Detectors in Nuclear and Particle Physics

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1. Introduction

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   - Beams
   - General demands on particle detectors

Introduction I

- Progress in nuclear and particle physics mainly driven by experimental observation
- Critically coupled with the development of new methods in particle acceleration and detection of particles
- Historical development:

1896	Discovery of X-rays w. photographic plate (Nobel prize W.C. Röntgen 1901)
1904	Research on cathode rays (Lenard window) (Nobel prize P. Lenard 1905)
1912	Evidence for cosmic radiation (electrometer) (Nobel prize V.F. Hess 1936)
1912	Invention of the cloud chamber (Nobel prize C.T.R. Wilson 1927)
1929	Birth of cosmic ray physics Observation of high energetic electrons and showers (Nobel prize W.W. Bothe 1954 "Coincidence method and discoveries made therewith")
1931	Lawrence proposal: Cyclotron (Nobel prize E.O. Lawrence 1939 "Invention and development of cyclotron ...")
1932	Cockroft-Walton linear accelerator for protons (Nobel prize Sir J.D. Cockroft u. E. Walton 1951 "Transmutation of atomic nuclei by artificially accelerated atomic particles")

Introduction II

1933 Discovery of the e^+, confirmation of development of electromagnetic showers due to $e^+ - e^-$ production
(Nobel prize P.M.S. Blackett 1948 "Development of Wilson cloud chamber method and his discoveries therewith")

1934 First evidence for Cherenkov radiation
(Nobel prize P. Cherenkov, I. Frank, I. Tamm 1958 "Discovery and interpretation of the Cherenkov effect")

1939 First measurements of the proton magnetic moment
(Nobel prize O. Stern 1943 "His contribution to the development of the molecular ray method ...")

1943 Fermis first reactor

1947 Confirmation of π^-
(Nobel prize C.F. Powell 1950 "His development of the photographic method and ...")

1953 First observations of charged particle tracks in a bubble chamber
(Nobel prize D.A. Glaser 1960 "For his invention of the bubble chamber")

1959 Proposal for an experiment to distinguish ν_e and ν_μ

1960 Realisation of neutrino beams at accelerators
(Nobel prize L. Lederman, M. Schwartz, J. Steinberger 1988 "for the neutrino beam method and ...")

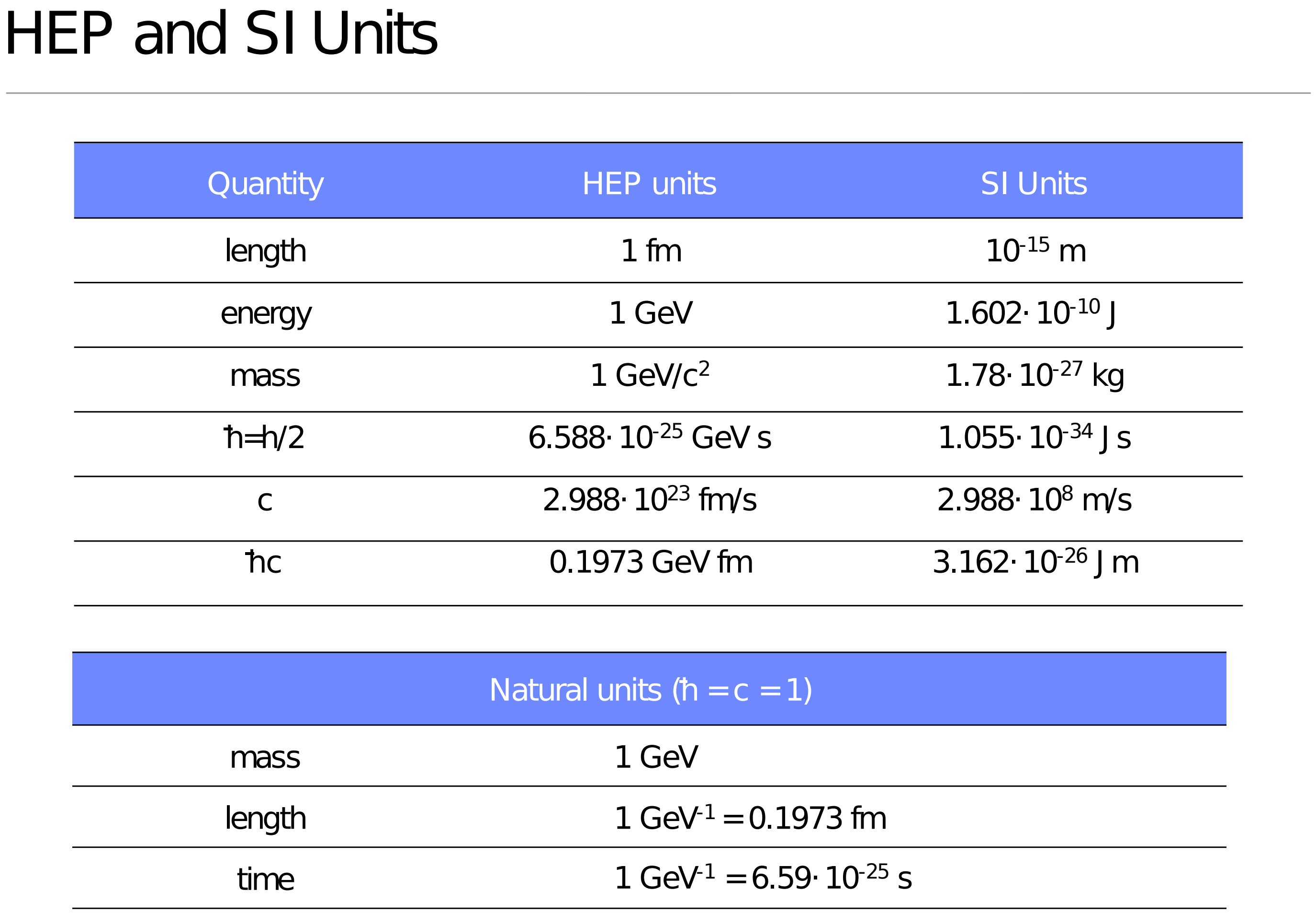
1960 First evidence for $\Sigma(1385)$

1961 First evidence for ω-meson
(Nobel prize L. Alvarez 1968 " ...discovery of a large number of resonance states made possible through his development of the hydrogen bubble chamber technique ...")

Introduction III

1968	Invention of the Multiwire Proportional Chamber (MPC) (Nobel prize G. Charpak 1992 “for his invention and development of particle detectors, in particular the multiwire proportional chamber”)
1983	First evidence for intermediate vector bosons W^+, W^-, Z^0 (Nobel prize C. Rubbia 1984, co-awardee S. van de Meer “stochastic cooling of proton beam ...”)
1986	Precision measurement of $g-2$ of the electron (Nobel prize H. Dehmelt and W. Paul 1989 “for the development of ion trap technique ...”)
1986	Neutrino oscillations in solar and atmospheric neutrinos (Nobel prize R. Davies and T.Koshiba 2002 “ ... development of neutrino detection techniques”)
1989-2000	precision measurements at LEP test QCD and establish the precise form of asymptotic freedom (Nobel prize D.J. Gross, H.D. Politzer, F. Wilczek “for the discovery of asymptotic freedom ...”)
1995	Discovery of the top quark by D0 and CDF, first $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV at the Tevatron in 1986
2013	Discovery of a Higgs boson by ATLAS and CMS, first pp collisions at $\sqrt{s} = 7$ TeV at the LHC 2010 (Nobel prize P. Higgs and F. Englert 2013 “ for the theoretical discovery of a mechanism ... recently confirmed through the discovery of the predicted fundamental particle ...”)

Units I



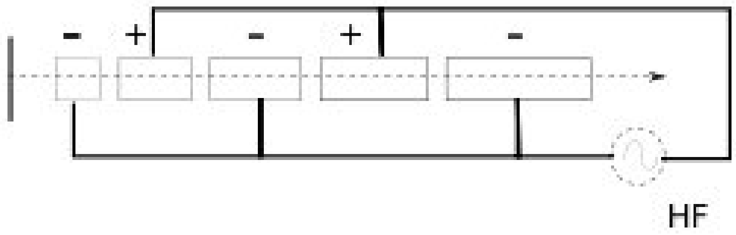
HEP and SI Units

Quantity	HEP units	SI Units
length	1 fm	10^{-15} m
energy	1 GeV	$1.602 \cdot 10^{-10}$ J
mass	1 GeV/c^2	$1.78 \cdot 10^{-27}$ kg
$\hbar = h/2$	$6.588 \cdot 10^{-25}$ GeV s	$1.055 \cdot 10^{-34}$ J s
c	$2.988 \cdot 10^{23}$ fm/s	$2.988 \cdot 10^{8}$ m/s
$\hbar c$	0.1973 GeV fm	$3.162 \cdot 10^{-26}$ J m

Natural units ($\hbar = c = 1$)	
mass	1 GeV
length	1 $\text{GeV}^{-1} = 0.1973$ fm
time	1 $\text{GeV}^{-1} = 6.59 \cdot 10^{-25}$ s

1.1 Beams I

- Non-controlled collisions: Cosmic radiation, beam energy and particle type cannot be controlled, many discoveries, extremely high energies
- Controlled experiments: particle accelerator - charged particle traverses potential difference
  - Particle traverses many successive potential differences
    LINAC - Linear accelerator

    RF cavity resonators , typically 8 MV/m
    future: e.g. ILC $>$ 35 MV/m
    The particles surf on the wavecrest through the cavities, scalable to very high energies, high cost due to length . . .
  - Particle traverses the same potential difference many times
    circular accelerator (cyclotron, synchrotron)
    again acceleration in RF cavities, magnetic field keeps particles on circular orbit
    cyclotron condition :

$$\begin{aligned} p &= eBR \\ p\,(GeV/c) &= 0.3 \cdot B\,(T) R\,(m) \end{aligned}$$

1.1 Beams II

conventional coils:		1.5 T
superconducting:	Tevatron	5 T
	LHC:	10 T

The particle loses energy by synchrotron radiation, the 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 energy per turn

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

e.g.: LEP $R = 4.3$ km, $E = 100$ GeV, $m_0 = 0.5$ MeV, $\gamma = 2 \cdot 10^5 \to \Delta E = 2.24$ GeV of 100 GeV
LEP maybe the last circular accelerator for electrons?
for protons, synchrotron radiation so far comparatively irrelevant
LHC in the LEP tunnel: $E = 7$ TeV, $\gamma = 7 \cdot 10^3 \to \Delta E = 3.4$ keV

- Beam hits stationary target “fixed target experiments”

$$p + p \to X \qquad \sqrt{s} = m_p\sqrt{2 + 2\gamma_p}$$

but high luminosity
e.g.: in 1 m liquid hydrogen, beam 10^{12} /s $\quad \mathcal{L} = 2 \cdot 10^{36}/\mathrm{cm}^2\,\mathrm{s}$

1.1 Beams III

- Colliding beams “collider experiminets” high energies $\sqrt{s} = 2 m_p \gamma_p$
  comparatively low luminosity
  e.g.: 10^{10} particles per bunch, 20 bunches per orbit, revolution frequency 1 MHz, beam size 10^{-2} cm^2

$$\mathcal{L} = \frac{10^6 \cdot 20 \cdot 10^{20}}{10^{-2}\mathrm{cm}^2 \cdot \mathrm{s}} = 2 \cdot 10^{29}/\mathrm{cm}^2\,\mathrm{s} \quad \mathrm{LHC} : 10^{34}/\mathrm{cm}^2, \mathrm{s}$$

Reaction rate:

$$R = \sigma \cdot \mathcal{L}$$

typical largest cross section → total inelastic cross section

$$p + p \qquad \text{at } \sqrt{s} = 10\,(7000)\ \mathrm{GeV},\ \sigma_{\mathrm{incl}} = 30\,(60)\ \mathrm{mb}$$

1 mb = 1 millibarn = 10^{-24} cm^2 $\cdot 10^{-3}$
inelastic rate typical “fixed target” experiment: $R = 3 \cdot 10^{-26}$ cm^2 $\cdot 2 \cdot 10^{36}/$ cm^2 s $\approx 6 \cdot 10^{10}/$s
inelastic rate for pp collider: $R = 3 \cdot 10^{-26}$ cm^2 $\cdot 2 \cdot 10^{29}/$cm^2 s $\approx 6 \cdot 10^{3}/$s
Usually much smaller cross sections are investigated: nb, pb, ...

- → 1 pb: 2 Hz for fixed target
- → $2/10^7$ s (year) for colliders but 1/100 s (LHC)

Criteria for the beam energy

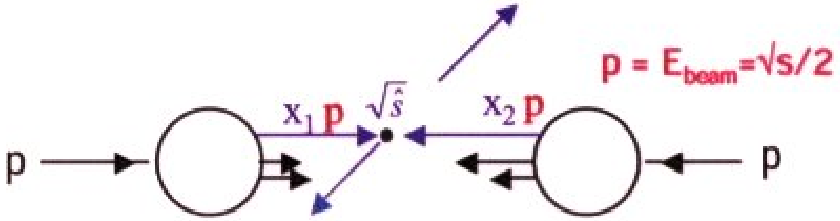
- Reaction rate, especially the importance of a threshold

$$\begin{array}{rl} e^+e^- \to Z^0 + \text{Higgs} & \sqrt{s} \geq m_{Z_0} + m_{\mathrm{Higgs}} \\ \text{at LEP} & \sqrt{s} = 208\ \mathrm{GeV} \to m_{\mathrm{Higgs}} \leq 116\ \mathrm{GeV} \end{array}$$

- Resolution of structures
  object of the dimensions Δx can be resolved with the wavelength

$$\bar{\lambda} = \frac{\hbar c}{pc} \leq \Delta x \qquad \text{or } pc \geq \frac{\hbar c}{\Delta x}$$

$$\begin{array}{lll} \text{Tevatron} & p \approx 1\ \text{TeV} & \Delta x \approx 10^{-16}\ \text{cm} \\ \text{LHC} & p \approx 10\ \text{TeV} & \Delta x \approx 10^{-17}\ \text{cm} \end{array}$$

$\mathrm{e}^+\mathrm{e}^-$ Colliders	**$\mathrm{pp}/\mathrm{p}\bar{\mathrm{p}}$ 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 → 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: $E_{\text{loss}} \sim \frac{E^4_{beam}}{R}\frac{1}{m_e^4}$ $E_{\text{loss}} \sim 2.5$ GeV/turn LEP 2 ($E_{\text{beam}} \sim 100$ GeV)	Synchrotron radiation is $\sim (m_p/m_e)^4 \sim 10^{13}$ smaller
- high energy more difficult → next machine: Linear Collider (ILC, CLIC, $\sqrt{s} = 800(3000?)$ GeV?) - clean environment → precision measurement machines	- high energy easier → discovery machines current machine: LHC, pp , $\sqrt{s} = 14\ TeV$ in the LEP ring more "dirty" environment

Electron Colliders Important for Testing Standard Model and Physics Beyond

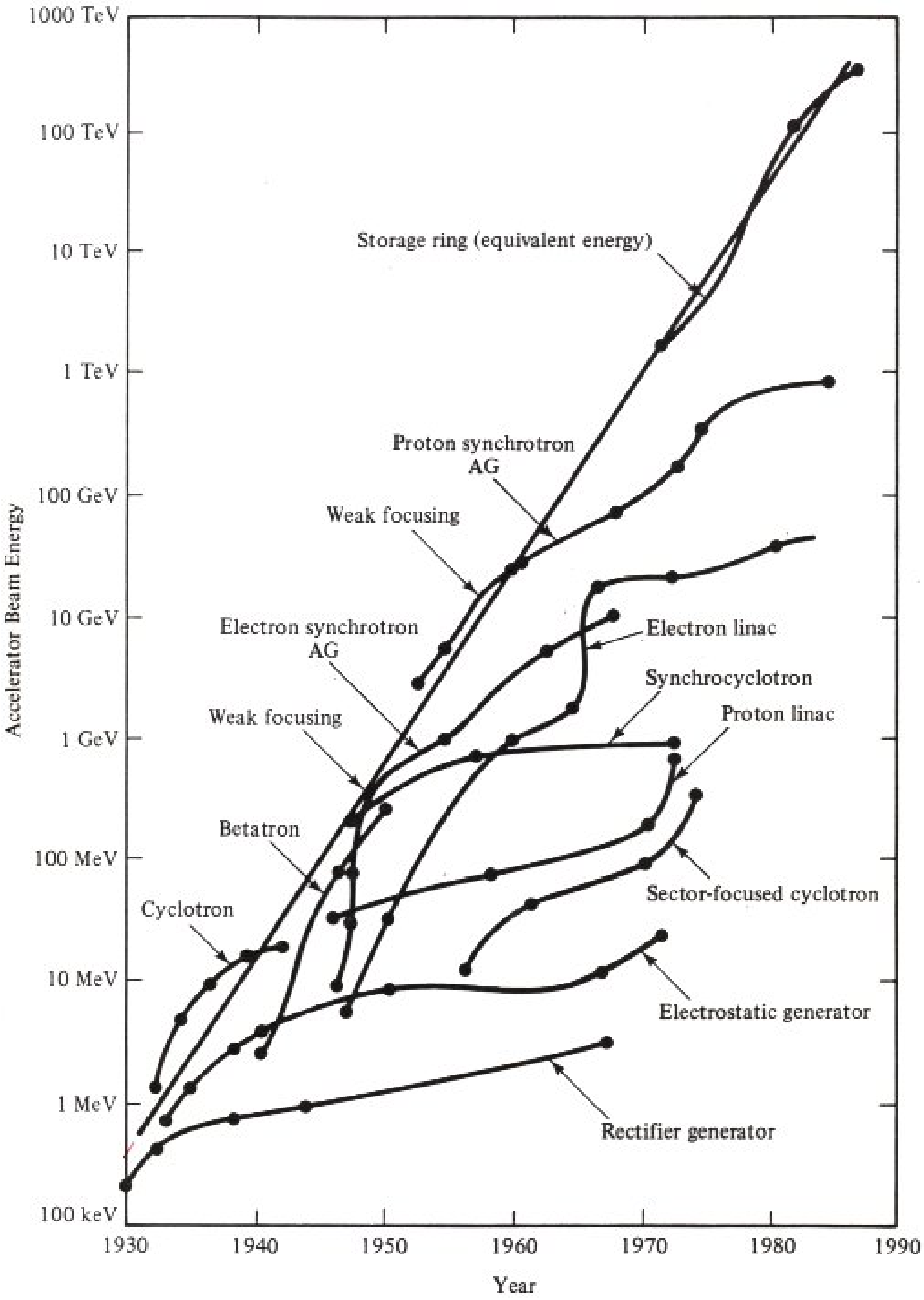
	where	start	end	energy (GeV)	length/ circumf. (km)	most relevant physics
Petra	DESY	1978	1986	23.5 + 23.5	2.3	discovery of gluons
CESR	Cornell/ USA	1979	...	6 + 6	0.77	spectroscopy hadrons with b and c quarks
PEP	Stanford/ USA	1980	1990	15 + 15	2.2	top search, indirect W/Z hint
Tristan	KEK/ Japan	1987	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 Important for Testing Standard Model and Physics Beyond

	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

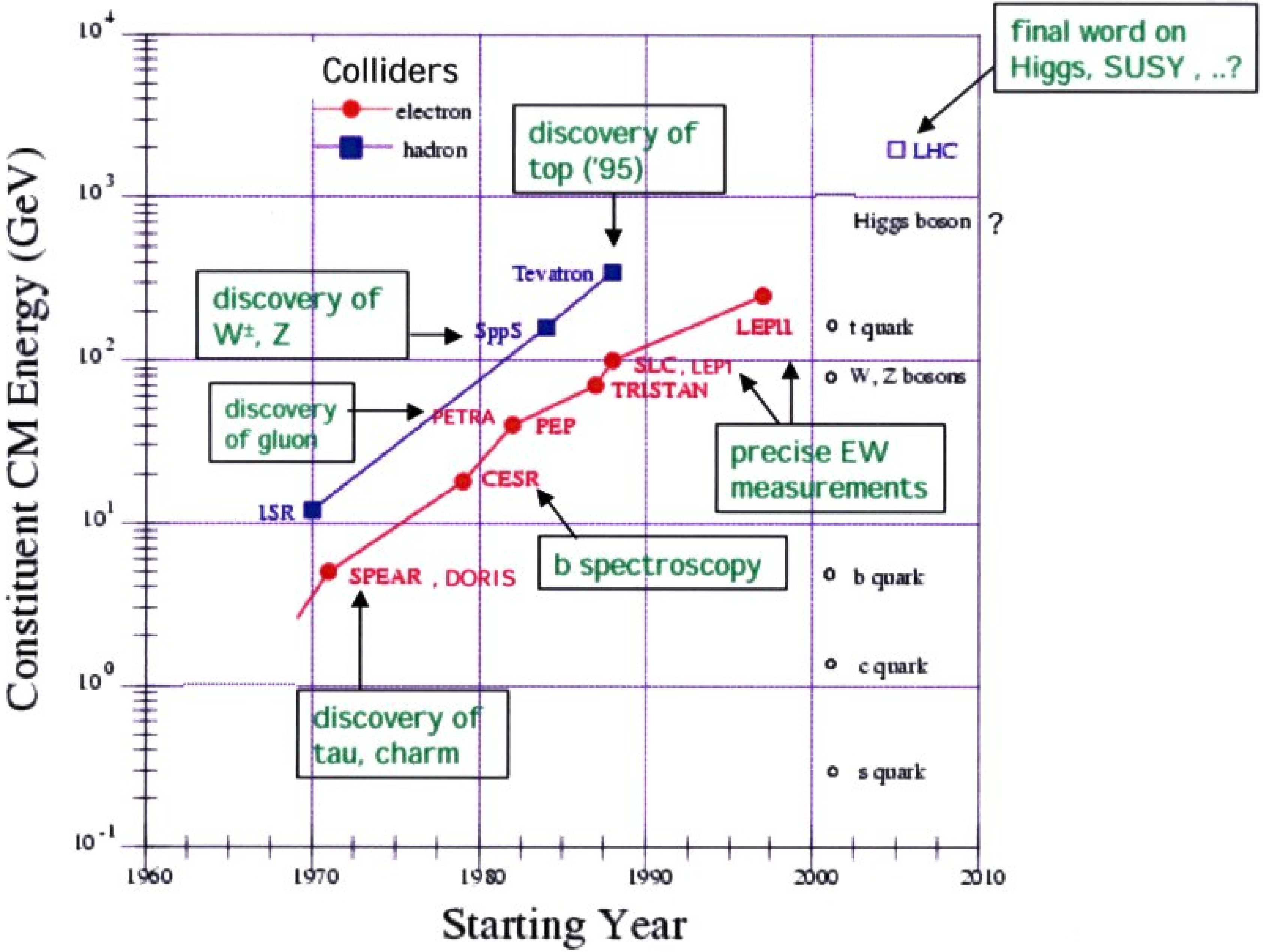
Sources of Neutrinos Important for Testing Standard Model and Physics Beyond

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



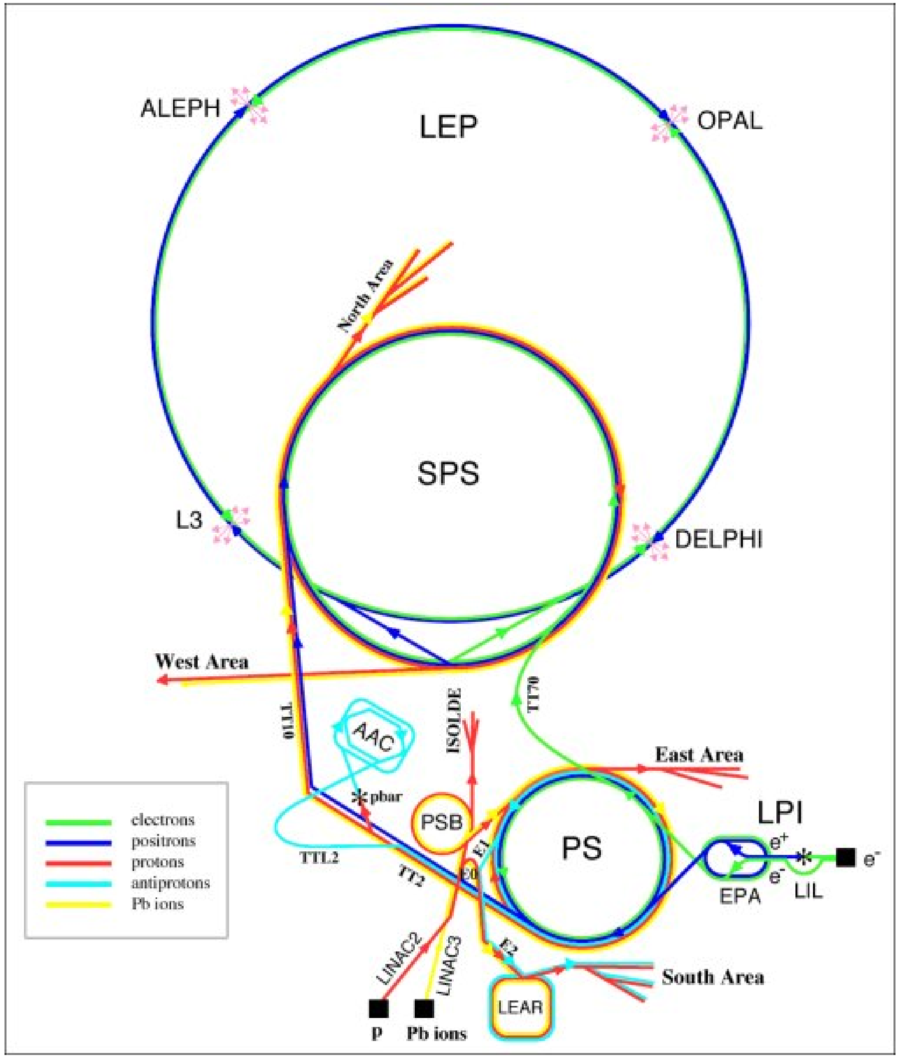
Energy growth of accelerators and storage rings. This plot, an updated version of M. Stanley Livingston's original, shows an energy increase by a factor of ten every seven years. Note how a new technology for acceleration has, so far, always appeared whenever the previous technology has reached its saturation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

Increase: factor 10 every 7 years.



Simplified and non-exhaustive summary of SM tests at Colliders

LEP: Large Electron Positron Collider



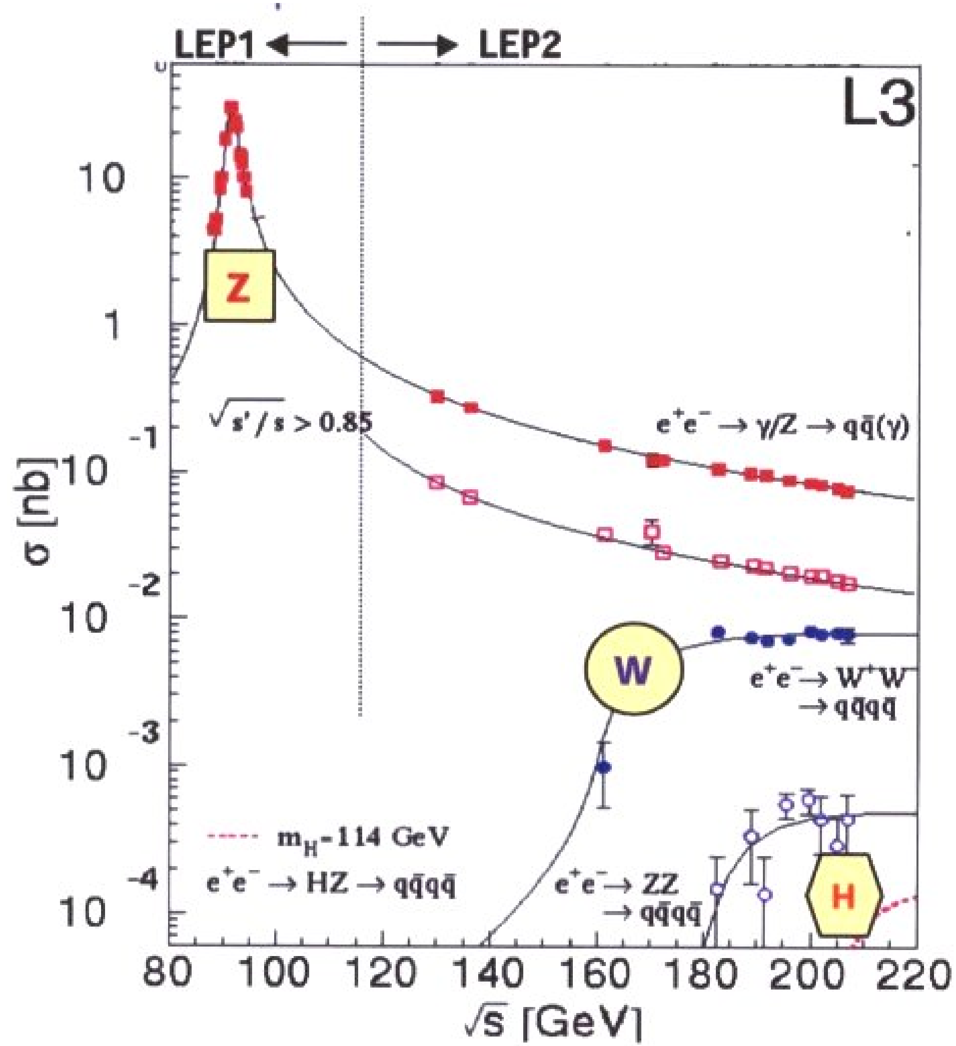
The LEP Storage Ring

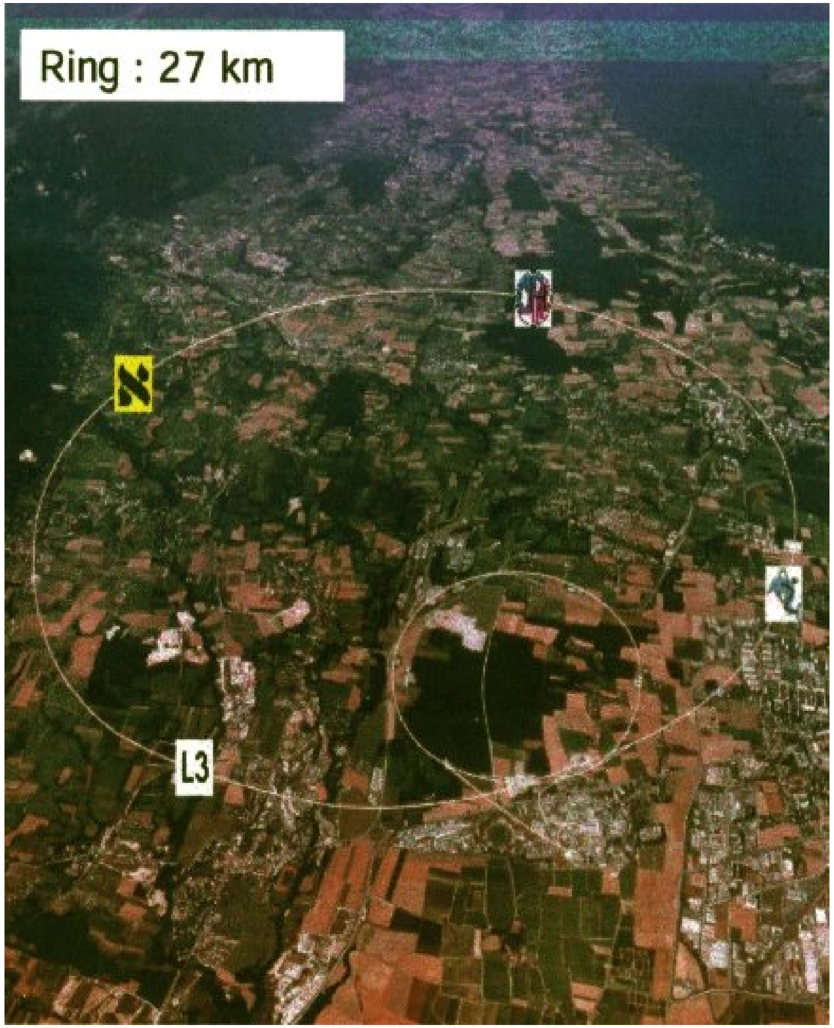
Some characteristic parameters

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: e^+e^- Collider at CERN

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

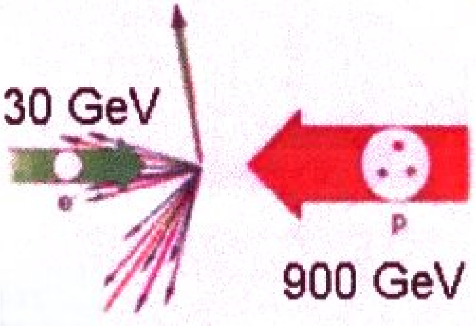


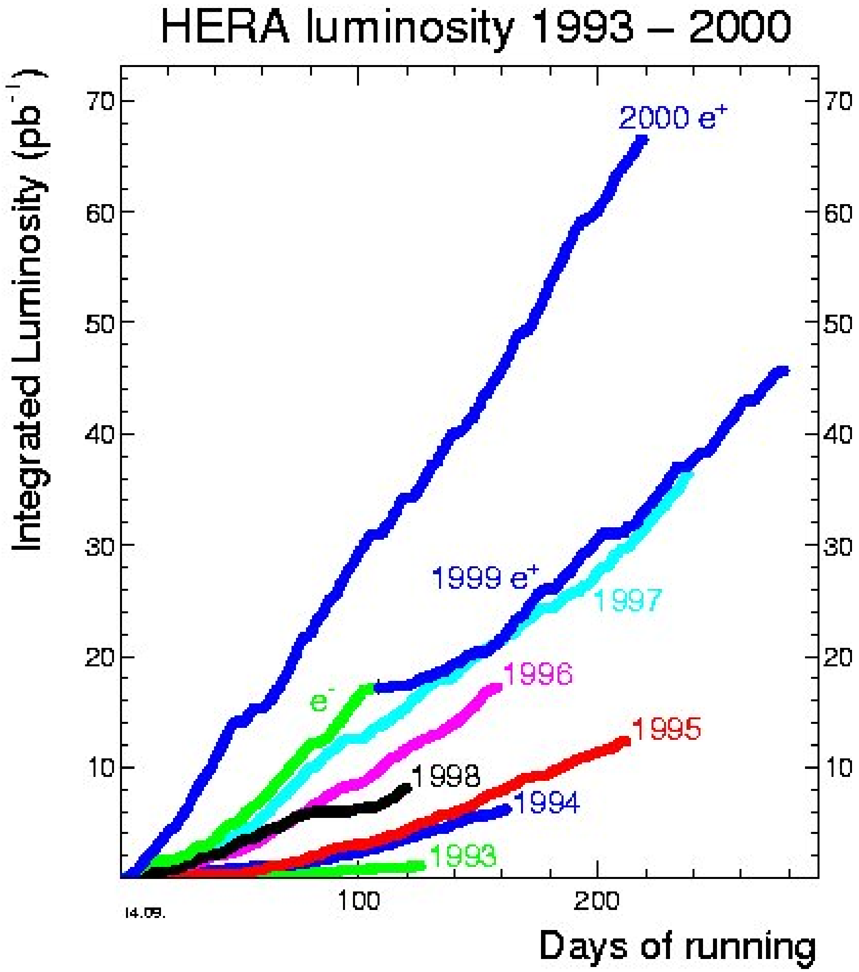


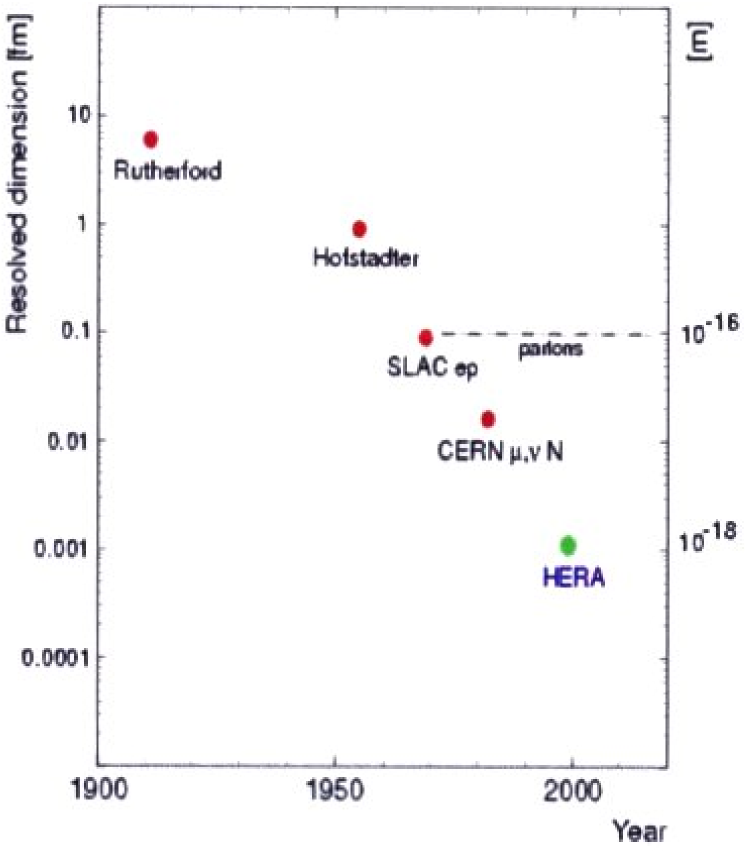
HERA: ep collider at DESY

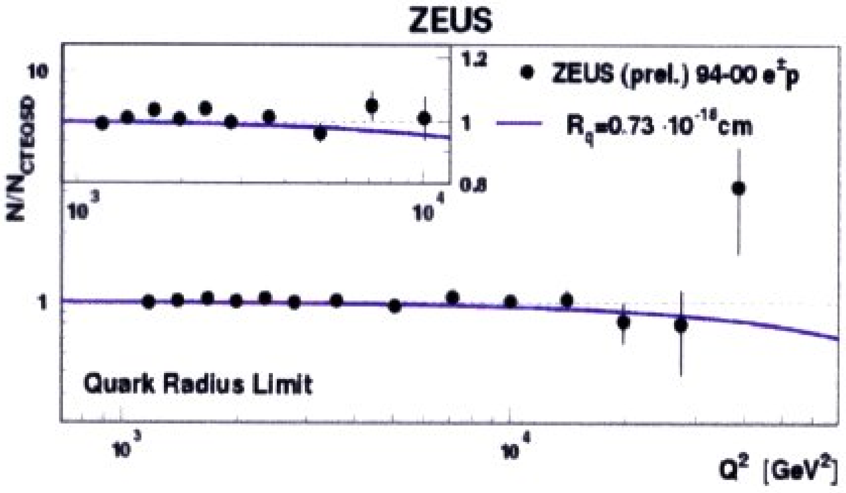
ep collisions allow to probe efficiently the proton structure, distribution of quarks and gluons, are quarks elementary?

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

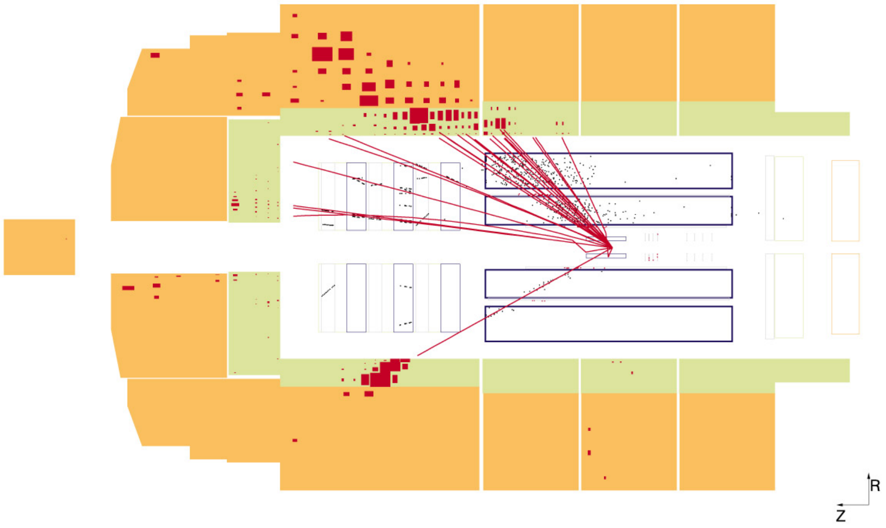








QCD with elementary quarks describes the scattering up to the highest accessible Q^2



the Tevatron: $\bar{p}p$ Collider at Fermilab

$R \sim 6.5$ km

$\sqrt{s} \approx 2$ TeV

Run 1	(1989-1996)	$\approx$ 200 top events → discovery of top $\approx$ 80000 W events, measurement of m_W and m_{top}
Run 2	(2001-2011)	$\geq 100\times$ more data → better measurements of m_W and m_{top}, searches for Higgs and new particles

LHC: Hadron collider at CERN, startup in 2009

LHC: Hadron collider at CERN

LHC machine parameters		
circumference		27 km
Bending radius		3 km
Dipole field		8.33 T
Orbit frequency		11 kHz
Bunch spacing		25 ns
Protons/bunch		10^{11}
Beam energy		
	pp	$7 + 7$ TeV
	PbPb	$2.7 + 2.7$ TeV/u
Peak luminosity		
	pp	10^{34} cm^{-2} s^{-1}
	PbPb	10^{27} cm^{-2} s^{-1}

1.2 General demands on particle detectors

- Particle detection
- Momentum or energy measurement
- Particle identification *electron - pion - kaon . . .*
- Reconstruction of the invariant mass of decay products $m^2_{\mathrm{inv}} = (\sum_i p_i)^2$, 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

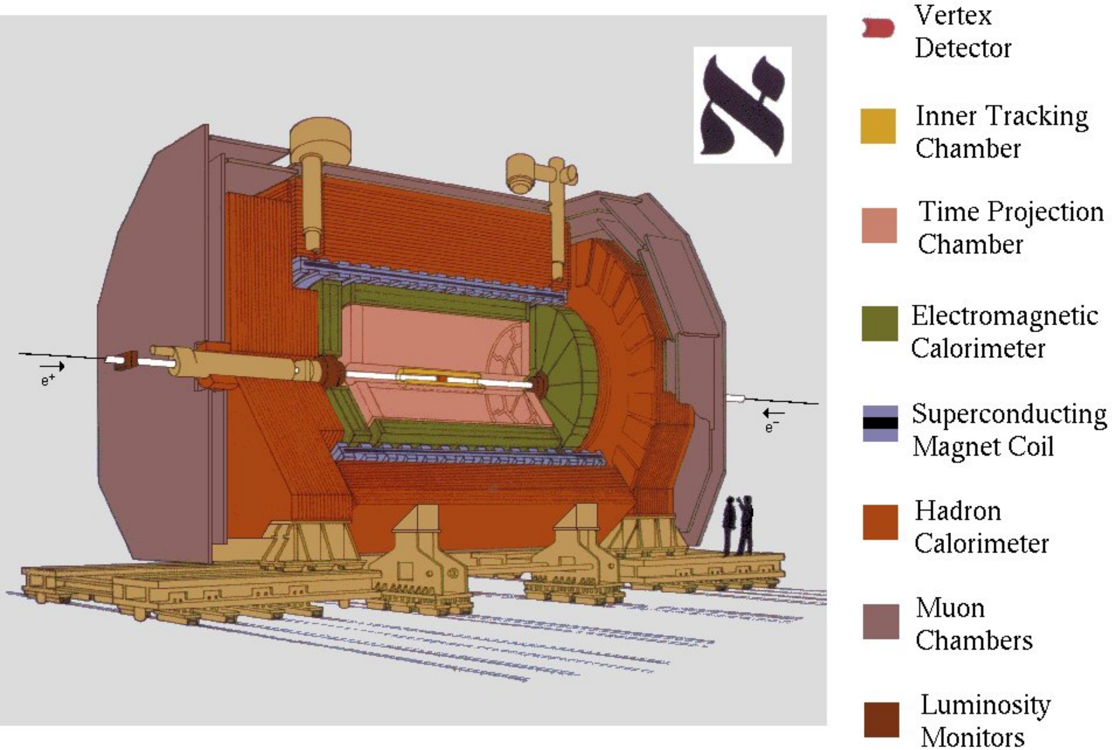
$$\tau c = \frac{\hbar c}{\Gamma} = 2\ \mathrm{fm} \qquad \tau \approx 10^{-23}\ \mathrm{s}$$

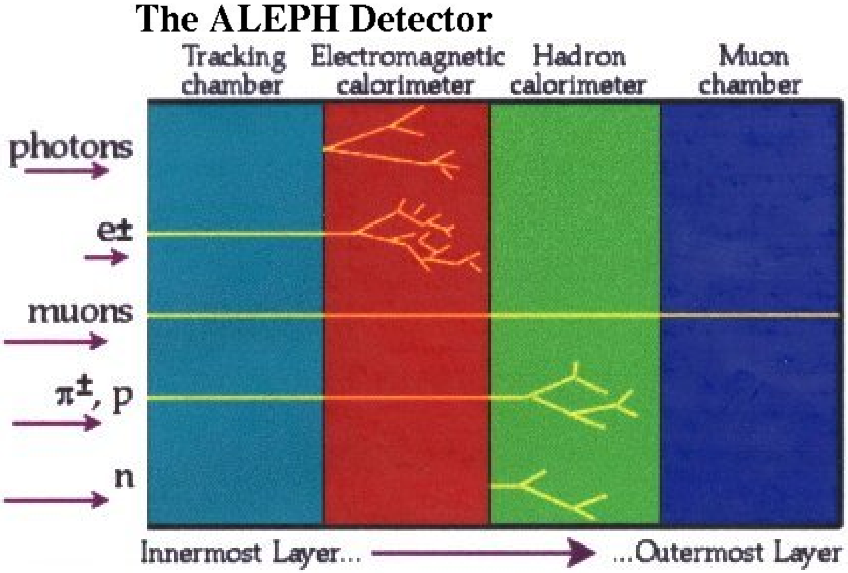
    decay via electromagnetic interaction: $\pi^0 \to \gamma\gamma$ $\tau = 10^{-16}$ s
  - quasi-stable particles:
    decay via weak interaction

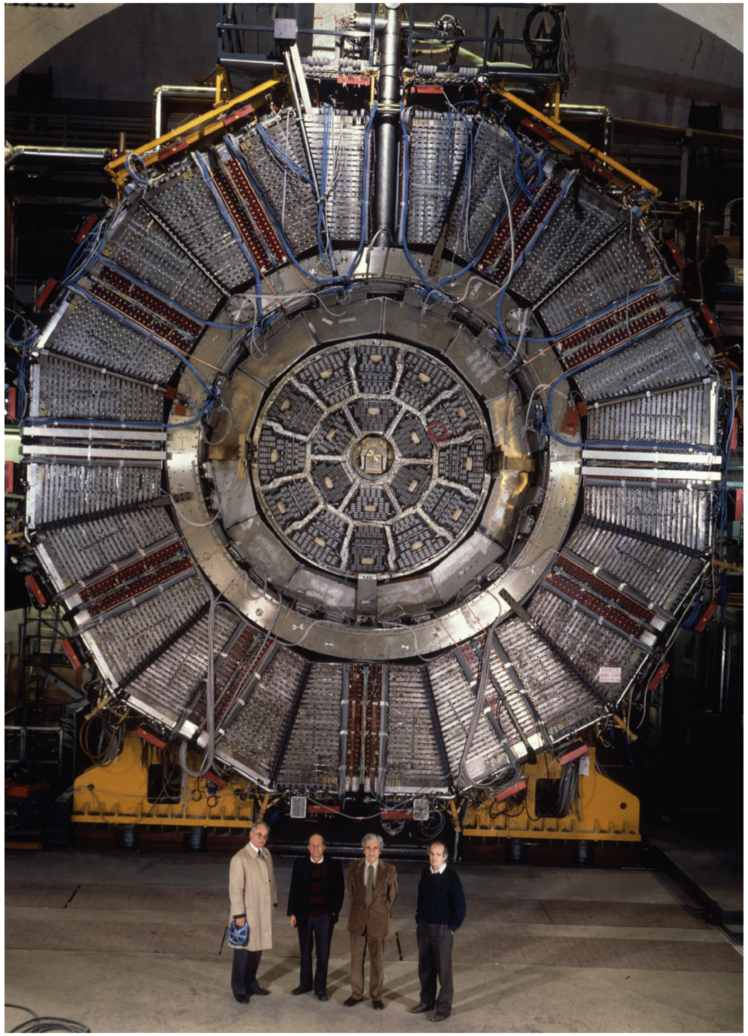
Some examples for decay length

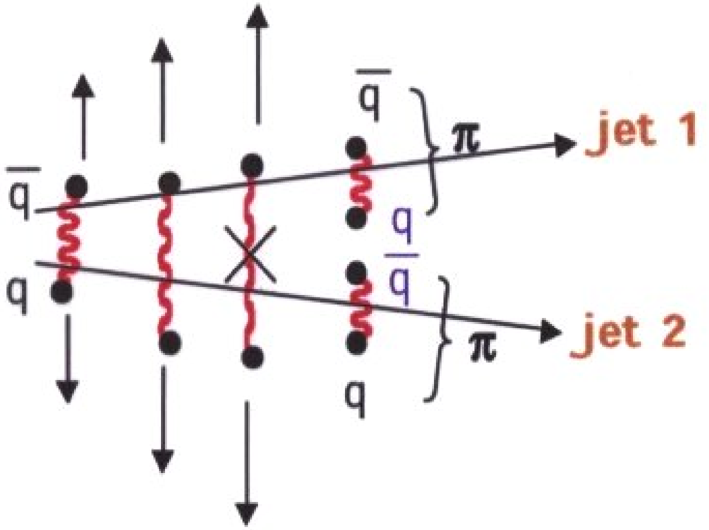
particle	τ	$c\tau$	decay length $\beta\gamma c\tau$ at $p = 10\ GeV/c$
n	889 s	$2.7 \cdot 10^{8}$ km	$2.9 \cdot 10^{9}$ km
Λ	$2.6 \cdot 10^{-10}$ s	7.9 cm	71 cm
$\pi^{\pm}$	$2.6 \cdot 10^{-8}$ s	7.8 m	560 m
$D^{\pm}$	10^{-12} s	0.31 mm	1.6 mm
$B^{\pm}$	$1.6 \cdot 10^{-12}$ s	0.49 mm	0.93 mm
τ	$3 \cdot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

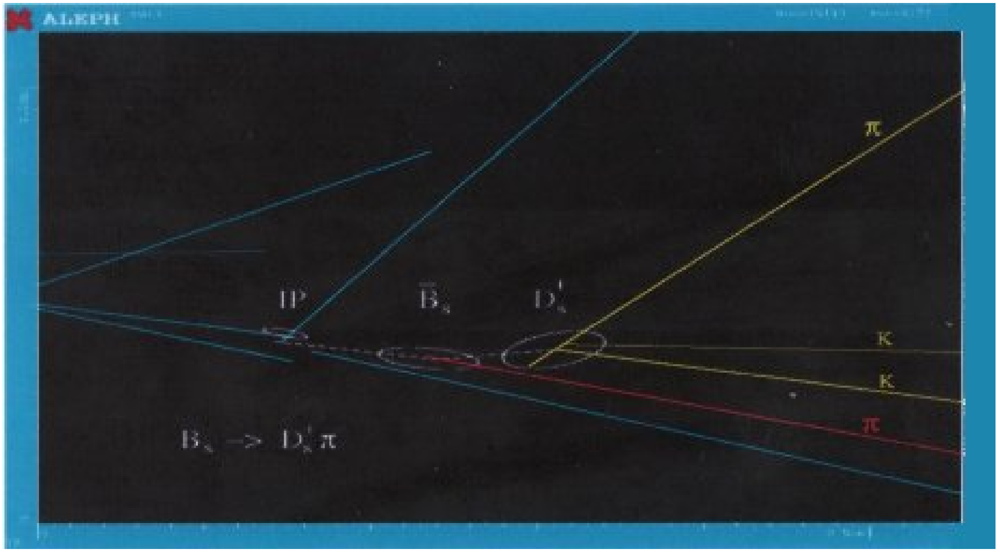
ALEPH: Apparatus for LEP Physics

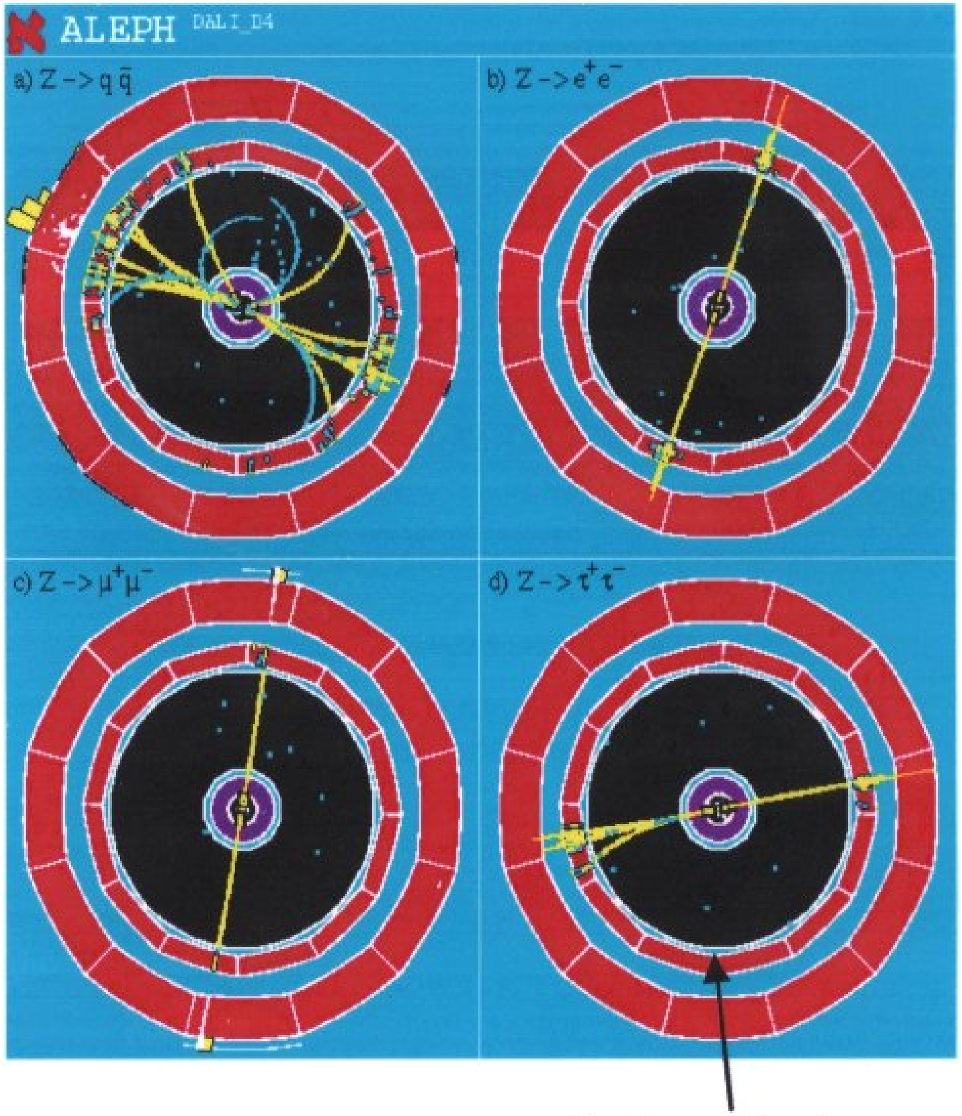






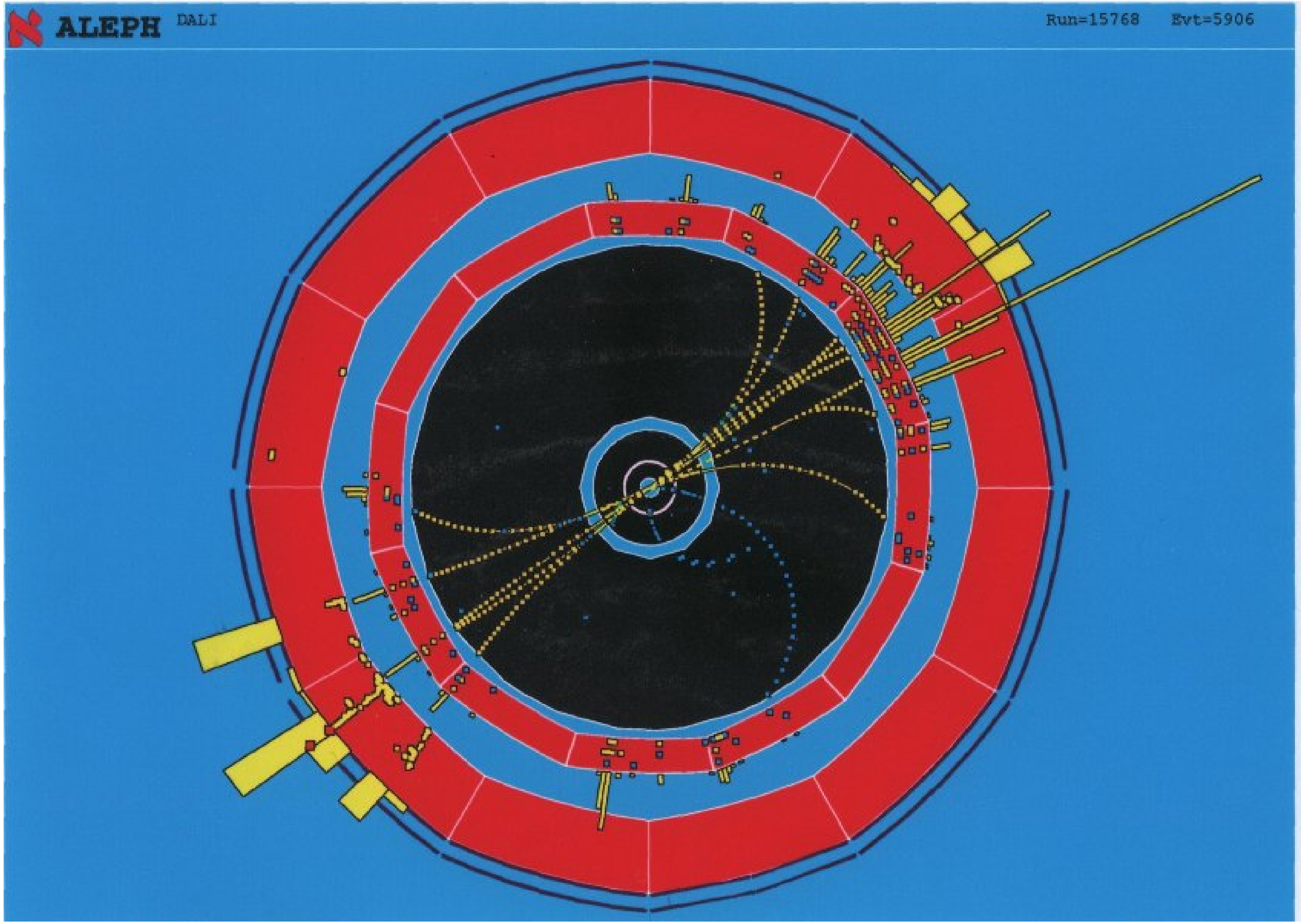




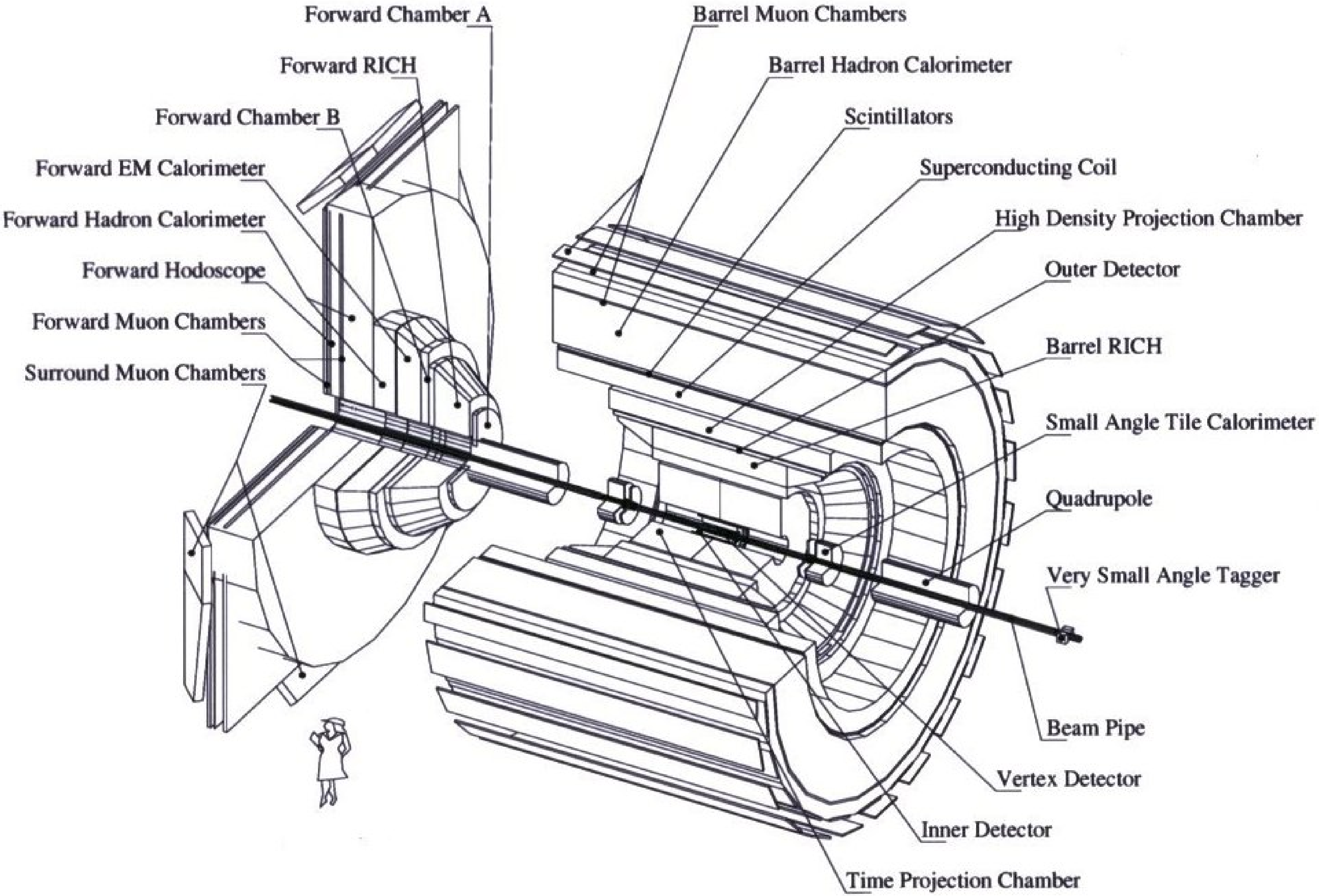


2 jets of hadrons
with low multiplicity
+ missing E carried
by neutrinos

ALEPH: Display of 2 Jet Events

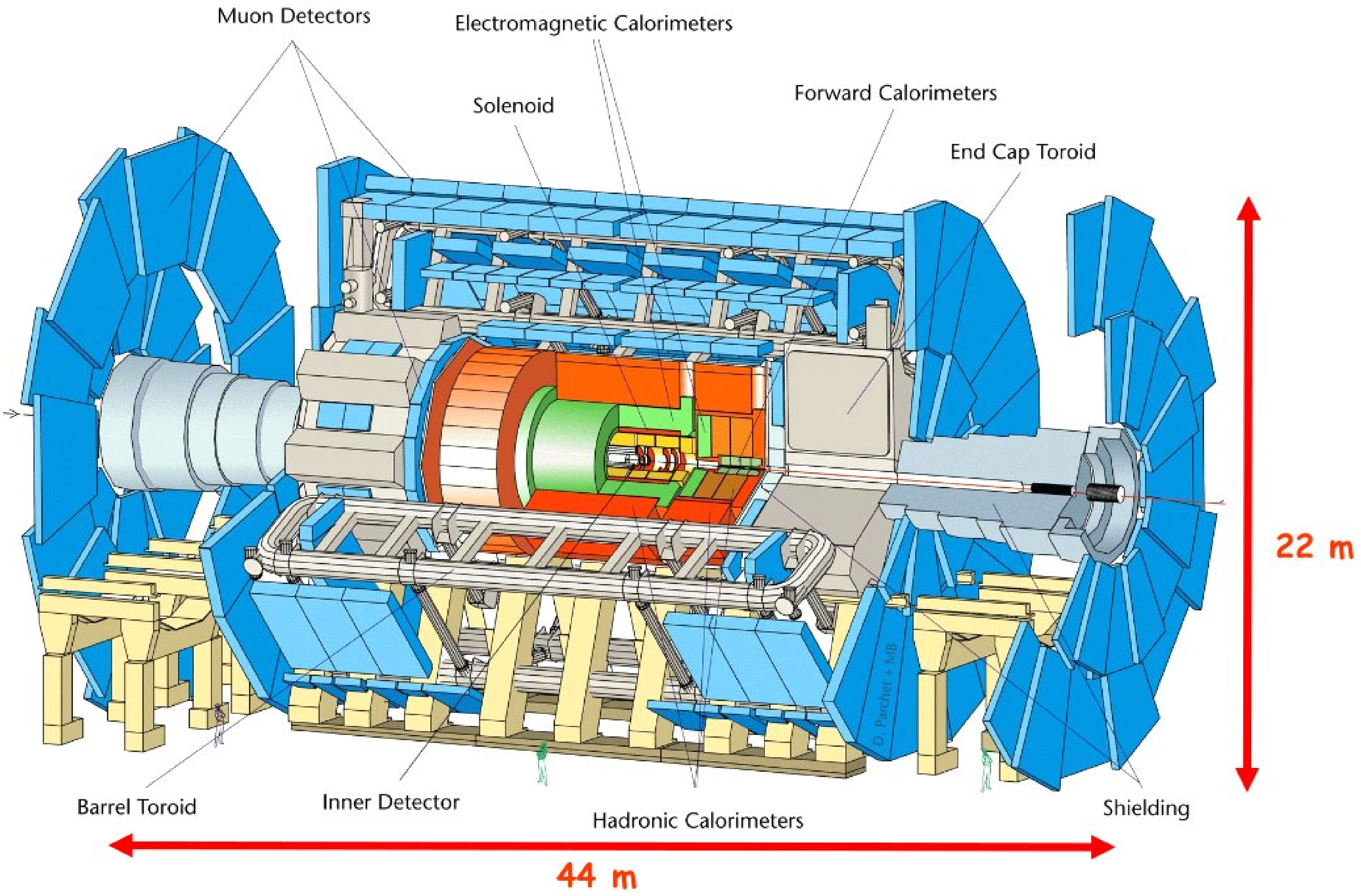


DELPHI: DEtector with Lepton, Photon and Hadron Identification

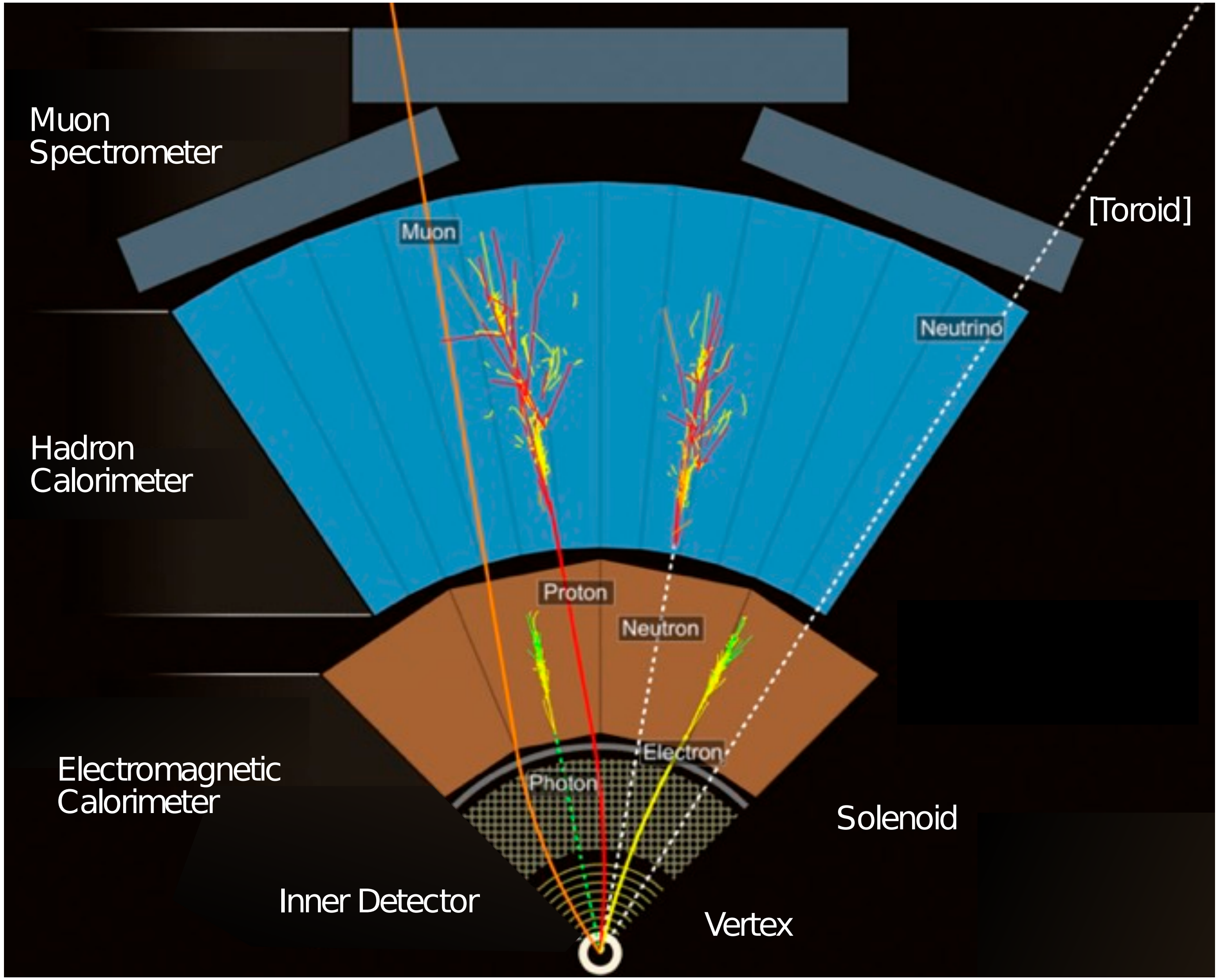


		ALEPH	DELPHI	L3	OPAL
magnet		superconducting	superconducting	normal	normal
fieldstrength		1.5 T	1.23 T	0.5 T	0.435 T
vertexdetector (SS)					
hit resolution	$r\phi$	12 μm	8 μm	7 μm	5 μm
	z	10 μm	9 μm	14 μm	13 mm
vertex detector					
hit resolution	$r\phi$	150 μm	85 μm	-	55 μm
	z	70 mm	-	-	40 mm (ΔT)
					0.7 mm (st.)
central detector		TPC	TPC	TEC	jet chamber
hit resolution	$r\phi$	180 μm	250 μm	50 μm	135 μm
	z	$\sim$ 1 mm	0.9 mm	-	45 mm
outer chambers					
hit resolution	$r\phi$	-	110 μm	-	15 mm
	z	-	35 mm	320 μm	300 μm
momentum resol.	$\sigma(\frac{1}{p_t})(\mathrm{GeV/c})^{-1}$	$0.6 \cdot 10^{-3}$	$0.6 \cdot 10^{-3}$	$0.6 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$
(cos $\theta \simeq 0$)				for $\mu^{\pm}$ only	
electromagnetic		lead-prop. tubes	HPC /lead glass	BGO	lead glass
calorimeter					
granularity	barrel	3 × 3 cm^2	$\sim$ 2 × 2 cm^2	2 × 2 cm^2	10 × 10 cm^2
	endcap	same as barrel	5 × 5 cm^2	same as barrel	same as barrel
energy resolution	σ_E/E	$0.18\sqrt{E/\mathrm{GeV}}$	$0.32\sqrt{E/\mathrm{GeV}}$	$0.02\sqrt{E/\mathrm{GeV}}$	$0.06\sqrt{E/\mathrm{GeV}}$
		$\oplus 0.01$	$\oplus 0.04$	$\oplus 0.01$	$\oplus 0.02$
hadronic energy		$0.85\sqrt{E/\mathrm{GeV}}$	$1.12\sqrt{E/\mathrm{GeV}}$	10% at 45 GeV	1 (at <15 GeV)
resolution			$\oplus 0.21$		to $1.2\sqrt{E/\mathrm{GeV}}$
luminosity detector		Si-W sampling	lead-scintillating	BGO +	Si-W sampling
		+ lead sandwich	tiles & mask	Si $r\phi$ strips	+ lead sandwich
fiducial acceptance	inner/outer radius	6.1/14.5 cm	6.5/42.0 cm	7.6/15.4 cm	6.2/14.2 cm
	$\theta_{\mathrm{min}}/\theta\mathrm{max}$	30/48 mrad	44/114 mrad	32/54 mrad	31/52 mrad

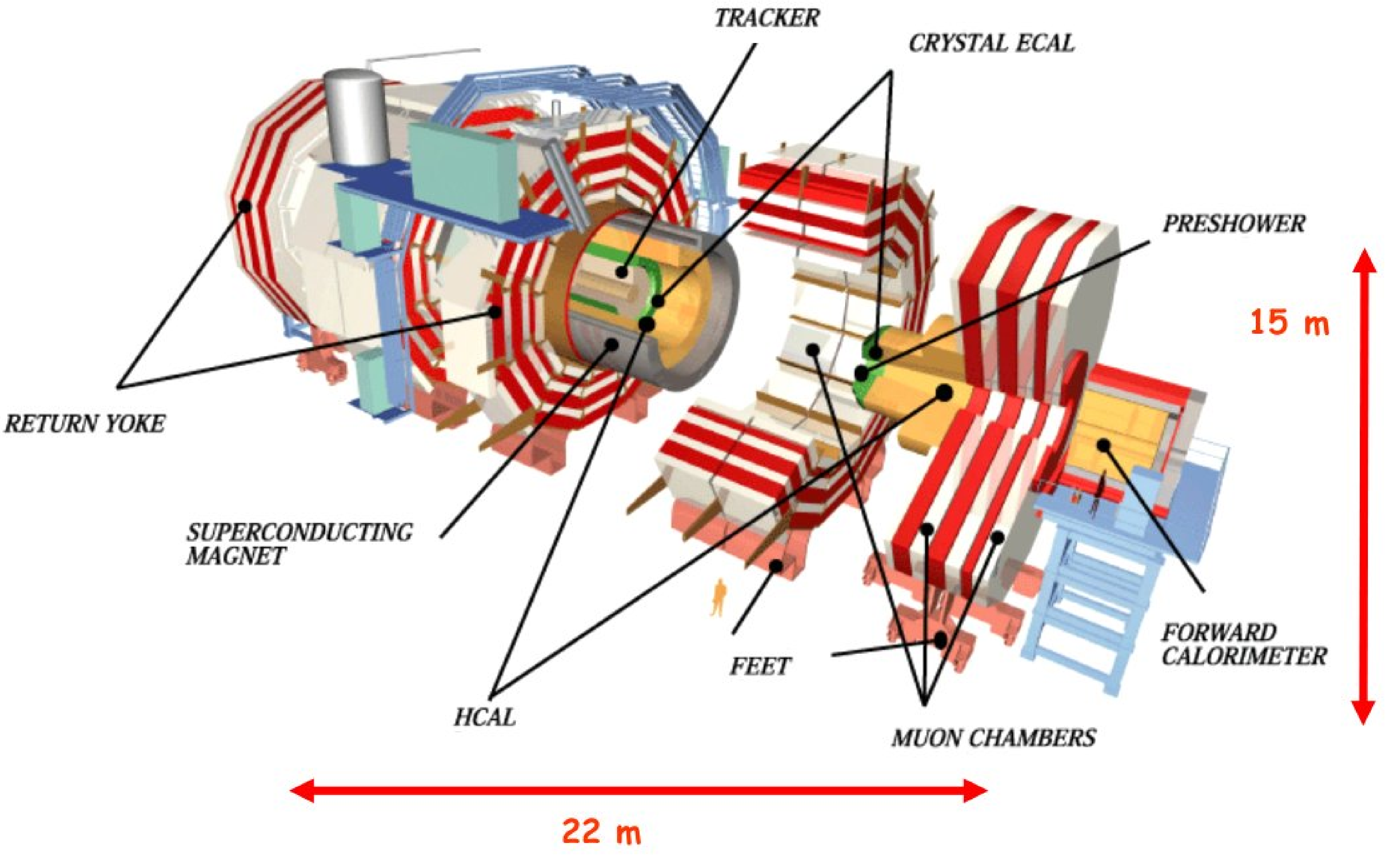
ATLAS: A Toroidal LHC ApparatuS



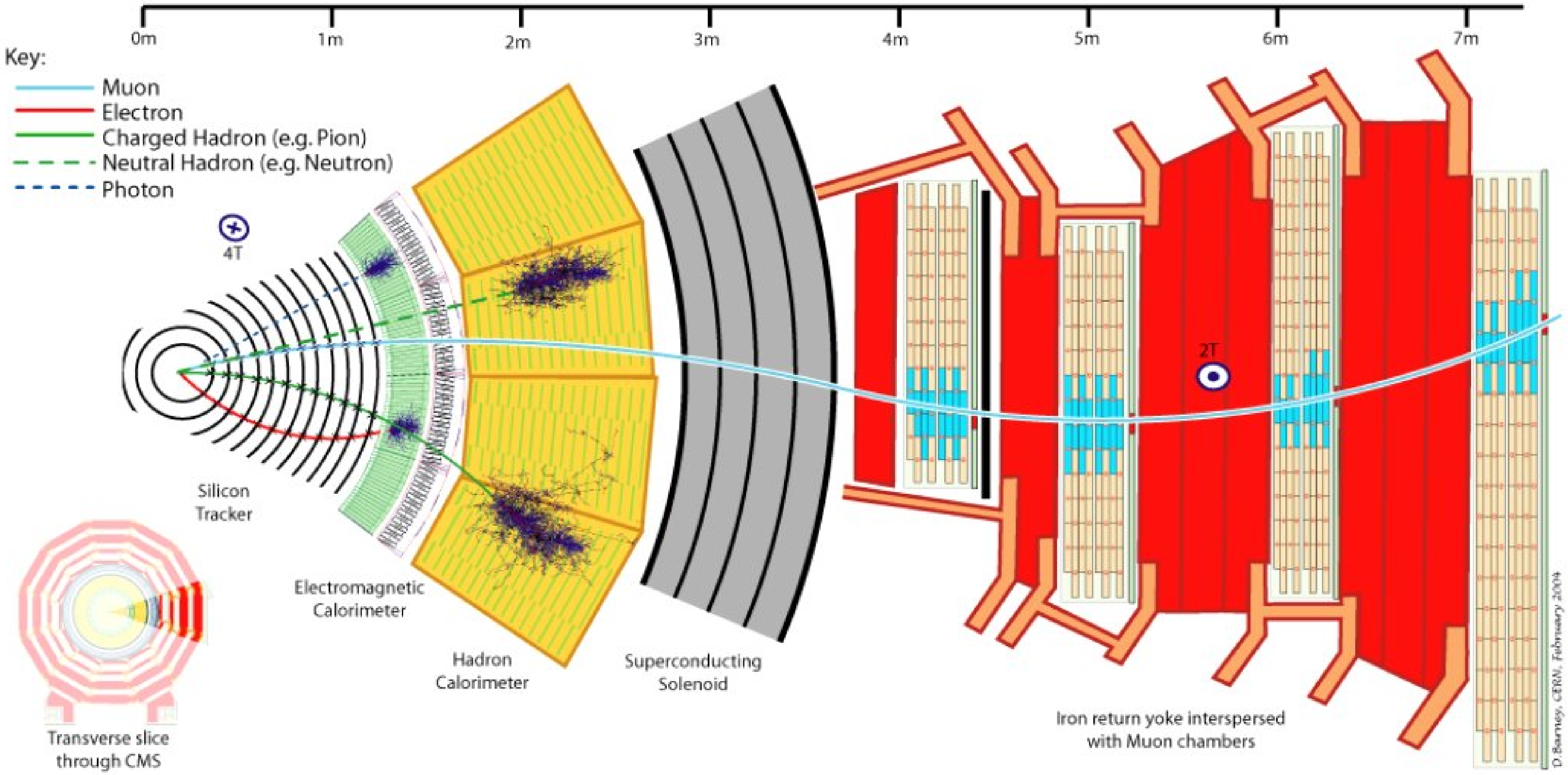
ATLAS: A Toroidal LHC ApparatuS



CMS: Compact Muon Spectrometer



Slice through CMS



ALICE: A Large Ion Collider Experiment