

# Twenty Years of Searching for the Higgs Boson: Exclusion at LEP, Discovery at LHC

*Protvino XXX, Russia, 23-27 June 2014*

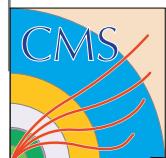
Dezső Horváth

on behalf of the CMS Collaboration

horvath.dezso@wigner.mta.hu

Wigner Research Centre for Physics,  
Institute for Particle and Nuclear Physics, Budapest, Hungary

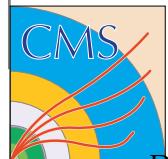
& ATOMKI, Debrecen, Hungary



# Outline

- The Higgs boson of the Standard Model
- Colliders at CERN
- Methods of the Search
- Exclusion at LEP
- Observation at LHC

With the support of the Hungarian OTKA Grants K-103917 and K-109703



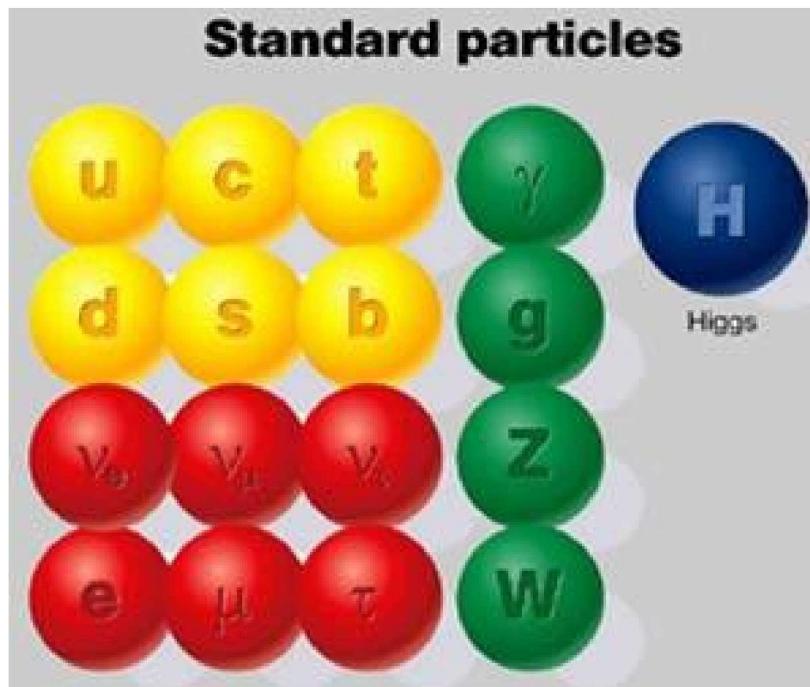
# References

- The LEP Collaborations: *Search for the Standard Model Higgs boson at LEP*, Phys. Lett. B 565 (2003) 61.
- The CMS Collaboration: *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B 716 (2012) 30-61.  
Long version: JHEP 1306 (2013) 081
- The ATLAS Collaboration: *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B 716 (2012) 1–29
- D. Horváth: *Twenty years of searching for the Higgs boson: exclusion at LEP, discovery at LHC*  
Modern Physics Letters A 29 (2014) 1430004.



# The Zoo of the Standard Model

## The elementary particles



3 fermion families:

1 pair of quarks and

1 pair of leptons in each

3 kinds of gauge bosons:  
the force carriers

All identified and studied!

+ the Higgs boson (!)

Color: the charge of the strong interaction  
colored quarks  $\Rightarrow$  colorless composite hadrons of 2 kinds  
hadrons = mesons ( $q\bar{q}$ ) + baryons ( $qqq$ )



# The Standard Model

Derive 3 interactions of local  $U(1)$ ,  $SU(2)$  and  $SU(3)$  symmetries

Unify and separate e-m  $U(1)$  and weak  $SU(2)$  interactions using spontaneous symmetry breaking:  
(Anderson-Brout-Englert- Higgs-Guralnik-Hagen-Kibble mechanism, 1963-64)

Add a 4-component, symmetry breaking BEH-field to vacuum.

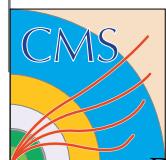
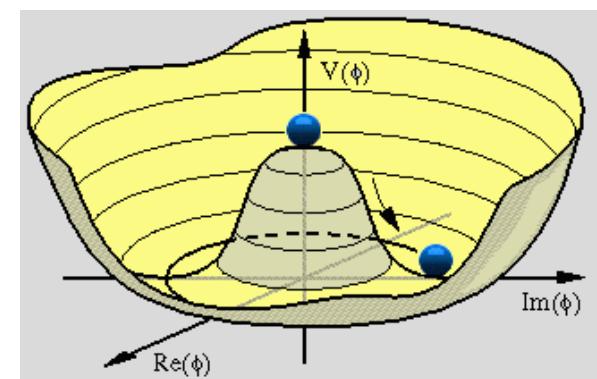
From the ruined  $U(1) \otimes SU(2)$  separate a good  $U(1)$  local symmetry



electromagnetism + zero-mass photon, OK!

Turn 3 d.f. of BEH-field to create masses for  $Z$ ,  $W^+$ ,  $W^-$ , get a correct weak interaction with 3 heavy gauge bosons.

4th degree of freedom: heavy scalar boson.



# Glory Road of the Standard Model

Present status (2012)

Includes hundreds of measurements of all experiments

$$\frac{|Expt - theory|}{expt. uncertainty}$$

Slightly deviating quantity used to change

Now it is forward-backward asymmetry of  
 $e^+e^- \rightarrow Z \rightarrow b\bar{b}$

LEP Electroweak Working Group:

<http://lepewwg.web.cern.ch/>



March 2012



# The Higgs boson of the Standard Model

Spinless, neutral, heavy particle

The scalar particle needed for renormalisation

SM: it must exist!

Many jokes were of the Higgs boson before the discovery

- The Higgs boson walks into a bar. The bartender says "Watch out, there were some guys looking for you."
- I'm trying to find a good Higgs joke. It may take years, but I'm sure it exists.
- The Higgs boson walks into a church. The priest says "Your kind is not welcome here". The boson replies: "But without me how can you have mass?" (*Mass: Inertia, people, ceremony*)
- The Higgs boson walks into a bar. The bartender does not understand...



# Luminosity: collision rate

Luminosity:

$$L = fn \frac{N_1 N_2}{A}$$

$$[L] = \text{s}^{-1} \text{cm}^{-2} \quad (\sim \text{flux})$$

$f$ : circulation frequency;  $n$ : nr. of bunches in ring;  
 $N_1, N_2$  particles/bunch;  $A$ : spatial overlap

Rate of reaction with cross section  $\sigma$  at efficiency  $\epsilon$

$$R = \epsilon \sigma L$$

Integrated luminosity:  $\int_{t_1}^{t_2} L dt$

measured in units of inverse cross-section:

$$[\text{pb}^{-1}, \text{fb}^{-1}]$$

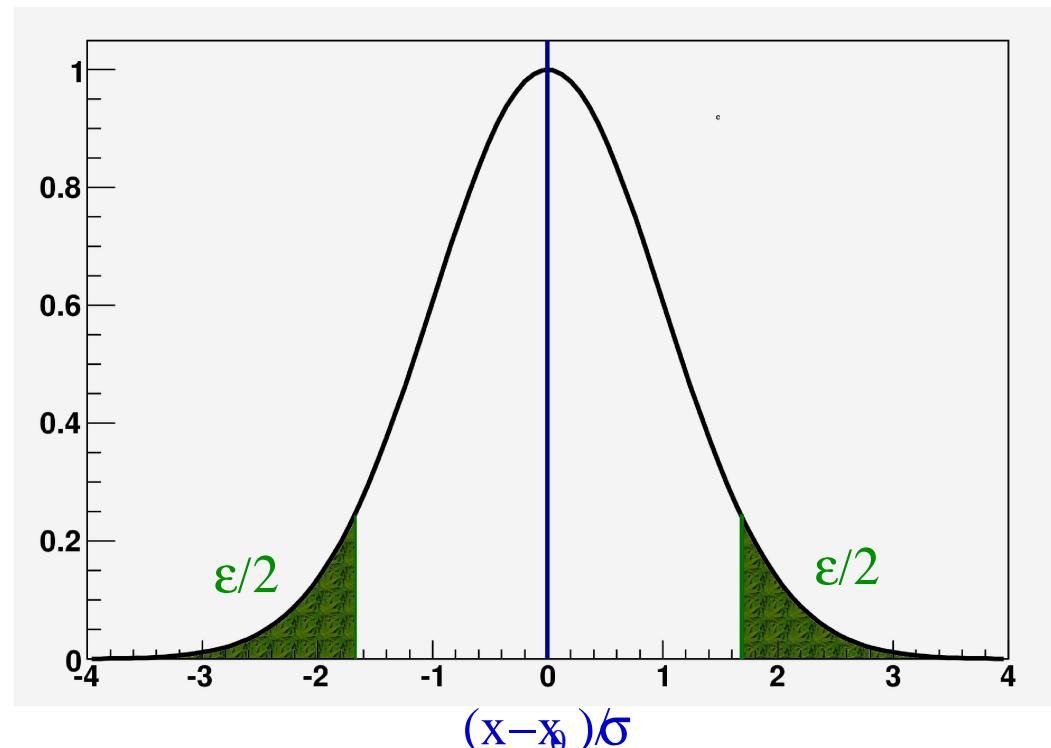


# Exclusion and Discovery

General convention in accelerator experiments:

Exclusion of a given phenomenon at  
 **$\geq 95\%$  confidence level.**

Observation of something new:  
 **$> 5\sigma$  above background.**



One-sided exclusion:  
 **$X > X_0$  at 95% CL if  $X_{\text{obs}} - X_0 > 1.64\sigma$**



# And what is $\sigma$ ?

The total uncertainty of the physics parameters  $P$  according to the best honest guess of the experimentalist.

It has a **statistical component**  
(from the number of observed events)

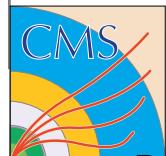
and **systematic** ones from various sources:

Monte Carlo statistics and inputs, calibration factors, efficiencies, etc. (**nuisance parameters  $\Theta$** ) could be added up with correlations accounted for with a

final uncertainty roughly:  $\sigma = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2}$

However, we derive the final uncertainty via marginalizing (integrating out) the nuisance parameters in likelihood  $\mathcal{L}$  using the related probability distributions  $\mathcal{W}$ :

$$\mathcal{L}(P; x) = \mathcal{W}(x|P) = \int \mathcal{W}(x|P, \Theta) \mathcal{W}(\Theta|P) d\Theta$$



# Blind Analysis

“A blind analysis is a measurement which is performed without looking at the answer. Blind analyses are the optimal way to reduce or eliminate experimenter’s bias, the unintended biasing of a result in a particular direction.”

A. Roodman: *Blind Analysis in Particle Physics*,  
<http://arxiv.org/abs/physics/0312102>, SLAC, 2003

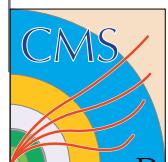
Originally coming from medicine

Basic analysis method of searches at LEP and LHC:

Optimize, prove and publish your analysis technique using simulations and earlier data only before touching new data in the critical region

CMS, 2012:  $110 < M_H < 140$  GeV blinded  
because of  $3\sigma$  excess observed in 2011

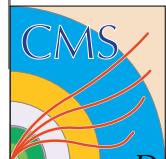
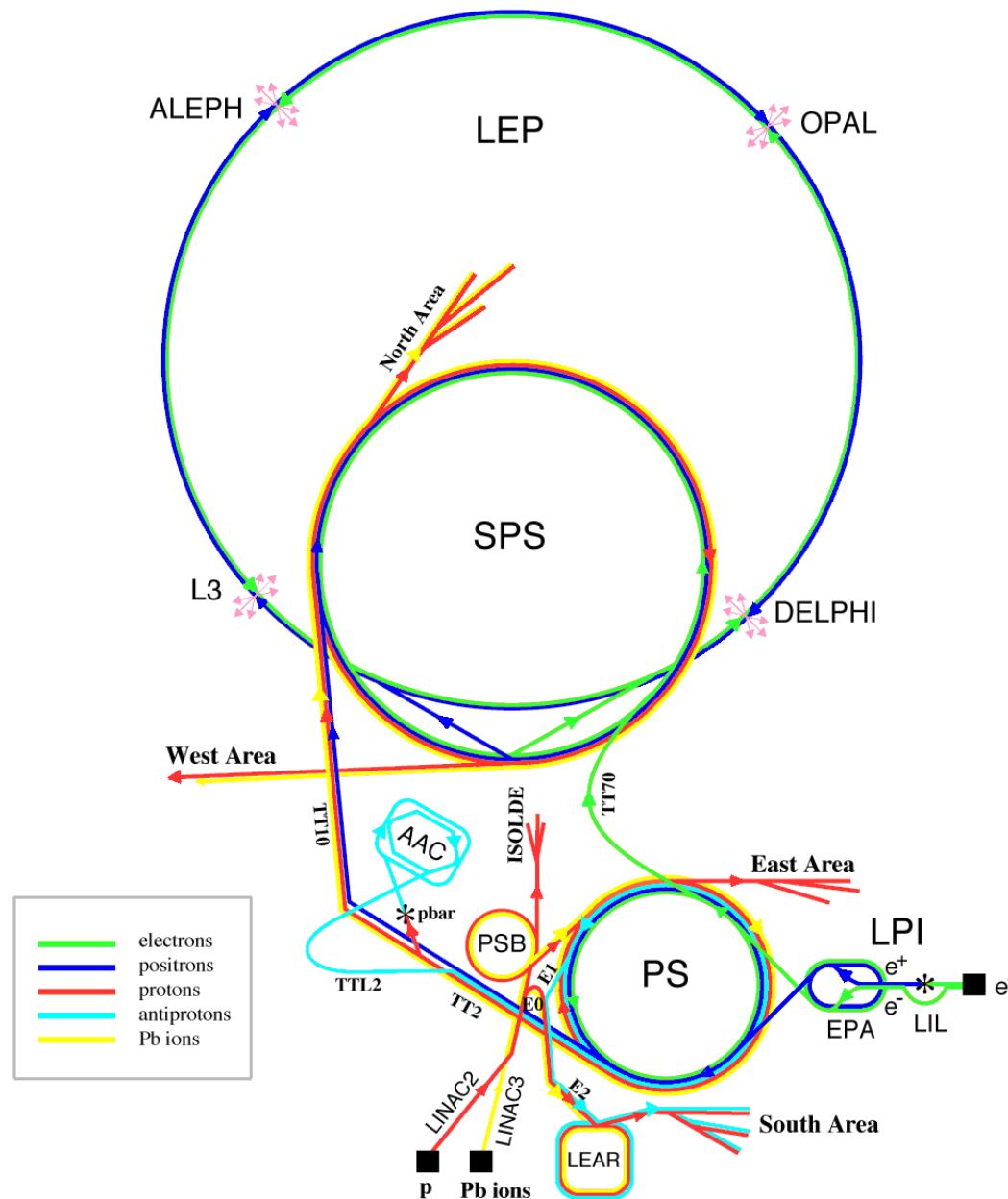
Simultaneous *unblinding* for all analysis channels



# The Large Electron Positron collider

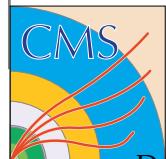


# Accelerators at CERN, LEP era



# The LEP Collider

Year	$E(e^+e^-)$ , GeV	$\int L dt/4$ , pb $^{-1}$	main goal
1989–94	~ 91	140	$Z^0$
1995	130–136	5	
1996	161–172	20	$W^+W^-$
1997	184	60	$WW, ZZ$
1998	189	190	$WW, ZZ$
1999	192–202	220	Higgs
2000	204–209	220	Higgs



# Search for the SM Higgs boson at LEP

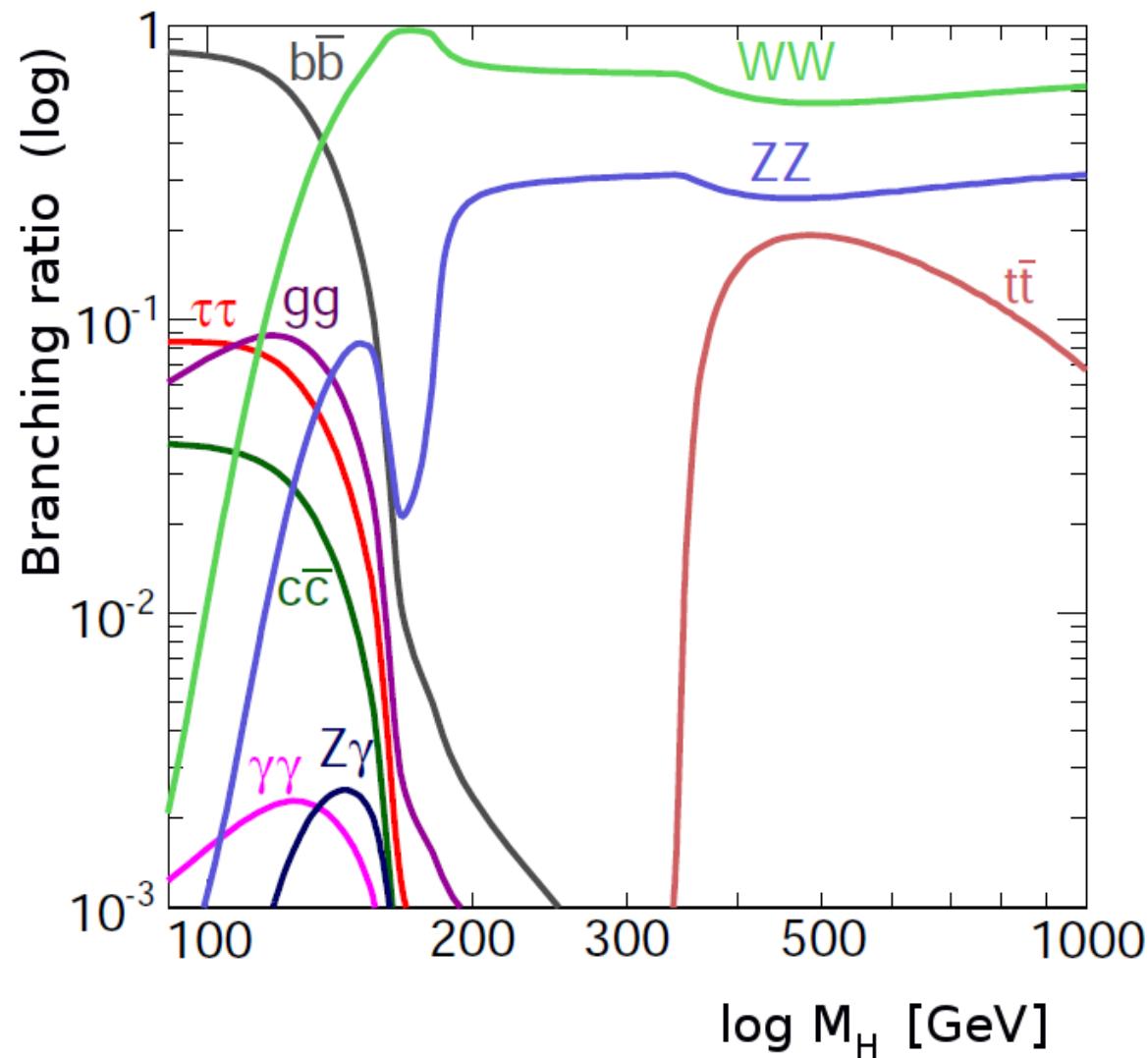
Dominant formation:

Higgs-strahlung

$$e^- e^+ \rightarrow ZH$$

Dominant decay:

$$H \rightarrow b\bar{b}$$



Various analyses for different  $Z$  decays



# What is observed: resonance

$\tau = \Gamma^{-1}$  lifetime  $\Rightarrow$  exp. decay:  $N(t) = N_0 e^{-\Gamma t}$

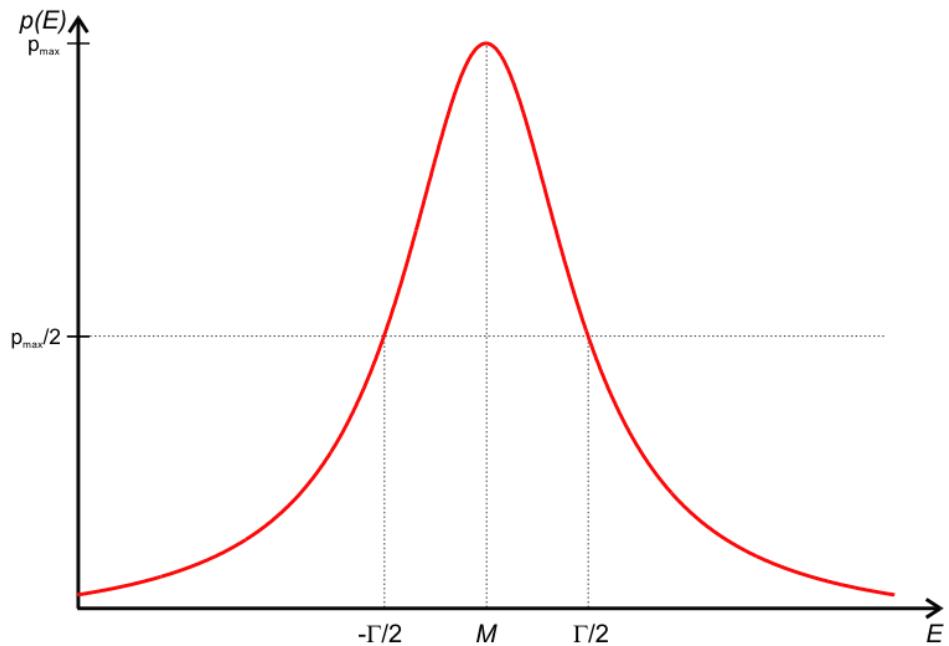
Probability distribution:

$$|\chi(E)|^2 = \frac{1}{(E-M)^2 + \Gamma^2/4}$$

Breit-Wigner equation

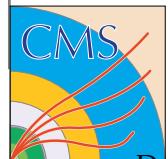
$$\left. \begin{array}{c} M \\ \Gamma \end{array} \right\} \text{resonance} \left\{ \begin{array}{c} \text{centre} \\ \text{width} \end{array} \right.$$

$$(\hbar = 1, c = 1)$$



Lorentz curve

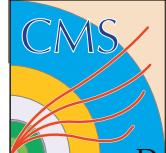
New particle discovery: resonance at decay energy corresponding to the particle mass



# Hunting the Higgs boson

- Compose a complete SM background using Monte Carlo simulation taking all types of possible events normalized to their cross-sections.
- Higgs signal: simulation of all possible production and decay processes with all possible Higgs-boson masses
- Put all these through the **detector simulation** to get events analogous to the measured ones.
- Optimize the event selection: reduce  $B$  background, enhance  $S$  signal via maximizing e.g.  
 $N_S/\sqrt{N_B}$  or  $N_S/\sqrt{N_S + N_B}$  or  $2 \cdot (\sqrt{N_S + N_B} - \sqrt{N_B})^\dagger$
- Calculate at experimental luminosity expected nr. of events for signal and background at various conditions.
- SM background  $\sim$  experiment? (**YES**  $\downarrow$  / **NO**  $\uparrow$ ).

<sup>†</sup>Bityukov and Krasnikov, 1999



# Hypothesis Testing: Test Statistic

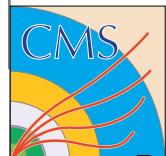
Likelihood ratio: signal+background/background  $Q = \mathcal{L}_{s+b}/\mathcal{L}_b$

Usually analysed and plotted:

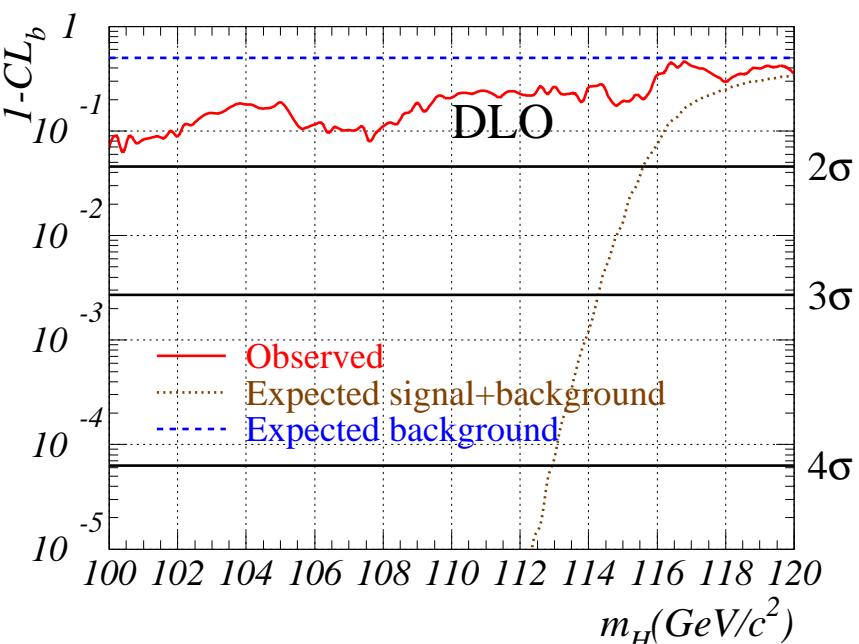
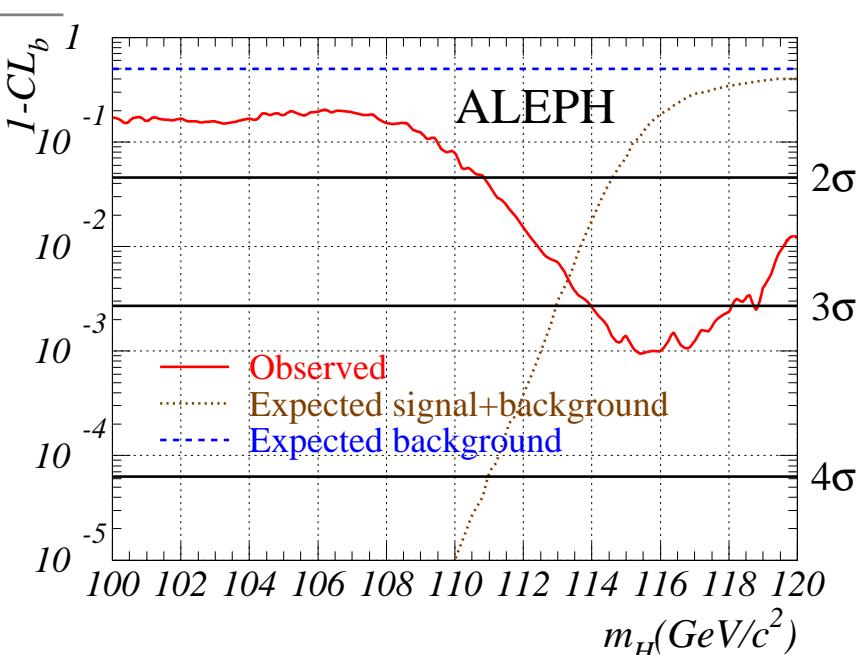
$$-2 \ln Q(m_H) =$$

$$2 \sum_{k=1}^{N_{\text{ch}}} \left[ s_k(m_H) - \sum_{j=1}^{n_k} \ln \left( 1 + \frac{s_k(m_H) S_k(x_{jk}; m_H)}{b_k B_k(x_{jk})} \right) \right]$$

- $n_k$ : events observed in channel  $k$ ,  $k = 1 \dots N_{\text{ch}}$
- $s_k(m_H)$  and  $b_k$ : signal and background events in channel  $k$  for Higgs mass  $m_H$
- $S_k(x_{jk}; m_H)$  and  $B_k(x_{jk})$ : probability distributions for events for Higgs mass  $m_H$  at test point  $x_{jk}$
- $x_{jk}$ : position of event  $j$  of channel  $k$  on the plane of its reconstructed Higgs mass and cumulative testing variable constructed of various features of the event like b-tagging, signal likelihood, neural network output, etc.



# No Higgs at LEP: $M_H > 114.4$ GeV

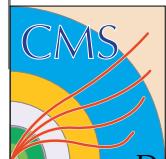


Expected and observed signal confidence level  
assuming background only

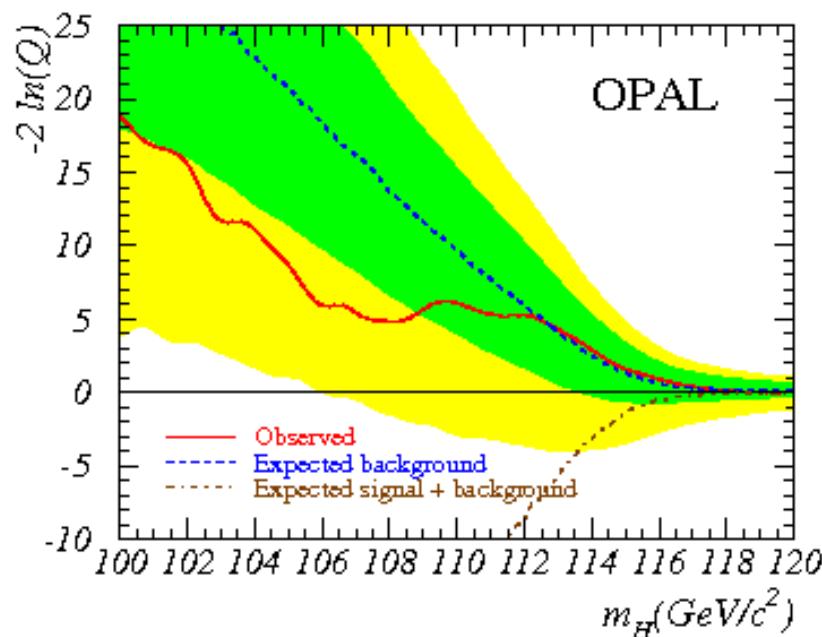
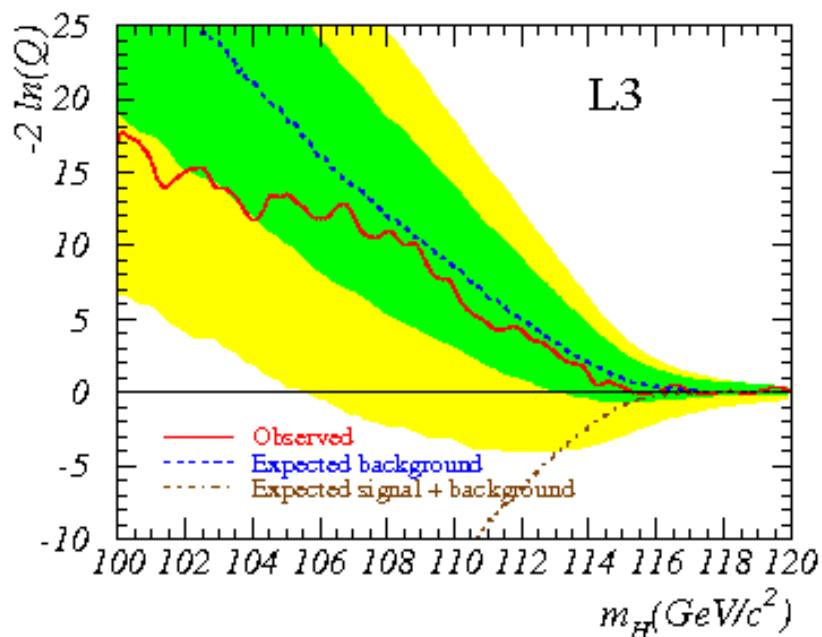
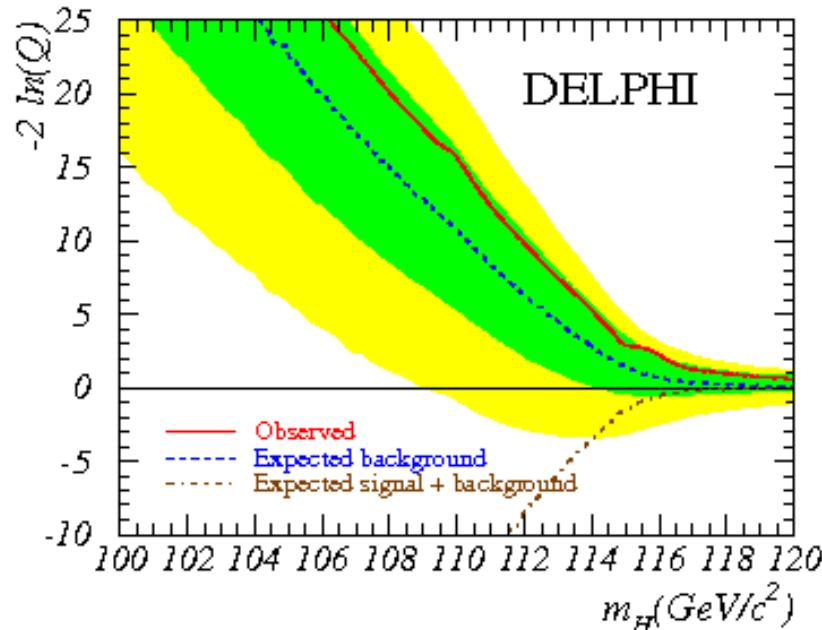
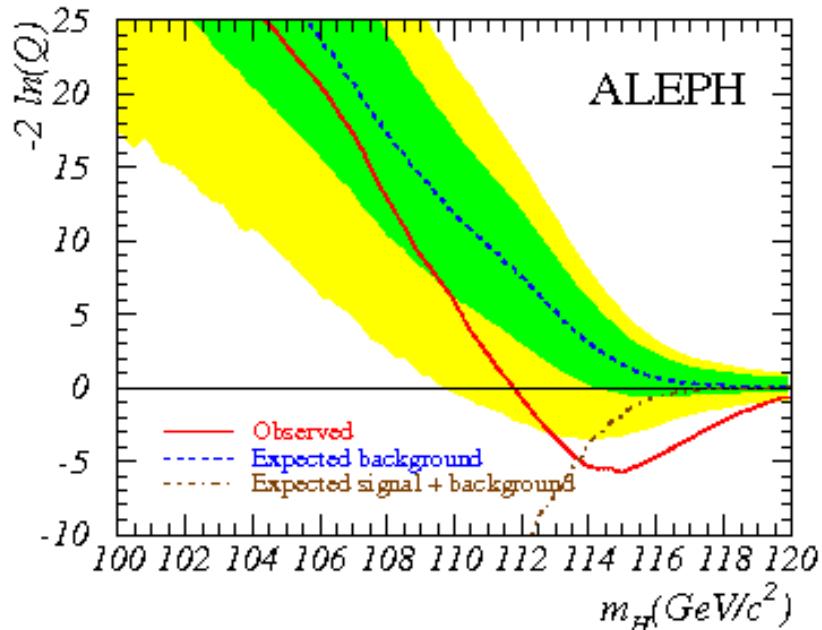
(ALEPH, DELPHI, L3 and OPAL: Phys. Lett. B 565 (2003) 61-75.)

Excess in ALEPH's 4-jet events at 115 GeV:

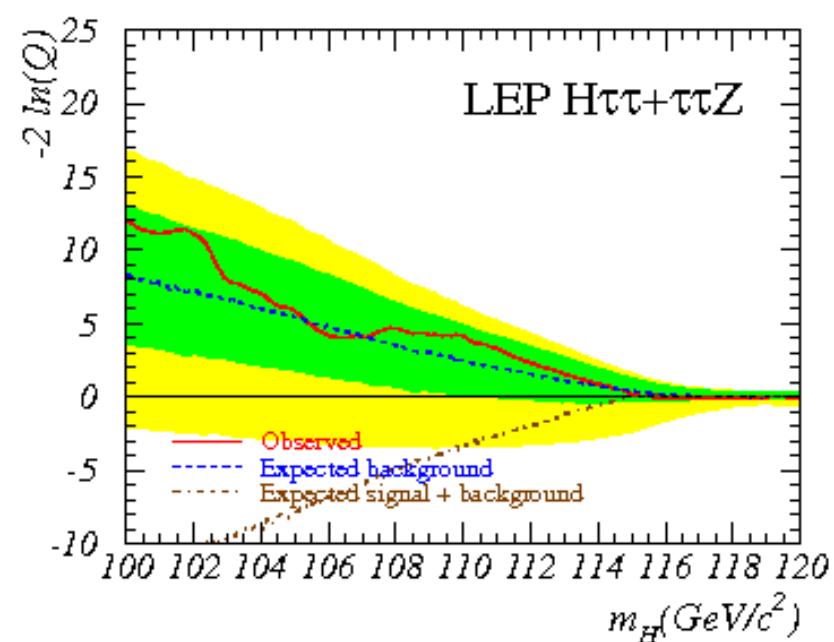
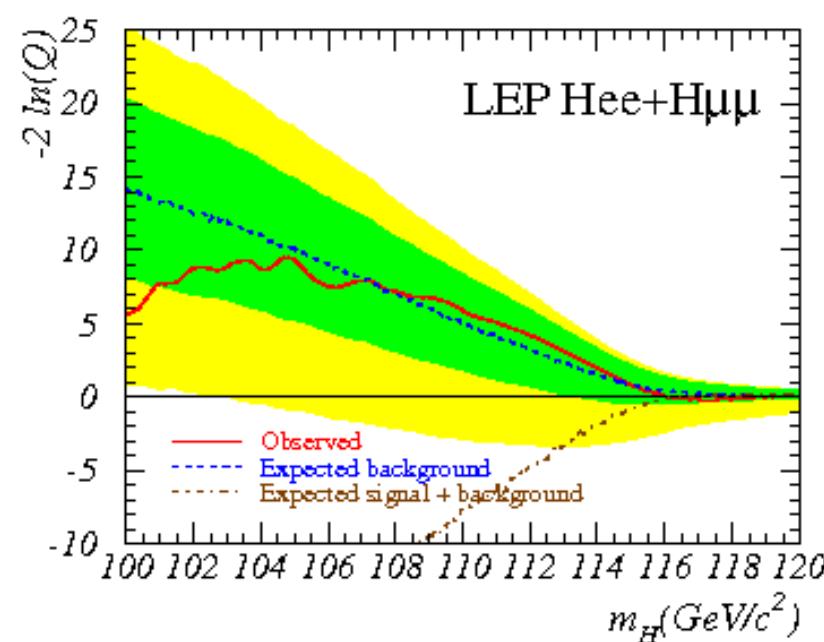
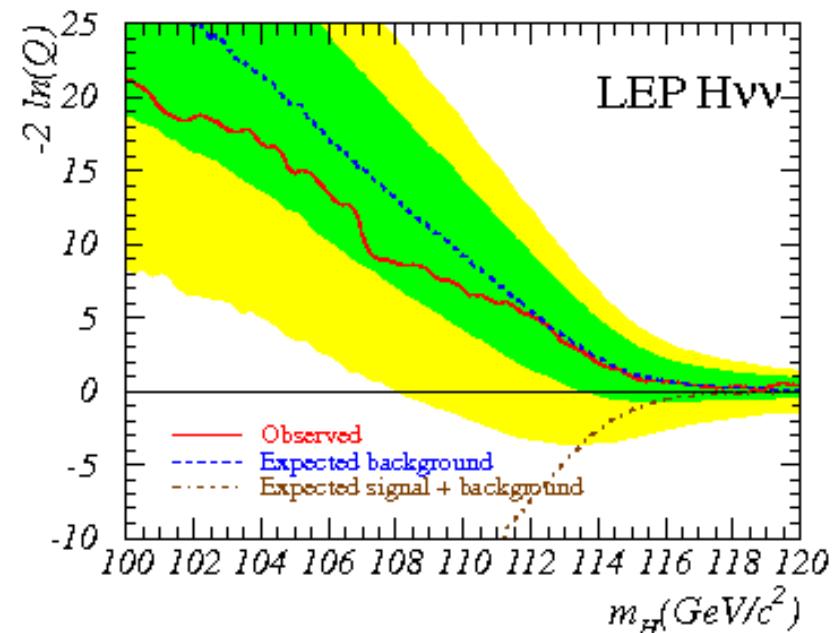
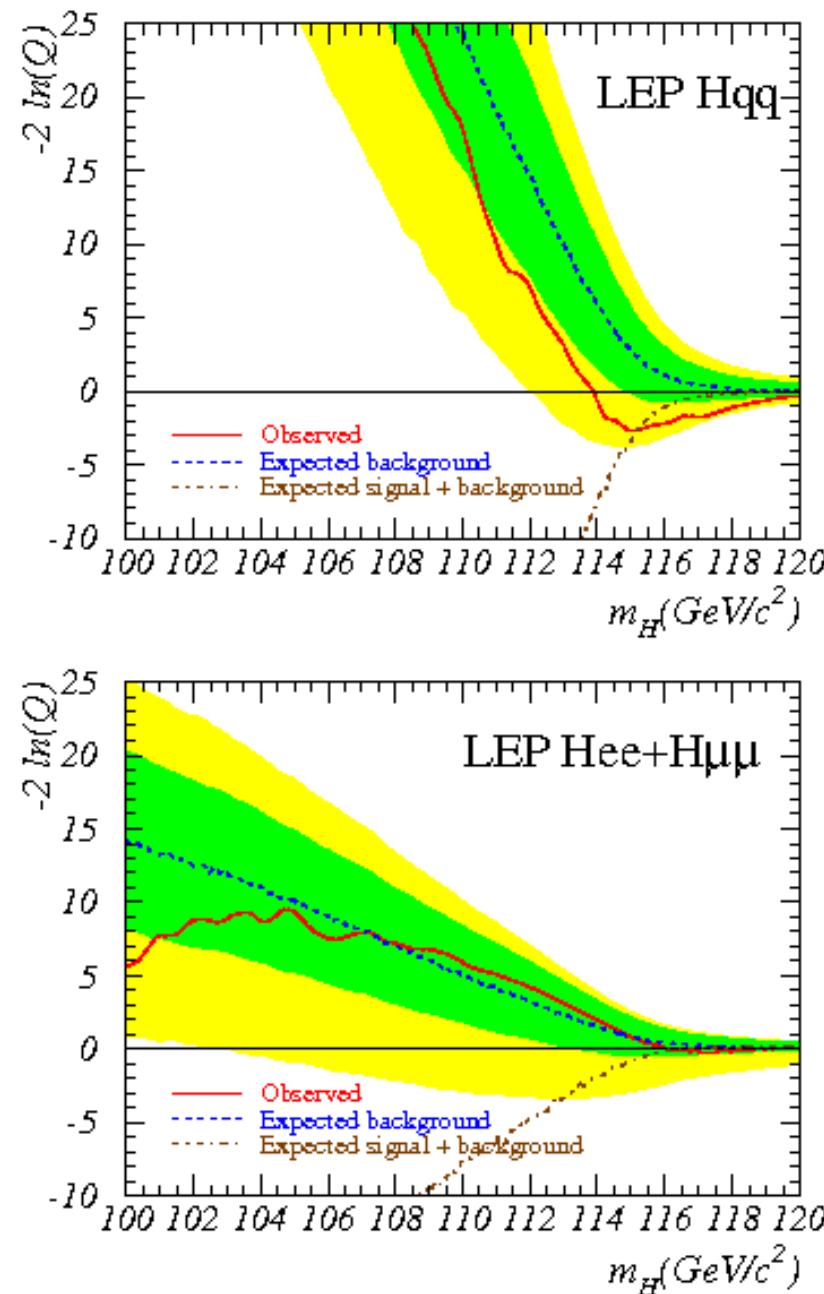
$$\bar{E}_{\text{LEP2000}} = 206 \text{ GeV} \quad m_H(115) + m_Z(91) = 206 \text{ GeV} !!$$



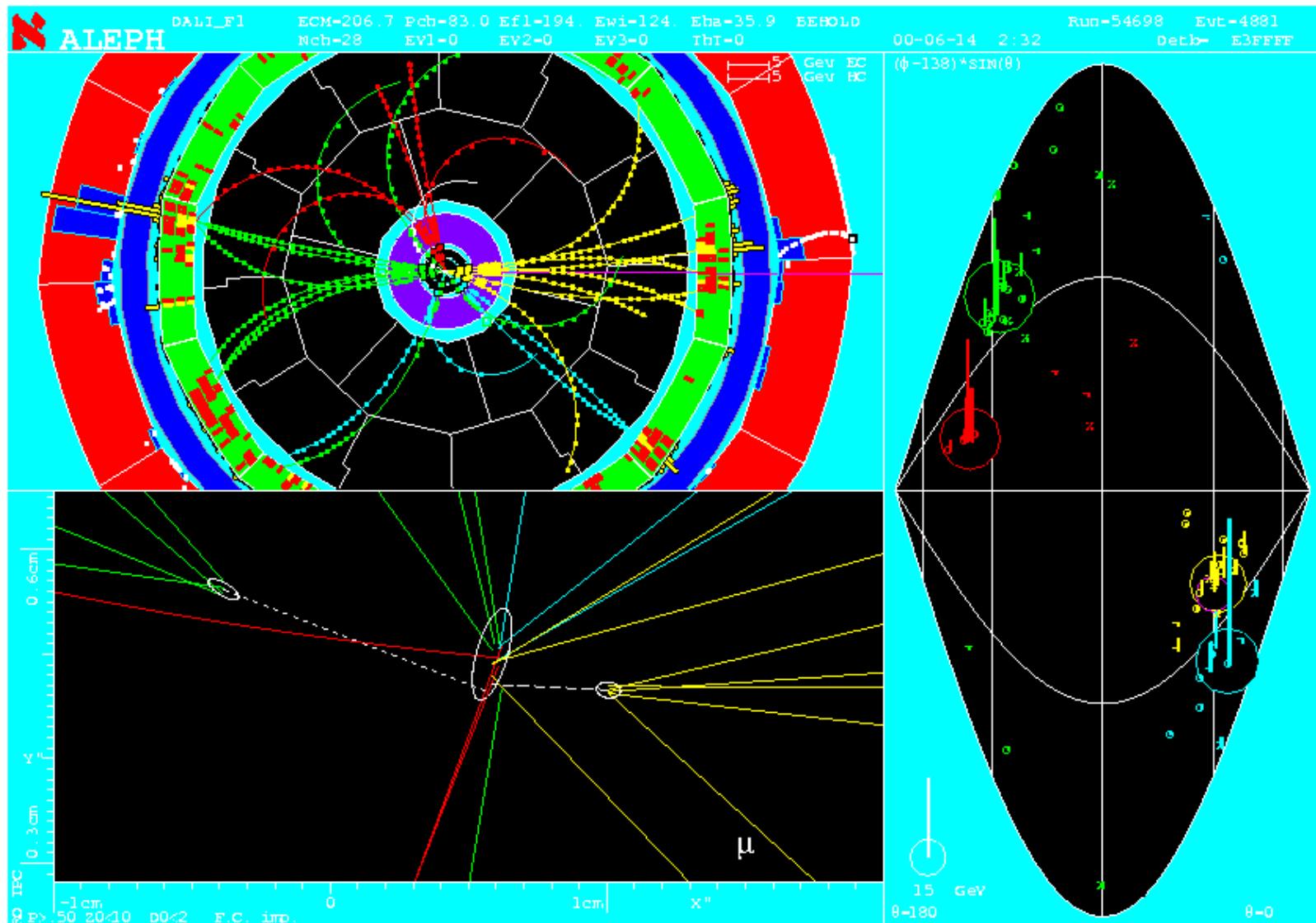
# LEP: exclusion by experiment



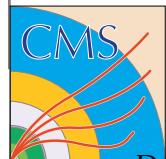
# LEP: exclusion by channel



# ALEPH event ( $e^+e^- \rightarrow bb\bar{q}\bar{q}$ )



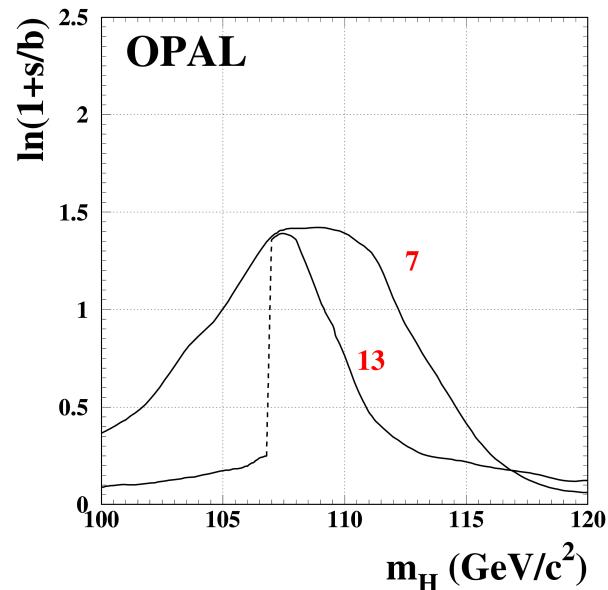
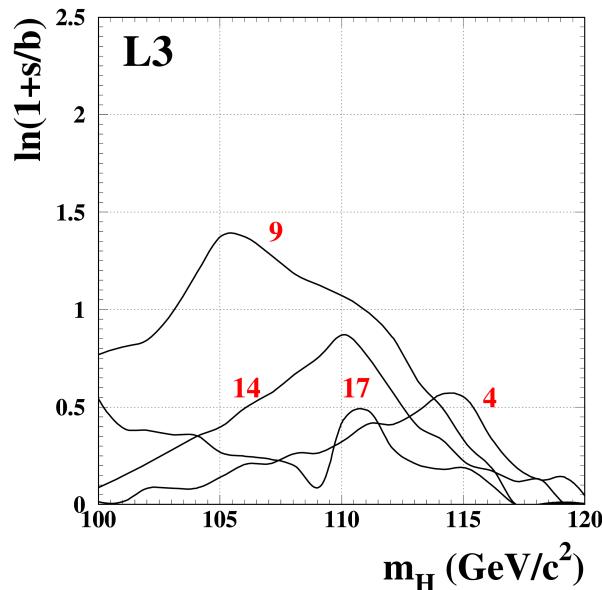
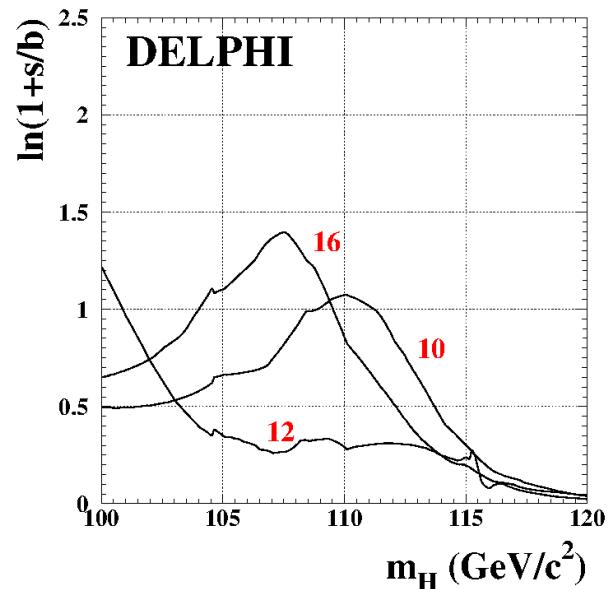
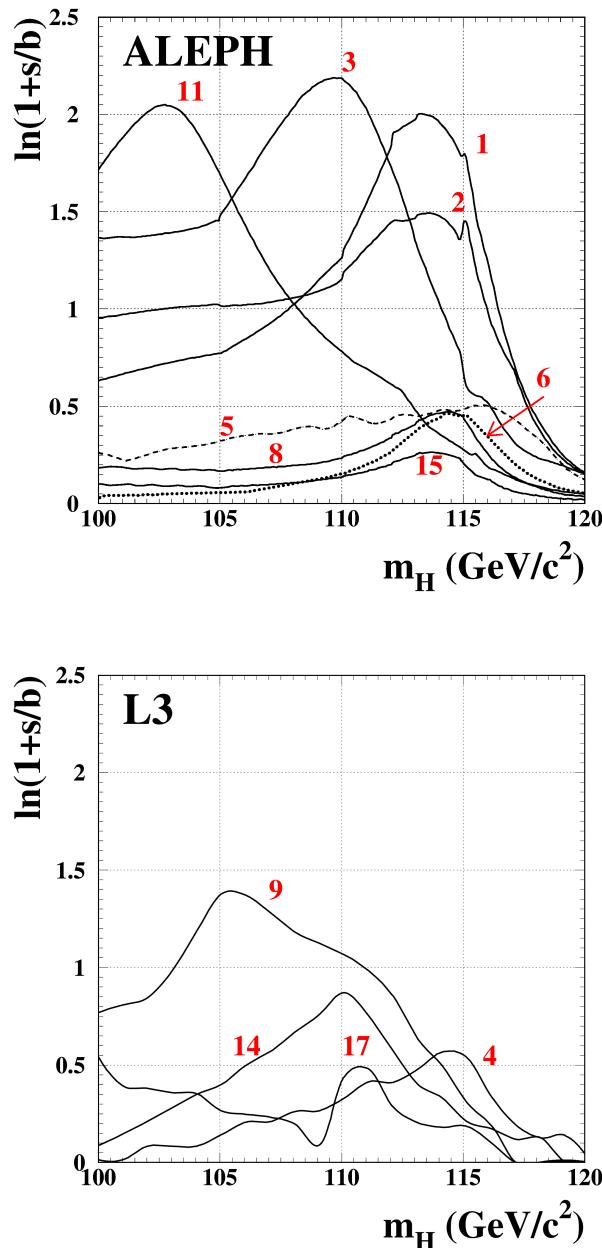
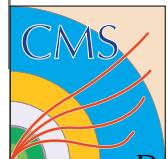
b quark: long lifetime  $\Rightarrow$  secondary vertex



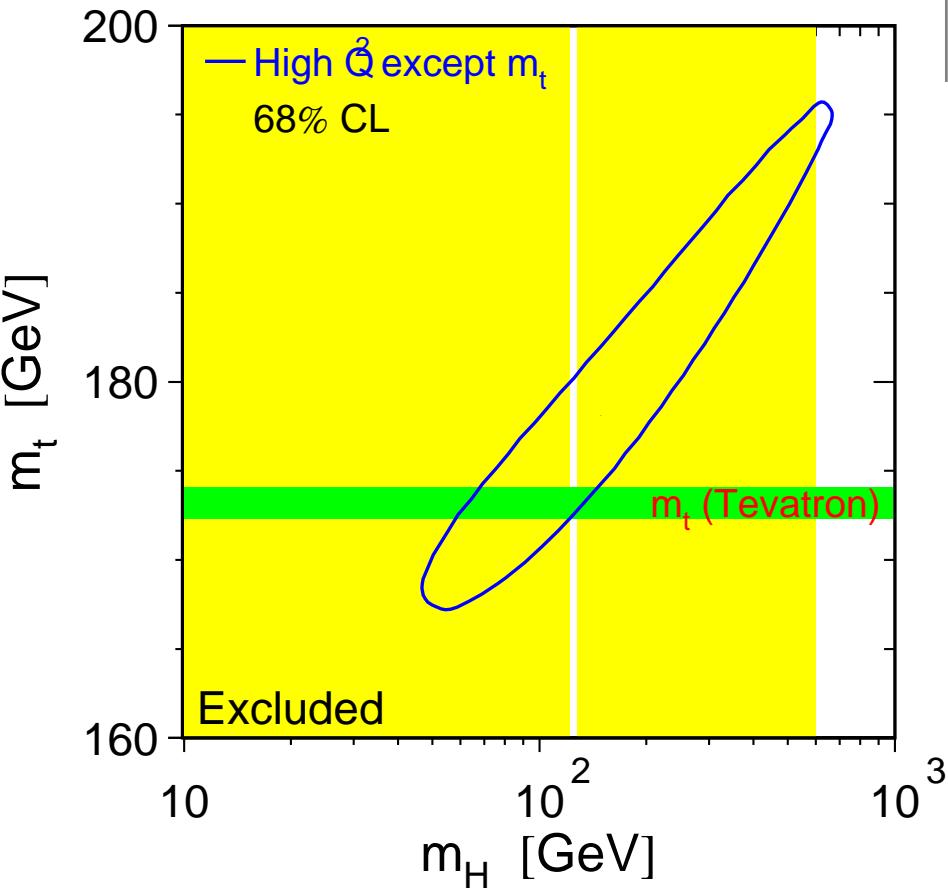
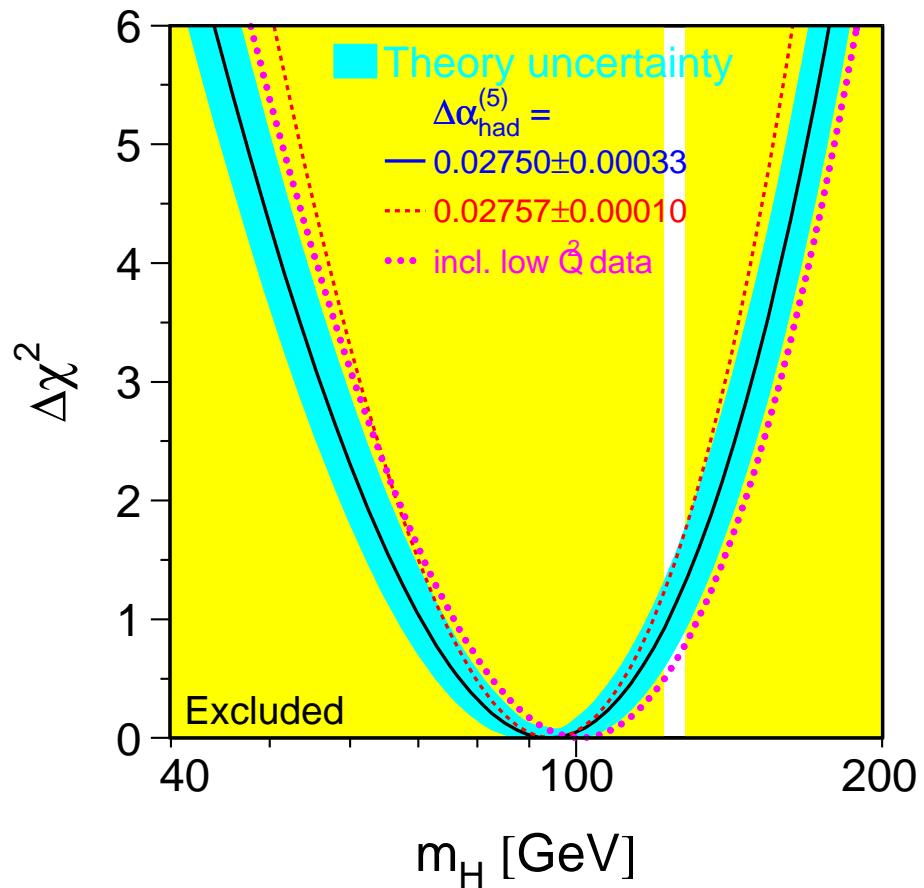
# LEP: spaghetti diagrams

Event weights  
*signal-likeness*  
vs. Higgs mass  
for 17 selected LEP  
events

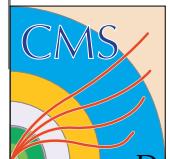
The LEP  
Collaborations,  
*Search for the*  
*Standard Model Higgs*  
*Boson at LEP*  
Phys. Lett. B  
565 (2003) 61.



# LEP: final results



The LEP Collaborations: Electroweak Measurements in Electron-Positron  
Collisions at W-Boson-Pair Energies at LEP,  
Physics Reports 532 (2013) 119-244.  
LHC exclusion (2011 data) included



# Accelerators of CERN now

LHC: Large Hadron Collider

SPS: Super Proton  
Synchrotron

AD: Antiproton Decelerator

ISOLDE: Isotope Separator  
On Line DEvice

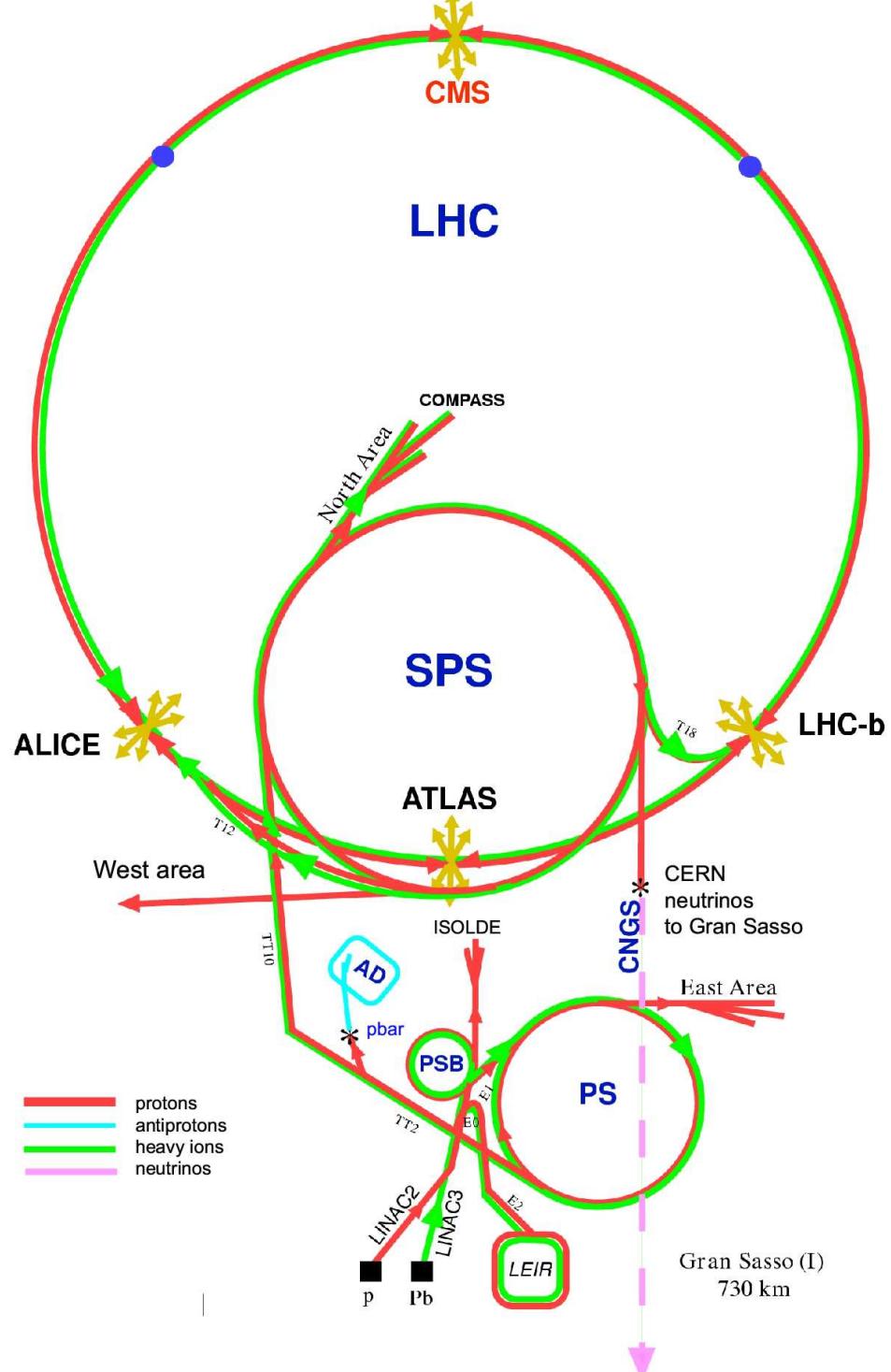
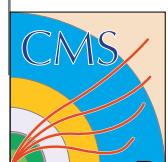
PSB: Proton Synchrotron  
Booster

PS: Proton Synchrotron

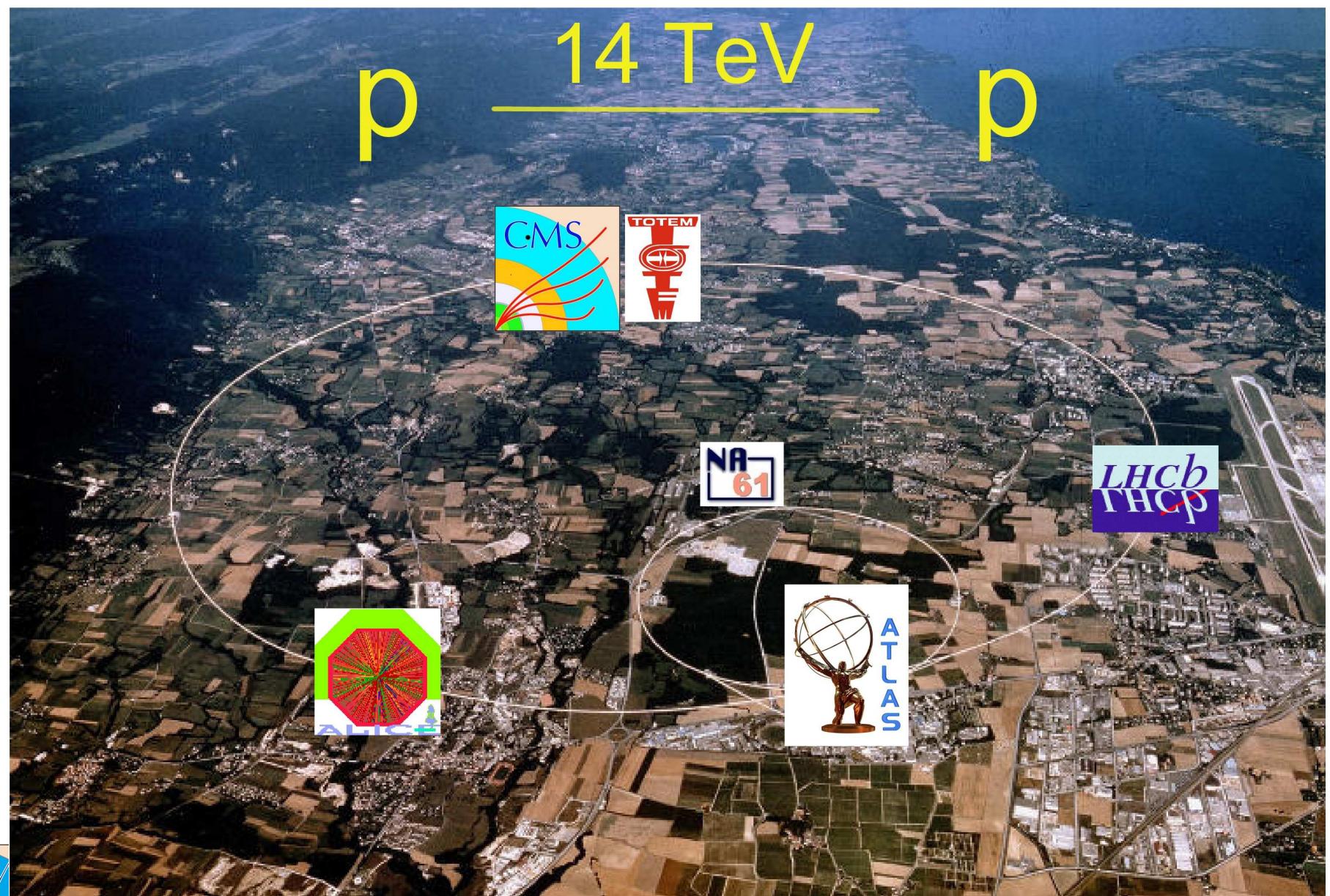
LINAC: LINear ACcelerator

LEIR: Low Energy Ion Ring

CNGS: Cern Neutrinos  
to Gran Sasso



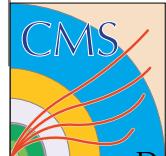
# LHC and its main experiments



# Steering magnets of LHC



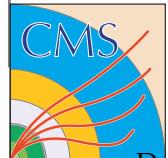
1232 superconducting magnets (before installation)  
 $(L = 15 \text{ m}, M = 35 \text{ t}, T = 1.9 \text{ K}, B = 8.3 \text{ T})$



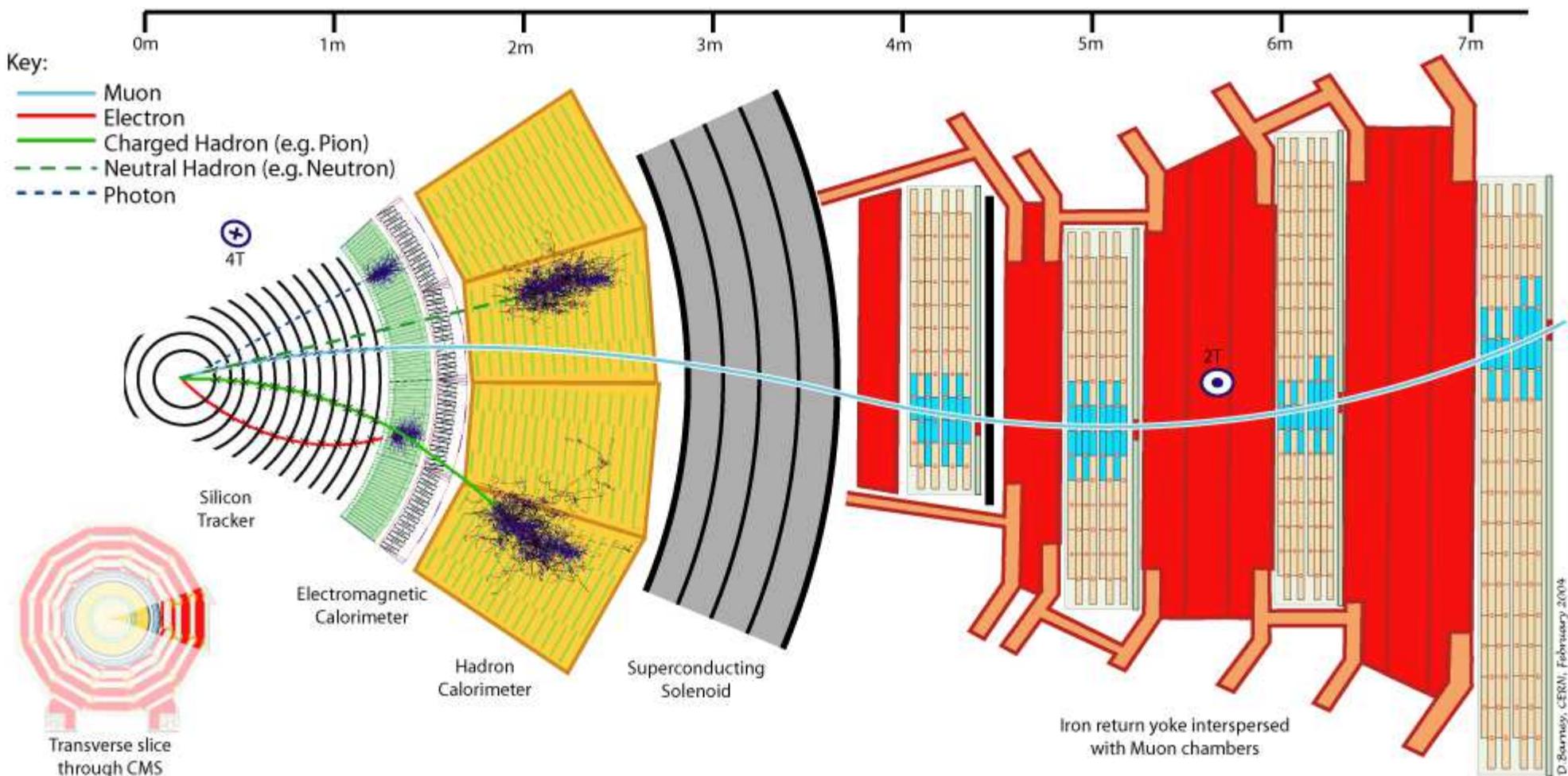
# Dipole magnets of LHC in the tunnel



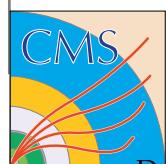
# Higgs Search at LHC



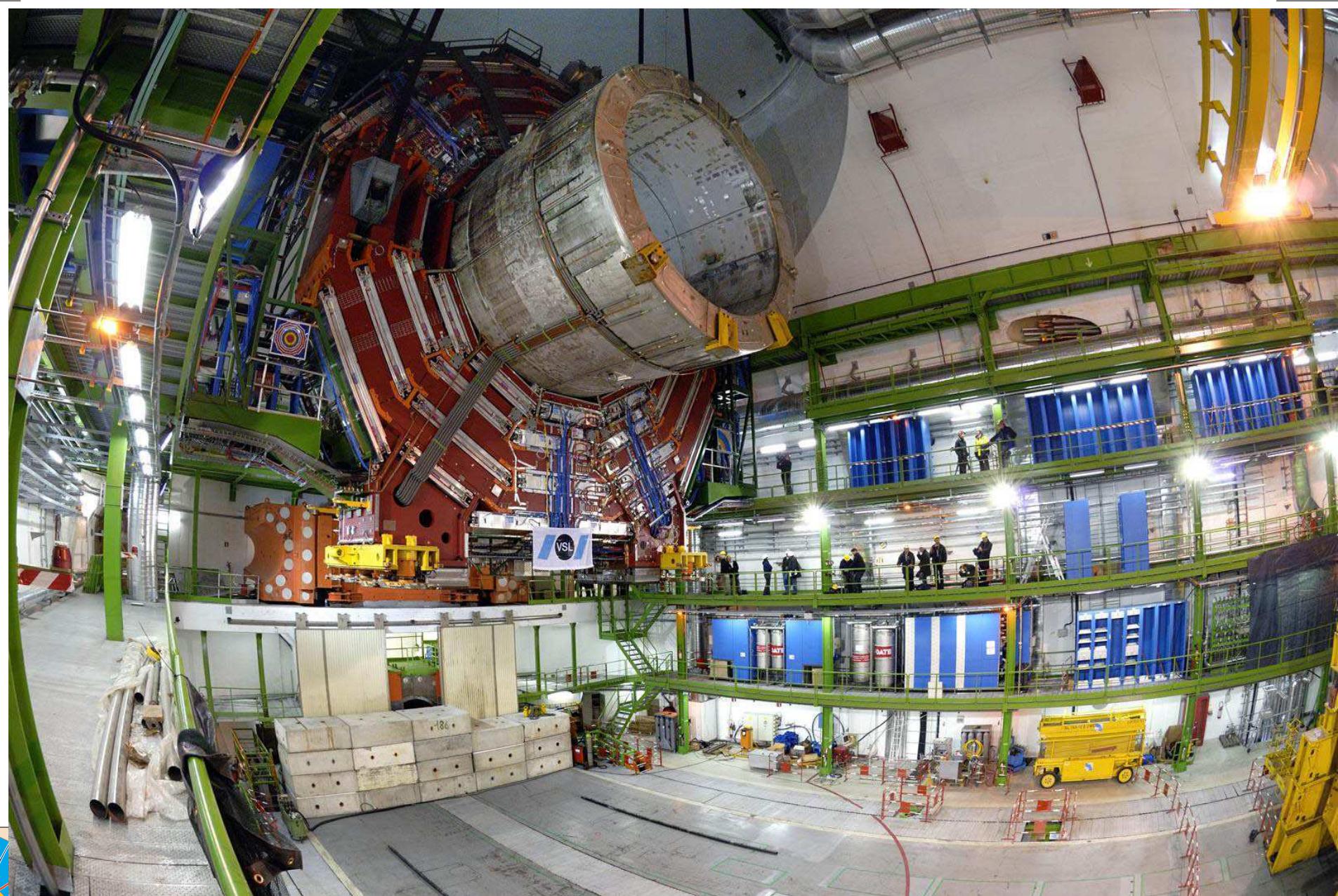
# CMS: Compact Muon Solenoid



14000 ton digital camera:  
100 M pixel, 20 M pictures/sec, 1000 GB/sec data  
Processes max 400 pictures/sec  $\Rightarrow$  intelligent filter!!

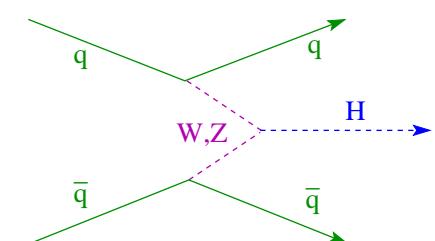
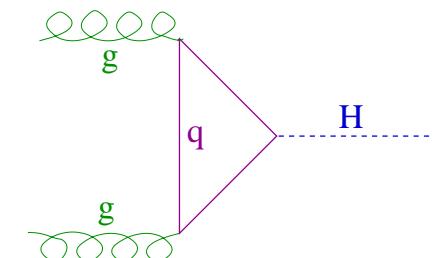
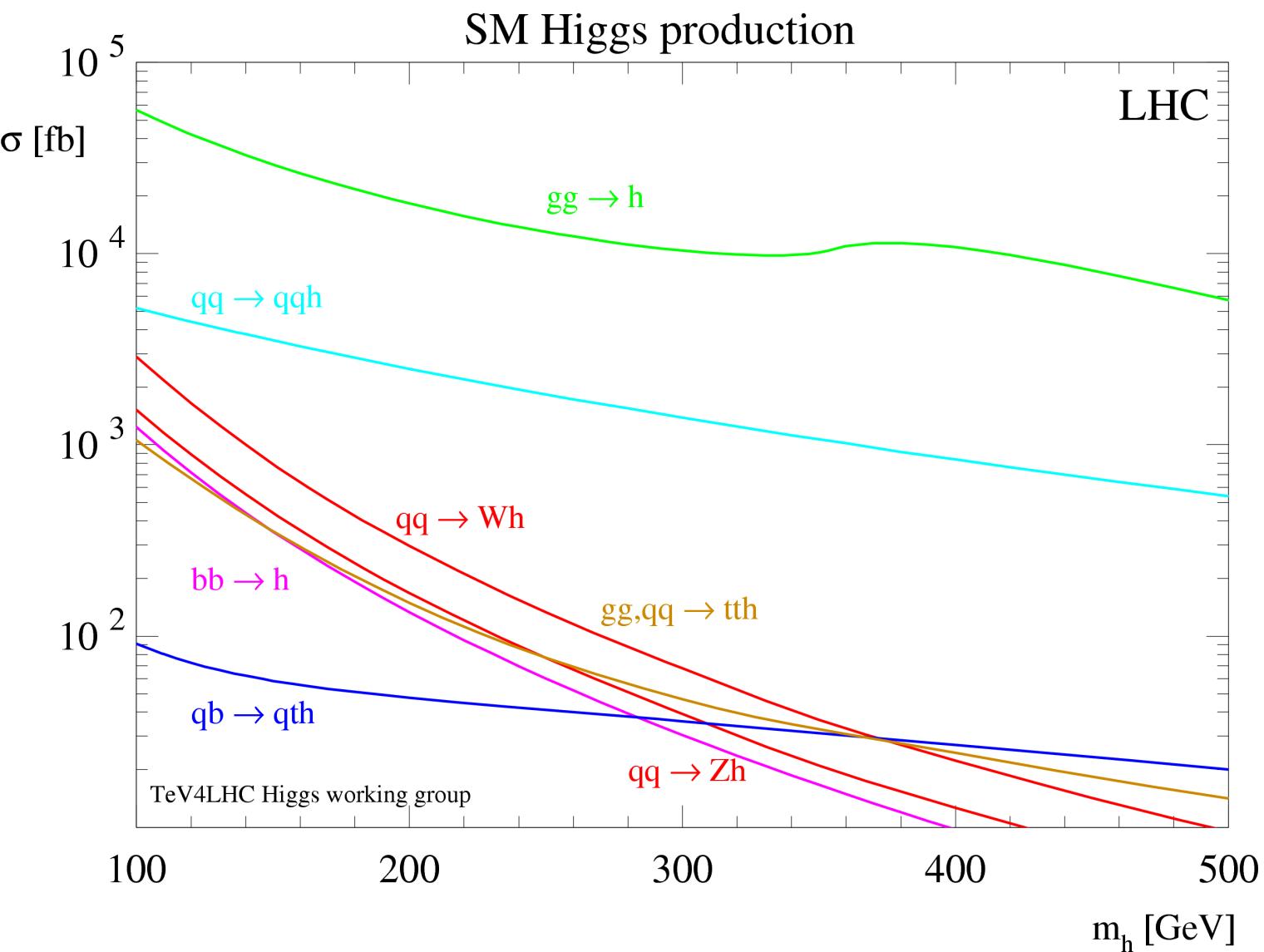


# The (Compact Muon) Solenoid itself



# Formation of the SM Higgs boson

## in p-p collisions at LHC



# Decay of the SM Higgs boson

March 2012

Not excluded by 2011

CMS data:

$114 < M_H < 127 \text{ GeV}$

(at 95% CL)

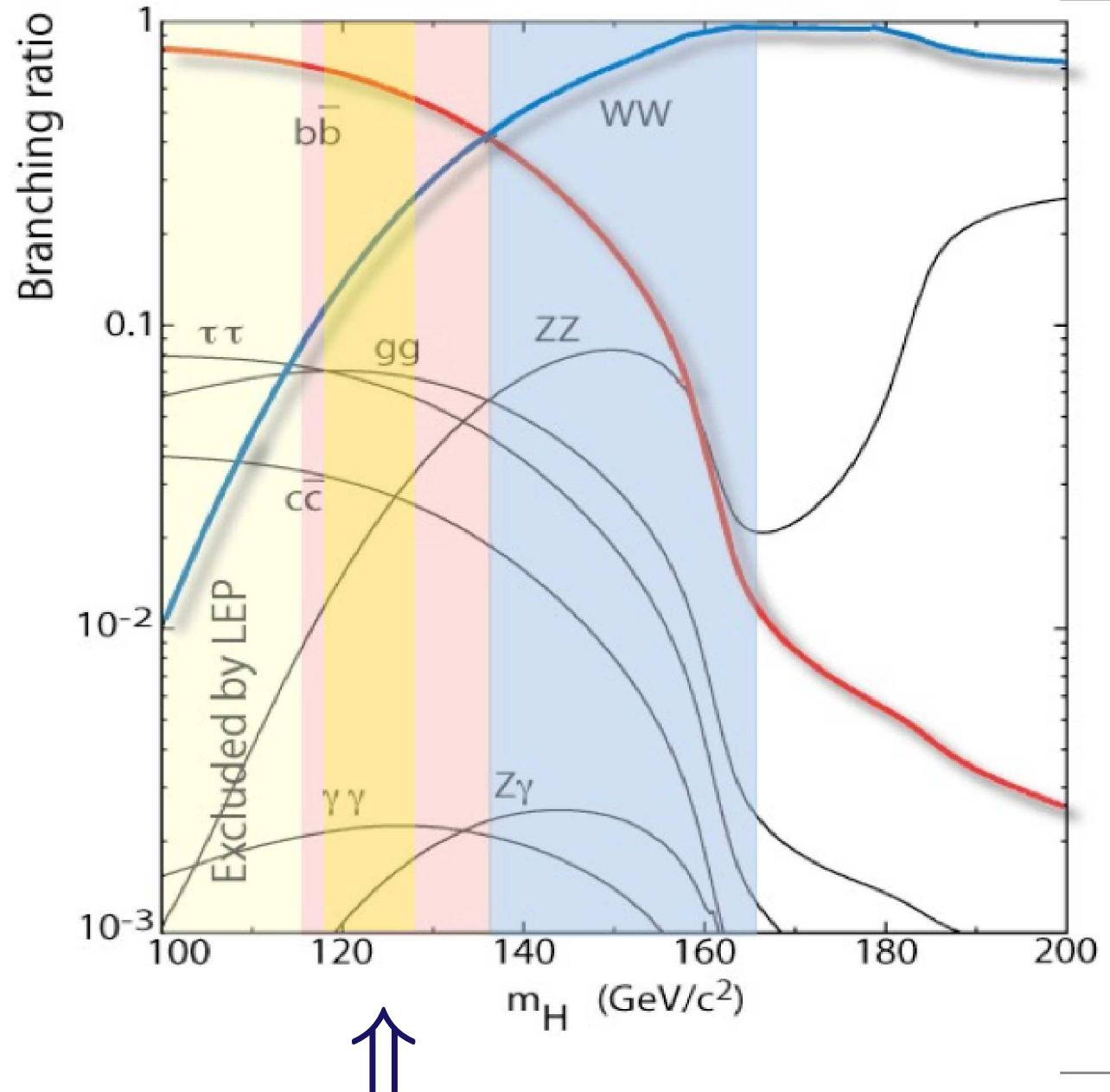
(where many decay  
processes contest)

Best identified:

$H \rightarrow \gamma\gamma$

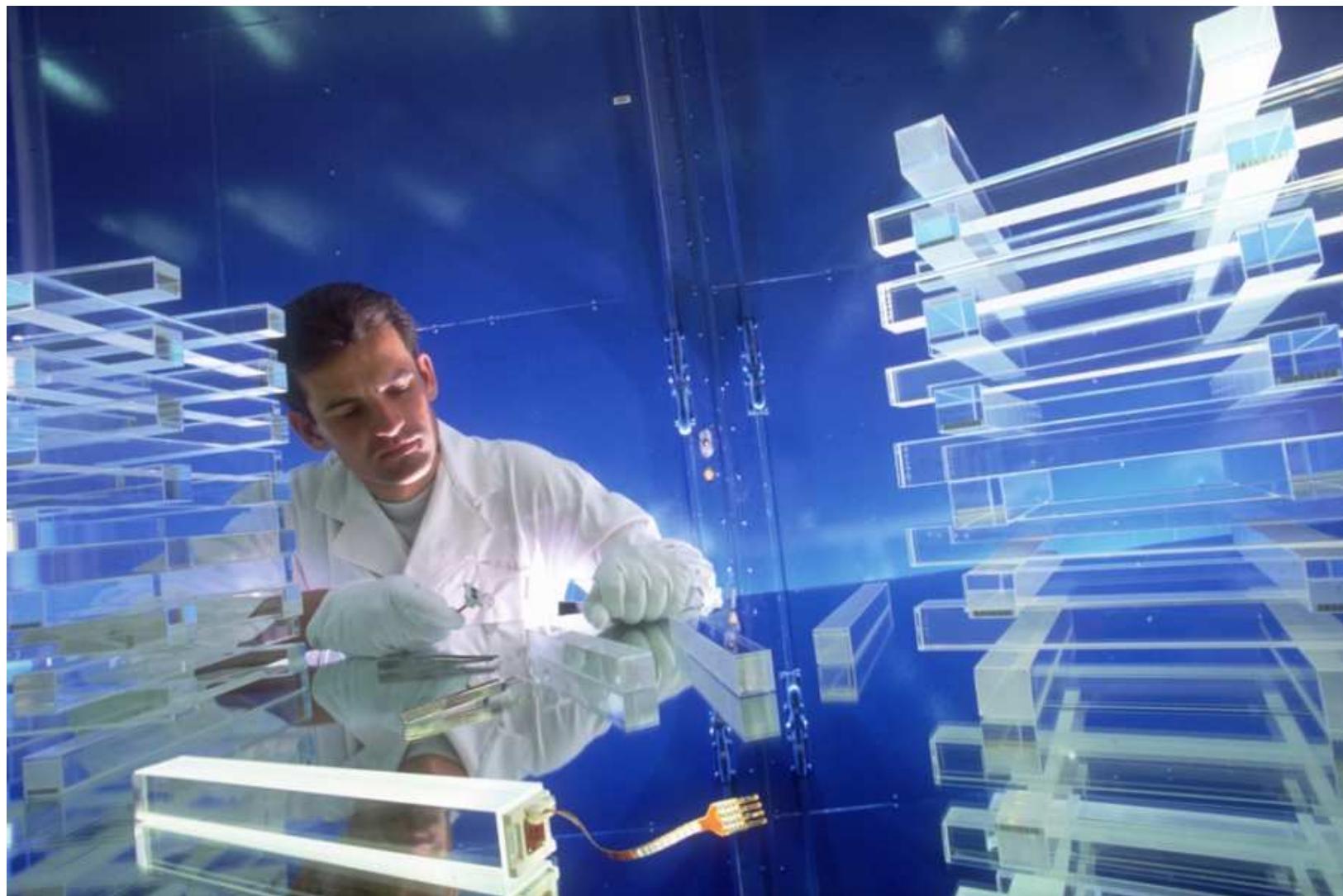
Excess observed

$2 - 3\sigma$  at  $\sim 125 \text{ GeV}!$

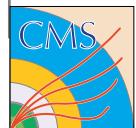


# CMS: elektromagnetic calorimeter

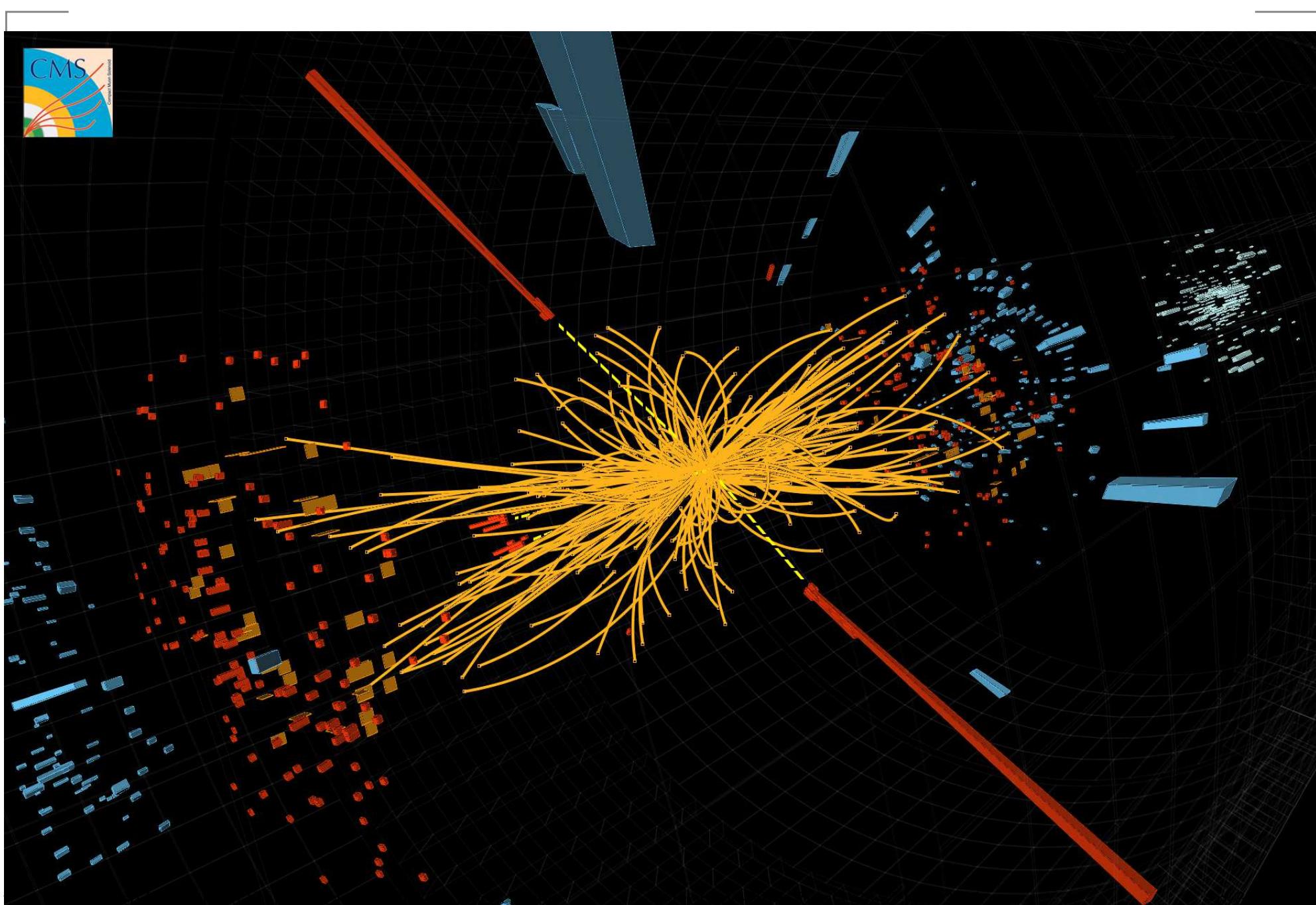
optimized for studying  $H \rightarrow \gamma\gamma$



75,848 PbWO<sub>4</sub> single crystal scintillators



# A CMS event: $H \rightarrow \gamma\gamma$ candidate



# 4 July 2012: we have something!

ATLAS and CMS, at LHC collision energies 7 and 8 TeV, in two decay channels  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ , at the same invariant mass of  $m \approx 126$  GeV see a new boson at a convincing statistical significance of  $5\sigma$  conf. level each with properties corresponding to those of the SM Higgs boson.

Matthew Chalmers: Nature on-line, 2 July 2012!  
“Physicists Find New Particle, but is it the Higgs?”

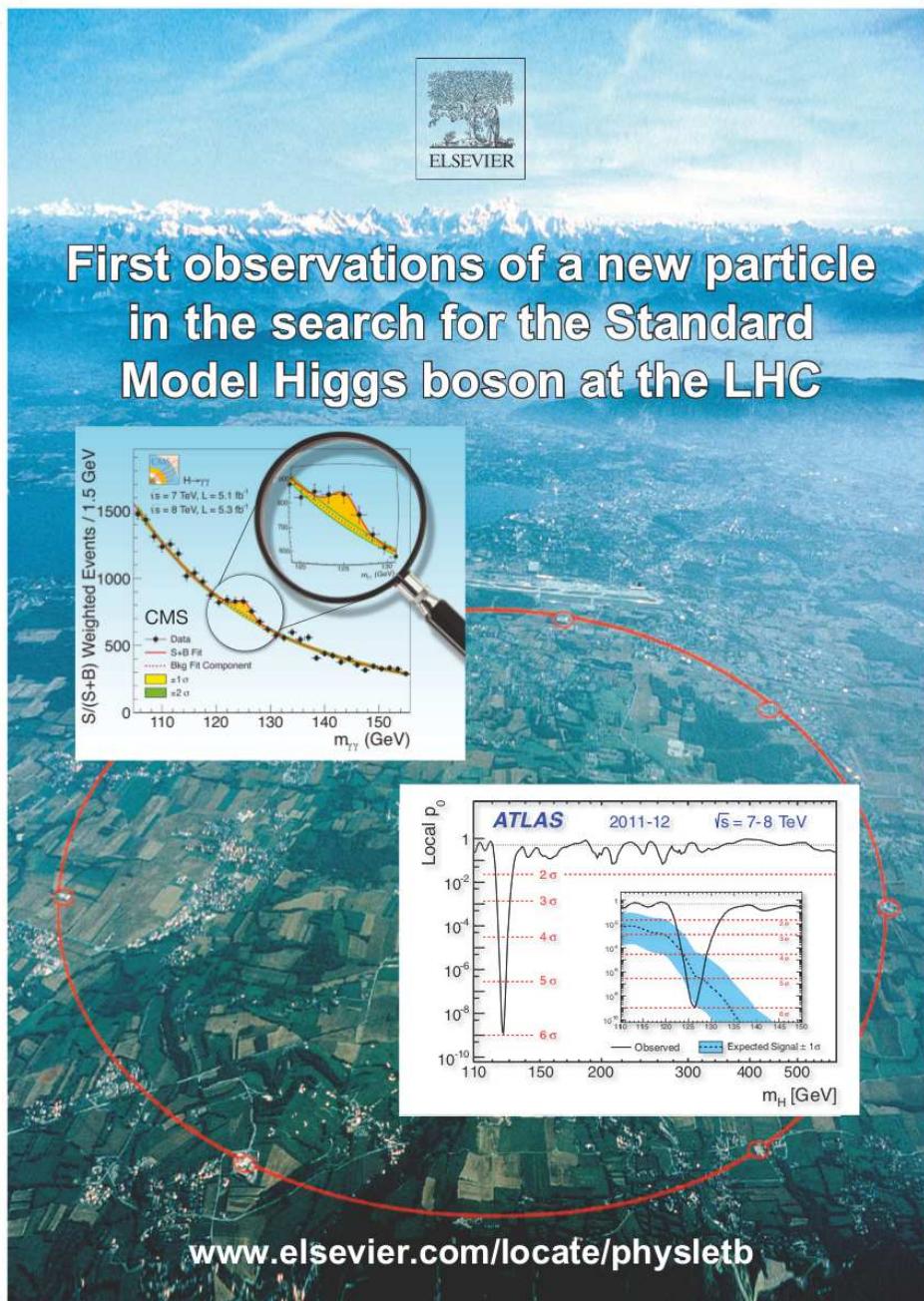


François Englert and Peter Higgs

It has to be shown to be the SM Higgs: Next lecture!



# CMS and ATLAS: A new boson



Physics Letters B 716 (2012) 1–29

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Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC <sup>☆</sup>

ATLAS Collaboration \*

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

## ARTICLE INFO

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## ABSTRACT

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately  $4.8 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 7 \text{ TeV}$  in 2011 and  $5.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$  in 2012. Individual searches in the channels  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ ,  $H \rightarrow \gamma\gamma$  and  $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$  in the 8 TeV data are combined with previously published results of searches for  $H \rightarrow ZZ^{(*)}$ ,  $WW^{(*)}$ ,  $bb$  and  $\tau^+\tau^-$  in the 7 TeV data and results from improved analyses of the  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  and  $H \rightarrow \gamma\gamma$  channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of  $126.0 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV}$  is presented. This observation, which has a significance of 5 standard deviations, corresponds to a background fluctuation probability of  $6.5 \times 10^{-9}$ , is compatible with the production and decay of the Standard Model Higgs boson.

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ATLAS 2031 authors

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Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC <sup>☆</sup>

CMS Collaboration \*

### CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation,

CMS: 2899 authors

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## ABSTRACT

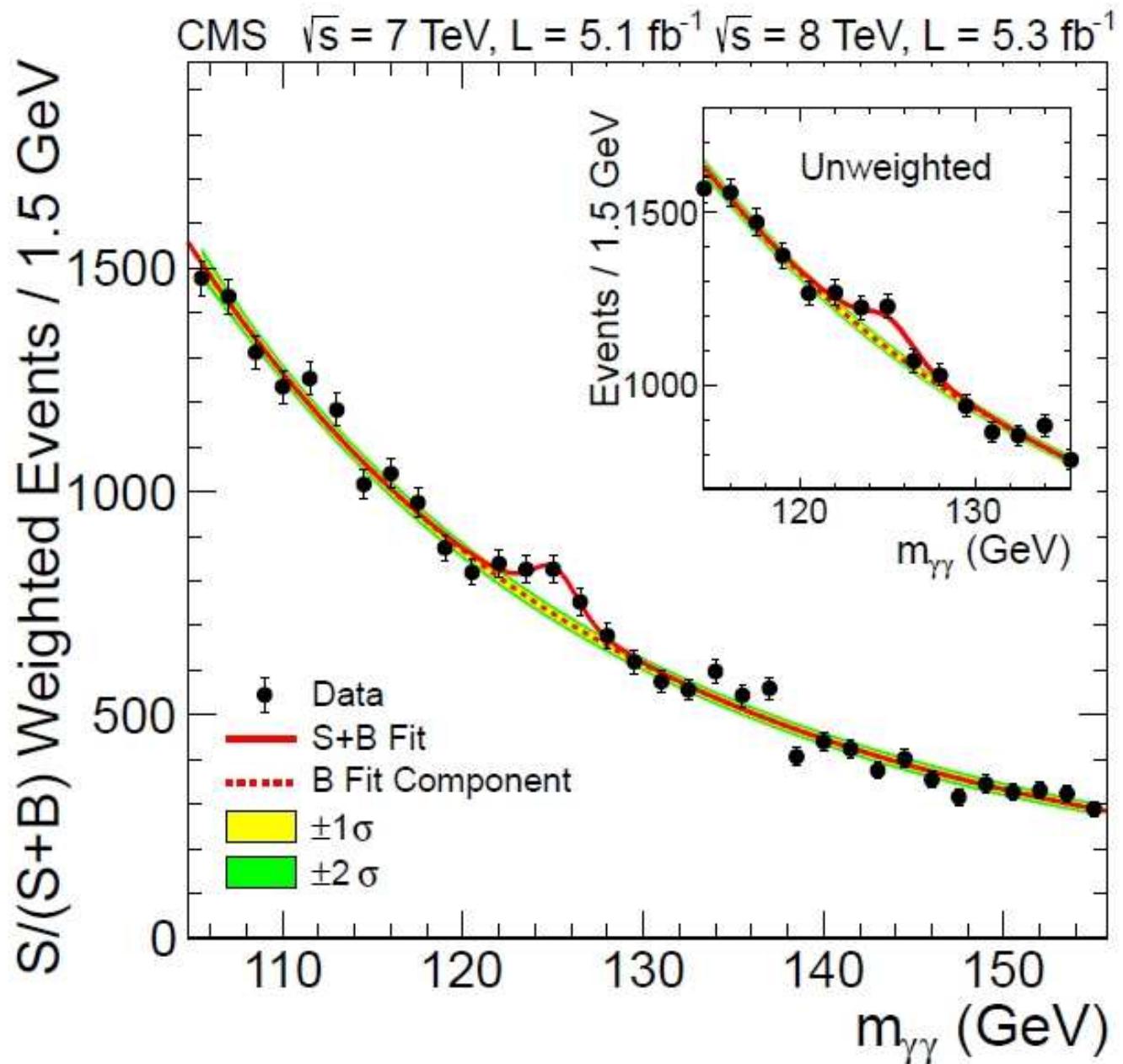
Results are presented from searches for the standard model Higgs boson in proton-proton collisions at  $\sqrt{s} = 7$  and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to  $5.1 \text{ fb}^{-1}$  at 7 TeV and  $5.3 \text{ fb}^{-1}$  at 8 TeV. The search is performed in five decay modes:  $\gamma\gamma$ ,  $ZZ$ ,  $W^+W^-$ ,  $\tau^+\tau^-$ , and  $bb$ . An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution,  $\gamma\gamma$  and  $ZZ$ ; a fit to these signals gives a mass of  $125.3 \pm 0.4 \text{ (stat)} \pm 0.5 \text{ (syst)} \text{ GeV}$ . The decay to two photons indicates that the new particle is a boson with spin different from one.

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# CMS: $H \rightarrow \gamma\gamma$ mass distribution

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in 16 pp.

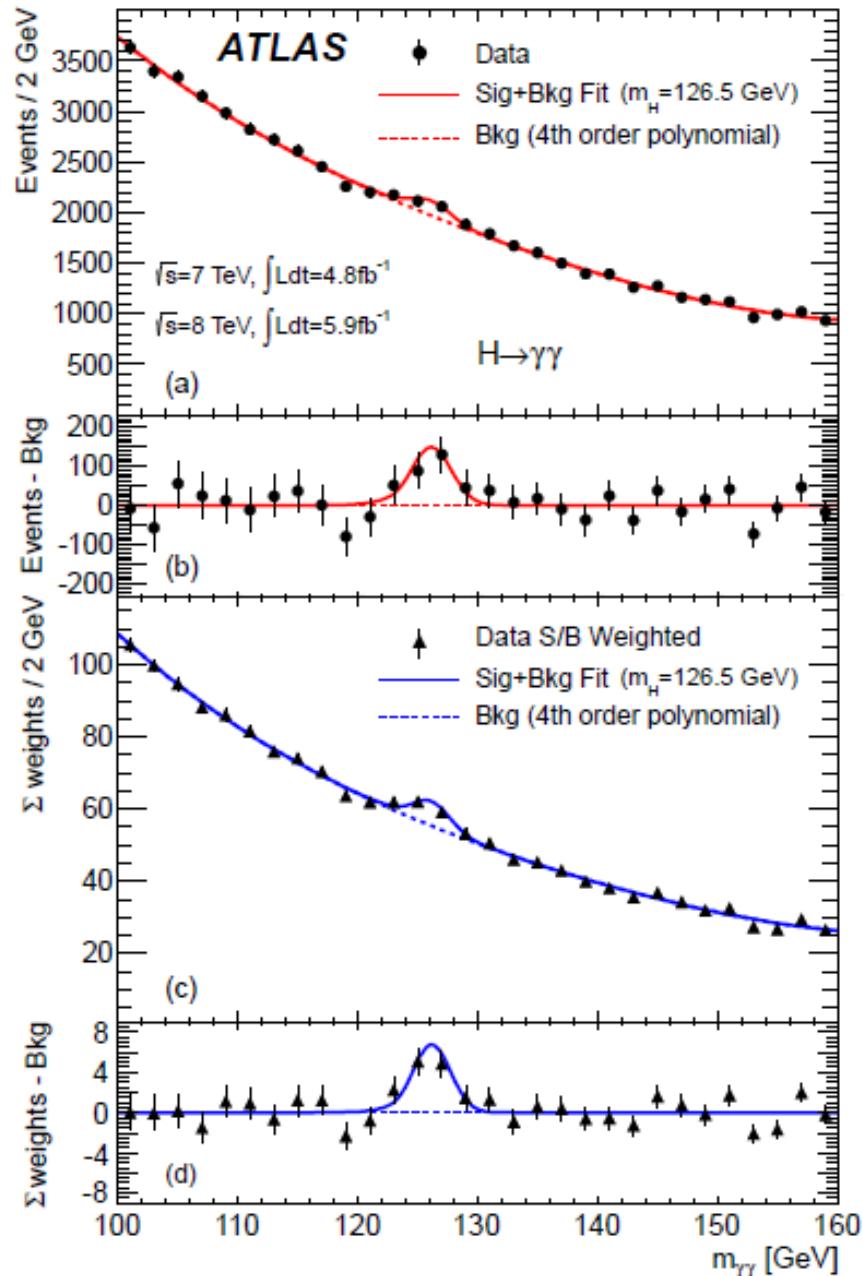


# ATLAS: $H \rightarrow \gamma\gamma$ mass distribution

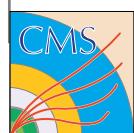
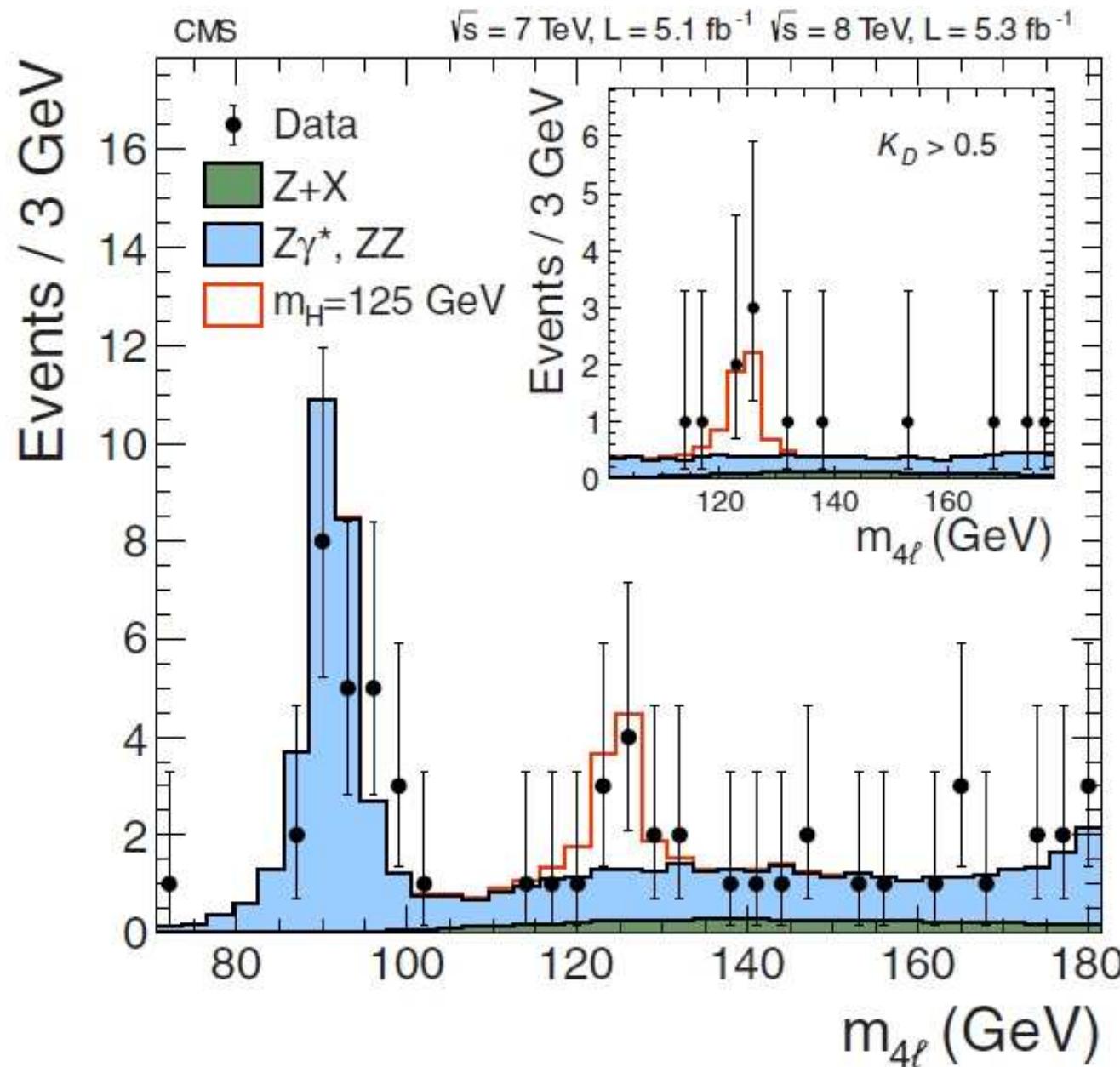
ATLAS Collaboration  
(2931 authors):

*Observation of a new particle in  
the search for the Standard  
Model Higgs boson with the  
ATLAS detector at the LHC*

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# CMS: $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$



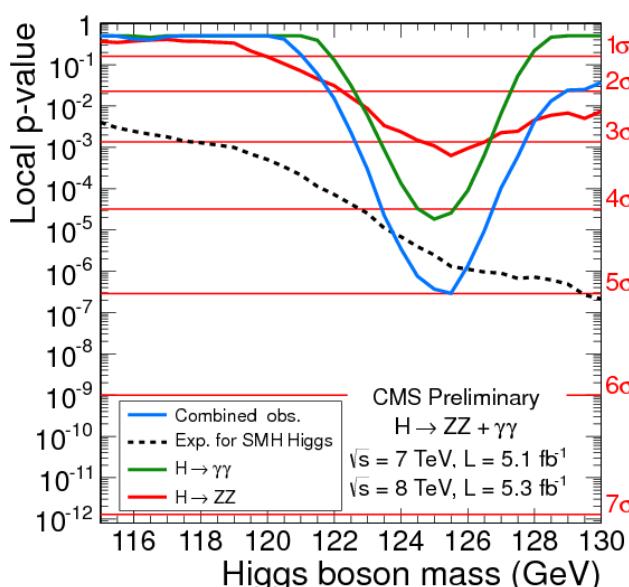
CMS:  $H \rightarrow ZZ^* \rightarrow \ell^+ \ell^- \ell^+ \ell^-$

CMS :  $H \rightarrow ZZ^* \rightarrow \ell^+ \ell^- \ell^+ \ell^-$  animated

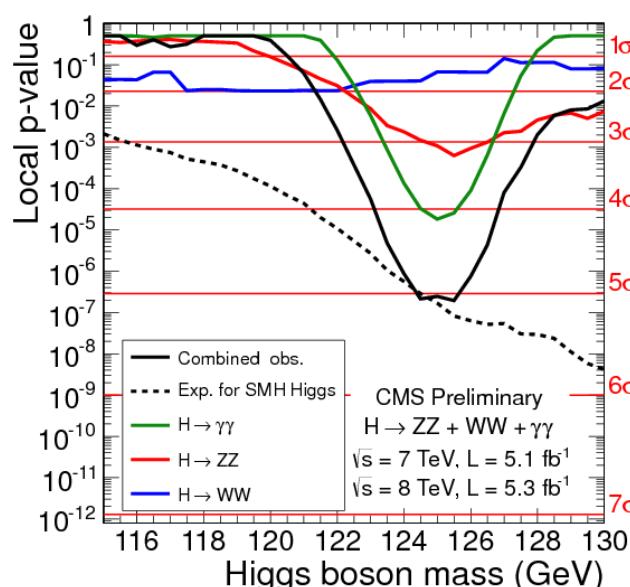


# CMS: $p$ -distributions (4 July 2012)

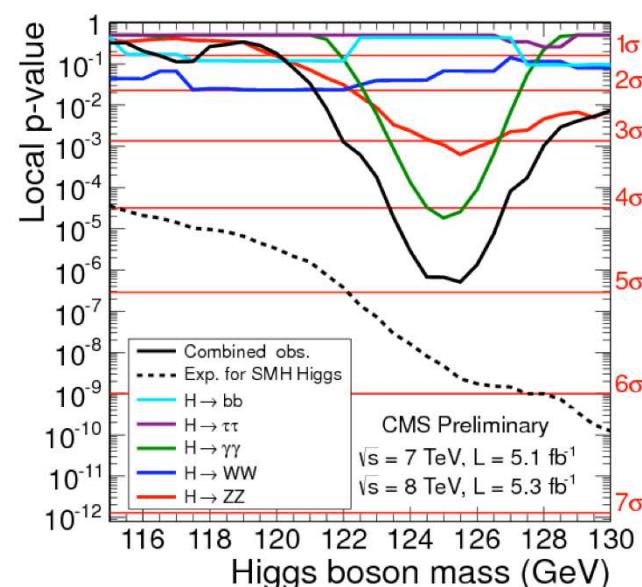
The probability that random fluctuation of the measured background could give the observed excess.



$\gamma\gamma$  and ZZ:  $5.0\sigma$



$\gamma\gamma$ , ZZ and WW:  $5.1\sigma$



All together:  $4.9\sigma$

ATLAS got the same:  $\gamma\gamma$  and ZZ:  $5.0\sigma$

Adding WW increased the ATLAS excess to  $6.0\sigma$



# Higgs Jokes after the Discovery

- The Higgs discovery unleashed a Big Bang of bad jokes.
- The Higgs discovery makes me feel heavier already. What we need instead is the anti-Higgs. A particle that takes mass away.
- Physicists *massively* celebrated the Higgs discovery.
- Are you there God Particle? It's me, Average Person that doesn't understand you.
- Better double check. I thought I discovered a Higgs boson under my couch last year but turned out to be an old marble.
- If we can control the Higgs field then we can really build Weapons of Mass Destruction.
- A top quark and a Higgs had a public break up on the weekend. The quark stormed off, complaining that the Higgs kept telling it how heavy it was and had nothing else to say.



# Conclusion

- We very probably observed **the Standard Model Higgs boson** or (unfortunately, much less probably) a Higgs boson of a more general model.
- **The new ATLAS and CMS results** will be presented by the next speaker.
- LHC will restart in 2015 at much higher energy and luminosity.
- Let us hope for **some deviation from the Standard Model** (although none seen yet).

**Thanks for your attention!**

