Concepts for Experiments at Future Colliders I

PD Dr. Oliver Kortner

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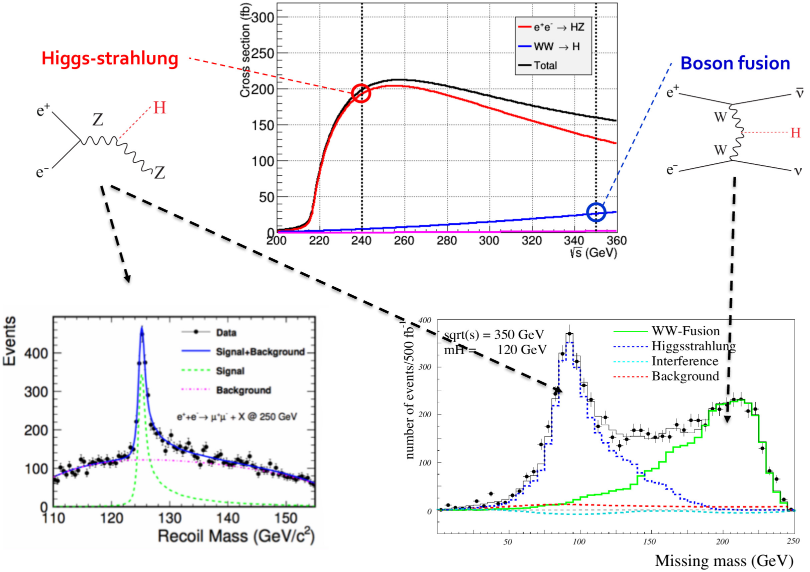
Addendum: FCC-ee detector concepts

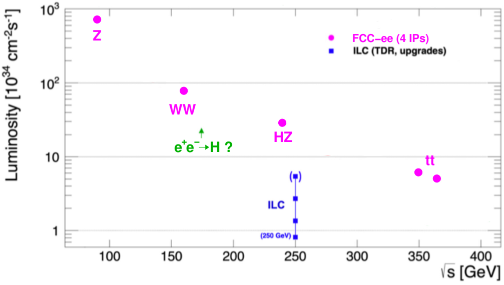
Higgs boson production at an e^+e^- Higgs factory



FCC-ee as Higgs factory plus EW and top factory

Higgs factory programme

- $2 \cdot 10^6$ HZ events (similar to the HL-LHC, but higher purity and selectrion efficiency) and 125,000 W^+W^- events.
- Precise measurements of Higgs couplings to fermions and bosons.
- Sensitivity to Higgs self-coupling at 2-4 σ level via loop diagrams.
- Unique opportunity to measure the electron coupling in $e^+e^- \to H$ at $\sqrt{s} = 125$ GeV.

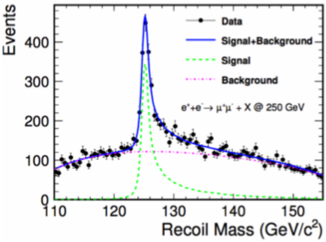


By changing the centre-of-mass energy of the collider the FCC-ee can also be operated as an electroweak and top quark factory.

- $\sim 100,000$ Z/s (1 Z/s at LEP).
- $\sim 10,000$ Ws/h (20,000 Ws in 5 years at LEP).
- $\sim 1,500$ top quarks/d.

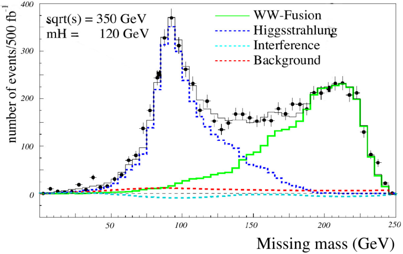
FCC-ee detector performance requirements

Higgs-strahlung



momentum resolution

WW fusion



jet energy resolution

$M_H = 125$ GeV	SM BF
bb	56.1%
WW*	23.1%
gg	8.2%
ττ	6.3%
ZZ*	2.6%
cc	2.9%
γγ	0.2%
Zγ	0.15%
ss	0.1%
μμ	0.02%

flavour tagging

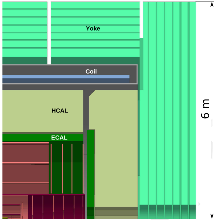
Particle ID

- $\frac{\delta p_T}{p_T} \sim 0.1\%$ for $p_T \sim 50$ GeV (to commensurate with beam energy spread).
- Jet energy resolution of $\frac{30\%}{\sqrt{E}}$ in multi-jet environment for Z/W separation.
- Superior impact parameter resolution for c and b tagging.

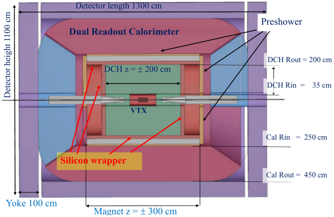
FCC-ee detector concepts

- 4 interaction zones at the FCC-ee allowing for 3 general-purpose detectors.
- 3 detector concepts with evolving designs: ILD, IDEA, ALLEGRO.

CLD/ILD

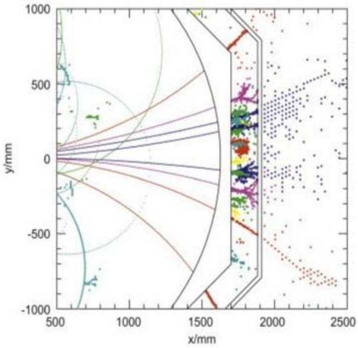


IDEA



ALLEGRO

Motivation for particle-flow hadron calorimeters



- Particle-flow algorithms construct individual particles and estimate their energy/momentum in the best suited subdetector.
- Particle-flow algorithms require highly granular subdetectors including the calorimeters.
- Particle-flow algorithms use the granularity to separate the neutral form the charged contributions and exploit the tracking system to measure charged particle momenta precisely.

E_{jet}	$=$	$E_{charged}$	$+ E_{\gamma}$	$+ E_{neutral\ hadrons}$
$Fraction$		65%	26%	9%

Charged track resolution	$\frac{\delta p}{p} \lesssim 0.1\%$
γ energy resolution	$\frac{\delta E}{E} \sim \frac{12\%}{\sqrt{E}}$
Neutral hadron energy resolution	$\frac{\delta E}{E} \sim \frac{45\%}{\sqrt{E}}$

Dual read-out based calorimeters

Starting idea

- Use scintillators to detect/measure the energy depositions of shower particles.
- Use Čerenkov light to measure the spead of light of relativistic charged shower paricles.

Scintillation signal S and Čerenkov signal C

$$S = E\left[f_{em} + \frac{1}{(e/p)_S}(1 - f_{em})\right],$$

$$C = E\left[f_{em} + \frac{1}{(e/p)_C}(1 - f_{em})\right].$$

If one knows $(e/p)_S$ and $(e/p)_C$, one gets

$$E = \frac{S - \chi \cdot C}{1 - \chi}$$

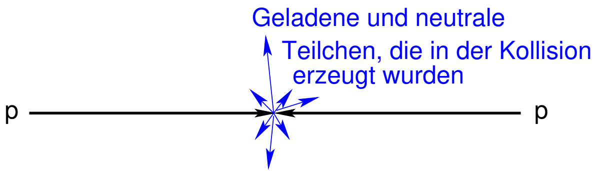
with

$$\chi := \frac{1 - (p/e)_S}{1 - (p/e)_C}$$

which is independent of E and the particle nature.

Recapitulation of important topics

Topology of a pp collision event



Particles which can be produced in a pp collision

Leptonen

- Neutrinos: stable, but only weakly charged. $\Rightarrow$ No interaction leading to a measurable electronic signal in the detector components.
- Electrons: stable, electrically charged. $\Rightarrow$ Electronic signals in the detector components.
- Muons: unstable, but ultrarelativistic, hence longlived in the laboratory system that they do not decay in the detector; electrically charged. $\Rightarrow$ Electronic signals in the detector components.
- τ leptons: unstable. $\Rightarrow$ Have to be detected via their decay products.

Further final state particles

Hadrons

- In the pp collision quarks and gluons are formed. Due to the quark confinement, we do not see quarks and gluons in the detector, by so-called "hadron jets" which are created from the initial quarks and gluons.
- Special role of two types of quarks:
  b quarks build longlived b hadrons which makes it possible to identify b quark jets.
  t quarks are so shortlived that they cannot build hadron. They can be identified by the decay $t \to Wb$.
- Jets contain mainly the lightes mesons, namely π^+, π^-, π_0 which are quasistable due to the large Lorentz boost.

Photons

Photons are stable. They are electrically neutral, but can create electromagnetic showers in the detector material which can be detected.

Interaction of charged particles with matter

Two effects in the passage of charged particles through matter:

- Energy loss.
- Deflection from the original trajectory.

Processes causing energy loss and deflection

- Inelastic scattering off atomic electrons in the traversed material.
- Elastic scattering off the nuclei of the traversed material.
- Emission of Čerenkov radiation.
- Nuclear reactions.
- Bremsstrahlung.

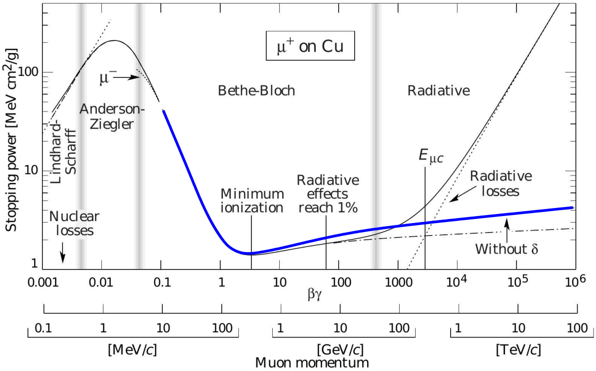
The radiation field of an accelerated charge is proportional to its acceleration a_{charge}. The energy of the radiation is proportional to $|\vec{E}|^2$ which is proportional to $a_{charge}^2 = \left(\frac{F}{m}\right)^2 \propto \frac{1}{m^2}$. Hence bremsstrahlung is only important for electrons, but not for heavy charged particles.

Energy loss of heavy charged particles

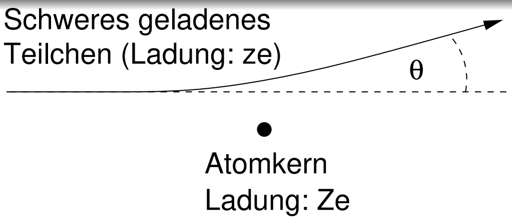
Heavy charged particles lose energy by excitation and ionization of atoms. The energy loss is described by the Bethe-Bloch formula:

$$-\frac{dE}{dx} = \frac{4\pi n z^2}{m_e c^2 \beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I(1-\beta^2)} - \beta^2\right)\right];$$

$\beta = v/c$: Velocity of the particle. E: Energy of the particle.
z: Charge of the particle. e: Elementary charge. n: Electron density of the material.
I: Average excitation potential of the material.



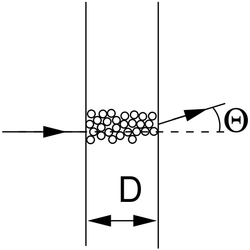
Multiple scattering



Scattering off a single nucleus:

$$\theta = \frac{\Delta p}{p} \propto \frac{z \cdot Z}{p}.$$

$$< \theta >= 0, 0 \neq \theta_0^2 := Var(\theta) \propto \frac{z^2 \cdot Z^2}{p^2}.$$



Scattering off many nuclei:

$$\begin{aligned} < \Theta > &= 0 \\ \Theta_0^2 := Var(\Theta) = \sum_{collisions} \theta_0^2 \propto D \cdot z^2 \cdot Z^2 p^{-2}. \end{aligned}$$

Hence $\boxed{\Theta_0 \propto \frac{\sqrt{D}}{p}.}$

The exact treatment gives

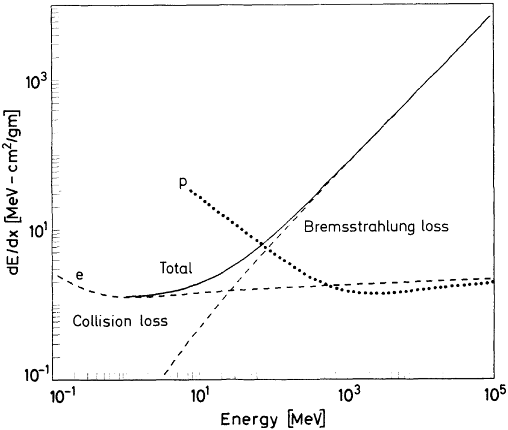
$$\theta_0 := \frac{13,6 \text{ MeV}}{E} \sqrt{\frac{d}{X_0}},$$

where the term under the square root happens to be equal to the radiation length X_0 of the material.

Energy loss of electrons (and positrons)

m_e is so small that the acceleration the electrons/positrons experience in collisions with atomic nuclei is so large that bremsquanta can be emitted.

$$\left.\frac{dE}{dx}\right|_{e^\pm} = \left.\frac{dE}{dx}\right|_{collisions} + \left.\frac{dE}{dx}\right|_{Bremsstrahlung} .$$



Critical energy E_k

$$\left.\frac{dE}{dx}\right|_{collisions}(E_k) = \left.\frac{dE}{dx}\right|_{Brems.}(E_k).$$

$E_k \approx \frac{800\ \text{MeV}}{Z+1/2}$, such that bremsstrahlung is the dominant process for $E_{e^\pm} > 1$ GeV.

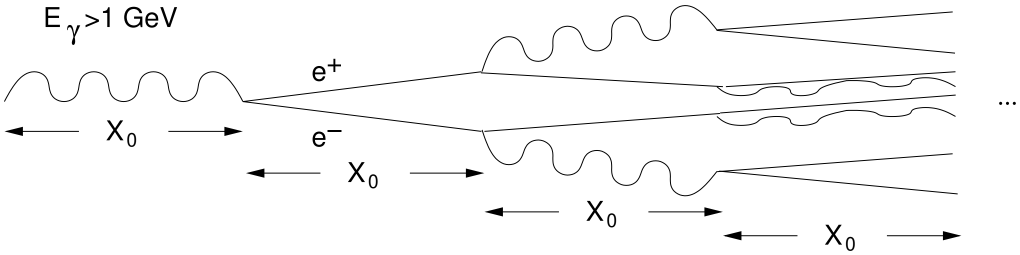
Interaction of photons with matter

Dominant processes

1. Photoelectric effect.
2. Compton scattering
3. e^+e^- pair production

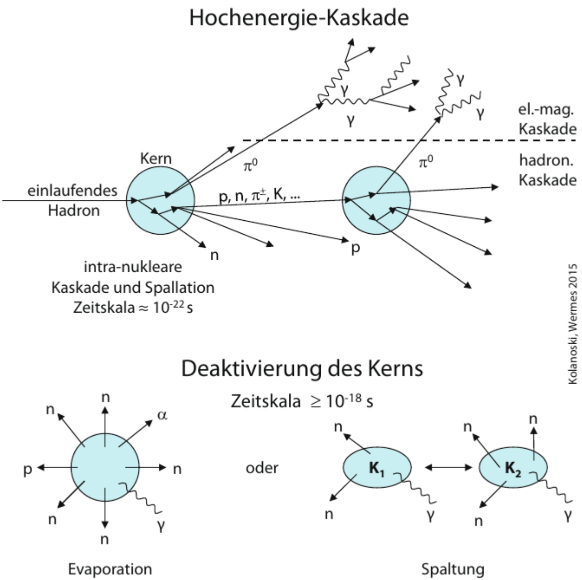
$\Rightarrow$ A beams of photons does not lose energy when passing through matter, but intensity because all three processes remove photons from the beam.

Electron photon showers



- After a distance $n \cdot X_0$: 2^n particles with energy $E_n \approx \frac{E_\gamma}{2^n}$.
- End of the cascade (shower), if $E_n = E_k$: $n = \frac{\ln \frac{E_\gamma}{E_k}}{\ln 2}$.
- Shower length: $n \cdot X_0 = X_0 \cdot \frac{\ln \frac{E_\gamma}{E_k}}{\ln 2}$.
- Transverse size of the shower independent of E_γ:
  $L_\perp \approx 4R_M = 4X_0 \frac{21{,}2 \text{ MeV}}{E_k}$.

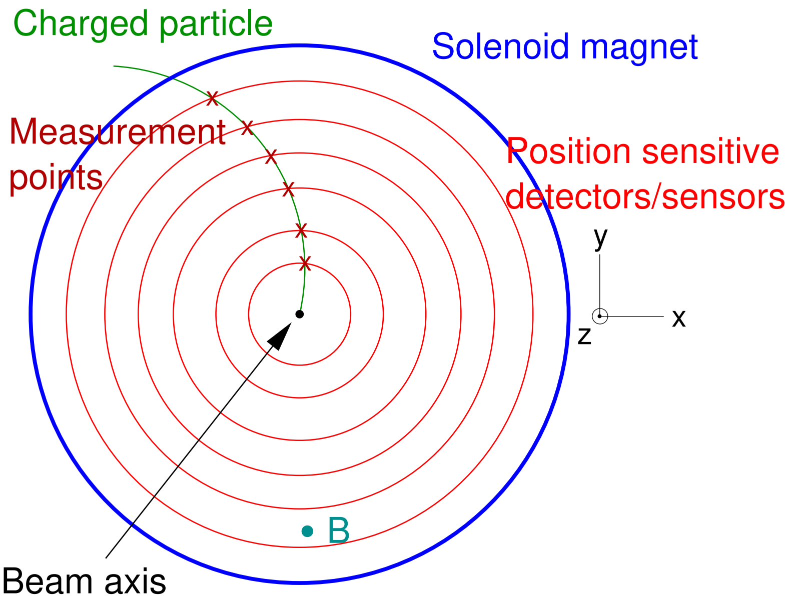
Hadron showers



Similar behaviour like electromagnetic showers:

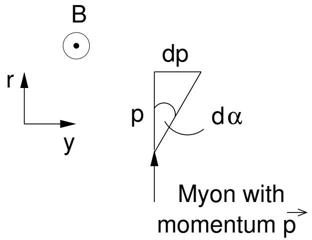
- Shower length proportional to $\lambda_A \approx 35\ \text{g}\,\text{cm}^{-2}\frac{A^{1/3}}{\rho} \gg X_0$.
- Transverse size independent of the energy of the primary hadron: λ_A.
- But much stronger variations of the shower size than in case of electromagnetic showers.

Basic structure of a particle detector at a hadron collider



Charged particle trajectories in the inner detector

$$d\alpha = \frac{dp}{p} = \frac{qvBdt}{p} = \frac{q}{p}B \underbrace{vdt}_{=ds=dr} = \frac{q}{p}Bds.$$



Hence we get

$$\alpha(r) \approx \frac{q}{p}\int_{r_0}^{r} B(s)ds$$

and

$$y(r) = \int_{r_0}^{r} \alpha(r')dr' = \frac{q}{p}\int_{r_0}^{r}\int_{r_0}^{r'} B(s)\,ds\,dr'.$$

Beispiel. $p = 1$ GeV. $r_0 = 0$. $B = 2$ T.
$\alpha(10$ cm$) = 60$ mrad. $y(10$ cm$) = 3$ mm.
$\alpha(1$ m$) = 0,6$ rad. $y(1$ m$) = 30$ cmm.

Momentum resolution in the inner detector

- Deflection angle at distance r from the pp interaction point:

$$\alpha(r) = \frac{q}{p} \int\limits_0^r B\, ds$$

- Total deflection angle: $\alpha := \alpha(r_{max})$ (r_{max} radius of the inner detector).
- Error propagation:

$$\delta\alpha = \frac{|q|}{p^2} \int\limits_0^{r_{max}} B\, ds \cdot \delta p = \alpha \cdot \frac{\delta p}{p} \Leftrightarrow \frac{\delta p}{p} = \frac{\delta\alpha}{\alpha}$$

$$\frac{\delta p}{p} = \frac{\delta\alpha}{\frac{|q|}{p} \int\limits_0^{r_{max}} B\, ds}$$

Momentum resolution in the inner detector

$$\frac{\delta p}{p} = \frac{\delta\alpha}{\frac{|q|}{p}\int\limits_0^{r_{max}} B\,ds}$$

- Contributions to $\delta\alpha$

$$\begin{aligned}\delta\alpha &= \sqrt{(\delta\alpha_{mult.\ scatt.})^2 + (\delta\alpha_{det.\ res.})^2} \\ &= \sqrt{\left(13,6\ \text{MeV}\sqrt{\frac{D}{X_0}}\right)^2 + (\delta\alpha_D)^2}\end{aligned}$$

Hence

$$\frac{\delta p}{p} = \frac{13,6\ \text{MeV}\sqrt{\frac{D}{X_0}}}{|q|\int B\,ds} \oplus \frac{\delta\alpha_D}{|q|\int B\,ds}\cdot p$$

$\Rightarrow$ Best possible momentum given by the ratio of multiple scattering and the magnetic field integral.

$\Rightarrow$ High momenta (small values of α): Momentum resolution determined by the ratio of the spatial resolution of the detector and the magnetic field integral. The momentum resolution degrades with increasing p.

Instrumentation of inner detectors

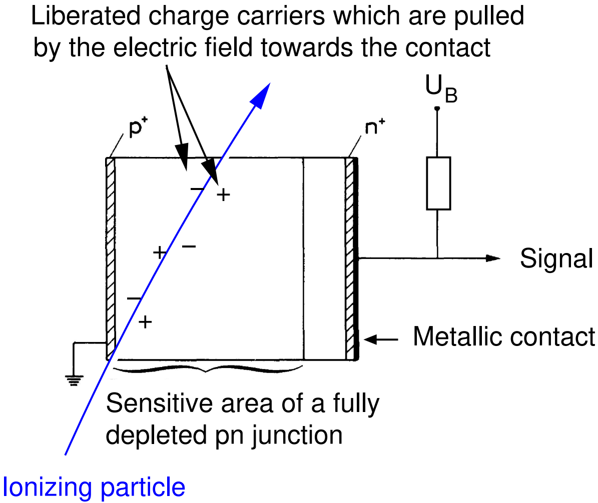
Requirements

- Littel amount of detector material to minimize the multiple scattering contribution to the momentum
- High position resolution to maximize the momentum resolution for highly energetic particles.
- High granularity to be able to separated tracks of individual particle for high particle densities.
- Radiation hardness.

Used detector types

- Originally gaseous ionization detectors were used. These have a small material budget, but limited spatial resolution, granularity, and radiation hardness.
- Nowadays: semiconductor detectors which offer high spatial resolution and high granularity.

Basic principle of a semiconductor detector



In order to prevent the creation of an ohmic contact with a deplection zone extending far into the semiconductor, contact surfaces with highly doped layers are used.

Calorimeter types

Nomenclature

Passive medium:	Material in which the shower develops.
Active medium:	Material in which the electronically detectable signals of the shower particles are created.

Two types of calorimeters

- Homogeneous calorimeters, in which the active material also serves as passive material.
- Inhomogeneous calorimeters or sampling calorimeters with alternating layers of active and passive materials.

Hadron calorimeters are always sampling calorimeters in order to limit their size. There are homogeneous and inhomgeneous electromagnetic calorimeters.

Energy resolution and linearity

Energy resolution

- The energy measurement in a calorimeter consist of the detection of the shower particles. The measured energy is proportional to the number of detected shower particles N leading to $\frac{\delta E}{E} = \frac{\delta N}{N} = \frac{1}{\sqrt{N}}$.
- In a real calorimeter contributions to the energy resolution from detector noise and mechanical and electronic non-uniformities must be taken into account:

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus \underbrace{\frac{b}{E}}_{El.\ noise} \oplus \underbrace{c}_{Non-uniformities}$$

Linearity

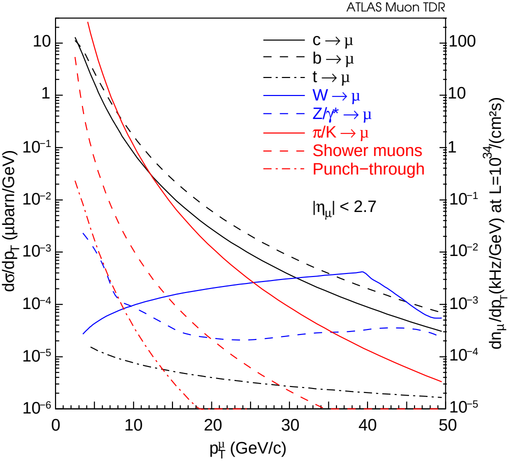
Not only $\frac{\delta E}{E}$ is important, but also that the measureed signal depends linearly on E.

Instrumentation of a calorimeter

- Scintillation counters are important detectors for the active part of a calorimeter.
- Material which emit a small flash of light when hit by radiation
  Important properties of the signal of a scintillation counter:
  - Above a certain minimum energy deposition, the amount of scintillation light is proportional to the deposited energy (in good approximation).
  - Fast response, i.e. the light signal is created a short time after the energy deposition.
- Liquid argon is also used as active medium in calorimeters.
- In liquid argon the noble gas has such a high density that the shower particle liberate many electrons by ionization.
- In order to collect these electrons the liquid argon is enclosed by two electrodes at high voltage.

Muon identification tasks at hadron colliders

Inclusive muon cross sections



Muon identification tasks

- Identification of "prompt" muons from c, b, t, W, and Z/γ decays.
- Rejection of muon from π/K decays, shower muons, and hadronic punch-through.

Muon identification strategy

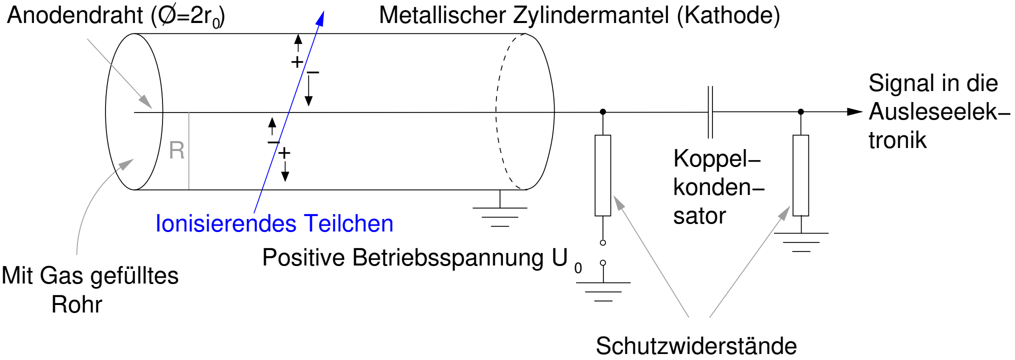
Muon identification concept

Goal	Solution
Minimization of hadronic punch-through	Muon system surrounding the calorimeters
Suppression of muons from π/K decays in flight	p_t measurement in the muon system with $\frac{\Delta p_t}{p_t} \lesssim 10\%$ + requirement of a well matching inner-detector track
Suppression of shower muons	As $\pi/K \to \mu$ + requirement of a small energy deposit in the calorimeters

Gaseous ionization detectors

- Only gaseous ionization detectors allow for a cost effective instrumentation of muon systems.

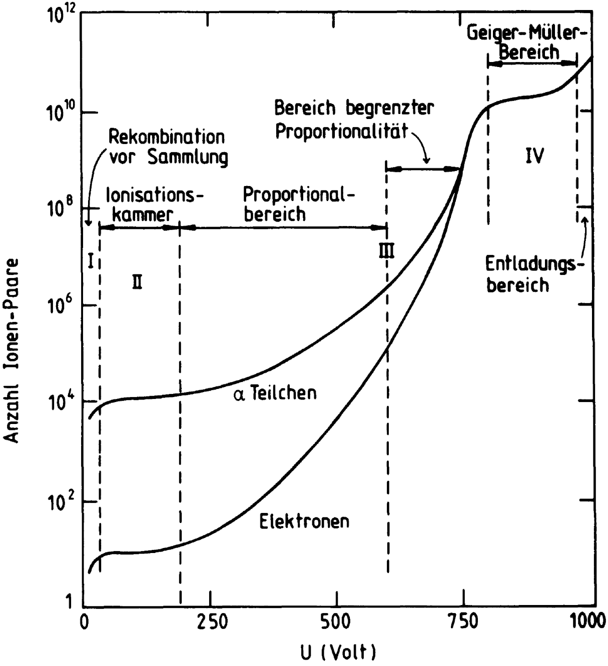
Explanation of the functioning principle using cylindrical tubes, filled with gas, as example



Radial electric field inside the tube: $E(r) = \frac{U_0}{\ln \frac{R}{r_0}} \frac{1}{r}$.

$\Rightarrow$ High field strength in the vicinity of the anode wire.

Signal strength as a function of U_0



Many thanks for your participation in the course!
I would be happy to meet you for the second part of the lecture in the summer semester.