Particle Accelerators and Experiments

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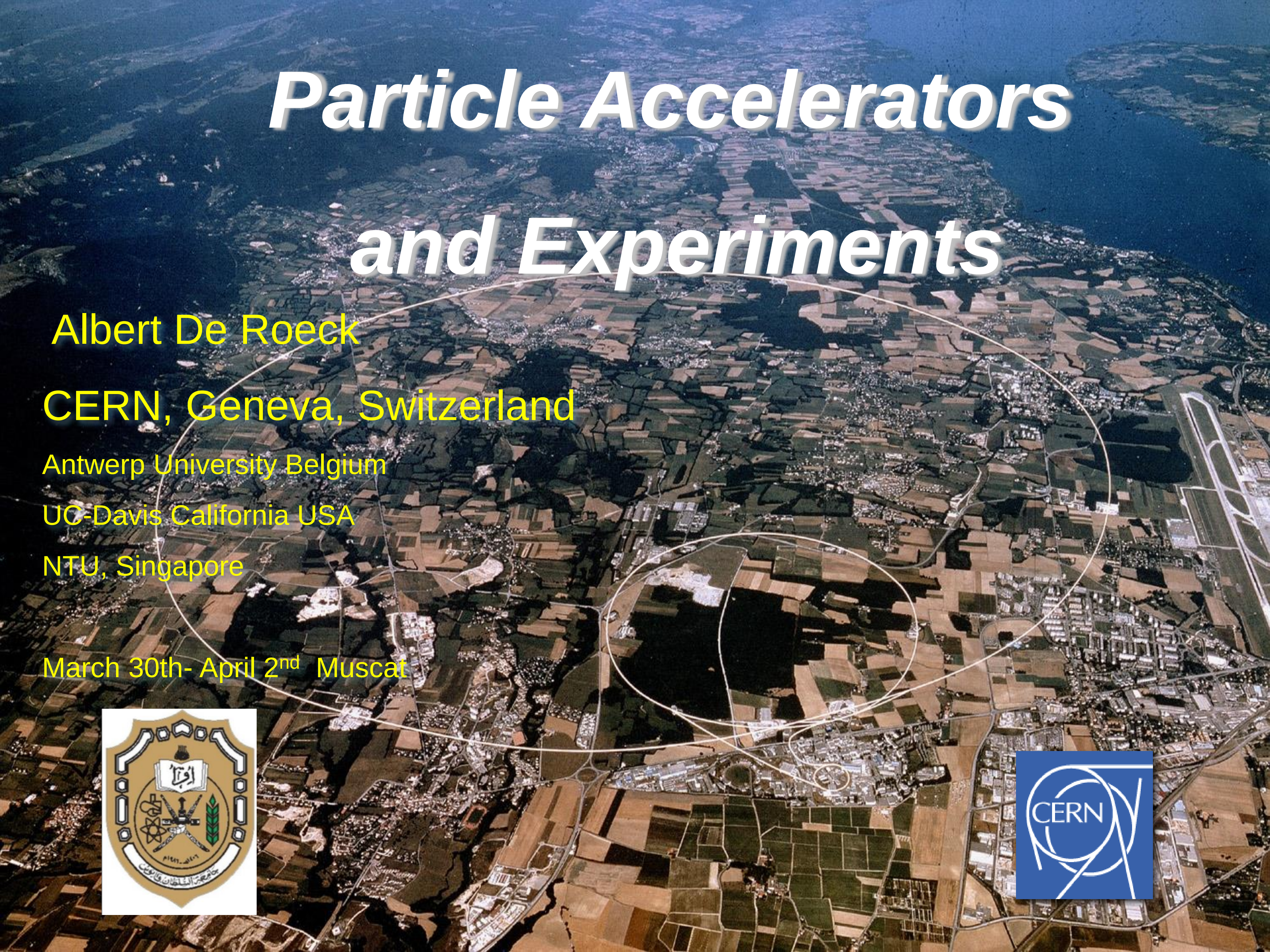
March 30th- April 2^{nd} Muscat

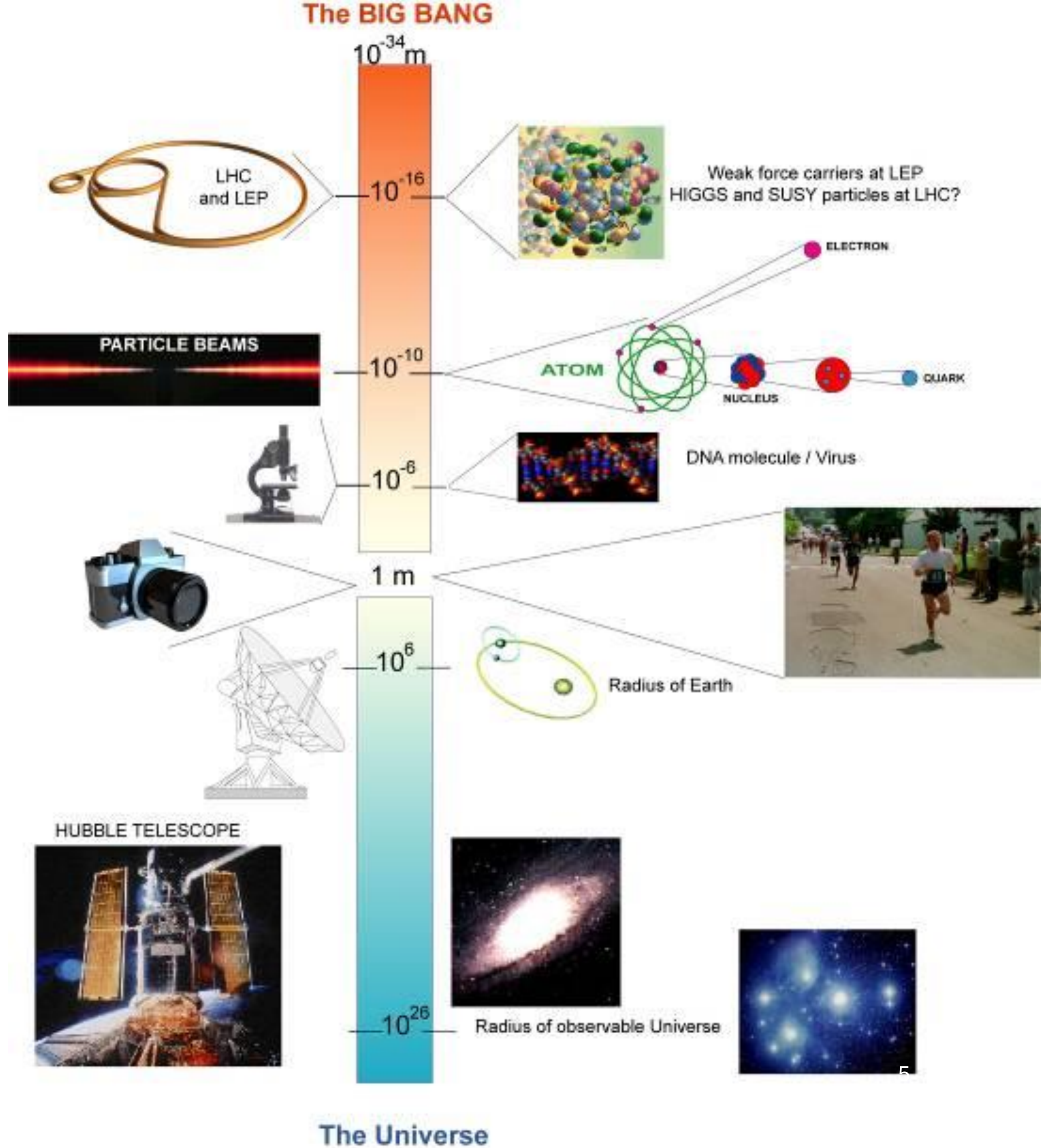


Part I

Accelerators

Different types of tools and equipment are needed to observe different sizes of object

Only particle accelerators can explore the tiniest objects in the Universe



Accelerators are Powerful Microscopes

They make high energy particle beams

that allow us to see small things.

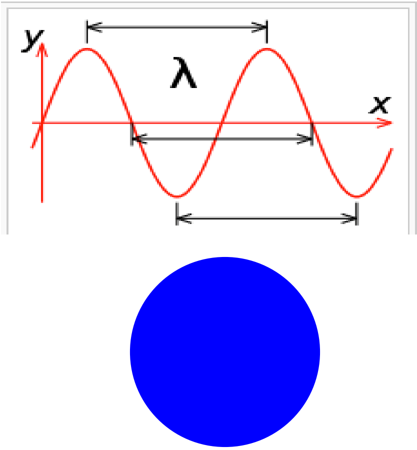
$$\lambda = \frac{h}{p}$$

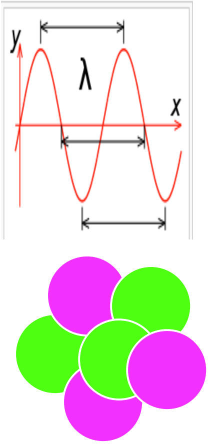
Planck constant

wavelength

momentum

~ energy





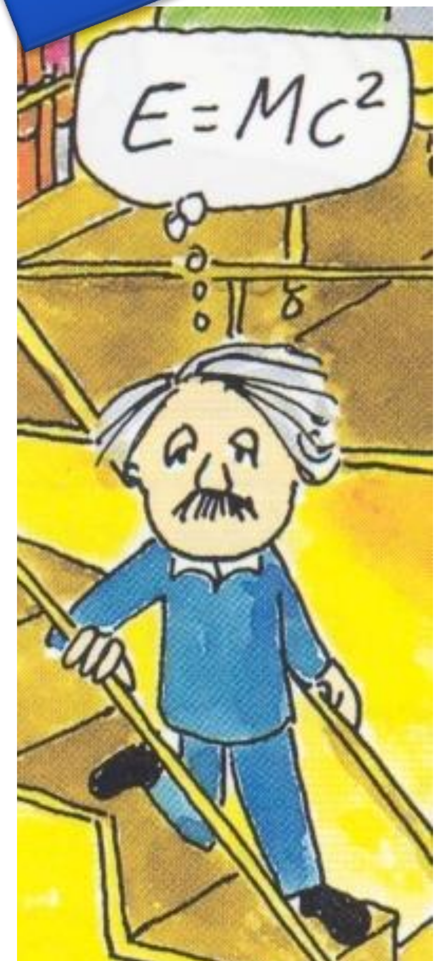
seen by low energy beam of particles

(poorer resolution)

seen by high energy beam of particles

(better resolution)

We can create particles from energy

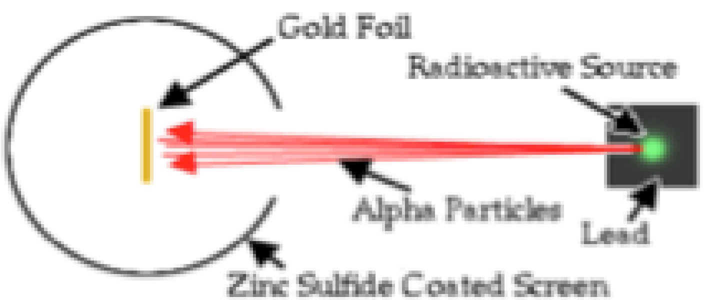


- Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.
- Produce particles that may have existed at the beginning of the Universe, right after the Big Bang

High Energy Physics Experiments

First High Energy Physics Experiments:

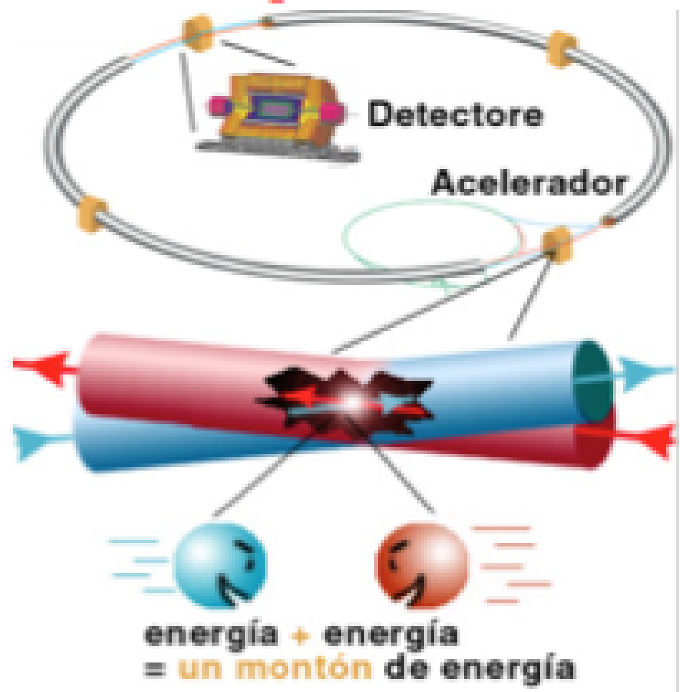
Beam on fixed target!



Rutherford experiment (1909)

High Energy Physics Experiments since mid 70's:

Colliding beams!

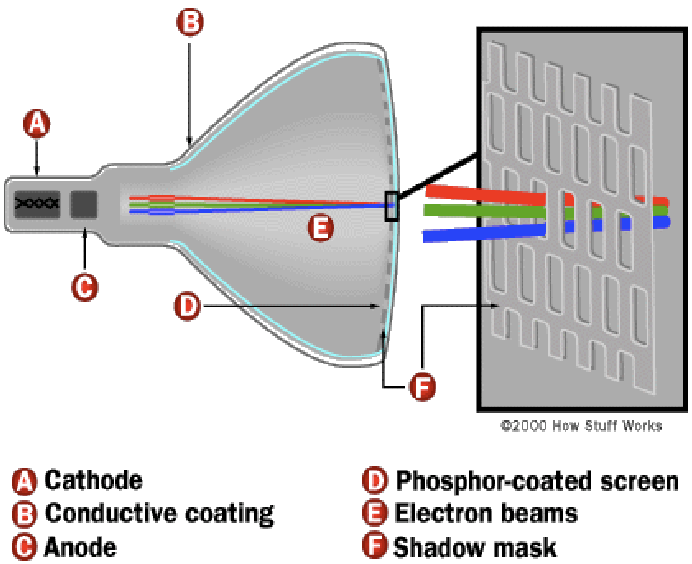


Centre of mass energy squared $s=E_1m_2$

Centre of mass energy squared $s=4E_1E_2$

Detectors techniques have followed these developments

Accelerators for Charged Particles



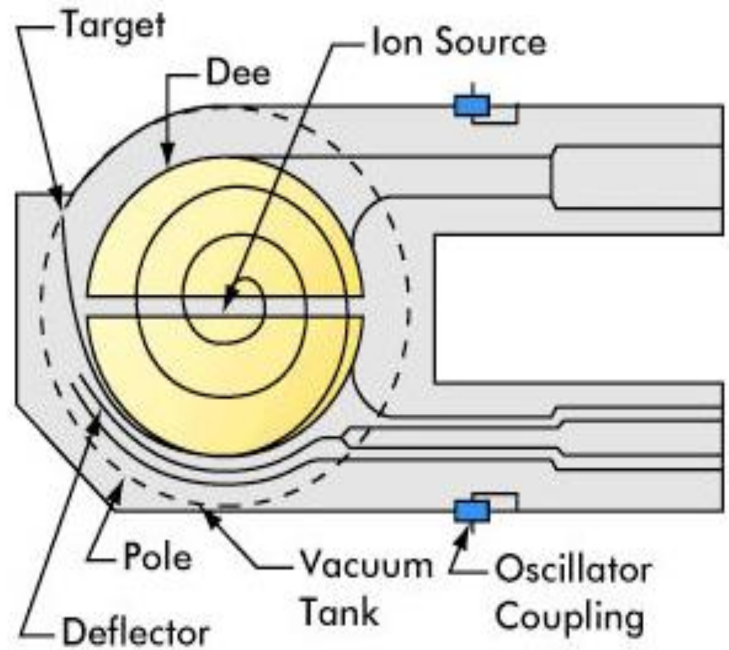
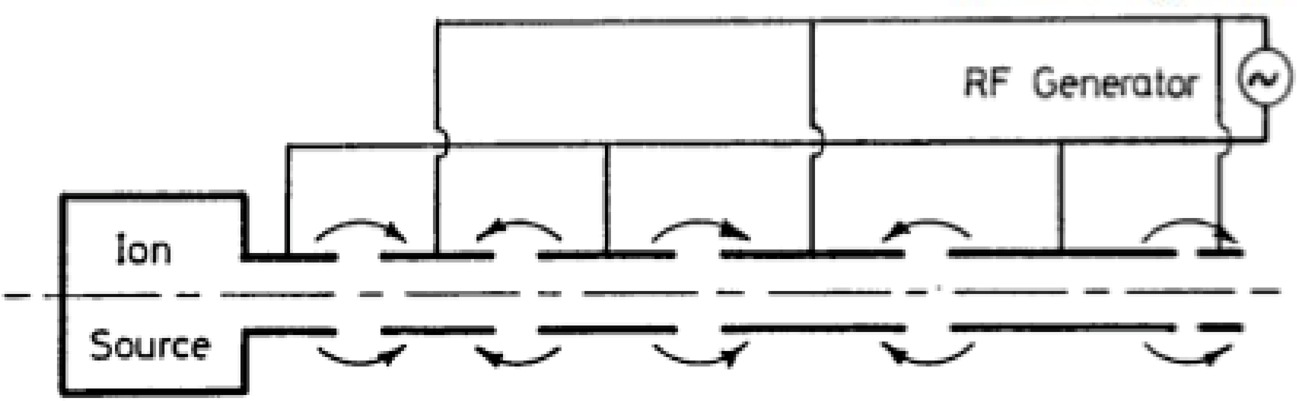


Photo courtesy SLAC

Schematic diagram of a cyclotron



Recent High Energy Colliders

Highest energies can be reached with proton colliders

Machine	Year	Beams	Energy ($\sqrt{s}$)	Luminosity
SPPS (CERN)	1981	pp	630-900 GeV	$6.10^{30} cm^{-2}s^{-1}$
Tevatron (FNAL)	1987	pp	1800-2000 GeV	10^{31}-$10^{32} cm^{-2}s^{-1}$
SLC (SLAC)	1989	e^+e^-	90 GeV	$10^{30} cm^{-2}s^{-1}$
LEP (CERN)	1989	e^+e^-	90-200 GeV	10^{31}-$10^{32} cm^{-2}s^{-1}$
HERA (DESY)	1992	ep	300 GeV	10^{31}-$10^{32} cm^{-2}s^{-1}$
RHIC (BNL)	2000	pp / AA	200-500 GeV	$10^{32} cm^{-2}s^{-1}$
LHC (CERN)	2009	pp (AA)	7-14 TeV	10^{33}-$10^{34} cm^{-2}s^{-1}$

Luminosity = number of events/cross section/sec

- Limits on circular machines
  - Proton colliders: Dipole magnet strength $\rightarrow$superconducting magnets
  - Electron colliders: Synchrotron radiation/RF power: loss $\sim E^4/R^2$

How Many Accelerators Worldwide?

a) 1-10

b) 10-100

c) 100-1,000

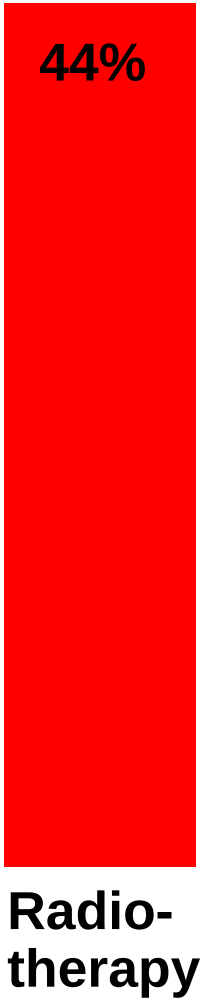
d) 1,000-10,000

e) > 10,000

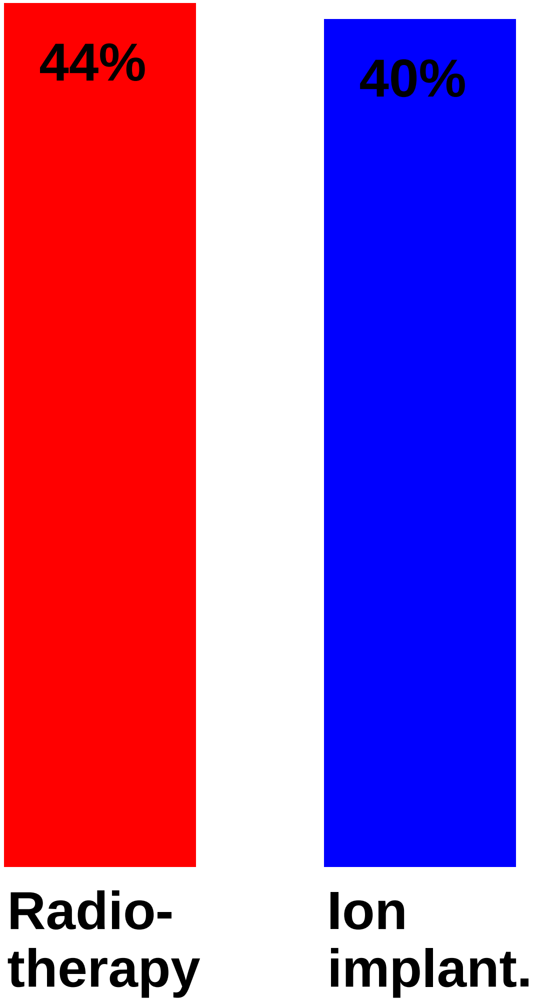
Accelerators Worldwide

> 25,000 accelerators in use

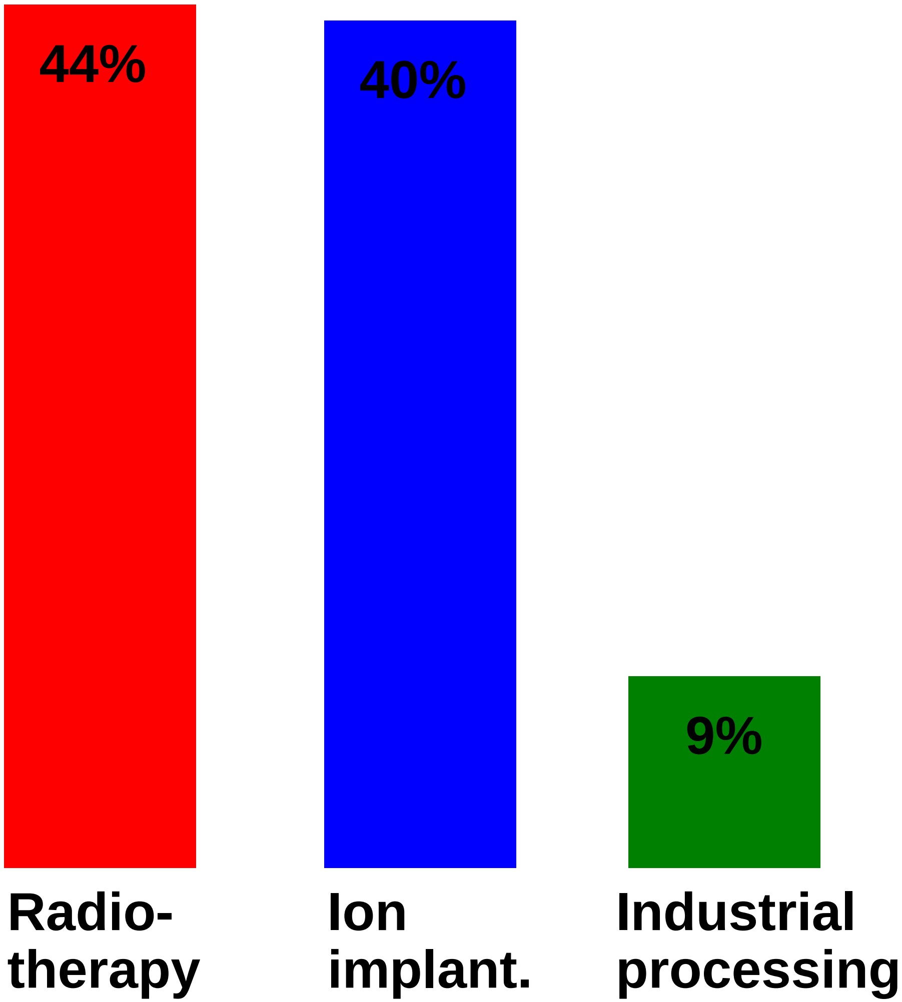
Accelerators Worldwide



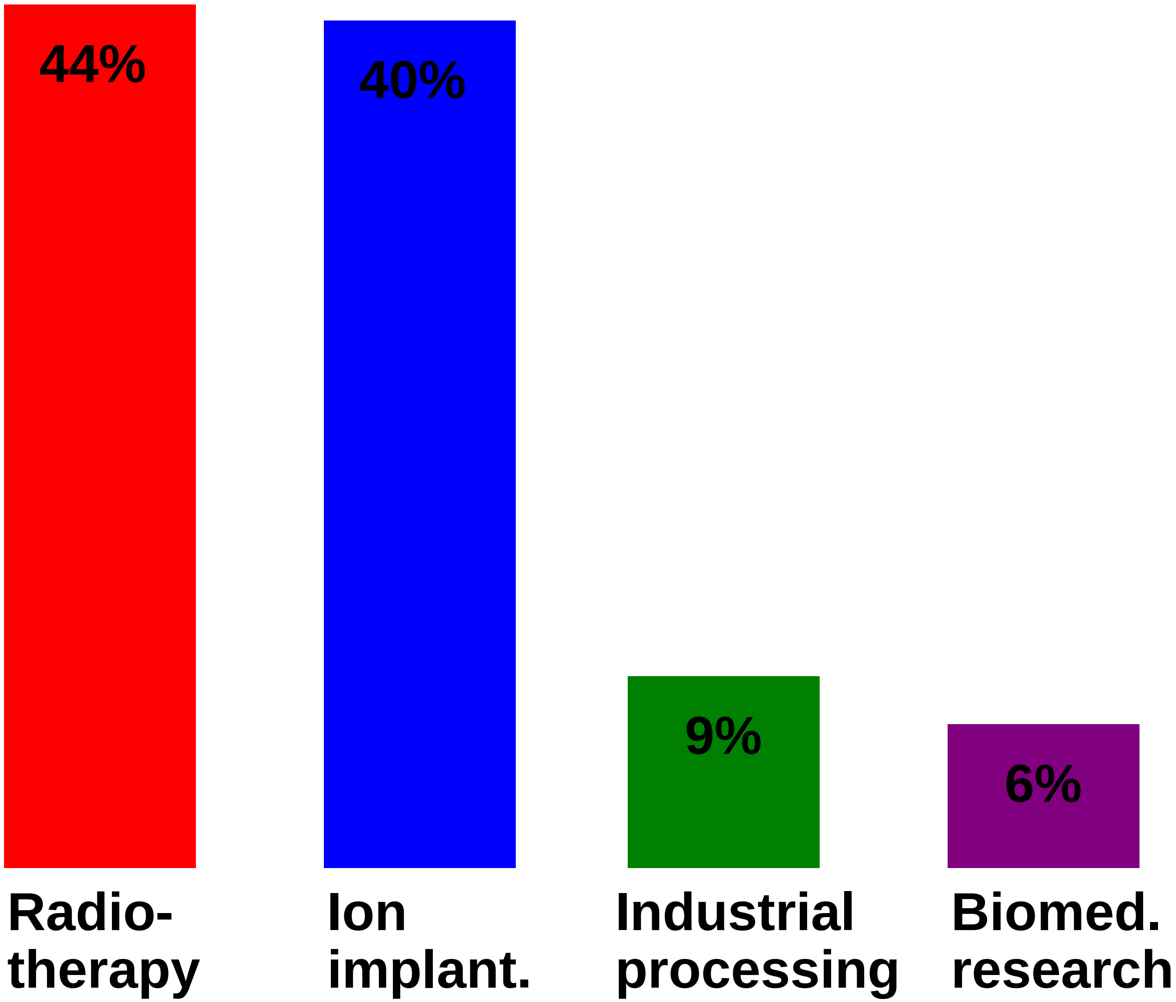
Accelerators Worldwide



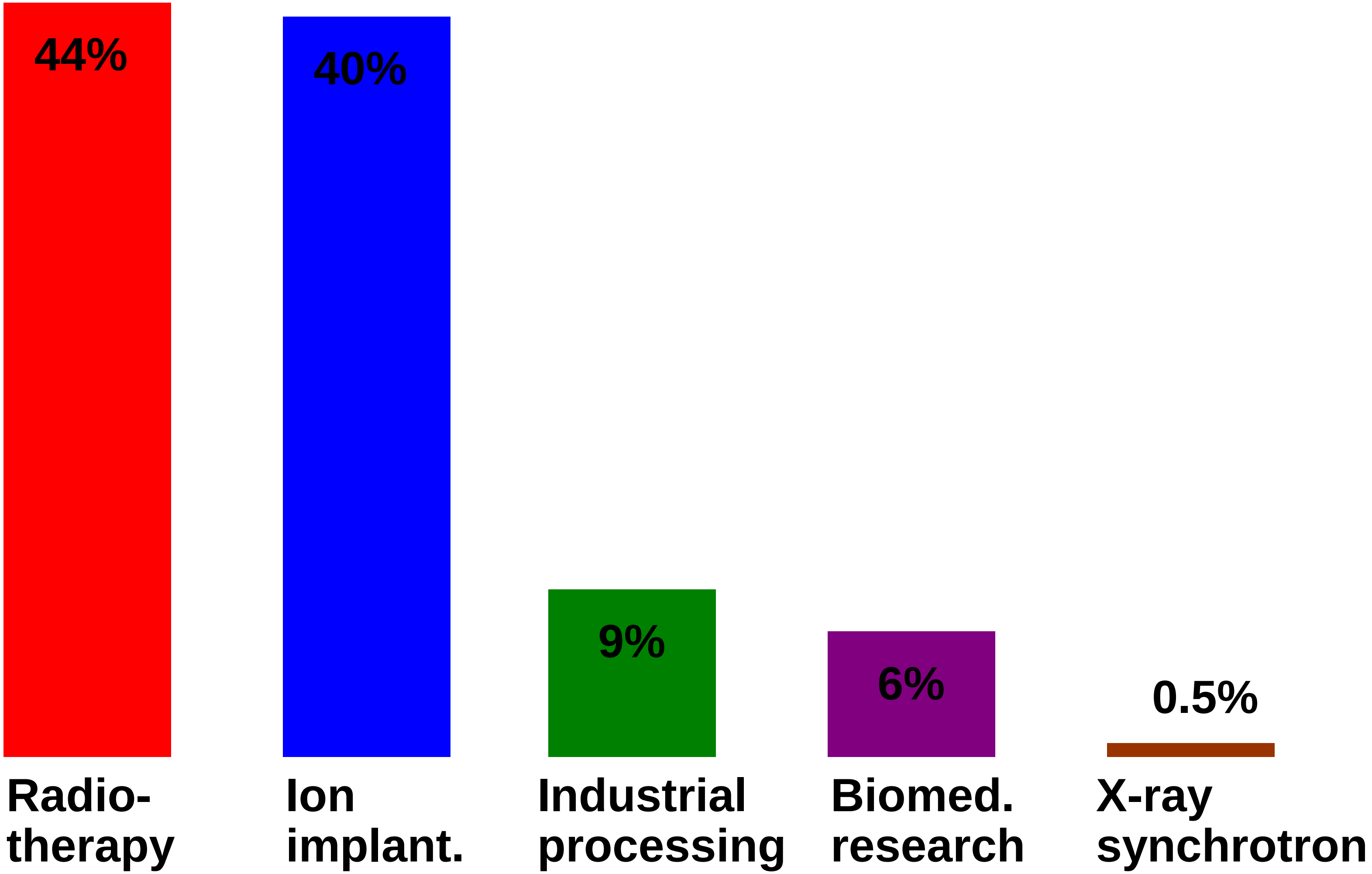
Accelerators Worldwide



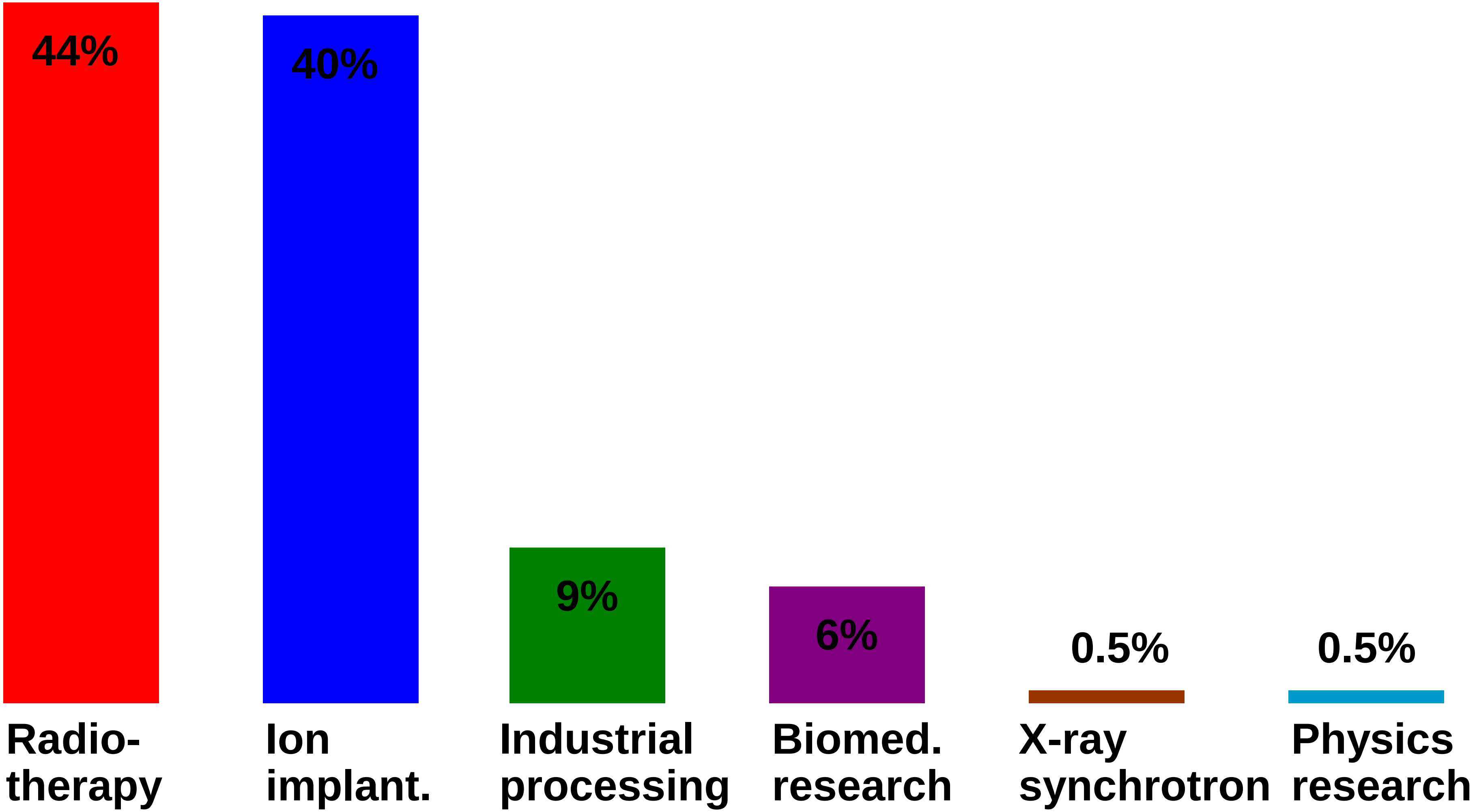
Accelerators Worldwide



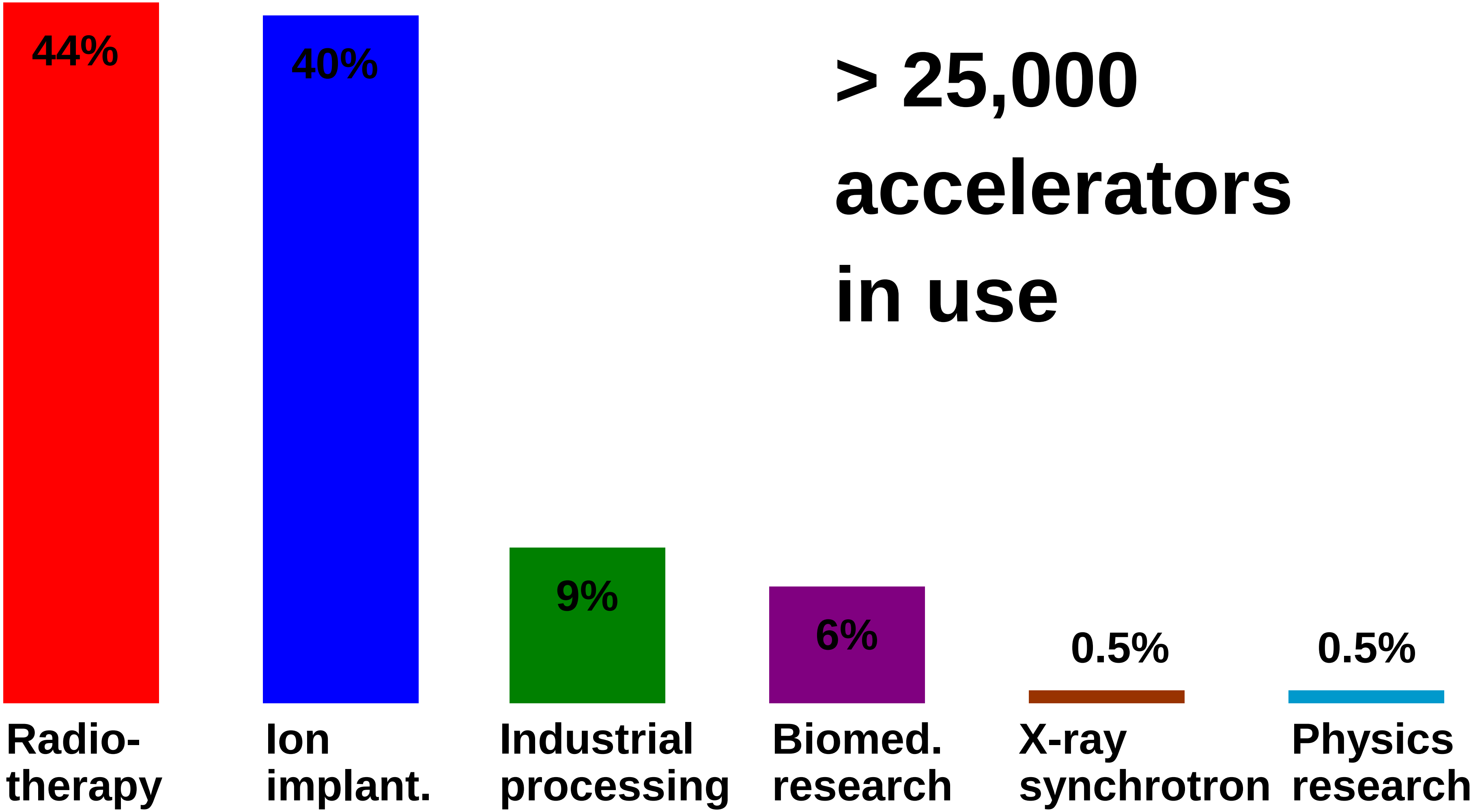
Accelerators Worldwide



Accelerators Worldwide



Accelerators Worldwide



> 25,000 accelerators in use

Scientific importance of accelerators

- **30% of physics Nobel Prizes awarded for work based on accelerators**

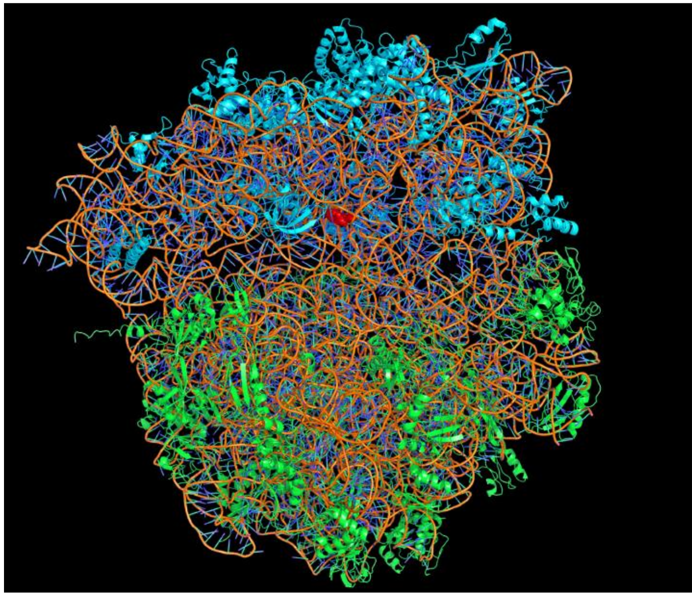
- **Increasing number of non-physics Nobel Prizes being awarded for work reliant on accelerators!**

2009 Chemistry Nobel Prize

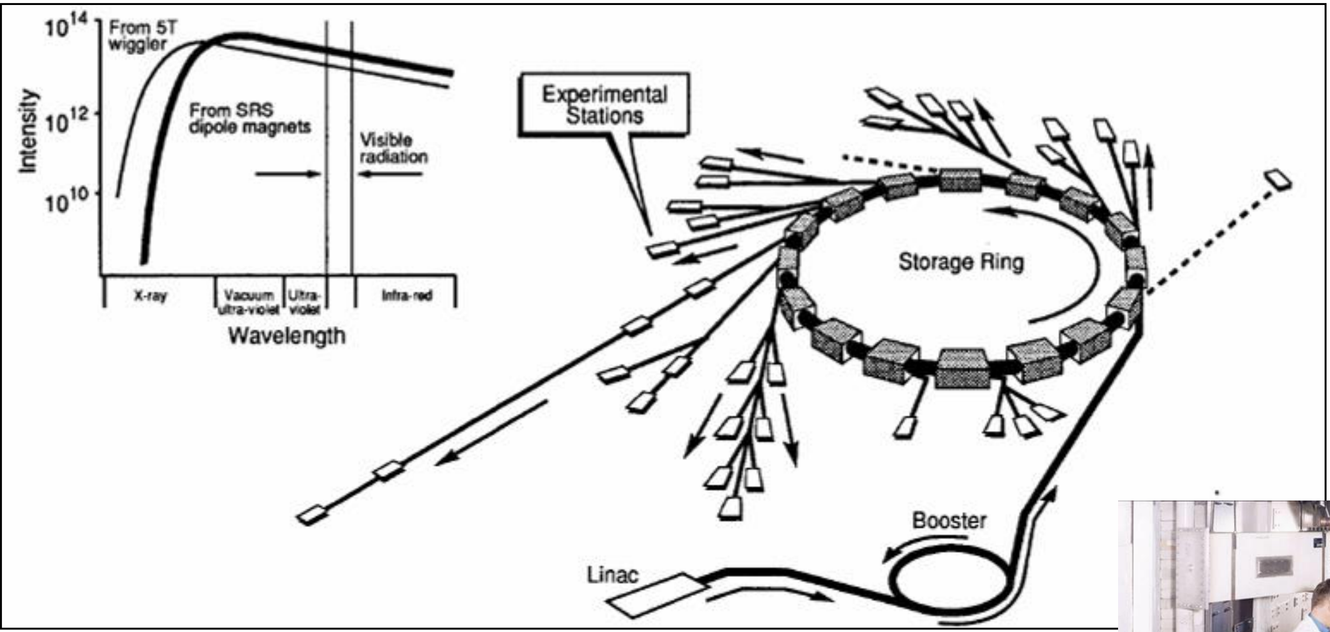
Ramakrishnan, Steitz, Yonath

‘studies of the structure and function of the ribosome’



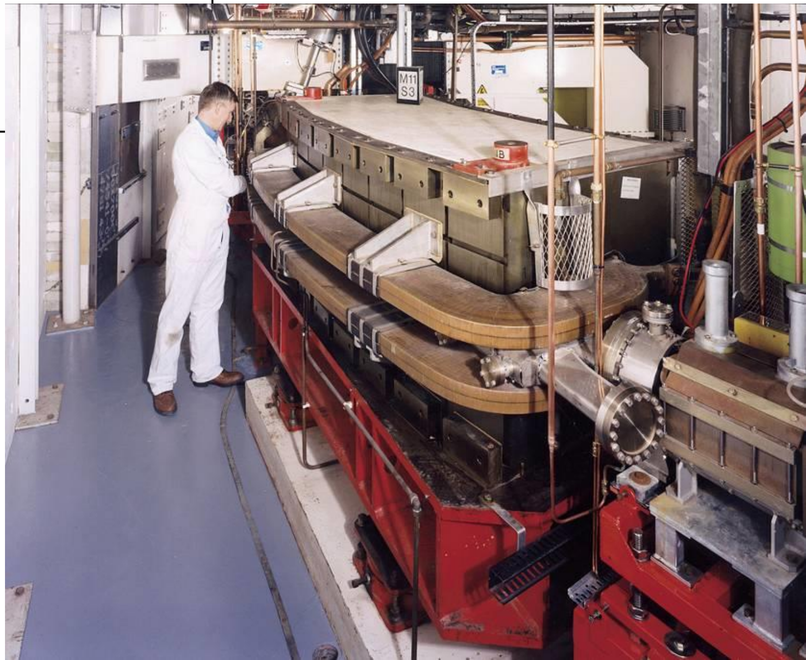



Accelerator X-ray sources



SRS

Daresbury, UK



Wavelength and momentum

- **Relationship between wavelength and momentum:**

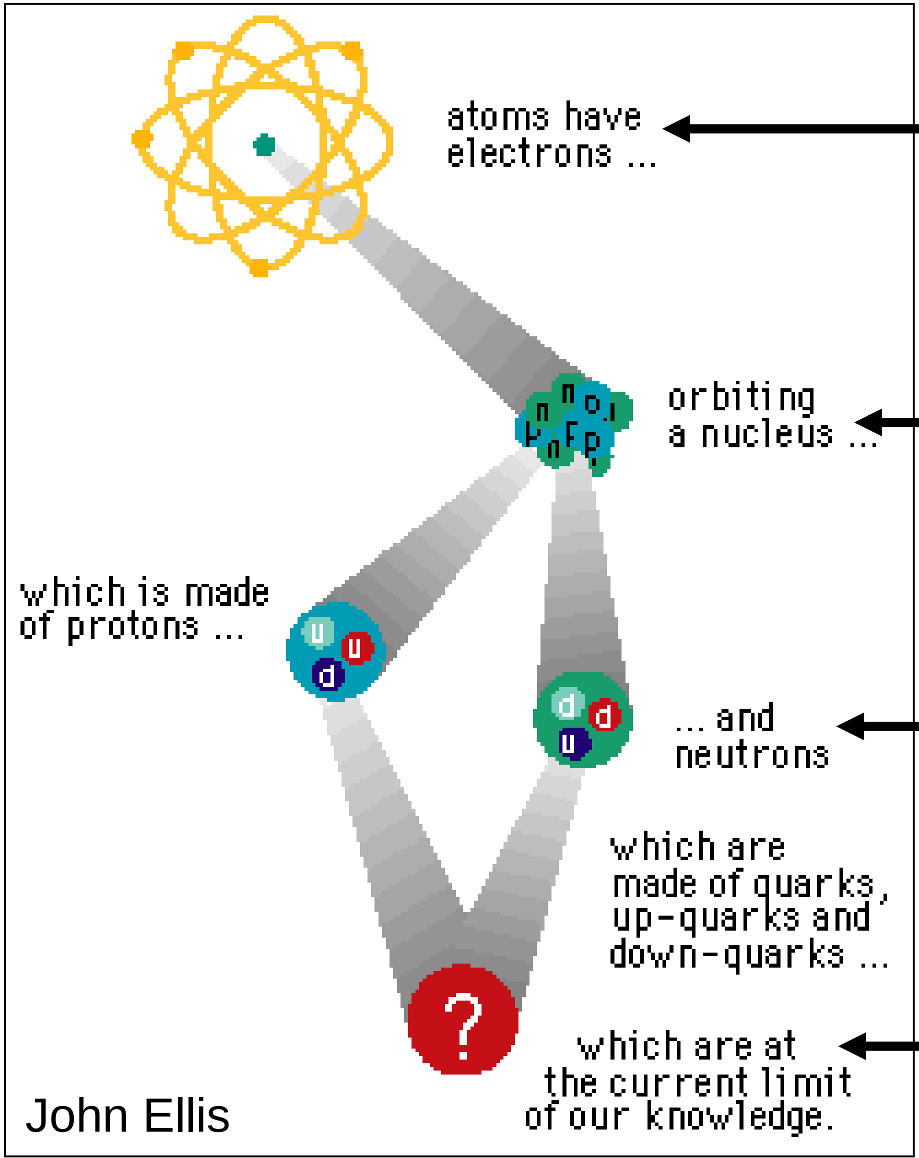
  wavelength* = *h*/*p **(de Broglie, 1924)**

  ***h* = Planck's constant = 6.63 x 10 $^{-34}$ Js**

  wavelength ~ 10 $^{-7}$ / *p* [eV]

p [eV]		*wavelength* [m]	probe:
1		10 $^{-7}$	light
10 ^{3}	(keV)	10 $^{-10}$	X-rays, neutrons
10 ^{6}	(MeV)	10 $^{-13}$	gamma rays
10 ^{9}	(GeV)	10 $^{-16}$	electrons
10 ^{12}	(TeV)	10 $^{-19}$	protons

Structure of matter



keV

MeV

GeV

TeV

Tour of some Accelerators

Beijing Electron Synchrotron (1 GeV)

Diamond Light Source (UK) (3 GeV)

Cornell Electron Storage Ring (5 GeV)

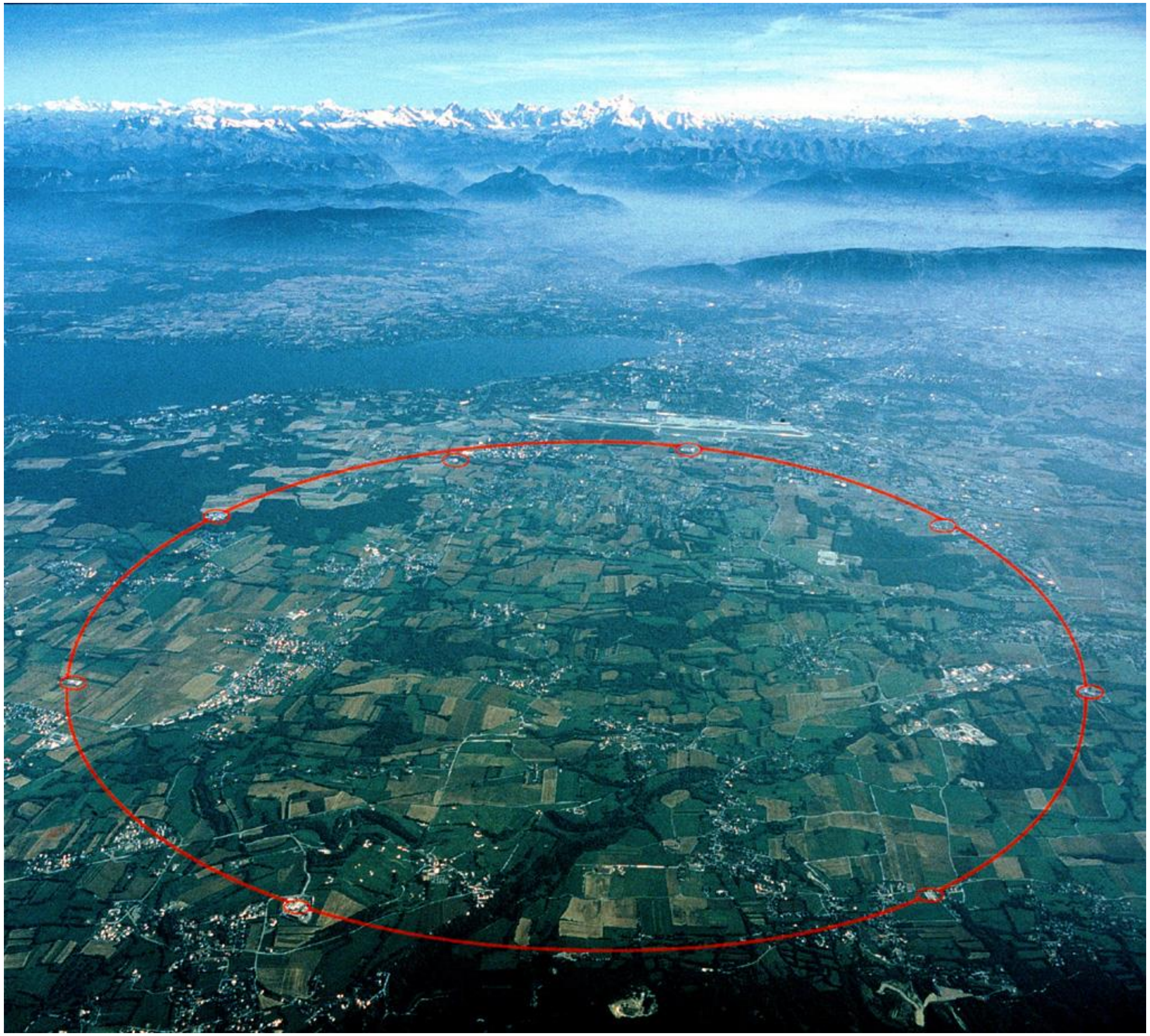
KEK-B (Japan) (8 GeV)

HERA (Hamburg) (30/820 GeV)

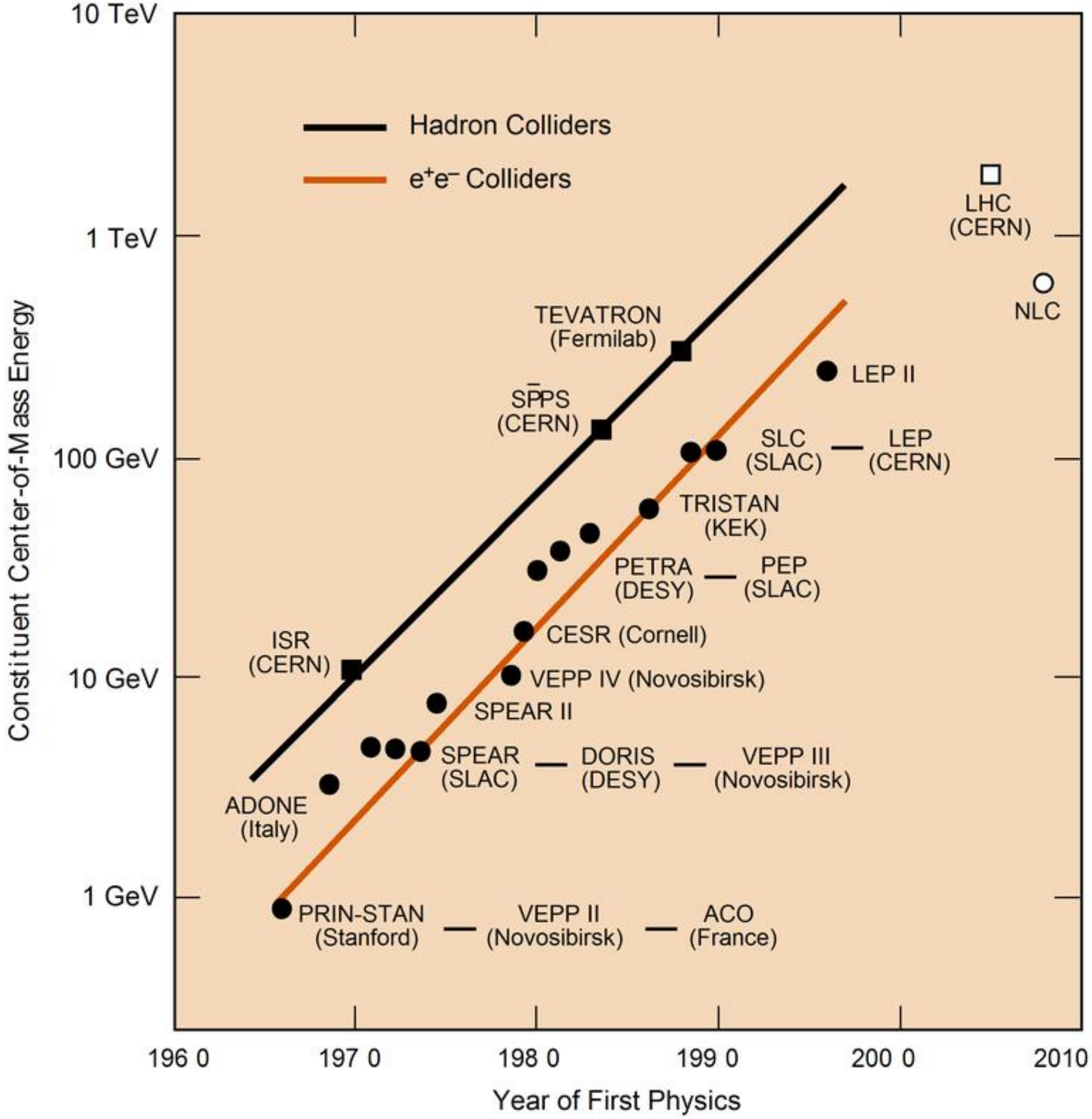
Tevatron (Fermilab) (1 TeV)

SLAC Linear Collider (50 GeV)

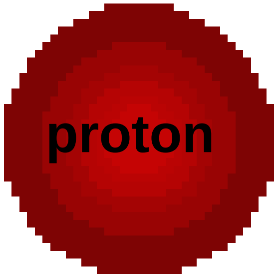
Large Electron-Positron Collider (LEP) (100 GeV)
Large Hadron Collider (LHC) (7 TeV)



Development of accelerators



How to accelerate particles to high energies?



protons and electrons carry electric CHARGE

→ feel electric force

Accelerating protons

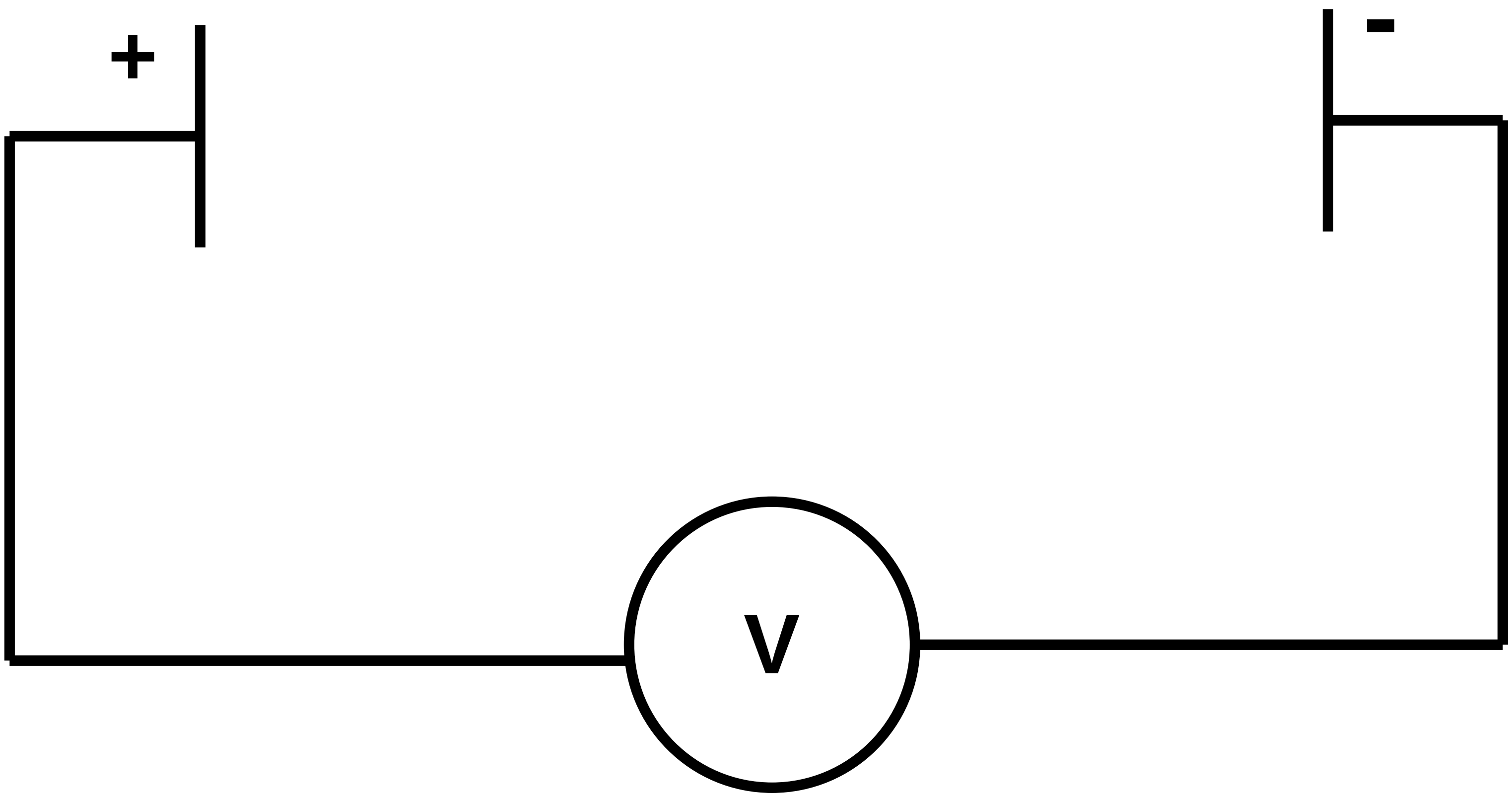
Apply an electric field → accelerate!

Accelerating protons

Apply an electric field → accelerate!

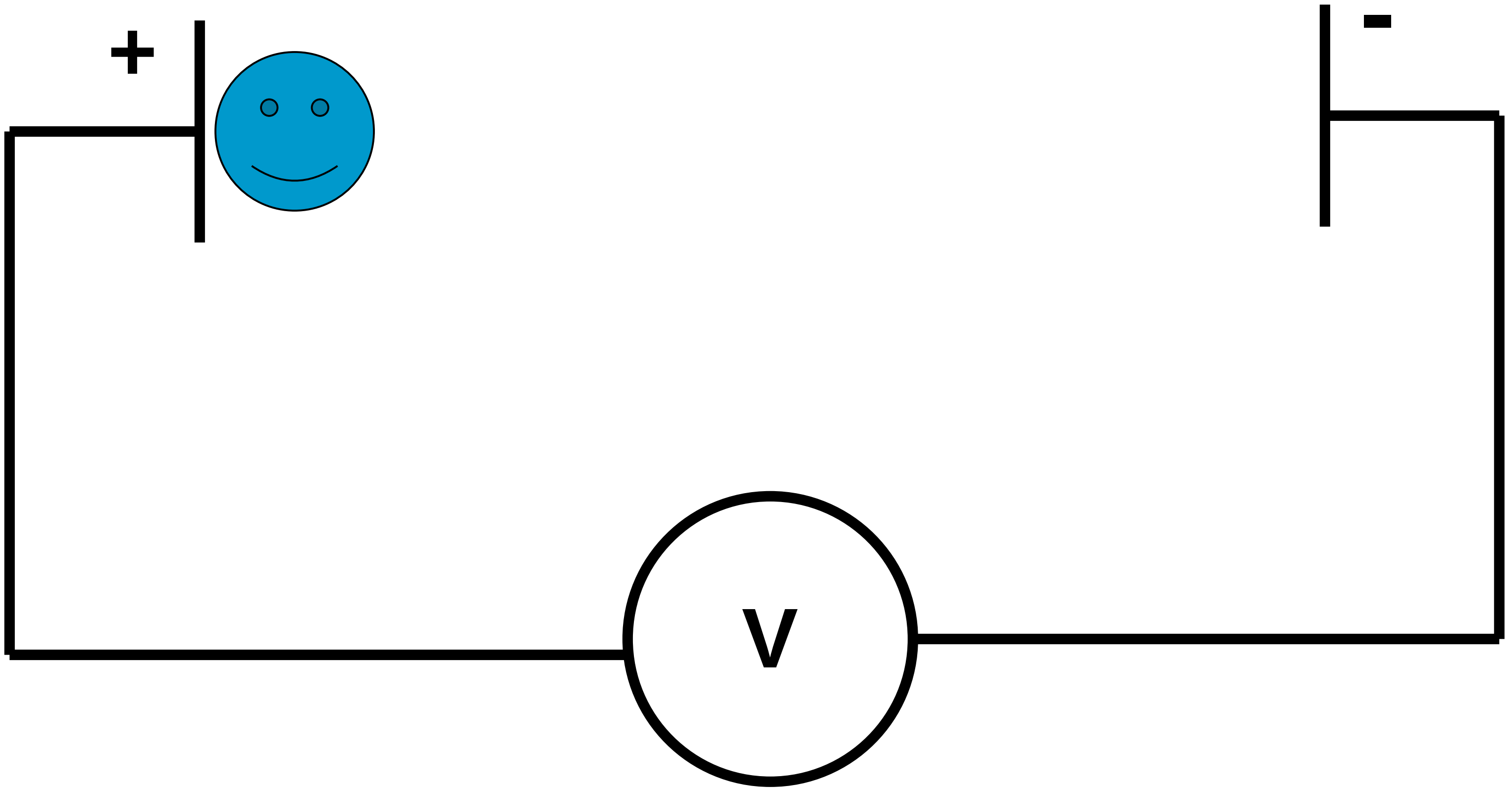
Accelerating protons

Apply an electric field → accelerate!



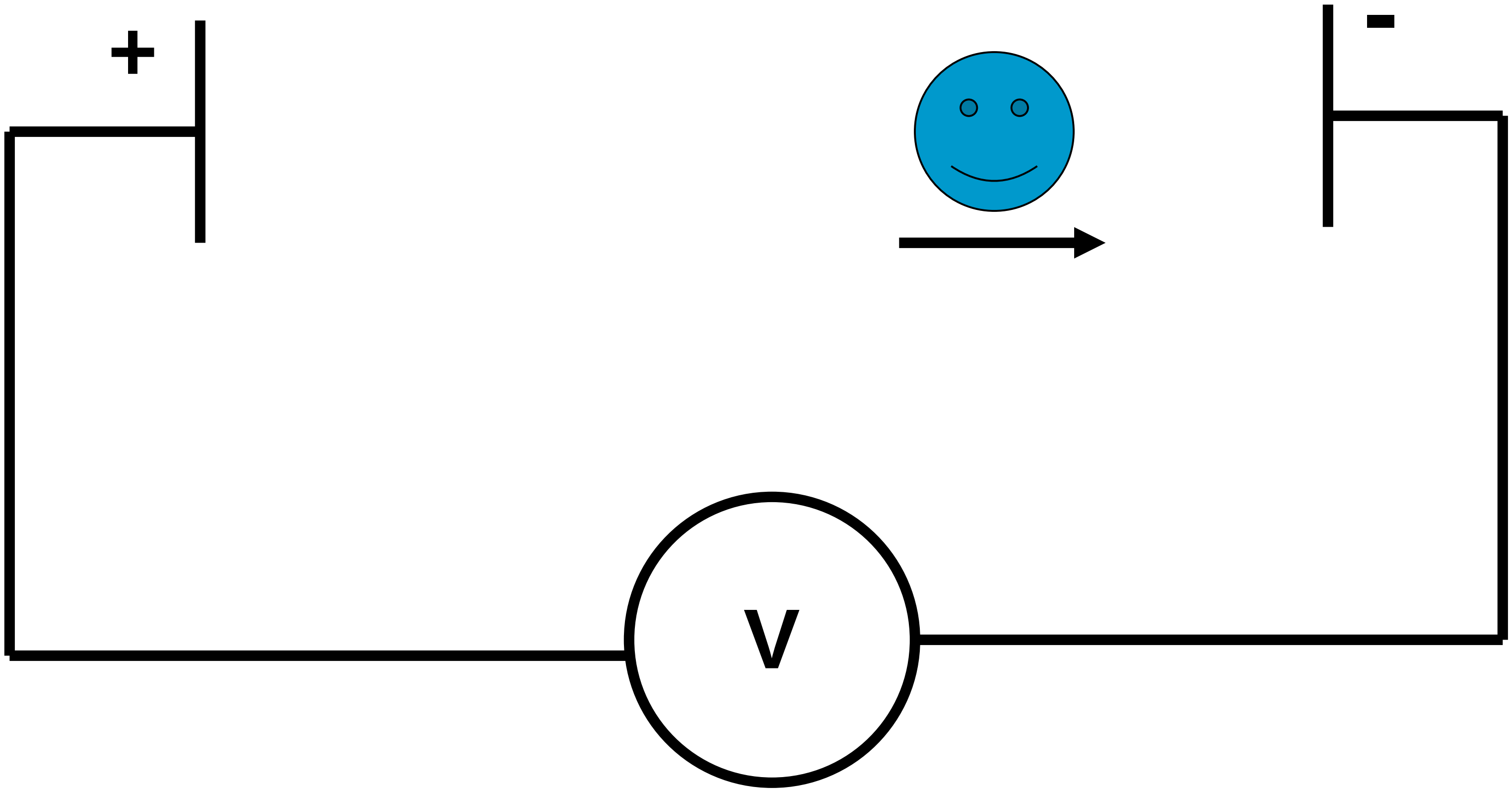
Accelerating protons

Apply an electric field → accelerate!

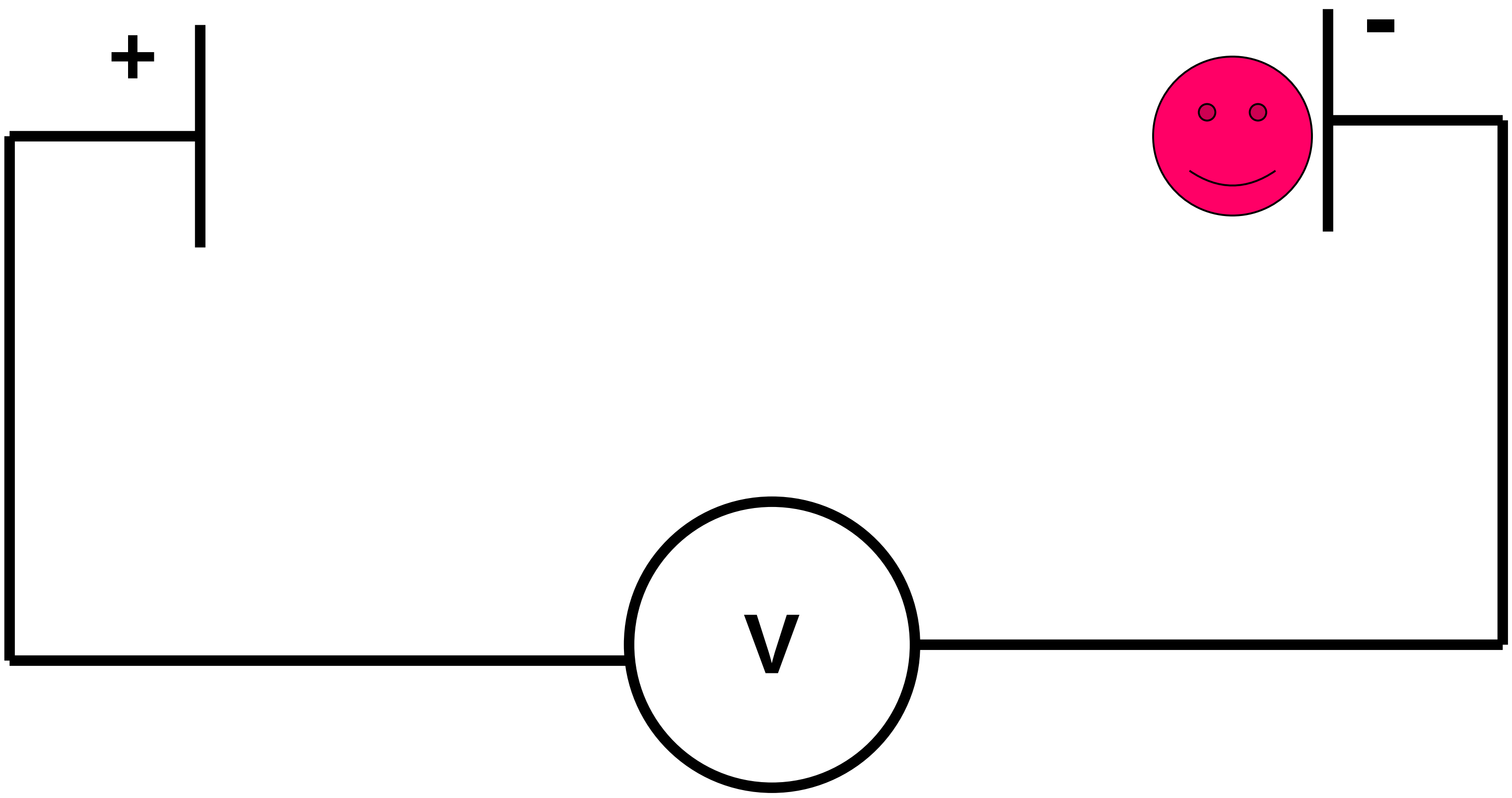


Accelerating protons

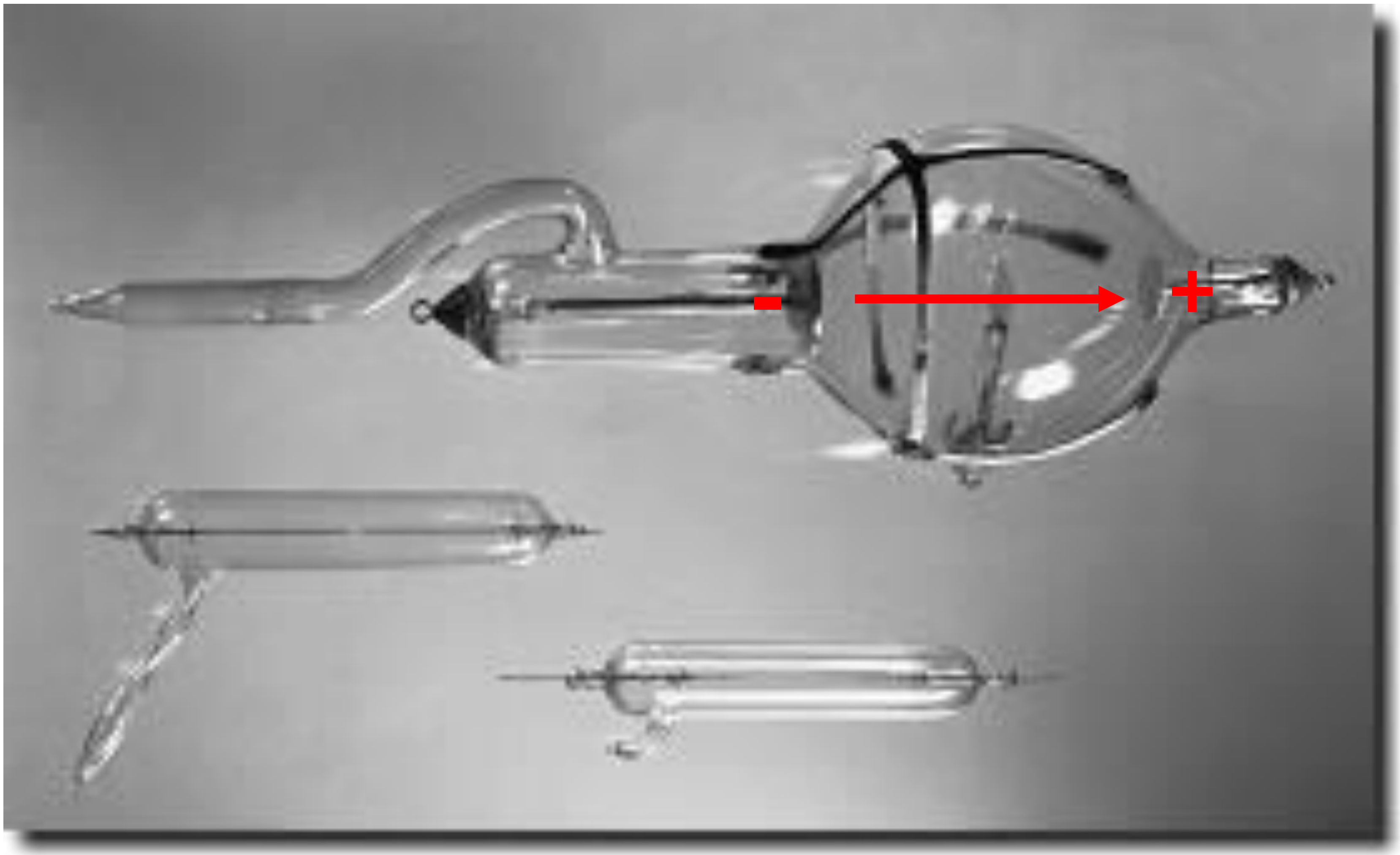
Apply an electric field → accelerate!



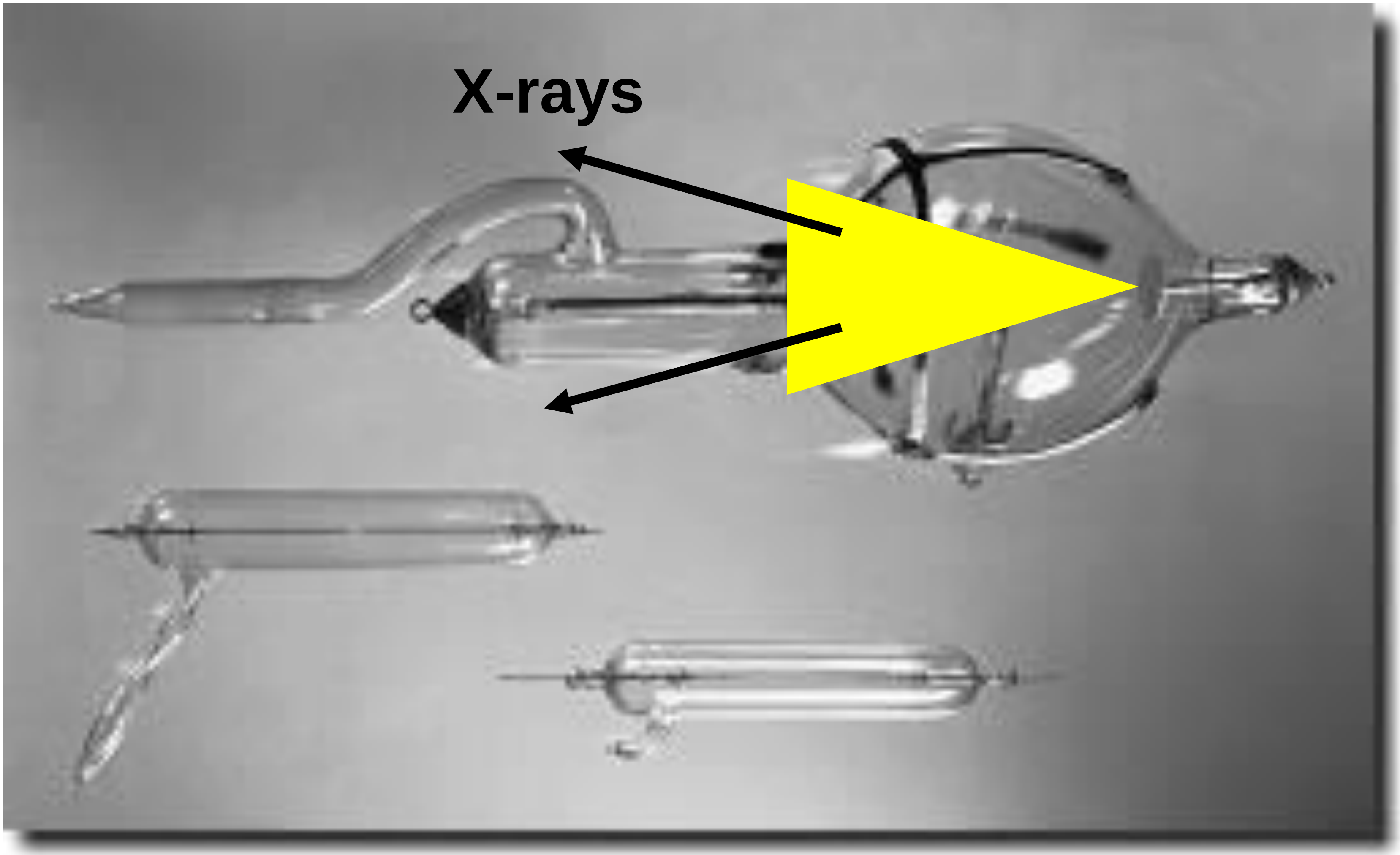
Accelerating electrons



The first (linear) accelerator



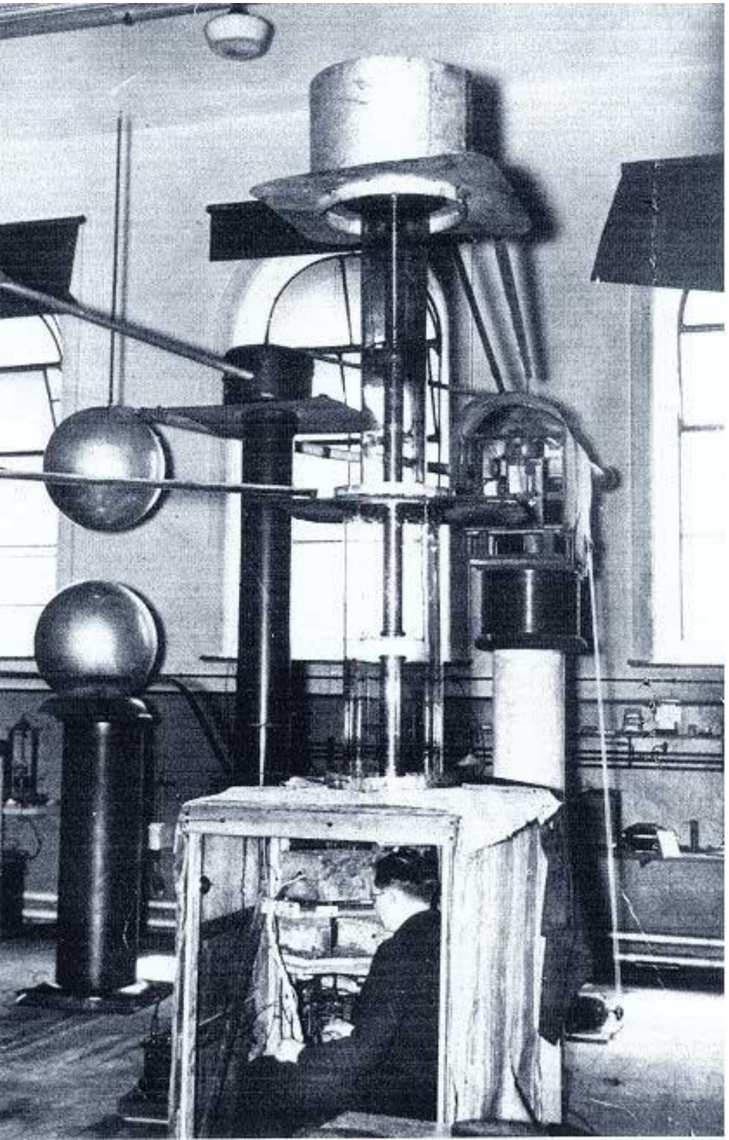
The first major accelerator discovery

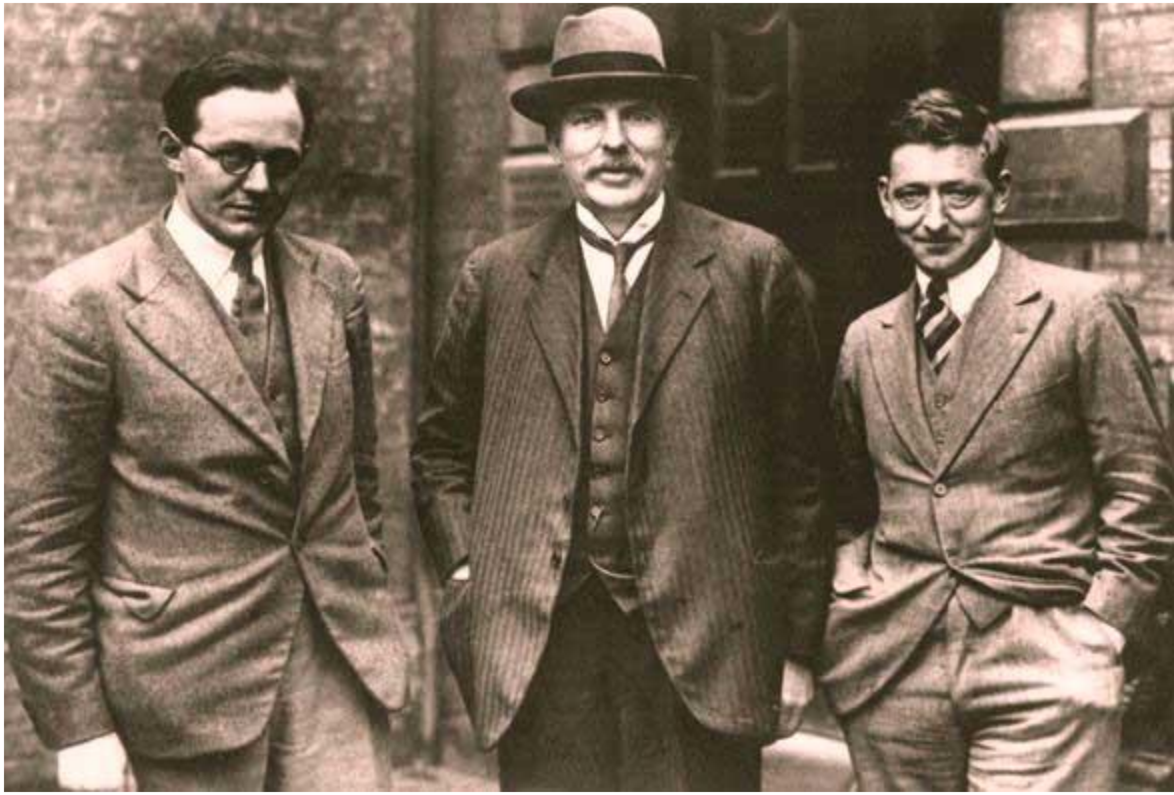


First use of an accelerator in medicine!

Mrs. Roentgen's hand

Cockcroft – Walton Accelerator





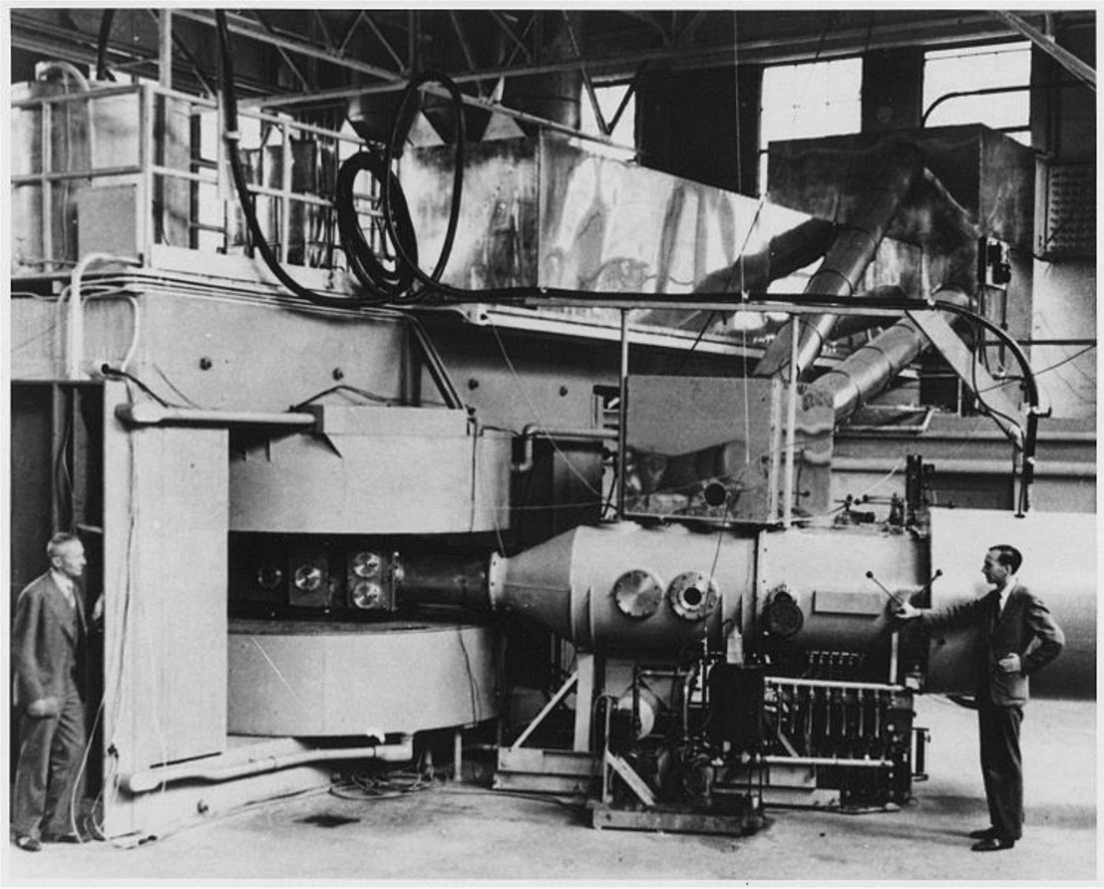
800,000 Volts

Van de Graaff Accelerator

1500,000 Volts

Lawrence Cyclotron

80,000 Volts



25,000,000 Volts

How to reach LHC energies?

- **We need 7000,000,000,000 Volts /proton beam**

  How to do this??

How to reach LHC energies?

- **We need 7000,000,000,000 Volts /proton beam**

How to do this??

?

How to reach LHC energies?

- **We need 7000,000,000,000 Volts /proton beam**

  How to do this??

?

- **Would need 10,000,000,000,000 AA batteries**

How to reach LHC energies?

- **We need 7000,000,000,000 Volts /proton beam**

  How to do this??

?

- **Would need 10,000,000,000,000 AA batteries**
- **5 x 10^{11} m = 3 x Earth's orbit radius around Sun**

How to reach LHC energies?

- We need 7000,000,000,000 Volts /proton beam

  How to do this??

?

- Would need 10,000,000,000,000 AA batteries
- 5 x 10^{11} m = 3 x Earth's orbit radius around Sun
- $10,000,000,000,000 – discount for bulk buy?!

Accelerating gradients

- **AA batteries:**

  1.5V / 5cm → 30 V / m

Accelerating gradients

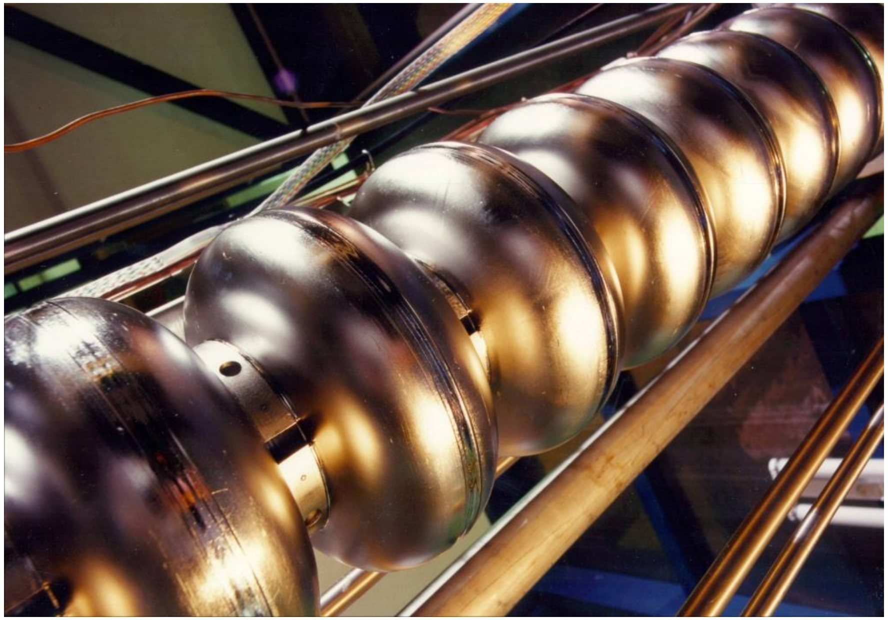
- **AA batteries:**

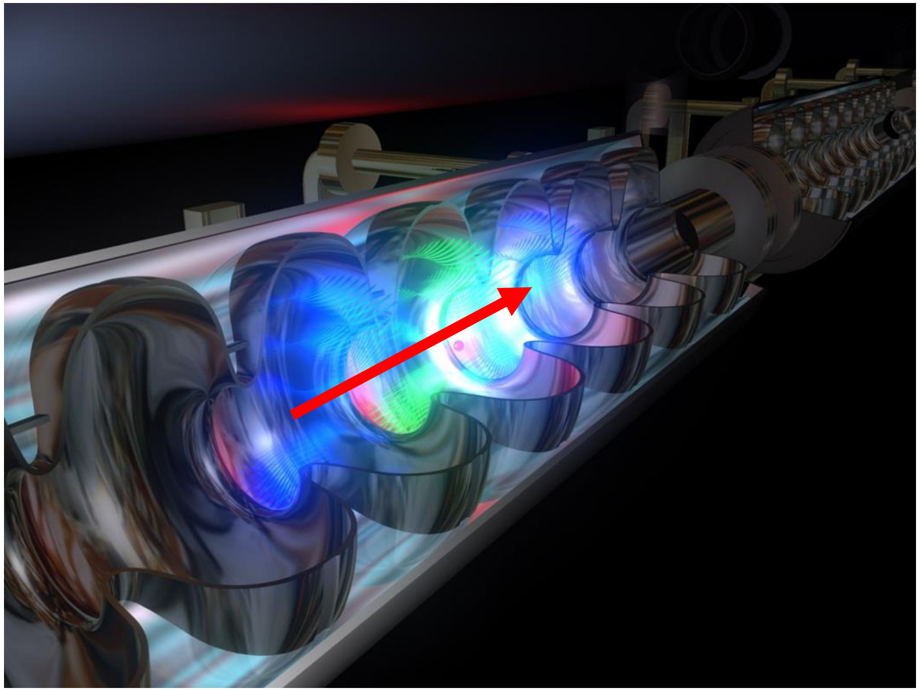
  1.5V / 5cm → 30 V / m

- **Radio-frequency cavities:**

  1-100 MV / m

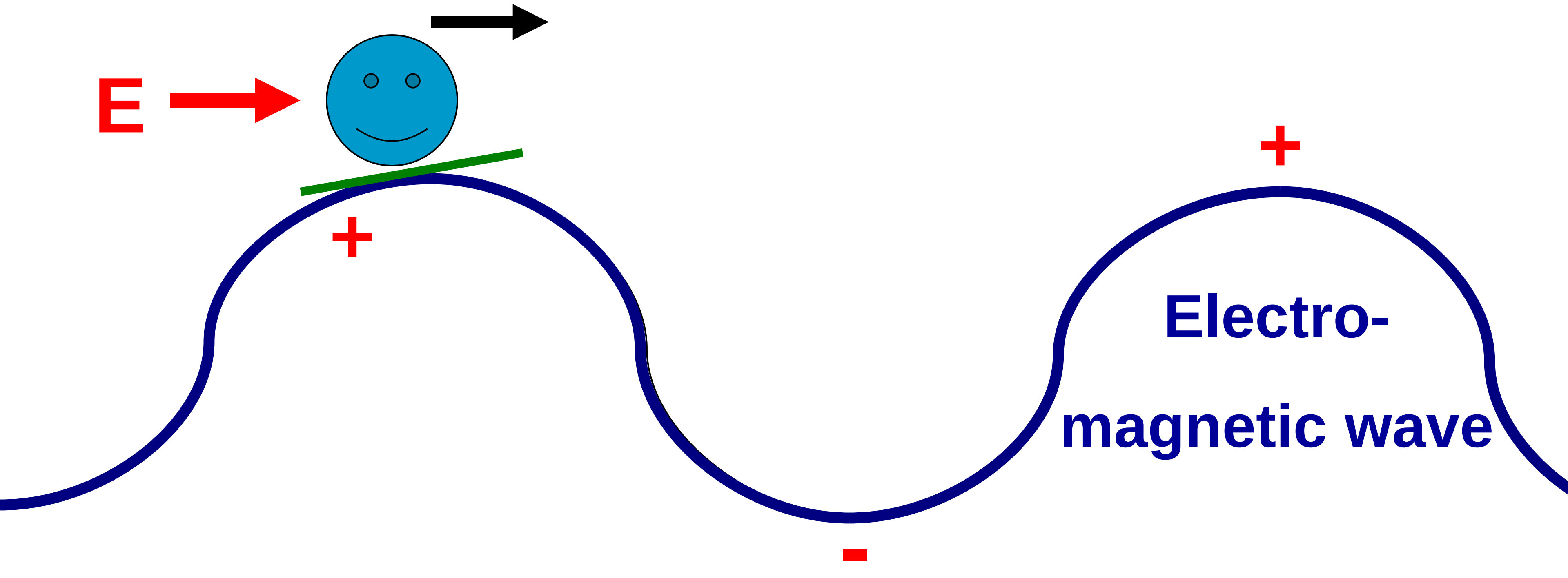
Niobium Accelerating Structures



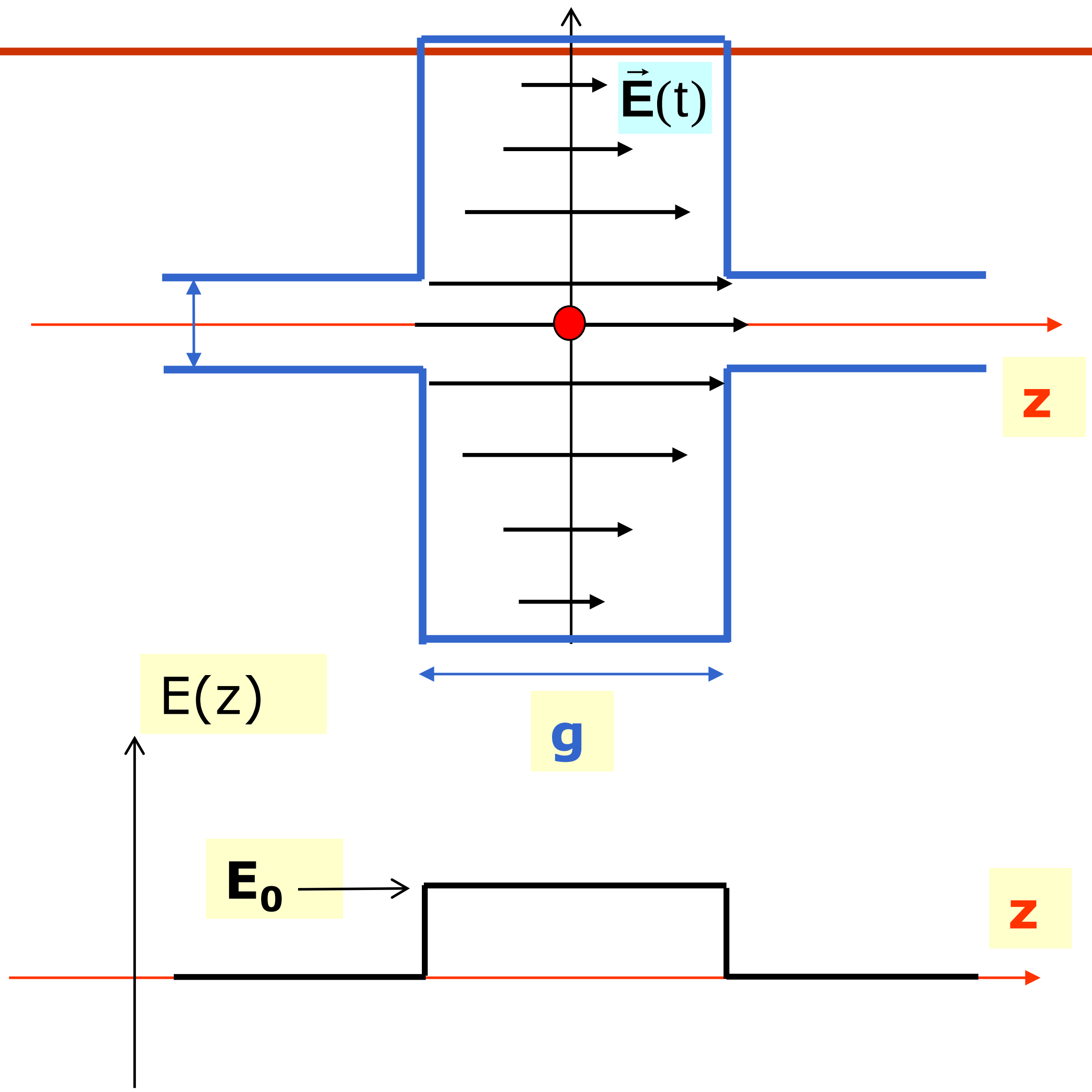


Surfer

Subatomic surfer



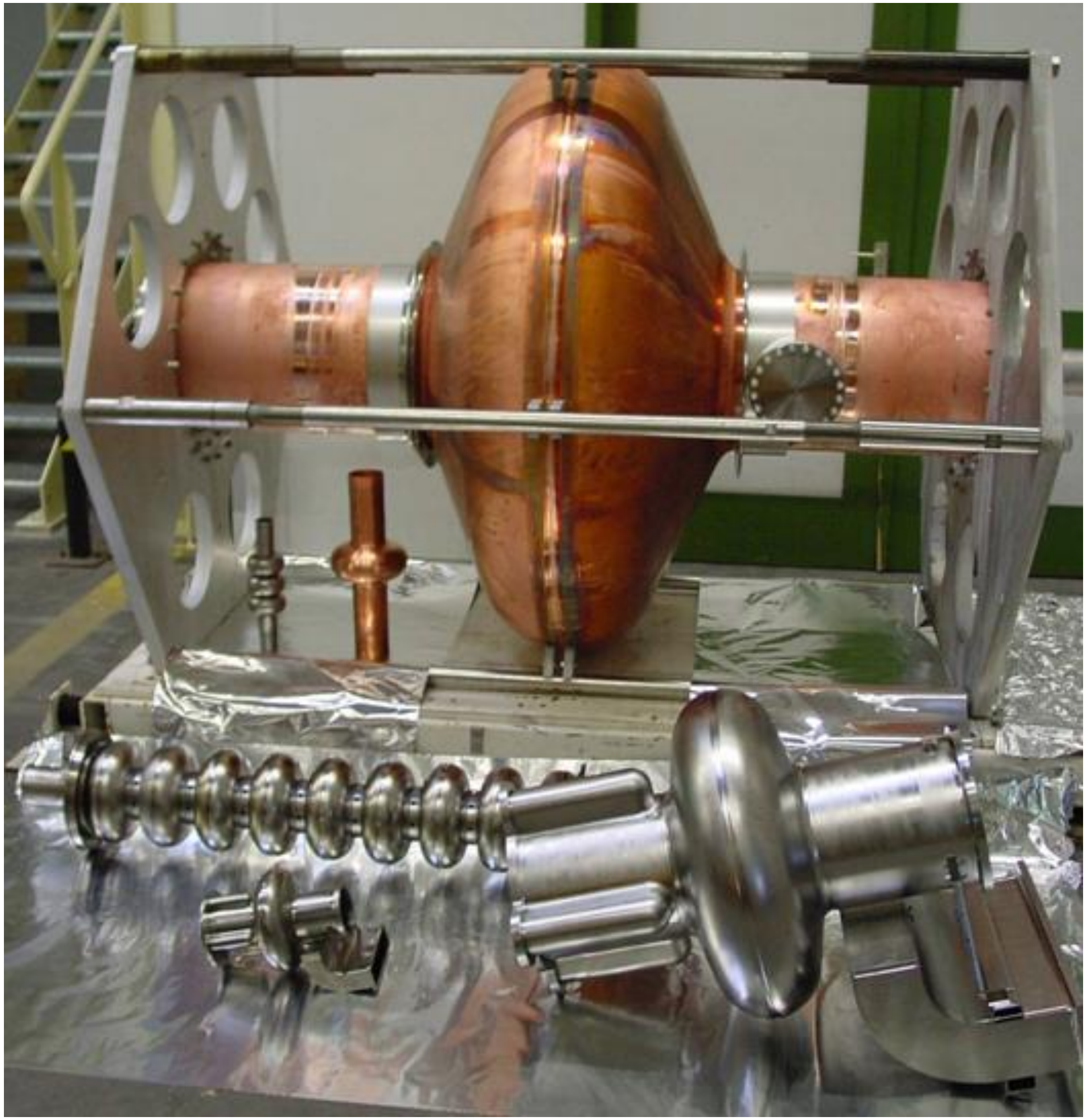
Acceleration in a cylindrical cavity



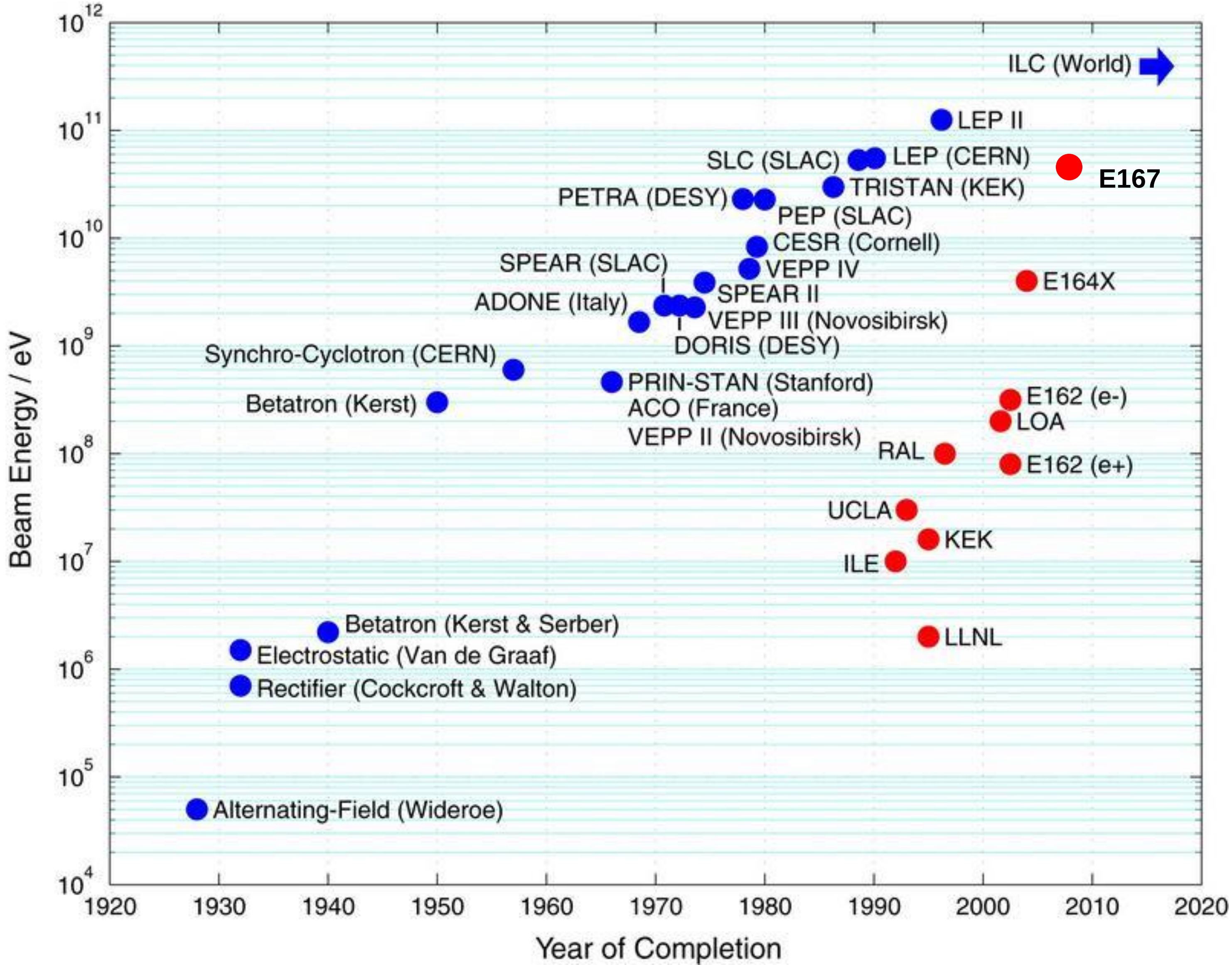
TM 010 mode

R. Schmidt

Typical accelerating cavities

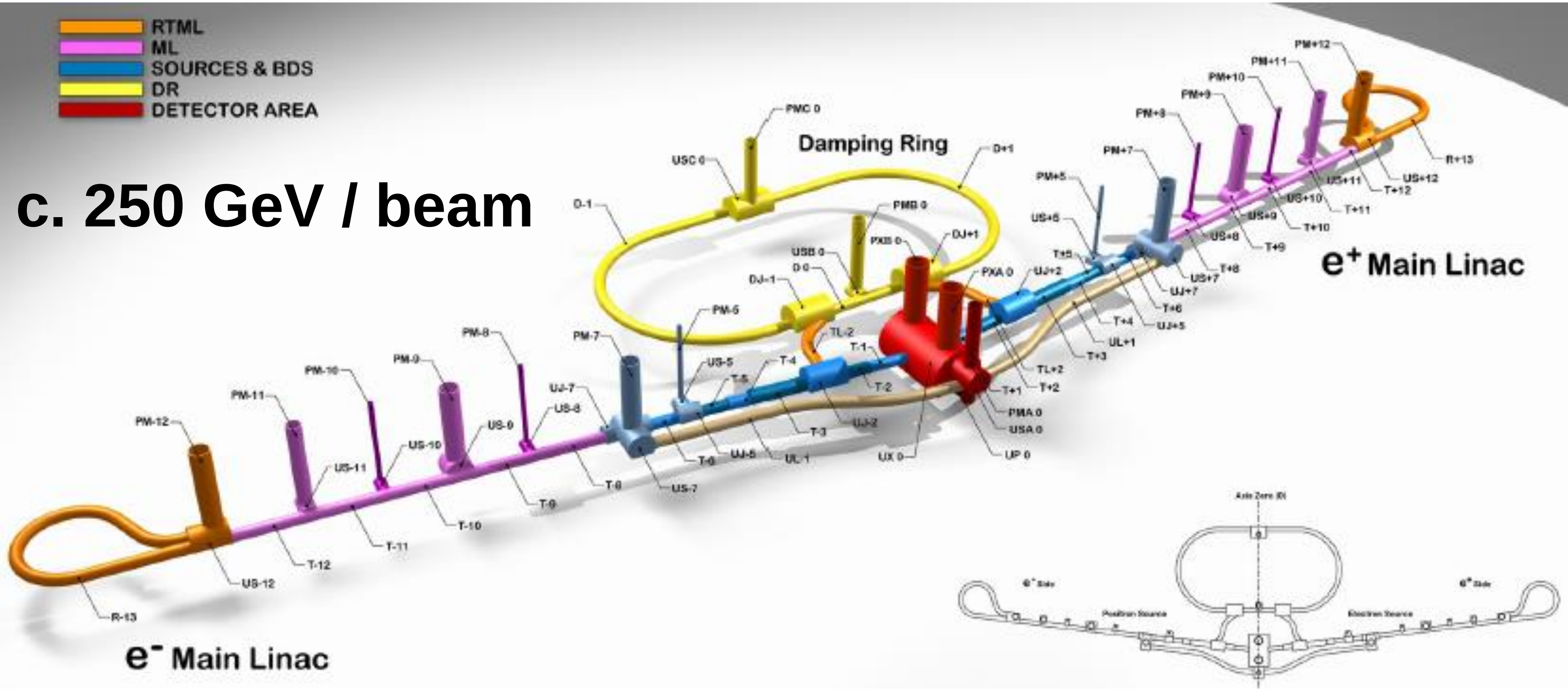


Electron accelerator development



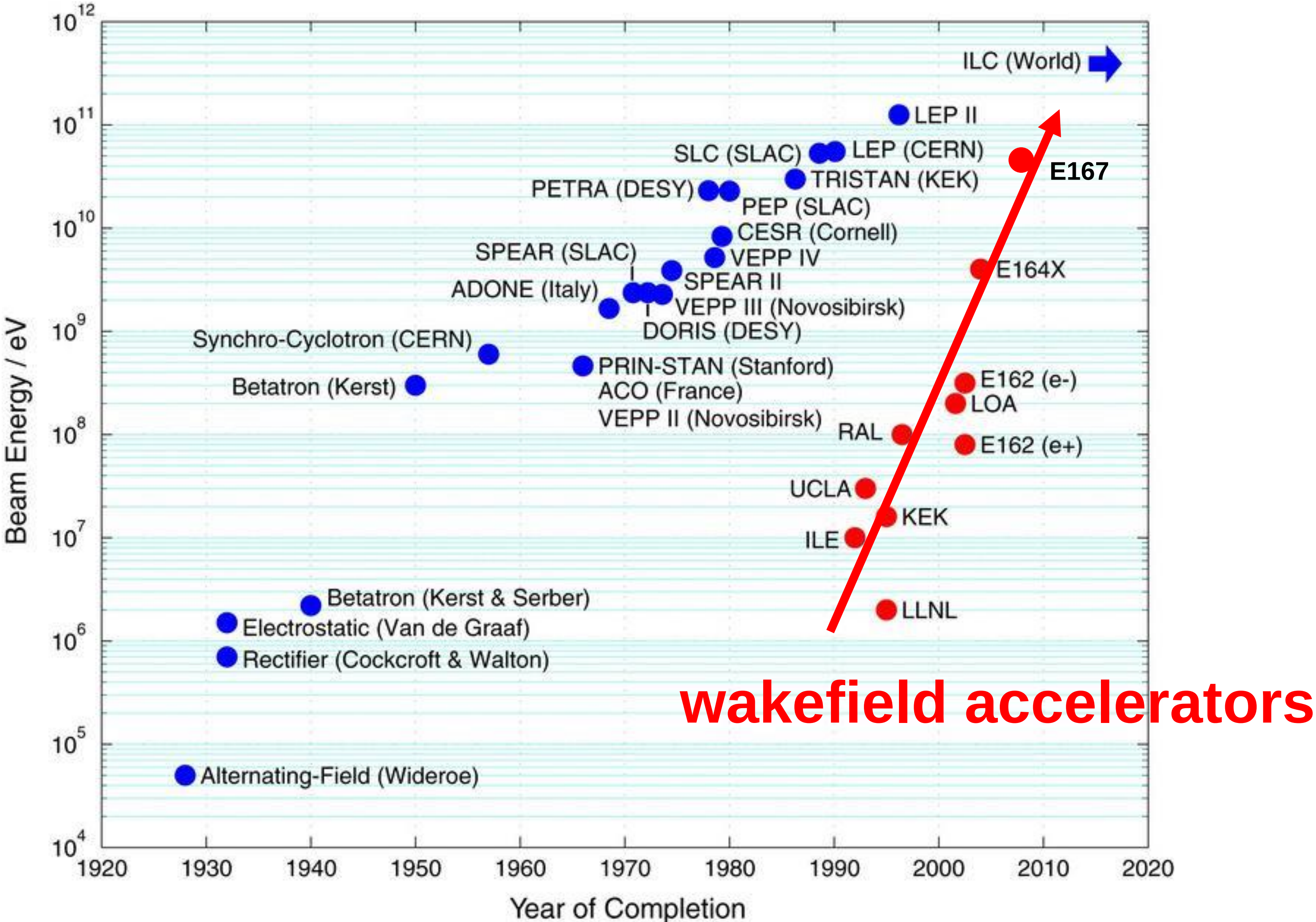
International Linear Collider

c. 250 GeV / beam

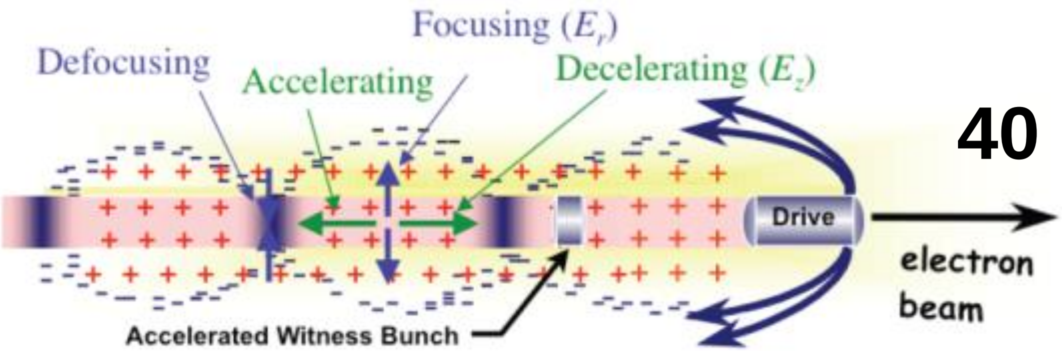


31 km

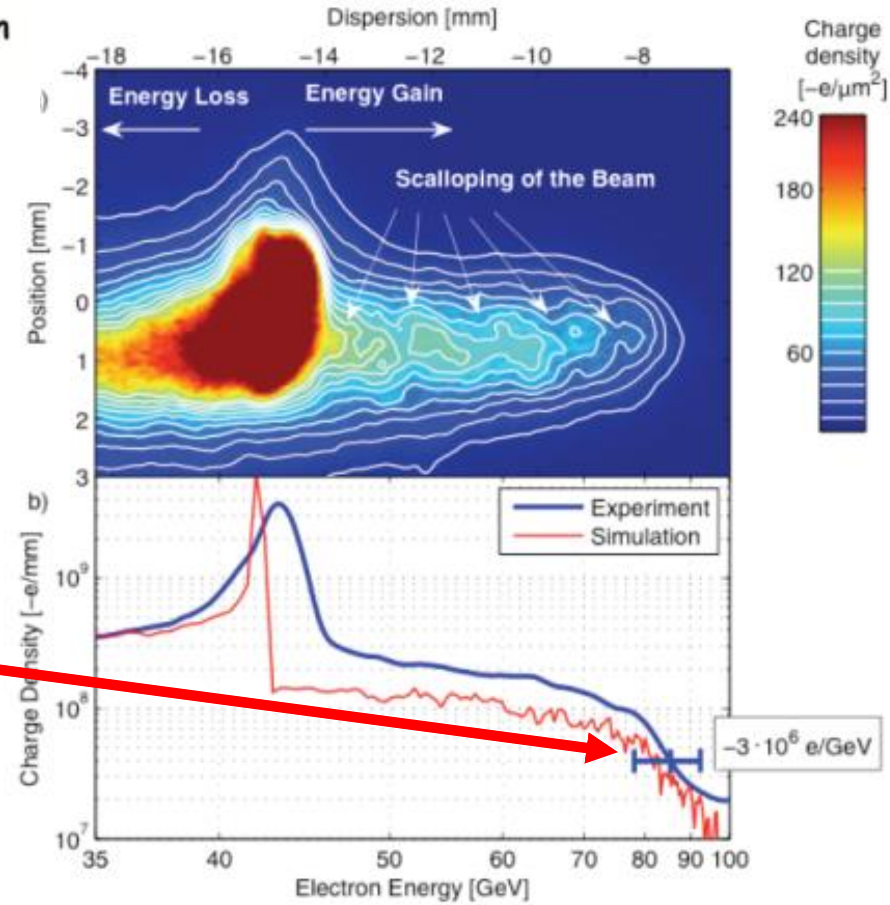
Electron accelerator development



Beam-driven plasma wakefield accelerators



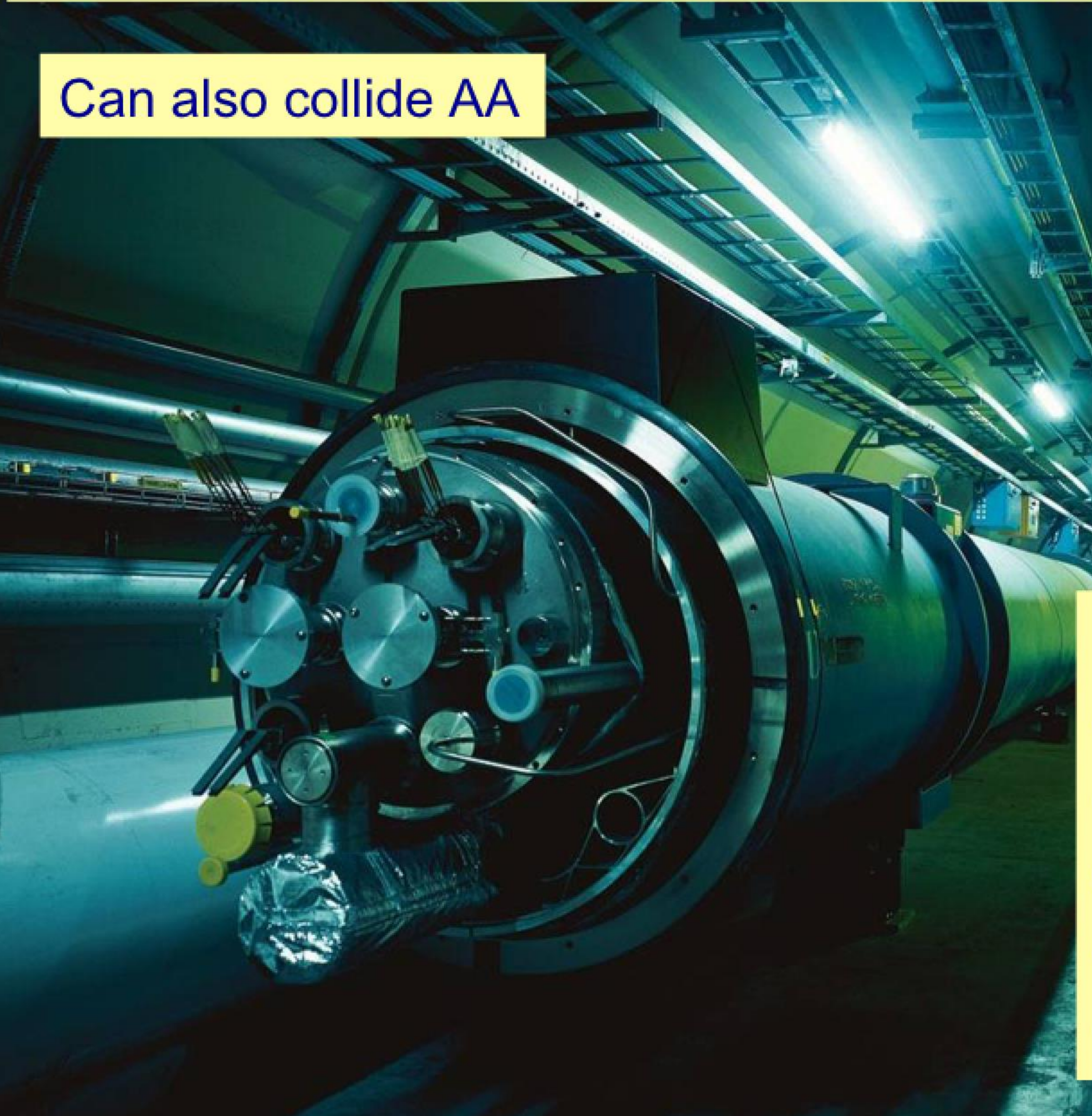
40 GeV



Some e- had their energy doubled to c. 80 GeV in 1m of plasma

The Large Hadron Collider = a proton proton collider

Can also collide AA



7 TeV + 7 TeV
(3.5/4 TeV + 3.5/4 TeV)

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

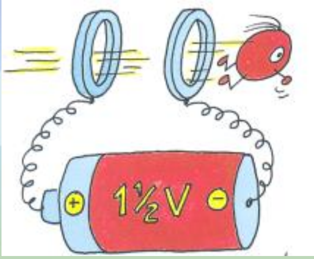
Primary physics targets

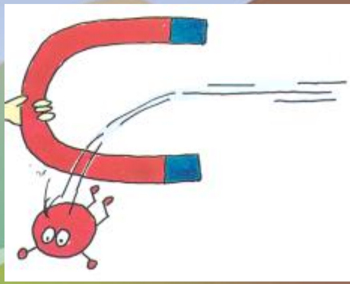
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

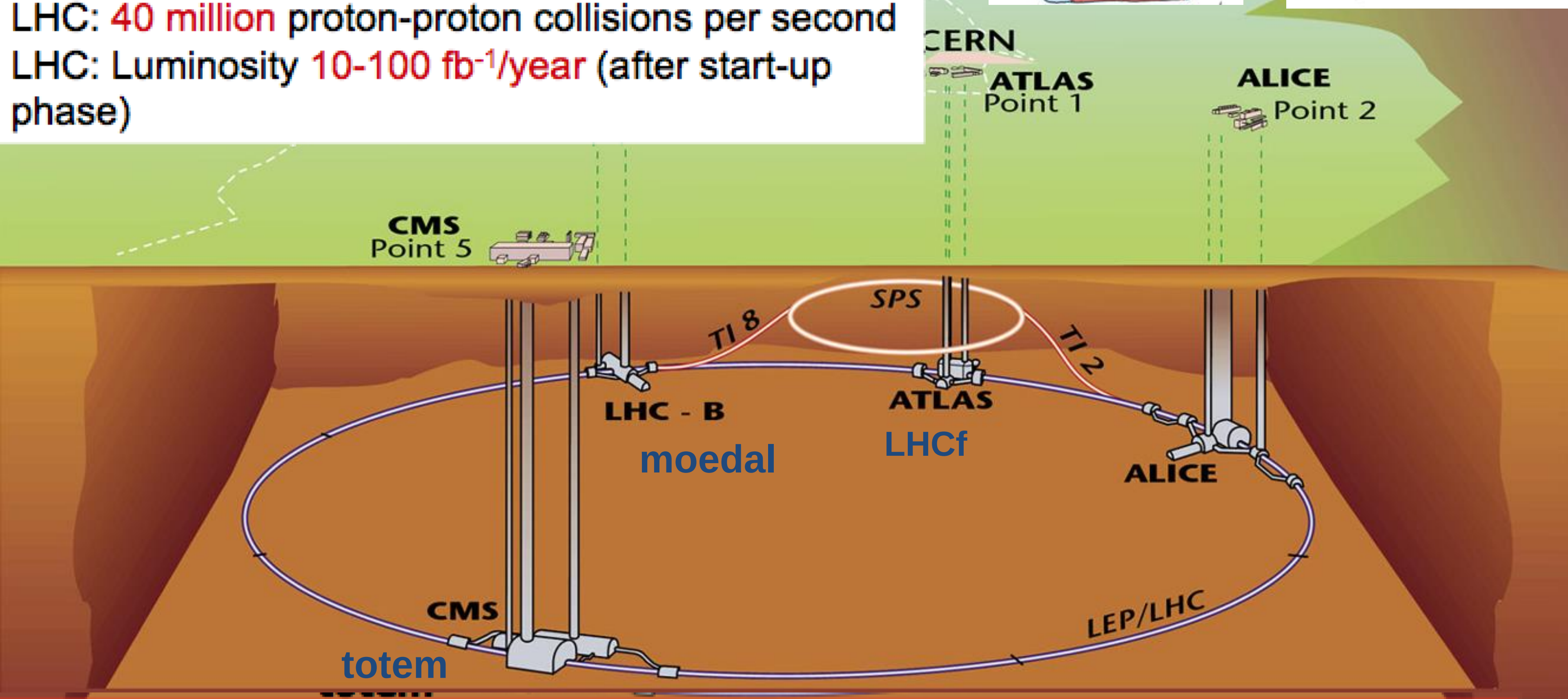
The LHC produced collisions from 2010 till beginning of 2013
LHC will restart in 2015 with collisions at an energy of 13 TeV

The LHC Machine and Experiments

LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)





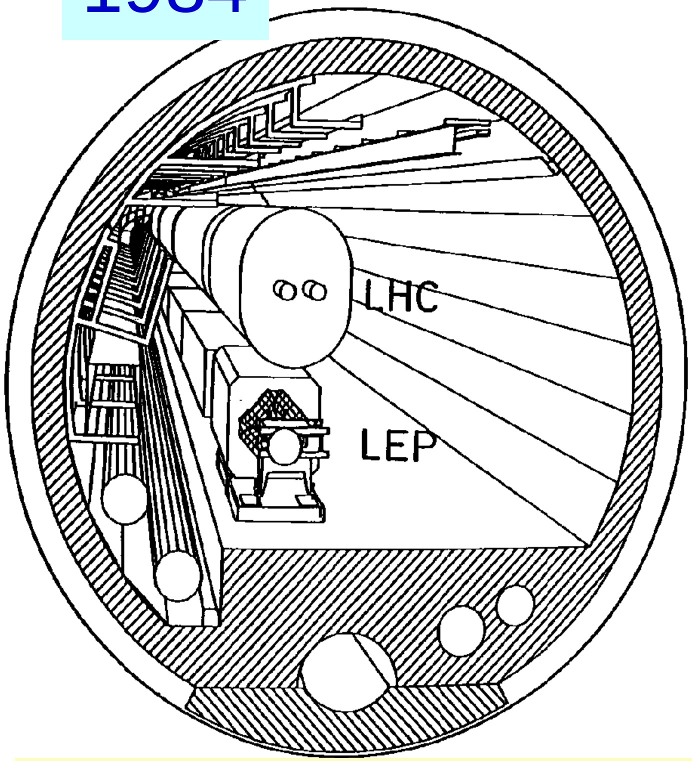


- •High Energy ⇒ factor 7 increase w.r.t. present accelerators
- •High Luminosity (# events/cross section/time) ⇒ factor 100 increase

The LHC: ~30 Years Already!

1984

ECFA 84/85
CERN 84-10
5 September 1984



LHC History

1982 : First studies for the LHC project

1983 : Z0/W discovered at SPS proton antiproton collider

1989 : Start of LEP operation (Z boson-factory)

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

1996 : LEP operation > 80 GeV (W boson -factory)

2000 : Last year of LEP operation above 100 GeV

2002 : LEP equipment removed

2003 : Start of the LHC installation

2005 : Start of LHC hardware commissioning

2008 : Expected LHC commissioning with beam

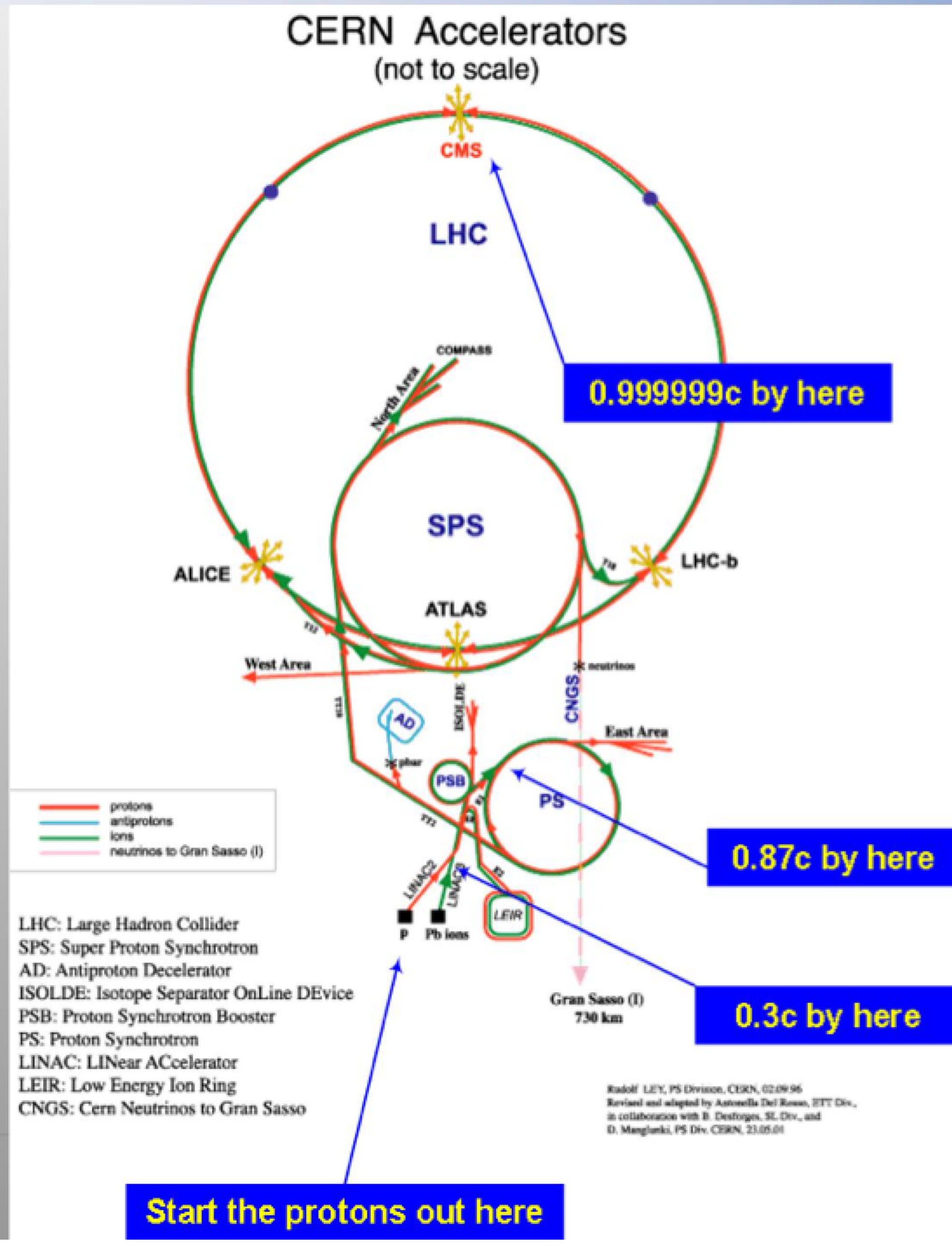
2009: Actual start of the LHC

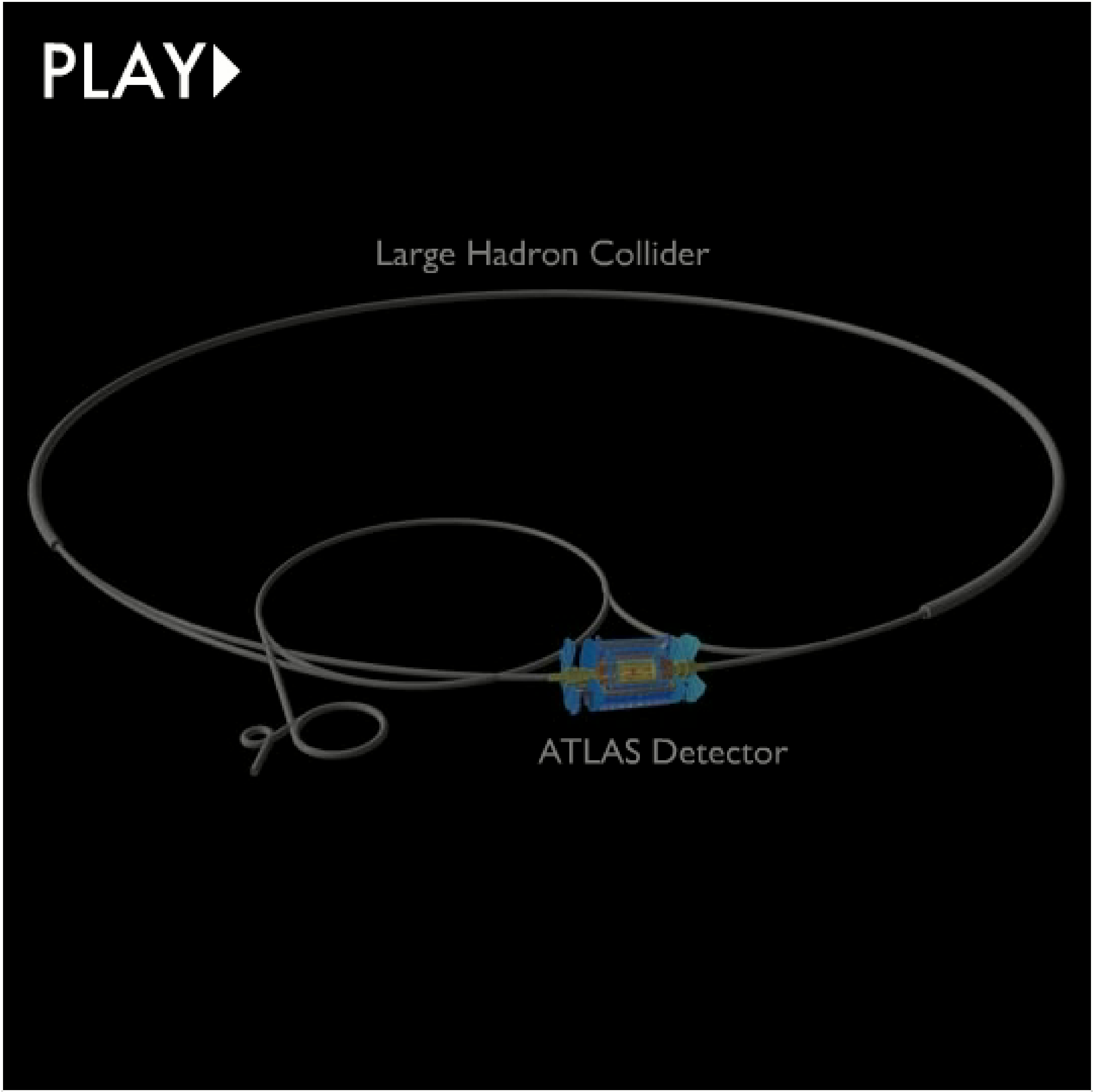
1984:	cms energy	10-18 TeV
	Luminosity	10^{31}-10^{33} $cm^{-2}s^{-1}$
1987:	cms energy	16 TeV
	Luminosity	10^{33}-10^{34} $cm^{-2}s^{-1}$
Final:	cms energy	14 TeV
	Luminosity	10^{33}-10^{34} $cm^{-2}s^{-1}$

Luminosity=# events/cross section/sec

The LHC is an Extraordinary Machine

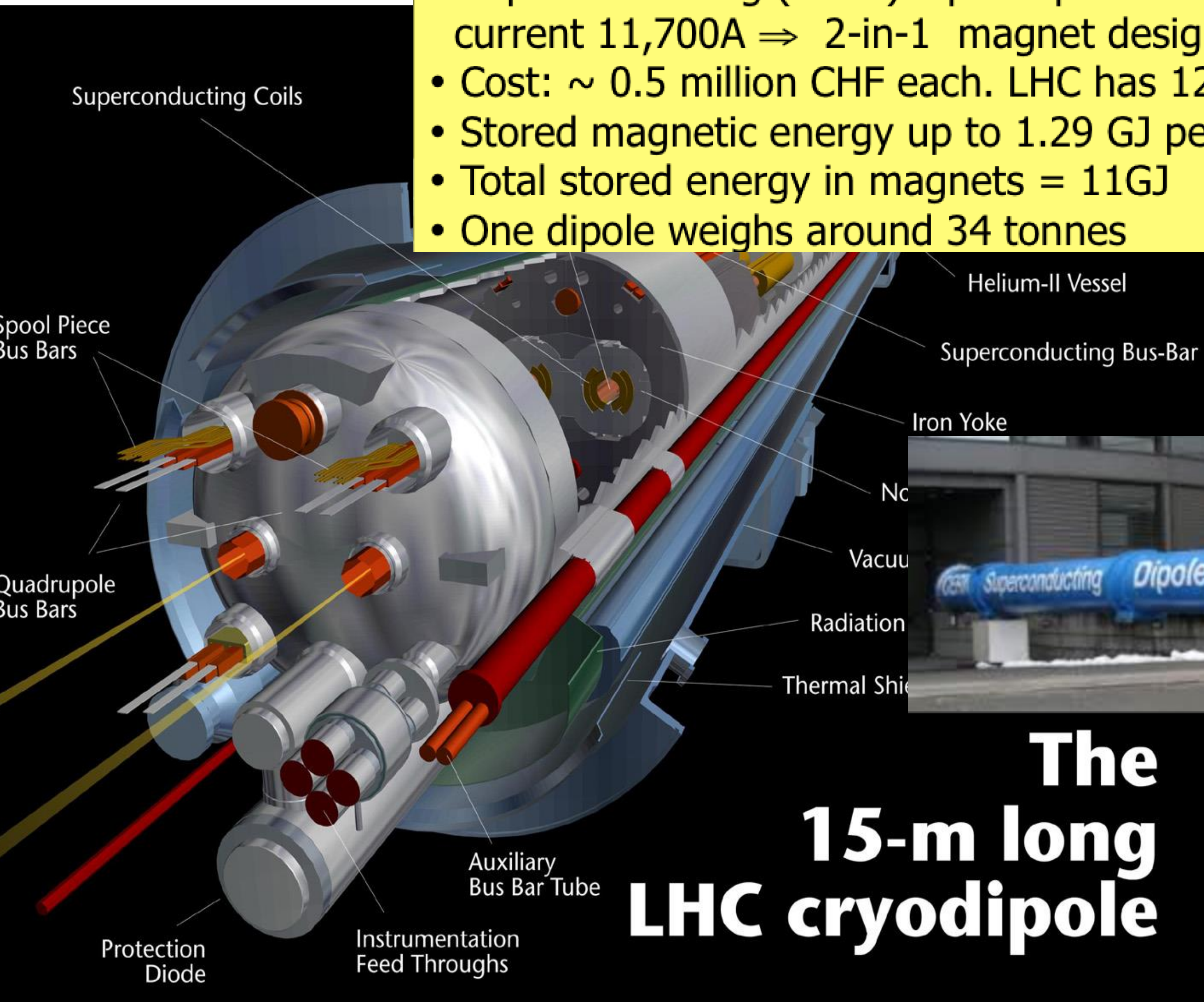
Linac → Booster → PS → SPS → LHC




PLAY
Large Hadron Collider
ATLAS Detector

The Cryodipole Magnets

- Superconducting (1.9 K) dipoles producing a field of 8.4 T – current 11,700A ⇒ 2-in-1 magnet design
- Cost: ~ 0.5 million CHF each. LHC has 1232 of them
- Stored magnetic energy up to 1.29 GJ per sector.
- Total stored energy in magnets = 11GJ
- One dipole weighs around 34 tonnes



The LHC is an Extraordinary Machine

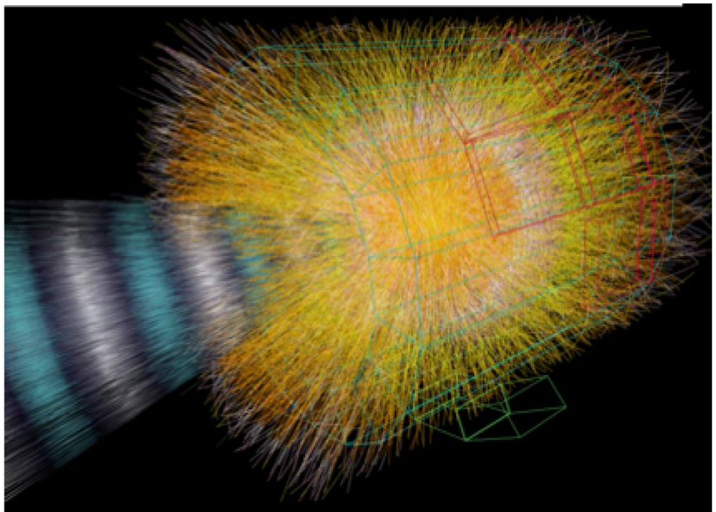
LHC facts

The LHC is ...

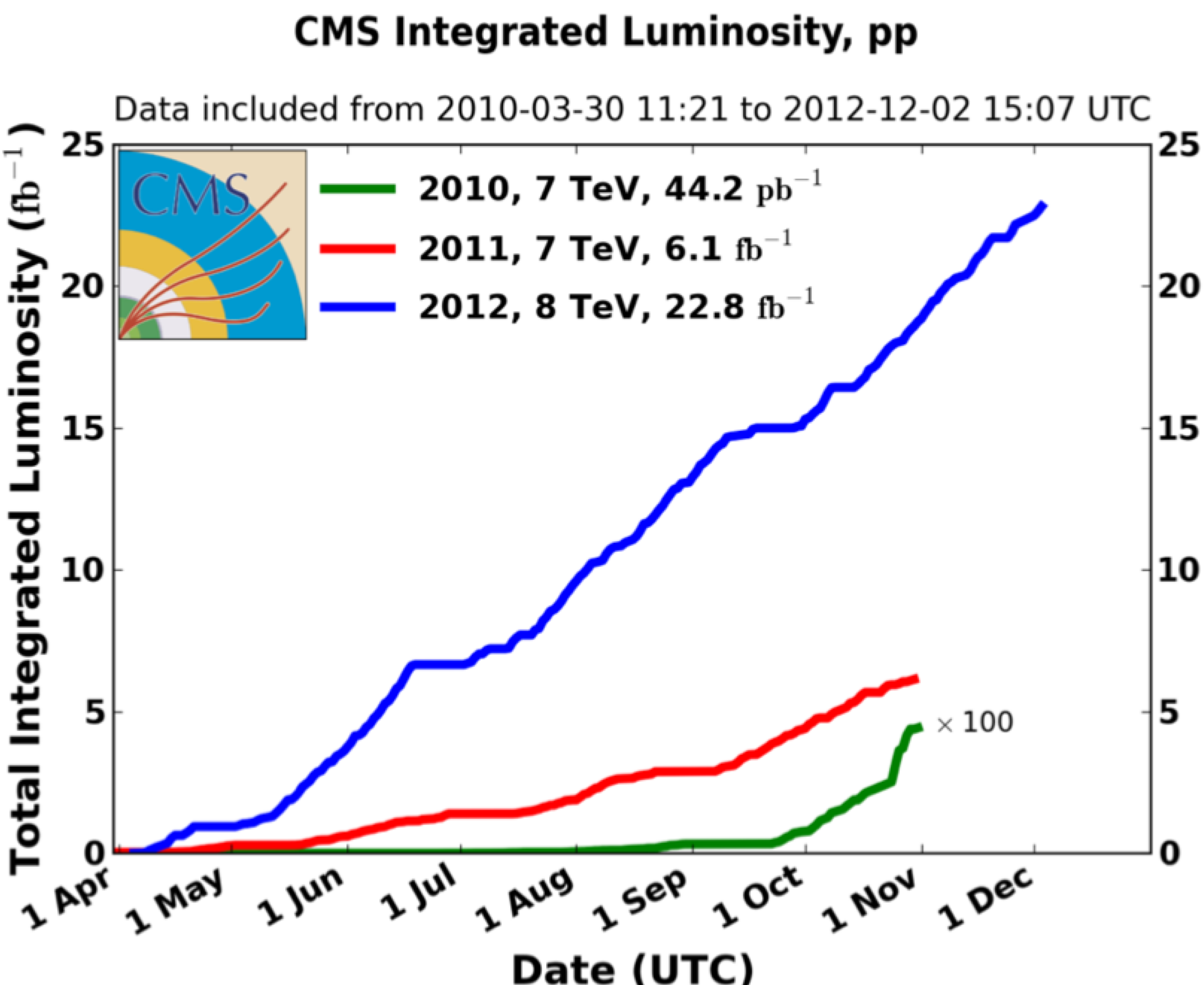
Colder than the empty space in the Universe: 1.9K ie above absolute zero

The emptiest place in our solar system. The vacuum is better than on the moon

Hotter than in the sun: temperature in the collisions is a billion times the one in the centre of the sun

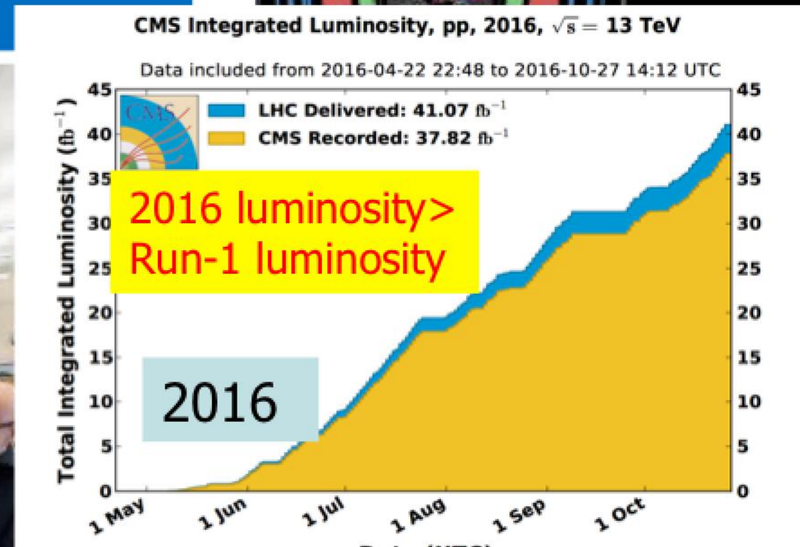


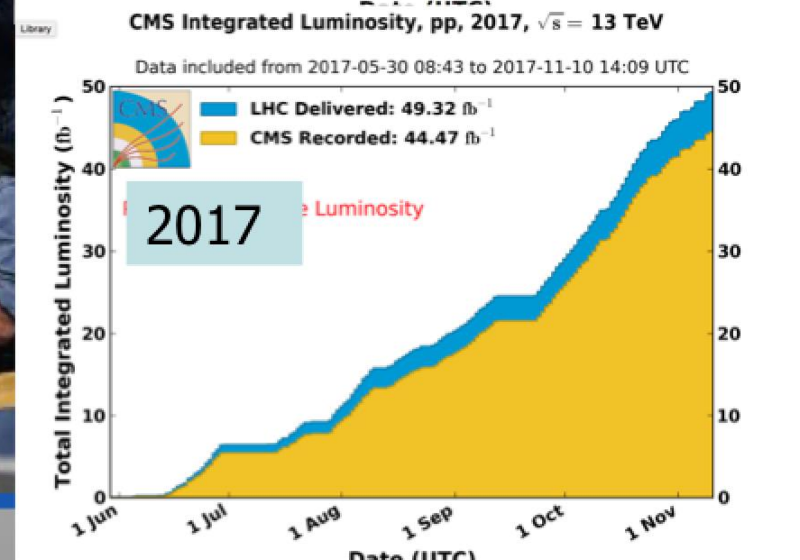
LHC Performance (2010-2012)



LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015 Run-2 starts





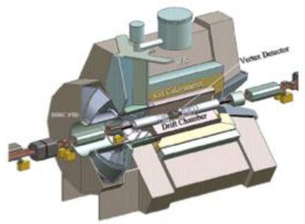
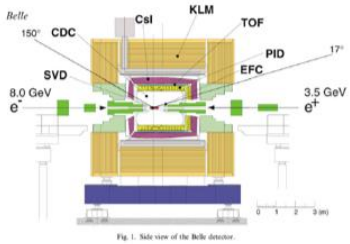
- 2010-2012: Run-1 at 7/8 TeV CM energy
- 2015-2018: Run-2 at 13 TeV CM Energy
- Collected so far at 13 TeV: ~ 80 fb^{-1}
- Expected by end of 2018: ~ 150 fb^{-1}

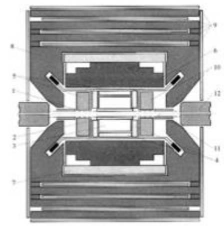
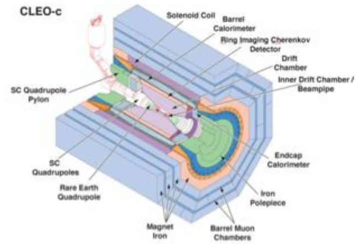
30-3-2018: The beam is back in the LHC

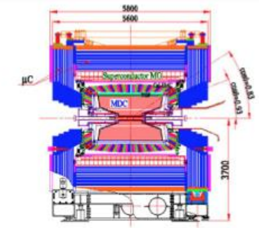
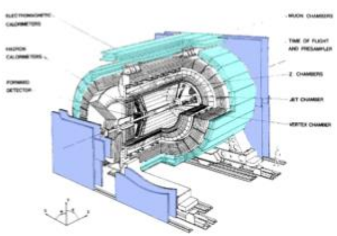
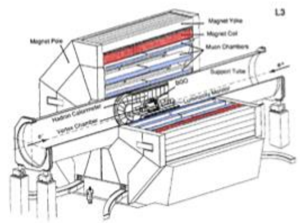
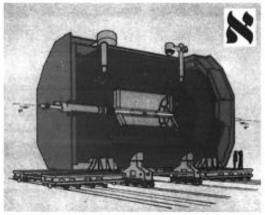
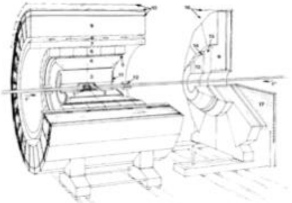
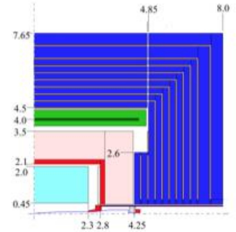
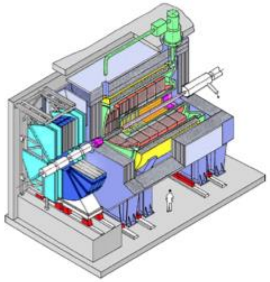
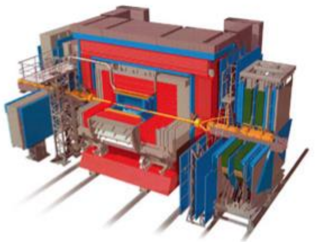
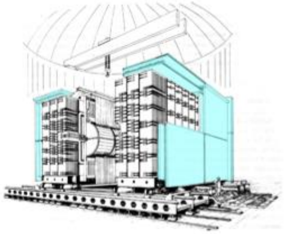
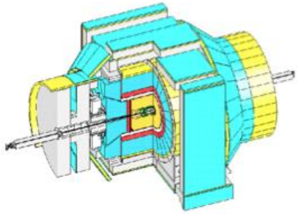
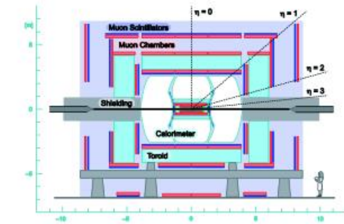
Part II

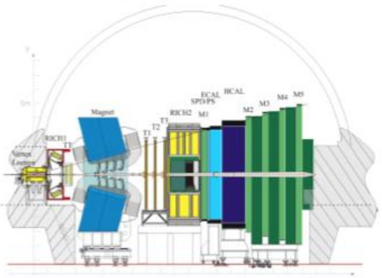
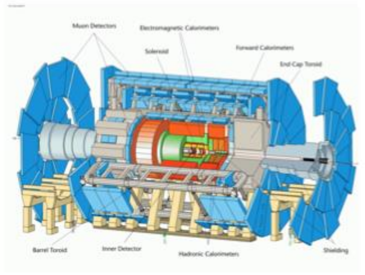
Detectors

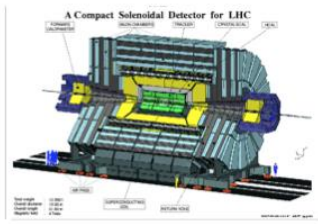
Collider Detectors Around the World

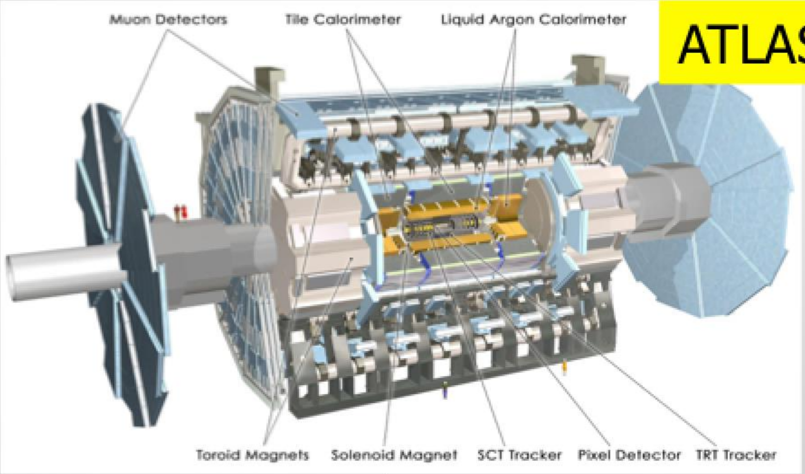



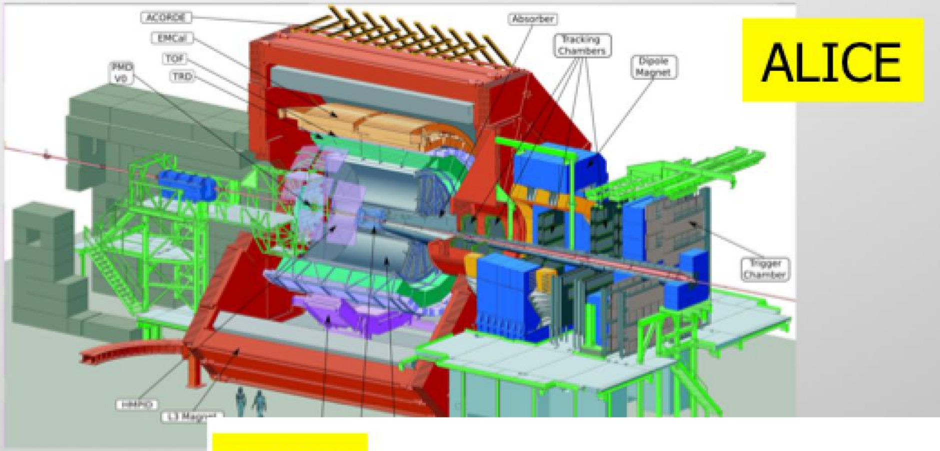












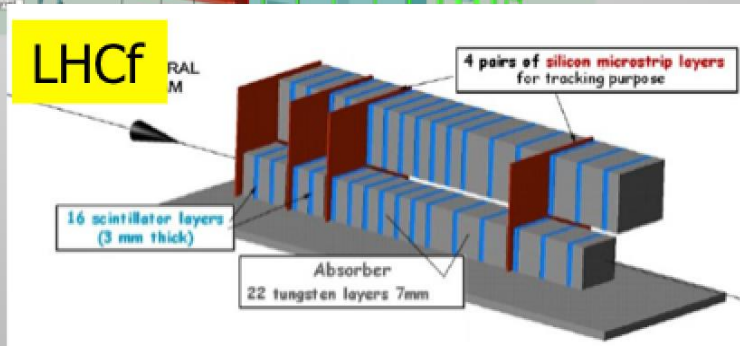




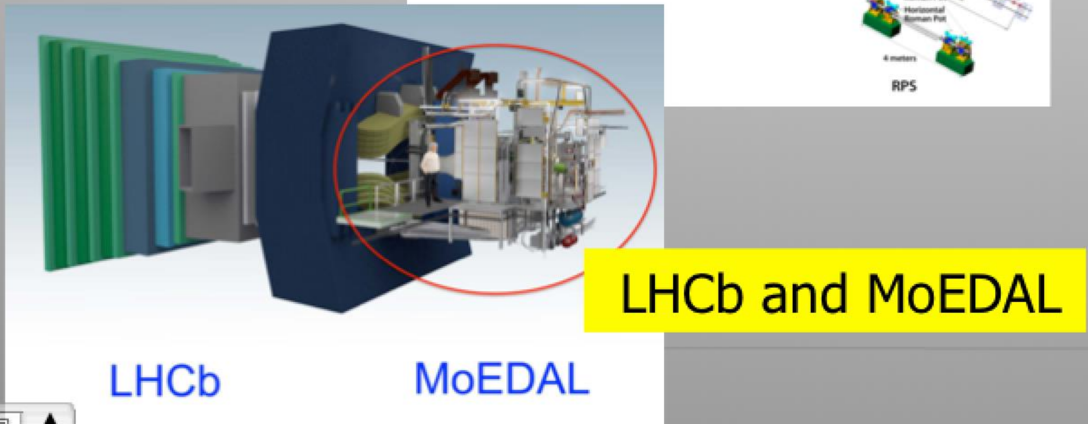


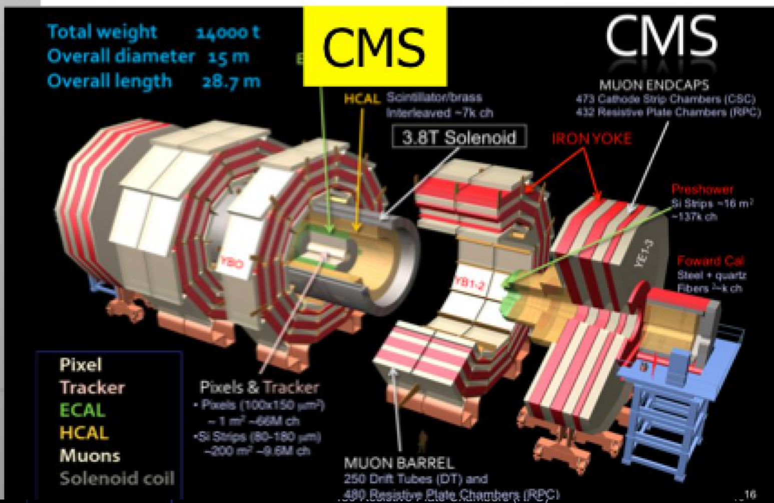
Experiments at the LHC

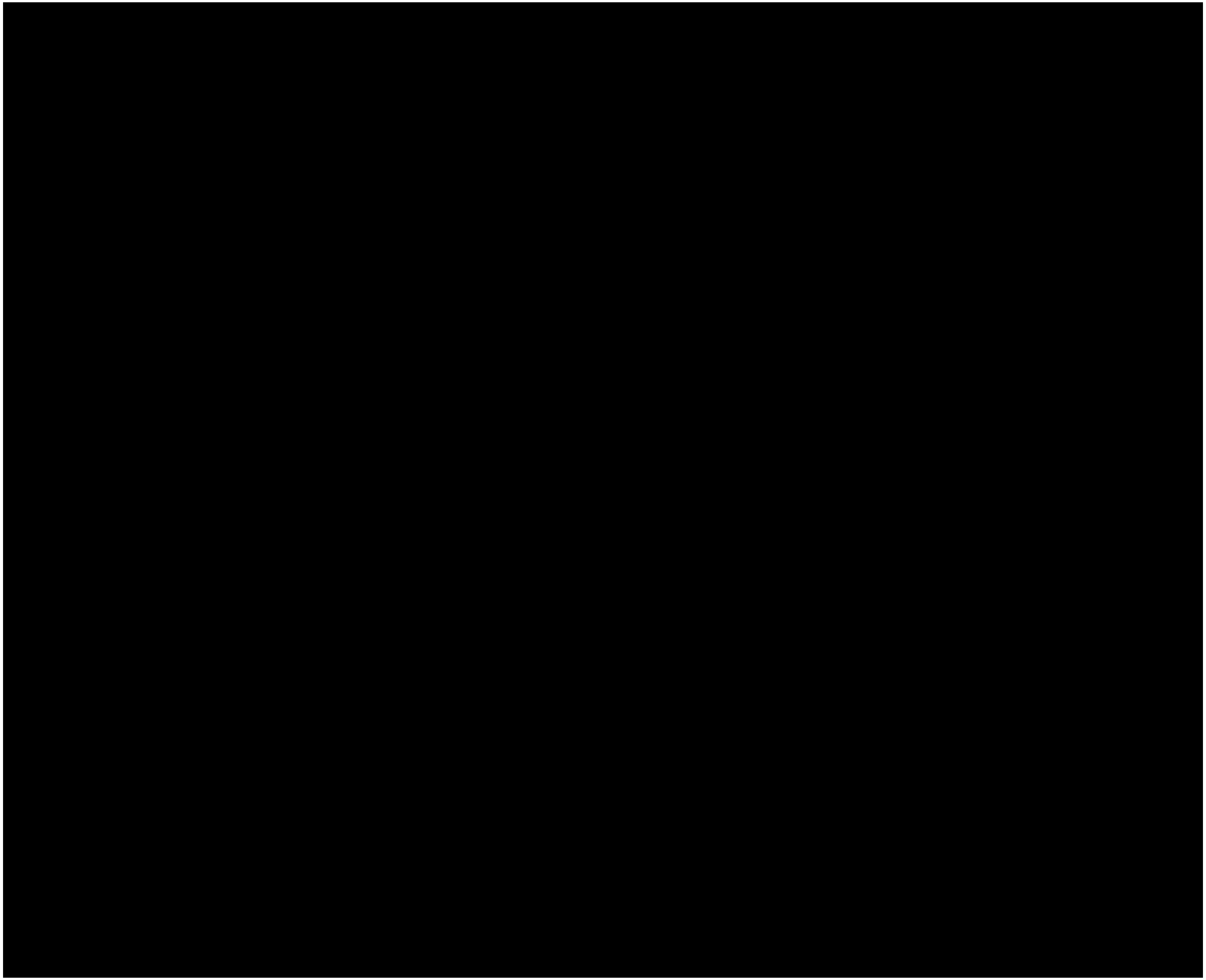


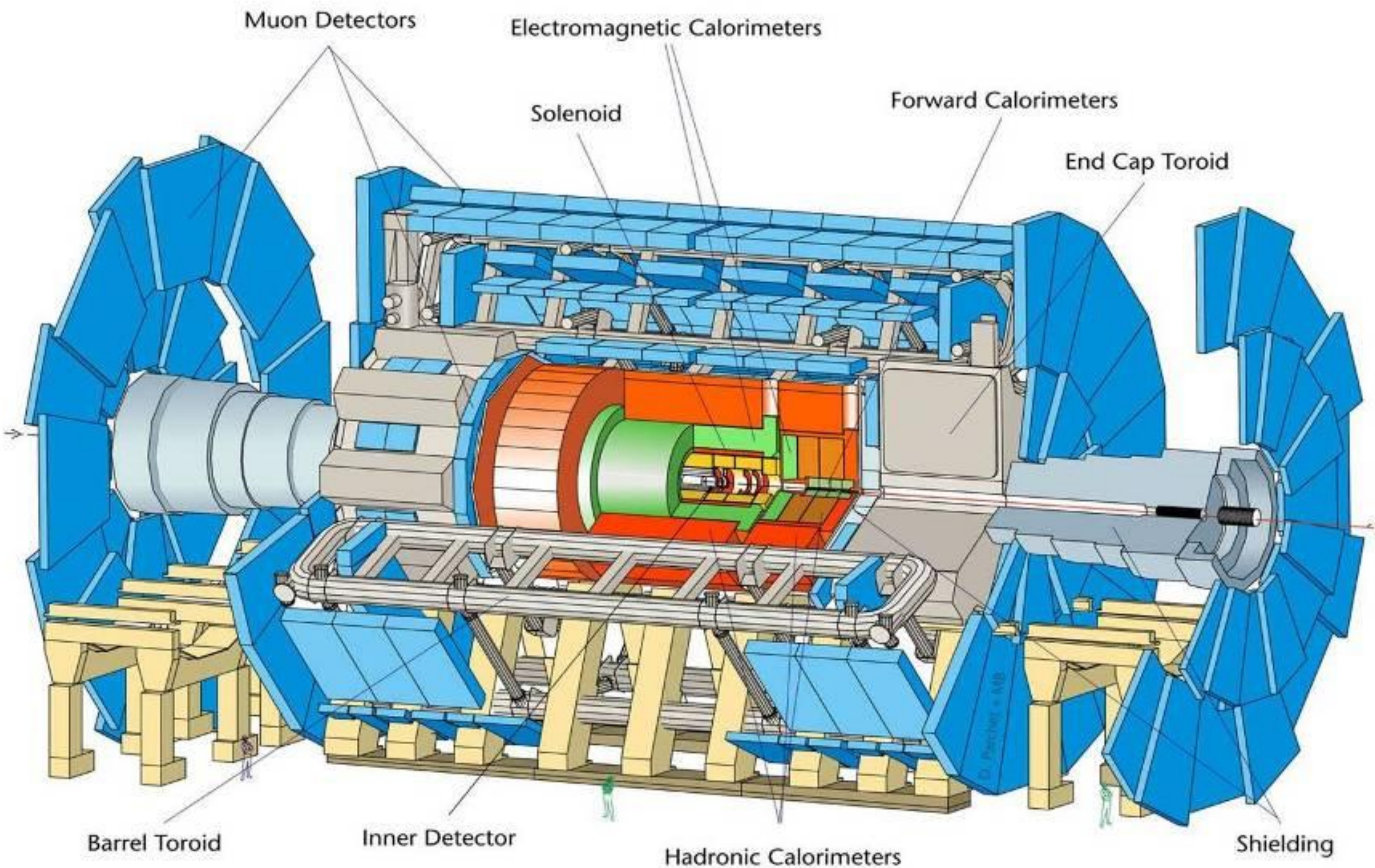






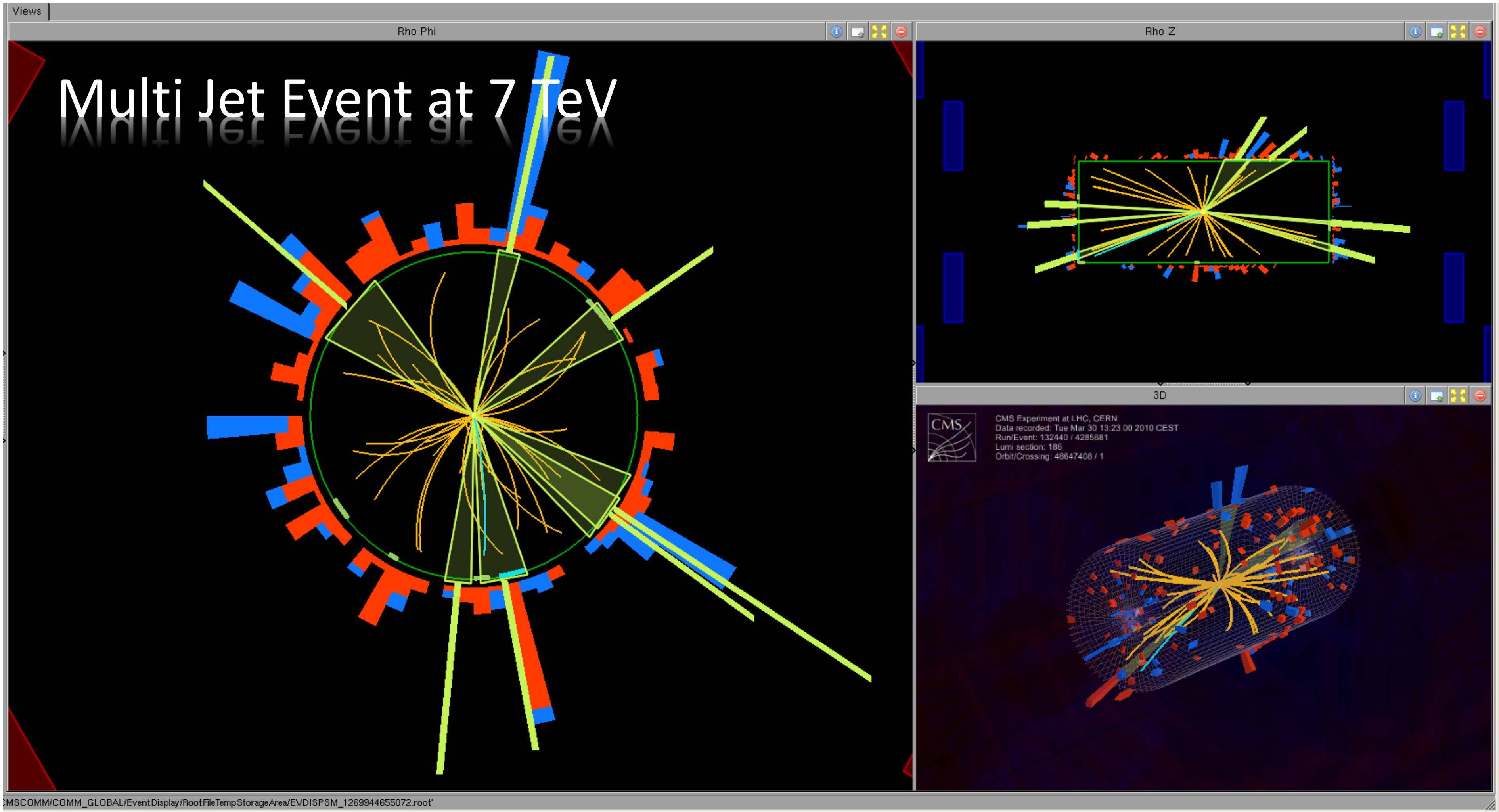






Length = 55 m Width = 32 m Height = 35 m but spatial precision ~ 100 μm

First Collisions at 7 TeV



31 March 2010….

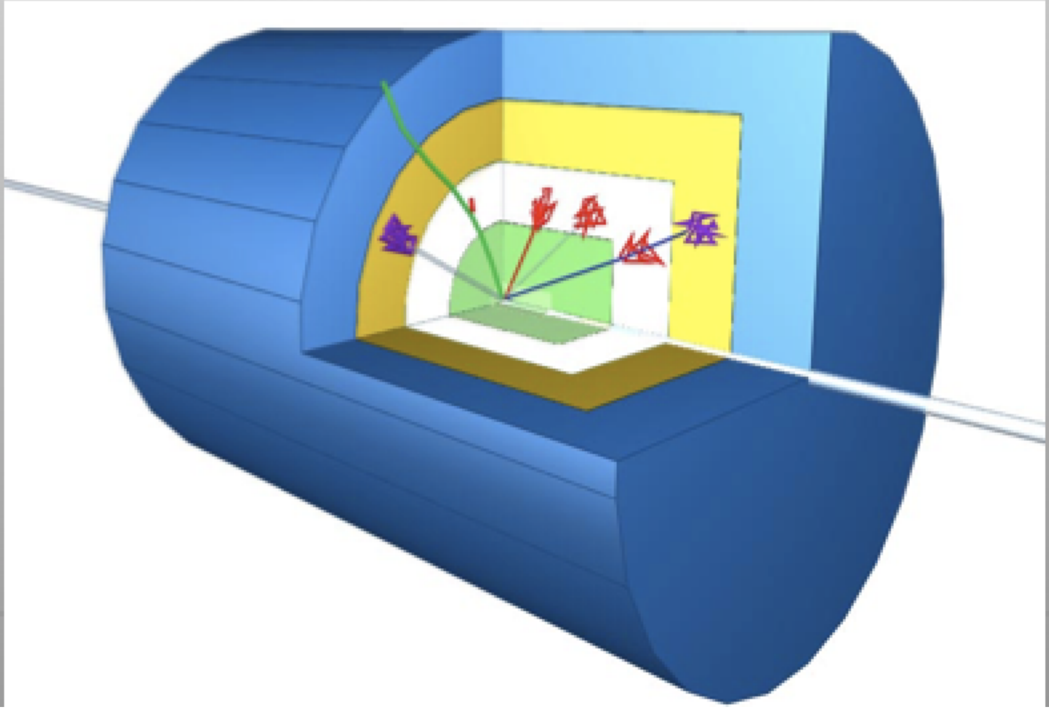
Schematic of a LHC Detector

Physics requirements drive the design!

Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

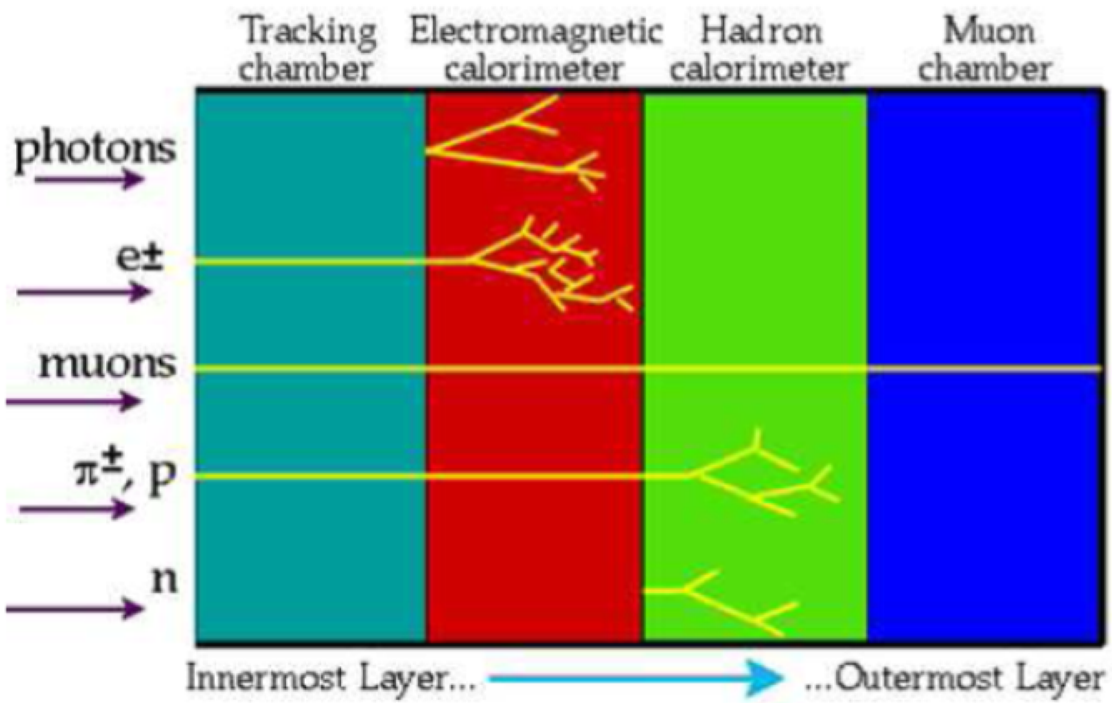
Such an experiment has ~ 100 Million read-out channels!!



Detectors at Accelerators

Particle Detection: What we "see" as particles:

For "stable particles" of life time $\geq 10^{-10}$ s:



For charged tracks : $\Delta p/p \propto p$,

for calorimetry : $\Delta E/E \propto \frac{1}{\sqrt{E}}$.

Note: apart from these general detector components:

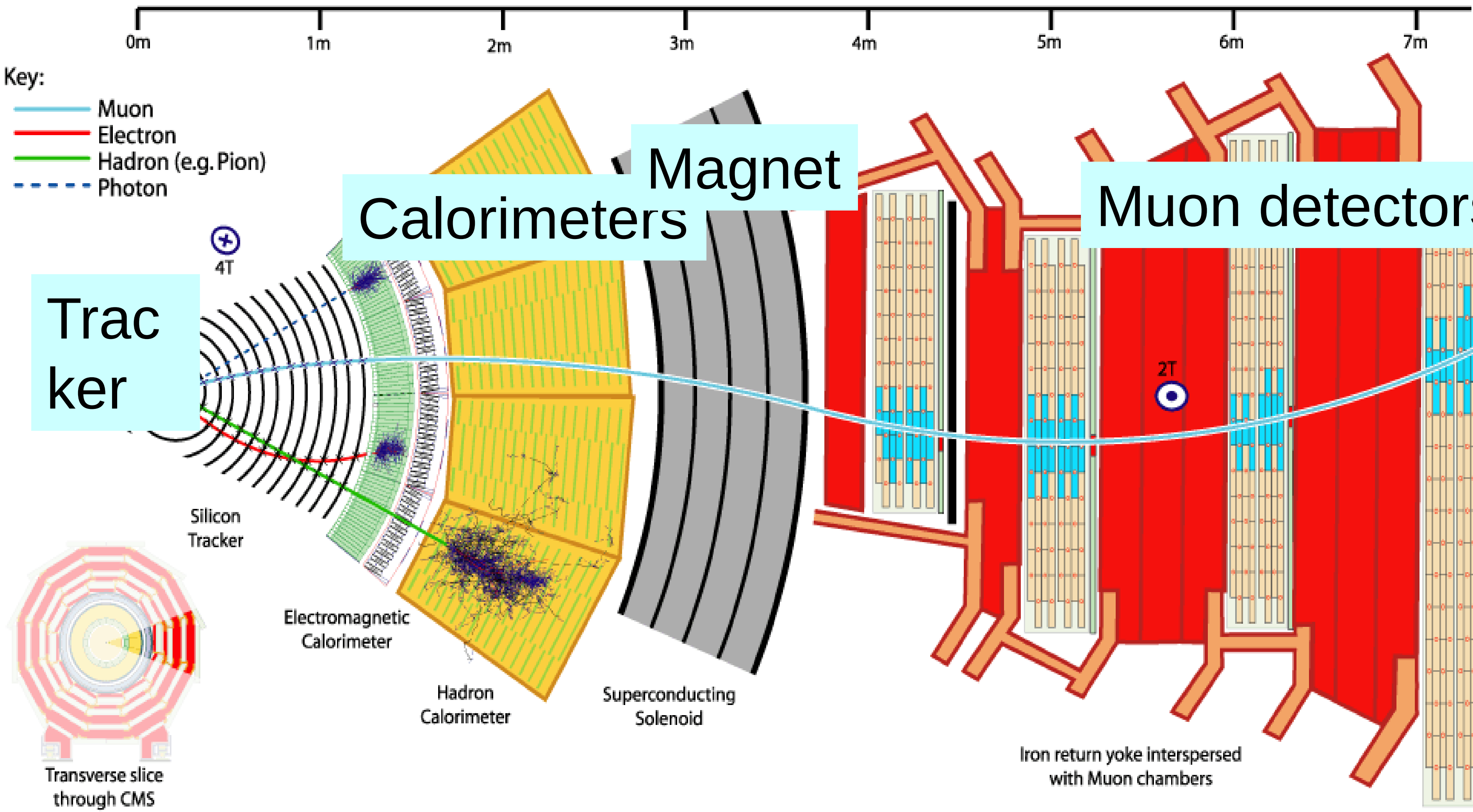
- Tracking
- Electromagnetic calo
- Hadronic calo
- Muon chambers

experiments may have special components

- Cherenkovs
- Roman pots
- Time of flight
- Photomultipliers
- Other particle ID
- …

as will be shown below

Particles in the detector



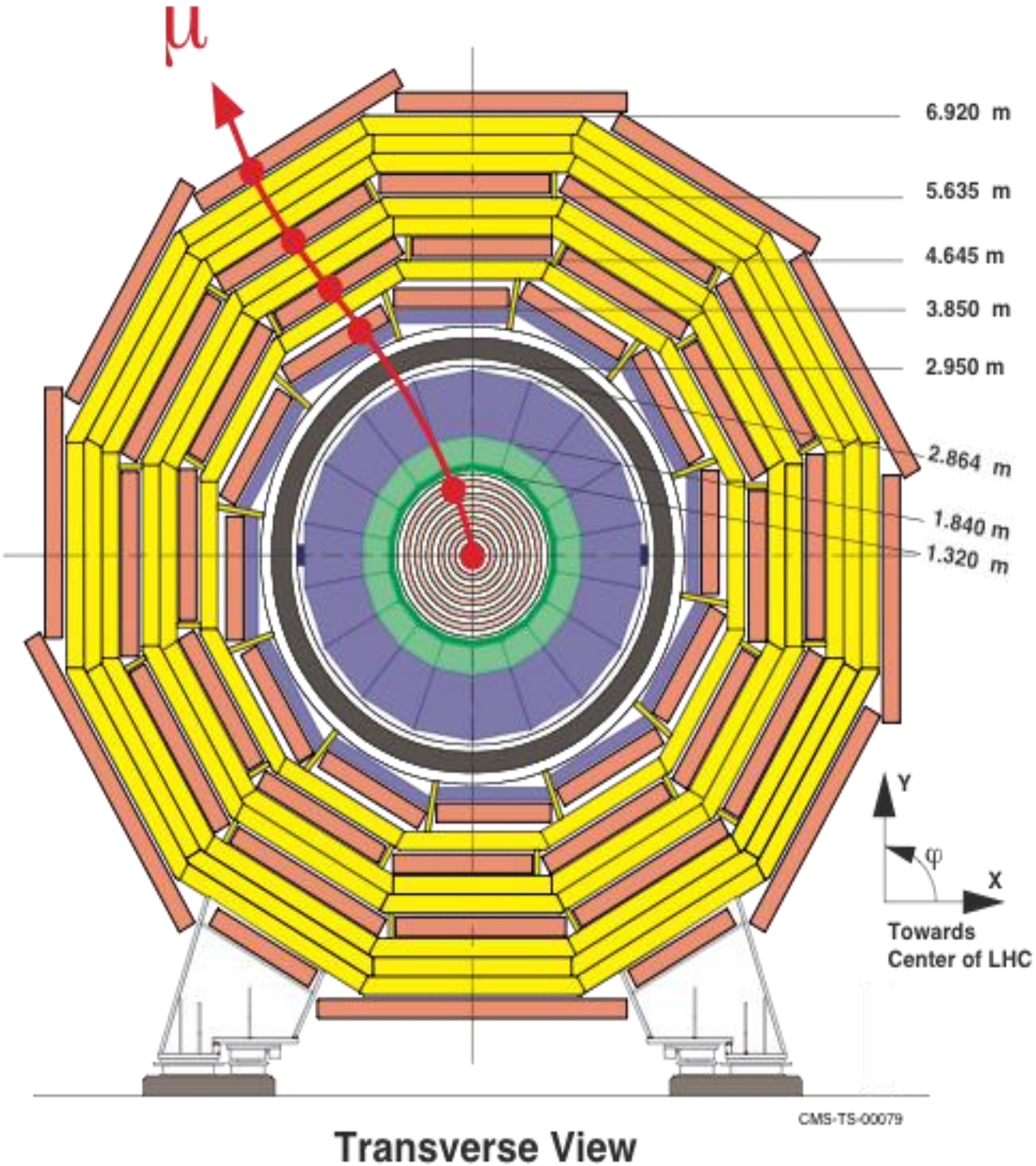
CMS Detector Design Priorities

Expression of Intent (EOI): Evian 1992

1. A robust and redundant Muon system
2. The best possible e/γ calorimeter consistent with 1.
3. A highly efficient Tracking system consistent with 1. and 2.
4. A hermetic calorimeter system.
5. A financially affordable detector.

Compact Muon Solenoid (CMS)

Letter of Intent (LOI): LHCC, TDR in 1994



Strong Field 4T

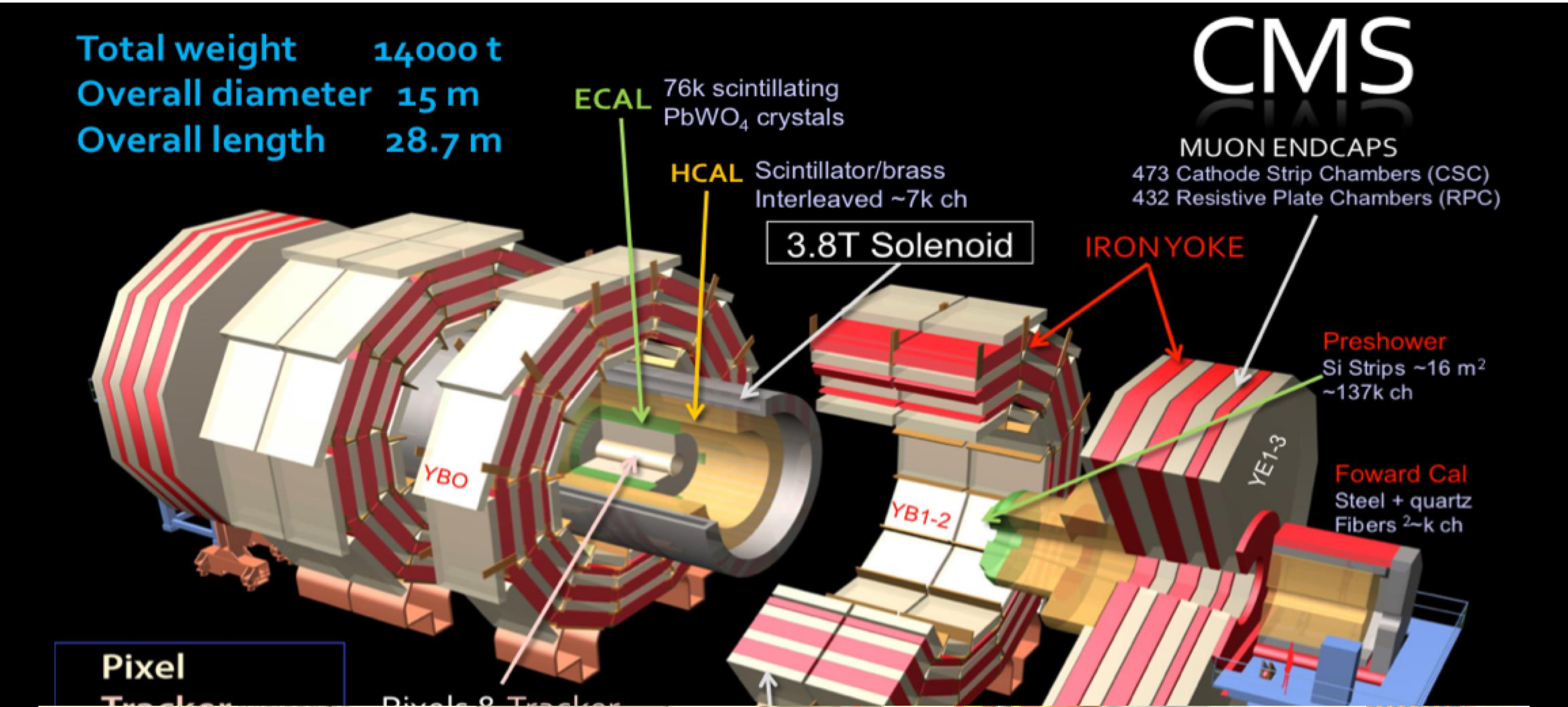
Compact design

Solenoid for Muon P_T trigger in transverse plane

Redundancy: 4 muon stations with 32 R-phi measurements

$\Delta P_t/P_t \sim 5\%$ @1TeV for reasonable space resolution of muon chambers (200μm)

The Compact Muon Solenoid Experiment



In total about

~100 000 000 electronic channels

Each channel checked

40 000 000 times per second (collision rate is 40 MHz)

An on-line trigger selects events and reduces the rate from 40MHz to 100 Hz

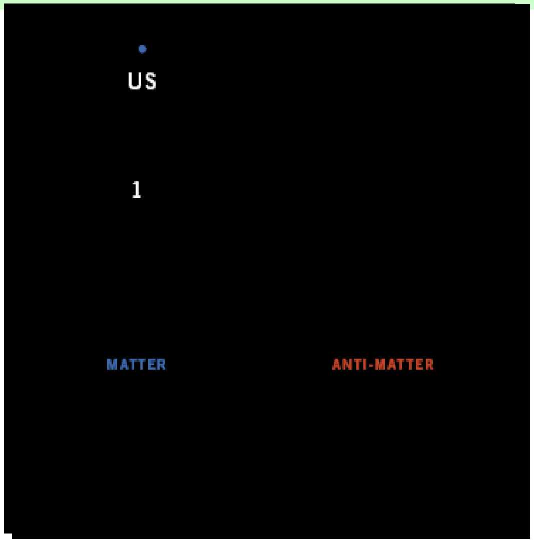
Amount of data of just one collisions

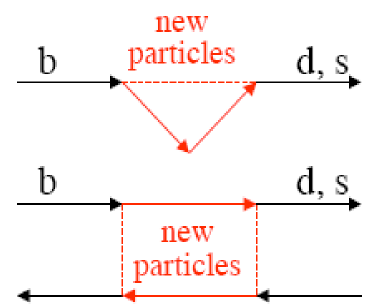
> 500 000 Bytes

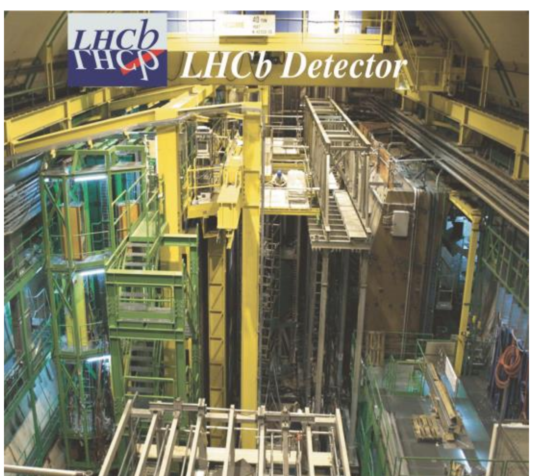
CMS before closure

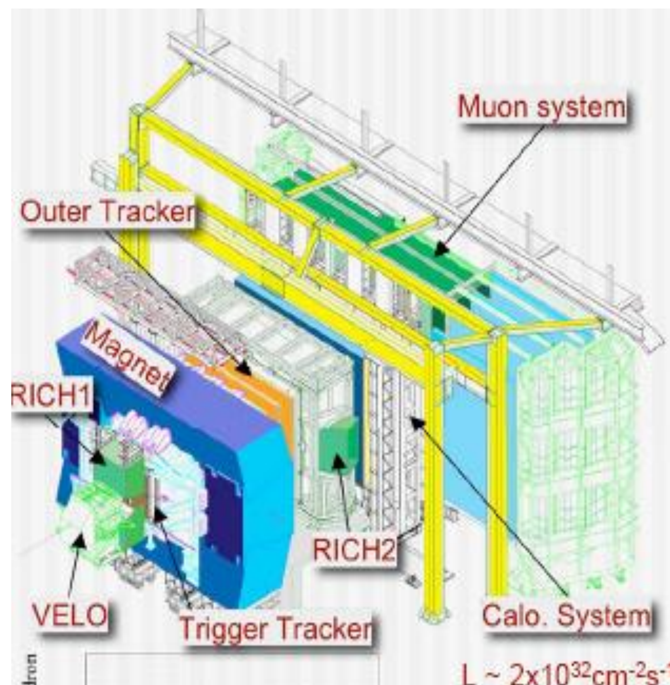
Other Experiments: Matter-Antimatter

The properties and subtle differences of matter and anti-matter using mesons containing the beauty quark, will be studied further in the LHCb experiment

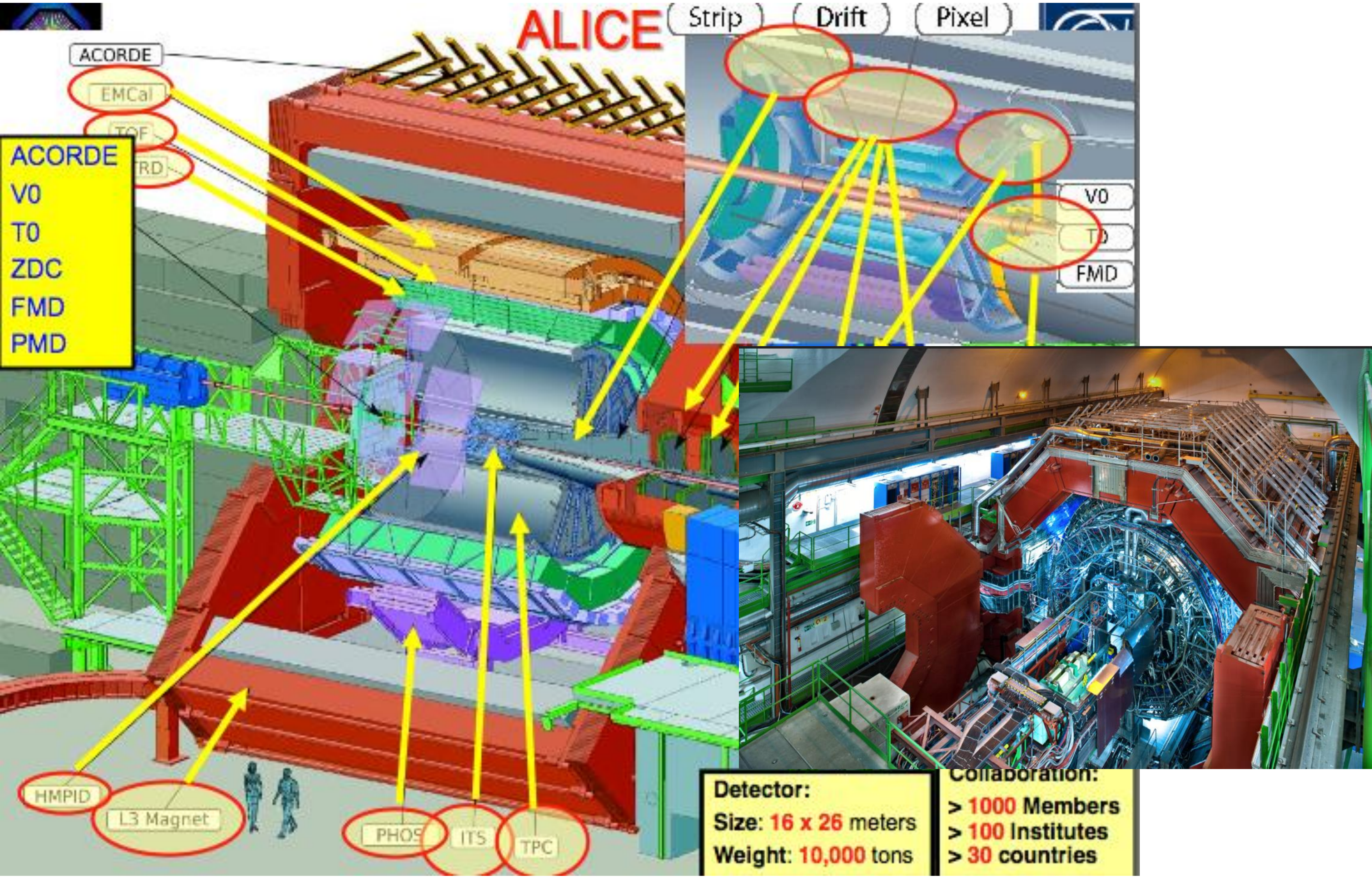








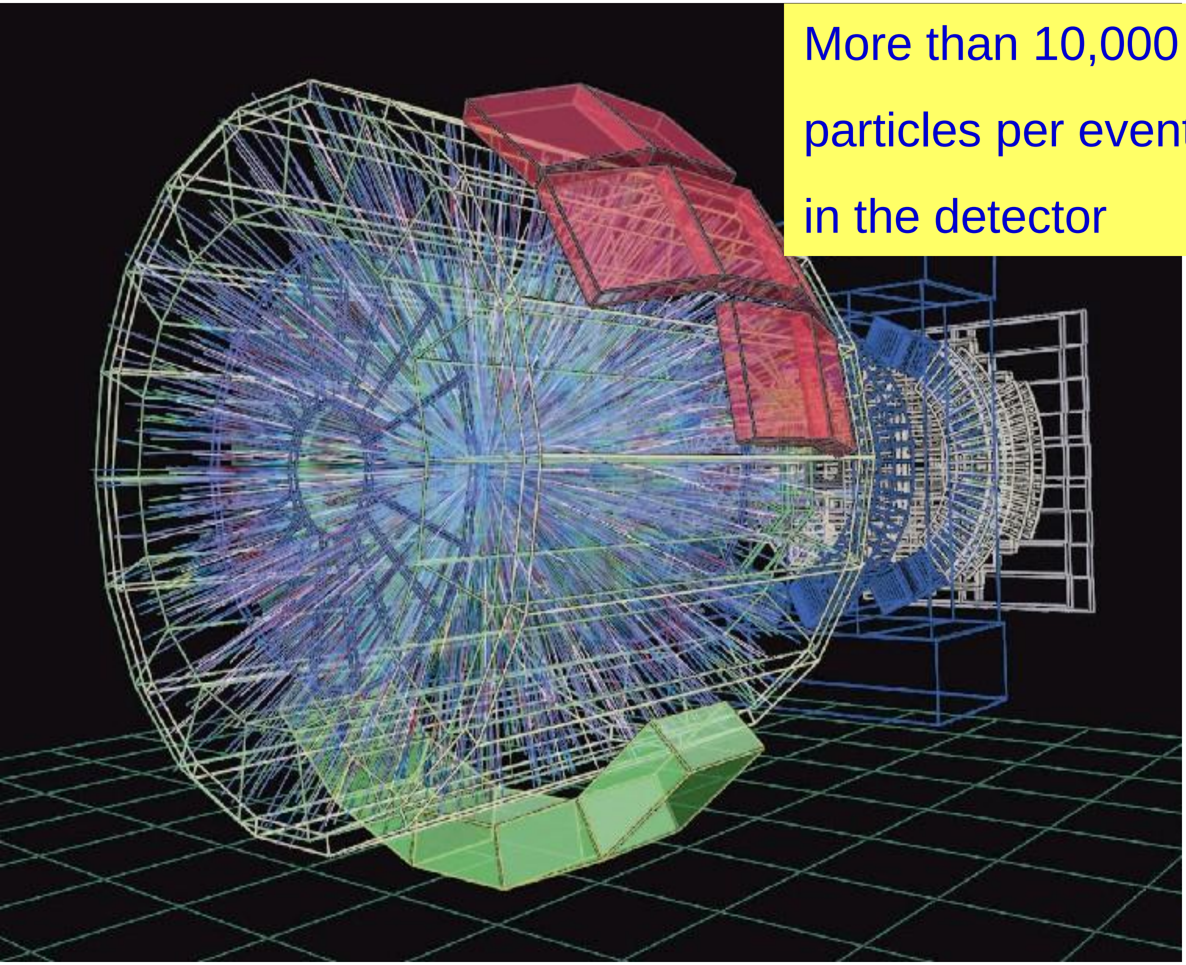
ALICE: Heavy Ion Physics at the LHC



Primordial Plasma

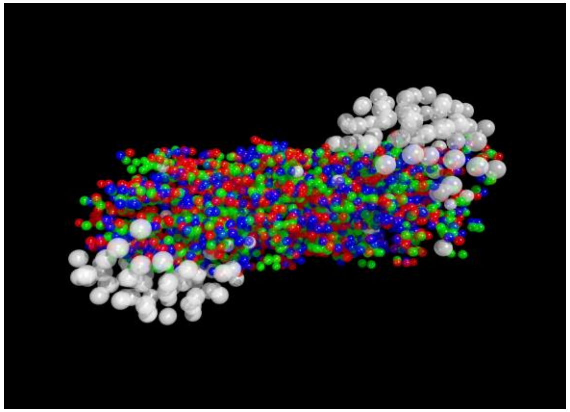
Lead-lead collisions at the LHC to study the primordial plasma,

a state of matter in the early moments of the Universe



More than 10,000 particles per event in the detector

A lead lead collision simulated in the ALICE detector

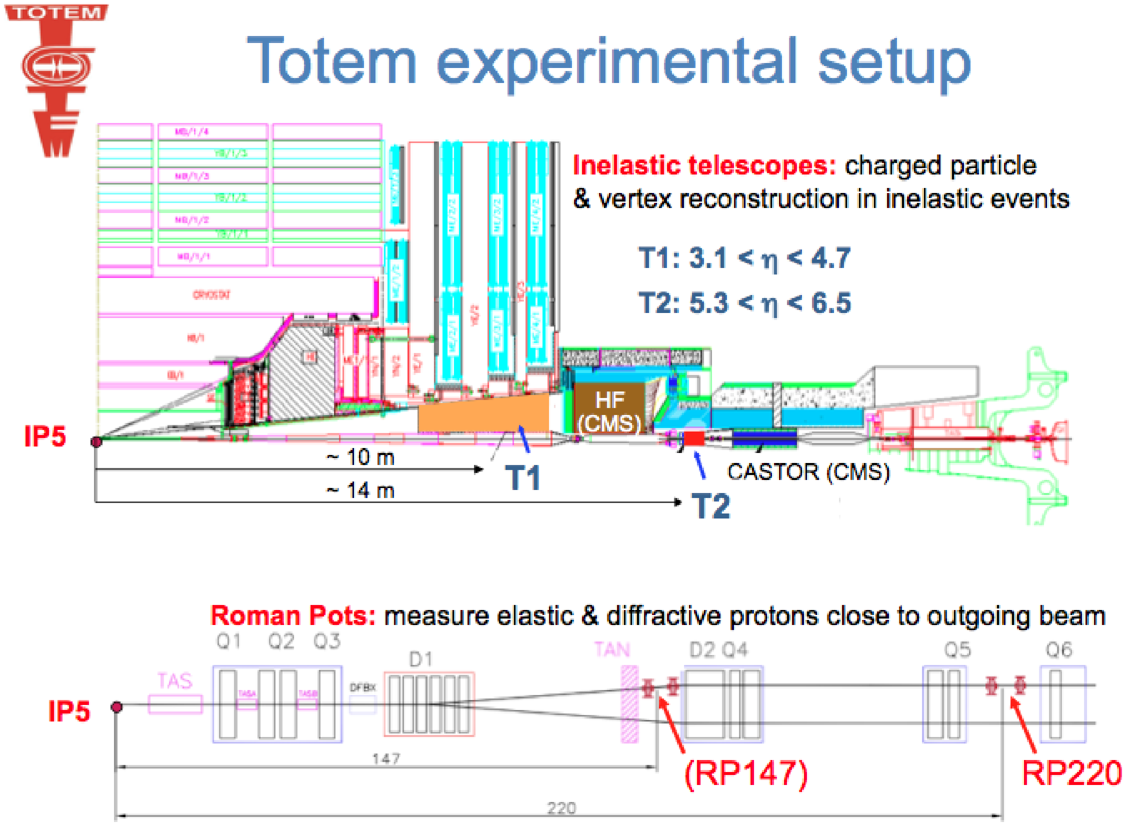


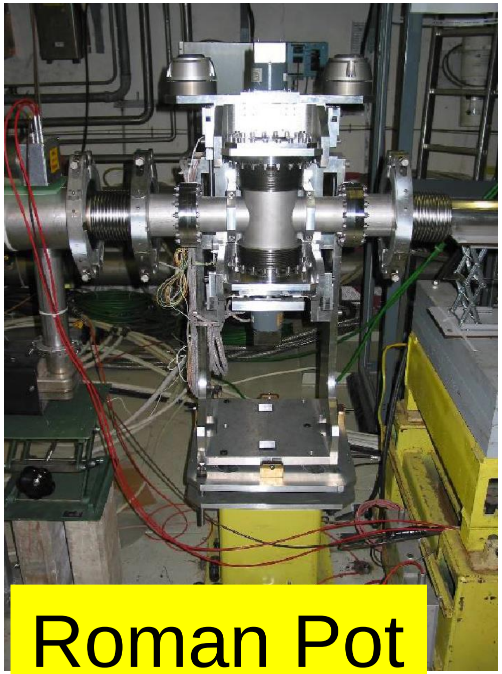
Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today

TOTEM Detector

TOTEM uses the same Interaction Point as CMS (IP5)

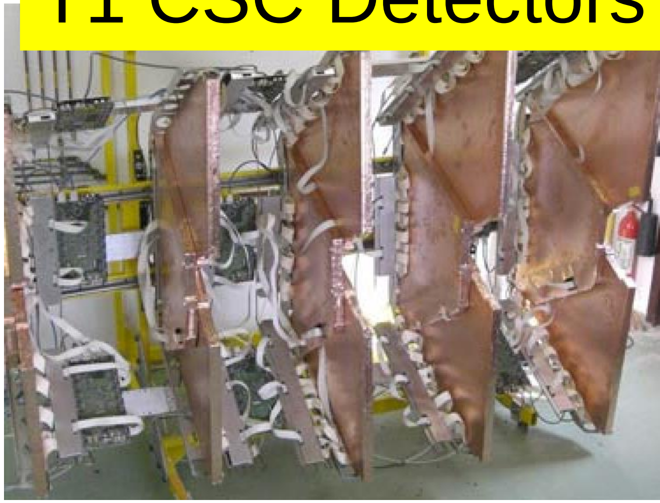
TOTEM has forward detectors and Near Beam Detectors (Roman Pots 150m-220m away from the IP)





Roman Pot

T1 CSC Detectors

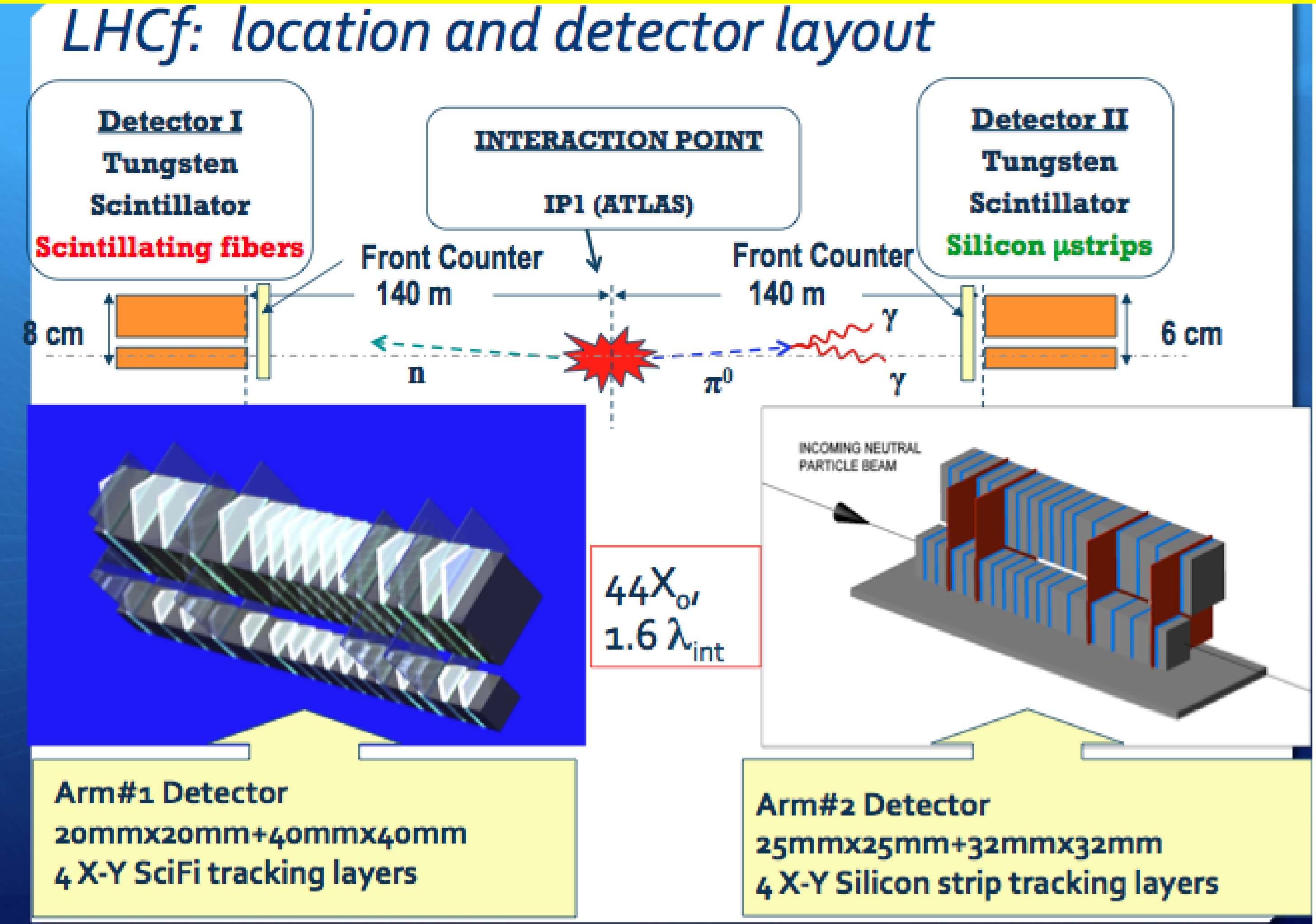


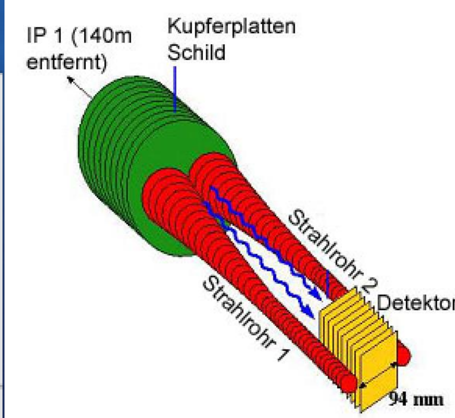
Physics Goals: Total cross section; Elastic cross section; Diffractive studies

LHCf Experiment

LHCf uses the same Interaction Point as ATLAS (IP1)

LHCf has forward detectors at zero degrees seen from the IP (140 away from the IP)

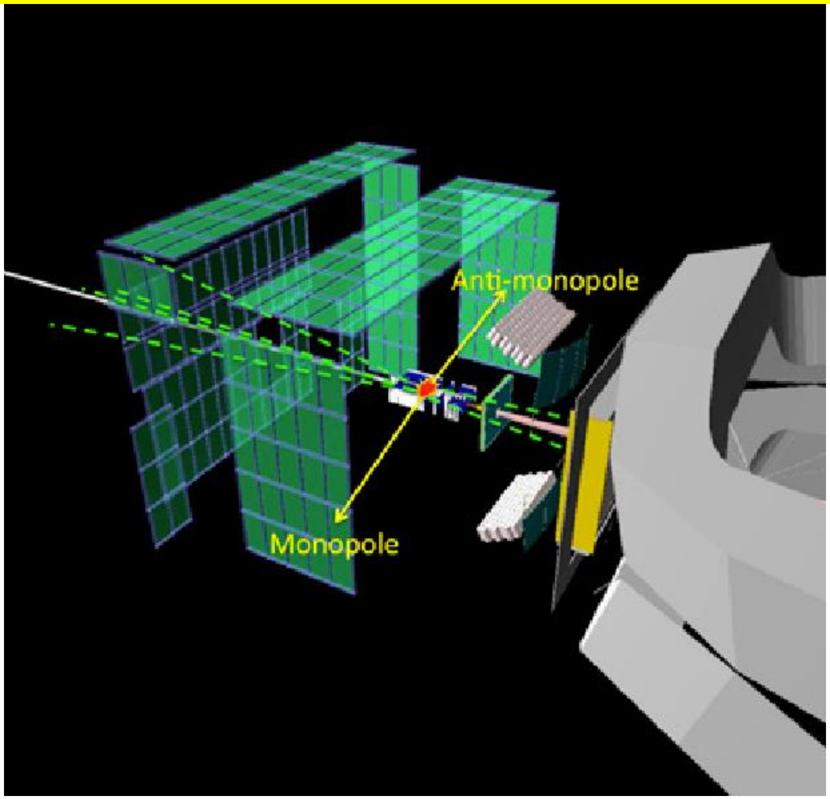


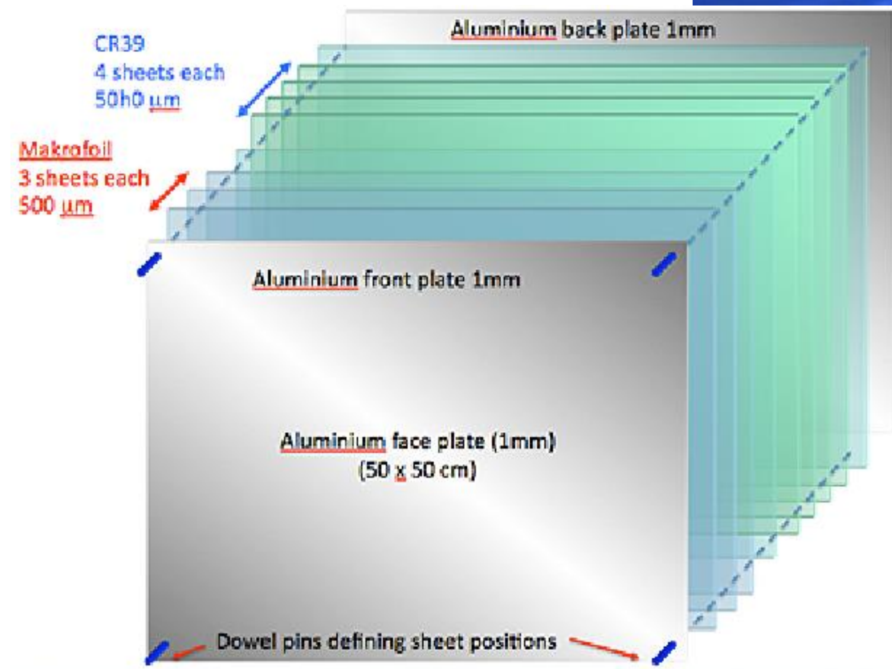


The MoEDAL Experiment

An experiment to look for heavily ionizing particles like monopoles

Uses the same interaction point as the LHCb experiment





The breaking of the polymeric bonds of plastic by a crossing charged particle

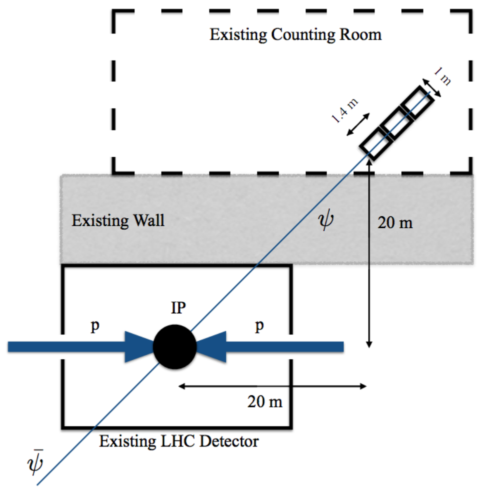
-> Heavily ionizing particles burn a hole in the polymer sheets!!!

Particles with Milli-Charges?

CMS search for fractional charged particle arXiv:1210.2311

Q=1/3e > 140 GeV; Q=2/3e >310 GeV (95% CL. dE/dx)

A "new" idea -> Hunting for particles with charges ~ 0.1-0.001e arXiv:1410.6816

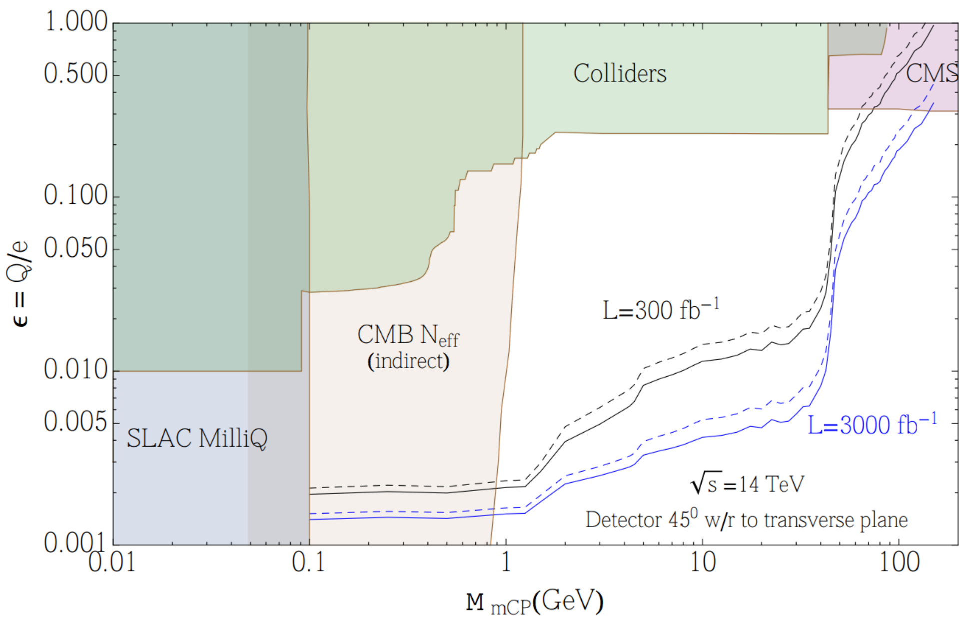


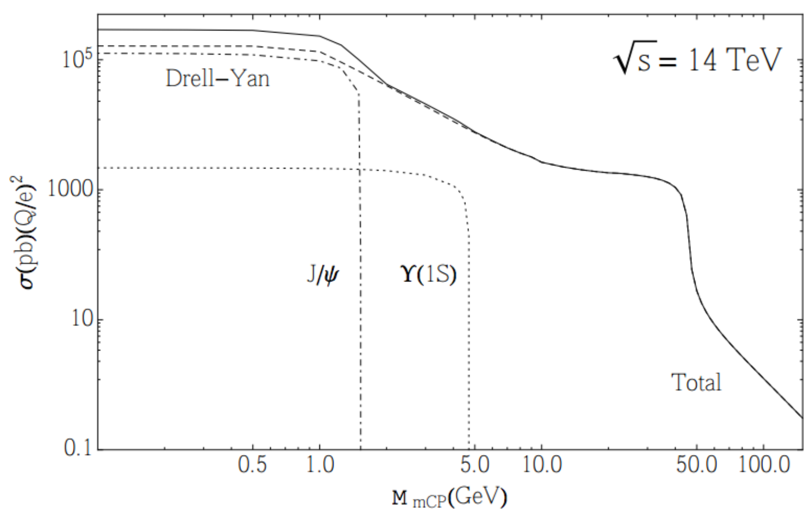
Looking for milli-charged particles with a new experiment at the LHC

Andrew Haas, Christopher S. Hill, Eder Izaguirre, Itay Yavin

(Submitted on 24 Oct 2014)

We propose a new experiment at the Large Hadron Collider (LHC) that offers a powerful and model-independent probe for milli-charged particles. This experiment could be sensitive to charges in the range $10^{-3}e - 10^{-1}e$ for masses in the range $0.1 - 100$ GeV, which is the least constrained part of the parameter space for milli-charged particles. This is a new window of opportunity for exploring physics beyond the Standard Model at the LHC.





End of Lecture 2