Physics Program

of the experiments at

Large Hadron Collider

Prof. dr hab. Elżbieta Richter-Wąs

Outline of this course

- Introduction to LHC, its experiments, physics programme and experimental challenges?
- ATLAS detector, requirements and expected physics performance
- The SM precision measurements : m_W, m_t, couplings
- The SM and MSSM Higgs
- Supersymmetry
- Extra dimensions and exotics
- B-physics
- Heavy ion physics

http://th-www.if.uj.edu.pl/~erichter/dydaktyka/Dydaktyka2011/LHCPhysics-2011

Many thanks to colleagues from LHC collaborations for making available large parts of material shown here.

Outline of this lecture

What is CERN and brief history toward the LHC?

What is the LHC ?

Why the LHC ?

The general purpose experiments: ATLAS and CMS

Brief overview of the physics programme

Experimental challenges

LHC at CERN laboratory

CERN: the world’s largest particle physics laboratory

- international organisation created in 1953/1954, initial membership: 12 countries
- Poland is a member starting from year 1991
- About 10 000 active physicists, computing scientists, engineers

situated between
Jura mountains and Geneva
(France/Swiss)

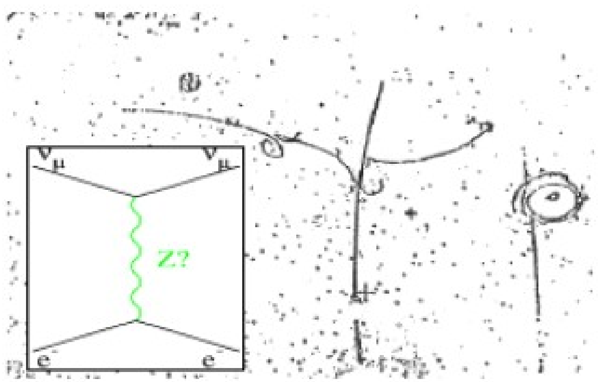
http://public.web.cern.ch

A brief historical overview: 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)

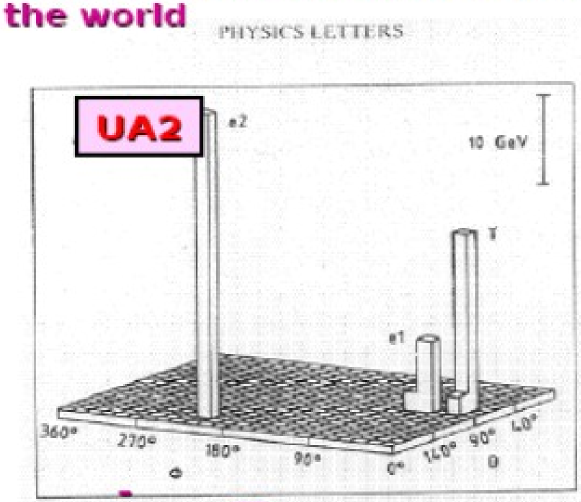


1974: Complete formulation of the standard model with $SU(2)_W \times U(1)_Y$ (Iliopoulos)

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



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

A brief historical overview: 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

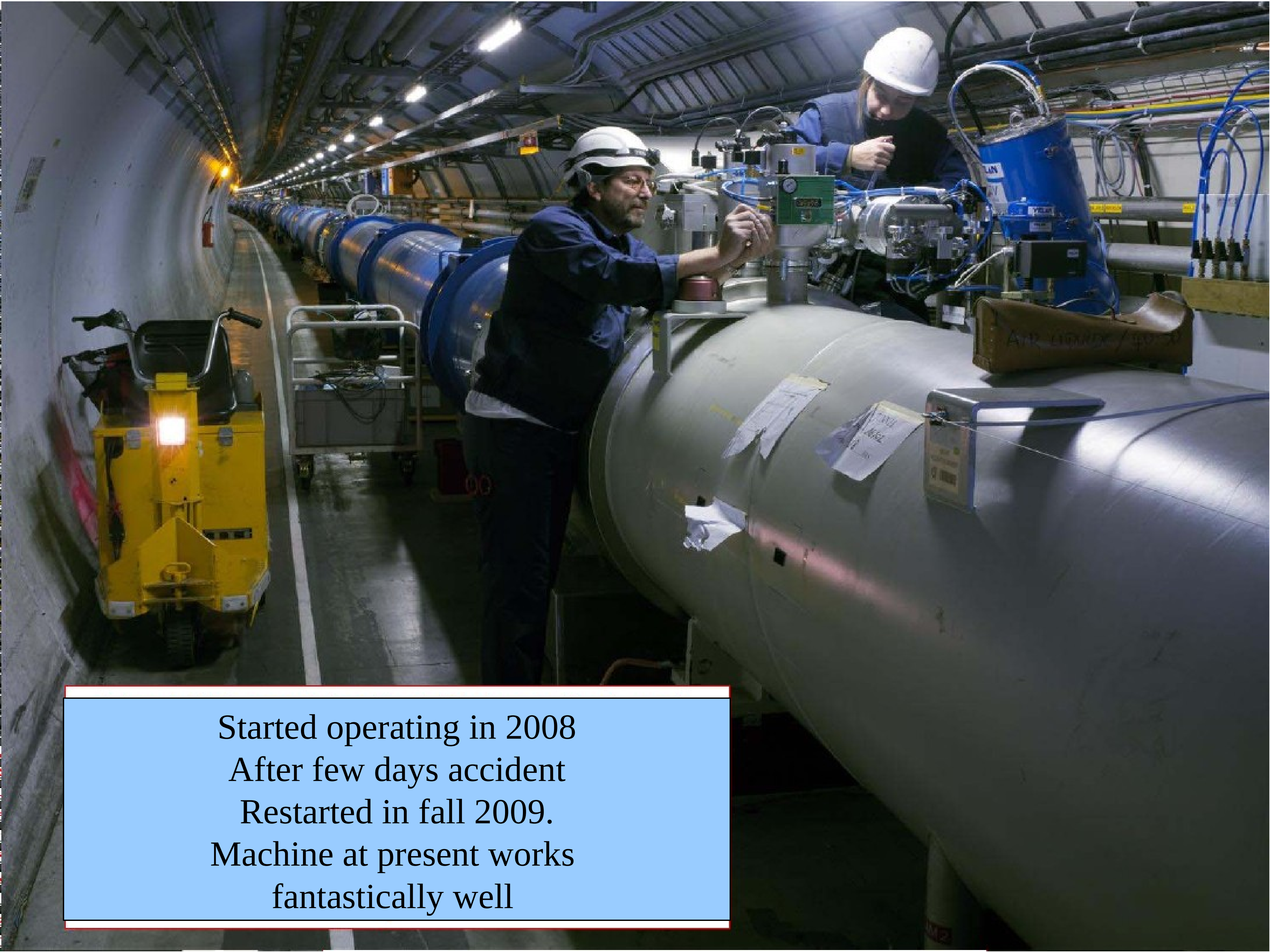
2001: LHC schedule delayed by two more years

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.

The LHC machine



Started operating in 2008
After few days accident
Restarted in fall 2009.
Machine at present works
fantastically well

The full LHC accelerator complex

Linac

↓

Booster

↓

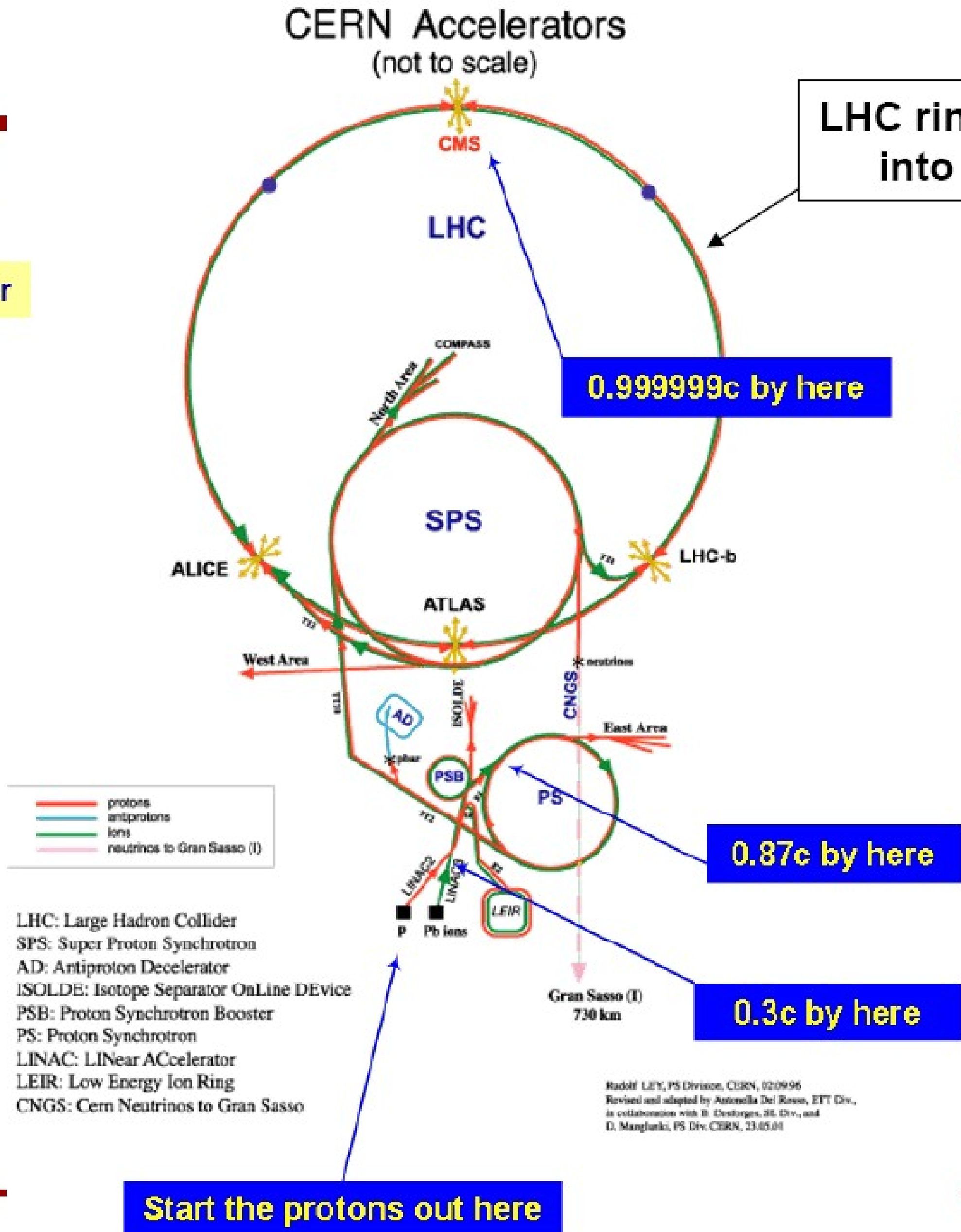
PS

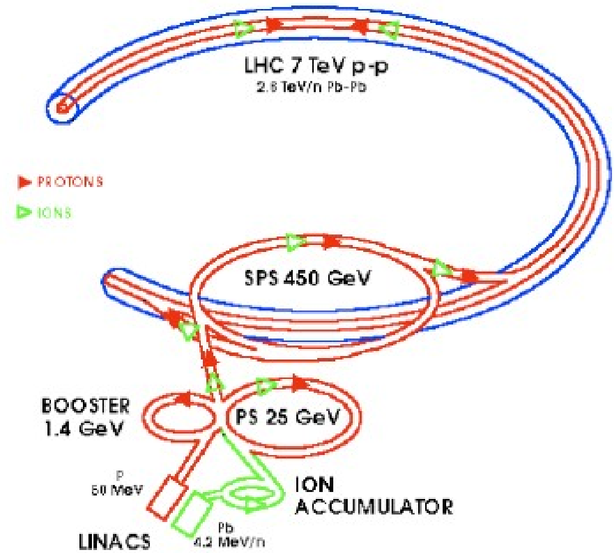
↓

SPS

↓

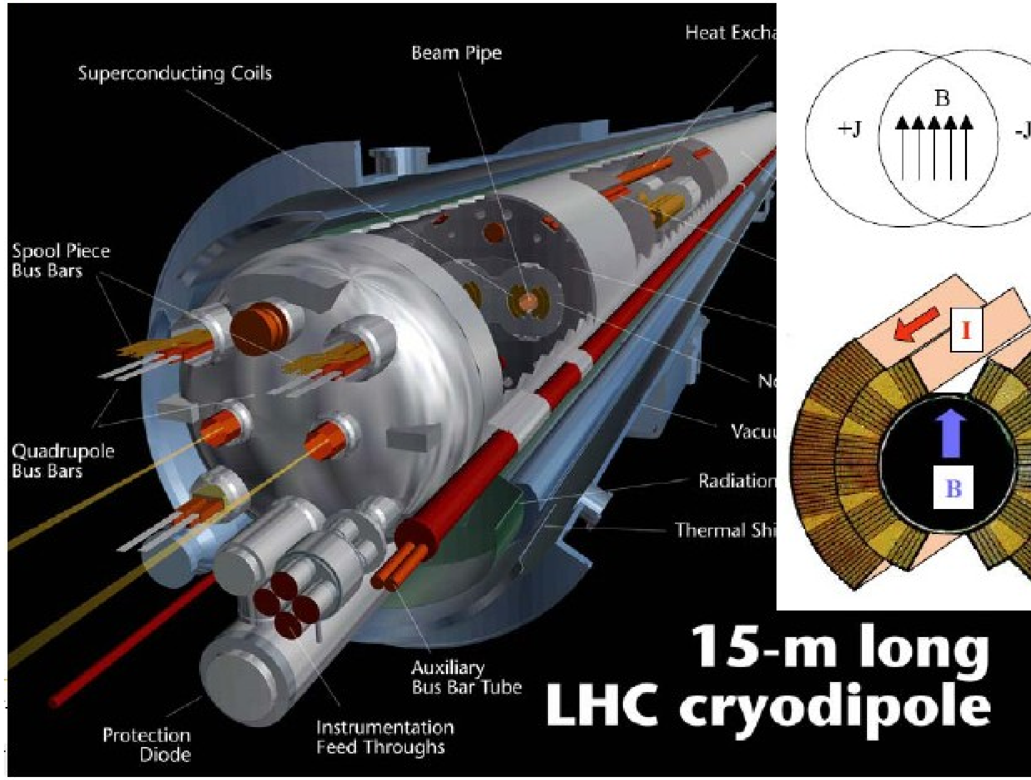
LHC

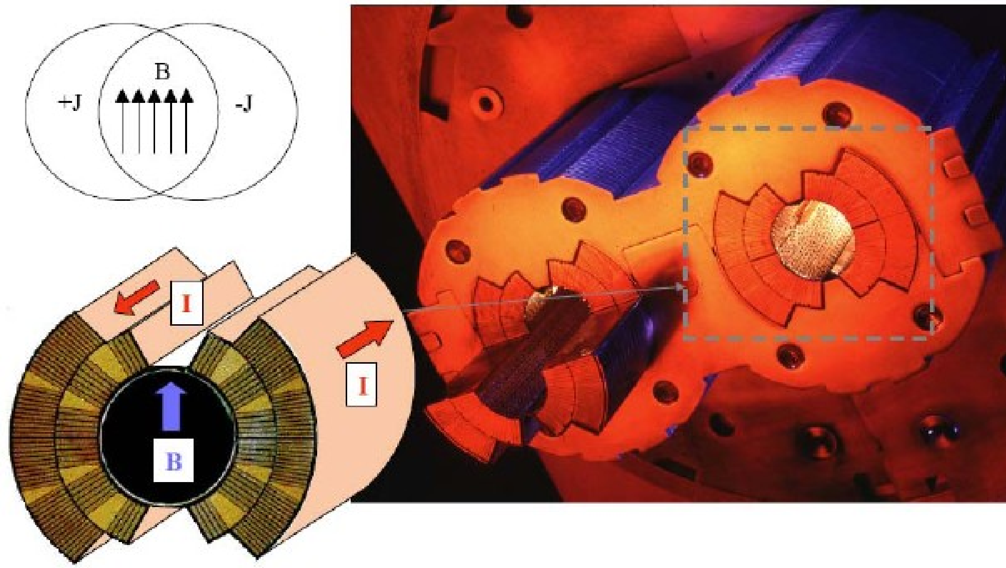




> 50 years of CERN history still alive and operational

LHC Accelerator Challenge: Dipole Magnets





Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) R(km)

Coldest Ring in the Universe ?
1.9 K (CMBR is about 2.7 K)

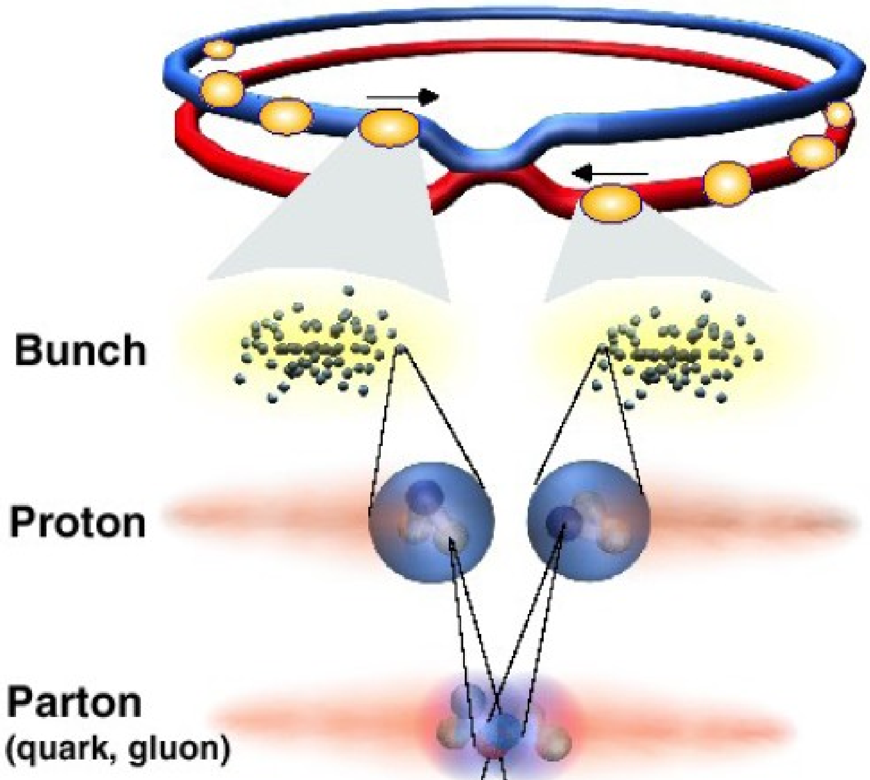
For p = 7 TeV and R = 4.3 km
⇨ B = 8.4 T
⇨ Current 12 kA

LHC magnets are cooled with pressurized superfluid helium

Descent of the last dipole magnet, 26 April 2007

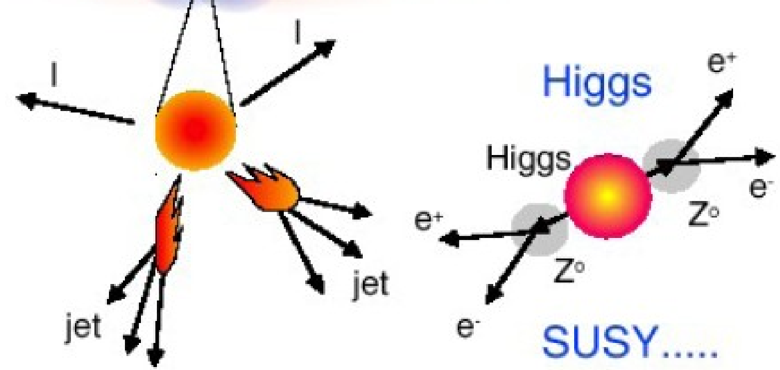
30’000 km underground transports at a speed of 2 km/h!

Collisions at LHC



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Particle



Selection of 1 in 10,000,000,000,000

Parameters of the LHC machine

	2010	2011	Nominal
Energy [TeV]	3.5	3.5	7
β* [m] (IP1,IP2,IP5,IP8)	3.5, 3.5, 3.5, 3.5	1.0, 10,1.0,3.0	0.55, 10, 0.55, 10
Emittance [µm] (start of fill)	2.0 – 3.5	**1.5 – 2.2**	3.75
Transverse beam size at IP1&5 [µm]	60	23	16.7
Bunch population	1.2×10^{11} p	$1.4\text{x}10^{+11}$ p	1.15×10^{11} p
Number of bunches	368	1380	2808
Number of collisions (IP1 & IP5)	348	1318	-
Stored energy [MJ]	28	110	360
Peak luminosity [$cm^{-2}s^{-1}$]	2×10^{32}	$3.3\text{x}10^{+33}$	1×10^{34}
Max delivered luminosity (1 fill) [pb^{-1}]	6.23	116 130.7	-
Longest Stable Beams fill [hrs]	12:09	25:59	-

LHC

2009 – 2012 :

sqrt(s) = 7-8 TeV, L ~ 10^{33}-10^{34} cm^{-2} s^{-1} , ∫ Ldt ≈ 10-15 fb^{-1}

2014 - 2017 :

sqrt(s) = 13-14 TeV, L ~ 1*10^{34} cm^{-2} s^{-1} , ∫ Ldt ≈ 50 fb^{-1}

2019-2021

sqrt(s) = 13-14 TeV, L ~ 2*10^{34} cm^{-2} s^{-1} , ∫ Ldt ≈ 300 fb^{-1}

2023-20XX

sqrt(s) = 13-14 TeV, L ~ 5*10^{34} cm^{-2} s^{-1} , ∫ Ldt ≈ 3000 fb^{-1}

Experiments

Four (five) large-scale experiments:

Cracow IFJ-PAN
-> ATLAS, ALICE, LHCb

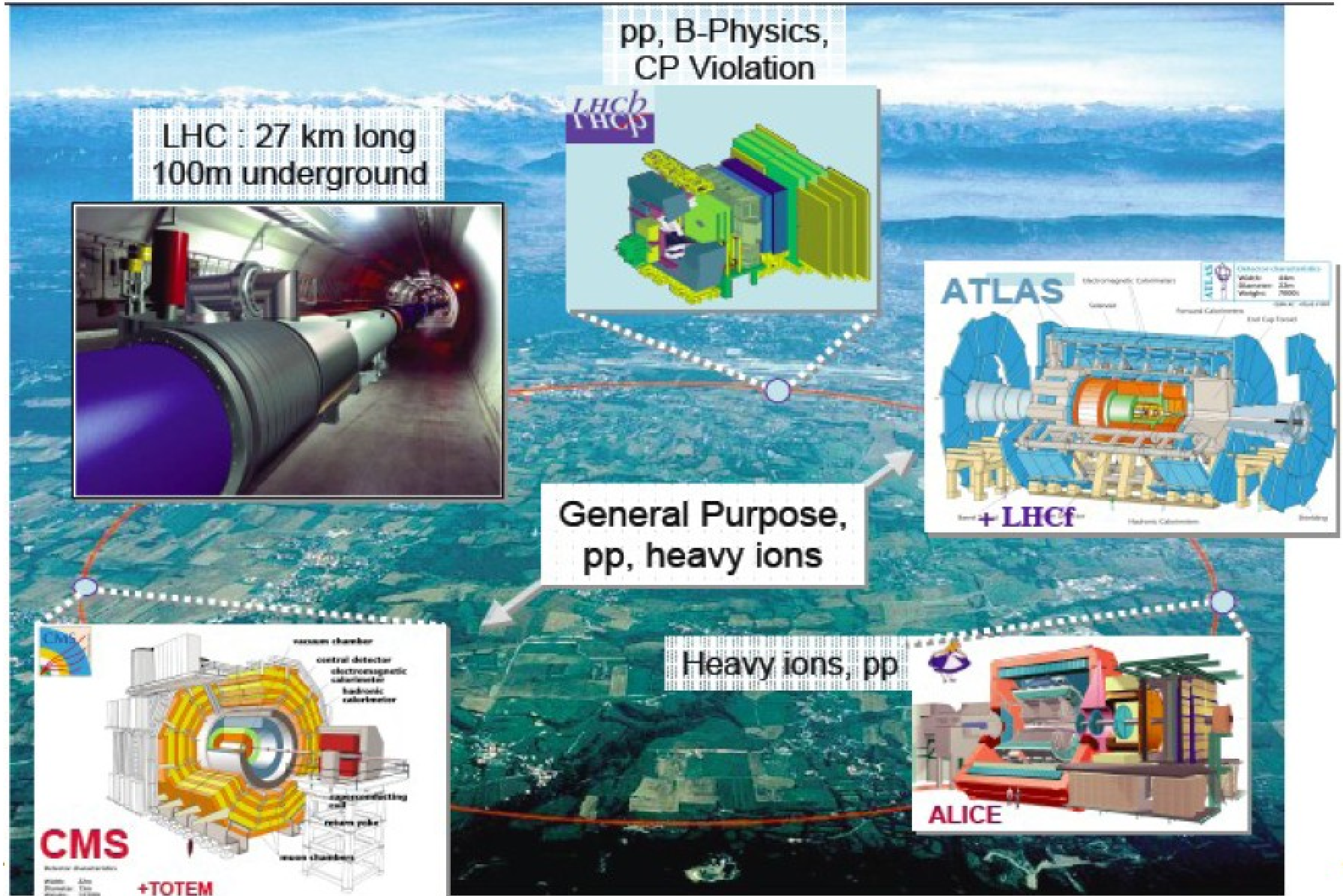
ATLAS
CMS
} general-purpose pp experiments

LHCb — pp experiment dedicated to b-quark physics and CP violation

ALICE — heavy-ion experiment (Pb-Pb collisions) at 5.5 TeV/nucleon $\rightarrow \sqrt{s} \cong 1000$ TeV
Quark-gluon plasma studies.

TOTEM (in CMS cavern) — Total Cross-Section, Elastic Scattering and Diffraction Dissociation

Large Hadron Collider@CERN



LHC is an unprecedented machine

- Energy

- Luminosity

- Cost : > 4000 MCHF (machine + experiments)

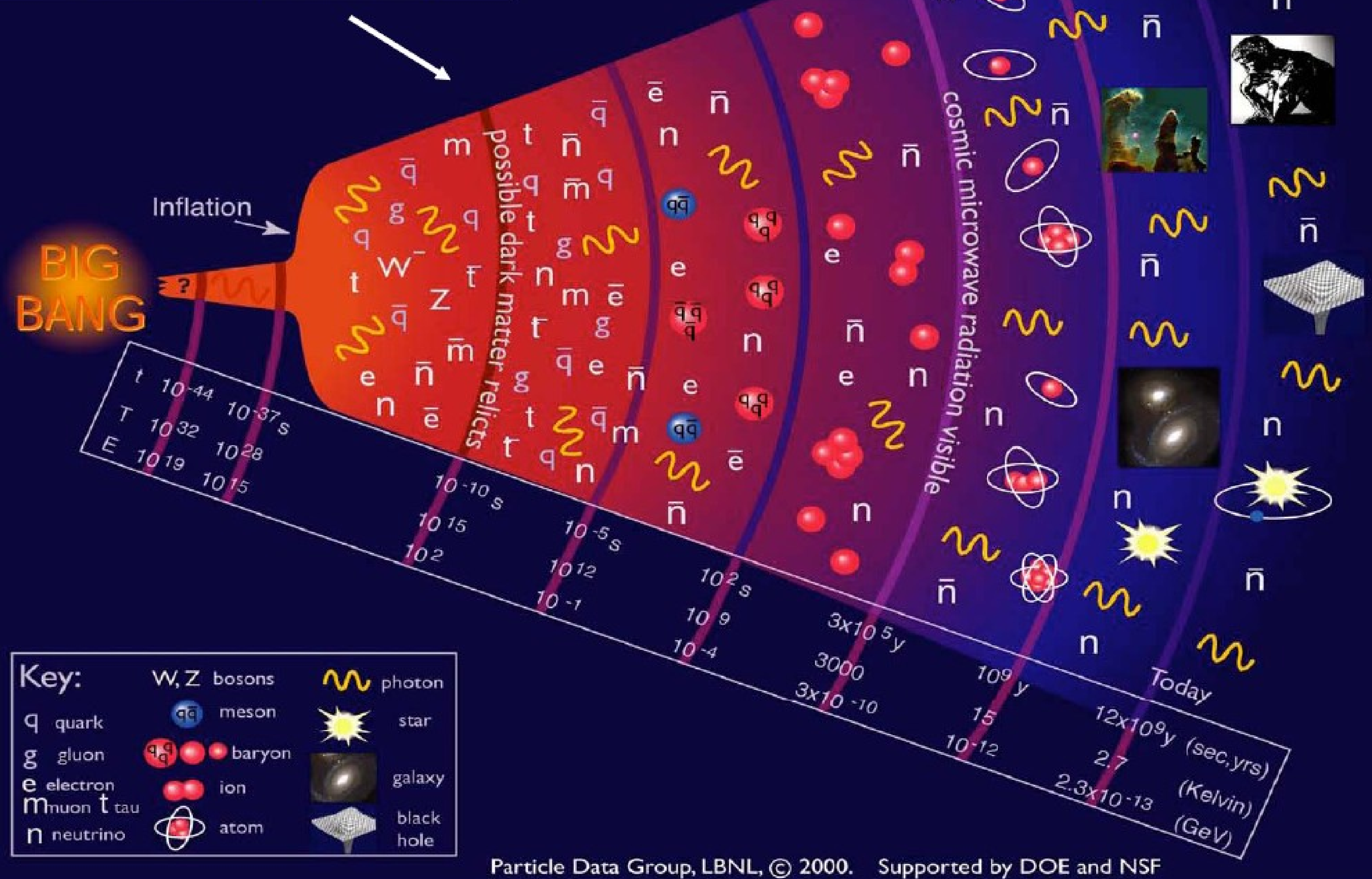
- Size/complexity of experiments :
  ~ 1.3-2 times bigger than previews collider experiments
  ~ 10 times more complex

- Human resources : > 4000 physicists in the experiments

WHY ?

History of the Universe

Fizyka którą będziemy badac odpowiada Warunkom które panowały tutaj



Several open questions and mysteries ….

What is the origin of the particle masses ?

What is the nature of the Universe dark matter ?

What is the origin of the Universe matter-antimatter asymmetry ?

What are the constituents of the Universe primordial plasma ~10 μs after the Big Bang ?

What happened in the first instants of the Universe life (10^{-10} s after the Big Bang) ?

Etc. etc.

The LHC will help solve these and other mysteries …

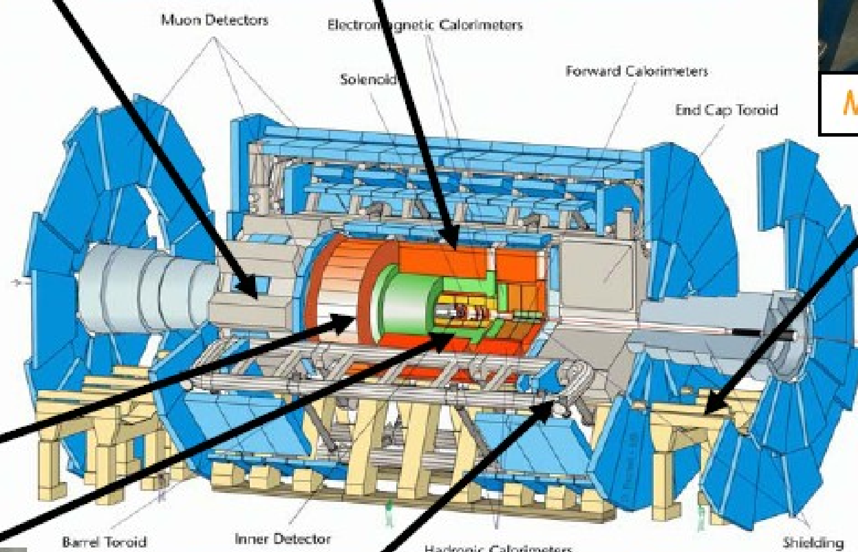
Detektory eksperymentów fizyki wysokich energii

- **Detektory** pozwalają na obserwację (rejestrację) serii oddziaływań, podjęcie decyzji czy oddziaływanie jest interesujące, identyfikację produkowanych cząstek, pomiar ich energii i pędu.

- Detektory dla zderzeń przy wysokich energiach muszą być duże, zbudowane z różnych poddetektorów (każdy dedykowany do rejestracji pewnego określonego typu sygnału). Niektóre poddetektory umieszczone są w polu magnetycznym (aby umożliwić pomiar pędu).

- **Metody pomiarowe** to pomiar absorpcji energii, rekonstrukcja toru na podstawie „śladów” zostawionych w poszczególnych warstwach detektorów, itd. itd...

ATLAS



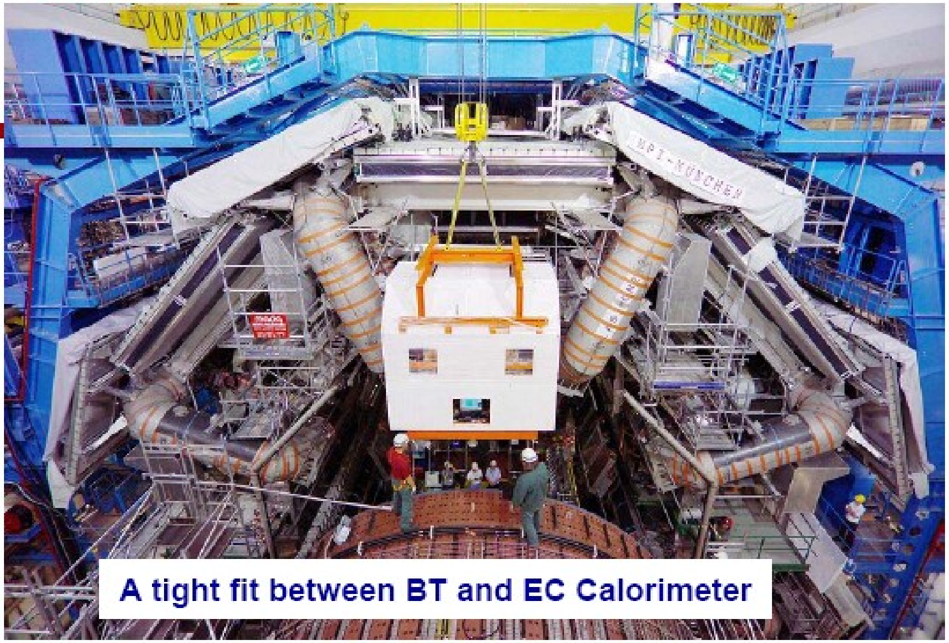
zdjecia

rok 2003

Długość : ~ 40 m
Promień : ~ 10 m
Waga : ~ 7000 ton

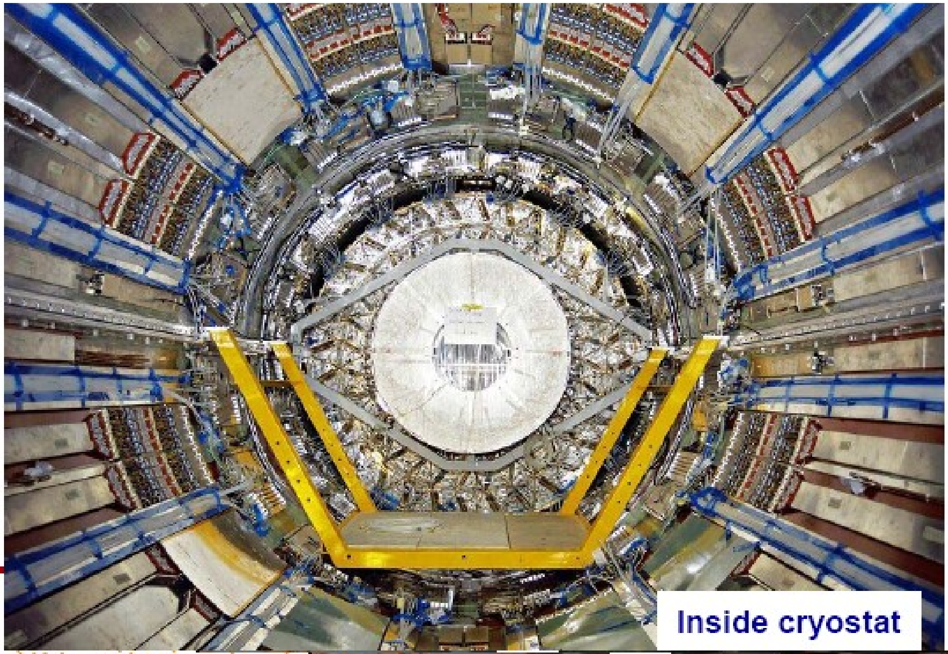
TRT+SCT barrel travelled to the pit, 24th Aug 2006

Through the parking area



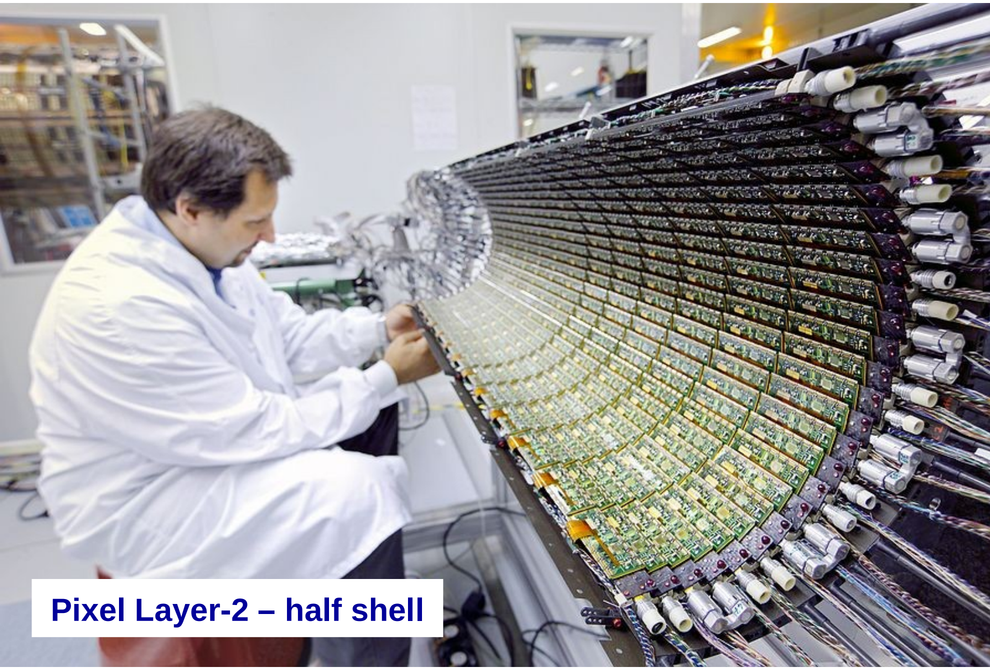
A tight fit between BT and EC Calorimeter

From the trolley to the support rails

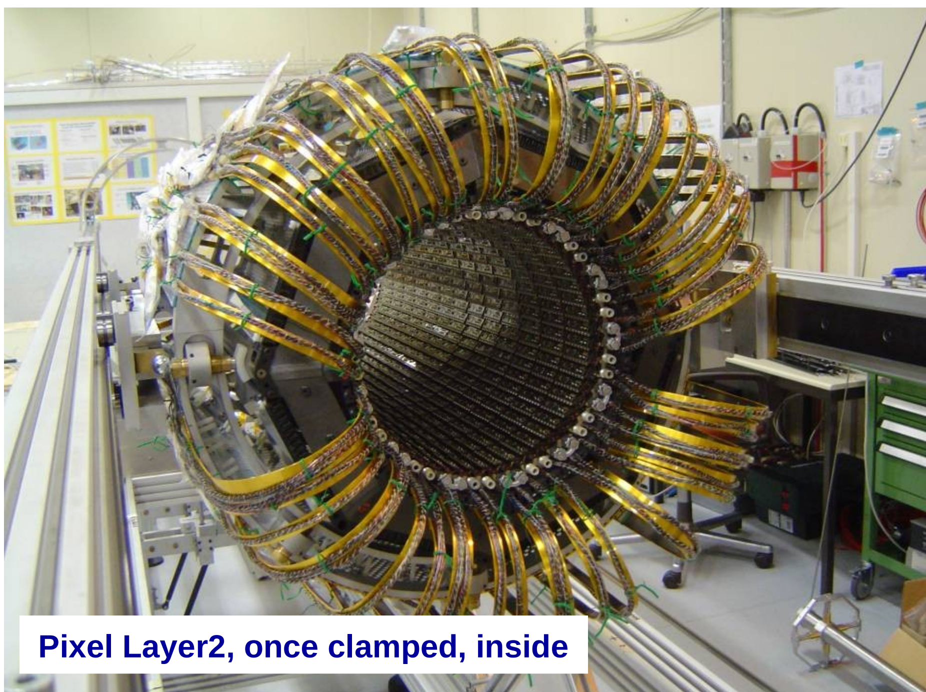


Inside cryostat

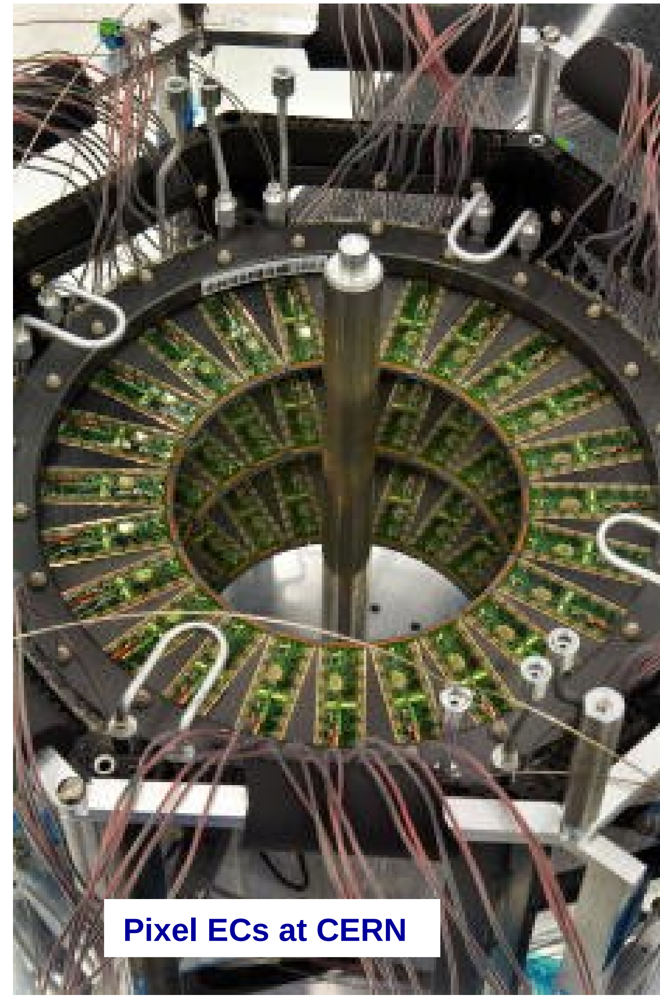
Lot of progress on the Pixels!



Pixel Layer-2 – half shell

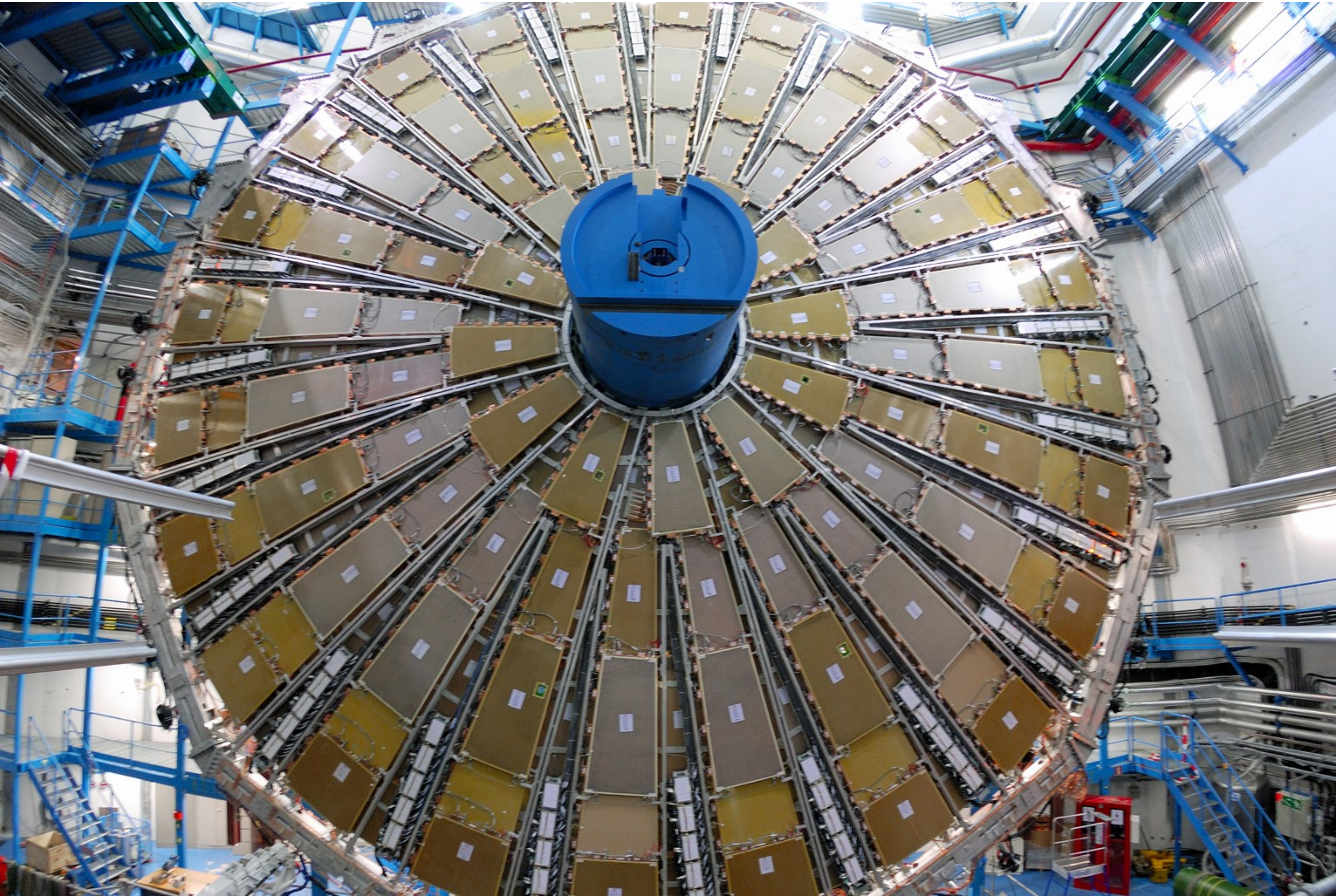


Pixel Layer2, once clamped, inside

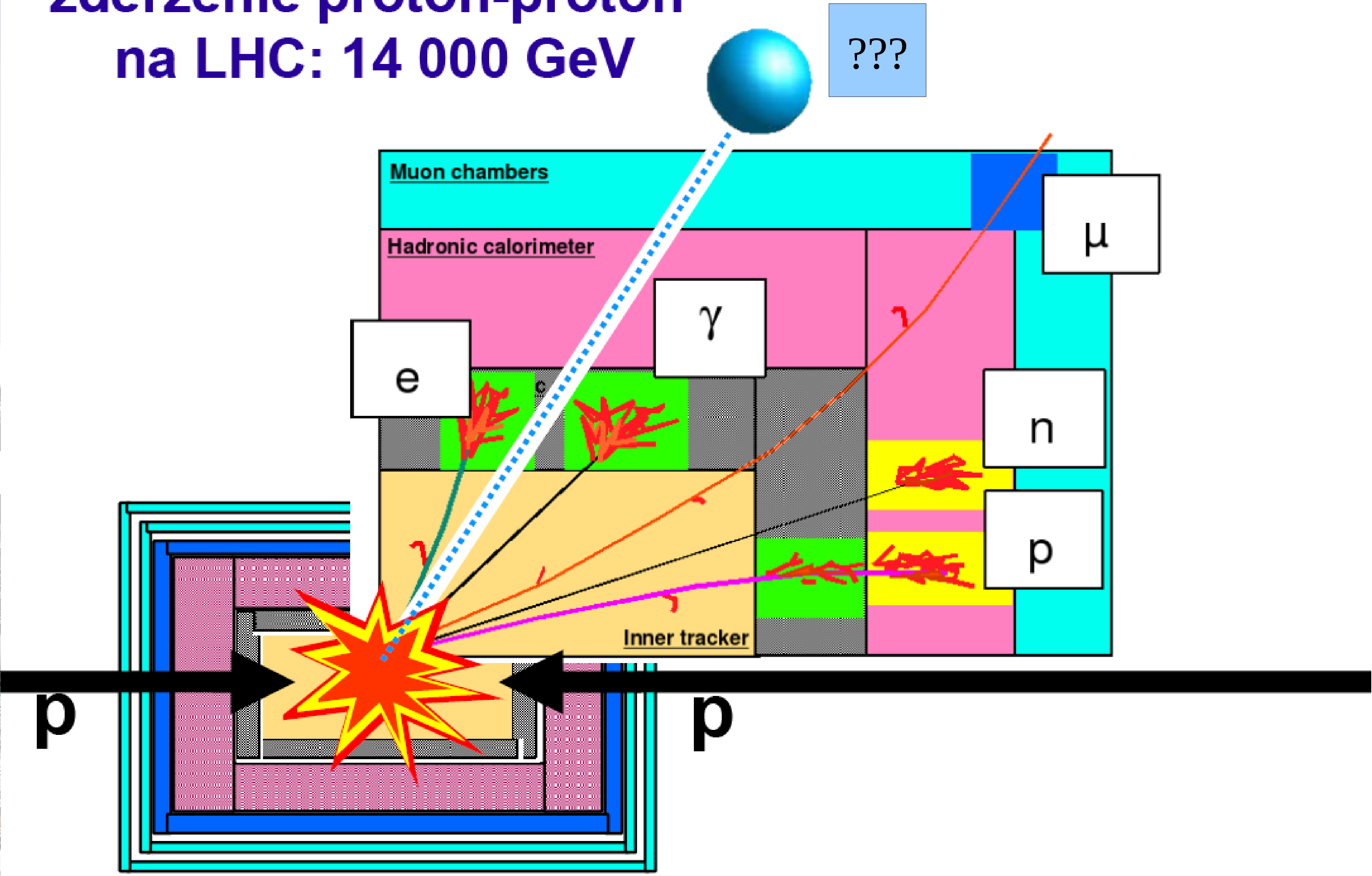


Pixel ECs at CERN

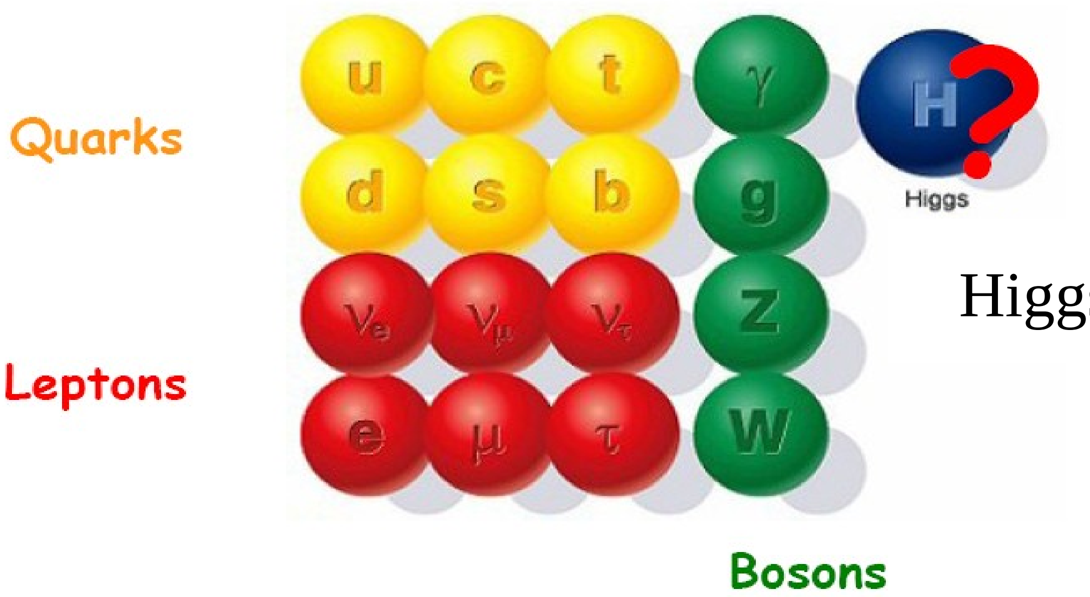
One more view of the first installed TGC Big Wheel



zderzenie proton-proton na LHC: 14 000 GeV



Standard Model

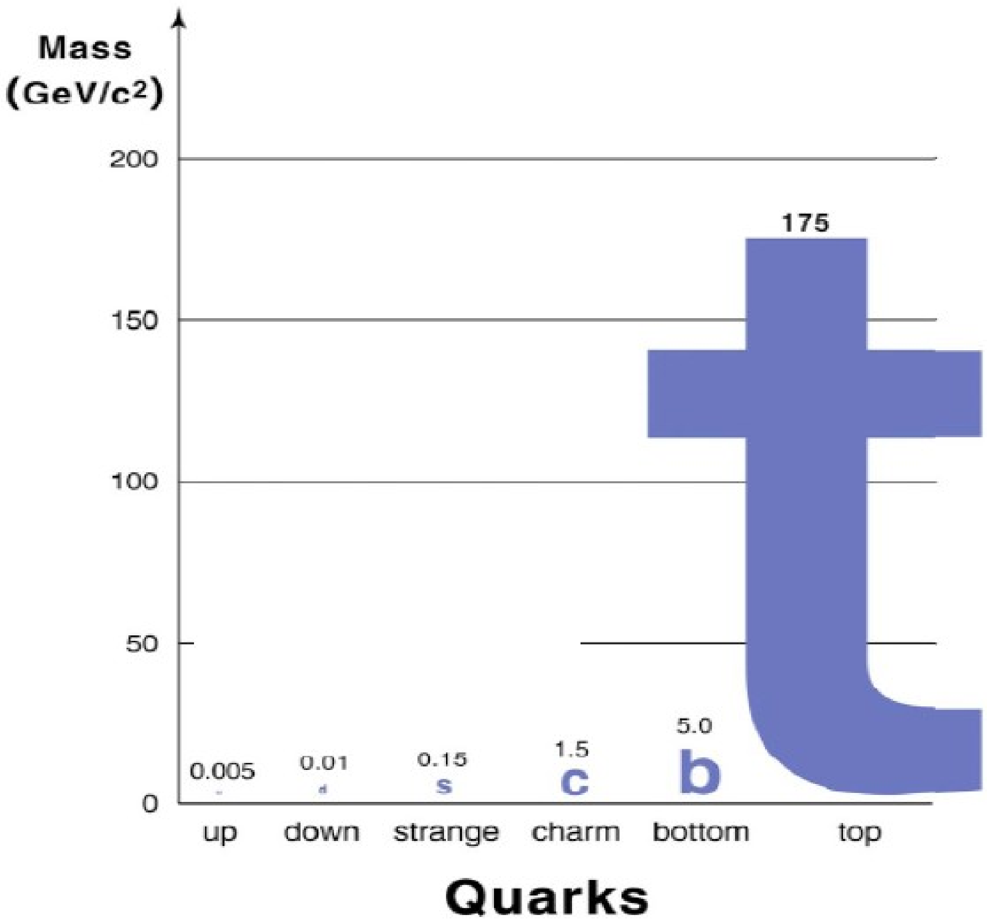


Higgs

A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery could be solved with the 'Higgs mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle (theory 1964, P. Higgs, R. Brout and F. Englert)

Peter Higgs



The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

The LHC will have sufficient energy to produce it for sure, if it exists

Francois Englert

What is the origin of the particle masses ?

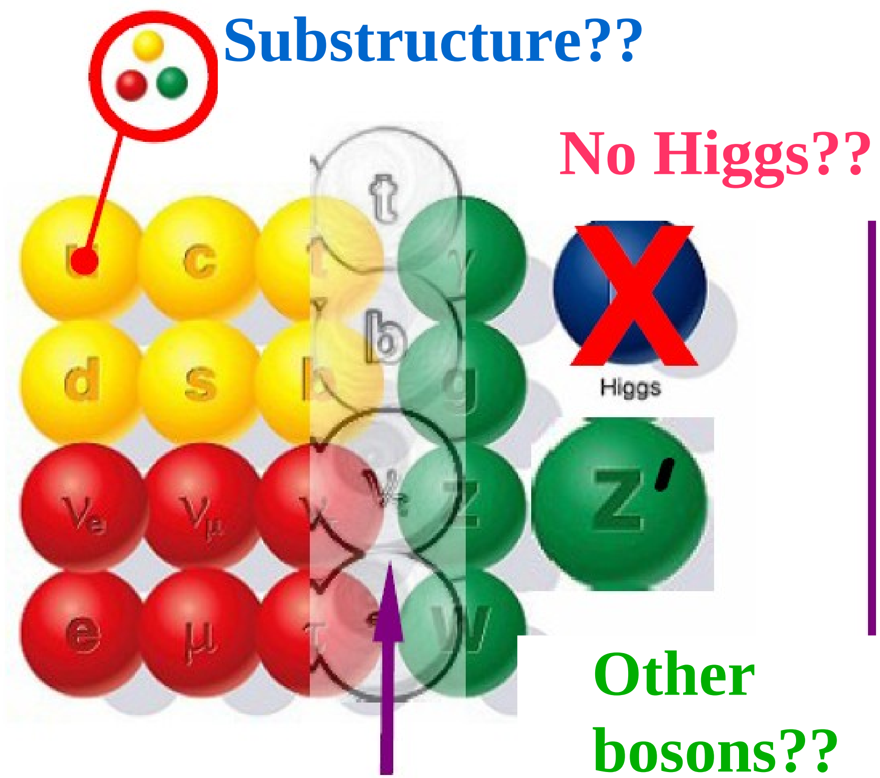
Mass of top quark (heaviest elementary particle observed) ≈ mass of Gold atom
Electron mass is 300 000 times smaller than top-quark mass
WHY ???

The mass mystery could be solved by the "Higgs mechanism", which predicts the existence of a new elementary particle : **the Higgs particle**

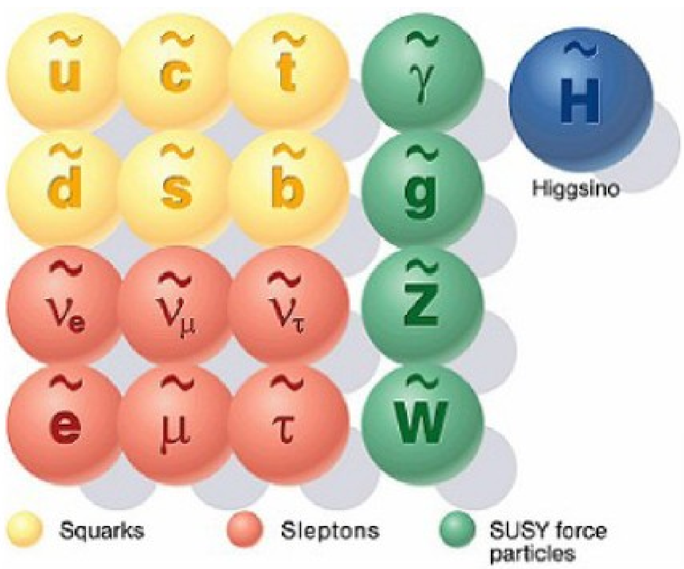
This particle has been searched for 20 years at accelerators all over the world and has not been observed yet.
The LHC has sufficient energy/intensity to produce it.

Note: a world without "Higgs" would be a very strange one ! Atoms (and thus all of us) would not have the size they have, the neutron could be lighter than the proton, chemistry may not exist, etc.

Extension of the Standard Model??

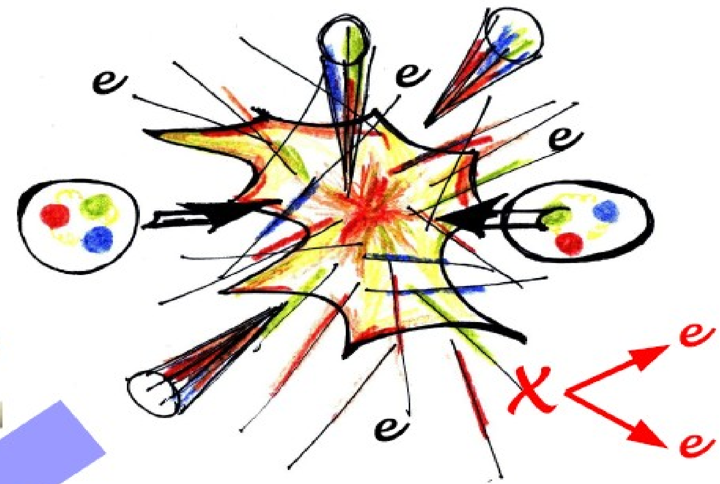


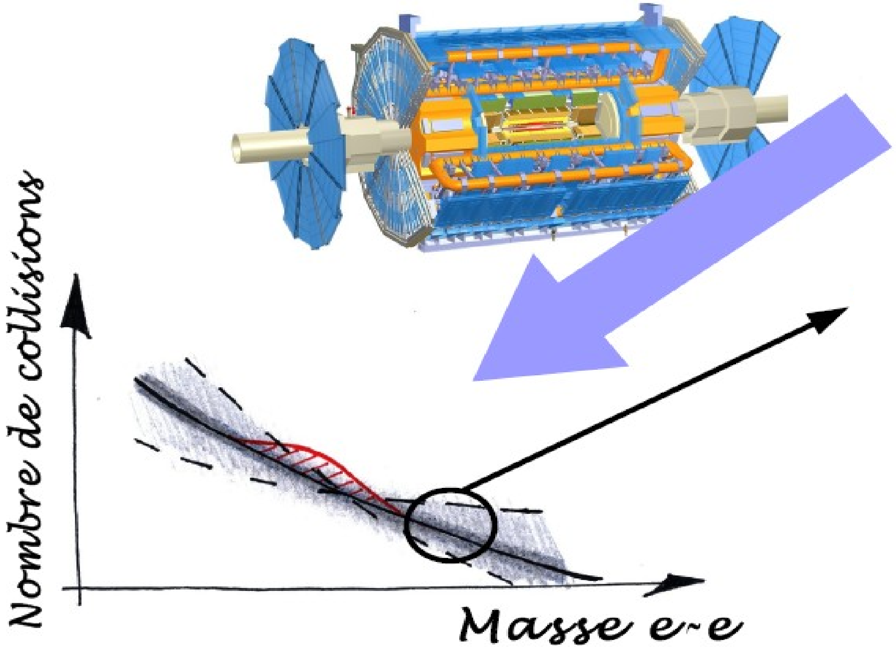
Other families of particles??



Supersymmetric partners ??

How we look for new particles?





We know well
“standard” particles
and their interaction
with detectors

Jak w ciągu 1 sekundy wybrać 1 spośród 10^7 ?

LHC (Large Hadron Collider) będzie zderzał przeciwbieżne wiązki protonów z energią środka masy 14 TeV. (Ta energia wystarczałaby na produkcję 15 000 protonów!)

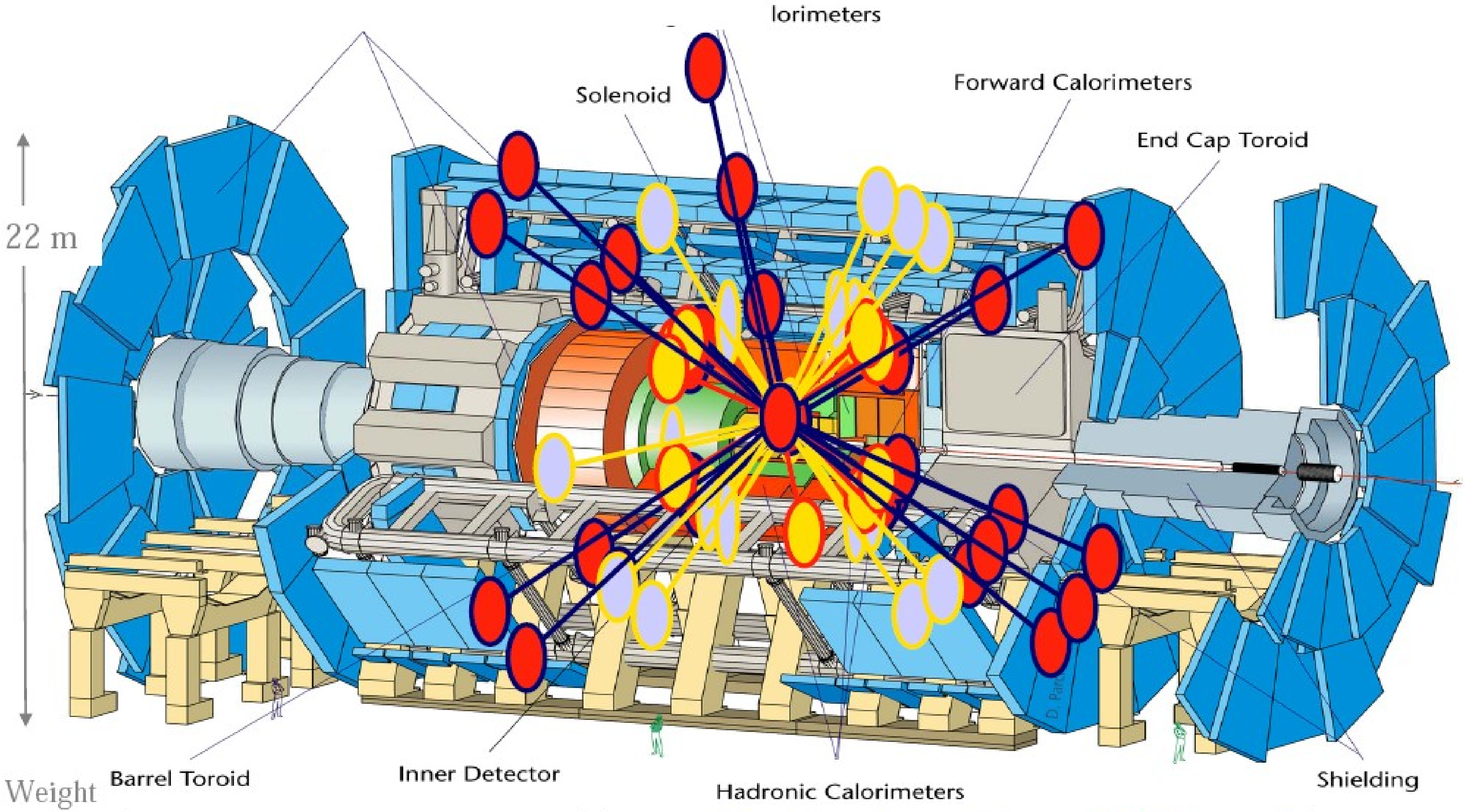
Wiązki protonów będą oddziaływały co 25 ns wewnątrz ogromnego detektora wypełnionego milionami kanałów odczytu elektronicznego.

Każde zderzenie wiązek to ~ 23 pp oddziaływań, każde produkujące strugę (~ 10^3) wychodzących cząstek.

Odstęp pomiędzy kolejnymi zderzeniami wiązek to tylko **25ns**

- 25ns to odległość 8m dla cząstek poruszających się z prędkością światła (to jest mniej niż promień detektora)
- Na raz w detektorze „fale cząstek" od 3 kolejnych zderzeń
- Tylko niewielka cześć tych oddziaływań może zostać zapisana „na taśmie" . System który podejmuje decyzje nazywa się TRIGGER.

- Interactions every 25 ns …
  - In 25 ns particles travel 7.5 m



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

Jak w ciągu 1 sekundy wybrać 1 spośród 10^7 ?

Co to znaczy niewielka część?

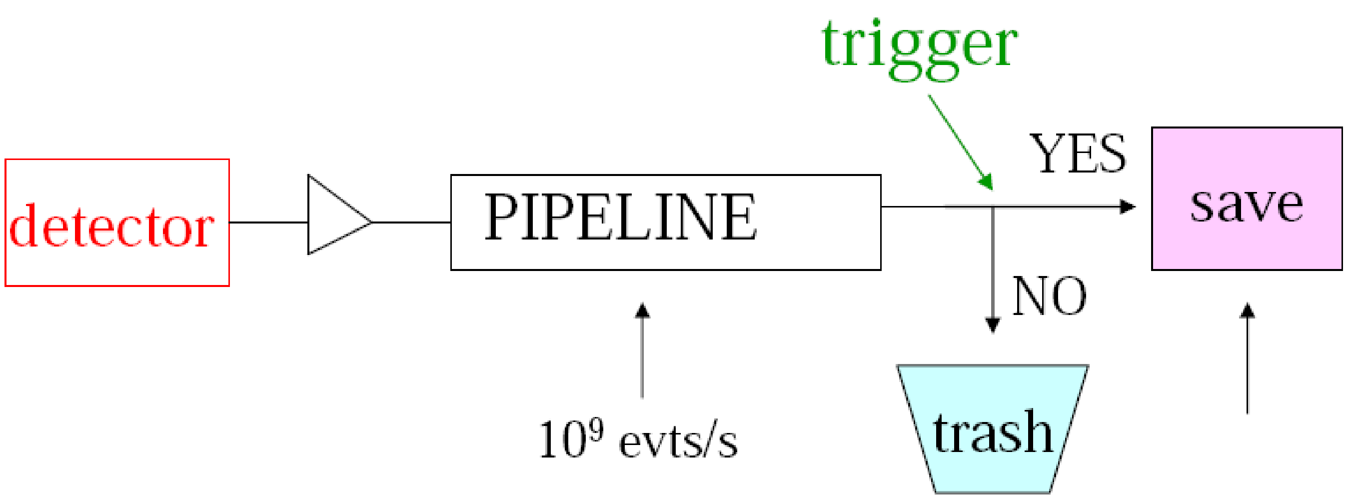
- 25ns ⇒ 40 x 10^6/s zderzeń
- 23 oddział/zderzenie ⇒ 23 x 40 x 106 /sek ~ 10^9 /sek oddział
- możemy zarejestrować tylko ~ 100/sek zderzeń ⇒ **redukcja 10^7**

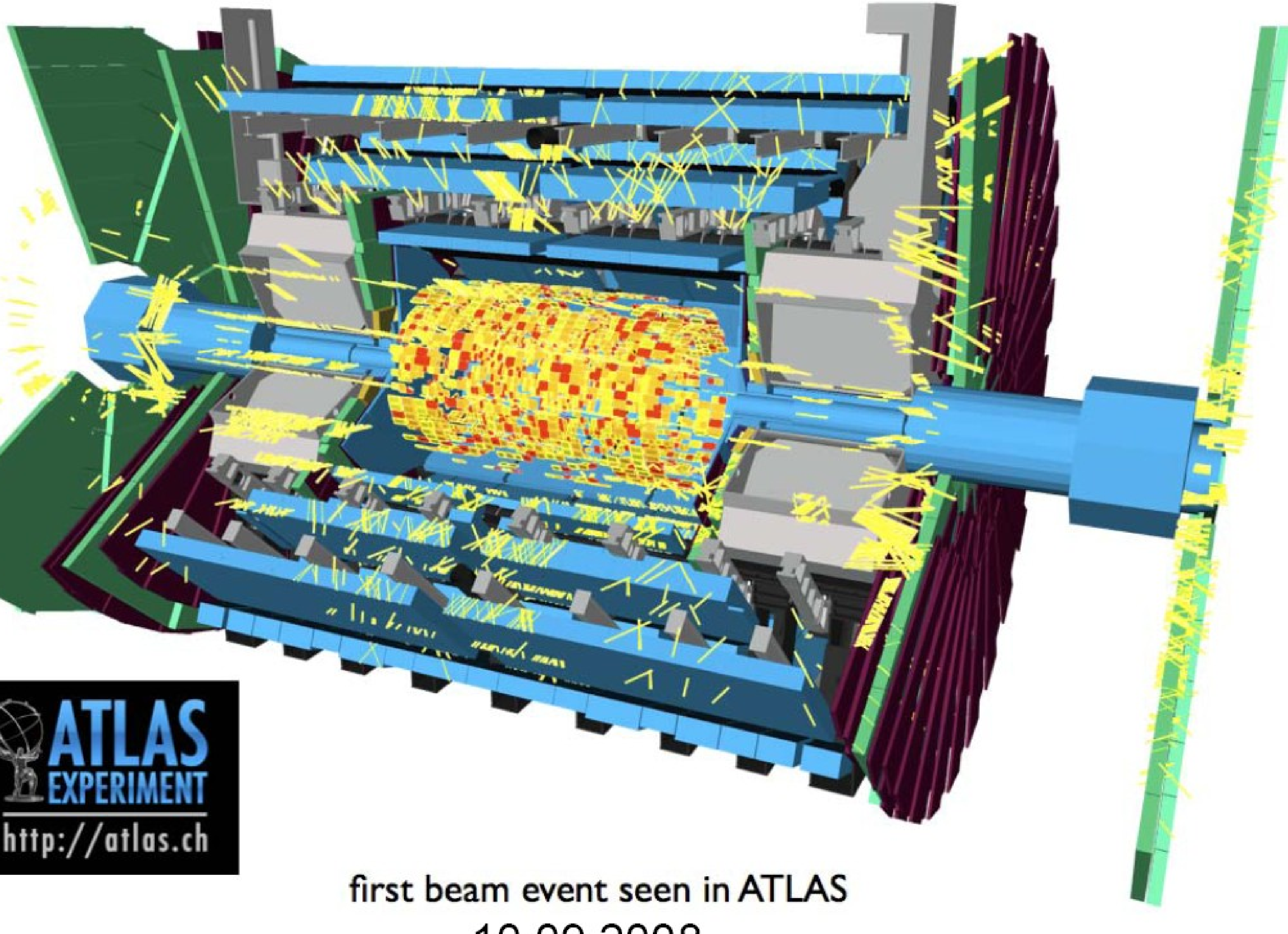
Ile informacji trzeba przetworzyć?

trigger elektron: 8bit x 40MHz x 7500 ~ 3 000 Gbit/sek

Czy można podjąć decyzje w 25ns?

nie można: czas rejestracji w detektorze dłuższy (ok. 50 x 25ns)
informacje trzeba wysłać do procesora (ok. 15 x 25ns)
informacje trzeba przetworzyć (ok. 10 x 25ns)





ATLAS EXPERIMENT
http://atlas.ch

first beam event seen in ATLAS
10.09.2008

Motivations for LHC

Motivation 1 : Origin of particle masses

Standard Model of electroweak interactions verified with precision 10^{-3} - 10^{-4} by measurements at LEP at $\sqrt{s} \geq m_Z$ and at the Tevatron at $\sqrt{s} = 1.8$ TeV

discovery of top quark in ‘94,
$m_{top} \cong 174$ GeV

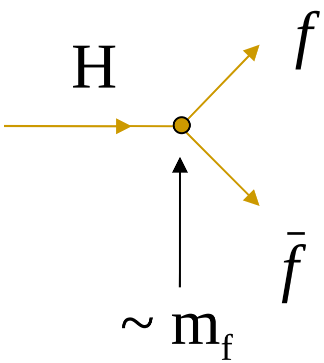
However: origin of particle masses not known.

Ex. : $m_\gamma = 0$

$m_{W, Z} \approx 100$ GeV

Motivation for LHC

SM : Higgs mechanism gives mass to particles
(Electroweak Symmetry Breaking)



$m_H < 1$ TeV from theory

However:

-- Higgs not found yet: only missing (and essential) piece of SM

-- present limit : $m_H > 114.4$ GeV (from LEP)

-- Tevatron may go beyond (depending on luminosity)

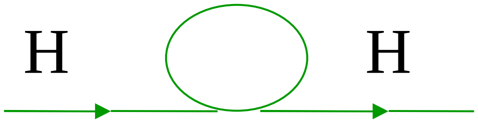
$\Rightarrow$ need a machine to discover/exclude

Higgs from ≈ 115 GeV to 1 TeV

Motivation for LHC

Motivation 2 : Is SM the "ultimate theory" ?

- Higgs mechanism is the weakest part of the SM:
  - -- "ad hoc" mechanism
  - -- due to radiative corrections



Λ : energy scale up to which SM is valid (can be very large).

$\Delta m_H^2 \sim \Lambda^2$

$\Rightarrow$ radiative corrections can be very large ("unnatural") and Higgs mass can diverge unless "fine-tuned" cancellations $\rightarrow$ " bad behaviour " of the theory

Motivation for LHC

Motivation 2 : Is SM the "ultimate theory" ?

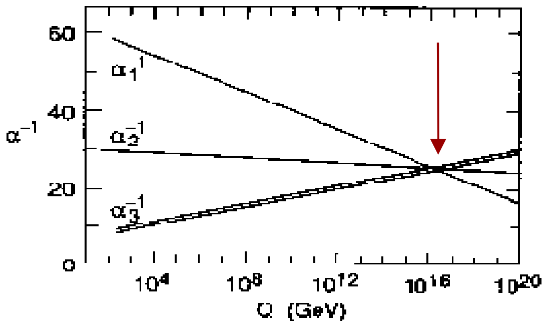
•Hints that forces could unify at high energy

$\alpha_{EM} \equiv \alpha_1 \approx 1/128 \approx 0.008$

$\alpha_{WEAK} \equiv \alpha_2 \approx 0.03$

$\alpha_S \equiv \alpha_3 \approx 0.12$

(all three at $\sqrt{s} = 100$ GeV)



- E-dependence of coupling constants proven experimentally
- Grand Unified Theories: EM/Weak/Strong forces unify at $E \sim 10^{16} \rightarrow$ beyond physics become simple (one force with strength α_G)

Motivation for LHC

- SM is probably low-energy approximation of a more general theory

- Need a high-energy machine to look for manifestations of this theory

- e.g. Supersymmetry : $m_{SUSY} \sim$ TeV

  Many other theories predict New Physics at the TeV scale

Motivation for LHC

Motivation 3 : Many other open questions

- Are quarks and leptons really elementary ?
- Why 3 fermion families ?
- Are there additional families of (heavy) quarks and leptons ?
- Are there additional gauge bosons ?
- What is the origin of matter-antimatter asymmetry in the universe ?
- Can quarks and gluons be deconfined in a quark-gluon plasma as in early stage of universe ?
- …. etc. …...

Motivation for LHC

Motivation 4 : The most fascinating one …

Unexpected physics ?

Motivation 5 : Precise measurements

Two ways to find new physics:

-- discover new particles/phenomena

-- measure properties of known particles as precisely as possible $\Rightarrow$ find deviations from SM

Motivation for LHC

LHC: known particles (W, Z, b, top, …)
produced with enormous rates thanks to
high energy (→ high σ) and L (→ high rate)

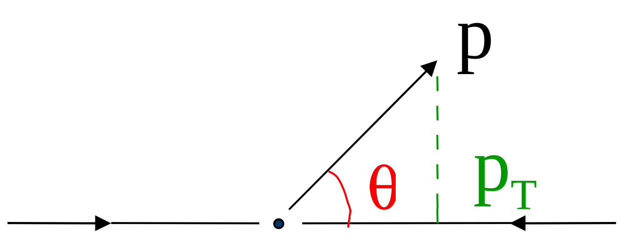
Ex. : 1 year at low luminosity

$5\ 10^8$ $W \to l\nu$
$5\ 10^7$ $Z \to ll$
10^7 tt pairs
10^{12} bb pairs

→ many precision measurements possible
thanks to large statistics
(stat. error ~ $1/\sqrt{N}$)

Note : measurements of Z parameters performed
at LEP and SLD, however
precision can be improved for :
-- W physics
-- Triple Gauge Couplings WWγ, WWZ
-- b-quark physics
-- top-quark physics

Phenomenology of pp collisions



Transverse momentum

(in the plane perpendicular to the beam) :

$$p_T = p \sin\theta$$

Rapidity: $\eta = -\log(\mathrm{tg}\,\frac{\theta}{2})$

$\theta = 90^o \rightarrow \eta = 0$

$\theta = 10^o \rightarrow \eta \cong 2.4$

$\theta = 170^o \rightarrow \eta \cong -2.4$

Total inelastic cross-section:

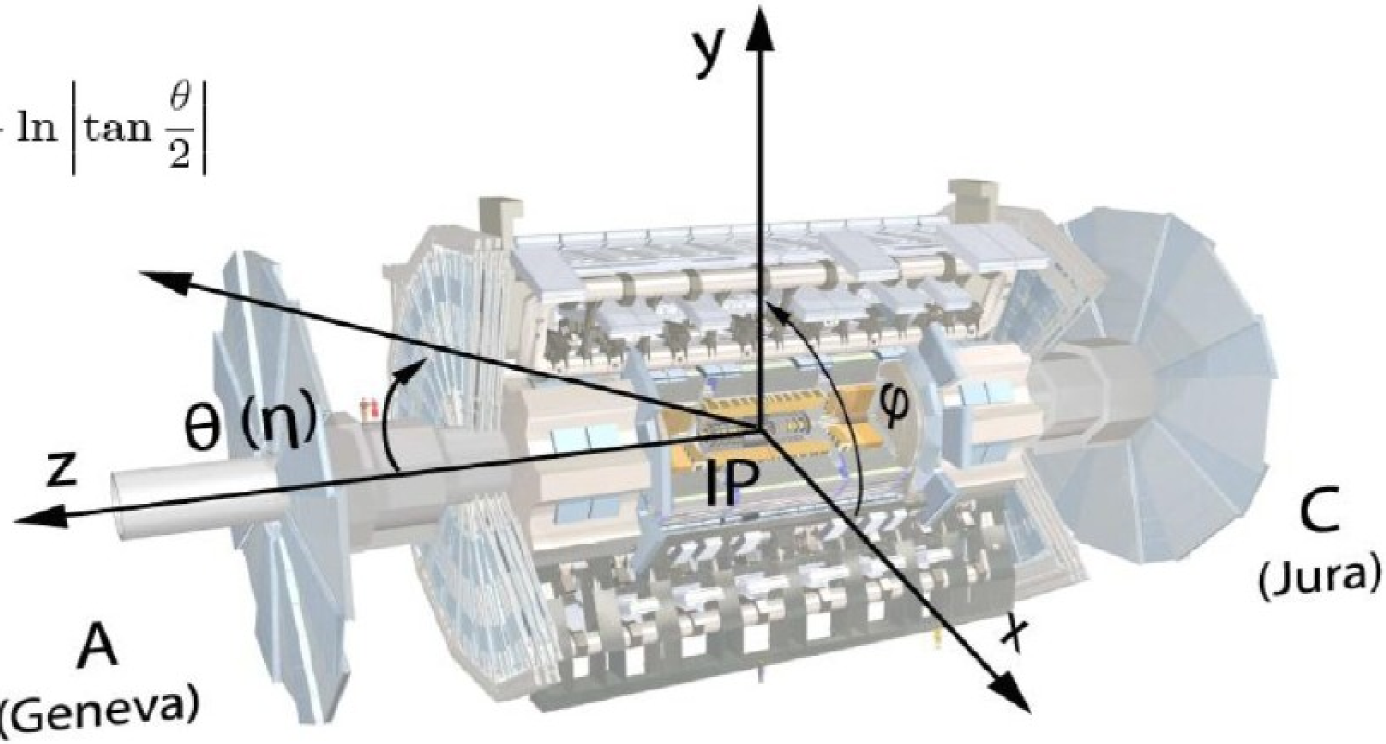
σ_{tot} (pp) = 70 mb $\qquad \sqrt{s}$ = 14 TeV

Rate = $\frac{\text{n. events}}{}$ = L x σ_{tot} (pp) = 10^9 interactions/s

10^{34} cm^{-2} s^{-1}

Kinematics

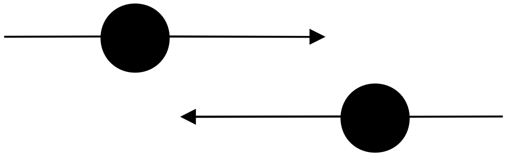
$$\eta = -\ln\left|\tan\frac{\theta}{2}\right|$$

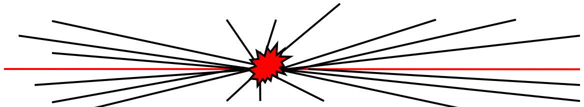


Phenomenology of pp collisions

Class 1:

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole " → small momentum transfer ($\Delta p \approx 1 / \Delta x$) → particles in final state have large longitudinal momentum but small transverse momentum (scattering at large angle is small)





$< p_T > \approx$ 500 MeV of charged particles in final state

charged particles uniformly distributed in ϕ

$$\frac{dN}{d\eta} \approx 7$$

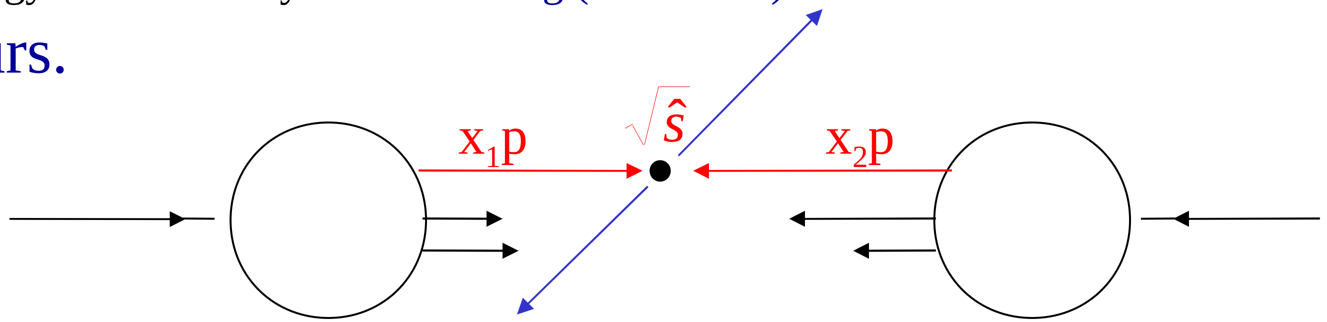
Most energy escapes down the beam pipe.

These are called minimum-bias events (" soft " events).
They are the large majority but are not very interesting.

Phenomenology of pp collisions

Class 2:

Monochromatic proton beam can be seen as beam of quarks and gluons with a wide band of energy. Occasionally hard scattering (" head on") between constituents of incoming protons occurs.



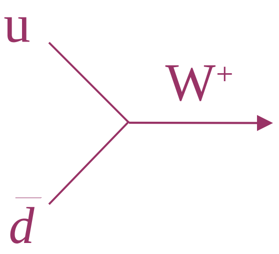
p ≡ momentum of incoming protons = 7 TeV

Interactions at small distance → large momentum transfer → massive particles and/or particles at large angle are produced.

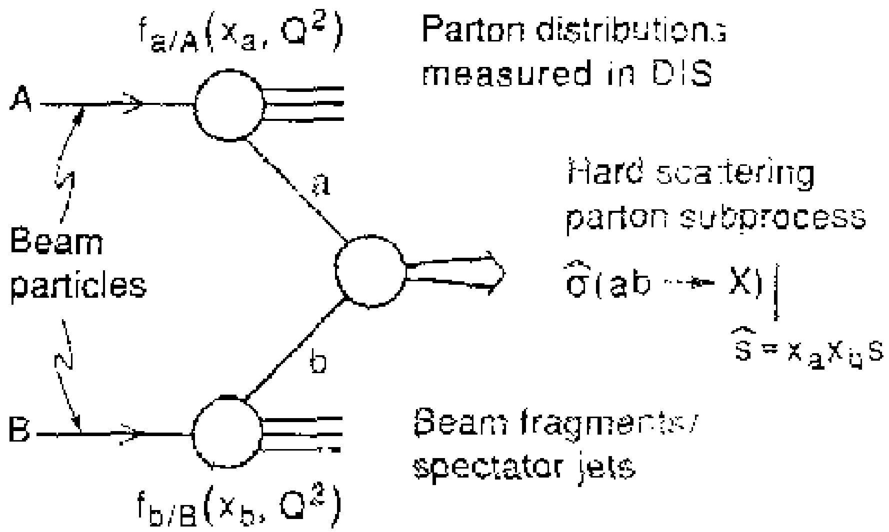
These are interesting physics events but they are rare.

Ex. $u + \bar{d} \rightarrow W^+$

$\sigma(pp \rightarrow W) \approx 150$ nb $\approx 10^{-6}\, \sigma_{tot}(pp)$



Unlike at e+e- colliders



- effective centre-of-mass energy $\sqrt{\hat{s}}$ smaller than √s of colliding beams: → to produce m ≈ 100 GeV x ~ 0.01
  to produce m ≈ 5 TeV x ~ 0.35

$$\left.\begin{array}{l} p_a = x_a\, p_A \\ p_b = x_b\, p_B \end{array}\right\}$$

$p_A = p_B = 7$ TeV

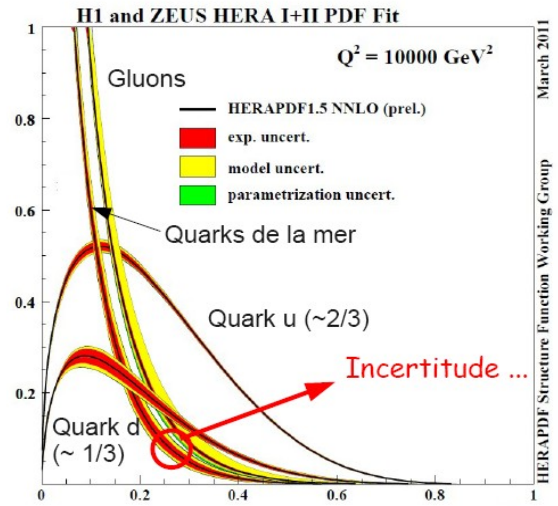
$$\sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx x\sqrt{s}$$

if $x_a \approx x_b$

Unlike at e+e$^-$ colliders

•<u>cross-section :</u>

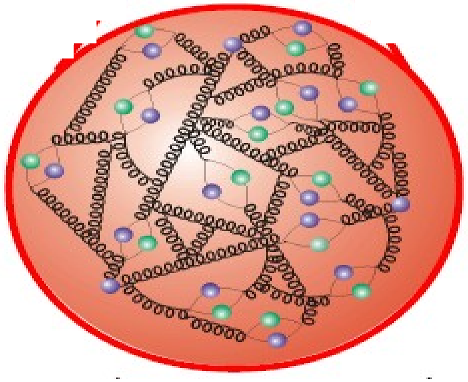
$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b)$$



$\hat{\sigma}_{ab}$ ≡ hard scattering cross-section

$f_i(x, Q^2) \equiv$ parton distribution function

$p \equiv uud$



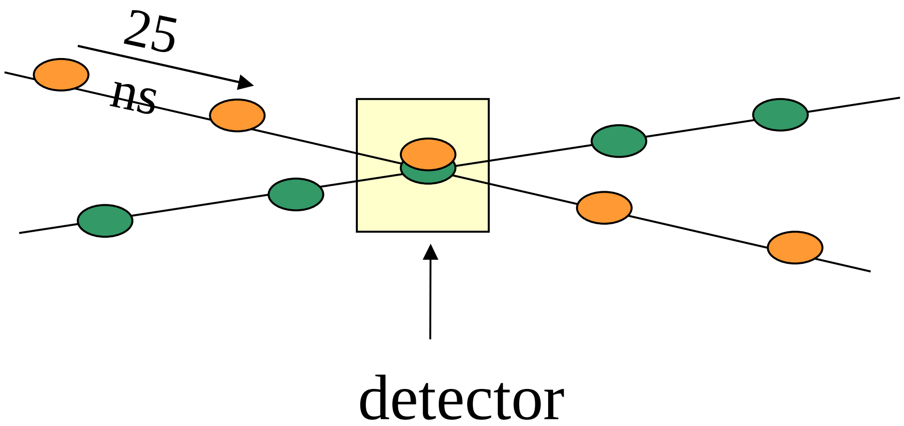
Two main difficulties: pile-up

Typical of LHC:

$R = L\sigma = 10^9$ interactions / second

Protons are grouped in bunches (of $\approx 10^{11}$ protons)

colliding at interaction points every 25 ns



⇒ At each interaction on average $\approx$ 25 minimum-bias events are produced. These overlap with interesting (high p_T) physics events, giving rise to so-called pile-up

~1000 charged particles produced over $|\eta| < 2.5$ at each crossing. However $< p_T > \approx 500$ MeV (particles from minimum-bias).

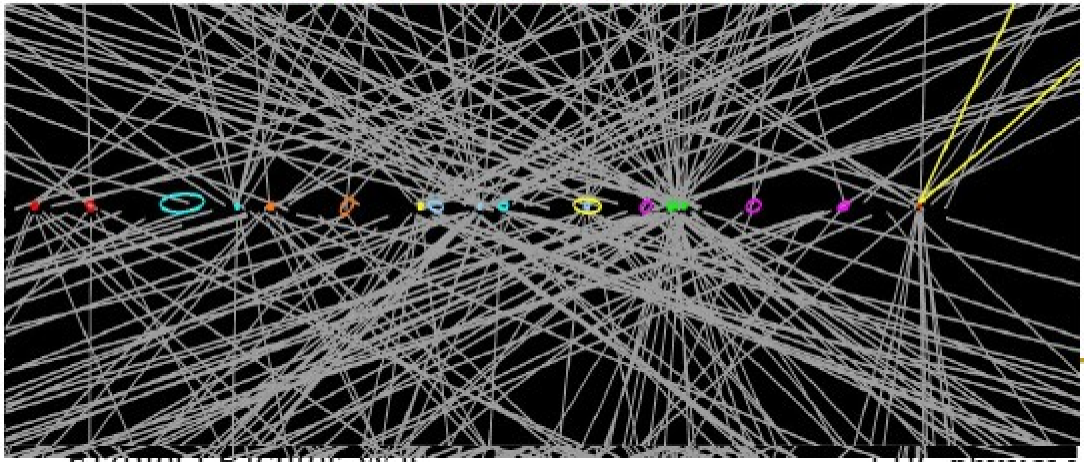
→ applying p_T cut allows extraction of interesting particles

Two main difficulties: pile-up

Example of Z → μμ decay with 20 reconstructed vertices

Total scale along z is ~ ± 15 cm, p_T threshold for track reco is 0.4 GeV

(ellipses have size of 20σ for visibility)



Two main difficulties: pile-up

Pile-up is one of the most serious experimental difficulty at LHC.

Large impact on detector design:

• LHC detectors must have fast response, otherwise integrate over many bunch crossings $\rightarrow$ too large pile-up

Typical response time : 20-50 ns

$\rightarrow$ integrate over 1-2 bunch crossings $\rightarrow$ pile-up of 25-50 minimum bias

$\Rightarrow$ very challenging readout electronics

• LHC detectors must be highly granular to minimise probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \rightarrow \gamma\gamma$ decays)

$\rightarrow$ large number of electronic channels

$\Rightarrow$ high cost

• LHC detectors must be radiation resistant: high flux of particles from pp collisions $\rightarrow$ high radiation environment

E.g. in forward calorimeters: up to 10^{17} n / cm^2

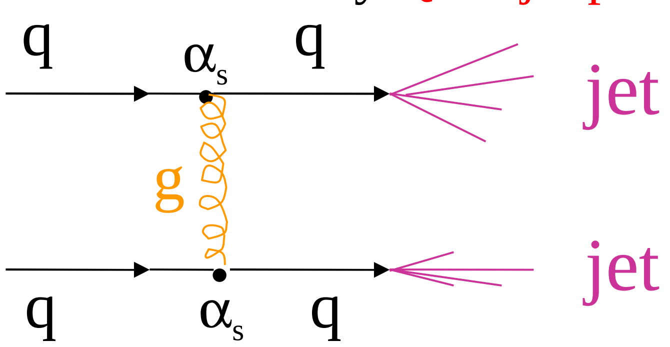
(10 years of LHC operation) up to 10^7 Gy

Note : 1 Gy = unit of absorbed energy = 1 Joule/Kg

Two main difficulties: QCD background

Common to all hadron colliders:

high-p_T events dominated by QCD jet production



- Strong production $\rightarrow$ large cross-section
- Many diagrams contribute: qq $\rightarrow$ qq, qg $\rightarrow$ qg, gg $\rightarrow$ gg, etc.
- Called " QCD background "

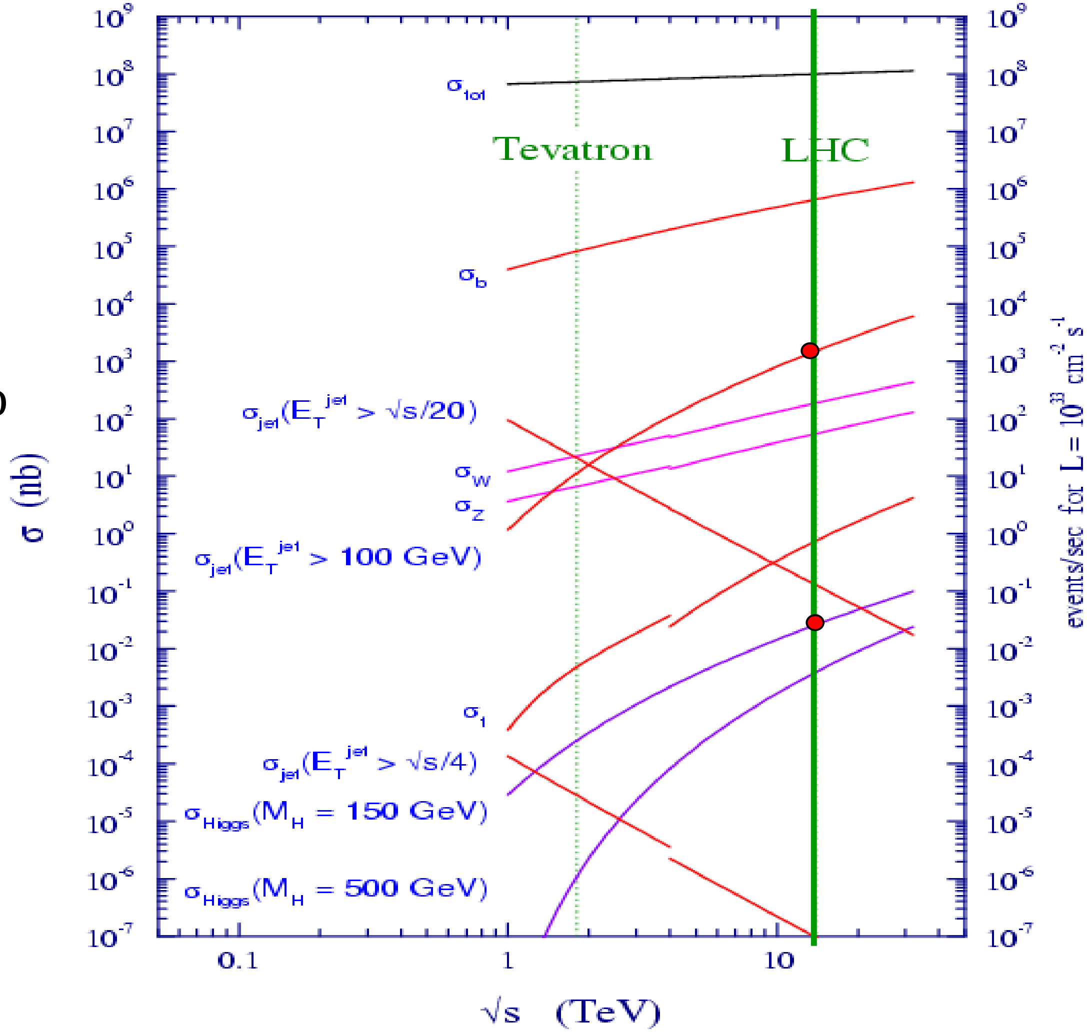
Most interesting are rare processes:

- involve heavy particles
- weak-force mediated production mechanisms (e.g. W production)

Proton - (anti) proton cross-section

To extract signal over QCD jet background must look at decays to photons and leptons
→ pay a prize in branching ratio

Ex. BR (W → jet jet) ≈ 70%
BR (W → lν) ≈ 30%



CMS and ATLAS detectors

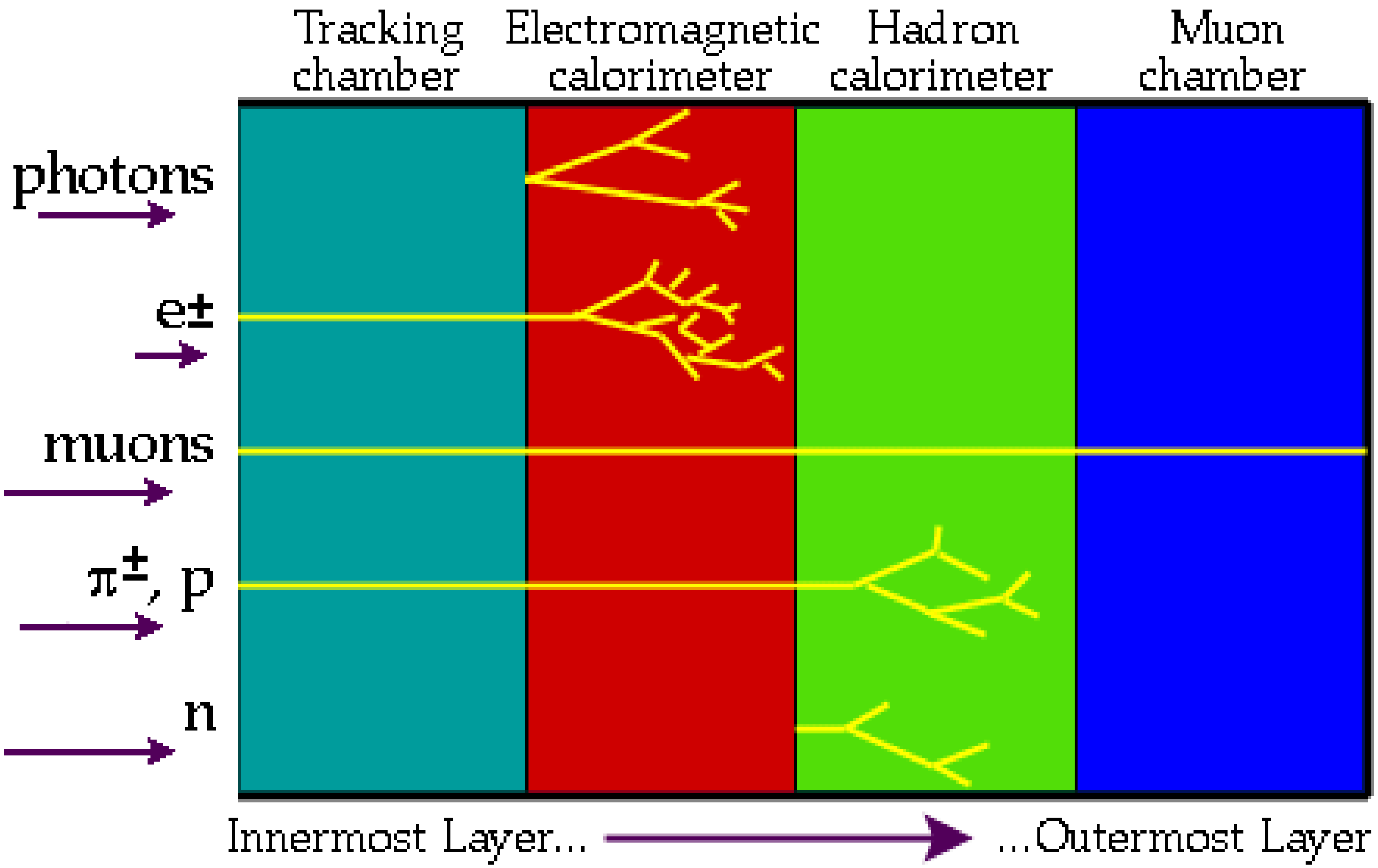
Don' t know how New Physics will manifest $\rightarrow$ detectors must be able to detect as many particles and signatures as possible:

e, μ, τ, ν, γ, jets, b-quarks, ….

$\rightarrow$ " multi-purpose" experiments.

- Momentum / charge of tracks and secondary vertices (e.g. from b-quark decays) measured in central tracker. Excellent momentum and position resolution required.
- Energy and position of electrons and photons measured in electromagnetic calorimeters. Excellent resolution and particle identification required.
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters. Good coverage and granularity are required.
- Muons identified and momentum measured in external muon spectrometer (+ central tracker). Excellent resolution over ~ 5 GeV < p_T < ~ TeV required.
- Neutrinos "detected and measured" through measurement of missing transverse energy E_T^{miss}. Calorimeter coverage over $|\eta|<5$ needed.

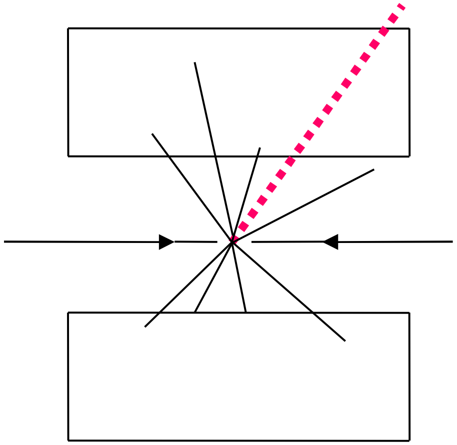
ATLAS and CMS detectors



ATLAS and CMS detectors

Detection and measurement of neutrinos

- Neutrinos traverse the detector without interacting
  $\rightarrow$ not detected directly



- Can be detected and measured asking energy-momentum conservation:

Hadron colliders: energy and momentum of initial state (energy and momentum of interacting partons) not known.
However: transverse momentum of the system = 0

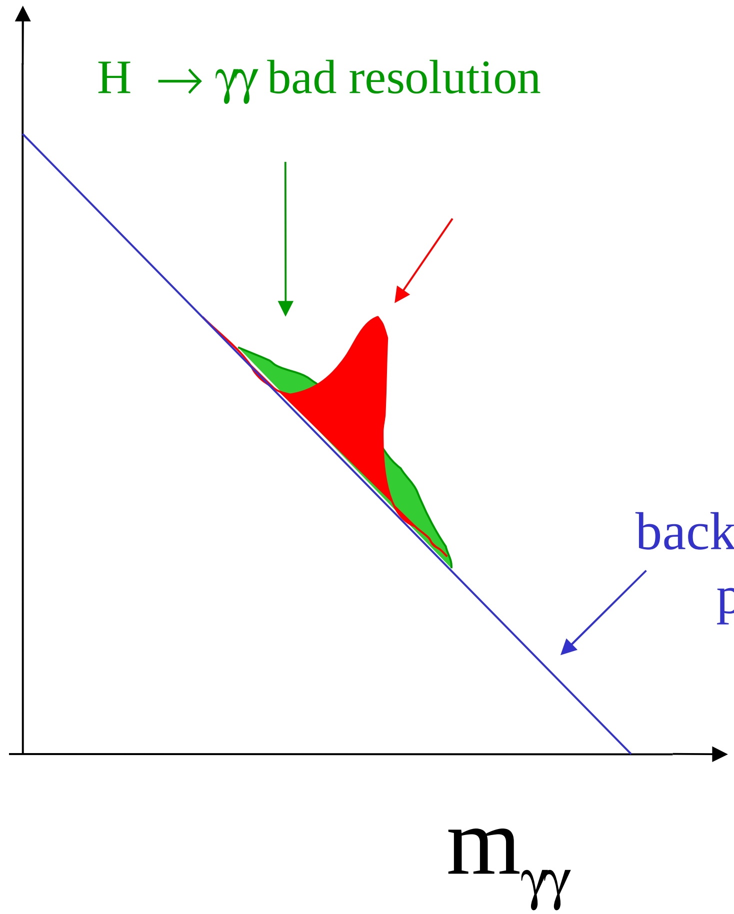
if a neutrino produced $p_T^f \neq 0$

$\rightarrow$ missing transverse momentum and $p_T^\nu = p_T^f = E_T^{miss}$

Examples of performance requirements

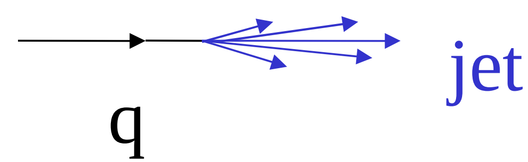
Excellent energy resolution
of EM calorimeters for e/γ and of the tracking devices for μ in order to extract a signal over the backgrounds.

Example : H $\rightarrow \gamma\gamma$

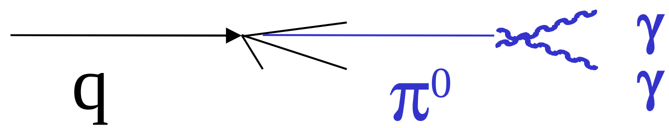


Examples of performance requirements

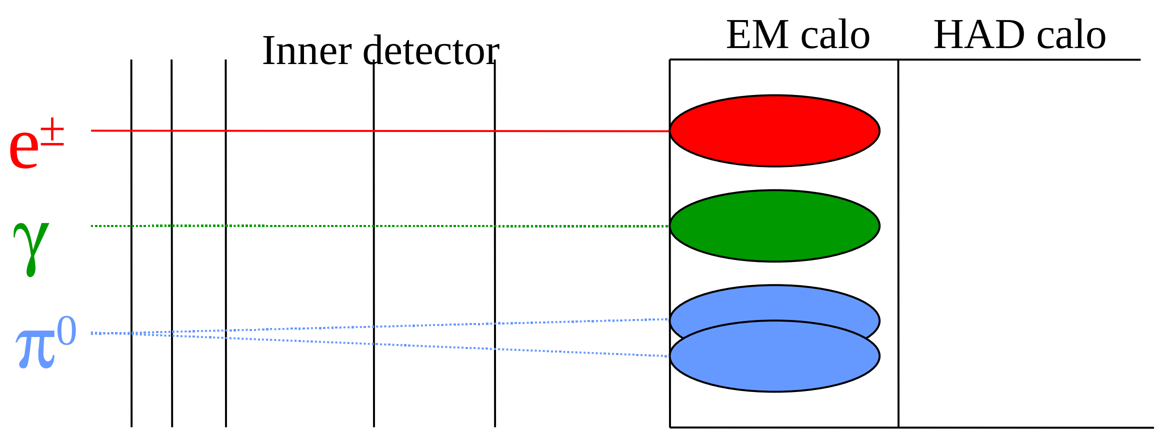
Excellent particle identification capability e.g. e/jet , γ/jet separation



number and p_T of hadron in a jet have large fluctuations



in some cases: one high-p_T π^0; all other particles too soft to be detected



d (γγ) < 10 mm in calorimeter → QCD jets can mimic photons.

Rare cases, however:

$$\frac{\sigma_{jj}}{\sigma(H \rightarrow \gamma\gamma)} \sim 10^8$$

$m_{\gamma\gamma} \sim 100$ GeV

need detector (calorimeter) with fine granularity to separate overlapping photons from single photons

Summary

LHC:

pp machine (also Pb-Pb)
$\sqrt{s}$ = 14 TeV
L = 10^{33}-10^{34} cm^{-2} s^{-1}
Start-up : 2007

Four large-scale experiments:

ATLAS, CMS	pp multi-purpose
LHCb	pp B-physics
ALICE	Pb-Pb

+ dedicated small experiment TOTEM

Very broad physics programme thanks to energy and luminosity: mass reach : ≤ 5 TeV

Summary

Very difficult environment:

-- pile-up : ~ 25 soft events produced at each crossing.
Overlap with interesting high-p_T events.

-- large background from QCD processes (jet production): typical of hadron colliders

Very challenging, highly-performing and expensive detectors:

-- radiation hard

-- fast

-- granular

-- excellent energy resolution and particle identification capability

-- complicated trigger