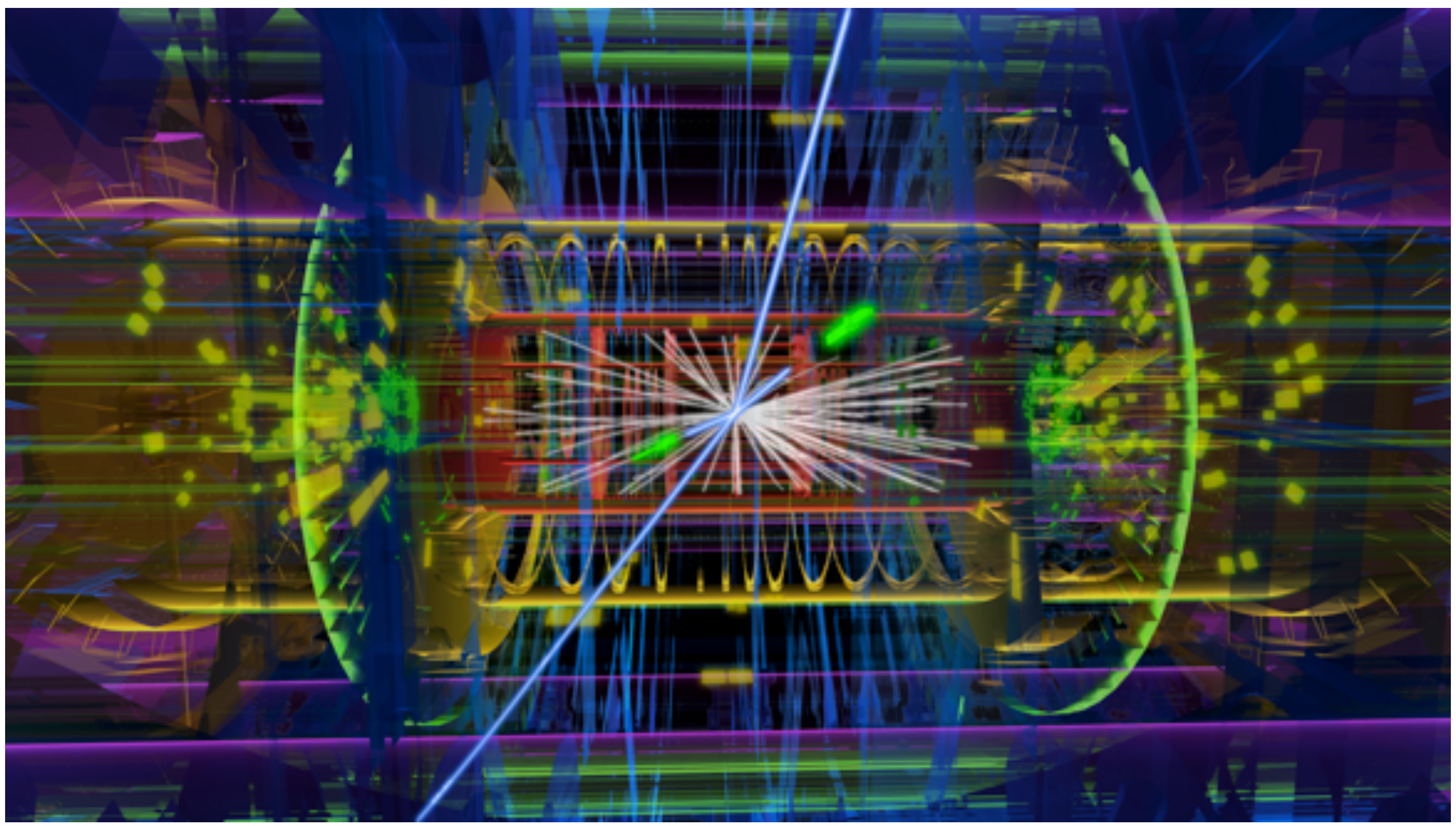
Exploring the fundamental building blocks of the universe: particle physics and the energy frontier



Michel Lefebvre
Physics and Astronomy
University of Victoria

- Matter and forces
- Collider and detector

UVic Continuing Studies
30 Nov 2012

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abstract

Humans have pondered over the building blocks of the universe since ancient times. Early attempts, including the "four elements" earth, water, air and fire, allowed limited understanding and predictions of natural phenomena. Spectacular progress has been made since, but many questions, such as the origin of mass and dark matter, remain. After a review of our current knowledge of matter and forces, this talk will introduce, in simple terms, how physicists probe the very fabric of nature with high-energy particle collisions, and boldly look where no one has looked before. Recent results from the Large Hadron Collider, located in Geneva, will be presented and discussed.

Matter and Forces

What is the world made of?

What holds it together?

Understanding nature's fundamental constituents and forces

Search for the fundamental

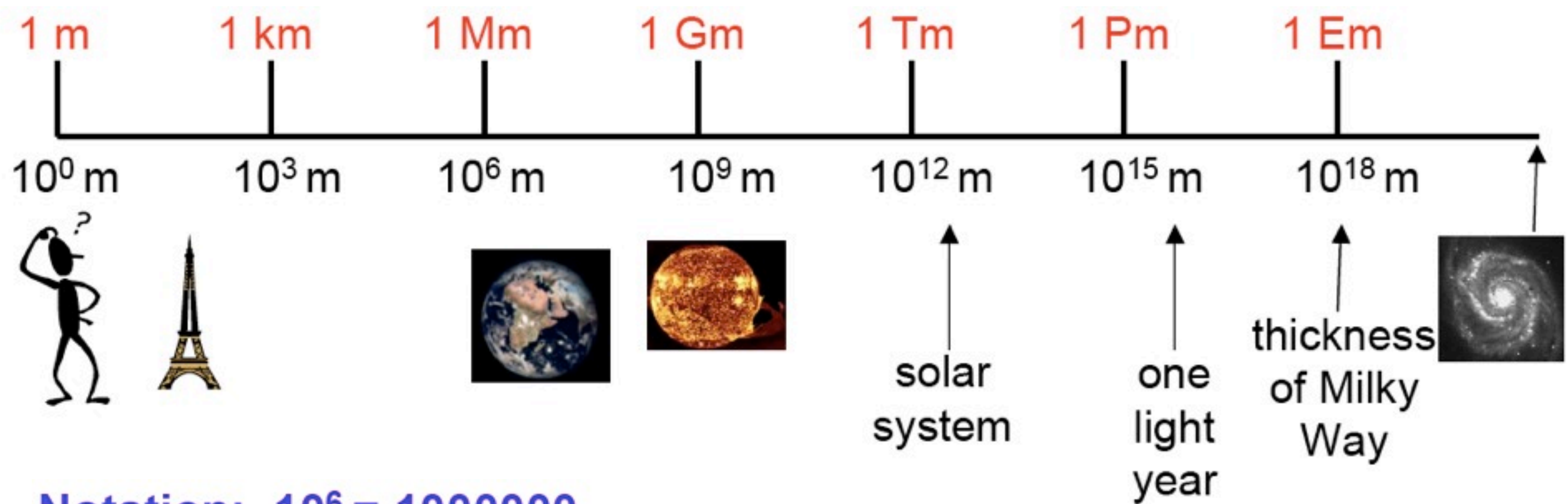
Why do so many things in this world share the same characteristics?

People have come to realize that the matter of the world is made from a few fundamental building blocks of nature.

The word "fundamental" is key here. By fundamental building blocks we mean objects that are simple and structureless -- not made of anything smaller.

Even in ancient times, people sought to organize the world around them into fundamental elements, such as earth, air, fire, and water.

Length Scales

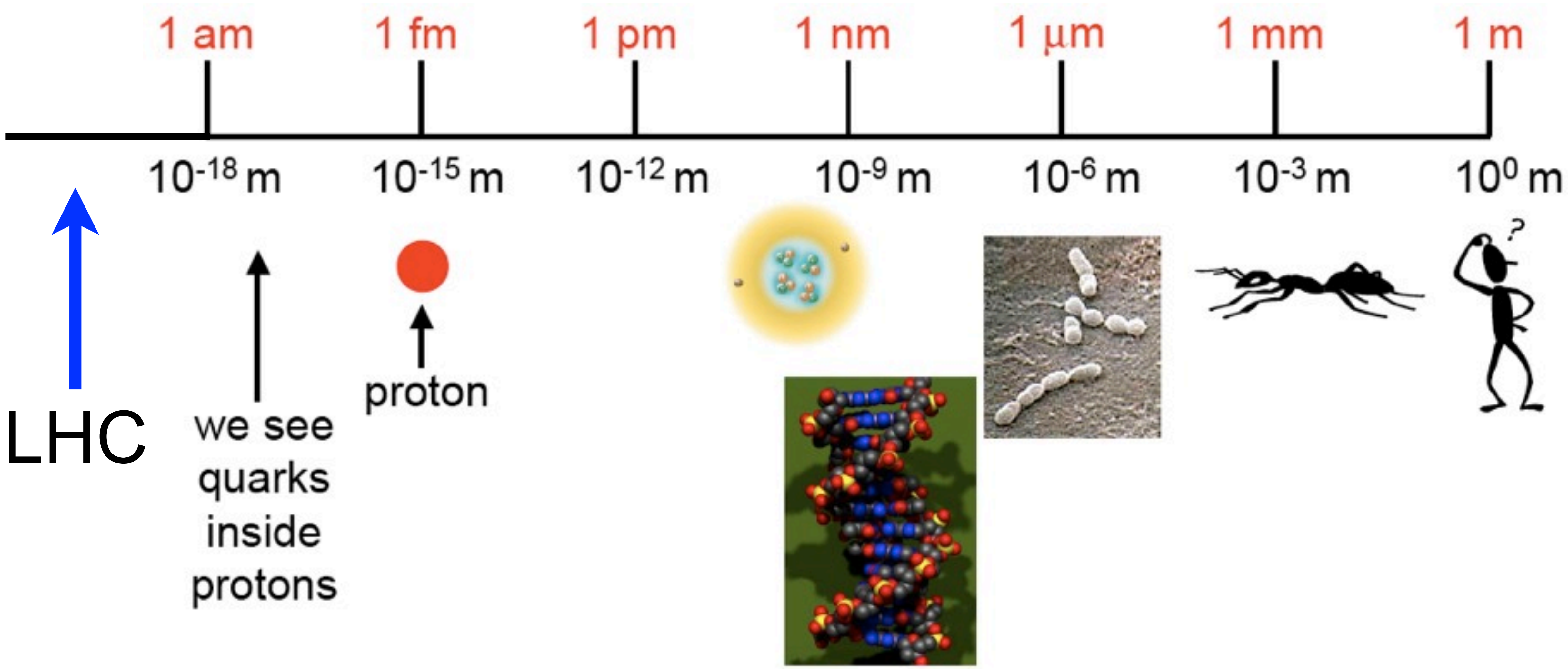


Notation: 10^6 = 1000000

6 zeros!

Astrophysics explores matter and space in its largest dimensions

Length Scales



Notation: $10^{-6} = 0.000001$

6th decimal place!

Particle Physics explores matter and space in its smallest dimensions

“Nothing exists except atoms and empty space; everything else is opinion.”

Democritus (ca. 460 BC - ca. 370 BC)

The atomic theory of matter

Leucippus and Democritus (450 BC)
First atomic theory (atomos = indivisible)

Dalton (1766-1844)
Atomic theory of matter
Explains the law of definite proportions: "*when two or more elements combine to form a compound, the proportions by mass of the elements are always the same*", eg H_2O is always formed of 1:8 of H:O by mass.

Avogadro (1776-1856)
Proposed that all gases at the same temperature, pressure and volume contain the same number of molecules.
$N_A = 6.02 \times 10^{23}$ molecules/mol

Boltzmann (1844-1906), ...
Kinetic theory of gases, based on the concept of atoms (and molecules)

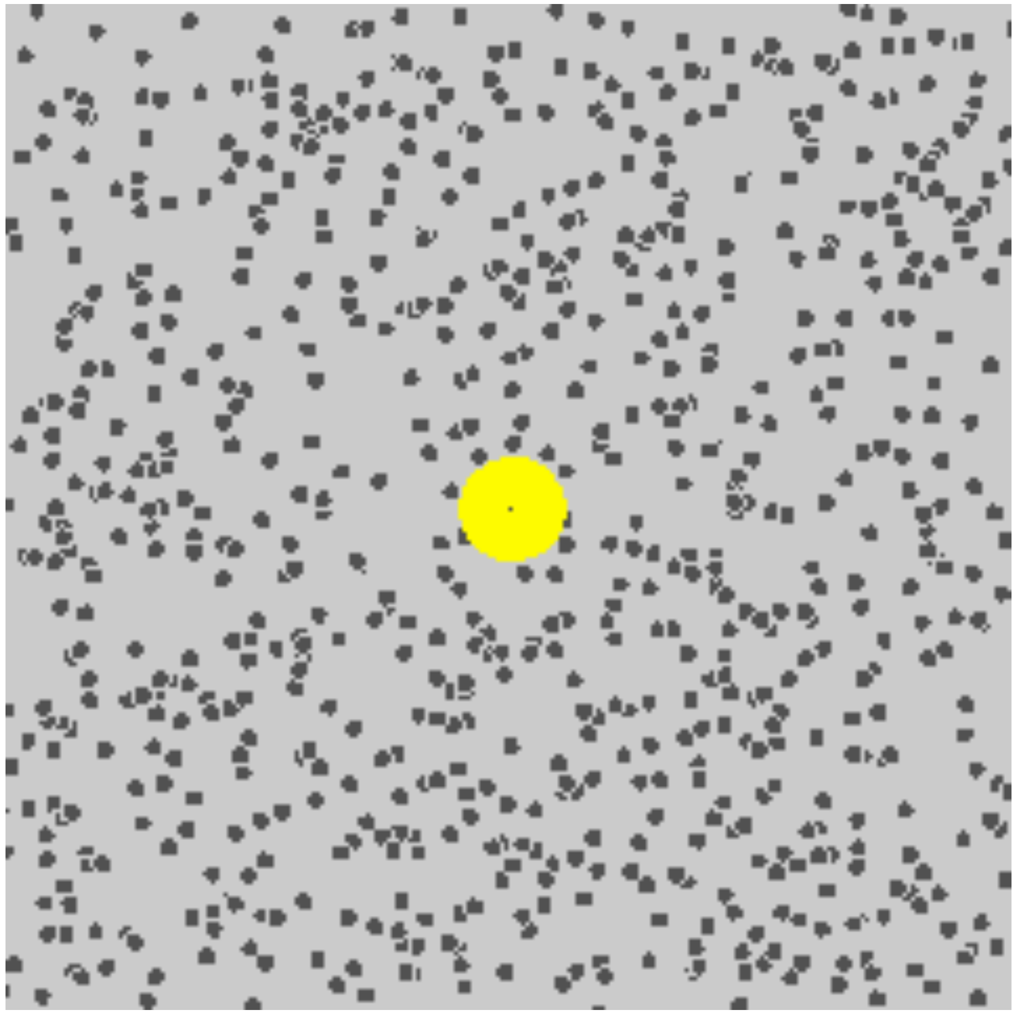
The atomic theory of matter

Brown (1773-1858), Lucretius (60 BC)

Brownian motion (Brown 1827)

Random walk due to momentum transfer from atomic collisions. Evidence for atoms!

Explained by Einstein in 1905...



wikipedia:
http://en.wikipedia.org/wiki/Brownian_motion

The atomic theory of matter

Perrin (1870-1942)

Einstein's theory on Brownian motion confirmed in 1908 in a series of four different types of measurements (Nobel in 1926)

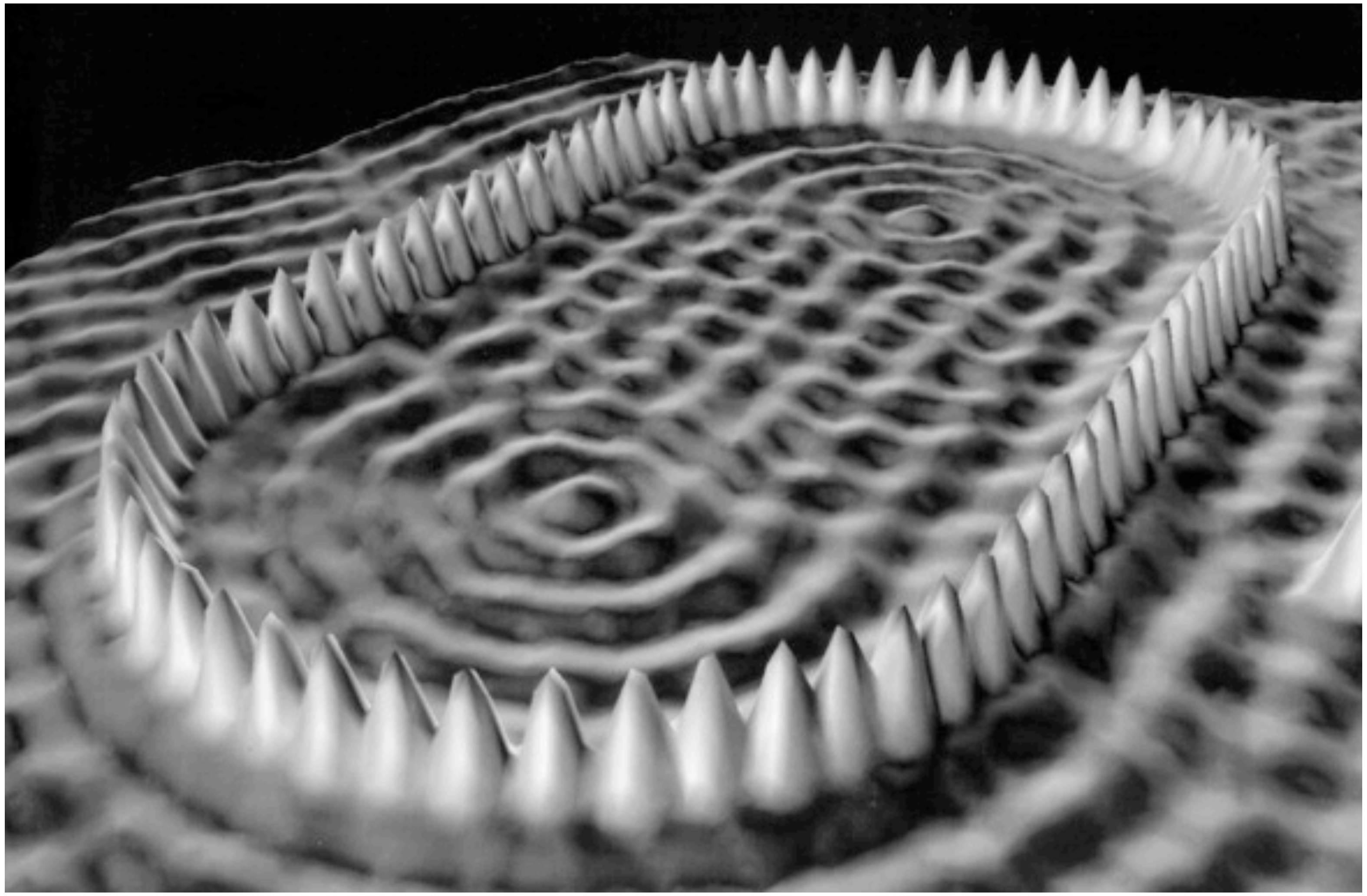
First accurate measurement of N_A

Opposition to the atomic theory remained for a while:

Mach (died 1916): (Wikipedia) "...Since one cannot observe things as small as atoms directly, and since no atomic model at the time was consistent, the atomic hypothesis seemed to Mach to be unwarranted, and perhaps not sufficiently "economical" "

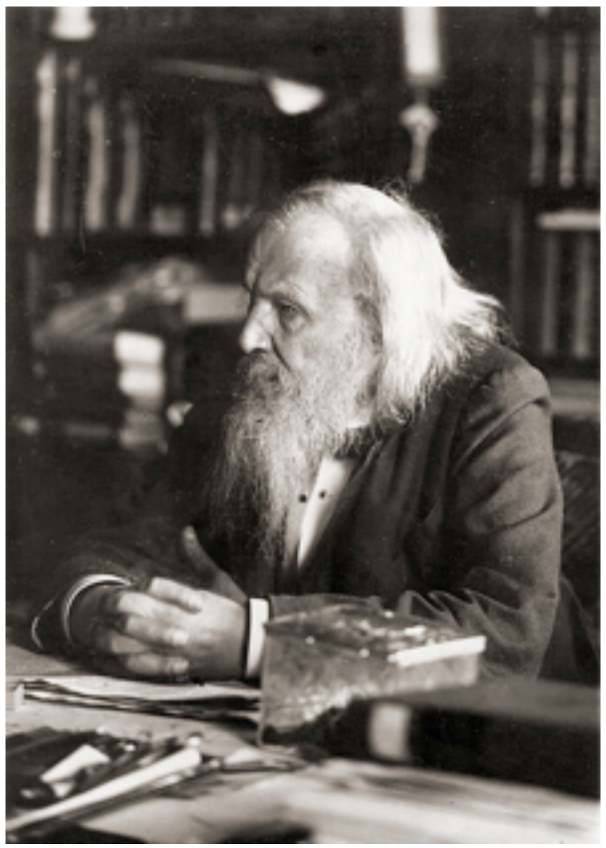
Seeing atoms

We can now see atoms, one at a time!



76 individually placed iron atoms on a copper surface

Physical and chemical classification



Dmitri Ivanovich
Mendeleev
1834-1907

Reihen	Gruppo I. — R^2O	Gruppo II. — RO	Gruppo III. — R^2O^3	Gruppo IV. RH^4 RO^2	Gruppo V. RH^3 R^2O^5	Gruppo VI. RH^2 RO^3	Gruppo VII. RH R^2O^7	Gruppo VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

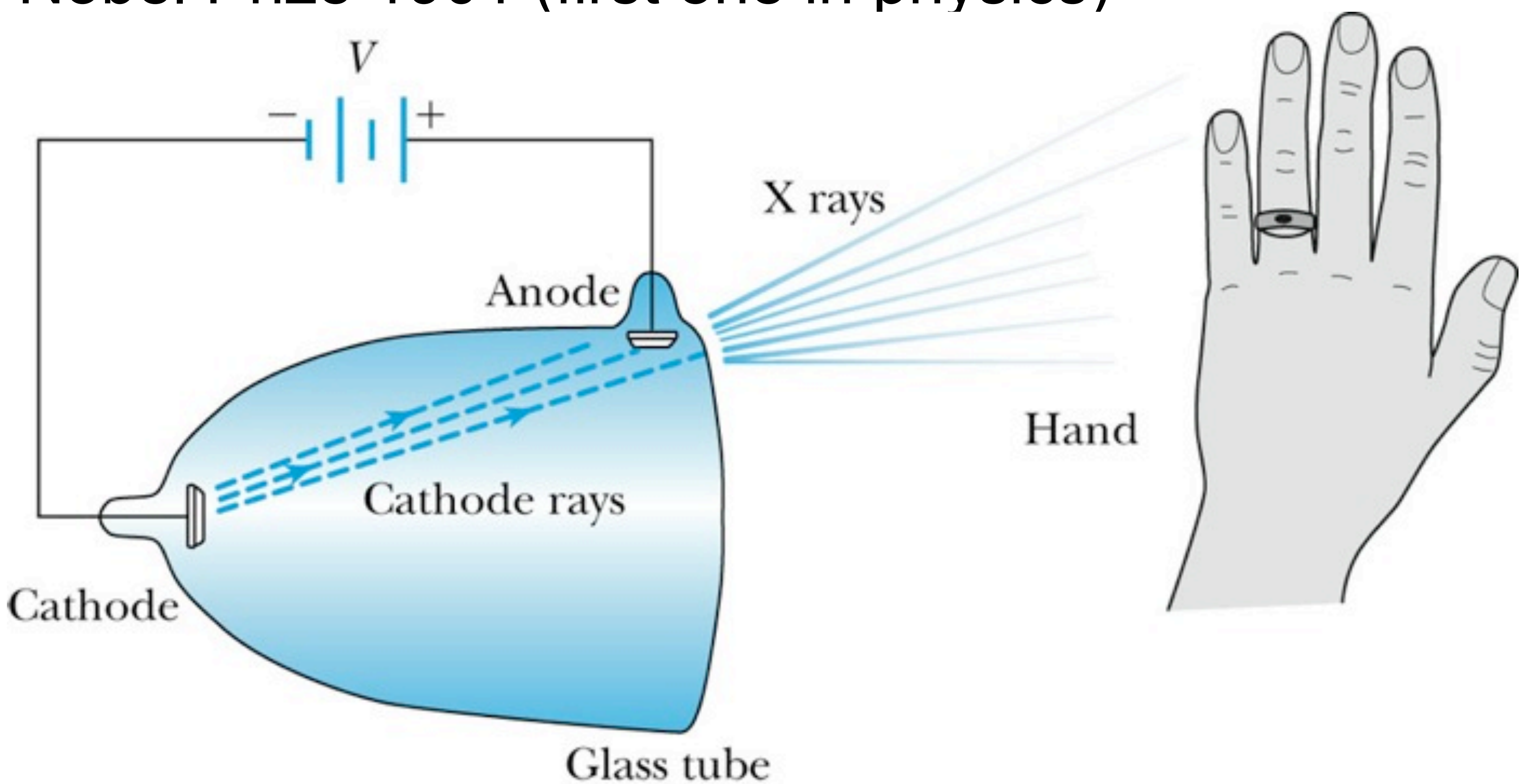
Mendeleev’s table, 1869

The Elements

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Discovery of X rays

Discovery of X rays by Röntgen, 1895.
Nobel Prize 1901 (first one in physics)



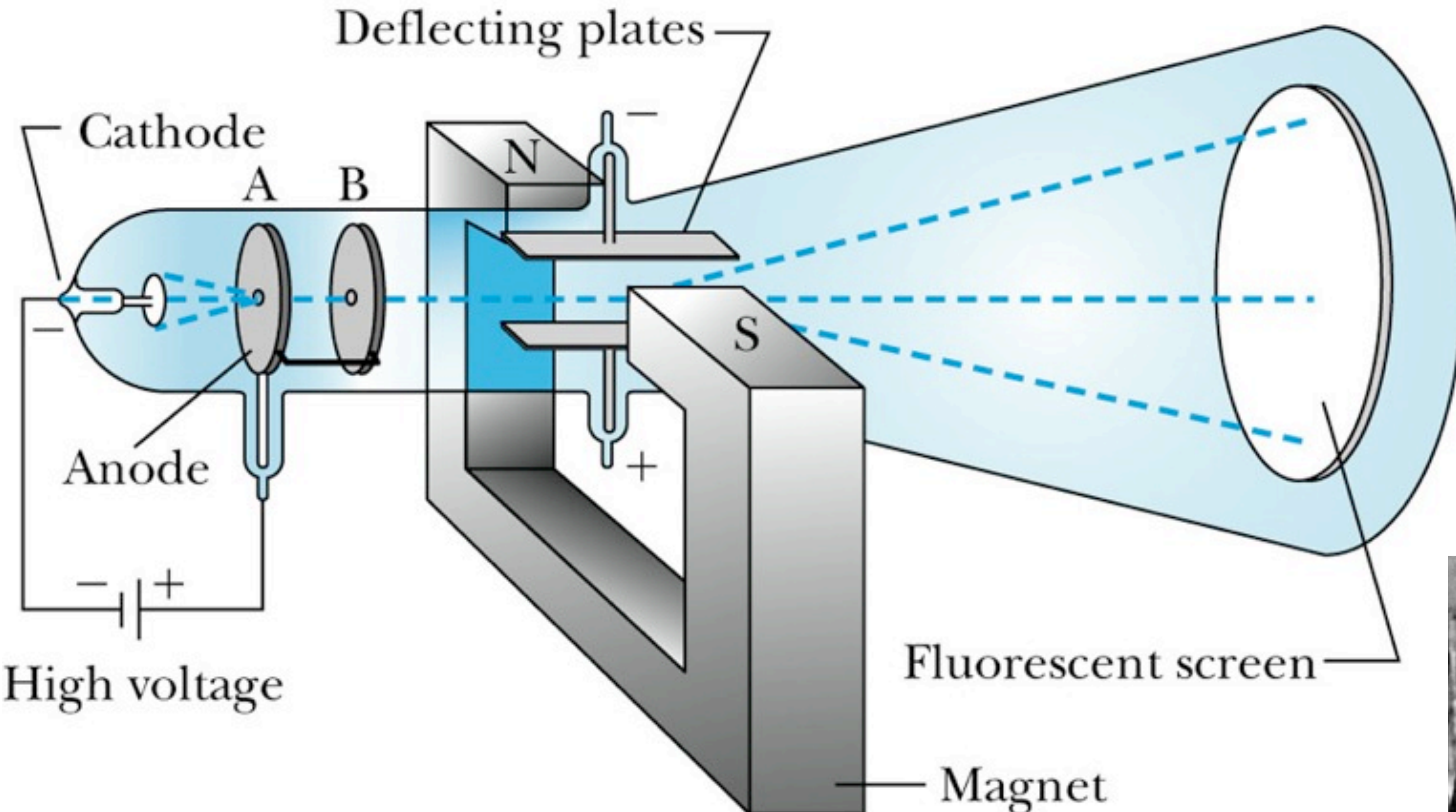
Turns out: “cathode rays” are electrons, and “X rays” are photons (light)!

X Rays are unaffected by magnetic fields and have a high penetrating power

Wilhelm Röntgen
(1845-1923)

Discovery of the electron

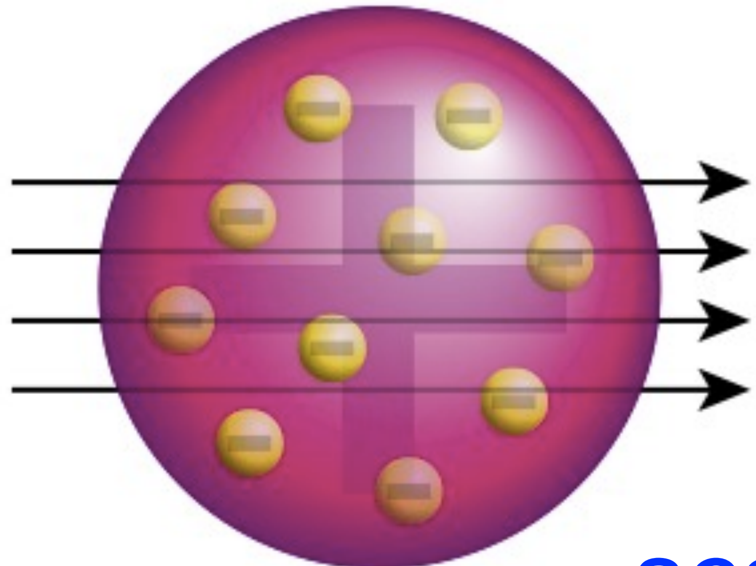
Discovery of the electron by J.J. Thomson (1897), Nobel Prize 1906



J.J. Thomson
(1856-1940)

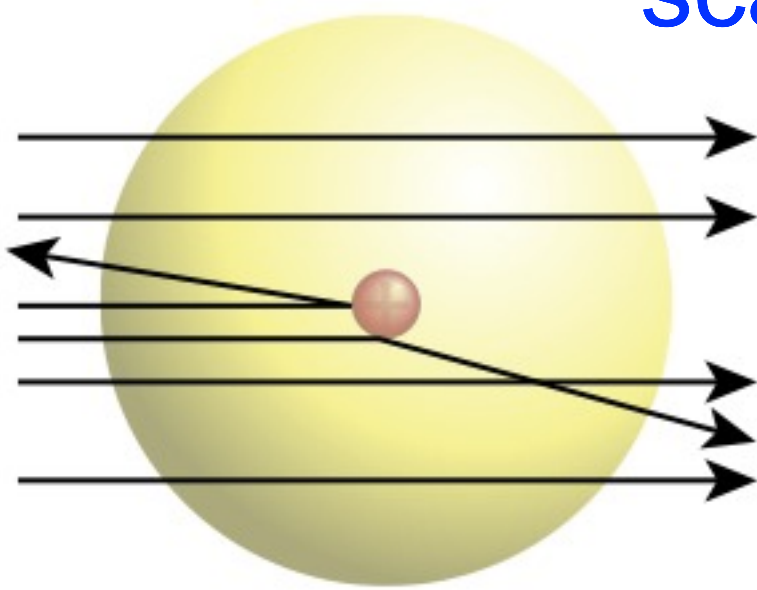
Thomson proved that cathode rays were made of negatively charged particles, affected by electric and magnetic fields! There is something inside atoms!!

Discovery of the atomic nucleus



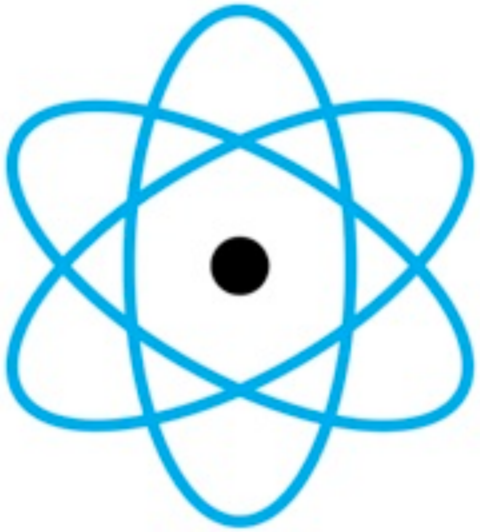
expected result...

alpha particle
scattering on gold foil

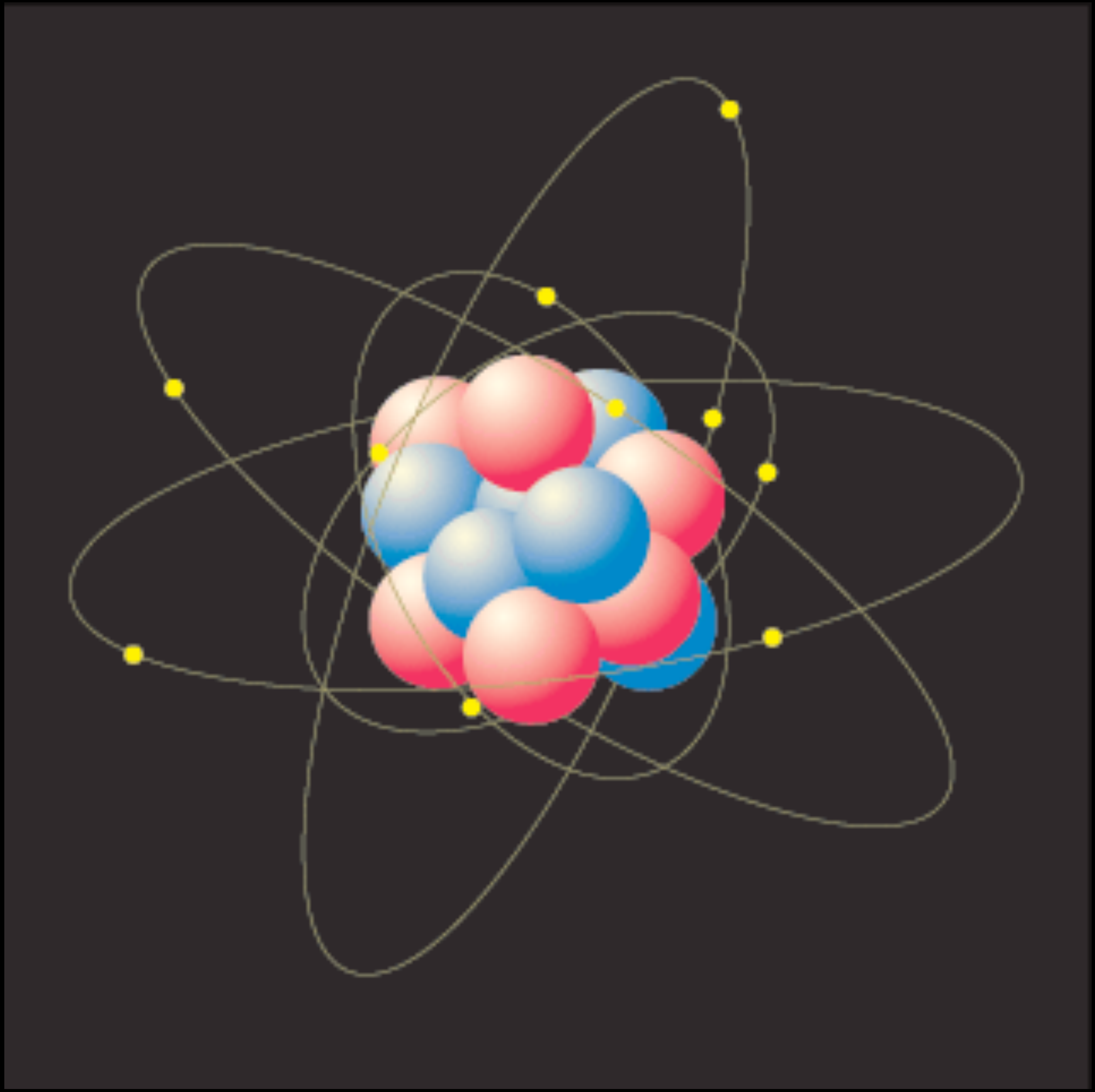


... the result!

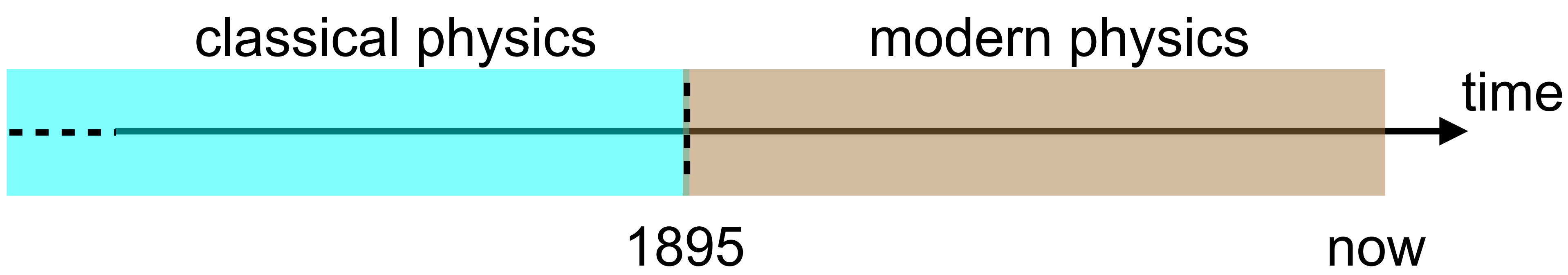
Ernest Rutherford
1871-1937



"It was almost as if you fired a 15 inch shell into a piece of tissue paper and it came back and hit you."



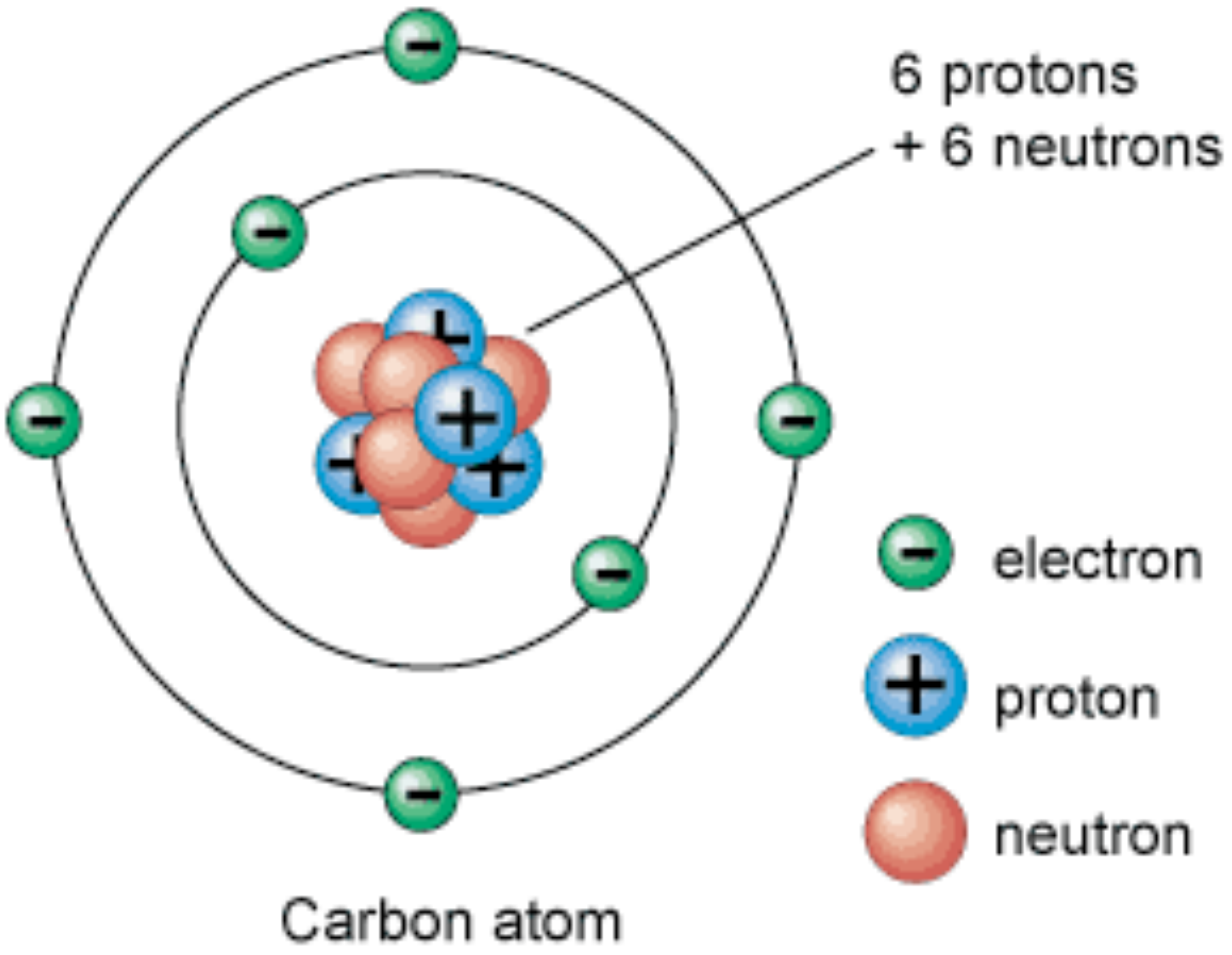
The birth of modern physics



Somewhat arbitrary date of 1895 as boundary between "classical" and "modern" physics... But monumental changes occurred in physics shortly after 1895.

1897: Discovery of the electron (J.J. Thomson)
1900: Planck's radiation law (Planck)
1905: Special Relativity (Einstein)
1905: The photon hypothesis (Einstein)
1911: Rutherford atom (Rutherford)
1912: Bohr atom (Bohr)

The atom and its nucleus



Isotopes

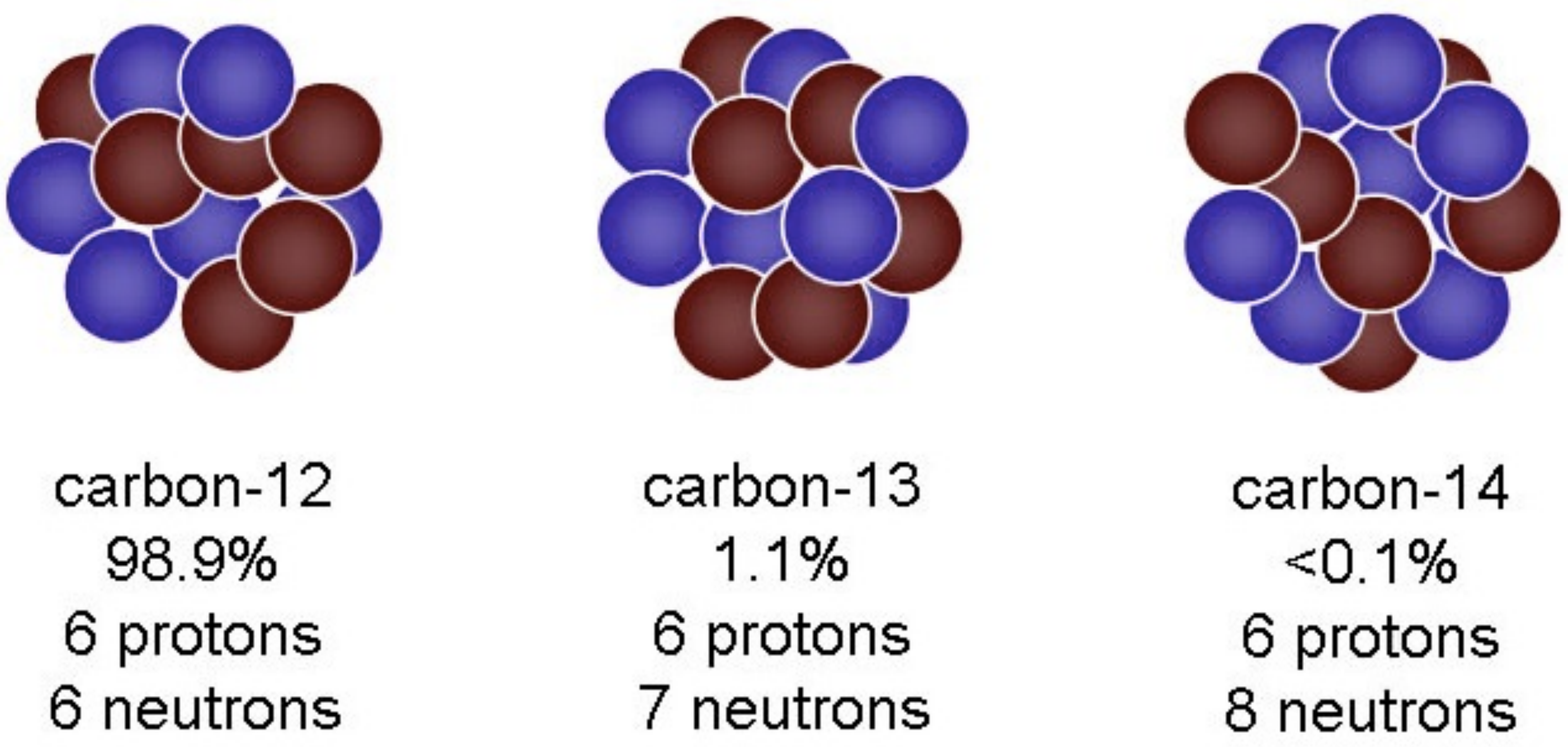
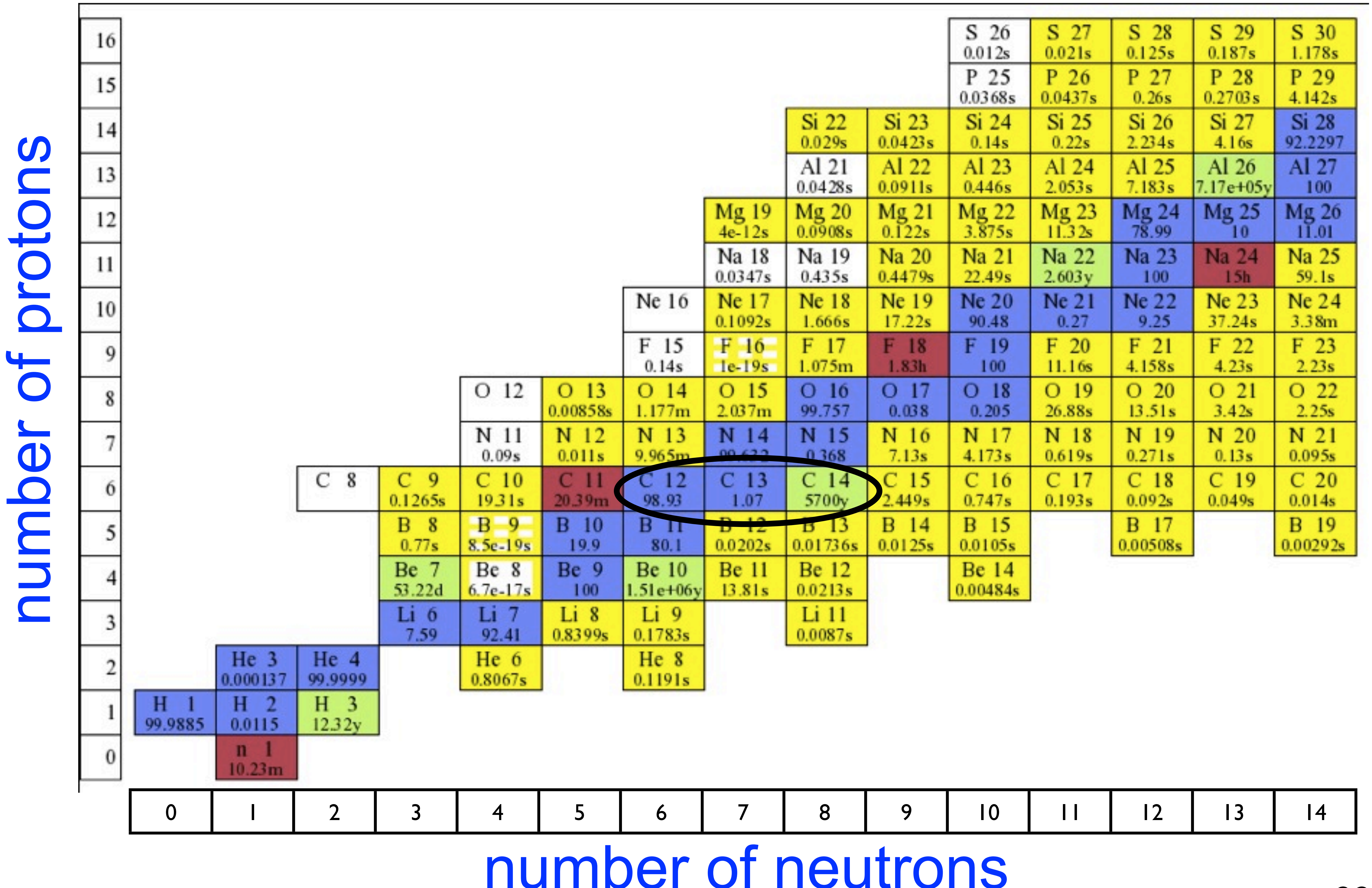

carbon-12
98.9%
6 protons
6 neutrons
carbon-13
1.1%
6 protons
7 neutrons
carbon-14
<0.1%
6 protons
8 neutrons

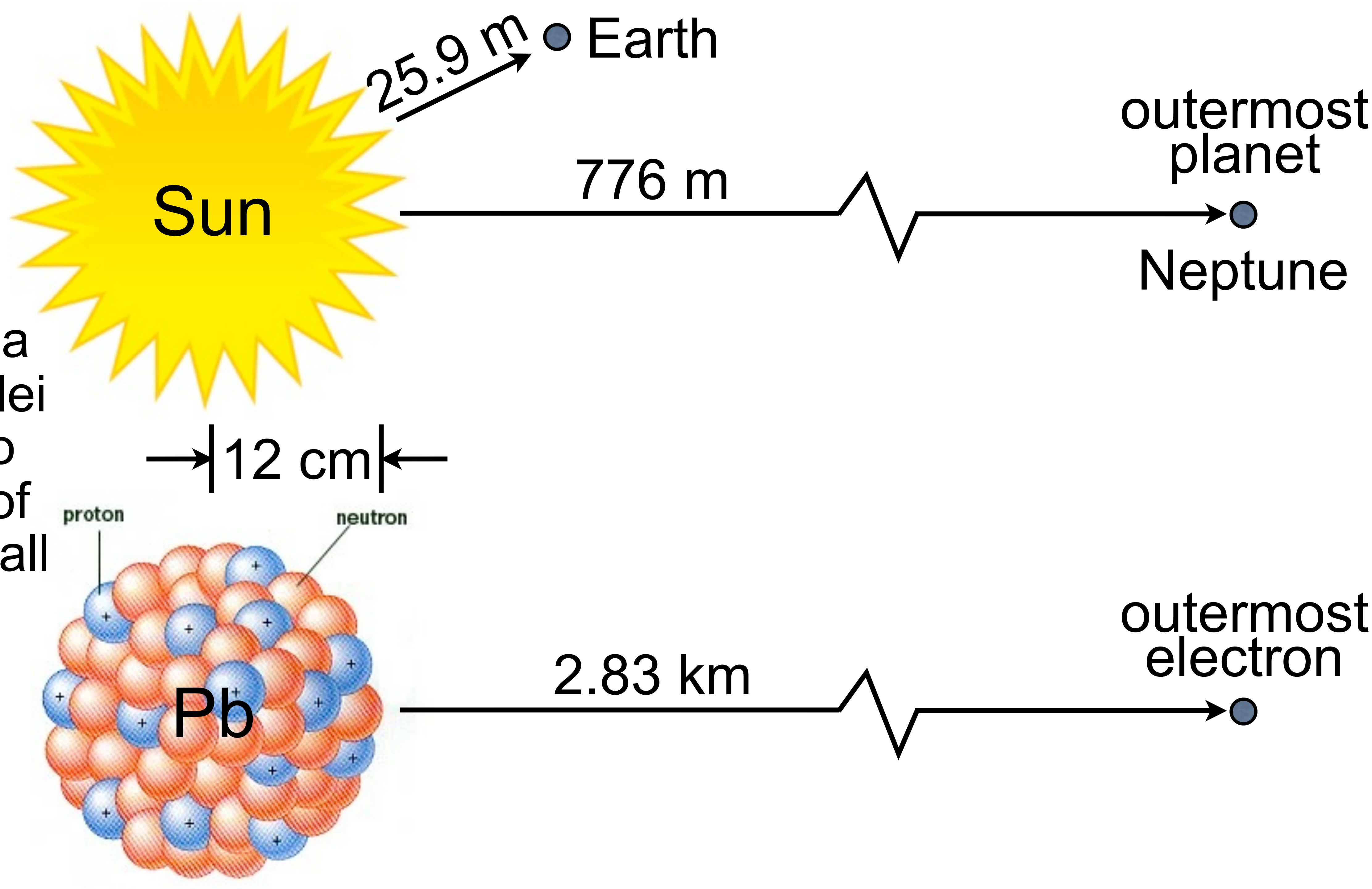
Table of nuclides



Length Scales

Relative scale of the solar system and an atom of lead

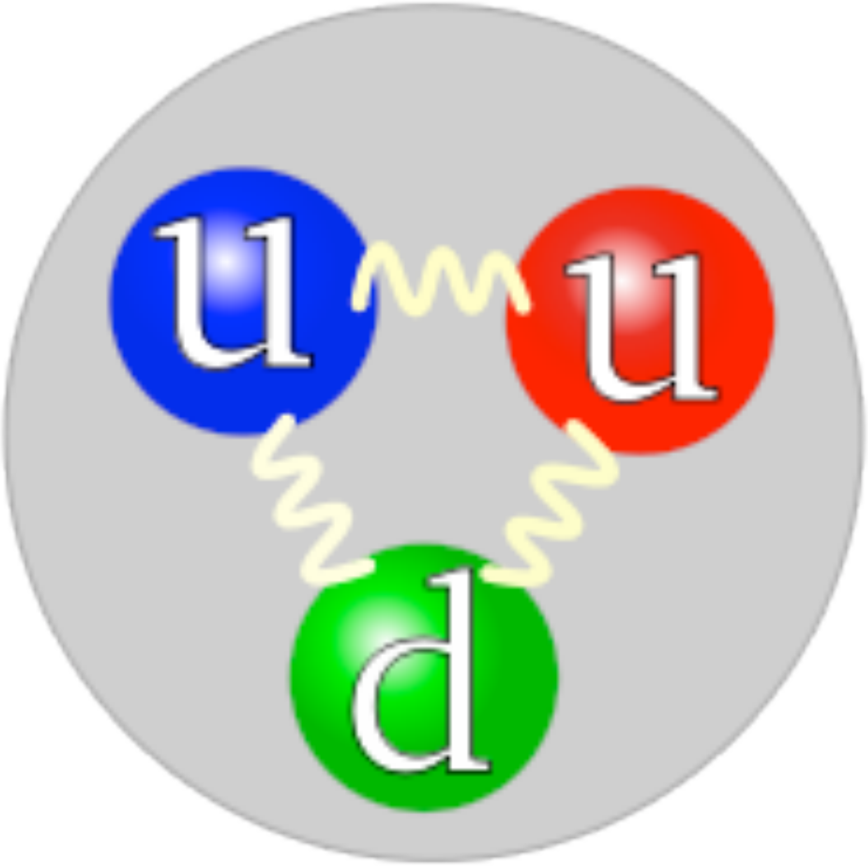
Sun and a ^{208}Pb nuclei scaled to the size of a basketball



Inside the proton

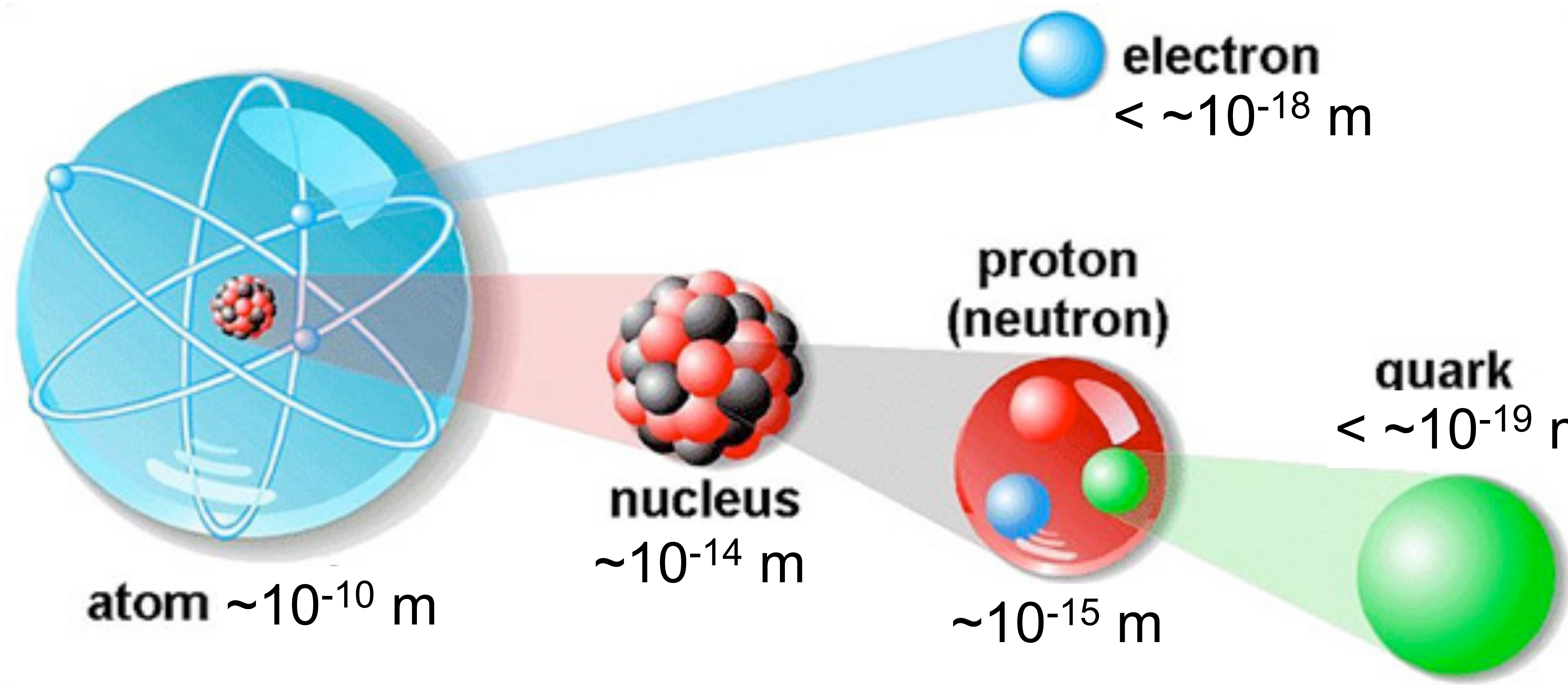
the **proton**: three bound quarks

held together by the strong force



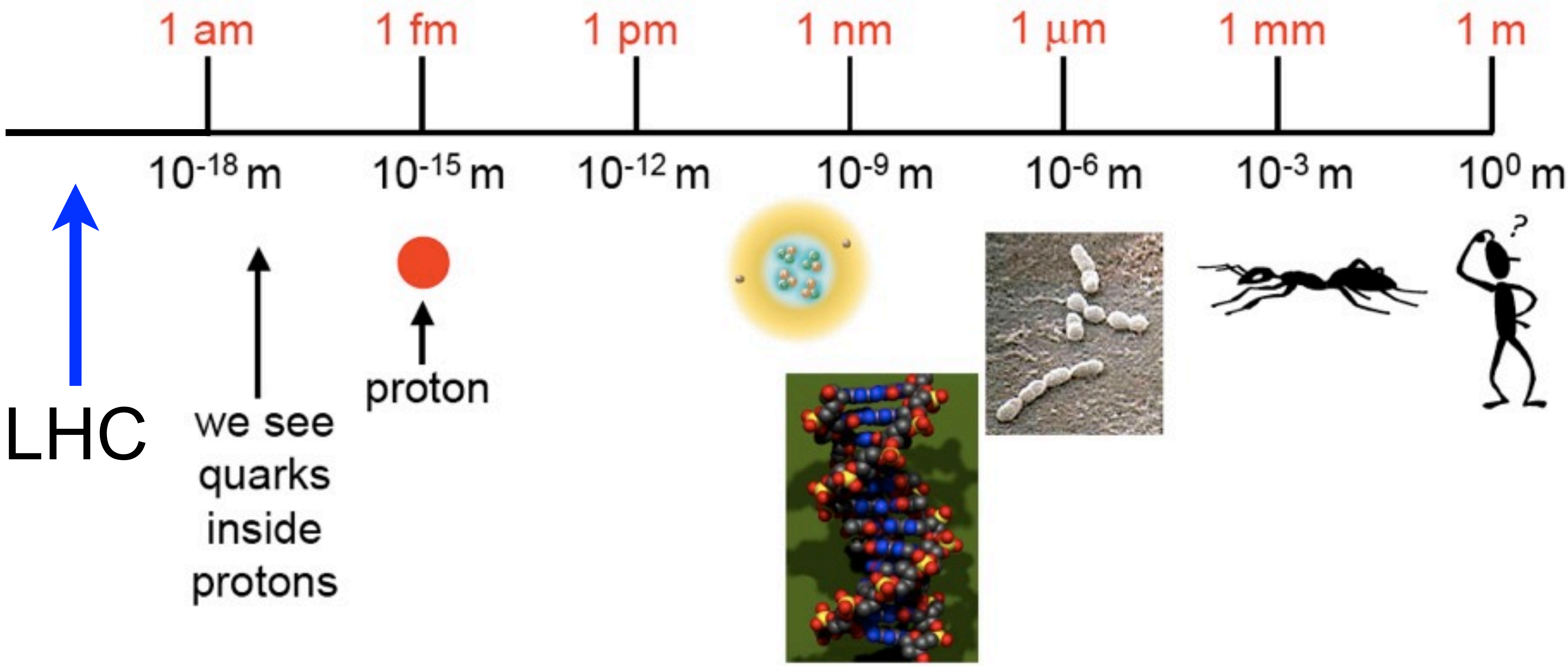
Inside the atom

~1910 ~1970



x10000 x10 x10000

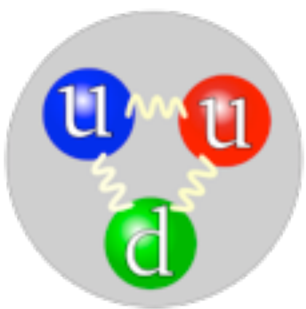
Length Scales



Notation: $10^{-6} = 0.000001$

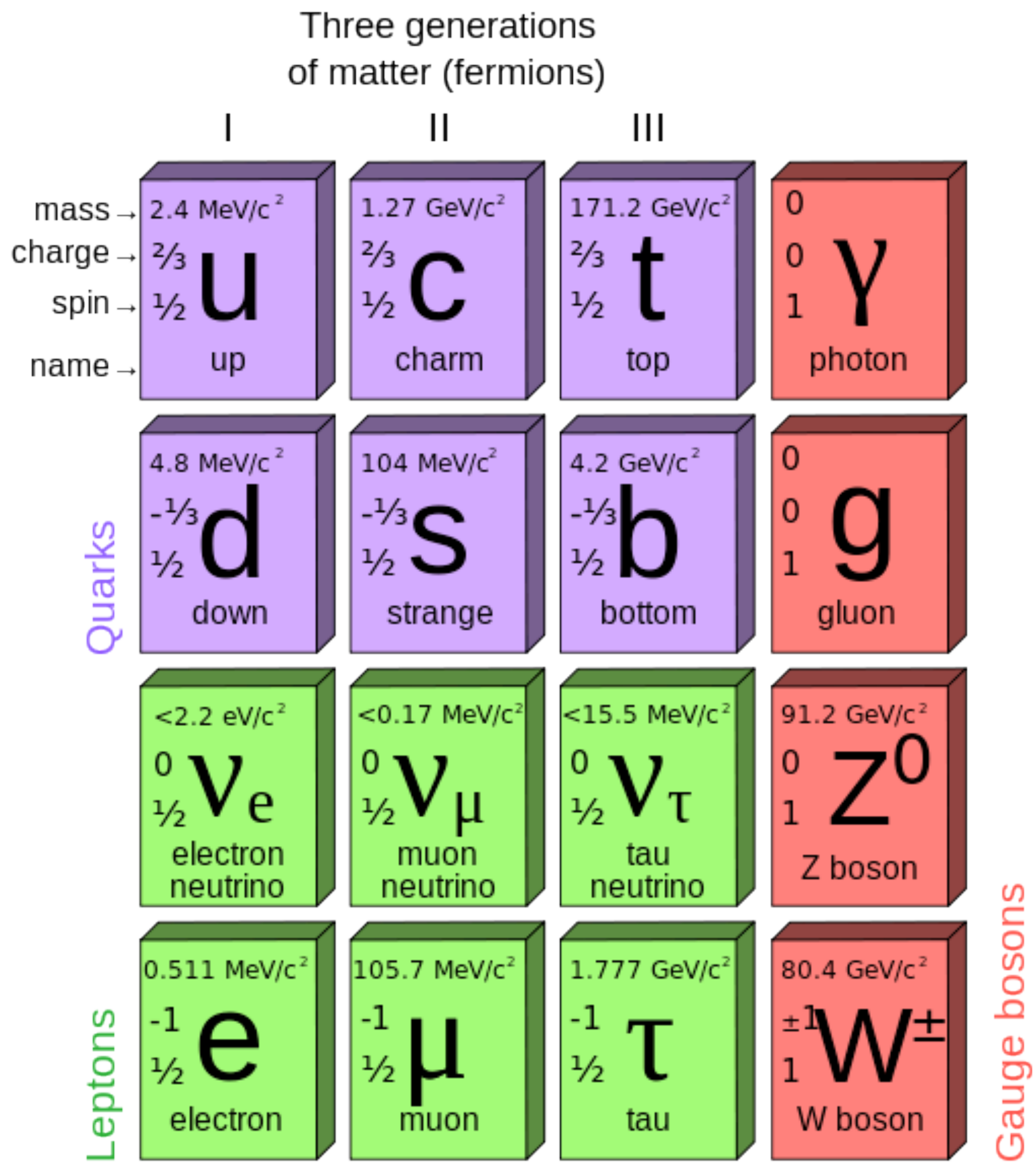
6^{th} decimal place!

Matter and Forces



the **proton**: three bound quarks

Matter: spin 1/2 fermions



Forces: mediated by spin 1 bosons

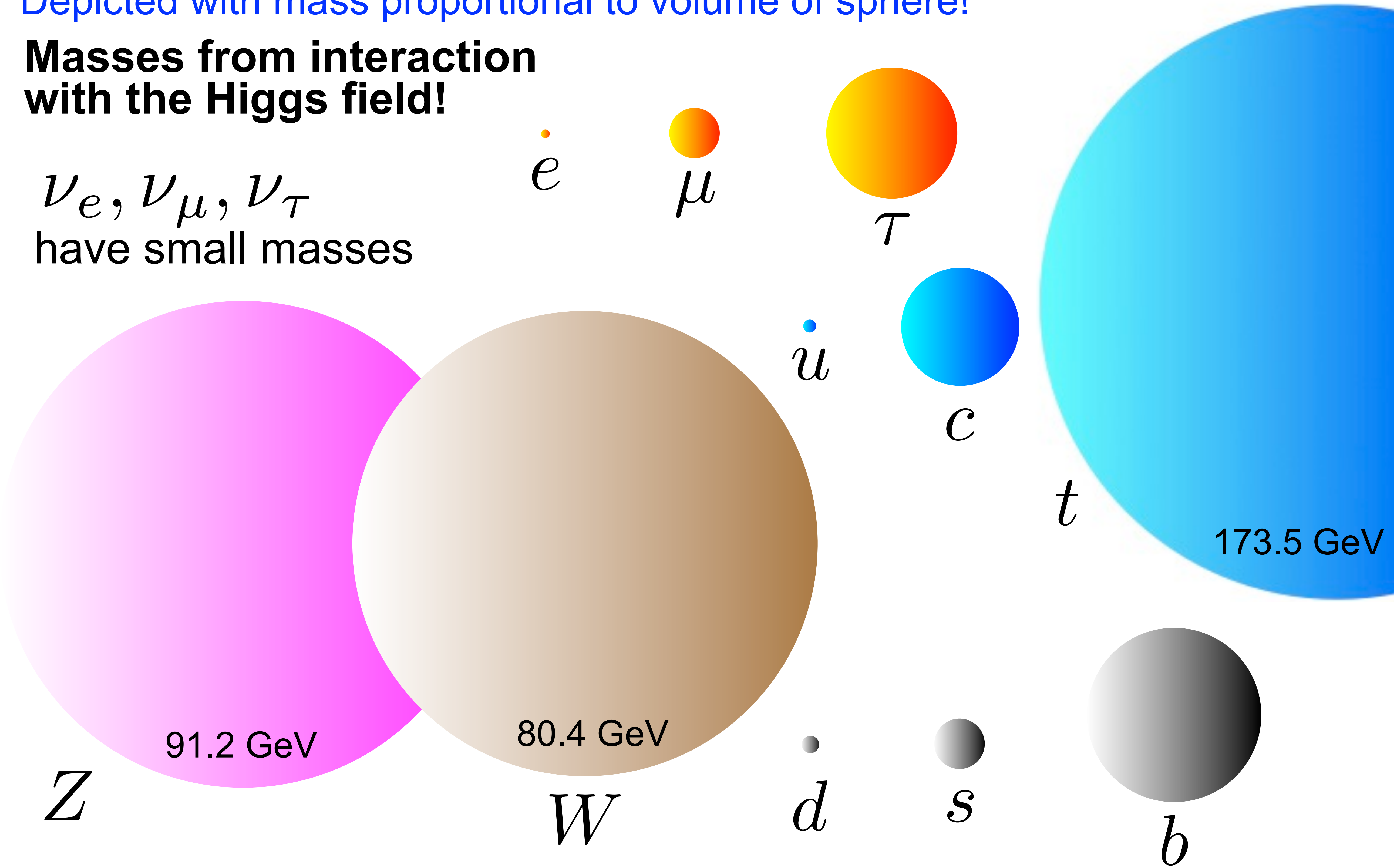
Fundamental Masses

γ, g
massless

Depicted with mass proportional to volume of sphere!

Masses from interaction with the Higgs field!

ν_e, ν_μ, ν_τ
have small masses



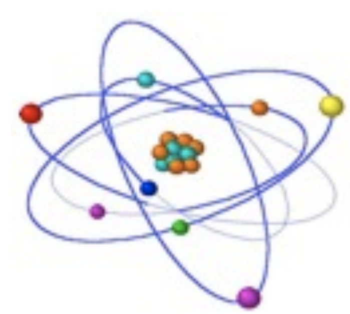
Fundamental Forces

	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

http://www.particleadventure.org/

slow H burning rate of the Sun

distinguishes left from right!



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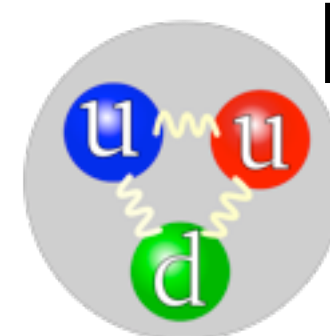
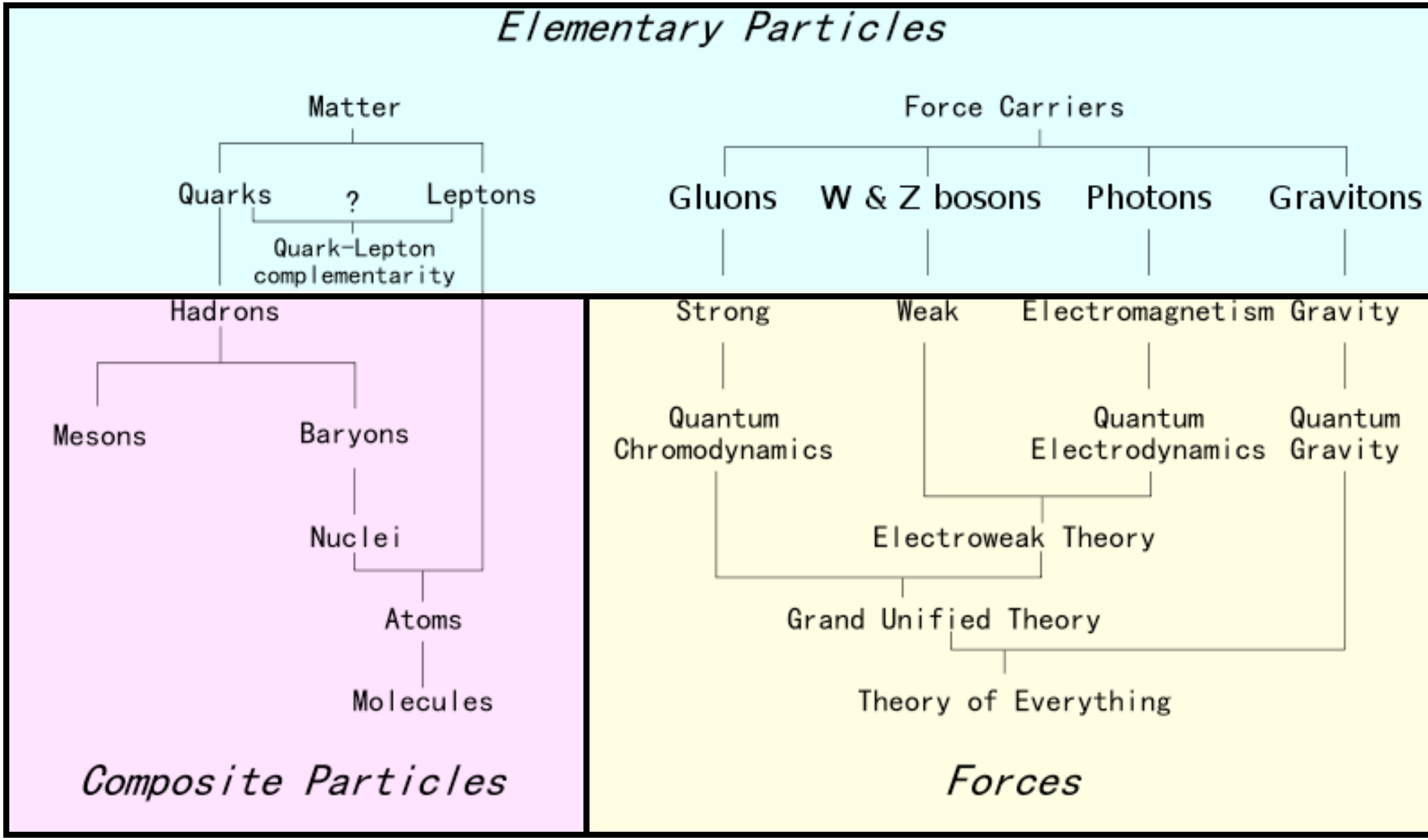


the nuclear force is a residual of the strong force

Particles and forces



Global symmetries

global symmetry ⇒ conservation law

homogeneity of space ⇒ momentum

homogeneity of time ⇒ energy

isotropy of space ⇒ angular momentum

isotropy of some abstract space ⇒ some "charge"

electric charge
colour charge

Mathematics and model building

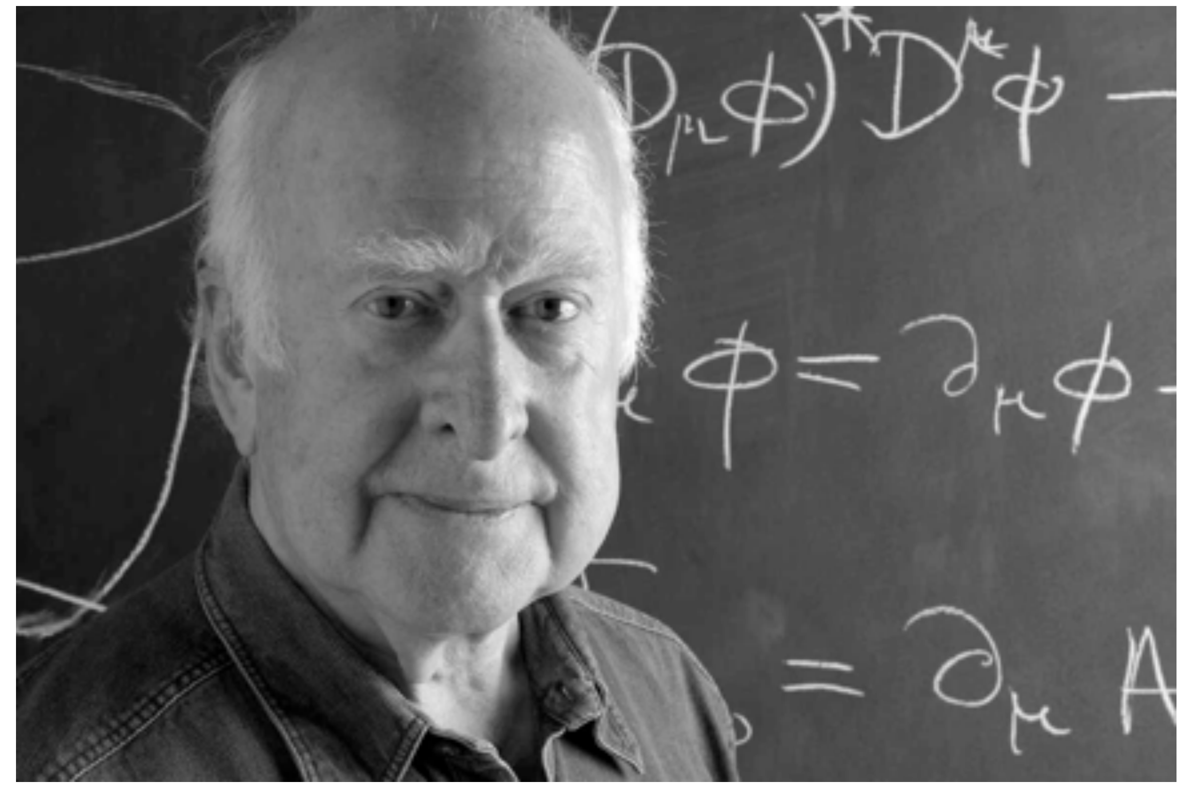
Our current understanding of the Laws of Nature is best formulated in the language of mathematics.

Abstract, but otherwise beautiful and often simple, concepts are difficult or impossible to grasp with our senses. They can be described using appropriate mathematical tools.

- Rotations is abstract spaces!
  - spin 1/2 fermions
- Extra spatial dimensions!

The Higgs mechanism

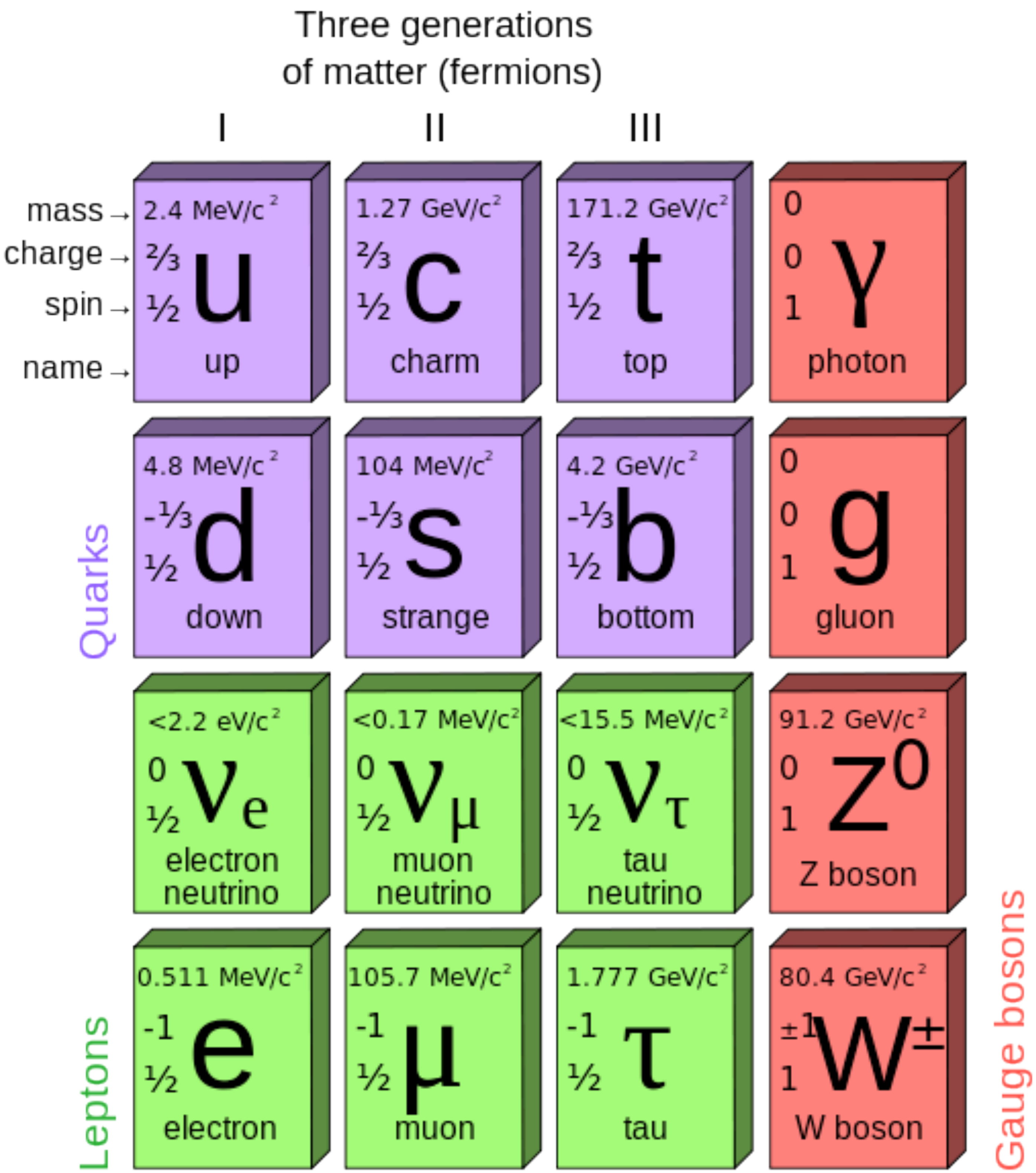
The Higgs Mechanism is such a mathematical construct that allows all particles to have mass while allowing the theory the keep powerful symmetries that predict all forces



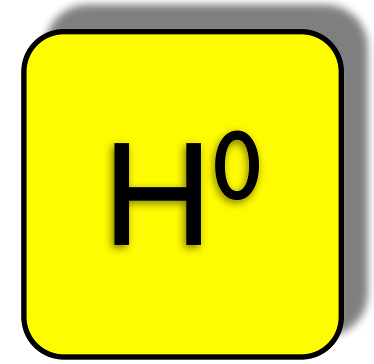
Peter Higgs
1929-

R. Brout, F. Englert, P. Higgs, G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble

The Standard Model

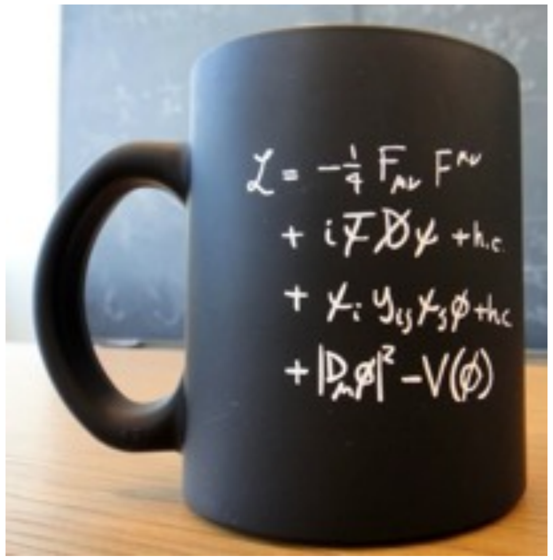


Higgs boson:
the missing piece



- The SM is a very successful theory
  - relativistic quantum fields
- All experimental measurements at the subatomic level agree with the SM to date!
- But it does not predict the mass of the Higgs boson!

The Standard Model



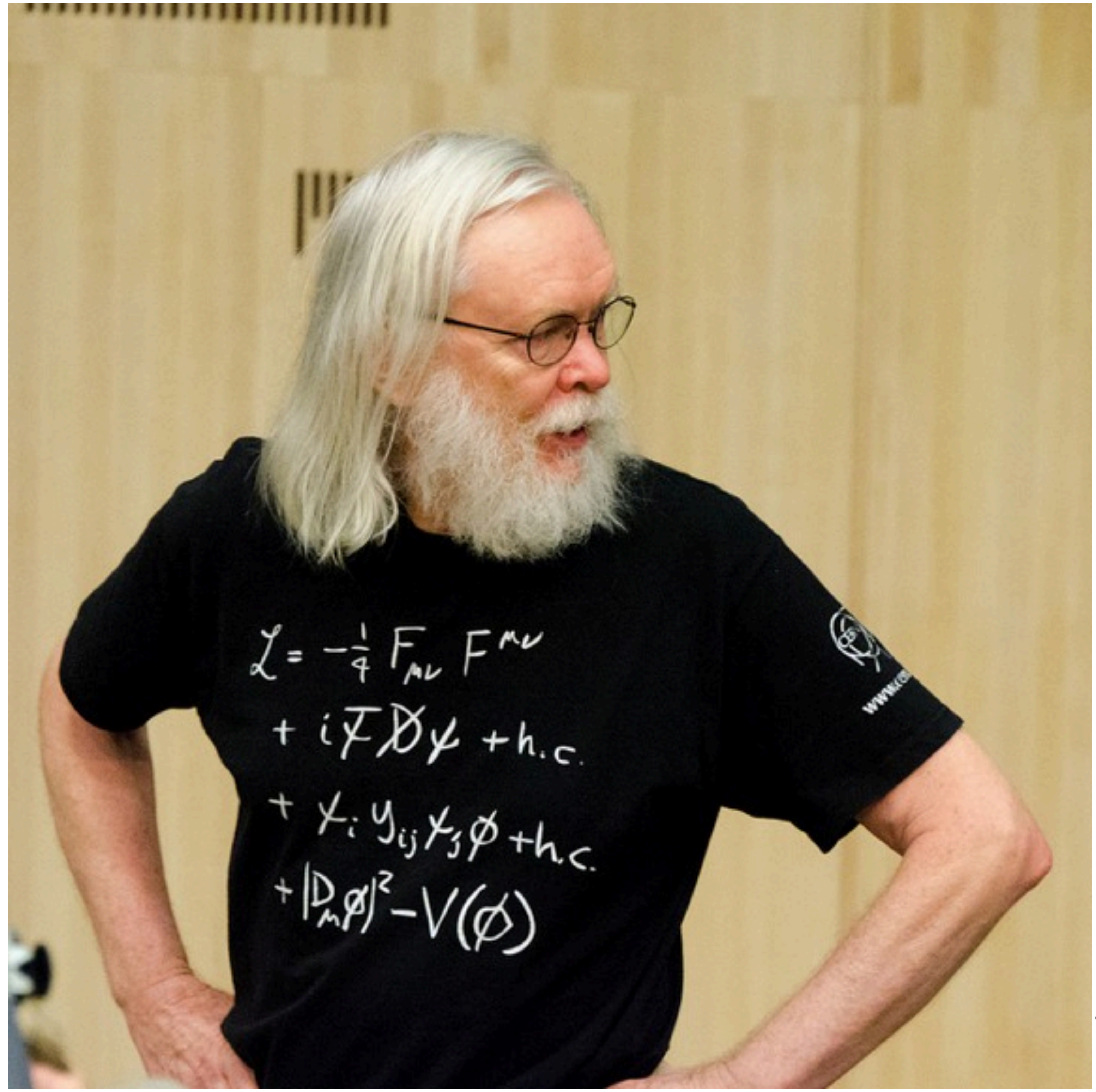
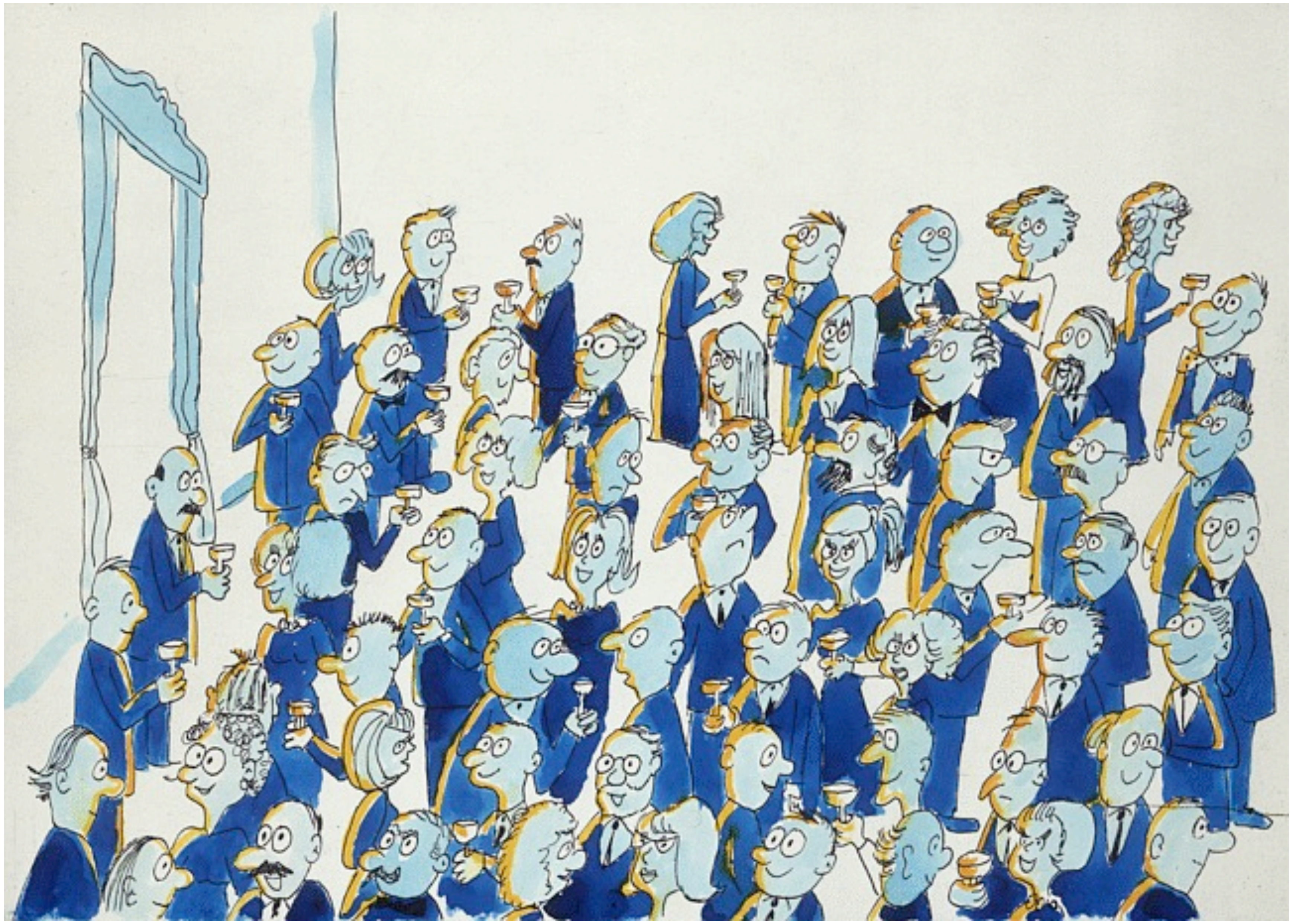


Photo: Josh Thompson

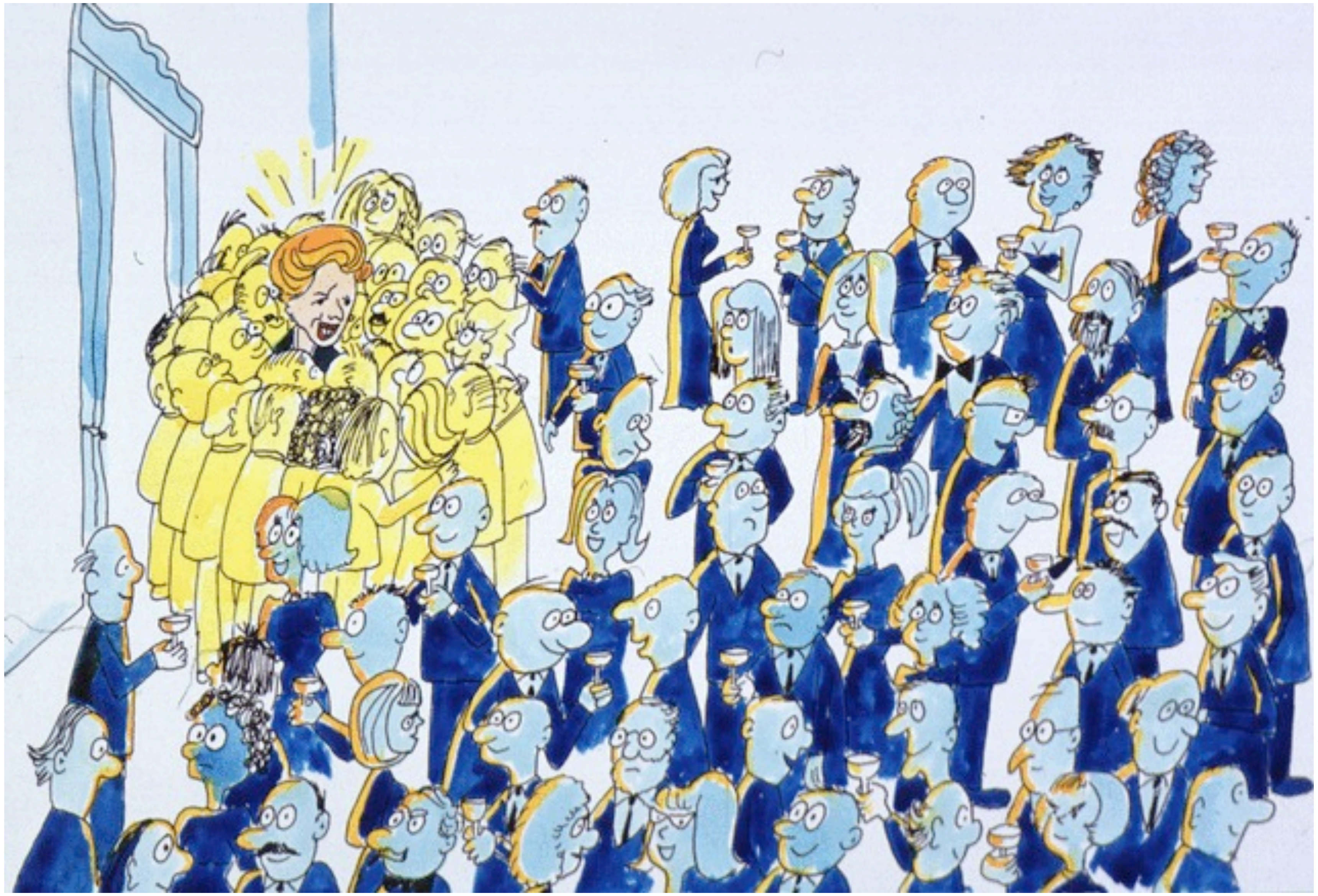
The Higgs Boson



From David Miller, UCL. Cartoon courtesy of CERN

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

The Higgs Boson



From David Miller, UCL. Cartoon courtesy of CERN

... a well-known person walks in, creating a disturbance as she moves across the room and attracting a cluster of journalists with each step. This increases her resistance to movement, in other words, she acquires mass, just like a particle moving through the Higgs field...

François Englert

The Higgs Boson

From David Miller, UCL. Cartoon courtesy of CERN

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

François Englert

The Higgs Boson

From David Miller, UCL. Cartoon courtesy of CERN

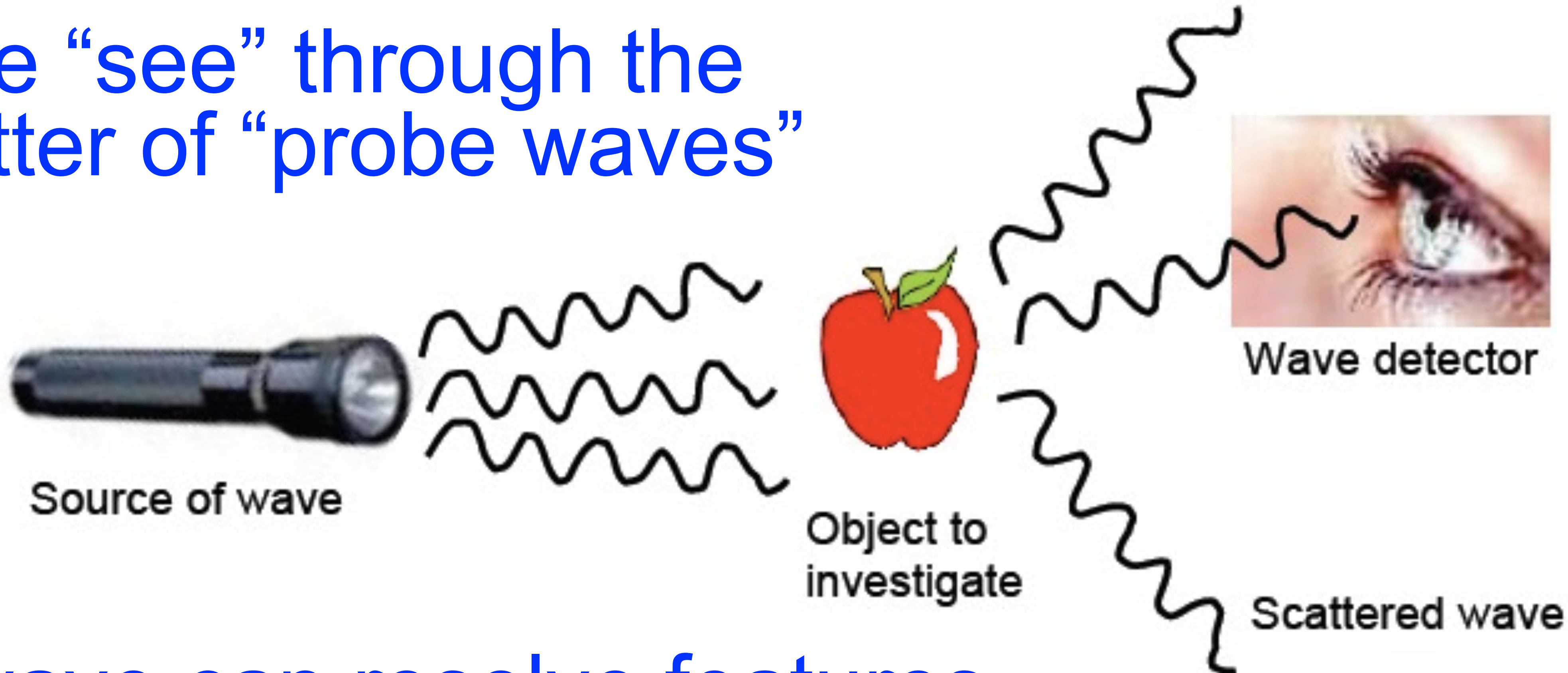
... it creates the same kind of clustering, but this time among the journalists themselves. In this analogy, these clusters are the Higgs particles.

François Englert

Collider and Detector

Scattering Experiments

We "see" through the scatter of "probe waves"

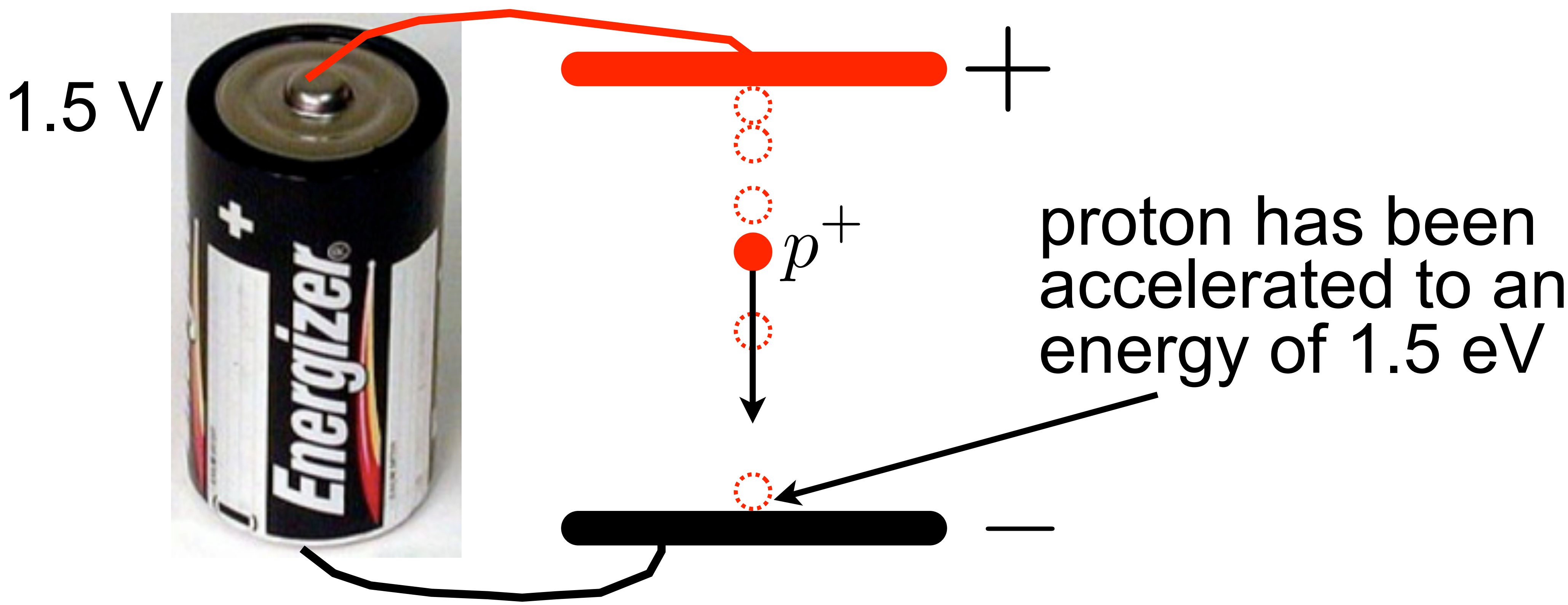


The wave can resolve features about the size of its wavelength

use particle "matter waves"

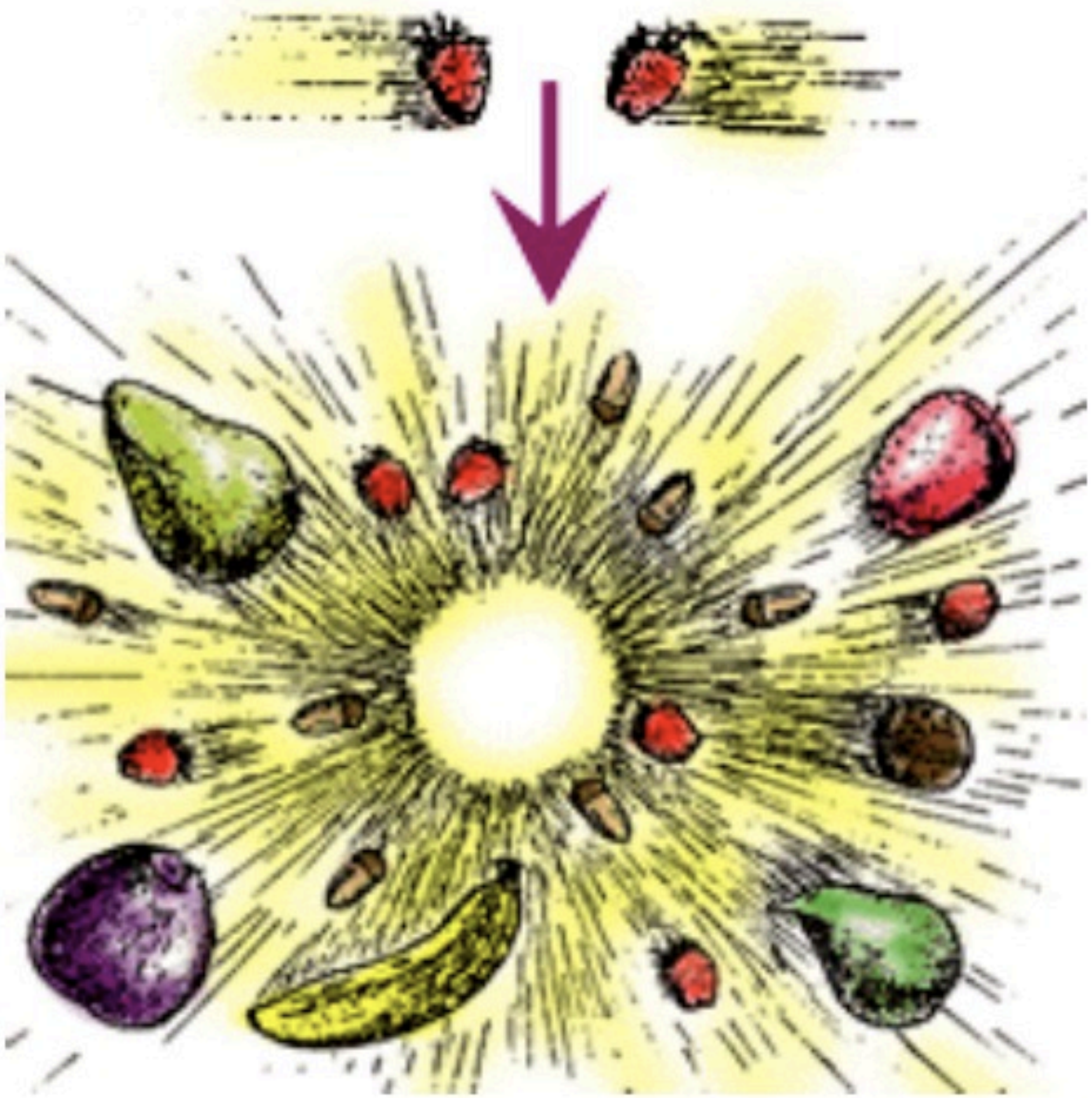
High energy particle ⇔ small matter wave!

Accelerating



- Here the proton gains 1.5 eV of energy
- Charged particles can also be accelerated using electromagnetic waves to reach much higher energies
  - 1 MeV = 1,000,000 eV
  - 1 GeV = 1,000,000,000 eV ~ mc^2 for proton!
  - 1 TeV = 1,000,000,000,000 eV

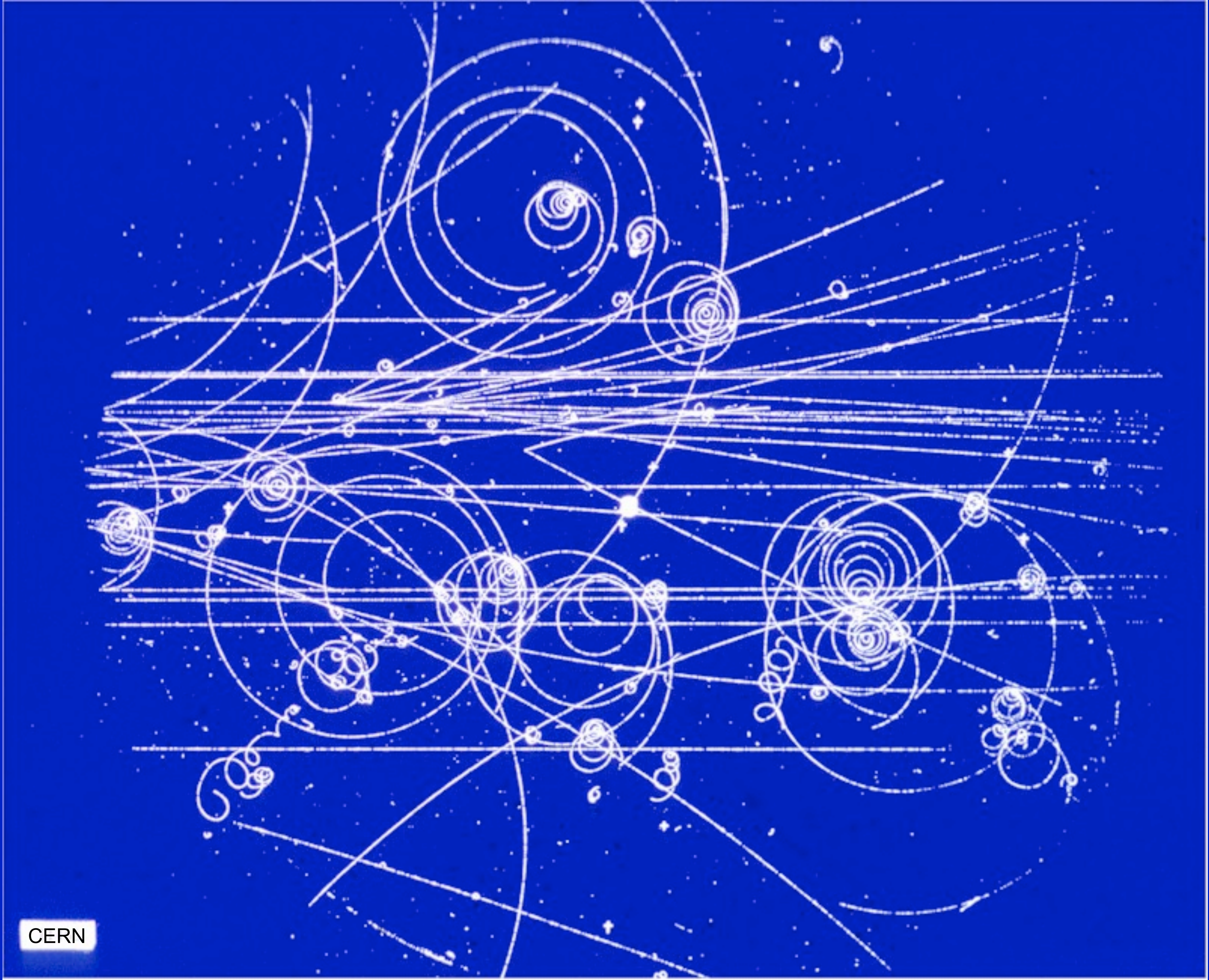
Colliding



Particles and antiparticles, perhaps new and unknown ones, can be produced from the pure energy available after the collision

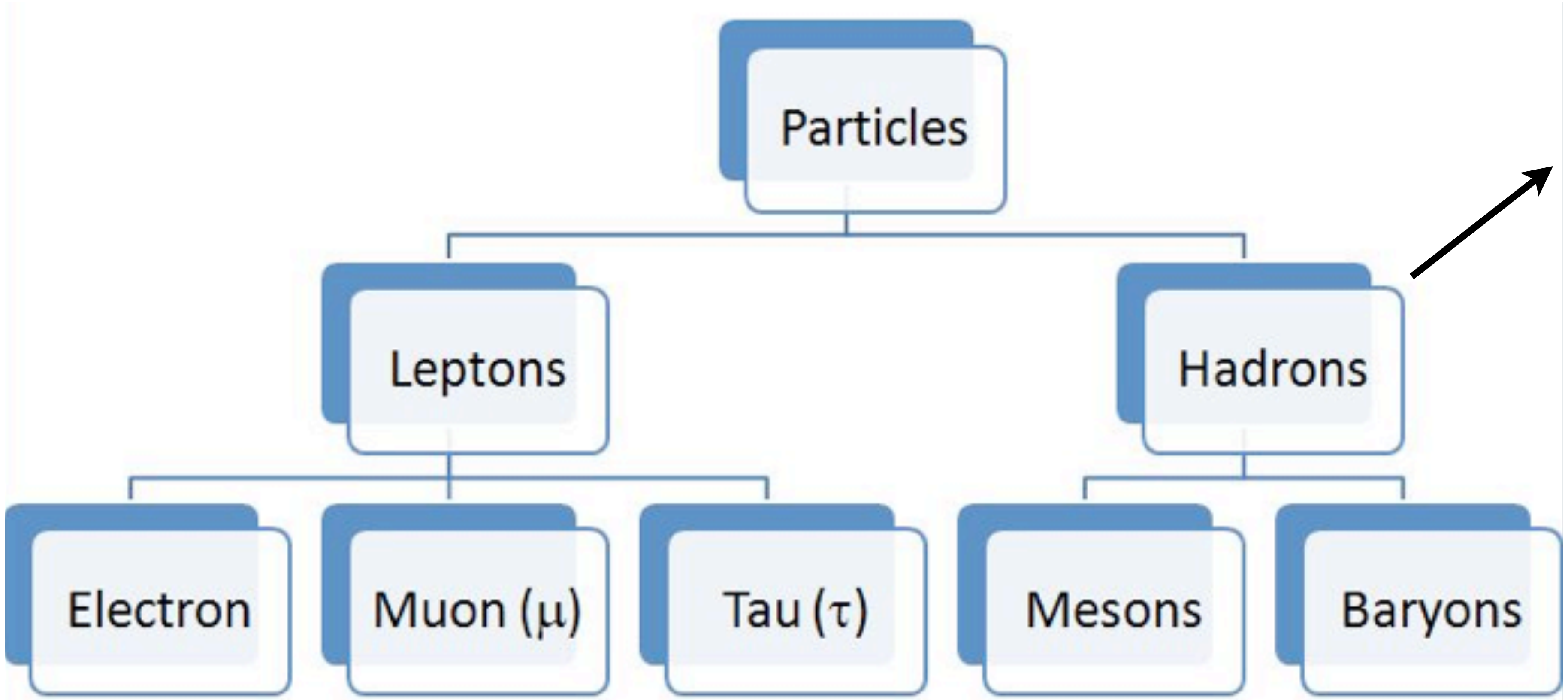
$$E = mc^2$$

New particles signal new physical laws!



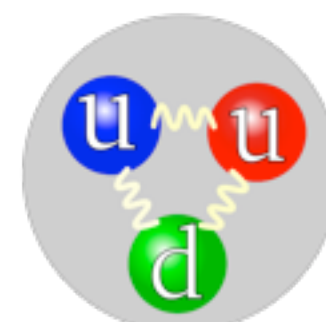
CERN

Hadrons



made of quarks

π^+



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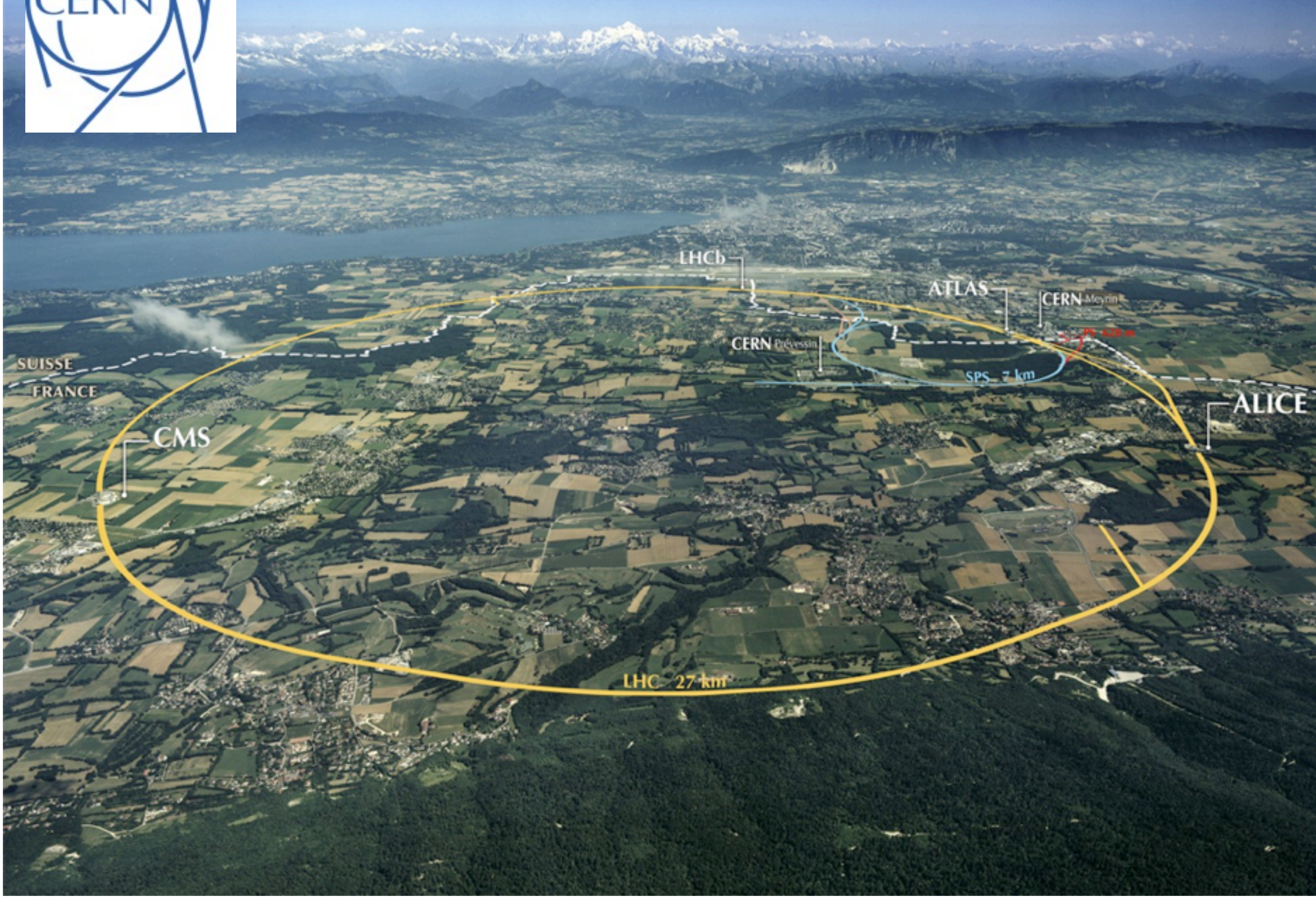
Arial view of CERN

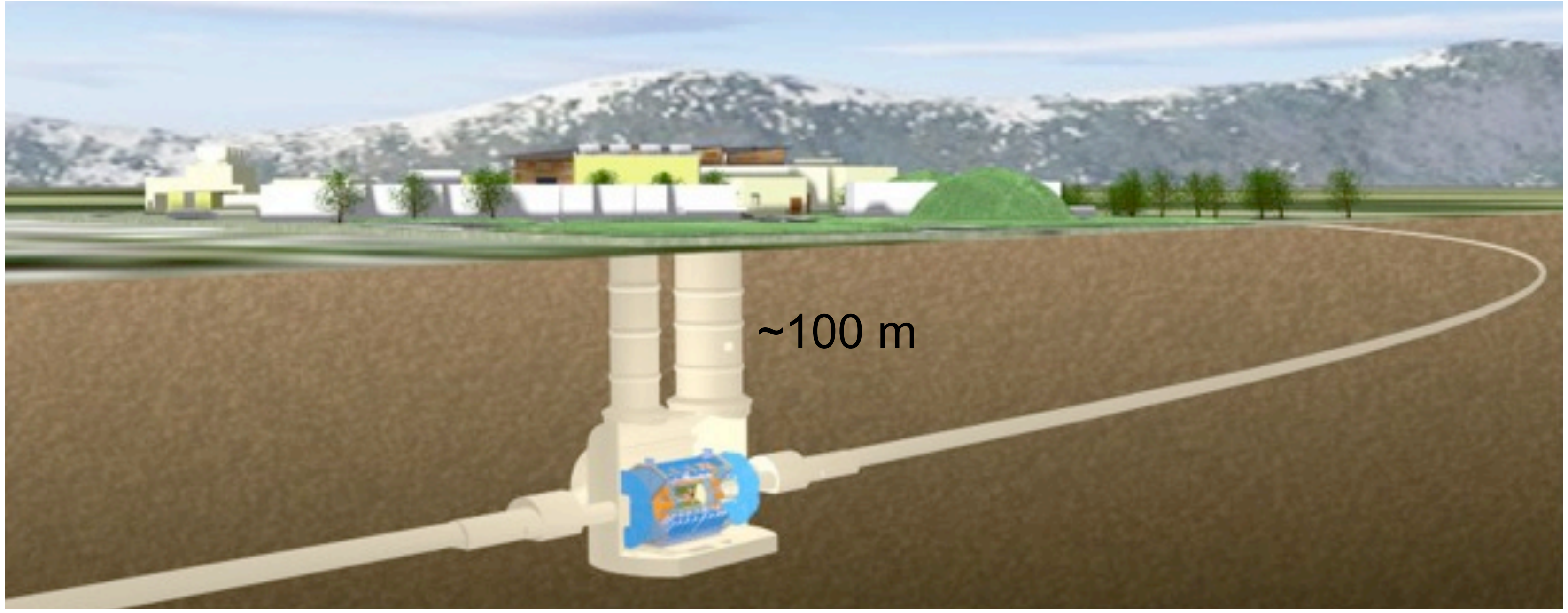


CERN PhotoLab CERN-MI-0807031

Getting around in the Large Hadron Collider

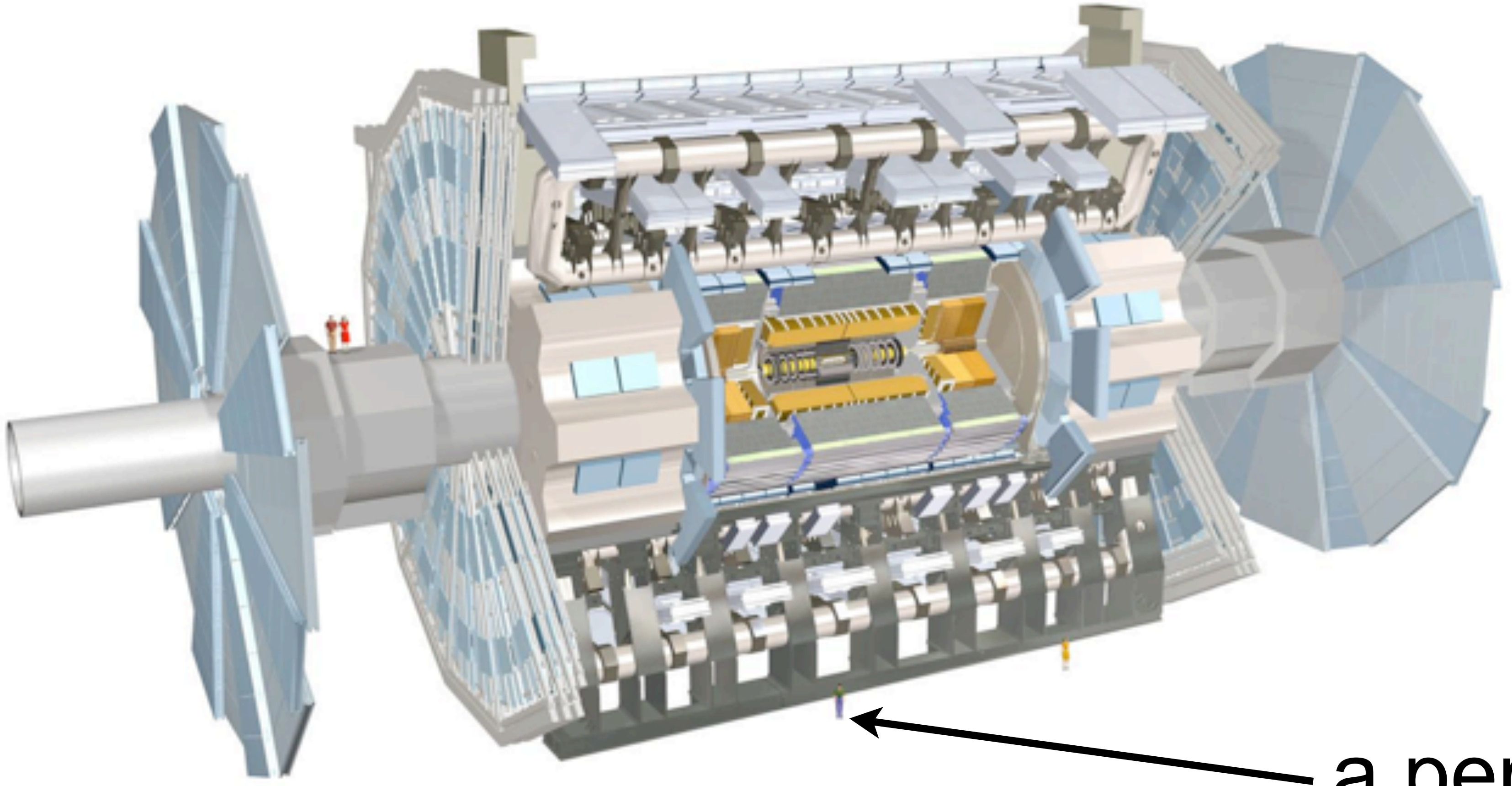
The ATLAS Experiment at CERN, http://atlas.ch

The ATLAS detector at the LHC

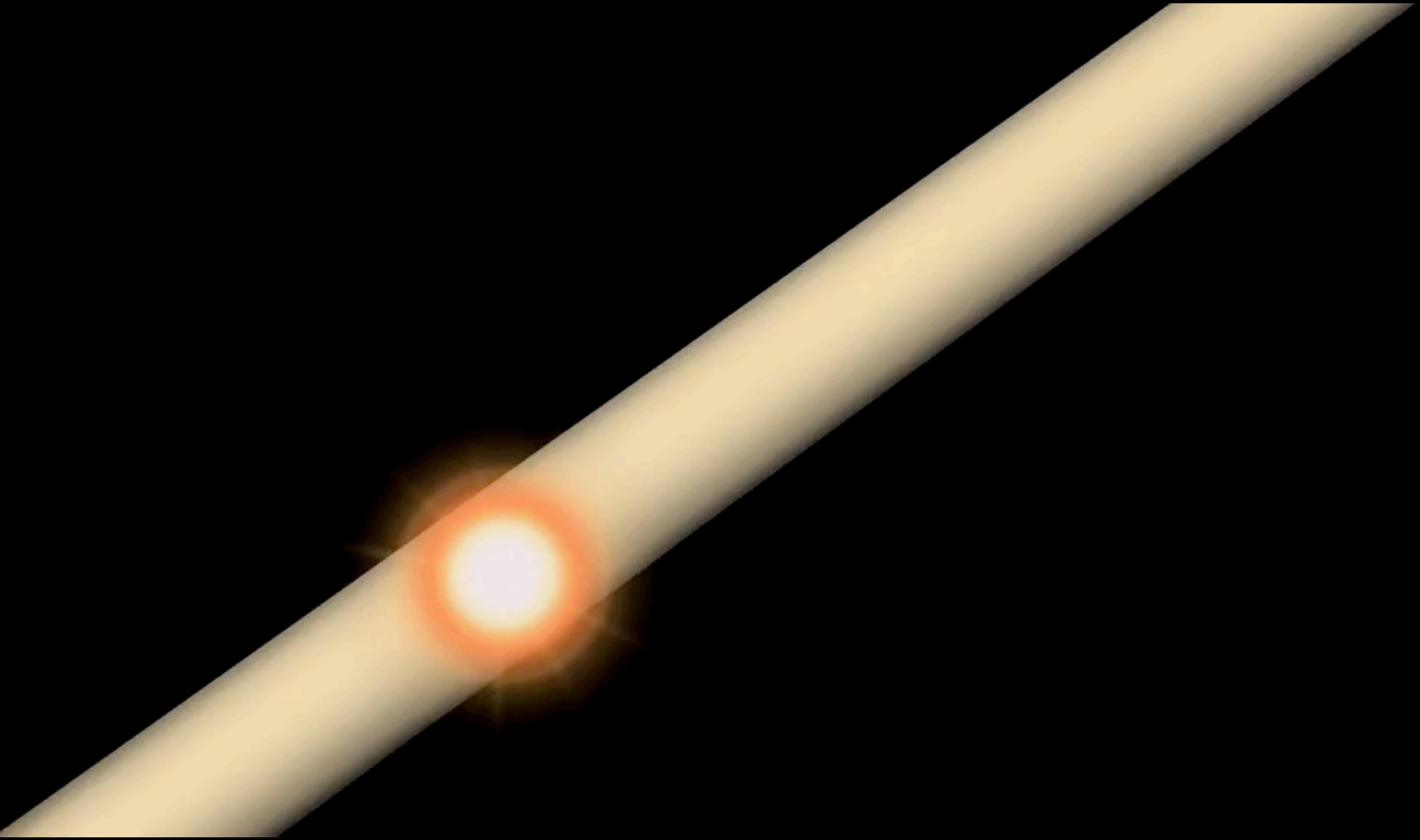


The ATLAS Experiment at CERN, http://atlas.ch

LHC magnets operate at 1.9 K
1232 dipoles (8.4 T, 34 t)
392 quadrupoles



a person!



http://www.atlas.ch/multimedia/4-muon-event.html

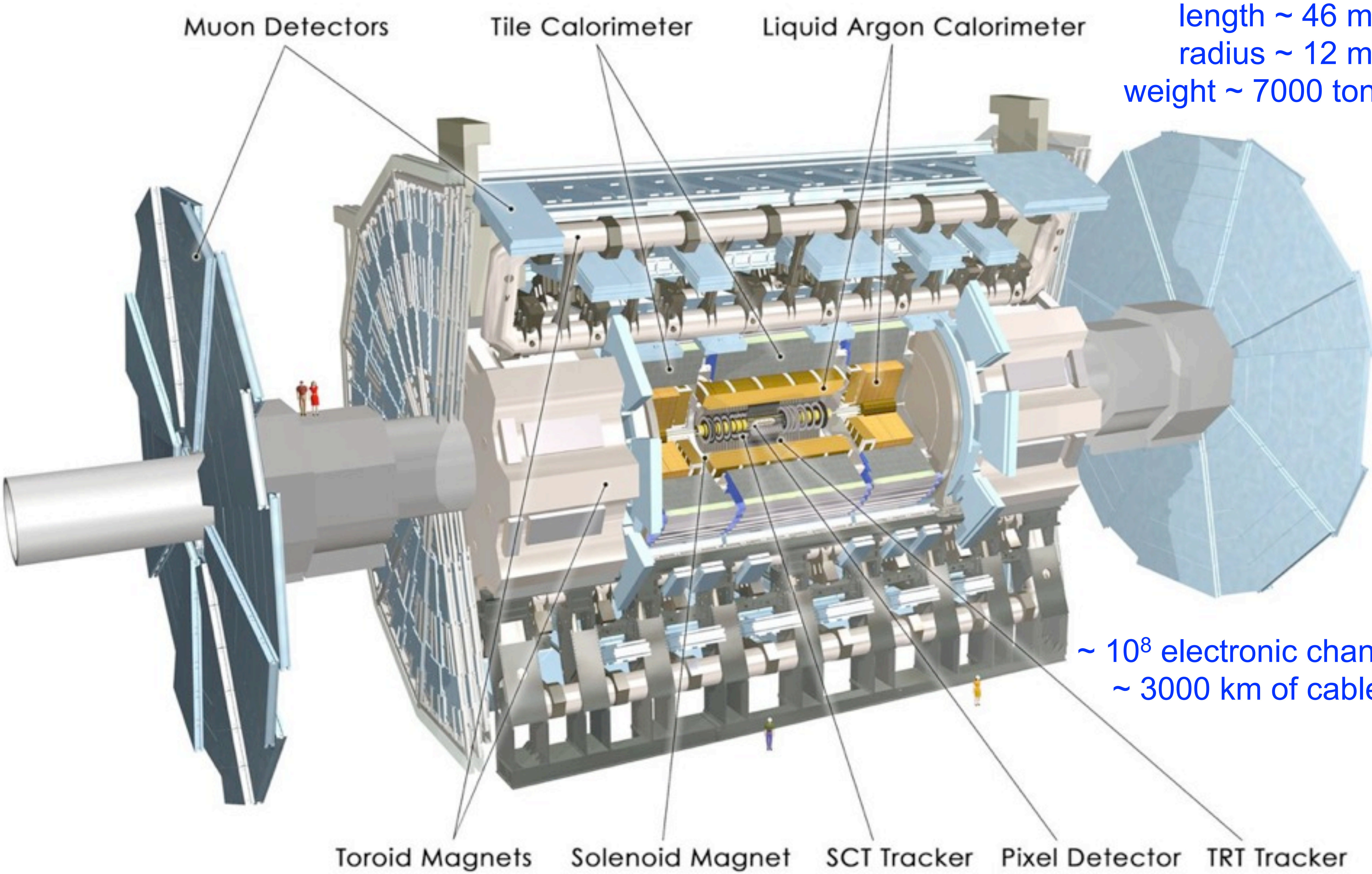
Historical Picture

The WWW was invented at CERN in the late 80's

The LHC was already a hot topic!

The first photographic image on the Web in 1992!

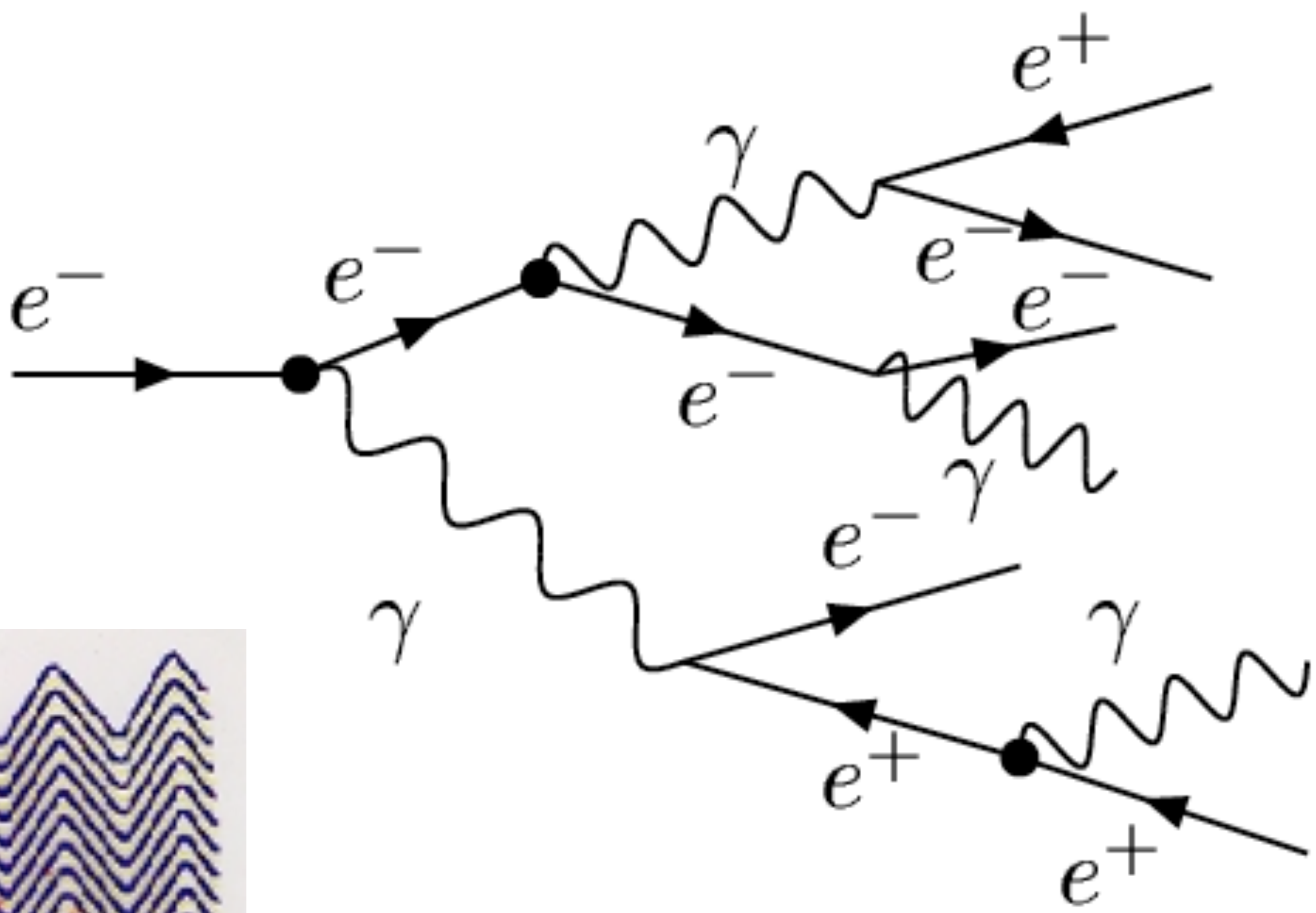
The ATLAS detector

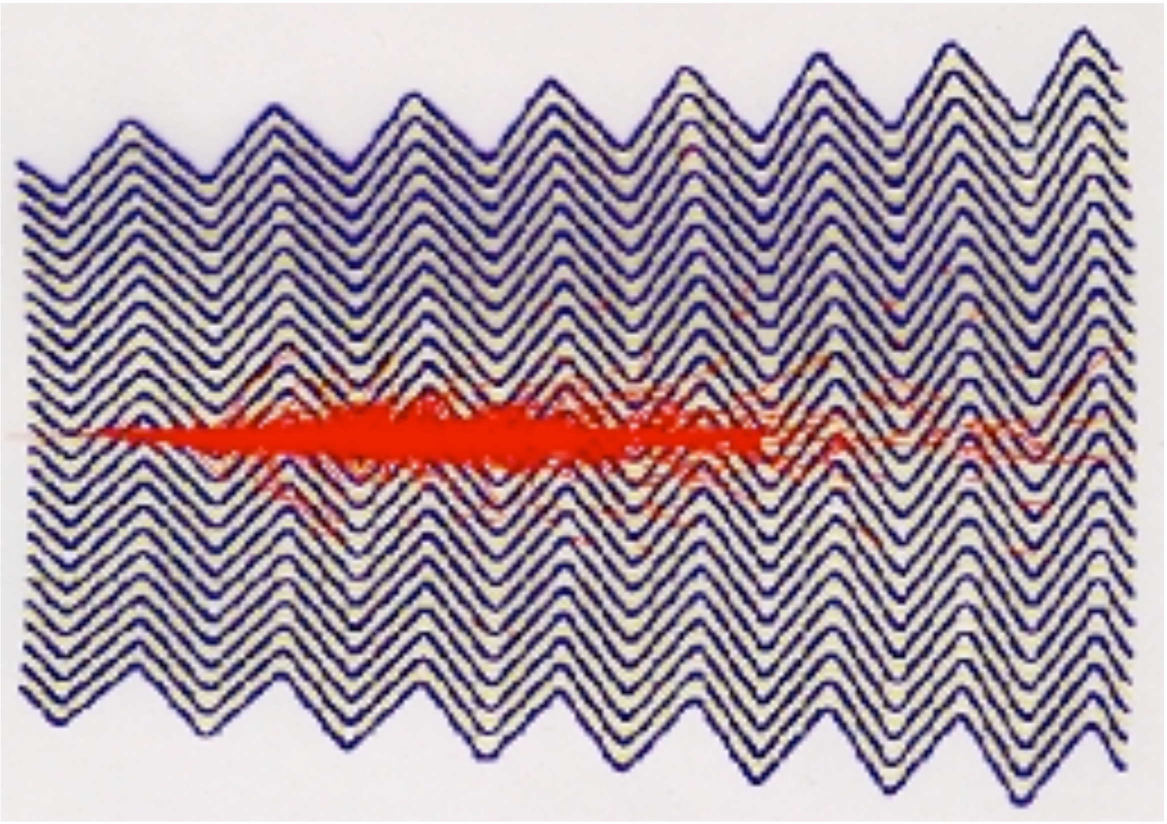


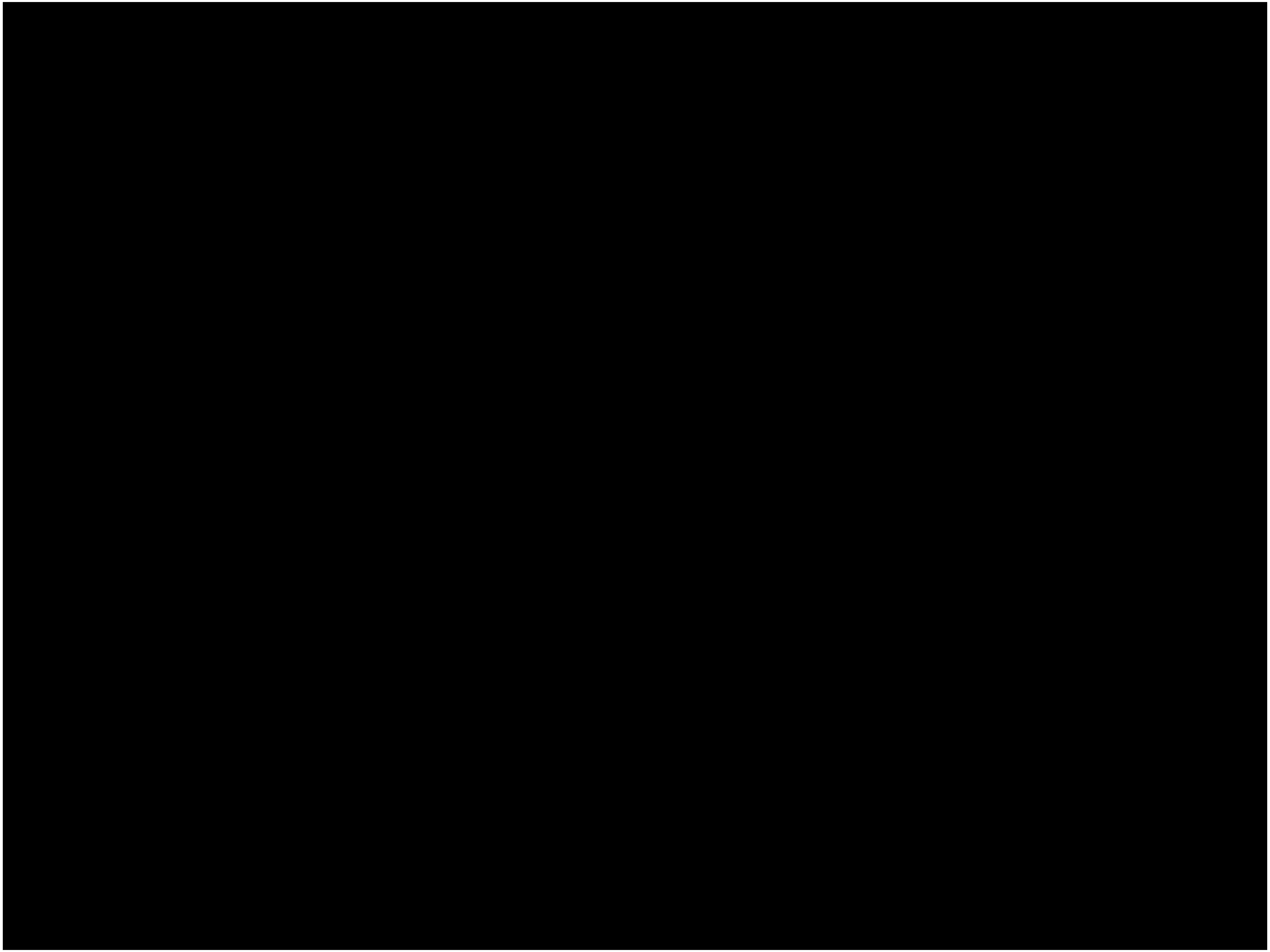
length ~ 46 m
radius ~ 12 m
weight ~ 7000 tonnes

~ 10^8 electronic channels
~ 3000 km of cables

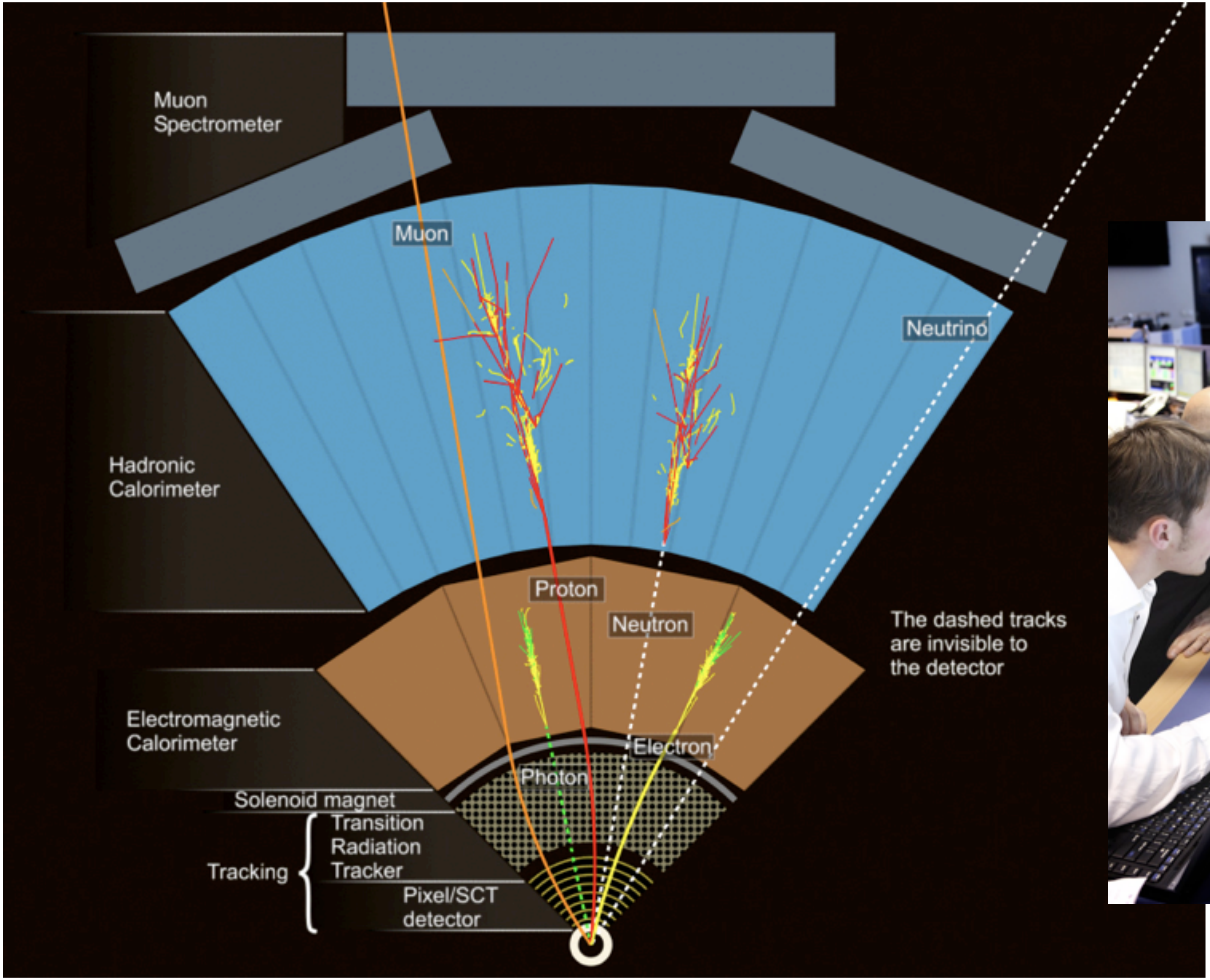
Electromagnetic shower



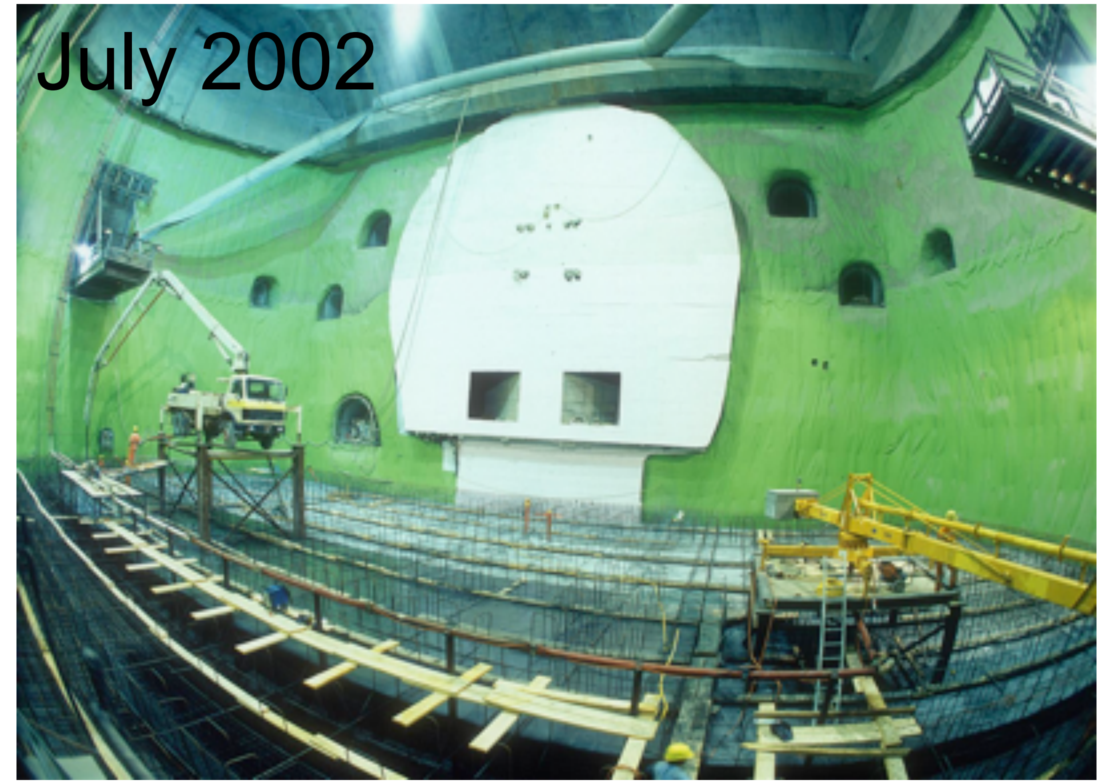


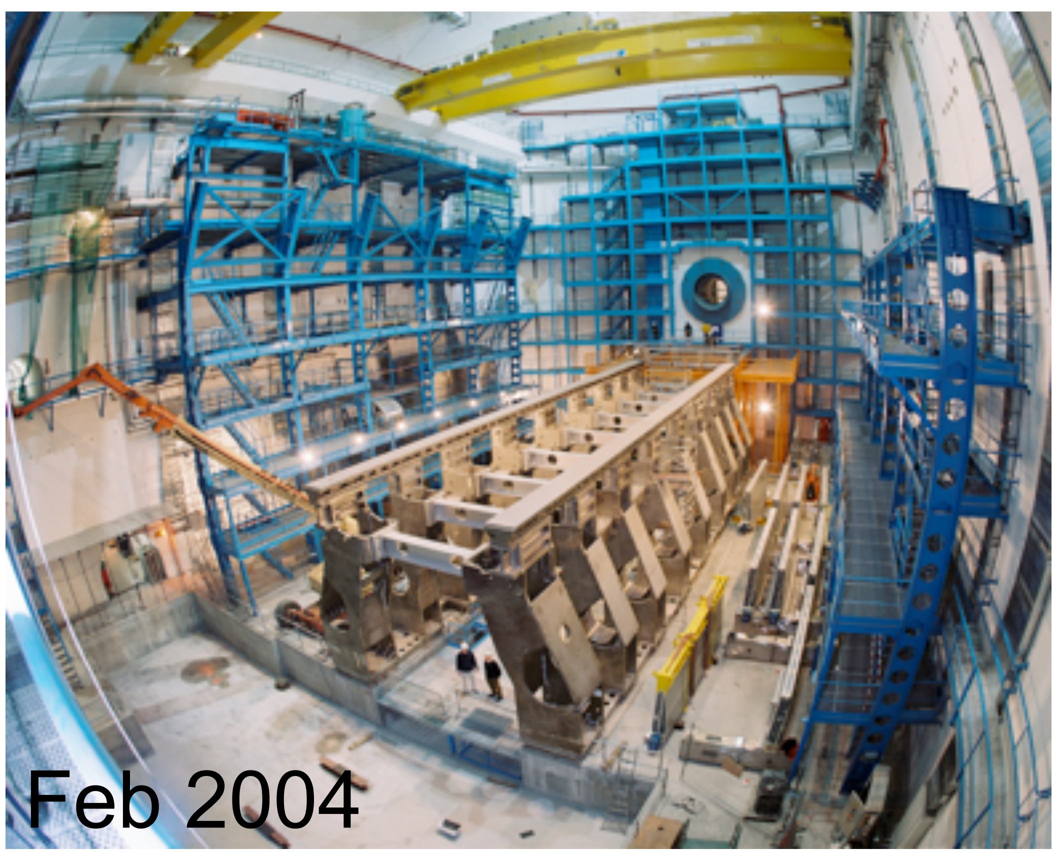


Particle identification in ATLAS

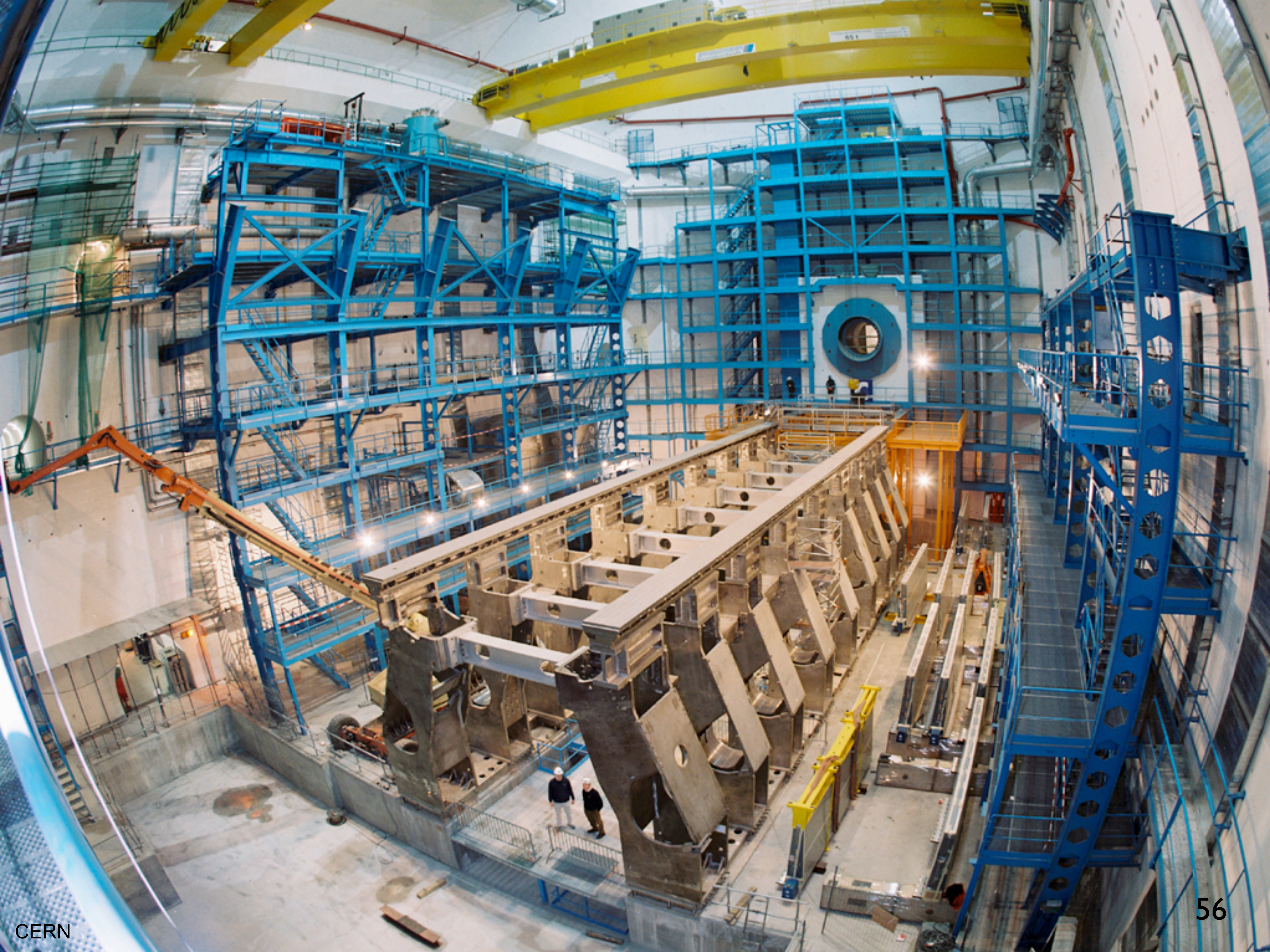


ATLAS cavern

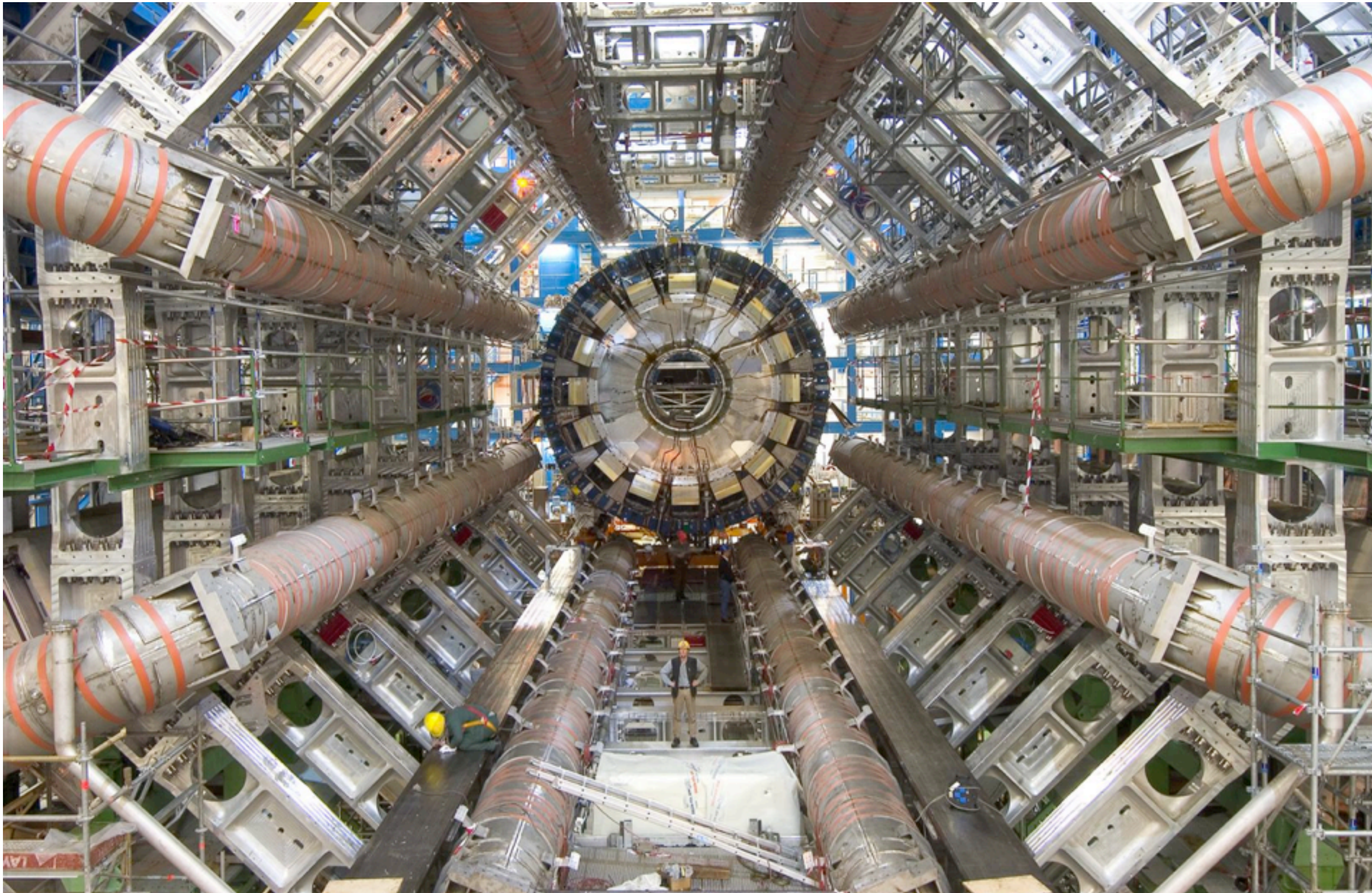




The ATLAS Experiment at CERN, http://atlas.ch

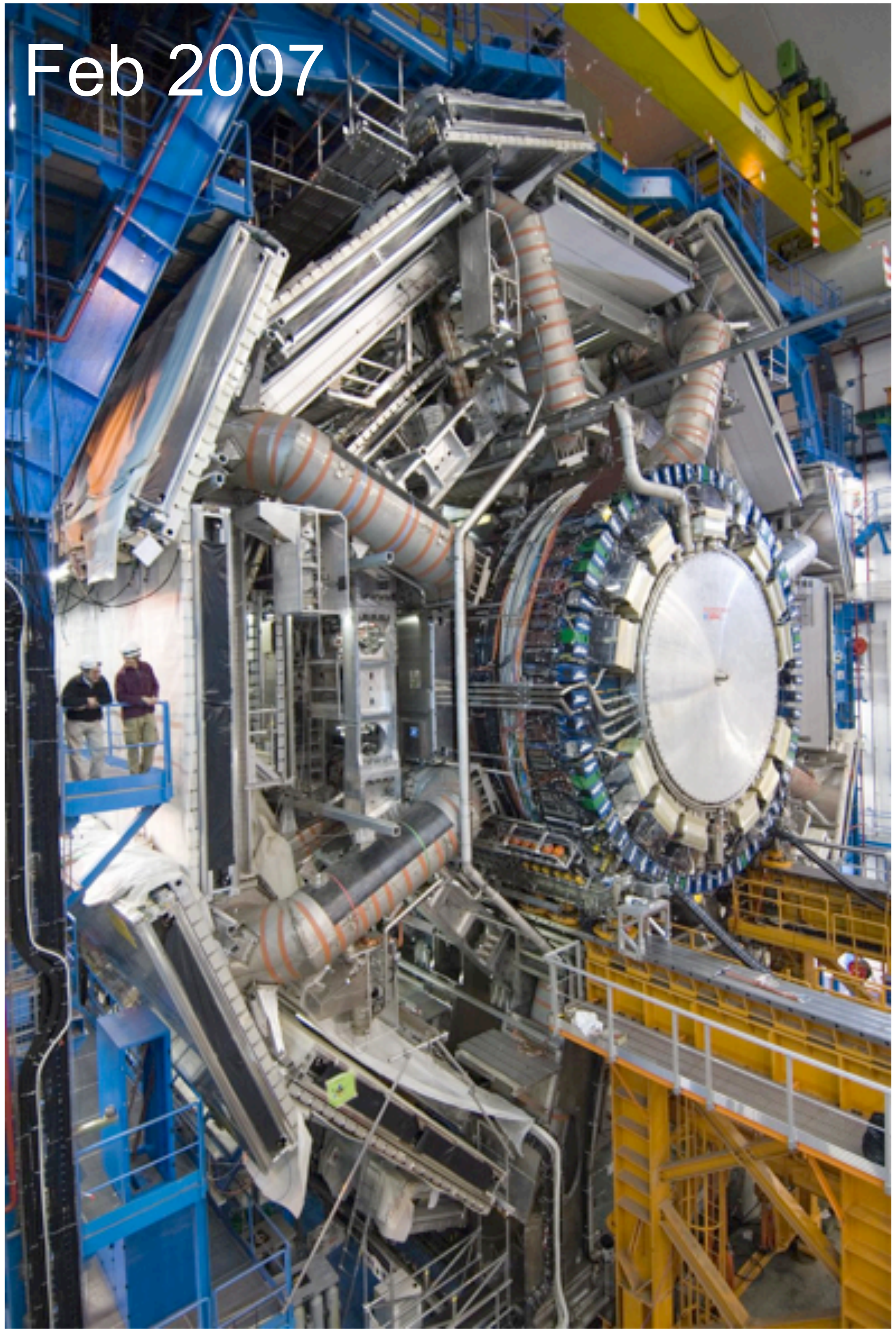

CERN

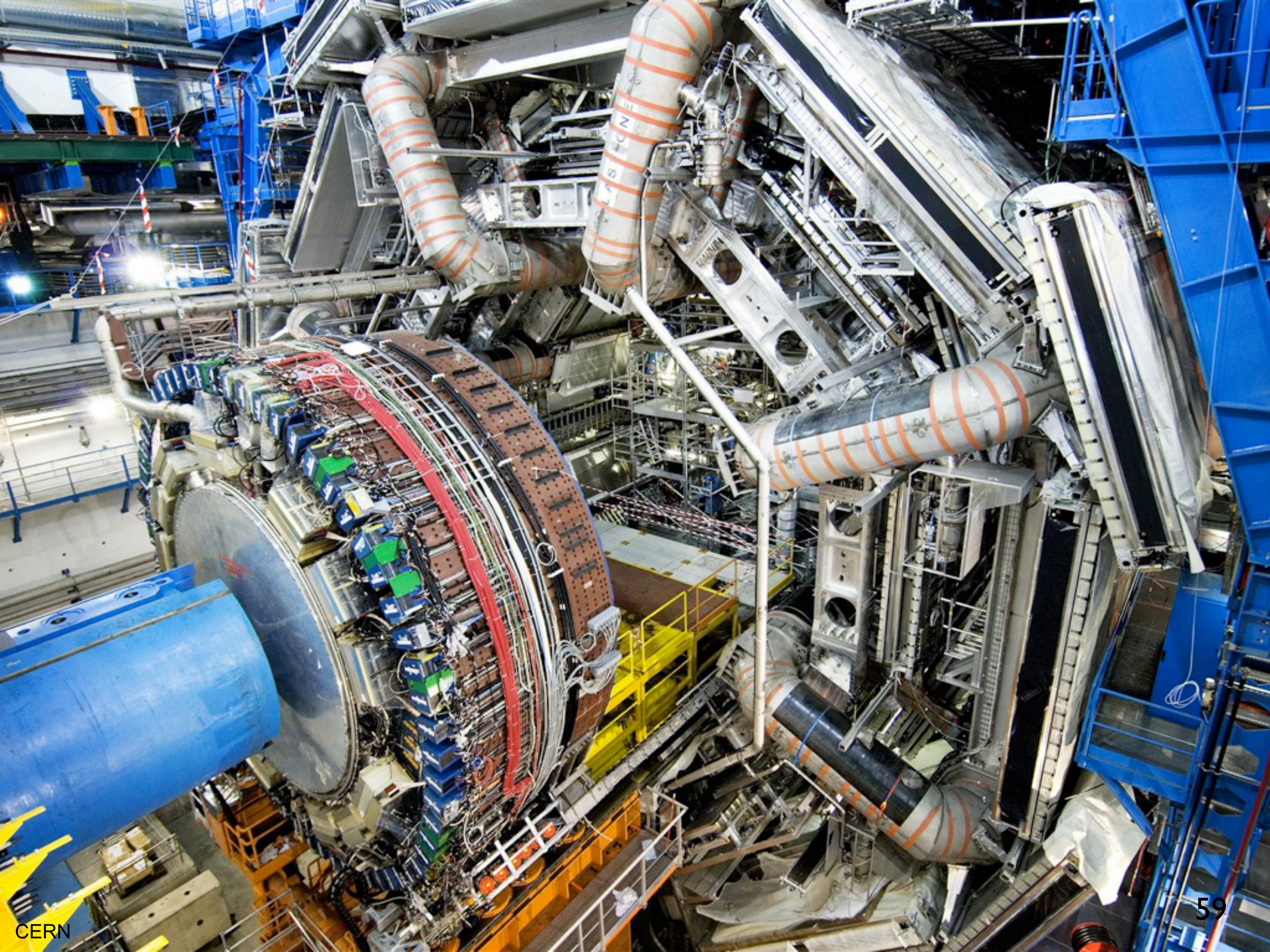
Barrel Toroids all installed (Nov 2005)



The ATLAS Experiment at CERN, http://atlas.ch

Moving the calorimeters in place

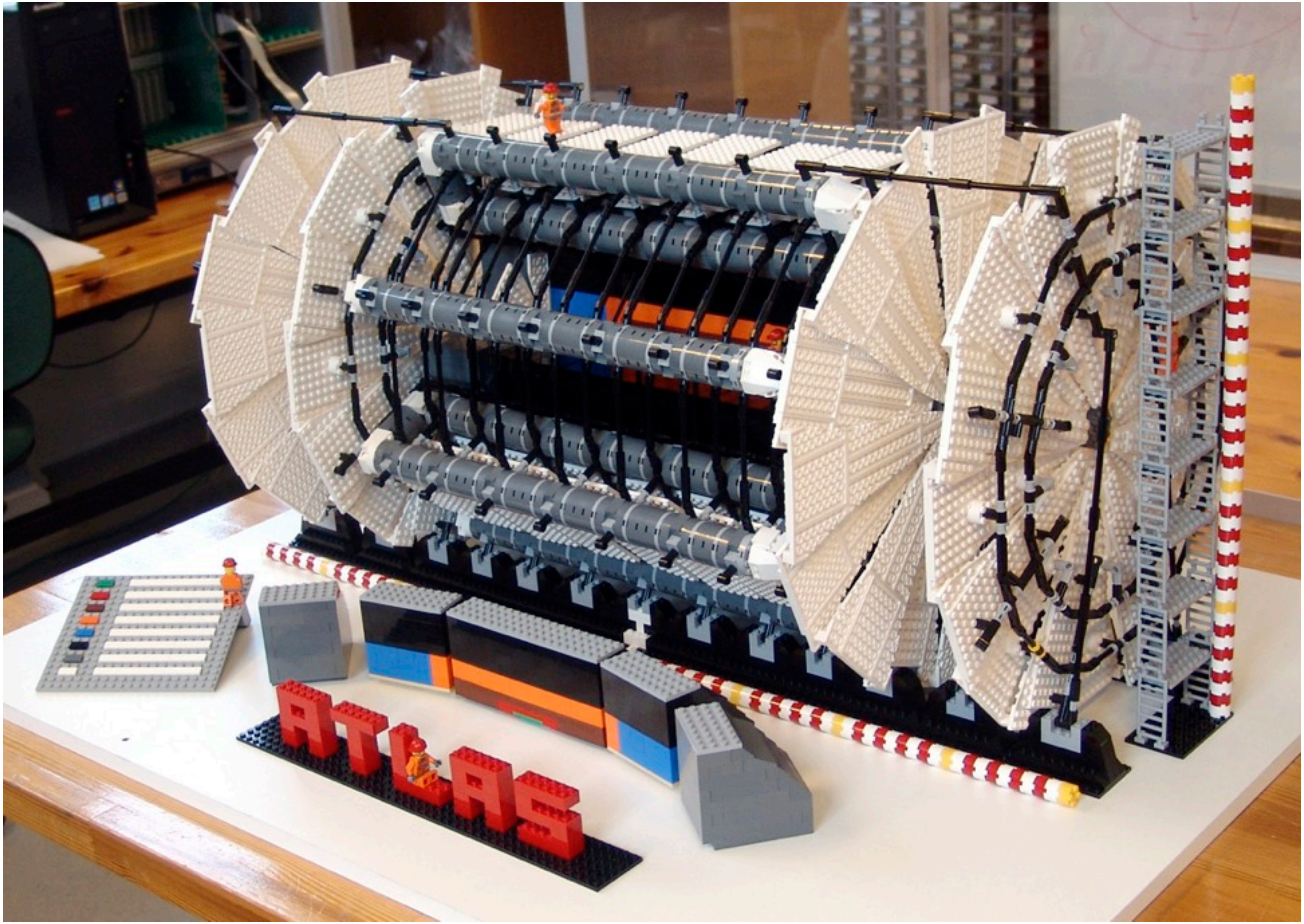




CERN

Closing of LHC beam pipe (16 June 2008)

The ATLAS Experiment at CERN, http://atlas.ch


ATLAS

The ATLAS Collaboration

- 38 countries
- 174 institutions
- 3000 scientific participants
  - about 1000 students

ATLAS EXPERIMENT
http://atlas.ch

ATLAS and Canada

Alberta
Carleton
McGill
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York

- ATLAS celebrated its 20th anniversary on Oct 1st
- Over 150 Canadian scientists participate in the ATLAS experiment
- ATLAS Canada Collaboration
  - Founded in 1992 ML, UVic
  - Spokesperson (07-) Rob McPherson, UVic/IPP
  - Deputy Dugan O'Neil, SFU
  - Physics Coordination Pierre Savard, UofT/TRIUMF
  - Computing Coordination Reda Tafirout, TRIUMF
- Contributions to the ATLAS detector construction
  - Calorimetry, cryogenics, electronics, trigger, ...
- Contributions to the LHC construction (TRIUMF)
- TRIUMF, Canada's nuclear and particle physics laboratory located in Vancouver
  - http://www.triumf.ca/

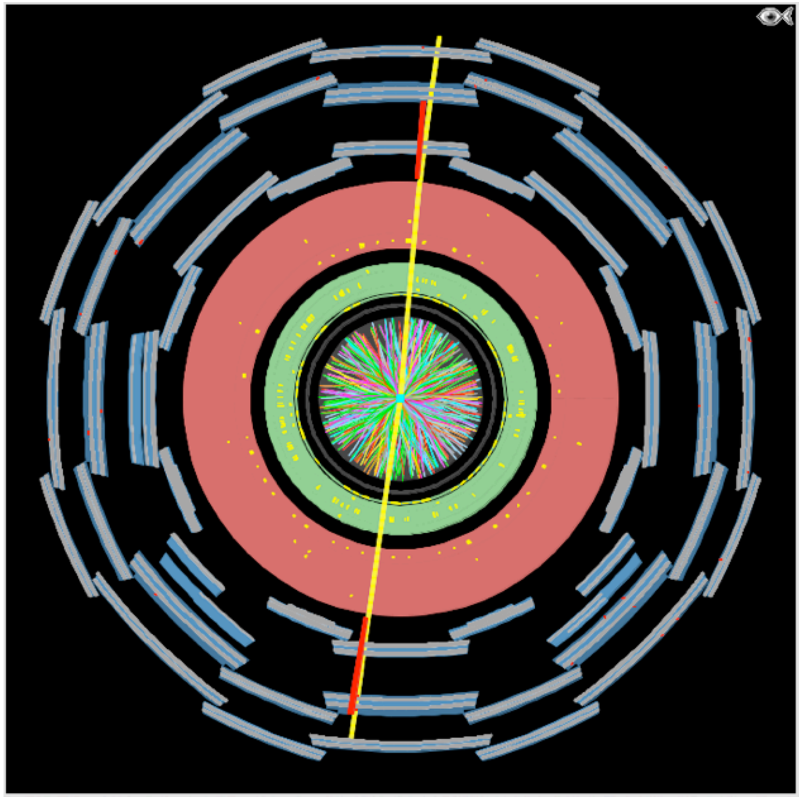
ATLAS Control Room: first 7 TeV Collisions

The ATLAS Experiment at CERN, http://atlas.ch

Busy in the ATLAS control room...

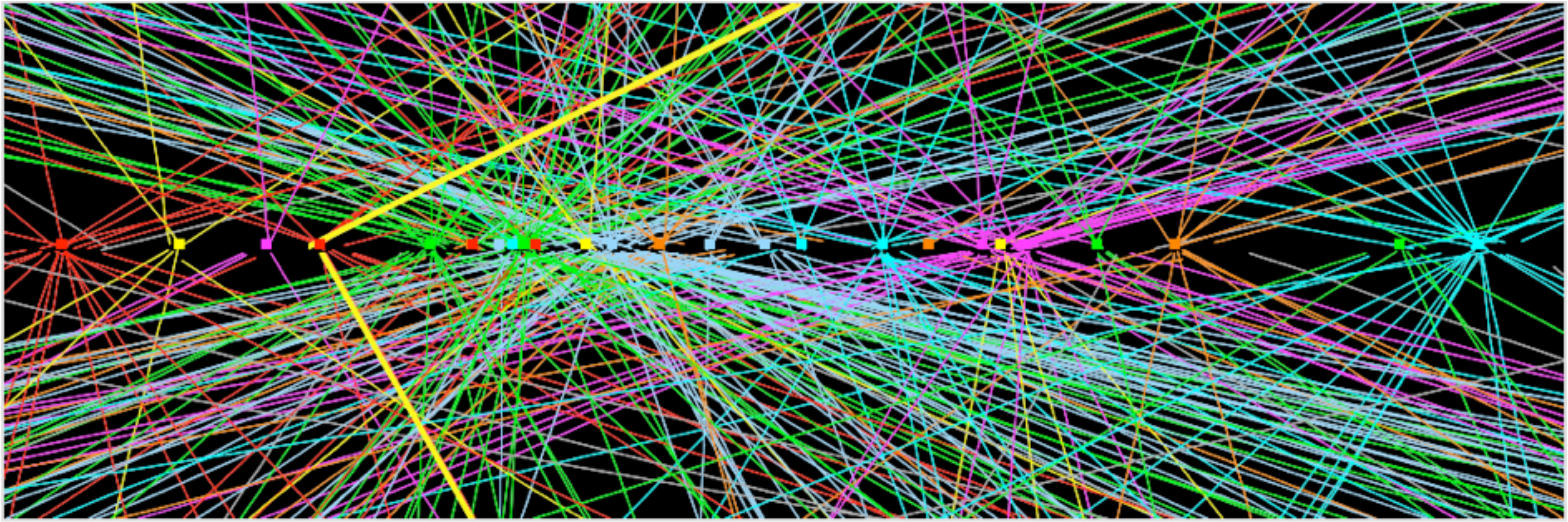
Experimental challenge: Pile-up

- In-time pile-up
  - due to multiple collisions per bunch crossing
  - **in 2012, ~20 events per bunch crossing!!**
- Out-of-time pile-up
  - superposition of signal from preceding (and following) bunch crossing



$Z \rightarrow \mu^+\mu^-$ event with 25 vertices

~1cm



SM production cross sections

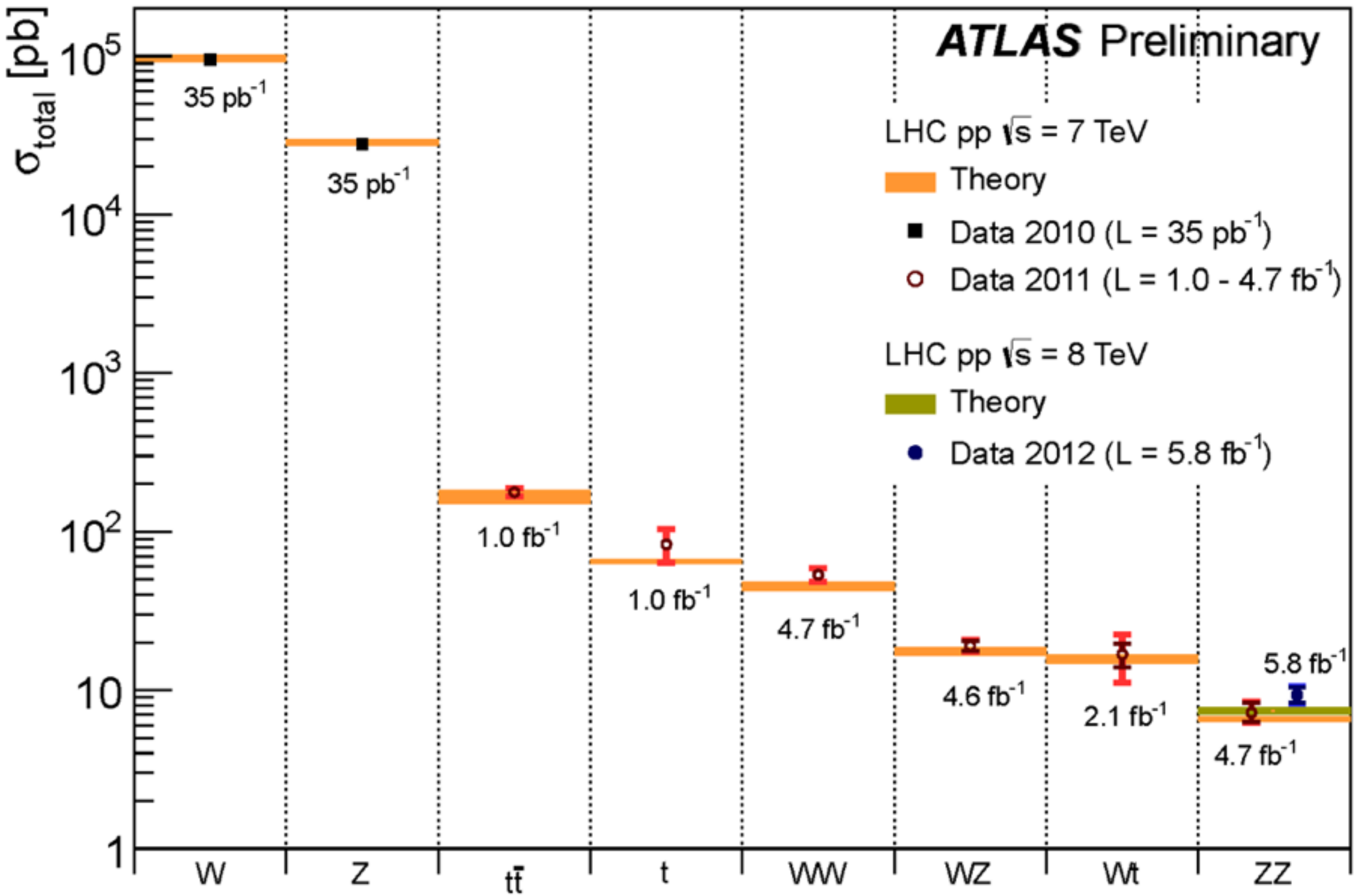


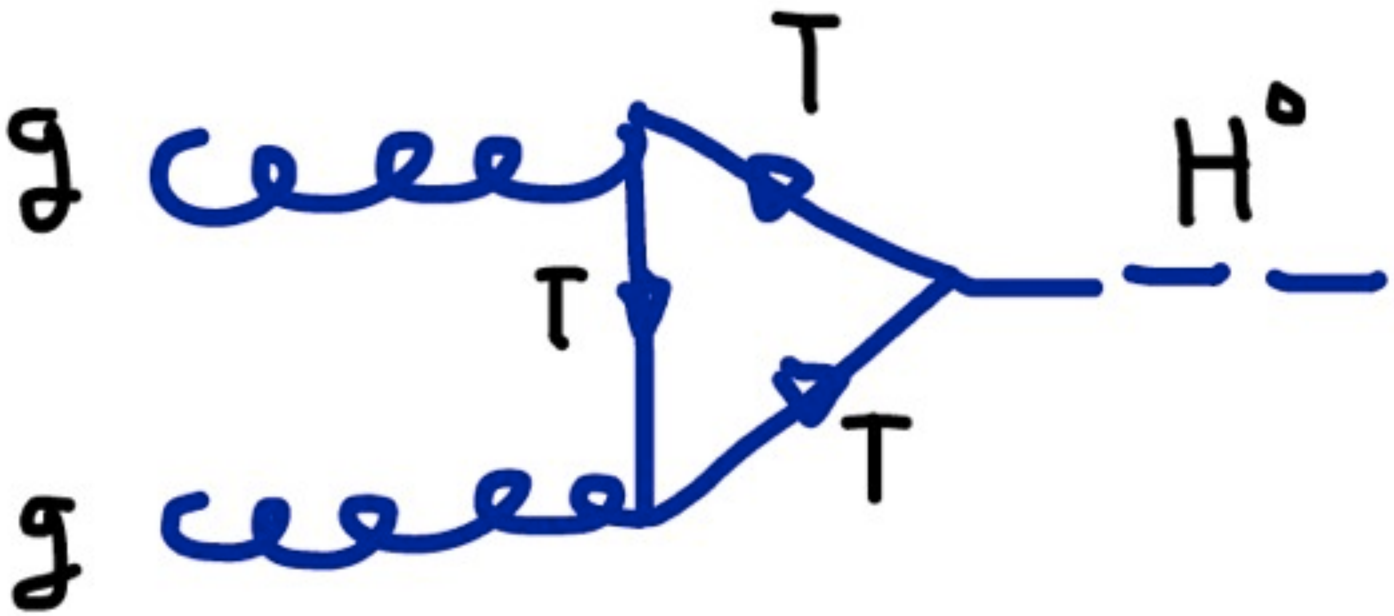
figure as of 2012/06/30

the **Higgs boson**: the missing piece

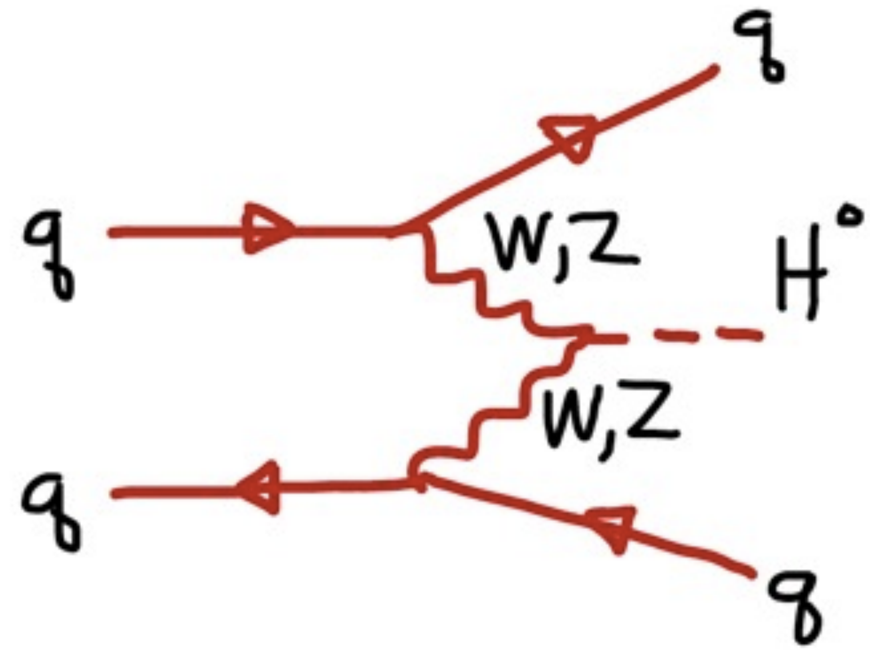
H^0

neither matter nor force

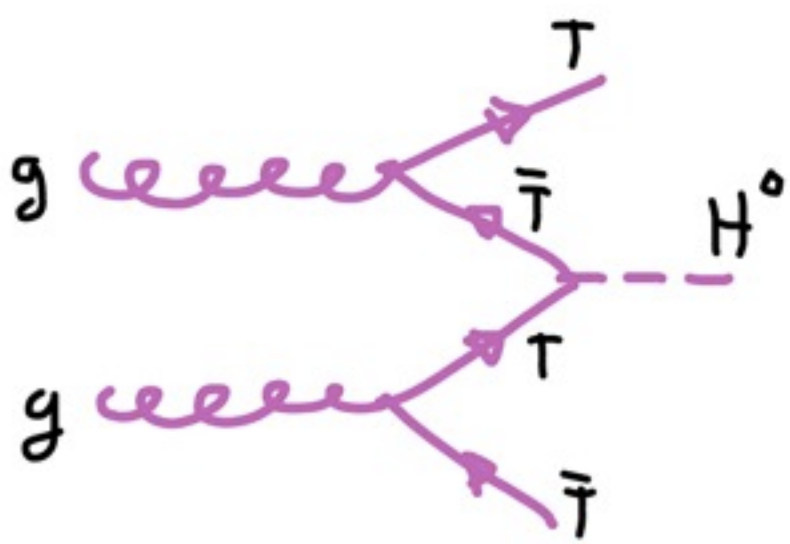
Higgs production



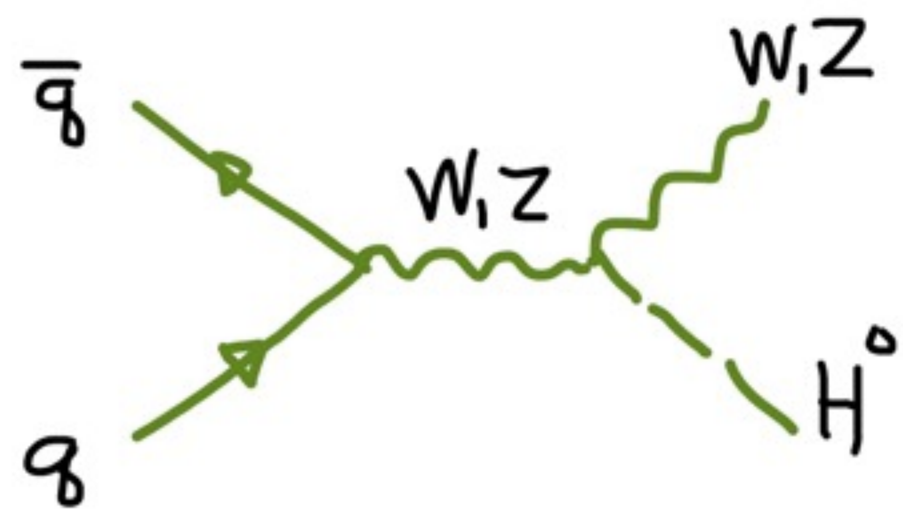
gluon fusion



W,Z fusion



top-antitop fusion



W,Z bremsstrahlung

Higgs decays

Many possible decay channels of the Higgs boson

~58% $H \rightarrow b\bar{b}$

~0.5% $H \rightarrow W\,W^{(*)} \rightarrow e\,\nu\,\mu\,\nu$

~6.3% $H \rightarrow \tau\,\tau$

Here the most important decays for searches, with fractions for M_H = 125 GeV:

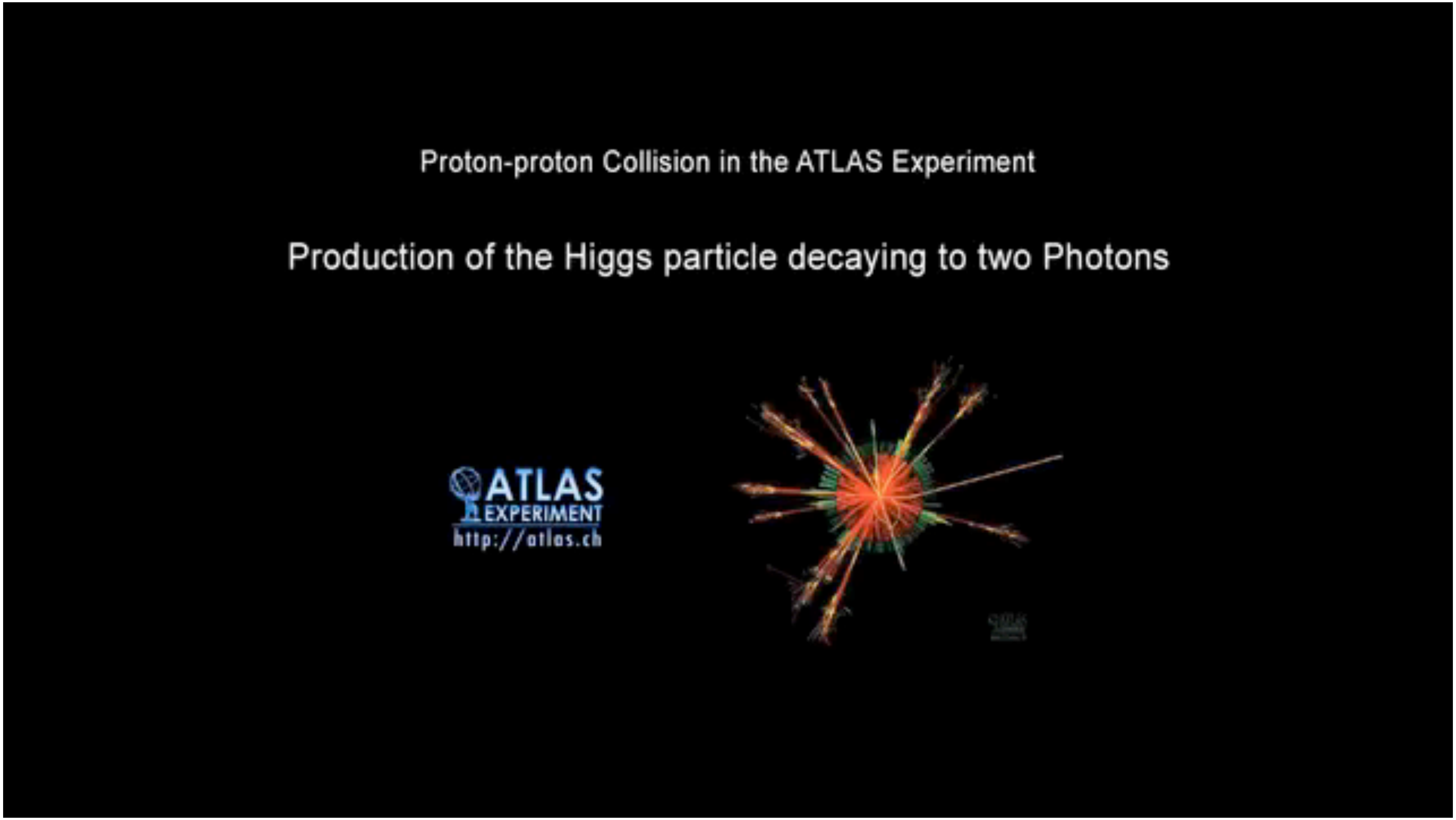
~0.23% $H \rightarrow \gamma\,\gamma$

~0.02% $H \rightarrow Z\,Z^{(*)} \rightarrow 4\ell$

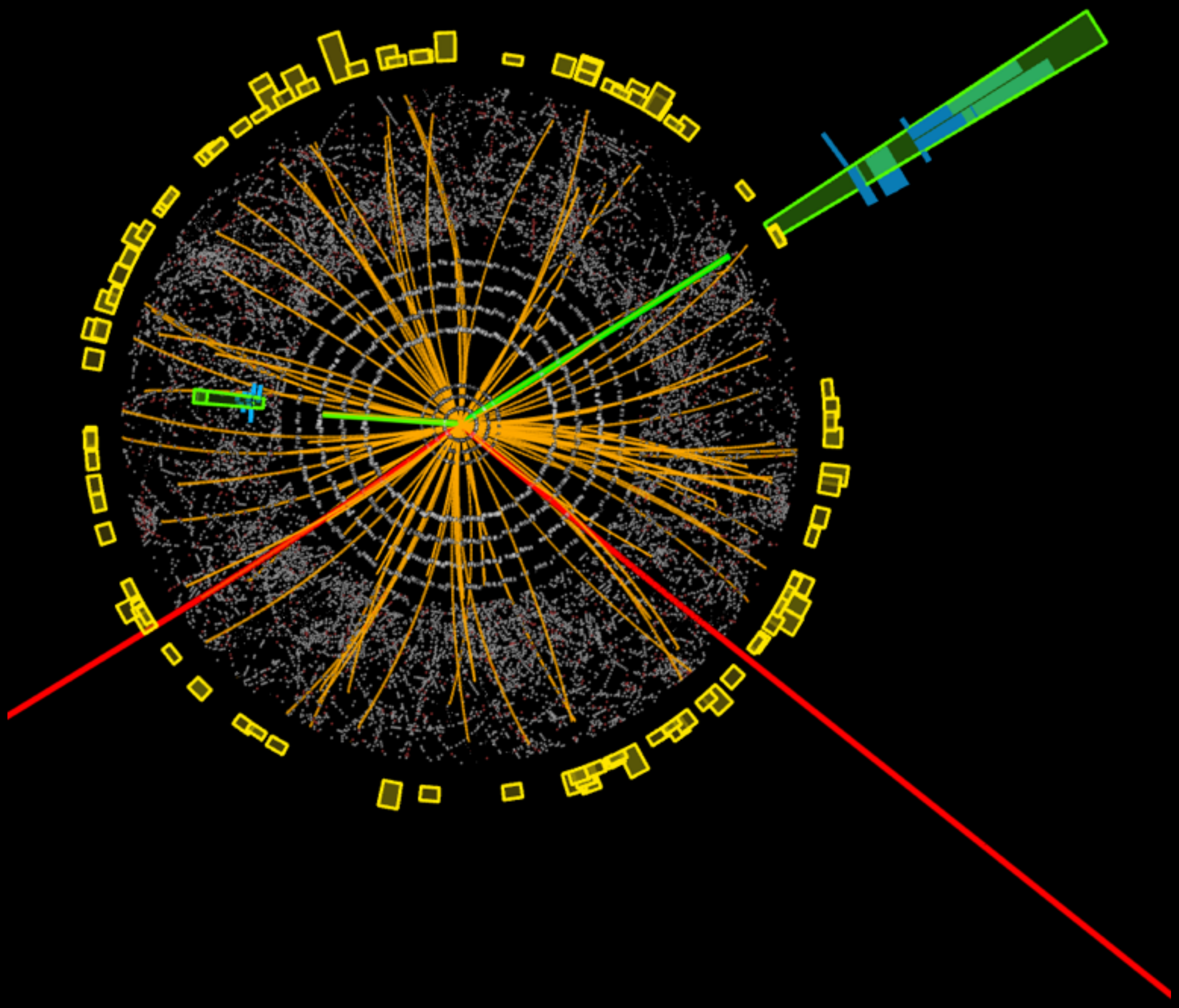
e or μ pairs

The cleanest channels are also the rarest...

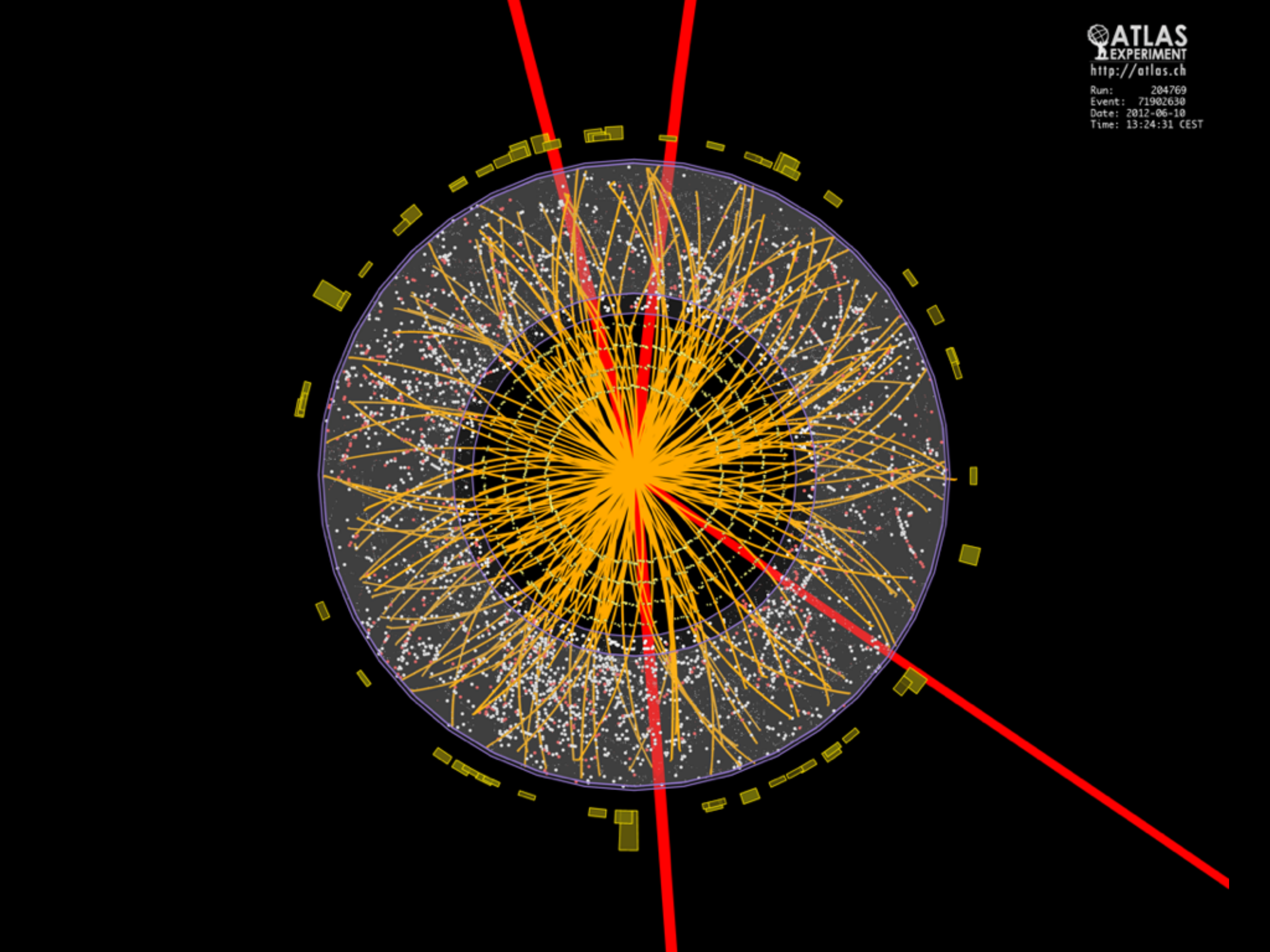
$p\,p \rightarrow H \rightarrow \gamma\,\gamma$



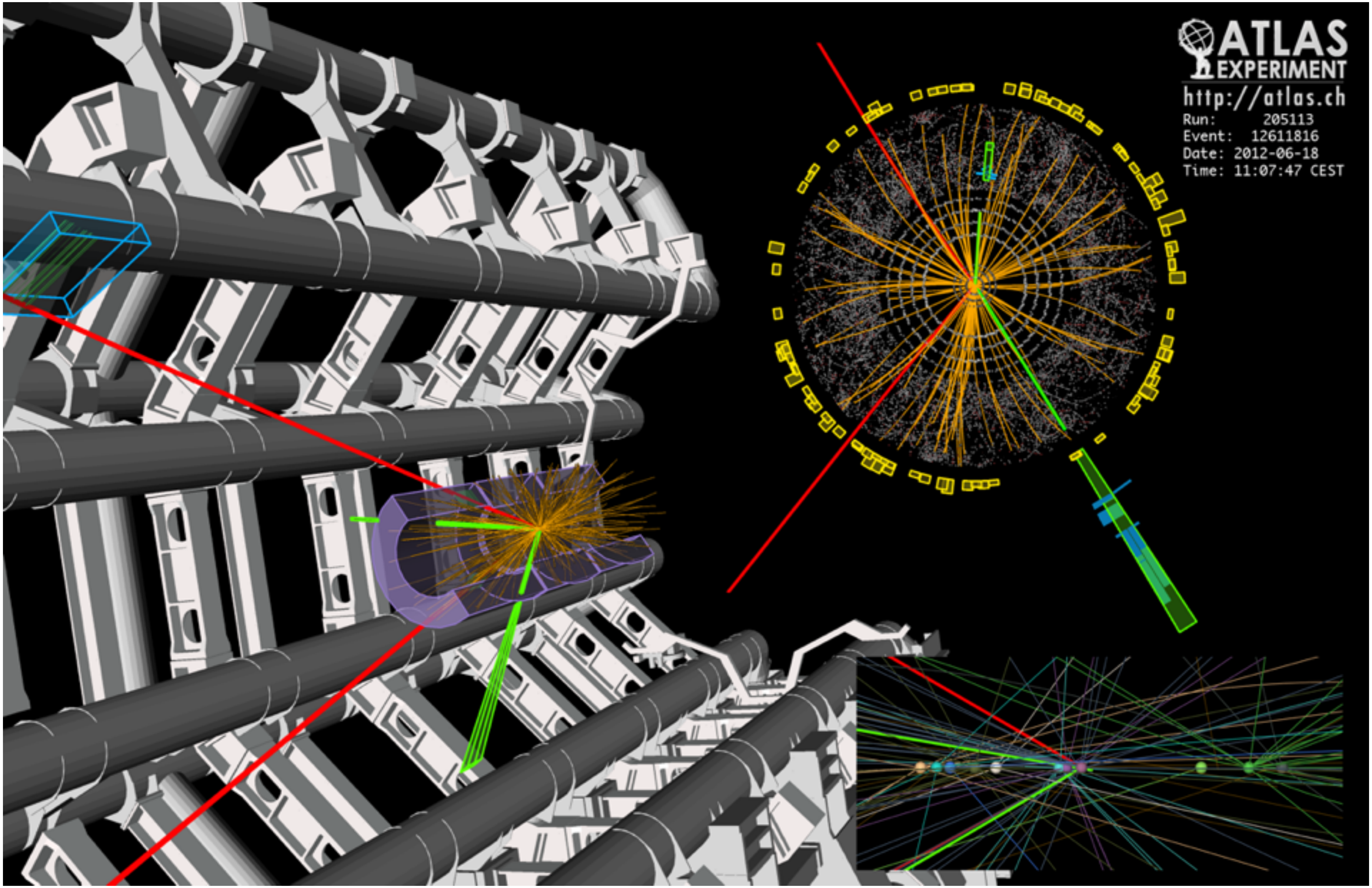
http://www.atlas.ch/multimedia/a-higgs-particle-decaying-2-photons.html



CERN


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

$H \to ZZ^{(*)} \to 4\ e$?

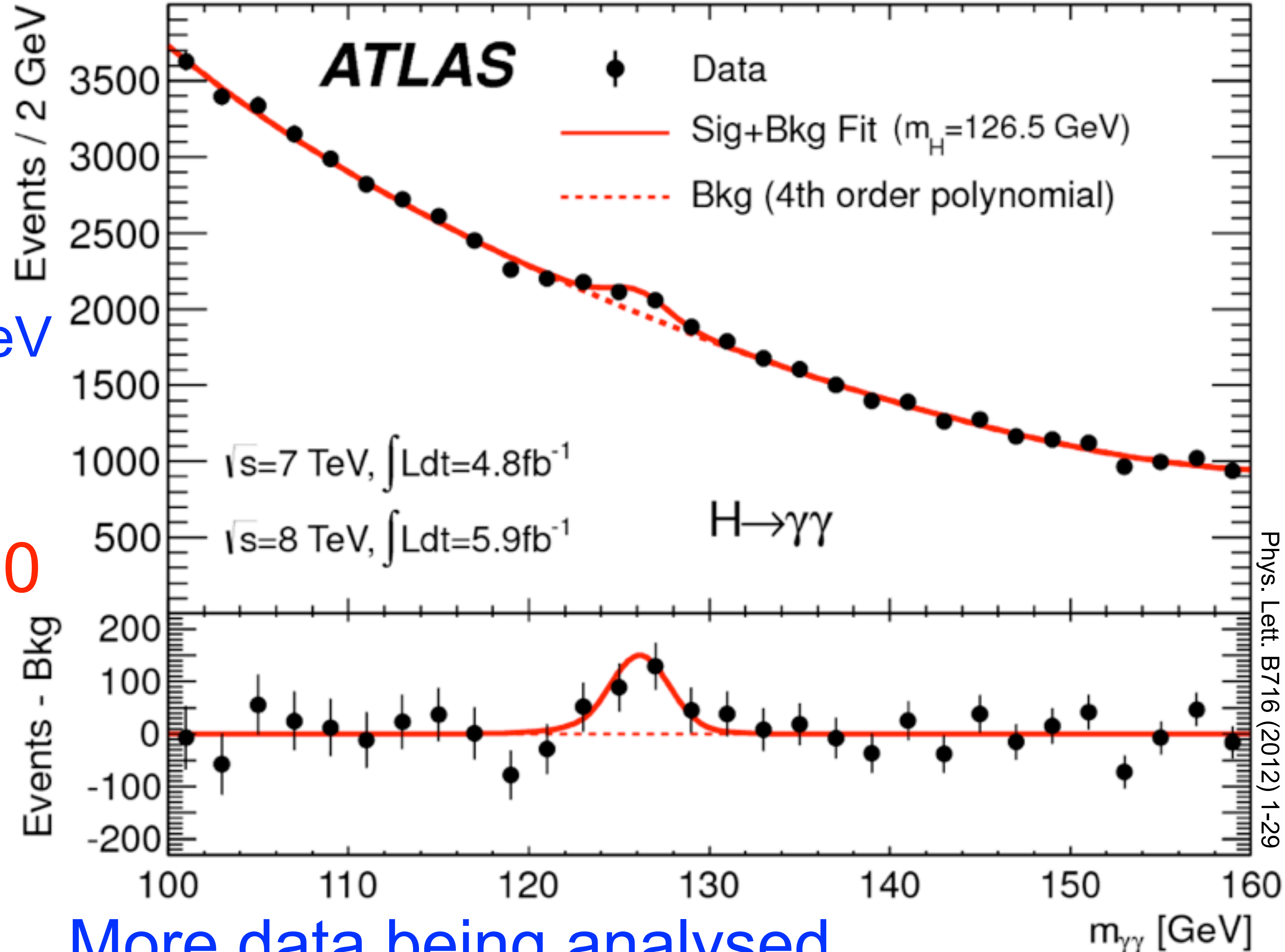

ATLAS
EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST

$H \rightarrow \gamma\ \gamma$

Excess of events!

M ~ 126.5 GeV
4.5 σ

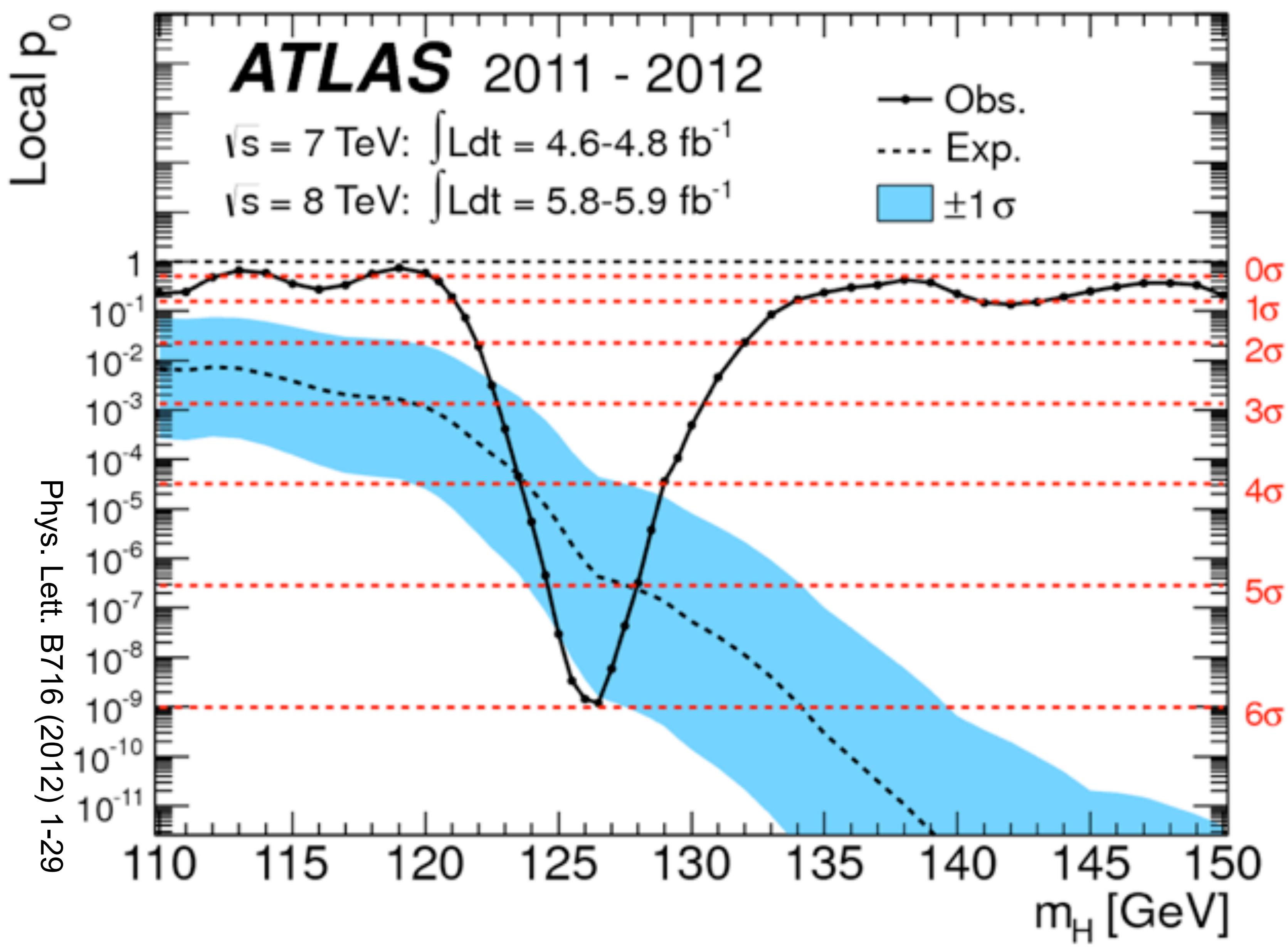
~1 / 300000 chance of being a statistical fluctuation



More data being analysed...

Observation of a new particle

- The five best channels are statistically combined
  - sophisticated treatment, including all systematic errors



Phys. Lett. B716 (2012) 1-29

p_0: test of background only hypothesis
$p_0 = 1.8 \times 10^{-9}$
local: 5.9 σ

~1 / 550,000,000 chance of being a statistical fluctuation of the background!

global: 5.1σ
for 100-600 GeV
1.7×10^{-7}
~1 / 5,900,000

$$M = 126.0 \pm 0.4\ (\text{stat}) \pm 0.4\ (\text{sys})\ \text{GeV}$$

4 July 2012 CERN and Melbourne

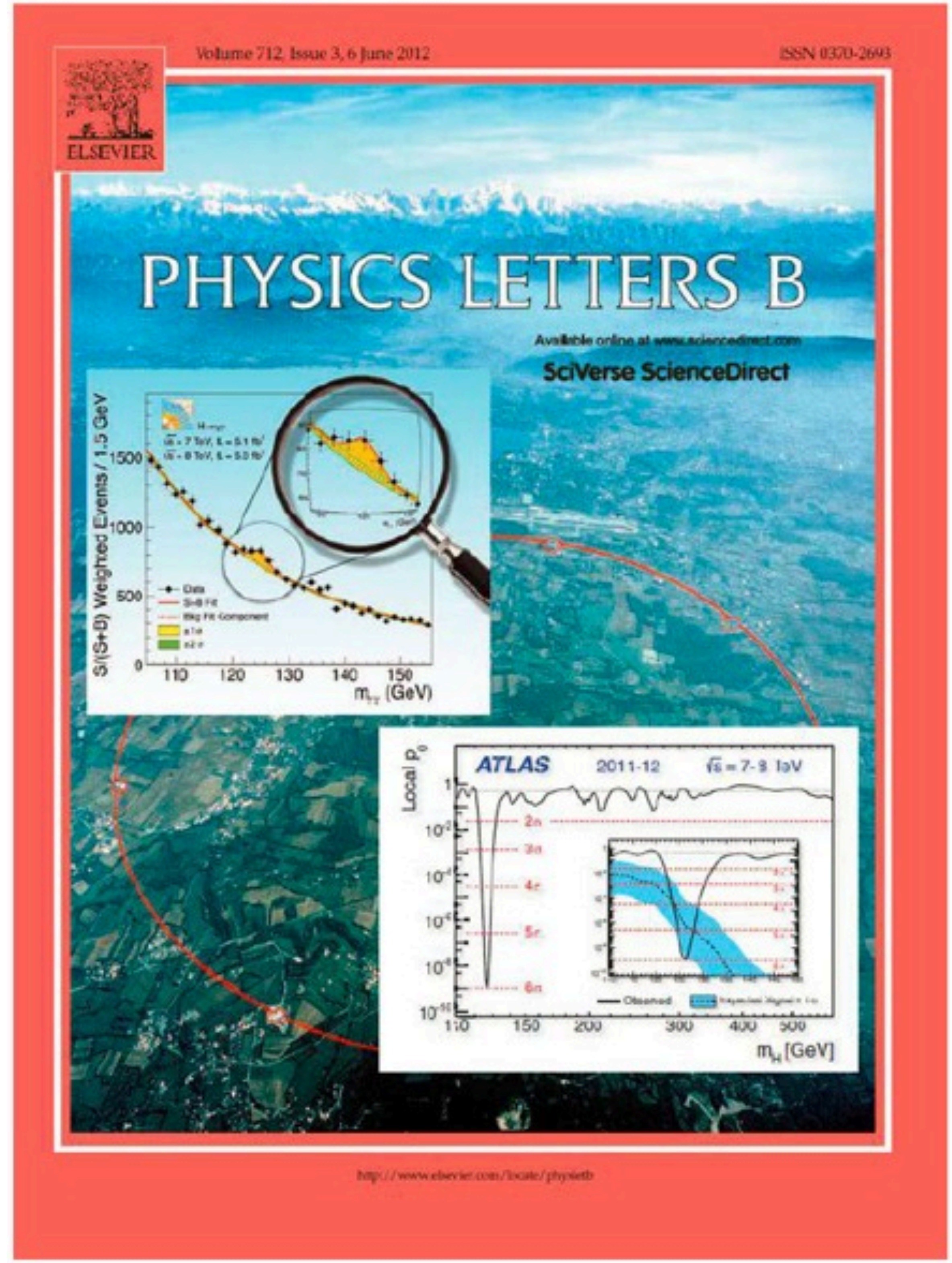
CERN, 09:00

ICHEP 2012, Melbourne, 19:00

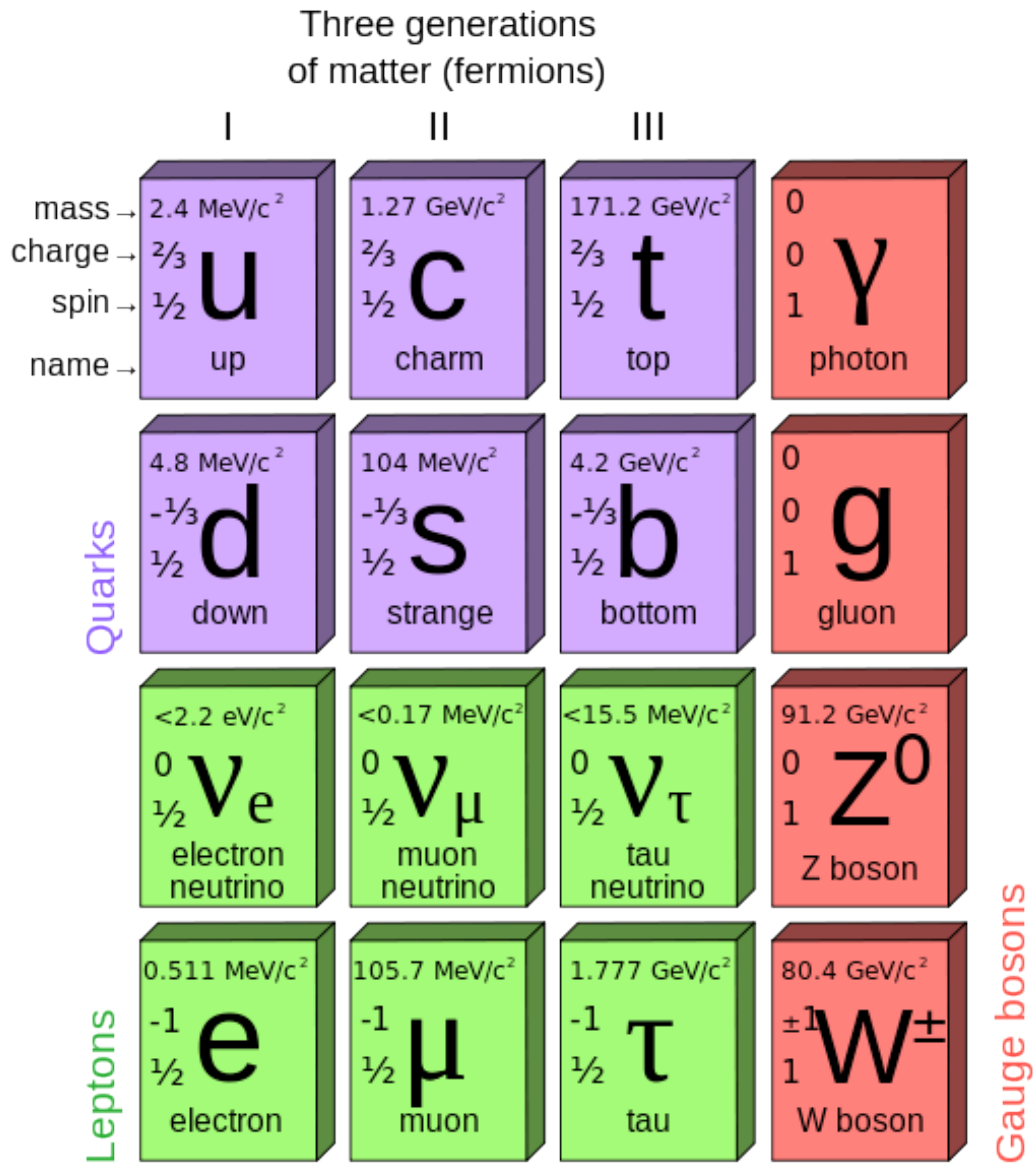
00:00 in Victoria!

Is it the Higgs boson?

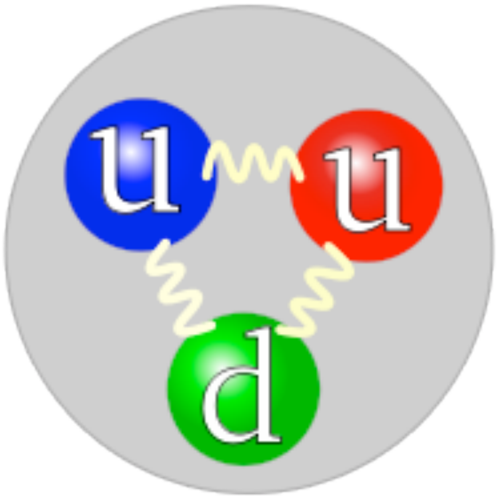
- We have discovered a new particle!
  - savour this privileged and historical moment
- So far, it looks like the predicted Standard Model Higgs boson
  - but about 25% error on properties
- Have we found the key to the mystery of the origin of mass?



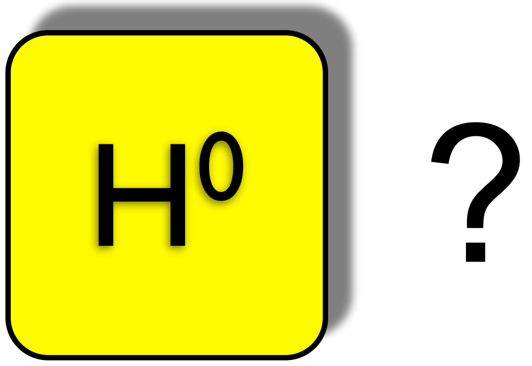
Phys. Lett. B 716 (2012) 1-29 (ATLAS)



the **proton**: three bound quarks



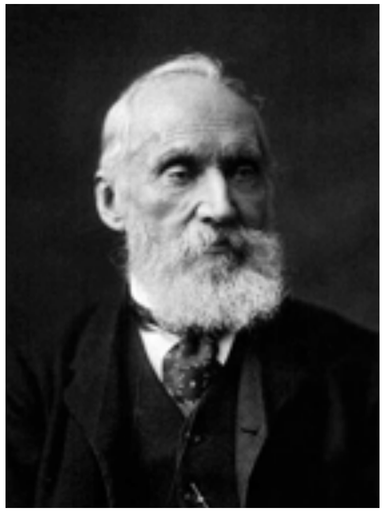
the **Higgs boson**: the missing piece



If it's the Higgs, is that it?

"*Our future discoveries must be looked for in the 6th place of decimals.*"
Albert A. Michelson, 1894

"*There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.*"
William Thomson (Lord Kelvin), 1900



Many more questions

- What is the nature of Dark Matter?
- Why is there more matter than antimatter?
- Can all forces be unified?
- Is SuperSymmetry realized in Nature?
- Are fundamental particles fundamental?
- Are there extra dimensions of space?
- Why three families of quarks and leptons?
- Why are neutrinos so light?
- What is Dark Energy?

Higgs Boson?

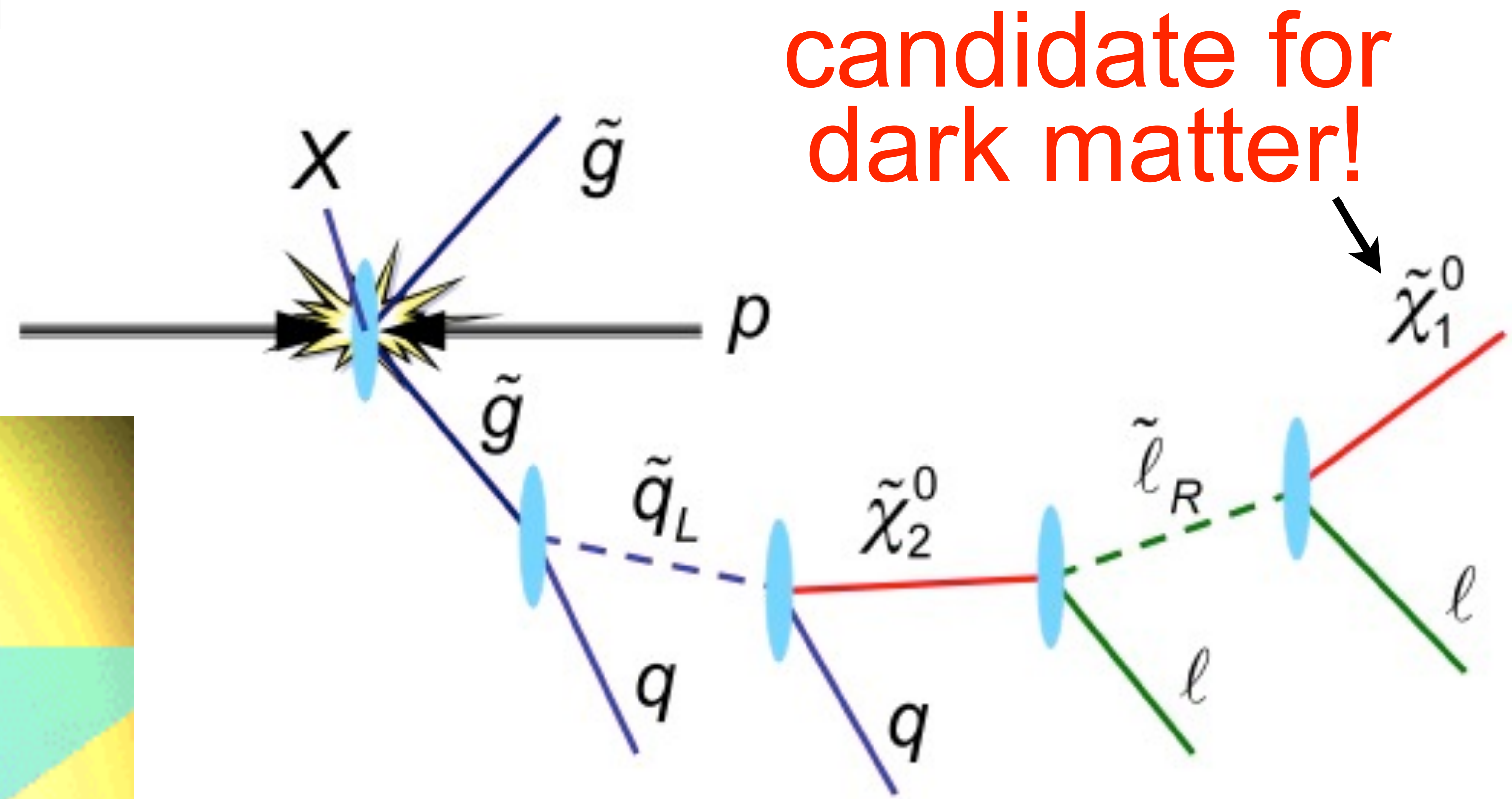
Dark Matter?

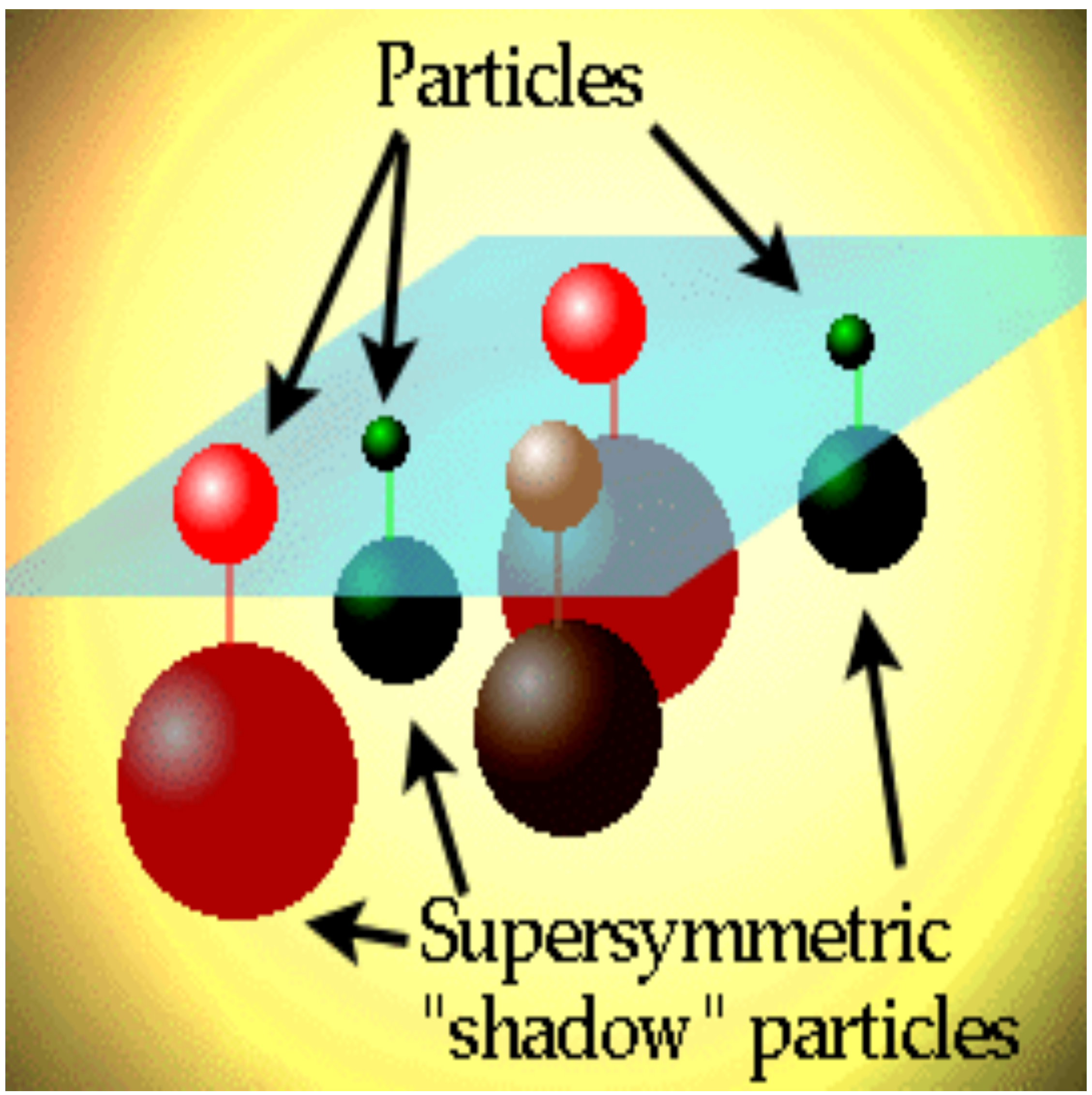
Dark Energy?

Extra Dimensions?

Supersymmetry

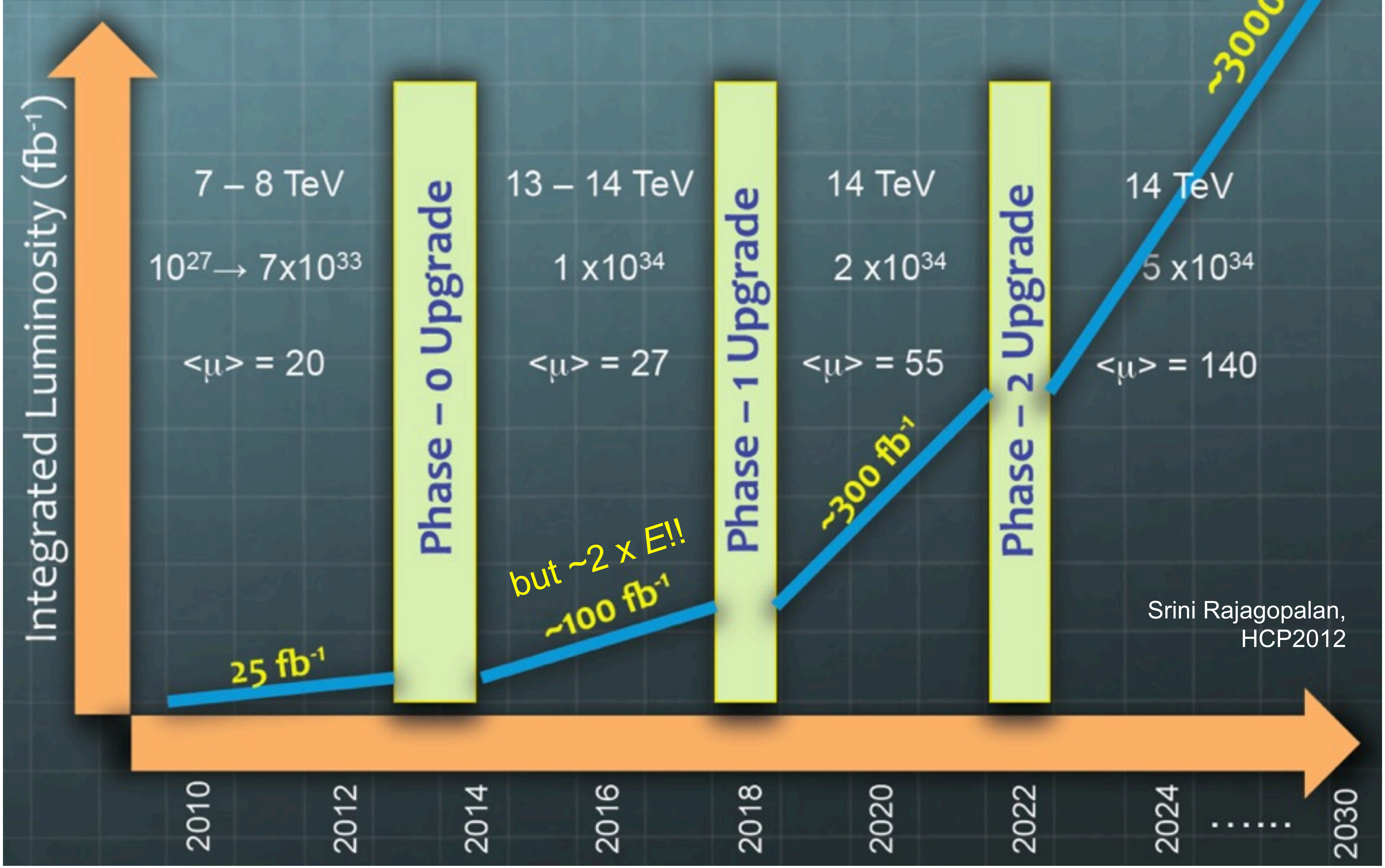
- Theoretical idea: extended symmetry of Nature
  - Wess and Zumino, 1974
  - establishes a symmetry between fermions (matter) and bosons (forces)



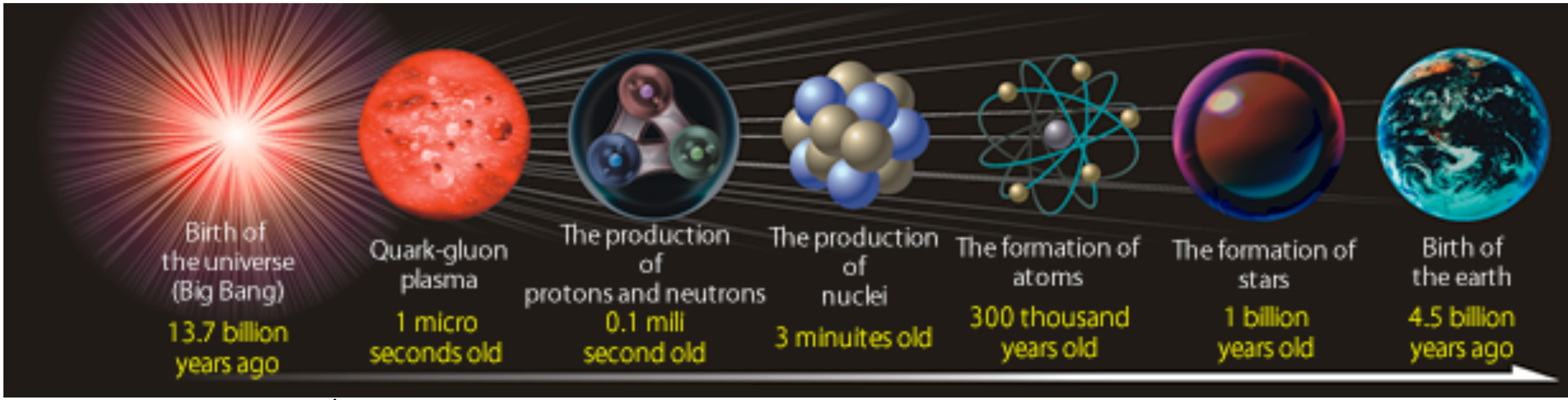


- Required in most theories of new physics
- Predicts super-partners of all particles!
  - "sparticles",not yet found: broken symmetry
- Many possible signatures sought for at the LHC!

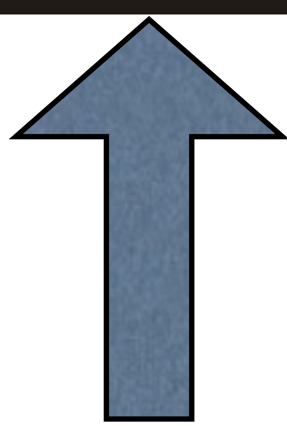
LHC forecast



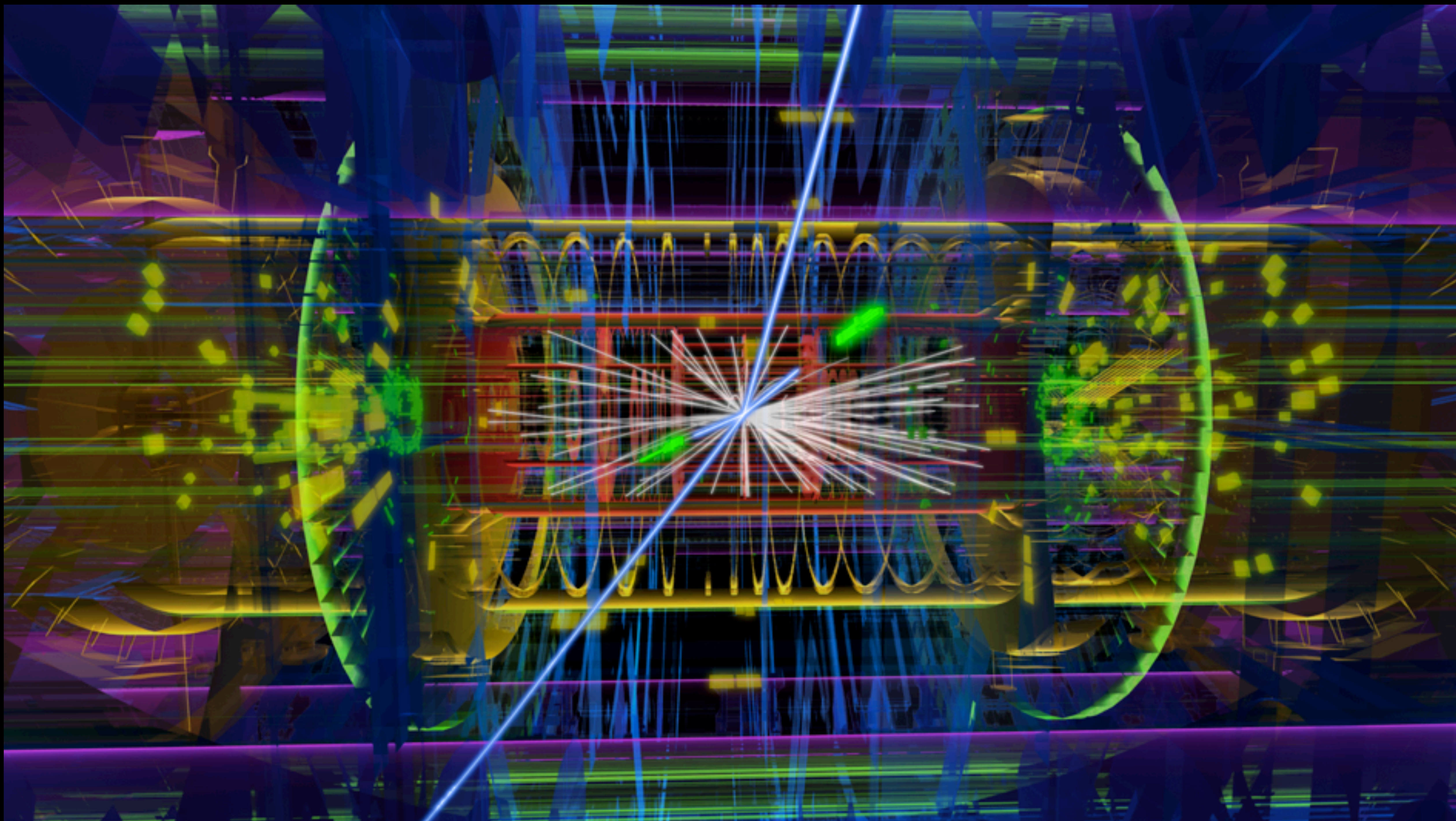
Particles and the Universe

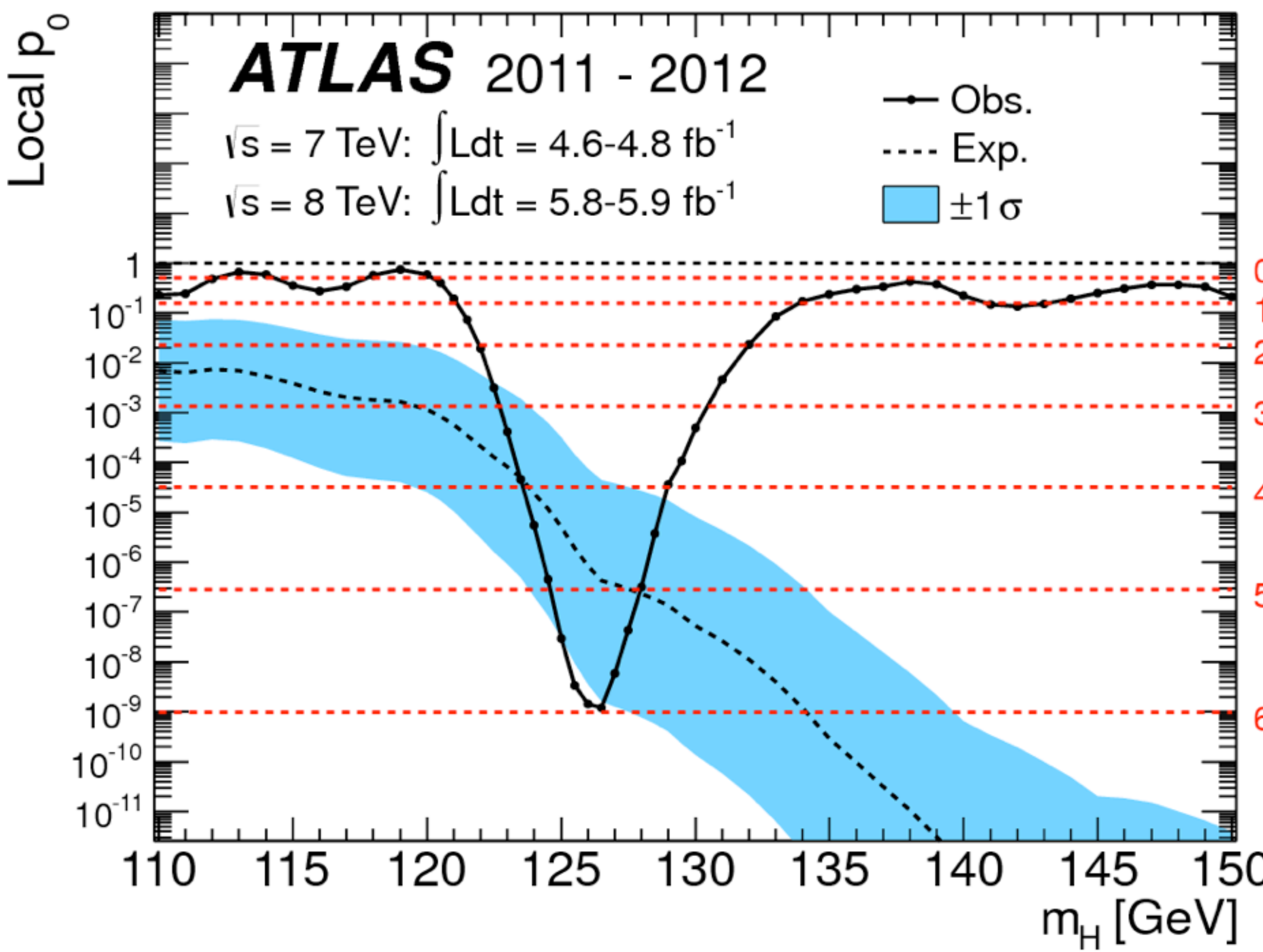


j-parc web site



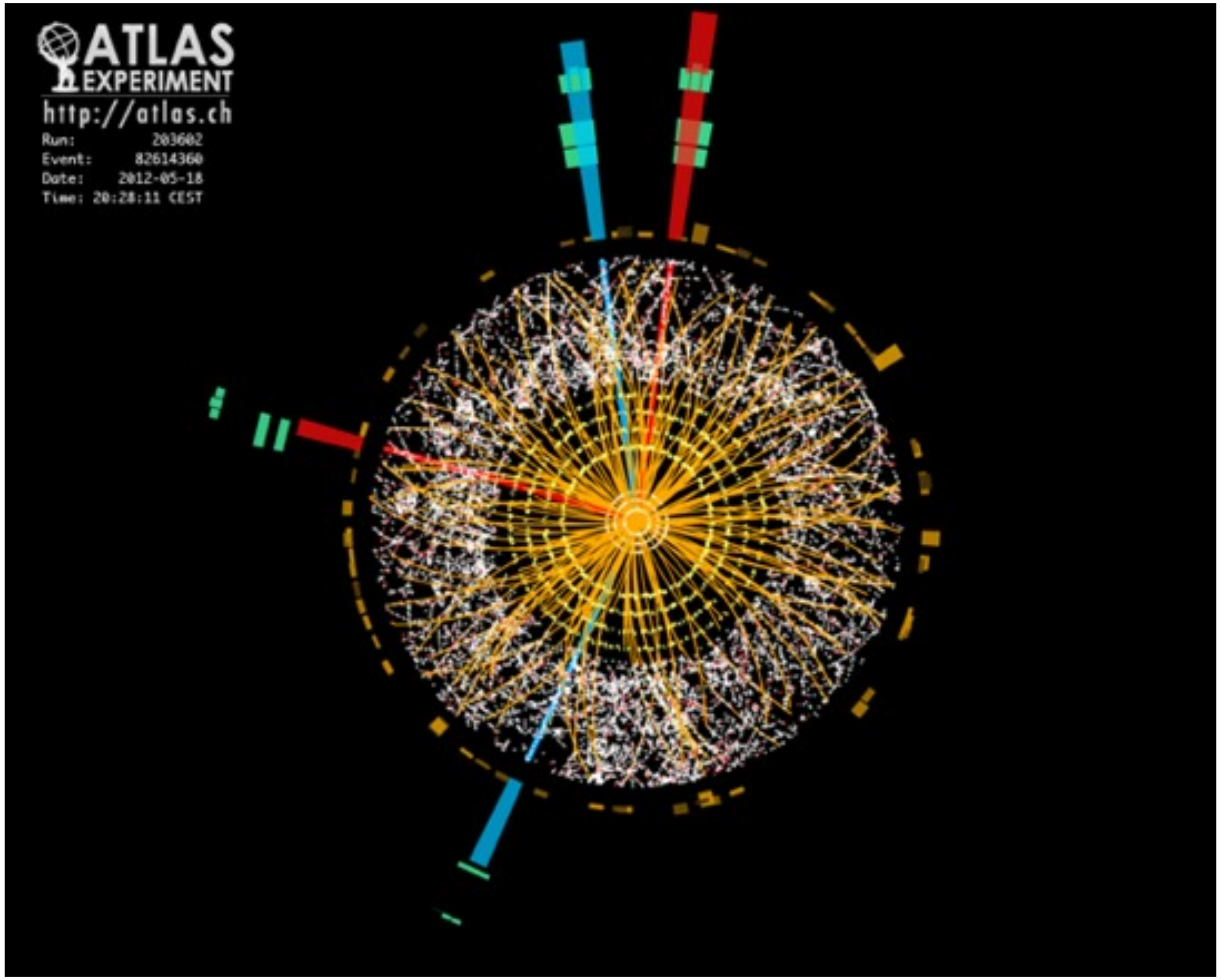
M101, European Space Agency & NASA

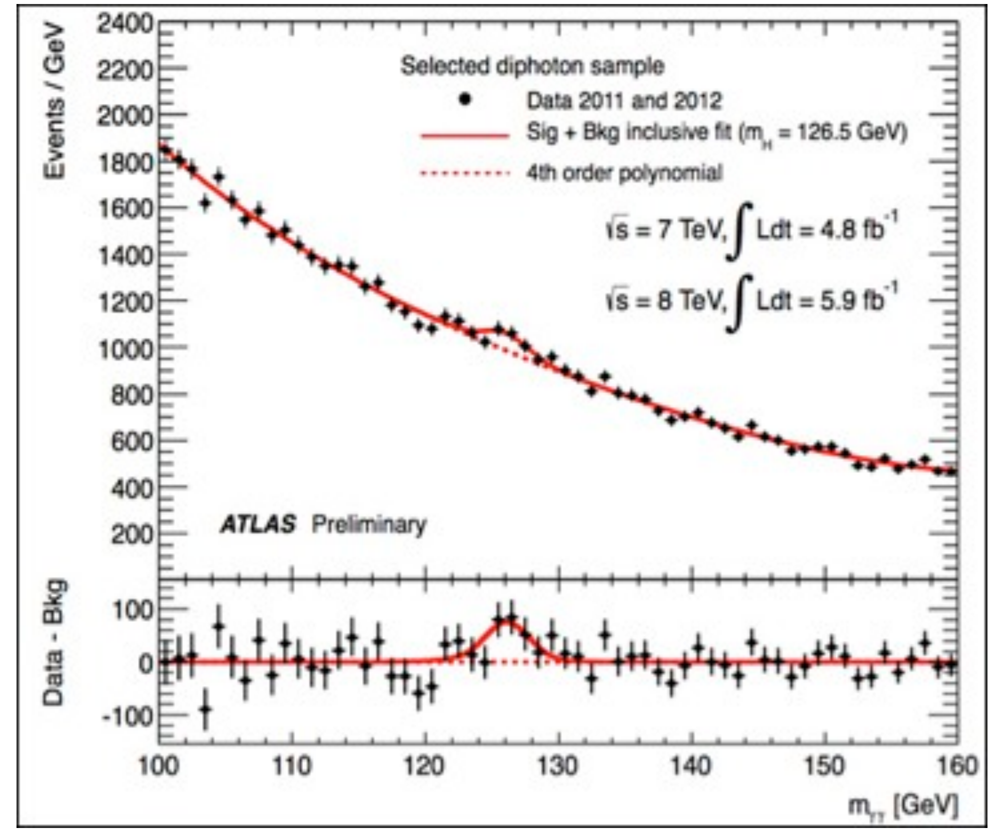

CERN



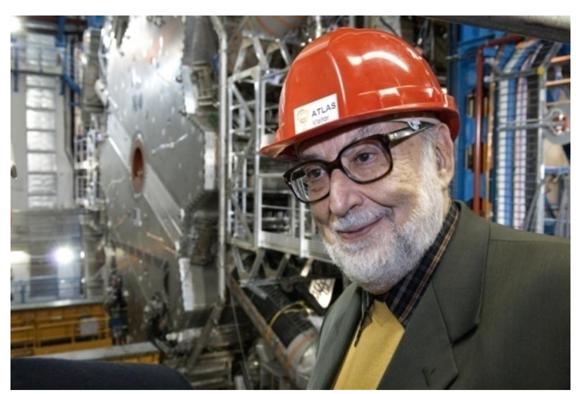
ATLAS 2011 - 2012
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb⁻¹
Obs.
Exp.
±1 σ
Local p0
mH [GeV]
0σ
1σ
2σ
3σ
4σ
5σ
6σ
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
110
115
120
125
130
135
140
145
150

The Higgs Boson ?





Peter Higgs visiting ATLAS
April 2008



François Englert

Physics at the Large Hadron Collider

More exciting discovering likely to come out of research at the Large Hadron Collider!

Good public web sites:
http://atlas.ch/
http://www.particleadventure.org/

Michel Lefebvre
lefebvre@uvic.ca