THE DISCOVERY OF THE HIGSS BOSON AND WHAT IT TELLS US ABOUT THE UNIVERSE

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CERN Croatian Teacher Programme

27. 03. 2024.

What it tells us about the Universe?

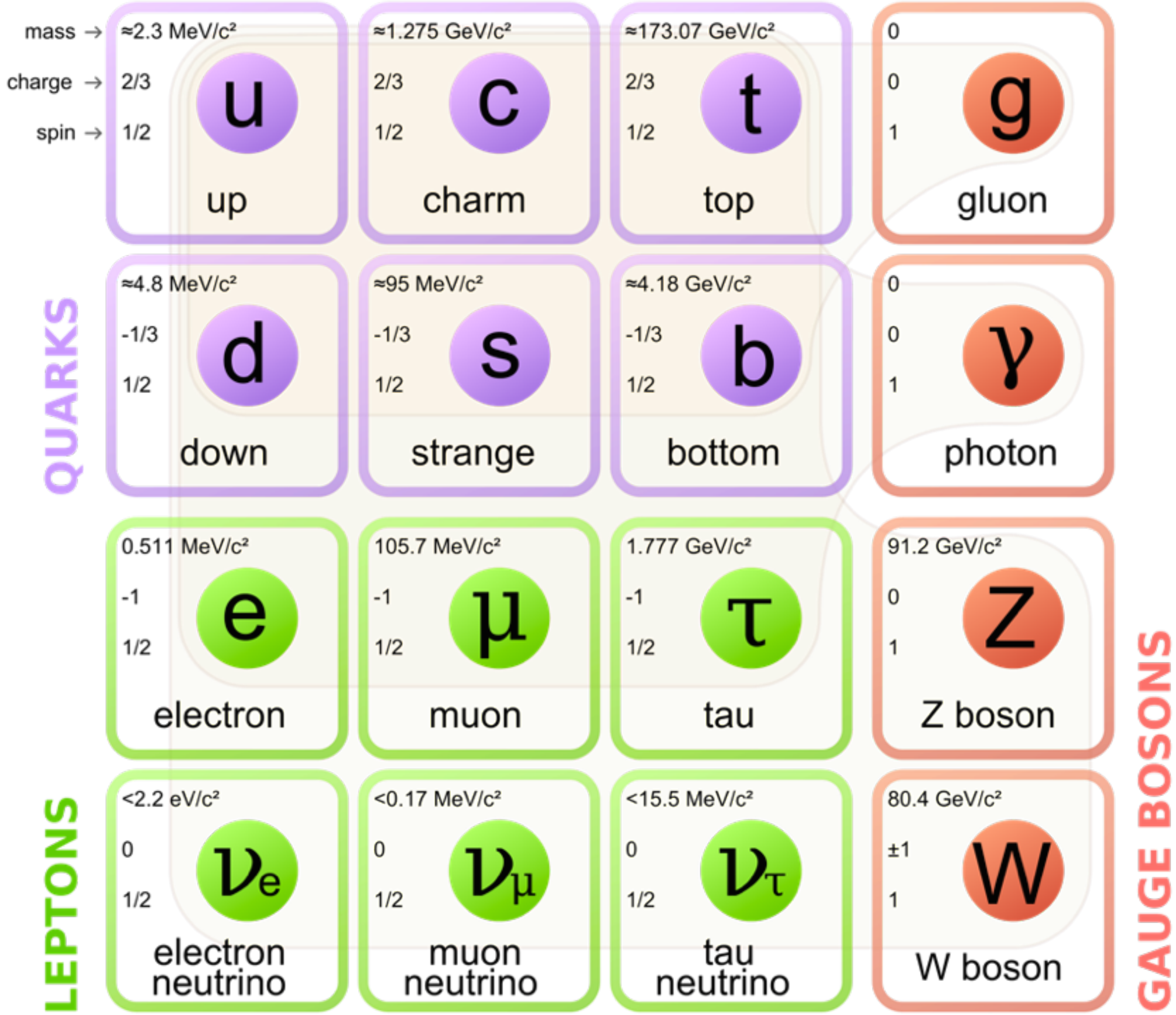
STANDARD MODEL

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G^{\alpha}_{\mu\nu} G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

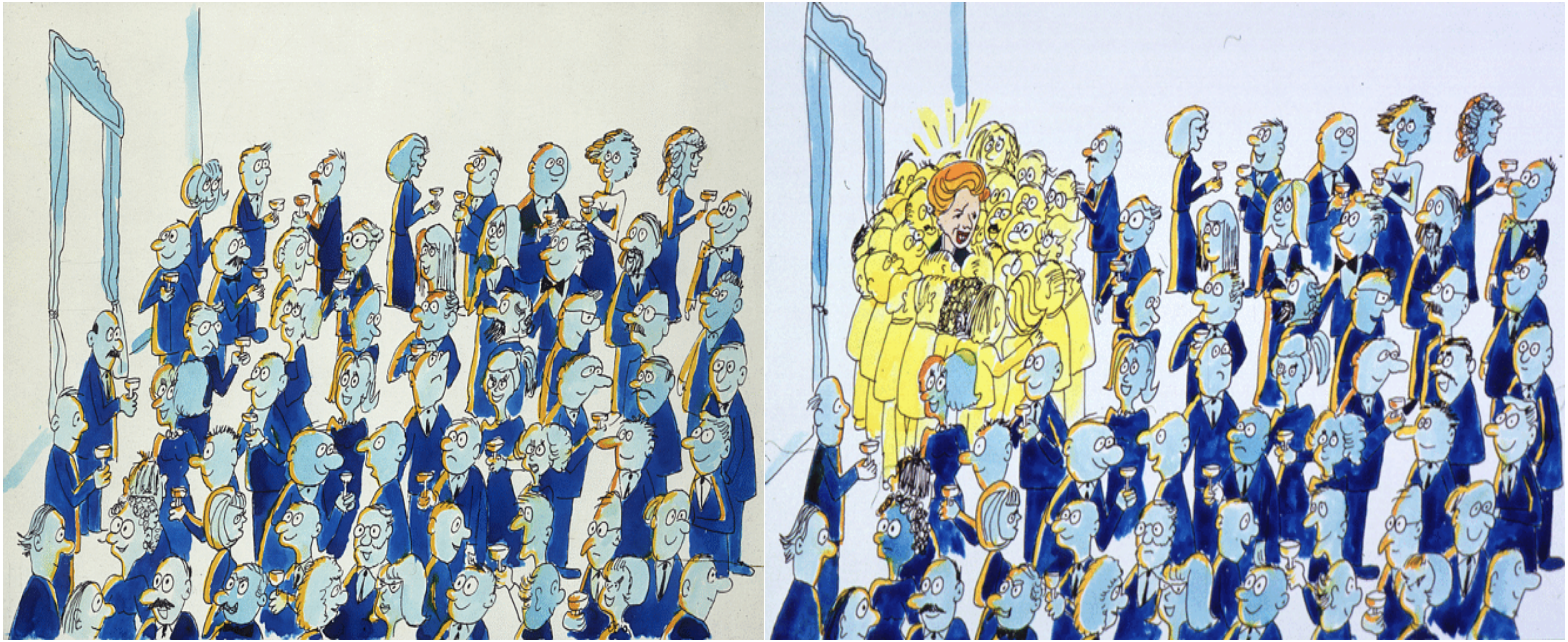
$$+ \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2} g\tau \cdot W_{\mu} - \frac{1}{2} g' Y B_{\mu}\right) L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2} g' Y B_{\mu}\right) R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{g''\left(\bar{q}\gamma^{\mu} T_a q\right) G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}}$$

Problem: all particles are massless!



THE HIGGS MECHANISM



THE HIGGS MECHANISM

HOW TO GIVE MASS TO PARTICLES?

- Imagine a particle interacting with a scalar field in CM:

$$L_{\text{CM}} = \frac{1}{2}m\dot{x}^2 - g\phi(t,x)$$

- Plugging it in the Euler-Lagrange equation we get: $m\ddot{x} = -g\dfrac{\partial\phi(t,x)}{\partial x}$
- If we switch to the STR, the free particle Lagrangian becomes:

$$L_{\text{STR}} = -mc^2\sqrt{1-\frac{\dot{x}^2}{c^2}}$$

- How can we couple it to a scalar field?
- Option $L_{\text{STR}} = -[mc^2 + g\phi(t,x)]\sqrt{1-\dfrac{\dot{x}^2}{c^2}}$ reduces to L_{CM} in the limit v << c.

HOW TO GIVE MASS TO PARTICLES?

- If we again plug it in the Euler-Lagrange equation, we get:

$$\frac{d}{dt}\frac{(m+g\phi(t,x))\dot{x}}{\sqrt{1-\dot{x}^2/c^2}} = -g\frac{\partial\phi(t,x)}{\partial x}\sqrt{1-\frac{\dot{x}^2}{c^2}}$$

- or in the limit of v<<c

$$\frac{d}{dt}[(m+g\phi(t,x))\dot{x}] = -g\frac{\partial\phi(t,x)}{\partial x}$$

- A very interesting and beautiful thing happens if the scalar field is constant $\phi(t,x) = C$:

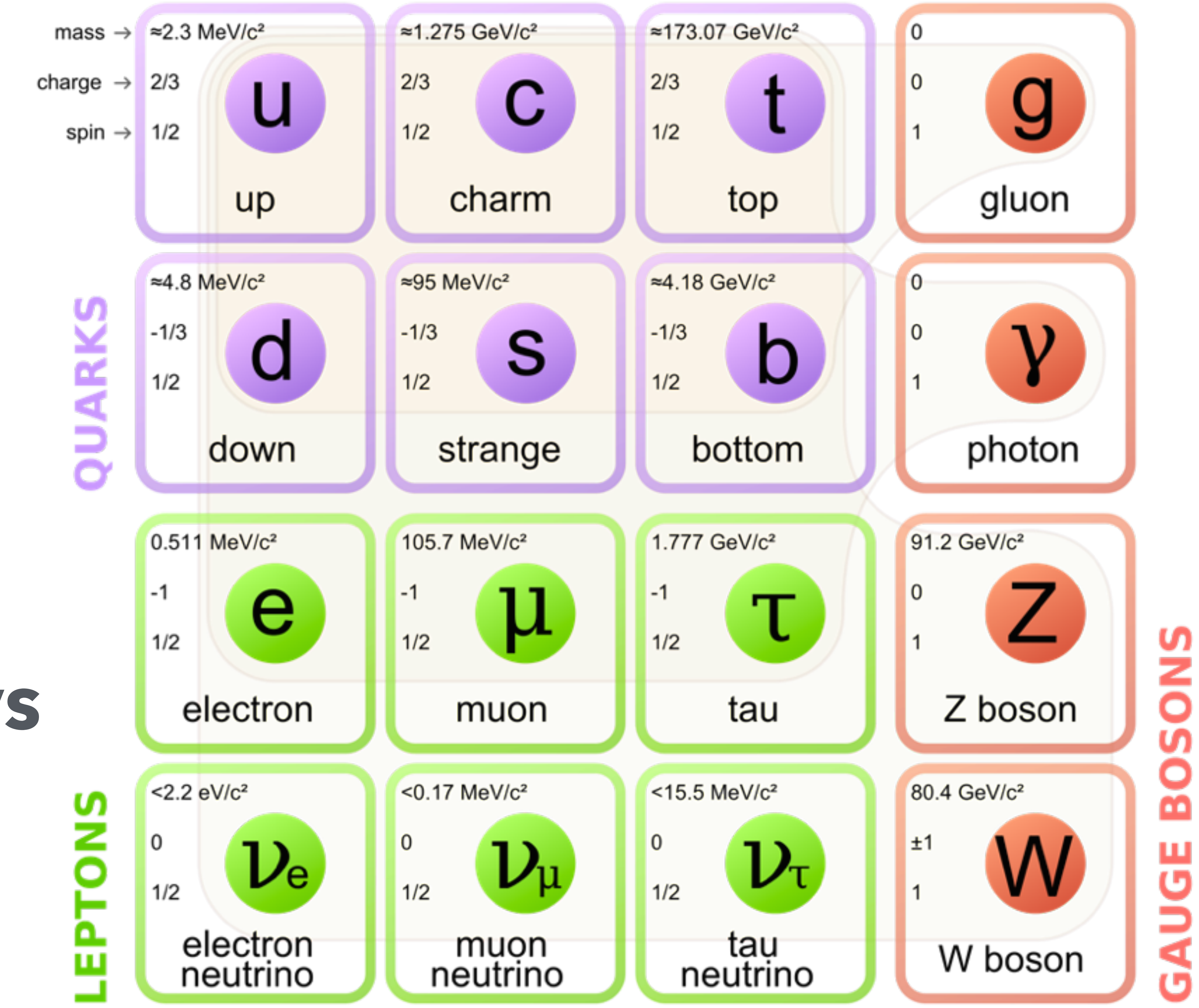
$$(m+g\phi(t,x))\ddot{x} = 0$$

- A particle of mass m interacting with the constant scalar field ϕ moves like a free particle of mass $m+\phi$!

IT IS NOT THAT SIMPLE!

Symmetries:

- Global Poincare
- Local $SU(3) \otimes SU(2) \otimes U(1)$



***Simply adding the mass term in the Lagrangian completely destroys the symmetries and in turn laws of conservation!**

SPONTANEOUS SYMMETRY BREAKING

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

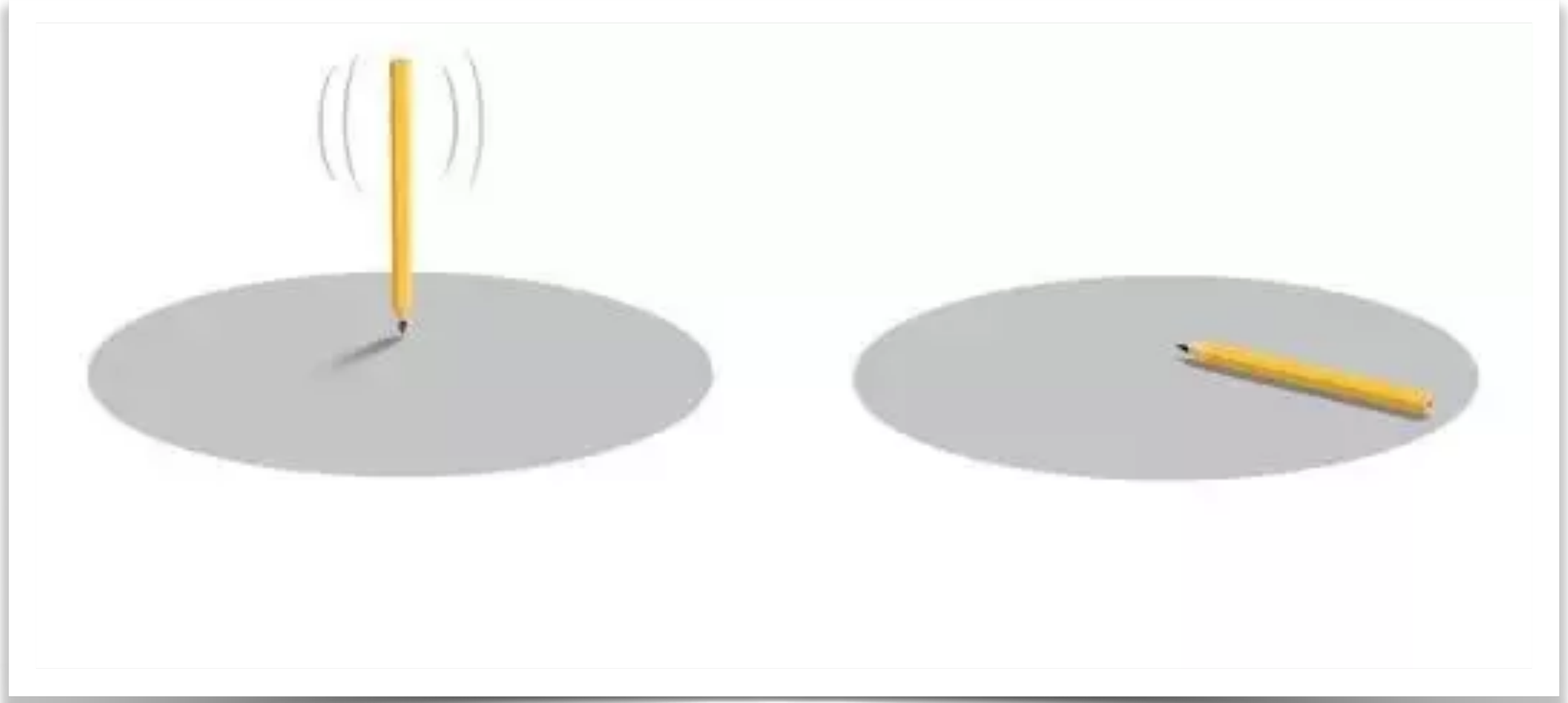
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

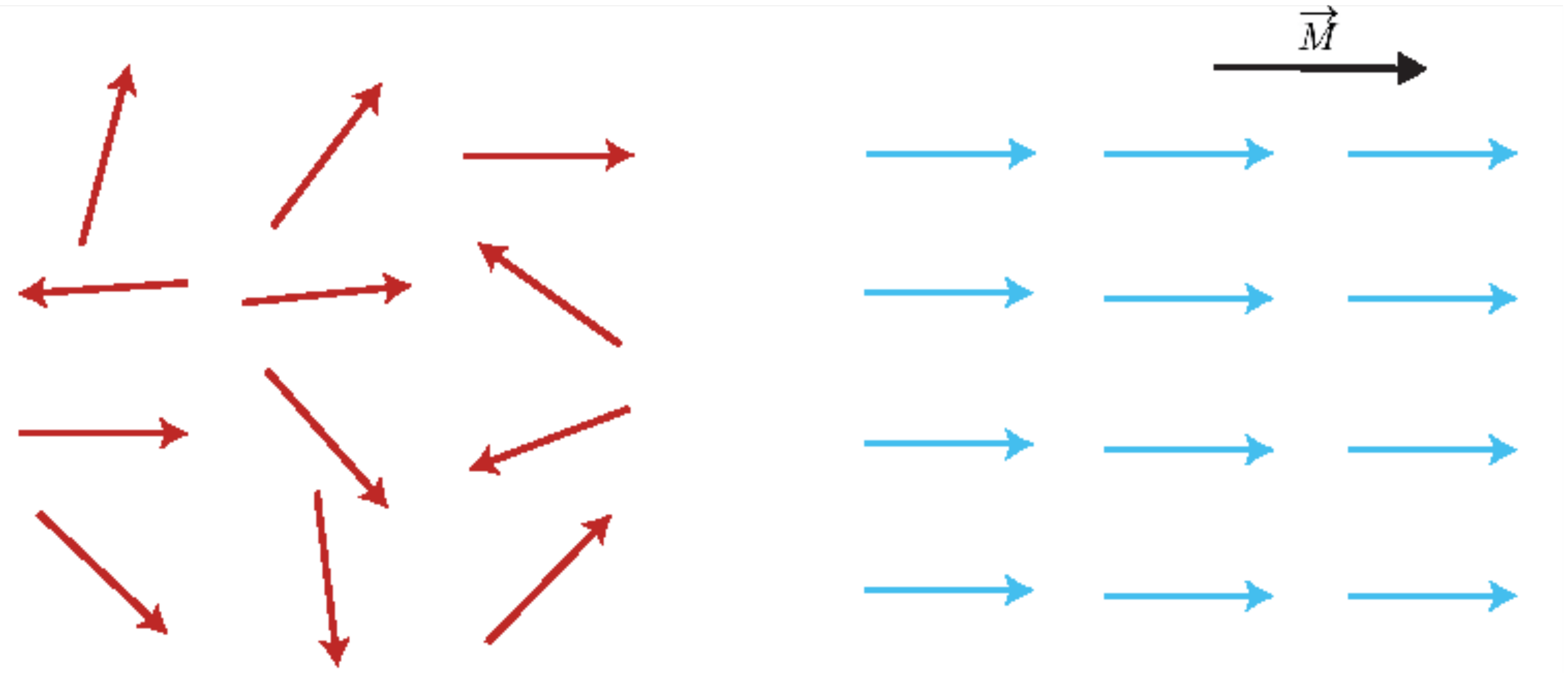
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)





(a) The ferromagnet for $T > T_c$. The global rotational symmetry is unbroken.

(b) The ferromagnet for $T < T_c$. The global rotational symmetry is spontaneously broken.

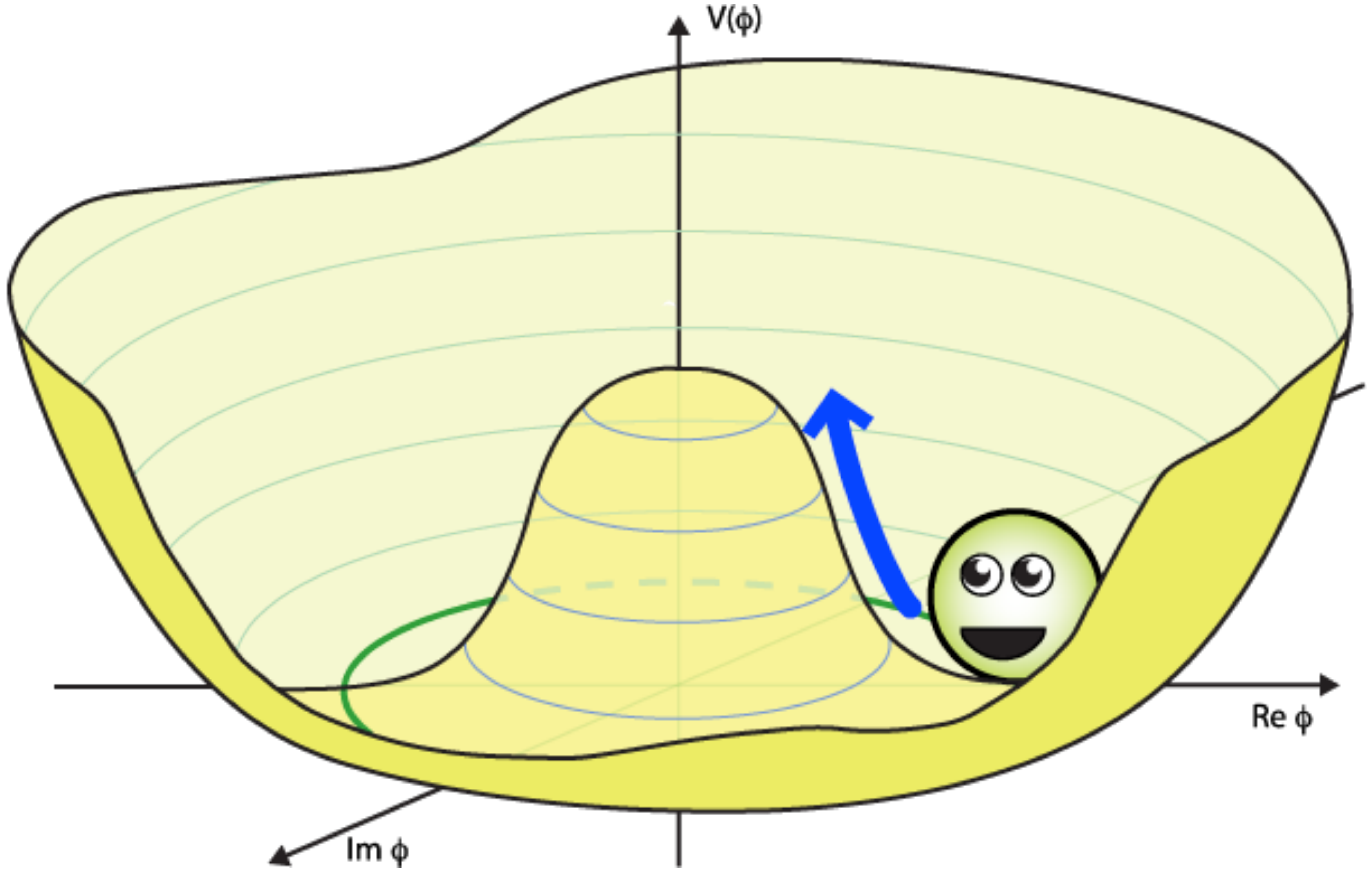
SOLUTION TO THE PROBLEM

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^{2} - V(\phi)}_{W^{\pm}, Z, \gamma \text{ and Higgs masses and couplings}}$$

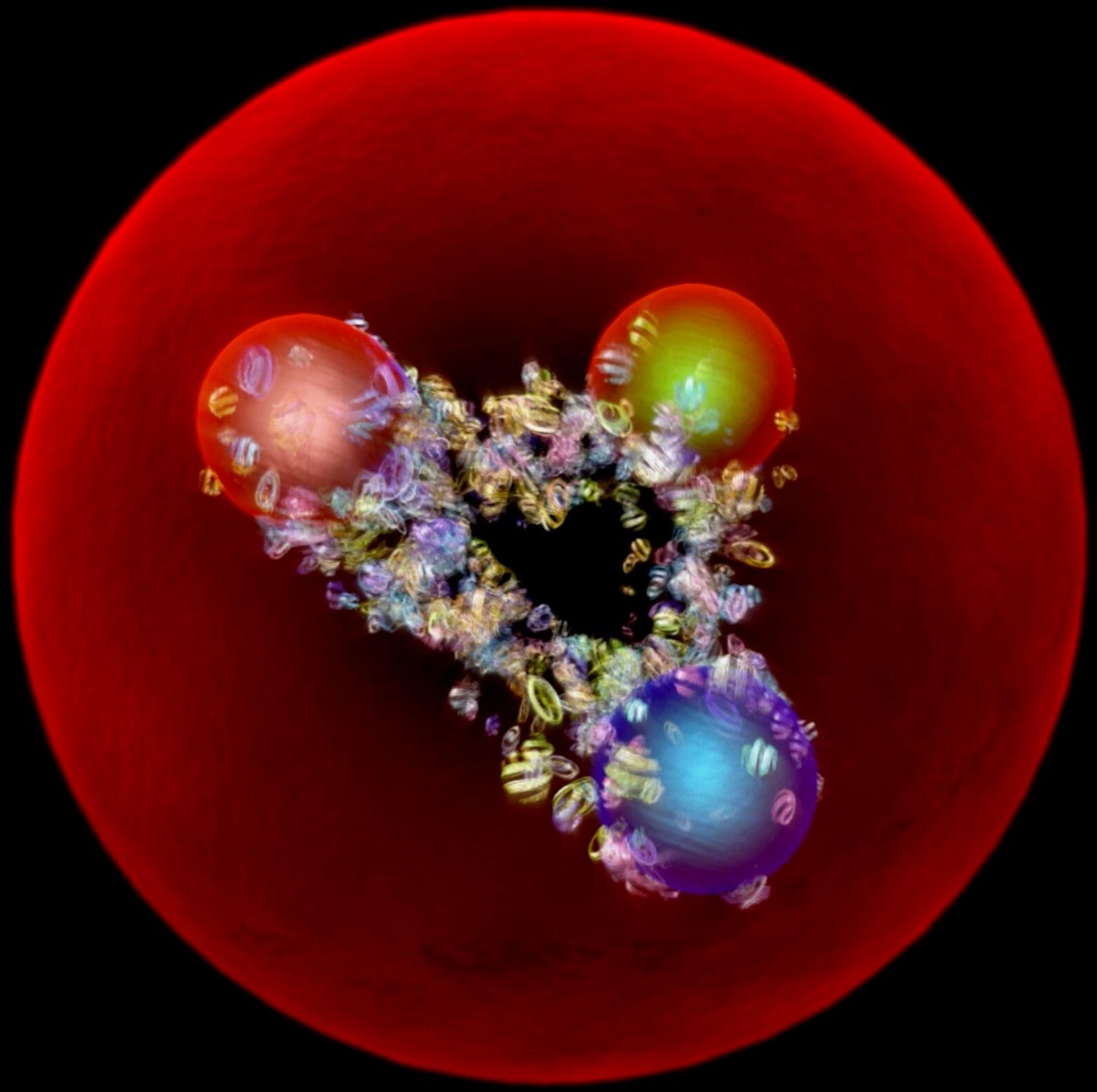
$$+ \underbrace{g''\left(\bar{q}\gamma^{\mu}T_{a}q\right)G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.\right)}_{\text{fermion masses and couplings to Higgs}}$$

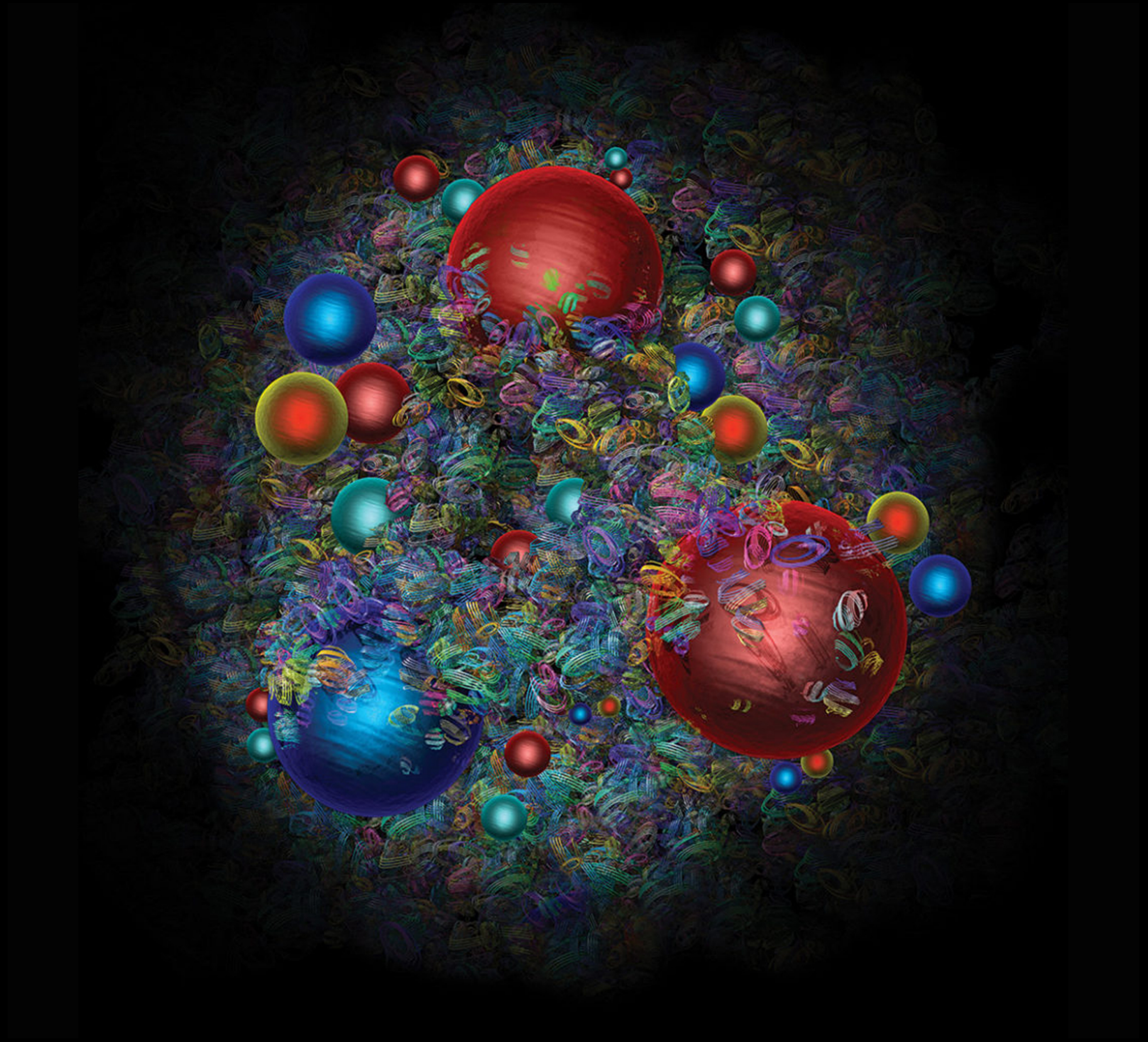


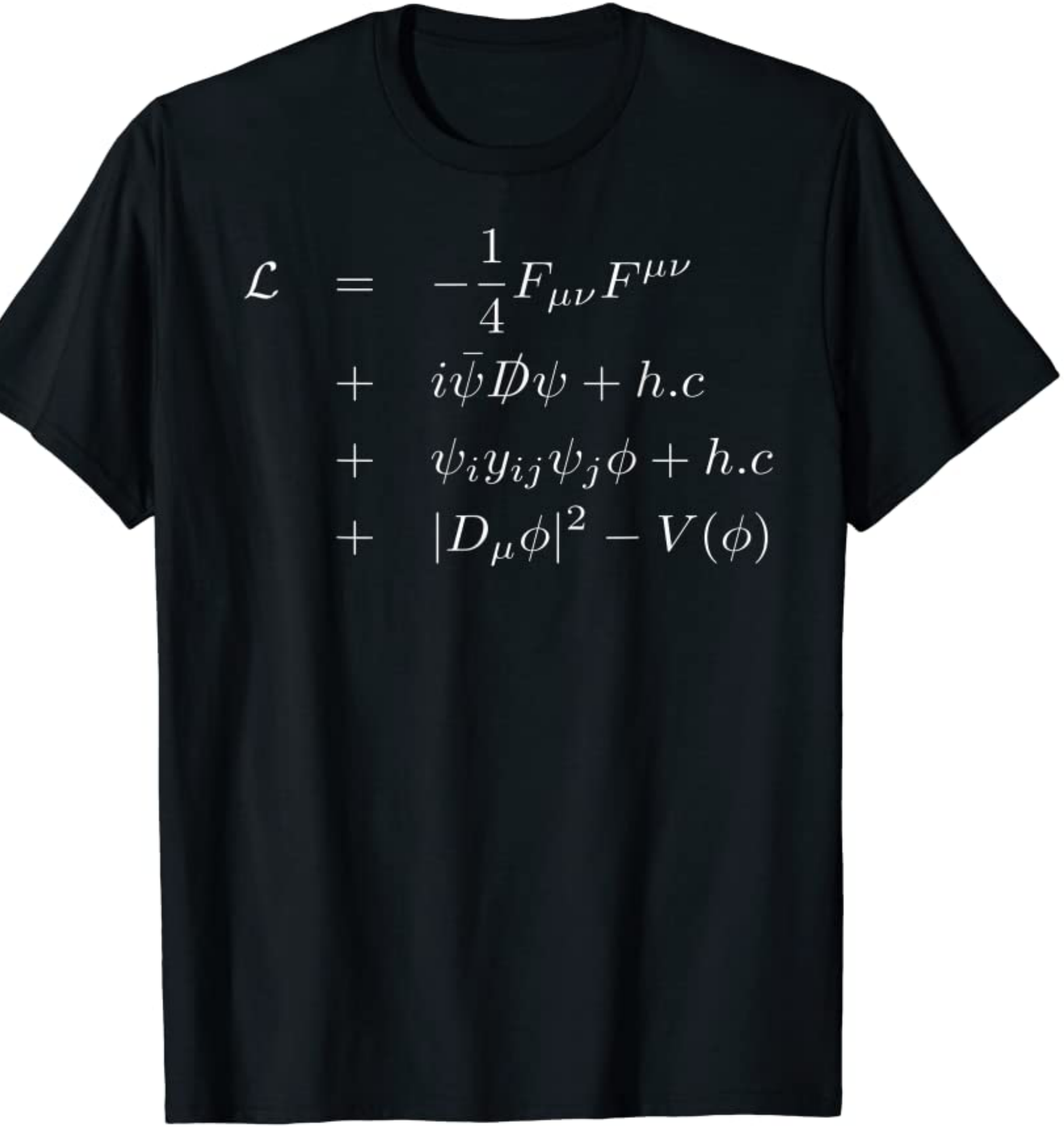
Now it is time to check if the nature is really like that!

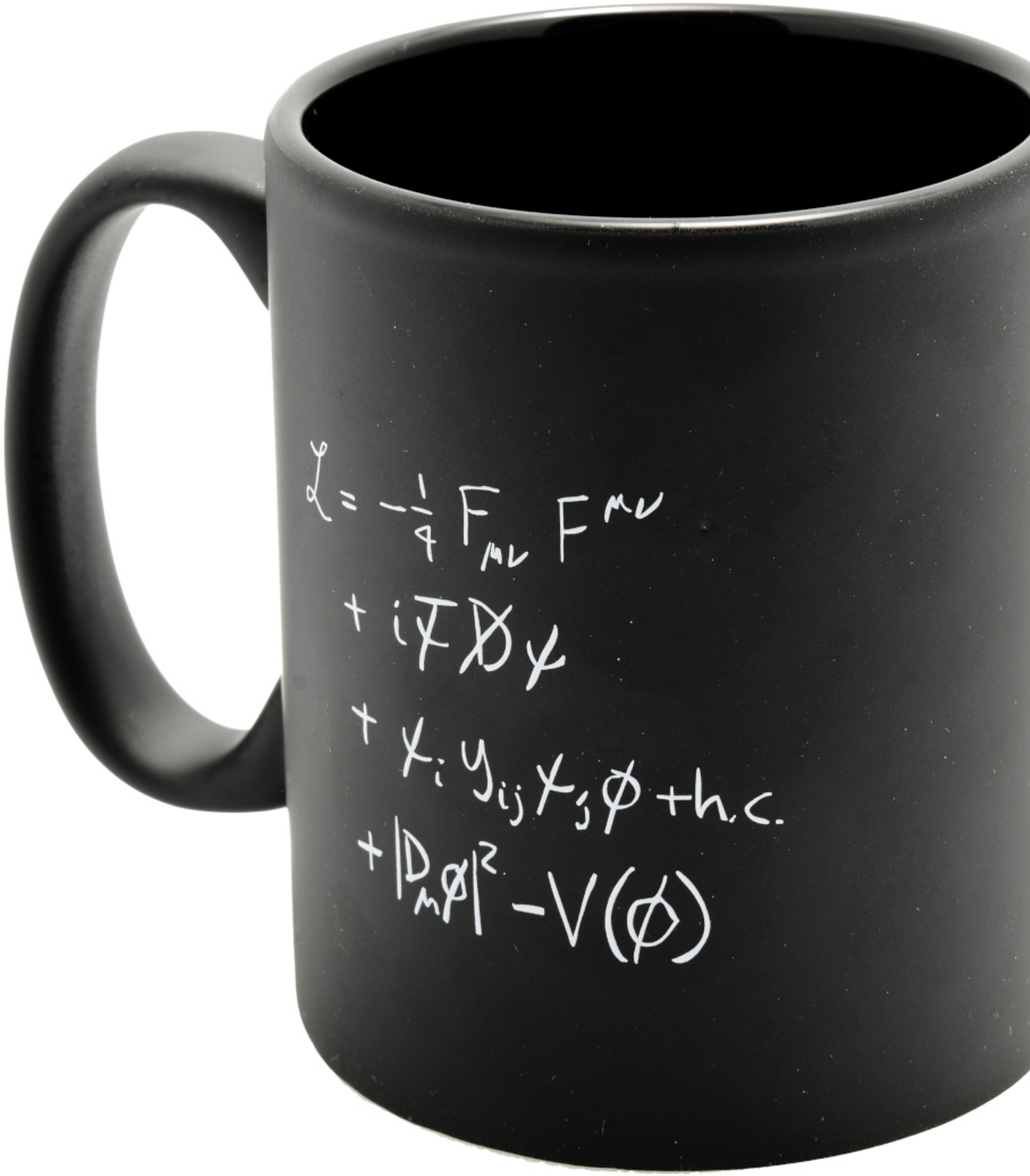

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

COLLIDING PROTONS



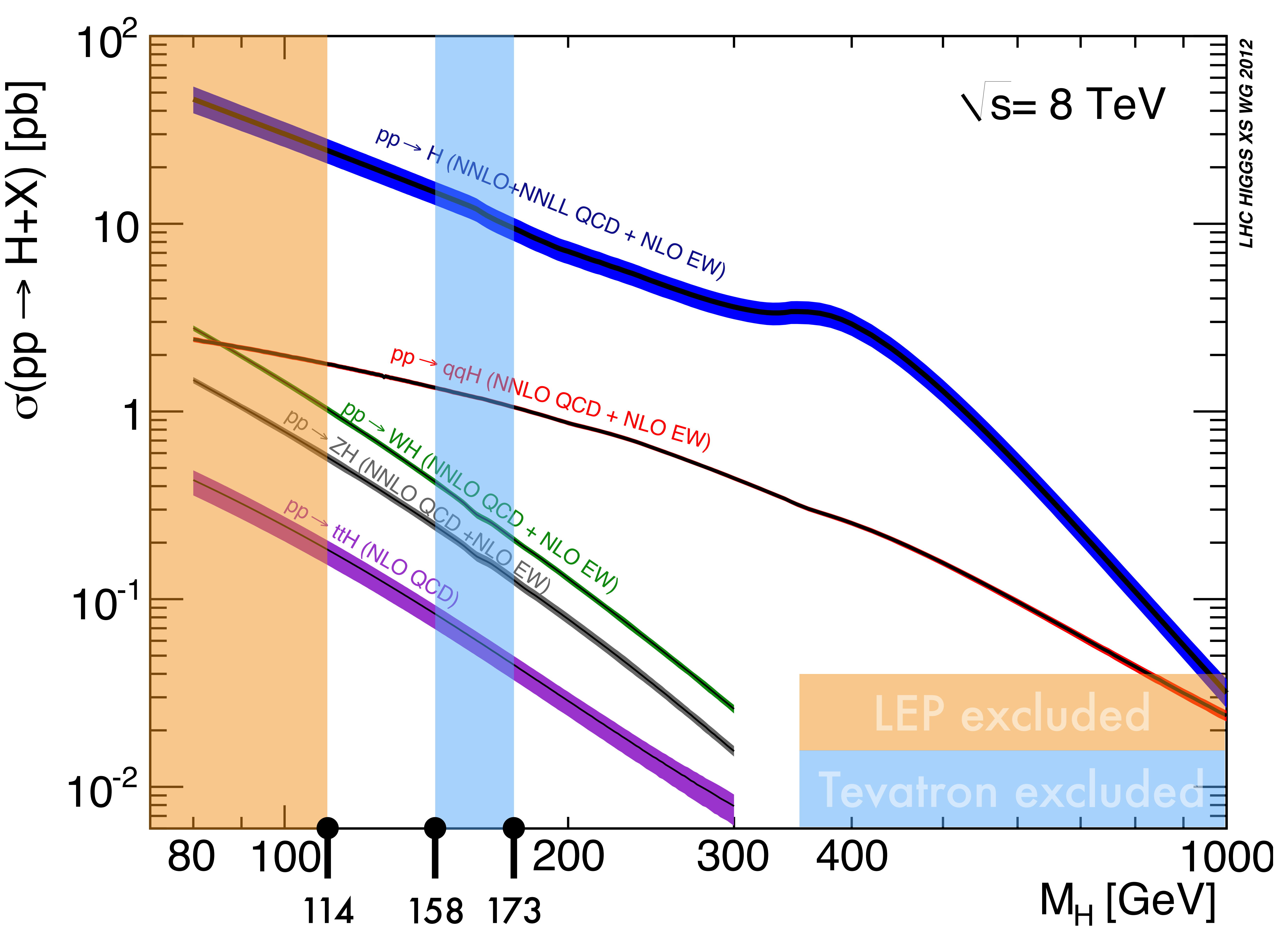


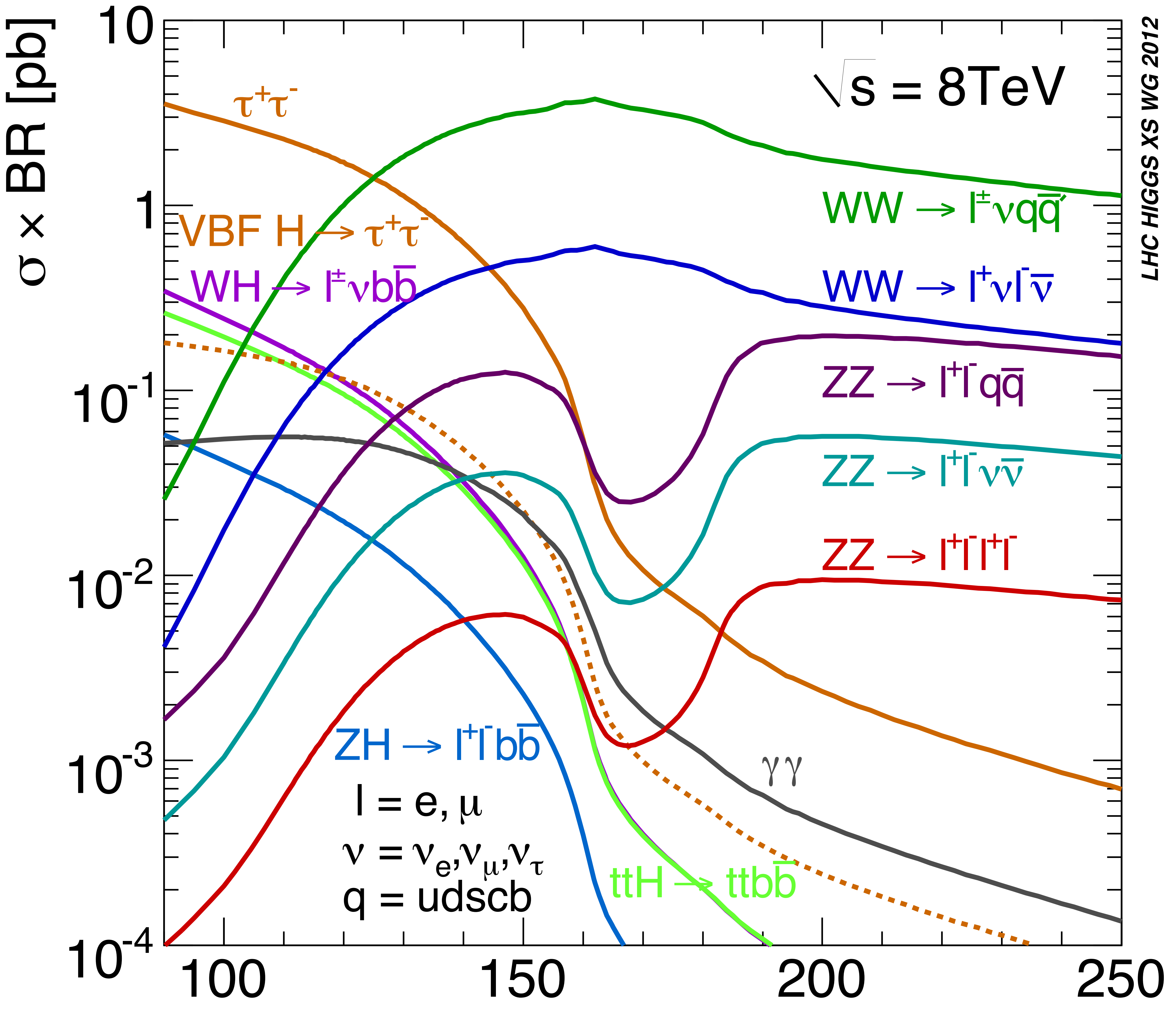

$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$+ \quad i\bar{\psi}\not{D}\psi + h.c$
$+ \quad \psi_i y_{ij}\psi_j\phi + h.c$
$+ \quad |D_\mu\phi|^2 - V(\phi)$


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi}\not{D}\psi$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

HIGGS BOSON PRODUCTION AND DECAY

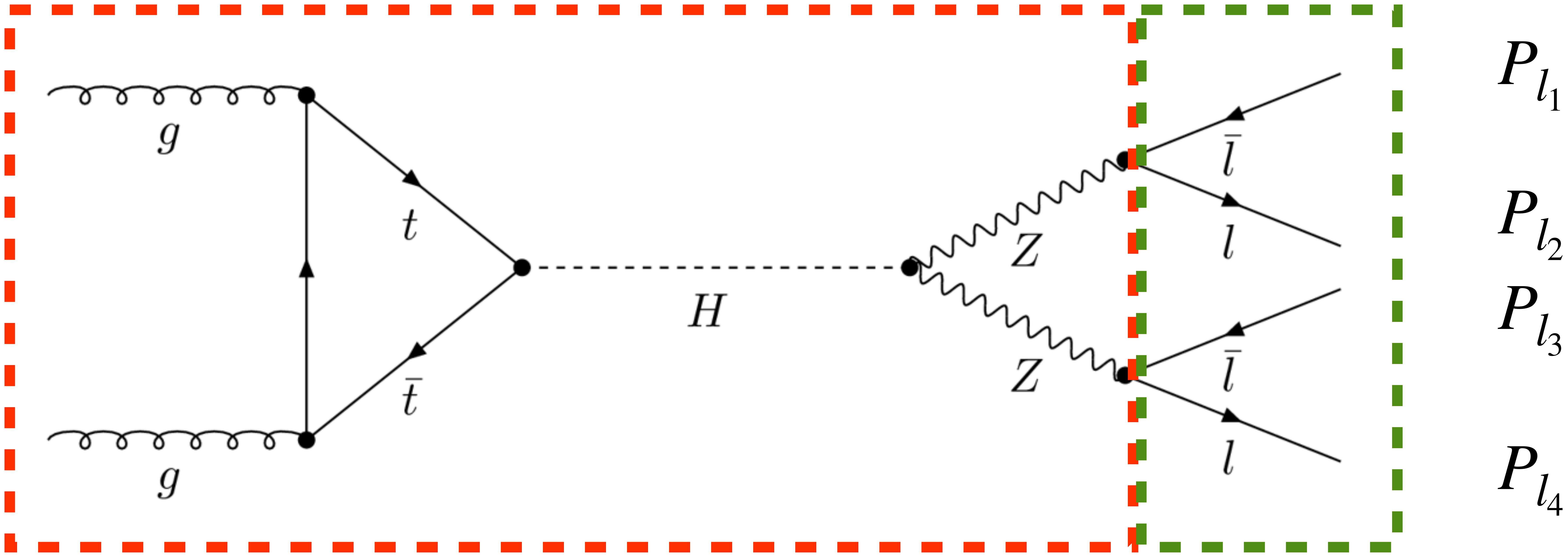
Only one Higgs boson produced in 1.000.000.000 pp collisions!





... and it decays almost immediately!

HOW DO WE LOOK FOR IT?



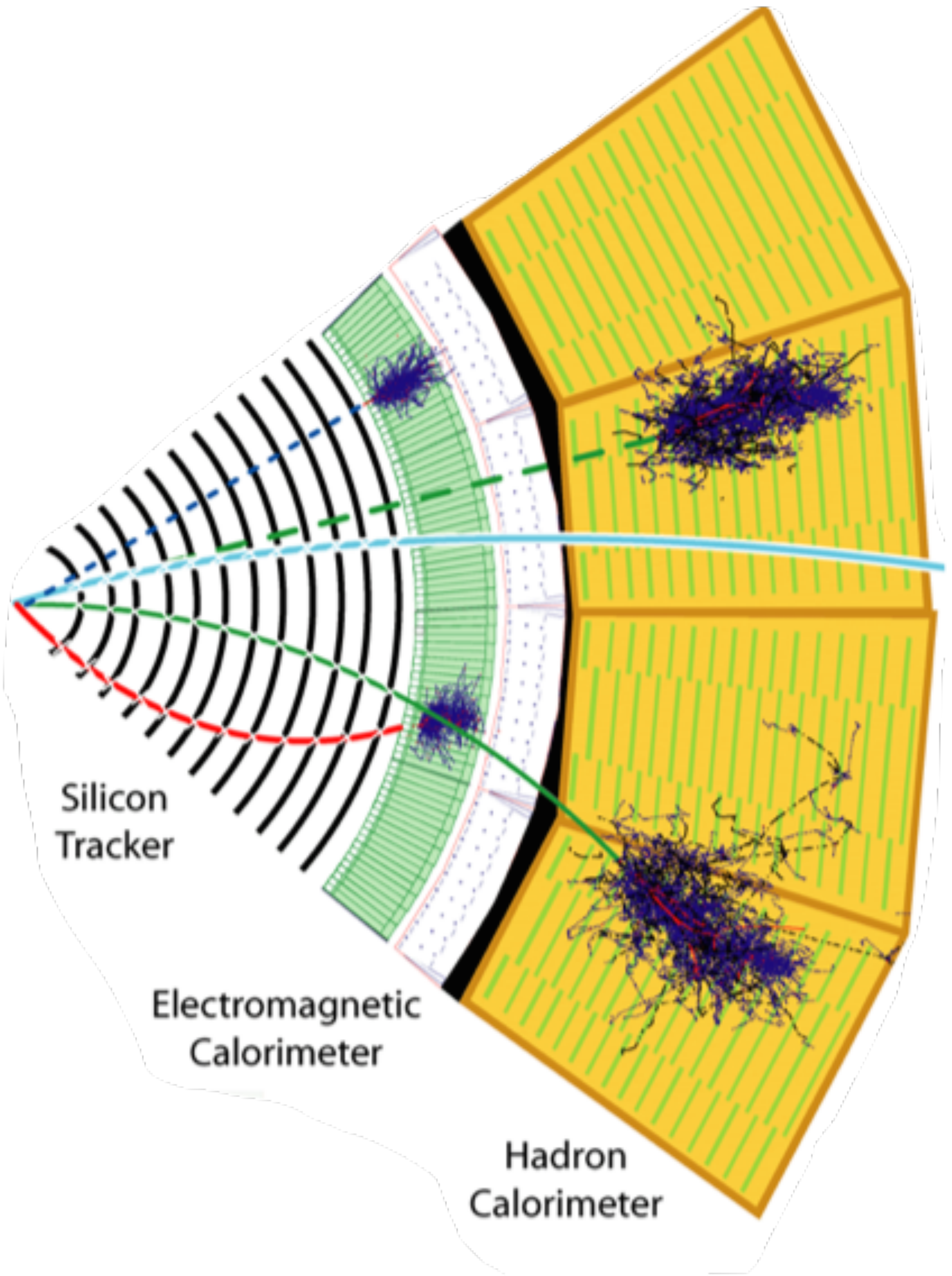
$$P_H = P_{l_1} + P_{l_2} + P_{l_3} + P_{l_4}$$

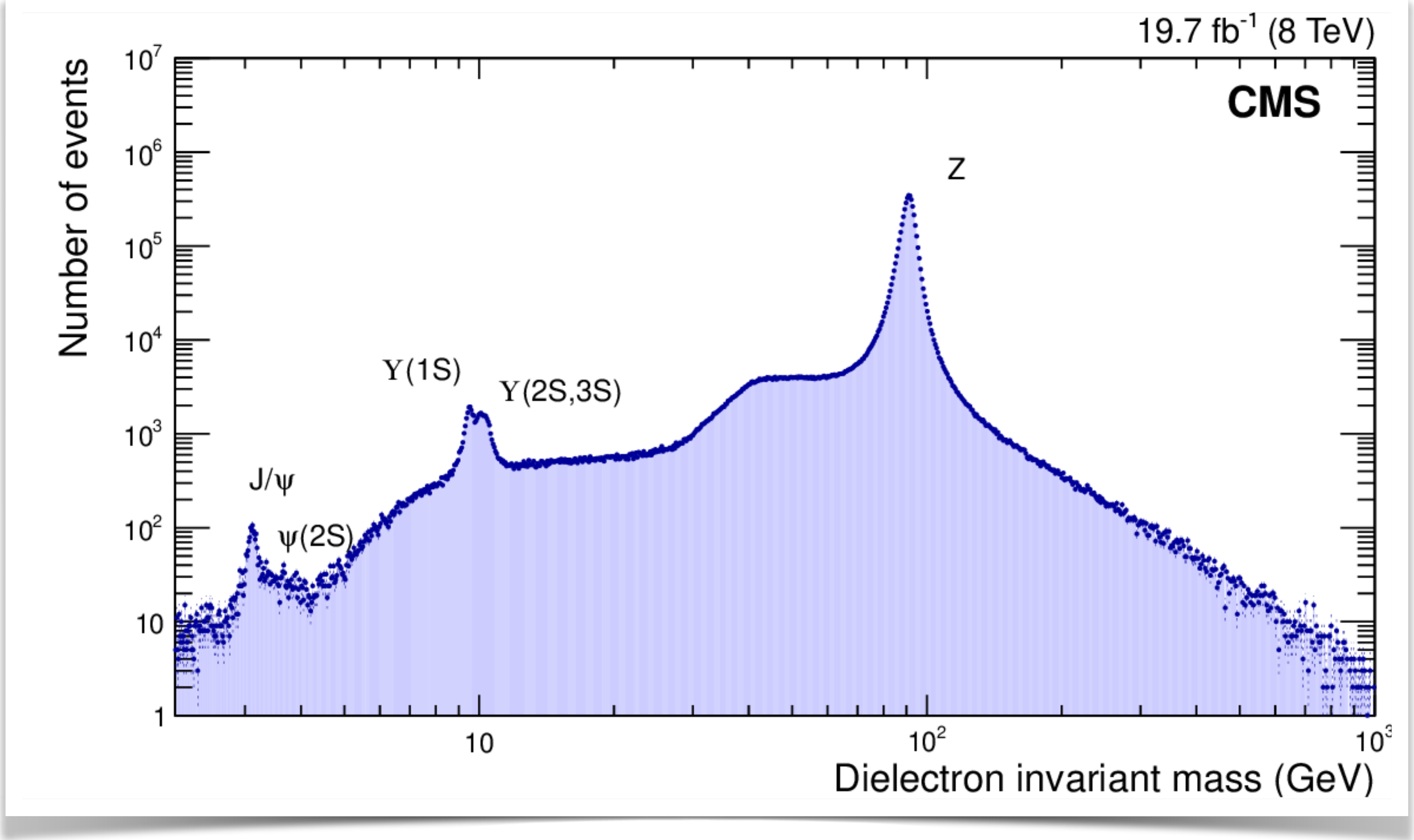
$$m_H^2 c^4 = E^2 - p_H^2 c^2$$

THE COMPACT MUON SOLENOID DETECTOR

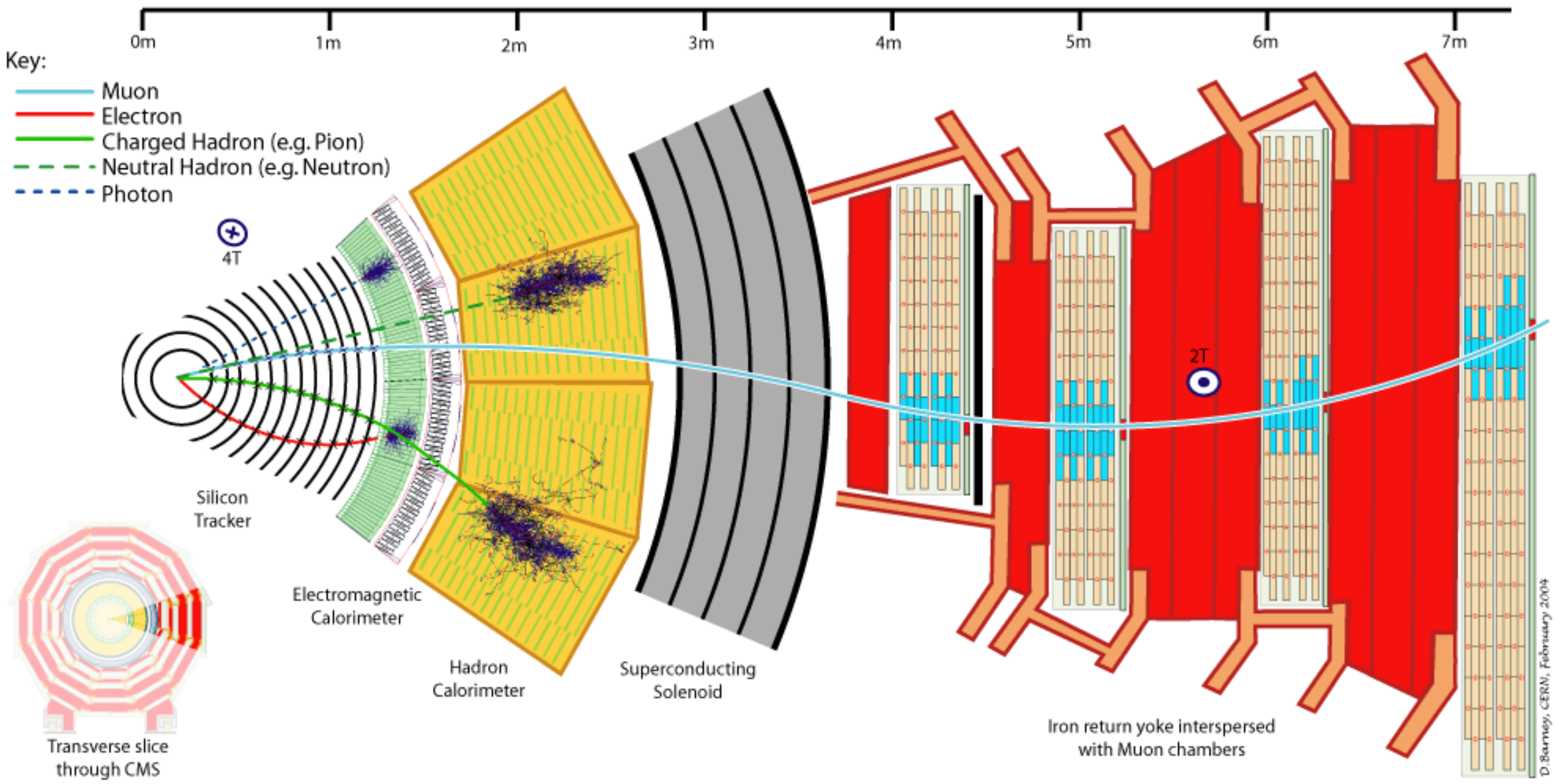

CMS TRIGGER
Standalone muon pair
Muons reconstructed only in the muon detectors
Tracker muon pair
Reconstructed also in the tracker
Hybrid muon pair
One muon of each type
μ
μ
μ
μ
μ
μ
Muon detectors
Tracker

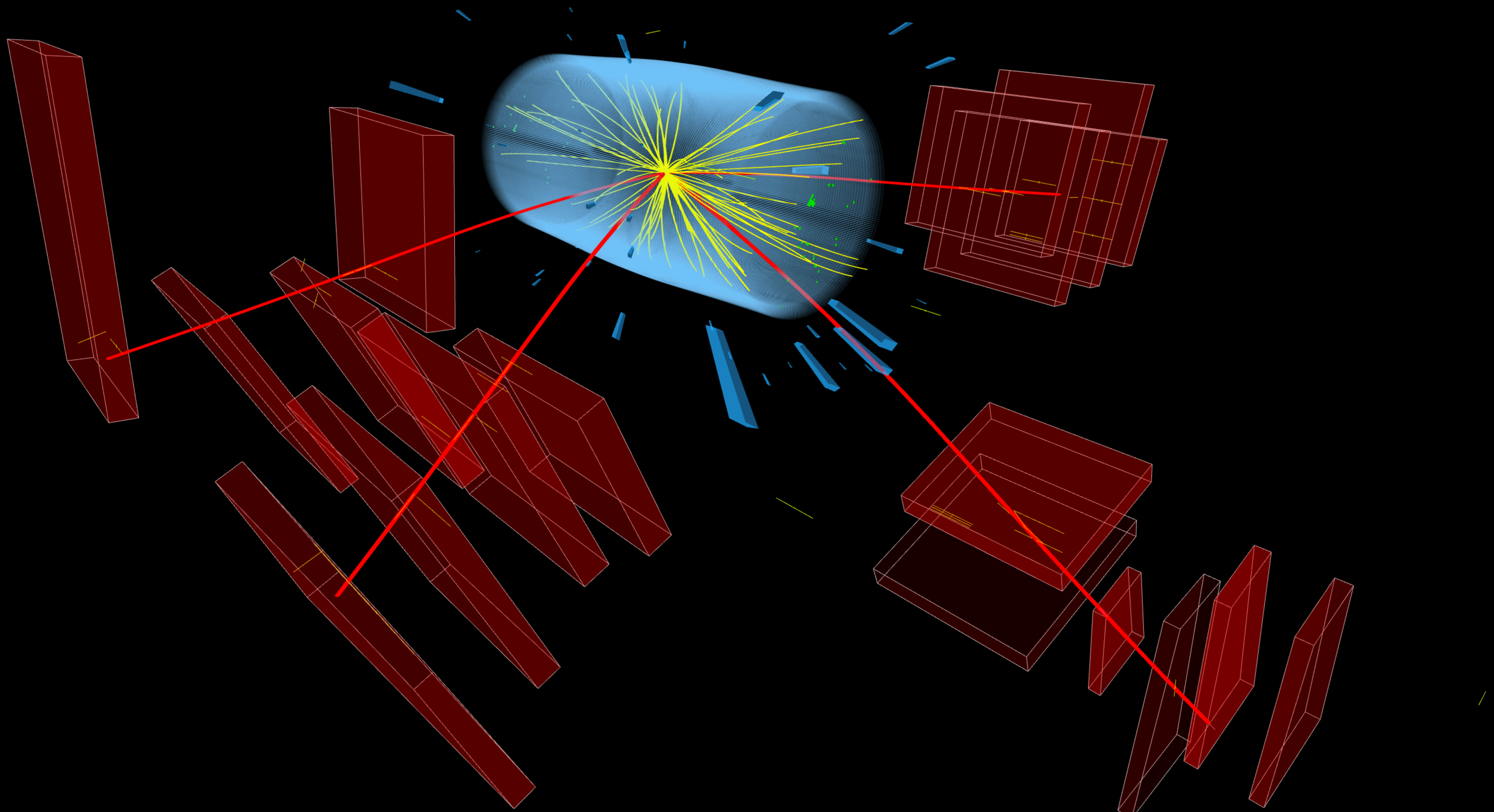
ELECTRON RECONSTRUCTION

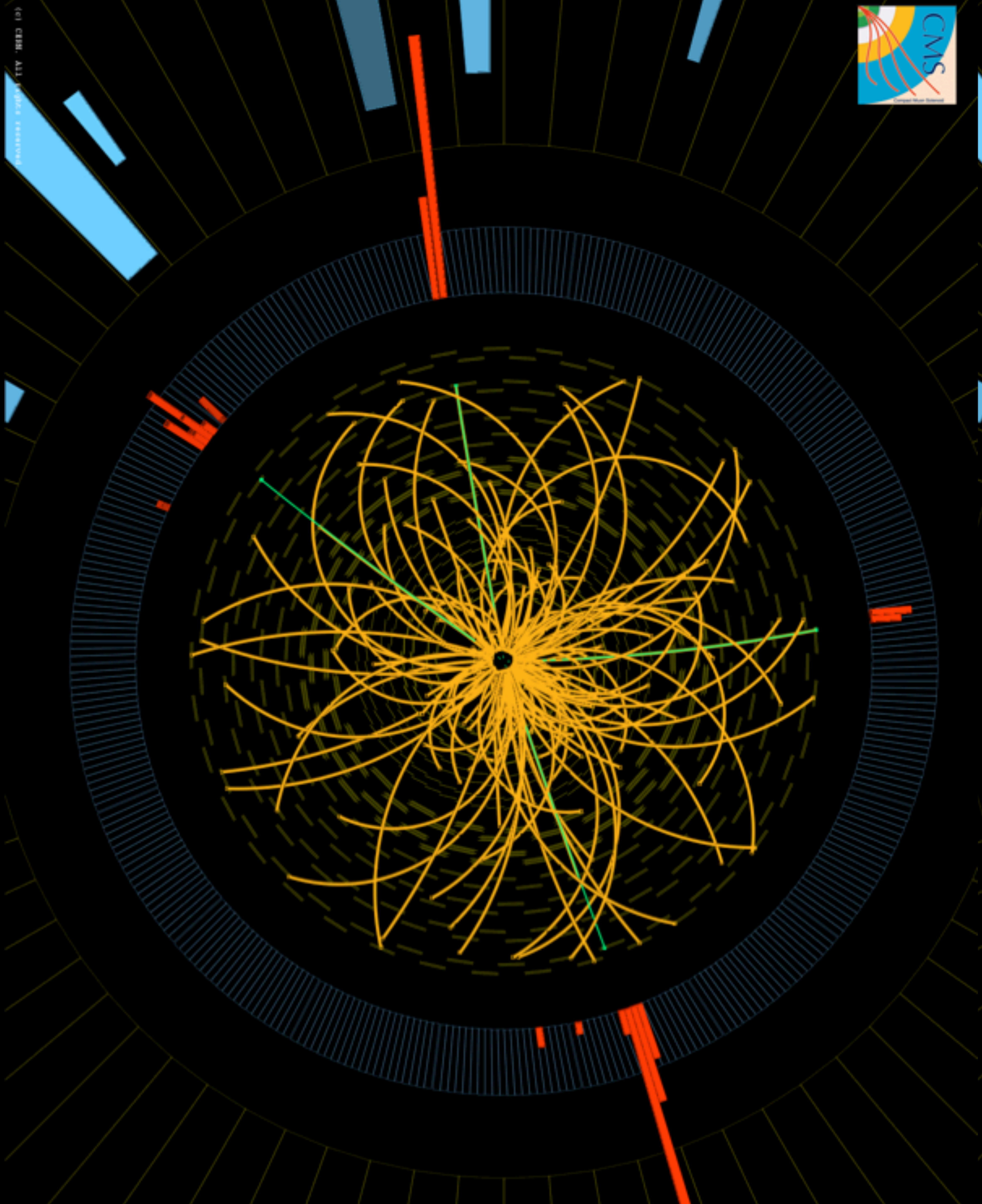


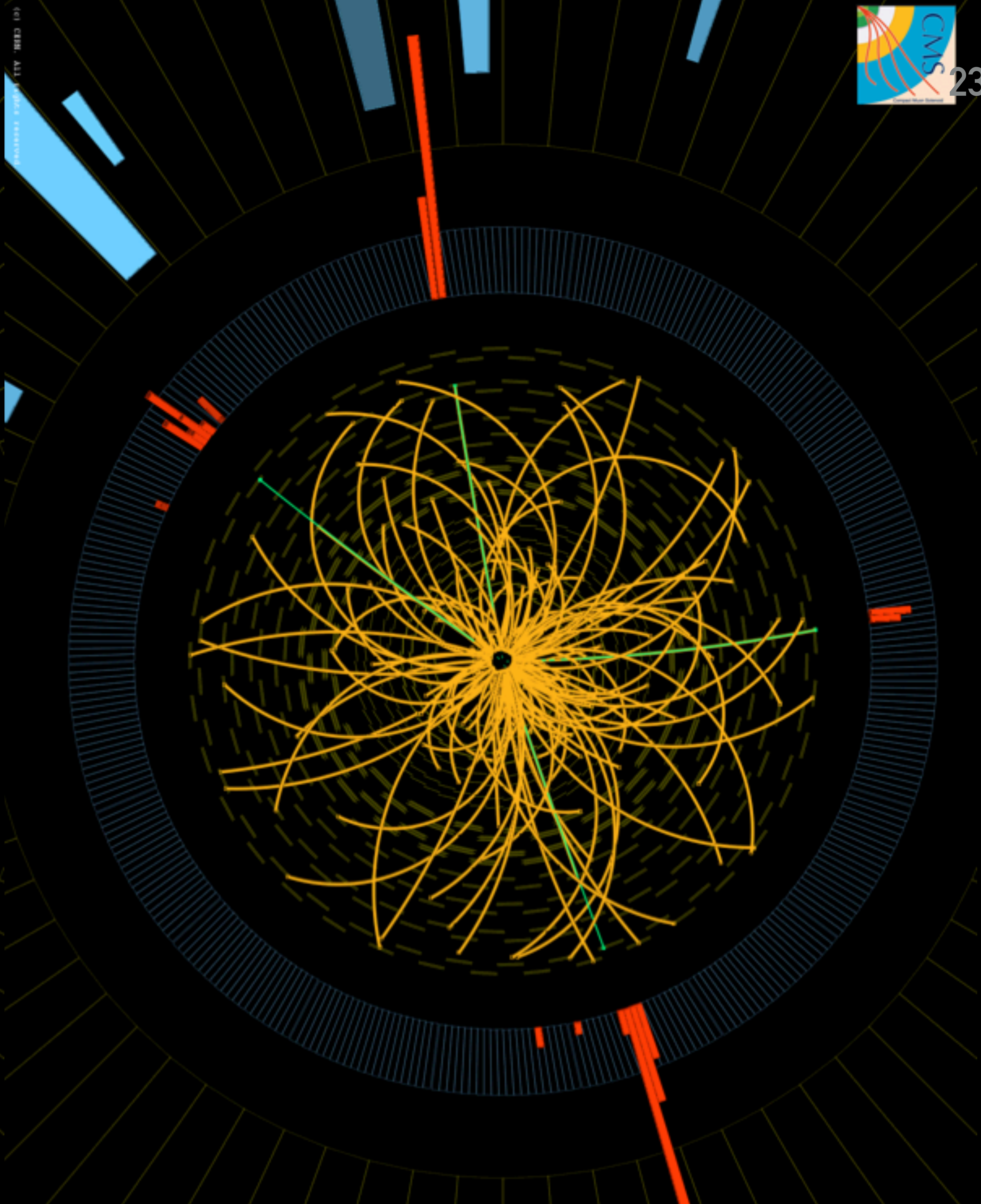


MUON RECONSTRUCTION

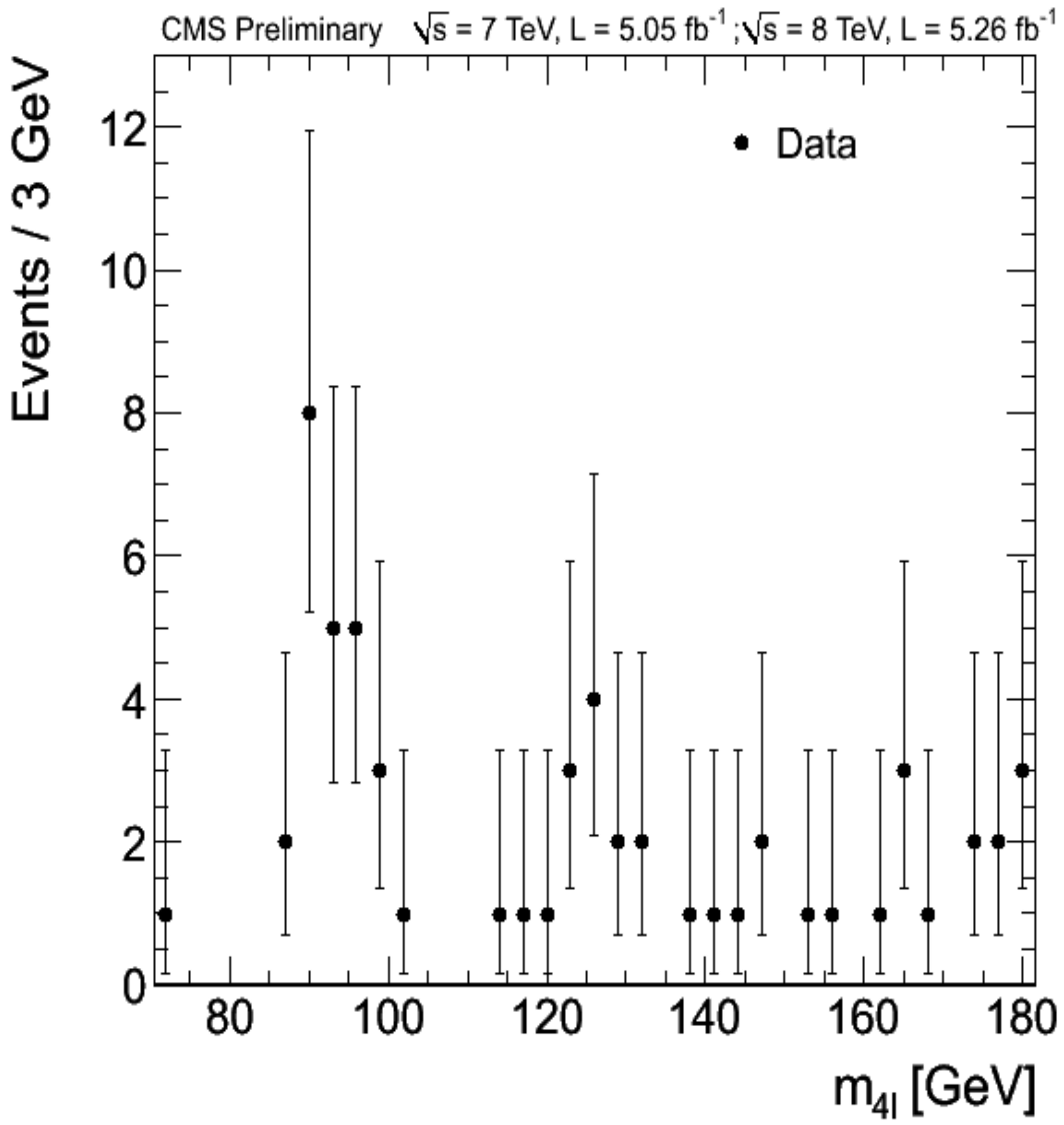




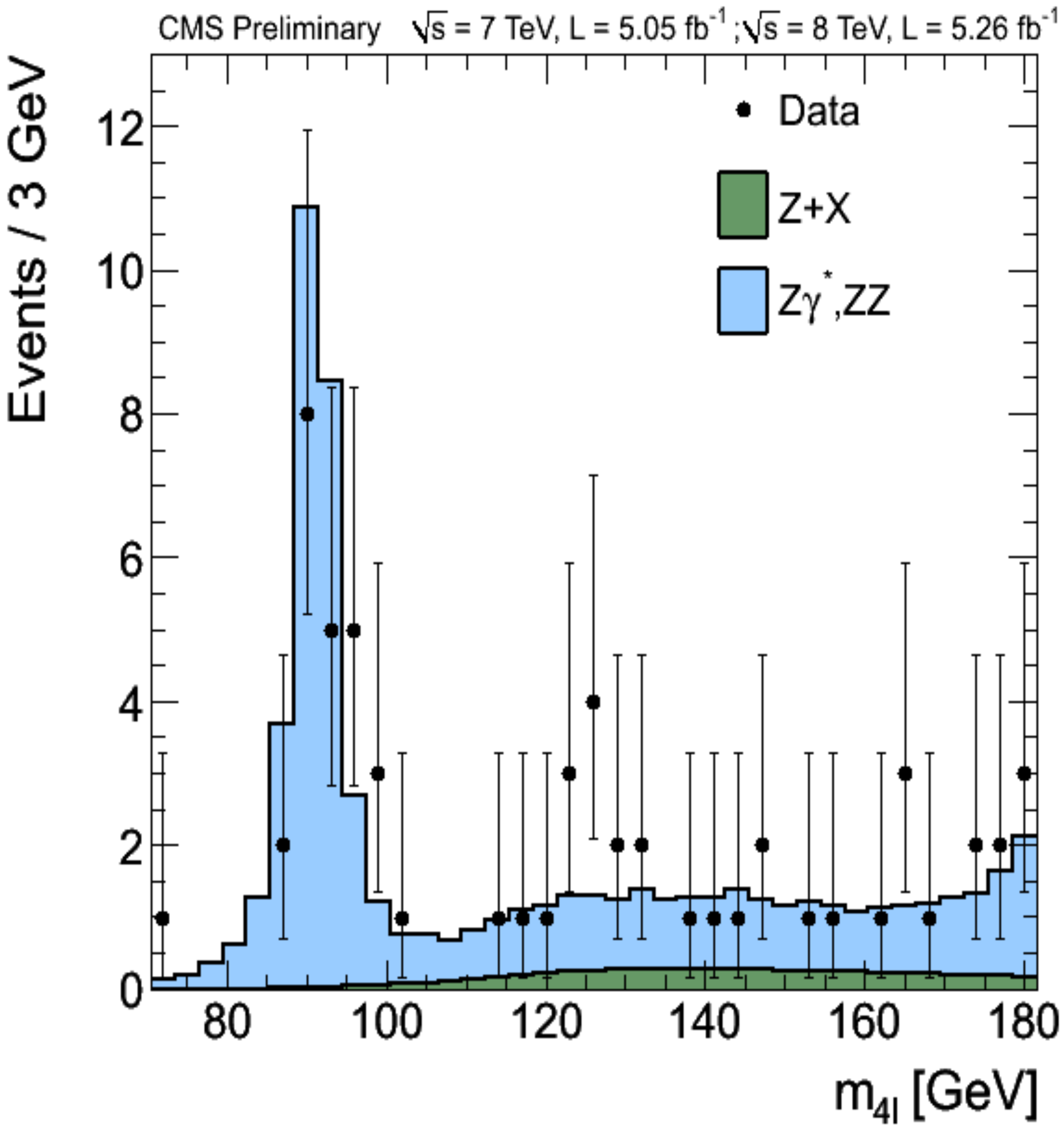




WHAT WE MEASURED



MEASURED + EXPECTED

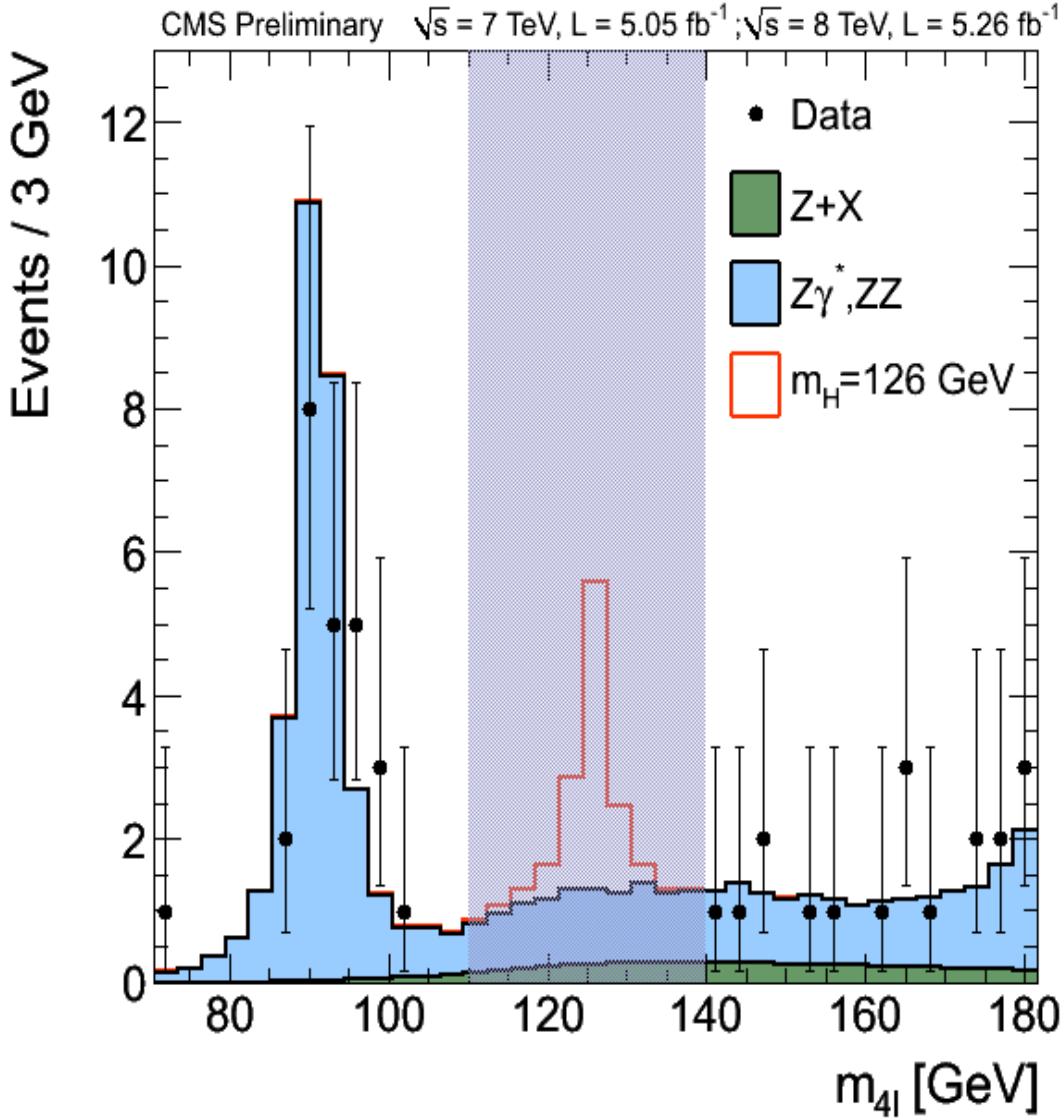


WE HAVE ALL AGREED…

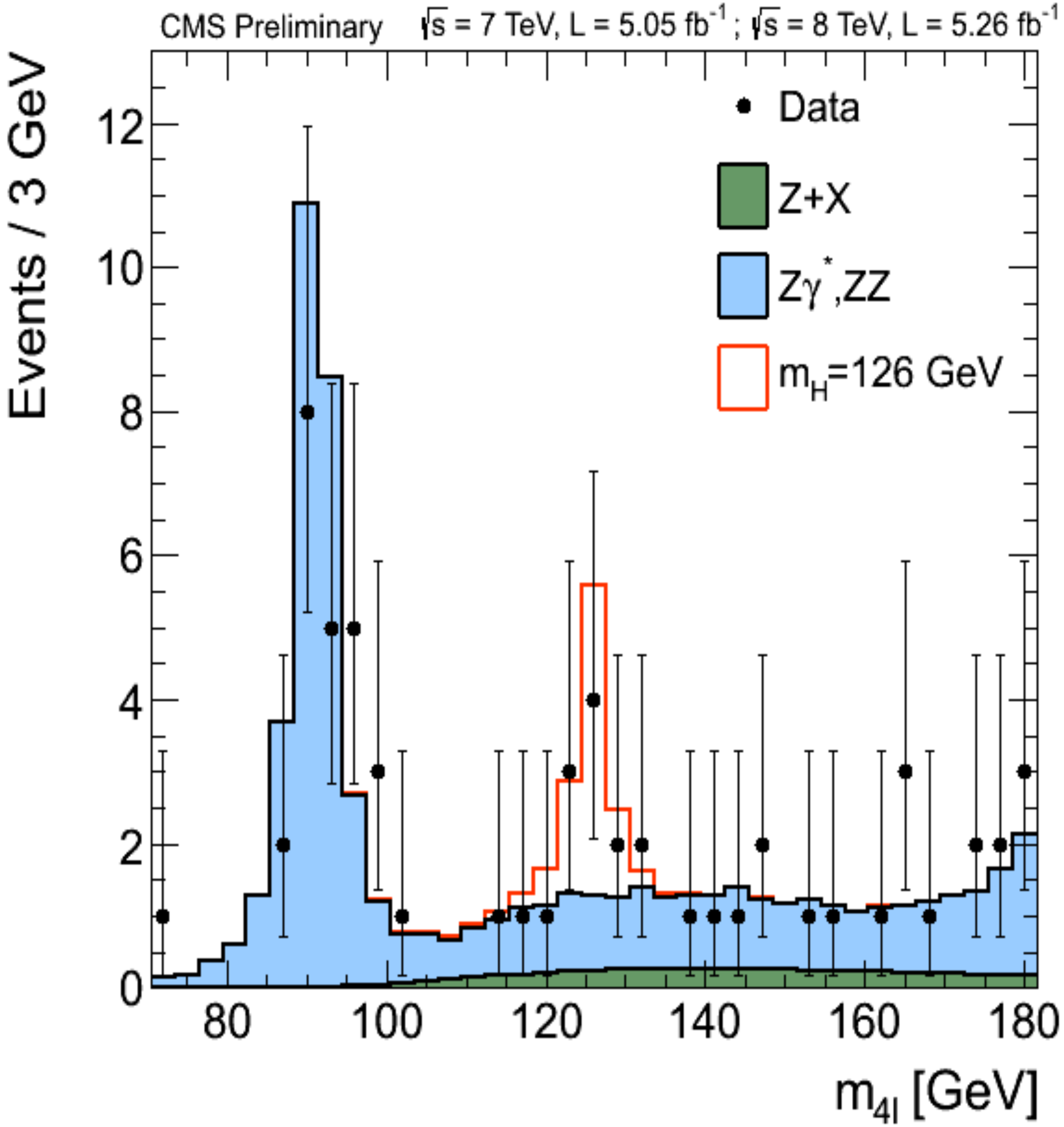
p-value	Significance (σ)	Agreement
0.159	1	$\sigma < 2 \rightarrow$ normal
0.023	2	$2 < \sigma < 3 \rightarrow$ interesting
1.35E-03	3	$3 < \sigma < 5 \rightarrow$ evidence
3.17E-05	4	
2.87E-07	5	$\sigma > 5 \rightarrow$ discovery

Discovery

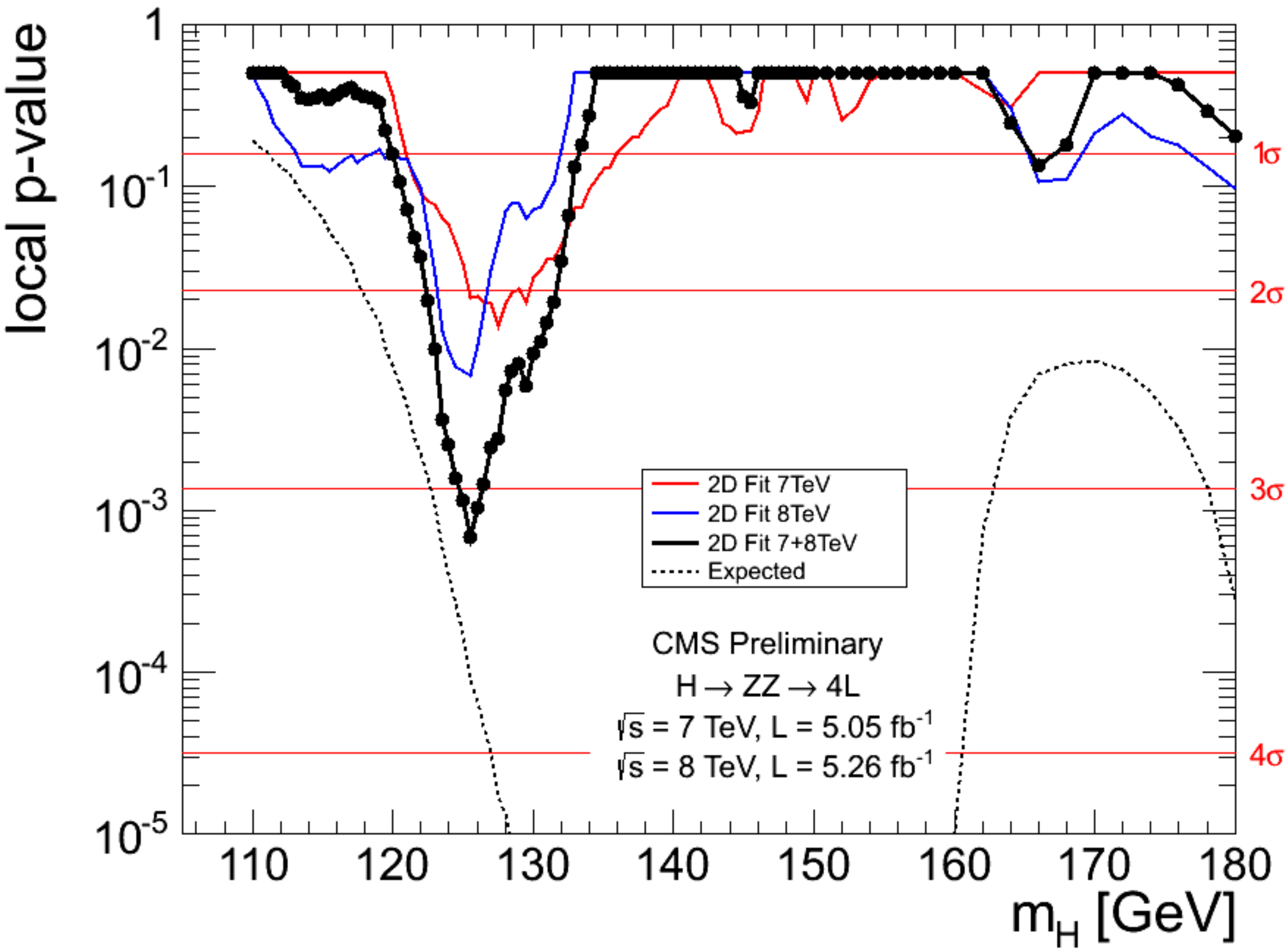
A POWERFUL TOOL - BLIND ANALYSIS



SOMETHING IS THERE!

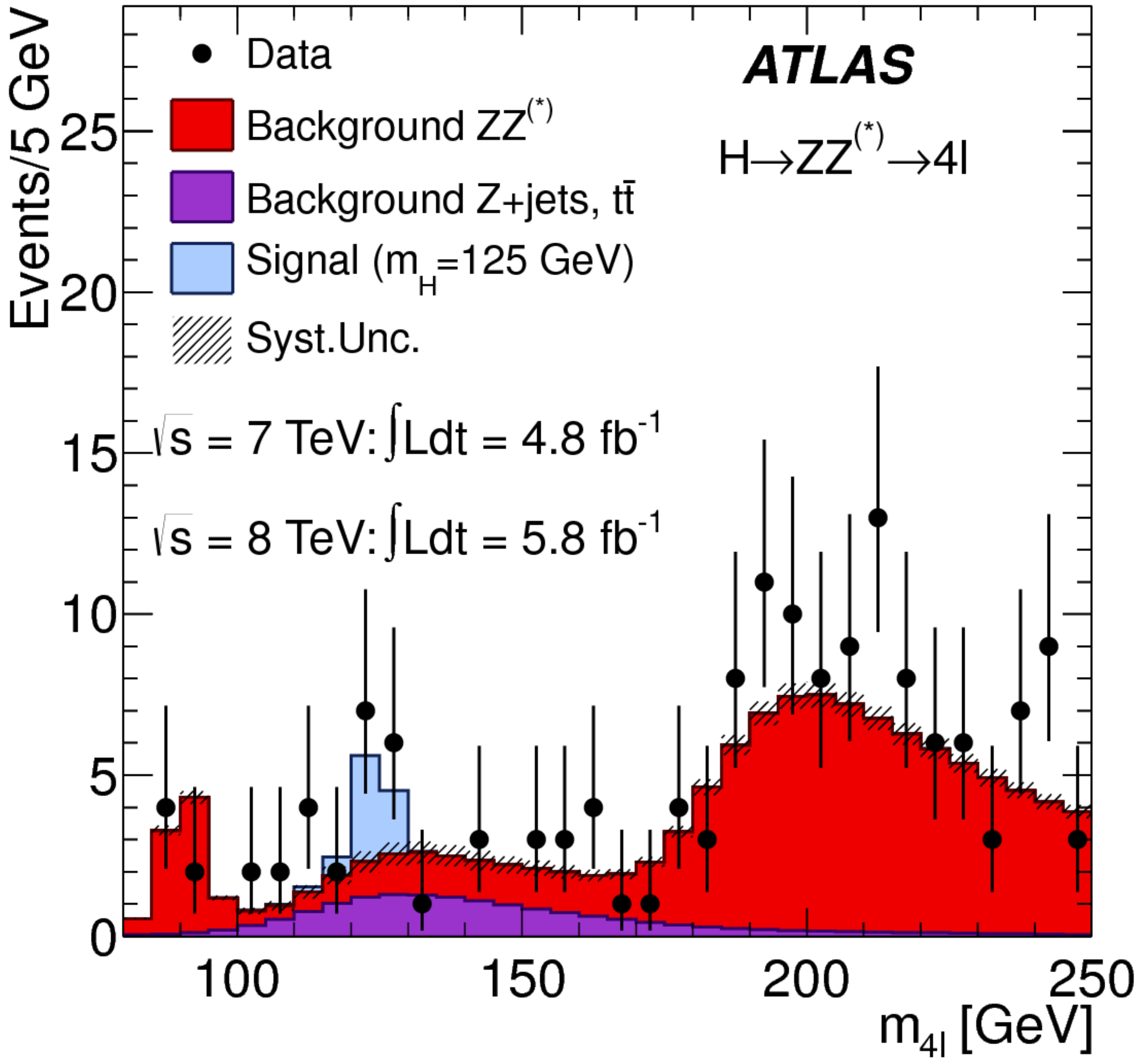


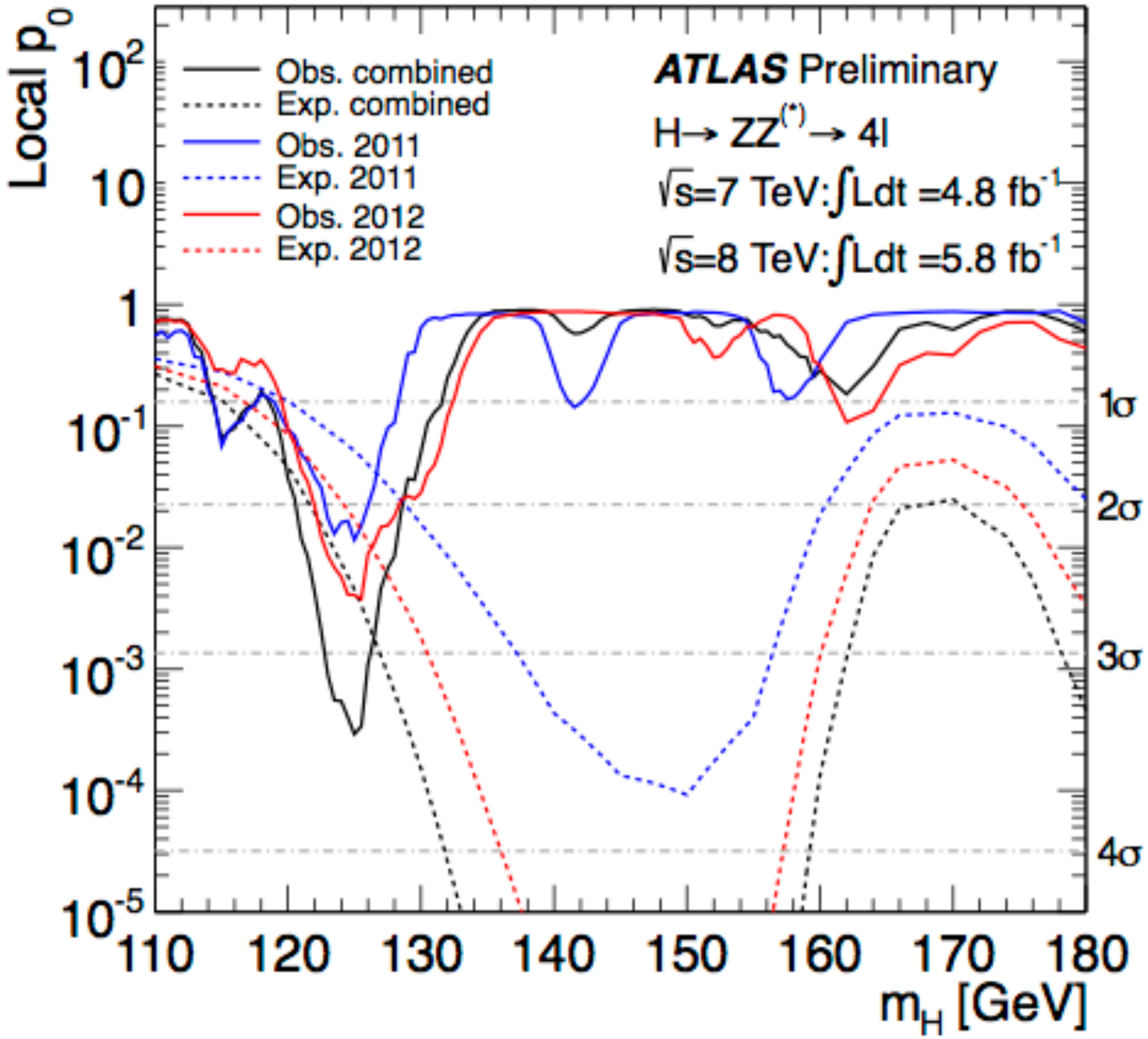
P-VALUE SCAN

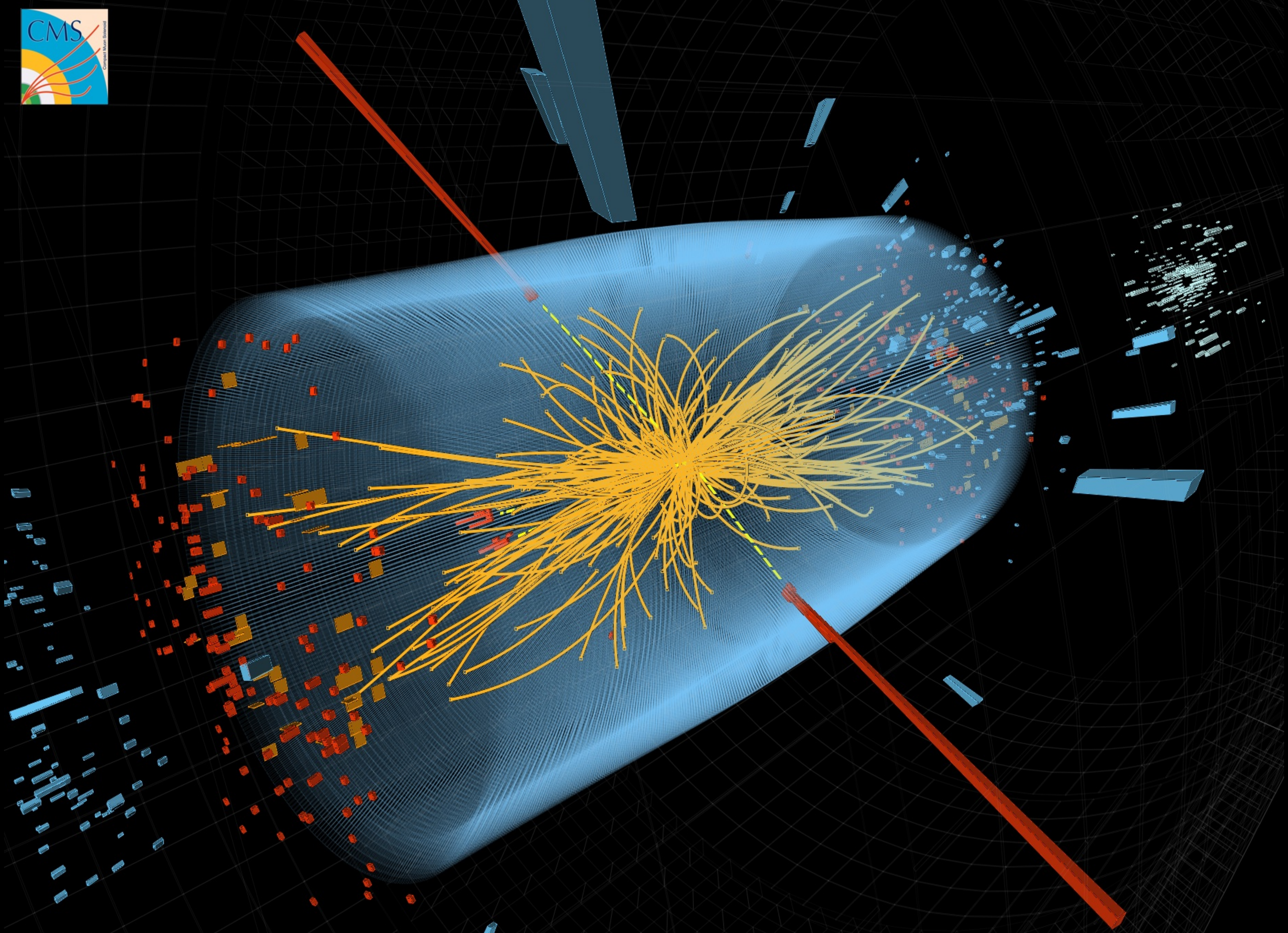


local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1σ
2σ
3σ
4σ
2D Fit 7TeV
2D Fit 8TeV
2D Fit 7+8TeV
Expected
CMS Preliminary
$H \rightarrow ZZ \rightarrow 4L$
$\sqrt{s}$ = 7 TeV, L = 5.05 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 5.26 fb^{-1}
110
120
130
140
150
160
170
180
m_H [GeV]

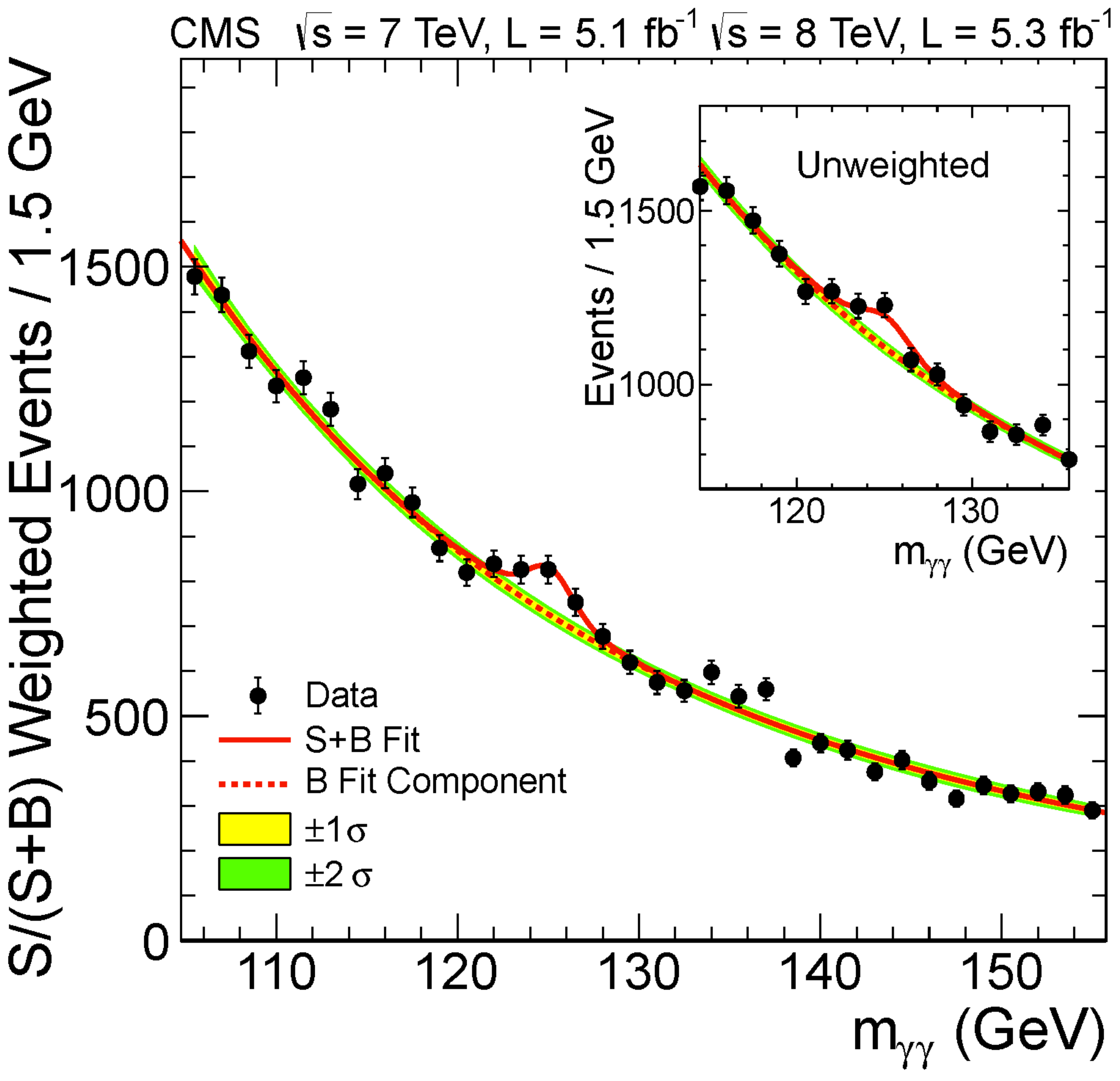
ATLAS RESULTS

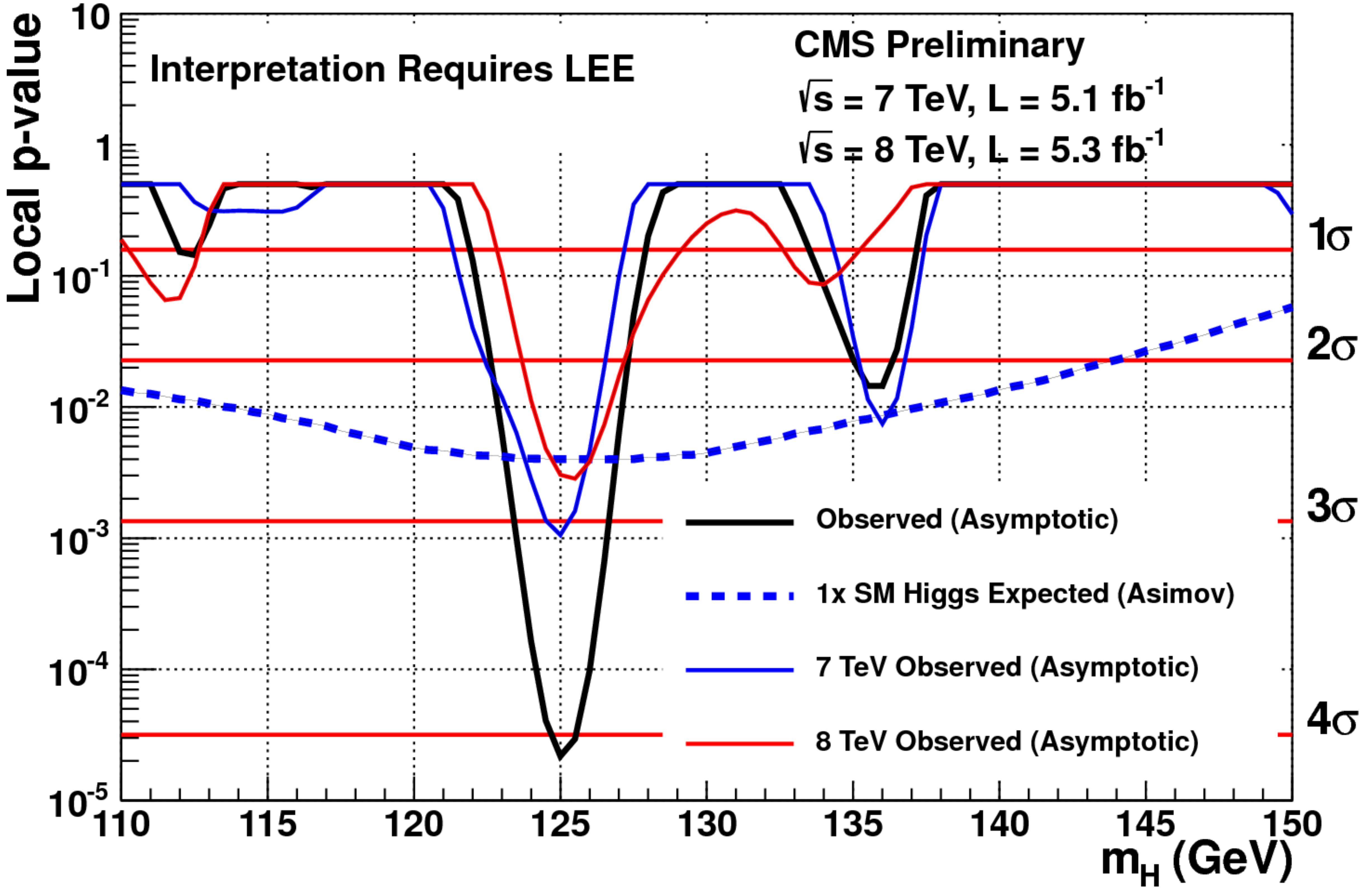




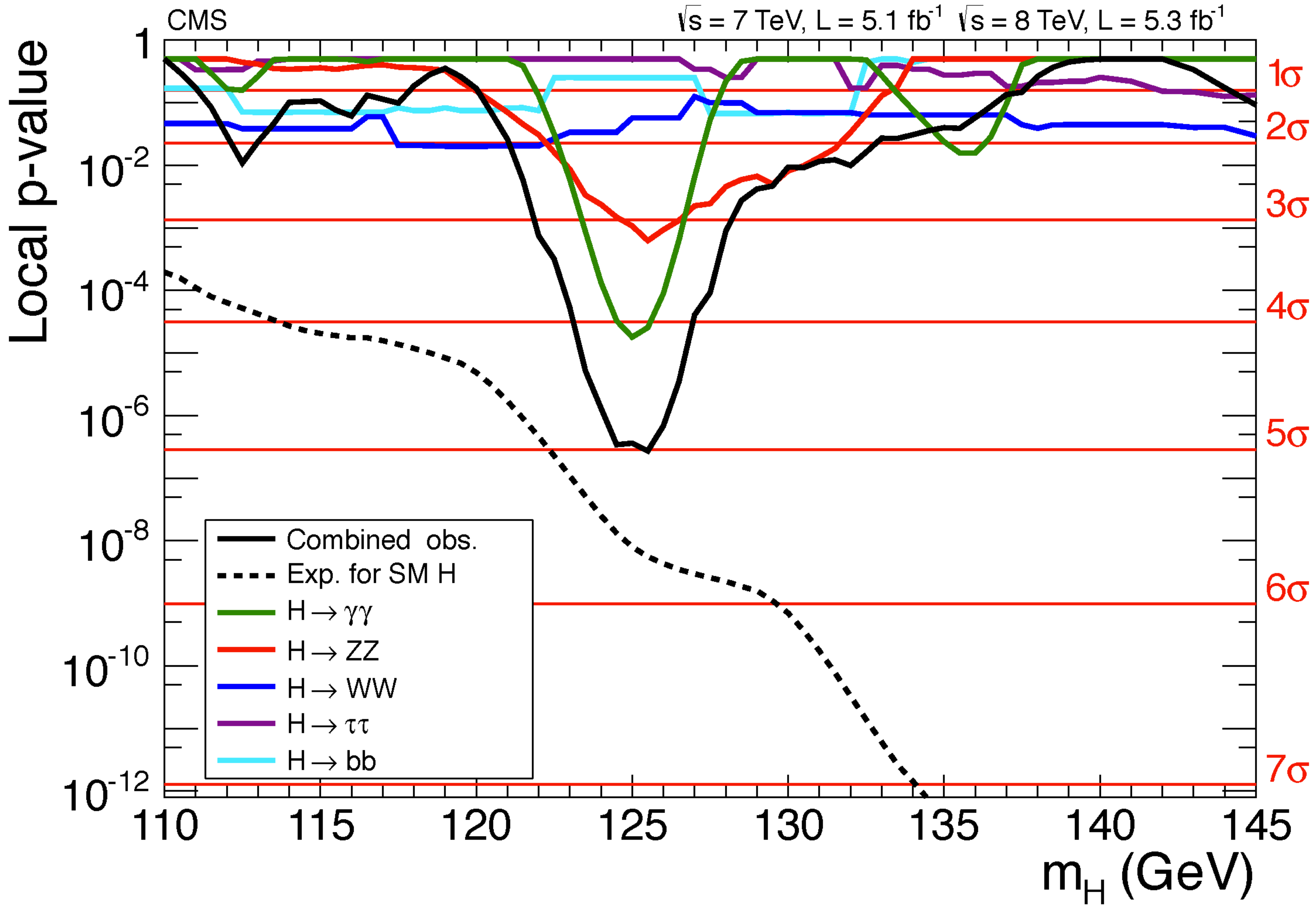


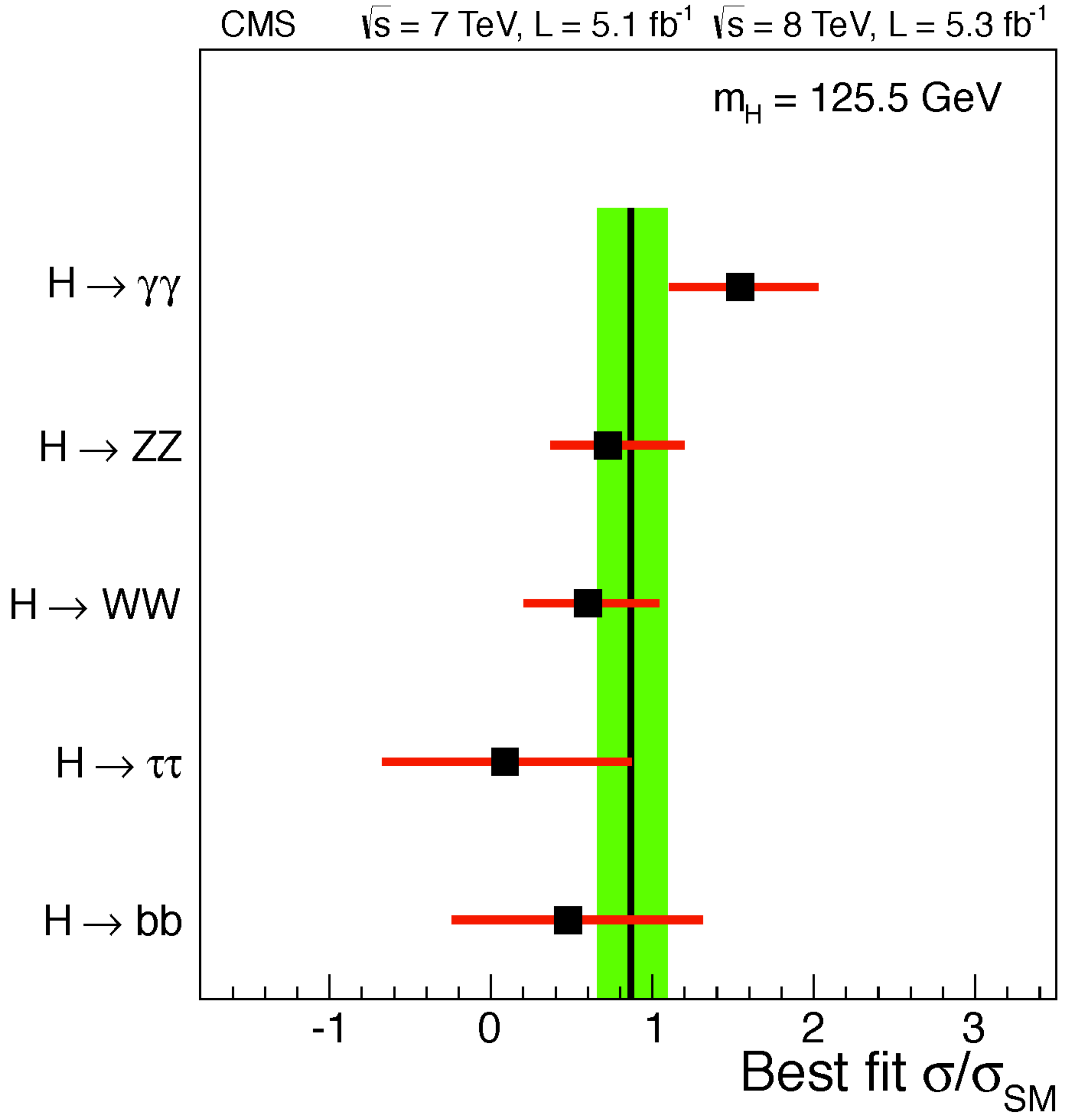
CMS H→$\gamma\gamma$





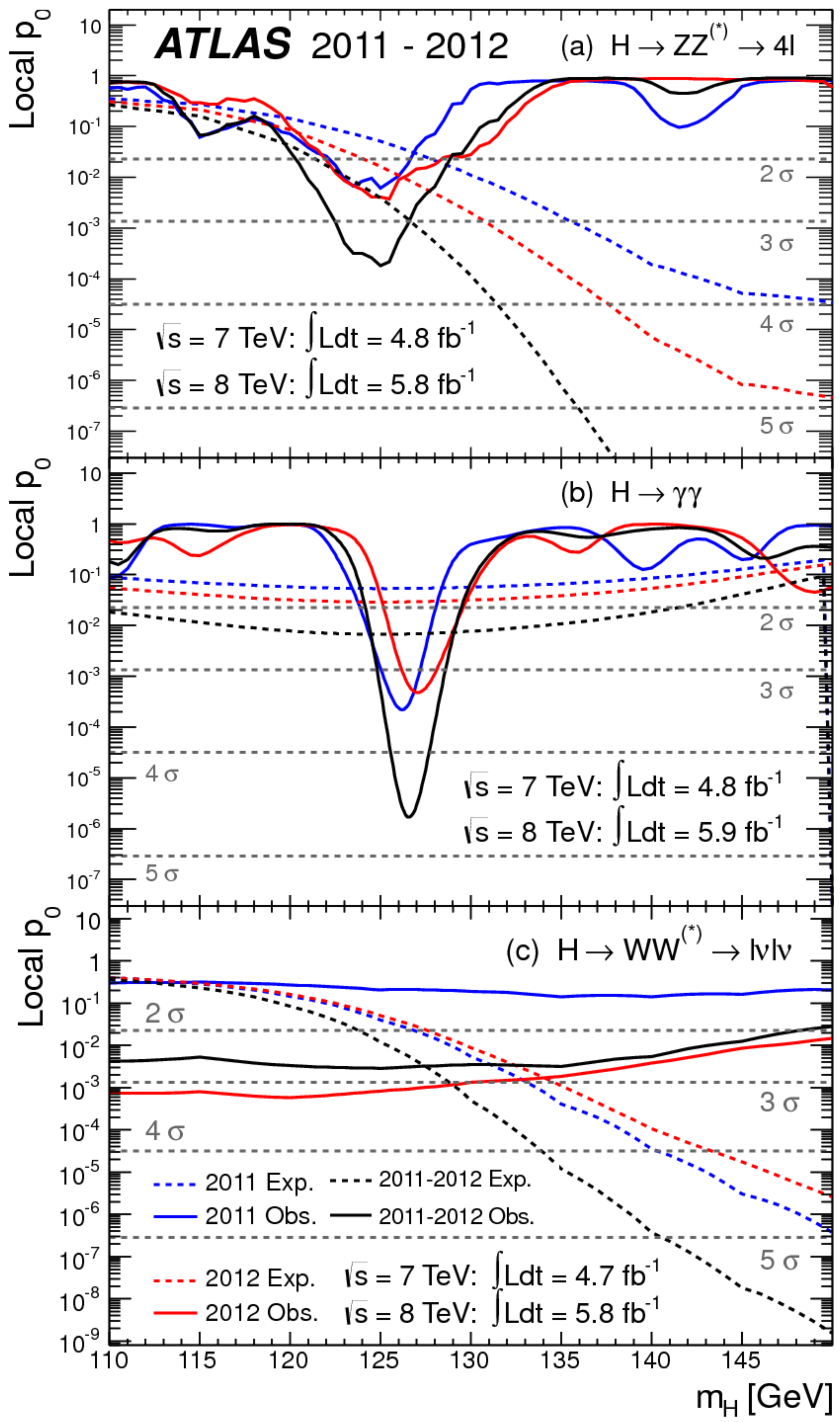
CMS COMBINATION

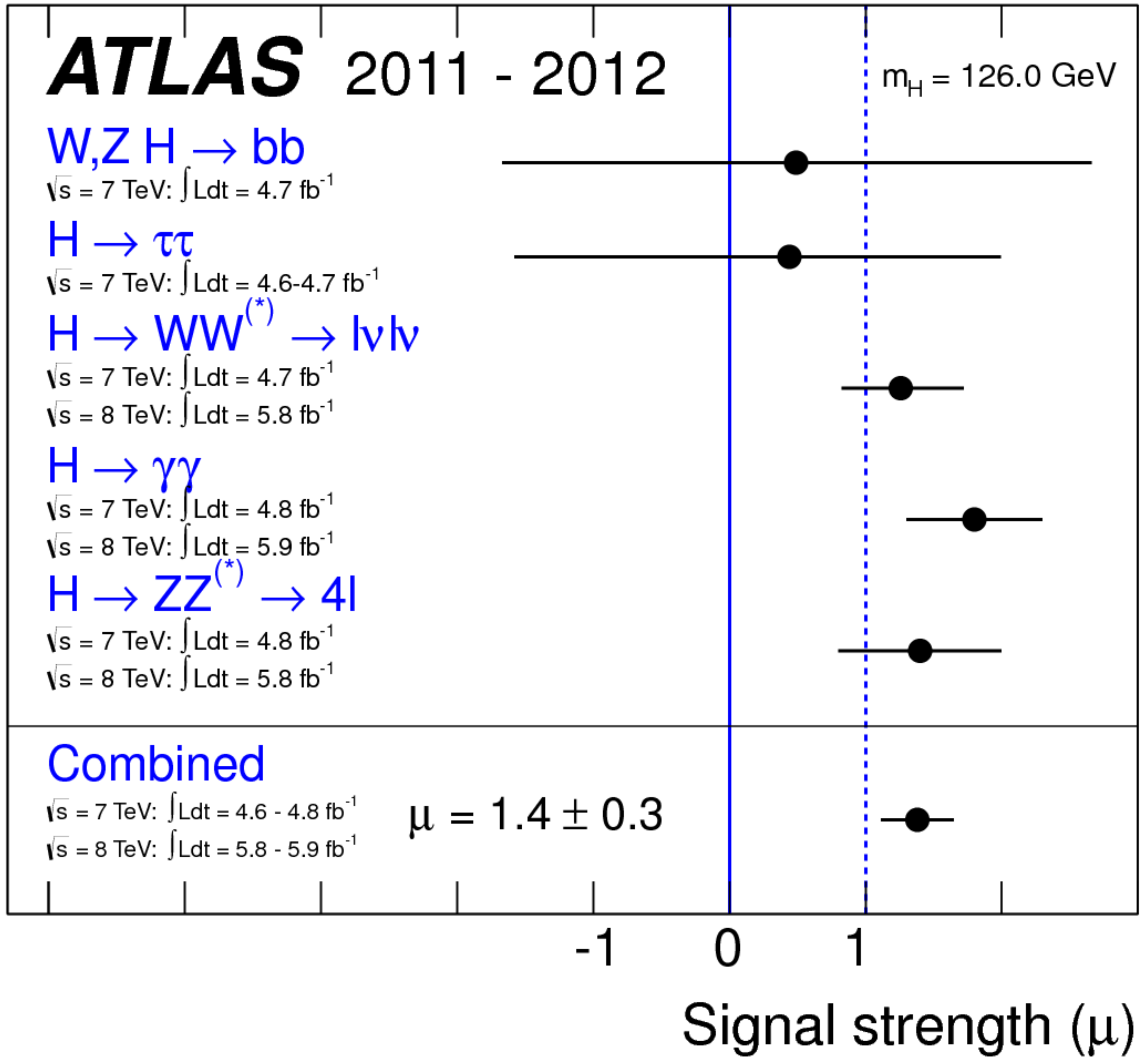




Significance = 5σ @ 125.5 GeV

ATLAS COMBINATION





Significance = 5.9σ @ 126.5 GeV

ELSEVIER

Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 30–61

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

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

CMS Collaboration*

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan[1], M. Friedl, R. Frühwirth[1], V.M. Ghete, J. Hammer, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler[1], W. Kiesenhofer, V. Knünz, M. Krammer[1], I. Krätschmer, D. Liko, W. Majerotto, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss,

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doi:10.1016/j.physletb.2012.08.021

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Abstract

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s}=7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3\pm0.4(\mathrm{stat.})\pm0.5(\mathrm{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 1–29

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

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.

ATLAS Collaboration*

G. Aad[48], T. Abajyan[21], B. Abbott[111], J. Abdallah[12], S. Abdel Khalek[115], A.A. Abdelalim[49], O. Abdinov[11], R. Aben[105], B. Abi[112], M. Abolins[88], O.S. AbouZeid[158], H. Abramowicz[153], H. Abreu[136], B.S. Acharya[164a, 164b], L. Adamczyk[38], D.L. Adams[25], T.N. Addy[56], J. Adelman[176], S. Adomeit[98], P. Adragna[75], T. Adye[129], S. Aefsky[23], J.A. Aguilar-Saavedra[124b, a], M. Agustoni[17], M. Aharrouche[81], S.P. Ahlen[22], F. Ahles[48], A. Ahmad[148], M. Ahsan[41], G. Aielli[133a, 133b], T. Akdogan[19a],

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doi:10.1016/j.physletb.2012.08.020

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Open Access

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 $126.0\pm 0.4\ (\text{stat})\pm 0.4\ (\text{sys})$ 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.

ALL MEASURED PROPERTIES AGREE WITH THE PREDICTIONS FOR THE SM HIGGS BOSON!

- What are the **charge**, **spin** and **parity** of particle X? What is the **mass**? ✓
- Is the new particle **produced** as predicted for the SM Higgs boson? ✓
- Does it **decay** as predicted for the SM Higgs boson? ✓
- Does particle X **interact** with other **known elementary particles** as predicted for the SM Higgs boson? ✓

The Nobel Prize in Physics 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

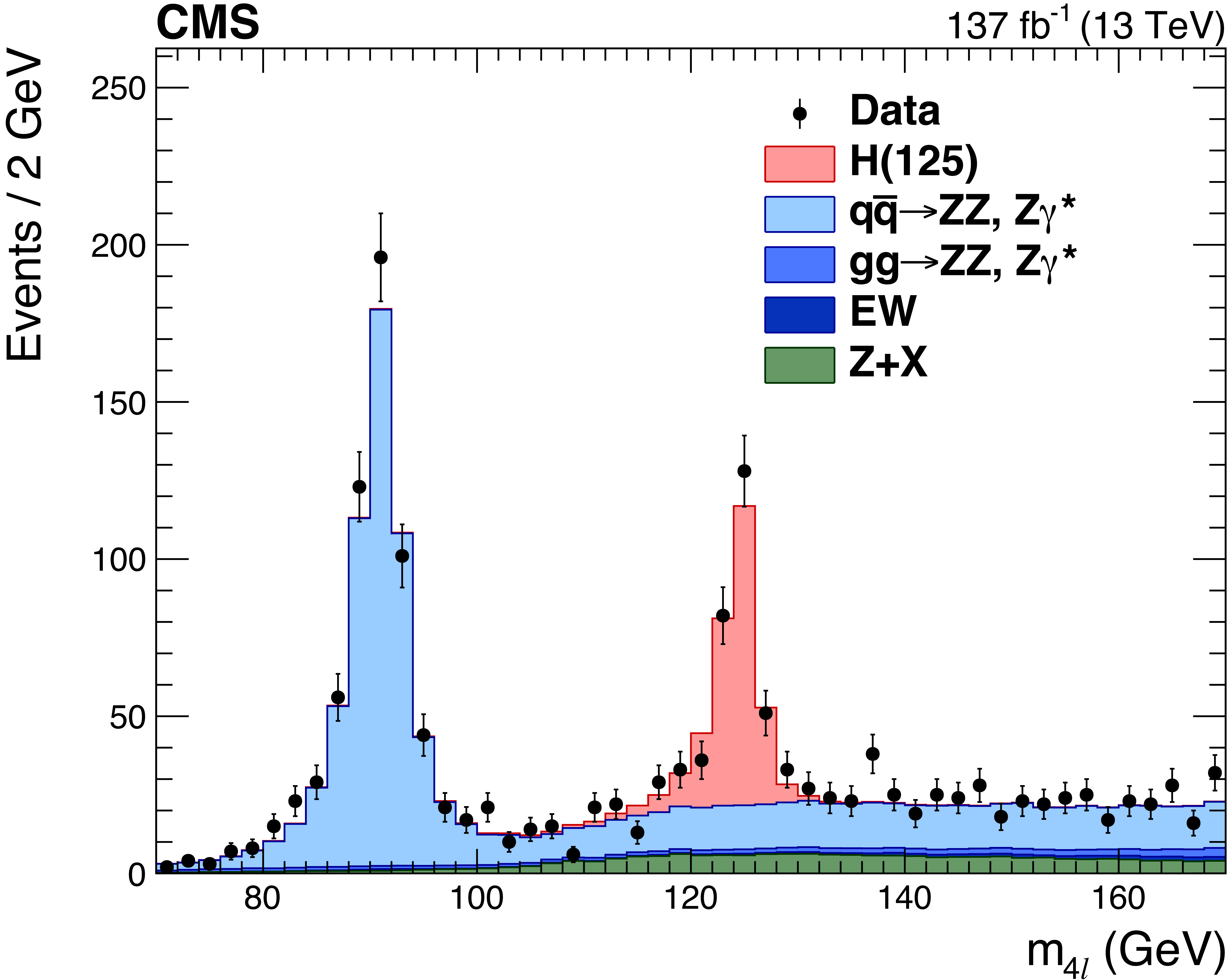
François Englert
Université Libre de Bruxelles, Brussels, Belgium

Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

04/07/2012

03/08/2013



CMS
137 fb-1 (13 TeV)
Events / 2 GeV
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
EW
Z+X
250
200
150
100
50
0
80
100
120
140
160
m4l (GeV)

CERN ZA UČENIKE I NASTAVNIKE

- **CERN Masterclass radionica** na jedan dan učenike srednjih škola pretvara u znanstvenike koji tragaju za Higgsovim bozonom

- **CERN Teacher Programme** ugošćuje nastavnike na nekoliko dana i uči ih o fizici elementarnih čestica gdje zajedno pripremaju materijale koje oni kasnije mogu iskoristiti u nastavi


Curiosity Is The Engine
Of Achievement.
Ken Robinson