Introduction to particle physics

France Excellence
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优秀硕士
法国
暑期学校

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Centre de physique des particules de Marseille

Physics for both infinities
4 July 2018

CNRS dépasser les frontières
IN2P3 Les deux infinis
Aix*Marseille université
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

Particle physics @ Summer school in Marseille

- This introductory lecture (YC, Wed 4/7, 9:00)
- Rest of the day:
  - *ATLAS experiment*, by Laurent Vacavant (14:00)
  - *LHCb experiment*, by Julien Cogan (16:00)
- Friday 6/7 afternoon:
  - *ATLAS data analysis* on computer, with Romain Kukla (postdoc) & Ana Dumitriu (PhD student)
- Tuesday 10/7 at 9:00:
  - *The future of particle physics*, by Romain Kukla

From the infinitely large to the infinitely small

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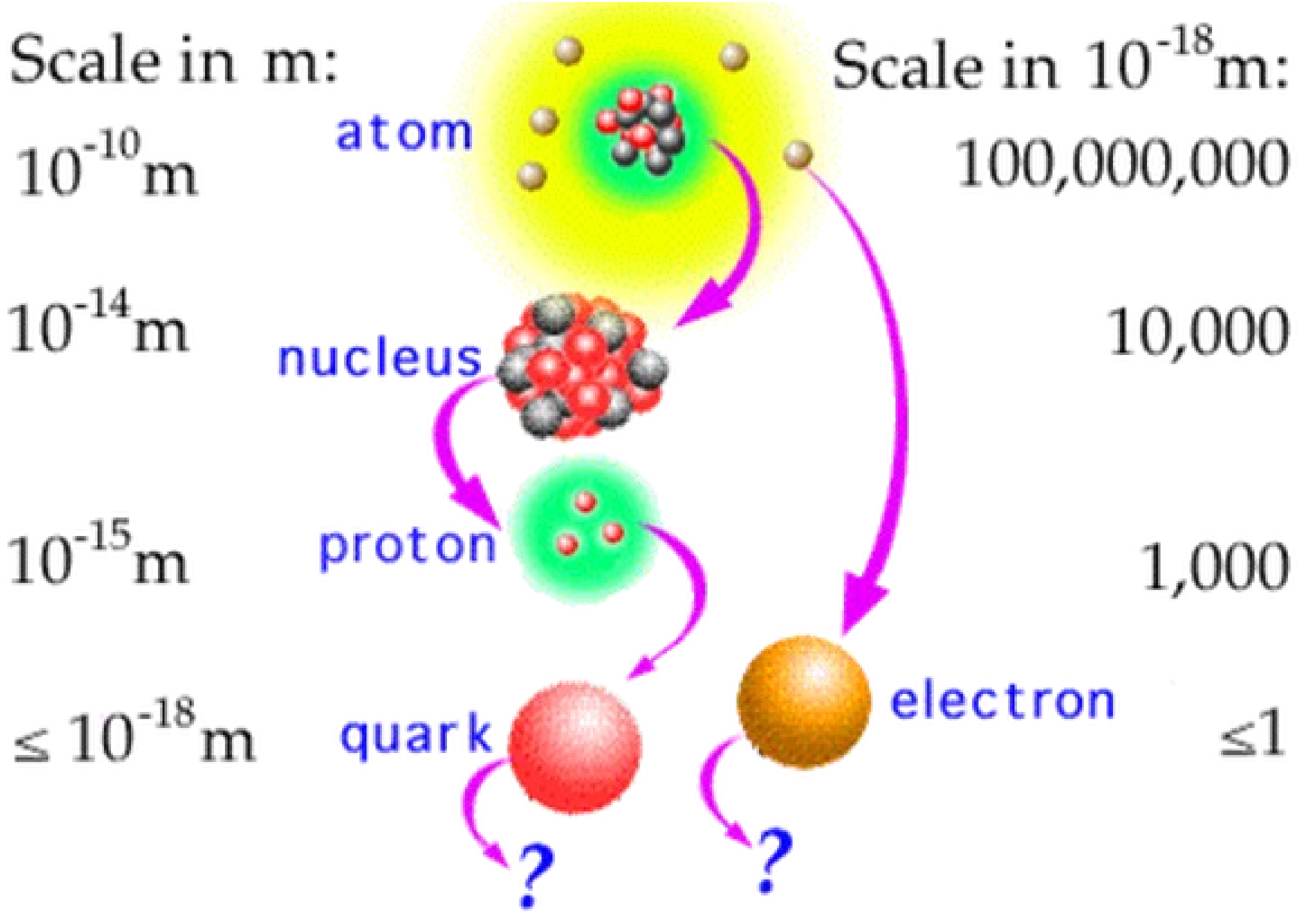
Distance scale in particle physics



If protons and neutrons were 10 cm apart, a quark or electron would measure less than 0.1 mm and an atom about 10 km

Particle physics

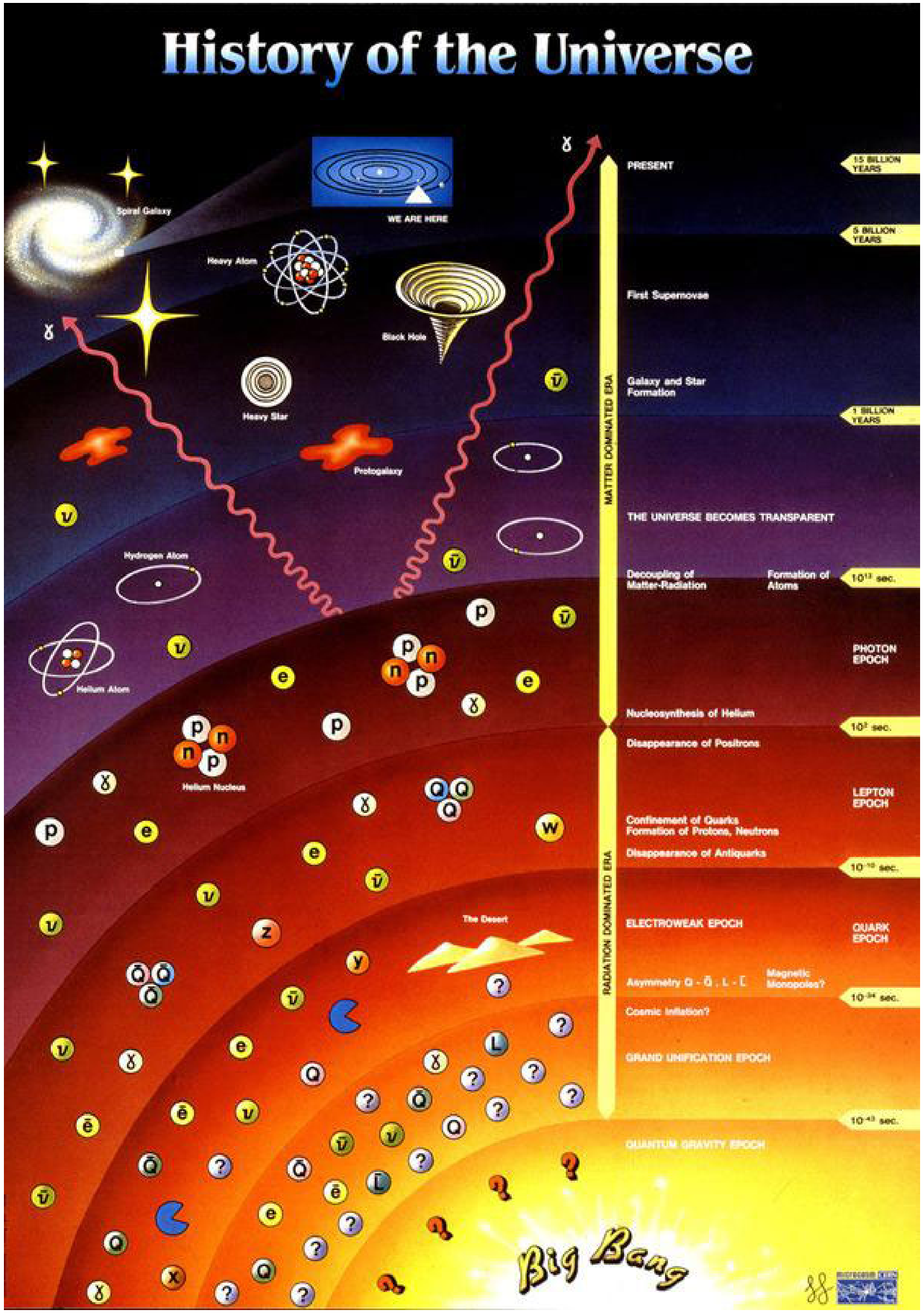
Study of elementary constituents of matter and their interactions

- *elementary* building blocks: “particles” without internal structure
- *interactions*: forces at play between these constituents

Present in the primordial universe, when it was dense and hot

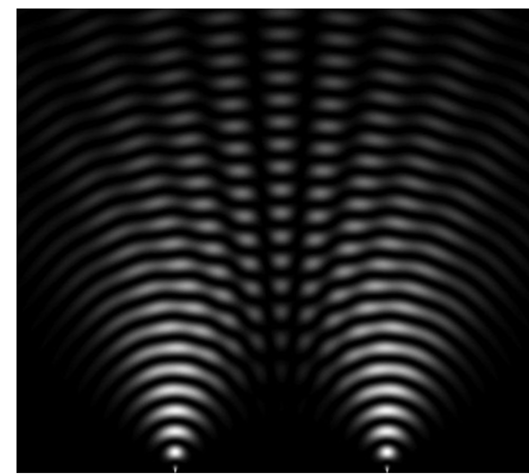
In today’s cold universe, most of these particles have disappeared

- artificially created in particle accelerators (colliders), reproducing conditions that prevailed in the very first instants of the universe
  - the more particles are accelerated,
    the more energy is at play,
    the further “back in time” one can go



Physics at the end of the XIXth century

- Newtonian mechanics [Newton (1643-1727)]
  - Principle of inertia (First law of motion)
  - Law of dynamics (Second law of motion)
  - Universal gravitation
- Analytical mechanics [Lagrange (1736-1813)]
  - Principle of least action
- Wave optics [Fresnel (1788-1827) – Young (1773-1829)]
  - Wave nature of light
- Electromagnetism [Maxwell (1831-1879)]
  - Unification of electricity & magnetism



- Existence of atoms: not proven – still debated
- Light: electromagnetic wave that propagates through *aether*

Conceptual revolutions

- According to Lord Kelvin in 1900 (British Association for the advancement of Science) :

  "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

- Nevertheless, the beginning of the XXth century sees two major changes of paradigm:
  - Special relativity
  - Quantum mechanics

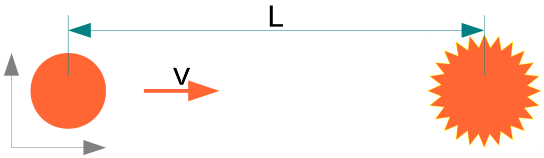
  (and later on general relativity)

Special relativity: spacetime

- Length contraction and time dilation
  - Flow of time depends on reference frame
    - proper time (t_0): time measured in object reference frame
    - time measured by (stationary) observer seeing object moving with velocity v:

$$t = \gamma\, t_0 \text{ where } \gamma = 1/\sqrt{(1-v^2/c^2)} > 1 \text{ (increases with } v\text{)}$$

  - Example: bomb programmed to detonate after 1 s

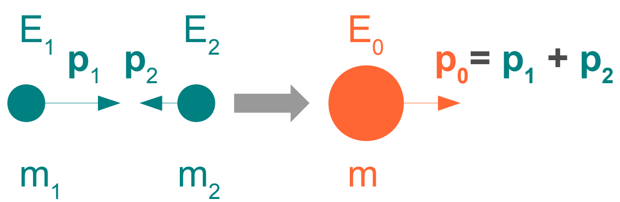


1)	v= 300 km/s	(0,1 % c)	→ L = 300 km	(t= 1s)
2)	v= 29 979 km/s	(10 % c)	→ L = 30 130 km	(t= 1s)
3)	v= 269 813 km/s	(90 % c)	→ L = 618 994 km	(t= 2s)
4)	v= 296 794 km/s	(99 % c)	→ L = 2 103 921 km	(t= 7s)
5)	v= 299 493 km/s	(99,9 % c)	→ L = 6 698 534 km	(t=22s)

To be taken into account when approaching limiting speed
(c, speed of light in vacuum)

Special relativity: mass and energy

- Mass-energy equivalence
  - Mass is a form of energy
    - If a body loses an amount of energy E, its mass decreases by $\Delta m = E/c^2$
    - $E_0 = m\,c^2$: rest energy (in reference frame with body at rest)
  - Total energy of a system: $E^2 = m^2c^4 + p^2c^2$ (p = momentum)
  - Conversion of kinetic energy into mass

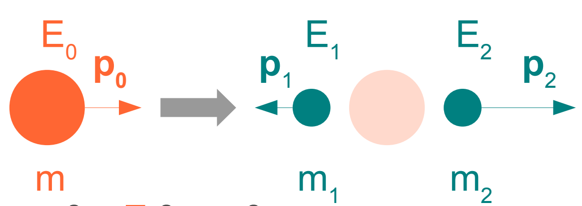


$E_0 = E_1 + E_2 = \sqrt{(m_1^2+p_1^2)} + \sqrt{(m_2^2+p_2^2)} = \sqrt{(m^2+p_0^2)}$

example : collision of protons with E = 7 TeV
→ available energy: E_0 = 14 TeV

In collisions, one can produce heavier objects than original particles!

  - Conversion of mass into kinetic energy



$m^2 = E_0^2 - p_0^2$
$= [\sqrt{(m_1^2+p_1^2)} + \sqrt{(m_2^2+p_2^2)}]^2 - [\mathbf{p}_1 + \mathbf{p}_2]^2$

example : decay of unstable particles

By identifying the nature of decay products, one knows their mass.
By also measuring their momentum, one can compute the mass (hence its nature) of the originating particle

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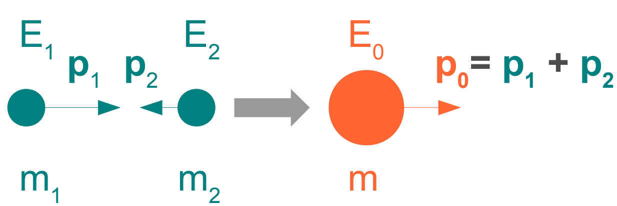

Conservation of energy

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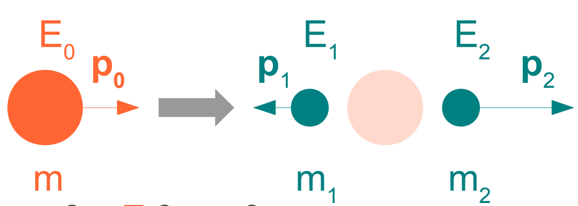

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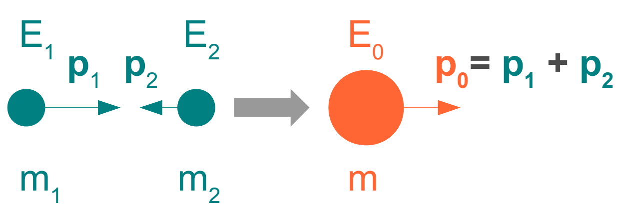

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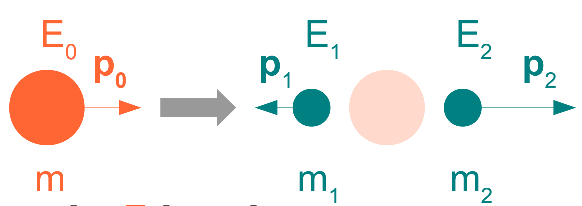

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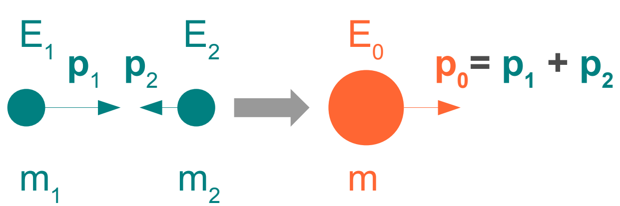

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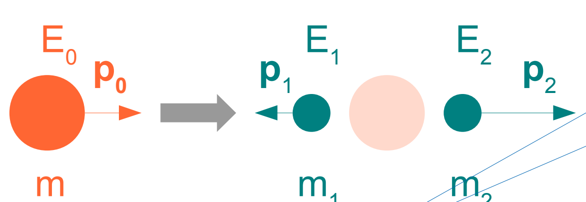

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Conservation of momentum

example : decay of unstable particles

By identifying the nature of decay products, one knows their mass.
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Units

- Usual units not very practical in particle physics
- Instead, use :
  - Energy : eV (*electron-volt*)
    - 1 eV = 1.6 10^{-19} J
    - energy gained by an electron in a 1V electric potential difference
- From mass-energy equivalence ($E^2 = m^2 c^4 + p^2 c^2$):
  - Momentum: eV/c
  - Mass: eV/c^2
    - 1eV/c^2 = 1.8 10^{-36} kg
  - Often using “natural” units:
    - $c = 1$
    - energy, momentum and mass in eV
- Usual multiples : keV (10^3), MeV(10^6), GeV(10^9), TeV (10^{12})

Quantum mechanics: wave-particle duality

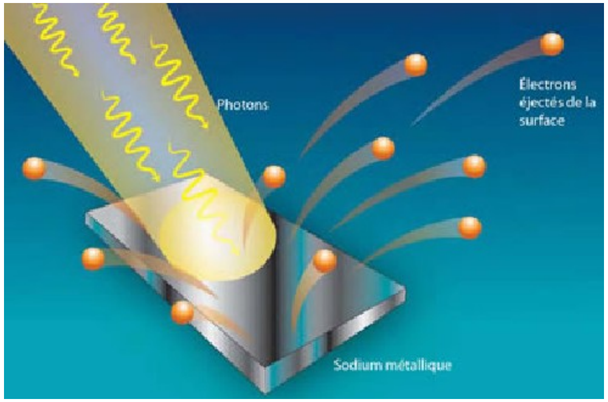
- At microscopic scales, objects have both *wave* and *particle* nature

  $E = h\nu$ $\qquad\qquad$ $p = h/\lambda$

  Planck's constant: $h = 6{,}63\ 10^{-34}$ J.s

  ▸ nothing equivalent in our macroscopic world → non-intuitive !

Photo-electric effect, Einstein, 1905

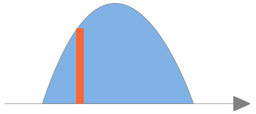


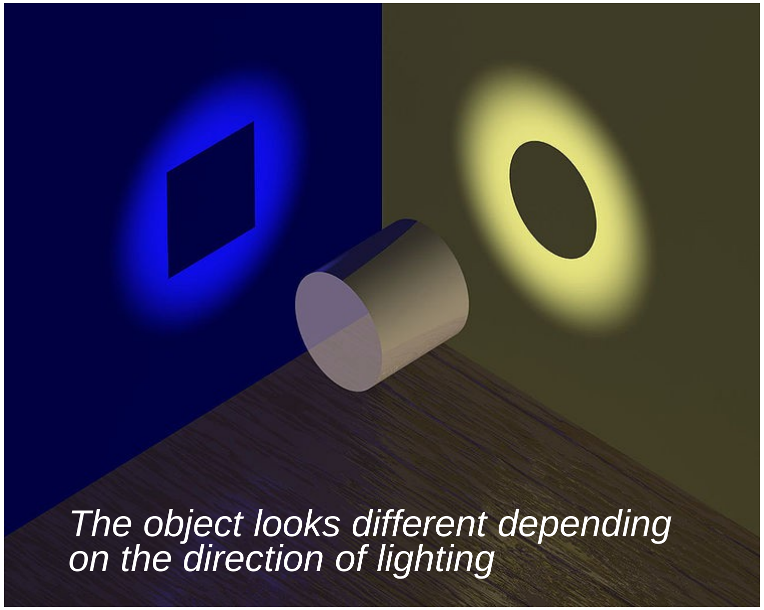
The photon is the carrier of the energy of the electro-magnetic wave

- Two antagonistic descriptions!
  - particle: point-like objet with well-defined position and momentum
  - wave: spread out object that can interfere

  ▸ quantum object: point-like properties follow probabilistic laws of associated wave.

  ex : position of a particle

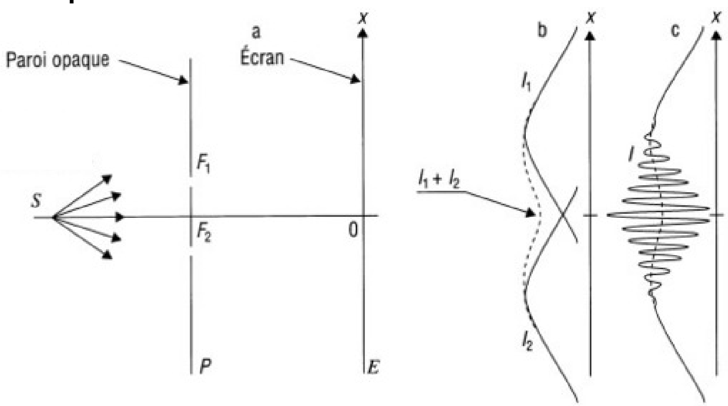




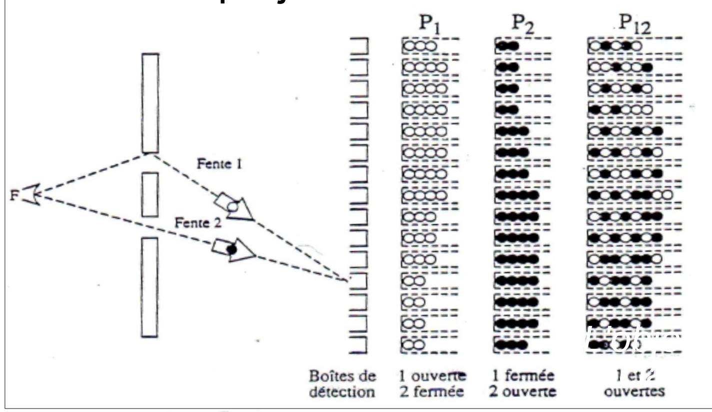
Quantum mechanics example

Double-slit experiment

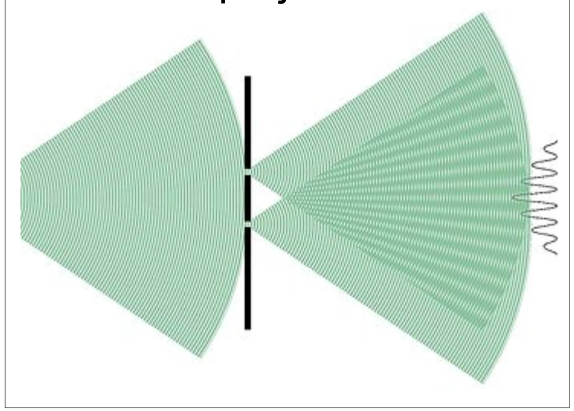
Experiment :



Case #1: projectile = marble



Case #2: projectile = wave



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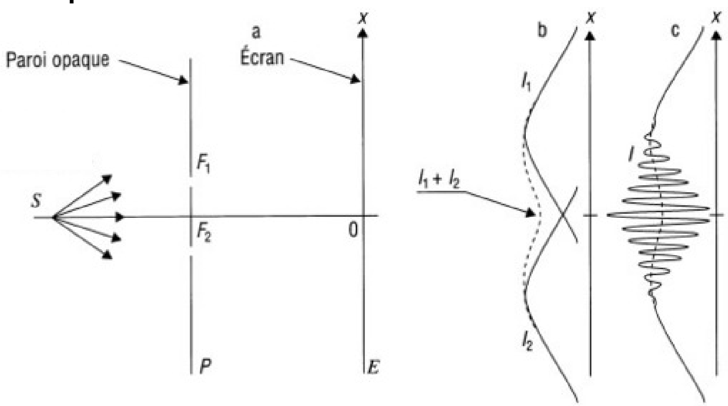

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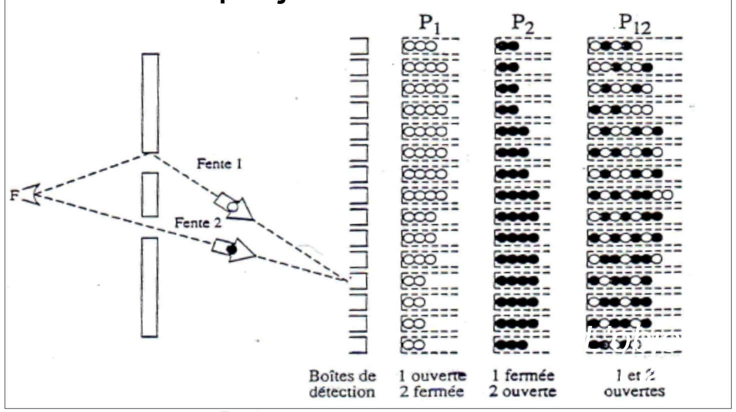

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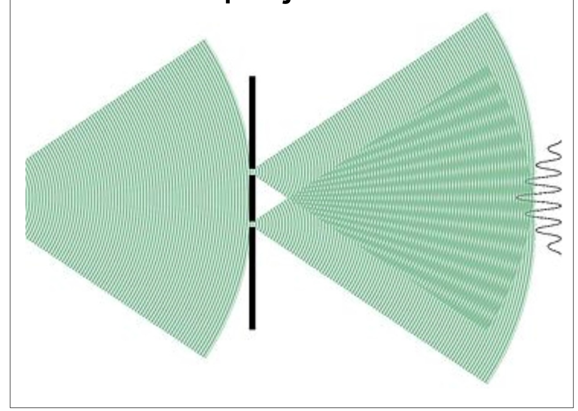
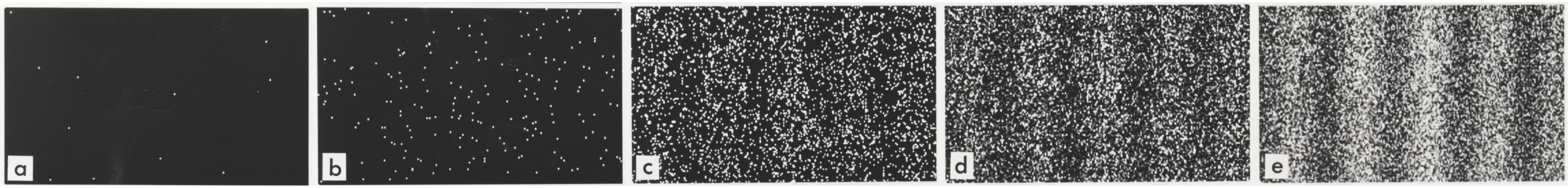


Case #3: projectile = quantum object (electron, photon)



- One can see *both* point-like impacts and interference patterns!

Quantum mechanics example

Double-slit experiment

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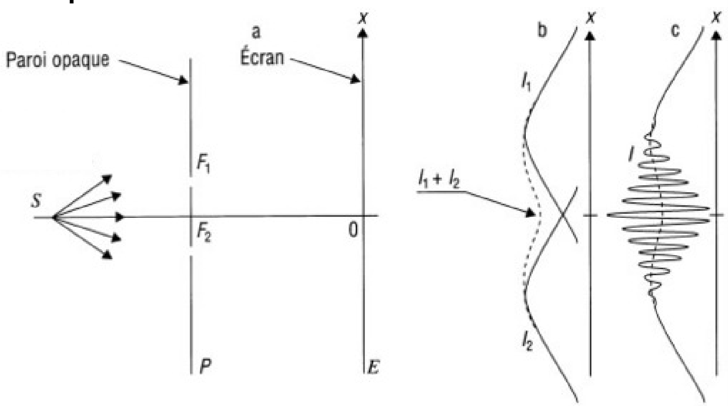

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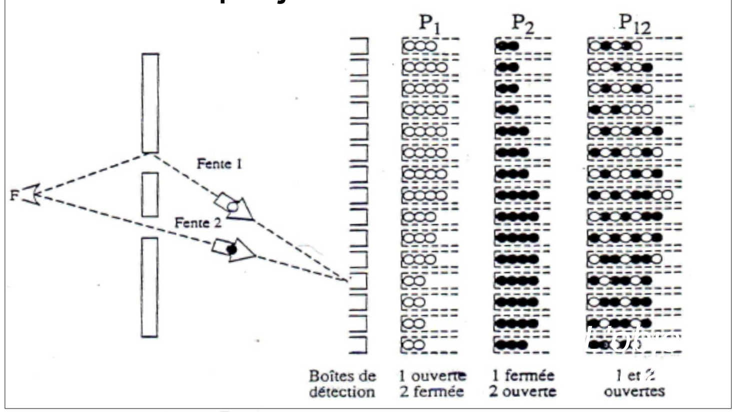

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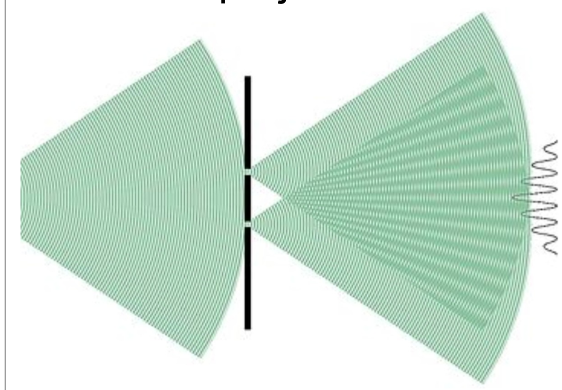

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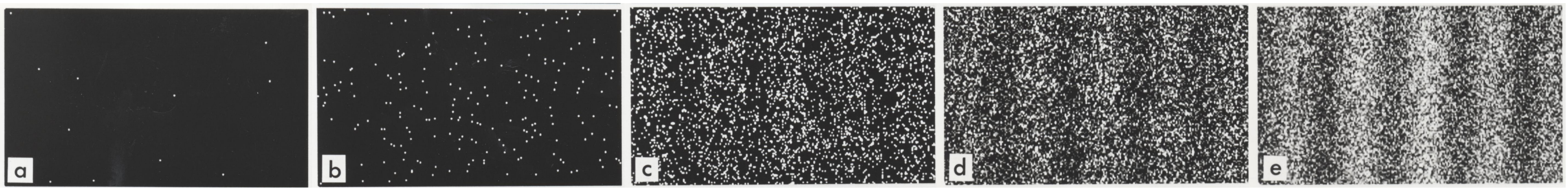
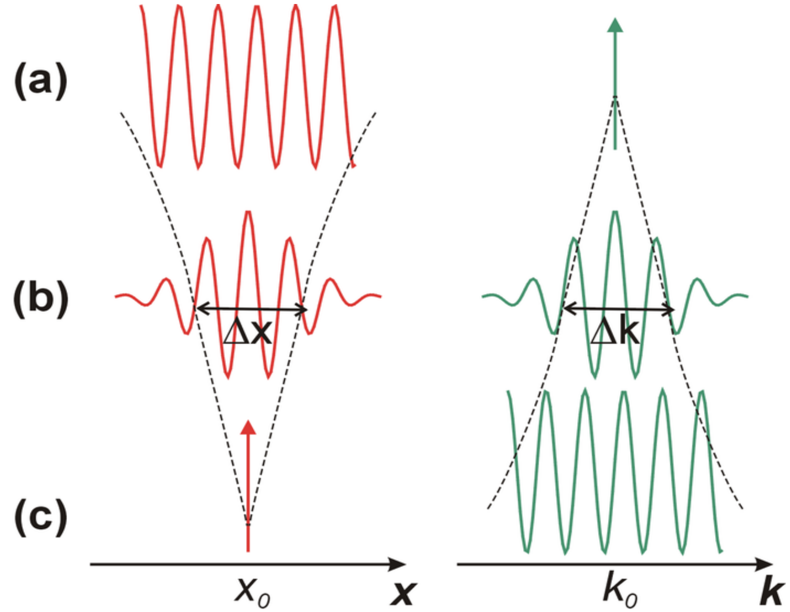


- One can see *both* point-like impacts and interference patterns!
- Note: if one detects which slit the particle goes through, the interference pattern disappears!

Quantum mechanics: uncertainty principle



(a) wave: A = cos (k.x)
- infinite spatial spread
- pure frequency

(b) wave packet: $A = \sum_k \cos(k.x)$
- limited spatial spread
- mix of frequencies

(c) particle : A = 1 if $x=x_0$, 0 otherwise ($\forall$ k)
- spatially localised
- no well-defined frequency

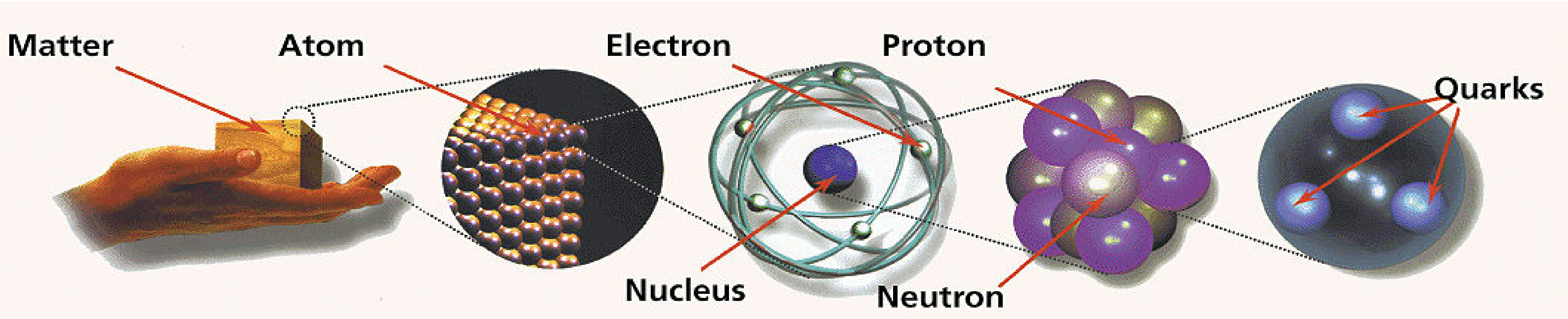
- Heisenberg relations (1927)
  - if position of particle known to Δx, its momentum is known to a precision Δp such that: $\Delta p.\Delta x > \hbar/2$
  - if timing of particle known to Δt, its energy is known to ΔE such that: $\Delta E.\Delta t > \hbar/2$
- Advantage of quantum fuzziness
  - an energy (ΔE) can be "borrowed" from vacuum during a time (Δt), sufficiently short for $\Delta E.\Delta t > \hbar/2$
  - … and since $E=mc^2$, (virtual) particles can be created and "live" for a short time (getting shorter the heavier the particle)

Quantum mechanics: interpretation

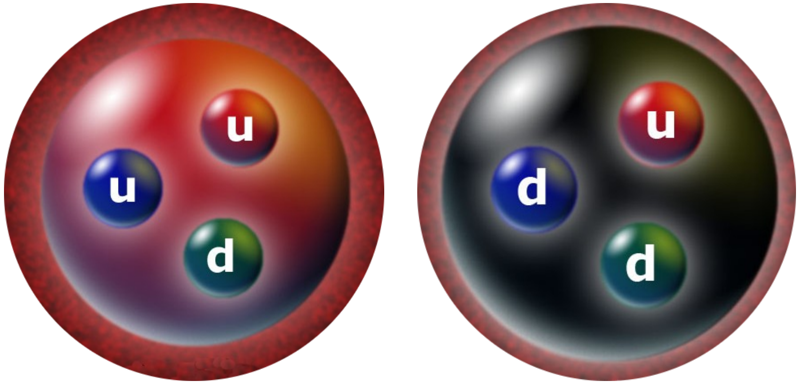
- Quantum mechanics: mathematical trick or reality?
  - Probabilistic aspects shocking to deterministic physicists
    - "God does not play dice with the universe", Einstein (1927)
  - Wave-particle duality
    - hard to interpret
    - debated for a long time
    - very active field of research

- Despite all its weirdness, all predictions of quantum mechanics are so far confirmed by experiments

What is the visible Universe made of?



- All visible matter, galaxies, viruses or human beings, are made up of up quarks (*u*), down quarks (*d*) and electrons
- Protons and neutrons are made up of 3 quarks



- They make up the nucleus
- Electrons orbit nucleus
- Neutrinos are produced in nuclear reactions within the core of stars

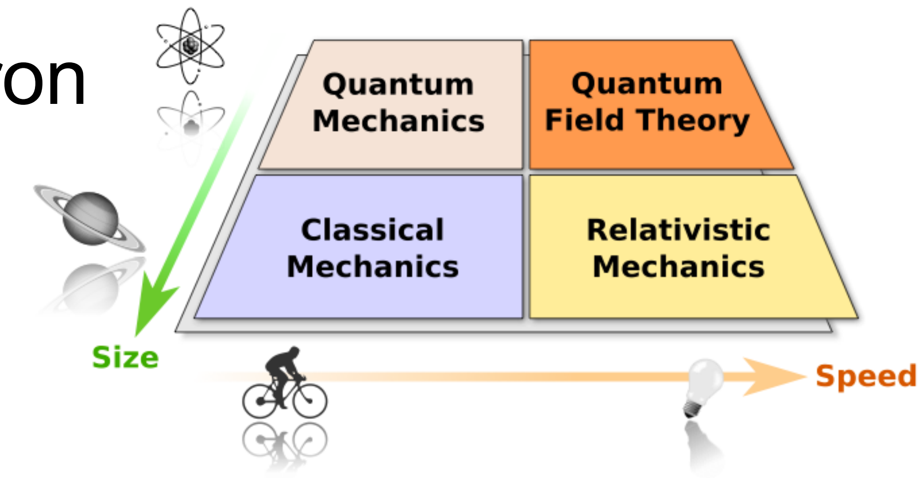
The positron

- Equation of motion of an electron

  [1928, Dirac]

  - quantum mechanics
  - relativistic case
  - Dirac equation with 2 solutions
    - electron
    - positron

$$\left(i\gamma^{\mu}\partial_{\mu}-m\right)\psi^{c}=0$$



- Observation:

  [1932, Anderson]

  - records in a Wilson cloud chamber a particle with the same properties as the electron but opposite electric charge

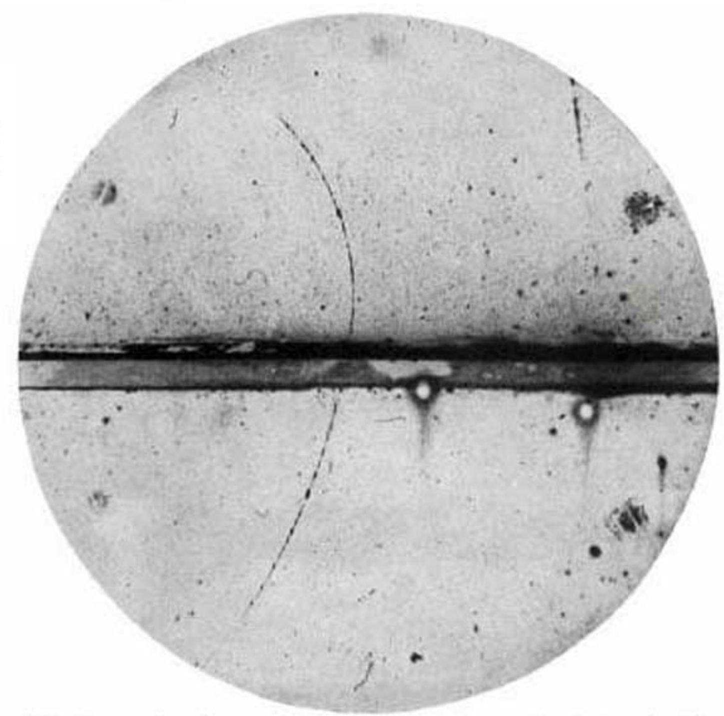
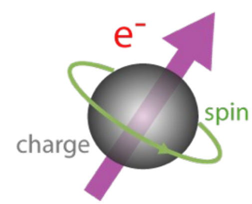


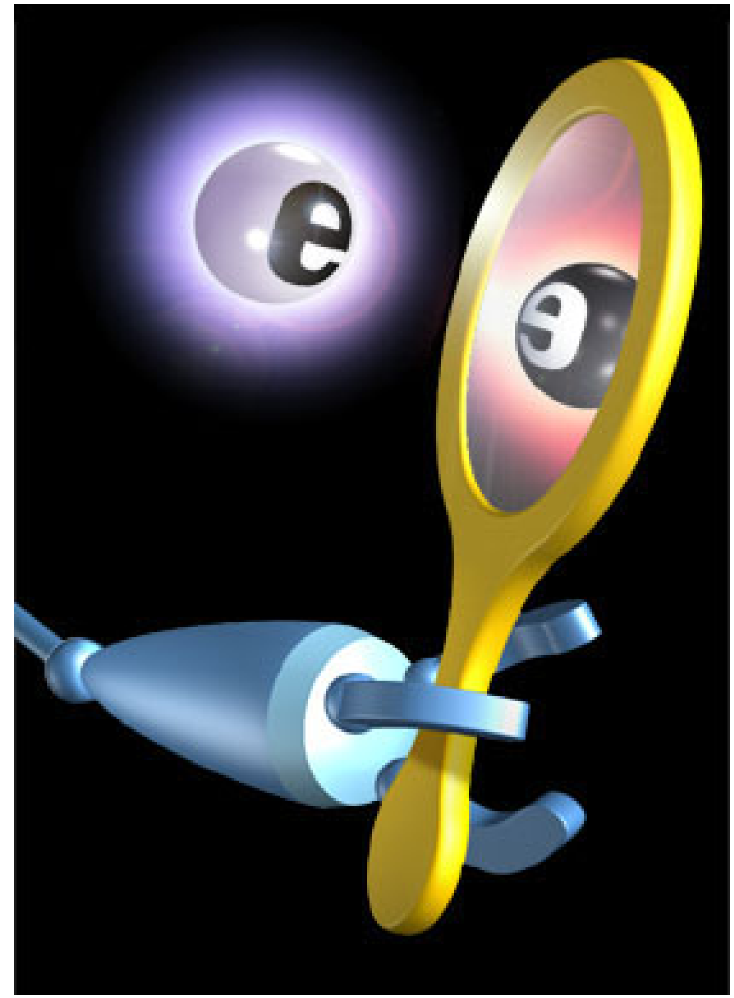
FIG. 1. A 63 million volt positron ($H\rho = 2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Antimatter

- Positron discovery means birth of antimatter
  - positron = anti-electron
- Generalisation: each particle is associated to its anti-particle with:
  - same mass
  - same *spin* (intrinsic angular momentum)



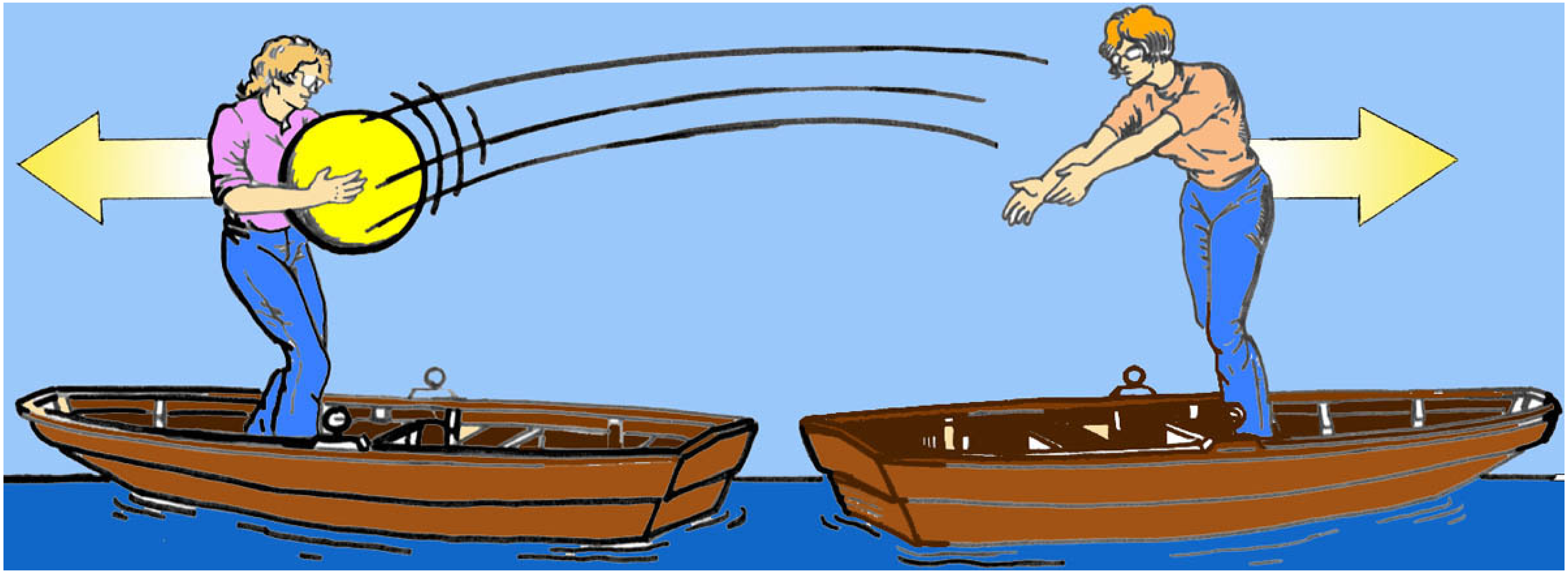
  - opposite charge(s)
- Antimatter behaves like matter (as seen in a mirror)
  - … but not quite exactly
    - there is a small asymmetry
    - very active field of research (and quite a theoretical puzzle)



convention:
anti-particle of x is called $\bar{x}$

Fundamental interaction

Exchange of particles (bosons) between matter particles (fermions, like quarks or electrons)



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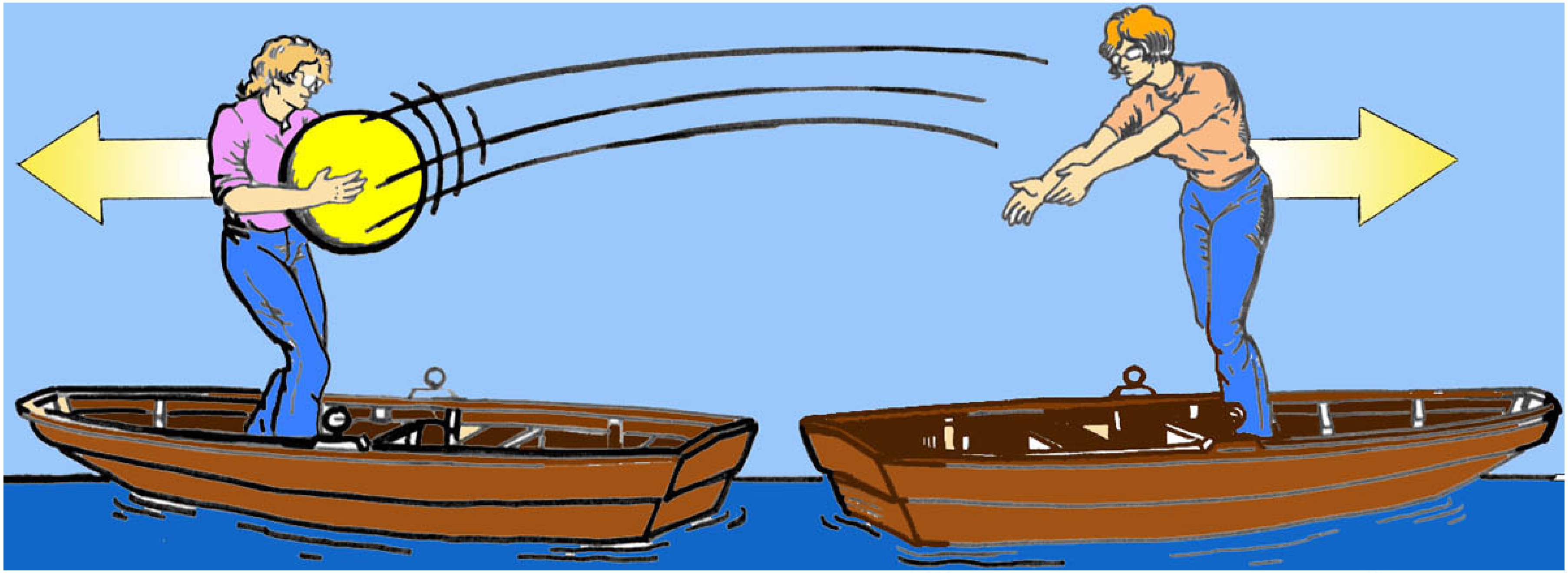
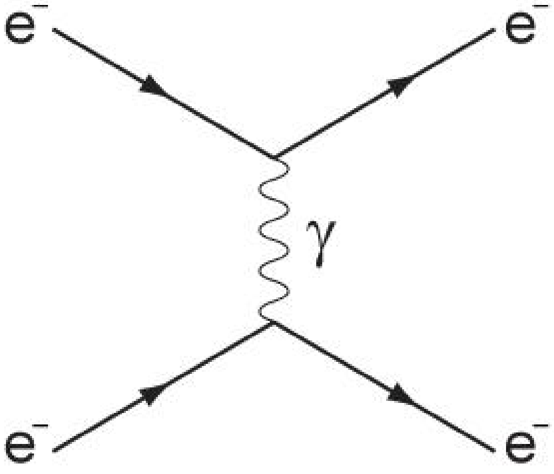


In particle physics :



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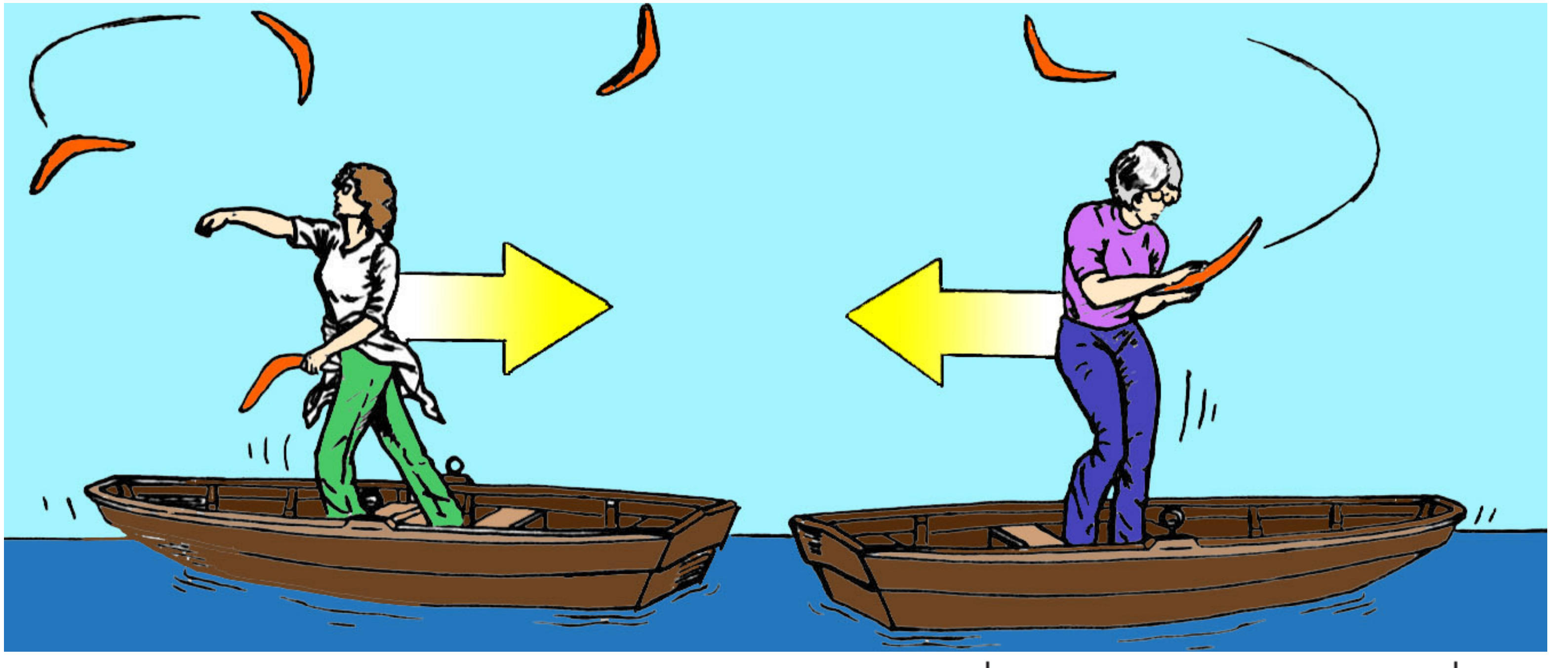

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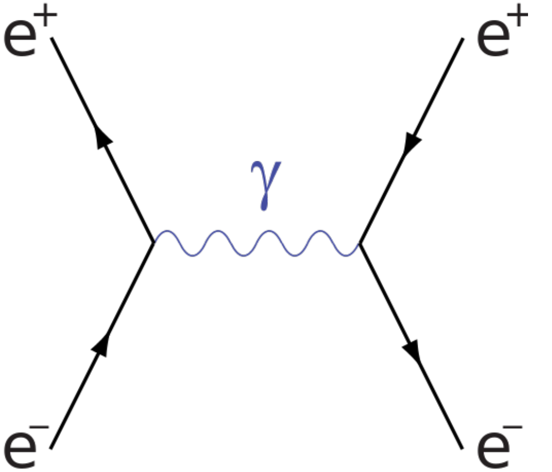

Forces

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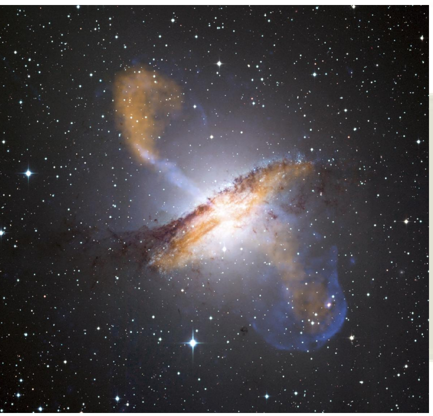
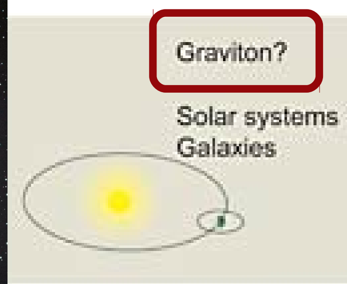
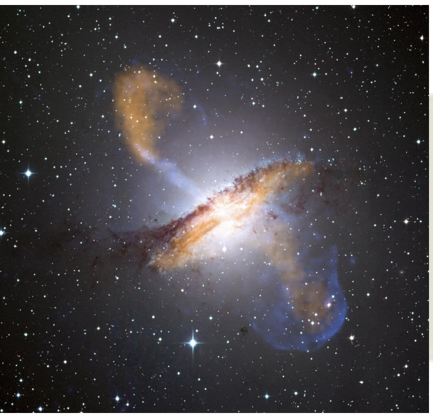
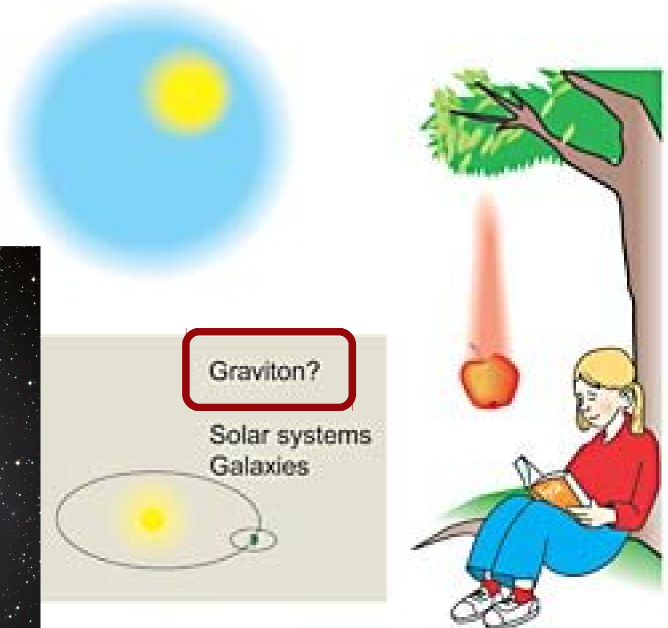




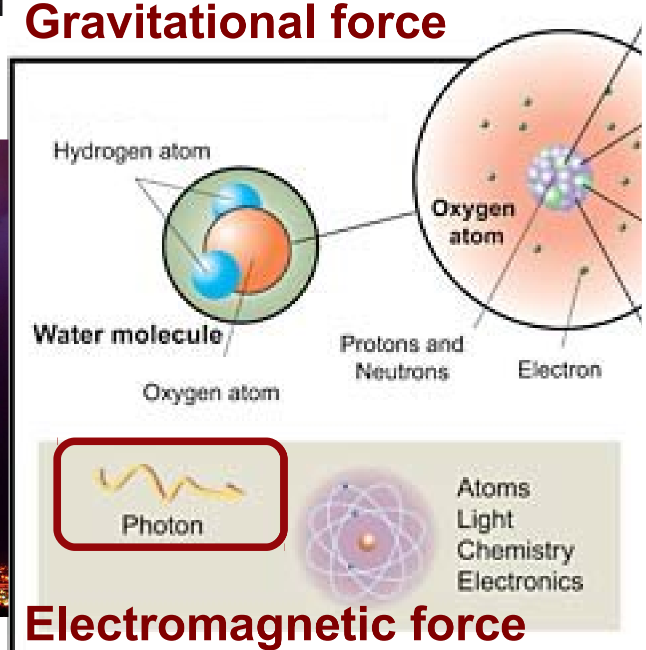
Gravitational force

Forces



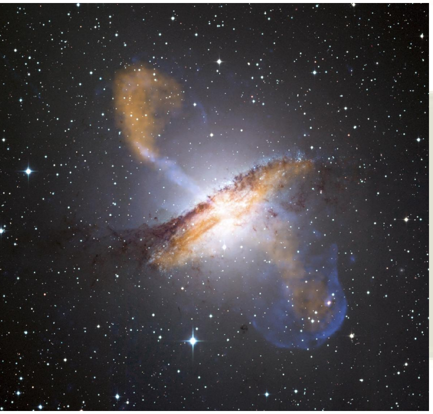


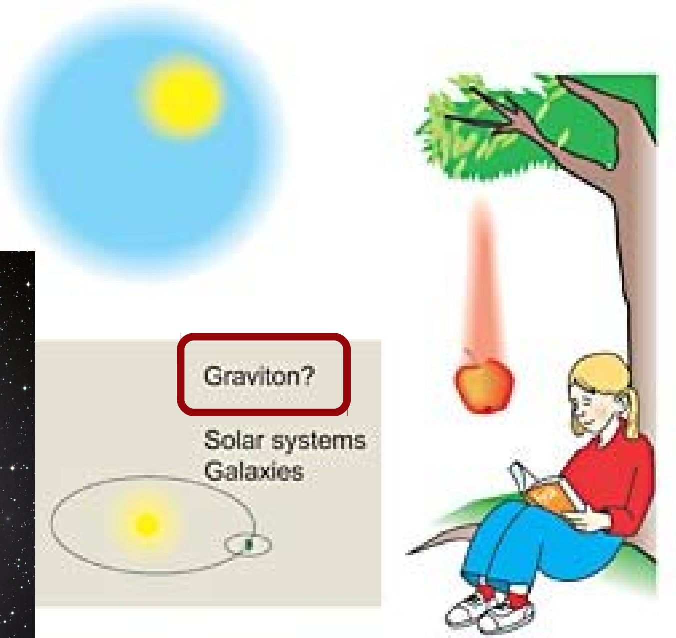
Gravitational force



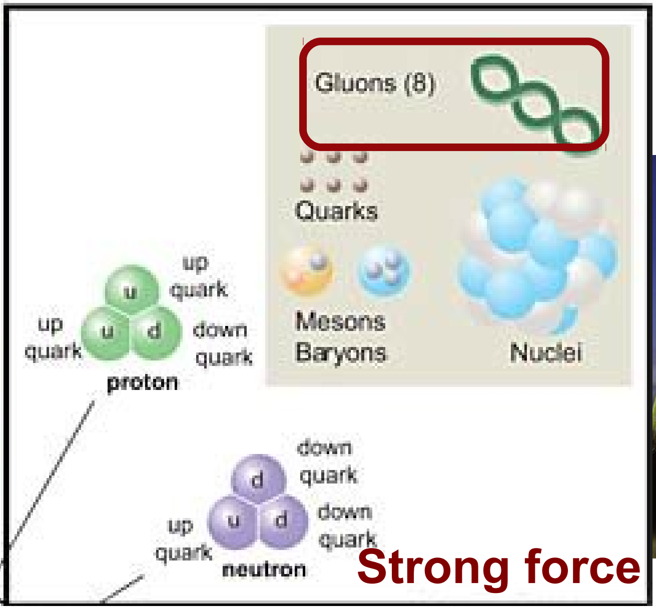
Electromagnetic force

Forces

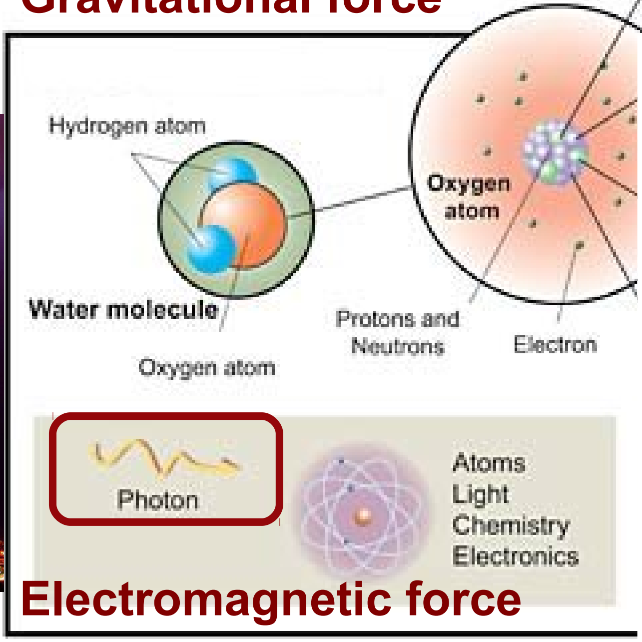




Gravitational force

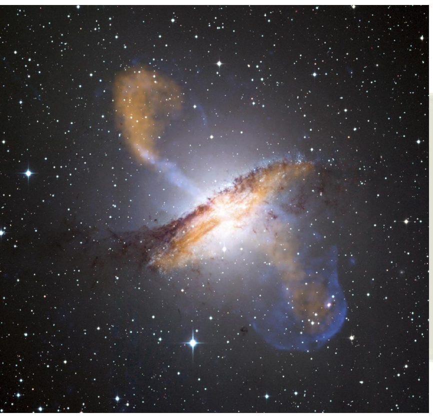


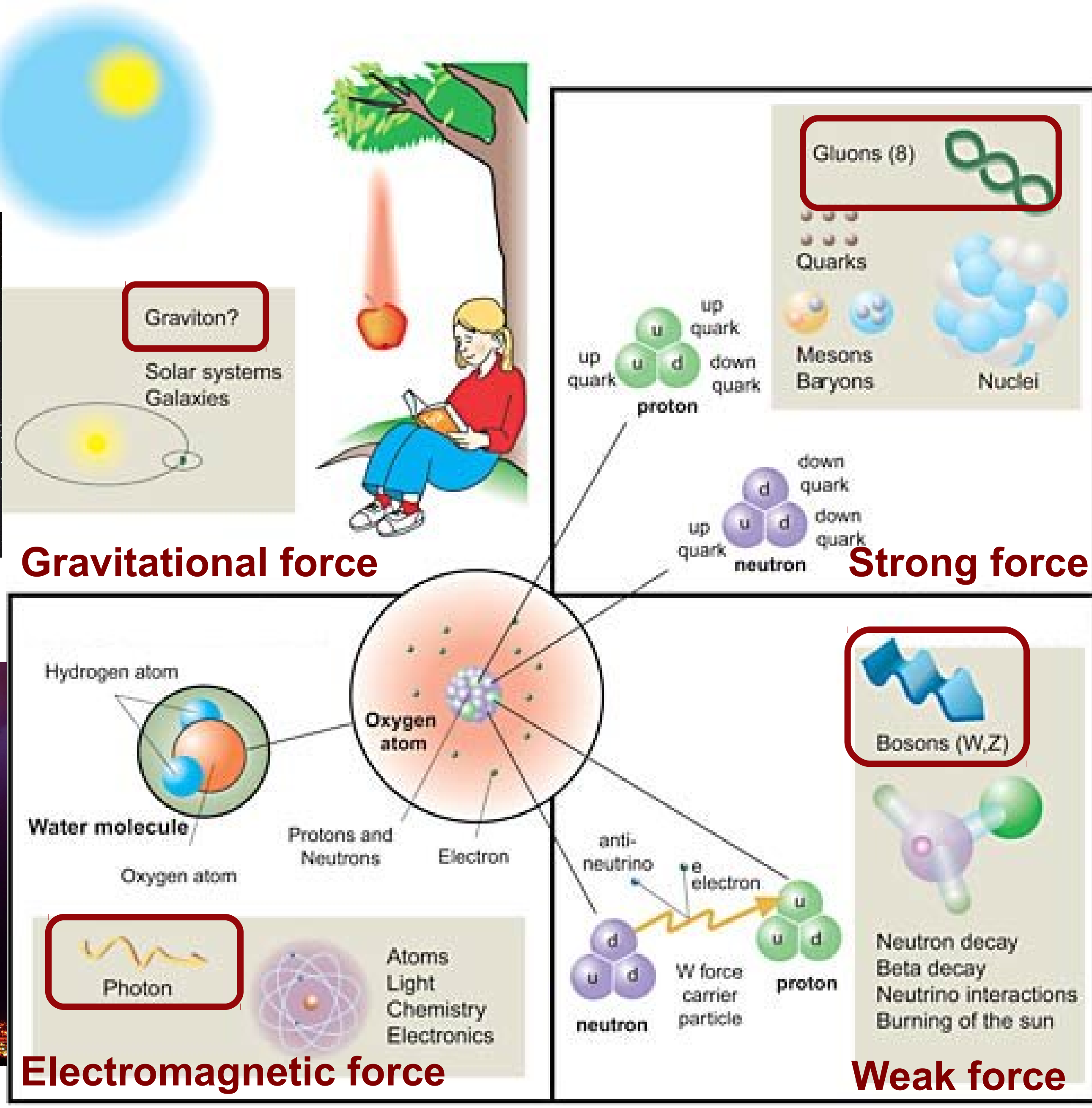
Strong force



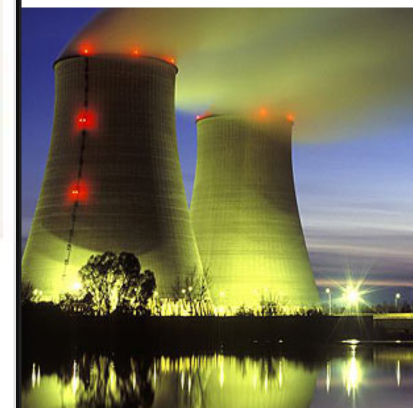
Electromagnetic force

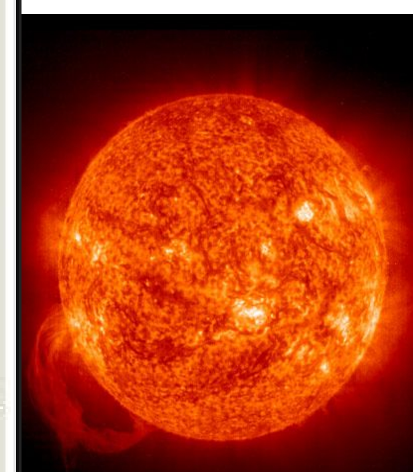
Forces



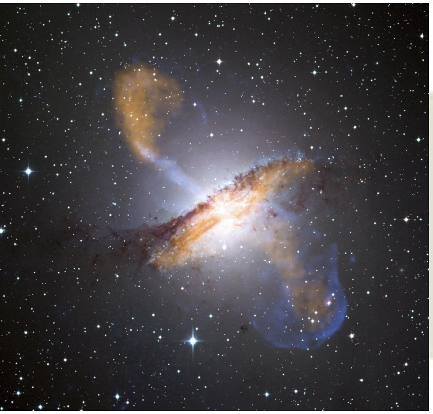


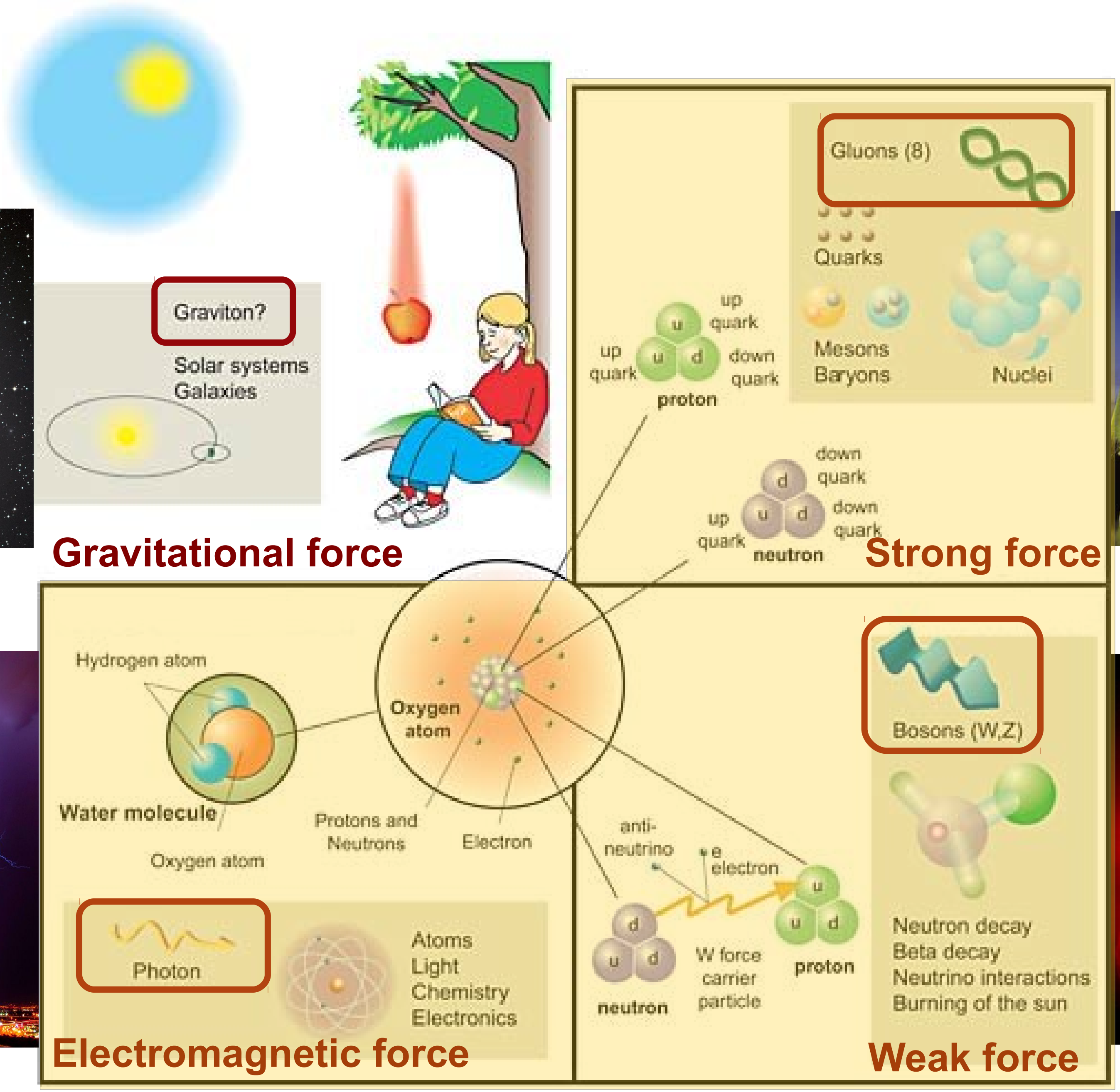
Graviton?
Solar systems
Galaxies
Gravitational force
Gluons (8)
Quarks
Mesons
Baryons
Nuclei
up quark
up quark
down quark
proton
down quark
down quark
up quark
neutron
Strong force
Hydrogen atom
Water molecule
Oxygen atom
Oxygen atom
Protons and Neutrons
Electron
Photon
Atoms
Light
Chemistry
Electronics
Electromagnetic force
Bosons (W,Z)
anti-neutrino
e electron
neutron
W force carrier particle
proton
Neutron decay
Beta decay
Neutrino interactions
Burning of the sun
Weak force





Forces

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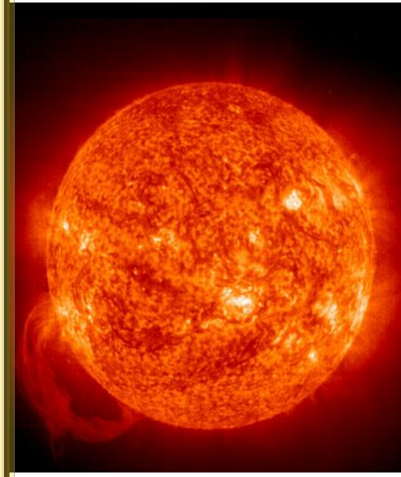
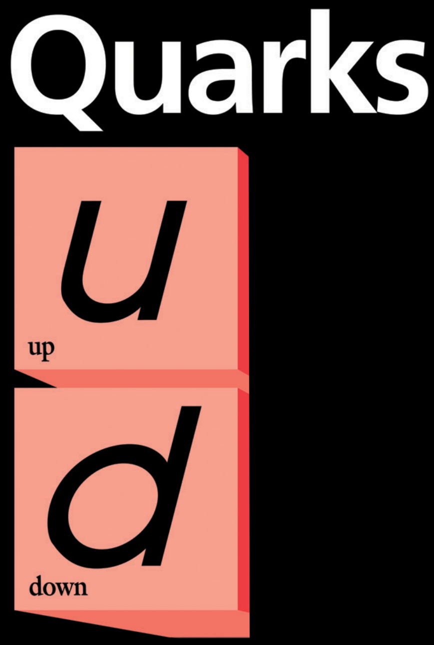
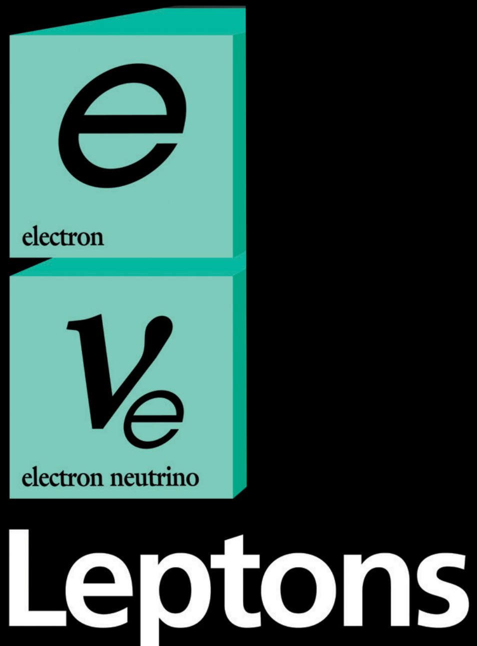


The Standard Model

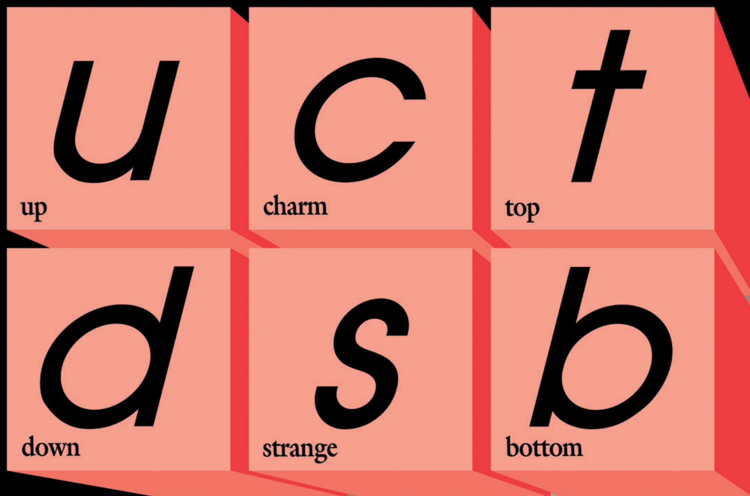


+ antimatter

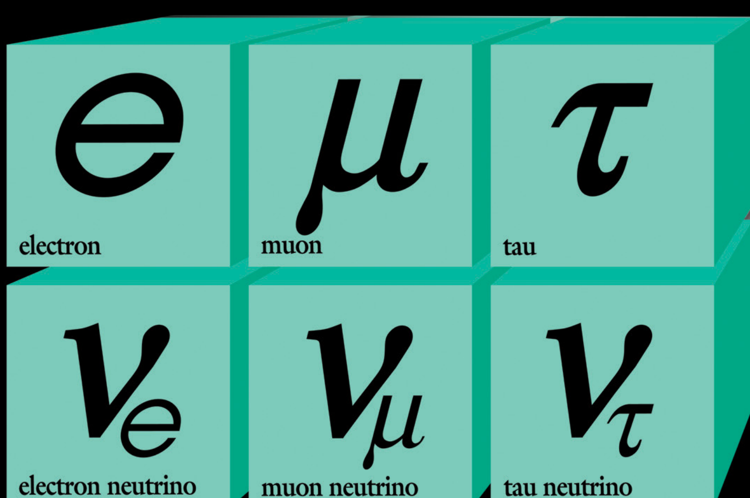


The Standard Model

Quarks

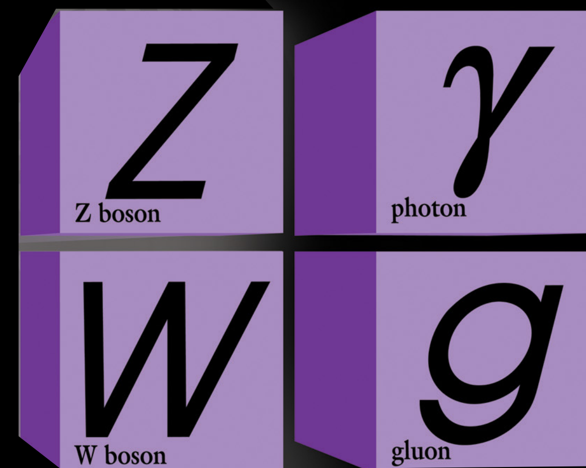


+ antimatter



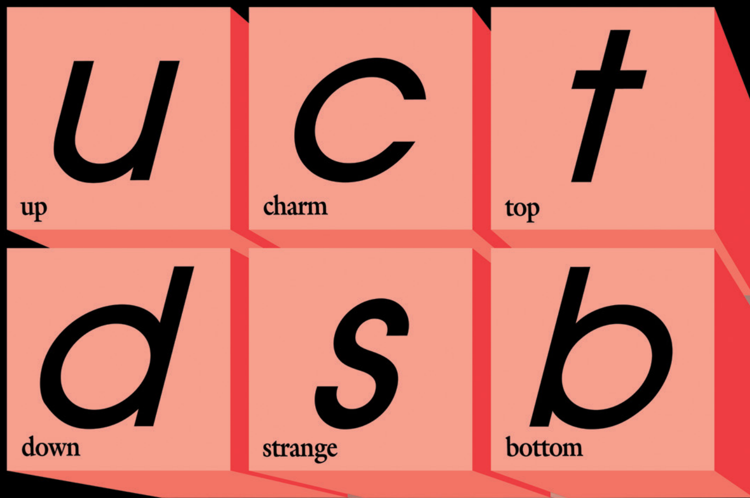
Leptons

Forces



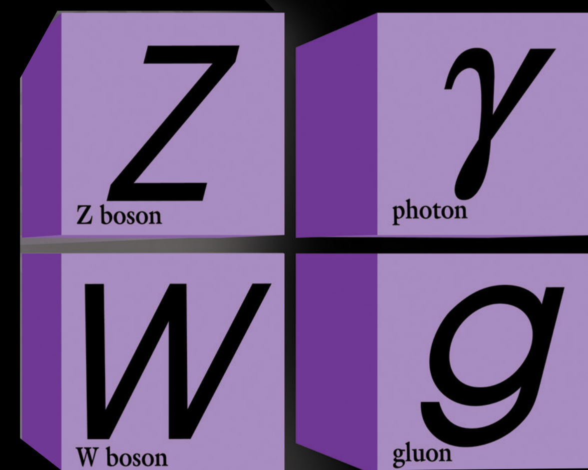
The Standard Model

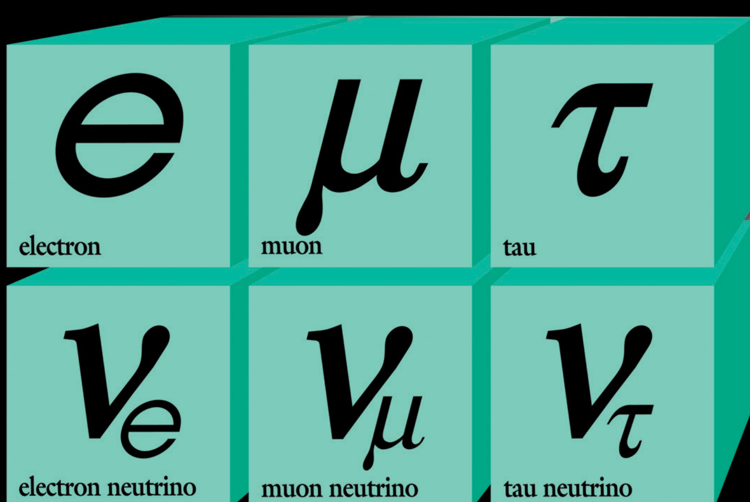
Quarks



+ antimatter

Forces

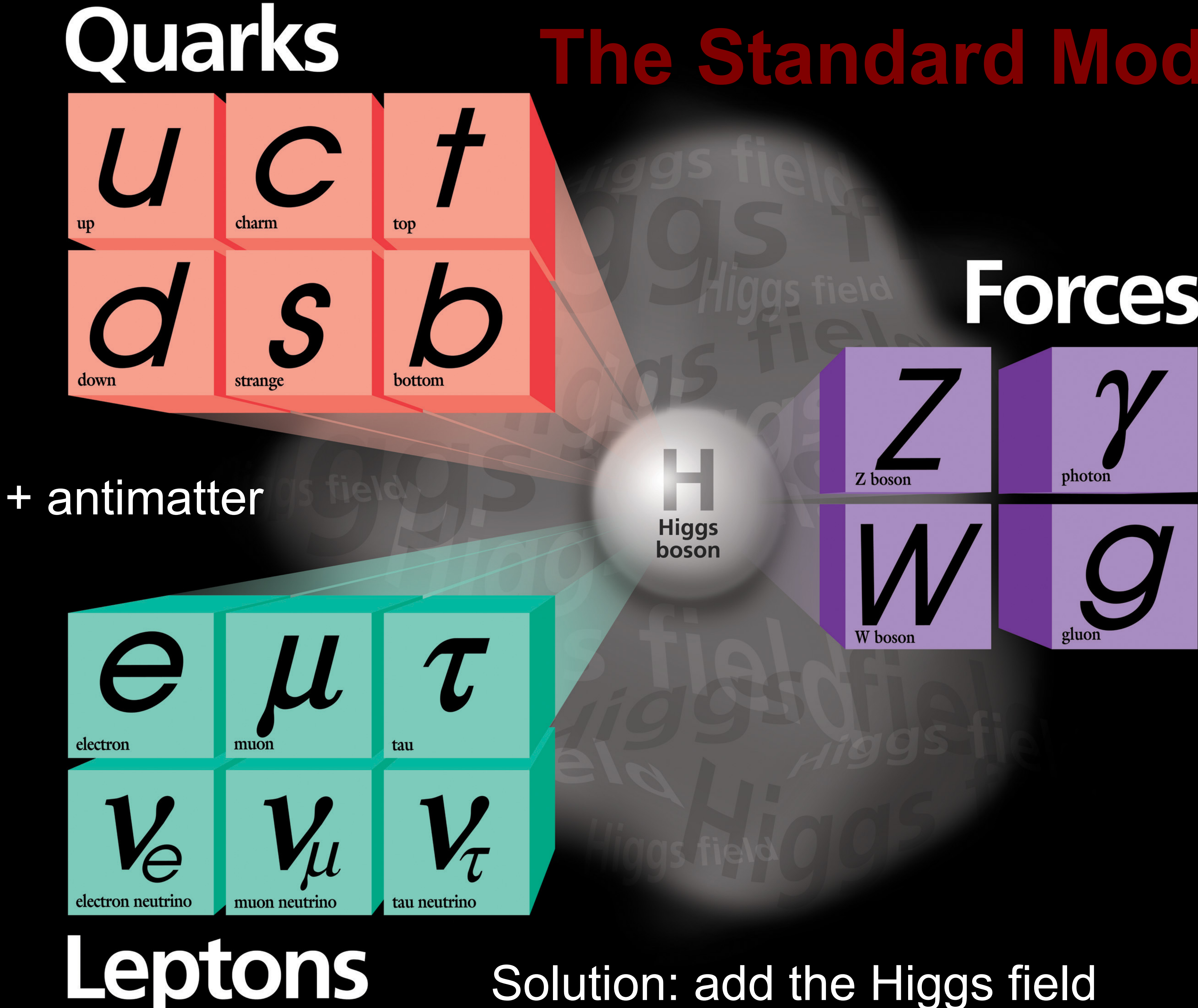




Leptons

All particles have zero mass, contrary to experimental results...

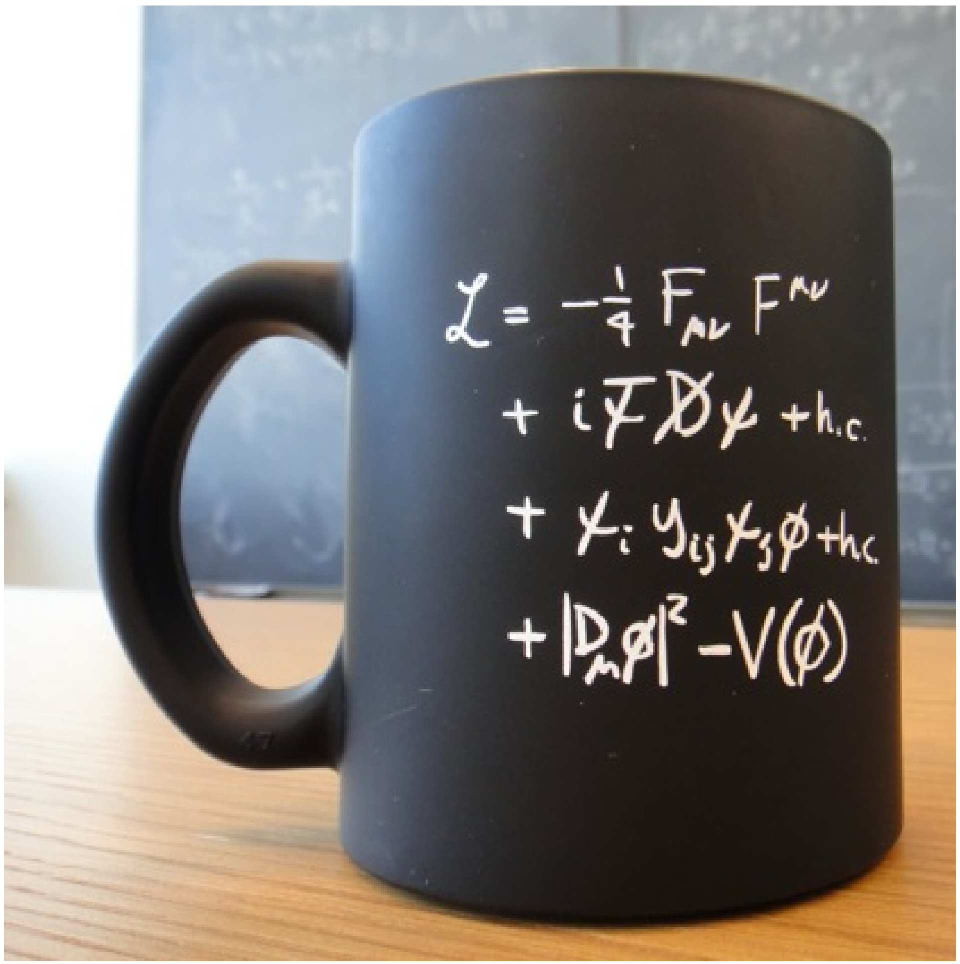
The Standard Model



Solution: add the Higgs field

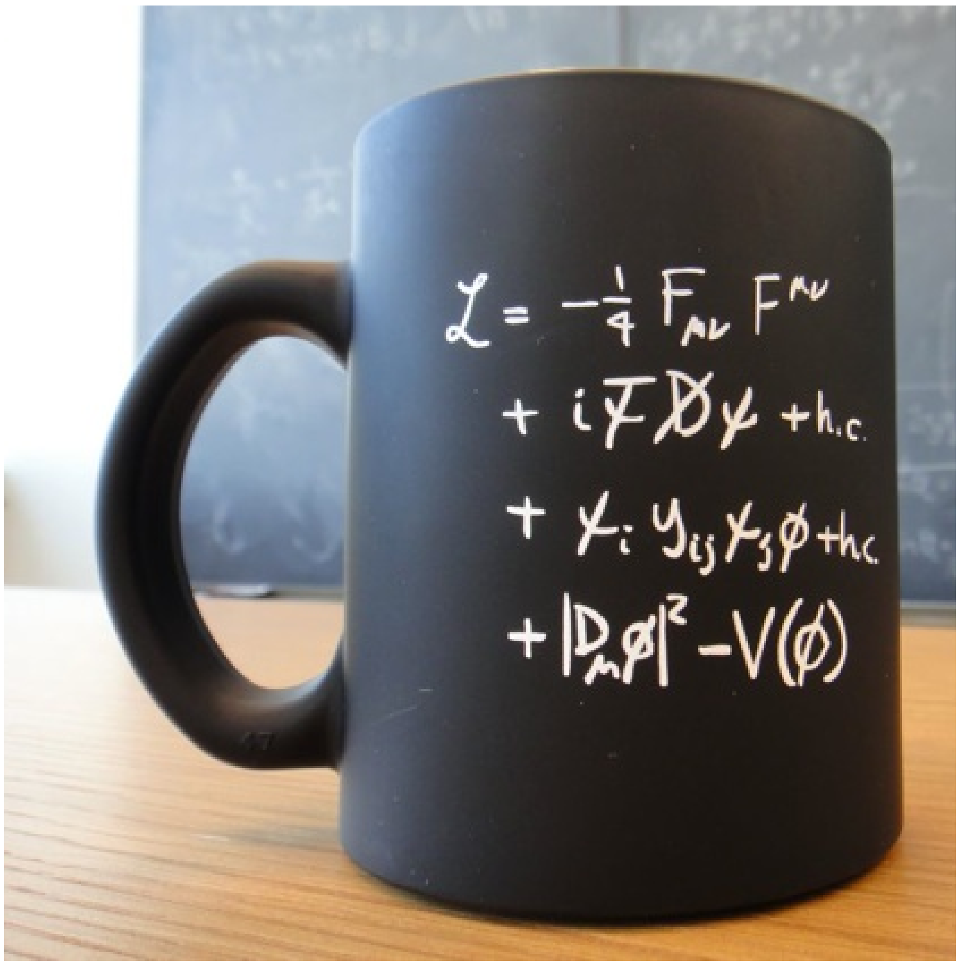
The Standard Model

- Condensed version



The Standard Model

- Condensed version



- Partial expansion...

$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \\
\tfrac{1}{2}\partial_\mu \boldsymbol{H} \partial_\mu \boldsymbol{H} - \tfrac{1}{2} m_h^2 \boldsymbol{H}^2 - \partial_\mu \boldsymbol{\phi}^+ \partial_\mu \boldsymbol{\phi}^- - M^2 \boldsymbol{\phi}^+ \boldsymbol{\phi}^- - \tfrac{1}{2}\partial_\mu \boldsymbol{\phi}^0 \partial_\mu \boldsymbol{\phi}^0 - \\
\tfrac{1}{2c_w^2} M \boldsymbol{\phi}^0 \boldsymbol{\phi}^0 - \beta_h [\tfrac{2M^2}{g^2} + \tfrac{2M}{g}\boldsymbol{H} + \tfrac{1}{2}(\boldsymbol{H}^2 + \boldsymbol{\phi}^0 \boldsymbol{\phi}^0 + 2\boldsymbol{\phi}^+ \boldsymbol{\phi}^-)] + \tfrac{2M^4}{g^2}\alpha_h - \\
i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + \\
Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \\
\tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [\boldsymbol{H}^3 + \\
\boldsymbol{H}\boldsymbol{\phi}^0 \boldsymbol{\phi}^0 + 2\boldsymbol{H}\boldsymbol{\phi}^+ \boldsymbol{\phi}^-] - \tfrac{1}{8} g^2 \alpha_h [\boldsymbol{H}^4 + (\boldsymbol{\phi}^0)^4 + 4(\boldsymbol{\phi}^+ \boldsymbol{\phi}^-)^2 + \\
4(\boldsymbol{\phi}^0)^2 \boldsymbol{\phi}^+ \boldsymbol{\phi}^- + 4\boldsymbol{H}^2 \boldsymbol{\phi}^+ \boldsymbol{\phi}^- + 2(\boldsymbol{\phi}^0)^2 \boldsymbol{H}^2] - g M W^+_\mu W^-_\mu \boldsymbol{H} - \\
\tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu \boldsymbol{H} - \tfrac{1}{2} i g [W^+_\mu (\boldsymbol{\phi}^0 \partial_\mu \boldsymbol{\phi}^- - \boldsymbol{\phi}^- \partial_\mu \boldsymbol{\phi}^0) - W^-_\mu (\boldsymbol{\phi}^0 \partial_\mu \boldsymbol{\phi}^+ - \\
\boldsymbol{\phi}^+ \partial_\mu \boldsymbol{\phi}^0)] + \tfrac{1}{2} g [W^+_\mu (\boldsymbol{H}\partial_\mu \boldsymbol{\phi}^- - \boldsymbol{\phi}^- \partial_\mu \boldsymbol{H}) - W^-_\mu (\boldsymbol{H}\partial_\mu \boldsymbol{\phi}^+ - \boldsymbol{\phi}^+ \partial_\mu \boldsymbol{H})] + \\
\tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (\boldsymbol{H}\partial_\mu \boldsymbol{\phi}^0 - \boldsymbol{\phi}^0 \partial_\mu \boldsymbol{H}) - i g \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \boldsymbol{\phi}^- - W^-_\mu \boldsymbol{\phi}^+) + \\
i g s_w M A_\mu (W^+_\mu \boldsymbol{\phi}^- - W^-_\mu \boldsymbol{\phi}^+) - i g \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\boldsymbol{\phi}^+ \partial_\mu \boldsymbol{\phi}^- - \boldsymbol{\phi}^- \partial_\mu \boldsymbol{\phi}^+) + \\
i g s_w A_\mu (\boldsymbol{\phi}^+ \partial_\mu \boldsymbol{\phi}^- - \boldsymbol{\phi}^- \partial_\mu \boldsymbol{\phi}^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [\boldsymbol{H}^2 + (\boldsymbol{\phi}^0)^2 + 2\boldsymbol{\phi}^+ \boldsymbol{\phi}^-] - \\
\tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [\boldsymbol{H}^2 + (\boldsymbol{\phi}^0)^2 + 2(2s_w^2 - 1)^2 \boldsymbol{\phi}^+ \boldsymbol{\phi}^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \boldsymbol{\phi}^0 (W^+_\mu \boldsymbol{\phi}^- + \\
W^-_\mu \boldsymbol{\phi}^+) - \tfrac{1}{2} i g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \boldsymbol{H} (W^+_\mu \boldsymbol{\phi}^- - W^-_\mu \boldsymbol{\phi}^+) + \tfrac{1}{2} g^2 s_w A_\mu \boldsymbol{\phi}^0 (W^+_\mu \boldsymbol{\phi}^- + \\
W^-_\mu \boldsymbol{\phi}^+) + \tfrac{1}{2} i g^2 s_w A_\mu \boldsymbol{H} (W^+_\mu \boldsymbol{\phi}^- - W^-_\mu \boldsymbol{\phi}^+) - g^2 \tfrac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \boldsymbol{\phi}^+ \boldsymbol{\phi}^- - \\
g^1 s_w^2 A_\mu A_\mu \boldsymbol{\phi}^+ \boldsymbol{\phi}^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \\
\bar{d}^\lambda_j (\gamma\partial + m_d^\lambda) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3}s_w^2 - \\
1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3}s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + \\
(\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
\gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\boldsymbol{\phi}^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \boldsymbol{\phi}^- (\bar{e}^\lambda (1+\gamma^5)\nu^\lambda)] - \\
\tfrac{g}{2} \tfrac{m_e^\lambda}{M} [\boldsymbol{H} (\bar{e}^\lambda e^\lambda) + i\boldsymbol{\phi}^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \boldsymbol{\phi}^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + \\
m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \boldsymbol{\phi}^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
\gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m_u^\lambda}{M} \boldsymbol{H} (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m_d^\lambda}{M} \boldsymbol{H} (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m_u^\lambda}{M} \boldsymbol{\phi}^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
\tfrac{ig}{2} \tfrac{m_d^\lambda}{M} \boldsymbol{\phi}^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
\tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
\partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
\partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} g M [\bar{X}^+ X^+ \boldsymbol{H} + \bar{X}^- X^- \boldsymbol{H} + \tfrac{1}{c_w^2} \bar{X}^0 X^0 \boldsymbol{H}] + \\
\tfrac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \boldsymbol{\phi}^+ - \bar{X}^- X^0 \boldsymbol{\phi}^-] + \tfrac{1}{2c_w} i g M [\bar{X}^0 X^- \boldsymbol{\phi}^+ - \bar{X}^0 X^+ \boldsymbol{\phi}^-] + \\
i g M s_w [\bar{X}^0 X^- \boldsymbol{\phi}^+ - \bar{X}^0 X^+ \boldsymbol{\phi}^-] + \tfrac{1}{2} i g M [\bar{X}^+ X^+ \boldsymbol{\phi}^0 - \bar{X}^- X^- \boldsymbol{\phi}^0]
\end{gathered}
$$

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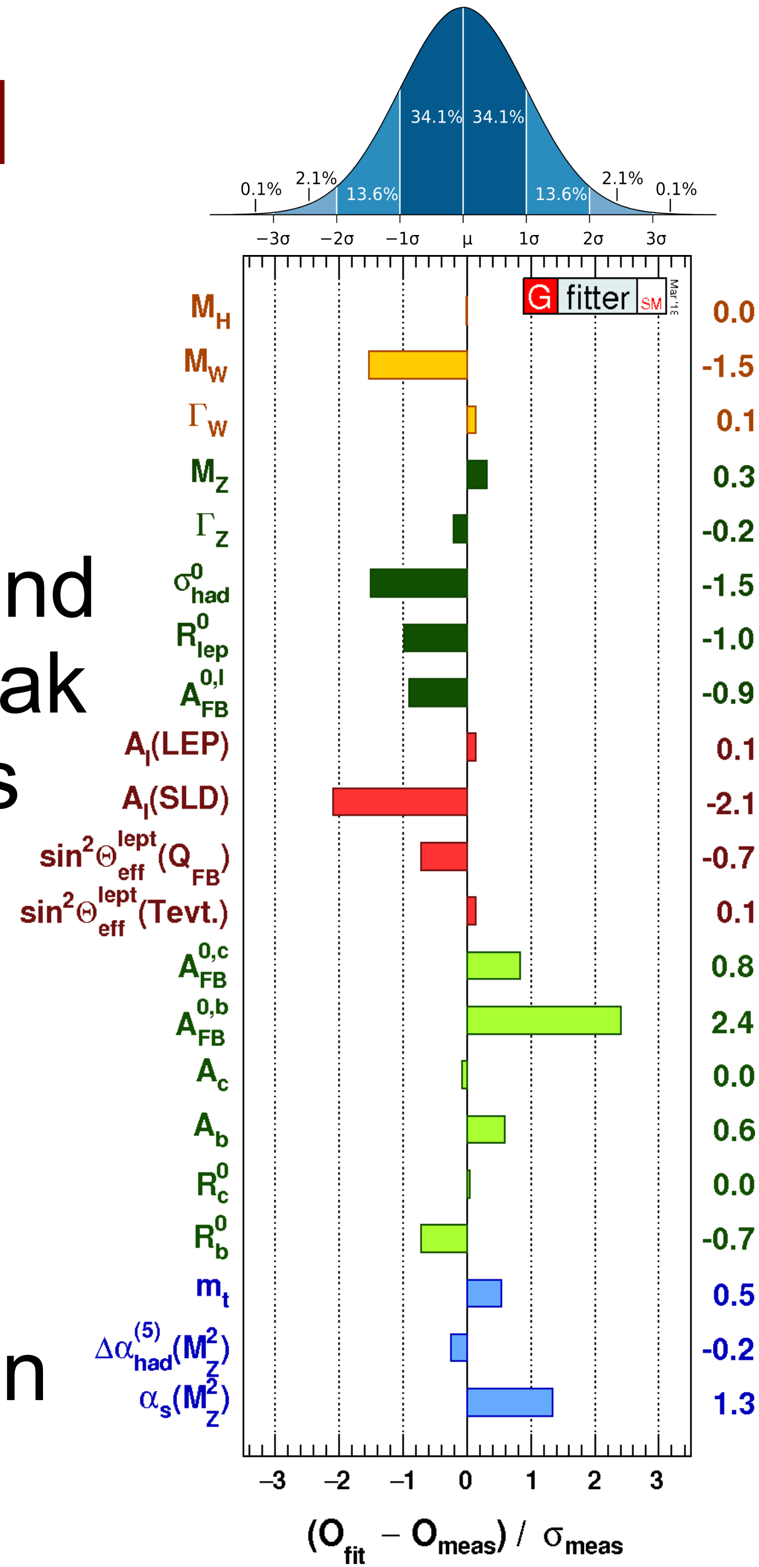
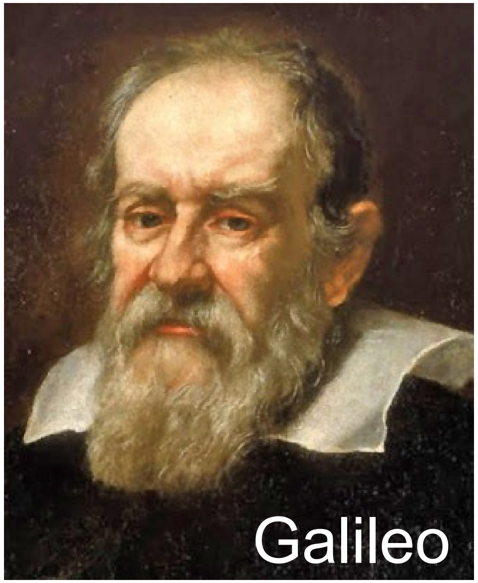
The Standard Model

- Theoretical model that explains about all observed and predicted phenomena in particle physics
- Describes elementary particles and their strong and electroweak (weak and electromagnetic) interactions
- Put together in 1960-70
- Based on symmetries, implying conservation laws
- Great success over the years: tested to unprecedented precision
- Largest deviation ~2.5σ

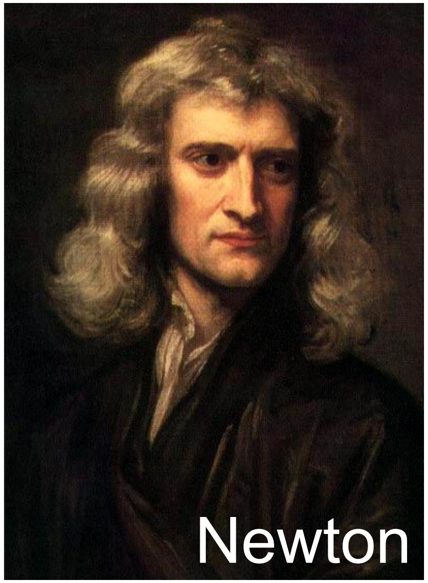


Mass



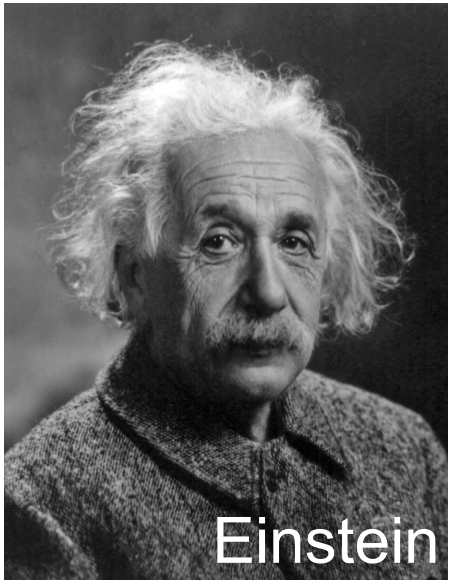
- Gravitational mass

$$P = mg$$



- Inertial mass

$$\Sigma F = ma$$



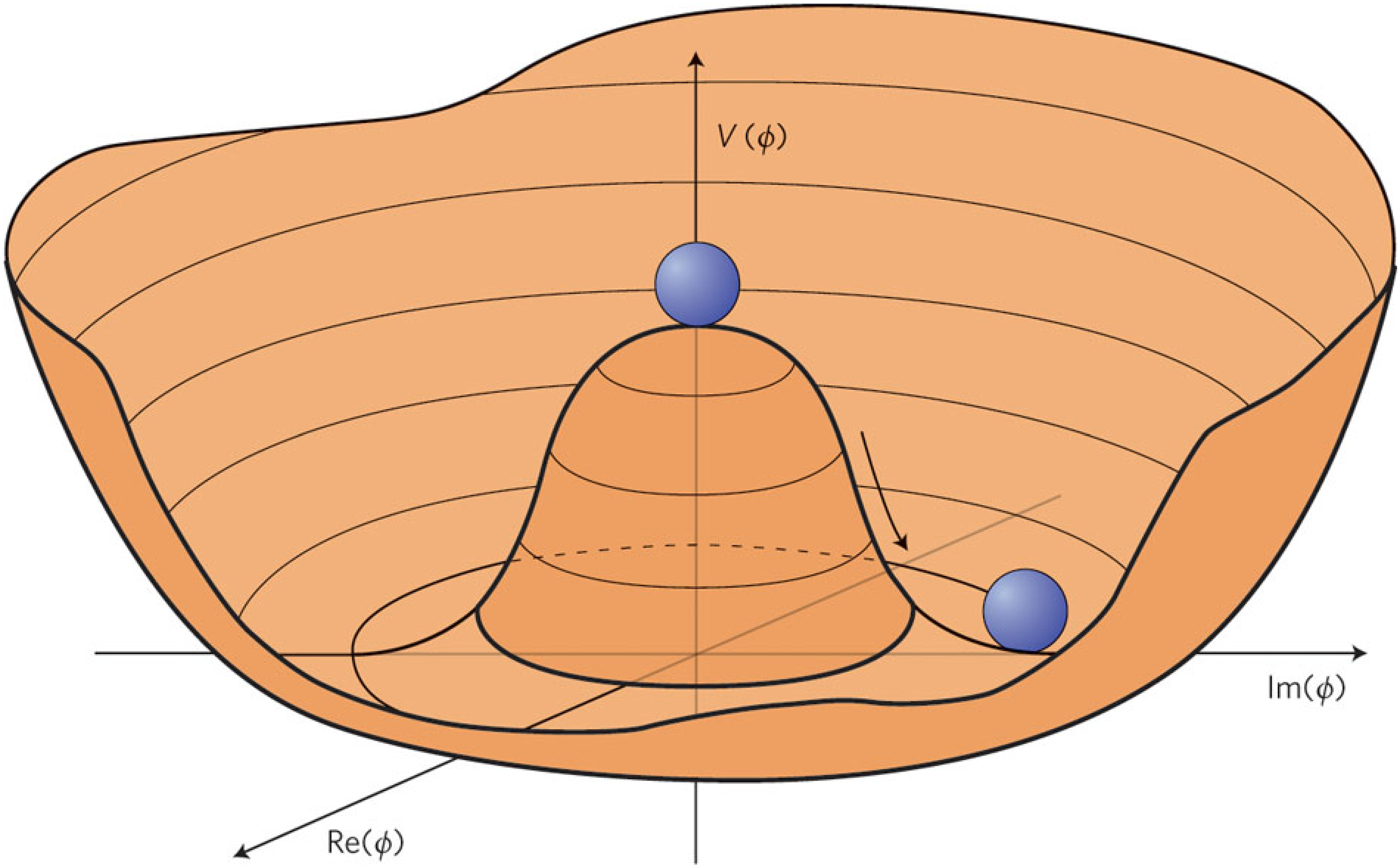
- Mass-energy equivalence

$$E = mc^2$$

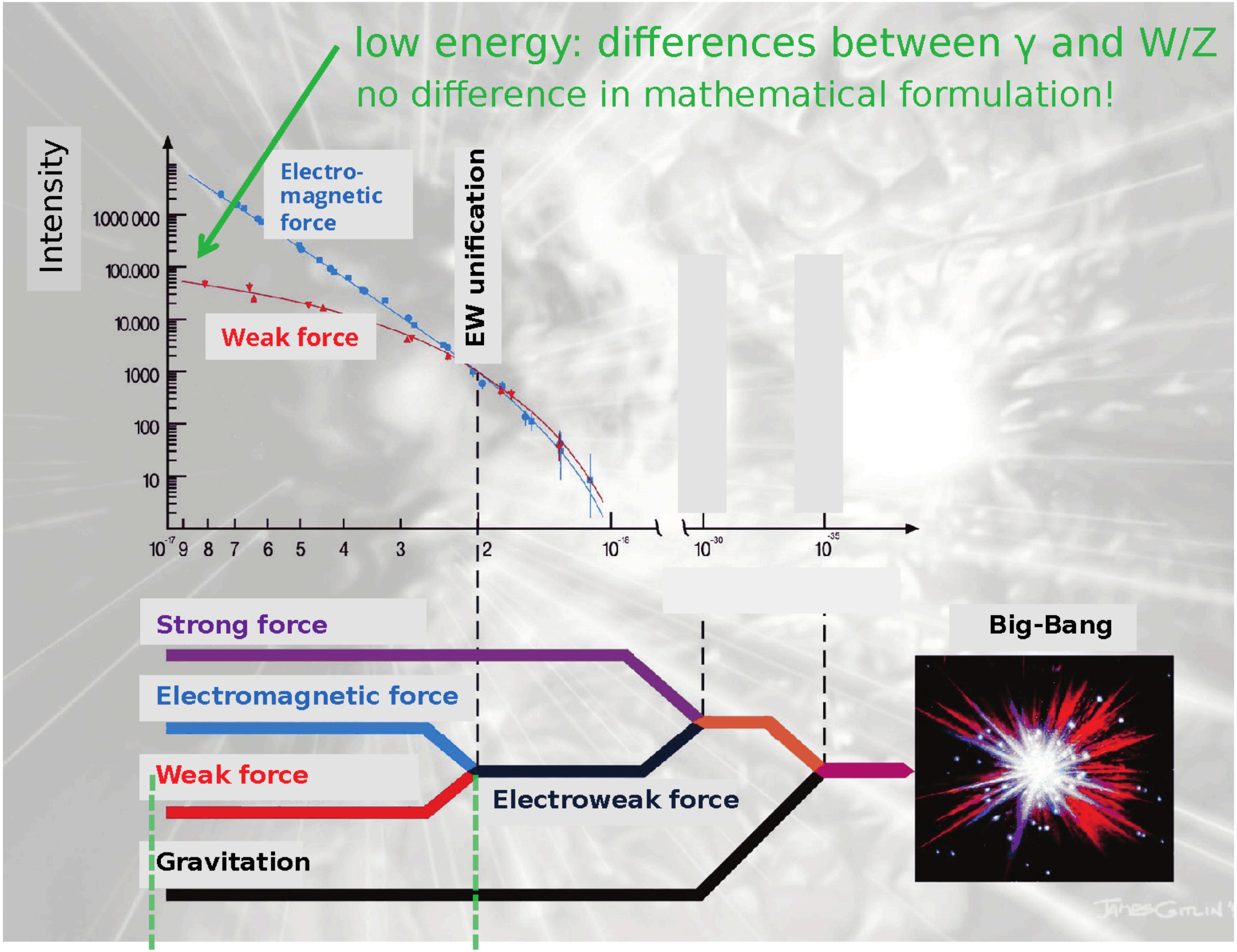
- Various interpretations of the same concept of mass
- From theory elementary particles are massless
  - The Universe as we know it does not exist...
  - Introduction of a mechanism to generate mass, without losing nice properties of model: spontaneous breaking of electroweak symmetry

Spontaneous breaking of electroweak symmetry

The Higgs potential: the “Mexican hat”



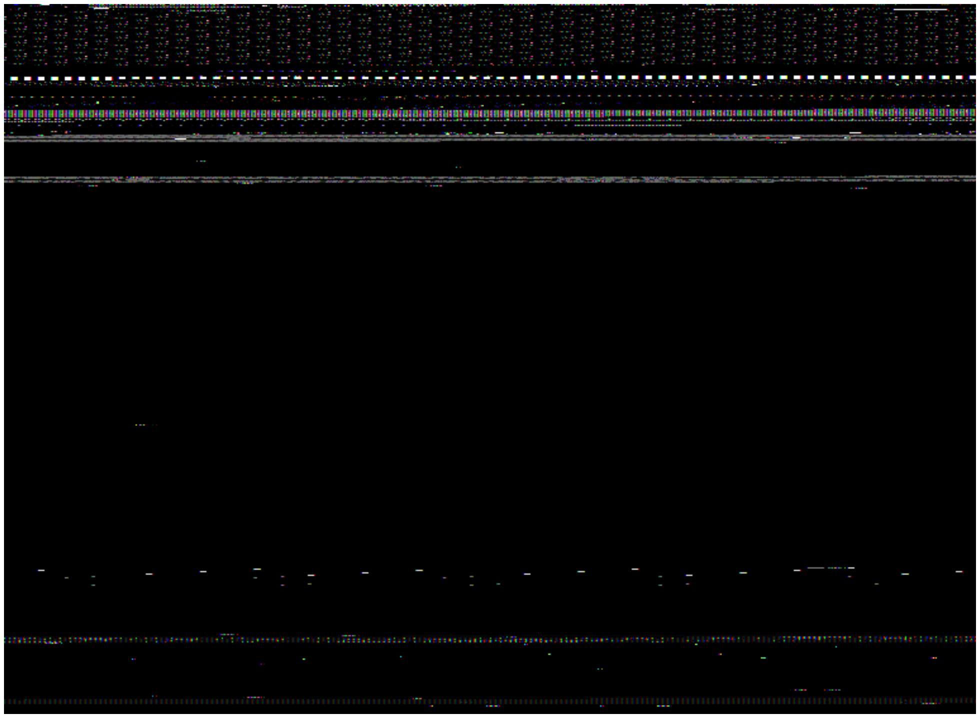
Electroweak unification

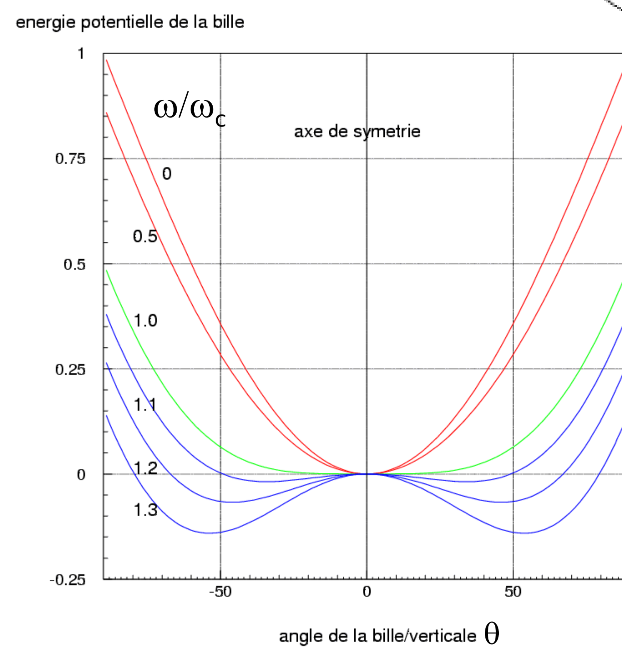


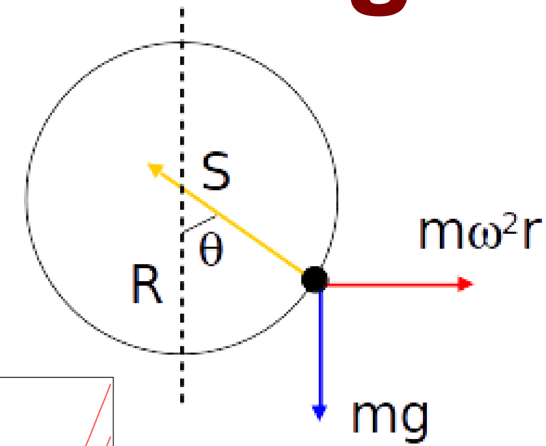
13.7 Gy (2.7 K) 10^{-12} s (10^{15} K)

© DESY

Spontaneous symmetry breaking



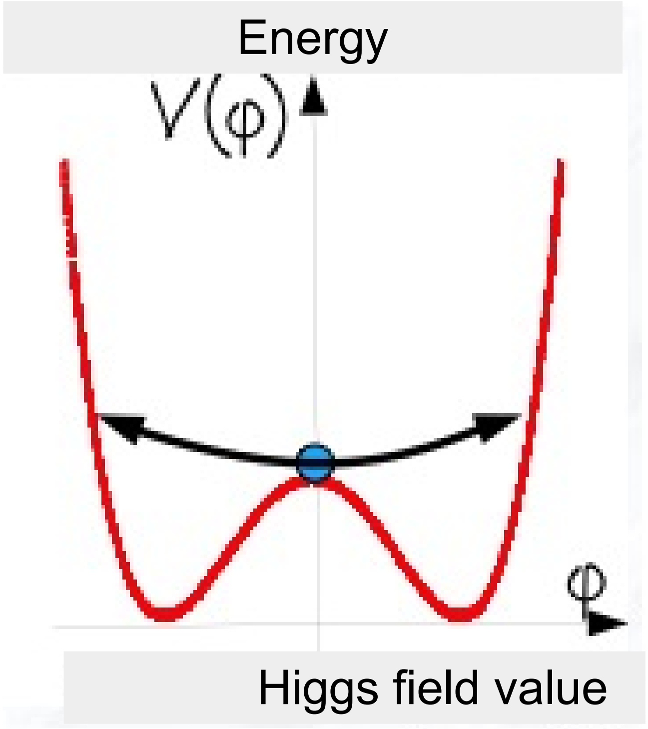




- Angular velocity ω $\Rightarrow$ critical velocity ω_c
  - if $\omega < \omega_c$: marble on symmetry axis
  - if $\omega > \omega_c$: 2 stable positions. The marble must "choose" one of them $\Rightarrow$ spontaneous symmetry breaking

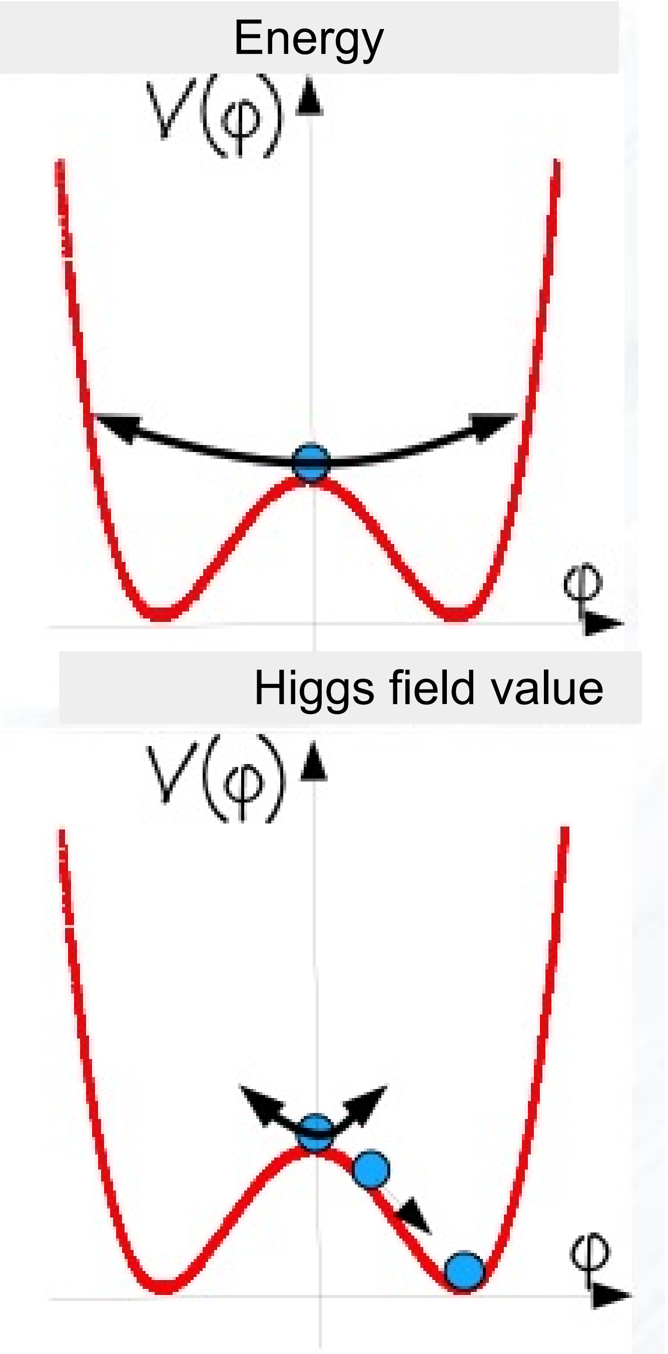
Electroweak symmetry breaking

- At high temperature, just after the Big Bang:
  - Higgs field is null in fundamental state
  - particles are massless

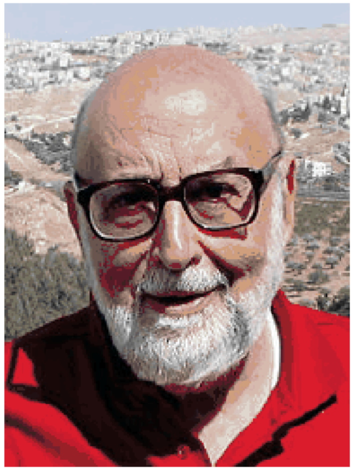


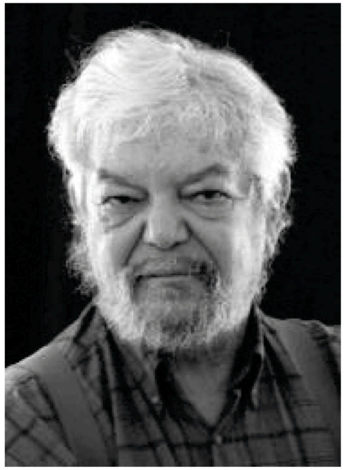
Electroweak symmetry breaking

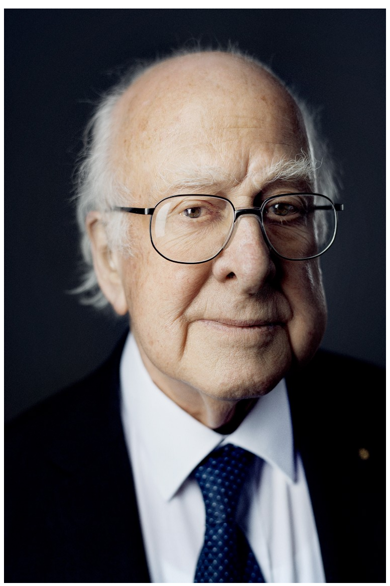
- At high temperature, just after the Big Bang:
  - Higgs field is null in fundamental state
  - particles are massless
- Temperature decreases (10^{-12} s after the Big Bang):
  - symmetry breaking
  - non-zero field
  - elementary particles acquire mass by **interacting with the Higgs field**



1964: The Higgs mechanism







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)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.[4-6] A those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

In the last paragraph we sketch a simple argument which renders these results reason-

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)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenome-

about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}=0, \qquad (2a)$$

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

$$\partial_\nu F^{\mu\nu}=e\varphi_0\{\partial^\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}. \qquad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

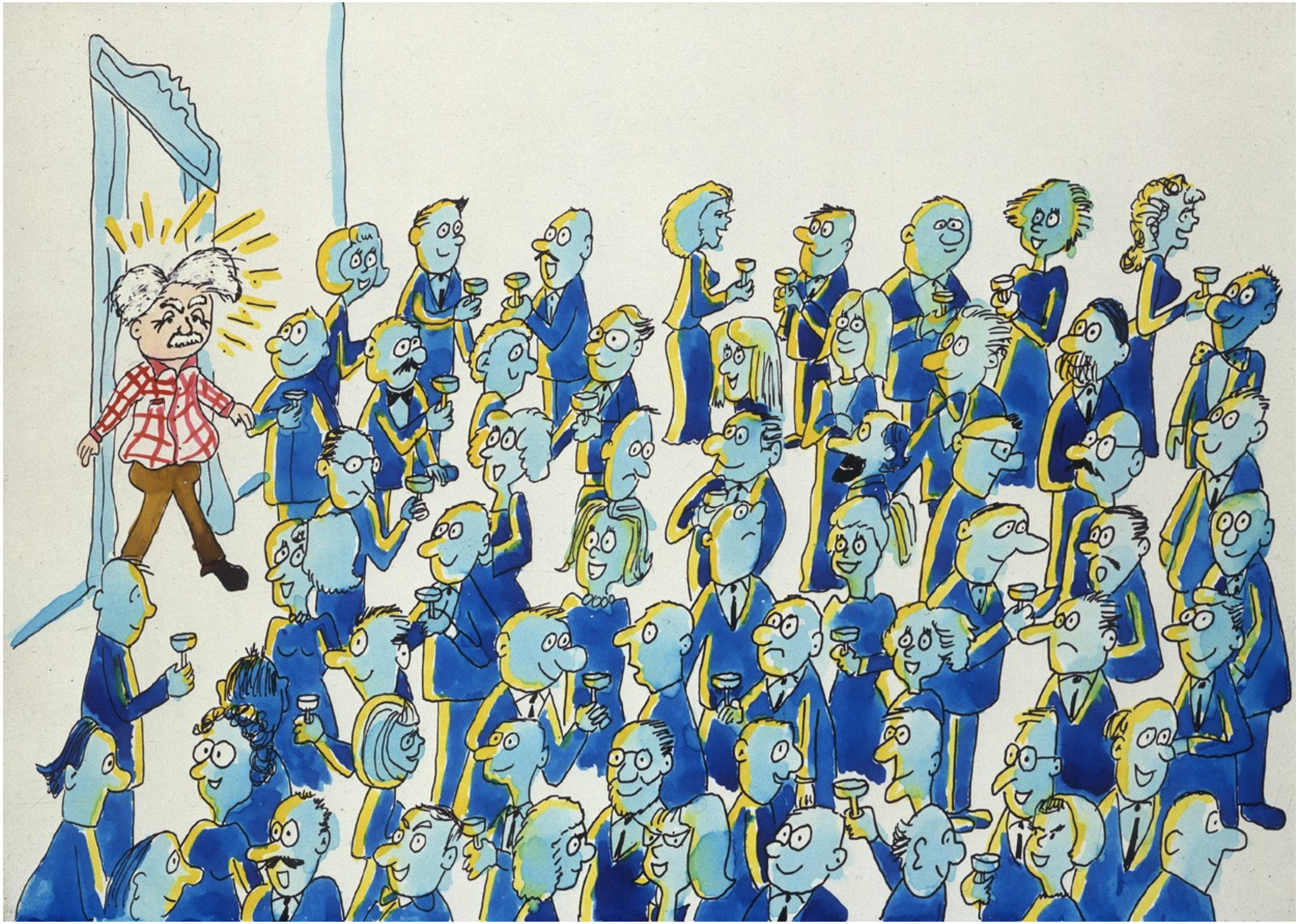
$$B_\mu=A_\mu-(e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

- Englert, Brout, Higgs, Guralnik, Hagen, Kibble publish within a few months
- Prediction: existence of the Higgs field, which would manifest itself with a new particle, the **Higgs boson**

Higgs mechanism in pictures

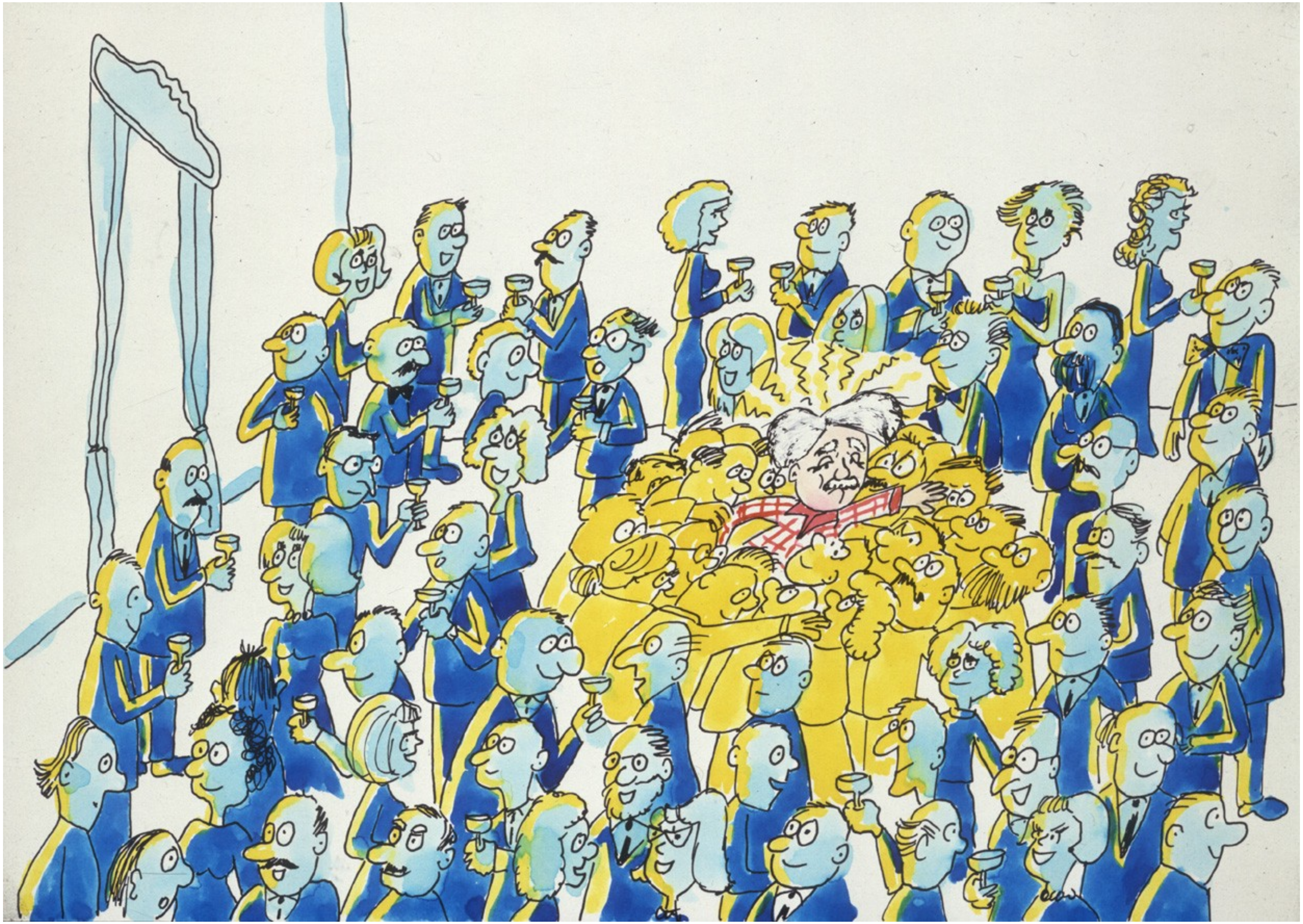
Imagine that a room full of physicists quietly chattering is like space filled only with the Higgs field...

Higgs mechanism in pictures



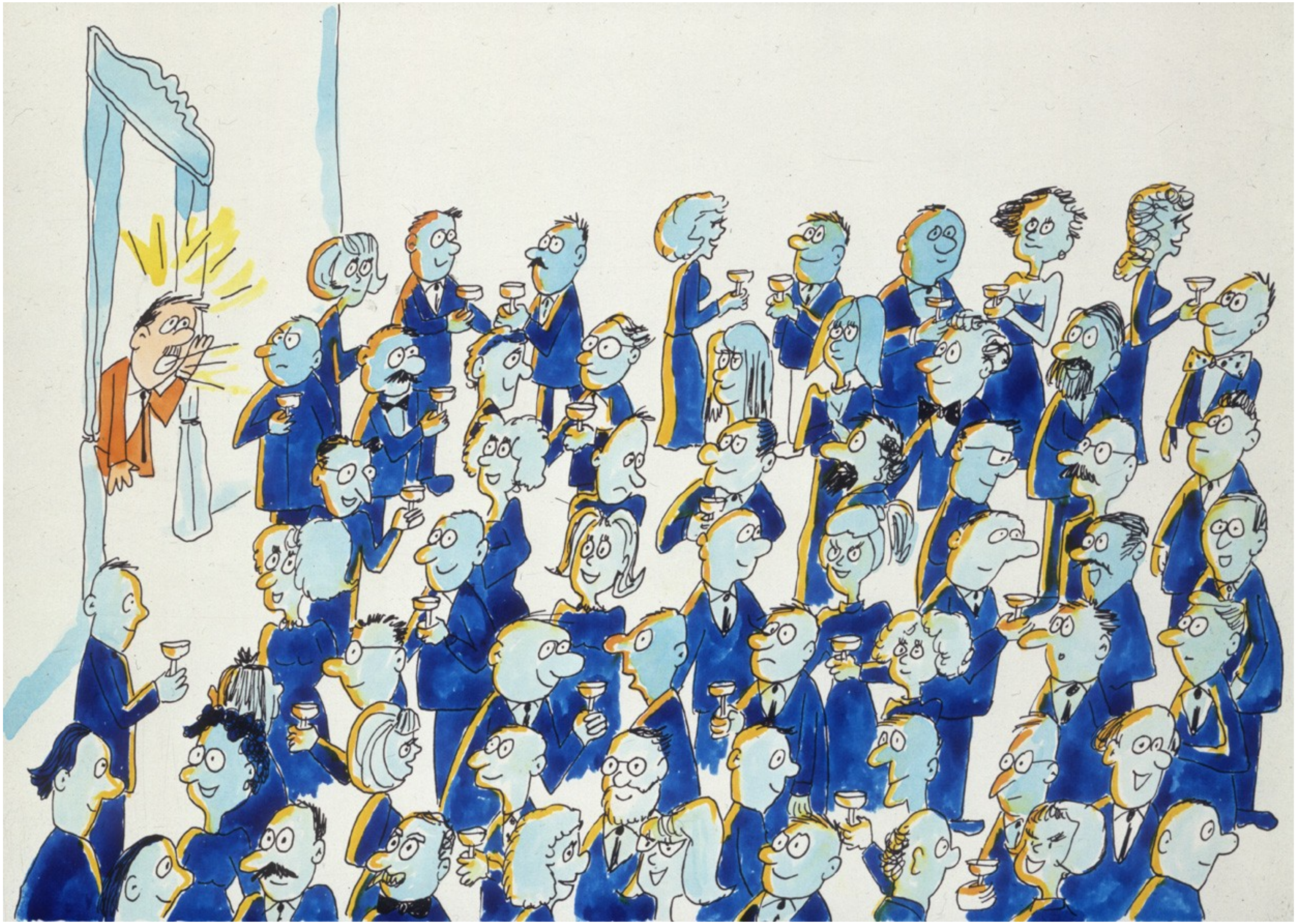
... a well known scientist walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step ...

Higgs mechanism in pictures



... this increase his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field ...

Higgs mechanism in pictures

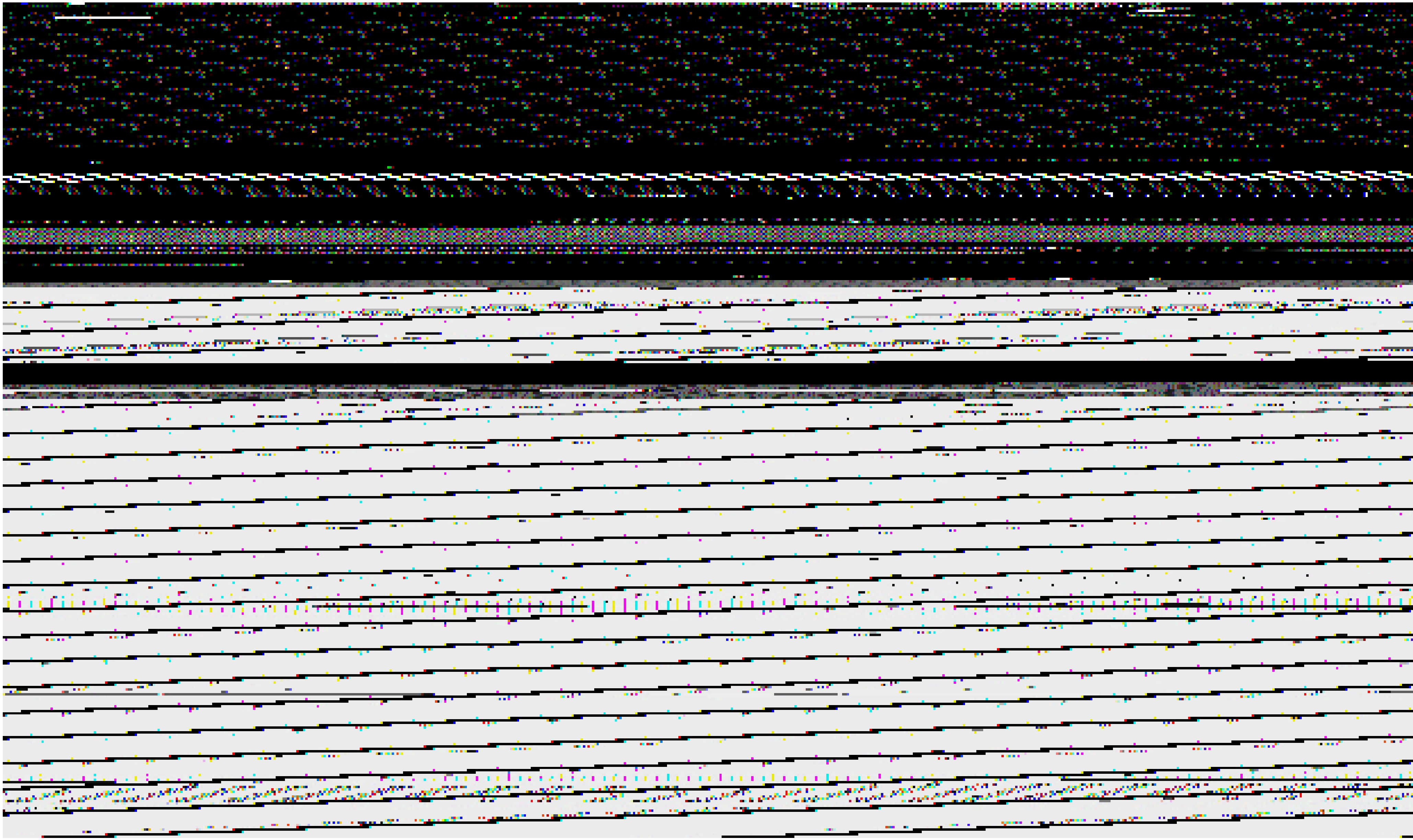


... if a rumour crosses the room ...

Higgs mechanism in pictures

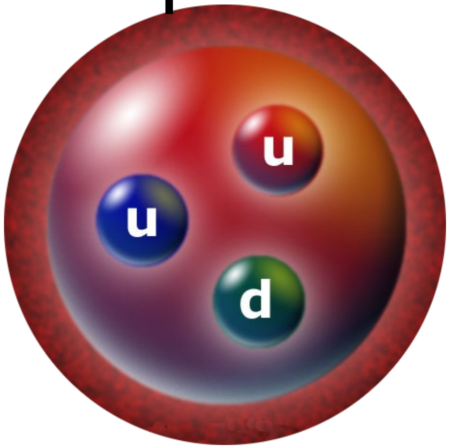
... it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.

Interactions with the Higgs boson



Mass

- Our mass: that of our atoms
- Mass of atoms: almost exclusively that of nucleus, made of protons and neutrons of mass ~1 GeV



- Proton, neutron: 3 quarks, mass ~10 MeV

Mass

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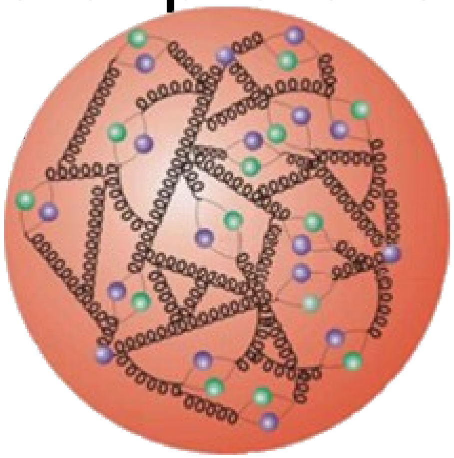
- Mass of atoms: almost exclusively that of nucleus, made of protons and neutrons of mass ~1 GeV



- In reality, lots of gluons, whose energy gives 99% of their mass to protons and neutrons ($E=mc^2$)

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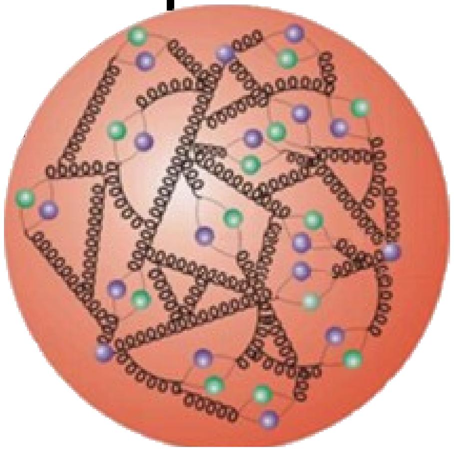

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- Higgs boson: explains "only" mass of elementary particles (quarks, electron [leptons], Z and $W^{\pm}$ bosons) and its own

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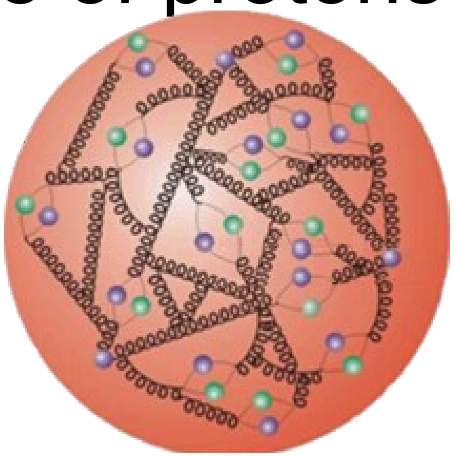
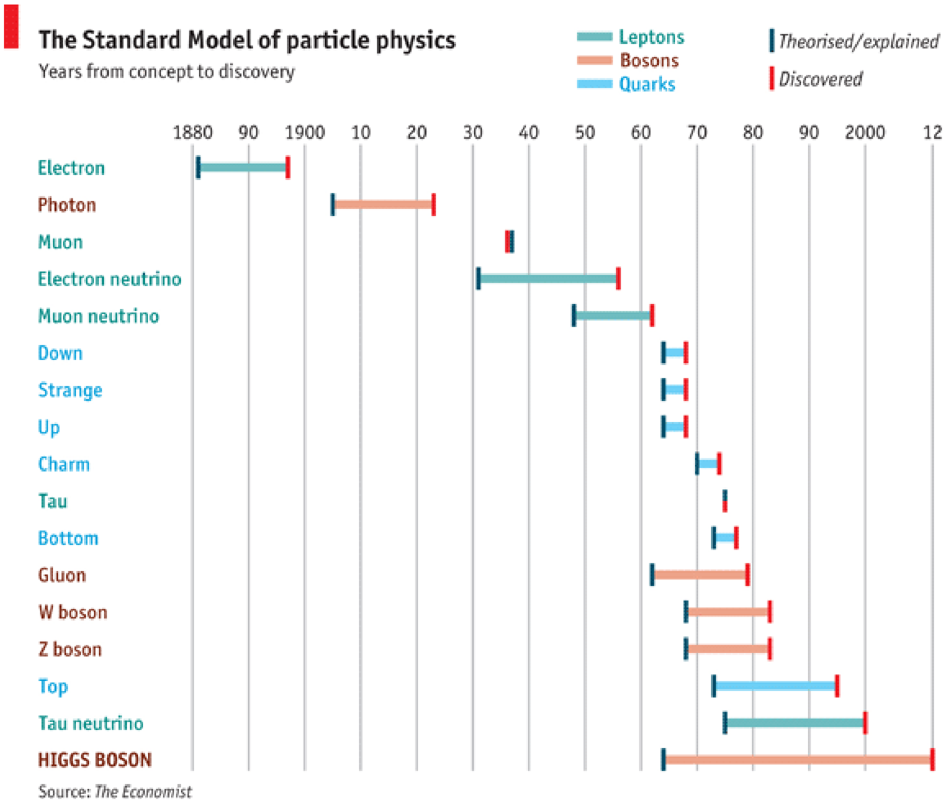


  - In reality, lots of gluons, whose energy gives 99% of their mass to protons and neutrons ($E=mc^2$)
- Higgs boson: explains "only" mass of elementary particles (quarks, electron [leptons], Z and $W^{\pm}$ bosons) and its own
- Not much? Without this, no atoms, no chemistry, no life or Universe as we know it...

Higgs boson discovery announcement on 4 July 2012

A long quest

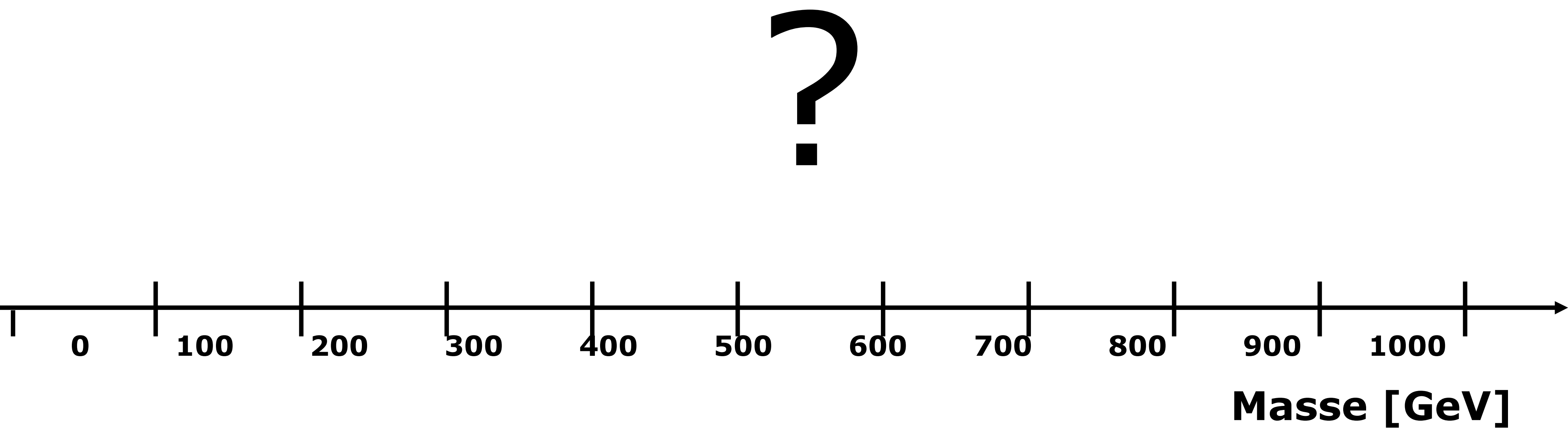


© The Economist

- Standard model: incredible success, except particles have no mass...
- Higgs boson: cornerstone of model to make theory and experiment agree
- 48 years between theoretical prediction and experimental discovery!

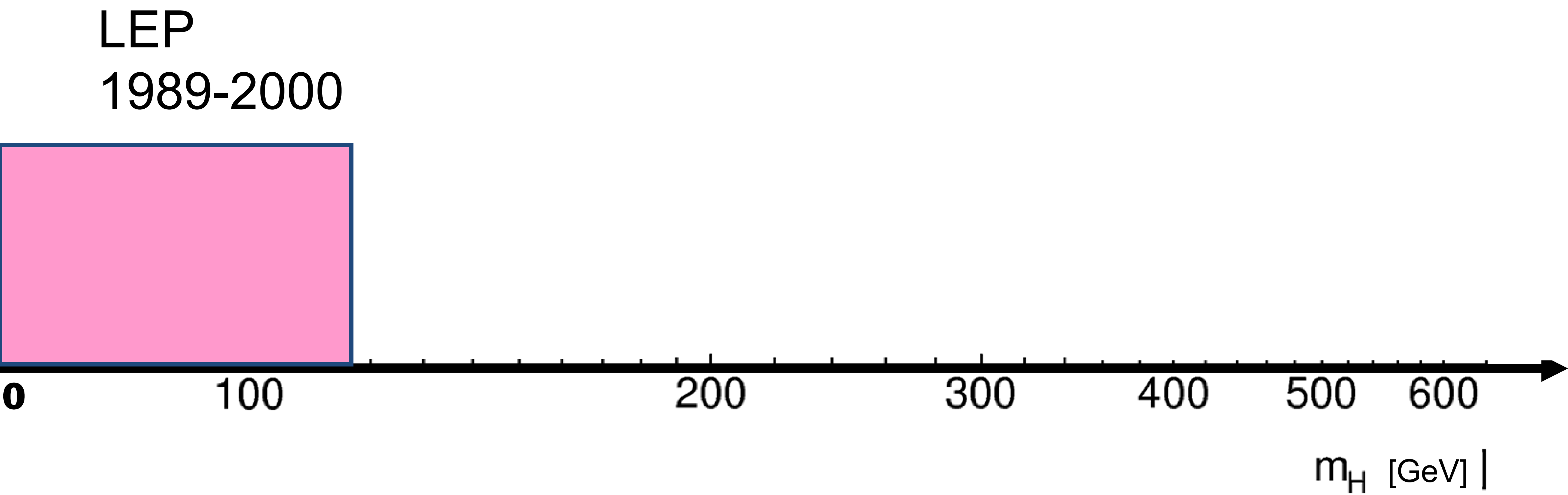
- Why? The theory predicts everything about the Higgs boson, except its mass! Had to look for it everywhere...

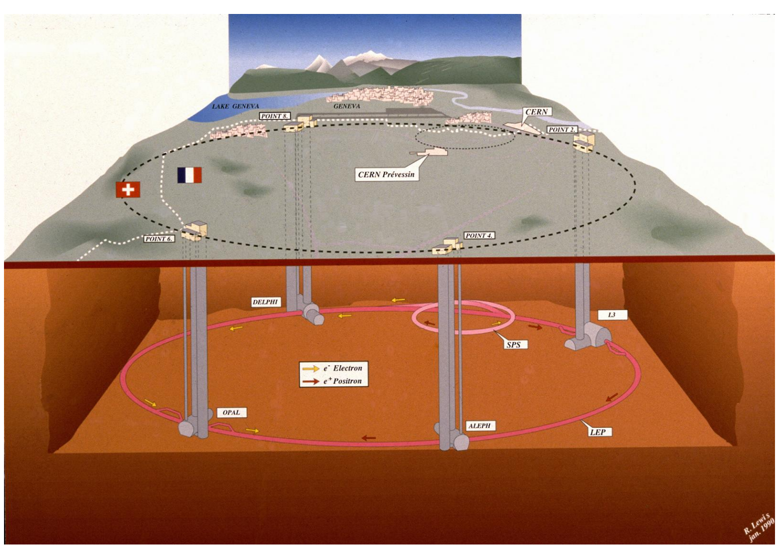
The Higgs boson hunt



- Only theoretical constraint: mass < 1000 GeV

The Higgs boson hunt





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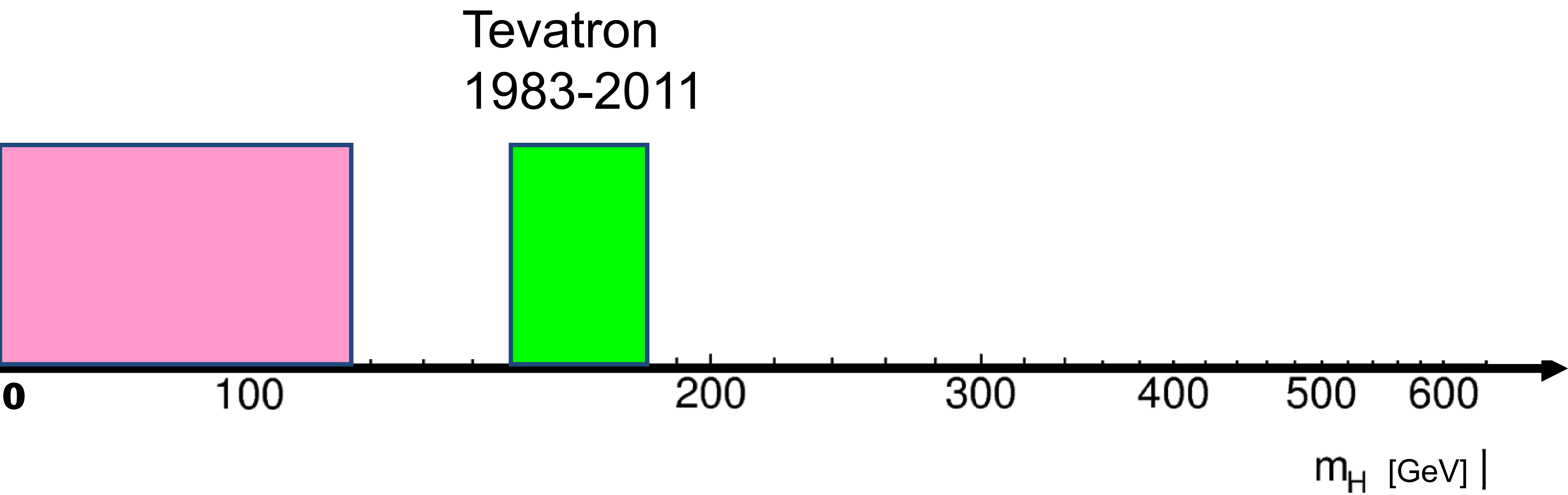
The Higgs boson hunt



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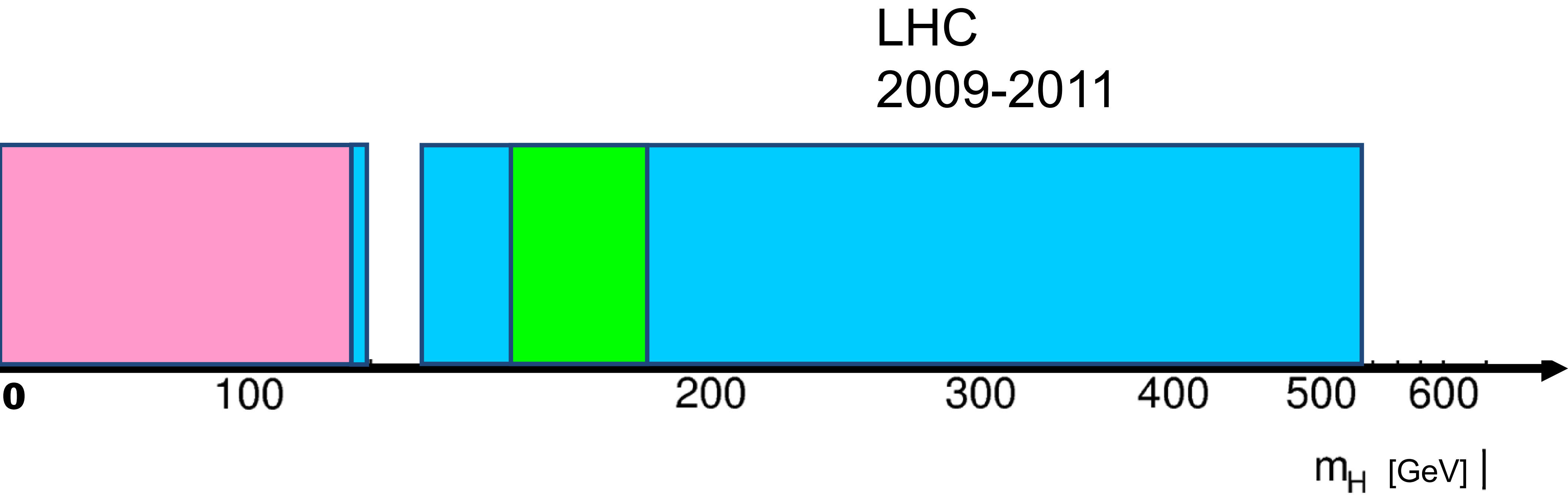
The Higgs boson hunt



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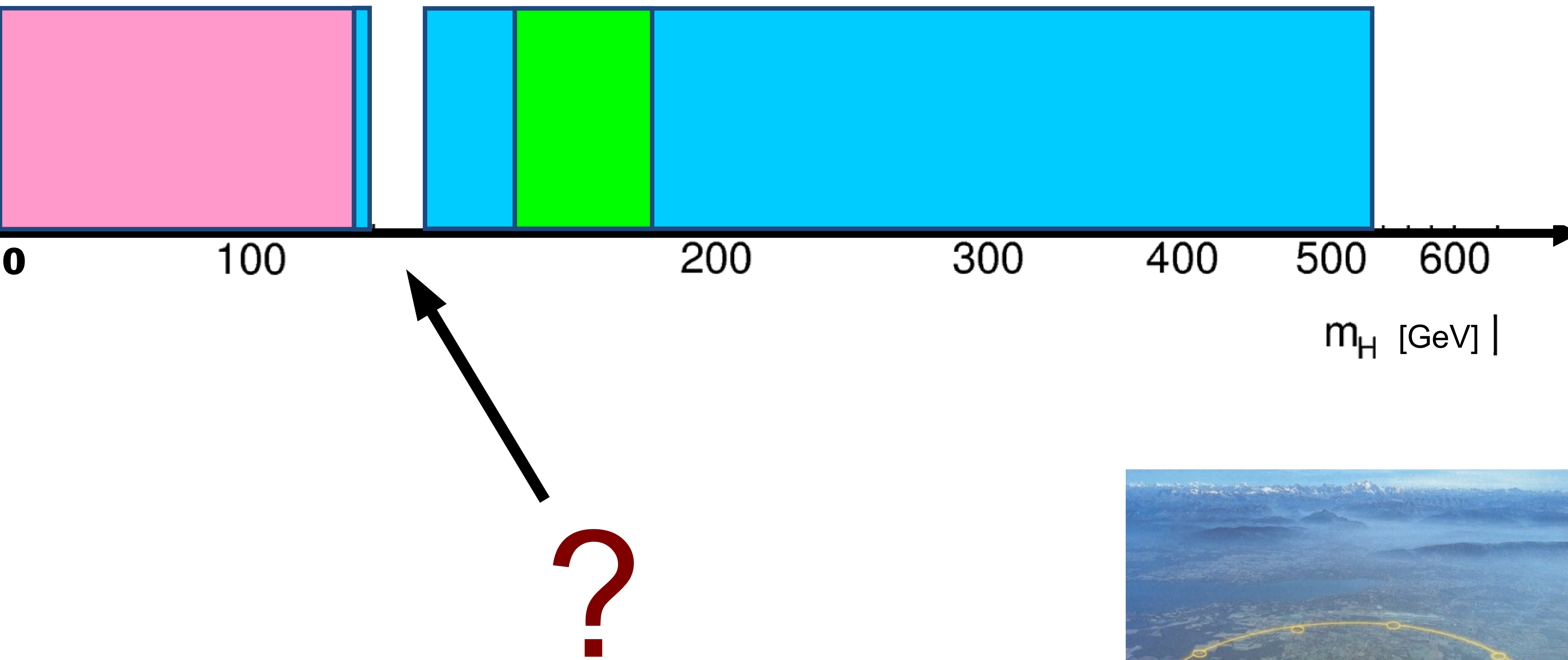
The Higgs boson hunt



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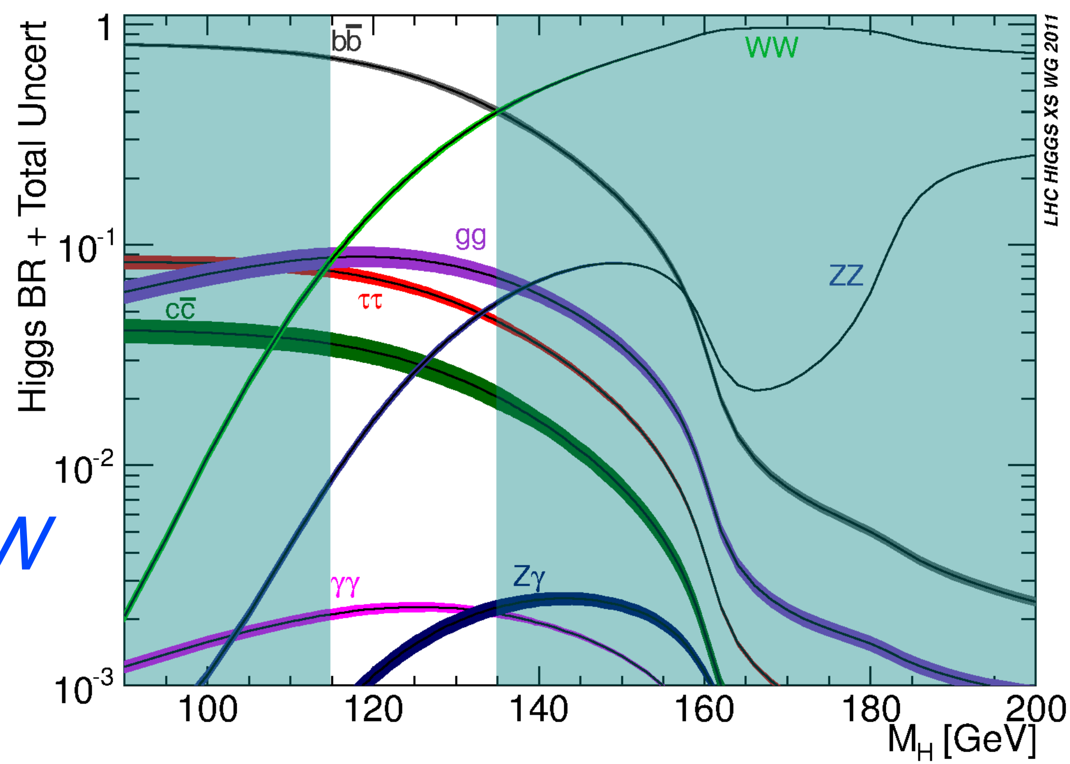
How do you go about it?

- Proton collision → ($E = mc^2$) → creation of a Higgs boson, once every 10 billion collisions
- Decays quickly, differently depending on its mass. Example at 125 GeV:
  - 58 times out of 100 in $b\bar{b}$
  - 21 times out of 100 in *WW*
  - 3 times out of 100 in *ZZ*
  - 2 times out of 1000 in γγ



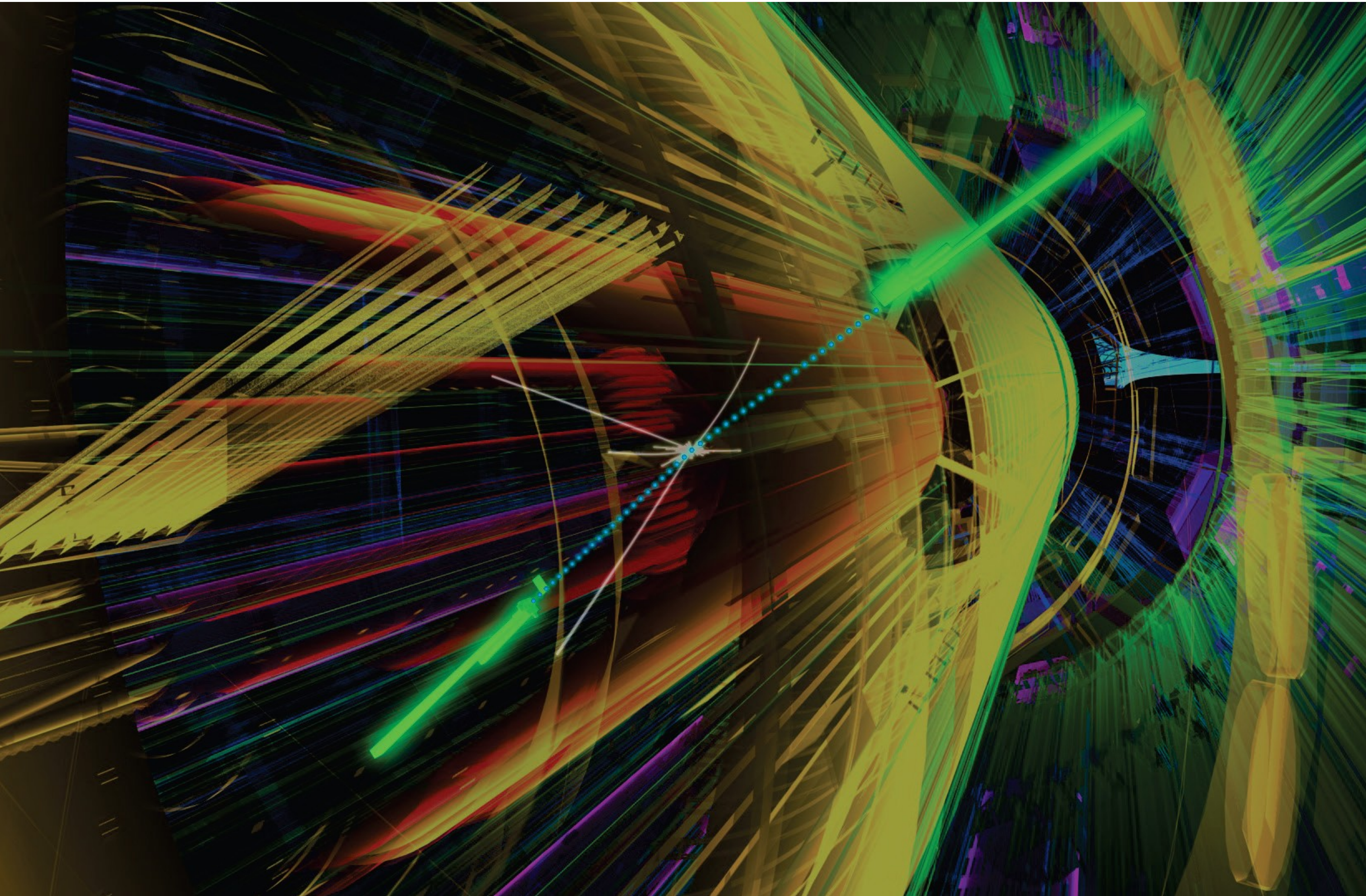
- Note: the most frequent decay mode does not have to be the easiest one to observe

See L. Vacavant

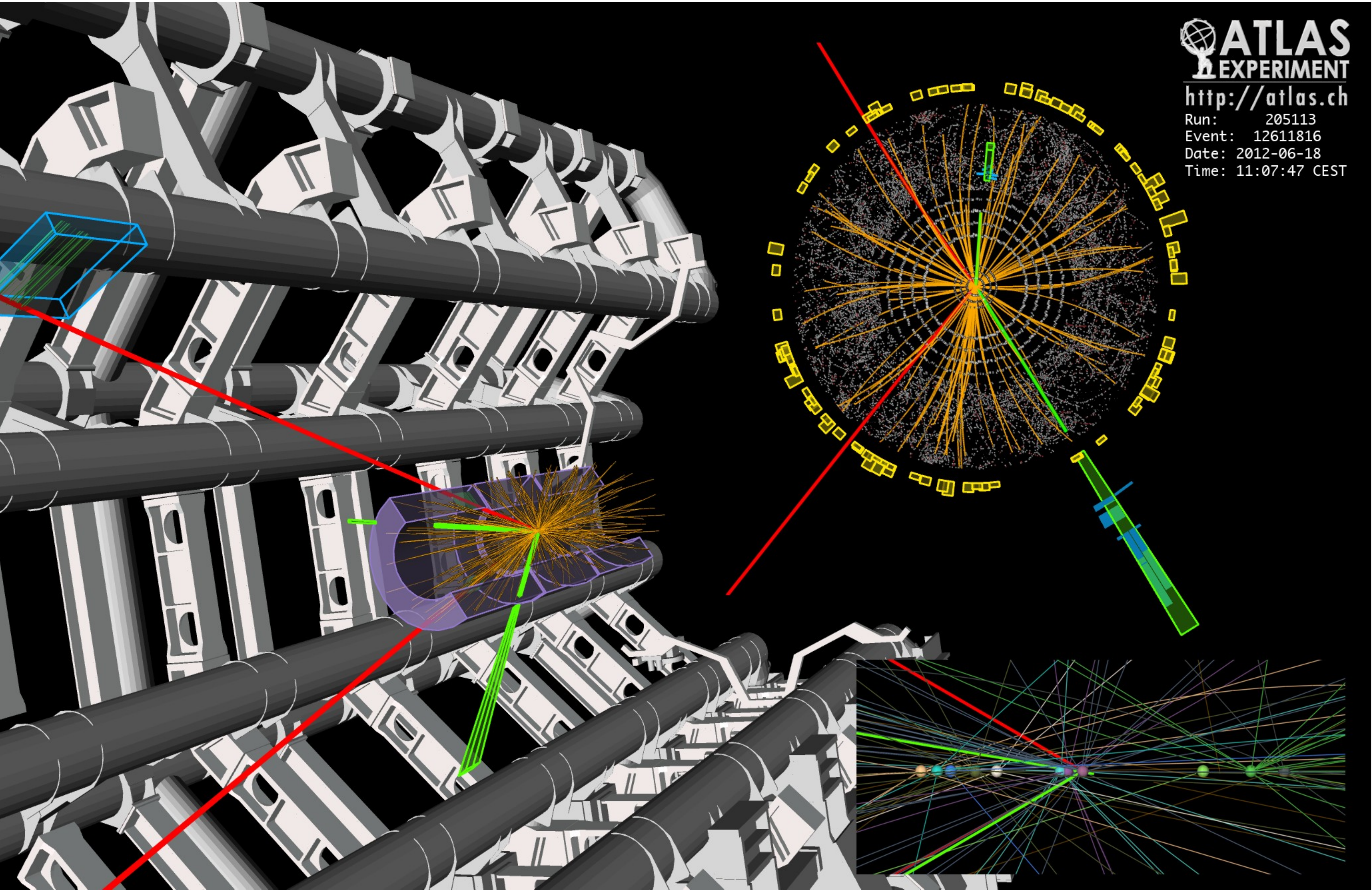
Even more difficult than a needle in a haystack

- The Higgs boson is not produced very often, one needs to analyse many, many collisions
- The trace of its decay in the detector maybe be mimicked by other processes, difficult to distinguish from what one is looking for
- A needle in a needle stack

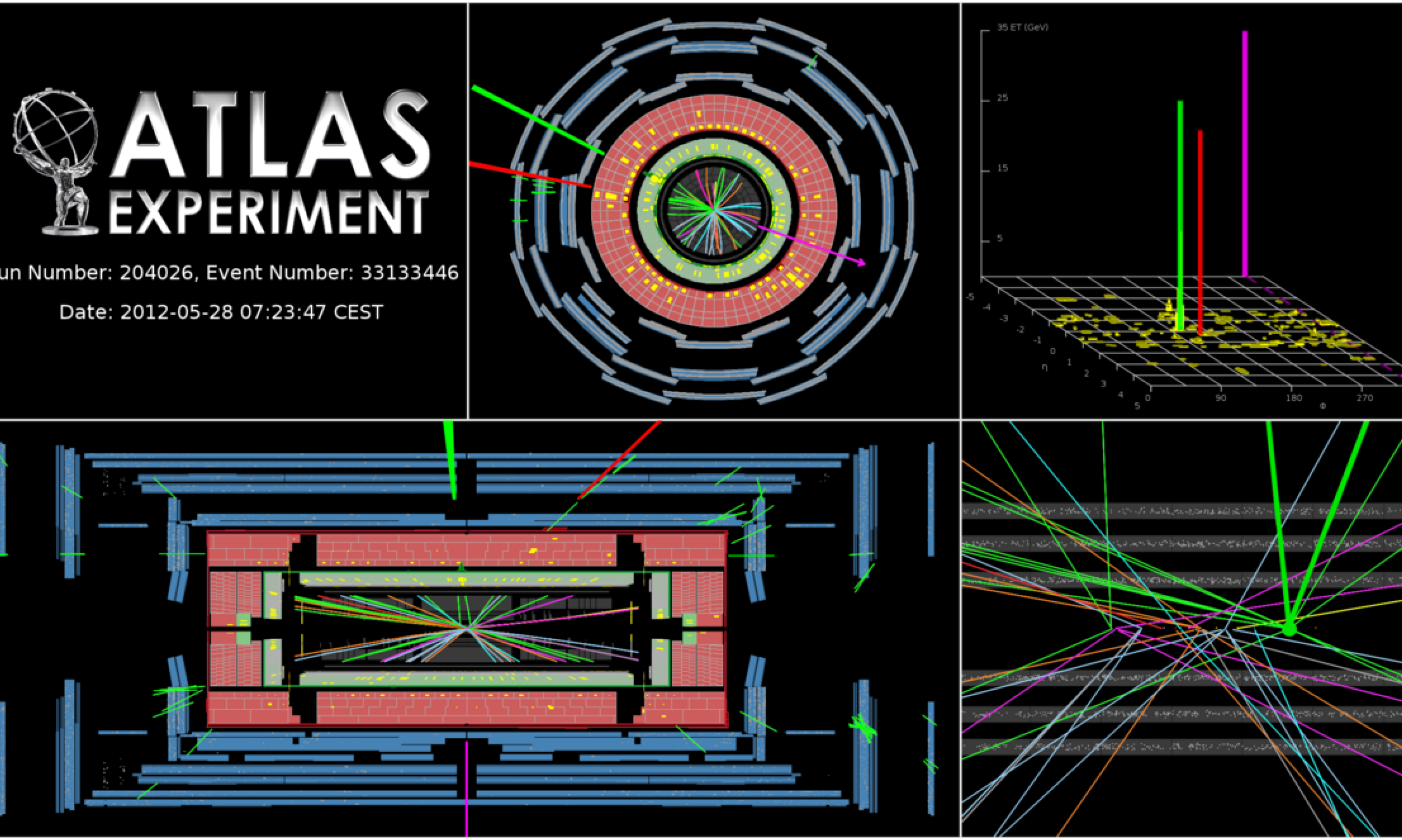
H→γγ candidate



$H \to ZZ^* \to ee\mu\mu$ candidate

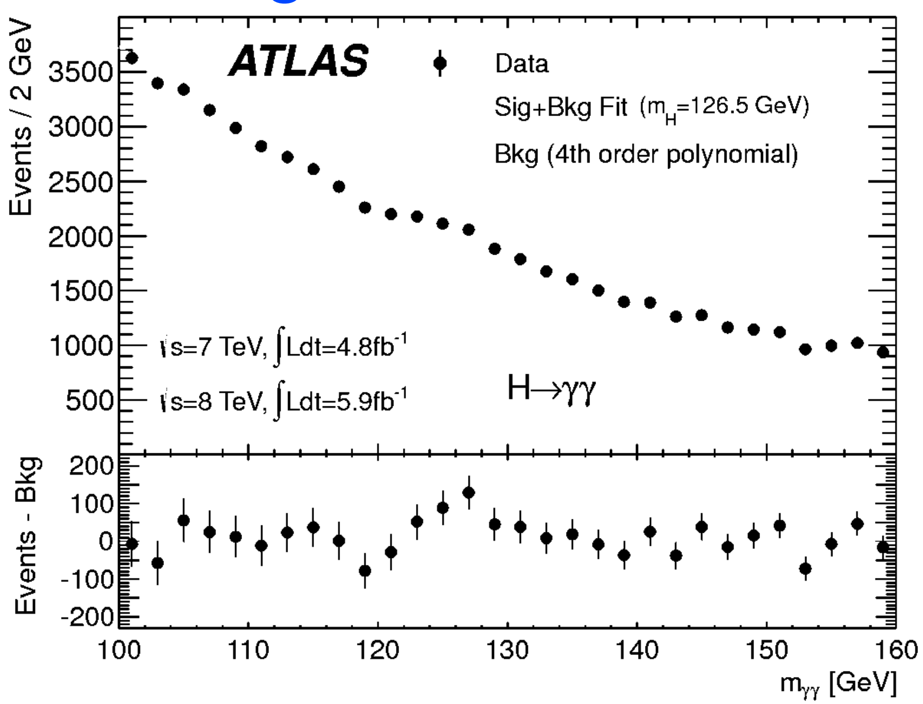


$H \rightarrow WW \rightarrow e\nu\mu\nu$ candidate



Measurement

- Higgs to 2 photons
  - Large background
  - Small peak with “a lot” of signal



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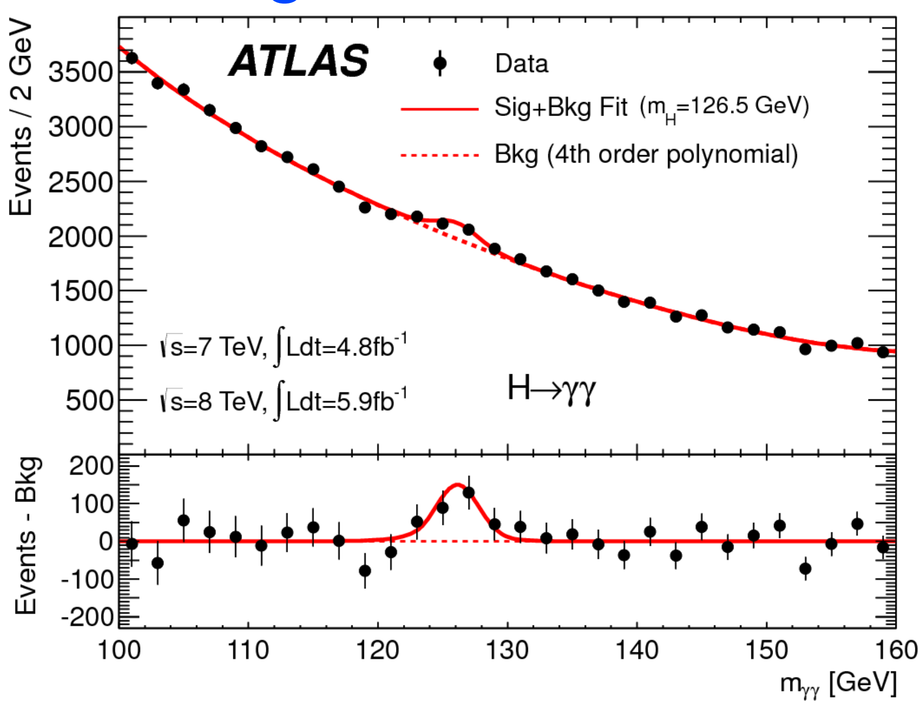

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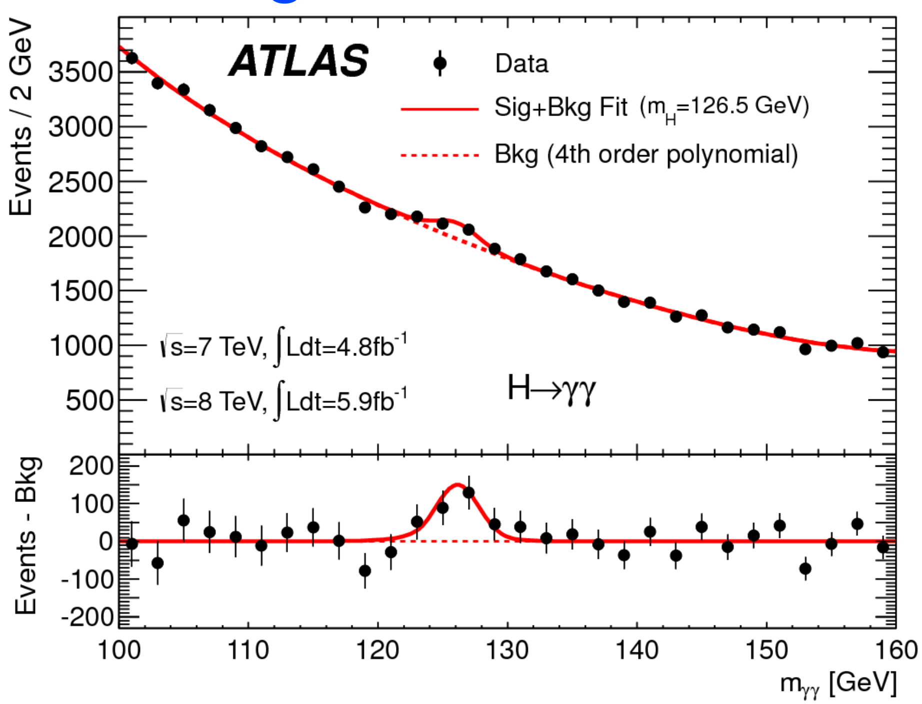
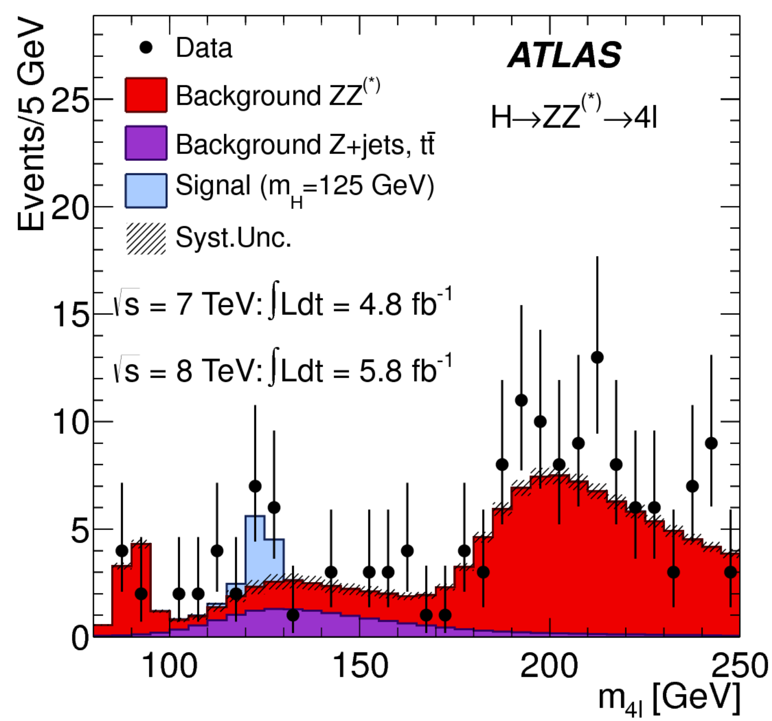


- Higgs to ZZ
  - Very little background
  - Very few events



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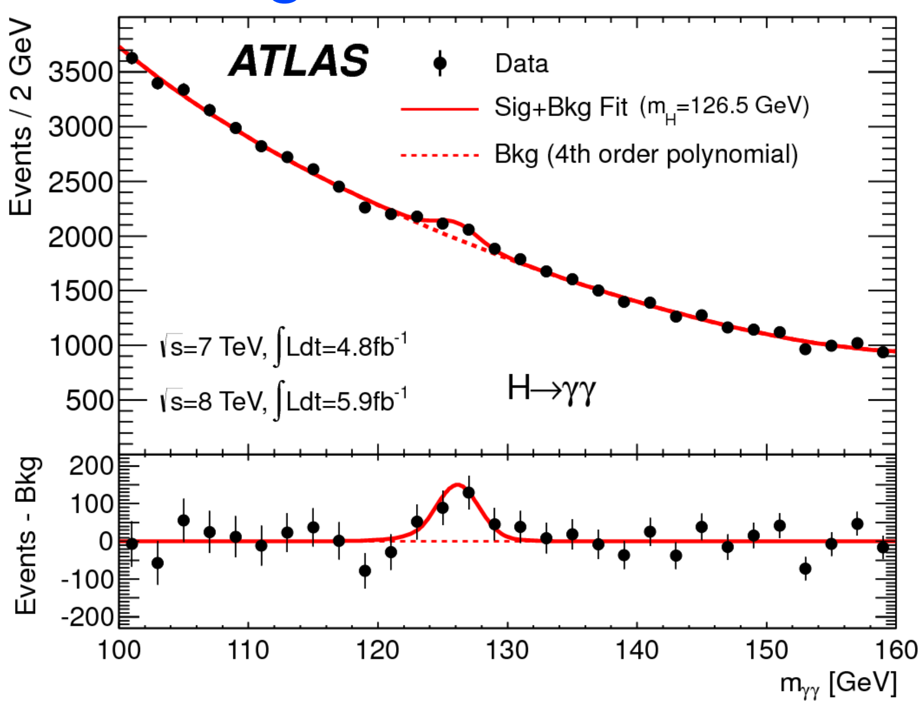

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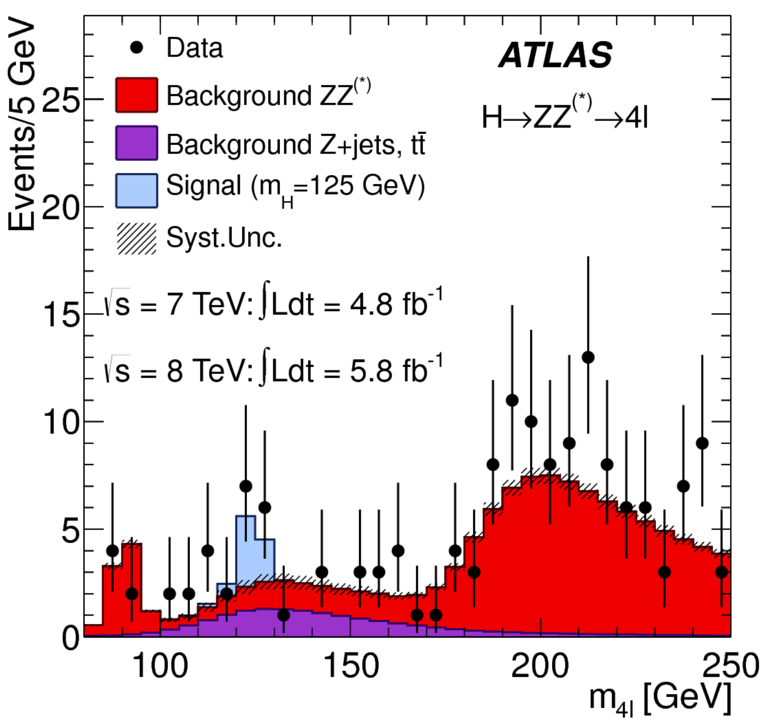
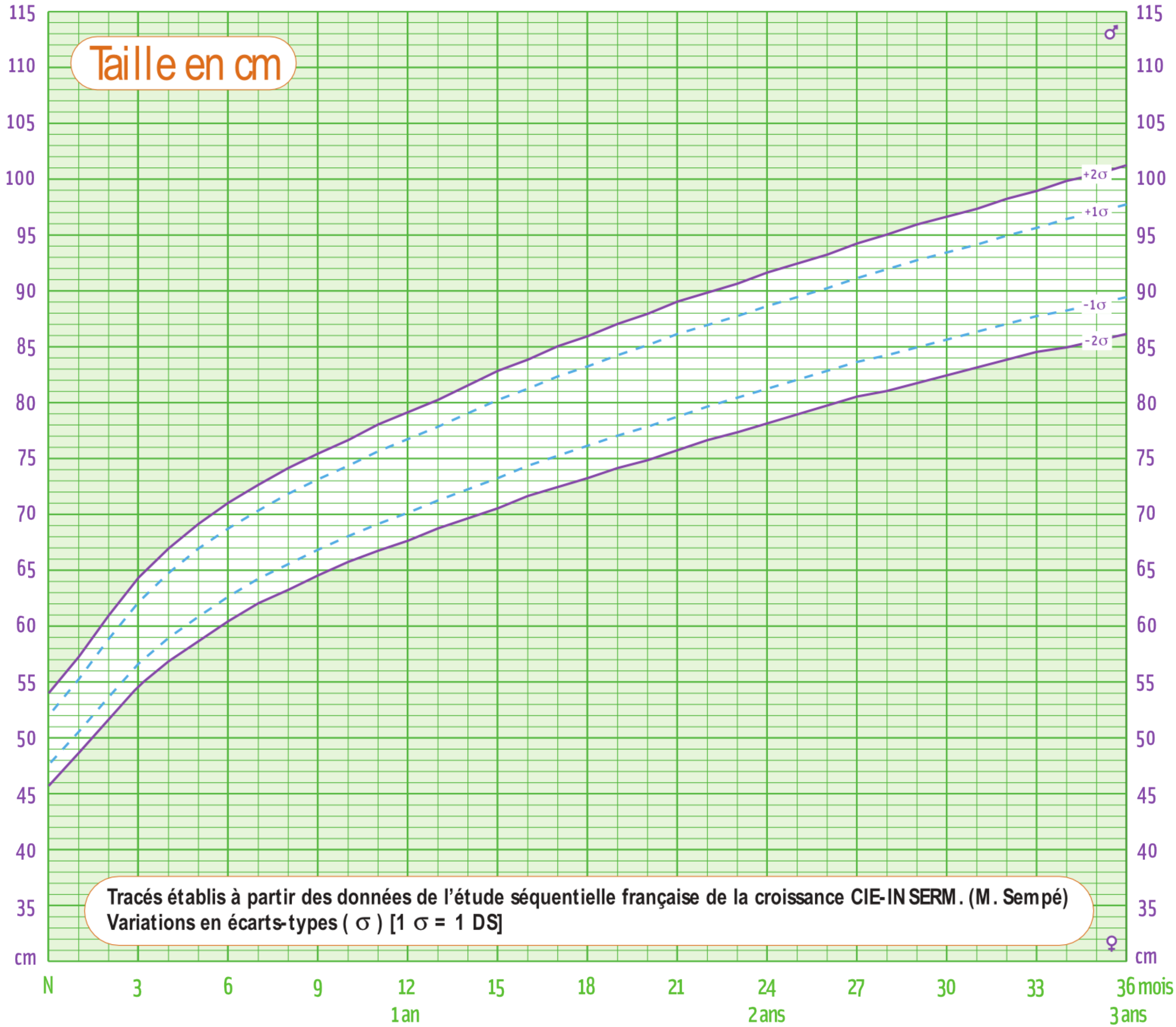
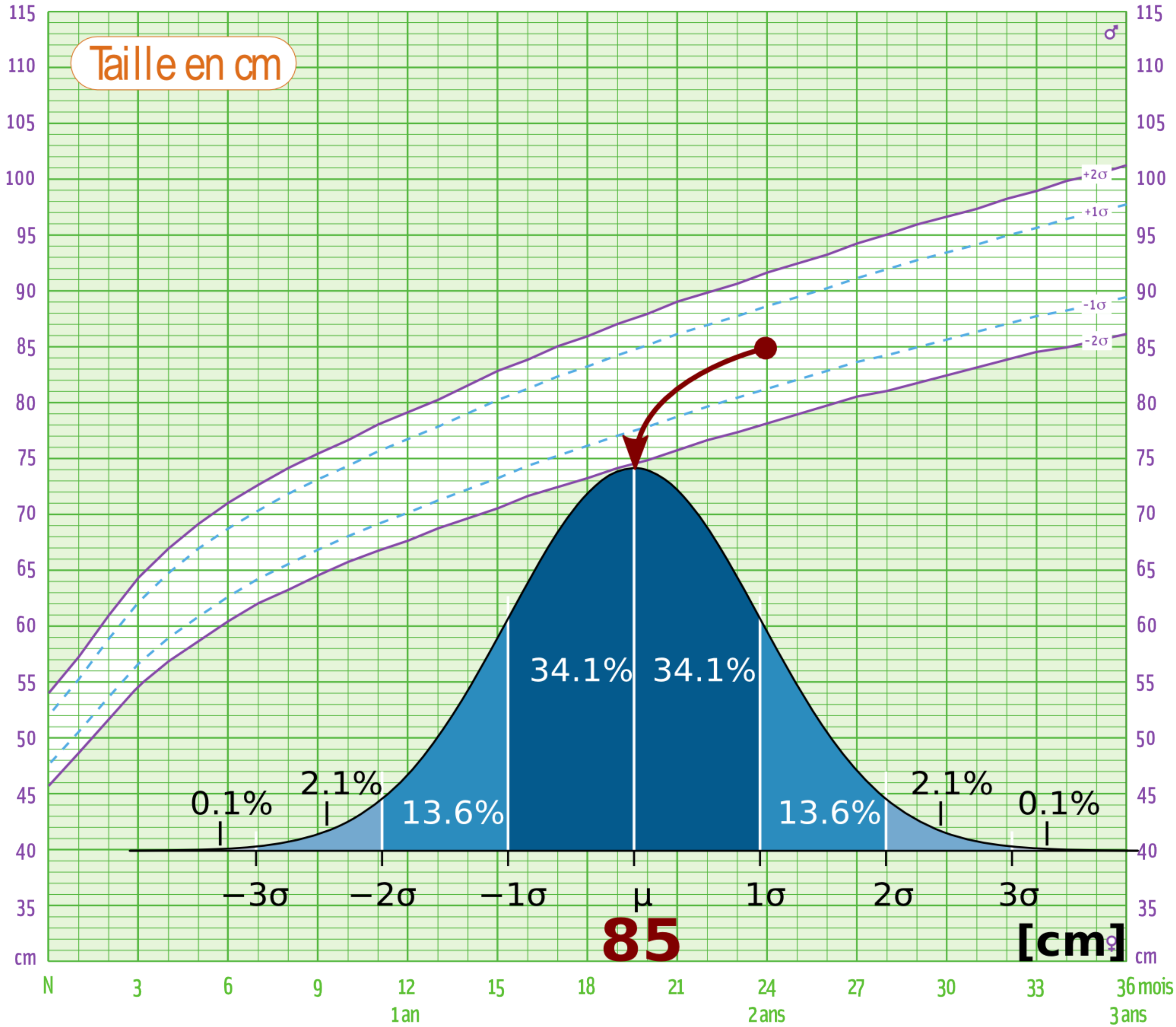


Is it significant?
Statistical tools to answer

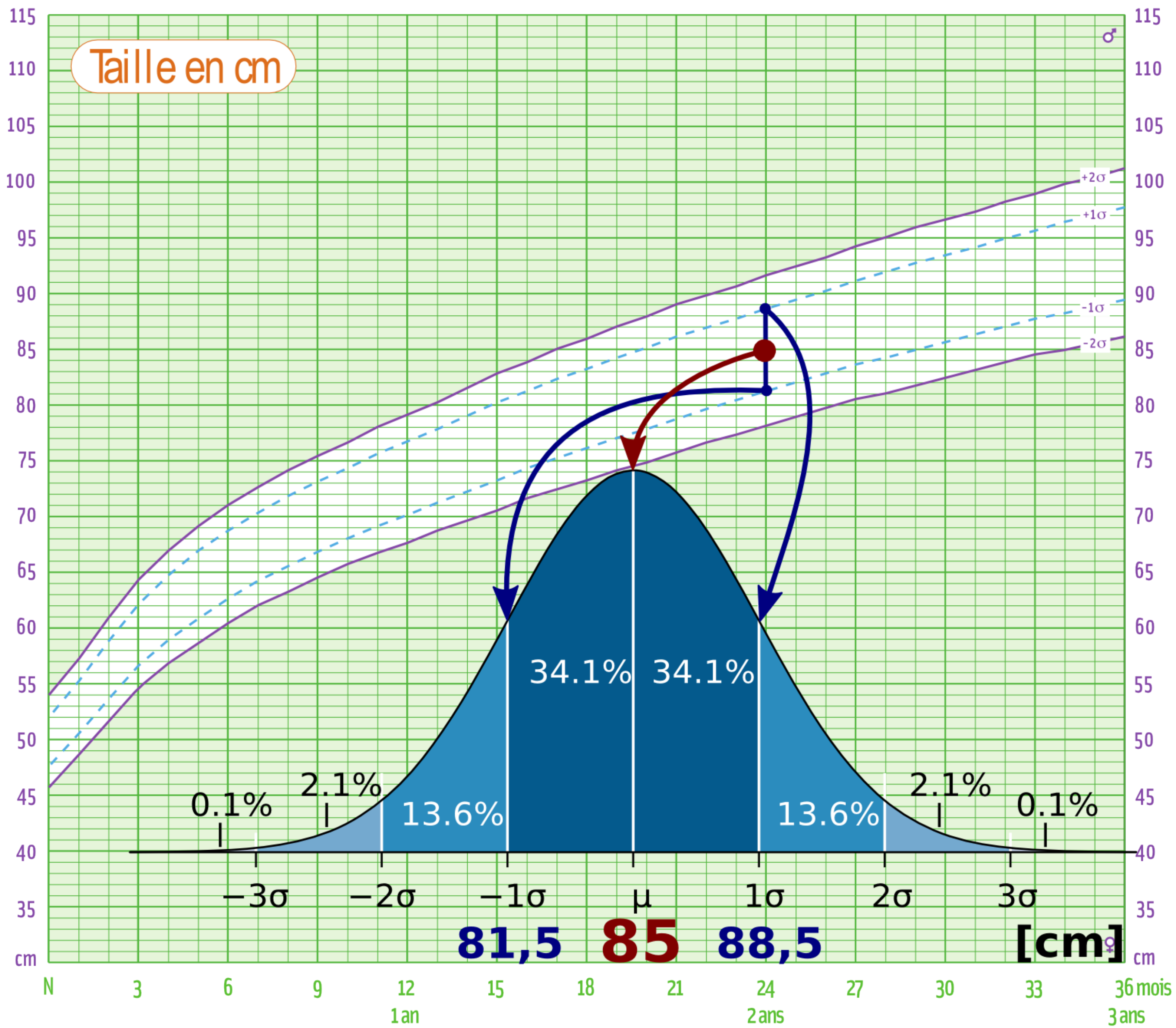
The Gaussian



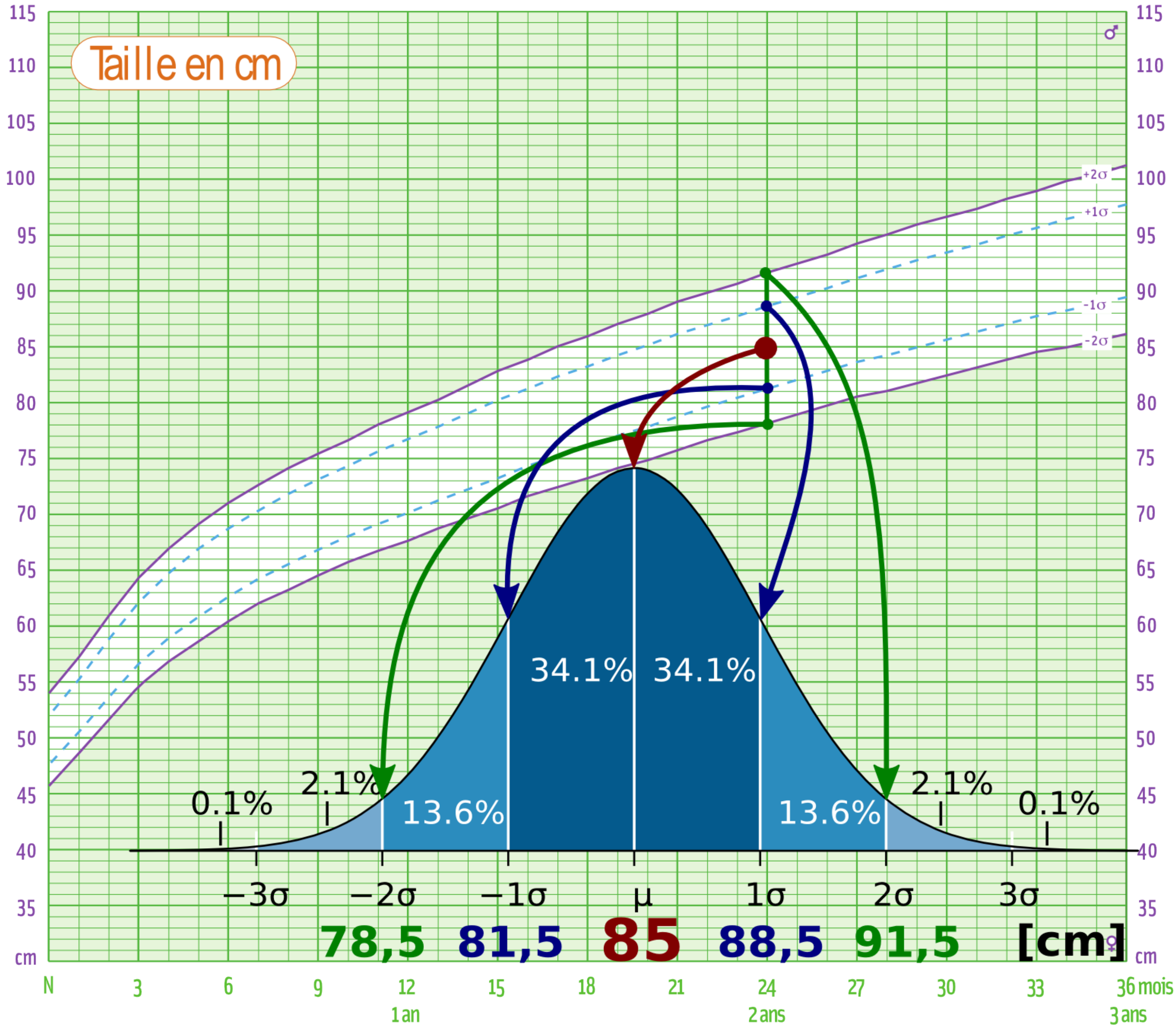
The Gaussian



The Gaussian

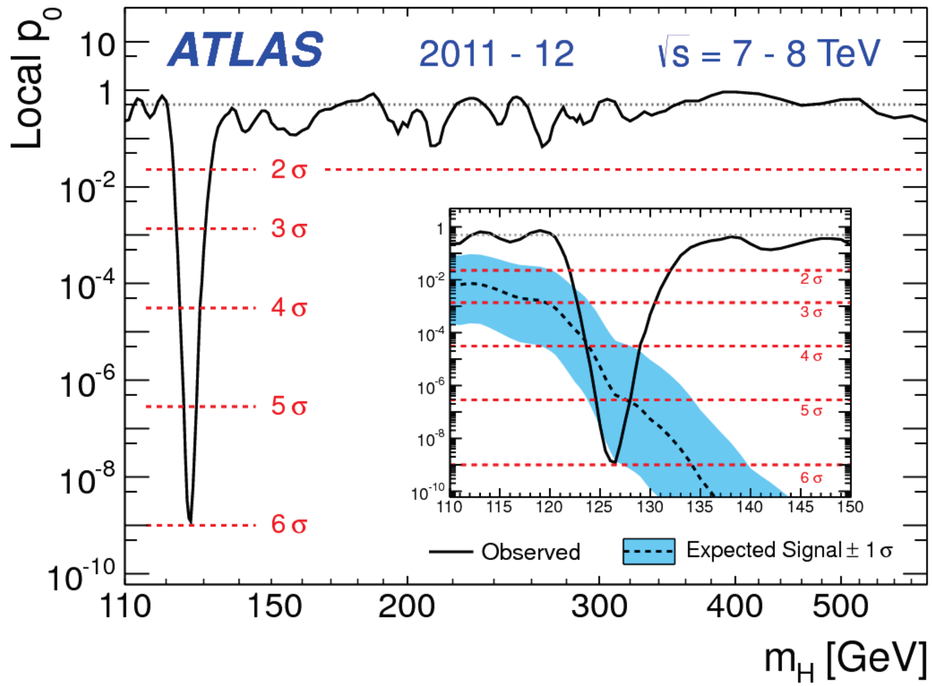


The Gaussian

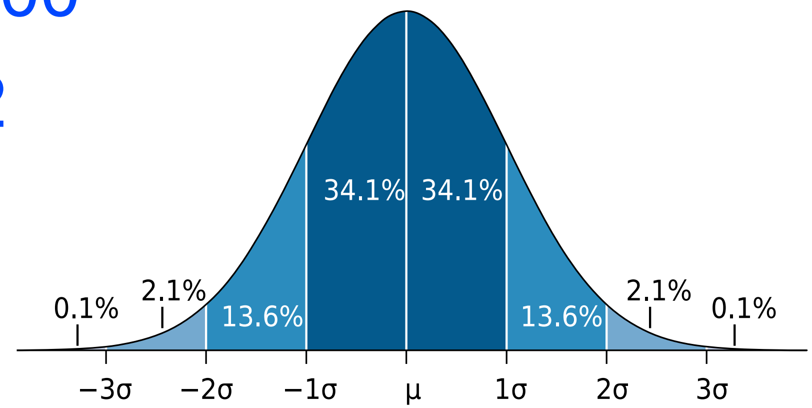


Higgs result: is it statistically significant?

- p-value p_0: probability that background events produce something that is as signal-like by chance

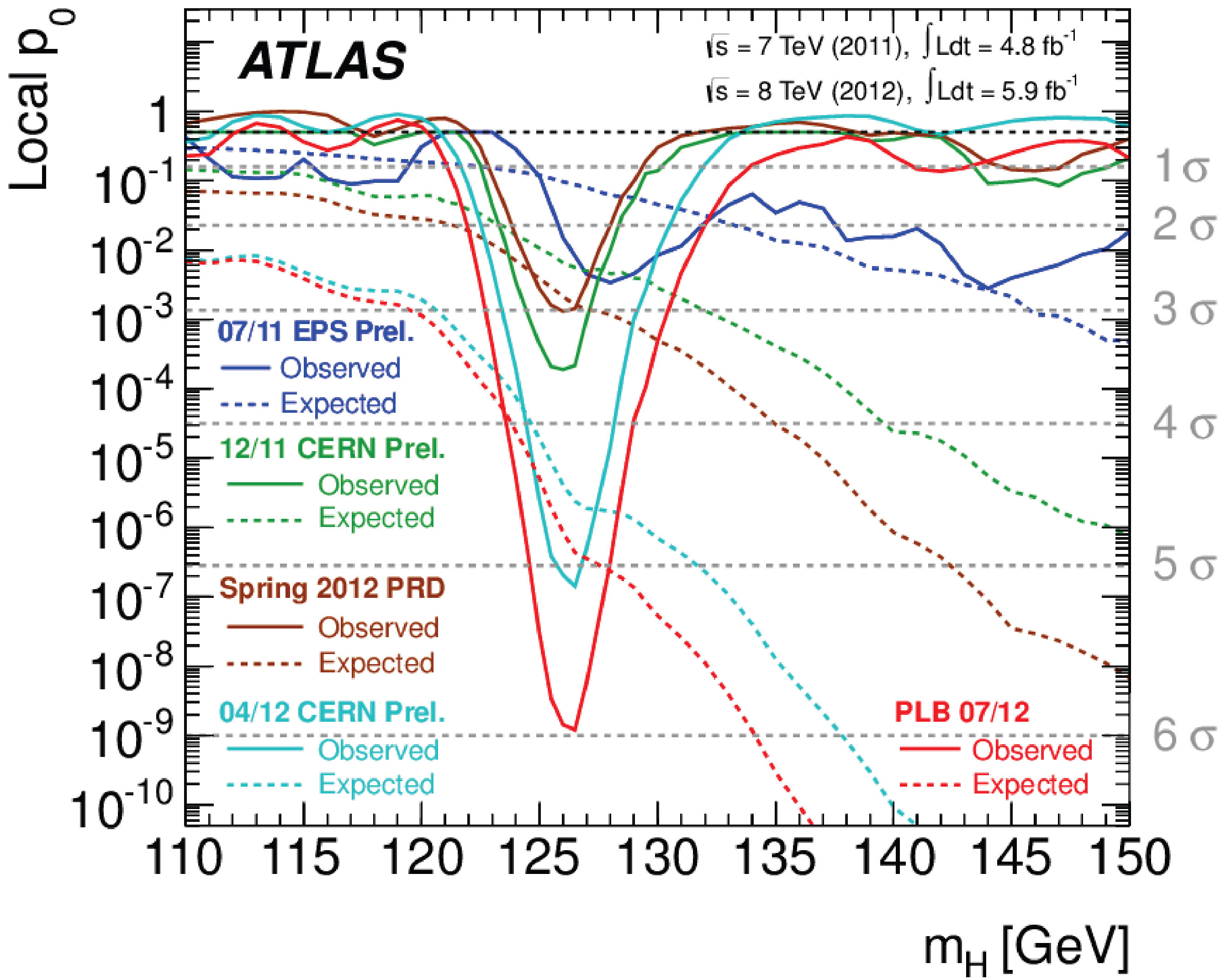


- Quantified in number of "σ":
  - 1σ: 1 chance out of 3 (too probable to conclude anything)
  - 3σ (evidence): 3 chances out of 1000
  - 5σ (observation): 1 chance out of 2 millions
  - 5,9σ: 3 chances out of 1 billion



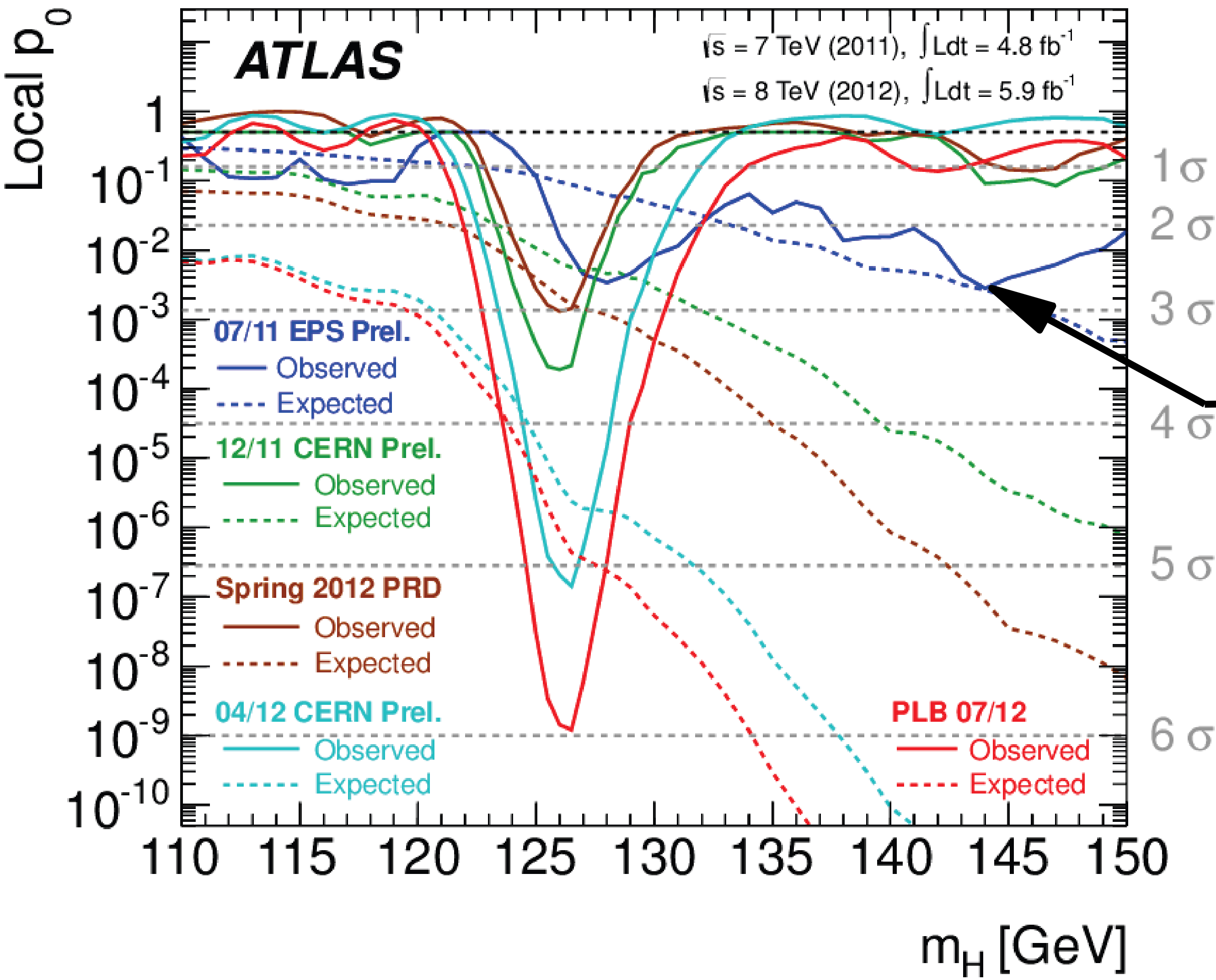
- We are therefore sure we saw something

Evolution with time
(until discovery)



- At first statistical fluctuations everywhere
- Then measurement stabilises

Evolution with time
(until discovery)

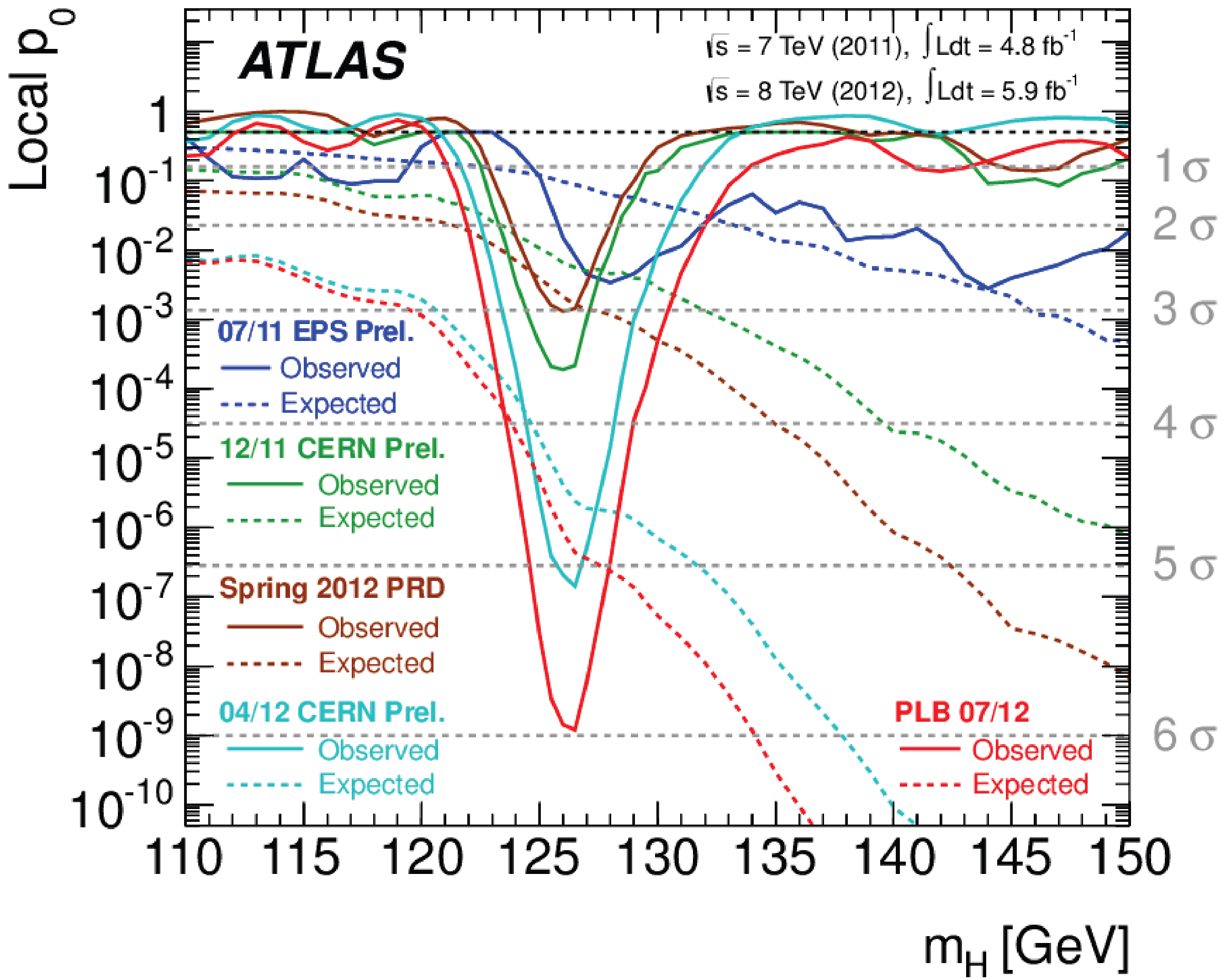


Excited theoreticians around the globe

- At first statistical fluctuations everywhere
- Then measurement stabilises

Evolution with time

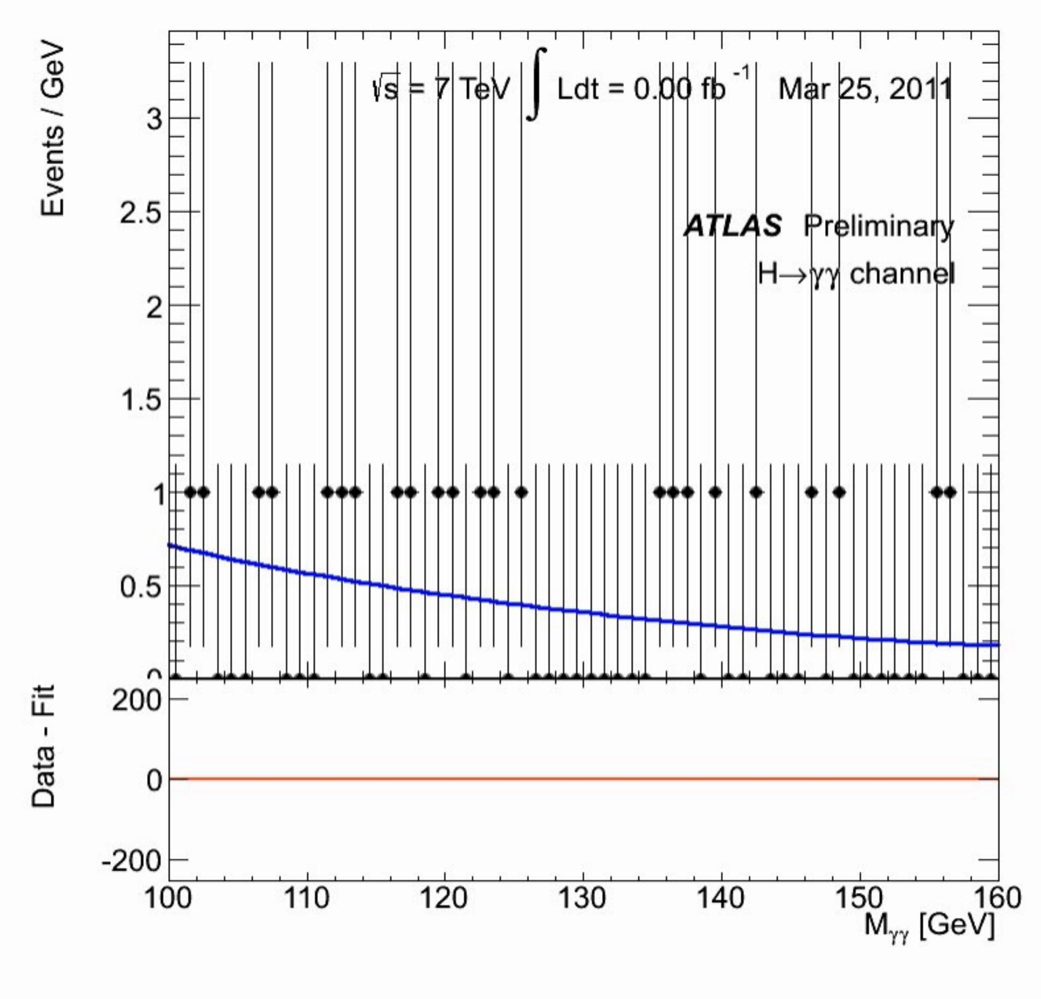
(until discovery)

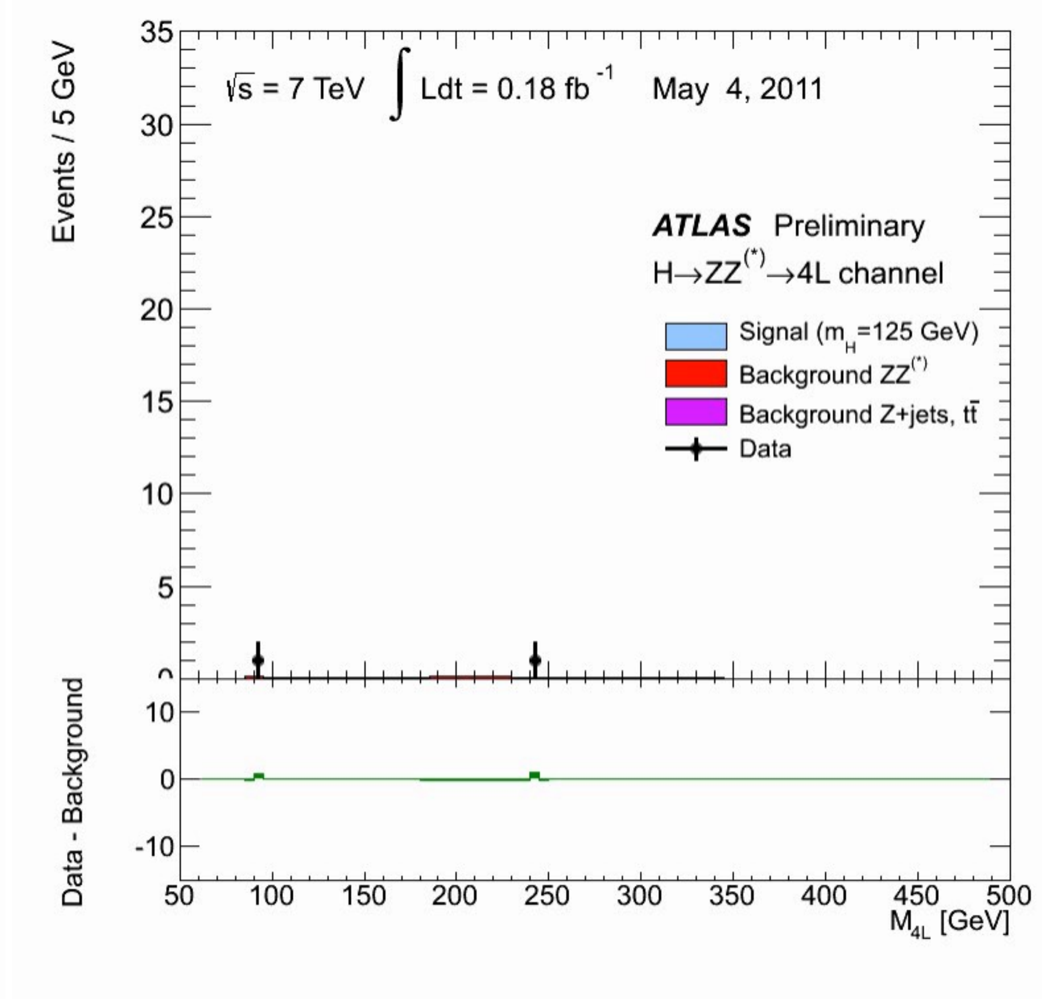


- At first statistical fluctuations everywhere
- Then measurement stabilises

Evolution with time

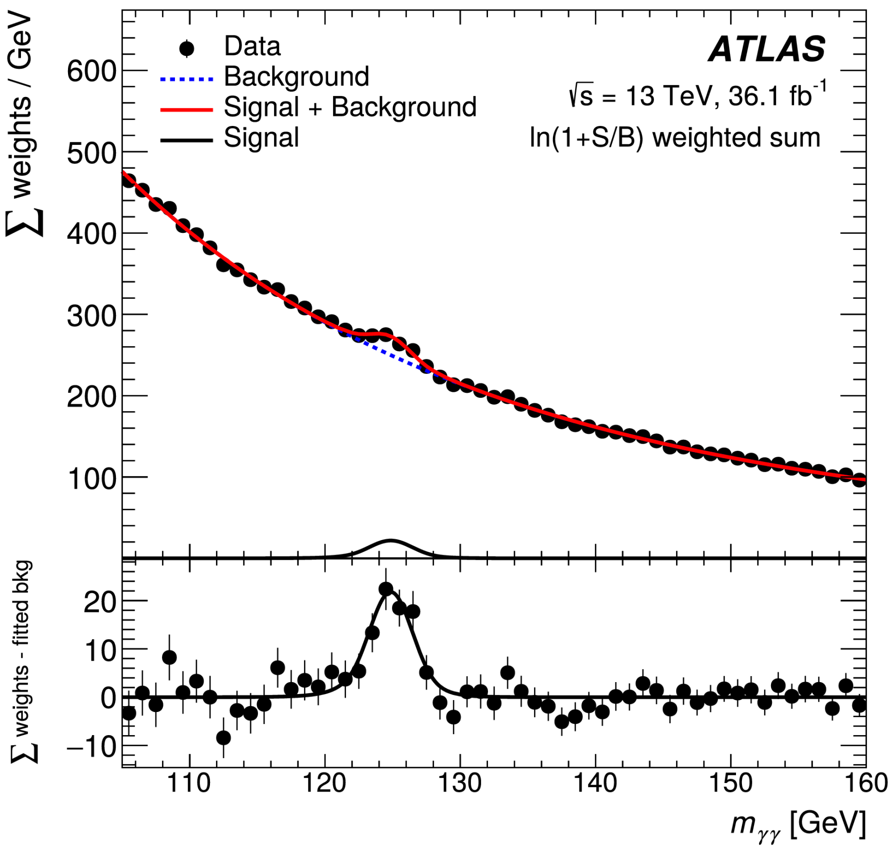
(until end of 2012)

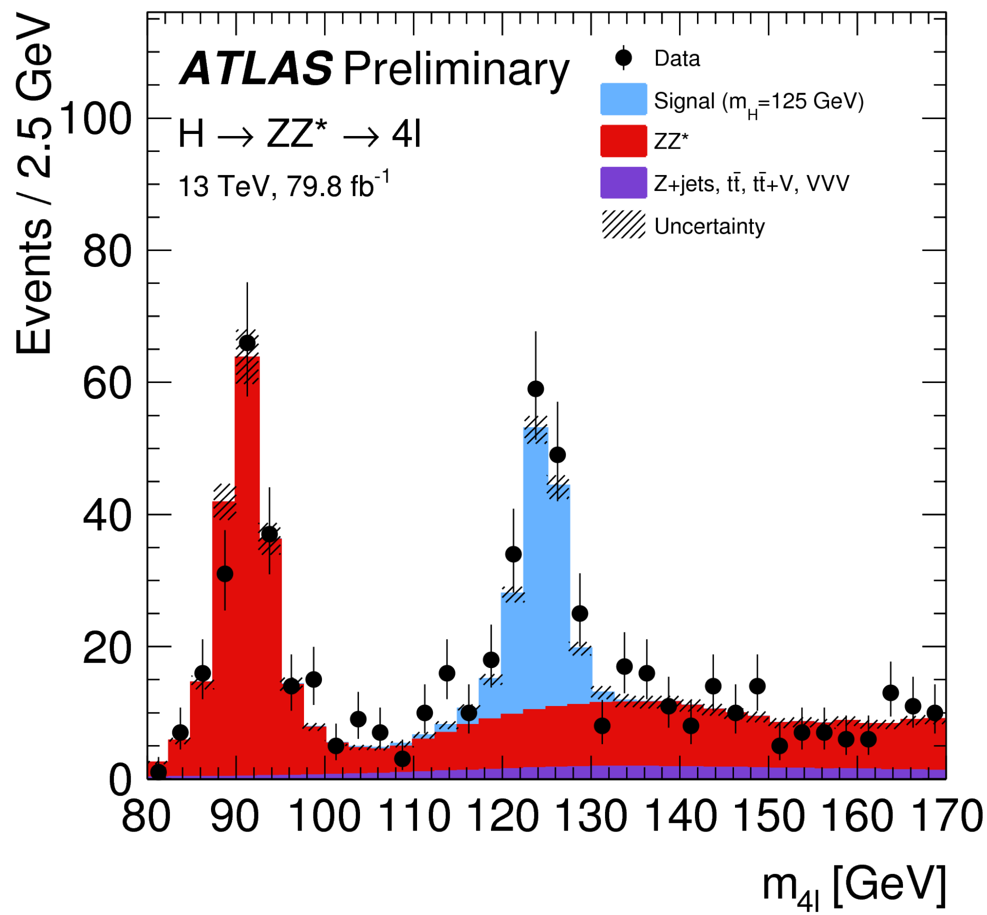




$H \rightarrow \gamma\gamma$ ***$H \rightarrow ZZ^* \rightarrow 4l$***

Evolution with time
(latest results)

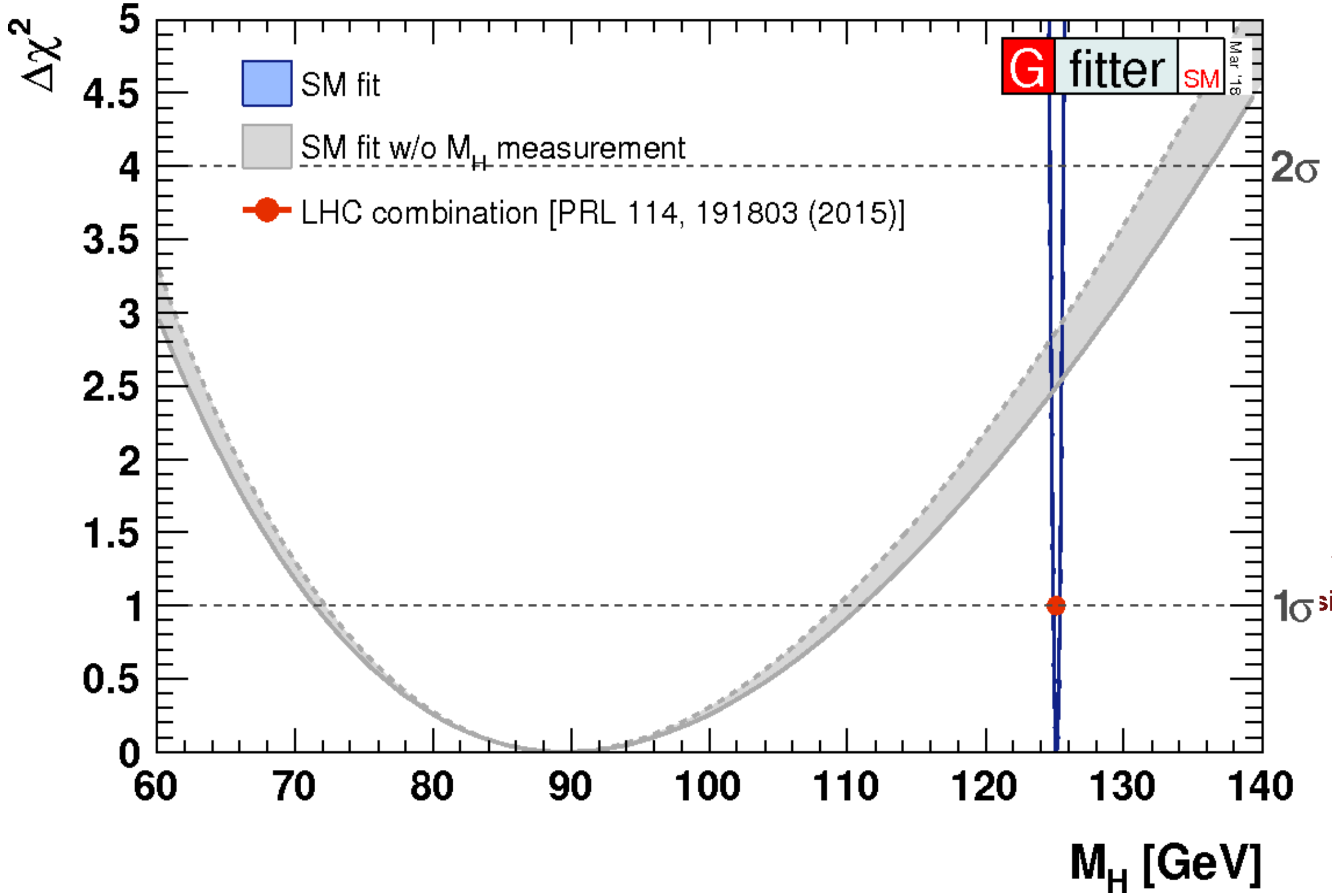


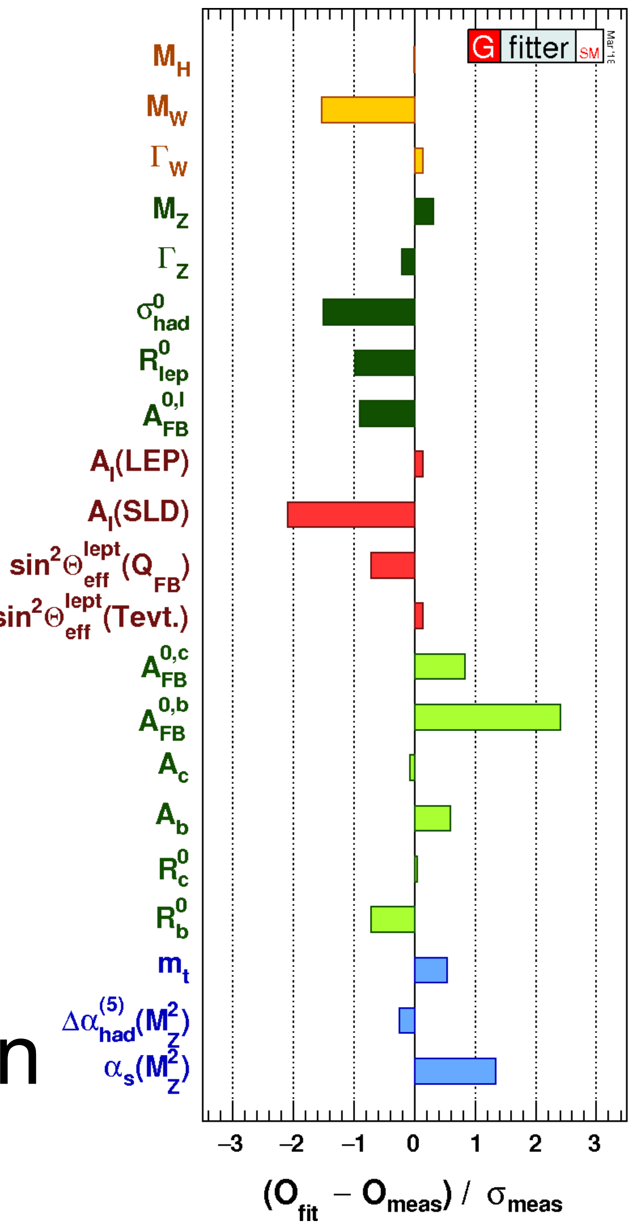


$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ^* \rightarrow 4l$

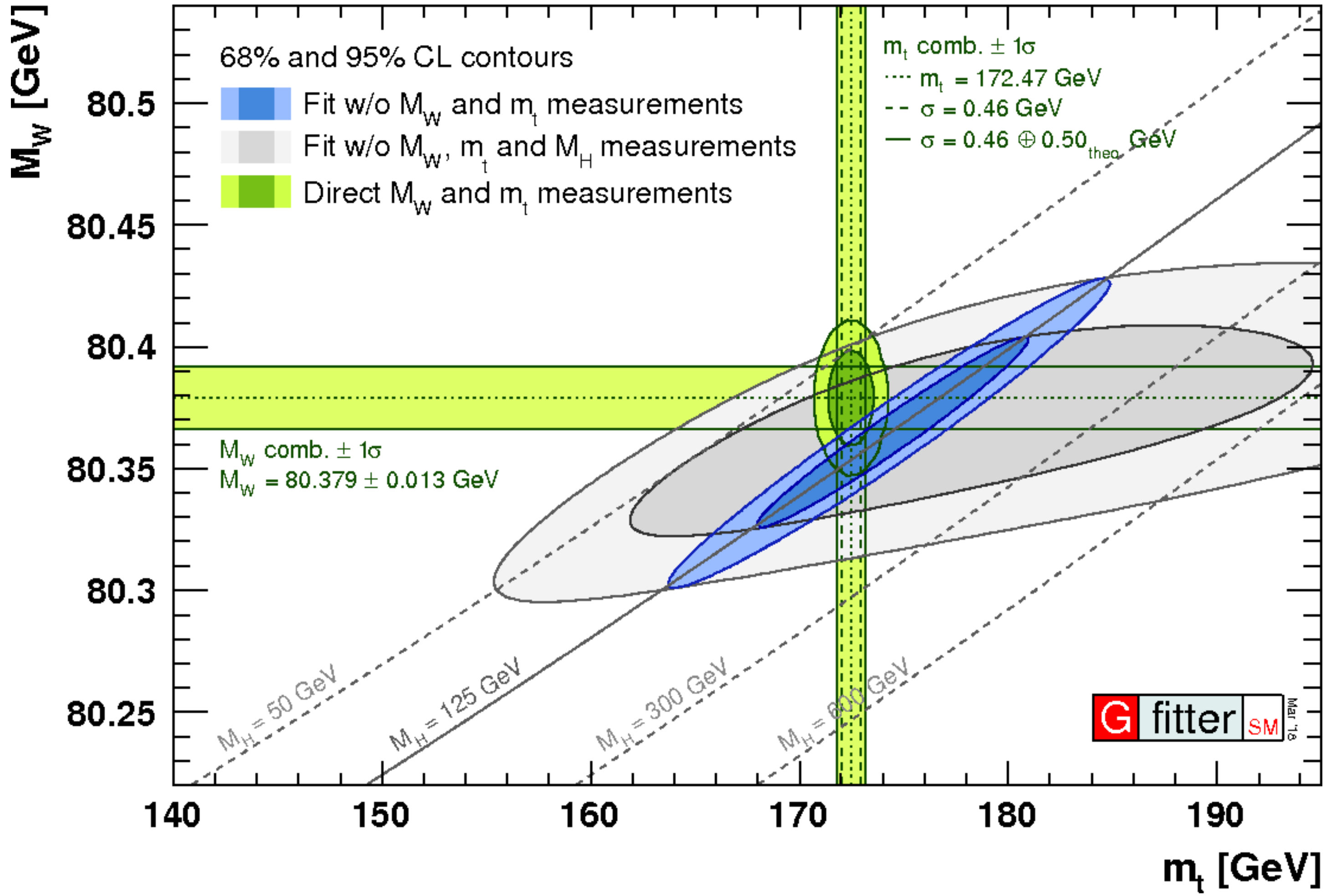
Consistent with other measurements in the standard model?





- Not very far from indirect prediction
- No “tension” with standard model

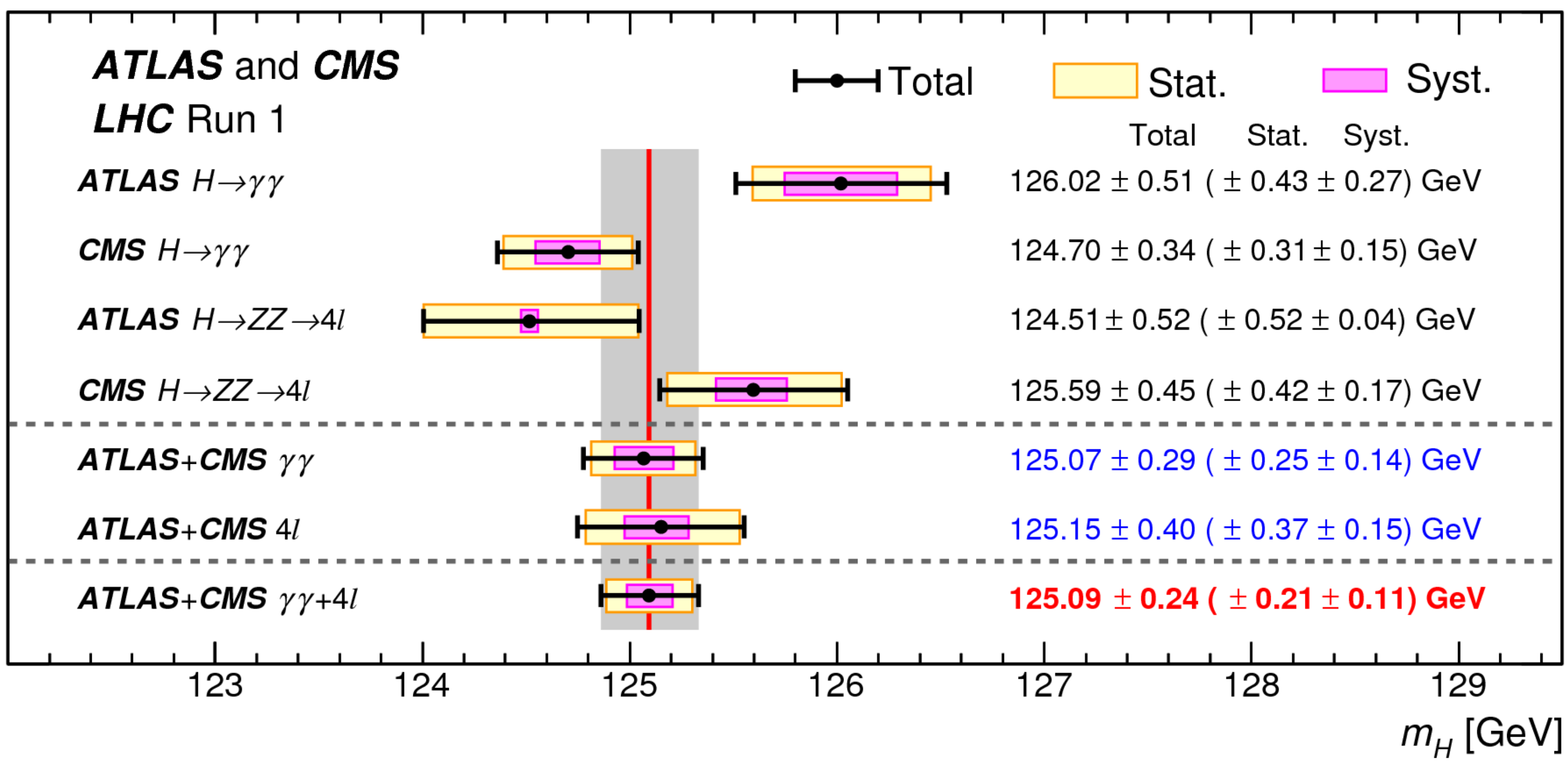
Consistent with other measurements in the standard model?



- Not very far from indirect prediction
- No "tension" with standard model

Is it the Standard model Higgs?

- Mass compatible with other SM measurements:
  - m_H = 125.09 ± 0.24 (0.21 stat. ± 0.11 syst.) GeV
    [ATLAS+CMS, March 2015, 2011-2012 dataset]
    (134 times the mass of the proton)



Is it the Standard model Higgs?

- Mass compatible with other SM measurements:
  - m_H = 125.09 ± 0.24 (0.21 stat. ± 0.11 syst.) GeV [ATLAS+CMS, March 2015, 2011-2012 dataset] (134 times the mass of the proton)
- Statistical significance keeps increasing
- Measurements in other decays modes
- New ATLAS and CMS results still consistents
- Property measurements:
  - Various channels/production modes, couplings, spin...
  - Confirm the standard model...

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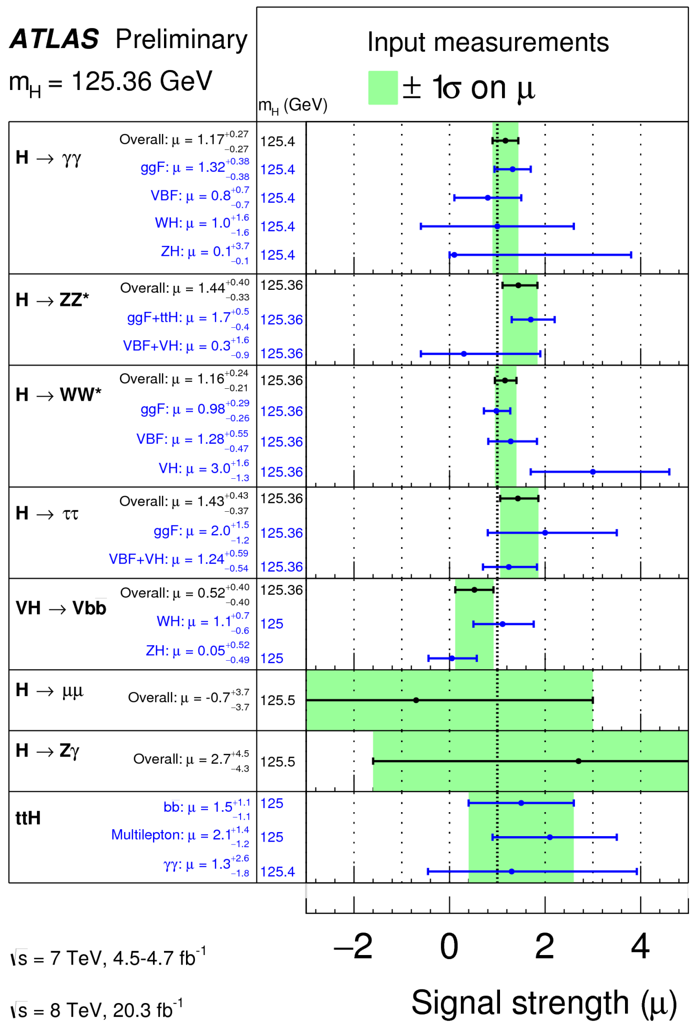
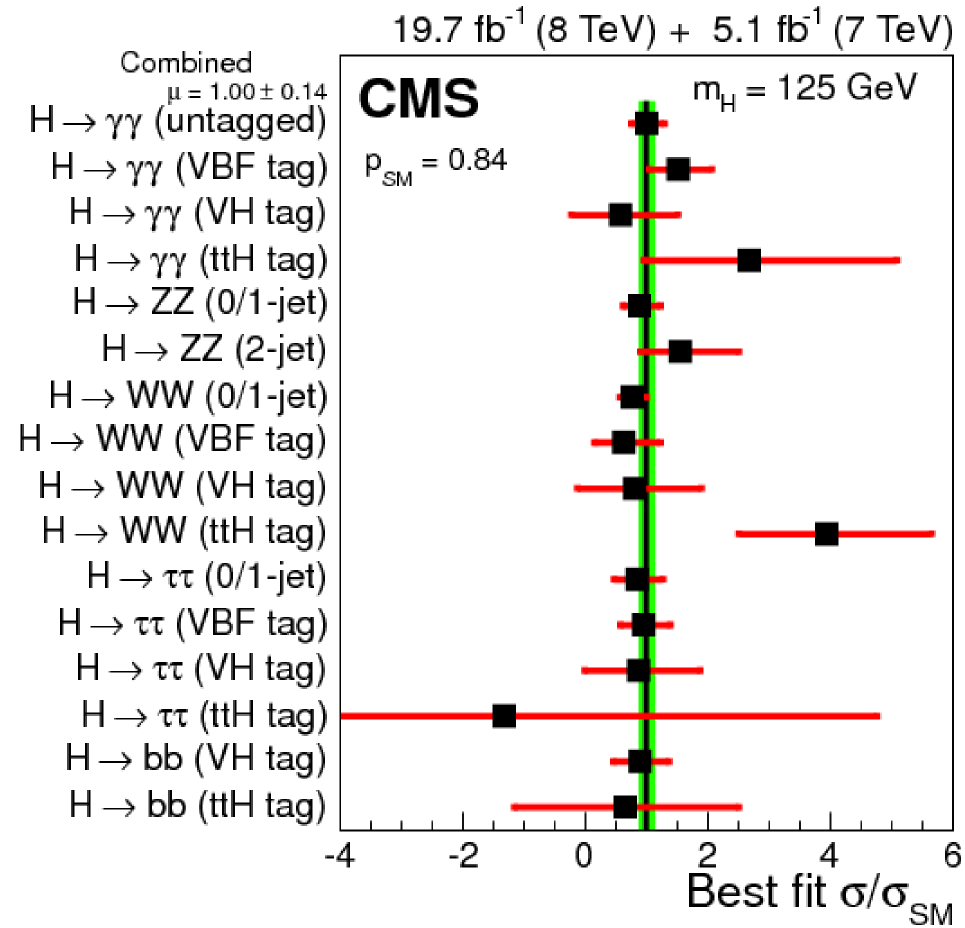
Measurements in several channels

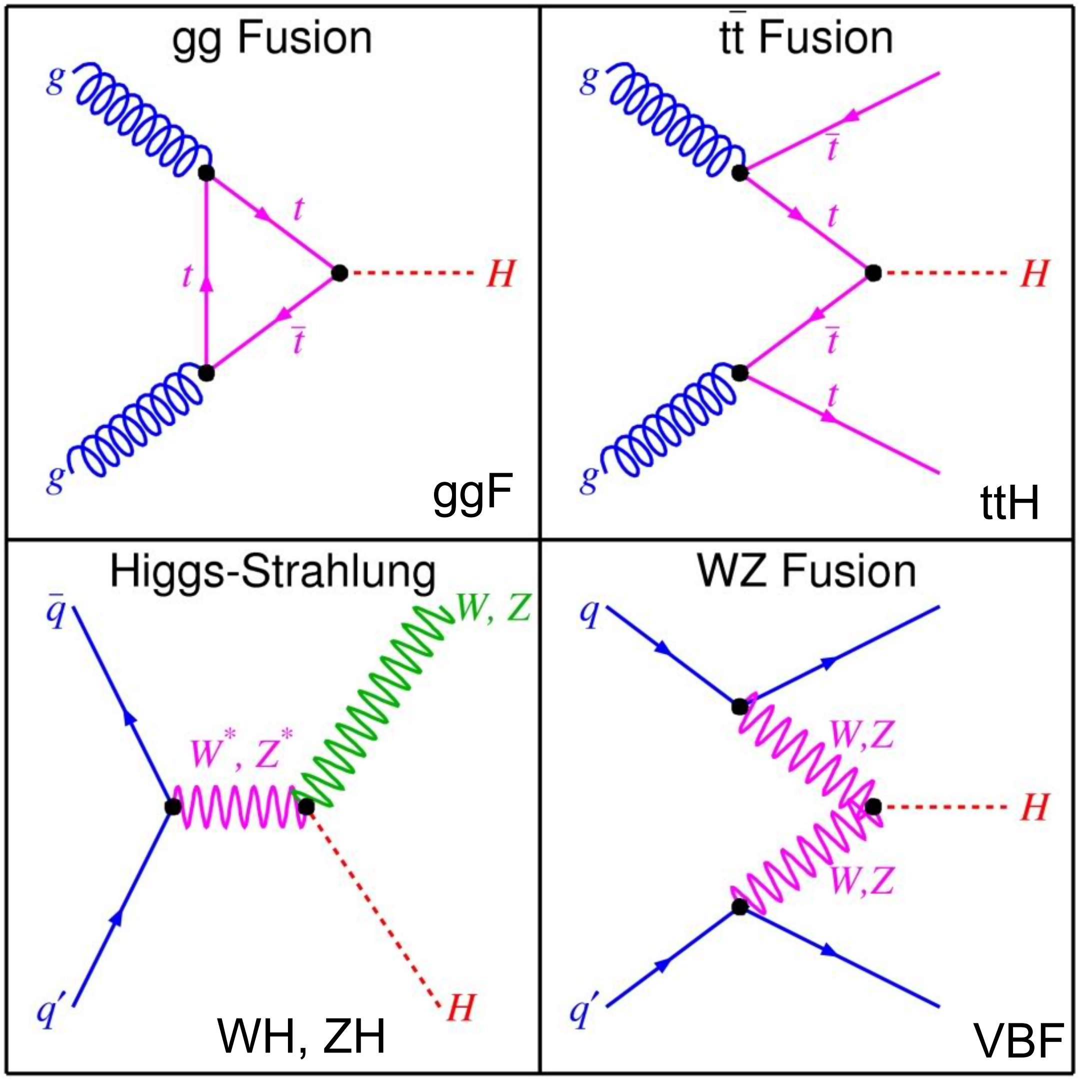




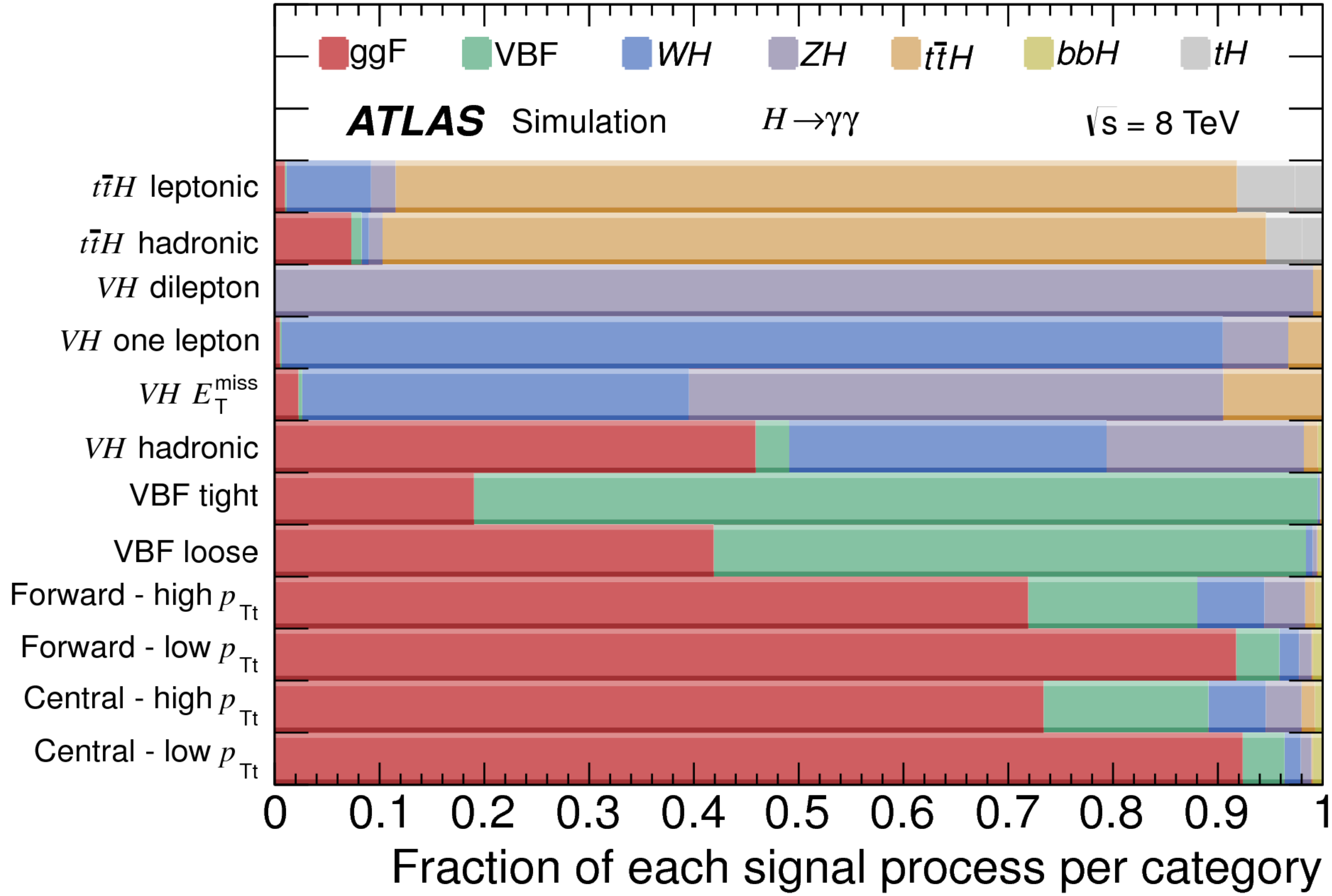
- $\mu = \sigma/\sigma_{SM} = 1$ if the particule is like the Higgs boson of the standard model
- So far very close to predictions

Higgs boson production

- Different production modes
- If standard model Higgs, proportions are known
- “Just” have to separate decay modes experimentally
- Easier said than done...

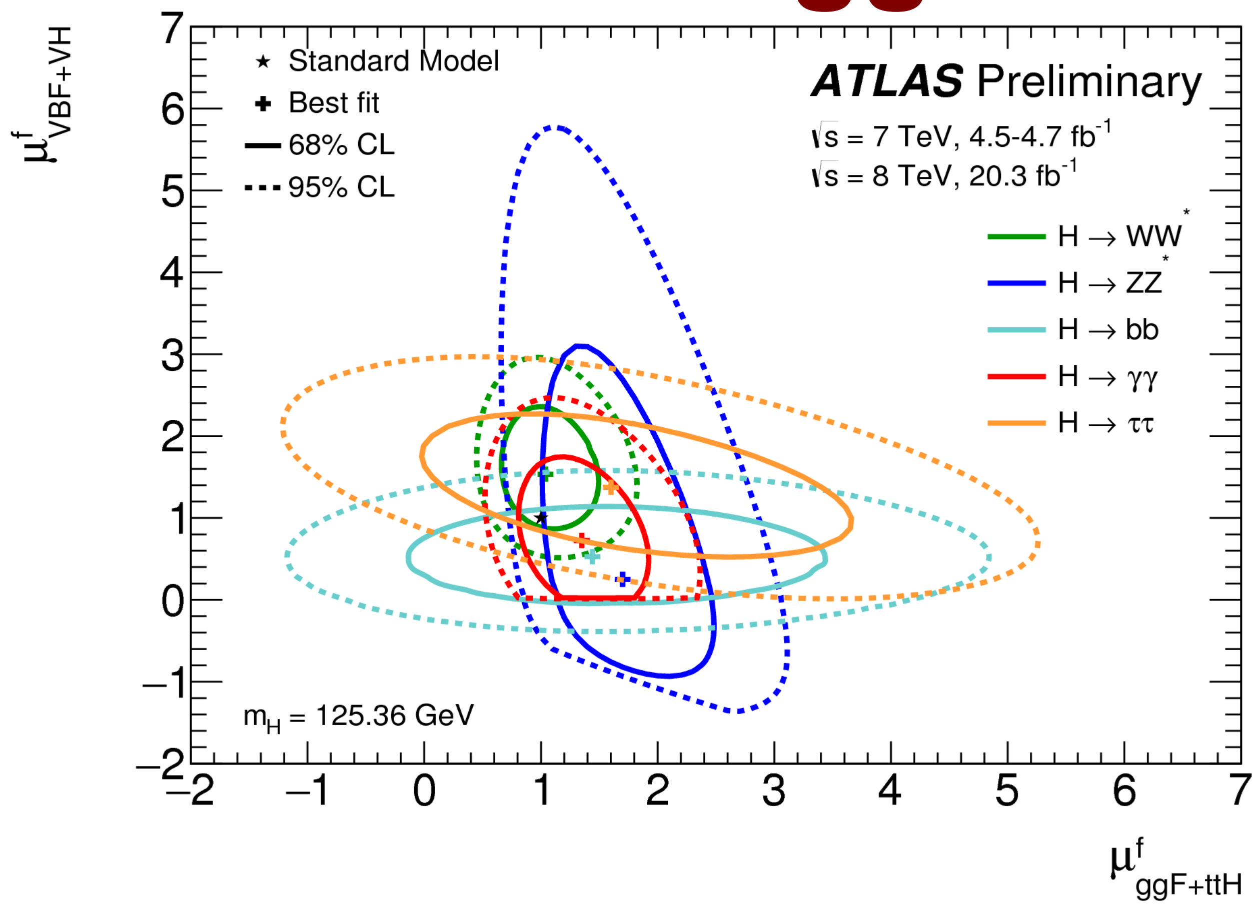


Separation of production channels



- Optimising analyses, one can target a specific production mode
- Never 100 % pure, but allows interesting measurements

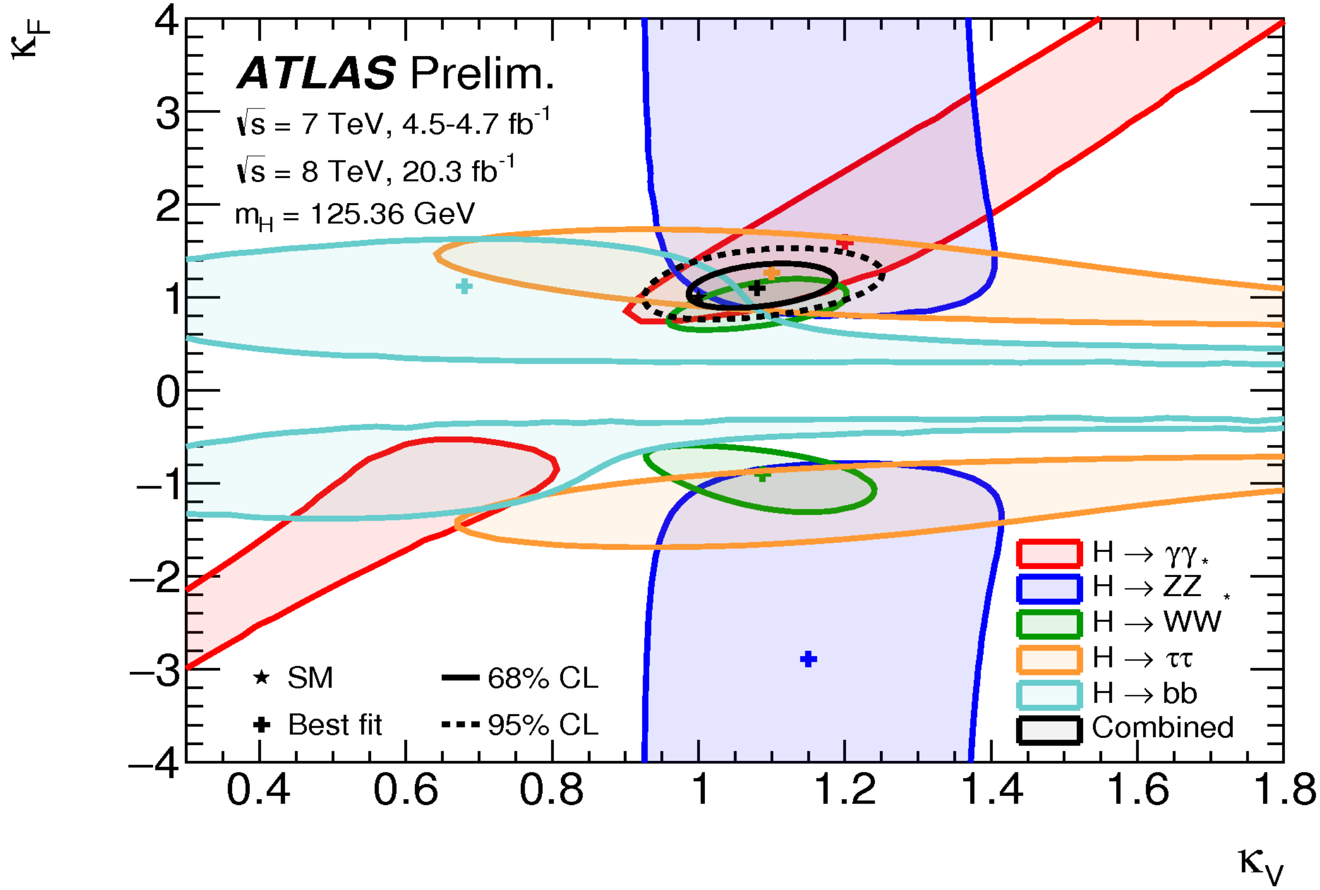
“VBF” or “ggF”?

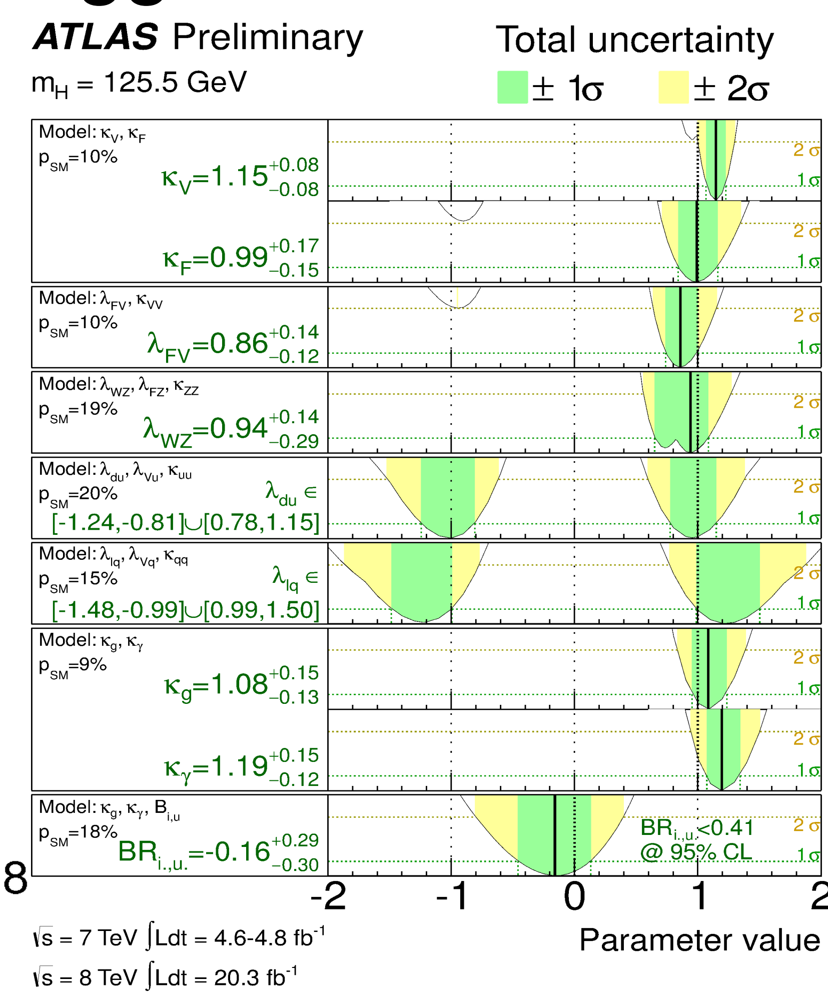


- μ = 1 if the particule is like the Higgs boson of the standard model
- All channels compatible among themselves and with standard model
- Evidence pour VBF≠0 → this boson plays a role in electroweak symmetry breaking

Coupling to fermions and bosons

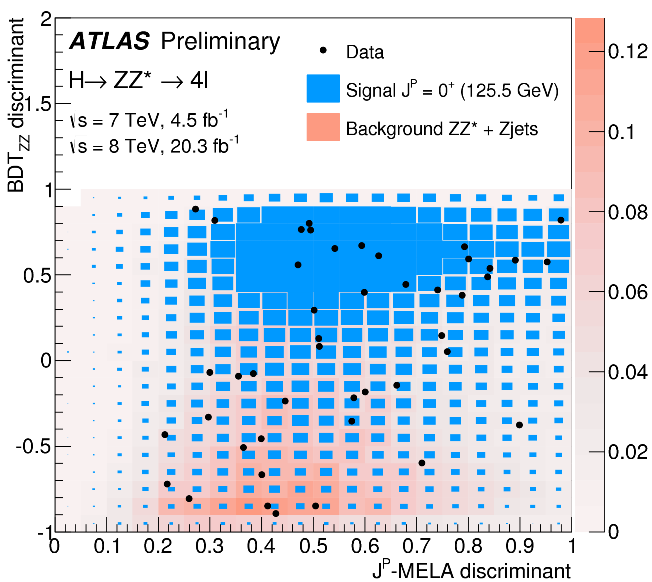
- Too many parameters to measure simultaneously
  - Group them and measure ratio to SM prediction, κ
- If κ = 1 the particule is like the Higgs boson of the standard model

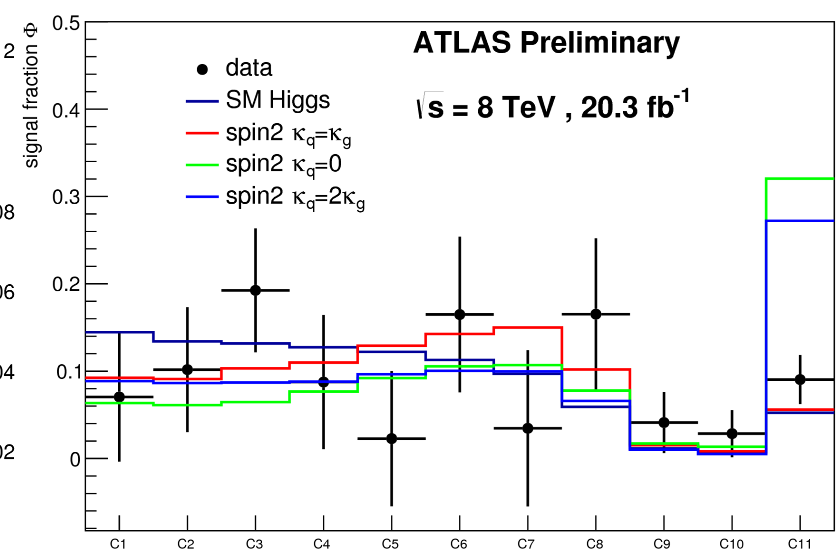


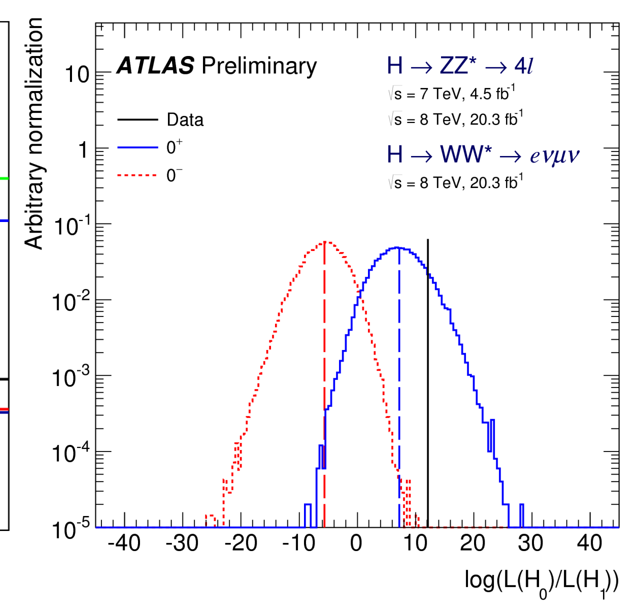


Spin and parity

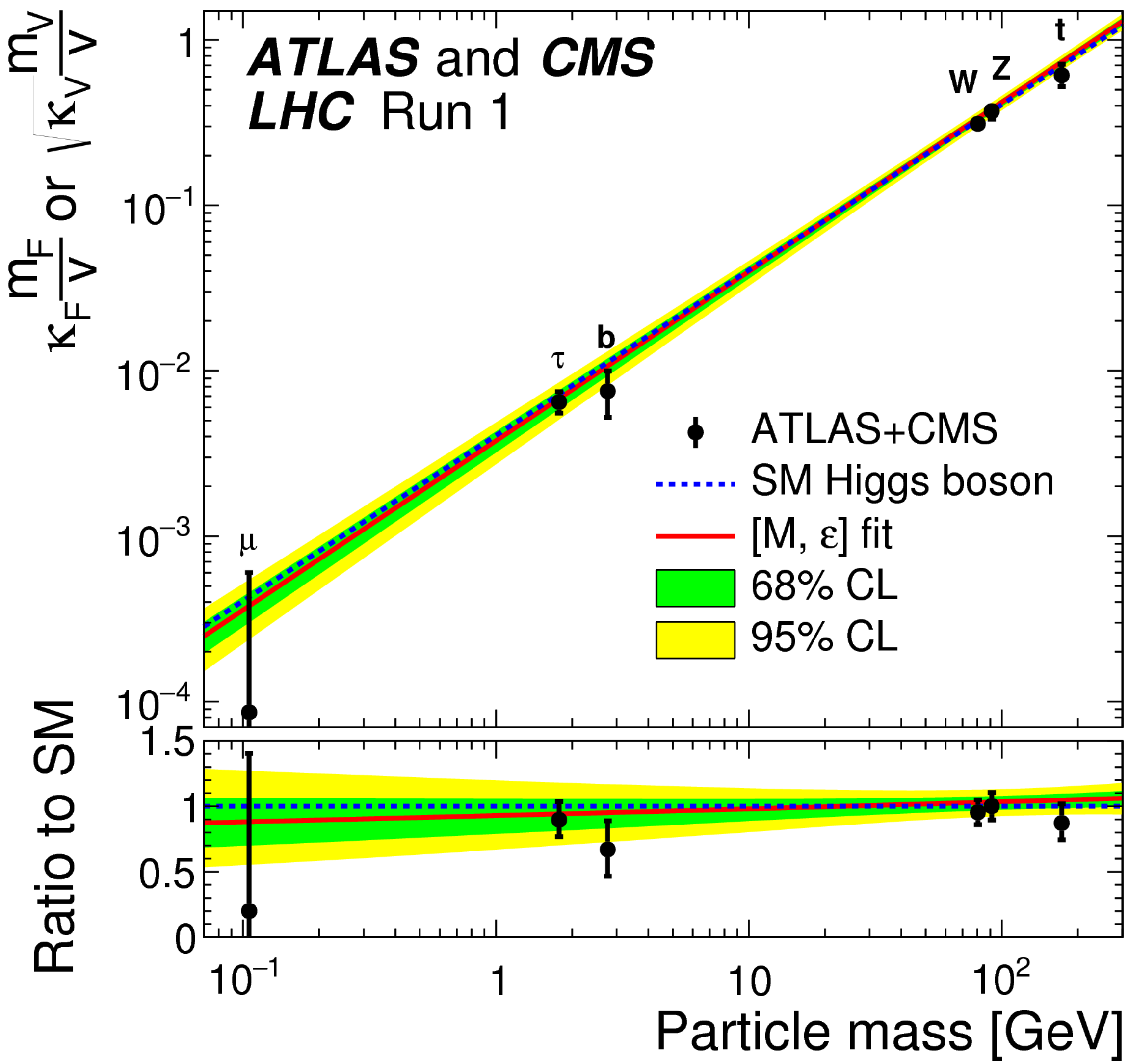
- Observation of $H \rightarrow \gamma\gamma$ implies integer spin, not 1
- Exclusion of spin 1^+, 1^-, 0^-, 2^+ more and more clear (more than 99 % confidence)
- Every time consistent with 0^+: like the standard model Higgs boson





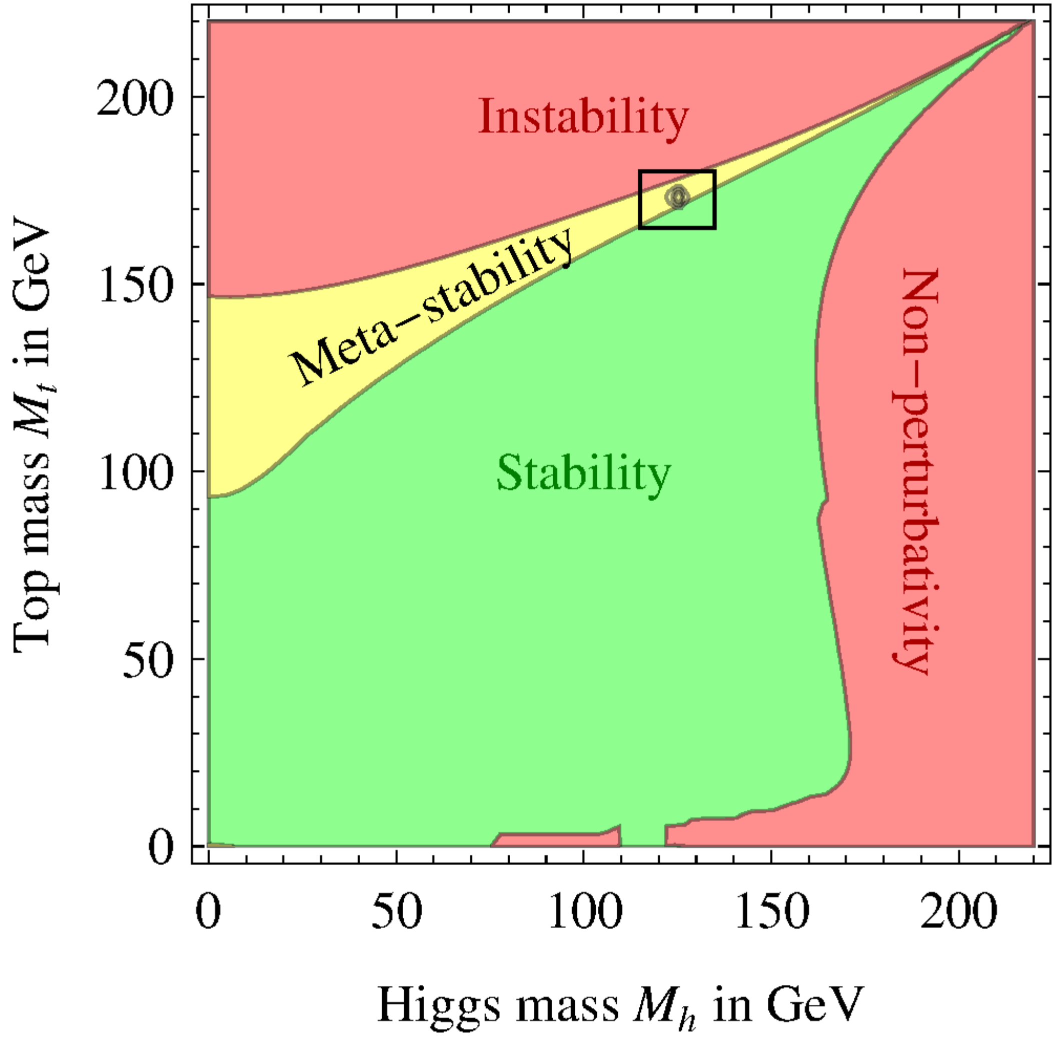


Particle masses and coupling to Higgs boson



- As expected from standard model

An unstable universe?



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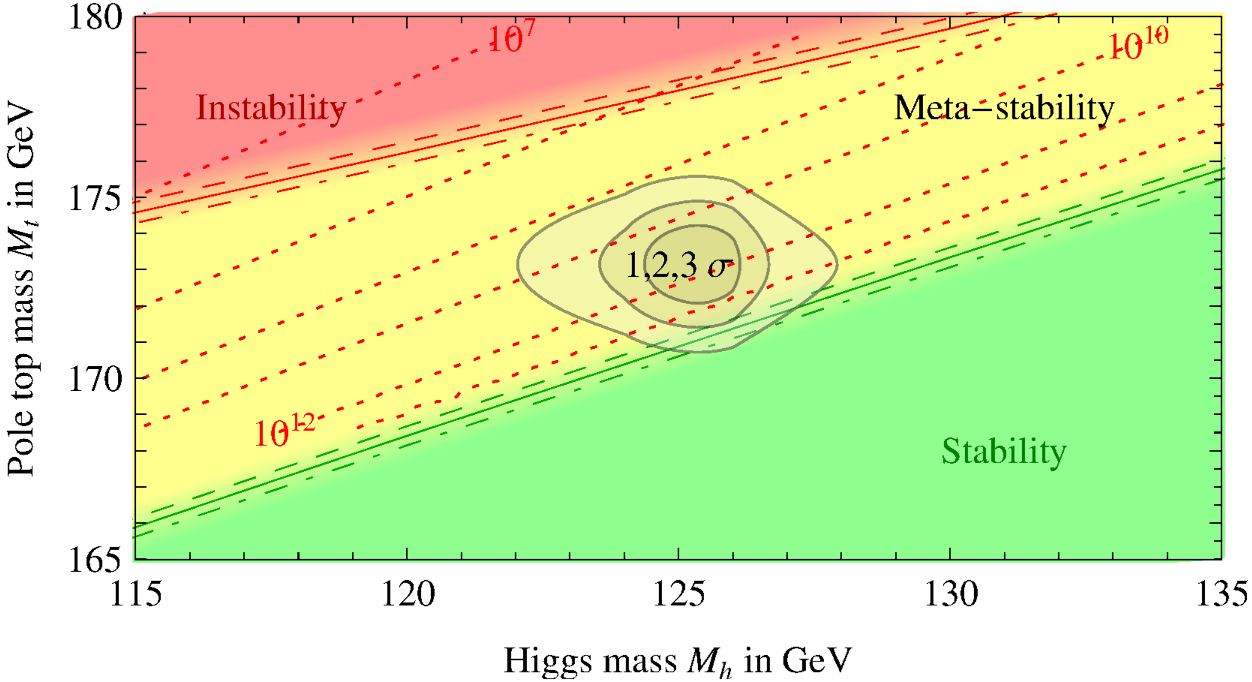
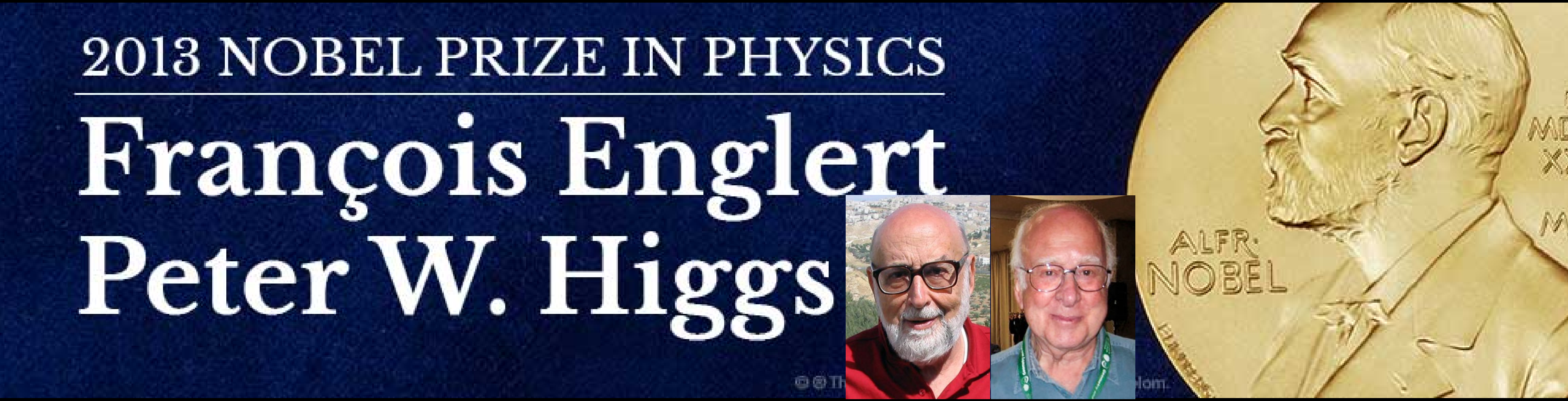


- Rather meta-stable, stable on the scale of the age of the Universe → we are safe!
- Need to improve precision on m_t to know more

Nobel prize in physics 2013



“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”

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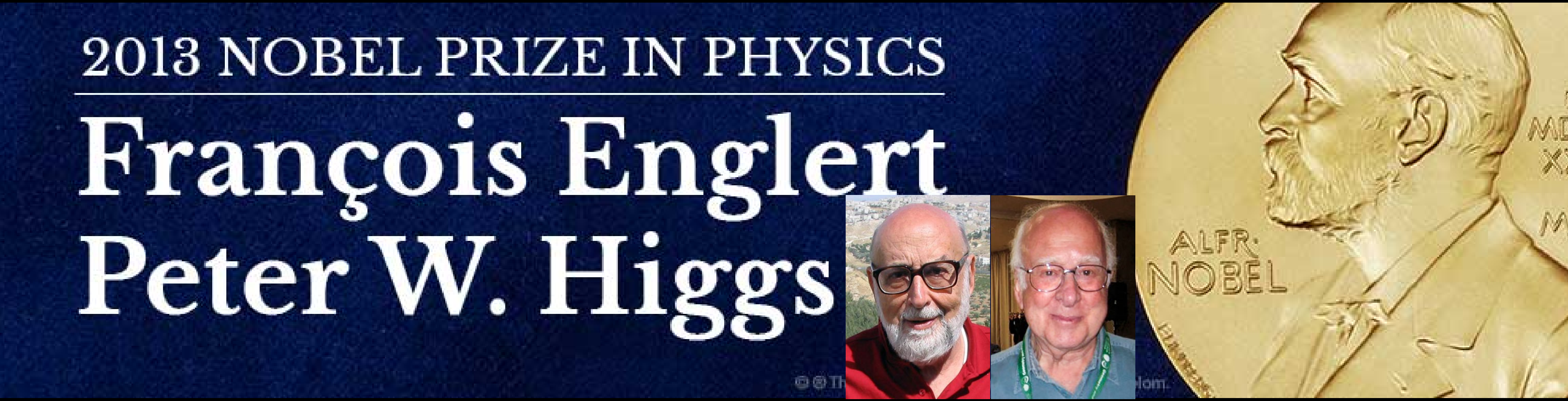

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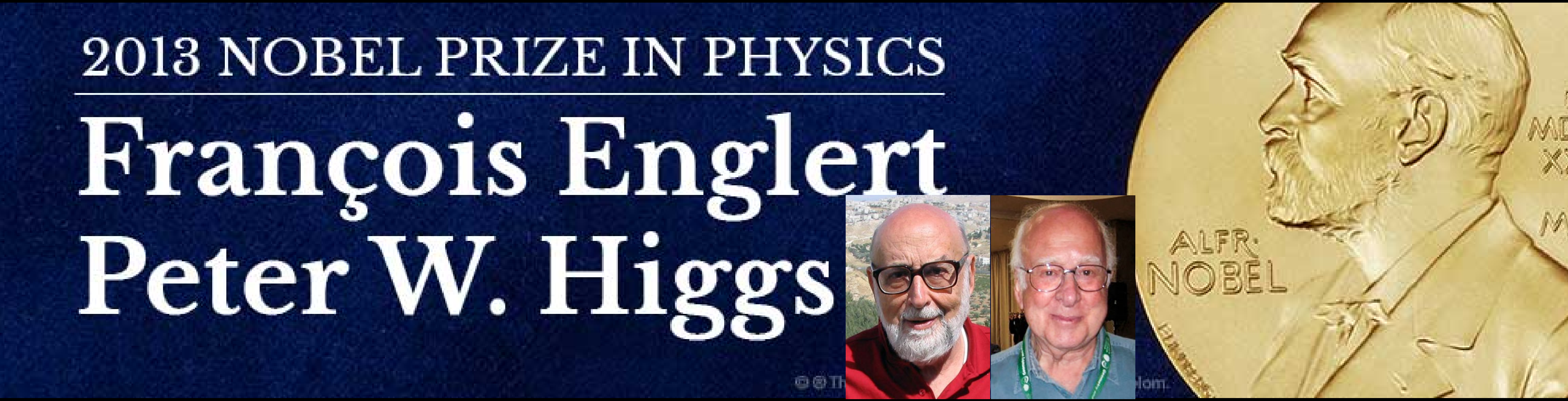

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CERN and the ATLAS & CMS experiments

What else?

What else?

Planck, March 2013

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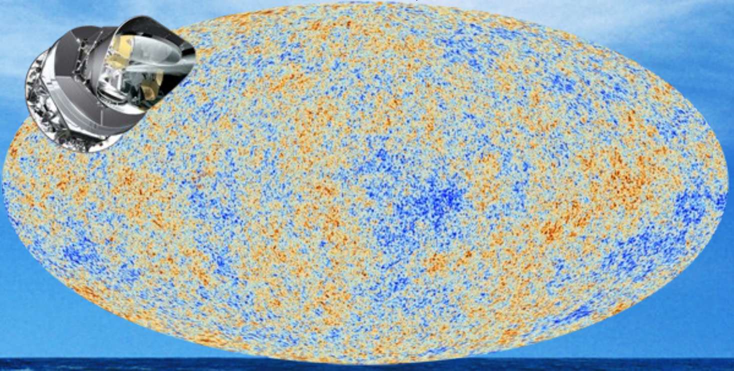
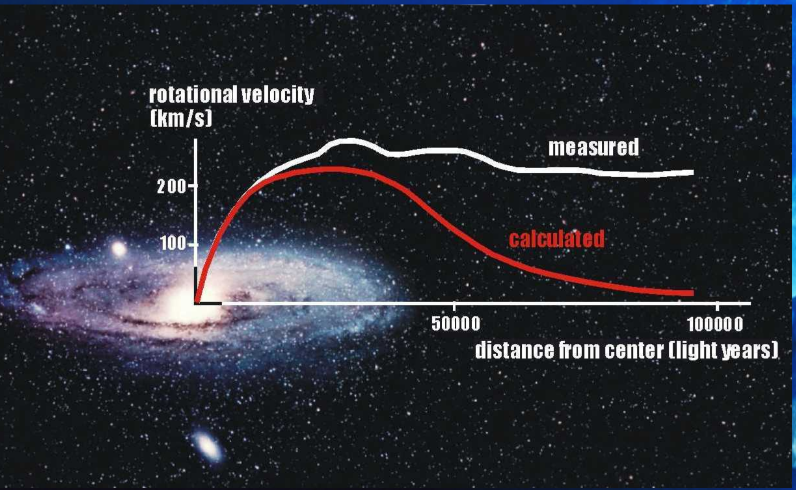


What else?

Our visible Universe

5% Standard model

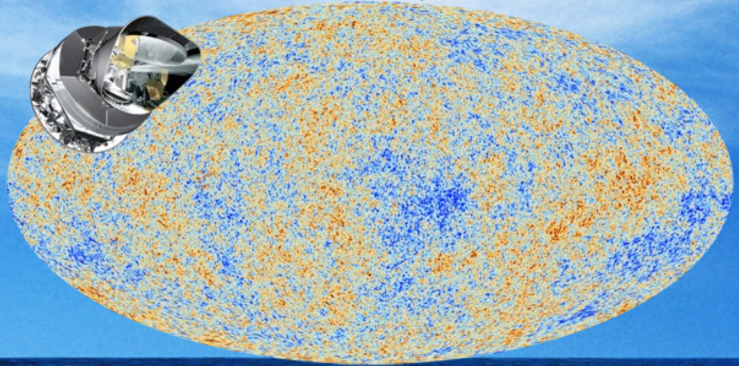
27% dark matter



- Do not know what it is, but have good reasons to think it is there
- Potential candidates observable at LHC (supersymmetry, …)?

Planck, March 2013

What else?



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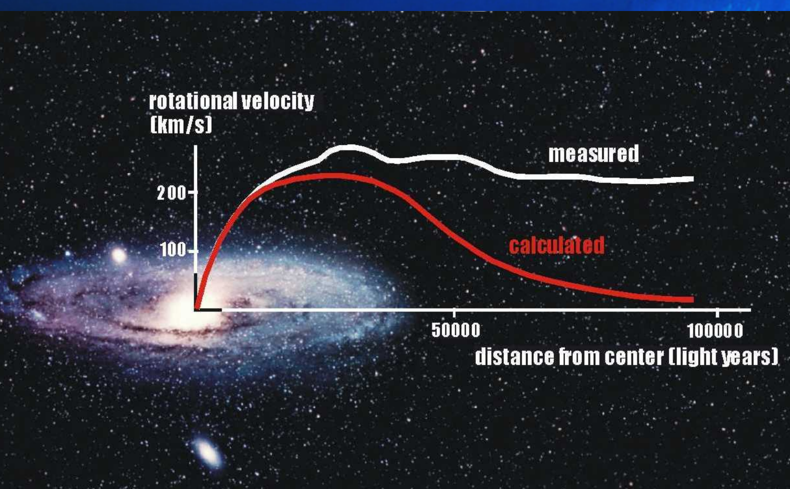
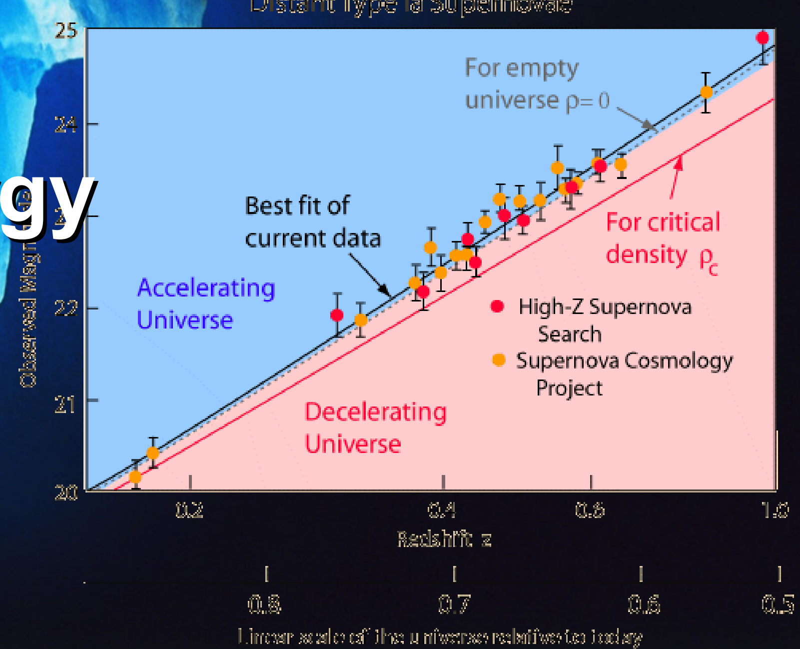


68% dark energy

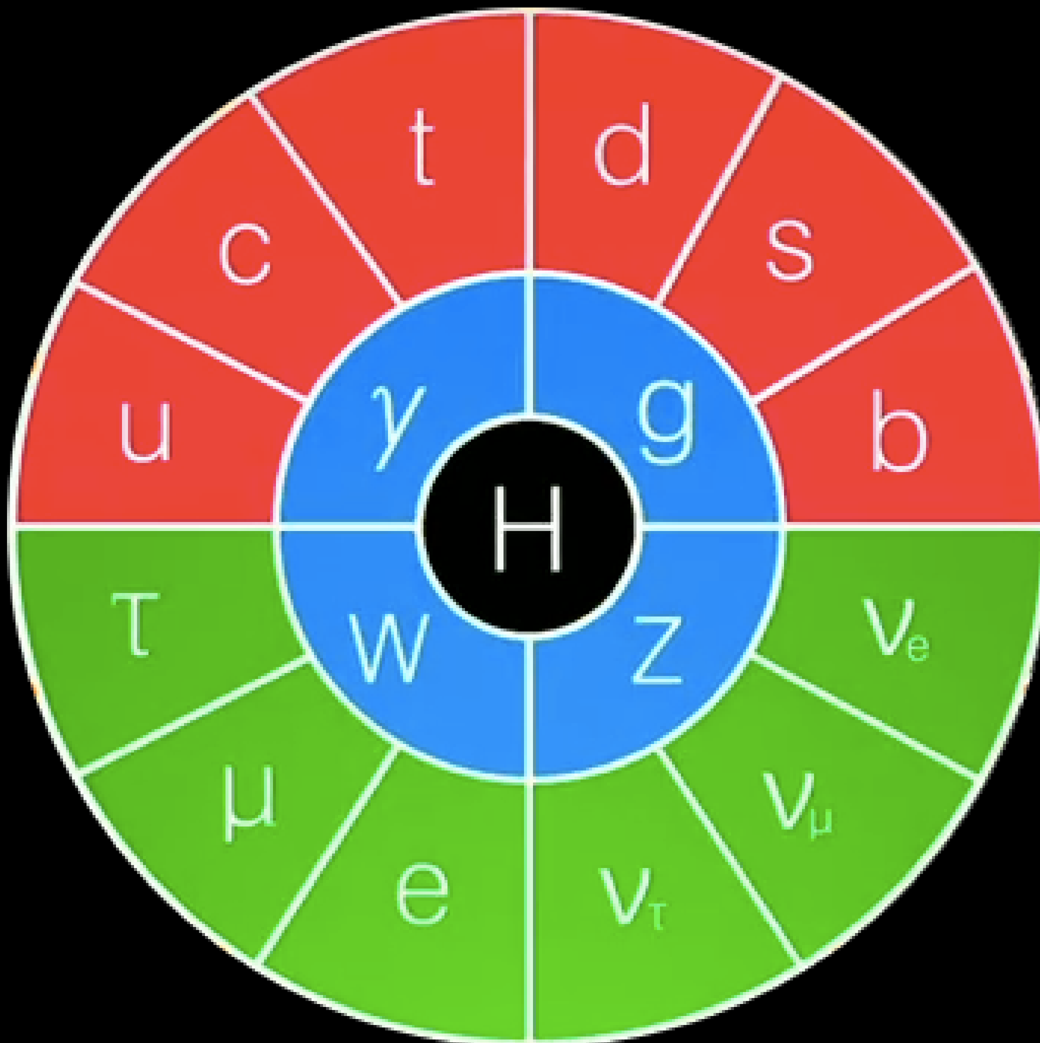
No clue whatsoever as to what it could be



See W. Gillard & al

Other theories

- The standard model does not explain everything:
  - Why three families?
  - Why such a wide spectrum of masses among elementary particles?
  - What are dark matter and dark energy?
  - Why has antimatter almost completely disappeared?
- Theoreticians have lots of ideas
- Many models make predictions that can be tested at LHC
- Supersymmetry, exotic models, extra dimensions of space, …
  - predict new particles, or have impact on already known phenomena
- Need experimental measurements to guide theoreticians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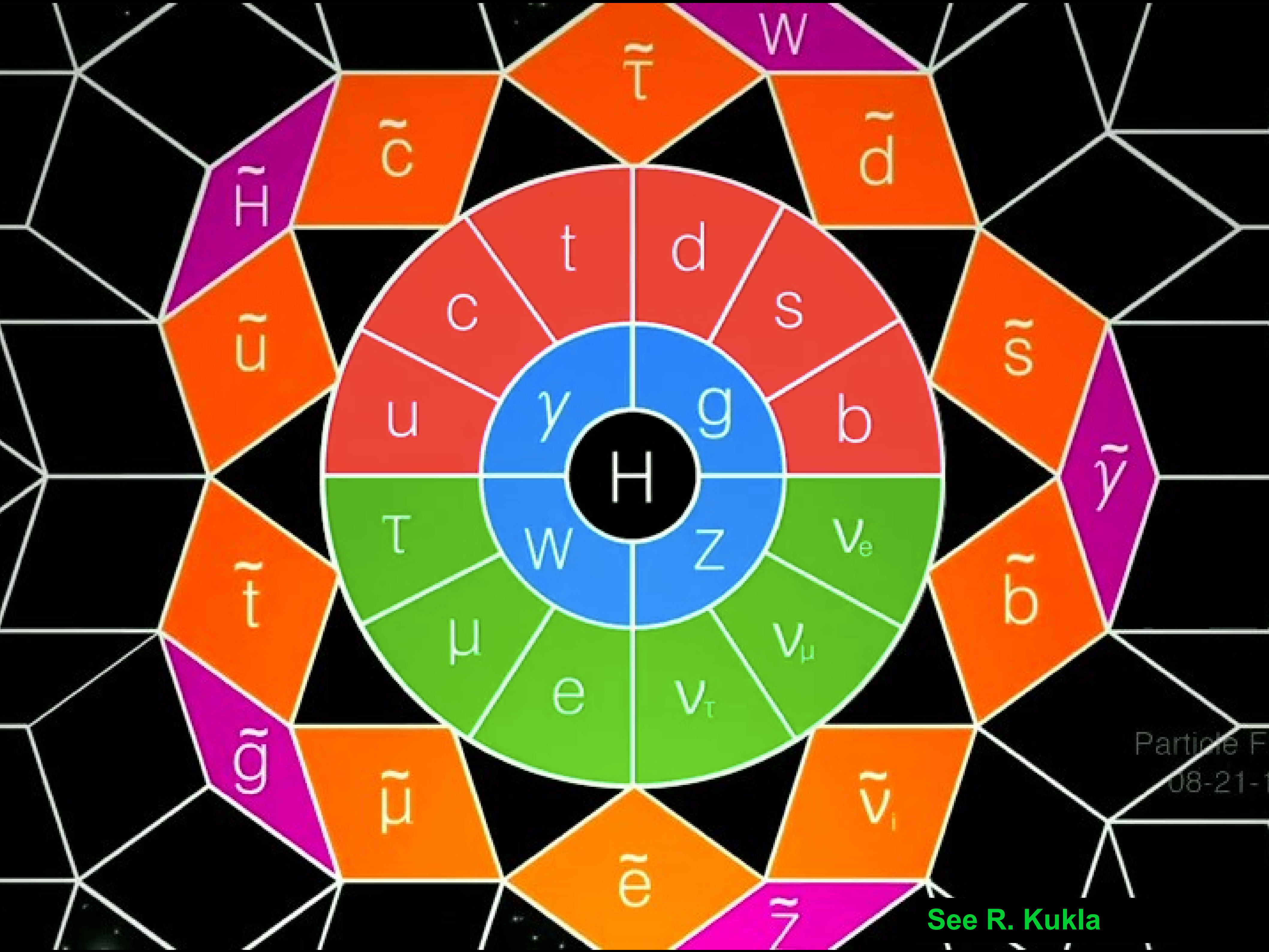
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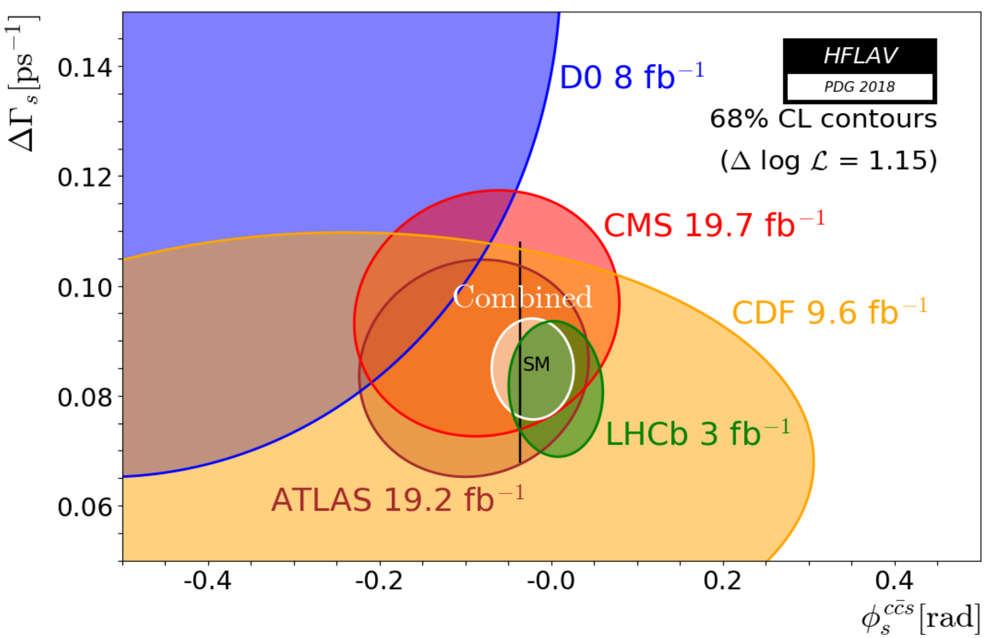
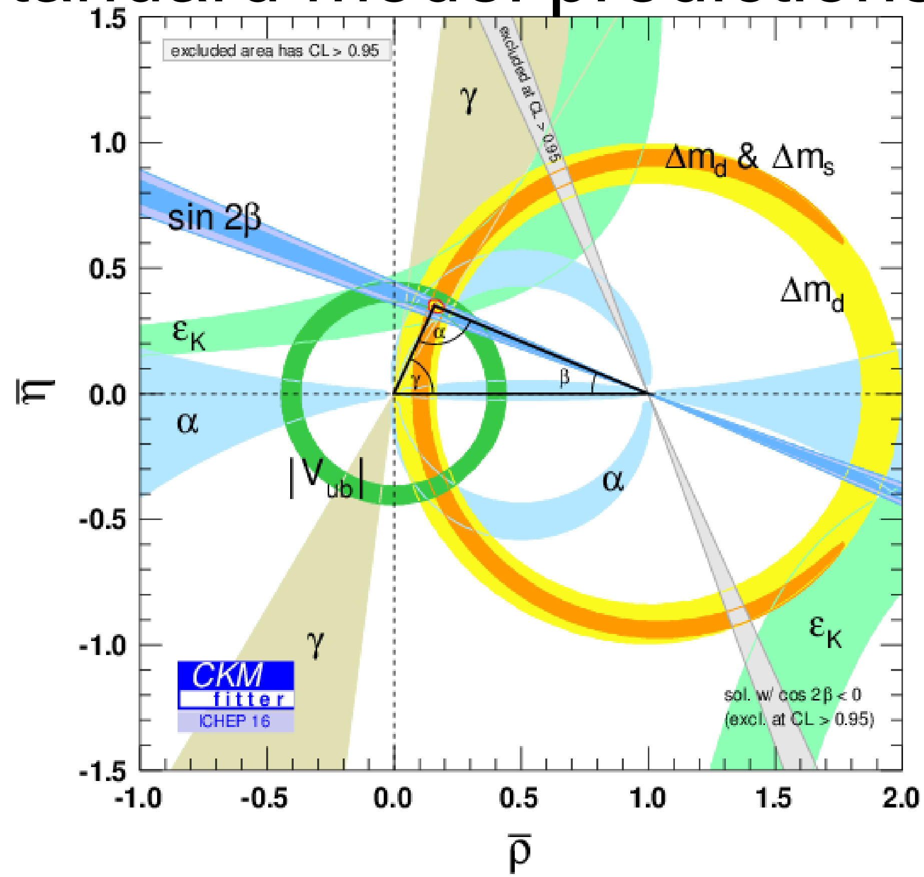
See R. Kukla

Matter-antimatter asymmetry

- Not enough antimatter in the Universe
- Precision measurements to characterise minute differences between matter and antimatter
- So far mostly compatible Standard model predictions





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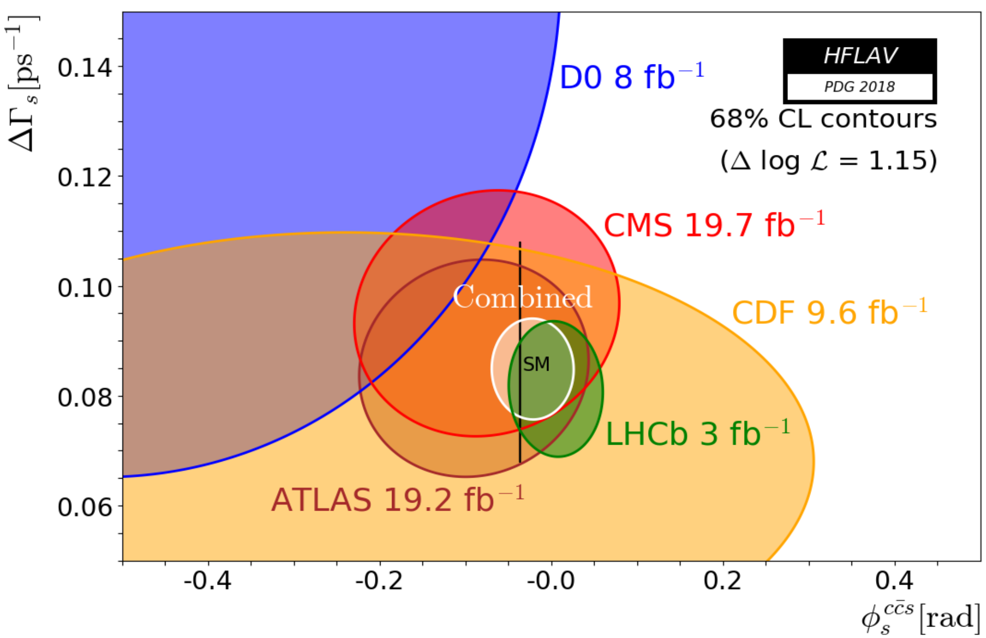

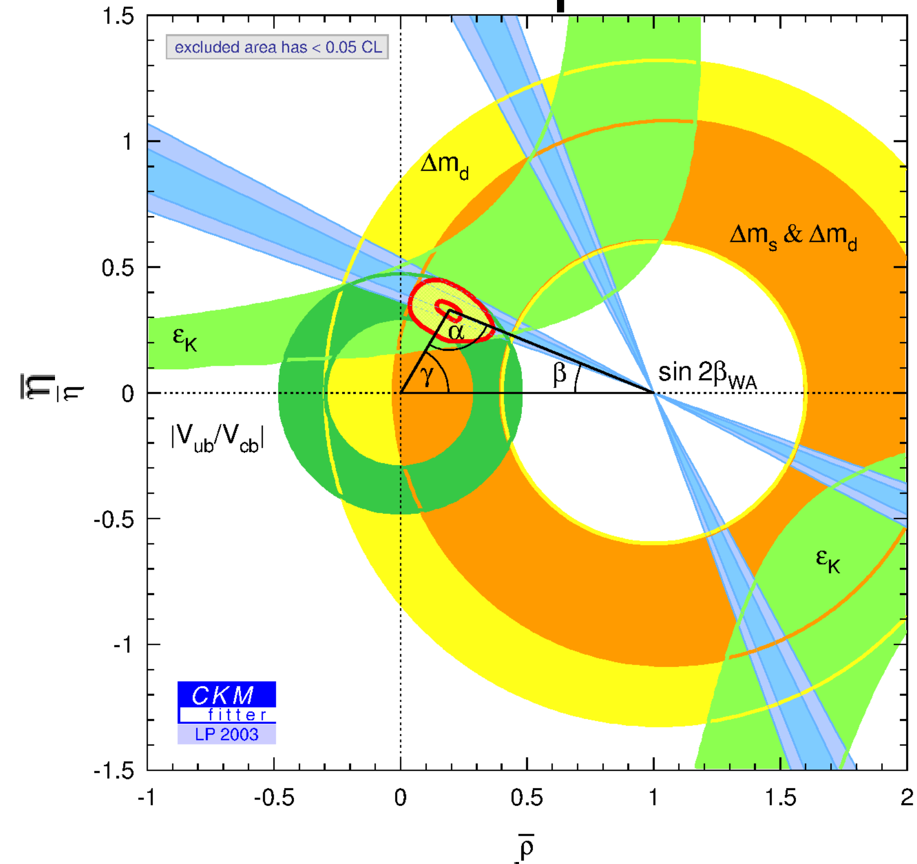

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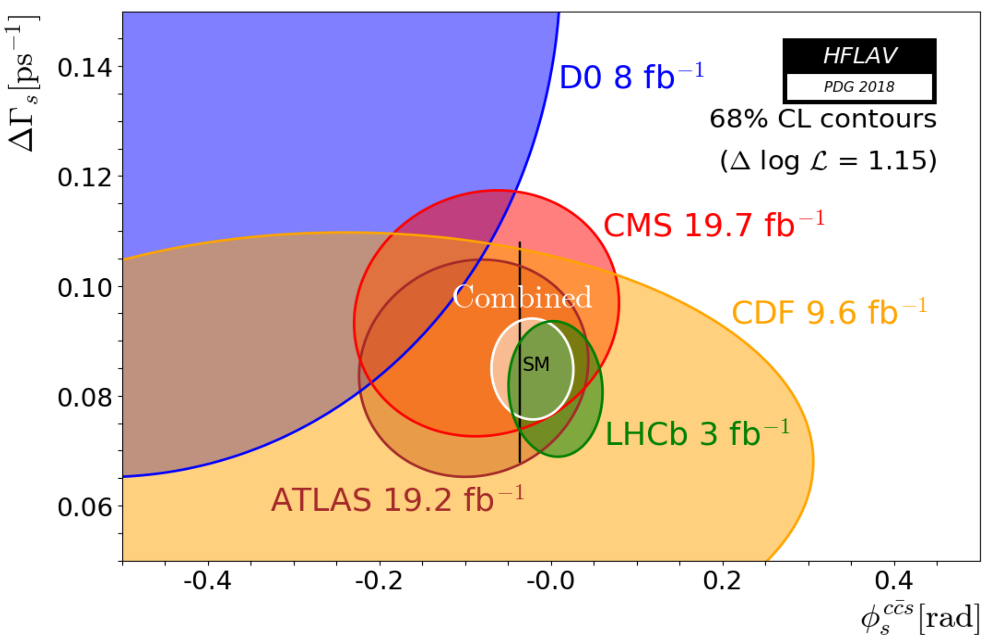
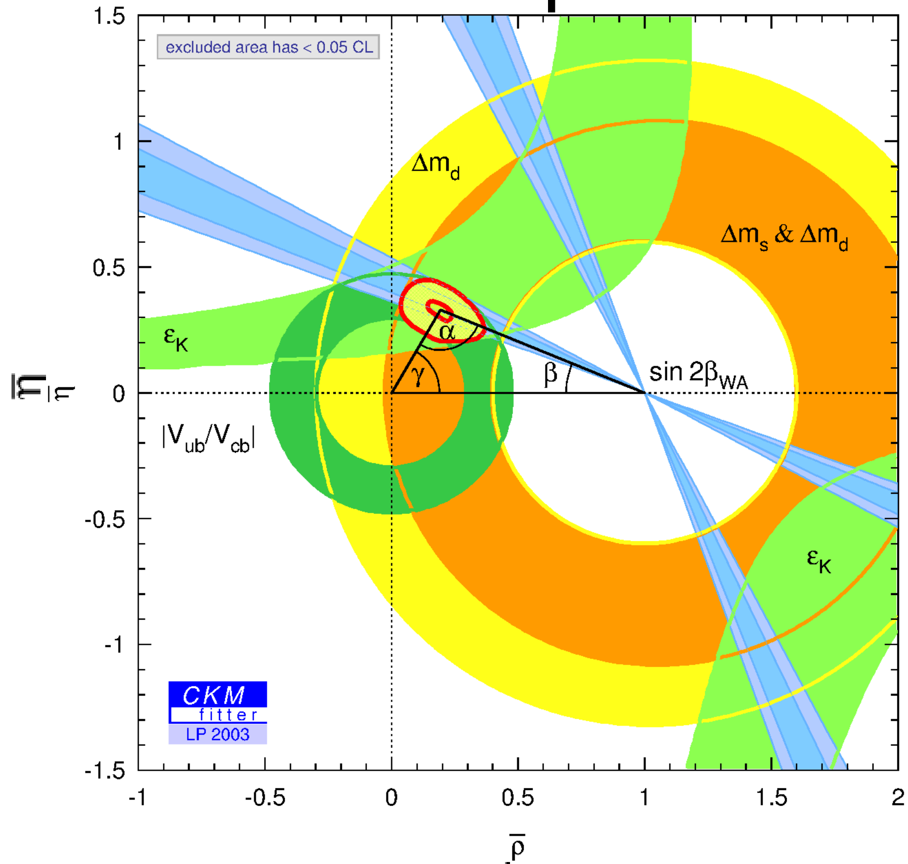
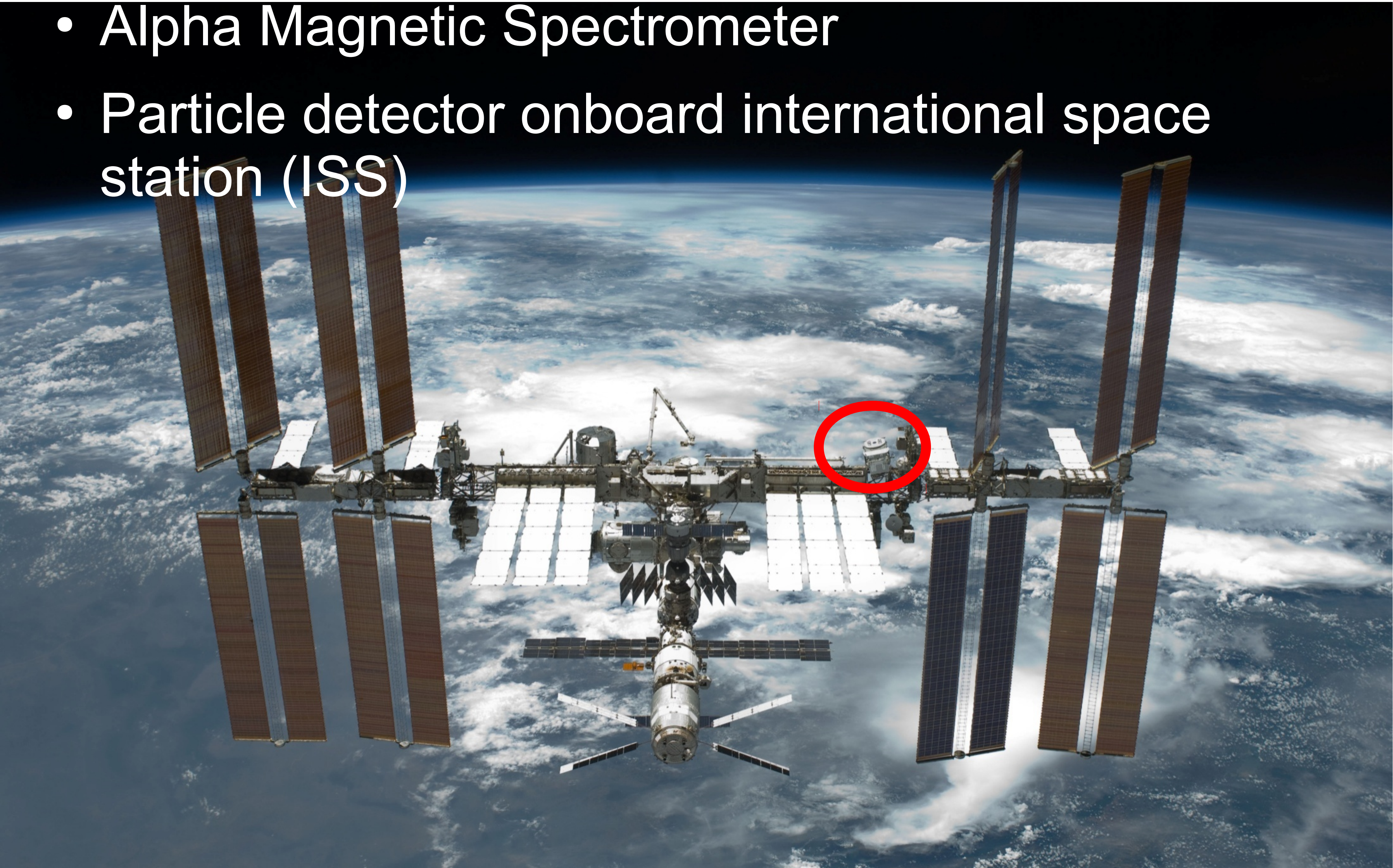




But other tantalising results from LHCb, see J. Cogan

Matter-antimatter asymmetry in space: AMS

- Alpha Magnetic Spectrometer
- Particle detector onboard international space station (ISS)



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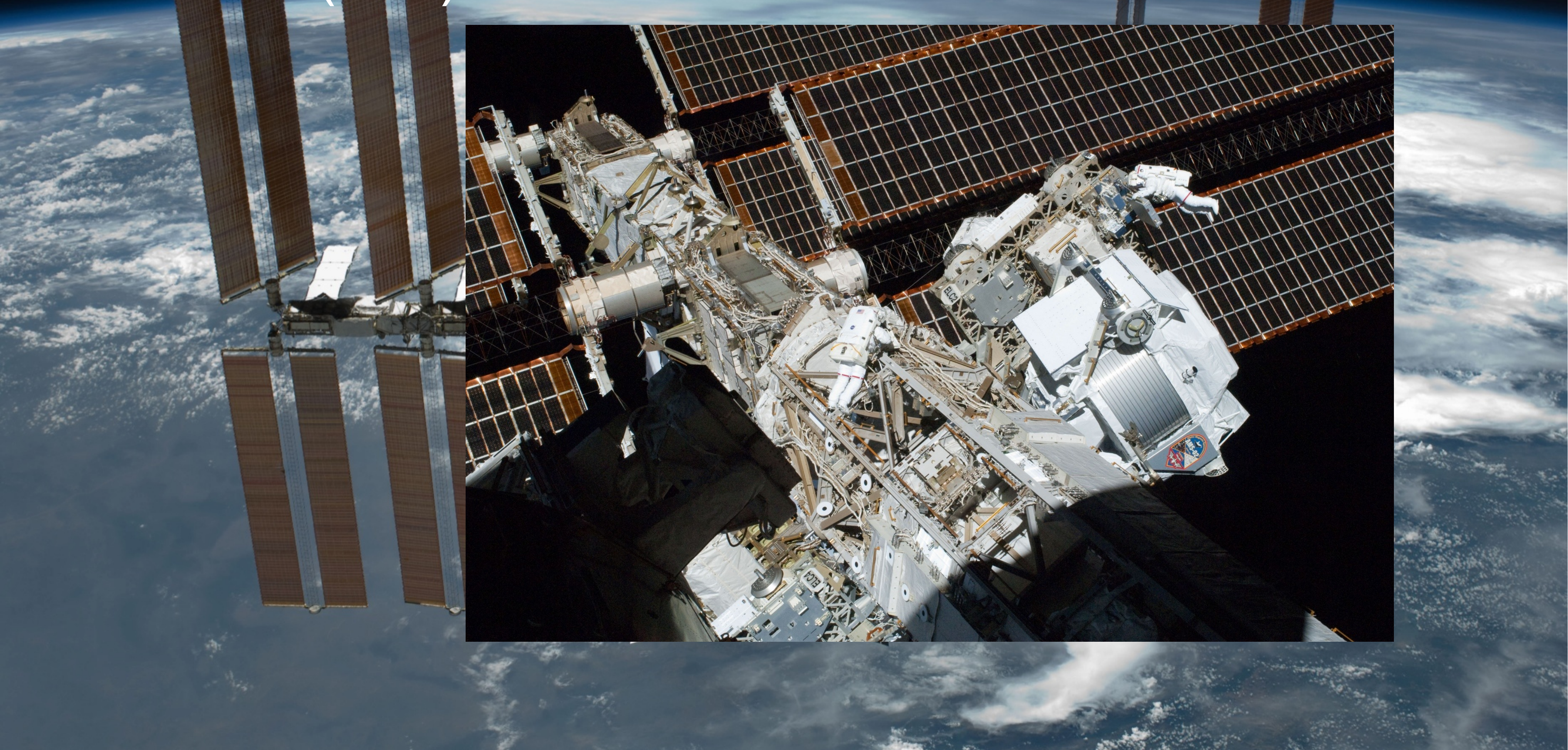
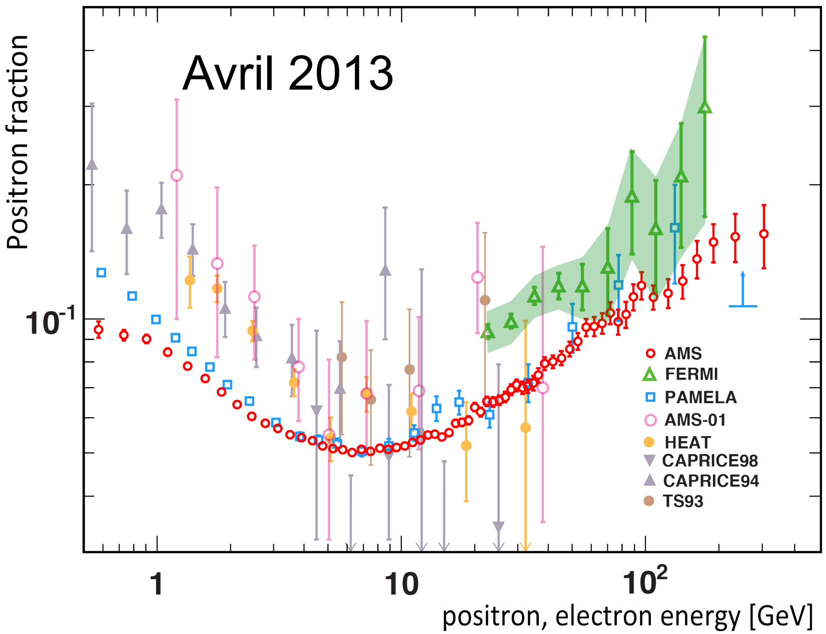


Matter-antimatter asymmetry in space: AMS

- Measures the ratio of electron and positron fluxes
- Confirmed already known positron excess
- But also excess of antiprotons and various elements
- Taking data until at least 2024



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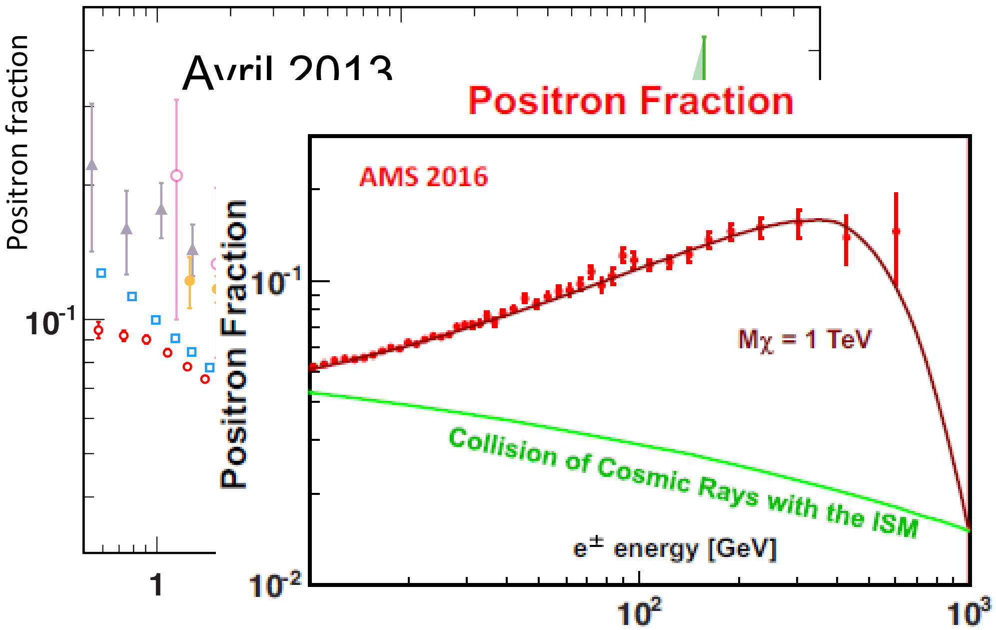

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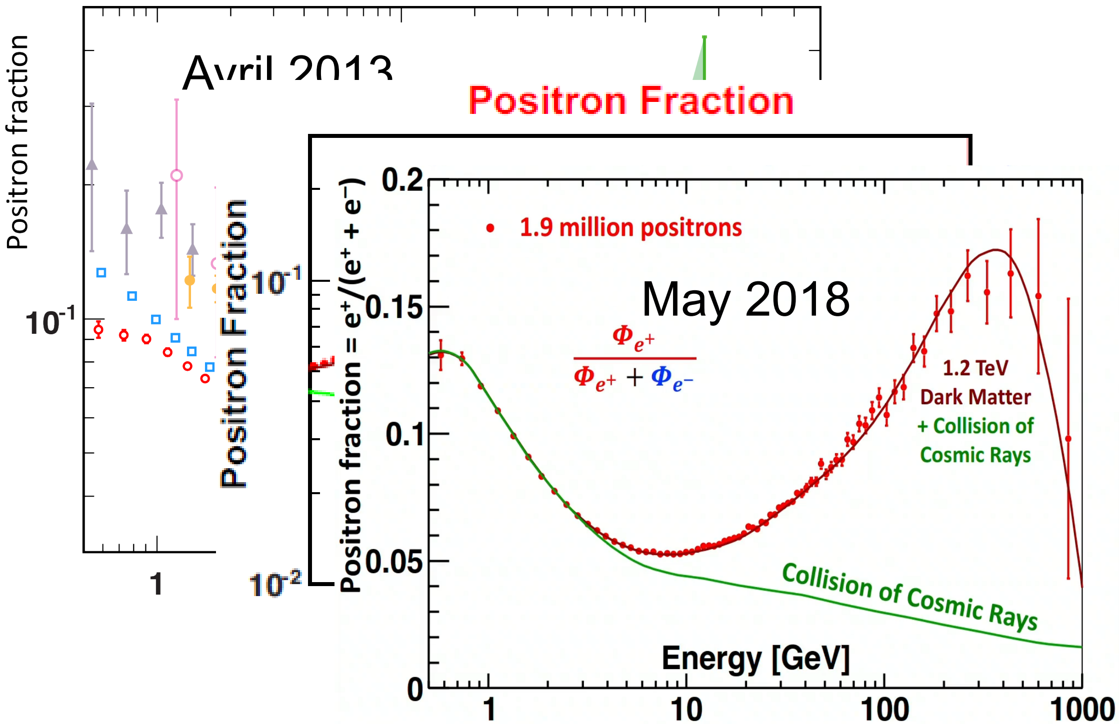

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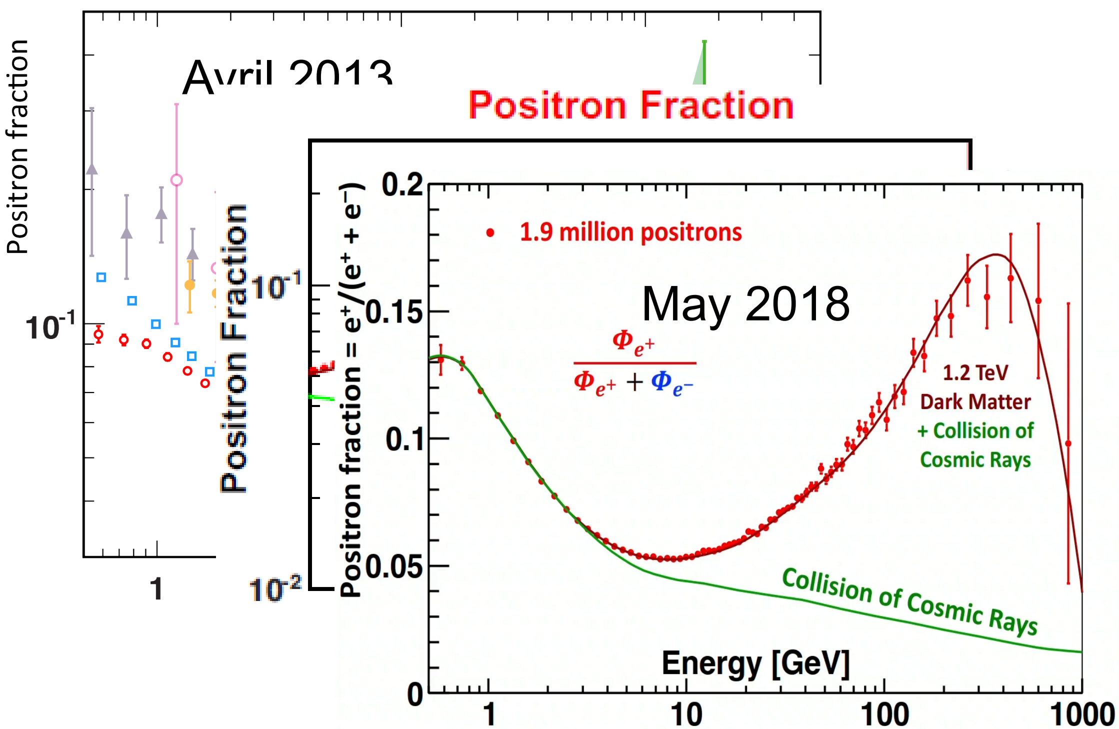
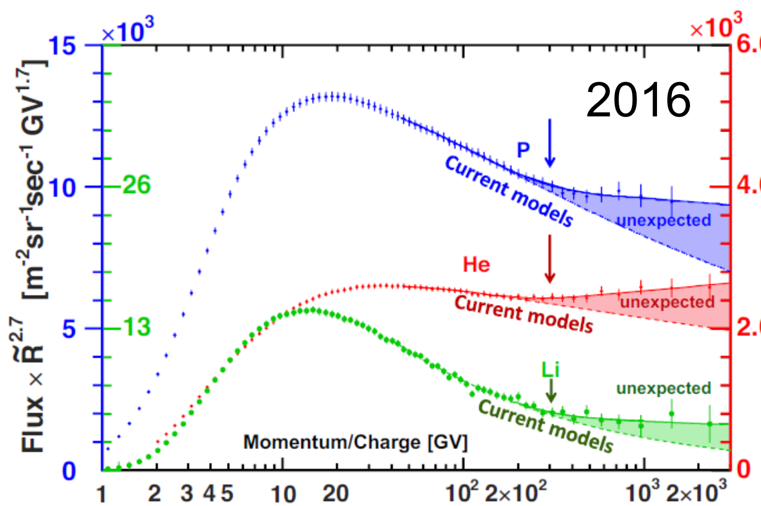
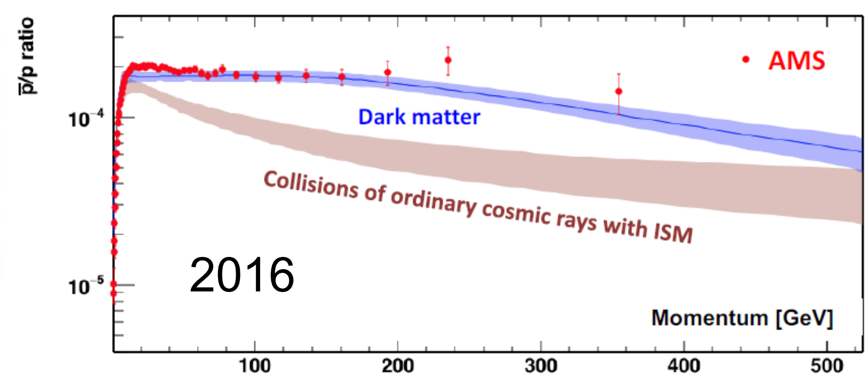


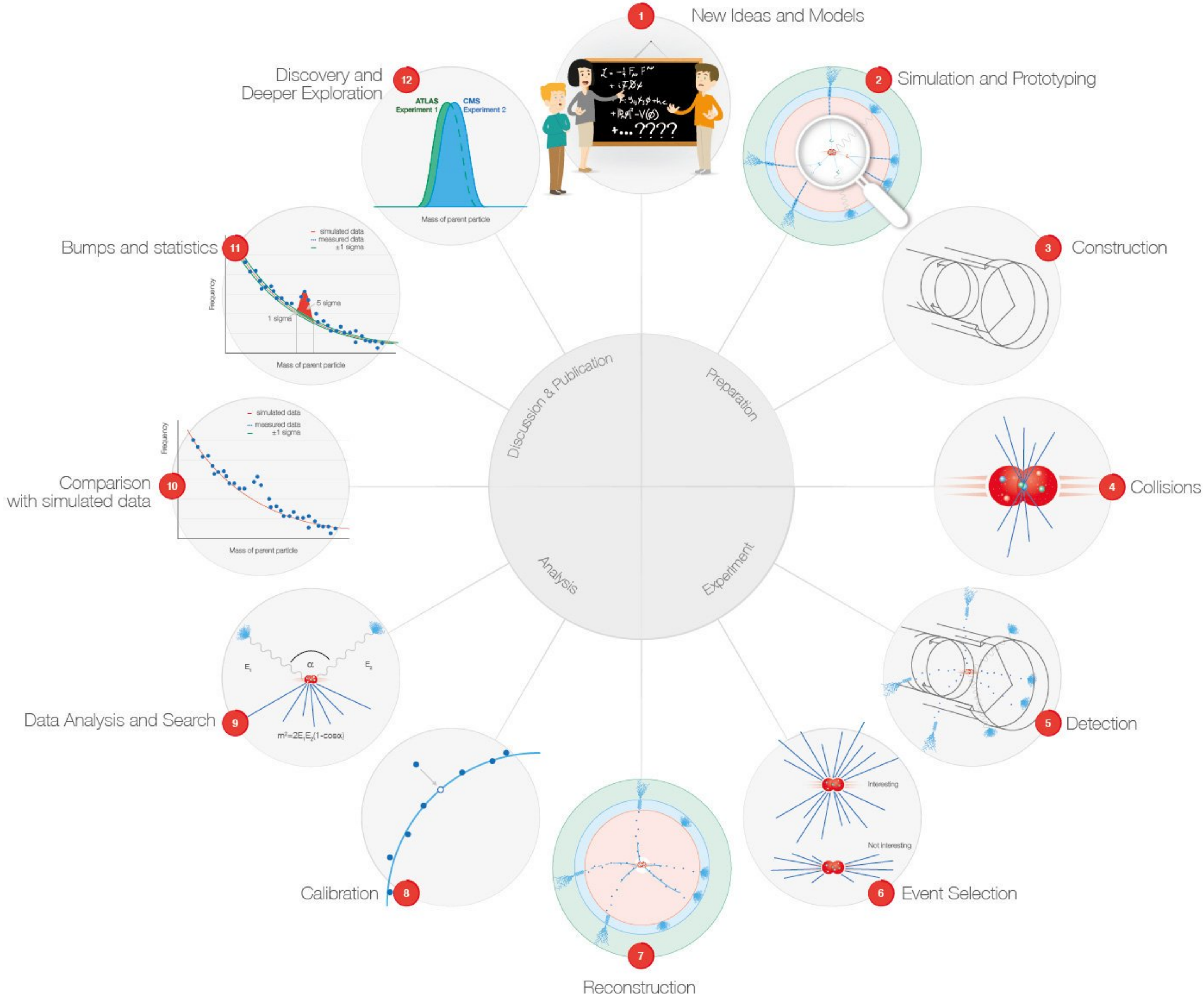




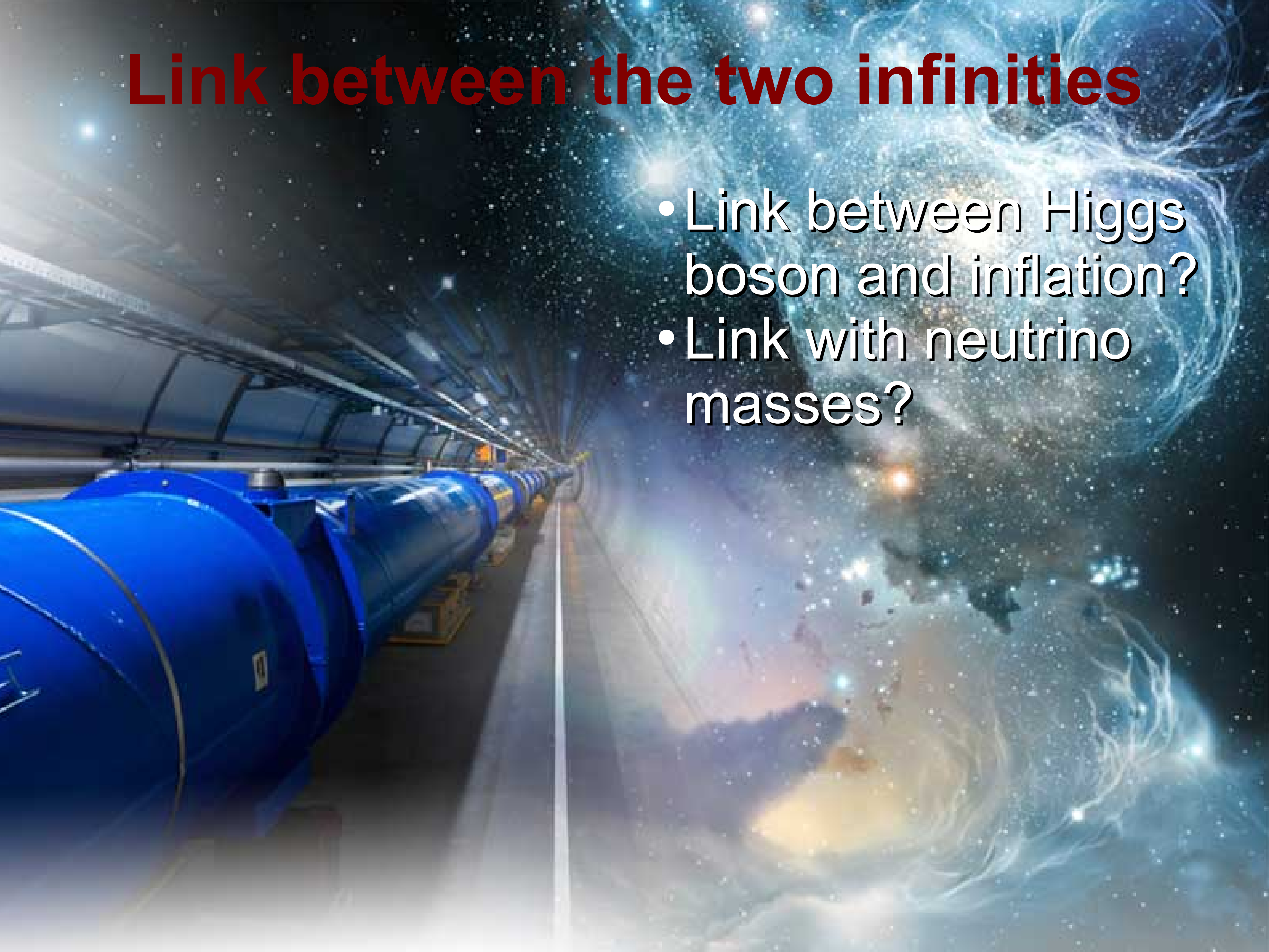
What now?

- Remember Lord Kelvin in 1900:
  - “There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.”
    - Oops, “just” missed quantum mechanics, special and general relativity...
- Safe bet: there is more to discover out there
- But: where?
- R. Kukla will tell you more about prospects next Tuesday

High energy physics life cycle



Link between the two infinities



- Link between Higgs boson and inflation?
- Link with neutrino masses?

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LHC Season 2:

- Study properties of observed boson
  - Deviations from standard model?
- Look for other Higgs bosons
  - Signs of new physics?

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- Link between Higgs boson and inflation?
- Link with neutrino masses?

LHC Season 2:

- Study properties of observed boson
  - Deviations from standard model?
- Look for other Higgs bosons
  - Signs of new physics?
- Look for dark matter candidates
- Matter-antimatter asymmetry
- Hope/wish for surprises!