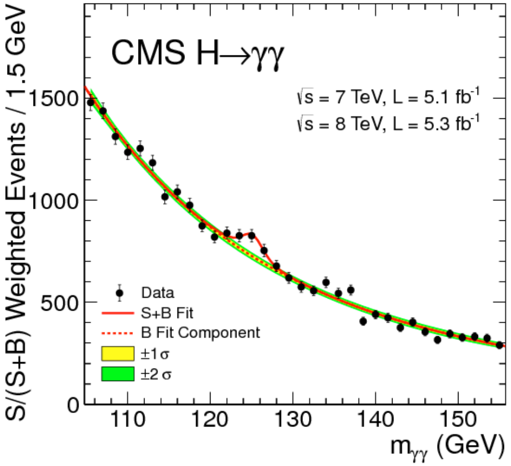
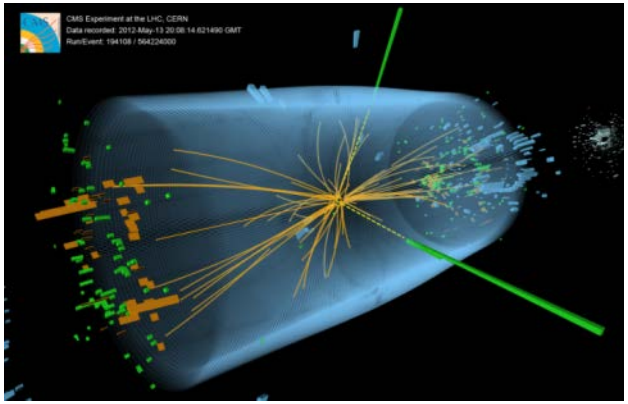
A new kind of particle: The 'higgs' discovery at the LHC

Lutz Feld, 1. Physikalisches Institut, RWTH Aachen

Physikalisches Kolloquium

21.1.2013





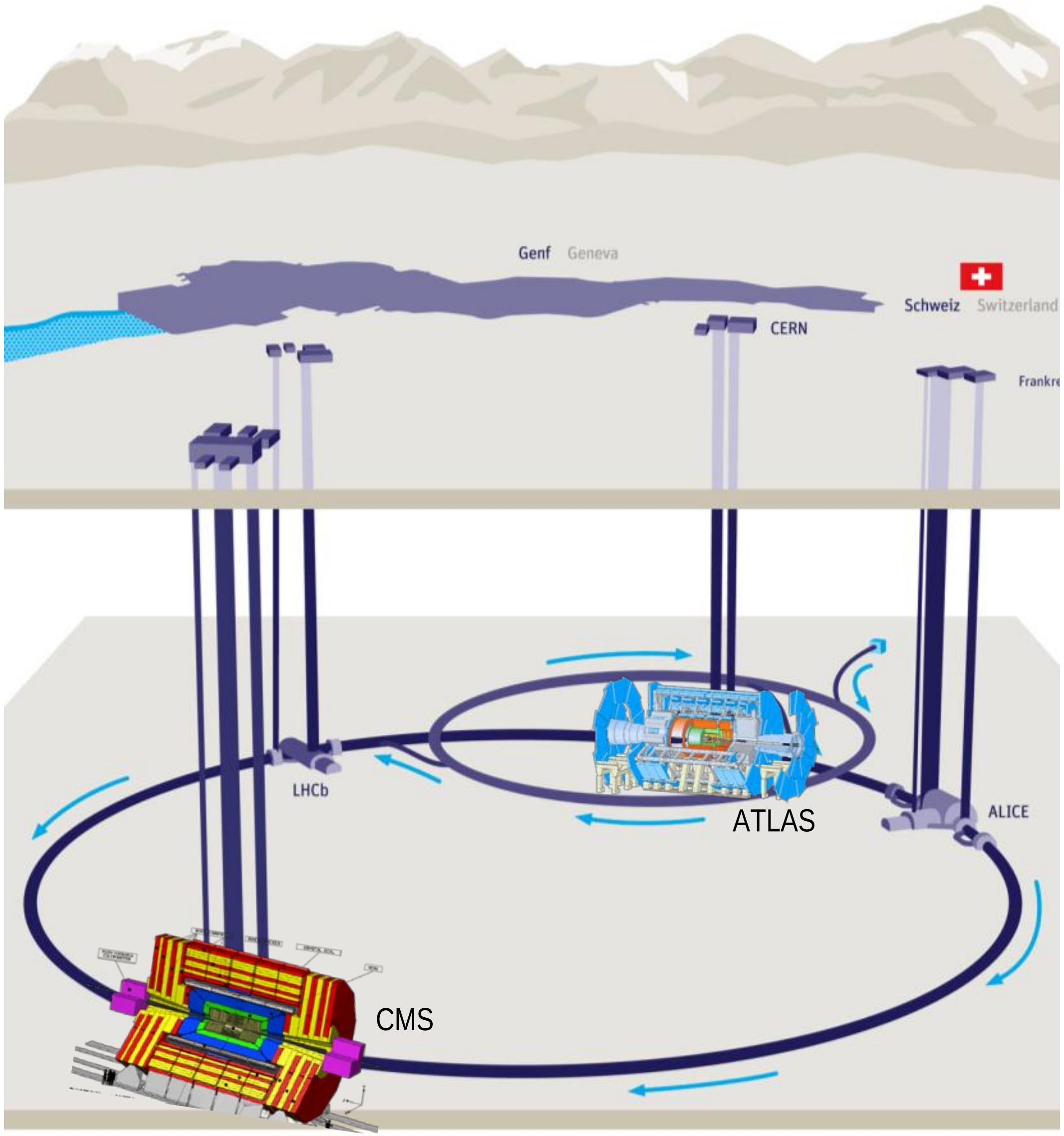
RWTH AACHEN UNIVERSITY

From the editorial:

The top Breakthrough of the Year—the discovery of the Higgs boson—was an unusually easy choice, representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers.

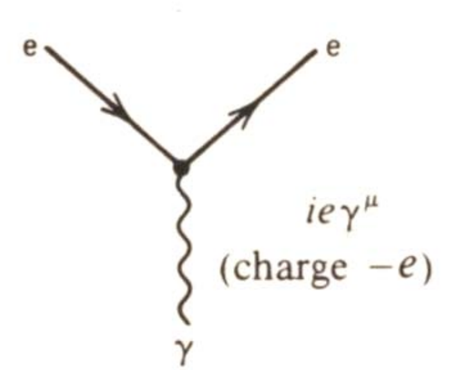
Overview

- **Introduction: The Higgs Boson**
- **LHC Accelerator and Experiments**
- **Observation of a new Boson**
- **Implications**
- **Summary**

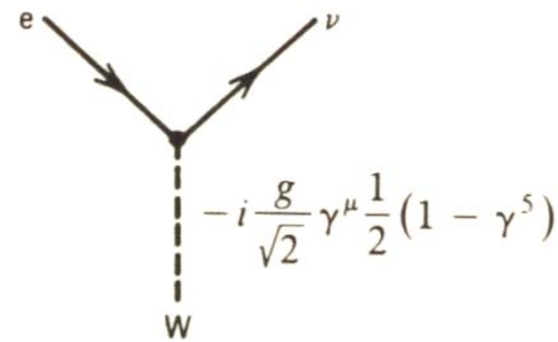


Introduction

- **electromagnetic and strong interactions :**
  - mediated by massless bosons: the photon γ and the gluons $g_{1...8}$
  - described by **U(1)** and **SU(3)** local gauge symmetries



- **weak interactions are different :**
  - mediated by massive bosons: $Z^0\left(m_Z \approx 91\text{ GeV}\right), W^\pm\left(m_W \approx 80\text{ GeV}\right)$
  - violate parity: distinguish between left- and right-handed states
  - description by **SU(2)$_L$** $\times$ **U(1)$_Y$** local gauge symmetry predicts massless gauge bosons
  - fermion mass terms $-m_e\bar{e}e = -m_e\left(\bar{e}_R e_L + \bar{e}_L e_R\right)$ are forbidden since L and R transform differently
  - furthermore: scattering of massive W bosons violates unitarity at high energy



Spontaneous symmetry breaking

introduce a field φ with $V(\varphi) = \mu^2 \varphi^\dagger \varphi + \lambda \left(\varphi^\dagger \varphi\right)^2 \qquad \mu^2 < 0,\ \lambda > 0$

local **SU(2)$_L$** $\times$ **U(1)$_Y$** gauge symmetry couples φ to gauge bosons γ, Z^0 and $W^\pm$,

e.g. $\quad \left|g\,\varphi W\right|^2$

ground state (vacuum) breaks gauge symmetry

$$\varphi = \varphi_0 + \Delta\varphi_1 + \Delta\varphi_2$$

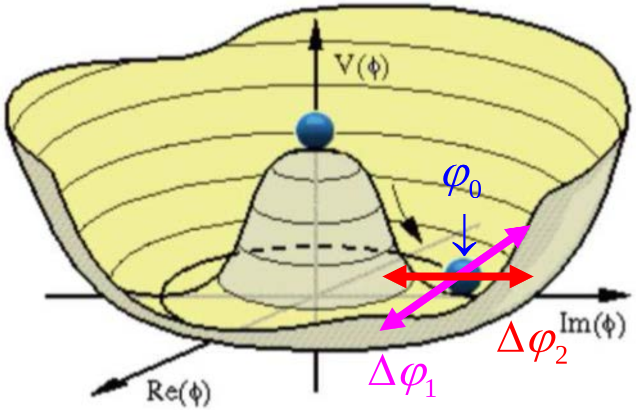
$$\left|g\,\varphi_0 W\right|^2 = m_W{}^2 W^2$$

$\Delta\varphi_1$ adds missing longitudinal state to gauge boson

$\Delta\varphi_2 \equiv H$ remains as a new, massive, scalar boson:

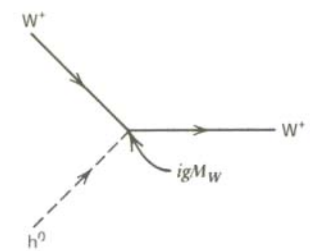
the 'higgs boson'

$M_H = \sqrt{2\lambda}\,\varphi_0$ with $\varphi_0 = 246$ GeV



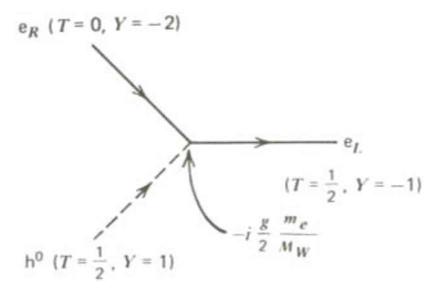
$$\left|g\,\varphi W\right|^2 = \left|g\left(\varphi_0 + H\right)W\right|^2 = \ldots g^2 \varphi_0 H W^2 \ldots = \ldots g M_W H W^2 \ldots$$

bosons couple to higgs boson proportional to their mass



fermions can be coupled to φ by Yukawa terms $-G_e \bar{e}_R \varphi e_L + c.c. = -m_e ee - \dfrac{m_e}{\varphi_0} eeH$

fermions couple to higgs boson proportional to their mass



φ has to be a scalar in order not to break Lorentz invariance of the ground state

A bit of history

– spontaneous breaking of gauge symmetry introduced into particle physics in 1964 by [Englert and Brout], [Higgs], and [Guralnik, Hagen and Kibble]

– based on earlier work to explain super-conductivity [Anderson] and low energy hadron interactions [Nambu]

– Higgs was the first to explicity mention the existence of a massive scalar particle (in 1964):

$$\{\partial^2 - 4\varphi_0{}^2 V''(\varphi_0{}^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \qquad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0{}^2)\}^{1/2}$; Eqs. (2a) and (2c)

– Weinberg, Salam and Glashow formed the electro-weak standard model in 1967

– t'Hooft showed in 1971 that such a theory is renormalisable

– experimental discovery of weak neutral currents (Z) 1973 (at RWTH)

– experimental proof of W and Z in 1983

The Higgs Field

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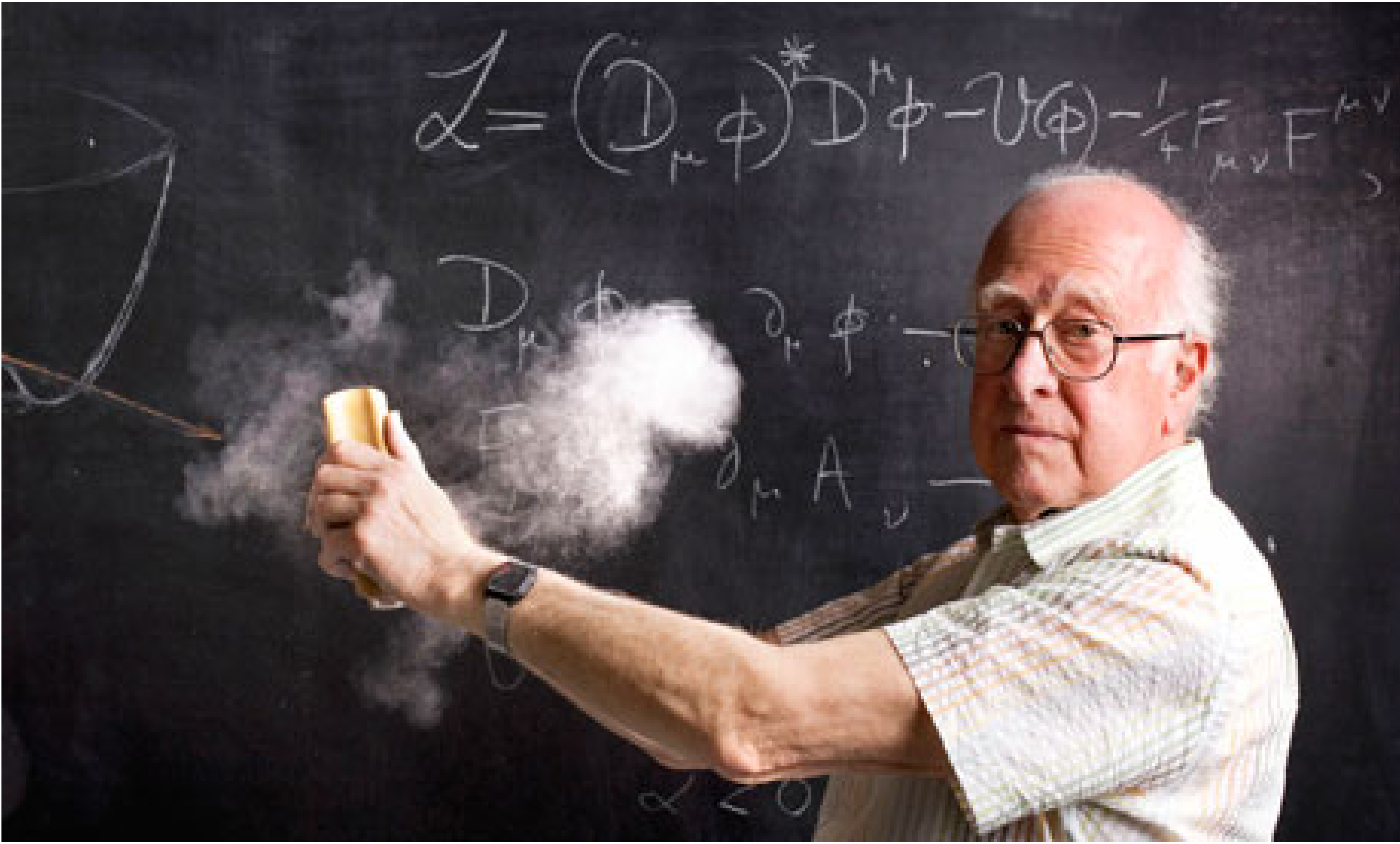


The Higgs Field

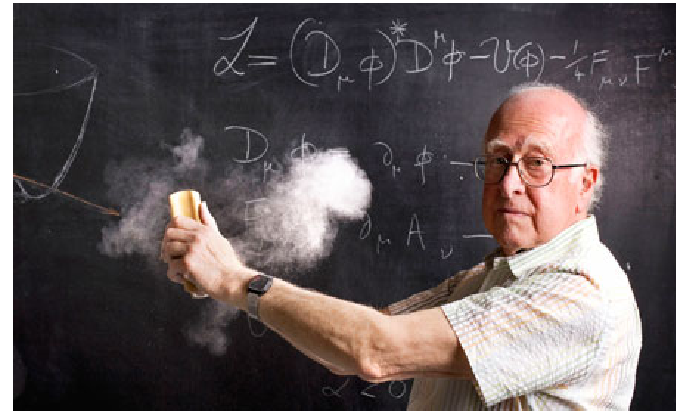
– fills all space

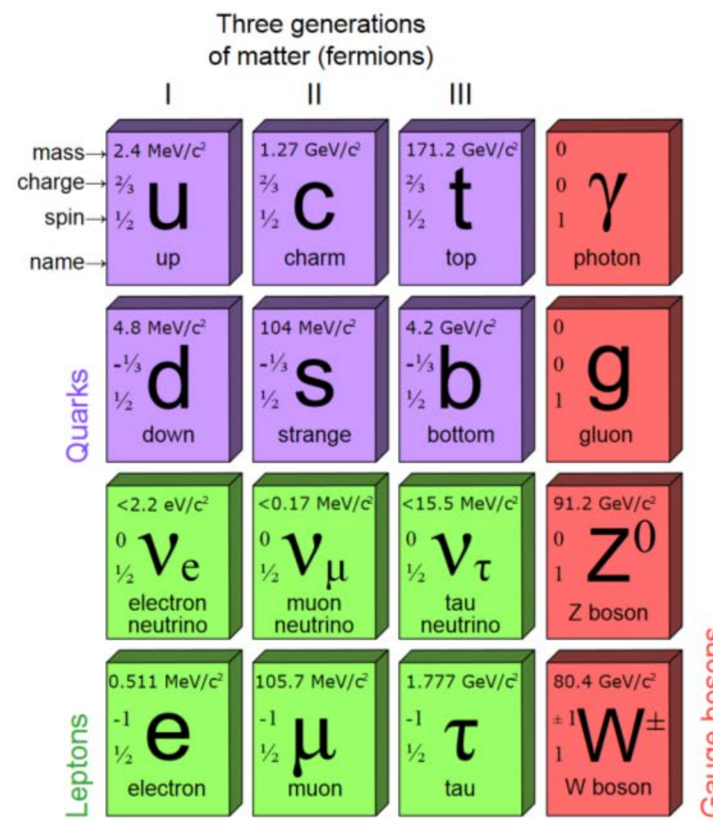
– generates the masses of bosons and fermions:
masses are in fact coupling strenghts

– breaks the electro – weak symmetry and mixes
$\gamma, W^{\pm}, Z$ from the $SU(2)_L \times U(1)_Y$ gauge bosons

Comment 1: it generates only about 1% of the proton mass
i.e. our mass (99% are kinetic energy of quarks and gluons)

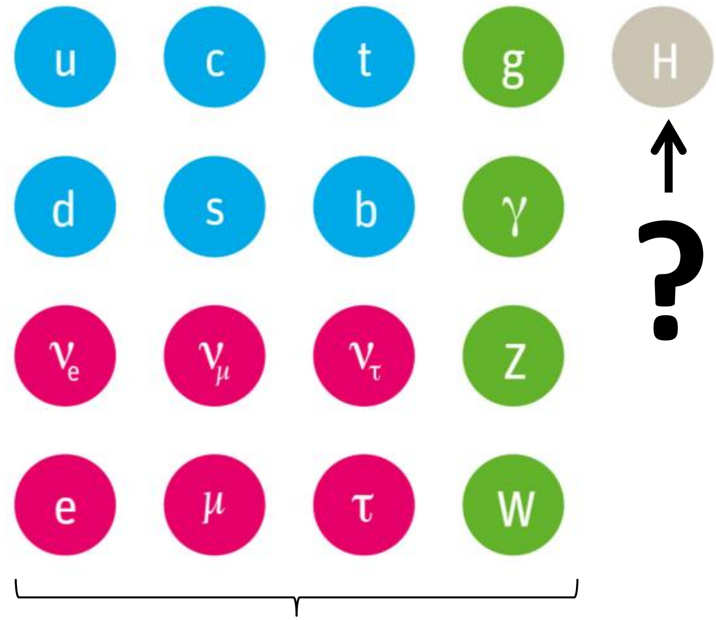
Comment 2: the mexican hat form of the potential is
not explained by the theory





The Higgs Particle

- excitation of higgs field
- **mass**: not predicted by theory
- **spin**: zero
- **parity**: even
- **couplings** to bosons and fermions: proportional to their mass
- regularizes WW scattering



experimentally established

verifying these properties will tell if a new particle actually is ‚the higgs‘

Theoretical Constraints on the Higgs mass

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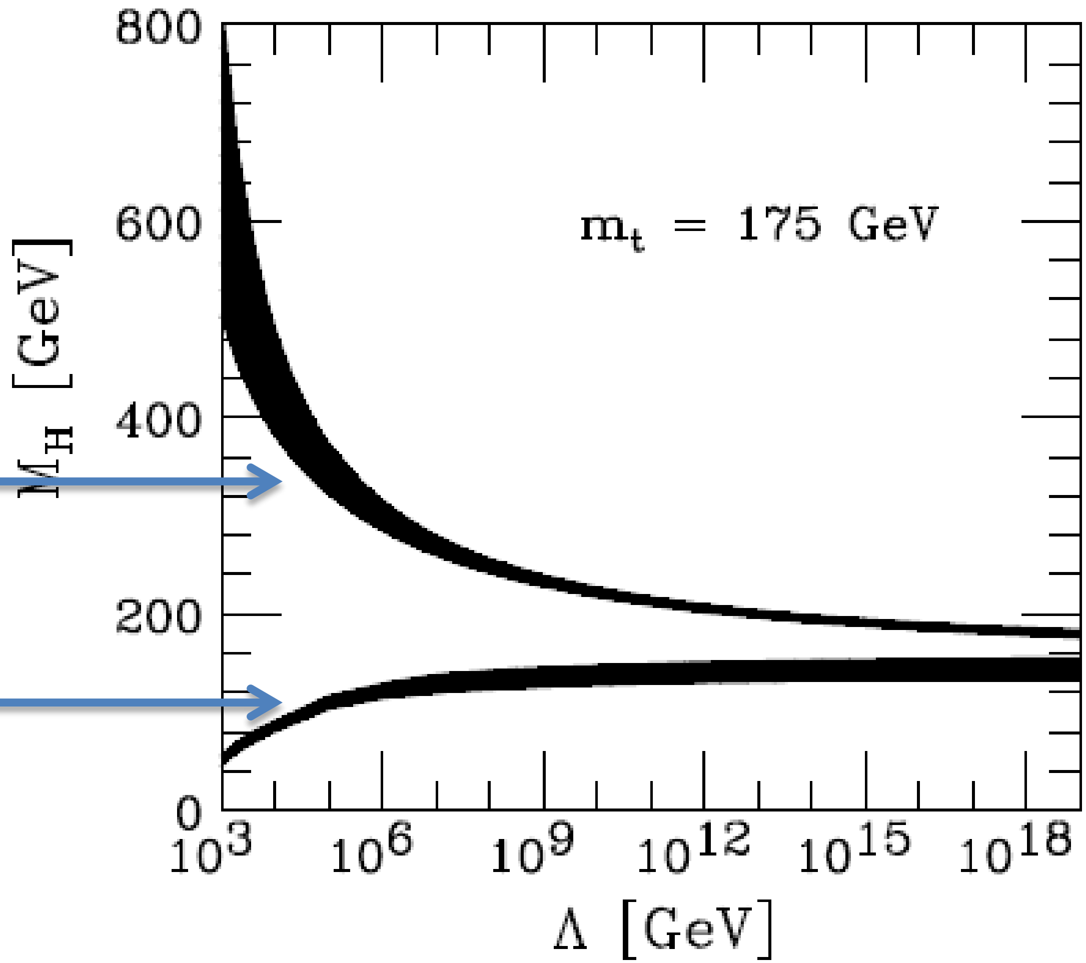
Higgs potential $V(\varphi) = \mu^2 \varphi^\dagger \varphi + \lambda (\varphi^\dagger \varphi)^2 \qquad \mu^2 < 0,\ \lambda > 0$

Higgs mass $M_H = \sqrt{2\lambda}\,\varphi_0$

λ is a running coupling $\rightarrow \quad \lambda = \lambda(\Lambda)$



for large M_H $(\text{large } \lambda(M_H))$:

λ will grow and violate unitarity at scale Λ

for small M_H $(\text{small } \lambda(M_H))$:

λ will go negative at scale Λ

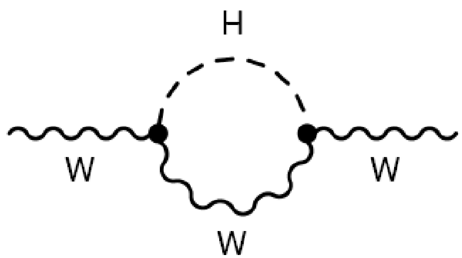
$\rightarrow$ rim of mexican hat bends down

$\rightarrow$ vacuum unstable

$\rightarrow$ M_H constrained to a certain range for the theory to remain valid up to a scale Λ

Experimental constraints on the Higgs mass

Indirect constraints



Global χ^2-fit of all precision electro-weak data to standard model gives a preferred higgs mass of

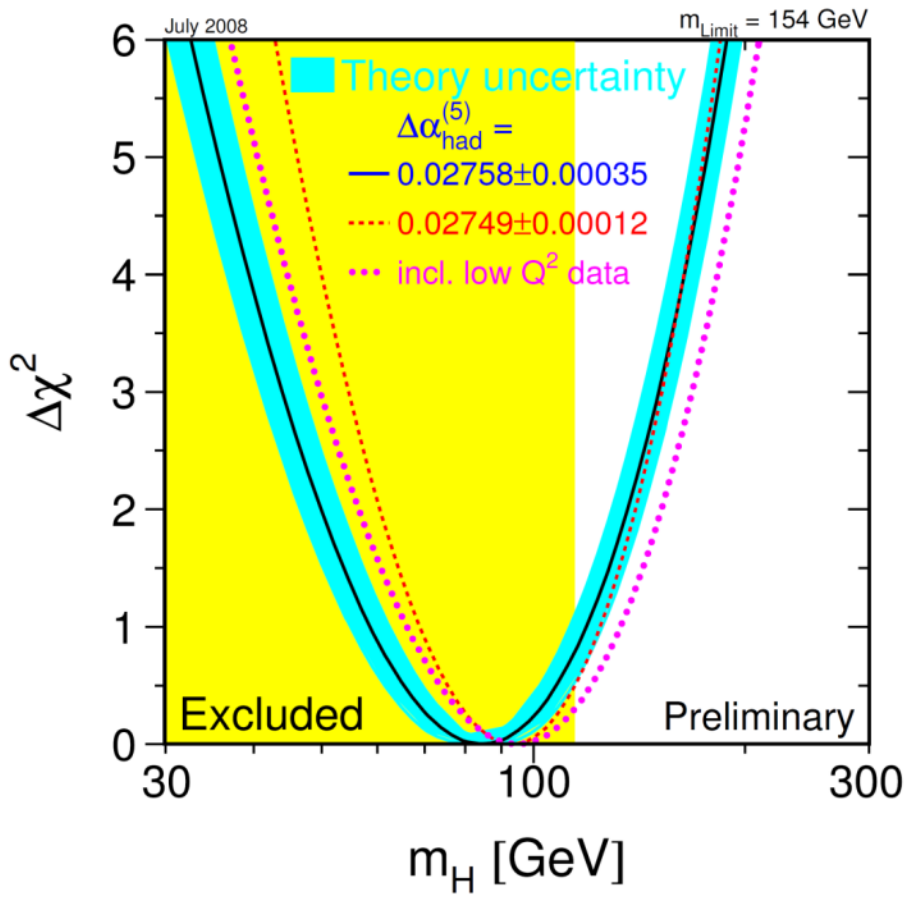
$$M_H = \left(92 \begin{matrix} +34 \\ -26 \end{matrix}\right) \text{ GeV} \quad (68\% \text{ CL})$$

Direct searches at LEP:

$$M_H > 114.4 \text{ GeV} \qquad (95\% \text{ CL})$$

Including this constraint gives

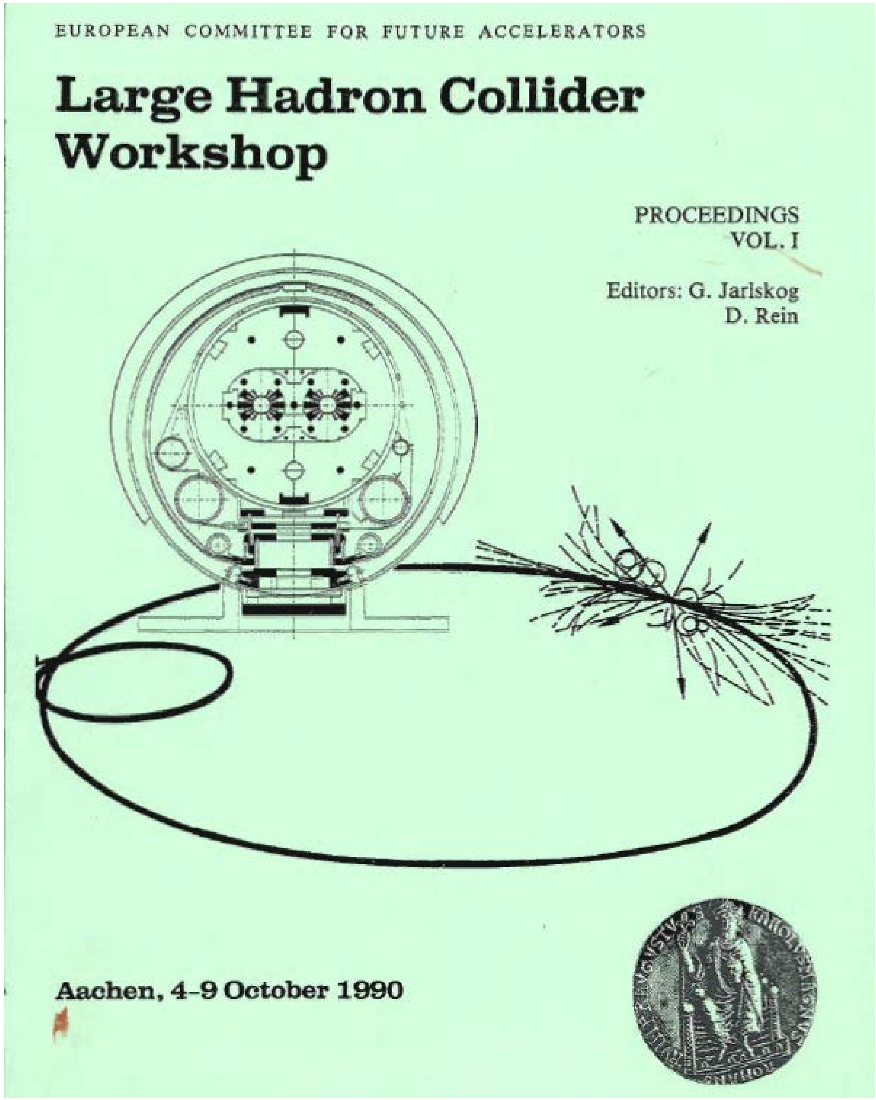
$$M_H < 185 \text{ GeV} \qquad (95\% \text{ CL})$$



How can we find the Higgs?

CERN Director General Rolf Heuer explaining the principle...

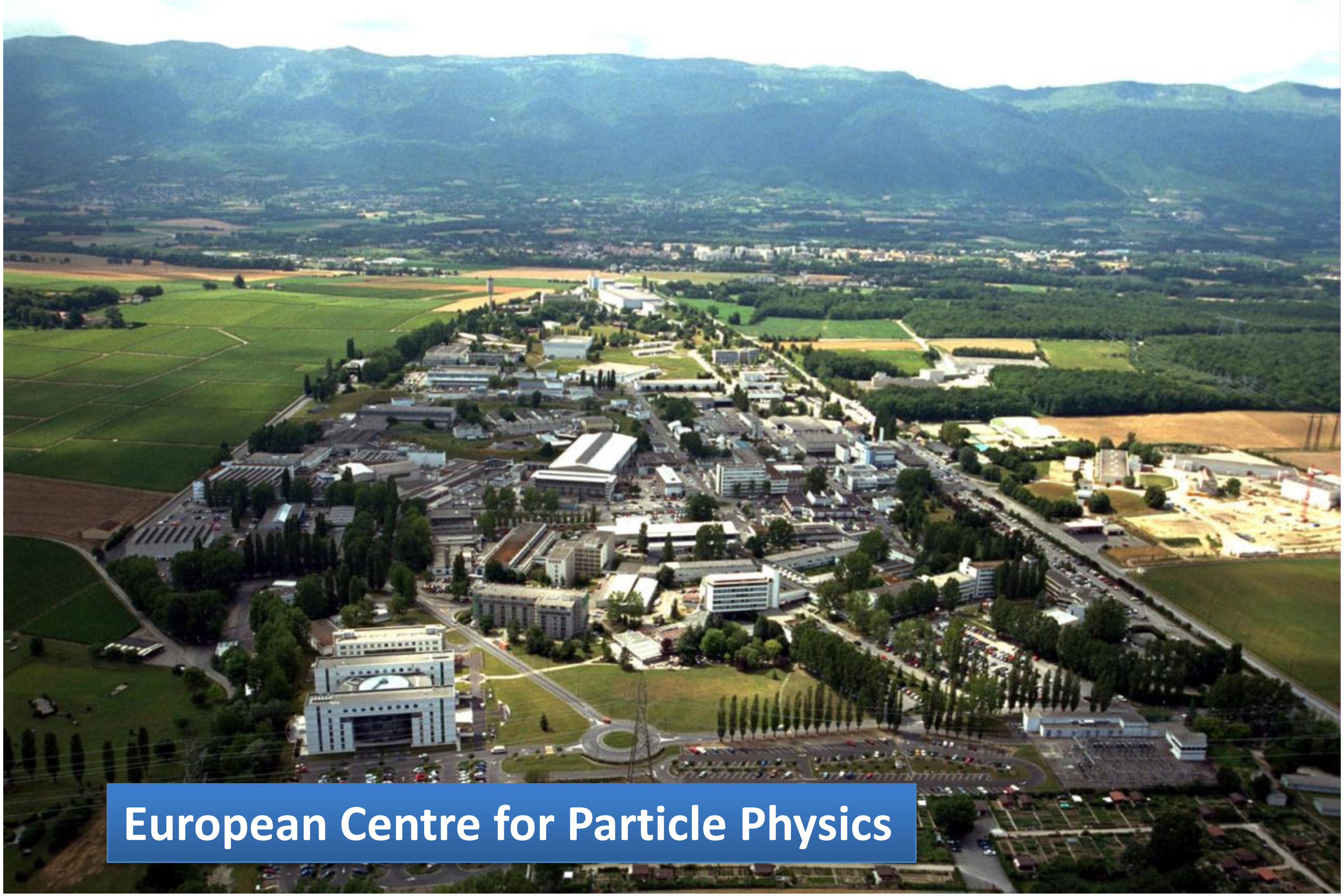
LHC Workshop Aachen 1990



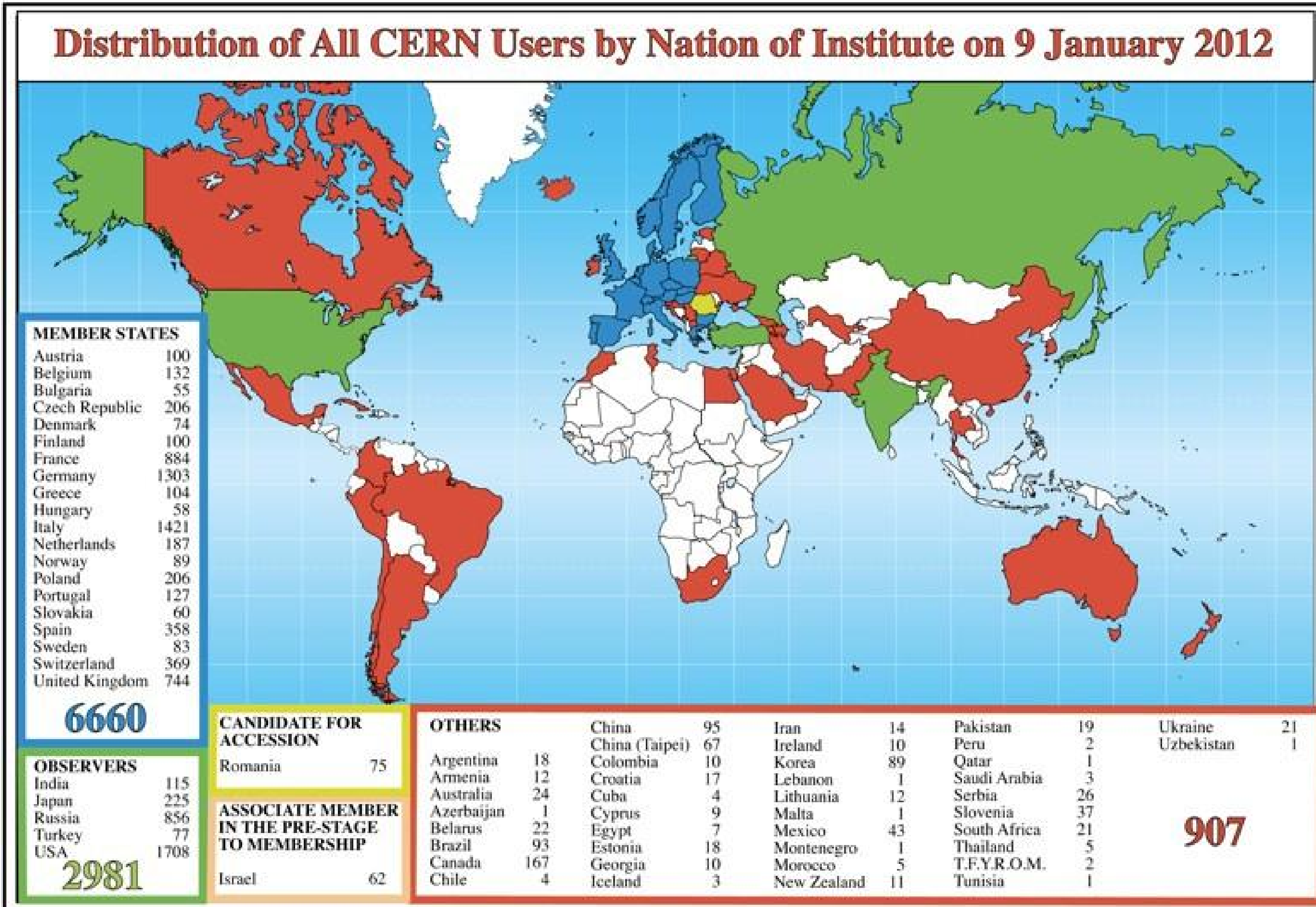
Carlo Rubbia,
CERN Director General (1990)

"Based on what we know today, we believe that the design parameters for the LHC are sound and the machine can be built."

CERN



CERN


Distribution of All CERN Users by Nation of Institute on 9 January 2012
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Germany 1303
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Hungary 58
Italy 1421
Netherlands 187
Norway 89
Poland 206
Portugal 127
Slovakia 60
Spain 358
Sweden 83
Switzerland 369
United Kingdom 744
6660
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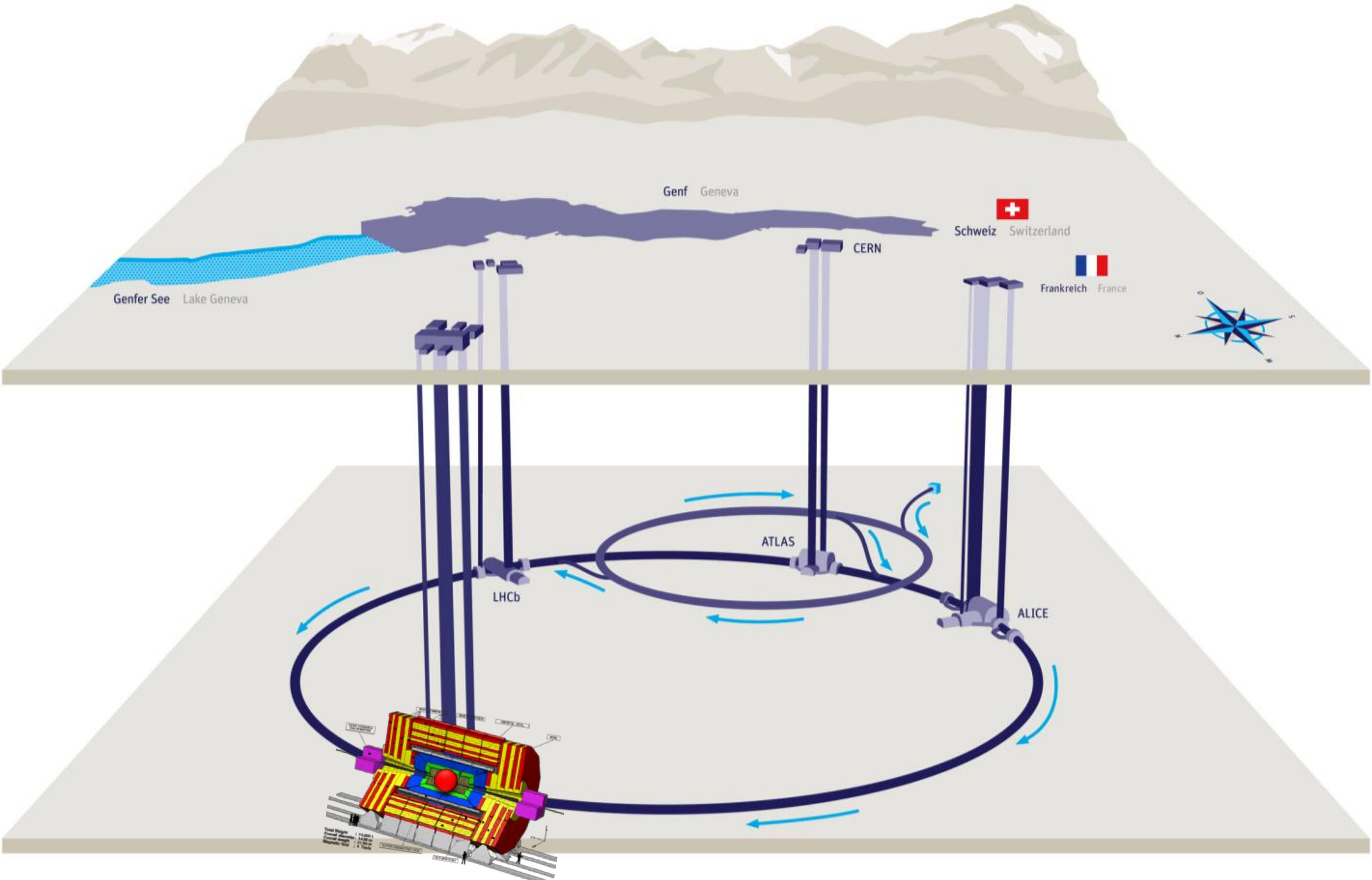
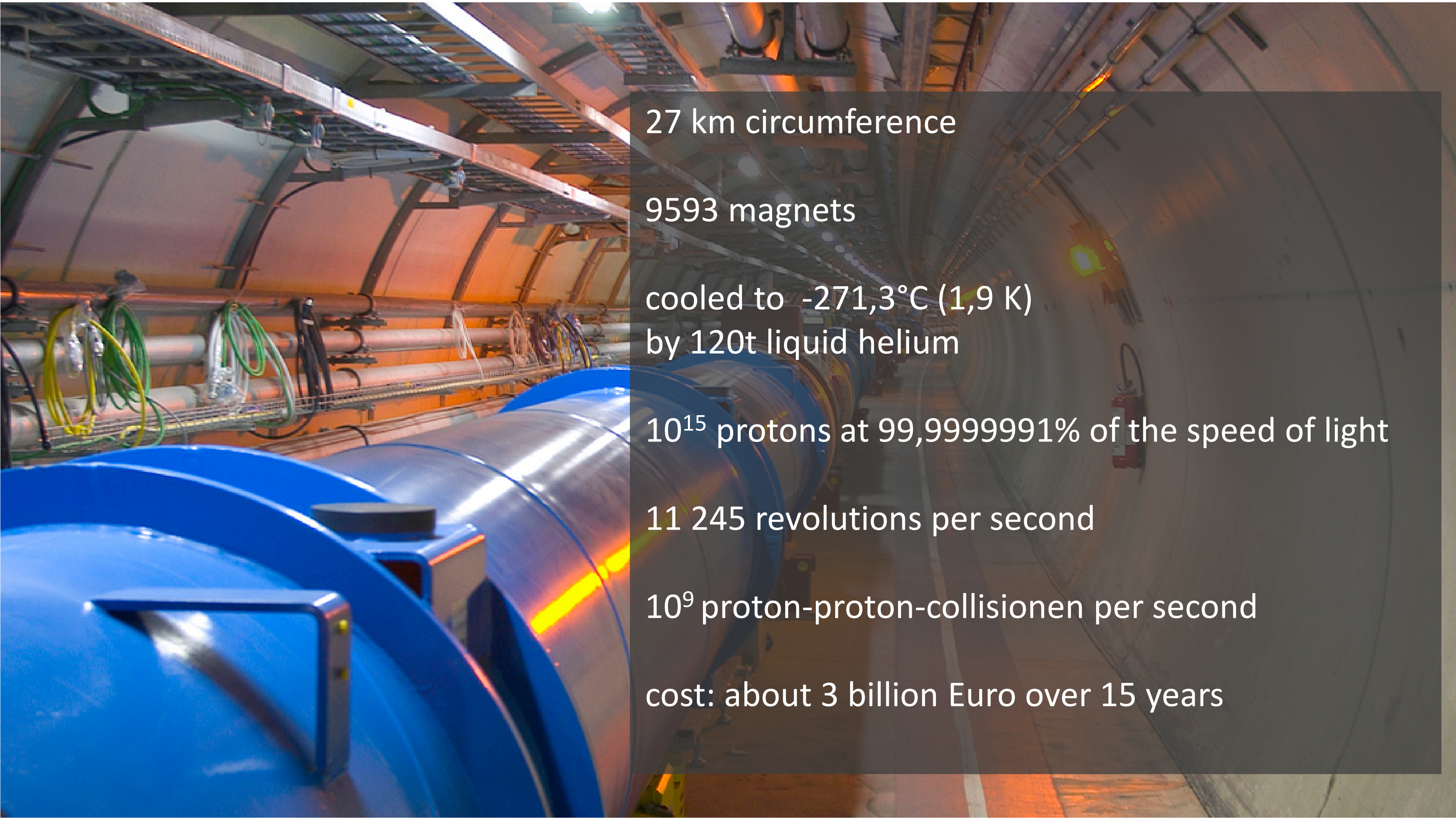
India 115
Japan 225
Russia 856
Turkey 77
USA 1708
2981
CANDIDATE FOR ACCESSION
Romania 75
ASSOCIATE MEMBER IN THE PRE-STAGE TO MEMBERSHIP
Israel 62
OTHERS
Argentina 18
Armenia 12
Australia 24
Azerbaijan 1
Belarus 22
Brazil 93
Canada 167
Chile 4
China 95
China (Taipei) 67
Colombia 10
Croatia 17
Cuba 4
Cyprus 9
Egypt 7
Estonia 18
Georgia 10
Iceland 3
Iran 14
Ireland 10
Korea 89
Lebanon 1
Lithuania 12
Malta 1
Mexico 43
Montenegro 1
Morocco 5
New Zealand 11
Pakistan 19
Peru 2
Qatar 1
Saudi Arabia 3
Serbia 26
Slovenia 37
South Africa 21
Thailand 5
T.F.Y.R.O.M. 2
Tunisia 1
Ukraine 21
Uzbekistan 1
907

Large Hadron Collider LHC at CERN


Genf Geneva
Schweiz Switzerland
CERN
Frankreich France
Genfer See Lake Geneva
ATLAS
LHCb
ALICE

LHC in figures



27 km circumference

9593 magnets

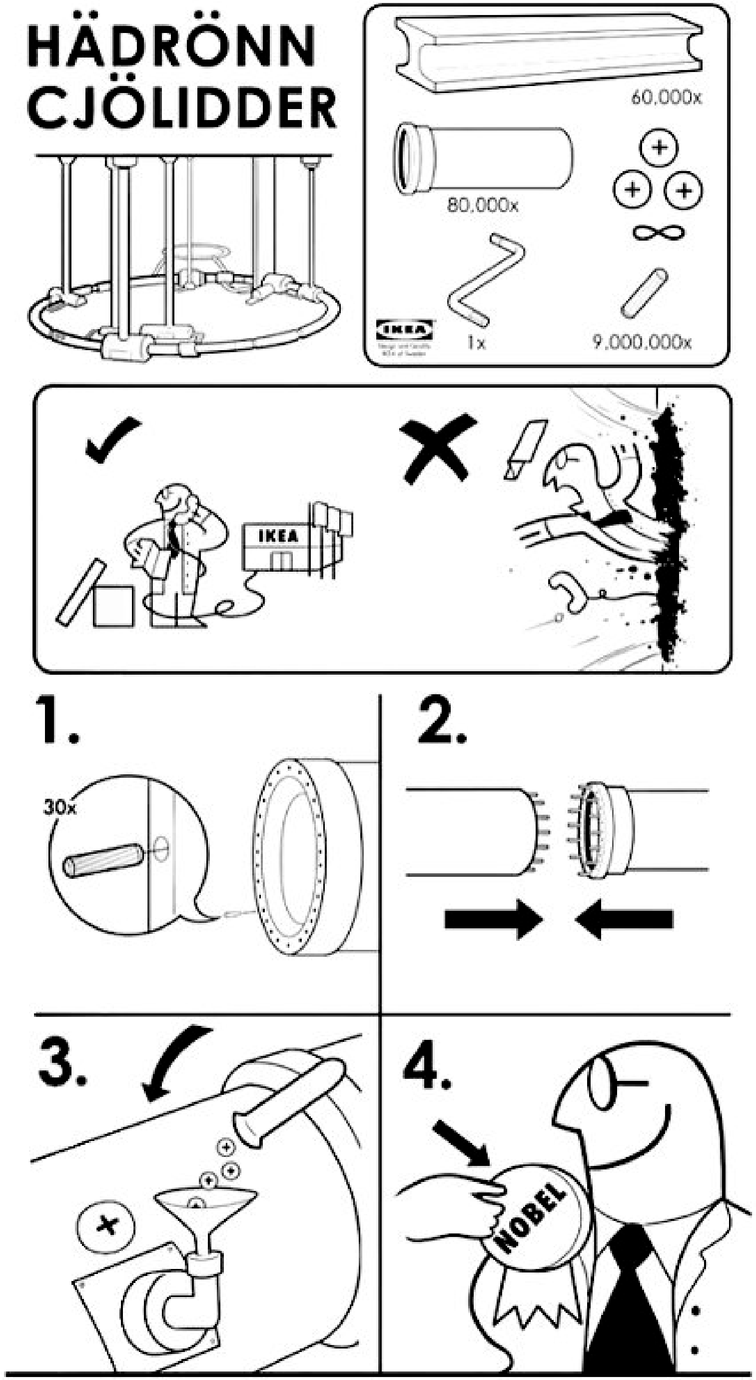
cooled to -271,3°C (1,9 K)
by 120t liquid helium

10^{15} protons at 99,9999991% of the speed of light

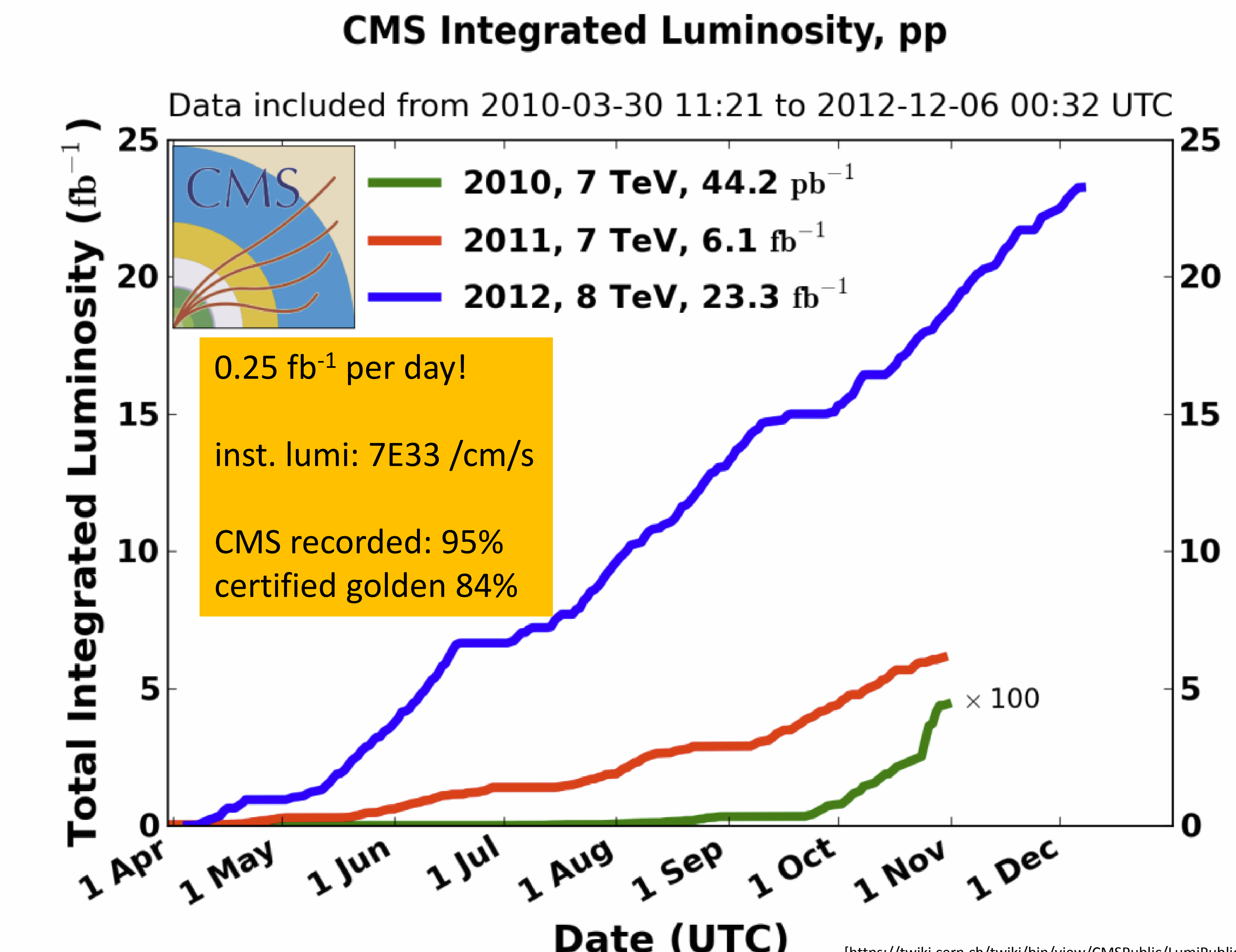
11 245 revolutions per second

10^9 proton-proton-collisionen per second

cost: about 3 billion Euro over 15 years


HÄDRÖNN
CJÖLIDDER
60,000x
80,000x
IKEA
1x
9,000,000x
IKEA
1.
30x
2.
3.
4.
NOBEL

Luminosity

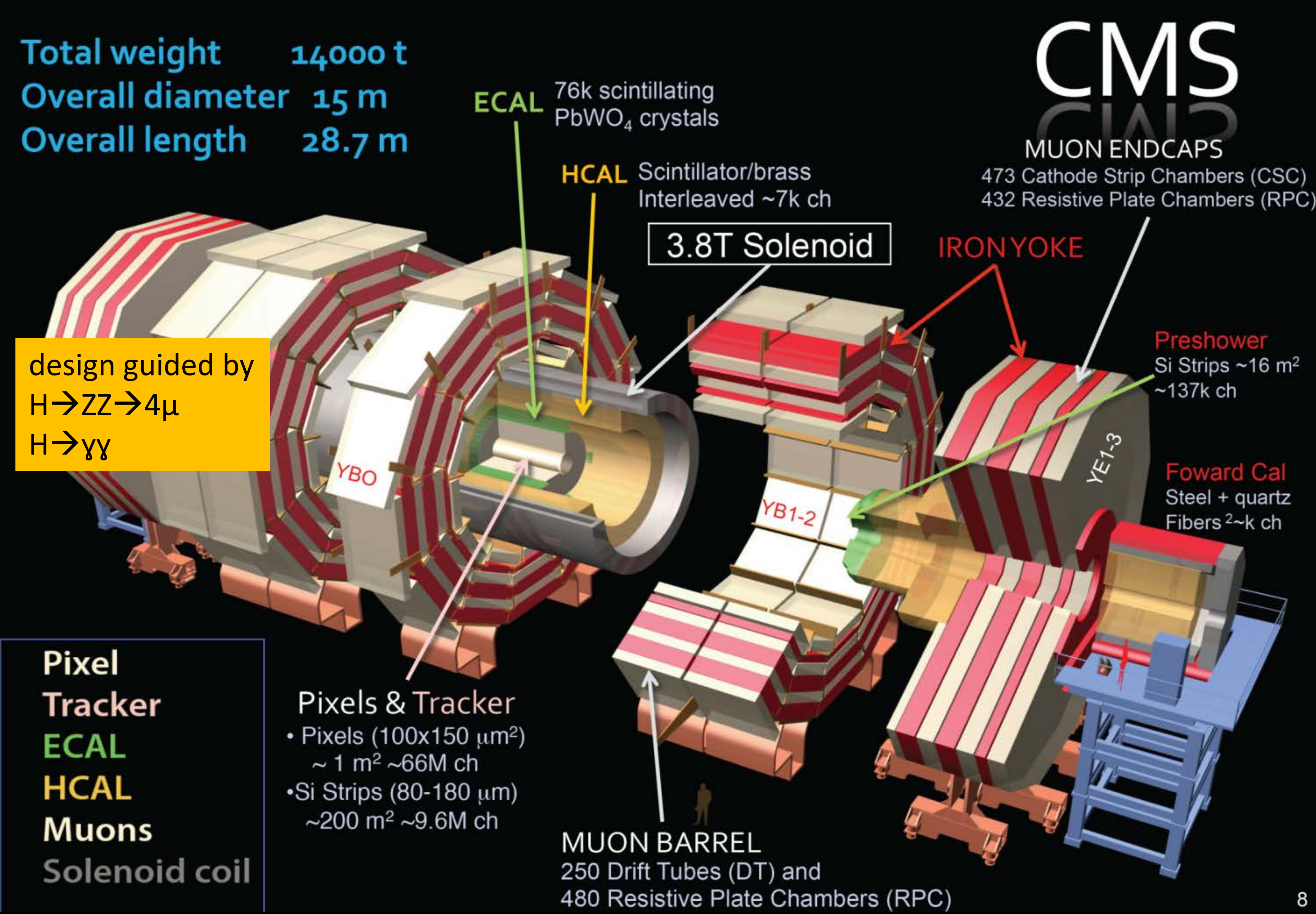


[https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults]

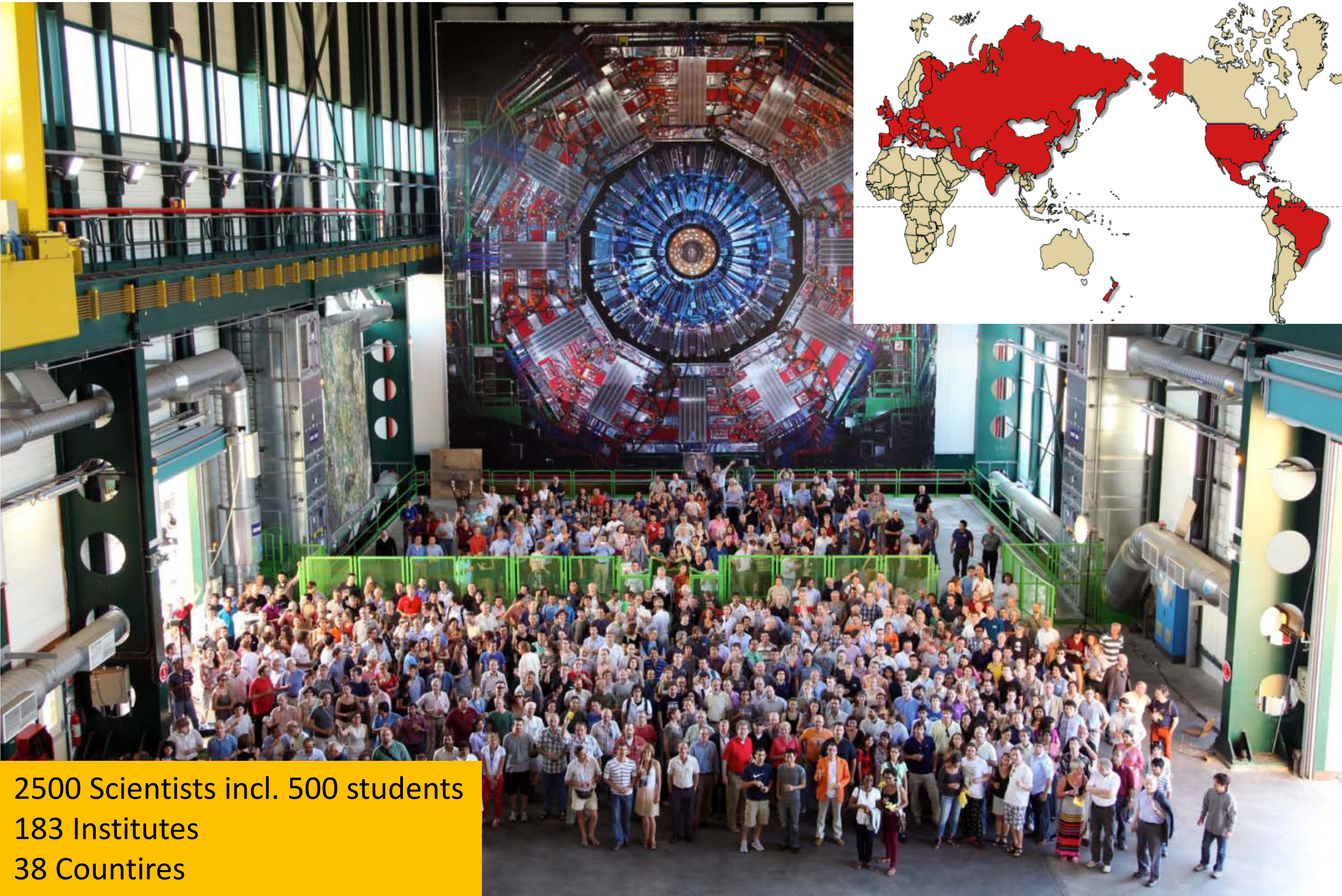
LHC Performance

Parameter	2010	2011	2012	Nominal
Beam Energy (TeV)	3.5	3.5	4	7
√s (TeV)	**7**	**7**	**8**	**14**
Protons per bunch (10^{11})	1.2	1.5	1.6	1.15
Number of bunches	368	1380	1380	2808
Bunch spacing (ns)	150	75/50	50	25
Norm. Emittance (mm rad)	2.4 – 4	1.9 – 2.4	2.2 – 2.5	3.75
Beta* (m)	3.5	1.5 – 1	0.6	0.55
Inst. Lumi (10^{34} $cm^{-2}s^{-1}$)	**0.02**	**0.4**	**0.76**	**1**
Pile-up	3	19	35	23
Int. Lumi (fb^{-1})	**0.05**	**5.5**	**23**	

$$\left.\begin{array}{l} \sigma_{inel} \approx 72 \text{ mbarn} \\ L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \end{array}\right\} \rightarrow \dot{N} = L\sigma \approx 720 \text{ MHz} \gg 40 \text{ MHz} \quad \rightarrow \quad \textbf{PILE-UP}$$

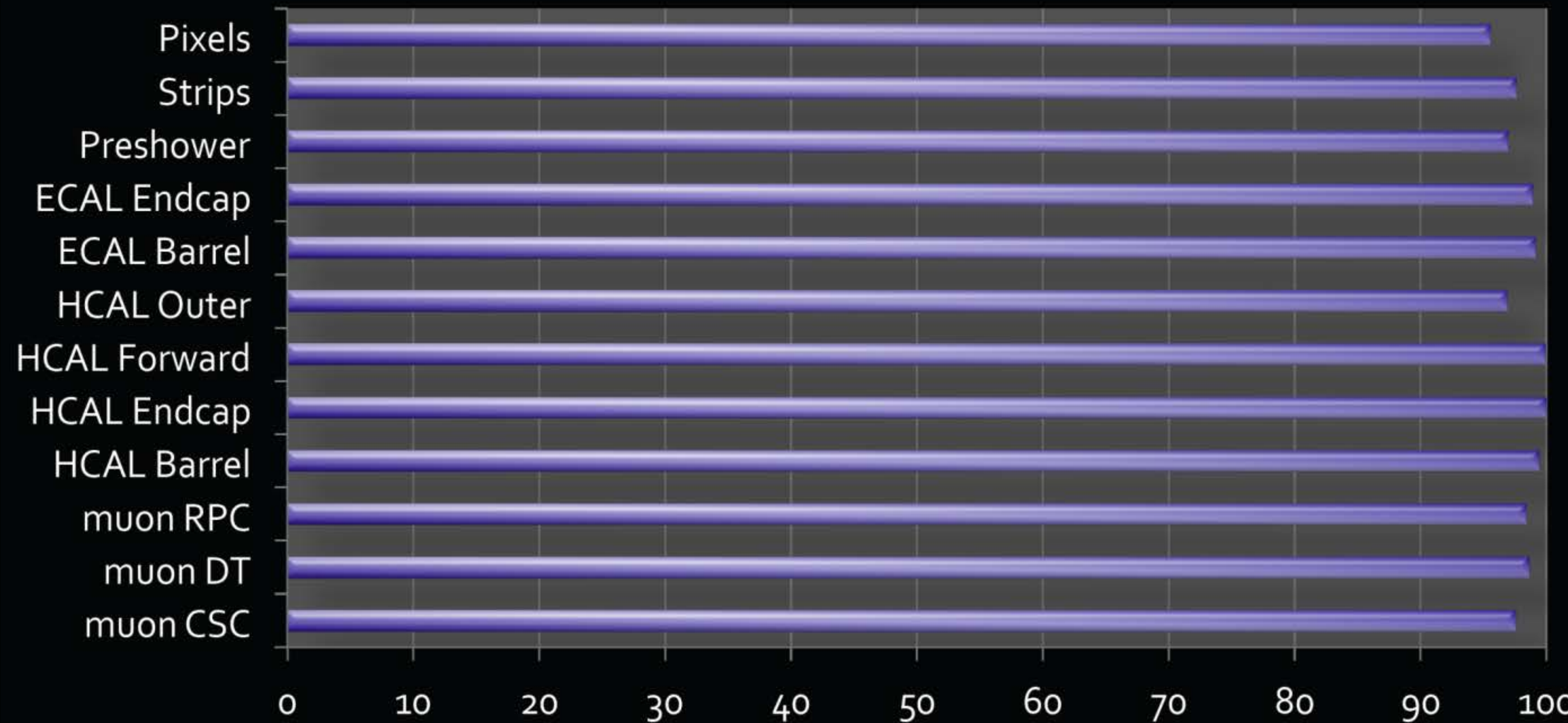

Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL 76k scintillating $PbWO_4$ crystals
HCAL Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers 2~k ch
design guided by
H→ZZ→4μ
H→γγ
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)
8

CMS Collaboration



2500 Scientists incl. 500 students
183 Institutes
38 Countires

Detector Performance

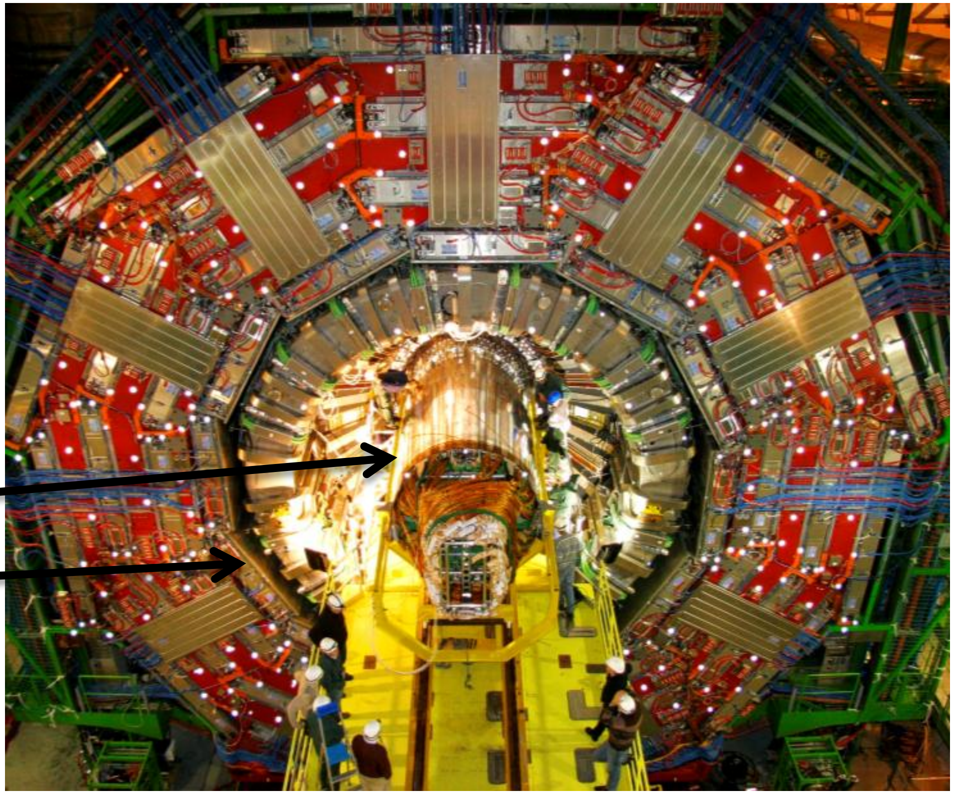


CMS Subsystem	muon CSC	muon DT	muon RPC	HCAL Barrel	HCAL Endcap	HCAL Forward	HCAL Outer	ECAL Barrel	ECAL Endcap	Preshower	Strips	Pixels
%Operational	97.55	98.6	98.4	99.4	99.96	99.88	96.88	99.11	98.89	96.9	97.61	95.5

October 3, 2012 CMS Wedi

Aachen in CMS

1. + 3. Physikalisches Institut: Profs. Erdmann, Feld, Hebbeker, Schael, Stahl
+ 26 physicists
+ 9 engineers
+ 24 PhD students
+ 27 students
+ 12 technicians



since 1994

R&D and construction of
Silicon Tracker
and Myon Chambers

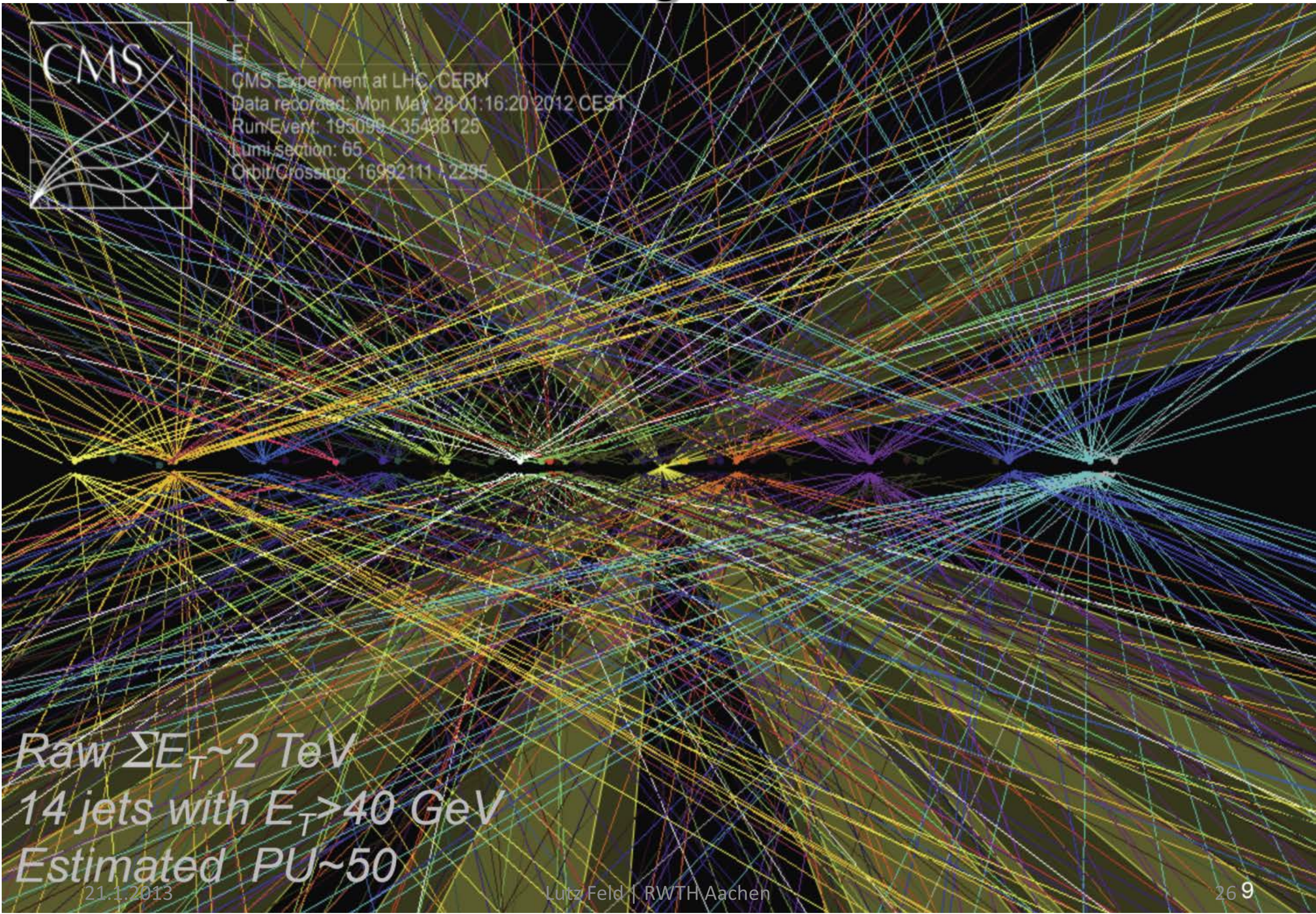
Tier-2 Computing Centre

Data analysis: Top-Quarks, Higgs, Supersymmetry, …

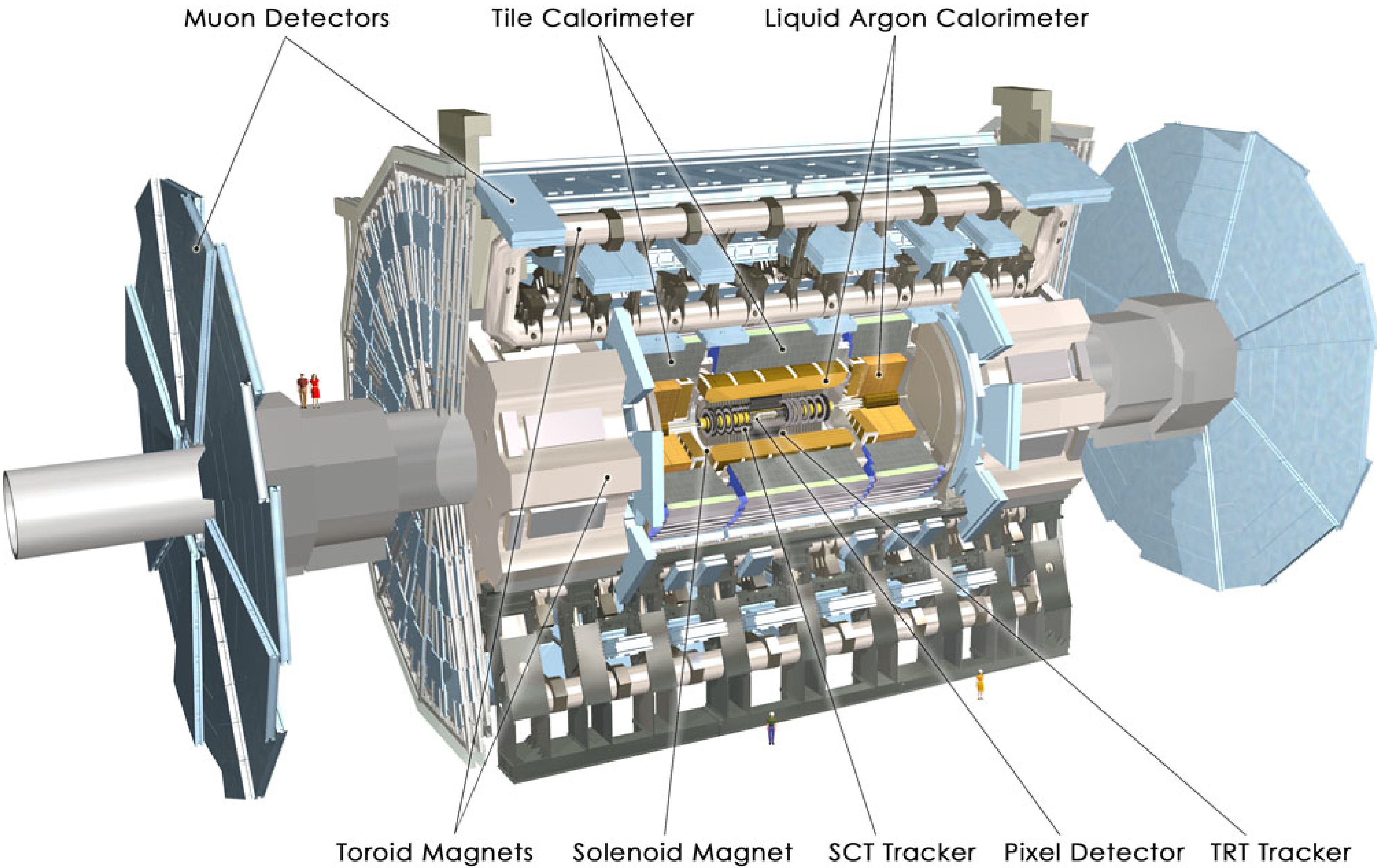
Upgrades of Pixel, Tracker and Myon System

DFG Graduate School: ‚Particle and Astro-particle Physics in the Light of LHC'

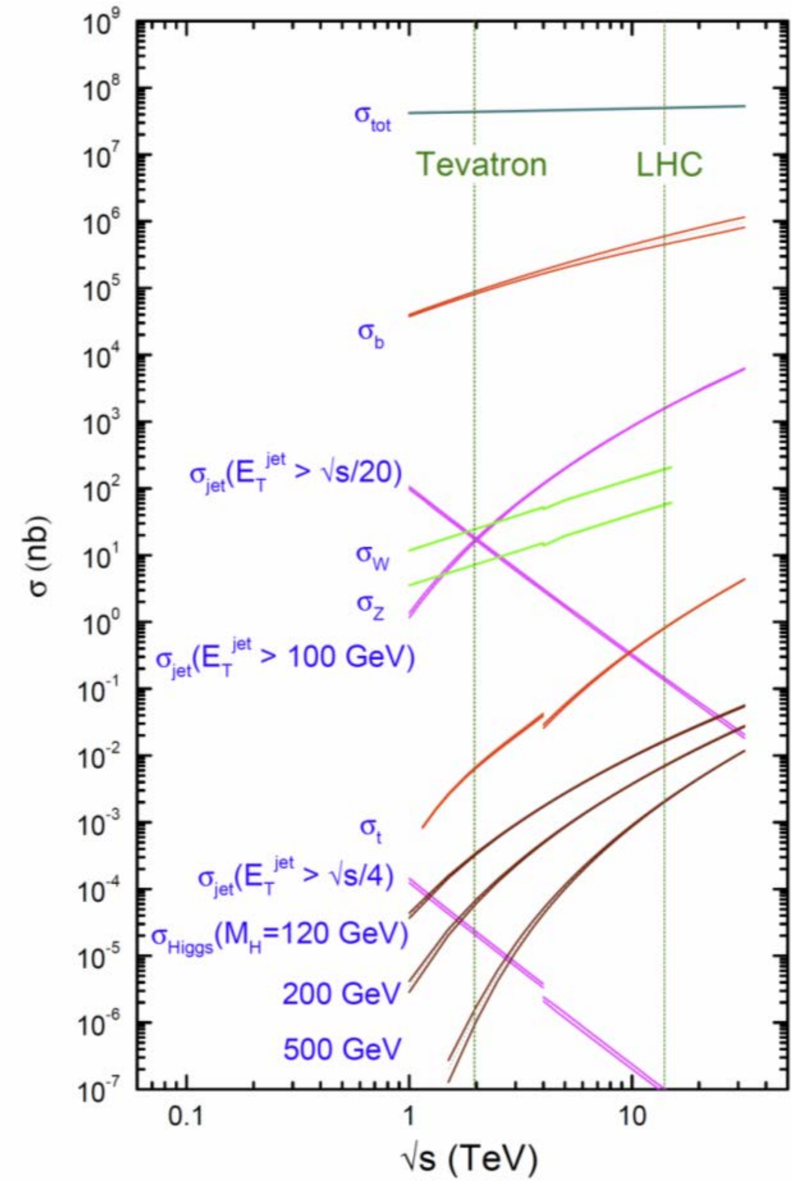
Pile-up is a real challenge!



The ATLAS Detector



Cross Sections



[J. Stirling, http://mstwpdf.hepforge.org/plots/plots.html]

total: 1 GHz

b: 10 MHz

W,Z: 1 kHz

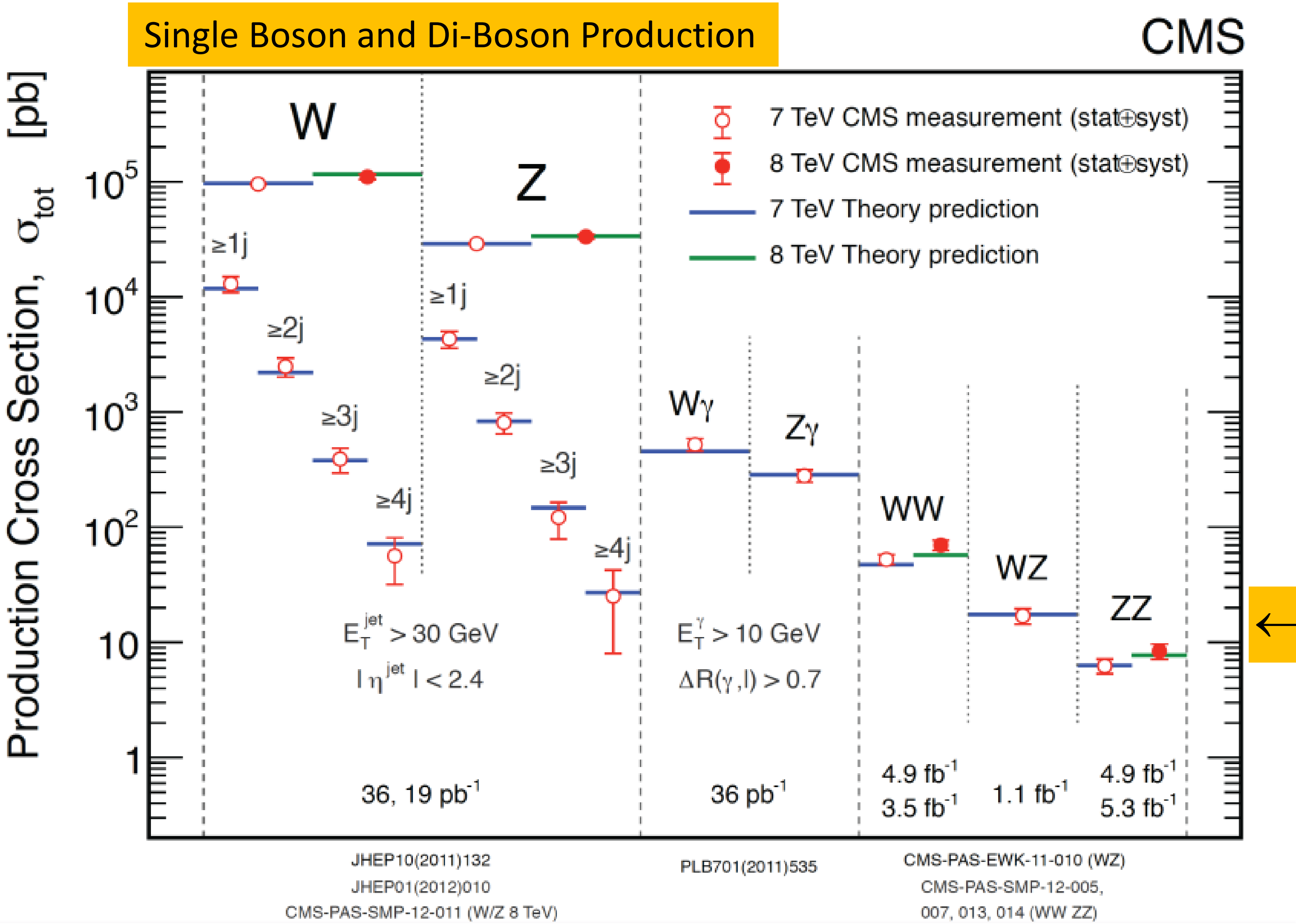
top: 10 Hz

higgs: 0.1 Hz

challenges:
trigger system
background suppression

Vector Boson Cross Section Measurements

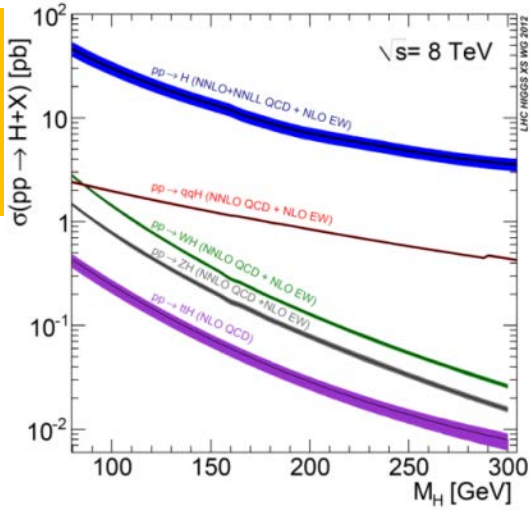
Single Boson and Di-Boson Production



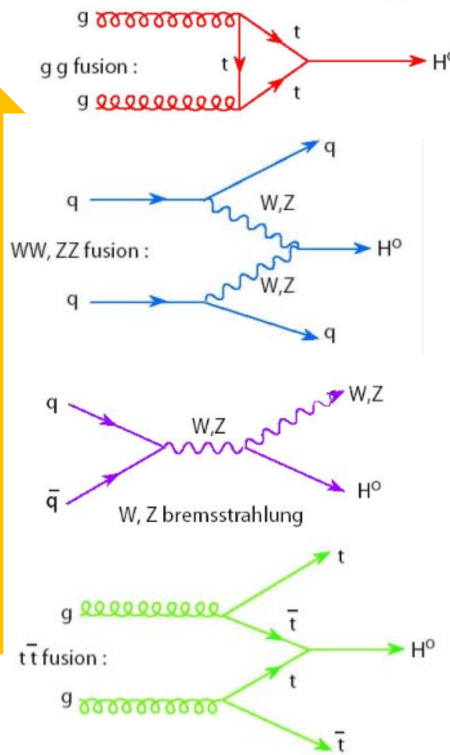
$\leftarrow \sigma(Higgs)$

The Higgs Boson

production



cross section



visibility

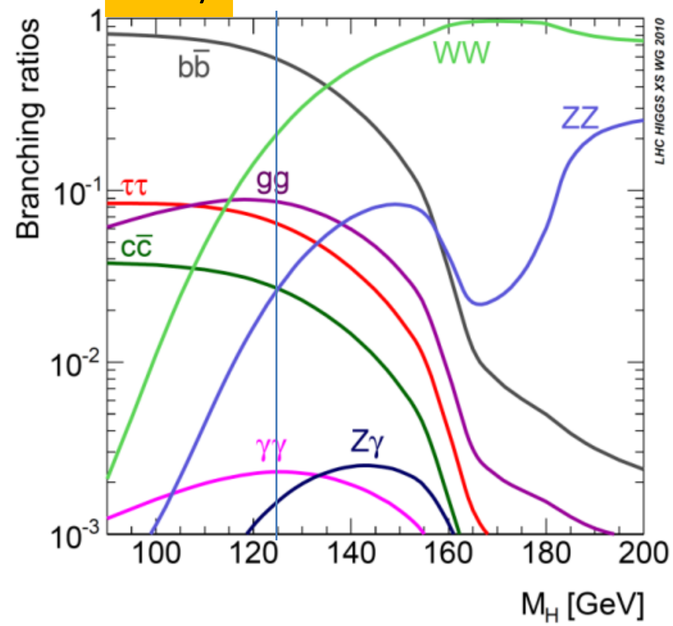
if $m_H \approx 125$ GeV then

$\sigma(pp \to H + X) \approx 15$ pb

$\to$ in $L = 5\ \mathrm{fb}^{-1}$: 75'000 higgs bosons

$\Gamma(H) \approx 4$ MeV

decay

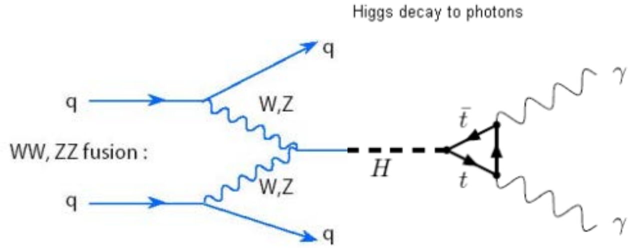


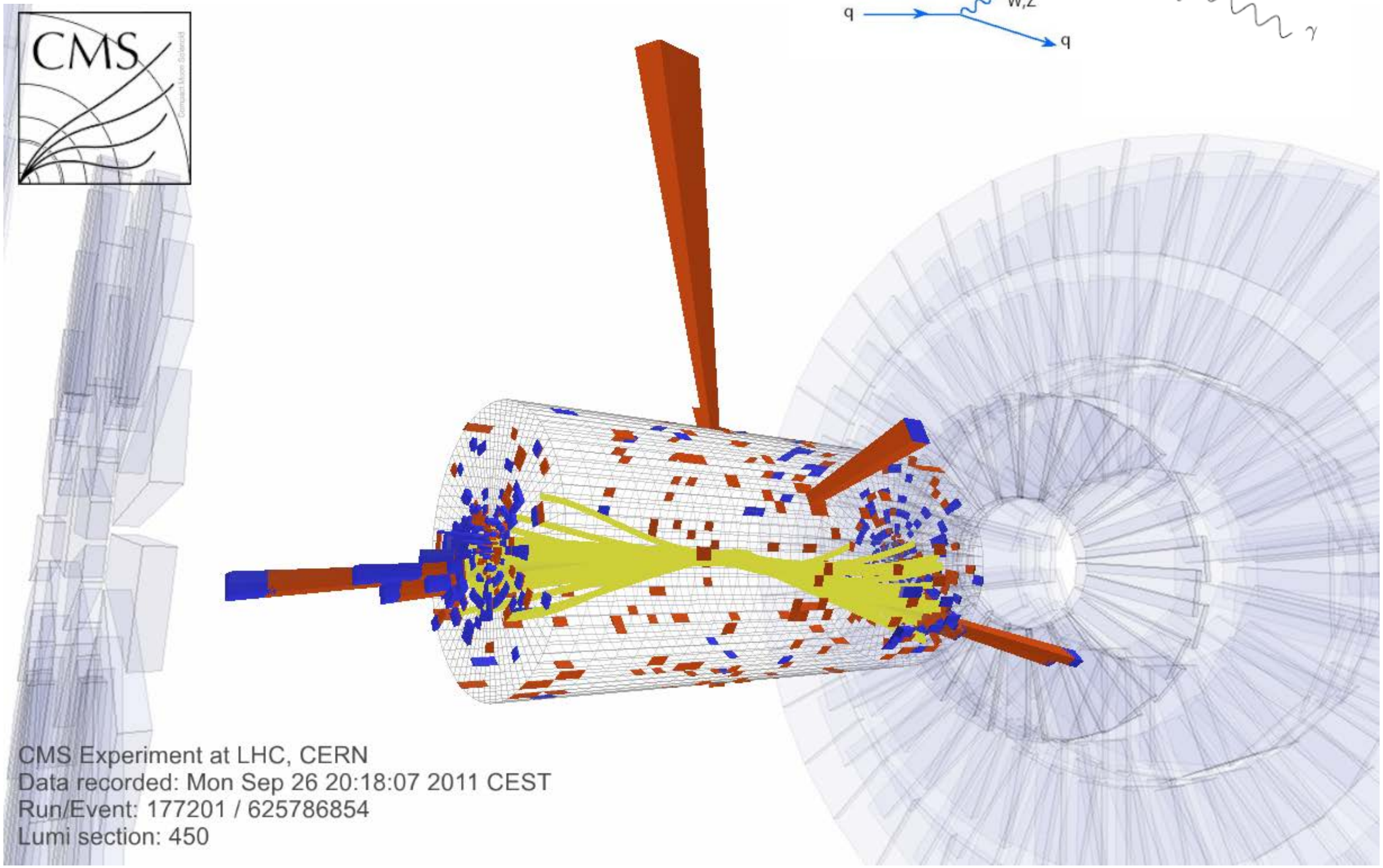
	H→γγ	H→ZZ	H→WW	H→bb	H→ττ
gg→H	+	+	+	-	+
qq→qqH	+		+		+
qq→VH			+	+	+
gg→ttH				+	

$\to$ analyses are split into different categories

mass resolution	1-3%	1-7%	20%	10%	20%

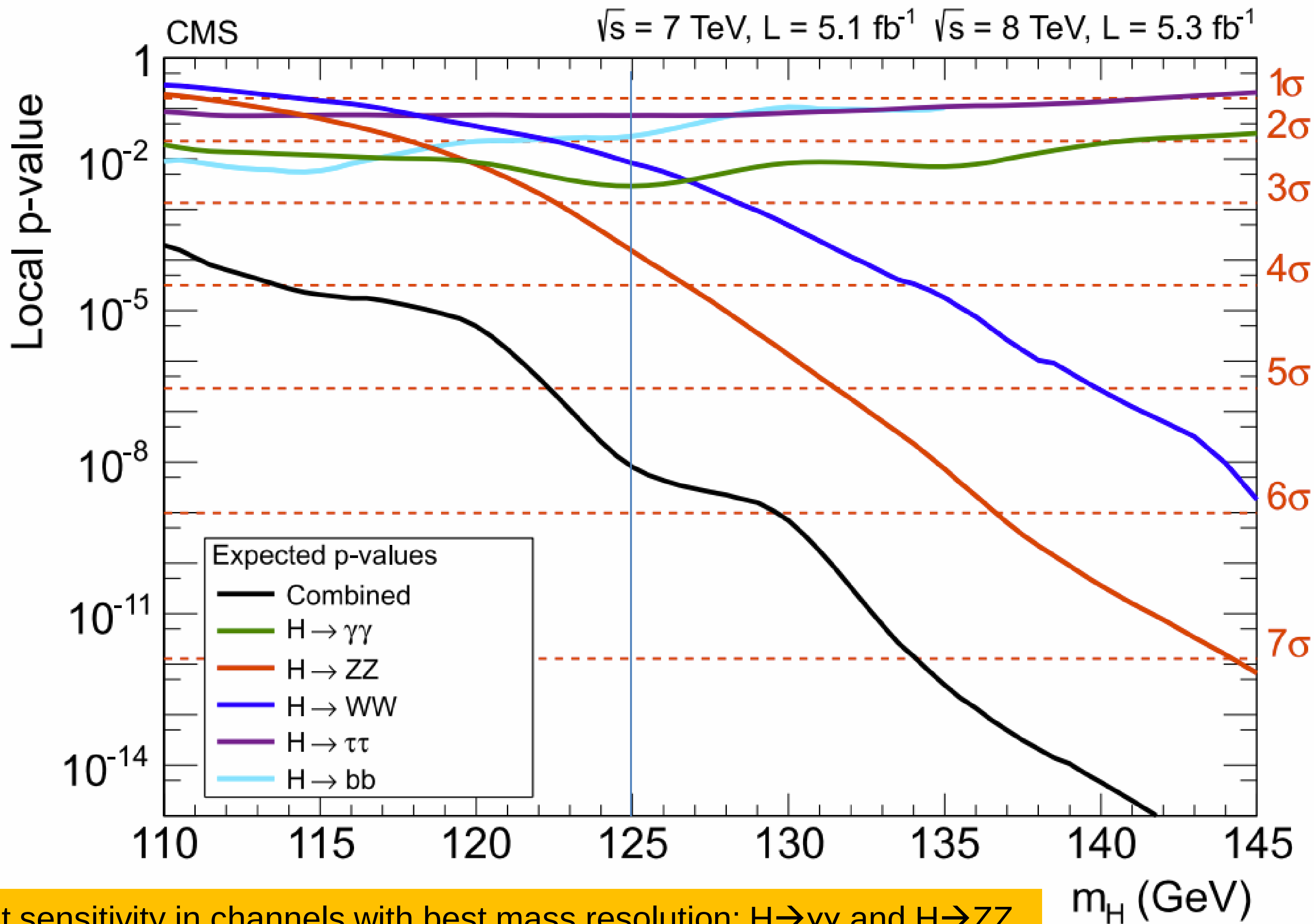
di-jet tagging: qq→qqH→qqɣɣ





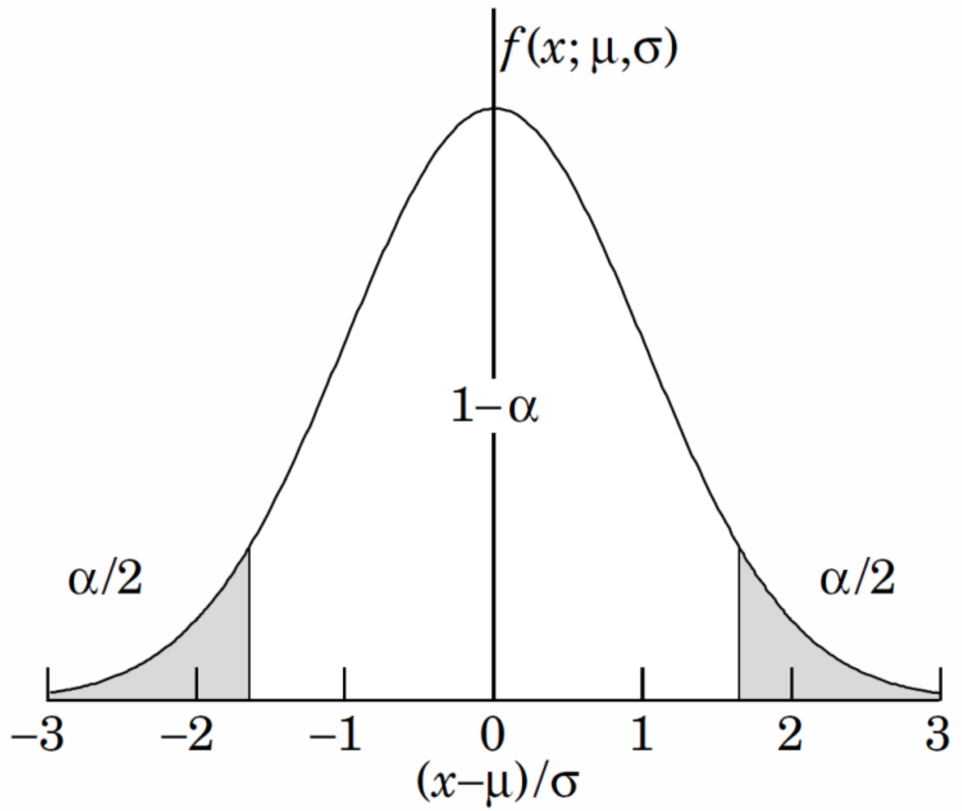
Sensitivity of different channels

p-value: probability that background fluctuates to an excess as large as expected from the SM higgs



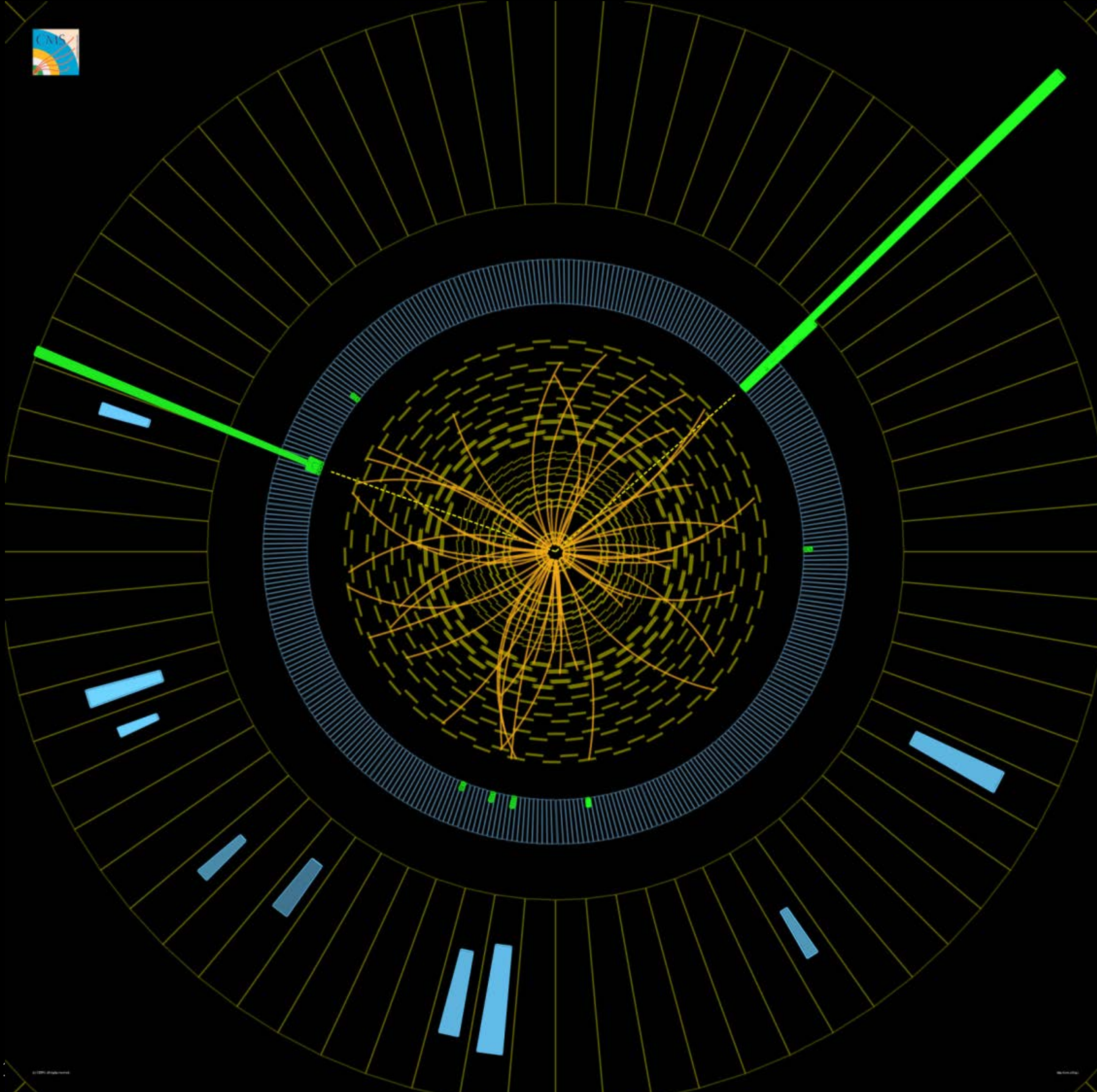
highest sensitivity in channels with best mass resolution: H→γγ and H→ZZ
mass resolution = significance!

Significance



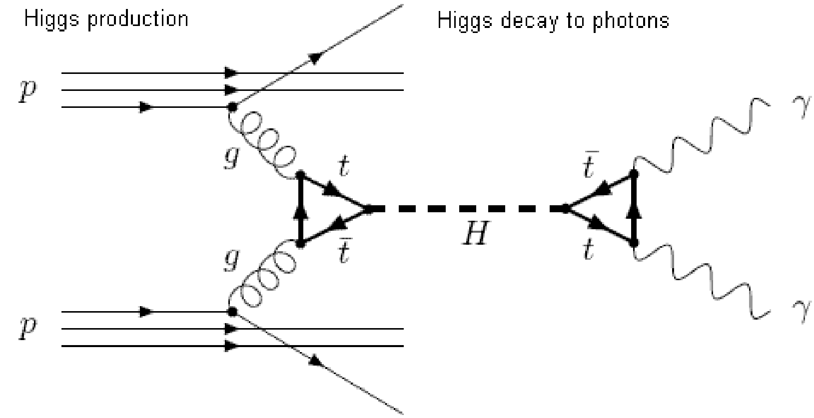
α	δ
0.3173	1σ
4.55×10^{-2}	2σ
2.7×10^{-3}	3σ
6.3×10^{-5}	4σ
5.7×10^{-7}	5σ
2.0×10^{-9}	6σ

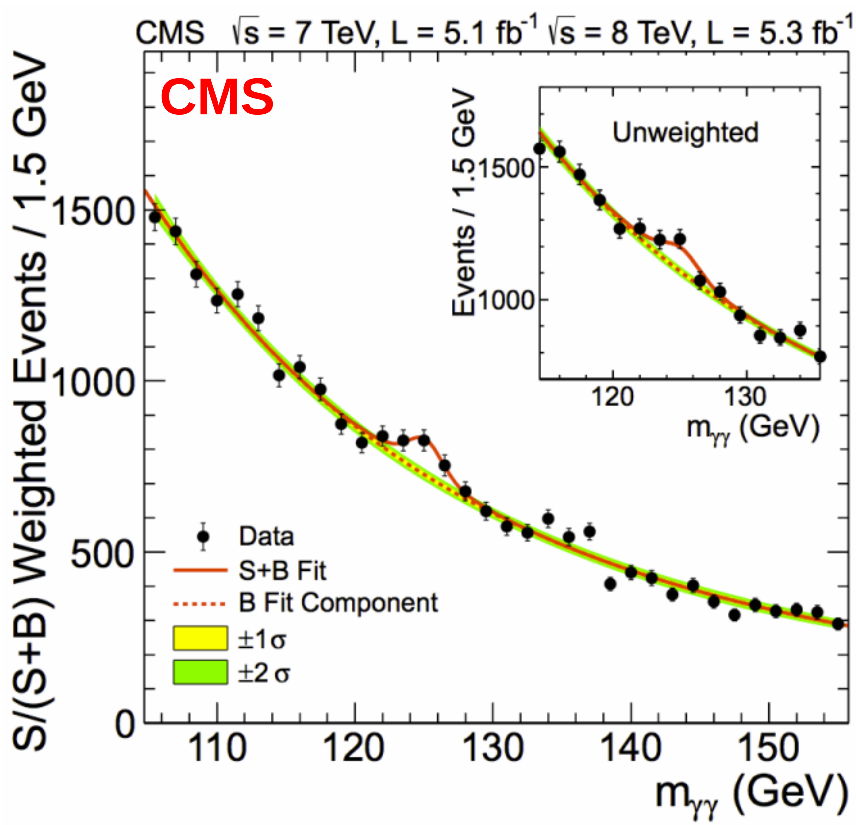
↑ background ↑ observation

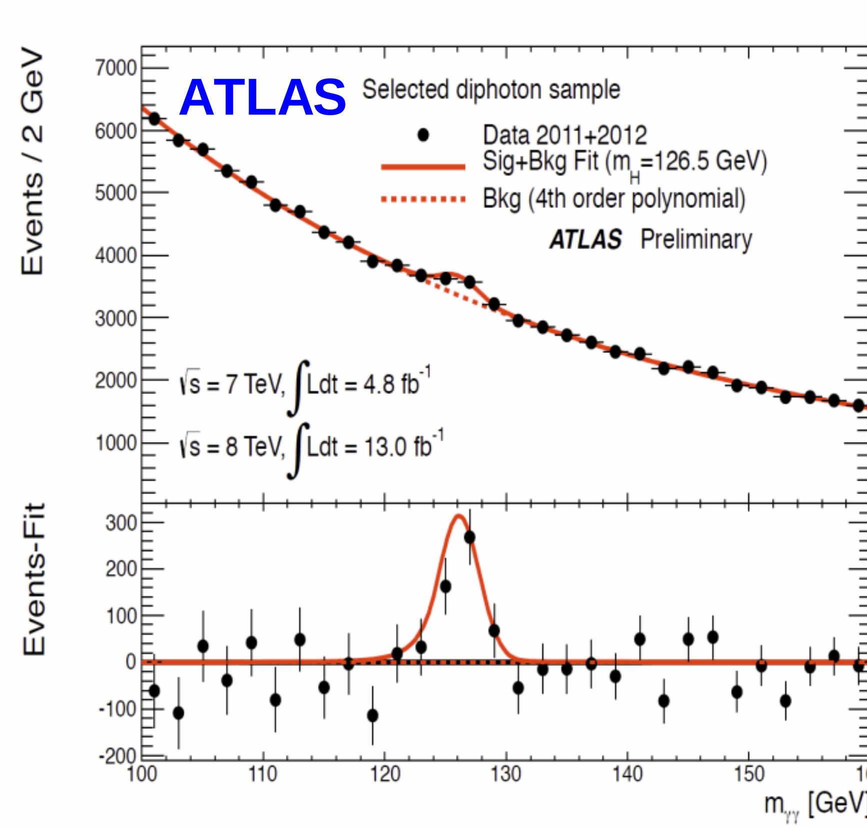


H→γγ

- ECAL energy resolution decides
- γγ mass resolution 3-4 GeV
- multi-variate analysis for photon ID and event classification

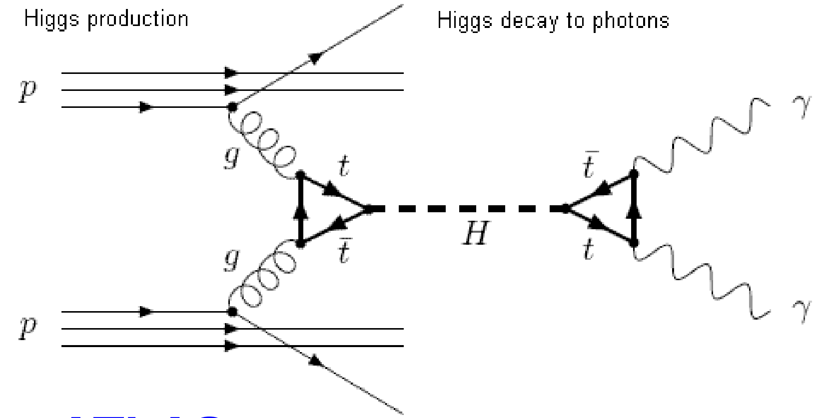




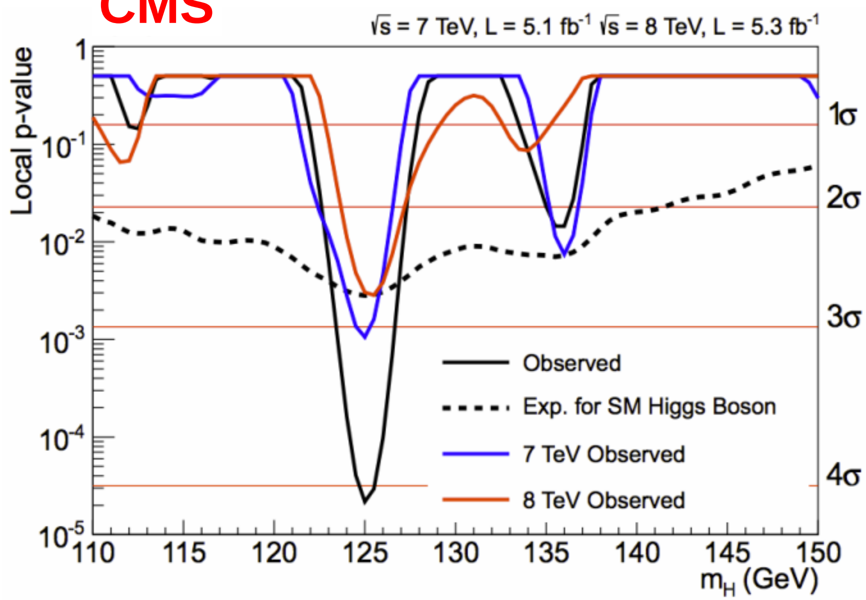


H→γγ

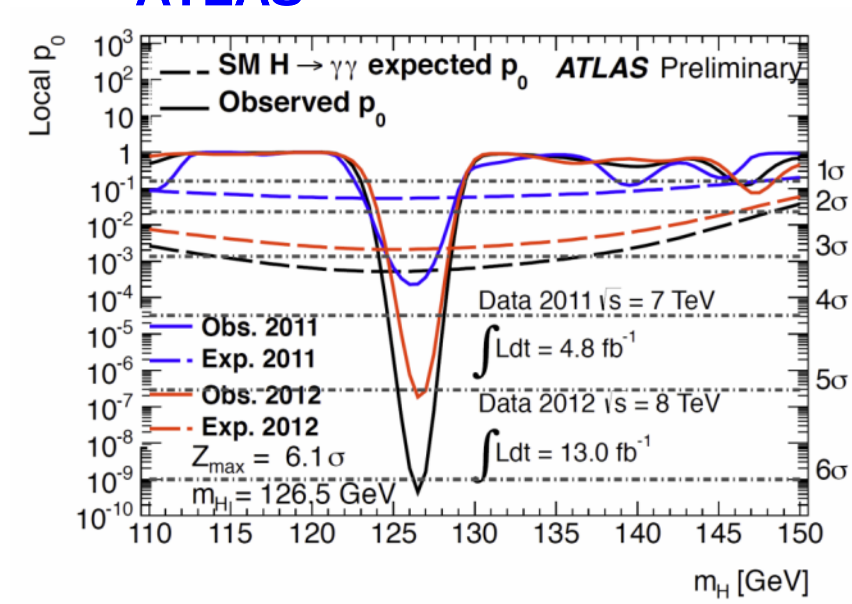
- ECAL energy resolution decides
- γγ mass resolution 3-4 GeV
- multi-variate analysis for photon ID and event classification



CMS

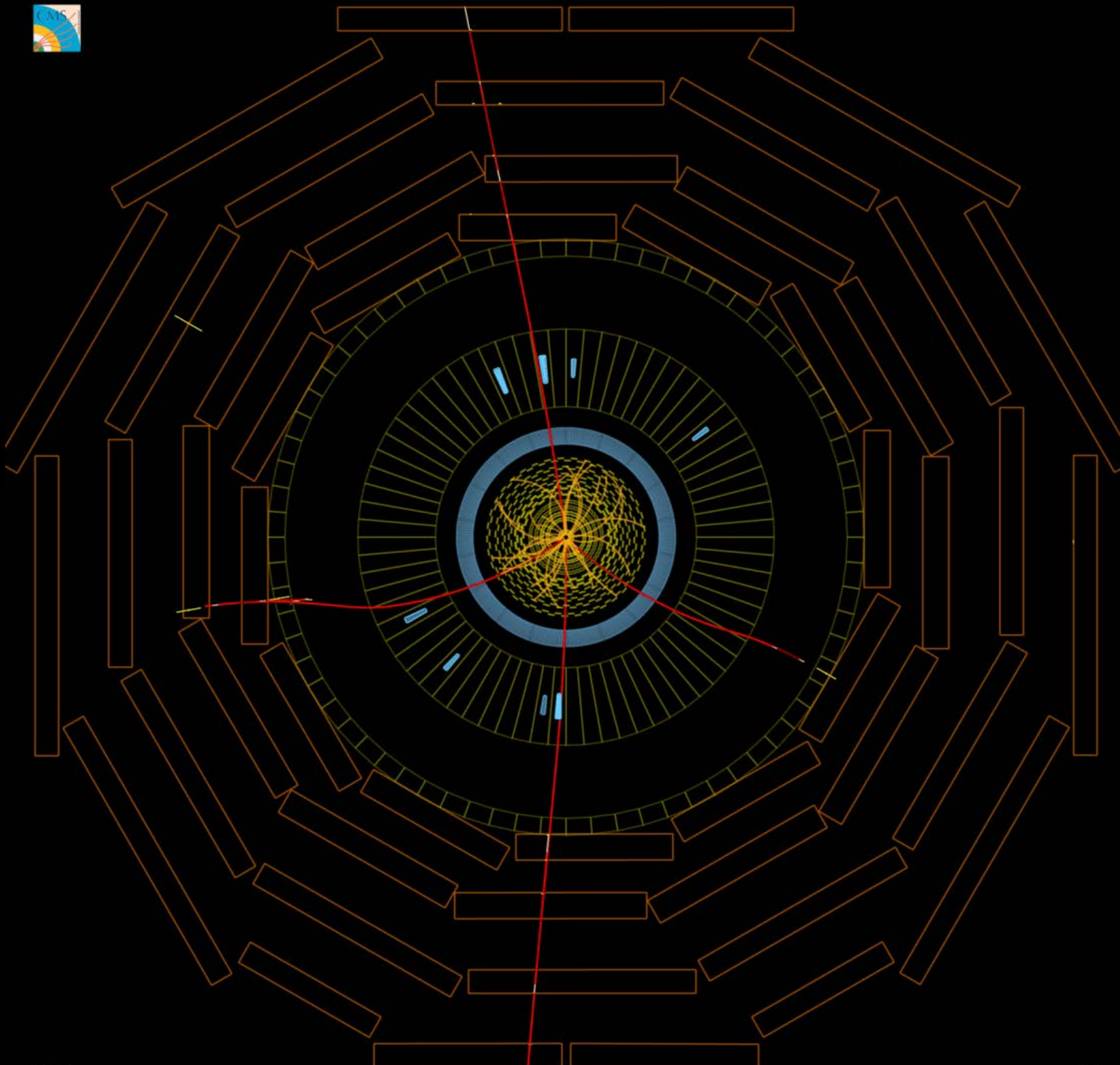


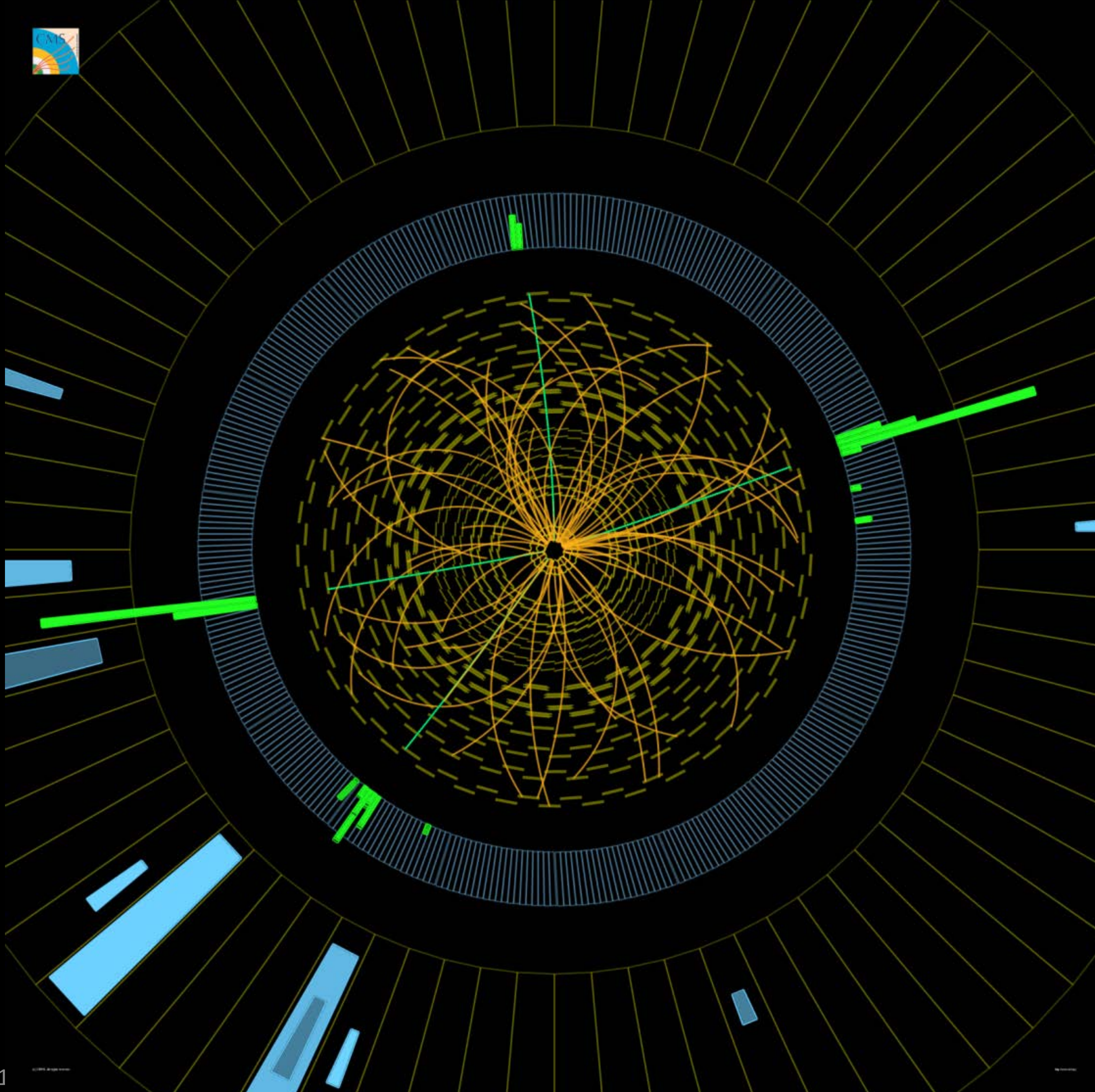
ATLAS



significance 4.1σ

significance 6.1σ





H→ZZ

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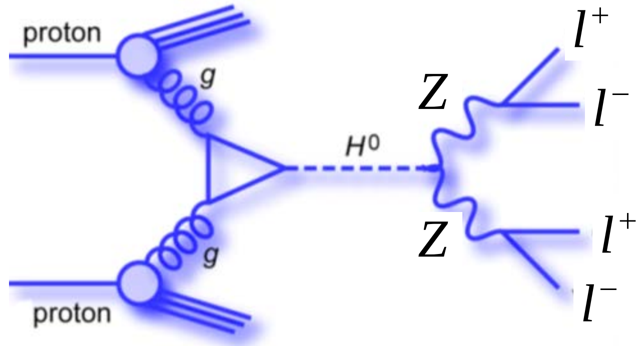
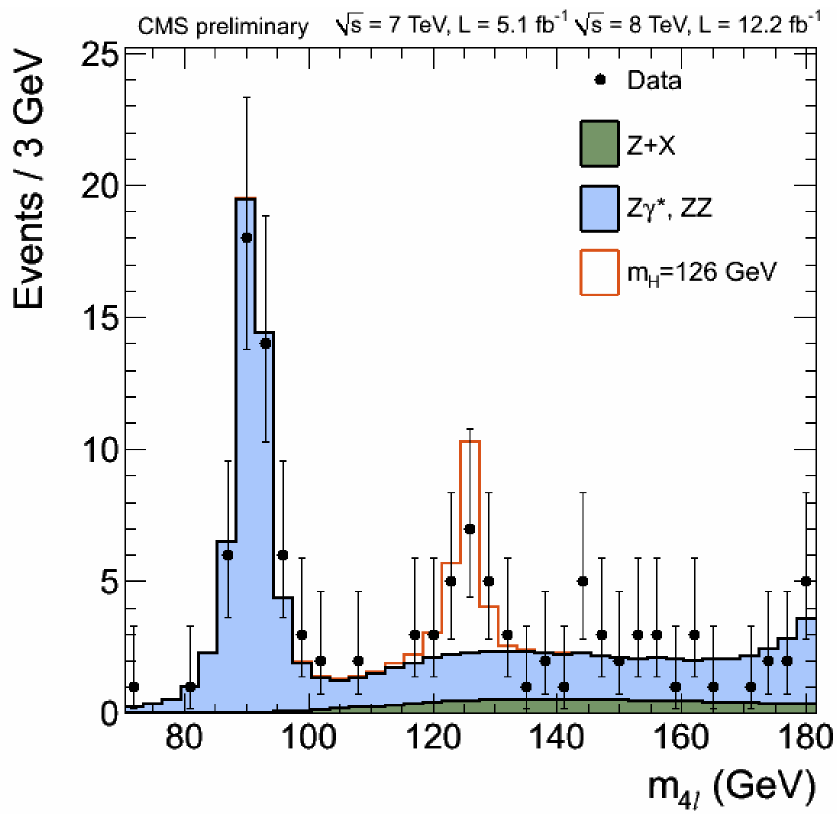
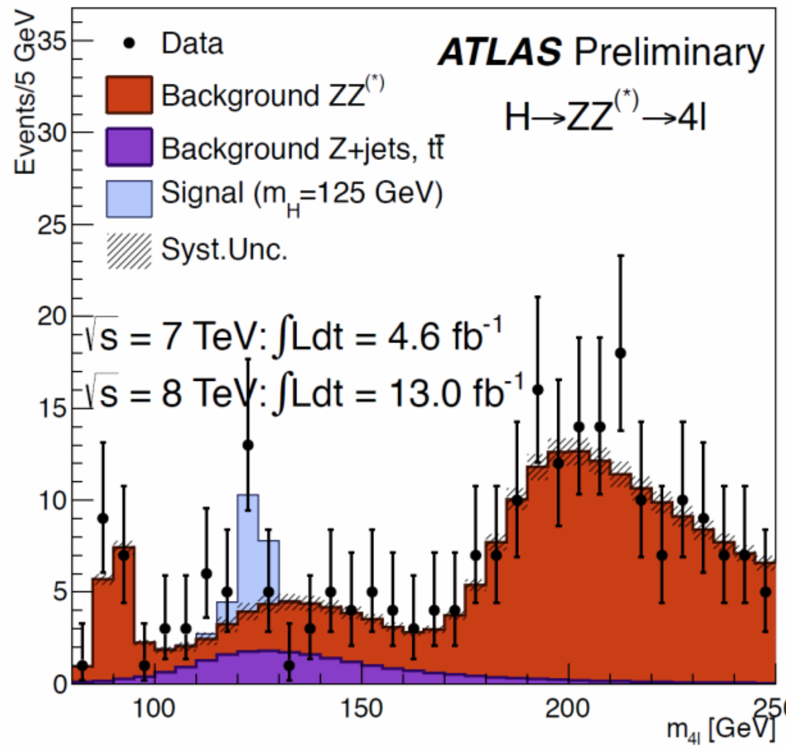


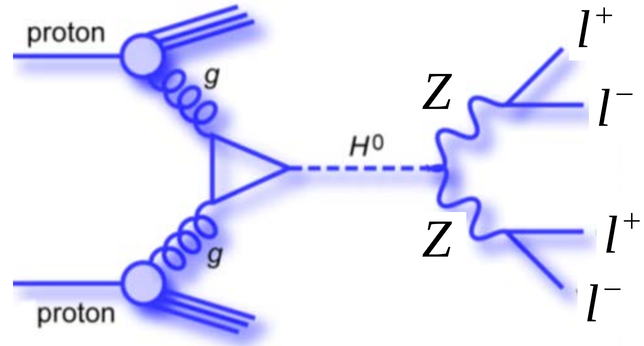
CMS



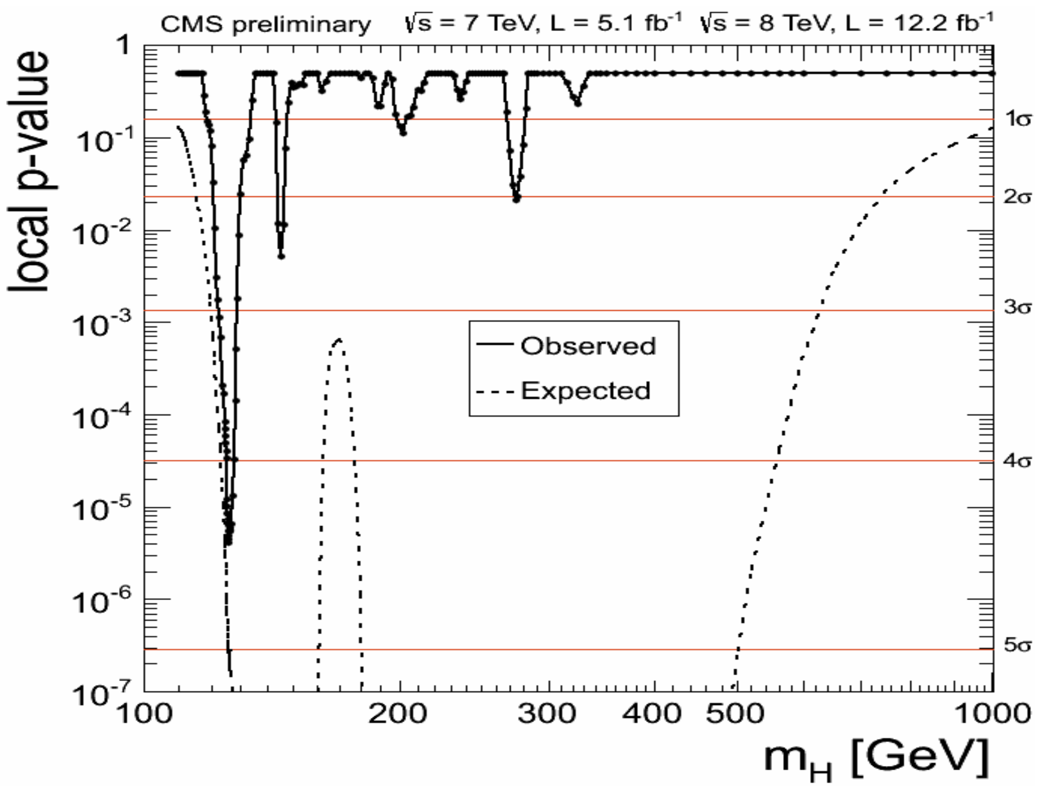
ATLAS



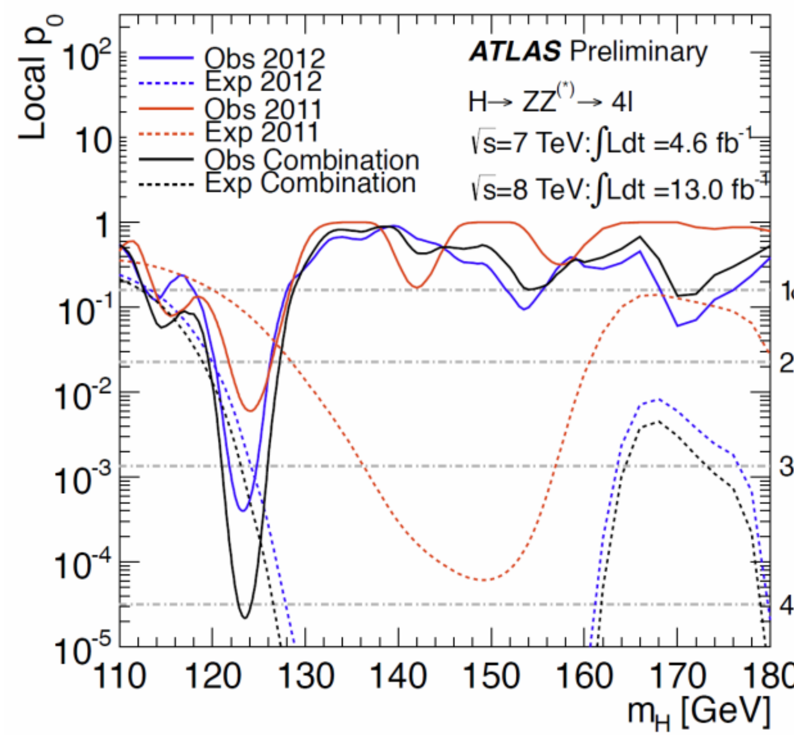
H→ZZ



CMS



ATLAS



significance 4.5σ

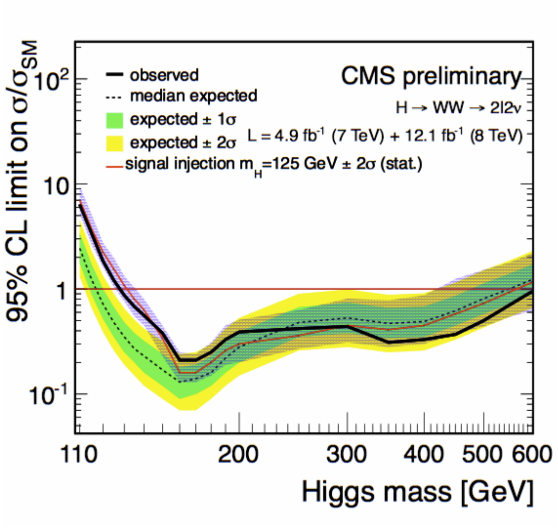
significance 4.1σ

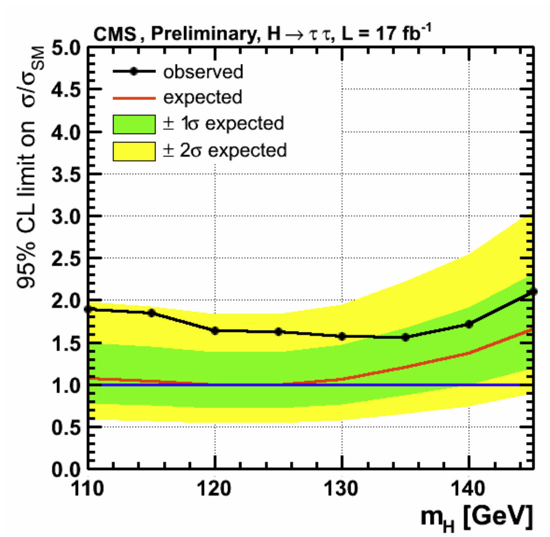
The low mass resolution channels

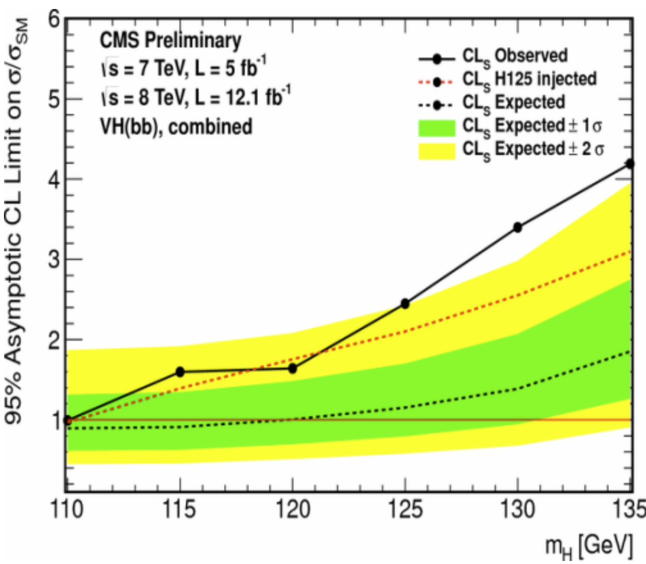
H→WW (gg→H, qq→qqH)

H→ττ (gg→H, qq→qqH,→VH)

H→bb (qq→VH)







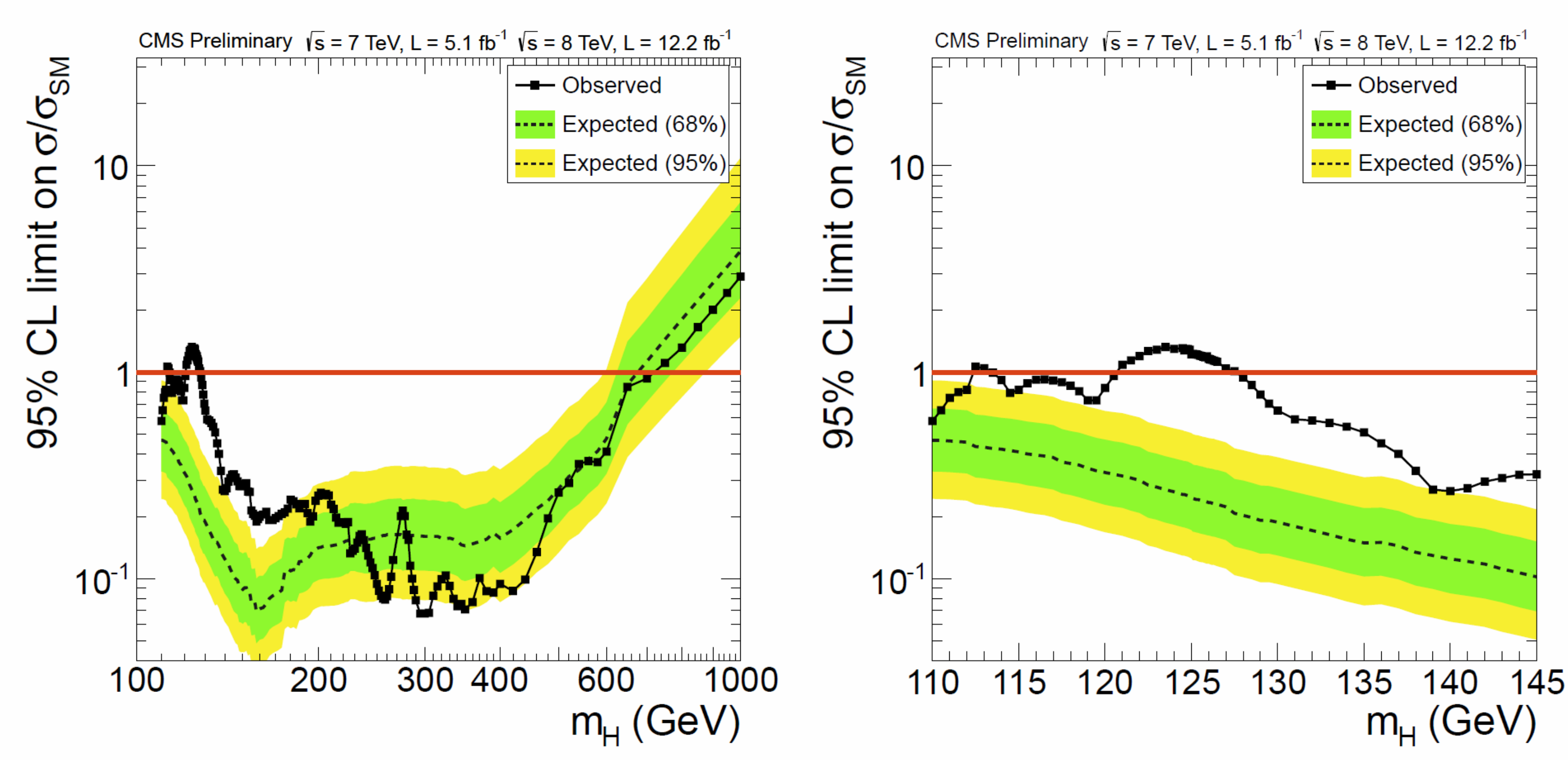
broad excess
observed : 3.1 sigma
expected: 4.1 sigma

mild excess
1.3 sigma

mild excess
2.2 sigma

Combination of all Observed Yields

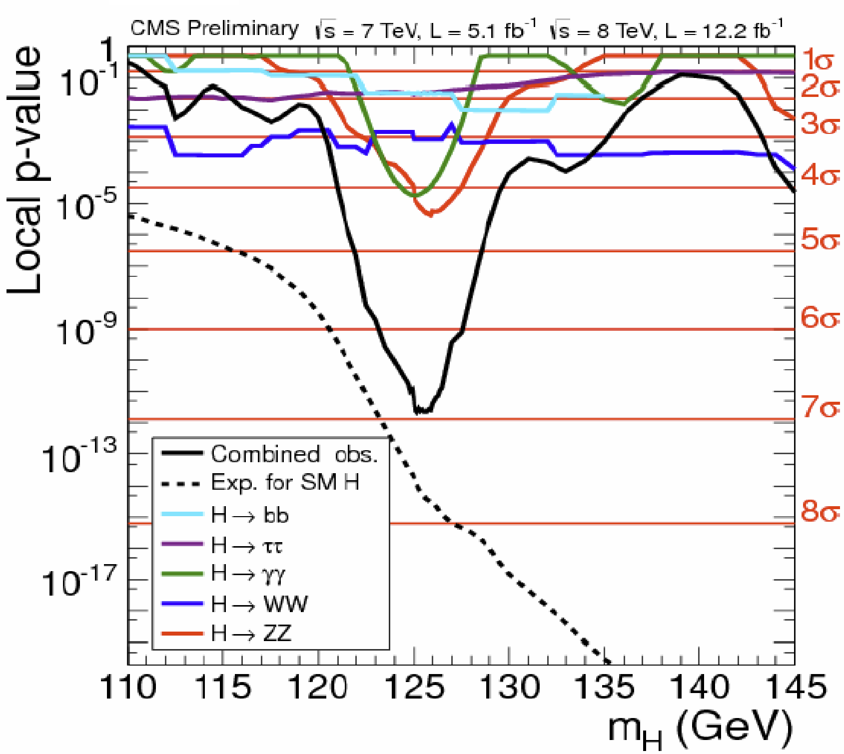
Testing the SM higgs hypothesis

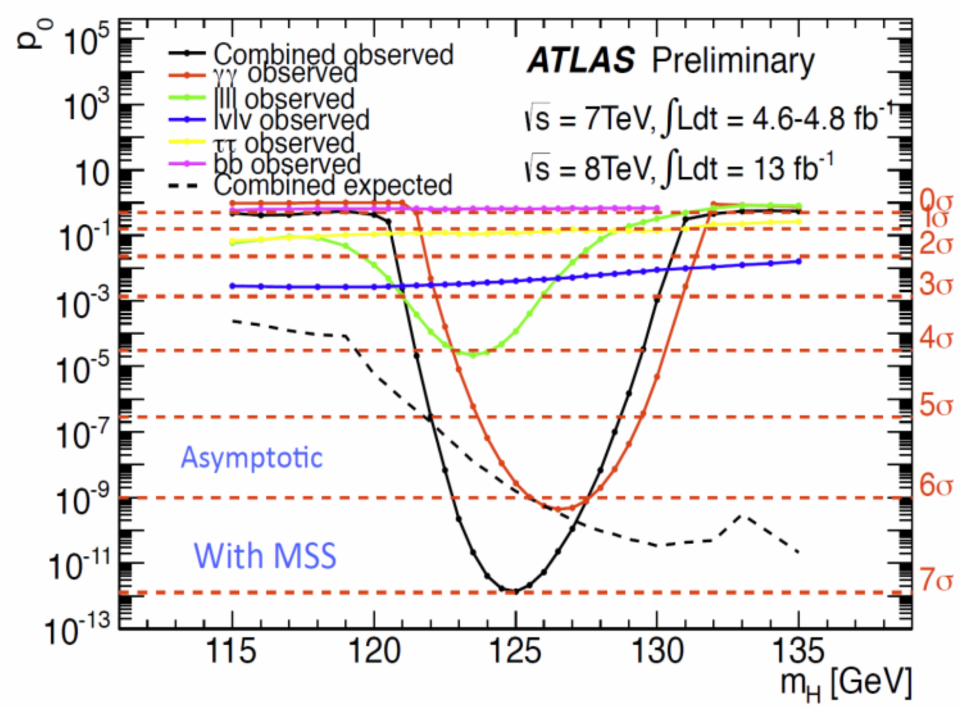


higgs masses excluded at 95% CL up to 700 GeV except between 121 and 128 GeV

Combination of all Observed Yields

CMS | Testing the background hypothesis | **ATLAS**





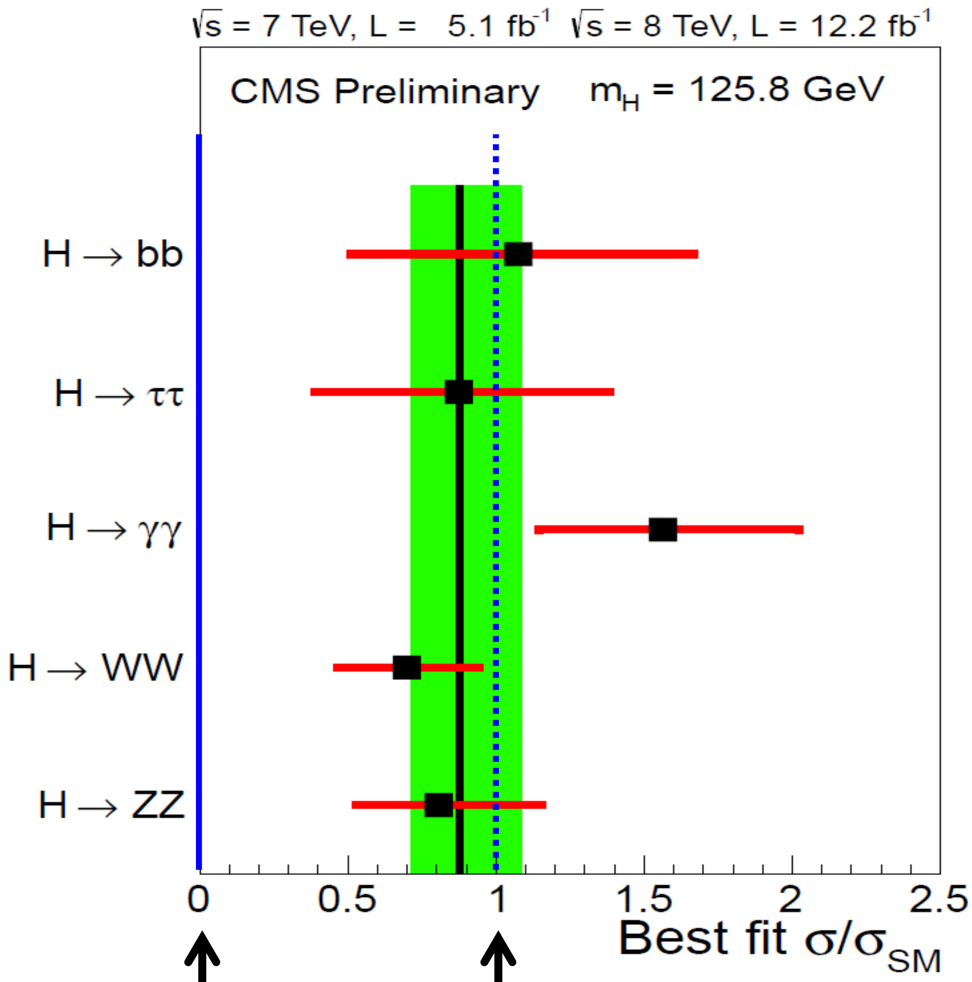
significance	
observed:	$6.9\,\sigma$
expected:	$7.8\,\sigma$

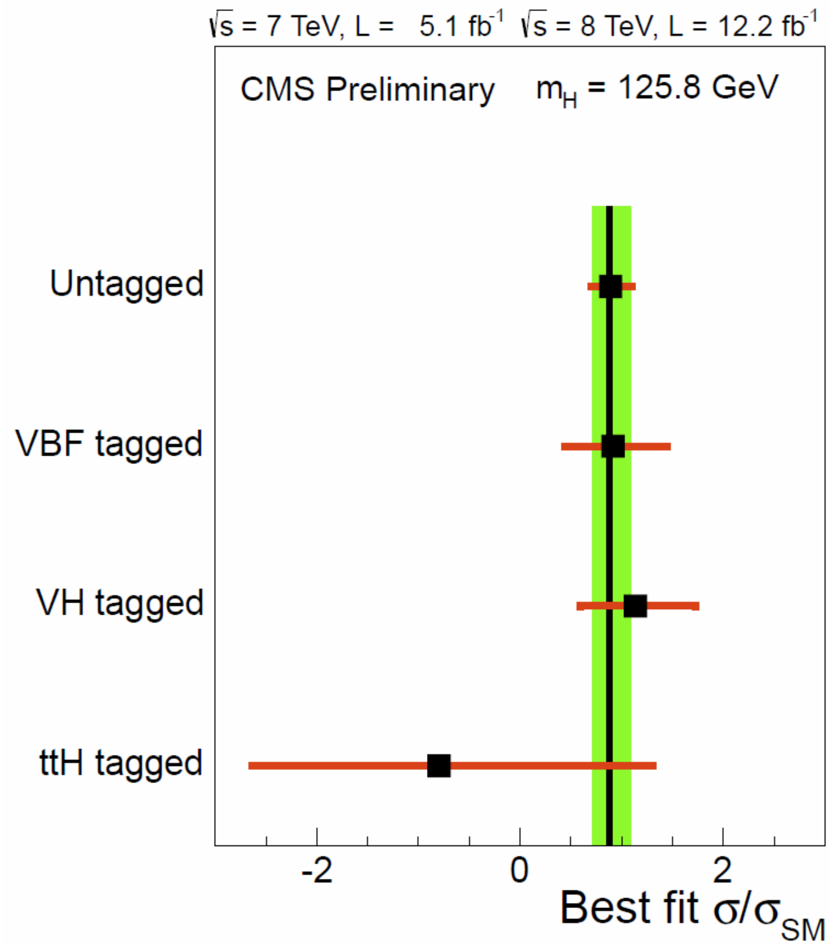
significance	
observed:	$7.0\,\sigma$
expected:	$5.9\,\sigma$

probability to observe 7σ in the absence of a signal: 10^{-12}

$10^{-12} = (50\%)^{40}$ i.e. like flipping a coin 40 times and getting 40 heads

All analysed Higgs decays





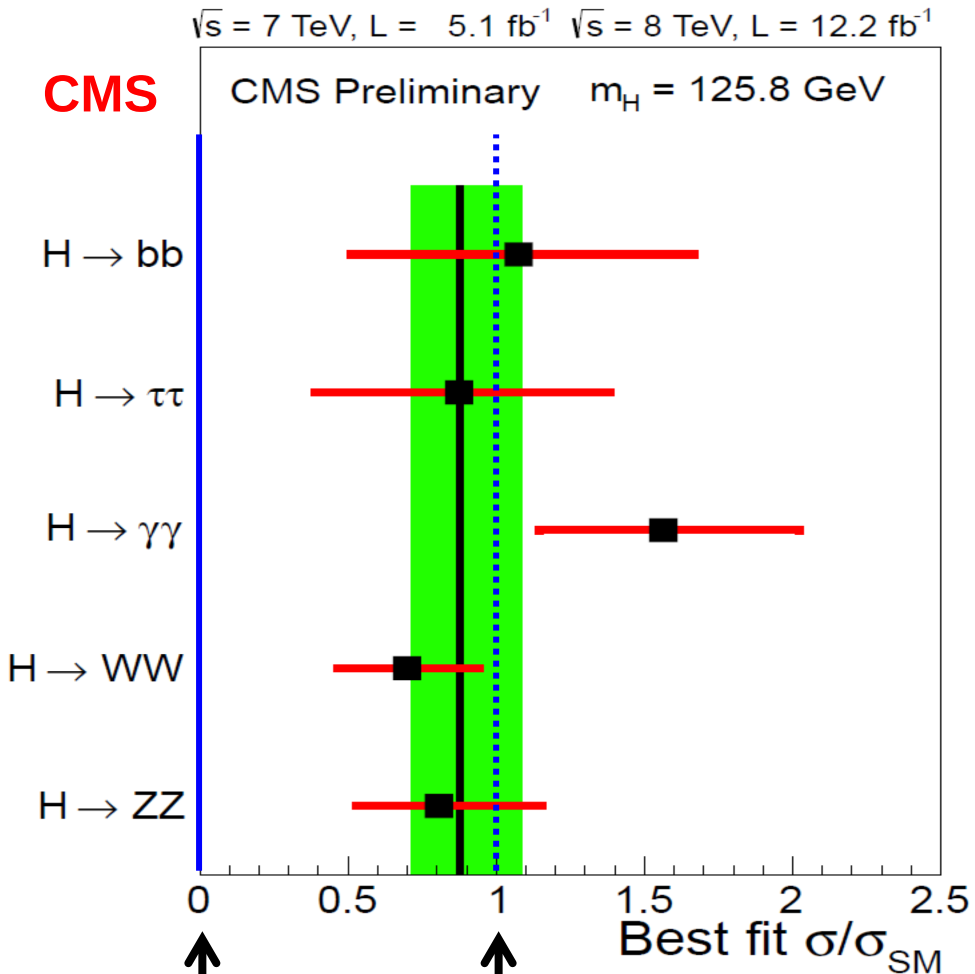
no Higgs

SM-Higgs

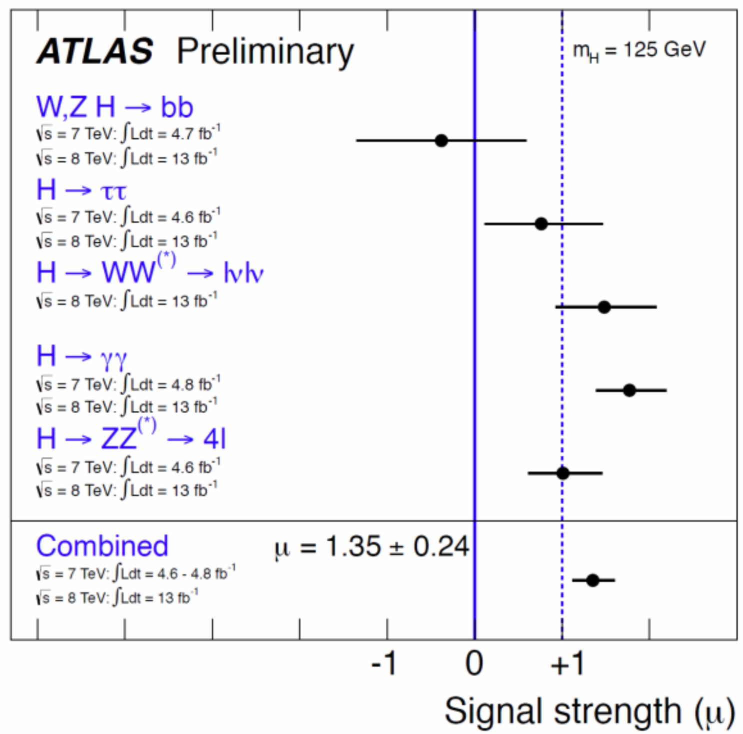
$$\mu = \frac{\sigma}{\sigma_{SM}} = 0.88 \pm 0.21$$

All analysed Higgs decays

CMS



ATLAS



error bars should be taken seriously!

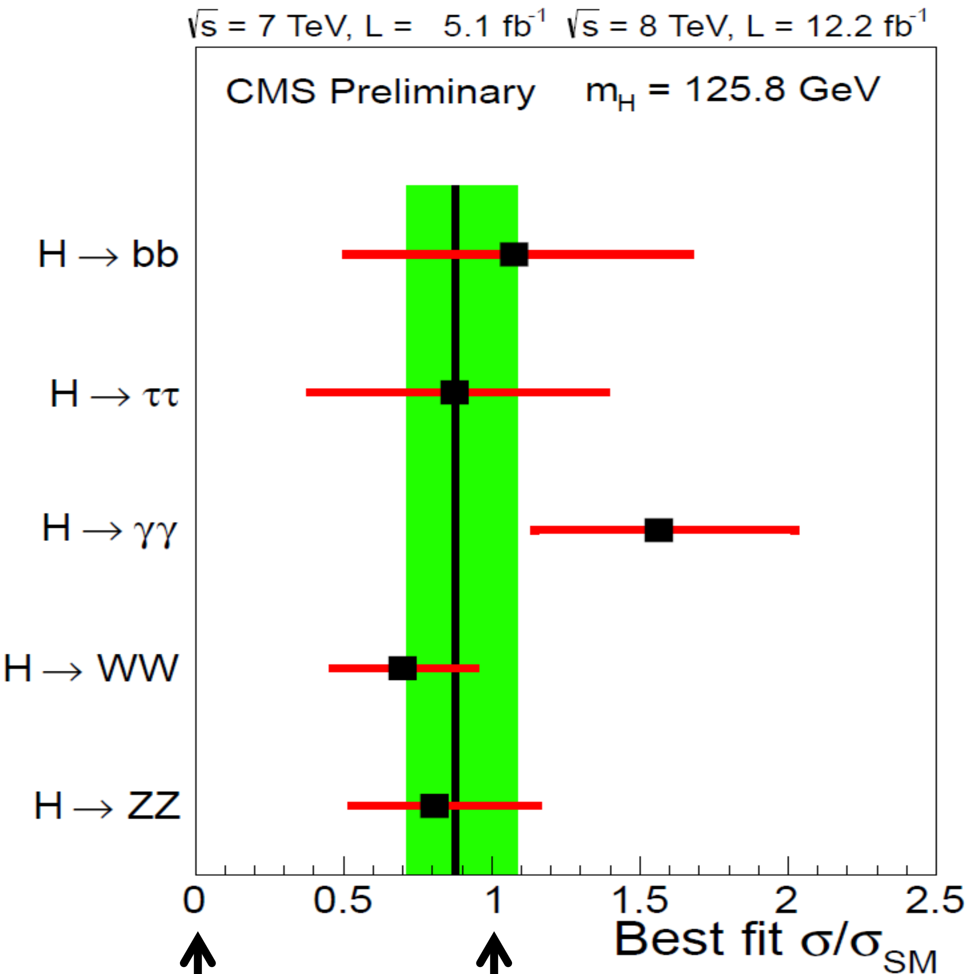
no Higgs

SM-Higgs

$$\mu = \frac{\sigma}{\sigma_{SM}} = 0.88 \pm 0.21$$

$$\hat{\mu} = 1.35 \pm 0.19\ (stat) \pm 0.15\ (syst)$$

All analysed Higgs decays



no Higgs

SM-Higgs

We have discovered a new particle!

Its mass is 125.8 ± 0.6 GeV.

It decays to $\gamma\gamma$

$\rightarrow$ spin 0 or 2

$\rightarrow$ its a boson

All known elementary particles are spin $1/2$ or 1

$\rightarrow$ a new kind of particle

Branching ratios as expected for SM Higgs

BUT: uncertainties are still large!

Need more data to find out what this new particle really is.

CERN Seminar 4. Juli 2012


Higgs-Teilchen
offenbar entdeckt
CMS
tagesschau 04.07.2012

RWTHAACHEN UNIVERSITY

CMS

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2012-220
2012/08/01

CMS-HIG-12-028

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration*

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 CMS experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$, and $\mathrm{b\bar{b}}$. An excess of events is observed above the expected background, 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 $125.3 \pm 0.4\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

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.

ATLAS

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS

CERN-PH-EP-2012-218
Accepted by: Physics Letters B

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

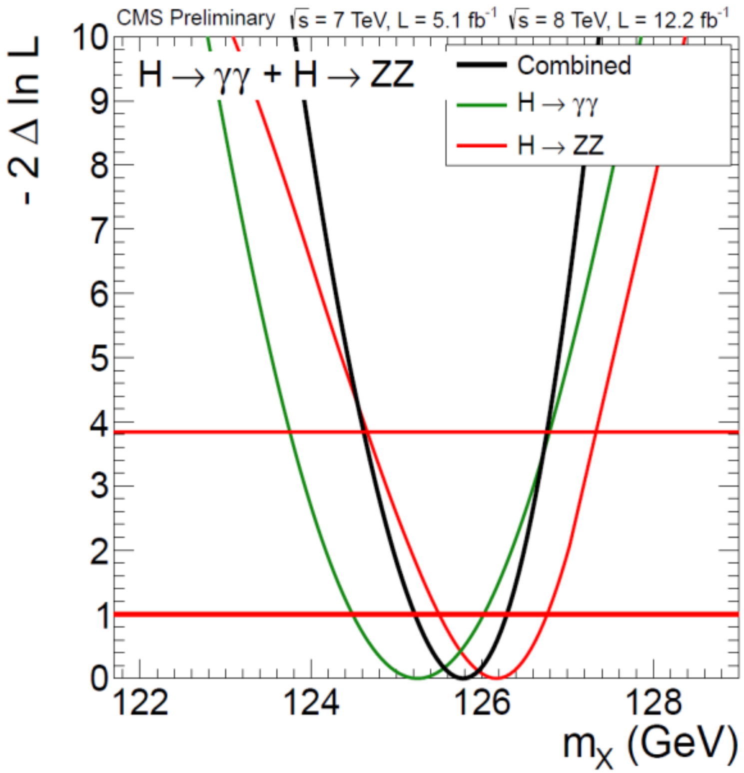
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Abstract

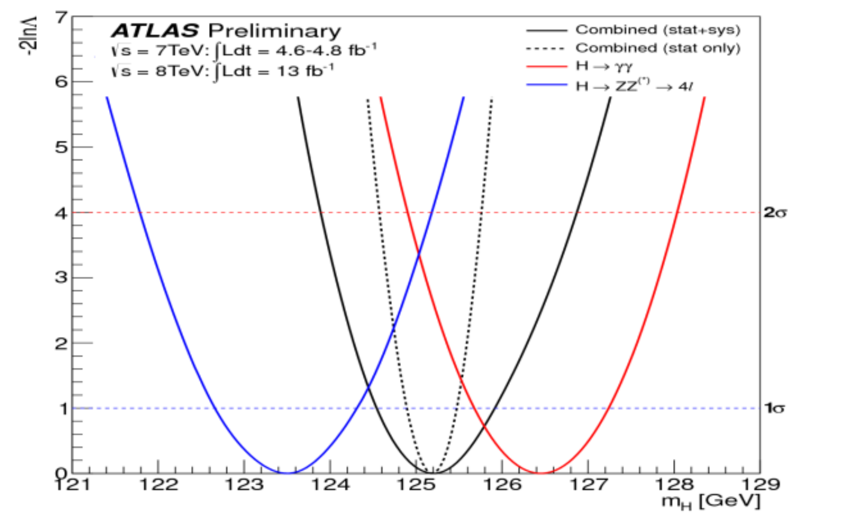
A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H\to ZZ^{(*)}\to 4\ell$, $H\to\gamma\gamma$ and $H\to WW^{(*)}\to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H\to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H\to ZZ^{(*)}\to 4\ell$ and $H\to\gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\,(\mathrm{stat}) \pm 0.4\,(\mathrm{sys})$ GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Observed Mass

CMS



ATLAS

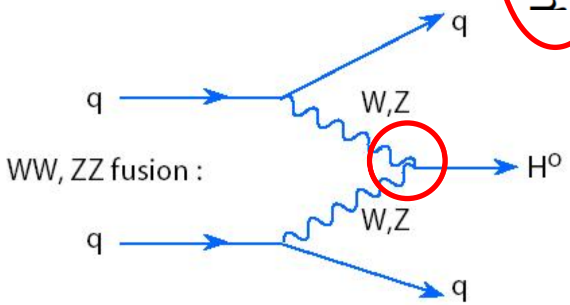


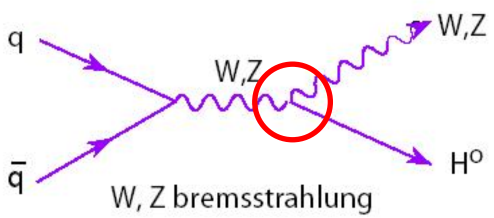
← 2.7σ disagreement →

Mass M = 125.8 ± 0.4 (stat) ± 0.4 (syst) GeV

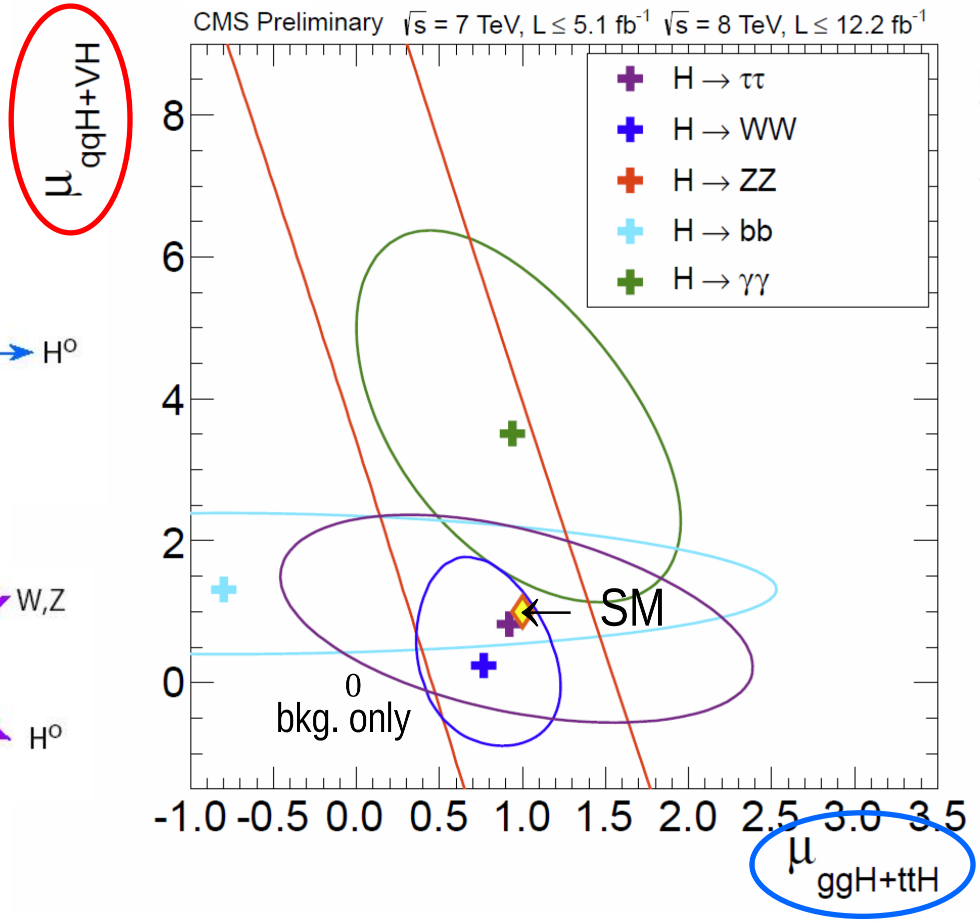
$$m_H = 125.2 \pm 0.3\ (stat)\ \pm\ 0.6\ (syst)\ \text{GeV}$$

Couplings

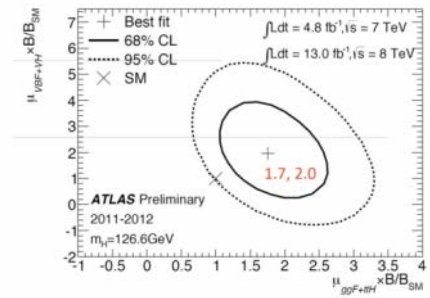




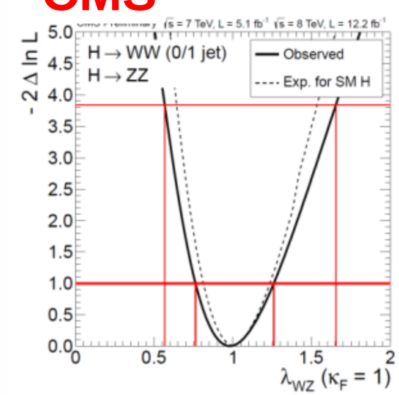
CMS



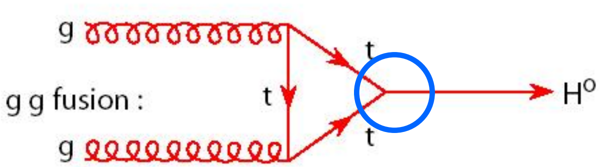
ATLAS

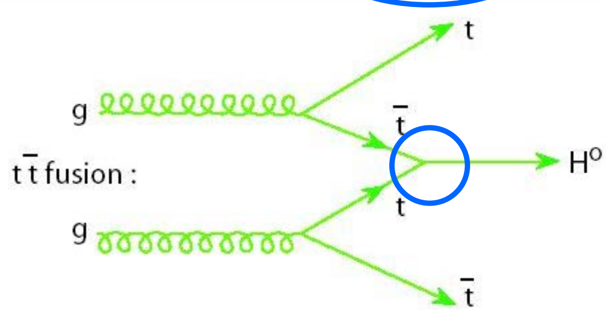


CMS

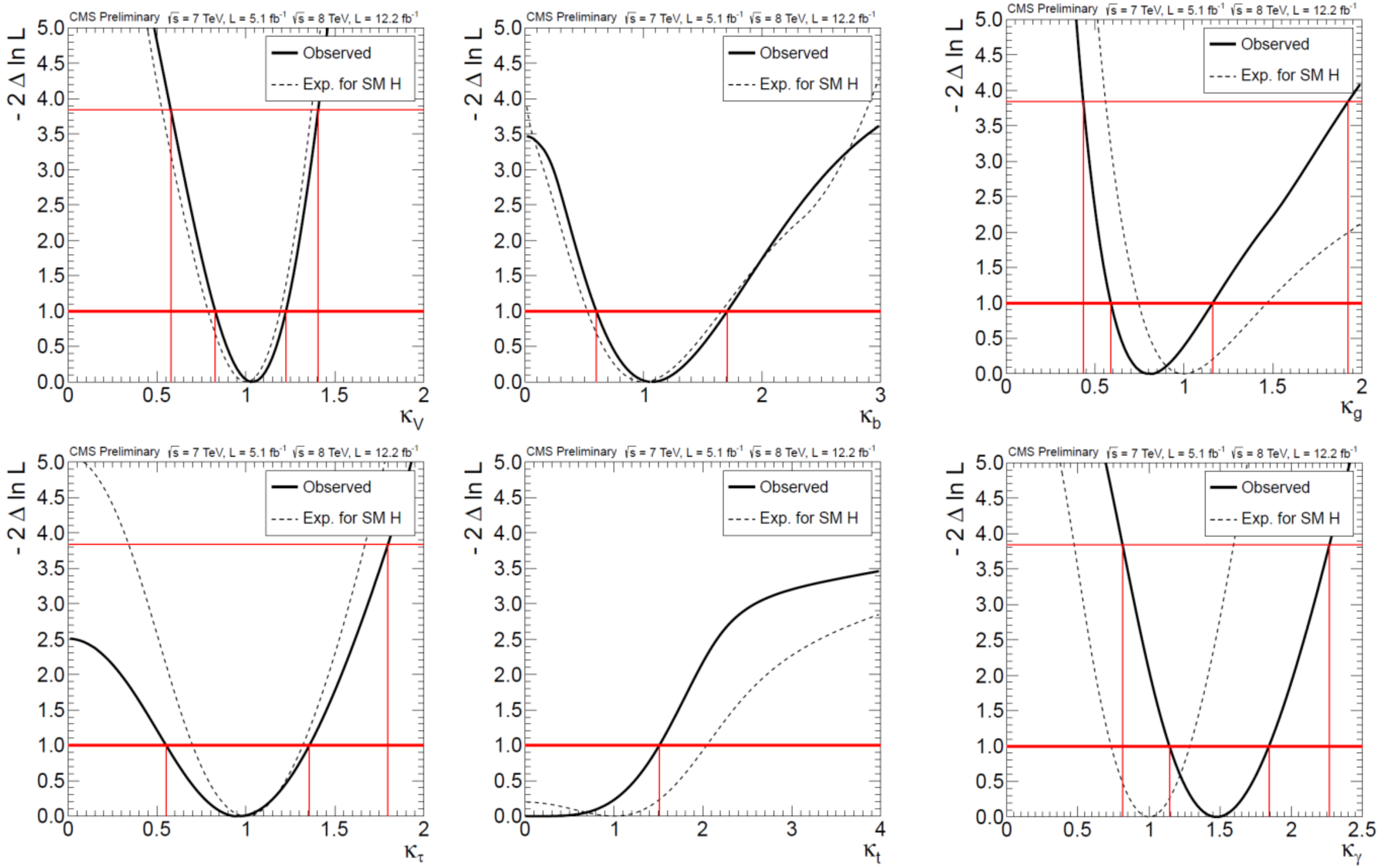


relative coupling to Z and W
as expected (custodial symmetry)





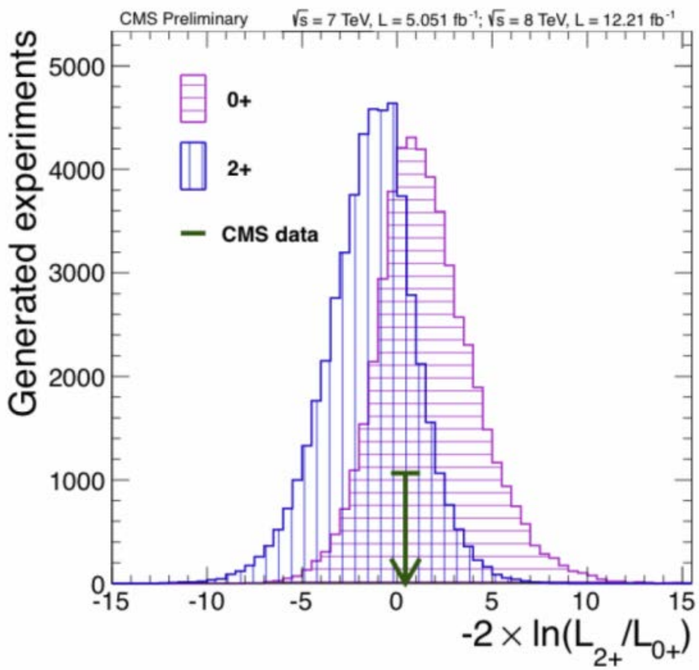
Couplings


CMS Preliminary √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 12.2 fb-1
Observed
Exp. for SM H
- 2 Δ ln L
κV
κb
κg
κτ
κt
κγ

Spin

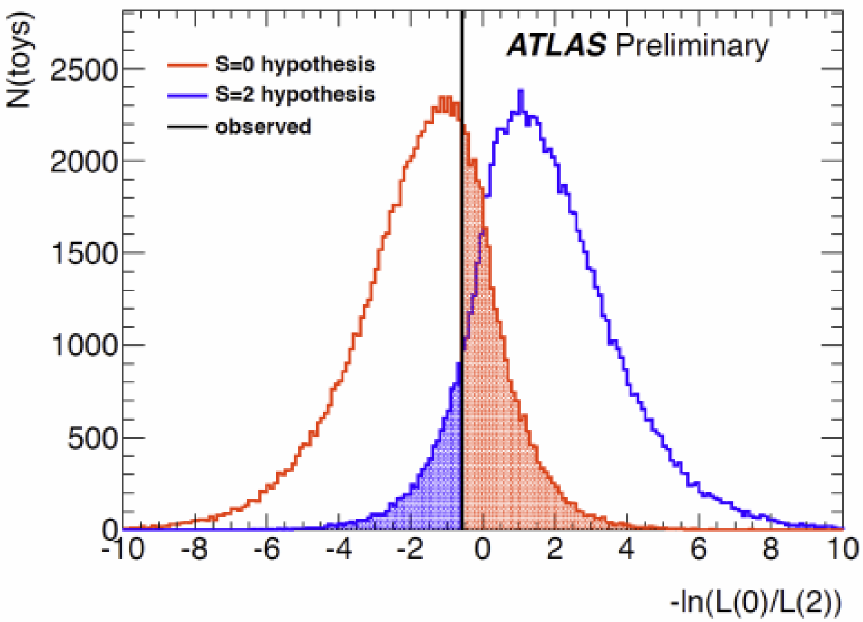
CMS

From lepton angles in $H \to ZZ \to 4l$:



ATLAS

Look at photon angle (Collins-Soper-Frame) in the channel $H \to \gamma\gamma$:



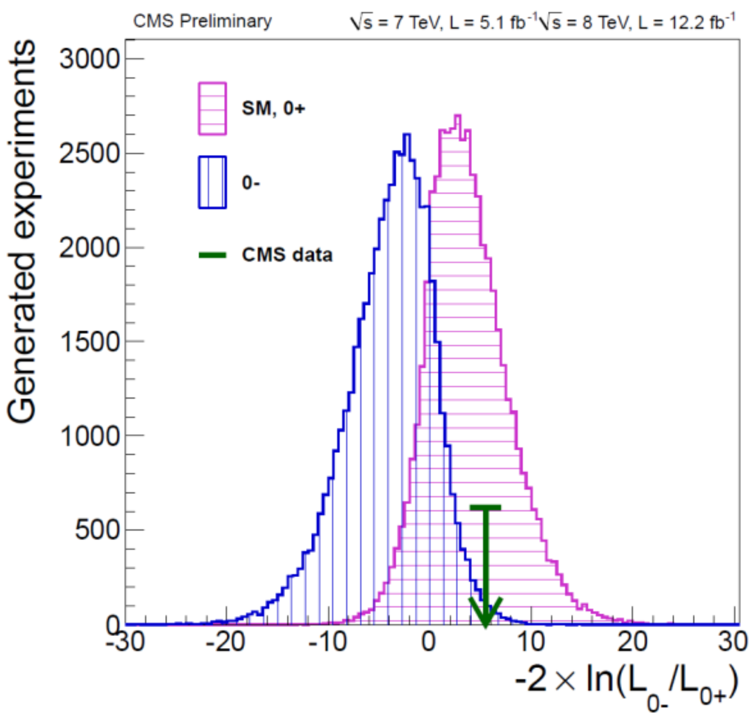
exclusion of spin 2^+ at 91% CL

Parity

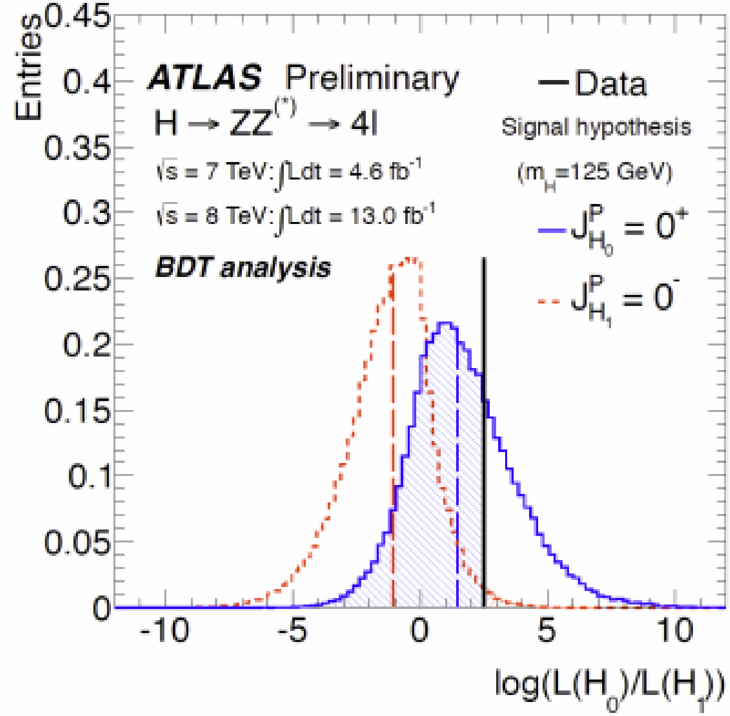
Look at kinematic correlations between the 4 leptons in the channel $H \to ZZ \to 4l$.

N.B. observation of this channel already implies that H cannot be a pure pseudo-scalar.

CMS



ATLAS

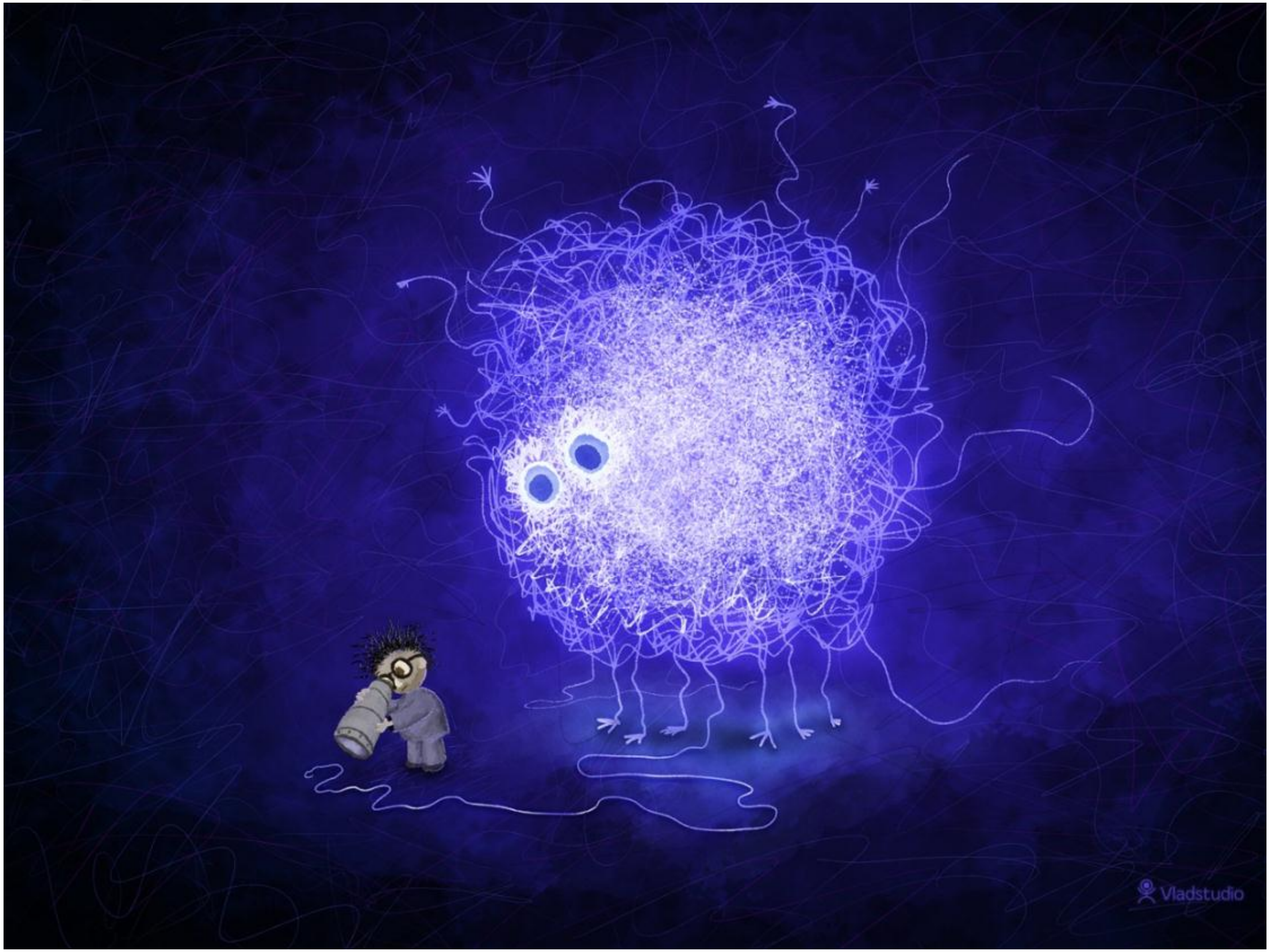


pure pseudo-scalar in fact excluded at 98%-99% CL

consistent with pure scalar state

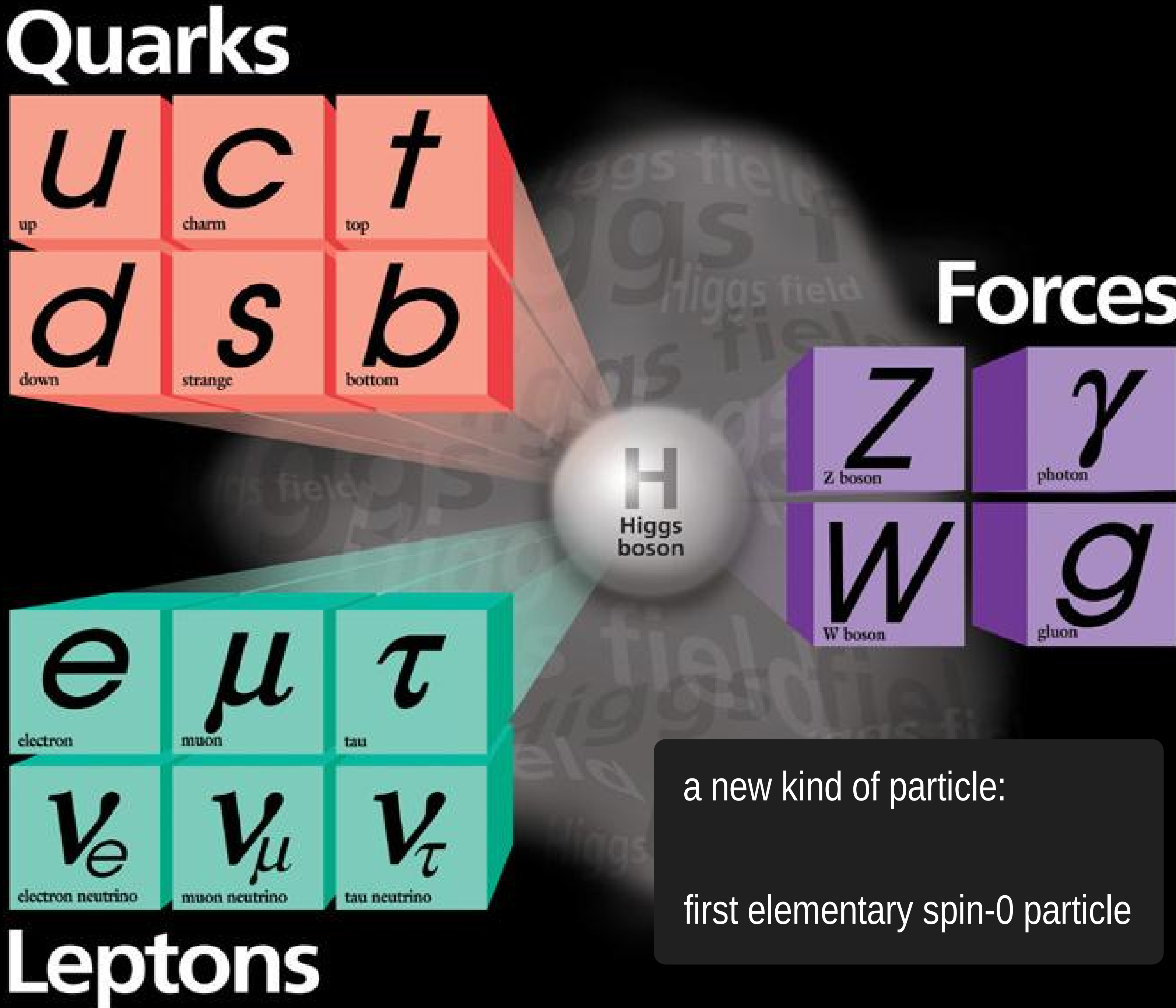
still room for a mixture and CP violation in the higgs sector

Implications



If the new boson is the/a higgs boson,

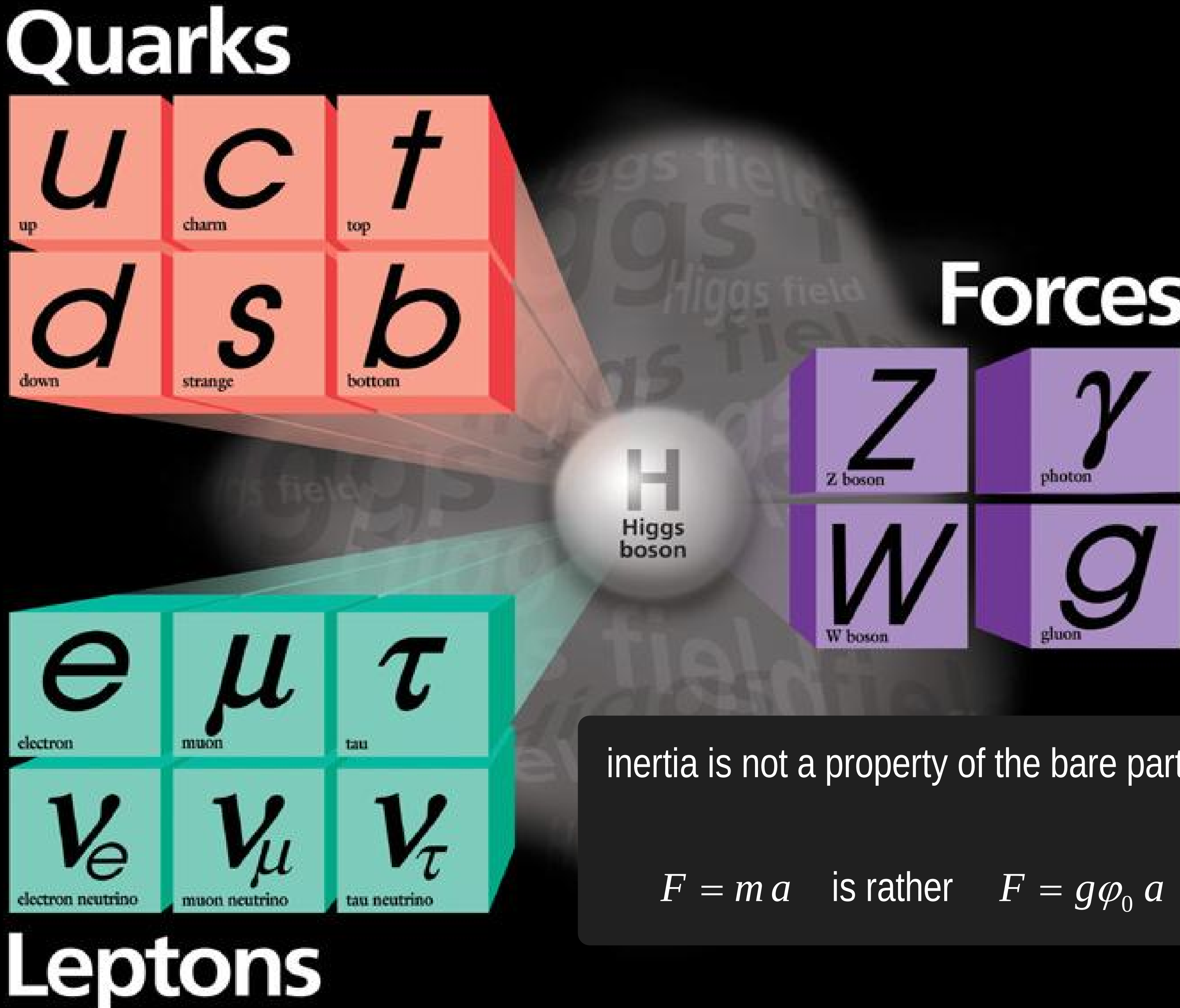
i.e. a scalar, related to spontaneous breaking of electroweak symmetry …



a new kind of particle:

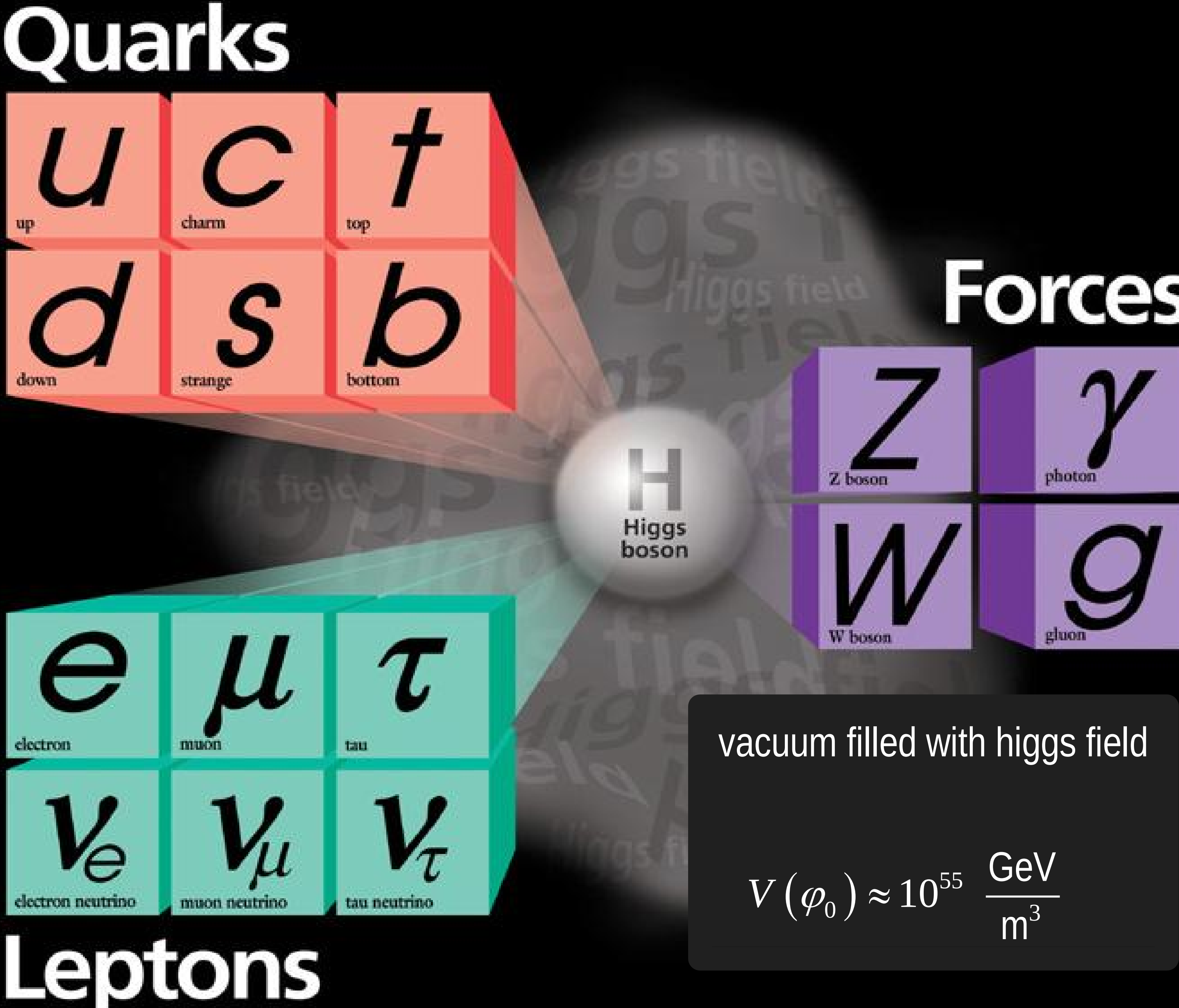
first elementary spin-0 particle

[Fermilab Visual Media Services]



inertia is not a property of the bare particles

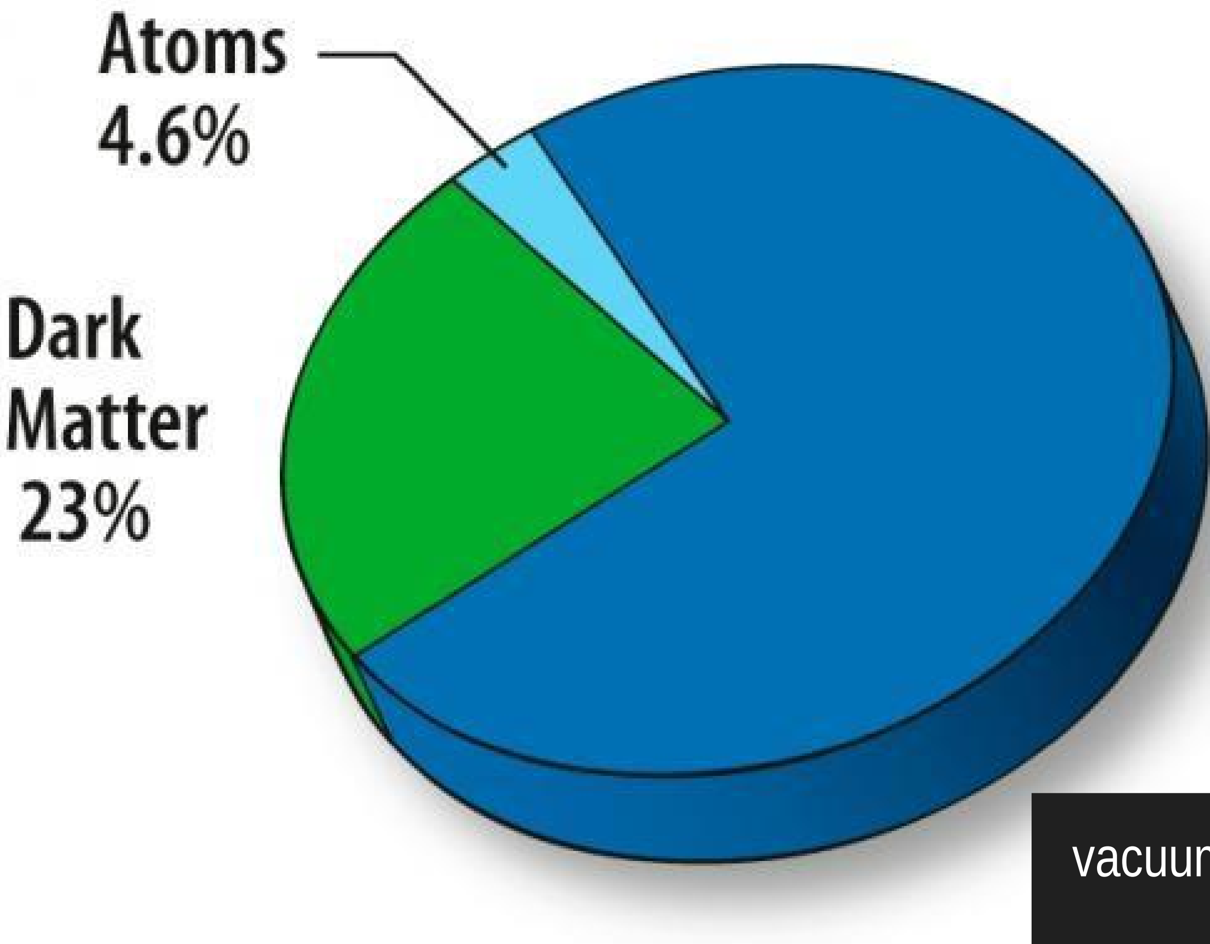
$F = m\,a$ is rather $F = g\varphi_0\, a$



vacuum filled with higgs field

$$V\left(\varphi_0\right) \approx 10^{55}\ \frac{\mathrm{GeV}}{\mathrm{m}^3}$$

[Fermilab Visual Media Services]



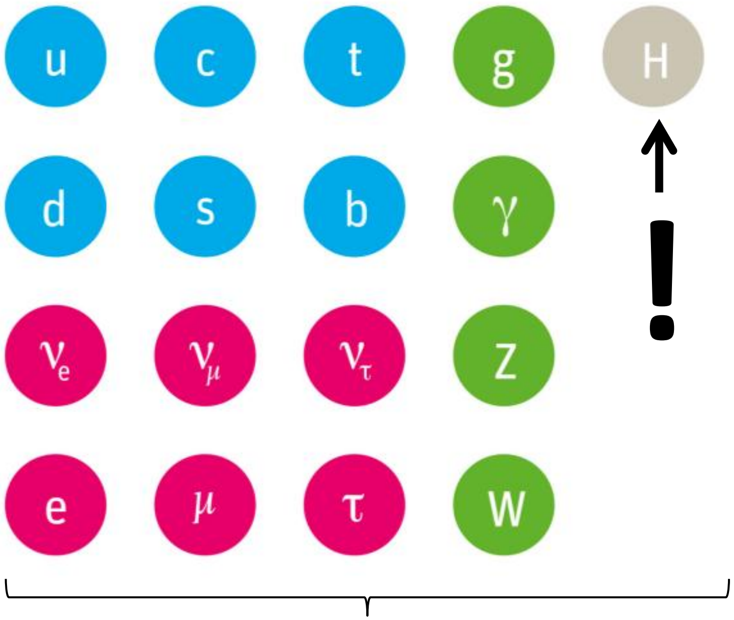
$$5\ \frac{\text{GeV}}{\text{m}^3}\quad (!)$$

if there is a higgs field
then there might be more
scalar fields around...
(link to inflation?)

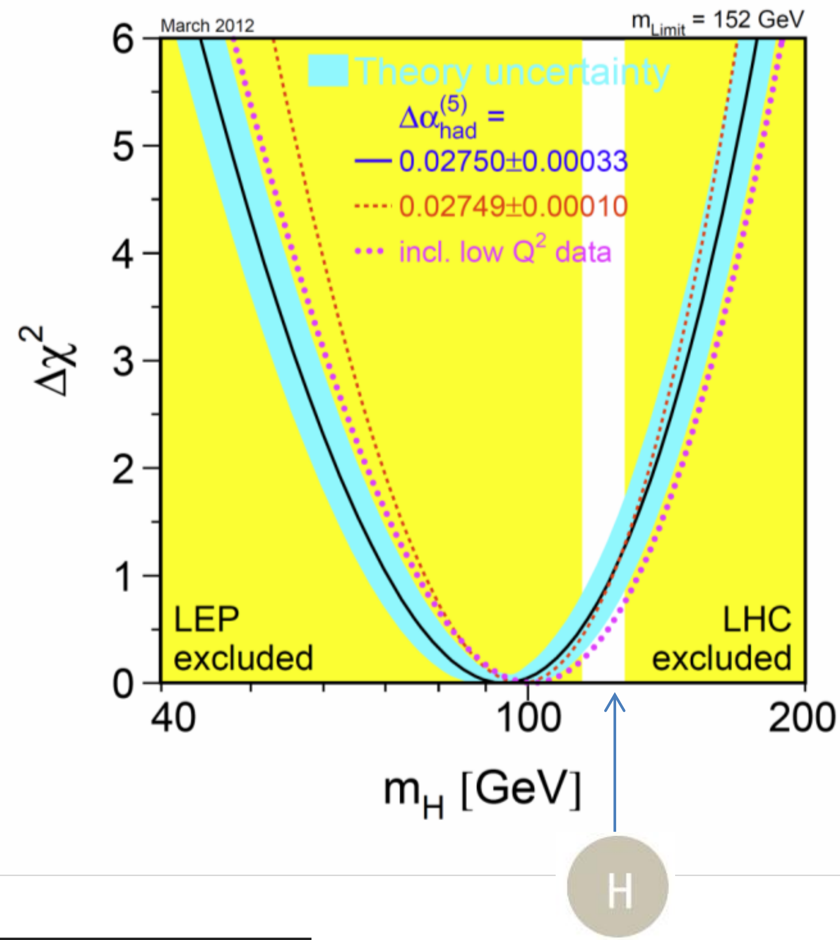
vacuum filled with higgs field

$$V(\varphi_0) \approx 10^{55}\ \frac{\text{GeV}}{\text{m}^3}$$

[Fermilab Visual Media Services]

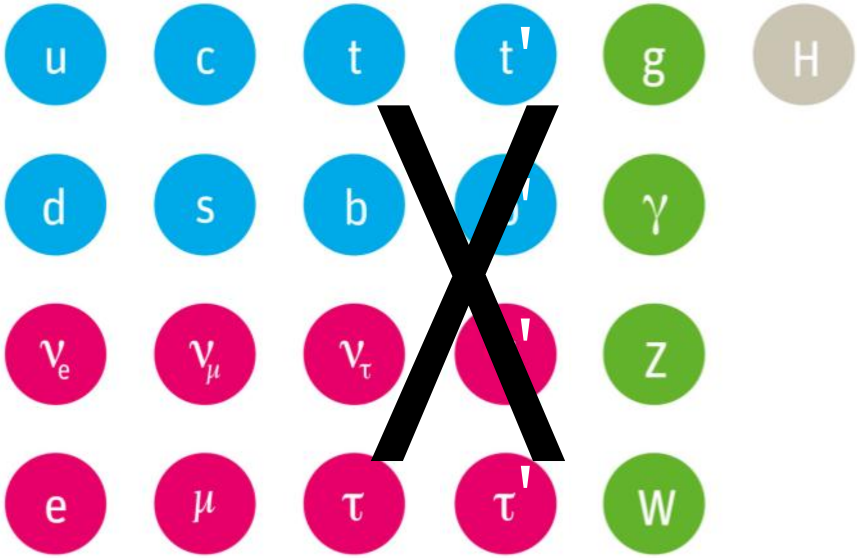


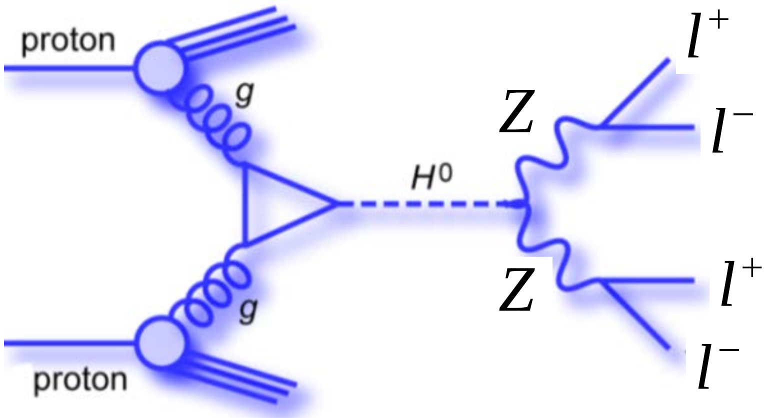
experimentally established



Standard Model is complete!

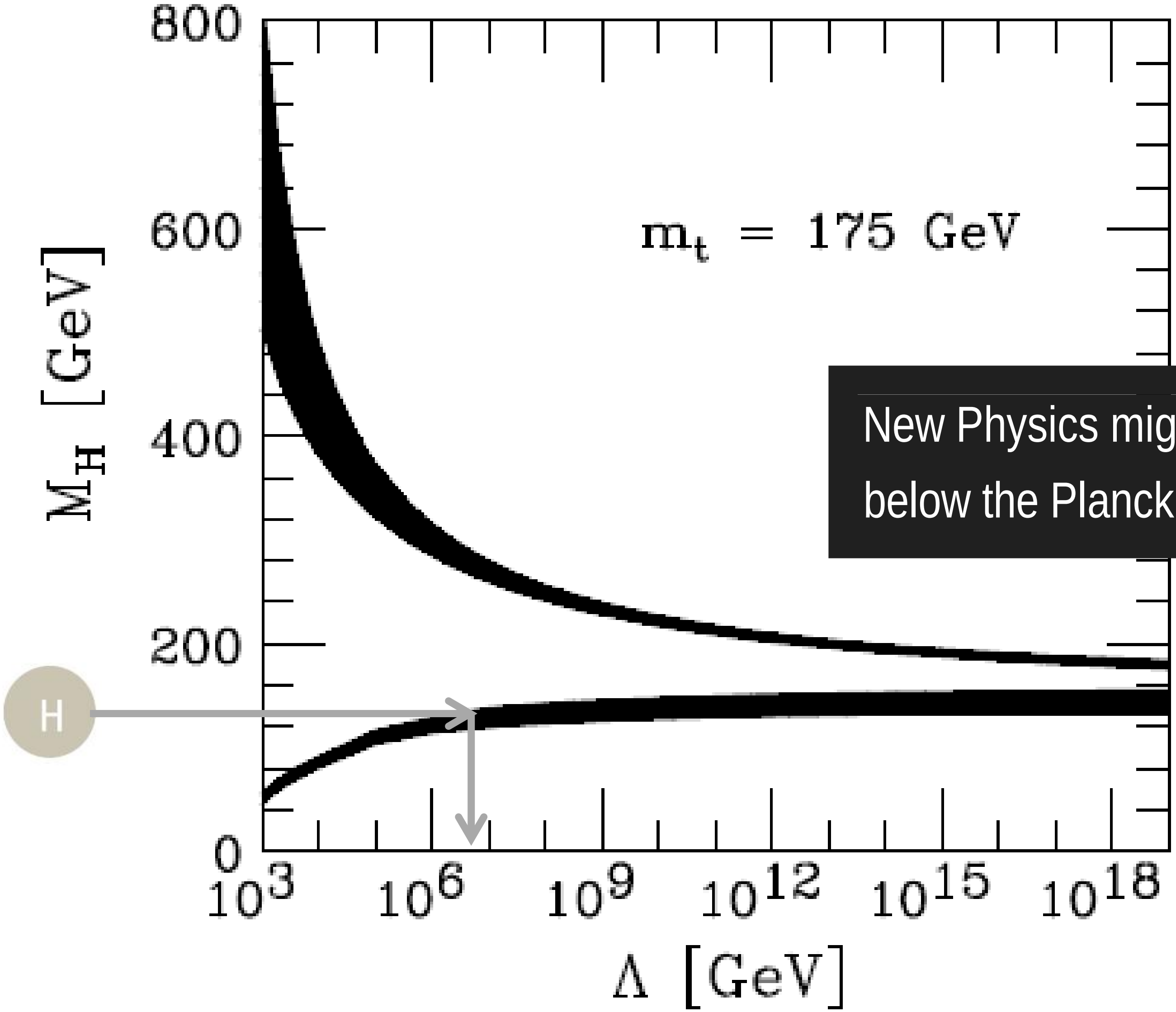
And it fits well!



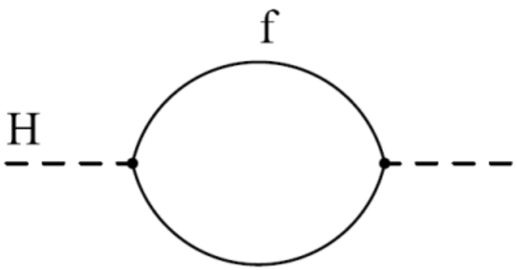


A 4th fermion generation is excluded!

Also: not a lot of room for other new physics in the loop ...

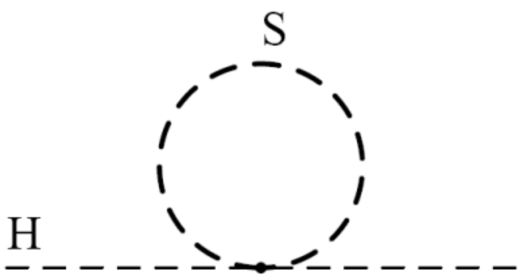


New Physics might appear well below the Planck scale!



$$M_H^2 = M_0^2 - \frac{|\lambda_t|^2}{8\pi^2}\left(\Lambda^2 + m_t^2\right) + O\left(\ln\frac{\Lambda^2}{m_t^2}\right)$$

Discovery of the higgs boson poses the hierarchy problem



$$M_H^2 = M_0^2 + \frac{\lambda_S}{16\pi^2}\left(\Lambda^2 + m_S^2\right) + O\left(\ln\frac{\Lambda^2}{m_t^2}\right)$$

Supersymmetry!

SUSY can explain the origin of spontaneous symmetry breaking

N.B. $M_H \gg 130$ GeV would have been incompatible with SUSY

... but maybe what we see is yet something else ...

Summary

2010-2012:

p p collisions:	6'000'000'000'000'000
recorded by ATLAS and CMS:	10'000'000'000
higgs bosons produced:	800'000
higgs boson candidates: around	400

a new boson has been discovered

7σ significance per experiment

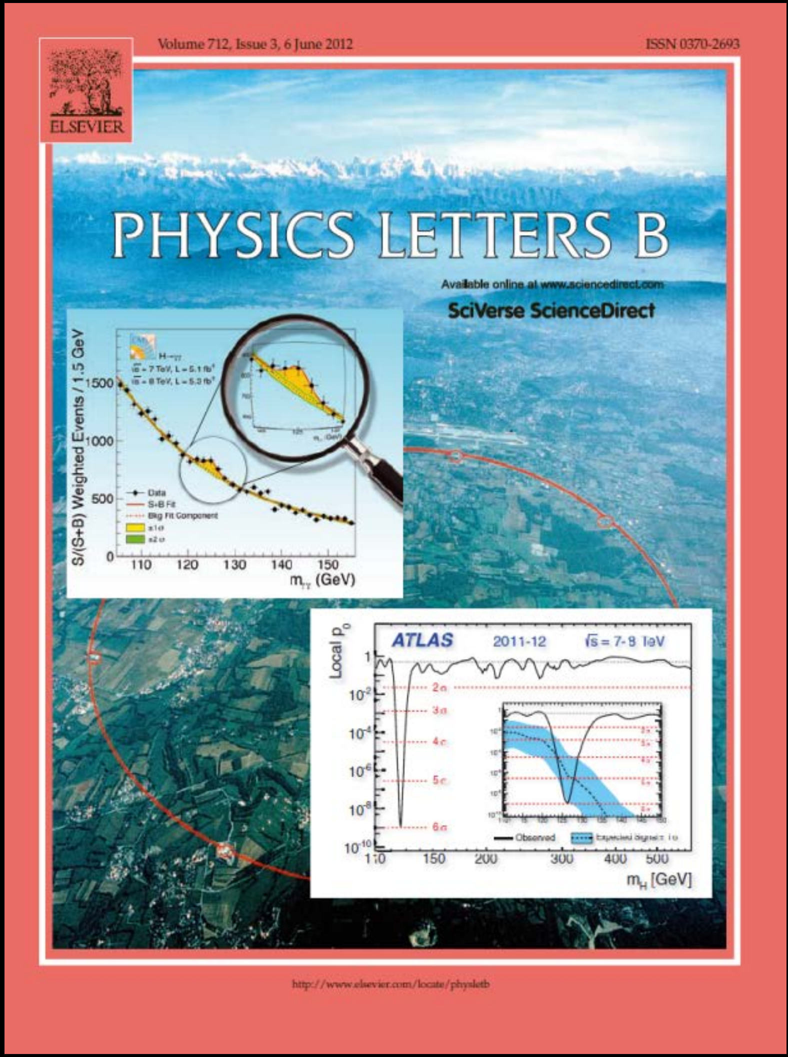
$M = 126$ GeV with 0.5% uncertainty

LHC has achieved one of its two main goals:

we have found

either the **higgs boson**

or **new physics**



2013/14: LHC shut-down

2015 ... a lot more data at $13.x$ TeV to study our new friend in detail

Additional Material

CMS Projection