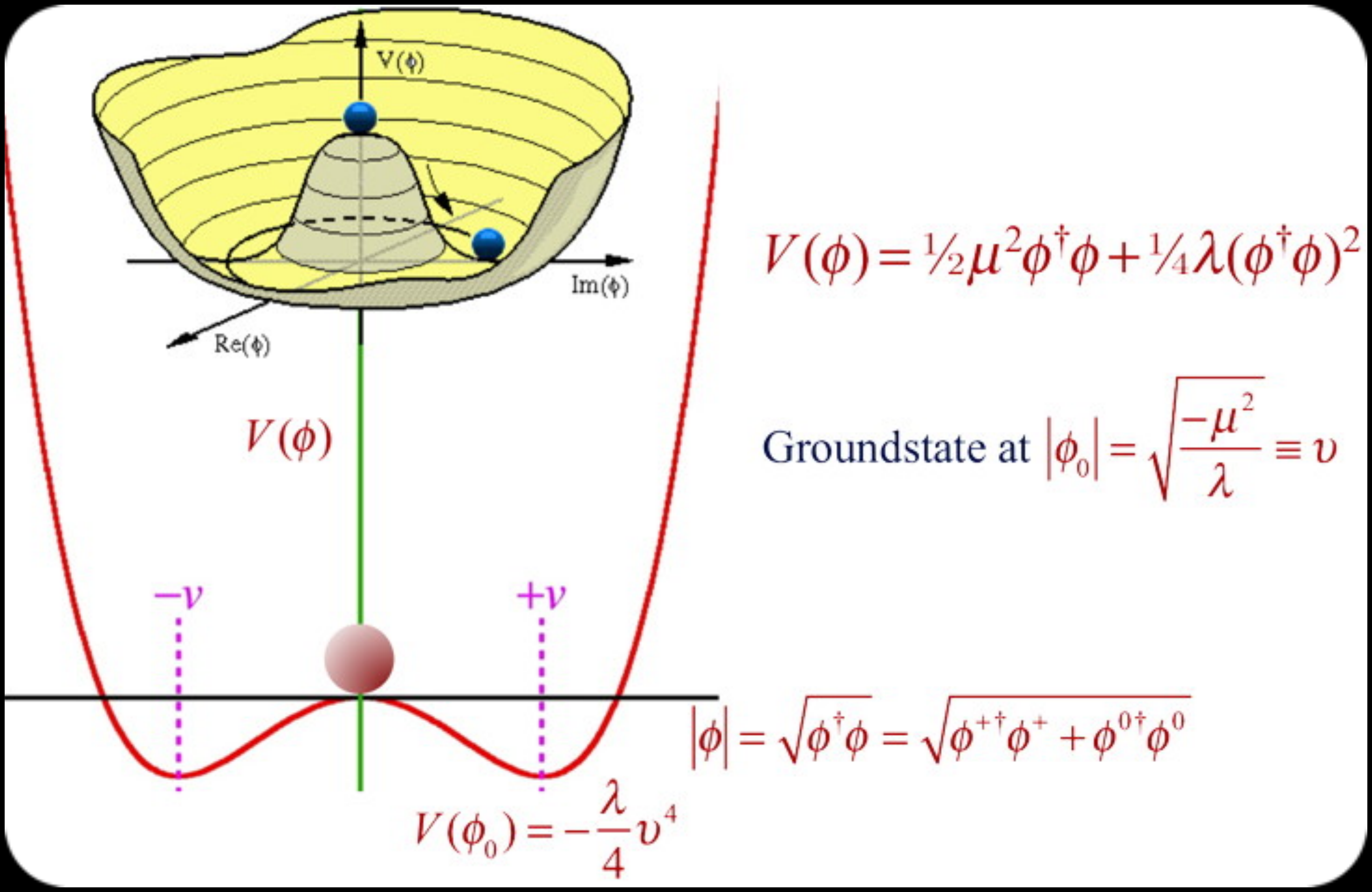
The Higgs mechanism and physics beyond the Standard Model



Panos Christakoglou

Nikhef and Utrecht University

The Standard Model (theoretical framework)

Quantum ElectroDynamics (QED)

The Nobel Prize in Physics 1965
Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman

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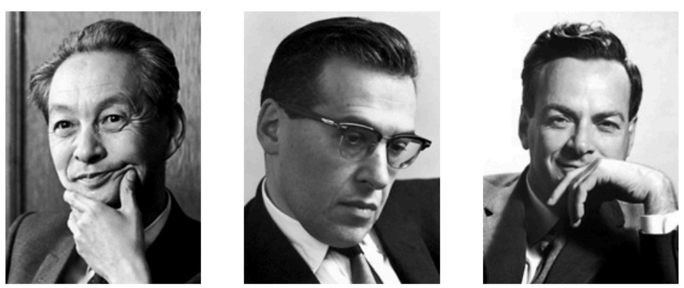
The Nobel Prize in Physics 1965



Sin-Itiro Tomonaga
Prize share: 1/3

Julian Schwinger
Prize share: 1/3

Richard P. Feynman
Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman *"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"*.

Electroweak Unification (GSW)

The Nobel Prize in Physics 1979
Sheldon Glashow, Abdus Salam, Steven Weinberg

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The Nobel Prize in Physics 1979

Sheldon Lee Glashow
Prize share: 1/3

Abdus Salam
Prize share: 1/3

Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Quantum ChromoDynamics (QCD)

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

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The Nobel Prize in Physics 2004

David J. Gross
Prize share: 1/3

H. David Politzer
Prize share: 1/3

Frank Wilczek
Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

The Standard Model (theoretical framework)

The Higgs mechanism

•

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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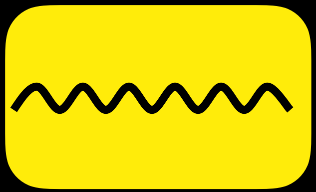
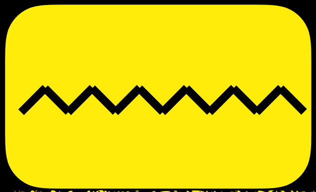
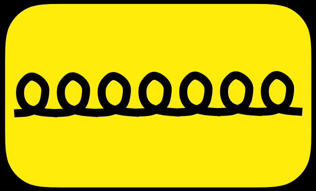
The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

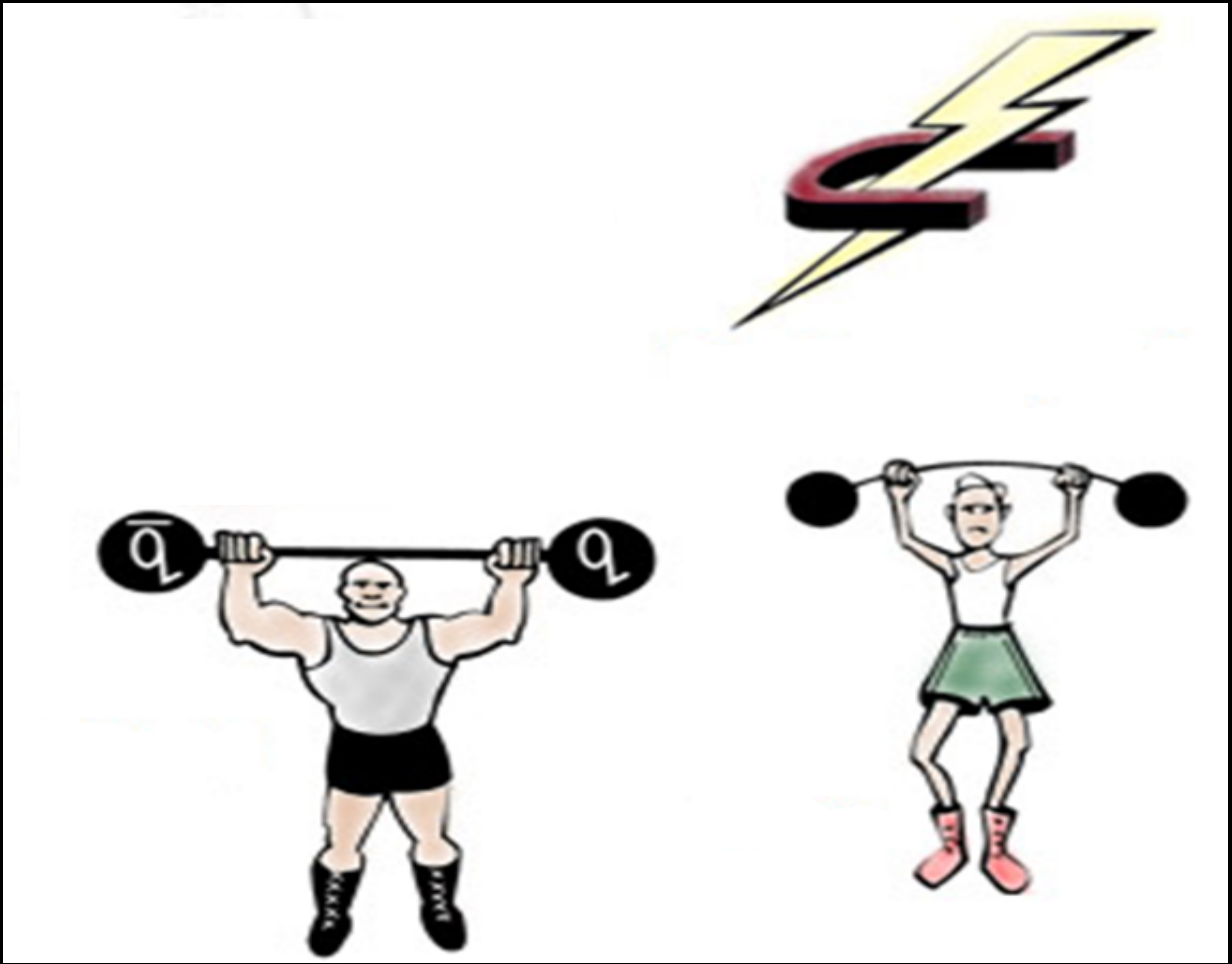
Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. 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"*

Symmetries and gauge transformations (strong)

Conserved quantities	Gauge transformation	Symmetry group	Field
Charge: ψ	$\Psi \rightarrow \Psi' = e^{i\alpha}\Psi$	U(1) (QED)	A_μ (1 photon) 
Weak isospin $\psi=\begin{pmatrix}\nu\\ e\end{pmatrix}$ $\psi=\begin{pmatrix}u\\ d\end{pmatrix}$	$\Psi \rightarrow \Psi' = e^{\frac{i\vec{\tau}\vec{\alpha}}{2}}\Psi$	SU(2) (weak)	A_μ (3 bosons, $W^\pm$, Z^0) 
Colour $\psi=\begin{pmatrix}r\\ g\\ b\end{pmatrix}$	$\Psi \rightarrow \Psi' = e^{\frac{i}{2}\sum_{i=1}^{8}\theta_a\lambda_a}\Psi$	SU(3) (QCD)	A_μ (8 gluons g) 

Forces and mediators



Transformations-symmetries-groups of the Standard Model

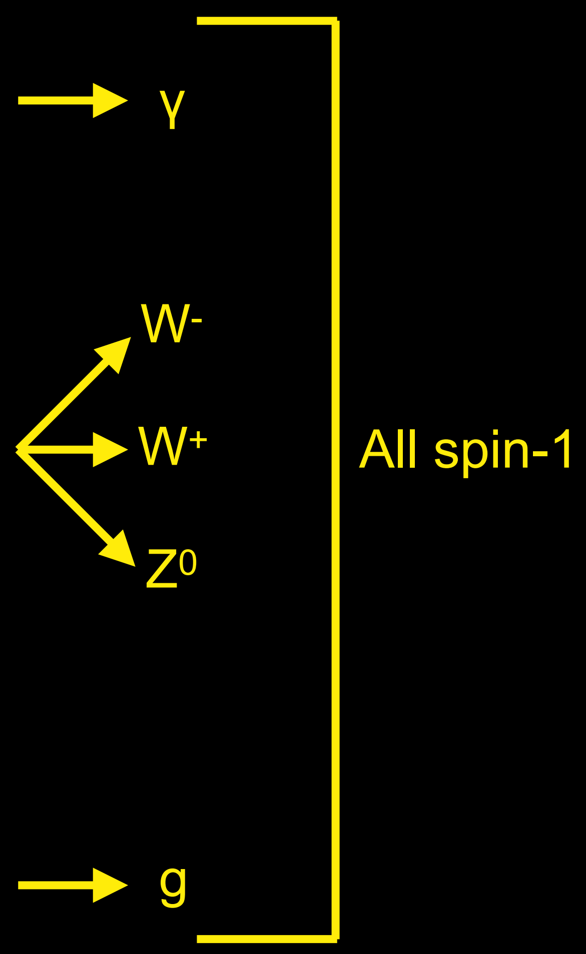
$$U(1)_Y \otimes SU(2)_L \otimes SU(3)_C$$

Rotations in hyper charge space described by the U(1) group

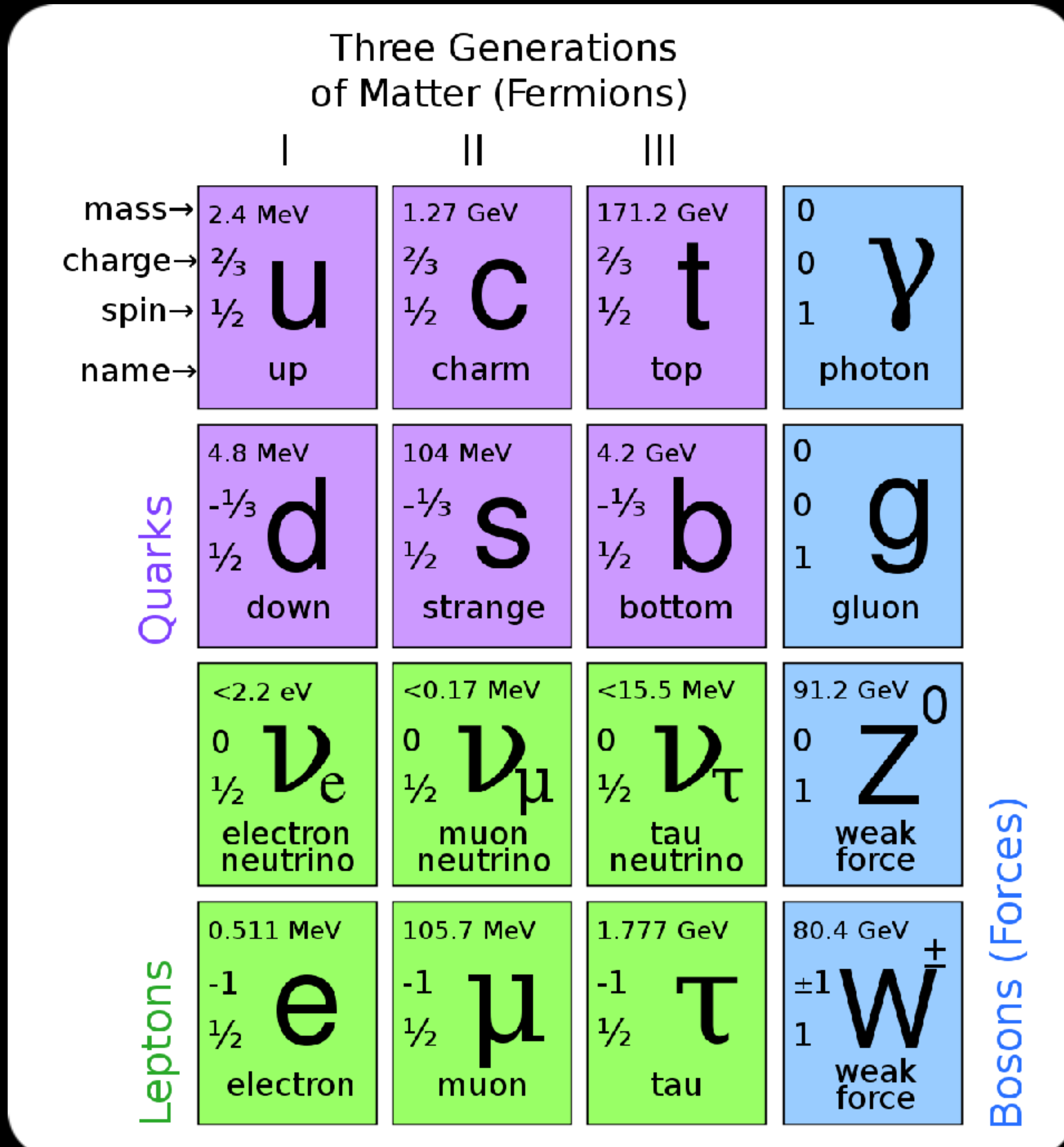
Rotations in colour space described by the SU(3) group

Rotations in weak isospin space described by the SU(2) group

- ✓ QED ⇒ transformations represented by 1x1 matrices ⇒ rotations in hyper charge ⇒ described by $U(1)_Y$ ⇒ 1 degree of freedom ⇒ 1 massless vector field ⇒ the photon
- ✓ Weak ⇒ transformations represented by 2x2 matrices ⇒ generators: Pauli matrices $\tau_i/2$ ⇒ rotations in weak isospin ⇒ described by $SU(2)_L$ ⇒ 3 degrees of freedom ⇒ 3 massive vector fields ⇒ the W & Z bosons
- ✓ QCD ⇒ transformations represented by 3x3 matrices ⇒ generators: Gell-Mann matrices $\lambda^\alpha/2$ ⇒ rotations in colour space ⇒ described by $SU(3)_C$ ⇒ 8 degrees of freedom ⇒ 8 massless vector fields ⇒ the gluons



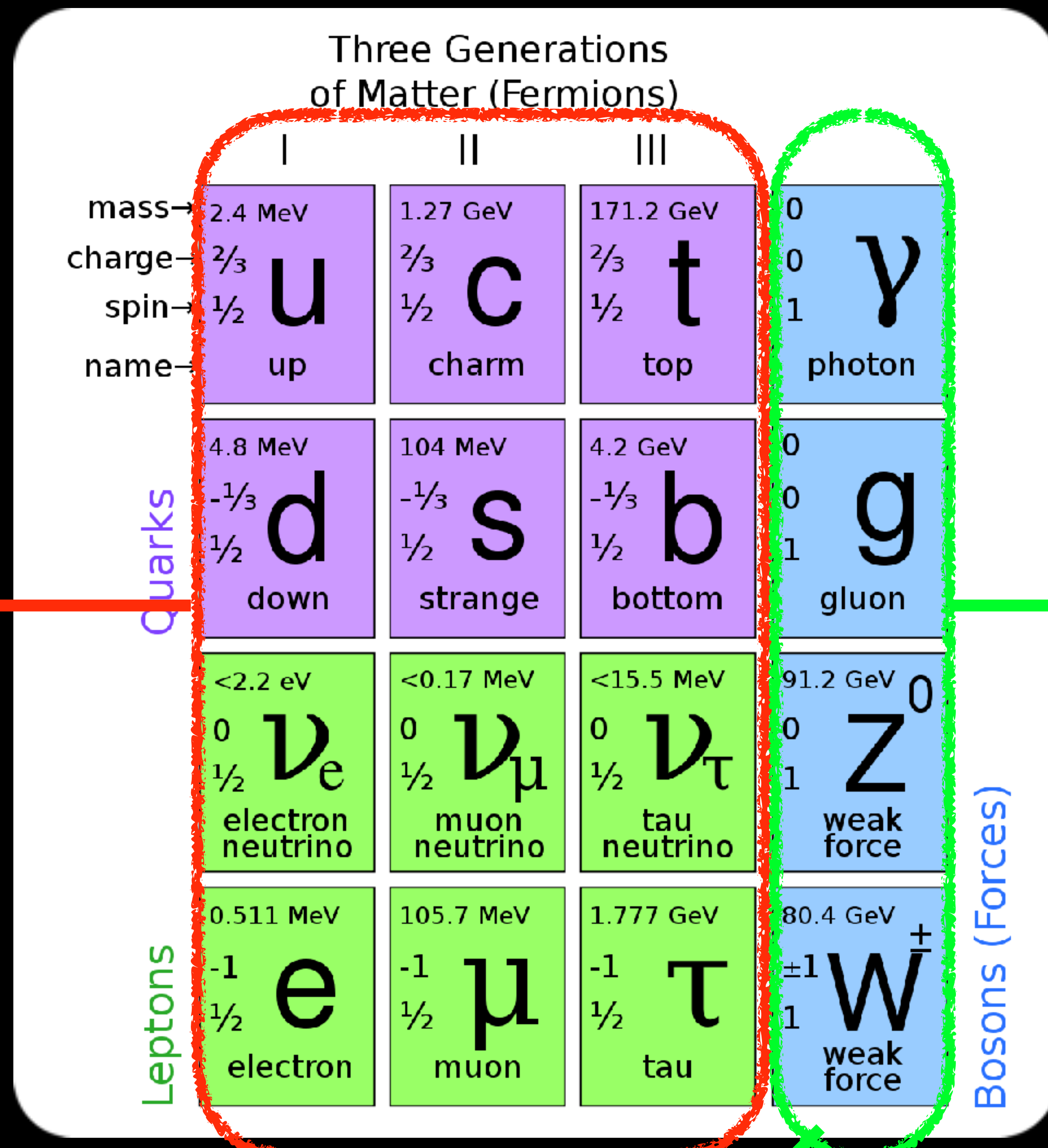
Periodic table of particles



Lagrangian formalism

$$\mathcal{L} = \overline{\Psi}(i\gamma_\mu D^\mu - m)\Psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

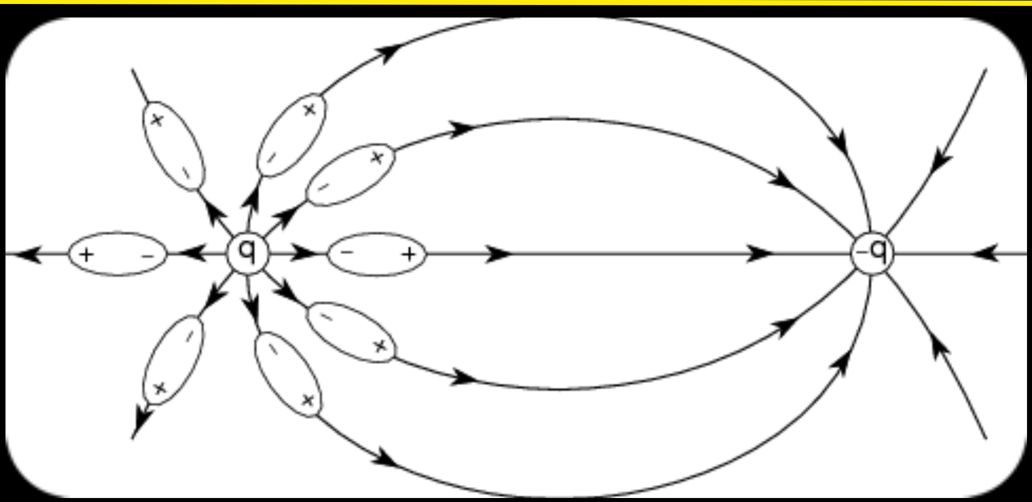
Fermion fields Ψ

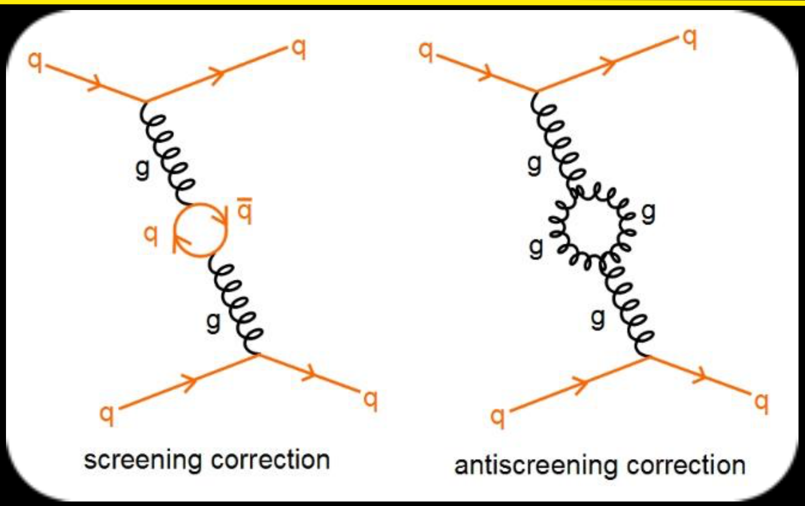


Gauge fields A_μ

Interaction through D between Ψ and A_μ

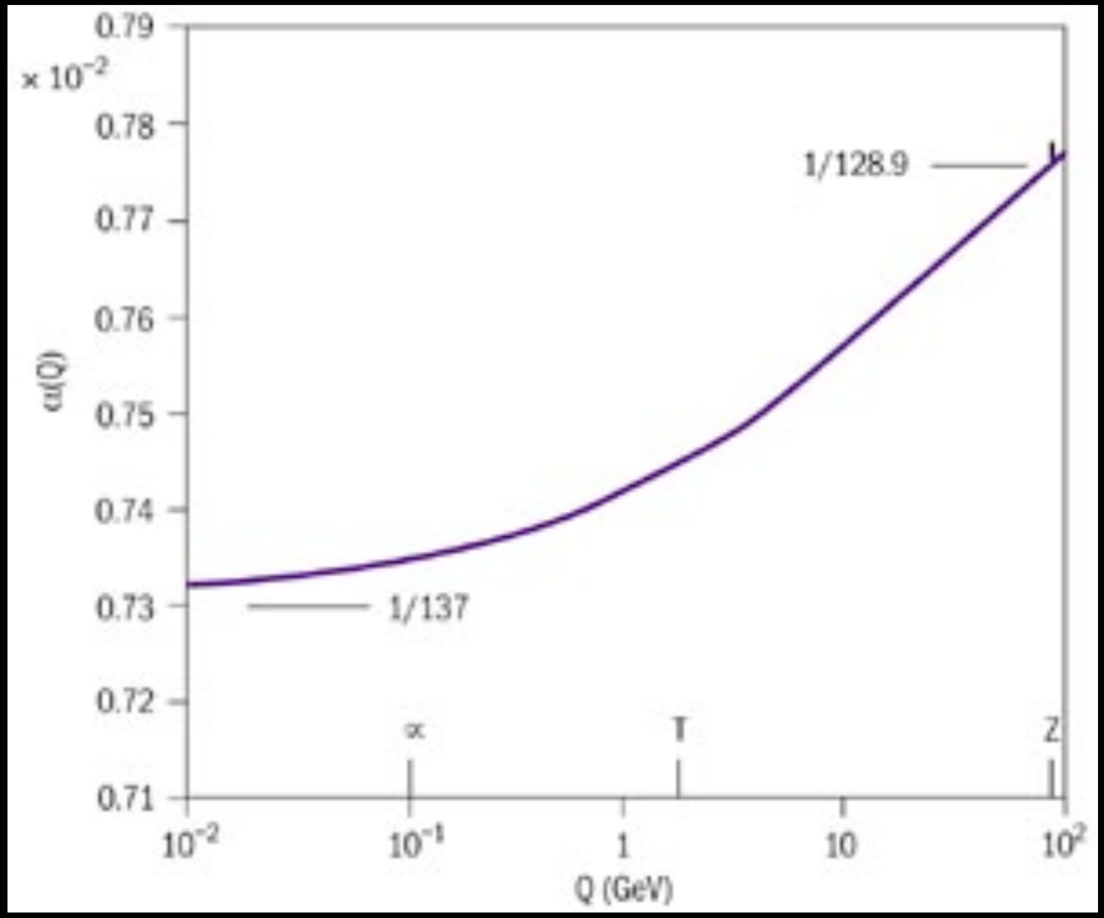
Coupling constants of the Standard Model (cont.)

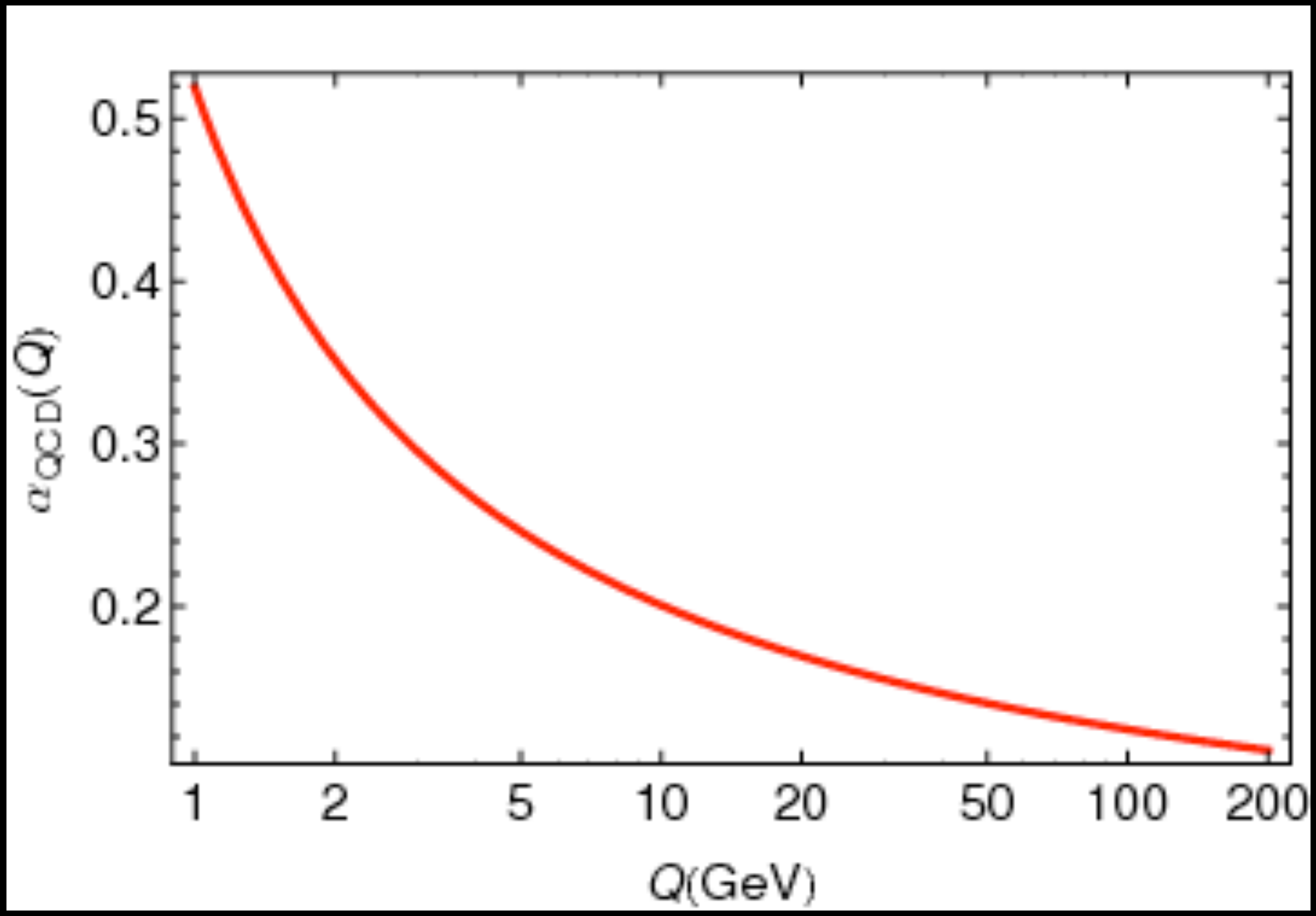




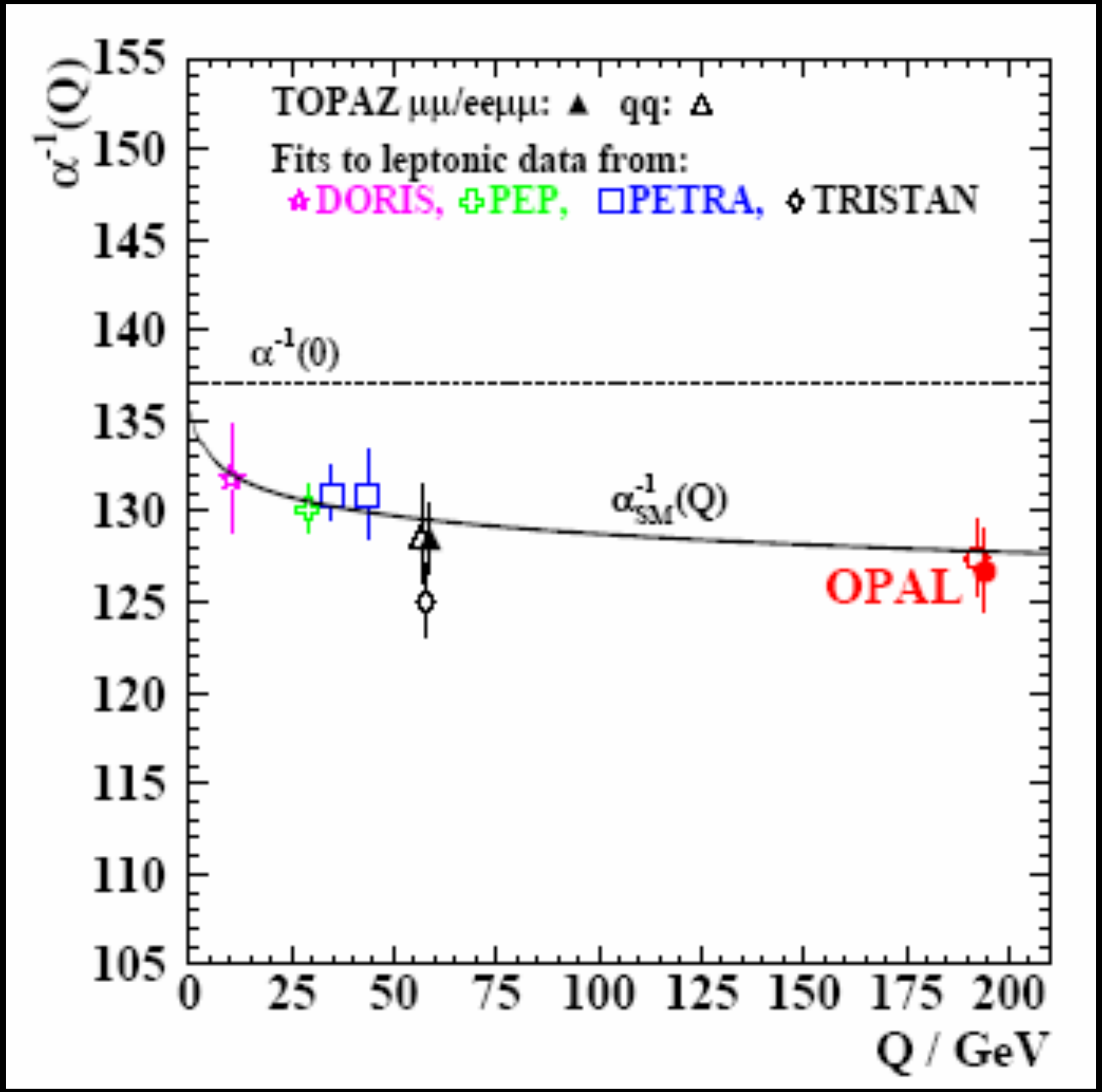
$$a(Q^2) = \frac{a(\mu^2)}{1 - \frac{a(\mu^2)}{3\pi}\ln\left(\frac{Q^2}{\mu^2}\right)}$$

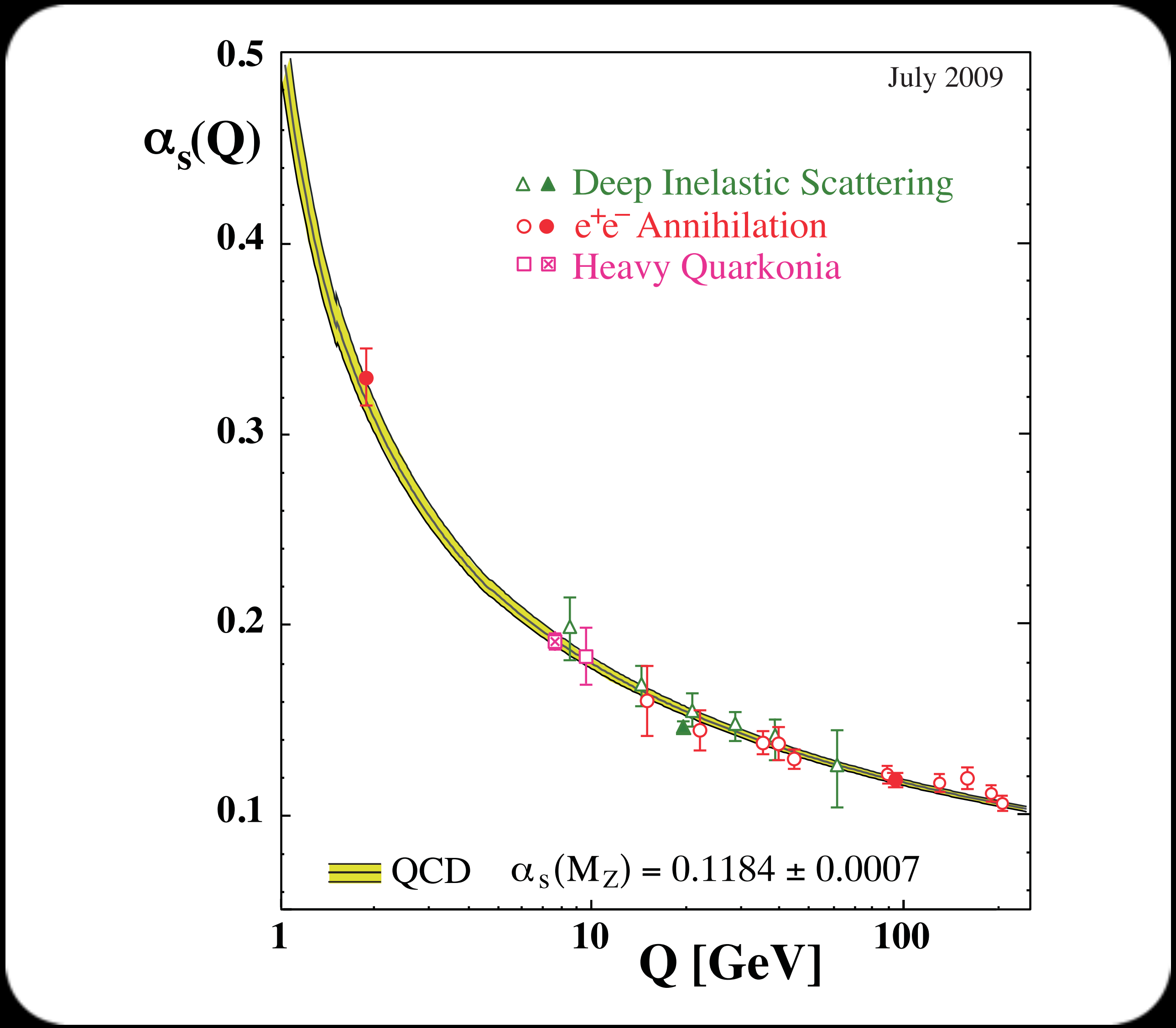
$$a_s(Q^2) = \frac{a_s(\mu^2)}{1 + \frac{a_s(\mu^2)}{12\pi}(11N_c - 2n_f)\ln\left(\frac{Q^2}{\mu^2}\right)}$$





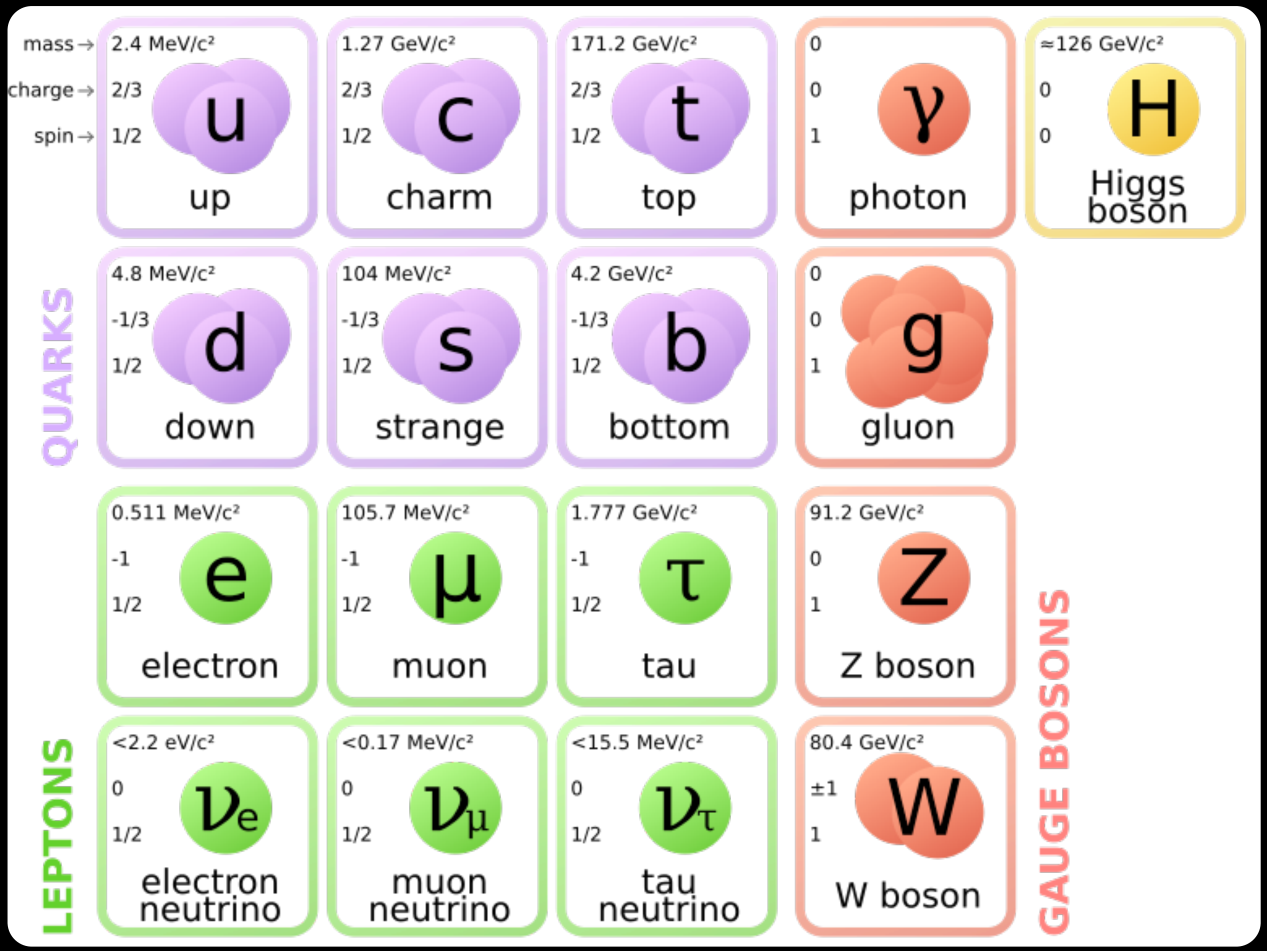
Coupling constants of the Standard Model (cont.)





The Higgs mechanism

- ✓ The Higgs boson was the last particle of the Standard Model to be discovered.
- ✓ It is a critical component of the Standard Model.
- ✓ Its discovery helps confirm the mechanism by which fundamental particles get mass.
- ✓ These fundamental particles of the Standard Model are the quarks, leptons, and force-carrier particles.

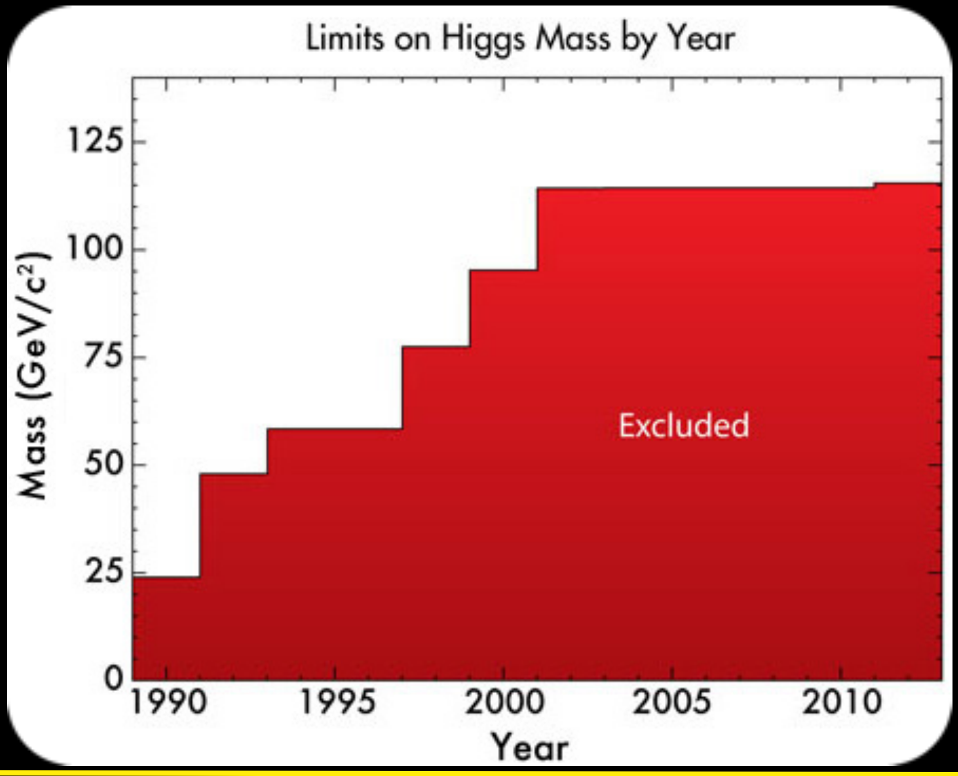


A bit of a history…

- In 1964, six theoretical physicists hypothesised a new field (like an electromagnetic field) that would permeate all of space and solve a critical problem for our understanding of the universe.
- Independently, other physicists were constructing a theory of the fundamental particles, eventually called the "Standard Model," that would prove to be phenomenally accurate.
- These otherwise unrelated efforts turned out to be intimately interconnected. The Standard Model needed a mechanism to give fundamental particles mass.
- The field theory was devised by Peter Higgs, Robert Brout, François Englert, Gerald Guralnik, Carl Hagen, and Thomas Kibble.

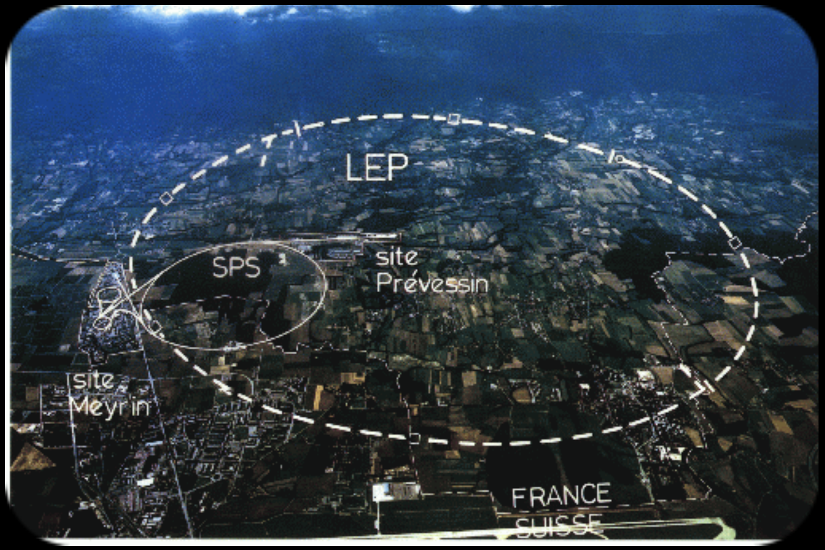
Constrains on the Higgs mass

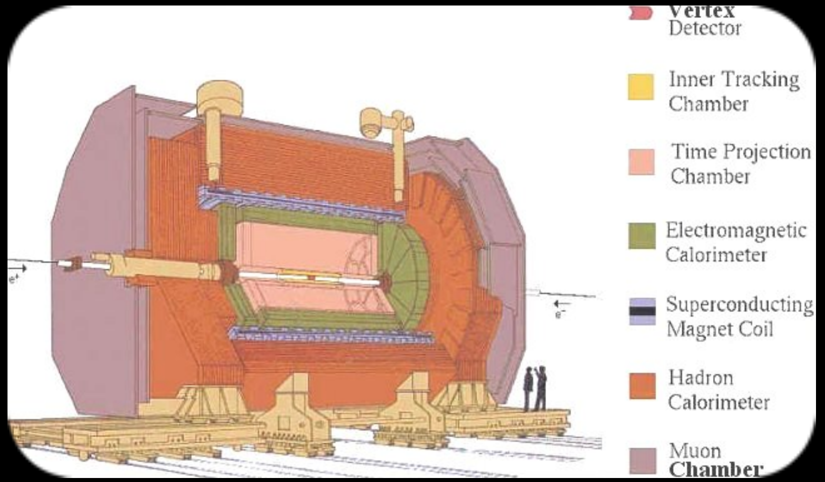
- In analogy with other quantum fields, there would have to be a particle associated with this new field
- It would have intrinsic spin of zero and therefore be a boson, a particle with integer spin
  - it soon became known as the Higgs boson
  - The only drawback was that no one had seen it.
  - Unfortunately, the theory that predicted its existence didn't specify the mass of the Higgs boson.
    - experiments at other accelerators had shown that the mass of a Higgs boson had to be greater than about 115 GeV/c^2

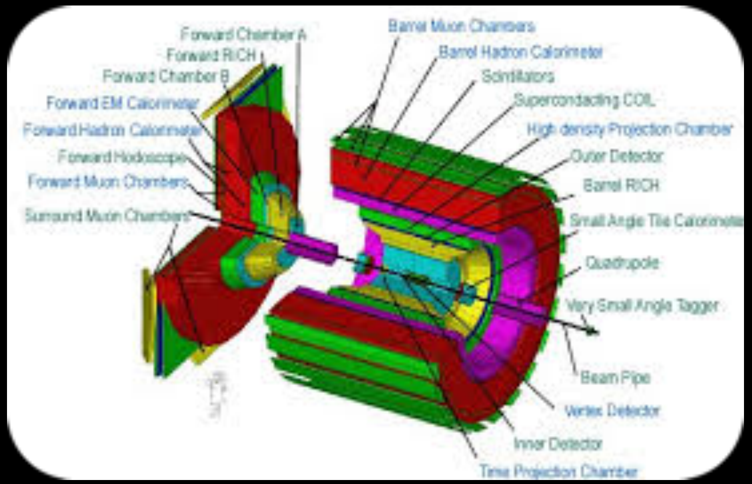


Large Electron-Positron collider @ CERN (LEP)

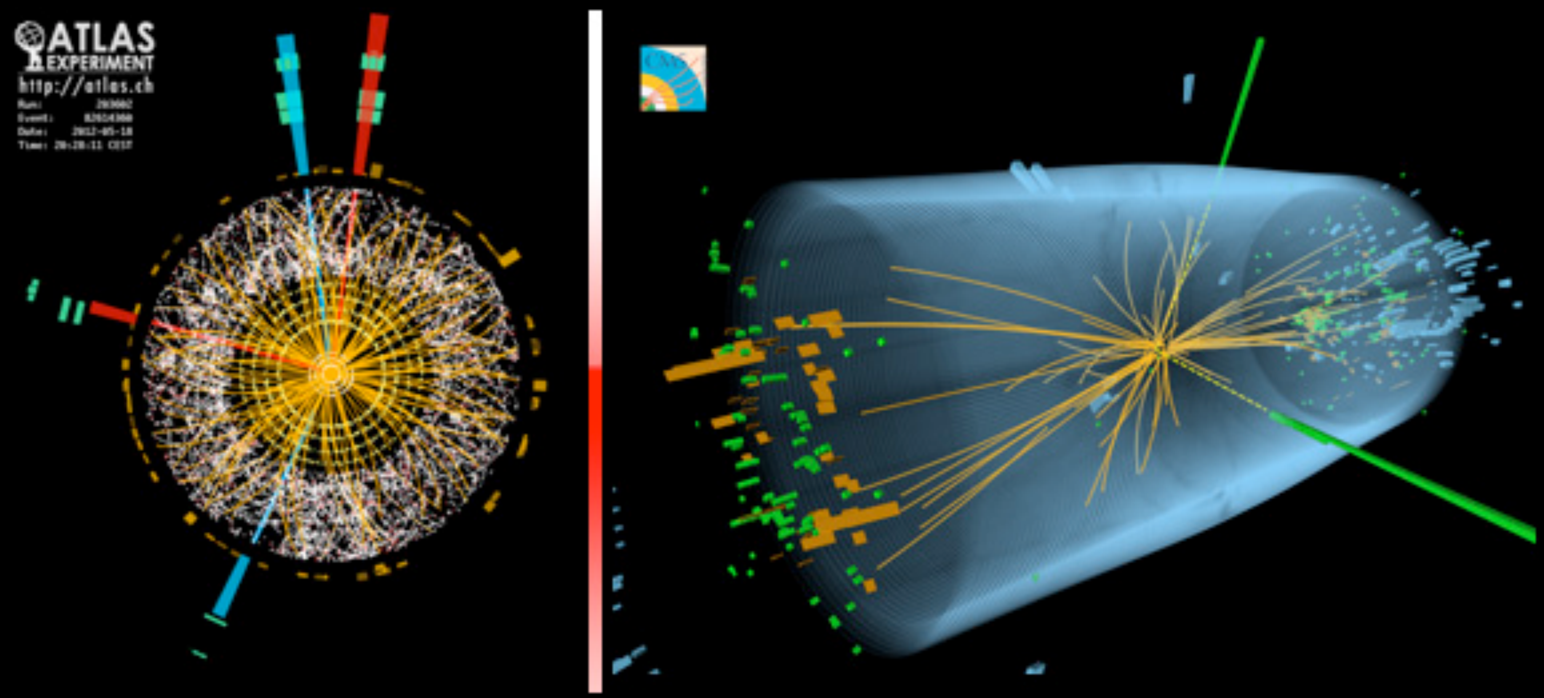
- ✓ In operation at CERN between 1989 and 2000
- ✓ Served four detectors: OPAL, DELPHI, L3, ALEPH
- ✓ Electrons on positrons with $\sqrt{s}$ = 90 up to 209 GeV (in 2000)
- ✓ Main results of the LEP experiments:
  - precision measurements of Z and W mass (discovered in 1983 at the Intersecting Storage Rings of CERN
- ✓ Around 2000 data hinted about the existence of a Higgs particle with a mass around 115 GeV
  - The lifetime of the accelerator was extended for a few months
  - The signal was not enough to claim a discovery
    - remained at 1.7σ and was at the extreme upper edge of the detection range of the experiments with the collected LEP data
  - There was a proposal to extend the LEP operation by another year in order to seek confirmation, which would have delayed the start of the LHC.
  - However, the decision was made to shut down LEP and progress with the LHC as planned





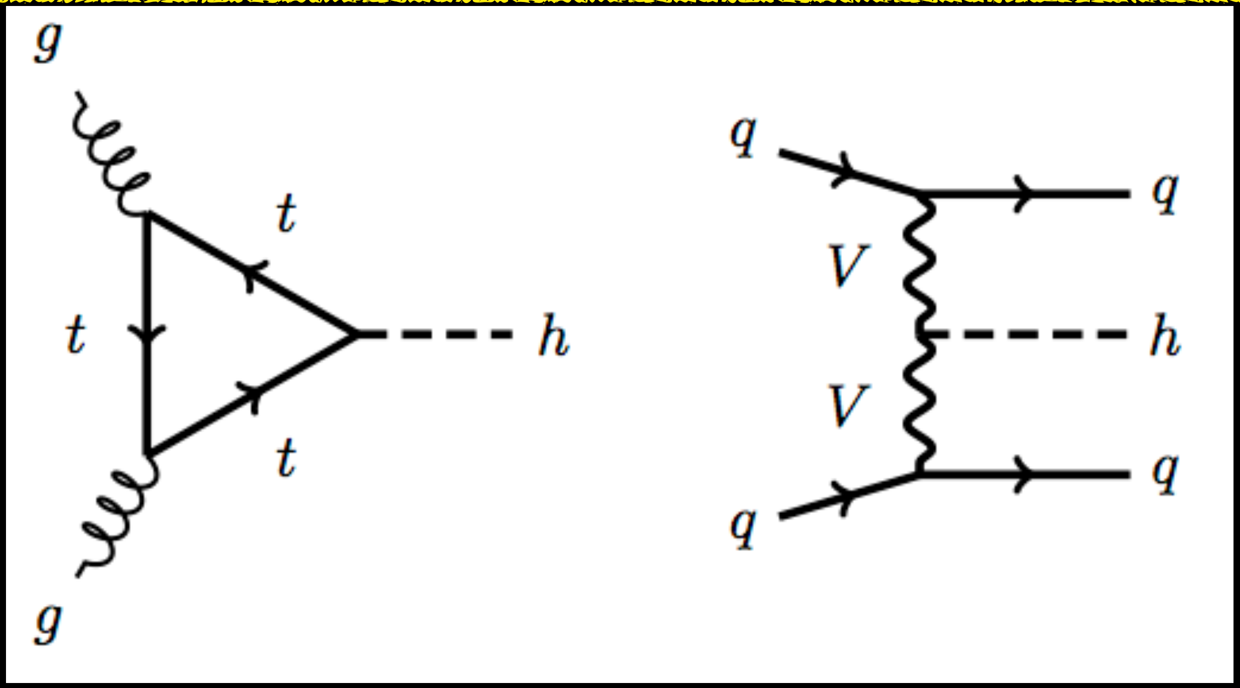


4th of July 2012 @ CERN

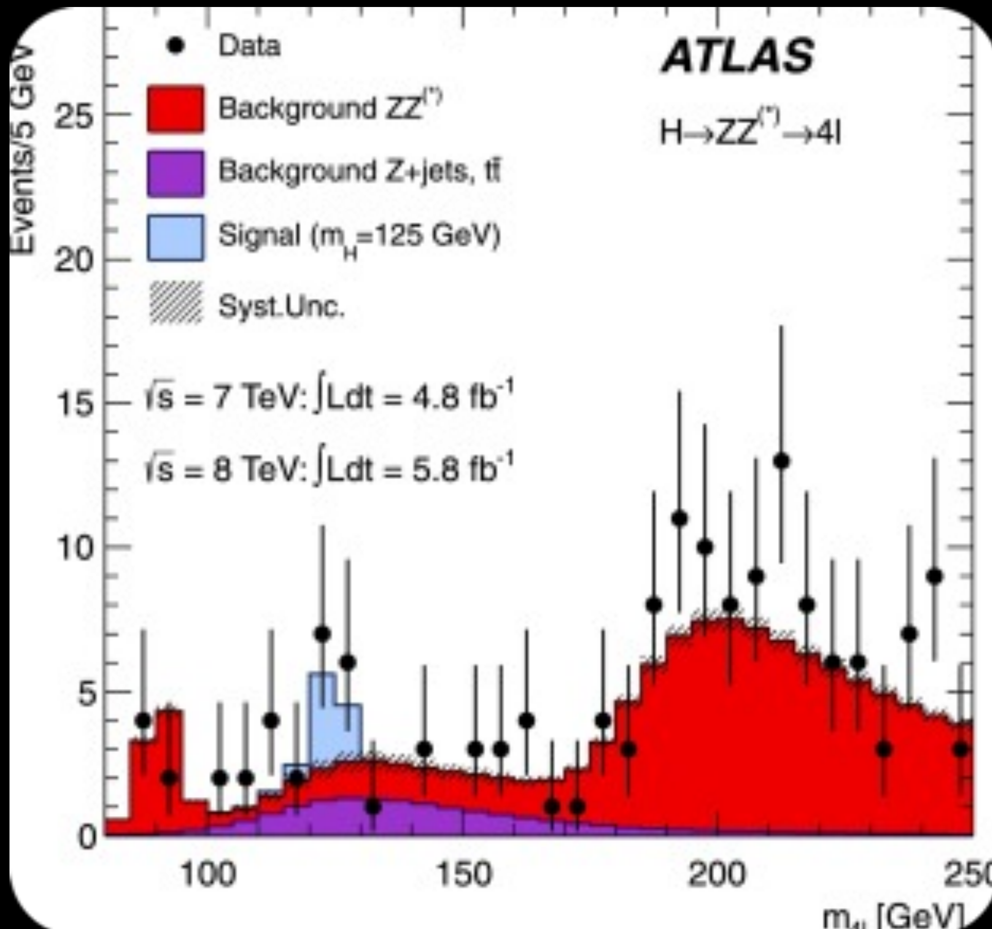


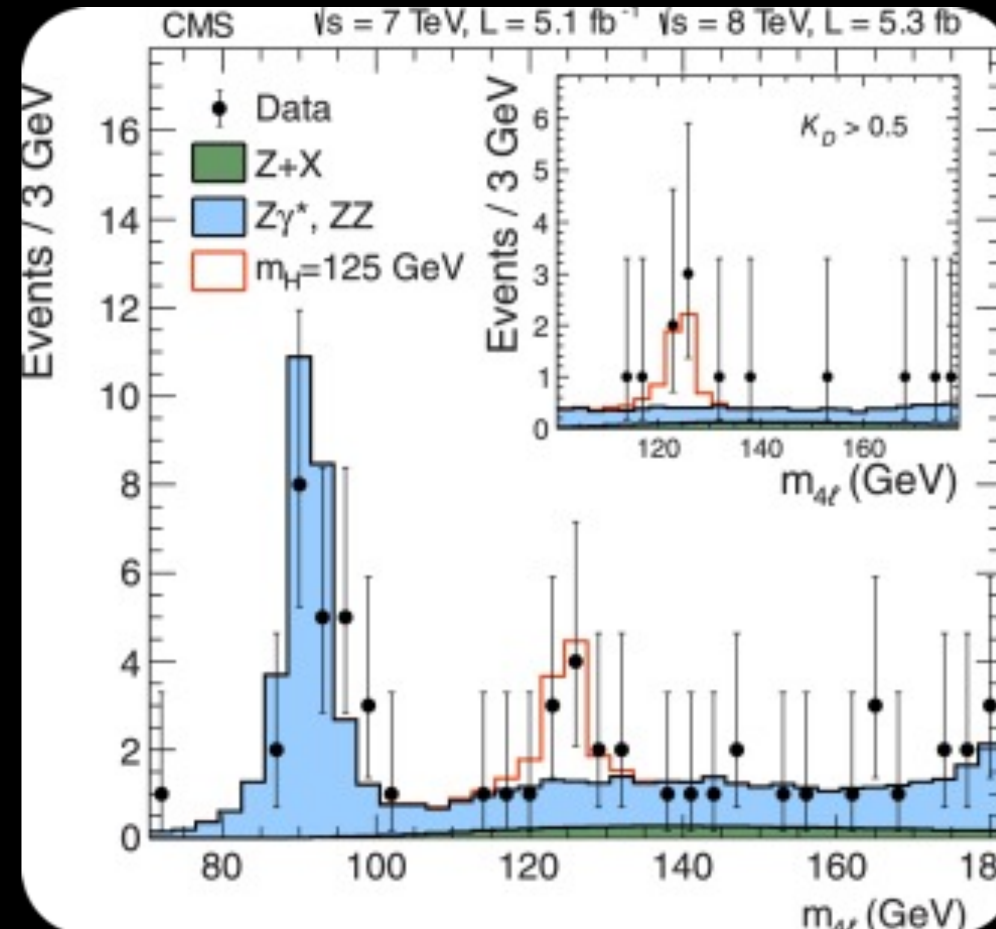
Main Higgs production mechanisms @ LHC

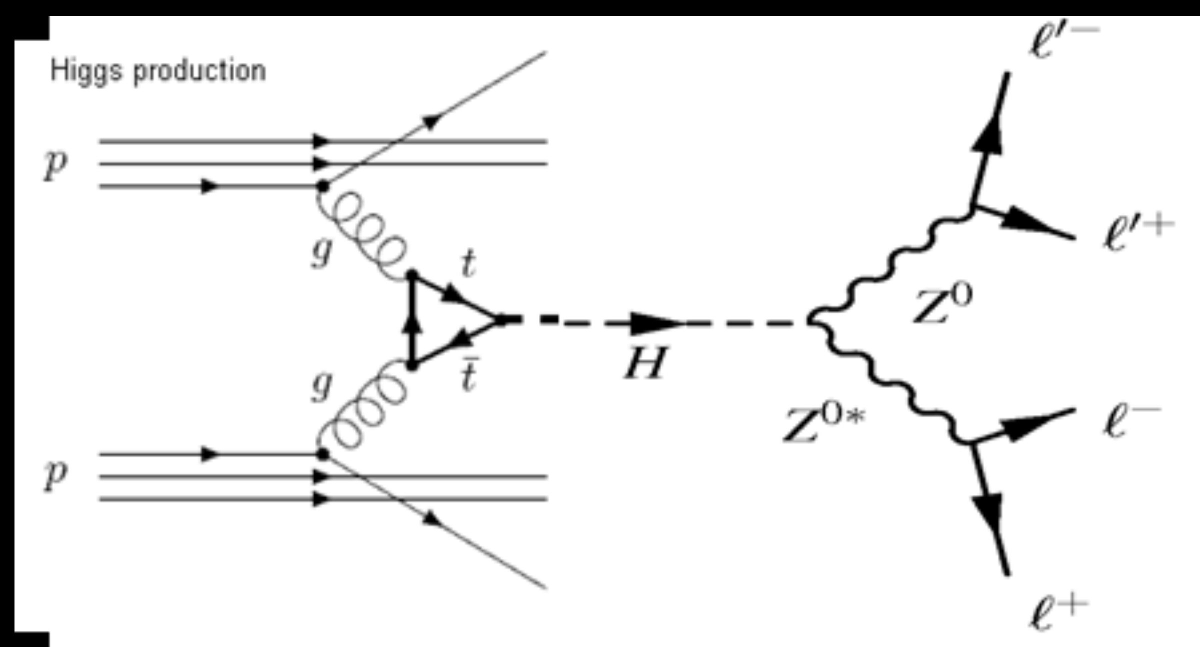
- ✓ gluon fusion through virtual top quarks (large coupling with H)
- ✓ vector boson (W or Z) fusion (large coupling with H)



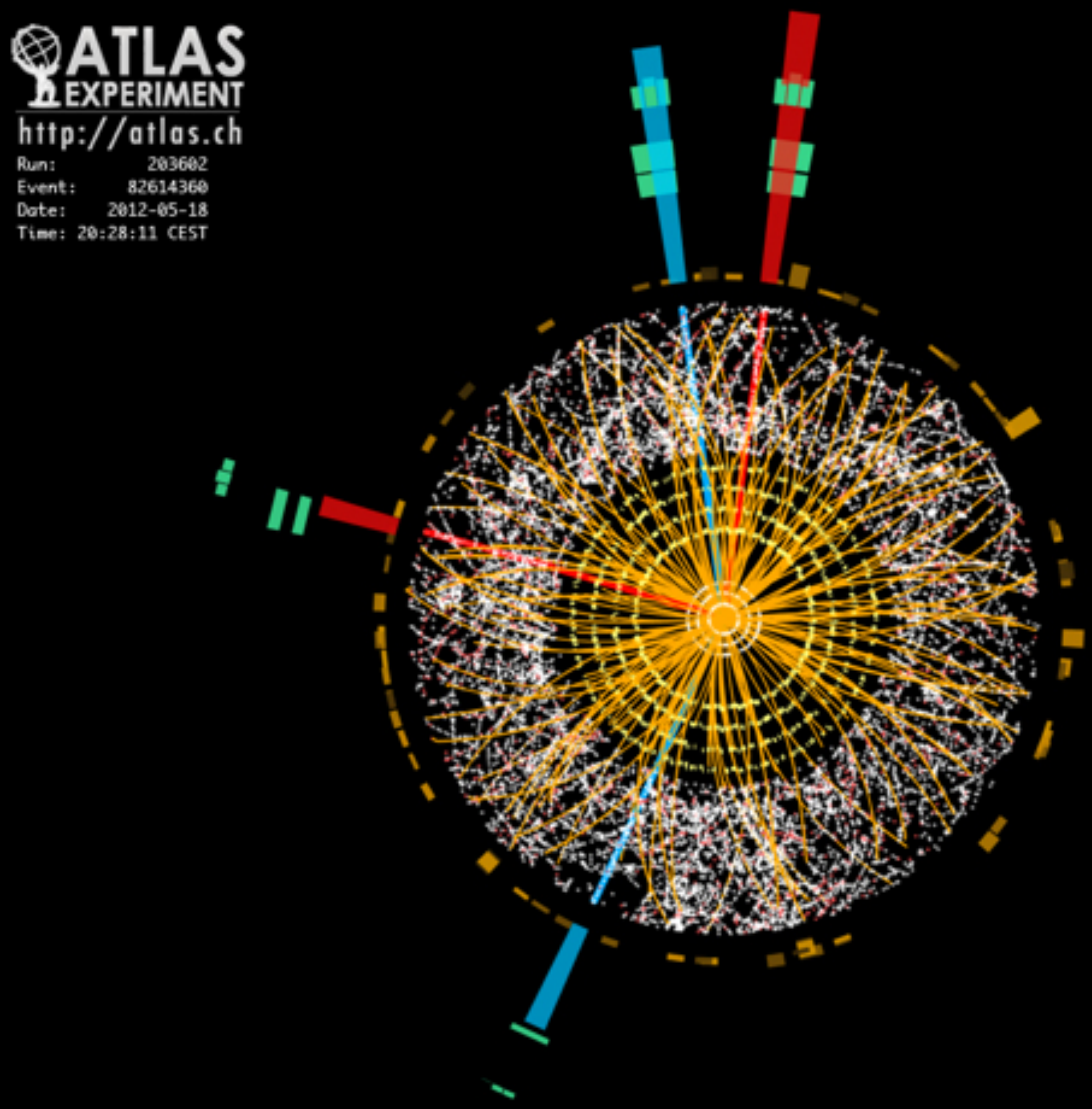
Higgs discovery: H → ZZ* → 4l



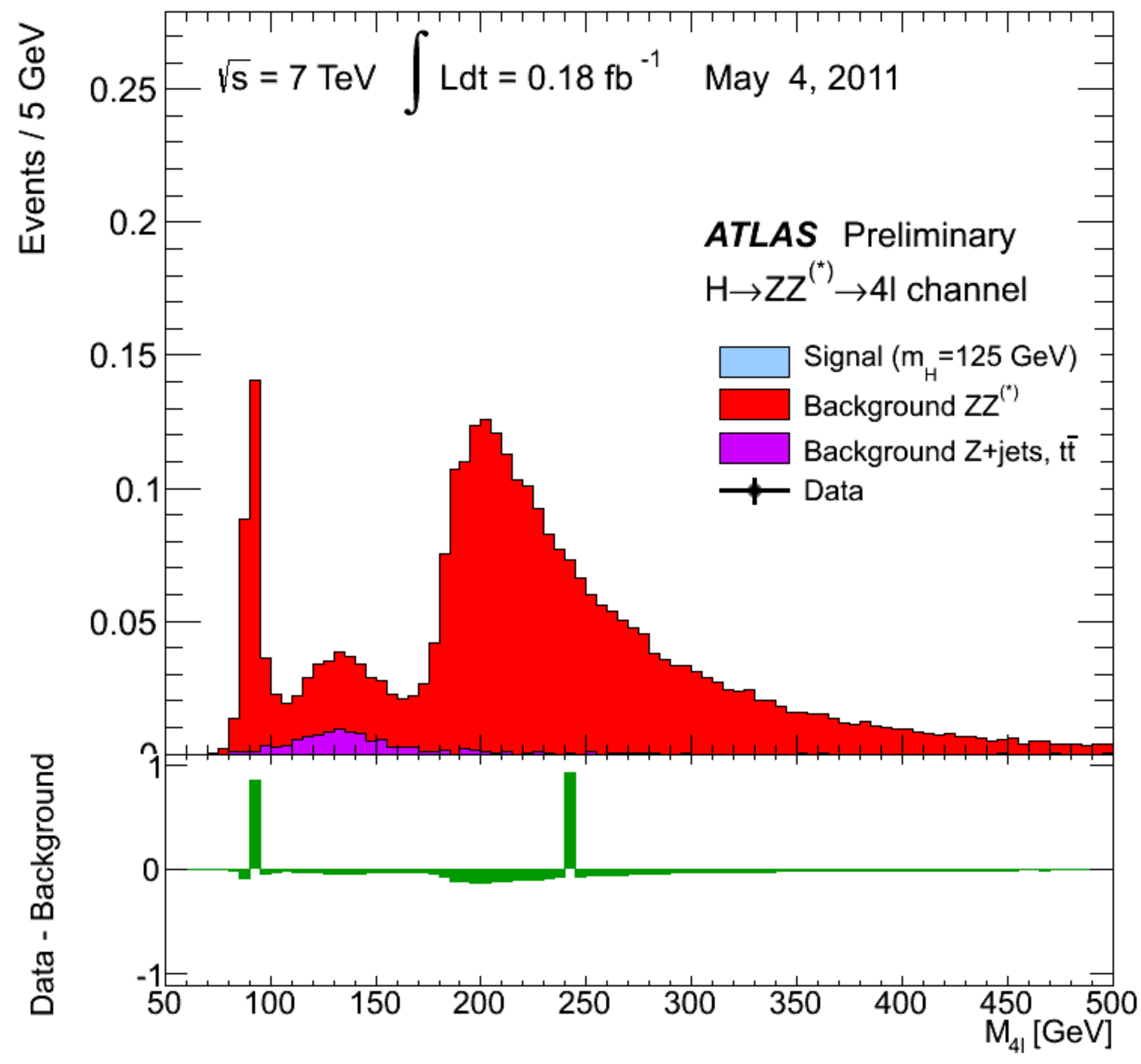




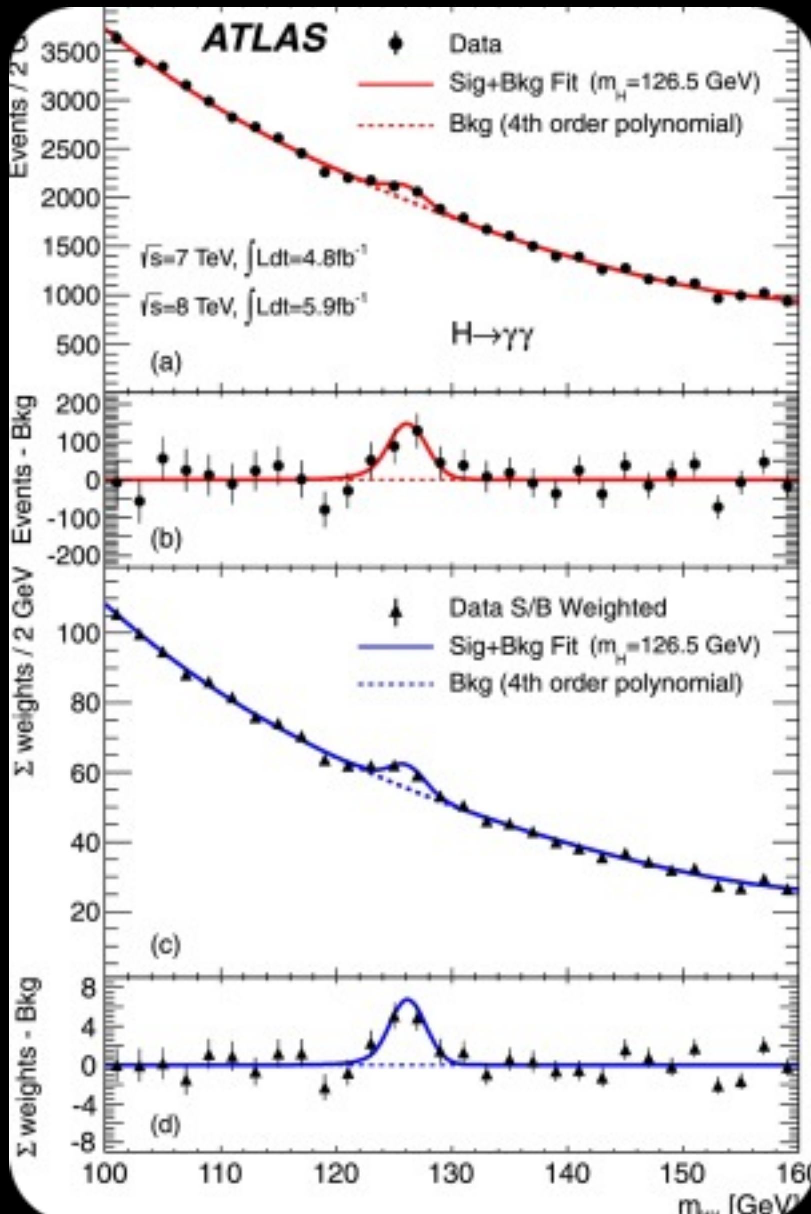
A Higgs event candidate: $H \rightarrow ZZ^* \rightarrow 4l$

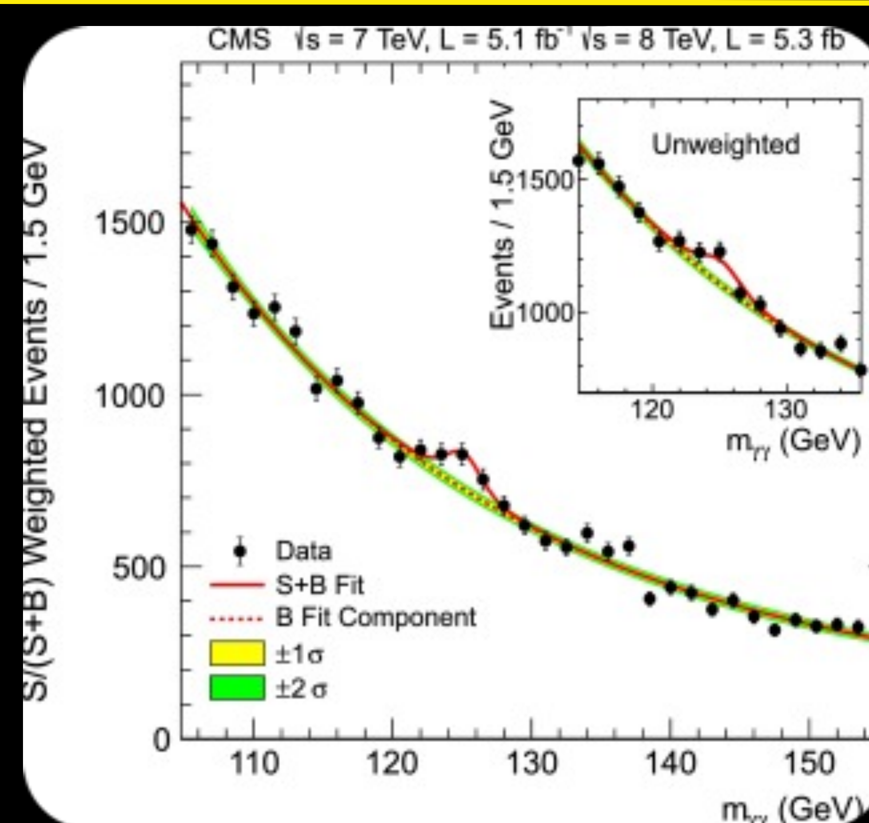


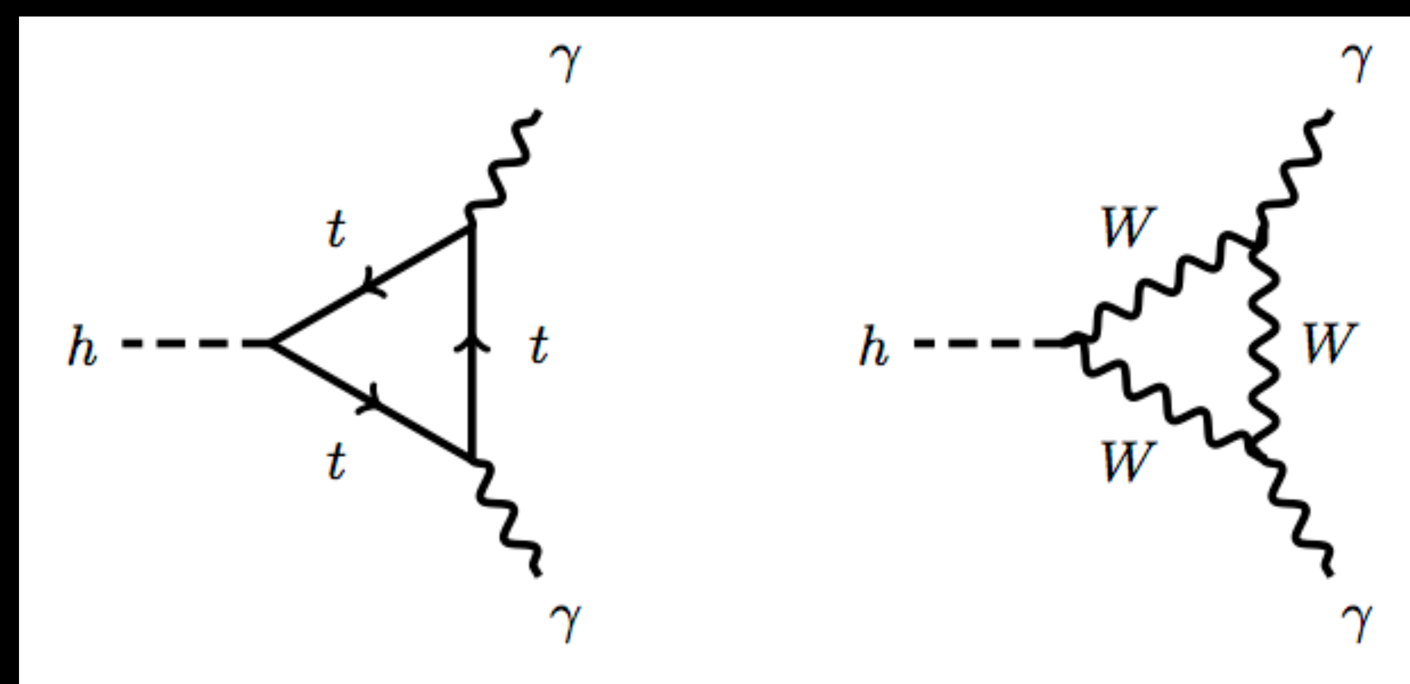
$H \rightarrow ZZ^{*} \rightarrow 4l$ signal = f(luminosity)



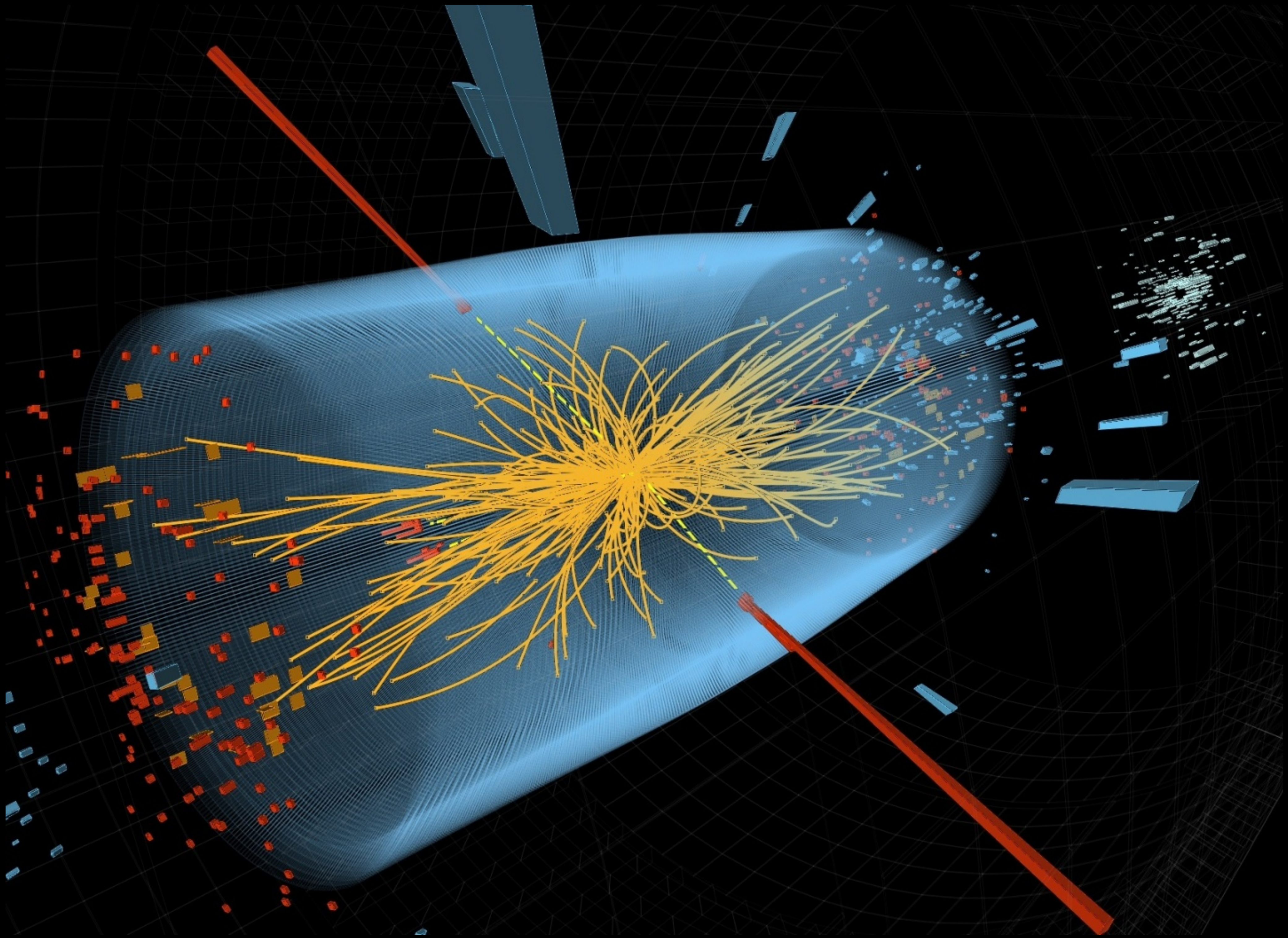
Higgs discovery: H → γγ



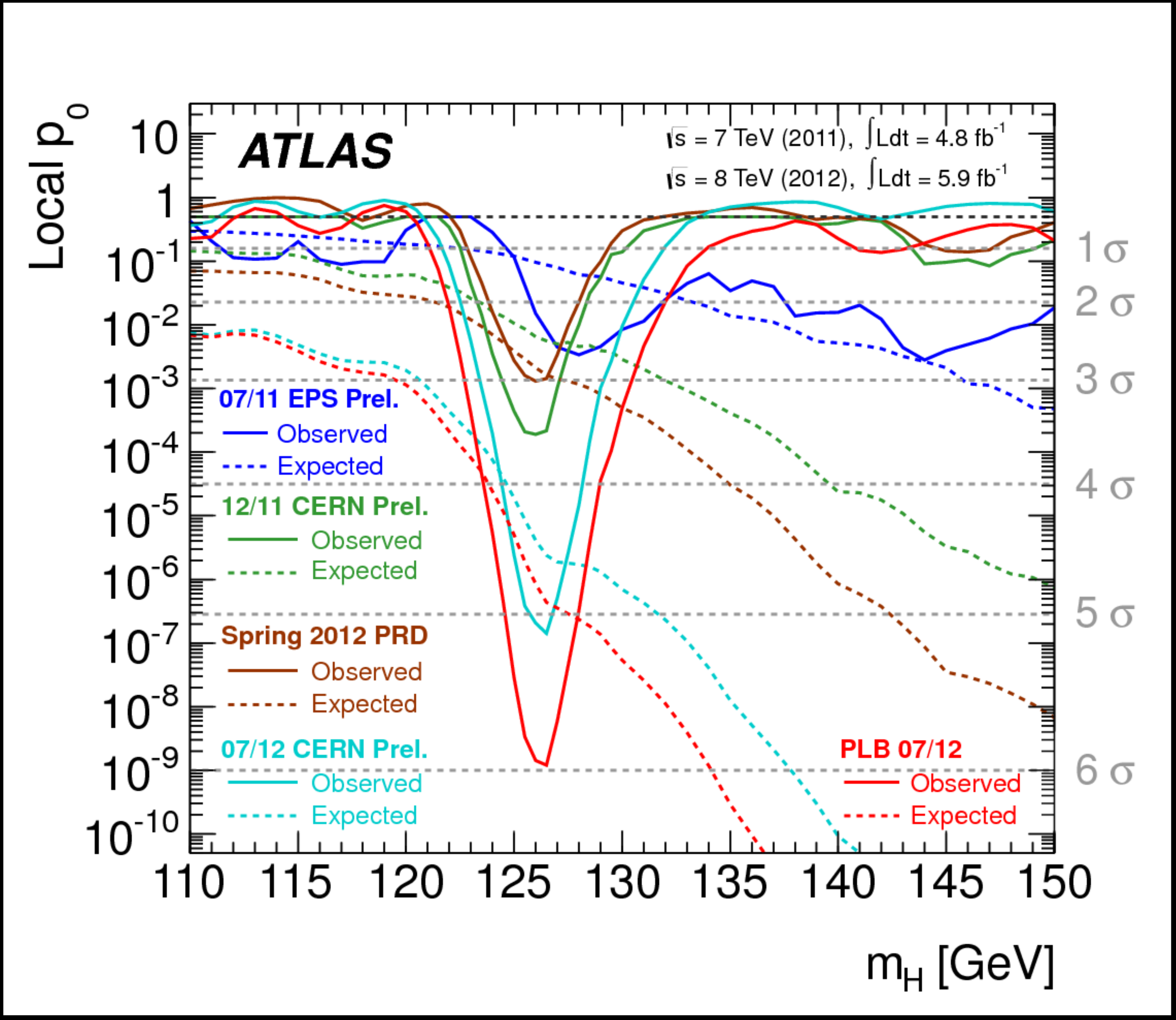




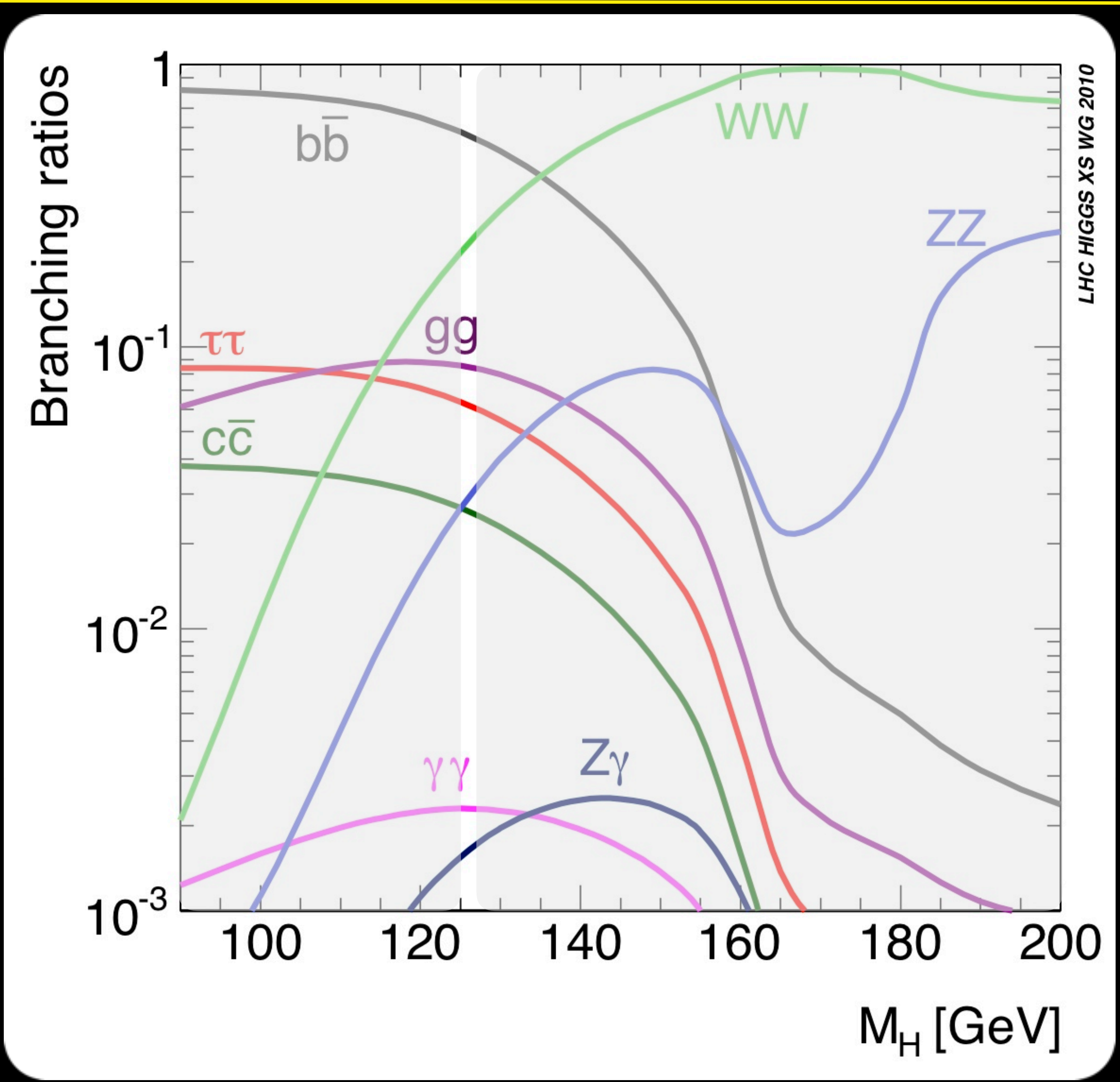
A Higgs event candidate: $H \rightarrow \gamma\gamma$



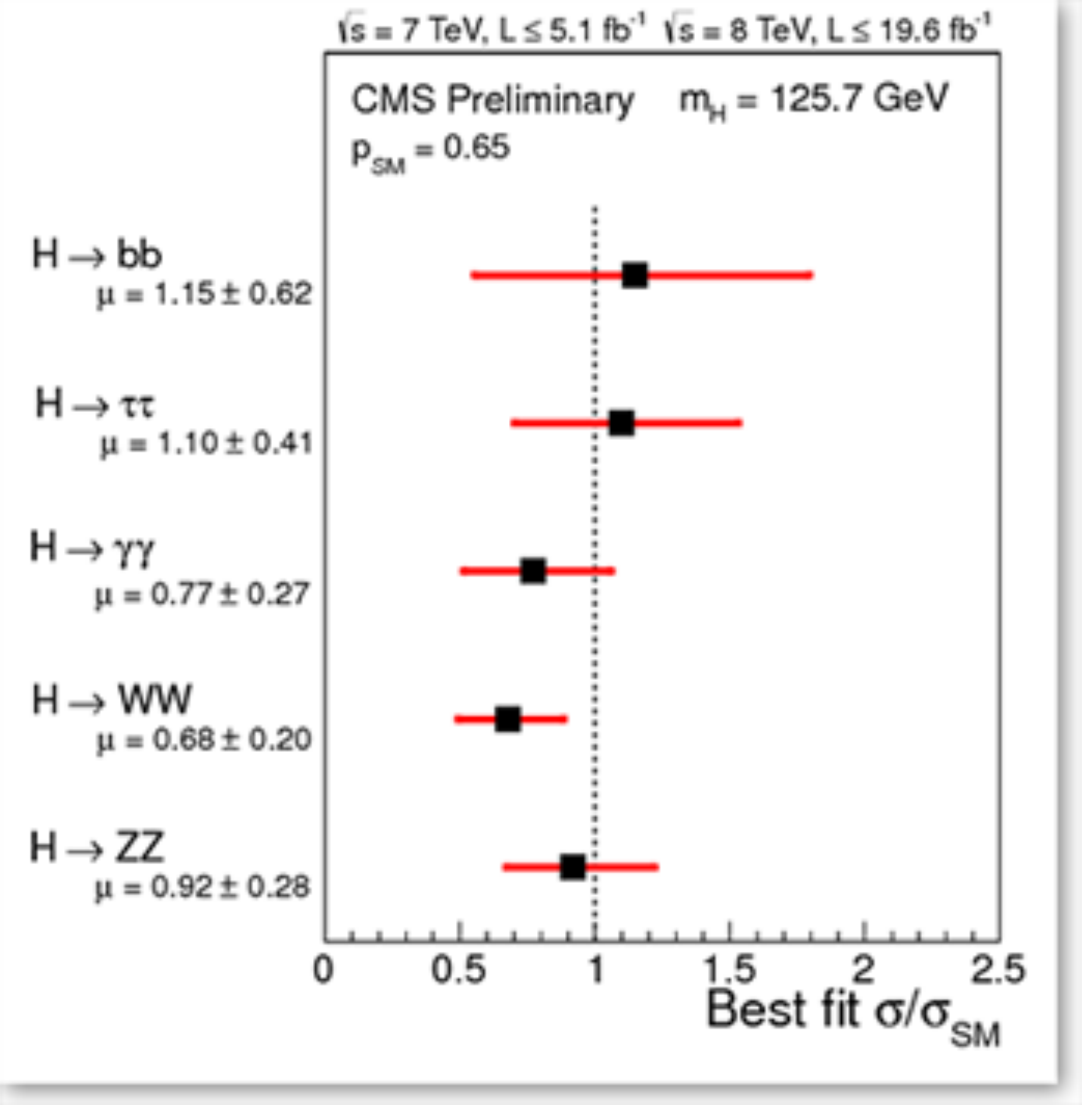
Signal vs time



Higgs decay channels



Is this the Standard Model Higgs?



- ✓ All the results from ATLAS and CMS have shown remarkable consistency
  - with the expected branching ratios to the five decay modes to different particles
  - with the expected spin (zero)
  - parity (positive)
- ✓ So far, all available evidence points to the new particle being the Standard Model Higgs boson.

Spontaneous symmetry breaking

- One of the great recent achievements of modern physics is a quantum field theory in which weak and electromagnetic interactions are understood to arise from a common symmetry
- This 'electroweak theory' has been validated in detail e.g. @ LEP @ CERN
- Although the weak and electromagnetic interactions are linked through symmetry, their manifestations in the everyday world are very different.
  - The influence of electromagnetism extends to infinite distances, whereas the influence of the weak interaction is confined to subnuclear dimensions.
  - This difference is directly related to the fact that the photon, the force carrier of electromagnetism, is massless, whereas the *W* and *Z* particles, which carry the weak forces, are about 100 times the mass of the proton.
  - According to the theory developed by Higgs et al, the giver of mass is a neutral particle with zero spin that we call the Higgs boson. In today's version of the electroweak theory, the *W* and *Z* particles and all the fundamental constituents--quarks and leptons--get their masses by interacting with the Higgs boson.
- There is a Higgs *field* filling space that interacts with the particles moving through it and giving some of them mass; and second, the Higgs *boson* is the particle we observe when we interact with a vibration in that field.
- The Higgs field introduces a drag to particles running around the field

What is missing from the Standard Model?

- Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?
- Why are there exactly three generations of quarks and leptons?
- Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
- What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?
- How does gravity fit into all of this?

What is missing from the Standard Model?

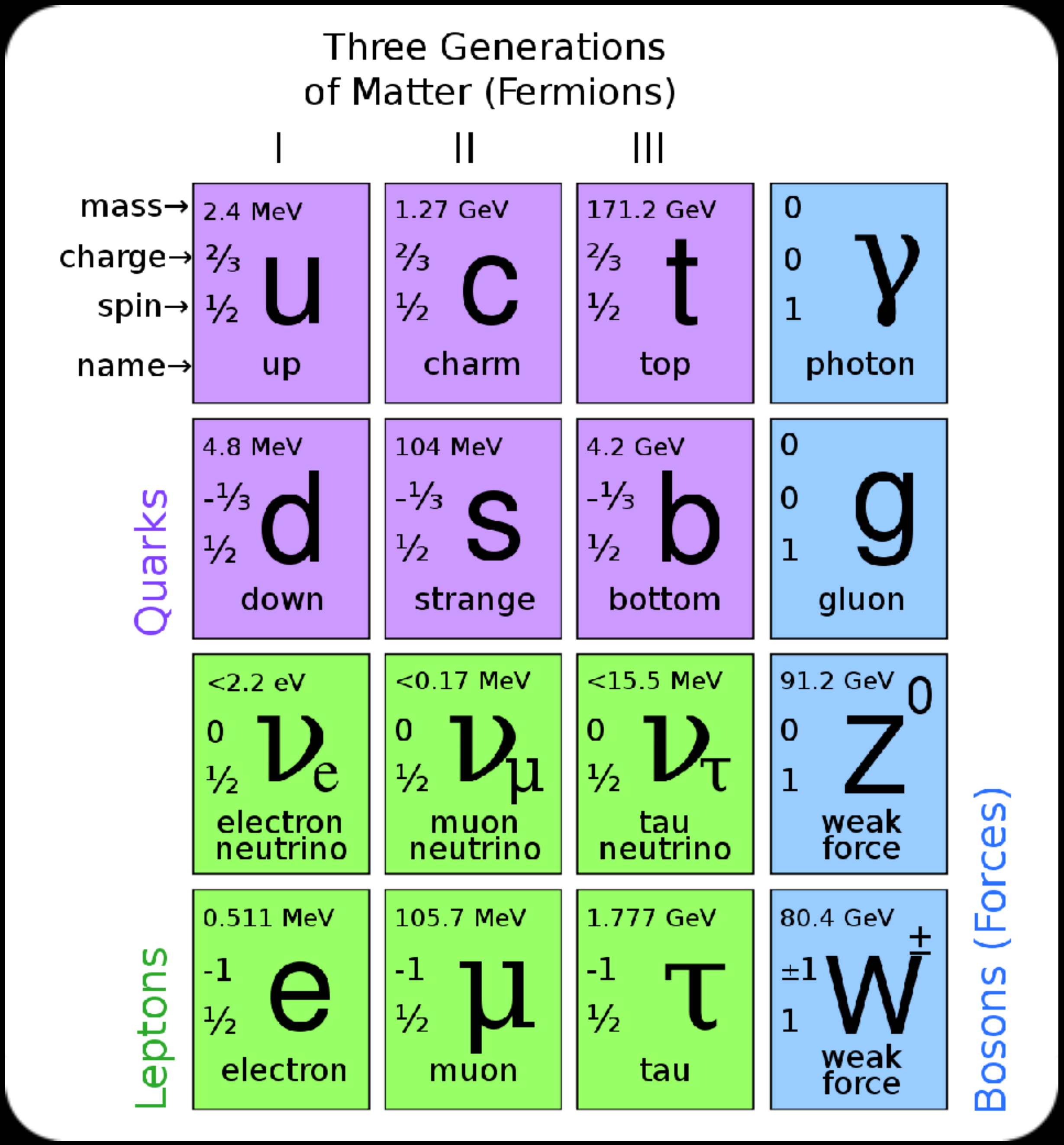
Matter-antimatter asymmetry in the Standard Model

- One of the conditions for generating matter (baryon) asymmetry is that a process is able to happen at a different rate to its antimatter counterpart
  - Violation of the CP invariance
- In the Standard Model CP violation appears as a complex phase in the CKM matrix (quark mixing matrix) of the weak interaction.
  - There may also be a non-zero CP-violating phase in the neutrino mixing matrix, but this is currently unmeasured.
  - There might also be a non-zero CP-violating in the QCD Lagrangian but there are stringent constrains on the upper limit of the “θ-term” that quantifies the degree of the CP-violating effects coming from measurements of the neutron electric dipole moment (nEDM)
    - The fact that this term is so small is also known as the **Strong CP problem**
- Are there domains of the universe where anti-matter dominates?
- Are there physics processes, beyond the Standard Model, that induce at the very early stages of the evolution of the universe an initial larger than the Standard Model expects asymmetry between matter and anti-matter?
  - Baryogenesis within the Standard Model (not enough!) or at the Grand Unified Theory (GUT) scale

What is missing from the Standard Model?

Why three generations?

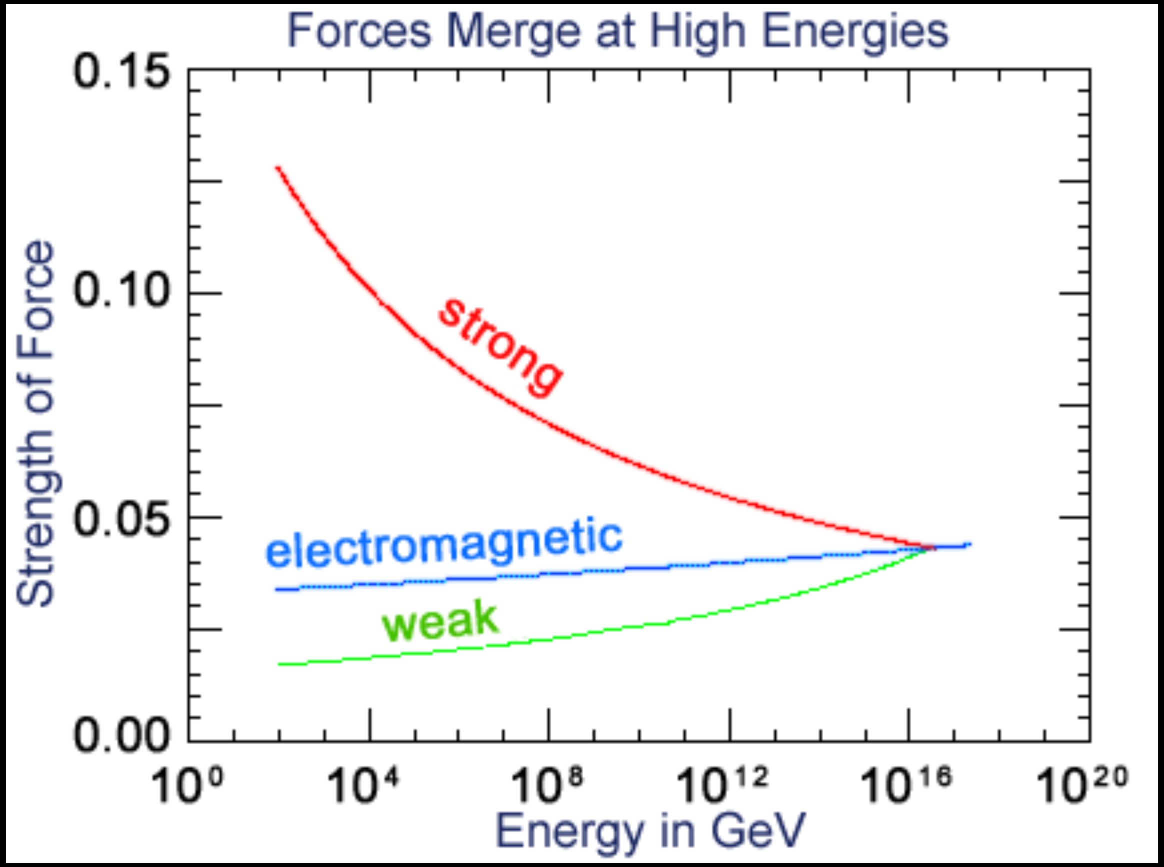
- ✓ There are three generations of quark and lepton pairs
- ✓ Why are there exactly three generations of matter?
- ✓ The generations increase in mass and higher generation particles tend to decay into lower generation particles.
- ✓ In the every-day world we observe only the first-generation particles (electrons and up/down quarks).
- ✓ We do not know why the natural world "needs" the two other generations, and we do not know why there are exactly **three** generations in total.



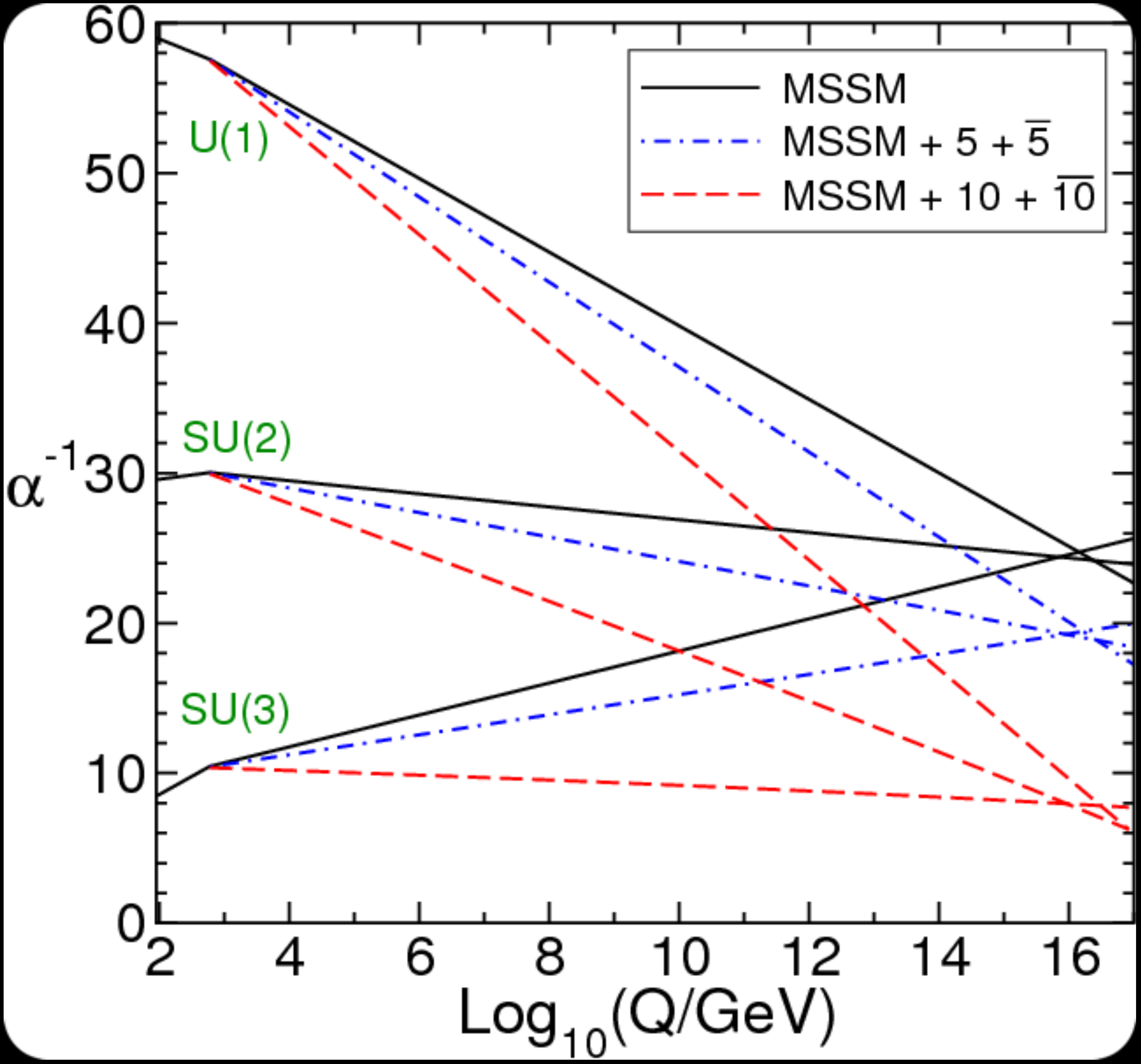
What is missing from the Standard Model?

Unification of forces

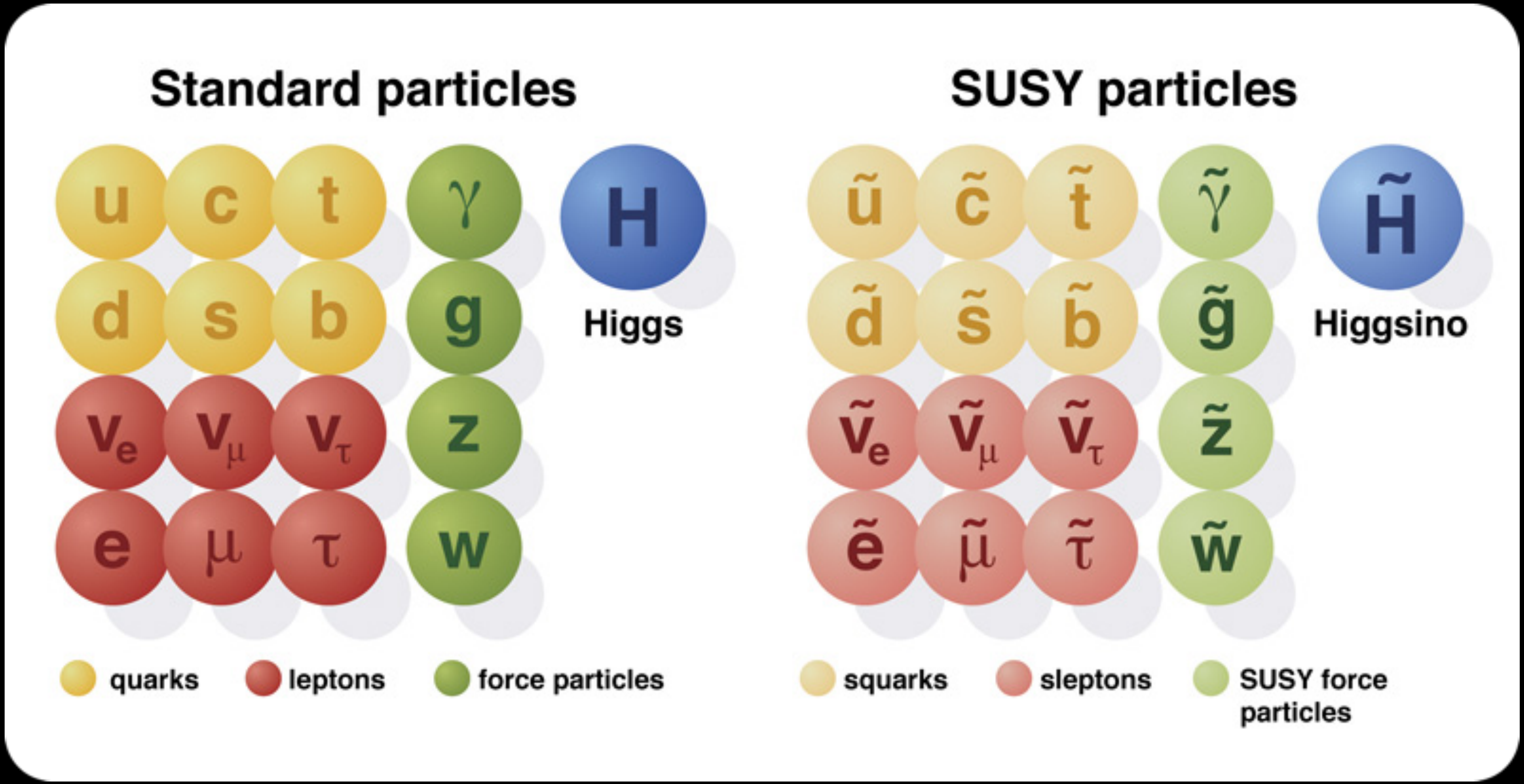
- Grand Unified Theory (GUT): one of the major goals of particle physics is to unify the various fundamental forces
  - could provide an elegant understanding of the evolution of the universe
  - a GUT will unify the strong, weak, and electromagnetic interactions
  - If a GUT of all the interactions is possible, then all the interactions we observe are all different aspects of the same, unified interaction.
    - However, how can this be the case if strong and weak and electromagnetic interactions are so different in strength and effect?
    - Strangely enough, current data and theory suggests that these varied forces merge into one force when the particles being affected are at a high enough energy.



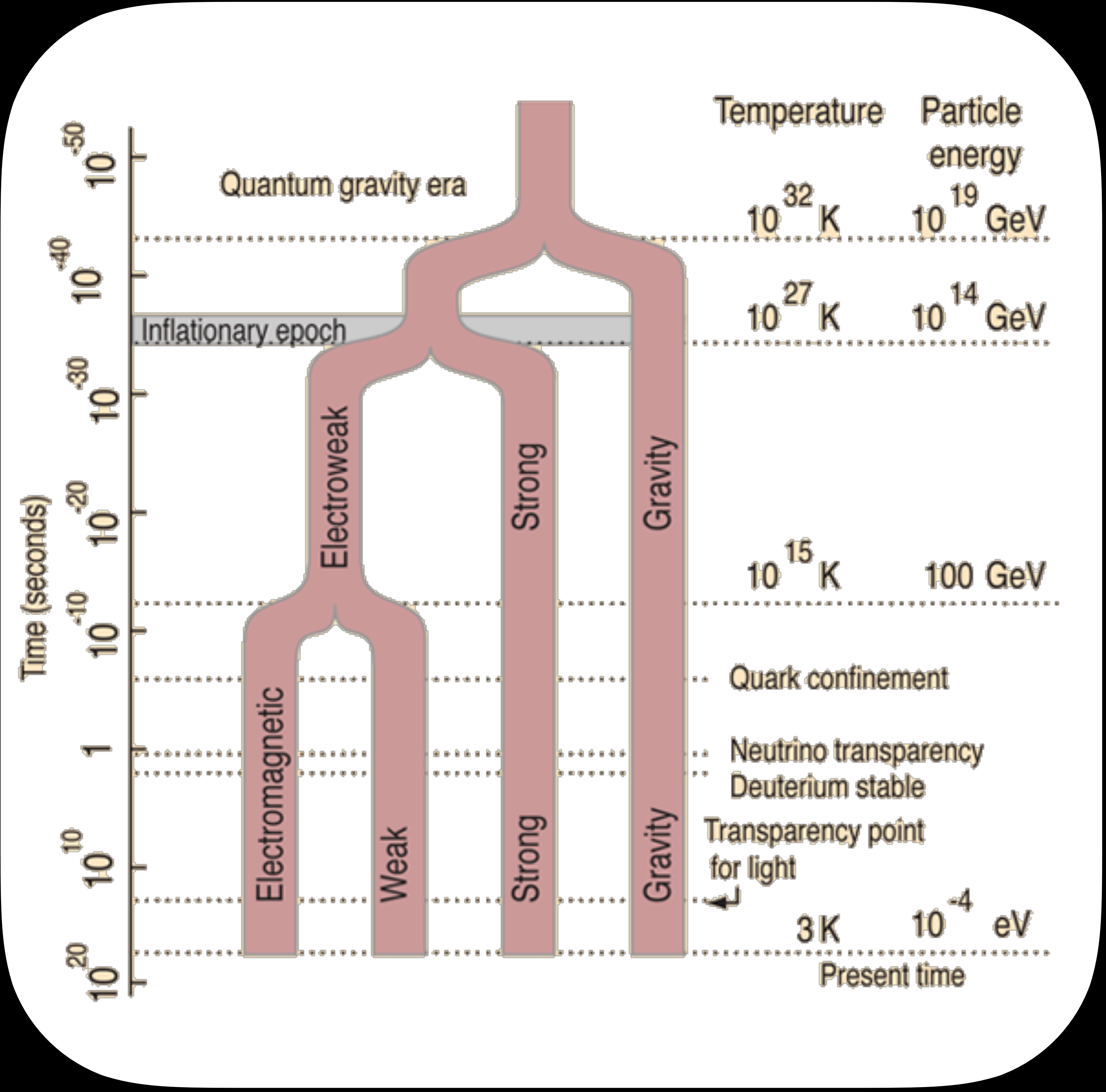
Example: Supersymmetry (SUSY)



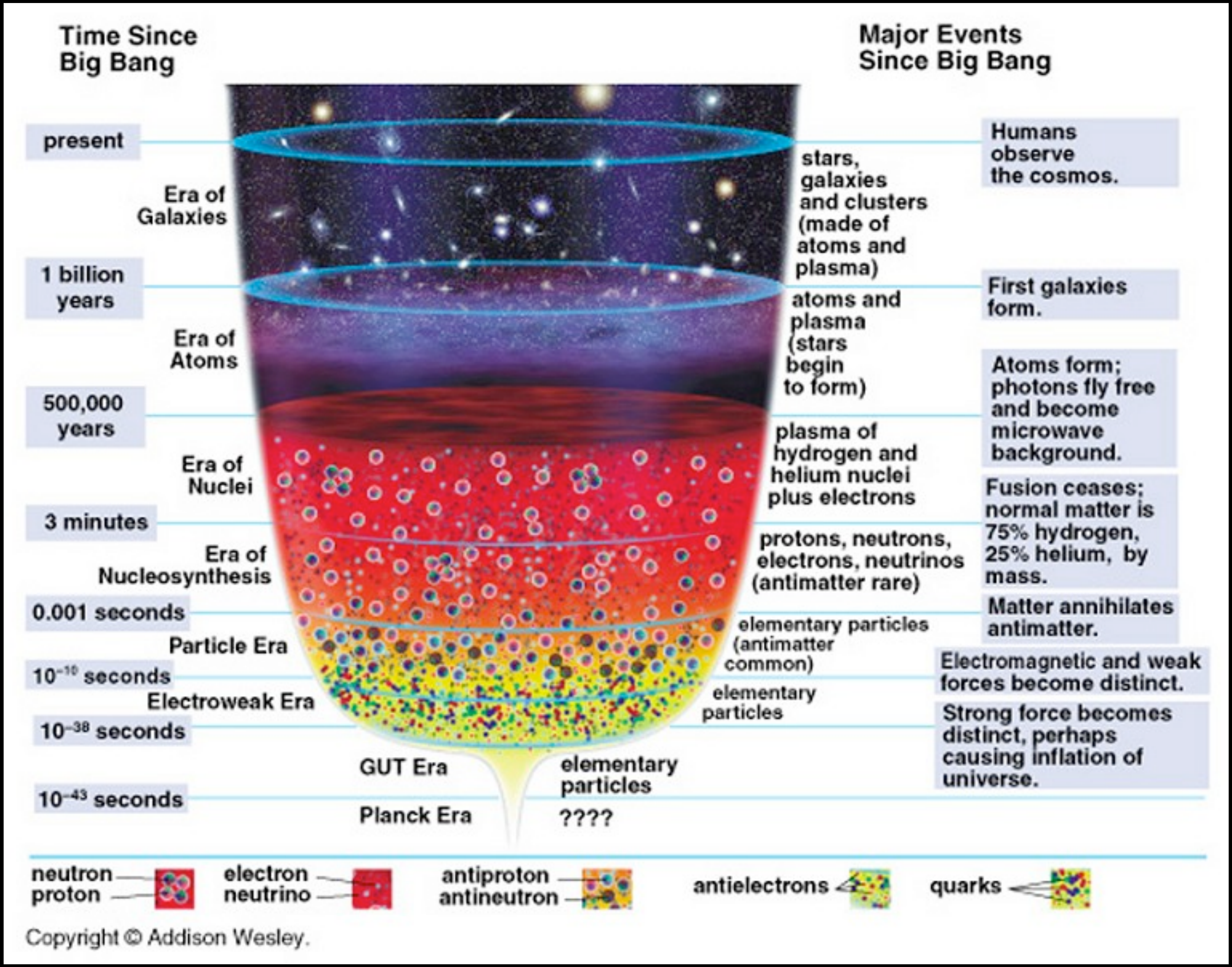
Example: Supersymmetry (SUSY)



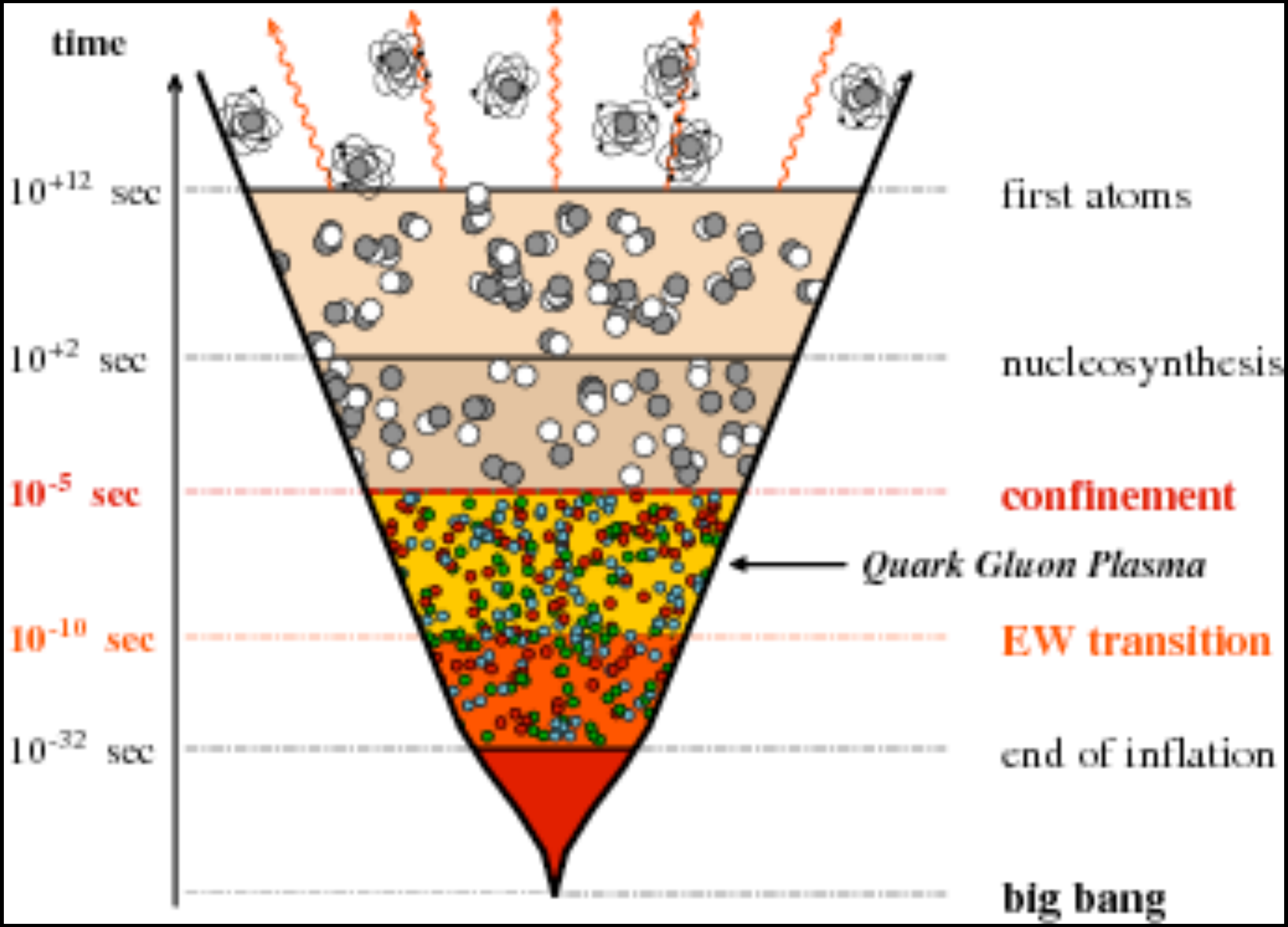
Grand Unified Theory (GUT)?



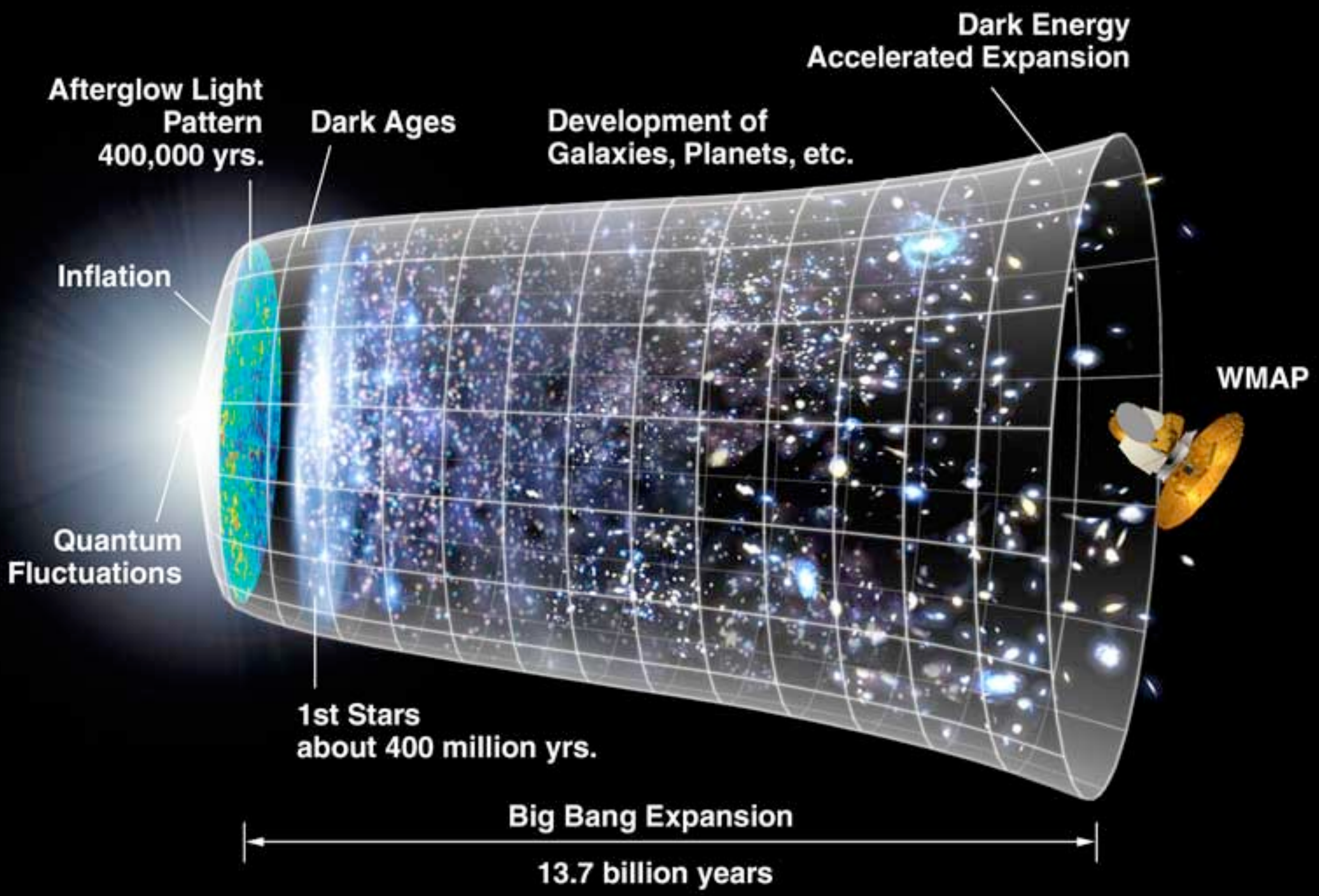
Going back in time: few μsec after the Big-Bang



Going back in time: few μsec after the Big-Bang



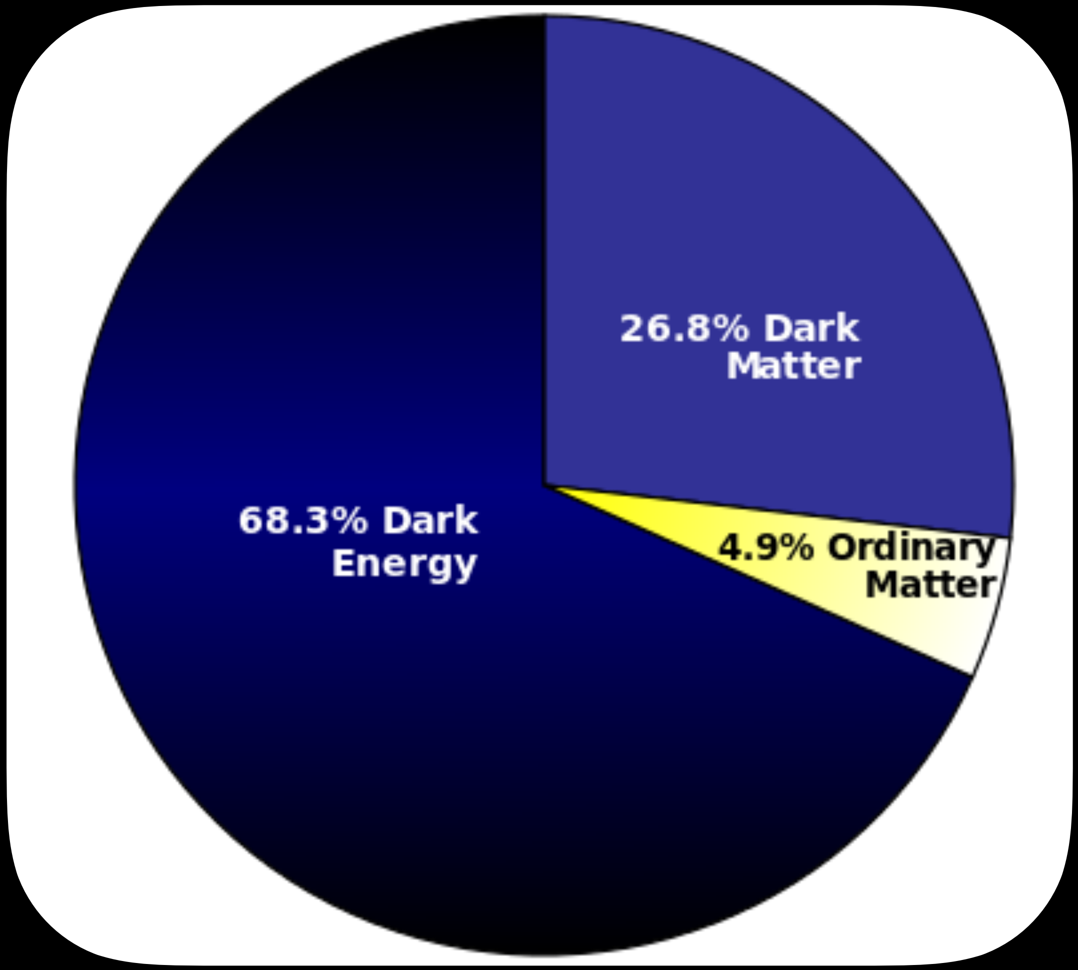
Evolution of the universe…



What is missing from the Standard Model?

Dark matter

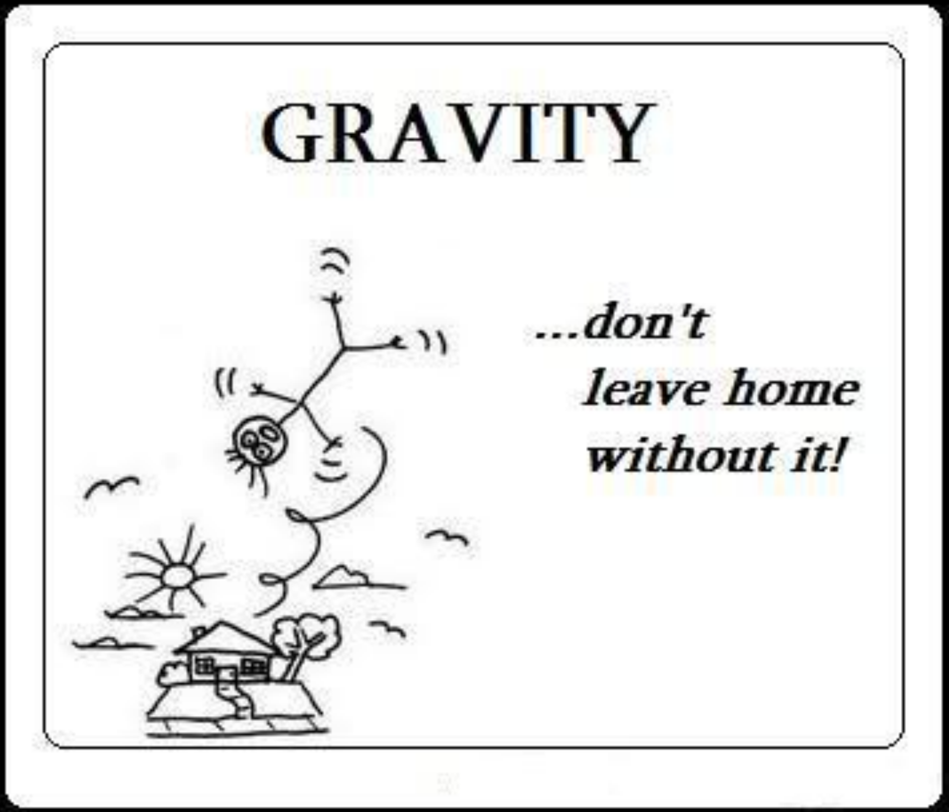
- Dark matter is an unidentified type of matter
  - it does not emit or interact with E/M radiation
  - postulated existence from its gravitational effects
    - the motions of visible matter,
    - gravitational lensing,
    - its influence on the universe's large-scale structure, on galaxies,
    - its effects in the cosmic microwave background.
  - Can consist of baryonic (less likely) or/ and non-baryonic (e.g. Weakly Interacting Massive Particles - WIMPs) components



What is missing from the Standard Model?

Gravity

- Gravity is weird….
  - It is clearly one of the fundamental interactions, but the Standard Model cannot satisfactorily explain it.
  - This is one of those major unanswered problems in physics today.
- In addition, the gravity force carrier particle has not been found.
  - Such a particle, however, is predicted to exist and may someday be found: the **graviton**.
- Fortunately, the effects of gravity are extremely tiny in most particle physics situations compared to the other three interactions,
  - so theory and experiment can be compared without including gravity in the calculations.
- The Standard Model works without explaining gravity.




"That's
all
folks!"