Reflexões sobre a Descoberta do Bóson de Higgs

S. F. Novaes

1911 1974 1995

1932 1948 1977

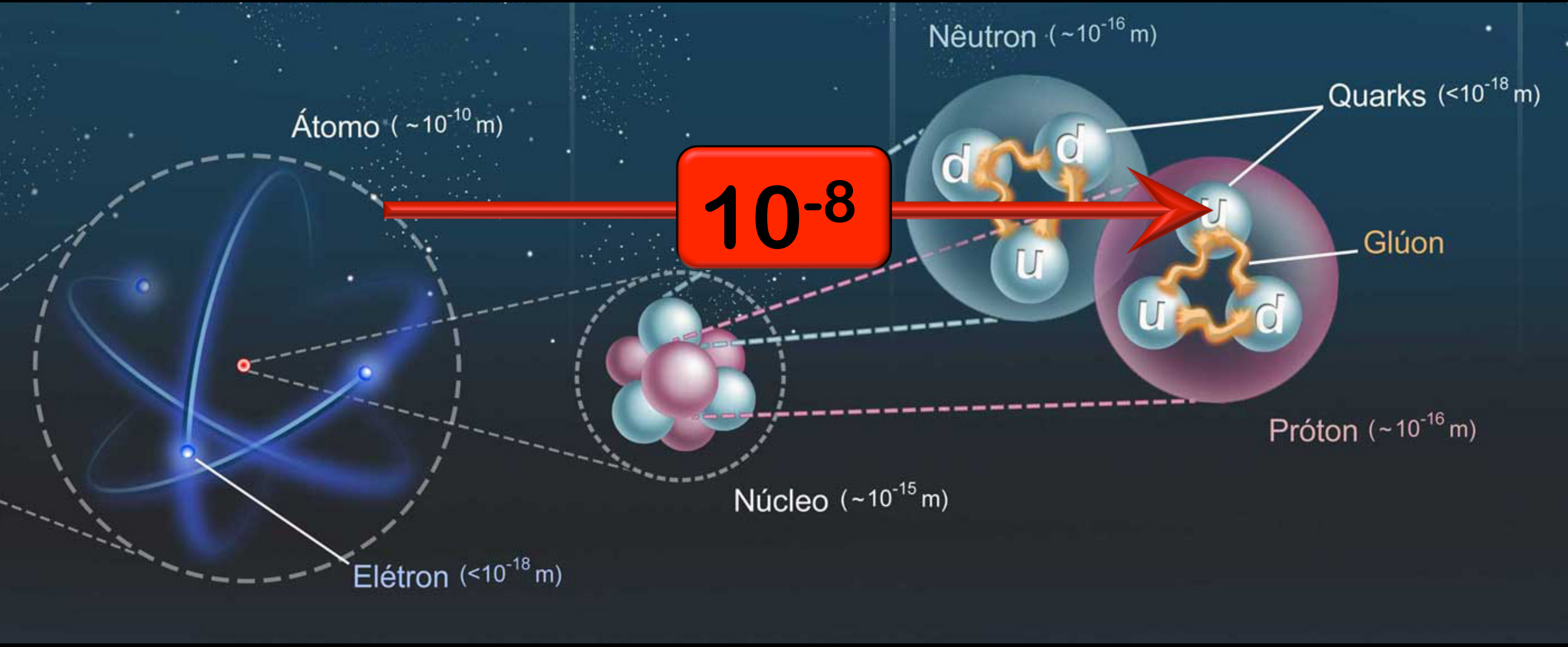
1905

1983

1979

1897 1937 1975

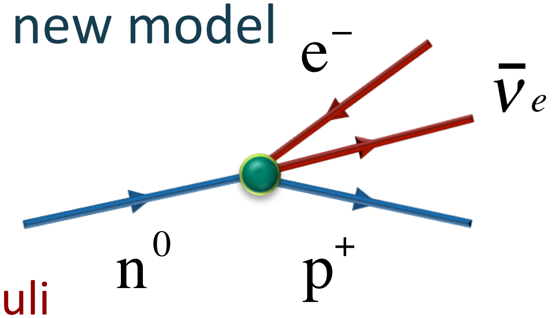
1934 1962 2000



Nêutron (~10^-16 m)
Quarks (<10^-18 m)
Átomo (~10^-10 m)
10^-8
d
d
u
u
u
d
Glúon
Próton (~10^-16 m)
Núcleo (~10^-15 m)
Elétron (<10^-18 m)

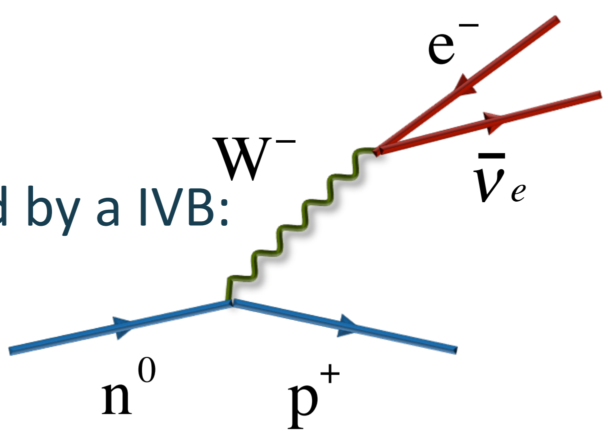
Constructing a Theory

- Quantum Electrodynamics (QED)
  - Foundations established by Dirac in 1927
  - Astonishing agreement with the experimental results
    - The best theory we have!
  - Became a prototype for the construction of new model
- Weak Interactions
  - Fermi proposes the first field theory description of the beta decay in 1934
    - Employs the neutrino recently proposed by Pauli
    - Loosely inspired by QED



$$L = \frac{G_F}{\sqrt{2}} \left(\bar{\psi}_p \gamma_\mu \psi_n\right)\left(\bar{\psi}_e \gamma^\mu \psi_\nu\right)$$

  - Schwinger (1957): Interaction is transmitted by a IVB:
    - Charged: charge-changing currents.
    - Very massive: short range



Further Developments

- Very successful after some improvements:
  - (V – A) structure (Lee & Yang, Wu, Feynman & Gell-Mann)
  - Strangeness (Cabibbo)
  - Quark model (Gell-Mann & Zweig)
- Describes very-well the low energy phenomena
  - However the theory violates unitarity for E ~ 500 GeV
  - Theory becomes inconsistent
- Several attempts to construct a consistent model:
  - Glashow (1961):
    - Describe weak and electromagnetic interactions in a unified way
    - First introduction of the neutral intermediate weak boson Z^0
    - The vector boson mass was introduced by hand
      - Theory was **not** renormalizable!

On the Spontaneous Symmetry Breaking

- Goldstone Theorem
  - When an exact continuous global symmetry is spontaneously broken, i.e. it is not a symmetry of the physical vacuum, the theory contains one massless scalar particle for each broken generator of the original symmetry group.

$$G(N) \to g(n)$$
$$\Downarrow$$
$$(N-n)\,GB$$

  - The unavoidable GB prevented the use of the SSB
  - A solid field theory result
    - ❑ Proven by Goldstone, Salam, Weinberg (1961)
    - ❑ Rigorous algebraic proof by Kastler, Robinson and Swieca (1962).

Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism

- 1964
  Example of a field theory with spontaneous symmetry breakdown, no massless GB, and massive vector boson
  - F. Englert and R. Brout,
    - Phys. Rev. Lett.13, 321-323 (26/Jun/1964)
  - P. W. Higgs,
    - Phys. Lett. 12, 132-133 (27/Jul/64)
  - Peter W. Higgs,
    - Phys. Rev. Lett.13, 508-509 (31/Aug/1964)
      - First version was rejected in Phys. Lett. B
      - Nambu was the referee
  - G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble,
    - Phys. Rev. Lett. 13, 585-587 (12/Oct/1964)

Impact on the Community

- Skepticism Everywhere
  - "They had been looking forward to tearing apart this idiot who thought he could get around the Goldstone theorem."

Sidney Coleman to Peter Higgs
about his seminar at Harvard in 1965

  - "Heisenberg and the many other senior physicists at the Munich conference thought these ideas were junk, and let me know with much enthusiasm that they felt that way."

Guralnik, IJMPA (2009)

- Dubious Utility
  - "My Princeton and Harvard seminars … clearly failed to persuade them that the combination of gauge theories and spontaneous symmetry breaking might be useful."
  - "Brout, Englert and I tried fruitless to find an application in hadronic flavour symmetry breaking."

Peter Higgs, IJMPA (2002)

The Breakthrough

- "At some point in the fall of 1967, I think while driving to my office at MIT, it occurred to me that I had been applying the right ideas to the wrong problem. It is not the ρ meson that is massless: it is the photon. And its partner is not the A_1, but the massive intermediate bosons, which since the time of Yukawa had been suspected to be the mediators of the weak interactions."

Steve Weinberg, Nobel Lecture (1980)

- "A model similar to ours was discussed by S. Glashow (1961); the chief difference is that Glashow introduces symmetry-breaking terms into the Lagrangian, and therefore gets less definite predictions."
- "Of course our model has too many arbitrary features for these predictions to be taken very seriously, but … "

Steve Weinberg, PRL 1967

The Model

- 1967
  - Weinberg:
    - Takes exactly the Glashow model
    - Adds the concept of SSB and Higgs mechanism
    - Estimation of W and Z masses
    - Suggests way to verify the existence of neutral currents

- "The weak and electromagnetic interactions could then be described in a unified way in terms of an exact but spontaneously broken gauge symmetry. And this theory would be renormalizable like quantum electrodynamics because it is gauge invariant like quantum electrodynamics."

  Steve Weinberg, Nobel Lecture (1980)

- Formulation of Standard Model
  - Led to 45 years of experiments and to the construction of 9 accelerators:
    - ISR, PETRA, SppS, TRISTAN, Tevatron, LEP, SLC, HERA, LHC, …

Following Years: Success

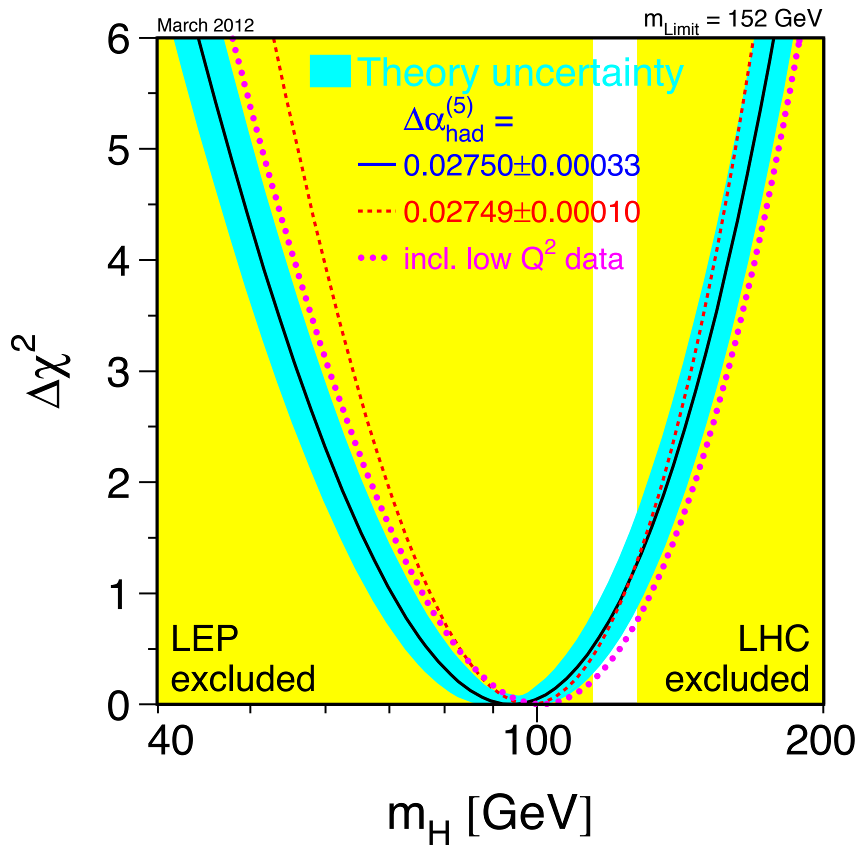
- 1970
  - Glashow, Iliopoulos and Maiani
    - ❑ Proposal of charmed quark (GIM mechanism)
- 1971
  - 't Hooft:
    - ❑ Proof of renormalizability of Yang-Mills theory with SSB invariance
- 1973 / 1974
  - Hasert et al. (CERN)
    - ❑ Experimental indication of the existence of weak neutral currents.
  - Benvenuti et al. (Fermilab):
    - ❑ Confirmation of the existence of weak neutral currents
- 1983
  - Arnison et al. (UA1 Collab.) and Banner et al. (UA2 Collab.):
    - ❑ Discovery of W and Z produced in proton-antiproton collisions

Meanwhile: The Hunt Starts

- 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, … 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.

Ellis, Gaillard, Nanopoulos (1976)

The Era LEP: A Decade of Precision Tests



17 parameters measured

Hint of a light Higgs boson

Reproduces the low energy phenomenology.
The amplitudes respect unitarity bounds.
GIM mechanism requires family structure.
CP violation described by the CKM matrix.

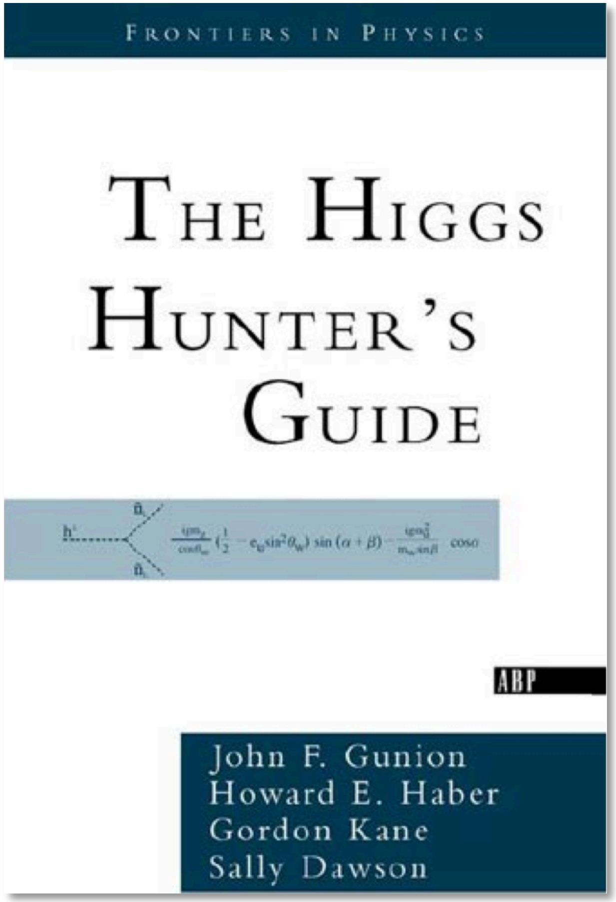
Predicts weak interaction via neutral current.

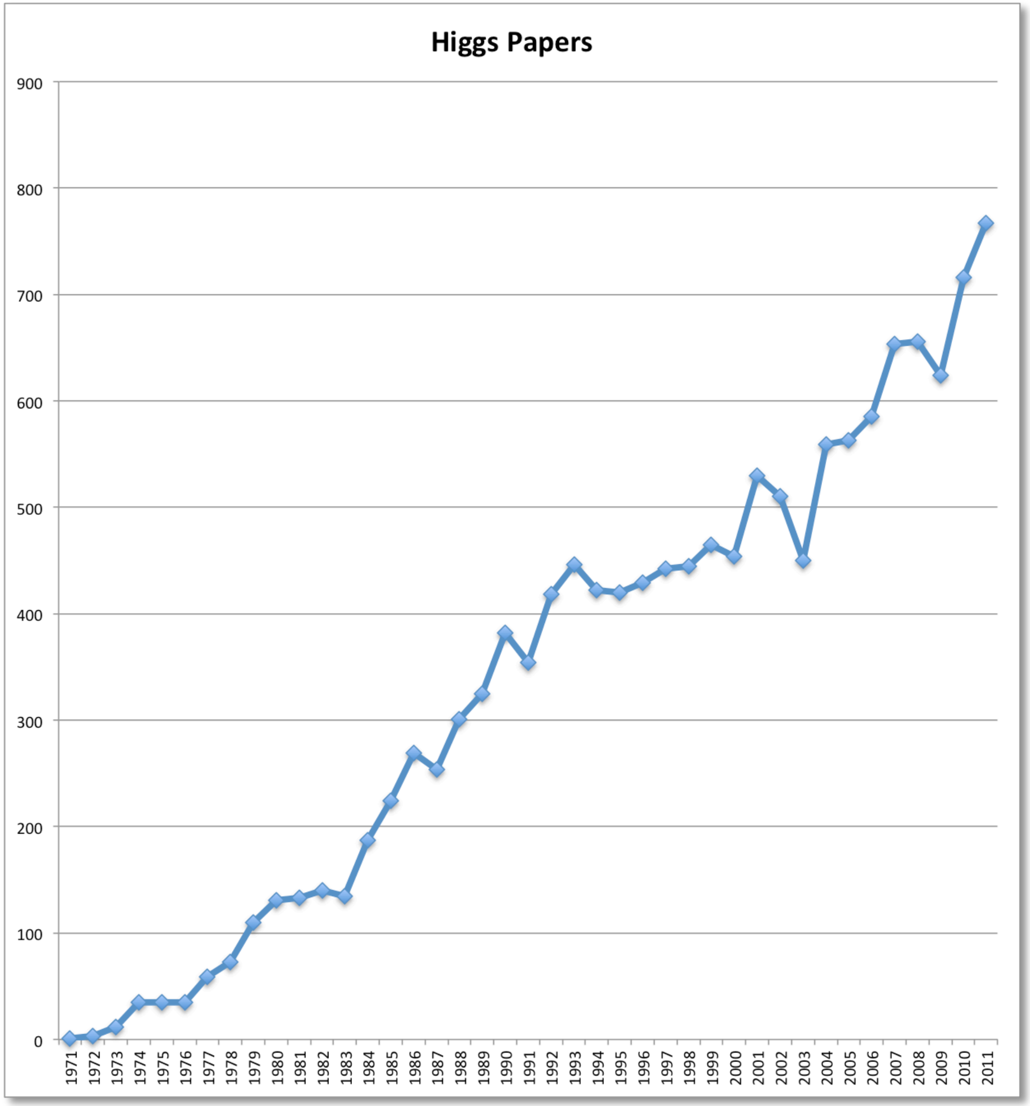
Predicts the mass of the vector bosons (W and Z).

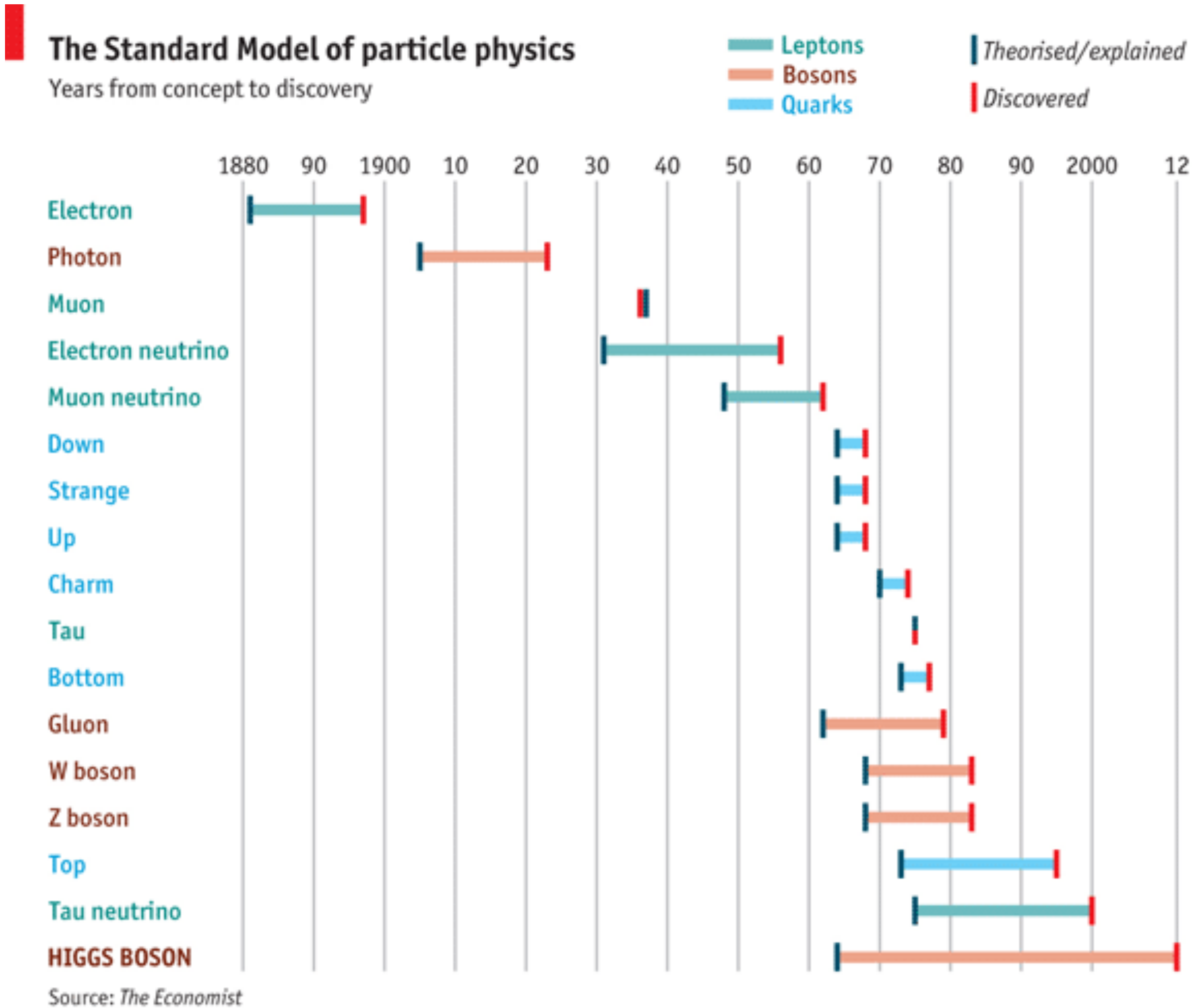
Predicts the existence of at least one Higgs boson.

Existence of W and Z were confirmed.
The existence of three families was established.
CP violation found also in the third generation.
Just the Higgs boson was missing!

A Long Journey







The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
Source: The Economist

Hunting the Higgs Boson

- On the top of the Glashow model, a SSB potential is added:

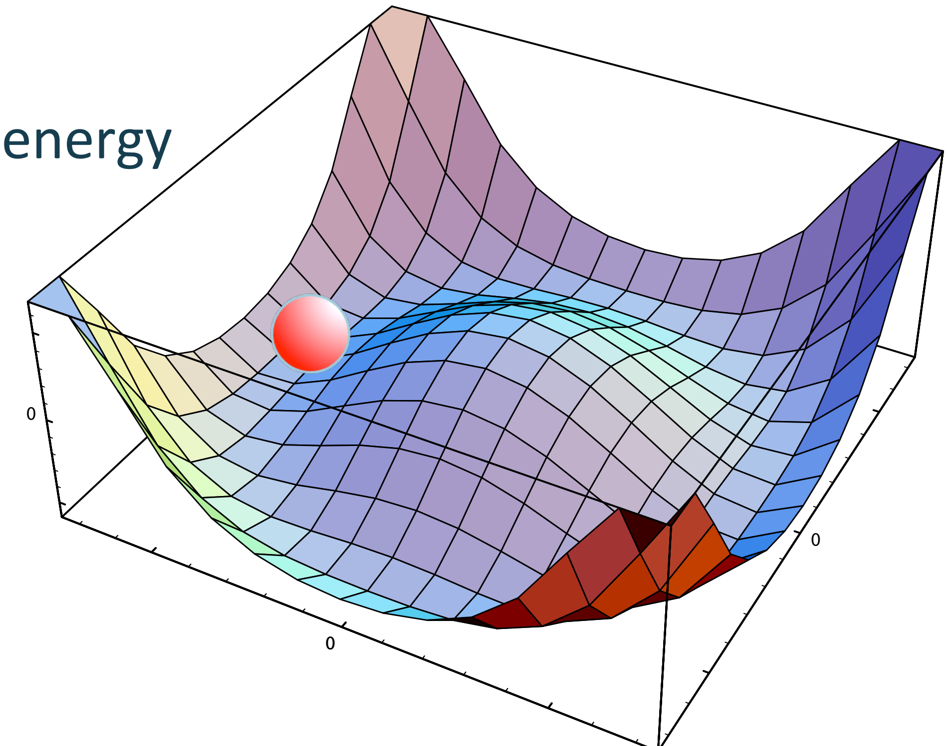
$$V\left(\phi^\dagger\phi\right) = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

- Ratio is determined by low energy

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

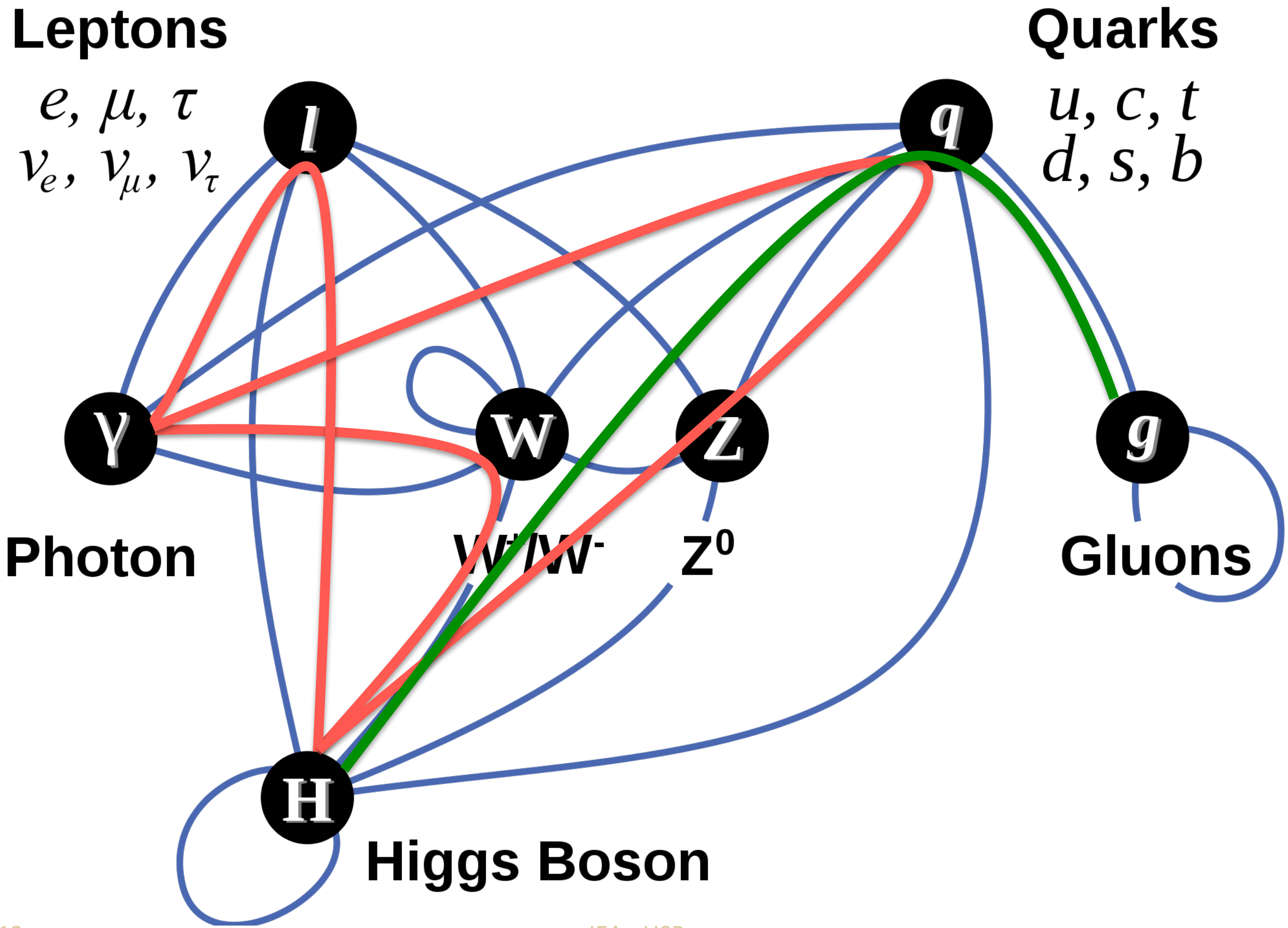
- However

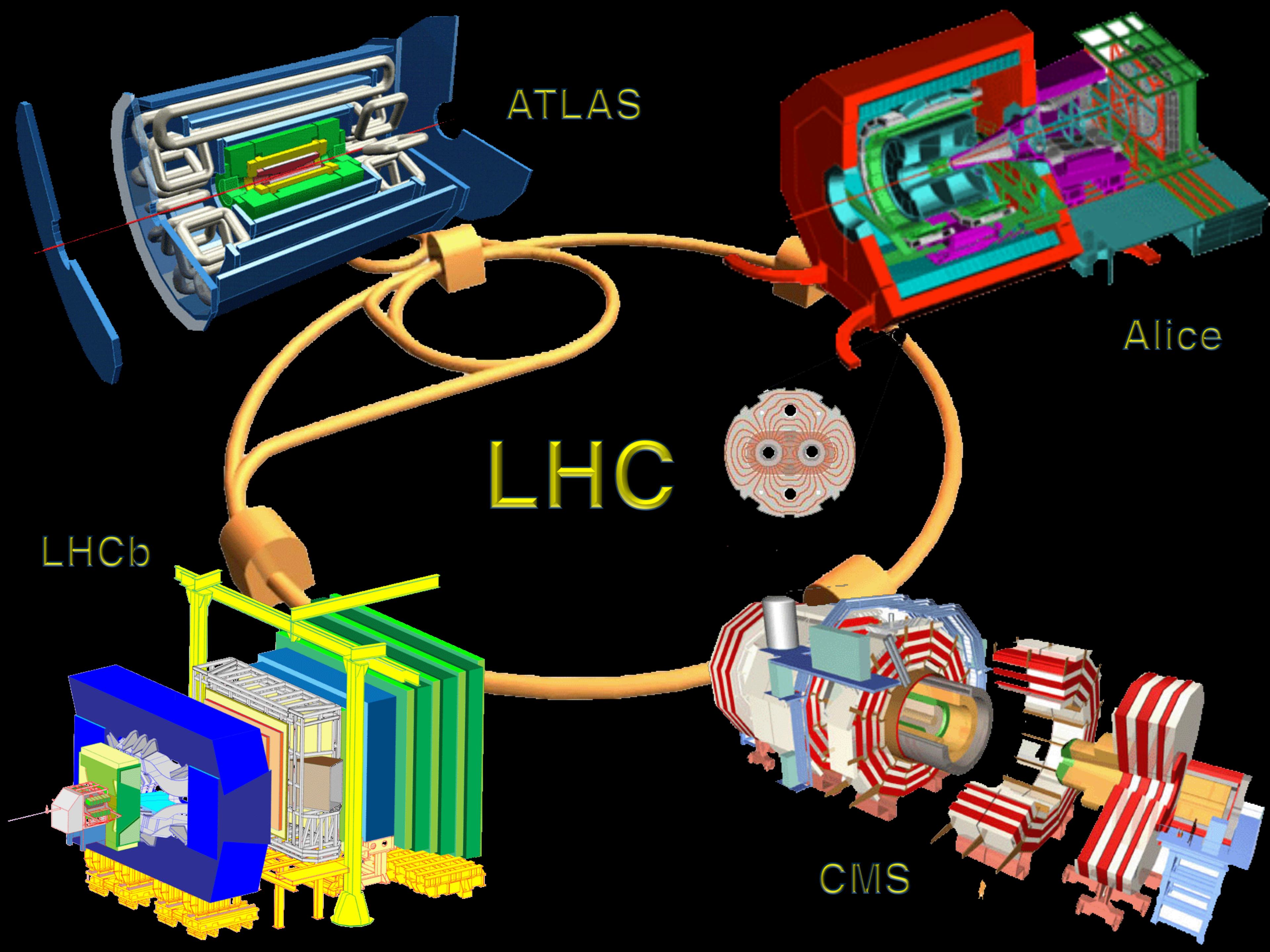
$$M_H = \sqrt{-\mu^2} = \sqrt{2\lambda}\, v$$



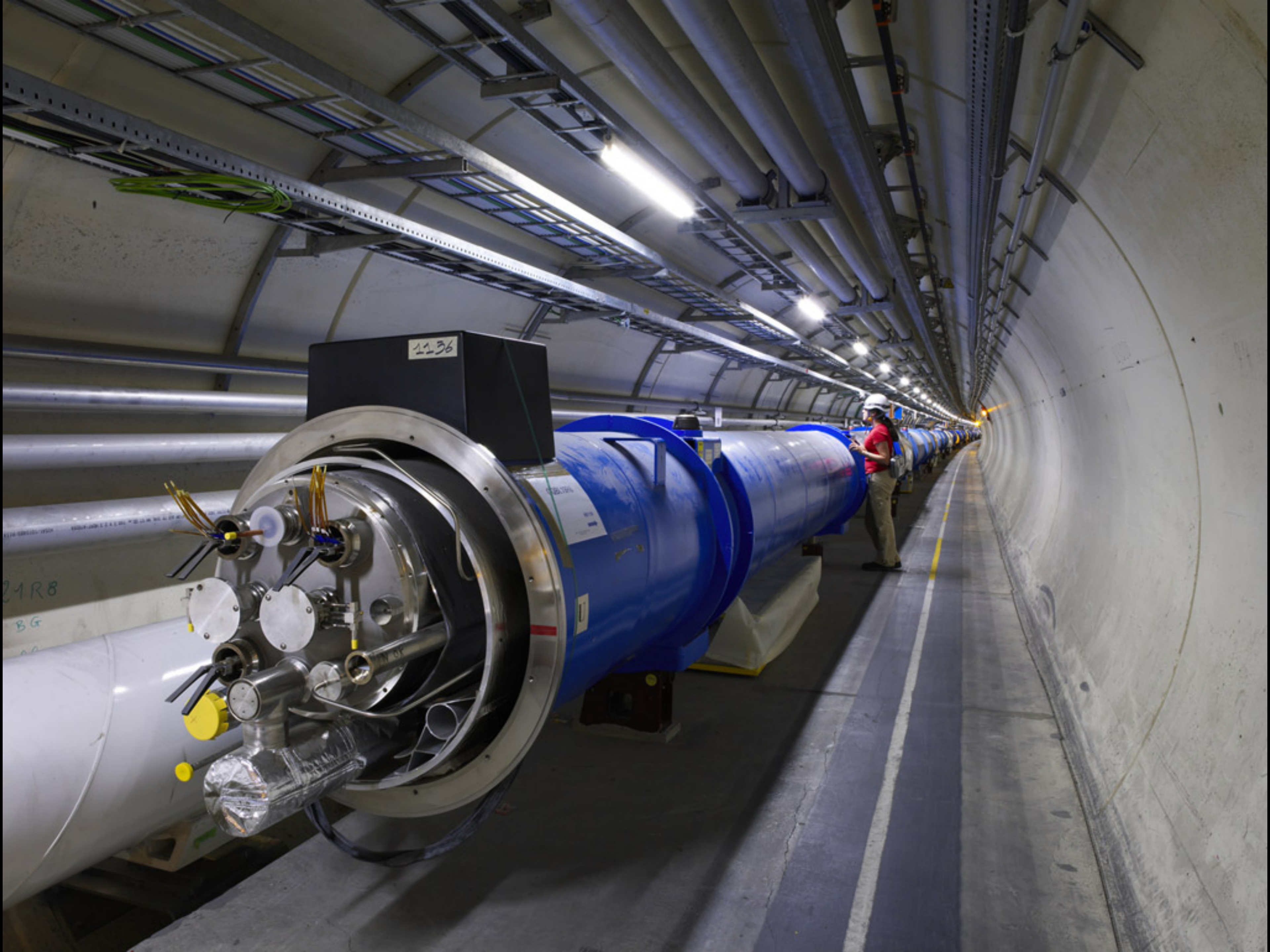
  - Mass is not predicted by the Standard Model
  - Decay channels are determined by mass

Standard Model

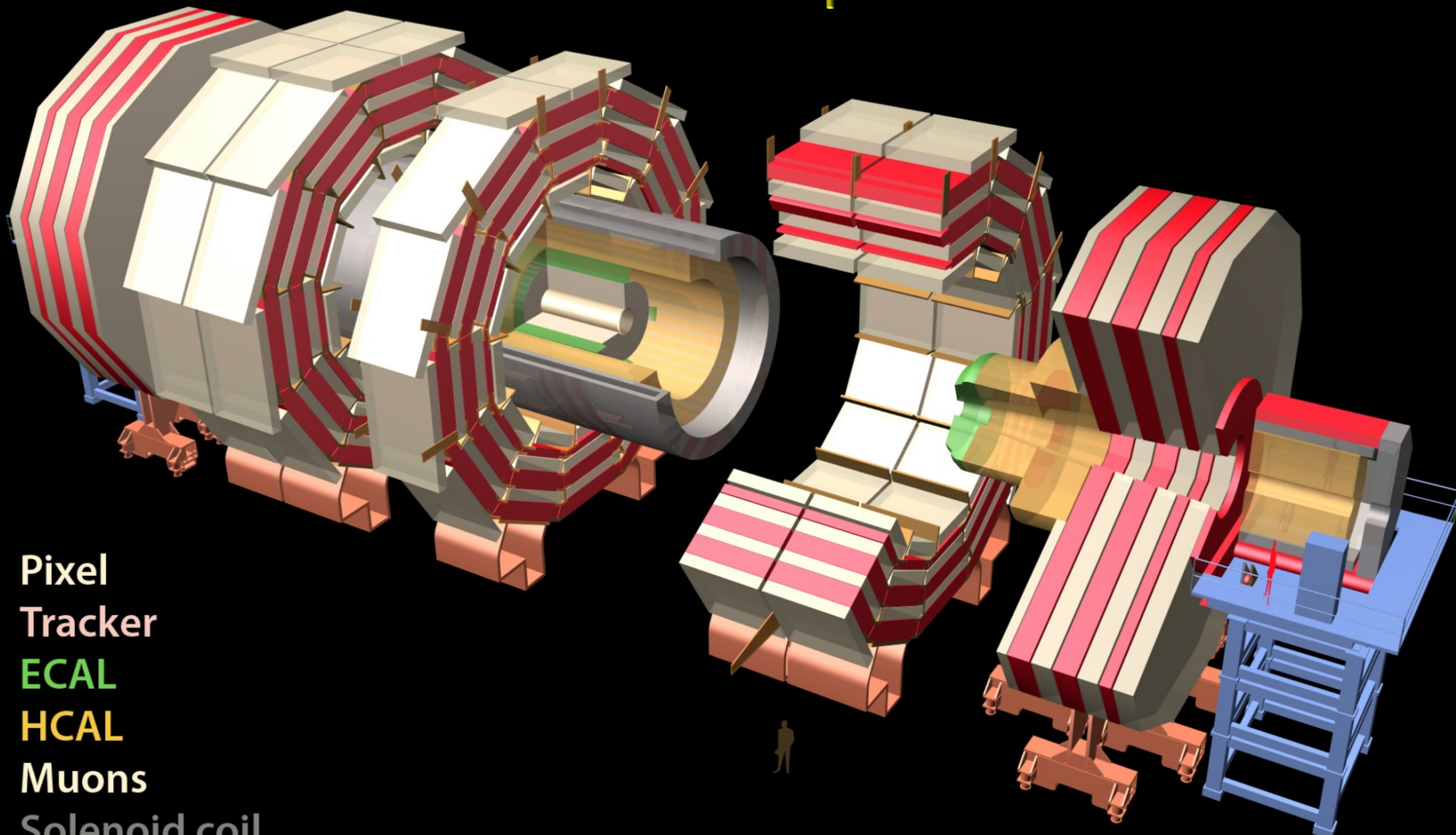



ATLAS
Alice
LHC
LHCb
CMS


Large Hadron Collider
Lake Geneva
CMS
LHCb
ALICE
ATLAS

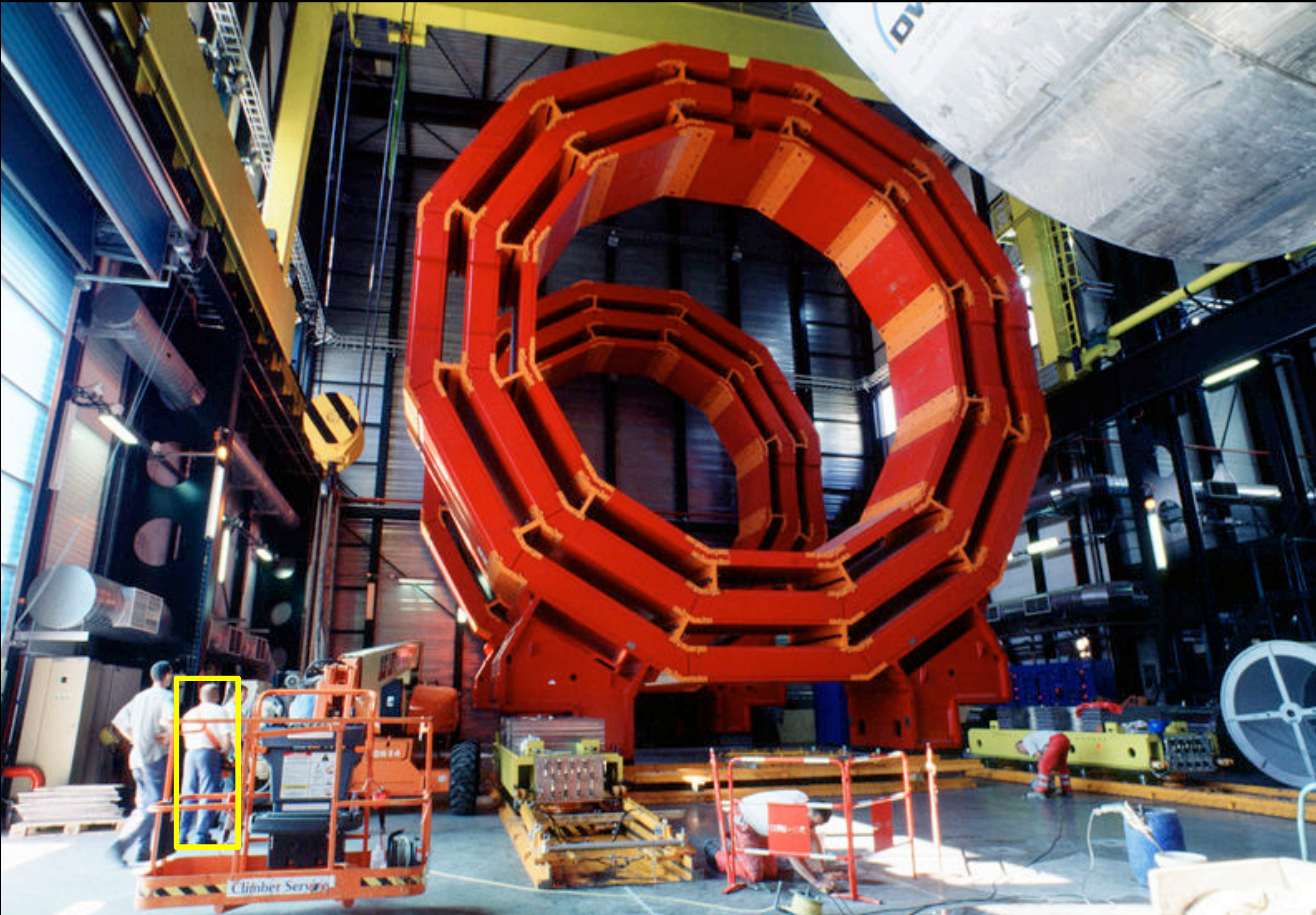

1136
21R8
BG

Compact Muon Solenoid



Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

| Weight: 14.000 ton. | Diameter: 15 m | Length: 21,6 m | Magnetic Field: 4 Tesla |

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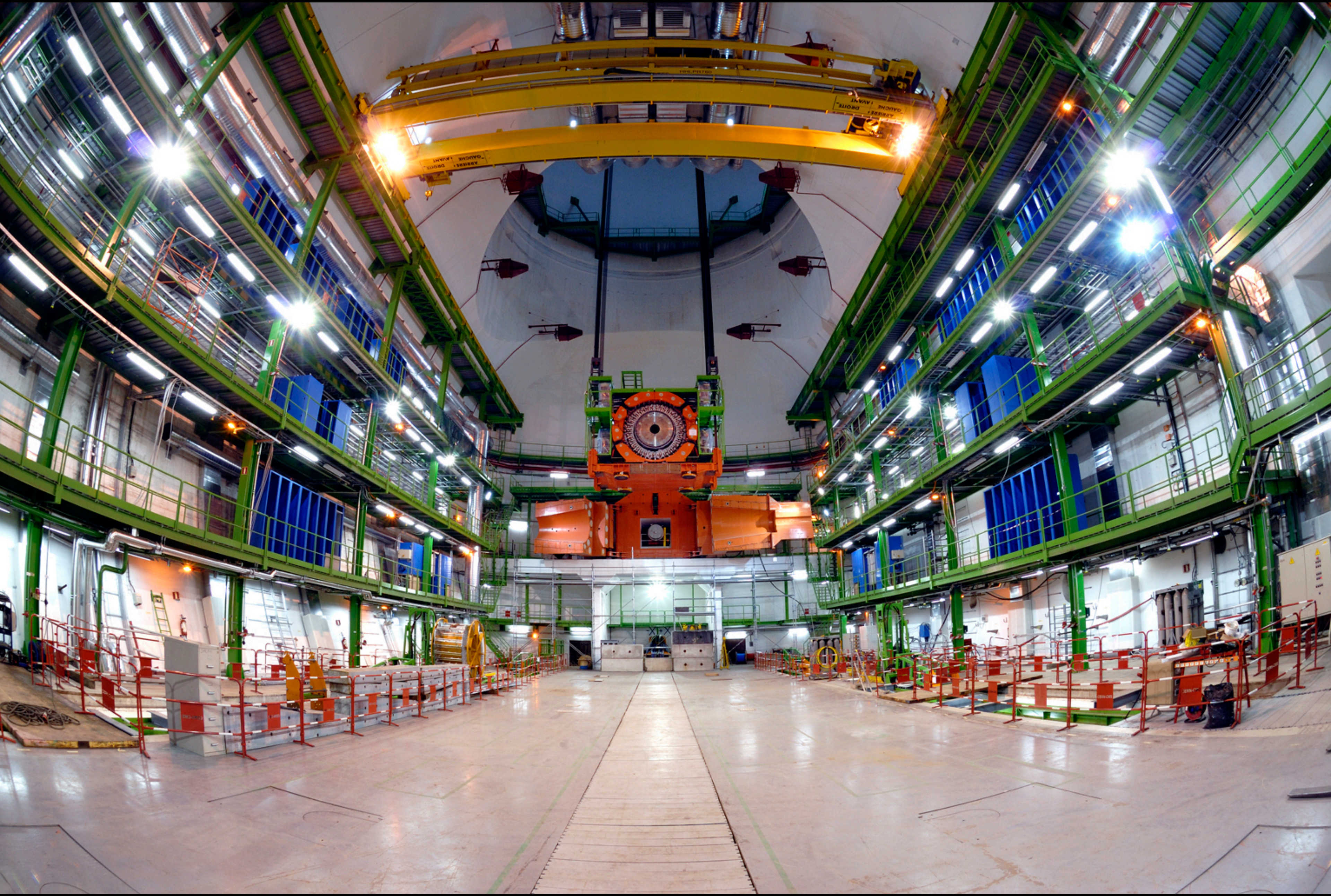
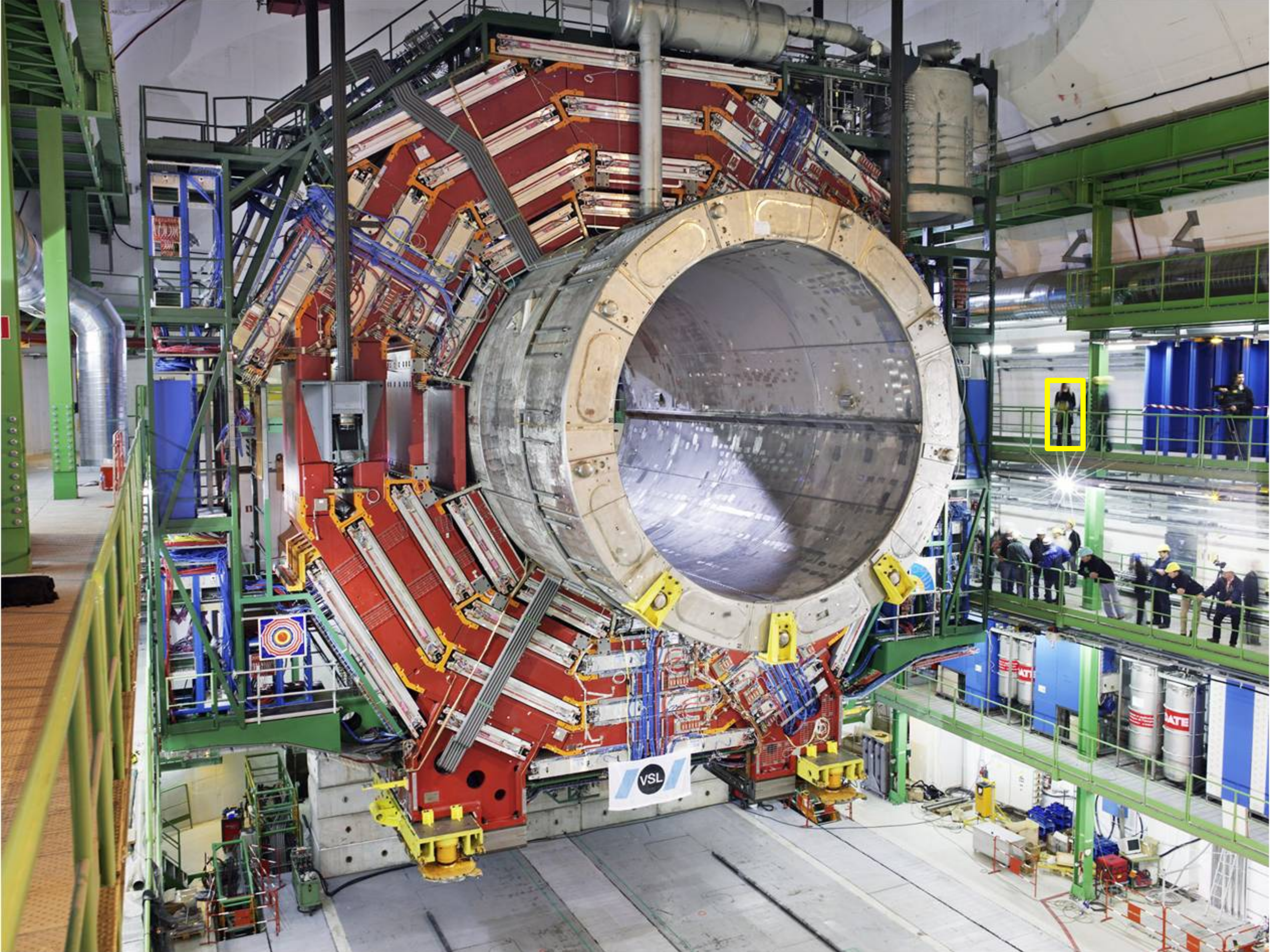
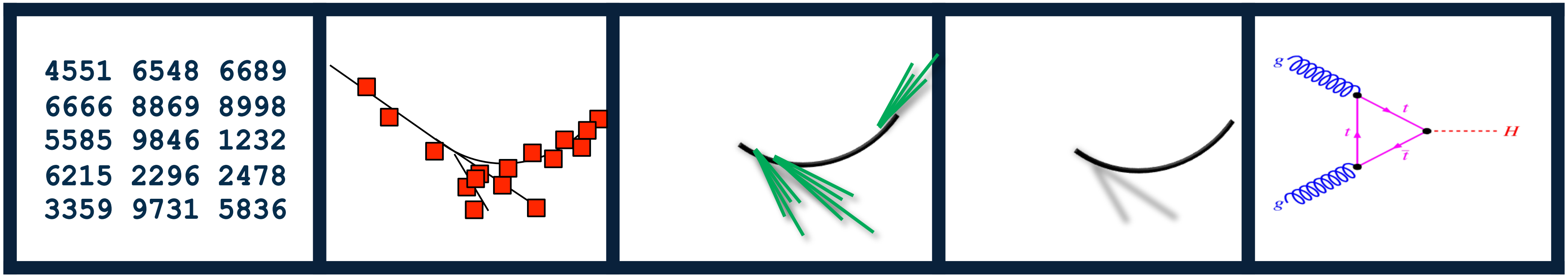



VSL

LHC Beam Pipe
27Km Long

From Bits to Physics



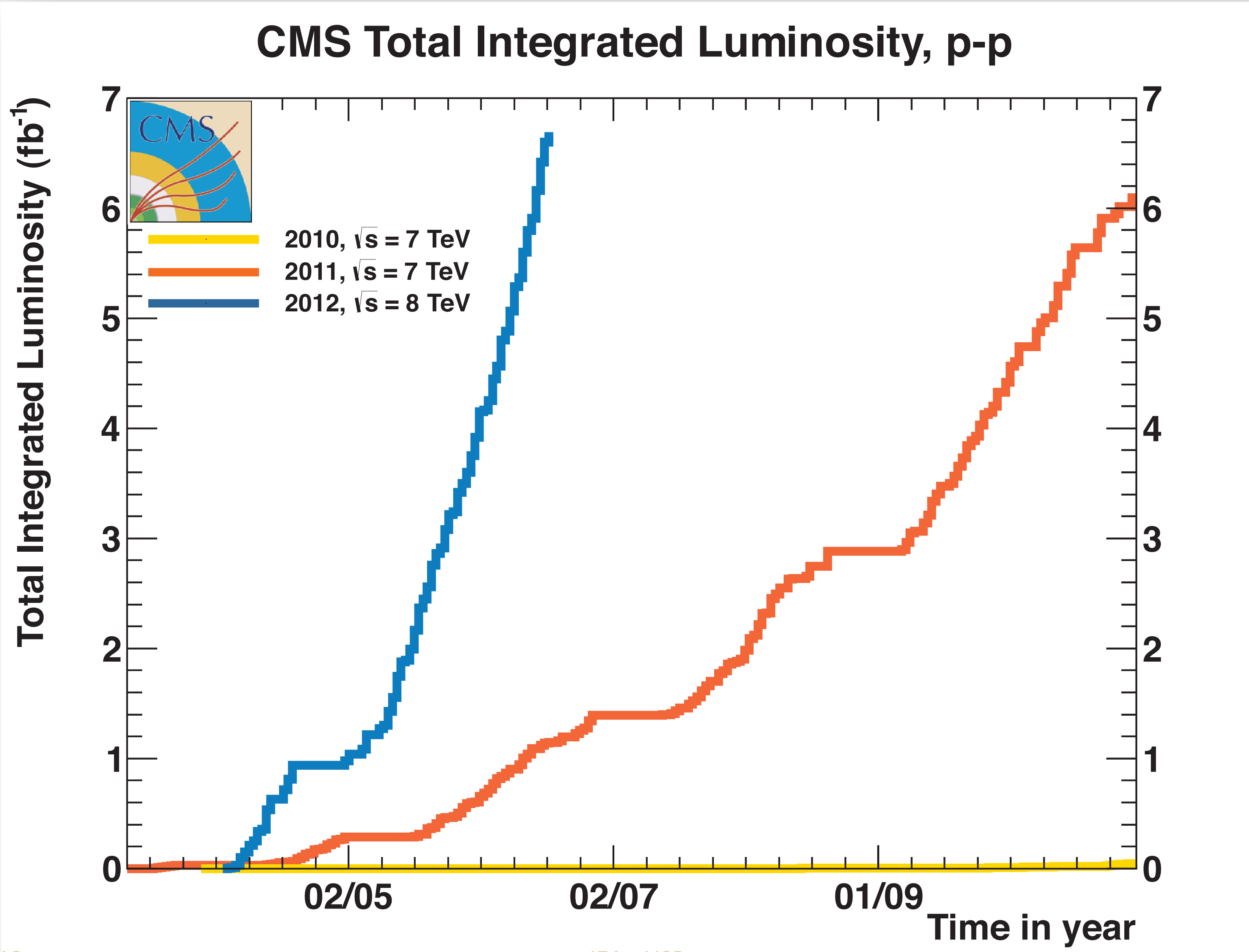
Raw Data | Detector Response | Interaction with matter | Decays and Fragmentation | Physical Phenomena

Alignment / Calibration
Conversion of bits in physical quantity

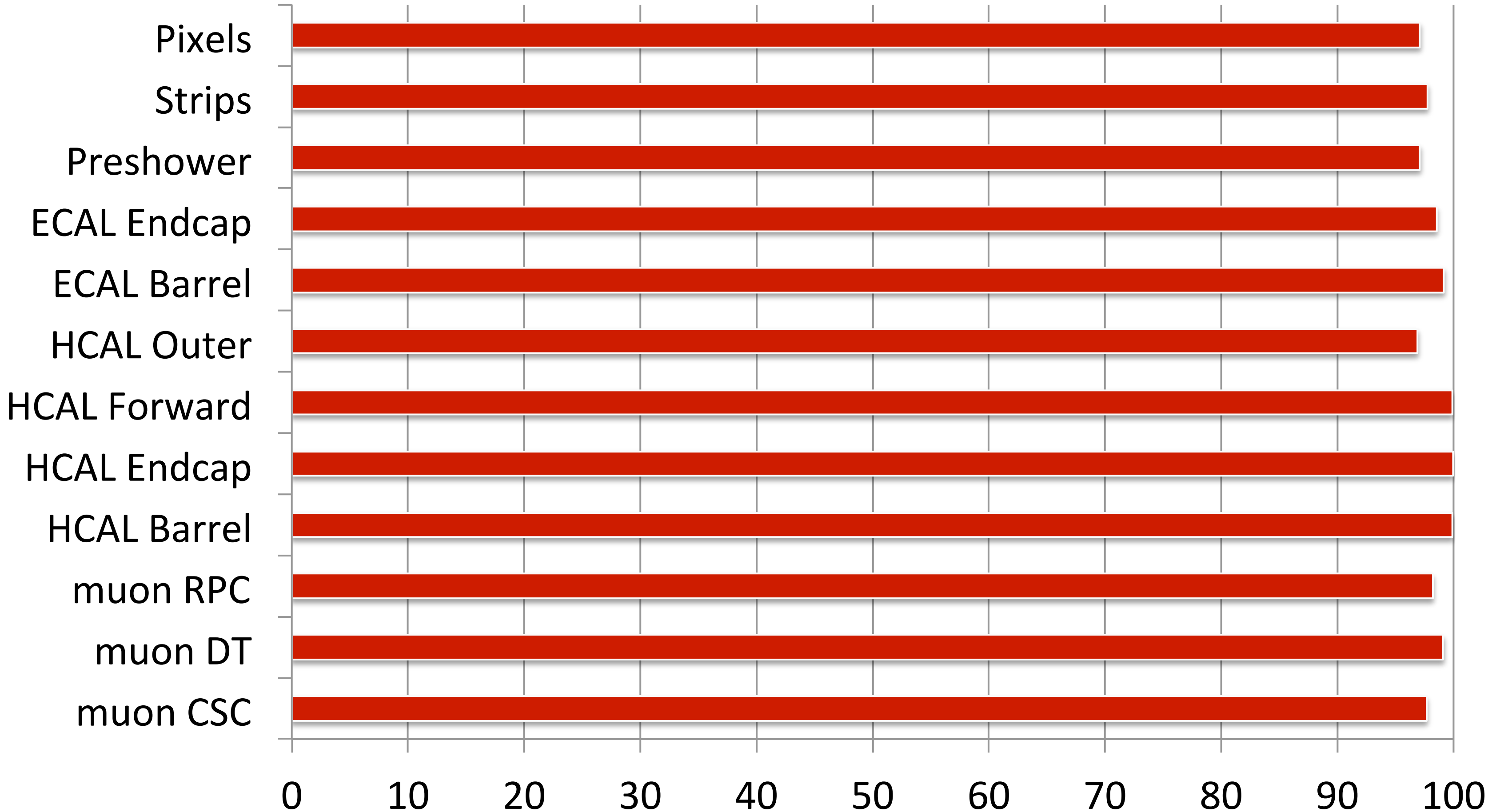
Reconstruction
Pattern Recognition & Particle ID

Physical Analysis
Comparison with Models

LHC Performance

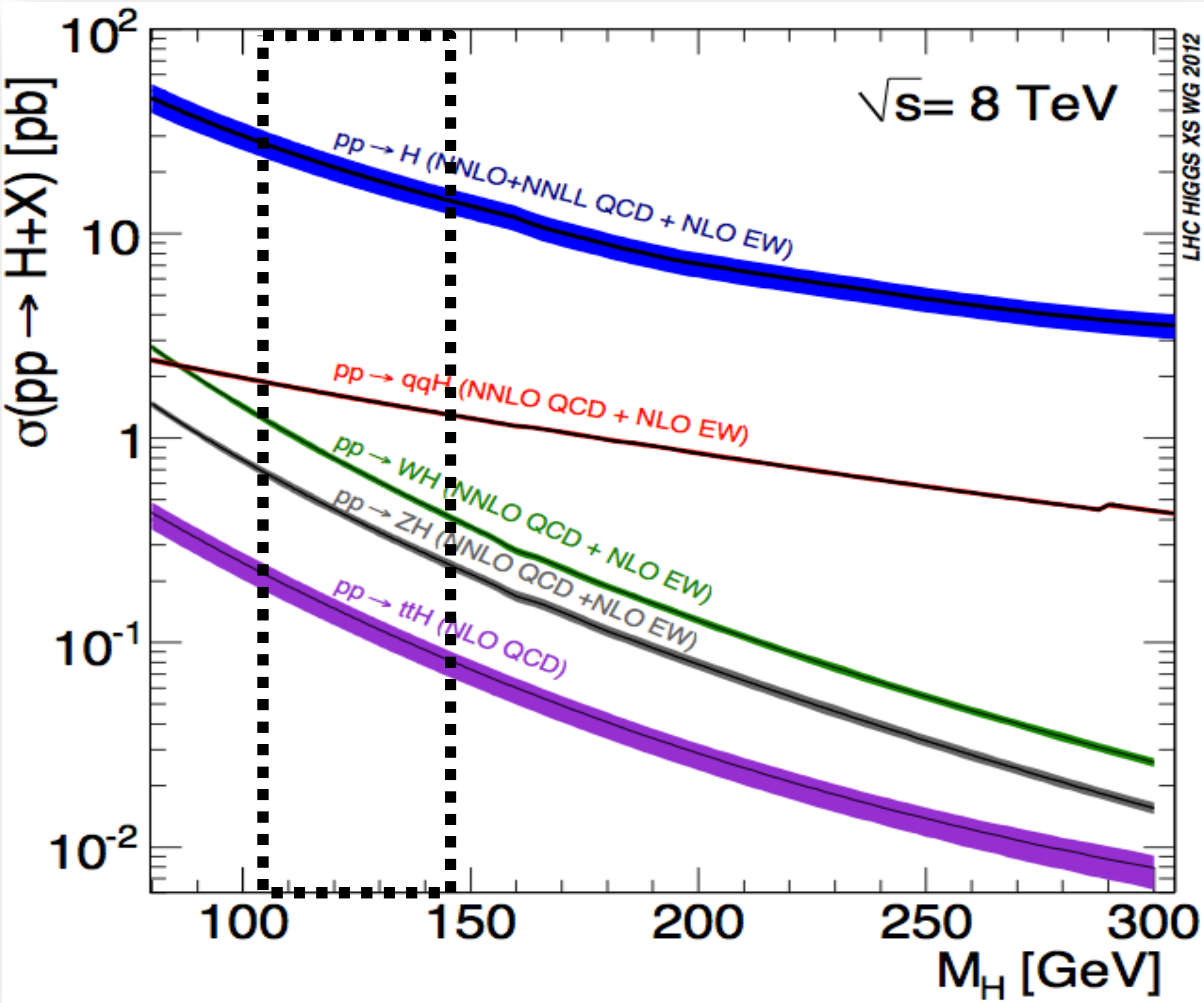


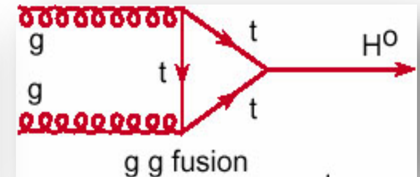
Detector Performance

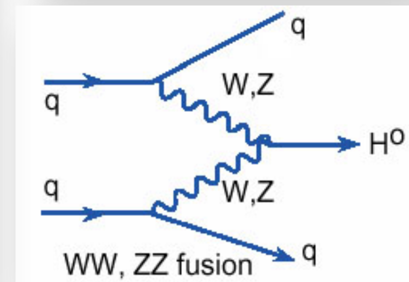


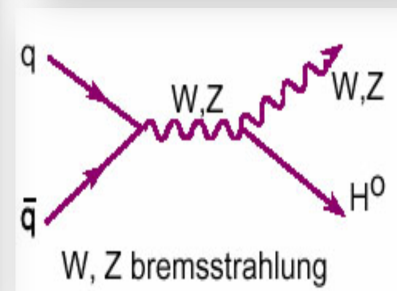
Pixel Tracker	Strip Tracker	Preshower	ECAL Barrel	ECAL Endcaps	HCAL Barrel	HCAL Endcaps	HCAL Forward	HCAL Outer	Muon DT	Muon CSC	Muon RPC
97.1%	97.75%	97.1%	99.16%	98.54%	99.92%	99.96%	99.88%	96.88%	99.1%	97.67%	98.2%

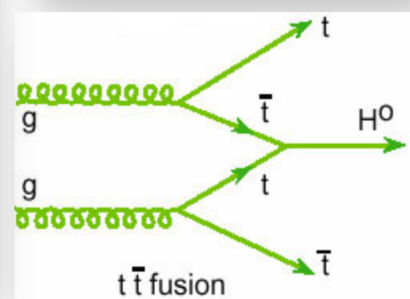
Higgs boson production





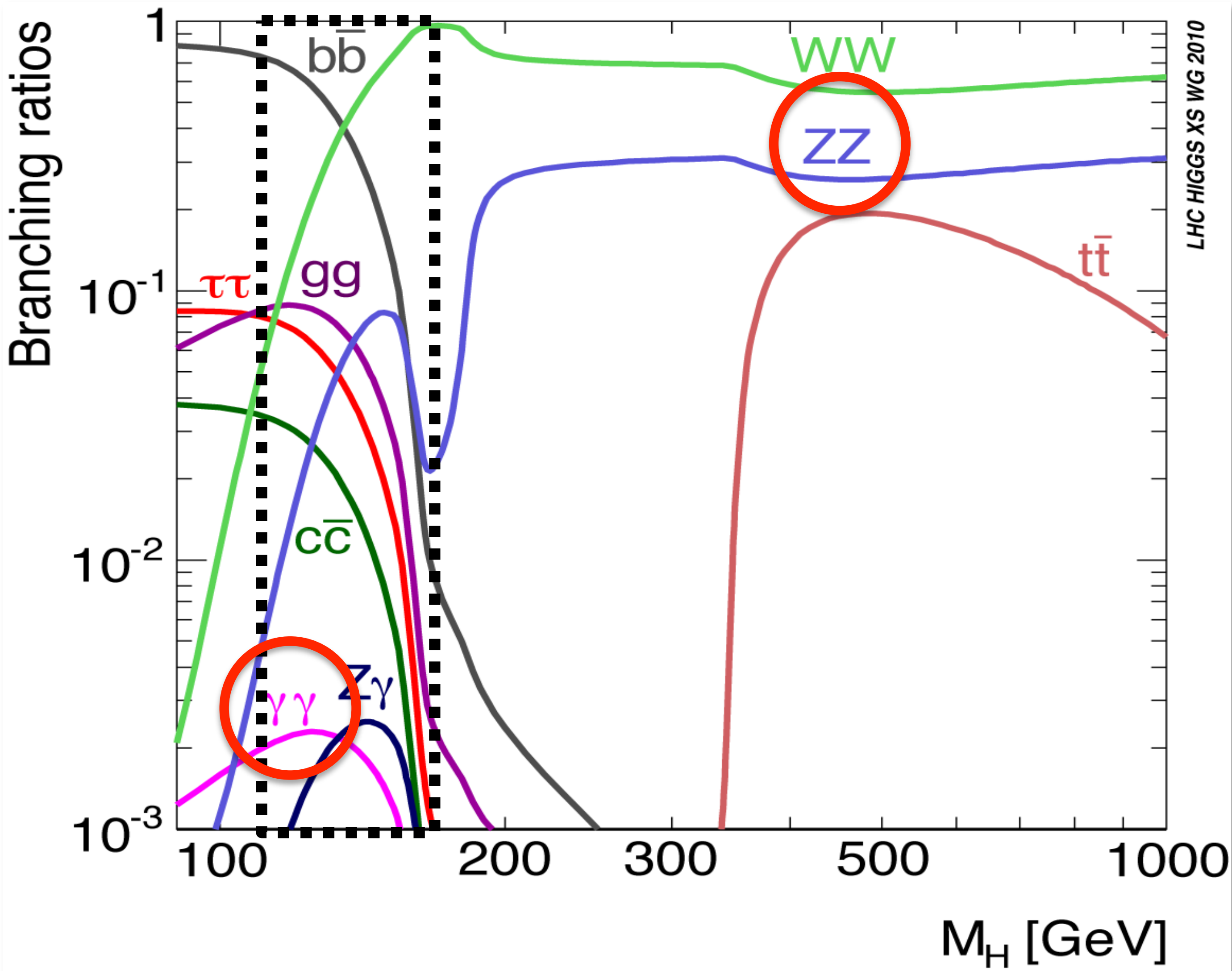


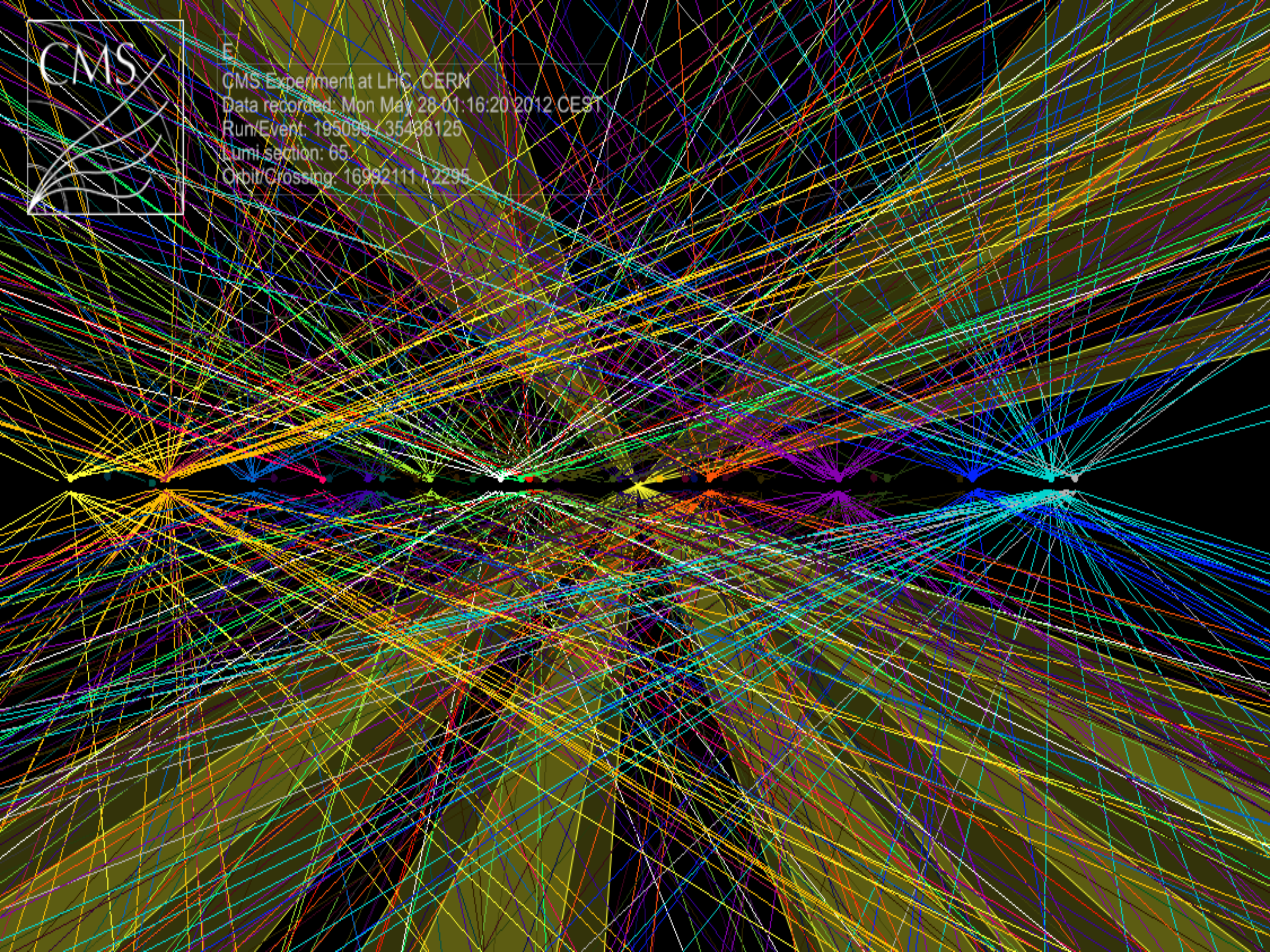


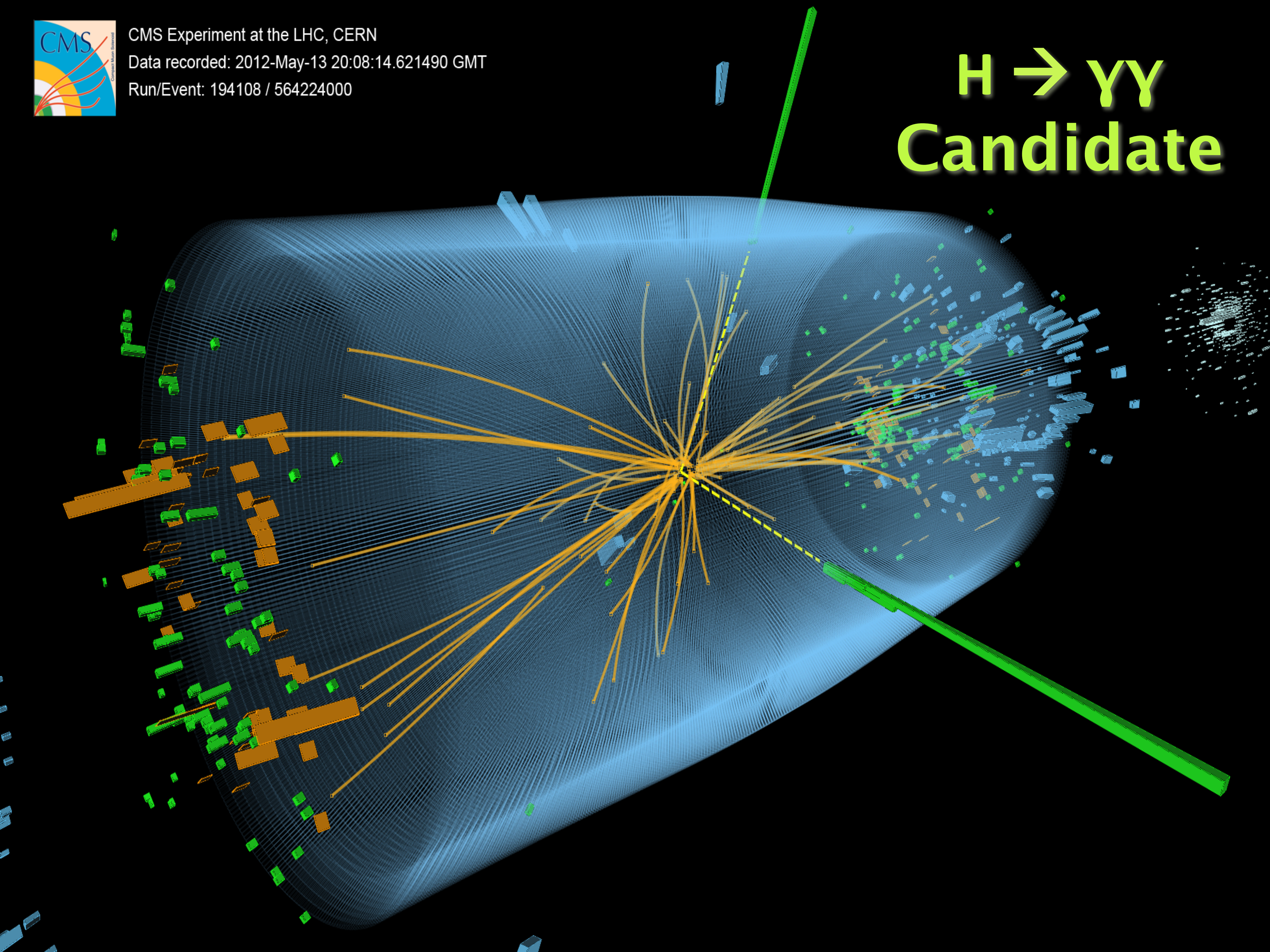


Higgs boson decays

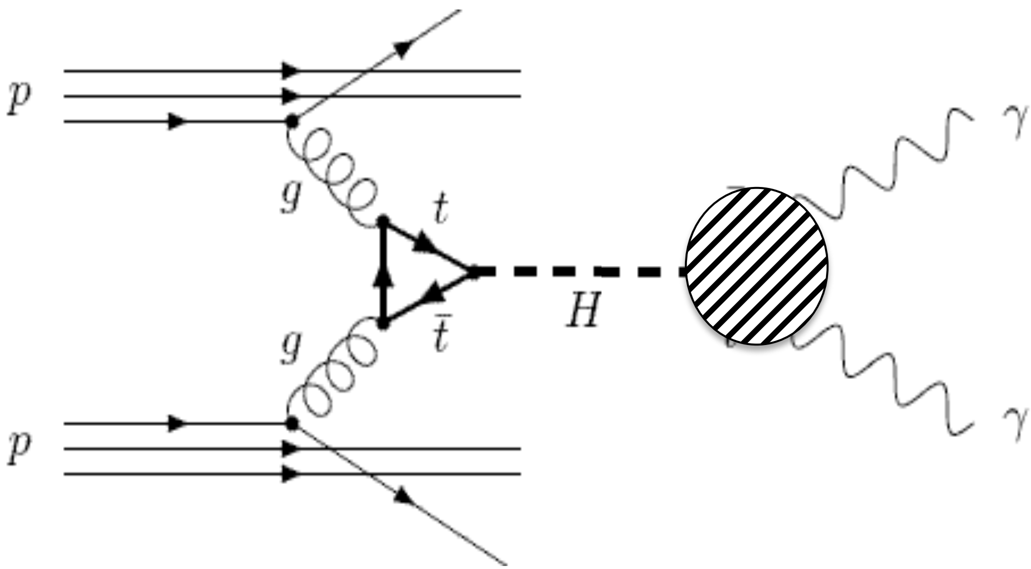
- 5 Channels
  - ❑ WW
  - ❑ ZZ
  - ❑ bb
  - ❑ ττ
  - ❑ ϒϒ
- Good mass resolution
  - ❑ ZZ → 4l
  - ❑ ϒϒ

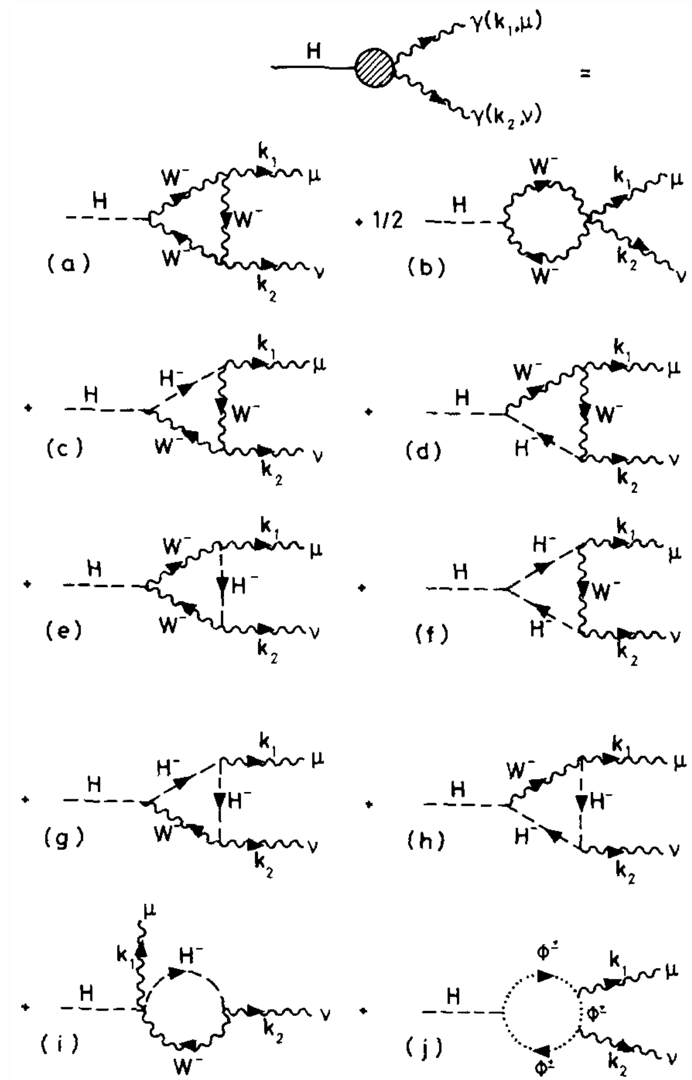



CMS
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
Candidate

$pp \to gg \to H \to \gamma\gamma$

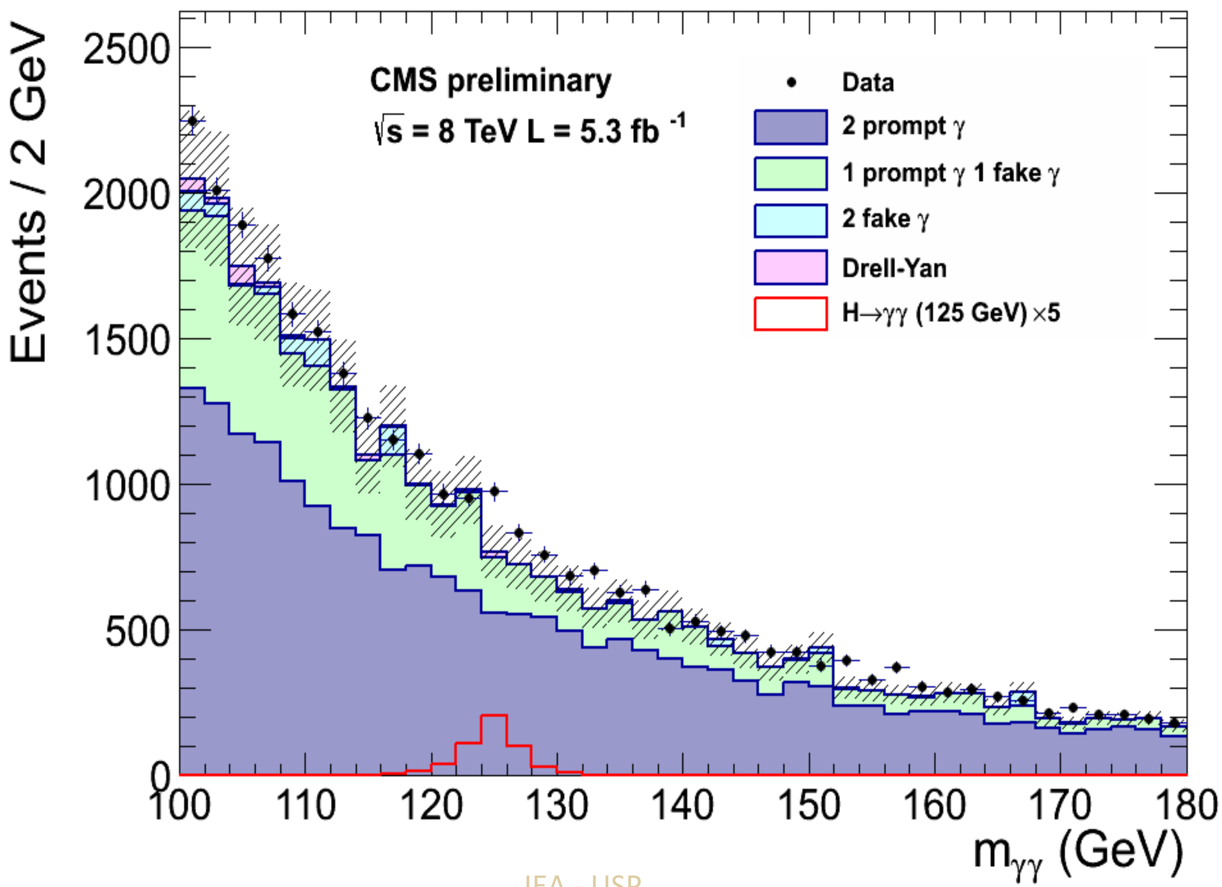




Ellis, Gaillard, Nanopoulos (1976)

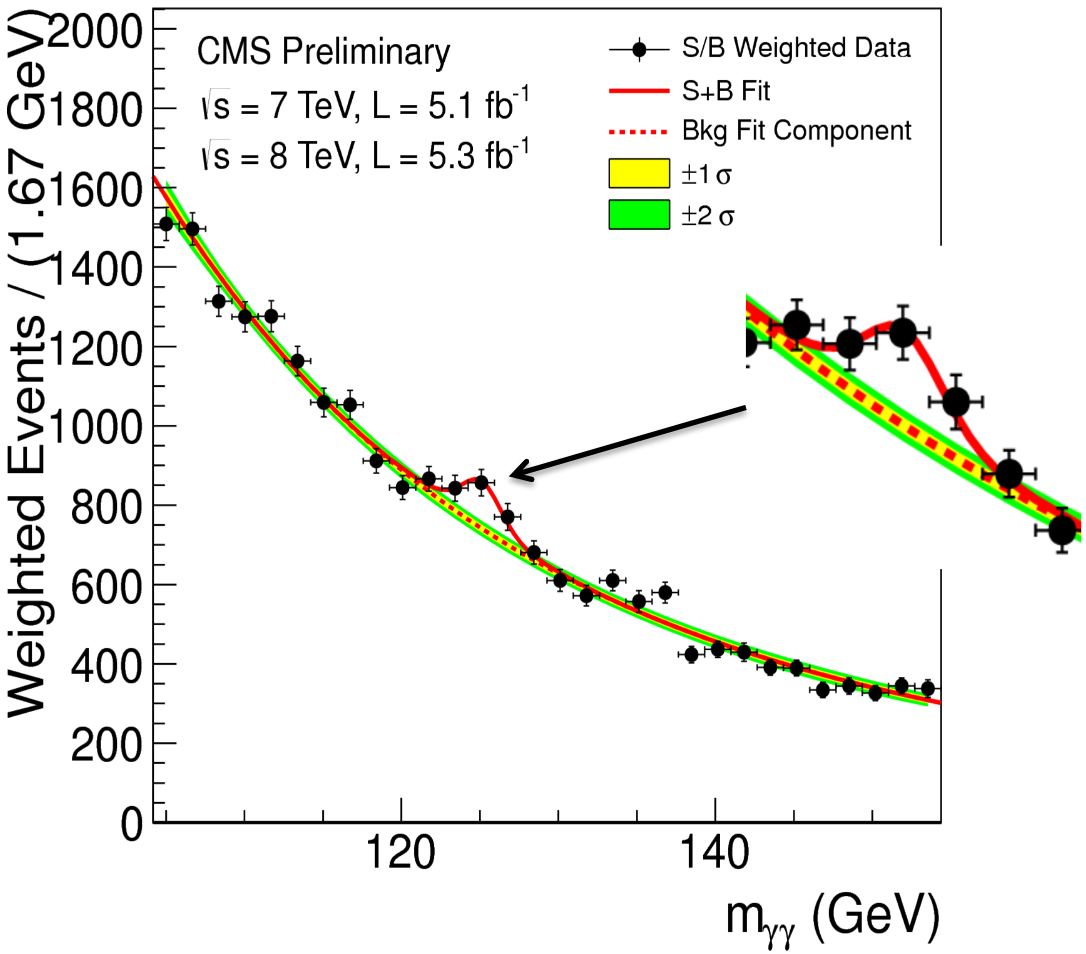
H → γγ

Search for a narrow mass peak with two isolated high E_T photon
Multi-Variate-Analysis (MVA) cross checked with cut based
Blind analysis proceedure

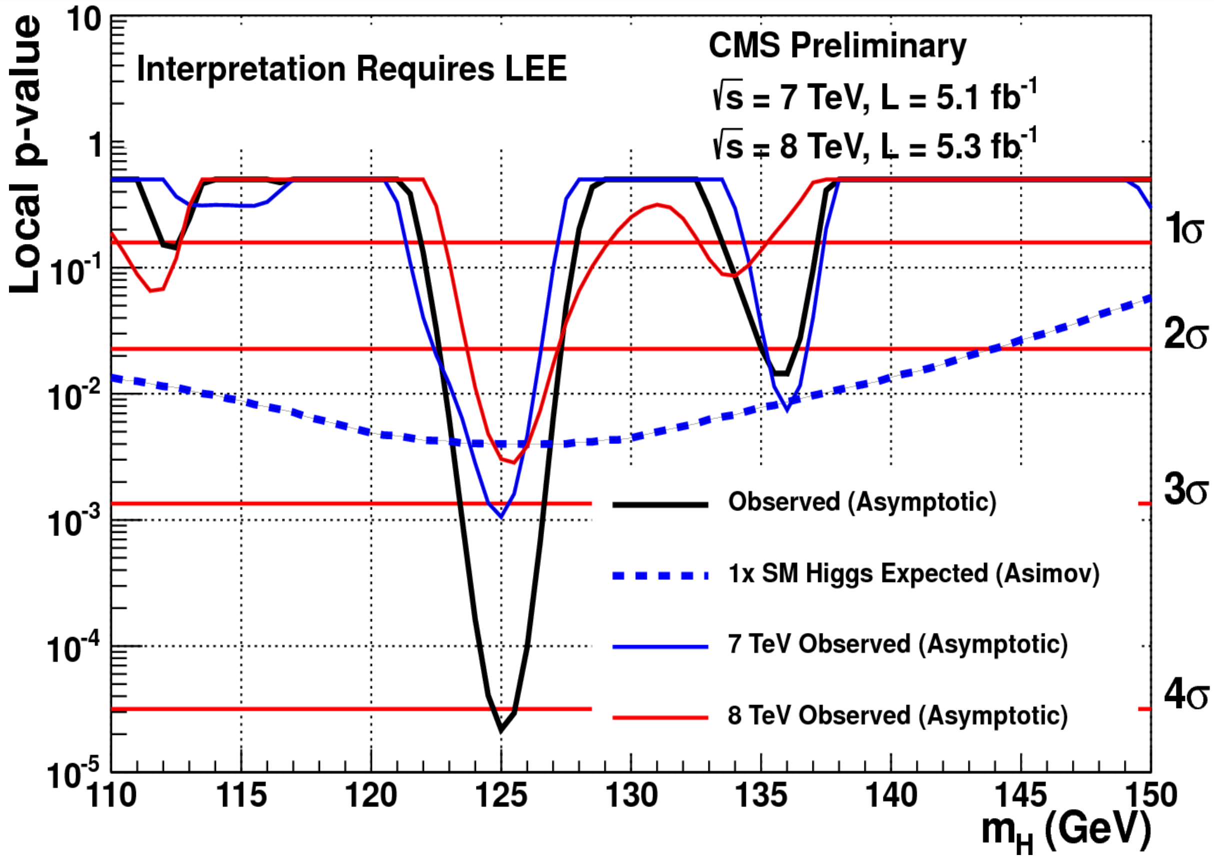


S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval



p-Values



Minimum local p-value at 125 GeV with a local significance of 4.1 σ

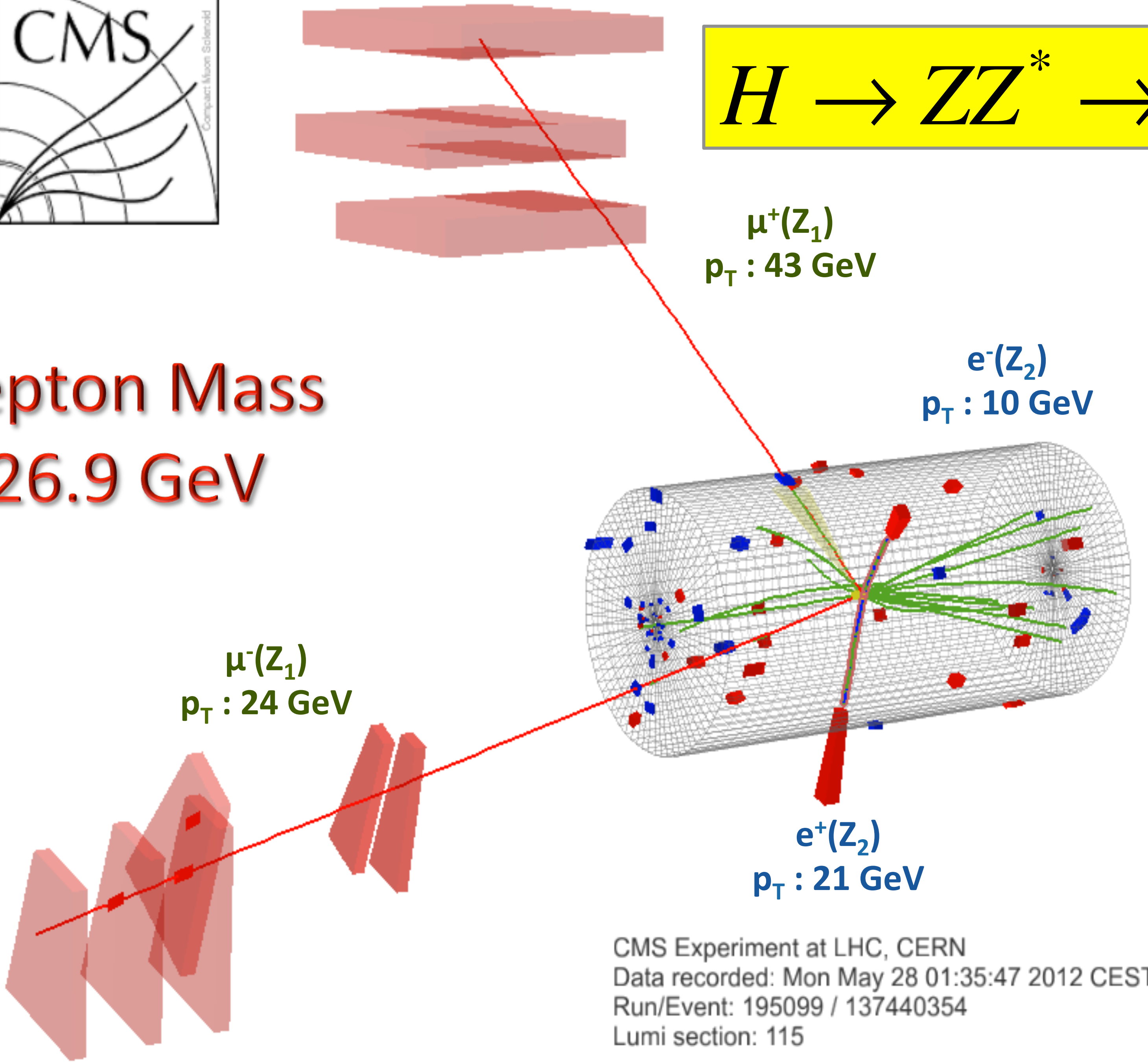
Similar excess in 2011 and 2012

Independent cross check analyses give similar results

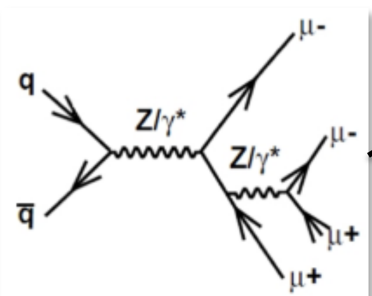
Global significance in the full search range (110-150 GeV): 3.2 σ

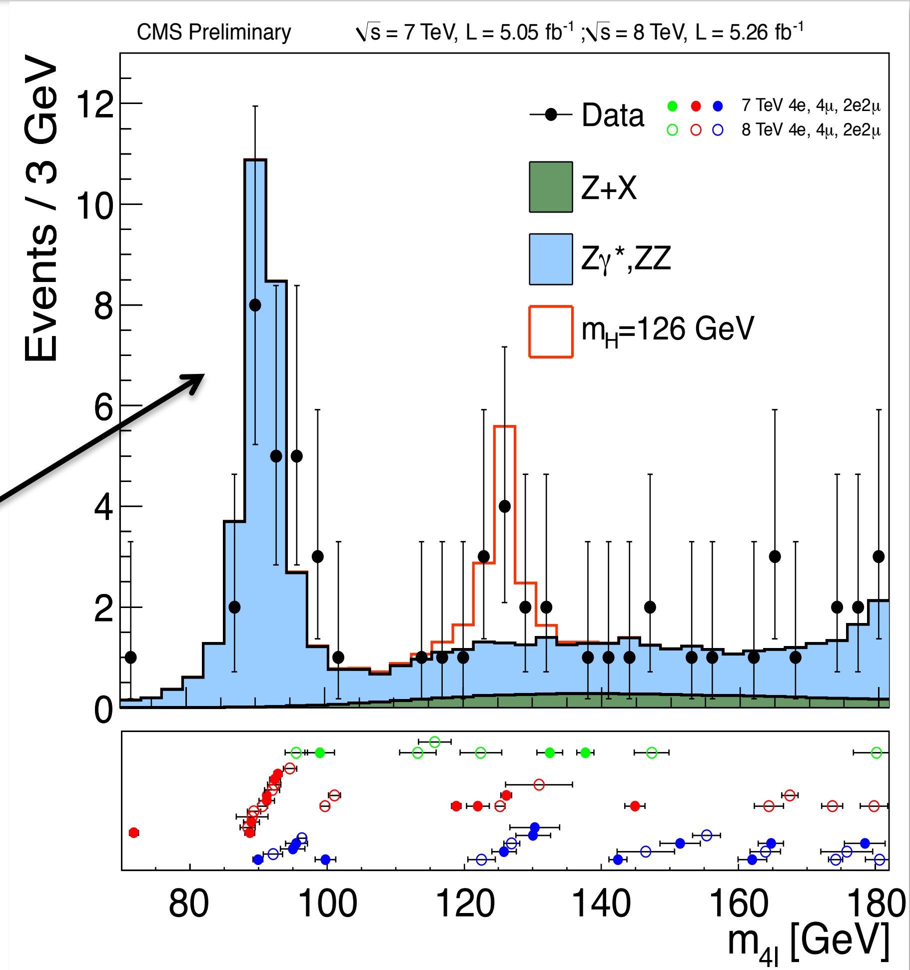
$H \to ZZ^* \to 4\ell$

4-lepton Mass
126.9 GeV



Results: M_{4l} Spectrum

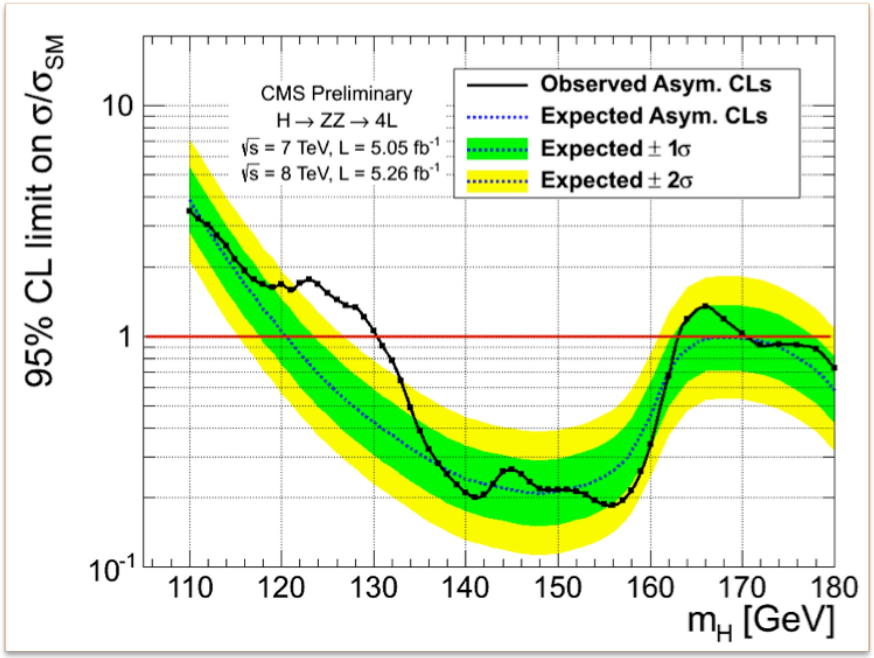


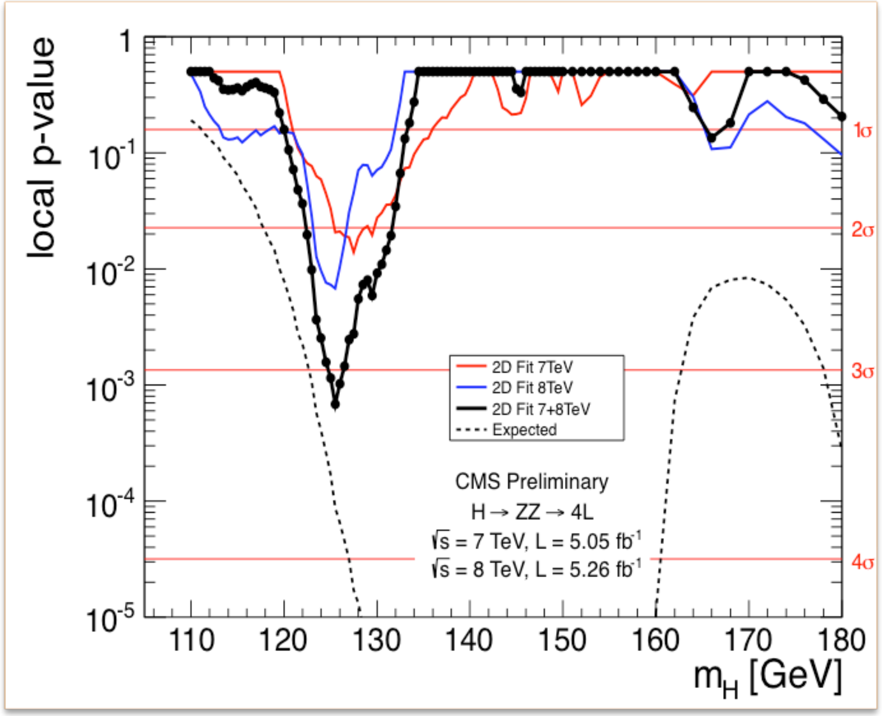


164 events expected in [100, 800 GeV]

172 events observed in [100, 800 GeV]

Limits and p-Values



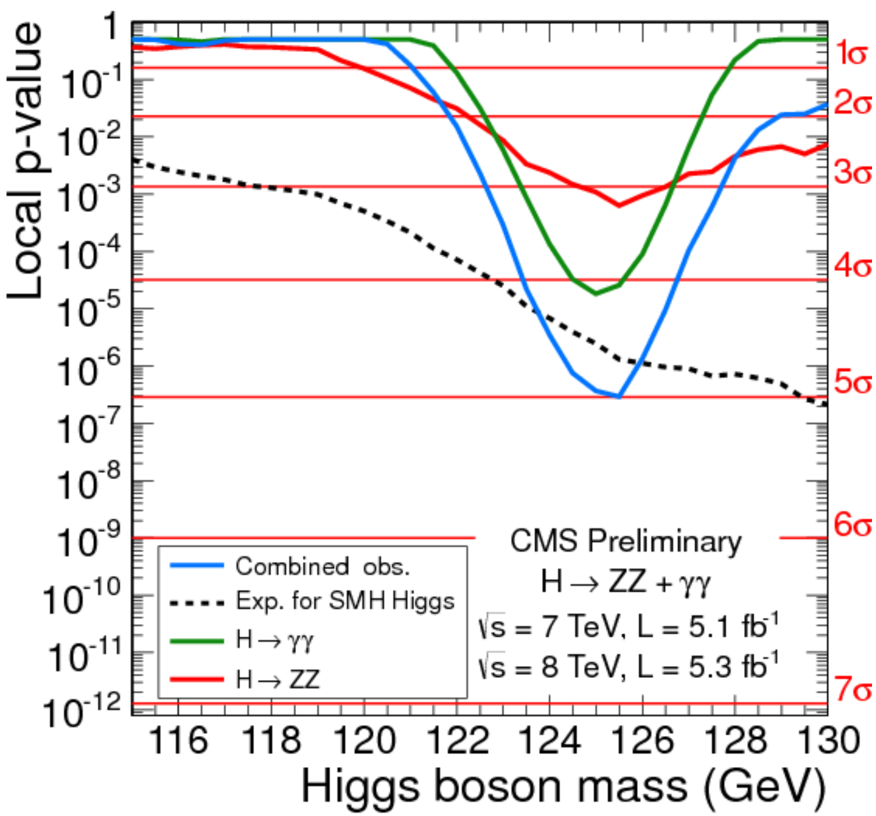


Expected exclusion at 95% CL: 121-550 GeV
Observed exclusion at 95% CL :
131-162 GeV and 172-530 GeV

Expected significance at 125.5 GeV: 3.8 σ

Observed significance at 125.5 GeV: 3.2 σ

High Mass Resolution Channels: γγ + 4l



- γγ:
  - 4.1 σ excess
- 4 leptons:
  - 3.2 σ excess

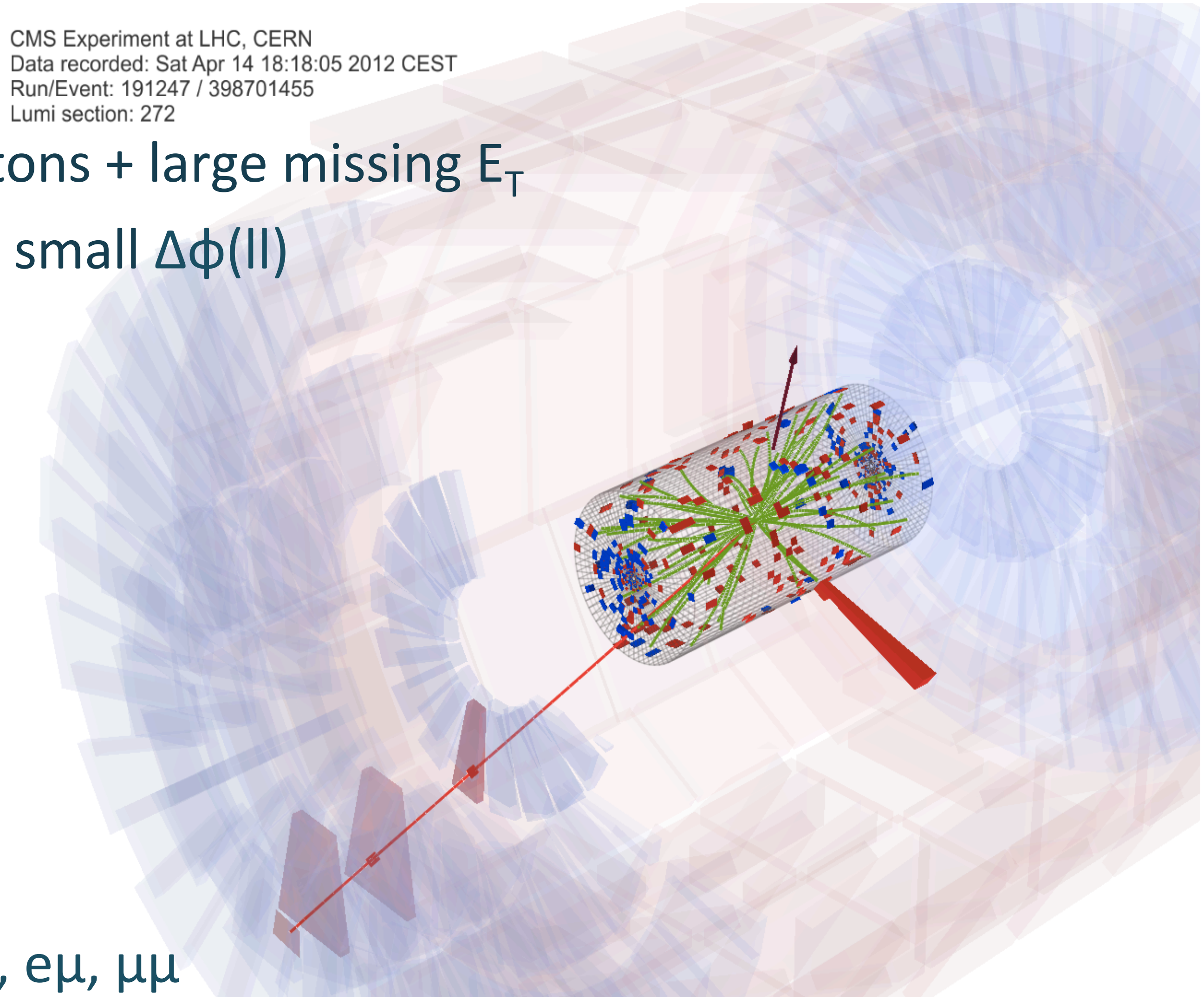
- Near the same mass 125 GeV

- Combined Significance:

  ❑ 5.0 σ

Other Channels

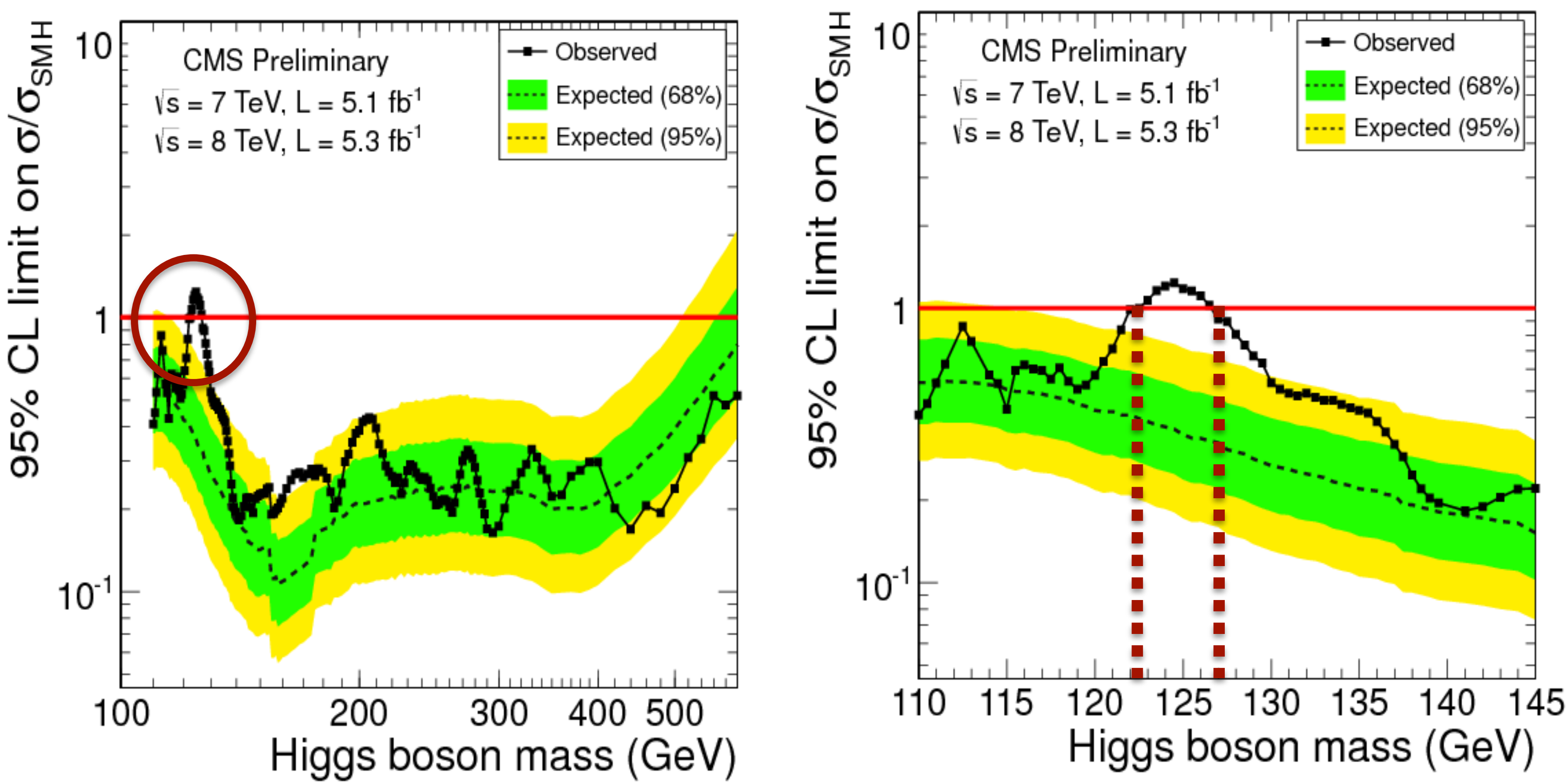
- H → WW
  - 2 high p_T leptons + large missing E_T
  - Large BR and small $\Delta\phi(ll)$



- VH → Vbb
  - V → lν, ll, νν

- H → ττ
  - ττ → $\mu\tau_h$, $e\tau_h$, eμ, μμ

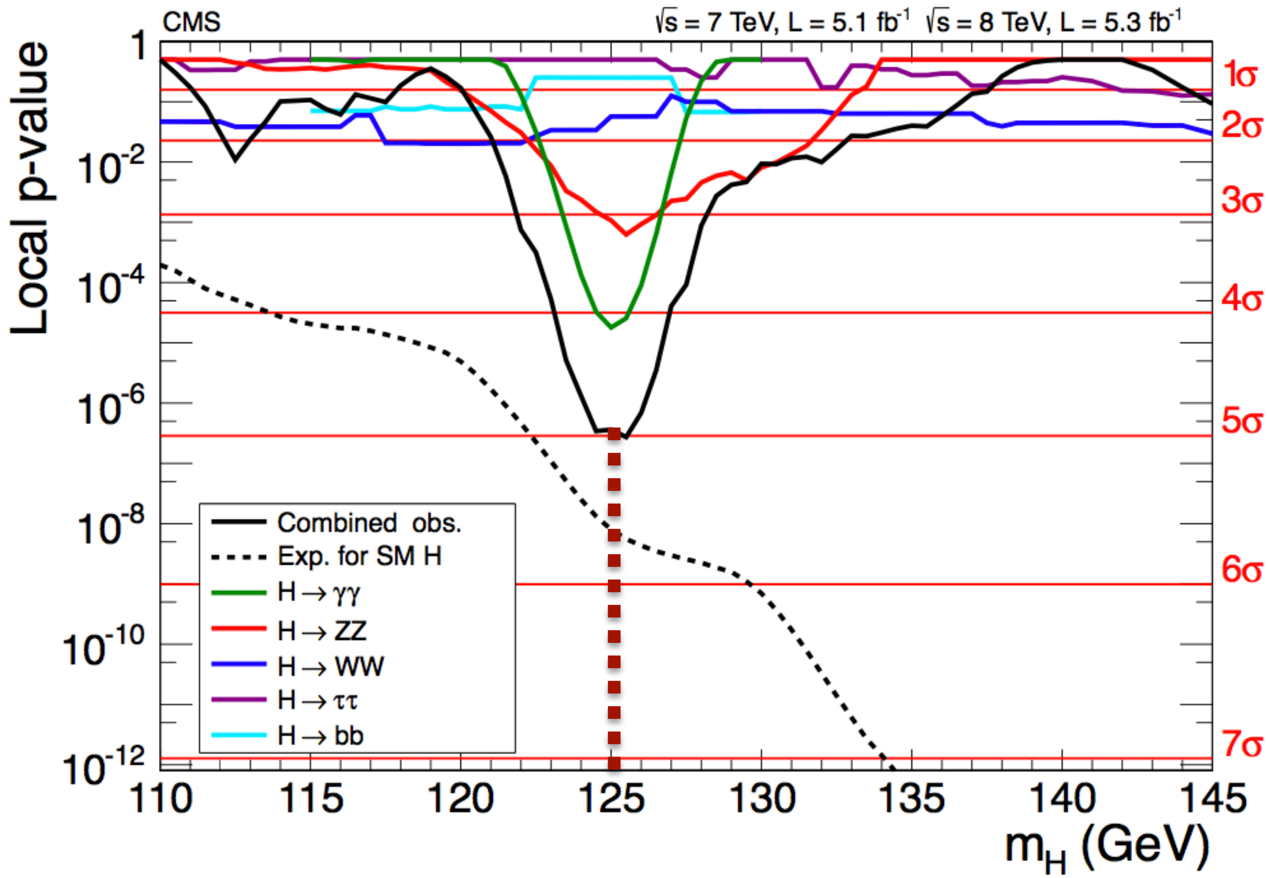
SM Higgs Exclusion



Excluded

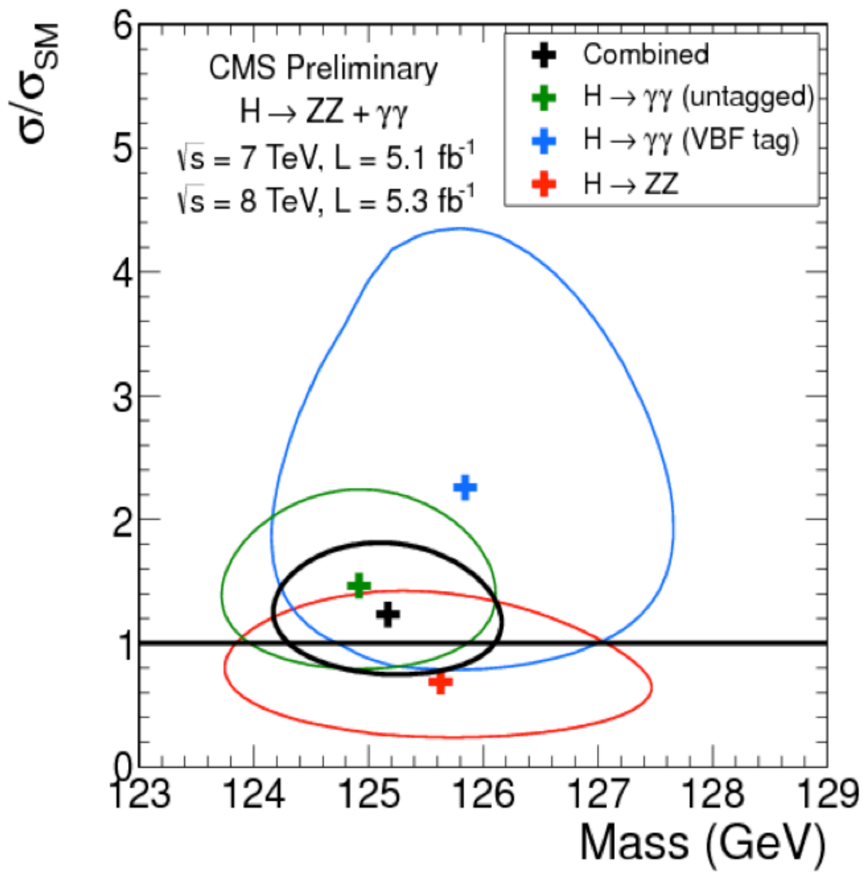
110 – 122.5 & 127 – 600 GeV at 95% CL

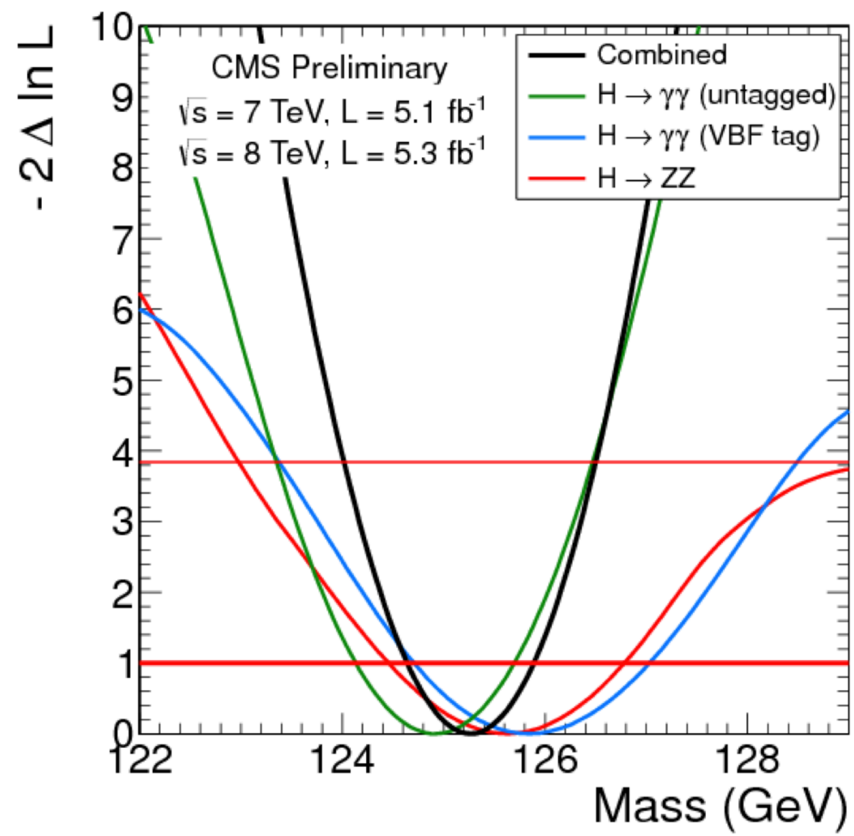
Characterization of the Excess



Combined significance of all channels around 125.5 GeV: 5 σ

Characterization of the Excess

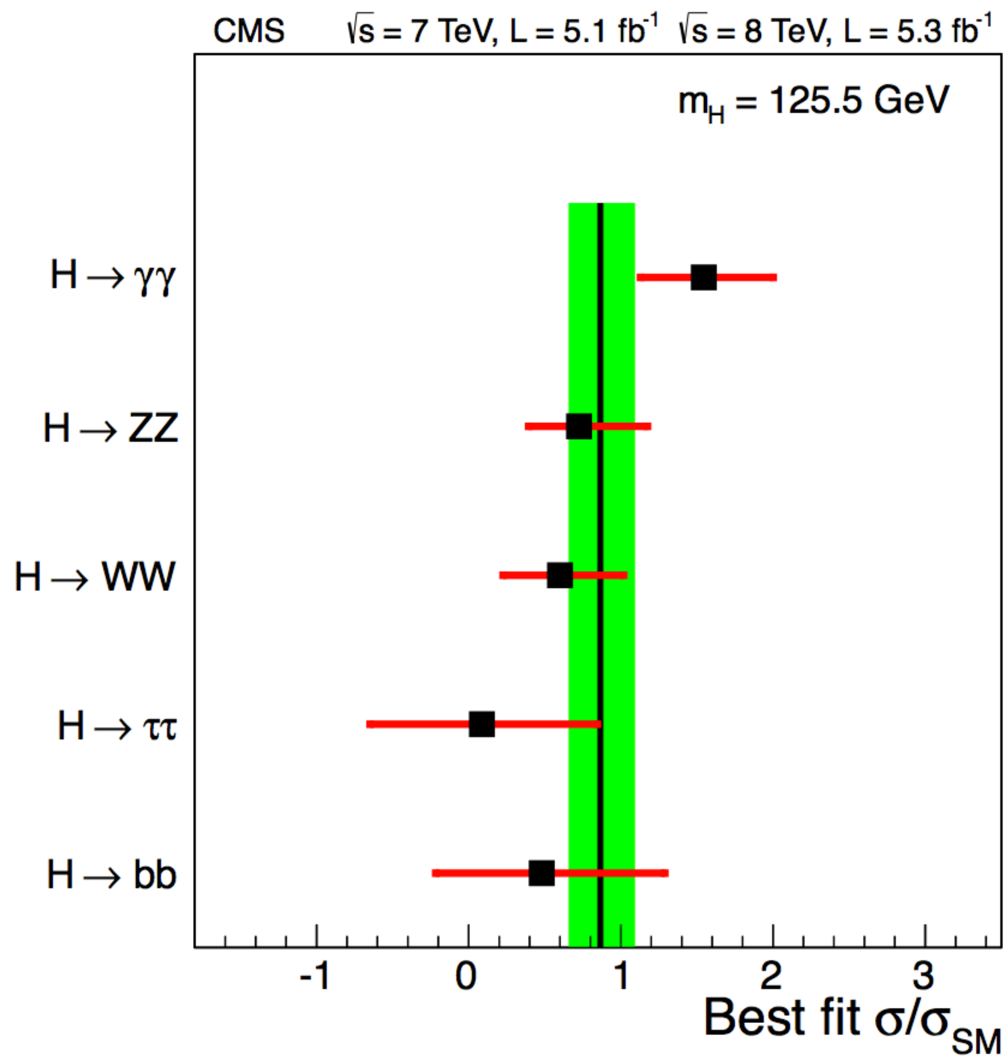




Likelihood for mass and signal strength in 3 high resolution channels

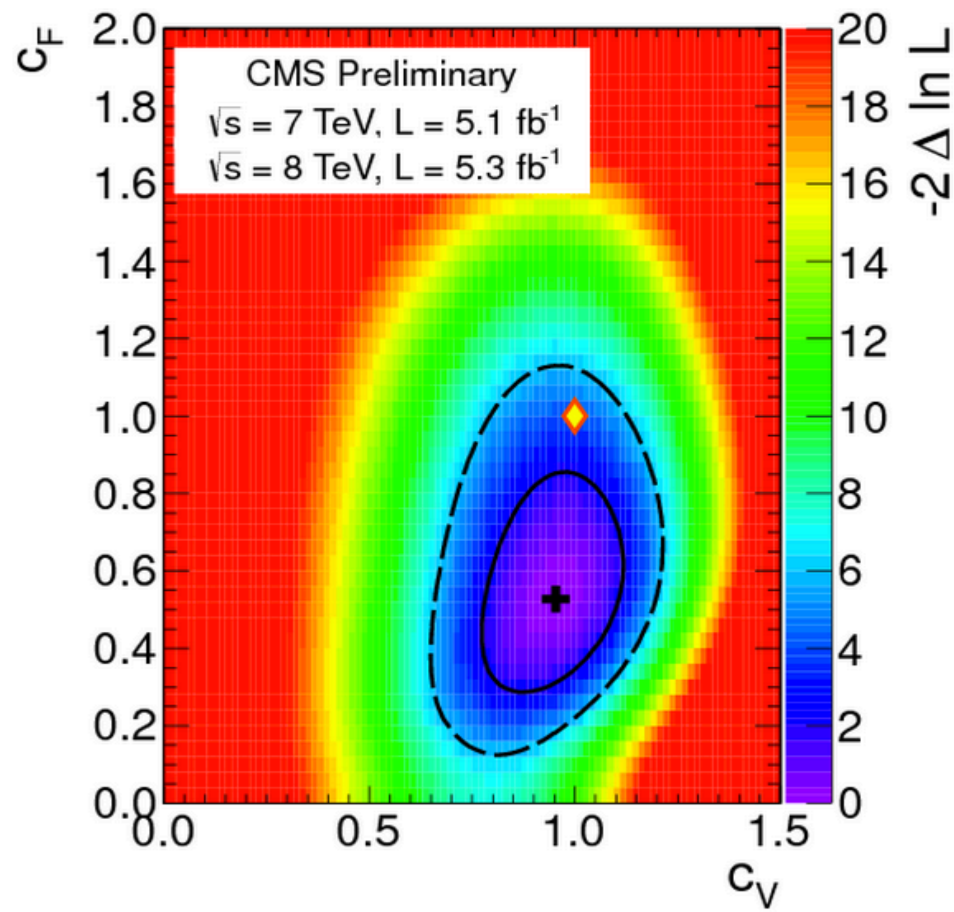
$M = 125.3 \pm 0.4\ (\text{stat}) \pm 0.5\ (\text{syst})$

Compatibility with SM Higgs



Fit to C_V and C_F

- Group the Higgs couplings:
  - "Vectorial" & "Fermionic"
- Modify SM prediction by:
  - C_V & C_F
- Use LO calculation for loop-induced couplings
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow gg$
- Agreement with the SM within the 95% C.L. range



Solid = 68% and Dashed = 95% CL

CMS Conclusion

A new boson was observed

with a mass of

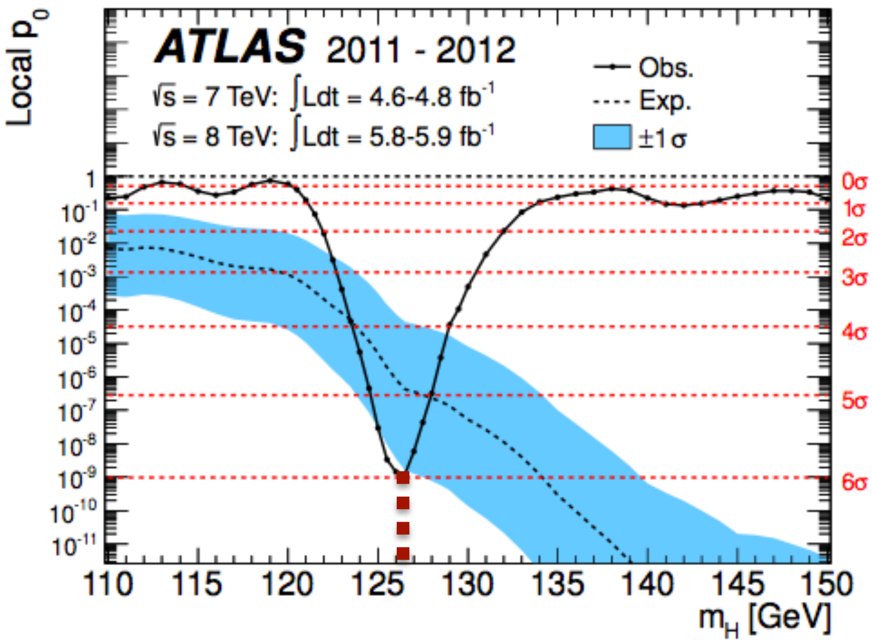
125.3 ± 0.4 (stat) ± 0.5 (syst)

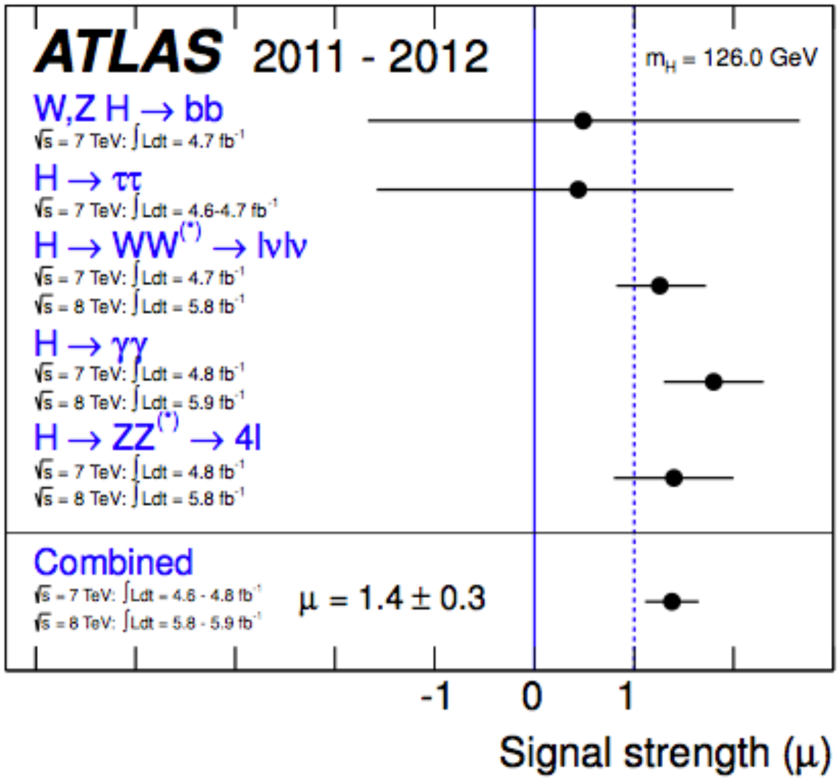
at significance level of

$5\ \sigma$

ATLAS: Characterization of the Excess

μ = 0 : background-only hypothesis
μ = 1 : SM Higgs boson signal + background.





Observed local p0 as a function of M_H

Signal strength parameter μ for M_H =126 GeV

ATLAS Conclusion

Clear evidence for the production of a neutral boson with mass of

126.0 ± 0.4 (stat) ± 0.4 (sys) GeV

and significance of

$5.9\ \sigma$

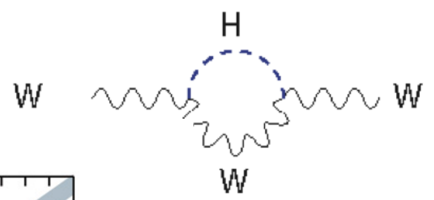
corresponding to a background fluctuation probability of

1.7×10^{-9}

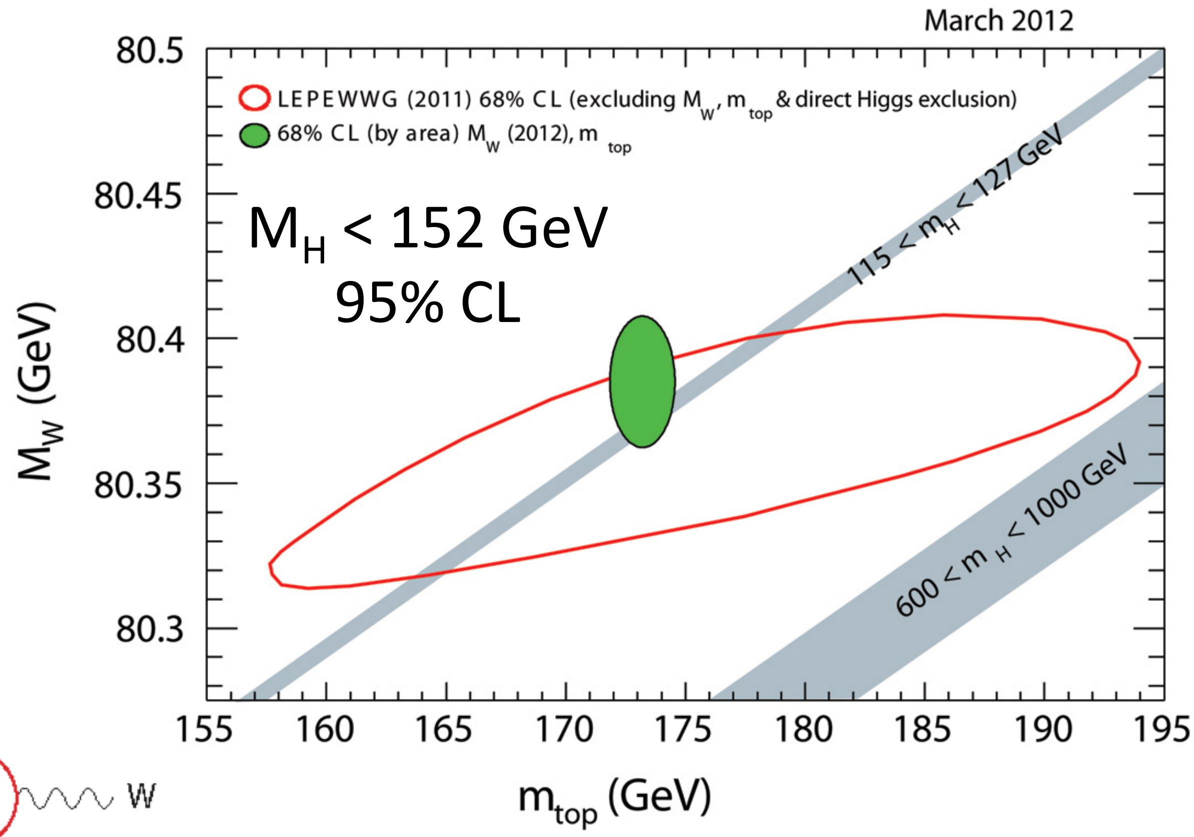

O Modelo Padrão
ESTRUTURA ELEMENTAR DA MATÉRIA

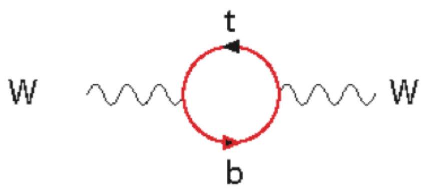

Simple and robust
Published for 2011 data
OLD GUYS RULE
GOT RUM?

Indirect Bound from Tevatron



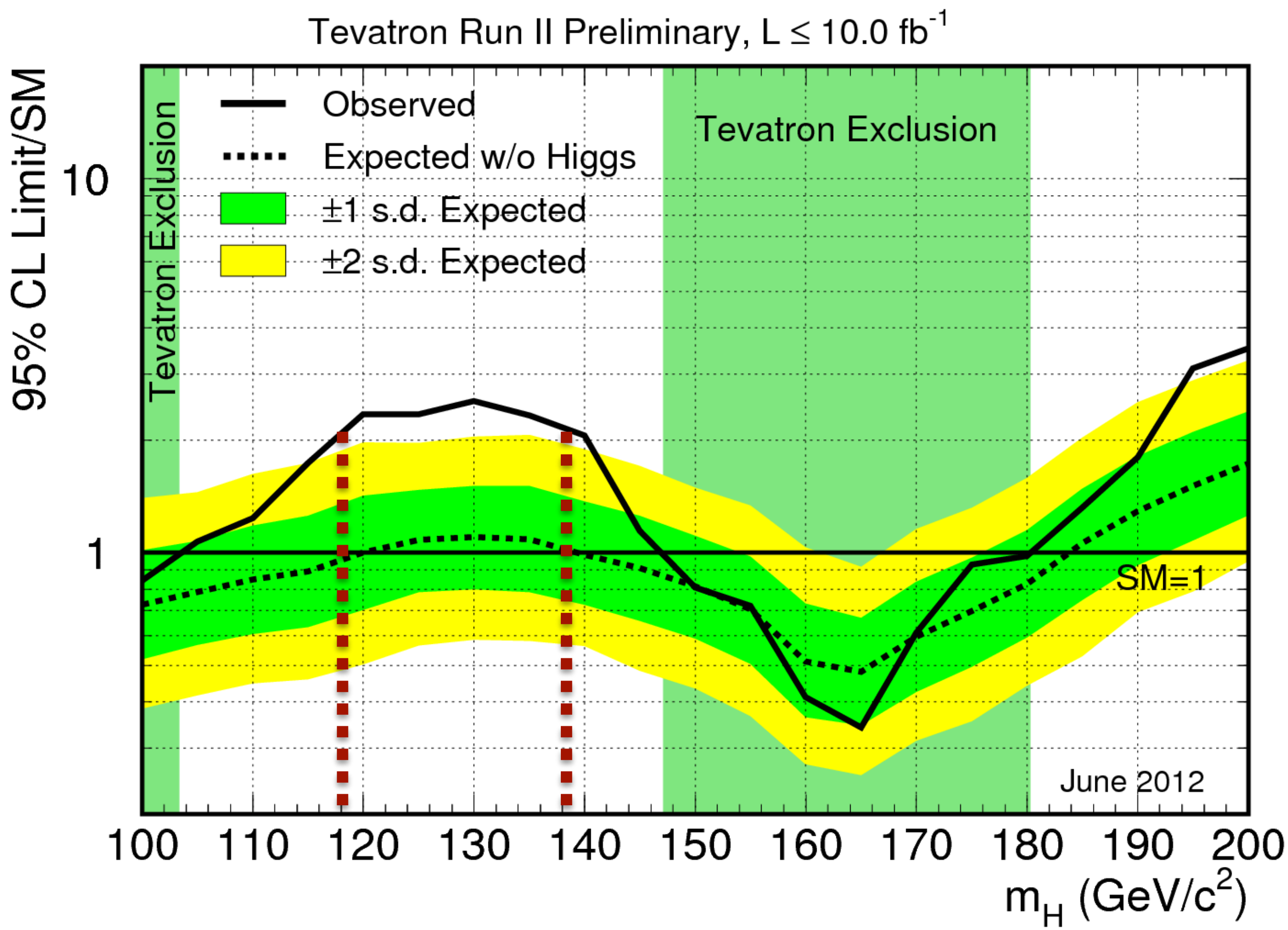
$\propto \log M_H$





$\propto m_{top}^2$

Tevatron Exclusion



CDF + D0 Conclusion

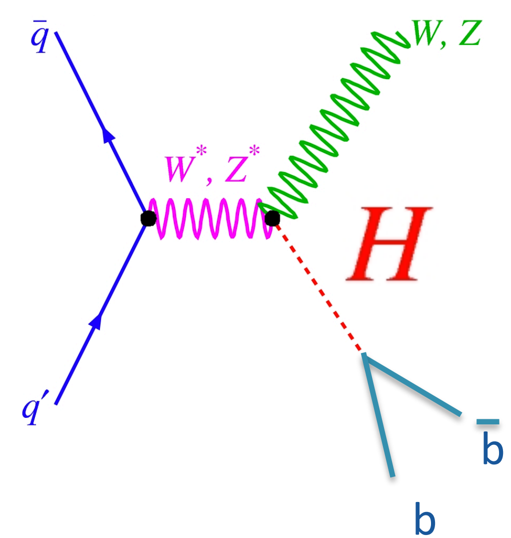
We observed an excess of events in the range

120-135 GeV.

with the global significance of

3.1 σ

Evidence for a new particle consistent with the standard model Higgs boson produced in association with a vector boson and decays to a bb pair.



I think we have it.
Do you agree?

Rolf-Dieter Heuer

Director General of CERN
4 July 2012