2. Particle Accelerators

2.1 Overview, previous colliders LEP and HERA

2.2 Why moving to a hadron collider?

2.3 Principles on particle accelerators

2.4 The *Large Hadron Collider* (LHC) at CERN

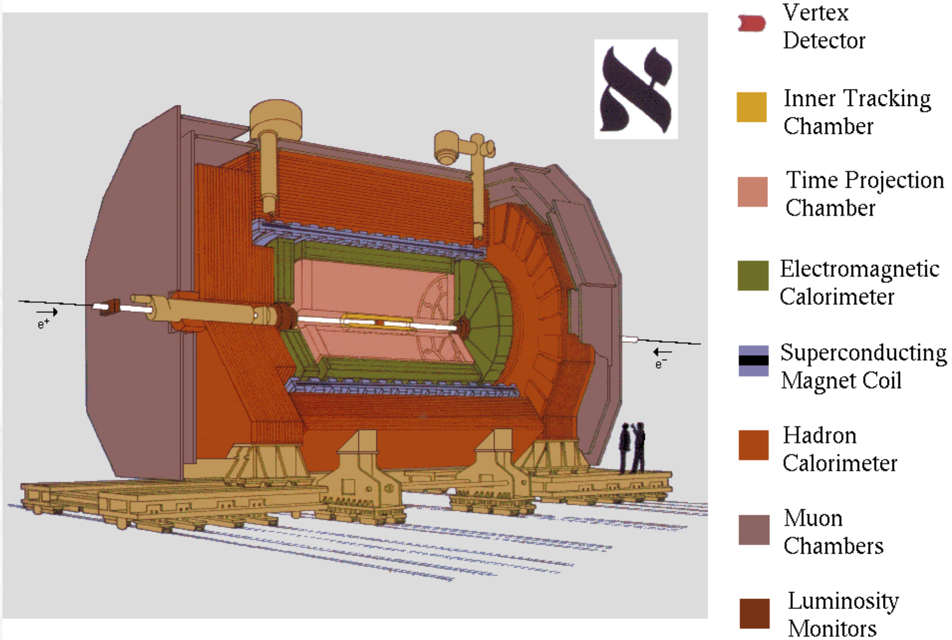
2.5 The Tevatron Collider at Fermilab

High Energy Particle Accelerators (last 20 years):

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	2015- …….

Experiments at the e+e- collider LEP

- e^+e^- collider, operating at CERN between 1989 and 2000
- $\sqrt{s}$ between 91 GeV (1989 –1995) and up to 209 GeV (→2000)
- Four experiments: **ALEPH, DELPHI, L3, OPAL**



The ALEPH Detector

Different features, however, all experiments suited for Standard Model physics and Higgs boson searches

Integrated luminosities:

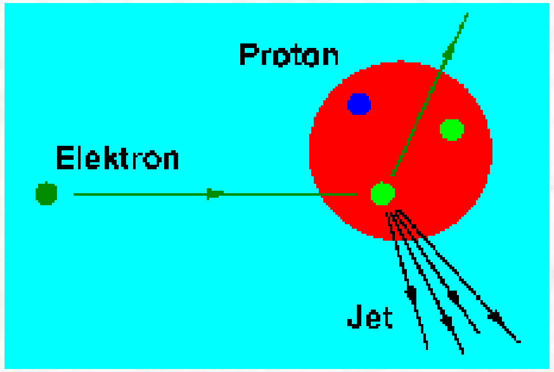
Integrated luminosities in pb^{-1}					
	ALEPH	DELPHI	L3	OPAL	LEP
$\sqrt{s} \geq 189$ GeV	629	608	627	596	2461
$\sqrt{s} \geq 206$ GeV	130	138	139	129	536
$\sqrt{s} \geq 208$ GeV	7.5	8.8	8.3	7.9	32.5

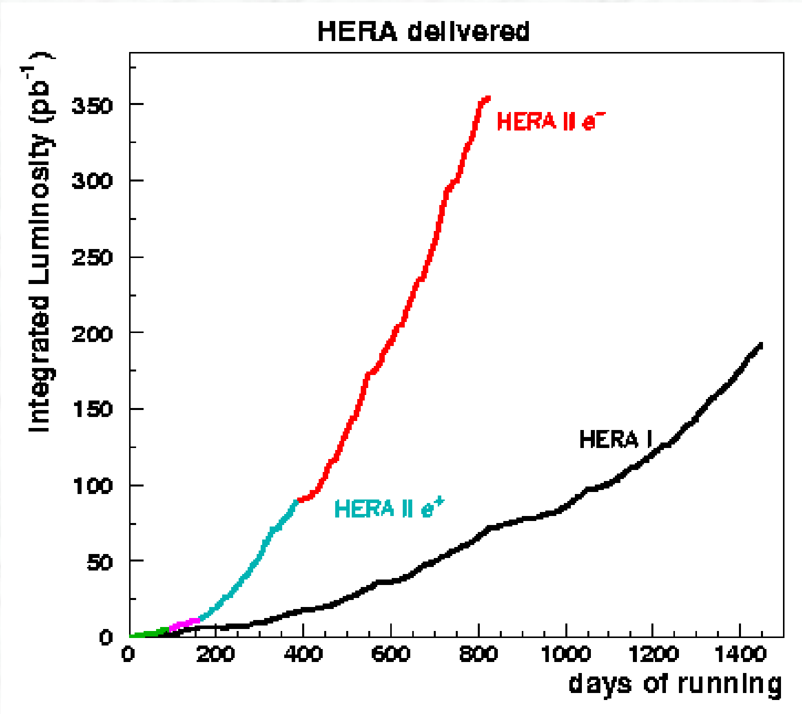
The ep collider HERA at DESY / Hamburg

Deep Inelastic Scattering of 30 GeV electron on 900 GeV protons

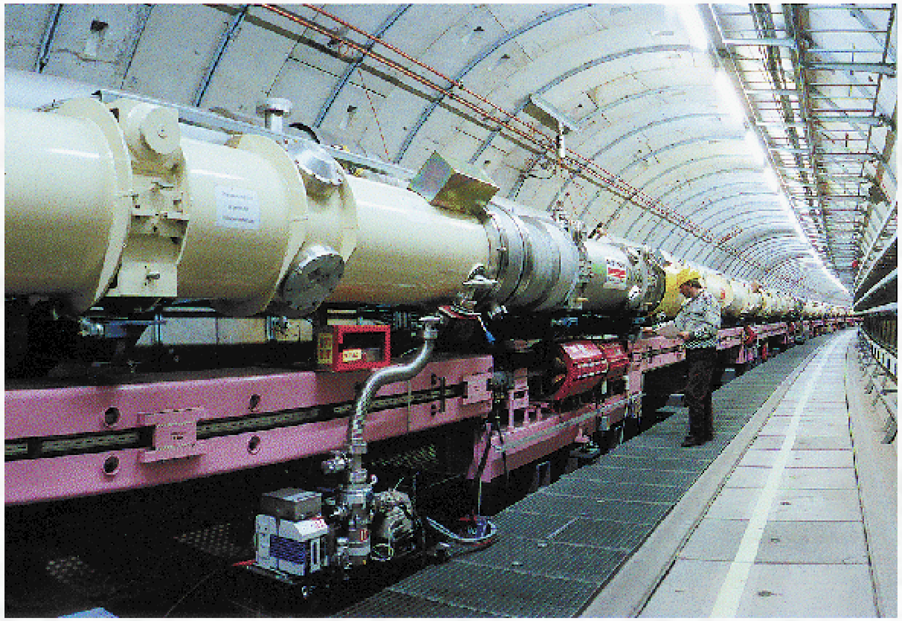
→ Test of proton structure down to 10^{-18} m

(stopped operation in June 2007)





HERA ep accelerator, 6.3 km circumference



2.2 Why Hadron Collider?

Key questions investigated in particle physics:

(i) Structure of matter; fundamental constituents $\lambda = h / p$

(ii) Search for new particles, new types of matter $E = m c^2$

For the investigation of both questions, high energies and thereby particle accelerators are needed

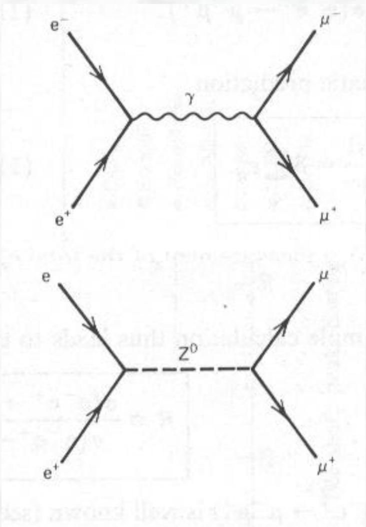
Important parameters of accelerators:

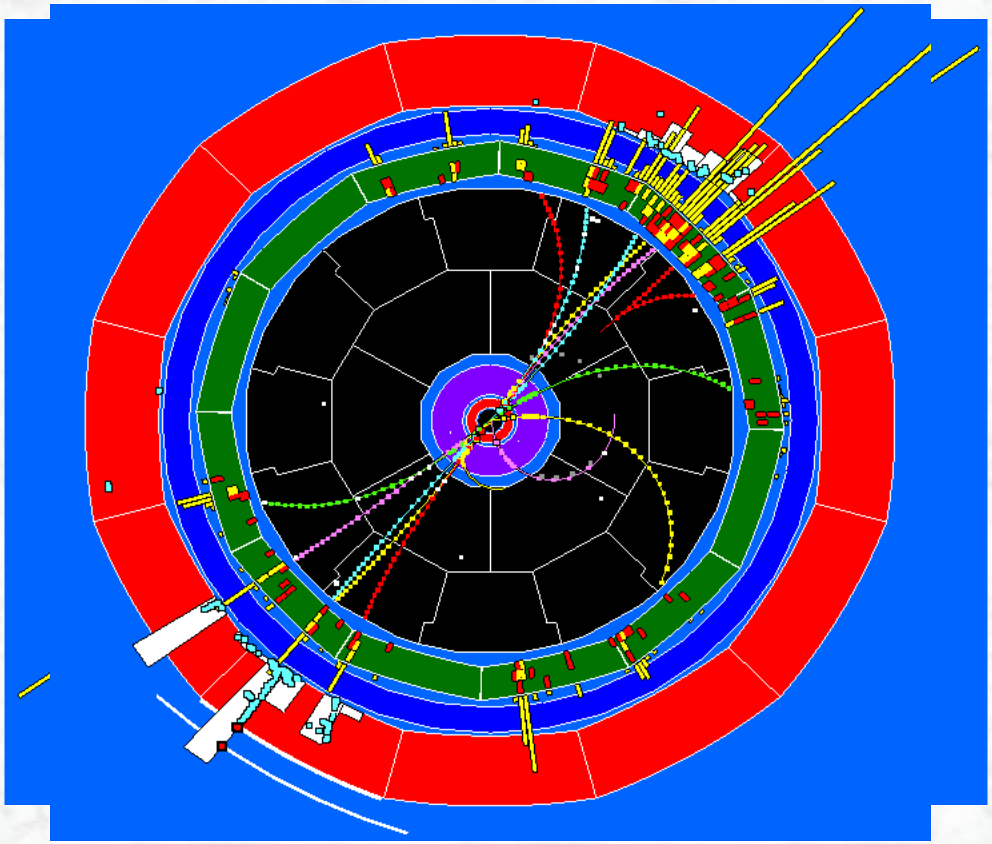
- Beam energy, centre-of-mass energy $\sqrt{s}$
- Type of particles (ee, ep, or pp) and form of accelerator
  (circular or linear accelerator)
- Luminosity L, or integrated Luminosity
  (measured in units of $cm^{-2}\ s^{-1}$)

Why a hadron collider ?

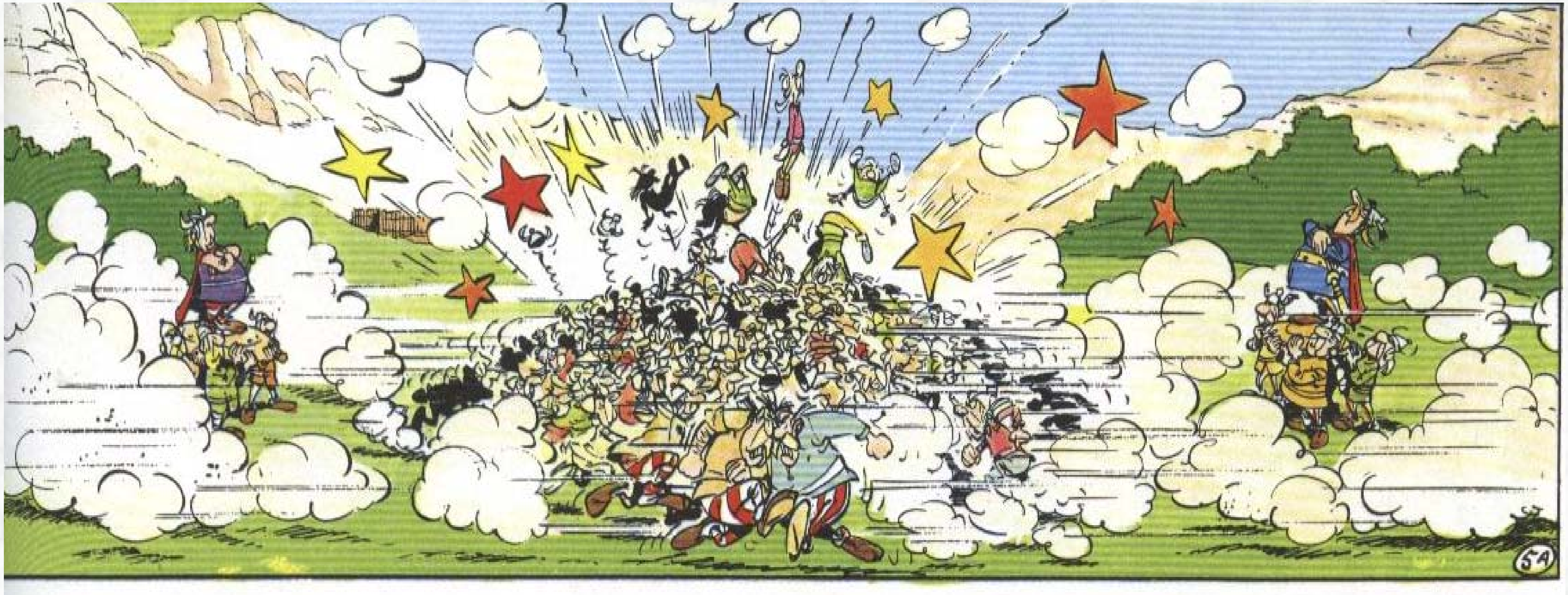
e^+e^- colliders are excellent machines for precision physics !!

- $e+$ e^- are point-like particles, no substructure → clean events
- complete annihilation, centre-of-mass system, kinematic fixed

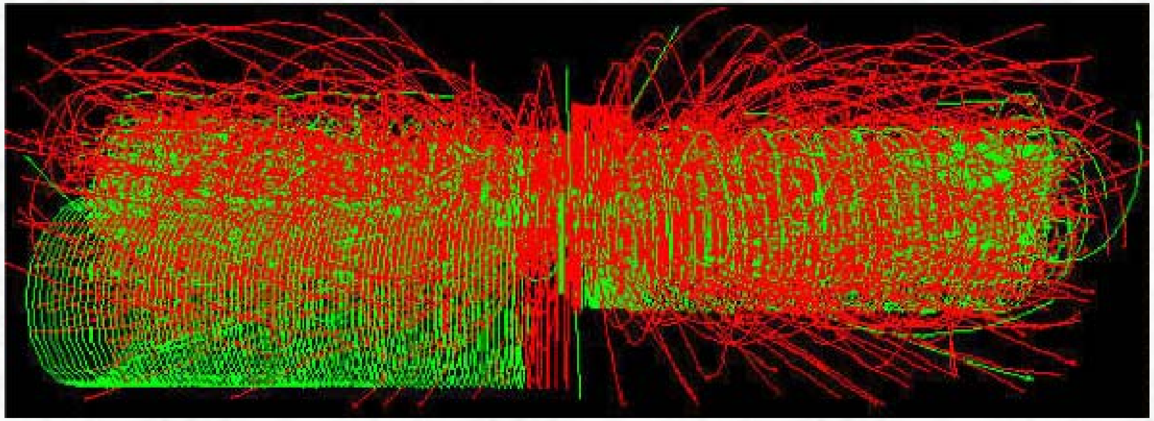


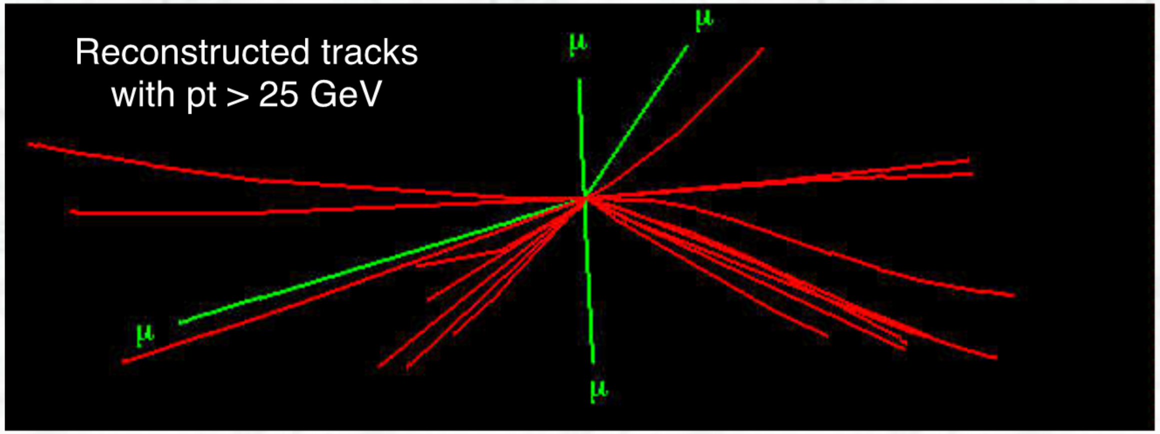


Proton proton collisions are more complex



Simulation of a pp collision at the LHC:
$\sqrt{s}$ = 14 TeV, L = 10^{34} cm^{-2} s^{-1}





Reconstruction of particles with high transverse momentum reduces the number of particles drastically
(interesting object largely kept, background from soft inelastic pp collisions rejected)

Main drawbacks of e^+e^- circular accelerators:

1. Energy loss due to synchrotron radiation
   (basic electrodynamics: accelerated charges radiate,
   x-ray production via bremsstrahlung, synchrotron radiation……)

   - Radiated power (synchrotron radiation):
     Ring with radius R and energy E

$$P = \frac{2\, e^2\, c}{3\, R^2} \left(\frac{E}{mc^2}\right)^4$$

   - Energy loss per turn:
     (2 GeV at LEP-II)

$$-\Delta E \approx \frac{4\,\pi\, e^2}{3\, R} \left(\frac{E}{mc^2}\right)^4$$

   - Ratio of the energy loss between protons and electrons:

$$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$

Future accelerators:

- pp ring accelerators (LHC, using existing LEP tunnel)
- or e^+e^- linear accelerators, International Linear Collider ILC or CLIC (under study / planning)

Limiting factors:

$e^+ e^-$ accelerators:

-Energy loss is circular rings
-Acceleration gradient in linear accelerators
(ILC design, 40 MV / m)
- Fixed centre-of-mass energy….

pp accelerators:

-More complex interactions due to proton substructure
-Only part of the pp centre-of-mass energy available in the hard scattering process (see later)
however: higher mass values can be reached with longer running times
-Magnetic field in bending magnets (8.3 T in LHC magnets)

Accelerators at the energy frontier

Livingston plot

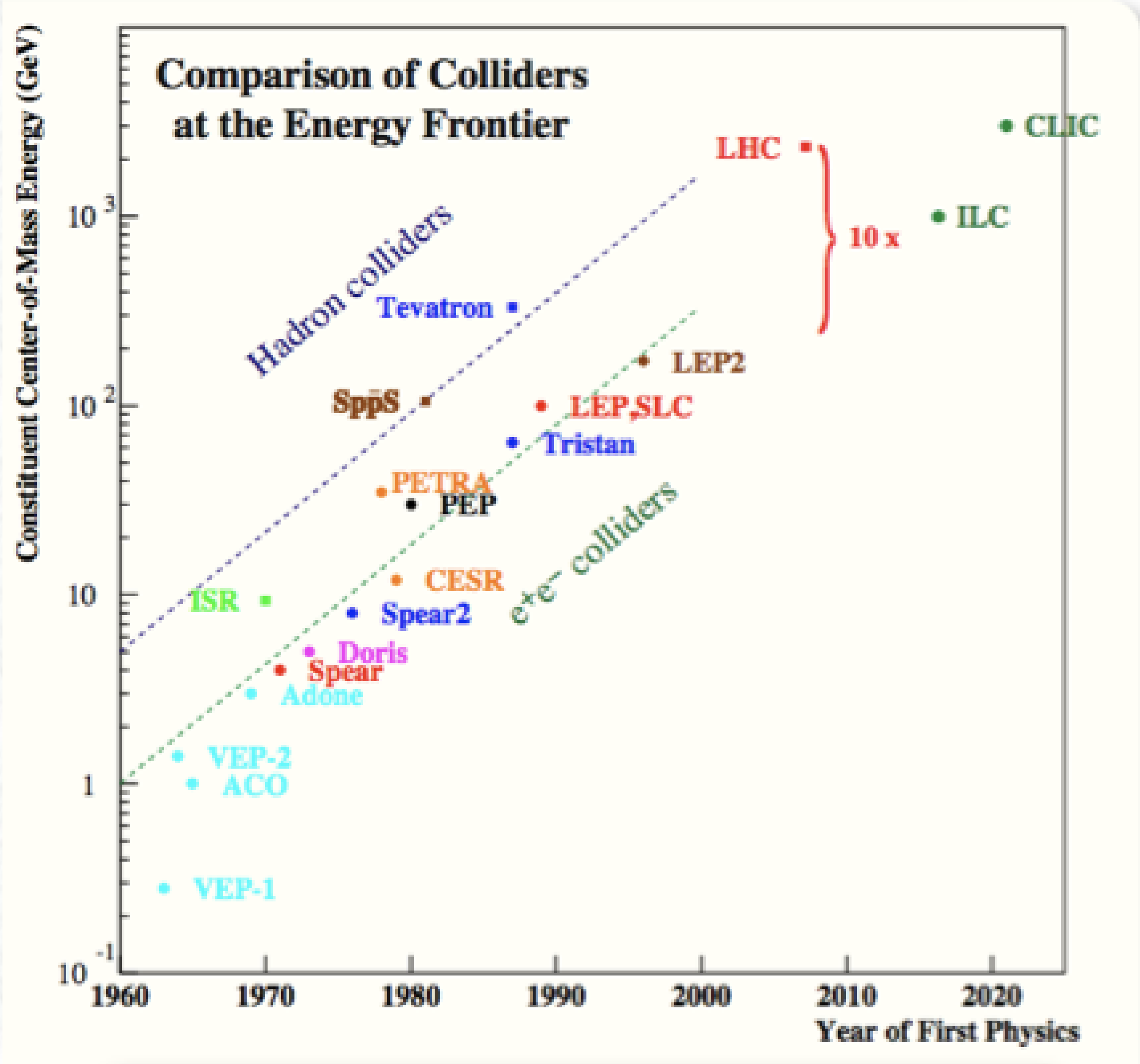
Exponential growth of √s with time (at least in the past)

Factor 4 every 10 years

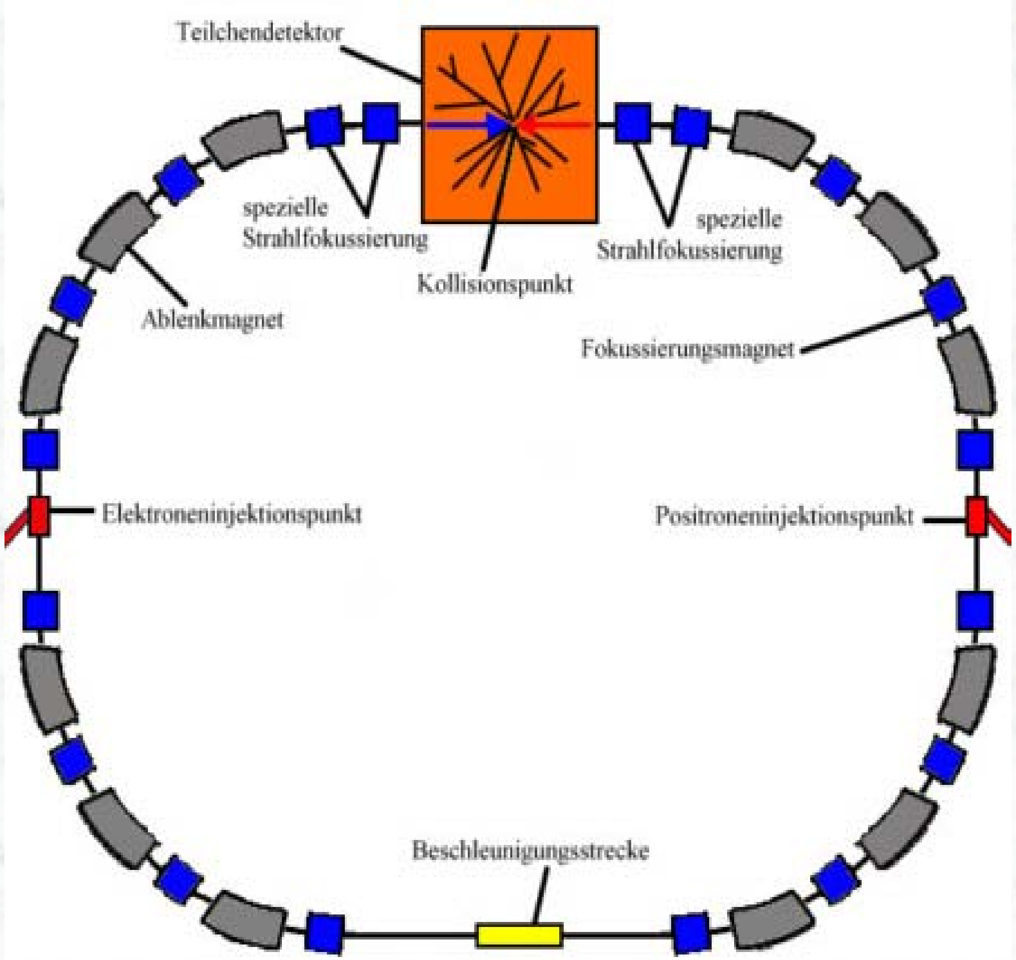
pp: discovery machines (W/Z, top, Higgs,….)

e^+e^-: precision (LEP, QCD and el.weak)

Both required !



2.3 Principles of particle accelerators

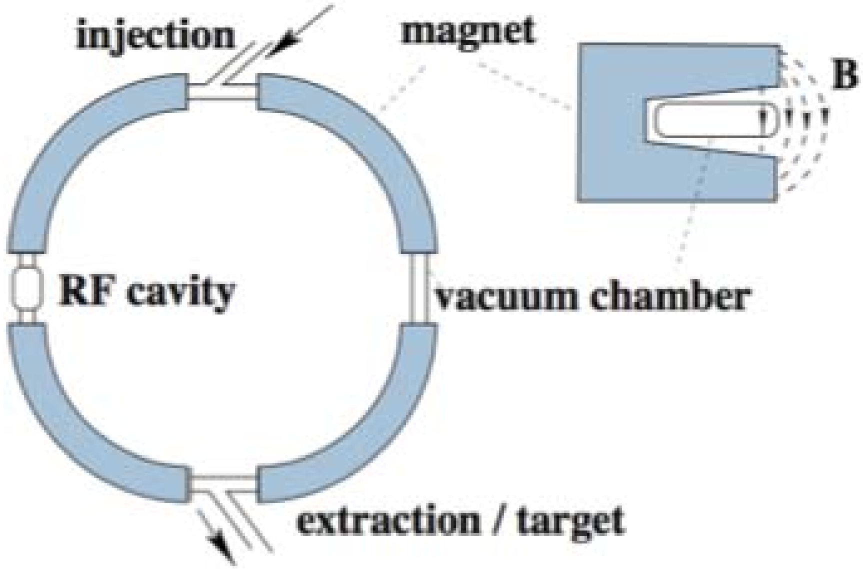


Circular accelerator principles

- Cyclotron: constant RF
  magnetic field radius ρ increases with energy
  used for smaller machines

- Synchrotron: ρ = const
  B increases with energy
  RF frequency adjusted slightly (β = 0.999 …..1.0)

Most High Energy accelerators and all CERN ring accelerators (PS, SPS, LEP, LHC) are of this type



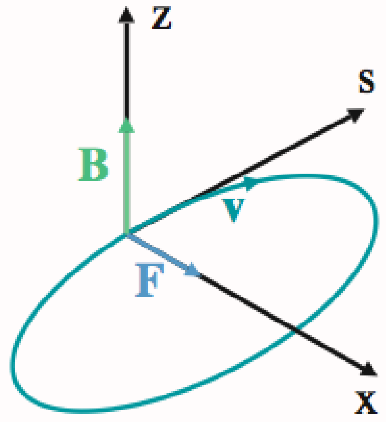
Basic parameters, Lorentz Force

$$F = q\,(E + v \times B)$$

charge q, normally $q = e$; $q = Z e$ for ions

- Electric field **E** provides the acceleration or rather energy gain
- The magnetic field **B** keeps the particles on their path

Circular motion for
$E = 0$
$v \perp B$



ρ is the radius of curvature for motion perpendicular to the static magnetic field. Often called
- gyromagnetic or Larmor radius in astroparticle physics
- bending radius for accelerators

Bρ known as magnetic rigidity, units Tm

$$B = \frac{p}{q\,\rho}$$

for $q = e$ numerically

$B\,[T] = p\,[GeV/c]\quad 3.336\ m / \rho$

high energy, $v = c$ "$p = E$"

$E < E_H = q\,B\,\rho$ Hillas criterion

LHC

- **Momentum $p = 7$ TeV/c**
- **LHC bending radius $\rho = 2804$ m**
- **Bending field B = 8.33 Tesla**
- **magnets at 1.9 K, super-fluid He**

Astroparticle

units 10^{-4}T = 1Gauss ; a.u. = 1.5×10^{11}m

Solar system $B = 10\mu G$ $E = 5$ TeV $\rho = 11$ a.u.

Intergalactic $B = 1nG$ $E = 5$ PeV (knee)

$\rho = 1.7\times10^{19}$m (4 % of galaxy-radius)

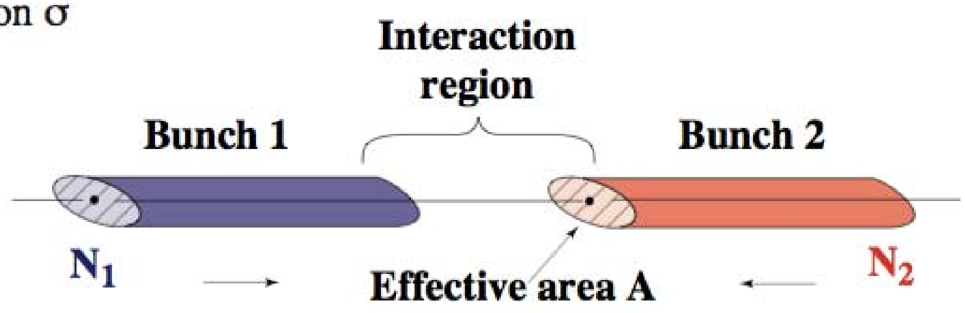
Luminosity and collision rates

Event rate for process with cross section σ

$$\dot{n} = \mathcal{L}\sigma$$

Luminosity from bunch crossings at frequency $f = f_{rev}\, n_b$

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$



for Gaussian bunches with rms sizes $\sigma_x\, \sigma_y$ $\mathbf{A} = 4\,\pi\,\sigma_x\,\sigma_y$

High luminosity: Large number of particles (N_1, N_2)
Small beam dimensions (A) in the interaction point
Large f (large number of bunches,
→ small time difference between bunch crossings)

LHC: $N = 1.15\ 10^{11}$, $n_b = 2808$ (number of bunches)
bunch separation: 25 ns (corresponds to 7.5 m)
A: beams squeezed (using strong, large aperture quadrupoles close to the interaction region) from σ = 0.2 mm to 16 μm

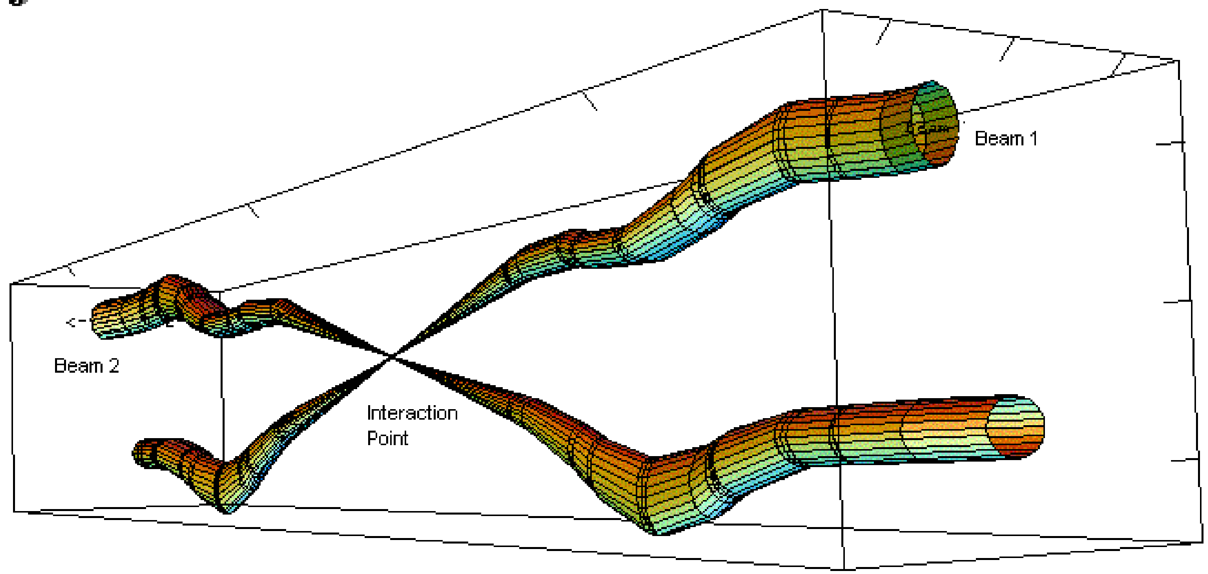
$$L = f\frac{N_1\ N_2}{4\pi\ \sigma_x\sigma_y} = f\frac{N}{4\pi\ \sigma^2}$$

for $N = N_1 = N_2$ particles per bunch with transverse r.m.s. beam size $\sigma = \sigma_x = \sigma_y$ and frequency f

Accelerator physicist express this often using the transverse emittance ε and the β function:

$$L = f\frac{N_1\ N_2}{4\ \sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$

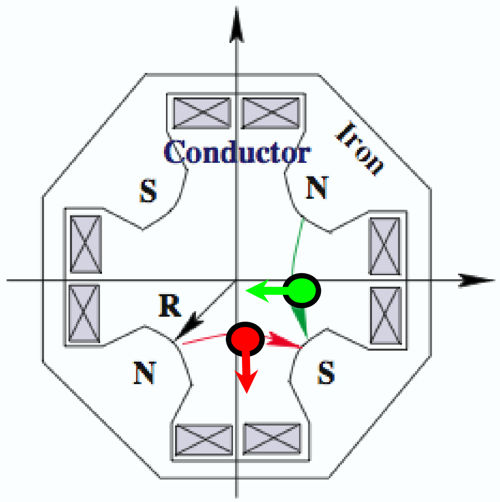
where $\epsilon = \pi\sigma^2/\beta$

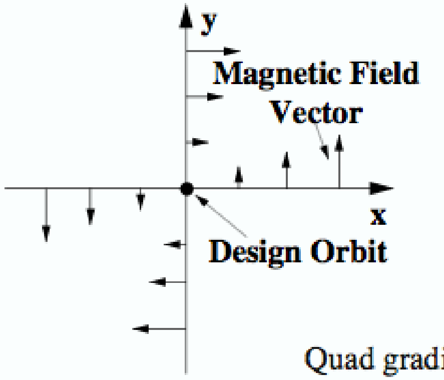


Relative beam sizes around IP1 (Atlas) in collision

Alternate gradient focusing

Quadrupole lens focusing in x, defocusing in y or vice versa





$B_x = k\,y$

$B_y = k\,x$

$B_z = 0$

$\nabla \times B = 0$

Quad gradients in the LHC

$K = 1/B\varrho \;\; \partial B_y / \partial x \approx 200$ T/m

$\mathbf{F} = e\,(\mathbf{v} \times \mathbf{B})$

here

$\mathbf{F} = e\,(0, 0, v) \times (B_x,\ B_y, 0)$

$\quad = e\,(-v\,B_y,\ +v\,B_x,\ 0)$

Combine F D

Defocusing when at small amplitude

Overall focusing

Normal (light) optics :

Focal length of two lenses at distance D

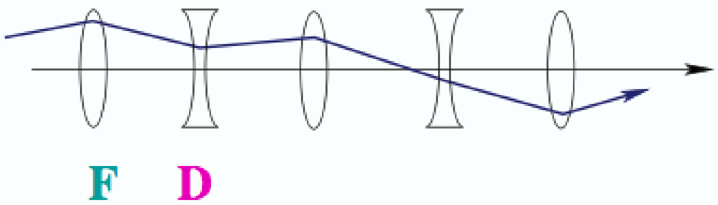
$1/f = 1/f_1 + 1/f_2 - D/f_1 f_2$

is overall focusing

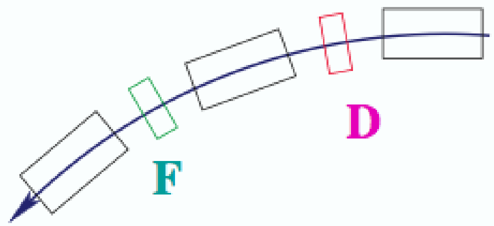
with $1/f = D/f^2$

for $f = f_1 = -f_2$

alternate gradient focusing



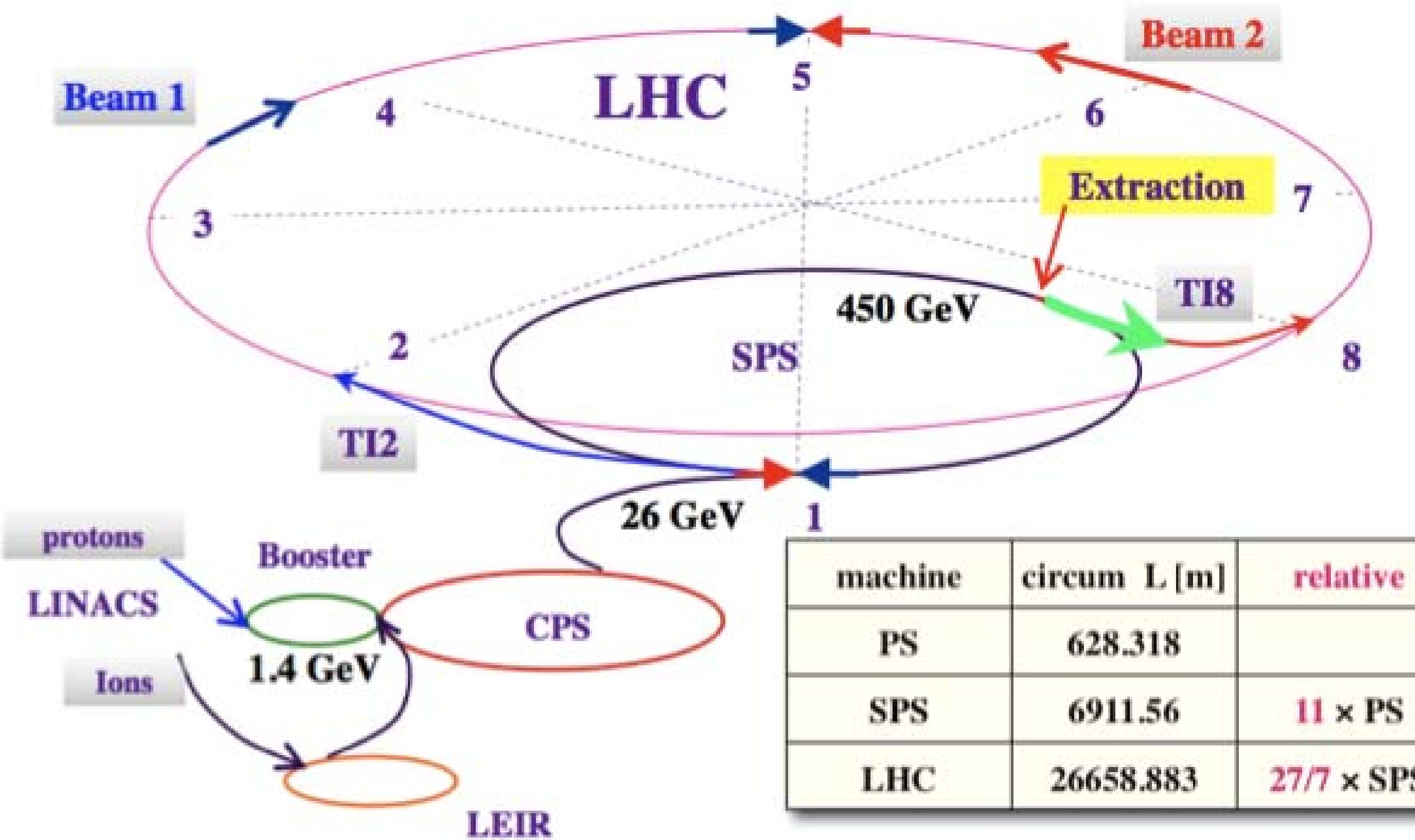
together with bending magnets FODO lattice



N. C. Christofilos, unpublished manuscript in 1950 and patent

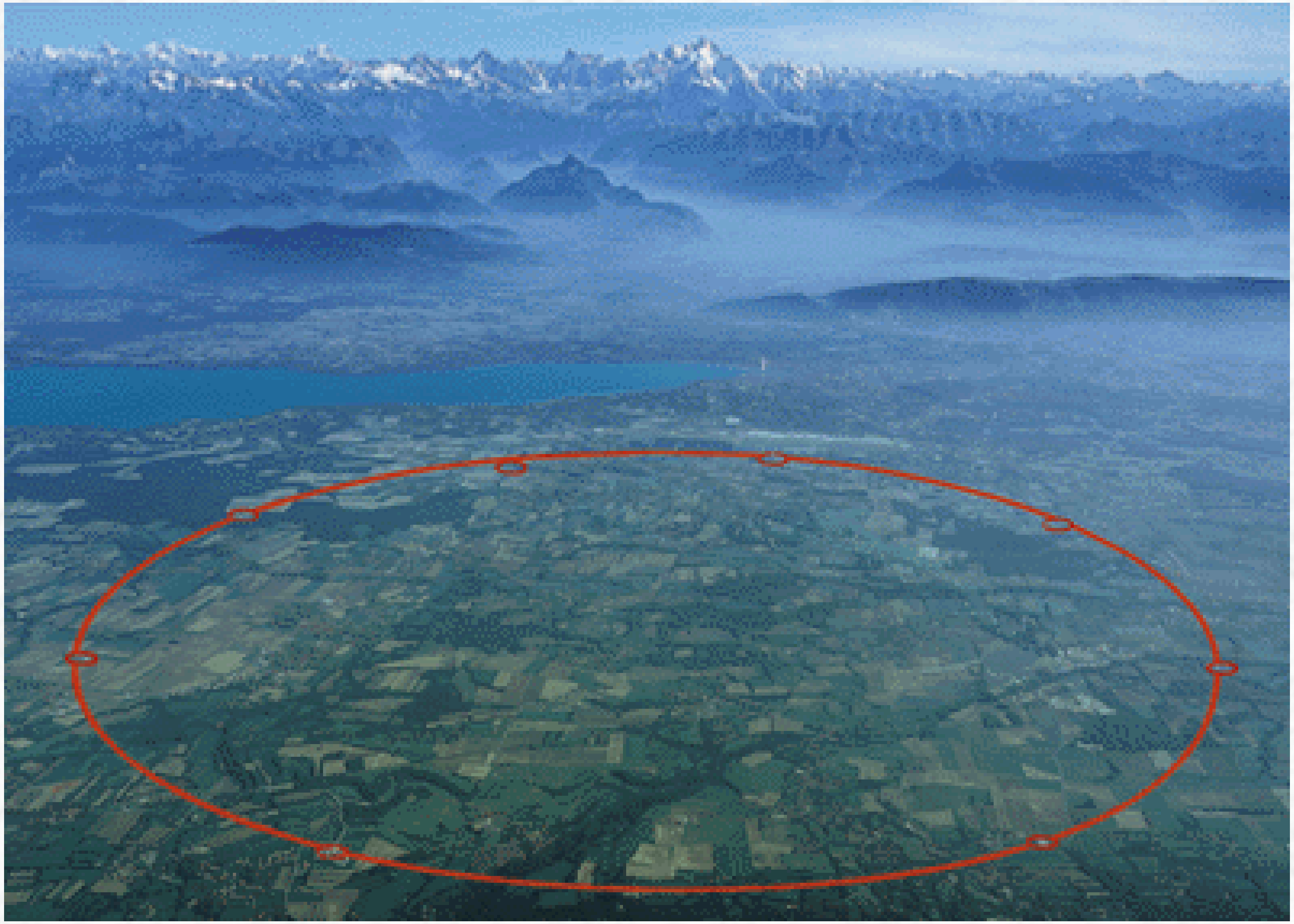
Courant, Snyder in 1952, Phys. Rev. 88, pp 1190 - 1196 + longer review in Annals of Physics 3 (1958)

The CERN accelerator complex: injectors and transfer



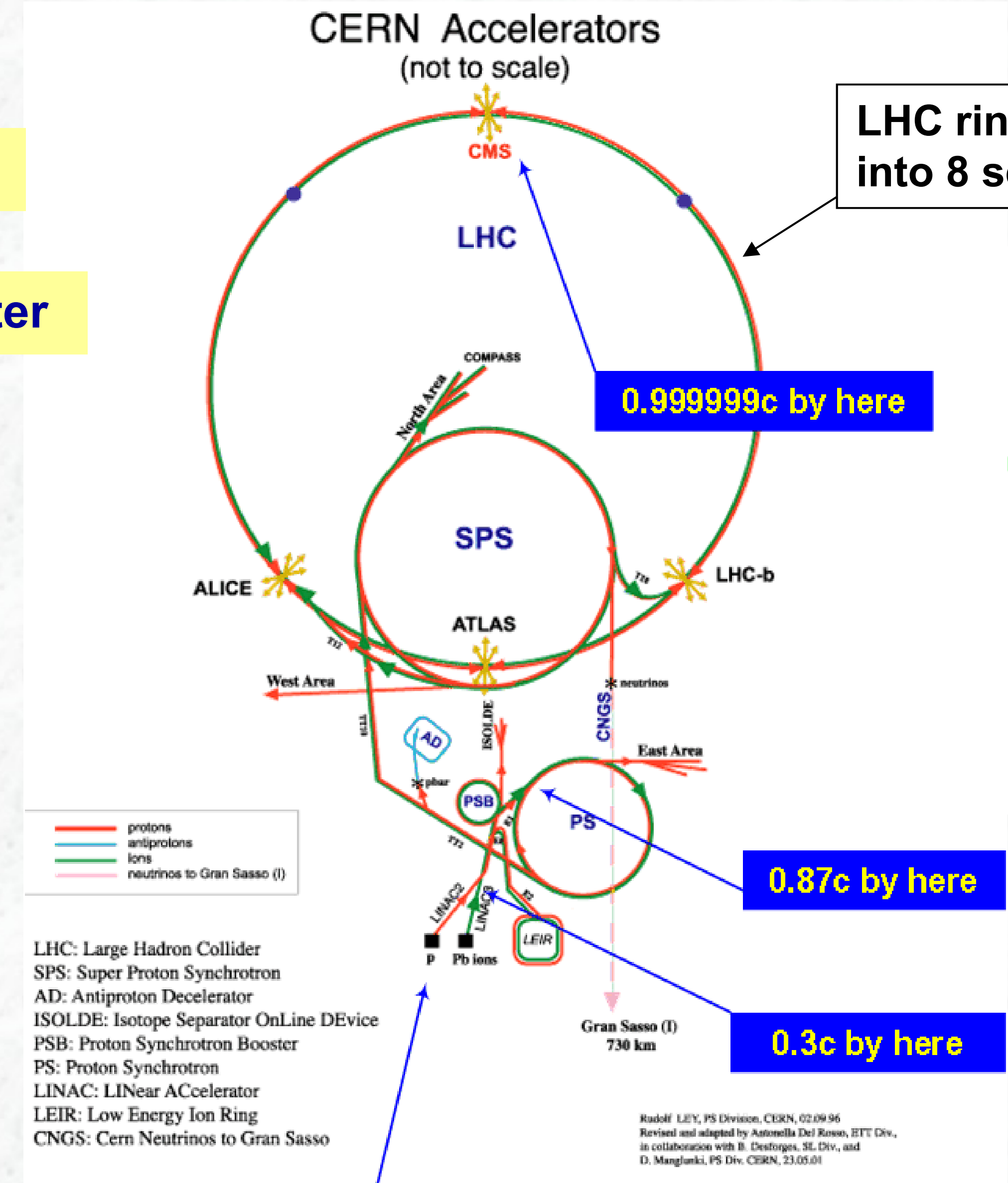
machine	circum L [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

3.3 The Large Hadron Collider (LHC)



The full LHC accelerator complex

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC



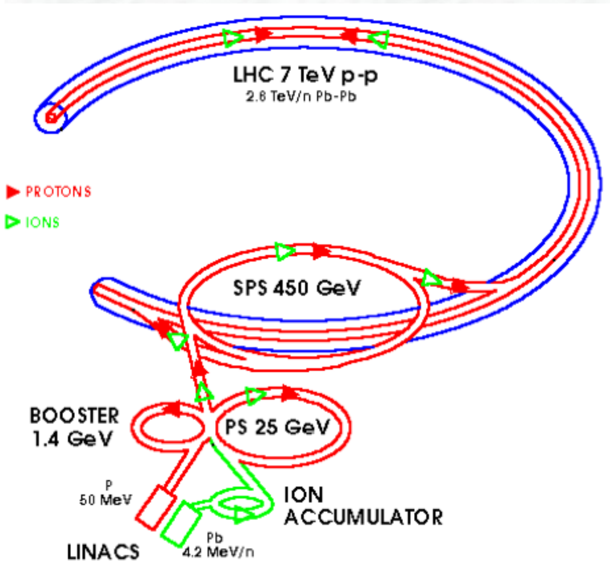
LHC ring is divided into 8 sectors

0.999999c by here

0.87c by here

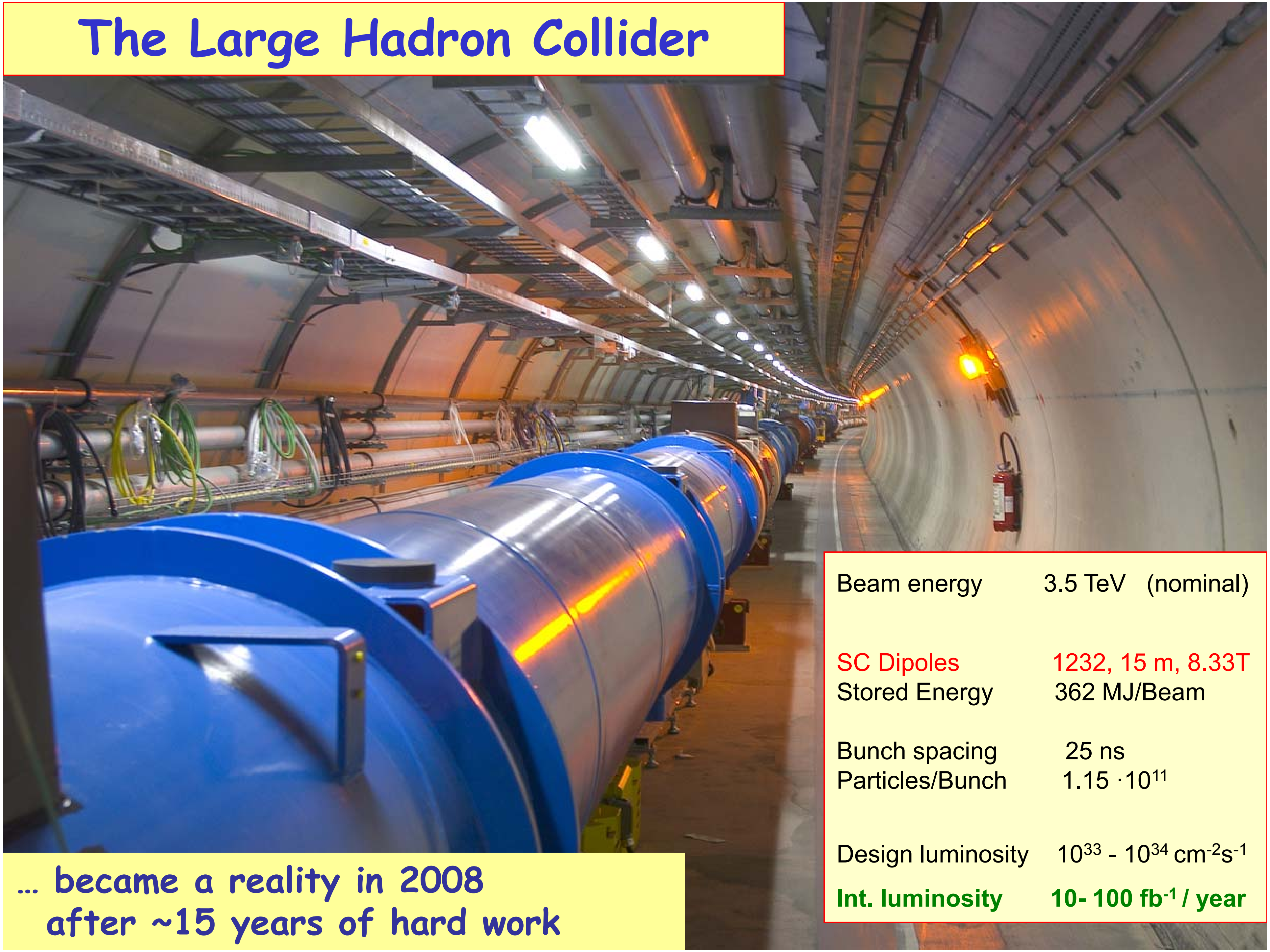
0.3c by here

Start the protons out here



> 50 years of CERN history still alive and operational

The Large Hadron Collider



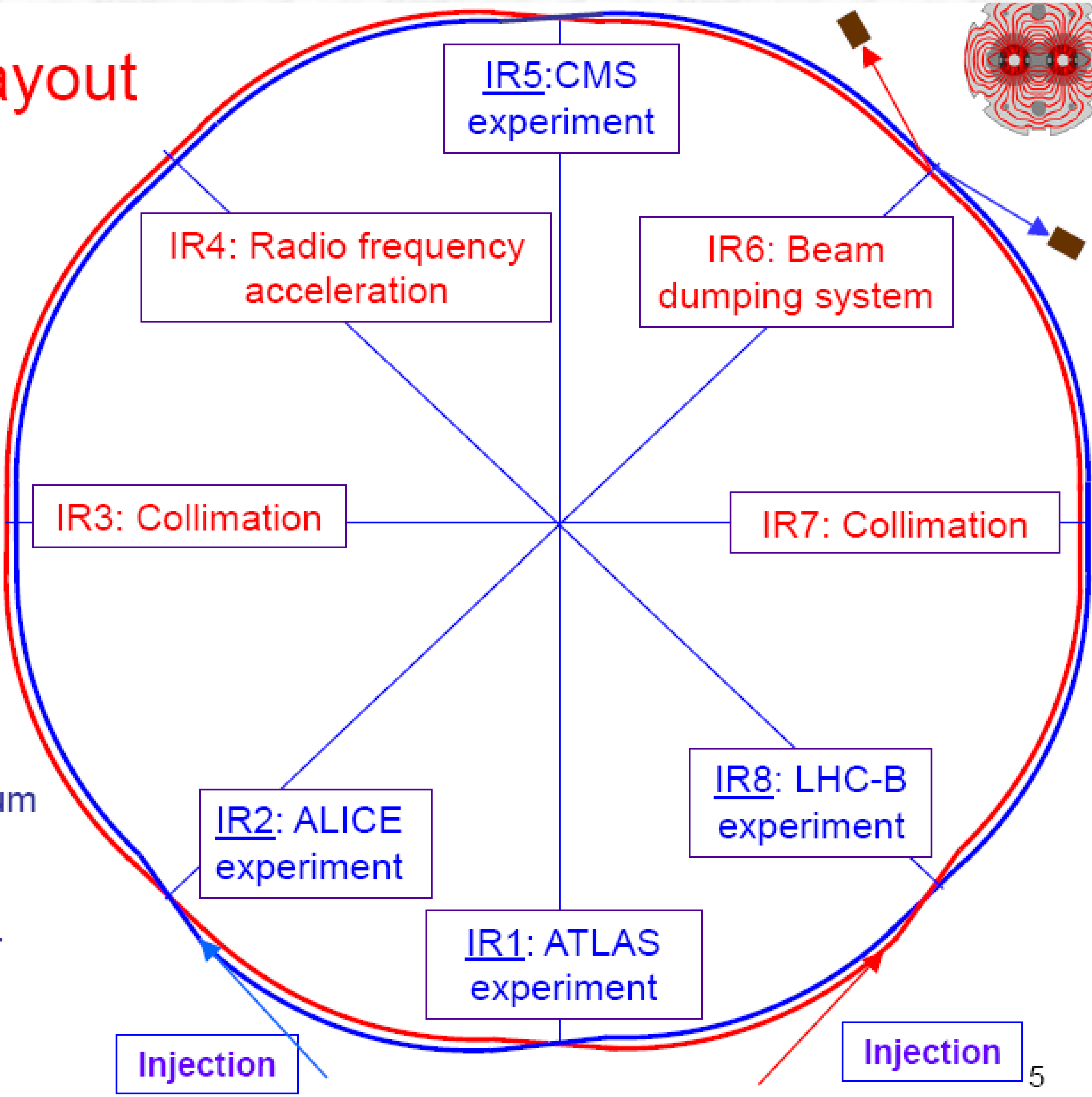
Beam energy	3.5 TeV (nominal)
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
Design luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$
Int. luminosity	**10- 100 fb^{-1} / year**

… became a reality in 2008
after ~15 years of hard work

LHC Layout

- 8 arcs (sectors)
- 8 long straight sections (700 m long):

  IR1 to IR8



- 2 separate vaccum chambers
- beams cross in 4 points

Important components of the accelerator

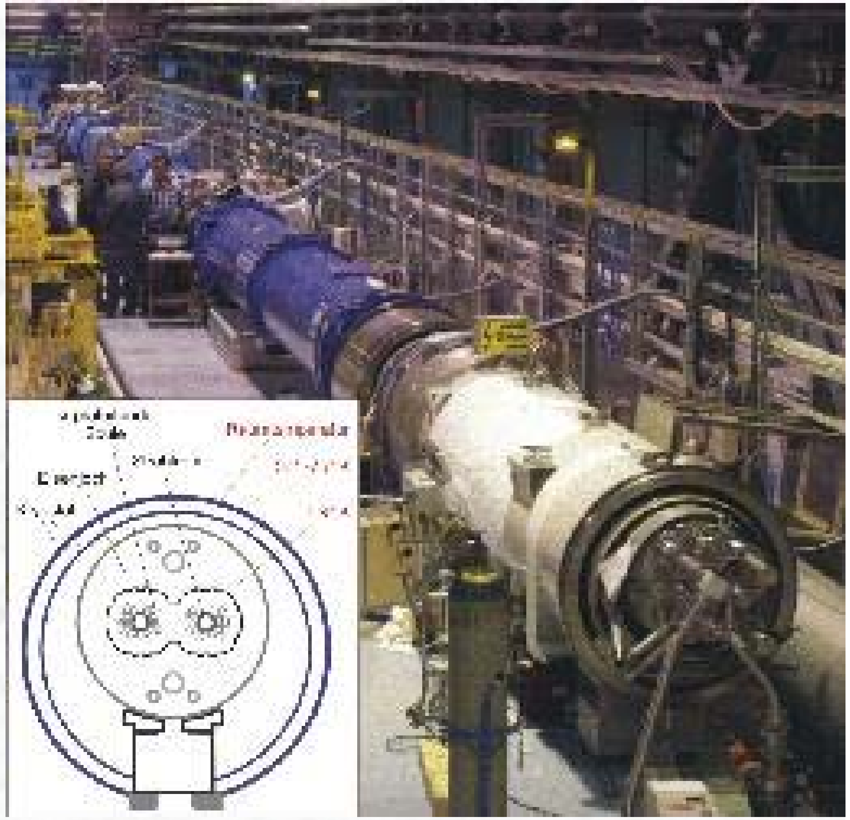
- Superconducting dipole magnets
  (the largest challenge)

  - Magnetic field of 8.33 Tesla
  - in total 1232, 15 m long
  - Operation temperature of 1.9 K
    (helium cooling)

Magnetic field for dipoles
p (TeV) = 0.3 B(T) R(km)

For p = 7 TeV and R = 4.3 km

⇨ B = 8.4 T
⇨ Current 12 kA



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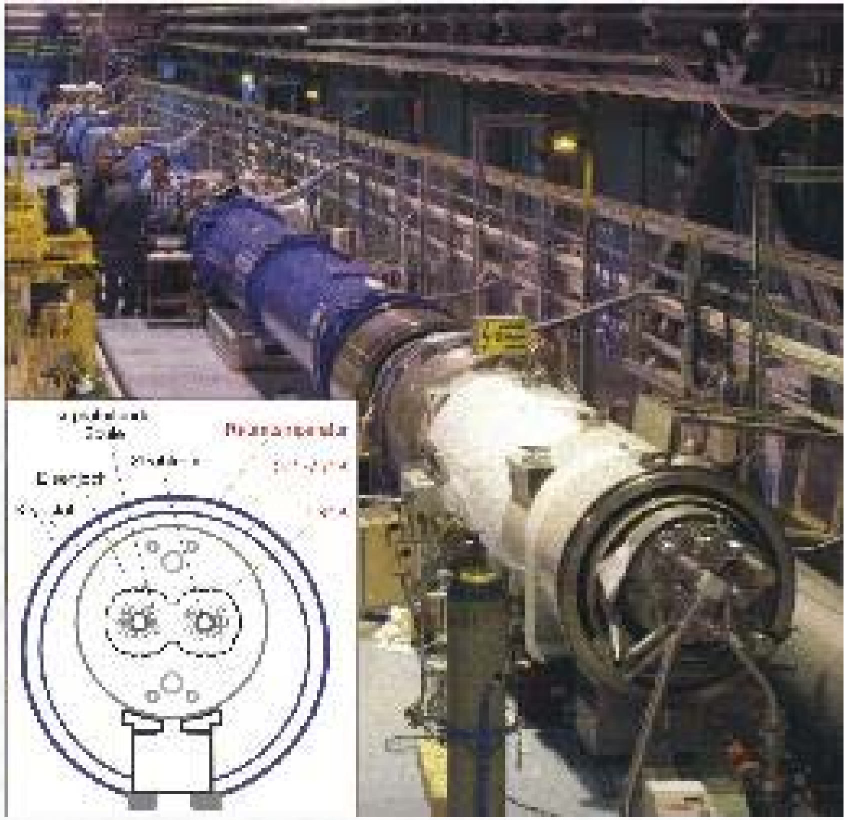
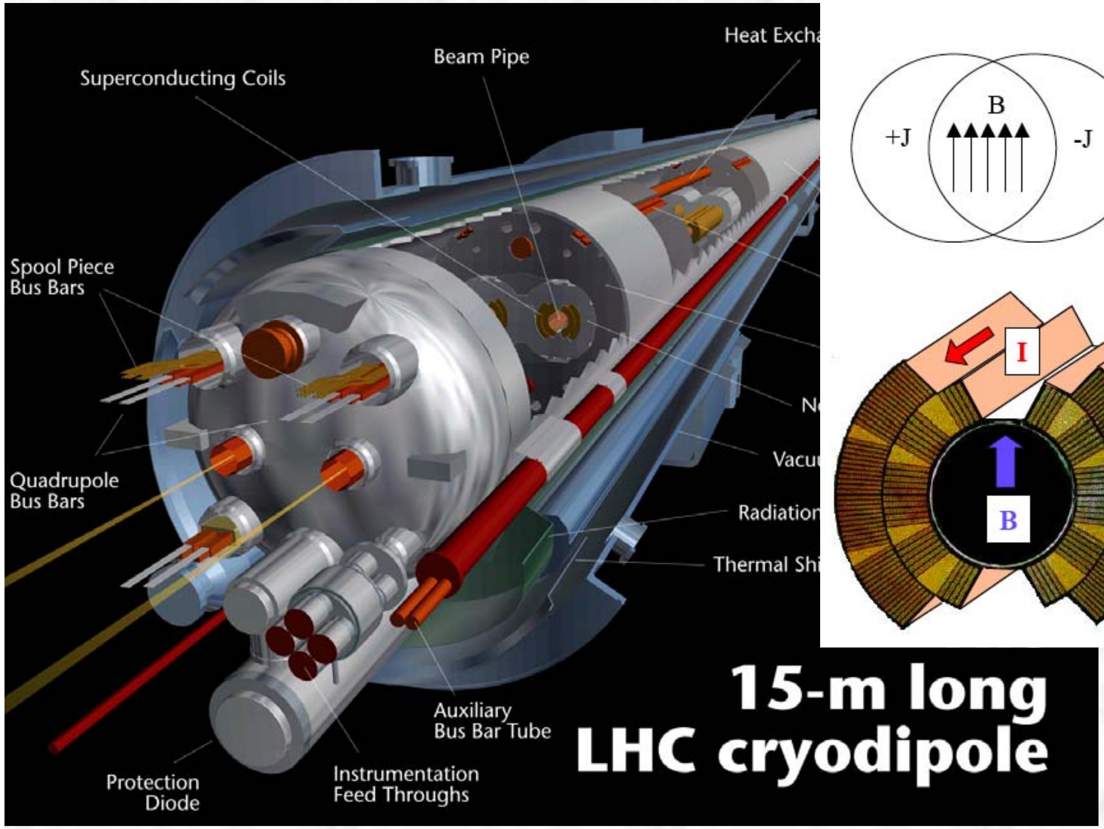


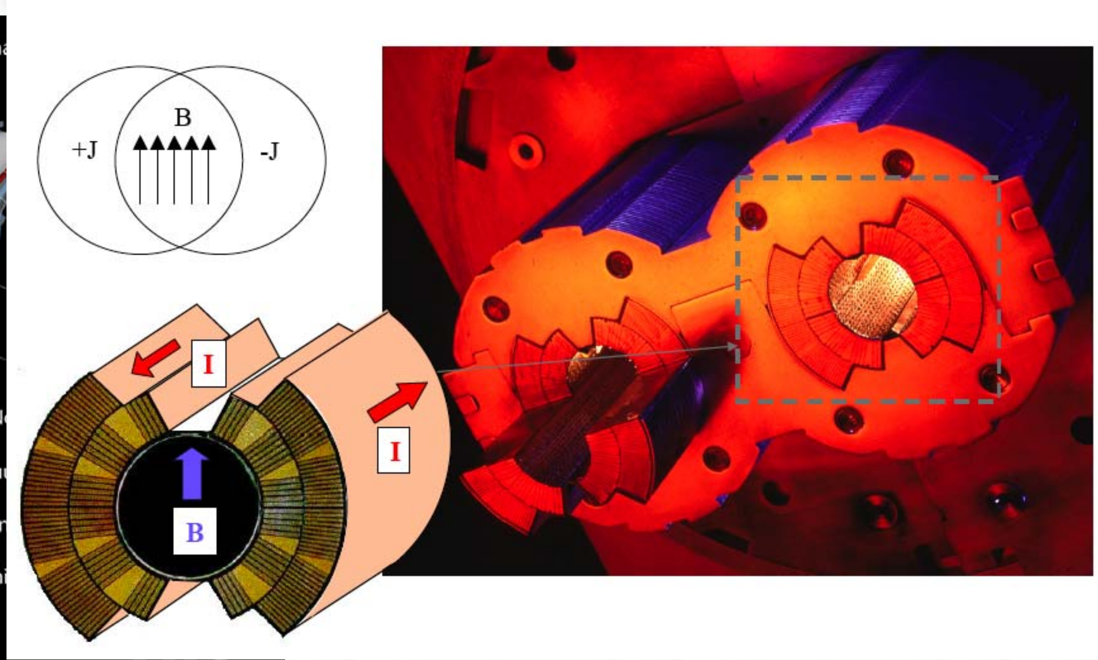
- Eight acceleration structures,
  Field gradient of 5 MV/m

- Unprecedented complexity

  (in total: ~10.000 magnets powered by 1.700 electrical circuits, large stored energy, complex protection systems)

LHC Accelerator Challenge: Dipole Magnets



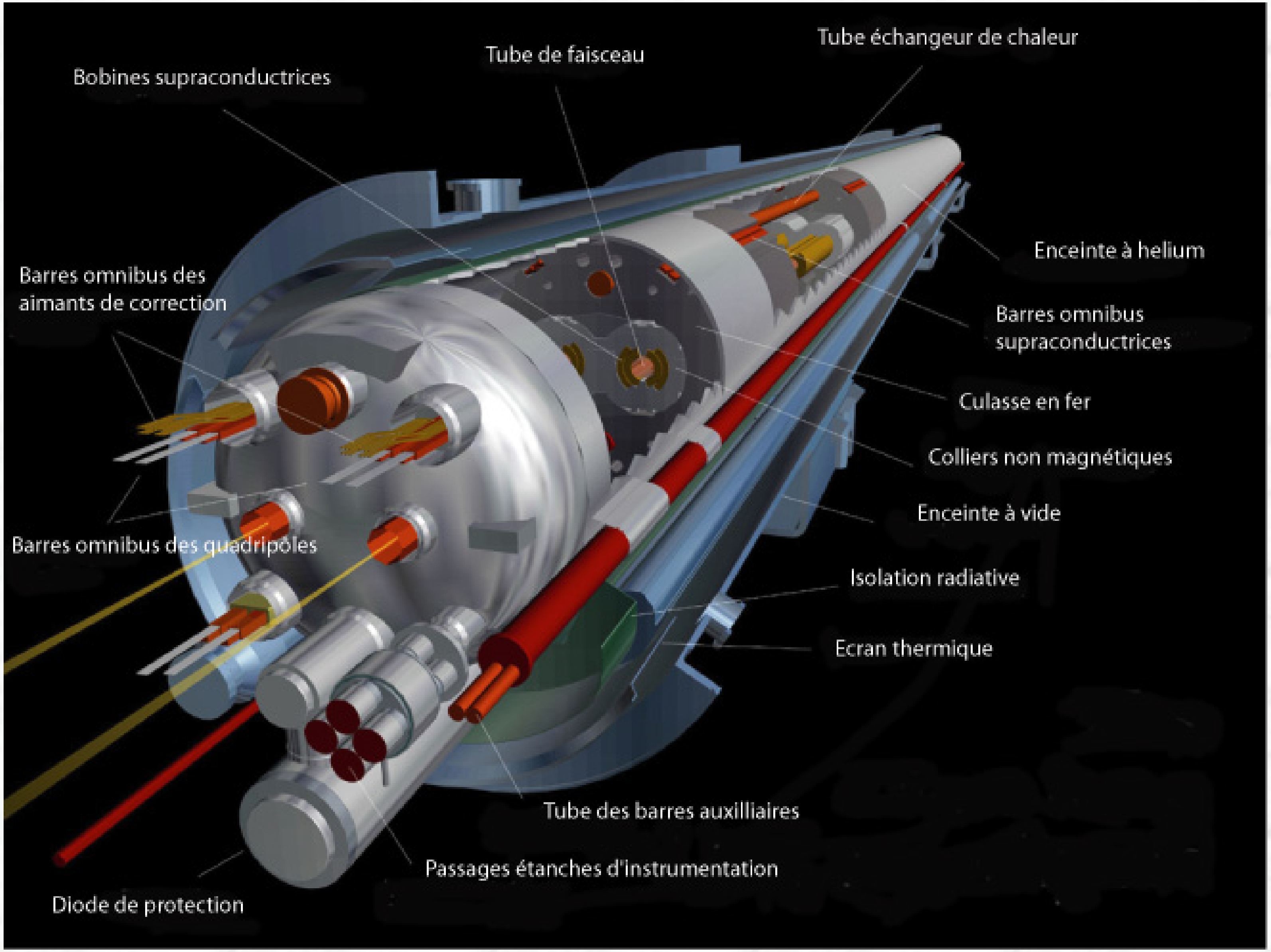


Coldest ring in the Universe ? 1.9 K

LHC magnets are cooled with pressurized superfluid helium

Two beams in one dipole magnet,
8.33 Tesla
(opposite magnetic dipole fields,
protons circulating in opposite directions)
15 m long, mass of 30 tons

A superconducting LHC dipole magnet

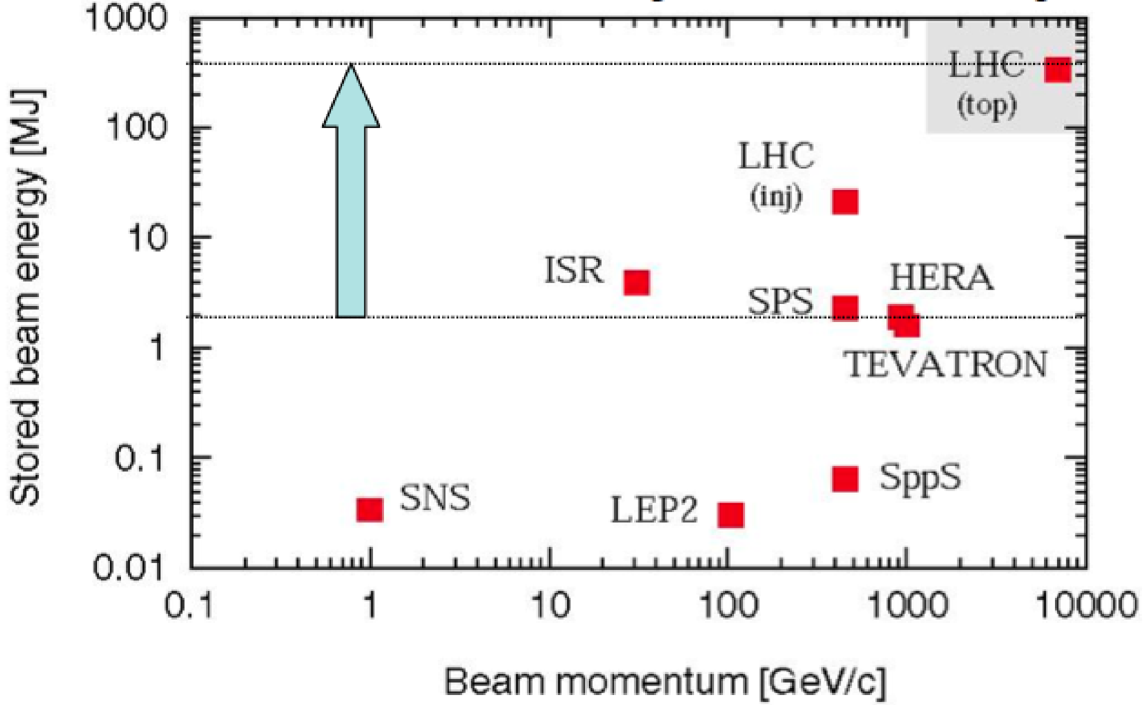


Descent of the last dipole magnet, 26 April 2007

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

The total stored energy of the LHC beams

Nominal LHC design: 3 x 10^{14} protons accelerated to 7 TeV circulating at 11 kHz in a SC ring



LHC: > 100 x higher stored energy and small beam size: ~ 3 orders of magnitude in energy density and damage potential. Active protection (beam loss monitors, interlocks) and collimation for machine and experiments essential.

Only the specially designed beam dump can safely absorb this energy.

Beam parameters, LHC compared to LEP

	LHC	LEP2
Momentum at collision, TeV/c	7	0.1
Nominal design Luminosity, $cm^{-2}s^{-1}$	1.00E+34	1.00E+32
Dipole field at top energy, T	1	1
Number of bunches, each beam	2808	4
Particles / bunch	1.15E+11	4.20E+11
Typical beam size in ring, µm	200-300	1800/140 (H/V)
Beam size at IP, µm	16	200/3 (H/V)

- **Energy stored in the magnet system: 10 GJoule**
- **Energy stored in one (of 8) dipole circuit: 1.1 GJ**
- **Energy stored in one beam: 362 MJ**
- **Energy to heat and melt one kg of copper: 0.7 MJ**

Kin. energy of Airbus A380, 560t at 700 km/h.

the LEP2 total stored beam energy was about 0.03 MJ

LHC: From first ideas to realisation

26 y

1982 : First studies for the LHC project

1983 : Z discovered at SPS proton antiproton collider

1989 : Start of LEP operation ~ 92 GeV, Z-factory

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

1996 : LEP2 operation towards ~ 200 GeV, W^+W^-

2000 : End of LEP operation

2002 : LEP equipment removed

2003 : Start of the LHC installation - infrastructure

2005 : Start of Magnet installation in LHC tunnel

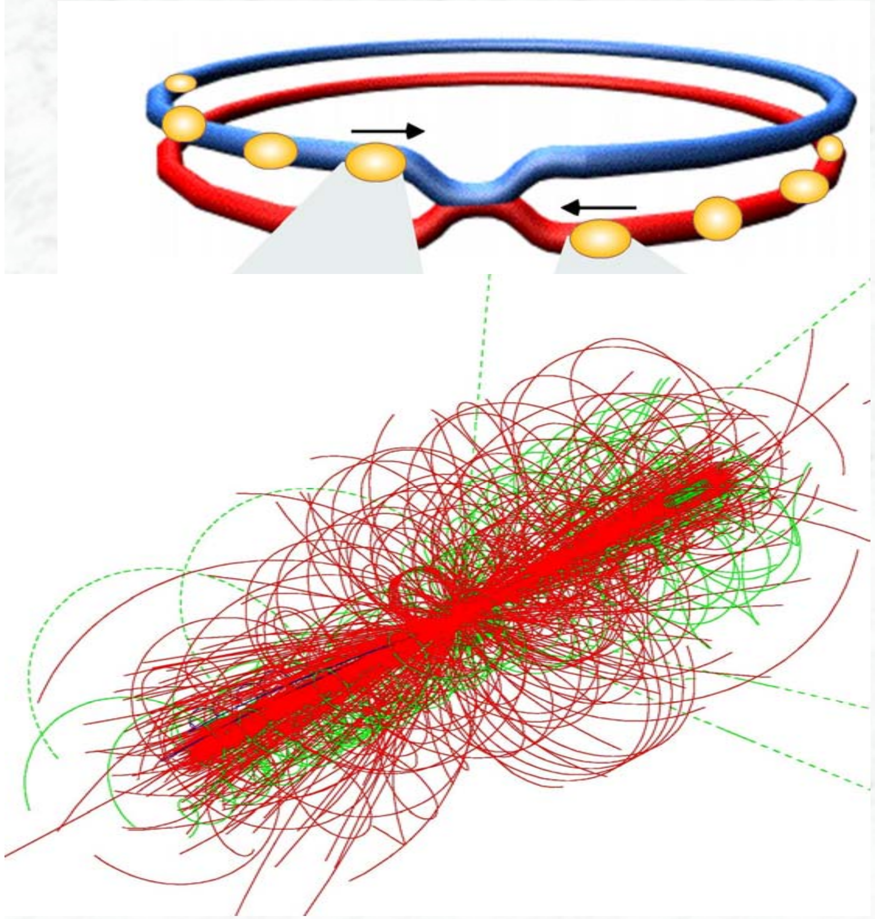
2007 : Installation complete, starting cooldown

2008 : Commissioning with beam and first collisions

14 y

7 y

Proton-proton collisions at the LHC



Proton–proton:

2808 x 2808 bunches
Separation: 7.5 m (25 ns)

10^{11} protons / bunch
crossing rate of p bunches: 40 Mio / s
Luminosity: L = 10^{34} cm^{-2} s^{-1}

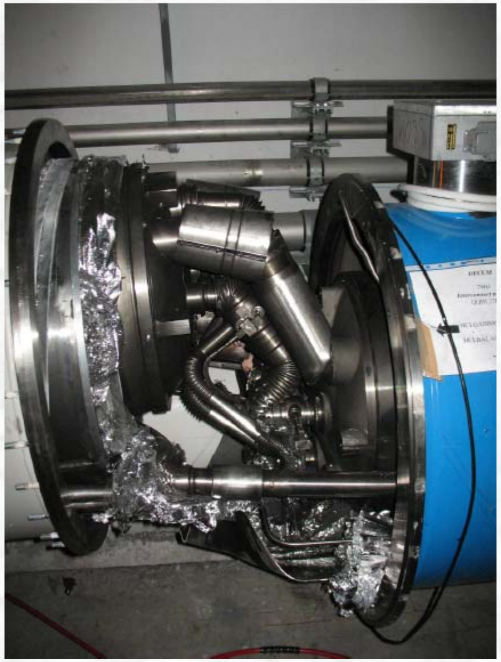
~10^9 pp collisions / s
(superposition of > 20 pp interactions per crossing: **pile-up**)

~1600 charged particles in the detector

⇒ high particle densities,
high requirements on detectors

An excellent LHC start: first beams – Sept 10, 2008

Incident on 19th Sep. 2008, repair, comeback…..



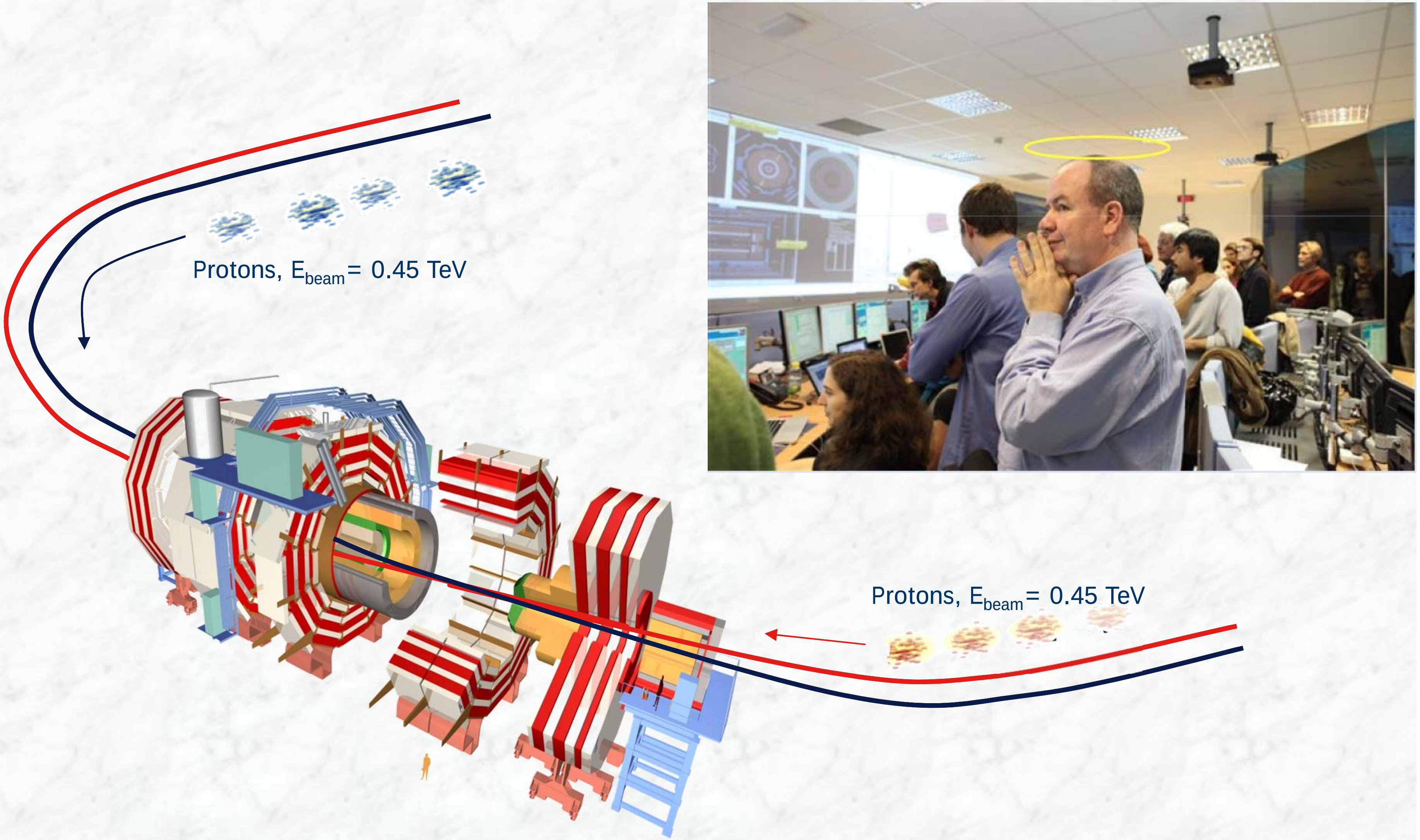
- A resistive zone developed in an electrical bus bar connection
- Electrical arc → punctured the helium enclosure
- Helium release under high pressure
- Relief discs unable to maintain the pressure rise below 0.15 MPa → large pressure forces

- Lot of repair work during 2009

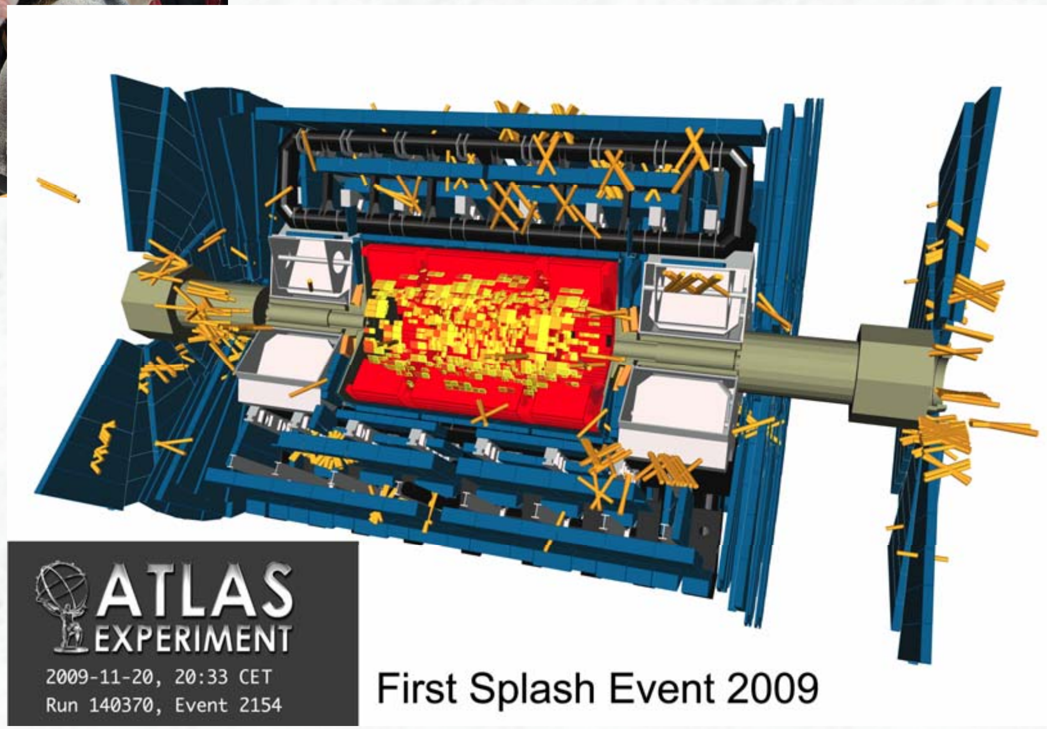
(14 quadrupole and 39 dipole magnets replaced, electrical interconnections repaired, larger helium pressure release ports installed,…..)

- A very successful re-start in Nov. 2009

LHC re-start in Nov. 2009



The first signals in the ATLAS experiment, 20. Nov 2009

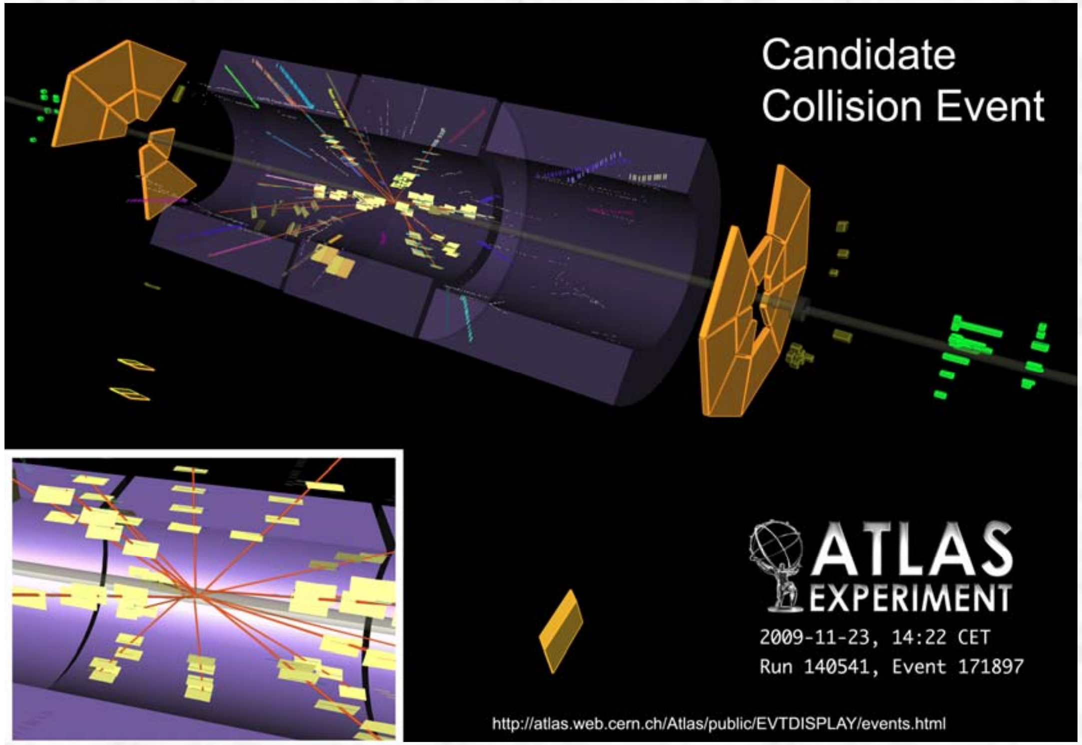


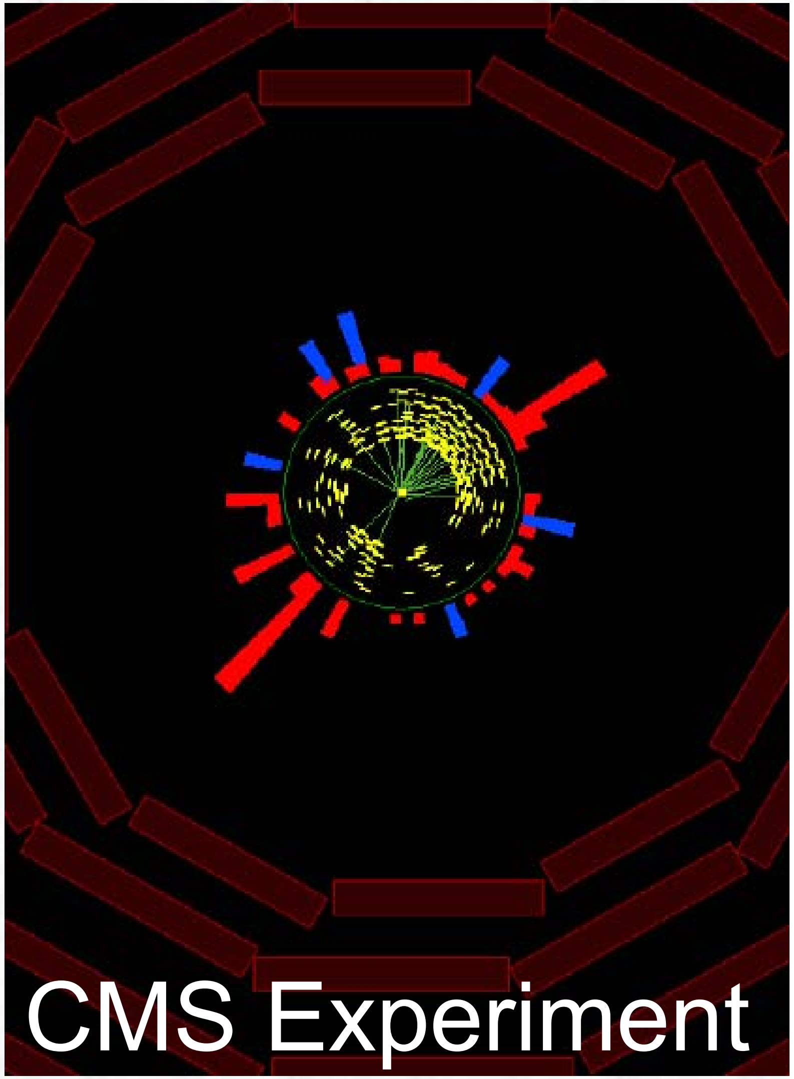
CMS in the BBC news

November 21, 2009

BBC NEWS

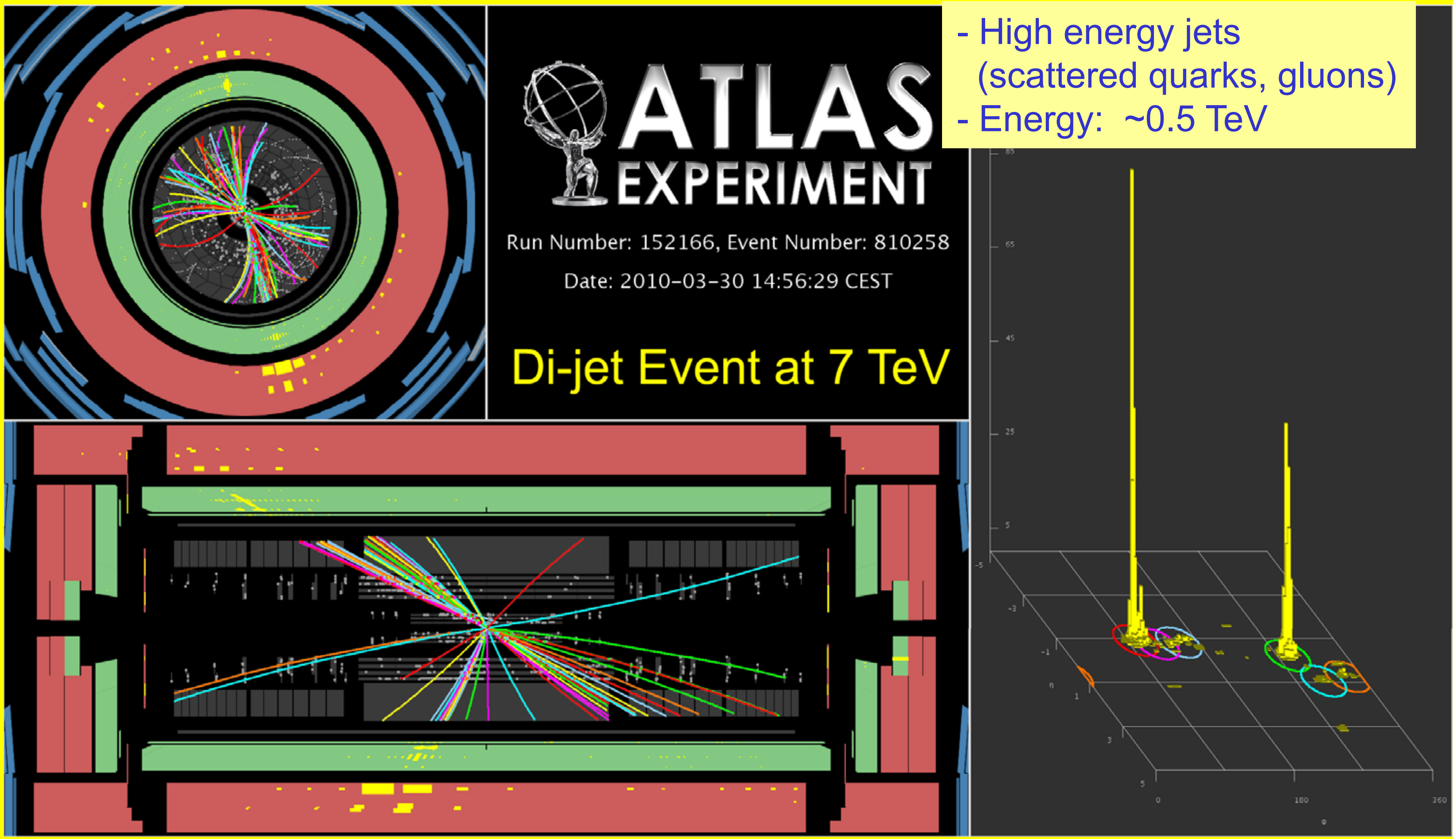
23. Nov 2009: First collisions at 900 GeV



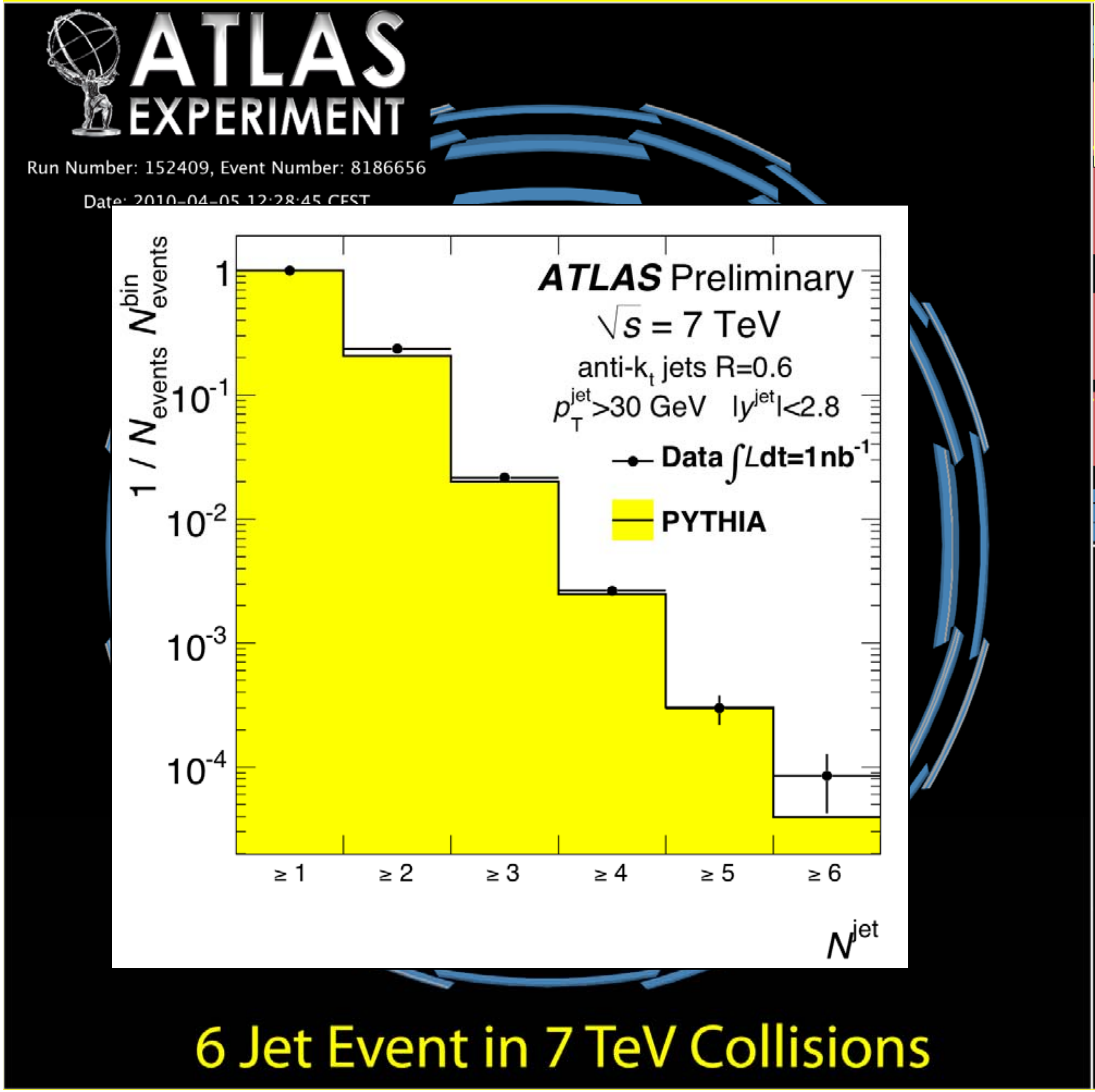


23rd Nov 2009

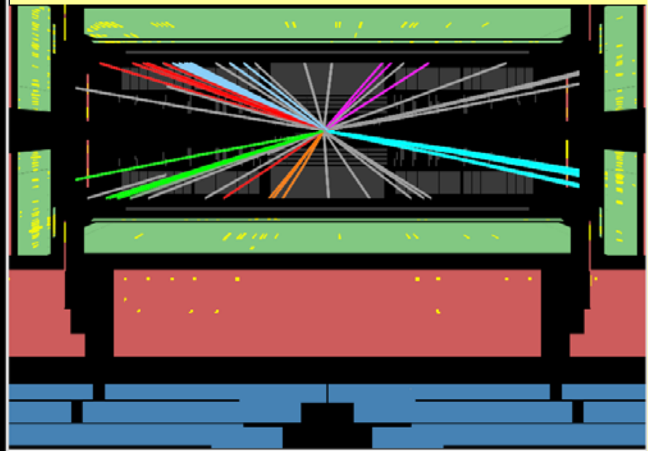
Since 30. March 2010: collisions at 7 TeV
(.... first interesting results appeared soon)

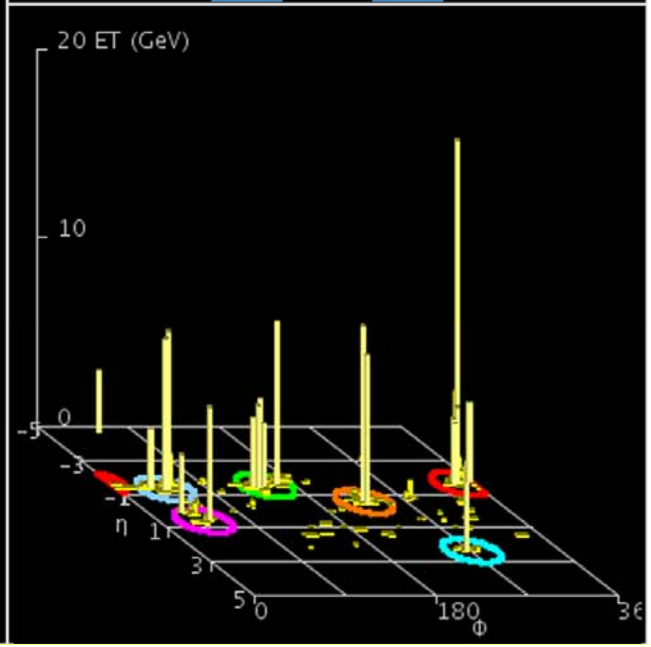


A six-jet event at 7 TeV

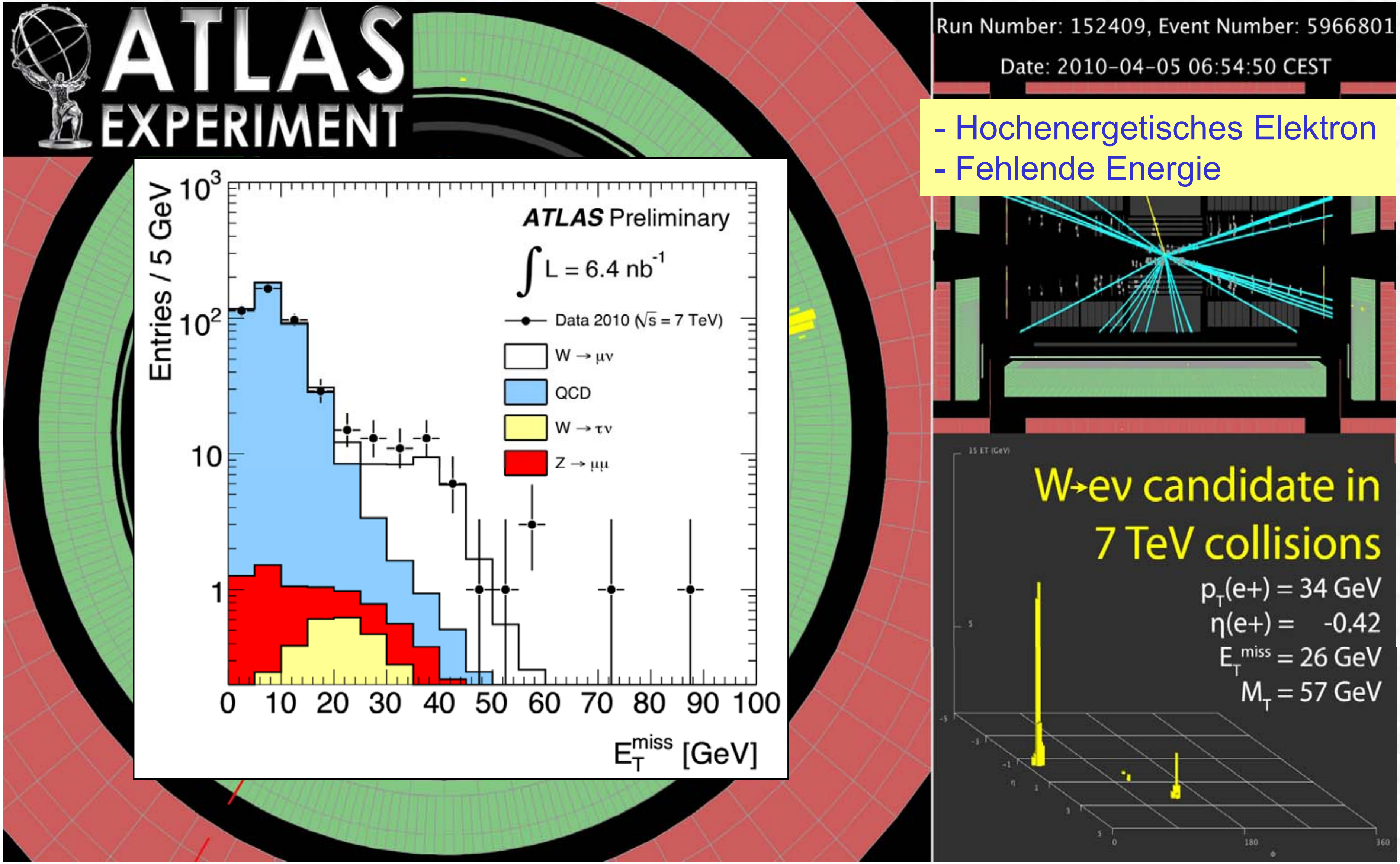


Hochenergetische Jets
(gestreute Quarks, Gluonen
abgestrahlte Gluonen)



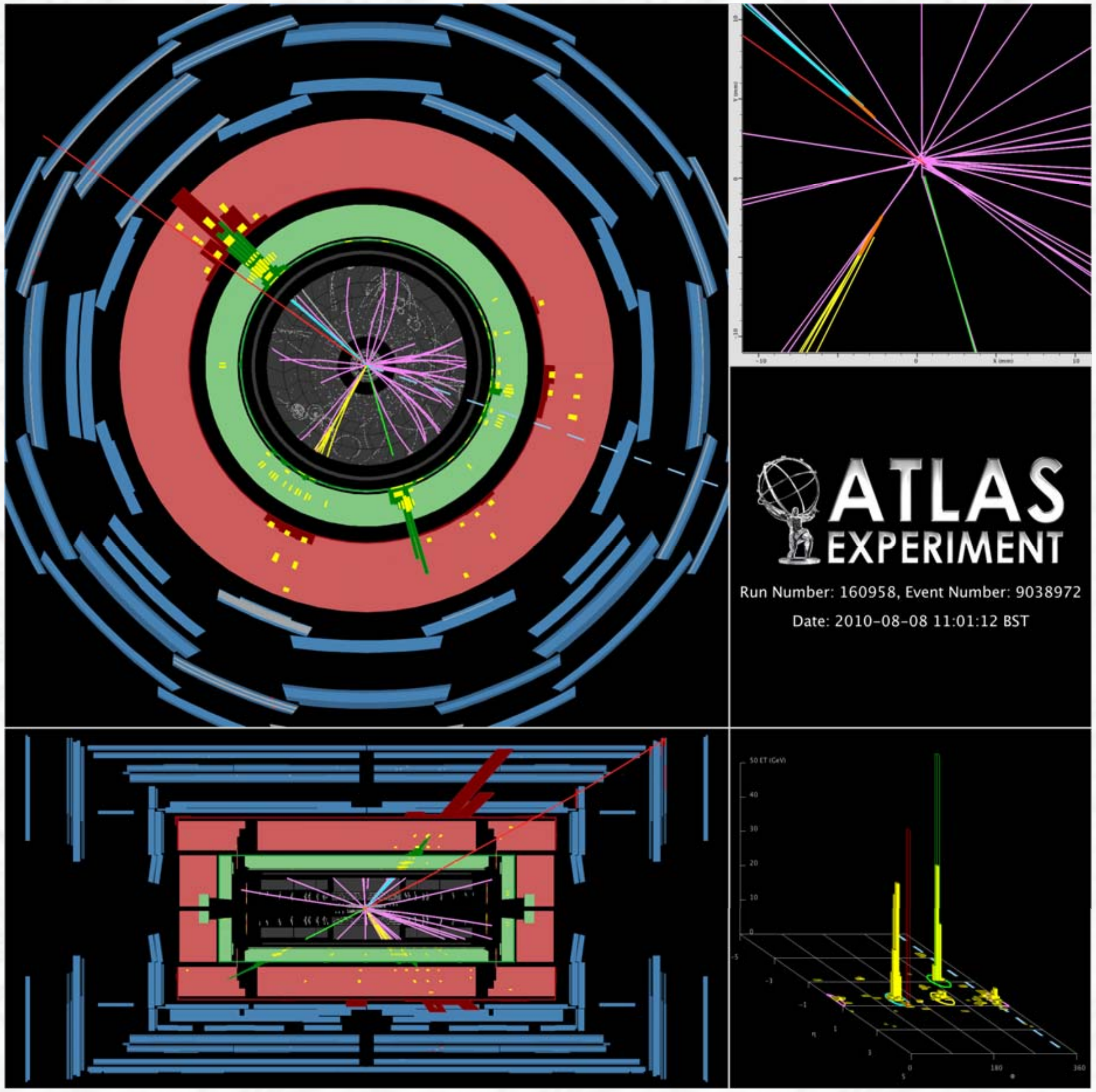


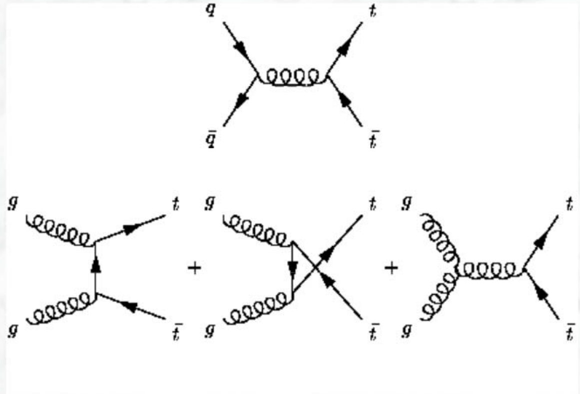
Production of W and Z bosons



- Hochenergetisches Elektron
- Fehlende Energie

Production of the first top quarks in Europe



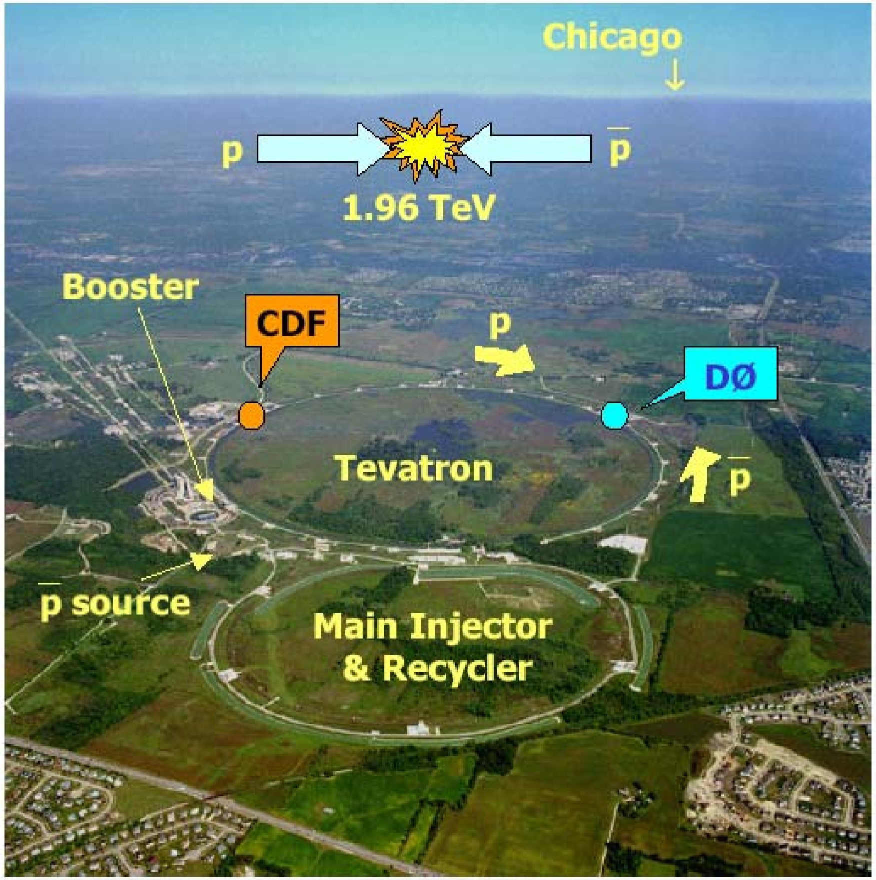


tt → Wb Wb → eνb μνb

The fragmentation products of b-quarks (B-Hadrons) have a life time of 1.5 ps

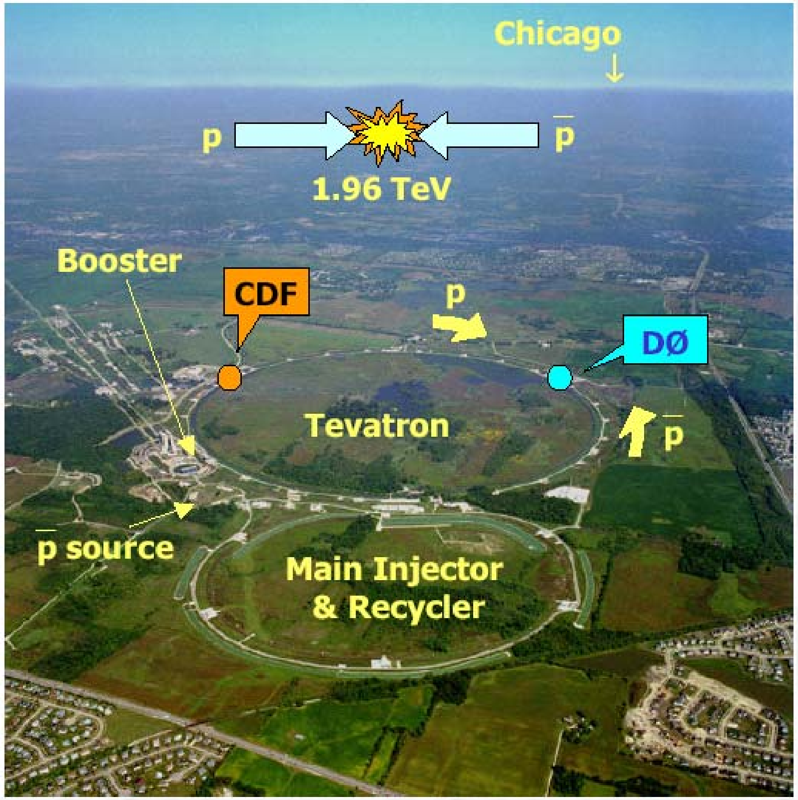
= decay distance of ~2.5 mm

1.4 The Fermilab Tevatron collider



The Tevatron Collider at Fermilab

- <u>Proton antiproton collider</u>
  - 6.5 km circumference
  - Beam energy 0.98 TeV, $\sqrt{s}$ = 1.96 TeV
  - 36 bunches, 396 ns separation (time between crossings)



- 2 Experiments: CDF and DØ

- Main challenges:
  - Antiproton production and storage

    → luminosity, stability of operation

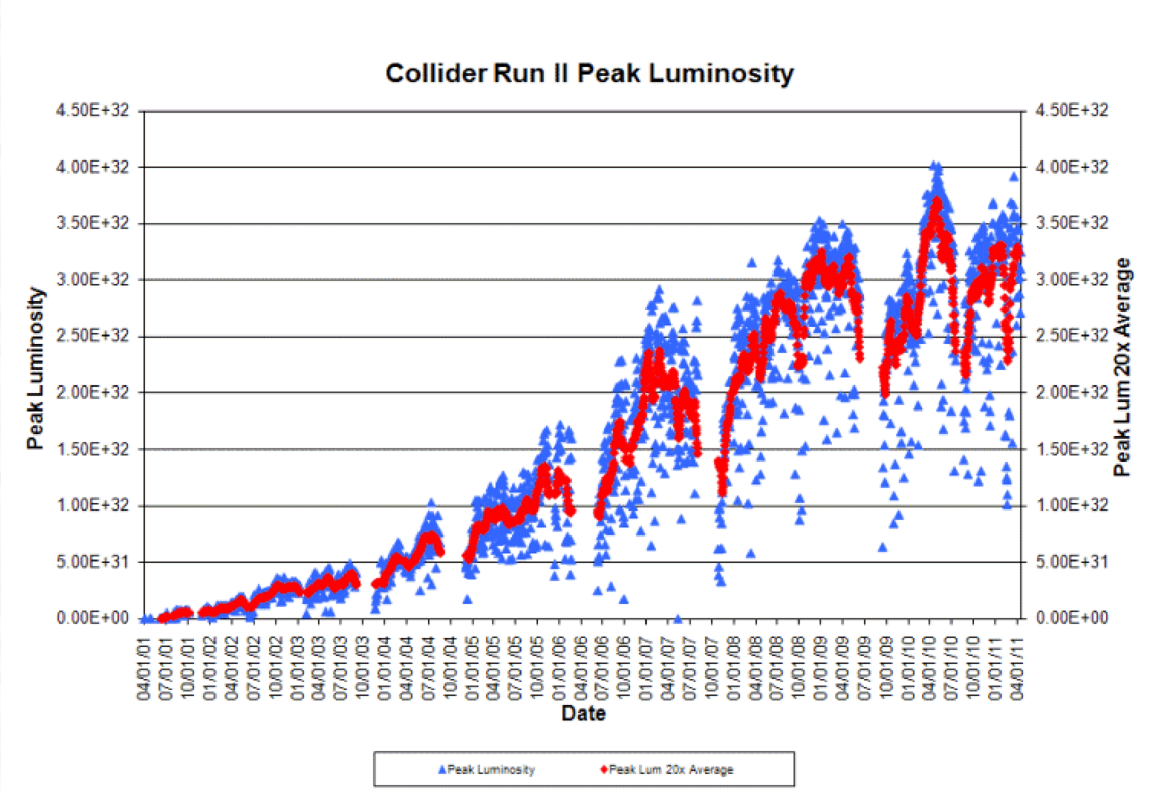
Collider is running in so called Run II (since 2001)

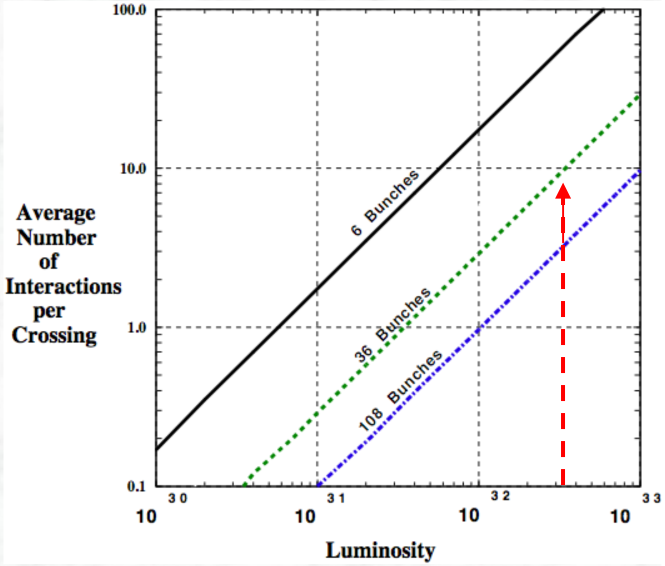
[Run I from 1990 – 1996, int. luminosity: 0.125 fb^{-1}, Top quark discovery]

- **March 2001 – Feb 2006: Run II a, $\int L\,dt$ = 1.2 fb^{-1}**
- **July 2006 - 2011: Run II b, $\int L\,dt$ = 10 -12 fb^{-1}**

Tevatron performance

Peak luminosities of the machine as a function of time

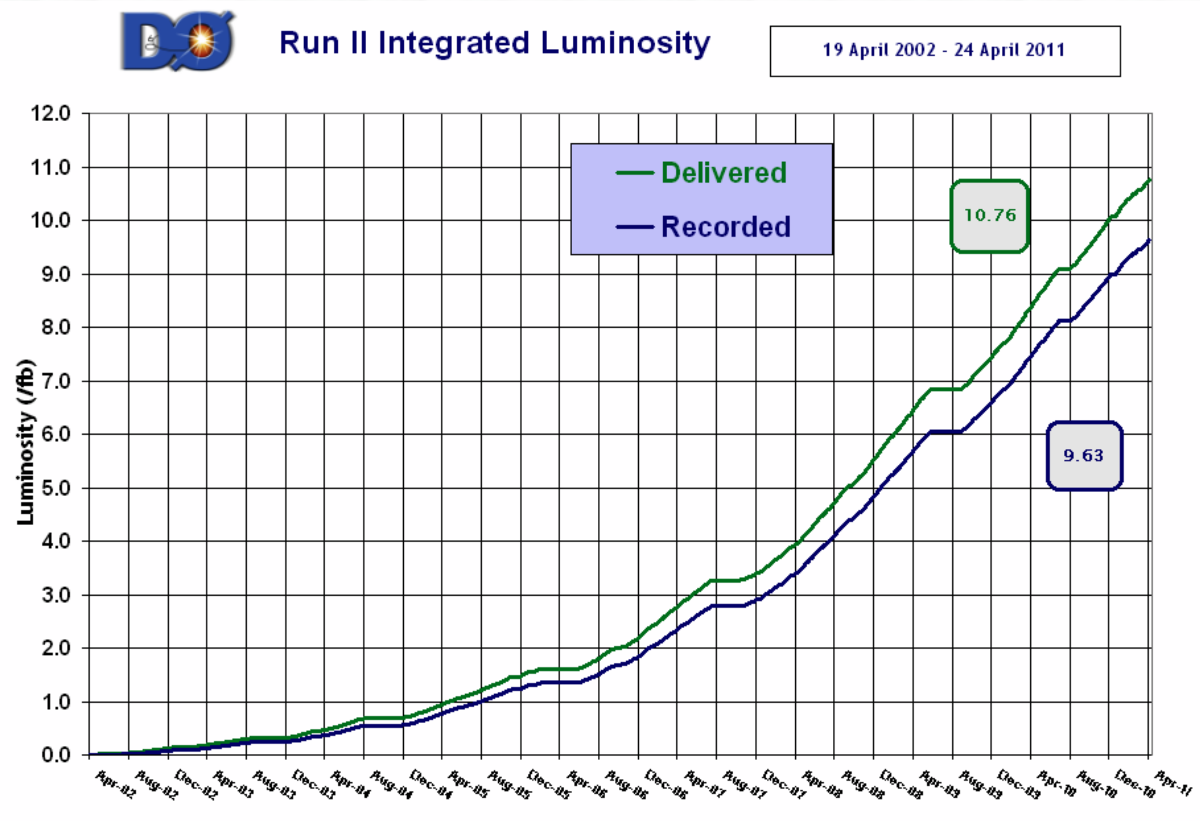




- Peak luminosity of $4 \cdot 10^{32}$ cm^{-2} s^{-1}
- Corresponds to ~10 interactions per bunch crossing
  (superposition of minimum bias events on hard collision)

The integrated Tevatron luminosity (until April 2011)

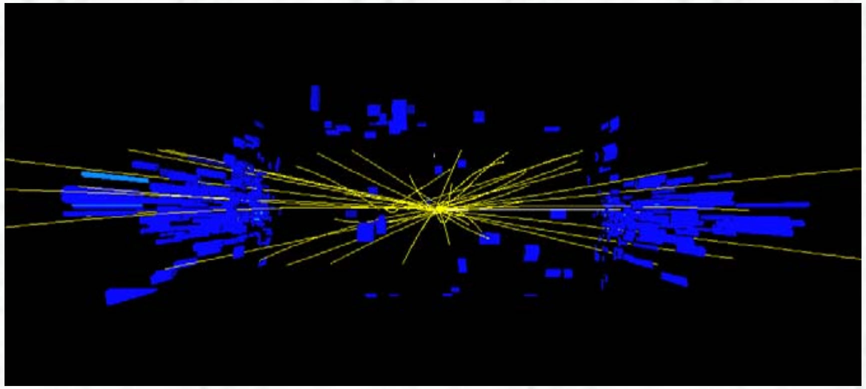
- After a slow start-up (2001 – 2003), the Tevatron accelerator has reached an excellent performance
- Today, Tevatron delivers a data set equal to Run I (~100 pb^{-1}) every 2 weeks
- Integrated luminosity delivered to the experiments so far ~ 10.8 fb^{-1}
- Anticipate an int. luminosity of ~12 fb^{-1} until end of 2011.

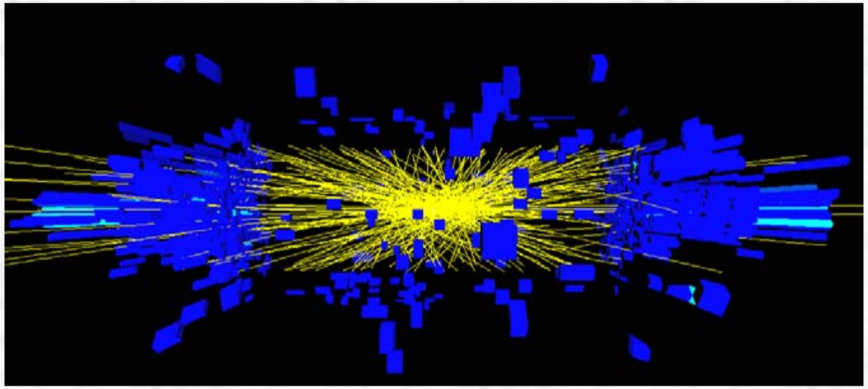


Data corresponding to an int. luminosity of up to ~8 fb^{-1} analyzed…

Challenges with high luminosity

Min. bias pileup at the Tevatron, at $0.6 \cdot 10^{32}$ cm^2s^{-1} ... and at $2.4 \cdot 10^{32}$ cm^2s^{-1}



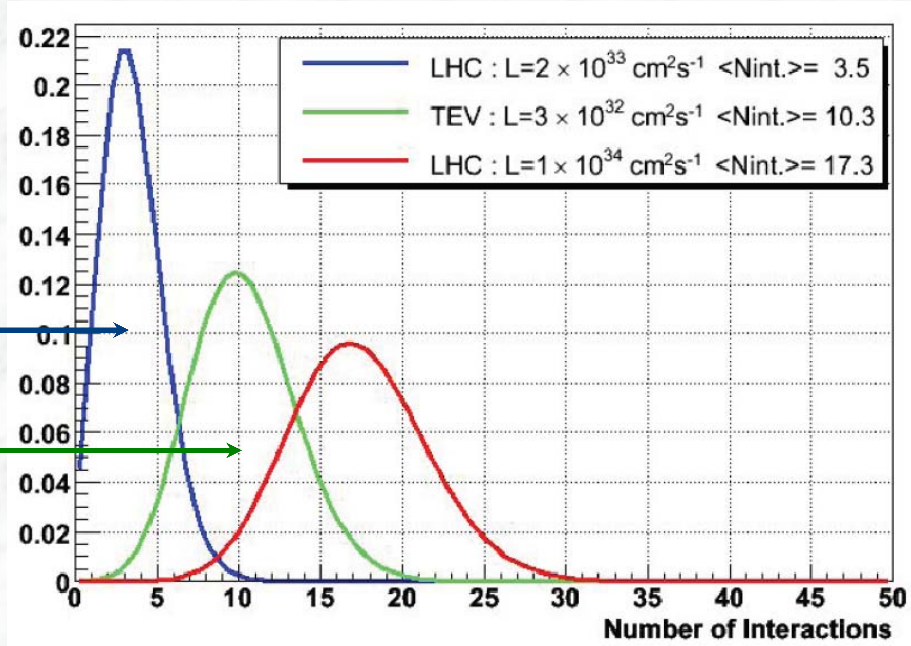


Average number of interactions:

LHC: initial “low” luminosity run

($L=2 \cdot 10^{33}$ cm^2s^{-1}): <N>=3.5

TeV: ($L=3 \cdot 10^{32}$ cm^2s^{-1}): <N>=10



Comparison of the LHC and Tevatron machine parameters

	LHC (design)	**Tevatron (achieved)**
Centre-of-mass energy	**14 TeV**	**1.96 TeV**
Number of bunches	**2808**	**36**
Bunch spacing	**25 ns**	**396 ns**
Energy stored in beam	**360 MJ**	**1 MJ**
Peak Luminosity	**10^{33}-10^{34} $cm^{-2}s^{-1}$**	**3.5×10^{32} $cm^{-2}s^{-1}$**
Integrated Luminosity / year	**10-100 fb^{-1}**	**~ 2 fb^{-1}**

- 7 times more energy (after initial 3.5 TeV phase)
- Factor 3-30 times more luminosity
- Physics cross sections factor 10-100 larger