Tracking in High Energy Physics

XIX Heidelberg Physics Graduate Days
2007

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Motivation

„Verehrte An- und Abwesende! Wenn Ihr den Rundfunk höret, so denkt auch daran, wie die Menschen in den Besitz dieses wunderbaren Werkzeuges der Mitteilung gekommen sind. Der Urquell aller technischen Errungenschaften ist die göttliche Neugier und der Spieltrieb des bastelnden und grübelnden Forschers und nicht minder die konstruktive Phantasie des technischen Erfinders ...

... Sollen sich auch alle schämen, die gedankenlos sich der Wunder der Wissenschaft und Technik bedienen und nicht mehr davon geistig erfasst haben als die Kuh von der Botanik der Pflanzen, die sie mit Wohlbehagen frisst“

A. Einstein zur Eröffnung der 7. Großen Deutschen Funkausstellung 1930

http://www.staff.uni-marburg.de/~naeser/einstein.htm

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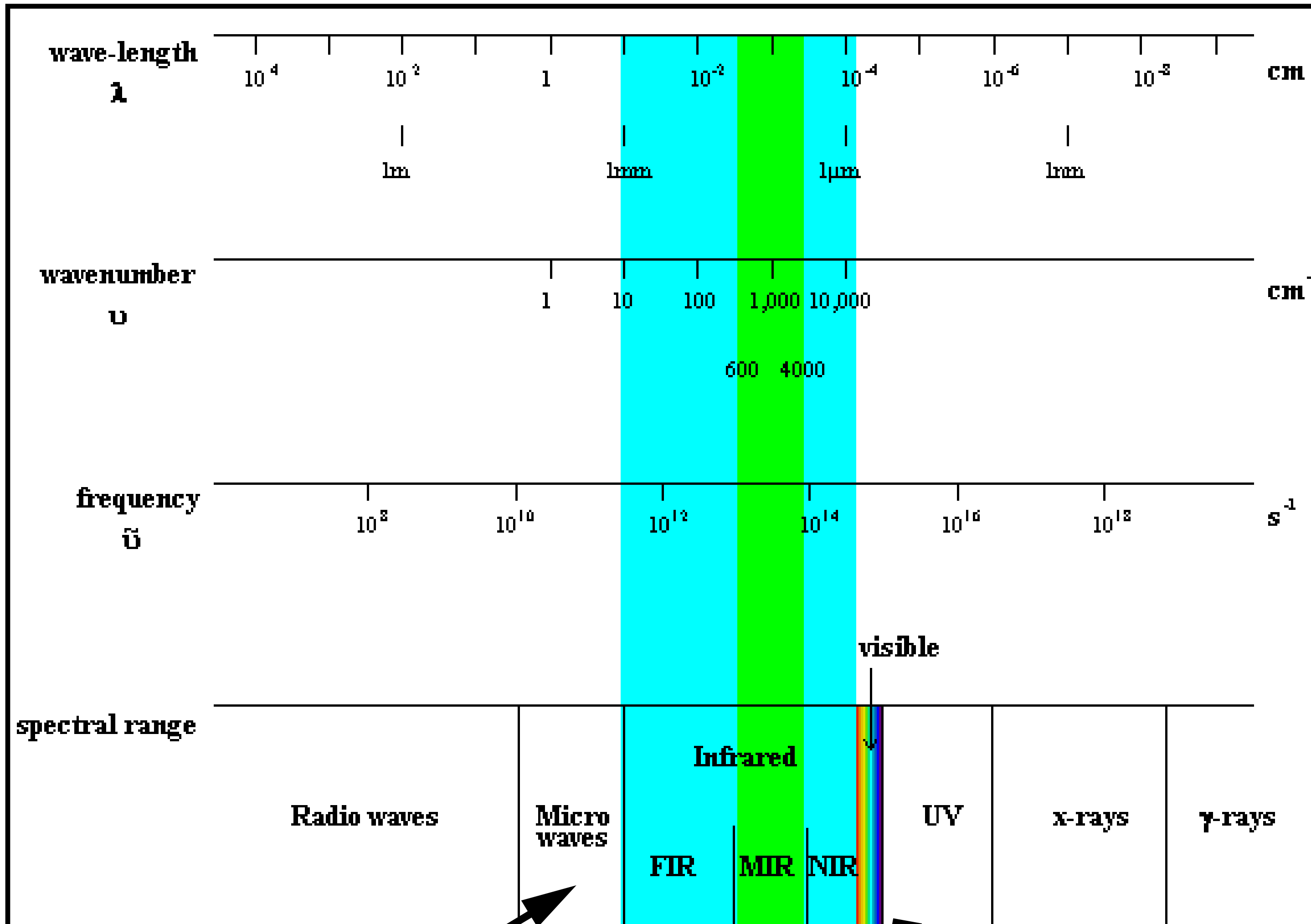
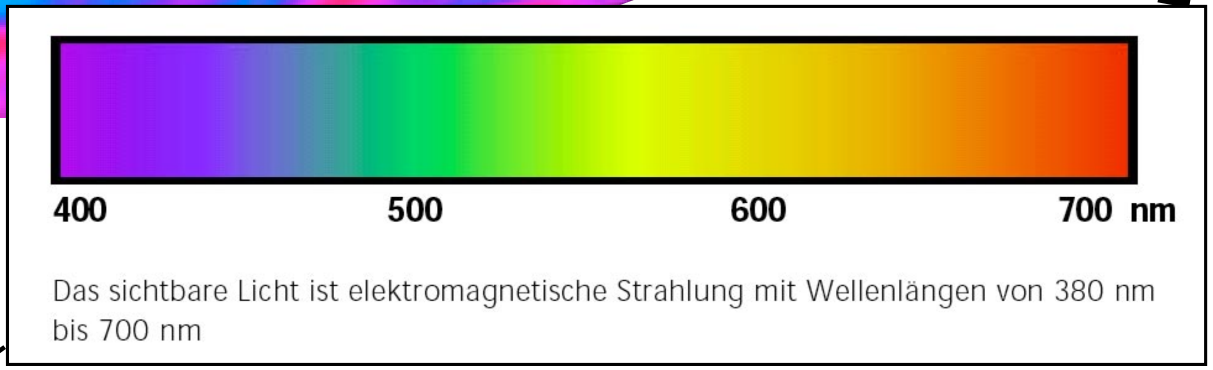
Outline of Lecture

- Monday
  - introduction
  - interaction of charged particles with matter
    - energy loss by ionization
    - multiple scattering
- Tuesday
  - momentum measurement in magnetic field
  - principles of gas detectors
    - gas amplification
    - gas properties
- Wednesday
  - examples for gas detectors at the LHC
- Thursday & Friday
  - solid state detectors: Guillaume Leibenguth

Introduction





Cosmic Ray
Background Radiation:
$T = 2.72$ K, $n_{\gamma} = 4 \times 10^{8}\ m^{-3}$

Literature

Text books:

K.Kleinknecht: *Detektoren für Teilchenstrahlung*
Teubner, 1992

W.R. Leo: *Techniques for Nuclear and Particle Physics Experiments*
Springer 1994

G.F.Knoll: *Radiation Detection and Measurement*
Wiley, 3rd edition

C.Grupen: *Teilchendetektoren*
BI Wissenschaftsverlag 1993

W.Blum, L.Rolandi: *Particle Detection with Driftchambers*
Springer, 1994

Review articles:

T.Ferbel: *Experimental Techniques in High Energy Physics*
Addison-Wesley 1987

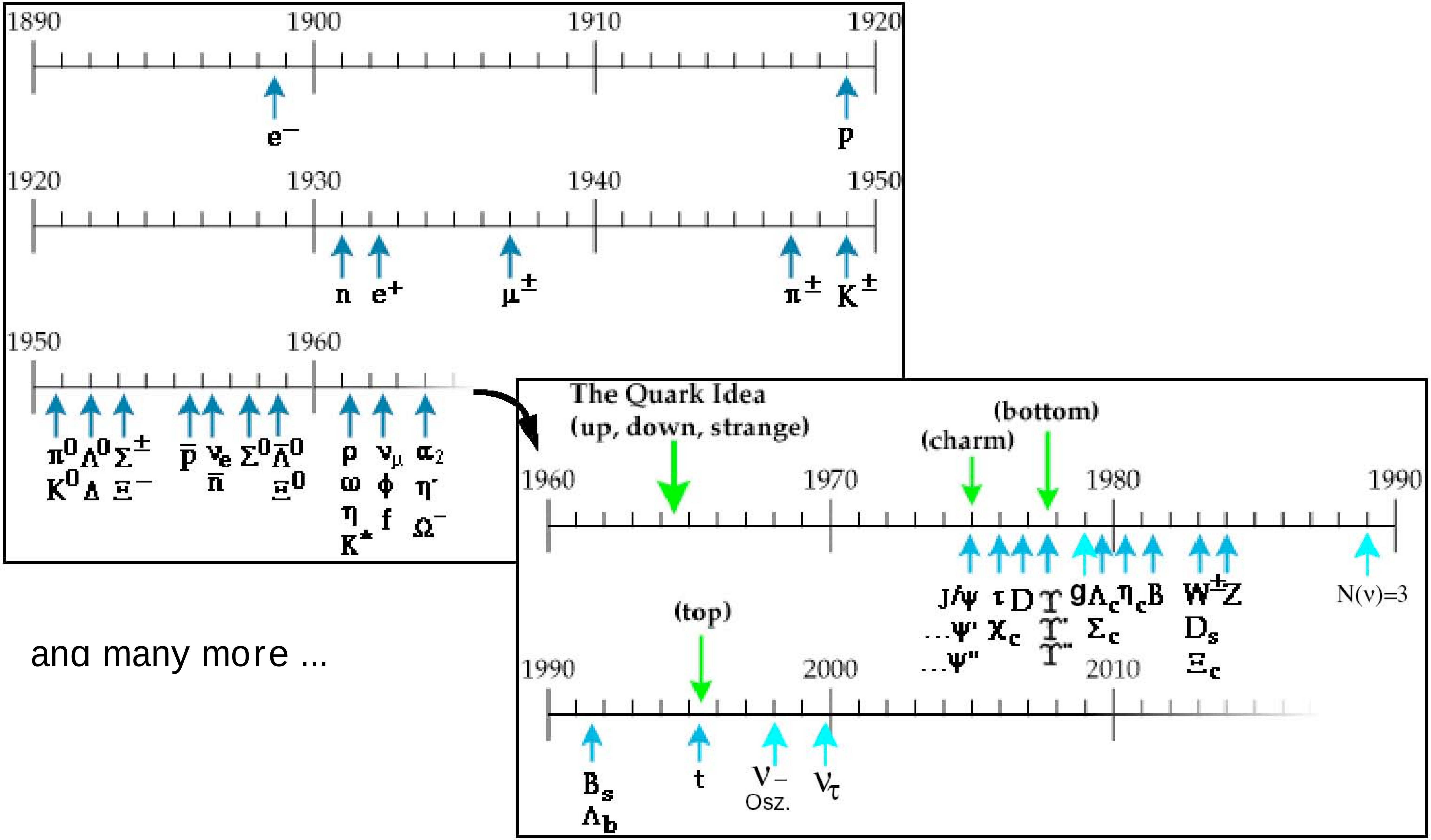
Other sources:

Particle Data Group: *Review of Particle Physics*
Eur. Phys. J. C15, 1-878 (2000)

R.K.Bock, A.Vasilescu: *The Particle Detector BriefBook*
Springer, 1998 and //physics.web.cern.ch/Physics/ParticleDetector/BriefBook/

Please note: Most of the figures in this lecture are taken from these sources or from publicly available talks on the web, without making explicit reference to them in each case.

What are the Objects?



and many more ...

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Fundamental Interactions

		Electro-weak force		
Forces	Strong force	Electro-magnetic force	Weak force	Gravity
Exchanged particles	Gluon	Photon	W,Z bosons	Graviton
Magnitude	1	0.01	10^{-5}	10^{-40}
	Nuclei Hadron Nuclear fusion Solar energy	Molecule, Atom Electronics Synchrotron rad. Aurora	Neutron decay Nuclei decay Neutrino Geothermy	Gravitation Galaxy Black Hole Stellar Pinwheel




Example	$\rho^0 \to \pi^+\pi^-$	$\pi^0 \to \gamma\gamma$	$K^0 \to \pi^+\pi^-$
Lifetime [s]	$\approx 10^{-24}$	$\approx 10^{-16}$	$\approx 10^{-10}$
$c\tau$ [mm]	$\approx 3 \times 10^{-13}$	$\approx 3 \times 10^{-5}$	≈ 30

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Detection of Particles and Radiation

The goal of experimental particle physics: measurement of

- particle properties
- reaction probabilities (→ cross sections)

This requires determination of:

- particle type (mass, charge, spin etc)
- momentum / energy of particle
- emission angles

Elements contributing to such measurements :

- position sensitive detectors → position, direction
- deflection in magnetic field → $|\vec{p}|$
- calorimetry: total energy absorption and measurement → E_{tot}
- mass determination → m
- Cherenkov radiation or time of flight → β
- transition radiation → γ

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Examples for Major Discoveries I

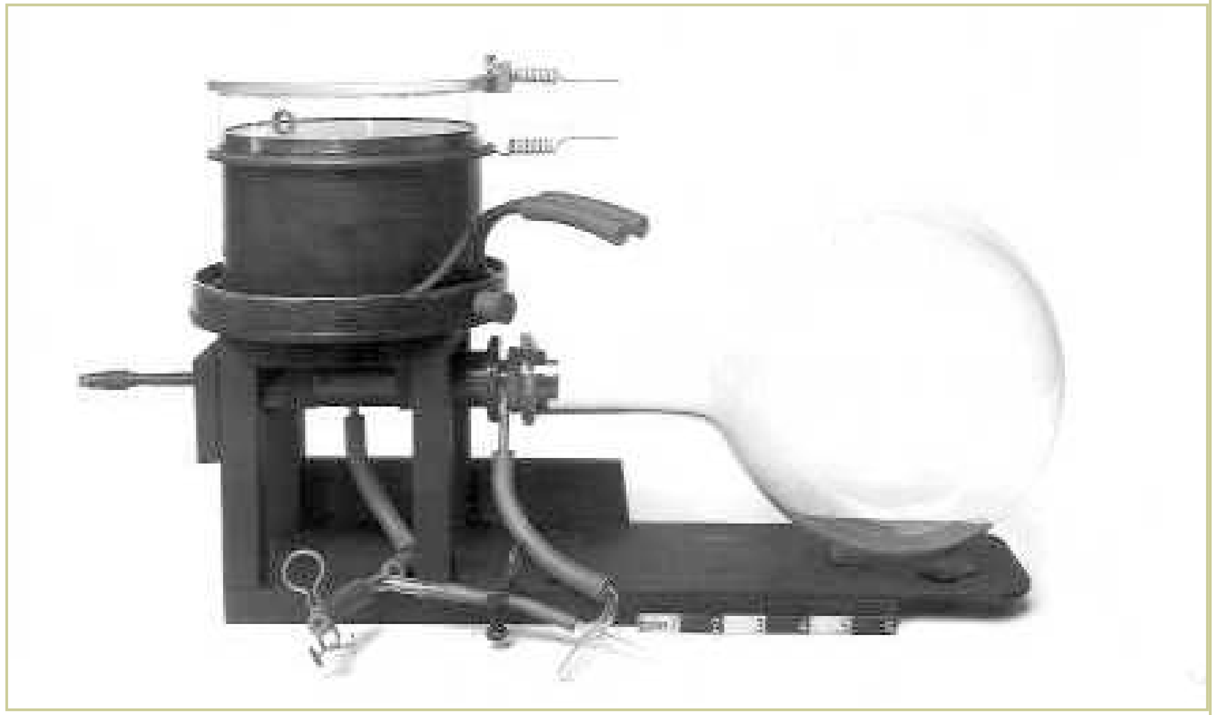
Transparency taken from R. Klanner Uni HH

Examples for major discoveries made possible by detector progress

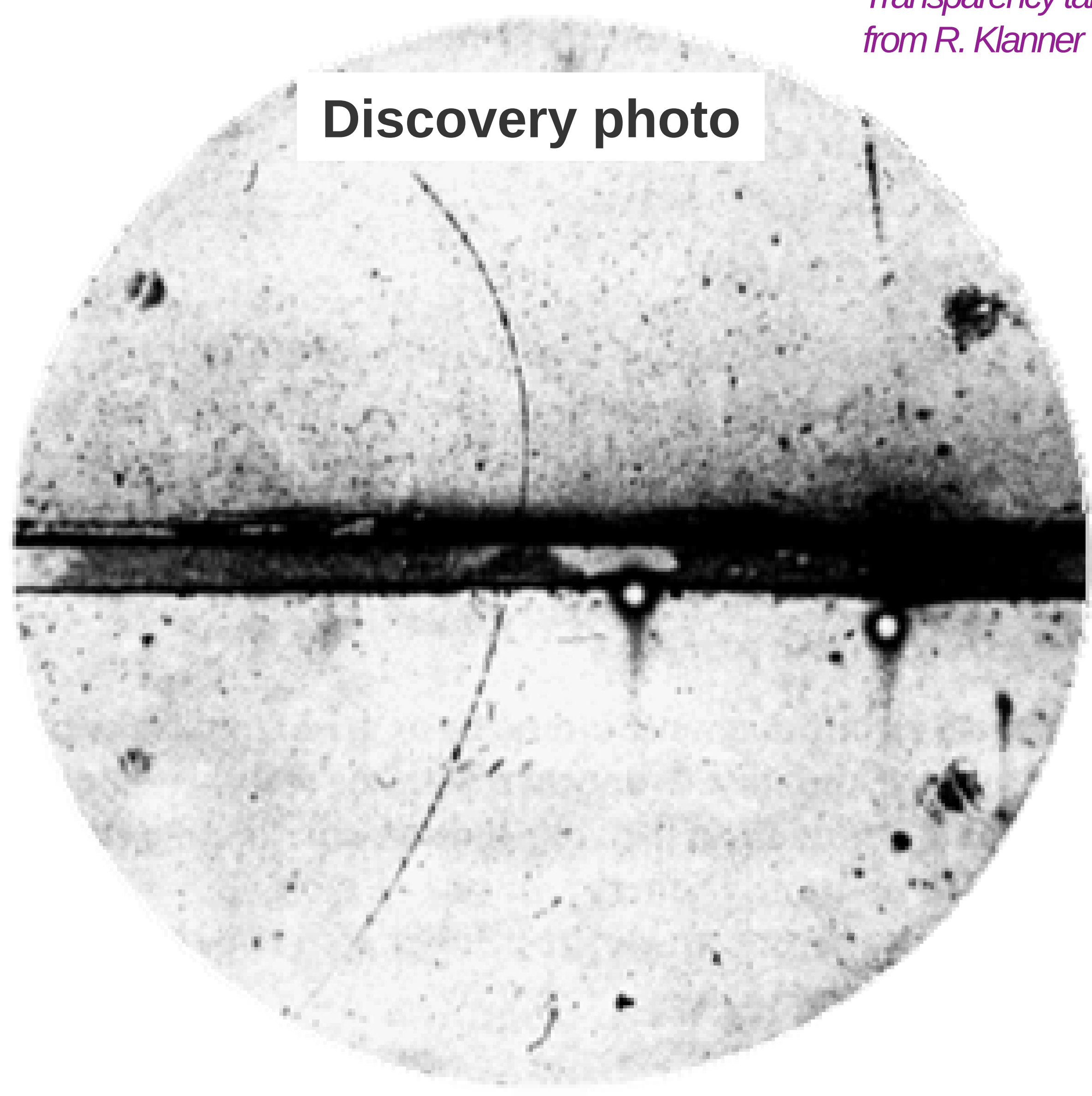
Discovery of positron by C.Anderson (Nobel prize 1936)

http://prola.aps.org/abstract/PR/v43/i6/p491_1

Cloud Chamber (C.T.Wilson Nobel prize 1927)



Adiabatic expansion → saturated vapour
Charged particles → ionisation → condensation of droplets



- ionisation → elementary charge
- curvature in mag.field → sign of charge + measure momentum
- energy loss in 6mm Pb (+ charge and momentum) → mass < 20 x m_e

→ **exclude proton** (2000 x m_e)

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Examples for Major Discoveries II

Transparency taken from R. Klanner Uni HH

Discovery of Ω^- at BNL (USA)

→ Quarkmodel demonstrated

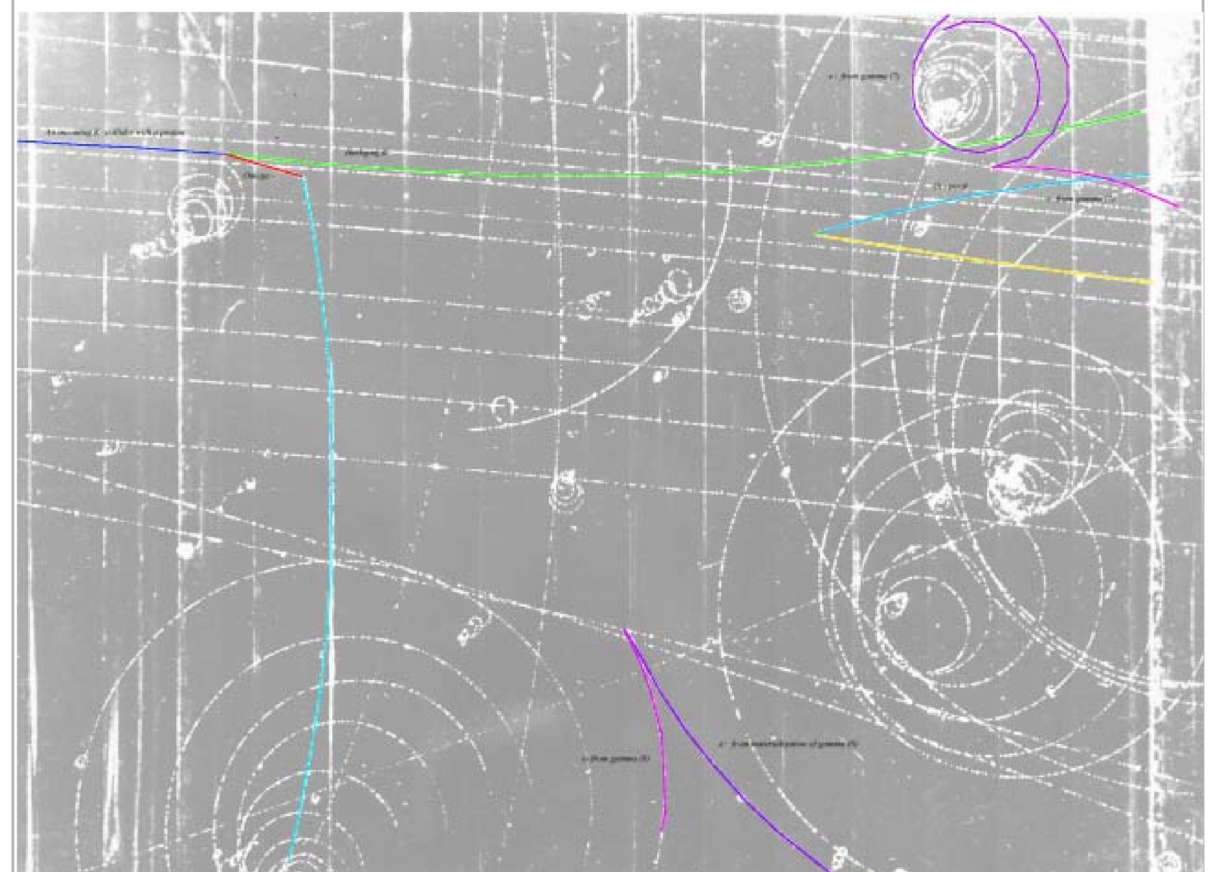
http://prola.aps.org/abstract/PRL/v12/i8/p204_1

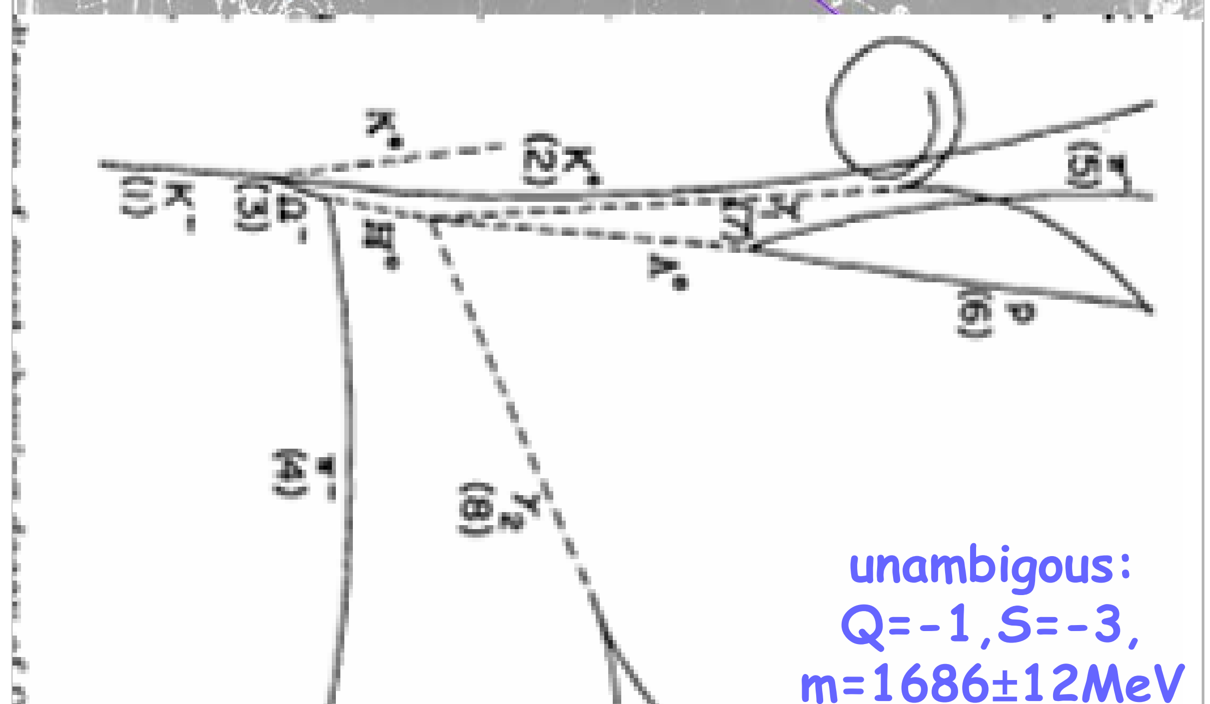
Bubble Chamber (D.Glaser - Nobel prize 1960) – dominated experimental particle physics until the eighties!

Fig. 1: The Gargamelle heavy-liquid bubble chamber, installed into the magnet coils, at CERN in 1970.

Liquid just below vapour pressure – after passage of particle ("event") fast (1ms) expansion → exceed vapour press.

Discovery Ω^- by a single event !!!





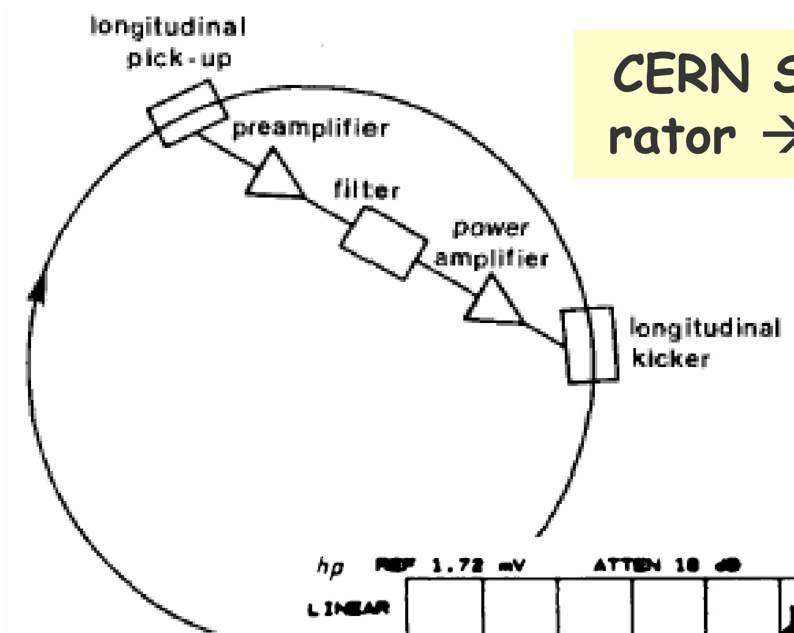
unambigous:
Q=-1,S=-3,
m=1686±12MeV

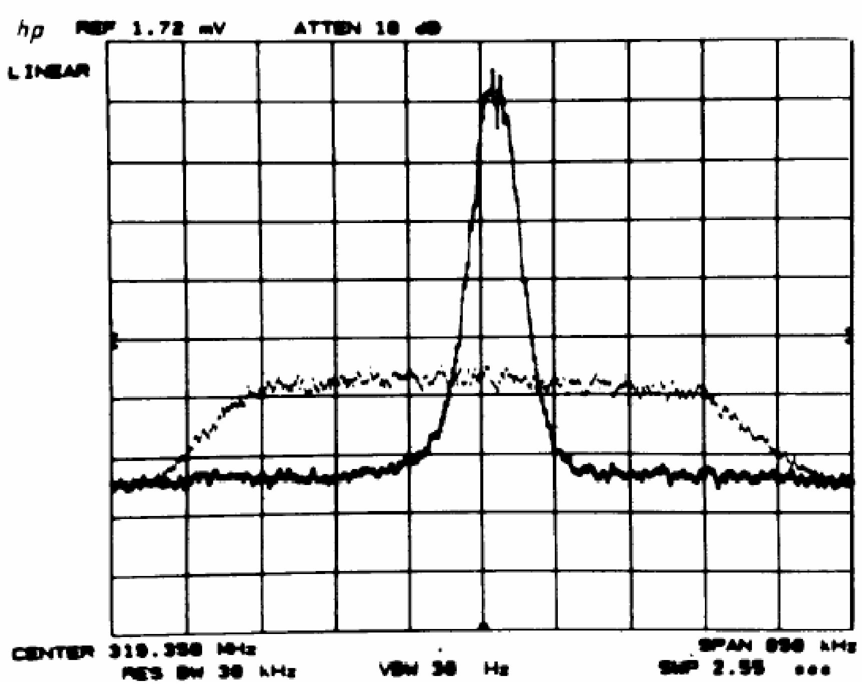
Examples for Major Discoveries III

Discovery of intermediate vector bosons $W^{\pm}, Z^0$, UA1 and UA2 at CERN in anti-p p interactions

(1984 Nobel prize C.Rubbia, S.v.d.Meer)

CERN SPC accele-rator → $\bar{p}p$ collider

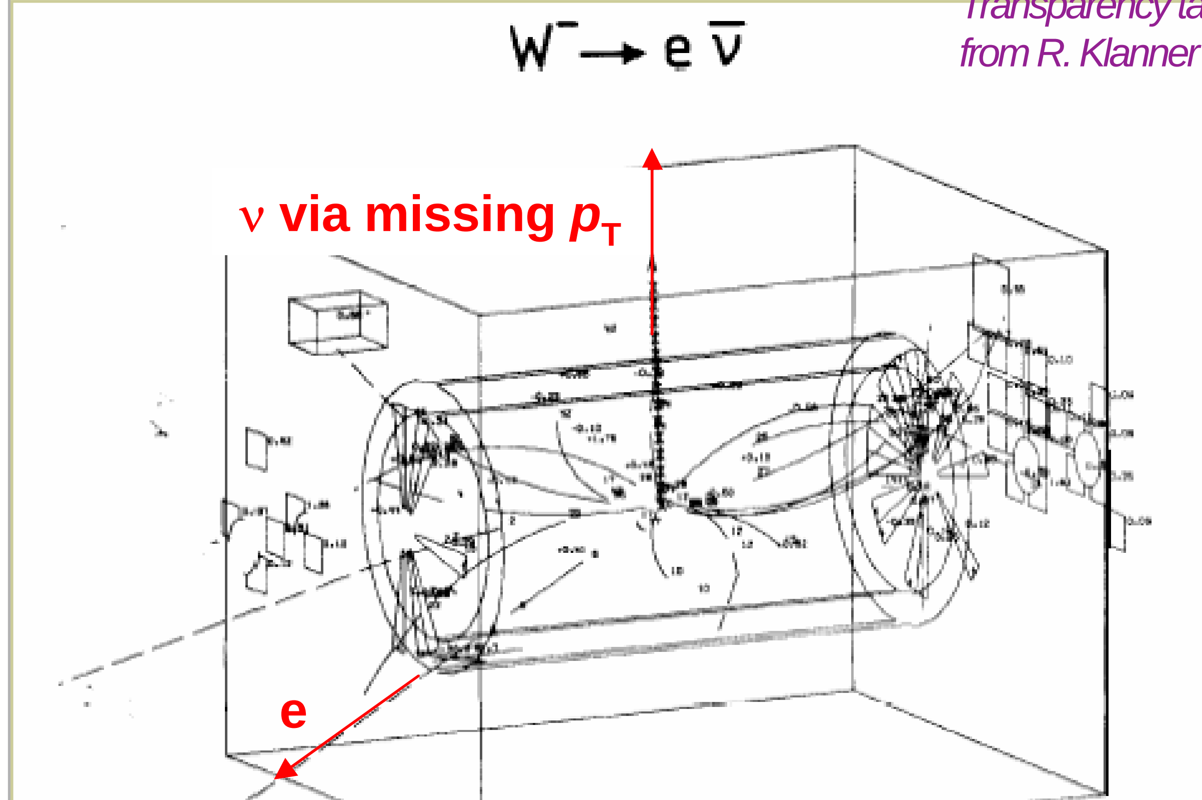


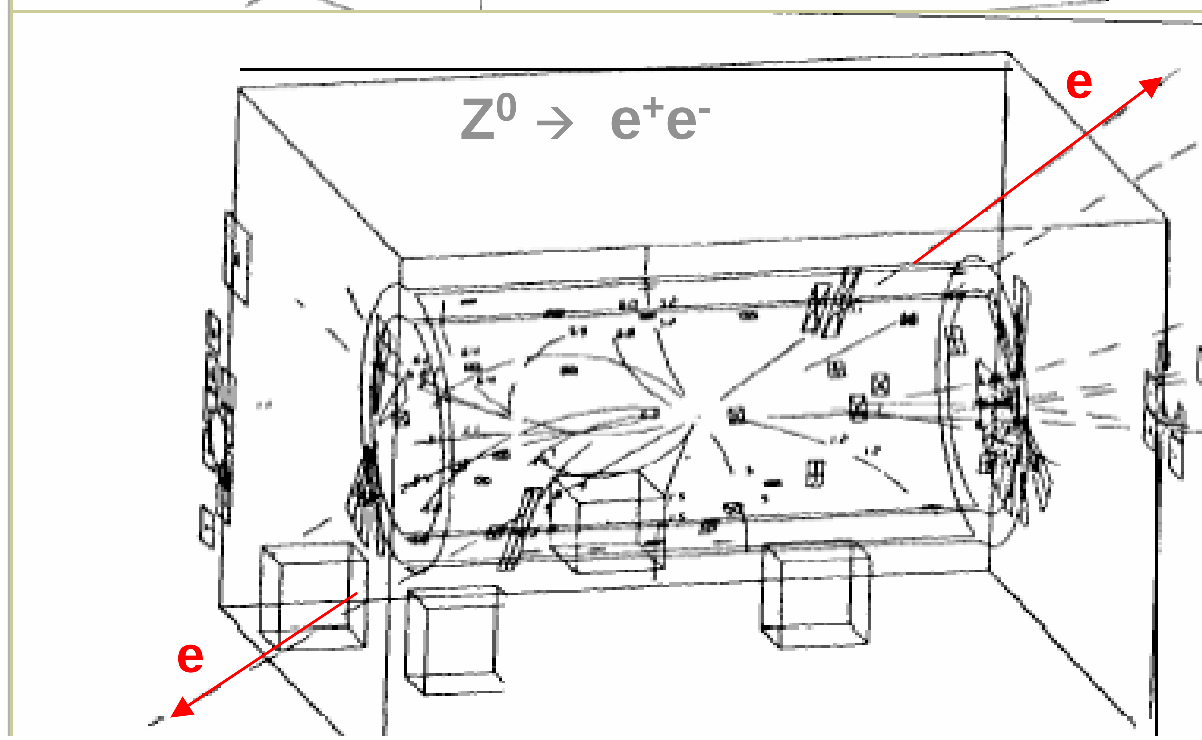


to store sufficient anti-p with small phase space→ stochastic beam cooling

+ development of large volume gaseous detector with FADC read-out

Transparency taken from R. Klanner Uni HH





Detector Requirements for Different Accelerators

Transparency taken from R. Klanner Uni HH

Requirements: (Physics) ⊗ (Parameters of event source [accelerator])

Accelerator	HERA (DESY)	LHC (CERN)	ILC (Linear Collider)
date	1992-2007	2007 - ????	2015 (?) - ????
physics	structure proton, strong+electroweak i.a. beyond standard model	high energy reach Higgs, top, BSM, SUSY strong+electroweak i.a.	precision reach Higgs, top, BSM, SUSY unification of forces
max. E[GeV] particles	27.5 e^+/e^- ⊗ 920 p	7000 p ⊗ 7000 p	500 e^+ ⊗ 500 e^- ($e\gamma$, $\gamma\gamma$)
length	2 x 6.3 km (Ø)	2 x 27 km (Ø)	*O* (2 x 15 km)
currents	110 mA ⊗ 55 mA	540 mA ⊗ 540 mA	10 mA ⊗ 10 mA
bunch crossing	96 ns	25 ns	~ 300 ns
luminosity	5×10^{31} $cm^{-2}s^{-1}$	10^{34} $cm^{-2}s^{-1}$	2-5×10^{34} $cm^{-2}s^{-1}$
event rate	~ 10 kHz	1 GHz	~ 1 kHZ
radiation dose	< 5×10^{12} n(equ.)/cm^2	10^{15} n(equ.)/cm^2	10^{12} n/cm^2(excl.forward)
Δp@100GeV/c	20 %	1.6 %	0.5 %
Δp(μ)@100GeV/c	10 %	1.6 %	0.5 %
ΔE(e)@100GeV	1 – 2 %	0.6 %	1 – 2 %
ΔE(had)@100GeV	4 – 6 %	5 – 10 %	3 %
Δposition@vertex	20 μm	20 μm	5 μm
trigger reduction	10^3	3×10^6	< 100

Criteria for an ideal Detector

Because in general there can be very complex event topologies one often aims at

reconstruction of full event kinematics (background rejection)

Most important:

- high efficiency
- high resolution
- high acceptance → try to cover full solid angle (4π)

also very important (partly conflicting demands):

- particle identification capability
- fast response
- high rate capability
- small dead time
- hermeticity
- longevity of detector components
- high reliability
- good accessibility (for repairs)
- low cost

Important Parameters characterizing Detectors

Transparency taken from R. Klanner Uni HH

A „**perfect** detector“ which cannot be calibrated is “**pefectly** useless”

(detector) ⊗ (readout) ⊗ (calibration) ⊗ (analysis) → all have to be understood !

Generic detector:

radiation/ particle → interaction energy deposit → signal light/charge → collect el.signal charge formation → el.signal processing → data recording → calibration → analysis

Efficiency:

- **acceptance:** (recorded events)/(emitted by source): [geometry x efficiency]
- **efficiency/sensitivity**: (recorded events/particles passing detector)
- **peak efficiency**: (recorded events in acc.window/particles passing detector]

Response (resolution):

(spectrum from mono-) energetic radiation)

response to 661 keV γs

- Ge-detector
- organic scintillator

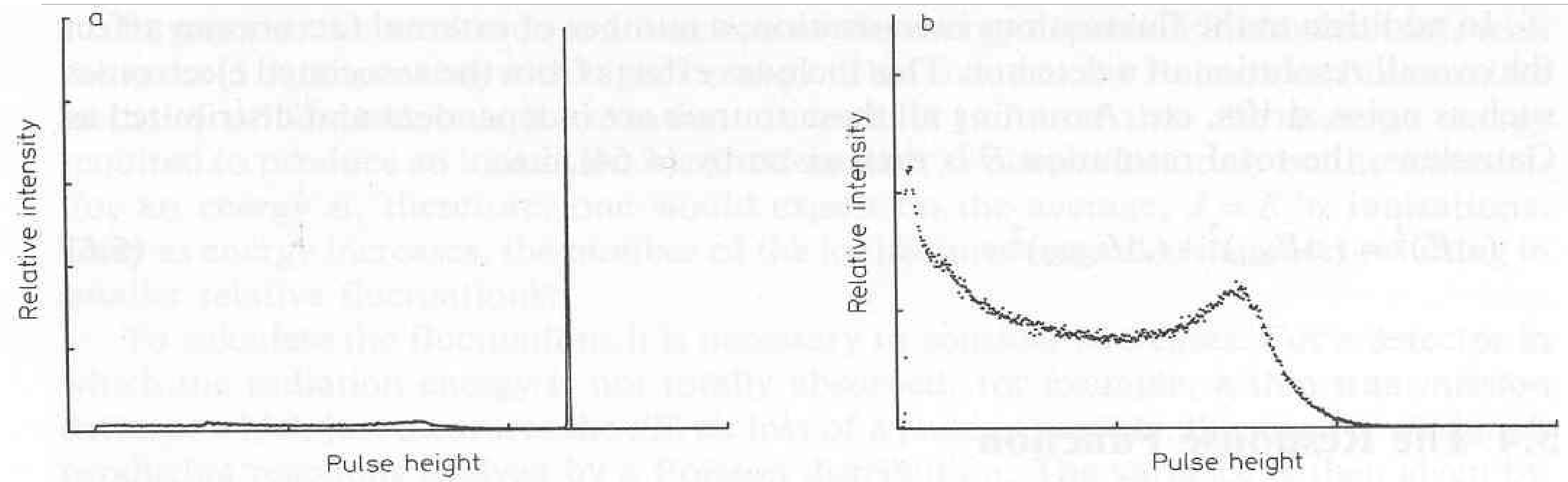


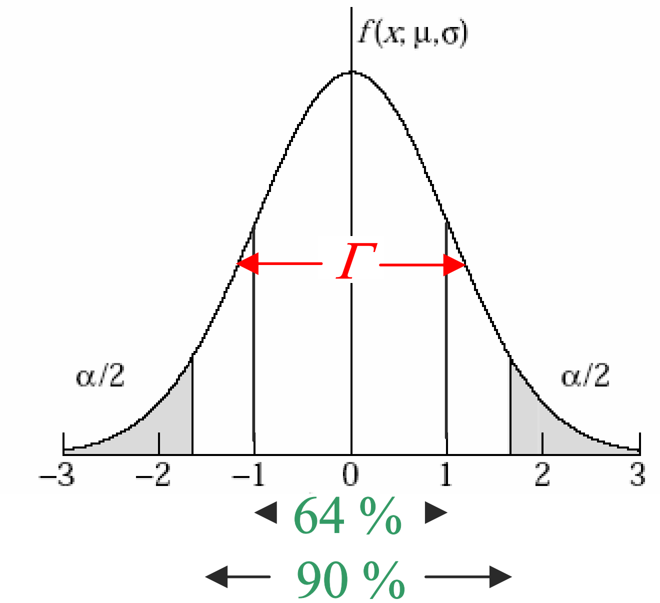
Fig. 5.2a, b. The response functions of two different detectors for 661 keV gamma rays. (**a**) shows the response of a germanium detector which has a large photoelectric cross section relative to the Compton scattering cross section at this energy. A large photopeak with a relatively small continuous Compton distribution is thus observed. (**b**) is the response of an organic scintillator detector. Since this material has a low atomic number Z, Compton scattering is predominant and only this distribution is seen in the response function

Response Function of Detector

- fact that response function is complicated is frequently ignored → wrong results !!

"good detector" aims for Gaussian response (with little non-Gaussian tails)

Calibration by N events with energy E



- mean:

$$< S > = \frac{1}{N}\sum_i^N S_i, \quad \delta < S > = \sigma / \sqrt{N}$$

- rms resolution (σ):

$$\sigma^2 = \frac{1}{N-1}\sum_i^N (S_i - < S >)^2, \quad \delta(\sigma) = \sigma / \sqrt{2N}$$

for Gauss f.: (separate two peaks): $\Gamma = 2\sqrt{2\ln 2}\,\sigma = 2.355\,\sigma$

for box with width a: $\sigma = a / \sqrt{12}$

frequently <S> is not the best choice: e.g. Landau distribution: $\sigma \to \infty$

(median, truncated mean, are sometimes better choices **!**)

Calibration: $< S > = f(E) \cong c \times E + ped$

$$\sigma = g(E), \ \sigma / E \cong c_{calib} + c_{stat} / \sqrt{E} + c_{noise} / E \ (e.g.\ for\ \ energy\ \ measurement)$$

- c, ped … calibration constants depend on position, time (T,p,V,…)
- if c(E) … non-linear response

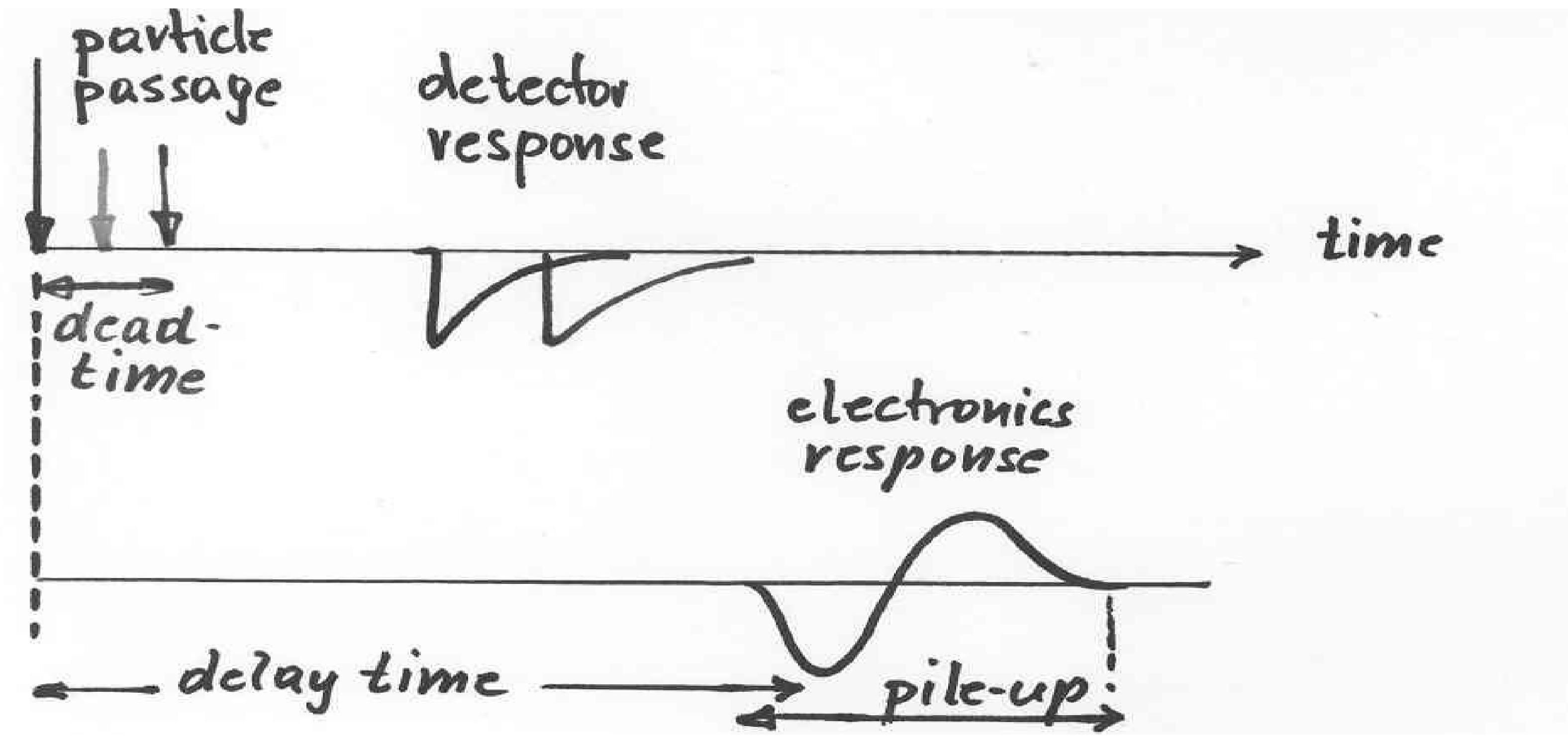
analogous for position-, time-, etc- measurements

Transparency taken from R. Klanner Uni HH

Example Time Response

Transparency taken from R. Klanner Uni HH

- **delay time:** time between particle passage (event) and signal formation
- **dead time:** minimum time distance that events can be recorded separately (depends on properties of detector and electronics ("integrating" or "dead") and on resolution criteria)
- **pile up effects:** overlapping events cause a degradation of performance
- **time resolution:** accuracy with which "event-time" can be measured



Example for counting losses due to dead time:

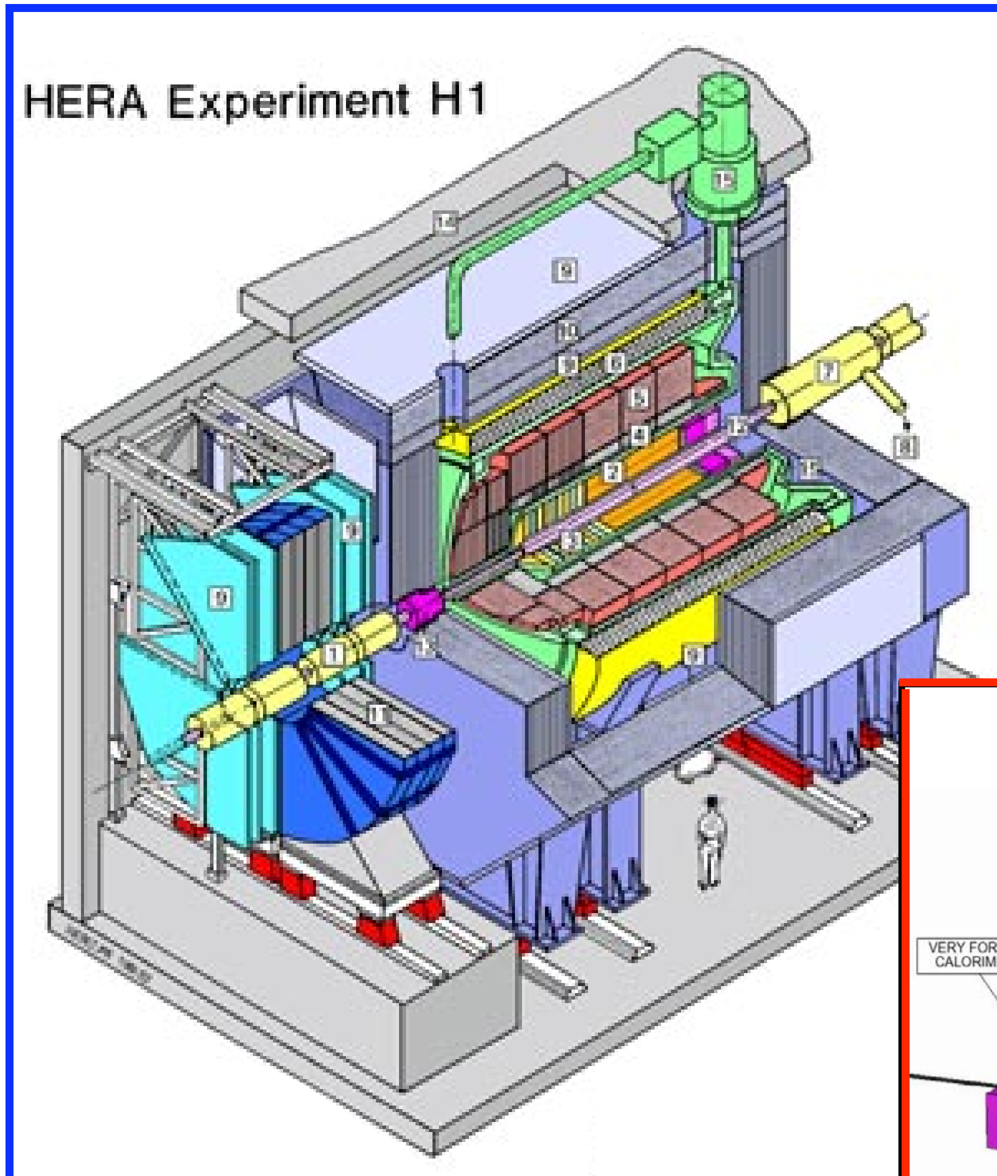
n… true interaction rate
m… recorded count rate
τ … system dead time

$$n = \frac{m}{1 - m \times \tau}$$

$m \times \tau$ is fraction time detector "dead" → rate at which true events lost: $n \times m \times \tau = n - m$

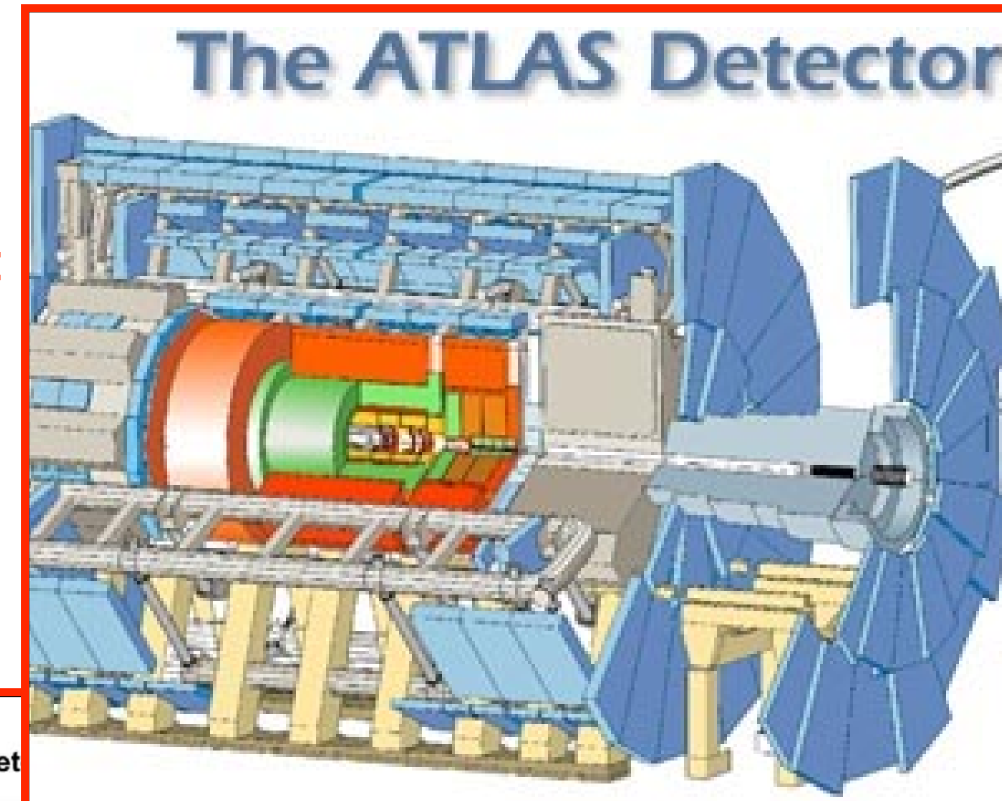
(for pulsed source – no effect if τ < 1/frequency)

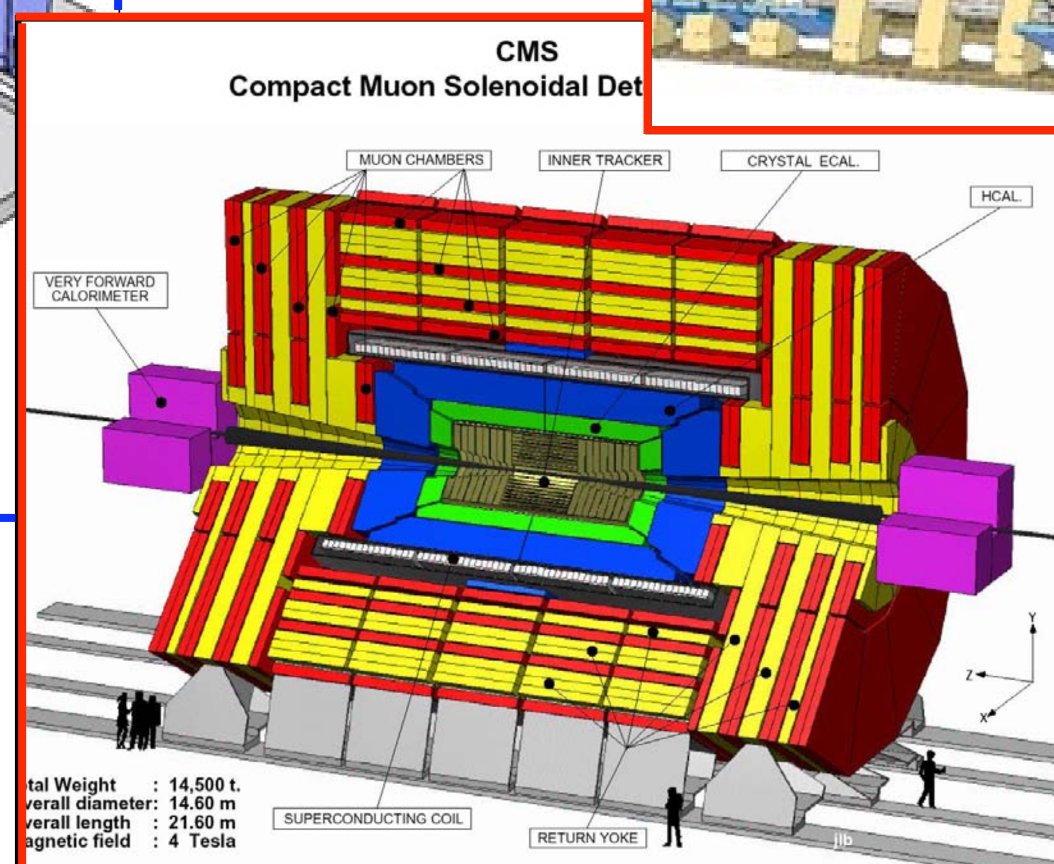
Modern Collider Detectors



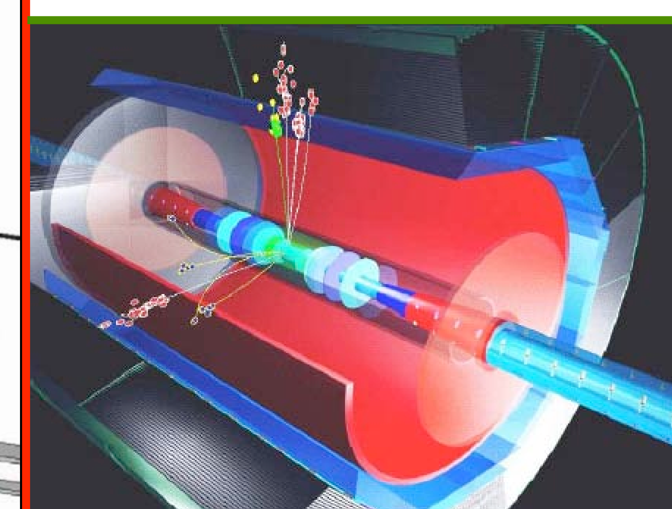
in operation: HERA/Tevatron

under construction:
LHC





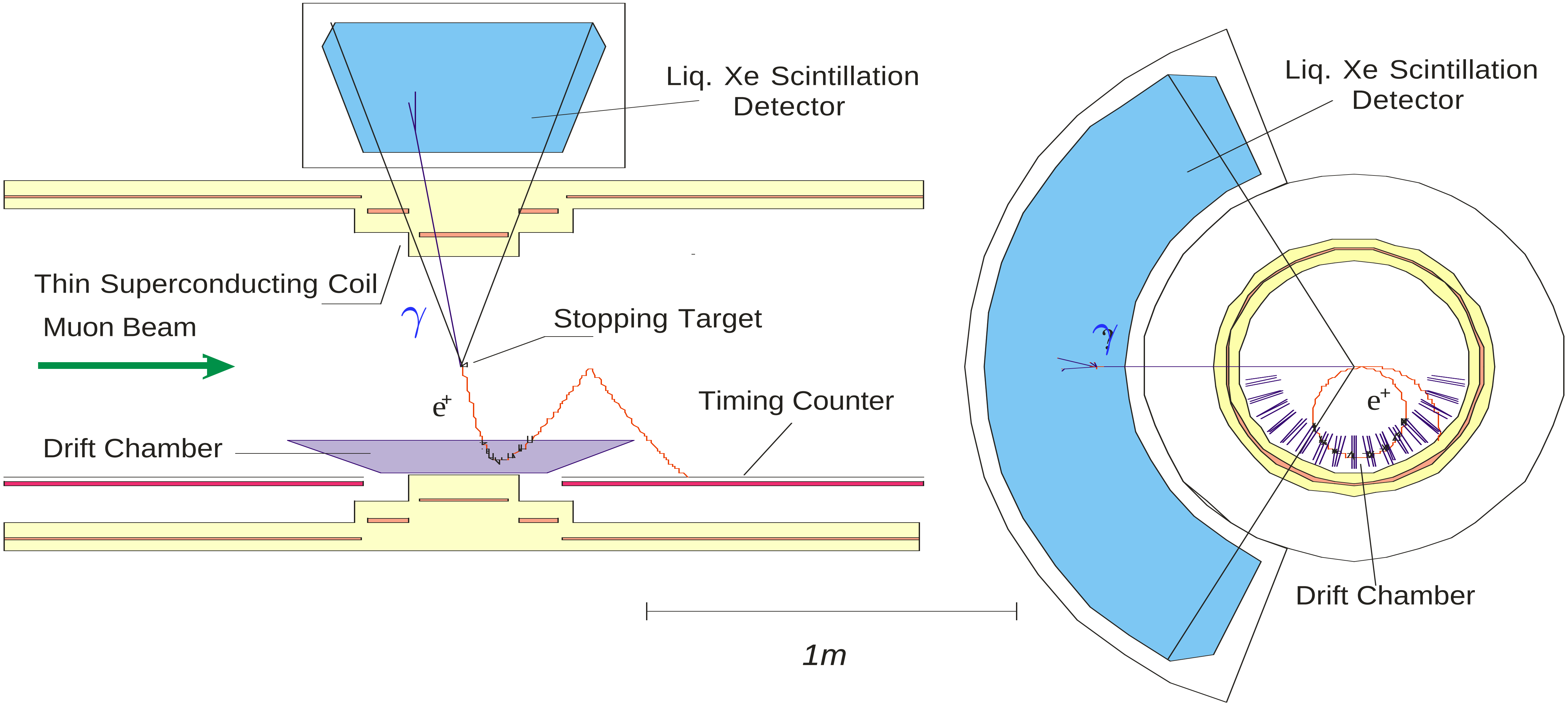
design phase: ILC



Search for Rare/Forbidden Decays

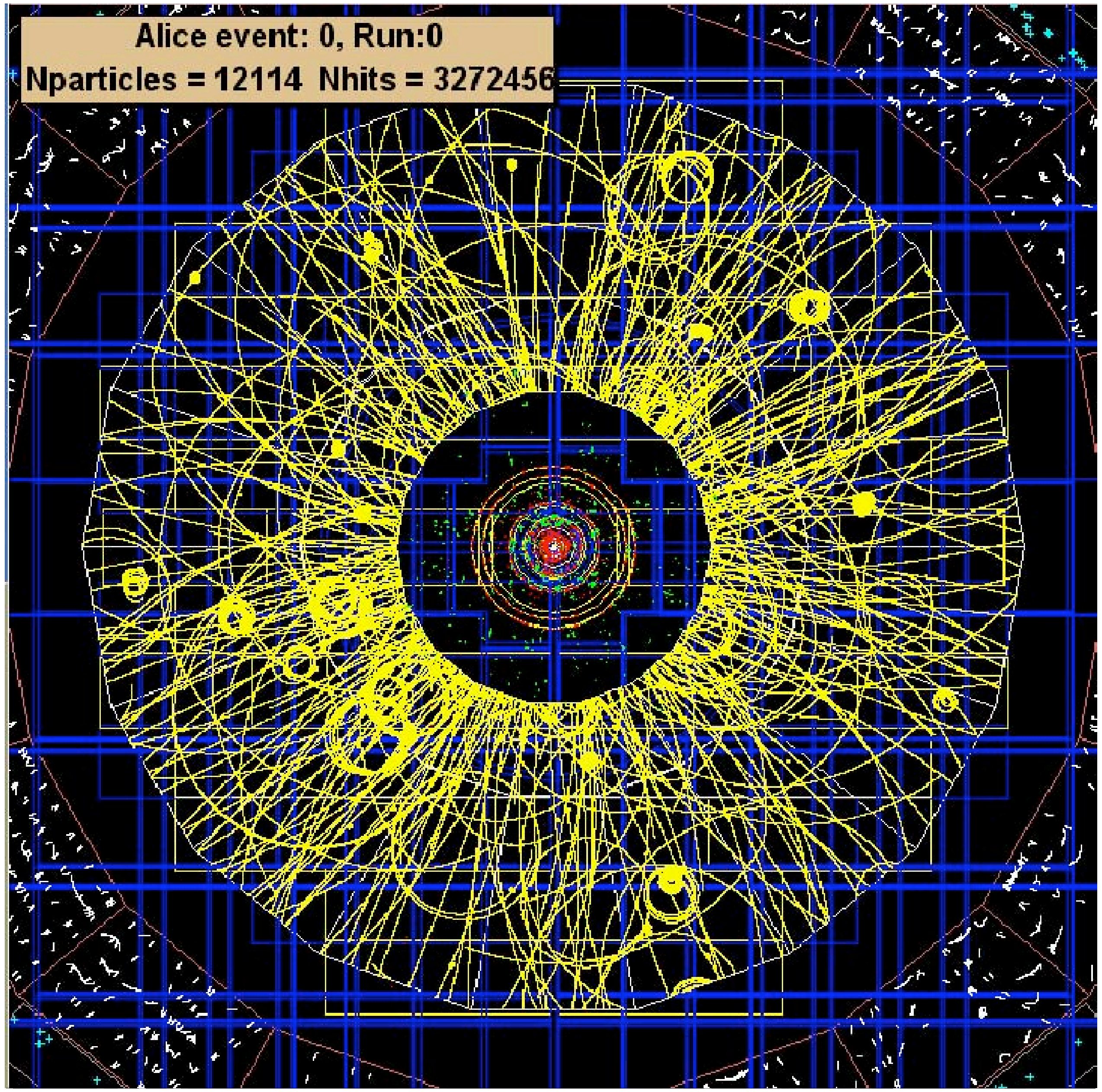
Experiment in preparation at Paul Scherrer Institut (PSI, Switzerland):

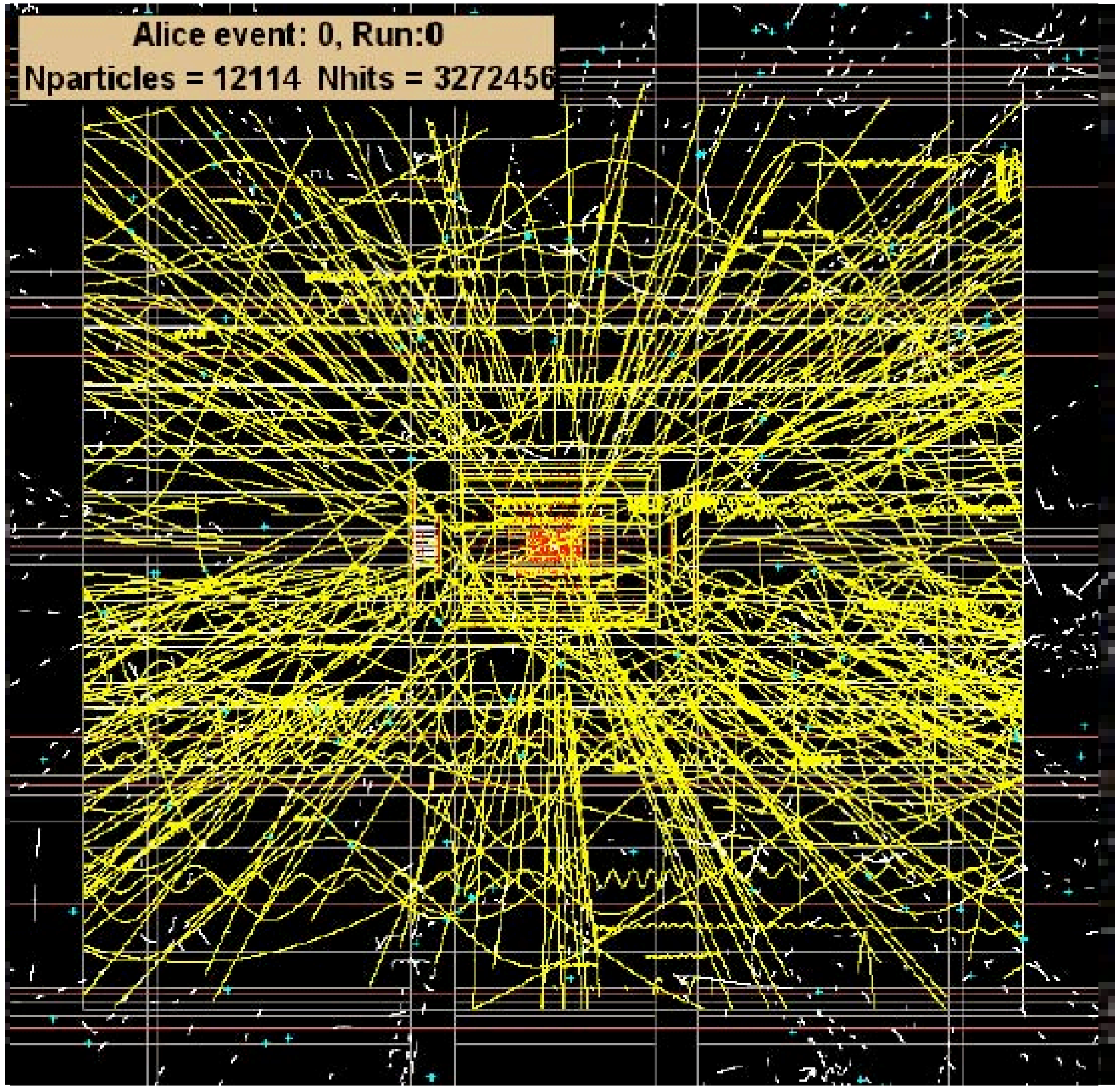
- search for lepton-number violating process: $\mu \rightarrow e\,\gamma$ sensitivity goal: 10^{-13} !
- needs excellent energy resolution, high event rate, but small track multiplicity per event
- start full data taking in 2007



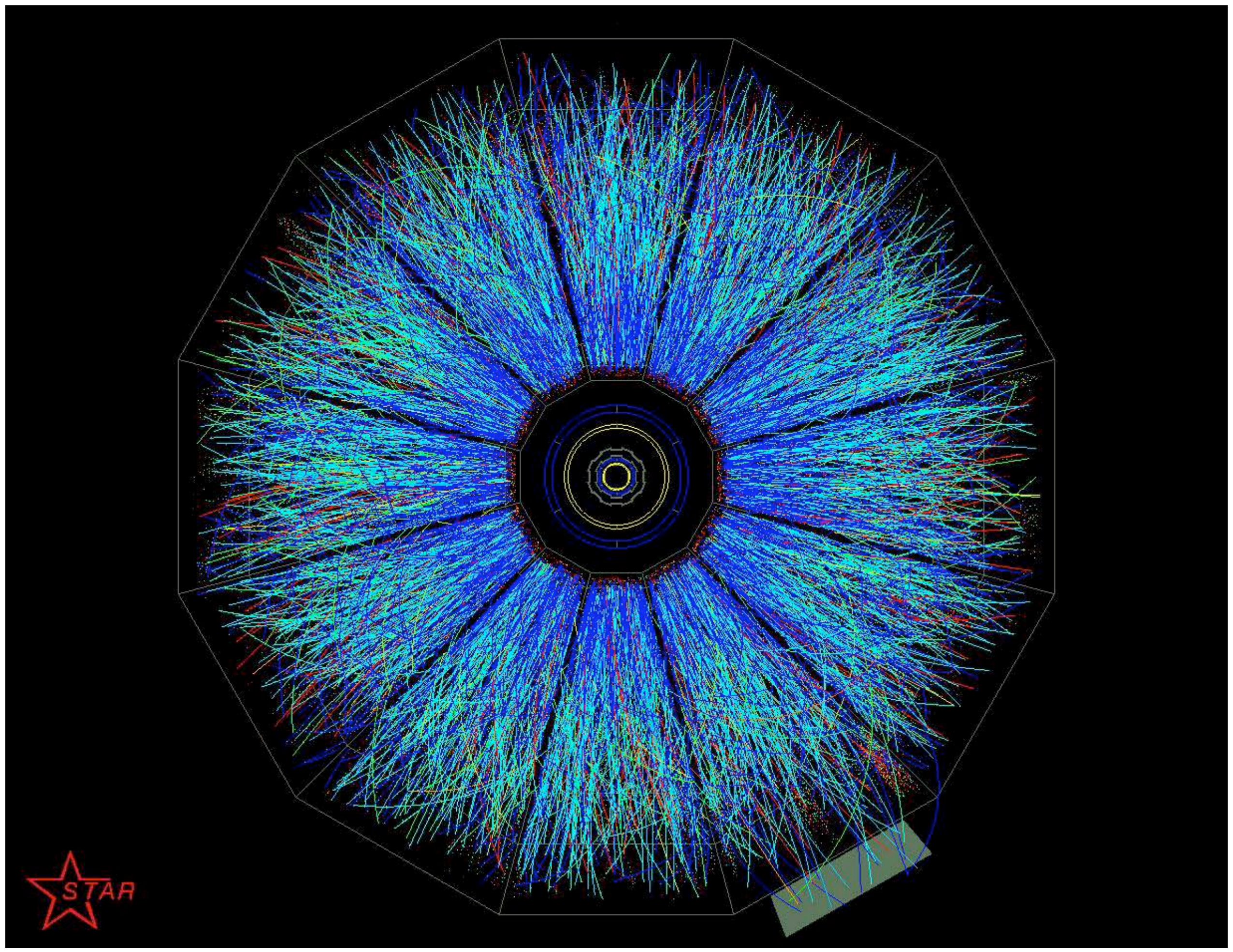
ALICE @ LHC

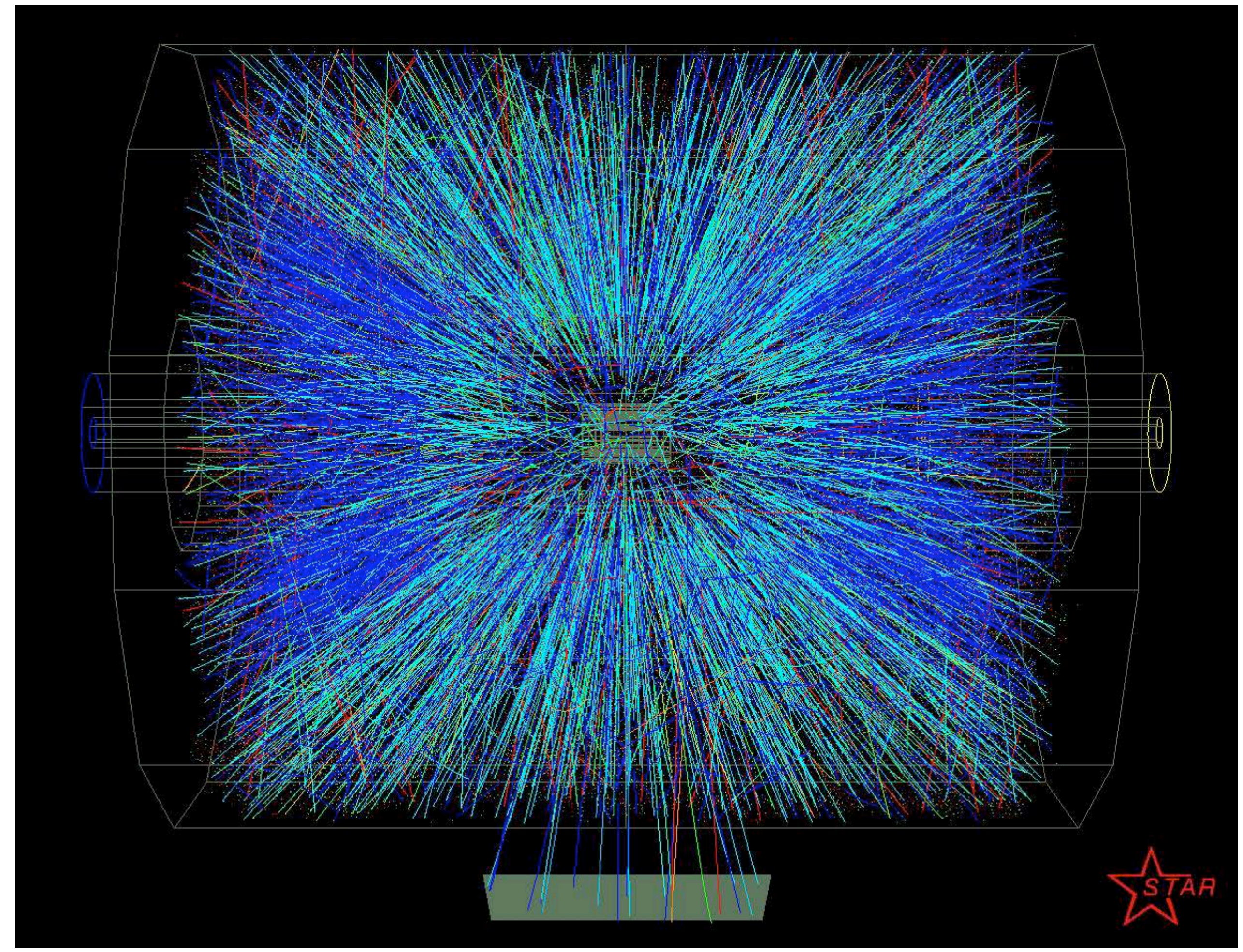
Heavy Ion Physics: this simulation shows 1/10 of all 10000-20000 expected tracks in a typical event. The separation of all these tracks puts very high demands on the position resolution and double hit seperation of the device.





Real Event in STAR at RHIC





≈ 2000 tracks per event

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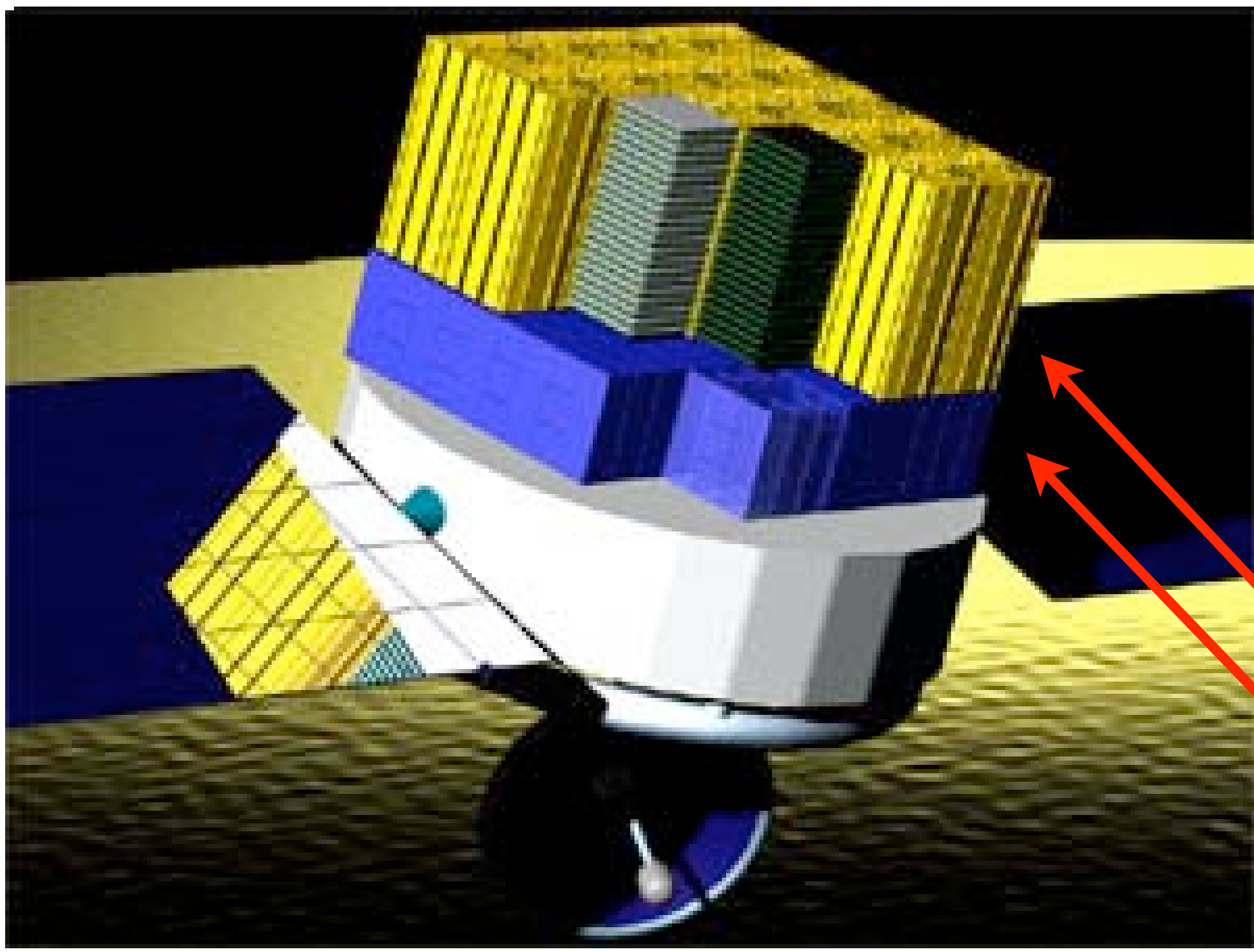
Satellite based Detectors

GLAST *The Gamma Ray Large Area Space Telescope*

Liftoff scheduled for August 2007



GLAST Gamma-Ray observatory for high energy photons in the range 20MeV to >300 GeV

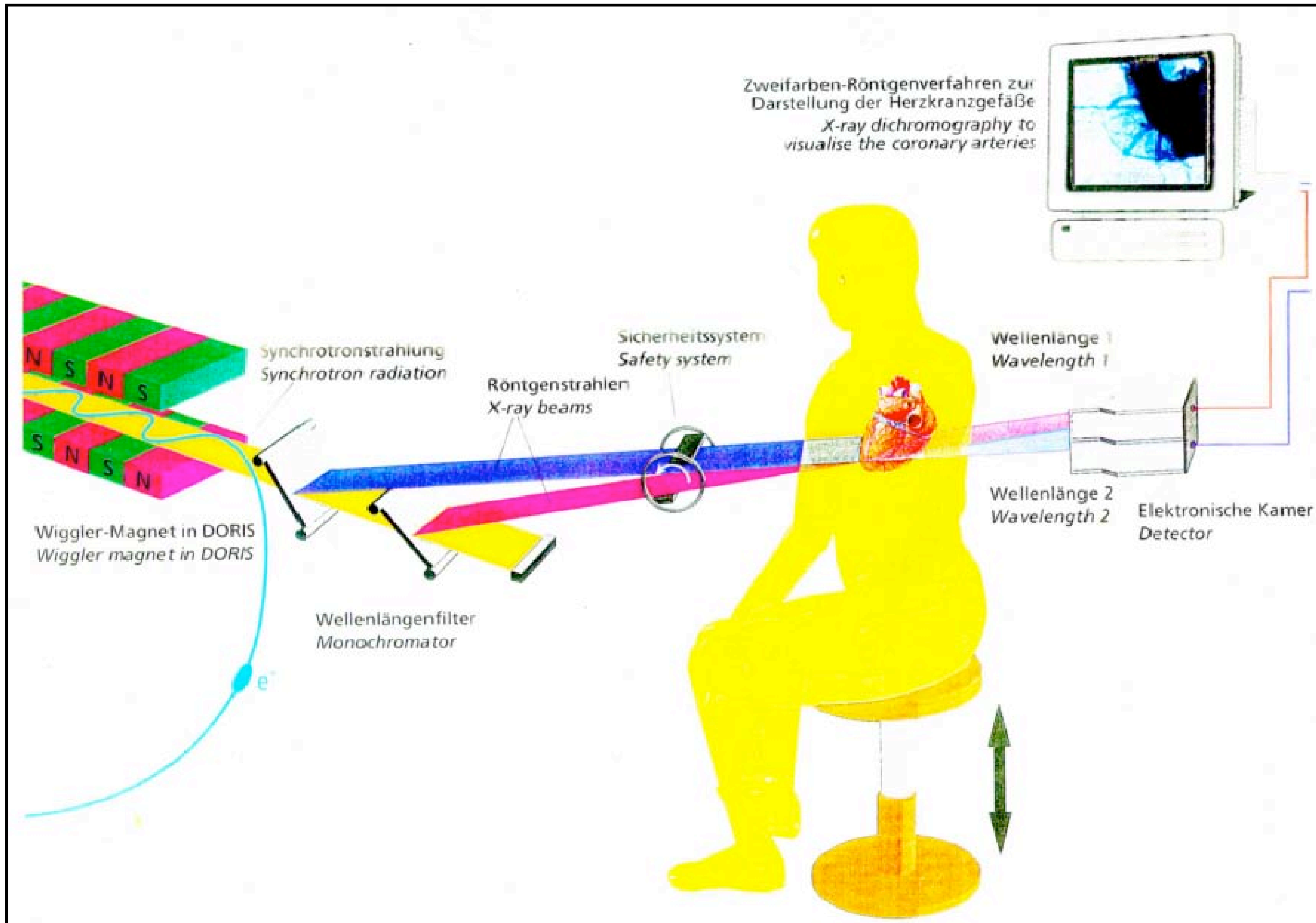
Astro particle physics

- history of star formation
- acceleration mechanism of AGN's
- sources of gamma ray bursts
- nature of dark matter

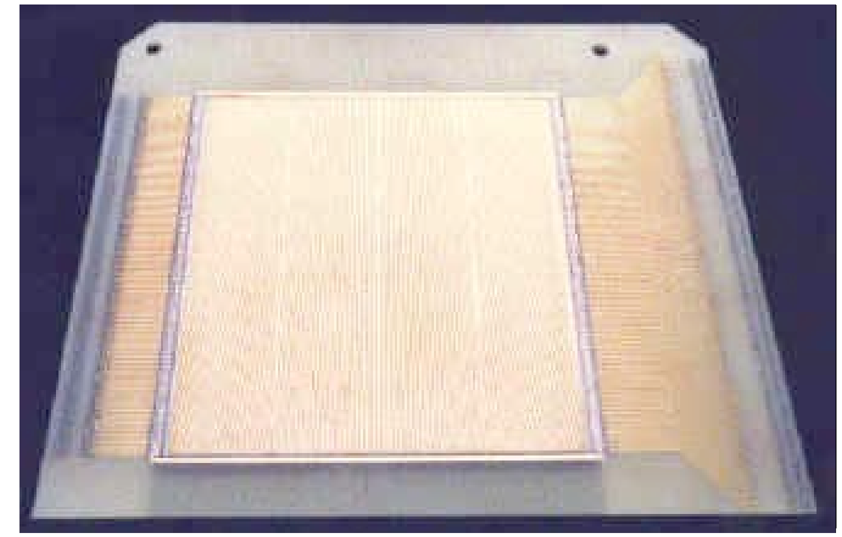
Components (need highest reliability !)

- precision tracker (Si-strips)
- calorimeter (CsI(Tl))
- data acquisition system
- anticoincidence detector

Applications in Medicine

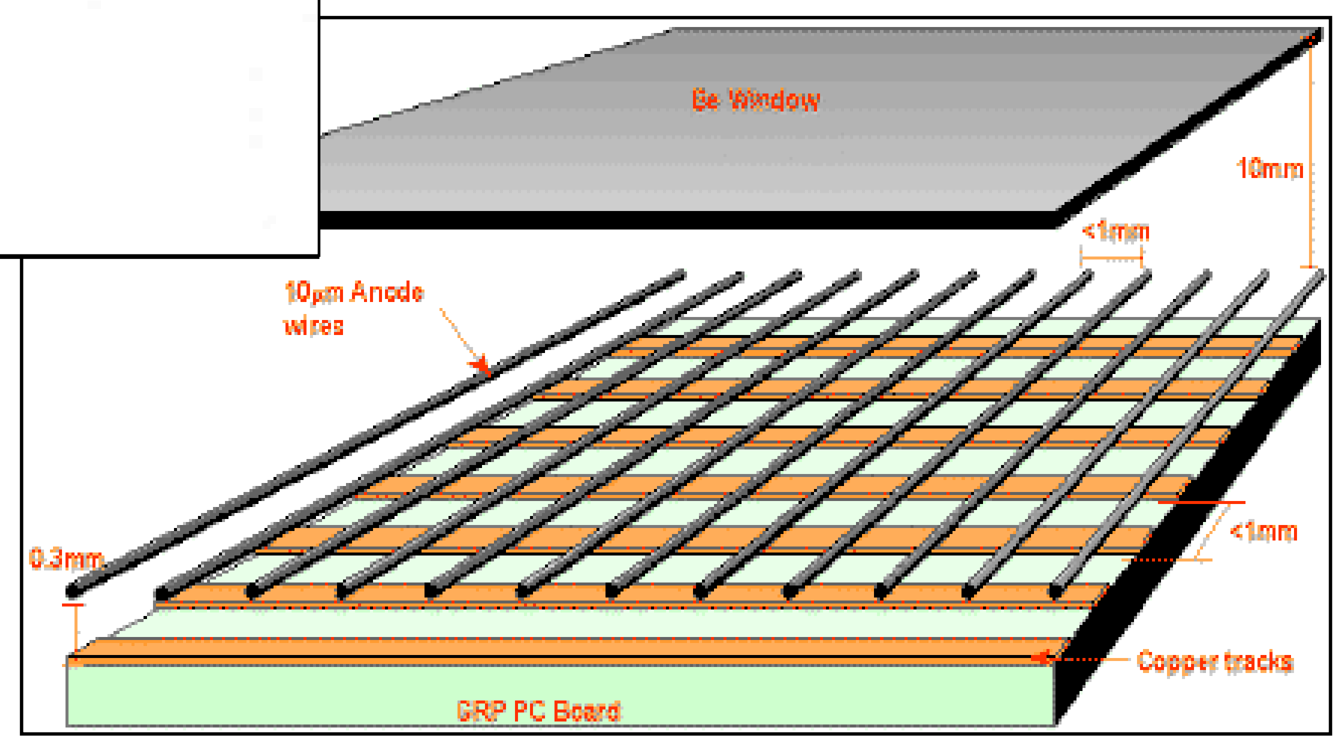


Non-invasive Koronary Angiography using synchrotron radiation



Imaging microgap detector:

Photon rates ≈ 10^6 mm^{-2} s^{-1}



Interplay between Physics and Technology

Almost all effects used in particle detectors are based on the electromagnetic interaction only. Most modern detectors convert the absorbed energy into an electrical signal.

The detection sensitivity and detector performance depends on

- statistical processes in the detector
- fluctuations in the electronics

To maximize detection sensitivity and resolution one must consider and optimize

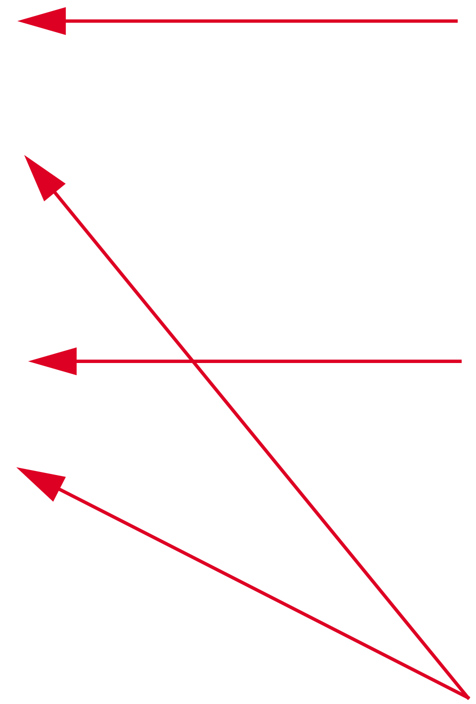
- signal formation in the detector
- coupling of the detector to the readout electronics
- noise generated in the electronics

Understanding of e.g. a modern tracking detector in high-energy physics or a medical imaging system thus requires knowledge of

- solid state physics
- semiconductor device physics
- semiconductor fabrication technology
- low-noise electronics techniques
- analog and digital microelectronics
- high-speed data transmission
- computer-based data acquisition systems

Interaction of Radiation with Matter

Charged Particles	Neutral Particles
heavy charged particles	neutrons
electrons	gamma radiation
	neutrinos



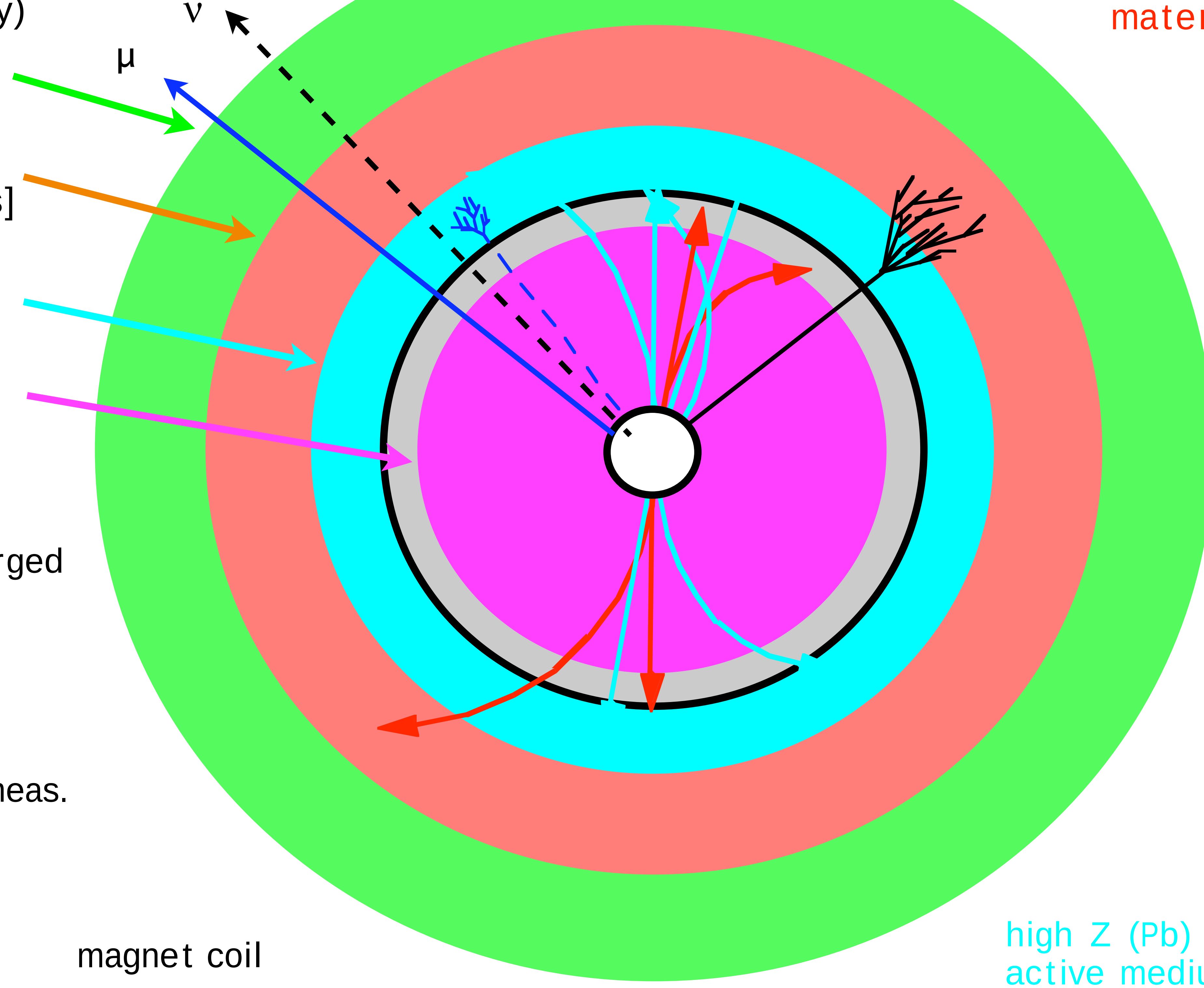
Coulomb-Interaction with electrons of medium
→ electrical signal in detector

Mainly "singular" interactions, resulting in energy transfer to charged particles

Cross Section of a typical Collider Detector

Particle type:

- neutrinos (missing energy)
- muons μ
- hadrons: p, π, K ...
  [quarks, gluons $\rightarrow$ jets]
- electrons, photons
- charged particles



- Track detectors for charged particles
  - gas detectors
  - solid state detectors
- Calorimeter for energy meas. (neutral & charged)
  - electromagnetic
  - hadronic

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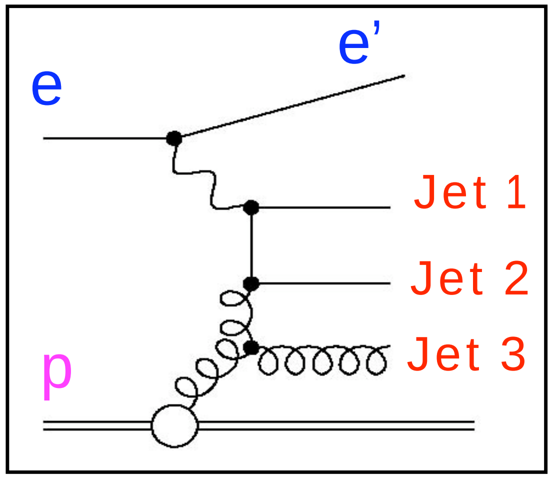
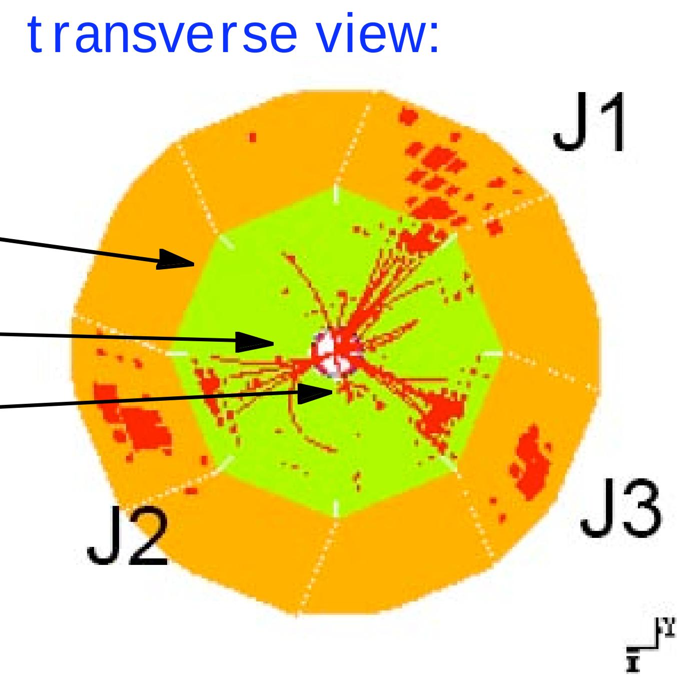
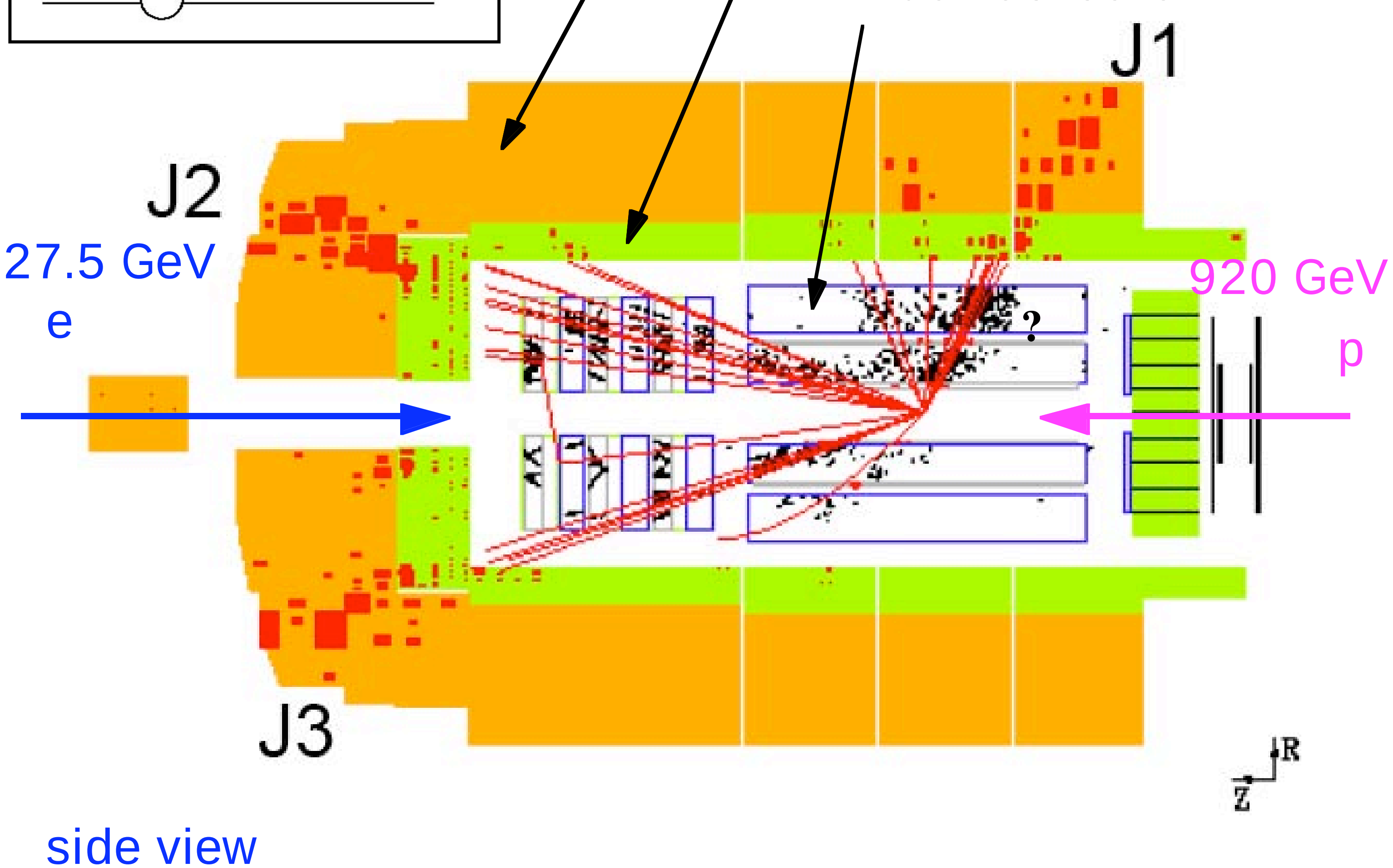
Example 1: HERA ep Event with 3 Jets







almost hermetic detector

⇒ detection of nearly all produced particles

exploit energy- and momentum conservation

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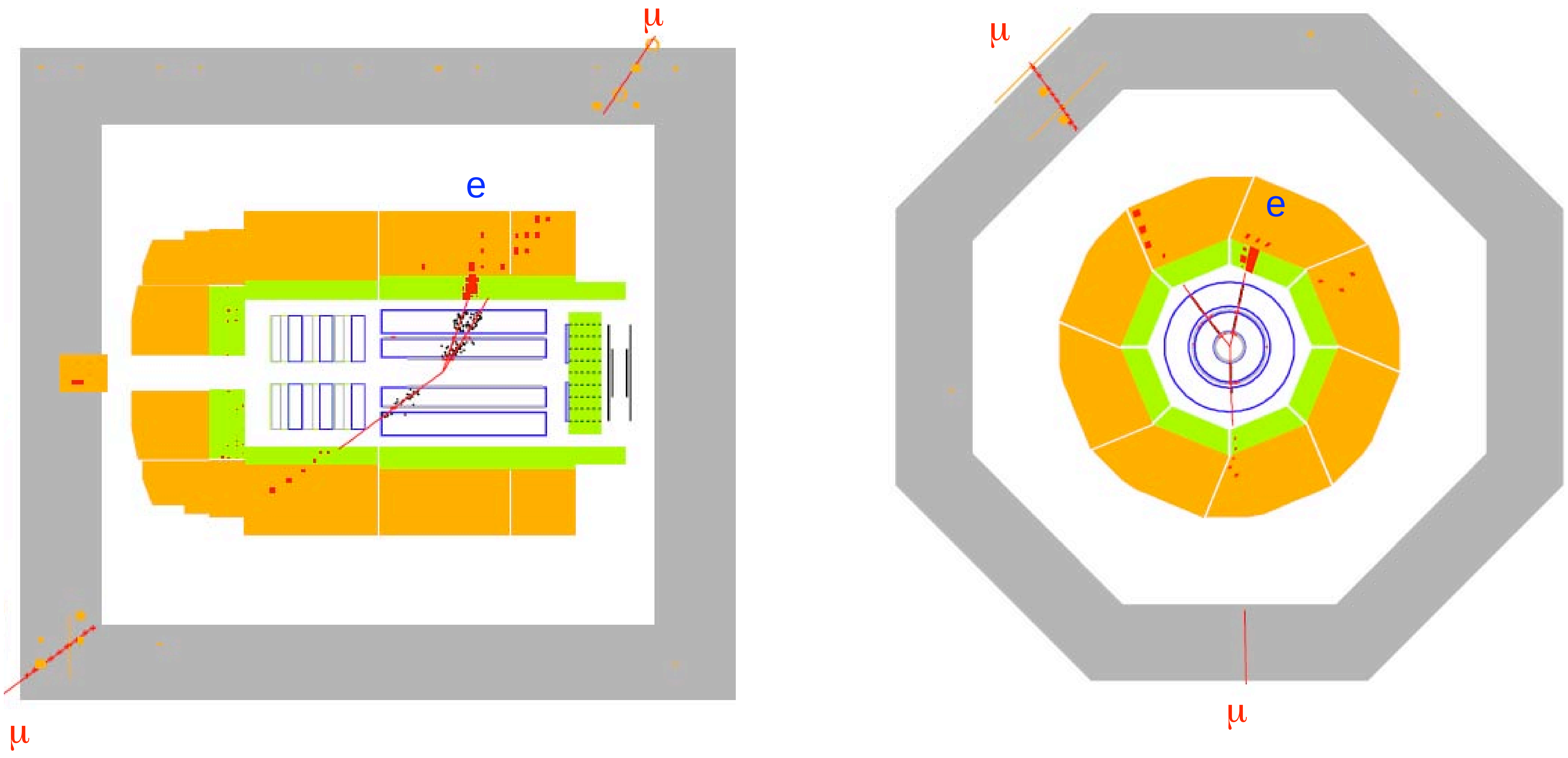
Example 2: Muon Detection

Because muons do not interact strongly and because of their large mass (compared to electrons) they don't shower so easily and thus can penetrate calorimeter and iron yoke



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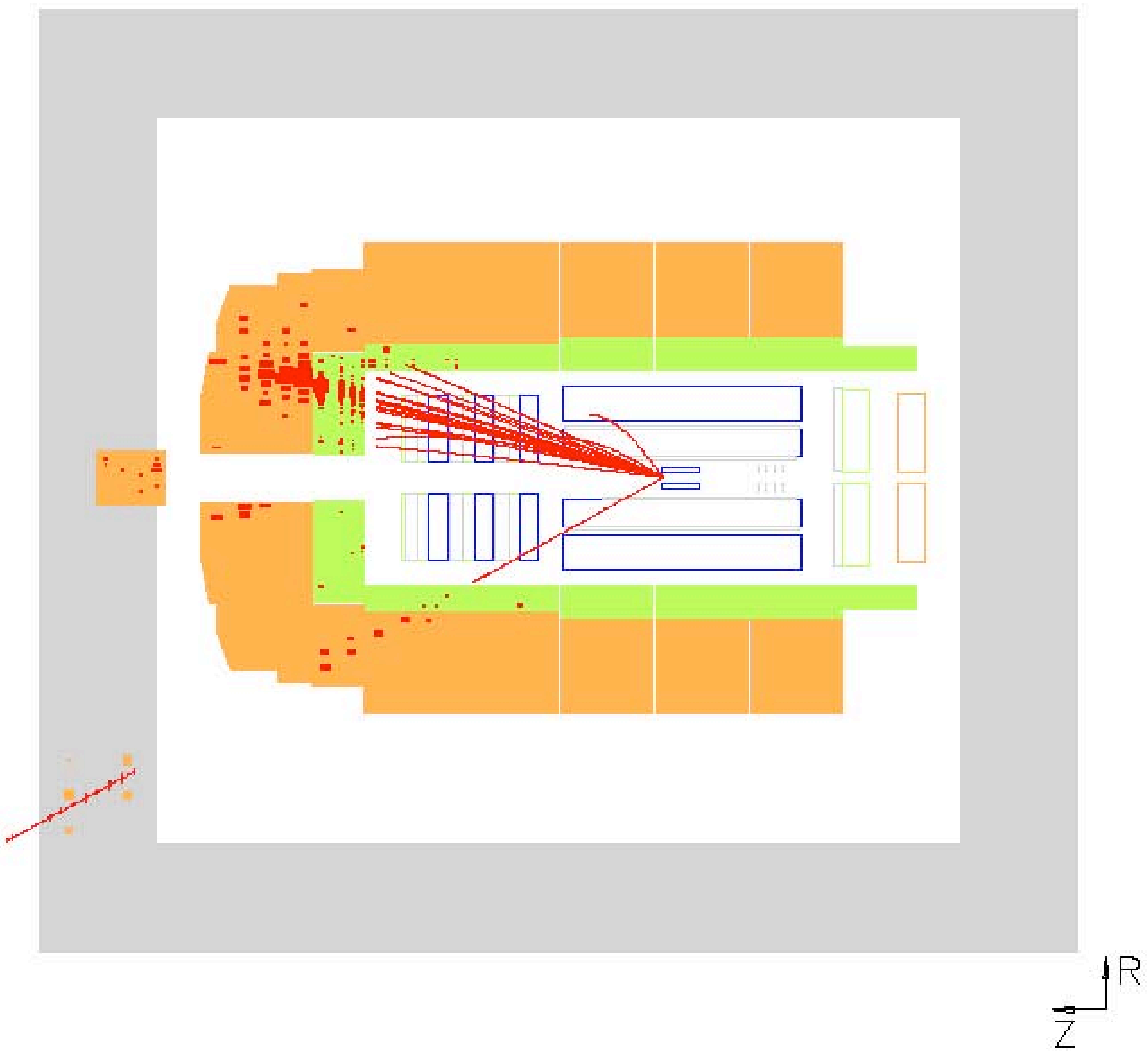
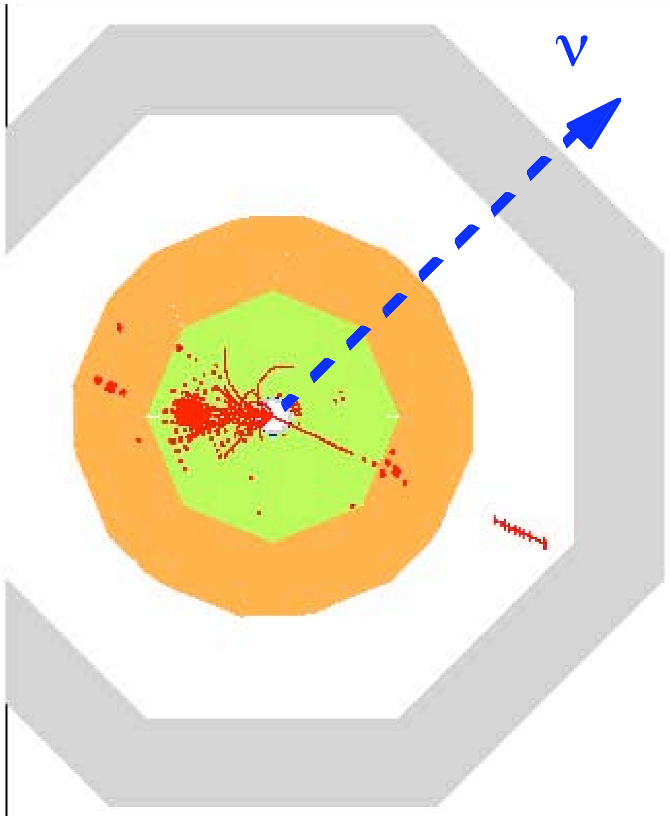
Example 3: Neutrinos

Event MUON-2

$$P_T^{\mu} = 28\,\mathrm{GeV}, P_T^{X} = 67\,\mathrm{GeV}, P_T^{miss} = 43\,\mathrm{GeV}$$



H1

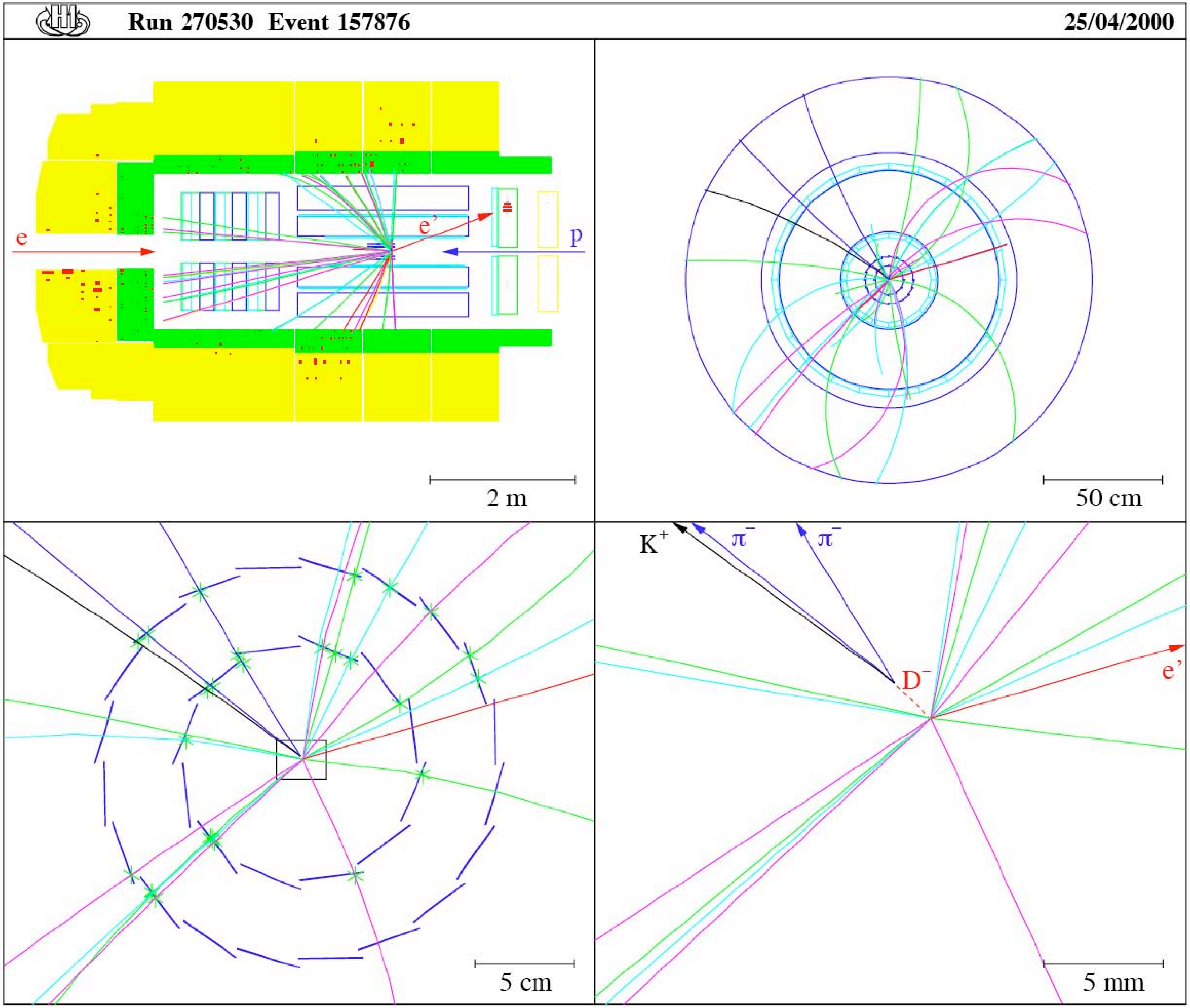


Missing transverse energy and transverse momentum:

$$\sum_i \vec{p}_{trans} = 43\mathrm{GeV}$$

carried away by neutrino ?

Example 4: Secondary Vertices



Some mesons containing heavy quarks (charm or beauty) only decay via the weak interaction.

example: $D^- \to K^+ \pi^- \pi^-$

Resulting lifetimes are relatively long:

$\tau \approx O(10^{-12}s)$ or

$c\tau \approx 100 - 500\ \mu m$

With the help of high precision track detectors one can distinguish if particles originate from secondary or primary vertex:

⇒ vertex detectors
[in most cases based on silicon]

Interaction of Charged Particles

There are two principal effects which characterize the passage of charged particles through matter:

- energy loss
- change of direction

both effects result from the following electromagnetic processes:

- inelastic collisions with shell electrons of medium
- elastic scattering off nuclei

relevant is the statistical sum of many such interactions.

In addition there are the following processes:

- bremsstrahlung
- emission of Cherenkov radiation
- nuclear reactions
- emission of transition radiation

which however in general occur much less frequent than atomic collisions.

For charged particles one must distinguish light particles (i.e. e^+, e^-) and heavy particles (i.e. all the rest: μ, π ,p , α , light nuclei, ...)

Energy Loss of Charged Particles in Matter

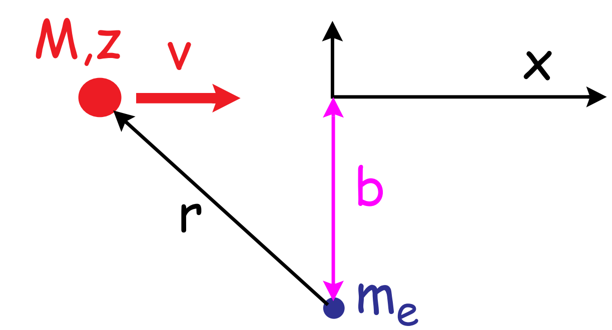
Several important physicists have contributed to the theoretical understanding of energy loss of charged particles in matter

- N. Bohr — classical derivation of $\langle \frac{dE}{dx} \rangle$
- Bethe & Bloch — quantum mechanical treatment of $\langle \frac{dE}{dx} \rangle$
- L. Landau — distribution function
- E. Fermi — density correction

- and several other physicists

Energy Loss of Heavy Charged Particles

The exact derivation is quite involved.* Here only the classical derivation, which was first performed by Bohr is given:



Energy loss mainly occurs through inelastic collisions with the shell electrons of the medium. Assuming (1) $M \gg m_e$ and (2) that the electrons before the collision are at rest => classically the change of momentum is given by:

$$\Delta p = \int_{-\infty}^{+\infty} F_{\mathrm{Coulomb}}\, dt$$

Since for symmetry reasons the longitudinal component averages to 0, only the transverse component is relevant:

$$F_{\perp} = F_{\mathrm{Coulomb}} \cdot \frac{b}{|\vec{r}|} = F_{\mathrm{Coulomb}} \cdot \frac{b}{\sqrt{x^2+b^2}}$$

with impact parameter b. Integration yields:

$$\Delta p(b) = \int_{-\infty}^{+\infty} F_{\perp}\, \frac{dx}{v} = \int_{-\infty}^{+\infty} \frac{ze^2 \cdot b}{(x^2+b^2)^{3/2}}\, \frac{dx}{v} = \frac{2ze^2}{vb}$$

and therefore

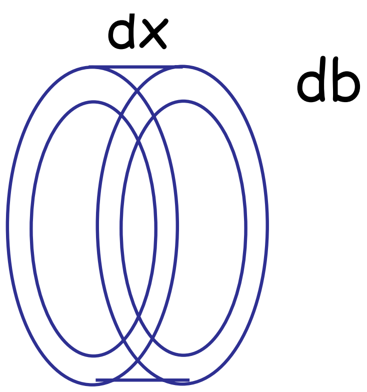
$$\Delta E(b) = \frac{\Delta p^2}{2m_e} = \frac{2z^2e^4}{m_e v^2 b^2}$$

with velocity v and charge z of the moving particle

* J. D. Jackson, Klassische Elektrodynamik, (Walter de Gruyter, Berlin, 1993) Kapitel 13.

Bohr's Classical Formula

The energy transfer to shell electrons in the ring b to b+db in a layer of thickness dx is given by (with N_e = density of electrons) :



$$-dE(b) = \Delta E(b) \cdot N_e \cdot dV = \frac{4\pi z^2 e^4}{m_e v^2} N_e \frac{db}{b} dx$$

Integration over valid range of impact parameters b_{min} to b_{max} yields:

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} N_e \ln \frac{b_{max}}{b_{min}}$$

The valid limits of integration follow from the maximum momentum transfer $\Delta p = 2m_e v$ (-> b_{min}) and the minimum energy transfer $\Delta E_{min} = I$, which must at least correspond to the excitation energy I (-> b_{max}):

$$b_{min} = \frac{ze^2}{m_e v^2} \;\; ; \;\; b_{max} = \frac{ze^2}{v}\sqrt{\frac{2}{m_e I}} \;\; \Rightarrow$$

This yields for the classical case of inelastic collisions:

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} \frac{Z}{A} N_A \cdot \frac{1}{2} \ln \frac{2m_e v^2}{I}$$

Bethe-Bloch Formula

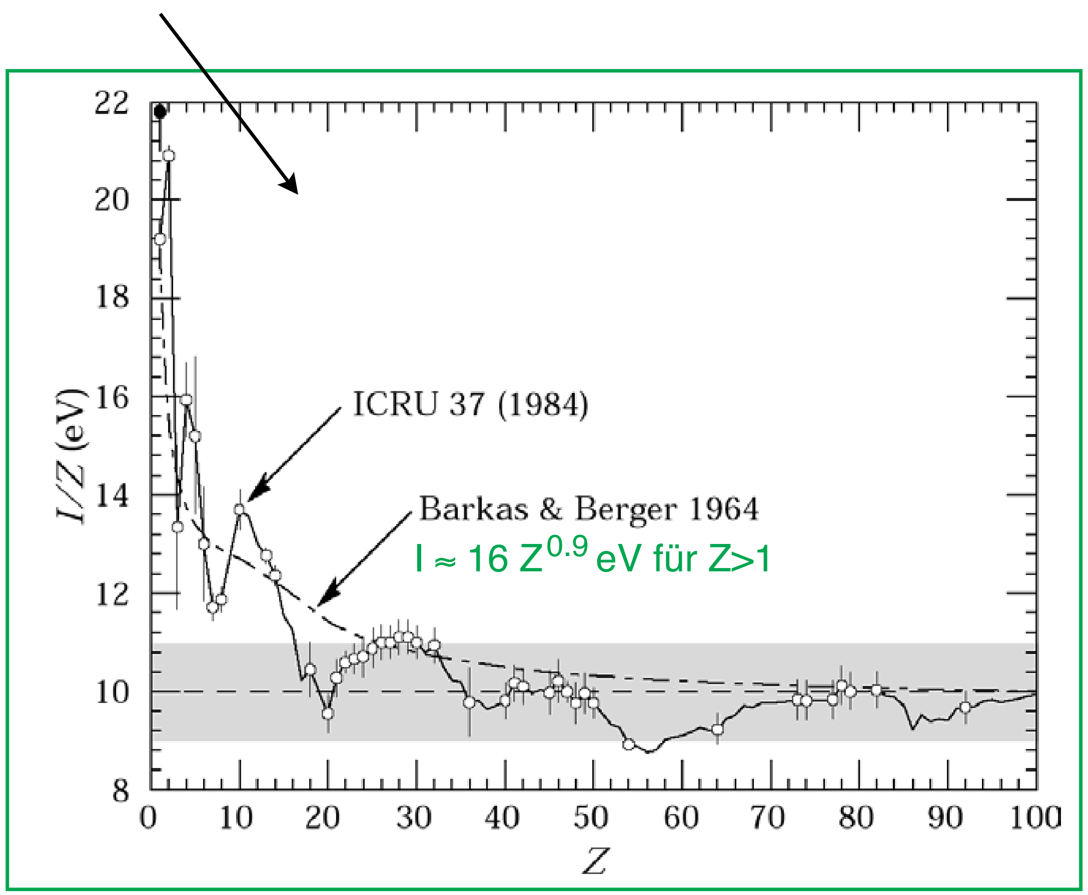
The correct quantum mechanical result is:

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \cdot \frac{1}{\beta^2} \cdot \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right] \quad \left[\frac{\text{MeV}}{(\text{g/cm}^2)} \right]$$

where $T_{max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$ is the maximum kinetic energy, which can be transfered to the electron in a single collision, N_A is the Avagadro number, r_e the classical electron radius and I the excitation energy in [eV].

Meaning of additional terms:

- δ density term due to polarization: important at high energies (leading to saturation of the relativistic raise)
- C/Z shell correction only relevant at low energies (when v ≈ velocity of electrons in the orbit –> capture processes are important)



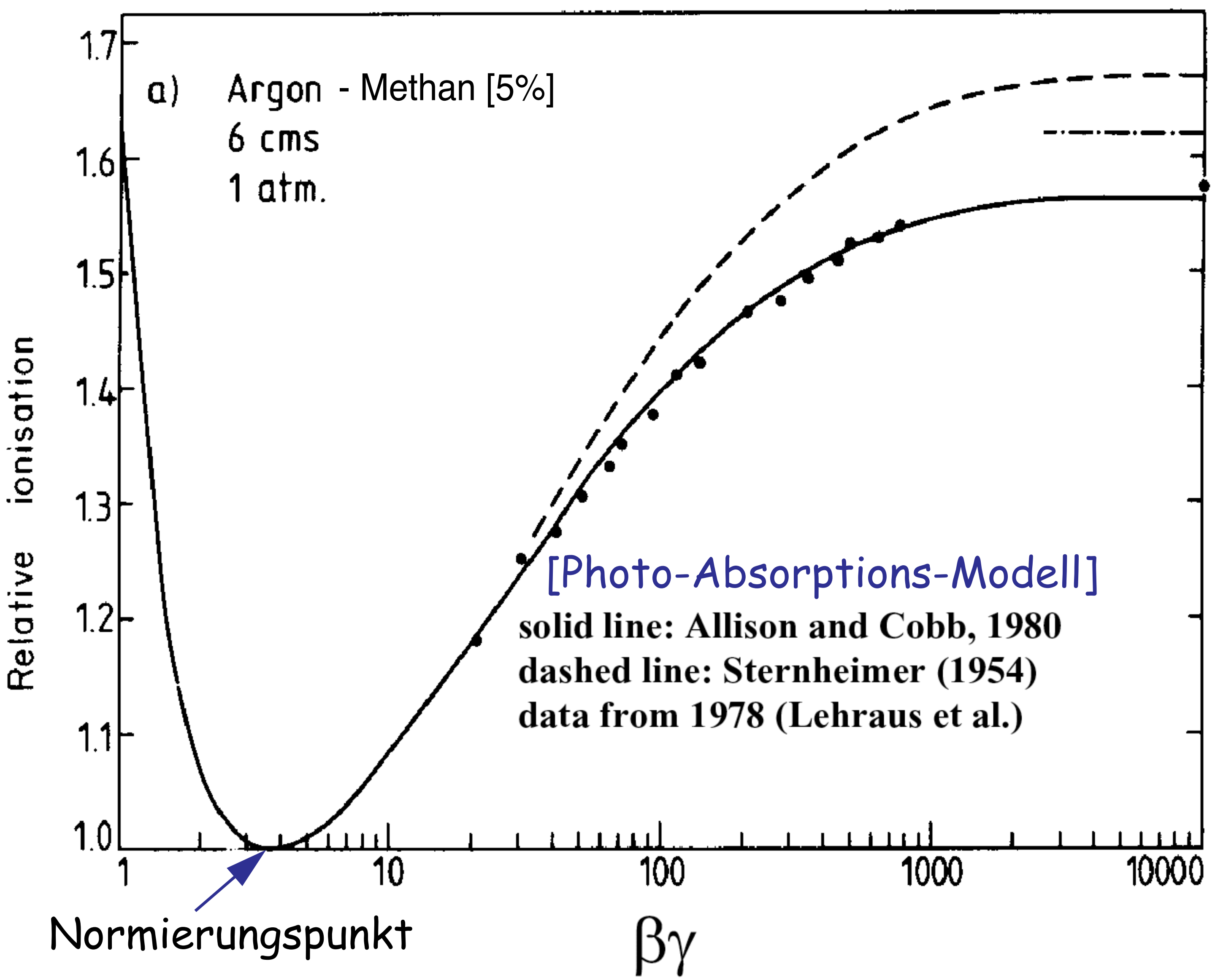
Range of validity of the Bethe-Bloch formula:

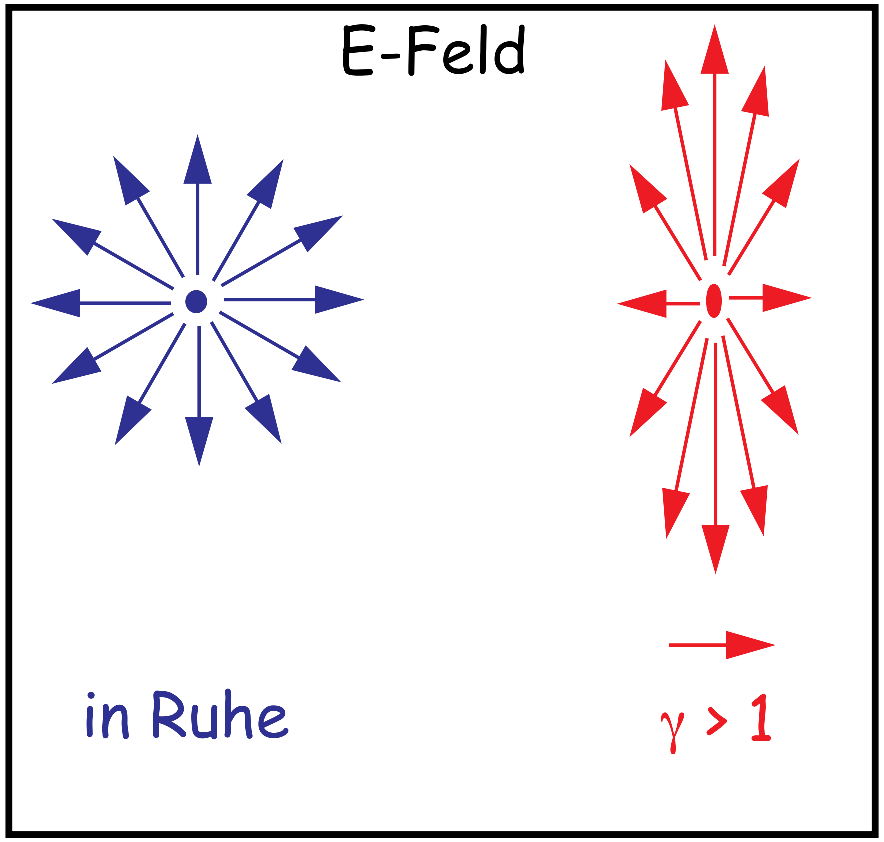
$$10\ \text{MeV/c} \leq p \leq 50\ \text{GeV/c}$$

For higher energies radiative processes dominant.

Relativistic Raise: Calculations and Measurements

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \cdot \frac{1}{\beta^2} \cdot \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right] \quad \left[\frac{\text{MeV}}{(\text{g/cm}^2)} \right]$$





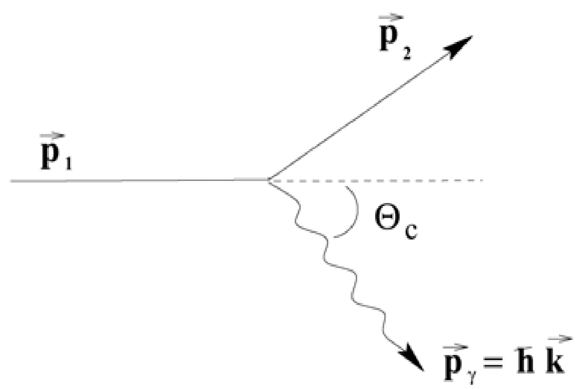
Classical explanation:

- transverse component of electric field of moving particle growths with factor γ
- saturation of dE/dx, once the extension of field comparable to distance between atoms

Fermi's Density Correction

This parameter takes into account, that the shell electrons of the atoms of the medium shield the transversely extended field of the relativistic particle. This leads to a reduction of the effective reach-through and therefore of the energy loss.

Physically the effect is related to the fact that the electromagnetic wave gets damped in the transverse direction by the dispersion in the medium (also related to Cherenkov effect).



$$p_1 - p_\gamma = p_2 \;\Rightarrow\; p_1^2 + p_\gamma^2 - 2p_1 p_\gamma = p_2^2 \;\Rightarrow\; p_1 \cdot p_\gamma = 0 \;\Rightarrow$$

$$\gamma M c^2 \hbar\omega = \gamma M \cdot \vec{v} \cdot \hbar\vec{k} \cdot c^2$$

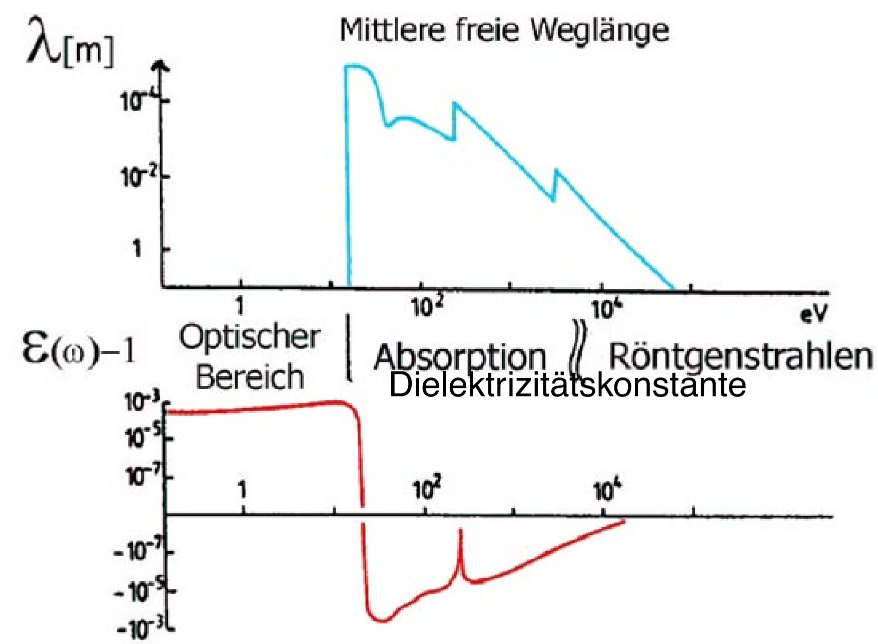
$$\boxed{\omega = \vec{v} \cdot \vec{k}} \qquad \sqrt{\varepsilon}\,\frac{v}{c}\cos\theta_C = 1$$

- density effect ⇒ Fermi plateau
- especially relevant in dense absorbers, e.g. iron or lead
- can be practically neglected for gases at 1 atm
- approximation for energetic particles

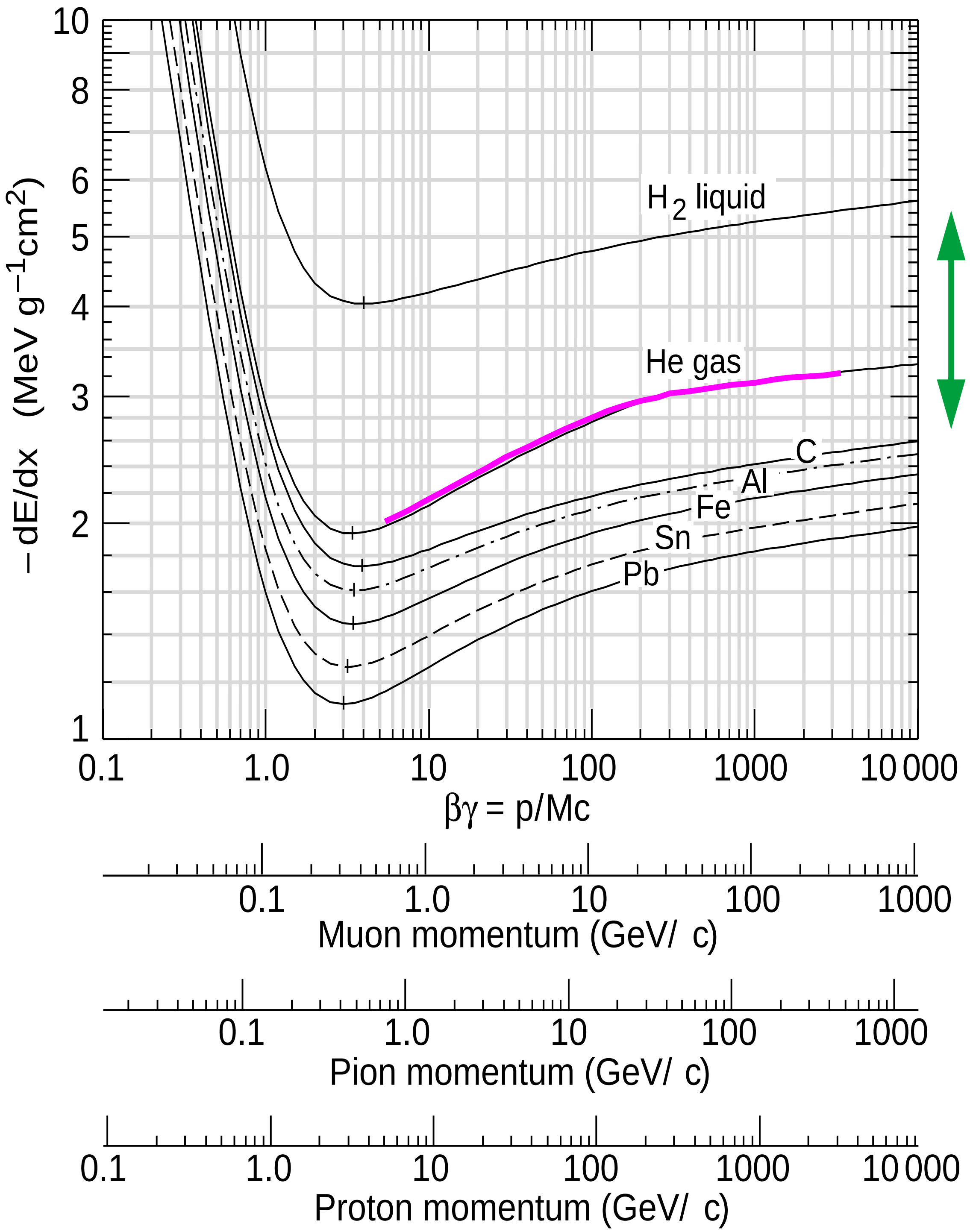
$$\frac{\delta}{2} = \ln(\beta\gamma) + \ln\frac{\hbar\omega_p}{I} - \frac{1}{2}$$

with plasma frequency $\hbar\omega_p = \sqrt{4\pi N_e r_e^3} \cdot m_e c^2/\alpha$

and electron density N_e



Material Dependence



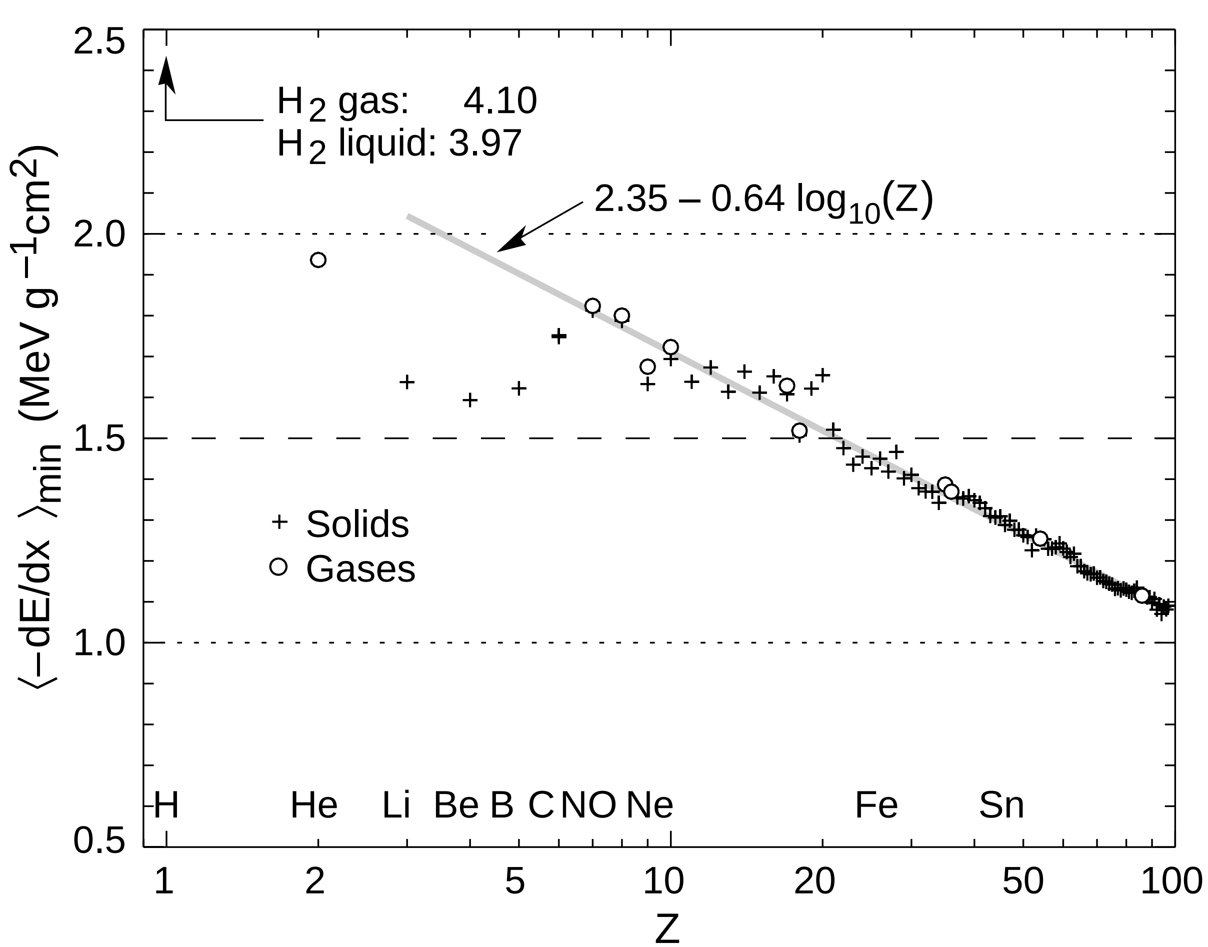
- logarithmic rise more pronounced for gases (He)

Energy loss is a function of Z/A, I, and the density ρ. Hence use instead :

$$X = x \cdot \rho \;\Rightarrow\; \frac{dE}{dX} = \frac{1}{\rho} \cdot \frac{dE}{dx} \quad [\text{MeV g}^{-1}\text{cm}^2].$$

⇒ dE/dX essentially a function of Z/A

"Stopping Power"



Energy Loss of Electrons

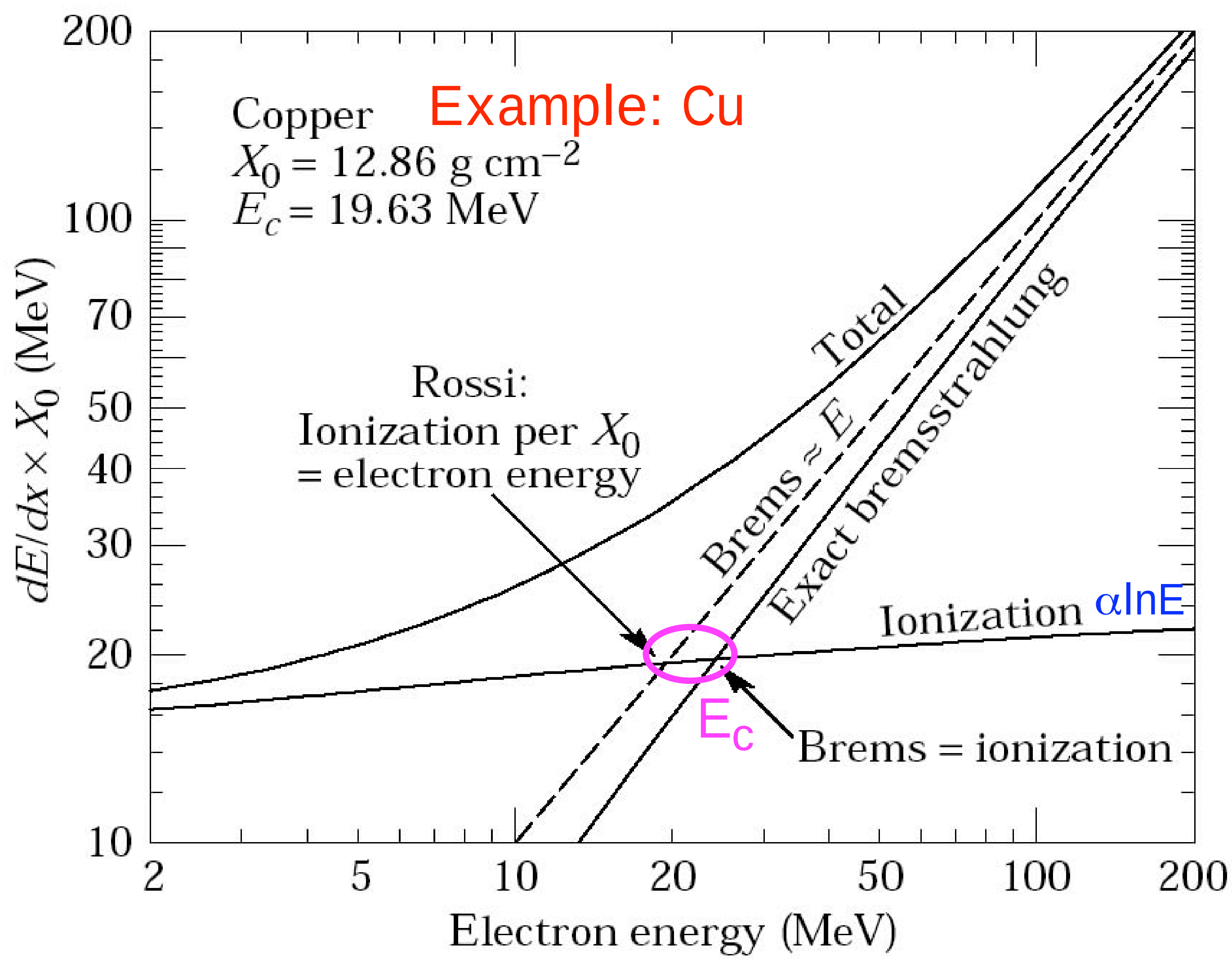
In addition to energy loss by ionisation high energy particles also loose energy due to interaction with the Coulomb field of the nuclei: Bremsstrahlung

Due to their small mass this effect is especially prominent for electrons (positrons):

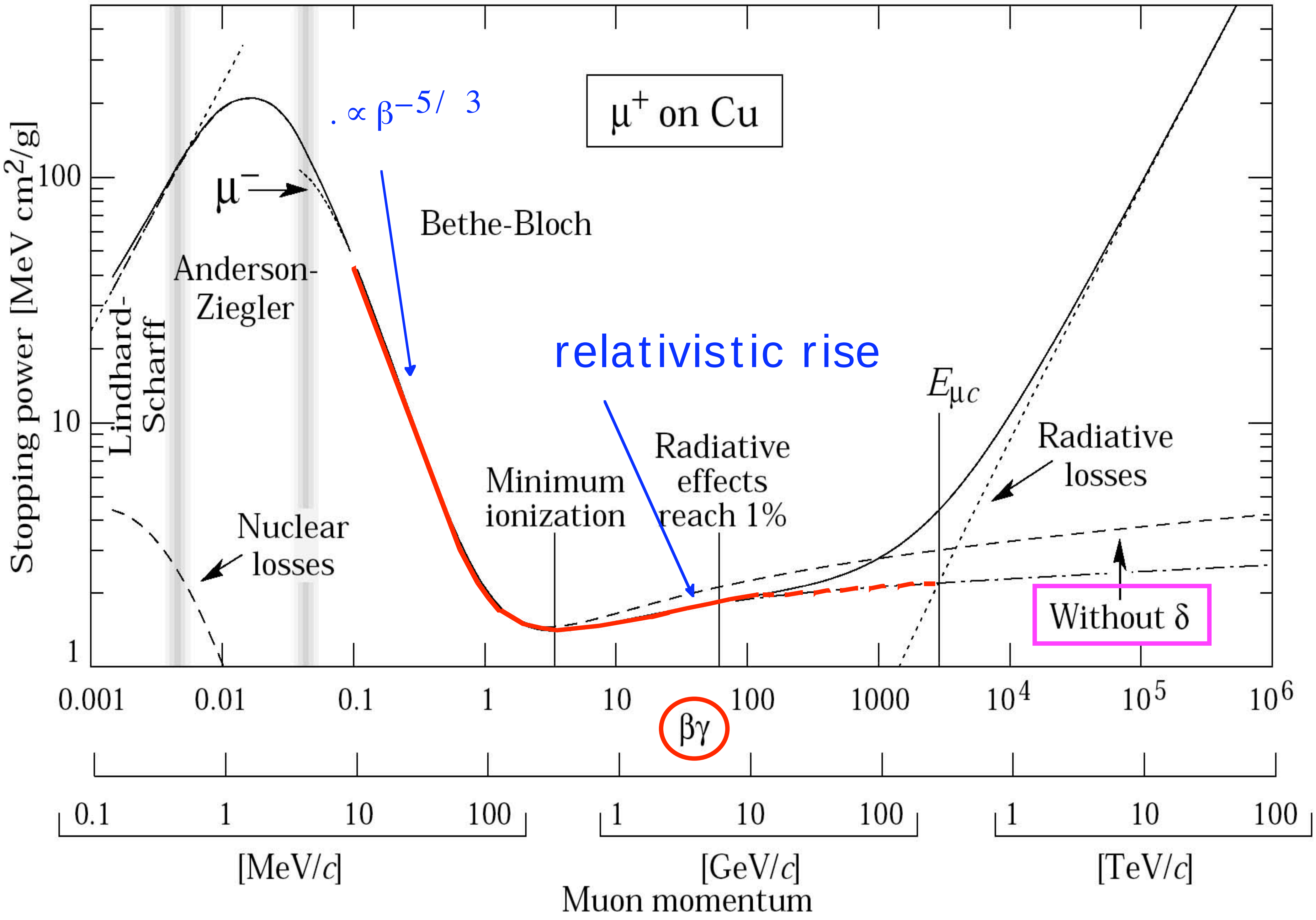
- $-dE/dx \propto Z^2 \cdot E/m^2$
- it is useful to introduce radiation length X_0
- energy attenuation: $E = E_0 \exp\left(\frac{-x}{X_0}\right)$
- approx.: $X_0 = \frac{716 \text{g cm}^{-2} A}{Z(Z+1)\ \ln(287/\sqrt{Z})}$
- critical energy E_c:

$$\frac{dE_{Brems}}{dx} = \frac{dE_{collision}}{dx}$$

- approximately: $E_c = \frac{610 \text{MeV}}{Z + 1.24}$



Energy Loss of Muons



MIP = minimum-ionising particles

dE/dx Applications for different Detector Types

Gas

- ionisation ⇒ proportional or drift chamber

Liquid

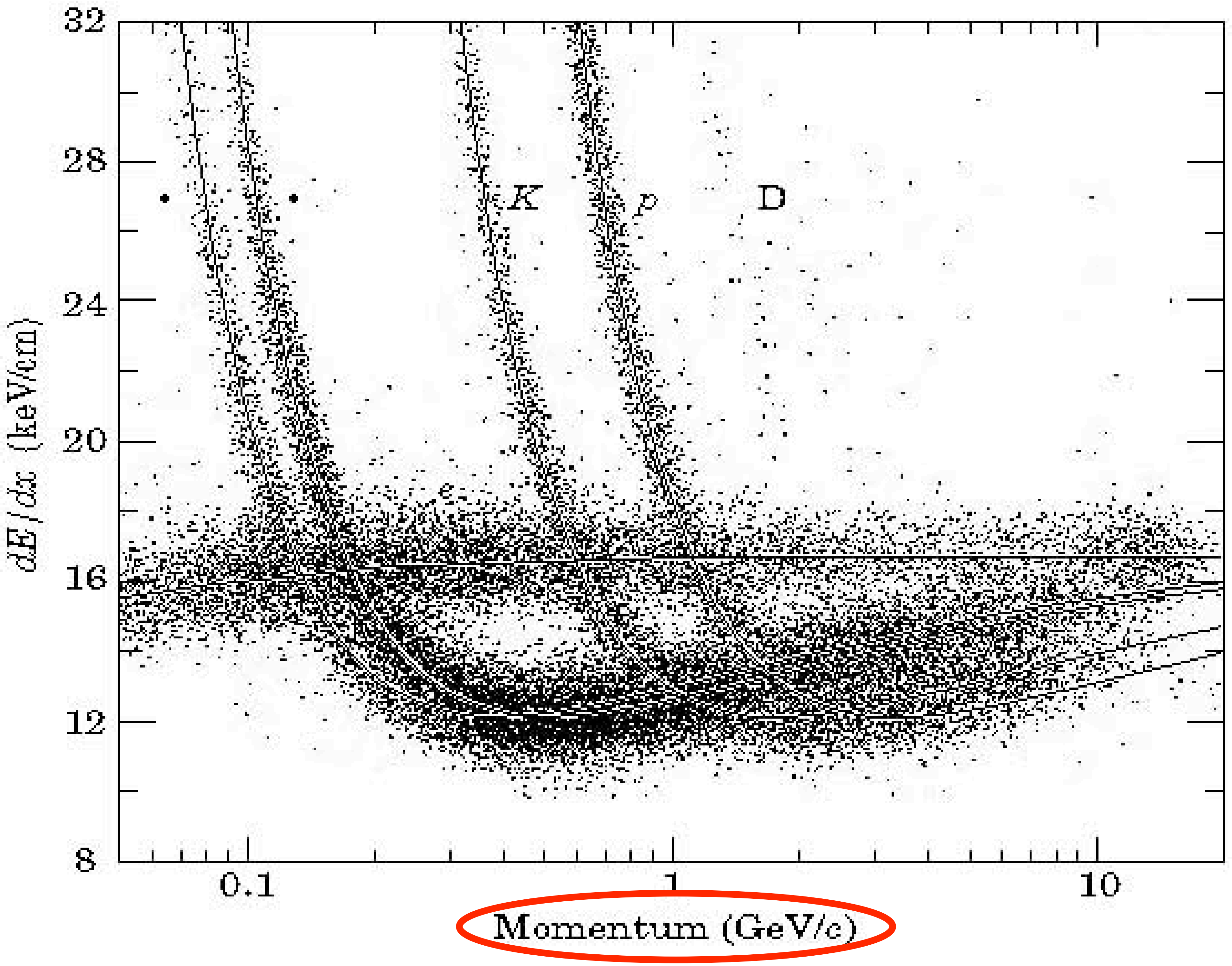
- local heating ⇒ bubble chamber
- ionisation ⇒ calorimeter (Liquid Argon or Krypton)

Solid

- excitation of electrons
  → conversion into light ⇒ scintillators
- creation of electron-hole pairs ⇒ solid state detectors

dE/dx in a TPC

Measurements in PEP4/9-TPC (Ar-CH_4 = 80:20 @ 8.5atm)



If dE/dx is plotted versus momentum of particle the curves are shifted horizontally for different masses

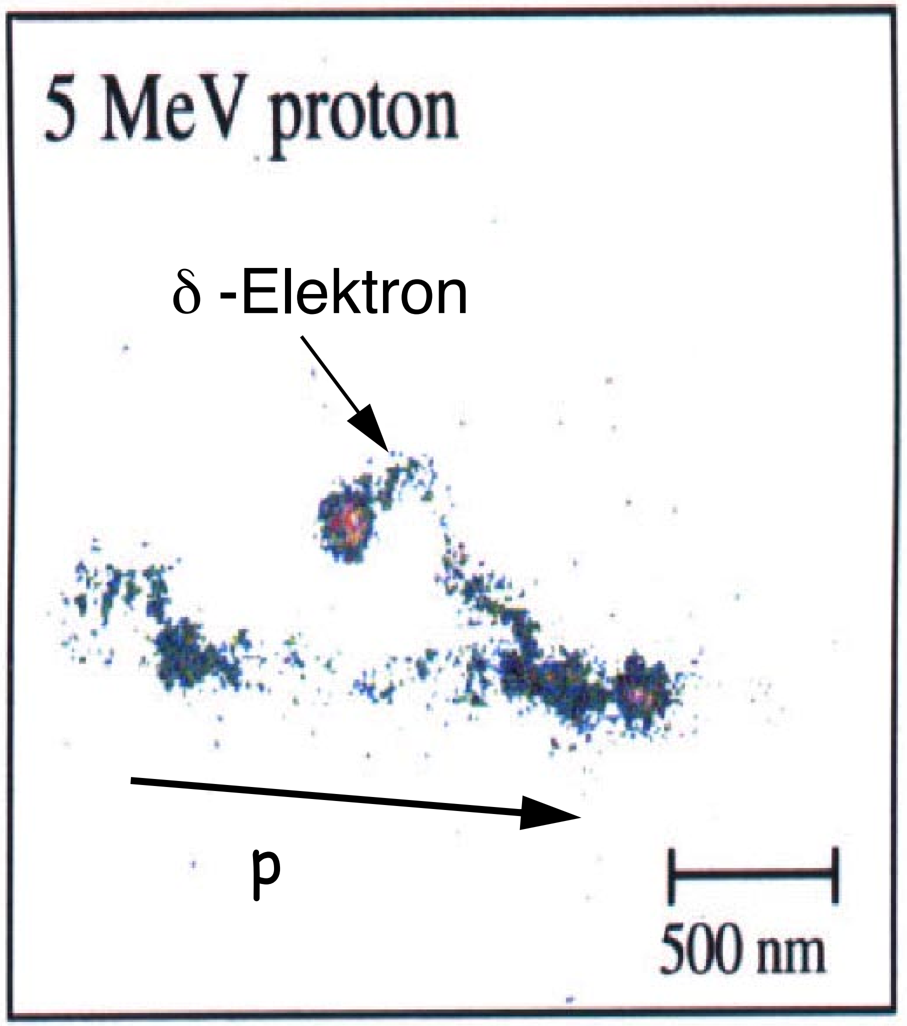
Application: if also the momentum of the particle is known the measurement of the specific ionisation can be used for particle identification

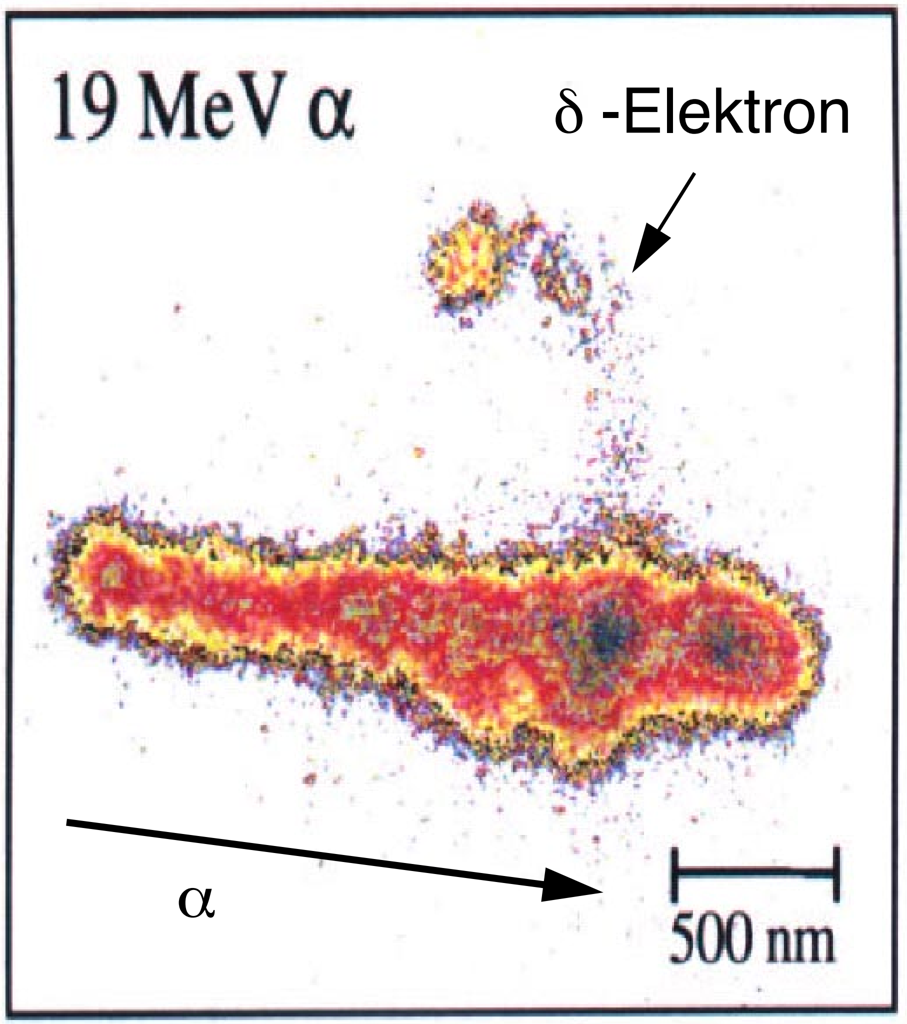
In this example each dot represents ≈185 single measurements in a drift chamber

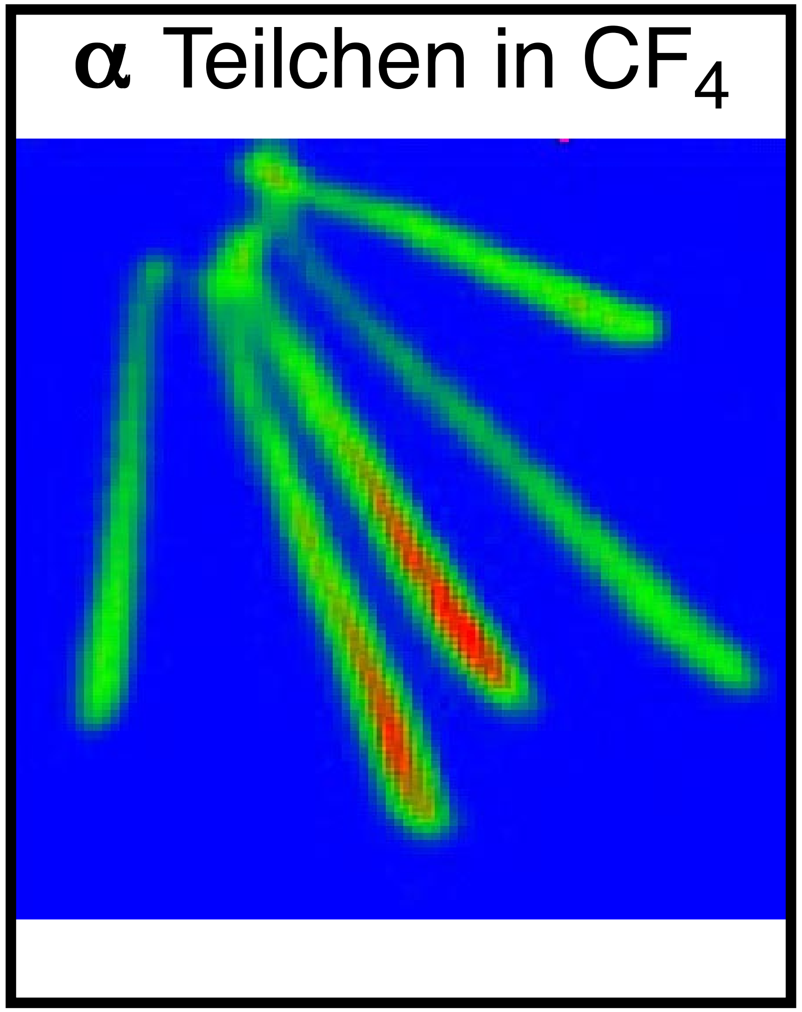
Ionization along the Track

Optical avalanche microdosimeter

Double gem microstrip gas chamber with CCD camera readout

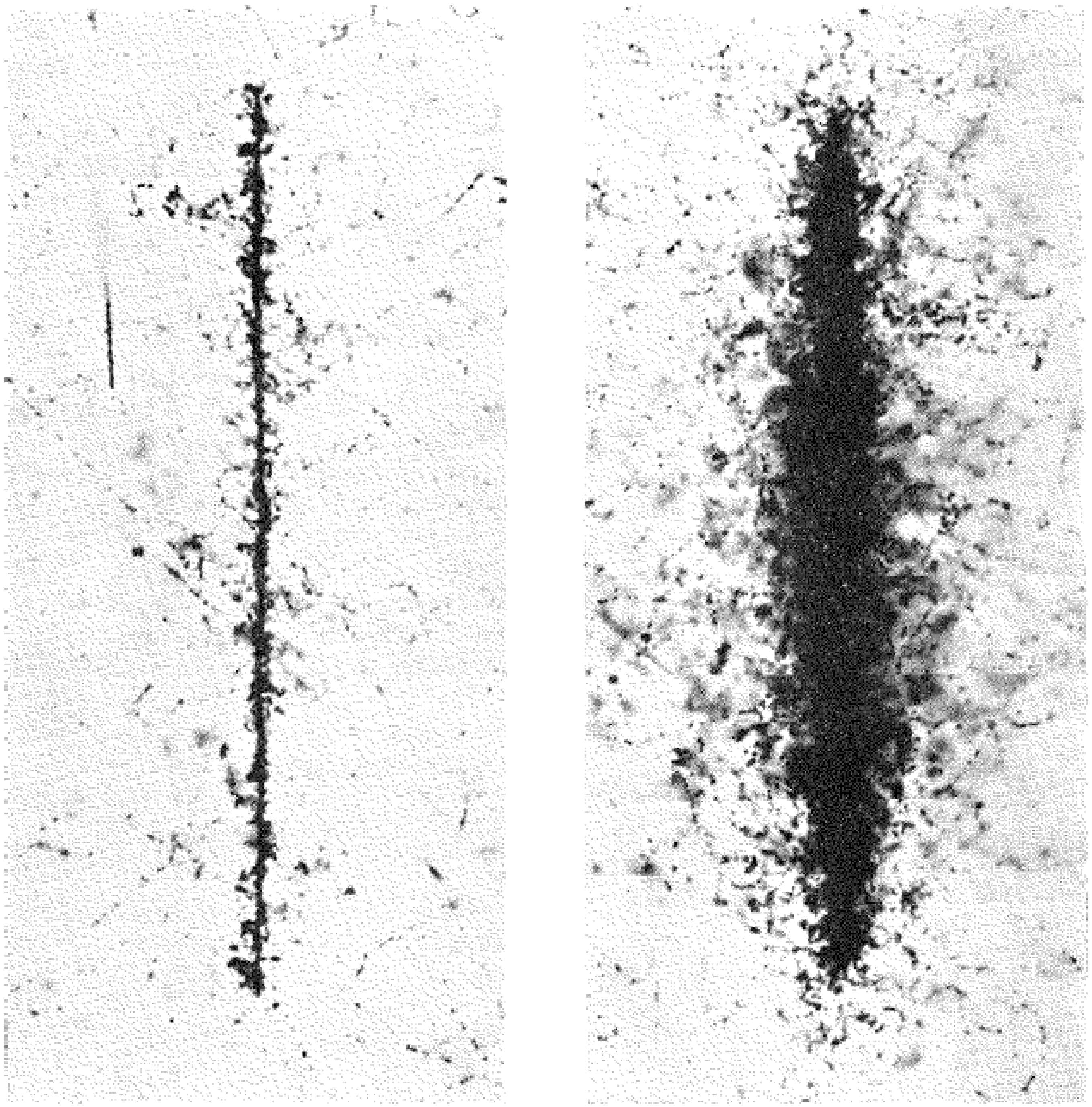






The increase of ionization at the end of the range due to the $1/\beta^2$-dependence of the energy loss is visible in all examples.

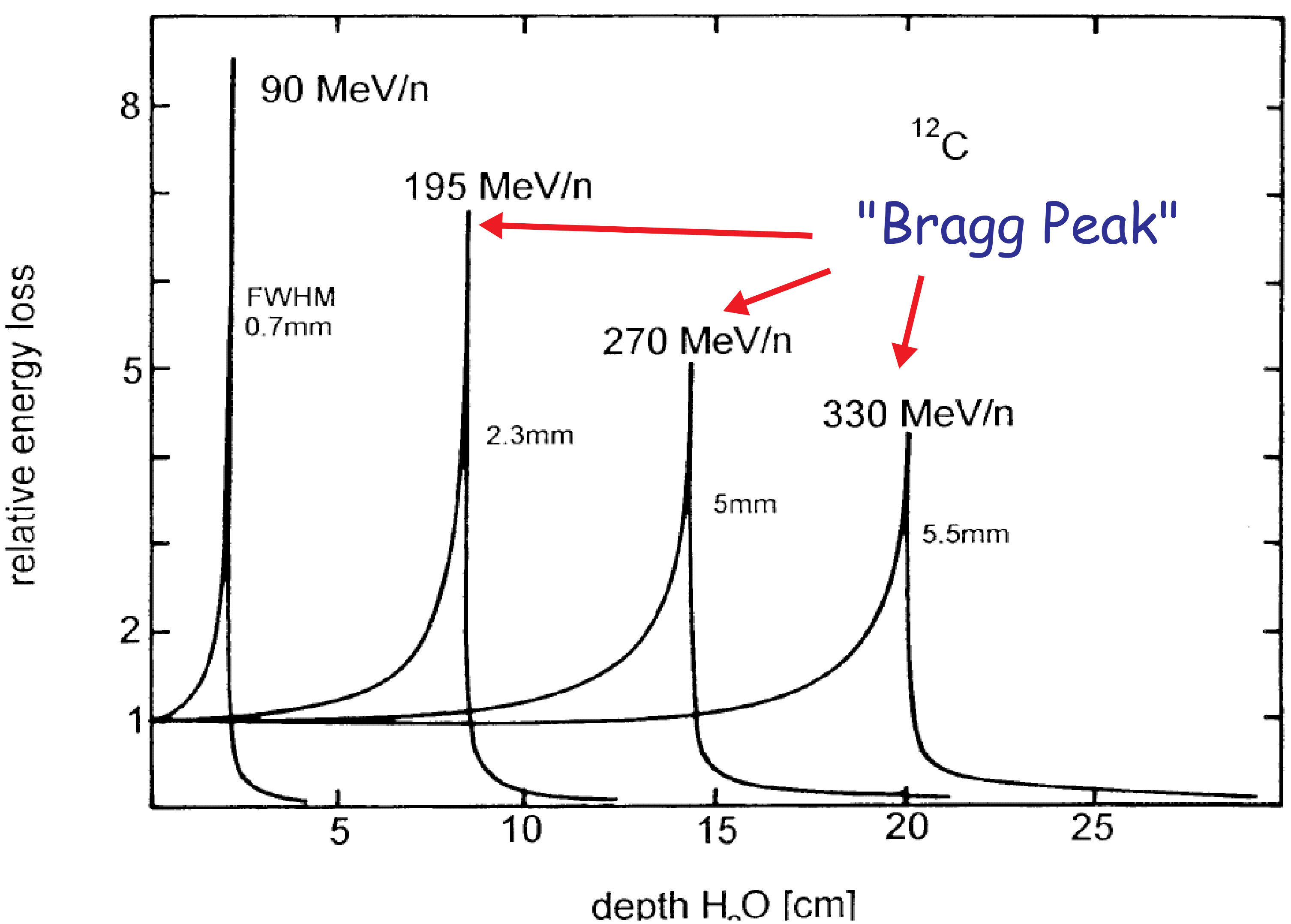
z-Dependence of Ionization



Relativistic ions in nuclear emulsion

Bragg-Peak and Medical Application

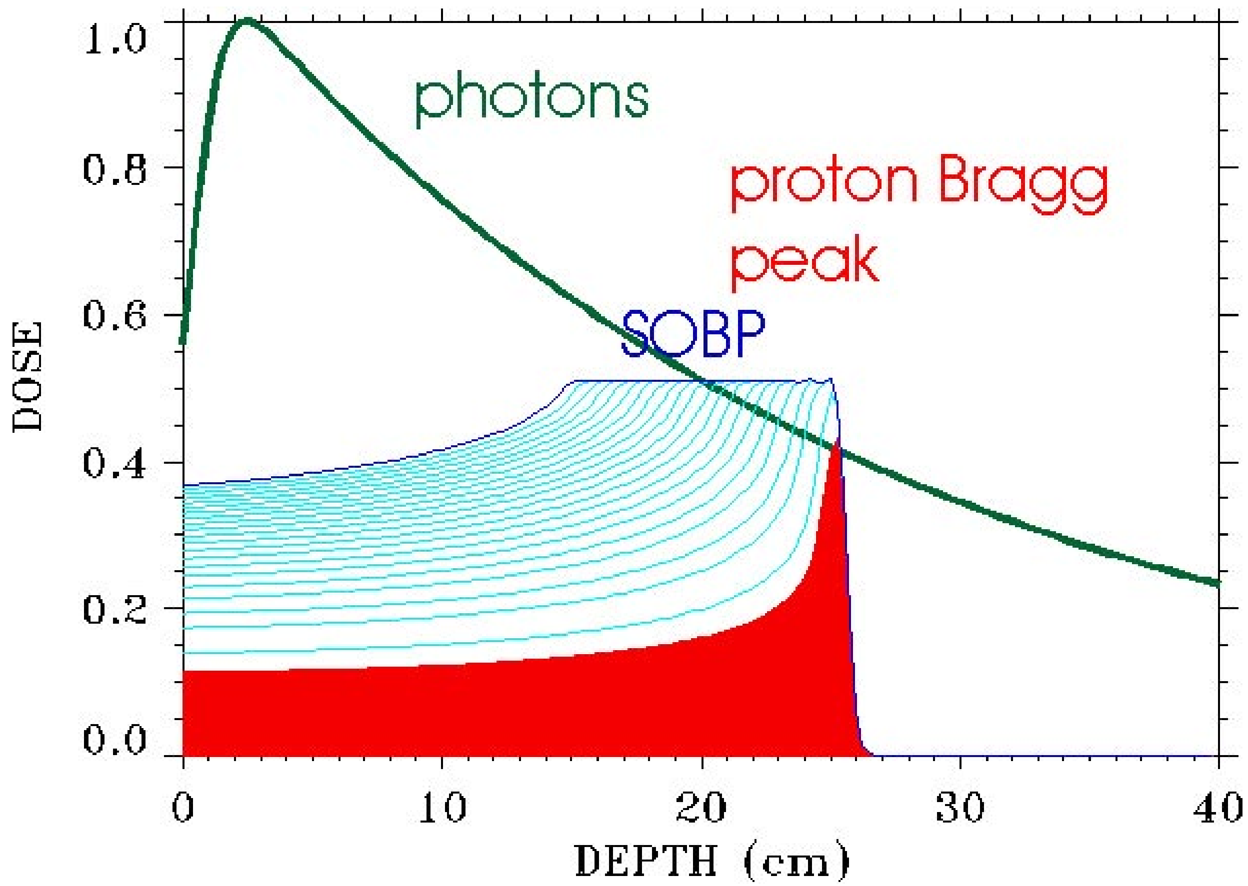
Ionisationsprofil von ^{12}C Ionen in Wasser

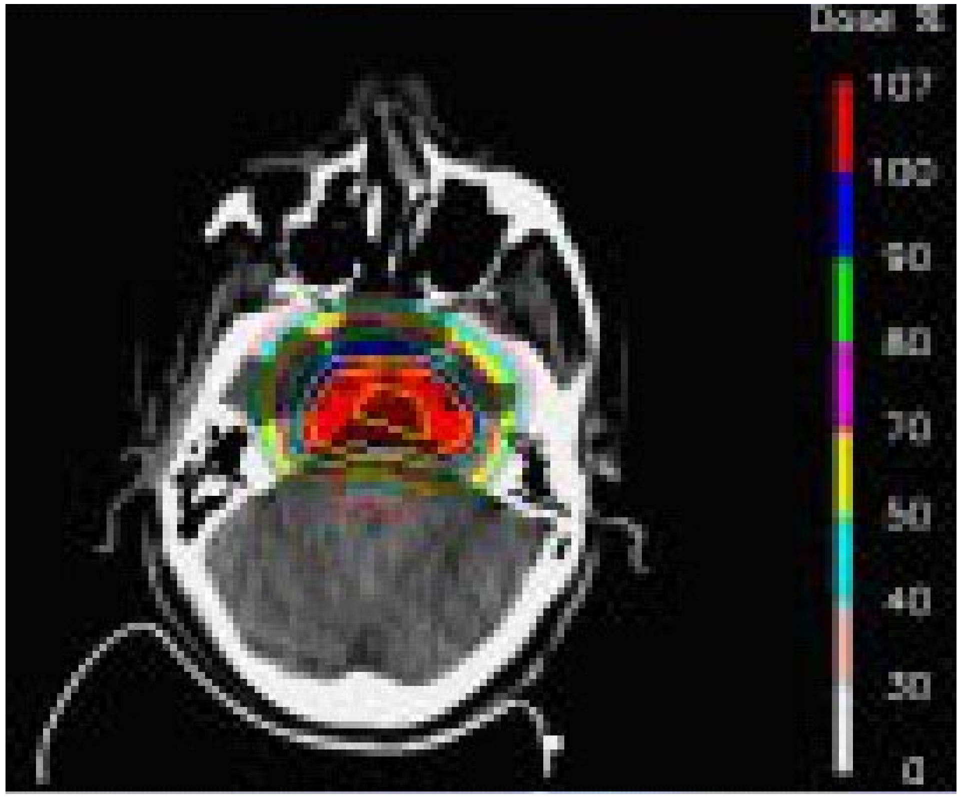


Applications in therapy:

better targeted treatment of tumors with reduced radiation damage of tissue in front due to concentration of energy loss at the end of the range (in contrast to X-ray treatment)

Example: Proton Therapy at PSI



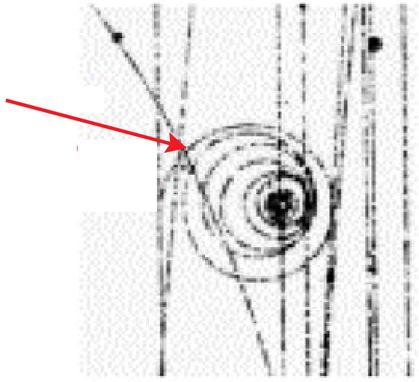


Spread out Bragg Peaks (SOBP) mit unterschiedlichen Absorbern ⇒ annähernd konstante Dosisverteilung im Bereich des Tumors

Landau Distribution

The Bethe-Bloch formula only gives the average energy loss. The total energy loss is the sum of many individual processes:

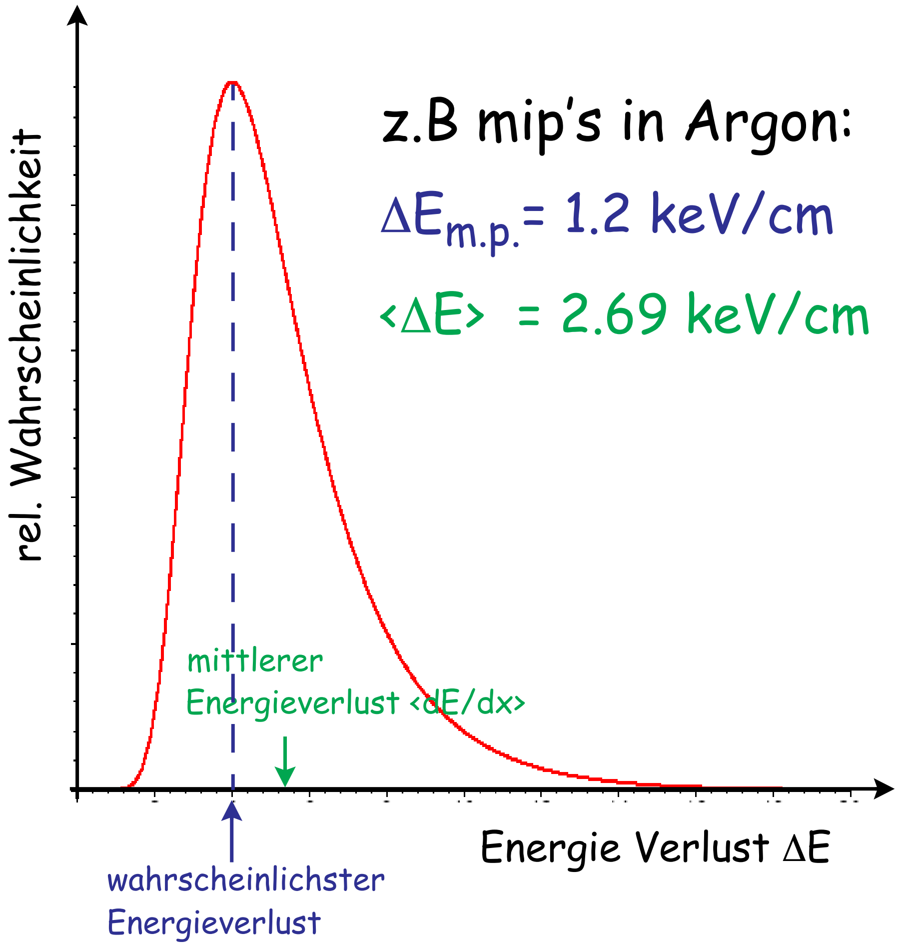
- thick layers ($(dE/dx) \cdot \delta x \gg T_{max}$):
  many collisions with small ΔE_i ⇒ in good approximation Gaussian distributed
- for thin layers (e.g. gases) two effects are important:
  - rare collisons with large ΔE (> ionization potential) ⇒ δ−electrons or knock-on electrons are liberated, which have sufficient energy to ionize themselves
  - energy loss due to Bremsstrahlung



⇒ asymmetric Landau distribution

$$P(\Delta E) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})} \quad \text{with} \quad \lambda = \frac{\Delta E - \Delta E_{mp}}{\xi}$$

ξ material constant

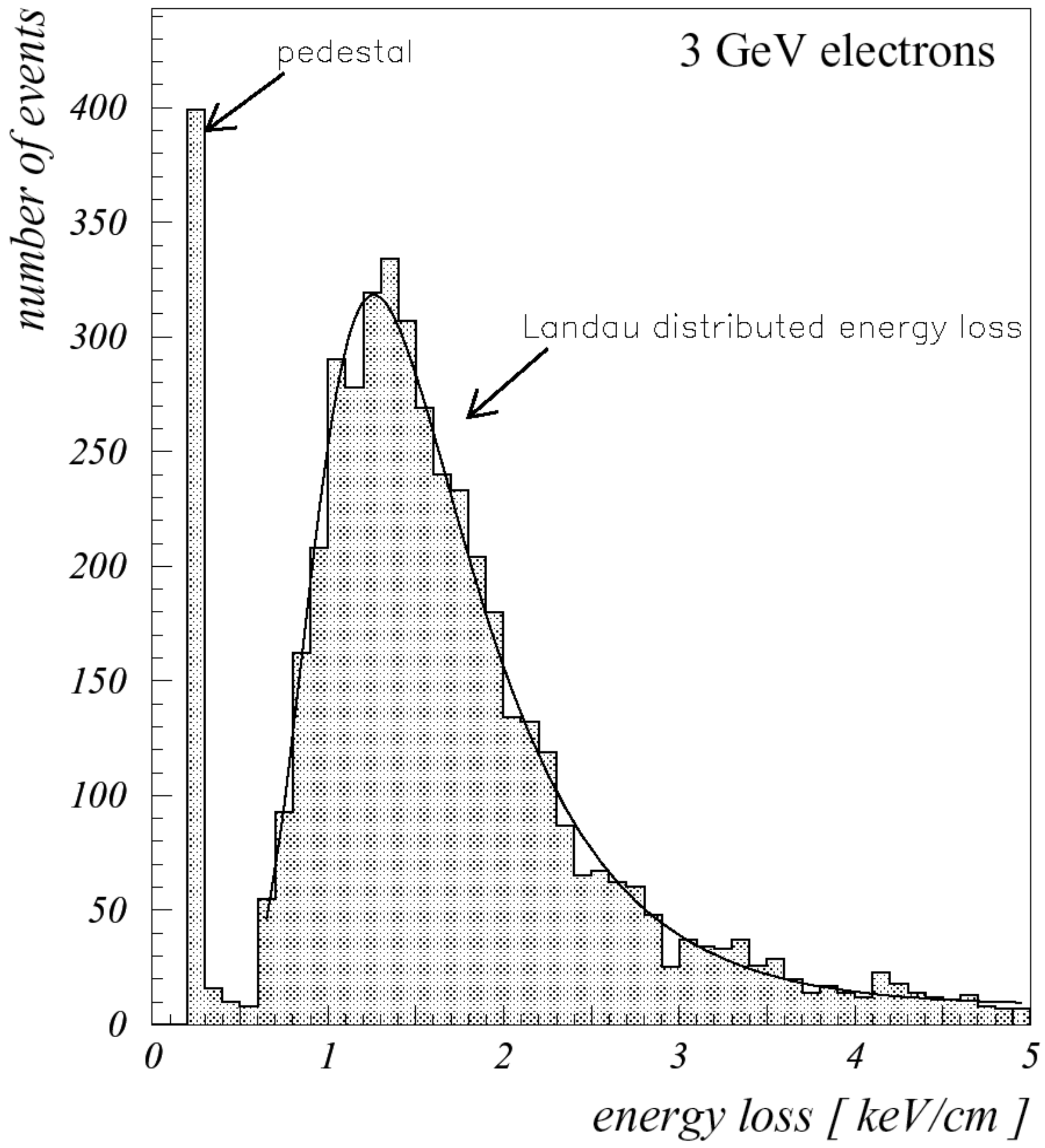


Alternative approaches by:

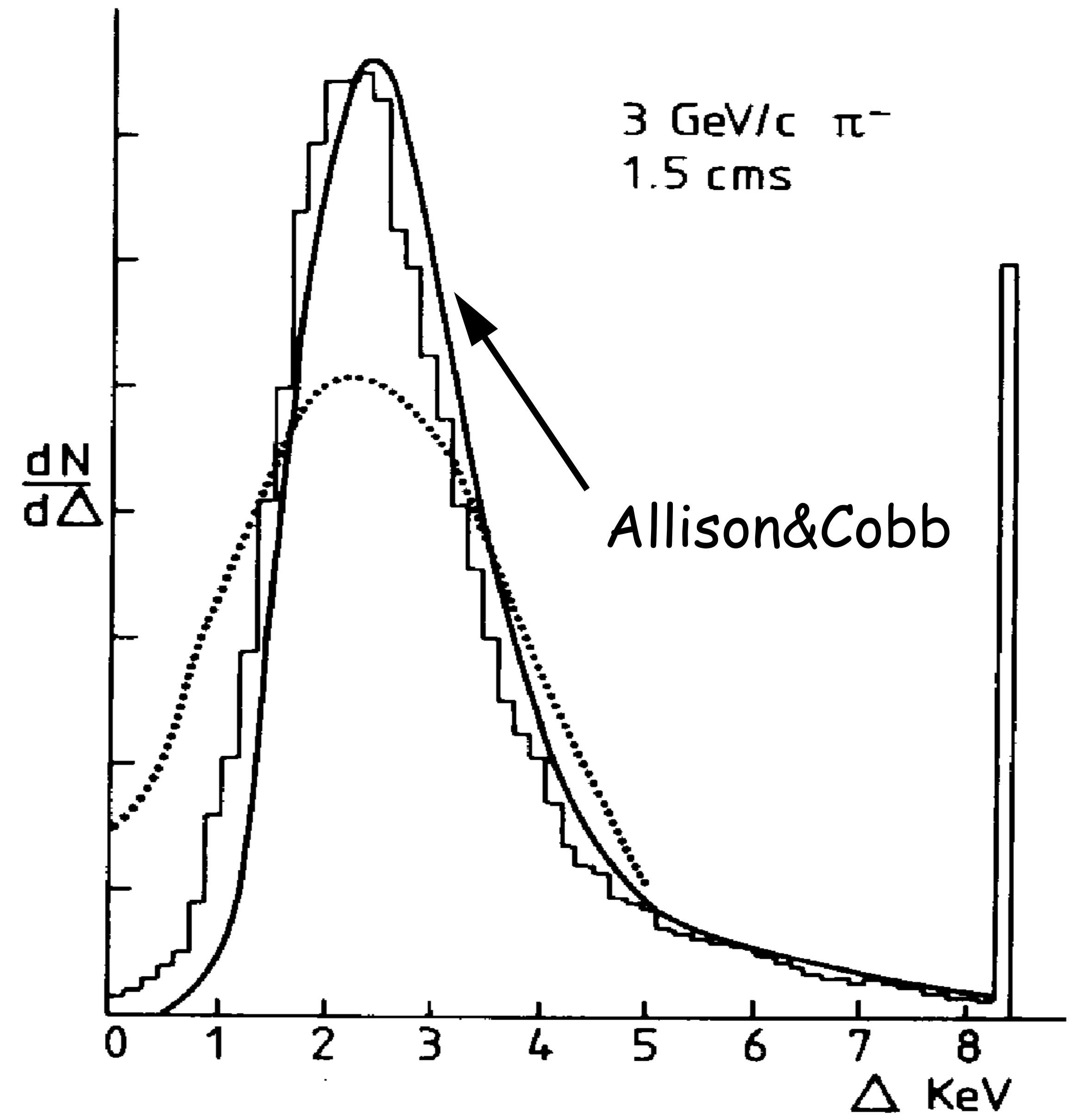
- Vavilov
- Blunck-Leisegang
- Symon
- Allison, Cobb

Example for measured Energy Loss

3 GeV electrons in a thin-gap multi wire proportional chamber(ALPEPH)



3 GeV pions in 1.5 cm gas mixture of Argon and 7% CH_4



Restricted Energy Loss

A given detector usually only measures the deposited energy and not the energy the particle has lost in total.

Significant differences for example occur in gas detectors, when part of the energy, which is transfered to the knock-on electron is lost for the measurement, since the knock-on electrons leaves the detector.

⇒ it is useful to introduce the so called restricted energy loss: only take into account the part of the energy loss processes with energy transfer $T < T_{cut}$

$$-\frac{dE}{dx}\bigg|_{\mathbf{T<T_{cut}}} = Kz^2\frac{Z}{A}\cdot\frac{1}{\beta^2}\cdot\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2\mathbf{T_{cut}}}{I^2} - \frac{\beta^2}{2}\left(1+\frac{\mathbf{T_{cut}}}{\mathbf{T_{max}}}\right) - \frac{\delta}{2}\right]$$

Note, that for $T_{cut} > T_{max}$ the standard Bethe-Bloch formula is recovered

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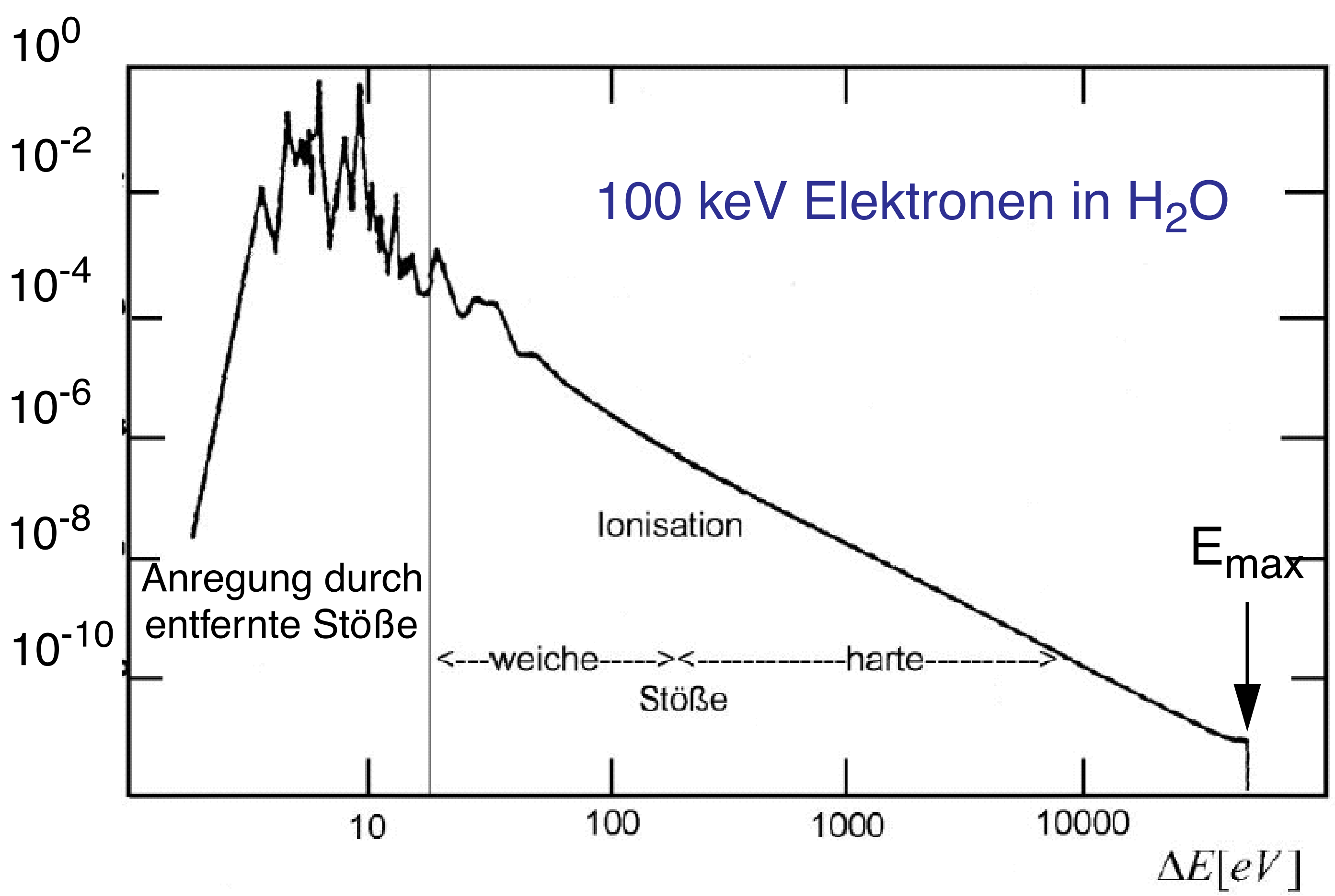
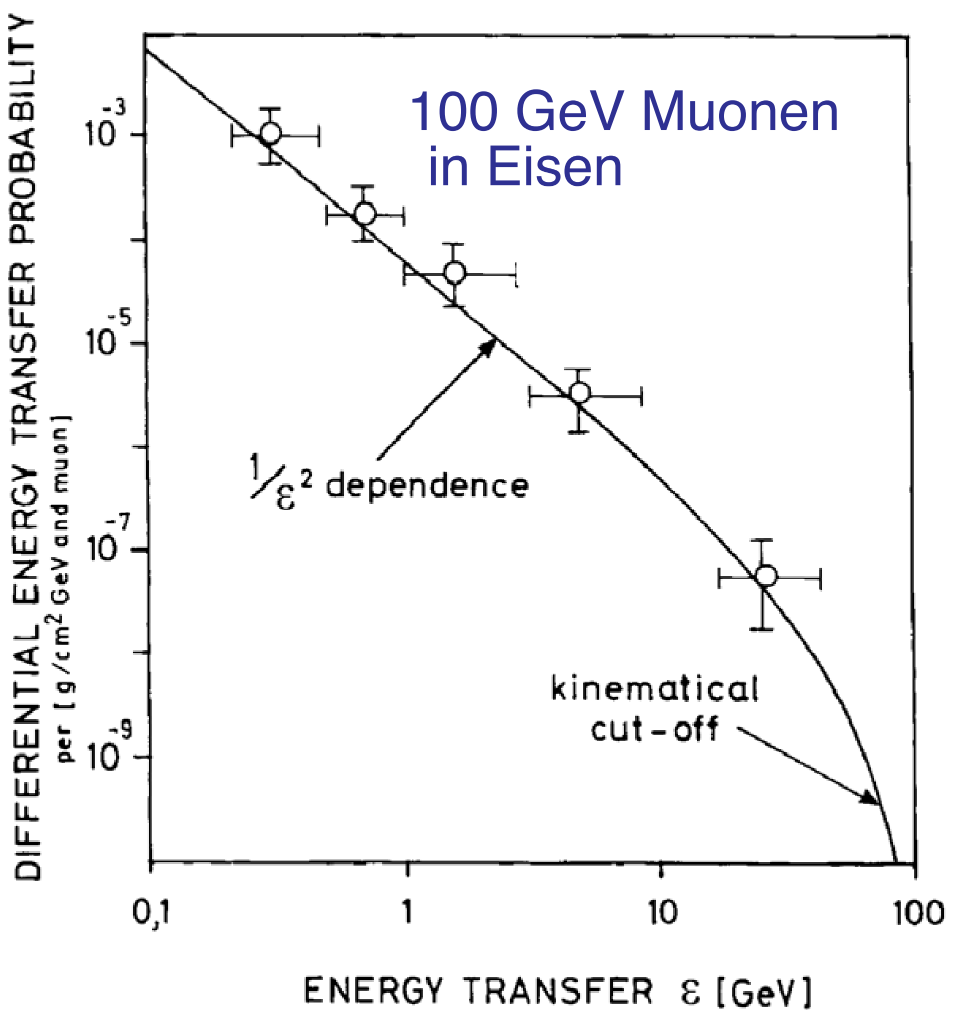
Energy Spectrum of δ-electrons

The distribution of secondary electrons with kinetic energy T , $I \ll T \le T_{max}$ is given by:

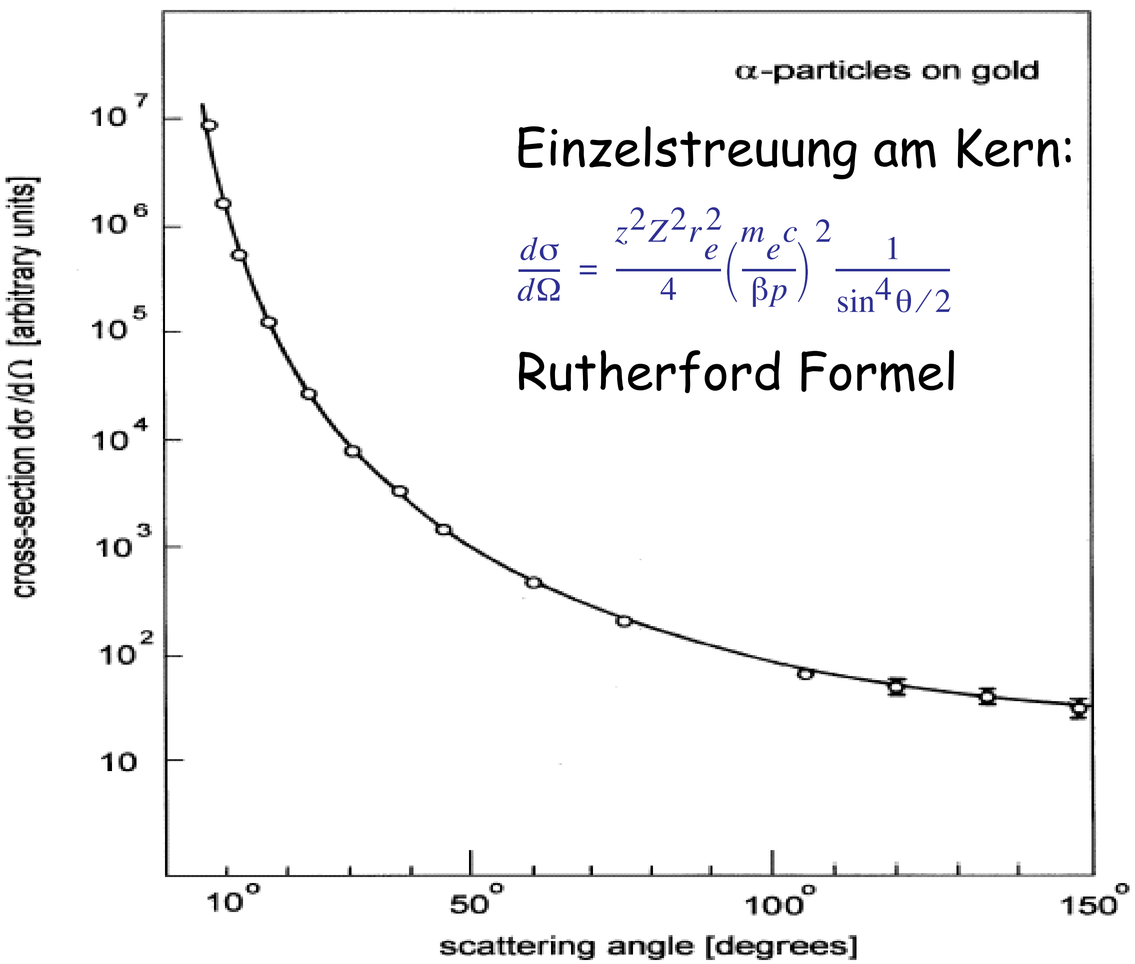
$$\frac{d^2N}{dTdx} = \frac{1}{2}Kz^2\frac{Z}{A}\frac{1}{\beta^2}\frac{F(T)}{T^2}$$

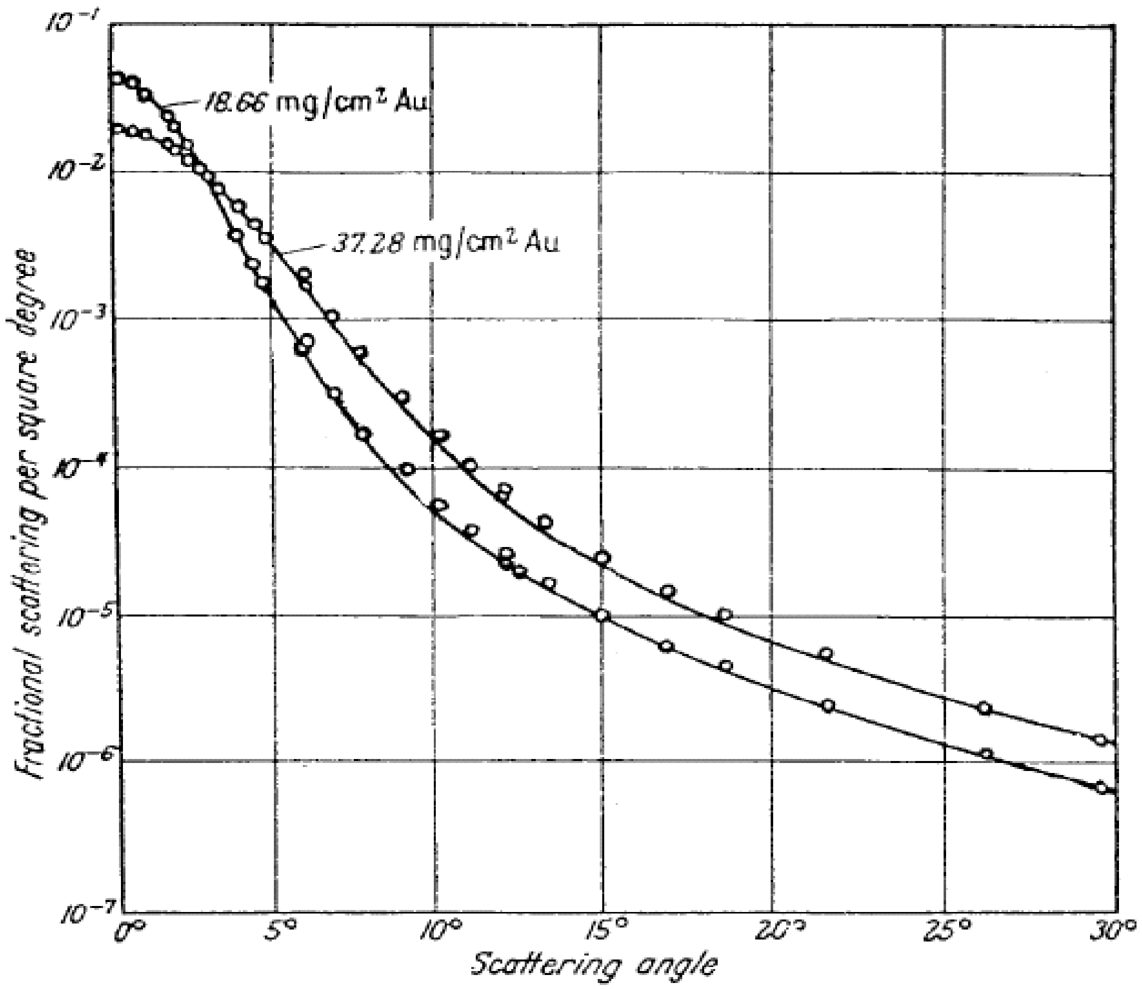
F(T) is spin dependent [$F(T) = (1-\beta^2 T/T_{max})$ for spin 0]. Integration from T_{cut} to T_{max} yields just the difference between normal and restricted Bethe-Bloch formula.





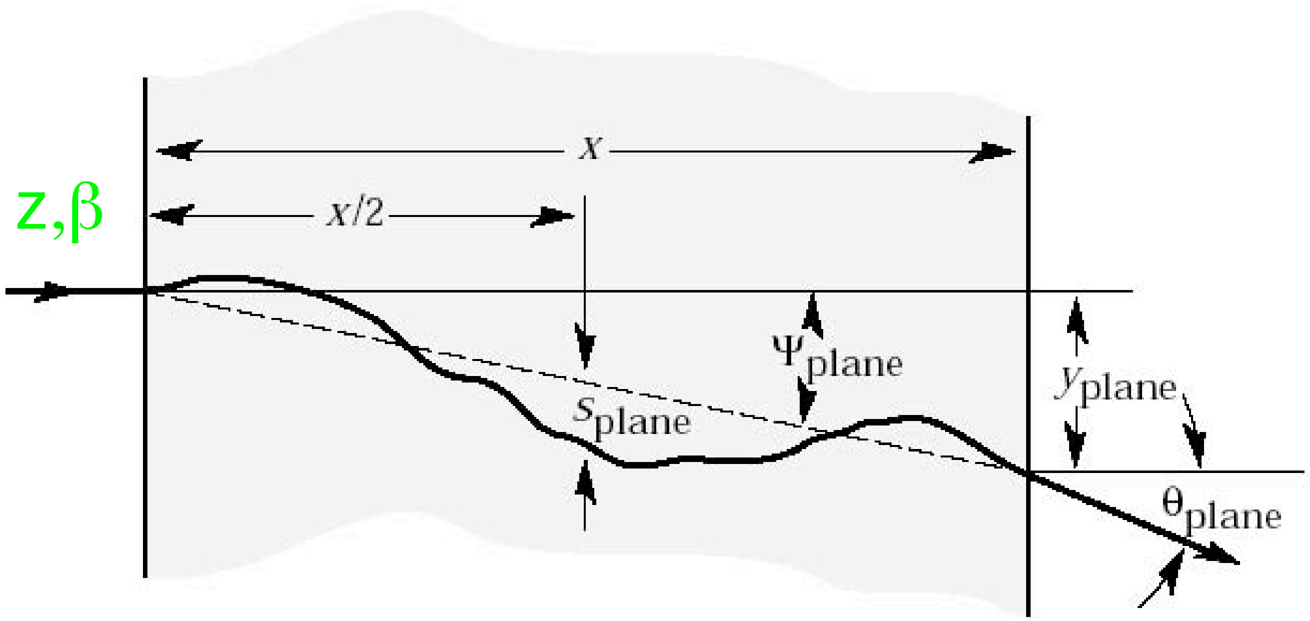
Coulomb Scattering





Important experimental consequence: multiple scattering often represents a serious limitation for the achievable resolution of direction or momentum measurement

Multiple Scattering

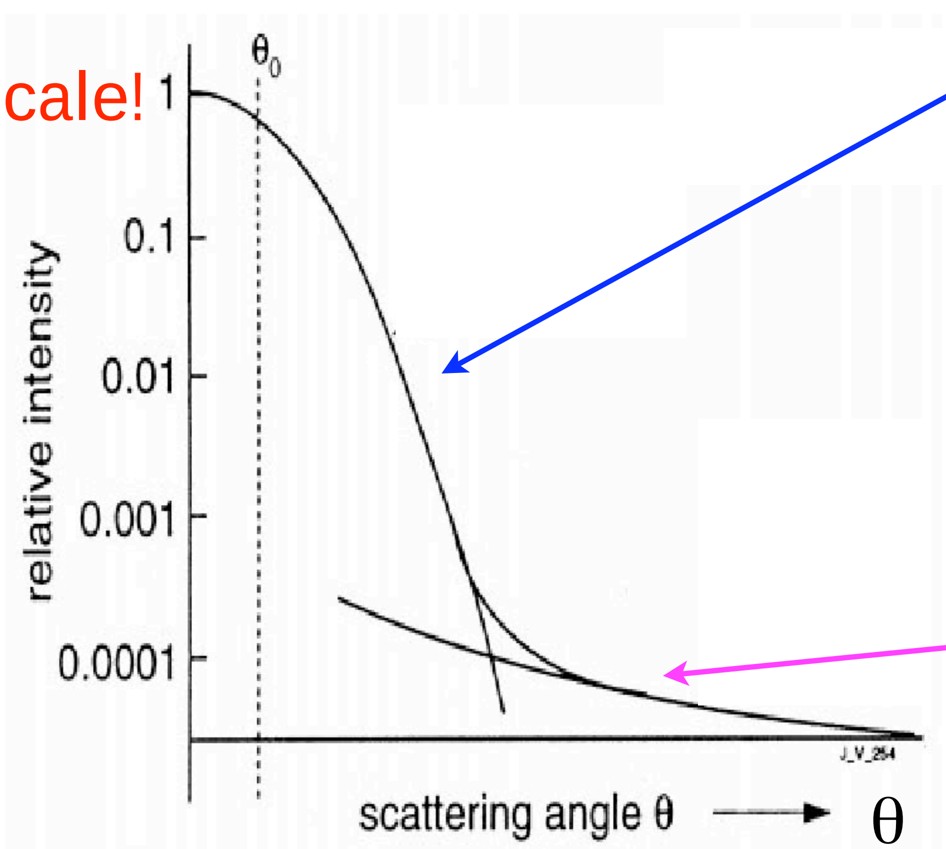


Scattering of charged particles off the atoms in the medium causes a change of direction:

the statistical sum of many such small angle scatterings results in a gaussian angular distribution with a width given by:

$$\theta_0 = \frac{13.6\mathrm{MeV}}{\beta pc} z \sqrt{\frac{x}{X_0}}\left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

log scale!



example: p = 1 GeV/c, d = 300μm Si, X_0=9.4cm
⇒ $\theta_0 \approx 0.8$ mrad. For 10cm distance this corresponds to 80μm, which is significantly larger than typical resolution of Si-strip detector

the less likely scattering off the atomic nuclei causes large scattering angles resulting in a deviation from a gaussian distribution at large angles

Properties of some Materials (PDG)

Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\|_{\min}$ [b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length [c] X_0 {g/cm^2}	X_0 {cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33
CO_2 gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]

Summary Part I

- properties of different particles require many different types of detectors
- rough classification
  - track/position detectors (non destructive) → Part II+III gas detectors
  - calorimeters (destructive) → [not covered in this lecture]
- basically all detectors based on electromagnetic interaction
- detectors also more and more used for other applications (e.g. medical appl.)

- energy loss of charged particles: Bethe-Bloch describes loss due to ionisation
  - $z^2/\beta^2 \rightarrow \ln E$ → Fermiplateau
  - minimum at $\beta\gamma \approx 3$: 1-2 MeV per gcm^{-2}

  - however light particles (electrons, muons) at high energies lose energy predominantly by bremsstrahlung: $-dE/dx \propto Z^2 \cdot E/m^2$

- multiple scattering

  - gaussian core of distribution with angular spread: $\theta_0 \sim \frac{1}{p}\sqrt{\frac{x}{X_0}}$

  - deviation from gaussion distributiun at large angles due to Rutherford scattering (nuclei)

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