Particle Detectors - Principles and Techniques

C. D'Ambrosio, T. Gys, C. Joram, M. Moll and L. Ropelewski

CERN – PH/DT2

The lecture series presents an overview of the physical principles and basic techniques of particle detection, applied to current and future high energy physics experiments. Illustrating examples, chosen mainly from the field of collider experiments, demonstrate the performance and limitations of the various techniques.

Main topics of the series are: interaction of particles and photons with matter; particle tracking with gaseous and solid state devices, including a discussion of radiation damage and strategies for improved radiation hardness; scintillation and photon detection; electromagnetic and hadronic calorimetry; particle identification using specific energy loss dE/dx, time of flight, Cherenkov light and transition radiation.

Outline

- **Lecture 1 - Introduction** C. Joram, L. Ropelewski
  - What to measure ?
  - Detector concepts
  - Interaction of charged particles
  - Momentum measurement
  - Multiple scattering
  - Specific energy loss
  - Ionisation of gases
  - Gas amplification
  - Single Wire Proportional Counter

cern.ch/ph-dep-dt2/lectures_PD_2005.htm

- **Lecture 2 - Tracking Detectors** L. Ropelewski, M. Moll
- **Lecture 3 - Scintillation and Photodetection** C. D'Ambrosio, T. Gys
- **Lecture 4 - Calorimetry, Particle ID** C. Joram
- **Lecture 5 - Particle ID, Detector Systems** C. Joram, C. D'Ambrosio

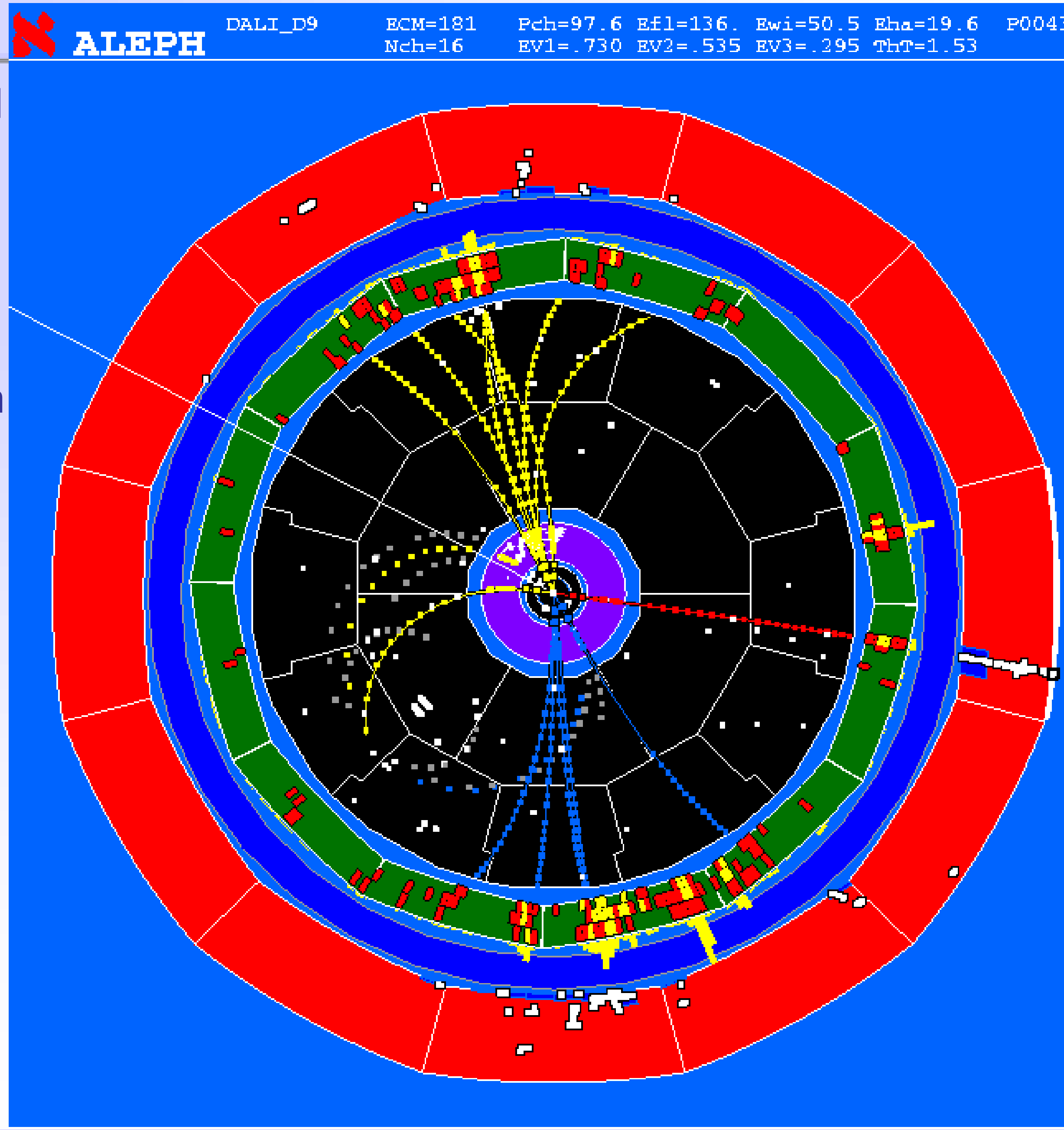
Literature

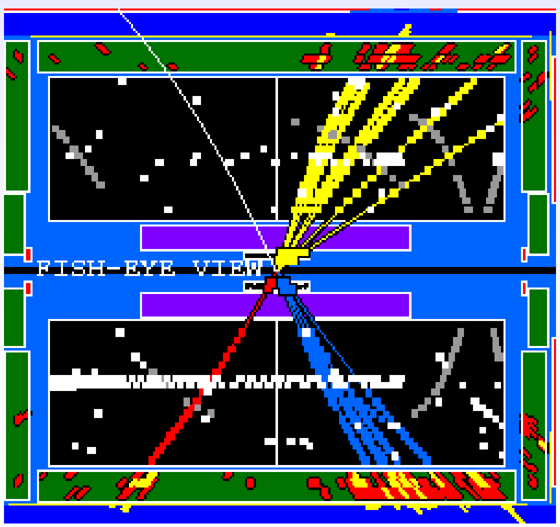
- **Text books** (a selection)
  - C. Grupen, Particle Detectors, Cambridge University Press, 1996
  - G. Knoll, Radiation Detection and Measurement, 3rd ed. Wiley, 2000
  - W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, 1994
  - R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992
  - K. Kleinknecht, Detectors for particle radiation , 2nd edition, Cambridge Univ. Press, 1998
  - W. Blum, L. Rolandi, Particle Detection with Drift Chambers, Springer, 1994
  - R. Wigmans, Calorimetry, Oxford Science Publications, 2000
  - G. Lutz, Semiconductor Radiation Detectors, Springer, 1999
- **Review Articles**
  - Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991.
  - Instrumentation in High Energy Physics, F. Sauli (editor), World Scientific, 1992.
  - Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.
- **Other sources**
  - Particle Data Book Phys. Lett. B**592**, 1 (2004) http://pdg.lbl.gov/pdg.html
  - R. Bock, A. Vasilescu, Particle Data Briefbook http://www.cern.ch/Physics/ParticleDetector/BriefBook/
  - Proceedings of detector conferences (Vienna CI, Elba, IEEE, Como)
  - Nucl. Instr. Meth. A

Introduction

A W^+W^- decay in ALEPH

e^+e^- ($\sqrt{s}$=181 GeV)
$\rightarrow W^+W^- \rightarrow qq\mu\nu_\mu$
$\rightarrow$ 2 hadronic jets
+ μ + missing momentum

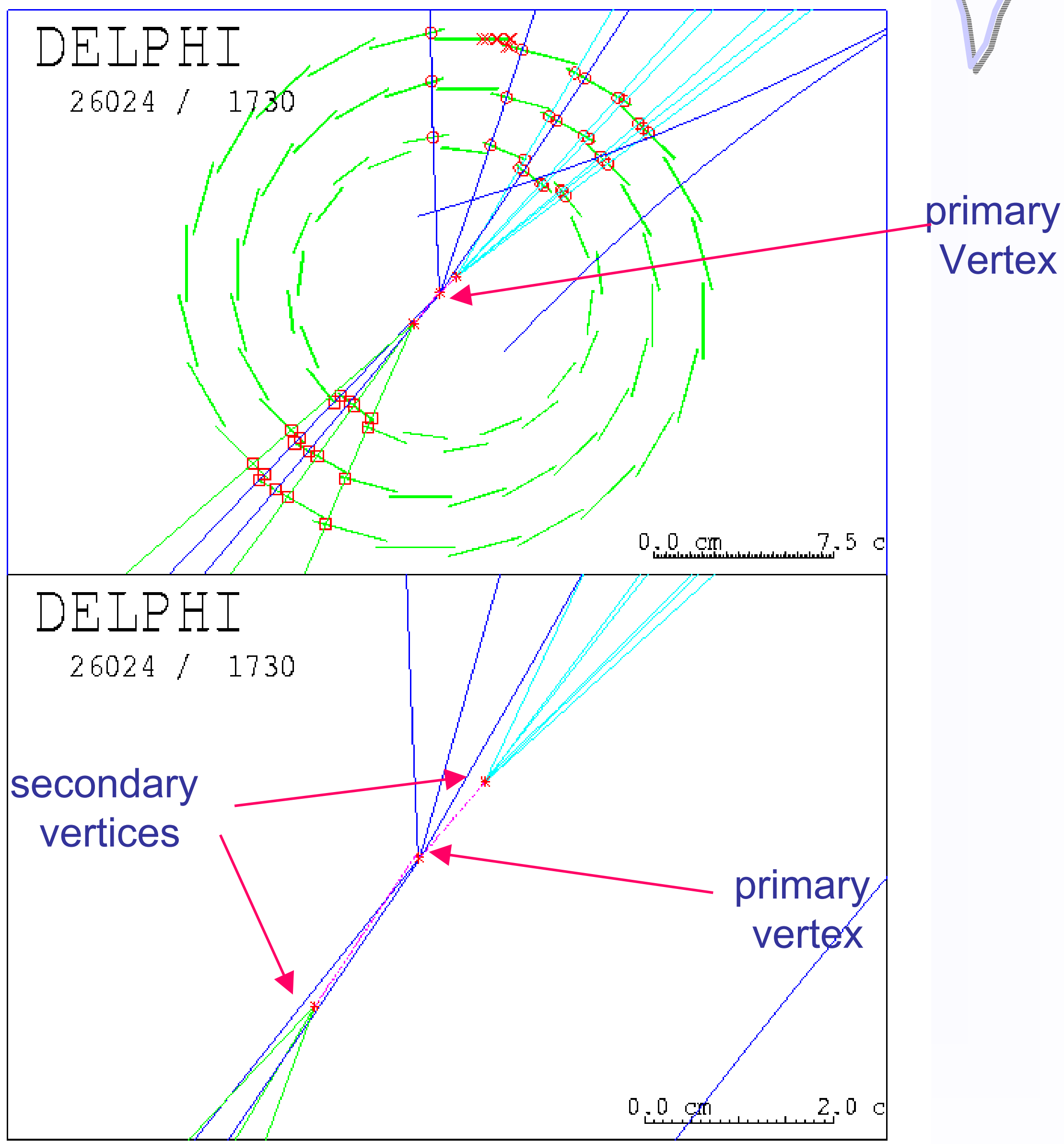




Introduction

Reconstructed B-mesons in the DELPHI micro vertex detector

$\tau_B \approx 1.6$ ps $l = c\tau\gamma \approx \gamma \cdot 500$ μm

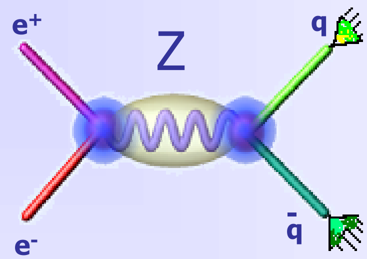


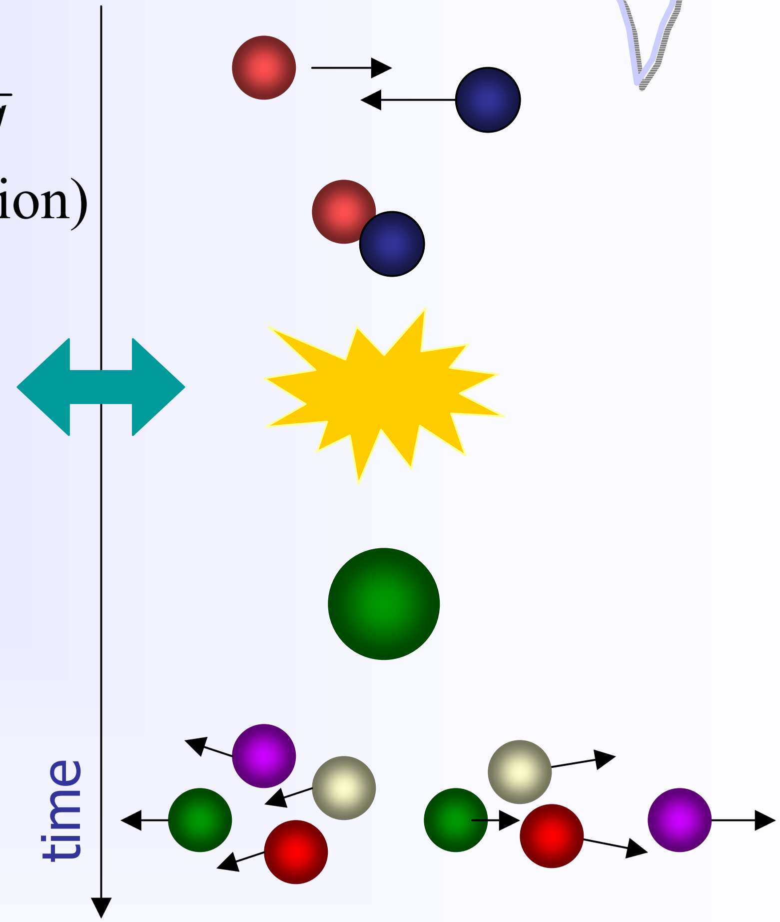
Introduction

$$e^+ + e^- \to Z^0 \to q\bar{q}$$

$$(+\,\text{hadronization})$$

Idealistic views of an elementary particle reaction





- Usually we can not 'see' the reaction itself, but only the end products of the reaction.
- In order to reconstruct the reaction mechanism and the properties of the involved particles, we want the maximum information about the end products !

Introduction

A simulated event in ATLAS (CMS) $H \rightarrow ZZ \rightarrow 4\mu$

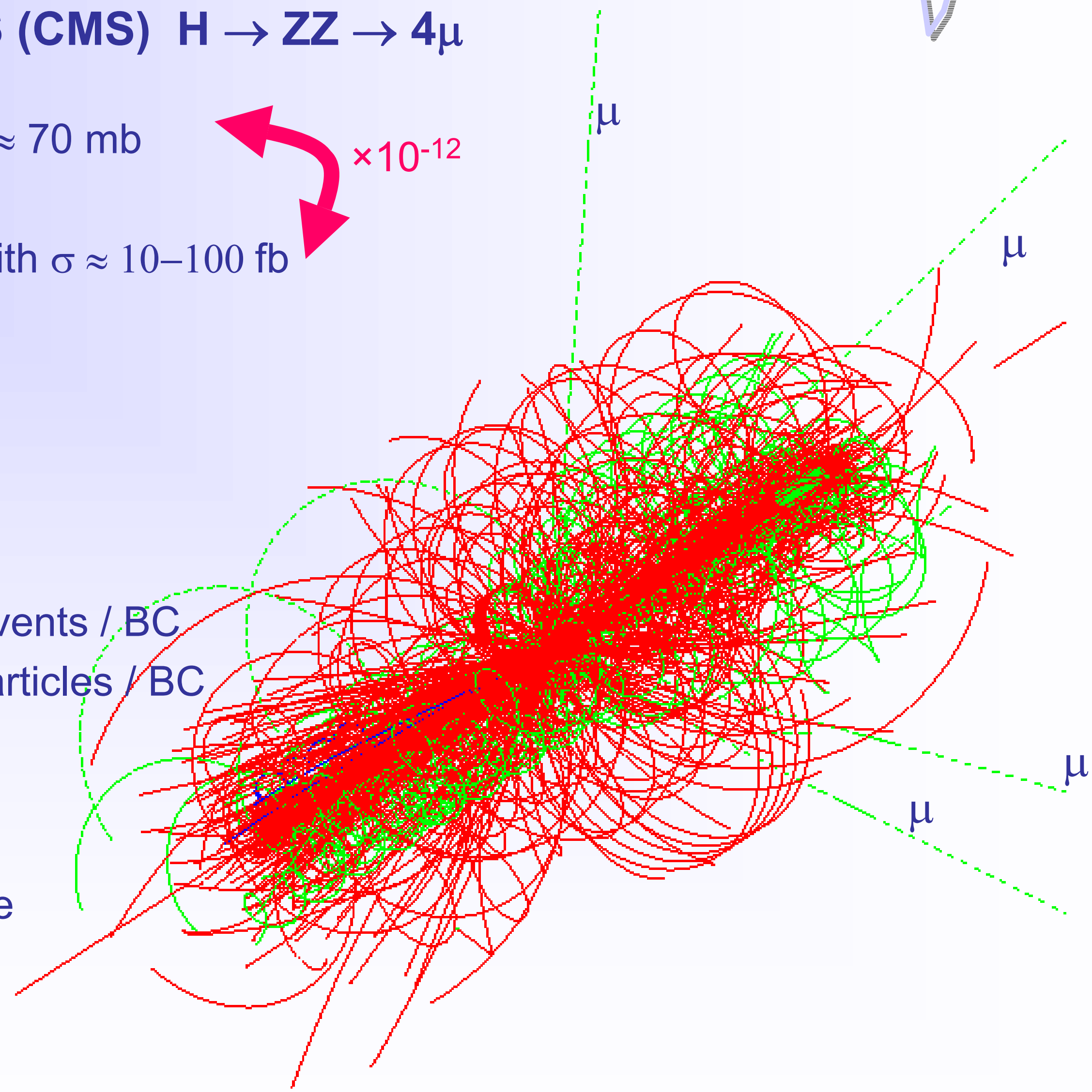
pp collision at $\sqrt{s}$ = 14 TeV, $\sigma_{inel.} \approx$ 70 mb

$\times 10^{-12}$

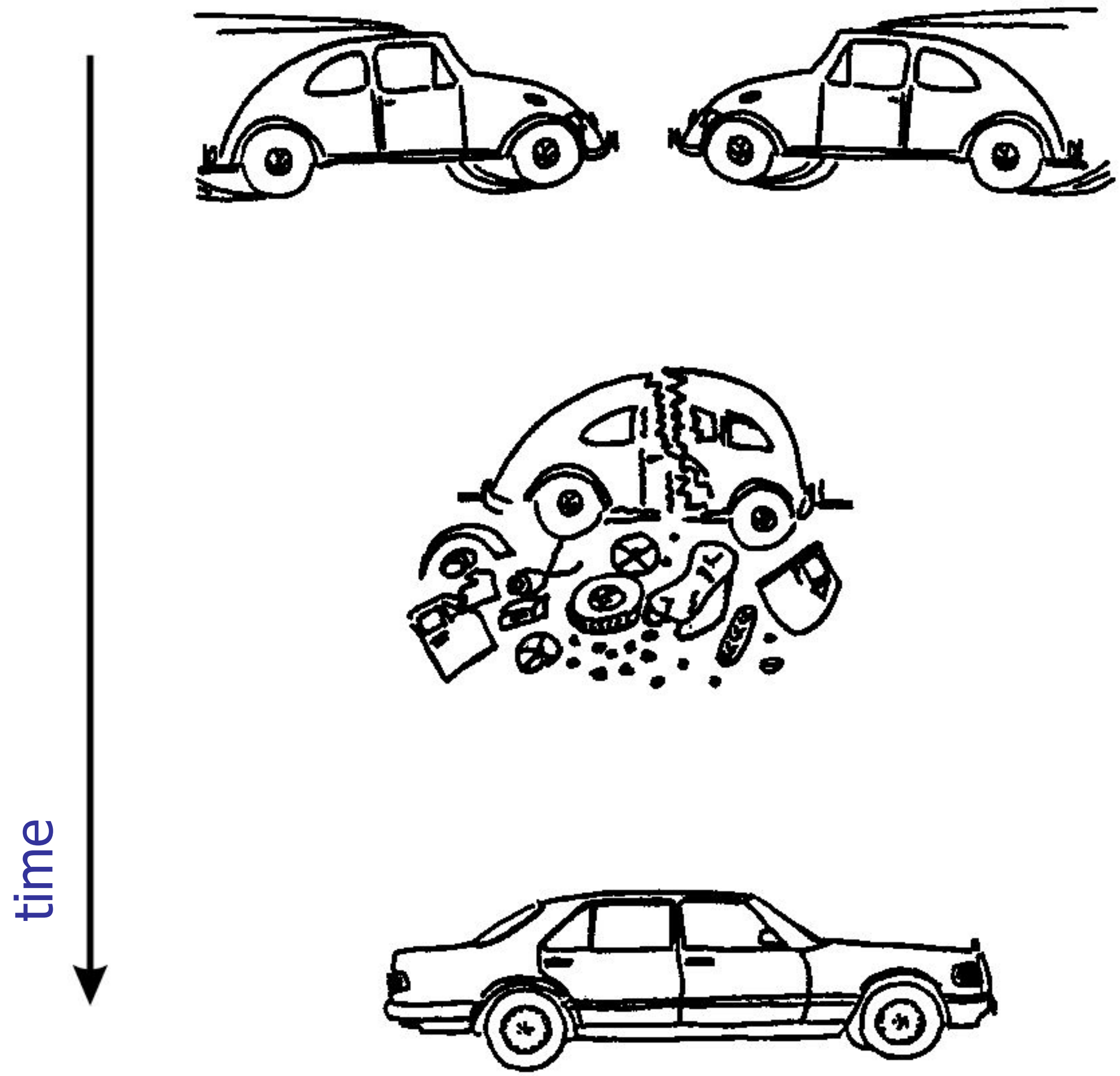
We are interested in processes with $\sigma \approx 10\text{–}100$ fb

L = 10^{34} cm^{-2} s^{-1},
bunch spacing 25 ns

$\approx$ 23 overlapping minimum bias events / BC
$\approx$ 1900 charged + 1600 neutral particles / BC



Brave people have started to think about a Super LHC upgrade to L = 10^{35} cm^{-2} s^{-1} !!!



Higgs production:
a rather rare event!

Cartoon by Claus Grupen, University of Siegen

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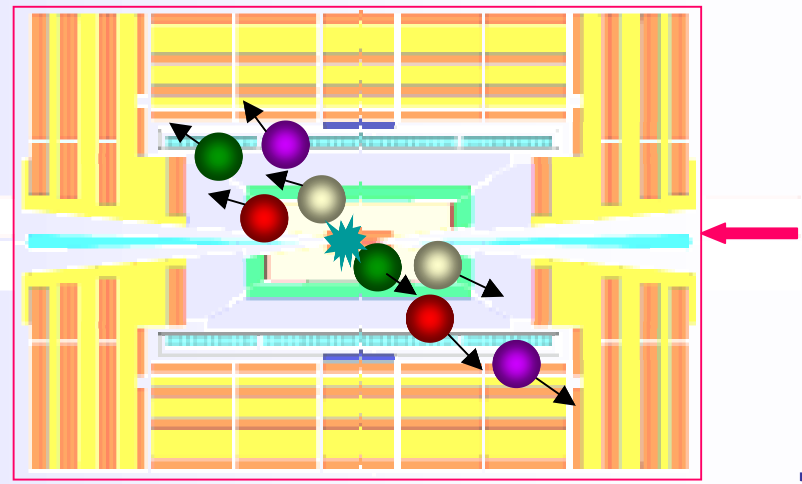
Introduction

The **‘ideal’** particle detector should provide…

- coverage of full solid angle (no cracks, fine segmentation)
- measurement of momentum and/or energy
- detect, track and identify all particles (mass, charge)
- fast response, no dead time

- practical limitations (technology, space, budget) !

e^+e^-, ep, pp, $p\bar{p}$



end products
- charged particles
- neutral particles
- photons

- **Particles are detected via their interaction with matter.**
- **Many different physical principles are involved (mainly of electromagnetic nature). Finally we will always observe ionization and excitation of matter.**

Detector Systems

- number of particles
- event topology
- momentum / energy
- particle identity

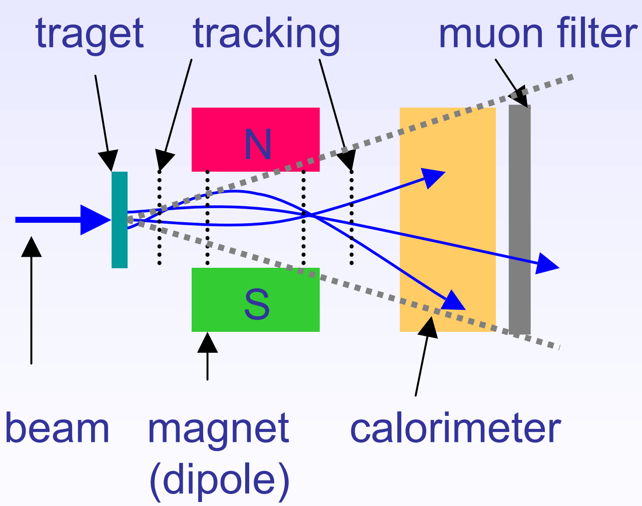
Can't be achieved with a single detector !

→ integrate detectors to detector systems

Geometrical concepts

Fixed target geometry

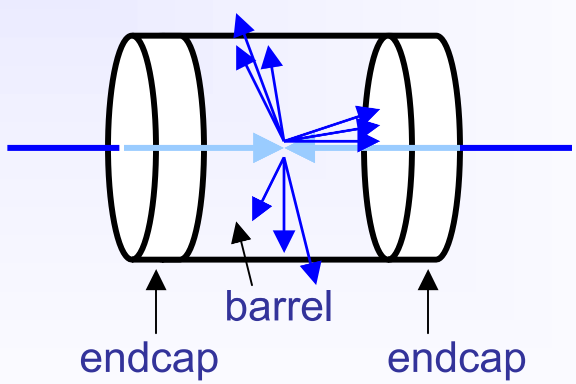
"Magnet spectrometer"



- Limited solid angle $d\Omega$ coverage
- rel. easy access (cables, maintenance)

Collider Geometry

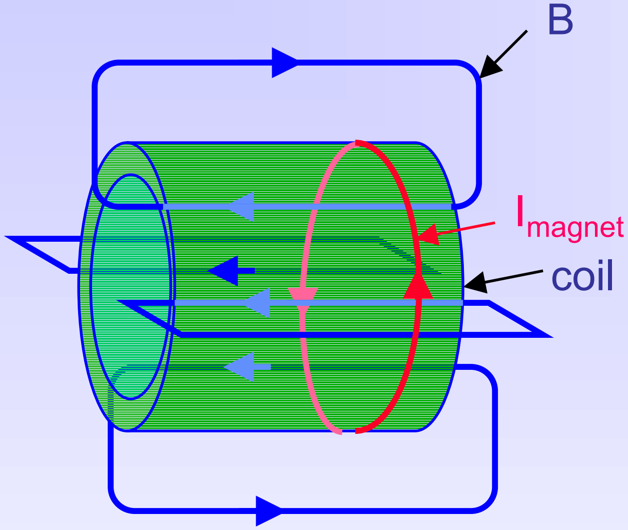
"4π multi purpose detector"



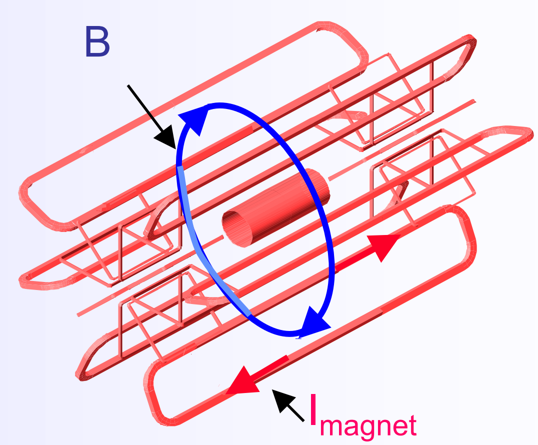
- "full" $d\Omega$ coverage
- very restricted access

Magnet concepts for 4π detectors

solenoid



toroid



\+ Large homogenous field inside coil
\- weak opposite field in return yoke
\- Size limited (cost)
\- rel. high material budget

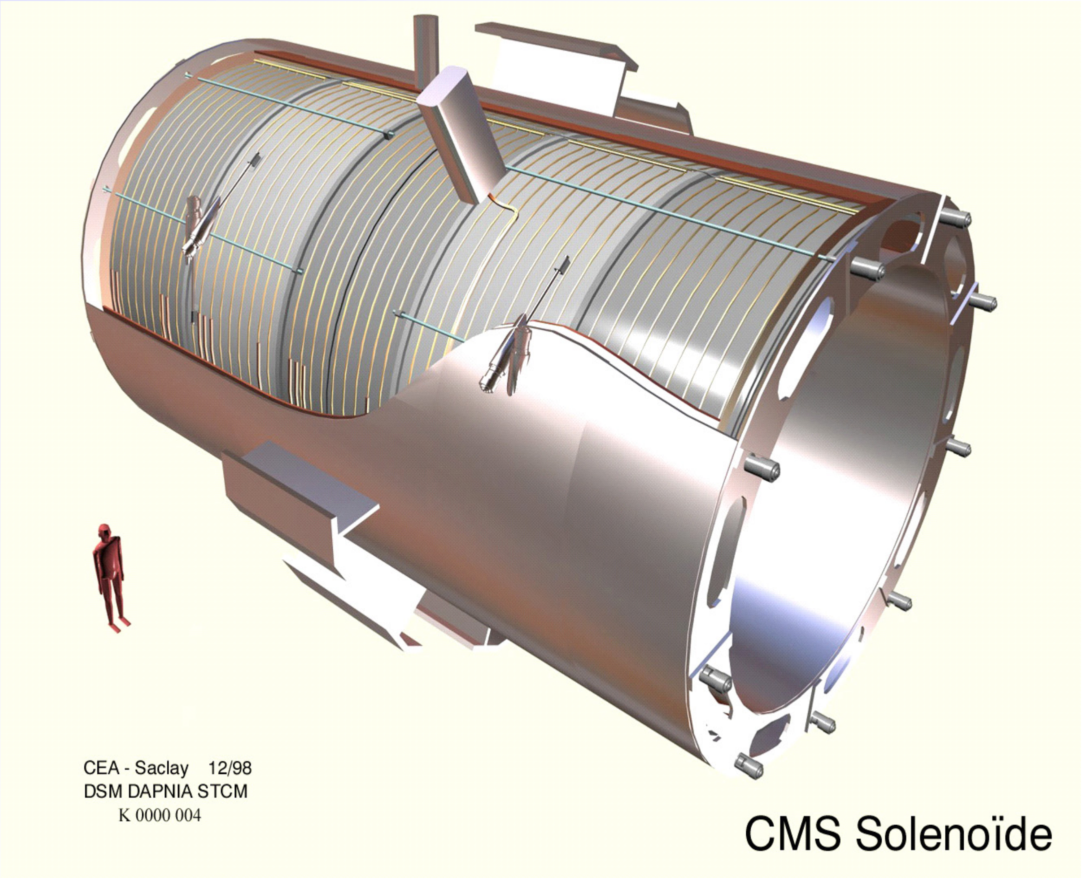
Examples:
- DELPHI: SC, 1.2T, Ø5.2m, L 7.4m
- L3: NC, 0.5T, Ø11.9m, L 11.9m
- CMS: SC, 4.0T, Ø5.9m, L 12.5m

\+ Field always perpendicular to $\vec{p}$
\+ Rel. large fields over large volume
\+ Rel. low material budget
\- non-uniform field
\- complex structure

Example:
- ATLAS: Barrel air toroid, SC, ~1T, Ø9.4, L 24.3m

2 ATLAS toroid coils

Artistic view of CMS coil



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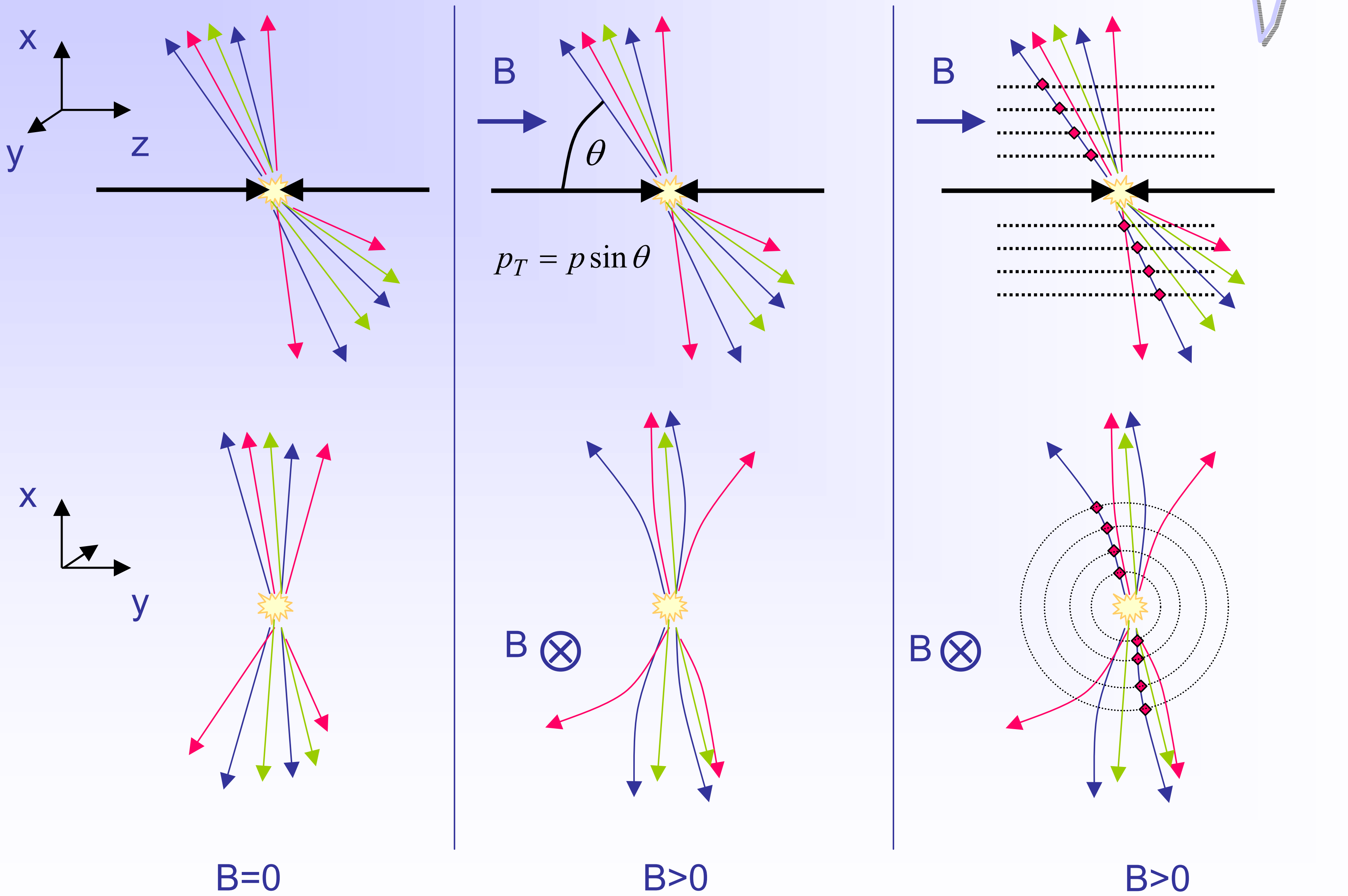
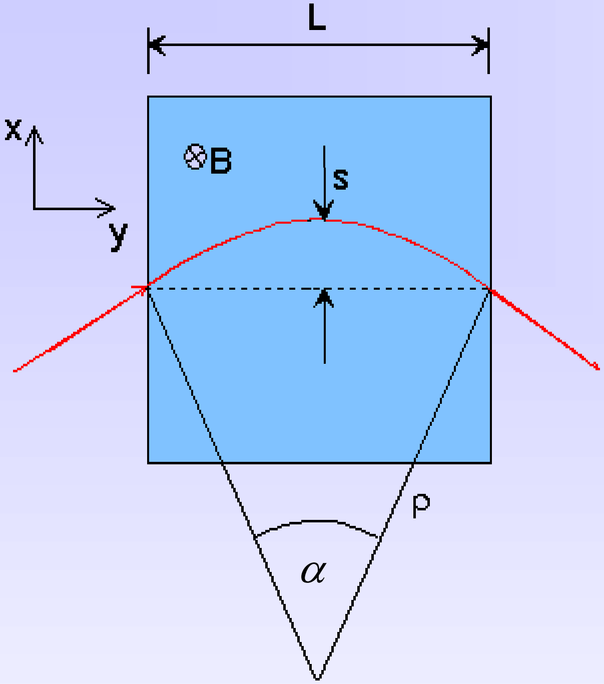
Momentum measurement



Momentum measurement



We measure only p-component transverse to B field !

$$p_T = qB\rho \quad \rightarrow \quad p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T \cdot m})$$

$$\frac{L}{2\rho} = \sin\alpha/2 \approx \alpha/2 \quad \rightarrow \quad \alpha \approx \frac{0.3L \cdot B}{p_T}$$

$$s = \rho(1-\cos\alpha/2) \approx \rho\frac{\alpha^2}{8} \approx \frac{0.3}{8}\frac{L^2 B}{p_T}$$

the sagitta s is determined by 3 measurements with error *s(x)*:

$$s = x_2 - \frac{x_1+x_3}{2} \qquad \left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)\cdot 8p_T}{0.3\cdot BL^2}$$

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \propto \frac{\sigma(x)\cdot p_T}{BL^2}$$

for N equidistant measurements, one obtains (R.L. Gluckstern, NIM 24 (1963) 381)

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$

(for N ≥ ~10)

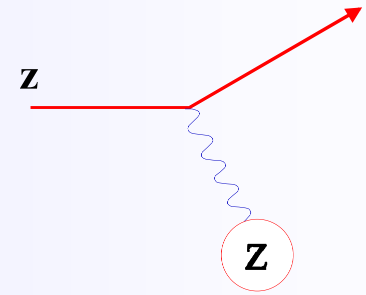
Interaction of charged particles

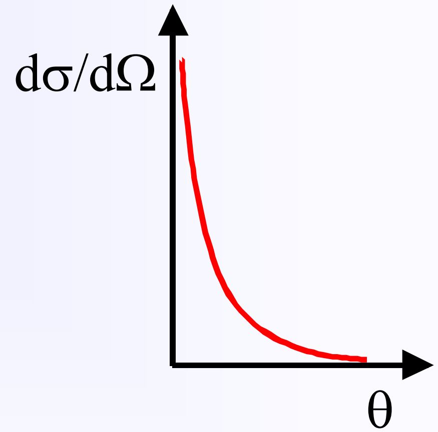
Scattering

An incoming particle with charge z interacts elastically with a target of nuclear charge Z.
The cross-section for this e.m. process is

$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \theta/2}$$

Rutherford formula





- Approximation
  - Non-relativistic
  - No spins

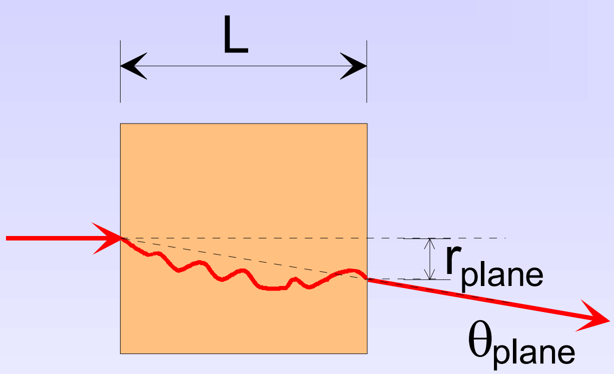
- Average scattering angle $\langle\theta\rangle = 0$
- Cross-section for $\theta \rightarrow 0$ infinite !

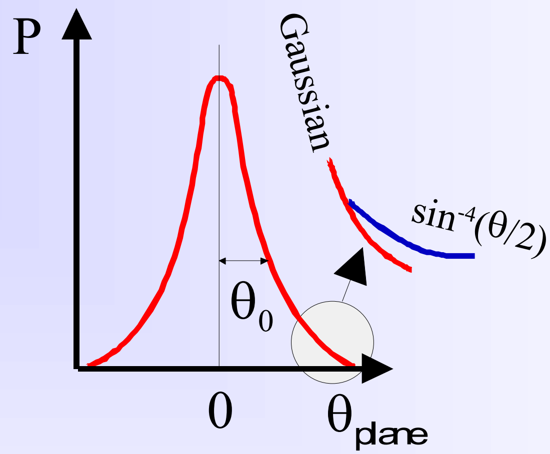
- Scattering does not lead to significant energy loss

Interaction of charged particles

In a sufficiently thick material layer a particle will undergo …

- **Multiple Scattering**

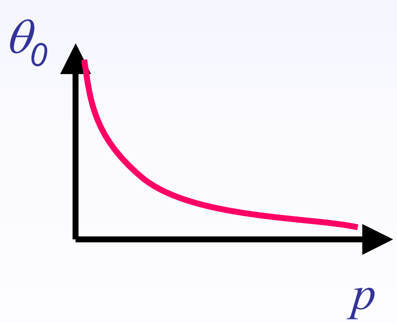


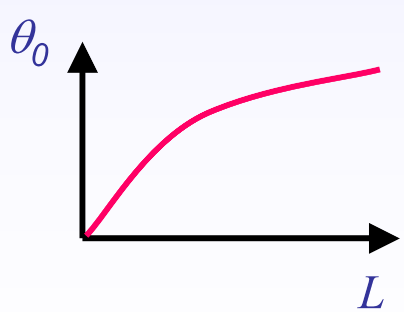


$$\theta_0 = \theta_{plane}^{RMS} = \sqrt{\langle \theta_{plane}^{\ \ 2} \rangle}$$

$$= \frac{1}{\sqrt{2}} \theta_{space}^{RMS}$$

Approximation $\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$ X_0 is radiation length of the medium (discuss later)





Interaction of charged particles

Back to momentum measurements:

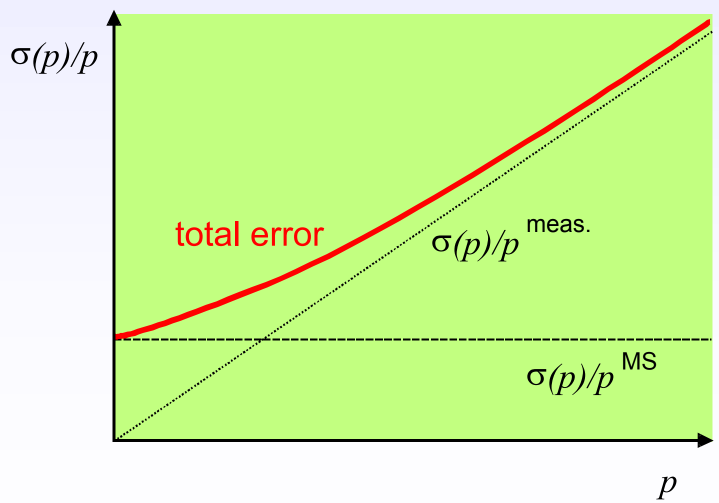
What is the contribution of multiple scattering to $\frac{\sigma(p)}{p_T}$?

remember $\frac{\sigma(p)}{p_T} \propto \sigma(x) \cdot p_T$

$\sigma(x)\Big|^{MS} \propto \theta_0 \propto \frac{1}{p}$

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = \text{constant}$$, i.e. independent of p !

More precisely: $$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = 0.045 \frac{1}{B\sqrt{LX_0}}$$



Example:

$p_t = 1$ GeV/c, $L = 1$m, $B = 1$ T, $N = 10$

$\sigma(x) = 200$ µm: $$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \approx 0.5\%$$

Assume detector (L = 1m) to be filled with 1 atm. Argon gas (X_0 = 110m),

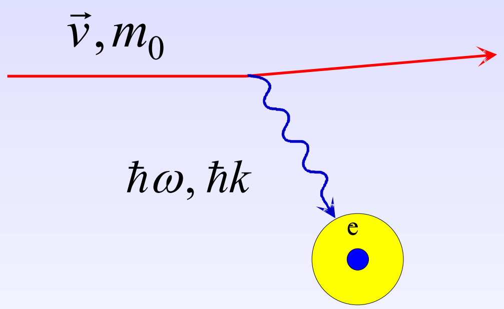
$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} \approx 0.5\%$$

Interaction of charged particles

Detection of charged particles

Particles can only be detected if they deposit energy in matter.
How do they lose energy in matter ?

Discrete collisions with the atomic electrons of the absorber material.



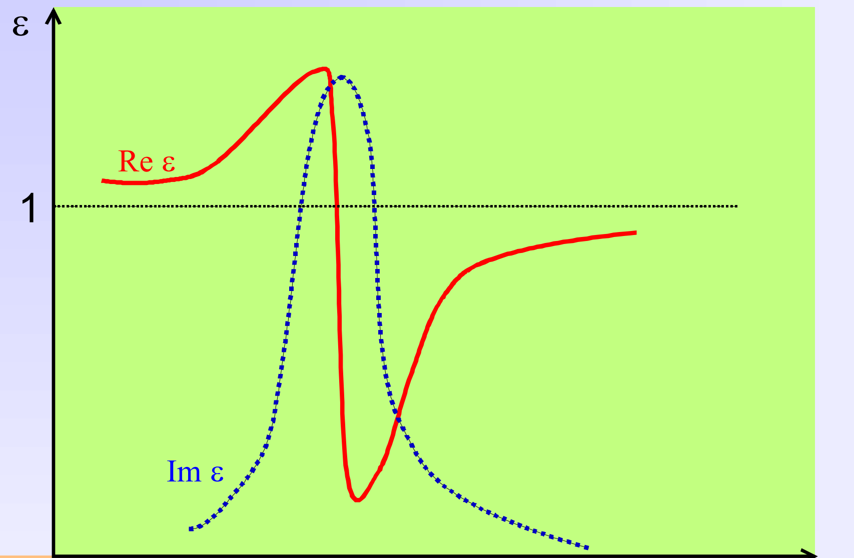
$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty NE \frac{d\sigma}{dE} \hbar\, d\omega$$

N : electron density

Collisions with nuclei not important ($m_e << m_N$) for energy loss.

If $\hbar\omega, \hbar k$ are in the right range ⇨ ionization.

Interaction of charged particles



regime:	optical	absorptive	X-ray
effect:	Cherenkov radiation	ionisation	transition radiation

Optical behaviour of medium is characterized by the complex dielectric constant ε

$\mathrm{Re}\sqrt{\varepsilon} = n$ Refractive index

$\mathrm{Im}\,\varepsilon = k$ Absorption parameter

Instead of ionizing an atom or exciting the matter, under certain conditions the photon can also escape from the medium.

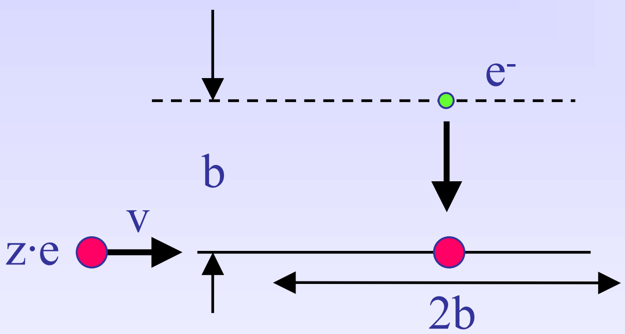
⇨ Emission of **Cherenkov** and **Transition** radiation. (See later). This emission of real photons contributes also to the energy loss.

Interaction of charged particles

Average differential energy loss $\left\langle \frac{dE}{dx} \right\rangle$

… making Bethe-Bloch plausible.

Energy loss at a single encounter with an electron



$$F_c = \frac{ze^2}{b^2} \qquad \Delta t = \frac{2b}{v} \qquad \Delta p_e = F_c \Delta t$$

$$\Delta E_e = \frac{(\Delta p_e)^2}{2m_e} = \frac{2z^2e^4}{b^2 v^2 m_e} = \frac{2r_e^2 m_e c^2 z^2}{b^2} \cdot \frac{1}{\beta^2}$$

Introduced classical electron radius $r_e = \frac{e^2}{m_e c^2}$

How many encounters are there ?

Should be proportional to electron density in medium $N_e \propto \frac{Z}{A} N_A \cdot \rho$

The real Bethe-Bloch formula.

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

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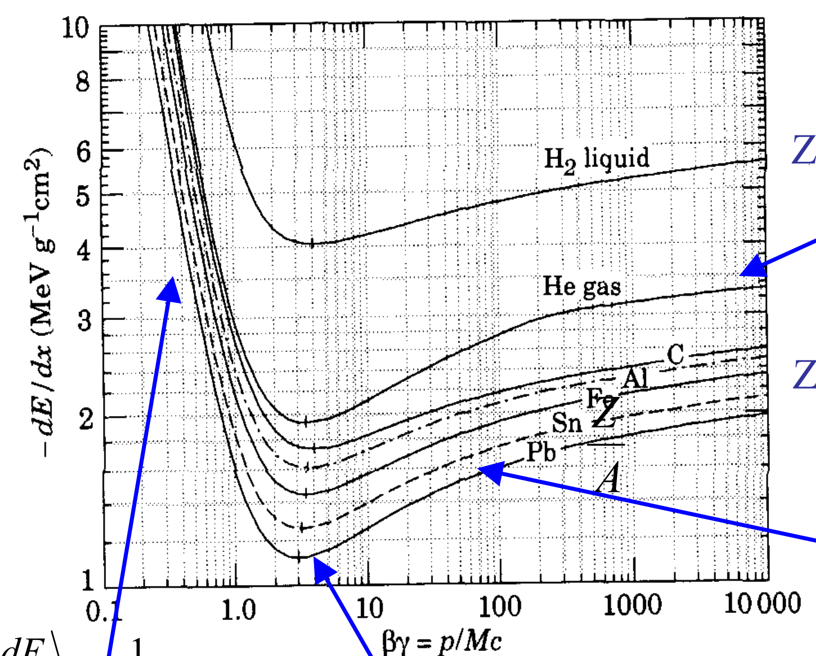
Interaction of charged particles

Energy loss by Ionisation only → Bethe - Bloch formula

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

- dE/dx in [MeV g^{-1} cm^2]
- valid for "heavy" particles ($m \geq m_\mu$).
- dE/dx depends only on β, independent of m !
- First approximation: medium simply characterized by Z/A ~ electron density



Z/A = 1

"Fermi plateau"

Z/A~0.5

$$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2\gamma^2$$

"relativistic rise"

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

"kinematical term"

$\beta\gamma \approx$ 3-4

minimum ionizing particles, MIPs

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Interaction of charged particles

Bethe - Bloch formula cont'd $\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$

- Formula takes into account energy transfers

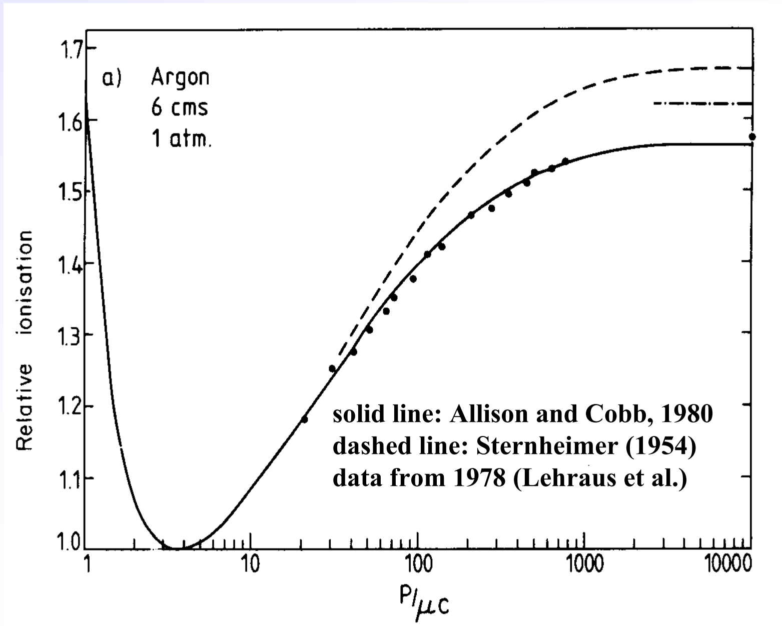
  $I \le dE \le T^{\max}$ I : mean excitation potential $I \approx I_0 Z$ with $I_0 = 10$ eV (approx., I fitted for each element)

- relativistic rise - ln γ^2 term - attributed to relativistic expansion of transverse E-field → contributions from more distant collisions.

- relativistic rise cancelled at high γ by "density effect", polarization of medium screens more distant atoms. Parameterized by δ (material dependent) → Fermi plateau

- many other small corrections

Measured and calculated dE/dx



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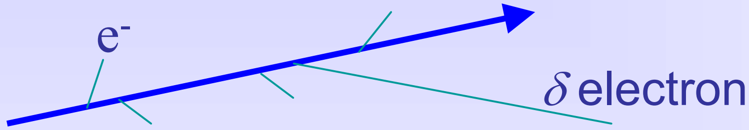
Interaction of charged particles

Real detector (limited granularity) can not measure <*dE/dx*> !

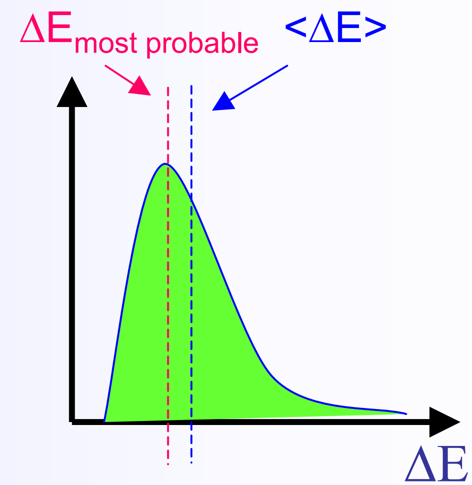
It measures the energy ΔE deposited in a layer of finite thickness δx.

For thin layers or low density materials:

→ Few collisions, some with high energy transfer.



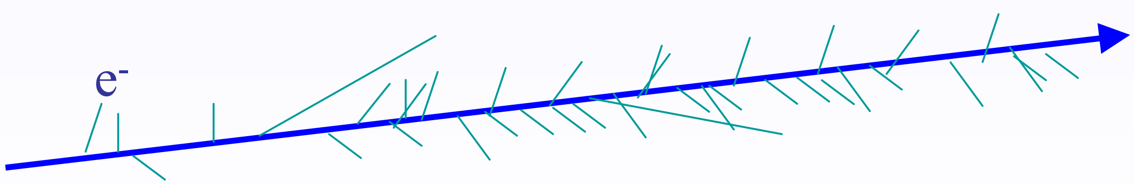
→ Energy loss distributions show large fluctuations towards high losses: "Landau tails"

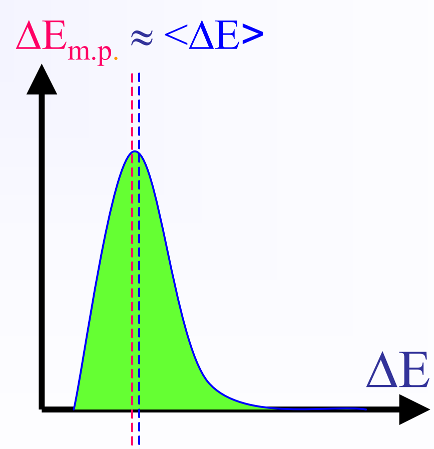


Example: Si sensor: 300 μm thick. $\Delta E_{m.p} \sim 82$ keV $\langle \Delta E \rangle \sim 115$ keV

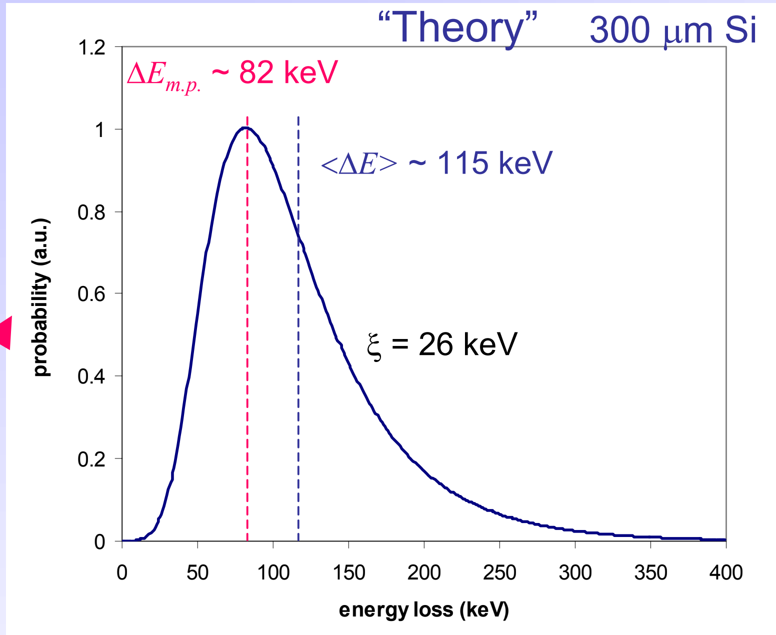
For thick layers and high density materials:

→ Many collisions.
→ Central Limit Theorem → Gaussian shaped distributions.





Interaction of charged particles



Landau's theory J. Phys (USSR) 8, 201 (1944)

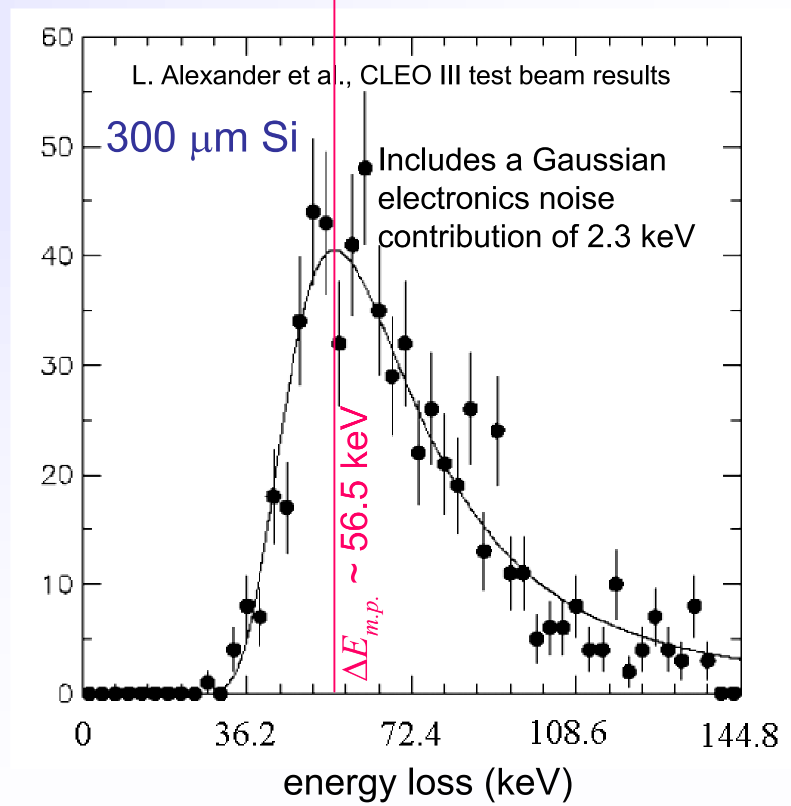
$$f(x,\Delta E) = \frac{1}{\xi}\Omega(\lambda) \qquad \Omega(\lambda) \approx \frac{1}{\sqrt{2\pi}}\exp\left\{-\tfrac{1}{2}(\lambda + e^{-\lambda})\right\}$$

$$\lambda = \frac{\Delta E - \Delta E_{m.p.}}{\xi}$$

$$\xi = \frac{2\pi N e^4}{m_e v^2}\frac{Z}{A}x$$

x (300 μm Si) = 69 mg/cm^2

charge collection is not 100%



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