Particle Detectors

Summer Student Lecture Series 2002

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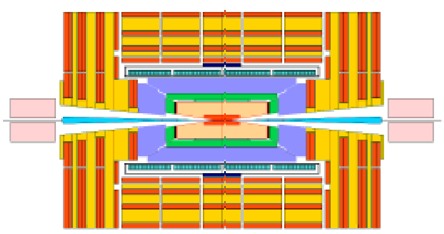
EP / TA1

From (very) basic ideas ~~1 + 1 = 2~~ $1 + 1 \approx 2$

to

rather complex
detector systems



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Outline + timing

- Introduction, basics
- Tracking (gas, solid state)

Thu/Mon (2x45 min)

- Scintillation and light detection
- Calorimetry
- Particle Identification

Tue/ Wed (2 x45 min)

- Electronics and Data Acquisition
- Detector Systems

Thu (45 min)

- Discussion session I — Fri, 5 June, 11:15
- Discussion session II — Wed, 10 June, 11:15

= Detector Exhibition

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Literature on particle detectors

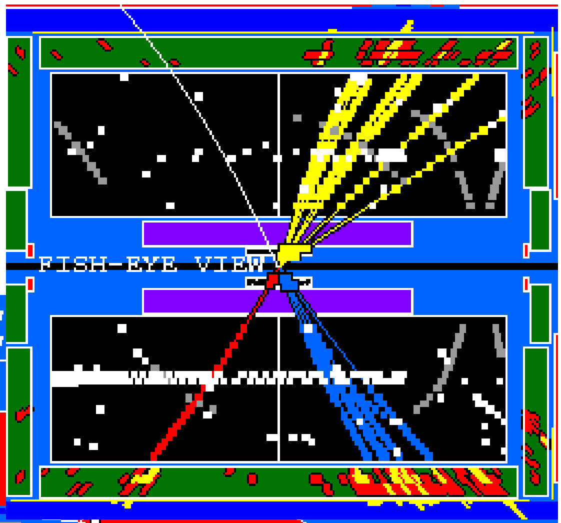
- Text books
  - C. Grupen, Particle Detectors, Cambridge University Press, 1996
  - G. Knoll, Radiation Detection and Measurement, 3rd Edition, 2000
  - W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd edition, Springer, 1994
  - R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992
  - W. Blum, L. Rolandi, Particle Detection with Drift Chambers, Springer, 1994
  - K. Kleinknecht, Detektoren für Teilchenstrahlung, 3rd edition, Teubner, 1992

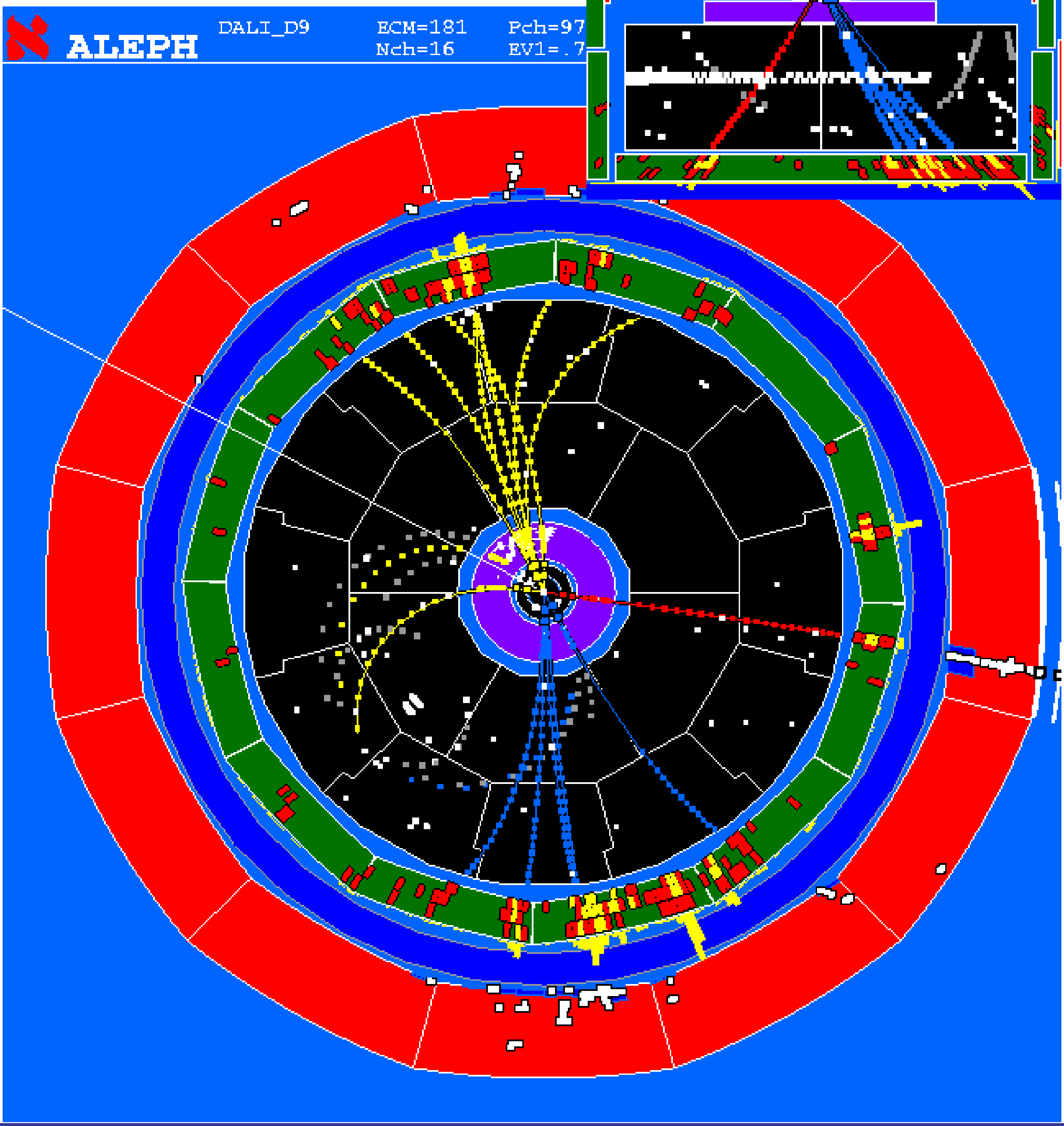
- Review articles
  - Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991.
  - Instrumentation in High Energy Physics, F. Sauli (editor), World Scientific, 1992.
  - Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.

- Other sources
  - Particle Data Book (Phys. Rev. D, Vol. 54, 1996)
  - R. Bock, A. Vasilescu, Particle Data Briefbook http://www.cern.ch/Physics/ParticleDetector/BriefBook/
  - Proceedings of detector conferences (Vienna VCI, Elba, IEEE)

A W^+W^- decay in ALEPH

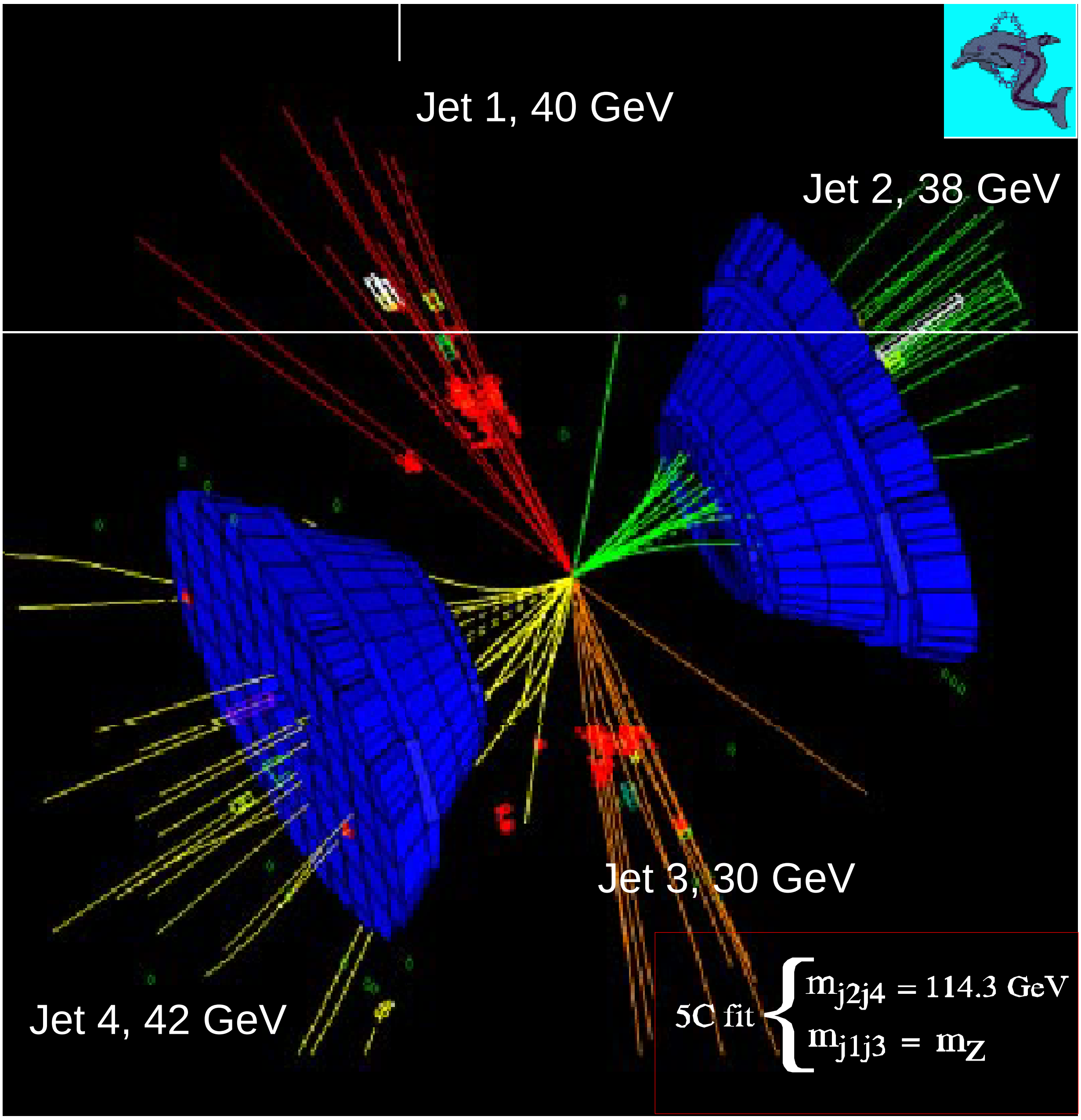
e^+e^- ($\sqrt{s}$=181 GeV)
$\rightarrow W^+W^- \rightarrow qq\mu\nu_\mu$
$\rightarrow$ 2 hadronic jets
+ μ + missing momentum





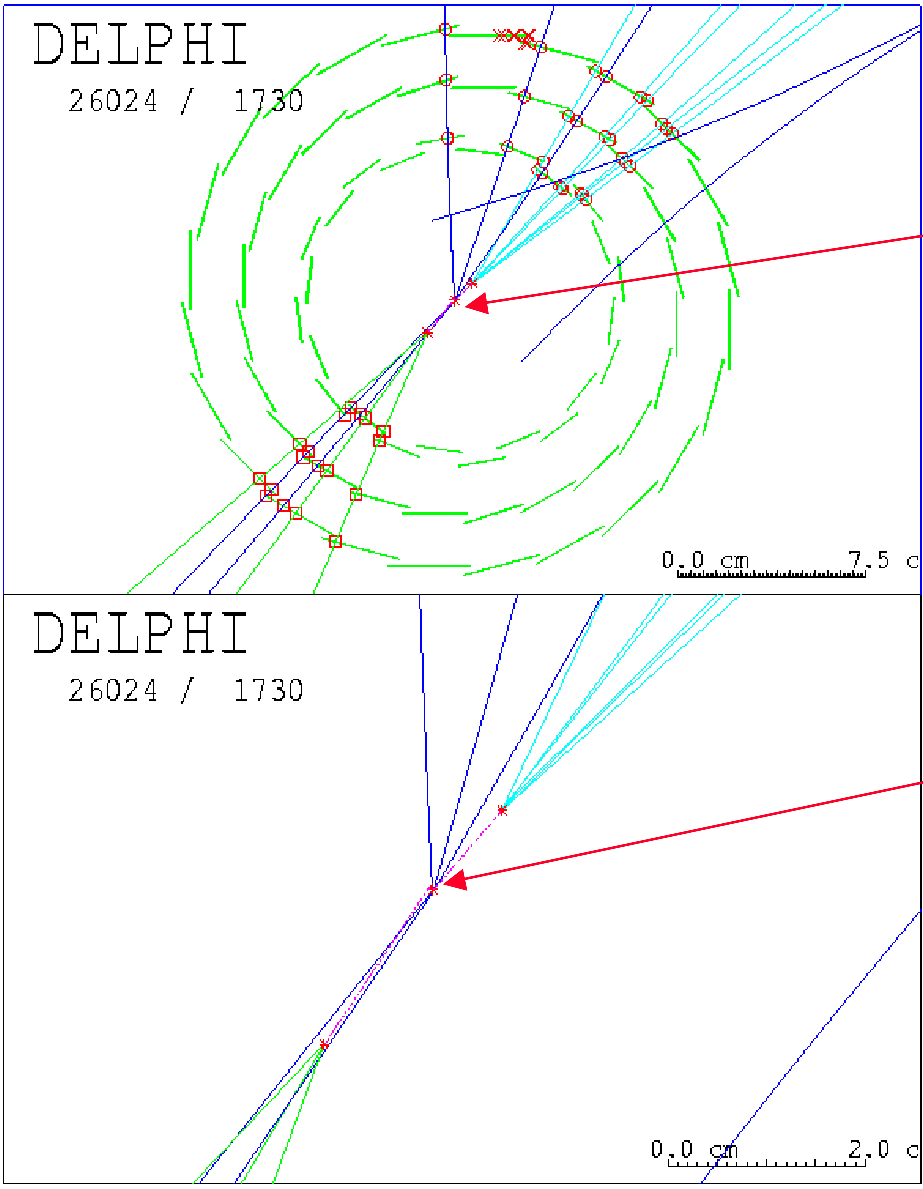
A 4-jet event in DELPHI (a Higgs candidate)

Possible underlying reaction:
e^+e^- ($\sqrt{s}$=205.5 GeV) $\rightarrow H^0Z^0 \rightarrow$ qqqq $\rightarrow$ 4 hadronic jets



Reconstructed B-mesons in the DELPHI micro vertex detector

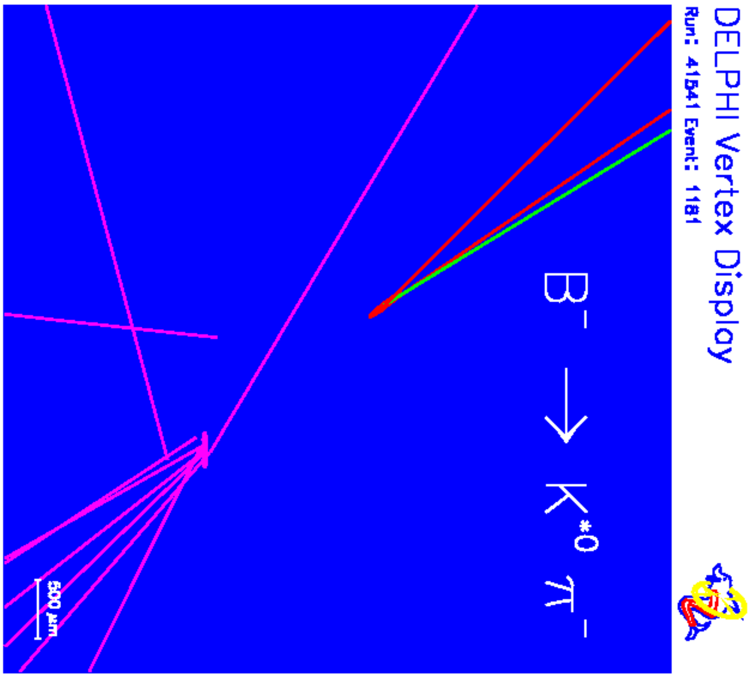
$\tau_B \approx 1.6$ ps $\quad l = c\tau\gamma \approx 500\ \mu m \cdot \gamma$



Primary Vertex

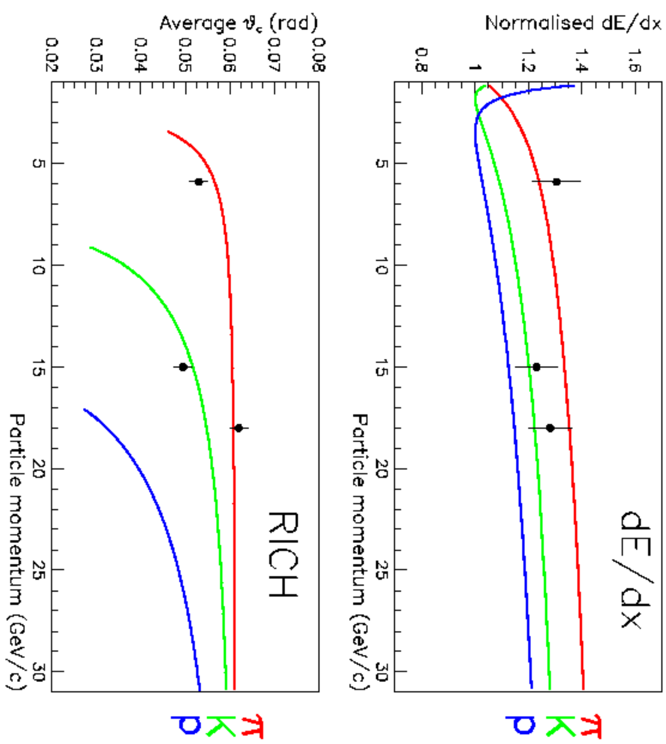
Primary Vertex

Particle identification methods

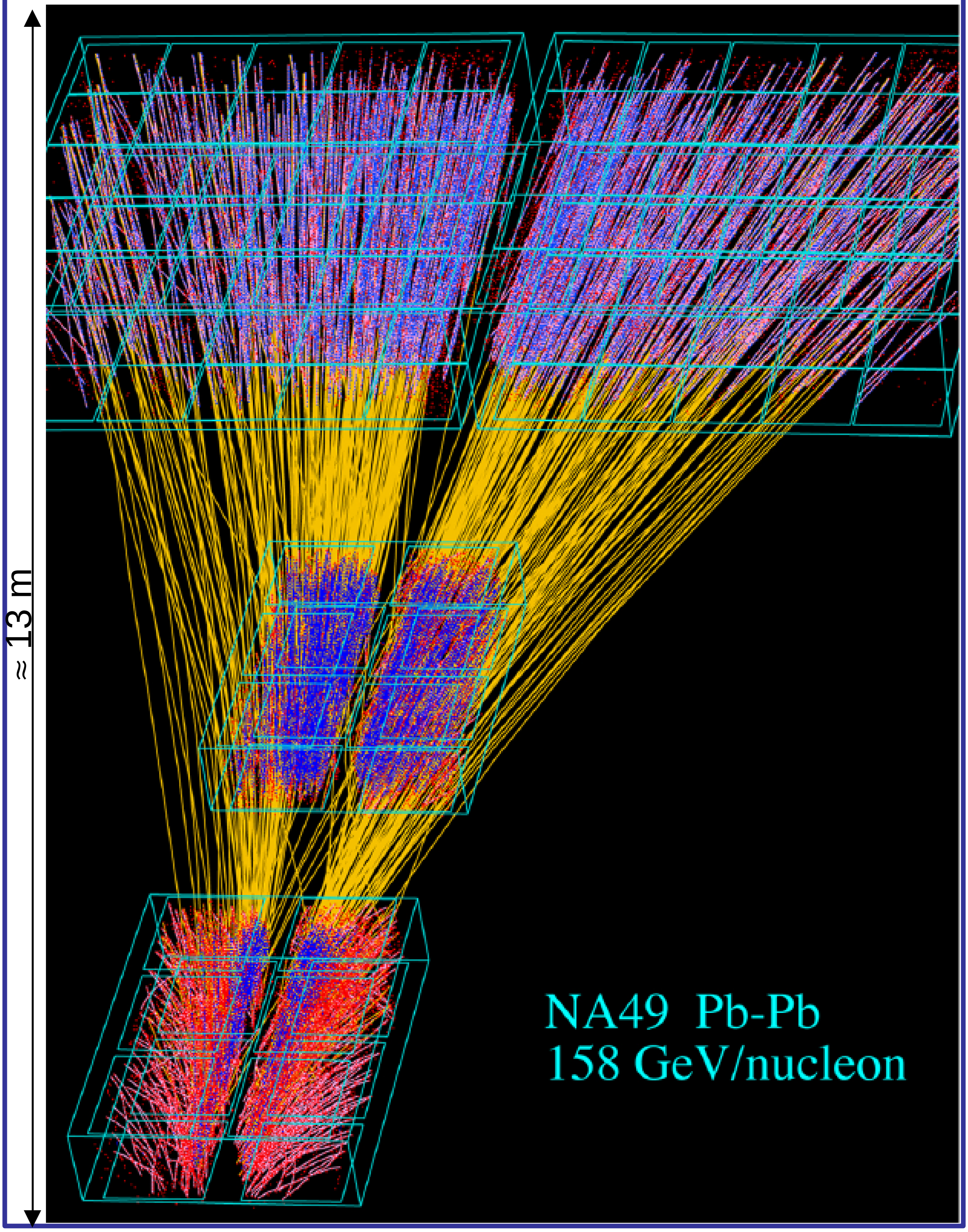


$$B^- \to K^{*} \pi^-$$
$$K^{*} \to K\pi$$

1 K + 2 π in final state



Introduction (backup)



A simulated event in ATLAS (CMS)

$H \rightarrow ZZ \rightarrow 4\mu$

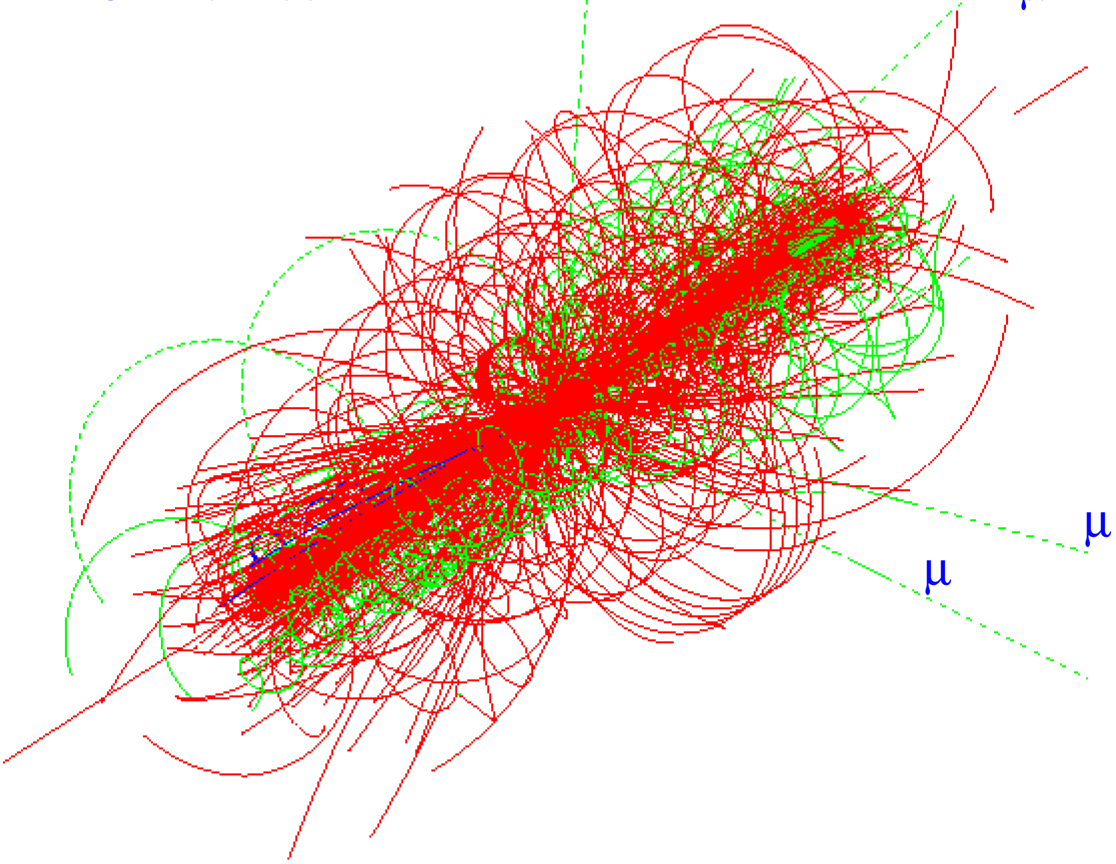
pp collision at $\sqrt{s}$ = 14 TeV

$\sigma_{inel.} \approx$ 70 mb

Interested in processes

with $\sigma \approx$ 10–100 fb

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



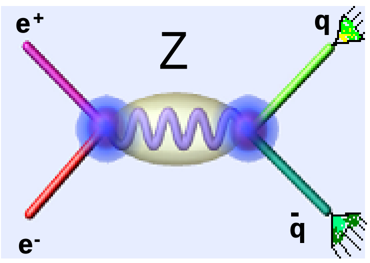
≈ 23 overlapping minimum bias events / BC

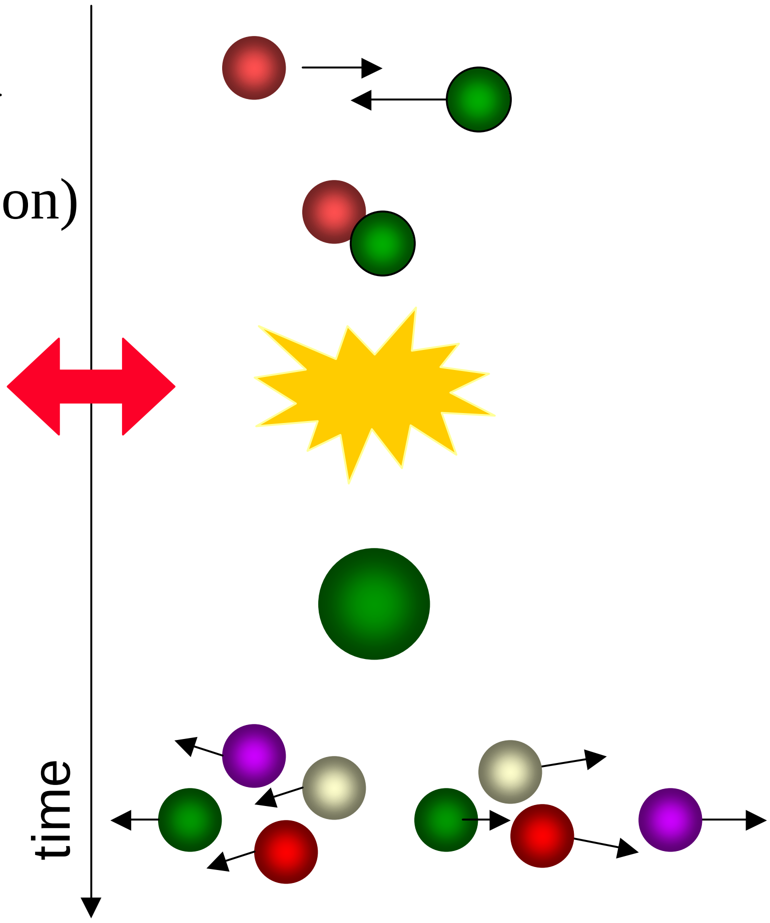
≈ 1900 charged + 1600 neutral particles / BC

Idealistic views of an elementary particle reaction

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

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



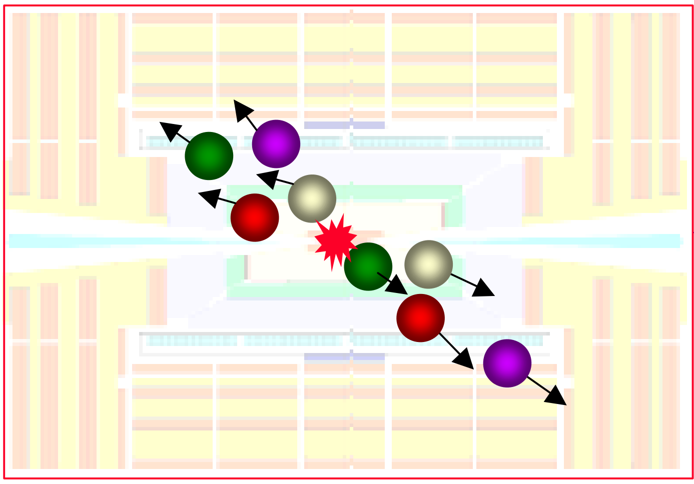


- Usually we can only ‘see’ the end products of the reaction, but not the reaction itself.
- In order to reconstruct the reaction mechanism and the properties of the involved particles, we want the maximum information about the end products !

The 'ideal' particle detector should provide…

detector

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



end products
- charged
- neutral
- photons

- 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)

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.

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Some important definitions and units

$$E^2 = \vec{p}^{\,2} c^2 + m_0^2 c^4$$

- energy E: measure in eV
- momentum p: measure in eV/c
- mass m_o: measure in eV/c^2

$$b = \frac{v}{c} \qquad (0 \le b < 1) \qquad g = \frac{1}{\sqrt{1-b^2}} \qquad (1 \le g < \infty)$$

$$E = m_0 g c^2 \qquad p = m_0 g b c \qquad b = \frac{pc}{E}$$

1 eV is a tiny portion of energy. 1 eV = $1.6 \cdot 10^{-19}$ J

$m_{bee} = 1g = 5.8 \cdot 10^{32}\ eV/c^2$

$v_{bee} = 1m/s \ \rightarrow E_{bee} = 10^{-3}\ J = 6.25 \cdot 10^{15}\ eV$

$E_{LHC} = 14 \cdot 10^{12}\ eV$

To rehabilitate LHC…

Total stored beam energy:

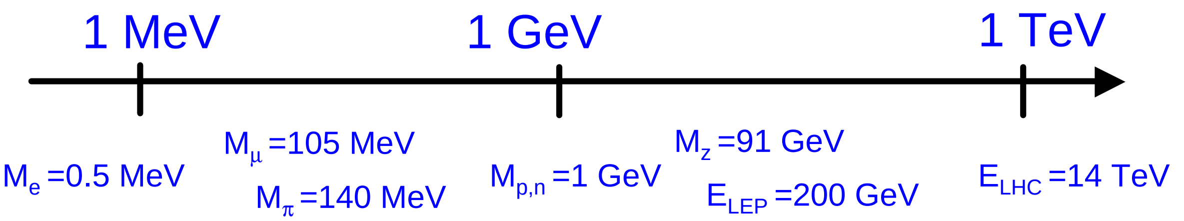
10^{14} protons * $14 \cdot 10^{12}$ eV $\approx 1 \cdot 10^{8}$ J

this corresponds to a 

$m_{truck} = 100$ T

$v_{truck} = 120$ km/h

Some important masses/energies



For lengths we will often use units like

- 1 μm (10^{-6} m), e.g. spatial resolution of detectors
- 1 nm (10^{-9} m), wavelength of green light λ = 500 nm
- 1 A (10^{-10} m), size of an atom
- 1 fm = 1 fermi (10^{-15} m), size of a proton

For times practical units are

- 1 μs (10^{-6} s), an electron drifts in a gas 5 cm
- 1 ns (10^{-9} s), a relativistic e^- travels 30 cm
- 1 ps (10^{-12} s), mean life time of a B meson

- Very useful relation: $\hbar c \approx 200 \text{ MeV} \cdot \text{fm}$

  e.g. convert λ ⇔ E of a photon $E = \frac{hc}{l} = 2p\frac{\hbar c}{l} \approx \frac{1240}{l}$

- To make the formulae less bulky, particle physicists

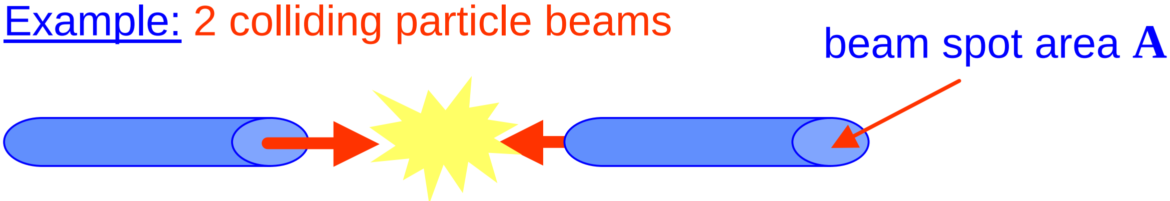
  set $\hbar = c = 1$

  e.g. $E^2 = \vec{p}^2 + m_0^2$ [E] = [p] = [m] = 1 eV

The concept of cross sections

Cross sections s or differential cross sections **d**s/**d**W are used to express the probability of interactions between elementary particles.

Example: 2 colliding particle beams



$\Phi_1 = N_1/t$ $\Phi_2 = N_2/t$

What is the interaction rate $R_{int.}$?

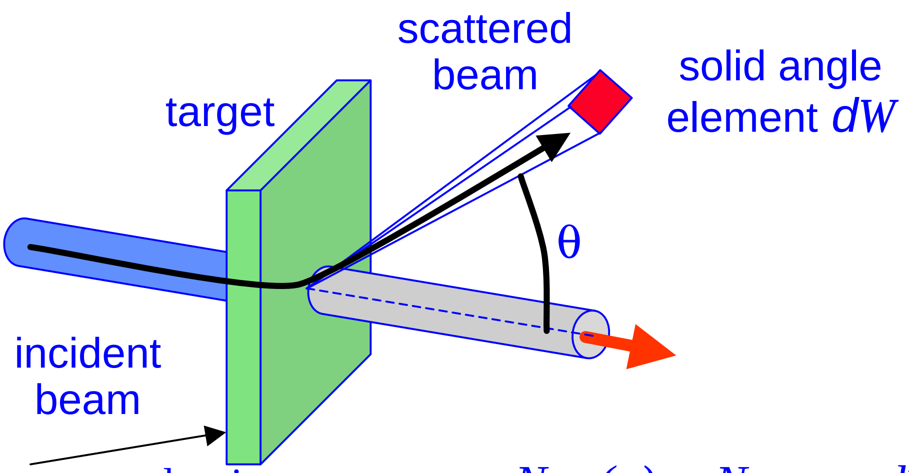
$$R_{int} \mu \underbrace{N_1 N_2 / (A \cdot t)}_{\text{Luminosity } L \; [\text{cm}^{-2}\,\text{s}^{-1}]} = s \cdot L$$

σ has dimension area !

Practical unit:

1 barn (b) = 10^{-24} cm^2

Example: Scattering from target



n_A = area density of scattering centers in target

$$N_{scat}(q) \mu N_{inc} \cdot n_A \cdot dW$$
$$= ds/dW\,(q) \cdot N_{inc} \cdot n_A \cdot dW$$

Tracking

Momentum measurement

Multiple scattering

Bethe-Bloch formula
/ Landau tails

Ionization of gases

Wire chambers

Drift and diffusion in gases

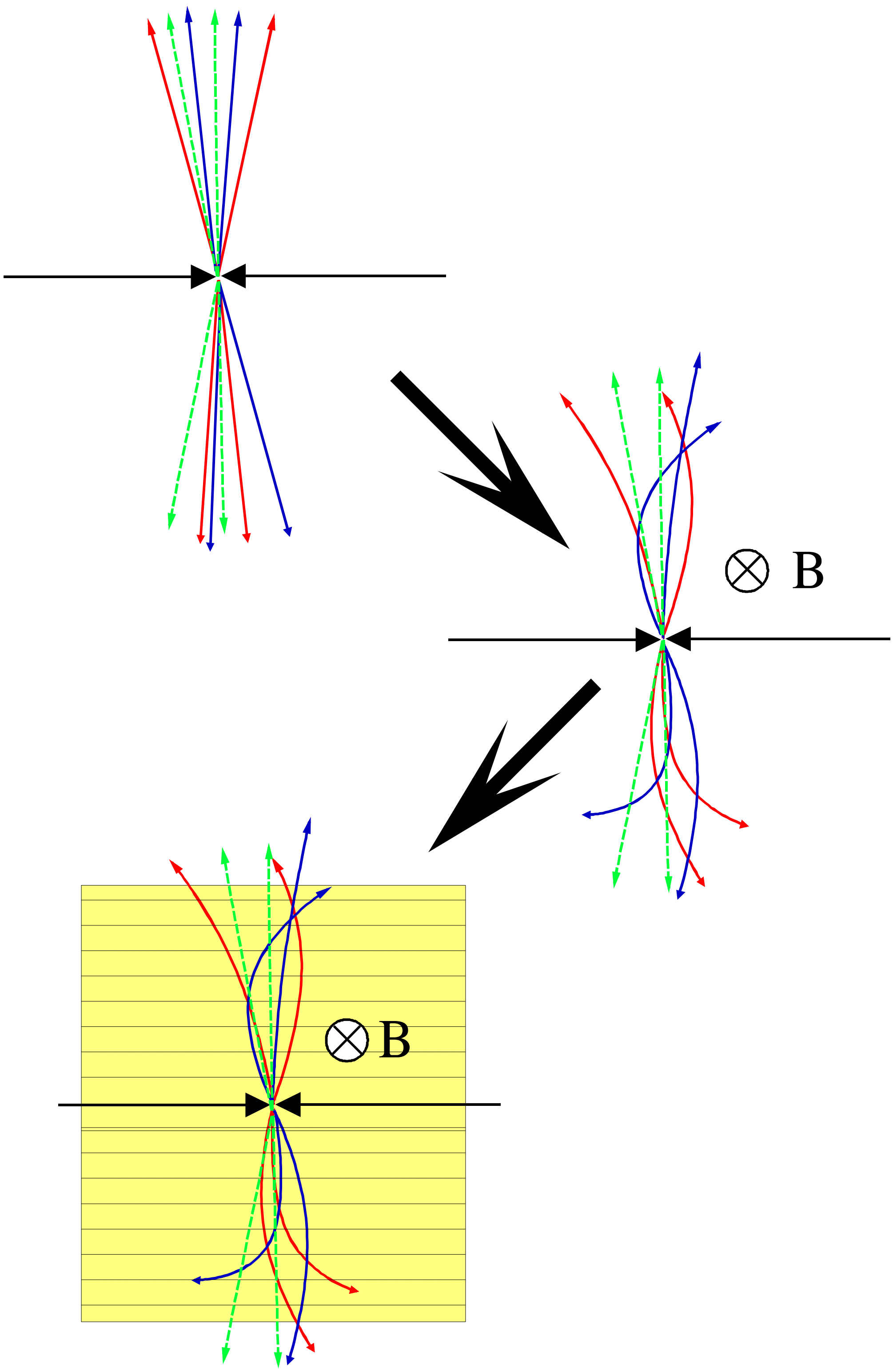
Drift chambers

Micro gas detectors

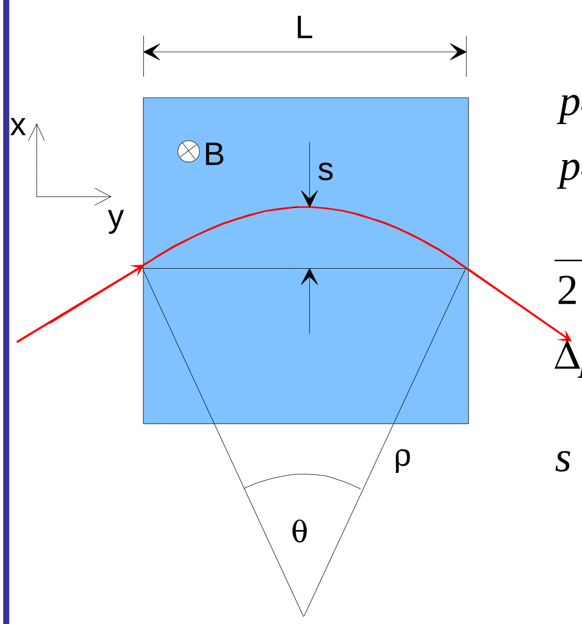
Silicon as a detection medium

Silicon detectors strips/pixels

Momentum measurement



Momentum measurement



$$p_T = qBr$$

$$p_T\ (\mathrm{GeV/c}) = 0.3Br \quad (\mathrm{T \cdot m})$$

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

$$\Delta p_T = p_T \sin q \approx 0.3L \cdot B$$

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

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

$$s = x_2 - \frac{x_1 + x_3}{2}$$

$$\left.\frac{s(p_T)}{p_T}\right|^{meas.} = \frac{s(s)}{s} = \frac{\sqrt{\frac{3}{2}}s(x)}{s} = \frac{\sqrt{\frac{3}{2}}s(x) \cdot 8p_T}{0.3 \cdot BL^2}$$

for N equidistant measurements, one obtains

(R.L. Gluckstern, NIM 24 (1963) 381)

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

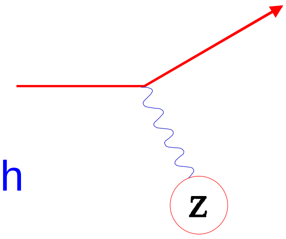
(for N ≥ ≈10)

ex: p_T=1 GeV/c, L=1m, B=1T, σ(x)=200μm, N=10

$$\left.\frac{s(p_T)}{p_T}\right|^{meas.} \approx 0.5\%$$

(s ≈ 3.75 cm)

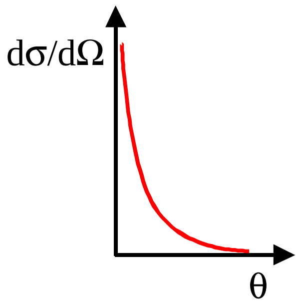
Scattering



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

$$\frac{ds}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{bp}\right)^2 \frac{1}{\sin^4 q/2}$$

Rutherford formula

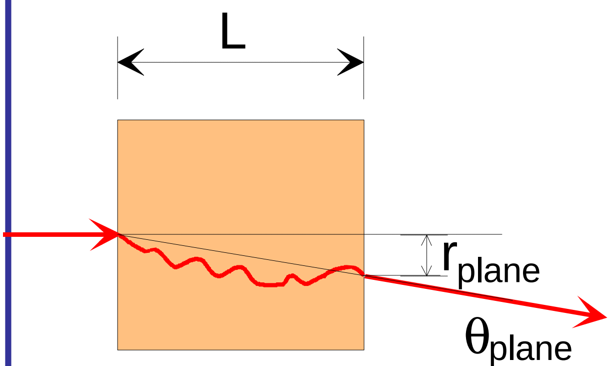


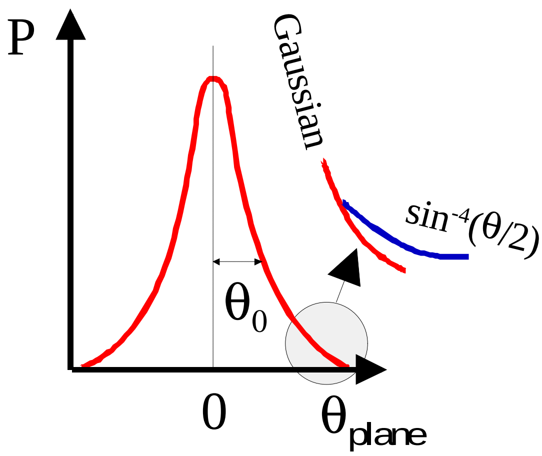
- Average scattering angle $\langle q \rangle = 0$
- Cross-section for $q \rightarrow 0$ infnite !

Multiple Scattering

Sufficiently thick material layer

→ the particle will undergo multiple scattering.





$$q_0 = q^{RMS}_{plane} = \sqrt{\langle q_{plane}^{\ 2} \rangle} = \frac{1}{\sqrt{2}} q^{RMS}_{space}$$

Approximation $$q_0 = \frac{13.6\ MeV}{bcp} z \sqrt{\frac{L}{X_0}} \left\{ 1 + 0.038 \ln\left(\frac{L}{X_0} \right) \right\}$$

X_0 is radiation length of the medium (discuss later)

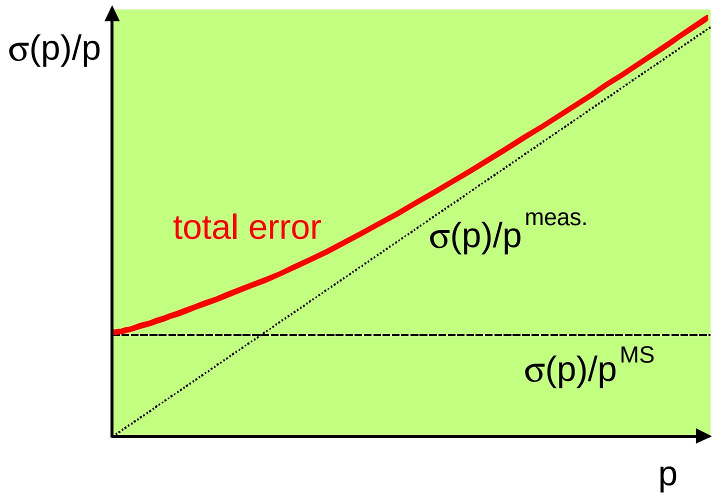
(accuracy ≤ 11% for $10^{-3} < L/X_0 < 100$)

Back to momentum measurements:

contribution from multiple scattering

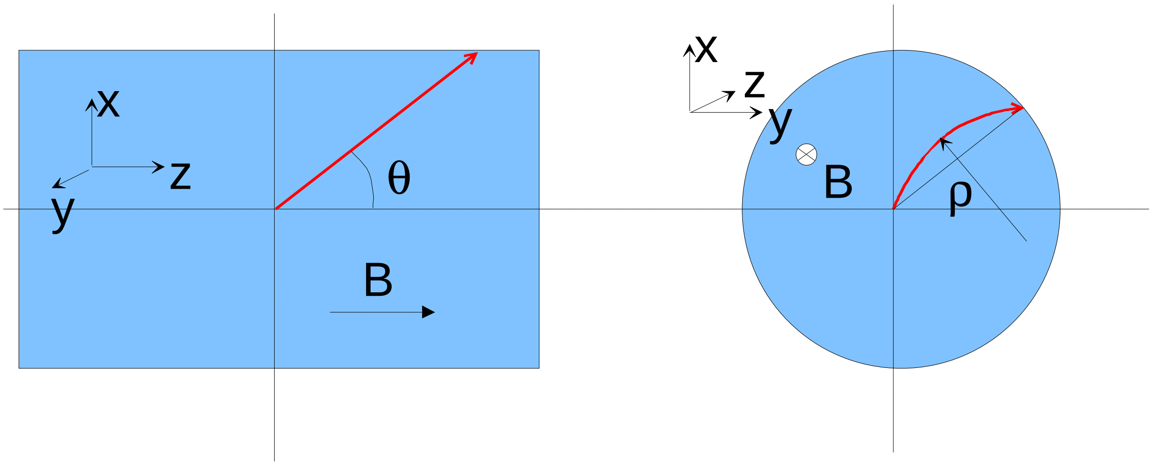
$$\Delta p^{MS} = p \sin q_0 \approx p \cdot 0.0136 \frac{1}{p} \sqrt{\frac{L}{X_0}}$$

$$\left. \frac{s(p)}{p_T} \right|^{MS} = \frac{\Delta p^{MS}}{\Delta p_T} = \frac{0.0136 \sqrt{\frac{L}{X_0}}}{0.3BL} = 0.045 \frac{1}{B\sqrt{LX_0}}$$ independent of p !



ex: Ar (X_0=110m), L=1m, B=1T $$\left. \frac{s(p)}{p_T} \right|^{MS} \approx 0.5\%$$

Momentum measurement in experiments with solenoid magnet:



$$p_T = p \sin q$$

polar angle has to be determined from a straight line fit x=x(z).

N equidistant points with error *s(z)*

$$s(q)\Big|^{meas.} = \frac{s(z)}{L}\sqrt{12(N-1)/(N(N+1))}$$

+ multiple scattering contribution…. } normally small

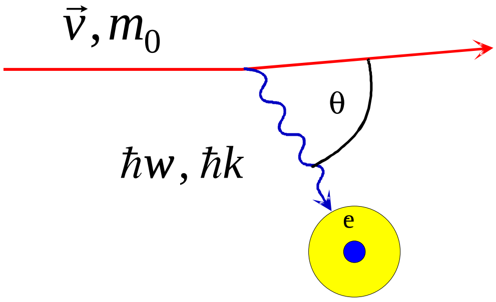
In practical cases: $\frac{s(p)}{p} \approx \frac{s(p_T)}{p_T}$

In summary: $\left.\frac{s(p)}{p}\right|^{meas.} \propto \frac{s(x)\cdot p}{BL^2}\frac{1}{\sqrt{N}}$

Detection of charged particles

How do they loose energy in matter ?

- Discrete collisions with the atomic electrons of the absorber material.



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

N : electron density

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

- If $\hbar w, \hbar k$ are big enough ⇨ ionization.

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

⇨ Emission of **Cherenkov** and **Transition** radiation. (See later).

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

Ionisation only → Bethe - Bloch formula

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

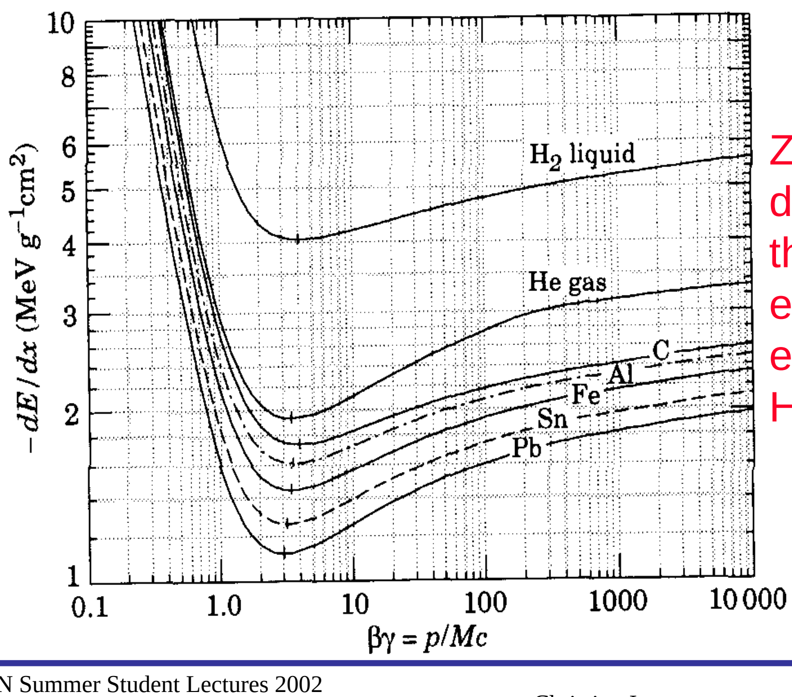
- dE/dx in [MeV g^{-1} cm^2]
- dE/dx depends only on β, independent of m
- Formula takes into account energy transfers

$$I \le dE \le T^{max} \qquad I : \text{mean excitation potential}$$

$$I \approx I_0 Z \ \text{ with } \ I_0 = 10 \text{ eV}$$

(rough approximation, I fitted for each element)

- Bethe-Bloch formula only valid for "heavy" particles ($m \ge m_\mu$).
- Electrons and positrons need special treatment ($m_{proj} = m_{target}$), in addition Bremsstrahlung!



Z/A does not differ much for the various elements, except for Hydrogen!

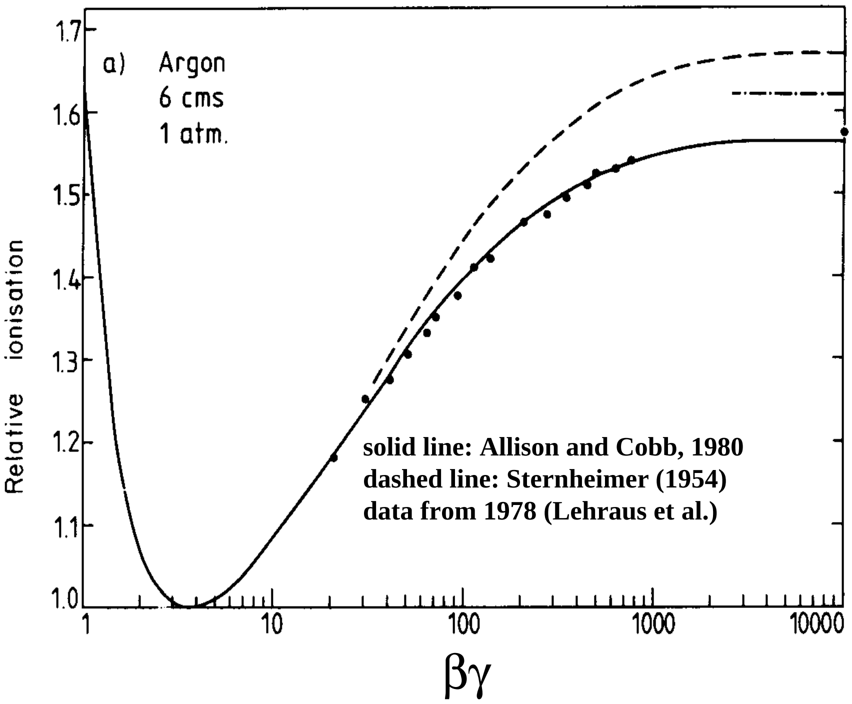
Bethe-Bloch formula

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

- dE/dx first falls $\propto 1/\beta^2$ (more precise $\beta^{-5/3}$), kinematic factor
- then minimum at $\beta\gamma \approx 4$ (minimum ionizing particles, MIP)

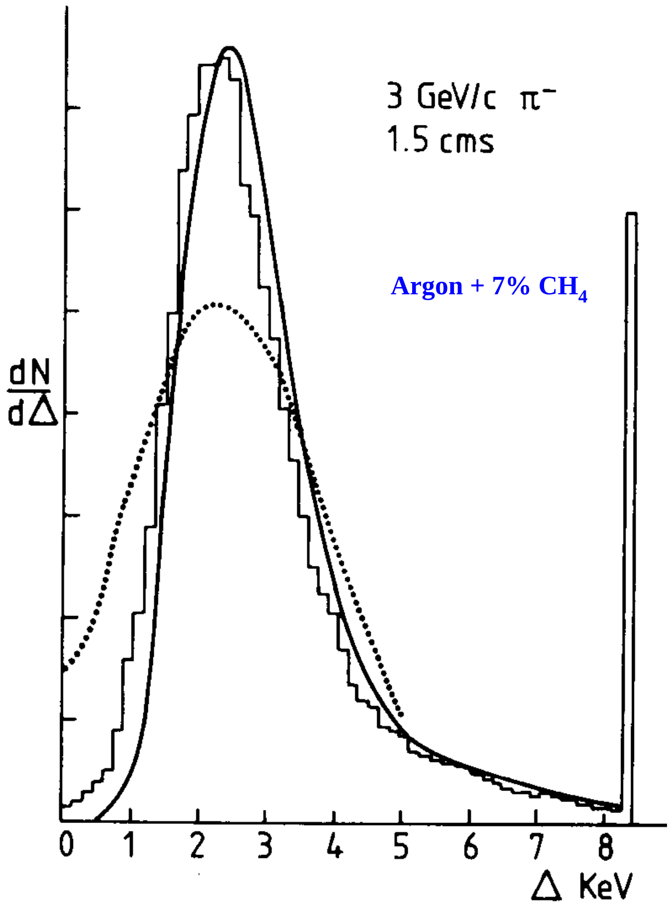
  (dE/dx $\approx$ 1 - 2 MeV g^{-1} cm^2)
- then again rising due to ln γ^2 term, relativistic rise, attributed to relativistic expansion of transverse E-field $\rightarrow$ contributions from more distant collisions.
- relativistic rise cancelled at high γ by "density effect", polarization of medium screens more distant atoms. Parameterized by δ (material dependent) $\rightarrow$ Fermi plateau
- many other small corrections

Measured and calculated dE/dx



Real detectors (limited granularity) do not measure <dE/dx>, but the energy ΔE deposited in a layer of finite thickness δx.

For thin layers (and low density materials):
$\rightarrow$ Few collisions, some with high energy transfer.
$\rightarrow$ Energy loss distributions show large fluctuations towards high losses: "Landau tails"

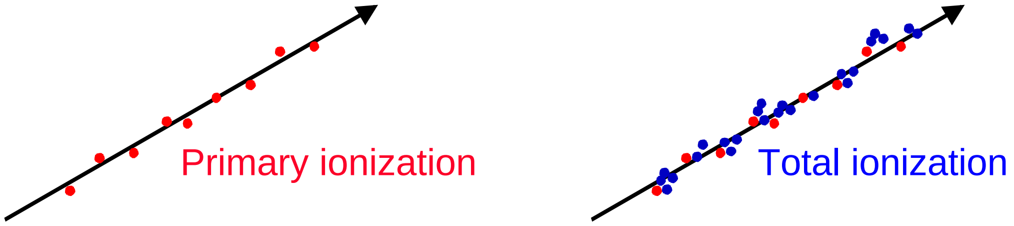


data: Harris et al. (1977)
dotted curve: Landau(1944)
solid curve: Allison and Cobb (1980)

For thick layers and high density materials:
$\rightarrow$ Many collisions.
$\rightarrow$ Central Limit Theorem $\rightarrow$ Gaussian shape distributions.

Primary and total ionization

Fast charged particles ionize the atoms of a gas.



Often the resulting primary electron will have enough kinetic energy to ionize other atoms.

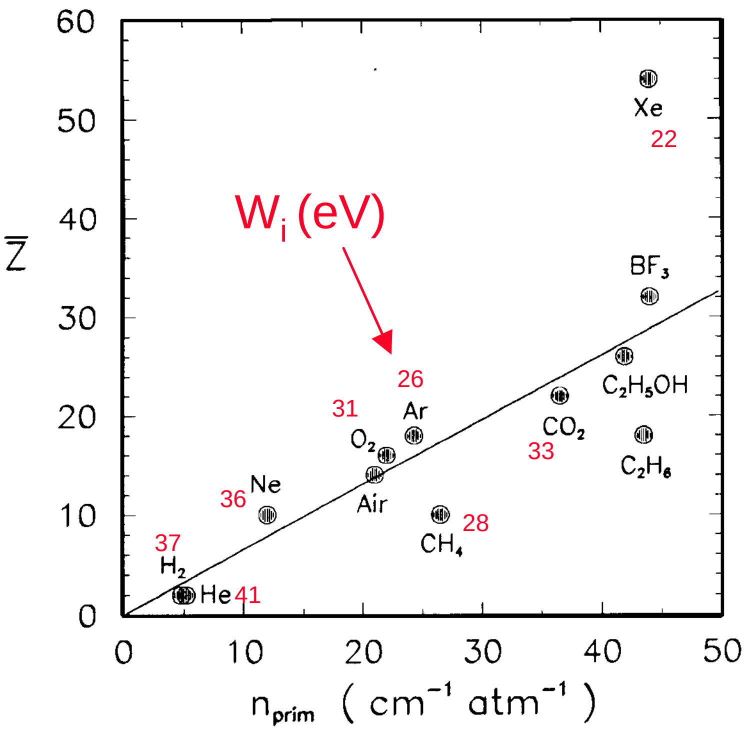
$$n_{total} = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx}\Delta x}{W_i}$$

$$n_{total} \approx 3 \ldots 4 \cdot n_{primary}$$

total number of created electron-ion pairs.
ΔE = total energy loss
W_i = effective <energy loss>/pair

Number of primary electron/ion pairs in frequently used (detector) gases.

(Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific,1992)



Proportional Counter

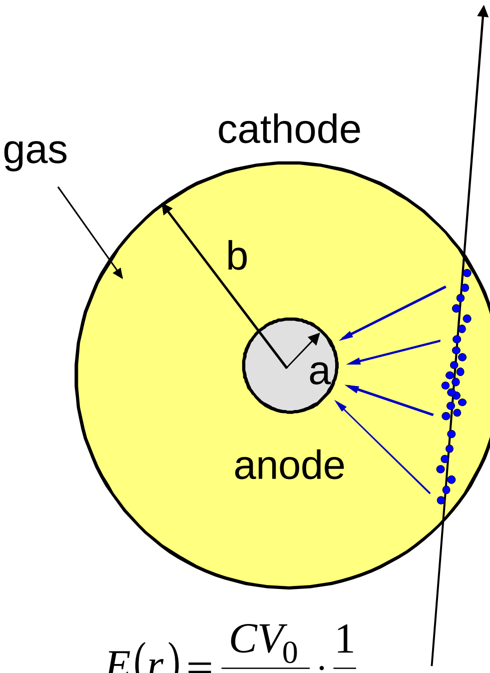
≈ 100 electron-ion pairs are not easy to detect!

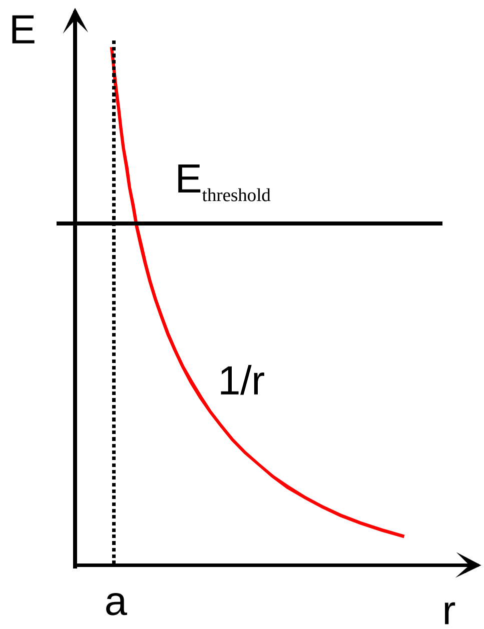
Noise of amplifier ≈1000 e^- (ENC) !

We need to increase the number of e-ion pairs.

<u>Gas amplification</u>

Consider cylindrical field geometry (simplest case):





$$E(r) = \frac{CV_0}{2\pi\epsilon_0} \cdot \frac{1}{r}$$

$$V(r) = \frac{CV_0}{2\pi\epsilon_0} \cdot \ln\frac{r}{a}$$

C = capacitance / unit length

Electrons drift towards the anode wire (≈ stop and go! More details in next lecture!).

Close to the anode wire the field is sufficiently high (some kV/cm), so that e^- gain enough energy for further ionization → <u>exponential increase</u> of number of e^--ion pairs.

$$n = n_0 e^{\alpha(E)x} \quad \text{or} \quad n = n_0 e^{\alpha(r)x}$$

α: First Townsend coefficient (e⁻-ion pairs/cm)

$$\alpha = \frac{1}{\lambda}$$

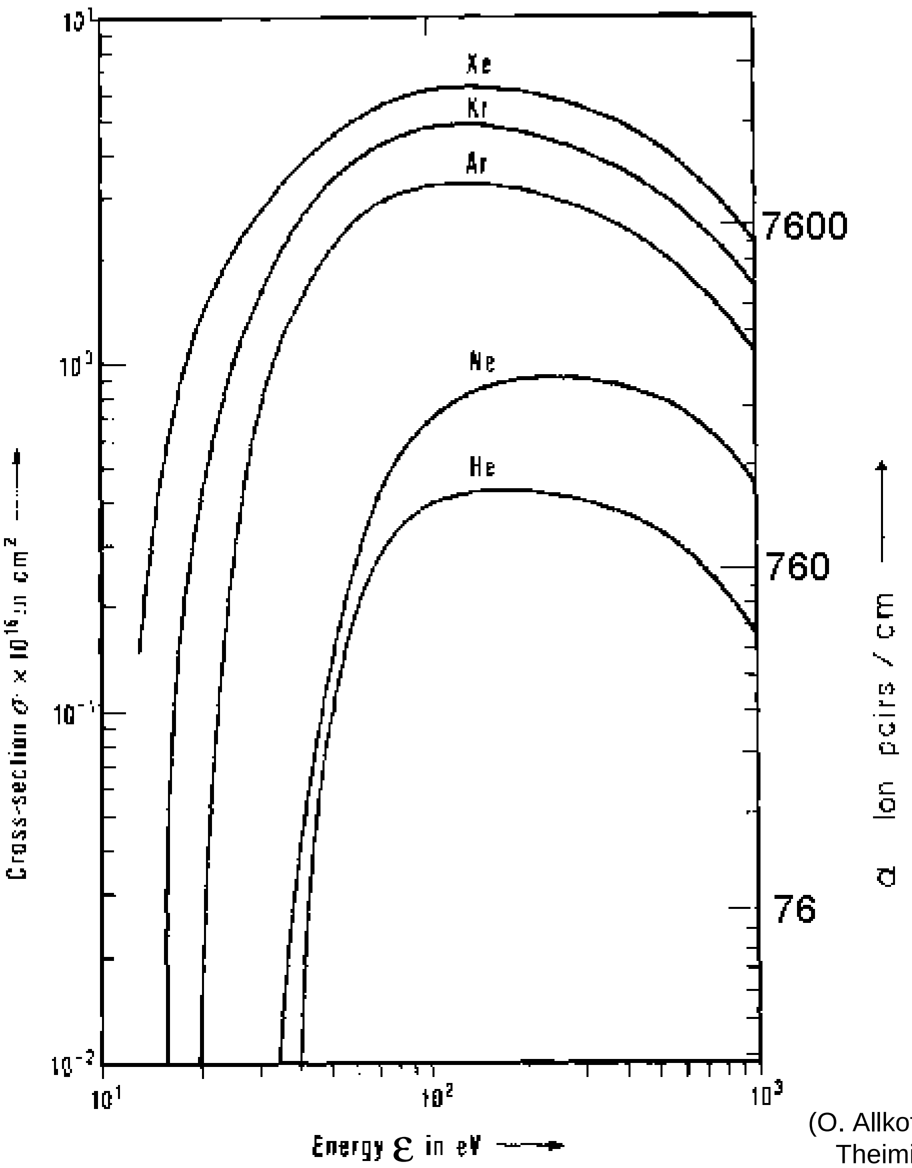
λ: mean free path

$$M = \frac{n}{n_0} = \exp\left[\int_a^{r_C} \alpha(r)dr\right]$$

Gain

$$M \approx k e^{CV_0}$$

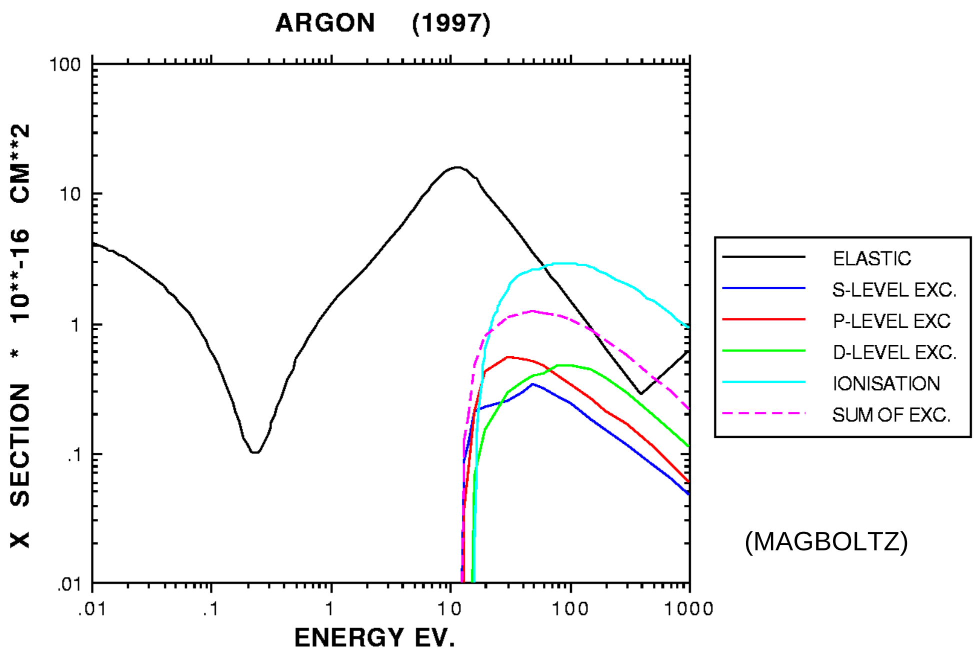
(F. Sauli, CERN 77-09)



(O. Allkofer, Spark chambers, Theimig München, 1969)

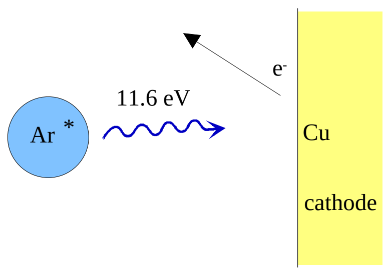
Choice of gas:

Dense noble gases. Energy dissipation mainly by ionization! High specific ionization.



De-excitation of noble gases only possible via emission of photons, e.g. 11.6 eV for Argon.

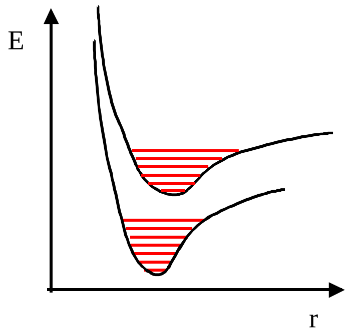
This is above ionization threshold of metals, e.g. Copper 7.7 eV.



→ new avalanches → permanent discharges !

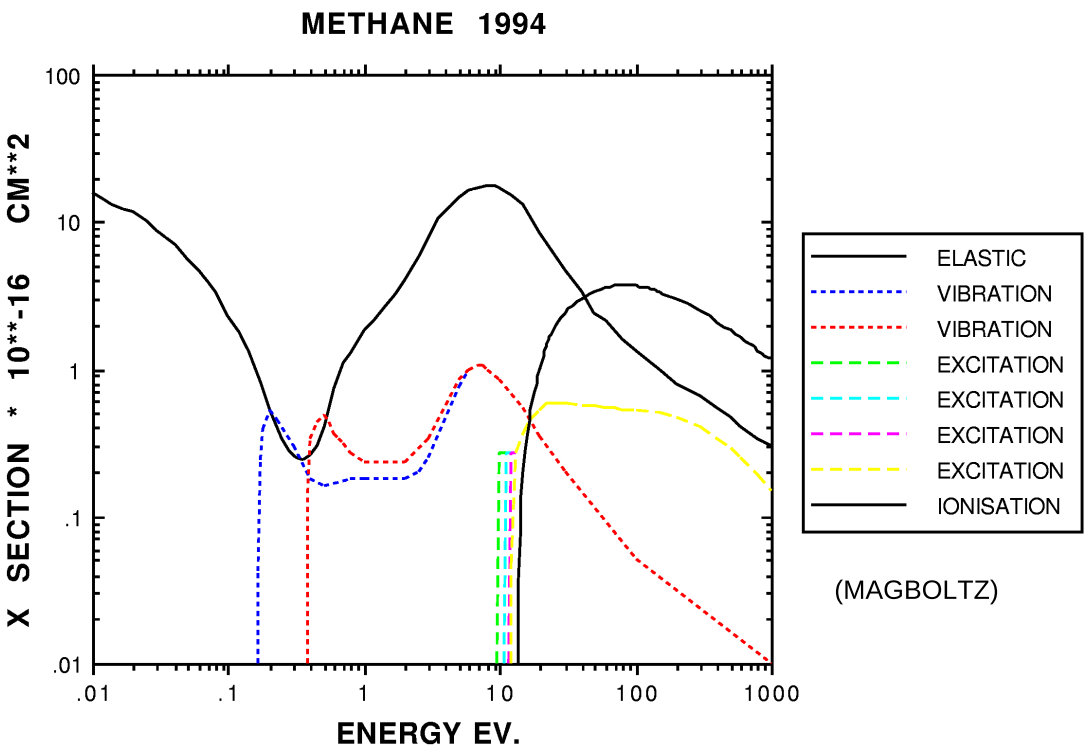
Solution: Add poly-atomic gases as quenchers.

Absorption of photons in a large energy range (many vibrational and rotational energy levels).

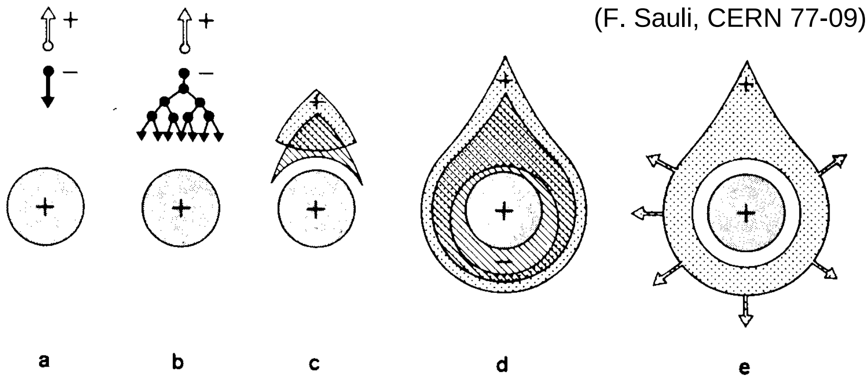


Energy dissipation by collisions or dissociation into smaller molecules.

Methane: absorption band 7.9 - 14.5 eV



Signal formation



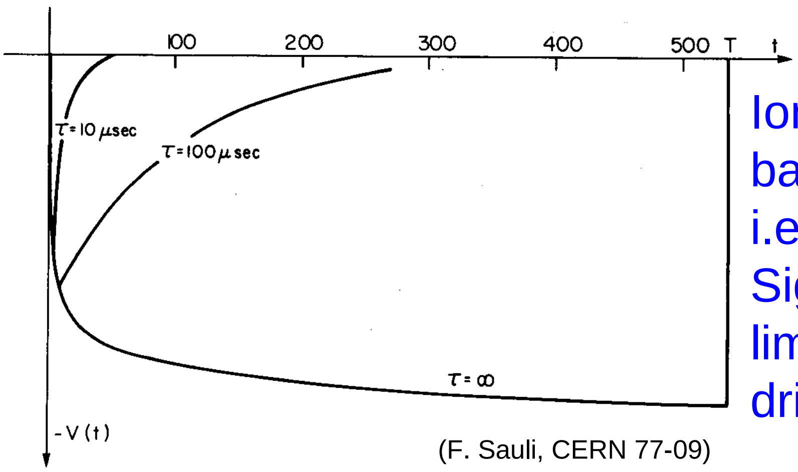
(F. Sauli, CERN 77-09)

Avalanche formation within a few wire radii and within t < 1 ns!

Signal induction both on anode and cathode due to moving charges (both electrons and ions).

$$dv = \frac{Q}{lCV_0}\frac{dV}{dr}dr$$

Electrons collected by anode wire, i.e. *dr* is small (few µm). Electrons contribute only very little to detected signal (few %).



(F. Sauli, CERN 77-09)

Ions have to drift back to cathode, i.e. *dr* is big. Signal duration limited by total ion drift time !

Need electronic signal differentiation to limit dead time.

Operation modes:

- ionization mode: full charge collection, but no charge multiplication.
- Proportional mode: above threshold voltage multiplication starts. Detected signal proportional to original ionization → energy measurement (dE/dx). Secondary avalanches have to be quenched. Gain 10^4 - 10^5.
- Limited Proportional → Saturated → Streamer mode: Strong photo-emission. Secondary avalanches, merging with original avalanche. Requires strong quenchers or pulsed HV. High gain (10^{10}), large signals → simple electronics.
- Geiger mode: Massive photo emission. Full length of anode wire affected. Stop discharge by cutting down HV. Strong quenchers needed as well.