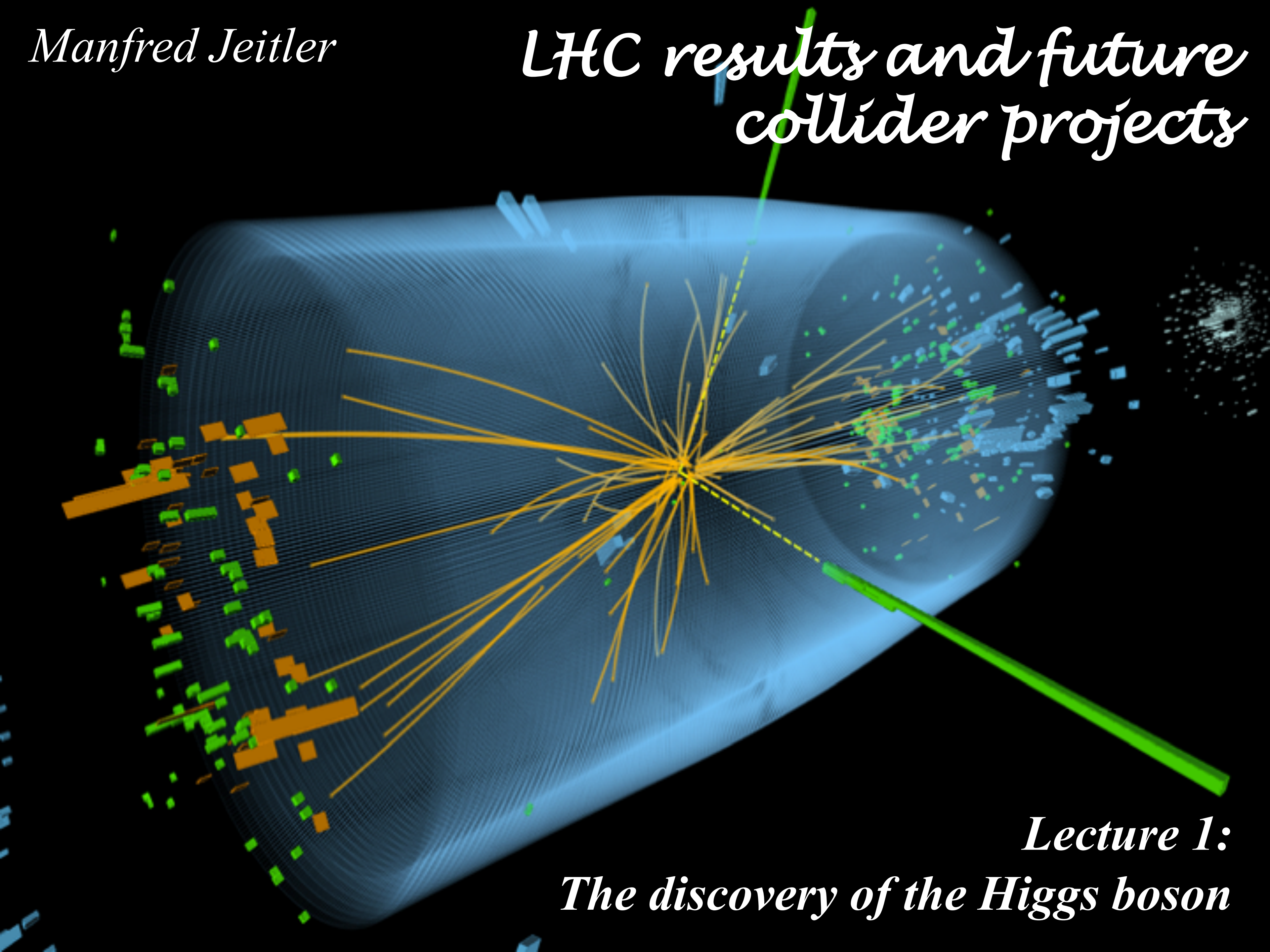
Manfred Jeitler

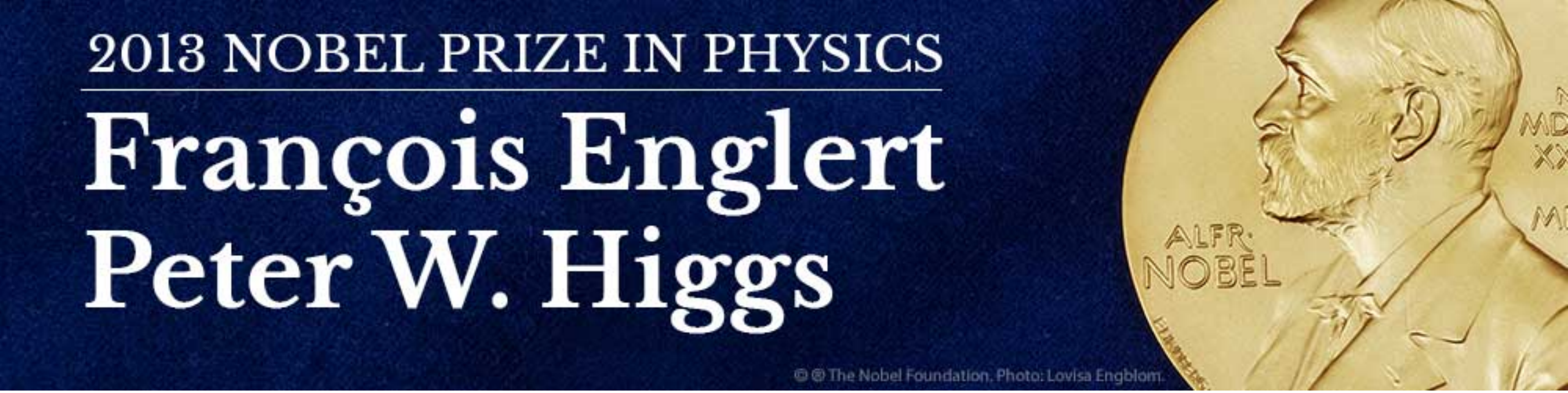
LHC results and future collider projects



Lecture 1: The discovery of the Higgs boson

THE BEH-MECHANISM, INTERACTIONS WITH SHORT RANGE FORCES AND SCALAR PARTICLES

KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES



8 October 2013

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

François Englert and Peter Higgs

"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"

The Seminal Papers

1964

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)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

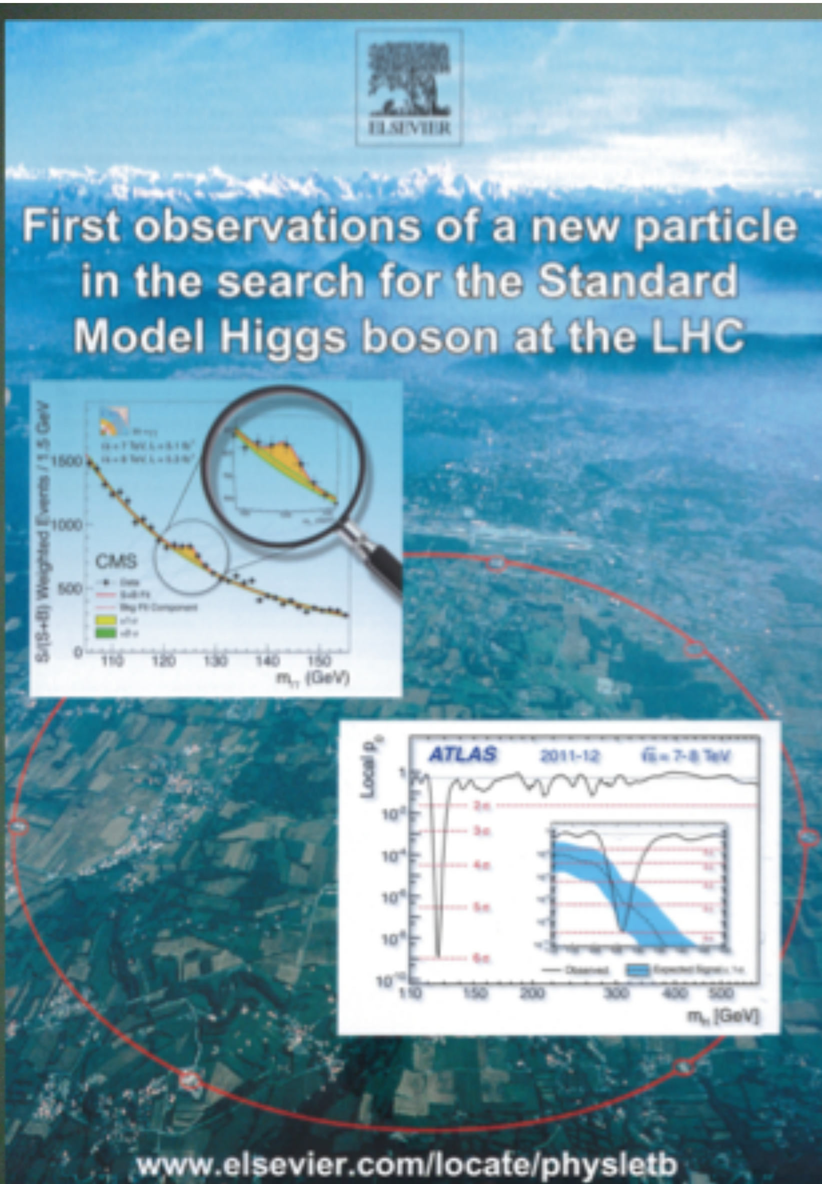
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

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)


Higgs Hunting 2014
Results and prospects in the electroweak symmetry breaking sector
July 21 - 23, 2014, Orsay-France
www.higgshunting.fr

Publication of results in Journal Physics Letters



THE UNIVERSITY OF EDINBURGH

SCHOOL *of* PHYSICS *and* ASTRONOMY
The University of Edinburgh
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Email info@ph.ed.ac.uk
www.ph.ed.ac.uk

Congratulations to both Atlas and CMS Collaborations and to the builders of the LHC on a magnificent achievement!

Peter Higgs

30 August 2012

8 October 2013

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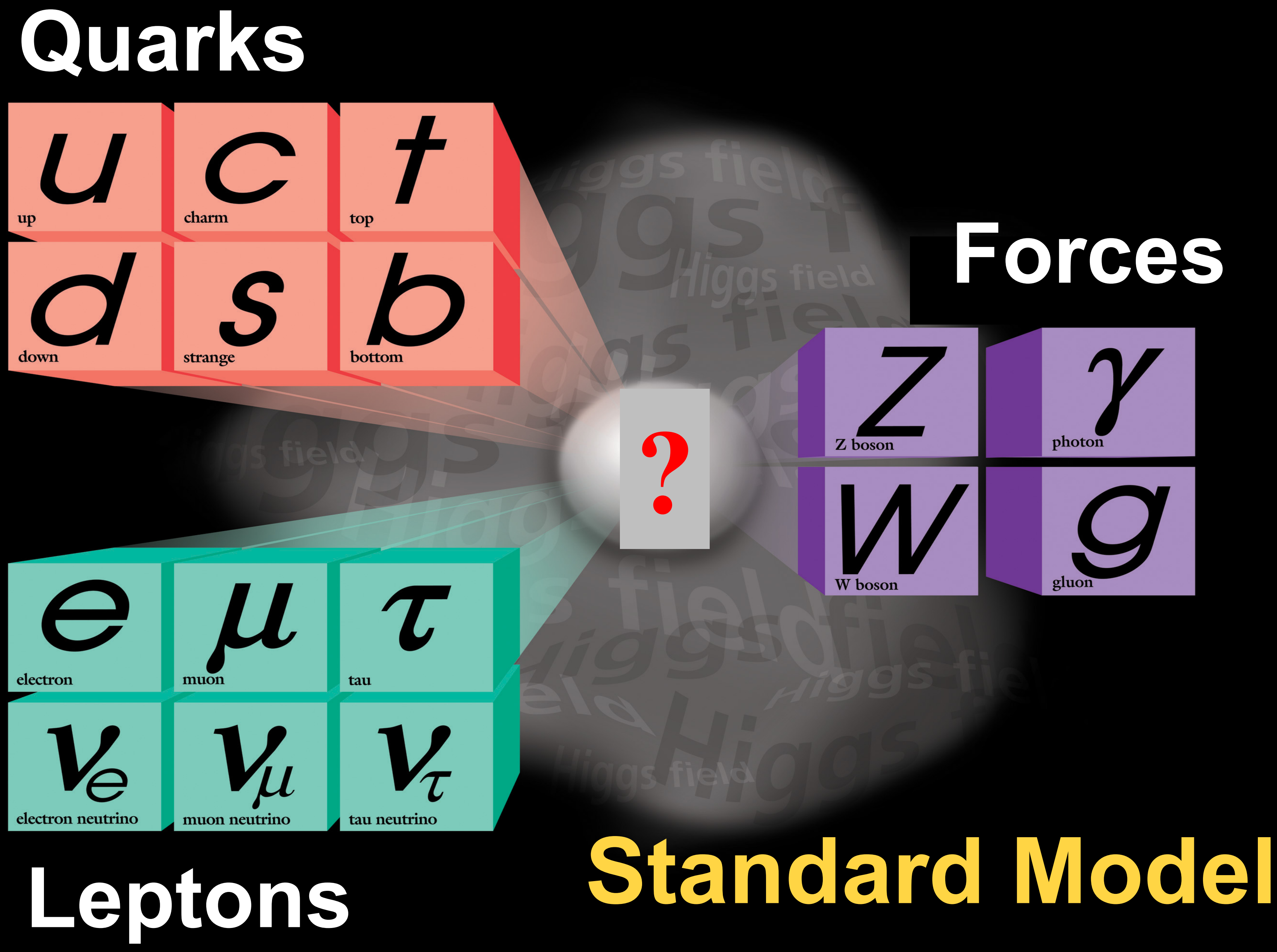
Quarks
u
up
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strange
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Forces
Z
Z boson
γ
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W boson
g
gluon
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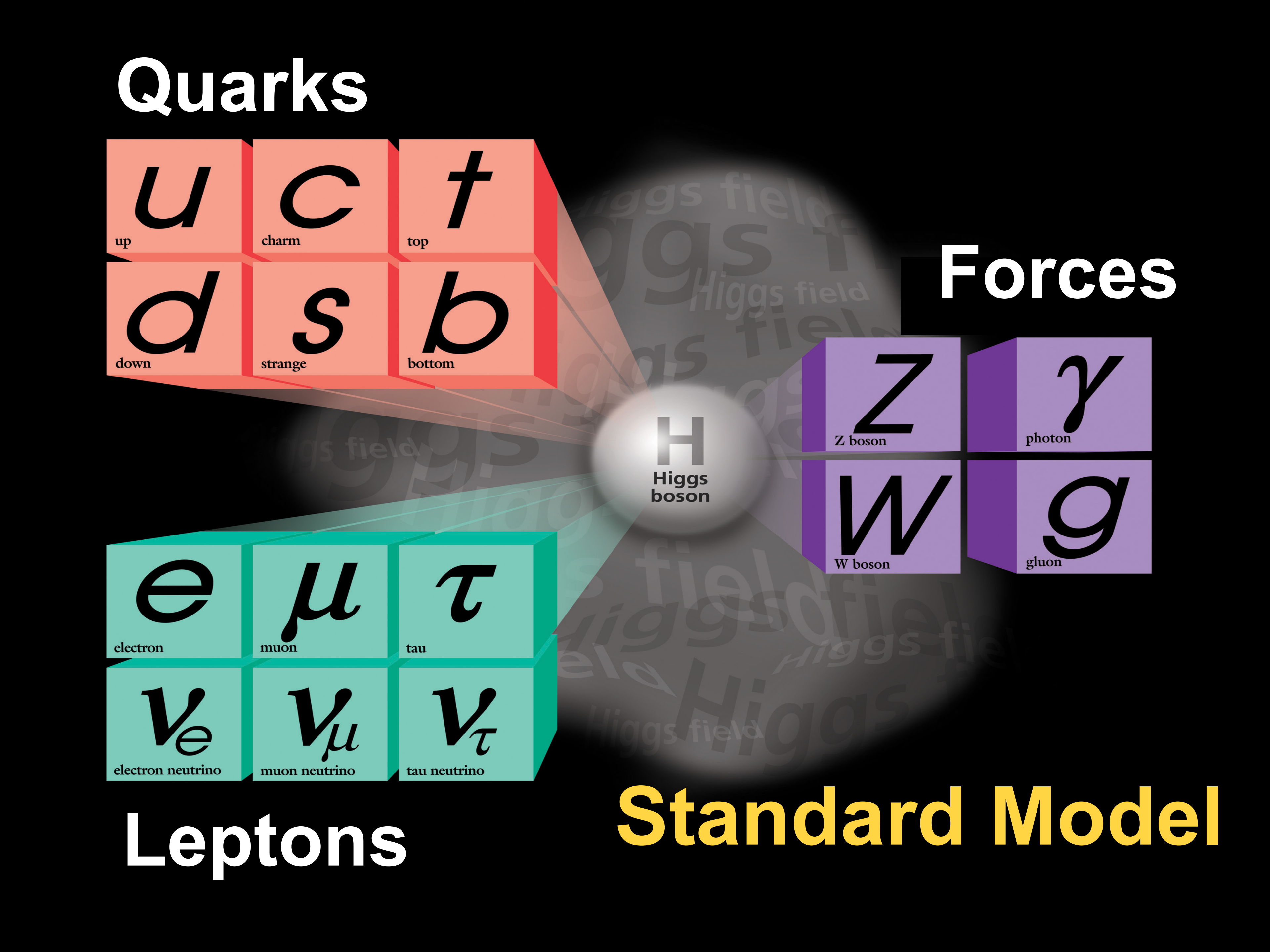
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Higgs field
Leptons
Standard Model


Quarks
u
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Forces
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Z boson
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photon
W
W boson
g
gluon
H
Higgs boson
Higgs field
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons
Standard Model

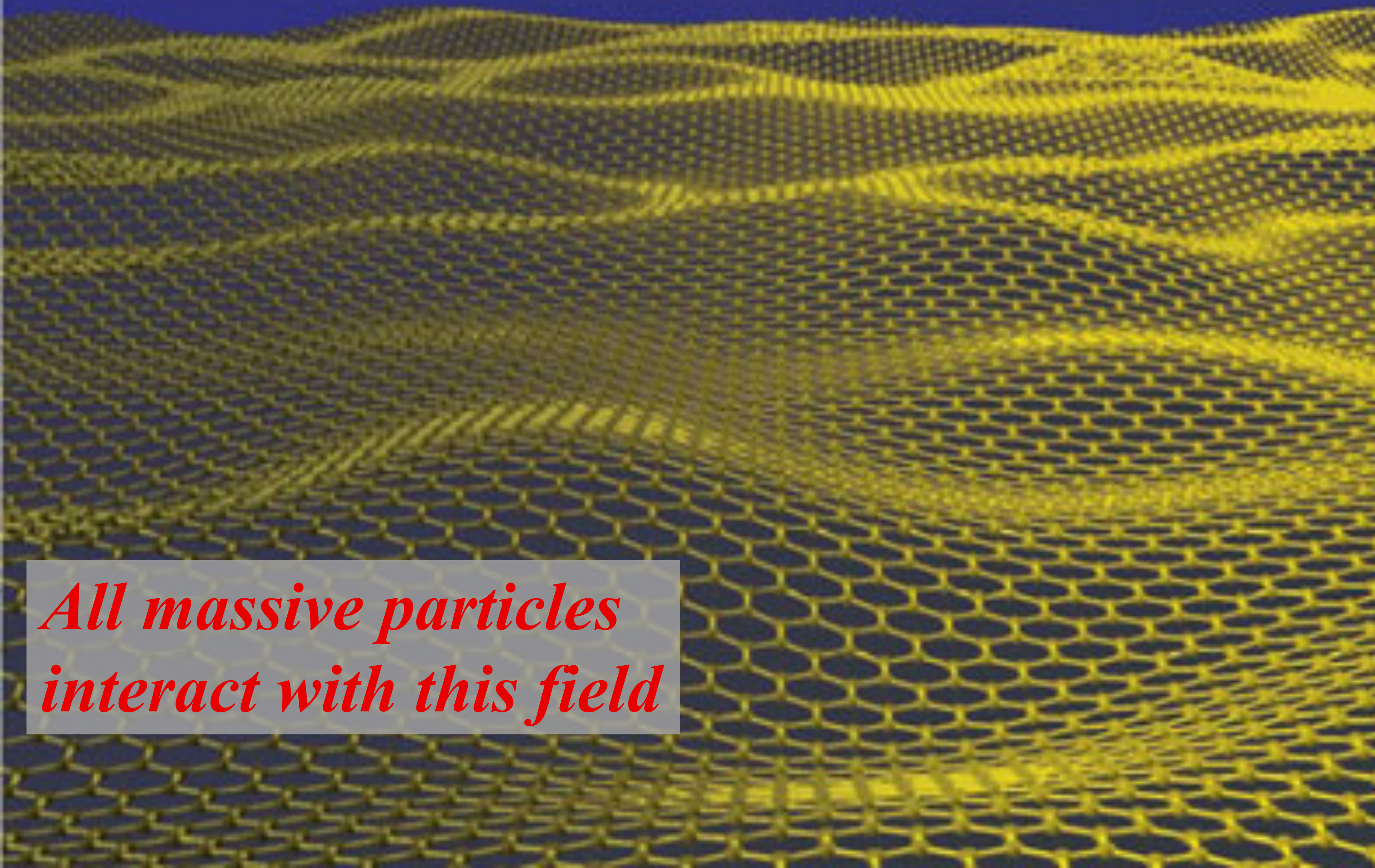
Why do we need a Higgs boson?

- The Standard Model describes all particles we know ...
- ... but all these particles would be massless!
  - most of the mass of the matter we see is due to the interaction between elementary particles
  - so, it is ***not true*** that "without the Higgs boson there would be no mass"

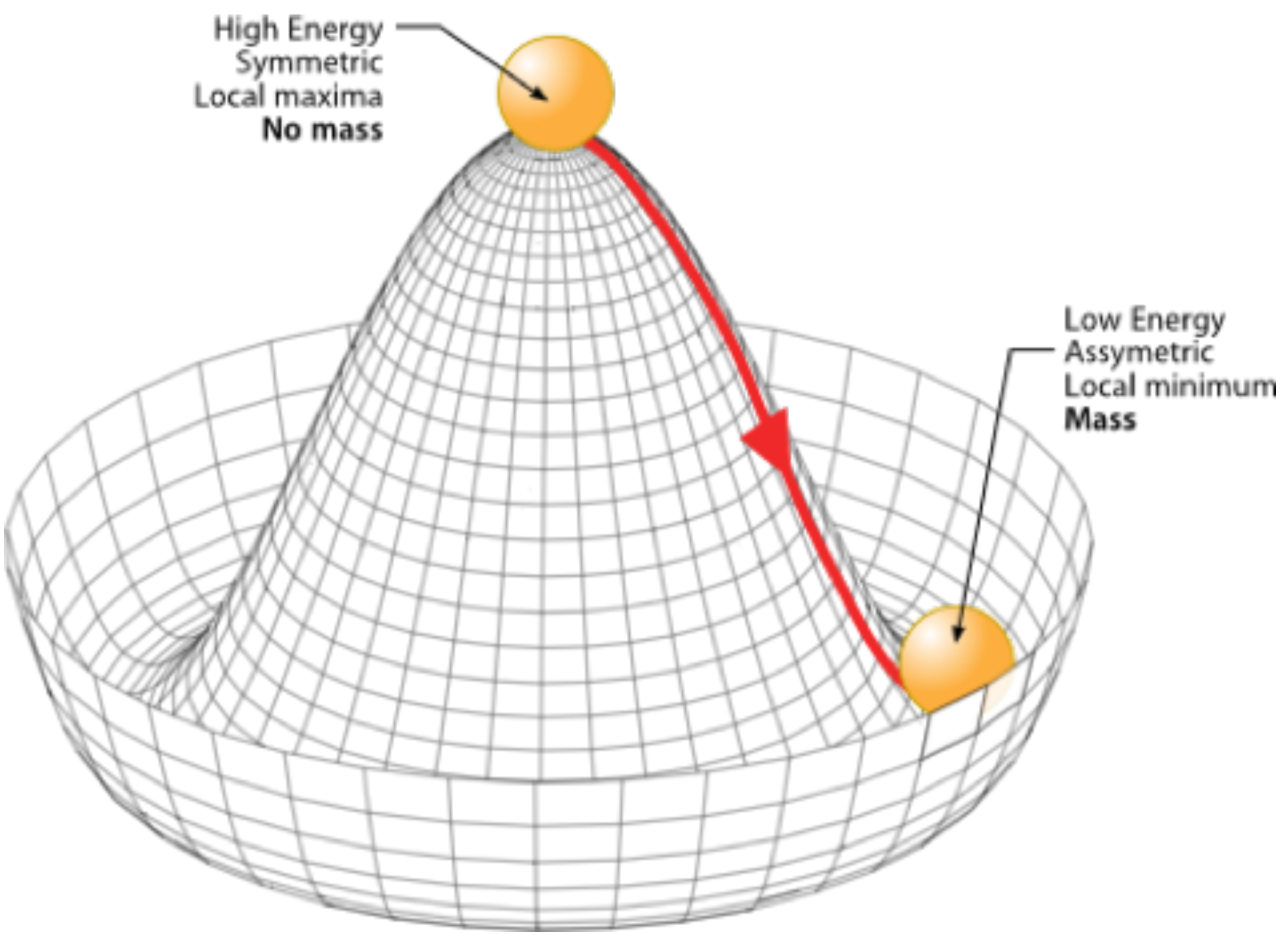
Why do we need a Higgs boson?

- The Standard Model describes all particles we know ...
- ... but all these particles would be massless!
  - most of the mass of the matter we see is due to the interaction between elementary particles
  - so, it is ***not true*** that “without the Higgs boson there would be no mass”
  - however, experiment shows that the elementary particles themselves also have some mass (and W and Z bosons are very heavy!)
  - adding mass terms “by hand” would destroy the theory
- The formulae of the Standard Model can be modified in a way to give mass to elementary particles …
- … but then the Model predicts a new particle: the Higgs boson
  - found only in 2012
  - had to exist if the Standard Model was correct!

Higgs field permeating all space



Spontaneous symmetry breaking

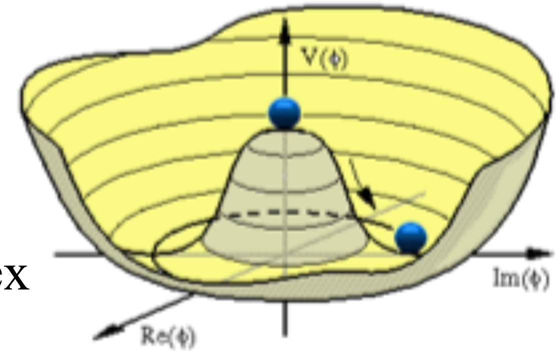


- Introducing mass “by hand” would destroy the theory
- keep basic symmetry but introduce non-zero mass by spontaneous symmetry breaking

“Mexican hat” potential

The Higgs mechanism

- The solution: Glashow-Salam-Weinberg used a model elaborated by several authors at the beginning of the 1960s
  - » the gauge symmetry of the model is conserved but the ground state of a new field "spontaneously" breaks the symmetry
    - analogous to ferromagnetism
- – the minimal solution introduces a doublet of complex scalar fields – 4 degrees of freedom – and a non-zero vacuum expectation value v (≈246 GeV)
  - » one component corresponds to a physical, electrically neutral scalar particle – the "Higgs boson"
  - » the remaining components add a new degree of freedom to the $W^\pm$ and Z bosons (longitudinal polarization); mass terms appear



$$L_{Higgs} = (D_\mu \Phi)^+ (D^\mu \Phi) + \mu^2 |\Phi|^2 - \lambda |\Phi|^4$$

$$m_H = \sqrt{2\lambda} v \qquad m_W = \frac{1}{2}\frac{ev}{\sin\Theta_W} \qquad m_Z = \frac{1}{2}\frac{ev}{\sin\Theta_W \cos\Theta_W} \qquad m_\gamma = 0$$

"Weinberg angle"

The Higgs mechanism

illustrated by David Miller

A uniform field can give mass to a passing particle

The Higgs mechanism

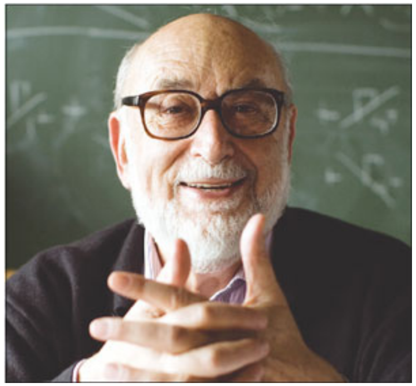
illustrated by David Miller

A uniform field can give mass to a passing particle

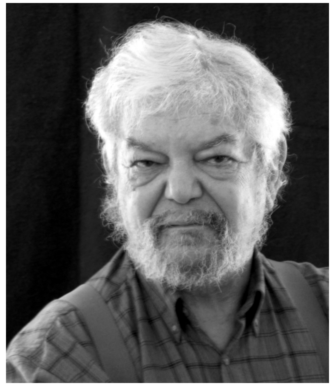
Even without a passing particle, the field can form "clusters":

this is the Higgs boson

(Prof. Peter) Higgs at the ATLAS experiment



F. Englert

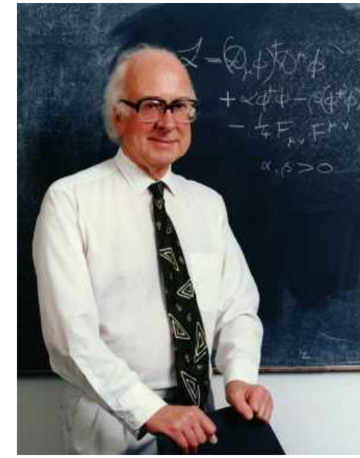


R. Brout
(1928-2011)

[F. Englert and R. Brout, *"Broken symmetry and the mass of gauge vector mesons"*, Phys.Rev.Lett.13(1964)321]

[P.W. Higgs, *"Broken symmetries, massless particles and gauge fields"*, Phys.Lett.12(1964)132]

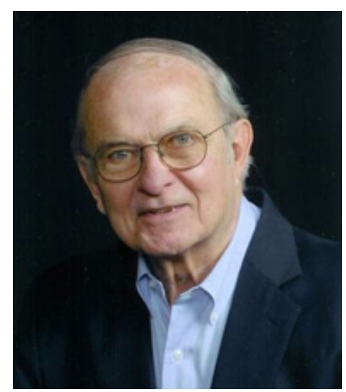
[P.W. Higgs, *"Broken symmetries and the masses of gauge bosons"*, Phys.Rev.Lett.13(1964)508]



P.W. Higgs

[G.S.Guralnik, C.R.Hagen, T.W.B.Kibble, *"Global conservation laws and massles particles"*, Phys.Rev.Lett.13(1964)585]

G.S. Guralnik



C.R. Hagen

T.W.B. Kibble

1964 theoretical studies

ICHEP Melbourne
4. Juli 2012


Die Presse

FREI SEIT 1848

KUNSTLIEBE

Physik. Am Kernforschungszentrum CERN in Genf hat man das lange gesuchte Teilchen gefunden, das allen anderen erst Masse verleiht, das Higgs-Boson. Ganz sicher ist man sich allerdings noch nicht.

Happy Higgs Day

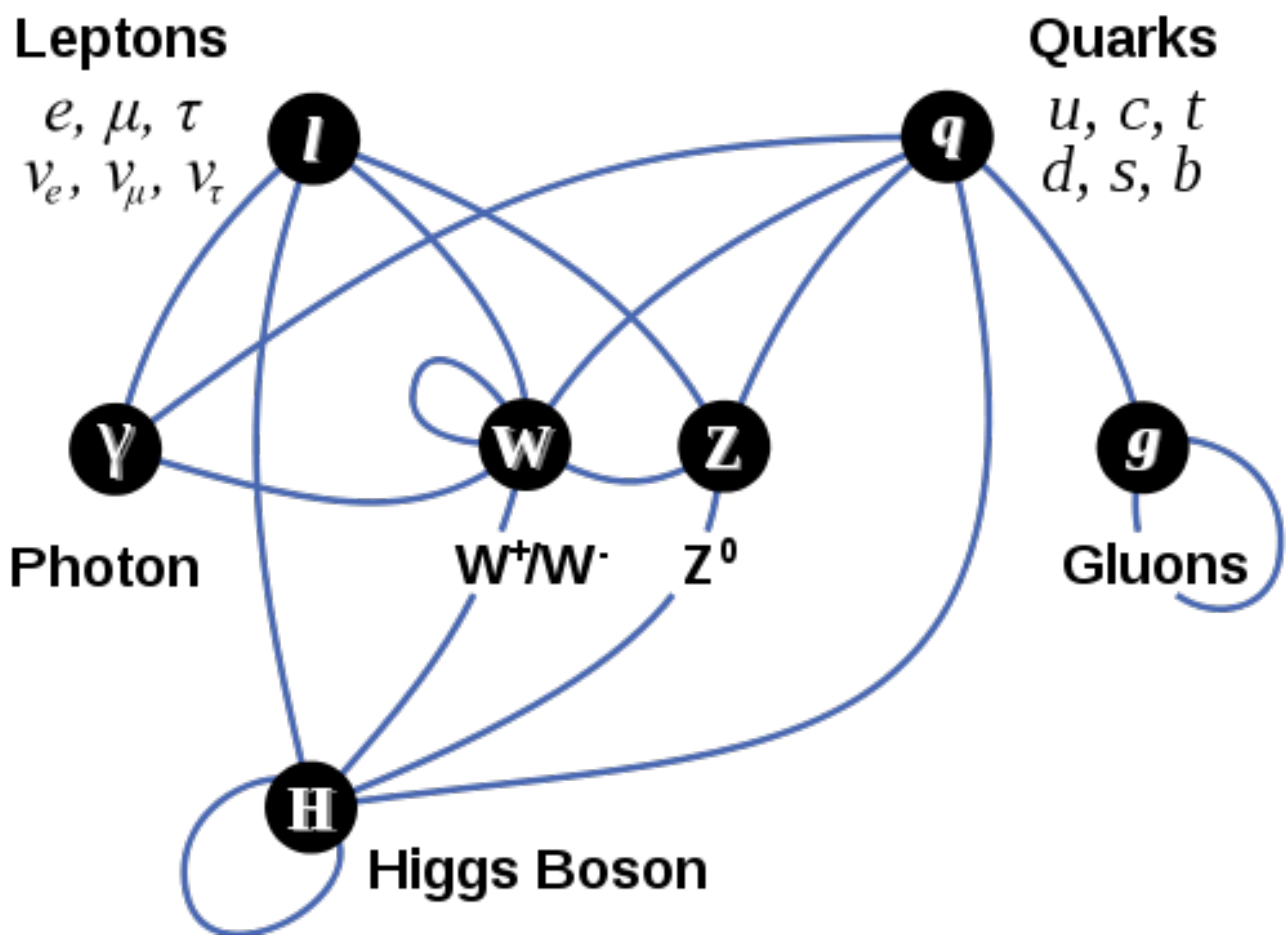
„Es geht darum, die Welt zu verstehen"

How can we "find" an elementary particle?

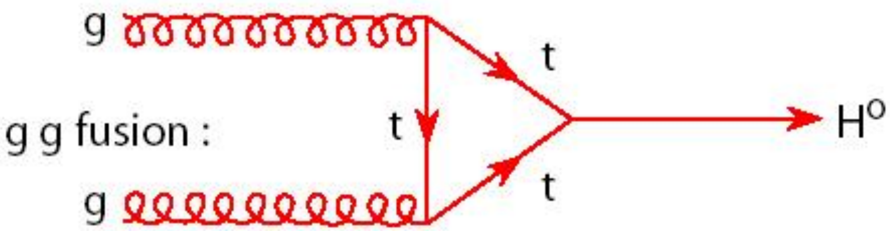
- most elementary particles are not stable
- many of them are so short-lived that they never reach our detectors
  - although travelling almost at the speed of light
  - in particular, this is also true for the Higgs boson
- what we see are decay products
  - "messenger particles"
  - they allow us to draw conclusions concerning the "mother" particle
  - in particular, we can calculate its mass:

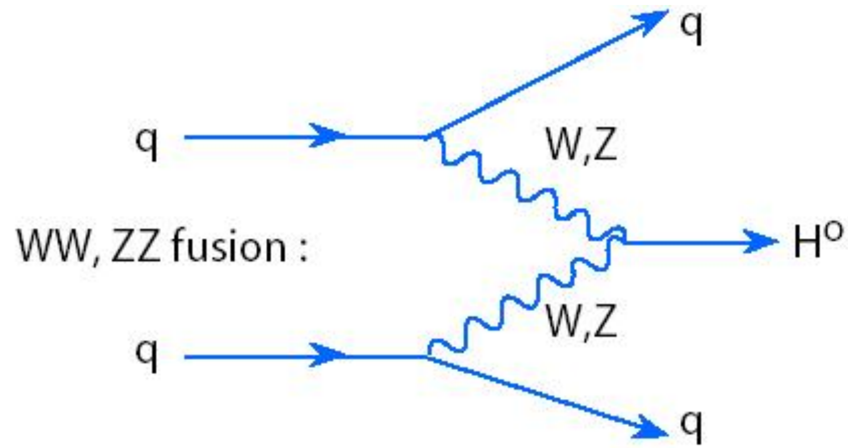
$$m = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

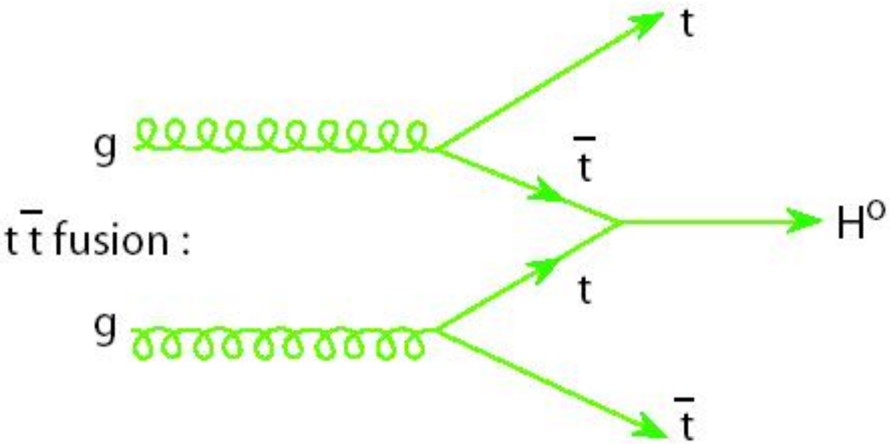
Higgs couples to all massive particles

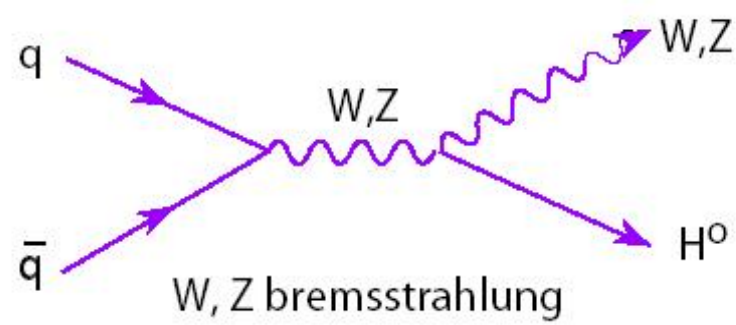


Higgs production

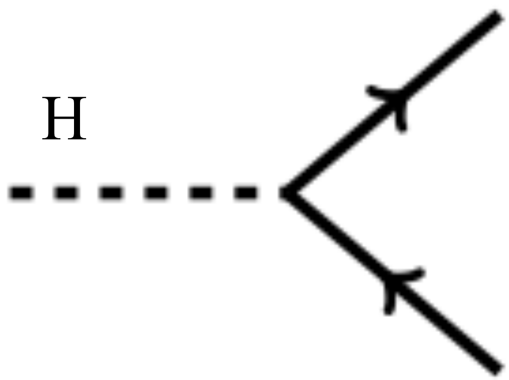


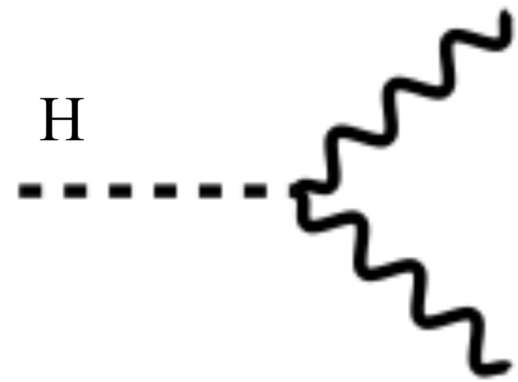




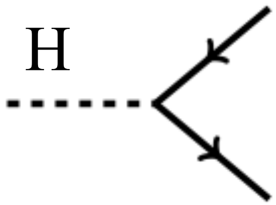


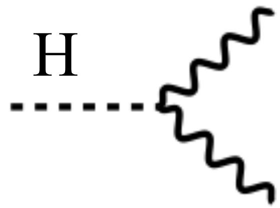
Higgs decays

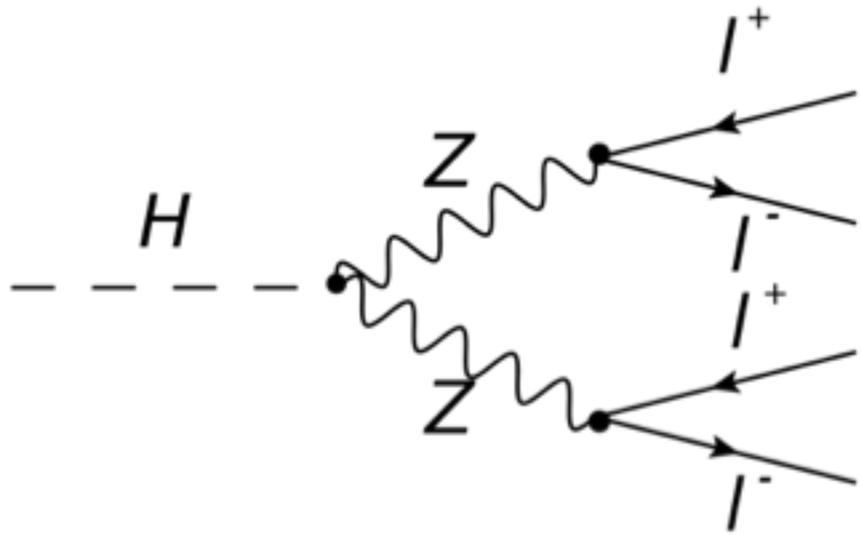




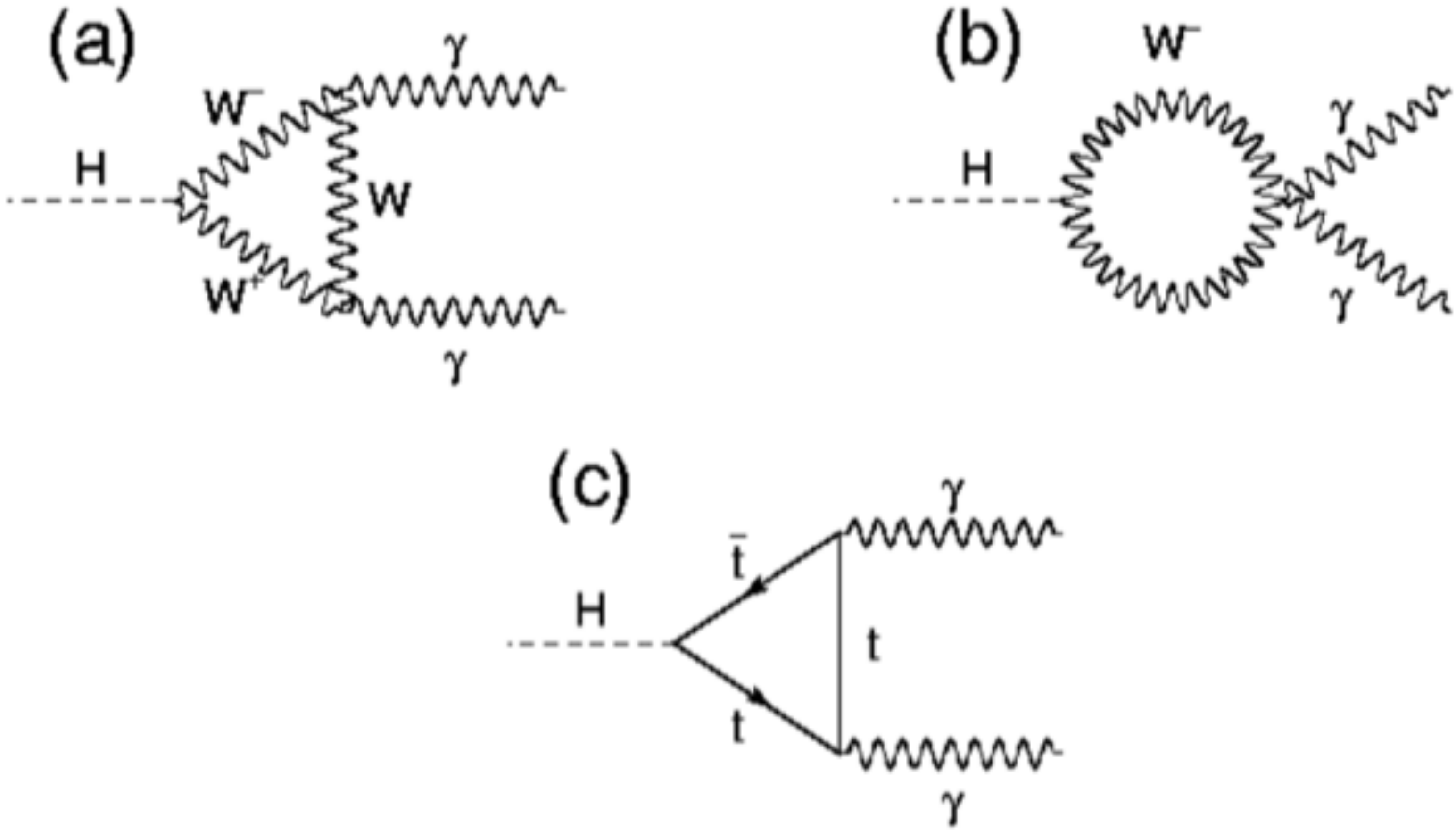
Higgs decays







Higgs decay to two photons



Higgs signatures

Higgs $\rightarrow b + \bar{b}$ (b quark and its antiquark)

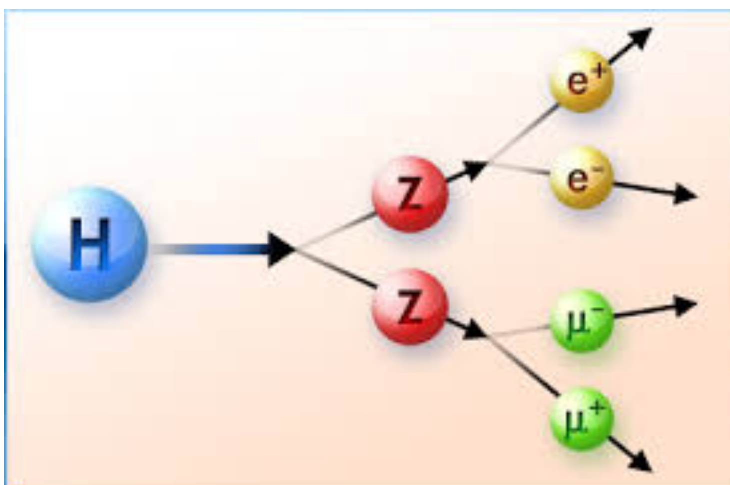
Higgs $\rightarrow \tau^+ + \tau^-$ (τ lepton and its antiparticle)

Higgs $\rightarrow \gamma + \gamma$ (two photons, also called gammas)

Higgs $\rightarrow W^+ + W^-$ (W boson and its antiparticle)

Higgs $\rightarrow Z^0 + Z^0$ (Two Z bosons)

$$H \rightarrow Z + Z^* \rightarrow e^+ + e^- + e^+ + e^-$$
$$H \rightarrow Z + Z^* \rightarrow e^+ + e^- + \mu^+ + \mu^-$$
$$H \rightarrow Z + Z^* \rightarrow \mu^+ + \mu^- + e^+ + e^-$$
$$H \rightarrow Z + Z^* \rightarrow \mu^+ + \mu^- + \mu^+ + \mu^-$$

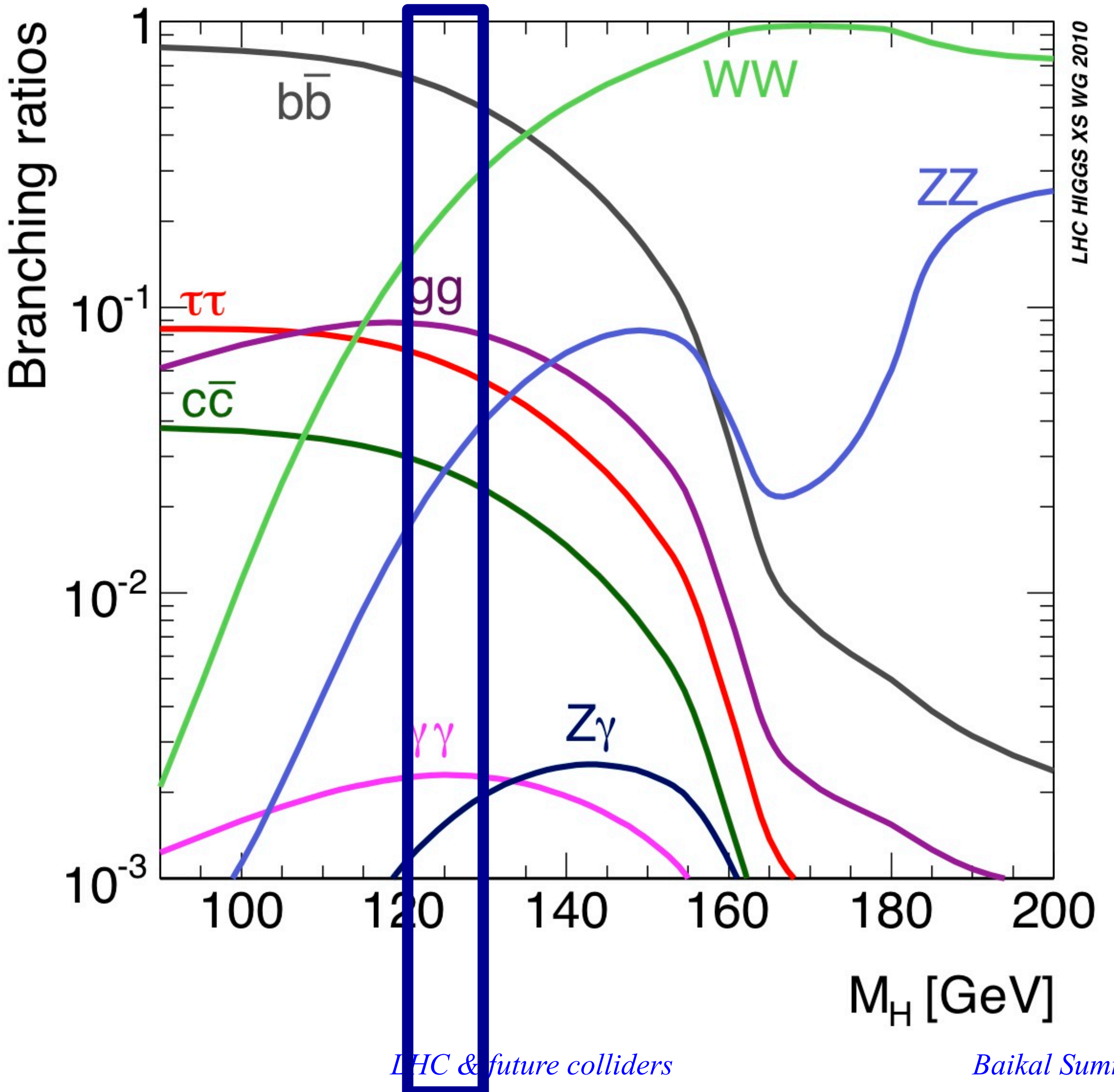


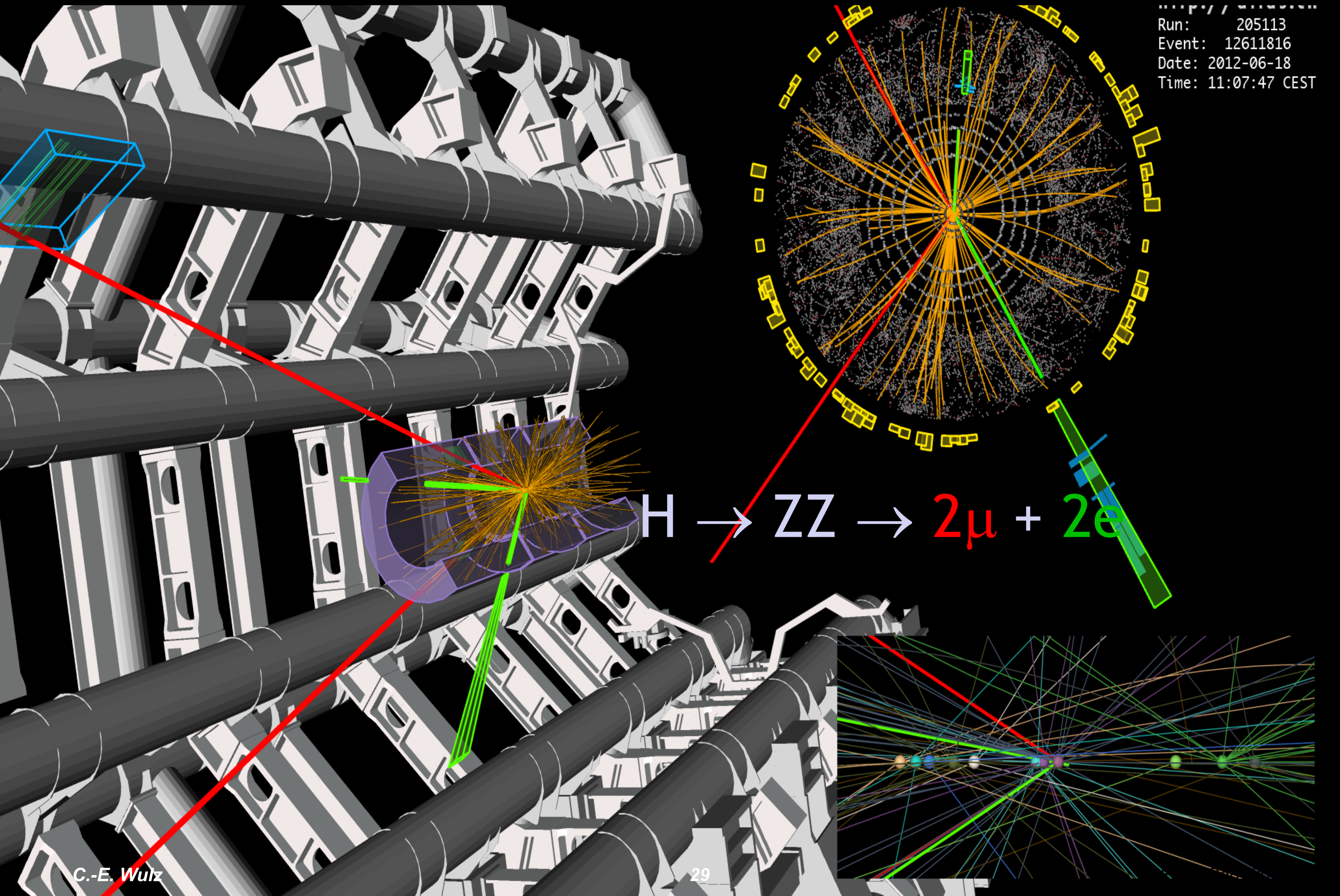
slide from 2011:

The Higgs boson

- cannot be lighter than 114.4 GeV/c2
  - excluded by direct searches (LEP, "Large Electron-Positron collider, CERN)
  - some people thought they caught a glimpse of it at LEP (but then LEP was turned off)
- should not be too heavy
  - else problems arise with the physics it's supposed to explain
- maybe "just around the corner" ?
  - not so good for LHC ("Large Hadron Collider", CERN): hard to disentangle from background
  - have to study lots of possible decay channels !
  - Fermilab ("Tevatron" collider, Chicago) has been trying hard to find it

Higgs decays (branching ratios)

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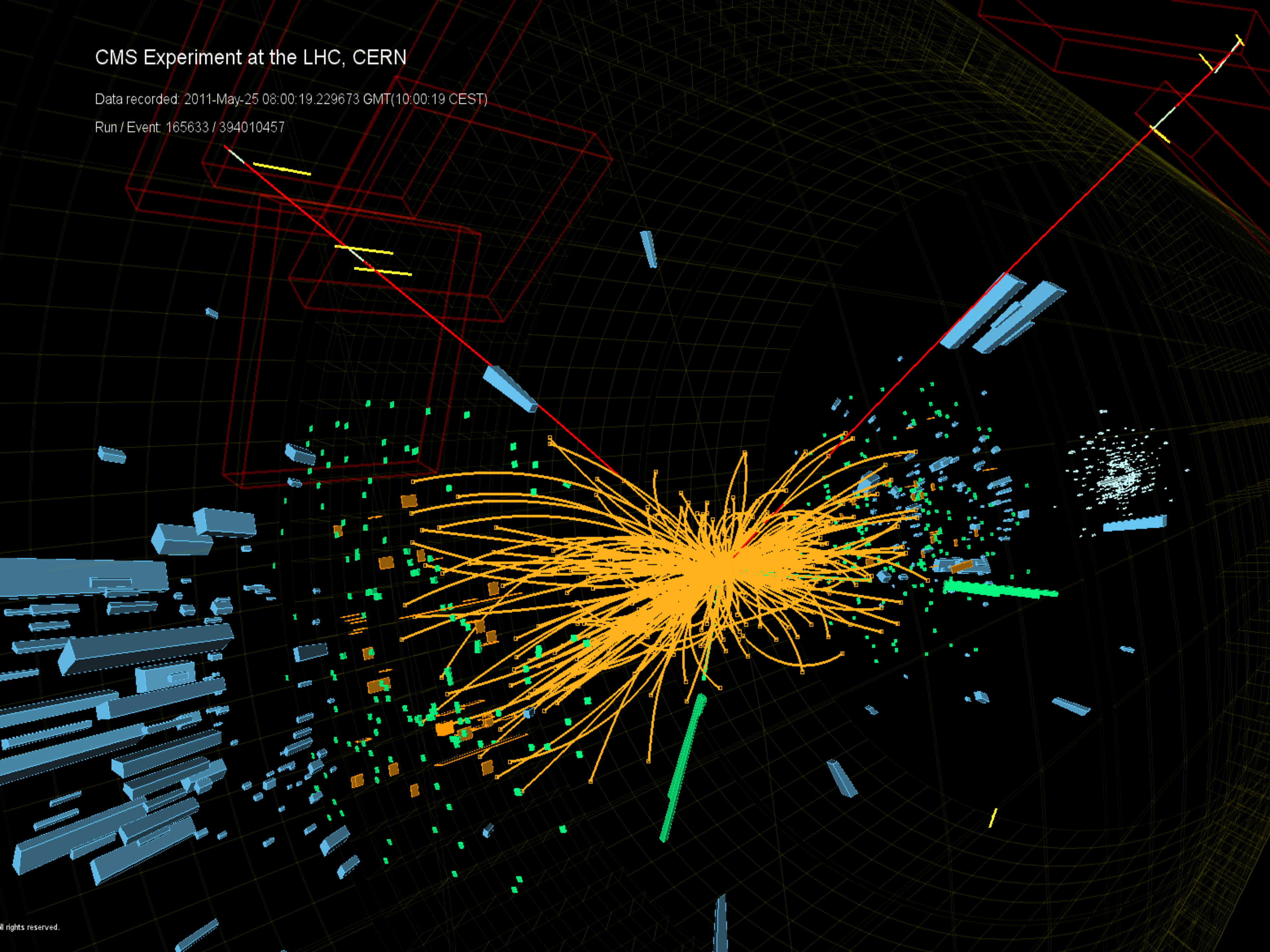
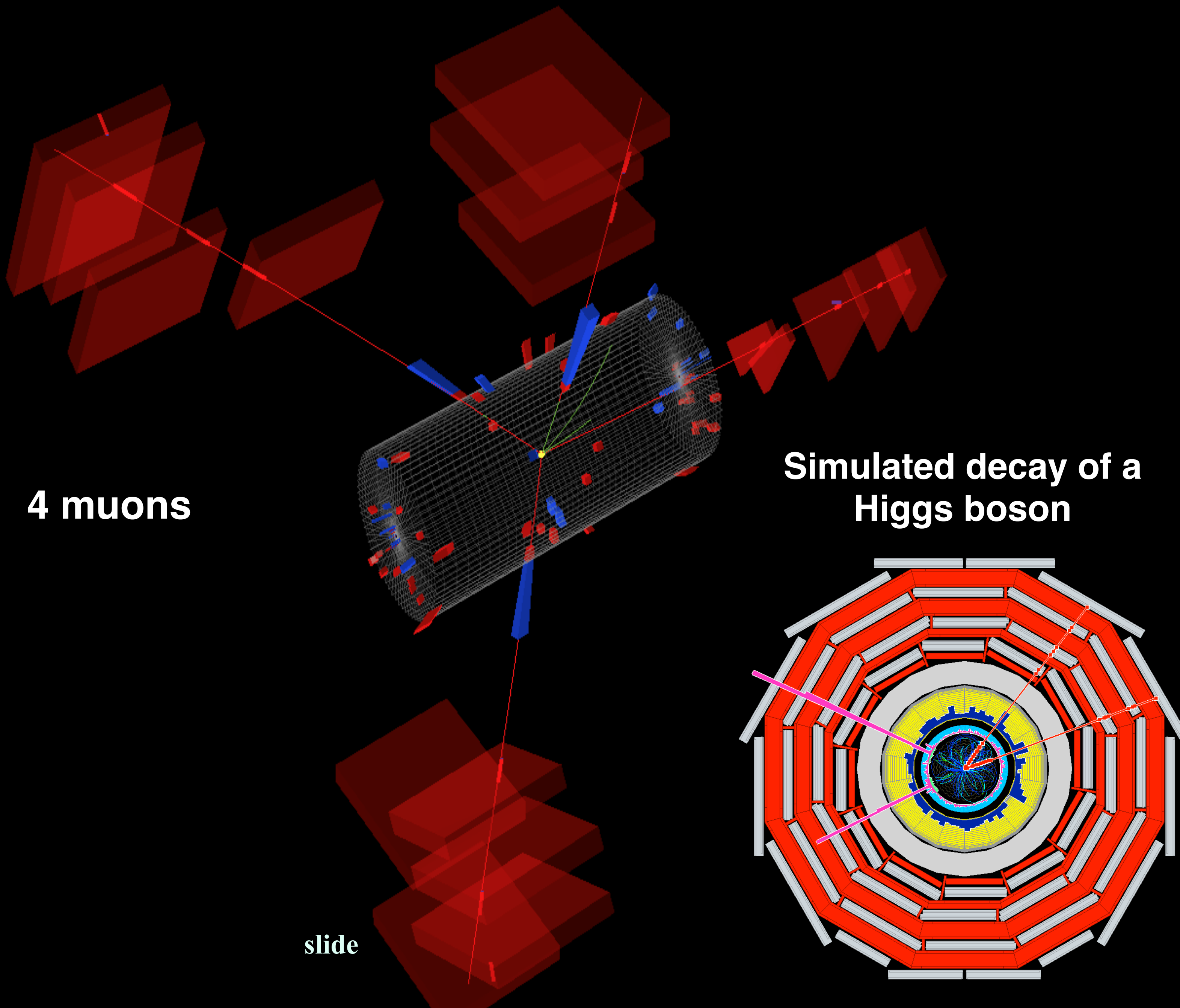
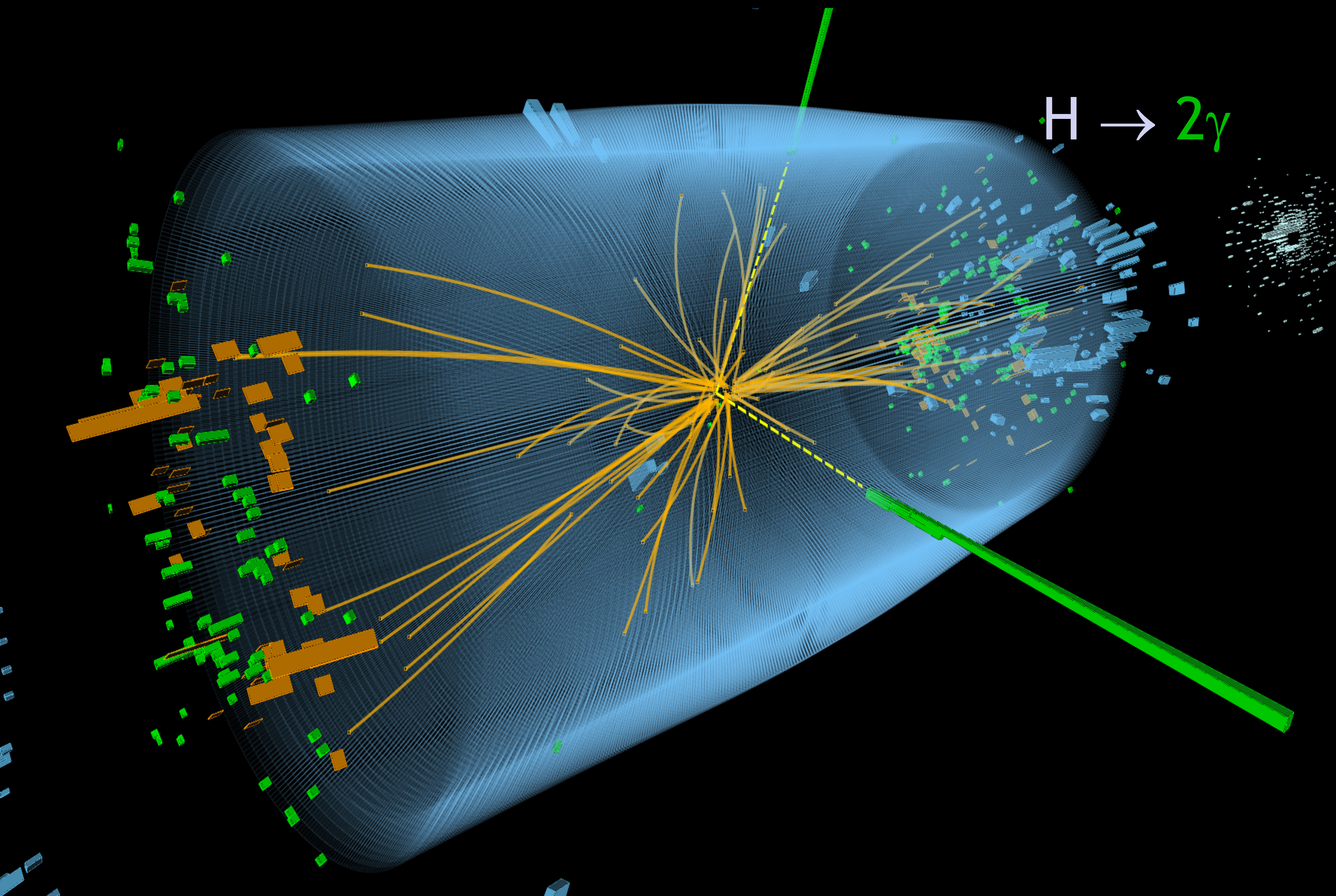
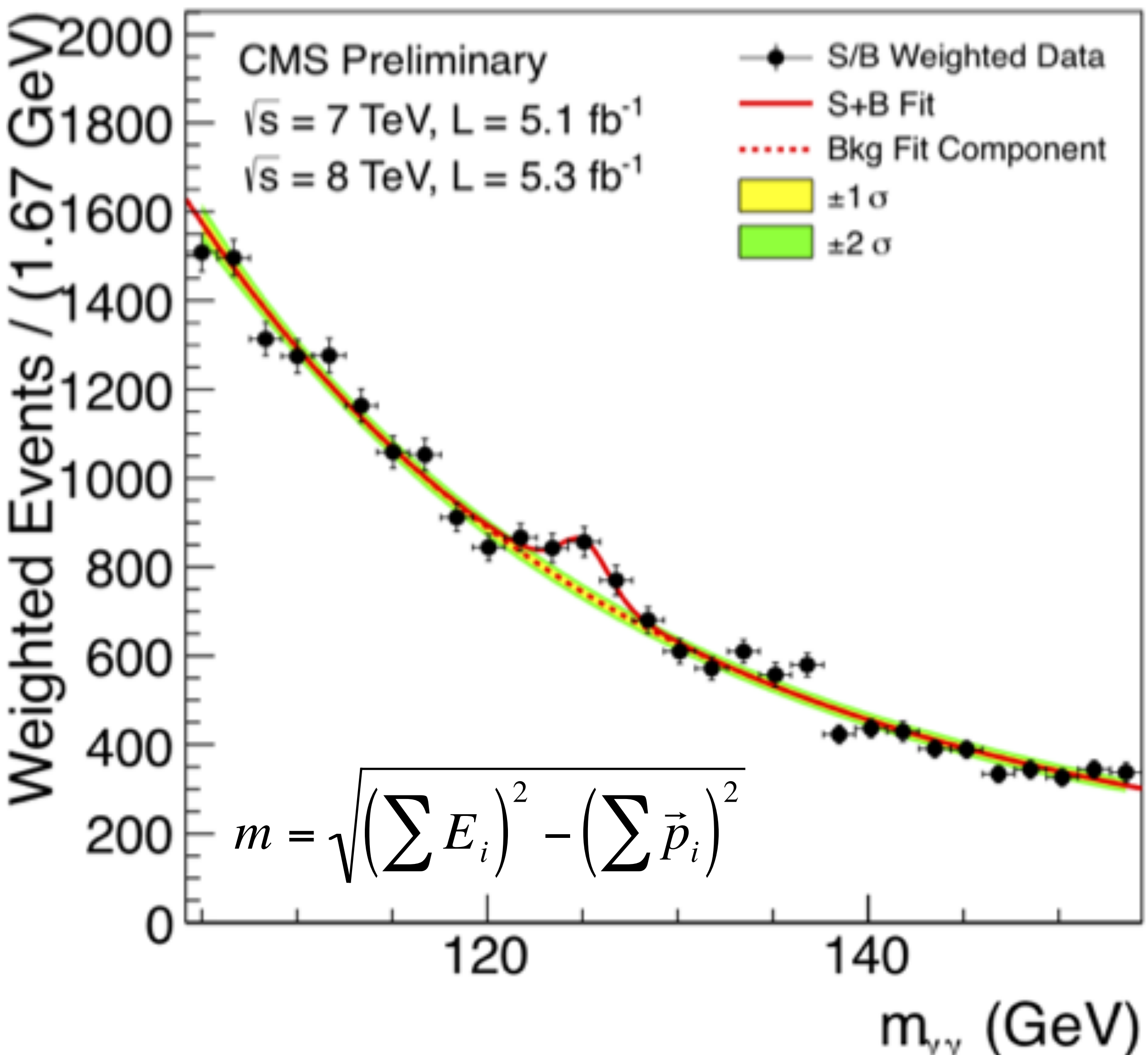
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST
H → ZZ → 2μ + 2e


CMS Experiment at the LHC, CERN
Data recorded: 2011-May-25 08:00:19.229673 GMT(10:00:19 CEST)
Run / Event: 165633 / 394010457
ll rights reserved.


4 muons
Simulated decay of a Higgs boson
slide

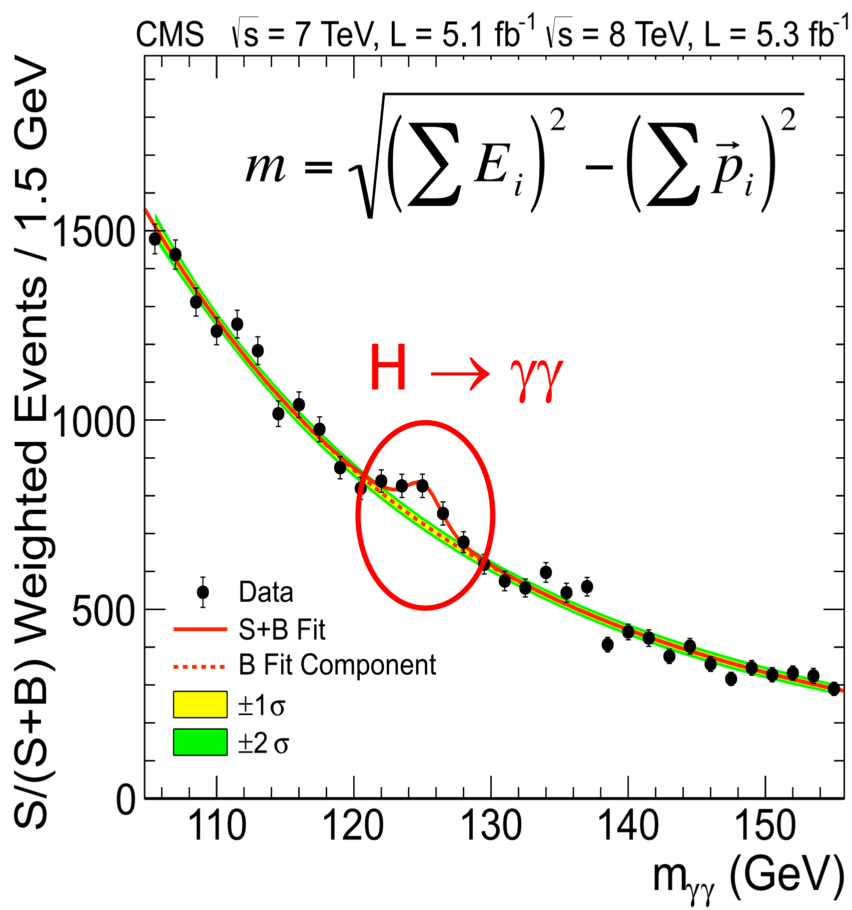

$H \to 2\gamma$

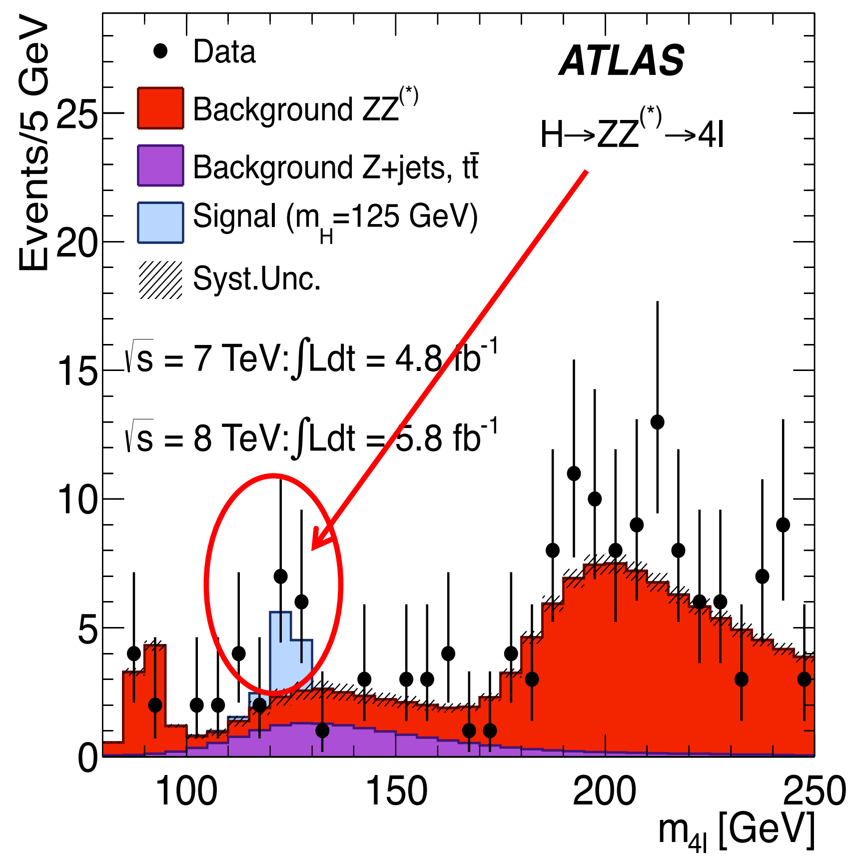


$$m = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

Higgs signal in γγ-channel

(decay into two photons)

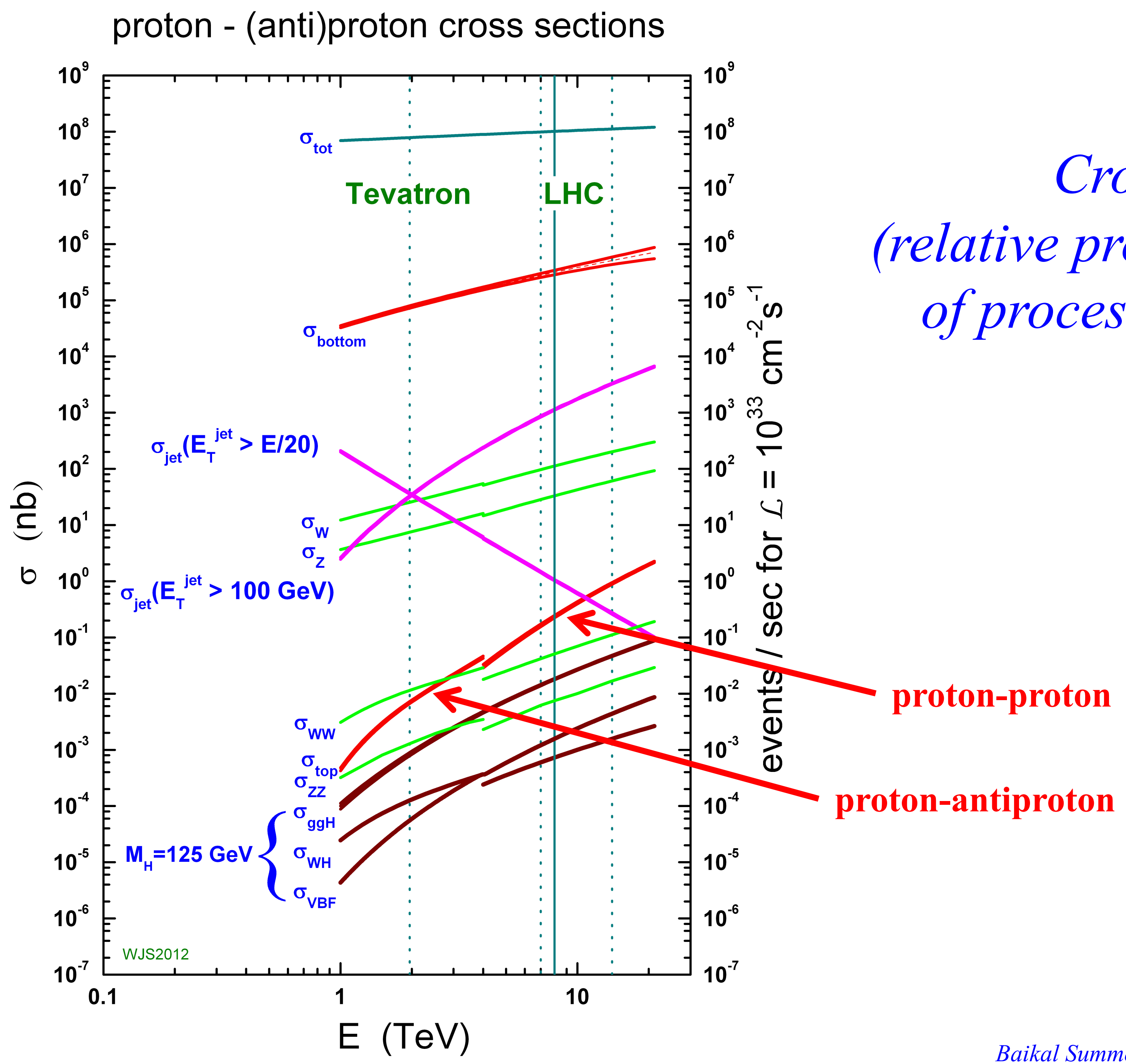

CMS √s = 7 TeV, L = 5.1 fb^{-1} √s = 8 TeV, L = 5.3 fb^{-1}
$m = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$
H → γγ
S/(S+B) Weighted Events / 1.5 GeV
Data
S+B Fit
B Fit Component
±1σ
±2 σ
$m_{\gamma\gamma}$ (GeV)


ATLAS
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
Data
Background $ZZ^{(*)}$
Background Z+jets, $t\bar{t}$
Signal (m_H=125 GeV)
Syst.Unc.
√s = 7 TeV: ∫Ldt = 4.8 fb^{-1}
√s = 8 TeV: ∫Ldt = 5.8 fb^{-1}
Events/5 GeV
m_{4l} [GeV]

The Higgs boson: looking for a needle in a haystack

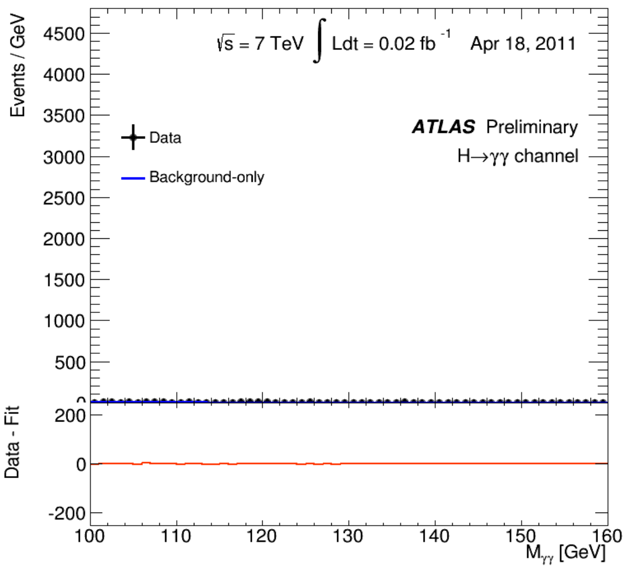
- an individual event cannot be identified for sure as showing a Higgs boson decay
- there are only "candidate events"
- only the statistical distribution proves its existence

Cross sections (relative probabilities) of processes at LHC

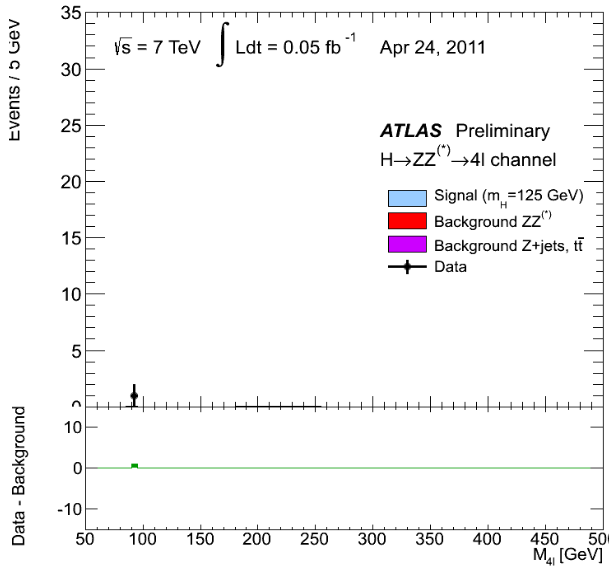


The Birth of a Particle

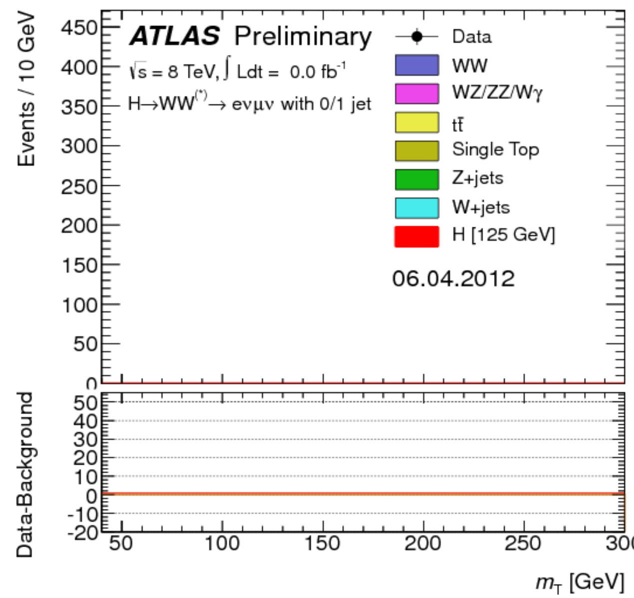
Diphoton



ZZ Four leptons



WW (lvlv)



Clear excesses in these three channels

Higgs Boson (ATLAS Preliminary data)

Sonification by Domenico Vicinanza

https://youtu.be/KjHvGyPlcT4

The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

Is it the right shape?

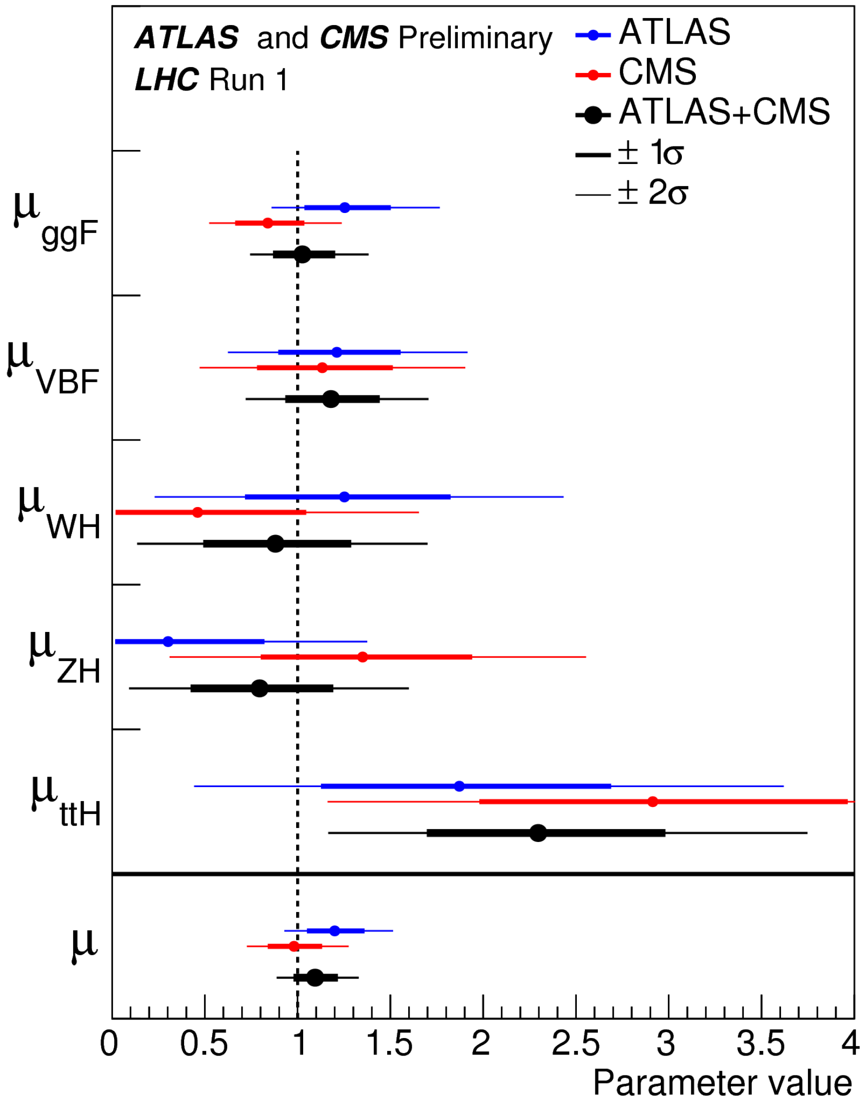
Is it the right size?

YES!

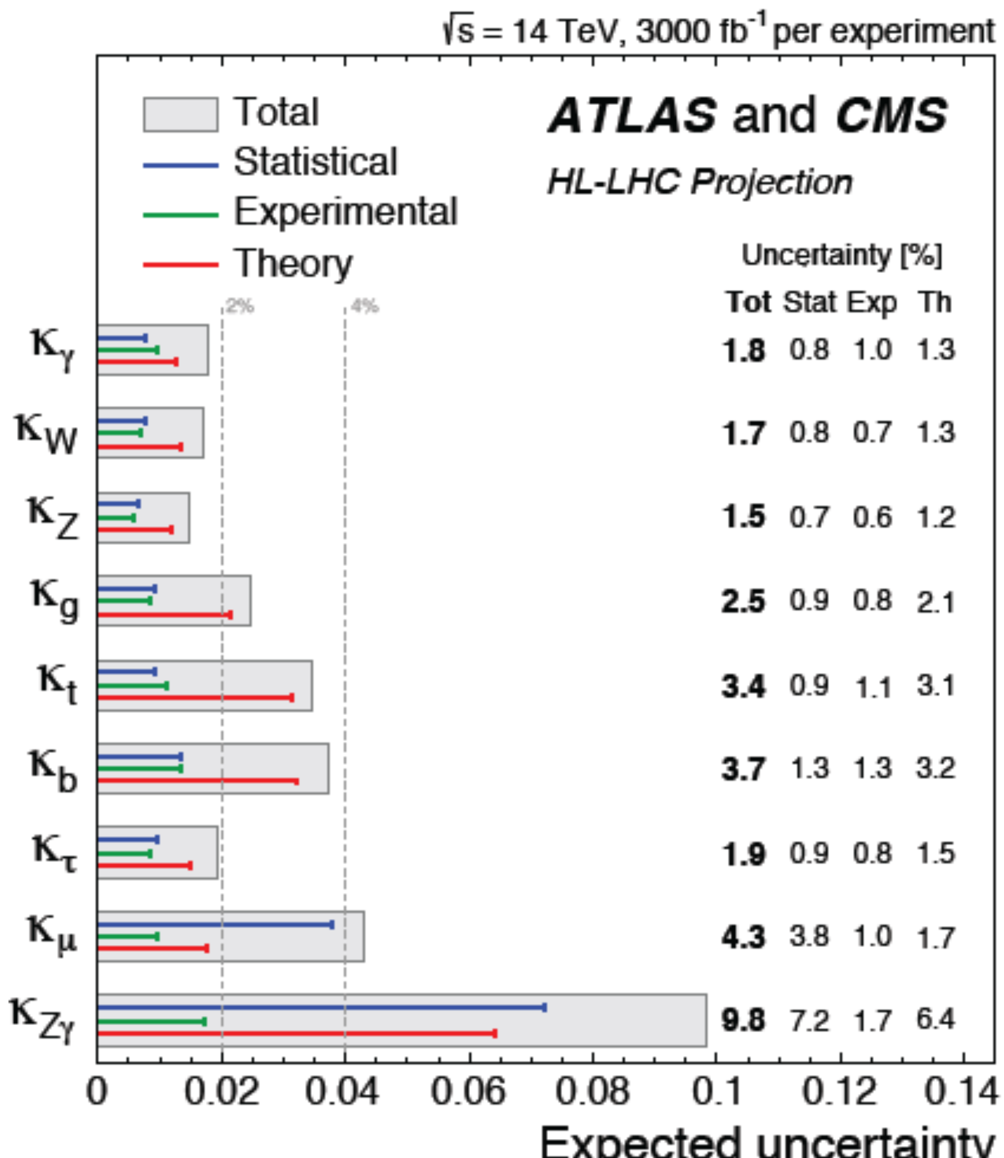
Properties

- Spin
  - must have spin=0
- Parity
  - must have positive parity
- coupling to fermions
  - first decays seen were decays into bosons
  - H → fermions ($\tau^+\tau^-$, bb) were established later

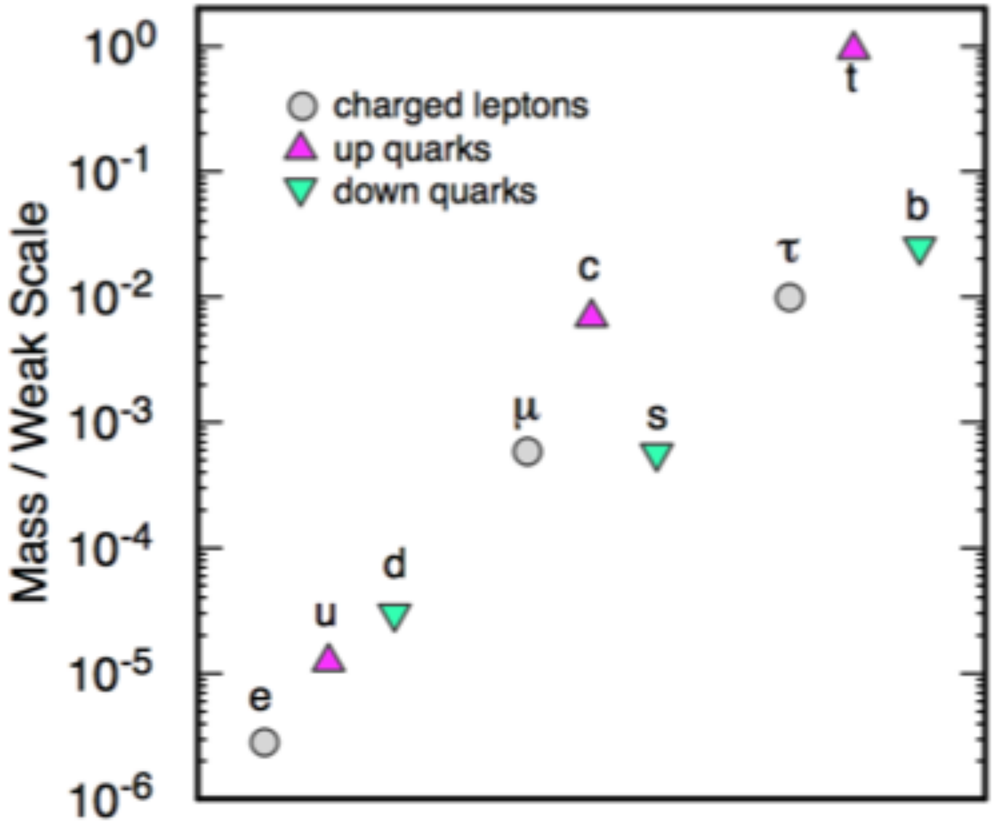
Higgs production channels: comparison to standard model value



Projection of precision to be achieved



Not explaining the flavor Hierarchy

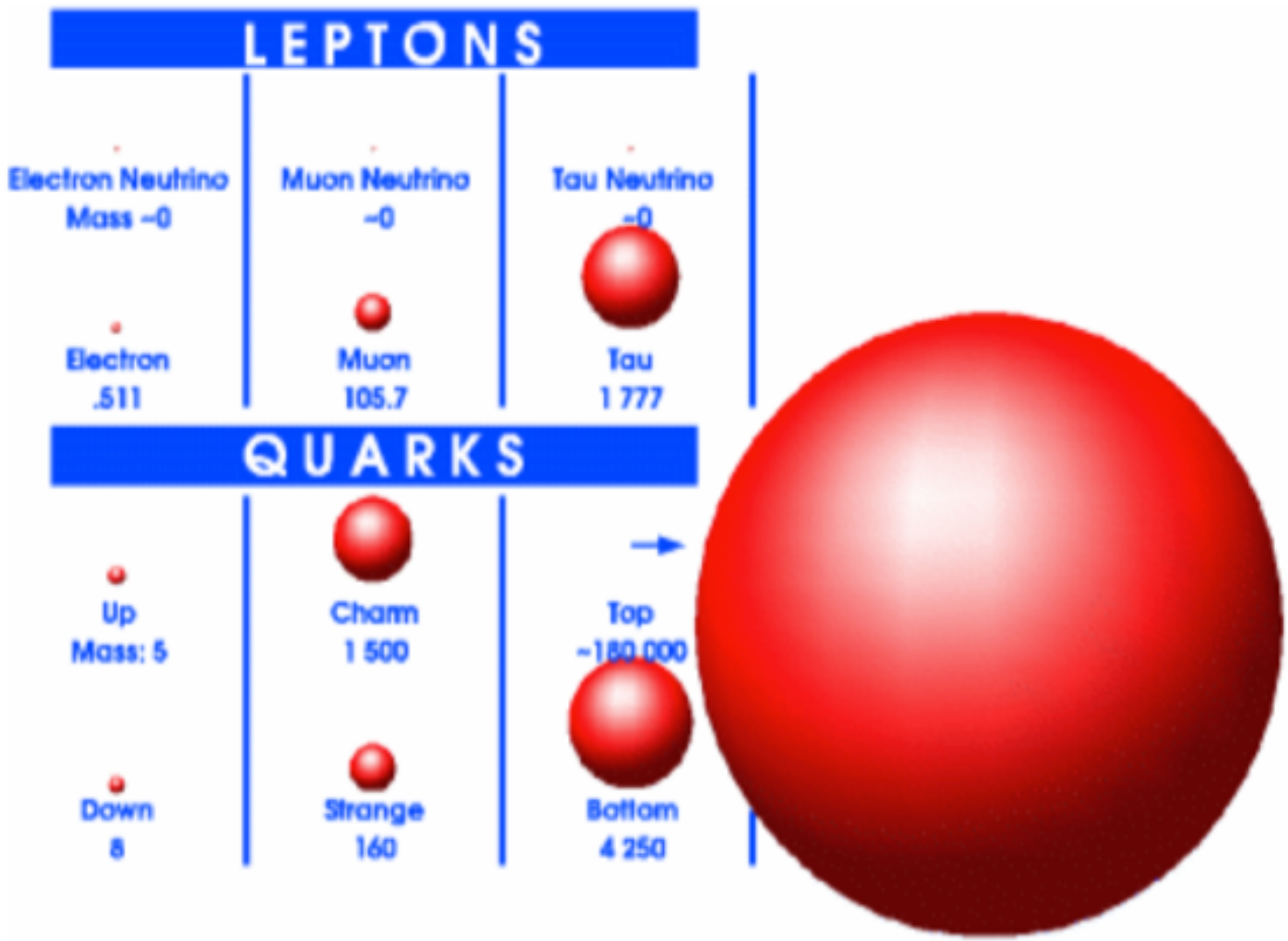


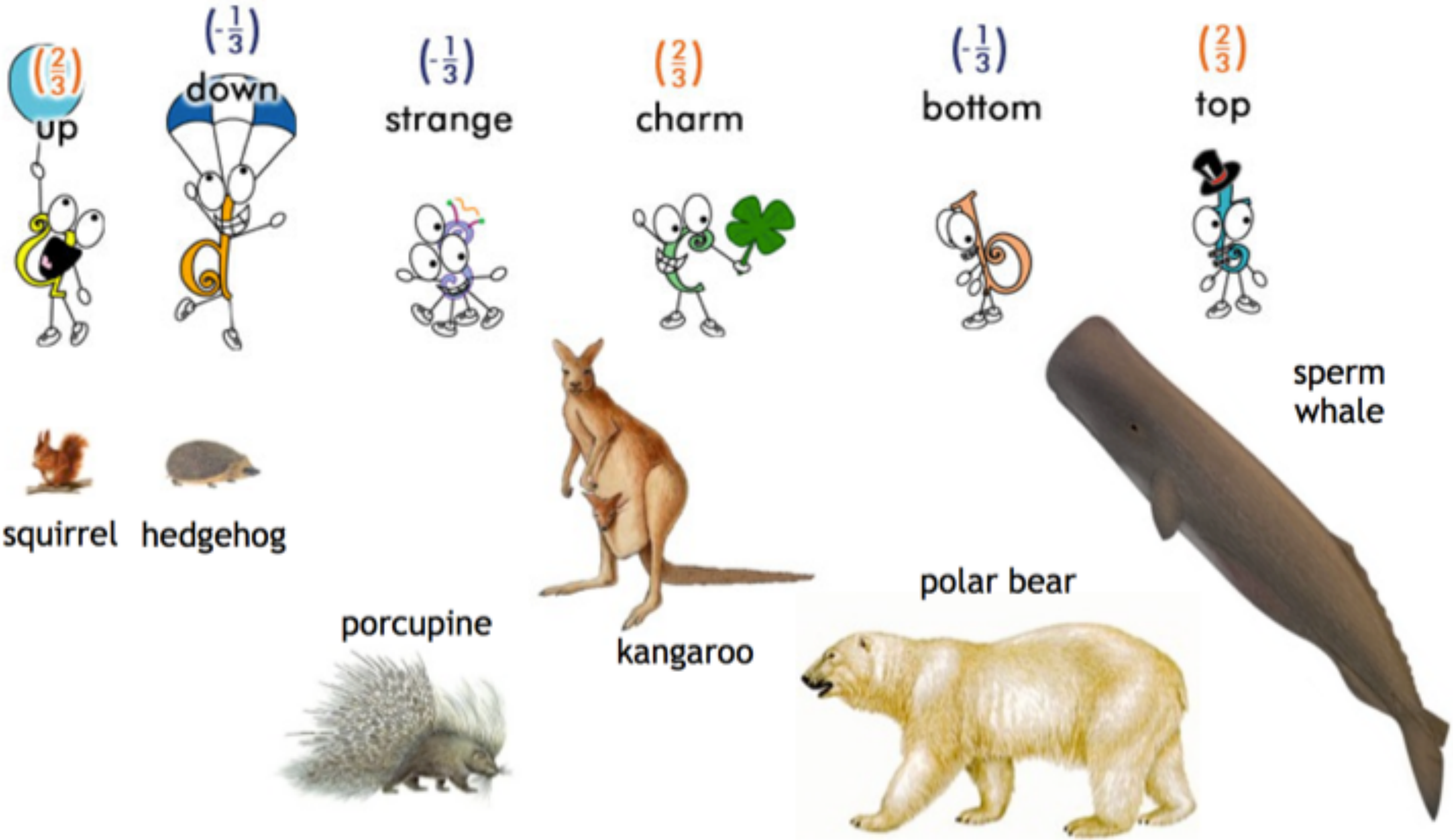
~6 orders of magnitude

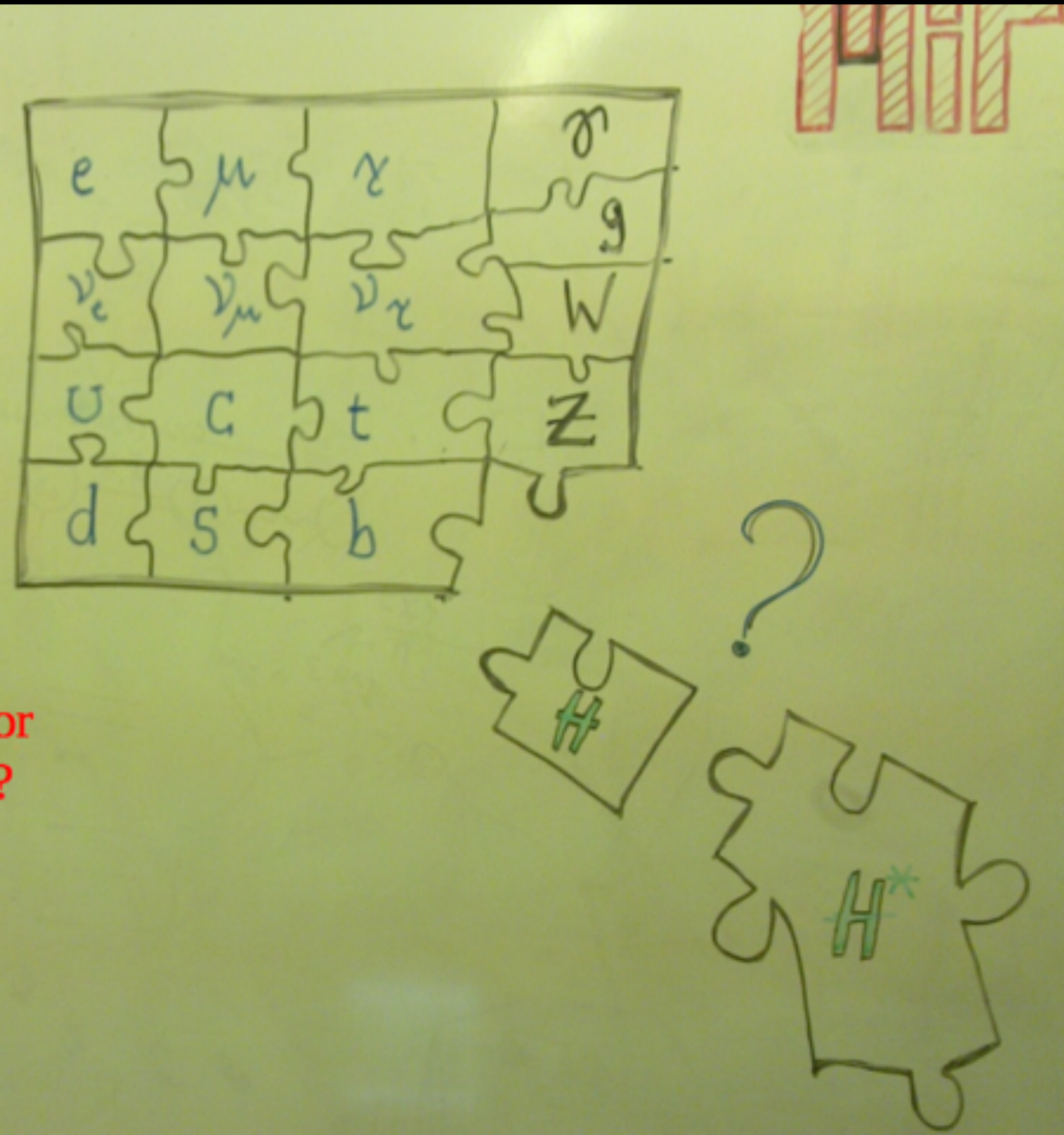
Neutrinos are not even on the scale!

The BEH sector includes most of the free parameters of the Standard Model

relative masses of elementary particles




(2/3) up
(-1/3) down
(-1/3) strange
(2/3) charm
(-1/3) bottom
(2/3) top
squirrel
hedgehog
porcupine
kangaroo
polar bear
sperm whale



The end of the puzzle or
just another beginning?

What's next?

- The Standard Model has been confirmed
- New questions arise
- The Standard Model does *not* give a complete description of the subatomic world
- Open questions:
  - "Fine-tuning" of Higgs mass
    - » Supersymmetry
  - Neutrino oscillations and masses
  - Dark Matter
  - Dark Energy
  - Gravitation
  - Extra Dimensions ?

BACKUP