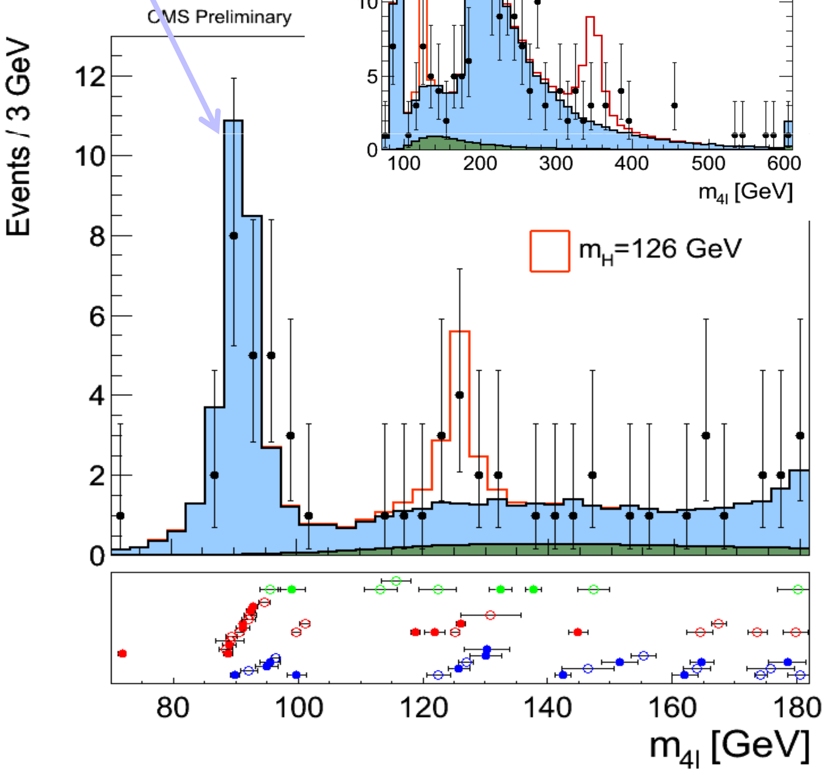


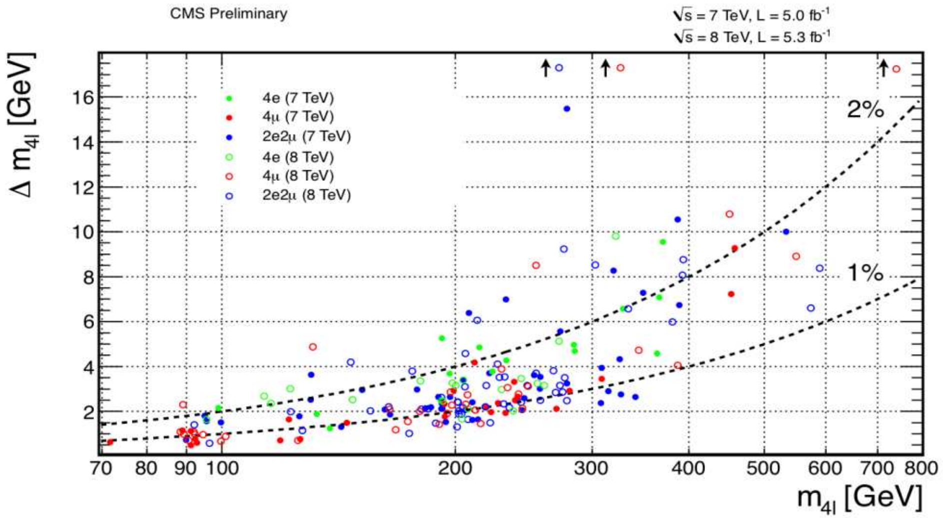


Yields for m_{4l}= [100 - 800] GeV:

expected: 164 ± 11 events

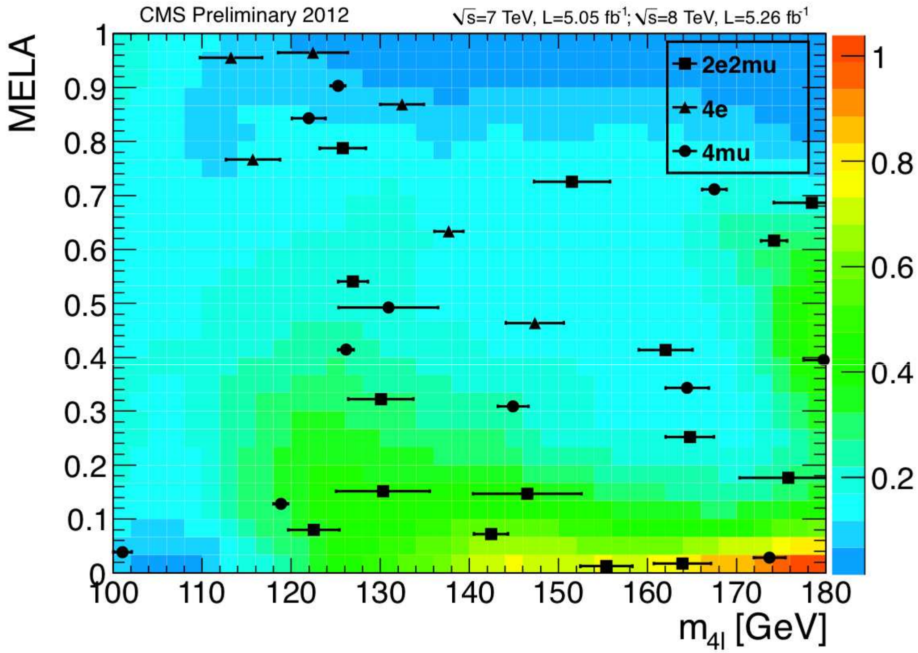
observed: 172



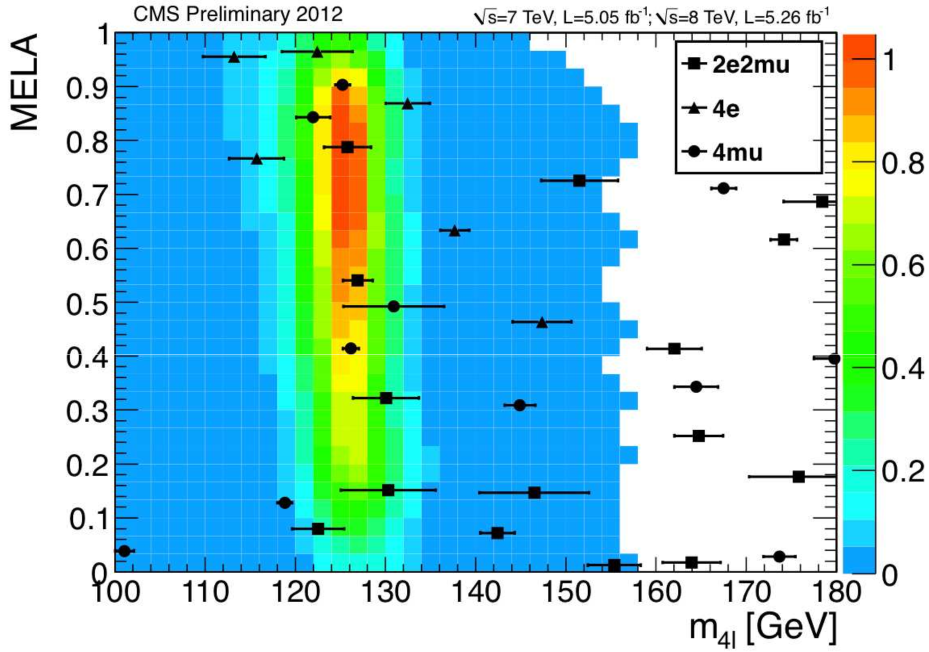


H→ZZ→4l: 2D Analysis

background



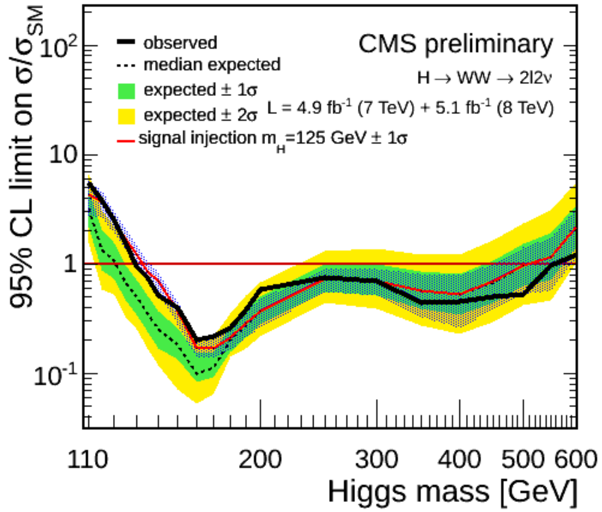
m_H = 126 GeV



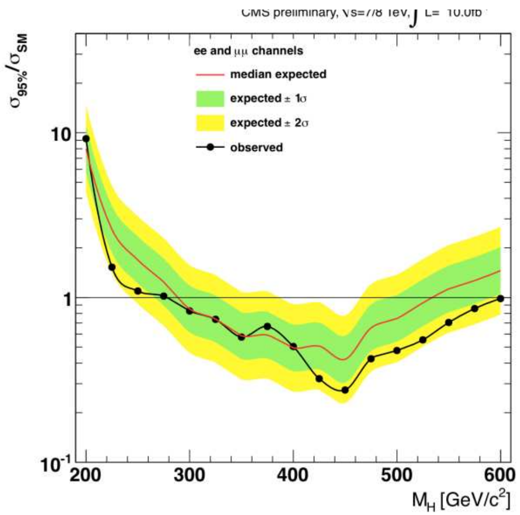
Final results extracted through 2D (m4l, KD) analysis

Other Channels

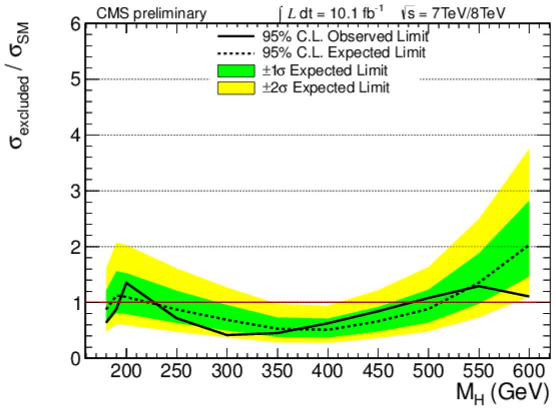
H→WW→2l2ν



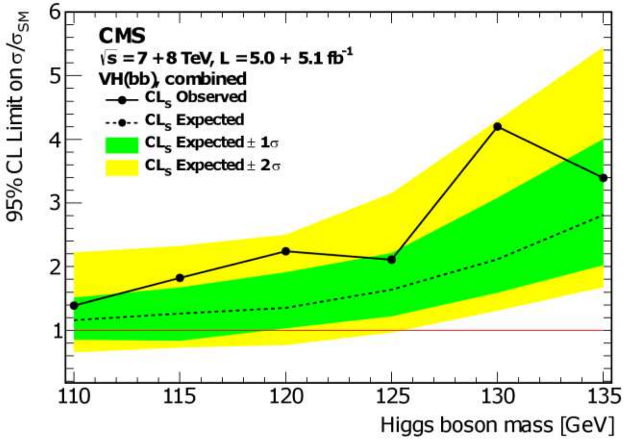
H→ZZ→2l2ν



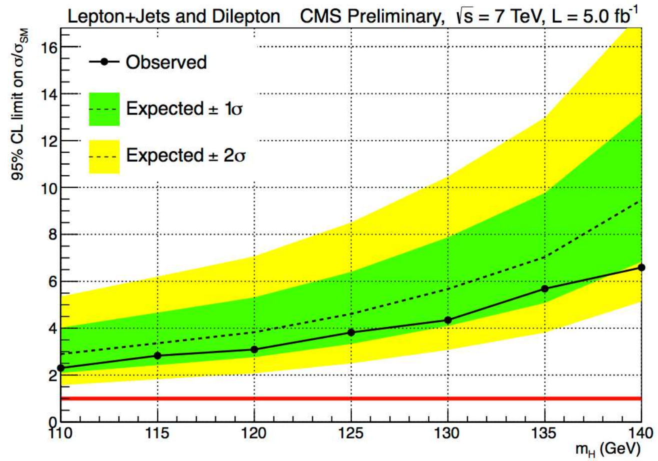
H→WW→lνjj



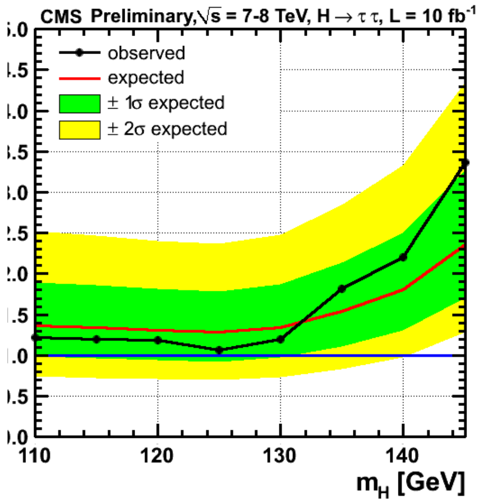
VH→bb



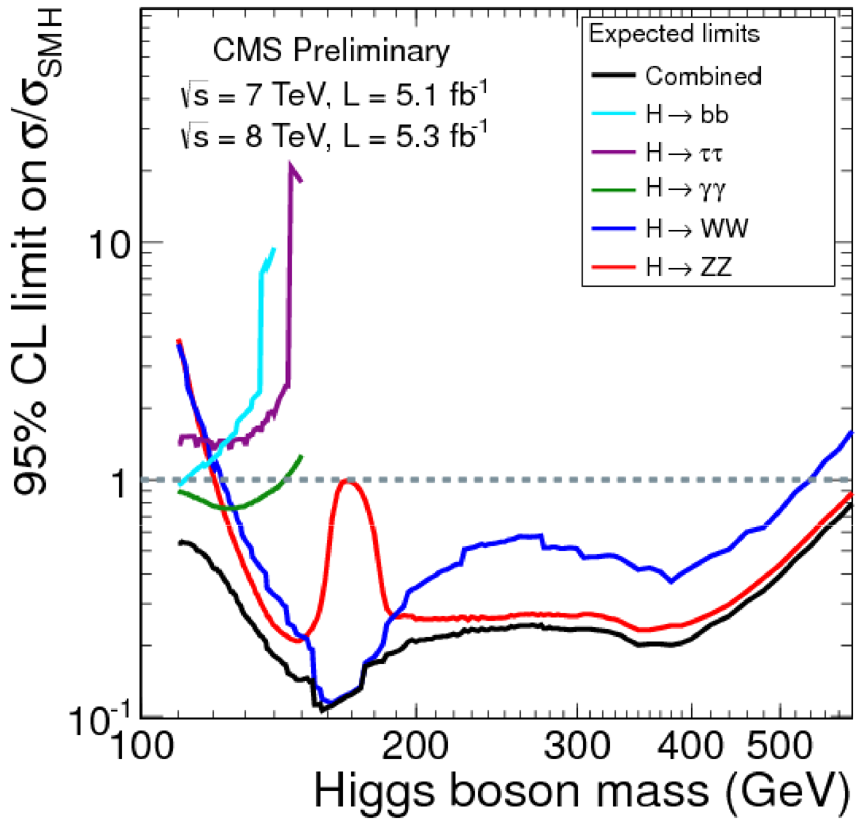
ttH(→bb)

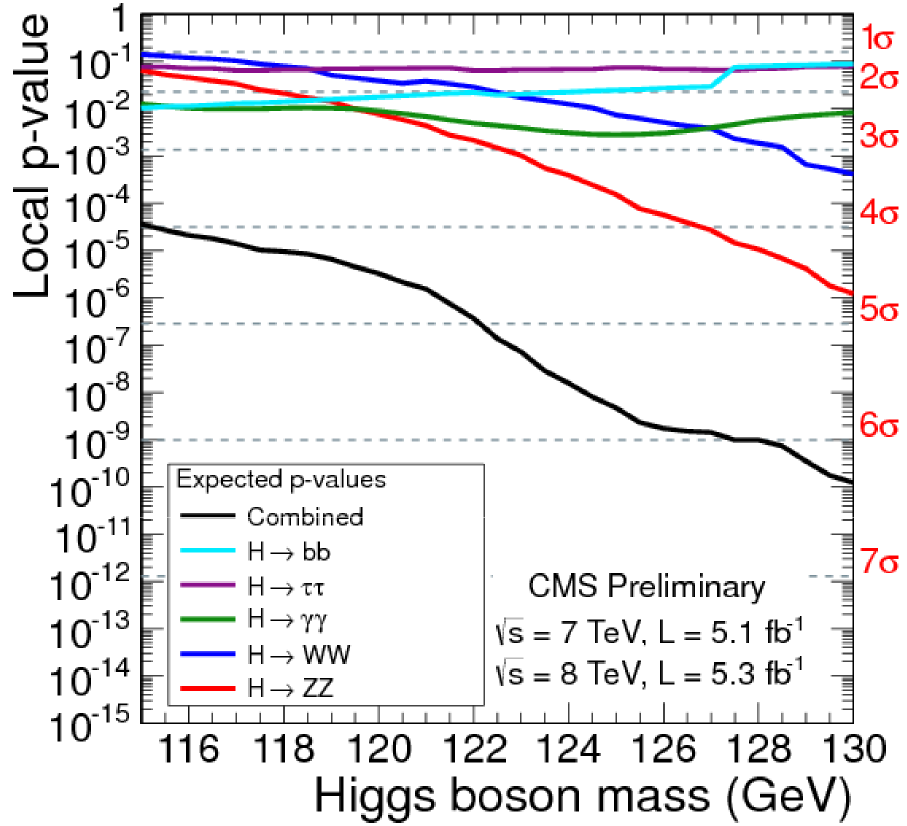


H→ττ



CMS Combination



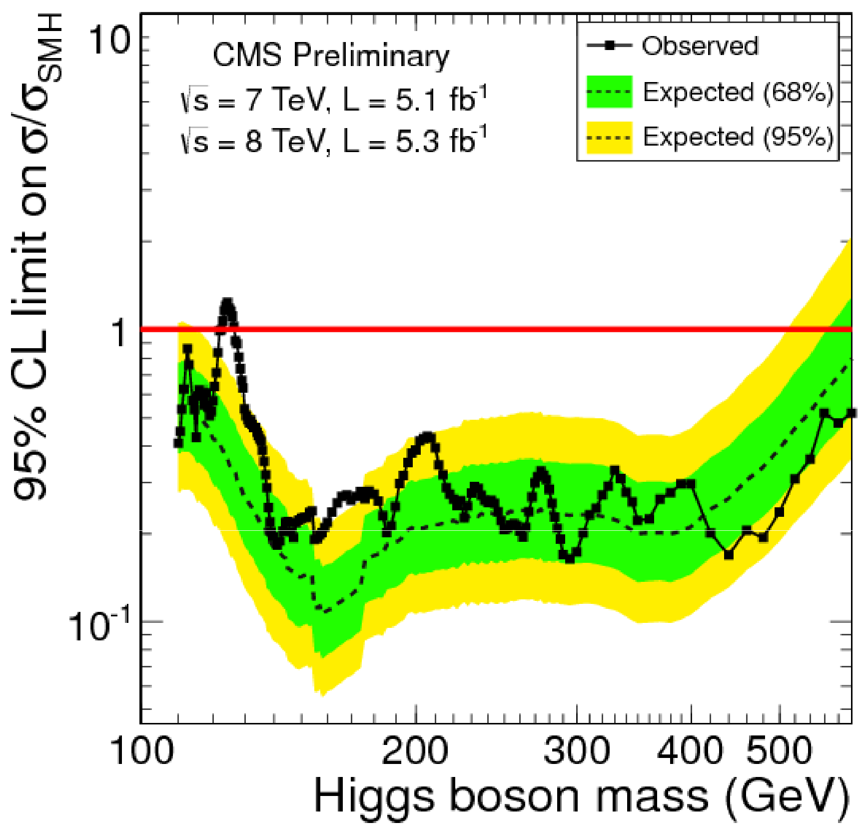


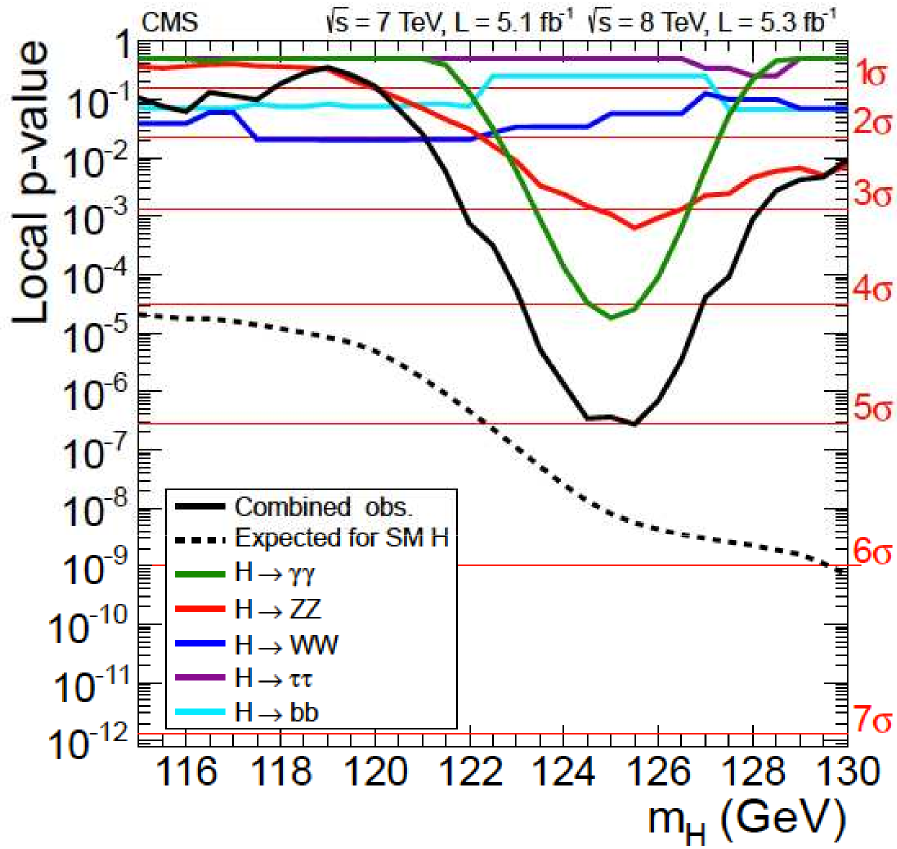
Expected exclusion over the full mass range à 95% CL

5 σ expected significance above 122 GeV (6 σ @ 125 GeV)

H→ZZ→4l channel most sensitive channel !

CMS Combination



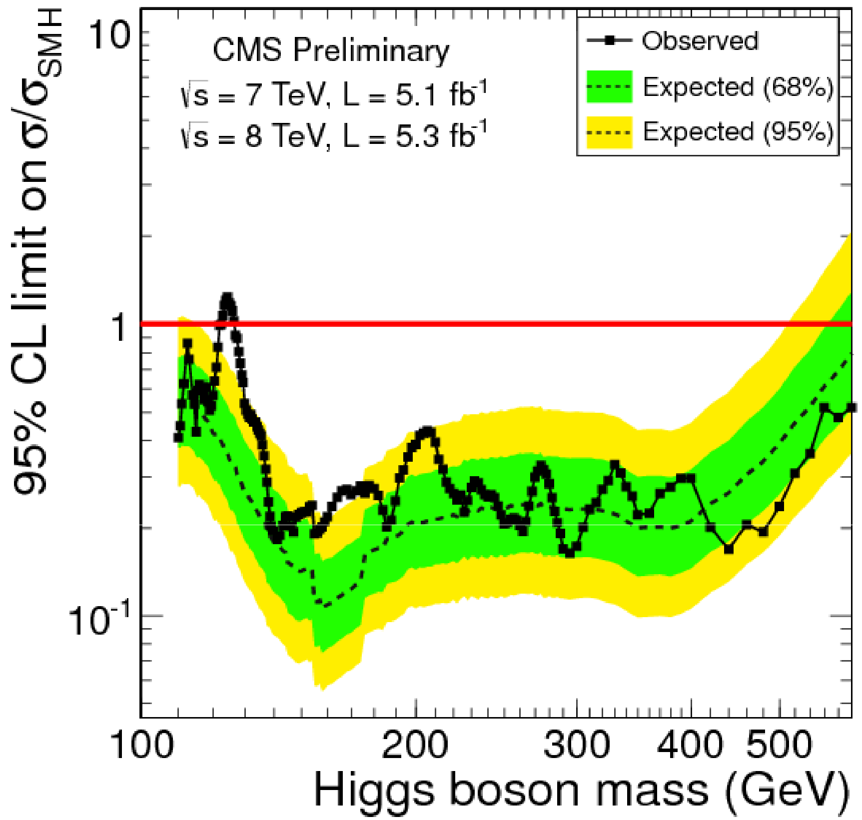


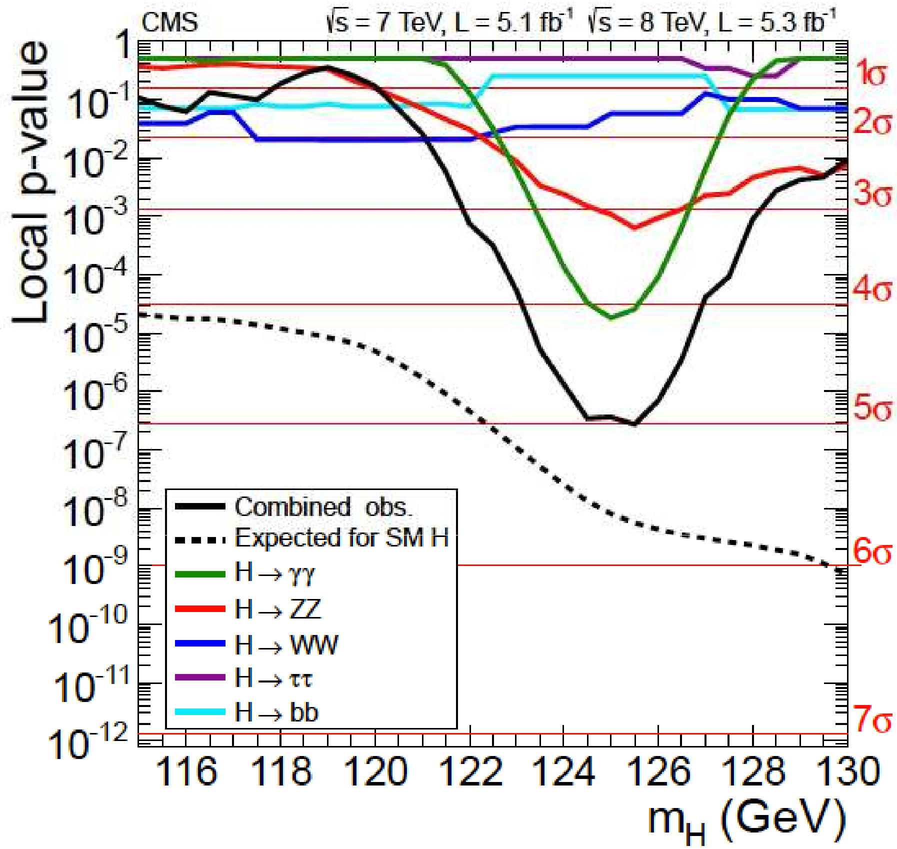
Observed Exclusion @ 95% CL:
110–122.5, 127–600 GeV

Hγγ : 4.1 σ (3.1 expected) [evidence]

HZZ: 3.2 σ (3.8 expected) [evidence]

CMS Combination



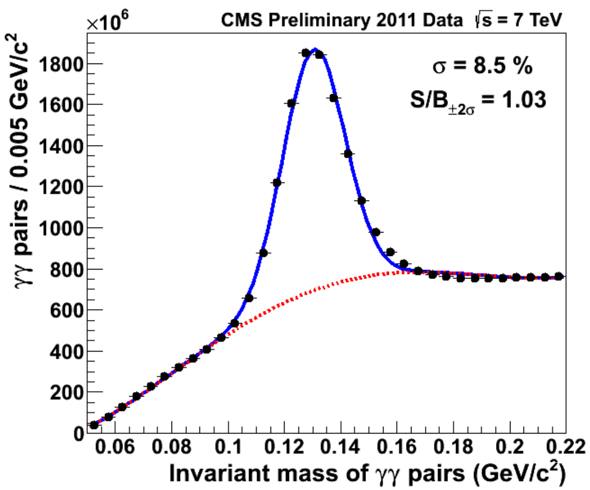


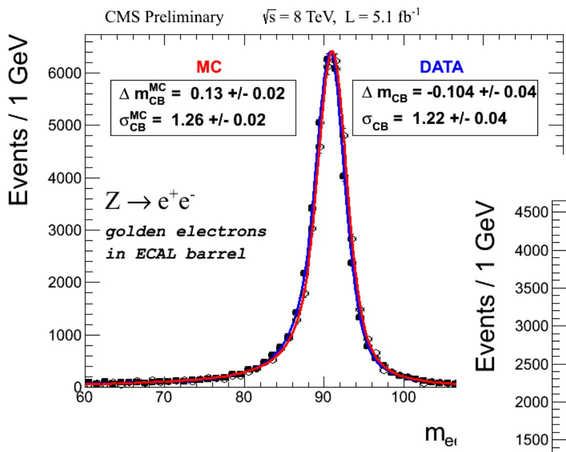
Observed Exclusion @ 95% CL:
110–122.5, 127–600 GeV

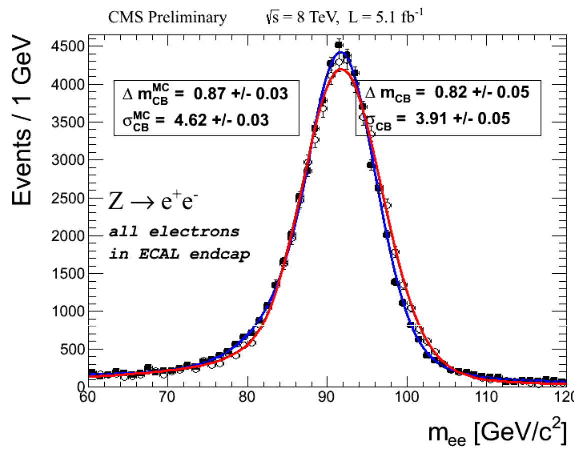
Observed Local Significance @125 GeV:
5.0 σ
Observation of a new state !

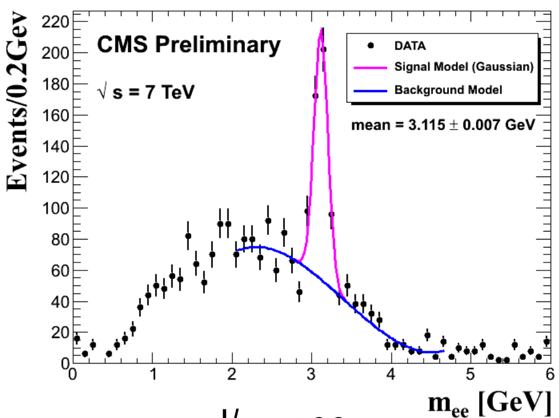
Mass Measurement

Use of all possible (standard) candles to control the lepton/photon scale

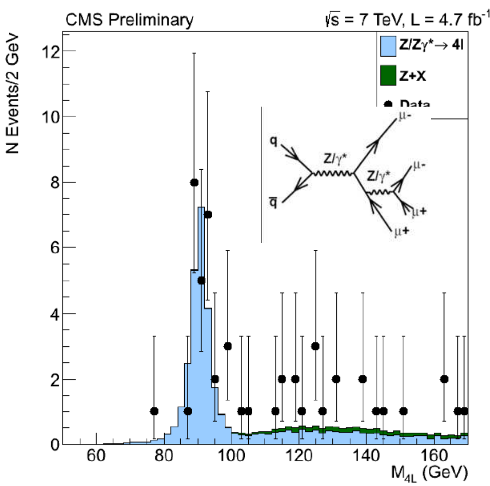




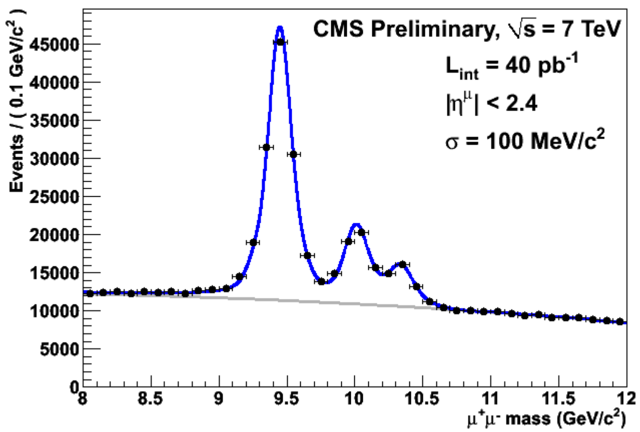




$J/\psi \rightarrow ee$
(important for E-p combination)



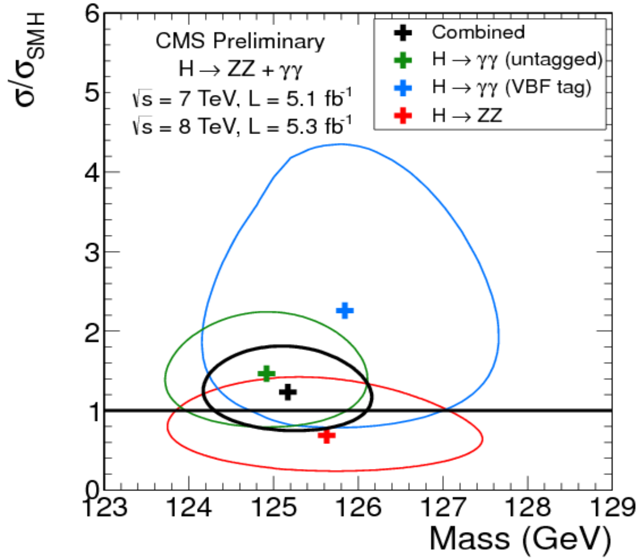
$Z \rightarrow 4l$
(could be used as cross-check with more statistics)



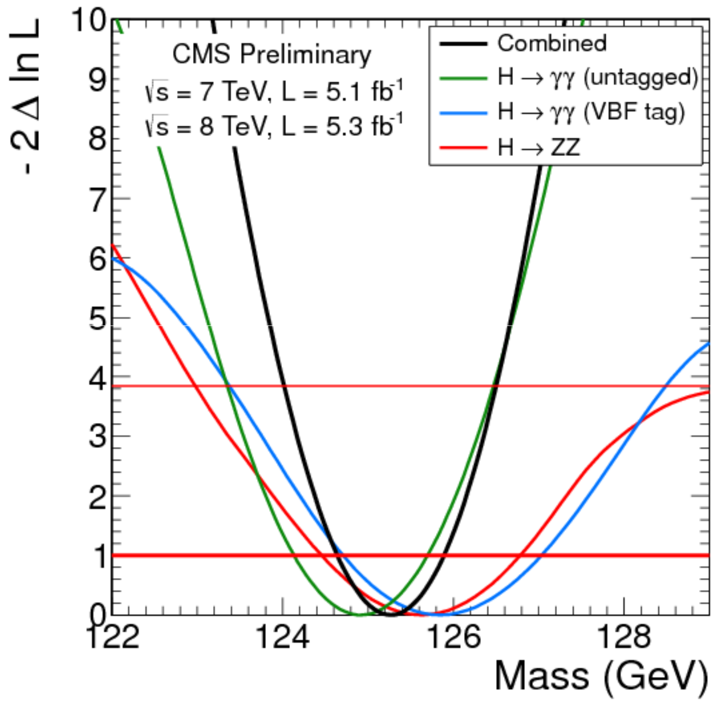
Mass Measurement

- With the highest mass resolution channels:
  - **ZZ→4l**
  - **γγ untagged**
  - **γγ with dijet tag**

- **Likelihood scan m / signal strength**
  overall signal strength free but
  relative yields from SM



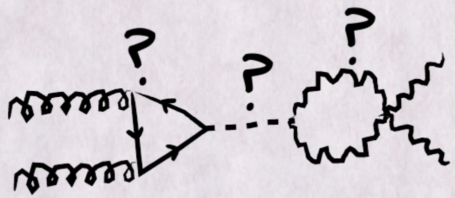
- Fit of mass with **freely floating signal strength** for the three final states, to minimize model dependence



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

= **125.3 ± 0.6 GeV**

Properties of h_{125}(*)

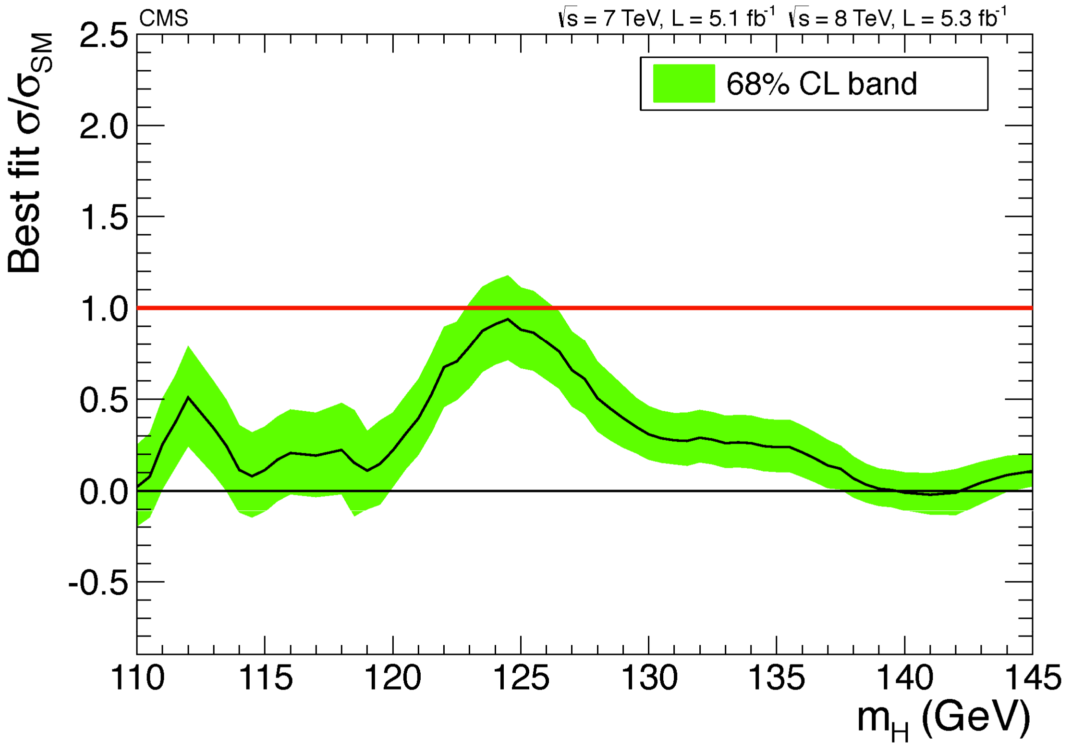


Shopping list:

- signal strength
- spin : 0 or 2 ($H \to \gamma\gamma$, Landau-Yang theorem)
- parity
- CP (even, odd, or admixture ?!?)
- couplings:
  - to vector bosons : ok, $H \to \gamma\gamma$, ZZ (and WW)
  - to fermions
  - proportional to mass
- one state or more states
- elementary or composite
- self-interaction

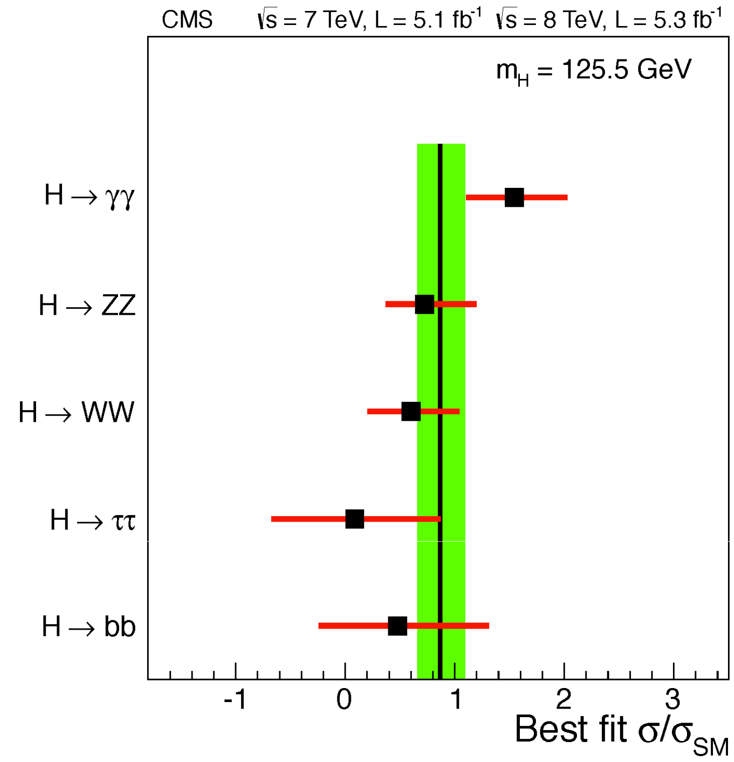
(*) stolen from R. Salerno

Compatibility with Standard Model



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

σ/σ_{SM} = 0.87±0.23

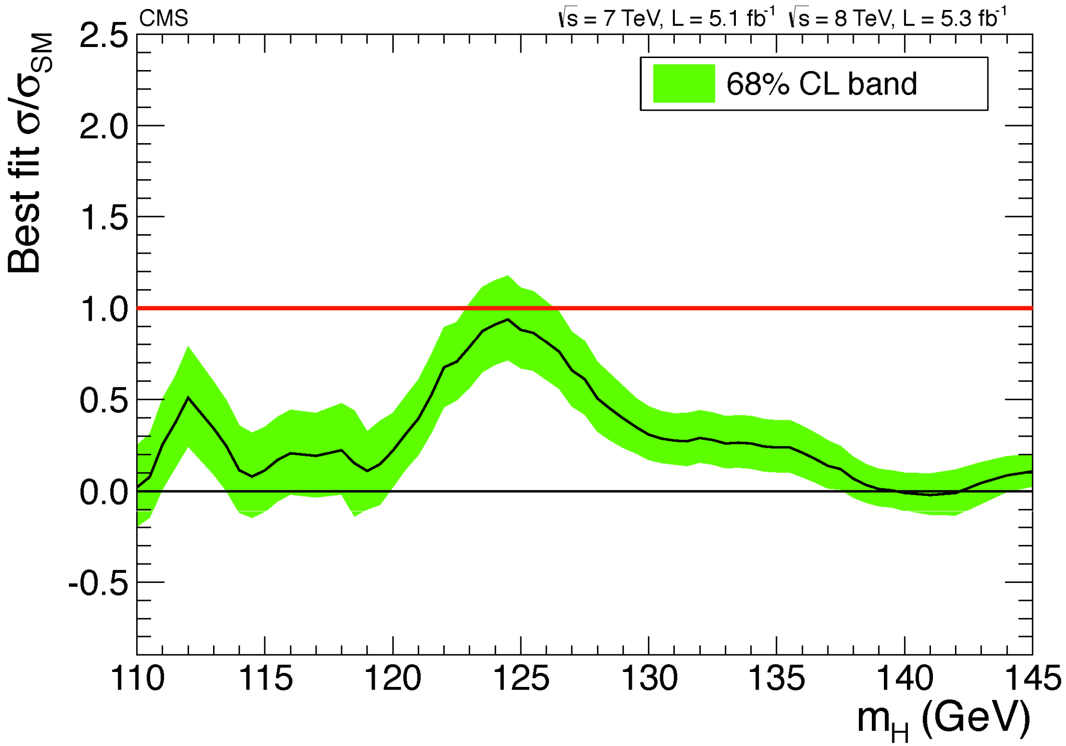


Signal strength σ/σ_{SM} combining channels by decay mode

(**HZZ: 0.7 +/- 0.4**, **H$\gamma\gamma$: 1.56 +/- 0.43**)

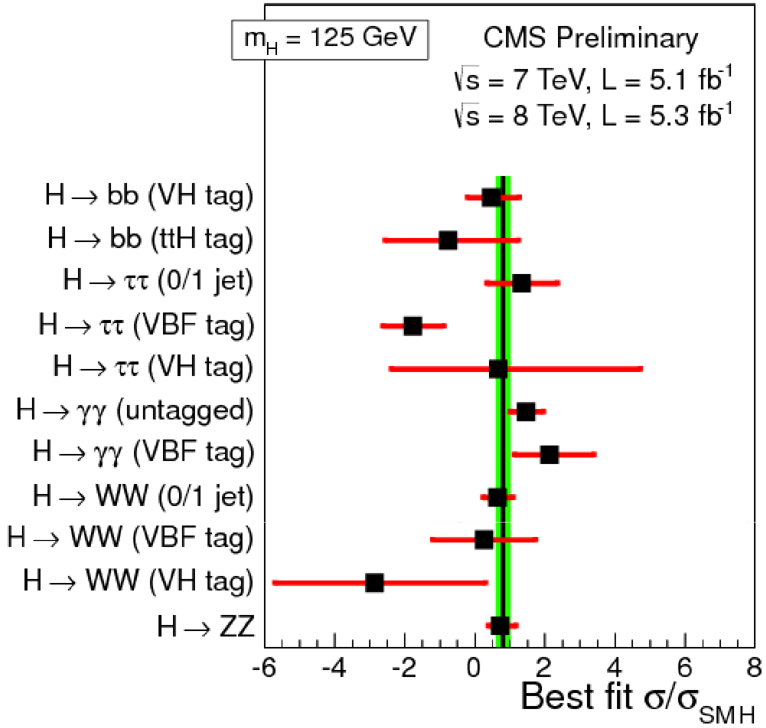
Compatible with SM Higgs within uncertainties

Compatibility with Standard Model



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

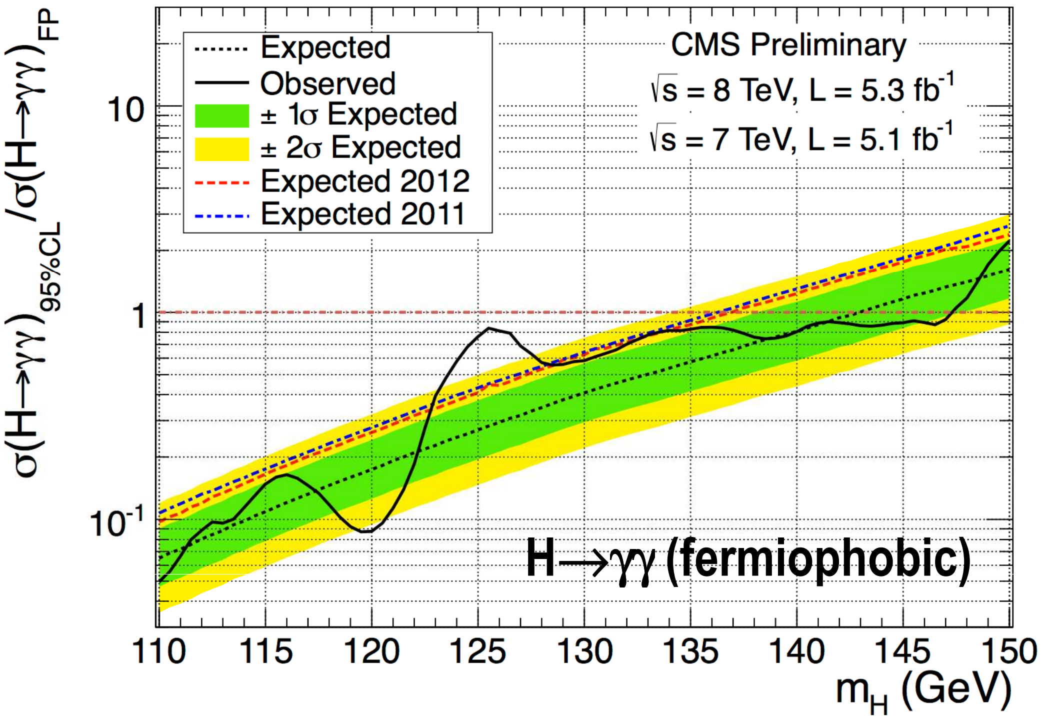
σ/σ_{SM} = 0.87±0.23

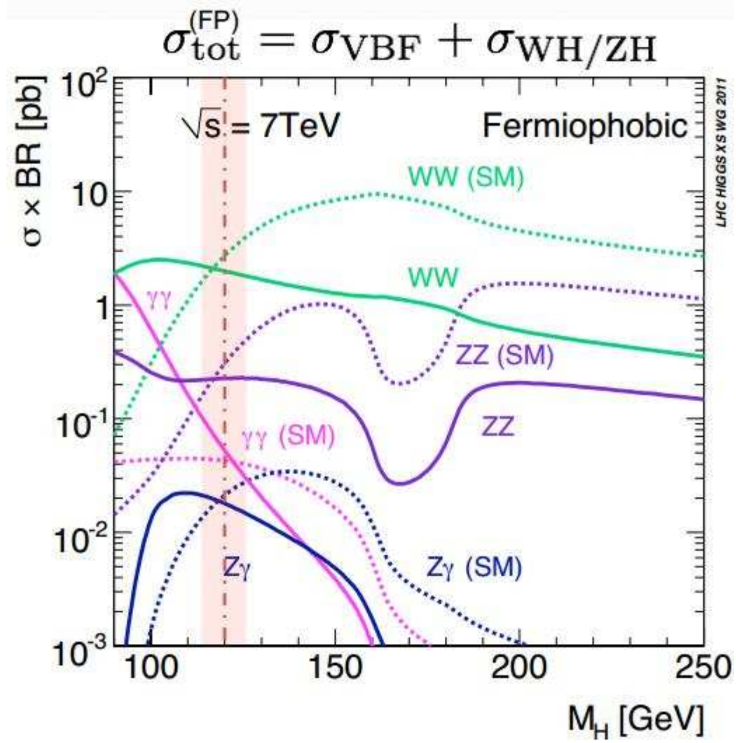


Signal strength σ/σ_{SM} combining channels by decay mode & categories

Compatible with SM Higgs within uncertainties

[Couplings] to fermions?





- Test model purely "fermiophobic"
- ggH or ttH production mode are forbidden

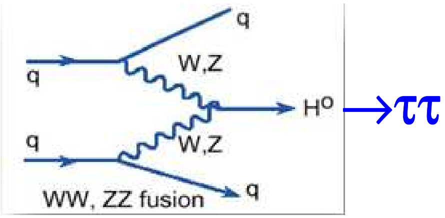
Excluded at 99% CL in the mass domain 110 – 134 GeV.

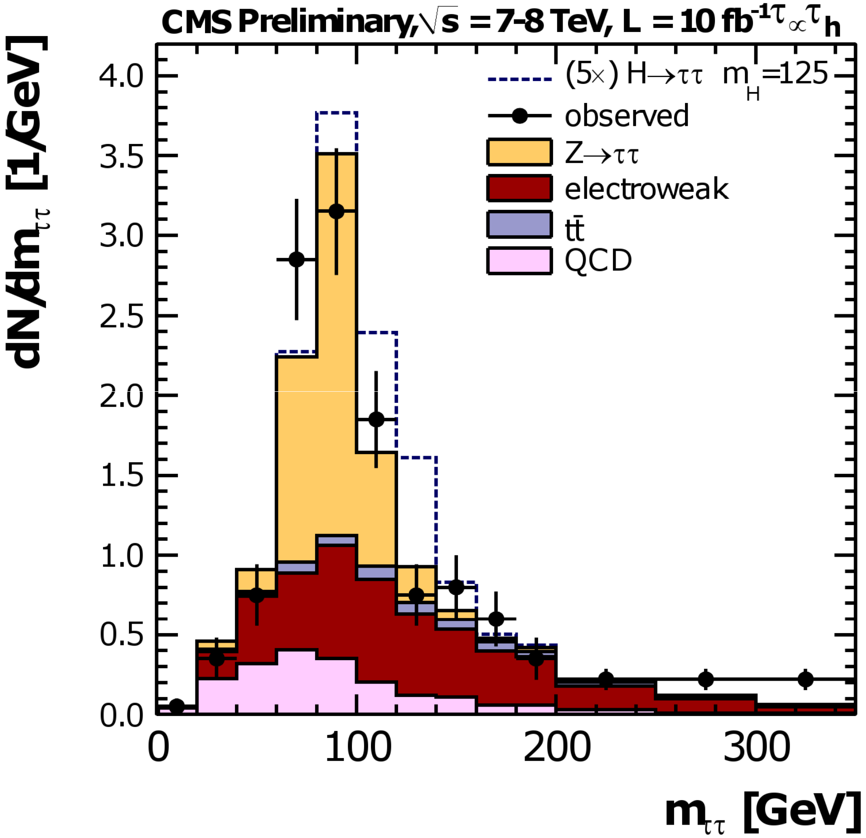
The new boson couples (at least) to quarks (*) ?

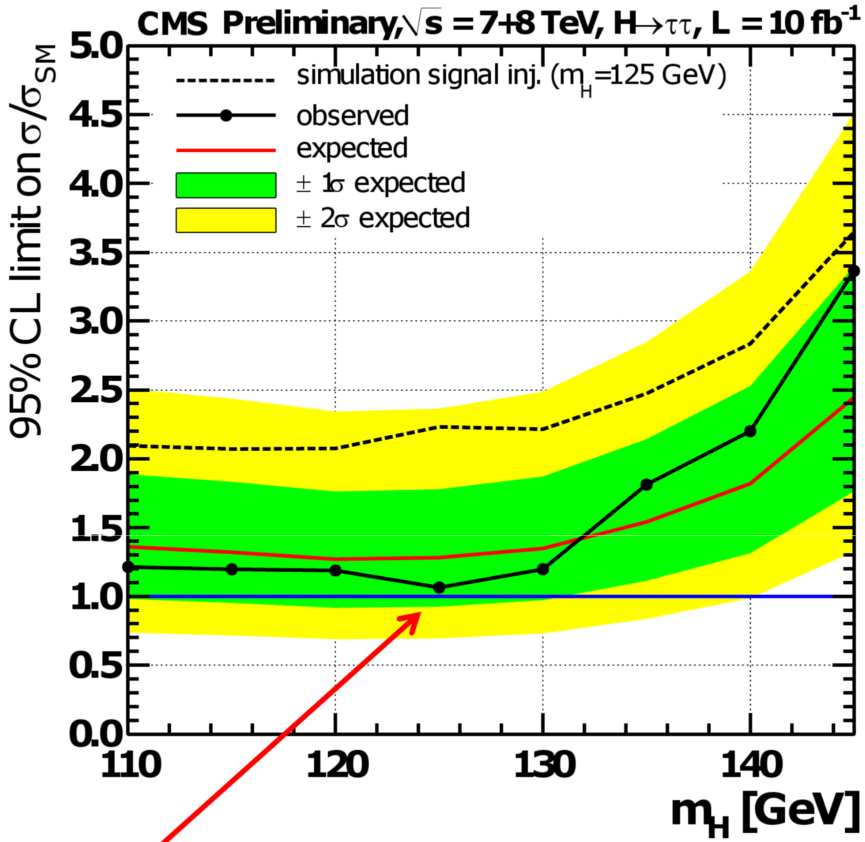
(*) strong indirect evidence of coupling to top via loop in ggH

CMS HIG-12-022 (July 2012)

[Couplings] to leptons?







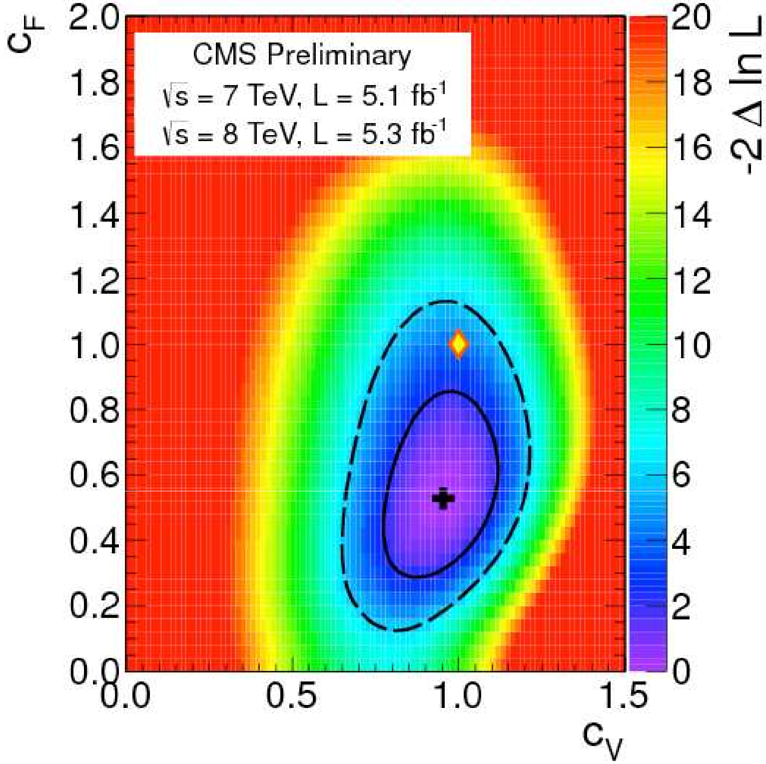
- **Excluded @ 93% CL (~2 sigmas effect…)**
- Need to see with more data (HCP ?)

[Couplings] Summary

- Test compatibility by introducing 2 parameters: CV, CF

  c_V and $c_F = c_b = c_t = c_T$

- LHC Cross Section WG also converging on an improved models for these kinds of fits.



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

Best CF fit driven by excess in VBF $\gamma\gamma$ **and deficit in $\tau\tau$.**

- **Compatible** (for the moment...) **with SM at 95% CL**
- **More data needed to draw any definite conclusion**

[Quantum Number] Spin: 0 vs 2

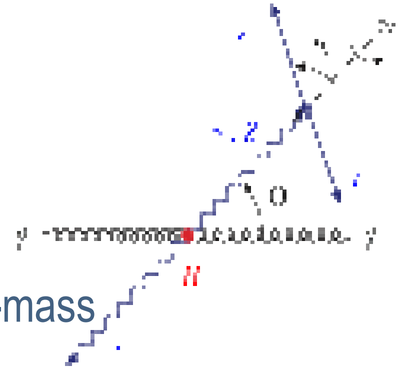
➢ **Spin 0 vs. Spin 2: gg→H →VV**

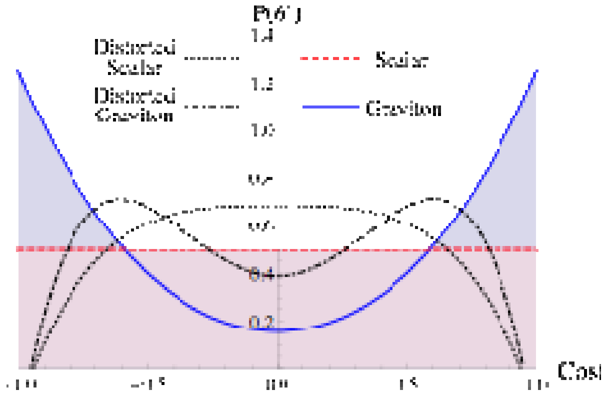
Assumption: resonnnace coupling the same way as massive KK gravitons

▪ gg→H →γγ and gg→H →Zγ

- Spin 0 flatcosθ*
- Spin 2: 2nd order polynomial in en cos²θ*

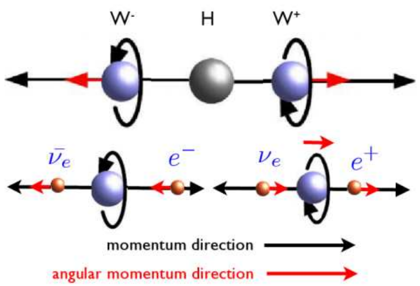
θ* : scattering production angle in the center-of-mass system of the photon pair at LHC.

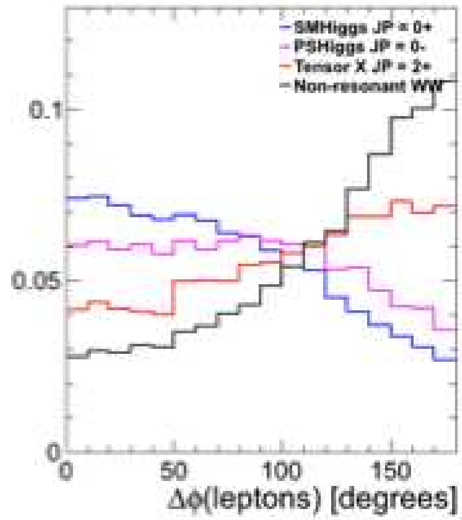




▪ gg→H→WW

- Spin 0: small Δφ(l,l), et small m_{ll} (spin correlation, H->VV, V-A structure)
- Spin 2: high $Δφ_{(l,l)}$



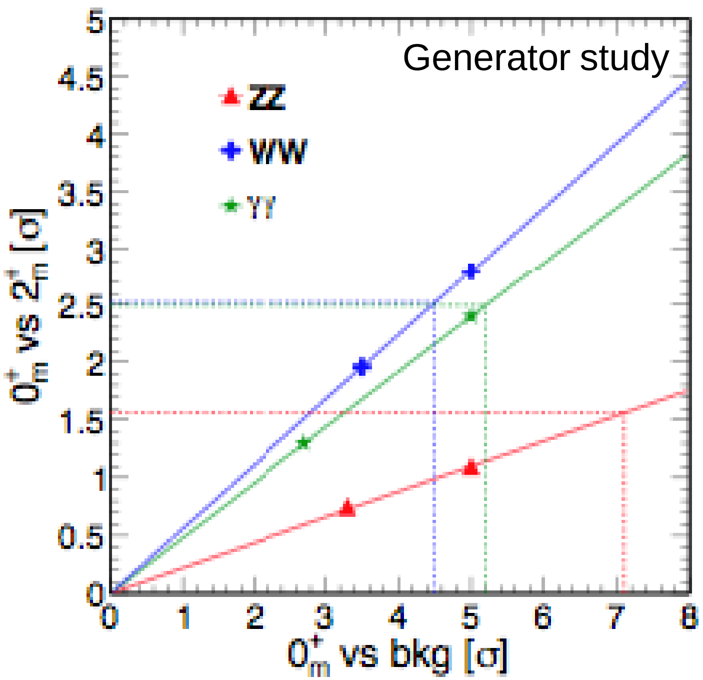


arXiV:1202.6660
arXiV:1208.4018
arXiV:1209.1037
arXiV:1209.5268

[Quantum Number] Spin: 0 vs 2

- Projections at 8 TeV with 35 /fb.
  (for gg→H→VV)

Expected hypotheses separation vs signal observation significance
(spin 0 vs spin 2 hypothesis).



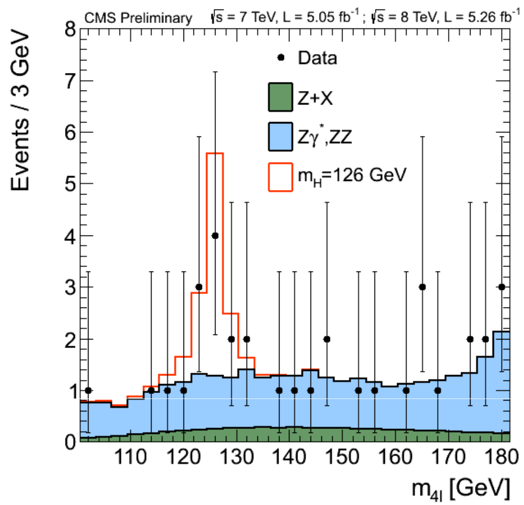
- **Projections à 8 TeV avec 35 /fb (generator study):**

scenario	$X \to WW$	$X \to \gamma\gamma$
0^+_m vs background	4.5	5.2
0^+_m vs 2^+_m	2.5	2.5

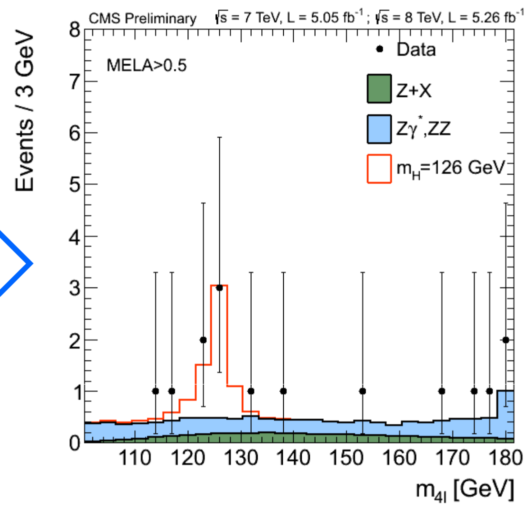
Would need to combine with ATLAS to separate spin 0 and spin 2 hypothesis

[Quantum Number] Parity

- **H→ZZ→ 4 leptons:**
  - CMS Strategy (at the time of ICHEP…)
    1) Separate signal from background: cut on KD

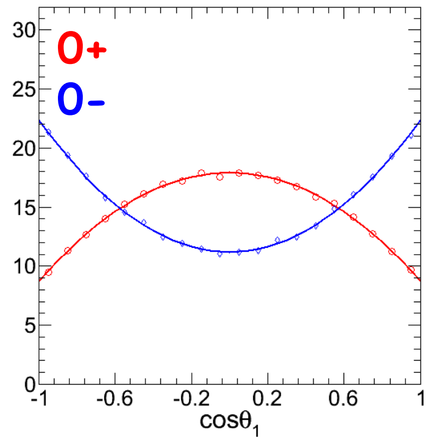


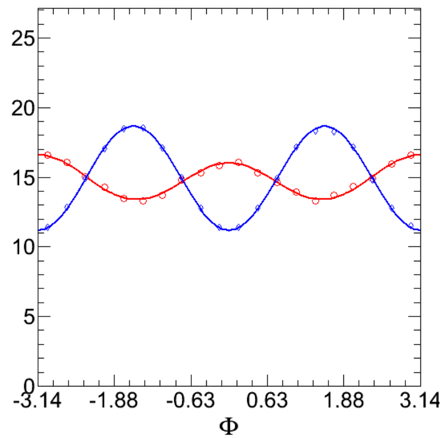
KD > 0.5



2) Build a new Discriminant to separate different spin/parity hypothesis (0+ vs 0-)

Based on 5 angles+2 masses

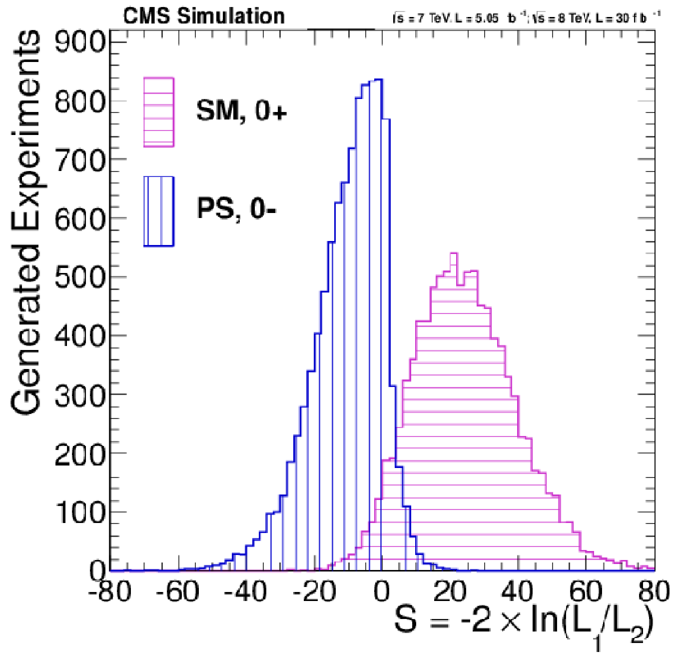




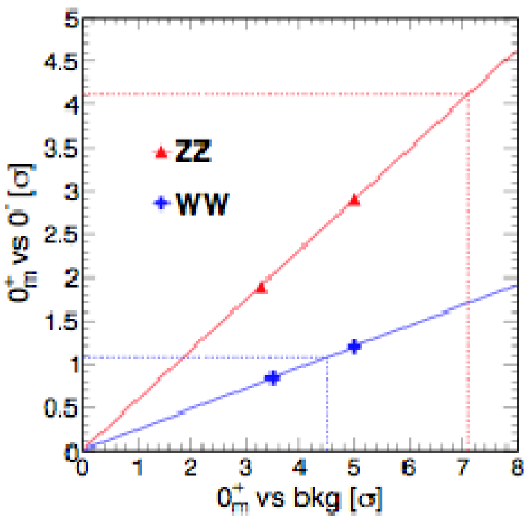
[Quantum Number] Parity

Results extracted through 2D (m4l, hypothesis-KD) fit

- **Expected Separation (full CMS sim)**
- **- ~ 2 sigmas for HCP**
- **- ~ 3 sigmas for Moriond**



➢ **Projections at 8 TeV with 35 /fb (generator study):**

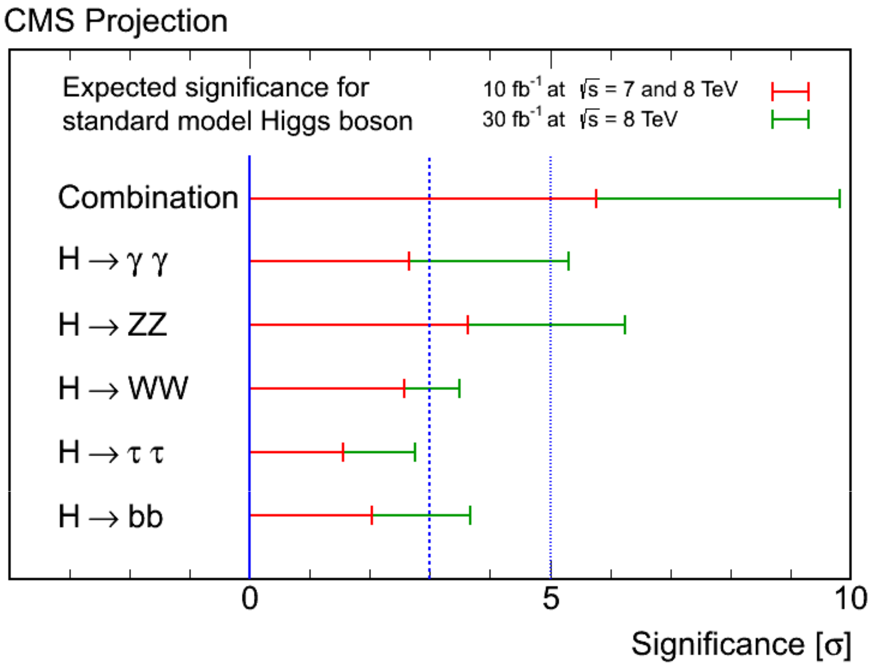


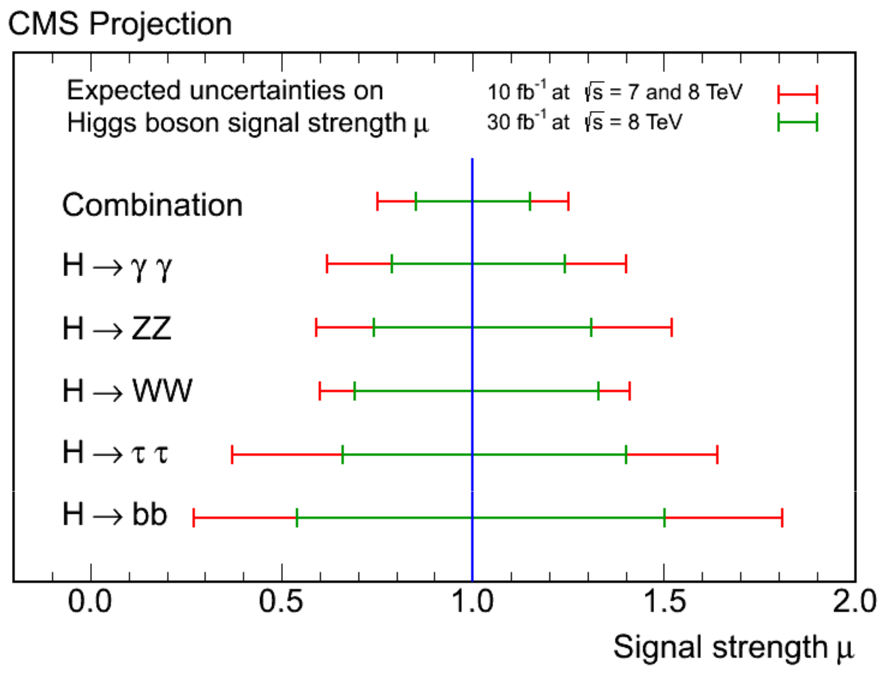
arXiV:1208.2692
arXiV:1208.4018

scenario	$X \to ZZ$	$X \to WW$
0_m^+ vs background	7.1	4.5
0_m^+ vs 0^-	4.1	1.1

To also consider: 0+/0- mixing…

Some Projections…

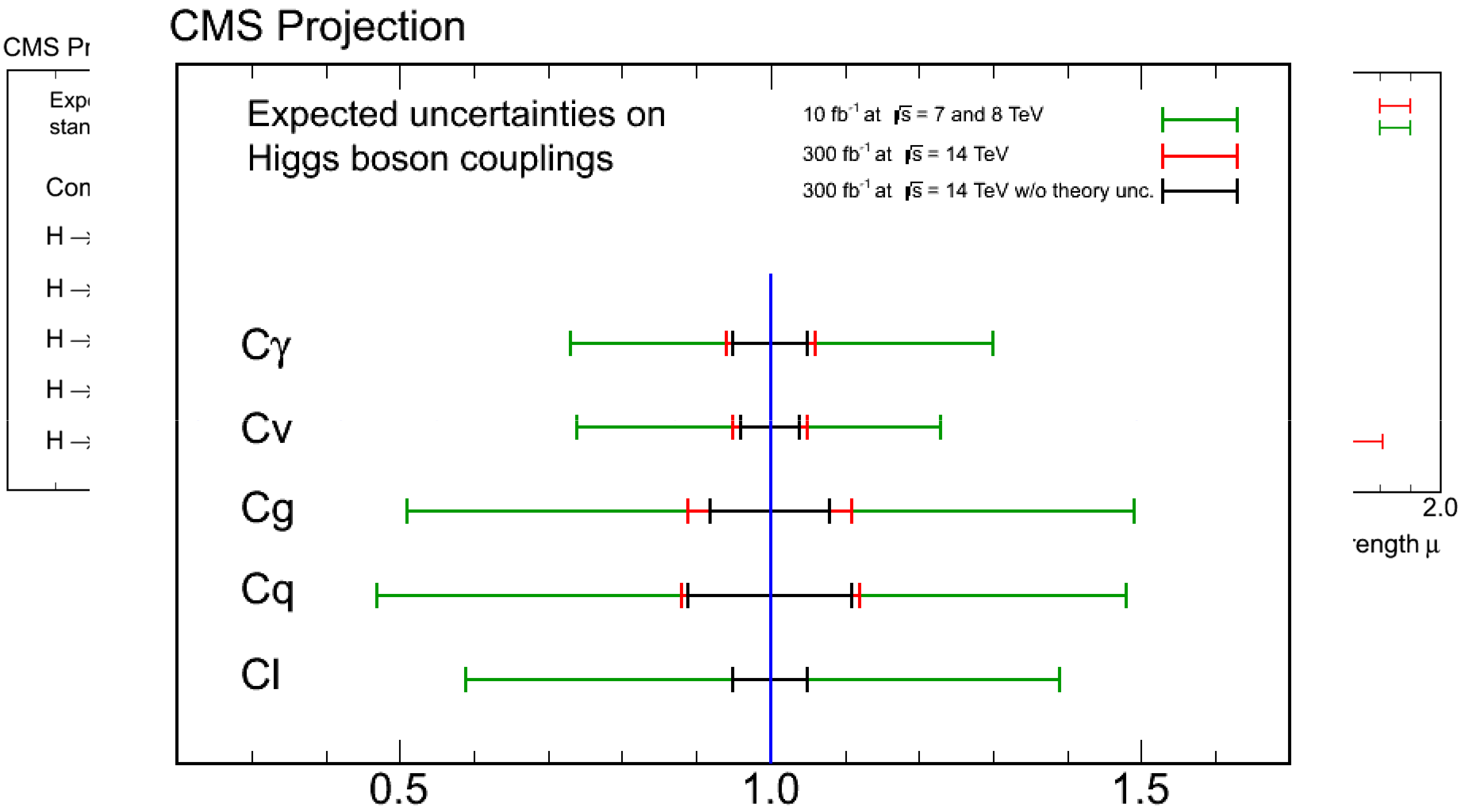




By Moriond:

- Observation in γγ & 4l alone.
- H→bb more sensitive than TeVatron
- H→ττ ~ 3 σ. May need to wait 2014 to have definite answer…
  - Exclusion: 0.85xSM

Some Projections…



Here: more degrees of freedom than (CV, CF) shown earlier

Conclusion

- **Discovery of new particle, very likely a scalar "Higgs-like" boson with ~10 fb-1.**
  - Mass (from HZZ & $H\gamma\gamma$): 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV

- Signal strength (0.87 +/- 23) and couplings compatible with SM, within uncertainties.
  - **Slight tension of the fermion side…**

- $H \rightarrow bb$ and $H \rightarrow \tau\tau$ not yet sensitive enough to discriminate SM expectation and null hypothesis
  - By the end of 2012 run, 3-4 σ expected in each channel…
  - **New update by HCP (next week…) ?**

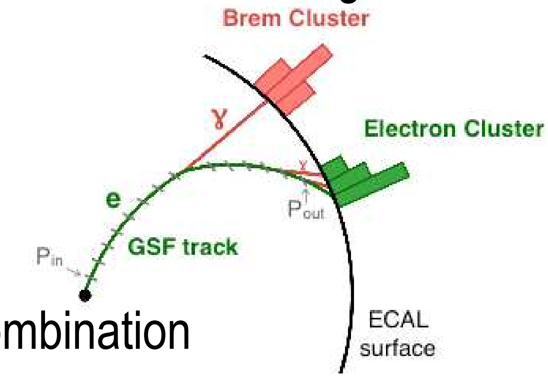
- Considerable amount of information on the nature of the new boson can be extracted with increasing statistics in 2012 (~30-35 fb-1 expected at the end of the run)
  - Mass,
  - compatibility with SM ($H \rightarrow \gamma\gamma$ "high" rate going back closer to SM or…?)
  - couplings
  - **spin/parity (~2-3 σ 0+ vs 0- expected separation)**

BACK UP

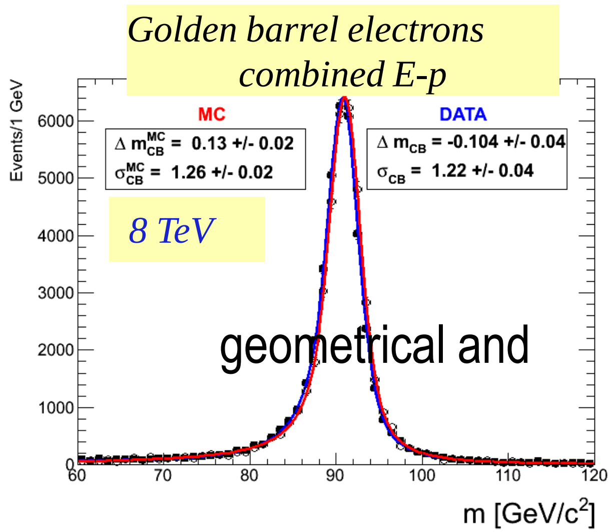
SLIDES

Electrons (H→ZZ, H→WW)

- Electrons in analysis $|\eta| \leq 2.5$ $p_T \geq 7$ GeV
  - Superclusters in ECAL ($E_T > 4$ GeV) + dedicated track finding and GSF fit (before candidate id.)
    - collect energy spread in phi
    - change of curvature and hit collection up to ECAL
  - ECAL-seed complemented by tracker-seed
  - Electron classes brem sensitive and momentum from E-p combination

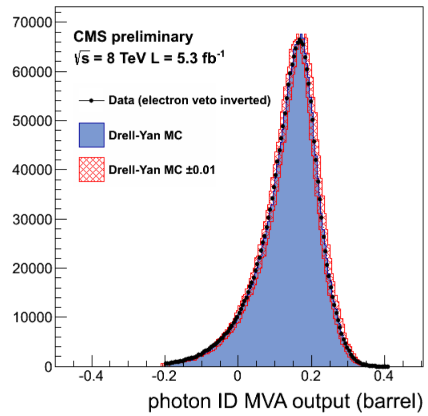


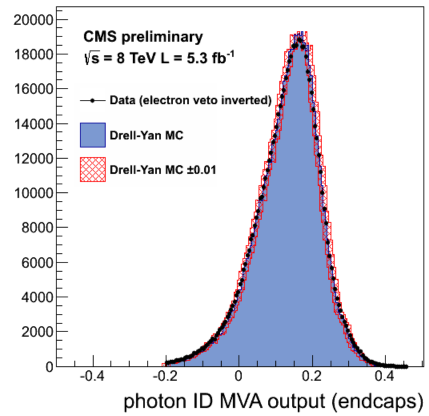
- Scale and resolution
  - Run-dependent energy scale, and MC smearing
  - Z peak for different electron categories
  - Control low p_T with J/ψ
- ID: Multivariate in 2012 (BDT)
  - Observables sensitive to brem, shower shape, geometrical and momentum matching ECAL – tracker – HCAL



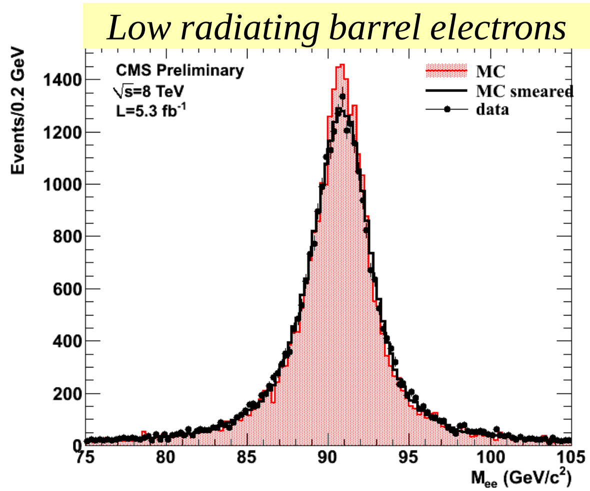
Photons ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$)

- Photon reconstruction:
  - $|\eta| \leq 2.4$ $p_T > 2$ GeV
  - Same clustering as electrons
- Photon ID:
  - Prompt photons / π^0 from jets
  - MultiVariate: shower shape, pre-shower, isolation, energy density,



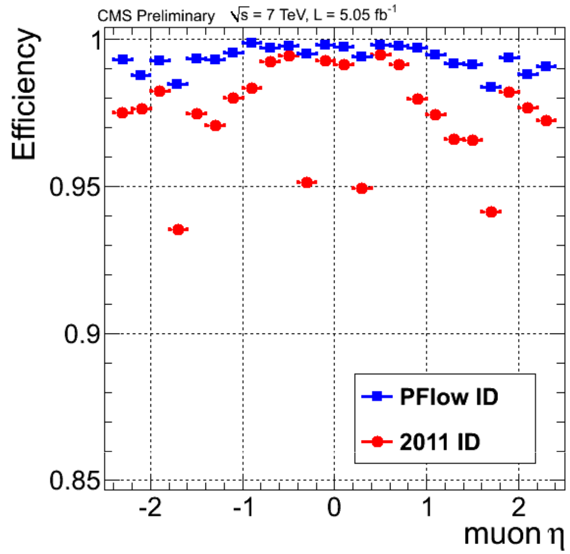


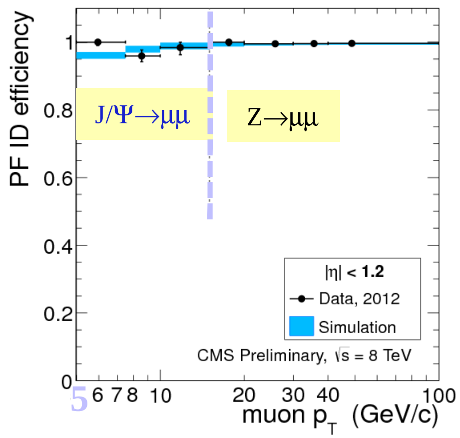
- Scale and resolution:
  - Energy corrected using a MC trained multivariate regression (η, φ, shower-shape, local cluster) → better resolution and flat response of energy scale versus Pile-Up (PU)
  - Run-dependent energy scale, and MC smearing
  - Scale, resolution and efficiencies events

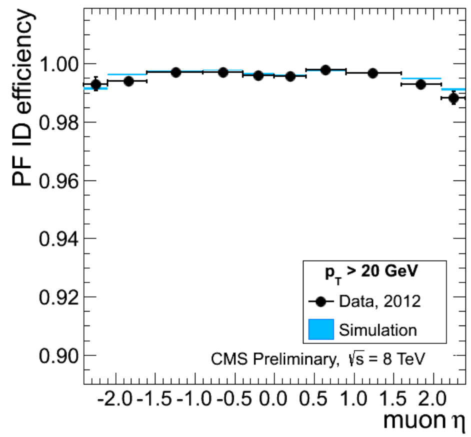


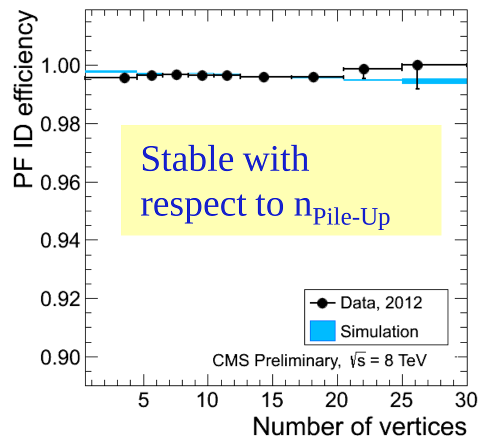
Muons (H→ZZ, H→WW)

- Muons in analysis $|\eta| \leq 2.4$ $p_T \geq 5$ GeV
  - Combination of inner tracker tracks and muon system tracks
  - Particle Flow (PF) ID:
    - inner and muon tracks quality and matching
    - can be 99 % efficient for same fake rate as in 2011
  - Efficiency measured via Z and J/ψ Tag&Probe



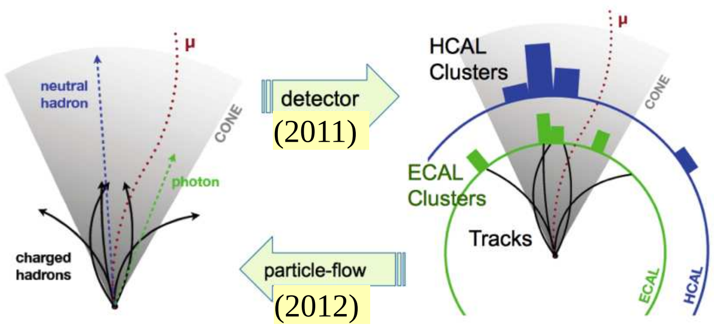


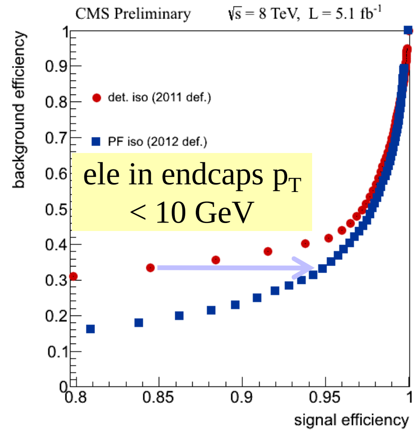




Isolation

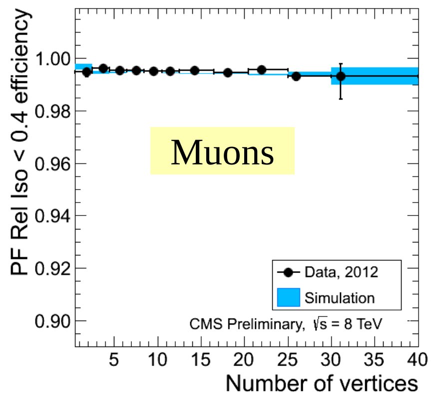
- Particle-based isolation
  - In DR cone(s) around the considered particle (lepton, photon) from charged and neutral hadrons, photons
  - No double counting for the charged particles, automatic removal of the considered particle





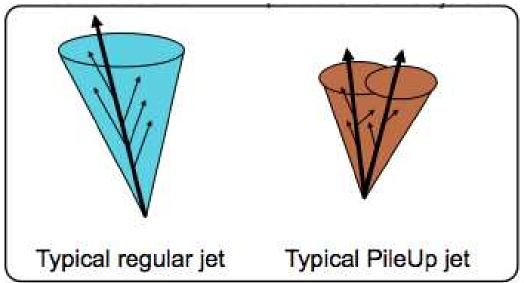
PU contribution

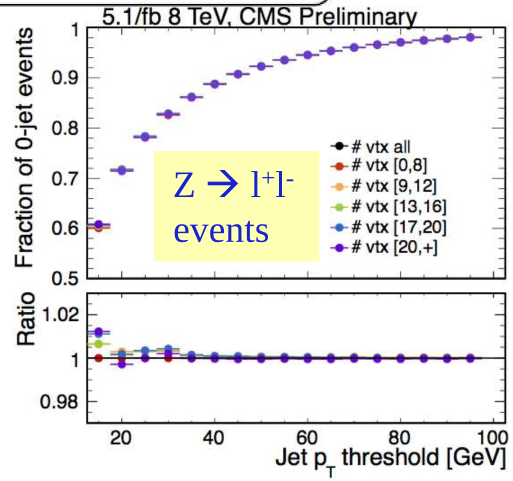
- Charged: negligible (required from the vertex)
- Neutrals: corrected using the average energy density from the PU and underlying event
- → quite stable with respect to n_{PU}

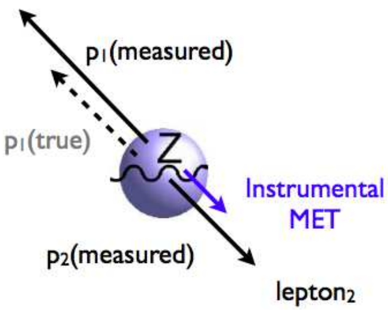


Jets - mE_T ($H \rightarrow WW$, $H \rightarrow \gamma\gamma$)

- Jets with Particle Flow:
  - $|\eta| \leq 4.7$ $p_T > 30$ GeV
  - Anti-k_T $\Delta R = 0.5$, jet energy correction
  - PU jets structure differs w.r.t. regular jets: PU jets from several overlapping jets merged together
  - Discriminant exploits shape, composition and tracking variables

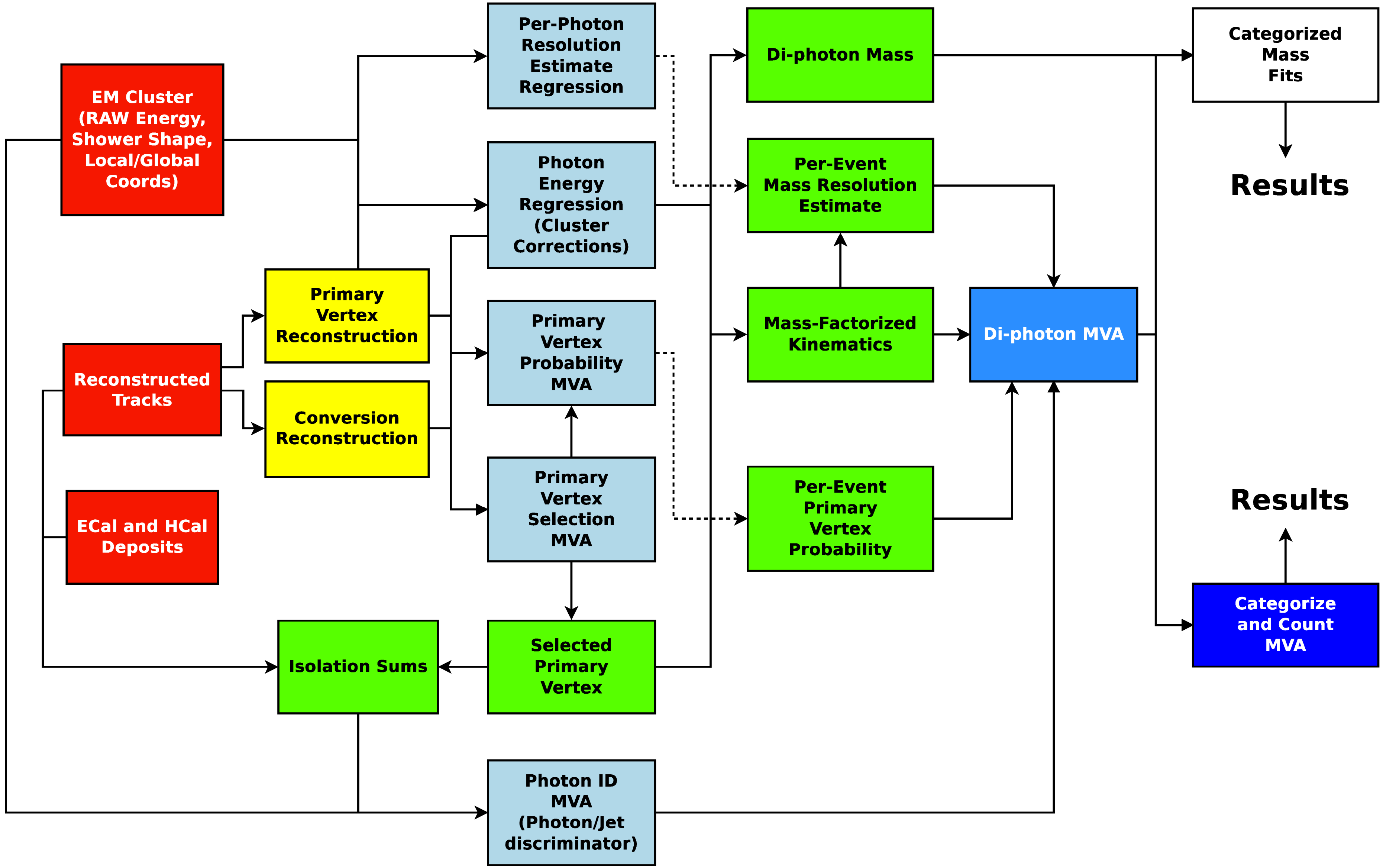




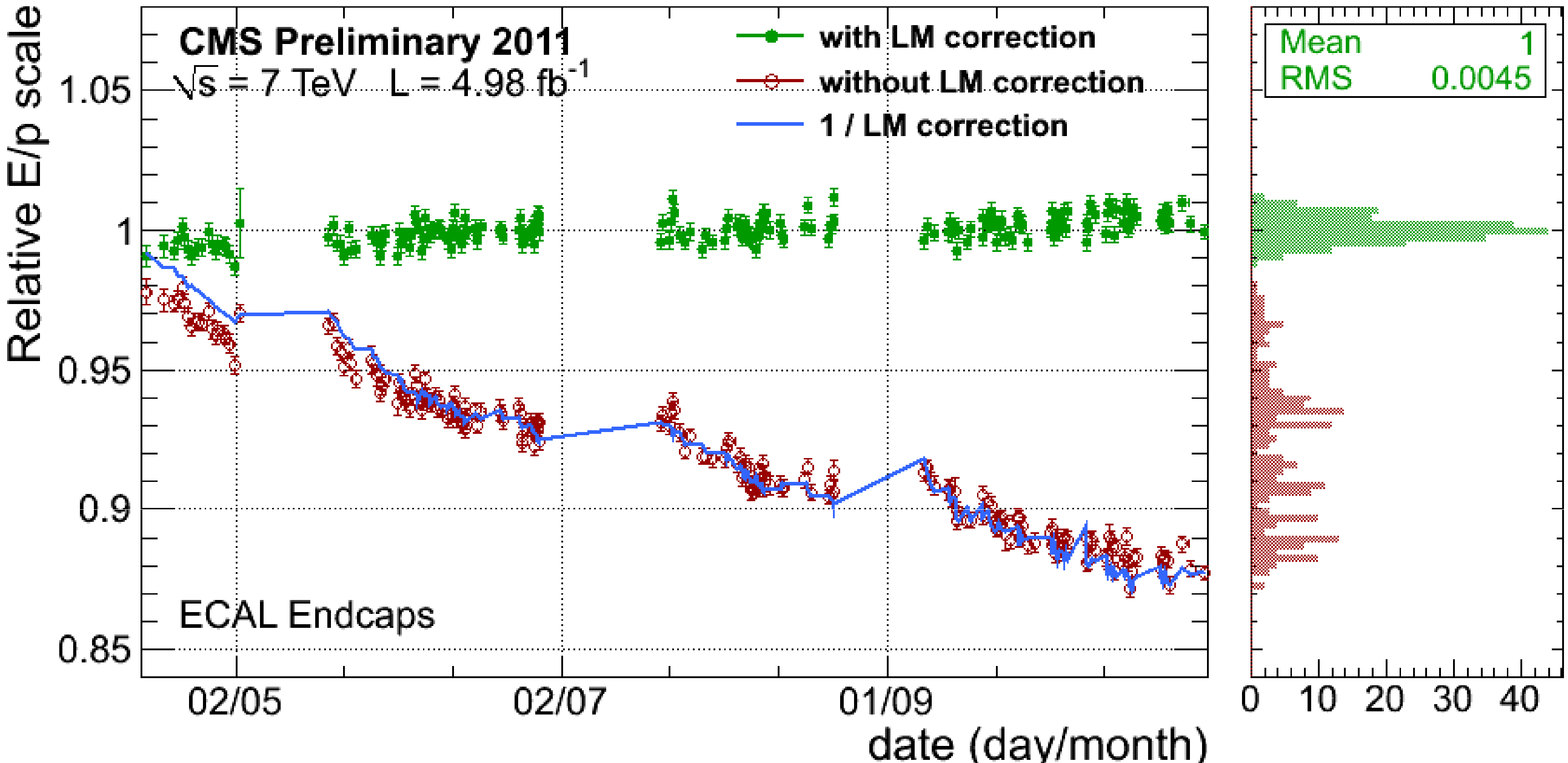


- mE_T:
  - Sum of all PF particles P_T →
  - Projected mE_T (transverse projection to the closer lepton) to avoid mE_T due to mismeasurement of leptons

H→γγ strategy



ECAL response over time (Endcap)

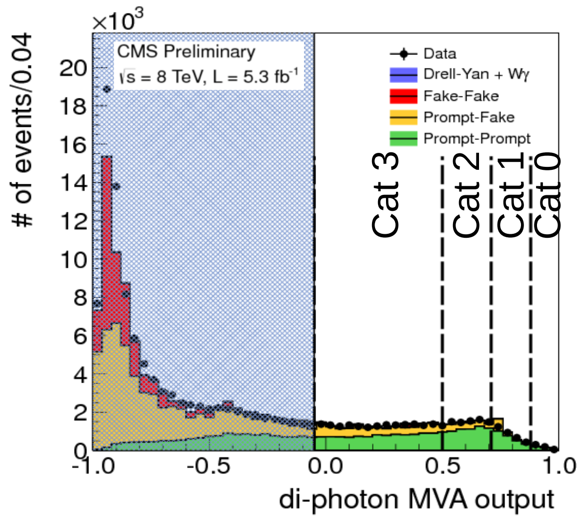


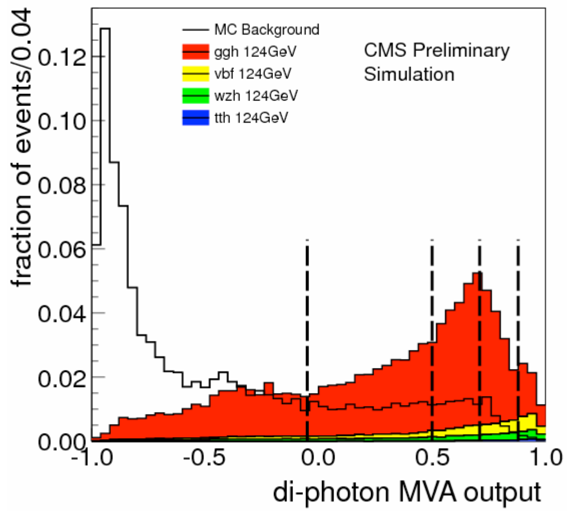
The electrons are selected from W->enu decays. Each point in the plot is computed from 12000 selected W->enu events with the reconstructed electron located in the ECAL Barrel (top) and in the ECAL Endcaps (bottom). The E/p distribution for each point is fitted to a template E/p distribution measured from data (using the entire 2011 dataset) in order to provide a relative scale for the E/p measurement versus time.

The history plots are shown before (red points) and after (green points) corrections to ECAL crystal response are applied. The magnitude of the average transparency correction for each point (averaged over all crystals in the reconstructed electromagnetic clusters) is indicated by the continuous blue line.

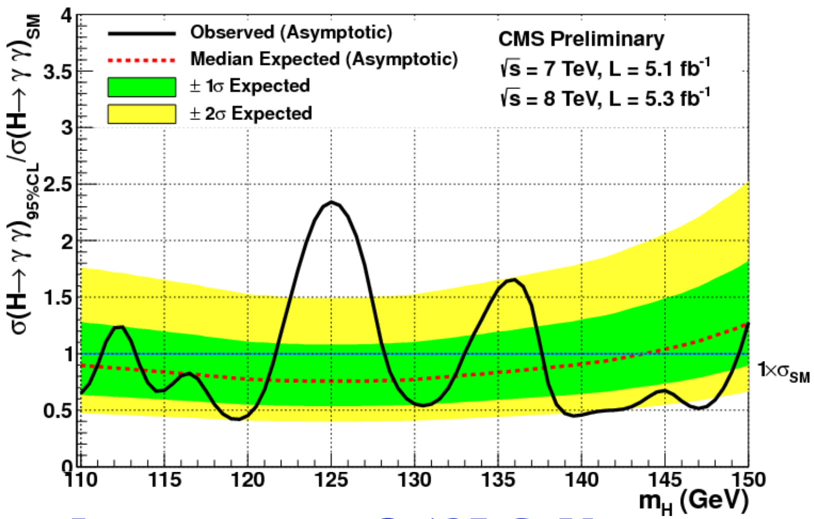
$H \rightarrow \gamma\gamma$ analysis: Classification

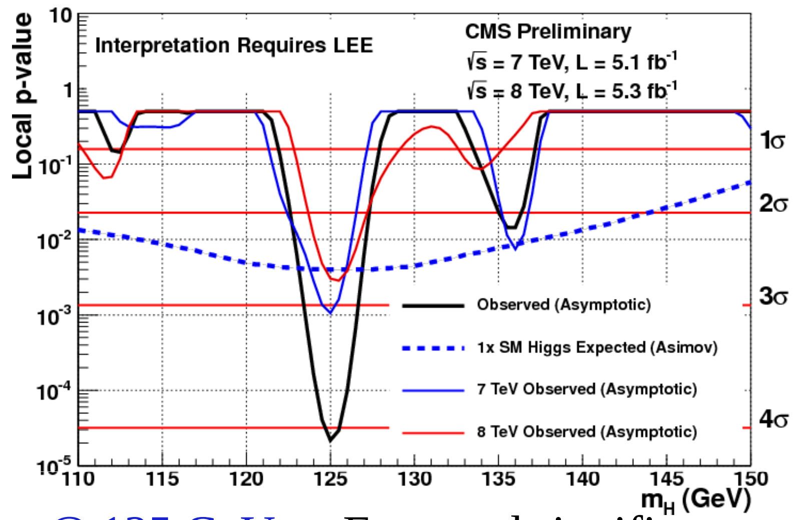
- **Analysis selection**
  - ID photons $p_{T1} > m_{\gamma\gamma} / 3$ $p_{T2} > m_{\gamma\gamma} / 4$
- **MVA Diphoton discriminant → categories**
  - High score
    - signal-like events
    - good $m_{\gamma\gamma}$ resolution
  - Designed to be $m_{\gamma\gamma}$ independent
  - Trained on signal and background MC
  - Input variables:
    - Kinematics variables: $p_{T\gamma} / m_{\gamma\gamma}$, η_γ, $\cos(\varphi_1 - \varphi_2)$
    - Photon ID
    - Per-event mass resolutions for the correct and incorrect choice of vertex





H → γγ results





Largest excess @ 125 GeV

Exp. 95% CL exclusion 0.76×SM

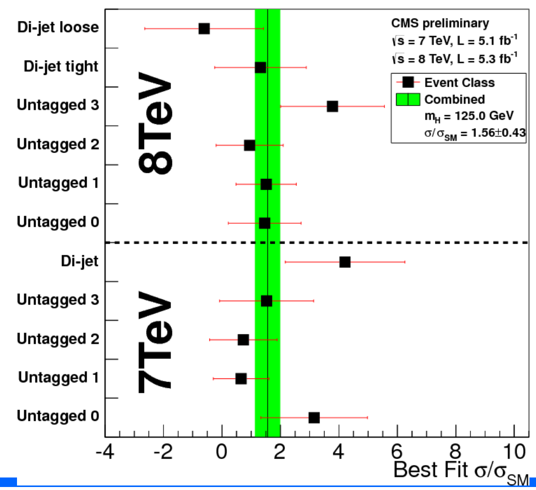
@ 125 GeV: Expected significance: 2.8 σ

Observed p-value: 4.1 σ

Combined best fit signal strength @125 GeV:

σ/σ_{SM} = 1.56 ± 0.43

consistent between different categories



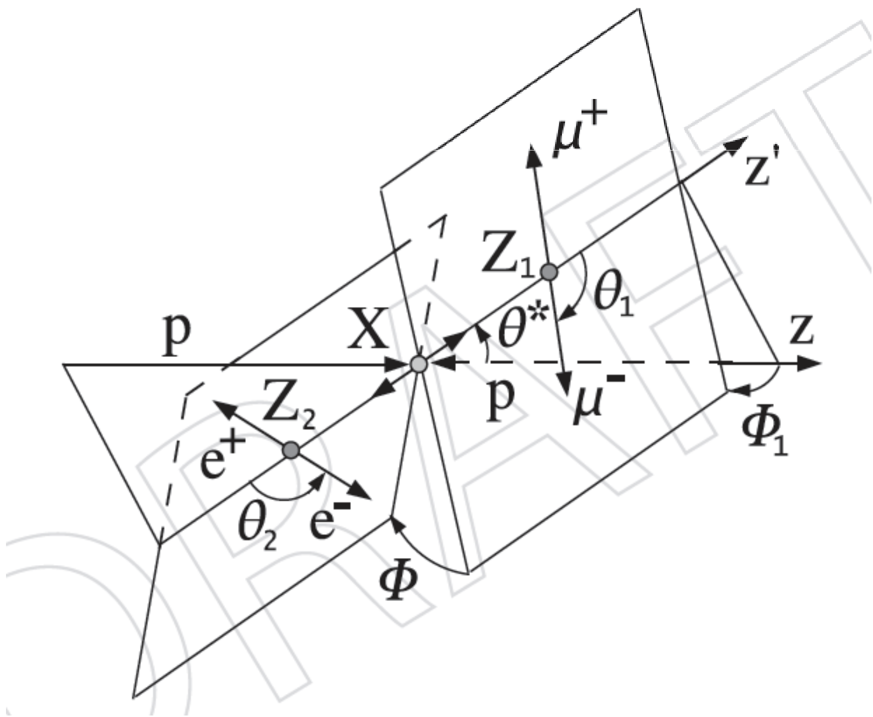
Angles

θ^*: angle between the parton collision axis z and X->ZZ decay axis z' (in X rest frame)

Φ_1: angle between zz' plane and plane of Z_1->ff (in X rest frame)

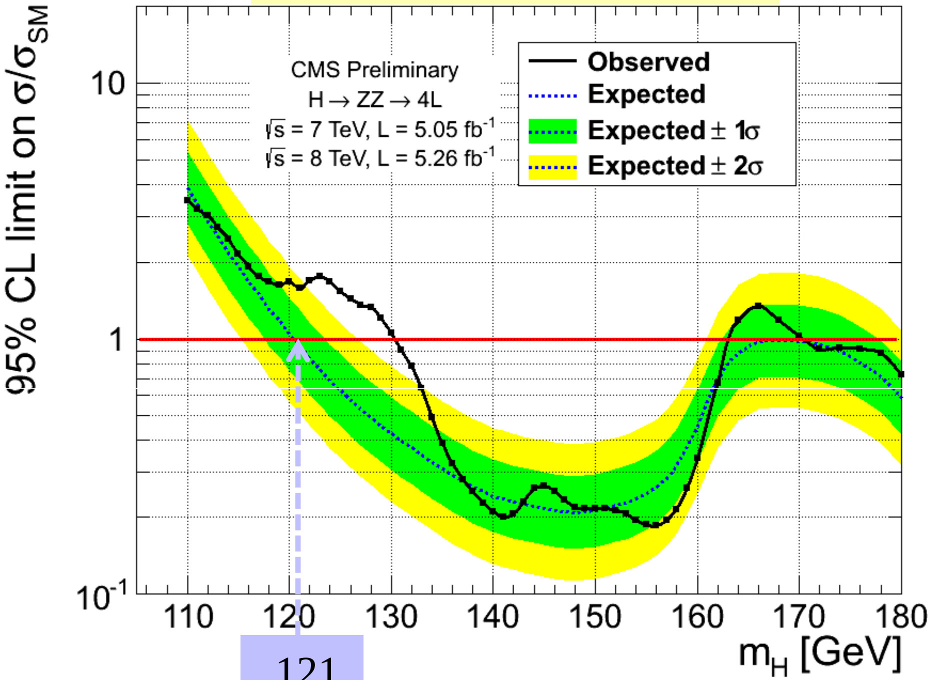
θ_i: angle between direction of fermions fi from Zi->$f_i f_i$ and direction oposite the X in the Z_i rest frame (i=1,2 for the first and second Z)

Φ: angle between the decay planes of the two Z systems (in X rest frame)



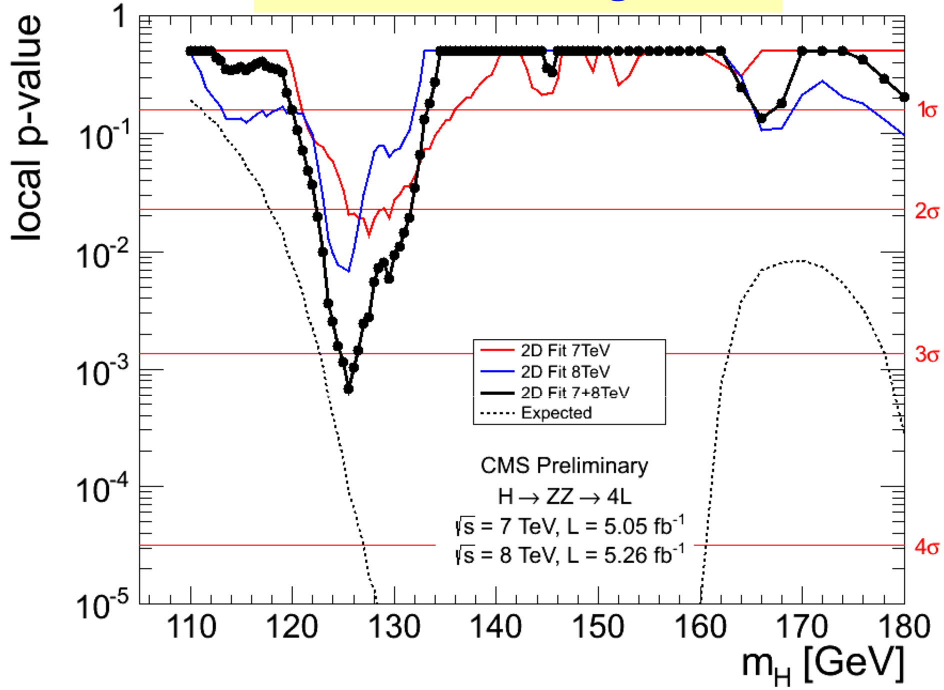
H→ZZ results

zoomed mass range



121

zoomed mass range



exp. exclusion of the SM Higgs [121 - 570]

obs. exclusion of the SM Higgs **[131 - 162] [172 - 525]**

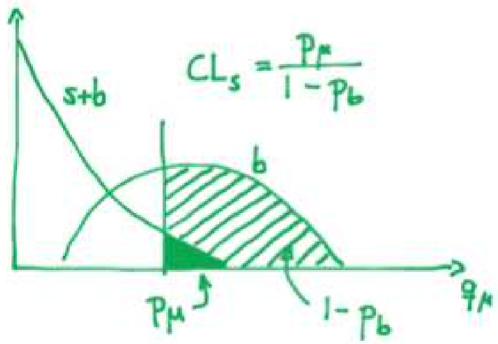
obs. **excess of events** in the region m_H ~ 125 GeV

m_H @ 125.5 GeV

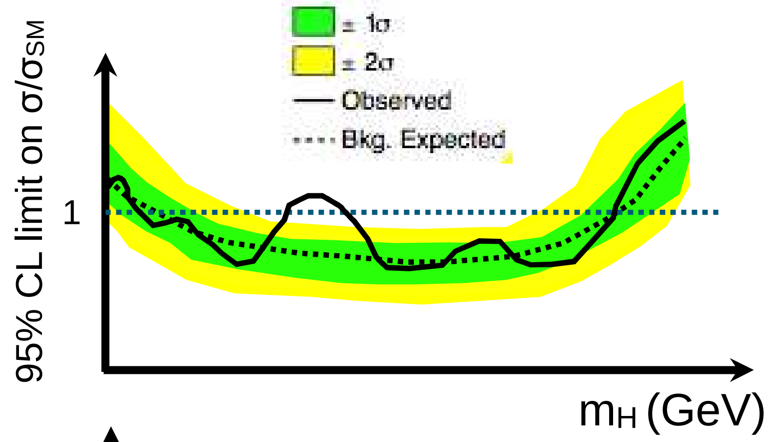
exp. local significance: 3.8 σ

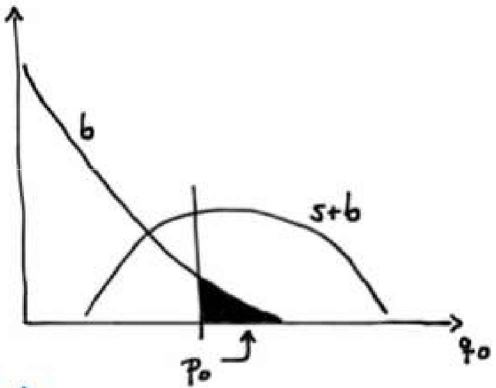
obs. local significance: 3.2 σ

Quelques définitions utiles…



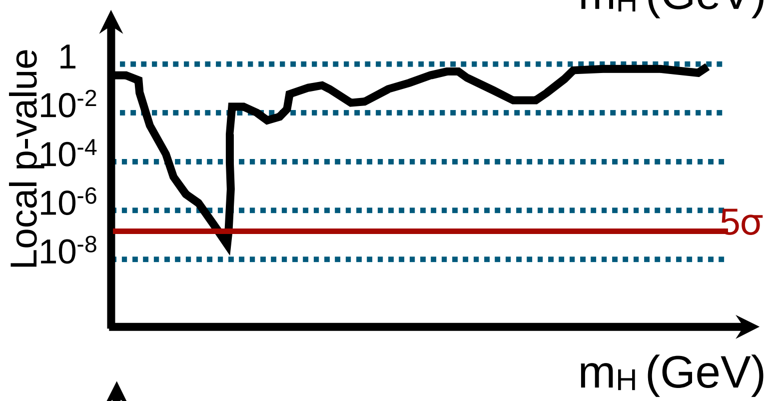
Test de compatibilité avec l'hypothèse signal+bruit de fond

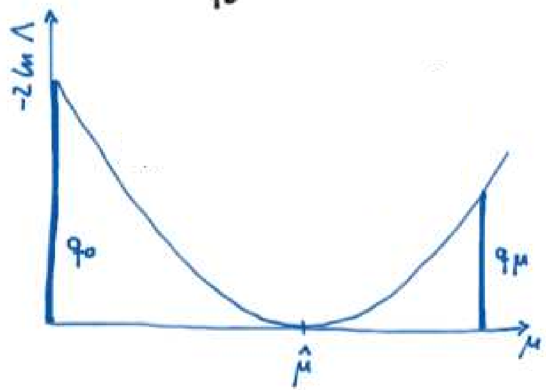




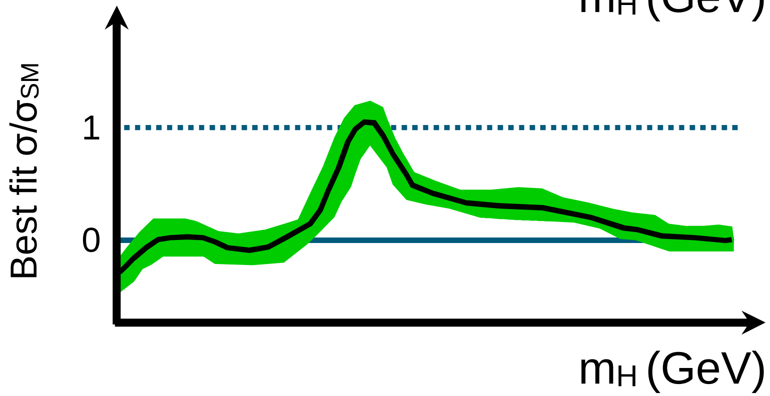
Quantifie la probabilité d'un excès par rapport au bruit de fond seul

5σ ~1/3 millions
3σ ~1/700



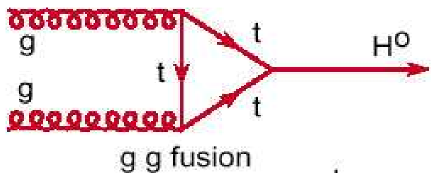


Evalue l'intensité du signal

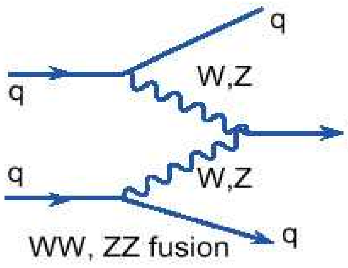


Un peu de Higgsologie…

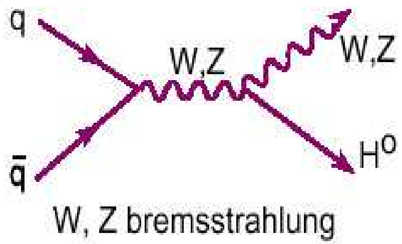
Production…



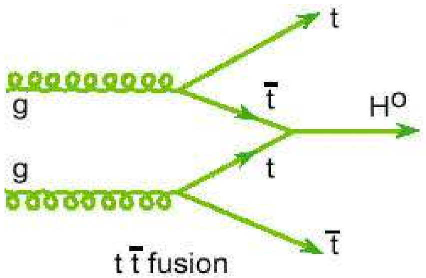
~87%



~7%

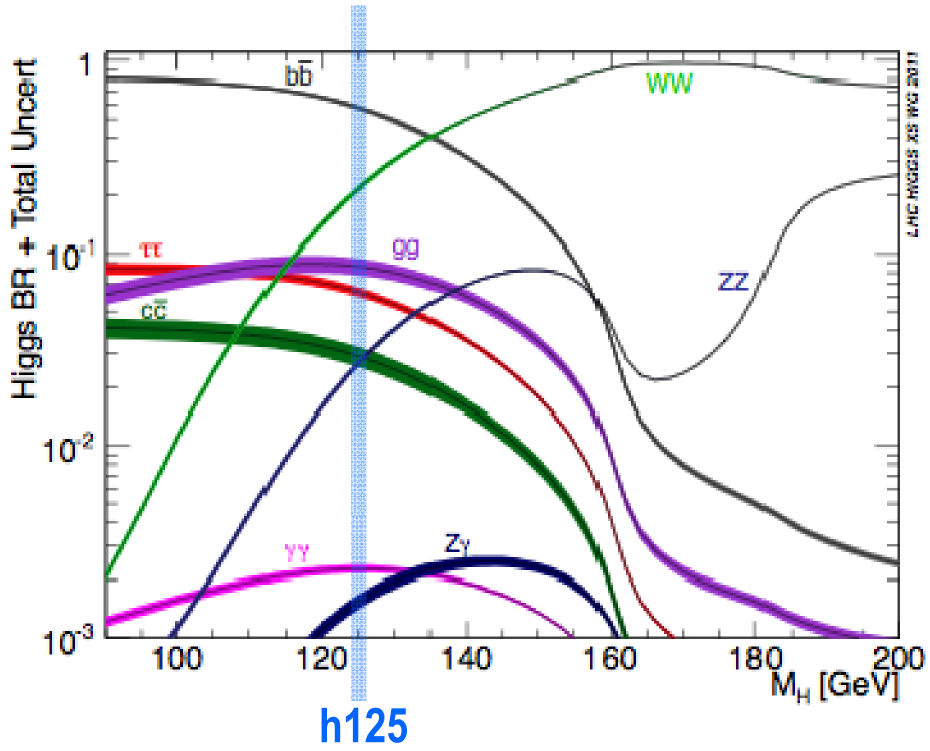


~5%



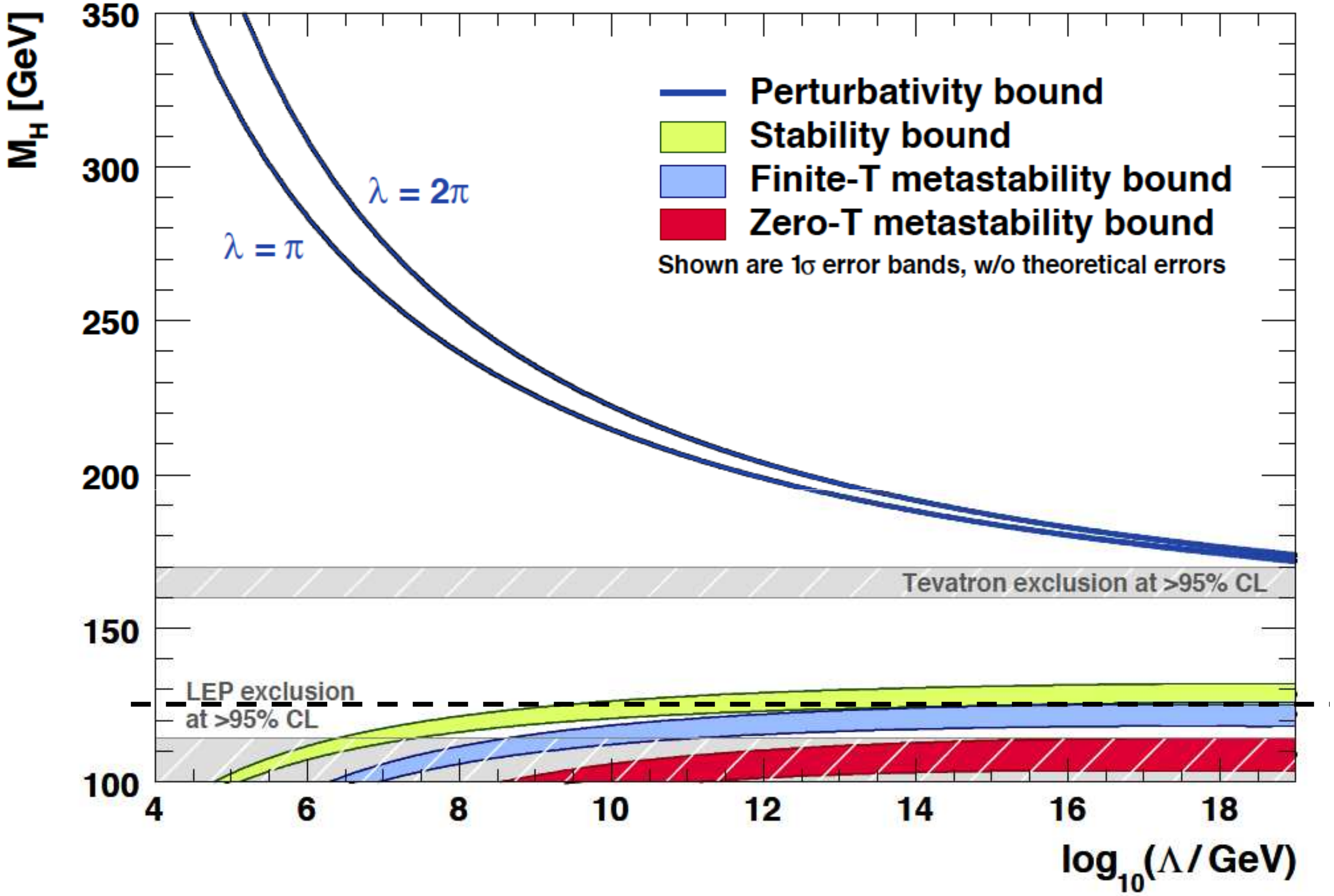
<1%

… et désintégration.



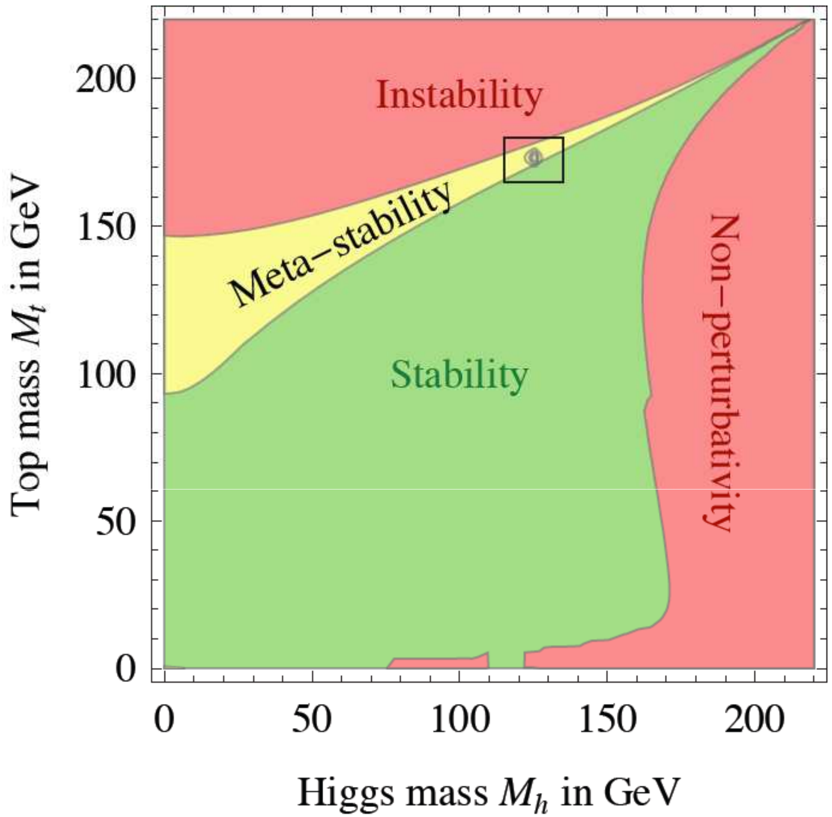
- De nombreux modes de désintégrations accessibles au LHC @ 125 GeV !
- Une chance pour les mesures de couplage !

Spéculations à l'échelle de Planck : Stabilité du vide



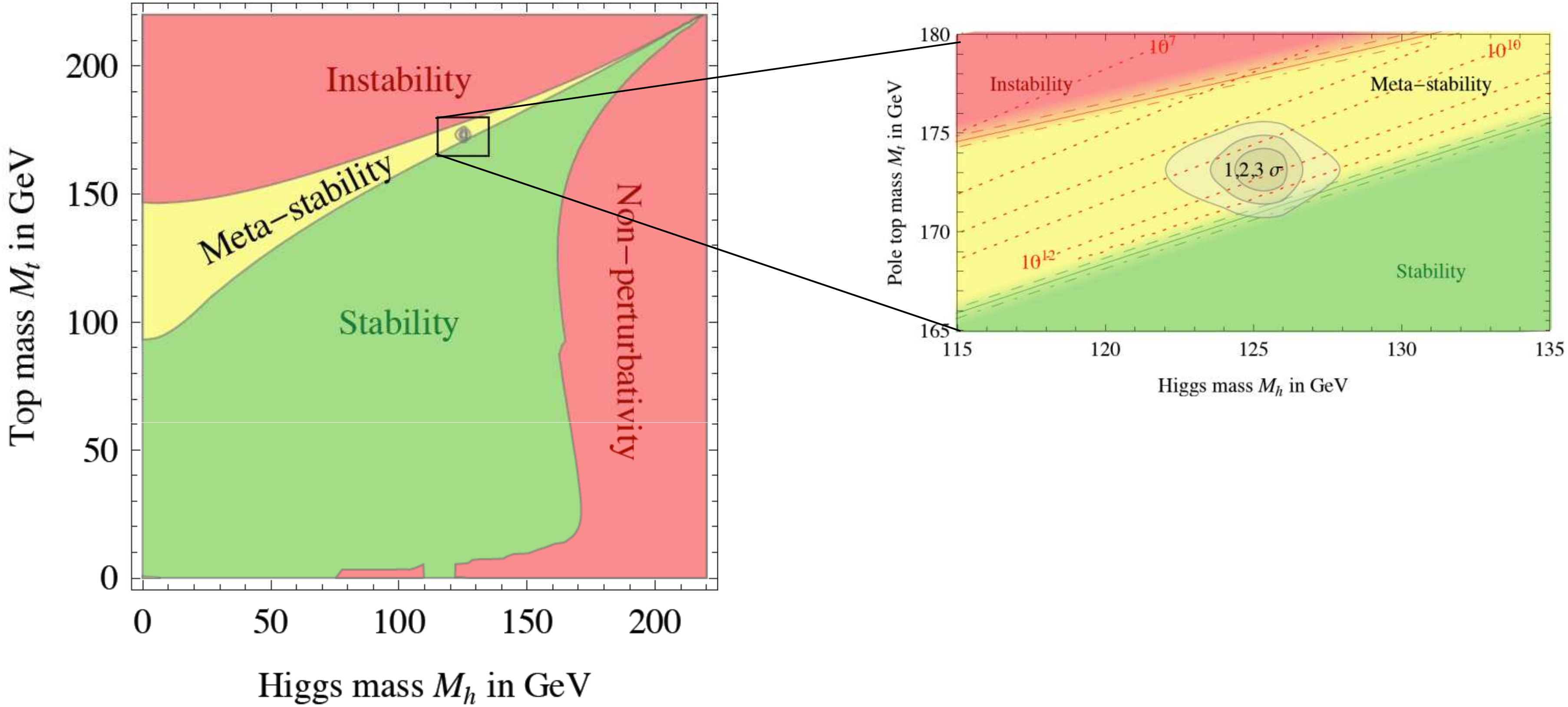
Pour mH ~ 125 GeV, nous sommes probablement dans une région où le potentiel de Higgs n'est pas stable…

Spéculations à l’échelle de Planck : une région particulière…



G. Degrassi et al., **JHEP 1208 (2012) 098**

Spéculations à l'échelle de Planck : une région particulière…



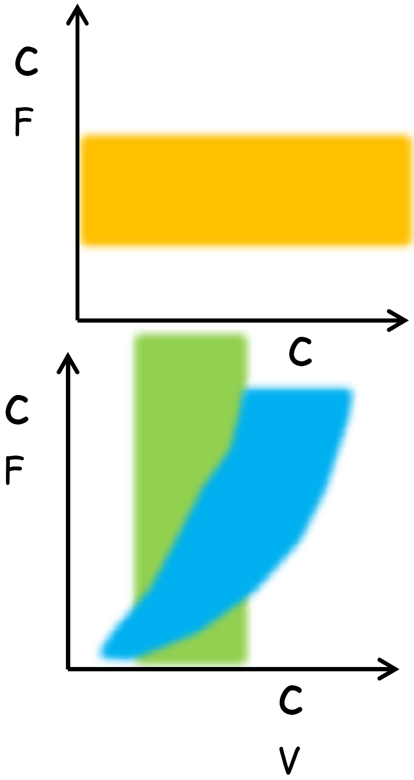
- **Nous vivons dans une région très particulière de l'espace des paramètres…**
- **Mesurer m_{top} & m_H avec grande précision est nécessaire !**

G. Degrassi et al., **JHEP 1208 (2012) 098**

Test des Couplages Fermioniques et Bosoniques

Test compatibility w.r.t SM predictions by introducing two parameters (c_V, c_F) modifying the expected signal yields in each mode through simple LO expressions

Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4 / C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^4 / C_F^2$



CP

arXiV:0708.0458

Difficult to separate a pure CP state from an admixture of CP-even and CP-odd components

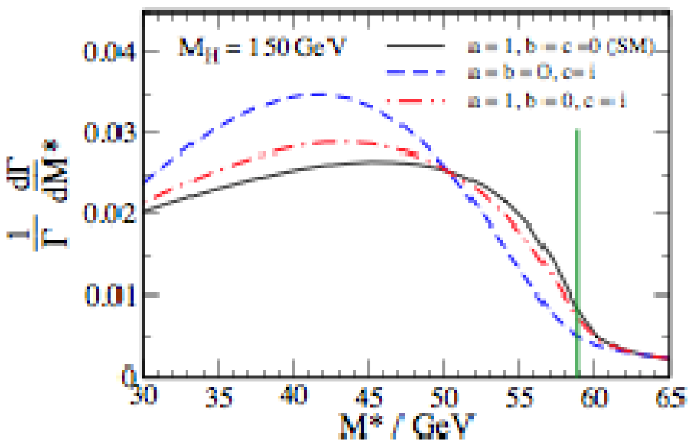
Profiting of the fully reconstructed kinematics of the H →ZZ decay modes

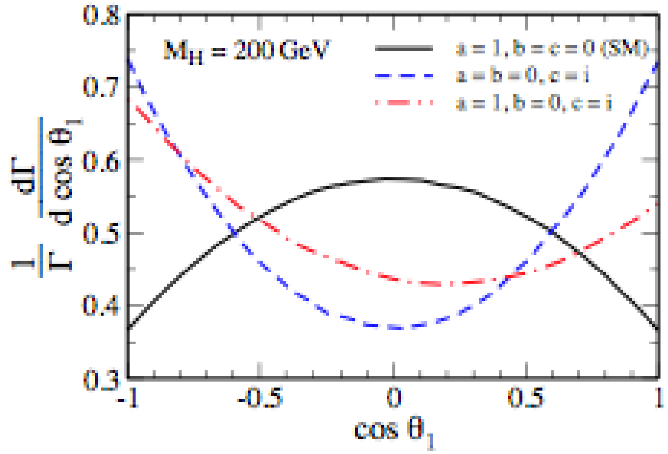
$$V^{\mu\nu}_{HZZ} = \frac{i g m_Z}{\cos\theta_W}\left[a\, g_{\mu\nu} + b\,\frac{p_\mu p_\nu}{m_Z^2} + c\,\epsilon_{\mu\nu\alpha\beta}\frac{p^\alpha k^\beta}{m_Z^2}\right]$$

SM coupling (CP even) — CP even — CP odd

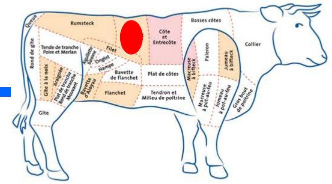
The SM is given by a=1, b=c=0
a can always be chosen to be real, but b and c can be complex

- m_{Z^*} hard to distinguish a CP mixed state
- Asymmetry for the CP mixed state in angular distributions





[Nombre Quantique] Spin : une approche naïve…



Nouveau boson : se désintègre en di-photons et ZZ.

Spin of particle	$\gamma\gamma$	ZZ^*	$\tau\tau$	bb
Spin 0	☺	☺	☺	☺
Spin 1	☹	☺	☺	☺
Spin 2	☺	☺	☹	☺
Seen?	Yes	Yes	Not yet	Not yet

Interdit par le théorème de Landau-Yang.

Il peut être de spin 0 ou 2

Couplings

Accurate prediction of the couplings

in SM and in any renormalized theory

$$\mathcal{L}^{eff}_{<m_h} \approx c_V\left(\frac{2m_W^2}{v}W_\mu^+ W_\mu^- + \frac{m_Z^2}{v}Z_\mu^2\right)h + c_b\frac{m_b}{v}\bar{b}bh + c_b\frac{m_\tau}{v}\bar{\tau}\tau h + c^\gamma\frac{2\alpha}{9\pi v}F_{\mu\nu}^2 h + c^g\frac{\alpha_S}{12\pi v}G_{\mu\nu}^2 h + \mathcal{L}(h \to inv)$$

in the SM:

$$c_V = c_b = c_\tau = c^\gamma = c^g = 1$$
$$\mathcal{L}(h \to inv) \approx 0$$

Assumptions

- The signals observed in the different channels originate from a single narrow resonance
- Zero-width approximation for the state
- CP-even state

$$(\sigma \times \mathrm{BR})(ii \to \mathrm{H} \to ff) = \sigma_{SM}(ii \to H) \times \mathrm{BR}_{SM}(\mathrm{H} \to ff) \times \frac{c_i^2 c_f^2}{c_\mathrm{H}^2}$$

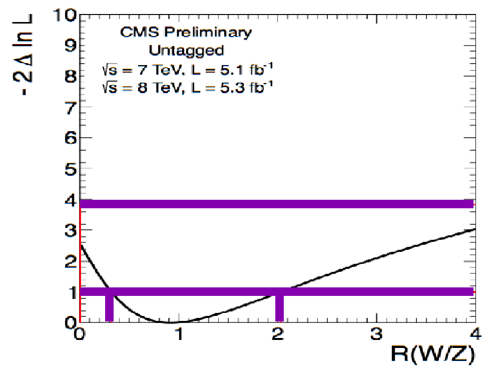
Couplings

Probing the custodial symmetry

Check that $c_V = c_W = c_Z$ using the WW and ZZ observed signal strength

Result compatible with SM
within the large uncertainties

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

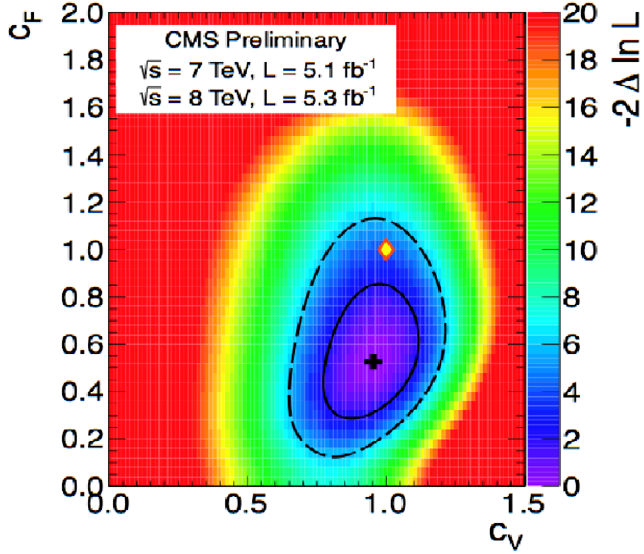


Scaling of fermions and bosons couplings

Introduced only two parameters
c_V and $c_F = c_b = c_t = c_\tau$

Best fit c_F driven to low values by
VBF γγ excess and ττ deficit

Data compatible with
SM prediction at 95% C.L.



Couplings

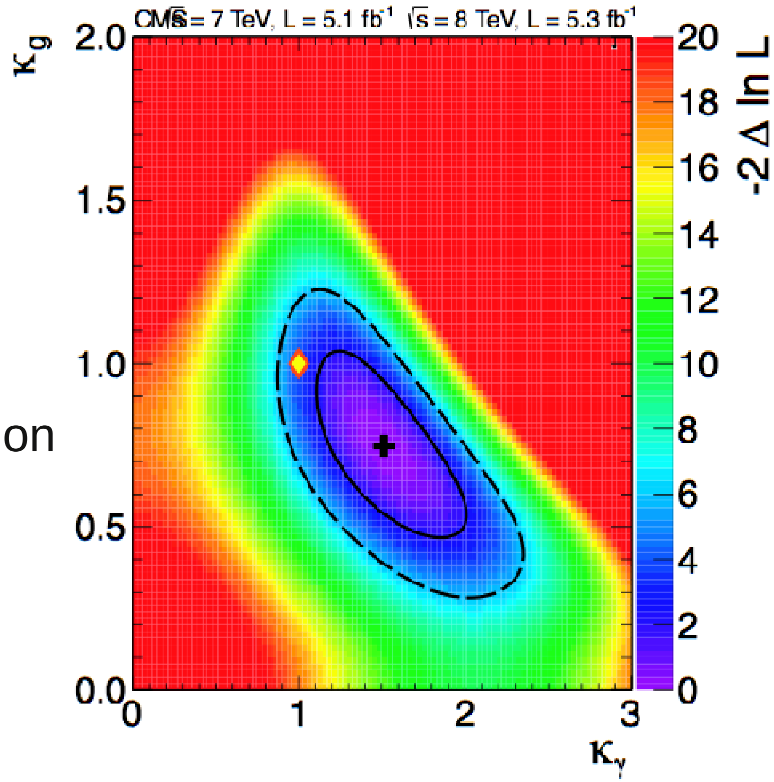
arXiV:1209.0040

Going from 2 to 5

Probing the fermion sector

In extension of the SM the Higgs bosons couple differently to different types of fermions

- up-type fermions vs down-type fermions
- quarks vs leptons



Probing the loop structure and invisible or undetectable decays

Allow new physics in loop-induced couplings to gluon and photons and assume no BSM decay modes

Parametrization without assumptions on new physics contributions

Spin

arXiV:0905.4314
arXiV:1208.6002

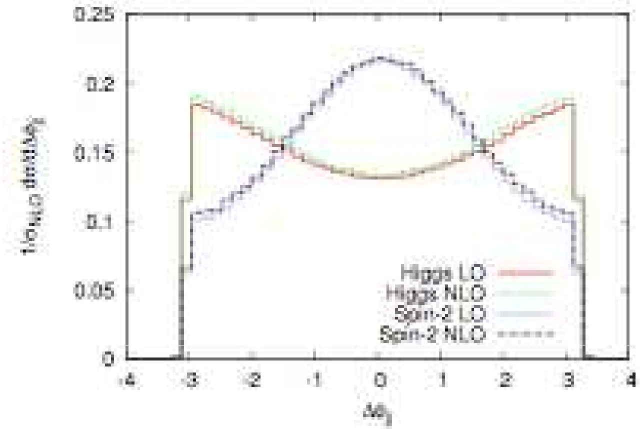
Spin 0 vs. Spin 2: VBF signature

VBF is expected to be the 7% of the SM production rate, jet tagging ID will reduce the experimentally observed rate even further

qq→H →VV

Azimuthal angle difference of the two tagging jets

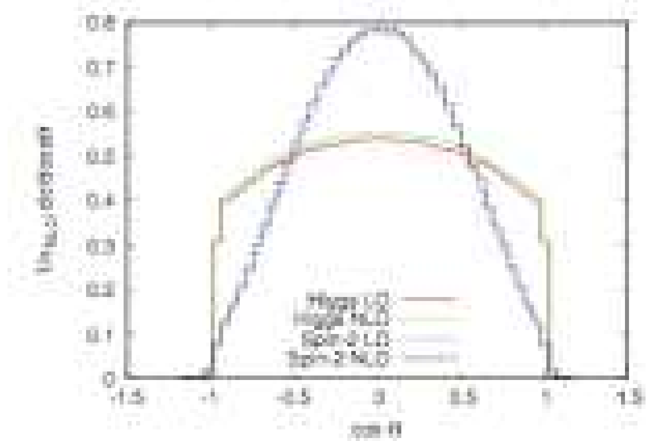
Independent of NLO corrections and Spin-2 couplings



qq→H →γγ

Angle between the momentum of an initial-state electroweak boson and an outgoing photon in the rest frame of the resonance

Analogous distribution: cosine of the angle between a final-state photon and the first or second tagging jet in the rest frame of the resonance



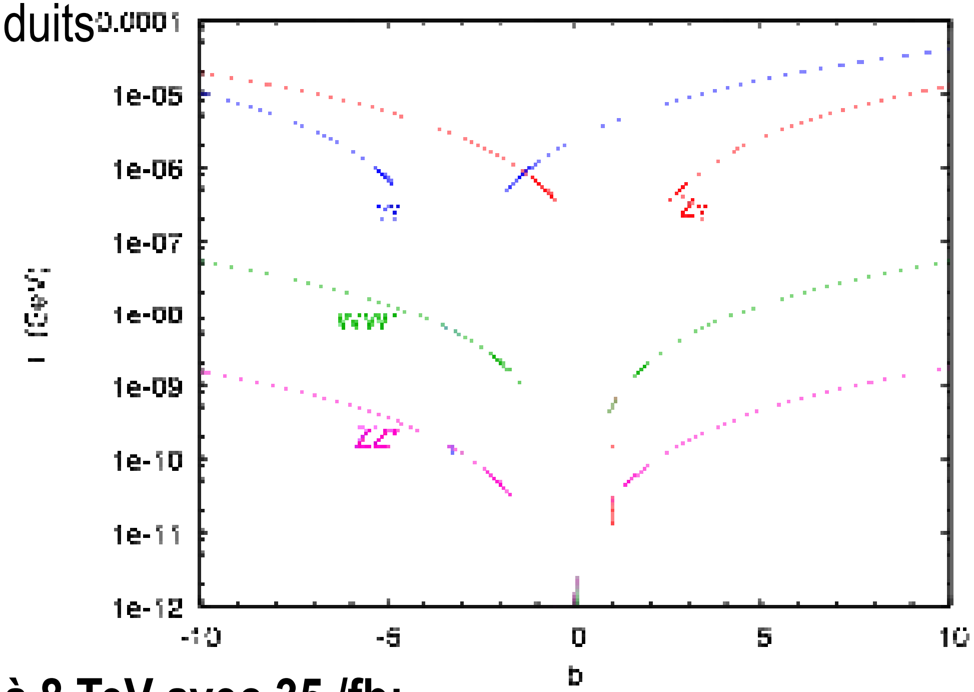
Spin 0 vs. Spin 2: VH signature

'Higgs' + gauge boson invariant-mass distribution

[Quantum Number] Parité

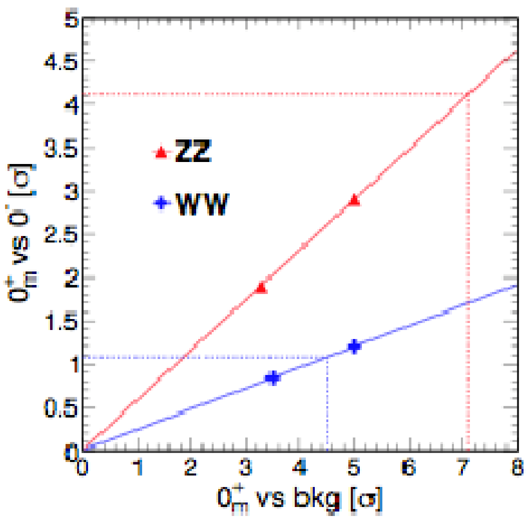
Tentant : hypothèse pseudo-scalaire (0-) est exclue…

Corrélations entre les BR's pseudo-scalaires induits par des boucles: γγ, Zγ, ZZ et WW



En utilisant les taux de γγ et ZZ observés, on peut prédire ceux de WW et Zγ:

Taux$_{(0-)\rightarrow WW}$ = (Taux$_{H\rightarrow WW}$) / 440
Taux$_{(0-)\rightarrow Z\gamma}$= (Taux$_{H\rightarrow Z\gamma}$) x 170



➢ **Projections à 8 TeV avec 35 /fb:**

scenario	$X \rightarrow ZZ$	$X \rightarrow WW$
0^+_m vs background	7.1	4.5
0^+_m vs 0^-	4.1	1.1

arXiV:1208.2692
arXiV:1208.4018

A considérer aussi: 0+/0- mixing…

BR

Production cross section at 8 TeV

>20K Higgs/fb

Decay branching ratio

Process	Cross Section (pb)
gg	19.5 (±14%)
VBF	1.6 (±3%)
VH	0.70 (±4%)
ZH	0.39 (±5%)
ttH	0.13 (±17%)

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

fermions

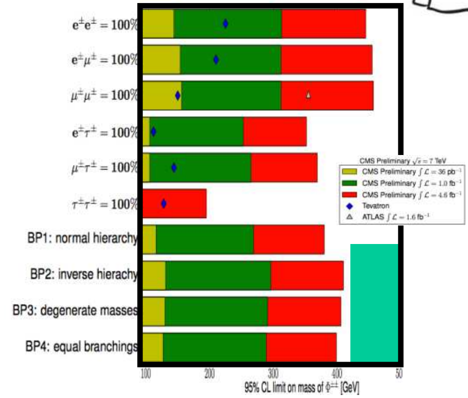
gauge bosons

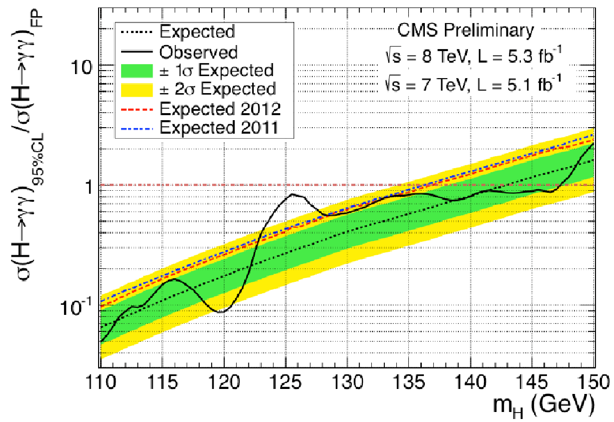
More states? Composite?

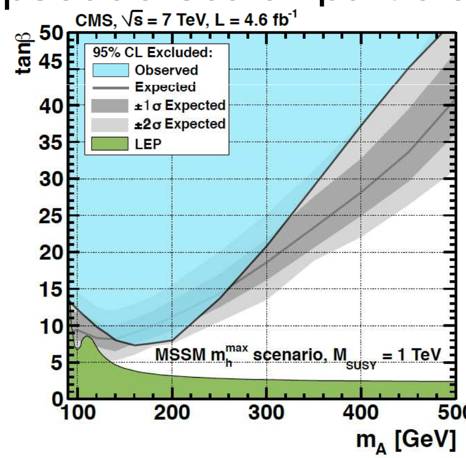
No evidence for any excess above backgrounds
Strong constraints imposed

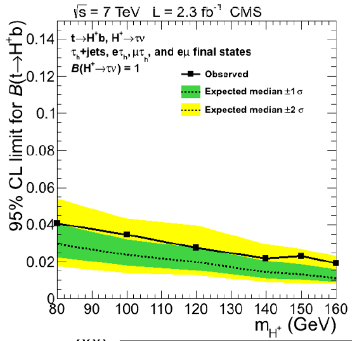
Fermiophobic / SM4 / Technicolor

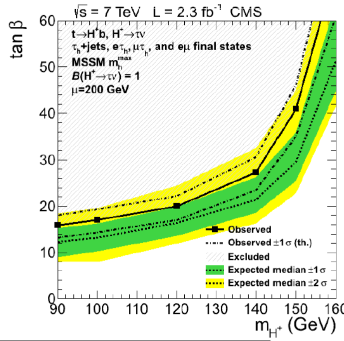
MSSM charged Higgs
MSSM neutral Higgs
Higgs doubly charged
Higgs decaying to light pseudo-scalar particles

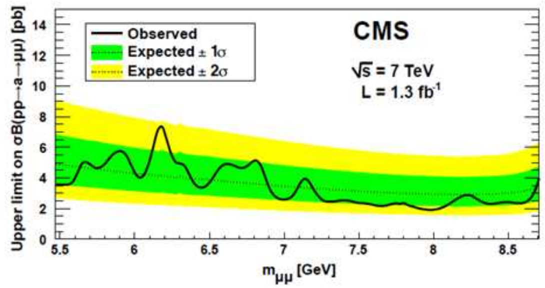


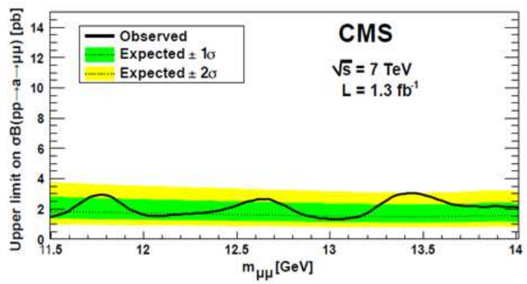


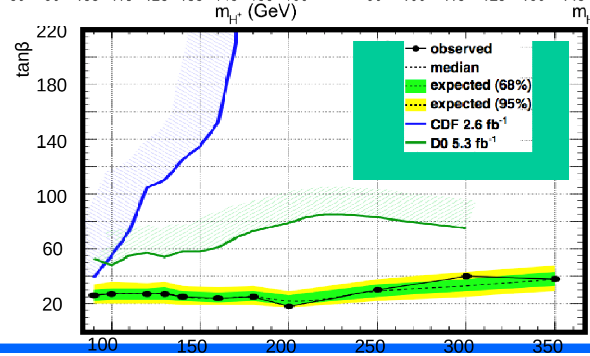












More states? Composite?

arXiV:1209.0040
arXiV:1003.3251

Decoupling limit

Many models has an extended Higgs sector allowing one Higgs boson SM like. The large uncertainties in the properties measurements leave room for these models

- The Two Higgs Doublet Models

different loop-induced couplings (top), enhanced $\gamma\gamma$ rate

- The Minimal Supersymmetric Standard Model

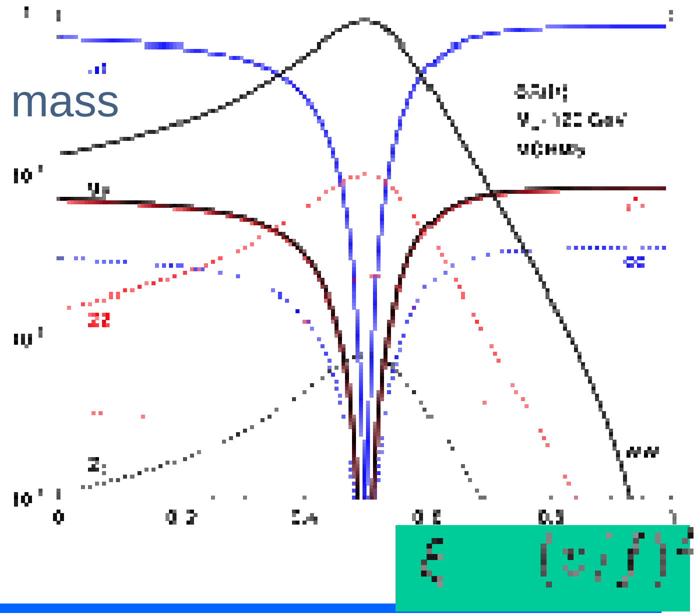
enhanced $\gamma\gamma$ rate and/or suppression of bb (and also $\tau\tau$)

- The Next to Minimal Supersymmetric Standard Model

3 CP-even Higgses ($h_{1,2,3}$) and two of them can be close in mass (almost degenerated) and one below the LEP limit

- A strongly interacting light Higgs

light and narrow Higgs-like scalar but it is a bound state from some strong dynamics, deviations from the SM Higgs couplings controlled by the parameter ξ



Self-interaction

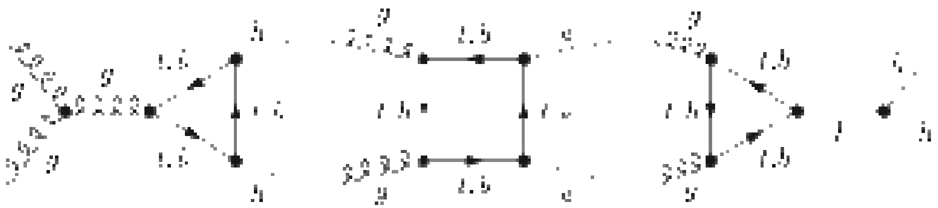
arXiv:0310056
arXiv:0211224
arXiv:0204087
arXiv:1206.5001

The measurement of the Higgs potential

Essential to fully reveal the nature of the mechanism responsible for EWSB

Two main components: the trilinear coupling (λ_{HHH}) and the quartic coupling (λ_{HHHH})

λ_{HHH} can be measured at LHC

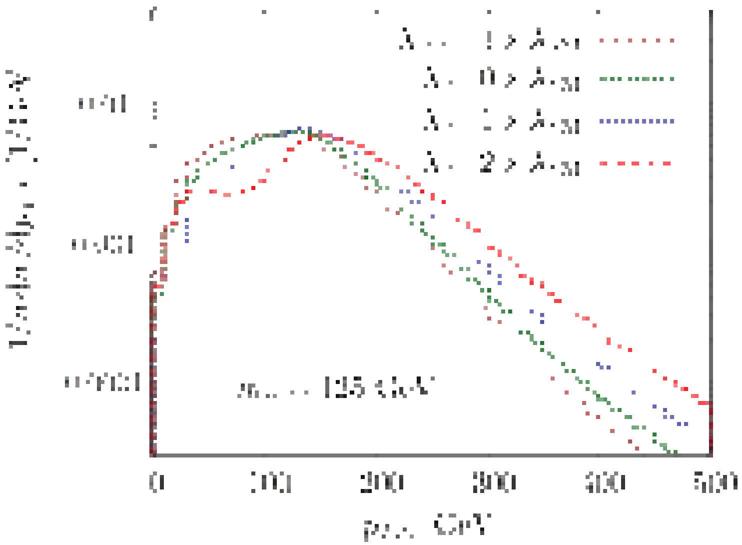


@ 14 TeV σ(pp → HH) = 34 fb

The HH → bbγγ channel has a BR of 0.27%

Predicted yield of ~10 events/100 fb^{-1} @ 14 TeV pp

After analysis cuts: S/B ratio ~0.7 (B is mainly ttH)

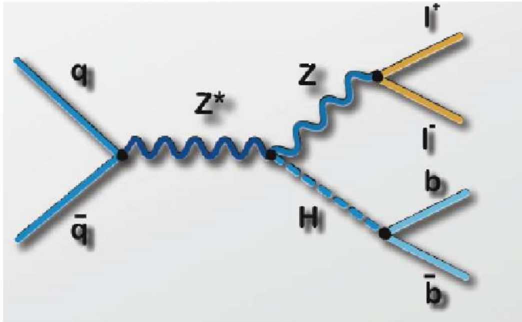


Using shape analysis to discriminate scenarii

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)

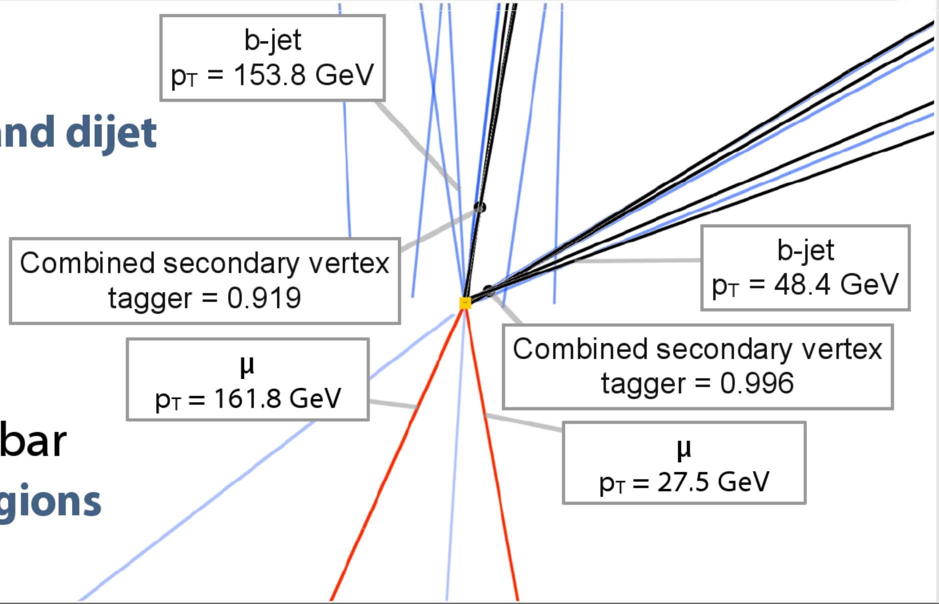
⇒Search in associated production with W or Z
final states with leptons, MET, and b-jets



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



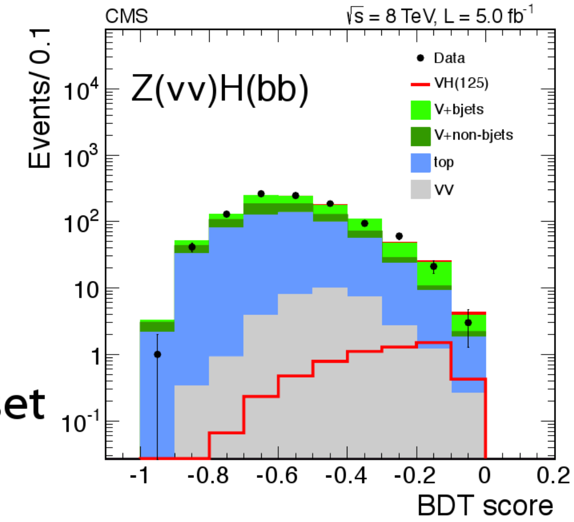
H→bb

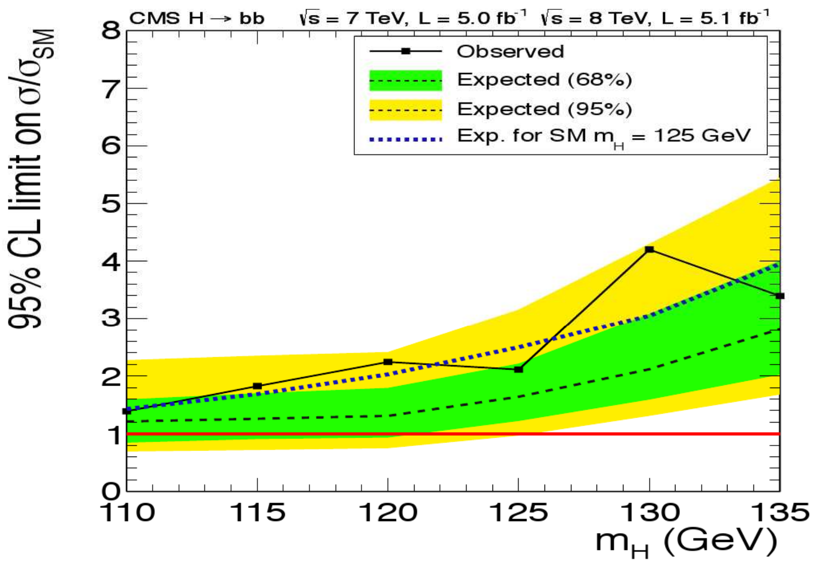
VH →Vbb (V→lν,ll,νν) - Results

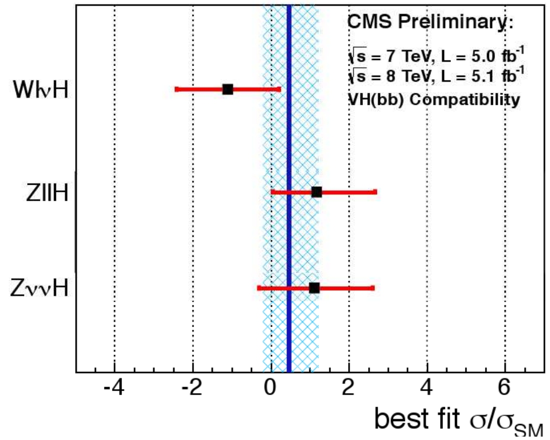
In 2012 many improvements w.r.t. 2011:

- 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

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

High σxBR at low mass

- **Sensitive to all production modes**
- **Probes coupling to leptons**
- **Enhanced σ x BR in MSSM**

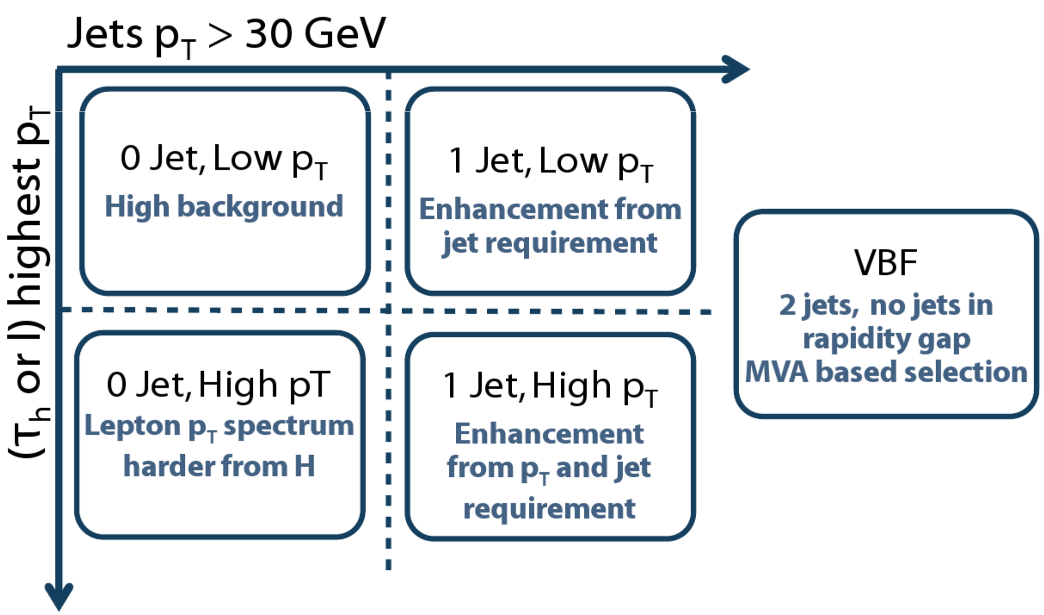
Challenging large backgrounds

DY→ττ, W+Jets, QCD

Analysis Strategy

Analysis divided into 5 categories mass resolution, S/B

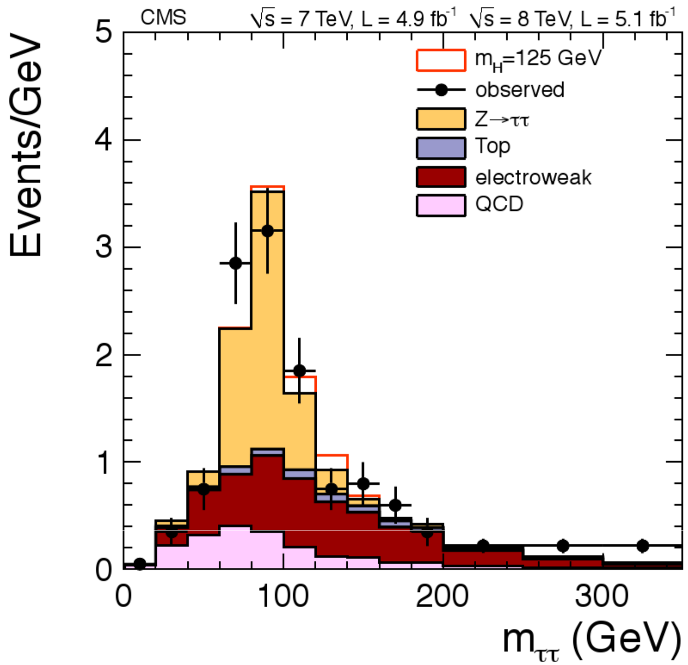
All categories are fit simultaneously

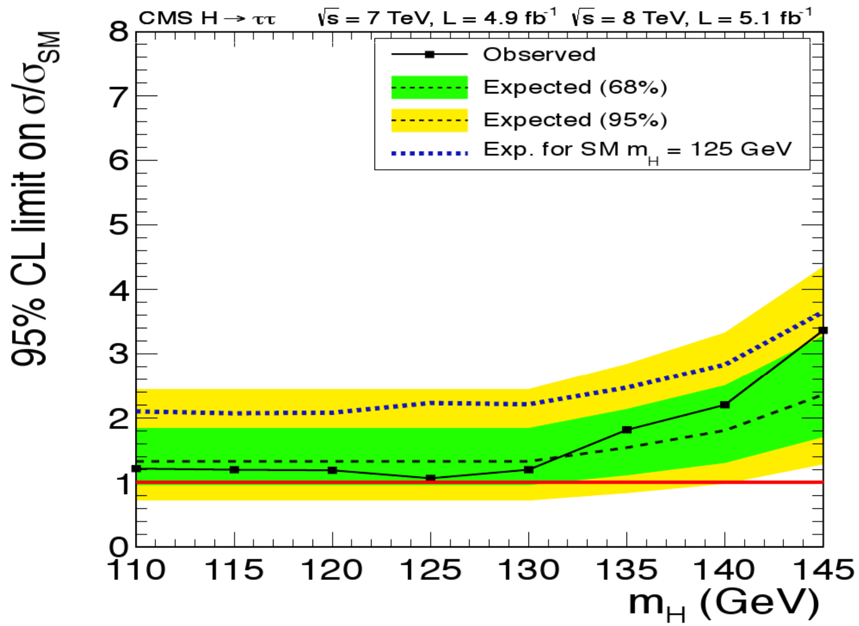


H →ττ →μτ$_h$, eτ$_h$, eμ, μμ - Results

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→ττ