Matter in Space and Time: What Do We Know?

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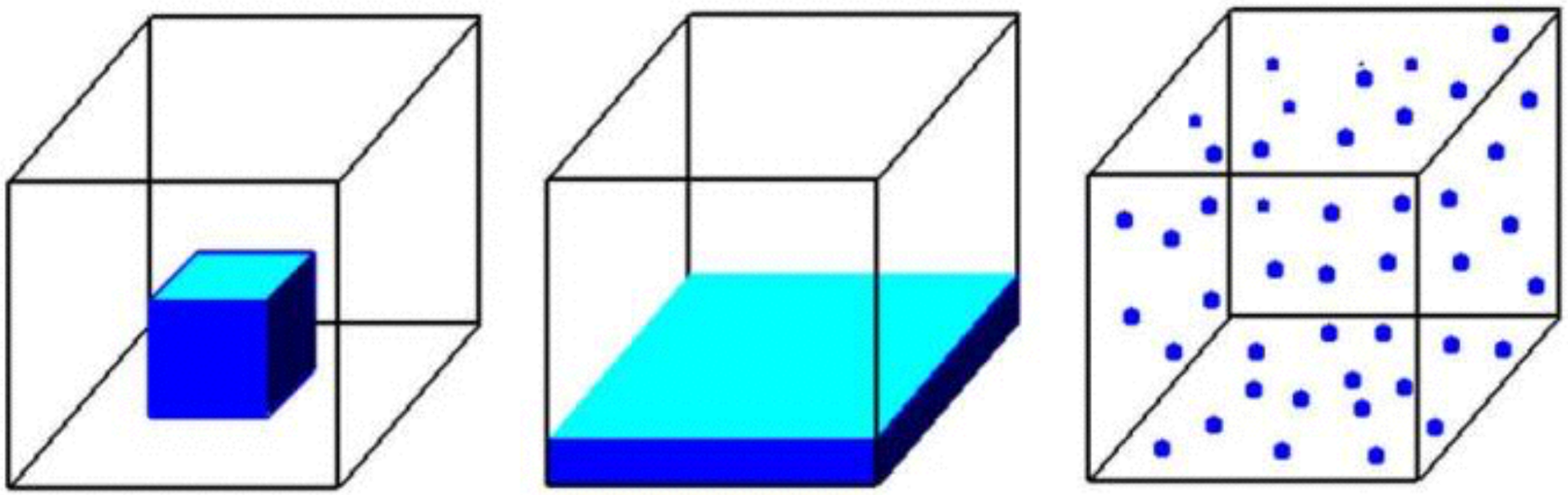
Johns Hopkins University

JHU QuarkNet meeting

Matter is anything that has mass and takes up space.

Phases of Matter



Solid

Holds Shape

Fixed Volume

Liquid

Shape of Container

Free Surface

Fixed Volume

Gas

Shape of Container

Volume of Container

What is Mass?

- We are all familiar with either inertial mass or gravitational mass

$$\vec{F} = m\vec{a} \text{ or } \vec{F} = m\vec{g}$$

they are equivalent in General Relativity

- Mass and Energy are equivalent

$$E = mc^2$$ in Special Relativity

- Mass is important even without Gravity (e.g. in vacuum)

- The Higgs Mechanism provides mass to elementary particles

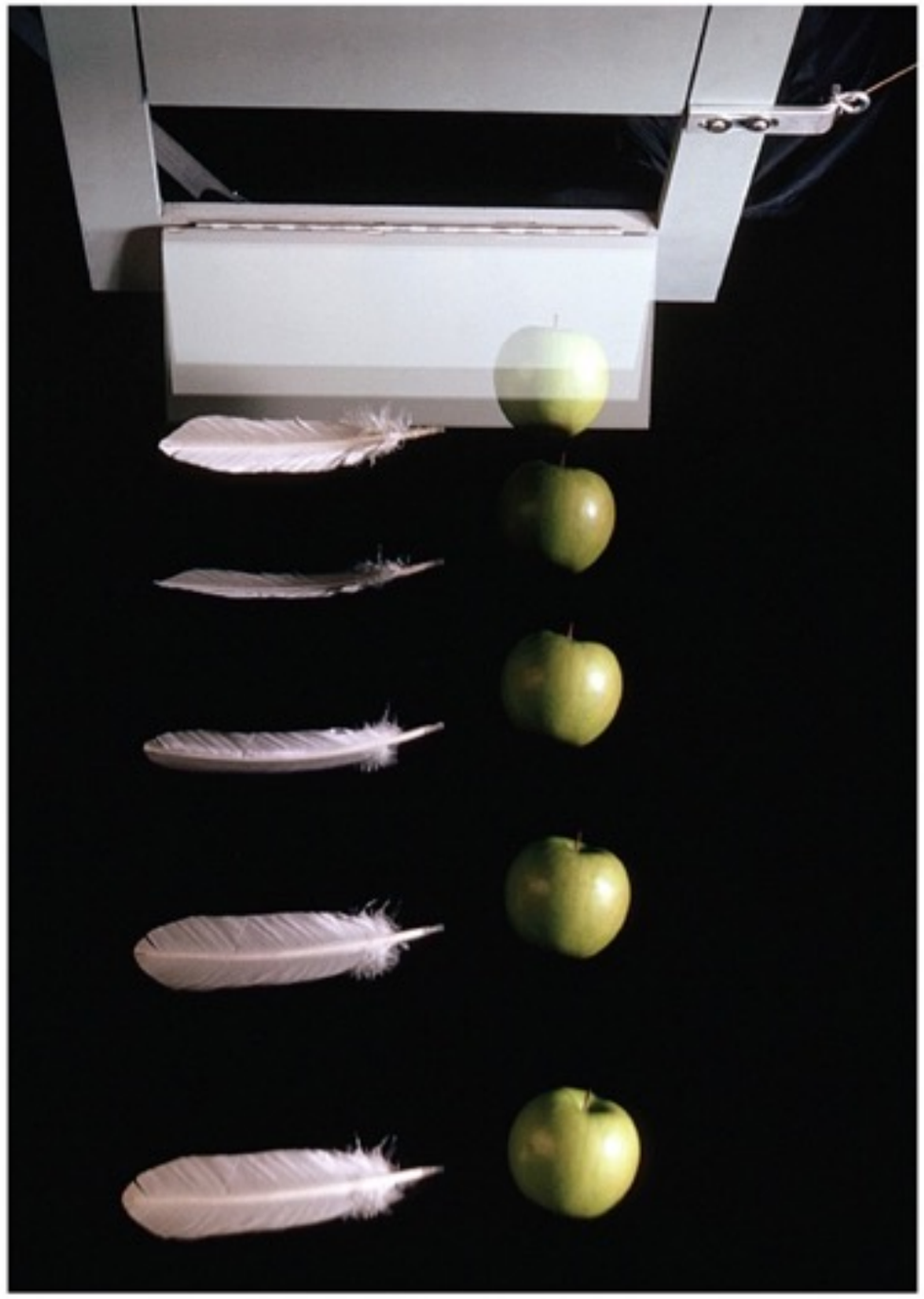
- Is our MASS due to the Higgs Mechanism ???

Gravity

$$F = G\frac{m_1 m_2}{r^2} \qquad \text{(Newton's law of gravitation).}$$

- Gravity is far-reaching and very important!
  - Holds us to the Earth
  - Holds Earth in orbit around the Sun
  - Holds the Sun together with the stars in our galaxy
  - Reaches out across intergalactic space to hold together the Local Group of galaxies
  - Holds together the Local Supercluster of galaxies
  - Pulls the supercluster toward the Great Attractor
  - Attempts to slow the expansion of the universe
  - Is responsible for black holes

Acceleration in free fall



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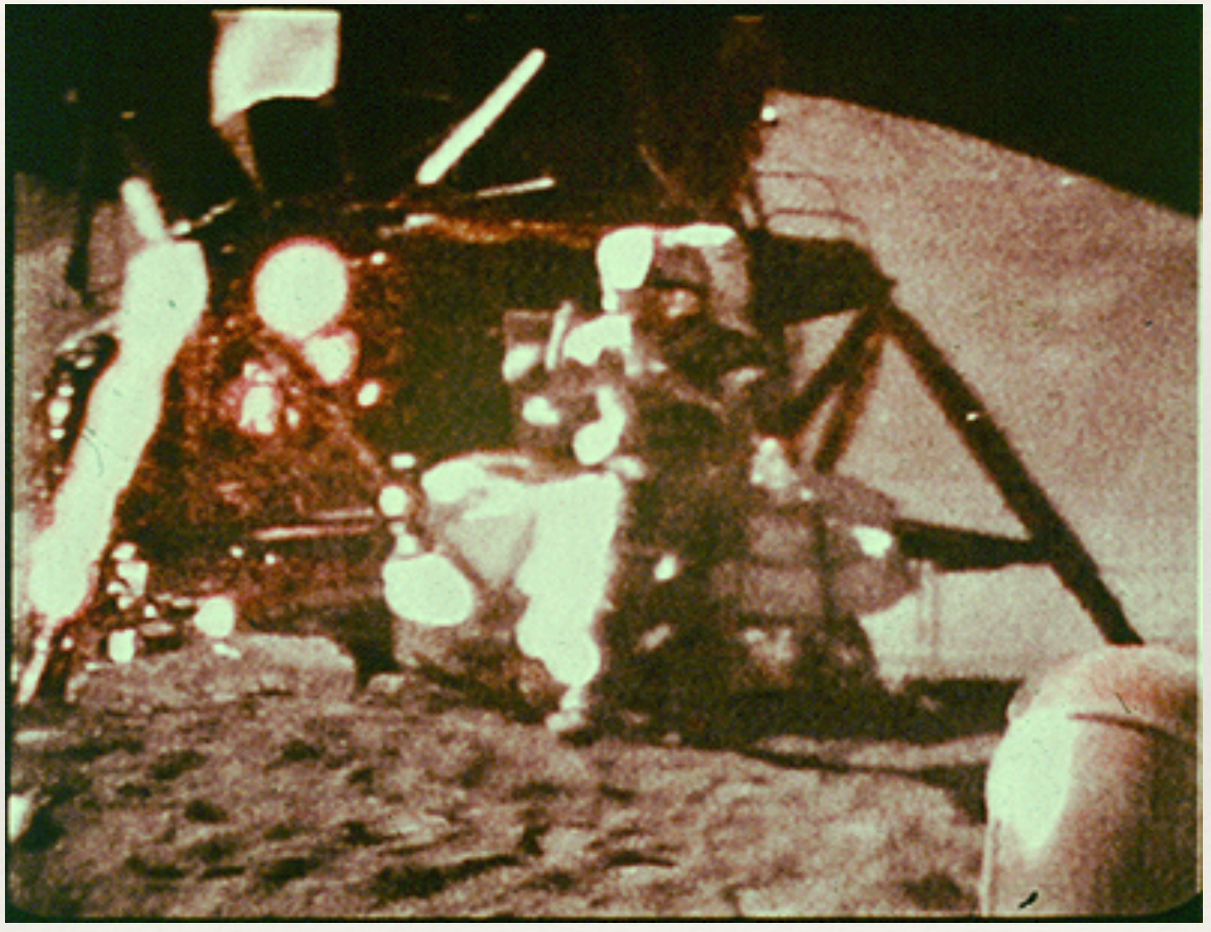
Dime and Feather fall

The Apollo 15 Hammer-Feather Drop

What is the difference between weight and mass?



$$a_g = \frac{GM_{\text{Moon}}}{r^2}.$$

$$\vec{F} = G\frac{m_1 m_2}{r^2}\hat{\mathrm{r}}.$$

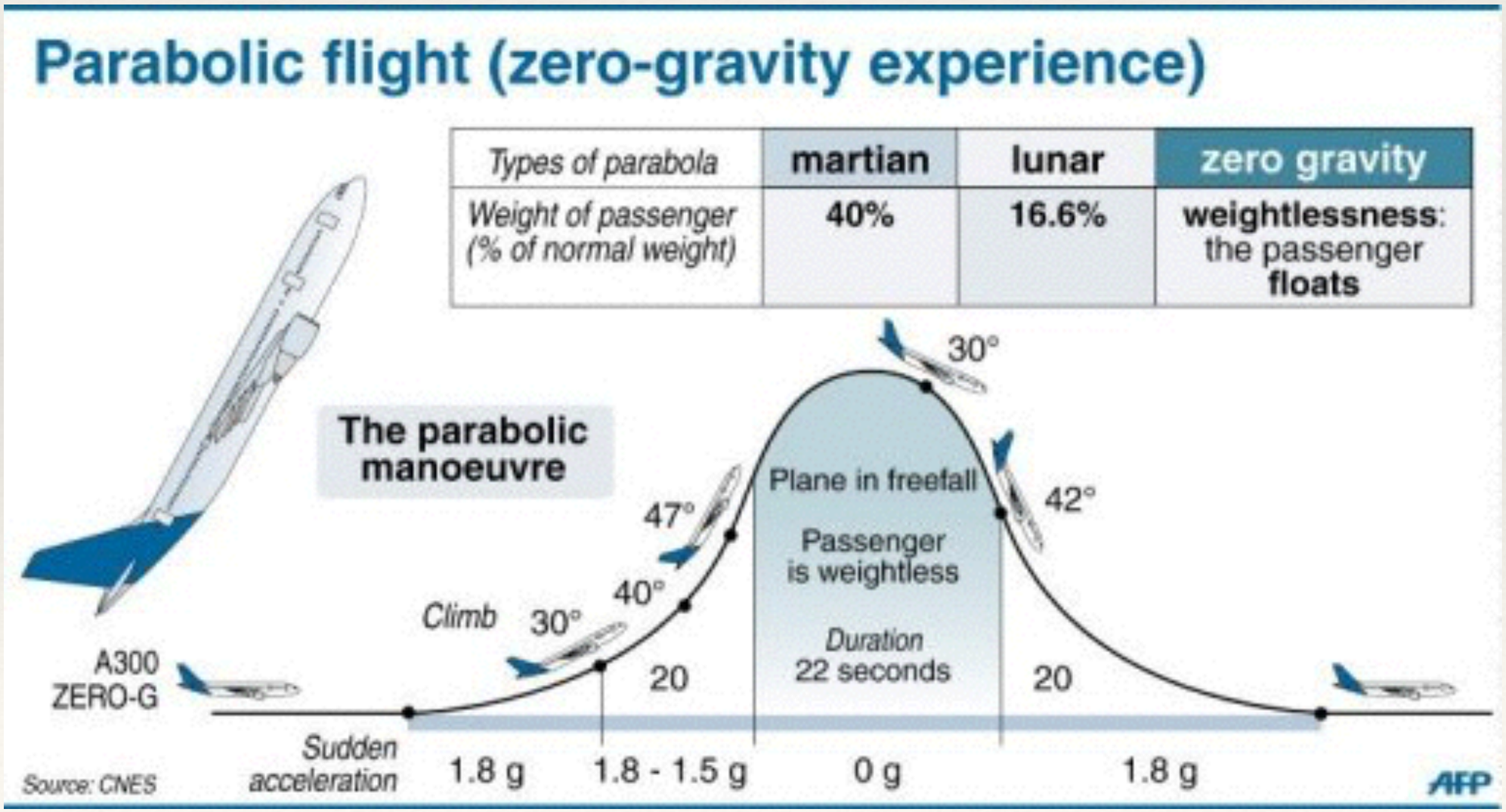
The Apollo 15 Hammer-Feather Drop

What is the difference between weight and mass?

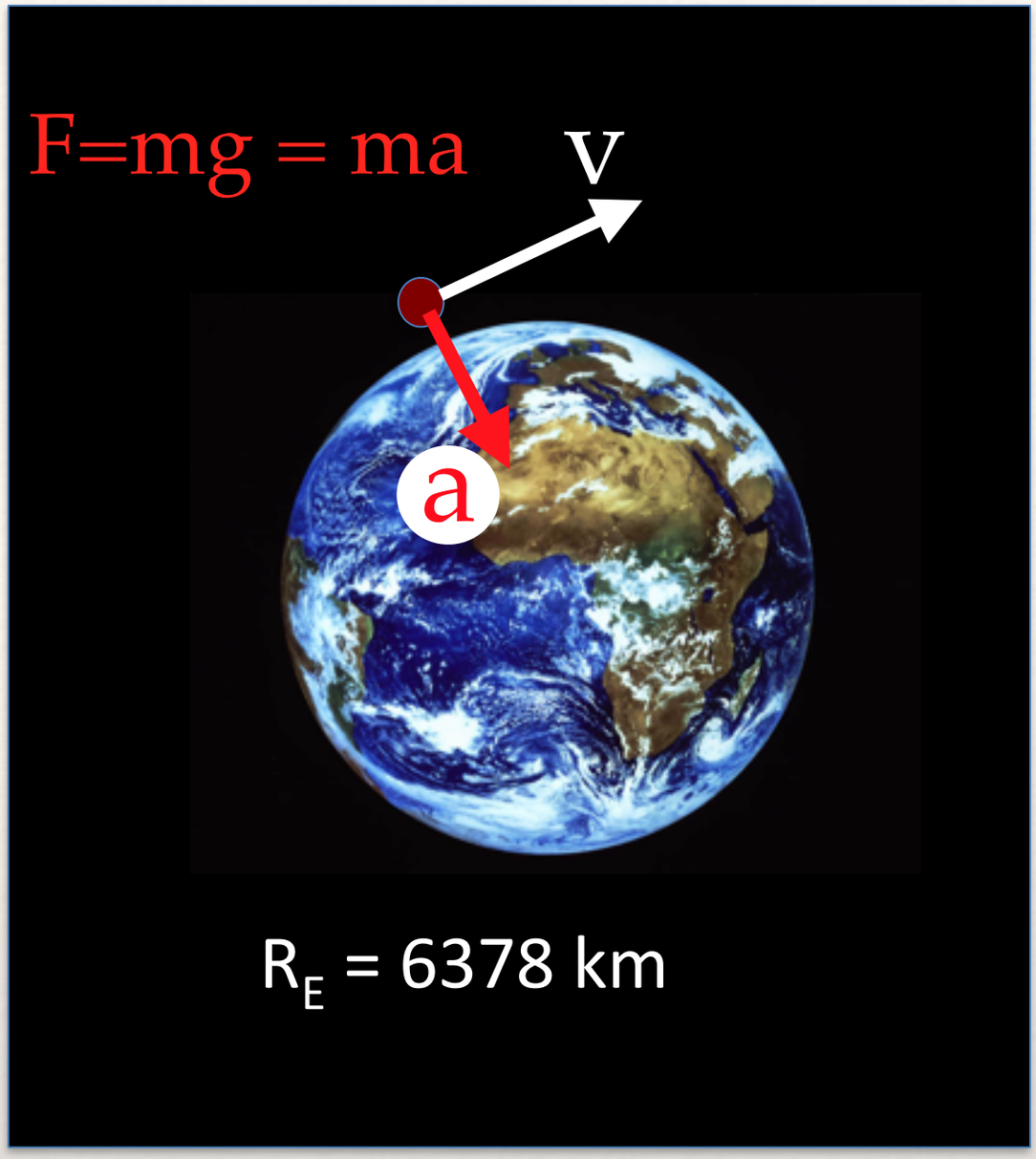
“Zero Gravity”

Zero G Corporation's Boeing 727

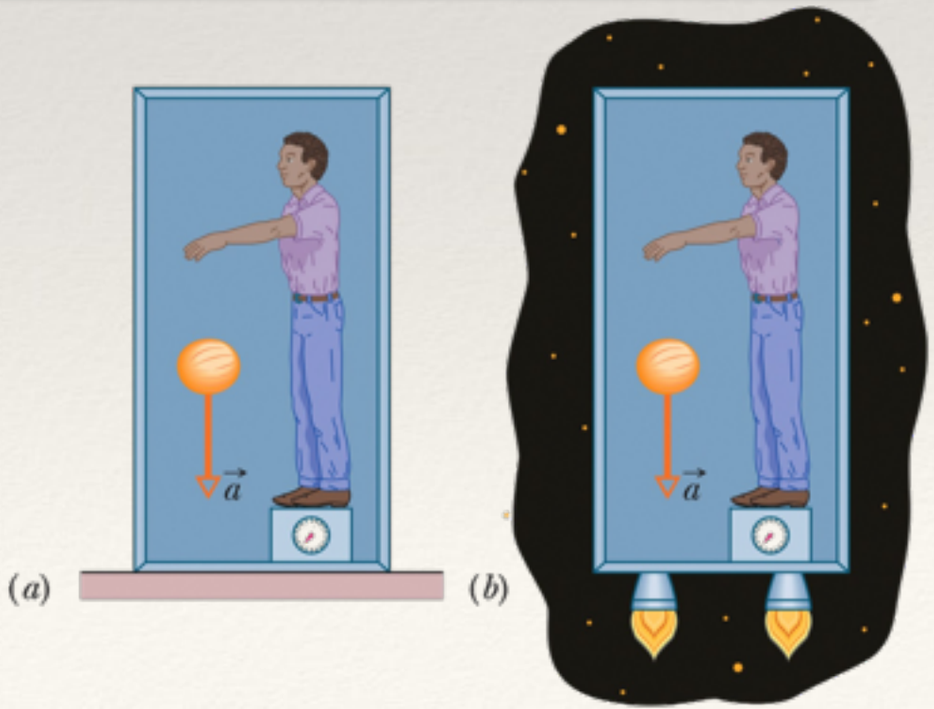
Russian Space Agency's IL-76 MDK



"Zero Gravity"
is not really
Zero Gravity,
only feels like
zero gravity



Theory of General Relativity
by Einstein



Planet Gravity

$$a_g = \frac{GM}{r^2}.$$

Earth 9.8 m/s²

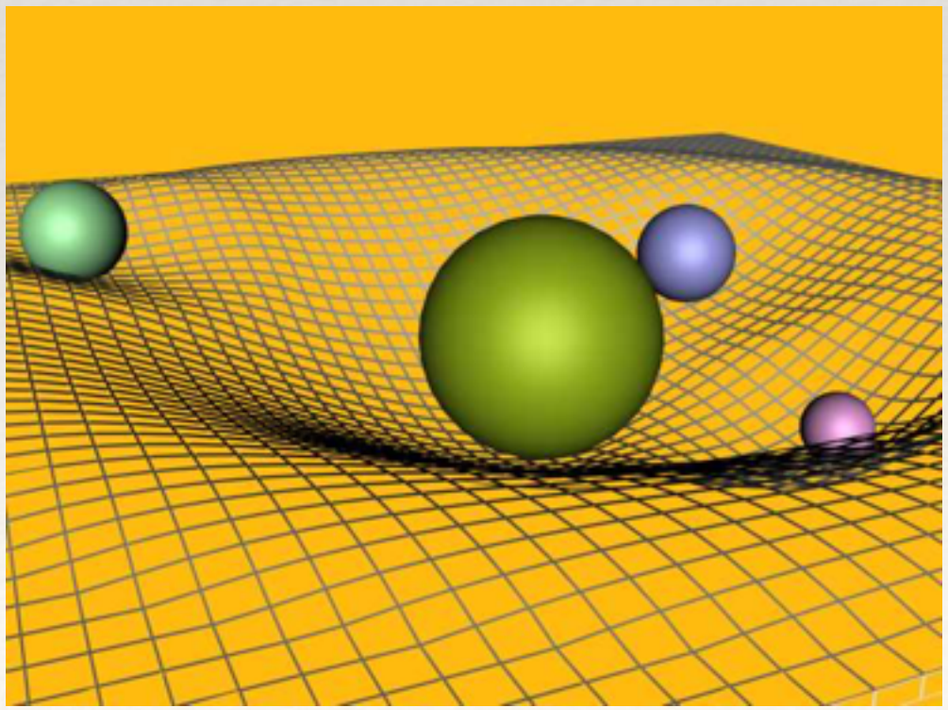
Moon 1.6 m/s²

Mars 3.7 m/s²

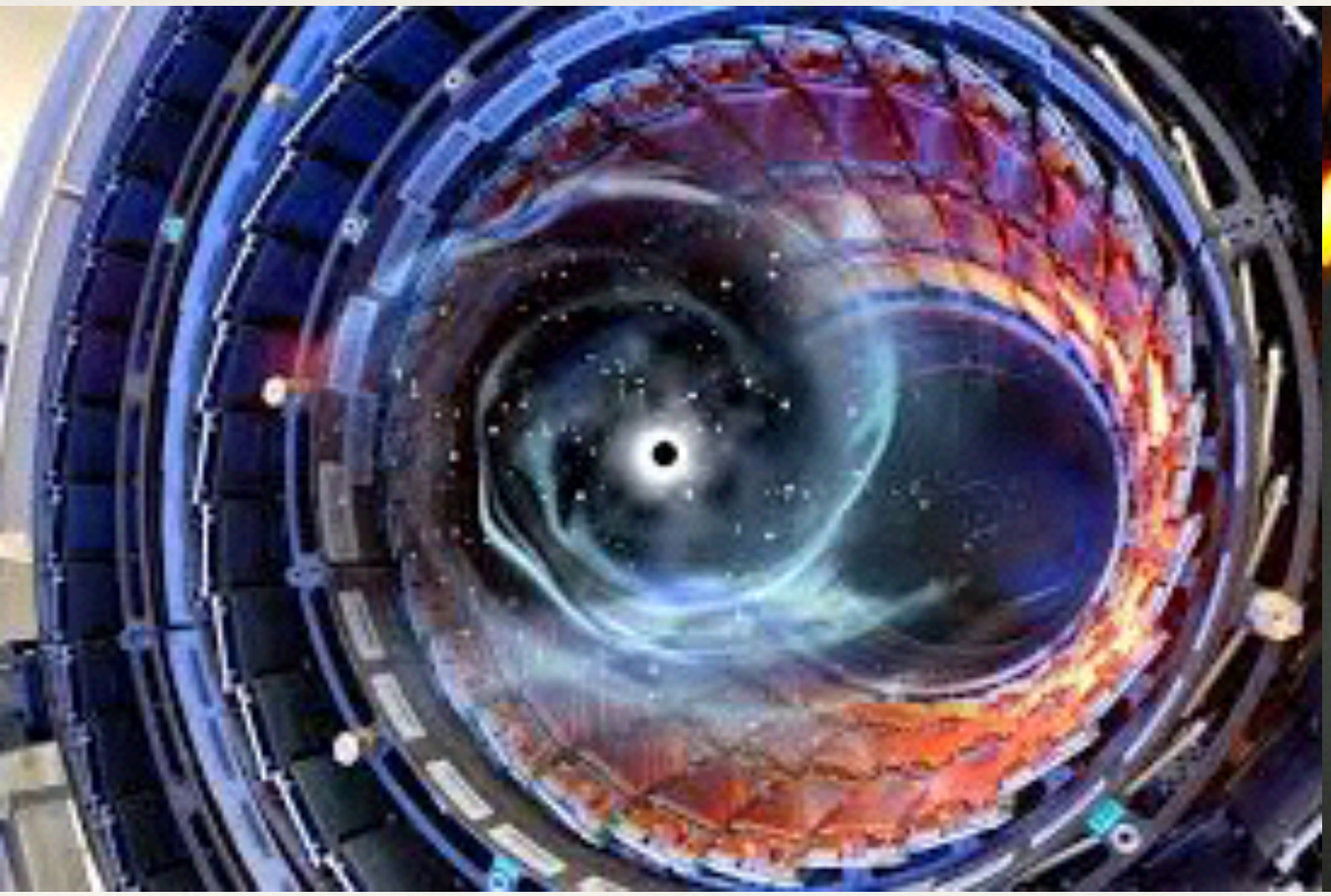
Jupiter 24.8 m/s²

Gravity, Spacetime, and Gravitons

- Gravity is an attractive force between masses
- On a large scale: explained as an effect of curved spacetime
- On a small scale: carried by a fundamental particle, the *graviton*
- How to connect all these things is still being worked out
- Are there gravitons? Are there extra dimensions of space? We still do not know all answers…

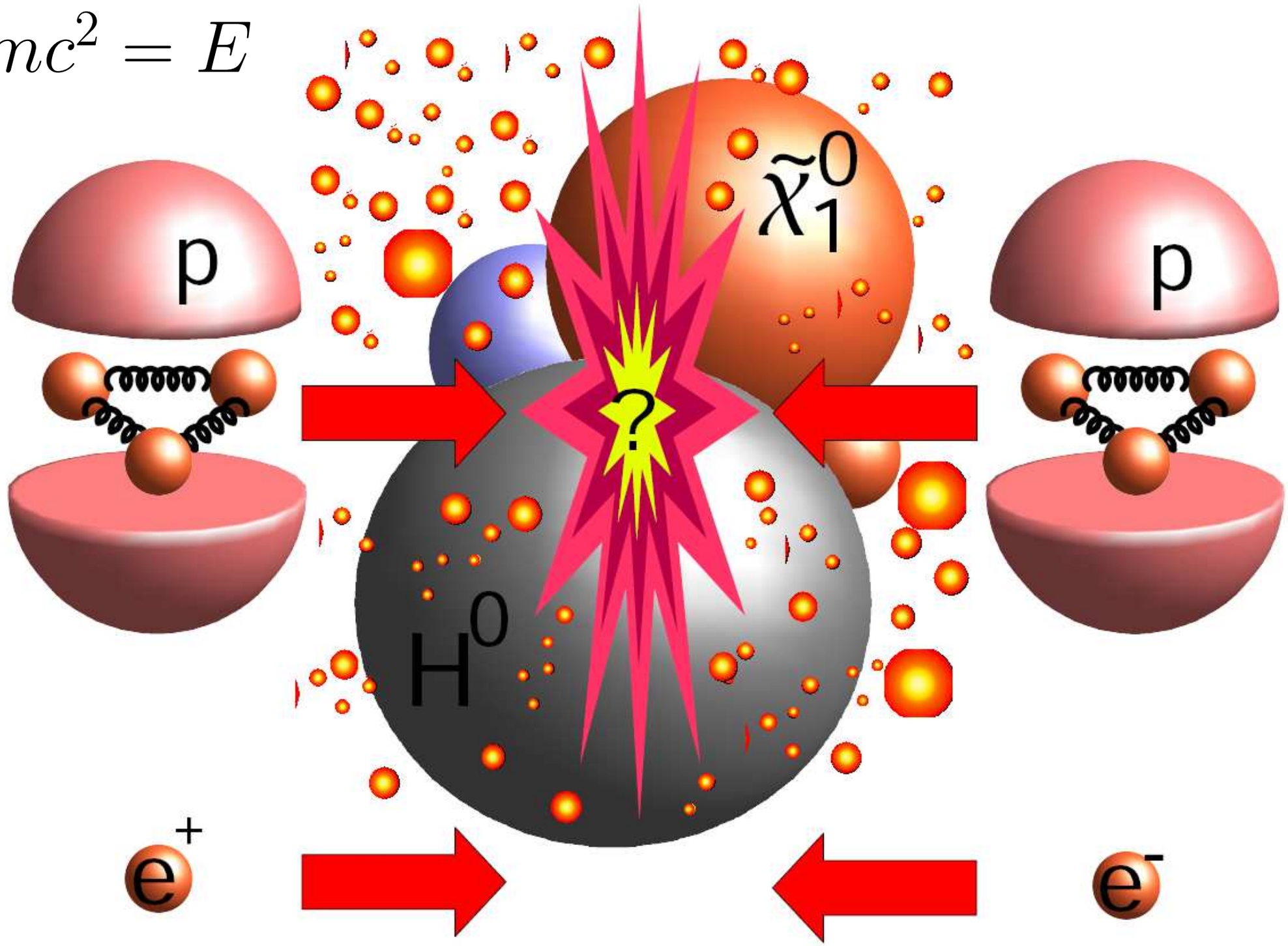


Gravity, General Relativity, and LHC



Reaching Highest Energy

- $mc^2 = E$



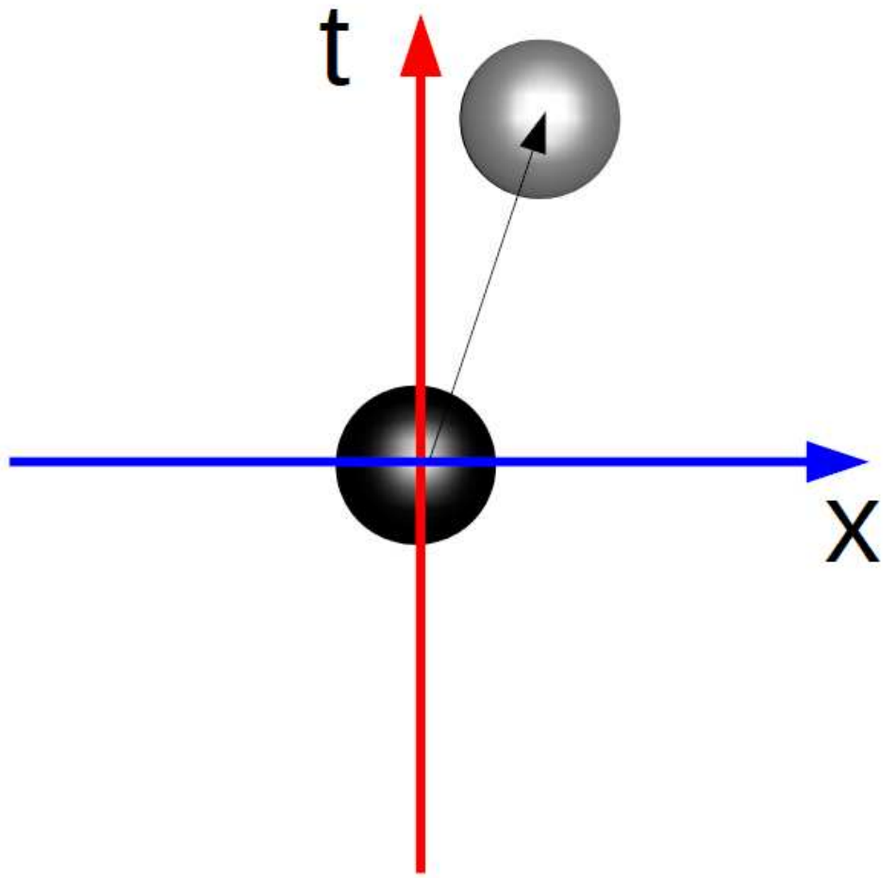
What is Space-Time?

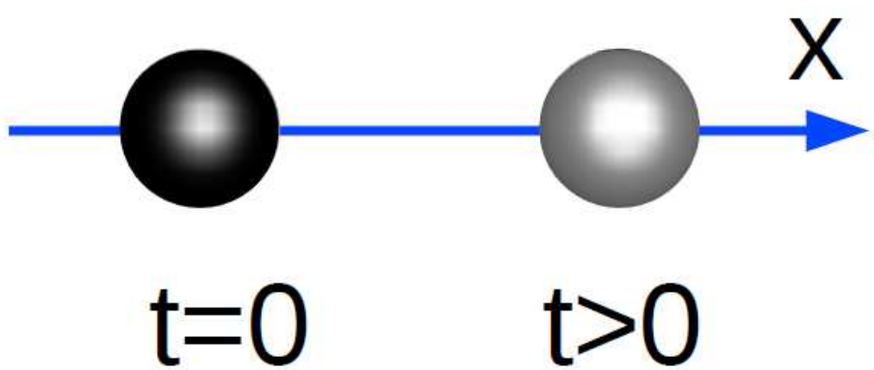
- Space-time: combination of space and time

  3 dimensions of space (though this is being questioned)

  time is the 4th dimension

- It is a mathematical model to write physics laws





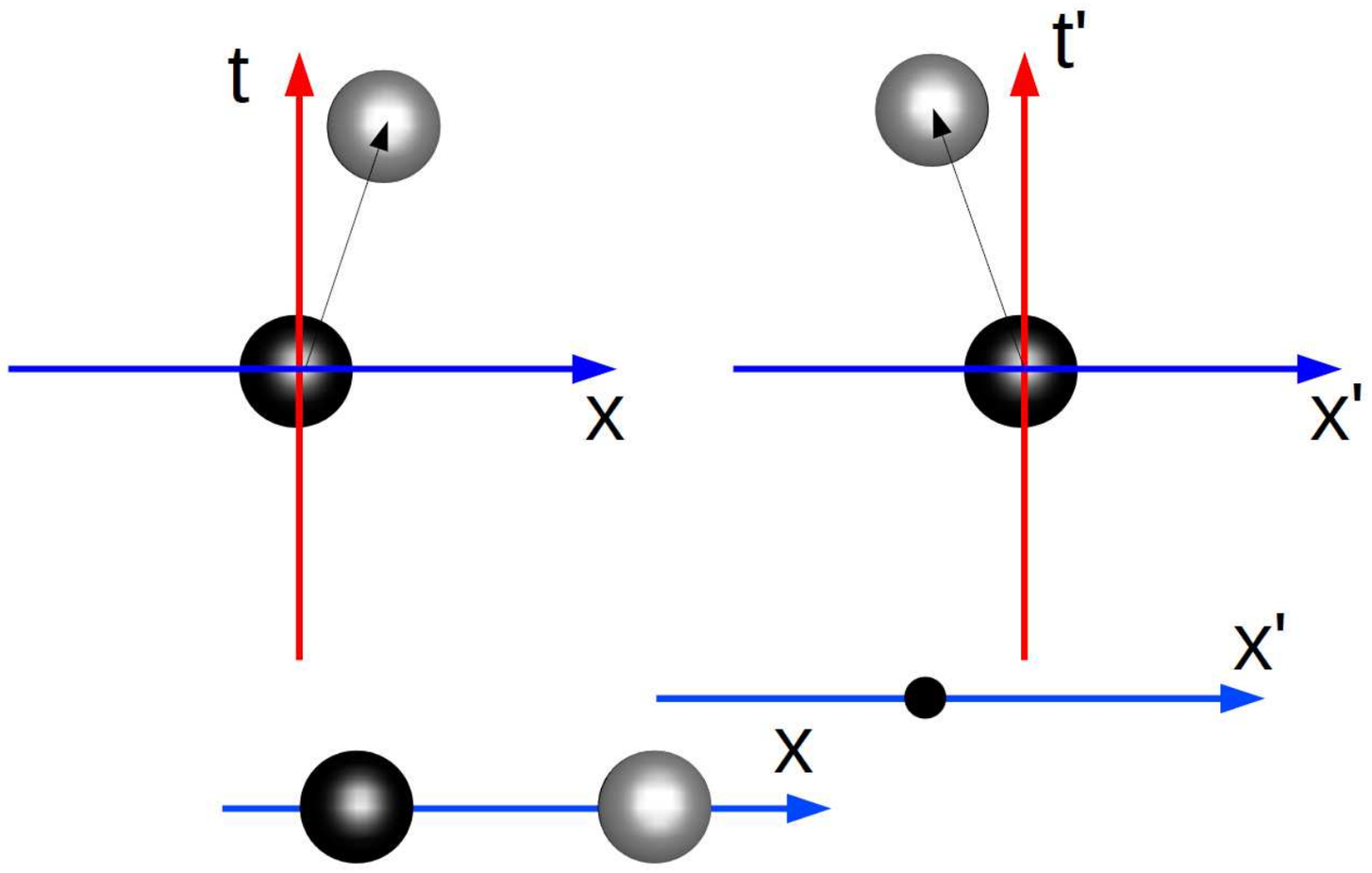
Space-Time

- Space-time in classical physics (Galilean transformation)

  $\Rightarrow$ time is absolute and independent of space

- In Special Relativity (and later General)

  $\Rightarrow$ time and space are related $\Rightarrow$ time different in frames



Consequence of Einstein's postulates

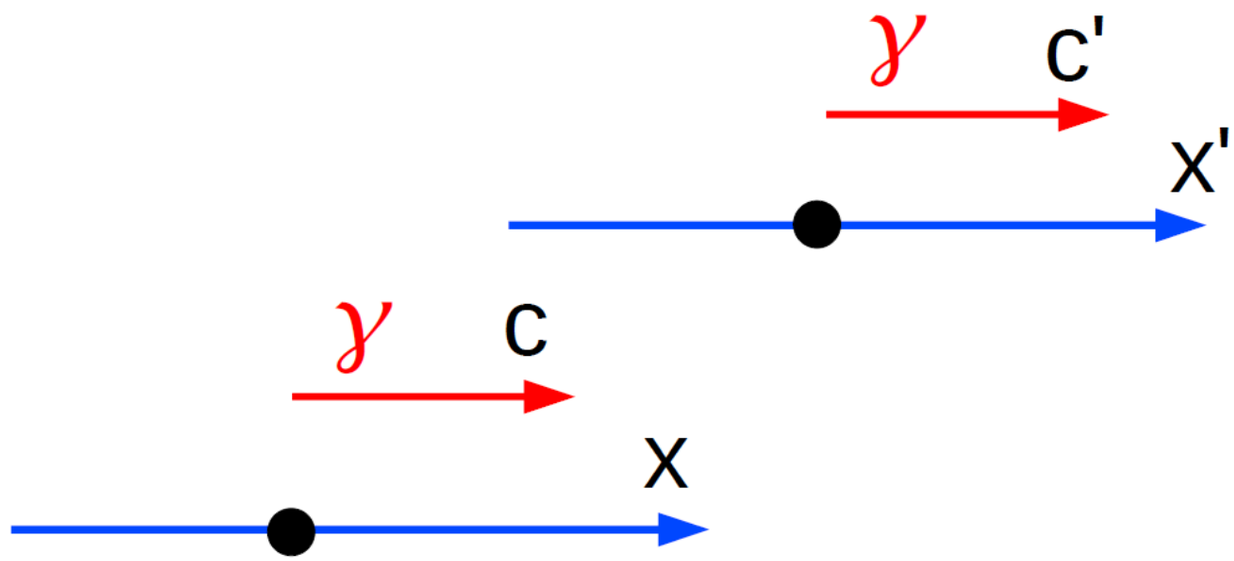
- Special Relativity

$$t = (t' + \frac{v}{c^2} \times x')/\sqrt{1 - \frac{v^2}{c^2}} \tag{5}$$

$$x = (x' + v \times t')/\sqrt{1 - \frac{v^2}{c^2}} \tag{6}$$

$$y = y' \tag{7}$$

$$z = z' \tag{8}$$



Did the trick work?

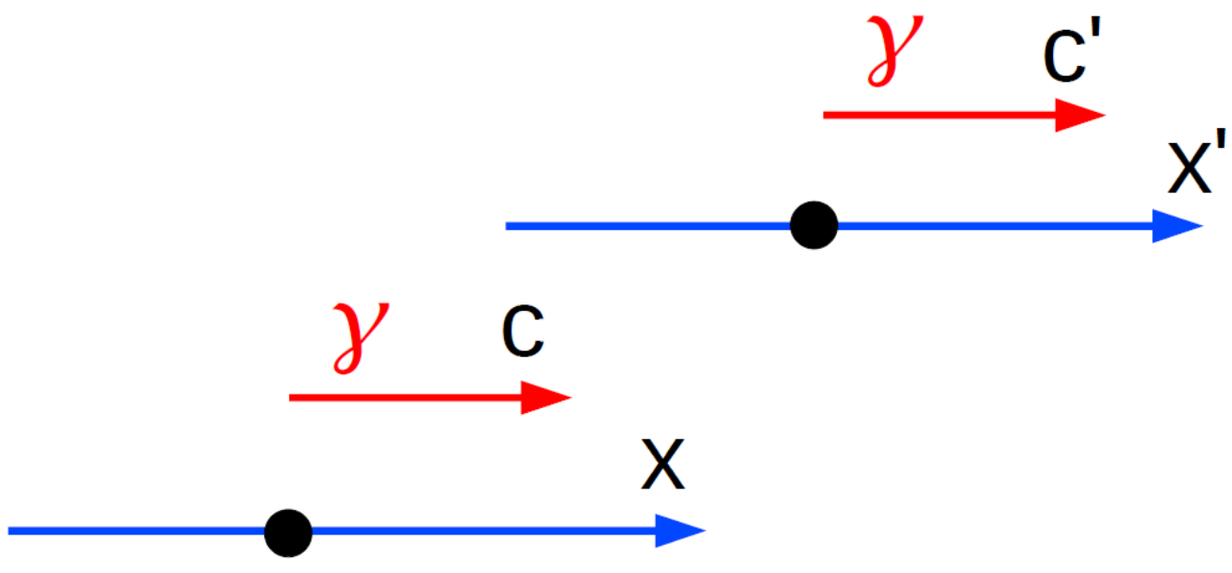
- A photon (light) will travel $x = c \times t$

$$x = (x' + v \times t')/\sqrt{1 - \frac{v^2}{c^2}} = c \times t$$

$$t = (t' + \frac{v}{c^2} \times x')/\sqrt{1 - \frac{v^2}{c^2}}$$

$$\Rightarrow (x' + v \times t') = (ct' + \frac{v}{c} \times x')$$

$$\Rightarrow c' = \frac{x'}{t'} = \frac{c-v}{1-v/c} \equiv c \quad \Rightarrow \text{same speed of light}$$



Time dilation

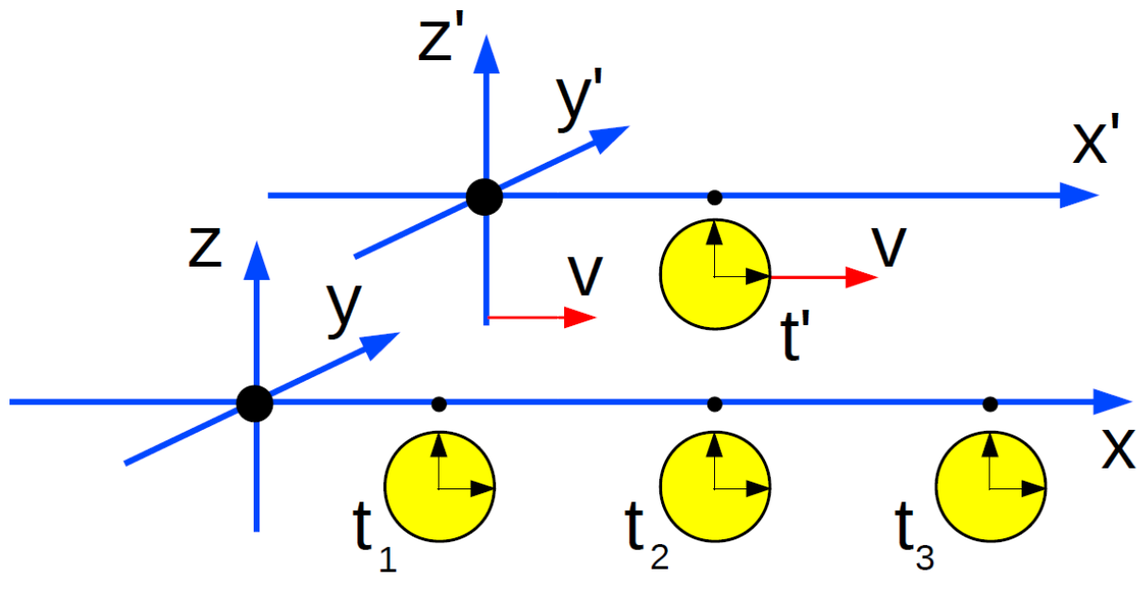
- Consider moving clock at $x' =$const in its own frame

$$\Delta t'_0 = (t'_2 - t'_1)$$

- Time between two events in our frame $\Delta t = (t_2 - t_1)$

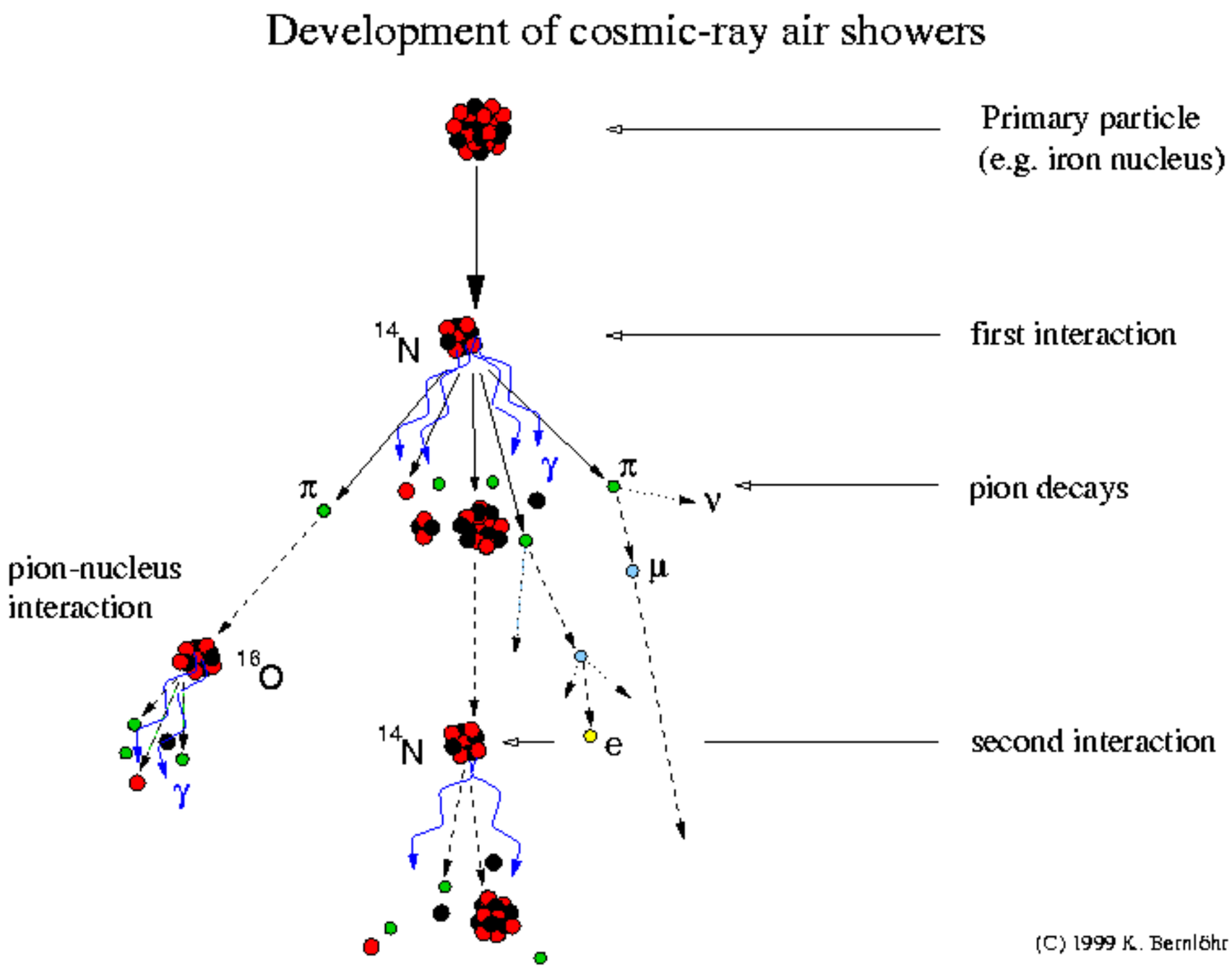
$$\Delta t = (t'_2 + \frac{v}{c^2}x')/\sqrt{1 - \frac{v^2}{c^2}} - (t'_1 + \frac{v}{c^2}x')/\sqrt{1 - \frac{v^2}{c^2}}$$

$$\Delta t = \Delta t'_0/\sqrt{1 - \frac{v^2}{c^2}}$$



Cosmic Rays: Source of Anti-Matter

- Observed muon $\mu^{\pm}$ like electron/positron, just heavy



Time dilation: muon

- Muon with $v = 0.9994 \times c$ and $\gamma = 1/\sqrt{1 - \frac{v^2}{c^2}} = 29$

- From our point of view

muon is moving speed $v \simeq c$

time dilated

$$\Delta t = \Delta t'_0 \times \gamma$$

– distance $\Delta L = 19$ km

– time $\Delta t = 64 \times 10^{-6}$ s

- From muon point of view

Earth is moving speed $v \simeq c$

distance contracted

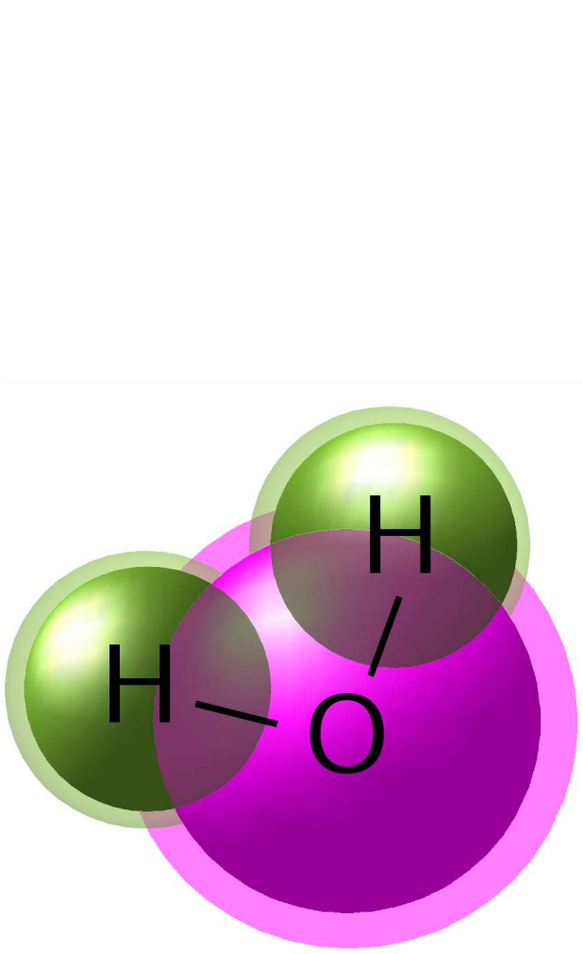
$$\Delta L'_0 = \Delta L / \gamma$$

$\Delta L'_0 = 659$ m

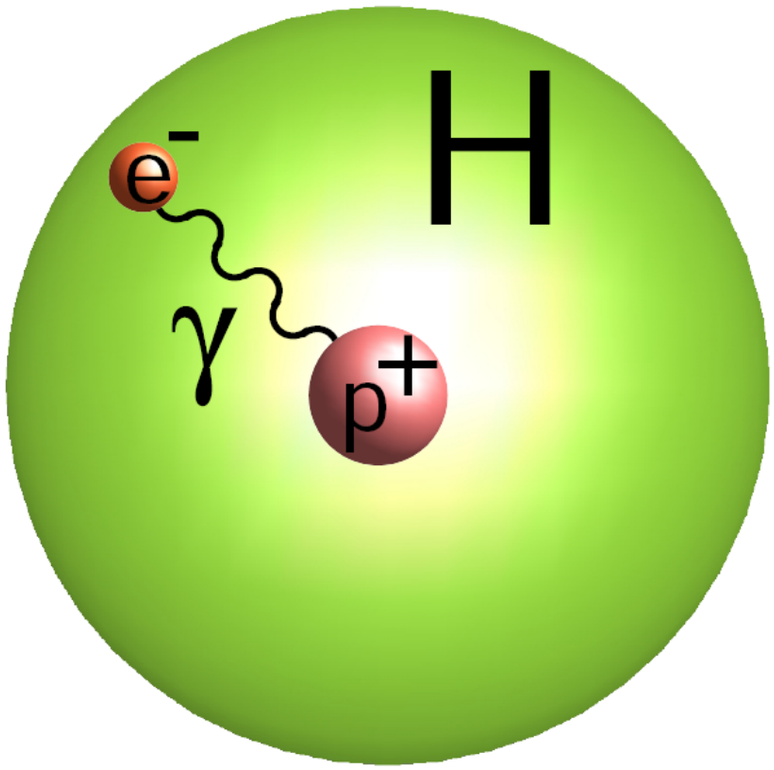
$\Delta t'_0 = 2.2 \times 10^{-6}$ s

What makes mass?

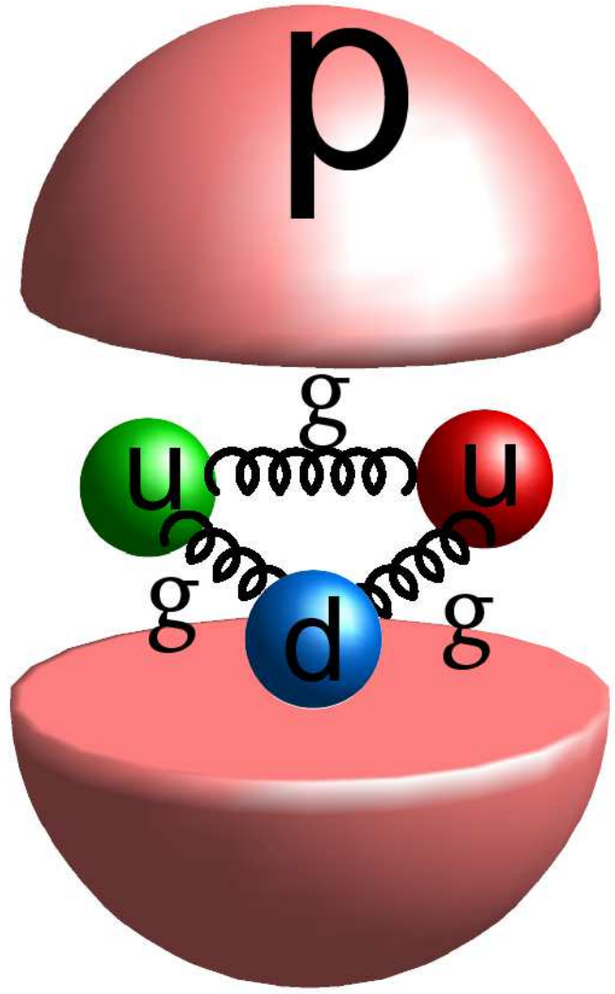
- What gives us mass?



Molecules



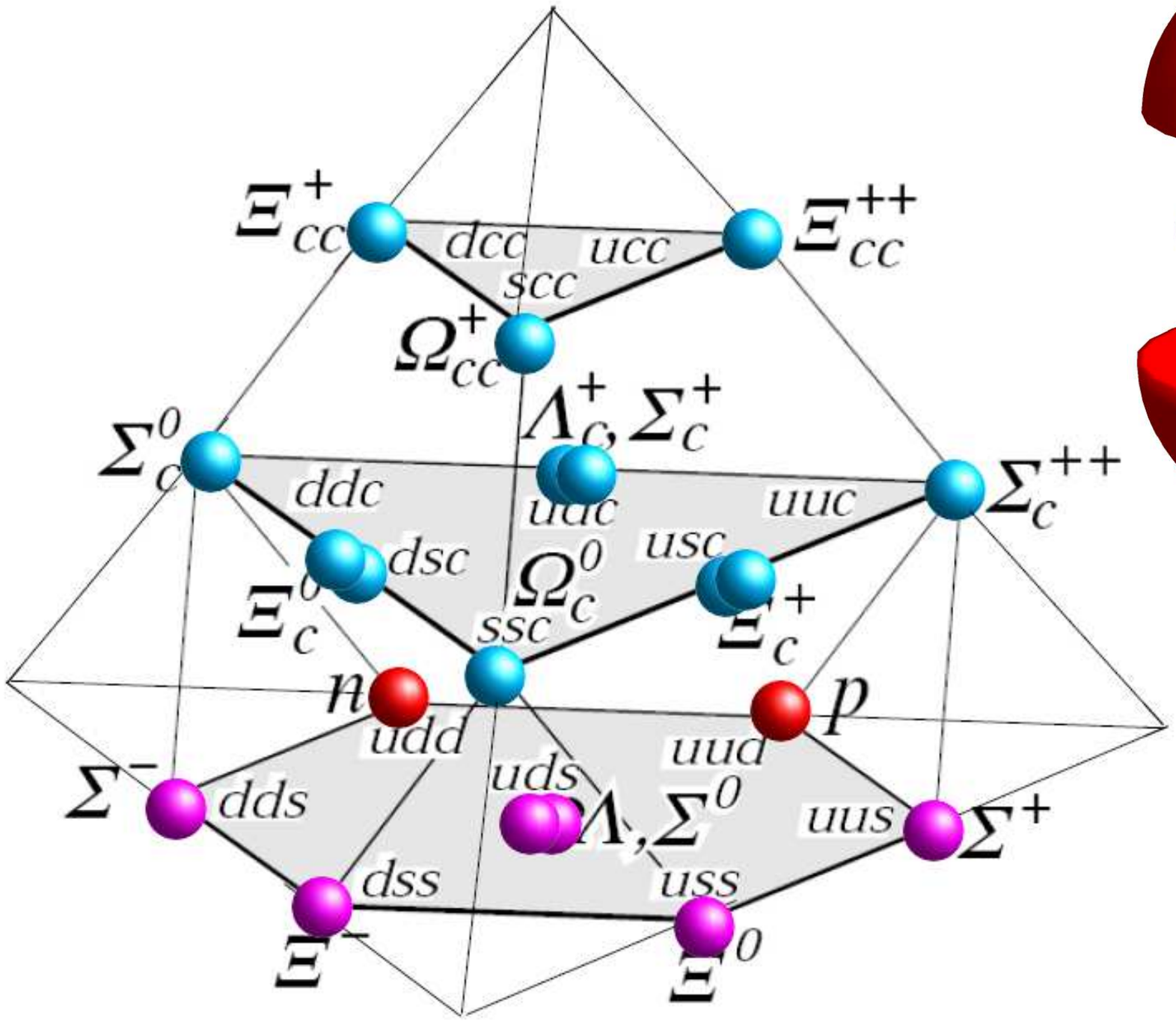
Atoms

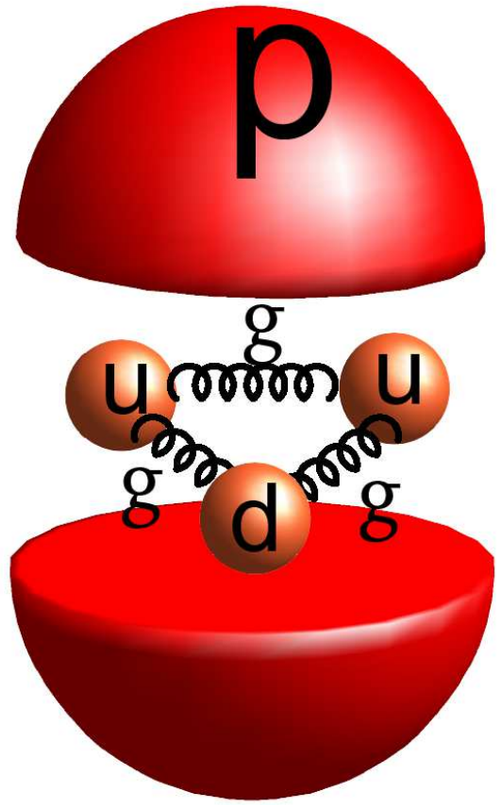


Nucleus

"Periodic Table" of Baryons: Proton, Neutron,...

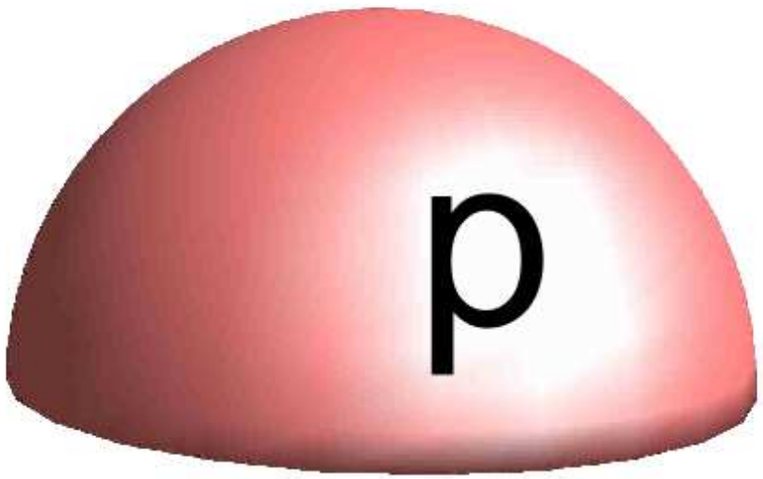
- Three quarks make up a Baryon:

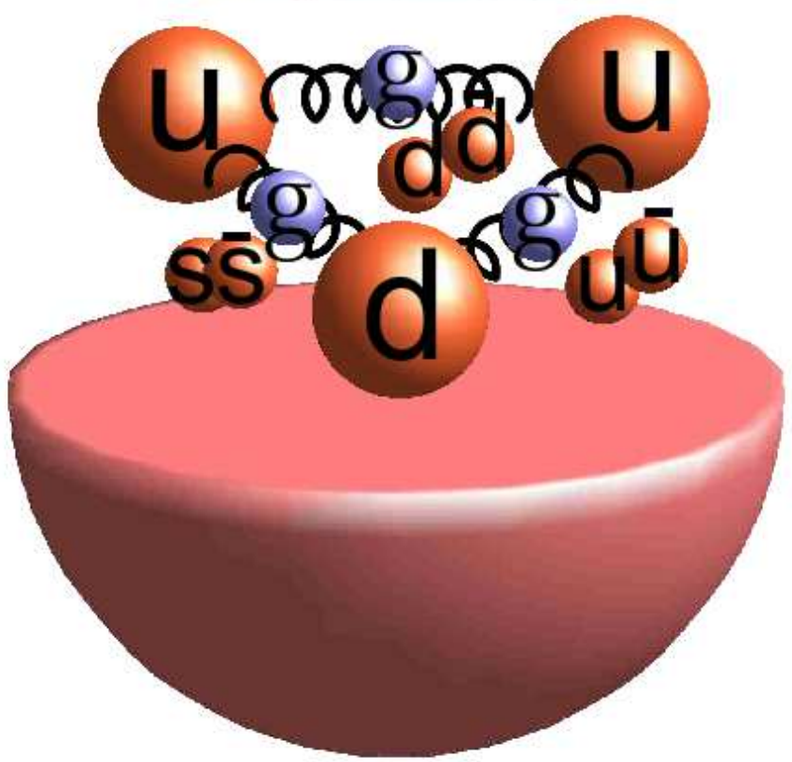




Mass of Matter

- Most of our mass is protons and neutrons
  - most mass is energy of quark-gluon soup: $m_p c^2 = E$





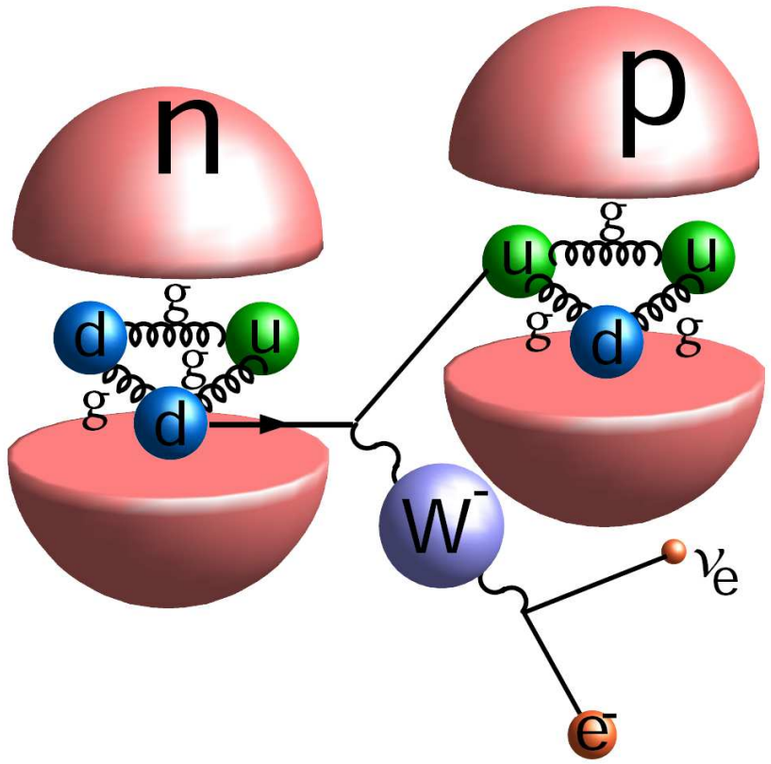
Mass from quark-glue soup energy:
$m_p c^2 = 938$ MeV $\simeq 1.7 \times 10^{-27}$ kg

Mass from the Higgs field:
$m_u c^2 \sim 3$ MeV, $m_d c^2 \sim 5$ MeV

but Higgs field is very important

But Higgs Mechanism is Very Important

- Makes Weak Interactions weak: mass of Z, W^-, W^+



similarly first step in sun fusion

$$p + p \to d + e^+ + \nu_e$$

- Recall: mass is very important without gravity (energy)
- Higgs Mechanism makes certain hierarchy of masses essential for our existence

Hypothetical Scenario: Different Quark Mass

- Again, normally proton is stable and neutron decays:

$$\mathrm{m}(n) > \mathrm{m}(p) + \mathrm{m}(e) + \mathrm{m}(\nu_e)$$

- Why is $\mathrm{m}(n) > \mathrm{m}(p)$

  – $\mathrm{m}(p) = 938$ MeV, $\mathrm{m}(n) - \mathrm{m}(p) = 1.3$ MeV

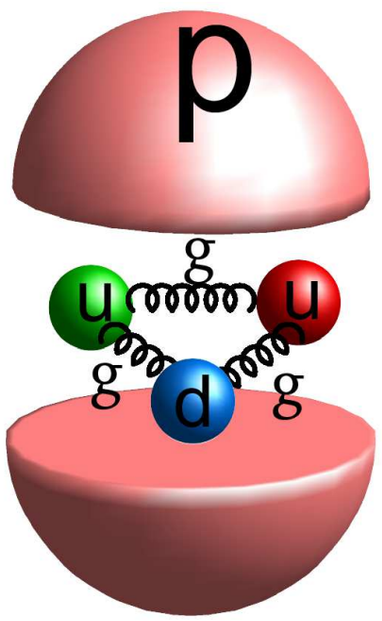
  – tiny difference makes a big difference!

  – naively expect $\mathrm{m}(p) > \mathrm{m}(n)$ if u and d were the same

  – but $\mathrm{m}(d) > \mathrm{m}(u)$

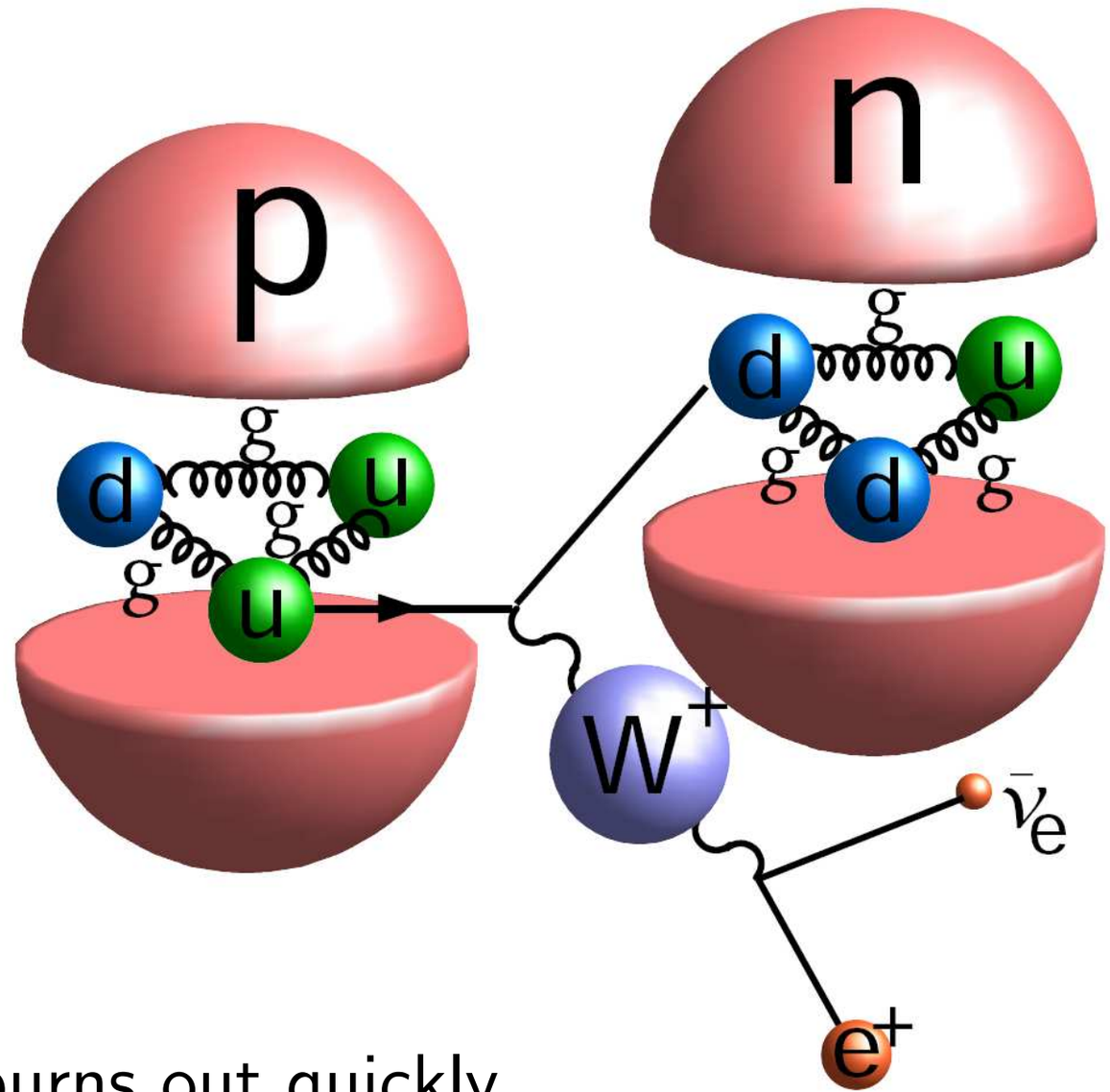
- New scenario:

  – what if $\mathrm{m}(d) \leq \mathrm{m}(u)$



Higgs Field in our Life

- Remove the Higgs field:
  - catastrophic decay of a proton
  - no H_2O (water), no life



- Origin of Sun light

  starts from Weak fusion

  $p + p \to d(pn) + e^+ + \nu_e$

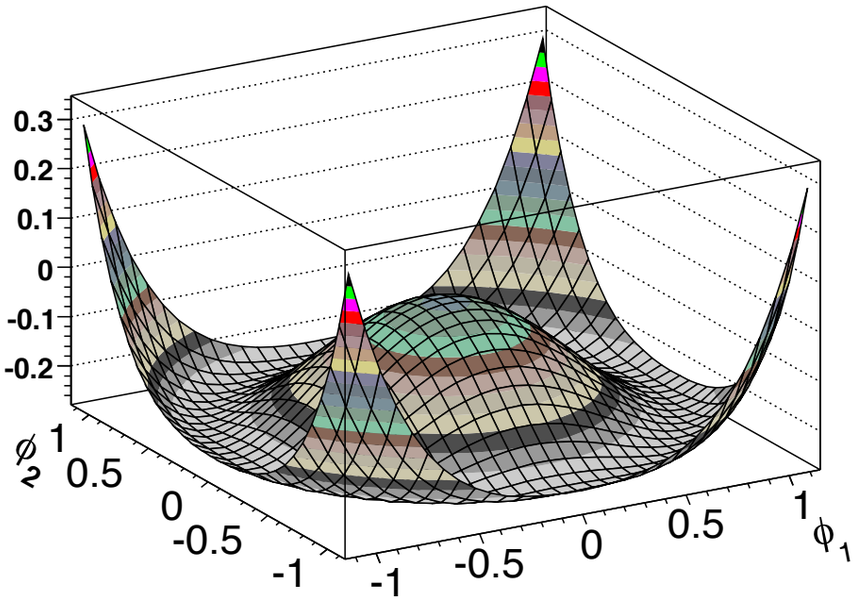
  slow burning due to heavy W^+

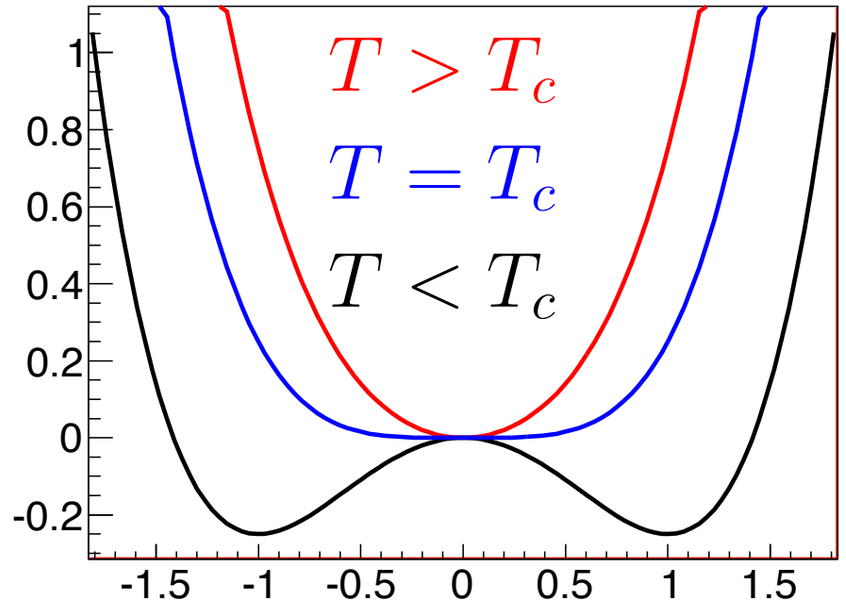
  Remove the Higgs field – Sun burns out quickly

The Englert-Brout-Higgs Mechanism

- Symmetry spontaneously breaks near minimum (vacuum) energy of Higgs field $(\phi_1, \phi_2, \phi_3, \phi_4)$

$$V = \frac{1}{4}\lambda\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]^2 + \frac{1}{2}\mu^2\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]$$





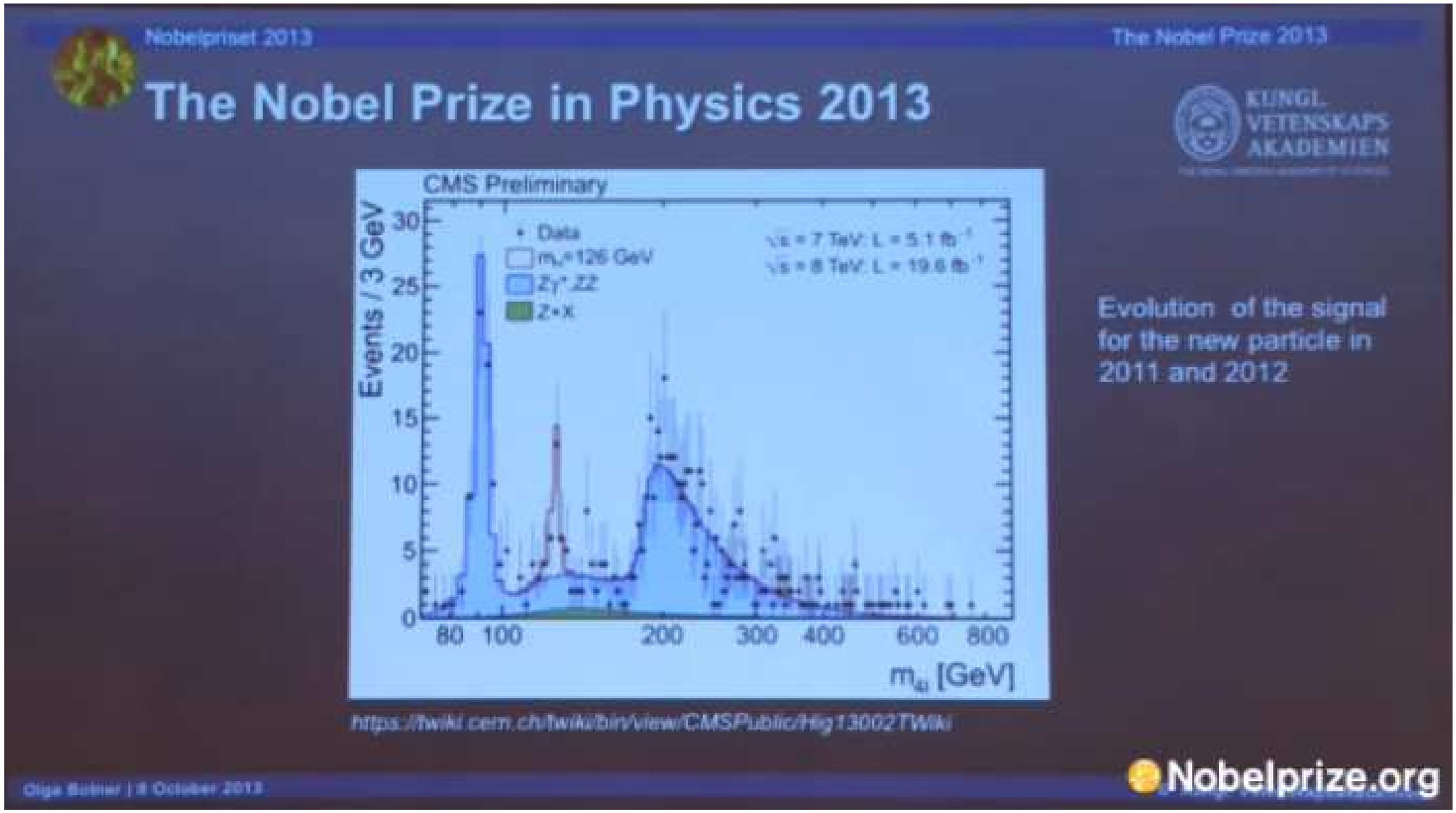
- Higgs particle described by one component of the Higgs field

$$h = \phi_1 - v$$

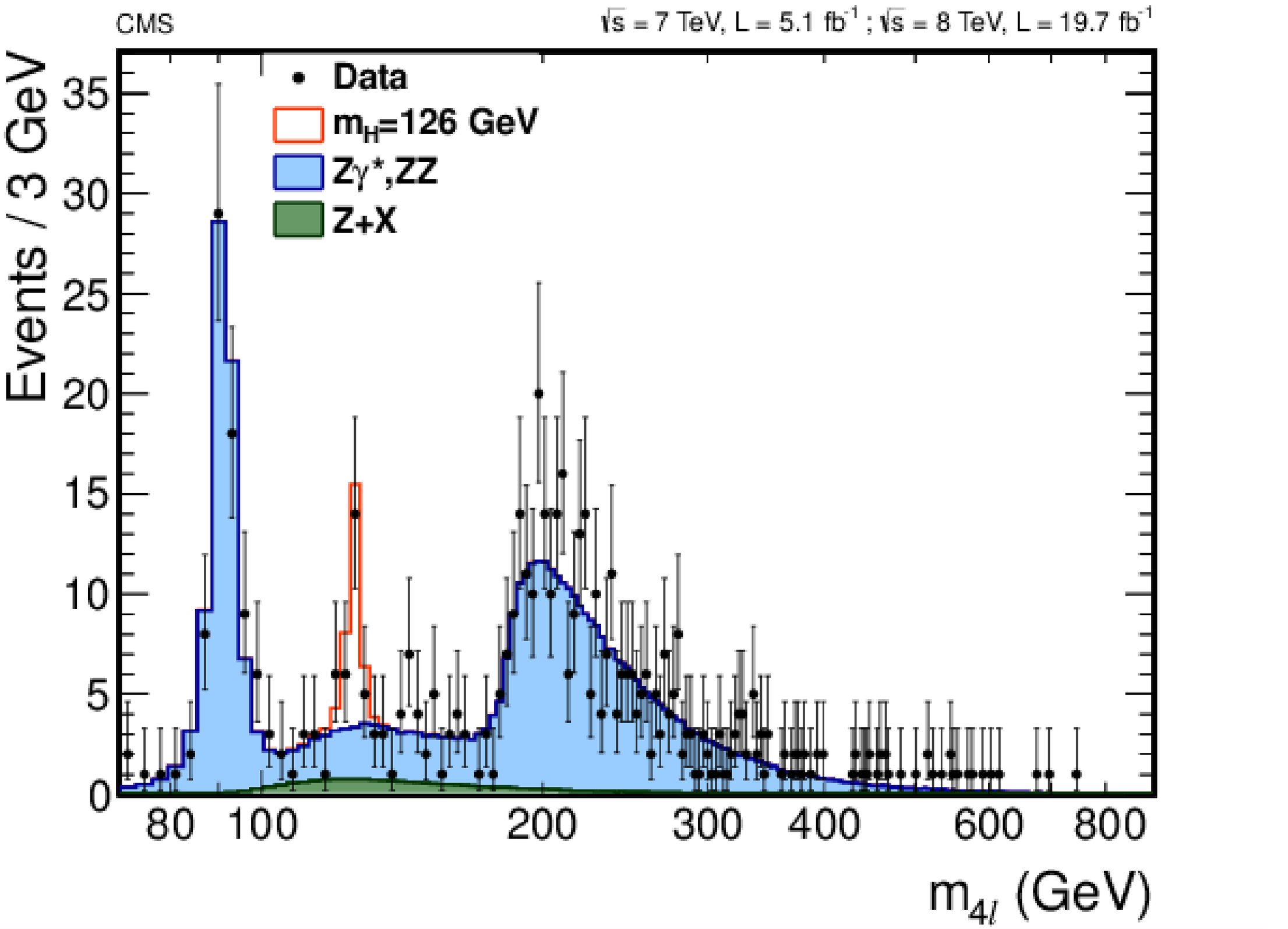
- The other Higgs field components ϕ_2, ϕ_3, ϕ_4 couple to Weak bosons Z^0, W^-, W^+ and generate mass, longitudinal polarization (not γ)

The Higgs Particle

- The Nobel prize for the Higgs mechanism
  - theoretical idea ∼50 years ago
- This idea became the reality with the Higgs particle
  - experimental discovery <2 years ago



$H \to ZZ \to 4\ell$



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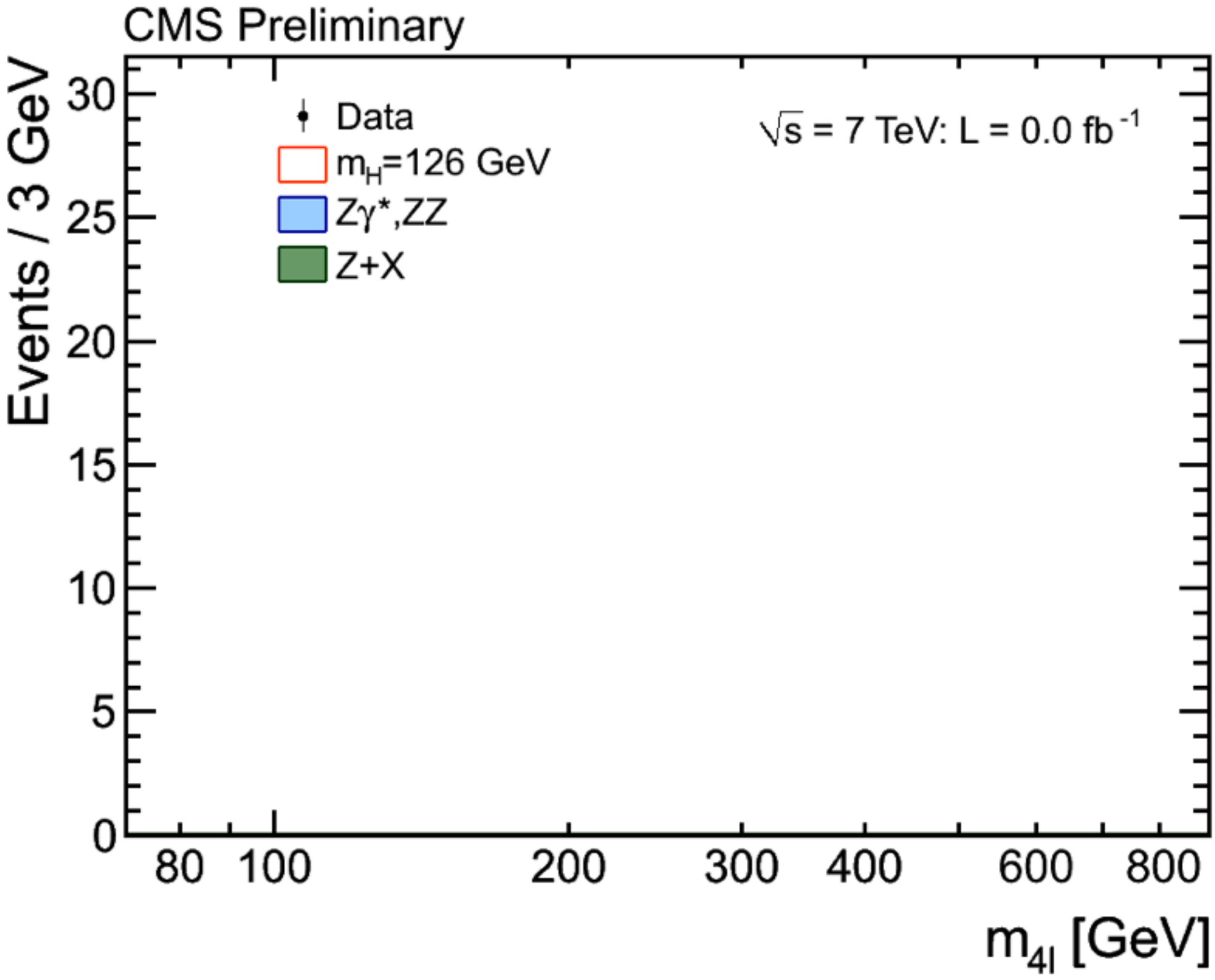

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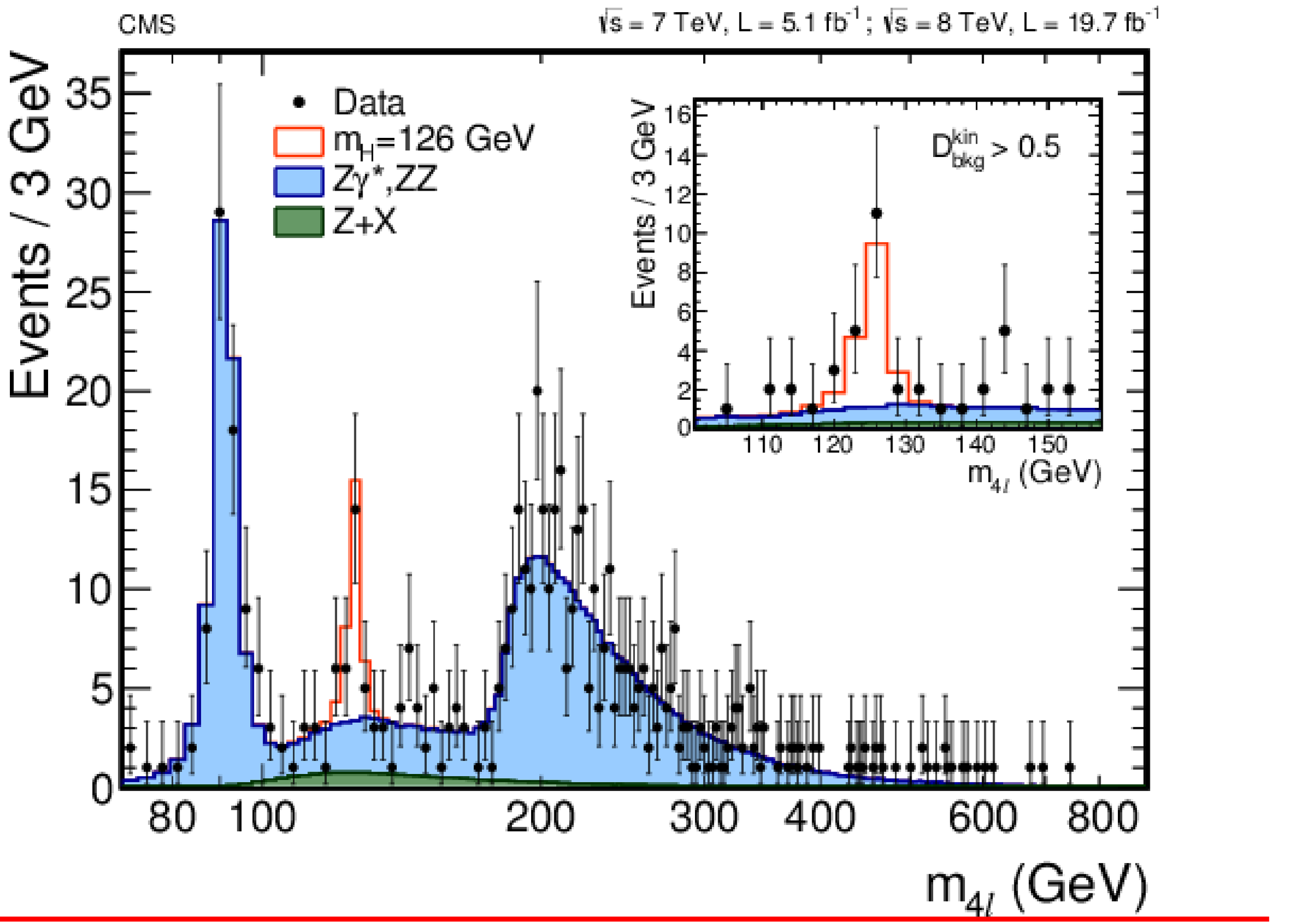
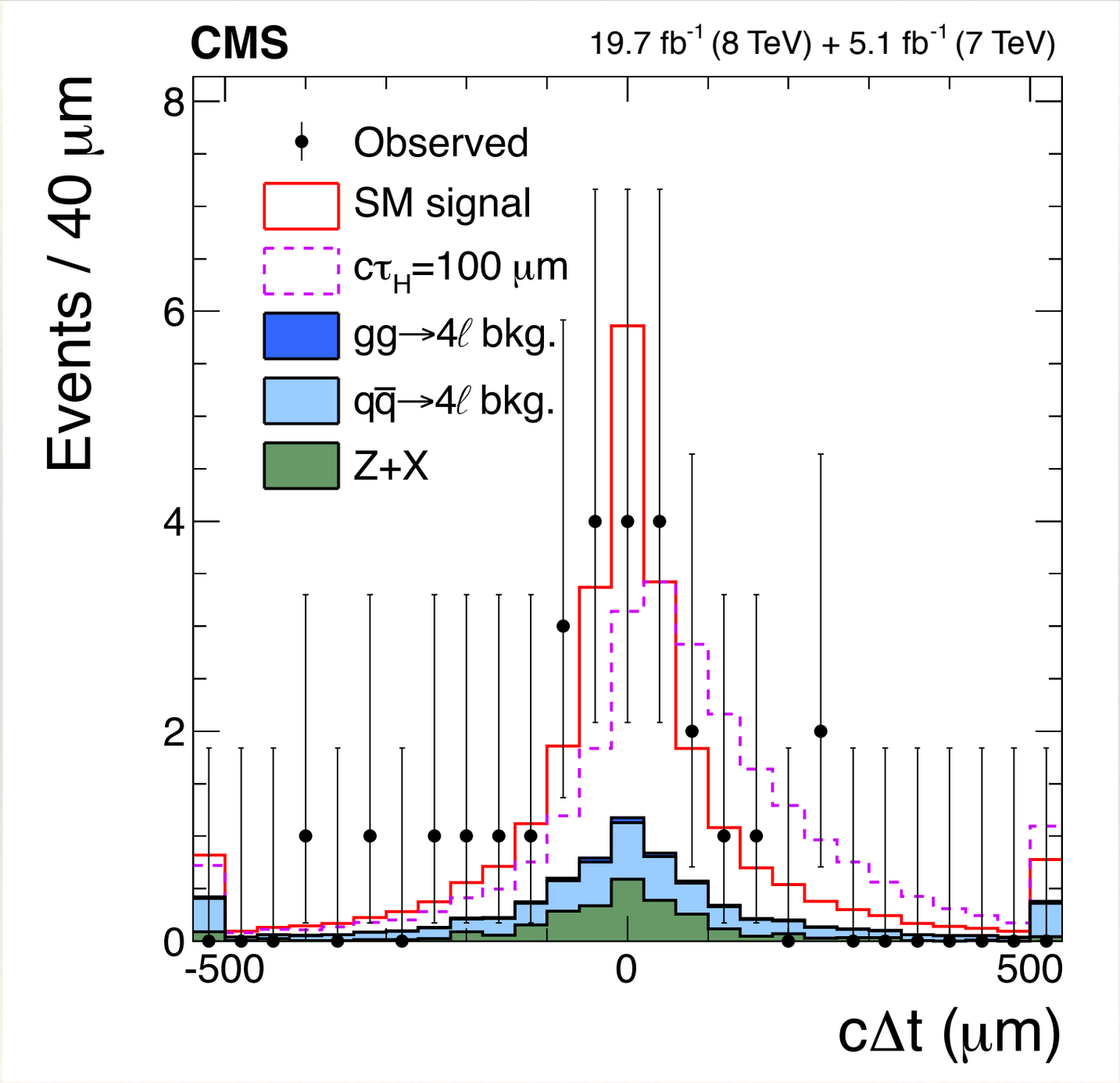
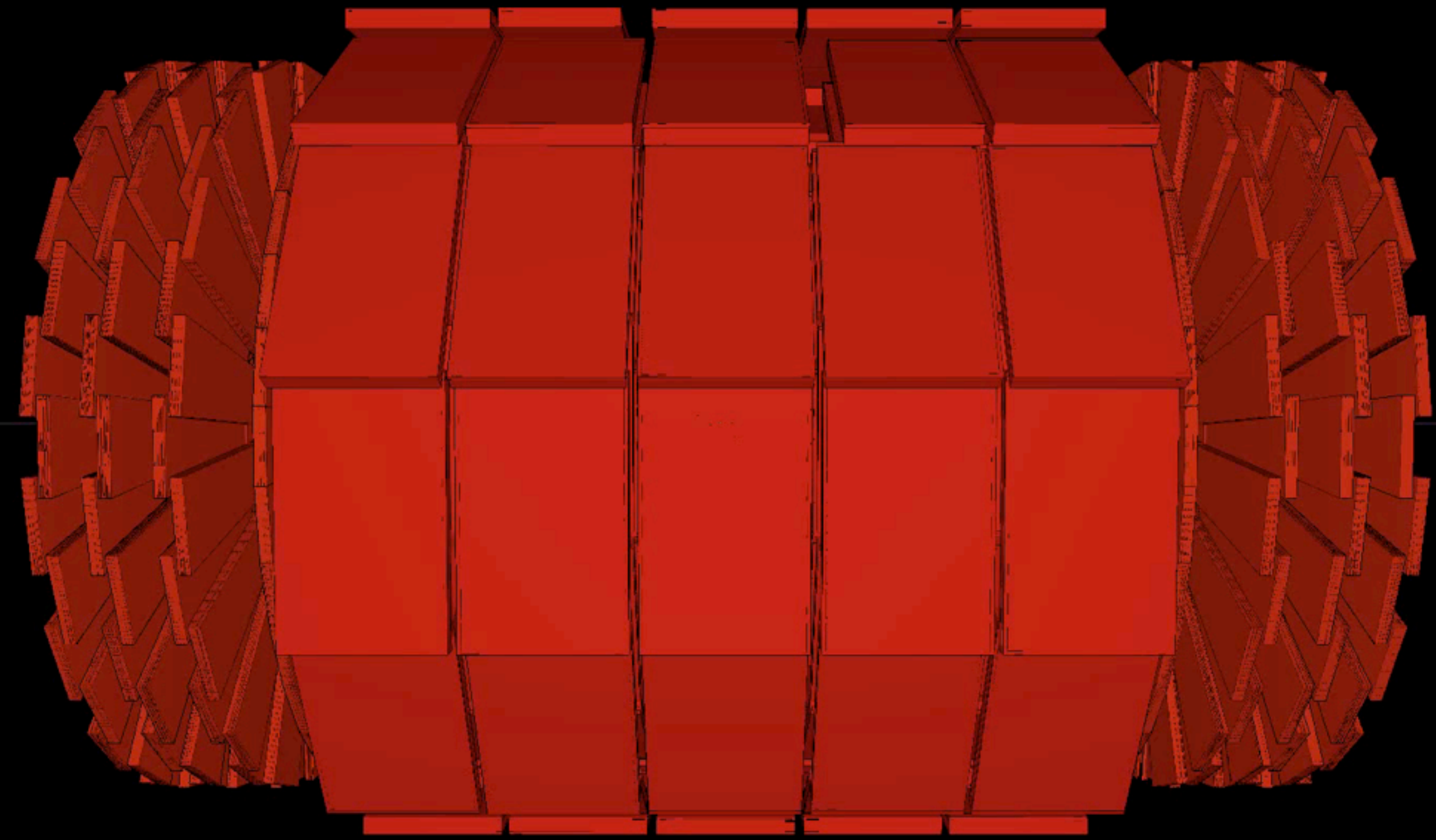


How Long Does The Higgs Boson Live?



CMS Experiment at the LH
Fri 2010–Sep–24 02:2
Run 146511 Event 5
C.O.M. Energ



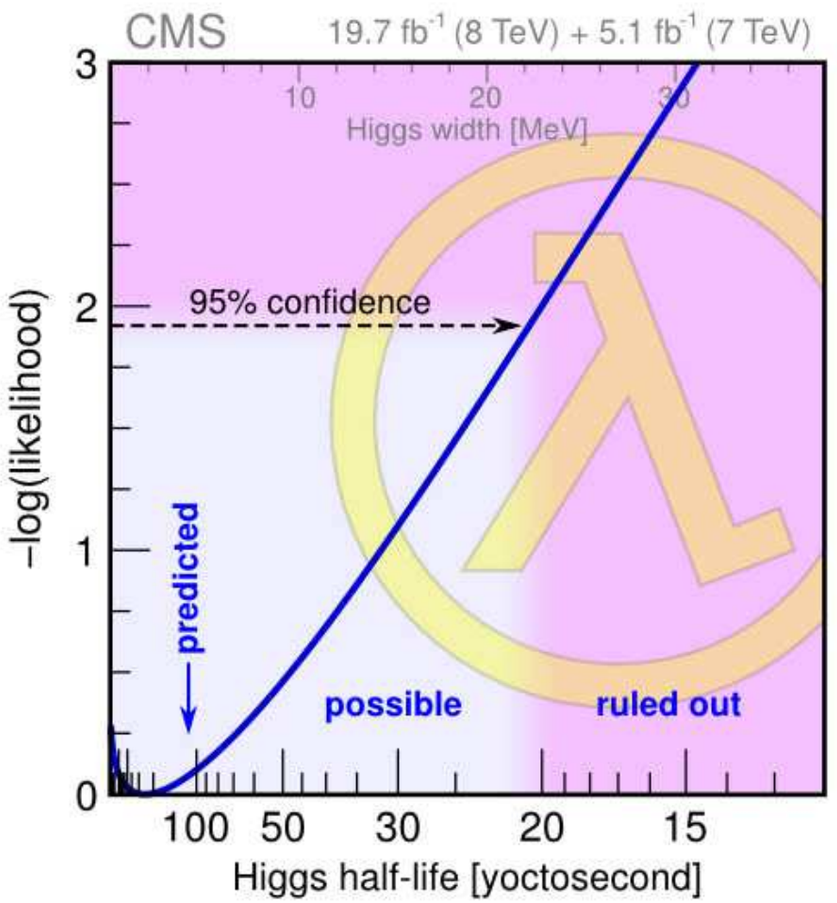
Higgs Boson Lifetime

- How long does the Higgs boson live?

$$\tau_H = \frac{\hbar}{\Gamma_H}\,, \qquad \text{expect } 1.6 \times 10^{-22} \text{ s}$$

we know it is not stable ($H \to ZZ$, ...)

observe 0.3×10^{-22} s $< \tau_H < \infty$



- Can we set a better upper bound?

  – expect $\sigma_v \sim 50\mu$m vertex resolution, $p \sim 50$ GeV

  – flight distance $\sim \frac{p}{mc} c\tau_H \sim 2 \cdot 10^{-14}$ m $= 20$ fm $\sim 4 \times 10^{-10} \times \sigma_v$

could reach 0.3×10^{-22} s $< \tau_H <$ (?) 0.4×10^{-12} s $< \infty$

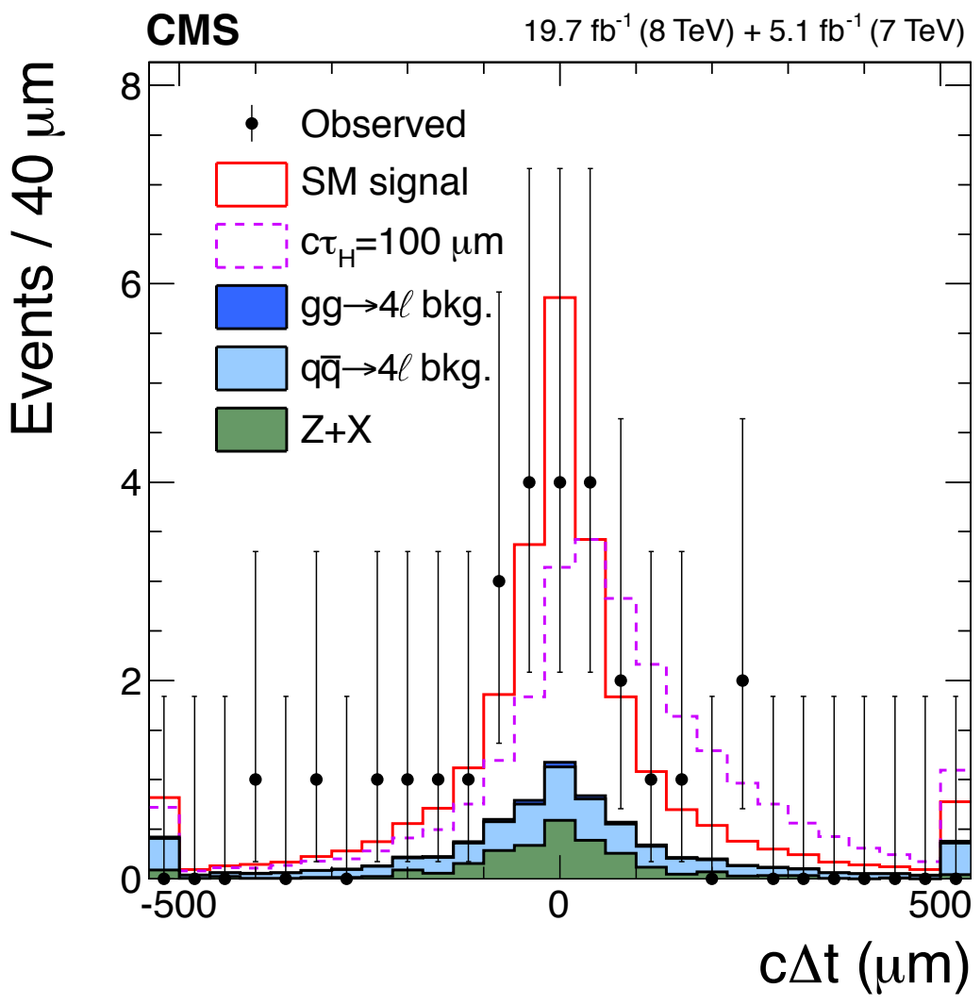
Higgs Boson Lifetime

- How long does the Higgs boson live?

$$\tau_H = \frac{\hbar}{\Gamma_H}, \quad \text{expect } 1.6 \times 10^{-22} \text{ s}$$

we know it is not stable ($H \to ZZ$, ...)

observe 0.3×10^{-22} s $< \tau_H < \infty$



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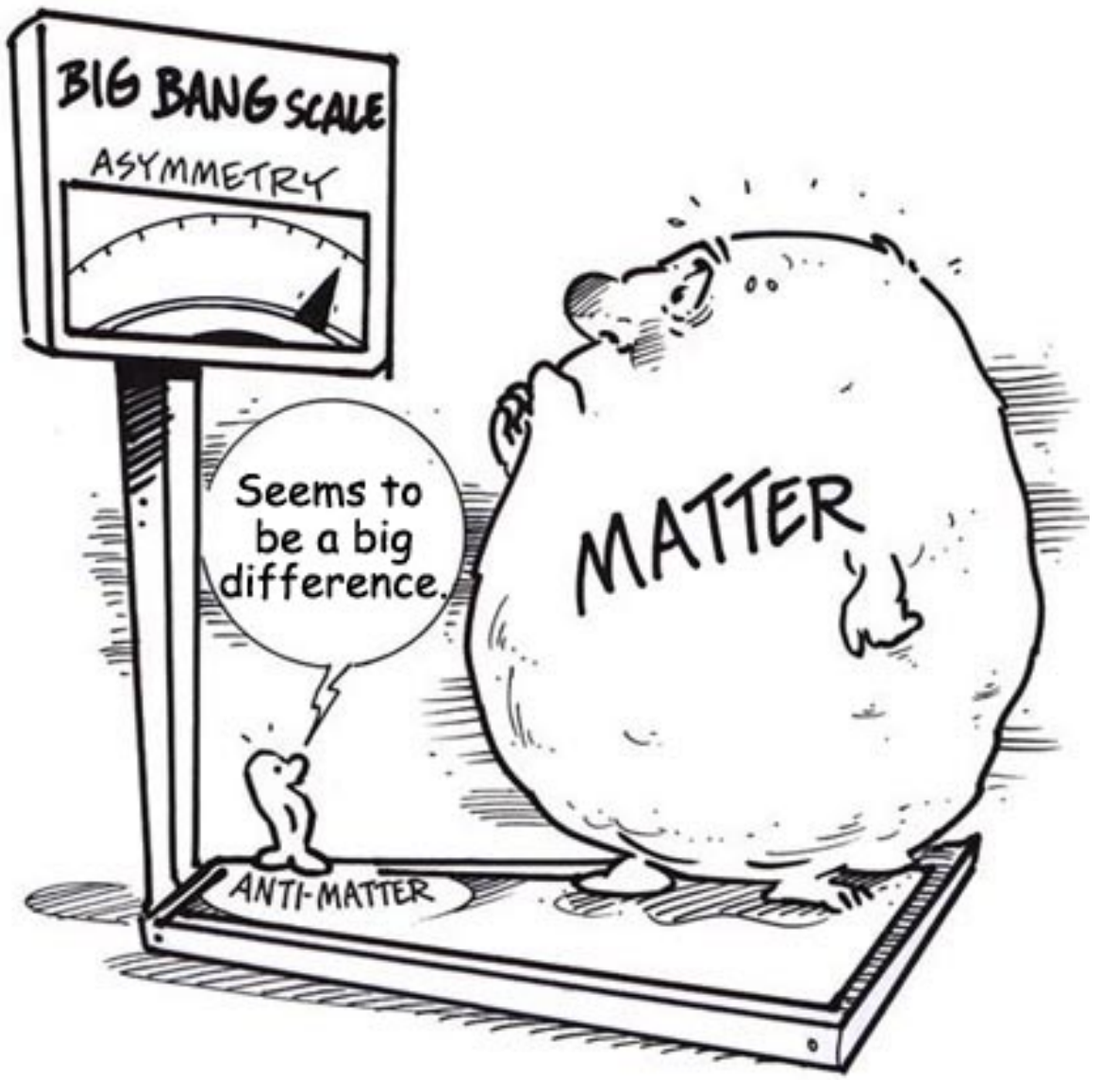
  - flight distance $\sim \frac{p}{mc} c\tau_H \sim 2 \cdot 10^{-14}$ m $= 20$ fm $\sim 4 \times 10^{-10} \times \sigma_v$

reach 0.3×10^{-22} s $< \tau_H <$ **0.19** $\times 10^{-12}$ s $< \infty$

Why Matter Dominates Over Anti-Matter

- Start with symmetric Big Bang
  - end up with matter asymmetry



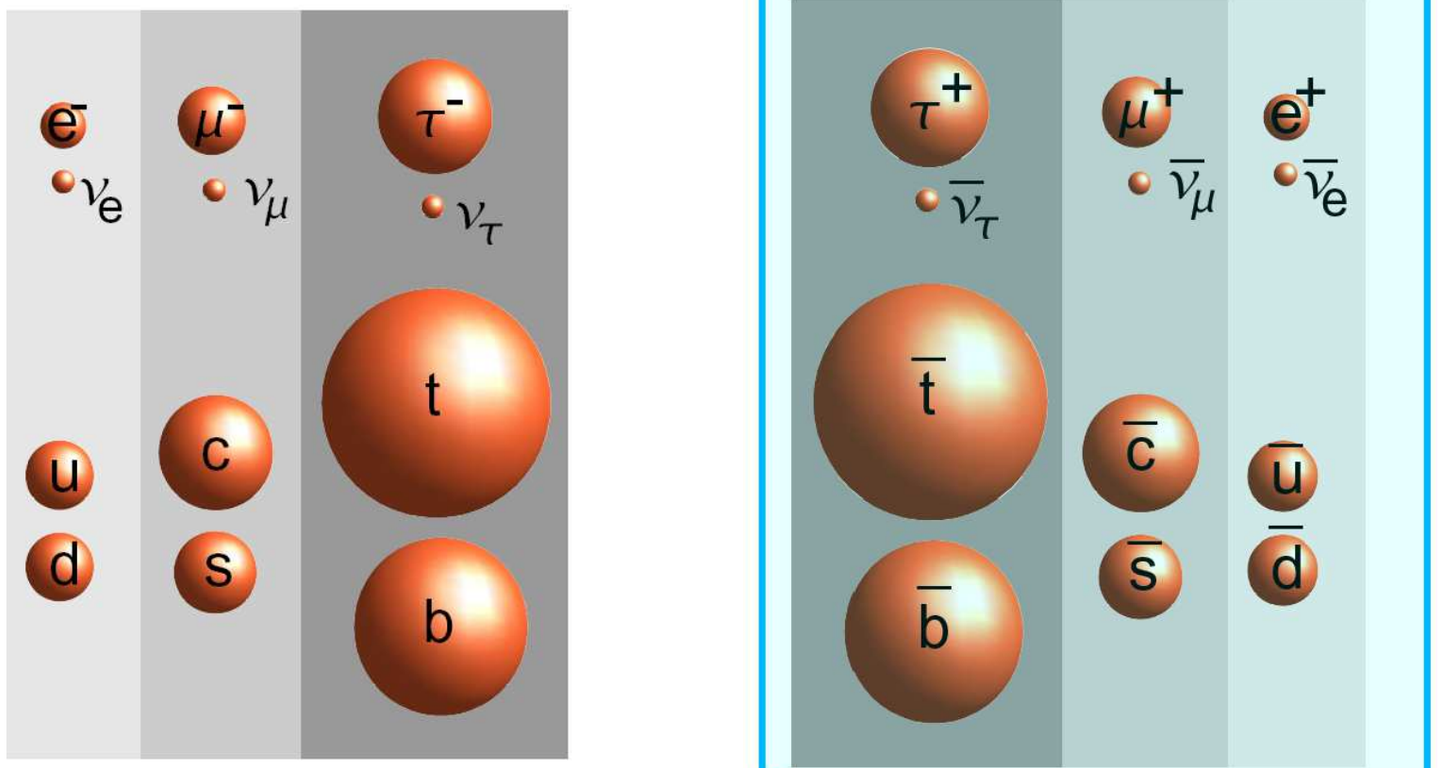
- Why does MATTER dominate (Sakharov, 1966):
  - CP-asymmetry
  - baryon non-conservation
  - non-equilibrium

Anti-Matter: Mirror Object of Matter

- matter

leptons

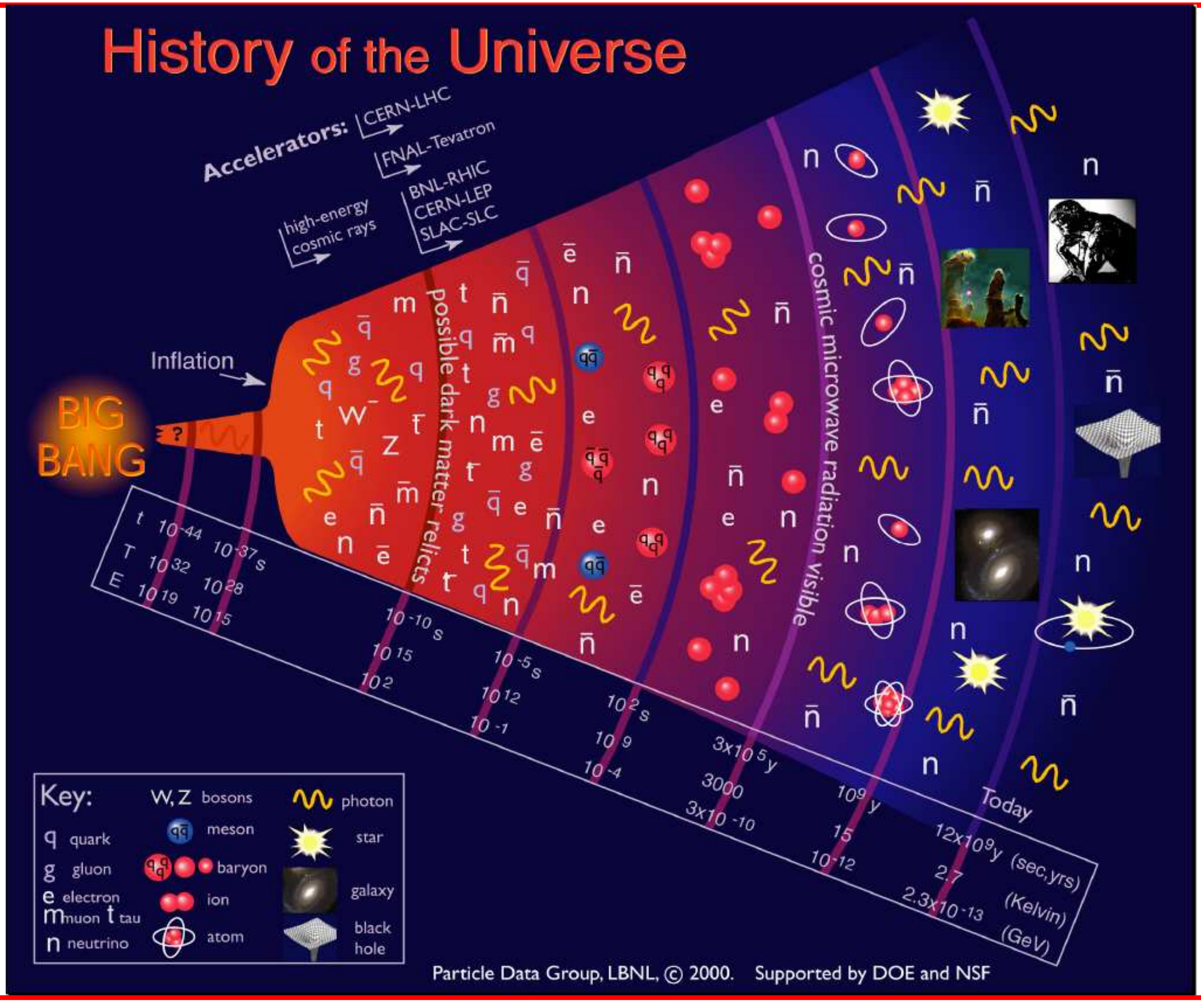
quarks

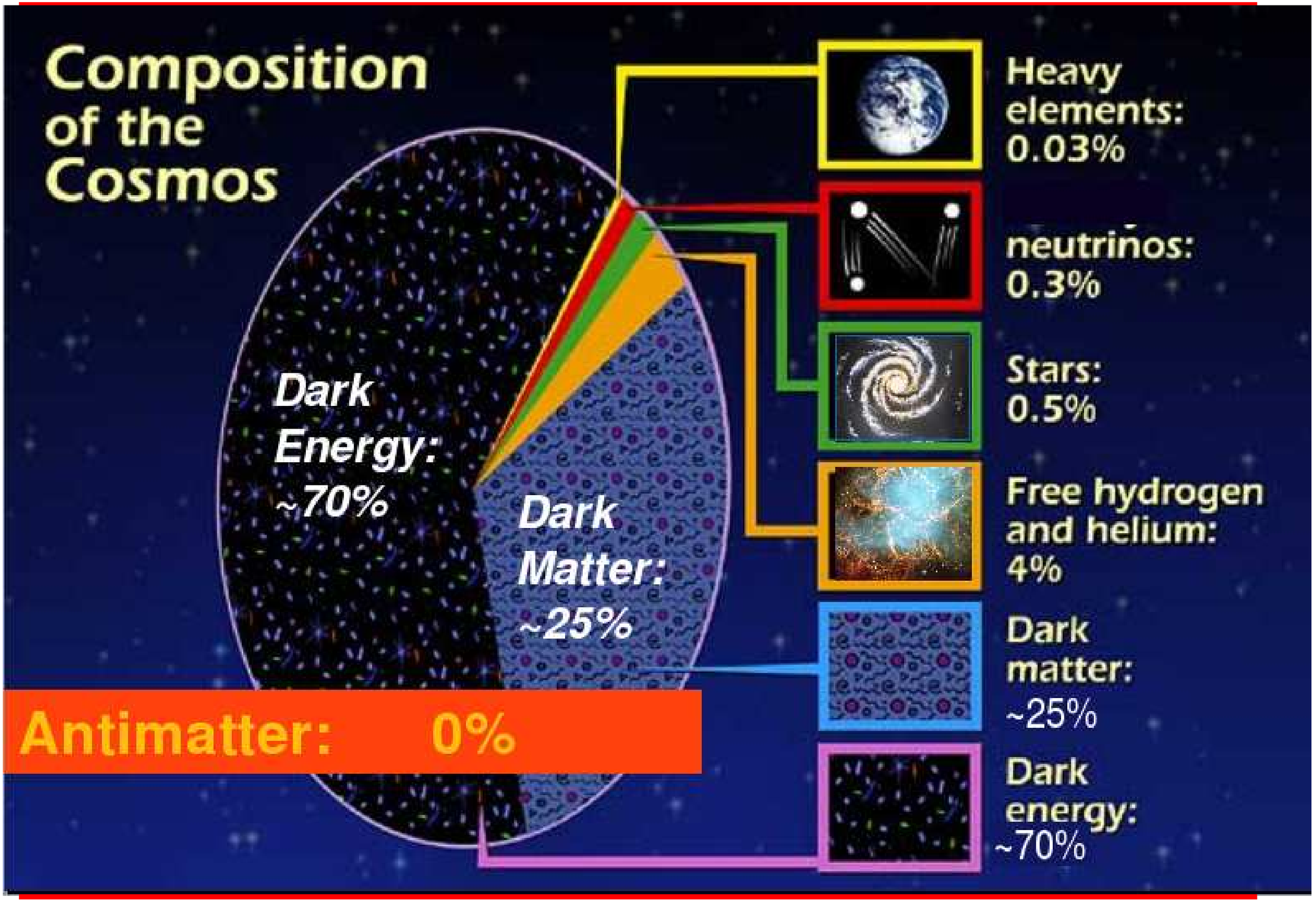


- Produced equal in Big Bang

  energy $\longrightarrow$ matter + antimatter

  anti-matter should behave differently than matter


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


Composition of the Cosmos
Dark Energy: ~70%
Dark Matter: ~25%
Antimatter: 0%
Heavy elements: 0.03%
neutrinos: 0.3%
Stars: 0.5%
Free hydrogen and helium: 4%
Dark matter: ~25%
Dark energy: ~70%

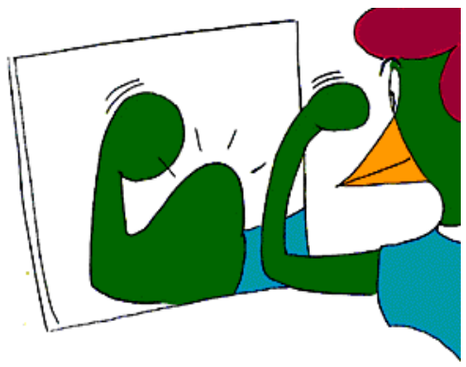
Example of CP Symmetry Violation

B^0 (anti-matter) $= \bar{b}d$

$B^0 \to K^+ + \pi^-$

$(\bar{b}d) \to (\bar{s}u) + (\bar{u}d)$

10% more often



$\bar{B}^0$ (matter) $= b\bar{d}$

$\bar{B}^0 \to K^- + \pi^+$

$(b\bar{d}) \to (s\bar{u}) + (u\bar{d})$

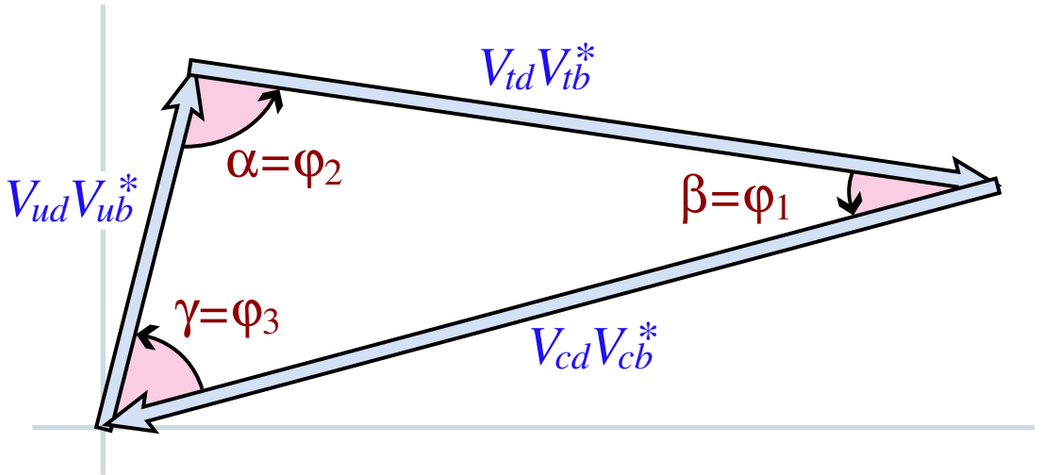
- Observed 10% difference in 2004 (*BABAR* and BELLE)
- First CP violation $\sim 0.2\%$ in K^0_L decays in 1964
- Cosmological question: how to tell matter vs anti-matter
  - communicate results to another Universe
    choice of "$+$" and "$-$" is arbitrary
  - we are made of d and u quarks
    which are more frequent in $B \to K^\pm\pi^\mp$ decays

Example of CP Violation: How It Works

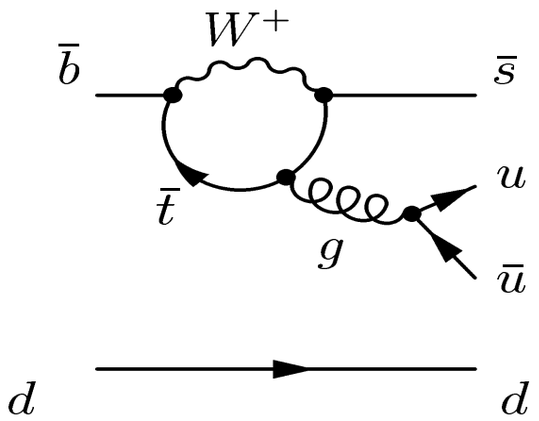
$B^0 \to K^+ + \pi^-$

$(\bar{b}d) \to (\bar{s}u) + (\bar{u}d)$

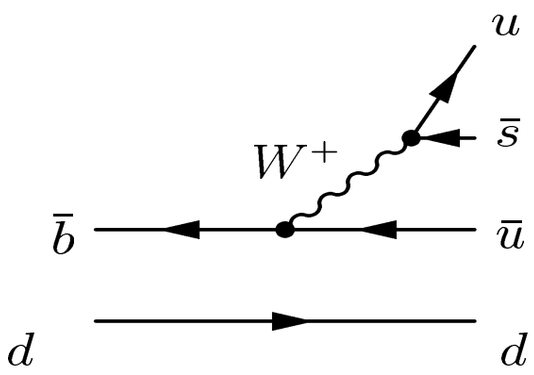
Feynman diagrams of decay



Penguin



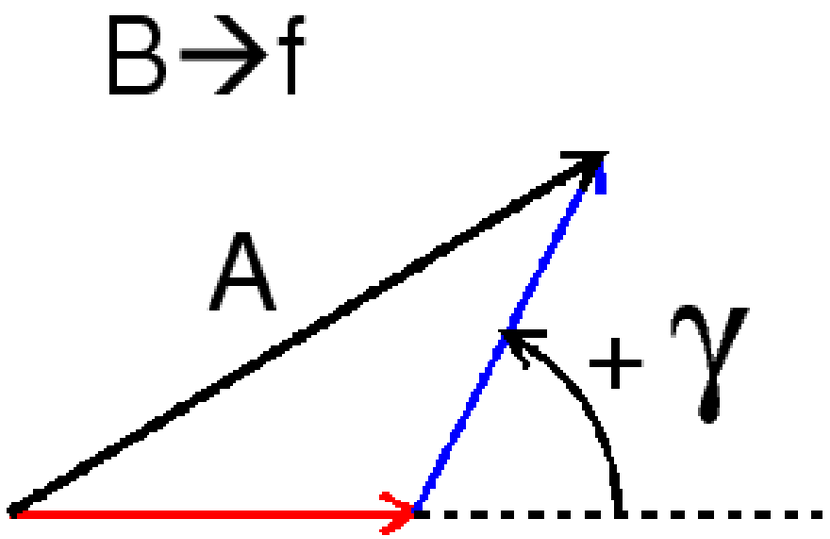
Tree



Probability from complex numbers

"amplitudes" (A) are vectors

Probability $\propto |A|^2 = |A_P + A_T|^2$

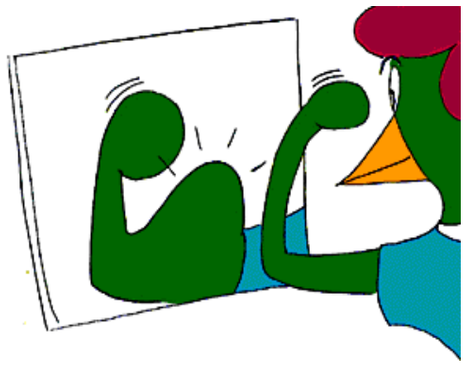


Example of CP Violation: How It Works

$B^0 \to K^+ + \pi^-$

$(\bar{b}d) \to (\bar{s}u) + (\bar{u}d)$

larger probability



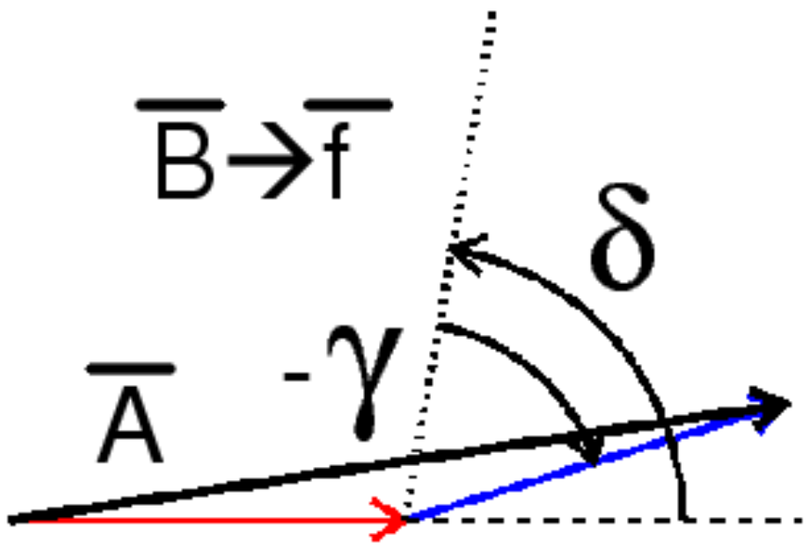
$\bar{B}^0 \to K^- + \pi^+$

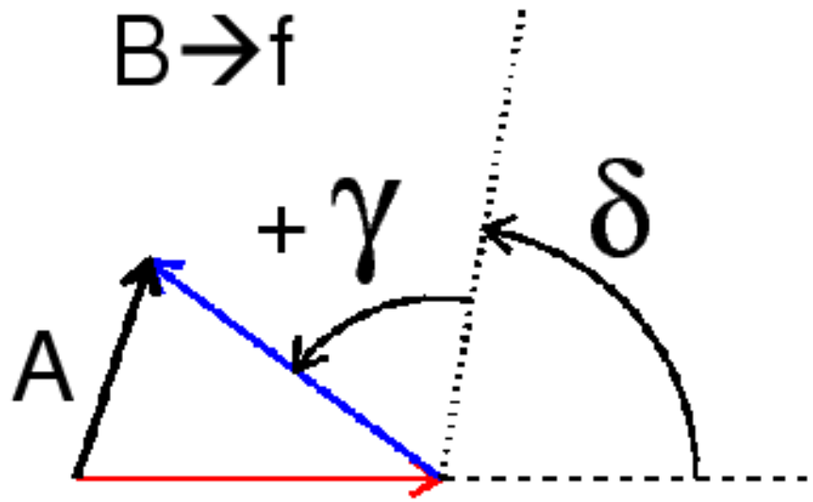
$(b\bar{d}) \to (s\bar{u}) + (u\bar{d})$

smaller probability

- Need overall "phase" difference (δ) between Penguin and Tree
- Angle (γ) changes sign under CP, "interference" of two amplitudes:

$$|\bar{A}|^2 = |\bar{A}_P + \bar{A}_T|^2 \qquad > \qquad |A|^2 = |A_P + A_T|^2$$

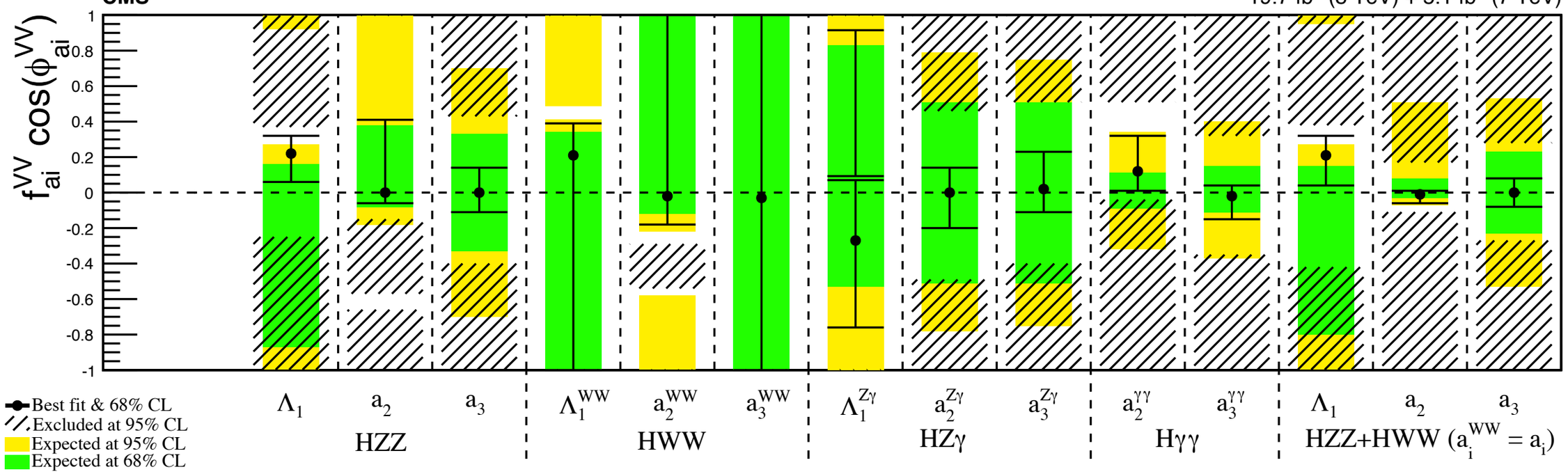




Is it the Higgs Boson?

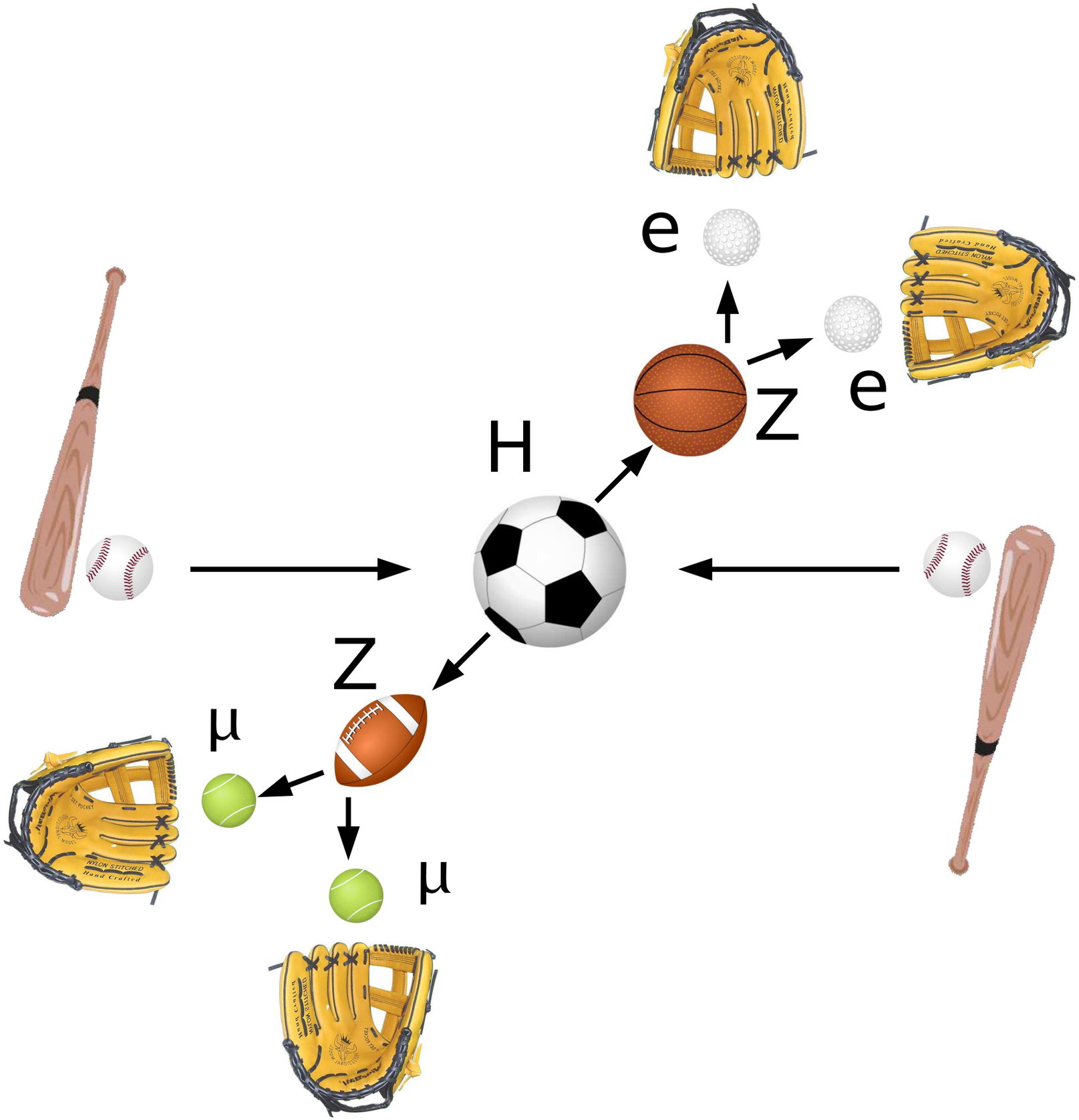
- We found the new boson, but is the Higgs boson?
  - all indications: it is consistent
  - its spin is 0
  - its symmetry (mirror image) is $+$

No CP violation with the Higgs boson seen (yet)

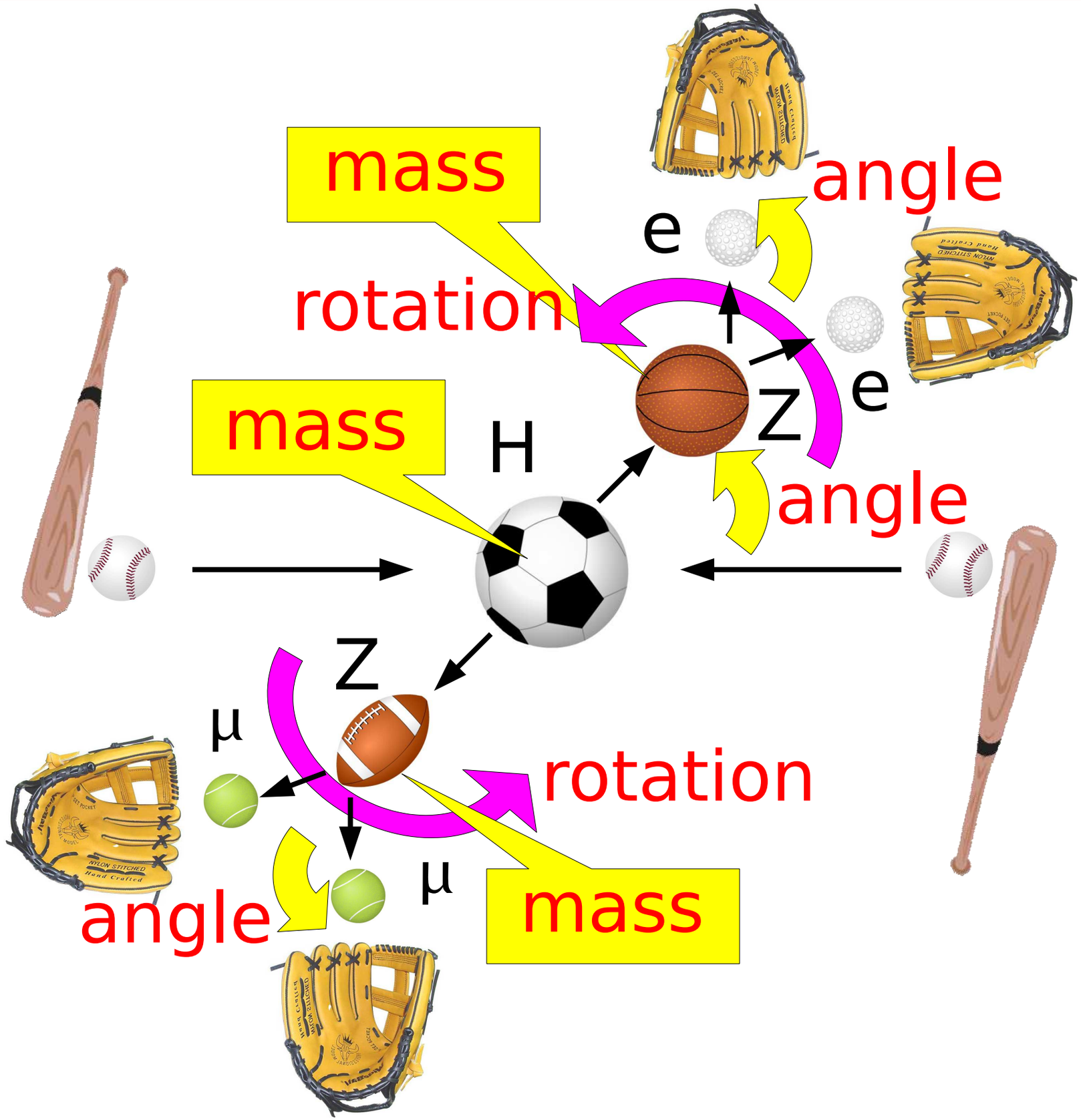


- New state of matter-energy never seen before (like vacuum 0^+)

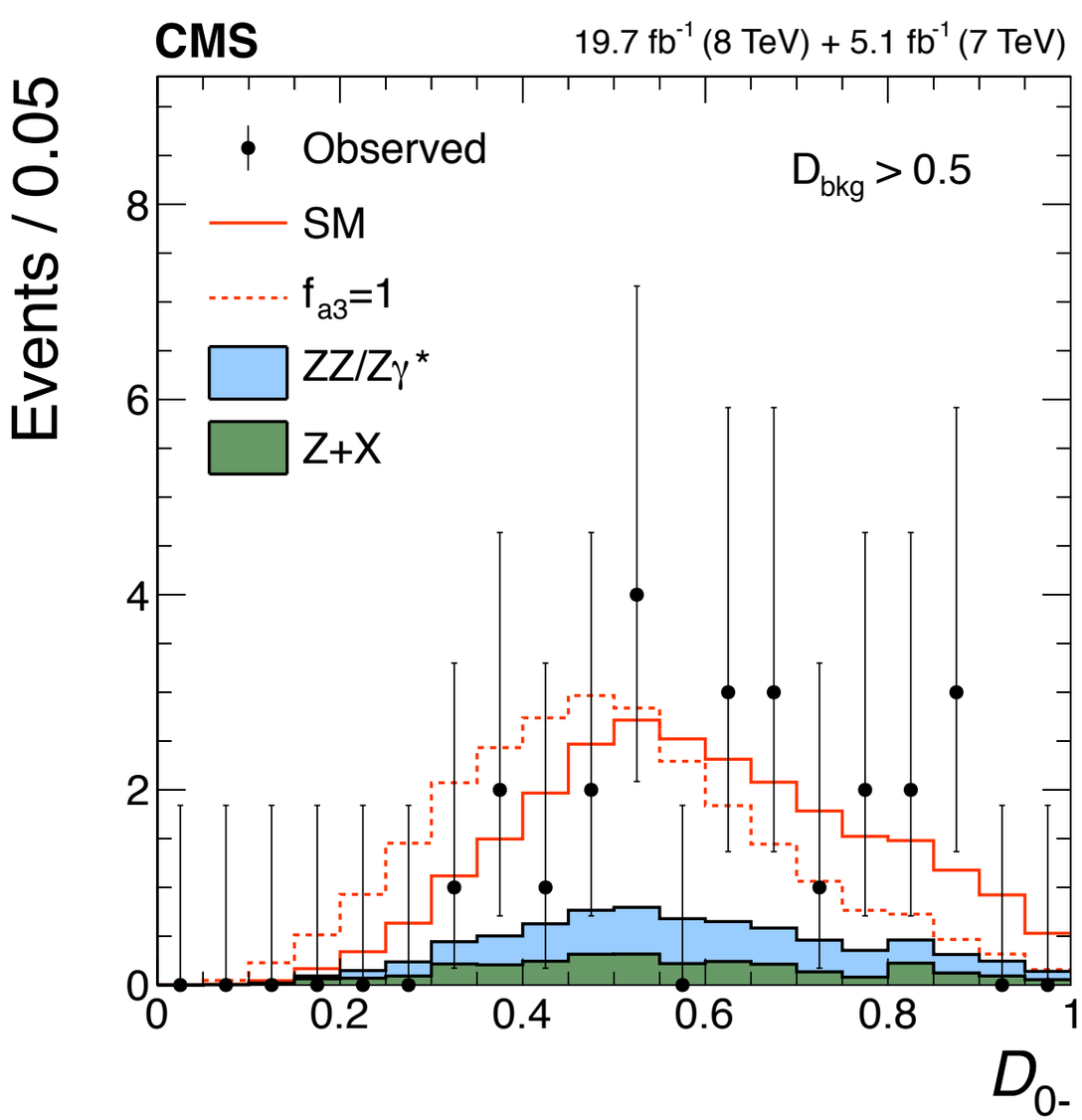
Data Analysis

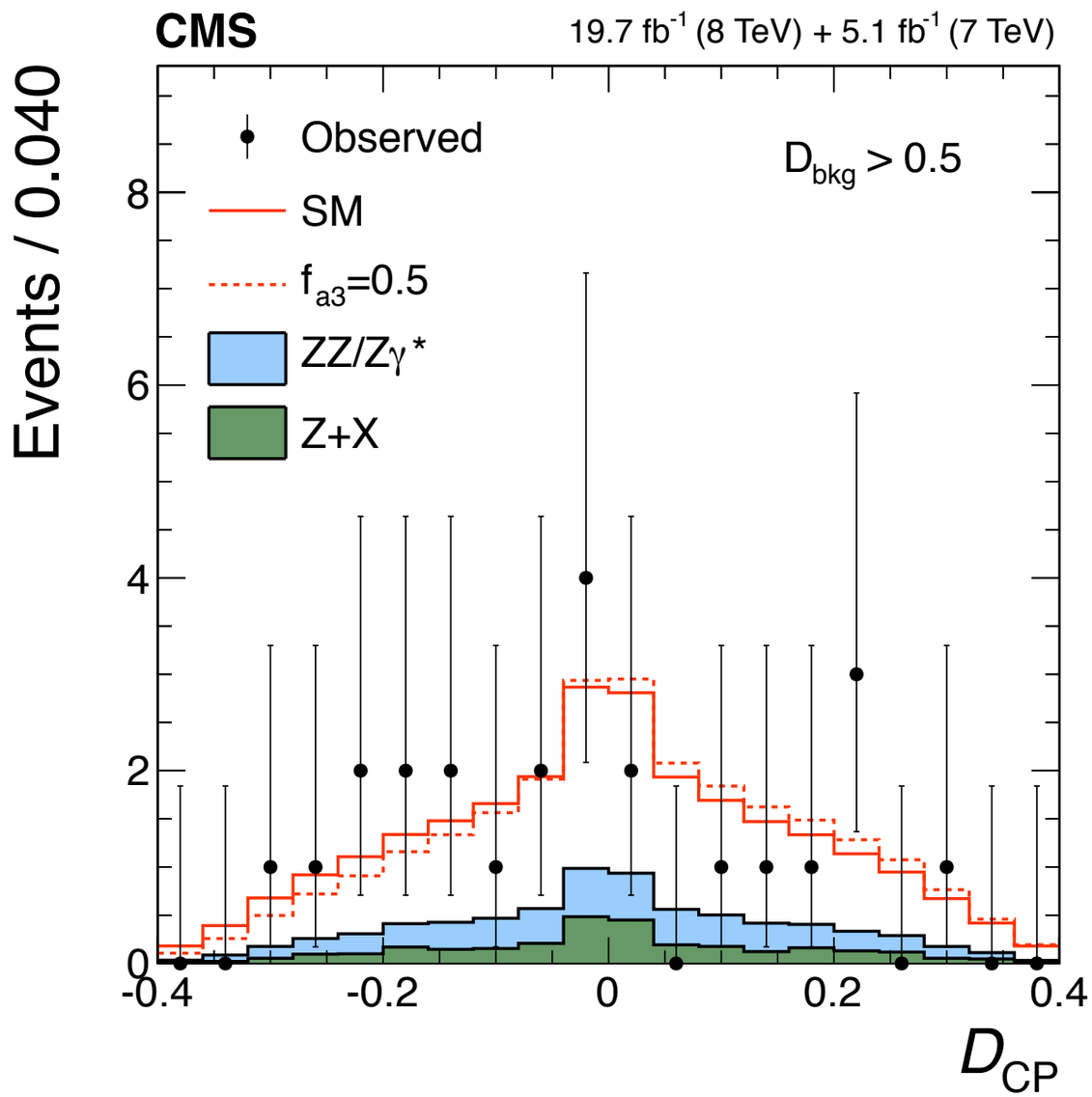


Data Analysis



How we look for CP violation with the Higgs Boson

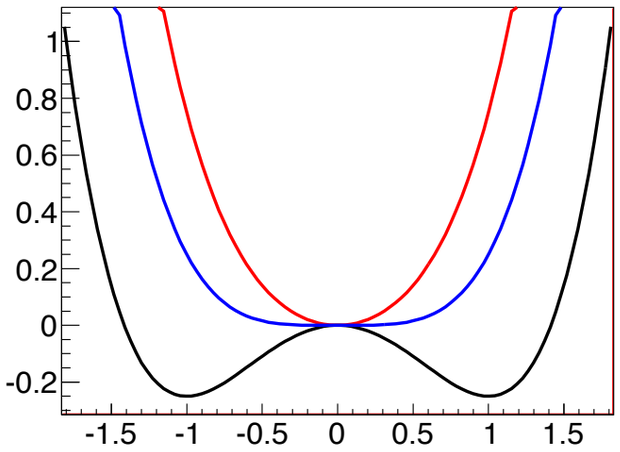


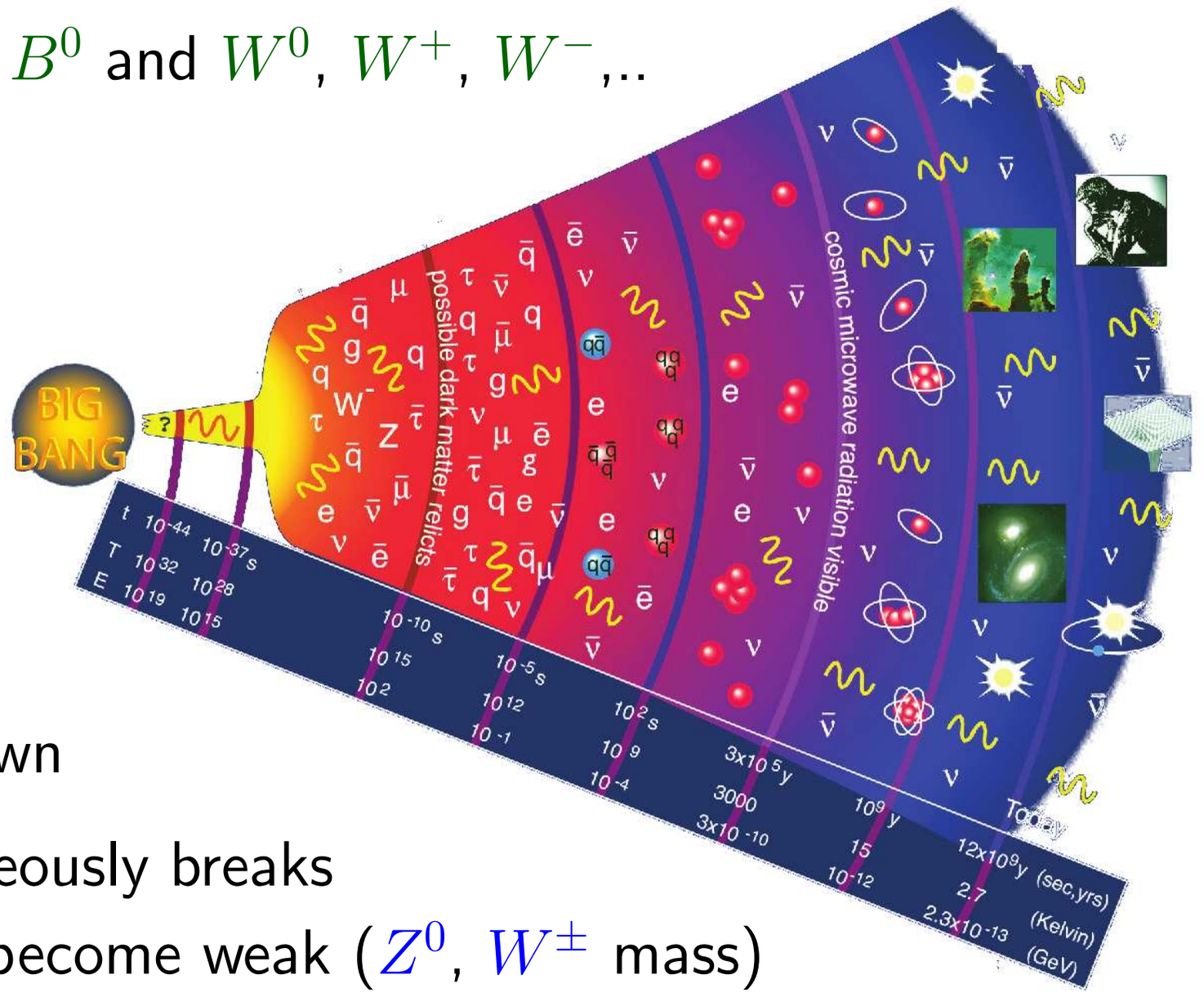


BACKUP

Path from Light to Heavy

- Early moments of the Universe
  - massless particles: B^0 and W^0, W^+, W^-,..
  - all forces unify



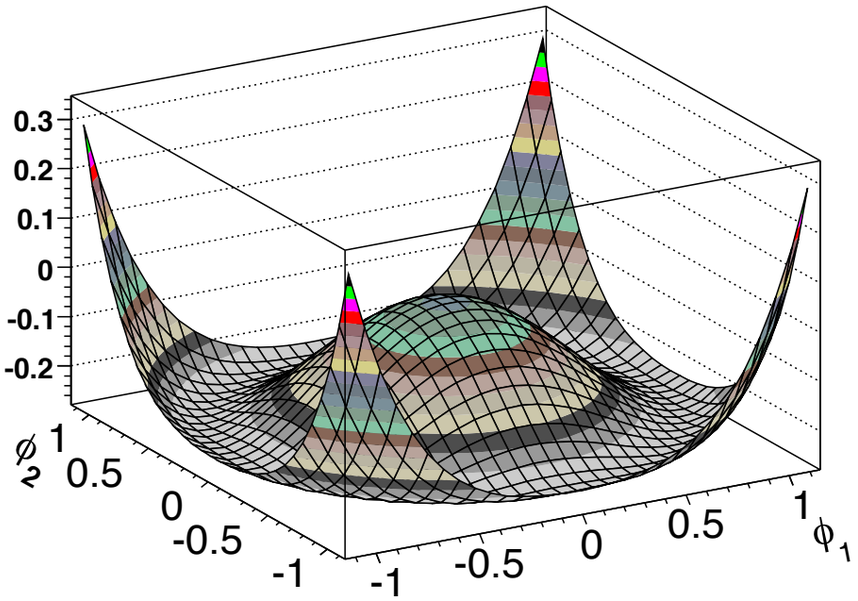


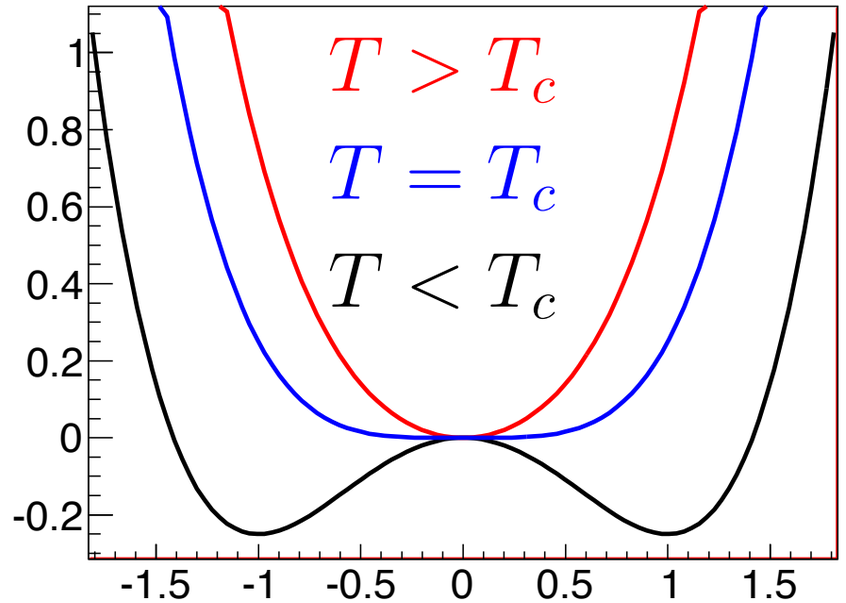
- As Universe cools down
  - symmetry spontaneously breaks
  - weak interactions become weak (Z^0, $W^\pm$ mass)
  - Higgs field – possible mechanism

The Englert-Brout-Higgs Mechanism

- Symmetry spontaneously breaks near minimum (vacuum) energy of Higgs field $(\phi_1, \phi_2, \phi_3, \phi_4)$

$$V = \frac{1}{4}\lambda\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]^2 + \frac{1}{2}\mu^2\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]$$





- Higgs particle described by one component of the Higgs field

$$h = \phi_1 - v$$

- The other Higgs field components ϕ_2, ϕ_3, ϕ_4 couple to Weak bosons Z^0, W^-, W^+ and generate mass, longitudinal polarization (not γ)

Idea - the Higgs Field

- Empty space filled with invisible "force" – the Higgs field

Idea - the Higgs Field

- The Higgs field clusters around the particle – gives mass

Idea - the Higgs Field

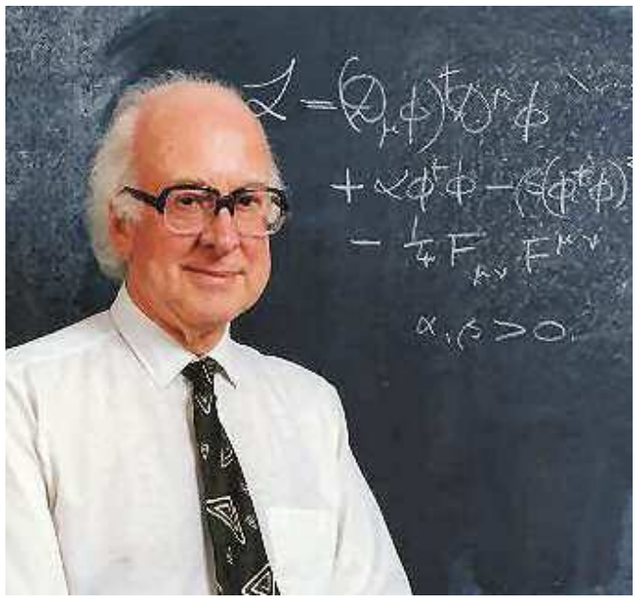
- Pass energy into the Higgs field (no particle)

Idea - the Higgs Field

- The Higgs particle cluster created from the Higgs field

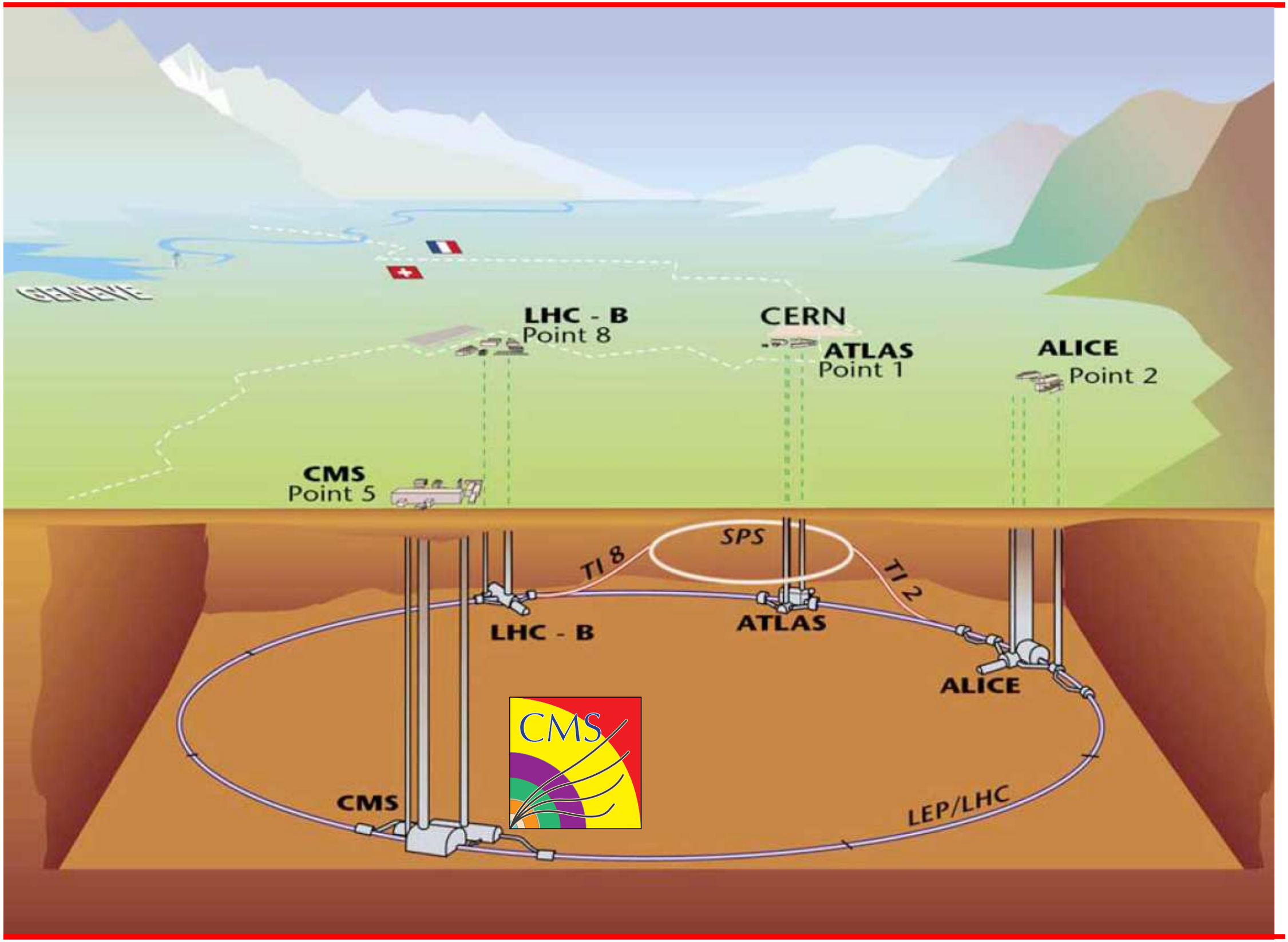
What is Higgs?

- There are several phenomena:
  - Peter Higgs
  - Higgs mechanism
  - Higgs field
  - Higgs particle (boson)

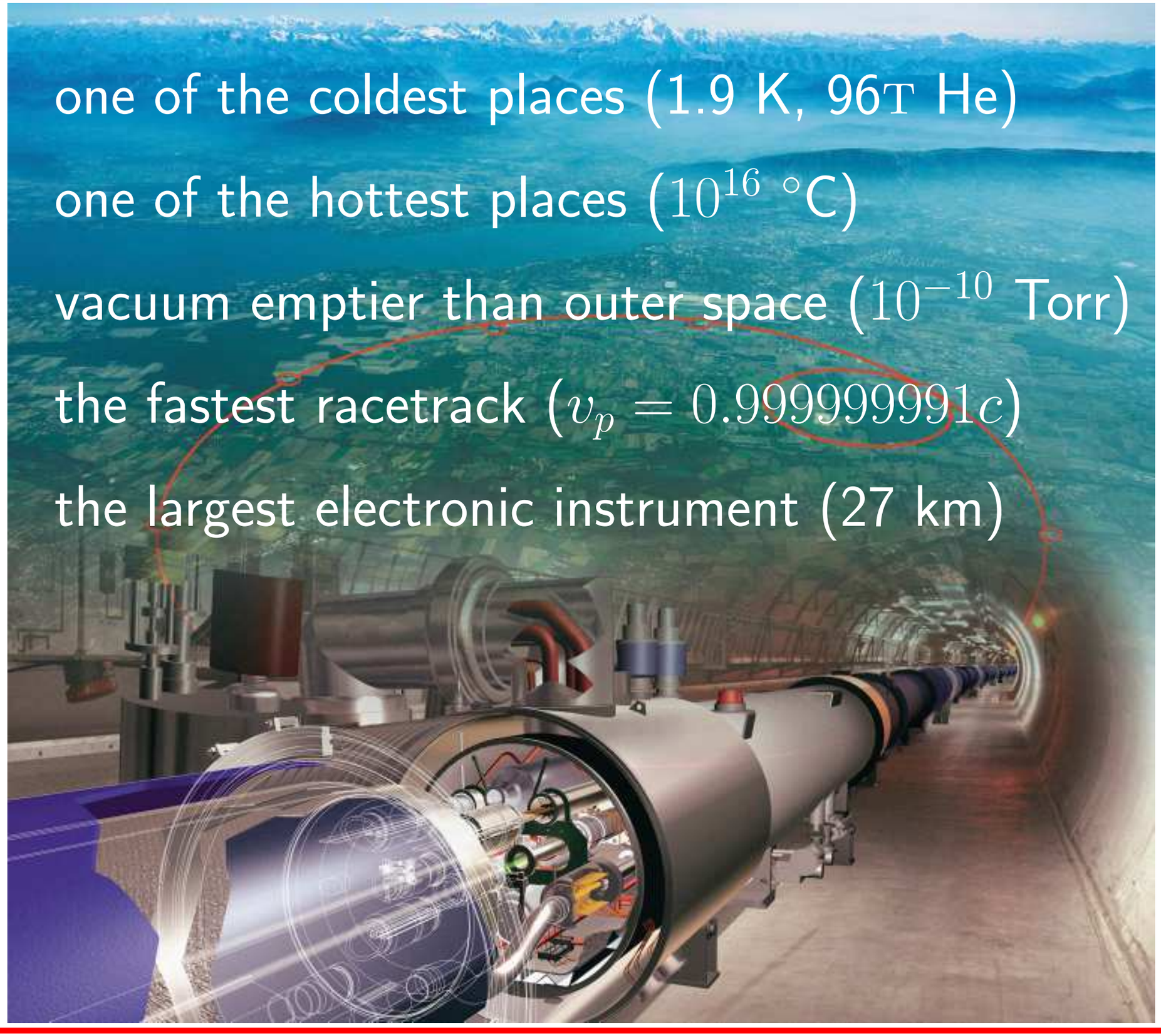


- People sometimes confuse these phenomena
  - especially the last two
- We have hard evidence for two:
  - 1964 article by Peter Higgs in *Physics Review Letters*
  - 2012 discovery of a new Boson by CMS and ATLAS

The Large Hadron Collider



The Large Hadron Collider



The Large Hadron Collider

- Enormous amount of data from LHC

  > 2000 trillion proton-proton collisions in 2011-2012

  > 20 billion events recorded, $\sim$0.6 Mbyte each (Petabytes)

  > 200 million Z^0 bosons

  > 200 thousand Higgs bosons produced – assuming we see it

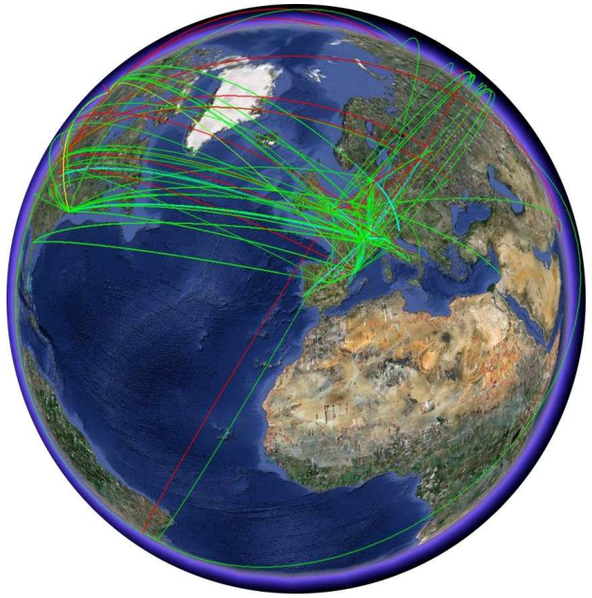
- LHC Computing Grid

  world's largest computing grid

  over 170 computing centers in 36 countries

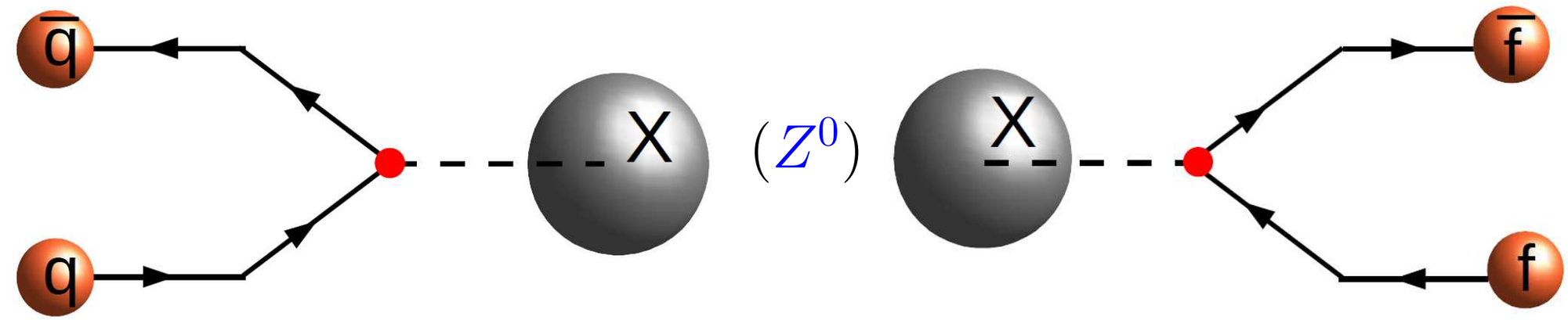
  $\sim$ 25 Petabytes / year (25×10^{15} bytes)

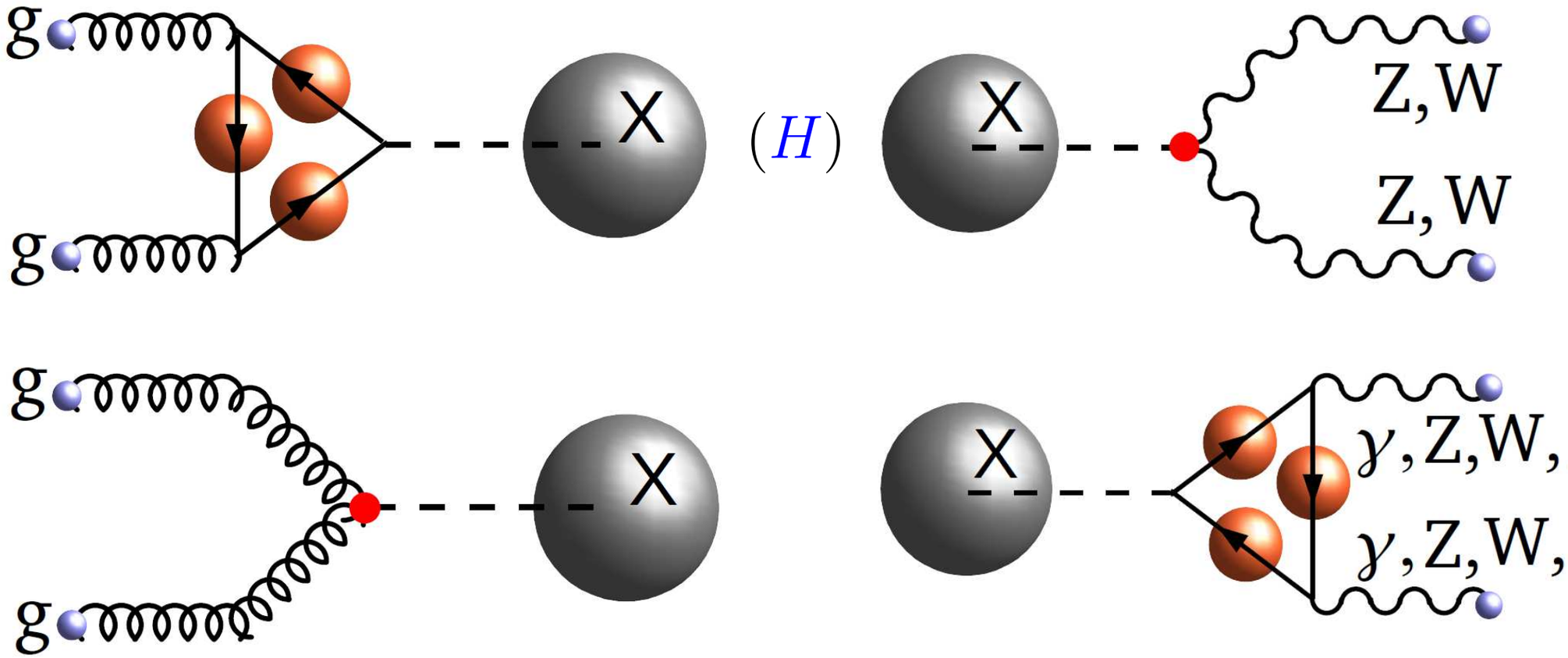
  ($>$ 5 million DVDs, comparable to Facebook storage)



Production of New Particles at LHC

- Particles are produced and decay: $X = Z^0$, Higgs, RS Graviton, ...

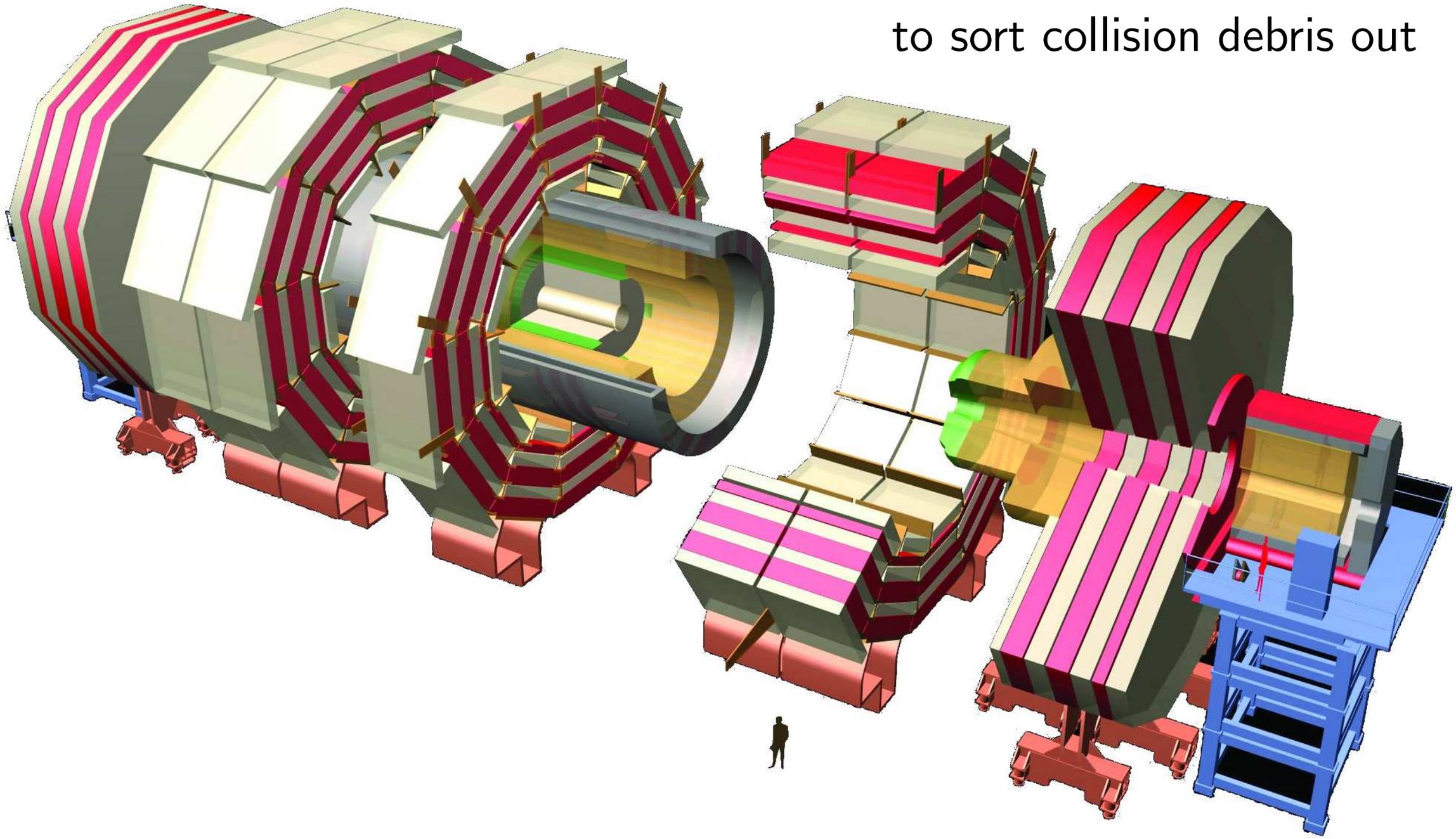




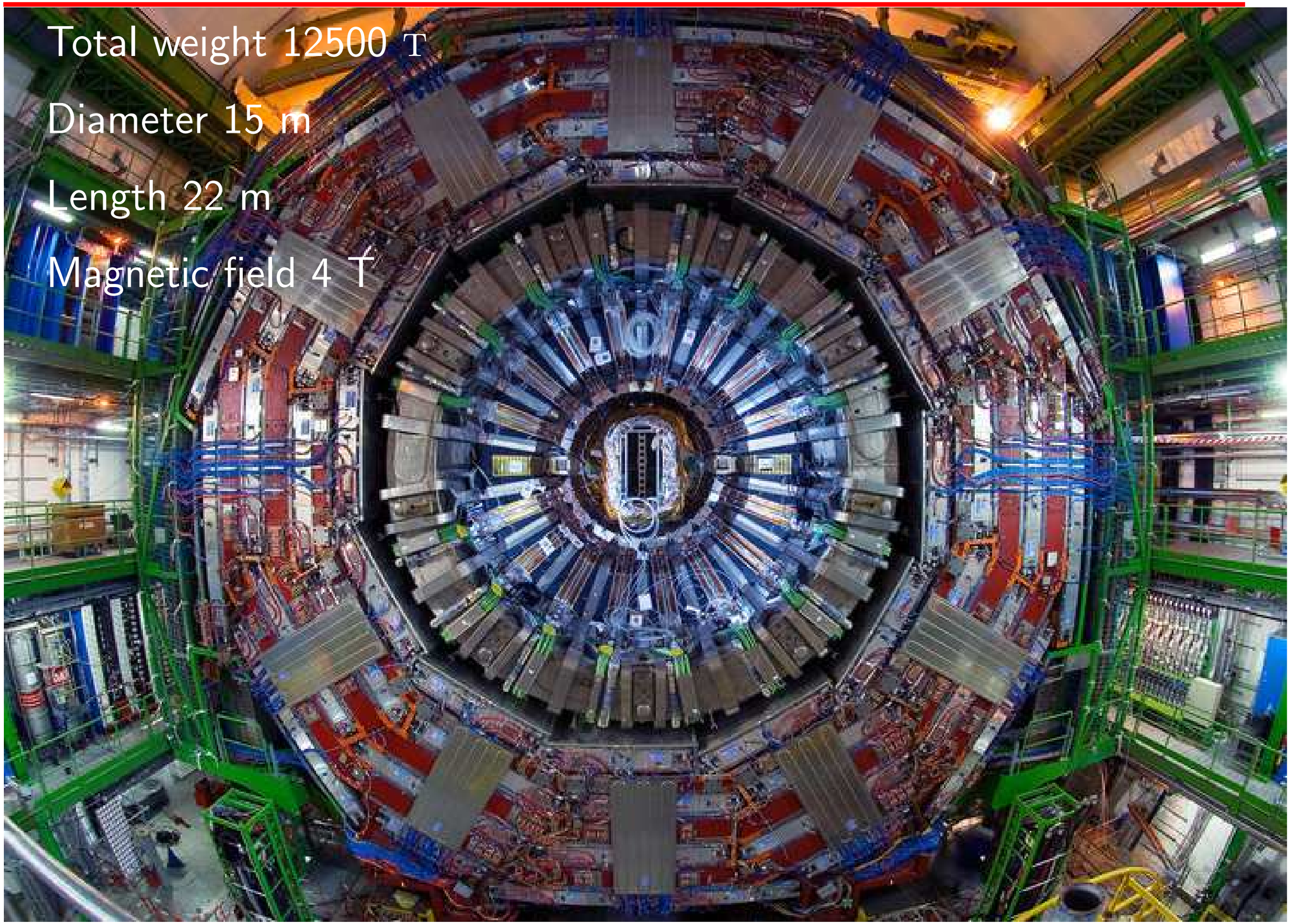
The CMS Detector

- Complex detector

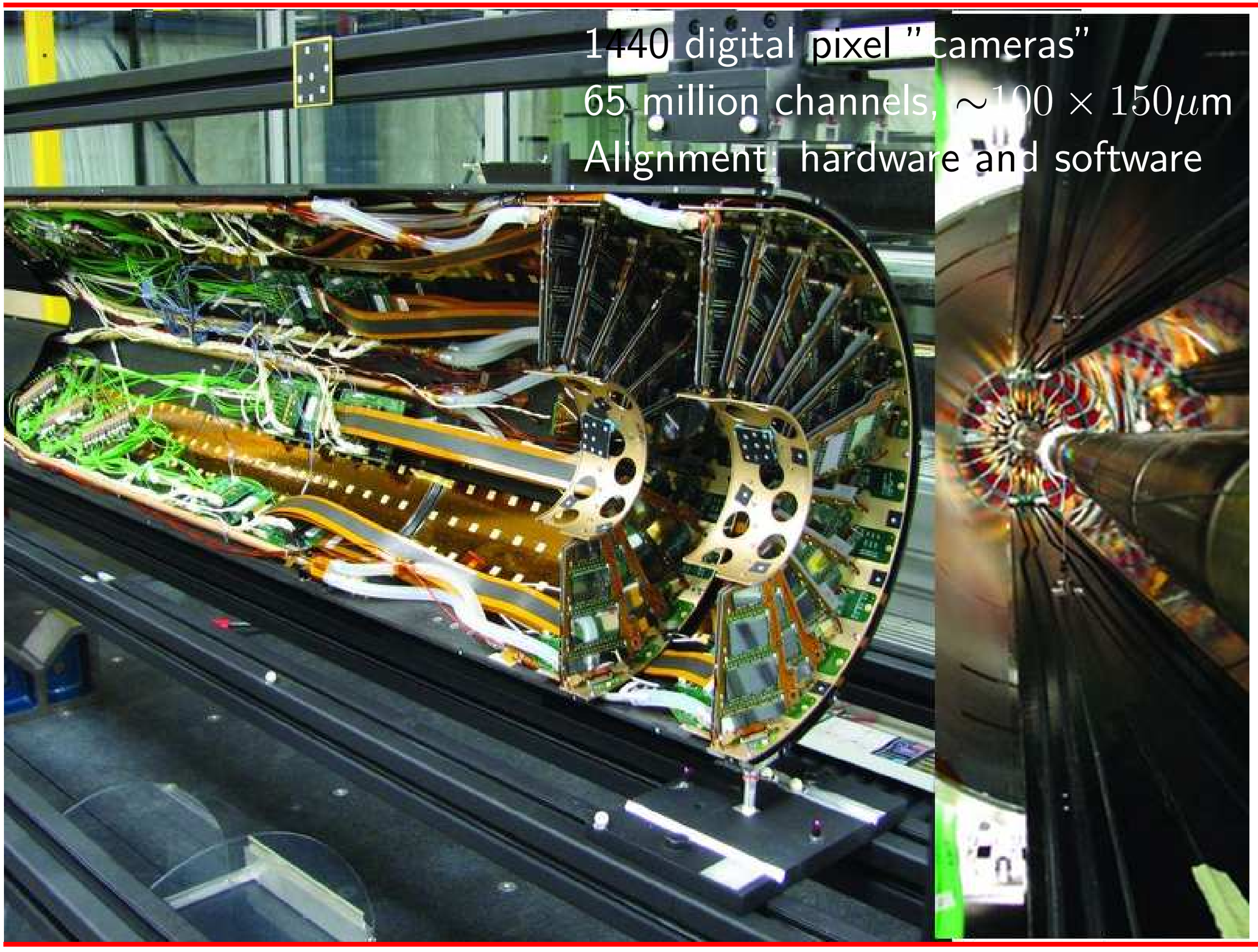
  to sort collision debris out



The CMS Detector



The Silicon Pixel Detector



1440 digital pixel "cameras"

65 million channels, $\sim 100 \times 150 \mu$m

Alignment: hardware and software

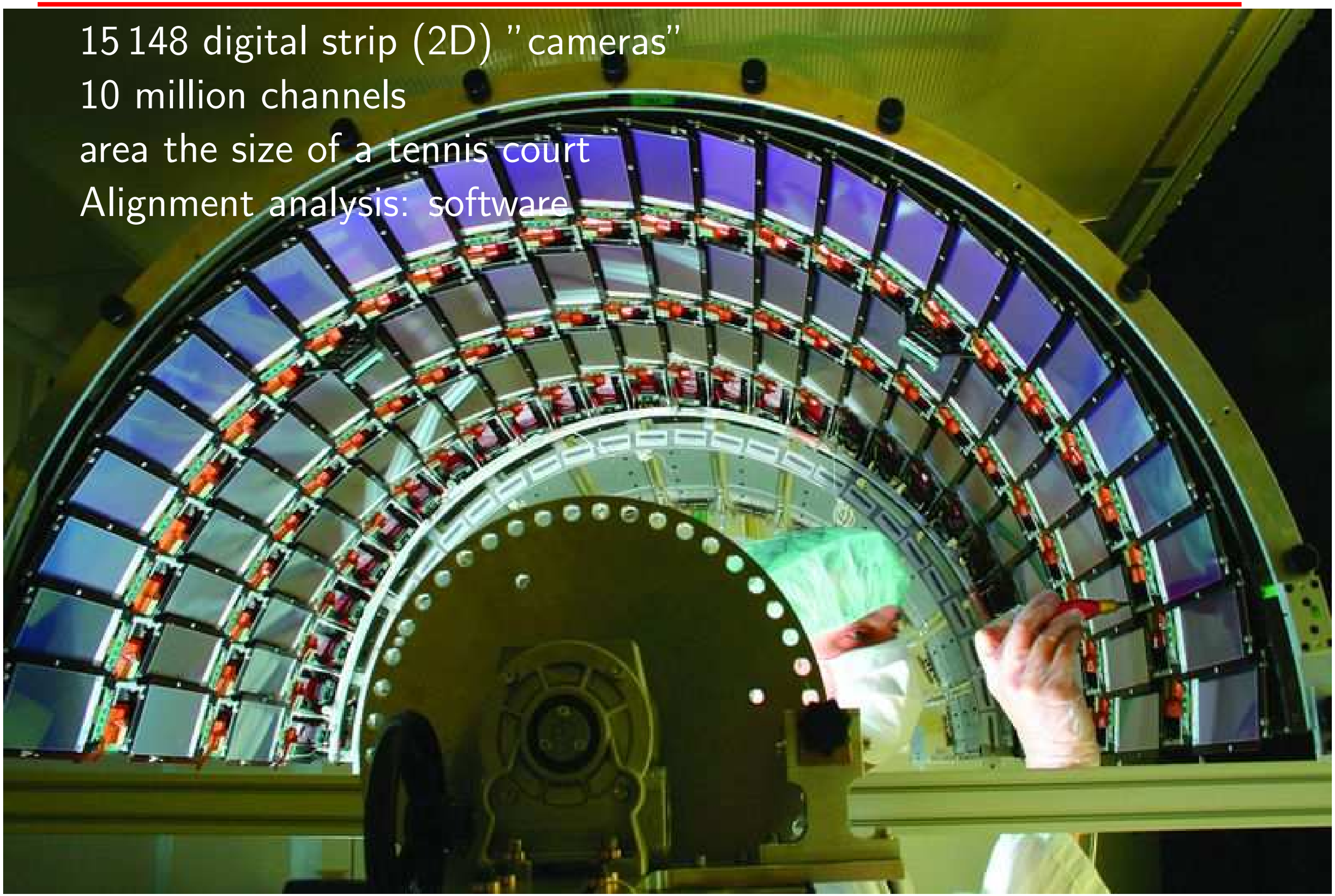
The Silicon Strip Detector

15 148 digital strip (2D) "cameras"

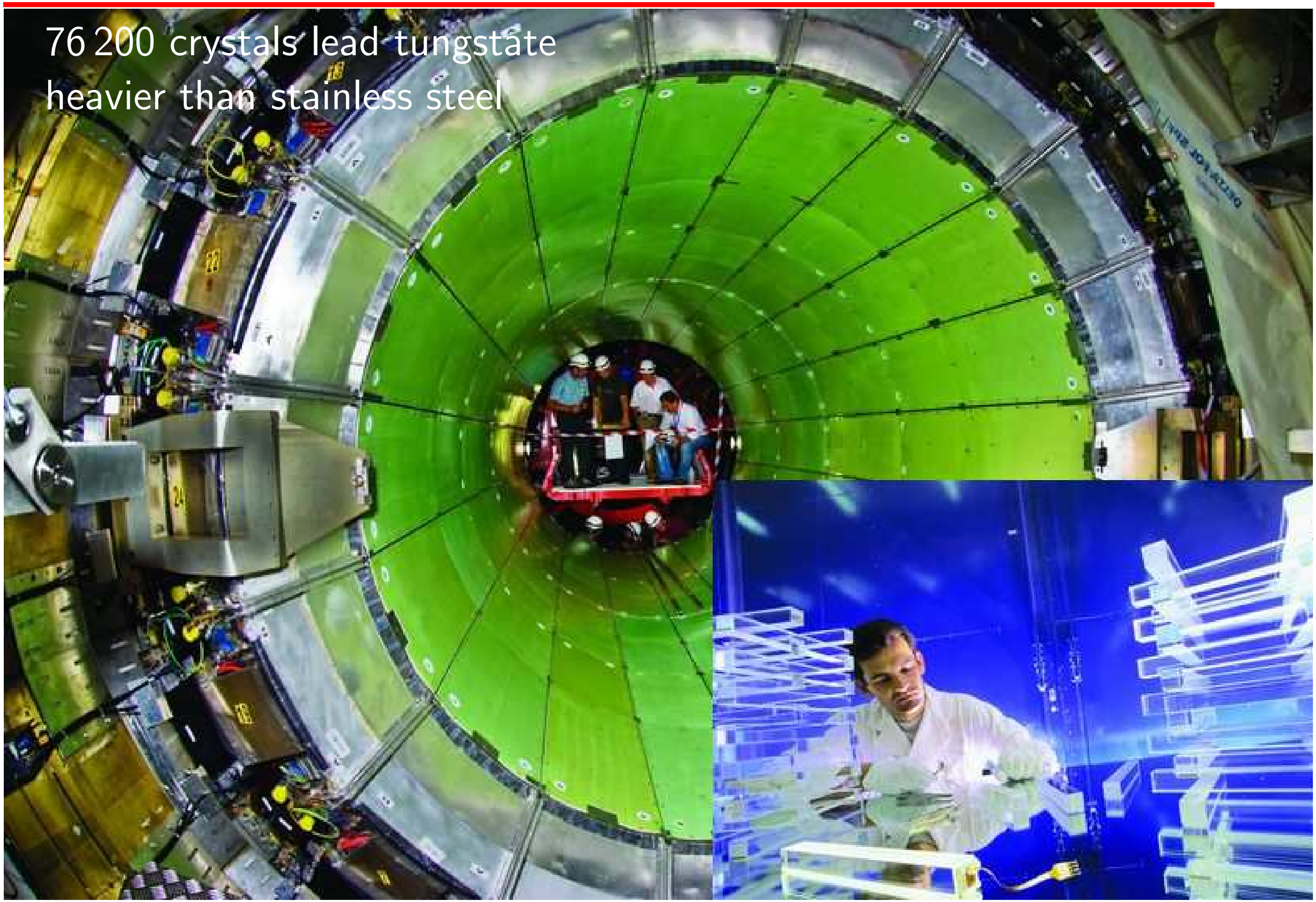
10 million channels

area the size of a tennis court

Alignment analysis: software



Electromagnetic Calorimeter



Hadronic Calorimeter and Muon System

Global Effort at the Large Hadron Collider

- 1991: first World Wide Web (http://www...) server at CERN

- 20 years later: LHC Computing Grid
  - distributed across 36 countries
  - 200,000 computer cores
  - 150 Petabytes of disk space

  Petabyte = Million Gigabytes

  1 Gigabyte $\simeq$ 1 CD

- Flow of data from one experiment alone (CMS):

  > 300 trillion proton-proton collisions in 2011

  > 3 billion "events" recorded on disk in 2011

Nobel Prize in Physics 2008

- $\frac{1}{2}$ Prize – Mechanism leading to matter-antimatter asymmetry – still not sufficient on cosmological scale
- $\frac{1}{2}$ Prize – related to the next topic

The Nobel Prize in Physics 2008
Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa

The Nobel Prize in Physics 2008
Nobel Prize Award Ceremony
Yoichiro Nambu
Makoto Kobayashi
Toshihide Maskawa

Photo: University of Chicago

Yoichiro Nambu

© The Nobel Foundation Photo: U. Montan

Makoto Kobayashi

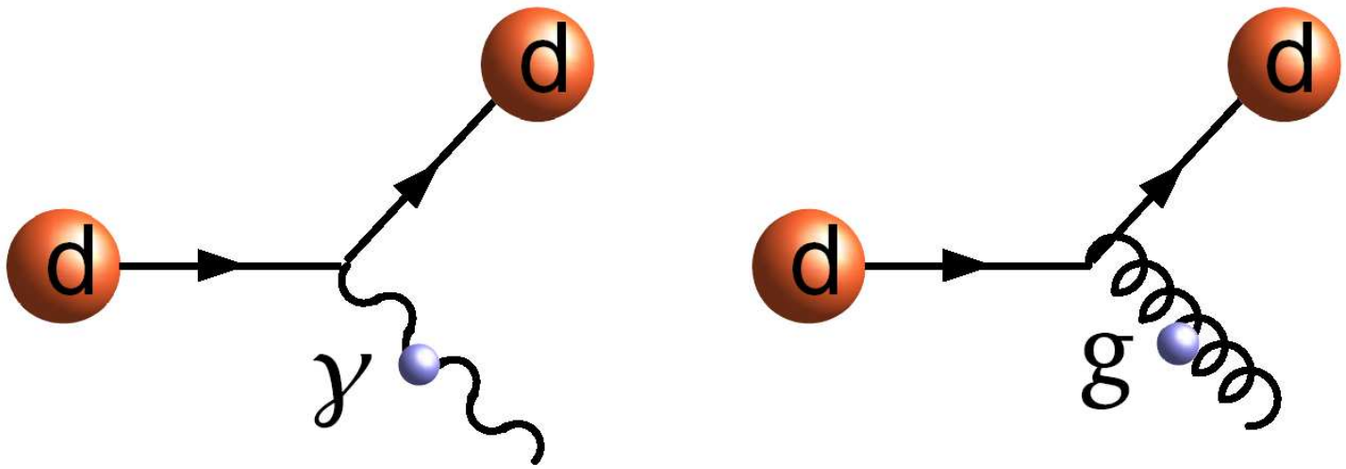
© The Nobel Foundation Photo: U. Montan

Toshihide Maskawa

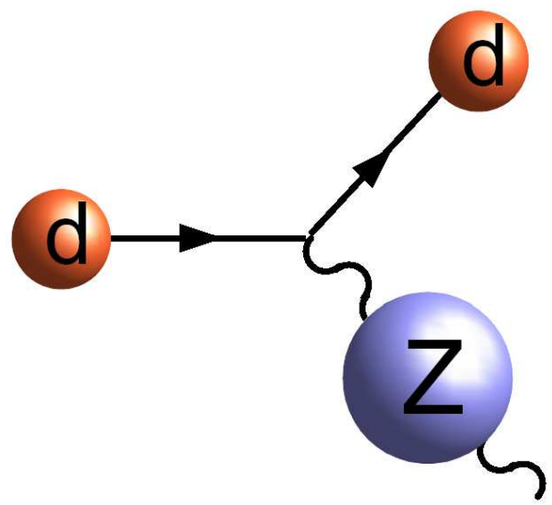
The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

Origin of Mass

- Created equal and massless in the Big Bang
  - light and glue carried by massless "bosons"



- As Universe cooled
  - sister "bosons" to light got mass (spontaneous symmetry breaking)



Need something else to explain these puzzles

- One idea: (super)symmetry

$Q|\text{fermion}\rangle = |\text{boson}\rangle$

$Q|\text{boson}\rangle = |\text{fermion}\rangle$

- Solve:

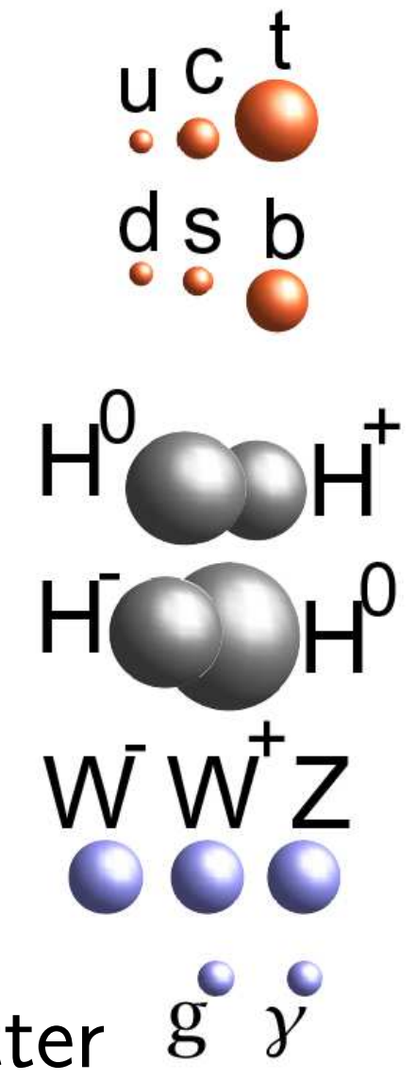
(1) natural light

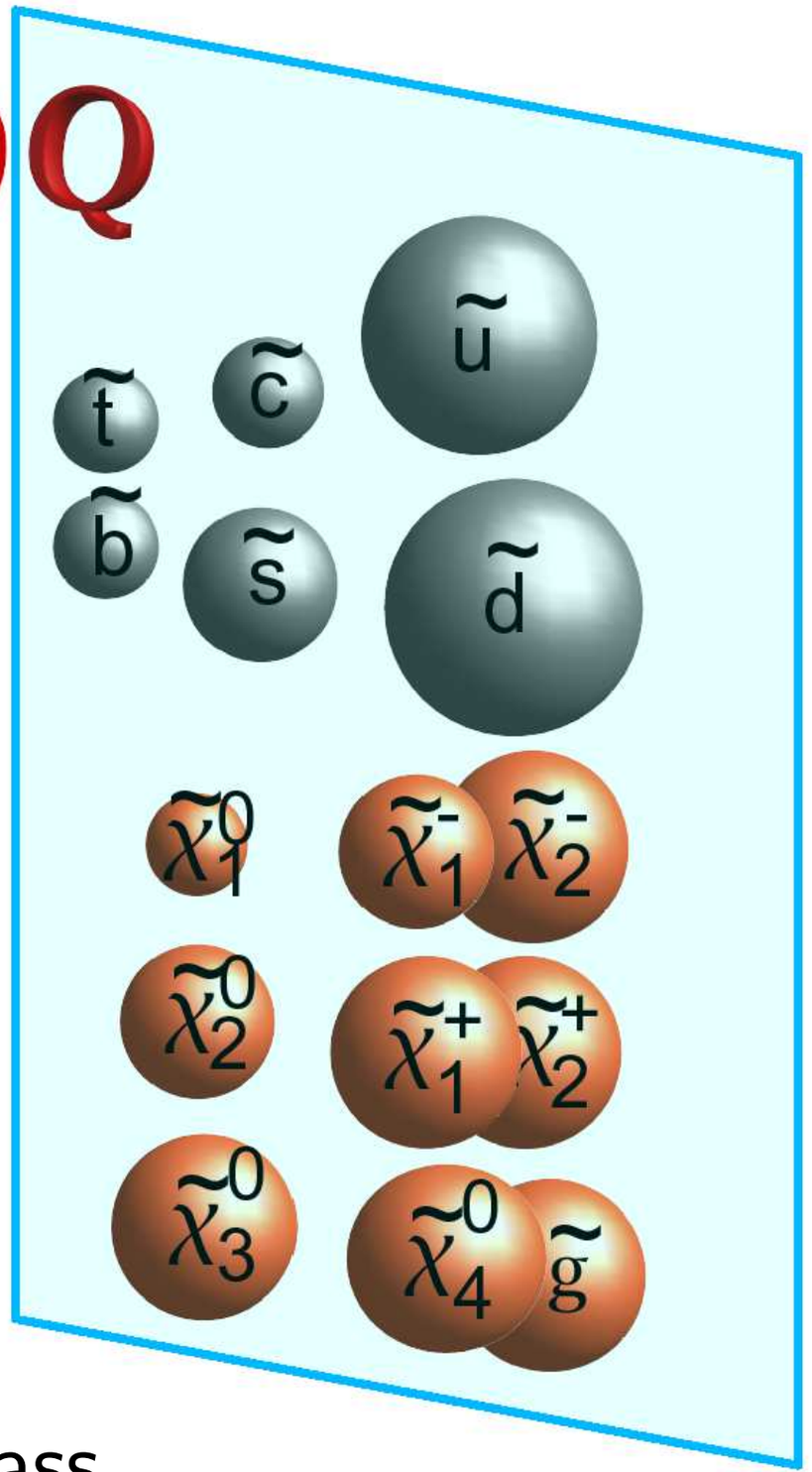
Higgs

(2) dark matter

lightest $\tilde{\chi}_1^0$

(3) large matter/antimatter





- May be just around the corner in mass...

LHC – The Big Bang Machine

- LHC program:

– test of the Higgs field

– may connect to dark energy

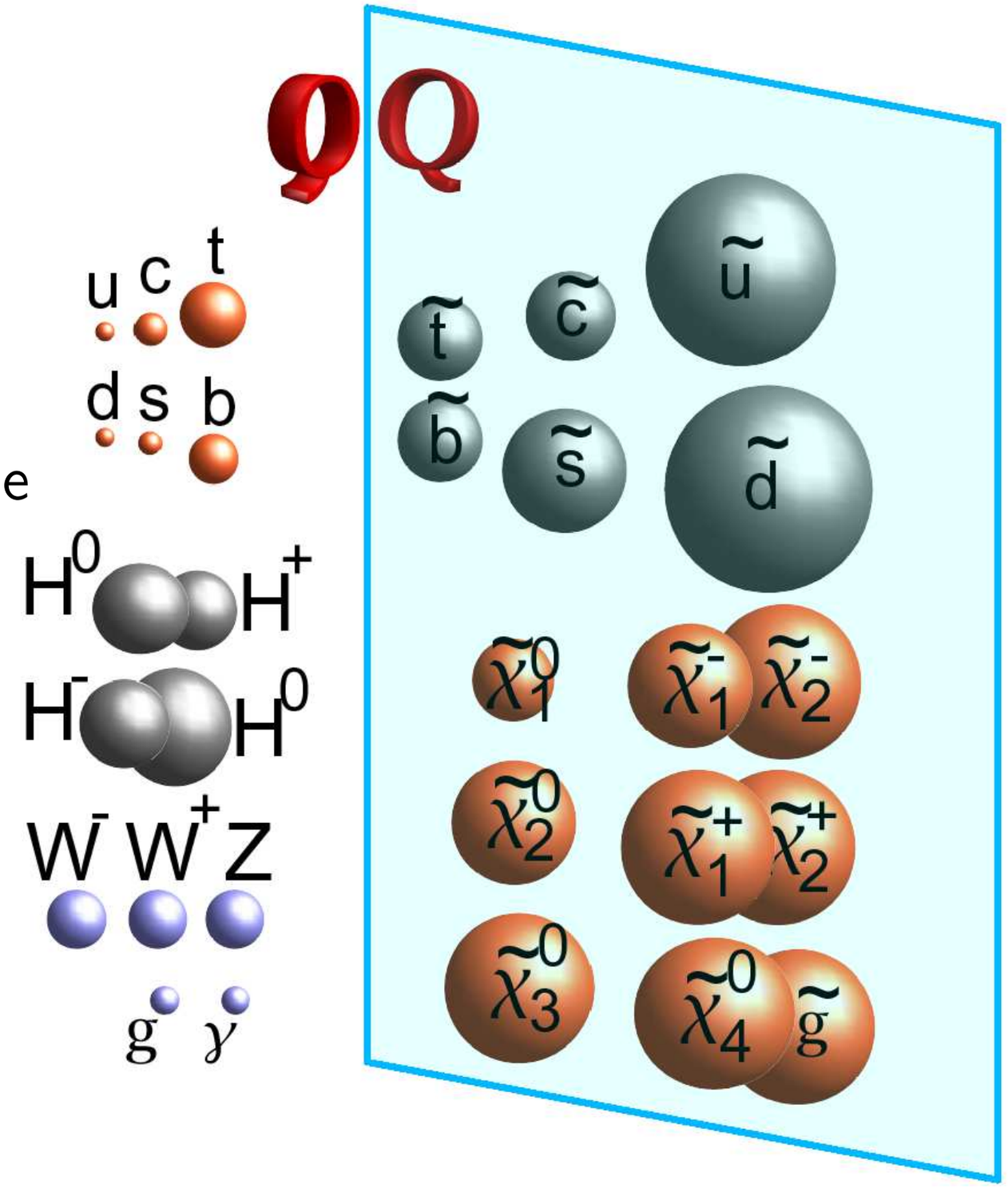
– may explain antimatter puzzle

– may produce dark matter

– re-create quark-gluon plasma

– extra dimensions of space ?

– prepare for unexpected ...



Reaching Highest Energy

- $mc^2 = E$