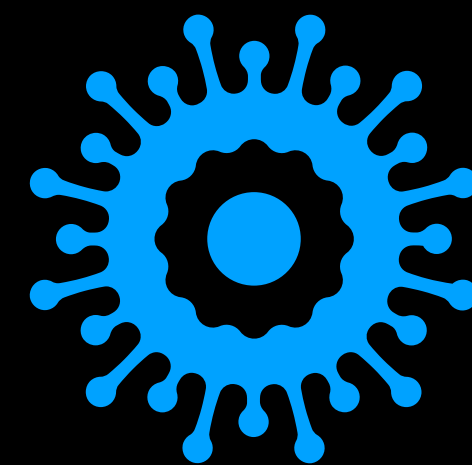


Higgs boson and the unification of forces

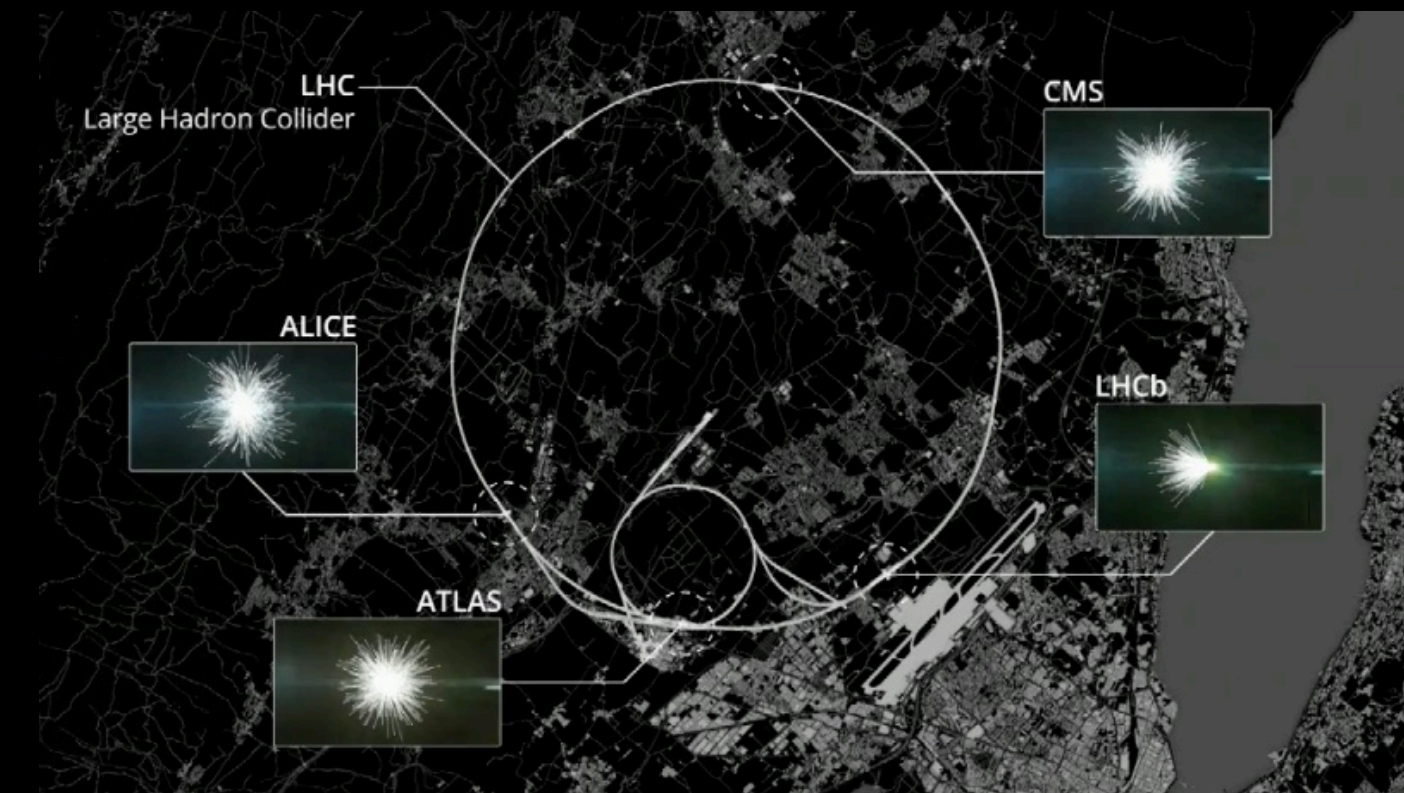


Saptaparna Bhattacharya

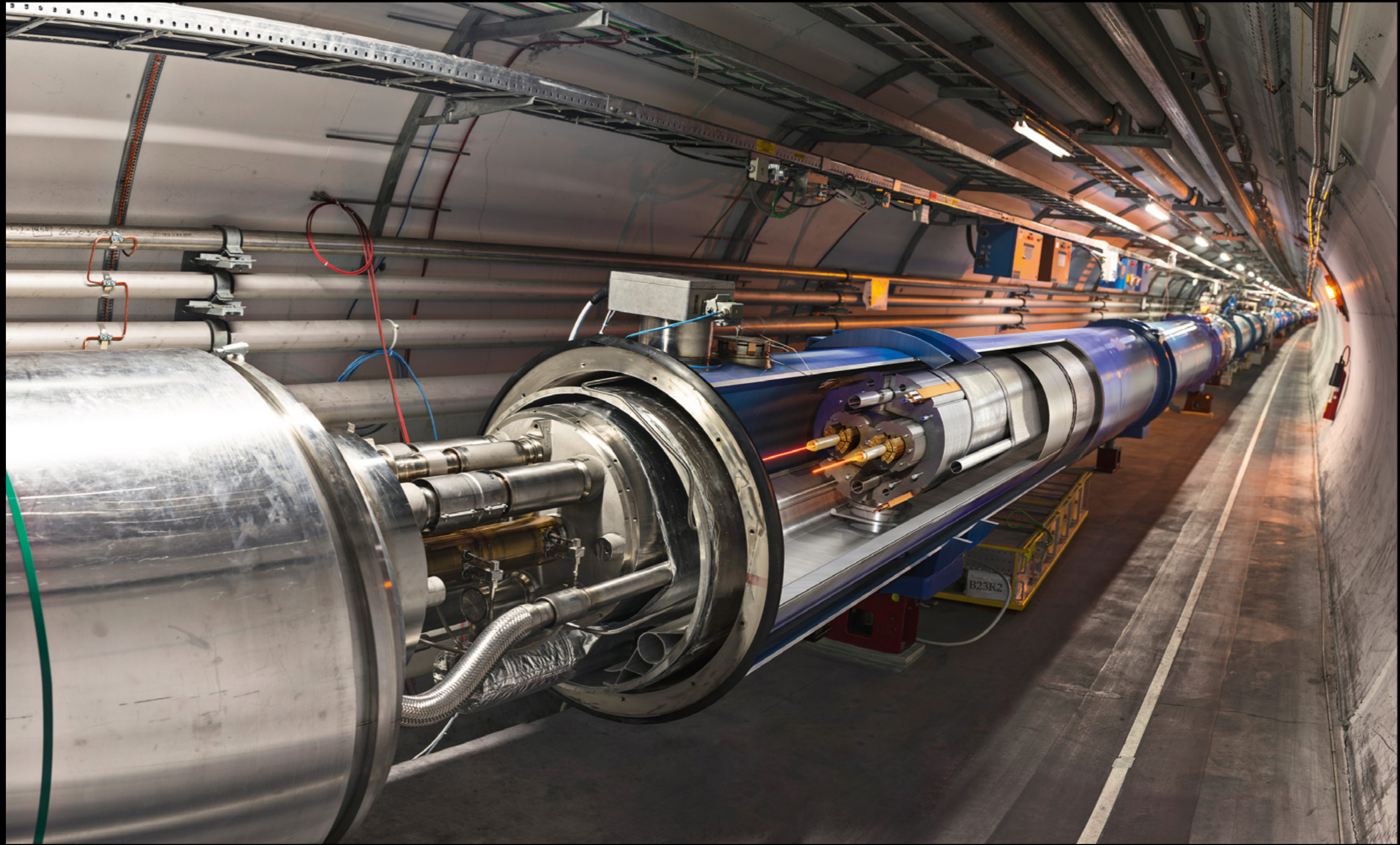
Observables



Instruments



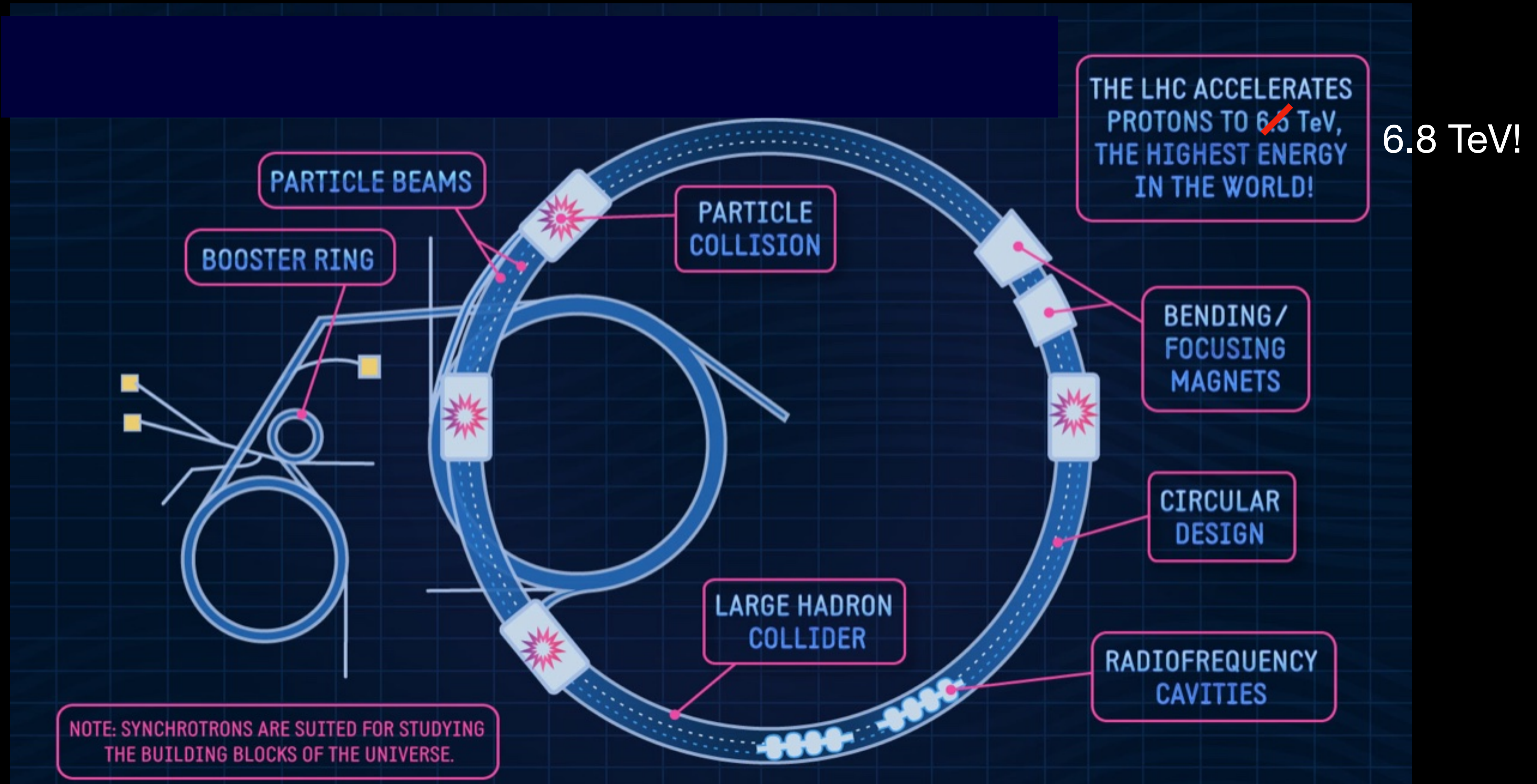
The Large Hadron Collider



The goals of the Large Hadron Collider

- Generate particle that arises from the excitation of the Higgs field
- Study unification of fundamental forces
- Elucidate the nature of dark matter

But what is the Large Hadron Collider?



The Large Hadron *Collider*

- Collider?
- Particles from two beams traveling in opposite directions are made to collide at four different points



The Large *Hadron* Collider

- Hadron?
 - It accelerates protons or ions → called a hadron
 - From the Greek “adros” meaning bulky

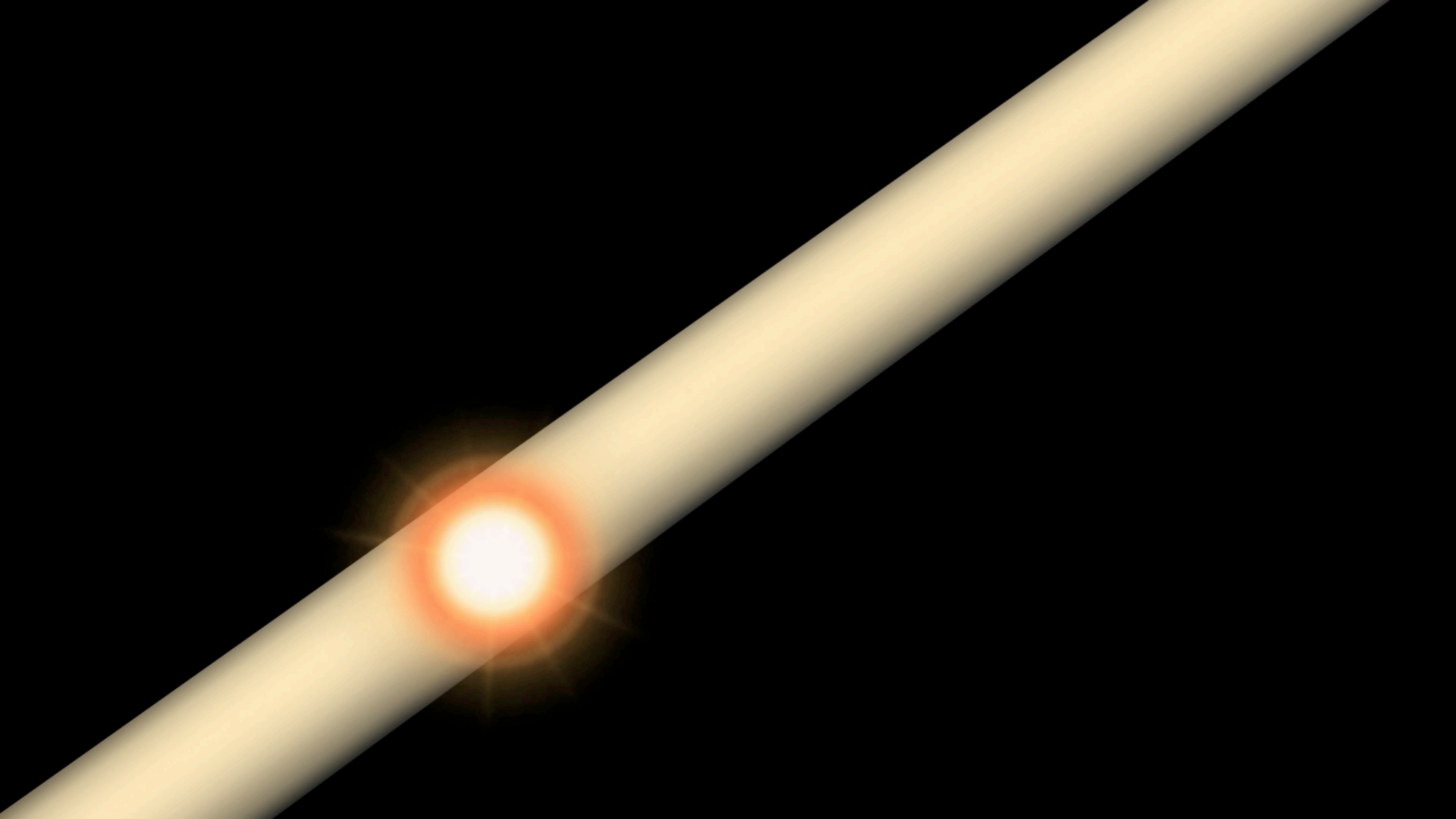
The *Large* Hadron Collider

- Large?
- Approximately 27 km in circumference

The Large Hadron Collider

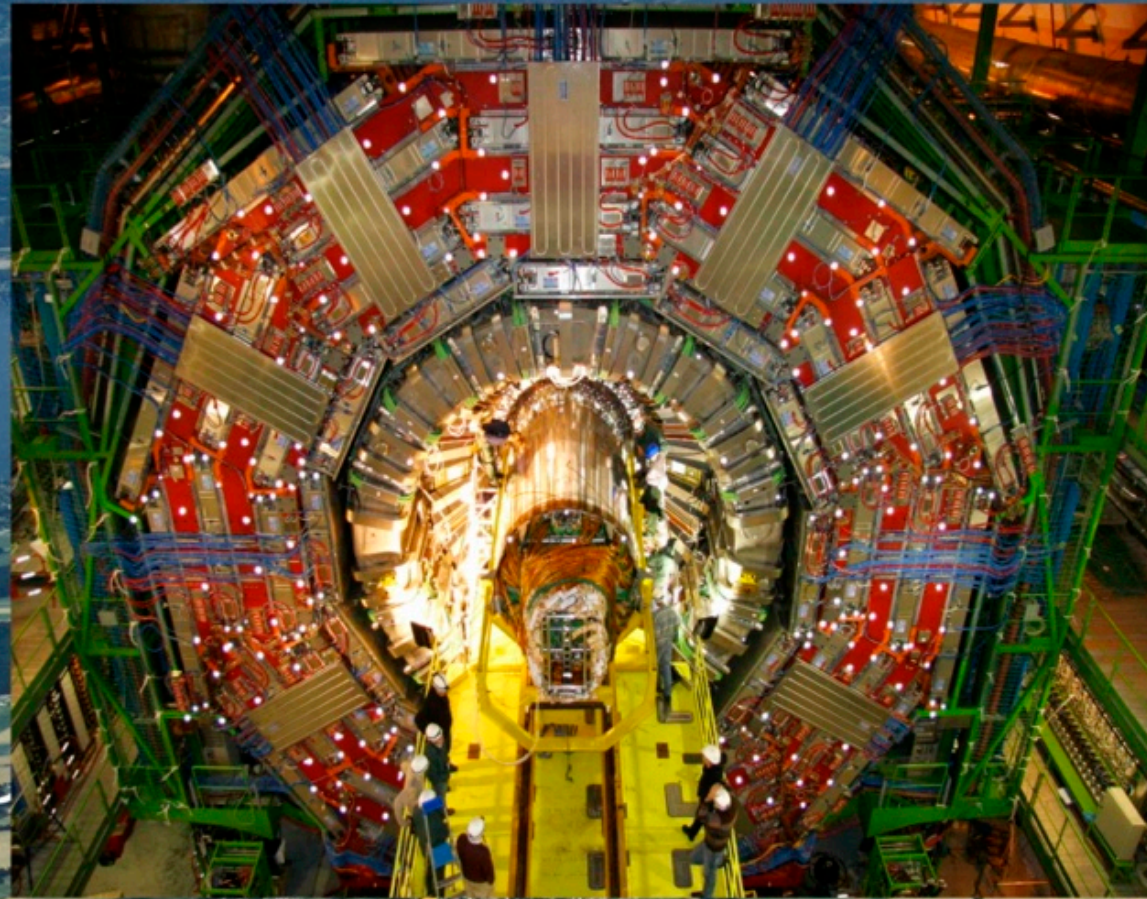


- Two particle beams travel at the speed of light in opposite directions in beam pipes that are kept at ultrahigh vacuum
- Guided around the accelerator ring by strong magnetic fields generated by super conducting electromagnets
- Super conducting state or zero resistance state achieved at -271.3°C 🥶 — this is colder than outer space!
- Achieved with vast distribution system of liquid helium

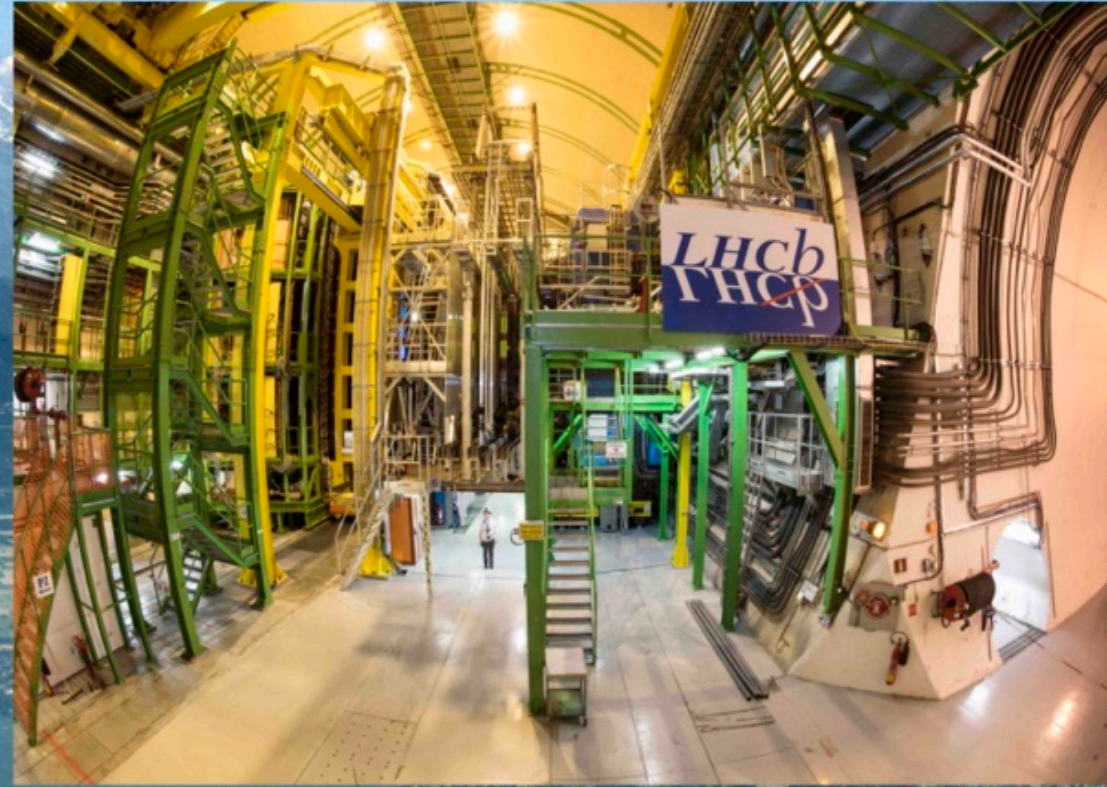


Sits 100 m underground

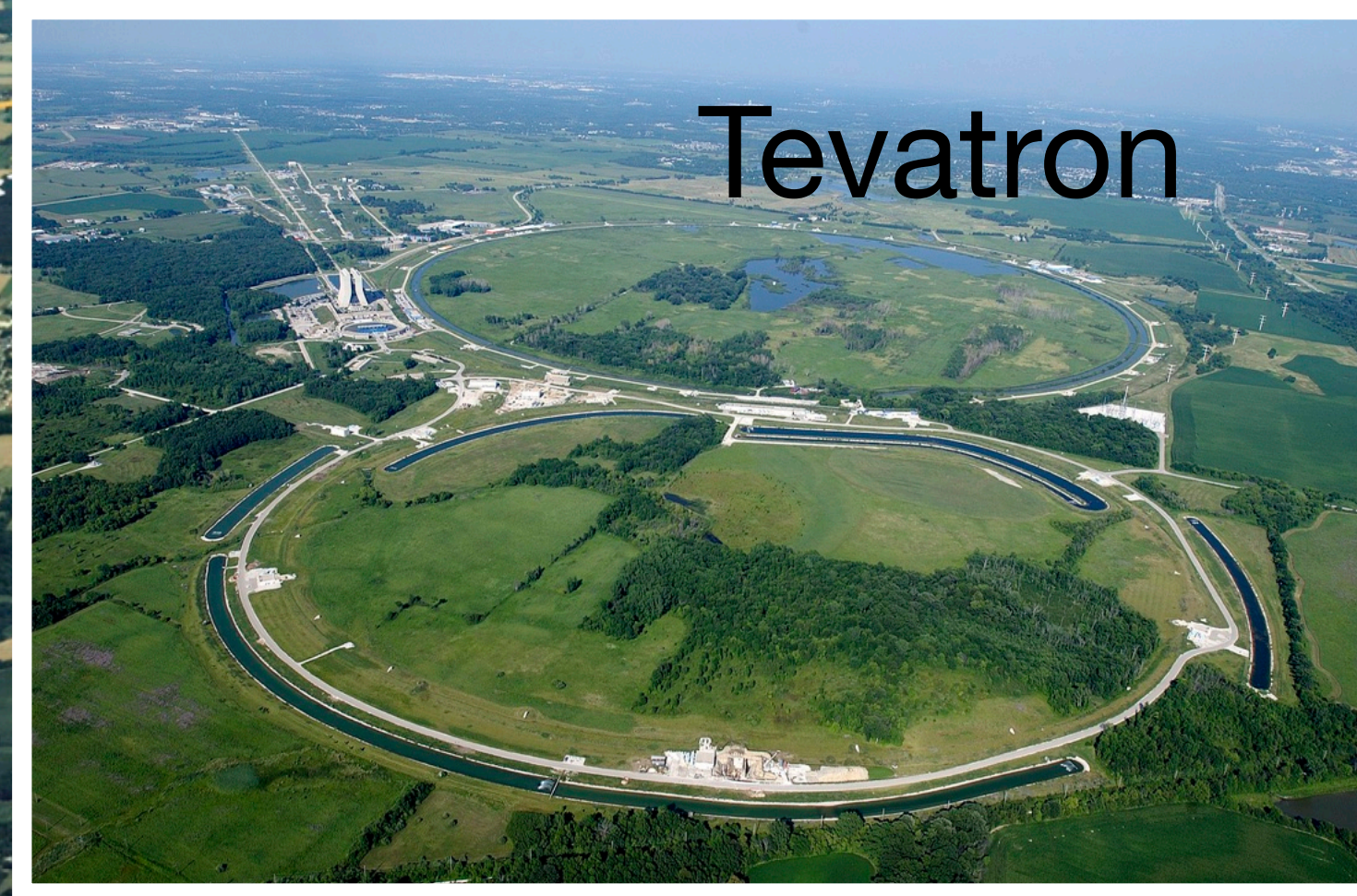




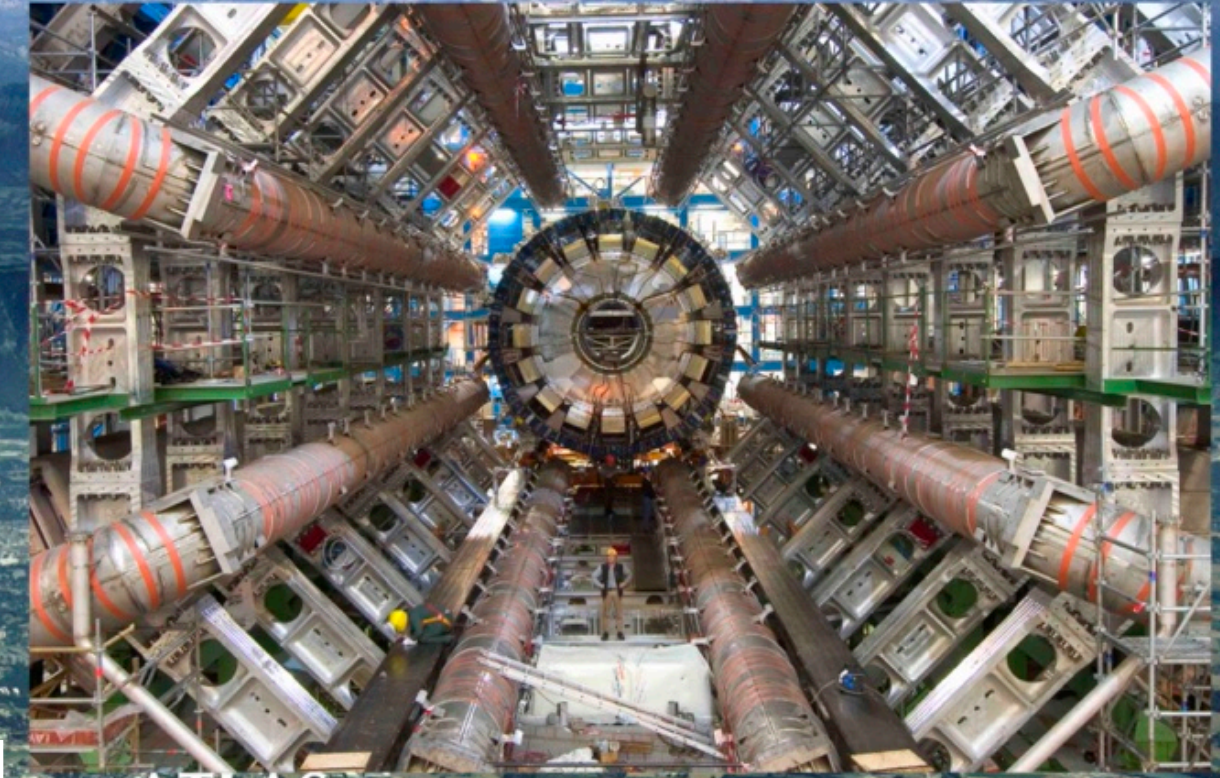
CMS



LHCb



Tevatron



ATLAS

CERN Meyrin

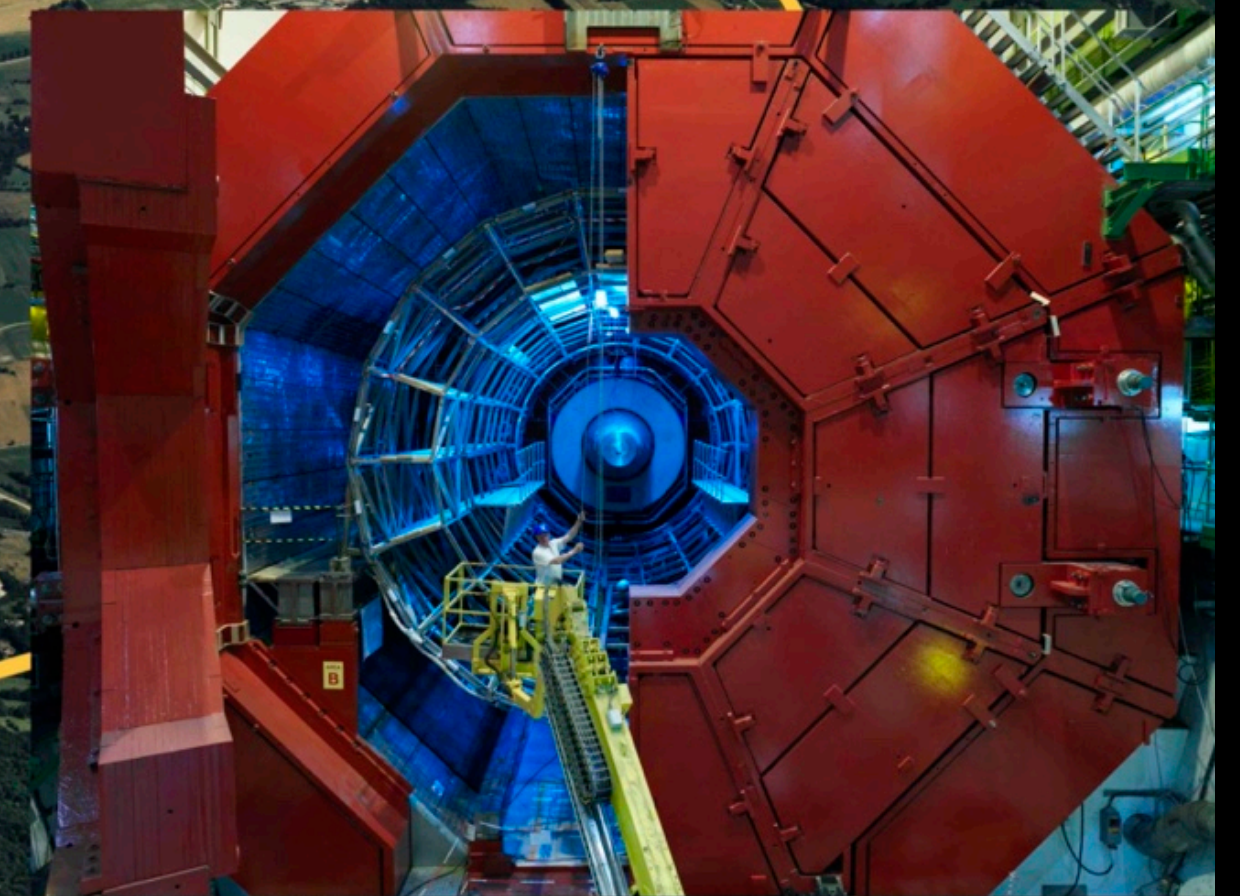
SPS 7 km

PS 6.28 m

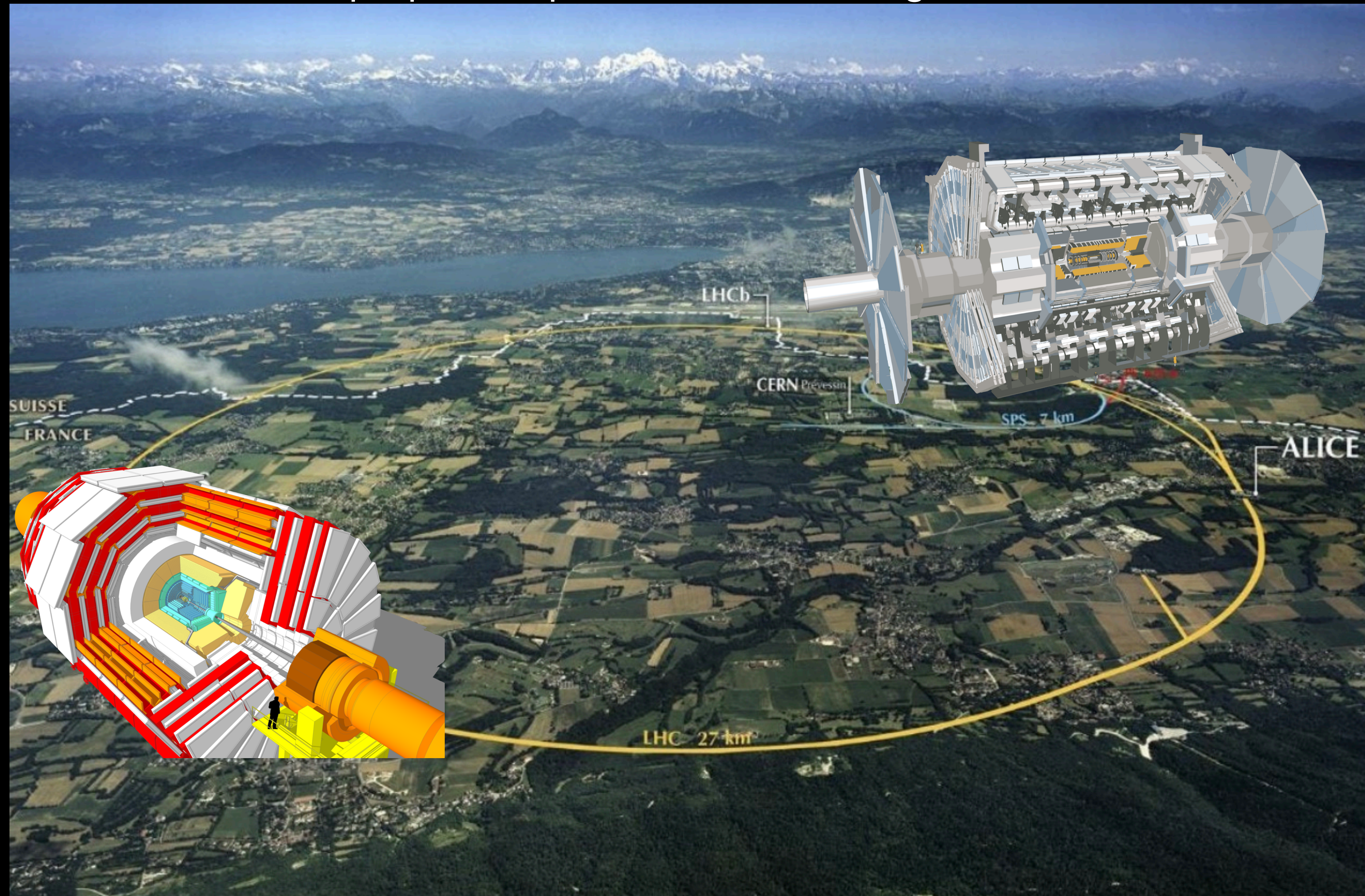
ALICE



LHC 27 km

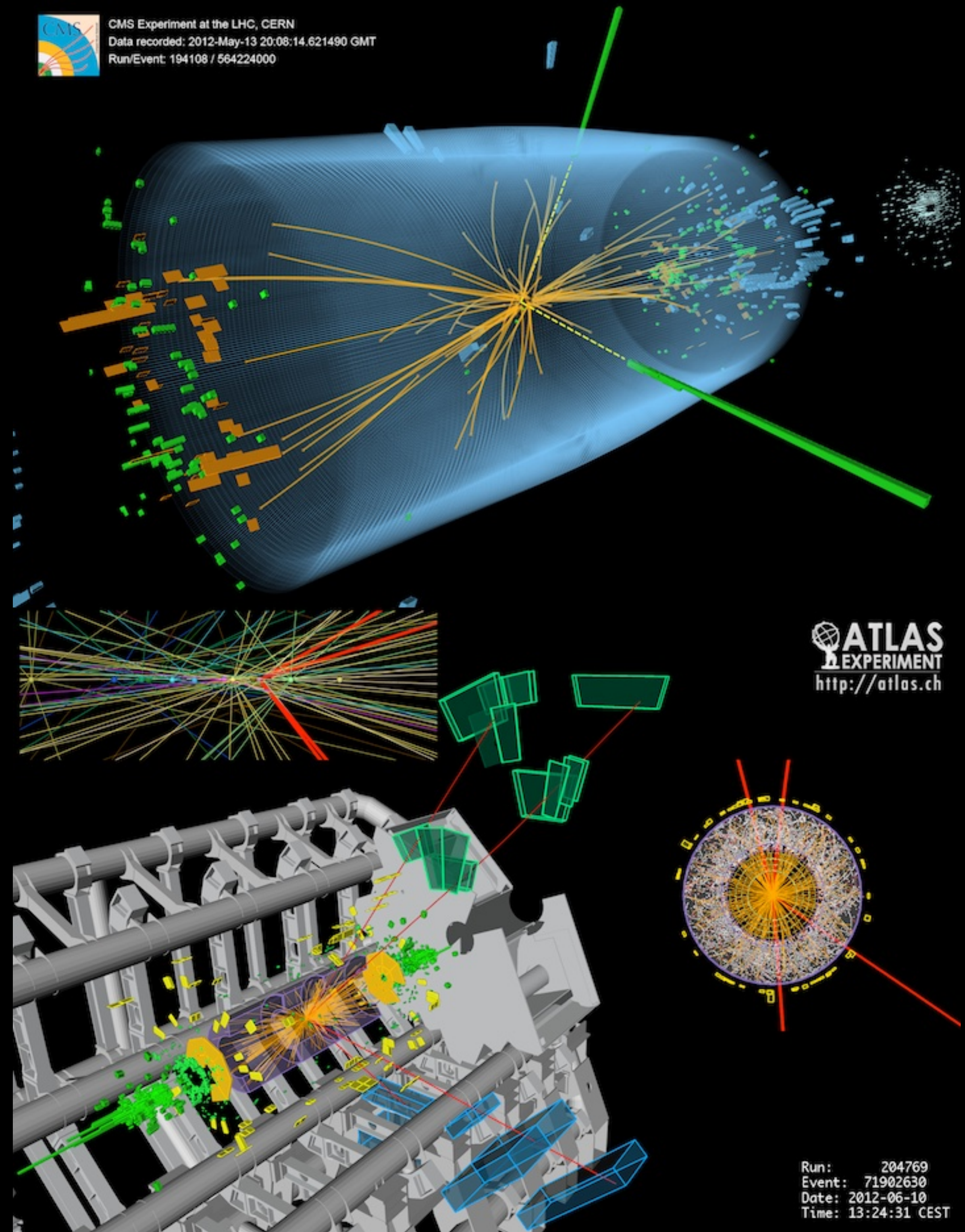
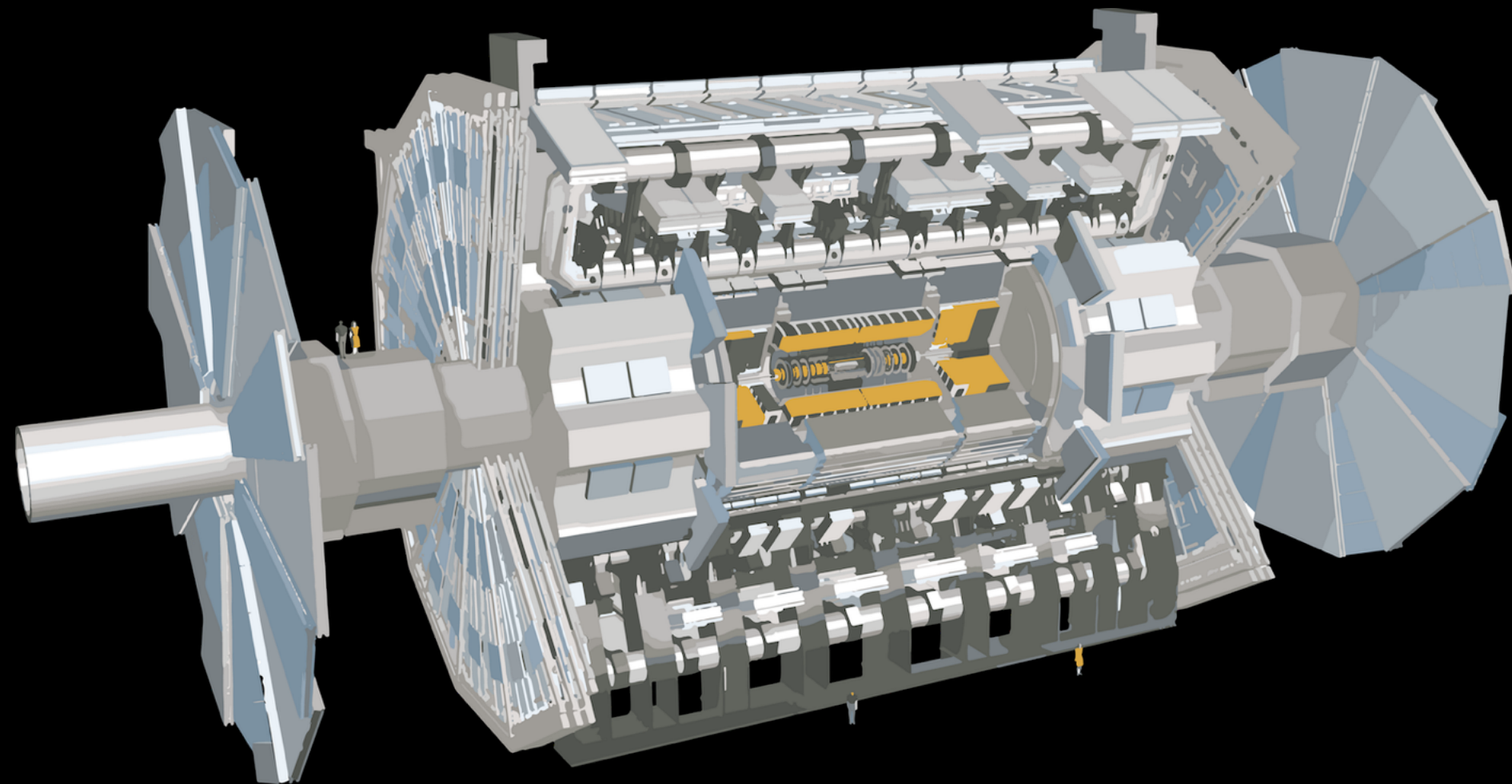
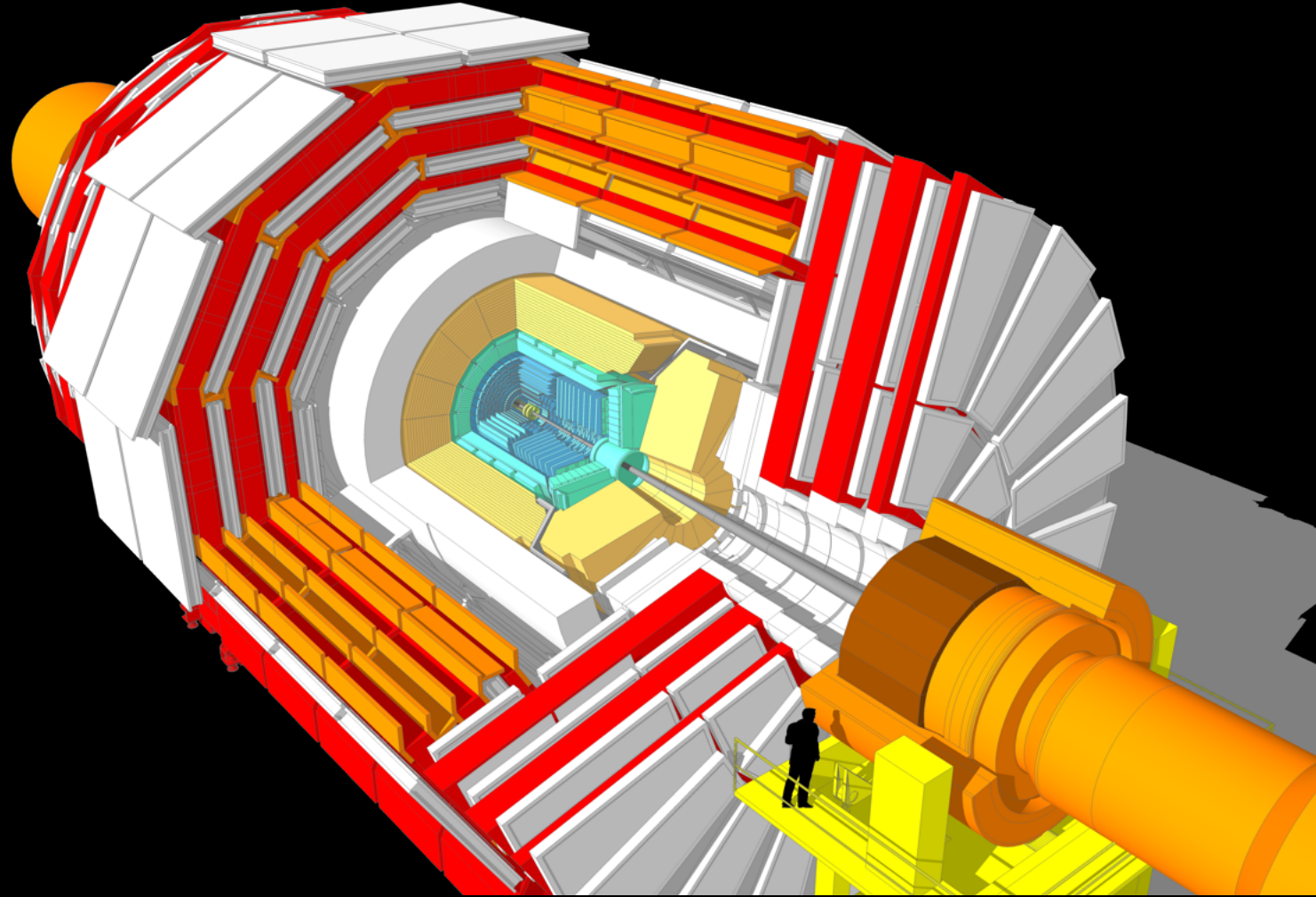


The two multipurpose experiments at the Large Hadron Collider





CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000



ATLAS
EXPERIMENT
<http://atlas.ch>

Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

- On July 4th, 2012
 - Two experiments at the LHC announced that they had observed a *new* particle!
 - This new particle was consistent with a Higgs boson as predicted by the Standard Model of Particle Physics
- Fourteen years later
 - We have measured the properties of this particle and have *very little* doubt that this is anything other than the particle predicted by the theory



HIGGS TURNED

1



In 2022

- 2012: I am born!
- 2013: First steps
- 2014: Who am I?
- 2015: Why am I alone?
- 2016: Not afraid of dark
- 2017: Trip to the tau-land
- 2018: From top to bottom
- 2019: I am getting precise
- 2020: Meet the 2nd generation
- 2021: How broad am I?
- 2022: I am charming!

From G. Landsberg



Higgs boson and the unification of forces

The idea of unification — motion of objects

- As physicists, we like to unify phenomena
- We see objects fallings
- We see planets in orbit
 - Are these phenomena related?
 - If so, what is the nature of this force
 - Are these phenomena manifestation of the same force?



The idea of unification — motion of objects

Mid-1600s

- Newton said “yes!”
- Let us call this force “gravity”

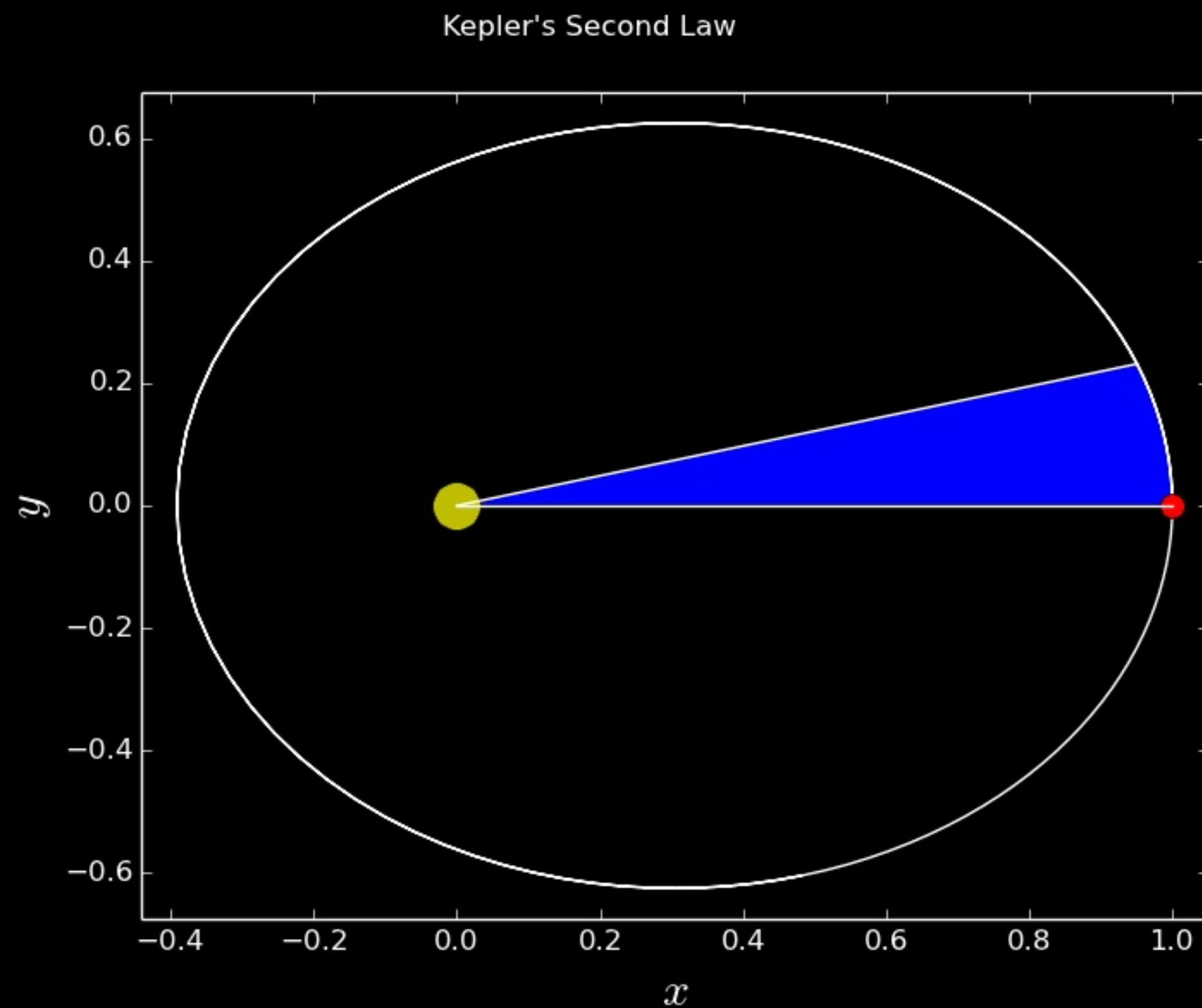


Image courtesy: *Wikimedia Commons*

The idea of unification — motion of objects

- It is the same phenomena that governs the trajectory of cannon balls and the motion of planets
- Major intellectual development



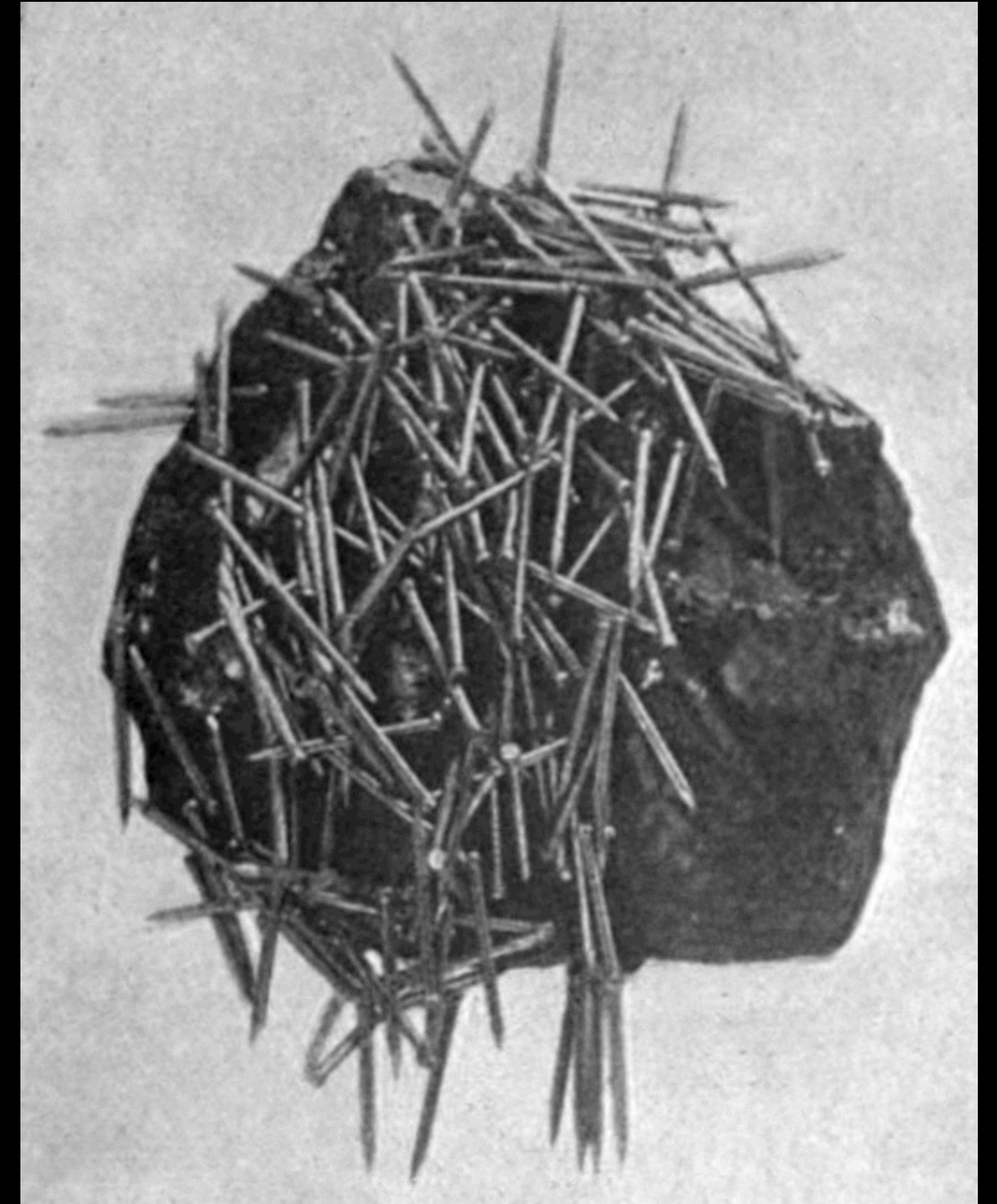
The idea of unification — electricity and magnetism

- We have identified the phenomena of lightning as manifestation of electricity
- Associated with matter that has electric charge
- Static electricity: common phenomena in winter



The idea of unification — electricity and magnetism

- We have identified the behavior of ferromagnetic metals as manifestation of magnetism
- The first manifestation of magnetism seen in lodestone (magnetite)
 - Attracts iron filings
 - Used to remove arrows embedded in a person's body or a compass for navigation



The idea of unification — electricity and magnetism

- Noticed by Faraday and others:
 - electric current inside a wire creates a magnetic field outside the wire
 - current induced in a moving wire in the presence of a magnetic field
- Intellectual leap in connecting electricity and magnetism

Electricity and magnetism:
Manifestation of the same phenomena

Mid-1800s

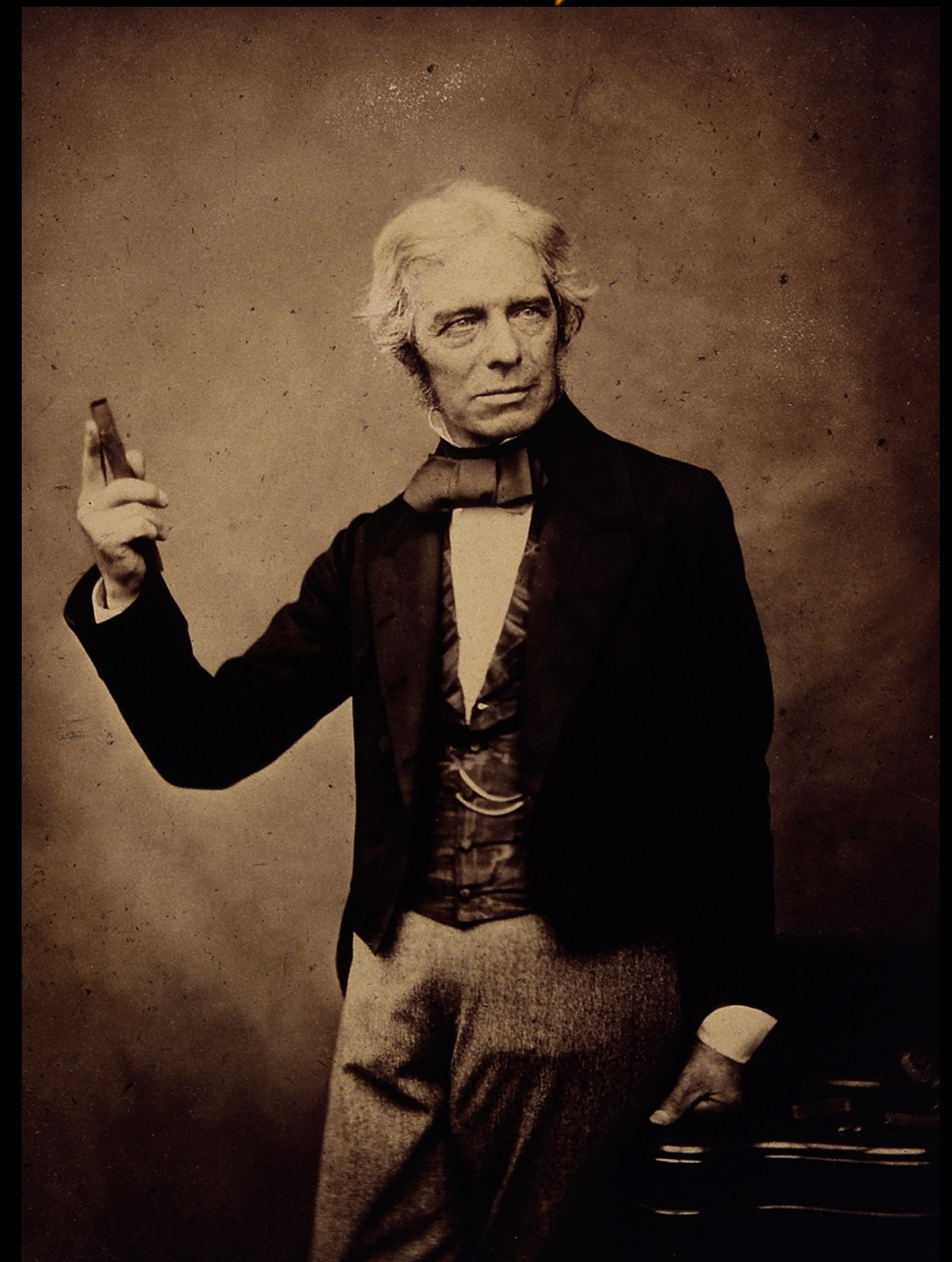
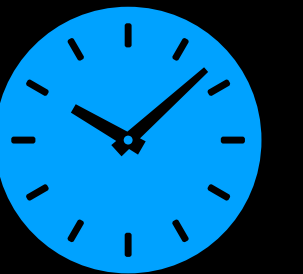


Image courtesy: Wikimedia Commons

The idea of unification — space and time

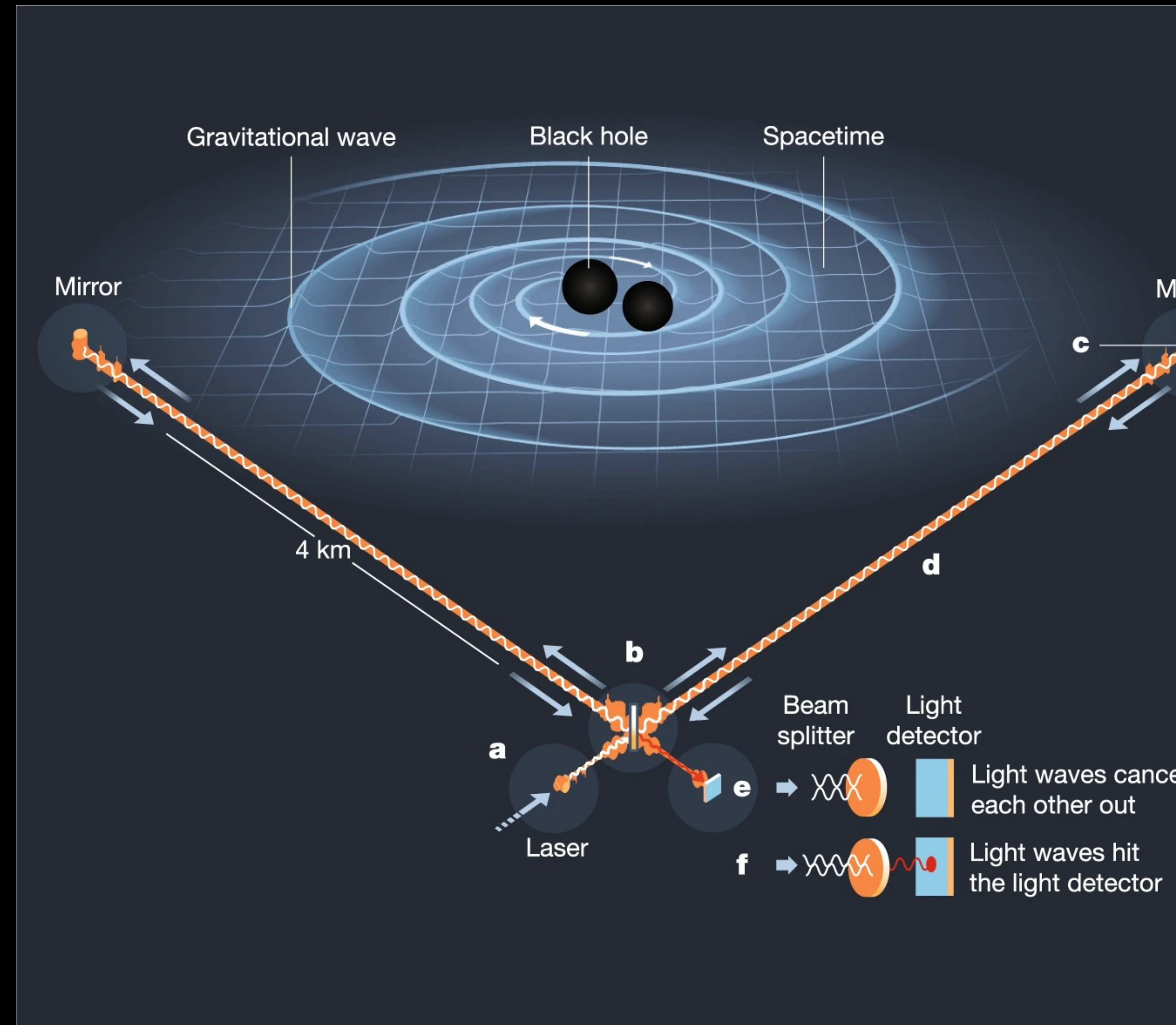
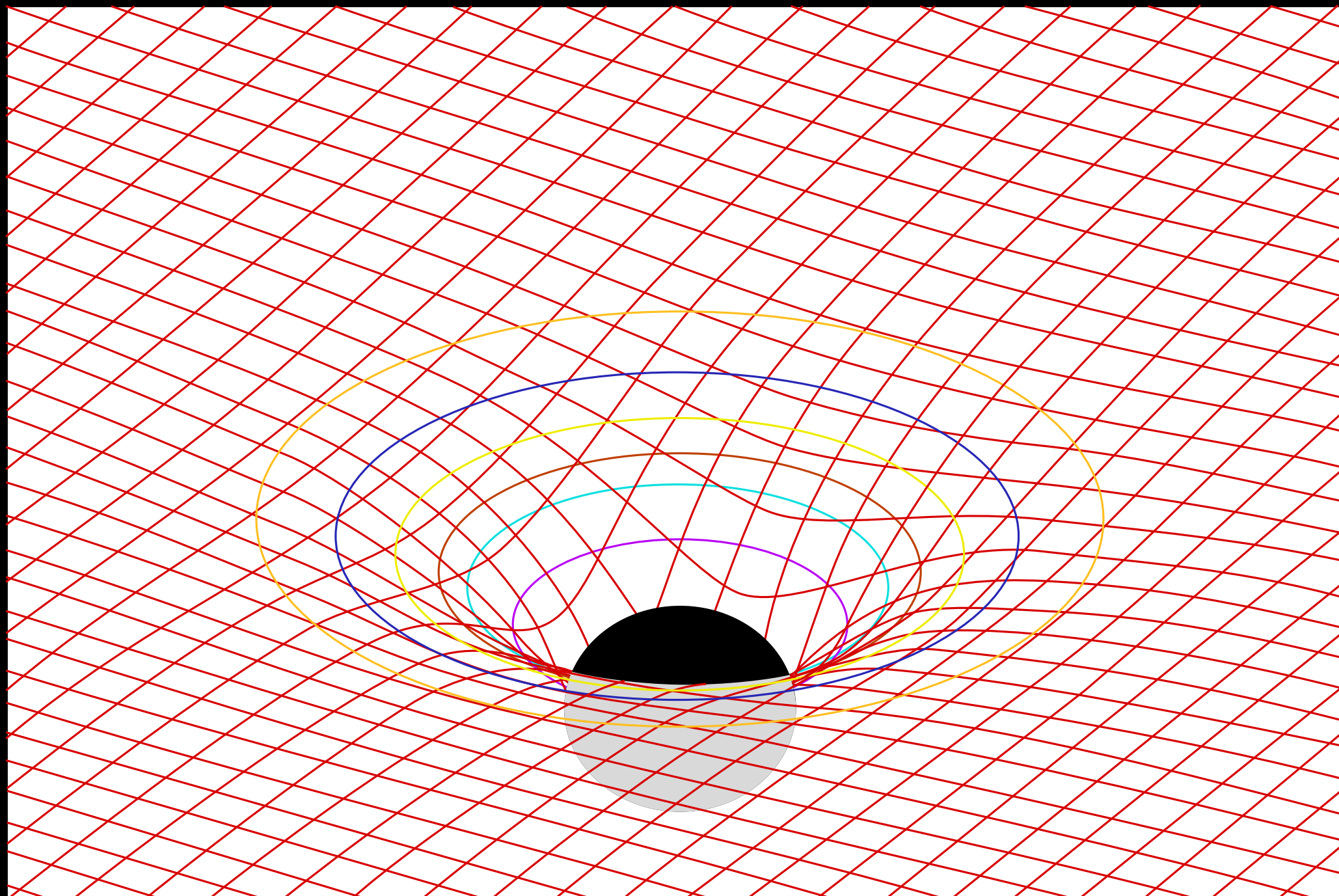
- Emerges from the idea of a frame of reference, an observer and an event
 - Reference frames can be *inertial (constant velocity)* and non-inertial (accelerating)
 - Define observer with a local coordinate system (x, y, z) and a clock
 - Event $\rightarrow$ point in space and instance in time
- Einstein's theory of special relativity:
 - The laws of physics are invariant in inertial frames
 - Speed of light in vacuum is same for all observers



Killed the idea of the
mysterious aether

The idea of unification — space and time

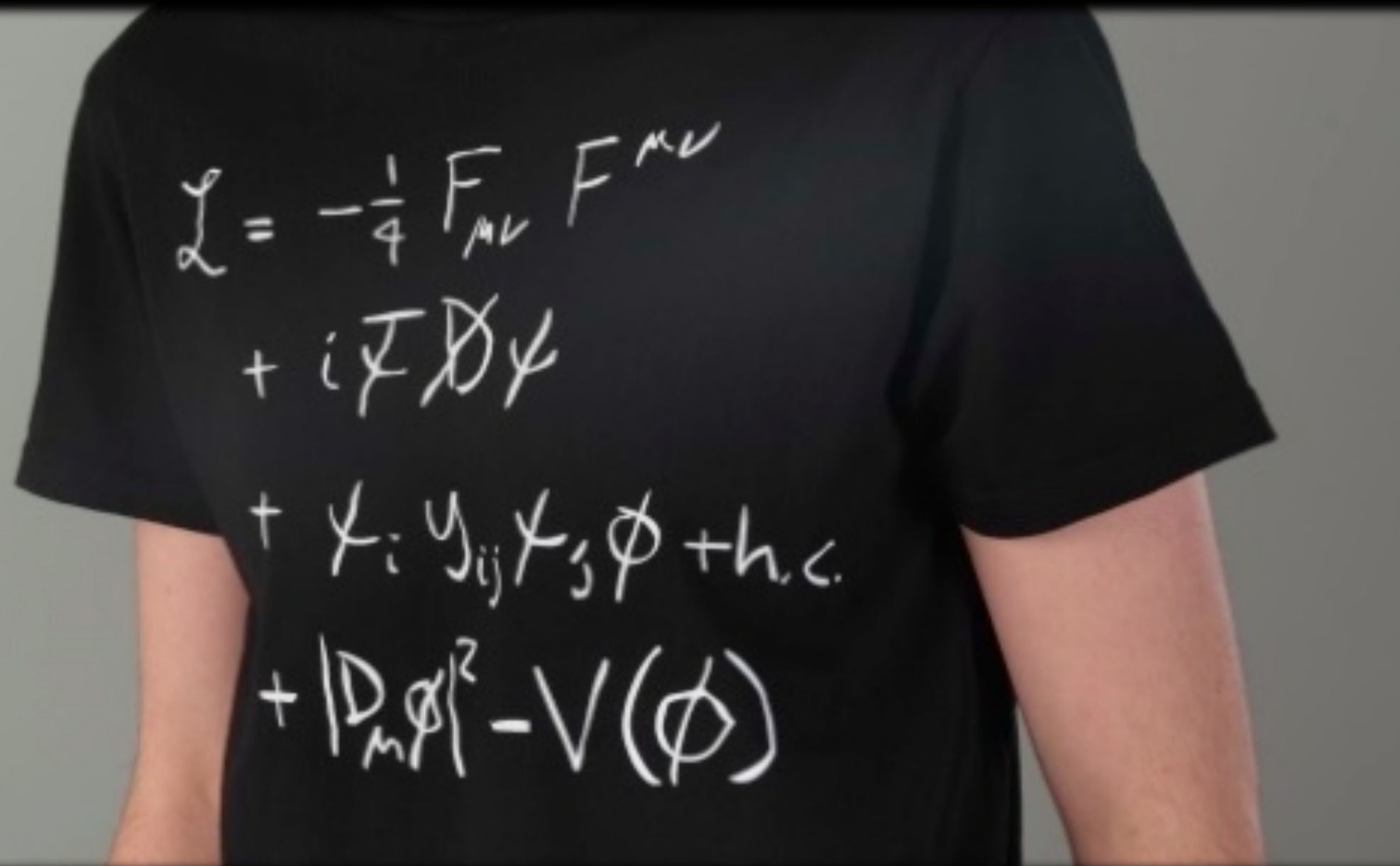
- Unification of space-time major intellectual leap of the 20th century
- Implies unification of mass and energy
- General relativity: gravity emerges as a geometric property of space and time



Standard Model of Particle Physics

Provides a description of the most fundamental
building blocks of matter

Focus on interactions of the
particles with the force
carriers



Standard Model of Elementary Particles											
three generations of matter (elementary fermions)						three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary)		
	I	II	III	I	II	III					
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0			$\approx 124.97 \text{ GeV}/c^2$	
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0			0	
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			0	
QUARKS	u up	c charm	t top	$\bar{u}$ antiup	$\bar{c}$ anticharm	$\bar{t}$ antitop	g gluon			H higgs	
	d down	s strange	b bottom	$\bar{d}$ antidown	$\bar{s}$ antistrange	$\bar{b}$ antibottom	γ photon				
	e^- electron	μ^- muon	τ^- tau	e^+ positron	μ^+ antimuon	τ^+ antitau	Z Z ⁰ boson				
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$\bar{\nu}_e$ electron antineutrino	$\bar{\nu}_\mu$ muon antineutrino	$\bar{\nu}_\tau$ tau antineutrino	W⁺ W ⁺ boson			W⁻ W ⁻ boson	
LEPTONS											
Fermions						Bosons					

Mediators of forces

Mediator of
weak forces:
responsible for
nuclear fission
and fusion

W

W-boson

g

Gluon

Mediator of strong
force: responsible
for holding the
proton together

Z

Z-boson

γ

Photon

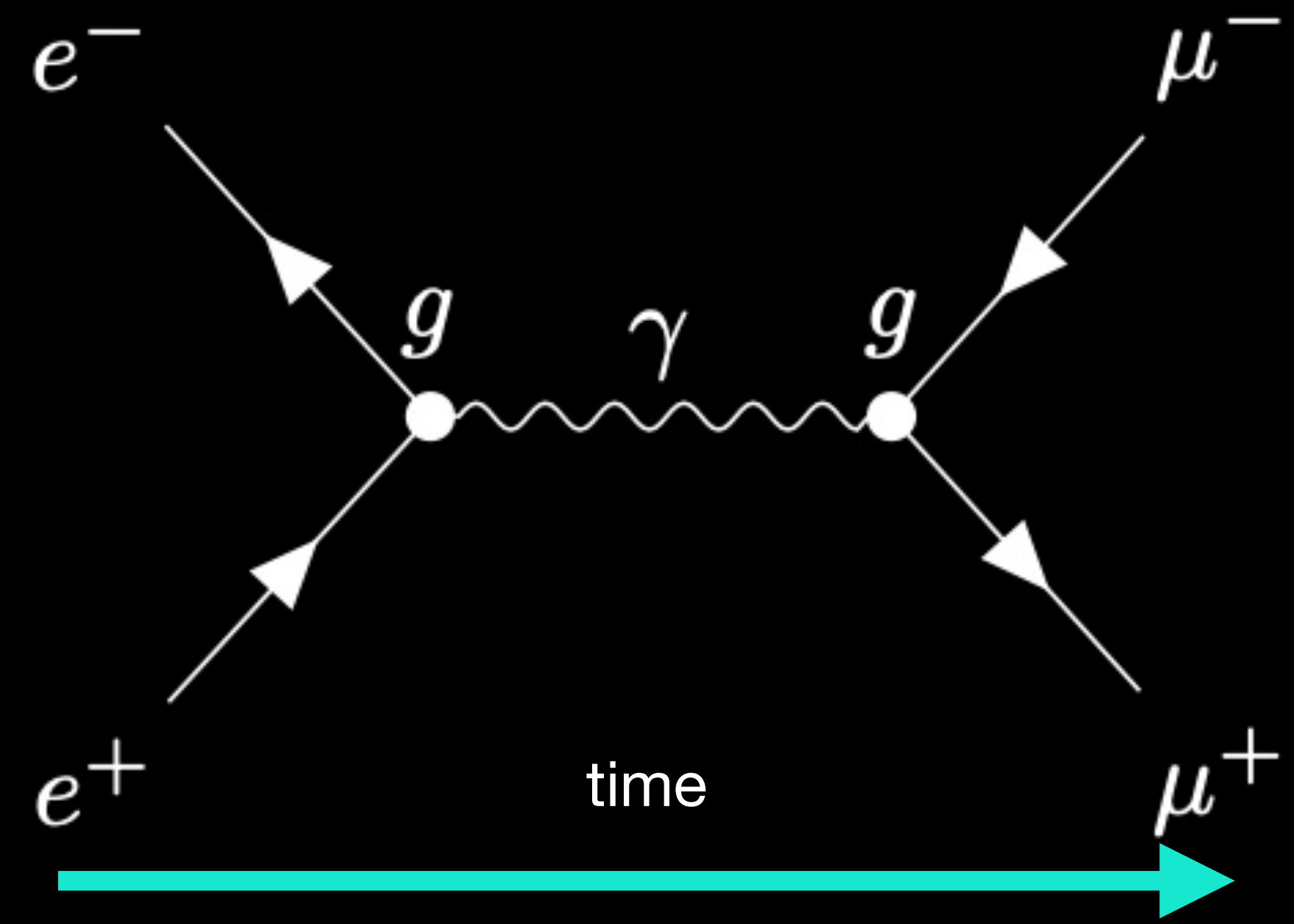
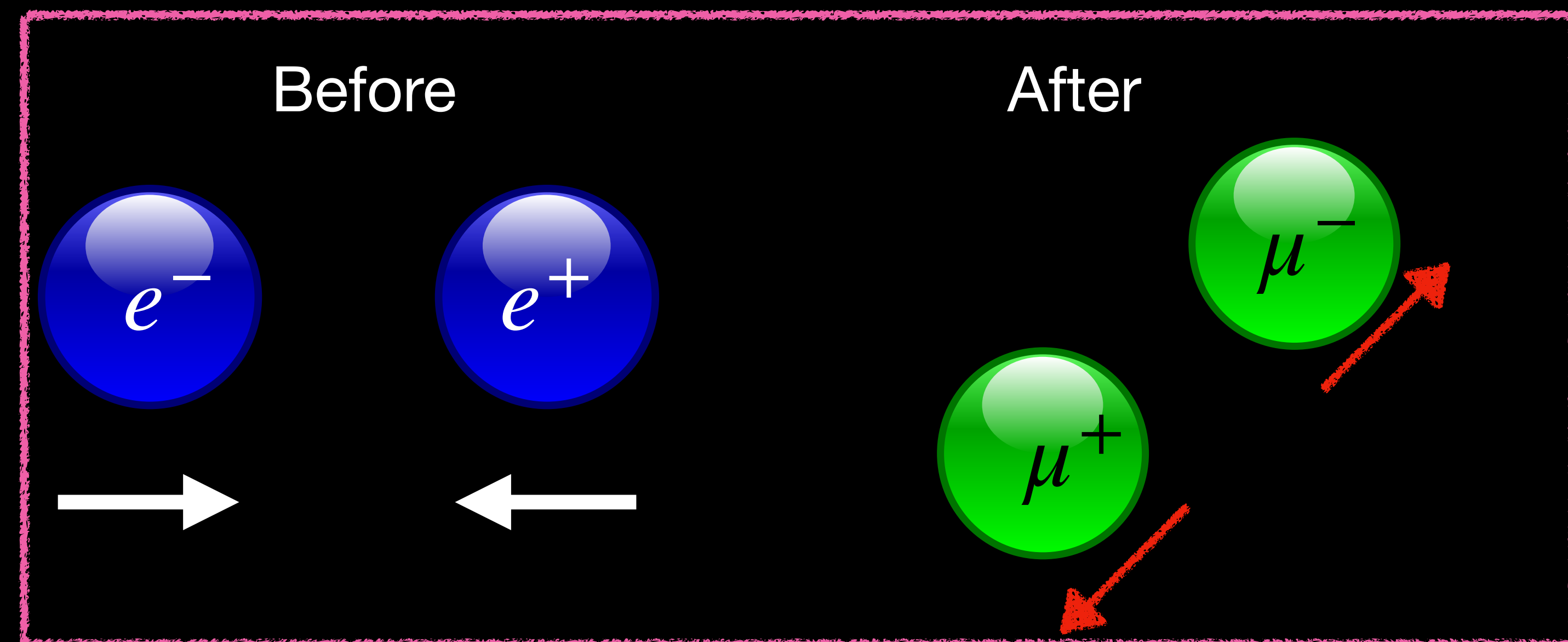
Mediator of
electromagnetic
interactions:
responsible for all
known
electromagnetic
phenomena

Some definitions

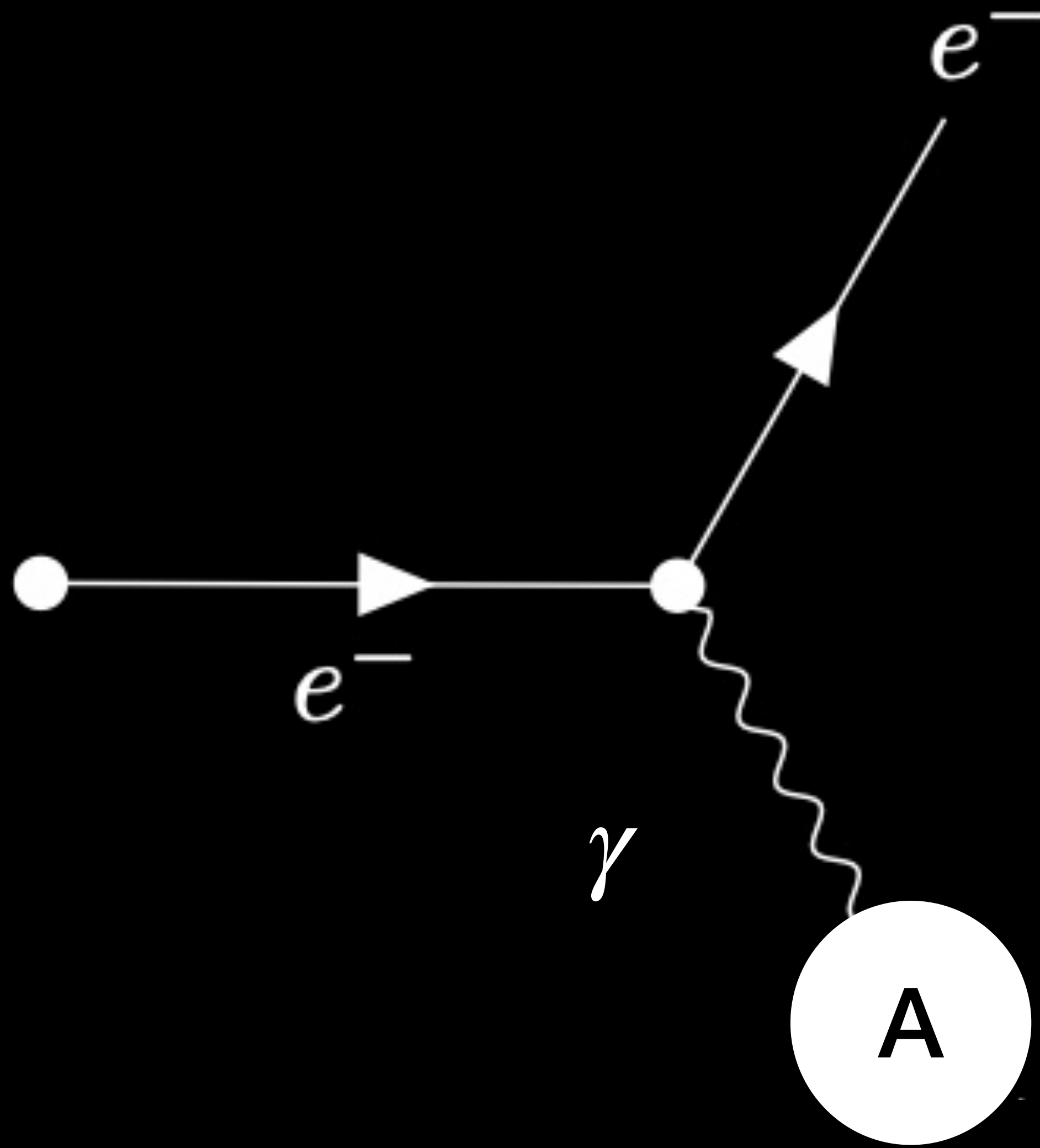
- **Quantum electrodynamics:** a quantum field theory that describes interactions between electrically charged fundamental particles and the photon
 - Extremely robust theory
 - Tested to ten parts in a billion (10^8)
- **Quantum chromodynamics:** a quantum field theory that describes interactions between color charged fundamental particles and the gluon
 - Responsible for almost all interactions at the Large Hadron Collider

Representing fundamental physics processes with “diagrams”

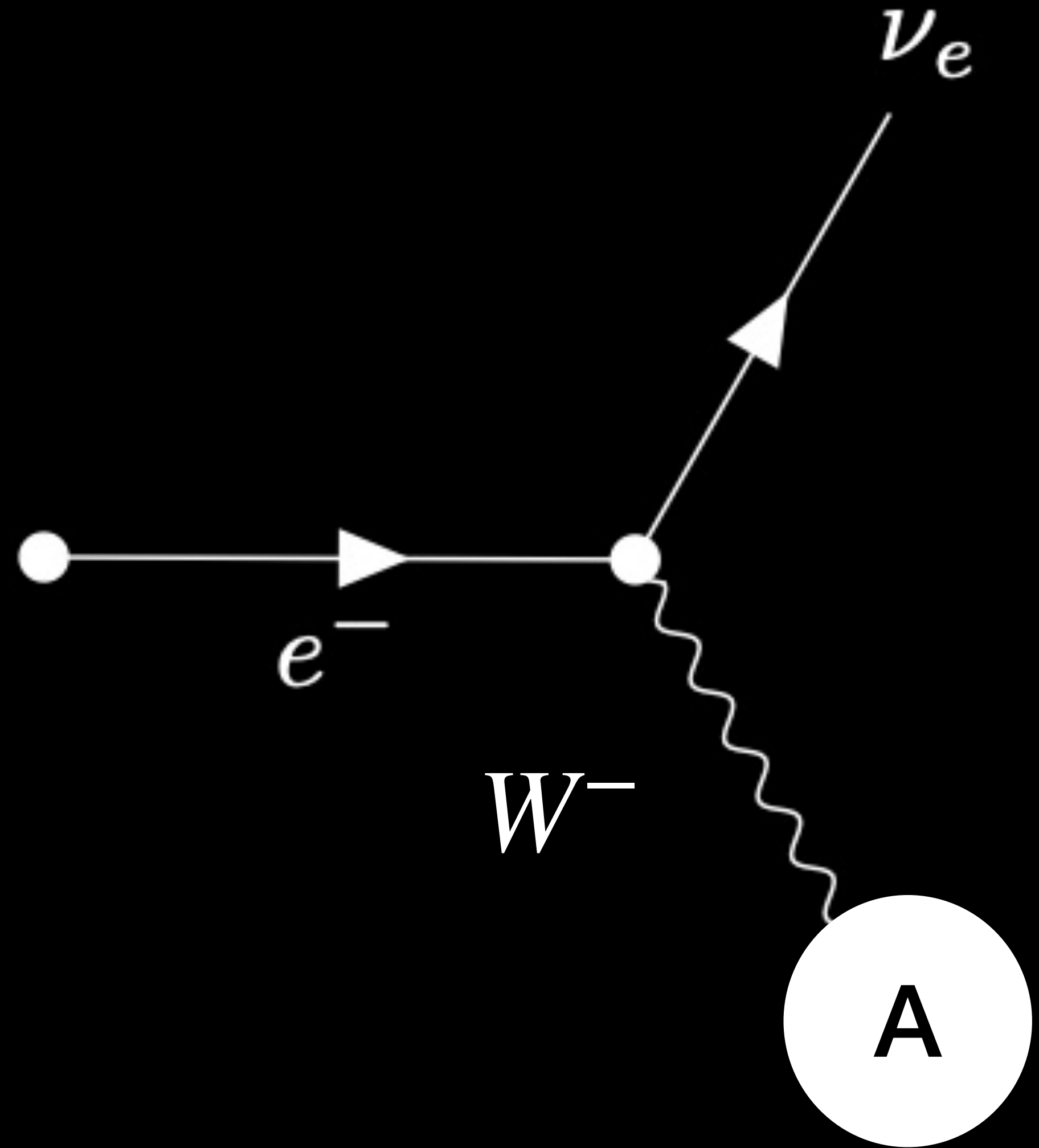
- Often useful to represent fundamental particle physics interactions pictorially
- Provides natural way to compute rates of reactions
- Diagram constructed in space-time
- At each vertex, strength of interaction is indicated



Unification of two fundamental forces



Electromagnetic interaction



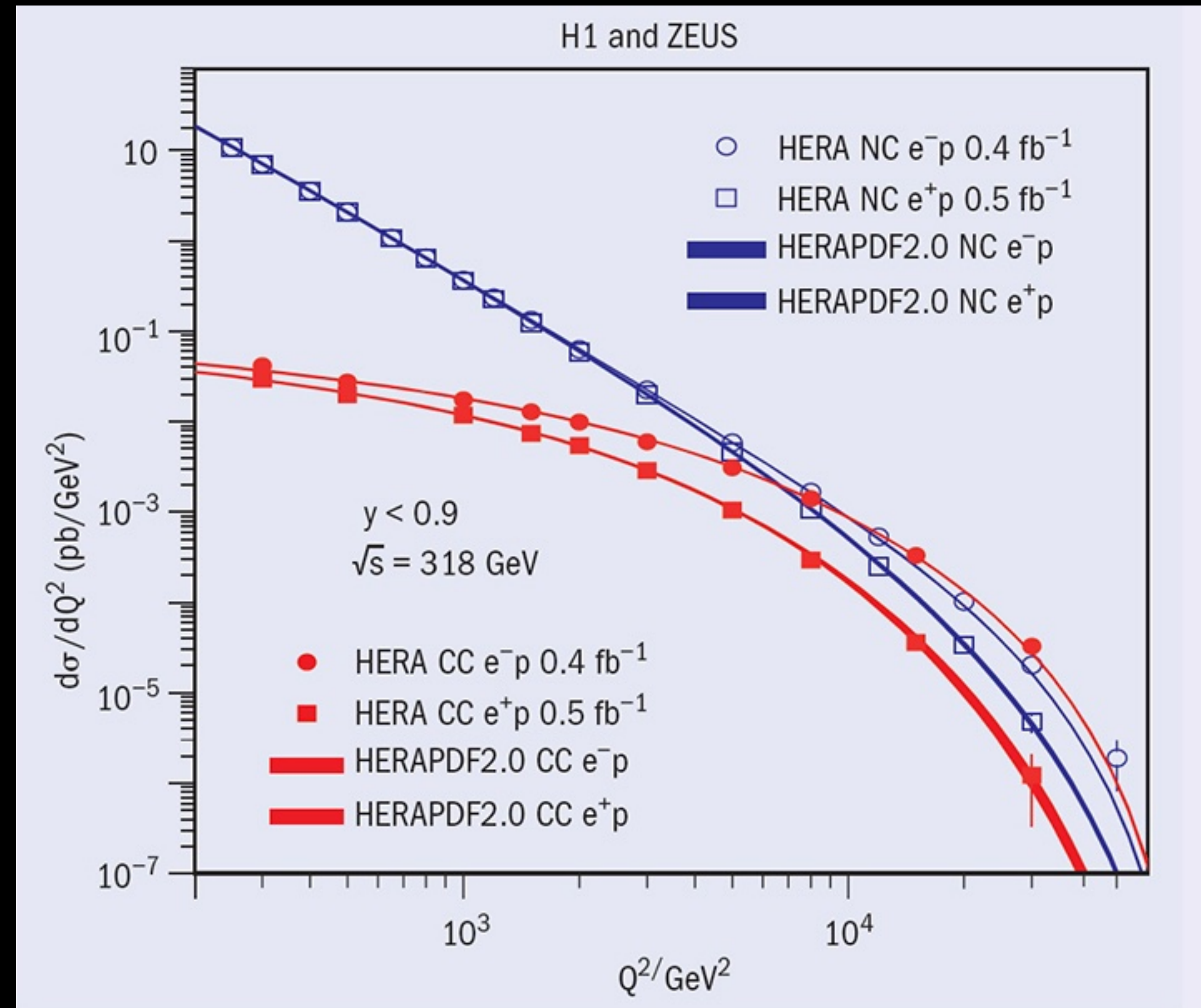
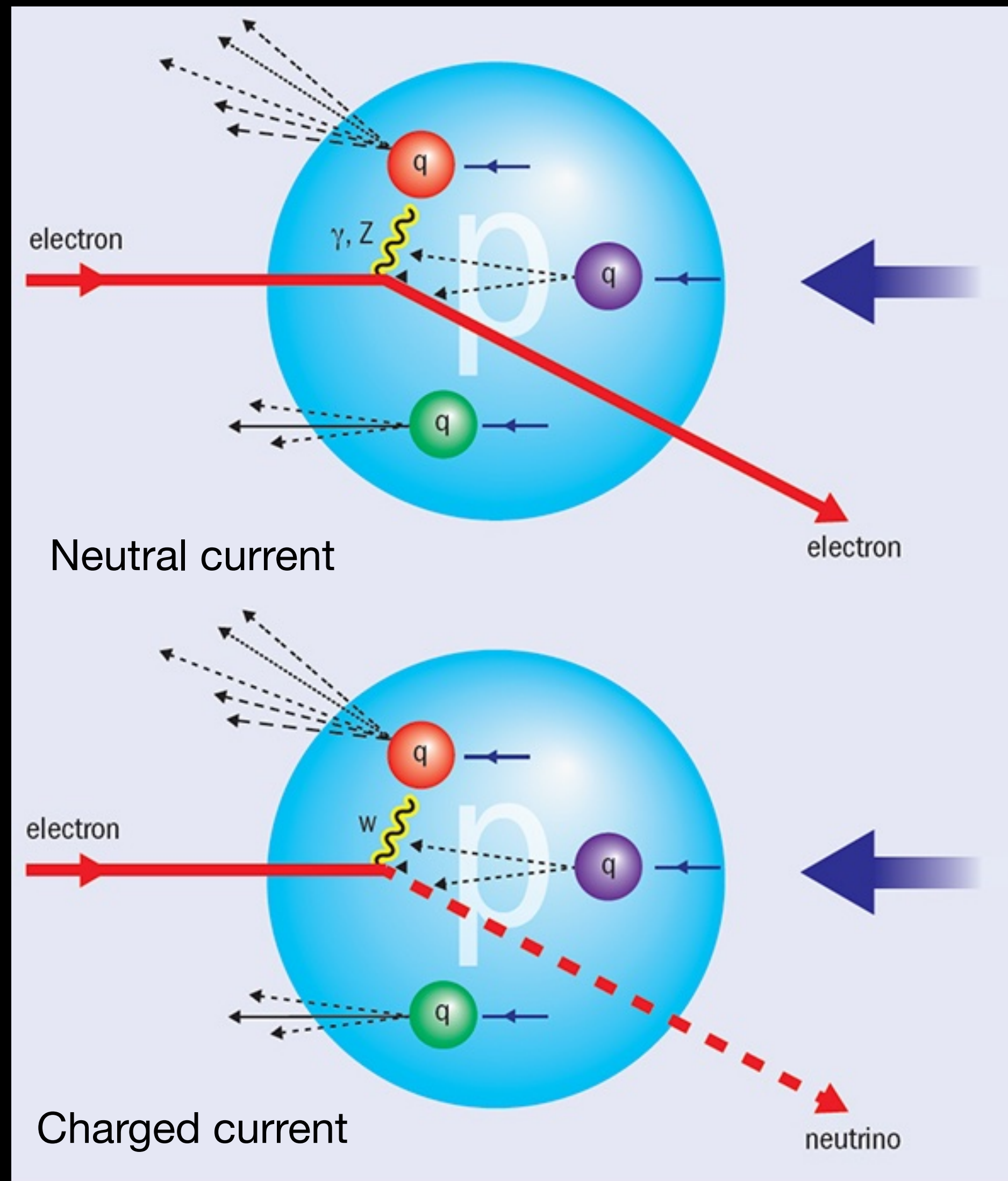
Weak interaction

Unification of two fundamental forces — electromagnetic and weak force

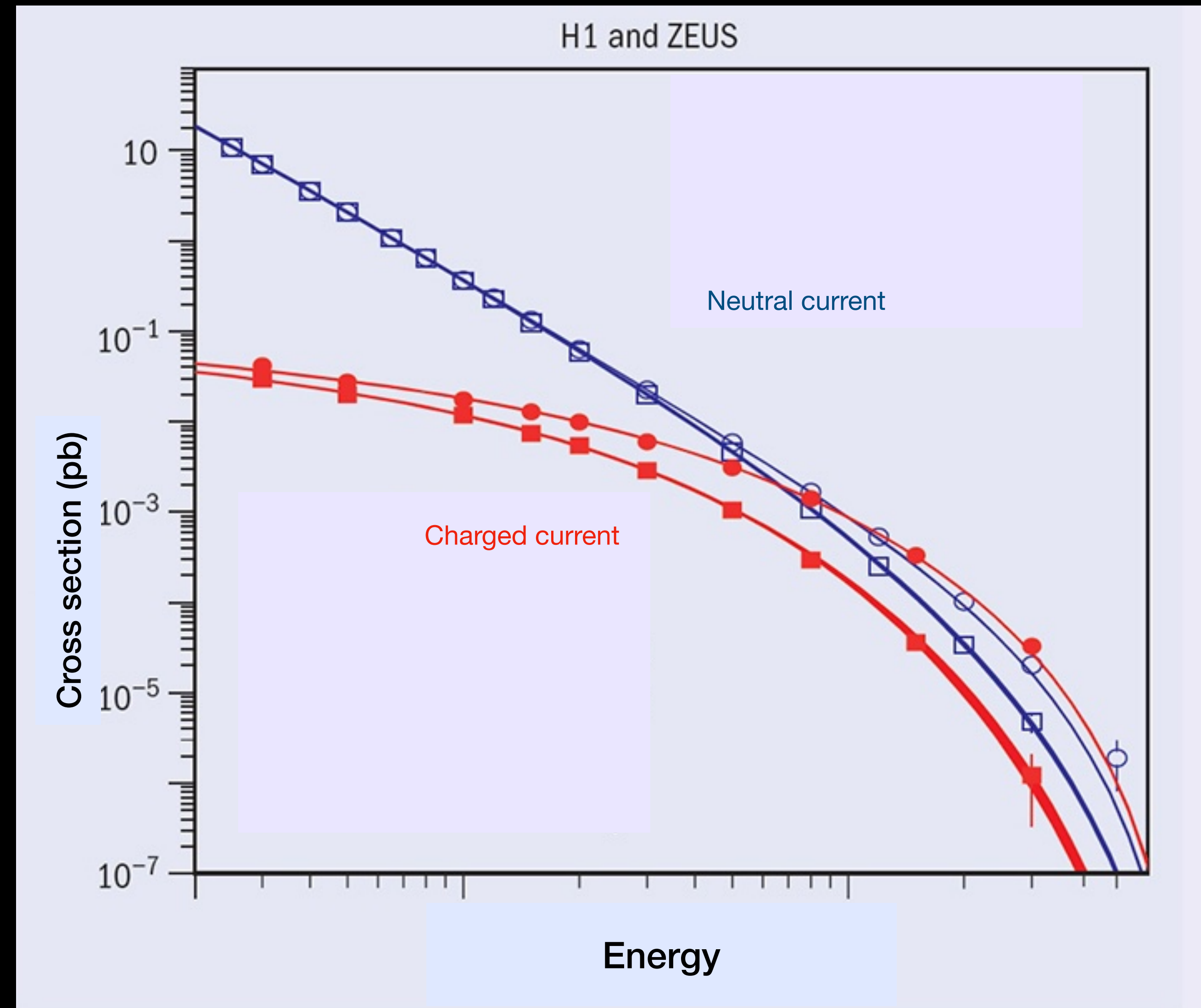
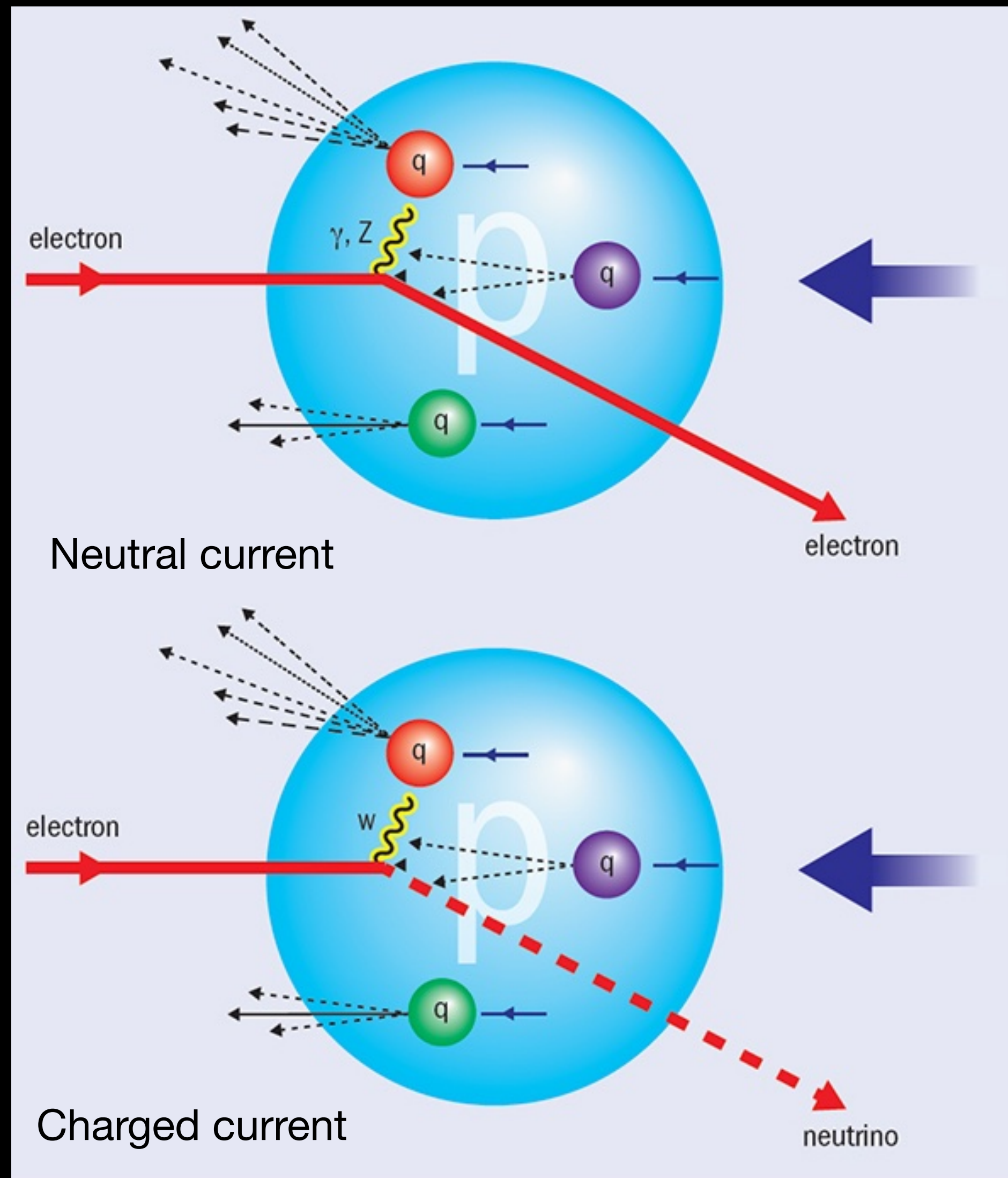
- Manifest very differently at low energies
- Unification observed at high energies
- First postulated by Sheldon Glashow, Abdus Salam, and Steven Weinberg
- Experimental verification came in the form of detection of $W^{\pm}$ and Z^0 bosons



Unification of two fundamental forces — electromagnetic and weak force



Unification of two fundamental forces — electromagnetic and weak force

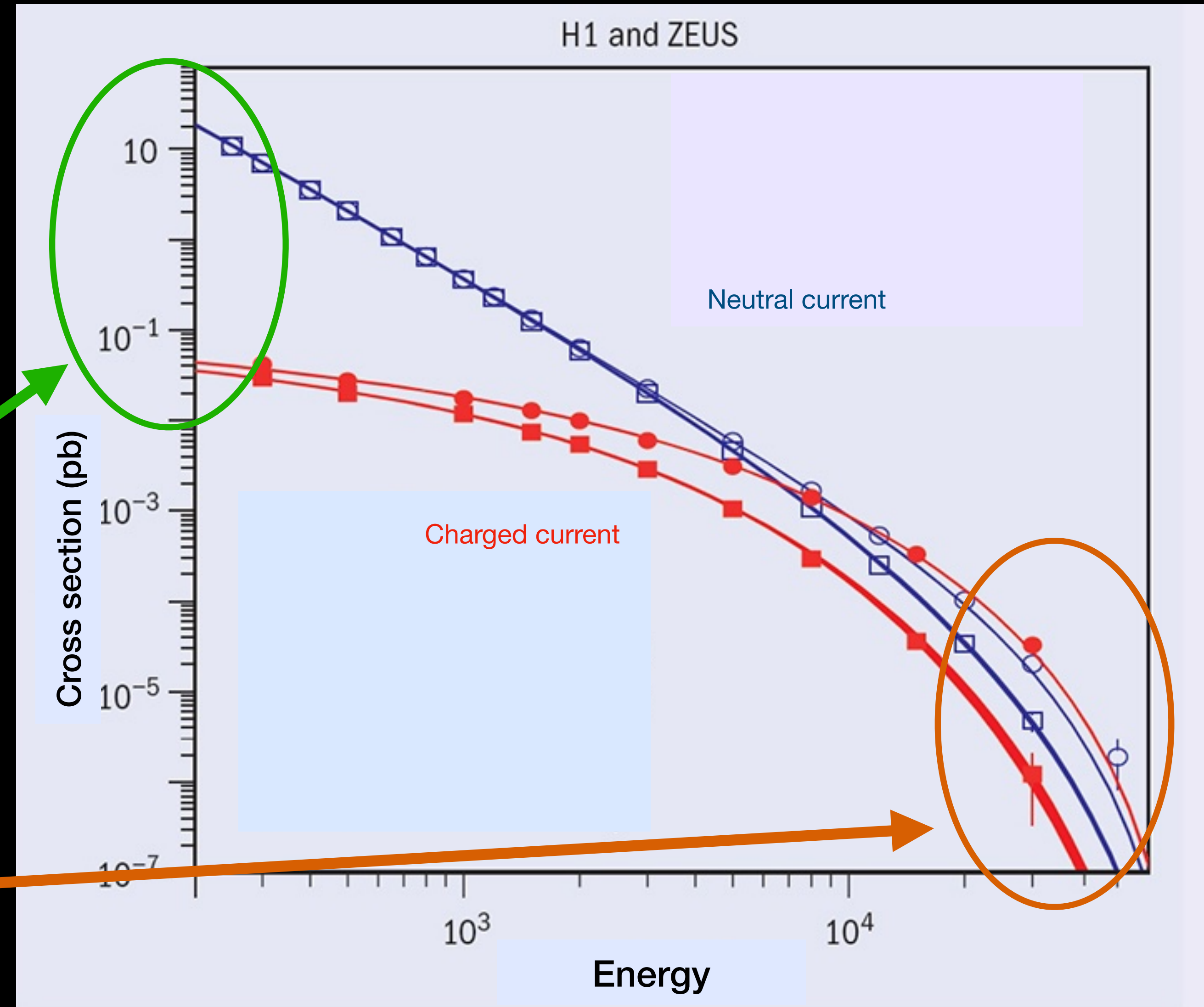


But unified only above a certain energy?

- So, what happens at low energy?
- This symmetry or the existence of a unified theory broken at low energies

Hidden symmetry

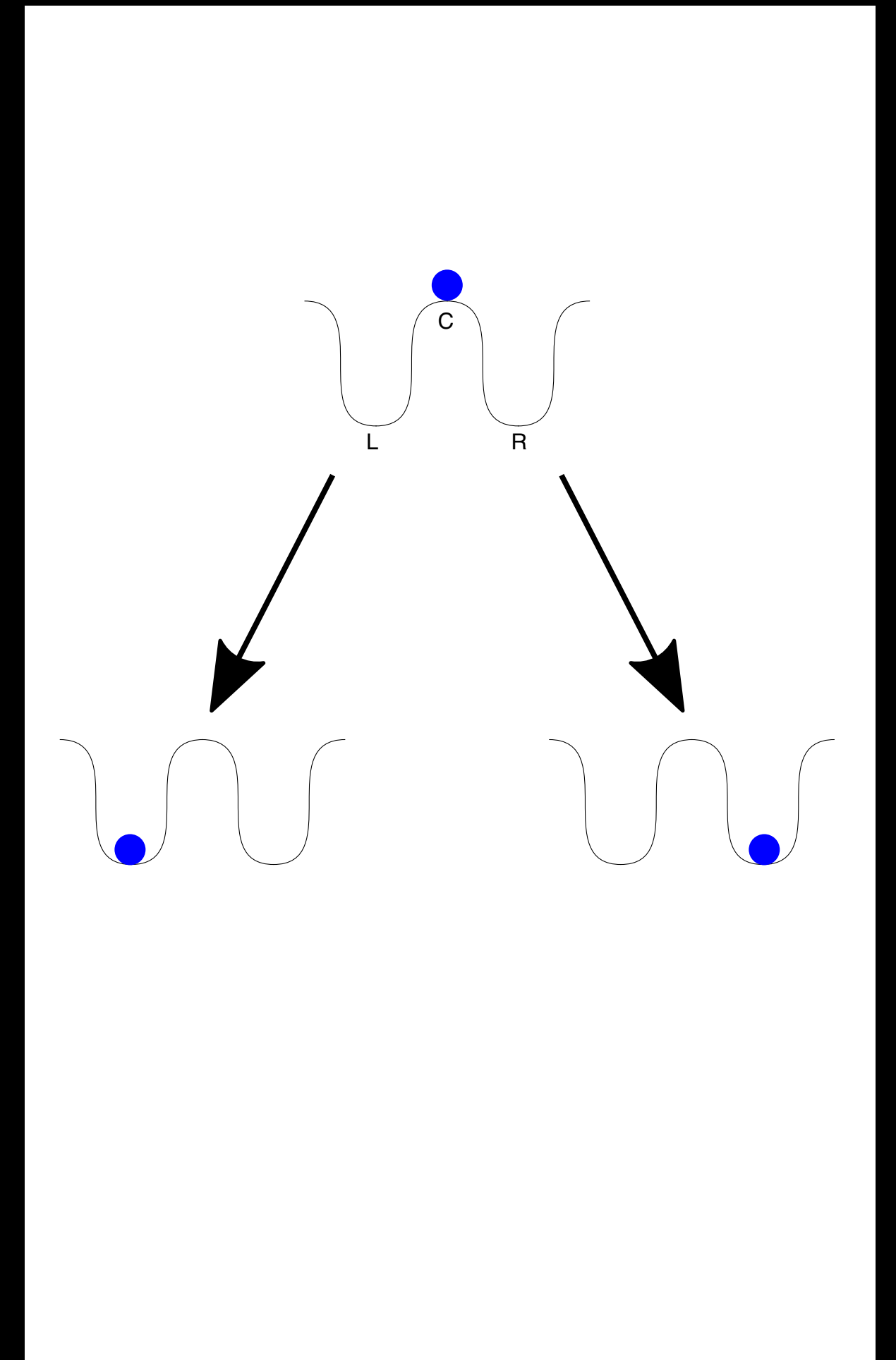
Symmetry manifest



Symmetry breaking

- Explicitly break symmetry
 - Write down equations that do not respect underlying symmetries of a theory
- Spontaneously break symmetry
 - Equations obey symmetry but choice of vacuum solution breaks symmetry

Symmetry breaking



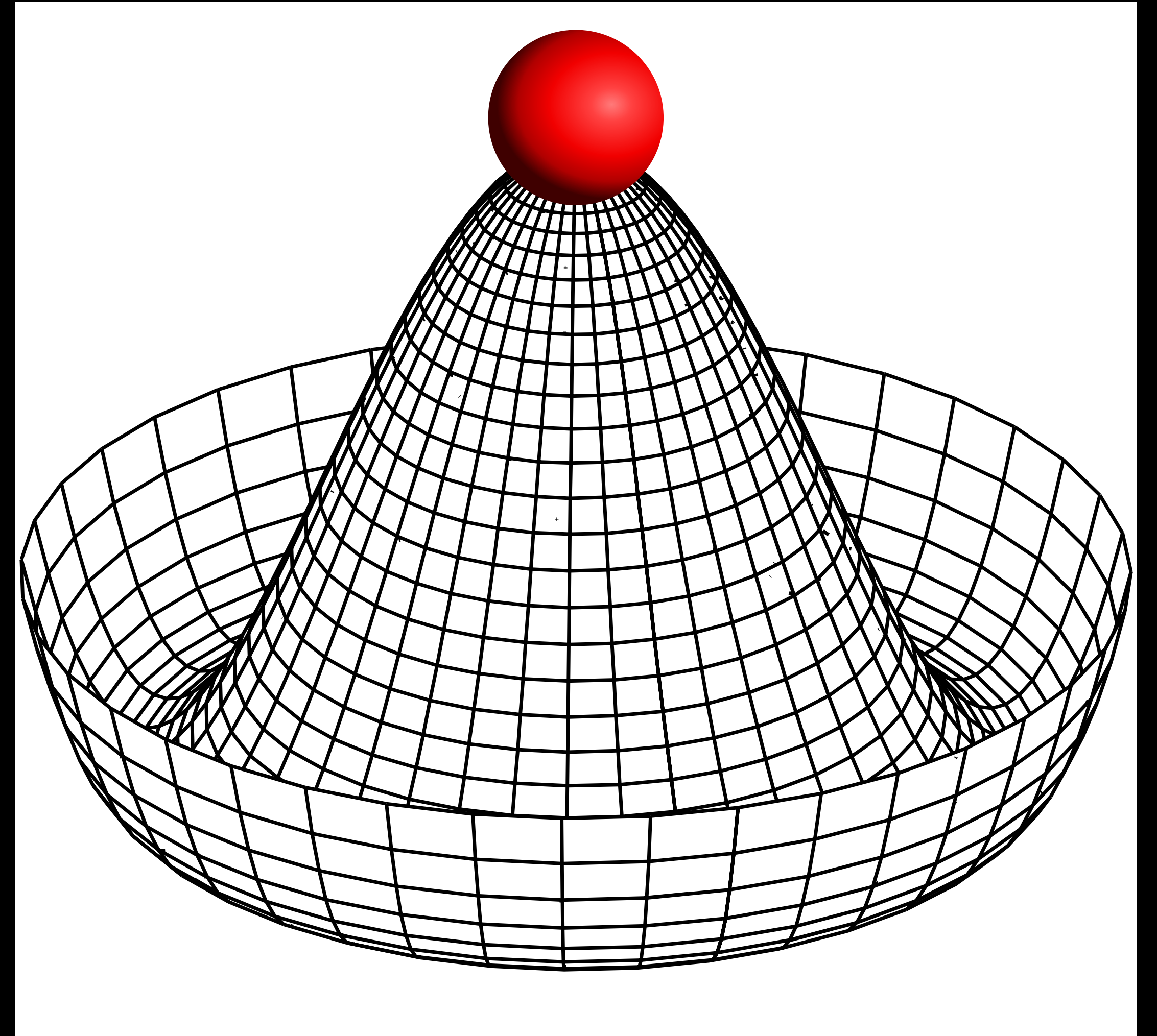
Make a choice. That determines the “choice” for the others

Why is the Higgs such a crucial discovery?

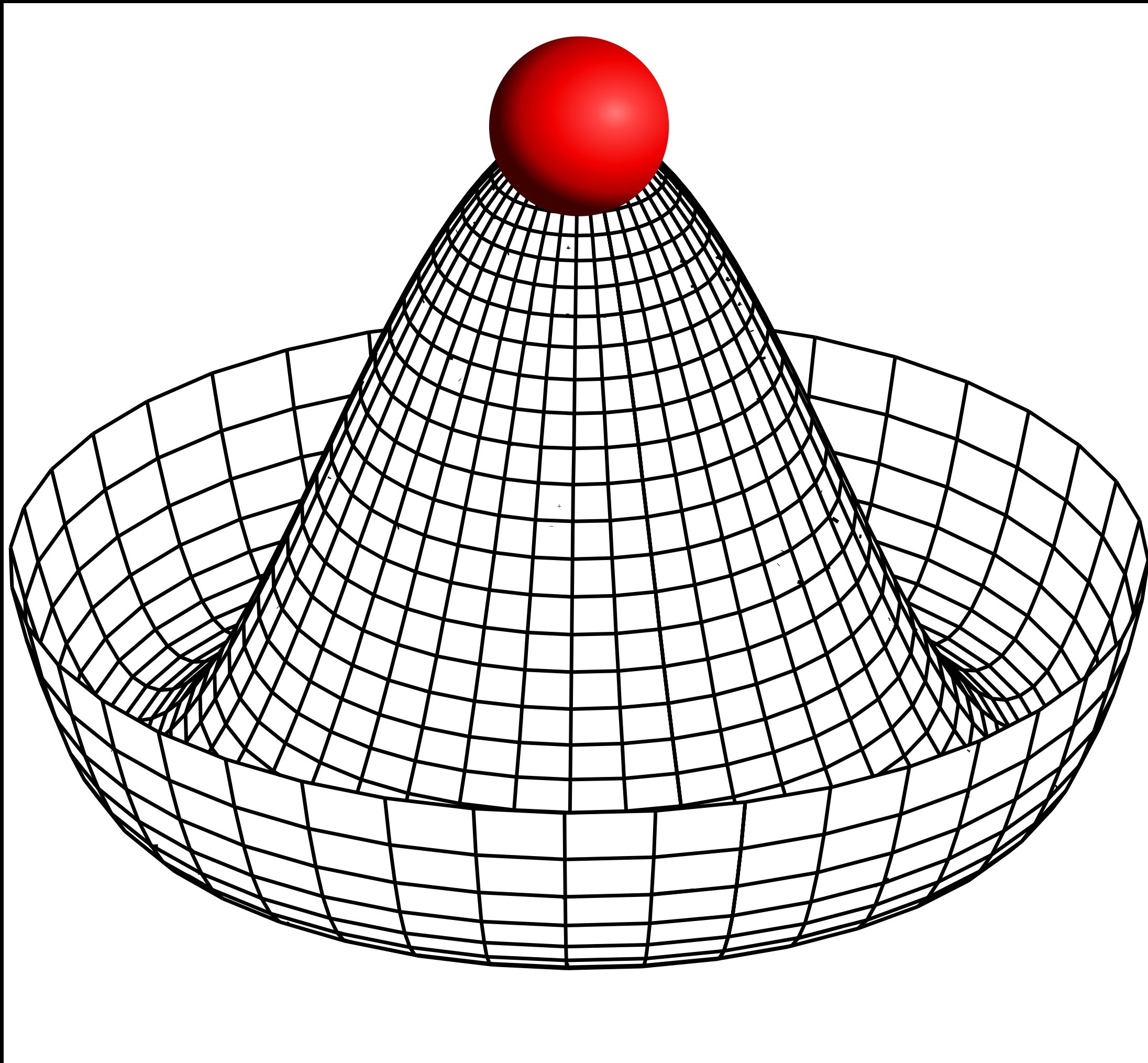
- The Higgs mechanism explains electroweak symmetry breaking
 - We just learned of the unification of electroweak theory
 - However, we have experimentally observed that electroweak symmetry is broken
 - The Higgs mechanism provides an explanation of this phenomena

The Higgs mechanism

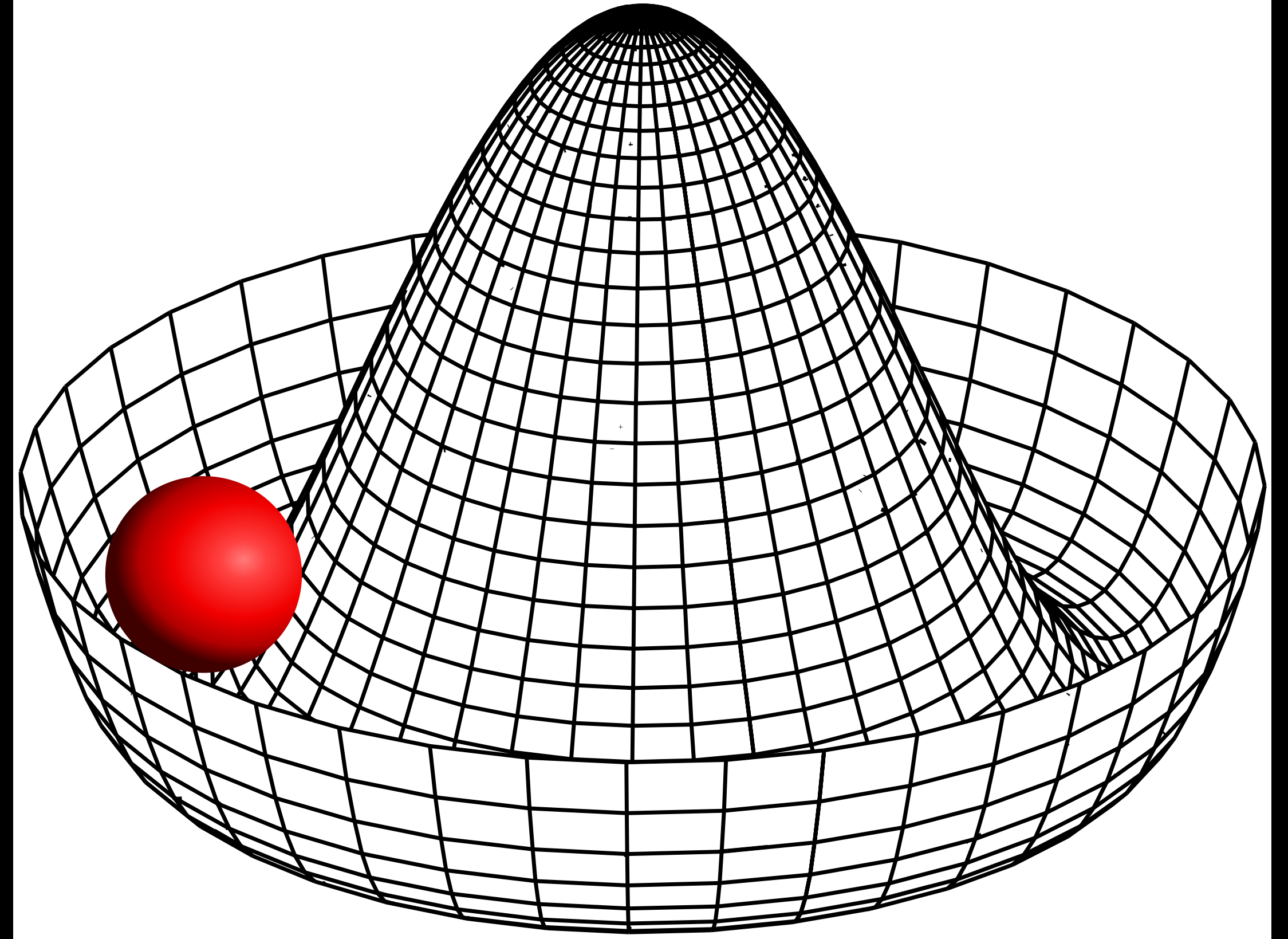
- In physics, we often write down a “Lagrangian” that we can then use to derive equations of motion
- Lagrangian = Kinetic energy - potential energy
- But what is the form of this potential energy?
 - $V = \mu^2\phi^2 + \lambda\phi^4$



The Higgs mechanism — let's spontaneously break the symmetry



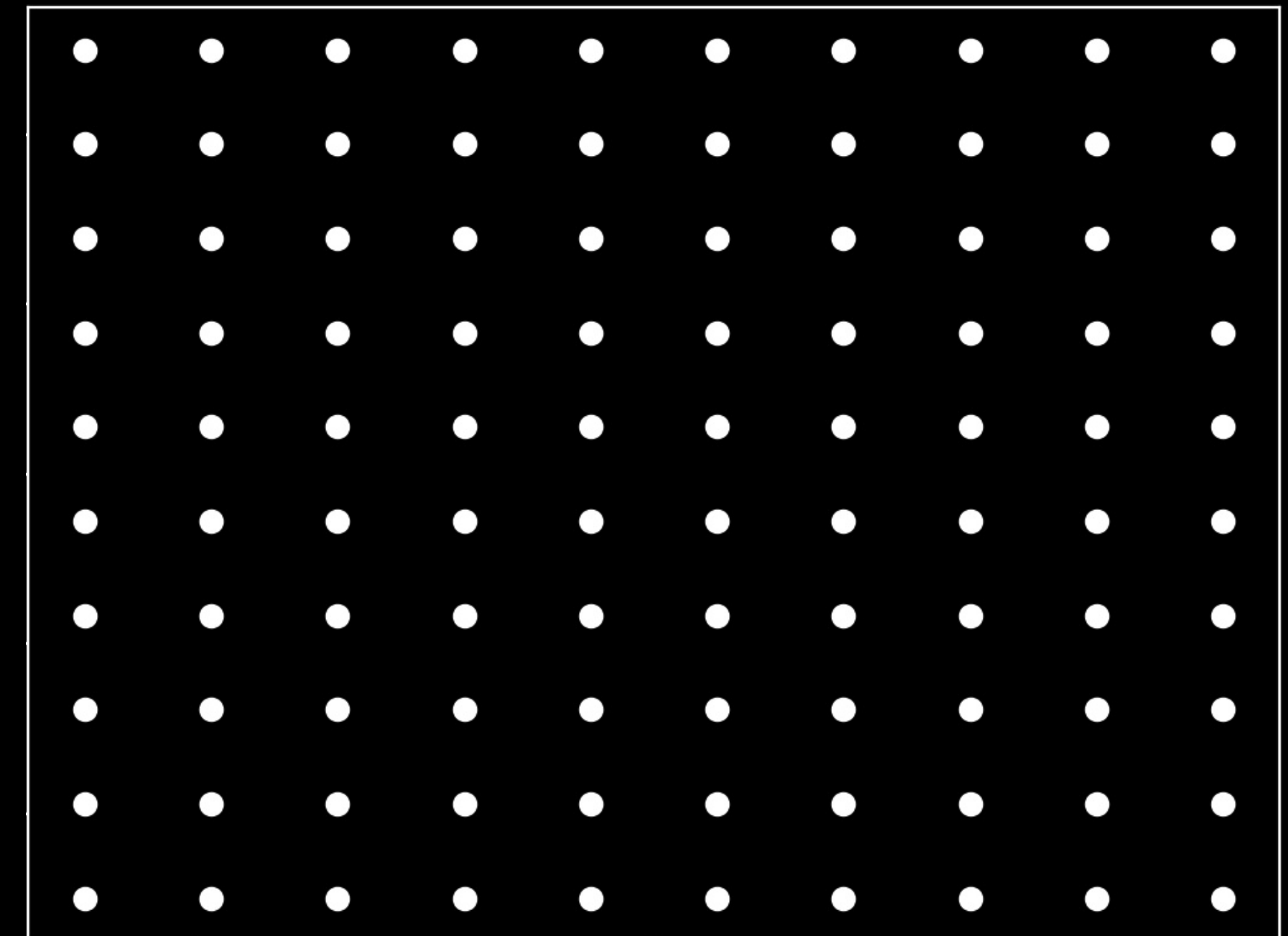
Nature prefers a minimum energy state



The Higgs mechanism — let's spontaneously break the symmetry

$$V = \mu^2 \phi^2 + \lambda \phi^4$$

- Minimum value of ϕ is equal to 246 GeV
 - It is referred to as the vacuum expectation value



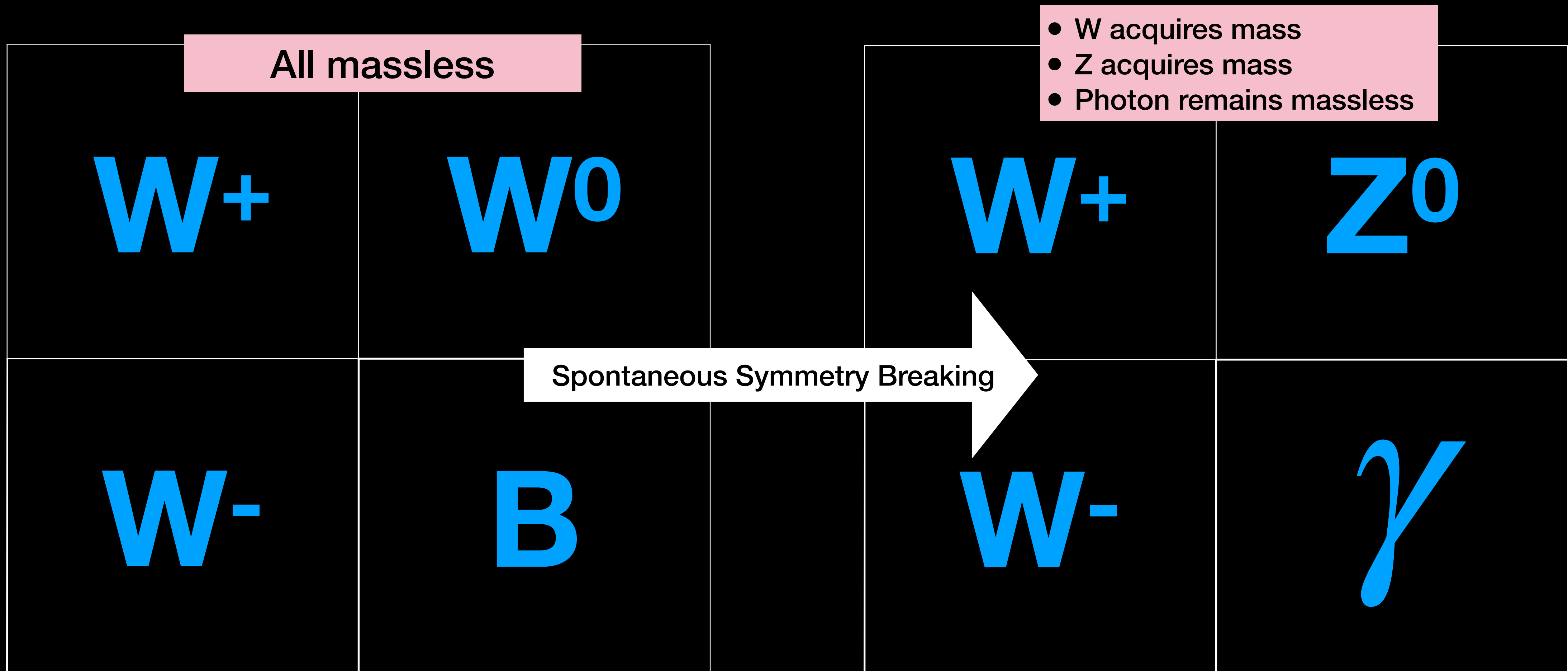
246 GeV at every point and extends everywhere in space

What have we learned so far...

- Unification of phenomena leads to complete description of Nature
- Unification of electromagnetism and the weak force achieved at high energies, but broken at low energies
- This spontaneous breaking of electroweak symmetry is achieved through the Higgs mechanism
 - (Gauge) bosons acquire mass, except the photon which remains massless
- Interaction with the Higgs gives masses to the fermions (leptons and quarks)

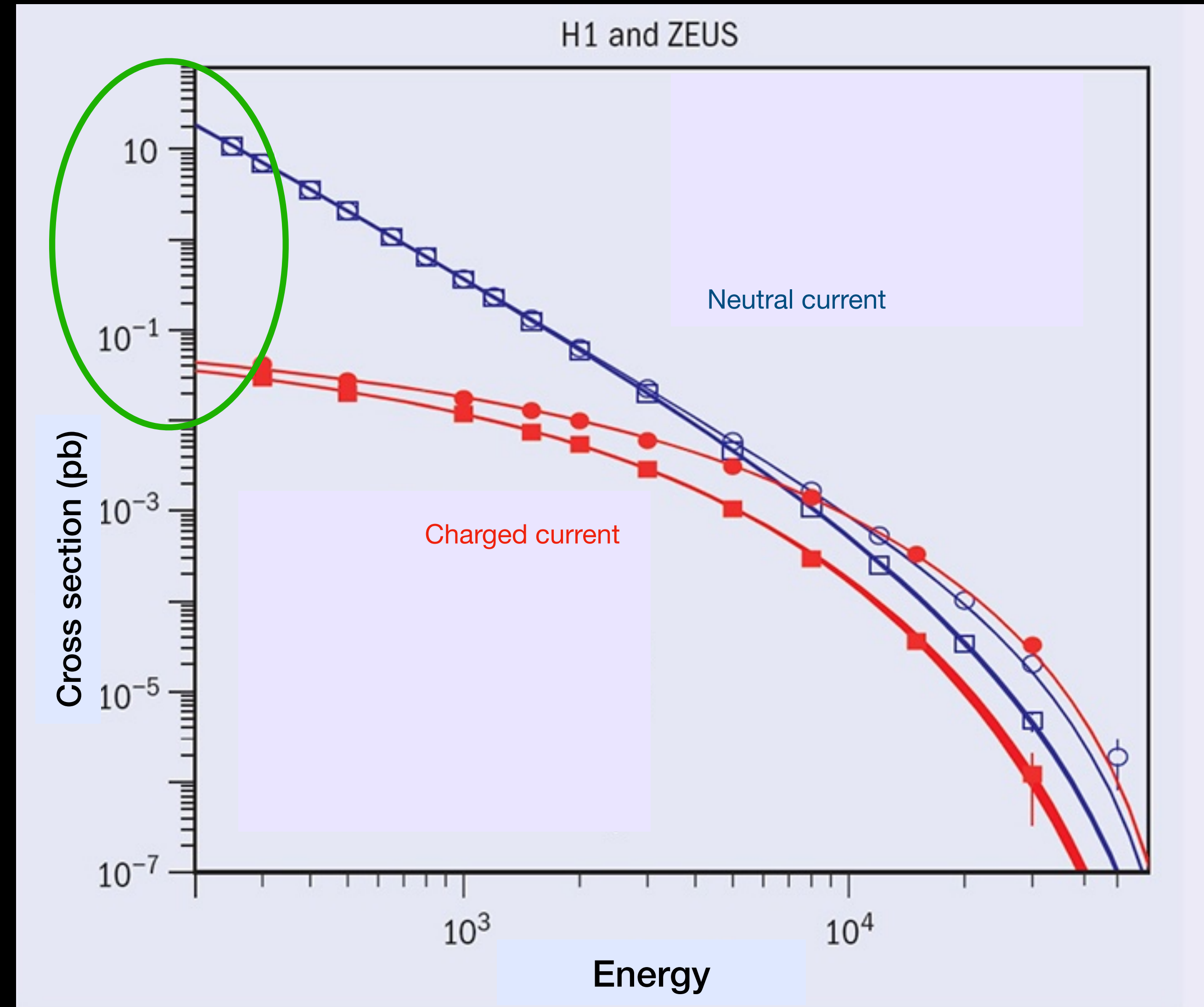
The Standard Model formulation before and after symmetry breaking

- Before symmetry is broken, theory consists of massless electroweak bosons



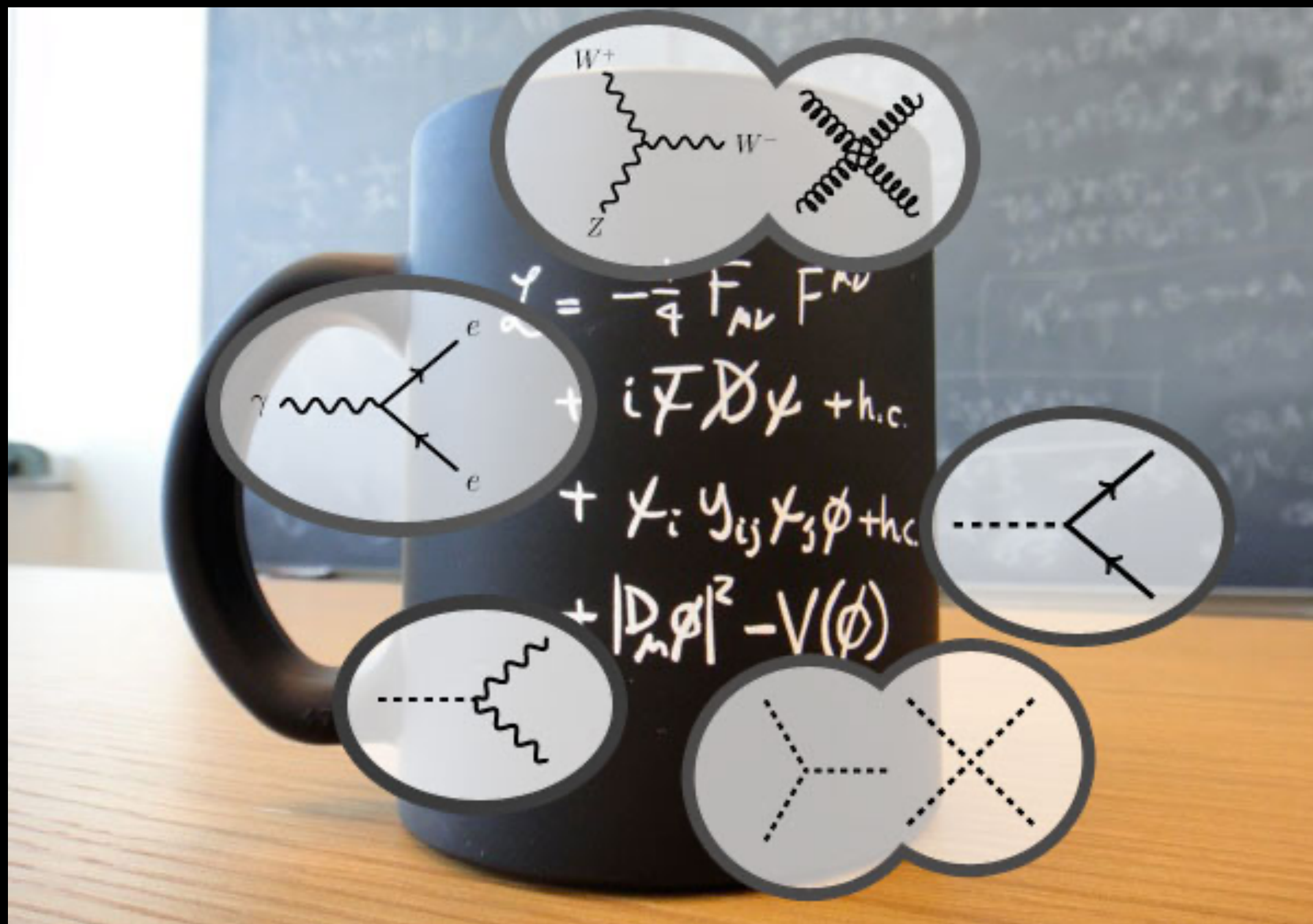
After symmetry is broken

- What exactly is happening at the low energy region?
- Only electromagnetic interaction
 - interaction completely driven by the energy of the process $\left(\frac{1}{Q^2}\right)$
- Weak interaction
 - proportional to $\frac{1}{m_W^2 + Q^2}$, m_W is large
 - $\frac{1}{m_W^2 + Q^2} \approx \frac{1}{m_W^2}$



But this only explains how the weak force carriers
(bosons) acquire mass...

- The other particles (fermions) in the standard model acquire mass via the interactions with the Higgs field



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

Strength of fermionic interaction

- Interaction of fermions (leptons and quarks) with the Higgs field proportional to the value of the mass of the fermion
- Referred to as a “Yukawa interaction”
- We are not sure of the neutrinos

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

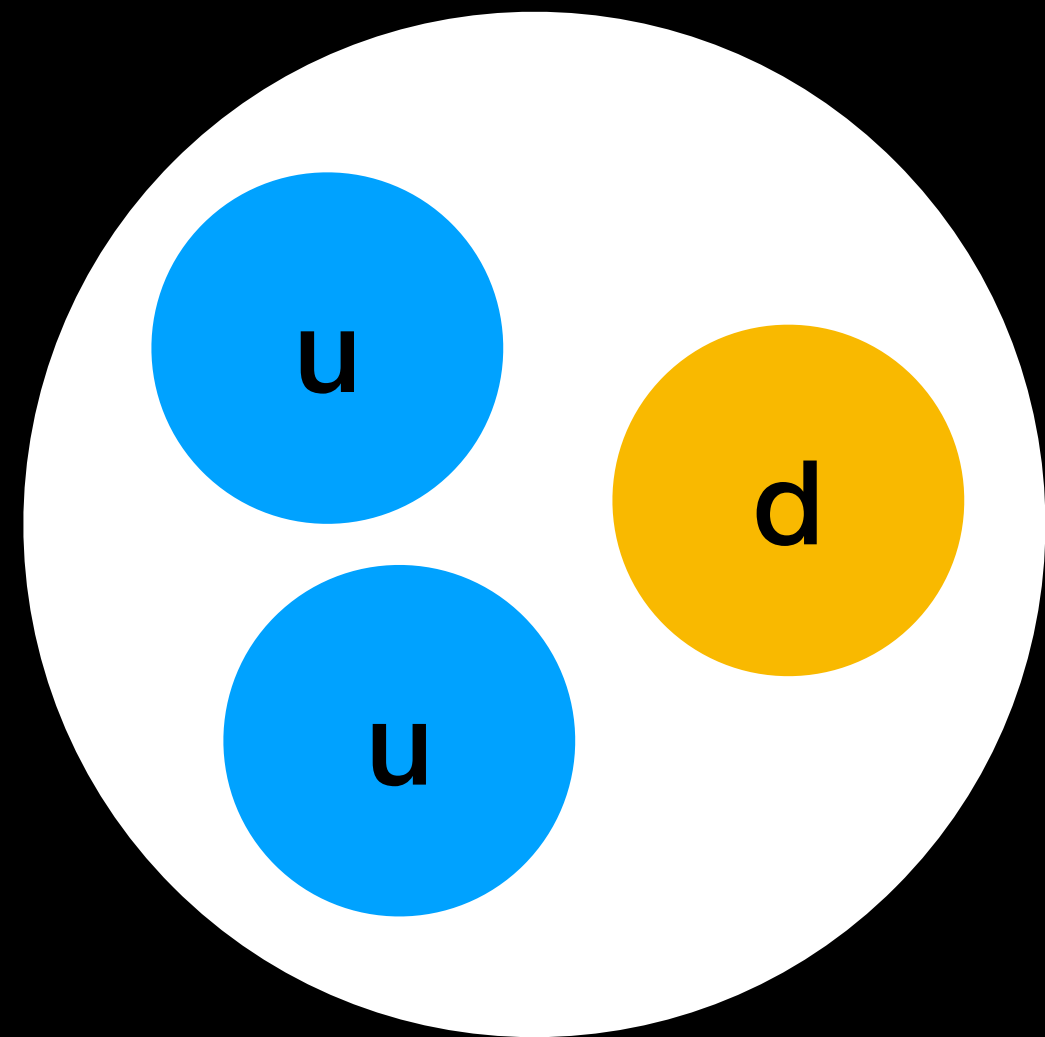
Consequences of the presence of the Higgs Boson



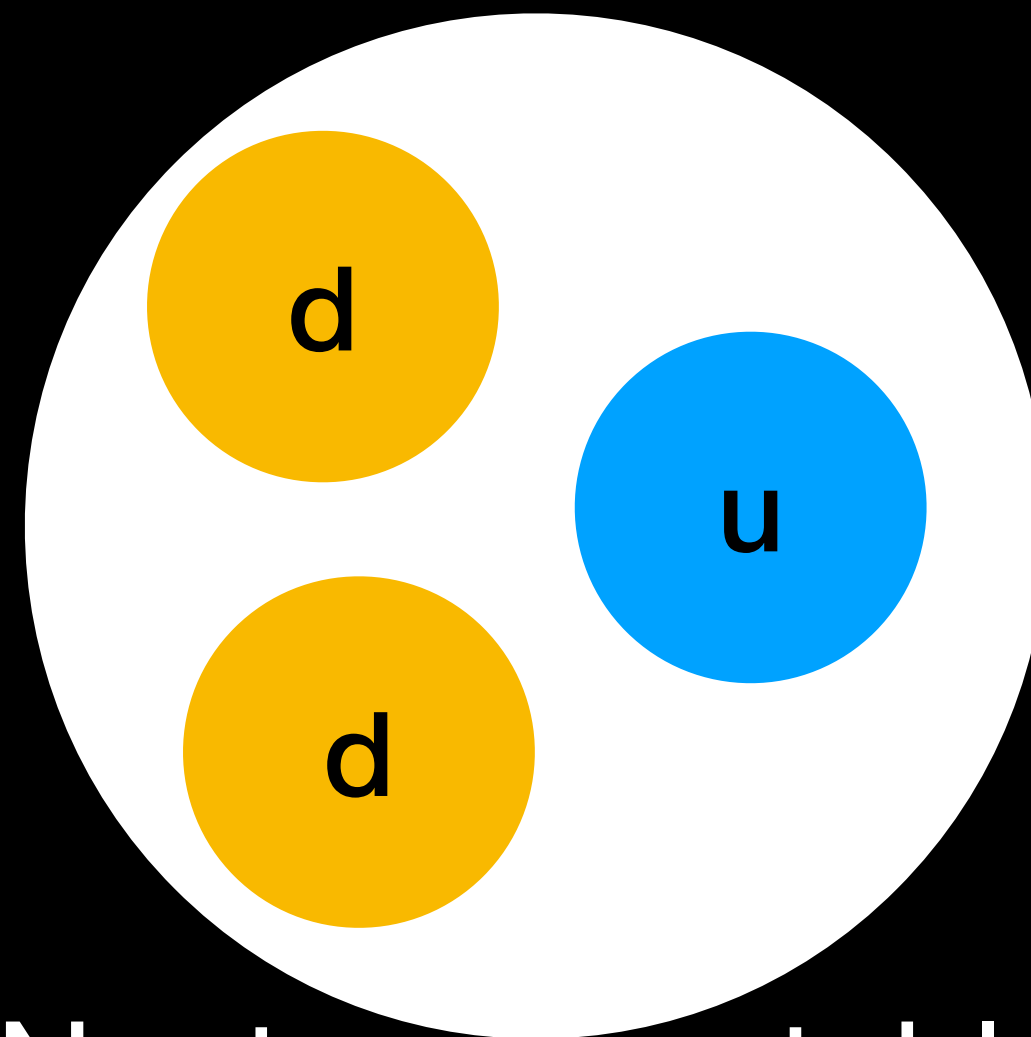
m_u

$<$

m_d



Proton: stable

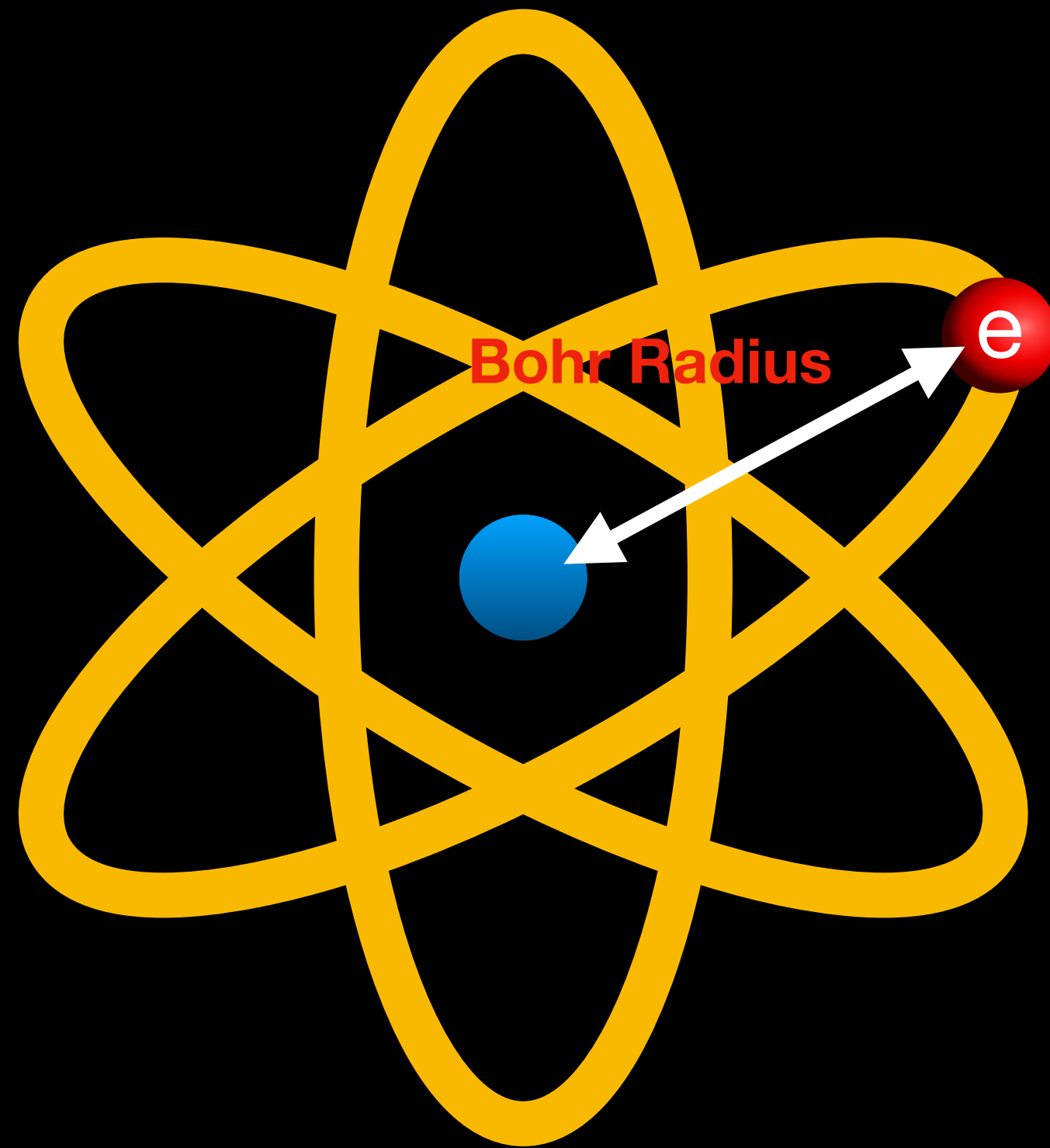


Neutron: unstable

- Down quarks are heavier than up quarks
- Consequences with regard to the stability of the proton

Ensures stability of the
Hydrogen atom

Consequences of the presence of the Higgs Boson



- The distance between the electron and the nucleus defined as the Bohr radius:

- $$a_0 = \frac{\hbar}{m_e c \alpha}$$

- If $m_e = 0$, no atoms can be formed

Consequences of the presence of the Higgs Boson

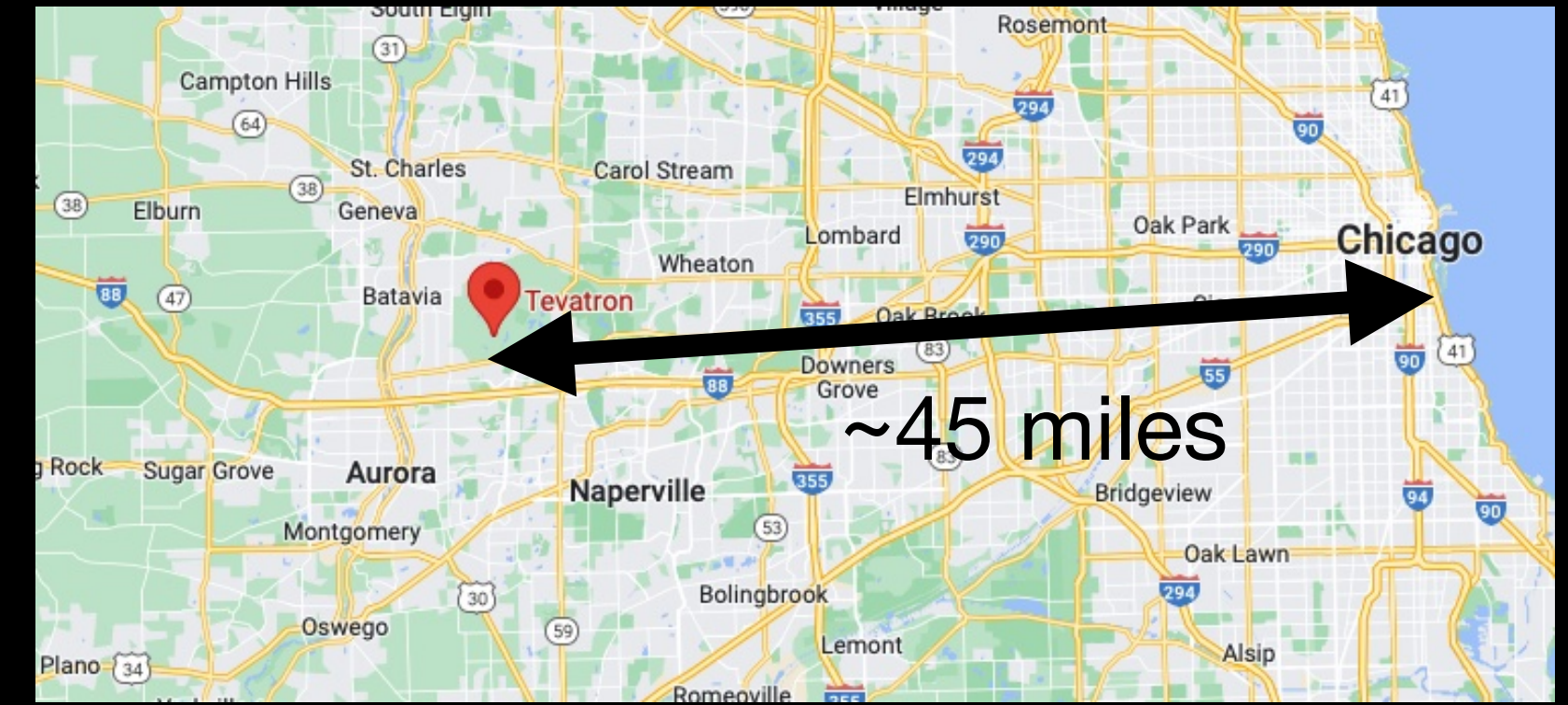
- A different value of the electron mass would alter the chemical reactions of all known elements

1 H Hydrogen																	2 He Helium														
3 Li Lithium	4 Be Beryllium															5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon										
11 Na Sodium	12 Mg Magnesi...															13 Al Aluminium	14 Si Silicon	15 P Phosph...	16 S Sulfur	17 Cl Chlorine	18 Ar Argon										
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Mangan...	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germani...	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton														
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybde...	43 Tc Techneti...	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon														
55 Cs Caesium	56 Ba Barium	57 La Lanthan...	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon														
87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfo...	105 Db Dubnium	106 Sg Seaborg...	107 Bh Bohrium	108 Hs Hassium	109 Mt MeitnerL...	110 Ds Darmsta...	111 Rg Roentge...	112 Cn Coperni...	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovi...	116 Lv Livermo...	117 Ts Tenness...	118 Og Oganes...														
																		58 Ce Cerium	59 Pr Praseod...	60 Nd Neodym...	61 Pm Prometh...	62 Sm Samarium	63 Eu Europium	64 Gd Gadolin...	65 Tb Terbium	66 Dy Dyspros...	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
																		90 Th Thorium	91 Pa Protacti...	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californi...	99 Es Einstein...	100 Fm Fermium	101 Md Mendele...	102 No Nobelium	103 Lr Lawrenc...



The Higgs is massive — what did we learn from previous experiments

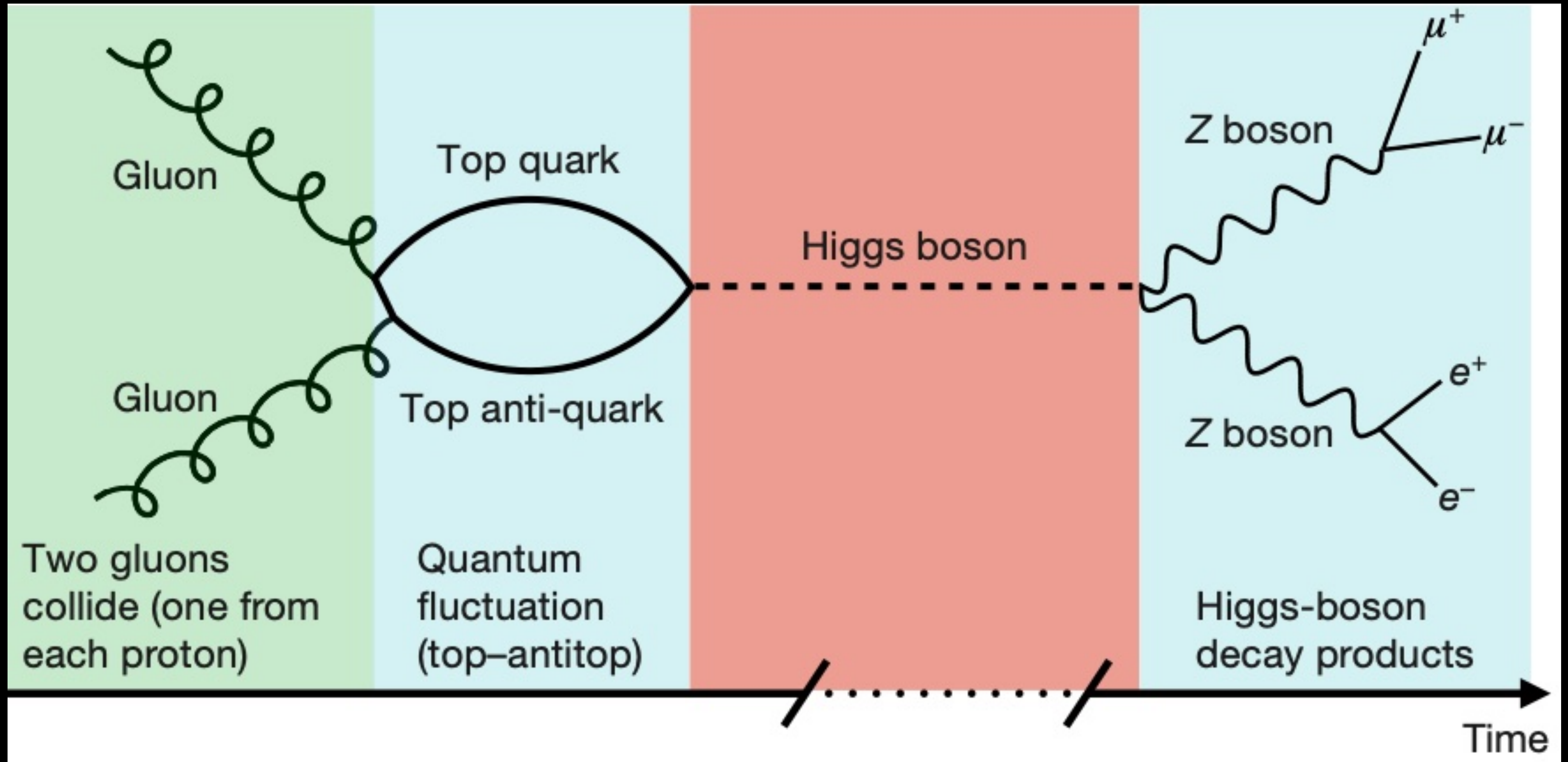
- What would guide our intuition as to how massive is the Higgs?
- We have not observed the Higgs in previous experiments → not light
- We know from the Tevatron that the mass of the Higgs boson lies between 115 and 135 GeV
 - $115 < m_H < 135 \text{ GeV}$
- For comparison, the mass of the proton is $\sim 1 \text{ GeV}$



How would we detect the Higgs?

- Build an experiment to make it possible for the Higgs to be generated
- Build a detector to study the debris from the collision

Production and decay of the Higgs boson



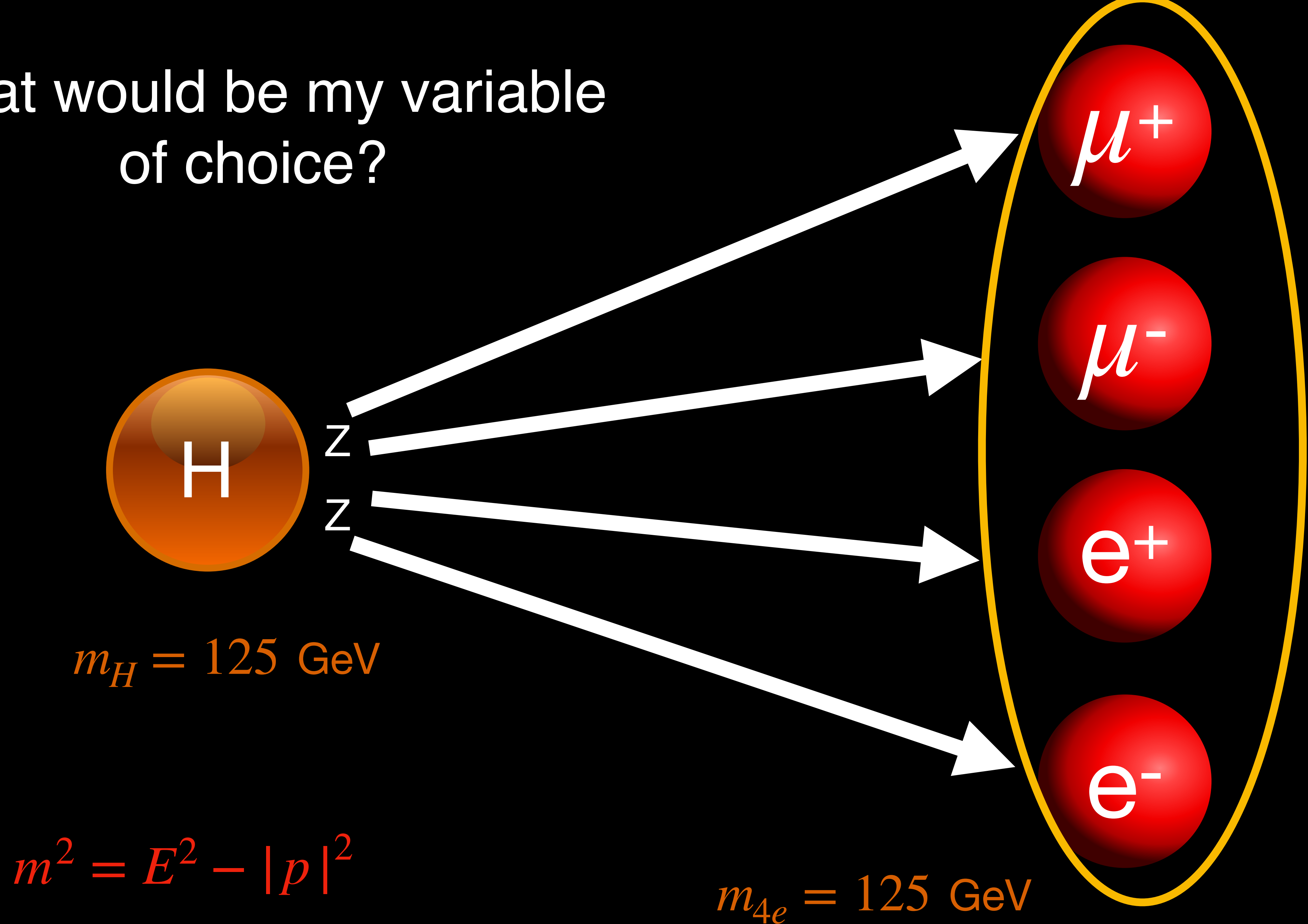
Needle in a haystack

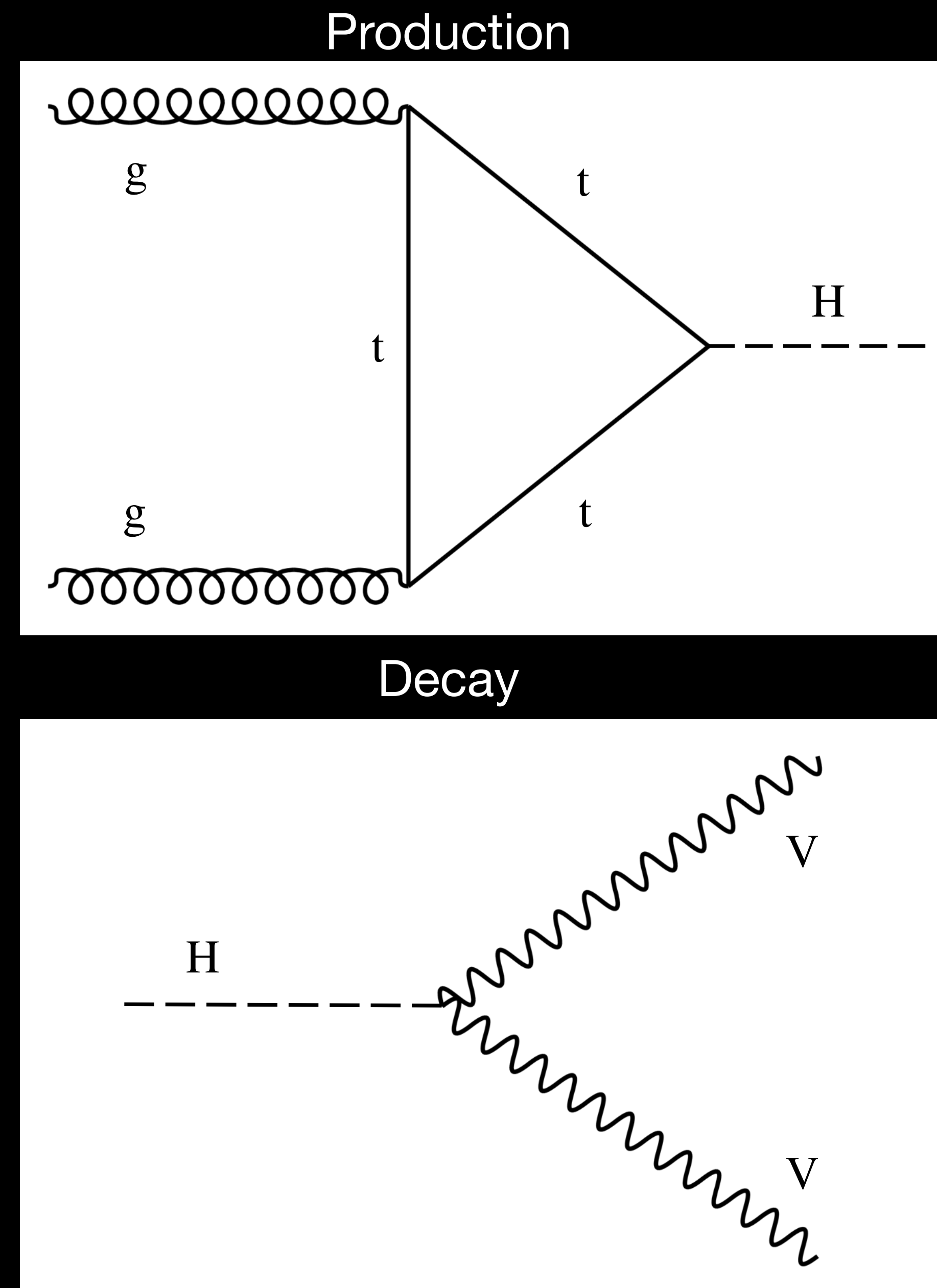
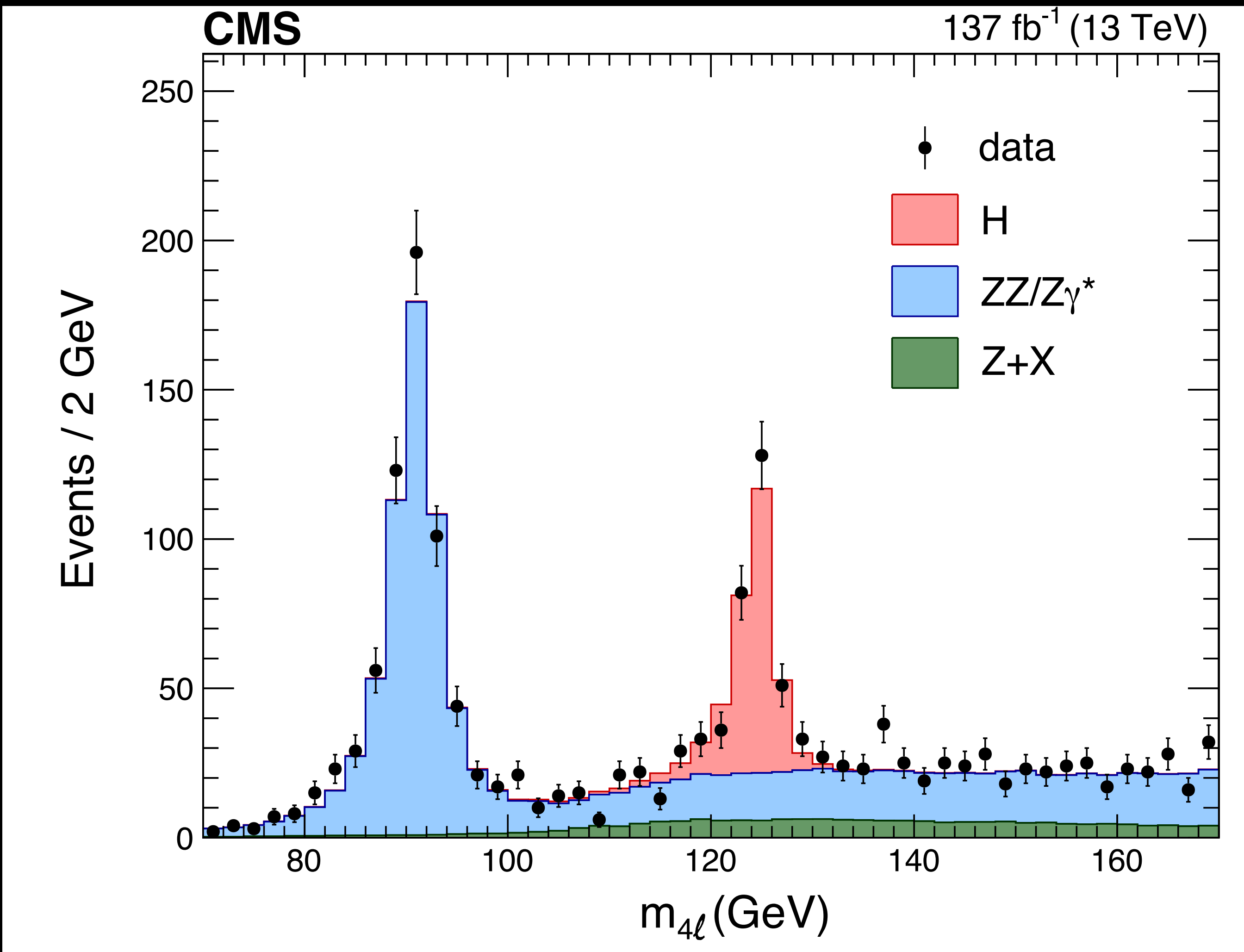


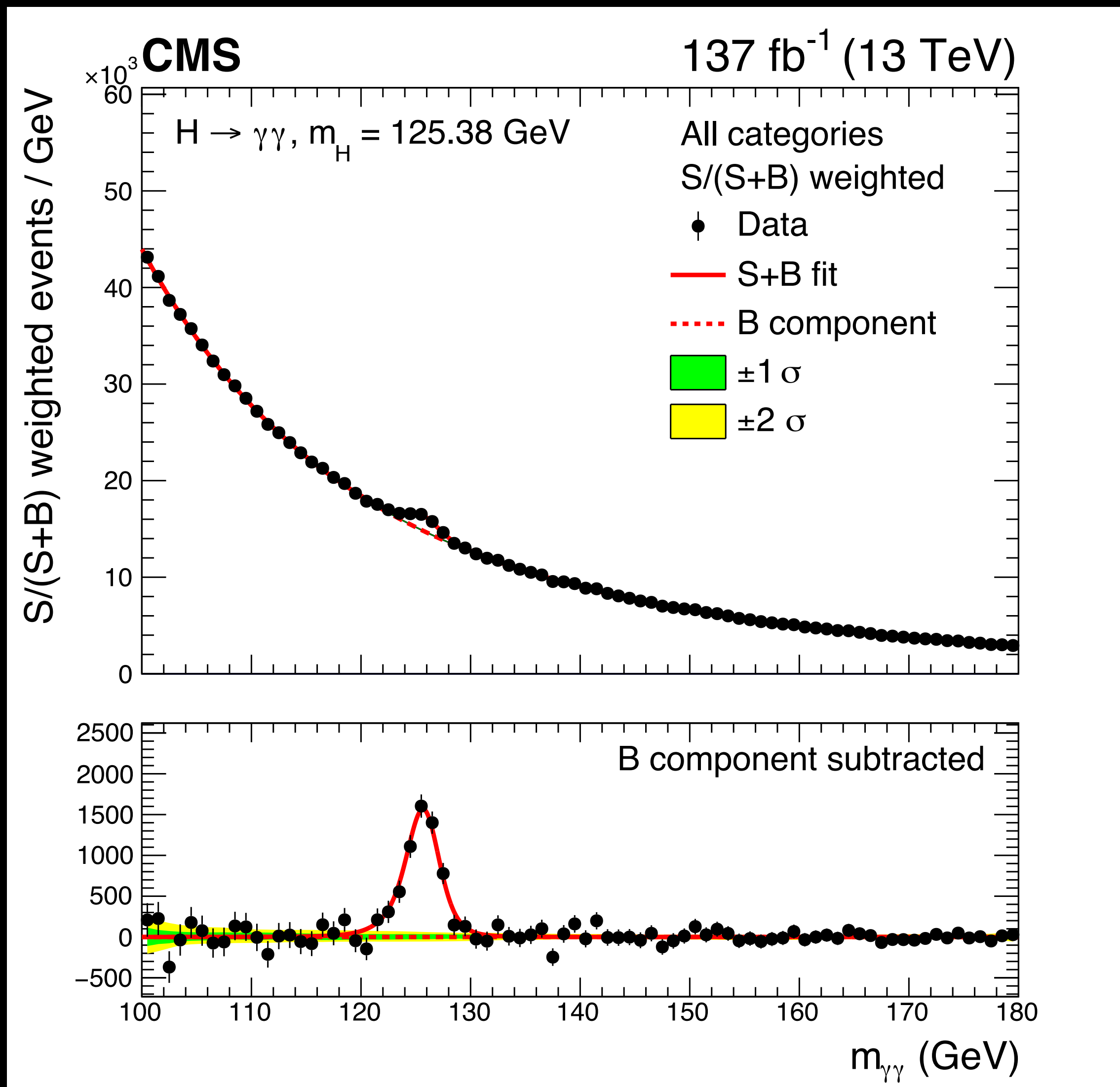
Needle in a haystack



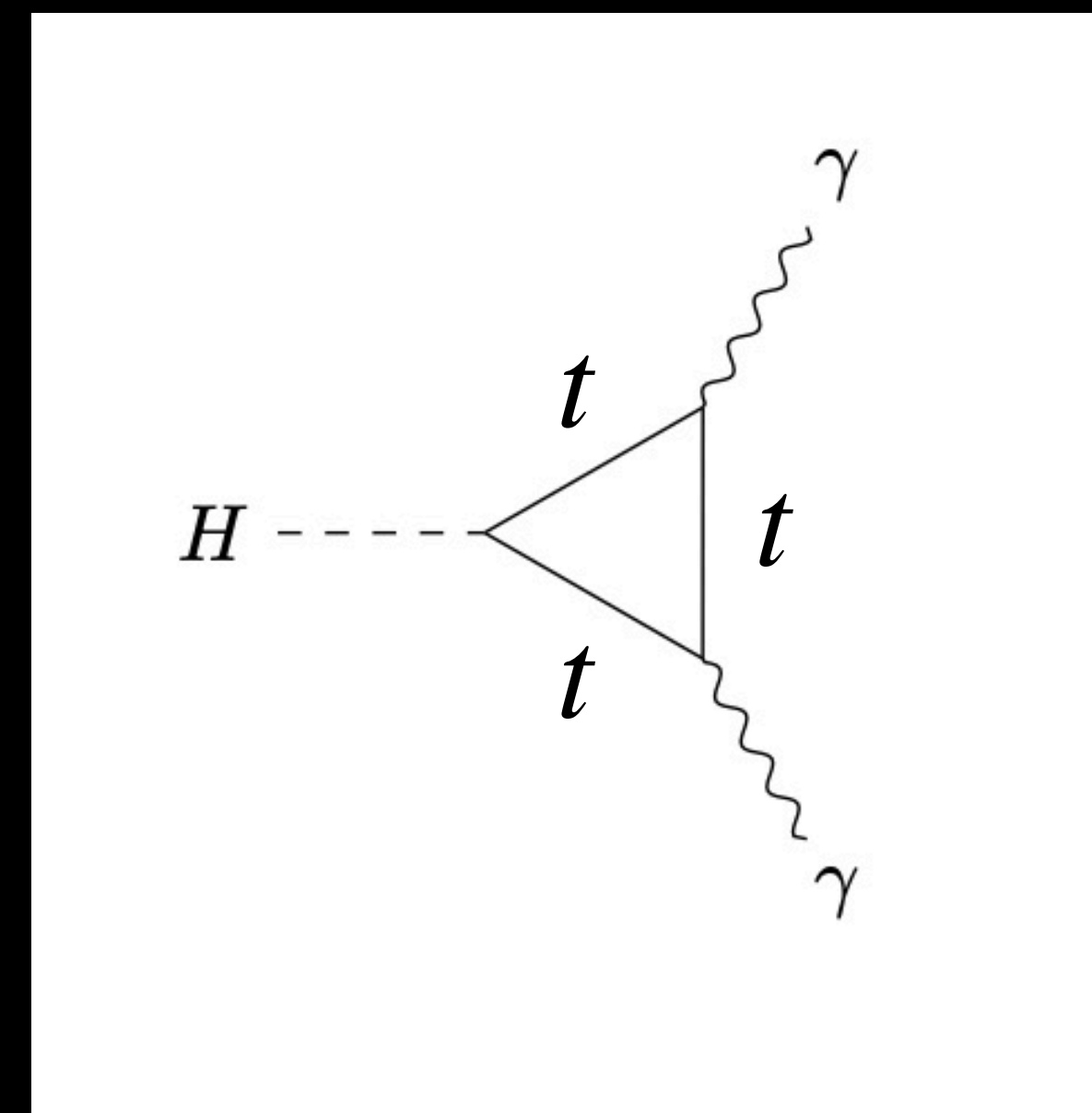
What would be my variable
of choice?



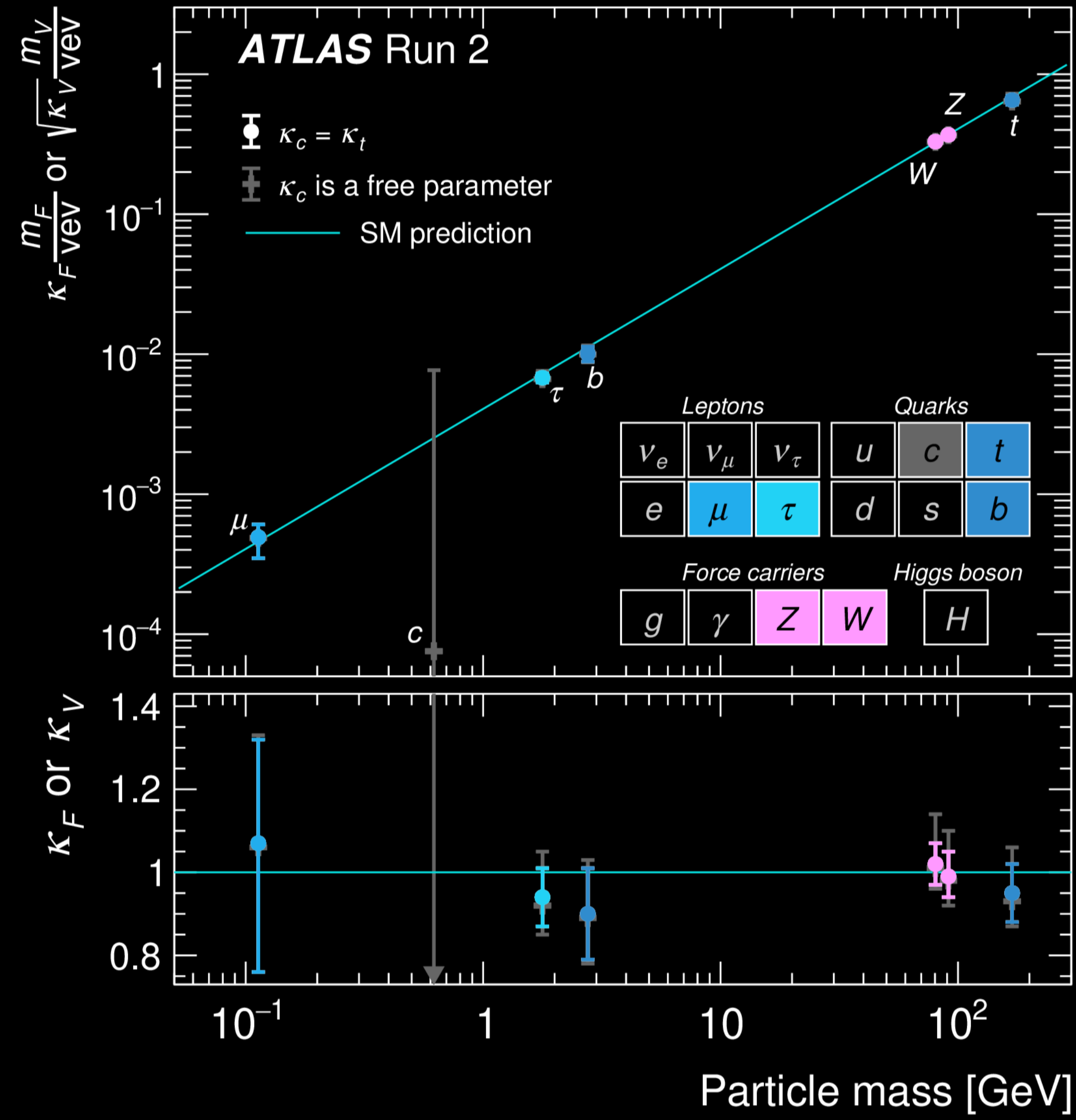




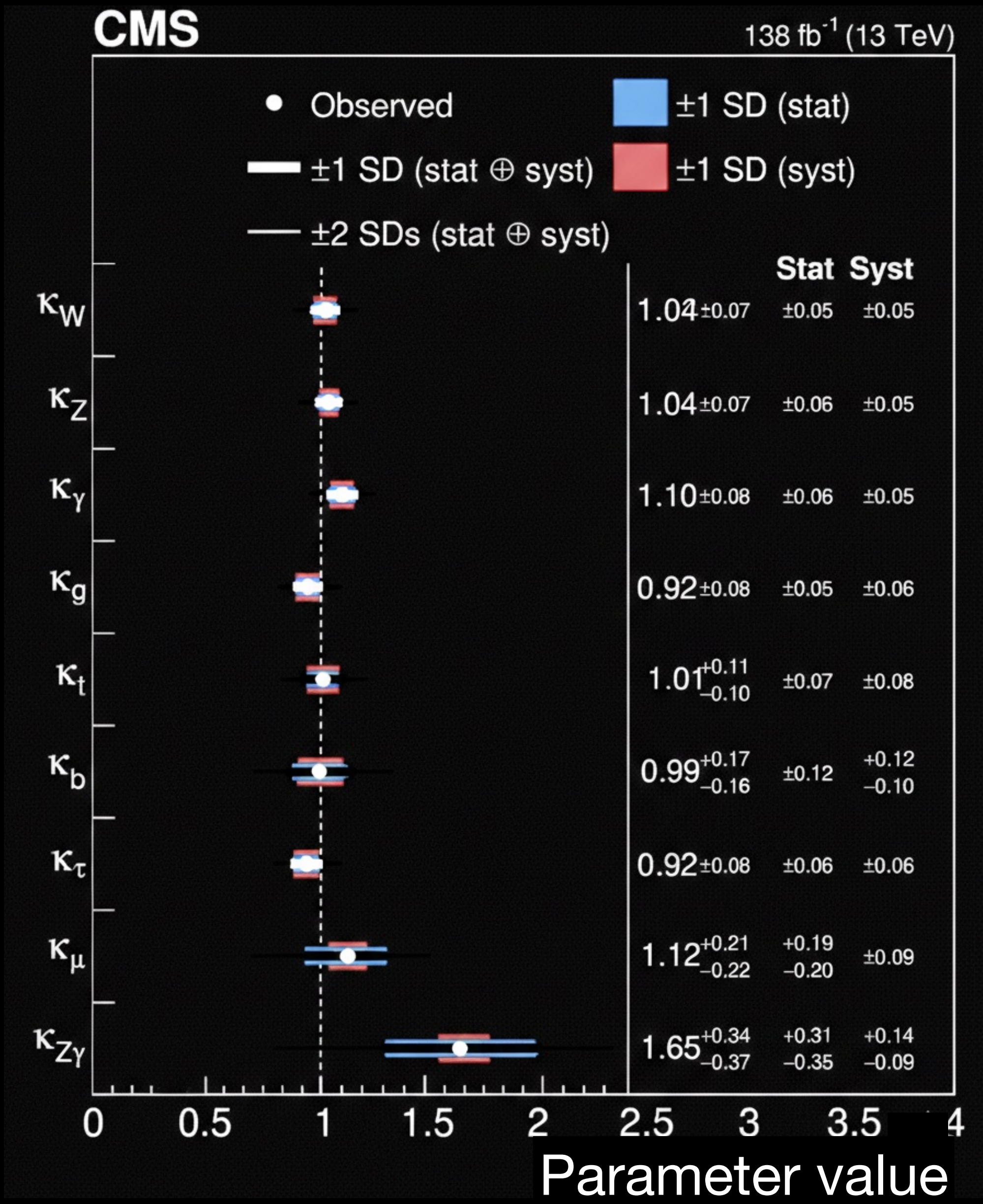
Decay



Incredible achievement of the ATLAS and CMS Collaborations!



<https://www.nature.com/articles/s41586-022-04893-w>



<https://www.nature.com/articles/s41586-022-04892-x>

The 2025 Breakthrough Prize in Fundamental Physics



“For detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN’s Large Hadron Collider.”

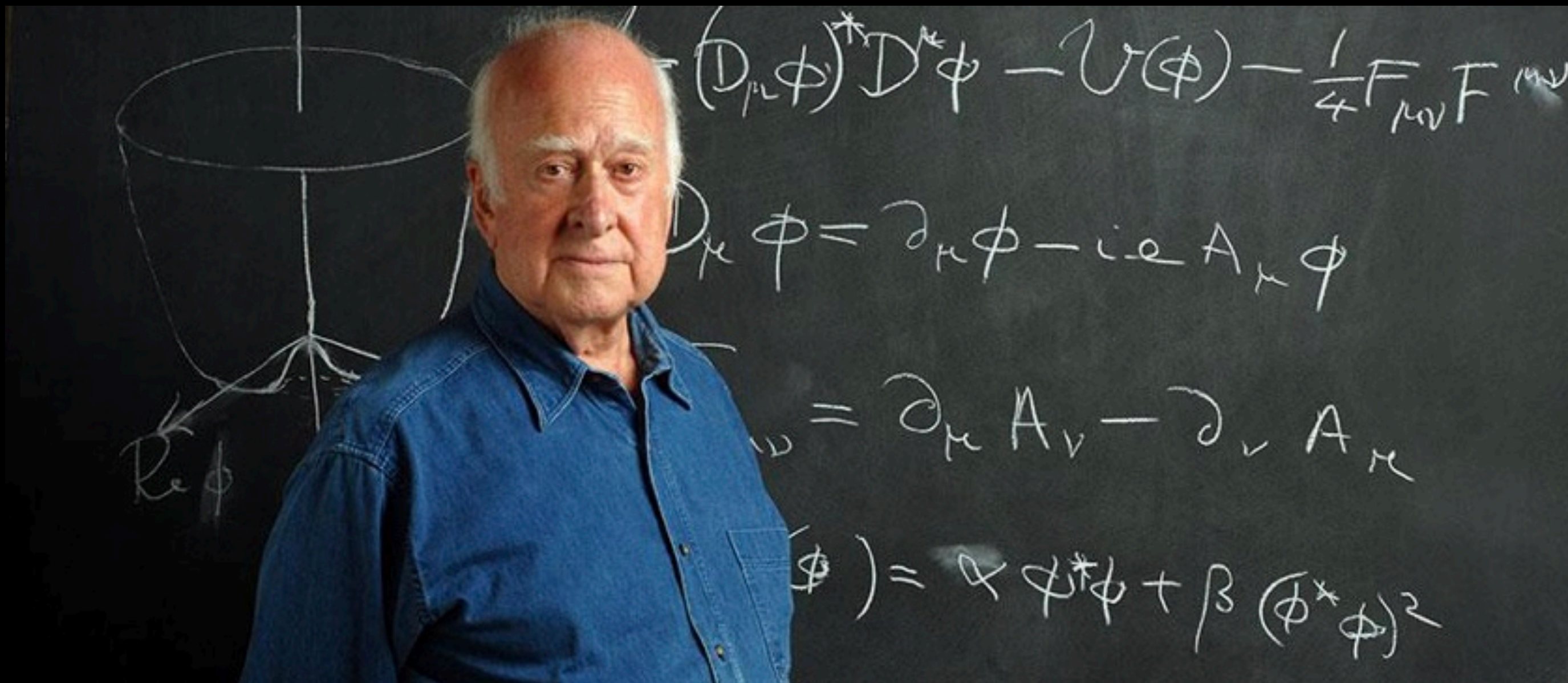


Takeaway message...

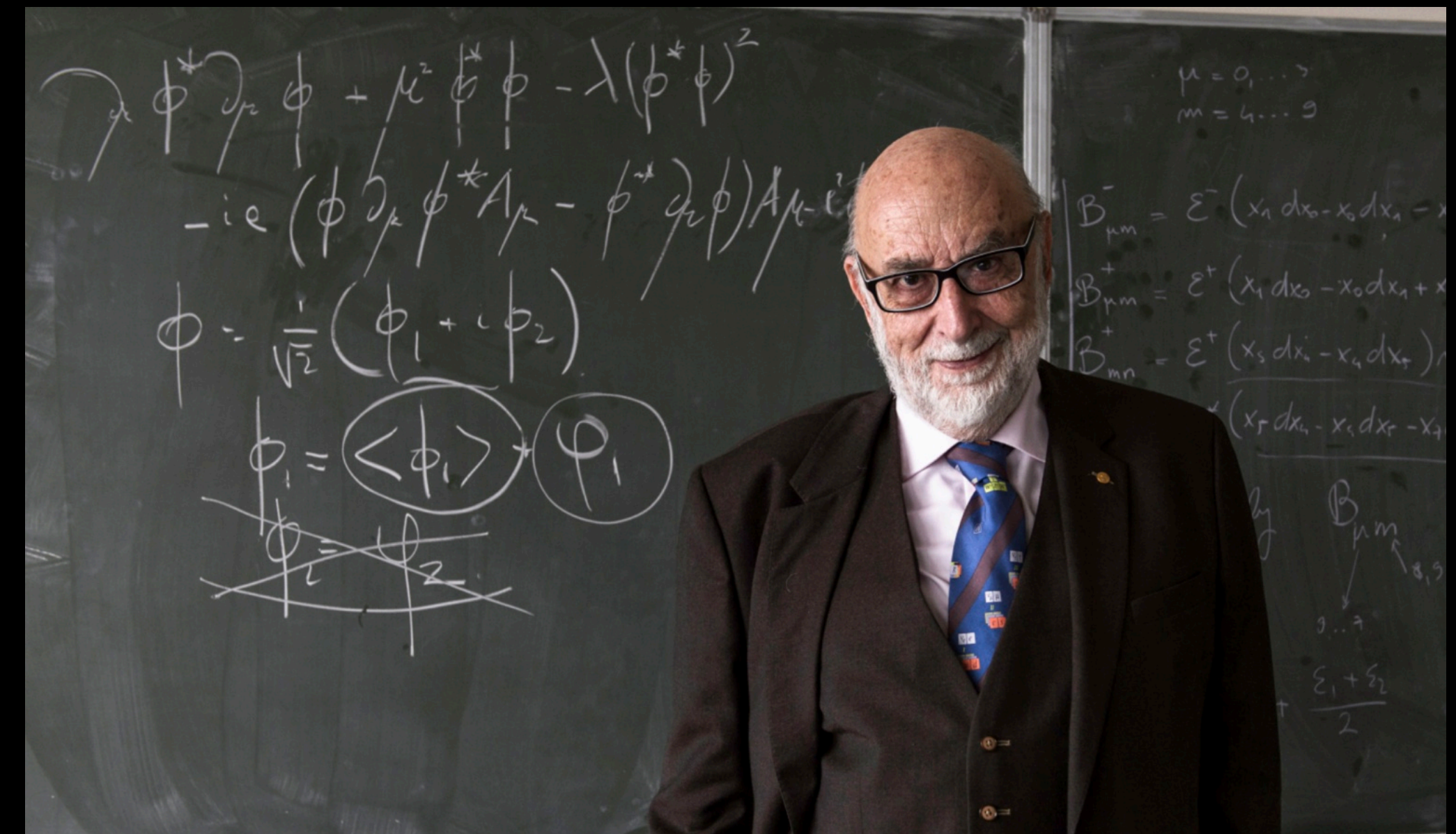
- The Higgs Boson is one of the greatest discoveries of the 21st century
- The aftermath of the discovery has far-reaching consequences in terms of understanding how our universe came to be
- Nearly fourteen years after the discovery of the Higgs Boson we are studying its properties with precision
- Any deviation from expectations → **New Physics!**

This talk is dedicated to the memory of

Professor Peter Higgs and Professor François Englert

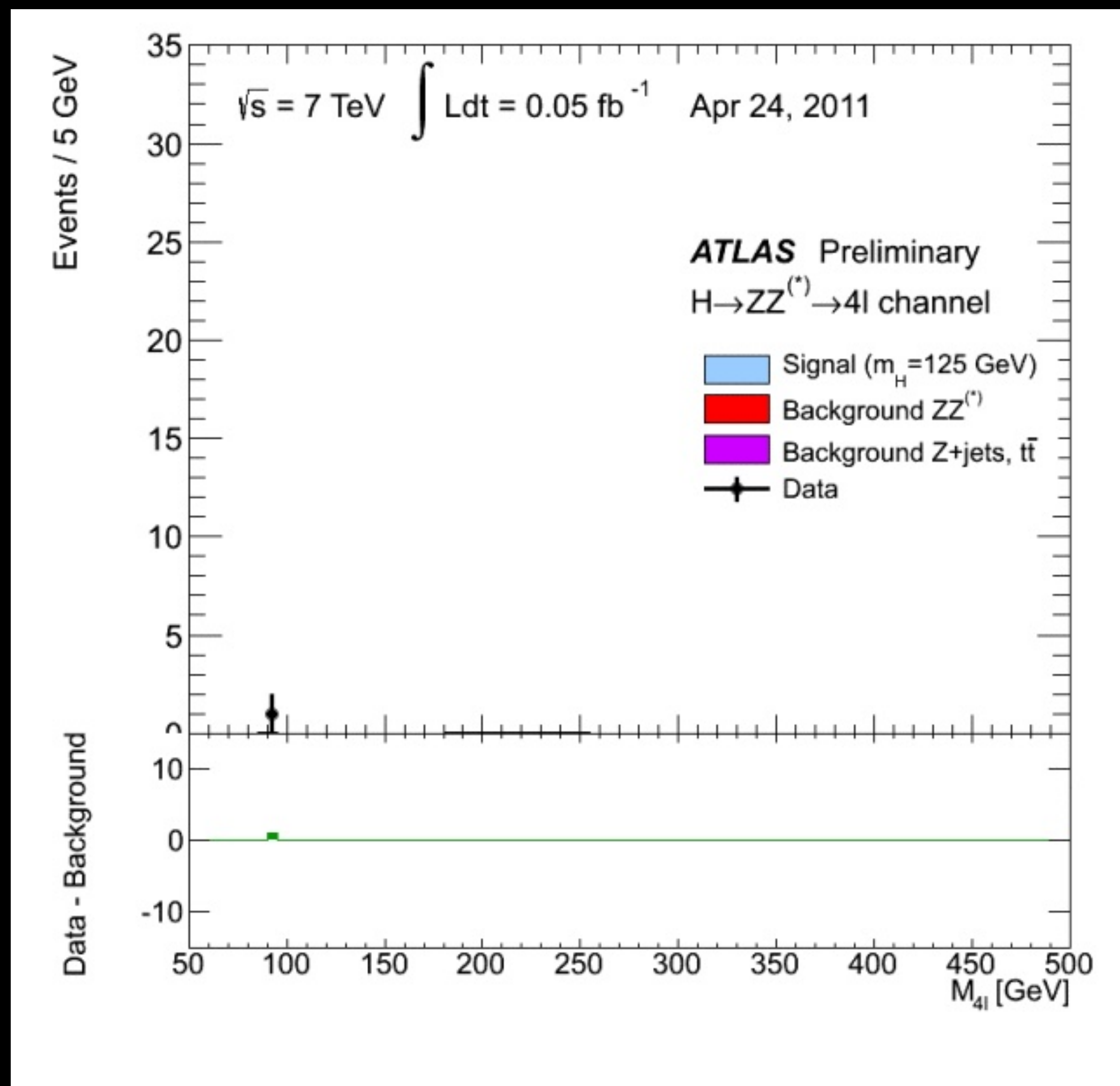


1929-2024

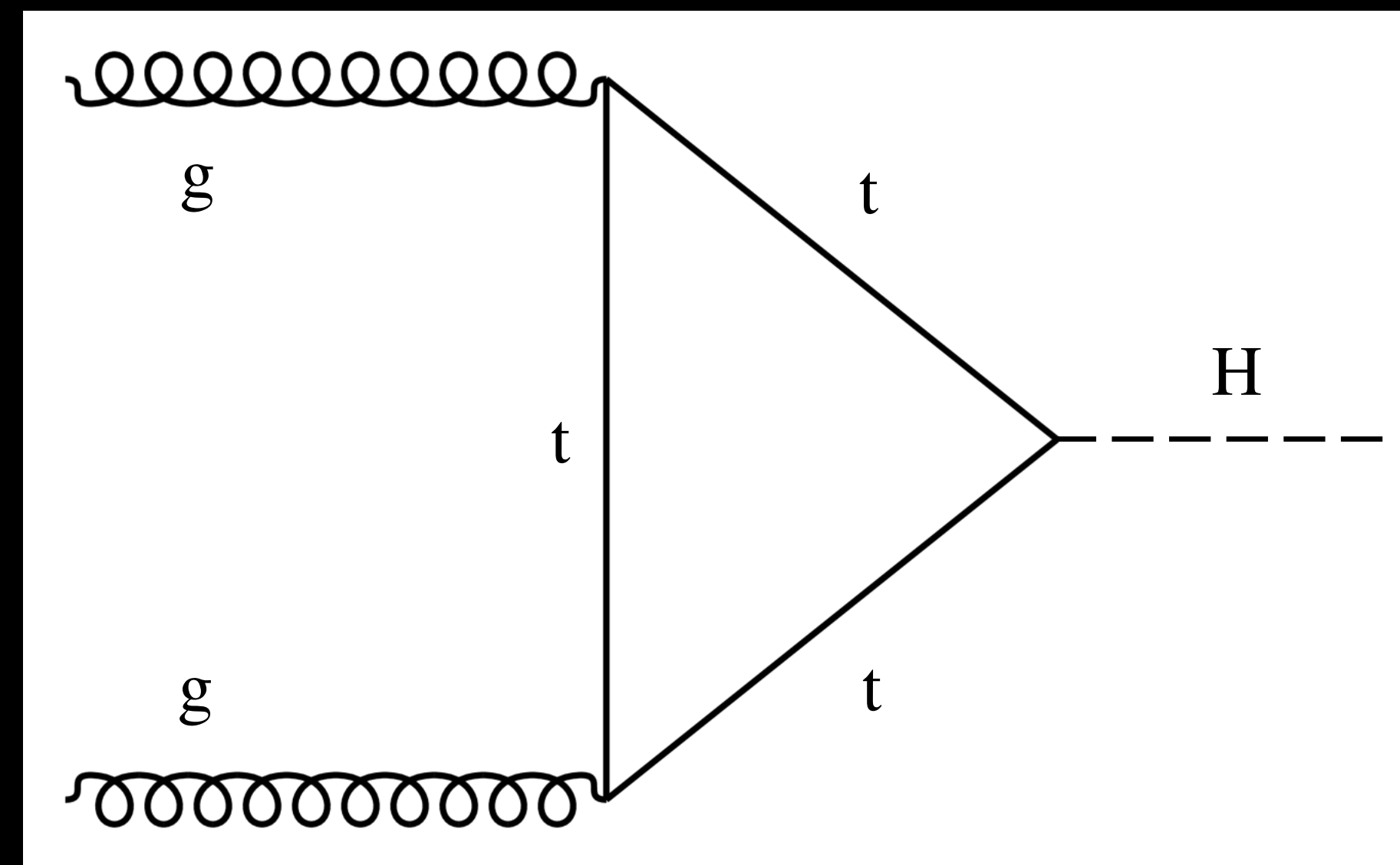


1932-2026

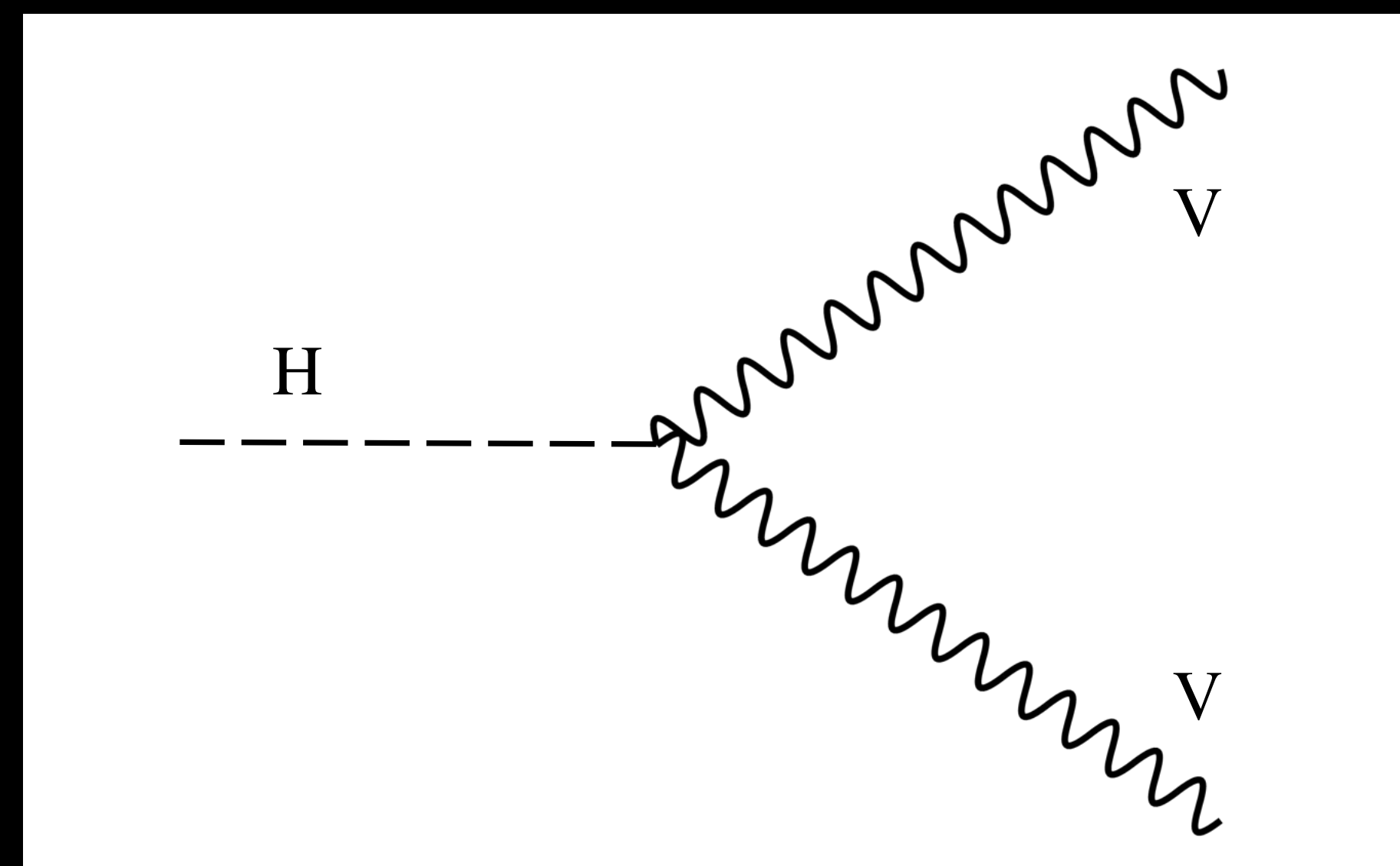
Additional Material



Production

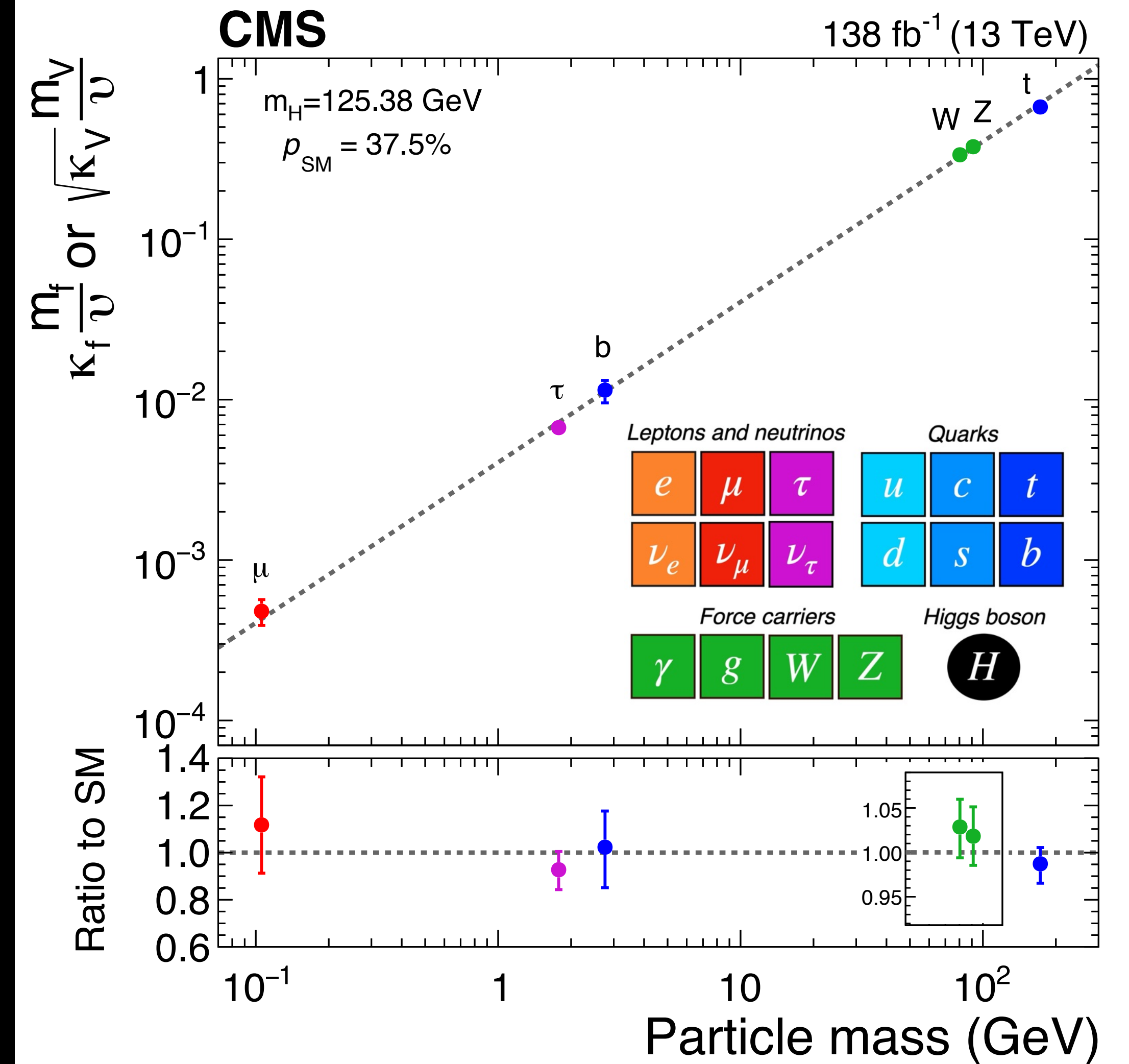
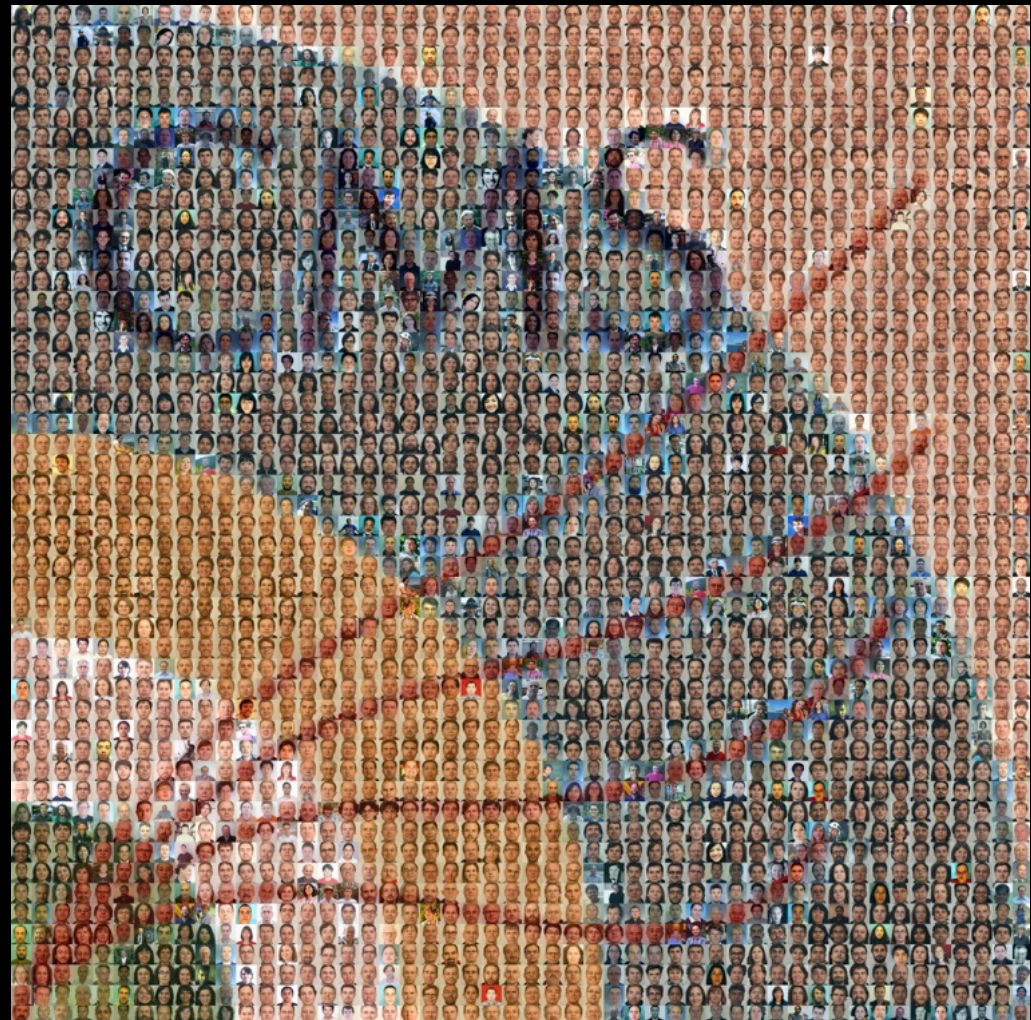


Decay



14 years after the Higgs discovery

Incredible achievement of the ATLAS and CMS Collaborations



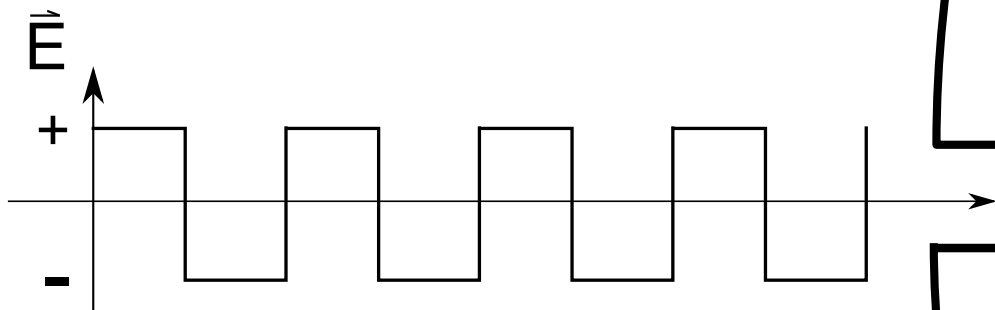
Cyclotron

Proposed by Ernest Lawrence and patented in 1932

- ① Ion source (negative charges here)
- ② Accelerated ions
- $\vec{B}$ Magnetic field
- $\vec{E}$ Electric field

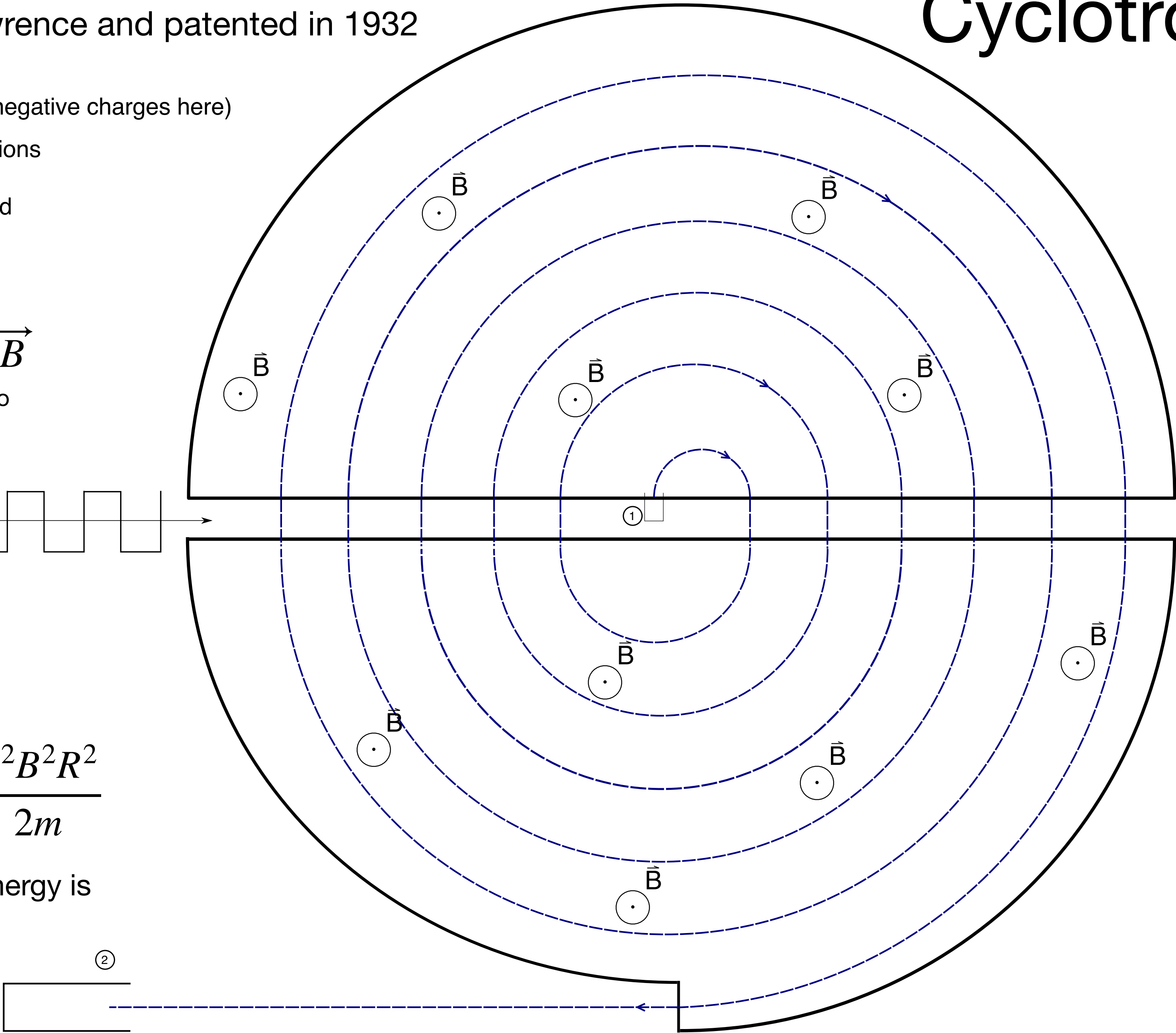
$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

B field acts perpendicular to the direction of motion



Kinetic $E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$

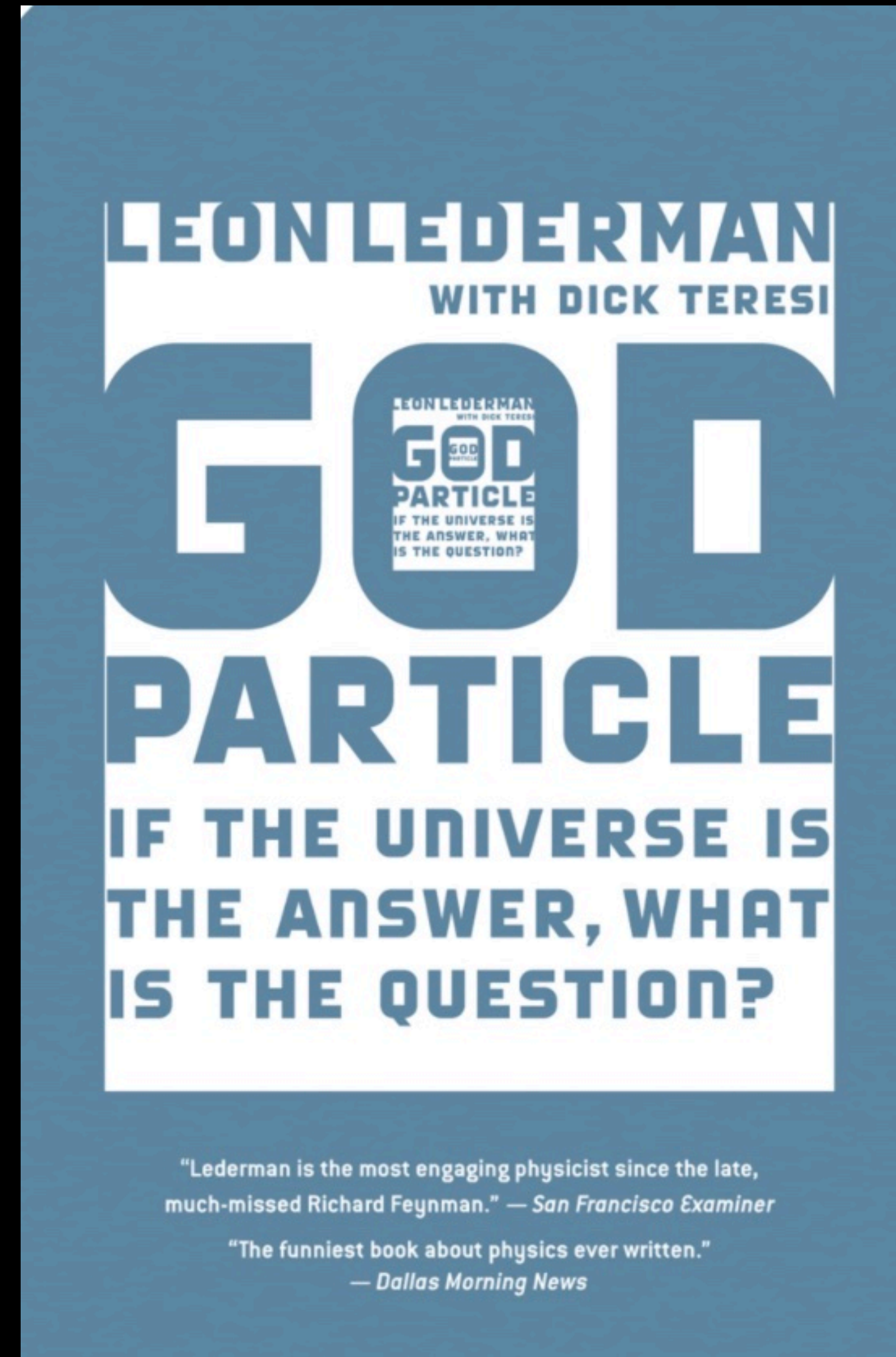
R = radius at which the energy is determined



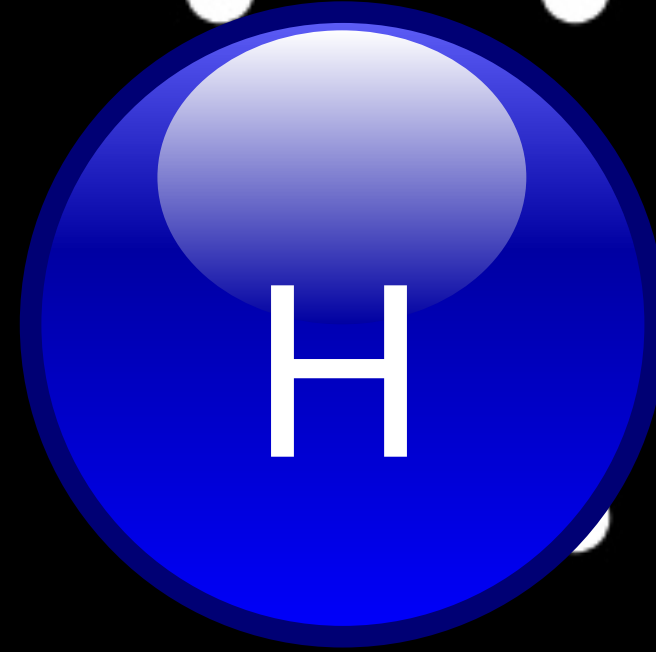
Higgs Boson is essential to
life on earth...

Some may even refer to the
Higgs Boson as the
“god particle”!

Physicists don't really like that term!



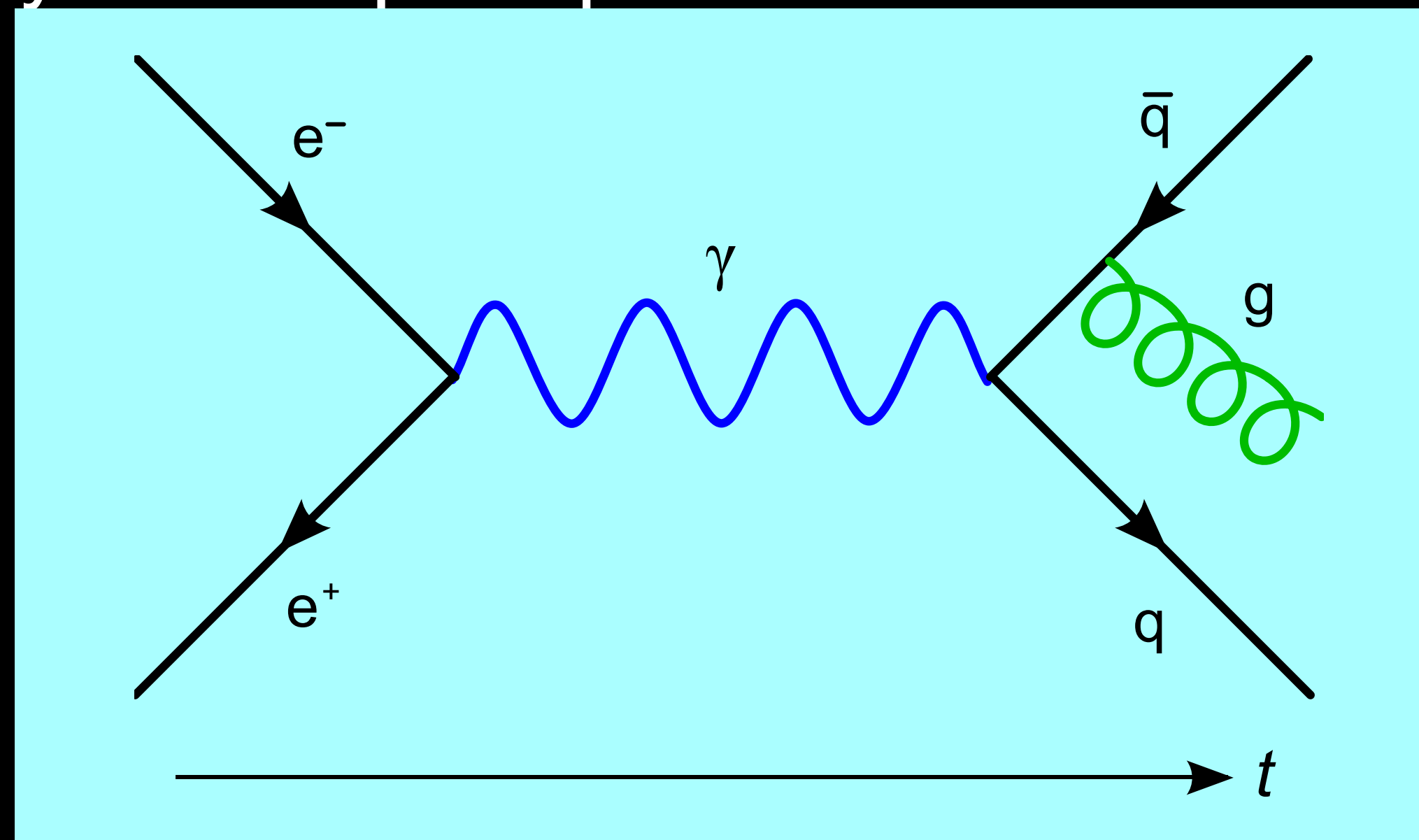
The only way to detect the Higgs field is by
producing the
Higgs boson

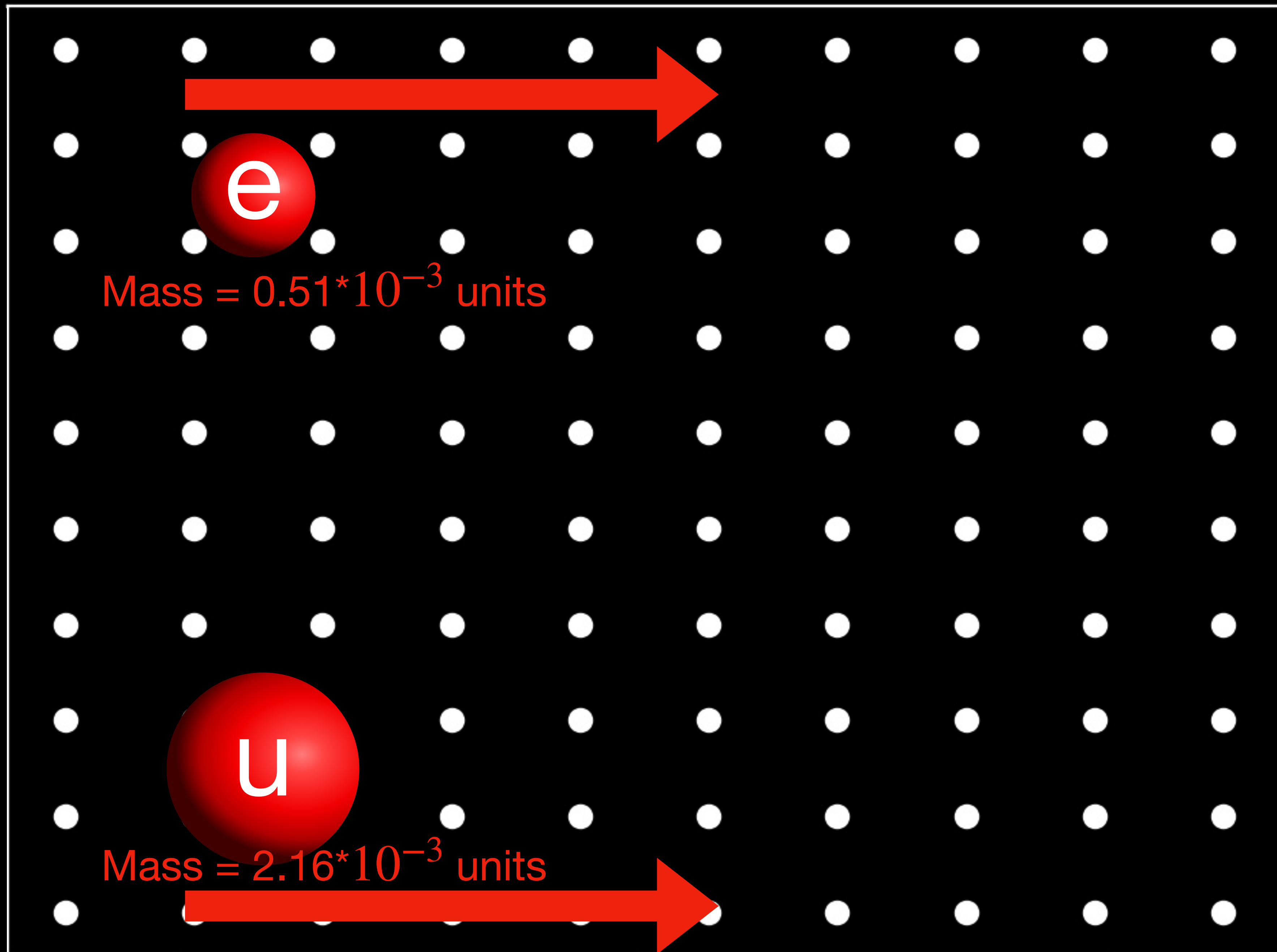


The Large Hadron Collider was built to find this
particle

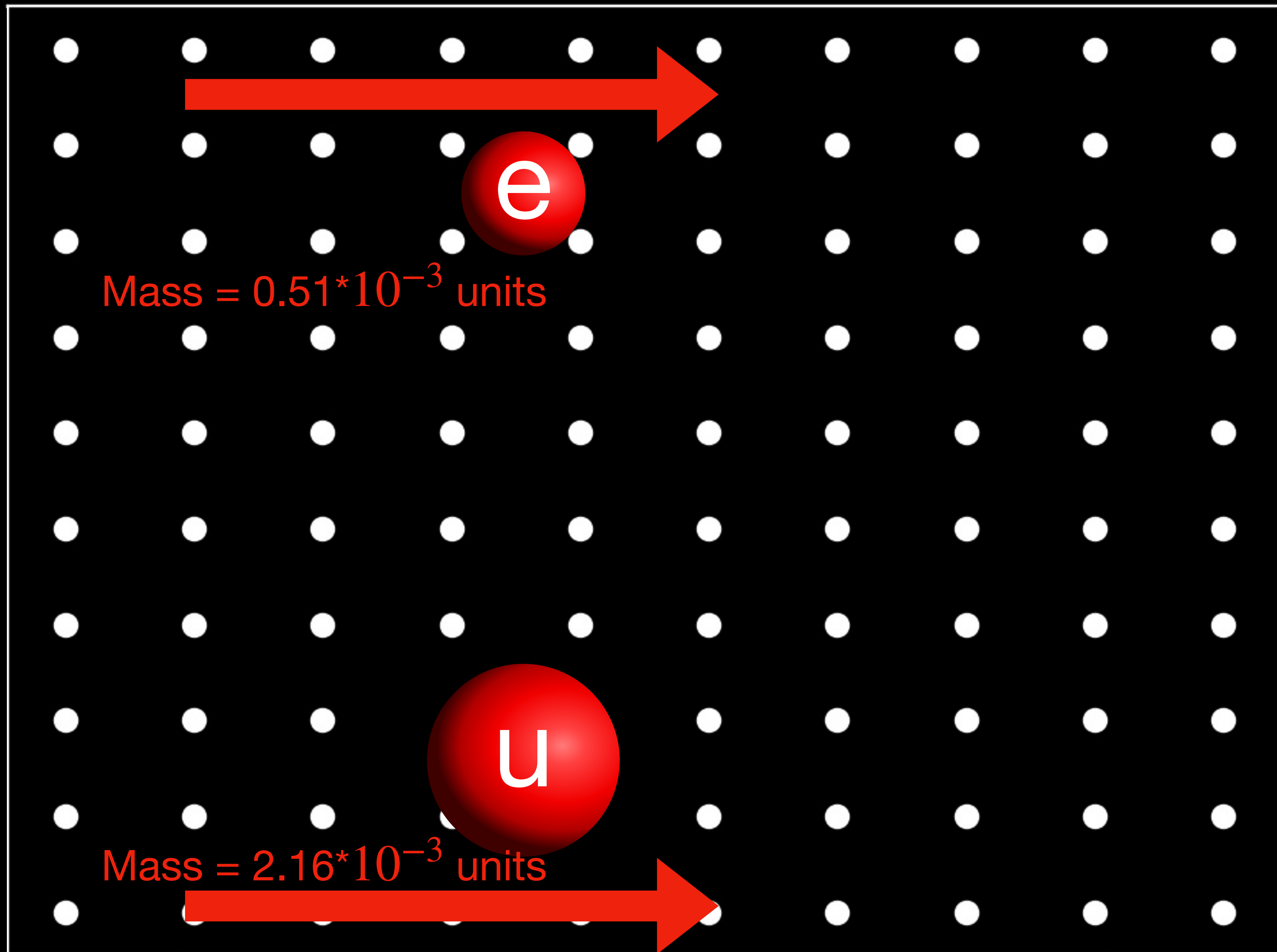
Representing fundamental physics process with “diagrams”

- Often useful to represent fundamental particle physics interactions pictorially
- Diagram constructed in space-time
- At each vertex, strength of interaction is indicated
- All conservation laws like charge, momenta conserved at each vertex
- Provides natural way to compute probabilities





Particles that interact with the Higgs field acquire mass

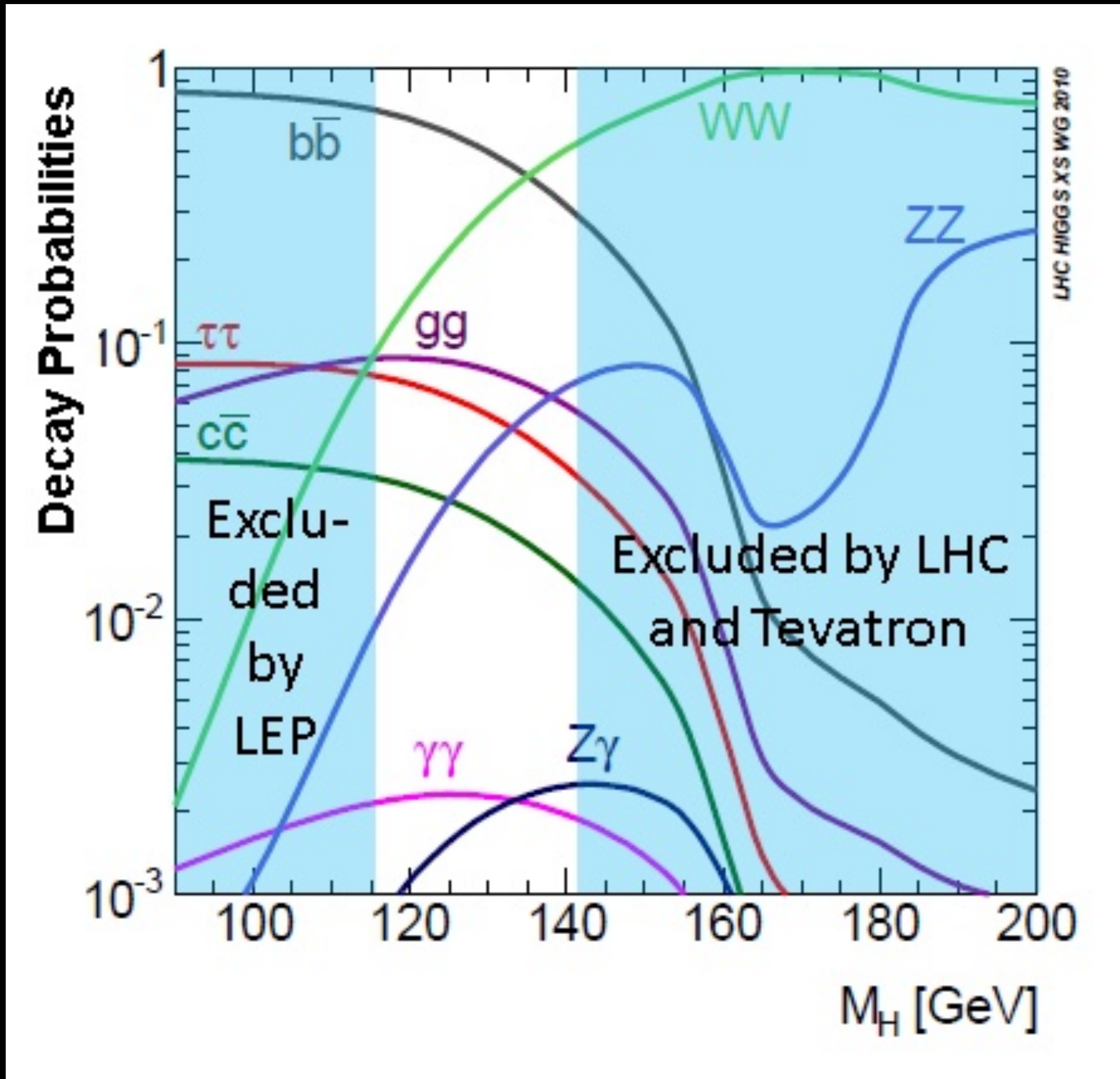


Mass = 0.51×10^{-3} units

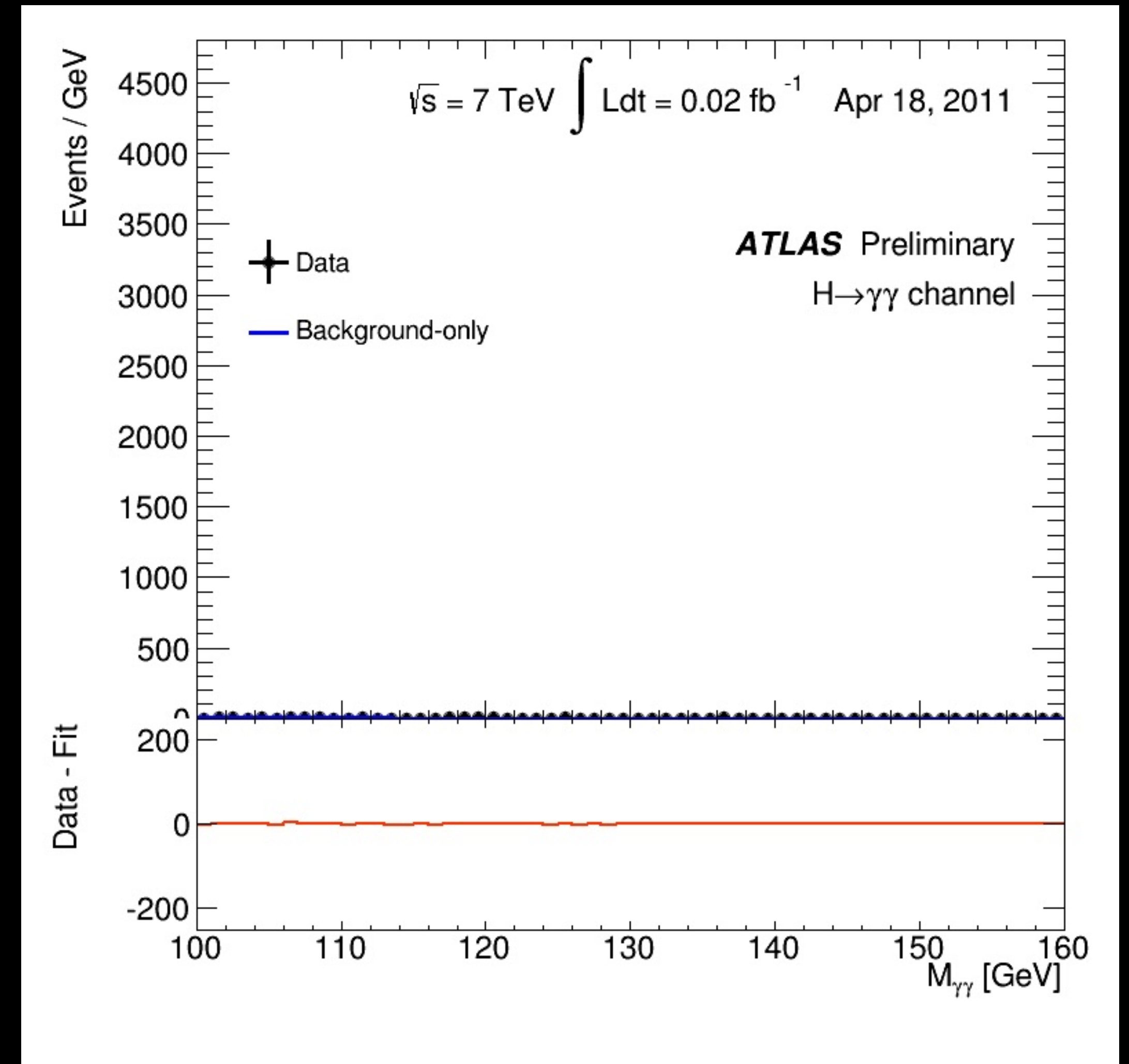
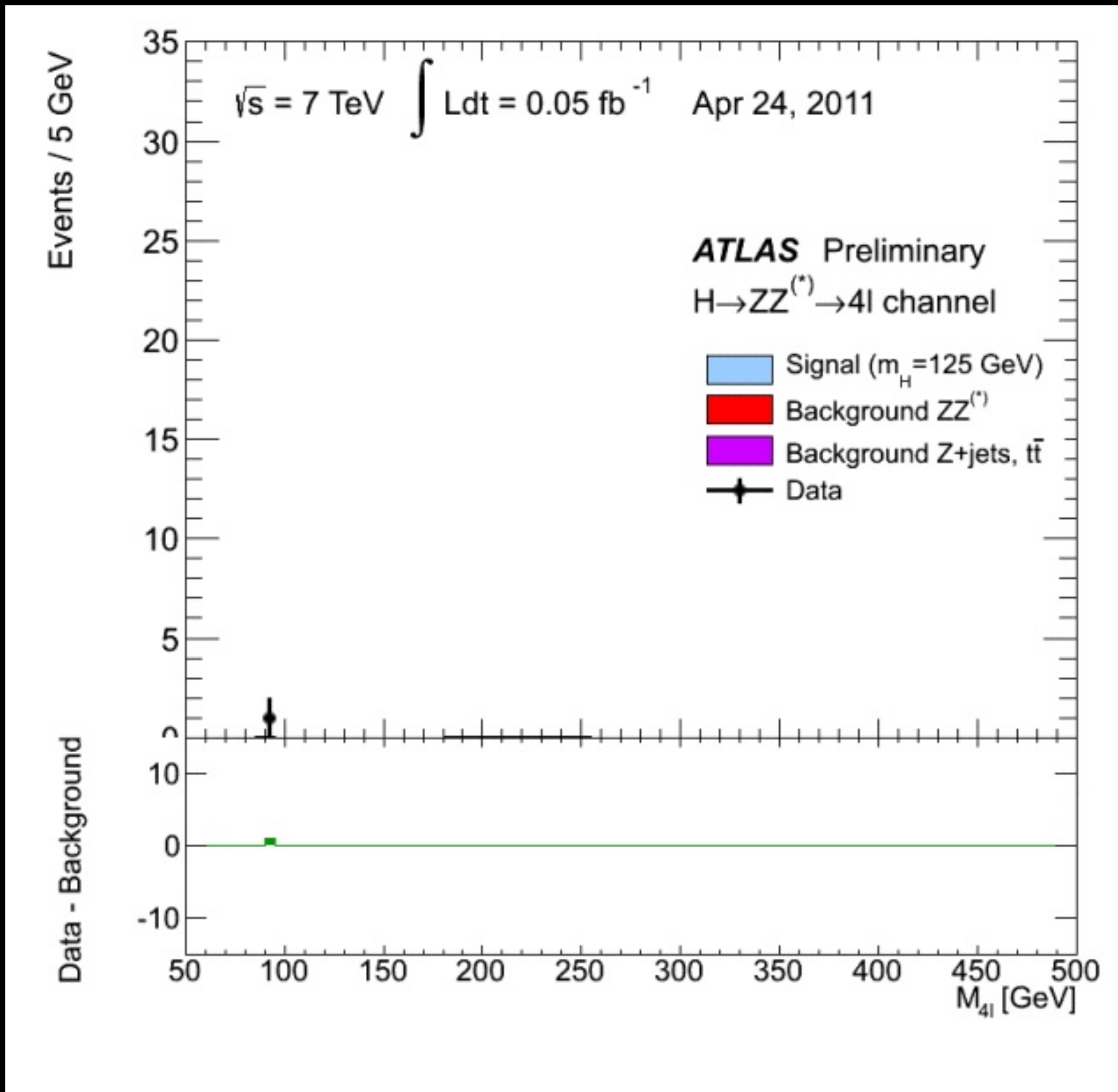
Mass = 2.16×10^{-3} units

Particles that interact with the Higgs field acquire mass

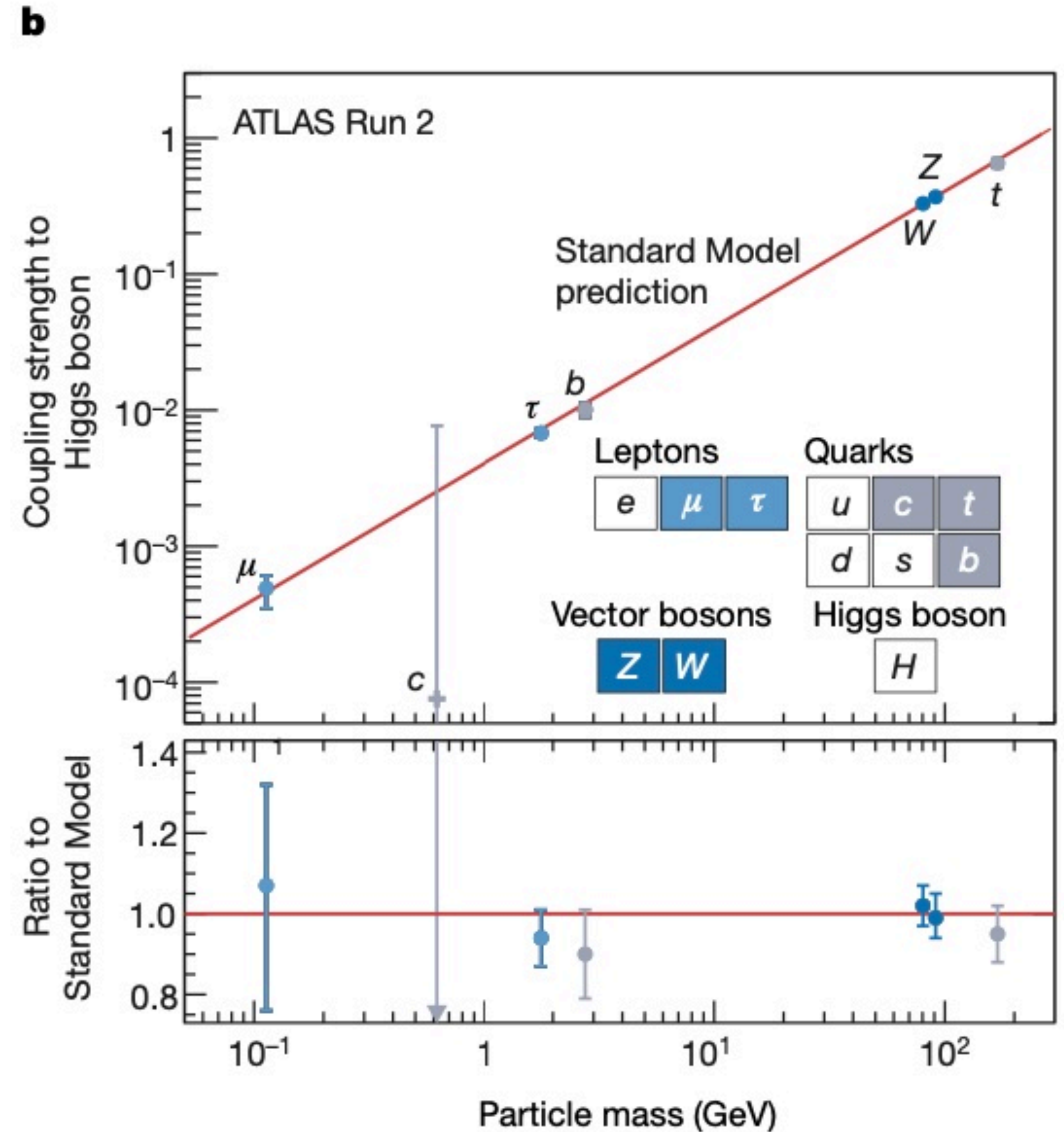
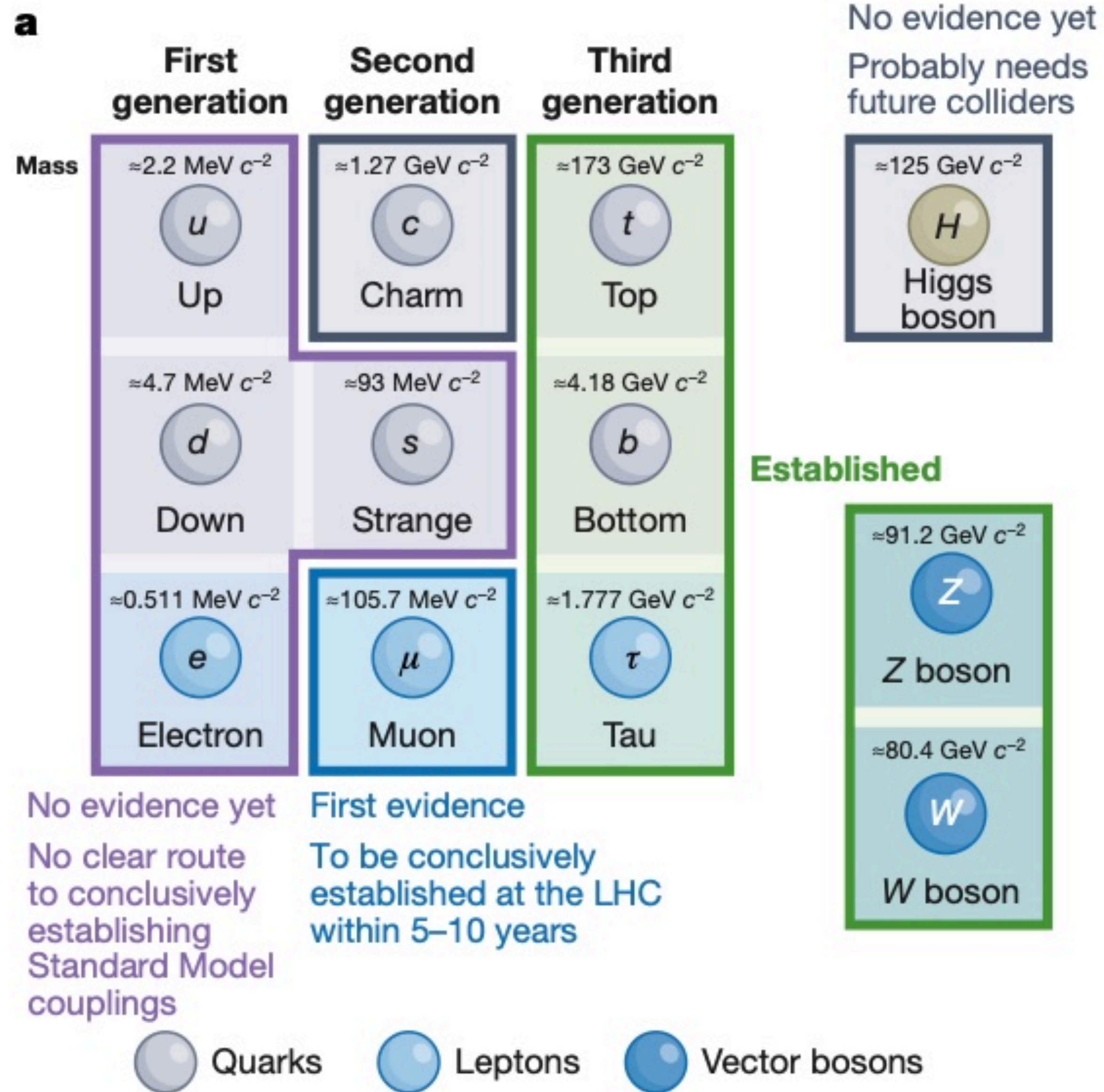
Can predict decay probabilities based on Higgs mass



At the time of the Higgs discovery...

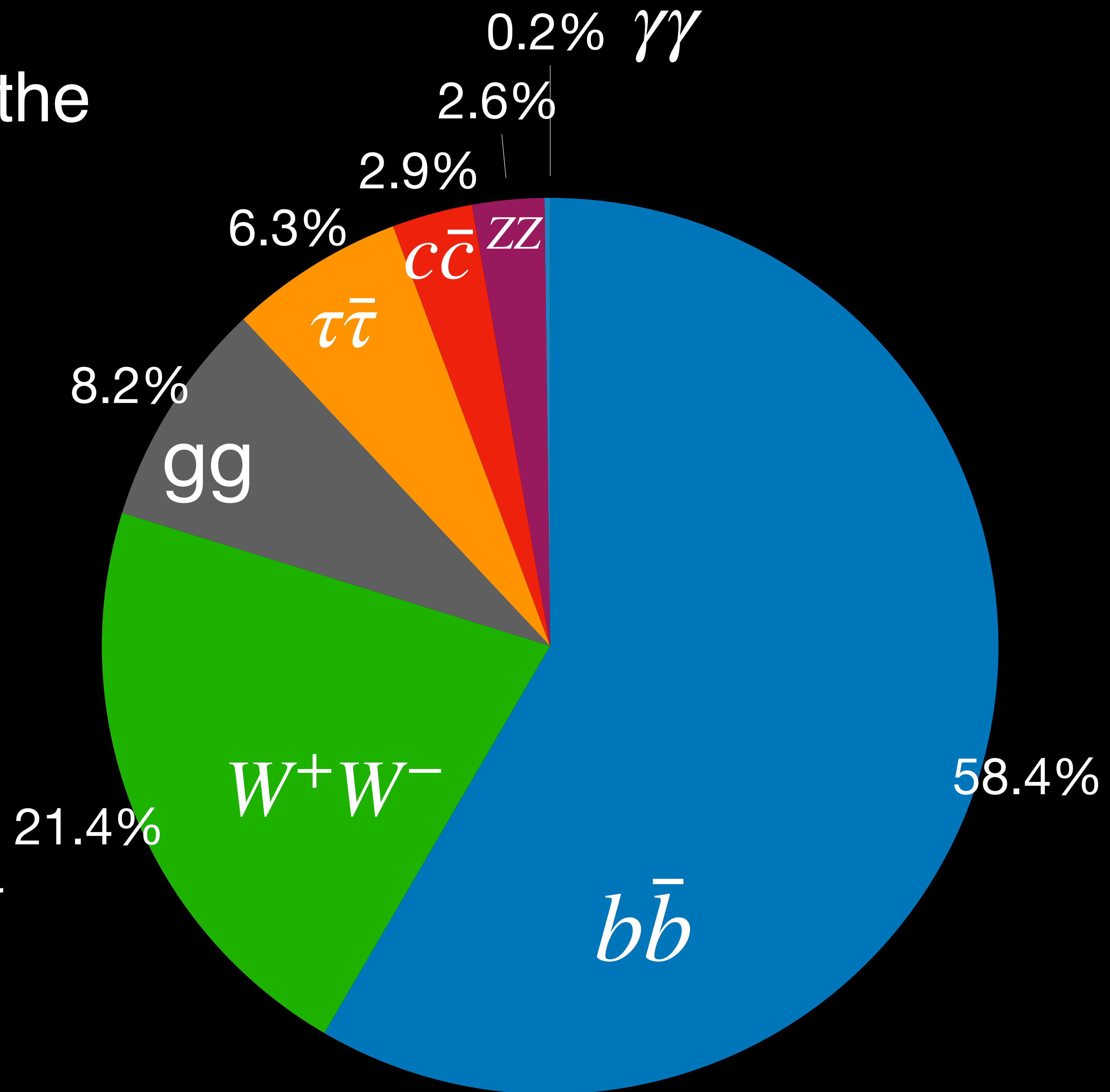


Where things stand today...



In how many ways can the Higgs decay?

- The Higgs mass of 125 GeV leads to some interesting consequences:
- A wide array of decay modes possible
- If the Higgs were 50 GeV heavier → detection through only two decay modes
- If the Higgs were 10 GeV lighter → detection through all W and Z bosons almost impossible



Provides a description of the most fundamental building blocks of matter

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi \\ & + \chi_i Y_{ij} \chi_j \phi + h.c. \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$
