

Fundamental interactions

Experimental methods

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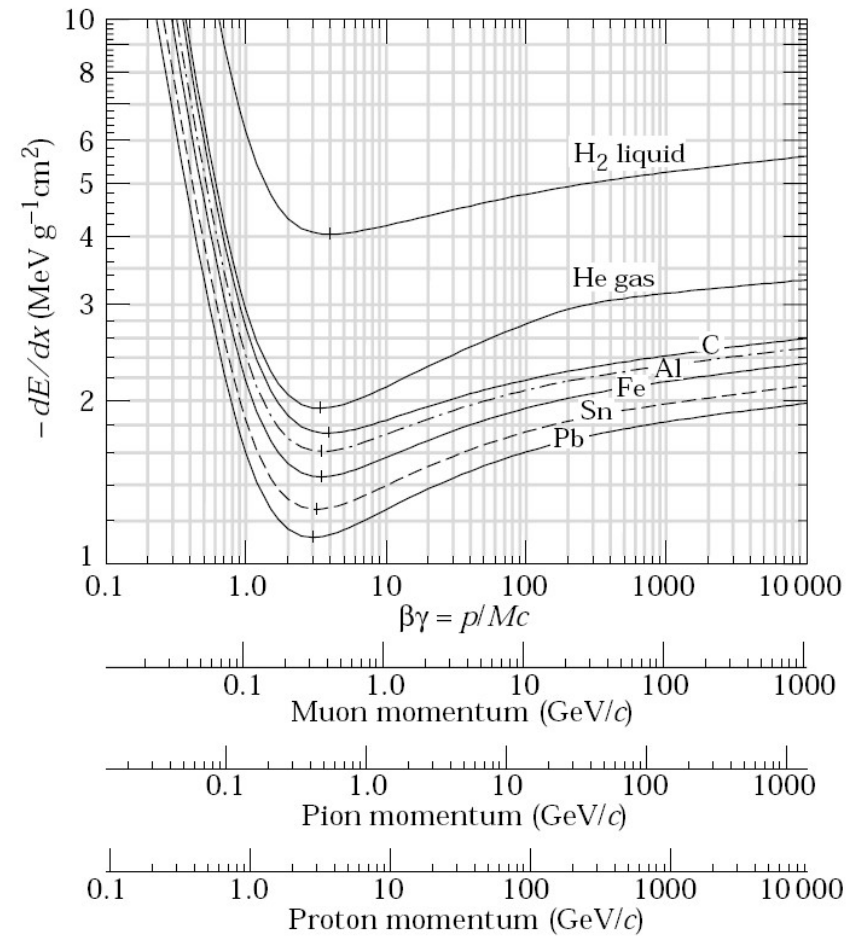
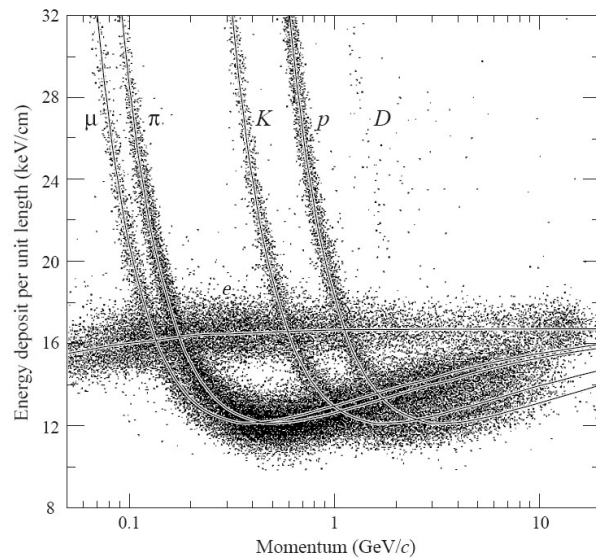
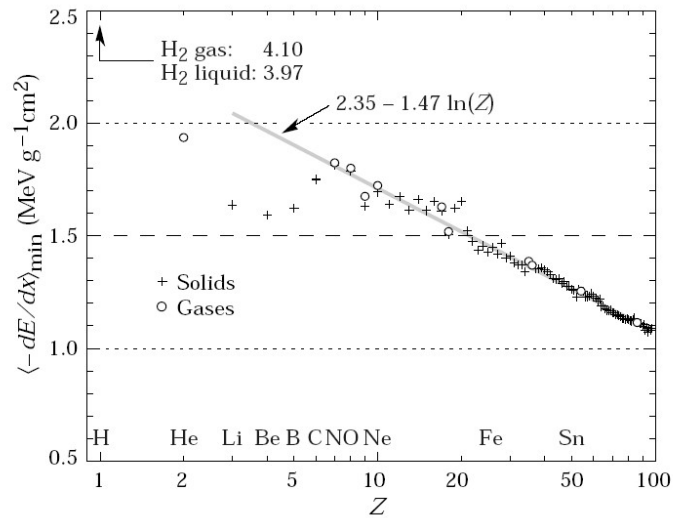
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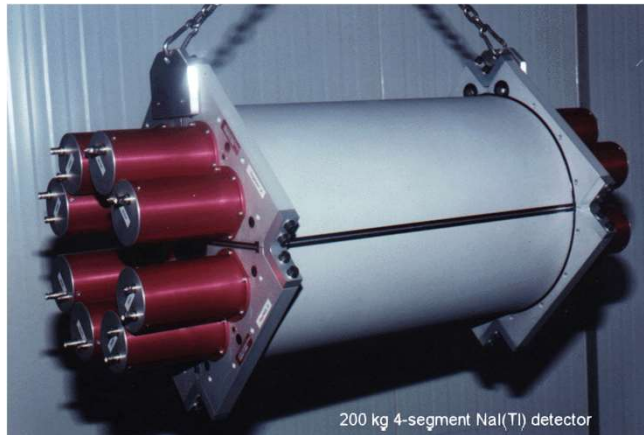


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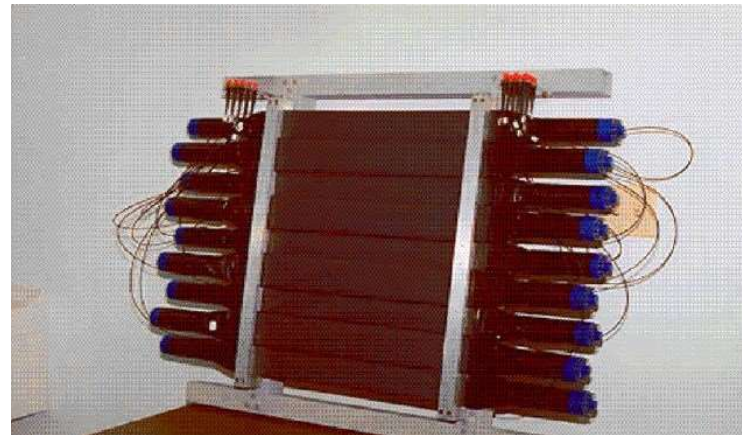
Charged particles: dE/dx



Scintillators



Large NaI(Tl) detector

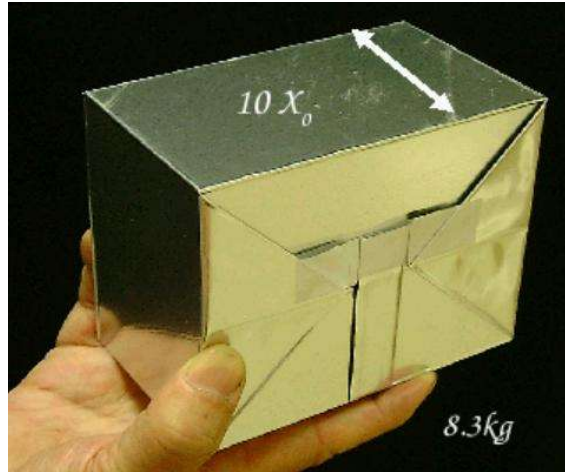


Plastic scintillator hodoscope

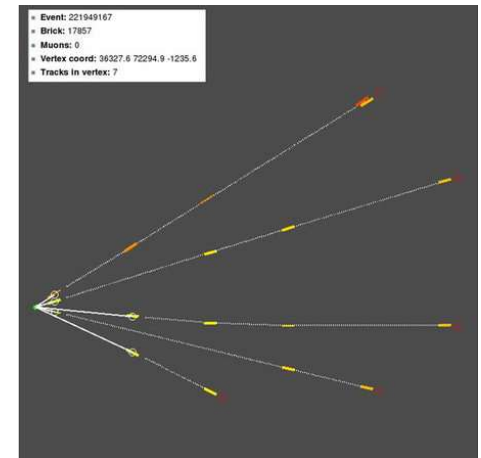
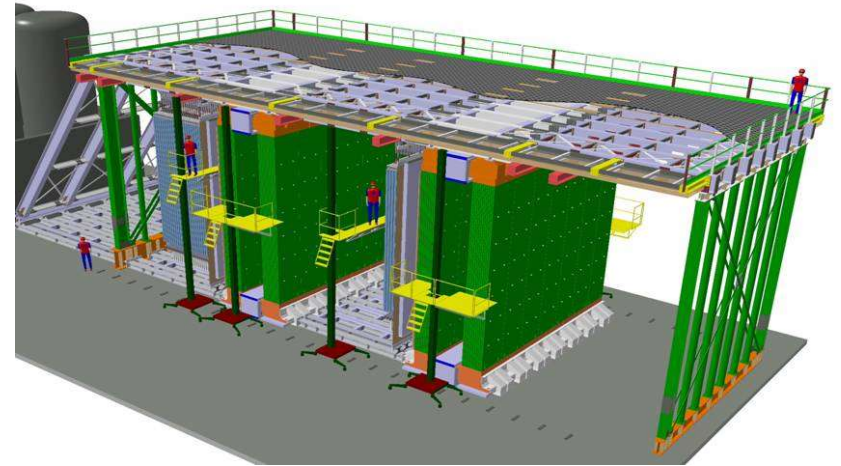
Measure:
**passage (and energy deposit)
of charged particles**

Photographic emulsions

Example: the OPERA
neutrino detector
at LNGS

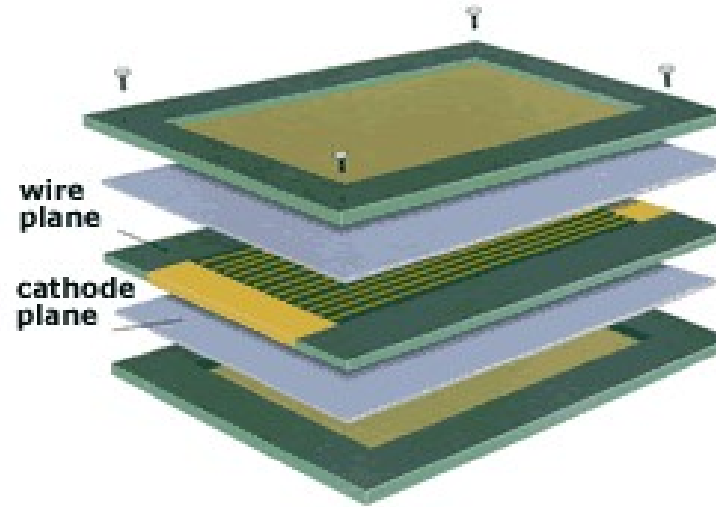


Measure:
**integrated tracks of
charged particles**

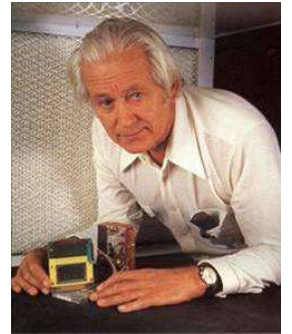


MWPC – Multi-Wire Proportional Chamber

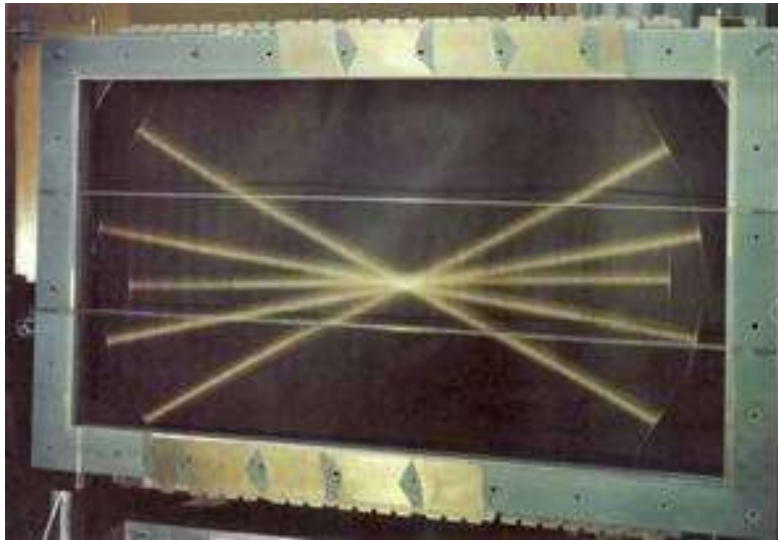
Thousands of wires
Simple, cheap,
limited resolution,
can be triggered, fragile



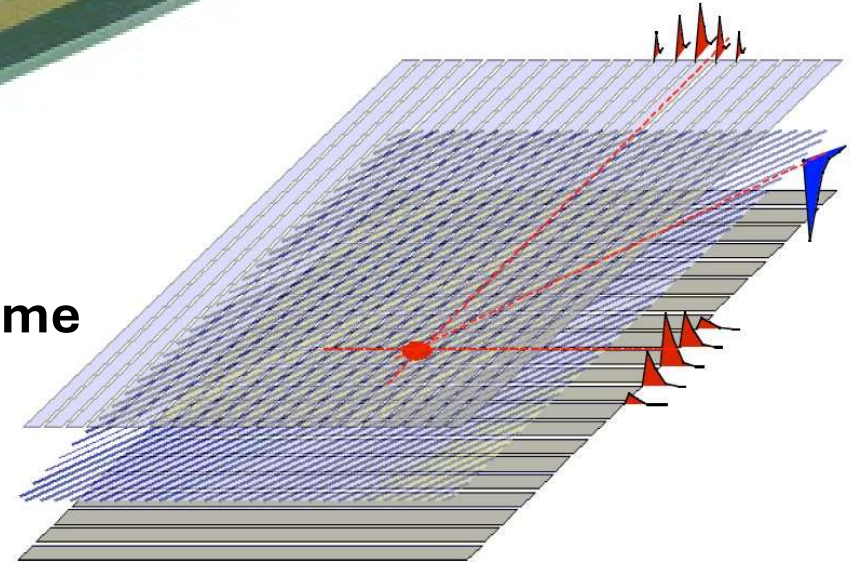
1992



Georges Charpak
(1924-2010)



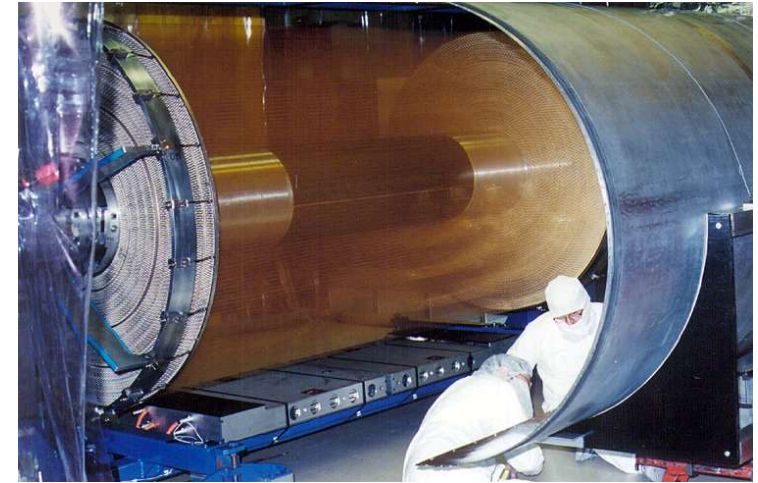
Measure:
**tracks of charged
particles at given time**



Drift chamber

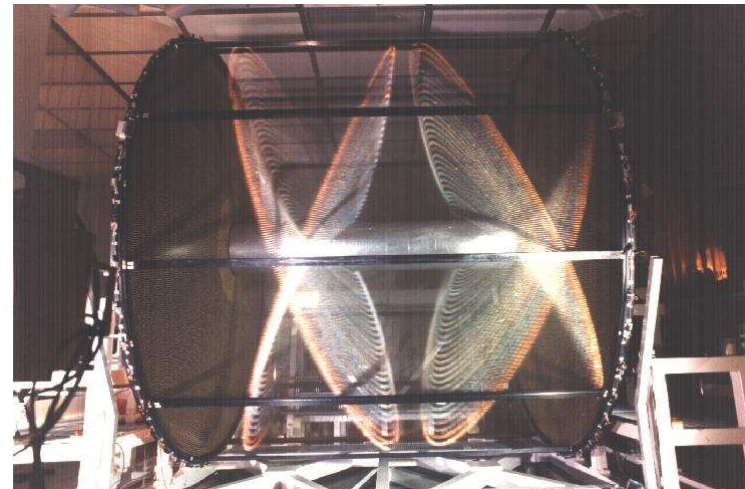
Exploit the calibrated drift time
to obtain a better position resolution

Measure: **tracks of charged particles**



BaBar (SLAC)

KLOE (Frascati)



Time projection chamber

Example: STAR experiment at Brookhaven
National Laboratory (USA)

Diameter and length about 4m

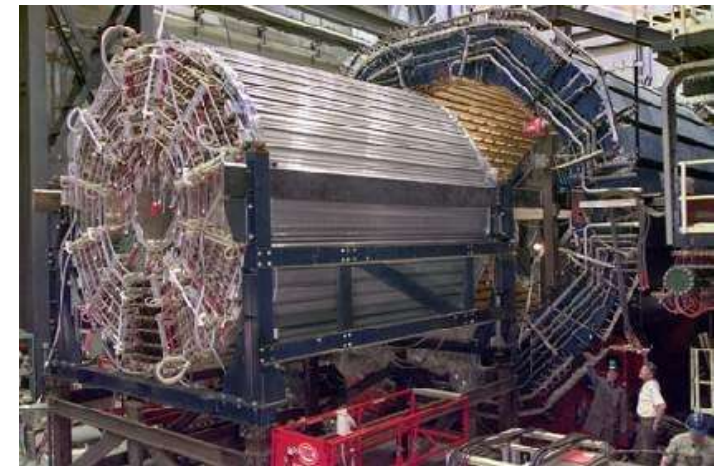
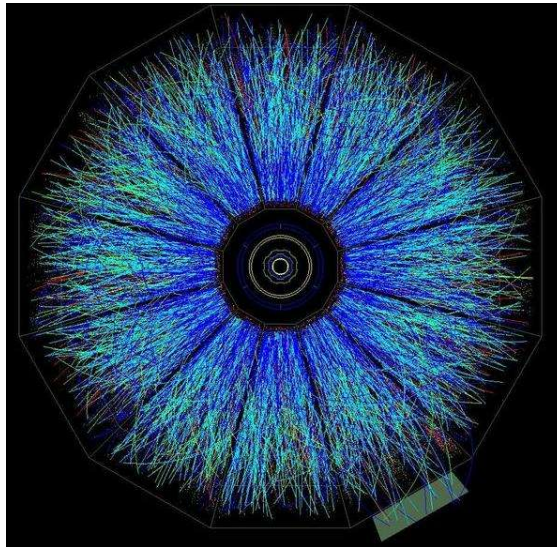
138000 pads, read by digitizers

to measure dE/dx and perform tracking

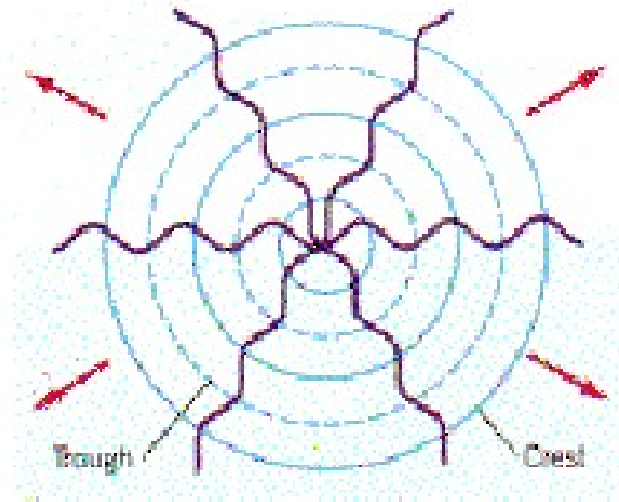
70M volume elements

Measure: **tracks of
charged particles**

Au+Au nuclei
collision
(100 GeV+100 GeV)

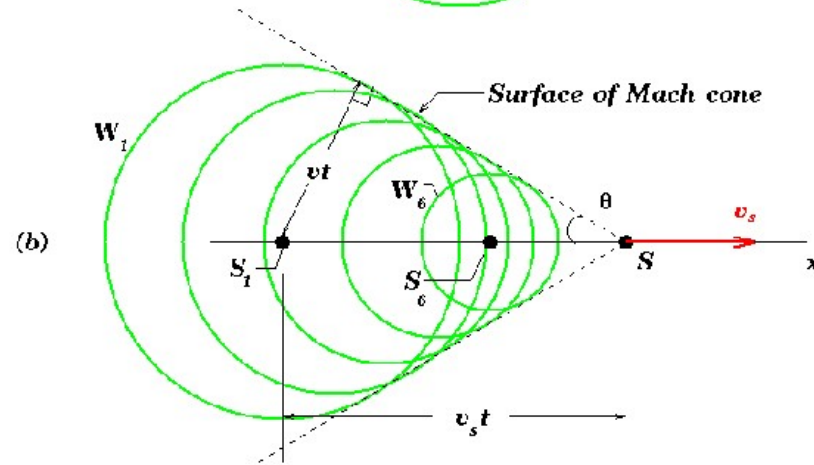
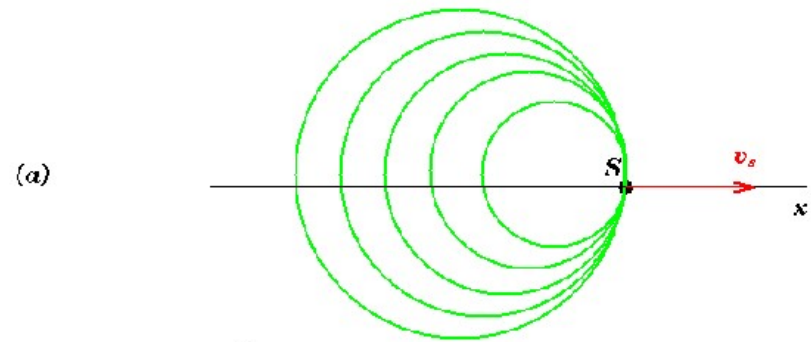


Cerenkov effect



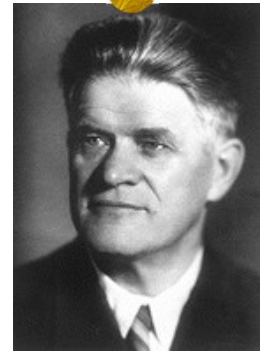
Wave fronts for $v < c/n$

Wave fronts for $v = c/n$



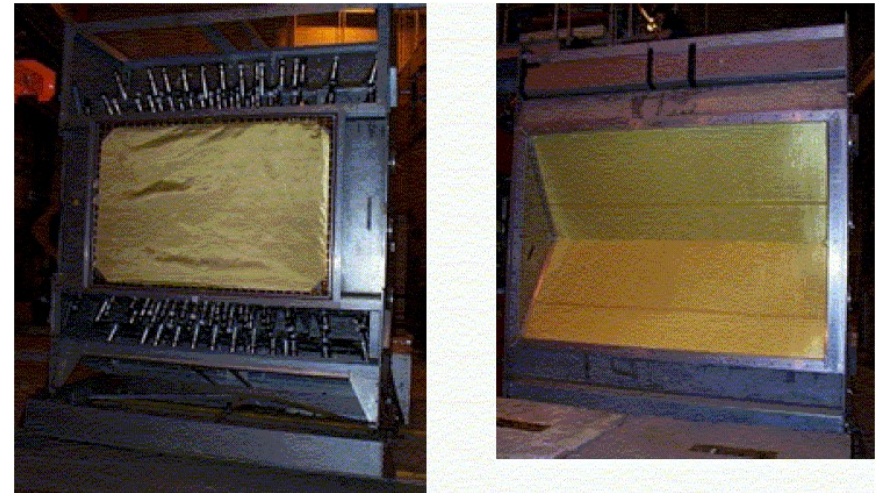
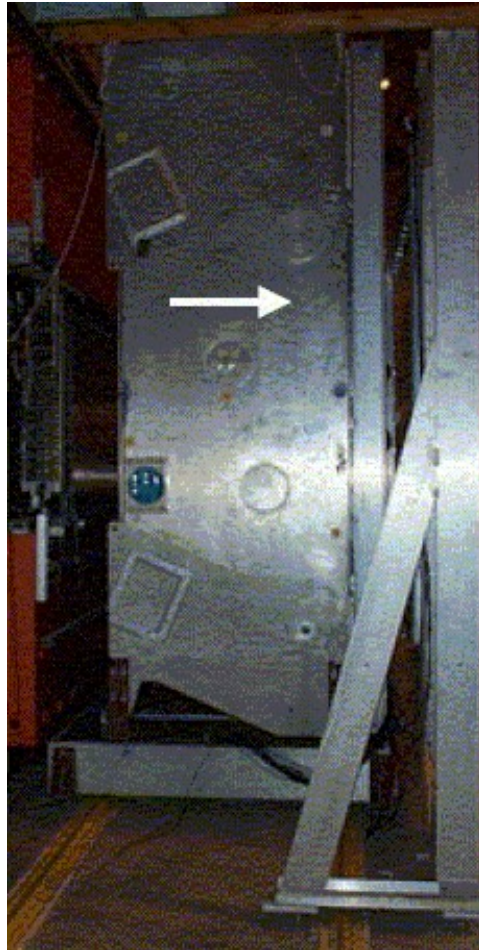
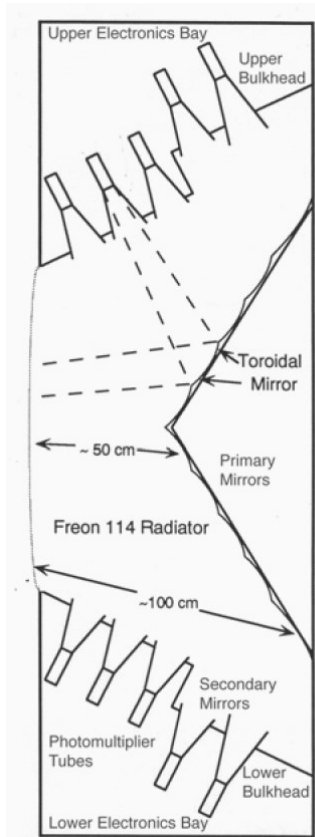
Wave fronts for $v > c/n$

1958



Pavel A. Cherenkov
(1904-1990)

Cerenkov detectors



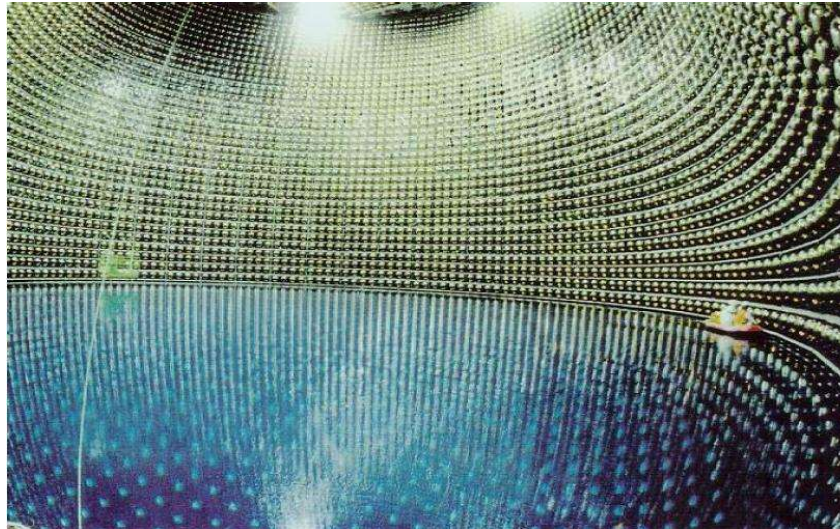
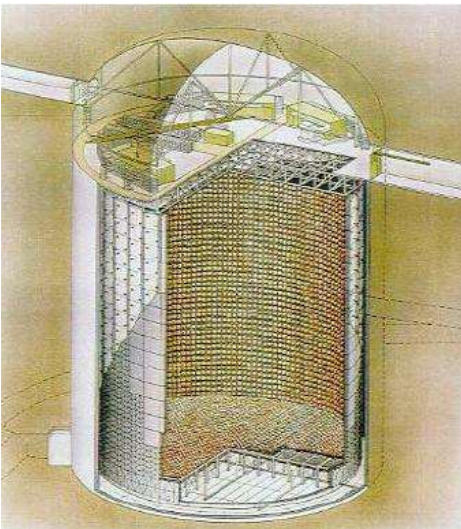
Threshold Cerenkov detectors

Measure:
**velocity of
charged
particle**

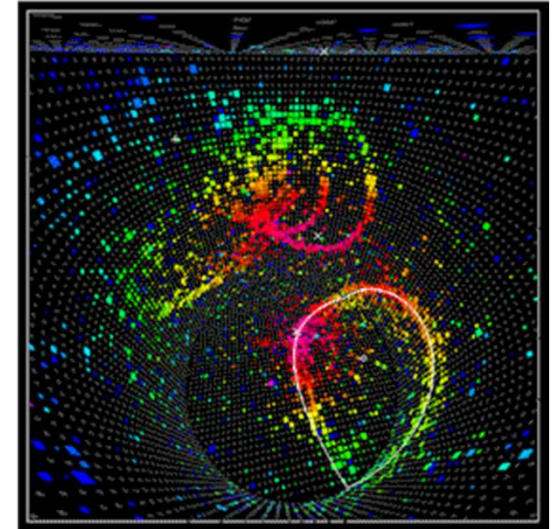
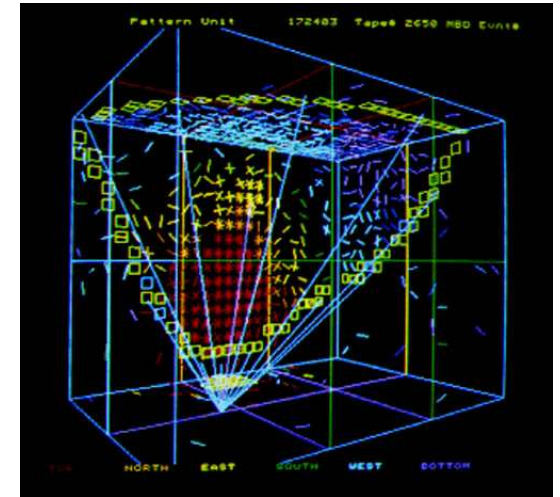


Ring-Imaging Cerenkov detectors (RICH)

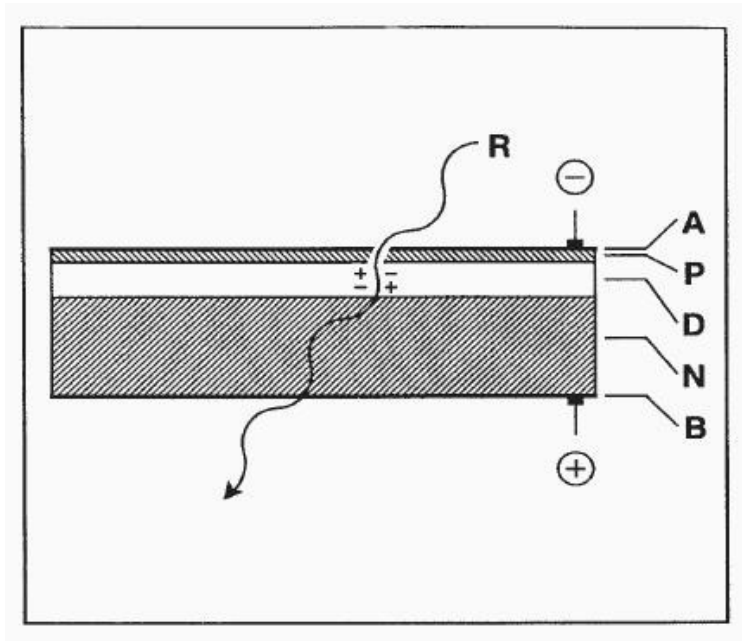
Measure:
velocity and direction
of charged particles



Example: SuperKamiokande detector in Japan

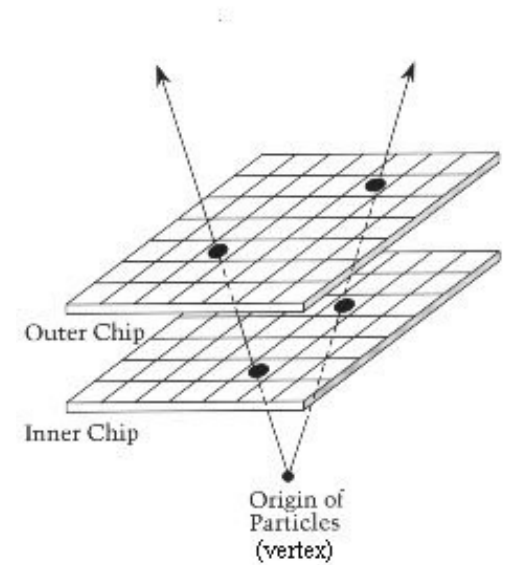


Semiconductor detectors



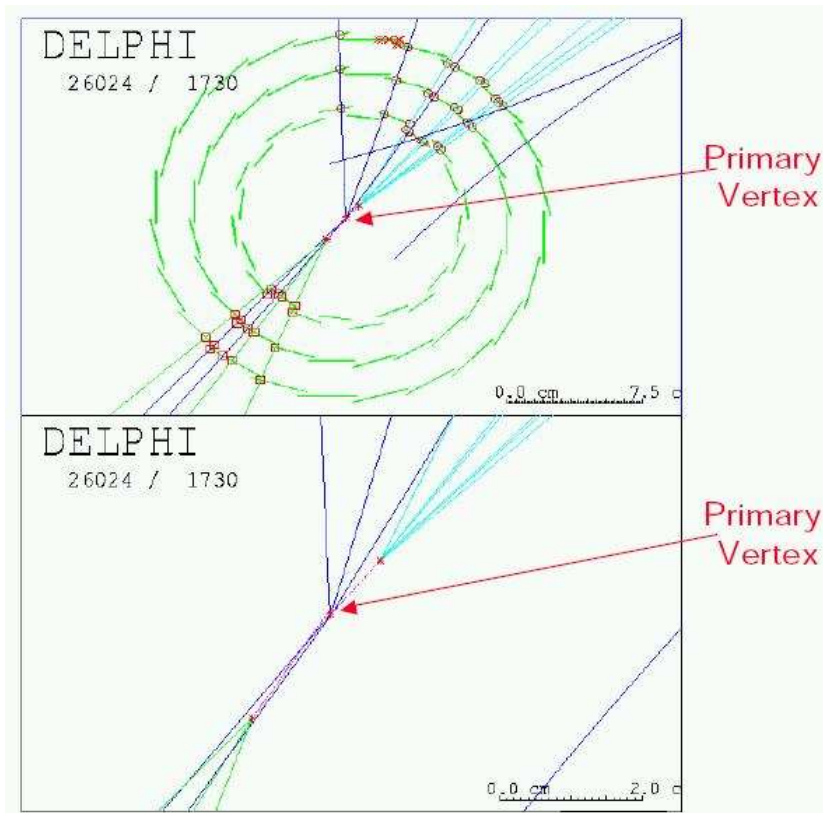
A: thin metal electrode (gold)
P: thin semiconducting p layer
D: depletion layer (3-10 mm)
N: semiconducting n layer
B: thin metal electrode

Measure: **passage of charged particle with $< 0(100 \mu\text{m})$ resolution**



Microvertex detectors

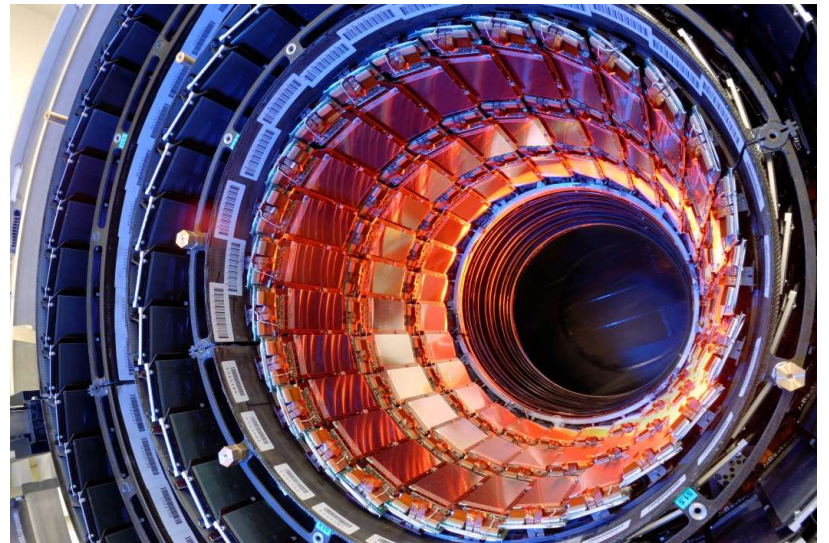
Arrays of semiconductor strips or pixels



BaBar Silicon Vertex Tracker



CMS Silicon Vertex Tracker

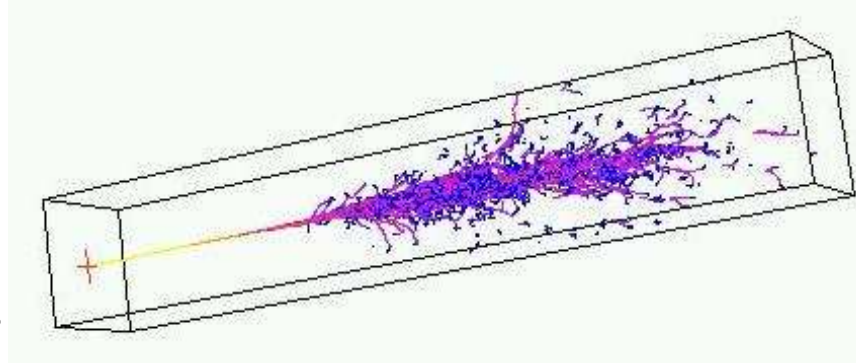


Particle detectors

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms ^a
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm ^{b,c,d}	2 ns	200 ns
Drift chamber	50–300 μm	2 ns ^e	100 ns
Scintillator	—	100 ps/n ^f	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [Ref. 6]	$\sim 175\text{--}450$ μm	~ 200 ns	~ 2 μs
Gas Micro Strip [Ref. 7]	30–40 μm	< 10 ns	—
Resistive Plate chamber [Ref. 8]	$\lesssim 10$ μm	1–2 ns	—
Silicon strip	pitch/(3 to 7) ^g	h	h
Silicon pixel	2 μm ⁱ	h	h

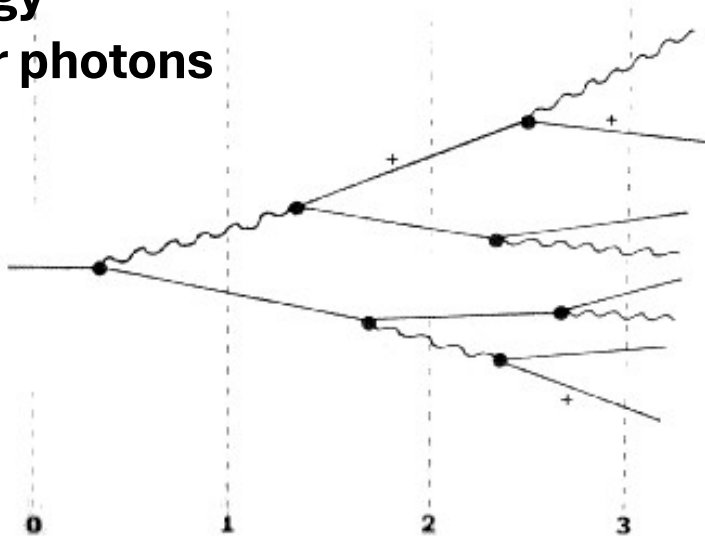
Electromagnetic showers

Cascade process of γ , e^+ , e^-
inside (preferably large-Z)
material
 e^+ , e^- can be measured
collectively by previous methods

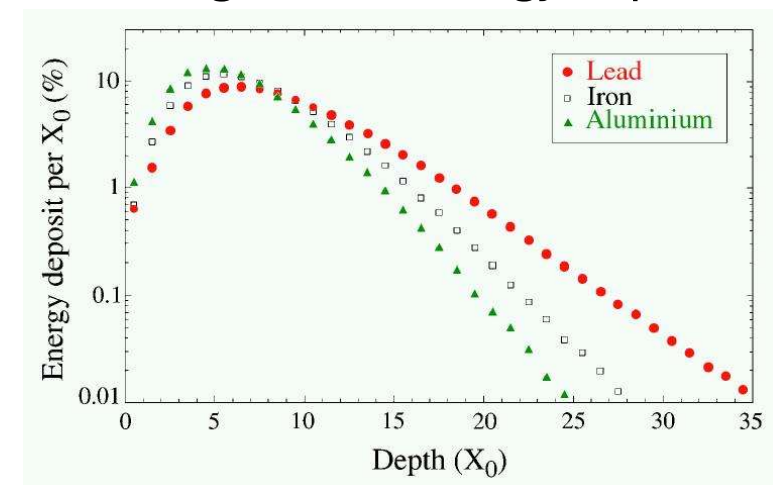


Bruno B. Rossi
(1905-1993)

Measure: **energy**
of electrons or photons

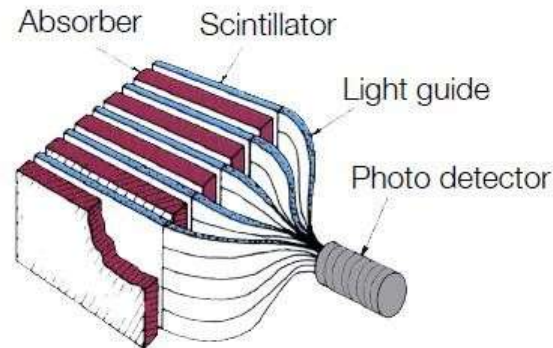


Longitudinal energy deposit

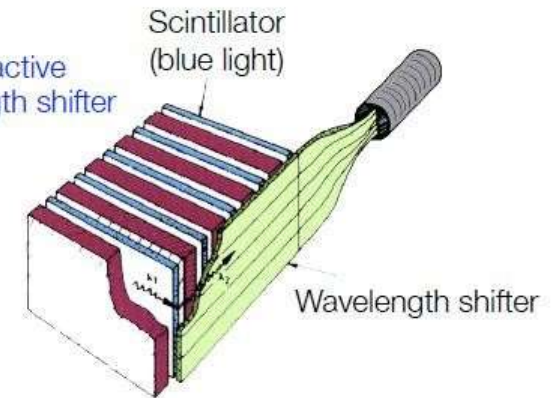


Sampling calorimeters

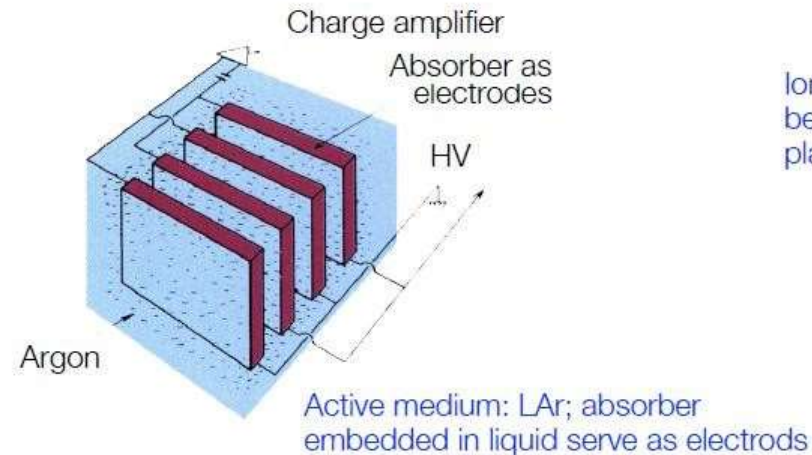
Scintillators as active layer;
signal readout via photo multipliers



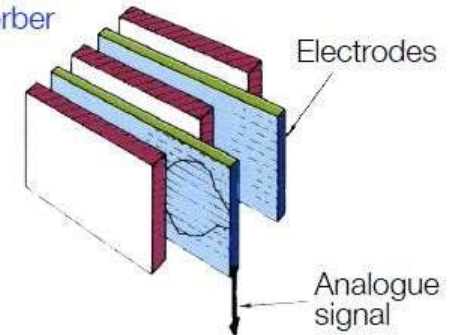
Scintillators as active layer; wave length shifter to convert light



Measure e^+ , e^- at different depths of the shower to estimate the total energy

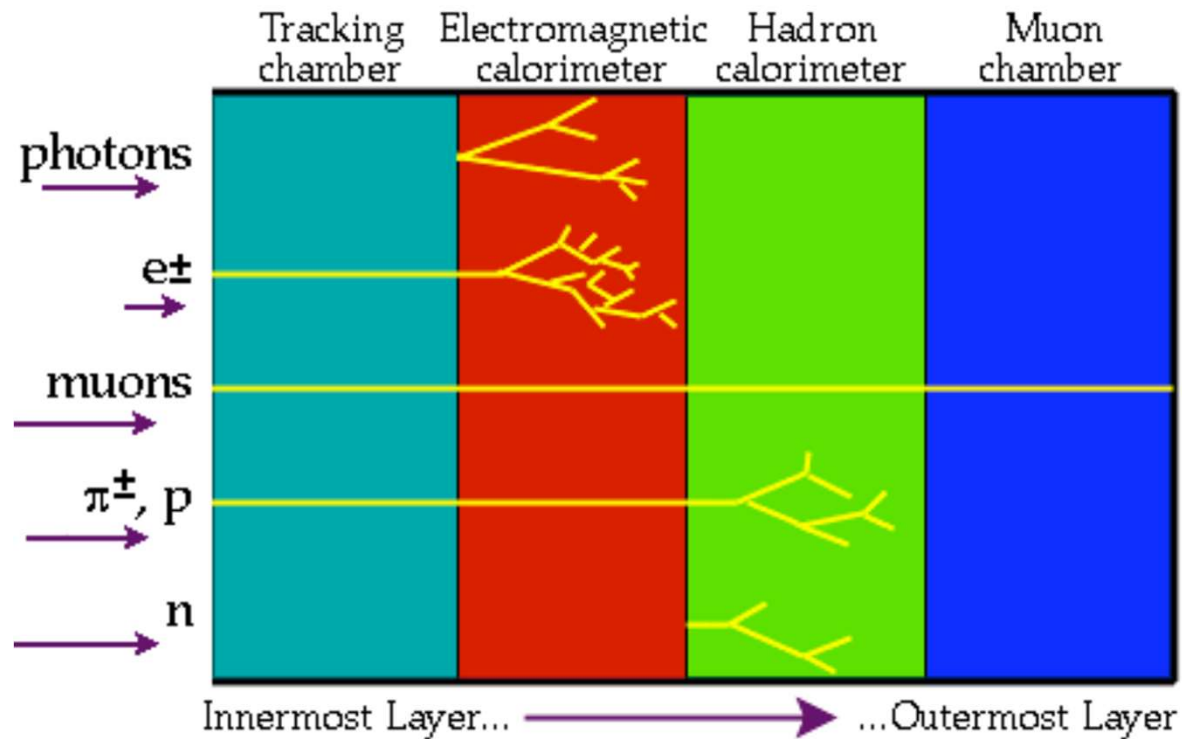


Ionization chambers between absorber plates



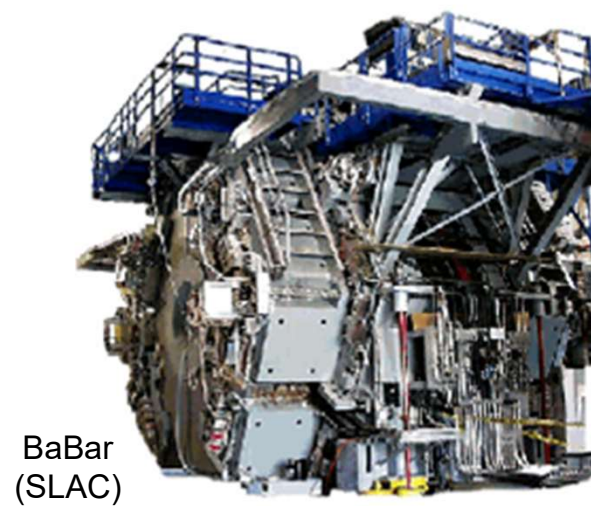
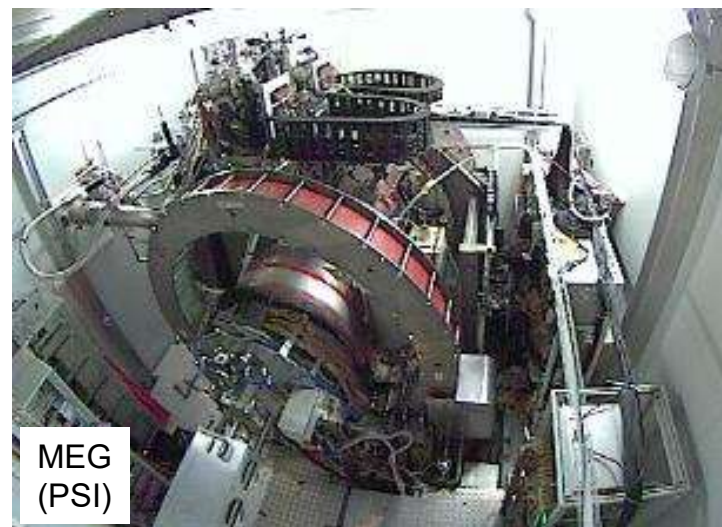
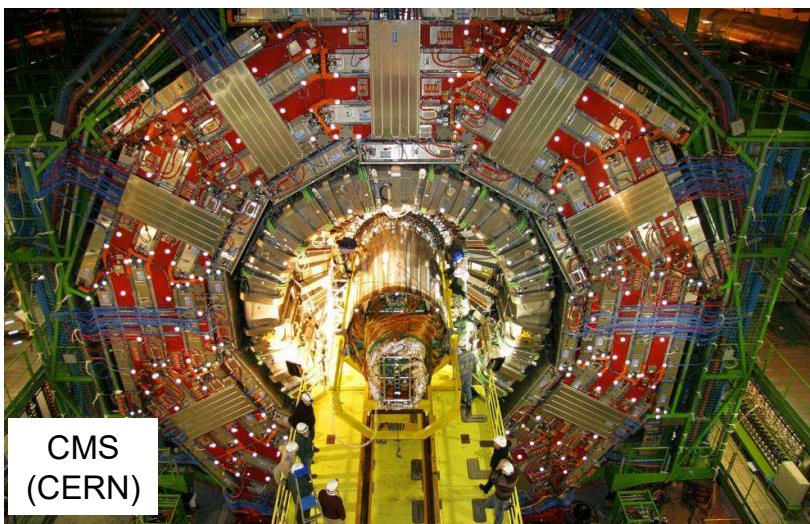
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Particle identification (PID)



Or simultaneous measurement of two cinematic quantities among
Energy, Momentum, Velocity $\rightarrow$ Mass

Detector systems



Lepton accelerators

Name	Location	Years	Particles	Energy	Intensity
MAMI	Mainz (D)	1975-	e^-	1.5 GeV	0.1 mA (150 kW)
ALBA	Catalunya (E)	2011-	e	3 GeV	
ELSA	Bonn (D)	1987-	e^-	3.5 GeV	
CEBAF	TJNAF	1995-	e^-	12 GeV	0.2 mA (1 MW)
SLAC Linac	SLAC	1966-	$e^+ e^-$	50 GeV	

$$\text{Beam power(W)} = E(\text{eV}) \times I(\text{A})$$

$$\text{Beam power(W)} = 1.6 \times E(\text{GeV}) \times I(10^{10} \text{ s}^{-1})$$

Hadron accelerators

Name	Location	Years	Particle s	Energy	Intensity
ELENA	CERN	2016-	$\bar{p}$	0.1 MeV	$1.8 \cdot 10^7 \bar{p}$
PS	CERN	1959-	p	26 GeV	$1 \cdot 10^{13}$ p/s (42 kW)
U-70	IHEP	1967-	p	76 GeV	$1.9 \cdot 10^{12}$ p/s (22 kW)
SPS	CERN	1976-	p,A	450 GeV	$4 \cdot 10^{12}$ p/s (290 kW)
MI	FNAL	1995-	P	120 GeV	$1.9 \cdot 10^{13}$ p/s (380 kW)
Main Ring+MI	FNAL	1983-2011	p	980 GeV	$2 \cdot 10^{13}$ p/s (3.2 MW)
AGS	BNL	1960-	p,A	33 GeV	$7 \cdot 10^{13}$ p/s (370 kW)
Main Ring	J-PARC	2009-	p	30 GeV	$1 \cdot 10^{14}$ p/s (500 kW)
ISIS	RAL (UK)	1984-	P	800 MeV	$1.2 \cdot 10^{15}$ p/s (180 kW)
HIP	PSI	1974-	p	590 MeV	$1.4 \cdot 10^{16}$ p/s (1.3 MW)

Particle colliders (1)

	VEPP-2000 (Novosibirsk)	VEPP-4M (Novosibirsk)	BEPC (China)	BEPC-II (China)	DAΦNE (Frascati)
Physics start date	2010	1994	1989	2008	1999
Physics end date	—	—	2005	—	—
Maximum beam energy (GeV)	1.0	6	2.5	1.89 (2.35 max)	0.510
Delivered integrated luminosity per exp. (fb^{-1})	0.25	0.05	0.11	24.6	≈ 4.7 in 2001-2007 ≈ 2.7 w/crab-waist ≈ 1.8 since Nov 2014
Luminosity ($10^{30} \text{ cm}^{-2}\text{s}^{-1}$)	50	20	12.6 at 1.843 GeV 5 at 1.55 GeV	1000	453
Energy spread (units 10^{-3})	0.71	1	0.58 at 2.2 GeV	0.52	0.40

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	SLC (SLAC)
Physics start date	1979	2002	1989	1989
Physics end date	2002	2008	2000	1998
Maximum beam energy (GeV)	6	6	100 - 104.6	50
Delivered integrated luminosity per experiment (fb^{-1})	41.5	2.0	0.221 at Z peak 0.501 at 65 – 100 GeV 0.275 at >100 GeV	0.022
Luminosity ($10^{30} \text{ cm}^{-2}\text{s}^{-1}$)	1280 at 5.3 GeV	76 at 2.08 GeV	24 at Z peak 100 at > 90 GeV	2.5
Energy spread (units 10^{-3})	0.6 at 5.3 GeV	0.82 at 2.08 GeV	0.7→1.5	1.2

Particle colliders (2)

	KEKB (KEK)	PEP-II (SLAC)	SuperKEKB (KEK)
Physics start date	1999	1999	2018
Physics end date	2010	2008	—
Maximum beam energy (GeV)	e^- : 8.33 (8.0 nominal) e^+ : 3.64 (3.5 nominal)	e^- : 7–12 (9.0 nominal) e^+ : 2.5–4 (3.1 nominal)	e^- : 7 e^+ : 4
Delivered integrated luminosity per exp. (fb^{-1})	1040	557	10.57
Luminosity ($10^{30} \text{ cm}^{-2} \text{ s}^{-1}$)	21083	12069 (design: 3000)	1.88×10^4
Energy spread (units 10^{-3})	0.7	e^-/e^+ : 0.61/0.77	e^-/e^+ : 0.64/0.81

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC Brookhaven	LHC (CERN)		
Physics start date	1992	1987	2001	2009	2015	2026 (HL-LHC)
Physics end date	2007	2011	—	—		
Particles collided	ep	$p\bar{p}$	pp (polarized)	pp		
Maximum beam energy (TeV)	e : 0.030 p : 0.92	0.980	0.255 55% polarization	4.0	6.5	7.0
Max. delivered integrated luminosity per exp. (fb^{-1})	0.8	12	0.38 at 100 GeV 1.3 at 250/255 GeV	23.3 at 4.0 TeV 6.1 at 3.5 TeV	160	250/y
Luminosity ($10^{30} \text{ cm}^{-2} \text{ s}^{-1}$)	75	431	245 (pk) 160 (avg)	7.7×10^3	2.1×10^4	5.0×10^4 (leveled)
Energy spread (units 10^{-3})	e : 0.91 p : 0.2	0.14	0.15	0.1445	0.105	0.129

Particle colliders (3)

