Wstęp do fizyki cząstek elementarnych: część eksperymentalna

- **Pięćdziesiąt lat badań cząstek elementarnych, nagrody Nobla, Model Standardowy**
- **Labolatorium CERN**
- **Eksperymenty LHC**
- **Detektory cząstek elementarnych**

Prof. dr hab. Elżbieta Richter-Wąs

Particle physics

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

Edward Witten

Aims to answer the two following questions:

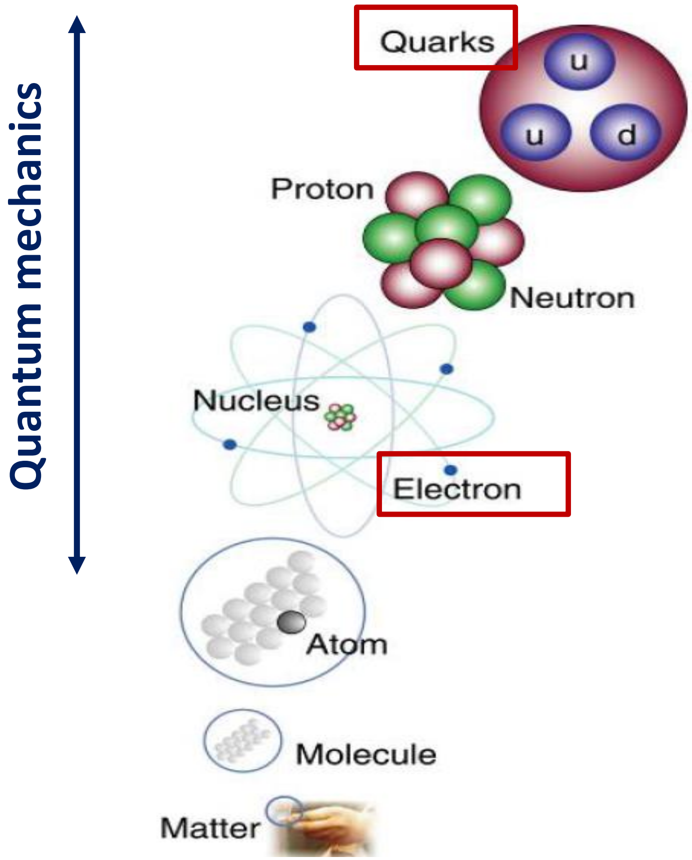
What are the elementary constituents of matter ?

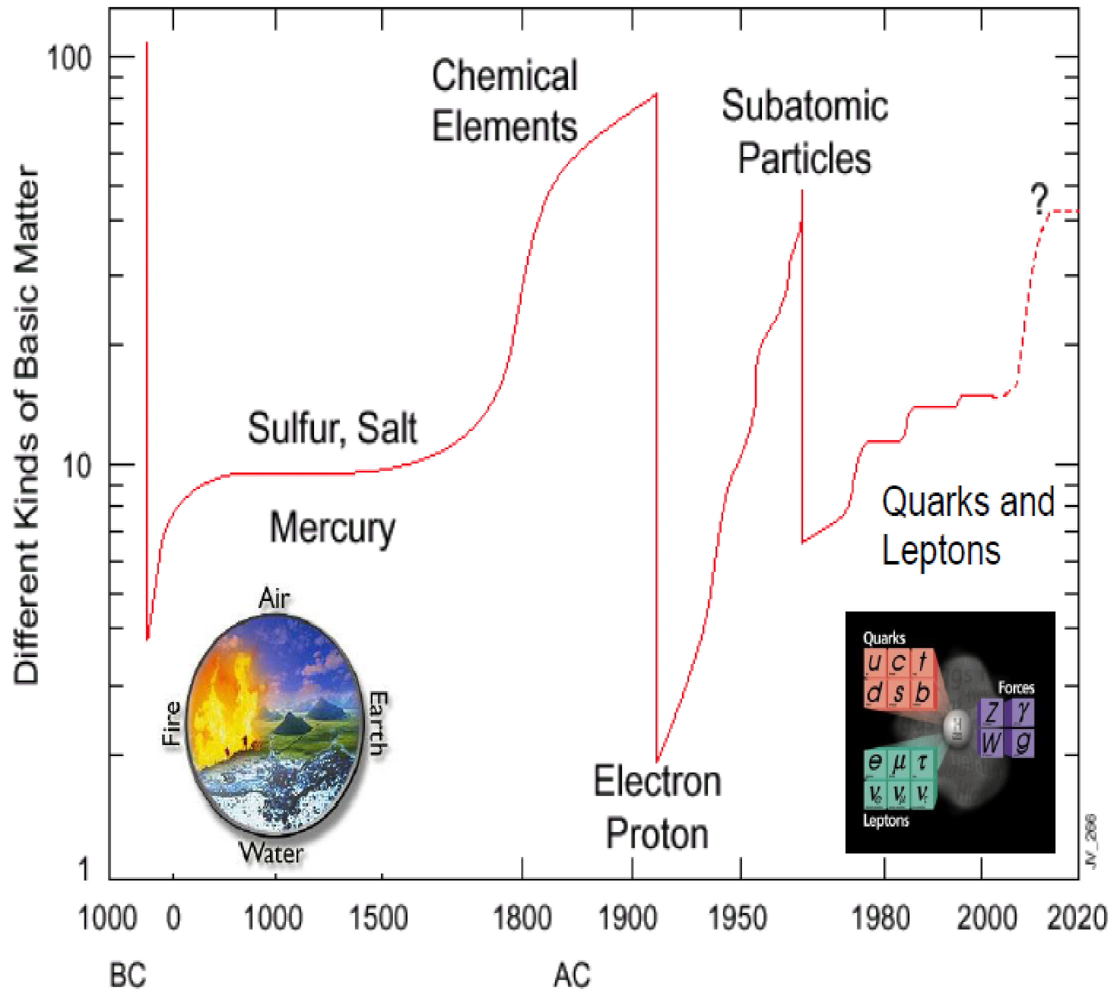
What are the forces that determine their behavior?

Experimentally

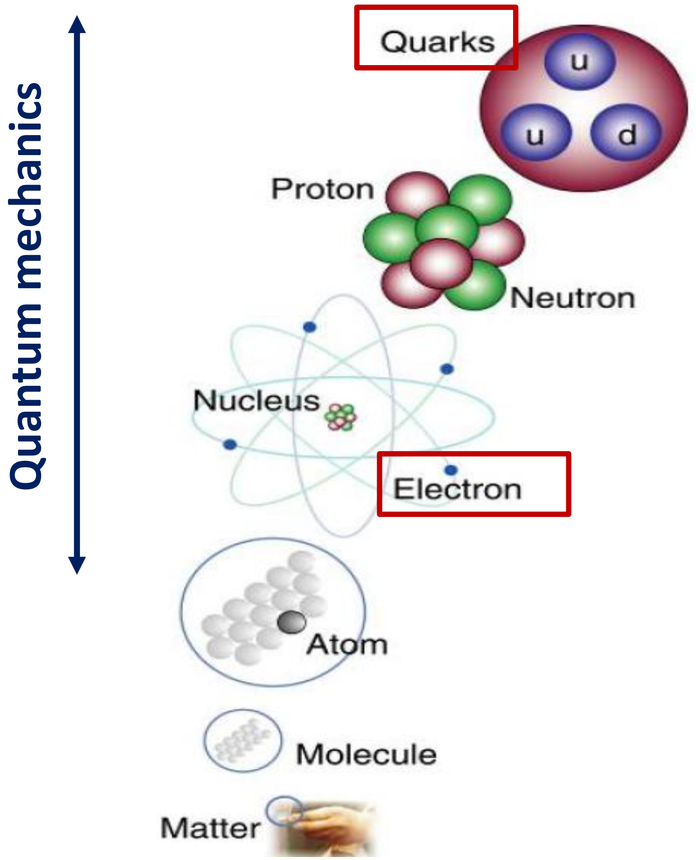
Get particles to interact and study what happens

Constituents of matter along History



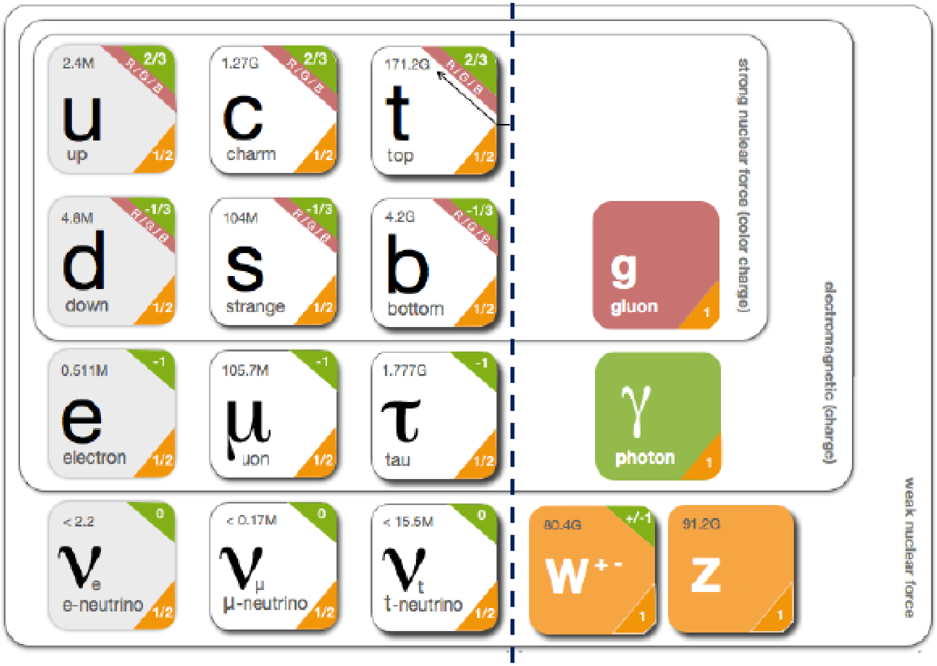


Particles of the Standard Model



Matter particles
(< 10 $^{-16}$ cm)

Interaction particles



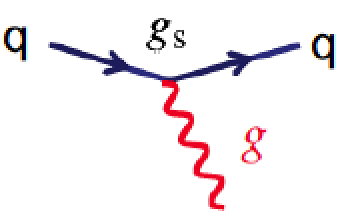
Higgs particle
Is not a matter particle and not a interaction particle

$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'} (\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q')H$$

Interactions

The interaction of gauge bosons with fermions is described by the Standard Model

STRONG



Only quarks

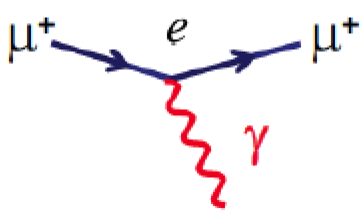
Never changes flavour

$\alpha_S \sim 1$

Gluons

massless

EM



All charged fermions

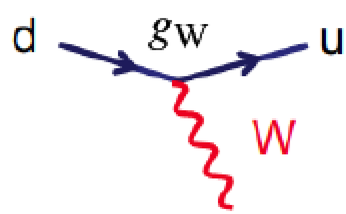
Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

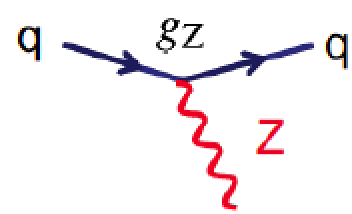
WEAK CC



All fermions

Always changes flavour

WEAK NC



All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

W+, W-

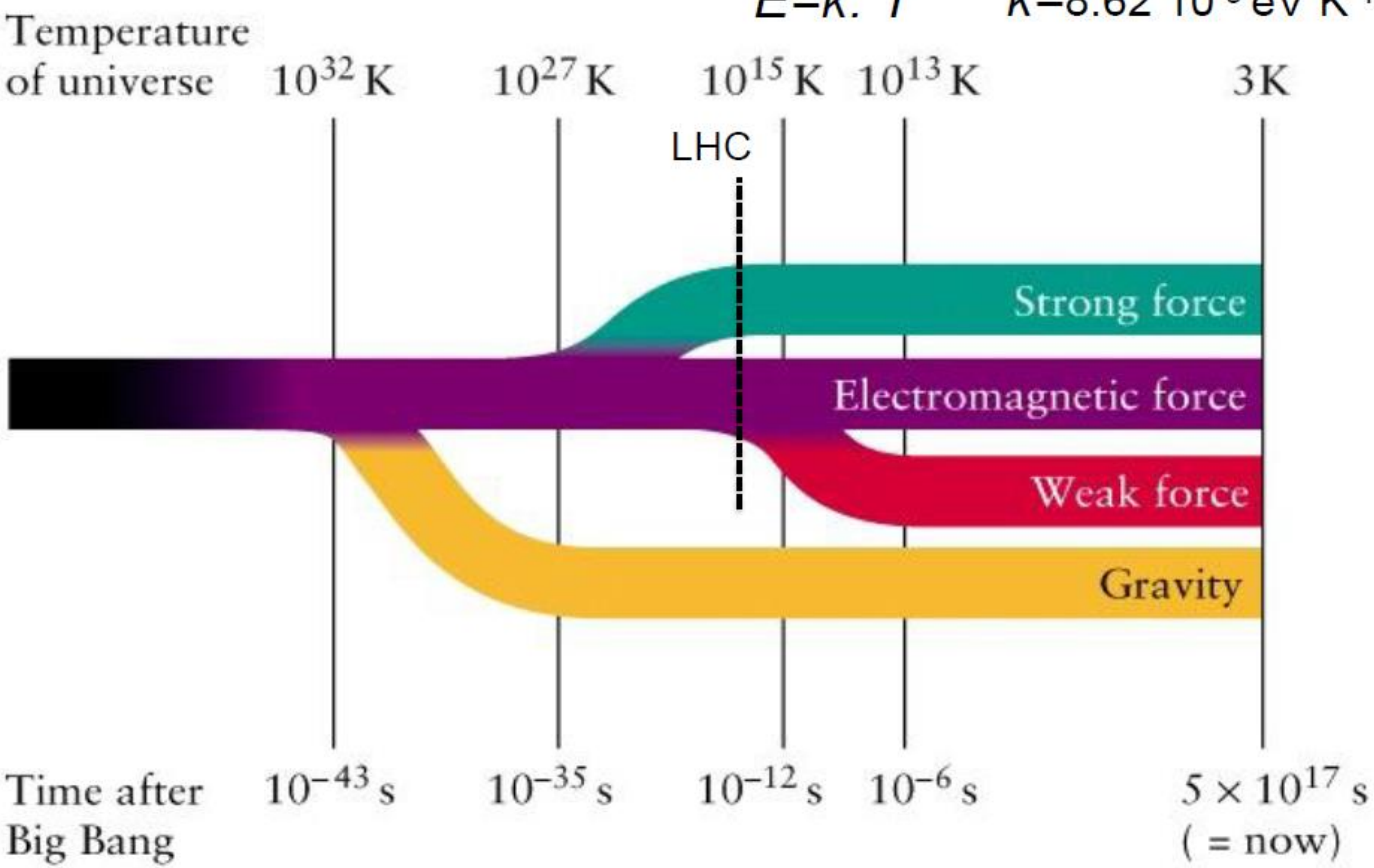
very massive

Z^0

very massive

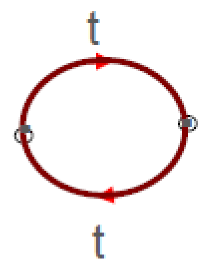
Forces and expansion of the Universe

$E = k.\ T \qquad k = 8.62\ 10^{-5}\ \mathrm{eV\ K^{-1}}$



Quantum field theory

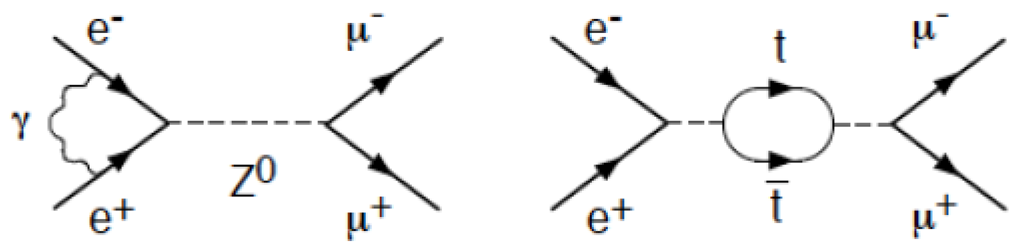
A particle-antiparticle pair can pop out of empty space ("the vacuum") and then vanish back into it



Vacuum Fluctuation
Involving top quarks

These are *Virtual* particles.

Other examples of Virtual particles:



This has far-reaching consequences

The structure of the universe depends on particles that ***don't exist in the usual sense***

We do not see these particles in everyday life

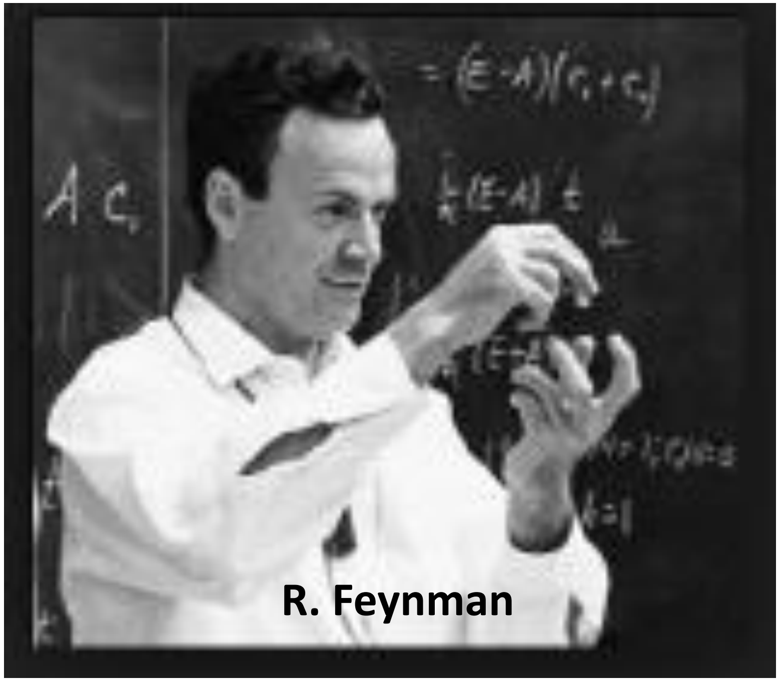
We must recreate the state of the early hot universe to make them

Theory has to be confirmed by experiment

„It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiments, it's wrong."

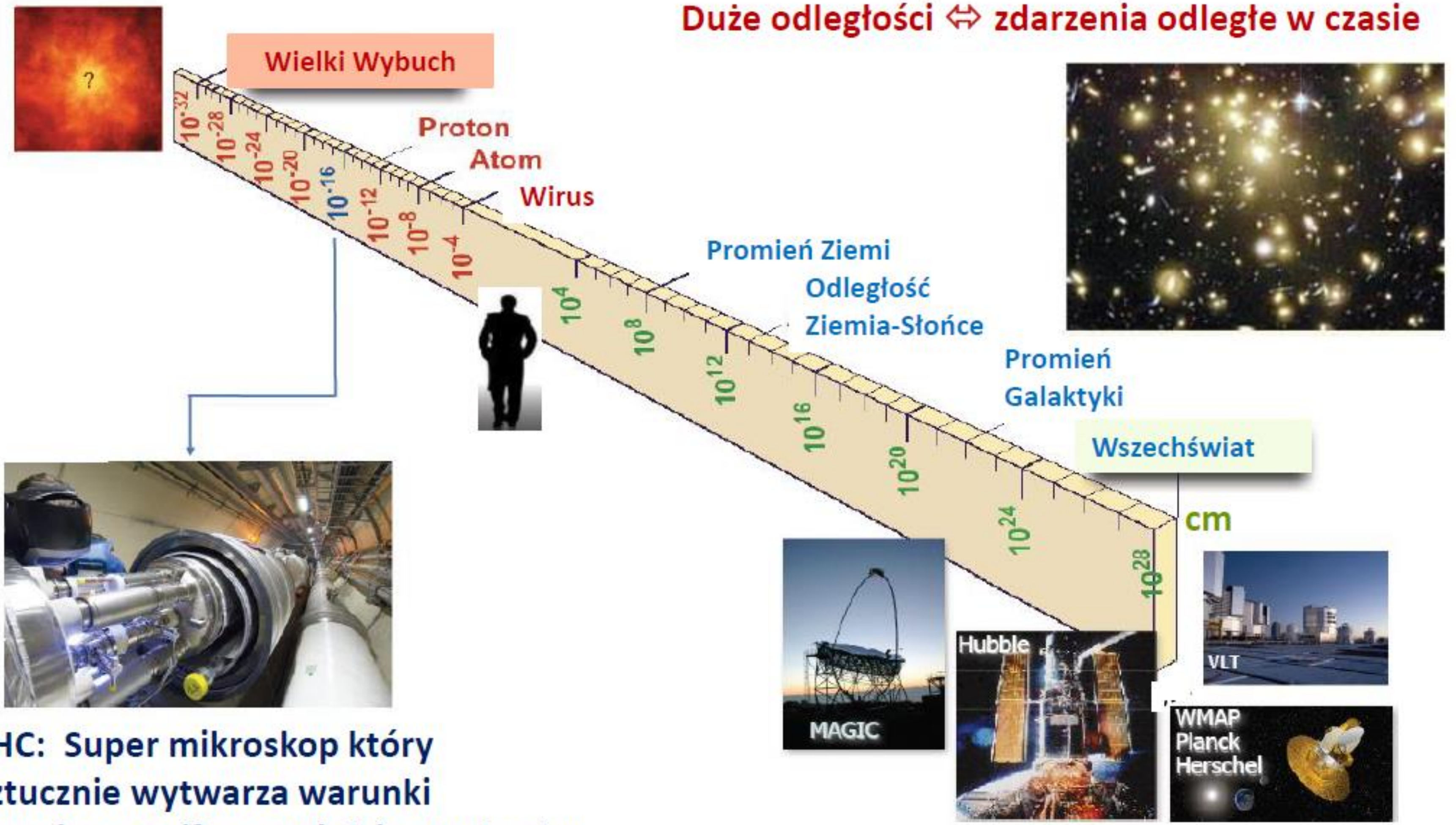
R. Feynman

(To nie ma znaczenia jak piękna jest twoja teoria, nie ma znaczenia jaki jesteś inteligentny. Jeżeli nie zgadza się z eksperymentem to ta teoria jest nieprawdziwa.)



W jaki sposób badamy cząstki elementarne, a w jaki strukturę wszechświata?

Duże odległości ⇔ zdarzenia odległe w czasie



LHC: Super mikroskop który sztucznie wytwarza warunki panujące 10^{-12}s po Wielkim Wybuchu

Małe odległości ⇔ bardzo duże energie

History of particle physics and Nobel prizes


Sin-Itiro Tomonaga


Julian Schwinger


Richard P. Feynman


Sheldon Lee Glashow


Abdus Salam


Steven Weinberg


Leon M. Lederman


Melvin Schwartz


Jack Steinberger


Carlo Rubbia


Simon van der Meer


Georges Charpak

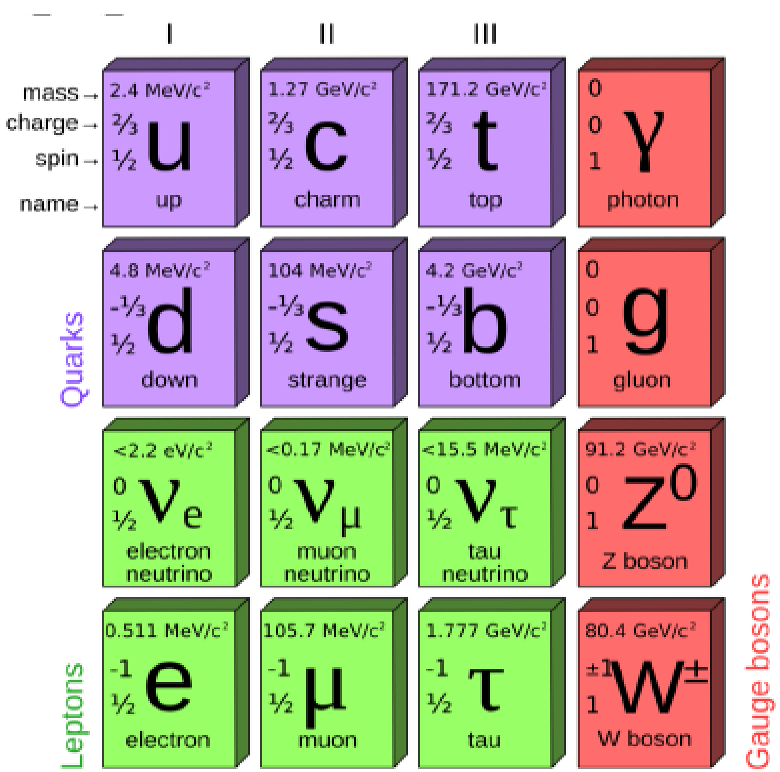

Gerardus 't Hooft

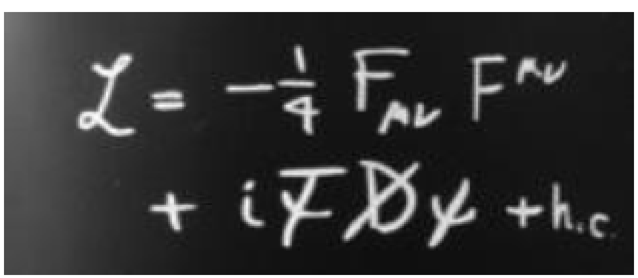

Martinus J.G. Veltman


M. Gell-Mann

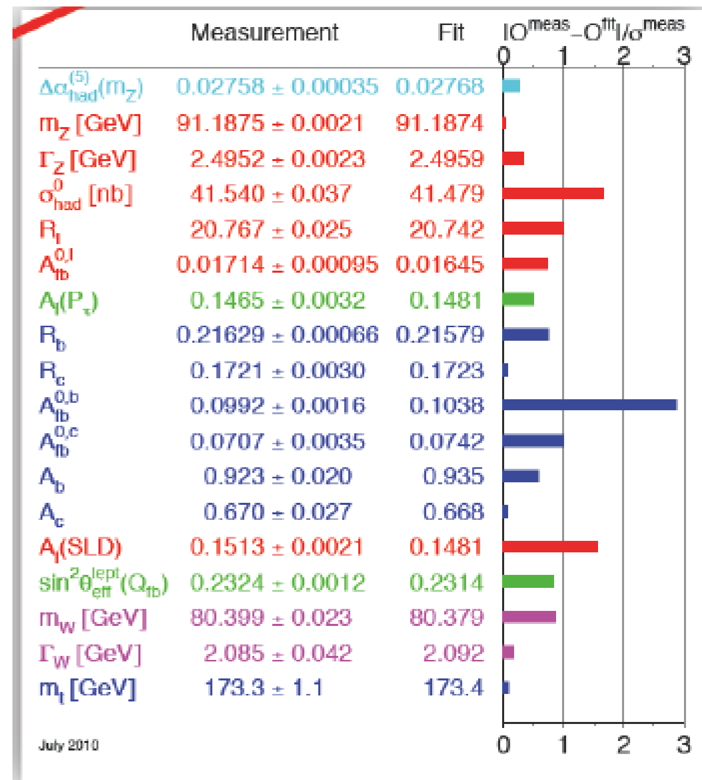
1957 – C. N. Yang, T. Lee
1965 – S. I. Tomonaga, J. Schwinger, R.P Feynman
1969 – M. Gell-Mann
1976 – B. Richter and S. Ting
1979 – S.L. Glashow, A. Salam, S. Weinberg
1980 – J. Cronin, V. Fitch
1984 – C. Rubbia, S. van der Meer
1988 – L. M. Lederman, M. Schwartz, J. Steinberger
1990 – J. Friedman, J. Kendall, R. Taylor
1992 - G. Charpak
1995 – M. Perl, F. Reines
1999 - G. tHooft, M. J. Veltman
2004 - D. J. Gross, H. D. Politzer, F. Wilczek
2008 – Y. Nambu, M. Kobayashi, T. Masakawa
2013 – F. Englert and P. Higgs

SM confirmed by the data





STANDARD MODEL OF ELEMENTARY PARTICLES



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

Confirmed at sub 1% level!

The Higgs

In the simplest model the interactions are symmetrical and particles do not have mass

The symmetry between the electromagnetic and the week interactions is broken:

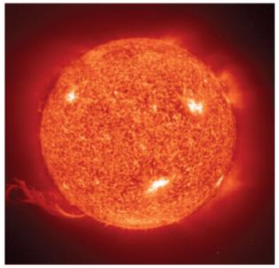
- Photon do not have mass
- W, Z do have a mass ~ 80-90 GeV

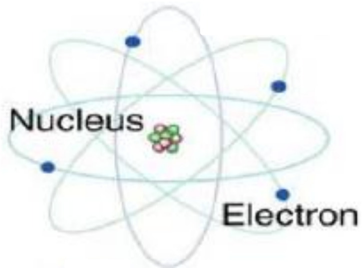
Higgs mechanism:

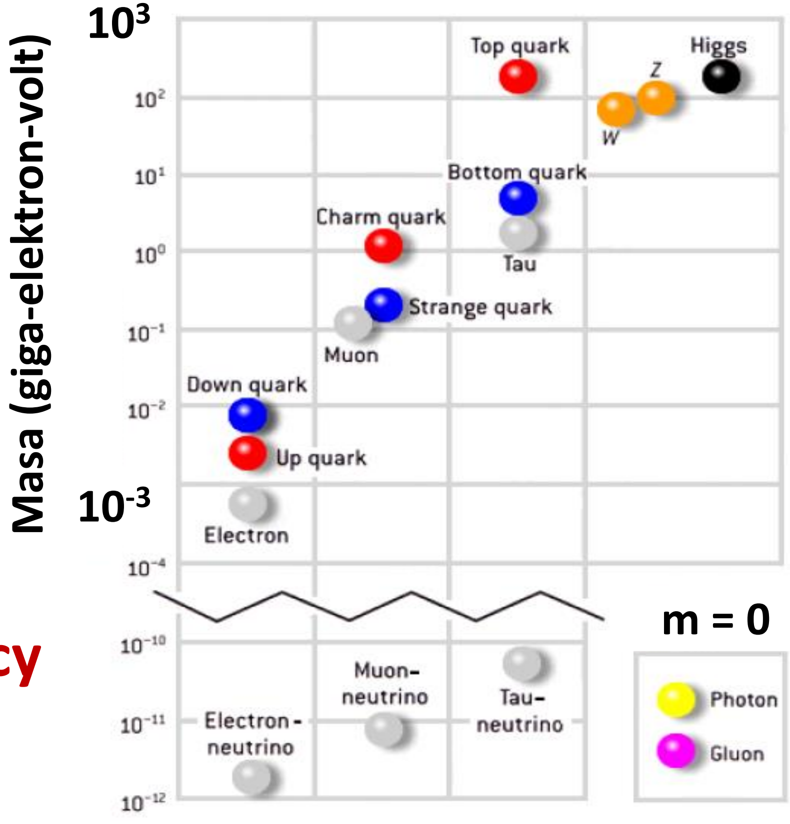
mass of W and Z results from the interactions with the Higgs field

Mass spectrum of elementary particles

Gdyby masa cząstki W była mniejsza to czas reakcji termojądrowych byłby krótszy i zachodziłby przy niższej temperaturze.


Tarcza Słońca





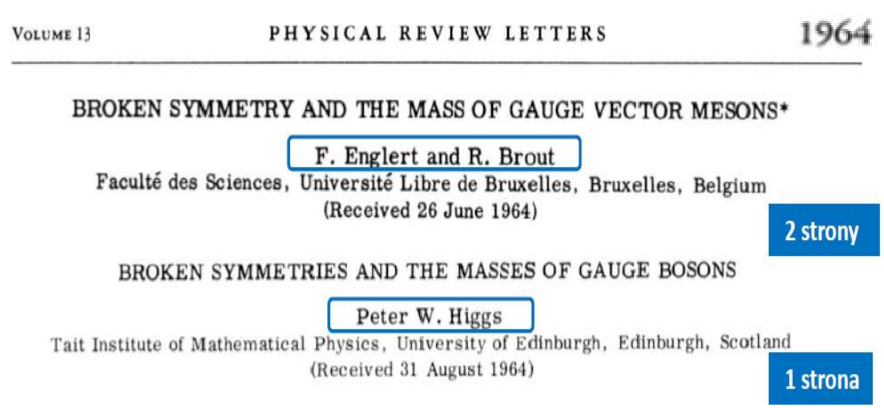
Masa elektronu jest 25 tysięcy razy mniejsza, ale gdyby była równa zero atom nie mógłby istnieć.

Przy innych wartościach masy cząstek elementarnych Wszechświat byłby zupełnie inny lub by nie istniał.

W dniu 4 lipca 2012, eksperymenty ATLAS i CMS na akceleratorze LHC w laboratorium CERN ogłosiły odkrycie nowej cząstki zgodnej z przewidywaniami tzw. mechanizmu Higgsa.

8 październik 2013
Królewska Szwedzka Akademia Nauk przyznaje Nagrodę Nobla w dziedzinie fizyki

„ za sformułowanie mechanizmu który wyjaśnia źródło masy cząstek elementarnych i który został potwierdzony poprzez odkrycie przewidywanej przez ten mechanizm cząstki elementarnej (eksperymenty ATLAS i CMS na LHC)”.



VOLUME 13 PHYSICAL REVIEW LETTERS 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)

2 strony

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)

1 strona

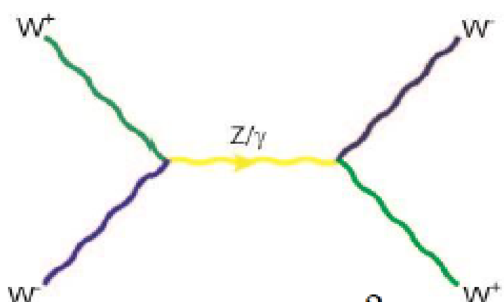
The Higgs: added bonus

Non-zero average value of the Higgs field can also give masses to the quarks, electrons and muons – to all point-like particles.

Old theoretical problem affecting the quantum theory of the weak force :

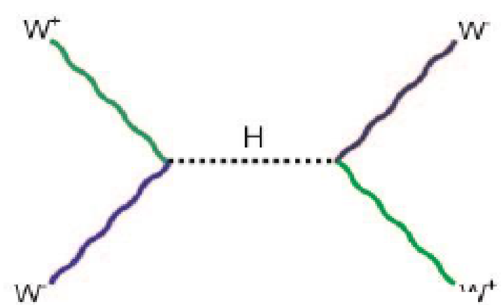
> the probability of two W's interacting becomes larger than 1 at high energies (> 1 TeV).

This is solved by the Higgs field!



$$\lim_{E\to\infty} \mathcal{A} \propto E^2$$

+



$$\lim_{E\to\infty} \mathcal{A} \propto \text{const.}$$

Beyond the Standard Model

The Standard Model answers many of the questions about the structure of matter. But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

Many possible theories

There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

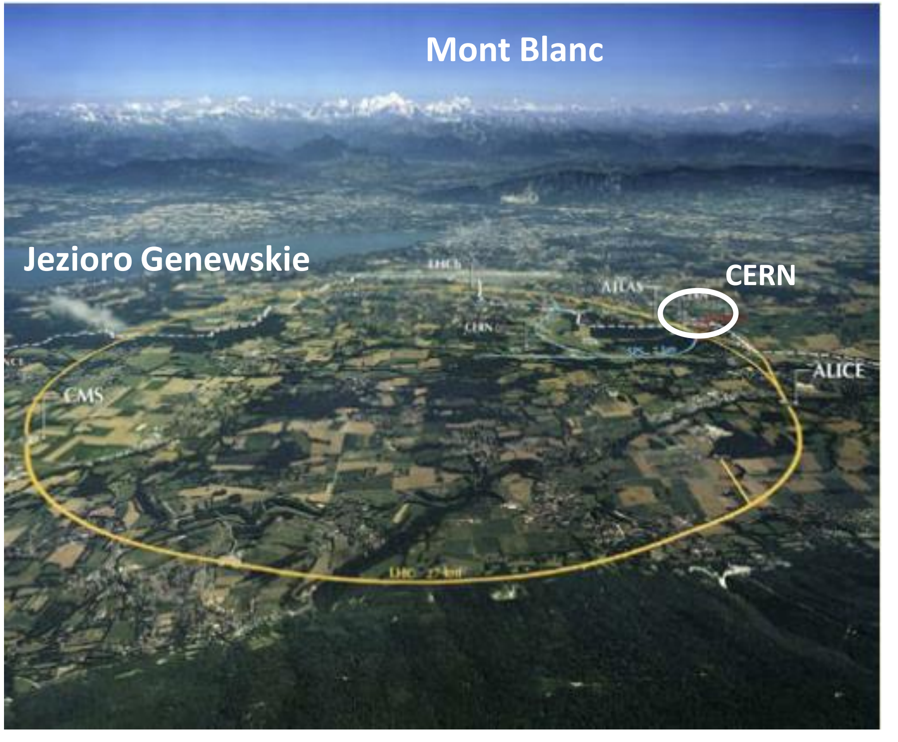
- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this could still be found at the LHC

Europejskie labolatorium CERN

Założone w 1954 roku, to największe na świecie laboratorium w dziedzinie badań oddziaływań cząstek elementarnych. Celem są badania podstawowe.

20 krajów członkowskich (Polska od 1992)
40 krajów stowarzyszonych
2 300 zatrudnionych osób
+ 10 000 naukowców



Projekt LHC (Wielki Zderzacz Hadronów) to ponad 30-letnie przedsięwzięcie wymagające wizji, talentów, pasji, determinacji i zmierzenia się z wyzwaniami technologicznymi.

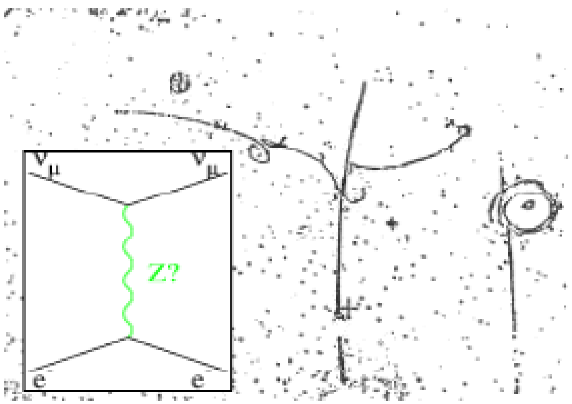
Od samego początku w przygotowaniu akceleratora i eksperymentów LHC uczestniczyły zespoły z Polski:
IFJ-PAN, AGH, Politechnika Krakowska, Uniw. Warszawski, IBJ-Świerk

A brief historical overwiew toward LHC

1964: First formulation of Higgs mechanism (P.W.Higgs)

1967: Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam)

1973: Discovery of neutral currents in ν_μ e scattering (Gargamelle, CERN)

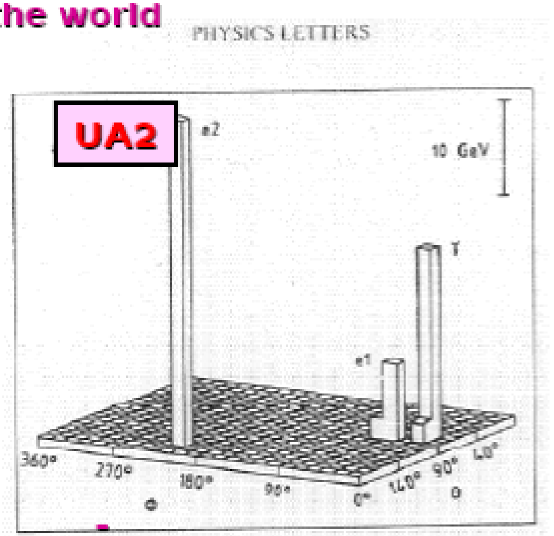


1974: Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$ (Iliopoulos)

1981: The CERN SpS becomes a proton-antiproton collider LEP and SLC are approved before W/Z boson discovery

1983: LEP and SLC construction starts W and Z discovery (UA1, UA2)

One of the first Z-bosons detected in the world



$q\bar{q} \rightarrow Z \rightarrow e^+ e^- \gamma$

A brief historical overwiew toward LHC

1984: Glimmerings of LHC and SSC

1987: First comparative studies of physics potential of hadron colliders (LHC/SSC) and e^+e^- linear colliders (CLIC)

1989: First collisions in LEP and SLC
Precision tests of the SM and search for the Higgs boson begin in earnest
R&D for LHC detectors begins

1993: Demise of the SSC

1994: LHC machine is approved (start in 2005)

1995: Discovery of the top quark at Fermilab by CDF (and D0)
Precision tests of the SM and search for the Higgs boson continue at LEP2

Approval of ATLAS and CMS

2000: End of LEP running

2001: LHC schedule delayed by two more years

2008: LHC started but after few days of operating with single beam very serious accident

2009: Restarted back just before Xmass with 900 GeV collision

2010: Since March collecting data at 7 TeV pp collision.
Time shared between machine commissioning and physics runs. About 10pb-1 collected by each experiment as of today.

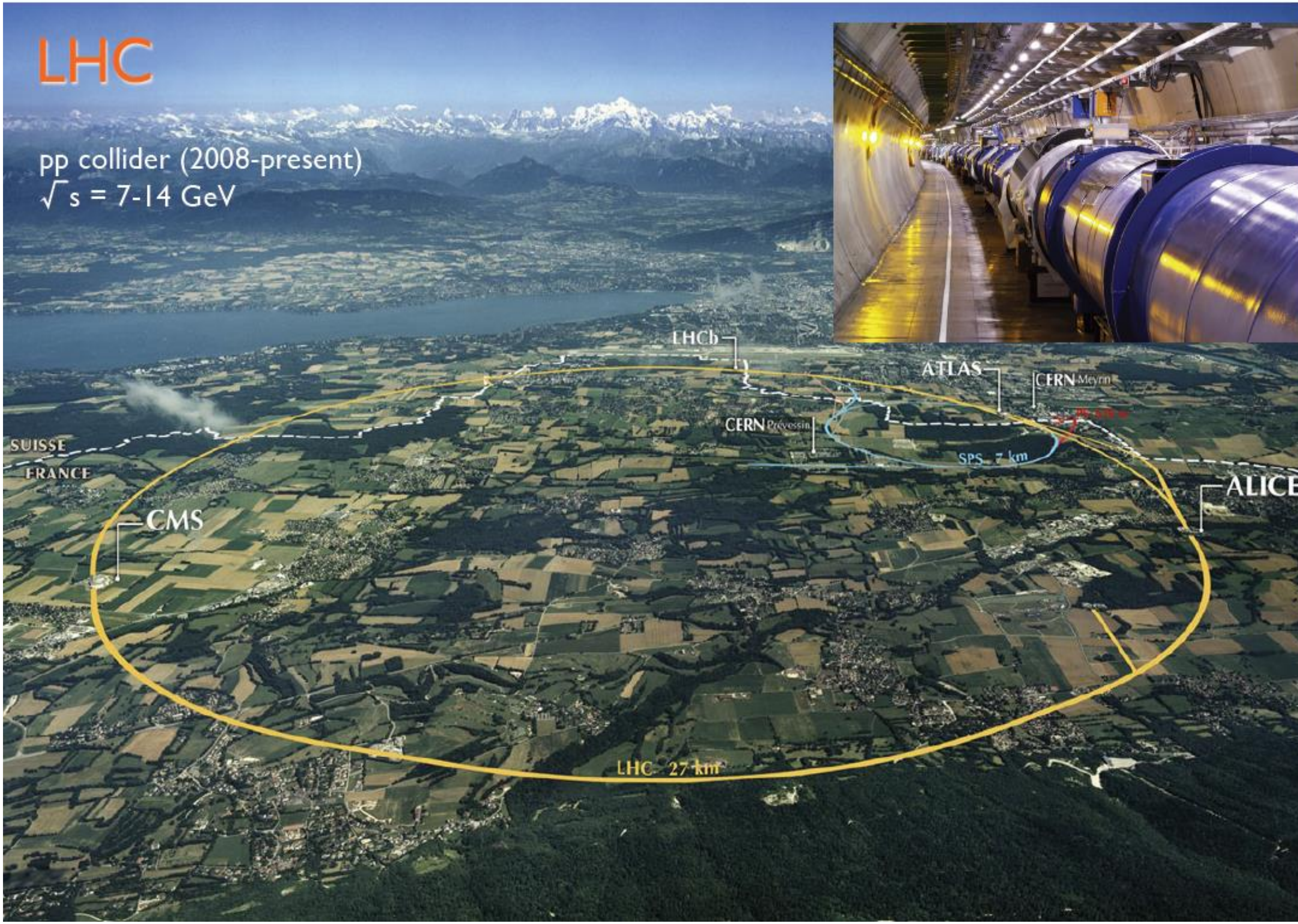
2012-2014: shut-down

2015: starting RunII at 13 TeV pp collision

LHC

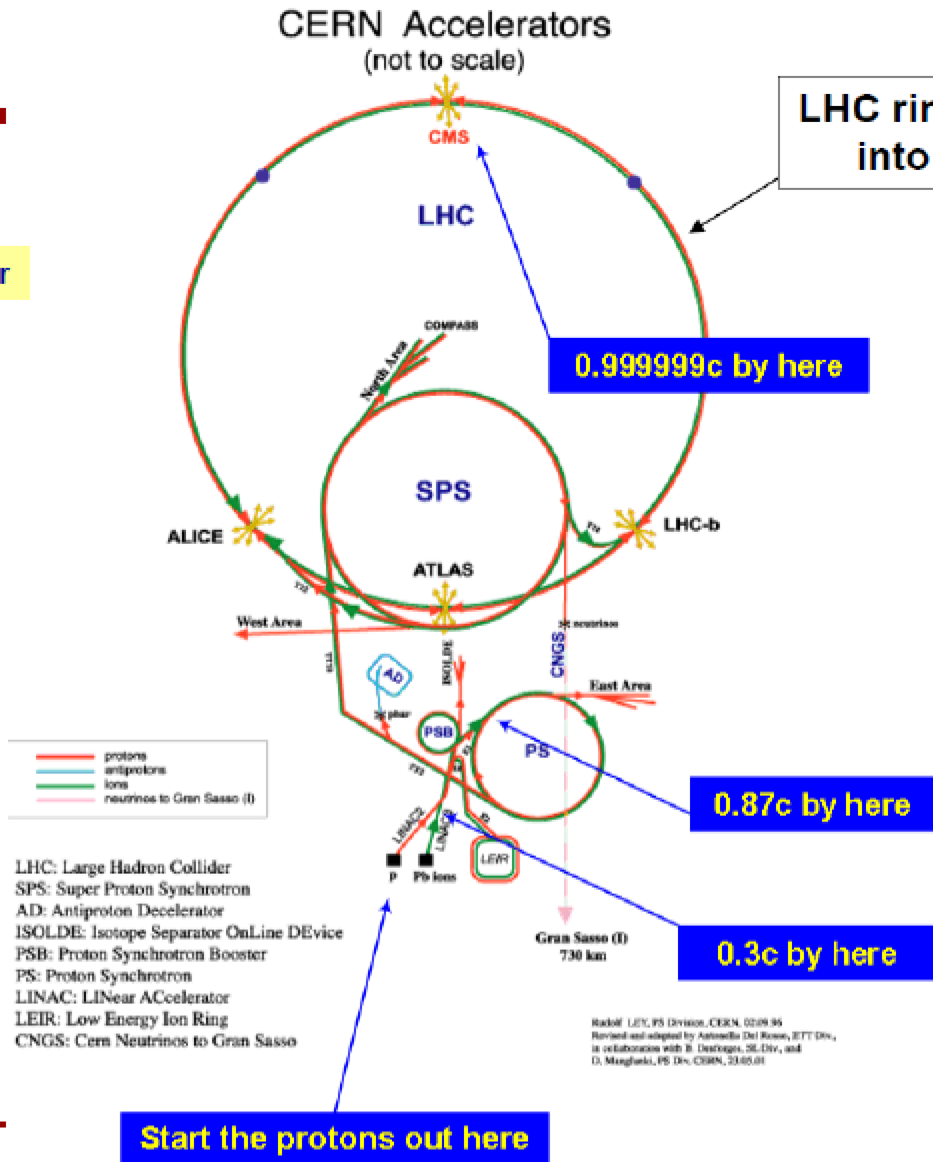
pp collider (2008-present)

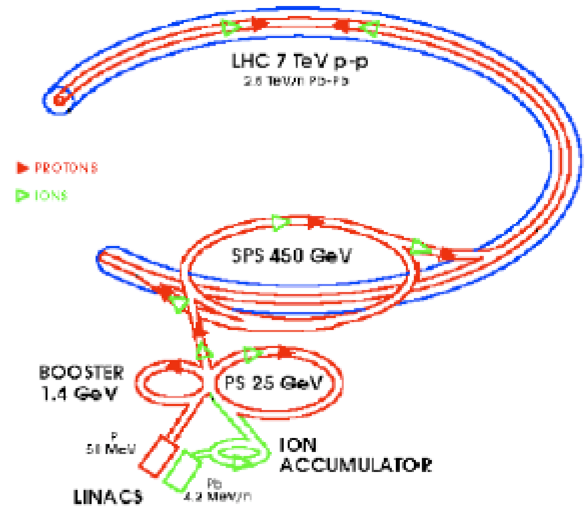
$\sqrt{s}$ = 7-14 GeV



The full LHC accelerator complex

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC



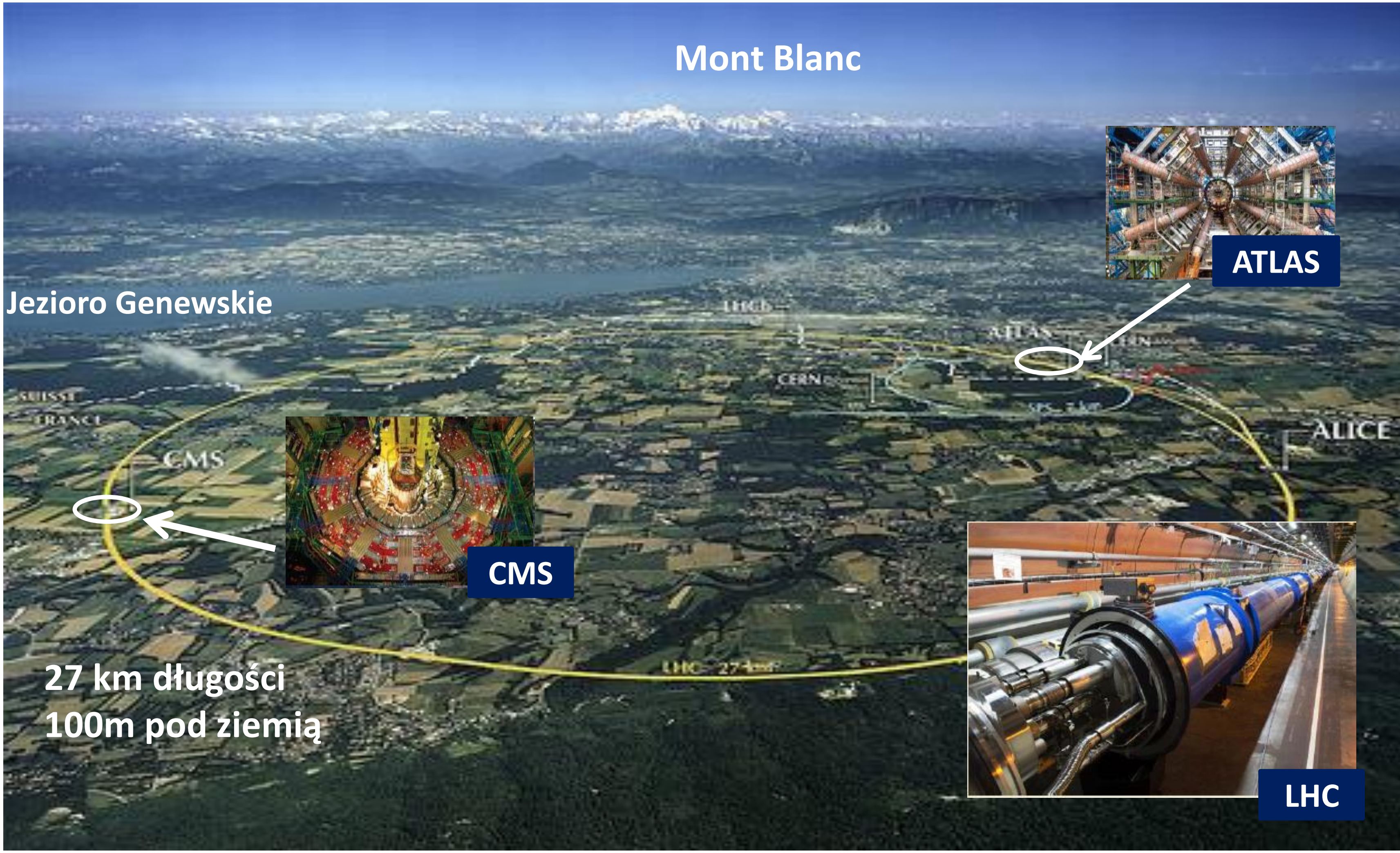


> 50 years of CERN history still alive and operational

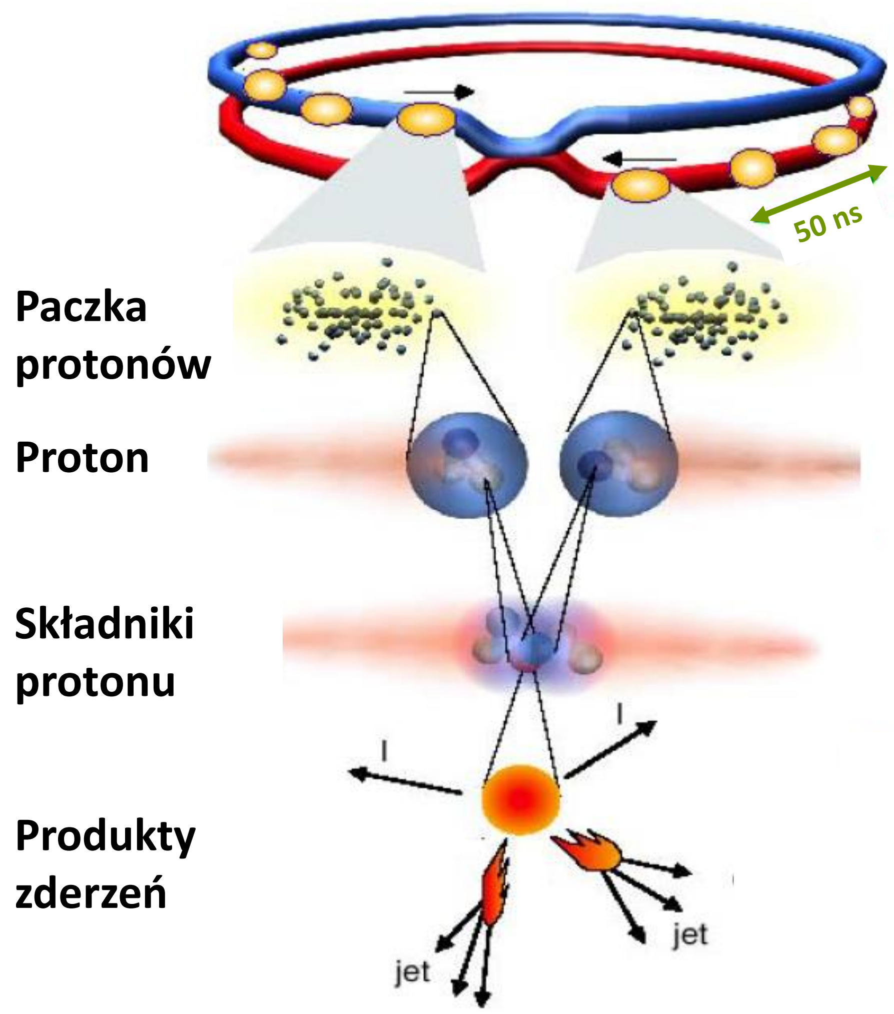
LHC: comparison to other colliders

	Start	Type	Max proton energy [GeV]	Length [m]	B Field [Tesla]	Lumi [$cm^{-2}s^{-1}$]	Stored beam energy [MJoule]
TEVATRON Fermilab Illinois USA	1983	p-pbar	980	6300	4.5	$4.3\ 10^{32}$	1.6 for protons
HERA DESY Hamburg	1992	p – e+ p – e-	920	6300	5.5	$5.1\ 10^{31}$	2.7 for protons
RHIC Brookhaven Long Island	2000	Ion-Ion p-p	250	3834	4.3	$1.5\ 10^{32}$	0.9 per proton beam
LHC CERN	2008	Ion-Ion p-p	**7000** Now 4000	26800	8.3	10^{34} Now 7.7×10^{33}	**362 per beam**
Factor			7	4	2	**50**	**100**

LHC (Large Hadron Collider)

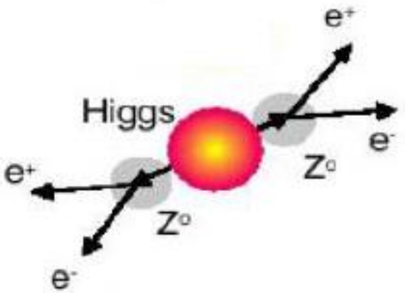


Zderzenia wiązek proton-proton



Proton-Proton	1380 paczek/wiązkę
Protonów/paczka	$1.7\ 10^{11}$
Energia wiązki	4 TeV

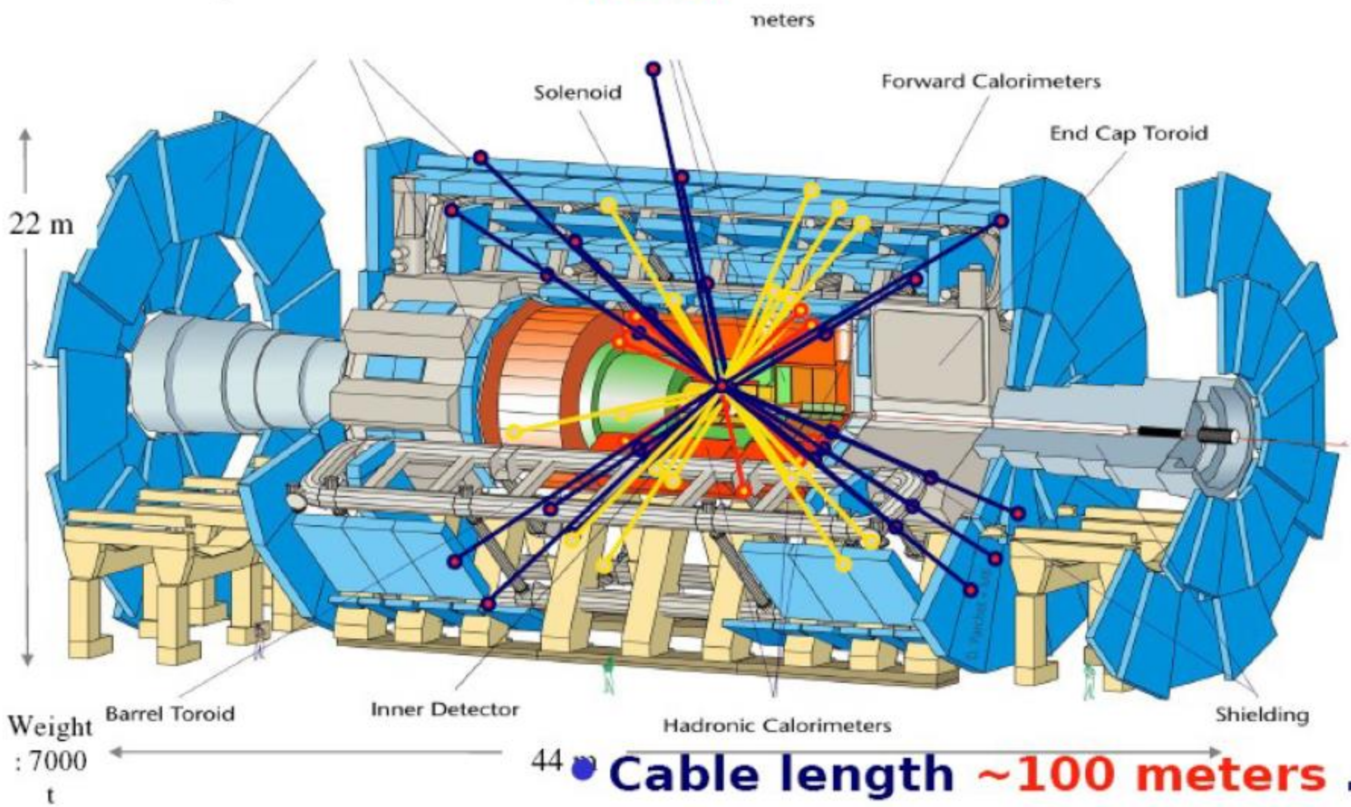
Każdy proton porusza się z prędkością bliską prędkości światła i niesie kinetyczną energię muchy w locie, okrąża pierścień akceleratora 1100 razy na sekundę.
Rozmiar poprzeczny wiązki: 16μm (4 razy mniejszy niż grubość ludzkiego włosa).
Każda z wiązek niesie energię pociągu TGV o dł. 200 m i jadącego z prędkością 155km/godz (360M Jula).



Takie zdarzenie pojawia się raz na 10 bilio-nów zderzeń

ATLAS detector

- **Interactions every 25 ns ...**
  - **In 25 ns particles travel 7.5 m**



- **Cable length ~100 meters ..**
  - **In 25 ns signals travel 5 m**

Detektor ATLAS i zespół badawczy

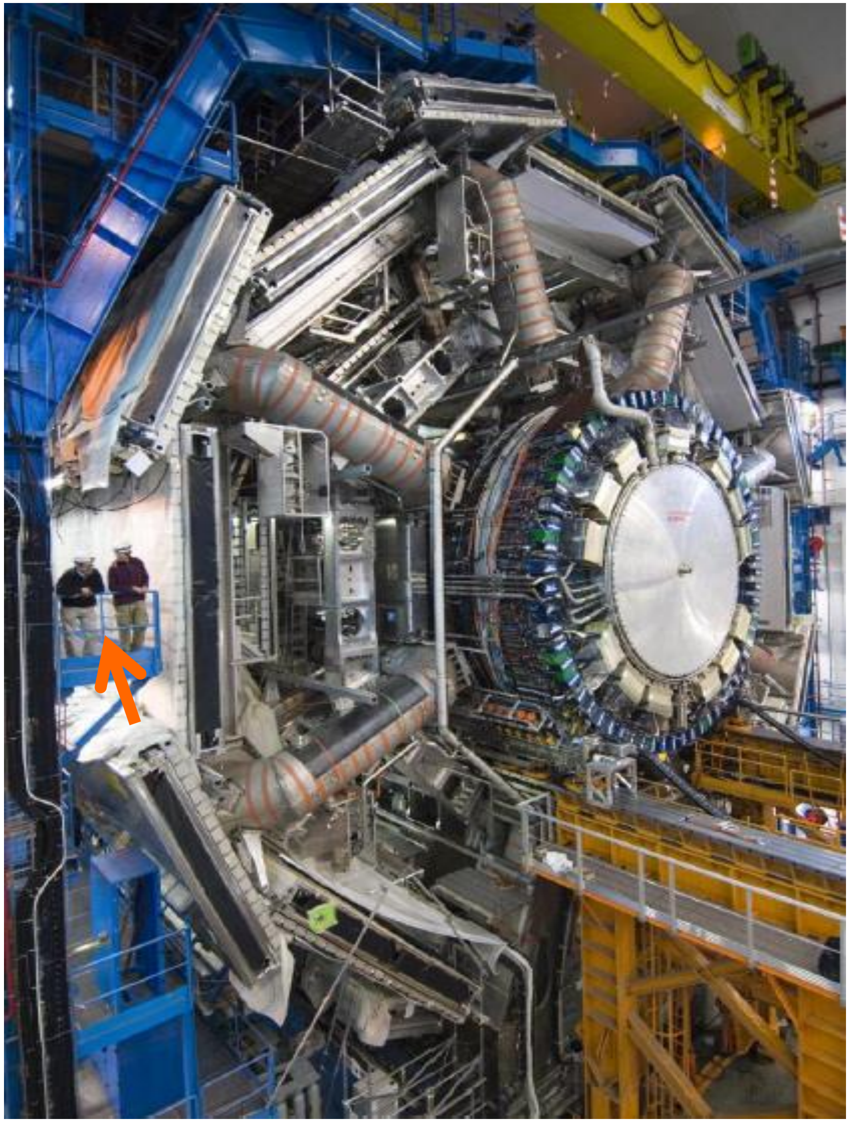
Detektor ATLAS:

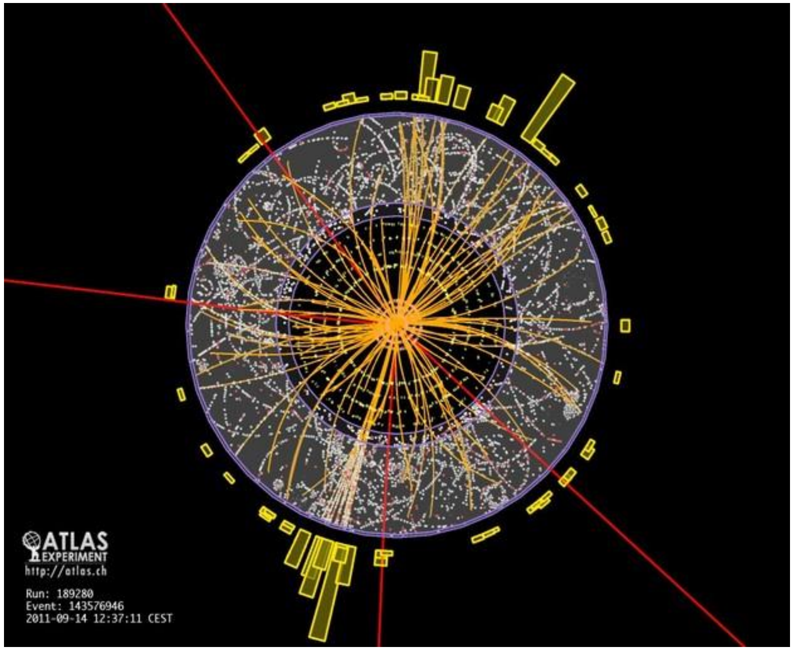
42m długości, 22 m średnicy; 3000 km kabli wyprowadzających sygnał; ponad 10^8 kanałów odczytu elektroniki; precyzja ustawienia elementów rzędu mikronów

Zespół badawczy:

Ponad 3000 fizyków, inżynierów i techników, w tym ponad 1000 doktorantów;
178 instytucji z 38 krajów;
Zespoły polskie:
IFJ-PAN, AGH i Instytut Fizyki UJ

Detektor ATLAS



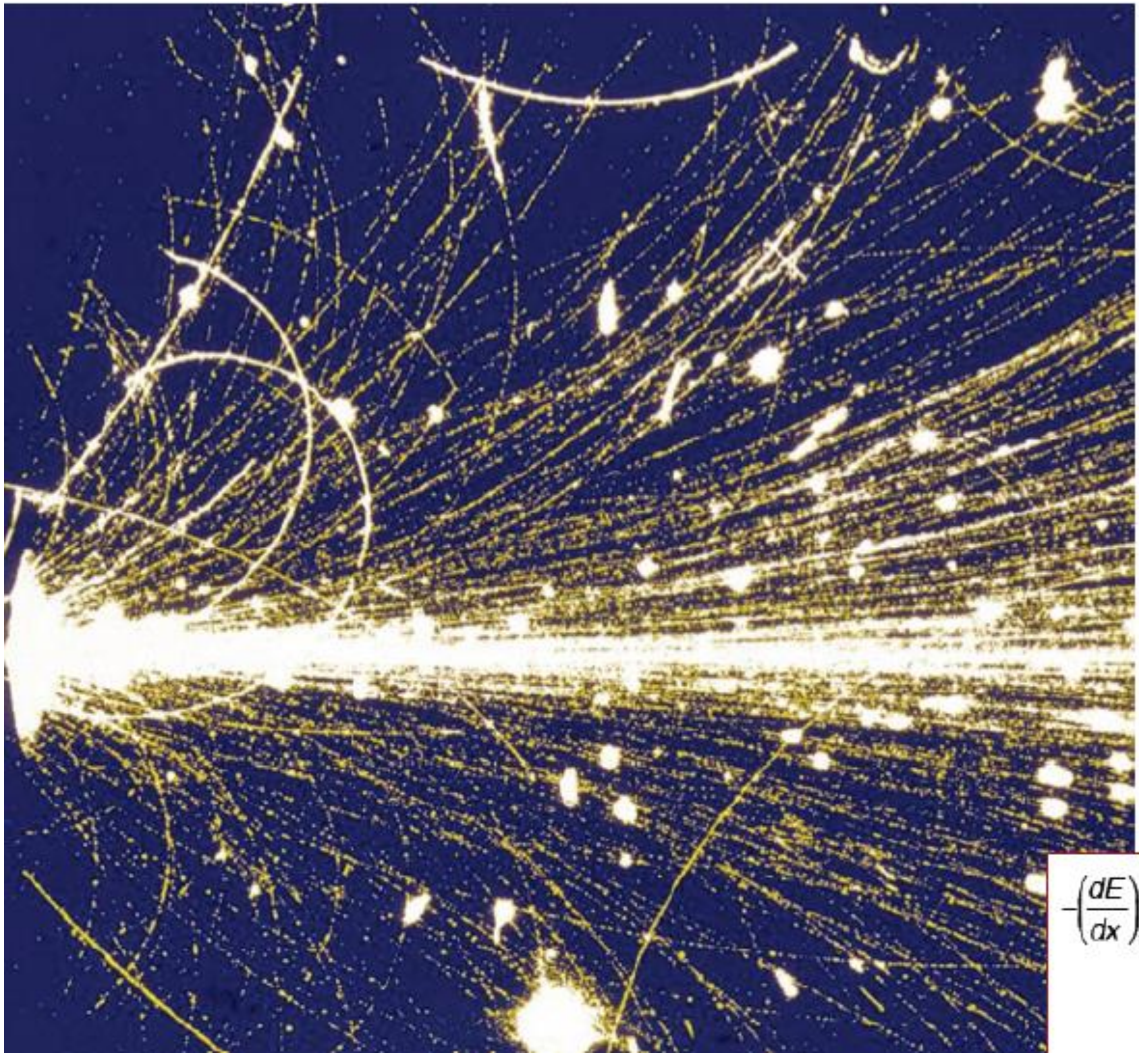


Analiza zarejestrowanych zderzeń:

W ciągu 3 lat każdy eksperyment zarejestrował na dyskach ponad 5 miliardów interesujących zderzeń = 20 Petabyte danych.

Gdyby zapisać je na płytkach CD to powstałby stos o wysokości 20 km.

Particle detection



Particles can be "seen" as the result of an interaction with matter (detector)

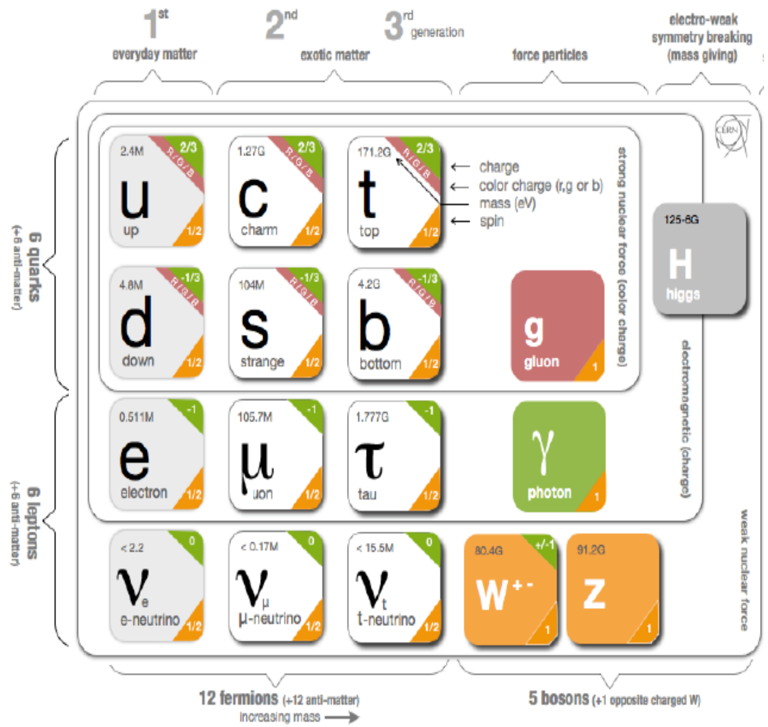
In the end, everything is converted to:

- optical pictures
- voltage/current signals

$$-\left(\frac{dE}{dx}\right)_{tot} = -\left(\frac{dE}{dx}\right)_{coll} - \left(\frac{dE}{dx}\right)_{rad} - \left(\frac{dE}{dx}\right)_{pair} - \left(\frac{dE}{dx}\right)_{photonucl} - \left(\frac{dE}{dx}\right)_{photoeff} - \left(\frac{dE}{dx}\right)_{compton} - \left(\frac{dE}{dx}\right)_{hadron}$$

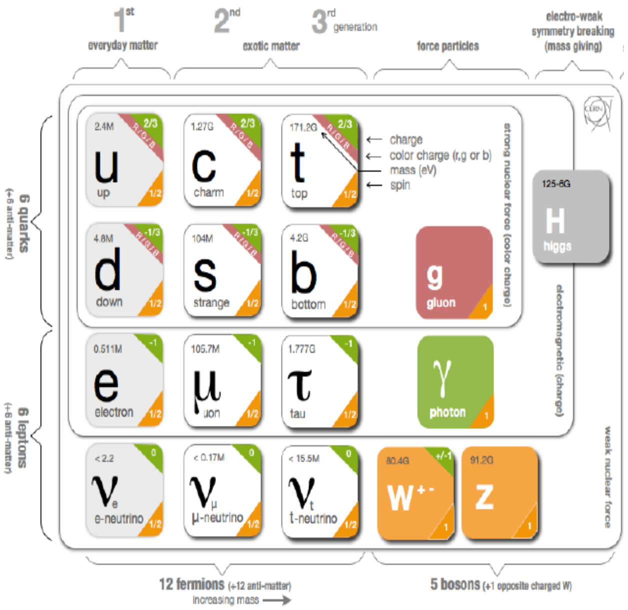
What can we detect?

- Directly observable particles must:
  - Undergo strong or EM interactions
  - Be sufficiently long-lived to pass the detectors
- We can directly observe:
  - Electrons, muons, photons
  - Neutral or charged hadrons
  - Pions, protons, kaons, neutrons,...
  - analyses treat jets from quark hadronization collectively as single objects
  - Use displaced secondary vertices to identify jets originating from b-quarks
- We can indirectly observe long lived weakly interacting particles (e.g. neutrinos) through **missing transverse energy**



What can we detect?

- Short-lived particles decay to long-lived ones
- We can only 'see' the end products of the reaction, but not the reaction itself
- In order to reconstruct the production/decay mechanism and the properties of the involved particles, we want the maximum information

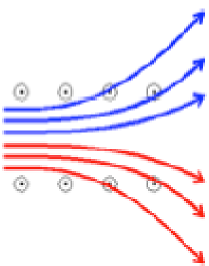


Paricle properties?

Which properties do we want to measure?

- Energy (calorimeter)
- Momentum (tracking)
- Charge (tracking)
  - Direction, bending in magnetic field
- Life-time (tracking)
- Mass:

$$E, \quad \vec{p} = \begin{pmatrix} p_1 \\ p_2 \\ p_3 \end{pmatrix} \Bigg\} \begin{pmatrix} E \\ \vec{p} \end{pmatrix}$$



$$F = q \cdot v \cdot B = m \cdot \frac{v^2}{R}$$

$$\Rightarrow q \cdot B \cdot R = m \cdot v = |\vec{p}|$$

$$E^2 = m^2 \cdot c^4 + \vec{p}^2 c^2 \Rightarrow m = \frac{\sqrt{E^2 - \vec{p}^2 c^2}}{c^2}$$

- **Spin and parity**

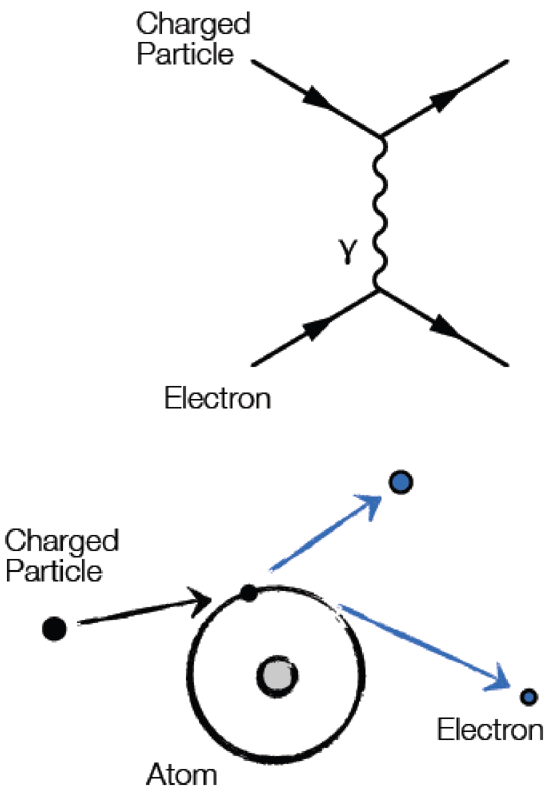
How we can detect particles

- In order to detect a particle, it must:
  - ✓ interact with the material of the detector
  - ✓ transfer energy in some recognizable fashion (signal)
- Detection of particles happens via their energy loss in the material they traverses

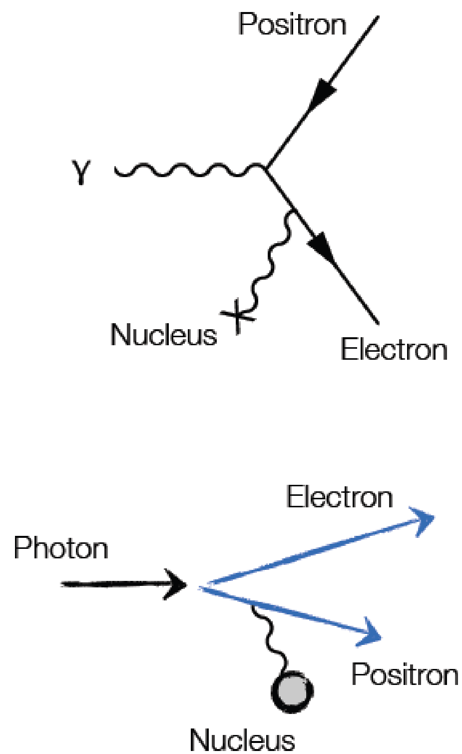
Charged particles	Ionization, Bremsstrahlung, Cherenkov, …	multiple interactions
Photons	Photo/Compton effect, pair production	single interactions…
Hadrons	Nuclear interactions	multiple interactions
Neutrinos	Weak interactions	

Examples of particles interactions

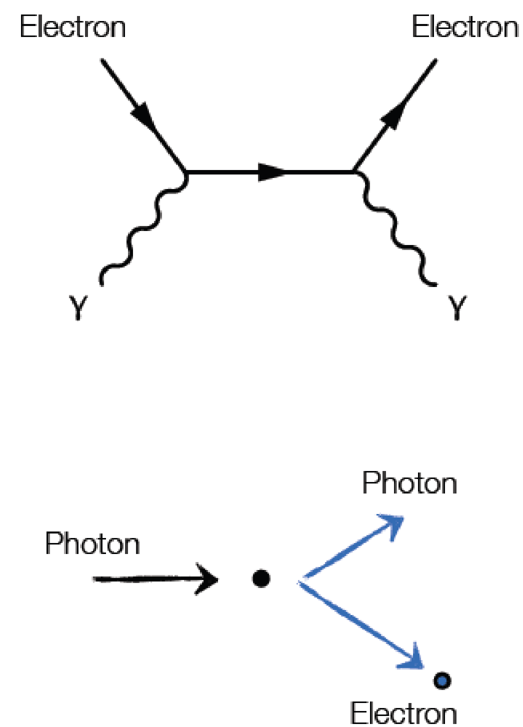
Ionization:



Pair production:

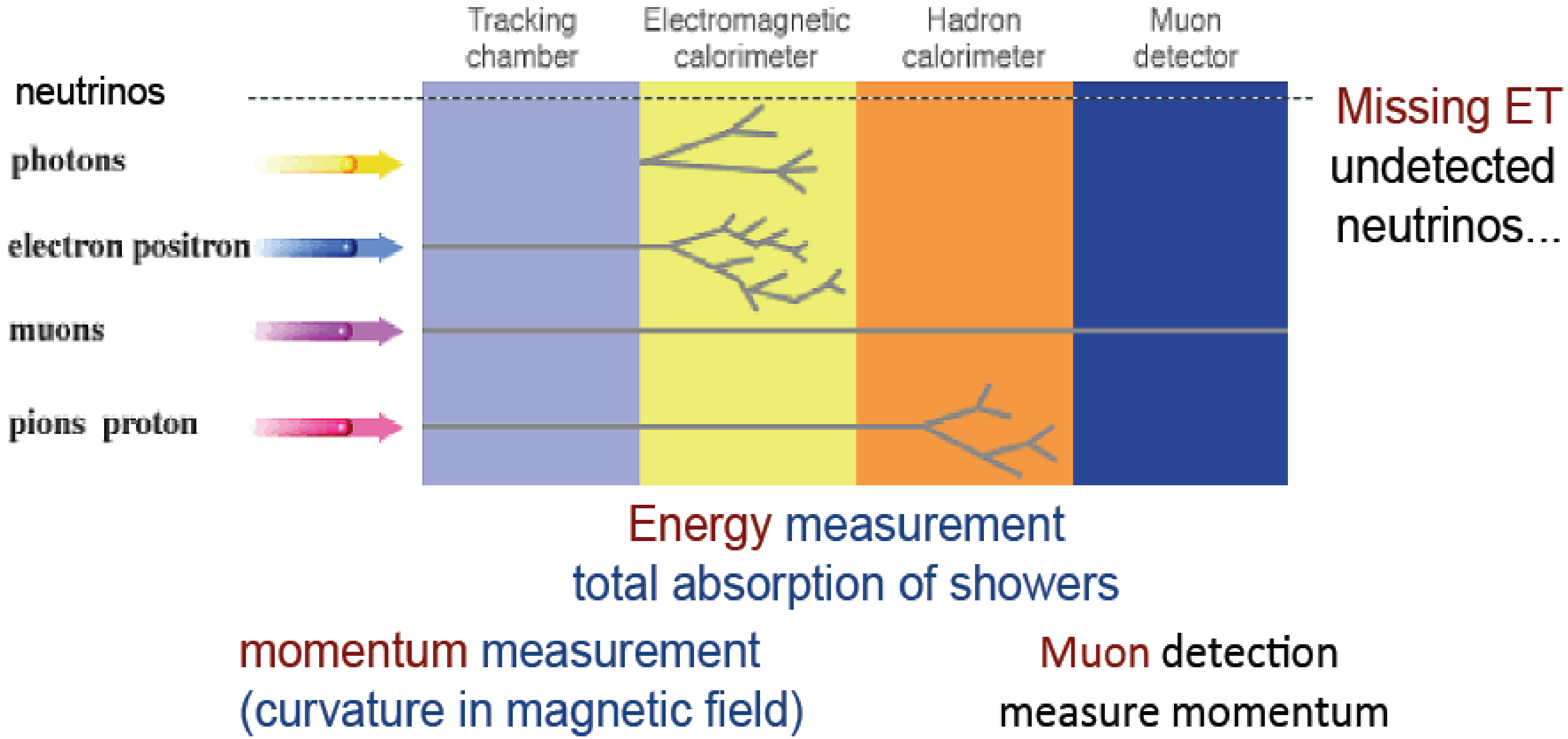


Compton scattering:



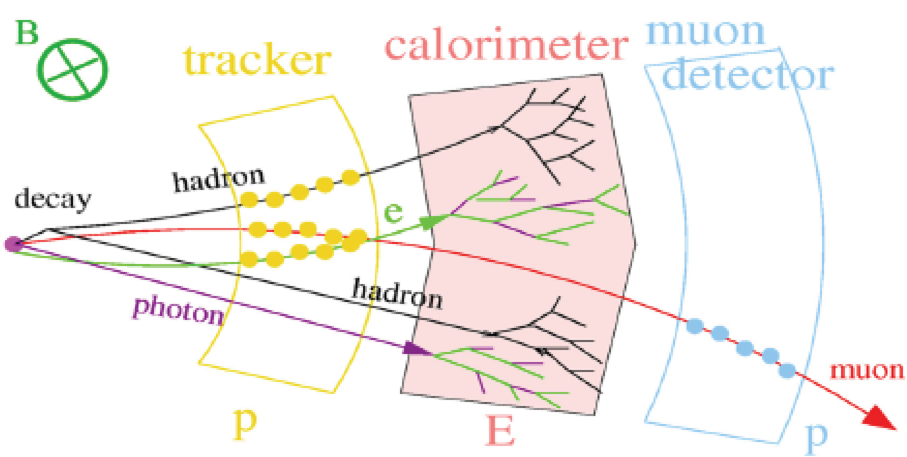
Passage of particles

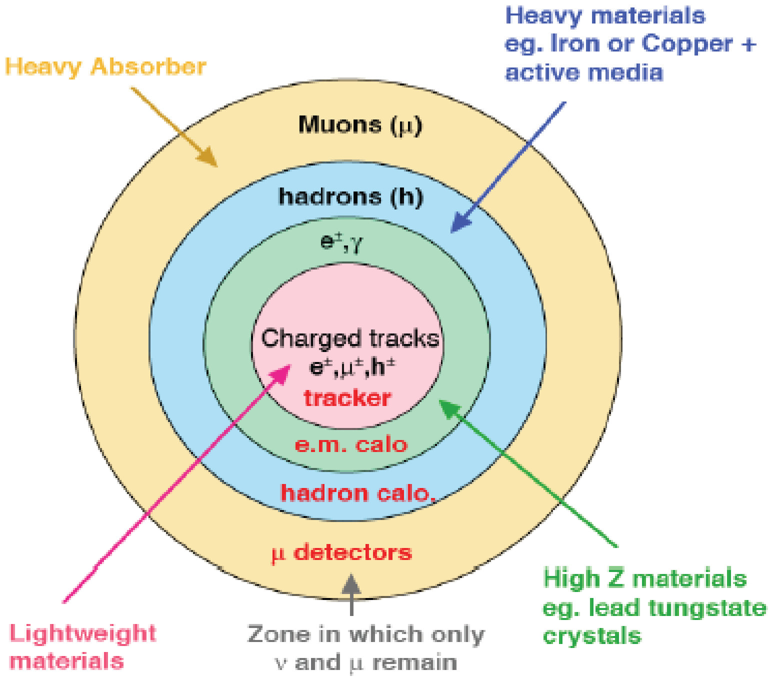
- "Onion"-like structure
- Each layer measures E and/or p of particles
- Redundancy of measurements



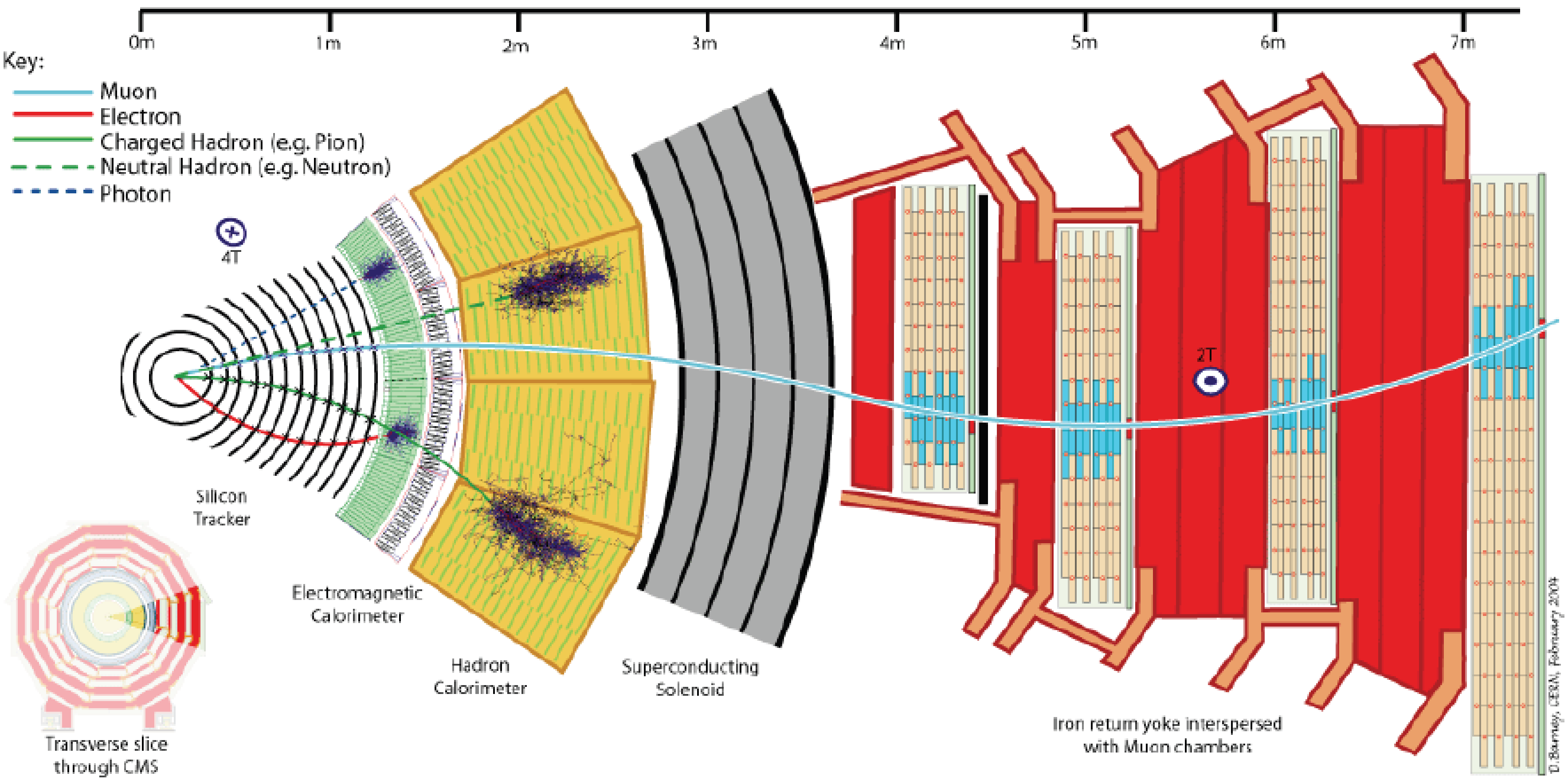
Detector layers

- Inner tracking
  - Measure charged particle (momentum)
- Magnetic field:
  - Measure momentum
- Calorimeters
  - Measure energy of all particles
- Outer tracking
  - Measure muons

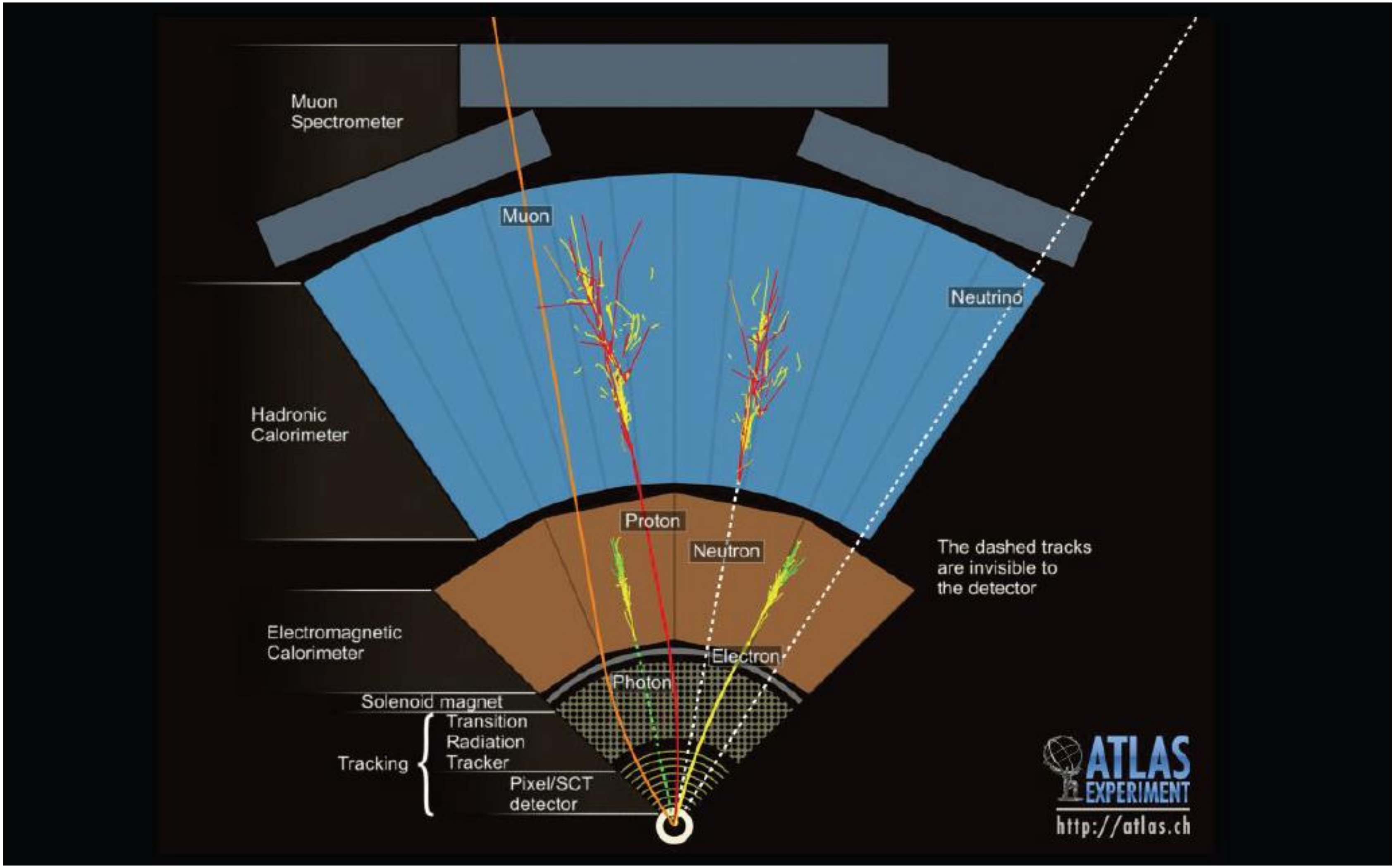




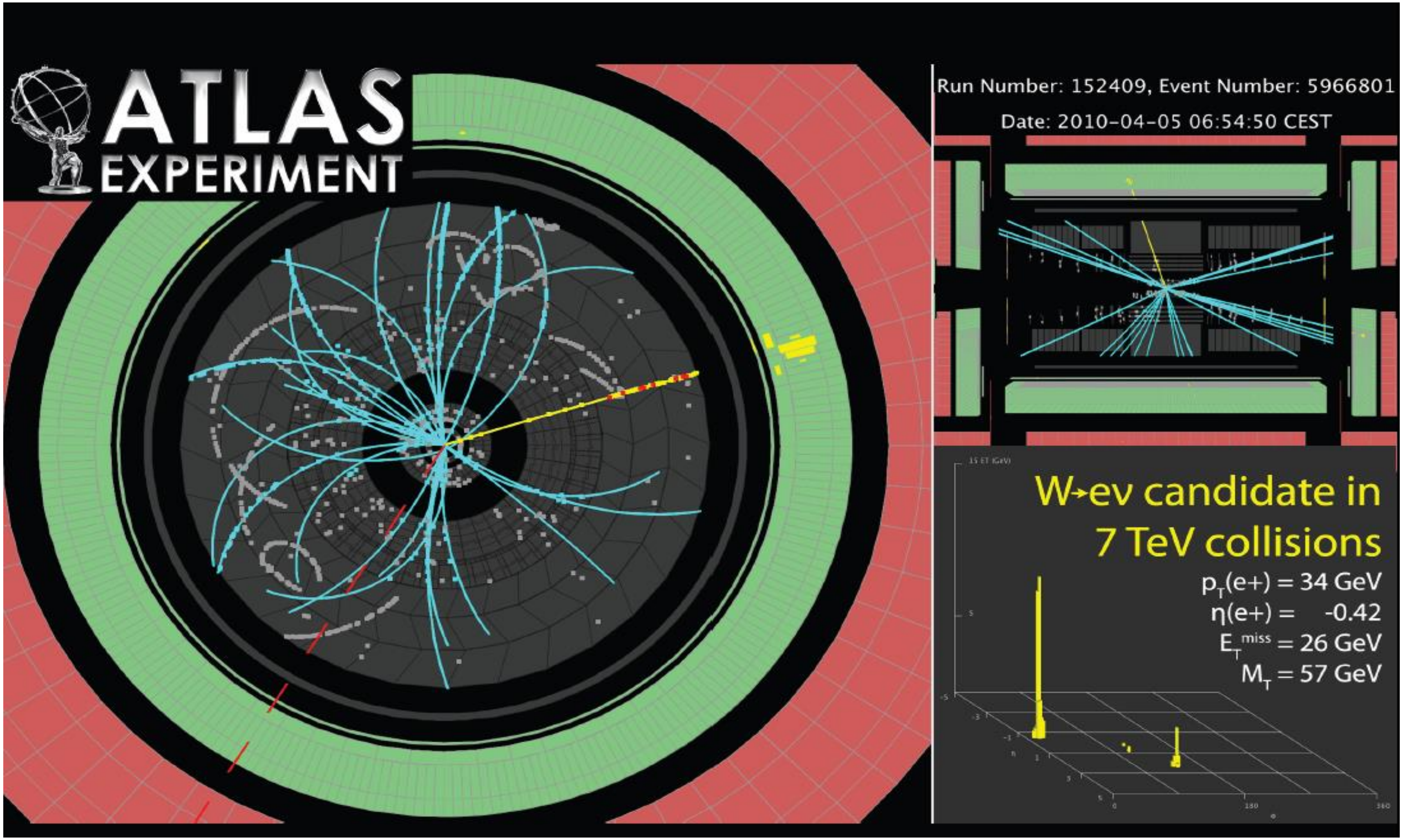
CMS experiment



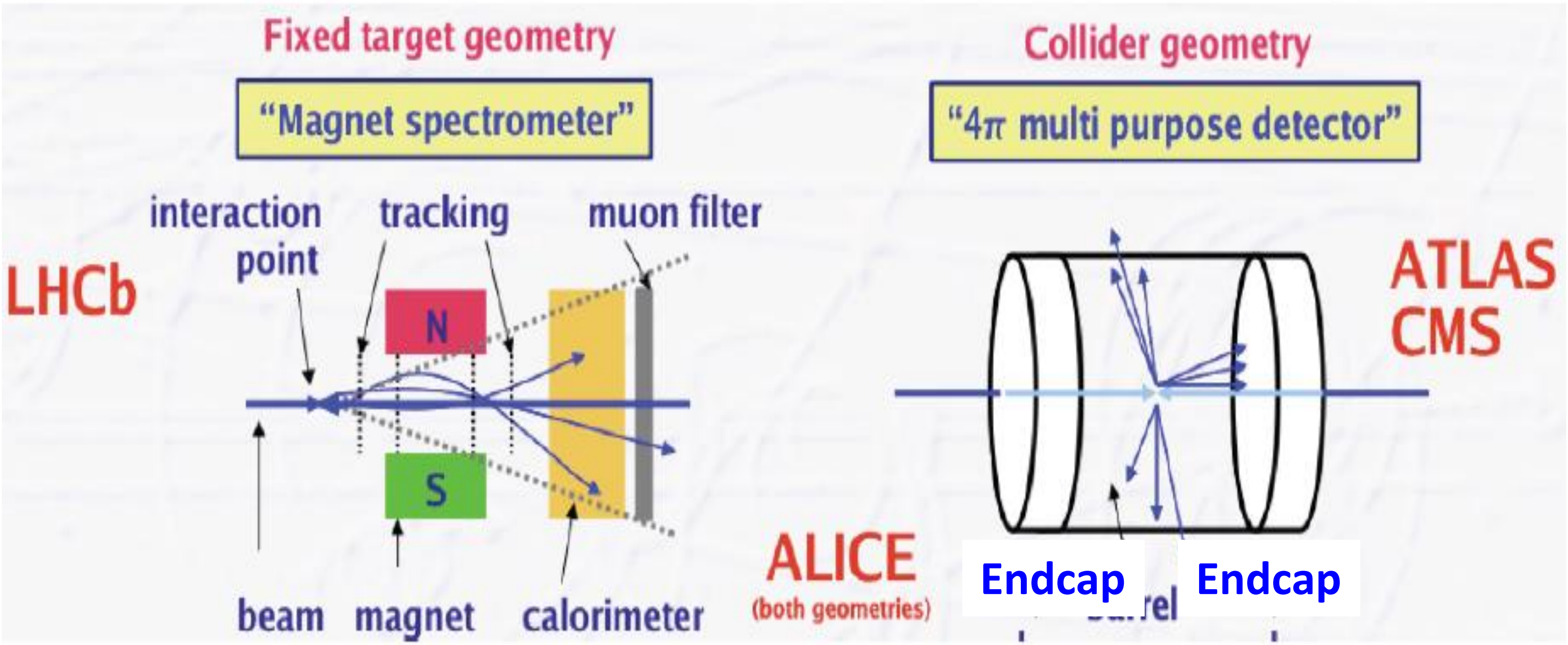
ATLAS experiment



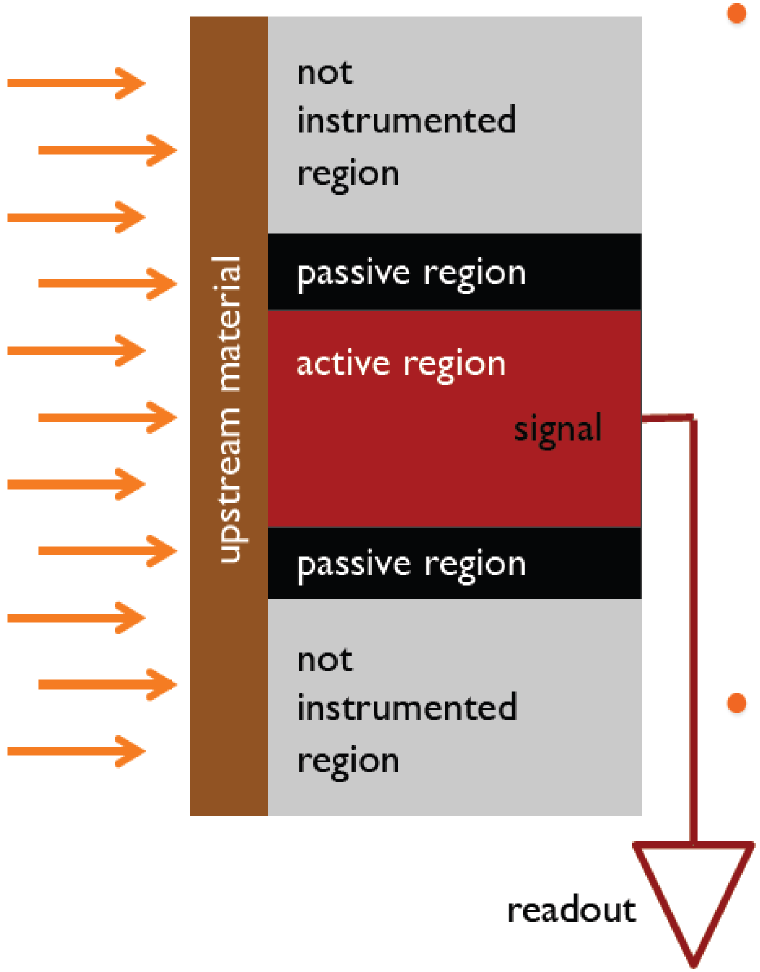
Event display



Fixed target vs Collider



Detectors are imperfect



- **Detection efficiency**

$$\varepsilon = \frac{N_{\mathrm{detected}}}{N_{\mathrm{incident}}} = M \cdot R \cdot D$$

  - ✓ M = P(entering active region)
    - Upstream material, entrance windows, …
  - ✓ R = P(generating signal)
    - Interaction cross sections, response, fluctuations, …
  - ✓ D = P(signal gets registered)
    - Readout properties, thresholds, …

- **Acceptance**
  - ✓ Instrumented/reactive region of the phase space (e.g. pseudorapity, azimuthal angle, but also energy/momentum)
    - dynamic range

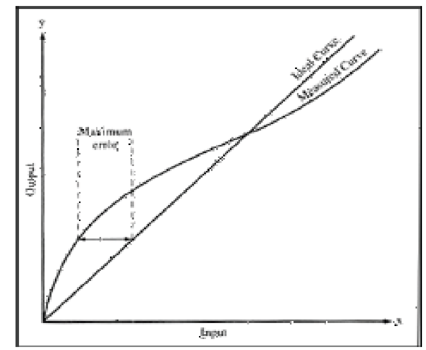
Detectors are imperfect

- Dead Time
  - ✓ Delay between particle entrance in detector and signal acquisition, in which the detector is rendered inactive (detector + readout)
  - ✓ Dead time efficiency

$$\varepsilon(T_d) = \frac{1}{N_{\text{detected}} T_d + 1}$$

- Trigger
  - ✓ Detector cannot acquire signals continuously…

- Response linearity



- Response resolution