La ricerca del bosone di Higgs, a LEP, Tevatron, LHC .... e oltre

Rottura spontanea della simmetria di gauge $SU(2)_L \otimes U(1)_Y$ in presenza di campi scalari

Richiamiamo le cose di base

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}_{Y=+1}$$

$$D_\mu \phi = [\partial_\mu + ig\mathbf{W}_\mu \cdot \frac{\tau}{2} + ig'(+\frac{1}{2})B_\mu]\phi$$

$$\mathcal{L}_{\phi W} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi);$$
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

$$\bar{\phi} = < 0|\phi|0 > = \begin{pmatrix} 0 \\ \eta \end{pmatrix}$$

$$\eta = \sqrt{\frac{-\mu^2}{2\lambda}}$$

$$Q = \begin{pmatrix} +1 & 0 \\ 0 & 0 \end{pmatrix}$$

Richiamiamo le cose di base

- Minimo in $\phi=\eta$; $V = \lambda(\varphi^+\varphi - \eta^2)^2$
- Coeff. del termine quadratico: $-2\lambda\eta^2(=\mu^2)$ negativo
- Oscillazioni intorno al vuoto

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \bar{\phi} + \xi(x)$$

$$\xi = \begin{pmatrix} \frac{\xi_1 + i\xi_2}{\sqrt{2}} \\ \frac{\sigma + i\xi_3}{\sqrt{2}} \end{pmatrix}$$

- Sviluppiamo la lagrangiana in potenze dei campi. Si trova:

$$\varphi^+\varphi - \eta^2 = \sqrt{2}\eta\sigma + \sigma^2 + \sum_{i=1,3}(\xi^i)^2$$

$$L = \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma + \sum_{i=1,3}\ \partial_\mu\xi^i\partial^\mu\xi^i) - \frac{1}{2}[(4\lambda\eta^2)\sigma^2 + 0\times(\xi^1)^2 + \ldots] + \text{"interazioni"}$$

- I campi ξ^i sono bosoni di Goldstone, come indicato dall' assenza di termini in $(\xi^i)^2$ nella Lagrangiana; σ rappresenta un campo scalare di massa $m^2=4\lambda\eta^2$

Gauge Unitaria

- 4 campi scalari, di cui 3 sarebbero i "bosoni di Goldstone"...ma

Con una trasformazione di gauge (dipendente dal punto), ogni spinore a due dimensioni può essere ridotto ad uno spinore della forma *giú* e *reale*:

$$\phi(x) = U(x) \begin{pmatrix} 0 \\ \rho(x) \end{pmatrix}$$

$\rho(x)$ reale e $U(x)$ una matrice di $SU(2)_L \otimes U(1)_Y$.

- i bosoni di Goldstone spariscono, i bosoni vettoriali W e Z prendono massa (è il meccanismo di Brout-Guralnik-Higgs !!!) e restiamo con un solo campo scalare neutro, σ(x), il ***bosone di Higgs***:

$$\rho(x) = \eta + \frac{\sigma(x)}{\sqrt{2}}$$

Il bosone di Higgs

- Il campo scalare rimasto, σ, prende il nome di ***bosone di Higgs***;
- L'accoppiamento del bosone di Higgs ai bosoni vettoriali e' fissato dalle loro masse e da η:

$$L_{\sigma VV} = [2\frac{\sigma}{\sqrt{2}\eta} + (\frac{\sigma}{\sqrt{2}\eta})^2](M_W{}^2 W^{+\mu} W_\mu + \frac{1}{2} M_Z{}^2 Z^\mu Z_\mu)$$

- Nota: ricordo che η lo conosciamo in quanto:

$$\frac{G}{\sqrt{2}} = \frac{g^2}{8M_W{}^2} = \frac{g^2}{8(g^2\eta^2/2)} = \frac{1}{4\eta^2} \qquad \eta = (\frac{1}{2\sqrt{2}G})^{1/2} \approx (\frac{10^5\,\mathrm{GeV}^2}{1.16\times 2.82})^{1/2} \approx 170\,\mathrm{GeV}$$

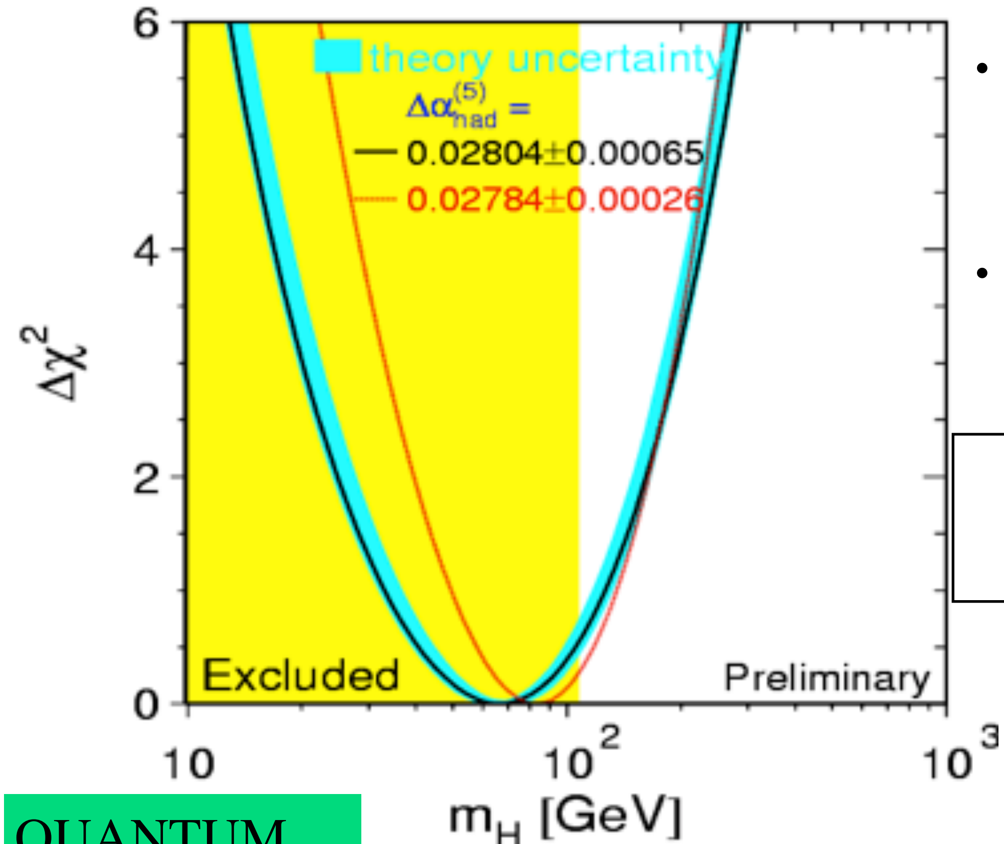
- La proporzionalita' dell' accoppiamento σ-VV alle masse di V ed il rapporto fissato da tra σ-VV e σ-σ-VV sono la firma del meccanismo di Higgs

$$m_H^2 = 4\lambda\eta^2$$

$$m_H = \sqrt{\lambda}(340)GeV$$

La massa del bosone di Higgs dipende dalla costante sconosciuta λ

M_H prediction from precision Electroweak Measurements:



- Includes all electroweak precision measurements;
- Constrained by direct m_W and m_{top} determinations;

$$m_H = (77^{+69}_{-39})\ \mathrm{GeV/c^2}$$

QUANTUM STABILITY

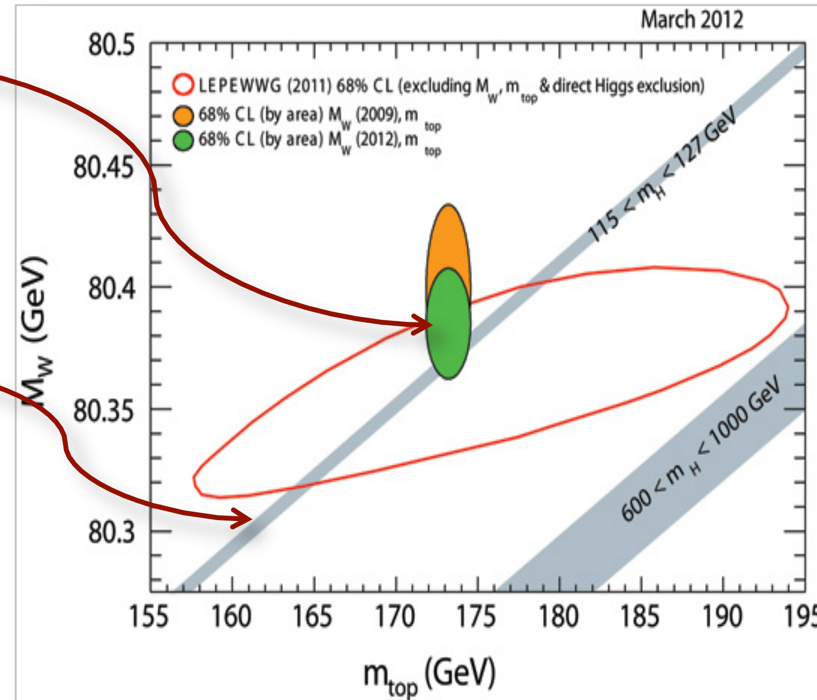
135-170 GeV $\Lambda = 10^{19}$

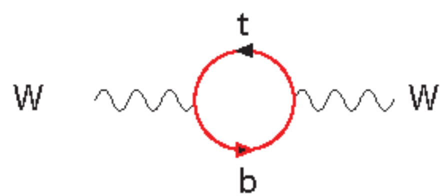
m_H < 188 GeV/c² at 95%C.L.

...few weeks before discovery 4 Luglio 2012 (J. Incandela, CMS)

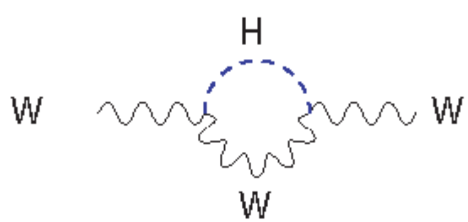
1. M_{top} vs. M_W
   - Tevatron M_W *Tour de Force!!*
     - m_W = 80385 ± 15 MeV (World Ave – Mar 2012)
   - Shifts for SM Higgs expectation

2. Colliders leave little space





$\sim M_t^2$



$\sim \ln(m_H)$

This is the main story of the past year

Eliminated ~475 GeV of the mass range.

9

Dalla teoria alla pratica: elettrone

- Il doppietto di Higgs (I_W=1/2, Y= -1/2) puo' accoppiare il doppietto dell' elettrone L (I_W=1/2, Y= -1/2) al singoletto e_R (I_W=1/2, Y= -2):

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix};\ l_L = \begin{pmatrix} (\nu_e)_L \\ e_L \end{pmatrix};\ e_R$$

- Accoppiamento trilineare:

$$L_e = g_e(\overline{e_R}\varphi^+ l_L + h.c.) = g_e[\overline{e_R}(\varphi^+)^+ \nu_{eL} + \overline{e_R}(\varphi^0)^+ e_L + h.c.]$$

- Nella configurazione di vuoto ($<\phi^+>_0=0$, $<\phi^0>_0=\eta$):

$$L_e = g_e(\overline{e_R} <\varphi^+>_0 l_L + h.c.) = g_e\eta(\overline{e_R} e_L + \overline{e_L} e_R) = g_e\eta\bar{e}e = m_e\bar{e}e$$

Dalla teoria alla pratica: VV e quark

- Accoppiamenti σ-VV e σ-σ-VV:

$$\mathcal{L}_{W-mass} = M_W^2 W^\mu W_\mu^\dagger + \frac{1}{2} M_Z^2 Z^\mu Z_\mu$$

$$\eta \to \eta + \sigma/\sqrt{2}$$

$$\mathcal{L}_{W-\sigma} = \mathcal{L}_{W-mass} + (\sqrt{2}\frac{\sigma}{\eta} + \frac{\sigma^2}{2\eta^2})(M_W^2 W^\mu W_\mu^\dagger + \frac{1}{2} M_Z^2 Z^\mu Z_\mu)$$

$$\mathcal{L}_{\sigma-VV} = 2(\sqrt{2}G_F)^{1/2}\,\sigma\,(M_W^2 W^\mu W_\mu^\dagger + \frac{1}{2} M_Z^2 Z^\mu Z_\mu)$$

- Accoppiamenti ai quark

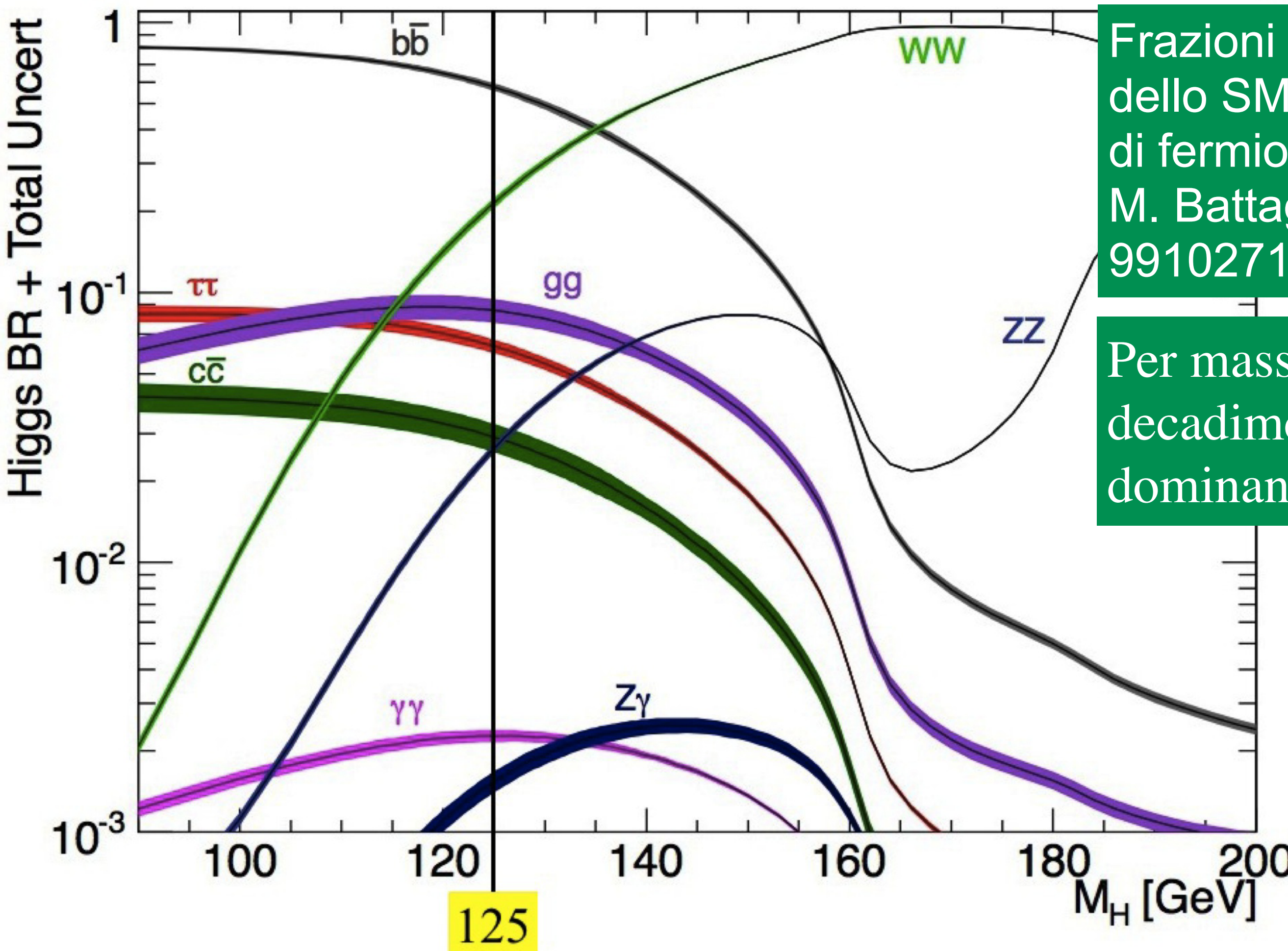
$$\mathcal{L}_{q-m} = \bar{D}_L U_{CKM} m_d D_R + \bar{U}_R m_u U_L + h.c. =$$

$$= \bar{D}_{fis} m_d D_R + \bar{U}_R m_u U_L + h.c.$$

$$\eta \to \eta + \sigma/\sqrt{2}$$

$$\mathcal{L}_{q-\sigma} = \left(\sqrt{2}G_F\right)^{1/2} \left[\bar{D}_{fis} m_d D_R + \bar{U}_R m_u U_L\right] + h.c.$$

Rapporti di decadimento del bosone di Higgs



Frazioni di decadimento dello SM Higgs in coppie di fermioni e VV.
M. Battaglia, hep-ph/9910271.

Per massa <130 GeV, il decadimento in b b-bar e' dominante

Risultati numerici (M=125 GeV)

- Nella Tabella, i risultati all'ordine più basso confrontati con il risultato di calcoli più avanzati, in cui sono tenute in conto le correzioni di ordine superiore dovute alle interazioni forti (QCD), nel caso dei quark, e quelle elettrodeboli, nella Teoria Standard. Questi ultimi valori sono ottenuti con il codice HDECAY. Nei decadimenti in coppie quark-antiquark, le correzioni di QCD sono determinanti ai fini di una predizione quantitativa.

Modi di decad.	Γ(MeV) (lowest order)	Γ(MeV) (tutte le correzioni)	Rapp. di decadimento (%) (corretti)
$b\bar{b}$	4.92	2.36	56.6
$\tau\bar{\tau}$	0.259	0.259	6.2
$c\bar{c}$	0.50	0.12	2.9
$W\ W^*$	0.779	0.941	22.5
$Z\ Z^*$	0.0839	0.119	2.9
$g\ g$	0.22	0.35	8.5
$\gamma\ \gamma$	0.0091	0.0096	0.23
Totale	6.77	4.17	99.8

Table 1:

1. La ricerca del bosone di Higgs al LEP

Una campagna di ricerca al LEP II per osservare un bosone di Higgs con massa fino a circa 115 GeV

$$e + e- \rightarrow Z + H$$

$$Z \rightarrow q + \bar{q}, l + \bar{l}, \nu + \bar{\nu}$$

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

Canali studiati:

1. 4 jets, com massa invariante di due jet = M_Z
2. 2 jet+ energia mancante (corrispondente a Z→nu+nu)
3. 2jet + 2 leptoni (corrispondente a Z→l+l-bar)
4. Nei jet, si applicava per quanto possibile il b tagging, per esaltare gli eventi con un possibile H

Eventi interessanti raccolti da ALEPH nell' estate 2000, nel canale 4 jets con b-tagging, massa 114 GeV;
Alla fine, sui 4 esperimenti, l' evidenza per un Higgs di 114 GeV e' di circa 2 standard deviations
Per arrivare a questo, sono state fatte analisi statistiche molto raffinate

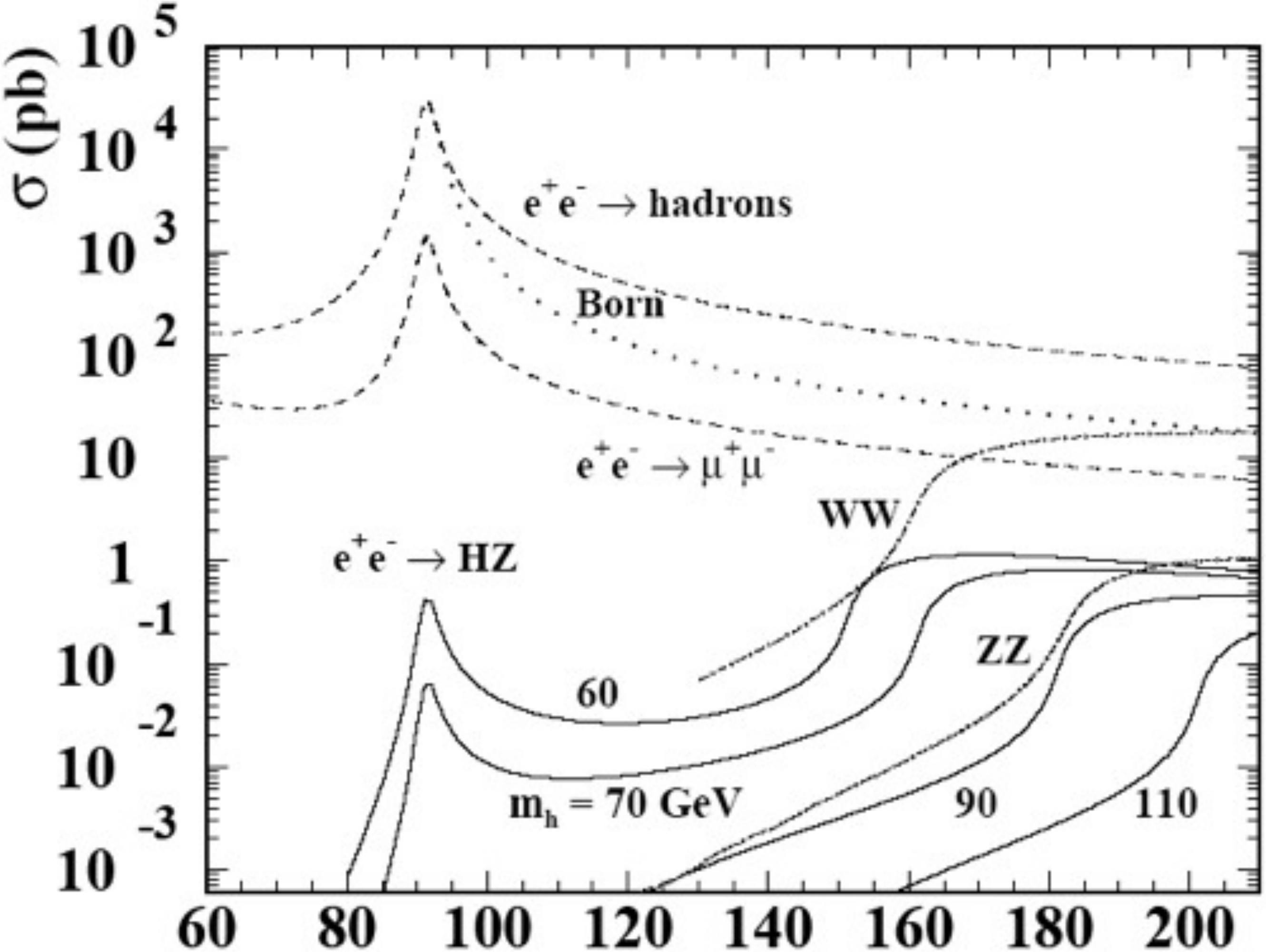
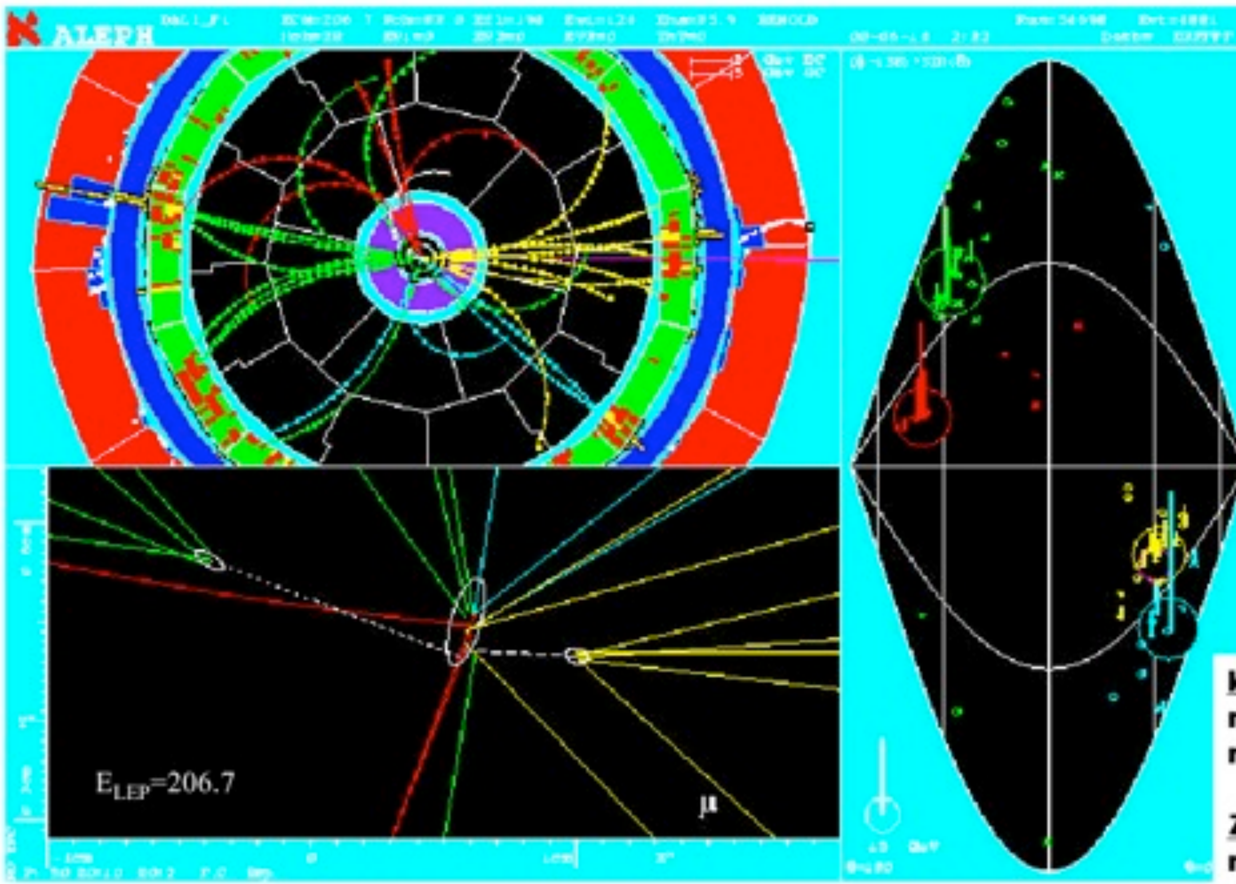


Figure 3: Cross sections, as a function of $\sqrt{s}$, for the Higgs-strahlung process in the SM for fixed values of m_{H^0} (full lines), and for other SM processes which contribute to the background.

ALEPH: candidate for e+e-→Z+H (Summer 2000)



2 b cand.

HZ hyp.
m_H=114 GeV
±3 GeV

NN = 0.996

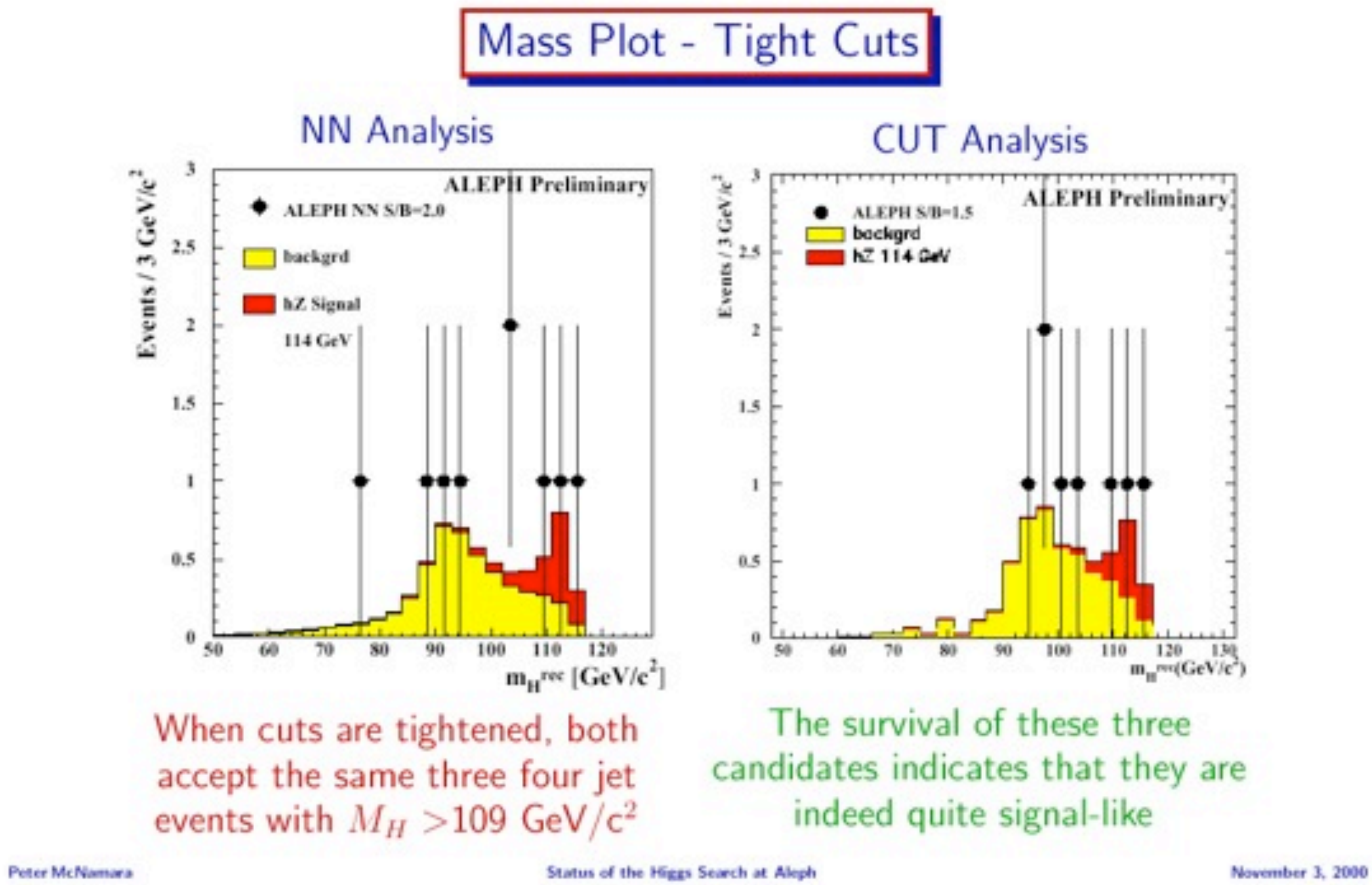
jet b-tag:

Z	
1	0.14
2	0.01
H	
3	0.99
4	0.99

kin. mass fit
m_H=112.4GeV
m_Z=93.3GeV

ZZ hyp.
m_Z=102 GeV
m_Z=91.7GeV

Mass plot by ALEPH (Sept. 2000)

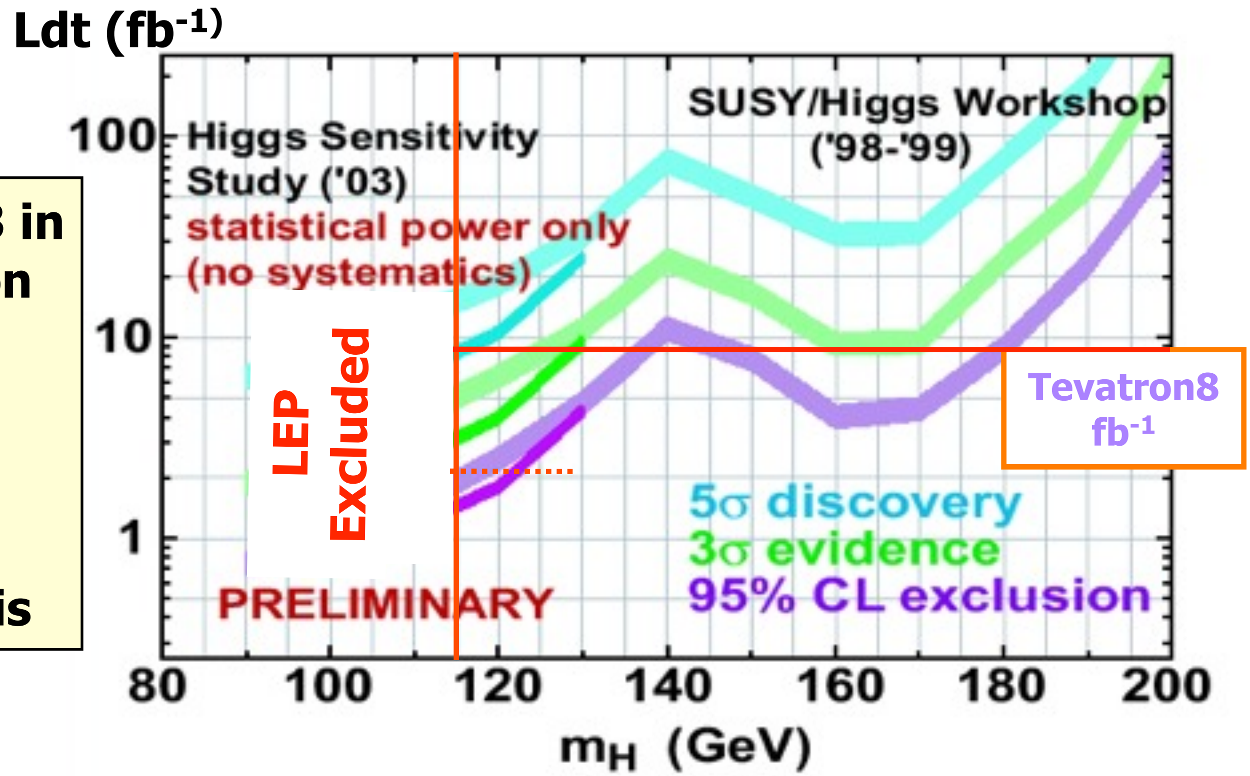


Tevatron SM Higgs Search: Outlook

Prospects updated in 2003 in the low Higgs mass region

W(Z) H→ lν(νν,ll) $b\bar{b}$

→ better detector understanding
→ optimization of analysis



Sensitivity in the mass region above LEP limit (114 GeV) starts at ~2 fb^{-1}
With 8 fb^{-1}: exclusion 115-135 GeV & 145-180 GeV,
5 - 3 sigma discovery/evidence @ 115 – 130 GeV

Higgs Boson at the LHC

- SM Higgs boson can be discovered at ≈ 5 σ after ≈1 year of operation (10 fb^{-1}/ experiment) for m_H ≈ 150 GeV
- Discovery faster for larger masses
- Whole mass range can be excluded at 95% CL after ~1 month of running at 10^{33} cm^{-2} s^{-1}.

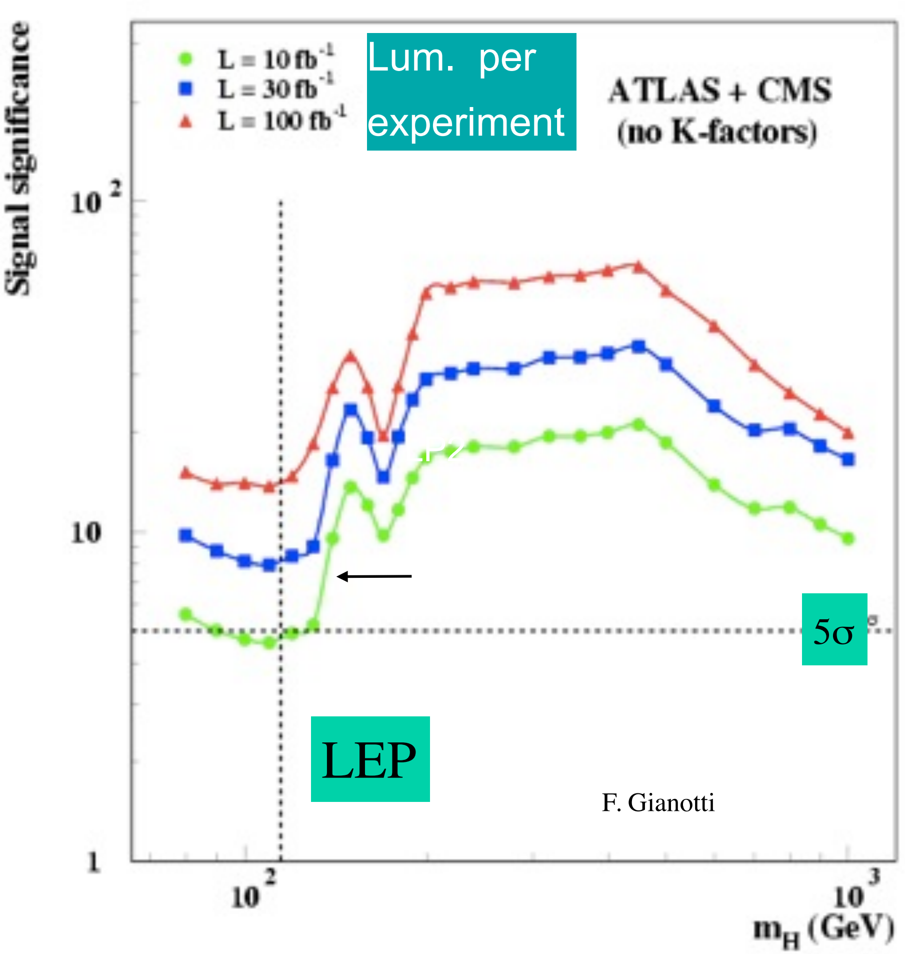
results are conservative:

-- no k-factors

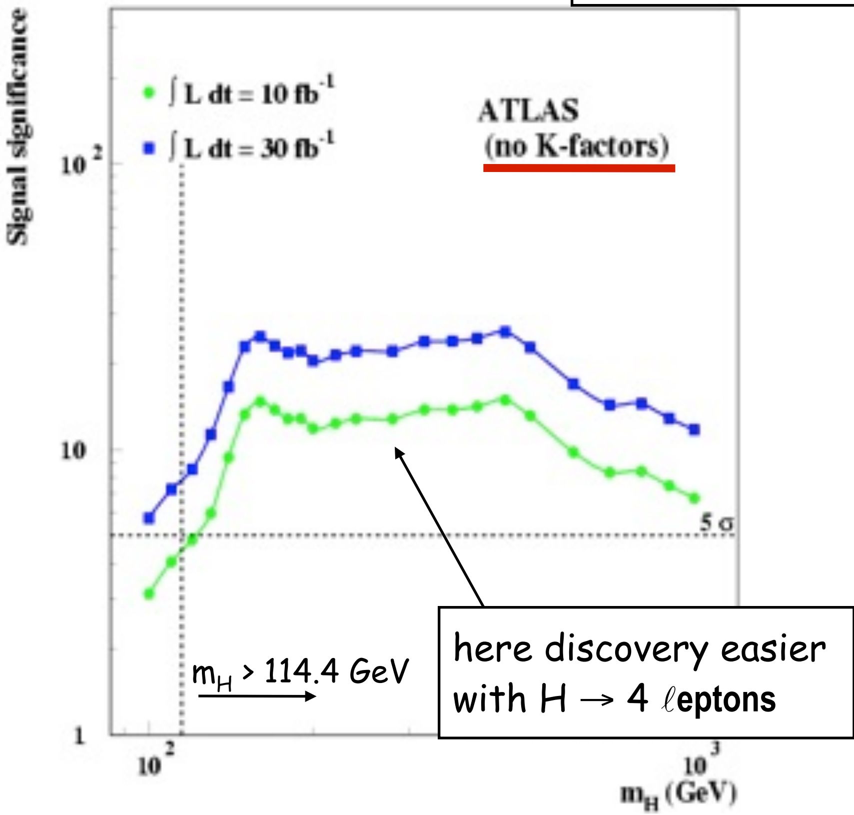
-- simple cut-based analyses

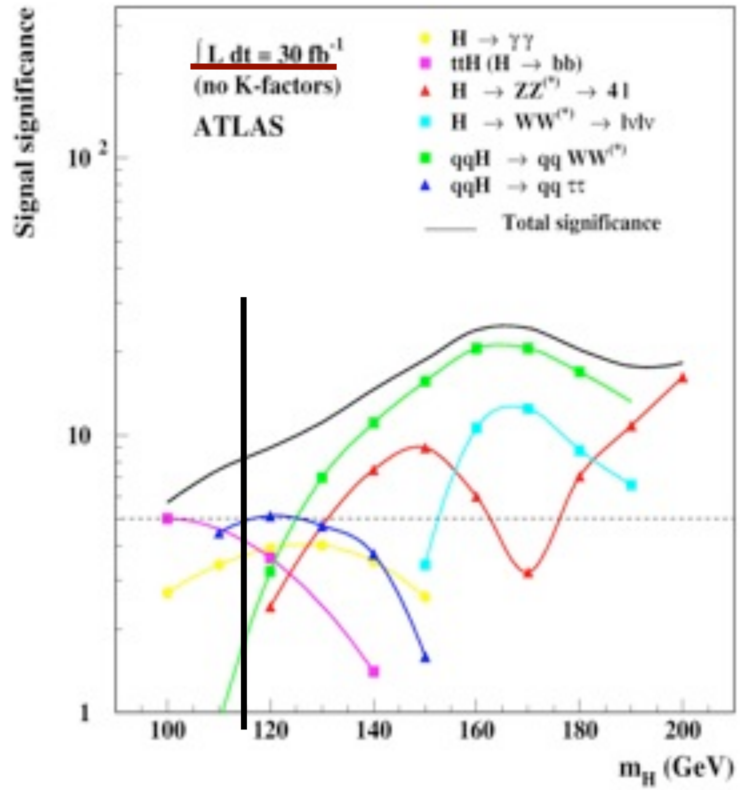
-- conservative assumptions on detector performance

-- channels where background control is difficult not included, e.g



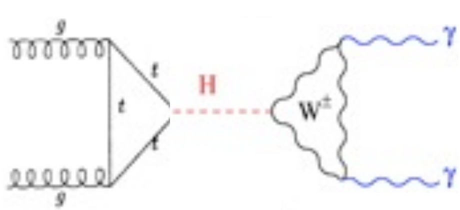
Standard Model Higgs @LHC



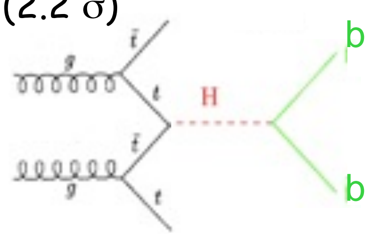


For m_H ~ 115 GeV and 10 fb^{-1}, 3 complementary channels accessible:

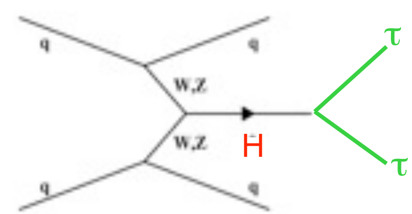
$H \to \gamma\gamma$ (2 σ)



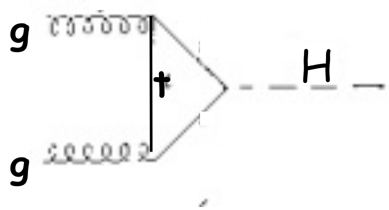
$ttH \to tt\ bb \to b\ell\nu\ bjj\ bb$ (2.2 σ)

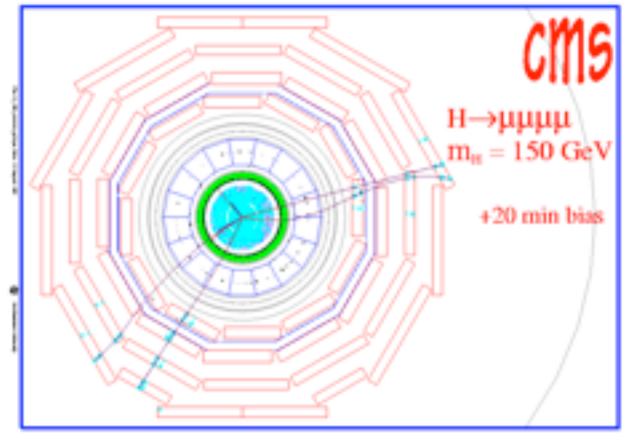


$qqH \to qq\tau\tau$ (2.7 σ)

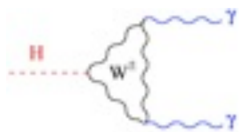


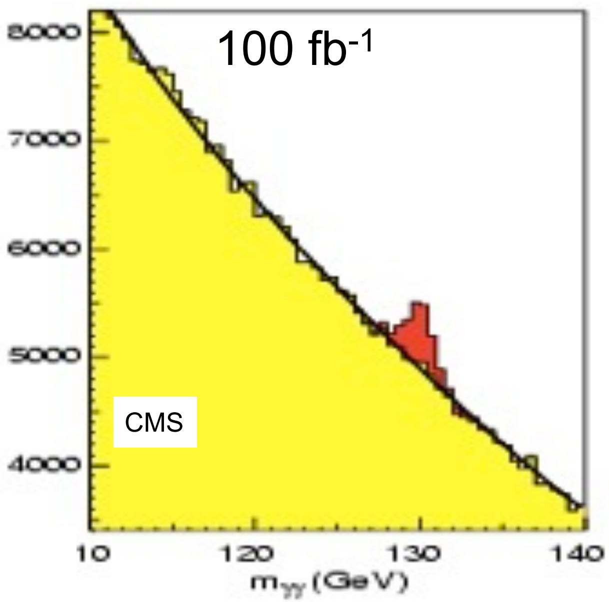
Among best channels at LHC :





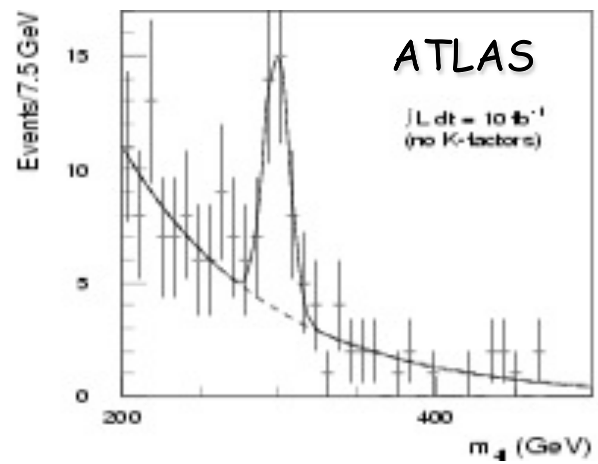
m_H < 150 GeV : $H \to \gamma\gamma$





Requires excellent EM calorimetry (E-resolution, γ/π^0 separation)

m_H > 130 GeV : $H \to ZZ^{(*)} \to 4e, 4\mu$



Requires good lepton E, p resolution and identification. Gold-plated channel at LHC

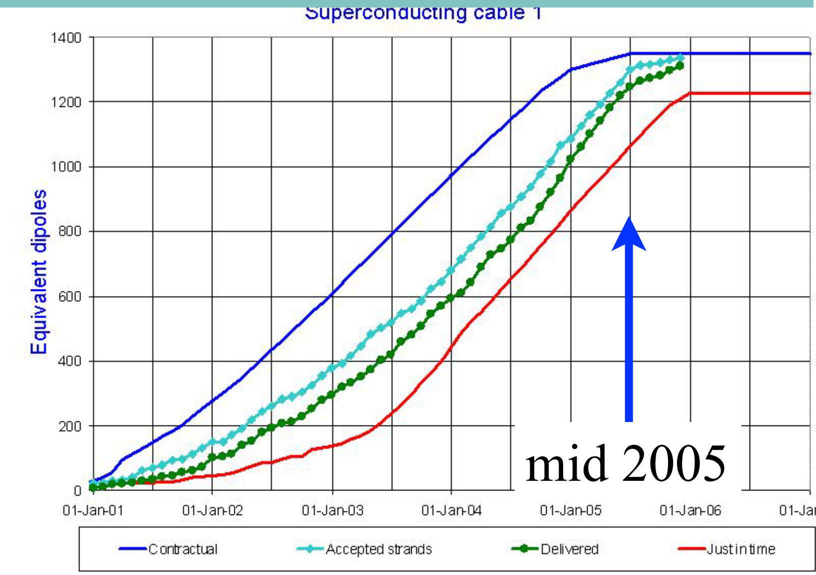
1. BUILDING LHC: A GREAT ENTERPRISE WHICH CERN LED WITH GREAT SKILL

1.1. LHC Schedule

- Contracts for dipole cold mass a[...] CERN has a double role: supplier of SC cables, end-customer of the dipoles. We must be prudent in defining the dipole delivery schedule, hence the LHC schedule.
- SC cable production to end mid 2005;
- last dipole delivered July 1st, 2006;
- Machine closed and cold: Oct. 2006;
- First beam: April 2007;
- First physics: mid 2007;
- Very solid foundation of the LHC confirmed by SC cable panel and Machine Advisory Committee.

L. Maiani. March 21, 2002 Committee of Council

CERN Council, March 2002



Updated 30 Nov 2005 Data provided by A. Verweij AT-MAS

•1.5 year delay due to problems with QRL

•another 1.5 year for the dipole accident

•resolved by Steve Myers

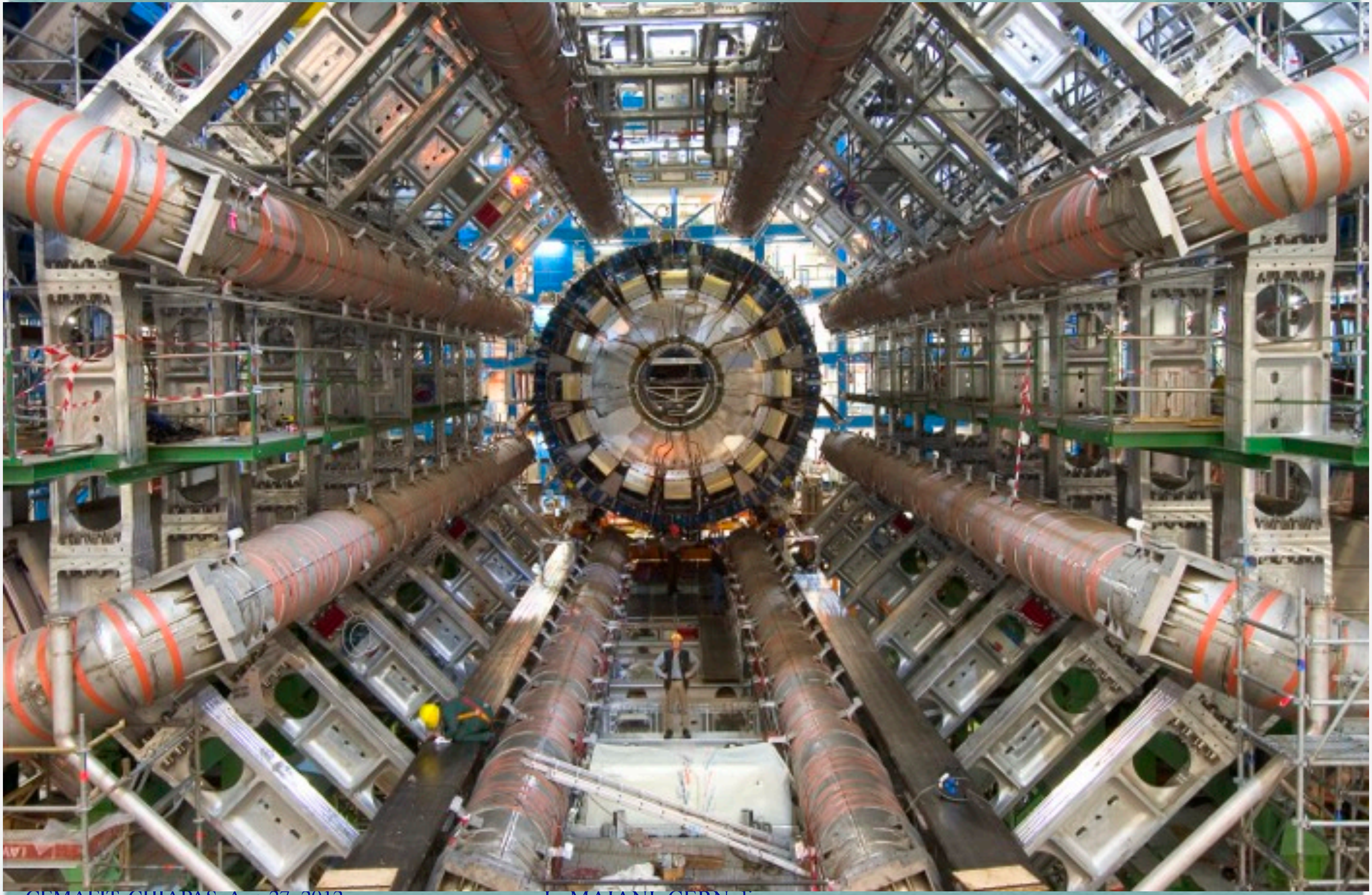
•useful beams: 2010

•Higgs physics: 2011

Sept. 10th 08: first beams

Lyn Evans and Lucio Rossi receive at CERN the last dipole

The ATLAS Detector at CERN



The CMS Detector at CERN

In the following years, we will recognize a clear discontinuity in physics: BEFORE and AFTER the 4th of July talks by CMS and ATLAS.

ATLAS final statement

We have looked for a SM Higgs over the mass region 110-600 GeV in 12 channels

We have excluded at 99% CL the full region up to 523 GeV except 121.8< m_H<130.7 GeV

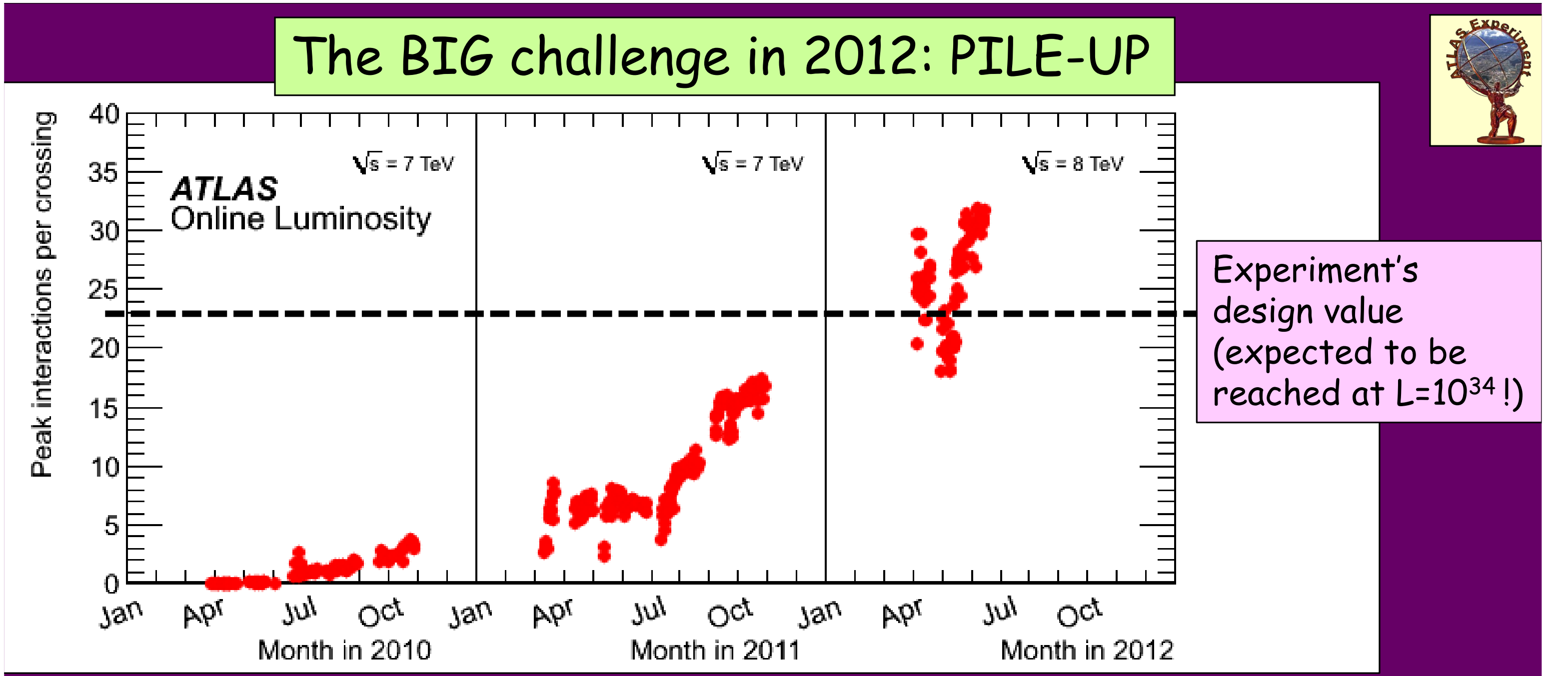
We observe an excess of events at m_H ~ 126.5 GeV with local significance **5.0 σ**

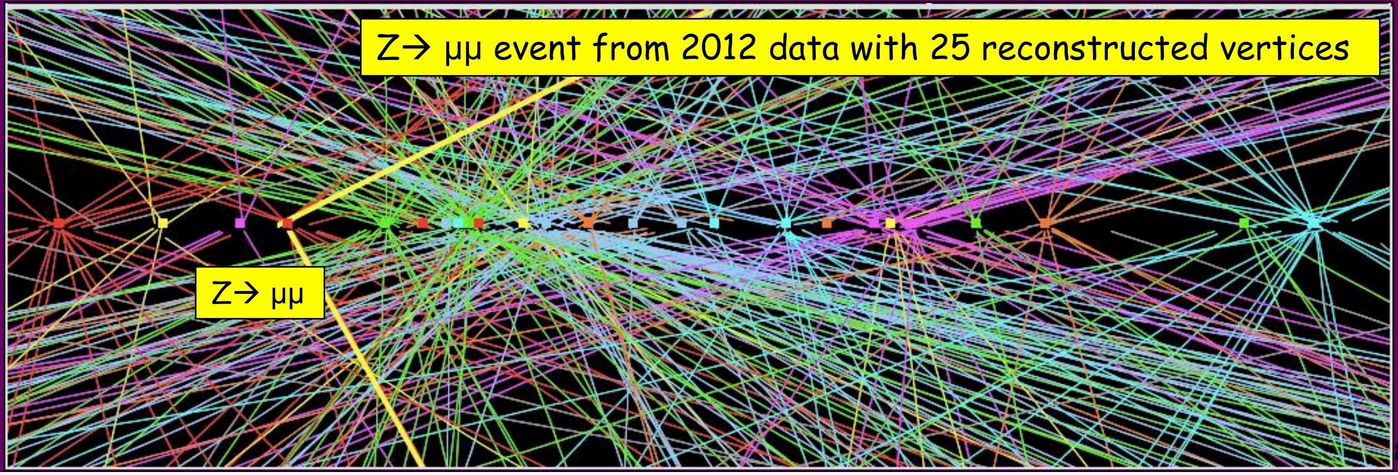
- The excess is driven by the two high mass resolution channels: $H \to \gamma\gamma$ (4.5 σ) and $H \to ZZ^* \to 4l$ (3.4 σ)
- Expected significance from a SM Higgs: 4.6 σ
- Fitted signal strength: 1.2 ± 0.3 of the SM expectation

CMS final statement

We have observed a new boson with a mass of **125.3 ± 0.6 GeV** at **4.9 σ** significance !

High luminosity: the price to pay is pile up!

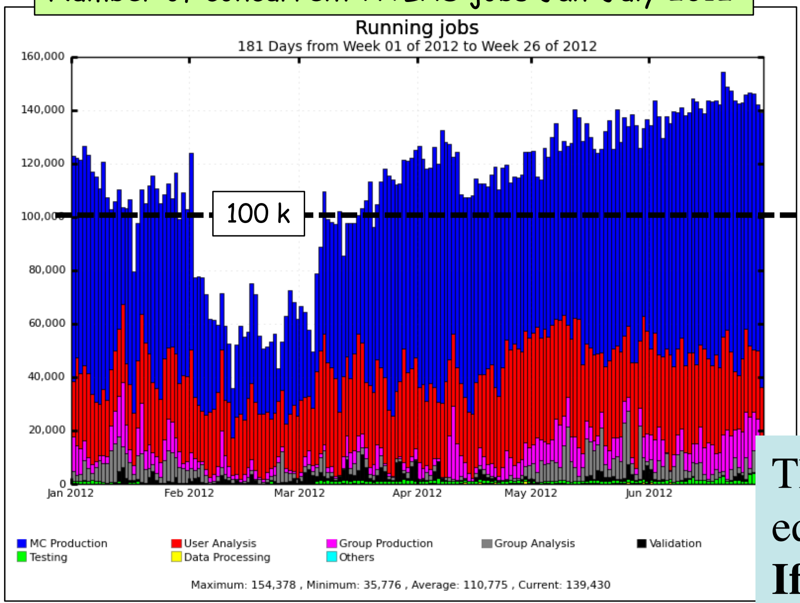




The LHC data GRID, launched in 2001… is working perfectly

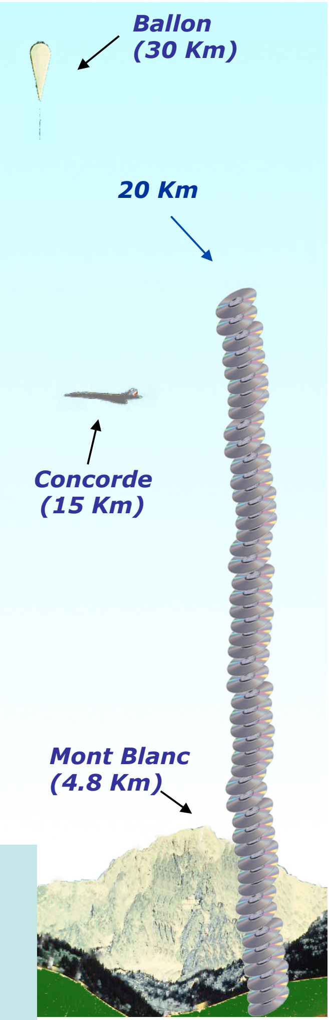
It would have been impossible to release physics results so quickly without the outstanding performance of the Grid (including the CERN Tier-0)

Number of concurrent ATLAS jobs Jan-July 2012



Includes MC production, user and group analysis at CERN, 10 Tier1-s, ~ 70 Tier-2 federations → > 80 sites

> 1500 distinct ATLAS users do analysis on the GRID



The data to be recorded in 1 year are equivalent to **15 millions DVD movies; If recorded on CDs, they would reach the height of 20 km !!**

- ❑ Available resources fully used/stressed (beyond pledg
- ❑ Massive production of 8 TeV Monte Carlo samples
- ❑ Very effective and flexible Computing Model and Operation team → accommodate high trigger rates and pile-up, intense MC simulation, analysis demands from worldwide users (through e.g. dynamic data placement)

12

1990 The LEP revolution

Processor farms : the 90's supercomputer

Found at the NOW project (http://now.cs.berkeley.edu)

- PC+Linux: the new supercomputer for scientific applications

obswww.unige.ch/~pfennige/gravitor/gravitor_e.html

www.cs.sandia.gov/cplant/

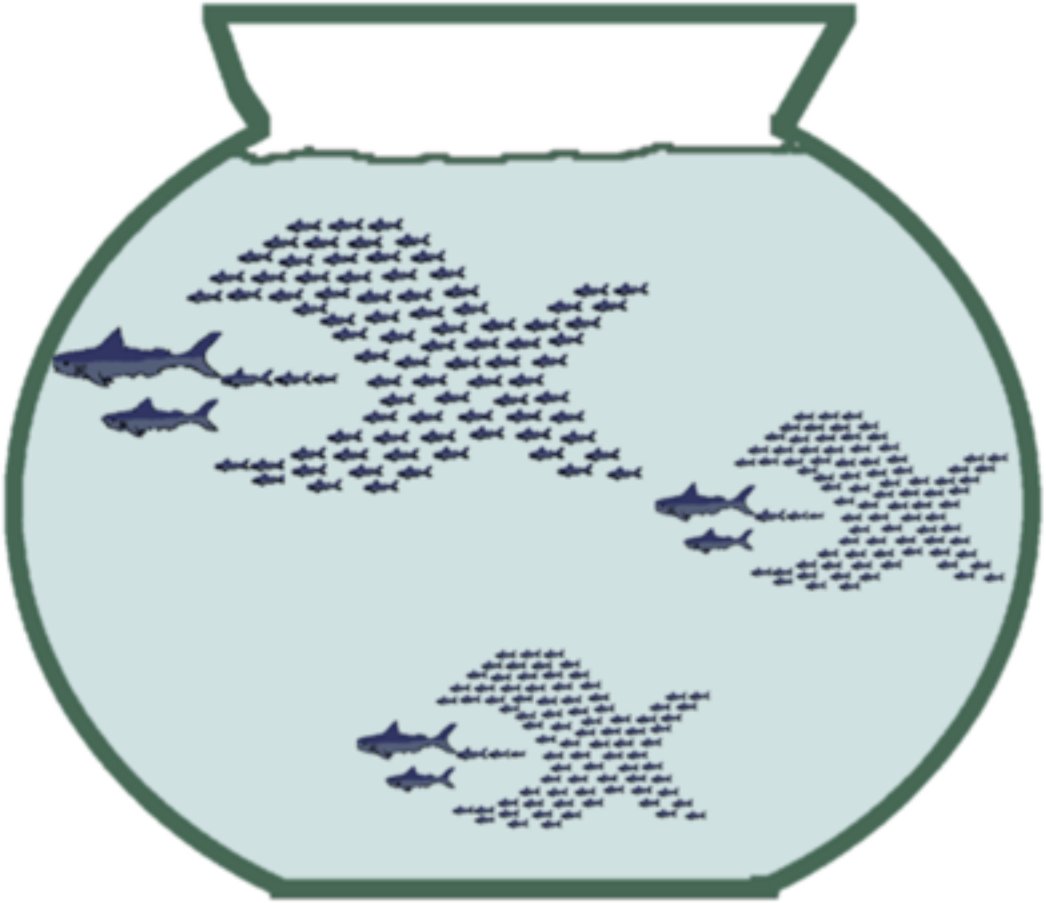
- Principle well established; farm examples abound

now.cs.berkeley.edu

www.ncsa.uiuc.edu/General/CC/ntcluster/

After commodity farms what next?

LHC Data GRID, 2001



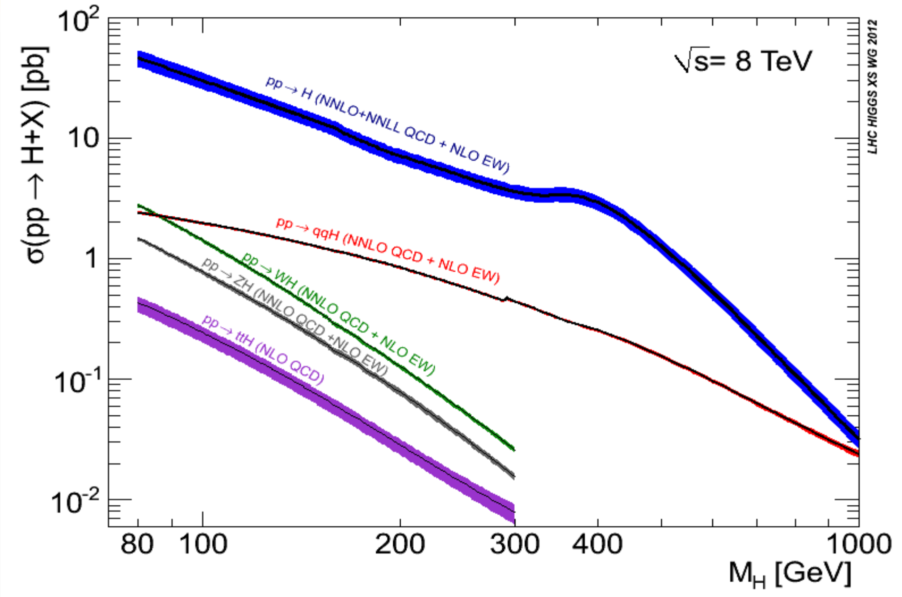
Fusion of global resources for data communication, data processing and data archive: Grid approach ?

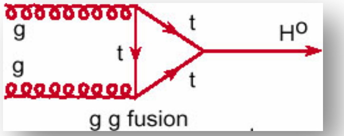
4. Summary of Data

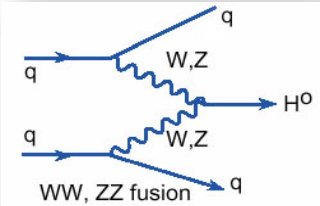
J. Incandelas

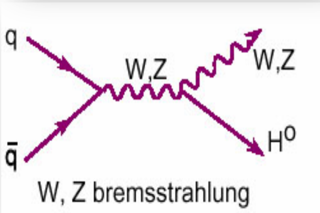
CMS

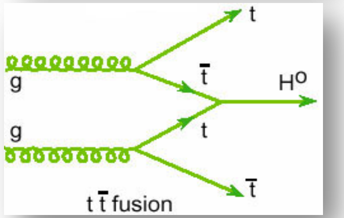
Higgs boson production







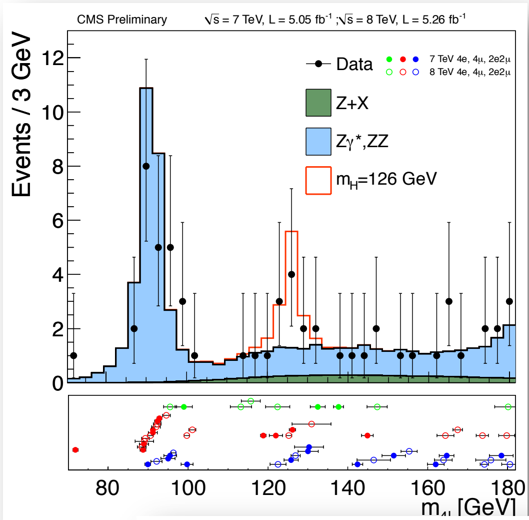


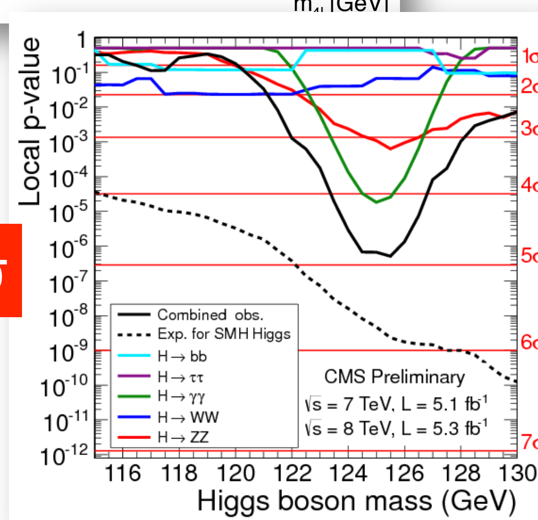


- $\sqrt{s}$=8 TeV: 25-30% higher σ than $\sqrt{s}$=7 TeV at low m_H
- All production modes to be exploited
  - gg VBF VH ttH
  - Latter 3 have smaller cross sections but better S/B in many cases

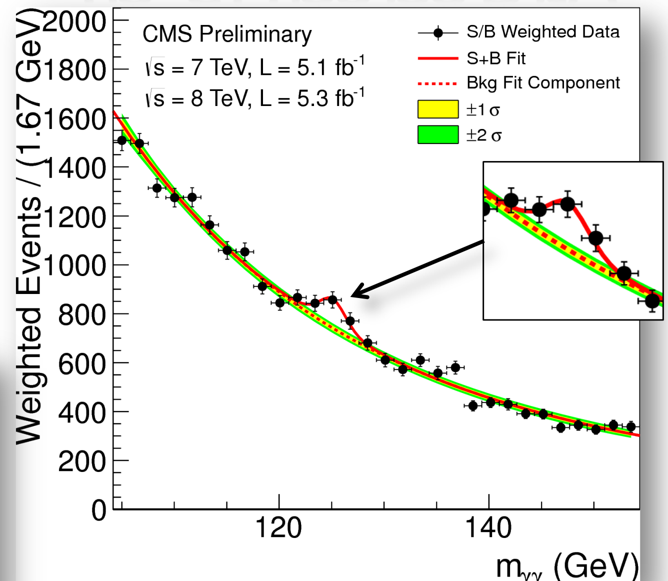
In summary

July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION





5σ

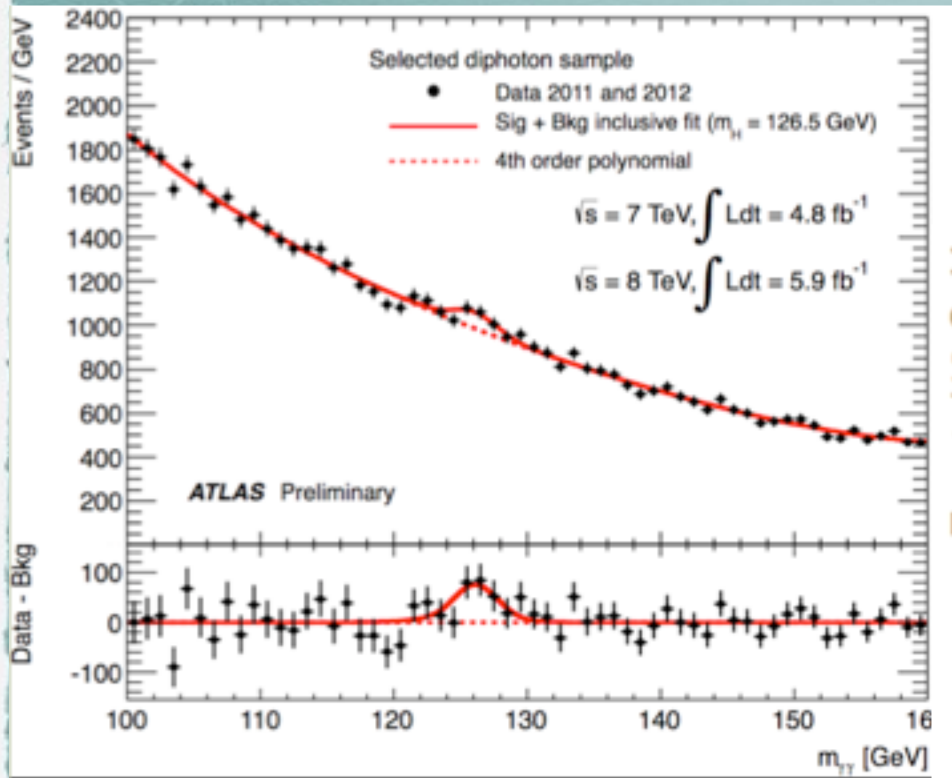


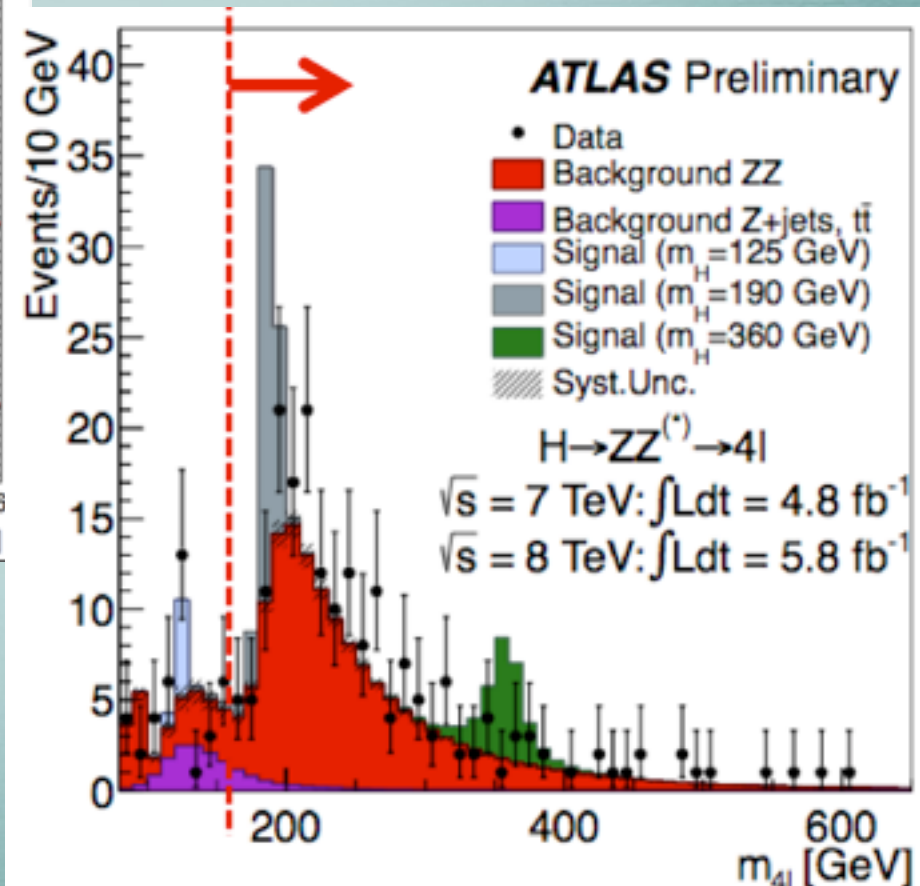
ATLAS

2 gammas: H-> $\gamma\gamma$

4 muons: H-> $\mu^+\mu^+\mu^-\mu^-$

F. Gianotti





Higgs ->gamma gamma

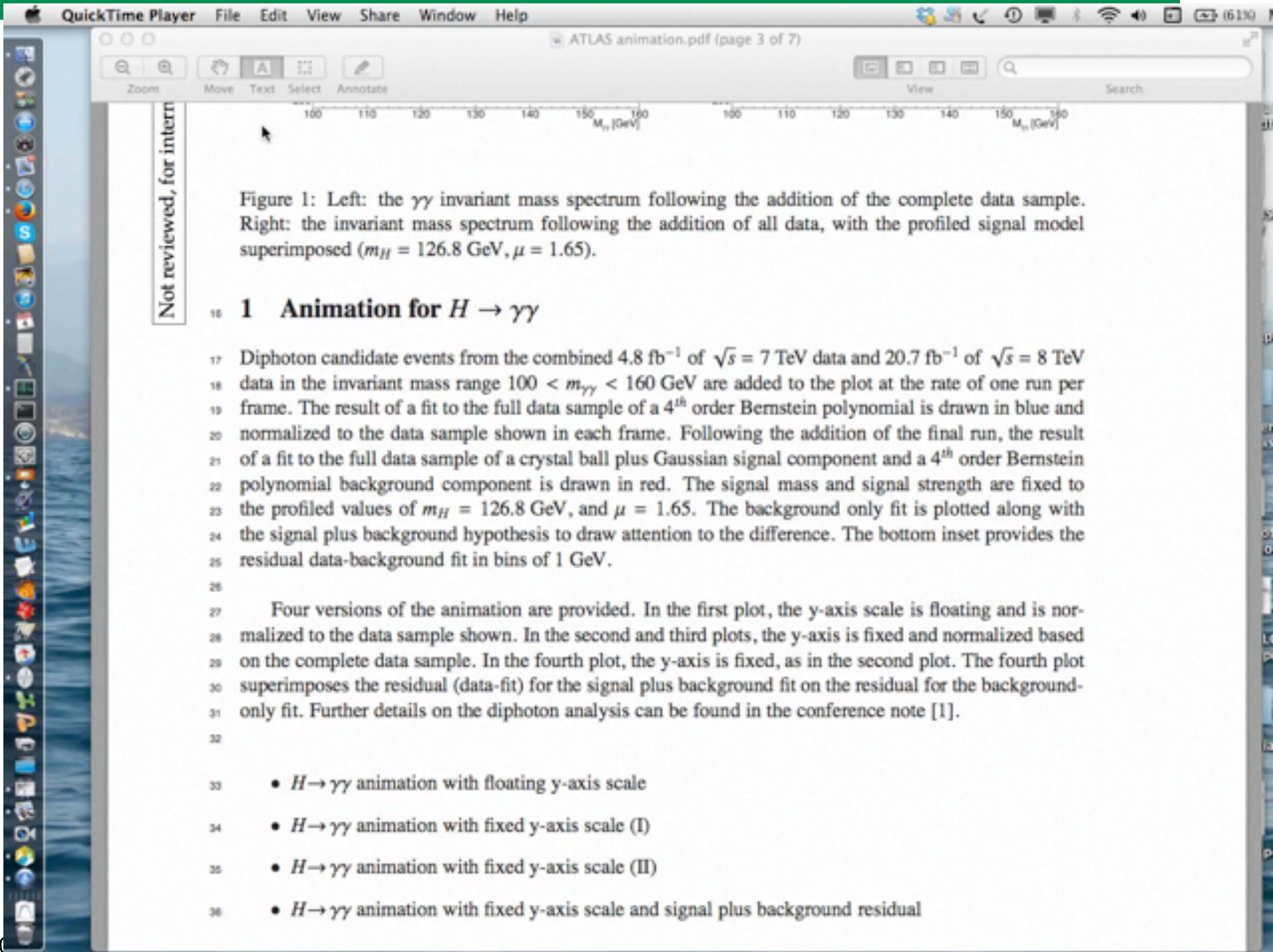


Figure 1: Left: the $\gamma\gamma$ invariant mass spectrum following the addition of the complete data sample. Right: the invariant mass spectrum following the addition of all data, with the profiled signal model superimposed ($m_H = 126.8$ GeV, $\mu = 1.65$).

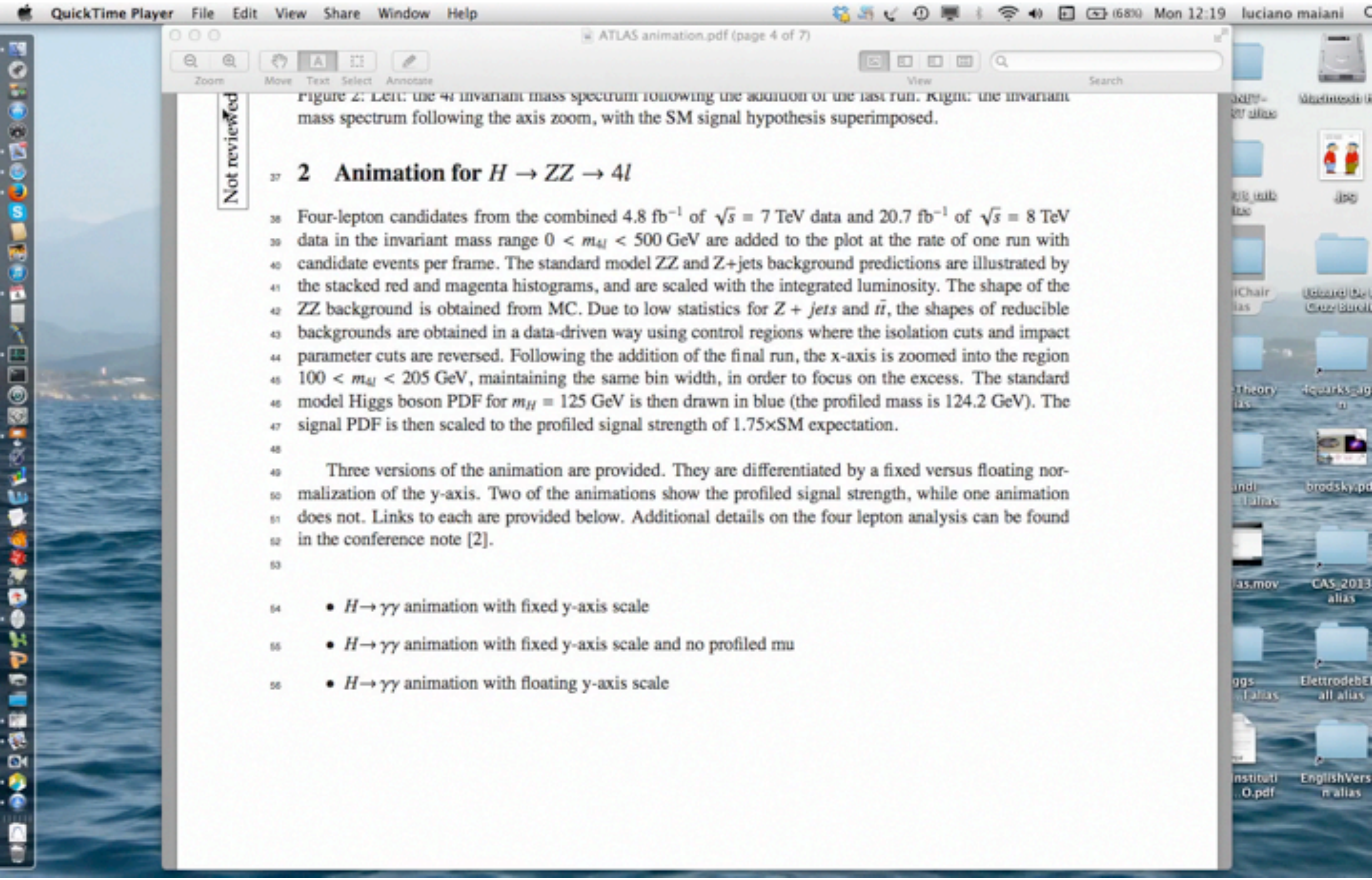
1 Animation for $H \rightarrow \gamma\gamma$

Diphoton candidate events from the combined 4.8 fb^{-1} of $\sqrt{s} = 7$ TeV data and 20.7 fb^{-1} of $\sqrt{s} = 8$ TeV data in the invariant mass range $100 < m_{\gamma\gamma} < 160$ GeV are added to the plot at the rate of one run per frame. The result of a fit to the full data sample of a 4th order Bernstein polynomial is drawn in blue and normalized to the data sample shown in each frame. Following the addition of the final run, the result of a fit to the full data sample of a crystal ball plus Gaussian signal component and a 4th order Bernstein polynomial background component is drawn in red. The signal mass and signal strength are fixed to the profiled values of $m_H = 126.8$ GeV, and $\mu = 1.65$. The background only fit is plotted along with the signal plus background hypothesis to draw attention to the difference. The bottom inset provides the residual data-background fit in bins of 1 GeV.

Four versions of the animation are provided. In the first plot, the y-axis scale is floating and is normalized to the data sample shown. In the second and third plots, the y-axis is fixed and normalized based on the complete data sample. In the fourth plot, the y-axis is fixed, as in the second plot. The fourth plot superimposes the residual (data-fit) for the signal plus background fit on the residual for the background-only fit. Further details on the diphoton analysis can be found in the conference note [1].

- $H \rightarrow \gamma\gamma$ animation with floating y-axis scale
- $H \rightarrow \gamma\gamma$ animation with fixed y-axis scale (I)
- $H \rightarrow \gamma\gamma$ animation with fixed y-axis scale (II)
- $H \rightarrow \gamma\gamma$ animation with fixed y-axis scale and signal plus background residual

Higgs -> 4 leptons



Not reviewed

Figure 2: Left: the 4l invariant mass spectrum following the addition of the last run. Right: the invariant mass spectrum following the axis zoom, with the SM signal hypothesis superimposed.

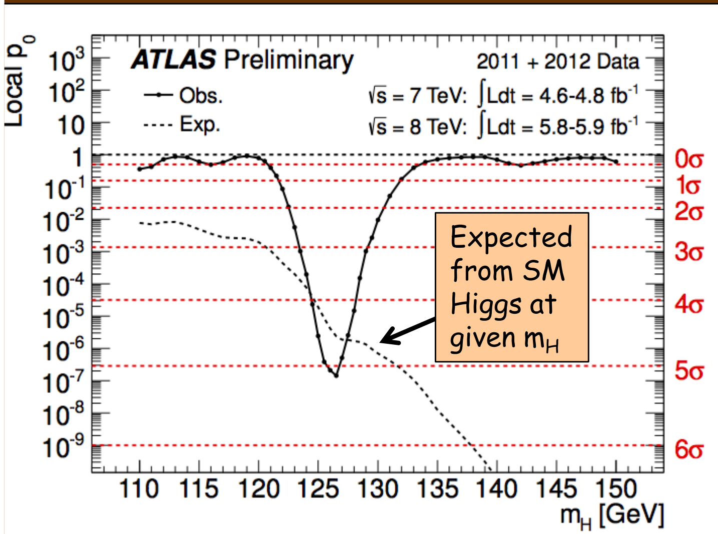
2 Animation for $H \to ZZ \to 4l$

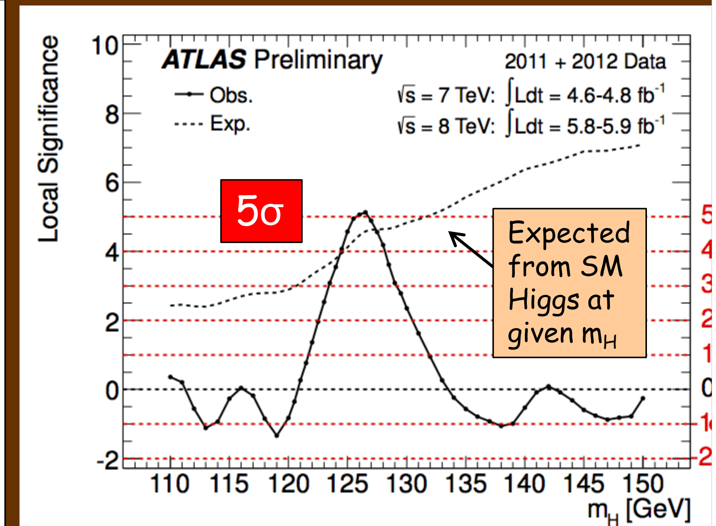
Four-lepton candidates from the combined 4.8 fb^{-1} of $\sqrt{s}$ = 7 TeV data and 20.7 fb^{-1} of $\sqrt{s}$ = 8 TeV data in the invariant mass range $0 < m_{4l} < 500$ GeV are added to the plot at the rate of one run with candidate events per frame. The standard model ZZ and Z+jets background predictions are illustrated by the stacked red and magenta histograms, and are scaled with the integrated luminosity. The shape of the ZZ background is obtained from MC. Due to low statistics for $Z + jets$ and $t\bar{t}$, the shapes of reducible backgrounds are obtained in a data-driven way using control regions where the isolation cuts and impact parameter cuts are reversed. Following the addition of the final run, the x-axis is zoomed into the region $100 < m_{4l} < 205$ GeV, maintaining the same bin width, in order to focus on the excess. The standard model Higgs boson PDF for $m_H = 125$ GeV is then drawn in blue (the profiled mass is 124.2 GeV). The signal PDF is then scaled to the profiled signal strength of 1.75×SM expectation.

Three versions of the animation are provided. They are differentiated by a fixed versus floating normalization of the y-axis. Two of the animations show the profiled signal strength, while one animation does not. Links to each are provided below. Additional details on the four lepton analysis can be found in the conference note [2].

- $H \to \gamma\gamma$ animation with fixed y-axis scale
- $H \to \gamma\gamma$ animation with fixed y-axis scale and no profiled mu
- $H \to \gamma\gamma$ animation with floating y-axis scale

Combined results: the excess





Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	5.0 σ
Probability of background up-fluctuation	3×10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

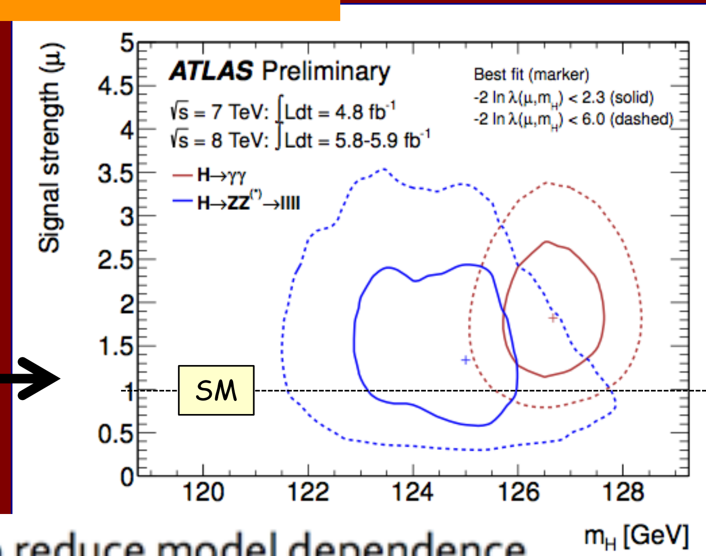
Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

The mass of the new particle

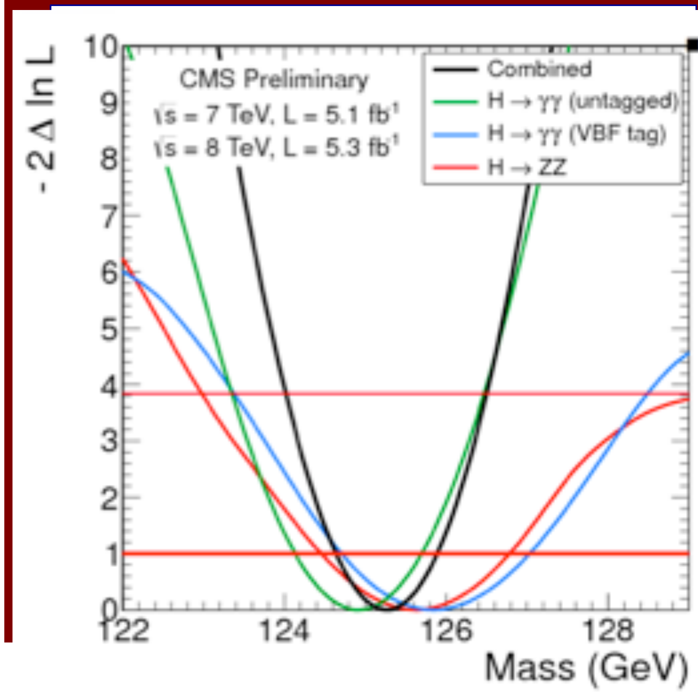
Combined results: consistency of the global picture

Are the 4l and γγ observations consistent ?

From 2-dim likelihood fit to signal mass and strength →curves show approximate 68% (full) and 95% (dashed) CL contours



ATLAS



To reduce model dependence, allow for free cross sections in three channels and fit for the common mass:

$m_X = 125.3 \pm 0.6$ GeV

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nnels,

CMS

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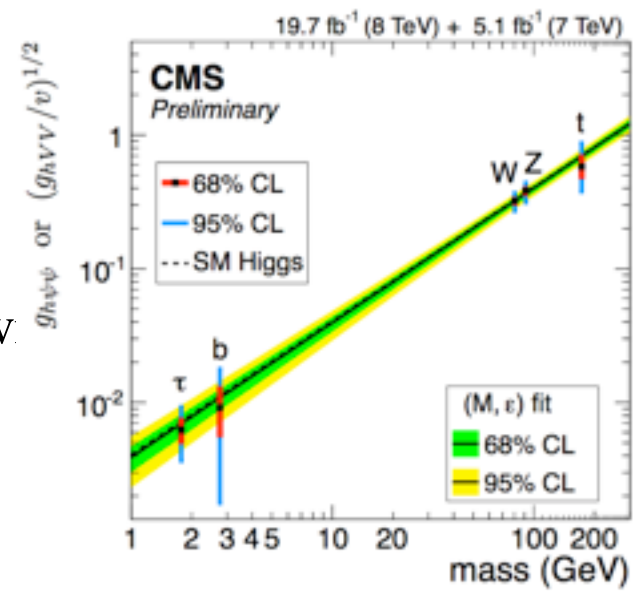
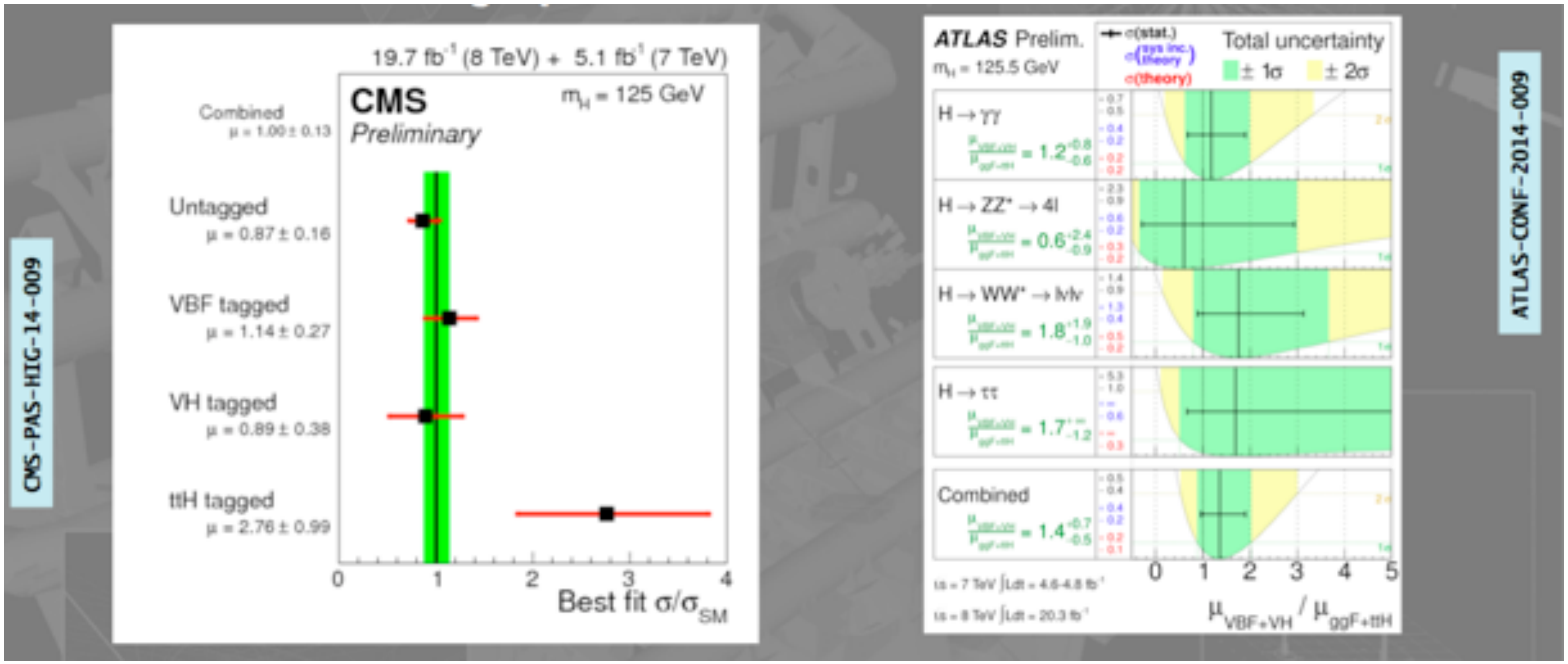
1. Being the Higgs boson: couplings to the other particles

- With the Higgs boson we are probing a physics which is very different from the one we are used with the gauge interactions
- In lowest order, the couplings of H to other particles are related to the masses:
    - g(H-f fbar) $\propto m_f$ (no e-μ universality !)
    - g(H-VV) $\propto m_V^2$ (coupling to the photon only in higher orders)
- large variations
- this is the signature of being the Higgs boson!

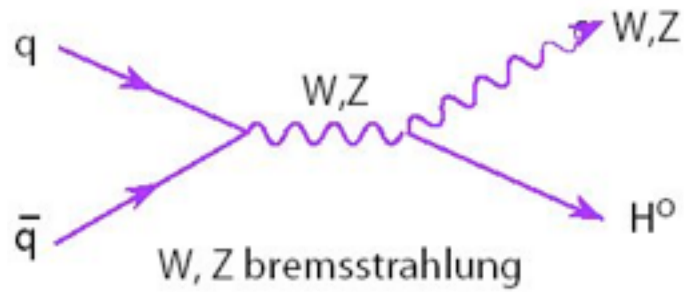


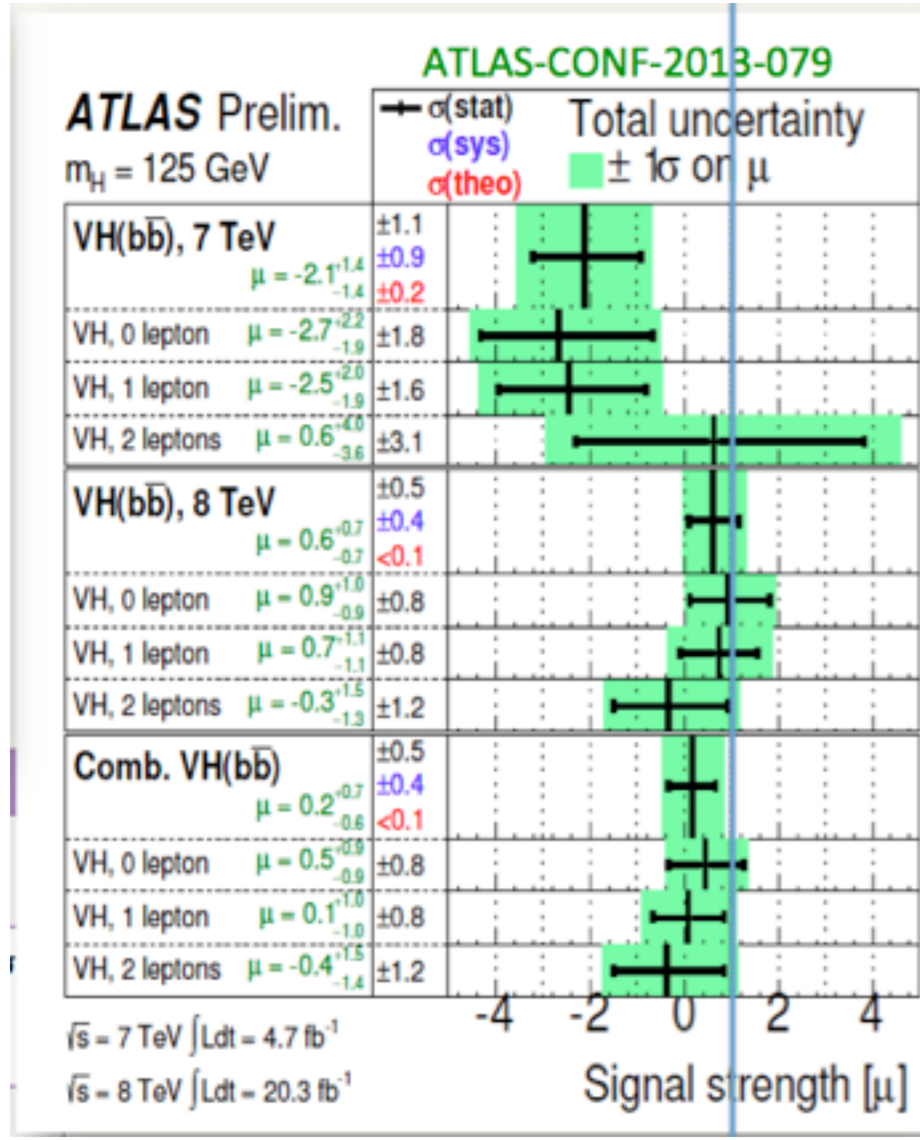
- After all, this is the most important message: mass vs. coupling correlation for all know particles

Higgs Boson Summary (J. Ocariz @ Invisibles)



- the b-b bar channel is one of the most interesting but also most elusive because of large background
- a strategy is to select for VH events





4. Unnatural: what is it?

- The Standard Theory is incomplete: missing parts imply mass scale >> W mass

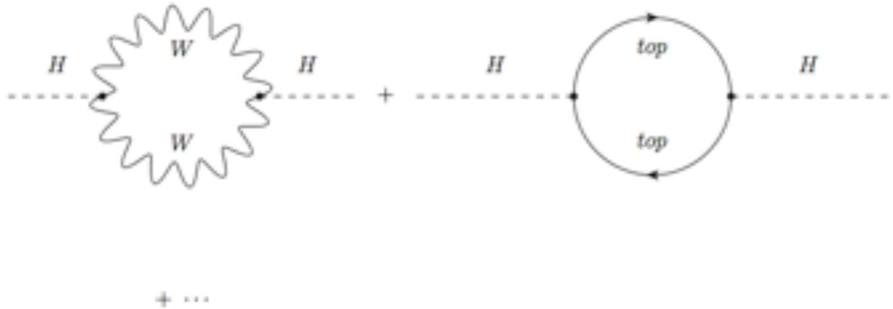
–Gravity: regulated by the Planck mass $M_P=1/\sqrt{G_{Newton}} = 10^{19}$ GeV

–Unification of the three gauge interactions of ST, Grand Unification mass $M_{GUT} = 10^{14}$ GeV

- How is it possible to have a low energy sector almost decoupled from the high energy scales?
- Spin 1/2 and 1 particles: in the zero mass limit a new symmetry is gained (chiral symmetry for spin 1/2, gauge symmetry for spin 1)
- higher order corrections to the mass do vanish in the limit where the bare mass vanishes
- thus, e.g. for the electron mass: $m_e(q^2)=m_0 \, \mathrm{Log}(q^2/M_{GUT})$ and the large mass is locked into Logs.
- In the Standard Model, no increased symmetry is gained by letting the mass

quadratic divergences

- Sometime unnaturalness of the Higgs is tyed to quadratic divergences and unnatural tuning between bare mass and rad corrections



$$\mu^2 = \mu_0^2 + \frac{\alpha}{\pi} \times Cost \times \Lambda^2 + \cdots$$

- this is however not necessary: even in regularization schemes with no quad div (e.g. dimensional reg. or Lee-Wick ghosts) the large mass will end up into the finite corrections, unless a symmetry reason does not prevent it.

alternatives

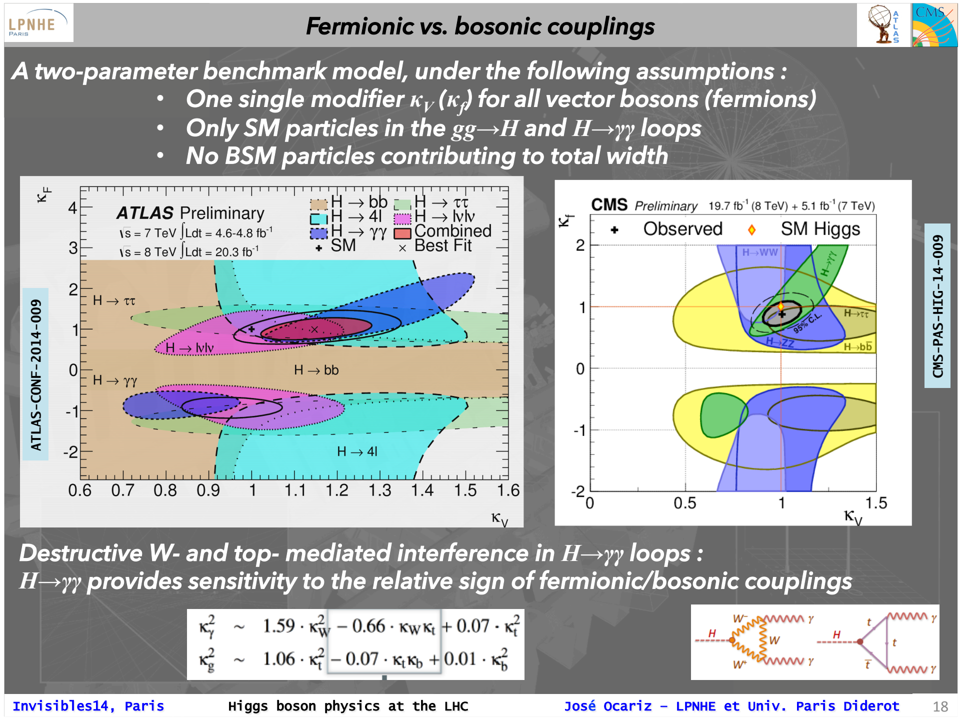
- ***Low energy supersymmetry*** relates scalars and fermions, whose mass is protected by chiral symmetry, and reduces the cutoff scale to M_{SUSY}, needed to be O(1TeV) for not too unnatural tuning, ... or
- ***No elementary scalars***, the Higgs boson is composite by fermion fields, tied together by forces at a scale O(1 TeV), called generically Technicolor forces.
- H could be much lighter than the high energy strong interactions scale, if it is a ***would-be-Goldstone boson*** of some symmetry.
- New strong-interactions at high energy: not indicated by electroweak precision data (which are becoming high-precision data).
- The value found for the Higgs boson mass speaks in favour of SUSY
- but we should keep ***both options*** open...for the time being.
- Important: it is not a matter of a factor of 2 or 4...
- The third option, which is becoming popular, is to ignore the problem...an a

If this is the answer...what was the question? (Financial Times)

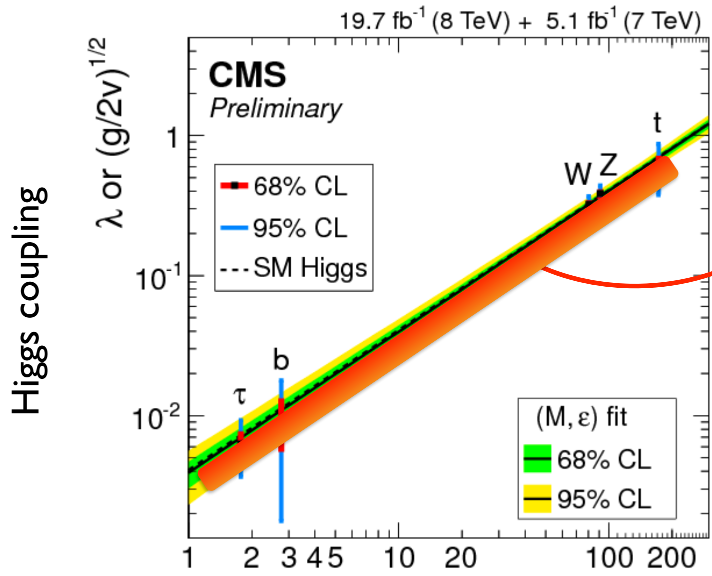
5. Precursors

- Before finding the particles implied by SUSY or by the extra strong interactions at high energy, one should detect ***anomalous couplings*** of the Higgs particle to vectors and fermions; deviations at few percent levels could be seen;
- the pattern of couplings may be quite complicated, but some simplification may help to orient us

present status is somewhat represented here:



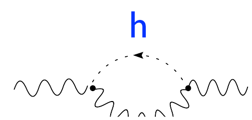
A better perspective to understand how close to a SM Higgs:



A. Pomerol @ Higgs Hunting 2014

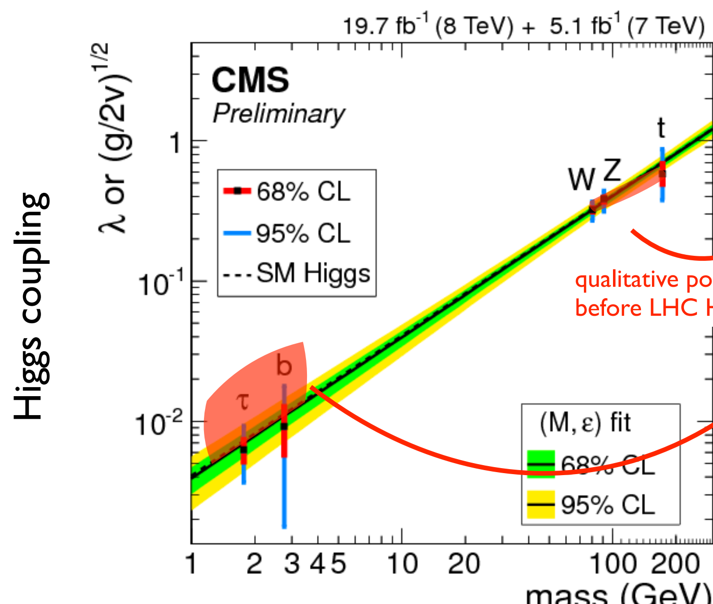
Composite Higgs
(reduction of couplings)

small effects already expected,
as EWPT (LEP1) put strong limits
to the coupling hVV
since it affects the Z propagator:



Looking for precursor signals

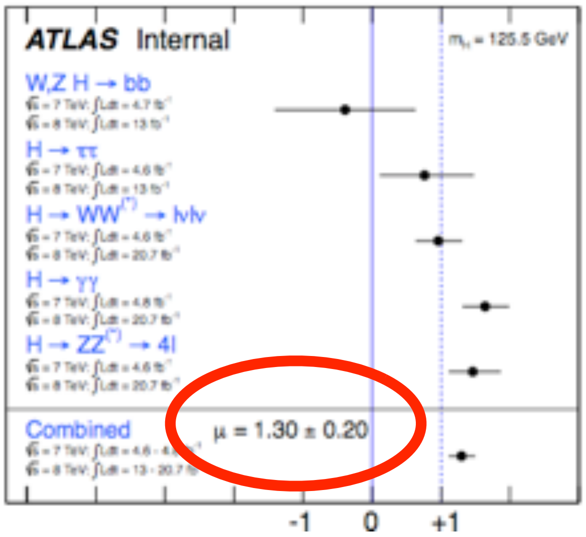
A better perspective to understand how close to a SM Higgs:

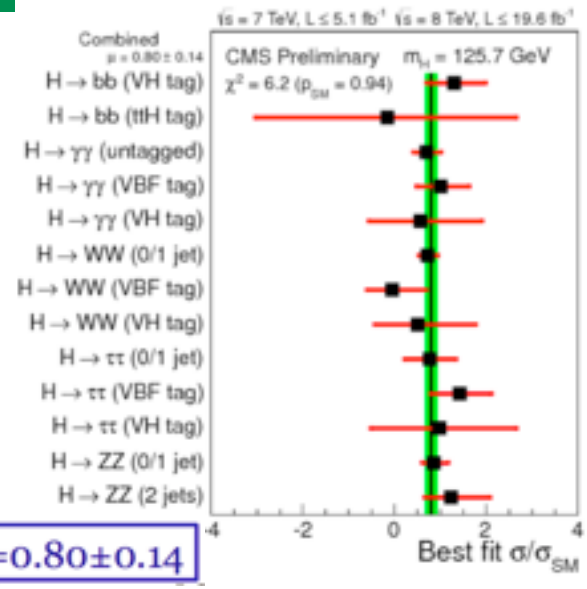


MSSM light Higgs

qualitative possible ranges
before LHC Higgs data

4. data and Three-couplings fit



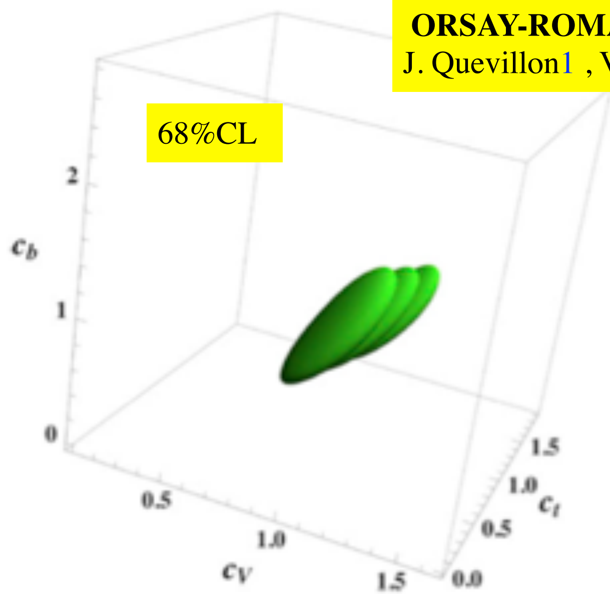


μ=0.80±0.14

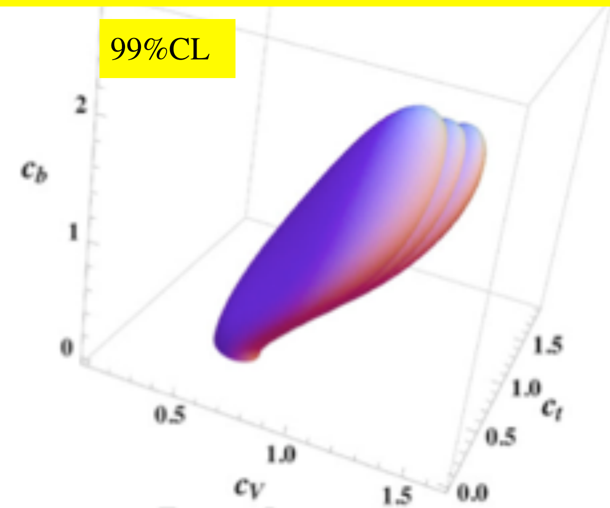
Fig. 4 Best-fit regions at 68 % CL (*green, left*) and 99 % CL (*light gray, right*) for the Higgs signal strengths in the three-dimensional space $[c_t, c_b, c_V]$. The three overlapped regions are associated to central and two extreme choices of the theoretical prediction for the Higgs rates

ORSAY-ROMA Collab.: A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon1 , V. Riquer, EPJ C in press, arXiv: 1307.5205

68%CL



99%CL



A first look: Composite PseudoGoldstone Higgs

A. Pomerol @ Higgs Hunting 2014

Composite PGB Higgs couplings

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

Giudice,Grojean,AP,Rattazzi 07
AP,Riva 12

$$\frac{g_{hWW}}{g_{hWW}^{SM}} = \sqrt{1-\frac{v^2}{f^2}}$$

f = Decay-constant of the PGB Higgs

(model dependent but expected f ~ v)

$$\frac{g_{hff}}{g_{hff}^{SM}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}}$$

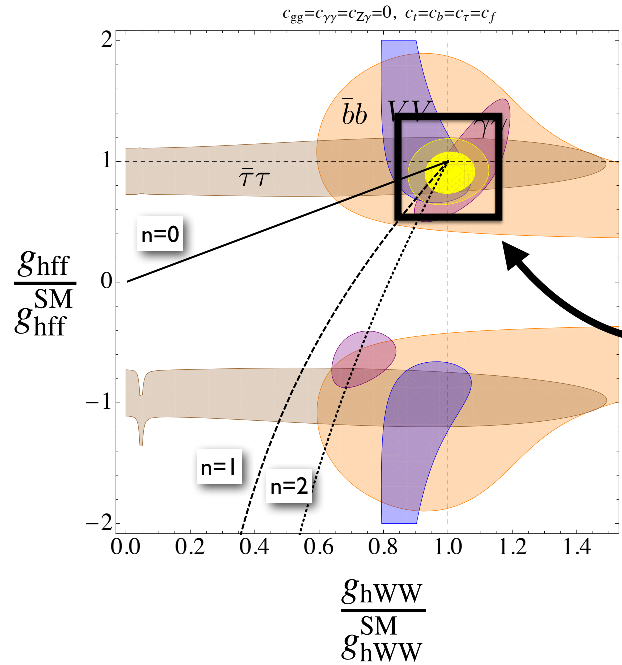
$n = 0, 1, 2, \ldots$

MCHM4 MCHM5

small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs

$$\xi \leq 0.1 \text{ from EW precision tests}$$

ATLAS+CMS:



arXiv:1303.1812

getting into the interesting region