





The physics of particle detectors - Introduction -

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Lectures + Journal Club

Web page:

http://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/

- Lectures by me (Silvia)
 Wednesday, 13:15 14:45/15:00
 Some exceptions (April 26, June 7, ...)
- Journal Club: Dirk Wiedner, Peter Glässel, (SM) Friday, time to be discussed INF 226, Room 1.106
- Visits to labs and to GSI (Friday possible?)

Credits (2+2), 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-Coulonwww.kip.uni-heidelberg.de/~coulon/Lectures/Detectors2013 R. Averbeckweb-docs.gsi.de/~averbeck/hd_ss13_inactive2015 J. Stachelwww.physi.uni-heidelberg.de/~fschney/detektoren/detec2016 S. Masciocchiwww.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors



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 $\Omega^{\text{-}}$ event seen in the 80" bubble chamber at the BNL Alternating Gradient Synchrotron









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Discovery of X-rays

1895: Wilhelm C. Roentgen Germany

Discovery of a new type of radiation (X for unknown) using a cathode ray tube:

- Air out, special gas in, high voltage difference applied → fluorescent glow
- Wrapped in black thick paper → green fluorescent light from barium solution on a plate, a few meters away
- New rays pass most substances, and cast shadows of solid objects on films



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



Discovery of radioactivity

1896: first detection of natural radioactivity (α and β decays) Henri Becquerel (mineralogist), Marie and Pierre Curie, Paris



Becquerel's (wrong) assumption: minerals made phosphorescent by visible light might emit x-rays. Wrap a photographic plate in black paper, place a phosphorescent uranium mineral on top of it and expose to sun. Accidental discovery in February 1896 (bad weather)

Discovery of radioactivity



Juny L & D. P. a lime lifting la 16 β-rays

Becquerel: photographic plate which was exposed to radiation from a uranium salt. Radiation resulted to be **charged**.

Soon after Marie and Pierre Curie identified other radioactive materials: Polonium, Radium, Thorium **Nobel prize physics 1903**

Luck is what happens when preparation meets opportunity

Seneca

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Rutherford scattering

1911: Rutherford (University of Manchester) with Geiger (visiting) and Marsden (undergraduate student) discover the atomic nucleus



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Rutherford scattering





Original experimental setup

Schematic view of Rutherford's scattering experiment

Geiger counter for α particles

IMPORTANT prototype of modern scattering experiments:

- Calibrated probe: α particles
- Calibrated interaction of probe with medium: EM interaction
- \rightarrow learn about structure of the probed medium: atoms have a nucleus

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Detection of cosmic rays

1912: Victor F. Hess discovers cosmic rays during balloon experiments (also in total solar eclipse)



Cosmic rays



Detector physics, Introduction, April 19, 2017

Hess's legacy: the HESS telescope

High Energy Stereoscopic System (HESS) telescope in Namibia (since 2004) to detect gamma rays from cosmic sources





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

Proposed in 1928 by Dirac as negative energy solution of Dirac's equation

Nobel prize for physics 1936



Discovery of the pion

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

Photographic emulsions:

- Grains of silver-halide
- Suspended in gelatin
- Ionizing particles create Ag grains
- Develop a photograph

Powell:

- Collaboration with industry: Kodak, Ilford
- New sensitizing methods
- State of the art microscopes

Nobel prize for physics 1950





Discovery of the pion

: 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, v_{u}





first neutrino beam facility at the BNL AGS

Mel Schwartz in front of the spark chamber

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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!

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Discovery of the W/Z bosons

1983: UA1 and UA2 experiments discover the W and Z bosons at the CERN SppS collider



UA1 detector



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Discovery of the top quark

1995: CDF and D0 discover the top quark at the FNAL Tevatron pp collider



no 'smoking gun' discovery but 'statistical evidence'

CDF detector

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) [lon 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)

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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 - 3

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:



Beams

• Circular accelerators: cyclotron, synchrotron Synchrotron radiation:

Particles lose energy by synchrotron radiation. Radiated power:

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

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, $m_0 = 0.5 \text{ MeV/c}^2$, $\gamma = 2 \times 10^5$

 $\rightarrow \Delta E$ = 2.24 GeV of 100 GeV

• LHC: E = 7 TeV, $m_0 = 938 \text{ MeV/c}^2 \rightarrow \Delta E = 3.4 \text{ keV}$ 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

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

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

Beam energy

Criteria to choose the beam energies

- Threshold, reaction rate
 - e+ e- \rightarrow Z⁰ + Higgs $\geq m_{Z0} + m_{Higgs}$ = 208 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

$$\bar{\lambda} = \frac{\hbar c}{pc} \le \Delta x \quad \Leftrightarrow \quad pc \ge \frac{\hbar c}{\Delta x}$$

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



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Colliders

e ⁺ e ⁻ Colliders	pp/p \bar{p} Colliders		
e⁺ e⁻ E _{beam} =√s/2	$p \longrightarrow \frac{x_1 p \sqrt{\hat{s}}}{\sqrt{\hat{s}}} \frac{x_2 p}{\sqrt{p}} \longrightarrow p$		
Energy of elementary interaction known	Energy of elementary interaction not known		
$\sqrt{\hat{s}} = E(e^-) + E(e^+) = \sqrt{s}$	$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} < \sqrt{s}$		
Only two elementary particles collide	Elementary interaction (hard) $+$ interaction of		
ightarrow clean final states	"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:	Synchrotron radiation is $\sim (m_p/m_e)^4 \sim 10^{13}$		
$E_{ m loss} \sim rac{E_{beam}^4}{R} rac{1}{m_e^4}$	smaller		
$E_{ m loss}\sim 2.5~{ m GeV}$ /turn			
LEP 2 ($\mathit{E}_{ m beam} \sim$ 100 GeV)			
- high energy more difficult	- high energy easier $ ightarrow$ discovery machines		
\rightarrow next machine: Linear Collider	current machine: LHC, pp , $\sqrt{s}=14$ $ TeV$		
(ILC, CLIC, $\sqrt{s} = 800(3000?)$ GeV?)	in the LEP ring		
- clean environment $ ightarrow$ precision	more "dirty" environment		
measurement machines			

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Electron and hadron colliders

colliders	
Electron	
colliders	
ladron	

	where	start	end	energy	length/	most relevant physics
					circumf.	
				(GeV)	(km)	
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

	where	Beam	start	end	energy	length/	most relevant physics
						circumf.	
					(TeV)	(km)	
SppS	CERN	рp	1981	1990	0.45 + 0.45	6.9	W,Z bosons
Tevatron	Fermilab/ USA	р <mark>р</mark>	1987	2011	0.9 + 0.9	6.3	top quark
SSC	Texas/ USA	рр	1996??		20 + 20	83.6	abandoned in 94
HERA	DESY	ер	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
		рр			0.25 + 0.25		
LHC	CERN	рр	2009		7 + 7	26.7	Higgs, SUSY?
		PbPb			562 + 562		Quark-gluon plasma

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Experiments with neutrinos

source	reaction	energy range	type
solar	fusion reactions	typically below 20 MeV	$ u_e $
reactor	eta-decay after fission	up to few MeV	$ u_e $
atmosphere	π - and μ -decay	GeV	$ u_{\mu} ext{ and } u_{e}$
accelerators	μ -decay	up to 100 GeV	$ u_{\mu}$



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Demands on detectors

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

decay via strong interaction: $ho
ightarrow \pi^+\pi^ \Gamma = 100 \text{ MeV}$

$$au c = rac{\hbar c}{\Gamma} = 2 \; {
m fm} \qquad au pprox 10^{-23} \; {
m s}$$

decay via electromagnetic interaction: $\pi^0 o \gamma\gamma$ $au = 10^{-16}$ s

- quasi-stable particles:

decay via weak interaction

Some examples for decay length								
	decay length							
particle	au	СΤ	$eta \gamma c au$ at ${\it p}=10~{\it GeV}/c$					
n	889 s	$2.7\cdot10^8km$	$2.9\cdot10^9$ km					
٨	$2.6\cdot10^{-10}$ s	7.9 cm	71 cm					
π^{\pm}	$2.6\cdot10^{-8}$ s	7.8 m	560 m					
D^\pm	$10^{-12}~ m s$	0.31 mm	1.6 mm					
B^{\pm}	$1.6\cdot10^{-12}~\text{s}$	0.49 mm	0.93 mm					
au	$3\cdot10^{-13}$ s	0.09 mm	0.5 mm					



LEP: Large Electron Positron Collider



The LEP Storage Ring

meters
Value
26658.88 m
3096 m
11245.5 Hz
352 MHz
pprox 20 GeV
104.5 GeV
$4 \text{ pb}^{-1} / \text{day}$
4, 8 or 12
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



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

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







QCD with elementary quarks describes the scattering up to the highest accessible Q²



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: √s_{NN} = 2.76 TeV
 2015: √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



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ATLAS: A Toriodal LHC ApparatuS



CMS: Compact Muon Spectrometer



CMS: Compact Muon Spectrometer





ALICE: A Large Ion Collider Experiment



ALICE TPC: the field cage

LARGEST TPC EVER BUILT

- Gas volume: ~92 m³ (active volume)
- Very light giant: 3% X₀ at mid-rapidity
- 72 readout chambers: Multi Wire Proportional Chambers with pad readout
- Half a million pads! (557,568 channels)



Upgrade of the ALICE TPC

Continuous readout to cope with the 50 kHz Pb-Pb interaction rate and record all minimum bias events
 → New readout chambers (no gating grid)
 GEM: Gas Electron Multiplier foils. Offer opportunity to reach low ion back-flow (IBF) in multiple GEM stacks



Hot QCD matter in heavy-ion collisions at the LHC

TPC upgrade: GEM chambers

- Low Ion Back Flow (<1%) achieved combining 4 GEM foils
- Momentum resolution and particle identification performance preserved: dE/dx resolution <12% at ⁵⁵Fe photopeak





GEM chamber assembly at GSI (clean room)

Framing and testing of large area GEM foils



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GEM chamber assembly at GSI (clean room)

Framing and testing of large area GEM foils



Chamber body prepared (Hd, F)



GEM chamber assembly at GSI (clean room)

Framing and testing of large area GEM foils



Hot QCD matter in heavy-ion collisions at the LHC

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

 \rightarrow 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

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$$pp: \sqrt{s} = 100 \text{ TeV}$$
$$Pb-Pb: \sqrt{s}_{NN} = 39 \text{ TeV}$$
$$p-Pb: \sqrt{s}_{NN} = 63 \text{ TeV}$$
$$\int L_{Pb-Pb} = 33 \text{ nb}^{-1}/\text{month}$$

Scope: CDR and cost review for the next European strategy (2018) Starting date targeted for 2035-2040