Detectors in Particle Physics

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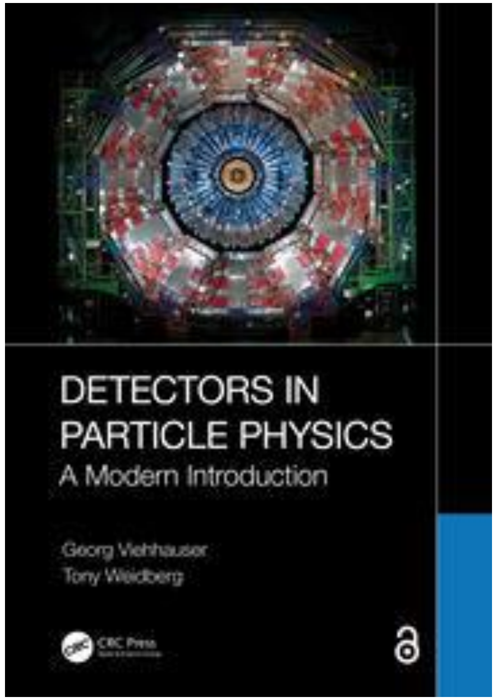

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Who we are

- Georg Viehhauser
  - Mostly hardware-focussed career
    - DELPHI Forward Chamber A
    - NA48 LKr calorimeter
    - ATLAS muon chambers
    - CLEO III RICH
    - Since 2001 ATLAS SCT and ATLAS Itk
    - More recently ePIC SVT
    - DRD deputy spokesperson
    - Main research interest: Support structures and thermal management of semiconductor tracking systems
- Tony Weidberg
  - Detector experiences:
    - CCD readout for a scintillating fibre detector at the CERN SPS $\bar{p}p$ collider
    - Played a major role in the founding of the ATLAS experiment and the design of the ATLAS SCT
    - Wide range of experience from detector R&D, assembly and integration of complex detector systems as well as evaluating their performance
    - Extensive experience in radiation hardness studies, particularly for optoelectronics and applications of reliability theory
- We both are academics at the University of Oxford and have a long experience in teaching undergraduate and graduate students there.

What we set out to do

- Write a textbook targeted at grad student level
  - Including exercises
- An “updated Kleinknecht”
- Around 200 pages
  - Final: 318 pages text
  - An additional 22 pages of references – this was one of the goals during writing, give starting points and then point the reader into the direction of the deeper reading
  - Because of the limited length we decided to omit otherwise interesting topics, like medical or safeguarding applications, and focus on detectors directly used in particle physics – hence the title
- Bridge the gap of simple, approximative “folklore” equations, which are widely used for quick estimates and the detailed, often very complex, physics that is made use of in simulation software
  - We wanted to show the reader where things are coming from
  - Researchers using simulation codes should get an idea of what the code they are using is built on
- Tony and I have many years experience in undergraduate teaching, and our experience is that students are quite capable of complex derivations
  - They just don’t expect them in detector physics
  - We therefore didn’t shy from including some more challenging derivations, in particular in the starting chapters

What emerged during the writing

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- Several narratives
  - Starting from the dielectric models (PAI), we could introduce straggling, and Cherenkov and transition radiation in a coherent arc (building on an approach developed by Wade Allison)
  - Discussion of detection based on moving charges, non-moving charges and excitation (even if the length of these discussions differ as they are of different importance)
  - Discussion of detection based on charges in gases, liquids and solids are treated at chapter levels equally (again length of discussion differs)
- By developing these narratives we hope that we were able to avoid throwing many different unconnected chunks at the reader
- One of our aspirations was to introduce the reader to onerous but necessary tasks associated with operation of real detectors, like alignment, calibration or data-driven measurements of detector performance
  - Also, the annoying practical issues associated with noise and radiation damage
- Another goal was to clean up the inconsistent notations and units used in our field
  - Motivated by our teaching experience

Chapter 1 Introduction

- Setting the context
- What is it we want to measure in particle physics?
- What particles can we observe directly in detectors?
- Introduce the stage: quick overview of experiments in particle physics

Chapter 2 Interactions of particles with matter

- Start with interaction of photons with matter and electromagnetic fields in matter
  - Important in themselves but also in preparation of dielectric models
- Charged particle energy loss
  - Start with Bethe theory, but then sketch out dielectric theory (PAI model) in some detail
  - This allows us then to develop a narrative for straggling, and for Cherenkov and transition radiation
- Multiple scattering
  - Sketch the basics of Molière theory – mostly to familiarize the reader with the concept, and to introduce the complexity of the problem
- Interactions of electrons with matter
  - Semi-classical derivation of a simplified expression of the radiation length using the Weizsäcker-Williams model (also in problems)
- Hadronic interactions and Interaction of neutrinos
- Key exercises
  - Calculation of photo-electric cross section, showing that $\sigma \sim E^{-7/2}$
  - Justification and use of Weizsäcker-Williams approximation to calculate radiation length
  - Derivation of Bethe equation using NRQM

Chapter 3 Electronic signals and noise

- Electrical signal generation with a derivation of Ramo-Shockley theorem
  - Essential for understanding signals from detectors! Used widely in book
- Derivation of noise sources: thermal and shot noise
- Practical discussion of interference noise and how to minimise it
- Very simple discussion of amplifiers
  - Use this to understand pulse shaping and optimising SNR
- Introduction into digitization
- Radiation effects on electronics
- Key exercises
  - Explanation why cascode is used in FE
  - Calculation of optimal shaping for unirradiated and radiated detectors
  - Calculation of noise from bias resistor, explains why we need large values for this resistor

- Treatment of charge movement in E and B fields
- Drift in gases, liquids and semiconductors
- Internal amplification and avalanche multiplication
  - PMTs
    - Principles of design for high quantum efficiency
- Key exercises
  - Understanding solution to Langevin equation
  - Walks reader through calculation of the distribution of avalanche sizes

Chapter 5 Response to excitation

- Introduction to scintillators: organic and inorganic
  - Need for wavelength shifters
  - Scintillating fibres
- Scintillation in liquid noble gases
- Introduction to radiation damage in scintillators and mitigation
- For clarification: Comparison of scintillation and Cherenkov radiation
- Exercises
  - Calculation of typical signals from a scintillating fibre

- Even if this is maybe of less relevance today we included this short section for completeness
  - Some historical interest
  - Might also be entertaining for colleagues who know already everything about mainstream detectors
- Emulsions (arguably still very relevant today)
- Cloud and bubble chambers
  - Even these have some applications nowadays
- Key exercises
  - Conditions for bubble growth

Chapter 7 Gaseous detectors

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- Start with discussion of choice of gases
- Discussion of signal generation in wire chambers
  - Role and development of ion drift
- Introduction to different techniques
  - Tried to not get bogged down in the myriads of technologies, but cover the main concepts
    - Resistive Plate Chambers
    - Wire Chambers
      - Multi-Wire Proportional chambers and their limitations
      - Thin gap chambers
    - MPGD: Micromegas and Gas Electron Multiplier (GEM)
    - Drift Chambers
- Photon detection in gaseous detectors
- Introduction to ageing in gas detectors
- Simulation of gas detectors
  - Introduction to software available
- Key exercises
  - Understanding stability of wires in an MWPC
  - Walks reader through calculation of time response from a proportional chamber
  - Factors affecting position resolution for drift chambers

Chapter 8 Liquid detectors

- Charge readout
  - Lack of stable avalanche multiplication
- Photon detection
- Complementarity of signals in combined readout
- Purity of liquid detection media
- Key Exercises
  - Understanding energy loss in liquid
  - Dual-phase TPC

Chapter 9 Semiconductor detectors

- Principle of operation and fabrication
- Silicon strip detectors
  - Calibration of silicon strip detectors
  - Leakage current and thermal management of silicon detectors
- Pixel detectors
- Photon detection with semiconductors and silicon detector applications with internal gain
- Monolithic active pixel sensors
- Radiation damage in semiconductor detectors
- 3D sensors
- Other semiconductors
- Key exercises
  - Basic properties of *pn* junctions
  - Pulse shapes and resolution in strip detectors
  - Leakage current and shot noise.
  - Temperatures and thermal stability
  - Photodiodes

Chapter 10 Tracking

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- Track reconstruction
- 4D Tracking
- Alignment
- Momentum measurement in magnetic fields
- Spectrometer magnets
- Vertex reconstruction and measurement
- Key exercises
    - Momentum and impact parameter measurements in different geometries
    - Effects of multiple scattering
    - Determining efficiencies

Chapter 11 Calorimetry

- Gamma spectroscopy sub-Kelvin cryogenic detectors
  - Mostly to introduce statistical energy measurement
- Electromagnetic cascades
  - Shower development and dimensions
  - Homogeneous calorimeters and resolution
  - Sampling calorimeters and resolution
  - Calibration
- Hadronic calorimeters
  - Shower development and dimensions
  - Energy measurement
  - Compensation
- Simulation of calorimeters
- Response to hadronic jets and particle flow
- Calibration of hadronic calorimeters
- Key exercises
  - Shower development
  - Resolution
  - Hadronic interactions

Chapter 12 Particle identification

- Time-of-flight, dE/dx, Cherenkov detectors, Transition radiation detectors and their combination
- Lepton identification (electrons, muons, taus)
- Missing E_{T}
- Neutrino flavour identification
- Jet tagging
- Key exercises
  - Measurement of vertex and reconstruction of Bs
  - Muon momentum measurement
  - e/π separation using a TRT

Chapter 13 Triggers

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- Start with basic trigger concepts
  - Thresholds, coincidences, efficiency vs purity, timing
- Complex triggers
  - Multi-level triggering and as example triggers at LHC
- Triggers for rare decay experiments
- Key exercises
  - Coincidence triggers
  - Trigger purity
  - Calculation of dead time versus trigger rate, readout time and buffer depth

Chapter 14 Detector systems and applications

- Discuss with examples issues of integration, service management (in particular powering), reliability, and demonstrate how the technologies introduced in the previous chapters can be combined to create a particle physics experiment
- Different contexts
  - Collider detectors
  - Neutrino experiments
  - Particle detectors for rare events
  - Particle detectors in space
- Key exercises
  - Magnetic field geometry and muon triggers
  - Powering

Acknowledgements

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- A broad textbook like this can only be written with support and contribution from many people
- We acknowledge the active help from Wade Allison, Christoph Amelung, Giles Barr, Hugo Beauchemin, Steve Biller, Pawel Bruckman de Renstrom, Paula Collins, Louis Fayard, Alfredo Ferrari, Neville Harnew, Peter Jenni, Malcolm John, Hans Kraus, Paul Lecoq, Michel Levebre, Tim Martin, Steve McMahon, Michael Moll, Peter Phillips, Meinhard Regler, Armin Reichold, Martin Tat, Rob Veenhof, Dave Wark, Morgan Wascko, Norbert Wermes and Steve Worm, who all gave us valuable inputs to this book
- There are many, many more who taught us everything we know about the subject
- Any remaining mistakes are ours

What we got wrong

- We added exercises to the different chapters during the writing
- In the rush to publish we never got around to work out the solutions to these problems
- Started to do this only after publication
  - At that point we realised that the problems in the book are riddled with mistakes…
- We have now complete solutions to the exercises with fixed problem sets
  - The fixed problem sets will be available on the author's book web site (https://ppdetectors.web.ox.ac.uk/)
  - Solutions will be given to teachers on request
- We have also found a (moderate) number of typos in the main text
  - Errata for these are also on the web site
  - Any further error reports are much appreciated

Final thoughts

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- We hope you and your students will enjoy this book
- We certainly have learned a lot during the writing
- We can wholeheartedly recommend the online version of this book due to its unbeatable value for money
  - Thanks to CERN it is available as open access:
- But maybe you prefer the paper copy, which will make us even happier