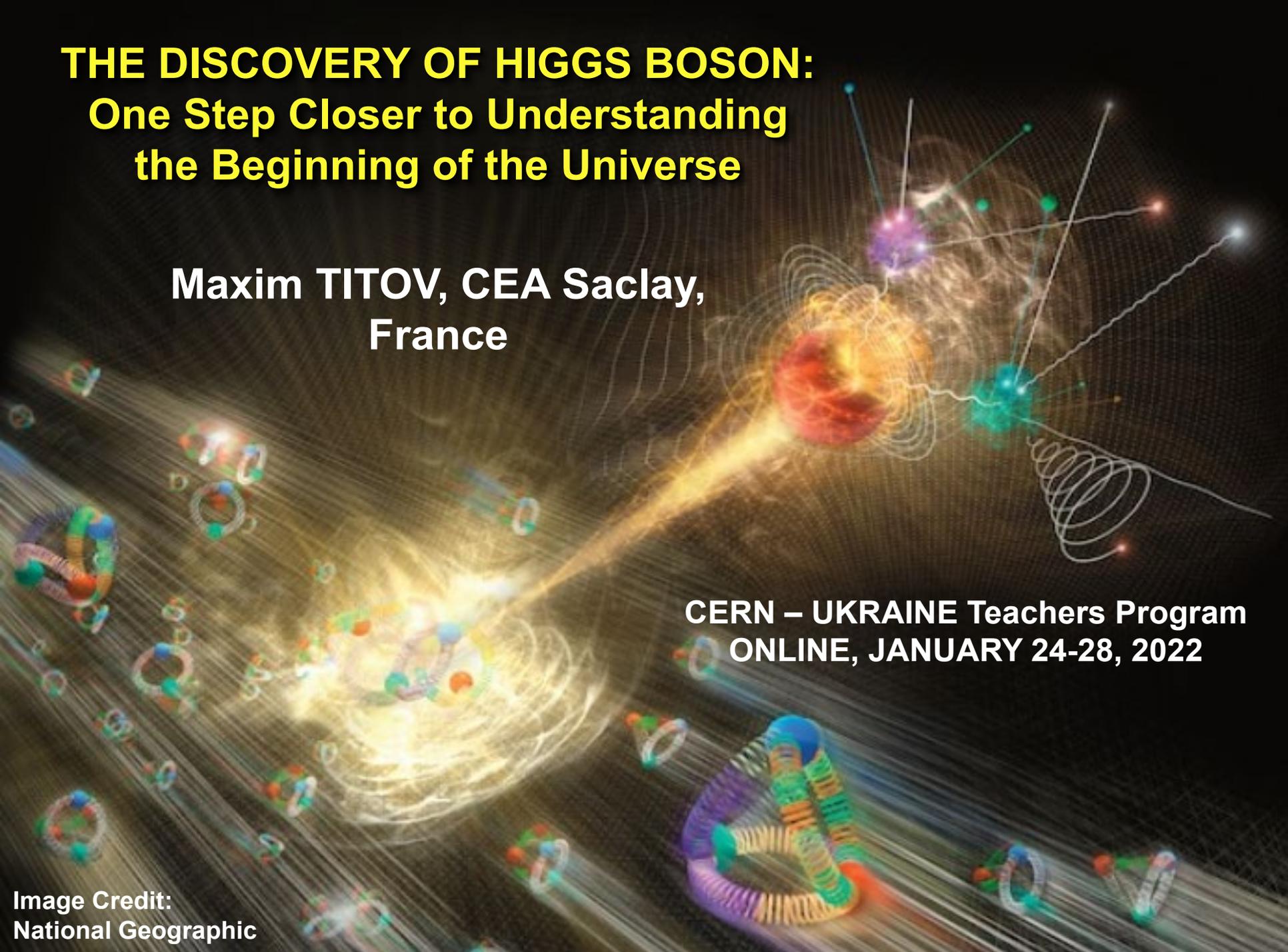


THE DISCOVERY OF HIGGS BOSON: One Step Closer to Understanding the Beginning of the Universe

Maxim TITOV, CEA Saclay,
France

CERN – UKRAINE Teachers Program
ONLINE, JANUARY 24-28, 2022



The Aim of Particle Physics

*(Elementary Particle Physics
and/or High Energy Physics)*

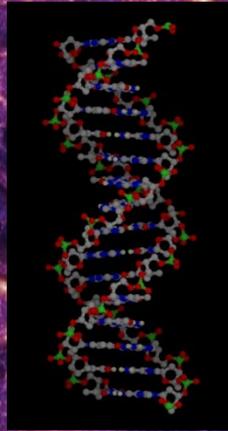
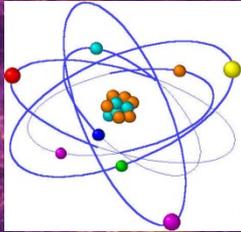
1. What is everything made of?
2. What holds it all together?

Particle physics is a modern name for centuries old effort to understand the laws of Nature

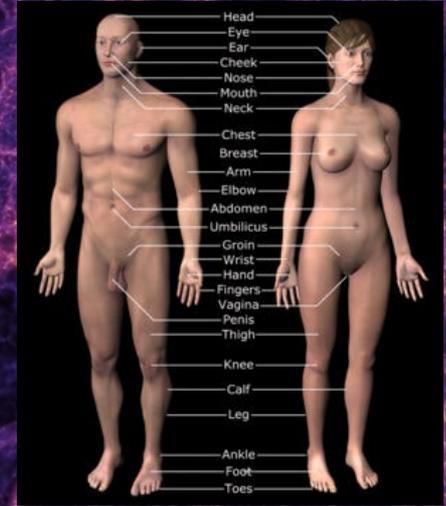
We are about to take a journey into the world of Higgs particle



What is everything made of ? What holds it all together ?



125

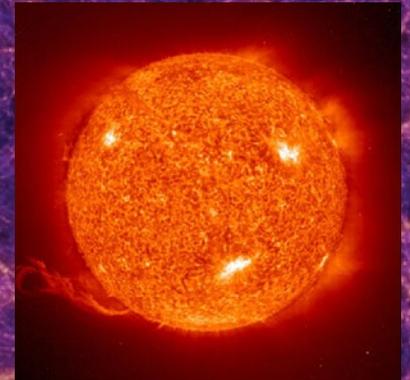


Where did we come from?

Why do we exist?



Colliding galaxies reveal dark matter



What is everything made of ? What holds it all together ?

The last stars will die out 120 trillion years from now, followed by 10^{106} years of just black holes.

Condensed, that's like the universe starting with 1 second of stars and then a billion billion billion billion billion years of just black holes.

Stars are basically the immediate after-effects of the Big Bang. A one-second sizzle of brightness before settling into eternal darkness.

We live in that one bright second.

Matter Content of Our Universe

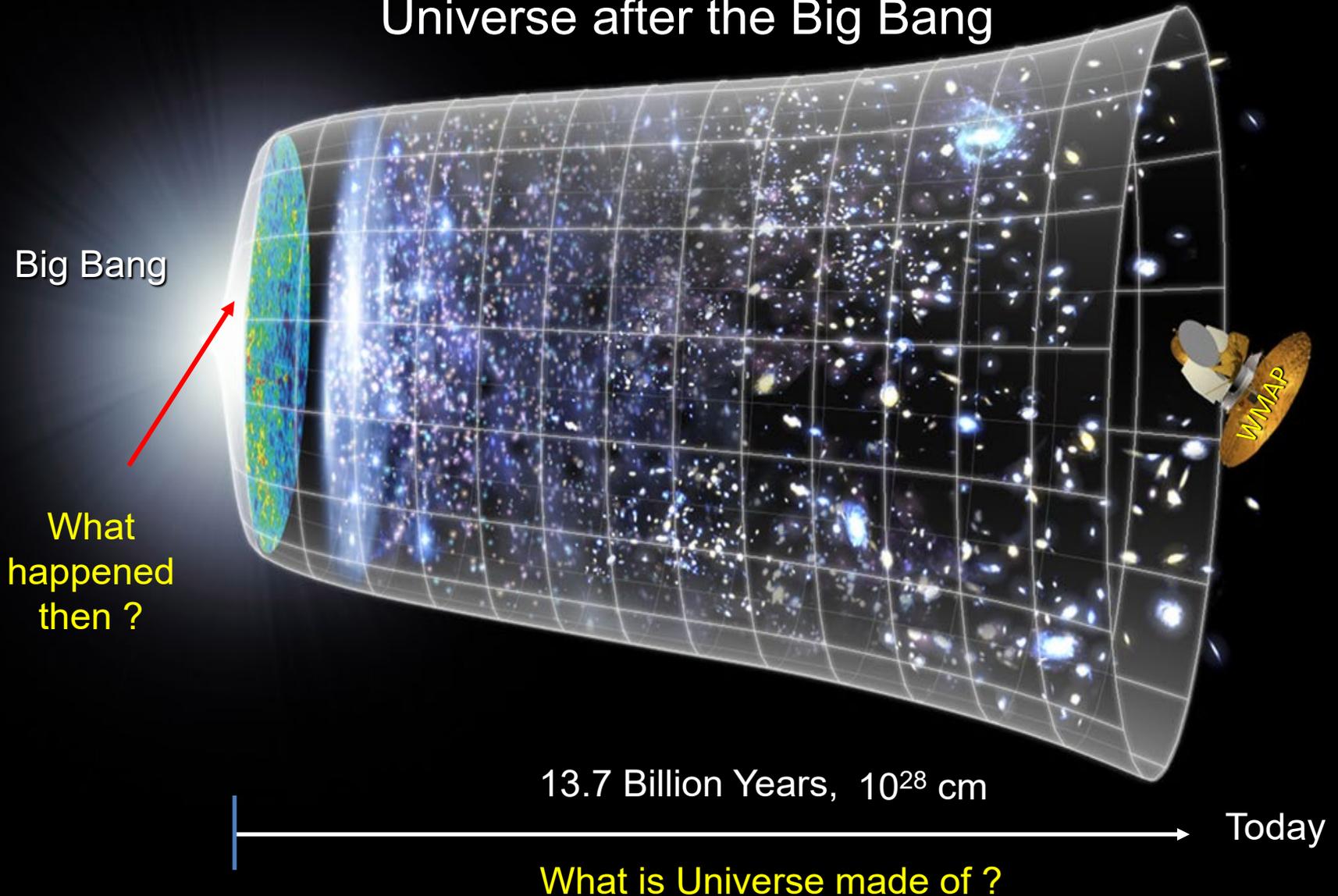
→ *We know only 5% of it ...*



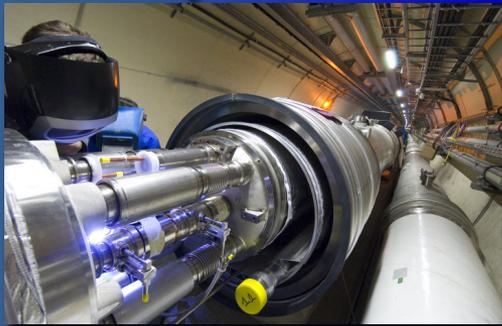
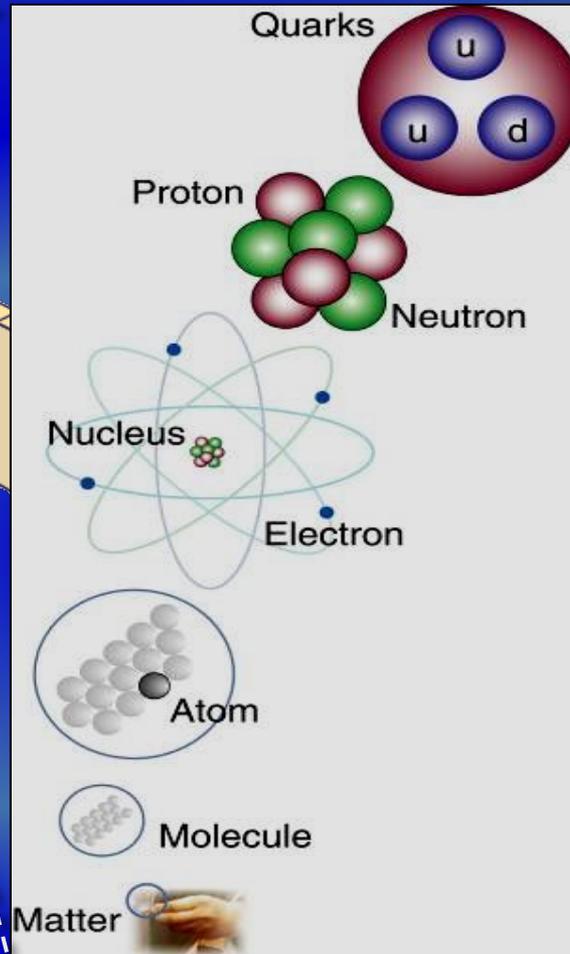
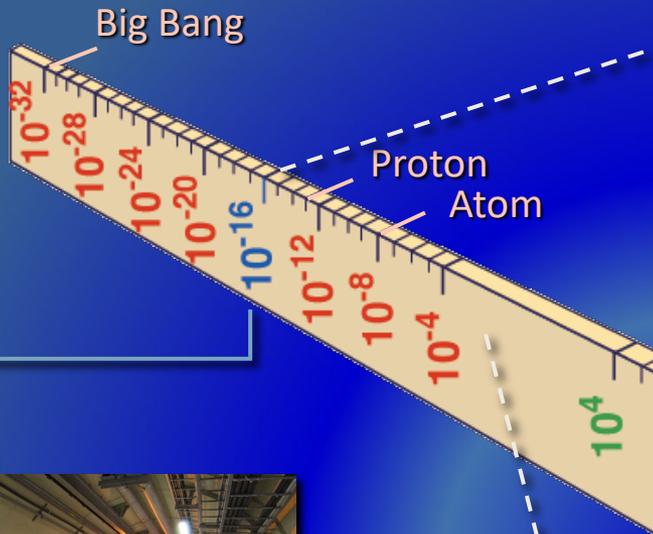
- ✓ **Dark Matter (27%)** → Can be detected only from its gravitational effects
- ✓ **Dark Energy (68%)** → Expansion of Universe is faster than “expected” (Big-Bang + relativity)

Today's Scientific Challenge

to understand the very first moments of our
Universe after the Big Bang

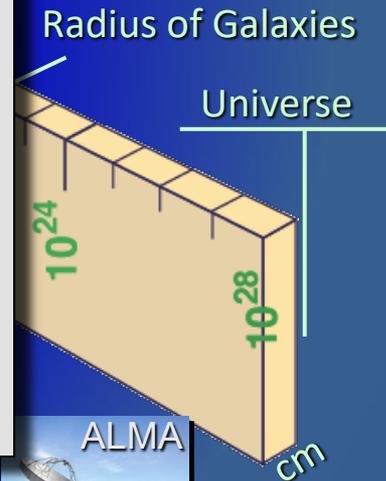


PHYSICS OF TWO INFINITIES



LHC

Super-Microscope



Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology



What is everything made of ? What holds it all together ?

Matter particles

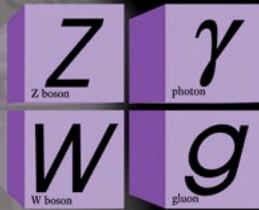
Quarks



Leptons



Universal Forces



Gravitational interaction



Strong

Gluons (8)



Quarks



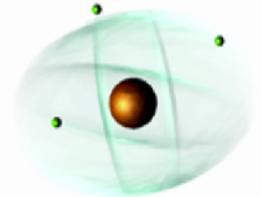
Mesons
Baryons



Nuclei

Electromagnetic

Photon



Atoms
Light
Chemistry
Electronics

Gravitational

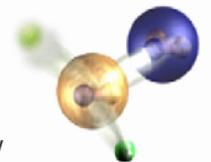
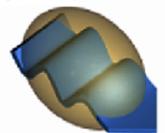
Graviton ?



Solar system
Galaxies
Black holes

Weak

Bosons
(W,Z)

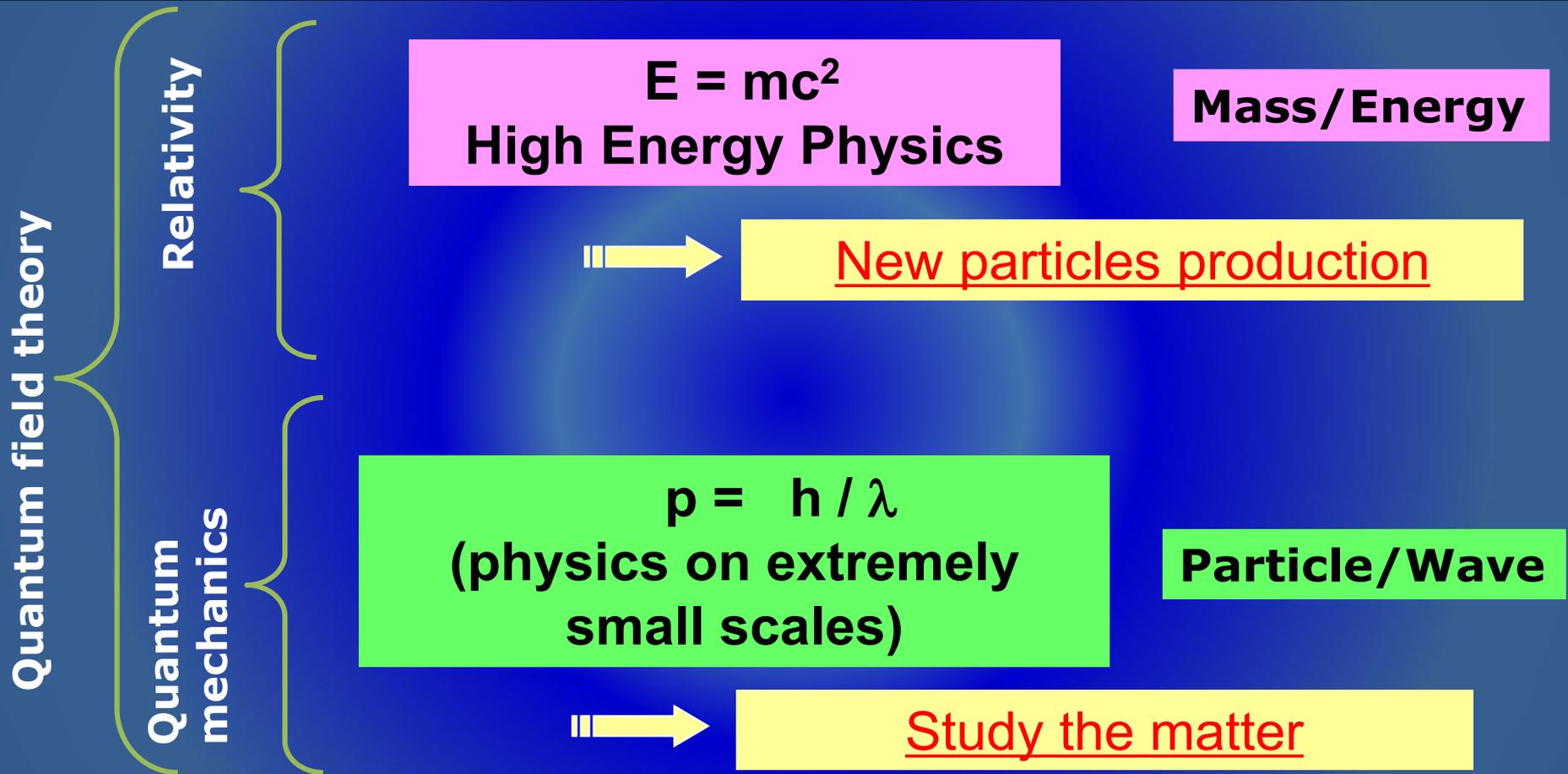


Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

The Particle World

The laws of « this world » are not really intuitive..

$$e = 1.602176462(63) \cdot 10^{-19} \text{ C}$$
$$m = 9.10938188(72) \cdot 10^{-31} \text{ kg}$$



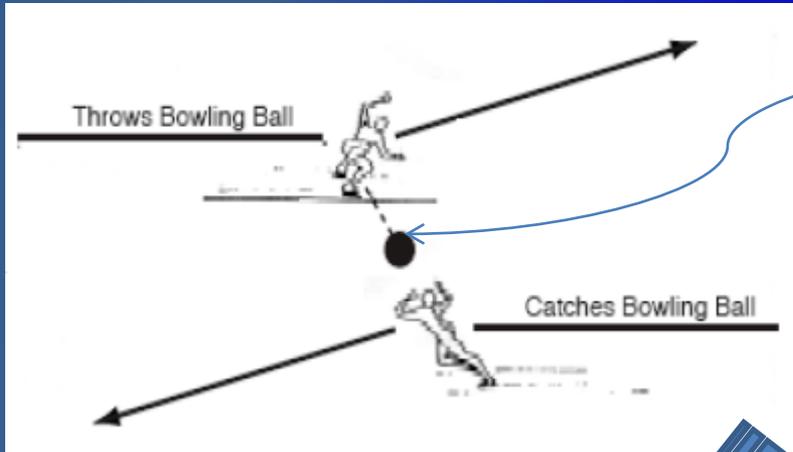
Particle world is described by quantum field theory

It is our main working tool for particles physics

It comes from the marriage between quantum mechanics and relativity

Feynman Diagrams: Forces as Interactions

All forces can be thought of as interactions between elementary particles

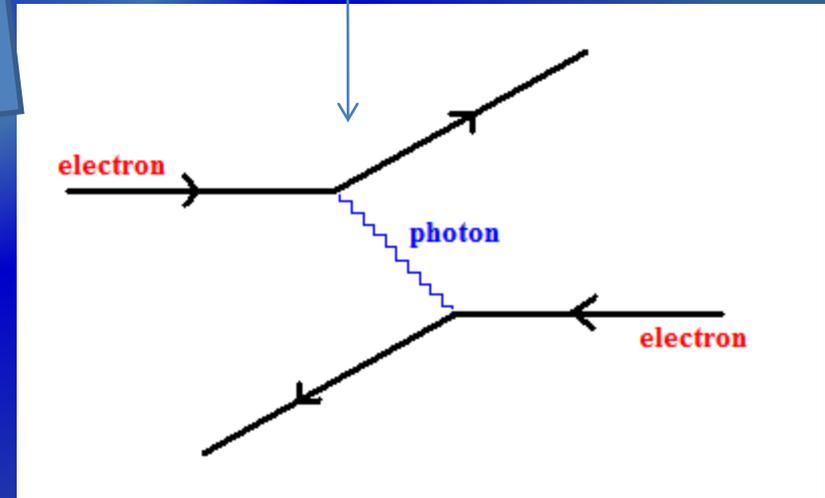


All forces are mediated by a force-carrying particle

- A Feynman diagram is a pictorial representation of a particular process (decay or scattering) at a particular order in perturbation theory.
- Feynman diagrams can be used to represent and calculate the probability amplitudes, \mathcal{M} , for scattering and decays.



Richard Feynman receiving the 1967 Noble prize in physics for his invention of this technique.

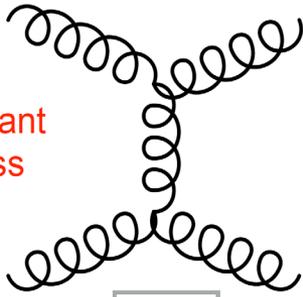


A Feynman Diagram for two electrons repelling each other

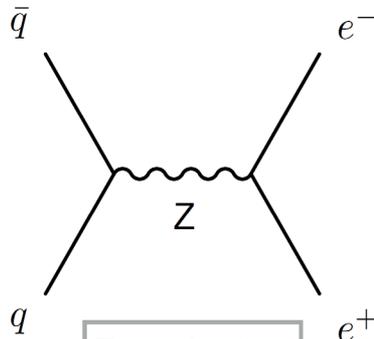
Feynman Diagrams Measured at LHC & Compared to Theory

Approximately ordered in decreasing reaction rate

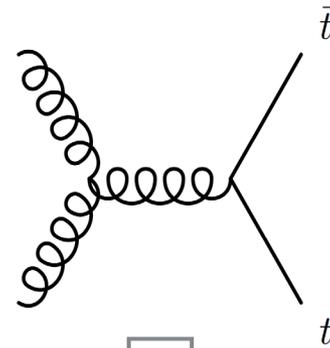
dominant process



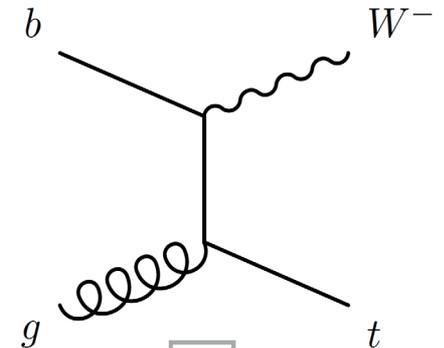
dijets



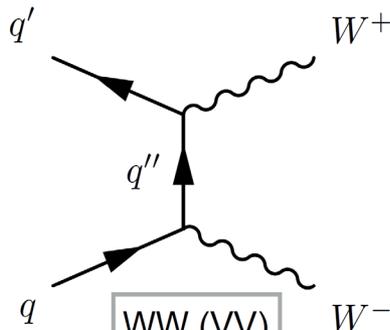
Z production



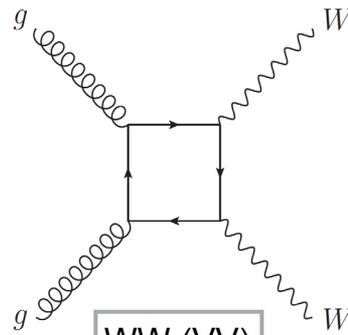
tt



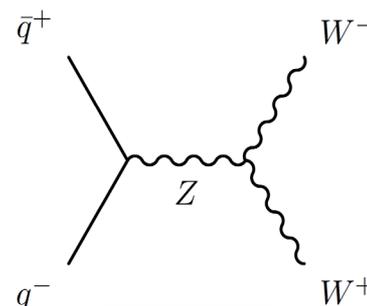
Wt



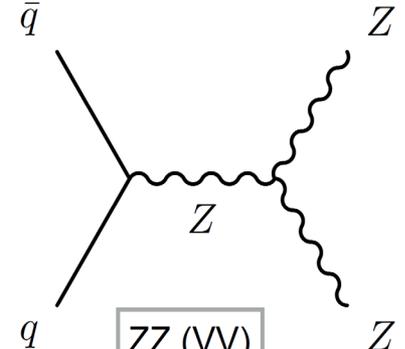
WW (VV)



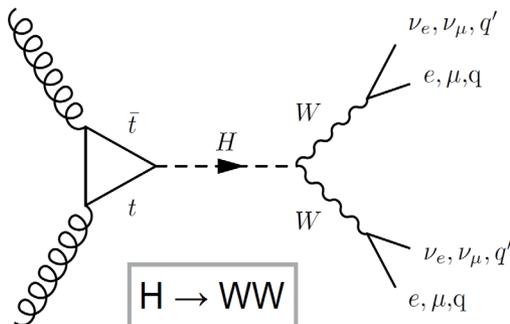
WW (VV)



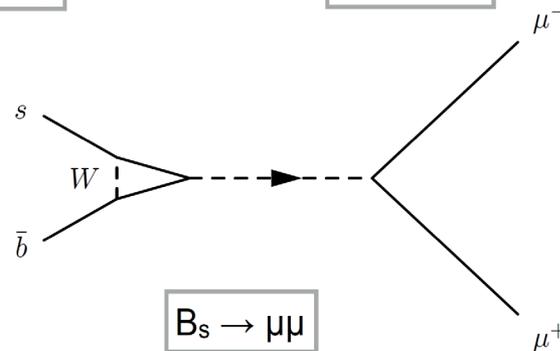
WW (VV)



ZZ (VV)



H to WW



Bs to mu mu

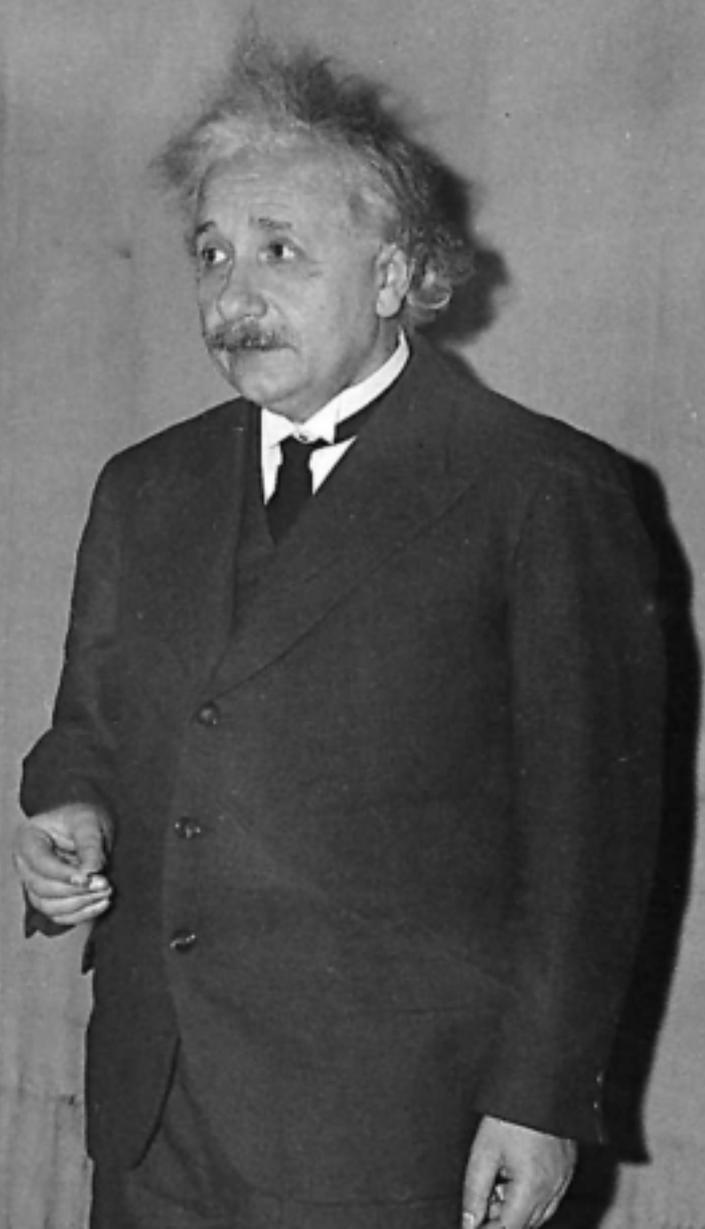
extremely rare

~~$E=mc^3$~~

We can create particles from energy

$E=mc^2$

~~$E=mc^7$~~

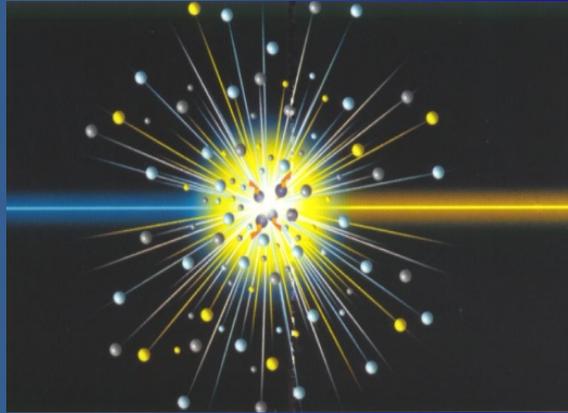


Tools of the Trade – Particle Accelerator

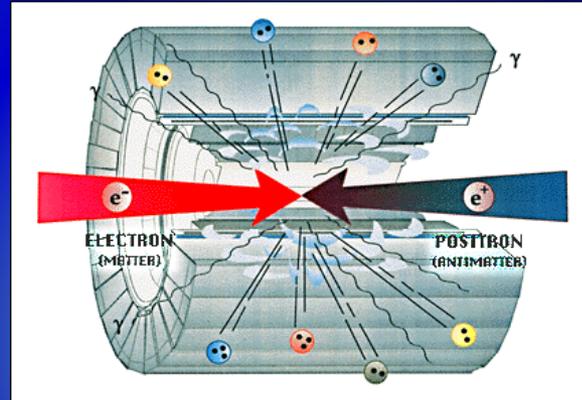
Collision of accelerated particles → “Grain” of energy → New Particles

High energies are needed to produce massive particles & look into smaller distances $E \sim 1/\lambda$

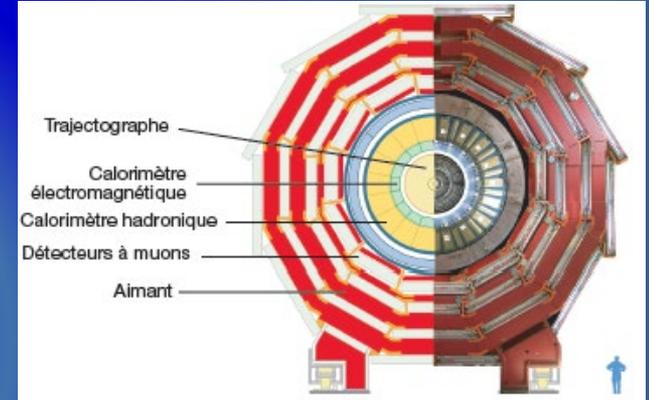
Accelerators



$$E = mc^2$$



Detectors



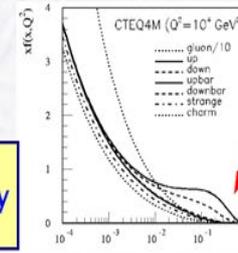
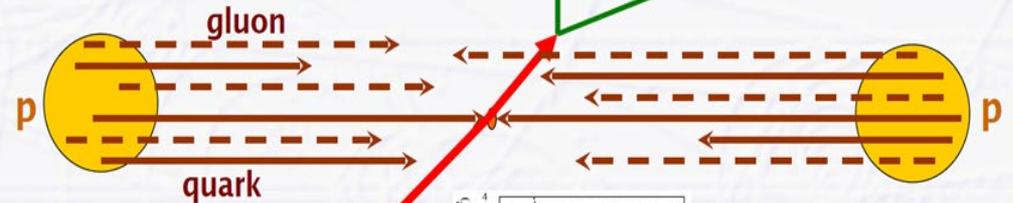
Power of resolution:

$$\lambda(m) = 1.24 \cdot 10^{-15} / P(\text{GeV}/c)$$

LHC (14TeV) → 9×10^{-17} m



Up to what mass new particles could be produced at LHC?



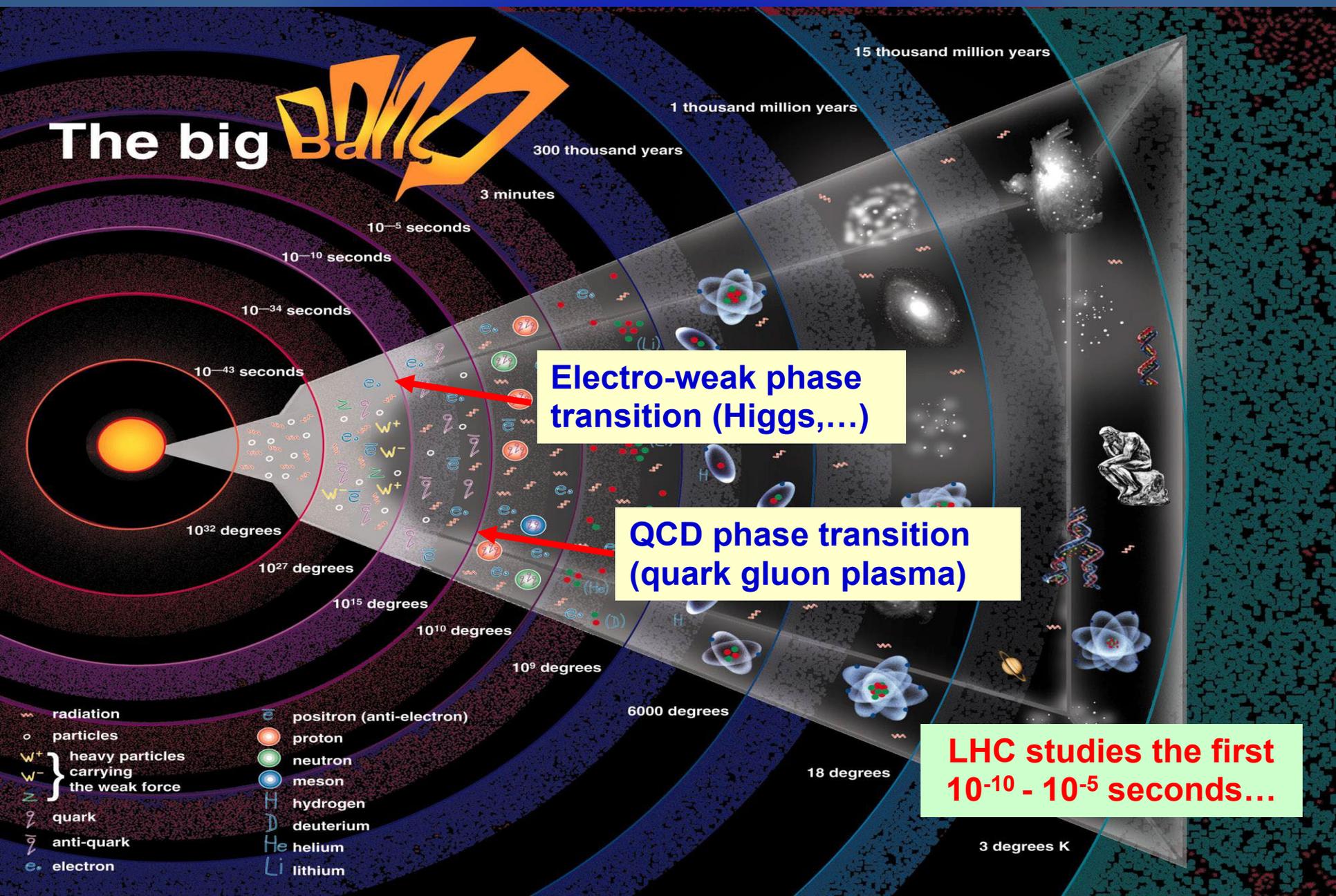
spectrum ends at $x \sim 0.35$

$$m_{\text{max}} = 0.35 \times 7 \text{ TeV (p)} \sim 2.5 \text{ TeV}$$

$$\sqrt{s}(\text{pp}) \sim 5 \times \sqrt{s}(\text{e}^+\text{e}^-, \text{ILC})$$

fraction x of proton momentum carried by partons

Brief History of Our Universe and Physics of LHC



13,7 billion years ago there were other things in the Universe – that we can “create” at the **Large Hadron Collider (LHC)** at **CERN**



Particles at LHC -
very small “objects”
of high energy –
are instruments to
go back in time



So we have built a Time Machine!

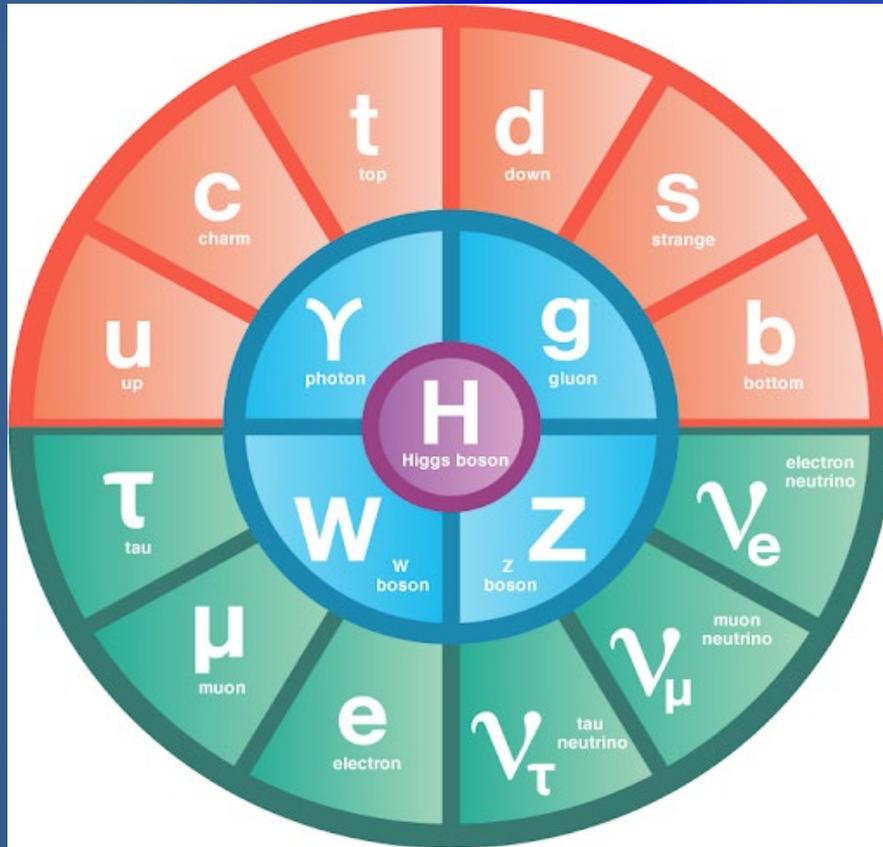
The Standard Model of Particle Physics

= Cosmic DNA

Some background and history

A Crowning Achievement of 20th Century Science

All our knowledge is today «codified» in **the Standard Model** :
Matter, Interaction, Unification Interaction, Unification



The new (final?) “Periodic Table” of fundamental elements

The Standard Model :

- ✓ **A quantum field theory:**
 $SU(3) \times SU(2) \times U(1)$
- ✓ Classify the matter particles in family (fermions)
- ✓ Explain the interactions through local gauge principle symmetry (bosons)
- ✓ Allow the particle to acquire masses through the Higgs mechanism
- ✓ **Without the Higgs, all particles are massless**
- ✓ **Without the Higgs, quantum corrections are infinite**
- ✓ **Has been tested with high precision at collider experiments**

Why do Things Weight ? ... The Massive Mystery

Newton ($F = ma$):

Weight proportional to Mass

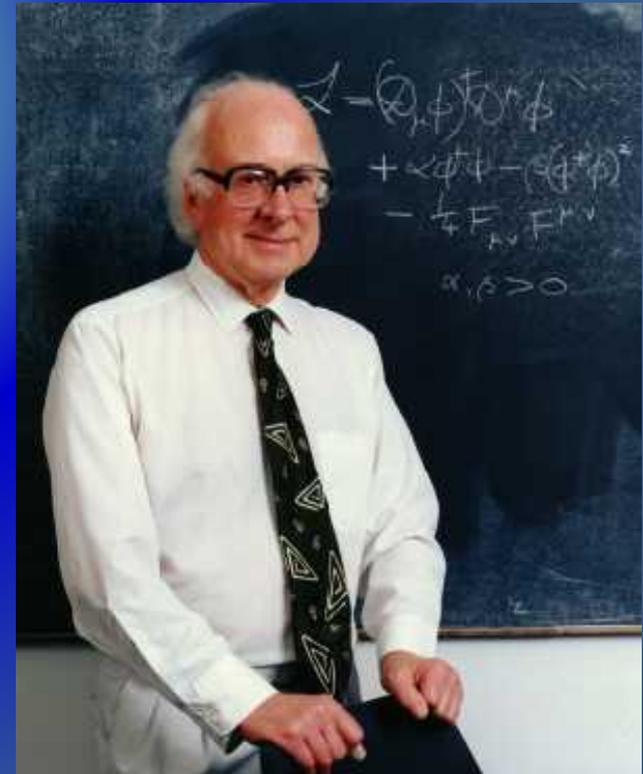
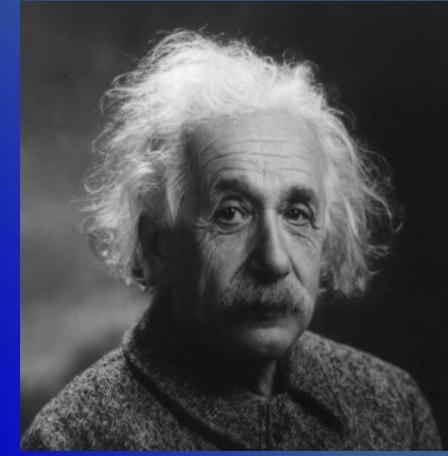
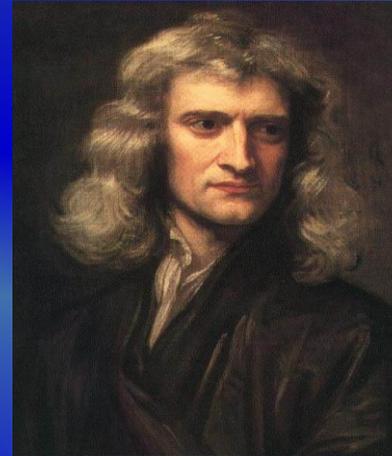
Einstein ($E=mc^2$):

Energy related to Mass

Mass curves space-time

Neither explained Origin of Mass

- ✓ Simplest theory – all particles are massless !!!
- ✓ **Where do the masses come from ?**
- ✓ Why do some fundamental particles have mass while others don't ?



**Are masses due to Higgs boson?
(the physicists' Holy Grail)**

The Seminal Papers – Higgs Particle Predicted in 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16

PHYSICAL REVIEW LETTERS

19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,[†] C. R. Hagen,[‡] and T. W. B. Kibble
Department of Physics, Imperial College, London, England

(Received 12 October 1964)

Why is Mass a (Theoretical) Problem ?

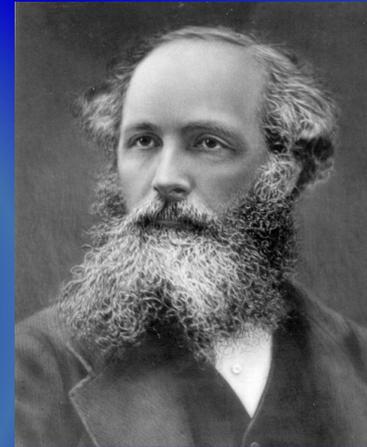
- Interactions of photon (A) unchanged if:

$$A \rightarrow A + (\textit{anything})$$

- Mass term for gauge boson

$$\frac{1}{2} M^2 A^2$$

- Violates *gauge invariance*
- So we understand why photon is massless



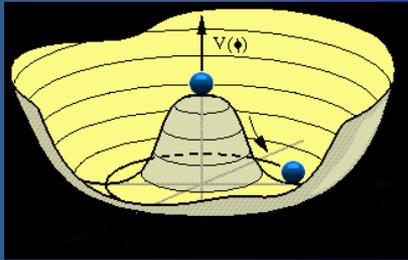
James
Maxwell,
1831---1879

The reason for inventing the Higgs is to explain mass

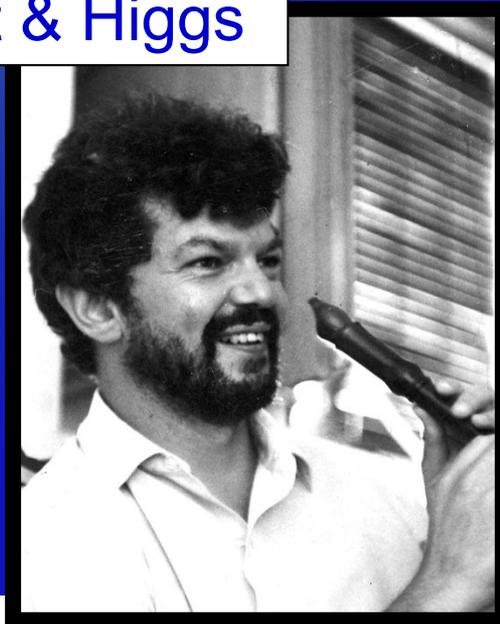
Higgs mechanism generates gauge invariant masses

The Englert – Brout – Higgs Mechanism

Englert, Brout & Higgs



Scalar field with at least one scalar particle



Guralnik, Hagen & Kibble

We consider, as our example, a theory which was partially solved by Englert and Brout,⁵ and bears some resemblance to the classical theory of Higgs.⁶ Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

$$\mathcal{L} = -\frac{1}{2}F^{\mu\nu}(\partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}) + \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \varphi^{\mu}\partial_{\mu}\varphi + \frac{1}{2}\varphi^{\mu}\varphi_{\mu} + ie_0\varphi^{\mu}q\varphi A_{\mu},$$

With no loss of generality, we can take $\eta_2 = 0$, and find

$$(-\partial^2 + \eta_1^2)\varphi_1 = 0,$$

$$-\partial^2\varphi_2 = 0,$$

$$(-\partial^2 + \eta_1^2)A_k^T = 0,$$

where the superscript T denotes the transverse part. The two degrees of freedom of A_k^T combine with φ_1 to form the three components of a

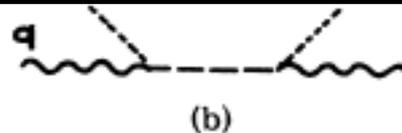
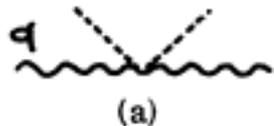
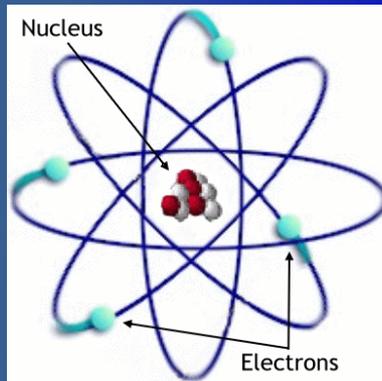


FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_{μ} propagator. (a) $\rightarrow (2\pi)^4 ie^2 g_{\mu\nu} \langle\varphi_1\rangle^2$, (b) $\rightarrow -(2\pi)^4 ie^2 (q_{\mu}q_{\nu}/q^2) \times \langle\varphi_1\rangle^2$.

The Higgs Boson was invented to explain why: the W and Z boson (and other ELEMENTARY PARTICLES) are heavy (gauge invariant way to give mass), while gluon and photon stays massless

If there were no Higgs Boson

- Higgs boson explains why electron has mass
- Radius of nuclei depend on electron mass



Radius is proportional to $1 / \text{mass (electron)}$

... there would be **no atoms**

→ massless electrons would escape at the speed of light

... there would be **no heavy nuclei**

... weak interactions would not be weak

→ **Life would be impossible**: everything would be radioactive

It's existence is a big deal!

So ... How do you get mass ?

THE HIGGS MECHANISM

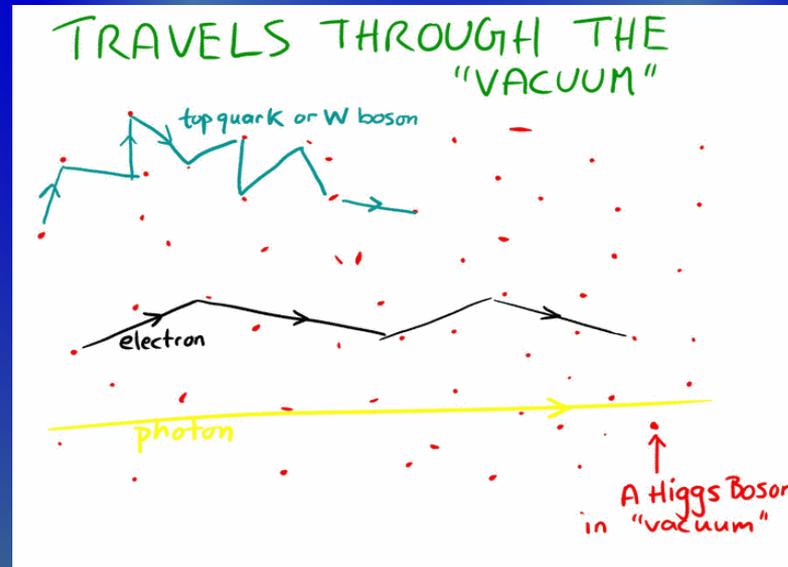
1) To understand the Higgs mechanism, imagine that a room full of physicists quietly chattering is like space filled only with the Higgs field....

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

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

4) if a rumour crosses the room ...

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



Higgs particle interacts with particles, thus slowing them down. This results in energy converted into mass.

THE HIGGS MECHANISM ... IN ACTION ...

- **H** boson is an excitation of the H field.
- **H** field - not **H** boson - creates particle masses.



- **H** field is responsible for masses of all elementary particles, atoms, chemistry - and life.
- **H** field is not responsible for most of our mass (proton mass comes from gluon interactions) & mass in universe
- **H** is not gravity!

The quantum theory predicts that the field has an associated quantum / particle:



H

The Higgs Boson!

We can create the Higgs boson in LHC experiments !
Finding the Higgs Boson would establish the
existence of this field!

Higgs Hunting Over the Years

30 Years of Experiments:

Accelerator	type, laboratory	energy \sqrt{s}	years of operation
LEP-I	e^+e^- collider, CERN	91 GeV	1989 - 1994
LEP-II	e^+e^- collider, CERN	209 GeV	1995 - 2000
HERA-I	ep collider, DESY	27 + 800 GeV	1992 - 2000
HERA-II	ep collider, DESY	27 + 920 GeV	2002 - 2007
TeVatron Run I	ppbar collider, Fermilab	1.8 TeV	1987 - 1996
TeVatron Run II	ppbar collider, Fermilab	1.96 TeV	2002 - 2011
LHC, phase I	pp collider, CERN	7 TeV	2010- 2012
LHC, phase II	pp collider, CERN	14 TeV	2014-

> 2010: a New Era in Fundamental Science

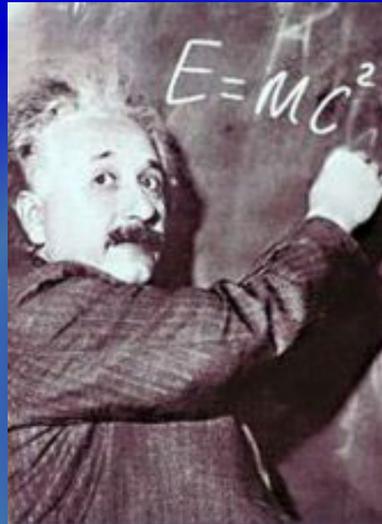
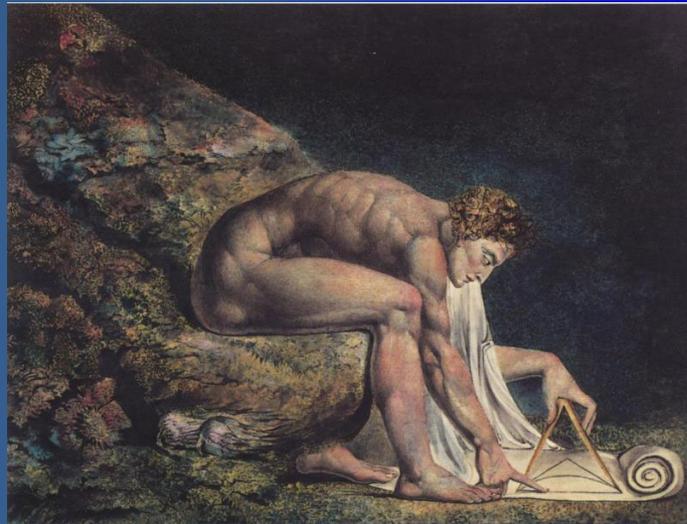


Exploration of a New Energy Frontier Large Hadron Collider (LHC)



CERN: Push forward the frontiers of knowledge.....

Seeking answers to questions about the Early Universe:



“Newton’s unfinished business”... **what is mass?**

Science’s little embarrassment... **what is 96% of the Universe made of?**

Nature’s favouritism... **why is there no more antimatter?**

The secrets of the Big Bang... **what was matter like within the first moments of the Universe’s life?**

Marvel of Technology – the world's fastest racetrack – LHC

Protons are accelerated around circular orbits by electric fields (superconducting RF cavities) → 1232 superconducting magnets, each 15 m long, operating at 8.3 T (200'000 x Earth's magnetic field) and 1.9K (-271°C) in superfluid helium.



Energy stored in LHC magnets:

1 dipole magnet $E_{\text{stored}} = 7 \text{ MJ}$
All magnets $E_{\text{stored}} = 10.4 \text{ GJ}$

The kinetic energy of an A380 at 700 km/hour



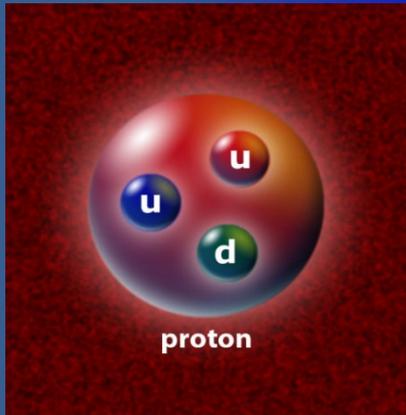
Energy stored in LHC beams

- Kinetic energy of 1 proton bunch:
 - $E_1 = (1.15 \times 10^{11} \text{ protons}) \times 7 \text{ TeV} = 129 \text{ kJ}$
- Kinetic energy of beam = 2808 bunches:
 - $E_{\text{beam}} = k \times E_1 = 2808 \times E_1 = 362 \text{ MJ}$

Enough to melt 5.6 tons of gold

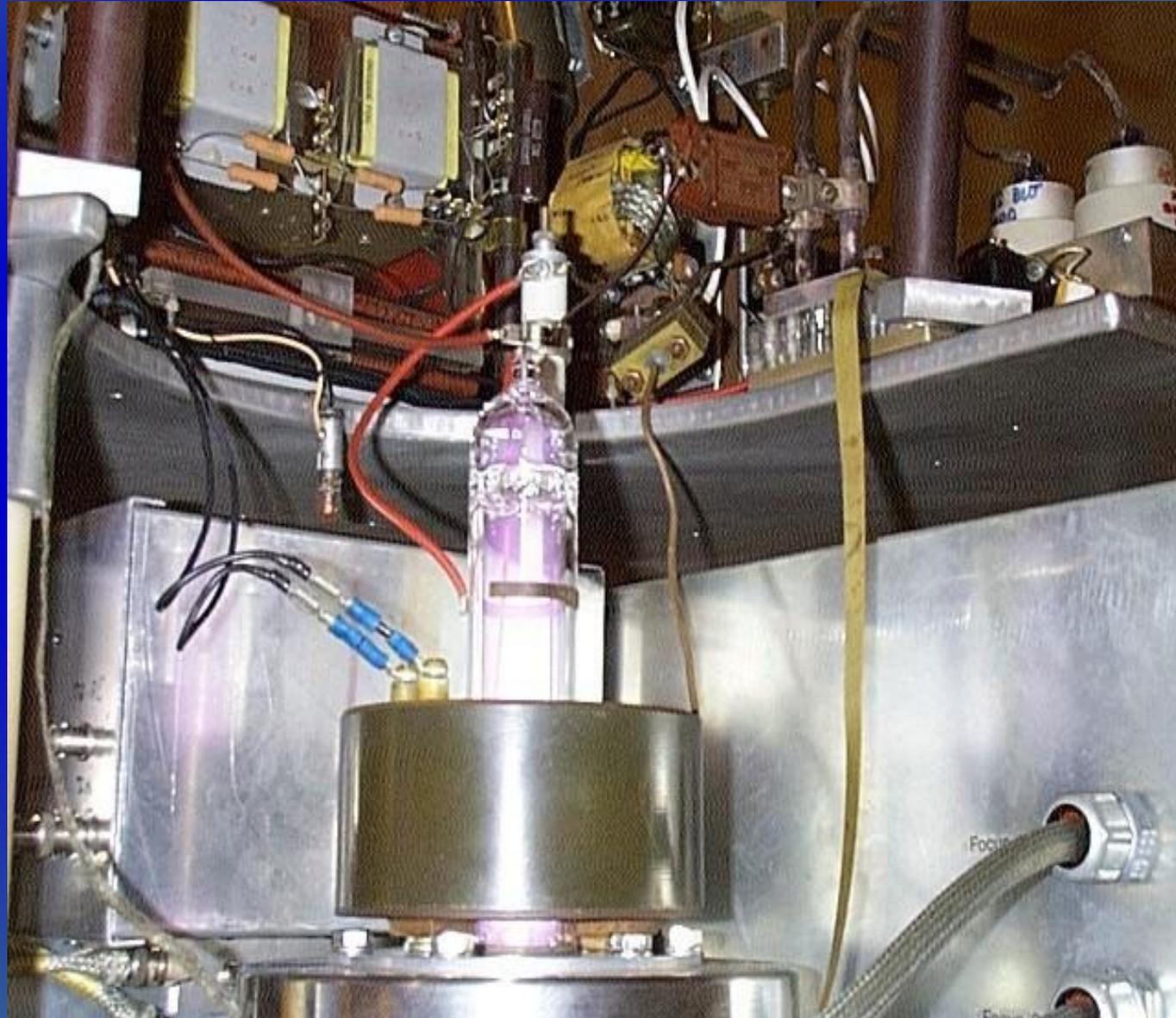
In the beginning ...

there is a single
bottle of hydrogen
gas

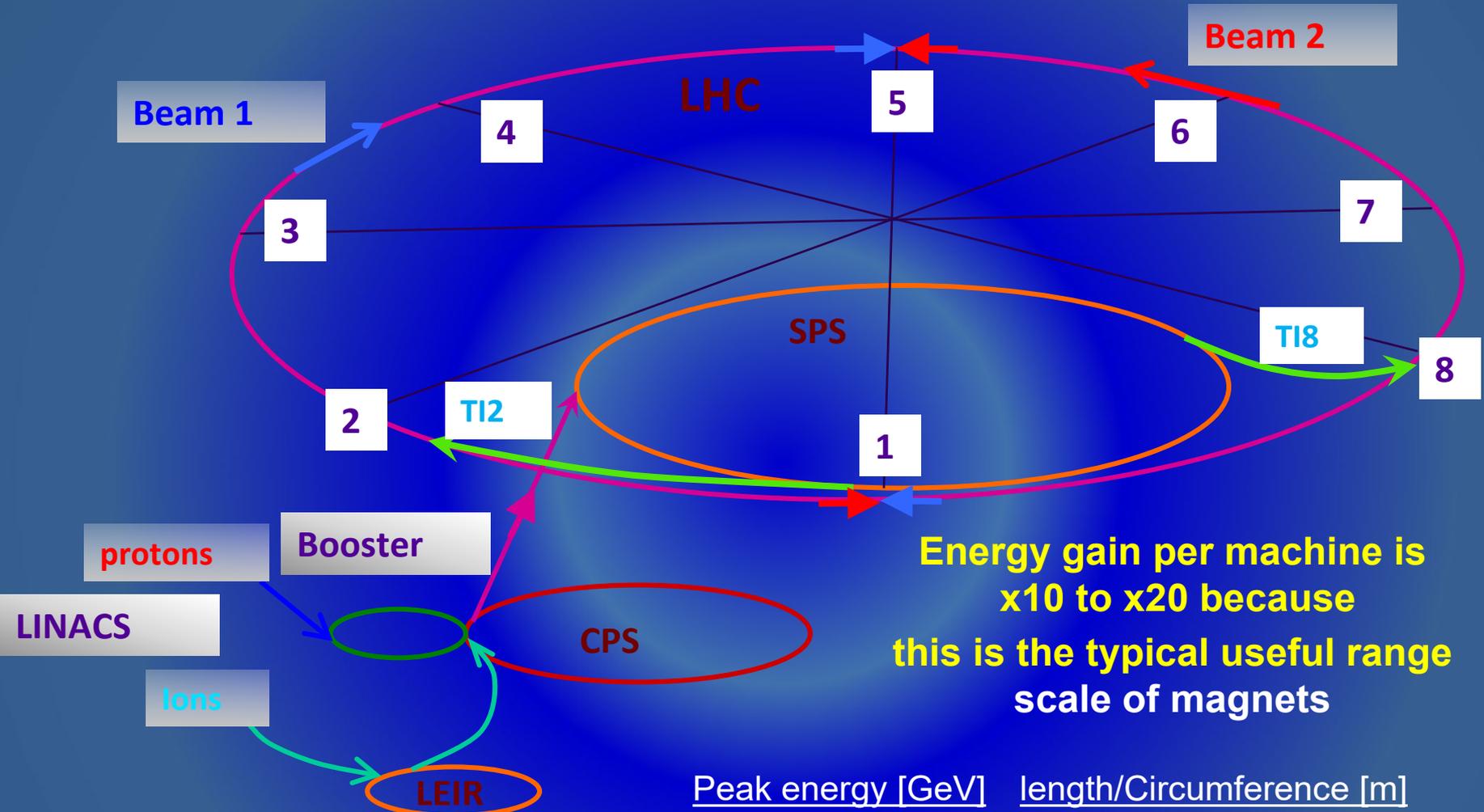


from which
protons (p^+)
are extracted

and accelerated
to ALMOST the
speed of light (c)...



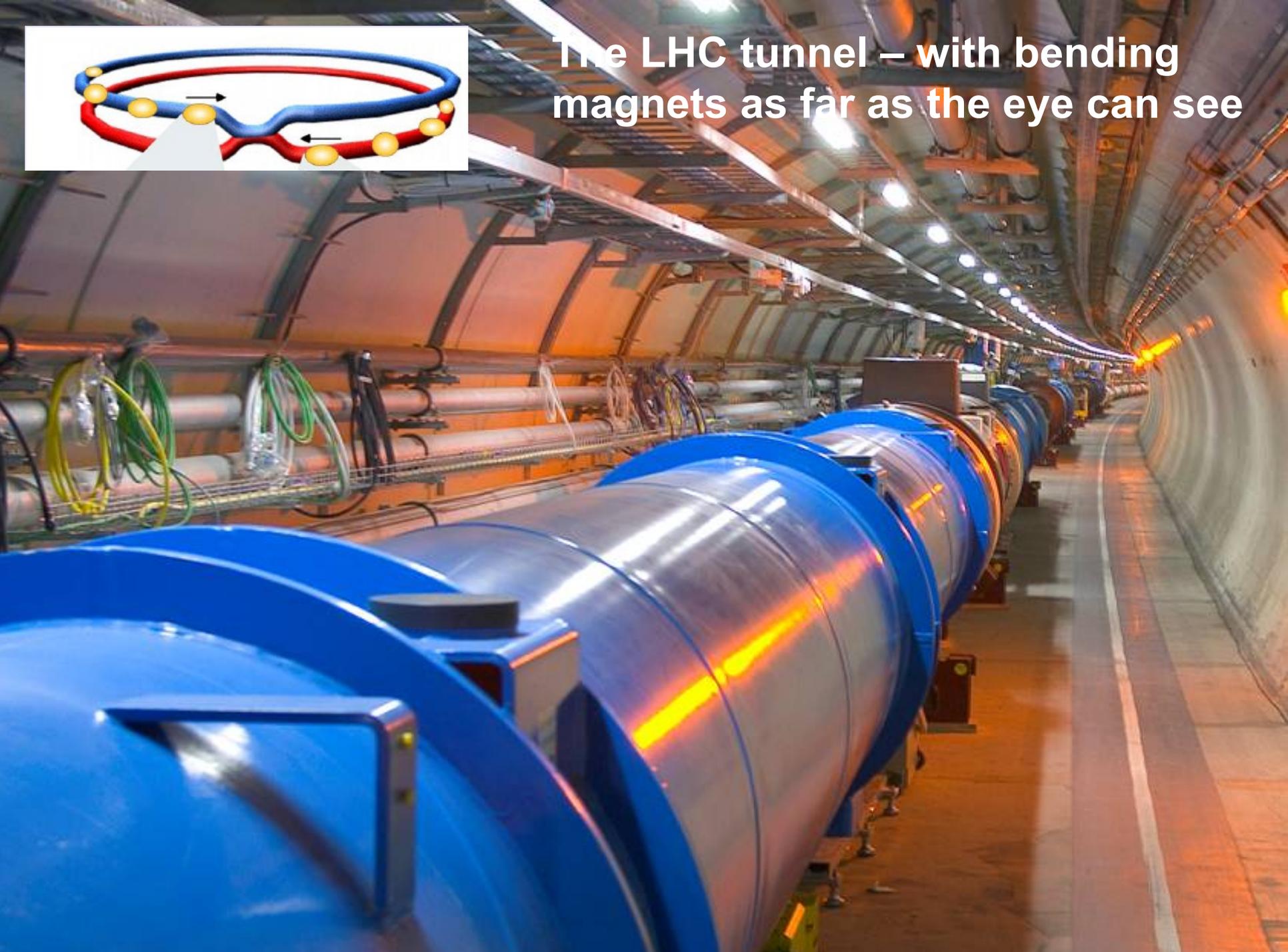
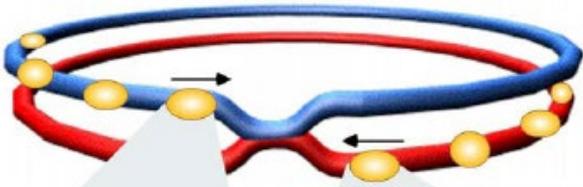
The LHC injector complex



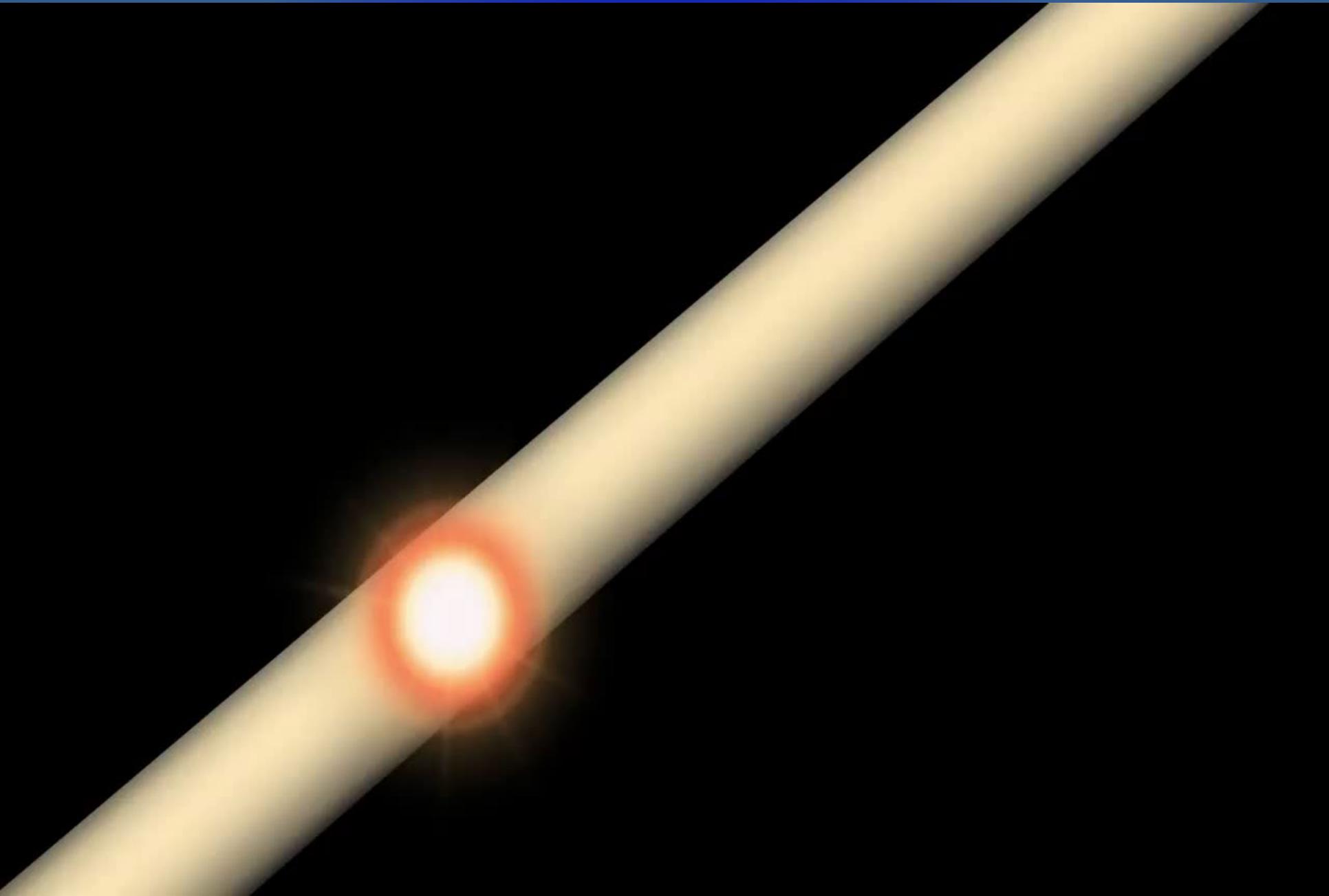
Energy gain per machine is
x10 to x20 because
this is the typical useful range
scale of magnets

	Peak energy [GeV]	length/Circumference [m]
Linac	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

The LHC tunnel – with bending magnets as far as the eye can see



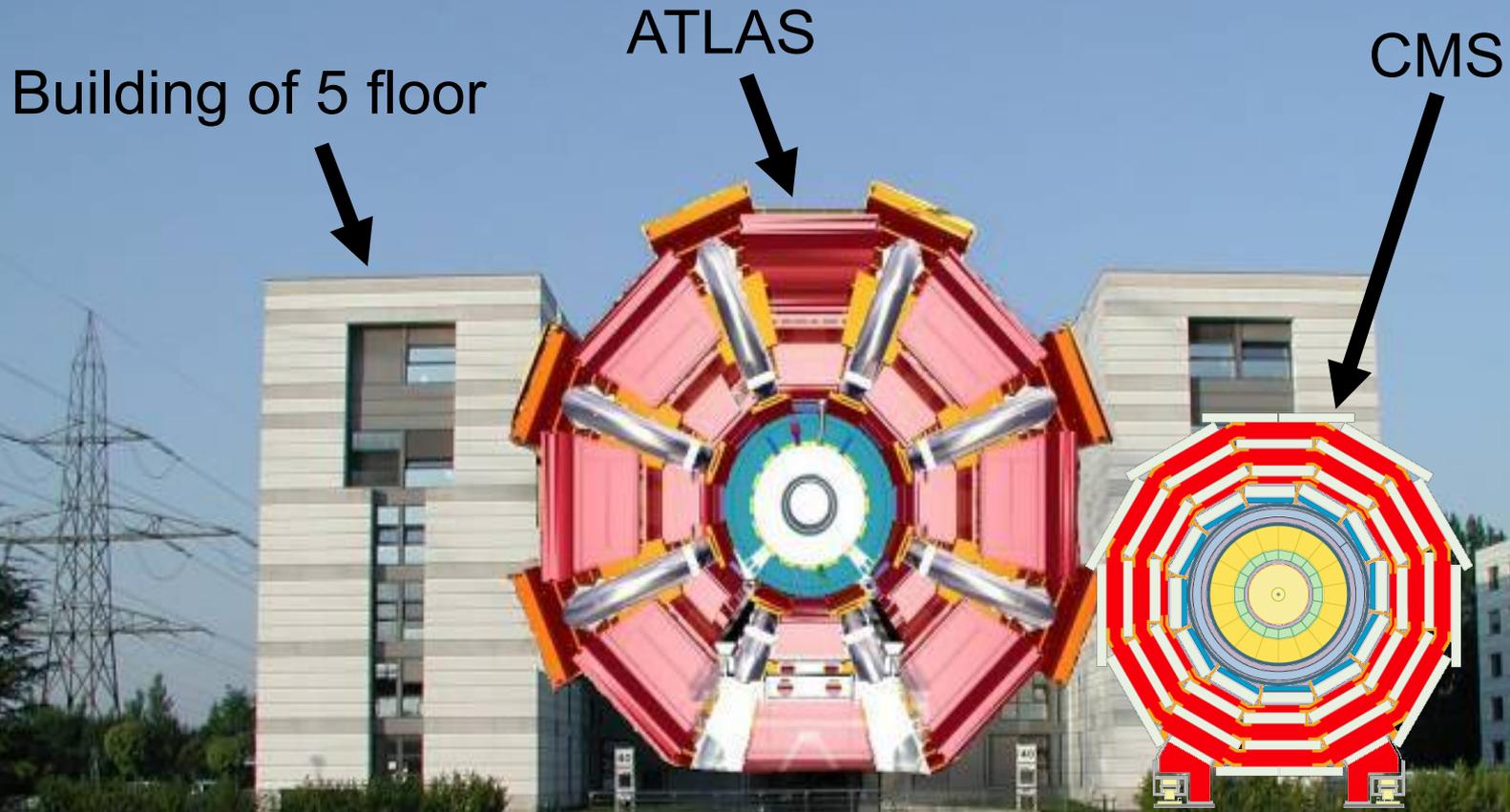
CERN Accelerator Complex



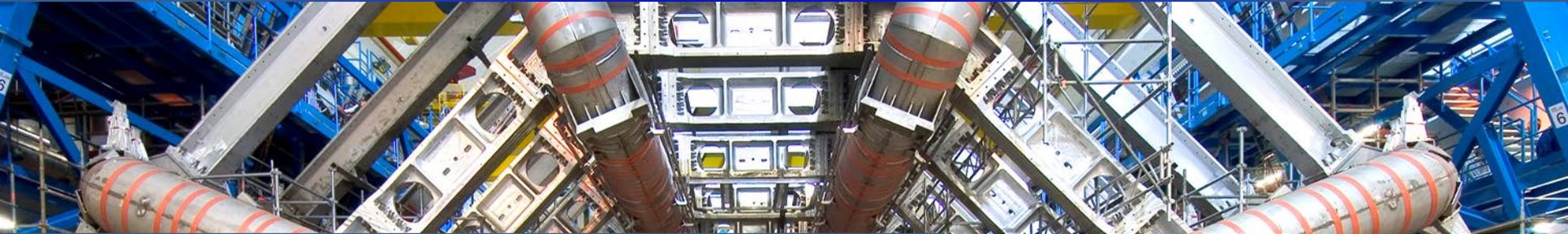
and its all done within view of
spectacular Mont Blanc!



ATLAS and CMS Experiments: Two Giants



The LHC Spectrometers: the largest and most complex “microscopes” we’ve ever built

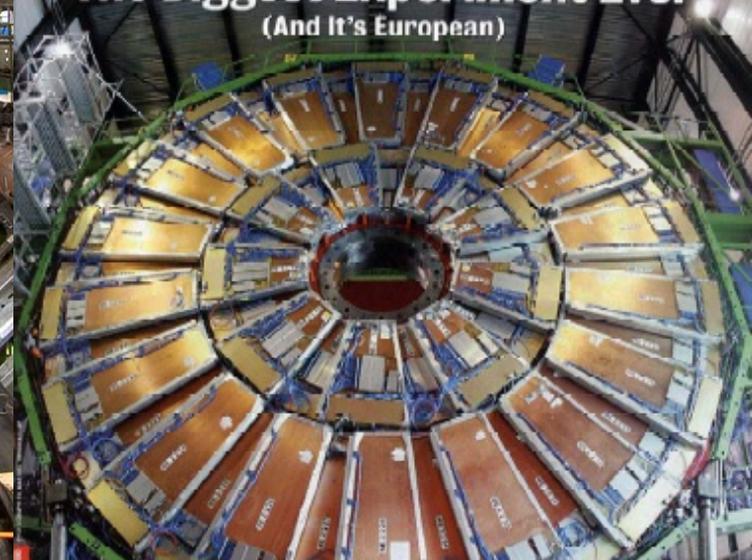


The opera *Les Troyens* by Berlioz, as shown in Valencia, St. Peterburg and Warsaw (2011) used a set design based on ATLAS Detector



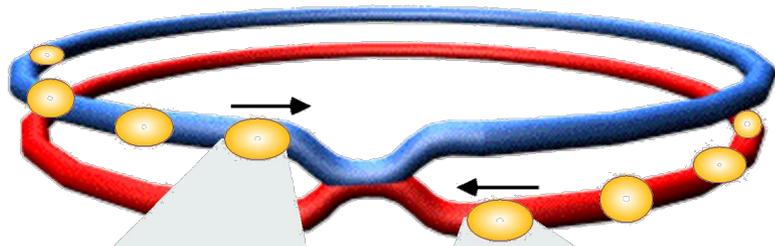
Newsweek

The Biggest Experiment Ever
(And It's European)



**The “Gothic Cathedrals”
of the 21st Century**

LHC Versatility: What is in this Data ?



Bunch

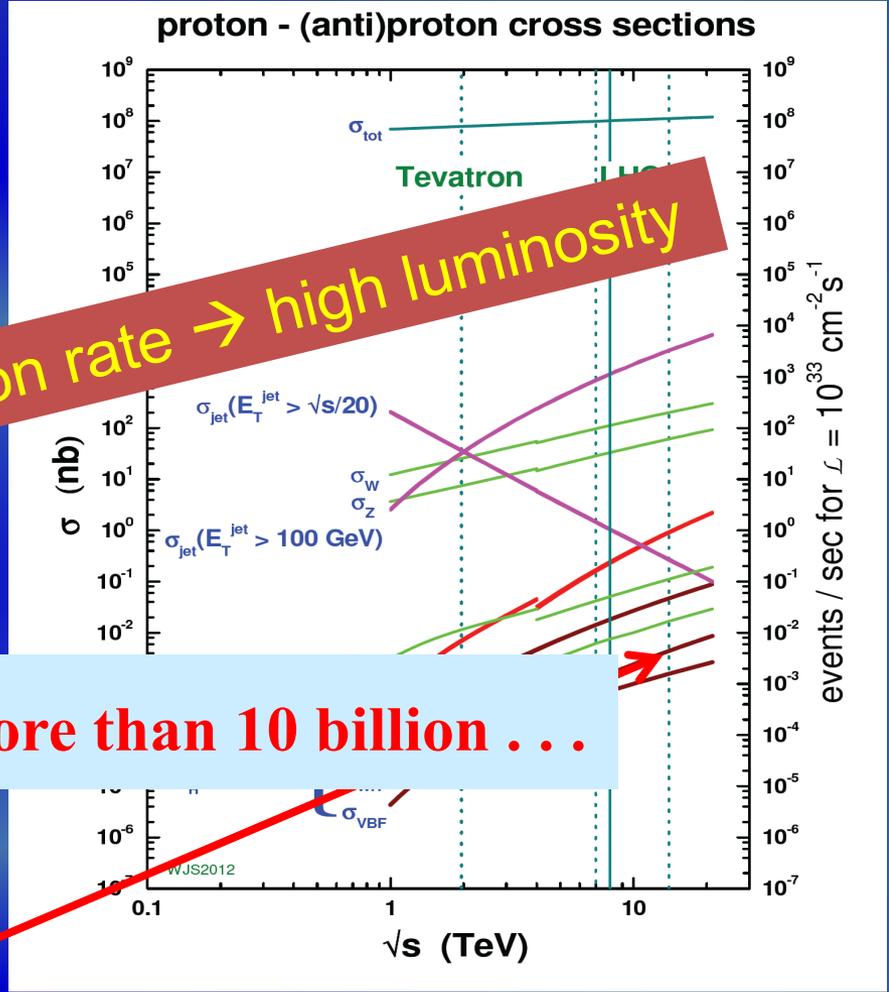
Need high statistics \rightarrow high collision rate \rightarrow high luminosity

Parton
(quark, gluon)

select 1 out of much more than 10 billion ...

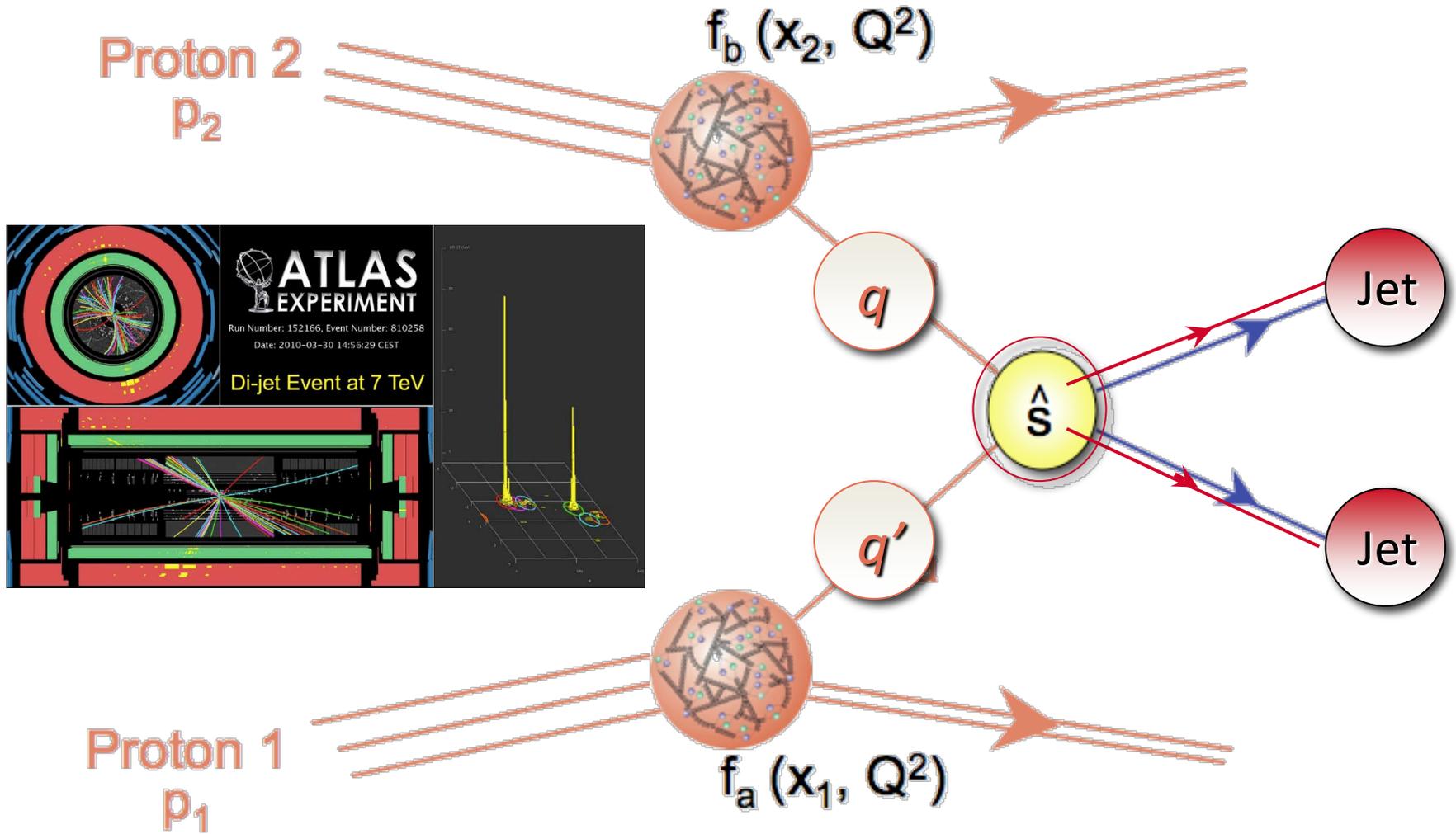
Both ATLAS and CMS have seen already:

Particle	# produced
H boson	\approx 8 million
t quark	\approx 280million
Z boson	\approx 8 billion
W boson	\approx 26 billion
b quark	\approx 160 trillion

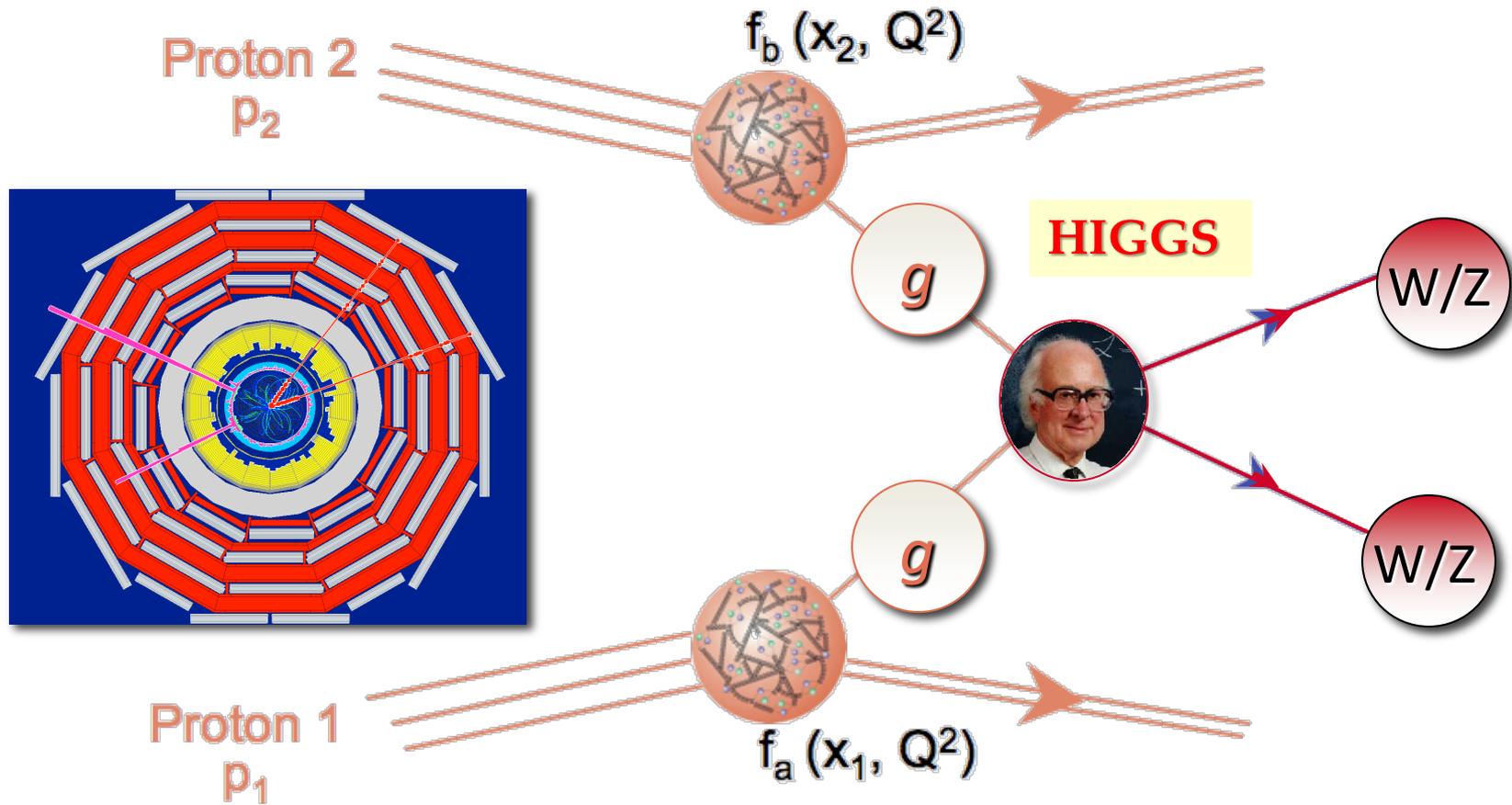


The LHC is an "EVERYTHING" factory (with additional background collisions)

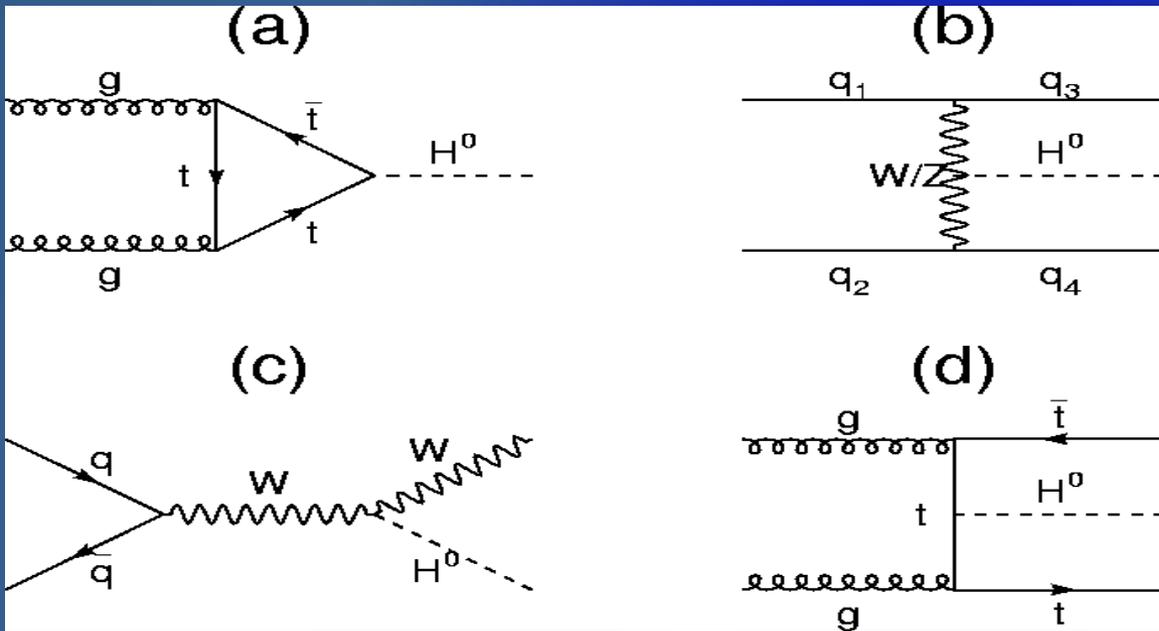
Basic (Di-Jet Production) Processes at the LHC



Higgs Production at the LHC



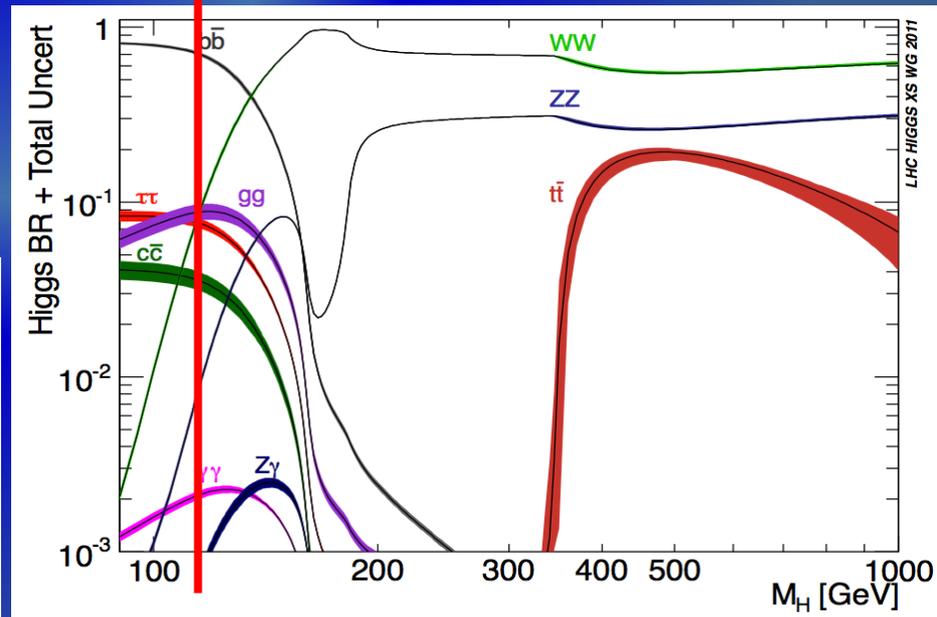
Higgs Production and Decay at the LHC



- Feynman diagrams:**
- Gluon fusion
 - Vector boson fusion
 - Assoc prod with W
 - Assoc prod with top

Higgs Decays @ 125 GeV:
Dream case for experimentalists
→ fun to measure them all !

- bb : large BR, Yukawa coupling
- $\tau\tau$: Yukawa coupling
- WW : large BR, gauge boson coupling
- ZZ : high S/B, high mass resolution, gauge boson coupling
- $\gamma\gamma$: high mass resolution, loop coupling



Higgs Discovery by Bump Hunting (Resonances)

Focus on high mass resolution & most sensitive channels

To start look for:

$$pp \rightarrow Higgs \rightarrow \gamma\gamma$$

$$pp \rightarrow Higgs \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$$

$$p + p \rightarrow H X \rightarrow Z^0 Z^{0*} X \rightarrow e^+ e^- \mu^+ \mu^- X$$

Compute (from the measured kinematics) :

$$m_H^2 = (E_{Z^0} + E_{Z^{0*}})^2 - (\vec{p}_{Z^0} + \vec{p}_{Z^{0*}})^2$$

Also for each Z^0 compute (e.g. for $Z^0 \rightarrow \mu^+ \mu^-$) :

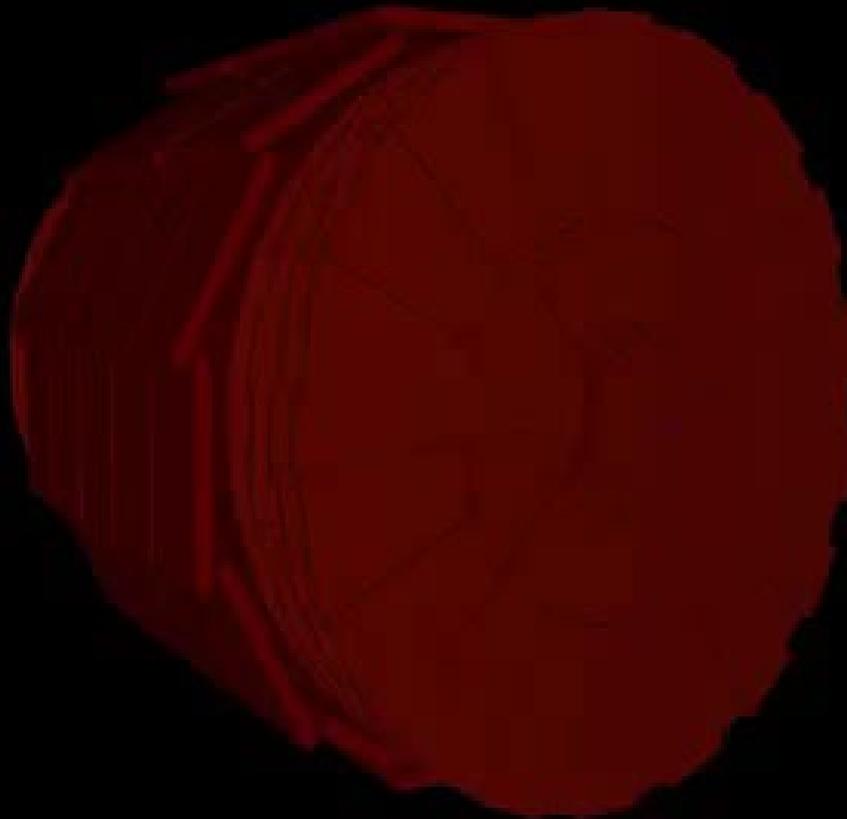
$$m_{Z^0}^2 = (E_{\mu^+} + E_{\mu^-})^2 - (\vec{p}_{\mu^+} + \vec{p}_{\mu^-})^2$$

The same for the other Higgs decay mode : $H \rightarrow \gamma\gamma$

In all cases we have to reconstruct tracks (EM clusters for photons) and measure momenta, energies and identify particles (charge and mass hypothesis).

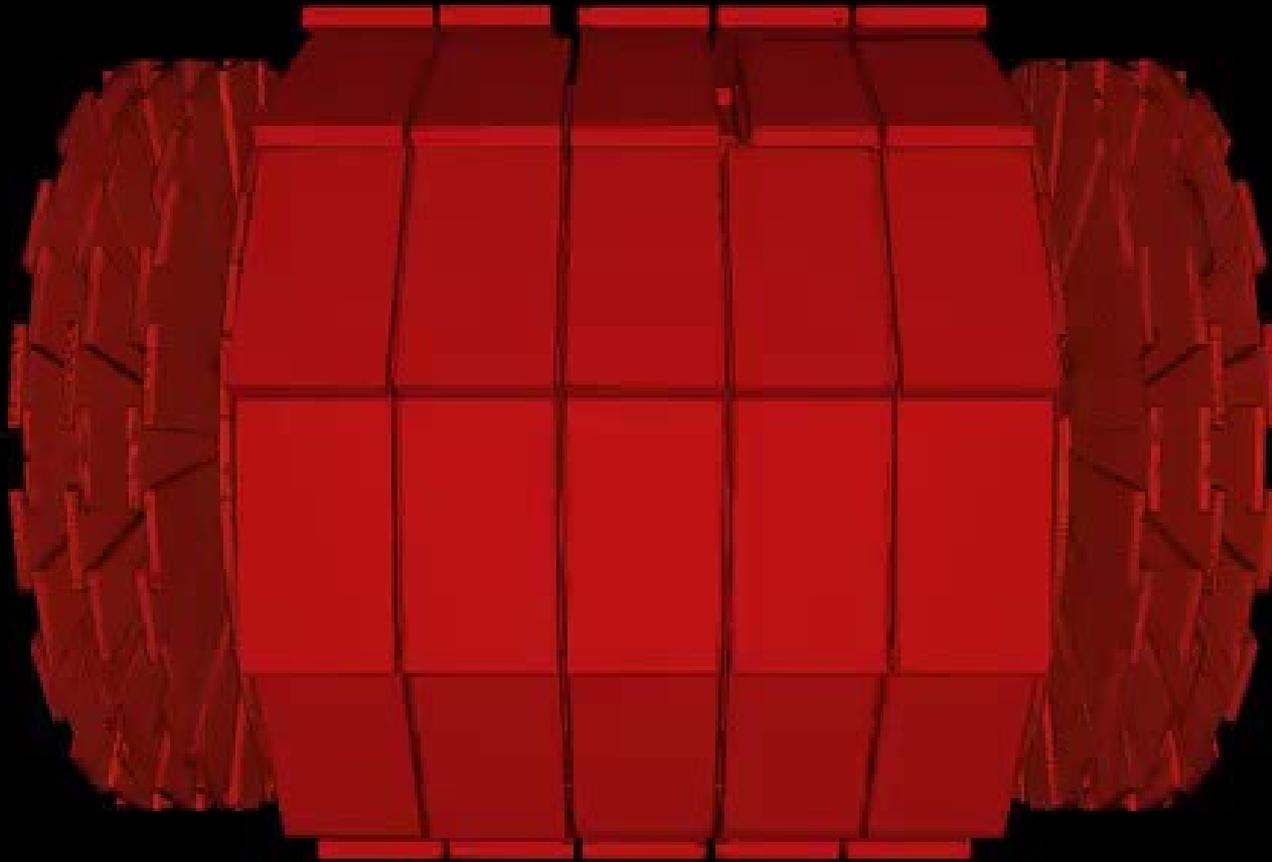
This is what a reconstructed $H \rightarrow \gamma\gamma$ Looks Like

CMS Experiment at the LHC, CMS
Sat 2012-11-09 22:14 CEST
Run 19459 Event 11194210
Collision Energy 7 TeV
H-Gamma Gamma candidate



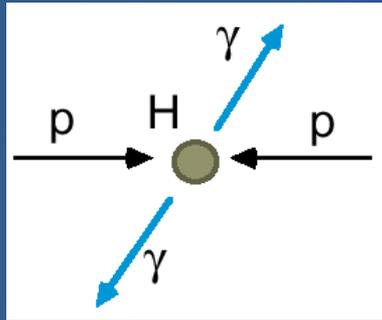
This is what a reconstructed $H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$ looks like

CMS Experiment at the LHC, CERN
Sun 2011-Aug-07 00:00:32 CET
Run 172822 Event 2554330033
C.O.M. Energy 7.00TeV
H \rightarrow ZZ \rightarrow 4mu candidate

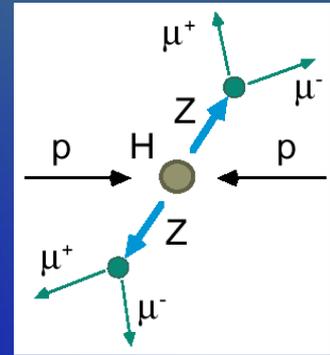


The Birth of a Higgs Particle – Evolution in Time

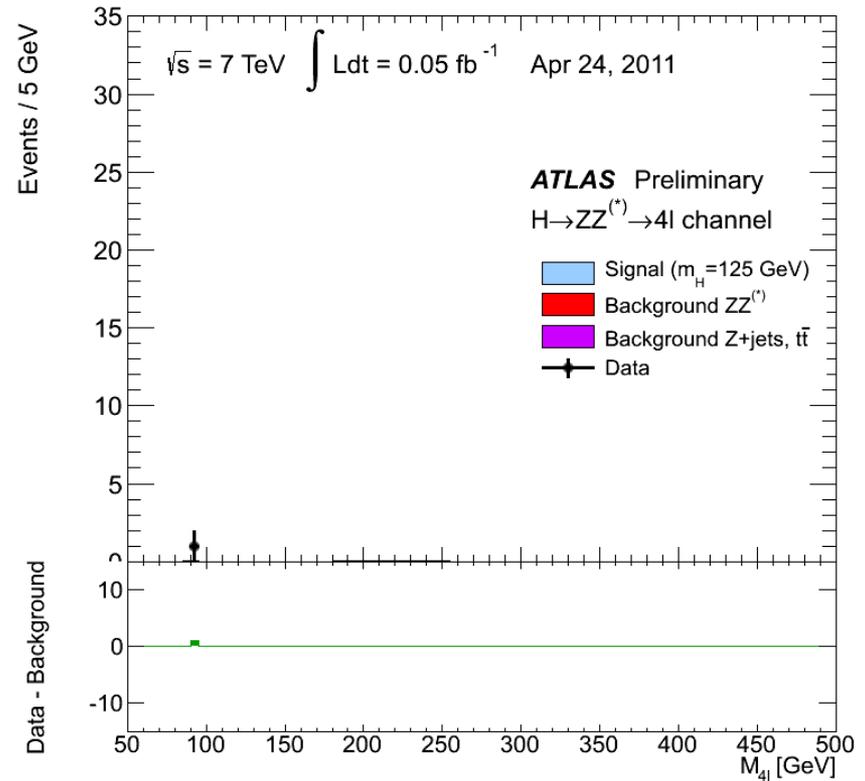
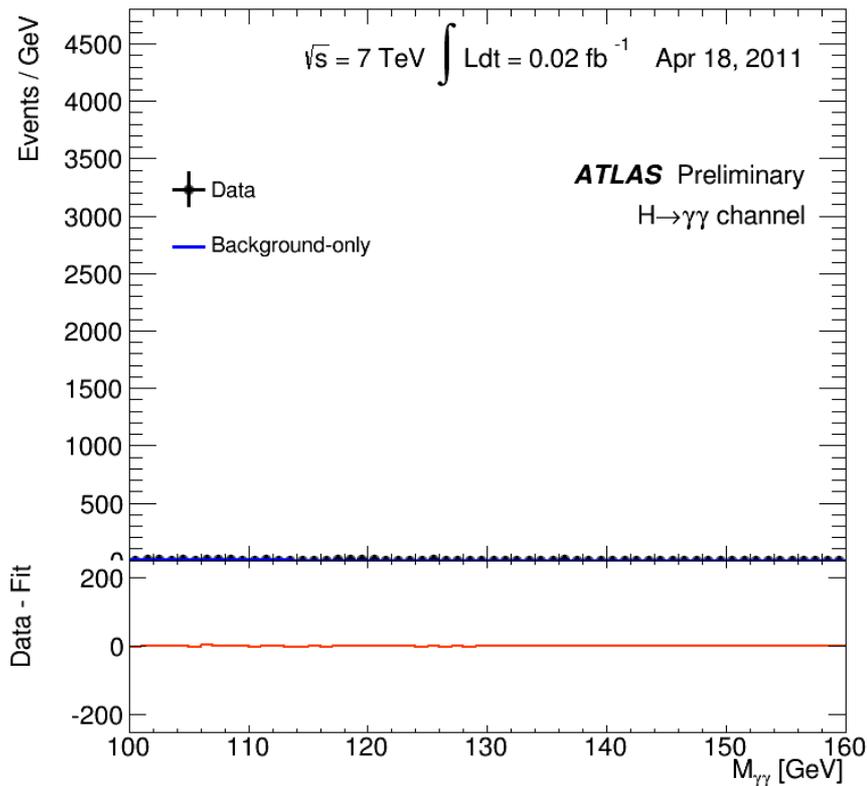
“History” of the data accumulation in 2011-2012:
bumps in the invariant mass signify a new particle,
found in two different ways (decay channels), at the
same mass – about $125 \text{ GeV}/c^2$



$$H \rightarrow \gamma\gamma$$



$$H \rightarrow ZZ$$



July 4, 2012 @ CERN:

“So, We have it – It is a Discovery”

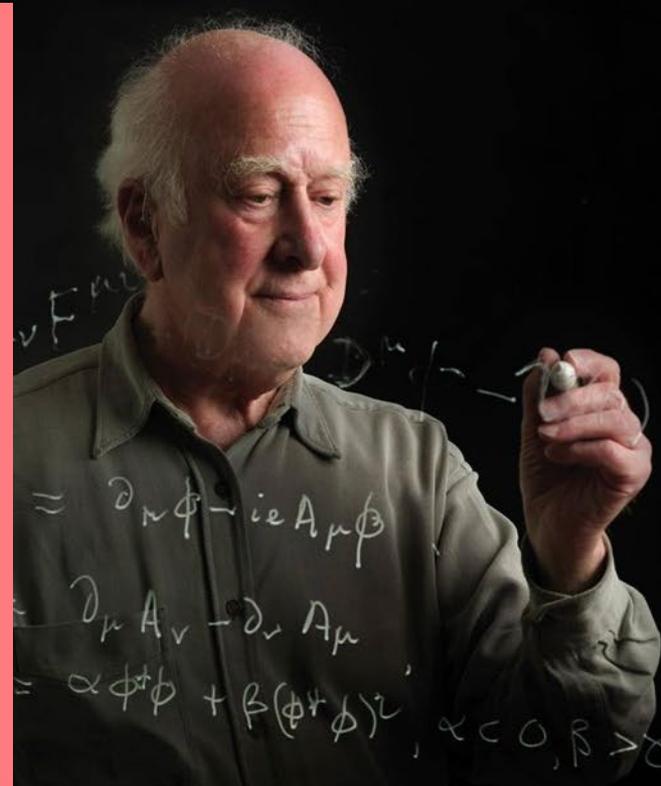
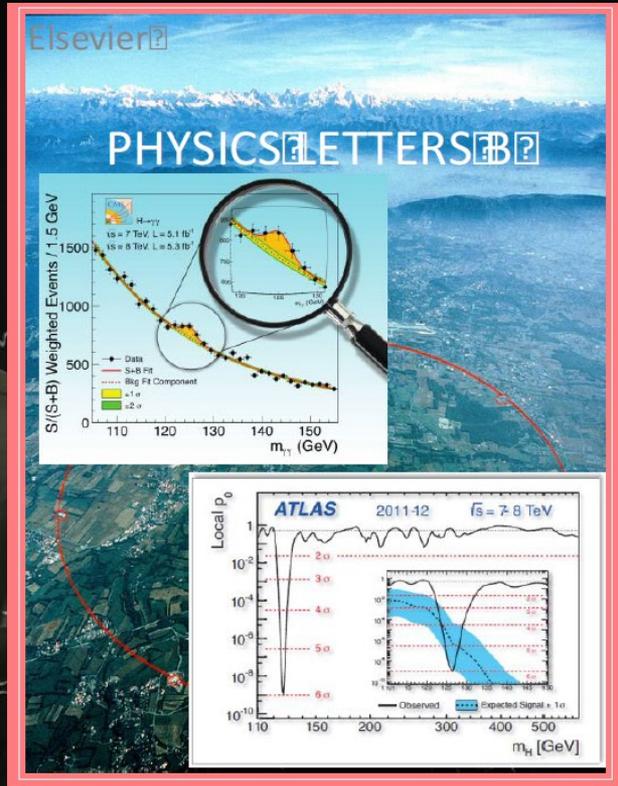
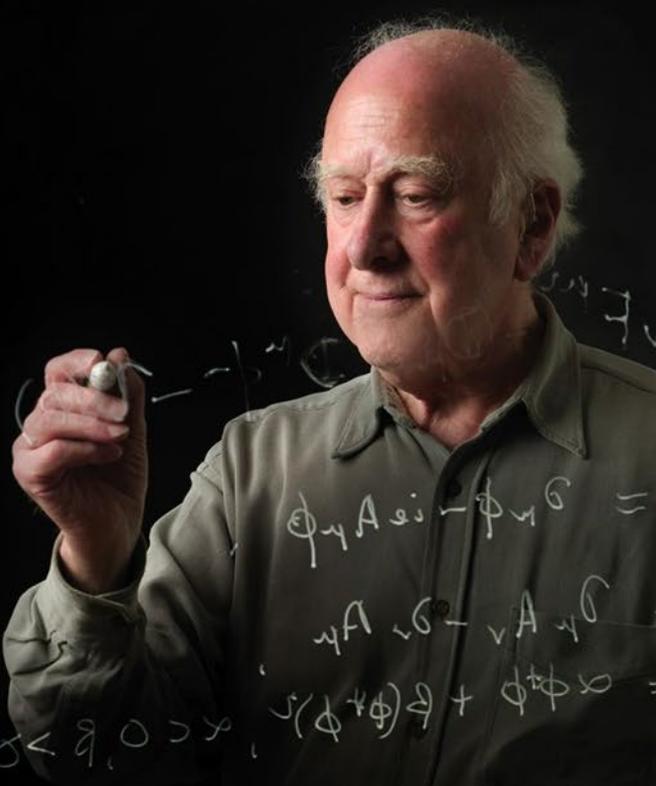
(Rolf-Dieter Heuer, CERN Director General)



Both ATLAS and CMS Collaborations have reported **observation of a narrow resonance ~ 125 GeV** consistent with long-sought **Higgs boson**

What did we know on that day: it is most probably “**A HIGGS BOSON**”
→ **had to establish** if it is “**THE HIGGS BOSON**” of the Standard Model

Most cited LHC papers so far... (> 12500 times)



The Higgs Boson: a landmark discovery

1964 - 2012 ...

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)



Special Physics Letters B edition with
ATLAS and CMS CMS papers
on the **Higgs Discovery**

About 50 years and Billion(s) of Dollars – The “God Particle” is no Longer a Theory

The New York Times
Wednesday, July 4, 2012 Last Update: 4:00 AM ET

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WORLD U.S. POLITICS NEW YORK BUSINESS DEALBOOK TECHNOLOGY SPORTS SCIENCE HEALTH ARTS STYLE OPINION

Rapid H.I.V. Home Test Wins Federal Approval
By DONALD G. MANEL, JR.
The OraQuick test, which uses a cheek swab and gives results in 20 to 40 minutes, is the first chance for Americans to learn in the privacy of their own homes whether they are infected.

As Bank Frames a Defense, Barclays' C.E.O. Resigns
By BEN PROFFER and MARK SCOTT
Ahead of a British parliamentary hearing, senior Barclays executives said they thought they had implicit approval from regulators to manipulate interest rates.

Fears of Fires Take Fireworks Out of July 4th Celebrations
By DAN FROSCH
Many U.S. cities and towns across the country have decided to scrap their annual display after claimed fireworks were said to be defective.

As Symbols Clash, Fireworks Lose Out to a Hamlet's Bald Eagles
By AARON EDWARDS
The Fire Department in Narrowsburg, N.Y., canceled its annual display after claimed fireworks were said to be defective.

Top Judge Helped Defeat Obama's Allies
By JEFFREY M. HANAUER

Higgs within reach
Our understanding of the universe is about to change...

The ATLAS and CMS experiments at CERN The experiments found hints of the new particle

Le Monde
Le coup de cœur de la rédaction

Science : la matière dévoilée

IMPÔTS CE QUI VA CHANGER

ALGÈRE L'INDÉPENDANCE

vkn.nl
NEWS OPINIE CULTUUR SPORT ECONOMIE REIZEN

Higgs of niet, het is een spectaculaire ontdekking

1. 'Een van geluk, Higgs-boson bestaat' - 14/07/12
2. Higgs-boson? 'veer waarschijnlijk gevonden' - 14/07/12
3. 'Maatschappij heeft mijn niklaas Higgs' - 14/07/12

The New York Times
ON THE WEB

Physicists Find Elusive Particle Seen as Key to the Universe
By DENNIS OVERBYE 8:18 PM ET

Researchers said they had discovered what looked for all the world like the Higgs boson, a long-sought particle that

Le Monde: Science: la matière dévoilée

La Repubblica: La particule de Dieu existe

WELT: 32 consejeros de Bankia

LA STAMPA: La particule qui fait accélérer notre histoire

THE AUSTRALIAN: Physique des particules La masse est citée

EUROPEAN: Physique des particules La masse est citée

TRIBUNE DE GENÈVE: ACCÉLÉRATEUR DE PARTICULES

SCIENCE AND TECHNOLOGY DAILY

科技日报: 上海交大首次高效人工合成青蒿素

Autos
Bligs
Books
Cartoons
Classifieds
Crosswords
Dining & Wine
Education
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Opmerkelijk

Le Monde.fr

EN CIDADES EUROPEAS EN CIDADES ESPAÑOLAS desde 15€ (por noche por persona) desde 17€

Le boson de Higgs découvert avec 99,9999 % de certitude

Les plus partagés

- Préparations au domicile et dans les bureaux de Nicolas Sarkozy 2525
- "Strip-tease": Comment l'ancien First Love (sans) aux campagnes 393
- Jean-Louis "Strip-tease" sera une mine formidabile pour un ethnologue de l'ex-2007 345
- La Syrie ou "Proche-Orient de la torture", selon HRW 315
- Le dossier de coalition de Jean-Louis Borloo déçoit les espérances de son client vedette 288
- Vous avez trop bu, ça arrive tous les jours 274
- Le séisme d'origine automobile: Sergio Pininfarina est mort 186
- Ben Azzouzi: Arabie saoudite démentie ou potassium 128

2013: Nobel Prize in Physics for Higgs Boson Discovery

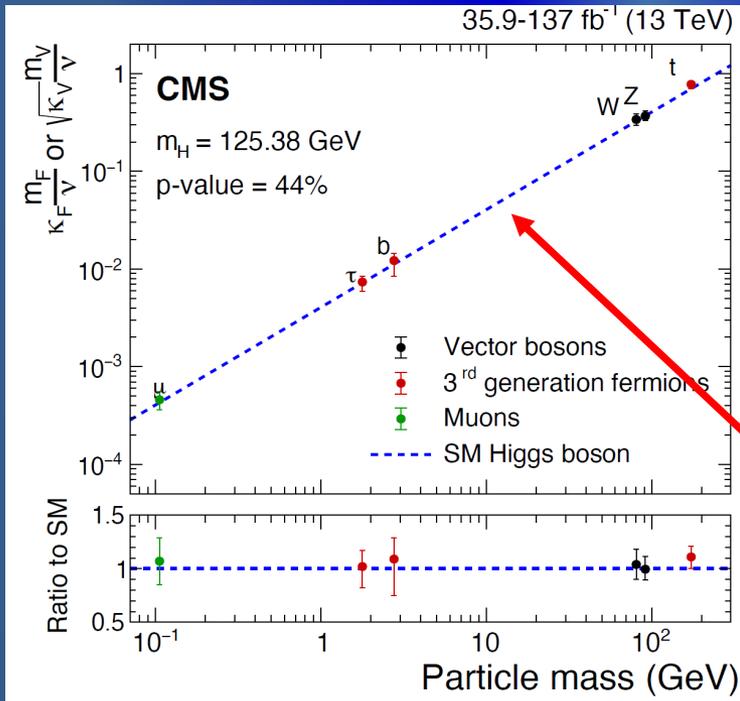
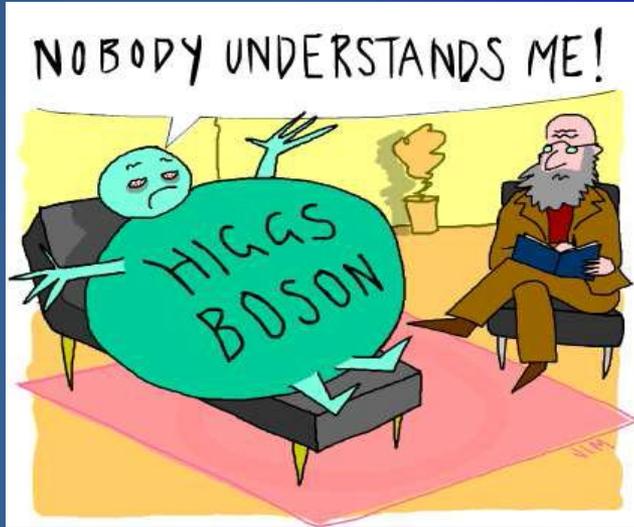


*'The Large Hadron Collider at CERN is the largest most complex machine in the world, possibly the universe. By smashing particles together at enormous energies, it recreates the conditions of the Big Bang. **The recent discovery of what looks like the "Higgs particle" is a triumph of human endeavour and international collaboration.** It will change our perception of the world and has the potential to offer insights into a complete theory of everything.'* **Stephen Hawking**

Historic Milestone: the Higgs is just Different

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons

- ✓ Higgs particle is the **only spin-0 (scalar) particle in the SM**, but it does the most important job (gives masses)
- ✓ Higgs is a totally new form of matter (neither matter nor force): **"FACELESS"**



FROM DISCOVERY TO PRECISION MEASUREMENTS

- ✓ Higgs couplings to fermions and gauge bosons **fixed in SM**
- ✓ **Do couplings scale with mass ?**
→ **A deviation from this pattern signals new physics!**

**We have only just
started to understand
the Higgs boson ...**

**... and we need to look
from every angle**

H





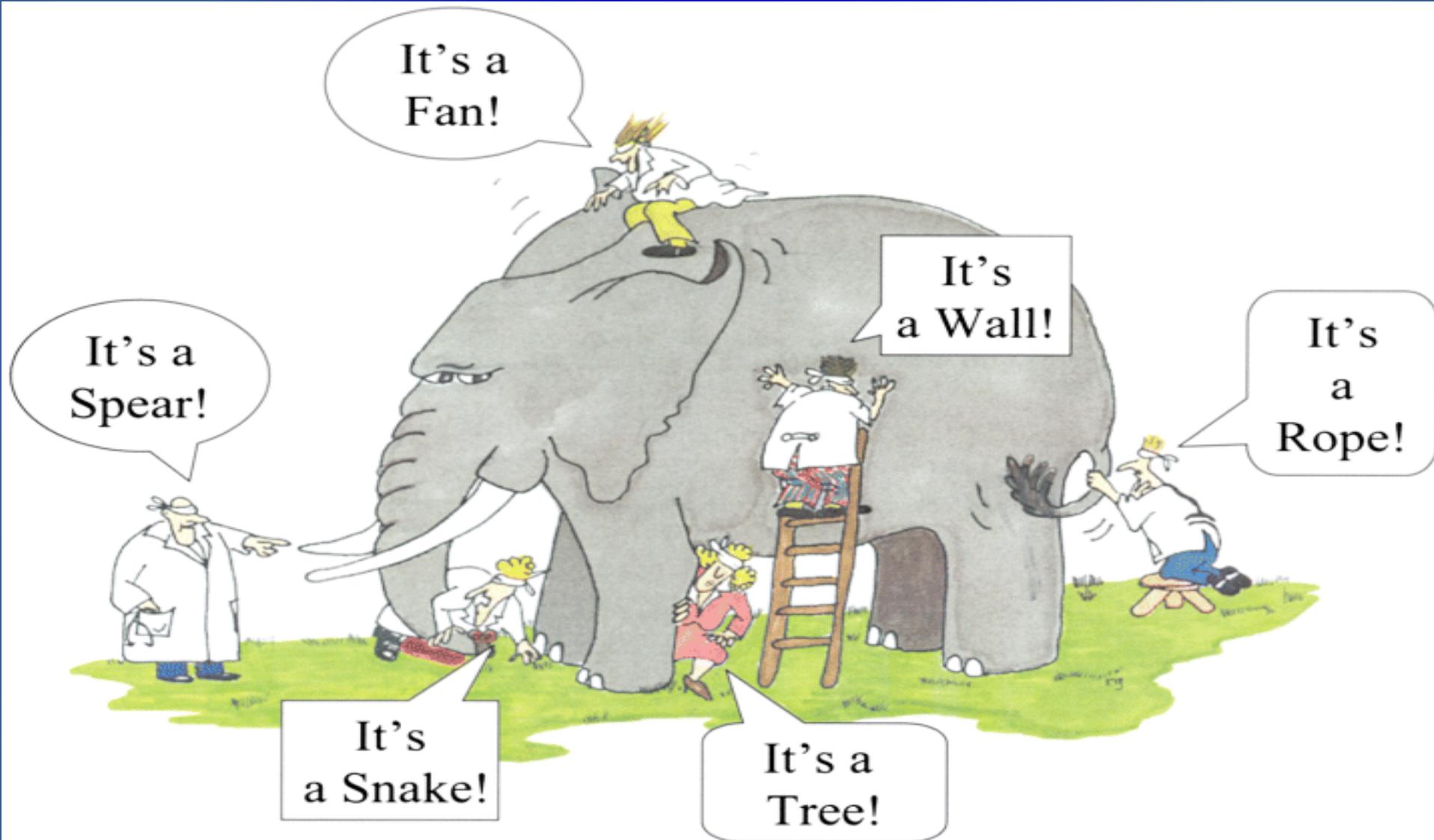
It's a
Spear!





It's
a Wall!

We have only started to understand the Higgs boson ...
... and we need to look from every angle



THE HIGGS BOSON

FINAL PIECE IN THE PUZZLE?

...but there must be a deeper relationship
between Higgs / mass / gravity / dark energy

Determine Higgs properties as precisely as possible to address fundamental questions:

... is it “**THE Higgs Boson**” (of the Standard Model) ? or one of several ?

... its properties could give information on **Dark Matter**

... its properties could give first hints on **Dark Energy**

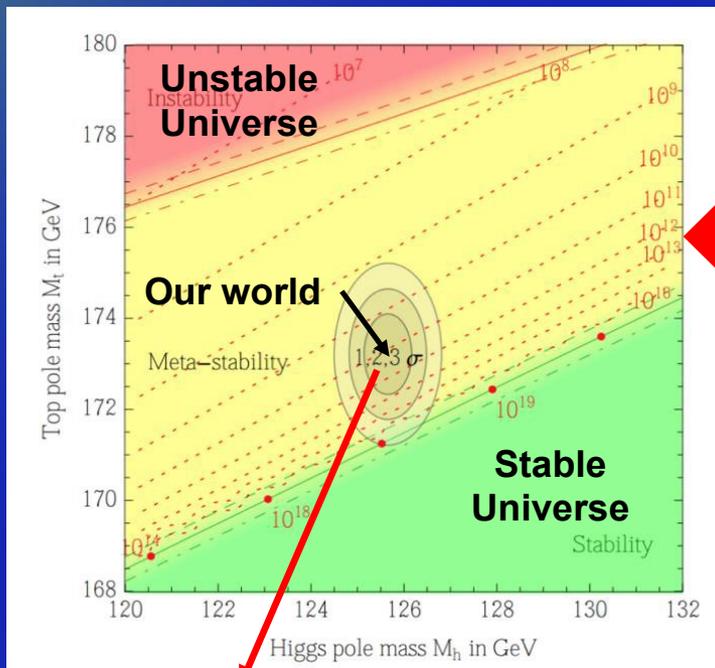
The "Fate of Our Universe" & Higgs Boson

Is Empty Space Stable ?

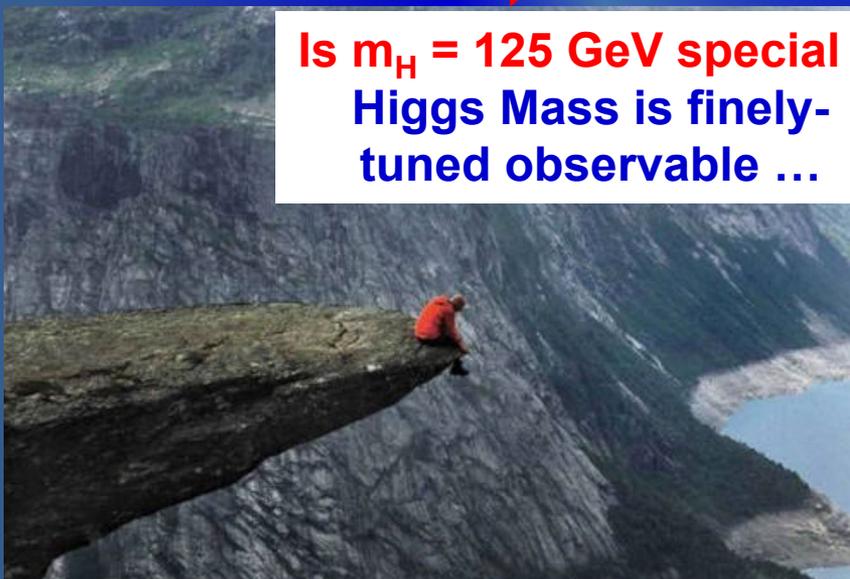
« Stability of the EW vacuum »

arXiv: 1403.6535

The universe seems to live near a critical condition

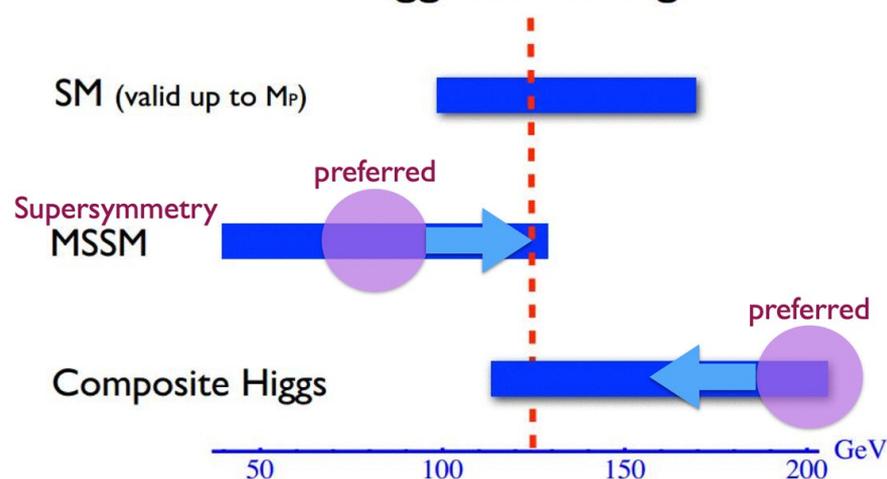


Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



Is $m_H = 125$ GeV special?
Higgs Mass is finely-tuned observable ...

Higgs mass range

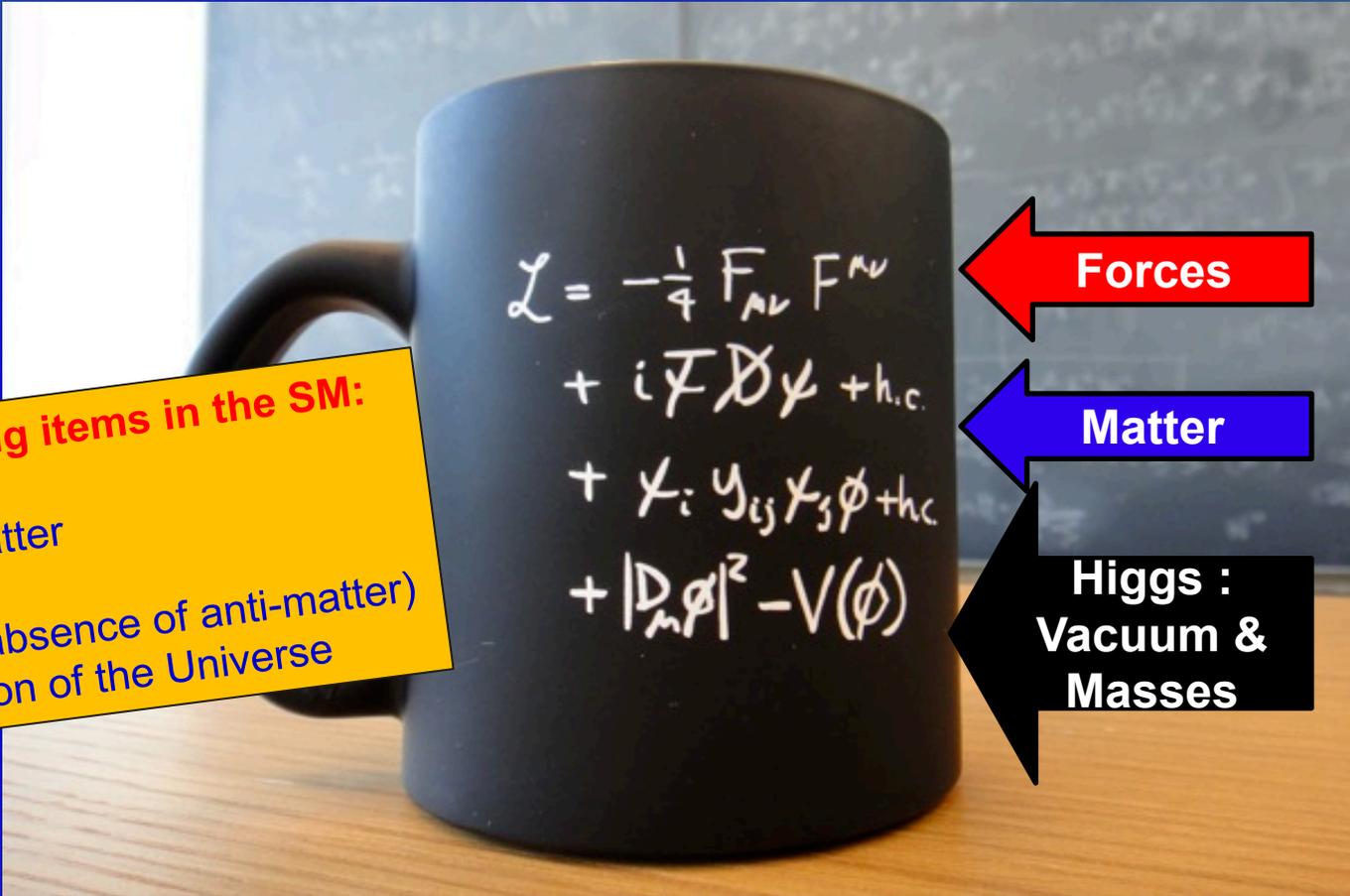


Beyond Standard Model: Puzzle is Sharpened

Lagrangians & coffee mugs

There are several missing items in the SM:

- non-baryonic dark matter
- neutrino mass
- baryon asymmetry (absence of anti-matter)
- accelerated expansion of the Universe


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

Forces

Matter

Higgs :
Vacuum &
Masses

No evidence of New Physics (YET) in the LHC data, beyond the SM
→ it may remain valid up to very high energies

Measure every facet of the Higgs → Lepton Collider (+ LHC)
→ See thursday lecture on Future Colliders

The Higgs: A new kind of field

The only fundamental scalar





Higgs discovery **not the end of an era**, but beginning of a **New Era**:

We enter a new **Scalar World !**

The Higgs Boson

Cosmic connections:

- primordial Big Bang inflation driven by **scalar** field
- today's inflation driven by **scalar** field: Dark Energy, cosmological constant (Nobel 2011)
- Higgs: **scalar** field
- world(s) born from chaos - of fluctuations of **scalar** field ?