# The discovery of the Higgs boson

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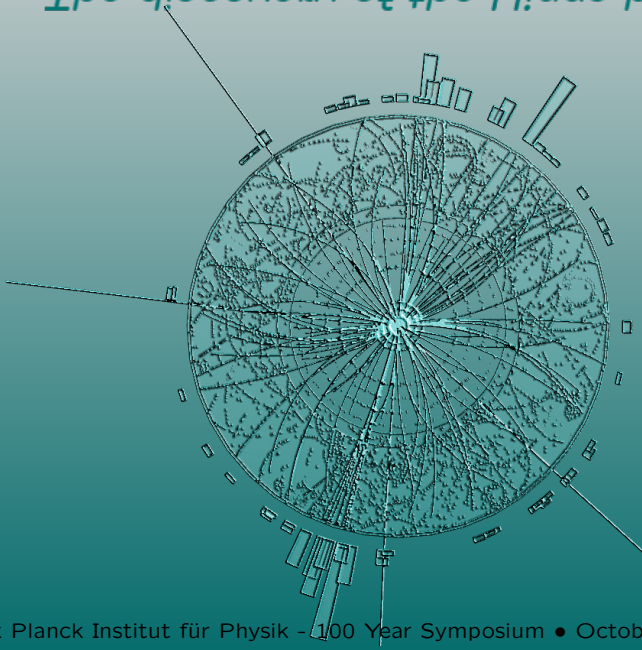


Sandra Kortner

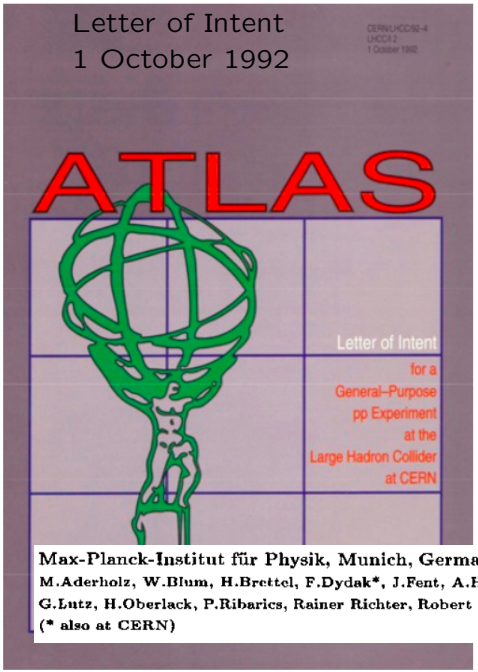
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Max Planck Institut für Physik - 100 Year Symposium • October $10^{th}$ - $12^{th}$, 2017

# That magic moment!

# A long journey

Letter of Intent
1 October 1992




**Max-Planck-Institut für Physik, Munich, Germany**
**M.Aderholz, W.Blum, H.Brettel, F.Dydak*, J.Fent, A.Halley, K.Jakobs, C.Kiesling, H.Kroha, E.Lorenz, G.Luetjens, G.Lutz, H.Oberlack, P.Ribarics, Rainer Richter, Robert Richter, P.Schacht, U.Stiegler, U.Stierlin, R.St.Denis, G.Wolf**
**(* also at CERN)**

## 1 Introduction and Overview

The ATLAS Collaboration proposes in this Letter of Intent a general-purpose pp experiment which would be operational at the startup of the Large Hadron Collider (LHC) in order to exploit its full discovery potential. The LHC offers a large range of physics opportunities, among which the origin of mass at the electroweak scale is a major focus of interest. The detector optimization is therefore guided by physics issues such as sensitivity to the largest possible Higgs mass range, but also for example by detailed studies of top quark decays, Supersymmetry searches, and sensitivity to large compositeness scales. The ability to cope with a broad variety of expected physics processes also demonstrates most importantly the detector's potential for unexpected new physics.

...

### 1.1 Basic Design Considerations

The Standard Model (SM) Higgs search can be used as a first benchmark for the detector optimization.

25 years of ATLAS at MPP!

# (Brout-Englert-)Higgs mechanism


P. W. Higgs

F. Englert and R. Brout, Phys. Rev. Lett. 13 (1964) 321-323
P. W. Higgs, Phys. Rev. Lett. 13 (1964) 508-509

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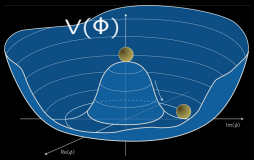
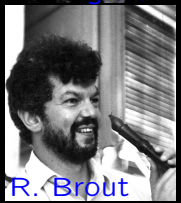
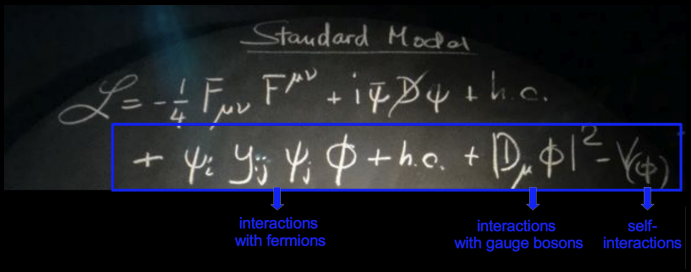
Elementary particles aquire mass by interacting with Higgs field $\phi$.




Electroweak symmetry spontaneously broken in the ground state.


F. Englert


R. Brout



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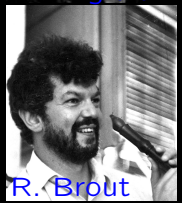


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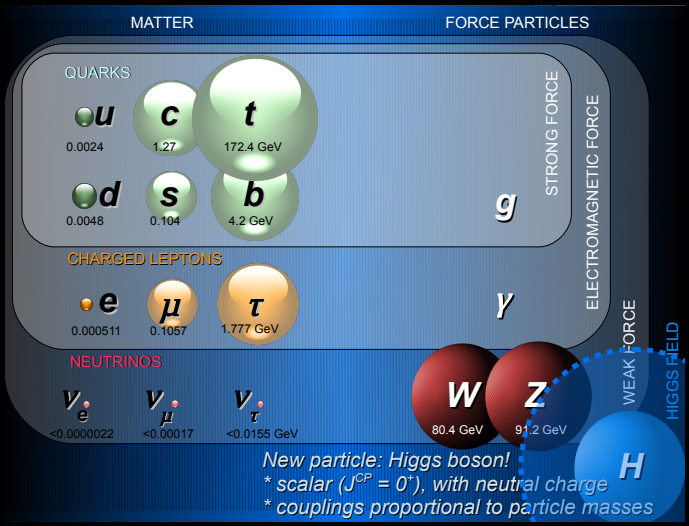
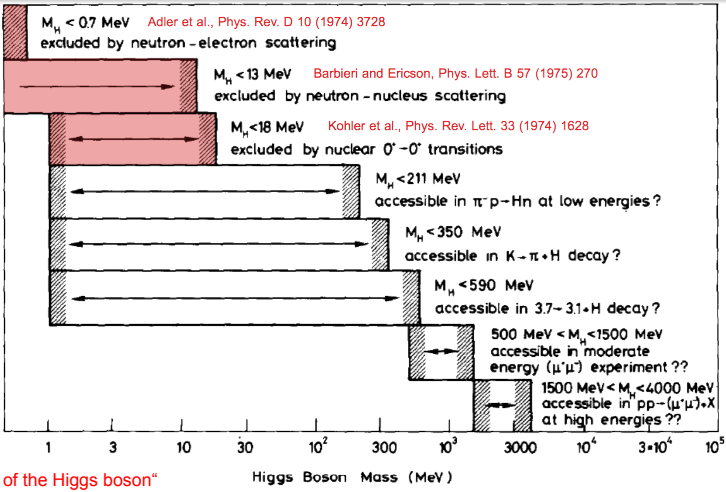


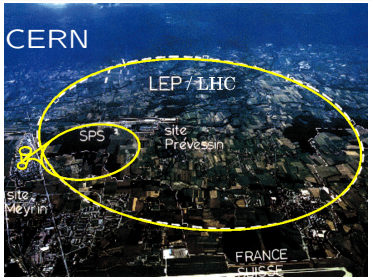
# First experimental and phenomenological attempts

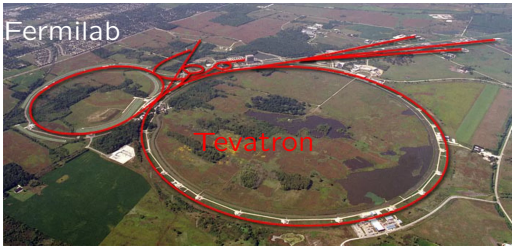



J. Ellis et al.,
„A phenomenological profile of the Higgs boson“
Nucl. Phys. B 106 (1976) 292-340

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

# And the hunt begins

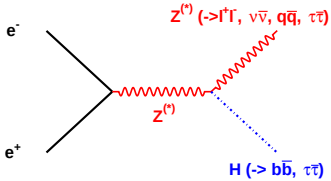



| Period | Collider | Type | $\sqrt{s}$ | $\int \mathcal{L}dt$ (fb$^{-1}$) |
|---|---|---|---|---|
| 1989 - 1994 | LEP I | $e^+e^-$ | 91.2 GeV | 0.2 |
| 1995 - 2000 | LEP II | $e^+e^-$ | 130-209 GeV | 0.8 |
| 1987 - 1996 | Tevatron I | $p\bar{p}$ | 1.8 TeV | 0.1 |
| 2002 - 2011 | Tevatron II | $p\bar{p}$ | 1.96 TeV | 10 |
| 2011 | LHC Ia | $pp$ | 7 TeV | 5 |
| 2012 | LHC Ib | $pp$ | 8 TeV | 20 |
| 2015 - 2018 | LHC II | $pp$ | 13 TeV | 70(+50) |
| 2021 - 2023 | LHC III | $pp$ | 14 TeV | 300 |
| 2026 - 2035 | HL-LHC | $pp$ | 14 TeV | 3000 |

# Direct searches at LEP and Tevatron

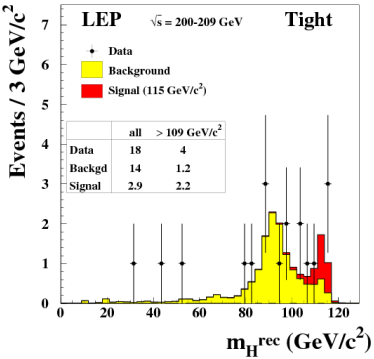
## LEP:




LEP I ($e^+e^- \to Z \to Hf\bar{f}$):
1995: $m_H > 58$ GeV at 95% CL.

LEP II ($e^+e^- \to ZH$):

Just before the planned shut-down in September 2000, few Higgs-like events at 115 GeV.




After one-month extended run and no additional signal, a difficult decision was made to switch the LEP off, in order not to delay the LHC.

# Direct searches at LEP and Tevatron

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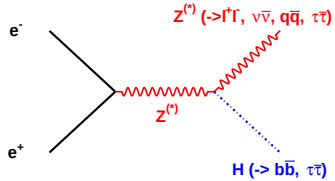


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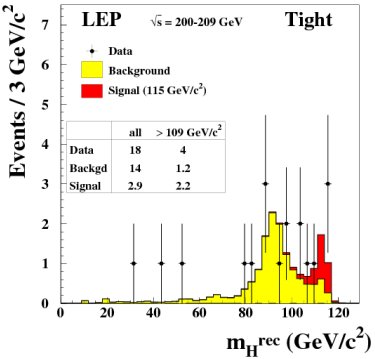


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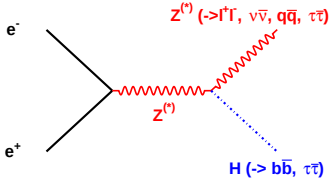
Baby HIGGS left by CERN in LEP
Size: 1.7σ
Weight: 115 GeV

Dream of a few??
or
Underlying reality??

(D.Froidevaux, Freiburg 2008)

# Direct searches at LEP and Tevatron

## LEP:

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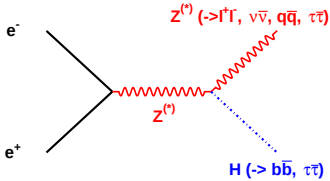


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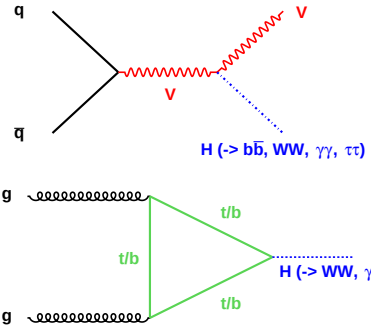
## Tevatron:

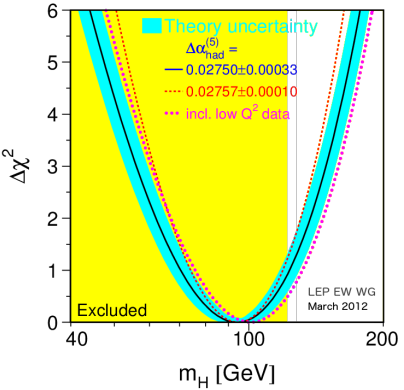



From 2008 on: starts to exclude higher masses.
By 2012:
$100 < m_H < 106$ GeV and $147 < m_H < 180$ GeV excluded at 95% CL.

# Indirect Higgs mass constraints

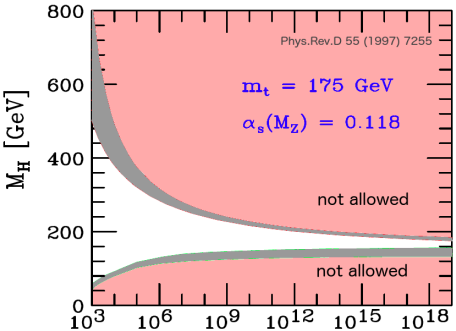
## EW precision data (LEP/SLC)

- Best-fit mass: $m_H = 94^{+29}_{-24}$ GeV.
- $m_H < 171$ GeV at 95% CL.




## Theory bounds

- became more stringent after the top-quark discovery at the Tevatron (1995).

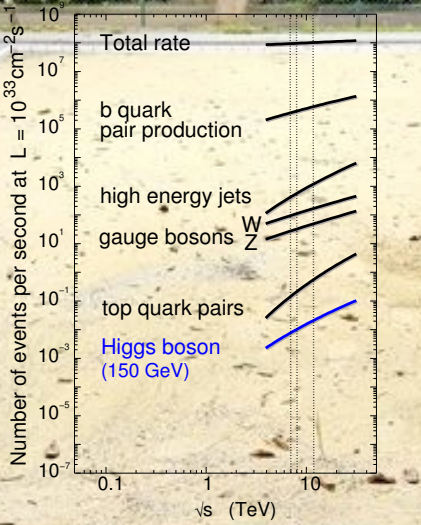



LHC designed to explore the entire allowed mass range, 100-1000 GeV.

⇒ Either fully exclude it (New physics.), or find it (Holy grail! And still new physics?).

# Higgs boson search at the LHC

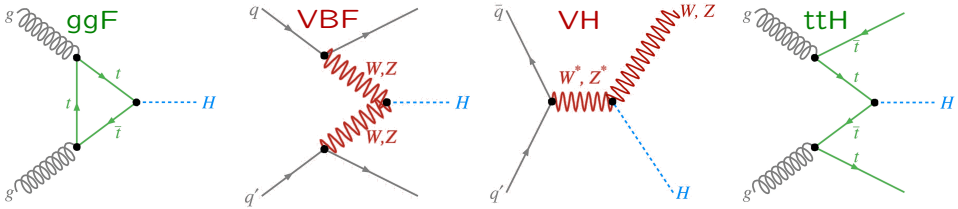
Or: How to find the right grains of sand?




1-5 Higgs bosons per 10 billion collisions.

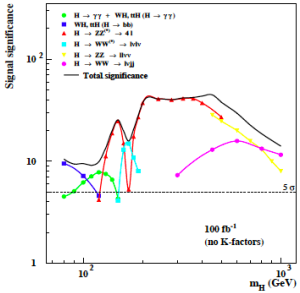
# Higgs boson search channels

Combination of different production and decay channels.




| | |
|---|---|
| $H \to \gamma\gamma$ | Excellent mass resolution, but large diphoton background. |
| $H \to ZZ^{(*)} \to 4\ell$ | Excellent mass resolution, but very low number of events. |
| $H \to W^+W^- \to \ell\nu\ell\nu$ | Large signal, but very poor mass resolution (neutrinos). |
| $H \to \tau^+\tau^-$ | Best accessible via $H$+jet production. |
| $H \to b\bar{b}$ | Best accessible via $VH$, $ttH$. |

**ATLAS DETECTOR AND PHYSICS PERFORMANCE**




**Technical Design Report**

Issue: 1
Revision: 0
Reference: ATLAS TDR 15, CERN/LHCC 99-15
Created: 25 May 1999

**Volume II**

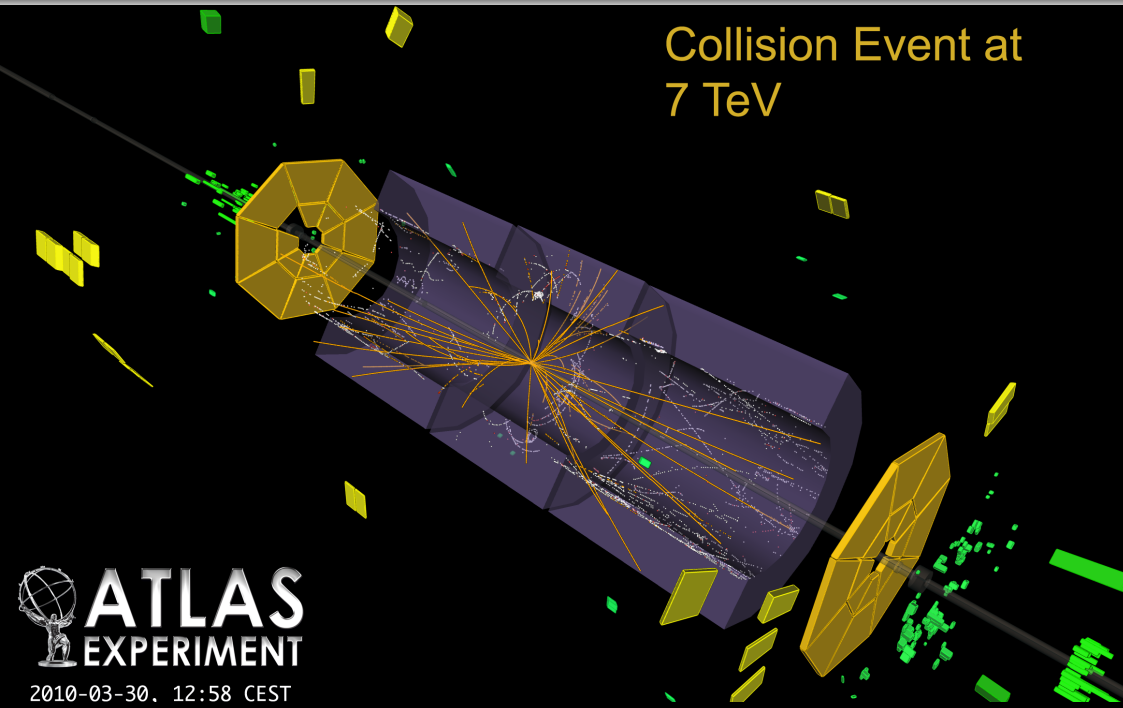
Continuous, untiring effort in improving theory predictions and experimental approaches.

LoI (1992): $H \to \gamma\gamma, WW, ZZ$.

Technical Design Report (1999):
Need up to 3 years of LHC running at 14 TeV for a discovery (by combining several channels).
10 years for the discovery of each key production and decay mode.

Just before the start of the LHC:
Optimized analyses and more channels.
Up to three times higher sensitivity, especially for low Higgs boson masses.

# Showtime

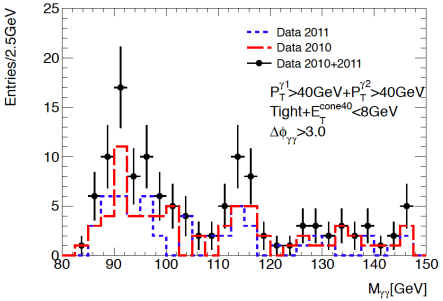

Collision Event at
7 TeV
ATLAS
EXPERIMENT
2010-03-30, 12:58 CEST

# Too bumpy too soon

**This Week's Rumor**

Posted on April 21, 2011 by woit

A commenter on the previous posting has helpfully given us the abstract of an internal ATLAS note claiming observation of a resonance at 115 GeV.




Internal ATLAS analysis document of one group was leaked.
(By a former LEP Higgs enthusiast?...)

→ Busy time over that Easter to scrutinize the analysis by the collaboration as fast as possible.

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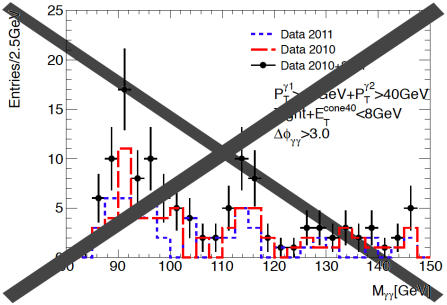


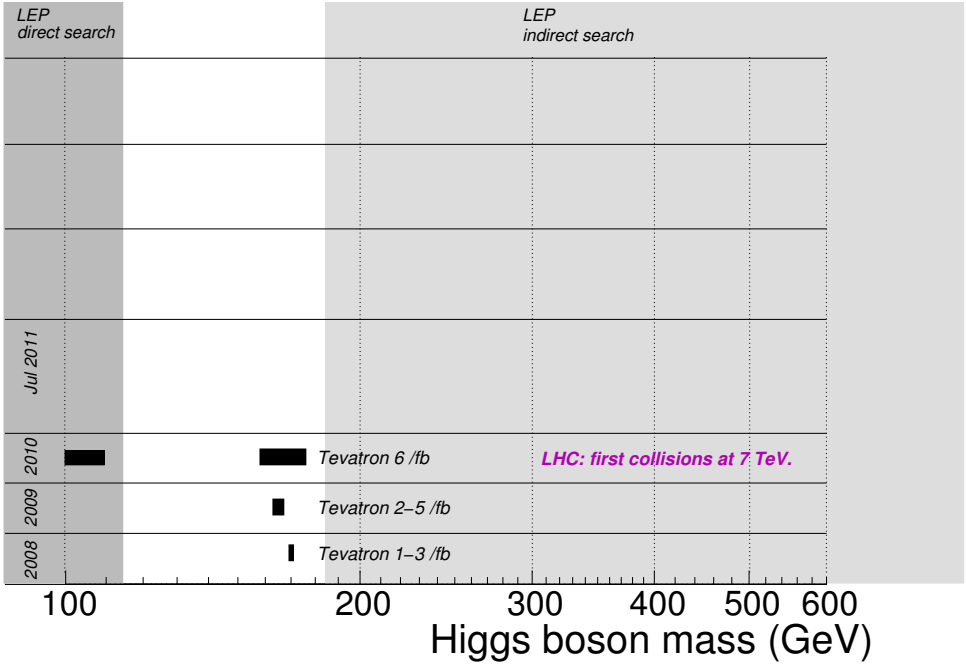

Internal ATLAS analysis document of one group was leaked.
(By a former LEP Higgs enthusiast?...)

→ Busy time over that Easter to scrutinize the analysis by the collaboration as fast as possible.

This just reinforced our collaboration rules:

- Only look at the data, once the analysis strategy has been settled and approved.
- Always cross-check by another independent analysis group.
- Keep confidential until the very last step of the collaboration approval
  Secrecy for the sake of scientific integrity.
  ... No matter how insisting journalists or non-ATLAS (i.e. CMS) colleagues may be.

# (R)evolution of the excluded mass range



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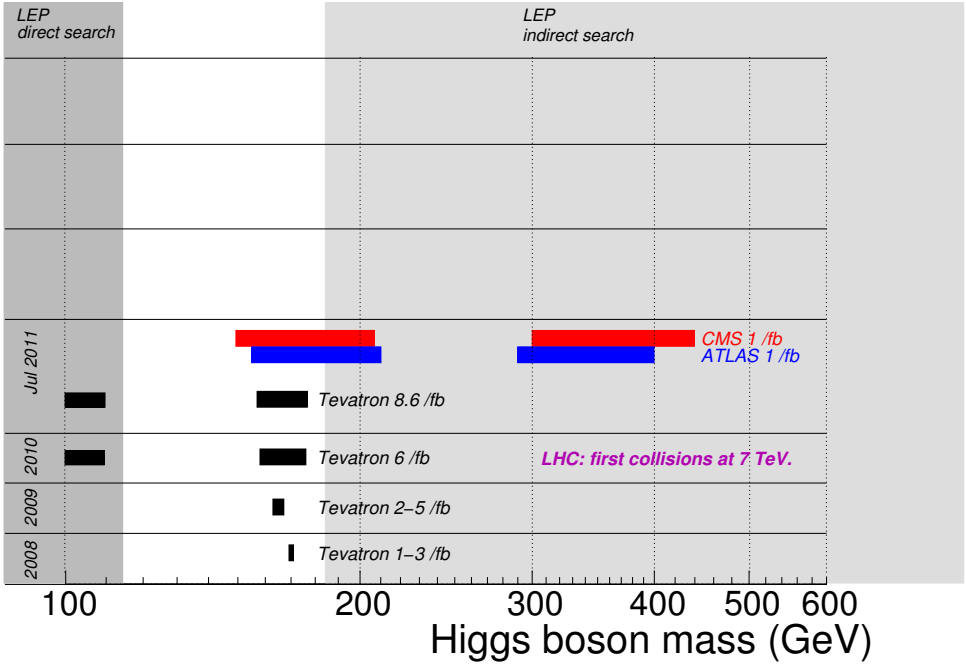

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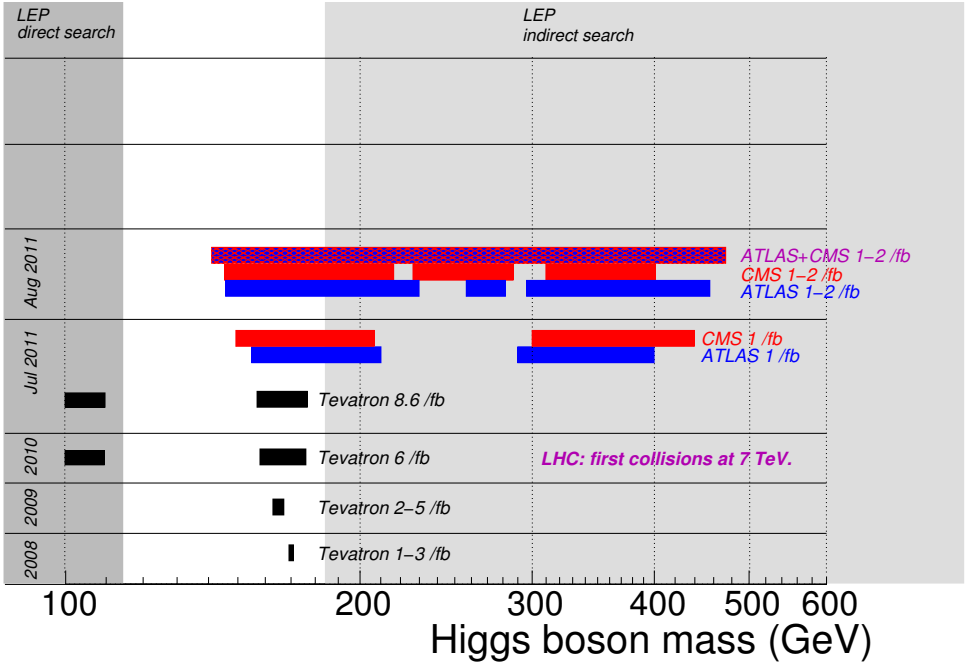

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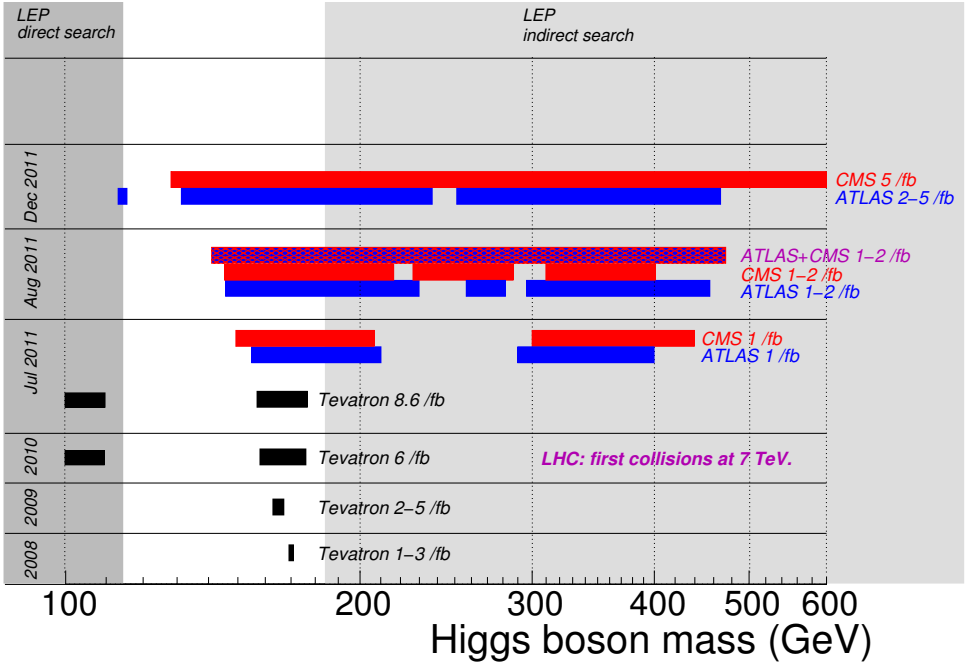

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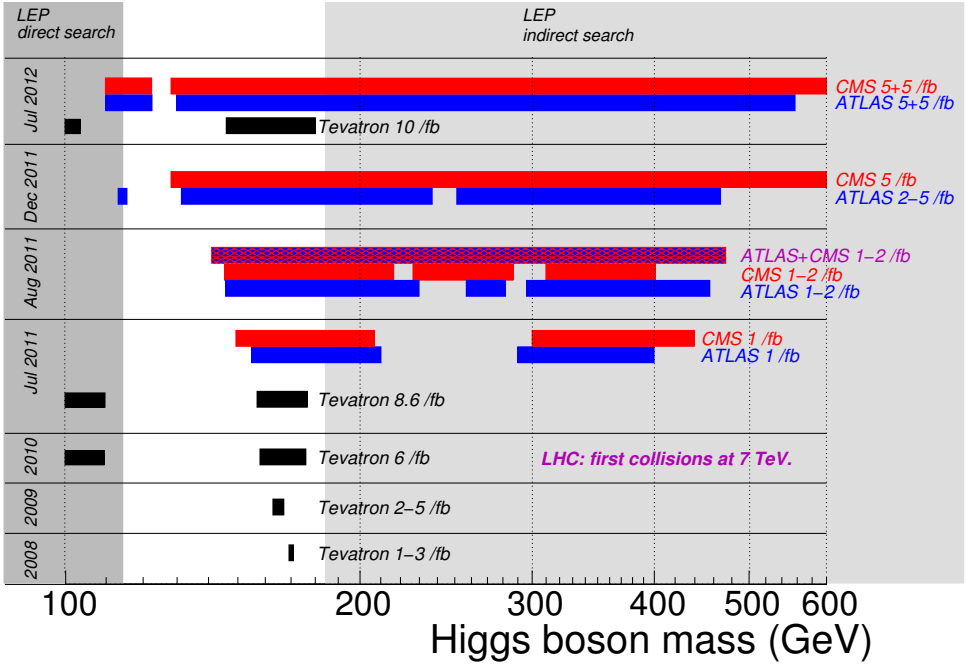

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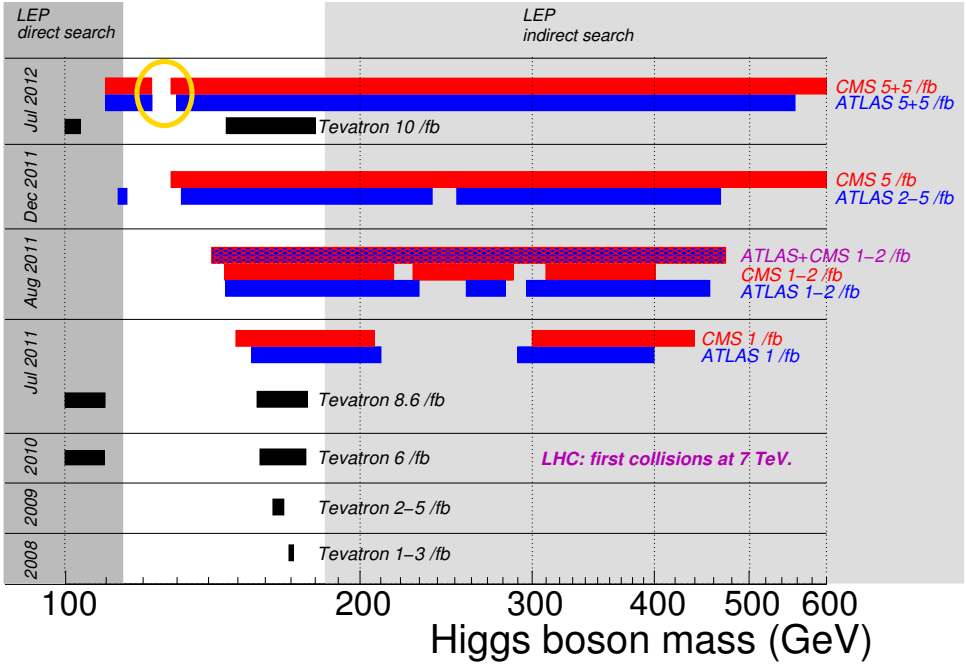

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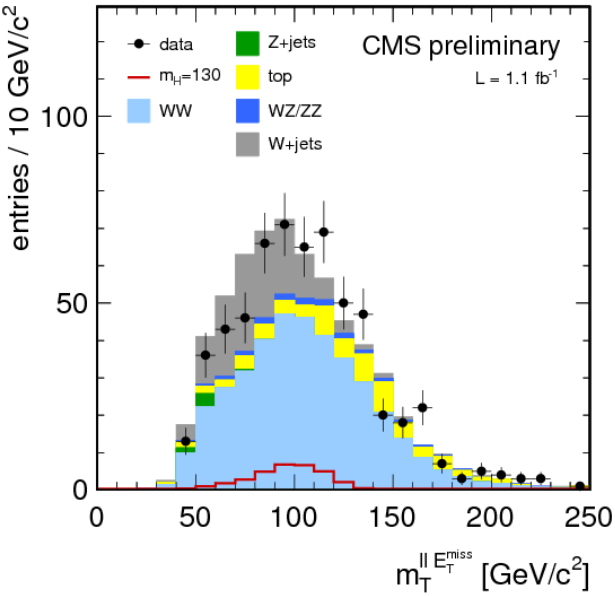

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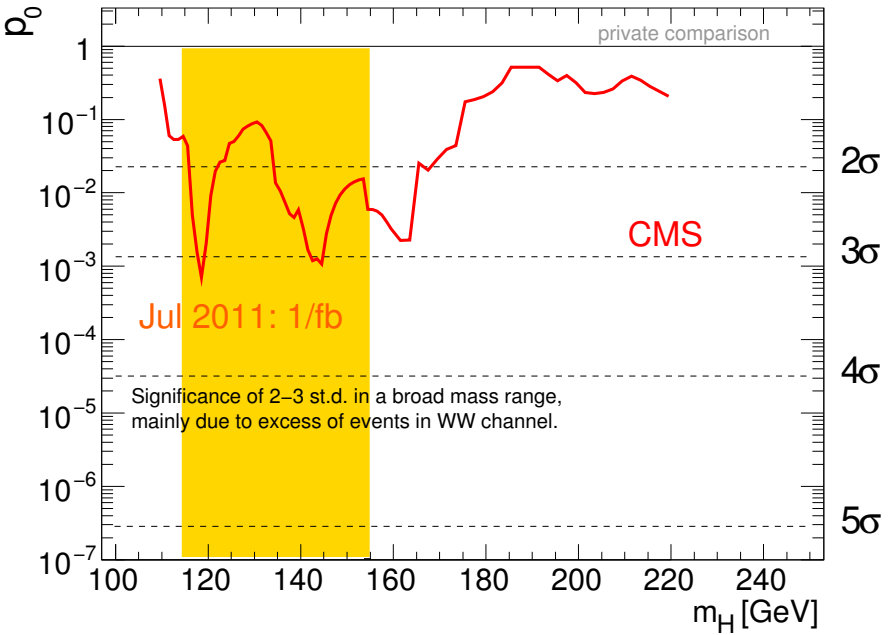

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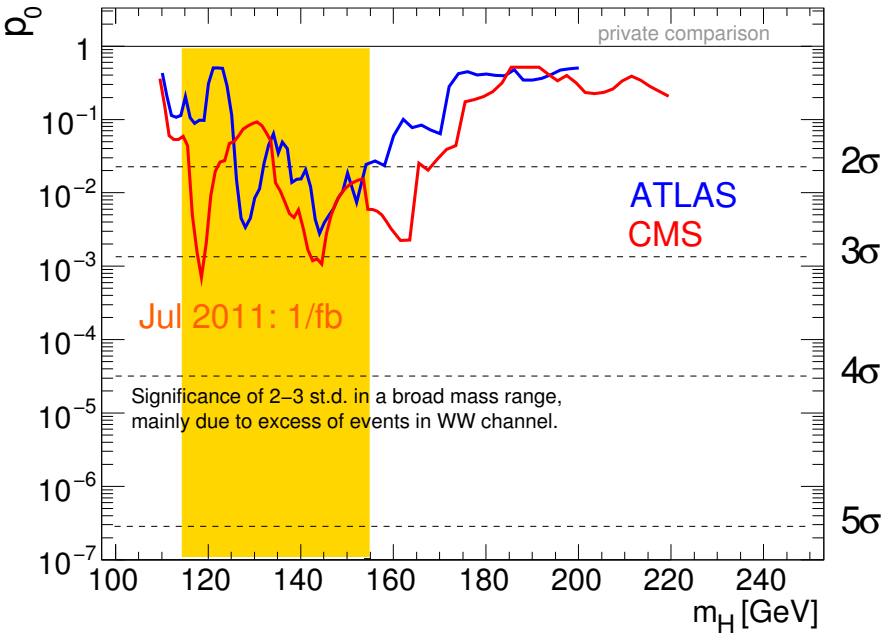

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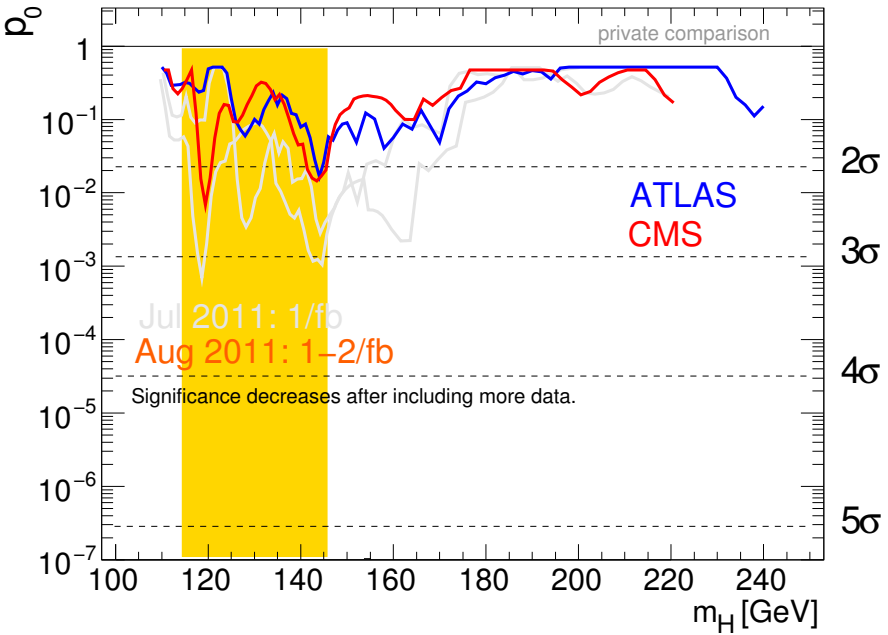

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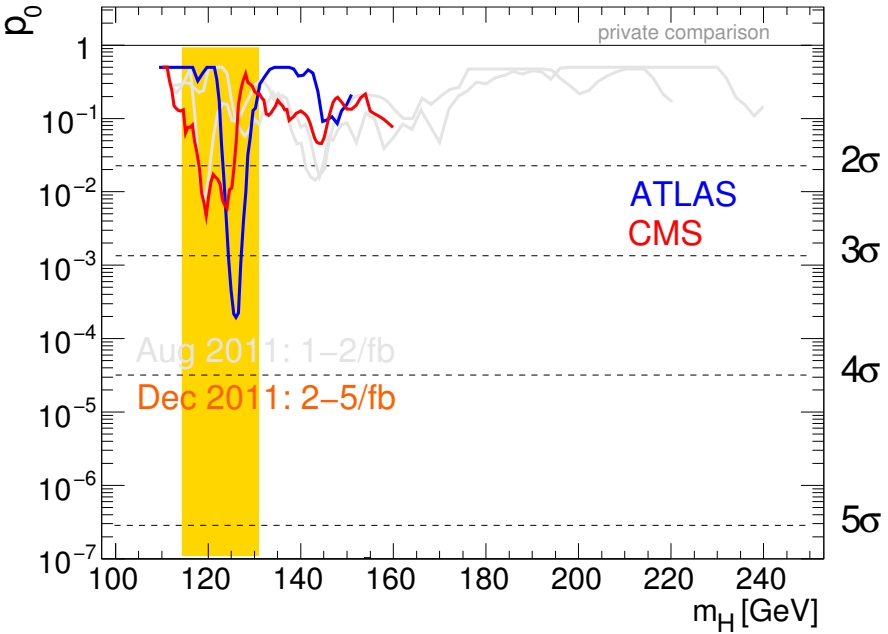

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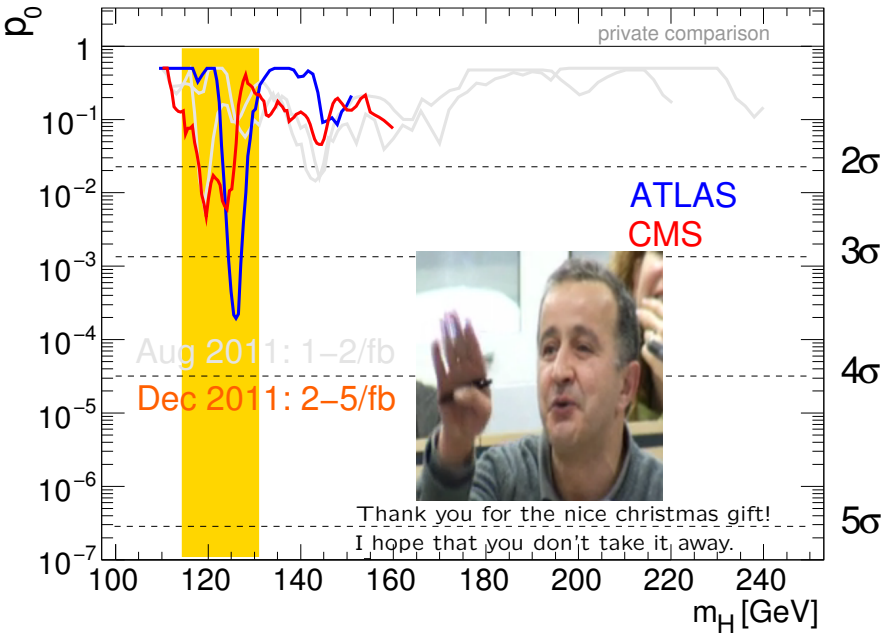

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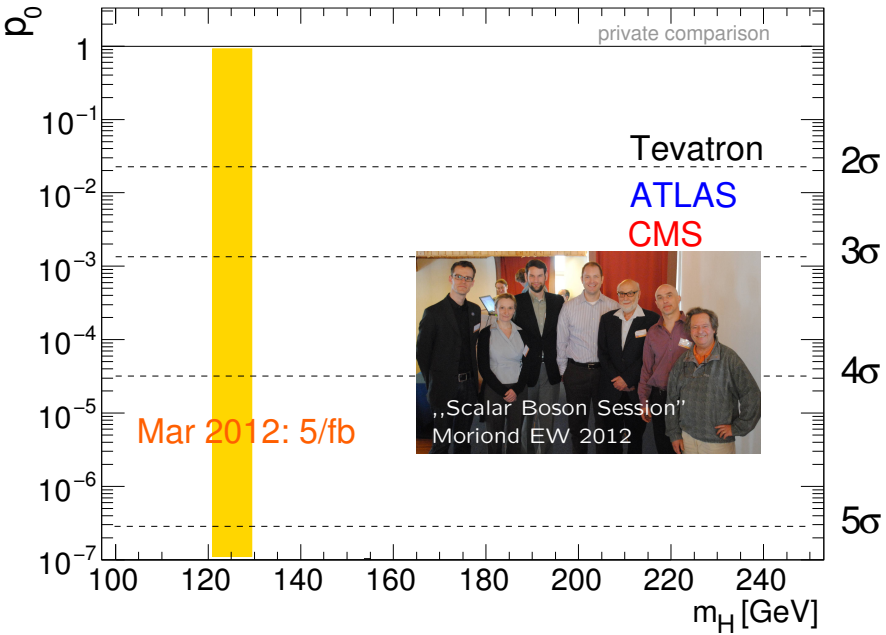

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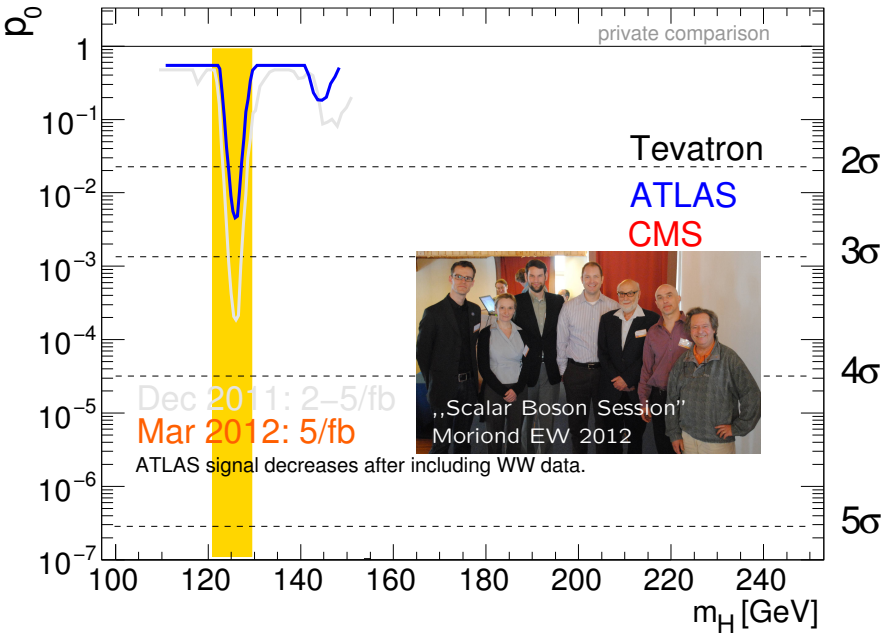

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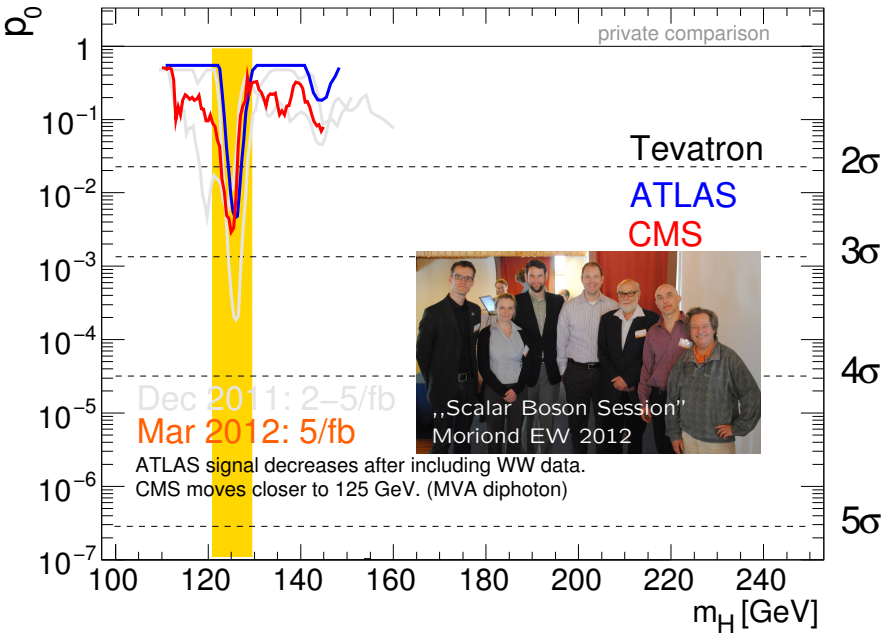

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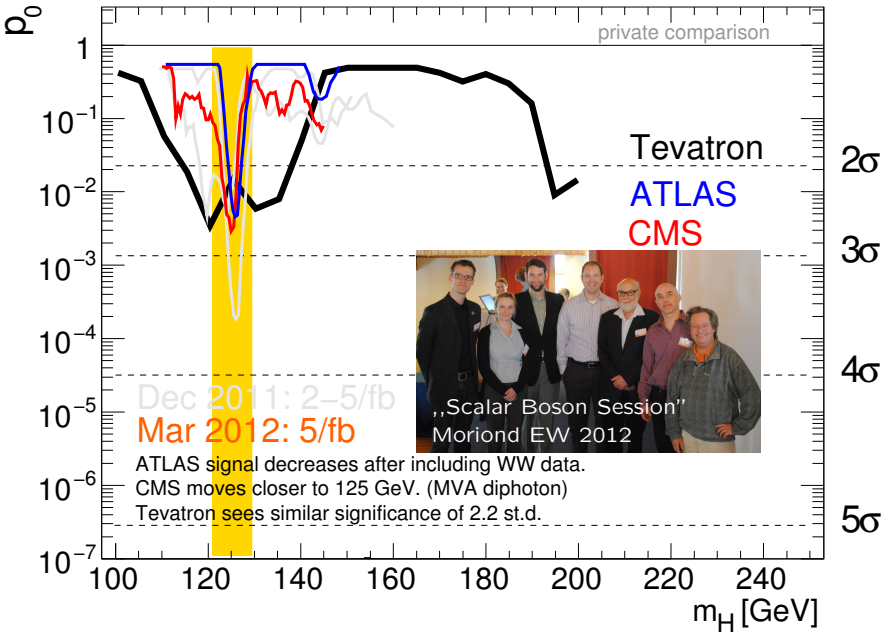


# CERN July seminar approaching

Von Bill Murray
Betreff **Two crucial questions**
An Sandra Kortner, Eilam Gross
Schlagwörter Wichtig

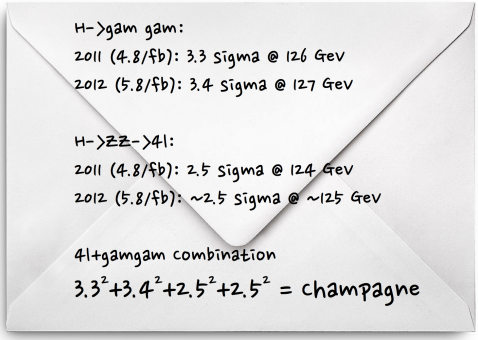
Mehr
6/23/12 9:26 PM

Dear Sandra and Eilam,
I would like to know:

1) Who is doing the T-shirts? July 4th is historic.

2) Do you have any plans for a party?

Bill



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Schlagwörter Wichtig

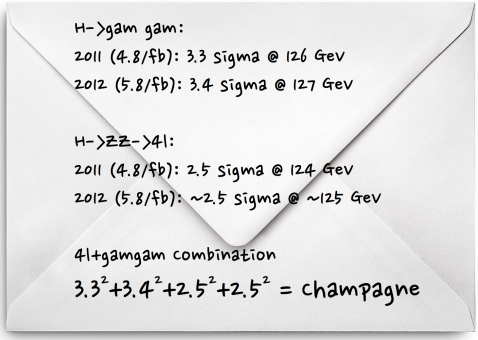
Mehr
6/23/12 9:26 PM

Dear Sandra and Eilam,
I would like to know:

1) Who is doing the T-shirts? July 4th is historic.

2) Do you have any plans for a party?

Bill




No champagne. Finalize, scrutinize, scrutinize again, keep confidential!

# CERN July seminar approaching

Von Bill Murray
Betreff **Two crucial questions**
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H->gam gam:
2011 (4.8/fb): 3.3 sigma @ 126 Gev
2012 (5.8/fb): 3.4 sigma @ 127 Gev

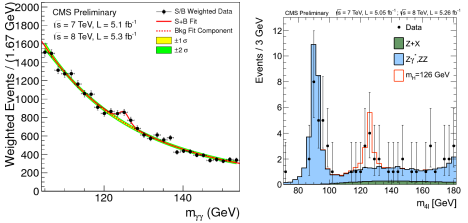
H->ZZ->4l:
2011 (4.8/fb): 2.5 sigma @ 124 Gev
2012 (5.8/fb): ~2.5 sigma @ ~125 Gev

4l+gamgam combination
$3.3^2+3.4^2+2.5^2+2.5^2$ = champagne

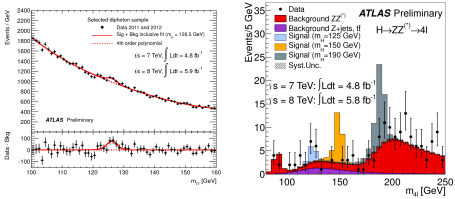
No champagne. Finalize, scrutinize, scrutinize again, keep confidential!

- July 2nd: Tevatron announces evidence for a new particle in search for SM $H \to b\bar{b}$. ($2.8\sigma$ at $m_H = 125$ GeV.)
- What is CMS seeing?

# July 4$^{th}$, 2012

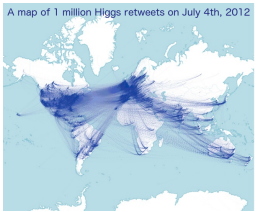



CMS Combined: 5$\sigma$ at 125 GeV.

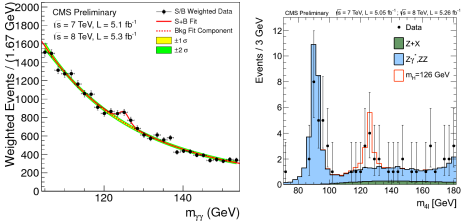



ATLAS Combined: 5$\sigma$ at 126.5 GeV.

R. Heuer:,,I think we have it!"



# July 4$^{th}$, 2012

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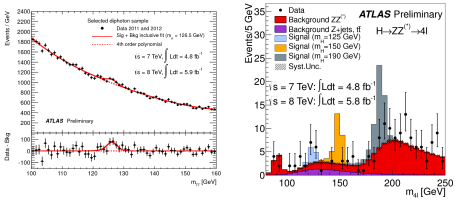



ATLAS Combined: 5$\sigma$ at 126.5 GeV.

Von Sandra Kortner
Betreff **ad-hoc champagne 14:20**
An Higgs working group

Dear Scalar Boson finders,

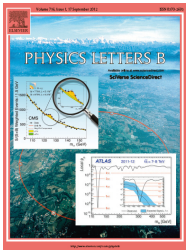
we will have an ***ad-hoc champagne celebration***
in Salle Bohr 14:20 today
(just before the WW approval).

Best,
Eilam and Sandra

# It is a Higgs boson

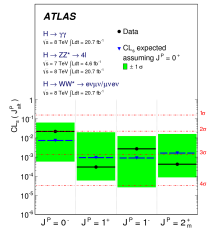
July 31$^{st}$, 2012:

Observation papers published.
Phys. Lett B (716) 2012 1
Phys. Lett. B 716 (2012) 30




Spring 2013:

Evidence of the spin-0 nature.
Phys. Lett. B 726 (2013) 120
PRL 110 (2013) 081803




October 8$^{th}$, 2013:

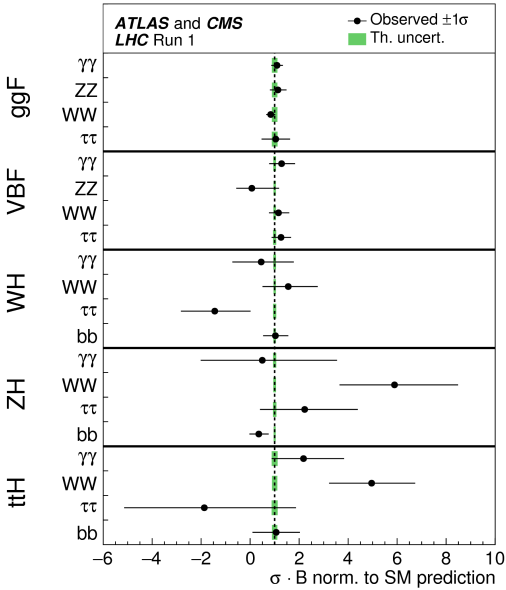
Nobel prize awarded to
F. Englert and P. W. Higgs.

# LHC Run-1 legacy (ATLAS+CMS combined)

Combined mass, $m_H$:
$125.09 \pm 0.21(stat.) \pm 0.11(syst.)$ GeV
Thank you, nature!

| | |
|---|---|
| $\gamma\gamma$: | $>5\sigma$ (each experiment) |
| $ZZ$: | $>5\sigma$ (each experiment) |
| $WW$: | $>5\sigma$ (each experiment) |
| $\tau\tau$: | $5.5\sigma$ (combined) |
| $b\bar{b}$: | $2.6\sigma$ (combined) |

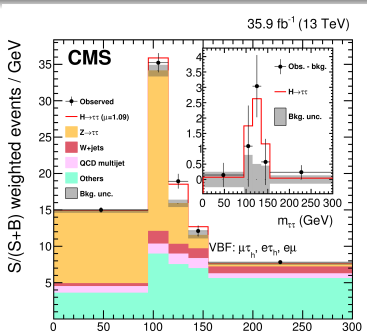
| | |
|---|---|
| ggF: | $>5\sigma$ (each experiment) |
| VBF: | $5.4\sigma$ (combined) |
| $VH$: | $3.5\sigma$ (combined) |
| $ttH$: | $4.4\sigma$ (combined) |



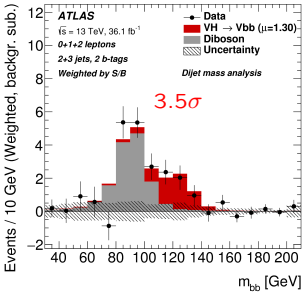

All couplings consistent with the Standard Model.

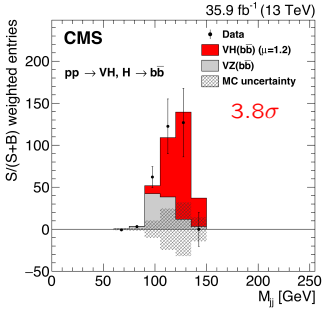
# Run-2 pushes already further

Observation of $H \to \tau\tau$ decays by CMS.
arXiv:1708.00373



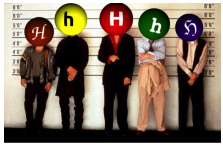

Evidence for
$H \to b\bar{b}$ decays
in $VH$ production.
arXiv:1708.03299,
arXiv:1709.07497



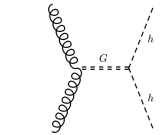




Still on the list: $ttH$, $H \to Z\gamma$, $H \to \mu\mu$ etc.

# SM is not enough - Higgs portal to discoveries

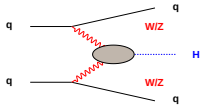



Additional Higgs bosons from an extended Higgs sector.




New resonances decaying into Higgs boson(s).

Dark matter interaction with the Higgs sector.




CP-violation (anomalous couplings).
Exotic Higgs decays (FCNC, lepton flavour violation).


etc ...

The discovery of the Higgs boson crowns an enormous scientific effort.