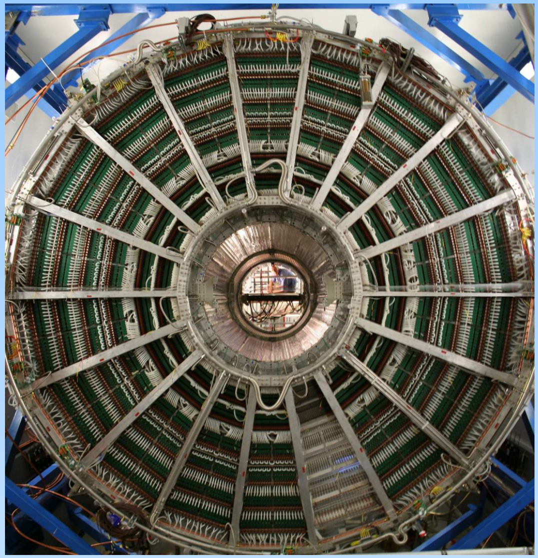
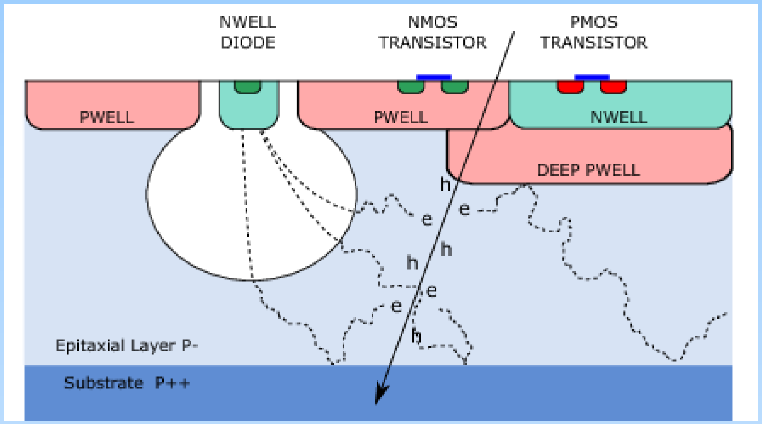




The physics of particle detectors - Introduction -

Silvia Masciocchi,
GSI and University of Heidelberg

SS2016, Heidelberg
April 20, 2016

Lectures + Journal Club

Web page:
http://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors/

Lectures by me (Silvia)
Wednesday, 9:15 – 10:45/11:00
INF 227, Room 2.403
No lecture on May 11, 2016

Journal Club: Dirk Wiedner, Peter Glässel, SM
Friday, time to be discussed
INF 226, Room 1.106

Credits, grades, exam ...

Outline

General discussion about the course

Today:

- Historical notes
- Beams, accelerators
- Experiments: an overview
- My own “historical notes”

Material from previous courses:

2011 H.-C. Schultz-Coulon www.kip.uni-heidelberg.de/~coulon/Lectures/Detectors

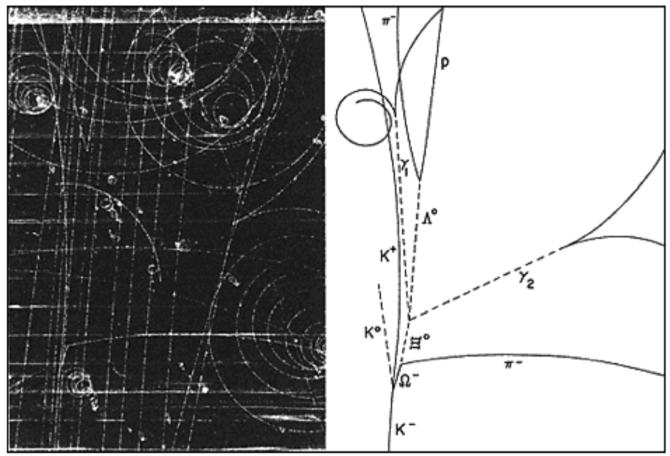
2013 R. Averbeck web-docs.gsi.de/~averbeck/hd_ss13_inactive

2015 J. Stachel www.physi.uni-heidelberg.de/~fschney/detektoren/detec

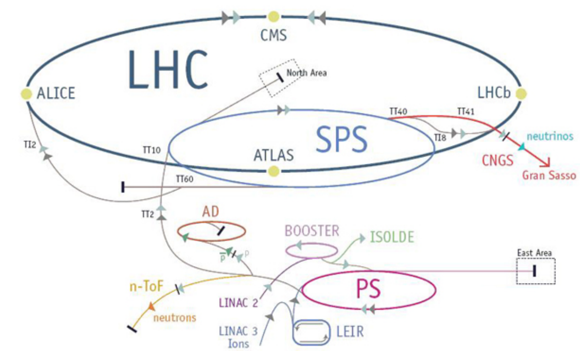
Historical notes

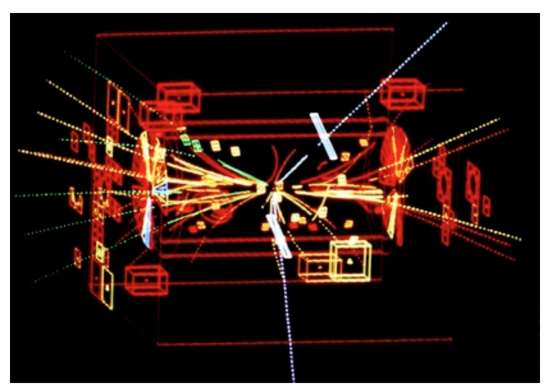
Progress in nuclear and particle physics has been

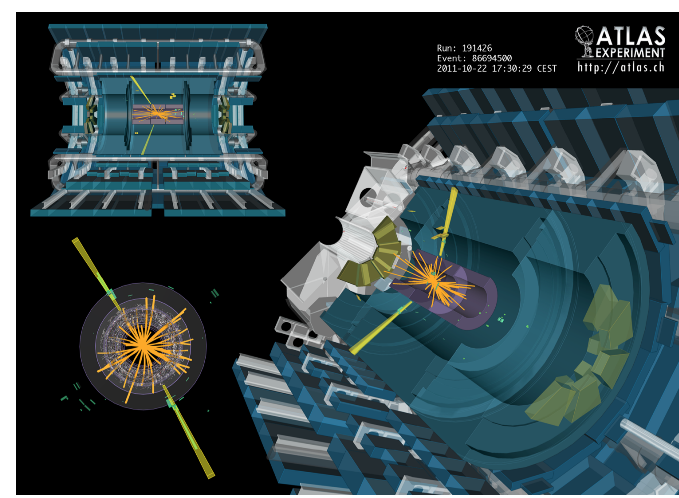
- mostly driven by experimental observations
- critically coupled with the development of new methods in particle acceleration and particle detection



first Ω⁻ event seen in the 80" bubble chamber at the BNL Alternating Gradient Synchrotron

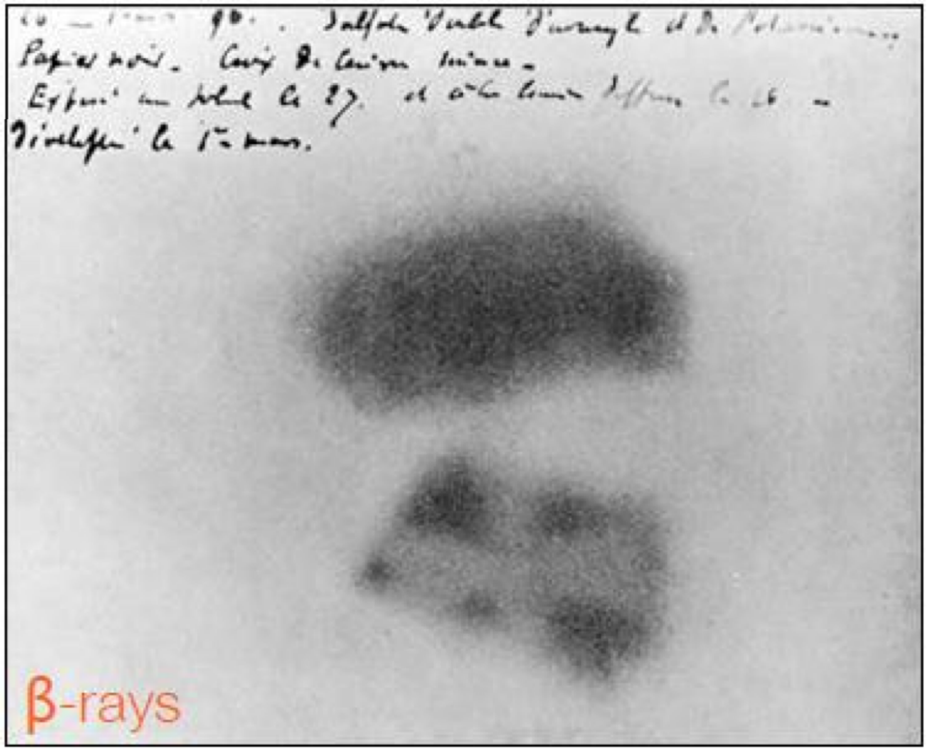






Detection of nuclear decays

1896: first detection of β- and γ-rays

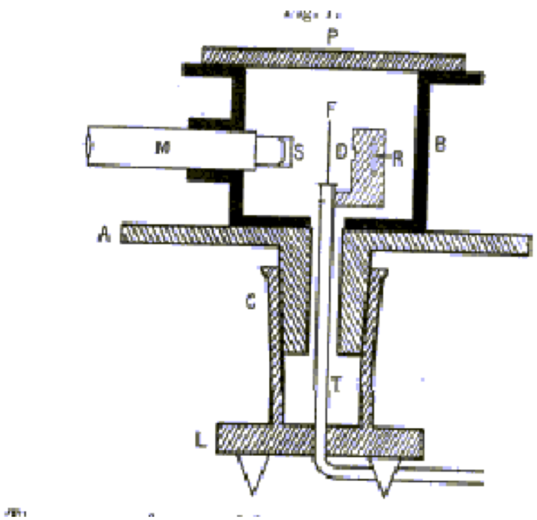


Bequerel: photographic plate which was exposed to radiation from a uranium salt

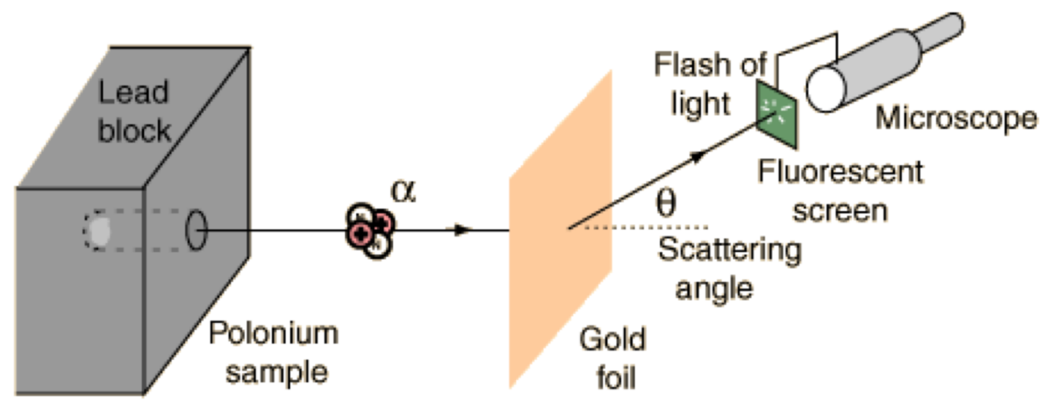
Röntgen: x-ray picture of R.A. Von Kölliker's hand

Rutherford scattering

1911: Geiger, Marsden and Rutherford discover the atomic nucleus



Original experimental setup



Schematic view of Rutherford's scattering experiment

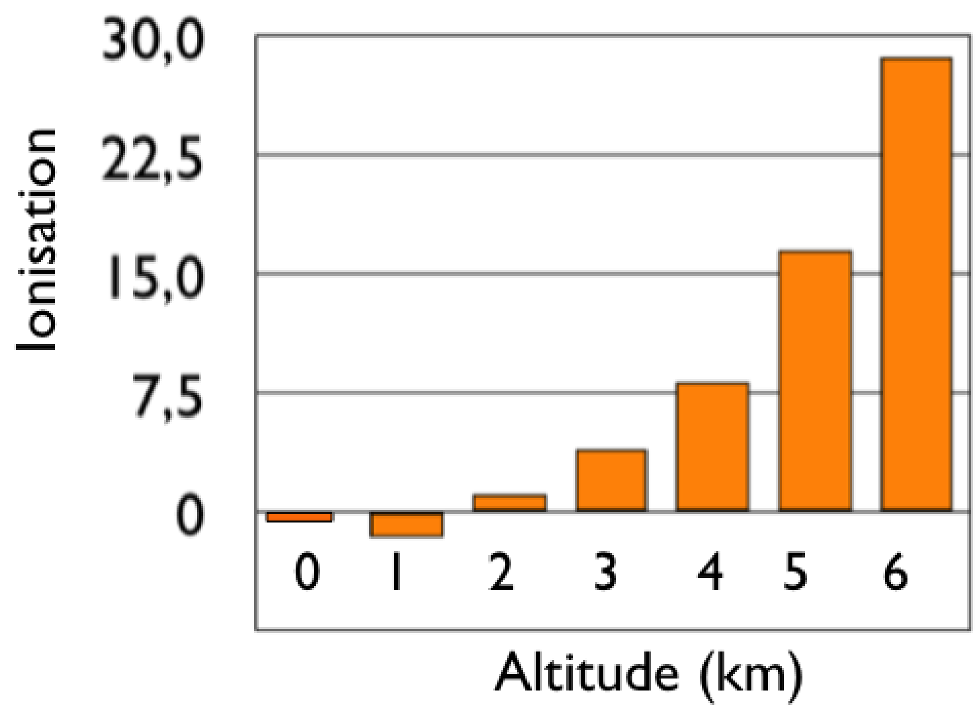
IMPORTANT prototype of modern scattering experiments:

- Calibrated probe: α particles
- Calibrated interaction of probe with medium: EM interaction

→ learn about structure of the probed medium: atoms have a nucleus

Detection of cosmic rays

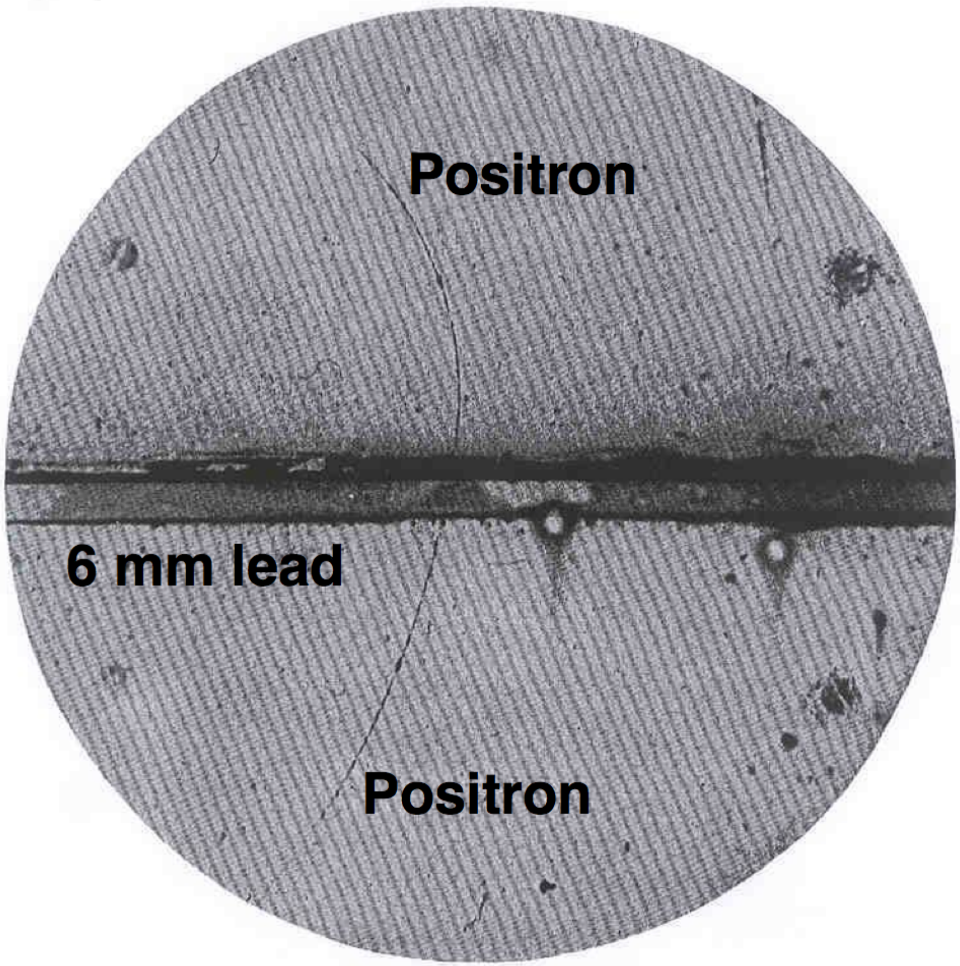
1912: Victor F. Hess discovers cosmic rays during balloon experiments



Measurements done with Wulf's electrometer

Discovery of anti-matter

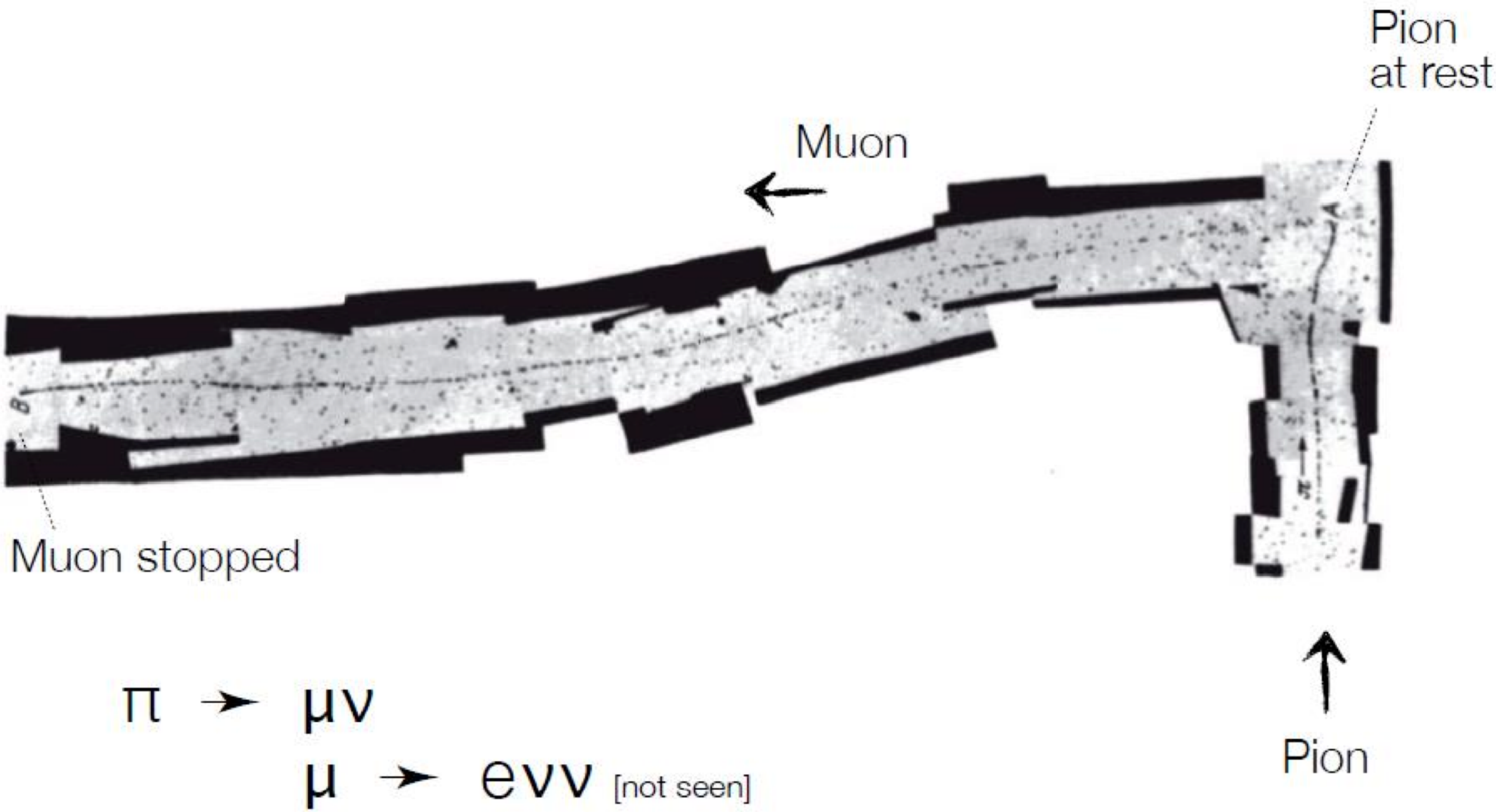
1932: Anderson discovers anti-matter when studying cosmic rays using a cloud chamber in a magnetic field



63 MeV positron passing through a lead plate emerging as a 23 MeV positron

Discovery of the pion

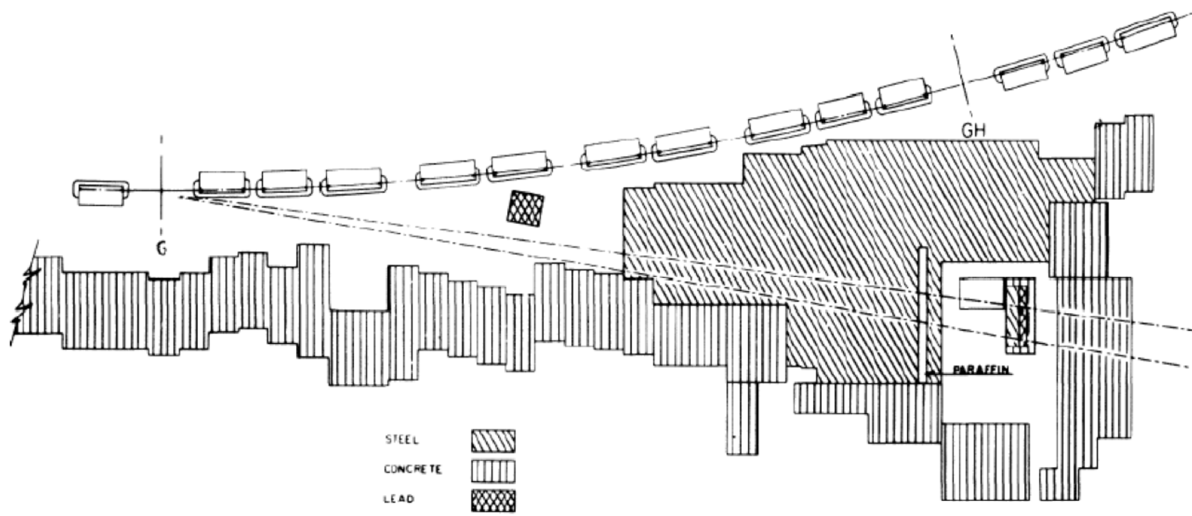
1947: Powell discovers the pion using the nuclear emulsion technique (still with cosmic rays!)



Discovery of the muon neutrino

1962: L. Lederman, M. Schwartz, and J. Steinberg discover the muonic neutrino, ν_μ

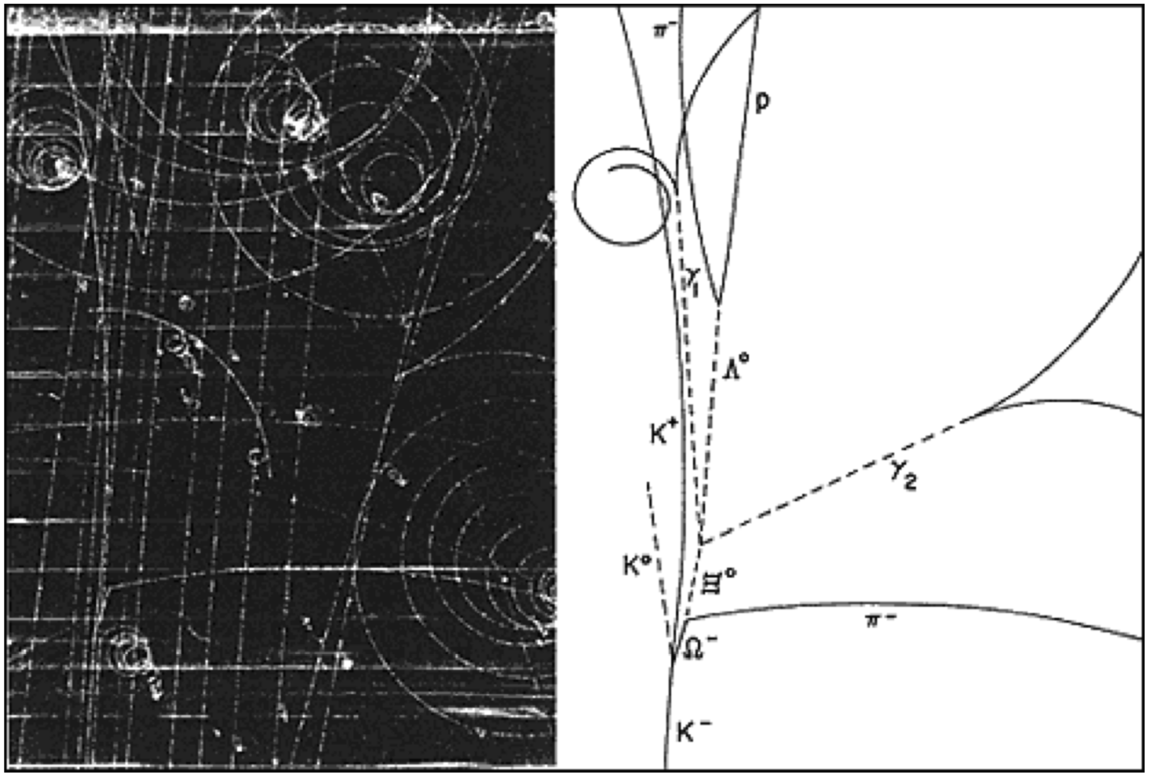
Mel Schwartz in front of the spark chamber



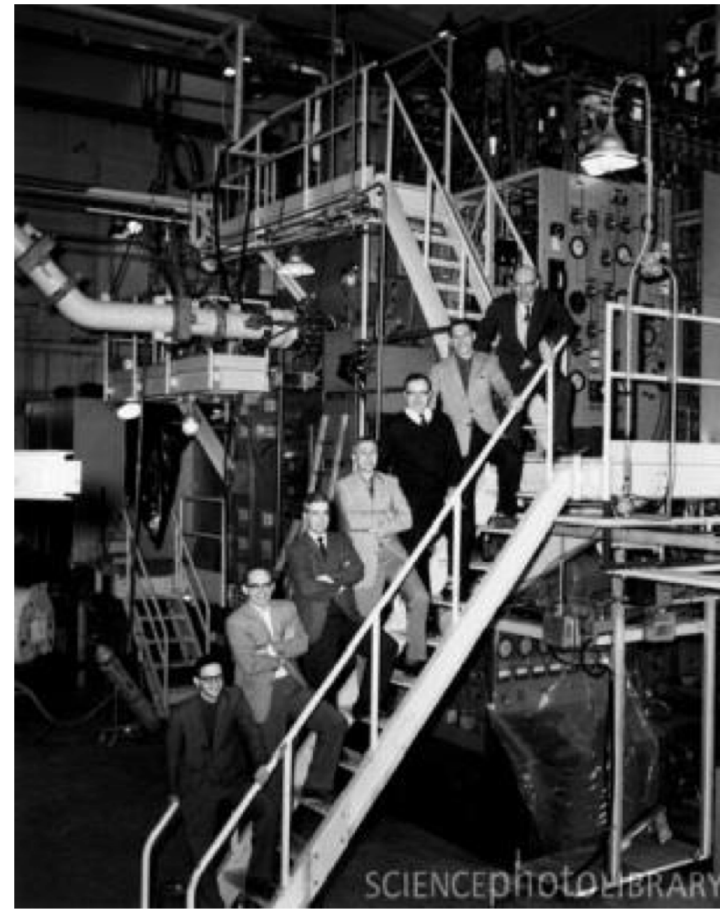
first neutrino beam facility at the BNL AGS

Observation of the Ω^-

1964: Samios et al. find the Ω^- baryon



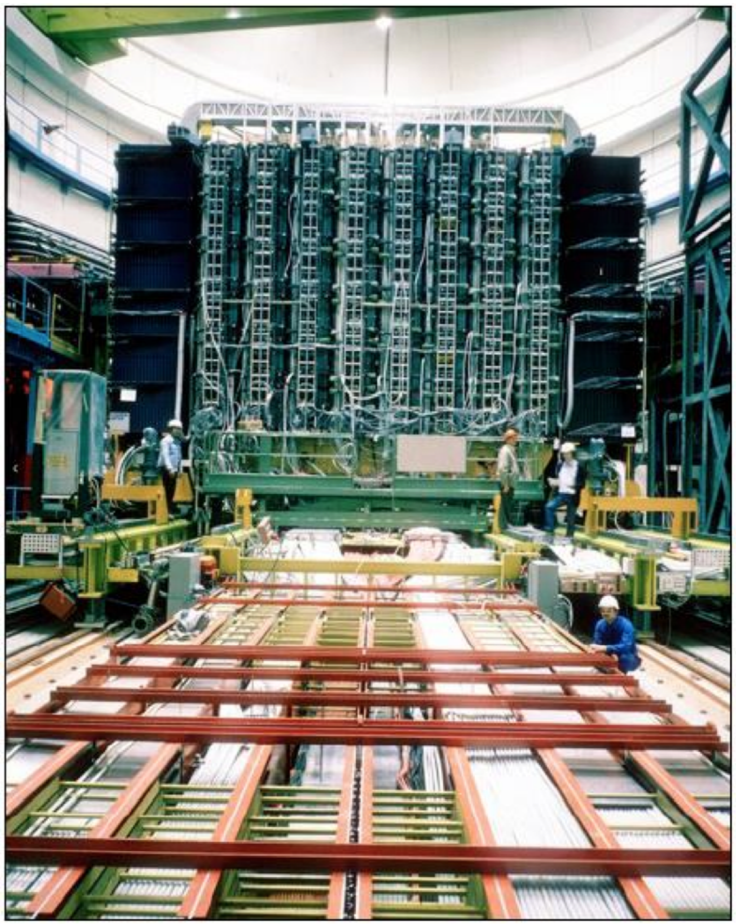
first Ω^- event seen in the 80" bubble chamber at the BNL Alternating Gradient Synchrotron



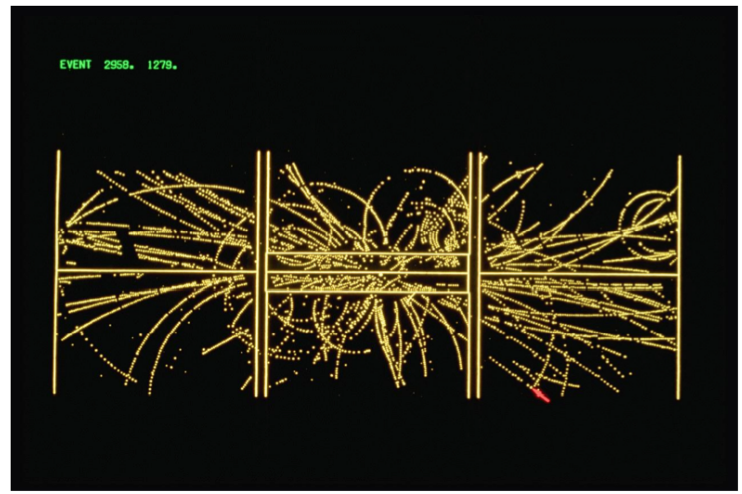
Existence of the Ω^- baryon (mass, charge, strangeness) was PREDICTED by the quark model!

Discovery of the W/Z bosons

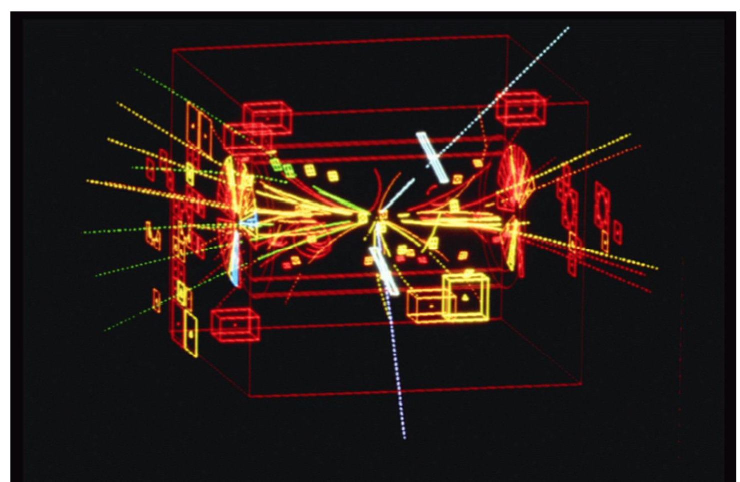
1983: UA1 and UA2 experiments discover the W and Z bosons at the CERN $Sp\bar{p}S$ collider



UA1 detector



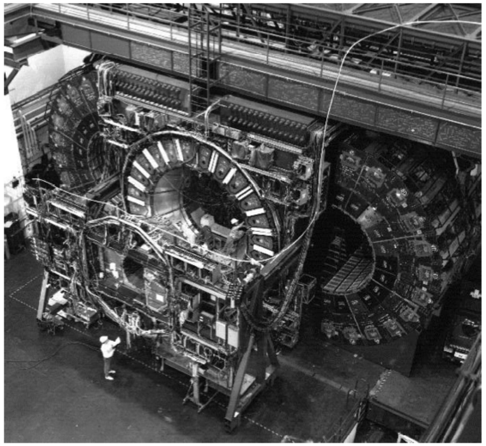
first W event in UA1: W→eν



first Z^0 event in UA1: $Z^0 \rightarrow e^+e^-$

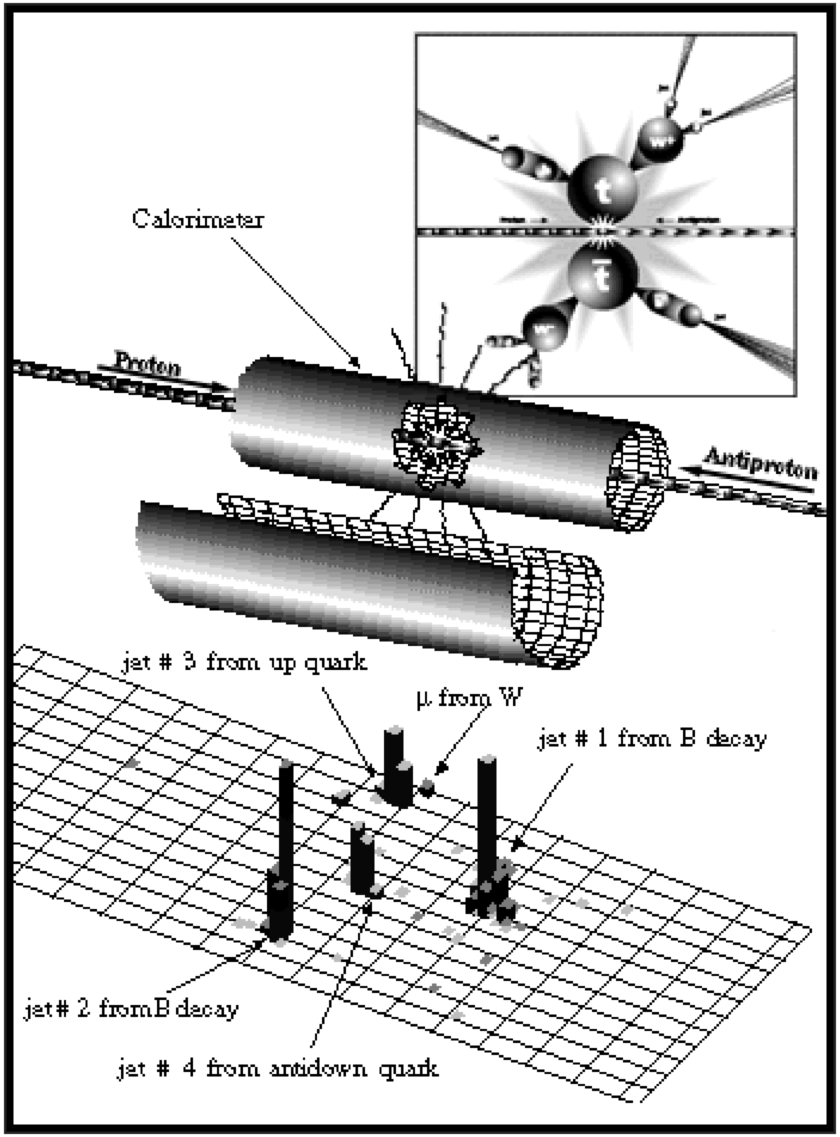
Discovery of the top quark

1995: CDF and D0 discover the top quark at the FNAL Tevatron $p\bar{p}$ collider



CDF detector

- **no 'smoking gun' discovery but 'statistical evidence'**



N. Hadley (D0): "We discovered the top quark not in one lightning stroke, but over long period of time, event by event. No single piece of evidence, no matter how strong, was enough to let us claim a discovery. We couldn't be sure we had found the top quark until we had seen so many events with the right characteristics that there was almost no chance the statistics were fooling us into making a false claim."

Some relevant Nobel prizes - 1

1901	Physics	Wilhelm C. Röntgen	X-rays (1896) [Photographic plate]
1903	Physics	Antoine H. Becquerel Marie Curie Pierre Curie	Radioactivity (1896/99) [Photographic plate & electrometer]
1905	Physics	Philipp Lenard	Lenard window (1904) [Phosphorescent material]
1908	Chemistry	Ernest Rutherford	Atomic nucleus (1911) [Scintillating crystals]
1927	Physics	Charles T. R. Wilson	Cloud chamber (1912)
1935	Physics	James Chadwick	Neutron discovery (1932) [Ionization chamber]
1936	Physics	Victor F. Hess Carl D. Anderson	Cosmic rays (1912) Positron discovery (1932) [Electrometer & cloud chamber]

Some relevant Nobel prizes - 2

1948	Physics	Patrick M. S. Blackett	e^+e^- Production ... (1933) [Advanced cloud chambers]
1950	Physics	Cecil F. Powell	Pion discovery (1947) [Photographic emulsion]
1953	Physics	Walter Bothe	Coincidence method (1924)
1958	Physics	Pavel A. Cherenkov	Cherenkov effect (1934)
1959	Physics	Emilio G. Segrè Owen Chamberlain	Antiproton discovery (1955) [Spectrometer; Cherenkov counter ...]
1960	Physics	Donald A. Glaser	Bubble chamber (1953)
1976	Physics	Burton Richter Samuel C.C. Ting	J/ψ discovery (1974) [AGS Synchrotron; pBe collisions] [SLAC e^+e^- collider; MARK I]
1980	Physics	James Cronin Val Fitch	CP violation (1963) [Spark chamber; spectrometer]

Some relevant Nobel prizes - 3

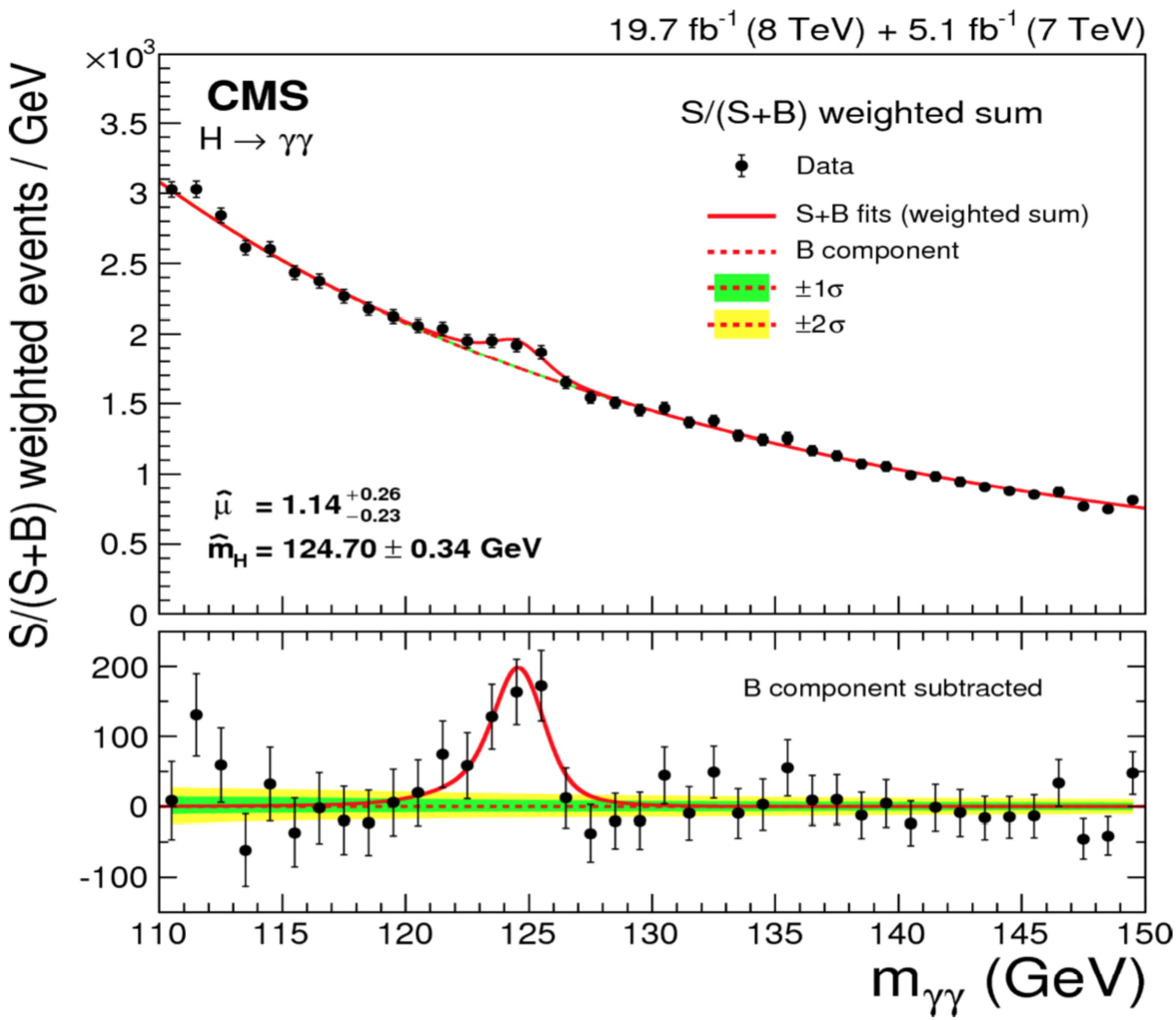
1984	Physics	Carlo Rubbia, Simon Van der Meer	W/Z discovery (1983) [SPS; 4π multi-purpose detector]
1988	Physics	Leon M. Lederman Melvin Schwartz Jack Steinberger	Muon neutrino (1962) [Neutrino beam; spark chambers]
1990	Physics	Jerome I. Friedman Henry W. Kendall Richard E. Taylor	Proton structure (1972+) [ep scattering; spectrometer]
1989	Physics	Hans G. Dehmelt Wolfgang Paul	Electron g-2 (1986) [Ion trap technique]
1992	Physics	Georges Charpak	Multi-Wire Chamber (1968)
2002	Physics	Raymond Davis Jr. Masatoshi Koshiba	Cosmic neutrino (1986) [Large area neutrino detector]
2013	Physics	Francois Engler Peter Higgs	Higgs mechanism [ATLAS and CMS]

Discovery of the Higgs: 2012

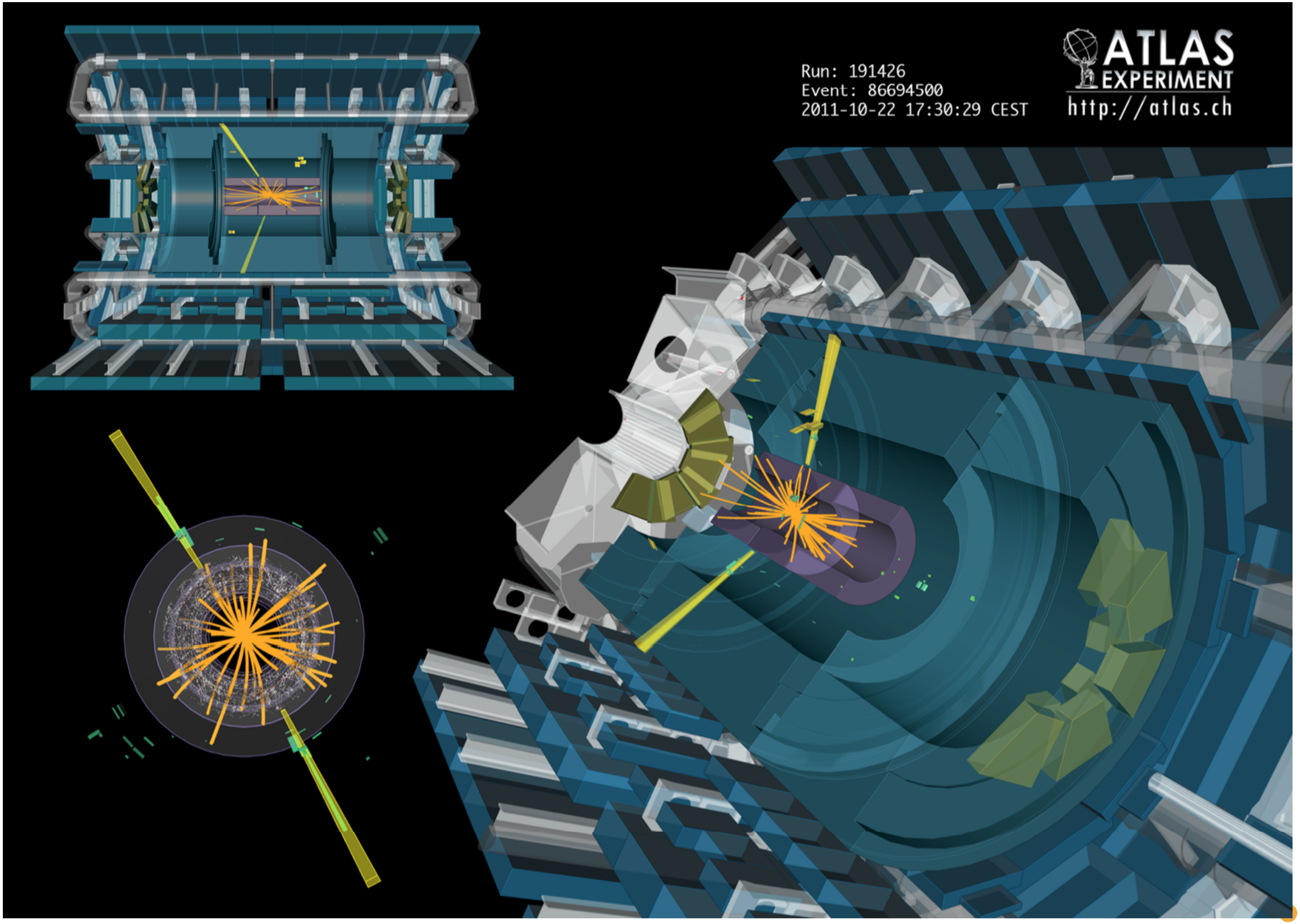
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Francois Engler & Peter Higgs (Nobelpreis 2013)

Discovery of the Higgs: 2012



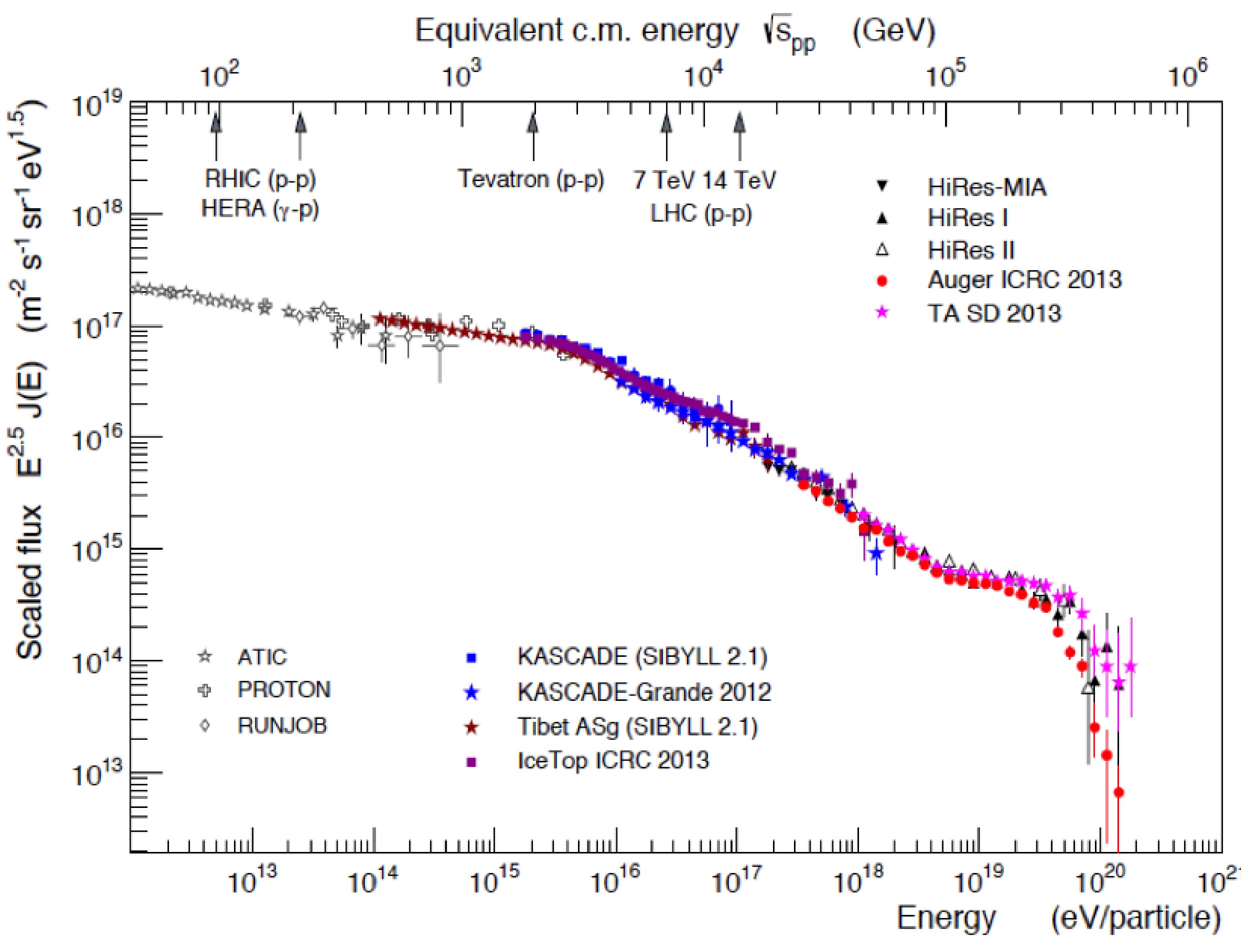
Discovery of the Higgs: 2012



Beams - 1

Uncontrolled collisions: cosmic radiation

- Beam energy and particle type not controlled
- Many discoveries
- EXTREMELY high energies



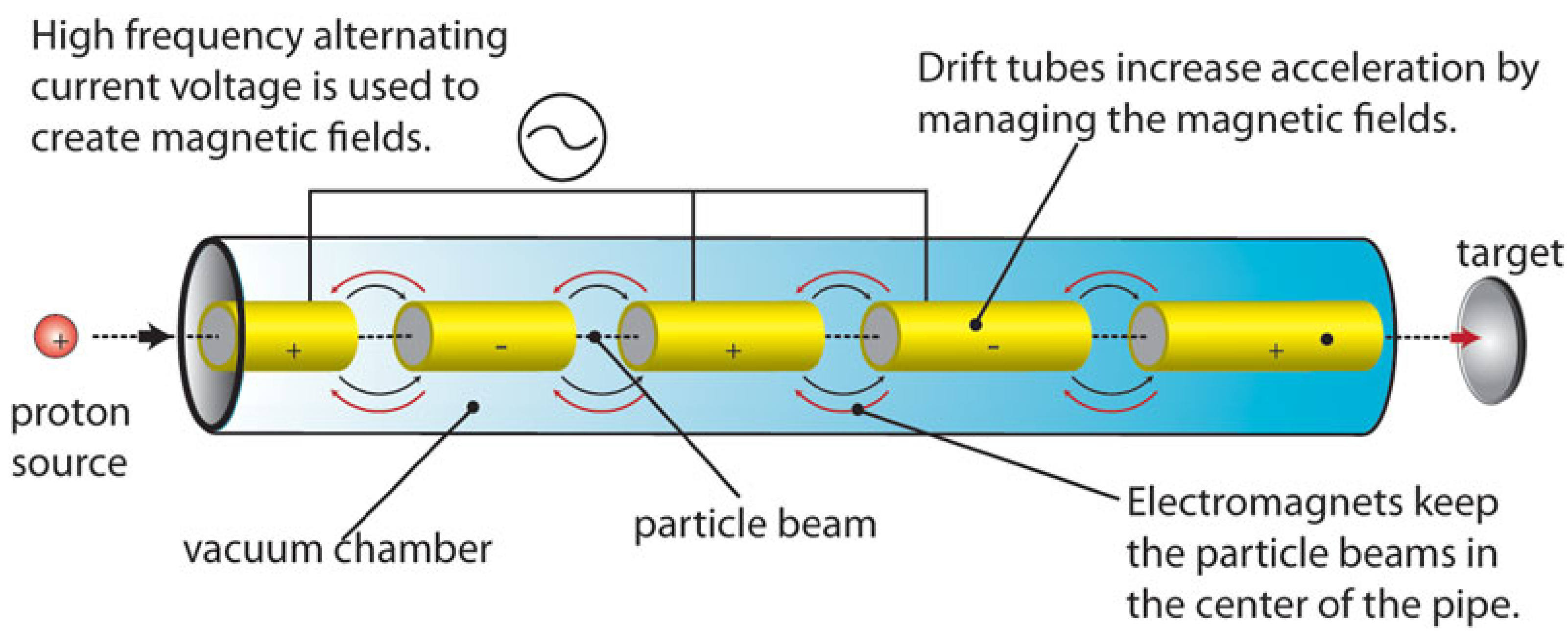
Beams - 2

Controlled collisions: particle accelerators

Charged particles traverse potential difference

- **Linear accelerator, LINAC**

  particles traverse many successive potential differences
  - RF cavity resonators, typically 8 MV/m (future ILC > 35 MV/m)
  - Particles surf on the wave-crest through the cavities
  - Scalable to very high energies, high cost due to length
  - Particles not “used” in collisions are lost



Beams

Controlled collisions: particle accelerators

Charged particles traverse potential difference

- **Circular accelerators: cyclotron, synchrotron**

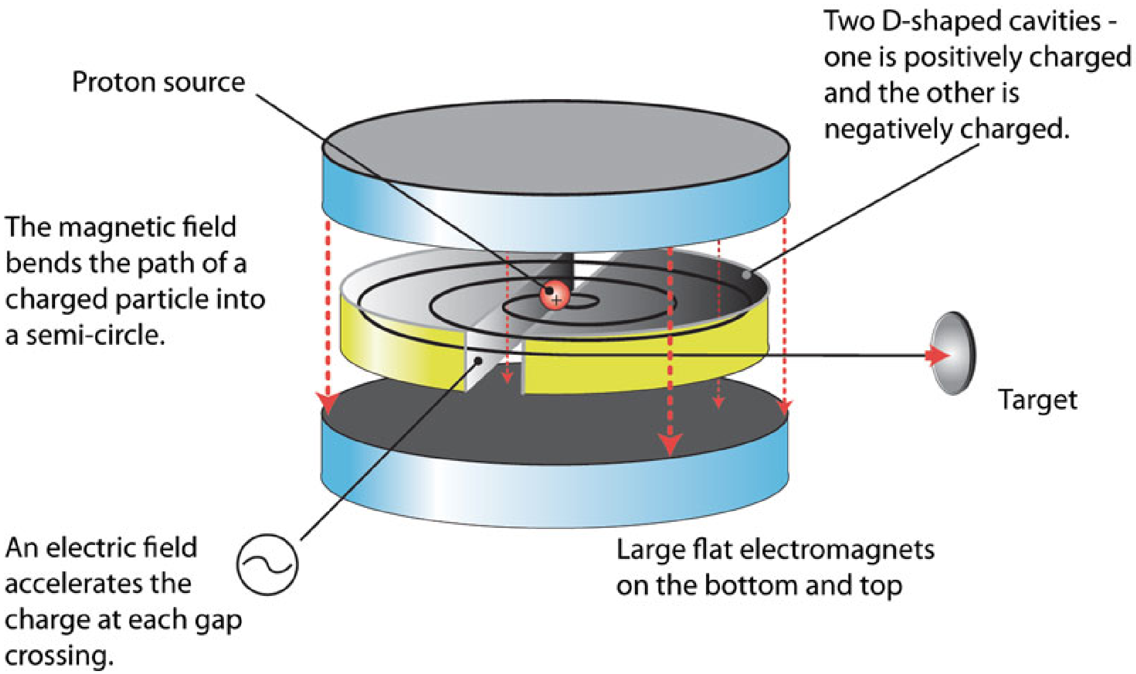
  Particles traverse the same potential difference many times

  - acceleration in RF cavities, magnetic field keeps particle on circular orbit
  - Cyclotron condition:

$$p = e\,B\,R$$

$$p\,(\mathrm{GeV}/c) = 0.3\,B(\mathrm{T})\,R(\mathrm{m})$$

Conventional coils: 1.5 T
Superconducting coils:
Tevatron: 5 T
LHC: 10 T
FCC: 16-20 T



Beams

- **Circular accelerators: cyclotron, synchrotron**

  Synchrotron radiation:

  Particles lose energy by synchrotron radiation. Radiated power:

$$P = \frac{2e^2c}{3R^2}\frac{\beta^4}{(1-\beta^2)^2} \xrightarrow[(\beta \to 1)]{} \frac{2e^2c\gamma^4}{3R^2}$$

  radiated power per turn:

$$\Delta E = \frac{4\pi}{3}\frac{e^2\gamma^4}{R}$$

  EXAMPLES:

  - LEP: R= 4.3 km, E = 100 GeV, m_0 = 0.5 MeV/c^2, $\gamma = 2 \times 10^5$

    → ΔE = 2.24 GeV of 100 GeV
  - LHC: E = 7 TeV, m_0 = 938 MeV/c^2 → ΔE = 3.4 keV

    comparatively irrelevant

Experiment "geometry"

Energy made available in a proton – proton collision:

$$\sqrt{s} = \sqrt{(E_1+E_2)^2-(\vec{p}_1+\vec{p}_2)^2}$$

- **Fixed target experiments**

$$\sqrt{s} = m_p\sqrt{2+2\gamma_p}$$

  - Available energy increases with square root of the beam energy only
  - But high interaction rate (or "luminosity")

- **Collider experiments**

$$\sqrt{s} = 2m_p\gamma_p$$

  - Available energy = full beam energy
  - But "low" luminosity

Beam energy

Criteria to choose the beam energies

- **Threshold, reaction rate**

  $e+ \; e- \rightarrow Z^0 + \text{Higgs}$ $\geq m_{Z0} + m_{Higgs}$

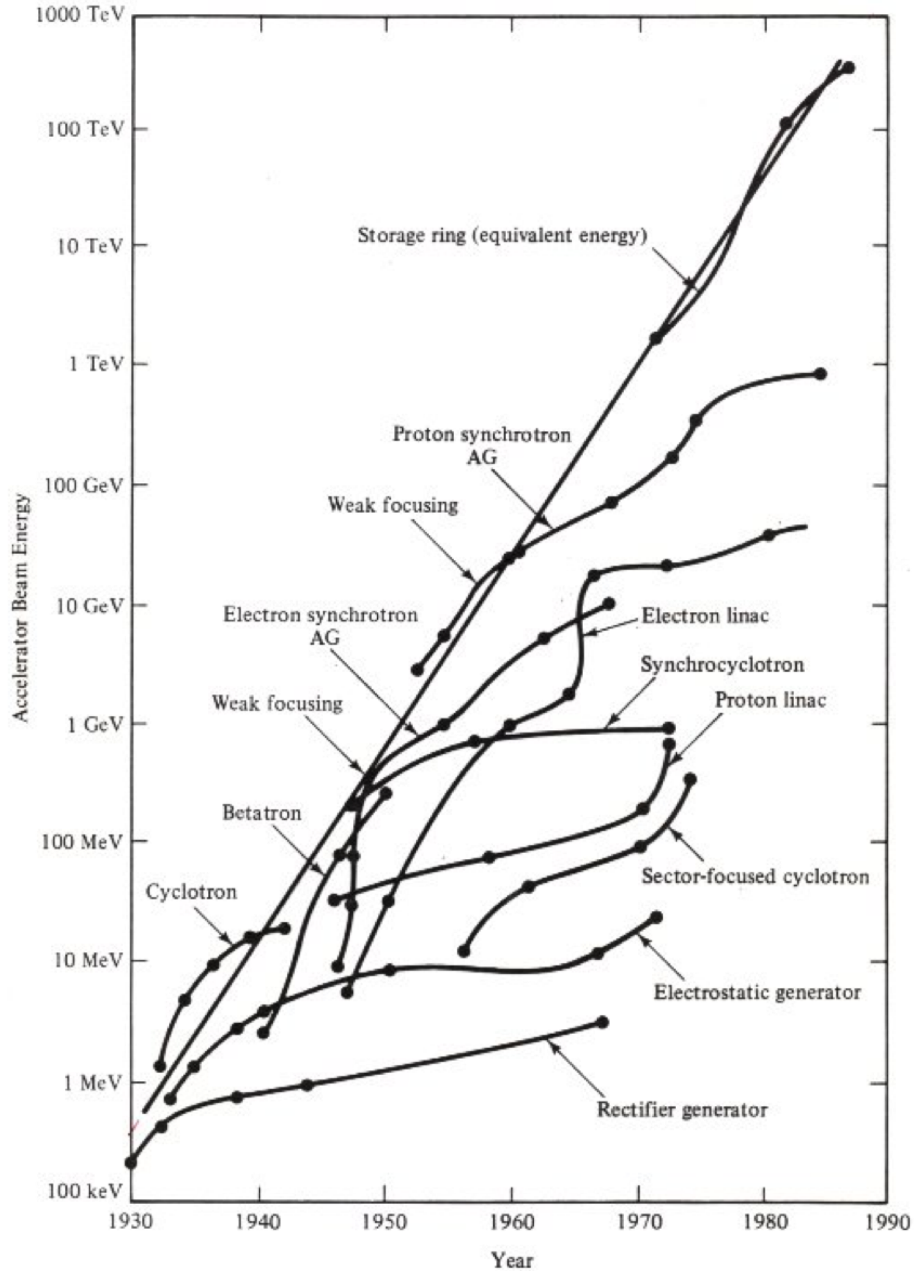
  $= 208 \text{ GeV} \rightarrow m_{Higgs} \leq 116 \text{ GeV}/c^2$

- Measurement of **"small" structures**: to resolve an object with dimension Δx, we need a probe with wave length λ

$$\bar{\lambda} = \frac{\hbar c}{pc} \leq \Delta x \quad \Leftrightarrow \quad pc \geq \frac{\hbar c}{\Delta x}$$

Current limit: LHC $\Delta x \approx 10^{-17}$ cm

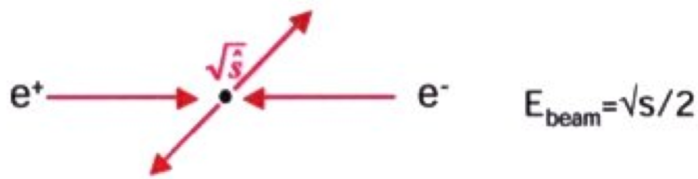
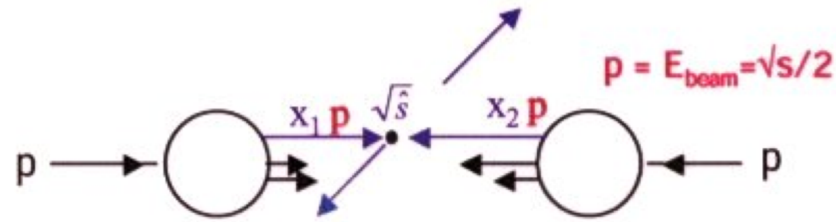
Accelerators



Energy growth of accelerators and storage rings. This plot, an updated version of M. Stanley Livingston's original, shows an energy increase by a factor of ten every seven years. Note how a new technology for acceleration has, so far, always appeared whenever the previous technology has reached its saturation energy. [From W. K. H. Panofsky, *Phys. Today 33, 24 (June 1980)*]

Increase in energy: factor of 10 every 7 years

Colliders

e^+e^- **Colliders**	$pp/p\bar{p}$ **Colliders**
	
Energy of elementary interaction known $\sqrt{\hat{s}} = E(e^-) + E(e^+) = \sqrt{s}$	Energy of elementary interaction not known $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} < \sqrt{s}$
Only two elementary particles collide $\rightarrow$ clean final states	Elementary interaction (hard) + interaction of "spectator" q,g (soft) overlapp in detector
Mainly EW processes	EW processes suffer from huge backgrounds from strong processes
$\sqrt{s}$ limited by $e^{\pm}$ synchrotron radiation: $E_{\mathrm{loss}} \sim \frac{E^4_{beam}}{R} \frac{1}{m^4_e}$ $E_{\mathrm{loss}} \sim 2.5$ GeV/turn LEP 2 ($E_{\mathrm{beam}} \sim 100$ GeV)	Synchrotron radiation is $\sim (m_p/m_e)^4 \sim 10^{13}$ smaller
- high energy more difficult $\rightarrow$ next machine: Linear Collider (ILC, CLIC, $\sqrt{s} = 800(3000?)$ GeV?) - clean environment $\rightarrow$ precision measurement machines	- high energy easier $\rightarrow$ discovery machines current machine: LHC, pp , $\sqrt{s} = 14$ TeV in the LEP ring more "dirty" environment

Electron and hadron colliders

Electron colliders

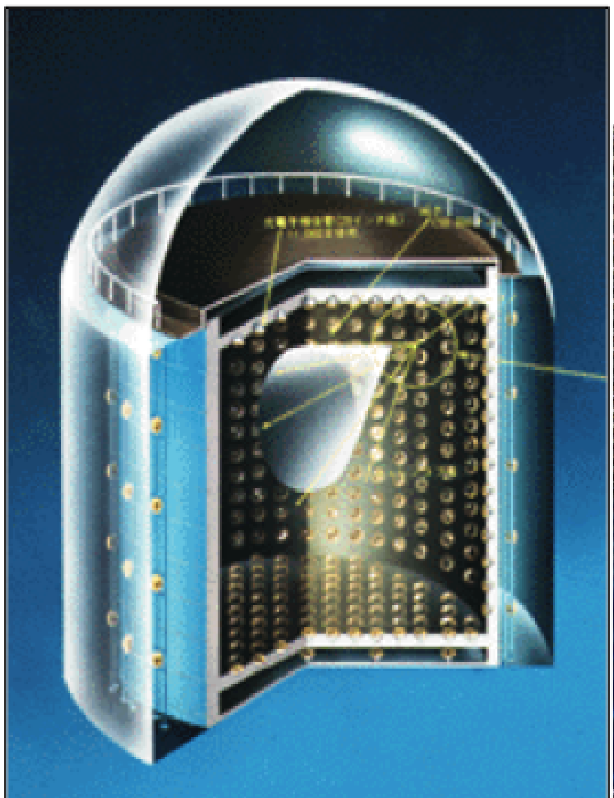
	where	start	end	energy (GeV)	length/ circumf. (km)	most relevant physics
Petra	DESY	1978	1986	23.5 + 23.5	2.3	discovery of gluons
CESR	Cornell/ USA	1979	...	6 + 6	0.77	spectroscopy hadrons with b and c quarks
PEP	Stanford/ USA	1980	1990	15 + 15	2.2	top search, indirect W/Z hint
Tristan	KEK/ Japan	1987	1995	32 + 32	3	top search
LEP	CERN	1989	2000	105 + 105	26.7	precision test of standard model
SLC	Stanford/ USA	1989	1998	50 + 50	1.45 + 1.46	precision test of standard model
PEP II	Stanford/ USA	1999	2008	9 + 3.1	2.2	CP violation in B
KEK-B	KEK/ Japan	1999	2010	8 + 3.5	3	CP violation in B

Hadron colliders

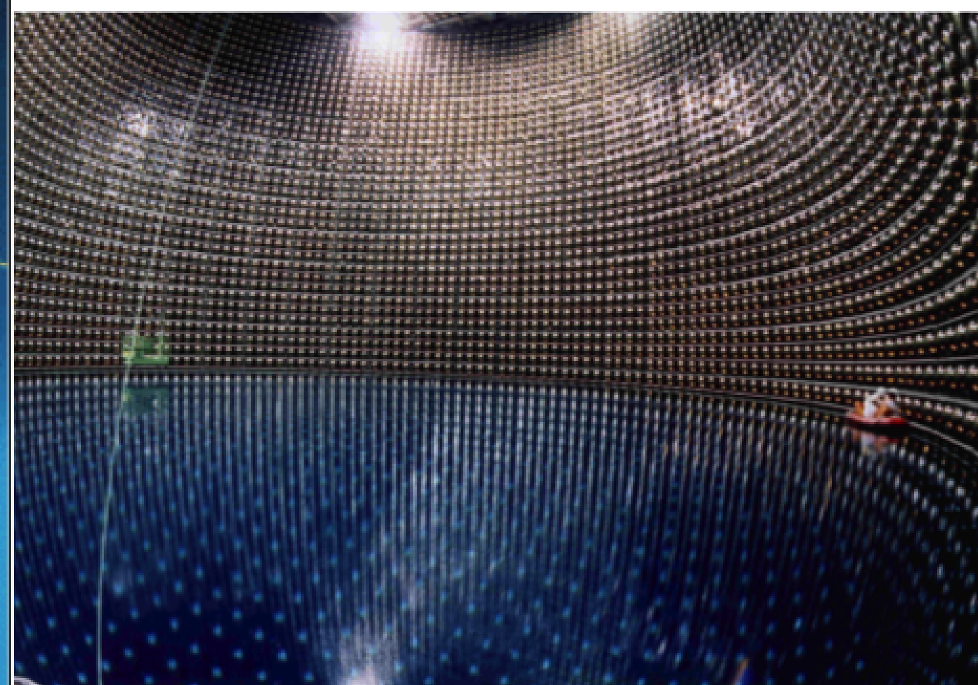
	where	Beam	start	end	energy (TeV)	length/ circumf. (km)	most relevant physics
Sp$\bar{p}$S	CERN	p$\bar{p}$	1981	1990	0.45 + 0.45	6.9	W,Z bosons
Tevatron	Fermilab/ USA	p$\bar{p}$	1987	2011	0.9 + 0.9	6.3	top quark
SSC	Texas/ USA	pp	1996??		20 + 20	83.6	abandoned in 94
HERA	DESY	ep	1992	2007	0.03(e) + 0.92(p)	6.3	precise nucleon structure
RHIC	BNL/ USA	AuAu	2000	...	19.7 + 19.7	3.8	Quark-Gluon plasma
		pp			0.25 + 0.25		
LHC	CERN	pp	2009	...	7 + 7	26.7	Higgs, SUSY? ...
		PbPb			562 + 562		Quark-gluon plasma

Experiments with neutrinos

source	reaction	energy range	type
solar	fusion reactions	typically below 20 MeV	ν_e
reactor	β-decay after fission	up to few MeV	ν_e
atmosphere	π- and μ-decay	GeV	ν_μ and ν_e
accelerators	μ-decay	up to 100 GeV	ν_μ



Superkamiokande: 50 kton water Cherenkov detector



Demands on detectors

- Particle detection
- Momentum or energy measurement
- Particle identification *electron - pion - kaon . . .*
- Reconstruction of the invariant mass of decay products $m_{\mathrm{inv}}^2 = (\sum_i p_i)^2$, four-momenta
- "Missing Mass" or "Missing Energy" for undetected particles like neutrinos
- Sensitivity to lifetime or decay length
  - stable particles: protons, $\tau \geq 10^{32} y$
    test of stability
  - unstable particles:
    decay via strong interaction: $\rho \to \pi^+\pi^-$ $\Gamma = 100$ MeV

$$\tau c = \frac{\hbar c}{\Gamma} = 2 \text{ fm} \qquad \tau \approx 10^{-23} \text{ s}$$

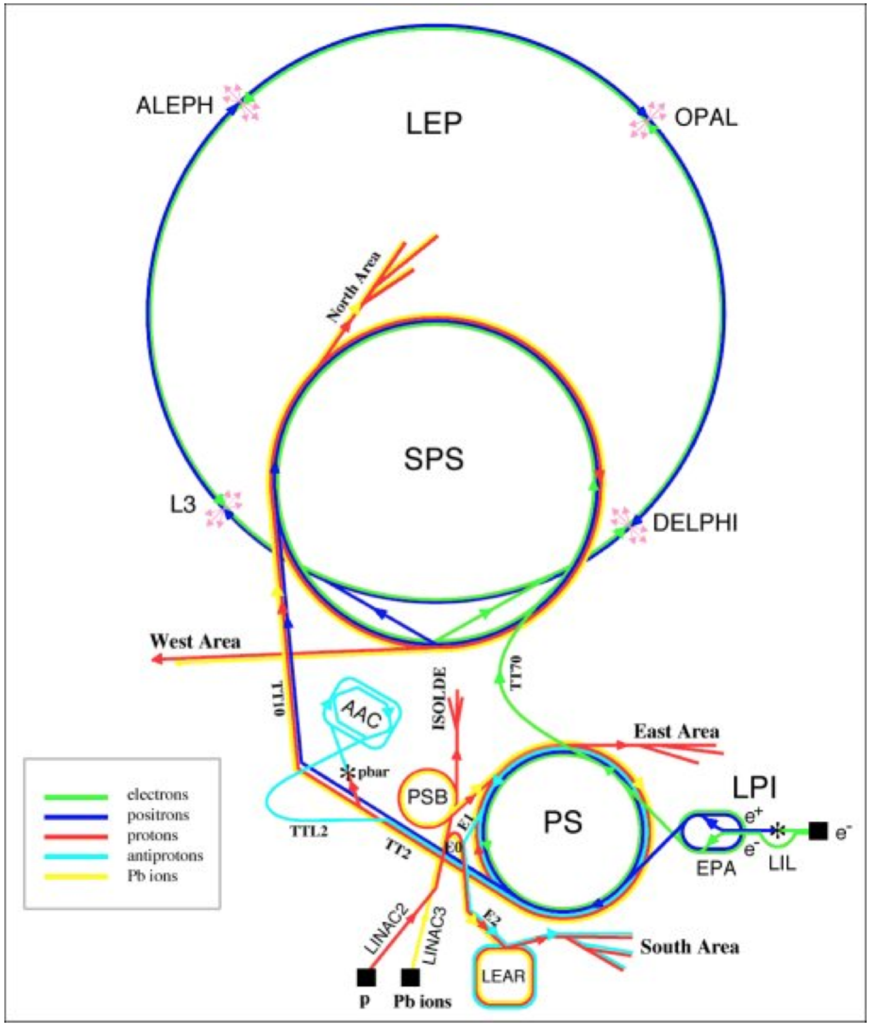
    decay via electromagnetic interaction: $\pi^0 \to \gamma\gamma$ $\tau = 10^{-16}$ s
  - quasi-stable particles:
    decay via weak interaction

Demands on detectors

Some examples for decay length

particle	τ	$c\tau$	decay length $\beta\gamma c\tau$ at $p = 10\ GeV/c$
n	889 s	$2.7 \cdot 10^8$ km	$2.9 \cdot 10^9$ km
Λ	$2.6 \cdot 10^{-10}$ s	7.9 cm	71 cm
$\pi^\pm$	$2.6 \cdot 10^{-8}$ s	7.8 m	560 m
$D^\pm$	10^{-12} s	0.31 mm	1.6 mm
$B^\pm$	$1.6 \cdot 10^{-12}$ s	0.49 mm	0.93 mm
τ	$3 \cdot 10^{-13}$ s	0.09 mm	0.5 mm

LEP: Large Electron Positron Collider



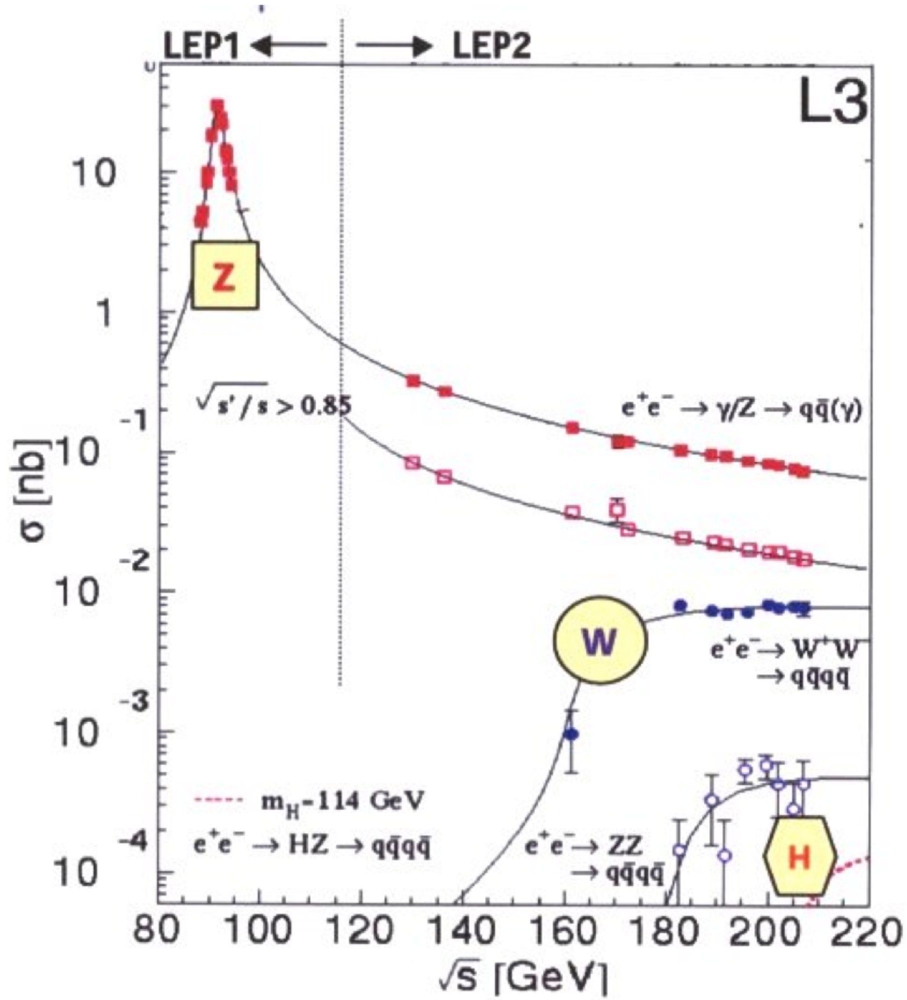
The LEP Storage Ring

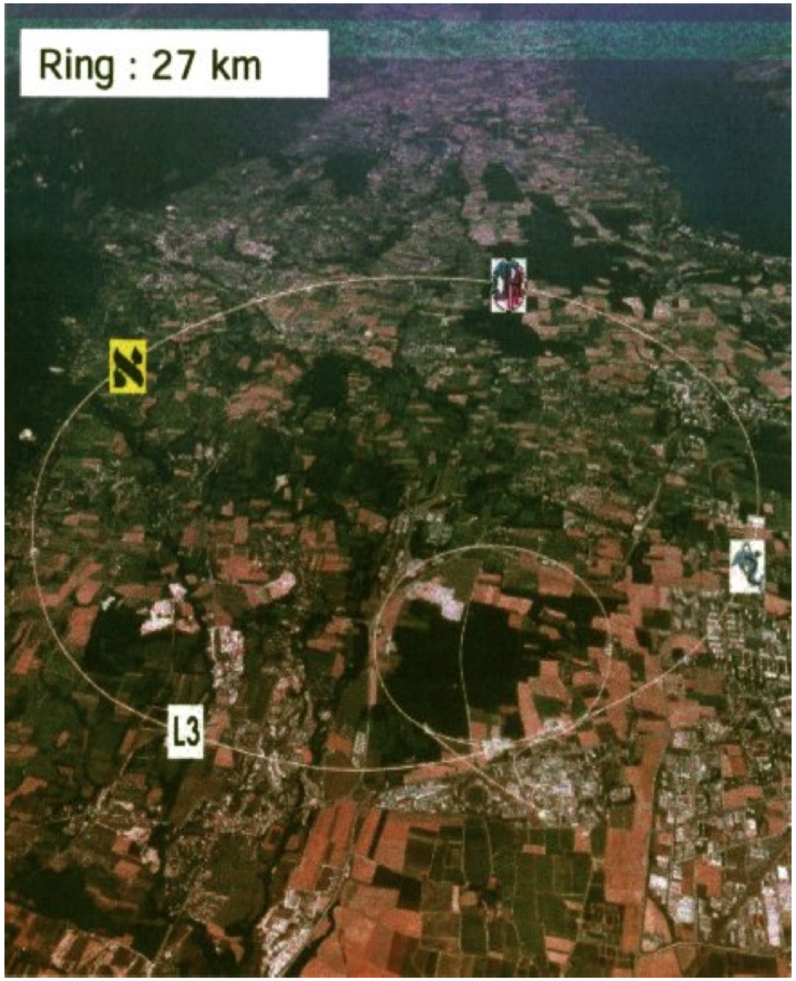
Some characteristic parameters

Parameter	Value
circumference	26658.88 m
magnetic radius	3096 m
revolution frequency	11245.5 Hz
RF frequency	352 MHz
injection energy	$\approx$ 20 GeV
achieved peak energy per beam	104.5 GeV
achieved peak luminosity	4 pb^{-1} /day
number of bunches	4, 8 or 12
typical current/ bunch	0.75 mA

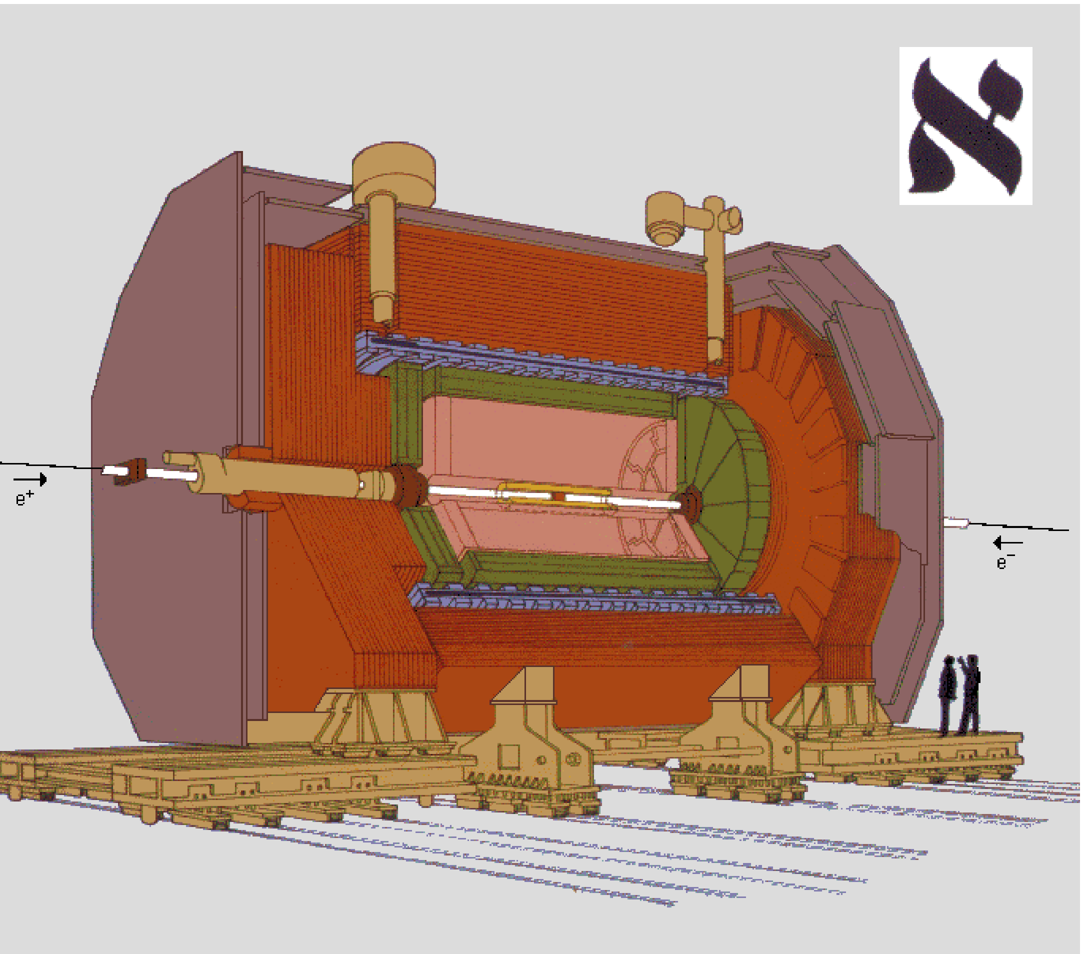
LEP: Large Electron Positron Collider

LEP1 (1989-1995) : $\sqrt{s} \approx m_Z \rightarrow 2 \cdot 10^7$ Z recorded $\rightarrow$ precise Z measurements
LEP2 (1996-2000) : $\sqrt{s} \rightarrow 209$ GeV $\rightarrow$ WW production, m_W, search for Higgs and new particles



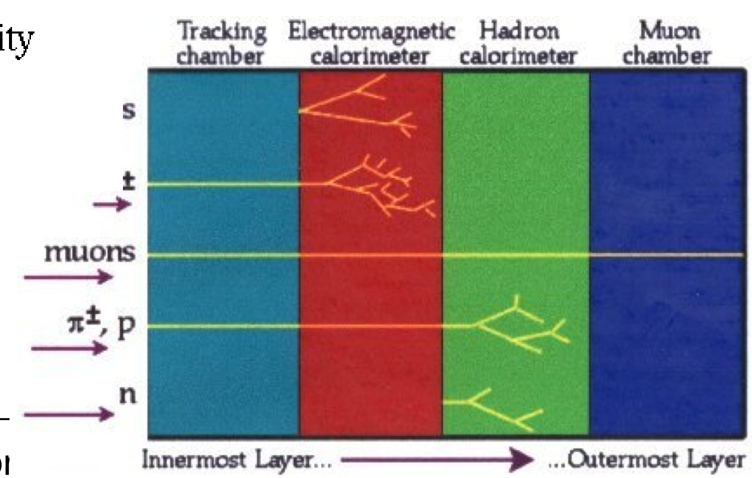


ALEPH

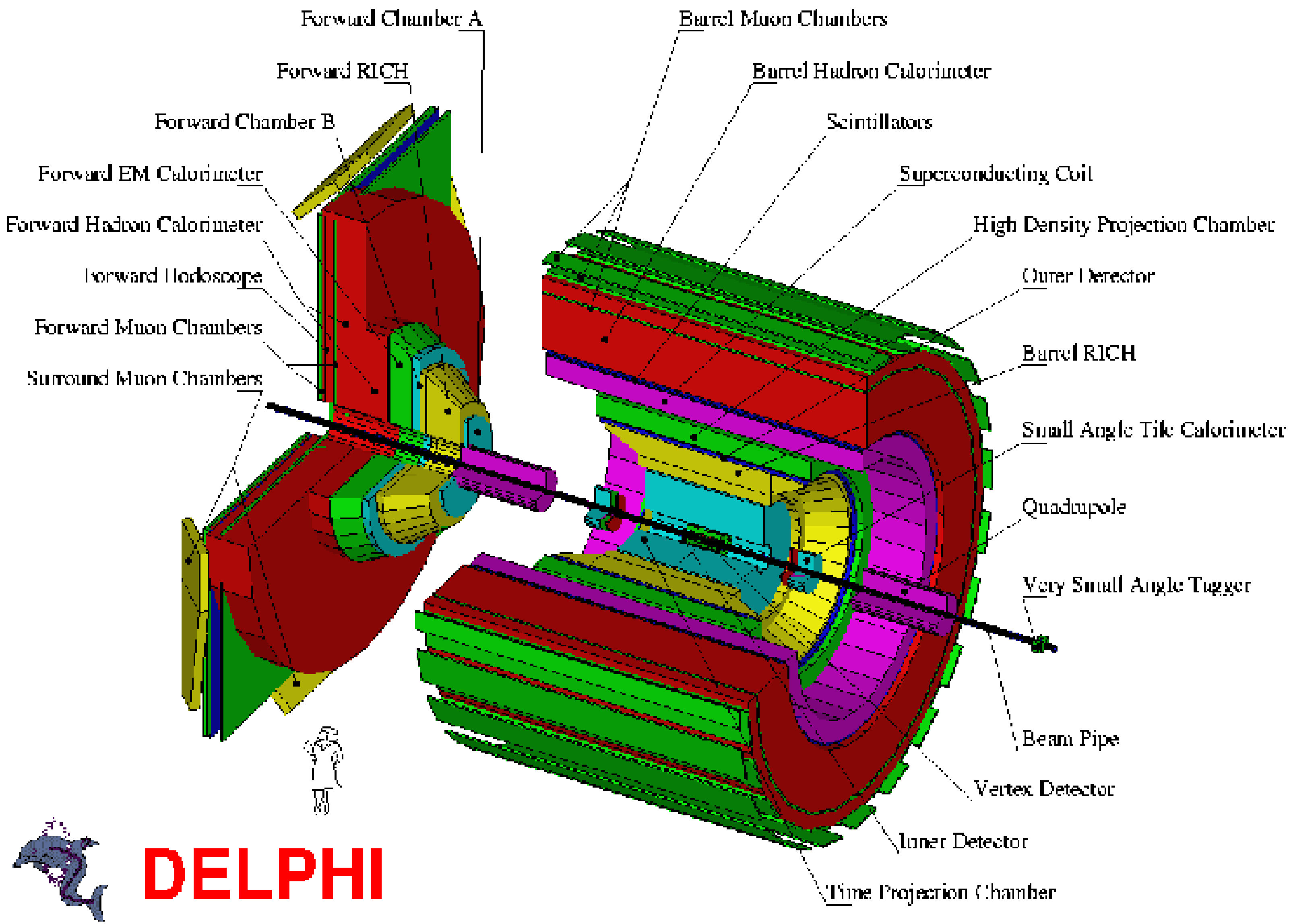


The ALEPH Detector

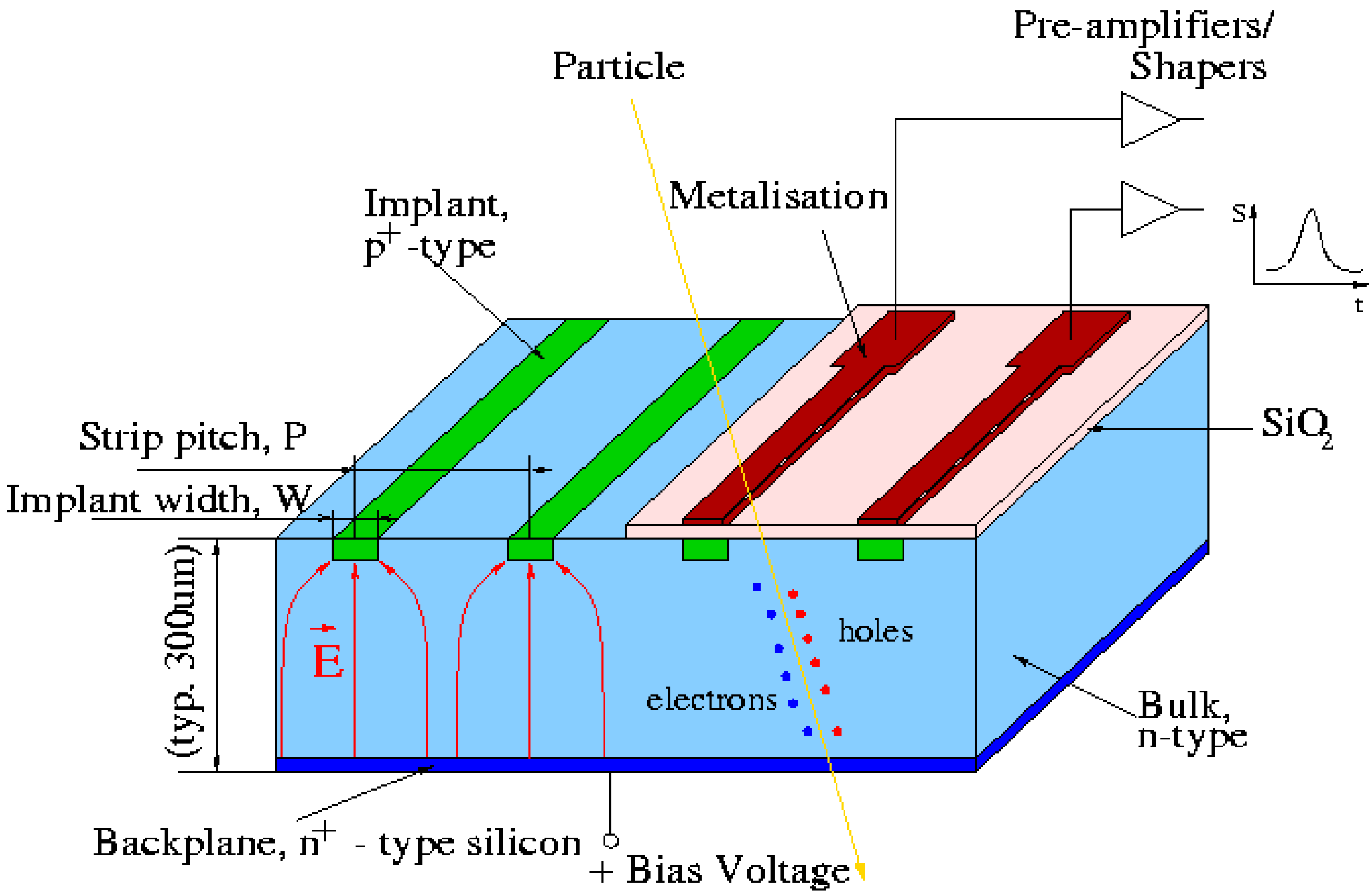
- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors



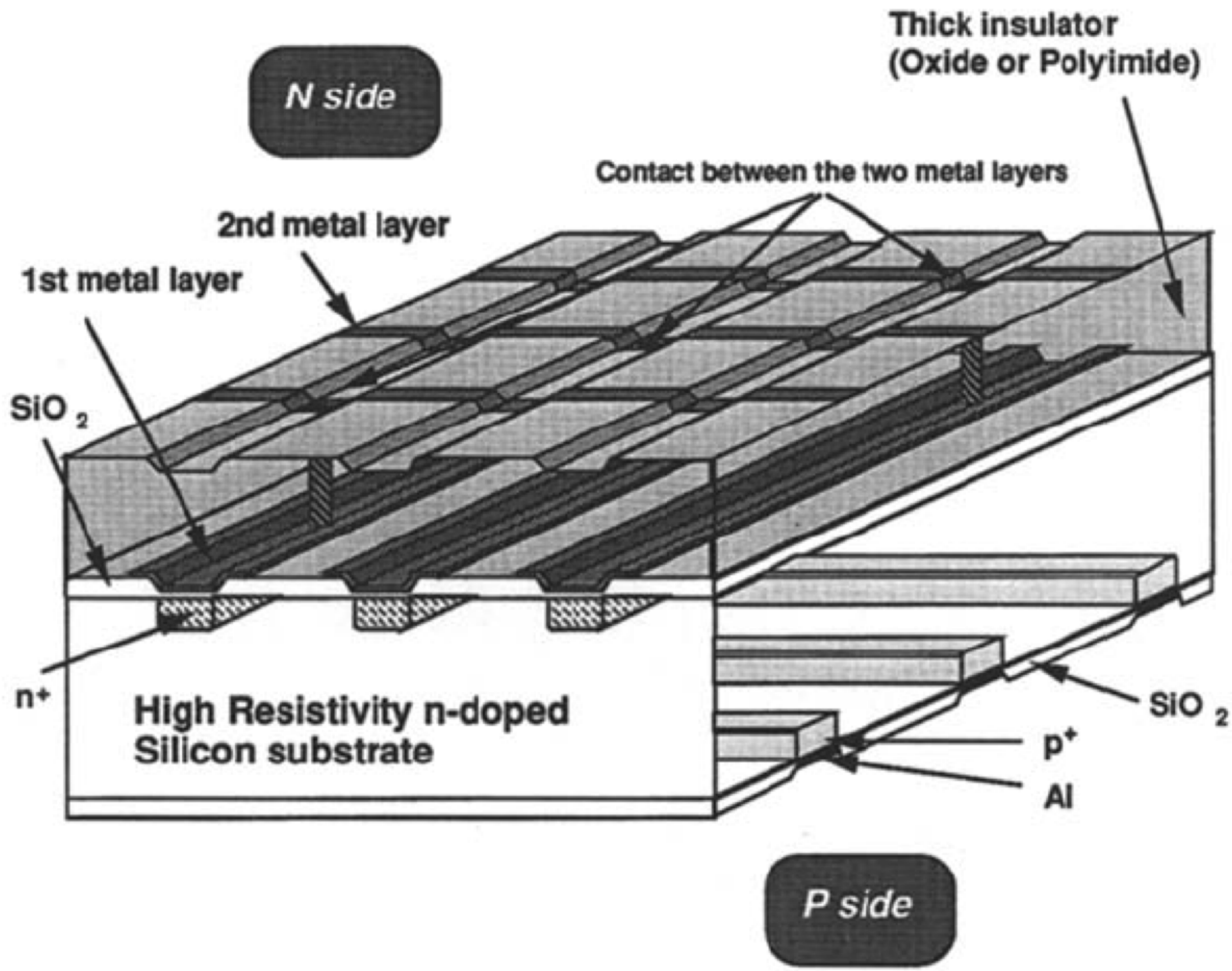
DELPHI: Detector with Lepton, Photon and Hadron Identification



Silicon microstrip detectors



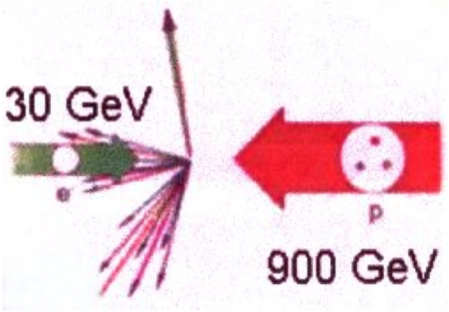
My diploma thesis: double-sided double-metal silicon microstrip detectors

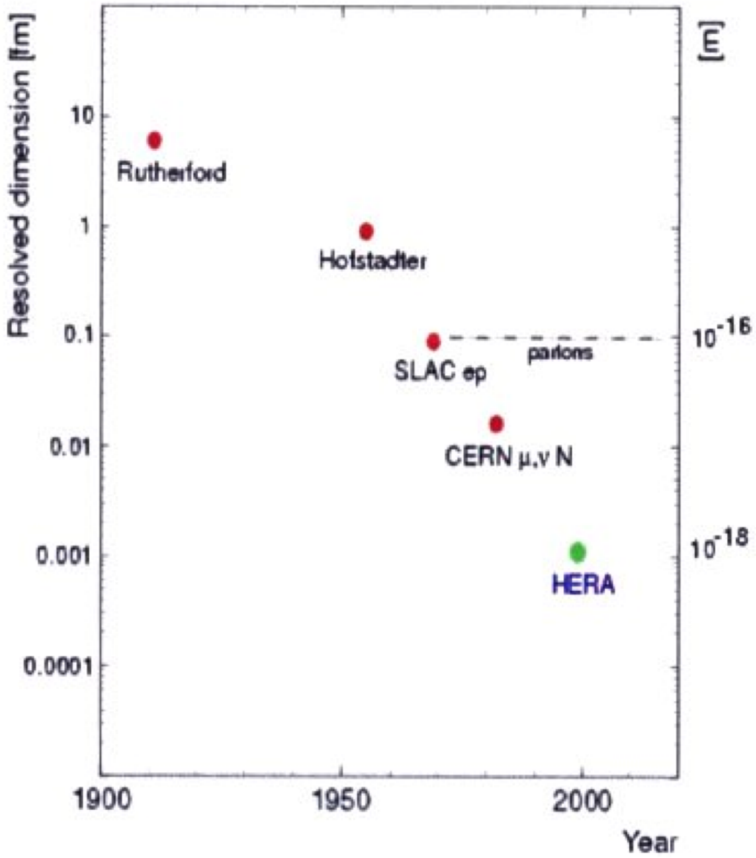


HERA: e-p collider at DESY

e-p collisions allow to probe the proton structure, the distribution of quarks and gluons, test if quarks are elementary

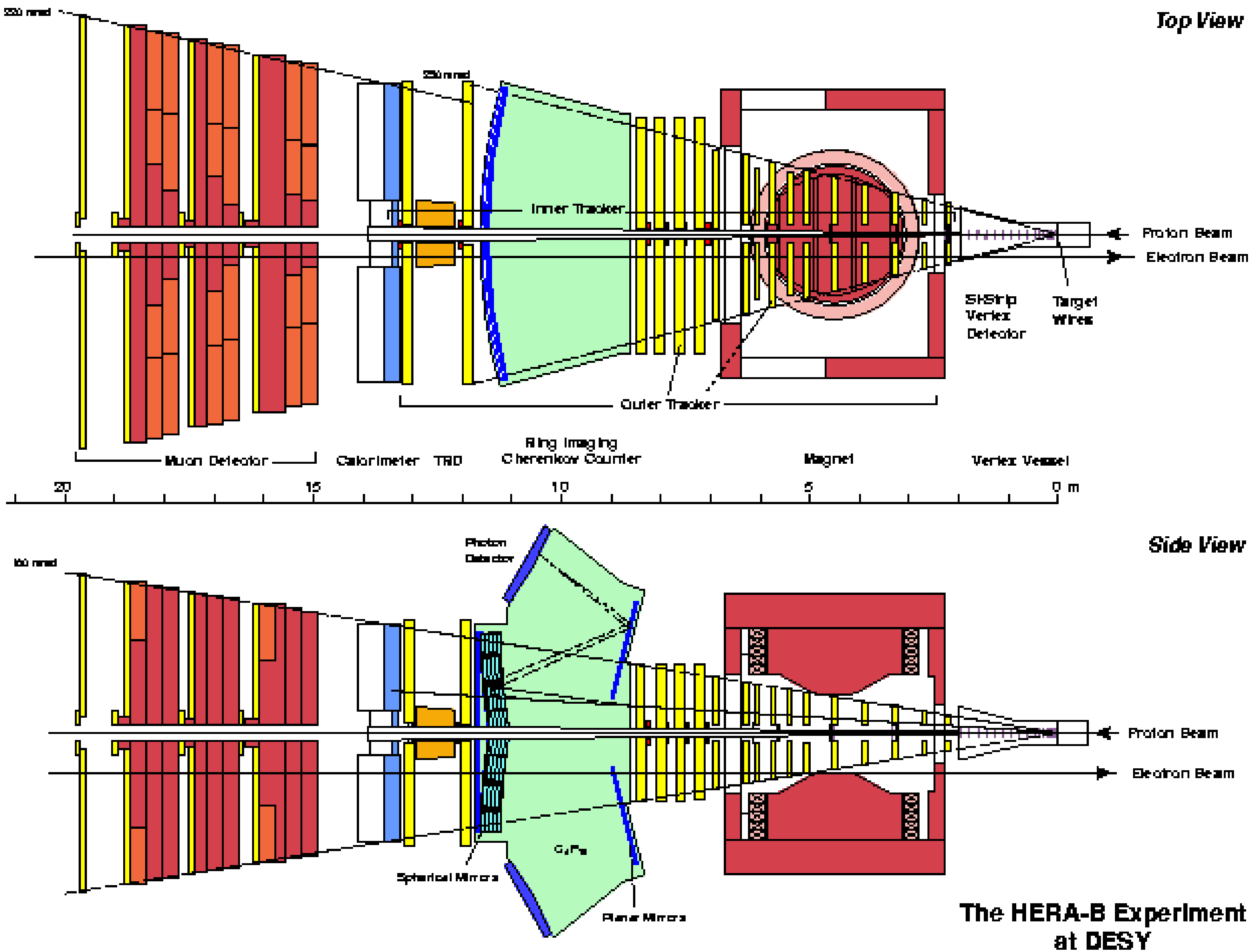
1994-2000 $\sim$ 0.1 fb^{-1} per experiment
2002-2006 $\sim$ 1 fb^{-1} per experiment





QCD with elementary quarks describes the scattering up to the highest accessible Q^2

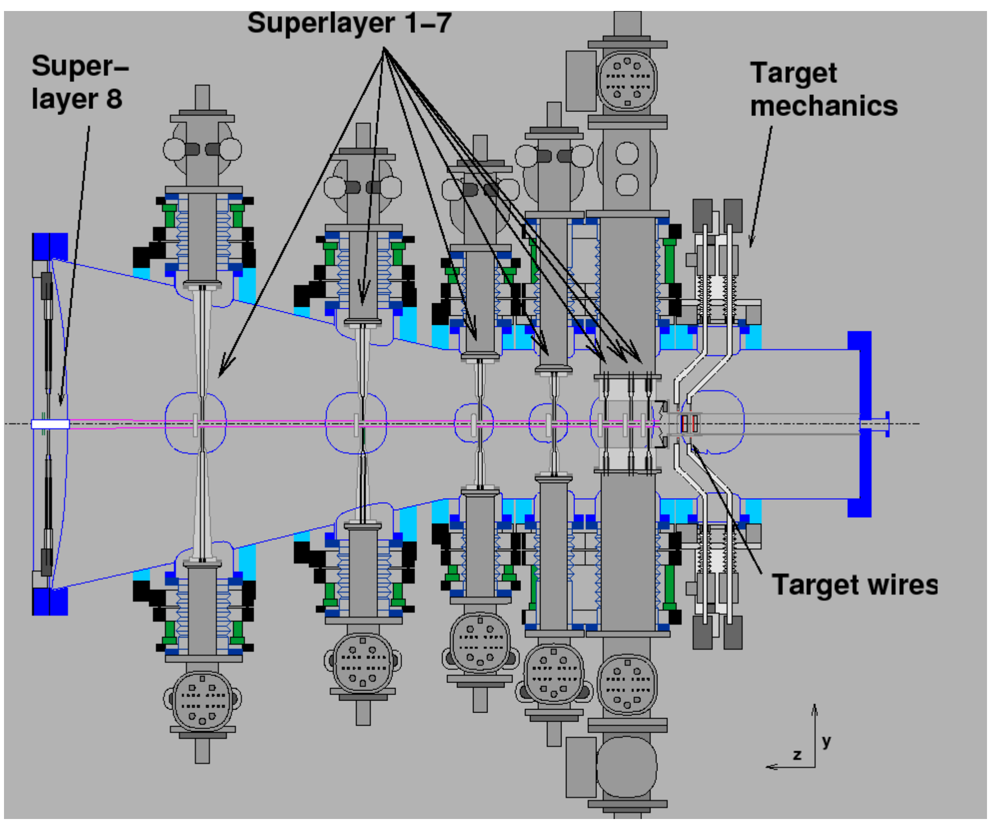
HERA-B experiment

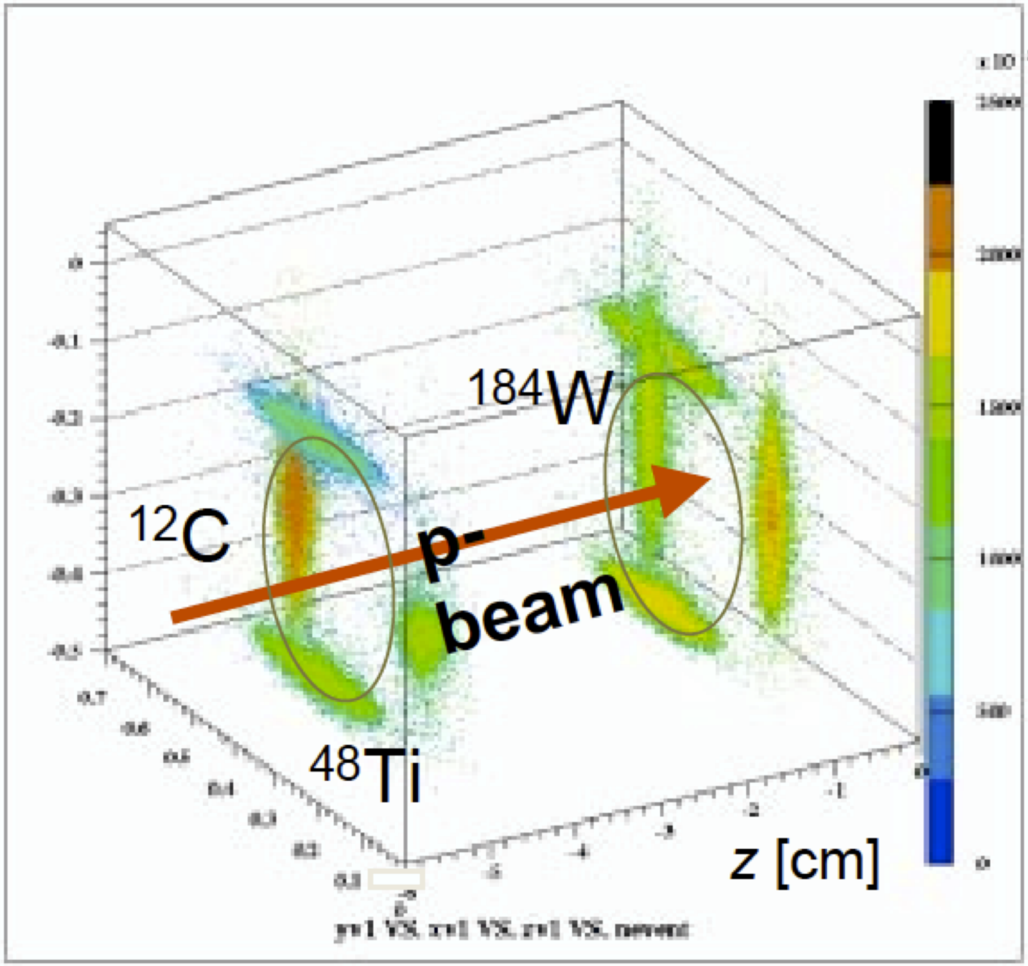


HERA-B experiment: proton-nucleus collisions

Vessel welded to the beam pipe, with Roman pot system hosting the silicon vertex detector

Movable target wires, made of different materials





Large Hadron Collider at CERN

In the LEP tunnel

Operation started in 2009

- ALICE, ATLAS, CMS, LHCb
- **pp: 0.9, 2.76, 7, 8, 13 TeV**
- **Pb-Pb**

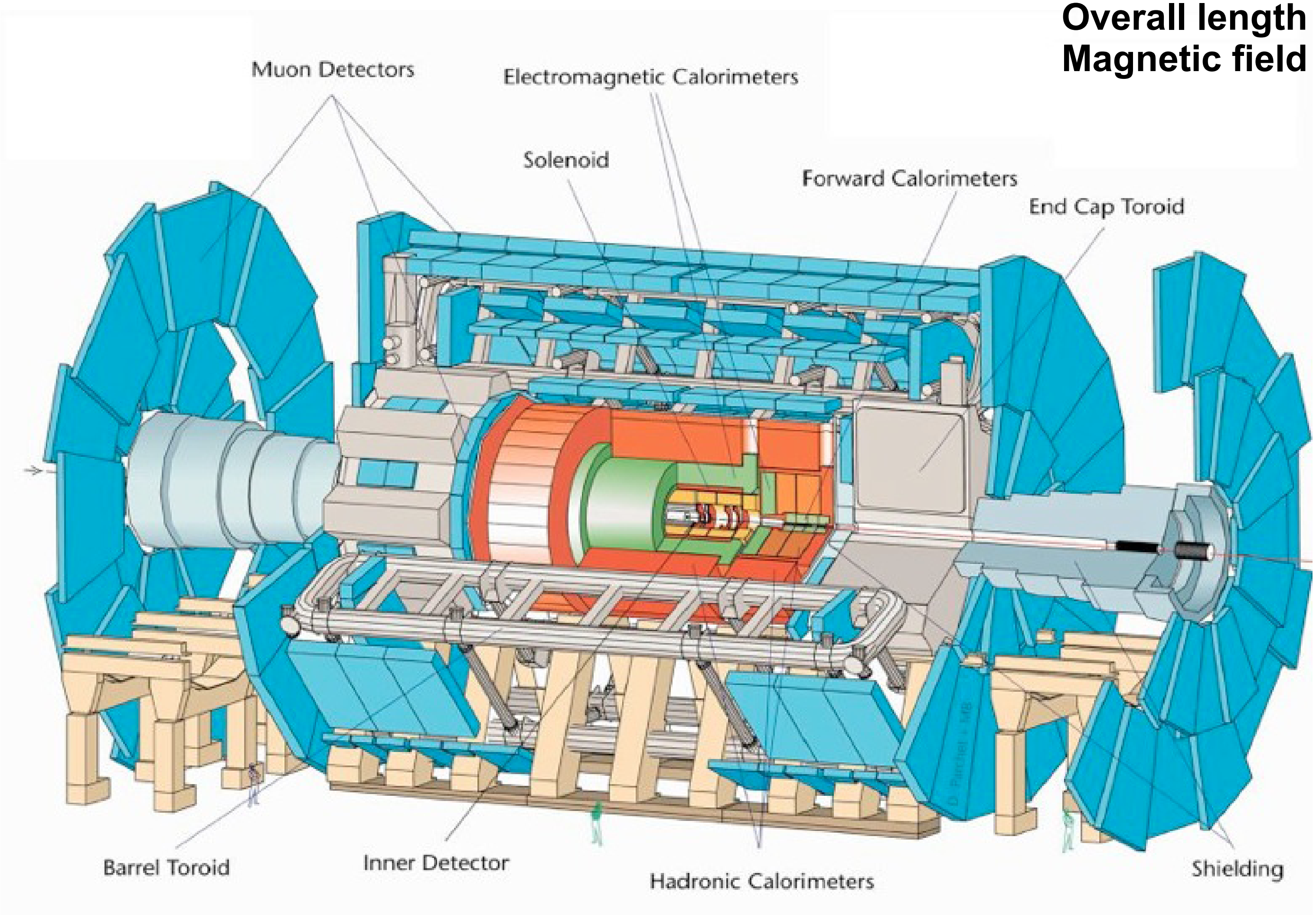
  2010-2011: $\sqrt{s_{NN}}$ = 2.76 TeV

  2015: $\sqrt{s_{NN}}$ = 5.02 TeV
- **p-Pb: 5.02 TeV in 2012-3**

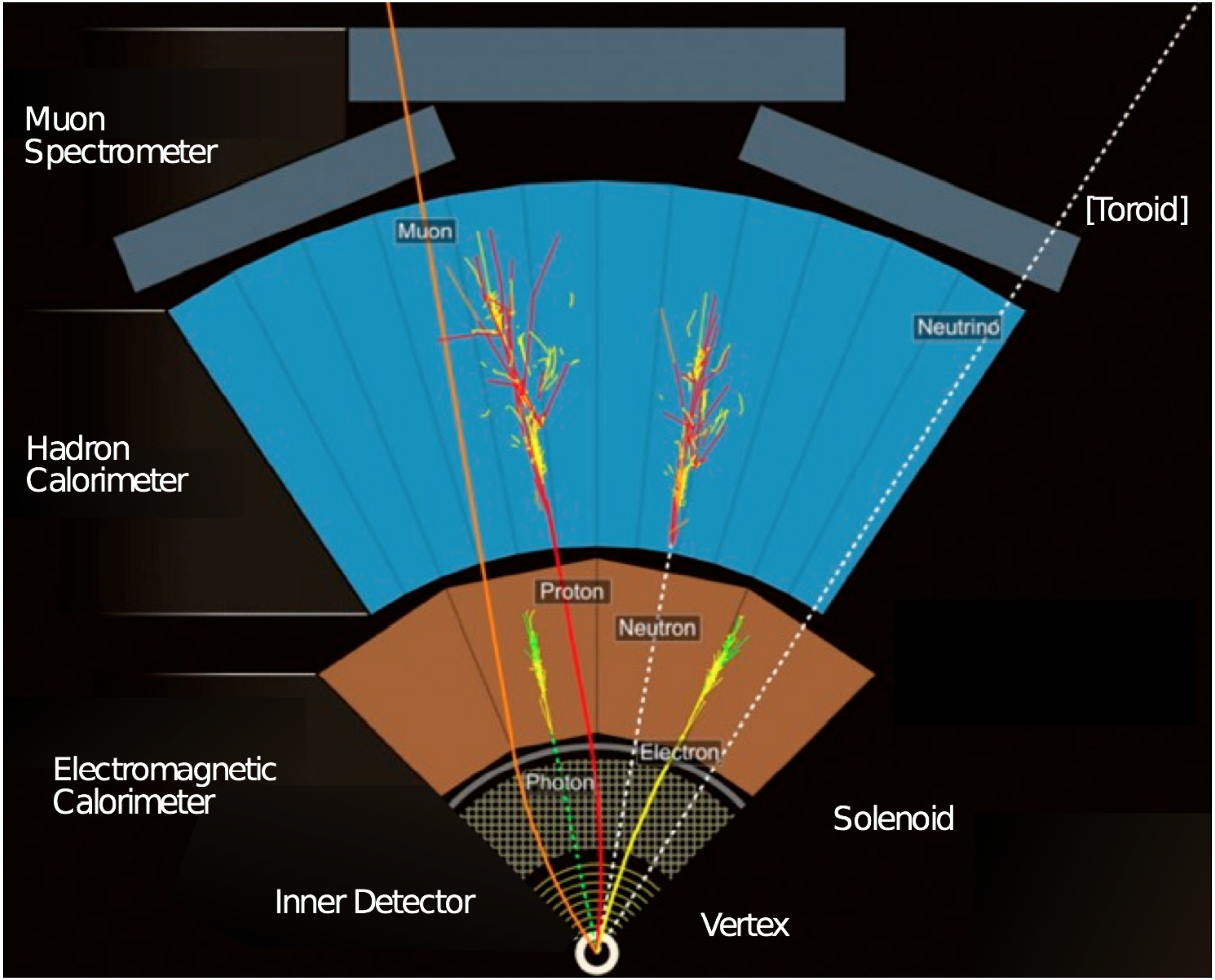
  5.02 and 8 TeV in 2016

ATLAS: A Toriodal LHC ApparatuS

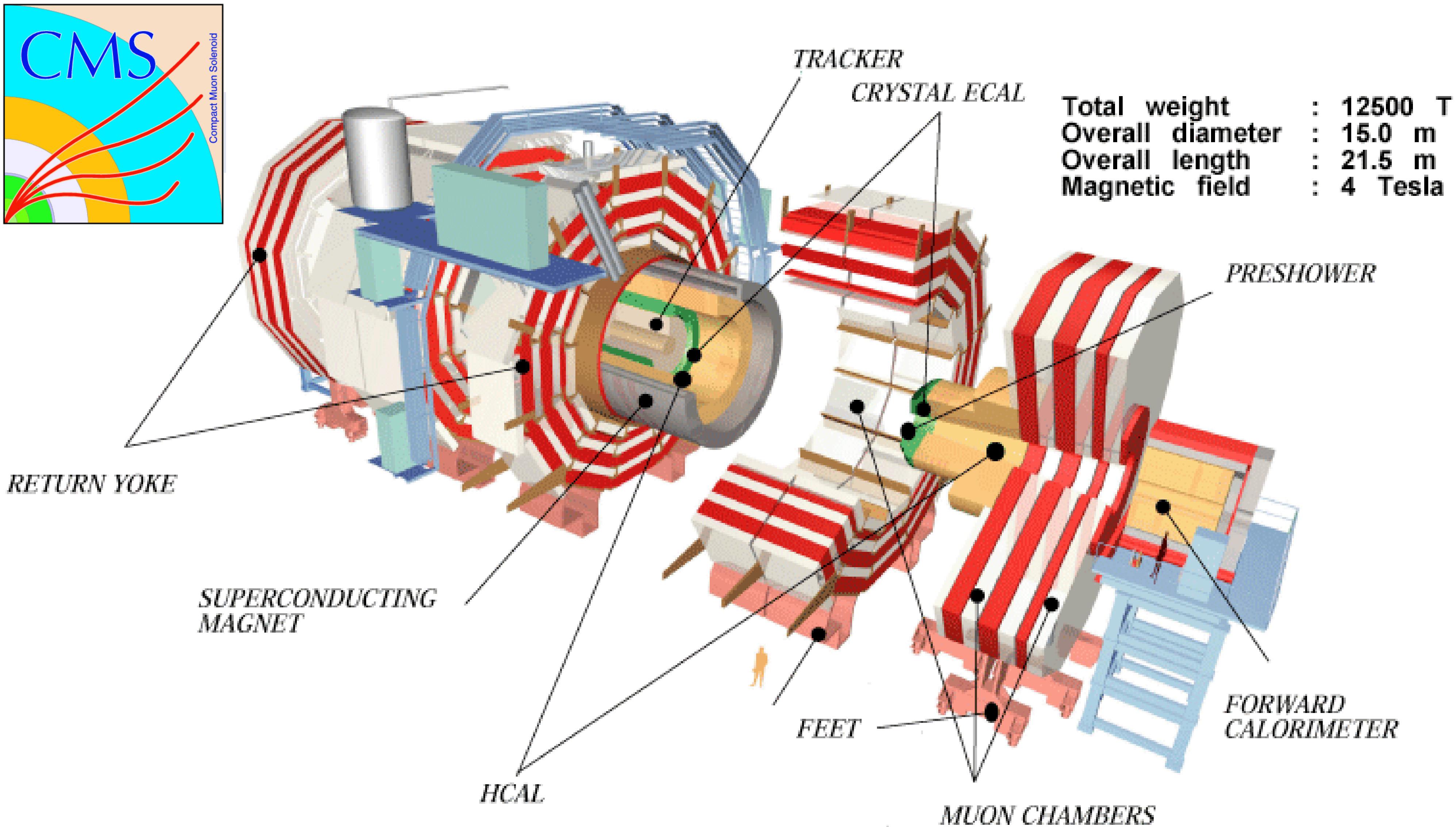
Total weight : 7000 T
Overall diameter : 25 m
Overall length : 44 m
Magnetic field : 2 Tesla



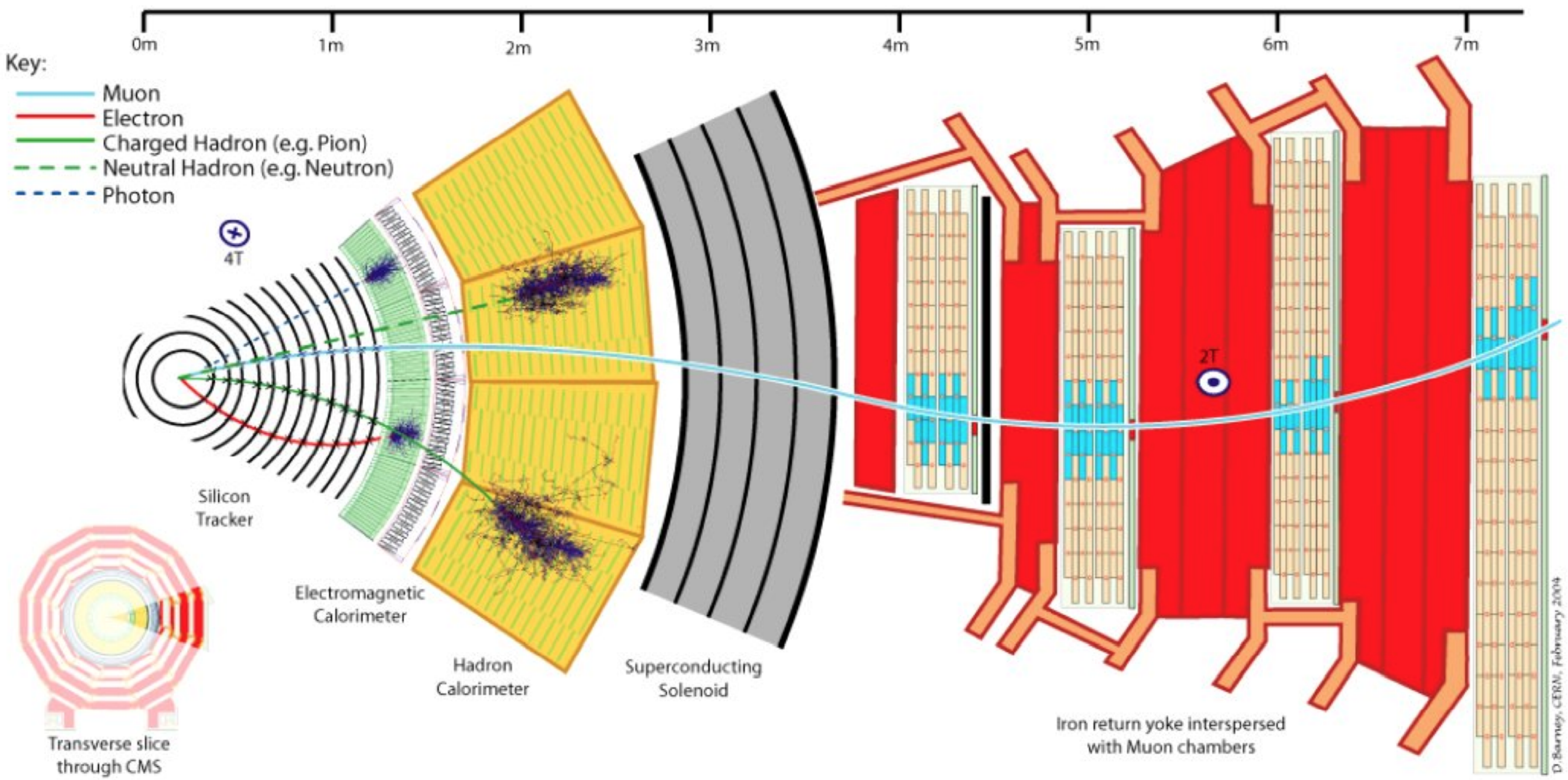
ATLAS: A Toriodal LHC ApparatuS



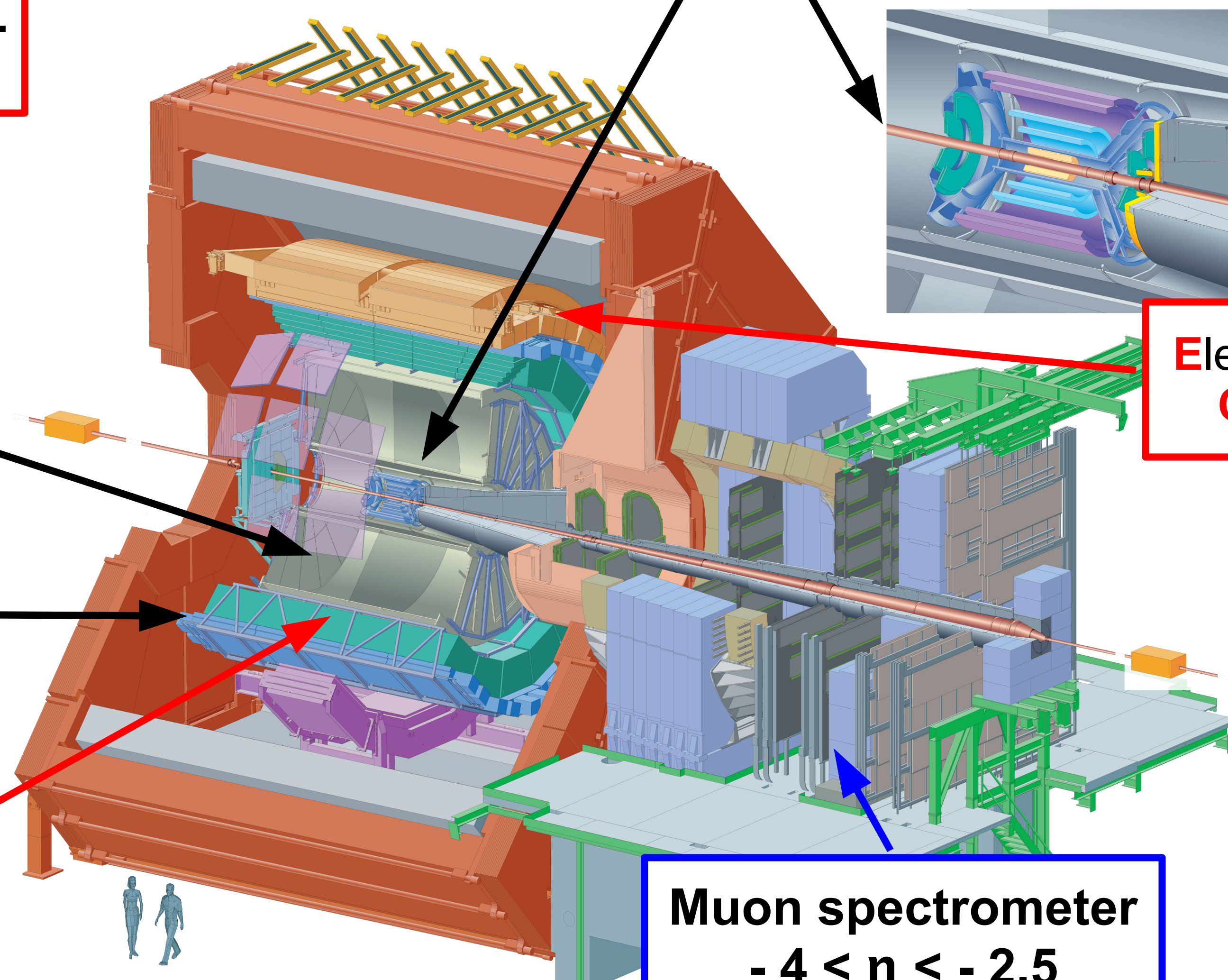
CMS: Compact Muon Spectrometer



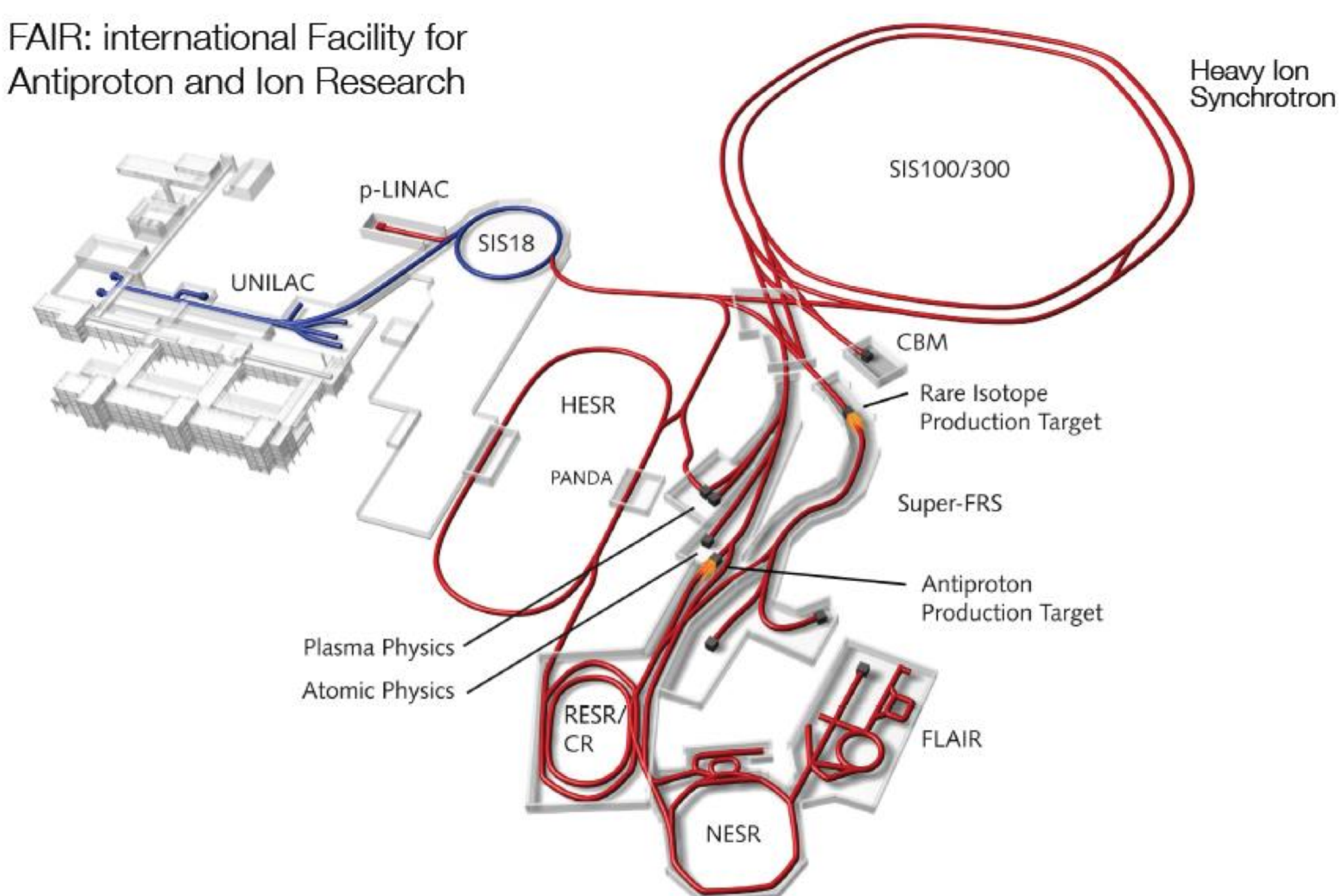
CMS: Compact Muon Spectrometer



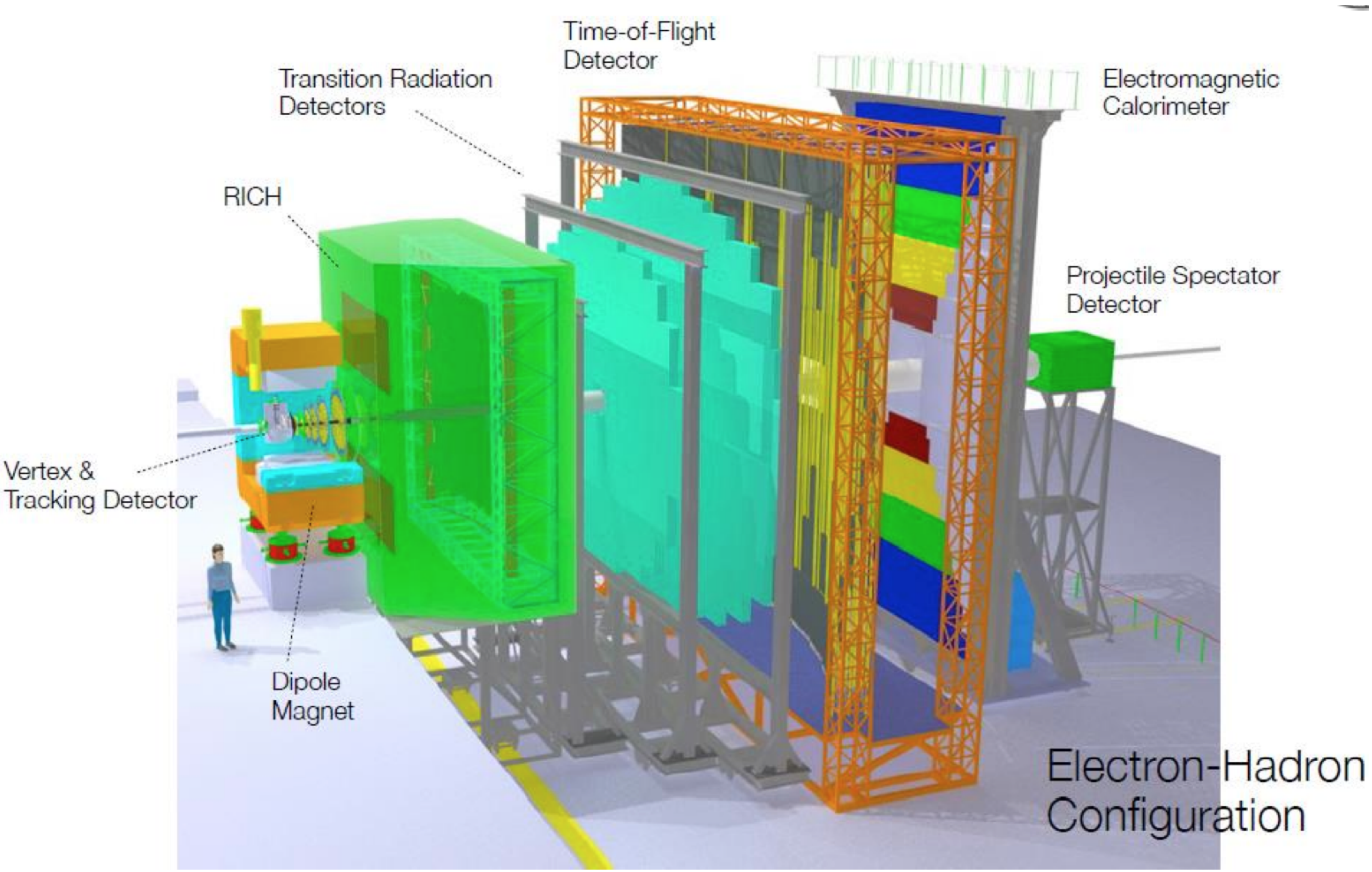
ALICE: A Large Ion Collider Experiment



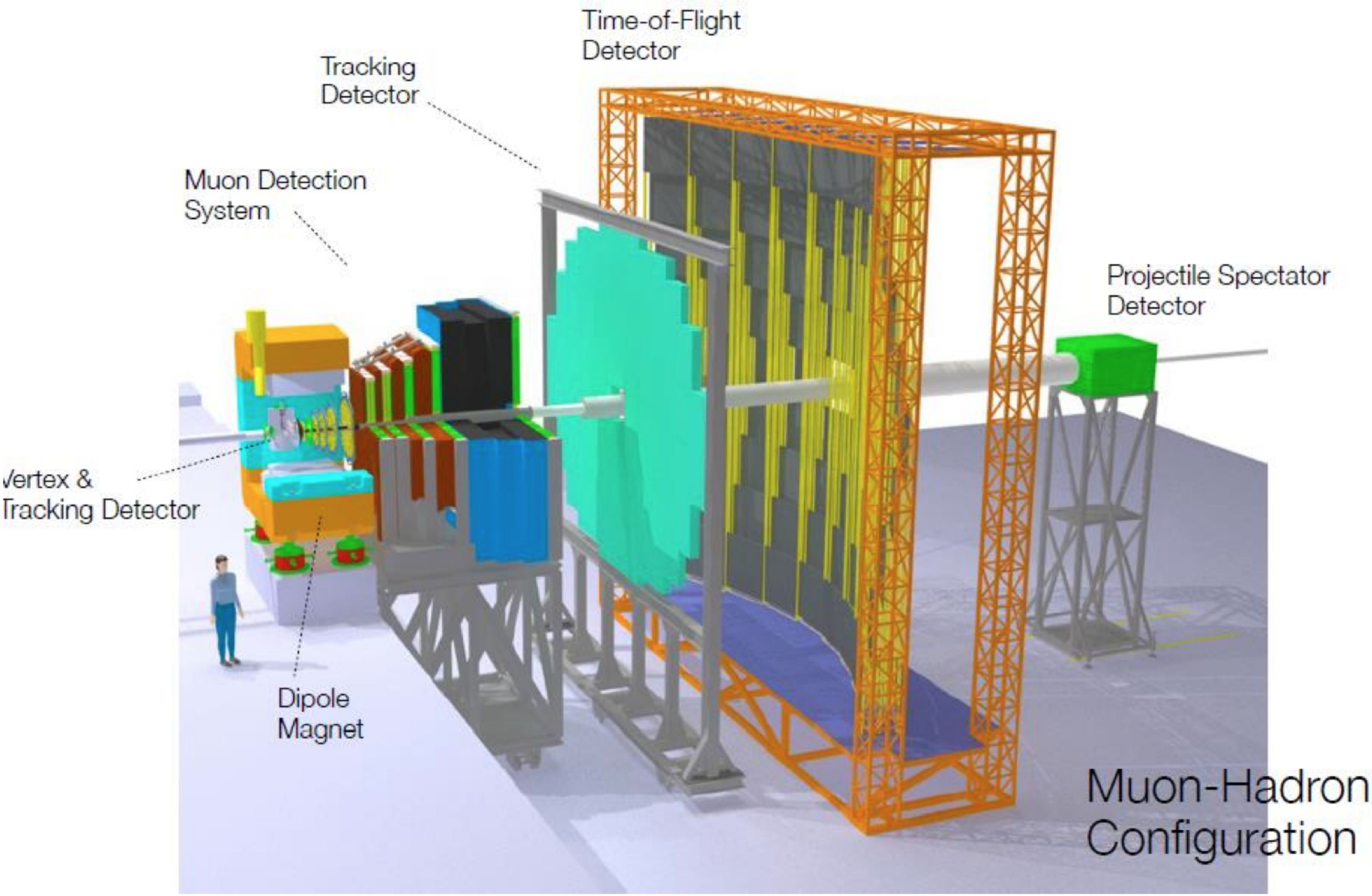
The FAIR project at GSI



CBM experiment



CBM experiment

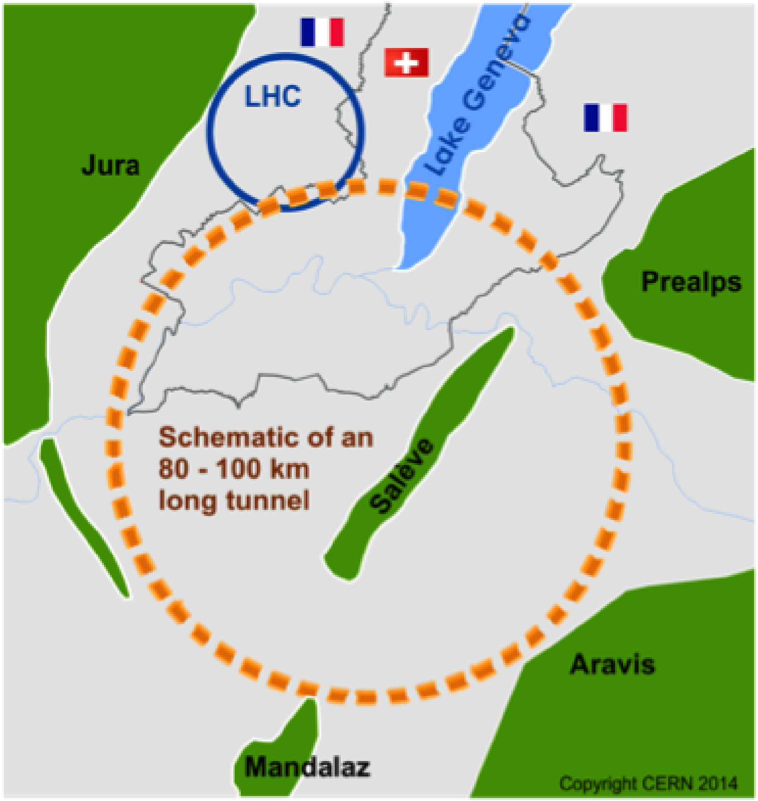


Beyond the LHC: Future Circular Collider

Design study by an international collaboration, initiated by CERN in 2014, for a

Future Circular Collider

- Proton-proton collider (FCC-hh)
  ~16 T → 100 TeV pp in 100 km
  ~20 T → 100 TeV pp in 80 km
  → defining infrastructure requirements
- e^+e^- collider (FCC-ee) as potential intermediate step
- p-e (FCC-he) option



Scope: CDR and cost review for the next European strategy (2018)

Starting date targeted for 2035-2040

The FCC

Design study by an international collaboration, initiated by CERN in 2014, for a

Future Circular Collider

- Proton-proton collider (FCC-hh)
  ~16 T → 100 TeV pp in 100 km
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  → defining infrastructure requirements
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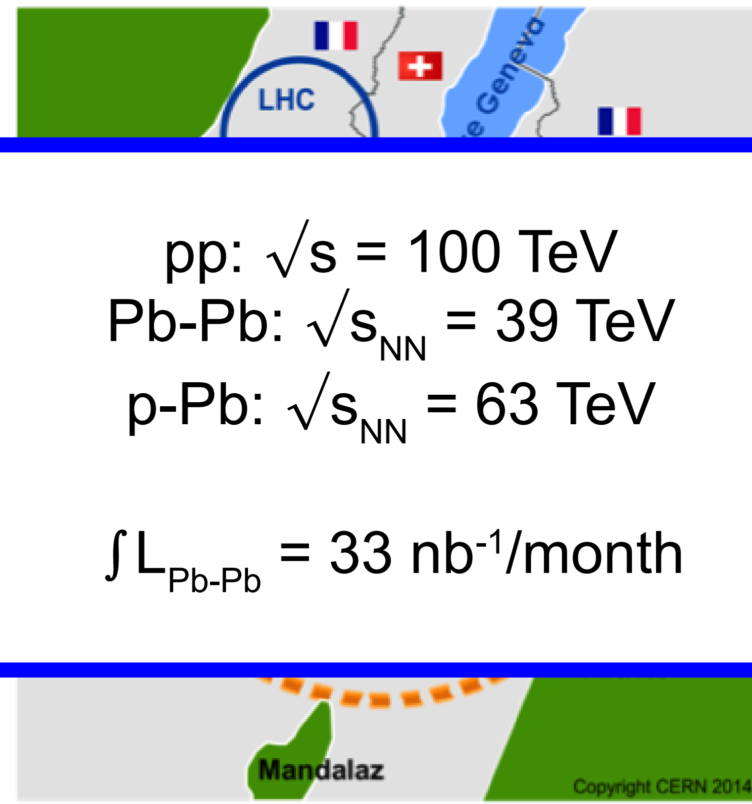

pp: $\sqrt{s}$ = 100 TeV
Pb-Pb: $\sqrt{s_{NN}}$ = 39 TeV
p-Pb: $\sqrt{s_{NN}}$ = 63 TeV

$\int L_{Pb\text{-}Pb}$ = 33 nb^{-1}/month

Scope: CDR and cost review for the next European strategy (2018)

Starting date targeted for 2035-2040

Title