Particle Detectors

Summer Student Lecture Series 2001

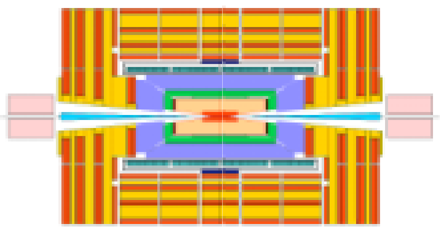
Christian Joram
EP / TA1

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

$1 + 1 \approx 2$

to

rather complex detector systems



Outline

- Introduction
- Tracking (gas, solid state)

} Tue/Wed (2x45 min)

- Scintillation and light detection
- Calorimetry
- Particle Identification

} Thu (2x45 min)

- Electronics and Data Acquisition
- Detector Systems

} Fri (45 min)

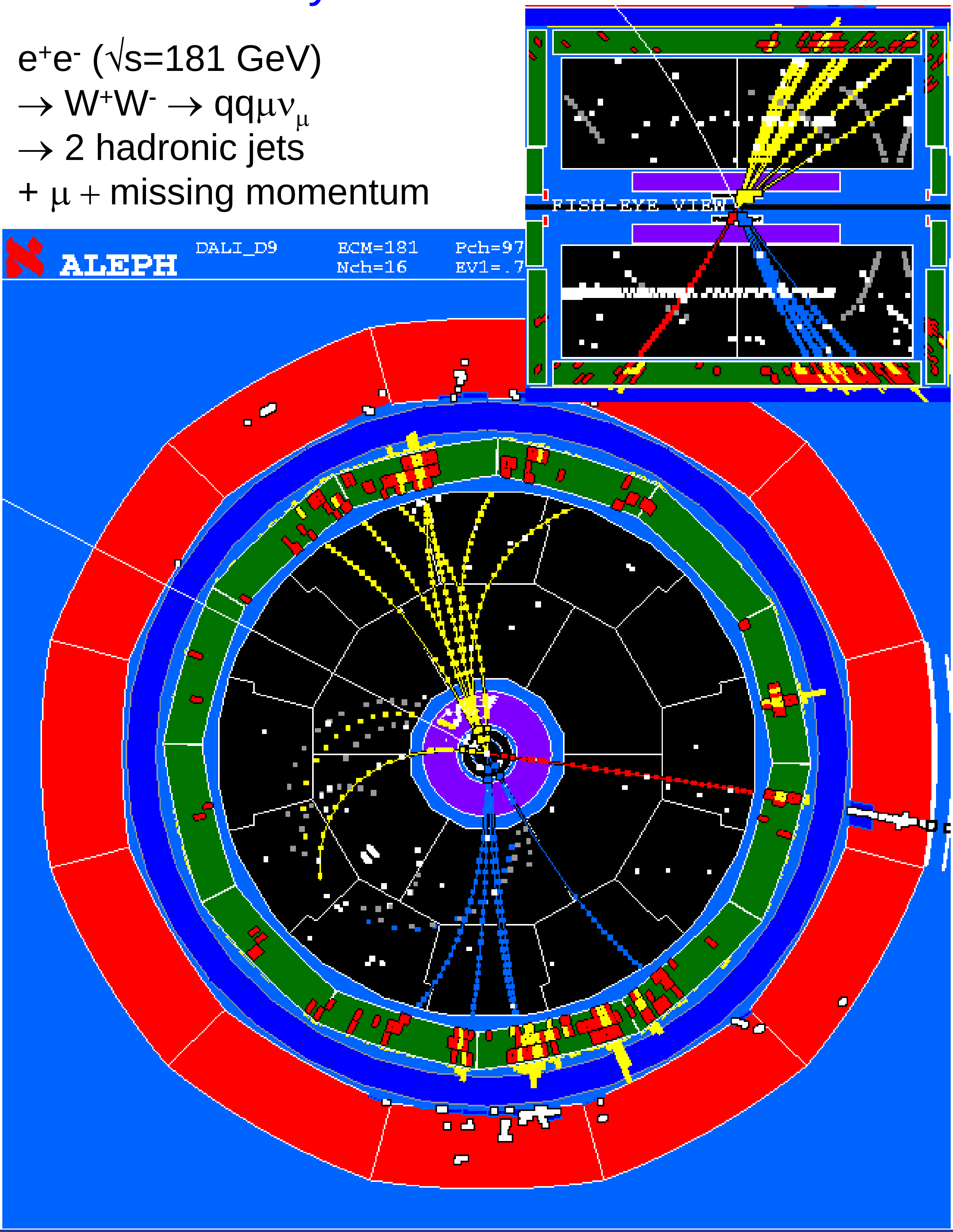
Literature on particle detectors

- 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)

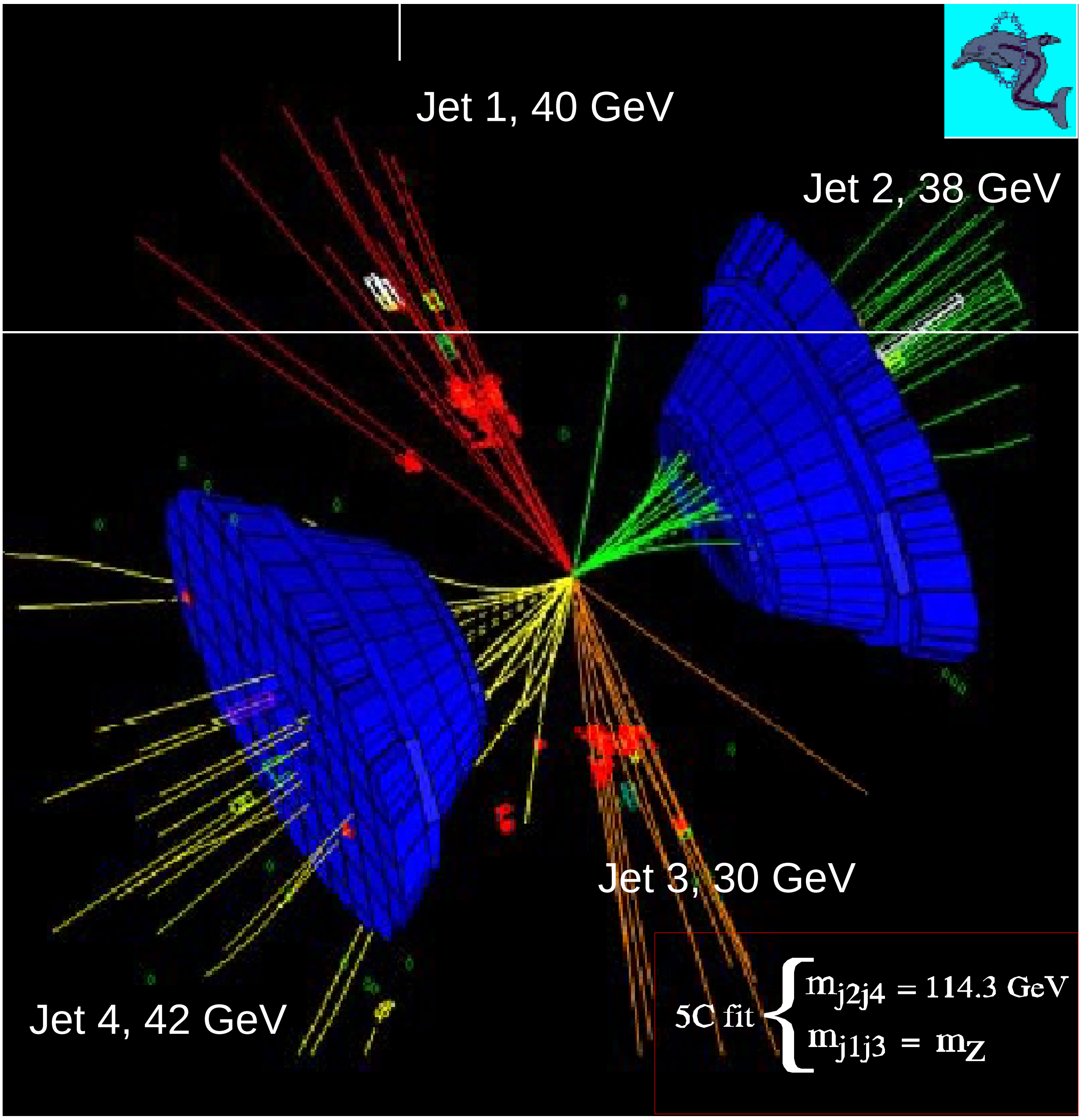
A W^+W^- decay in ALEPH

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



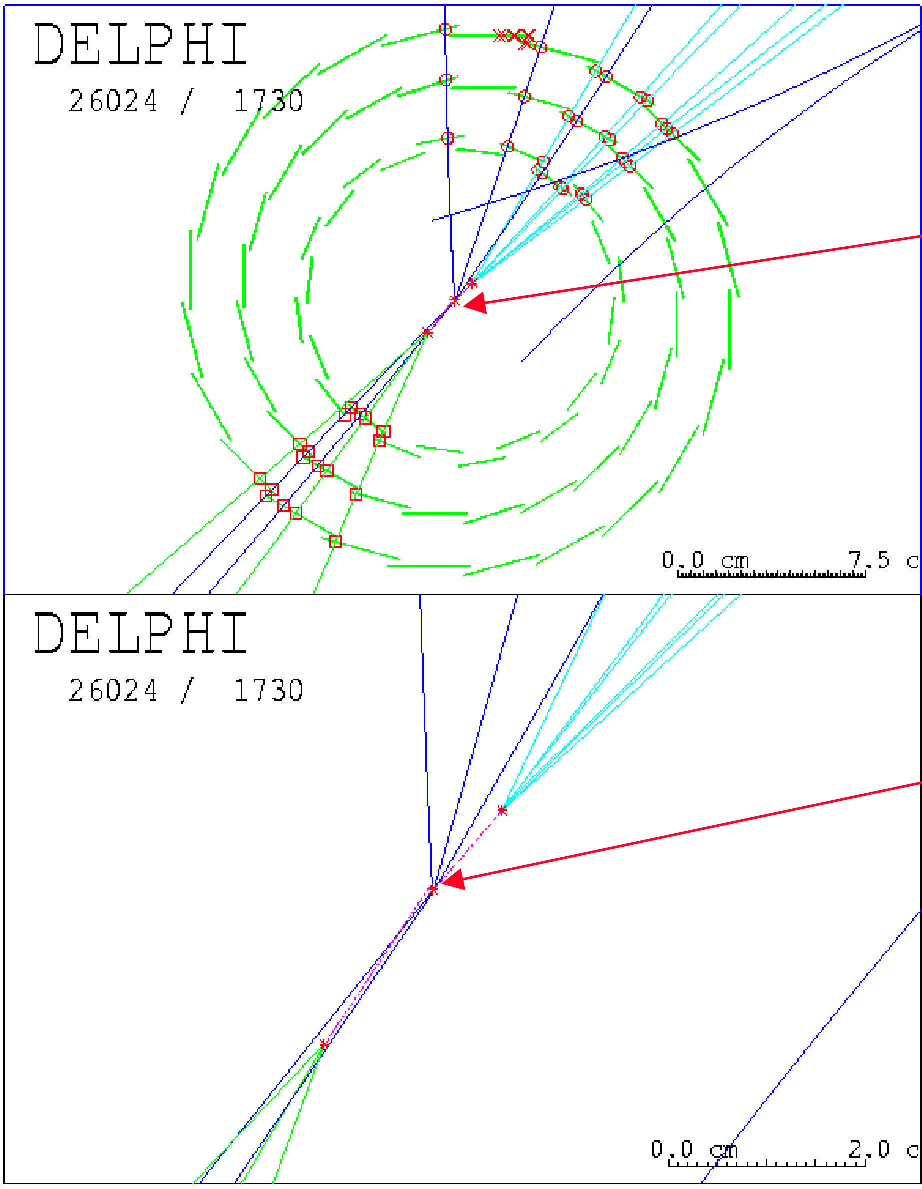
A 4-jet event in DELPHI (a Higgs candidate)

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 $l = c\tau\gamma \approx 500\ \mu m \cdot \gamma$

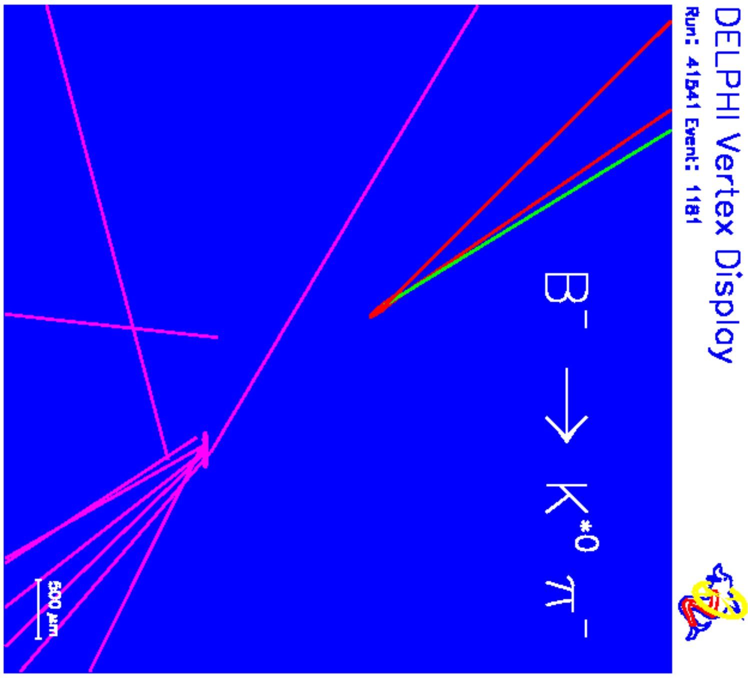


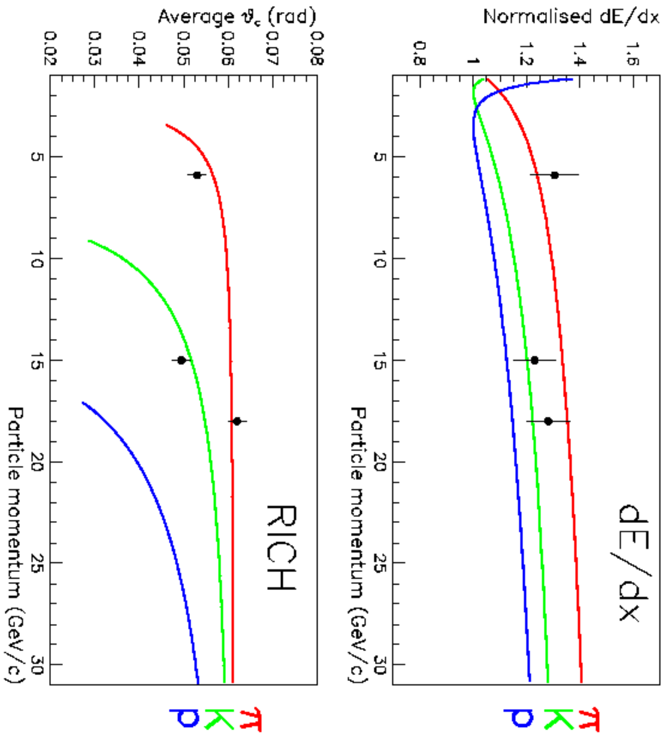
Particle identification methods

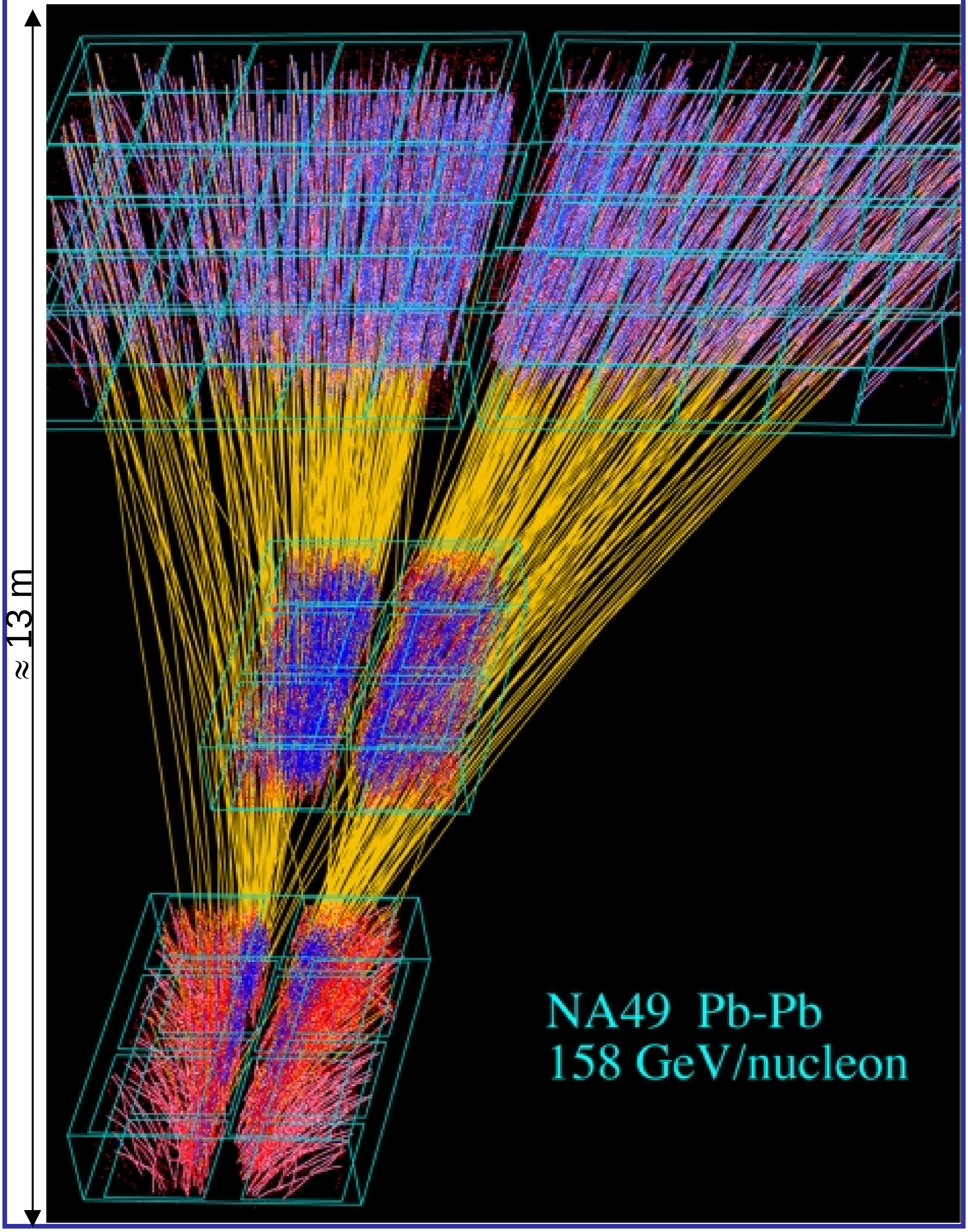
$B^- \to K^* \pi^-$

$\quad\; \hookrightarrow K\pi$

2 K + 1 π in final state






≈ 13 m
NA49 Pb-Pb
158 GeV/nucleon

A simulated event in ATLAS (CMS)

$H \rightarrow ZZ \rightarrow 4\mu$

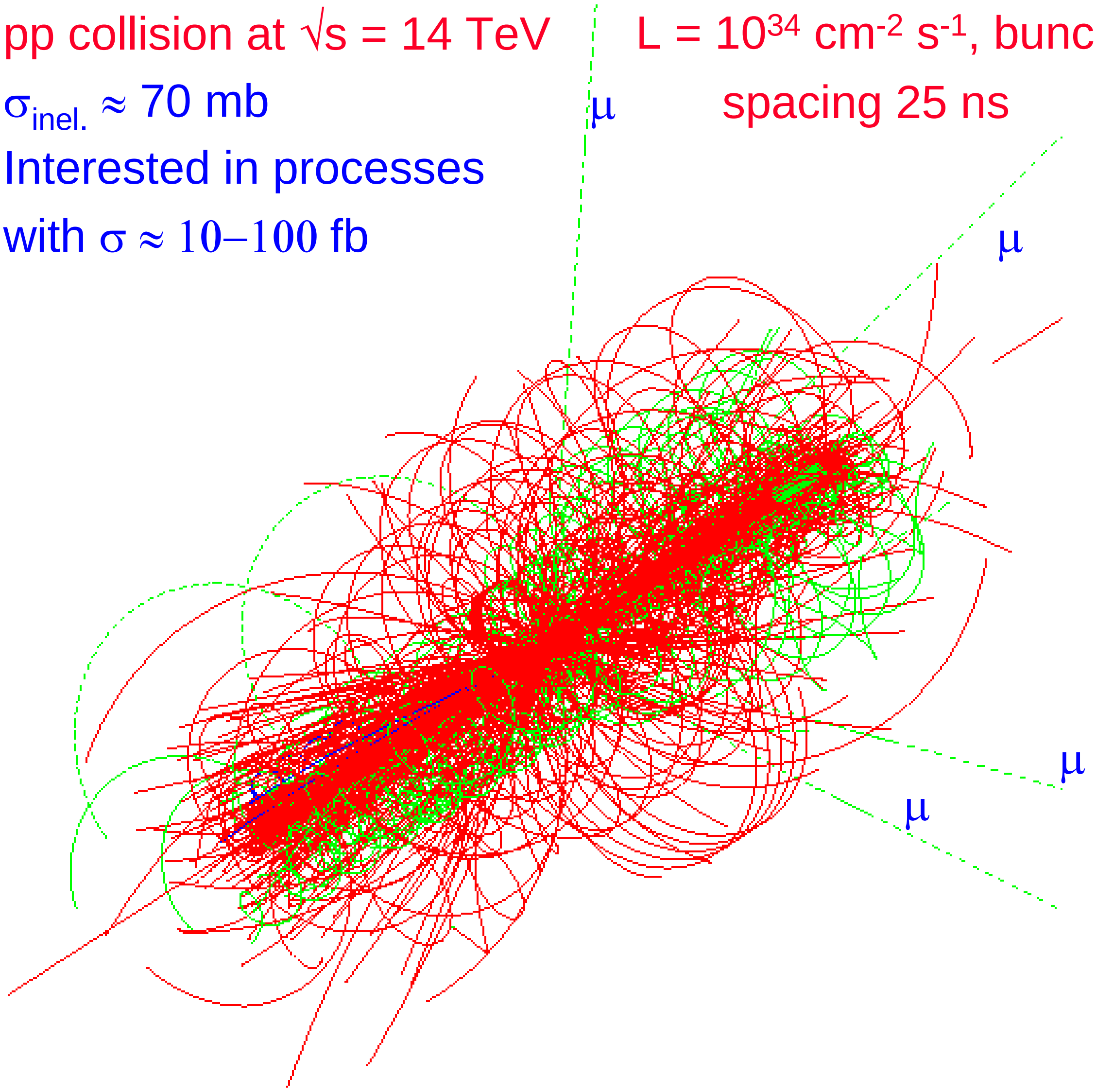
pp collision at $\sqrt{s}$ = 14 TeV

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

Interested in processes

with $\sigma \approx 10\text{–}100$ fb

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



≈ 23 overlapping minimum bias events / BC

≈ 1900 charged + 1600 neutral particles / BC

The 'ideal' particle detector for high energy physics experiments

High energy collisions ($e^+e^-, ep, pp, p\bar{p}$)
$\rightarrow$ production of a multitude of particles (charged, neutral, photons)

The 'ideal' detector should provide….

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

ionization and **excitation** of matter.

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

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$E = m_0\gamma c^2 \qquad p = m_0\gamma\beta c \qquad \beta = \frac{pc}{E}$$

1 eV is a tiny portion of energy. 1 eV = $1.6\cdot10^{-19}$ J

m_{bee} = 1g = $5.8\cdot10^{32}$ eV/c^2

v_{bee}= 1m/s $\rightarrow$ E_{bee} = 10^{-3} J = $6.25\cdot10^{15}$ eV

E_{LHC} = $14\cdot10^{12}$ eV

To rehabilitate LHC…

Total stored beam energy:

10^{14} protons * $14\cdot10^{12}$ eV $\approx$ $1\cdot10^{8}$ J

this corresponds to a

m_{truck} = 100 T

v_{truck} = 120 km/h

Some important masses/energies

1 MeV — 1 GeV — 1 TeV

M_e =0.5 MeV

M_μ =105 MeV

M_π =140 MeV

$M_{p,n}$ =1 GeV

M_z =91 GeV

E_{LEP} =200 GeV

E_{LHC} =14 TeV

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: $\hbar c \approx 200\ \mathrm{MeV} \cdot \mathrm{fm}$

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

- To make the formulae less bulky, particle physicists set $\hbar = c = 1$

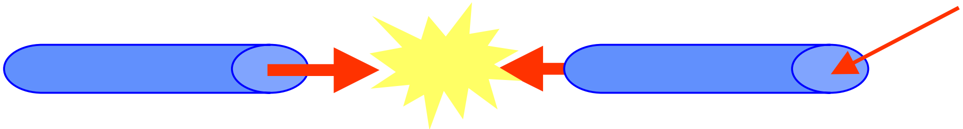
  e.g. $E^2 = \vec{p}^2 + m_0^2$ [E] = [p] = [m] = 1 eV

The concept of cross sections

Cross sections **σ** or differential cross sections **dσ/dΩ** are used to express the probability of interactions between elementary particles.

Example 2 colliding particle beams

beam spot area **A**



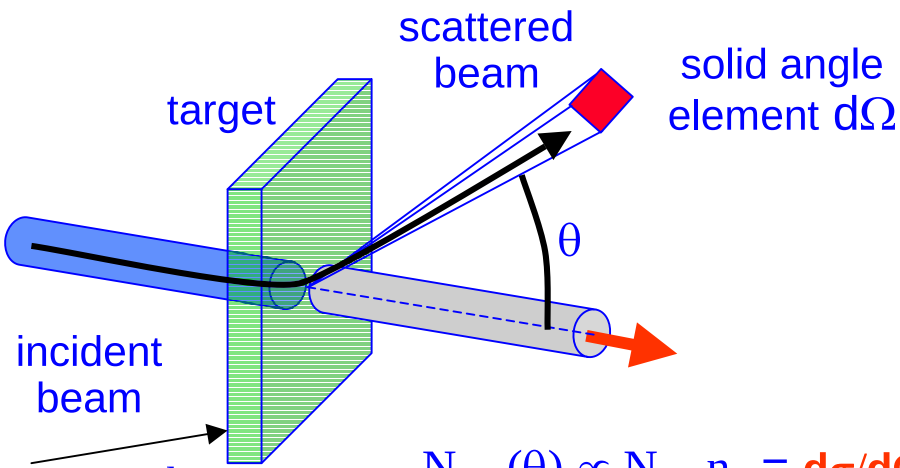
$\Phi_1 = N_1/t$ $\Phi_2 = N_2/t$

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

$$R_{int} \propto \underbrace{\Phi_1 \Phi_2 / A}_{\text{Luminosity } L \ [cm^{-2} s^{-1}]} = \sigma \cdot L$$

σ has dimension area !
Practical unit:
1 barn (b) = 10^{-24} cm^2

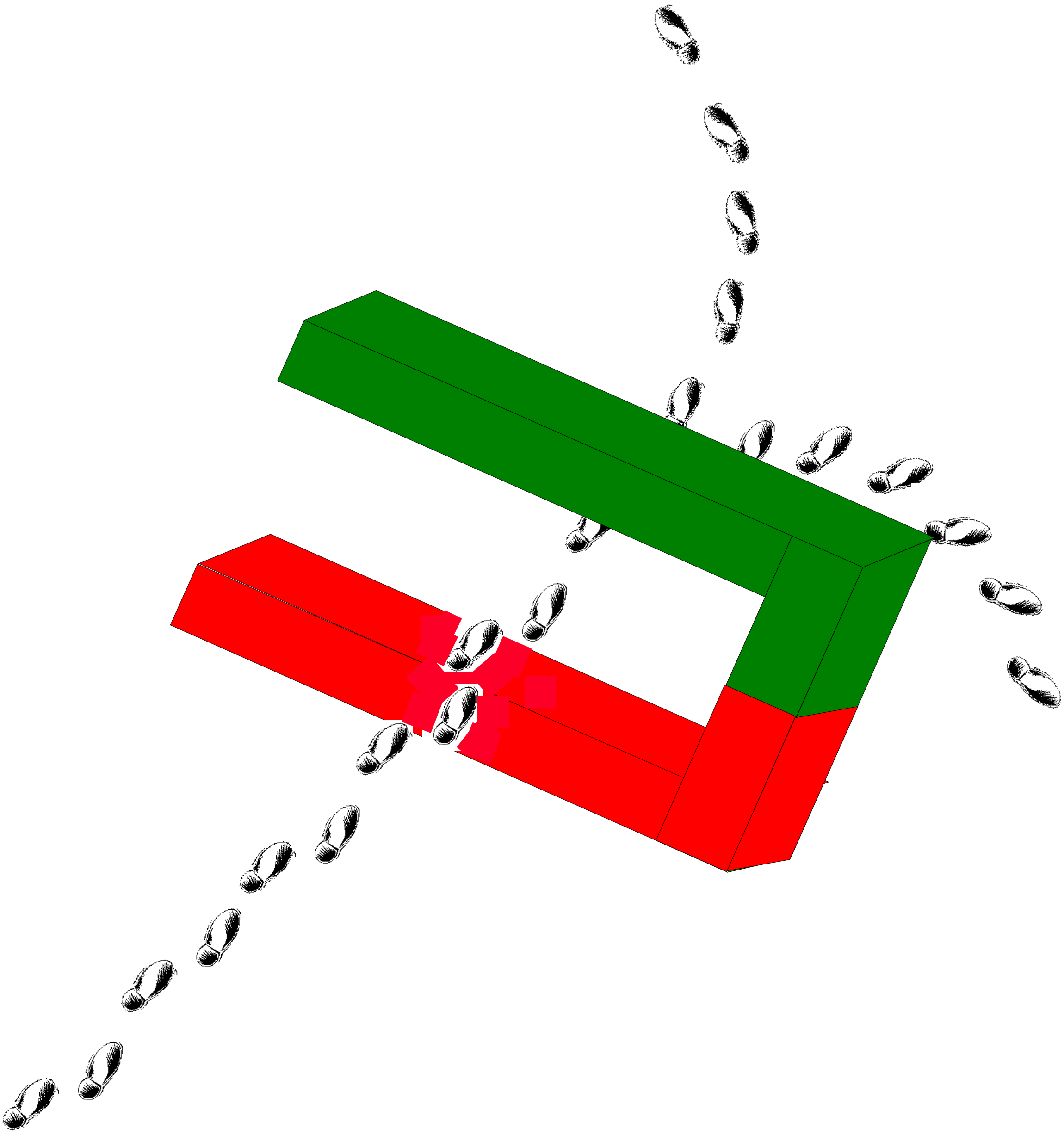
Example: Scattering from target

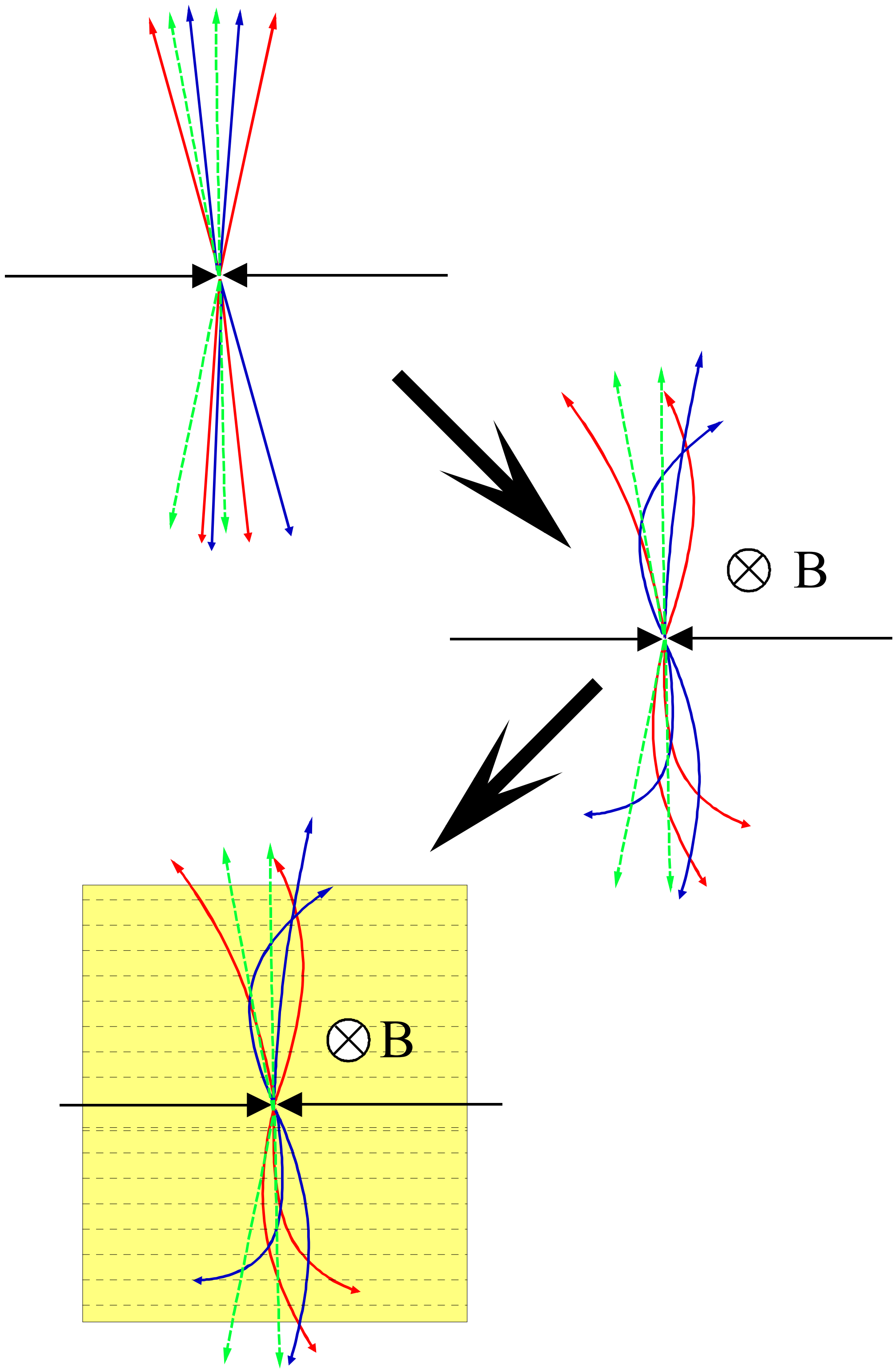


$$N_{scat}(\theta) \propto N_{inc.} n_A = \mathbf{d\sigma/d\Omega}\,(\theta) \cdot N_{inc} \cdot n_A$$

n_A = area density of scattering centers in target

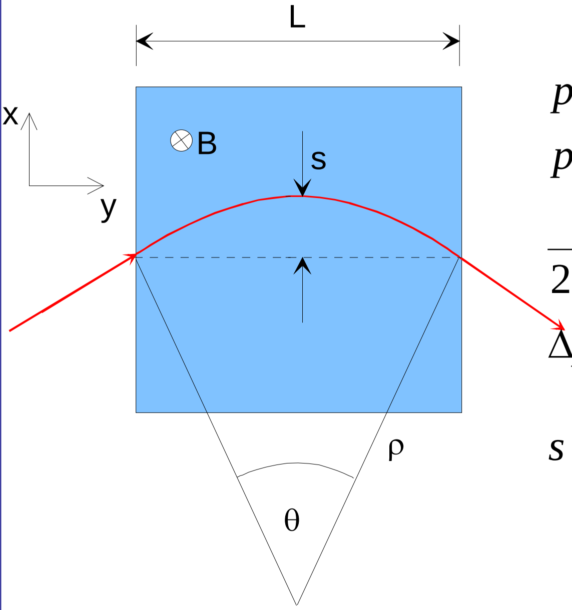
Tracking





⊗ B
⊗B

Momentum measurement



$$p_T = qB\rho$$
$$p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T \cdot m})$$
$$\frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \quad \rightarrow \quad \theta \approx \frac{0.3L \cdot B}{p_T}$$
$$\Delta p_T = p_T \sin\theta \approx 0.3L \cdot B$$
$$s = \rho(1-\cos\theta/2) \approx \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2 B}{p_T}$$

the sagitta s is determined by 3 measurements with error $\sigma(x)$: $s = x_2 - \frac{x_1 + x_3}{2}$

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

for N equidistant measurements, one obtains

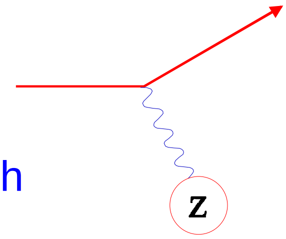
(R.L. Gluckstern, NIM 24 (1963) 381)

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$ (for N ≥ ≈10)

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

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \approx 0.5\%$$ (s ≈ 3.75 cm)

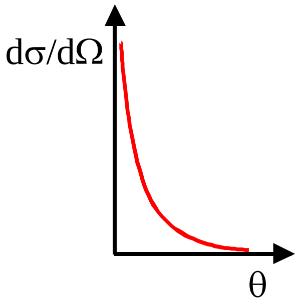
Scattering



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

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

Rutherford formula

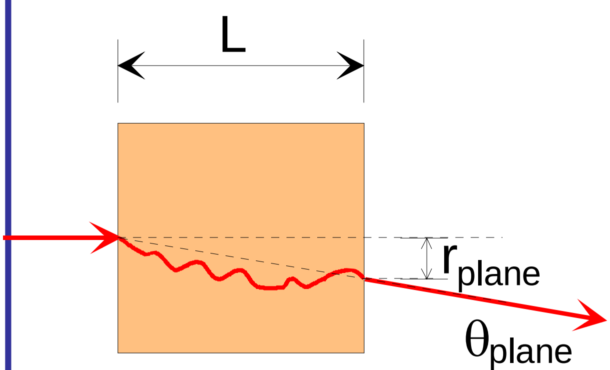


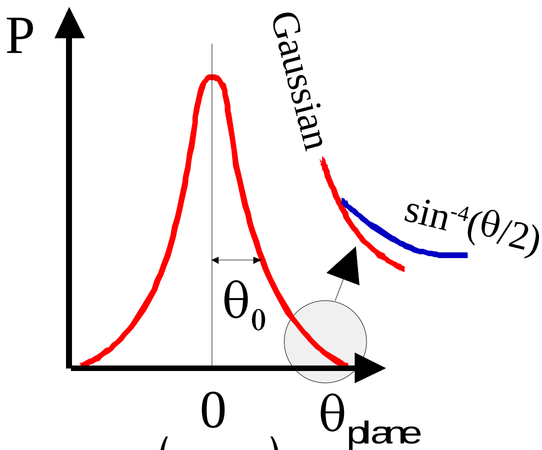
- Average scattering angle $\langle\theta\rangle = 0$
- Cross-section for $\theta \to 0$ infnite !

Multiple Scattering

Sufficiently thick material layer

→ the particle will undergo multiple scattering.





$$\theta_0 = \theta_{plane}^{RMS} = \sqrt{\langle\theta_{plane}{}^2\rangle} = \frac{1}{\sqrt{2}}\theta_{space}^{RMS}$$

$$P(\theta_{plane}) = \frac{1}{\sqrt{2\pi}\theta_0}\exp\left\{-\frac{\theta_{plane}{}^2}{2\theta_0^2}\right\}$$

Approximation $$\theta_0 = \frac{13.6\,MeV}{\beta c p} z \sqrt{\frac{L}{X_0}}\left\{1+0.038\ln\left(\frac{L}{X_0}\right)\right\}$$

X_0 is radiation length of the medium (discuss later)

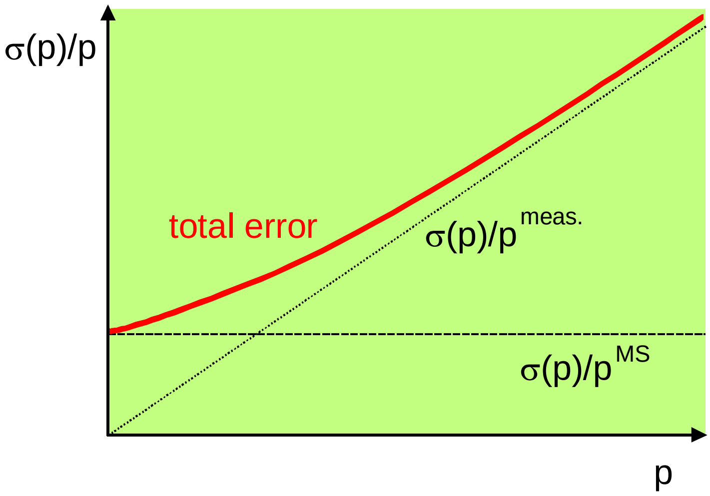
(accuracy $\leq$ 11% for $10^{-3} < L/X_0 < 100$)

Back to momentum measurements: contribution from multiple scattering

$$\Delta p^{MS} = p \sin\theta_0 \approx p \cdot 0.0136 \frac{1}{p}\sqrt{\frac{L}{X_0}}$$

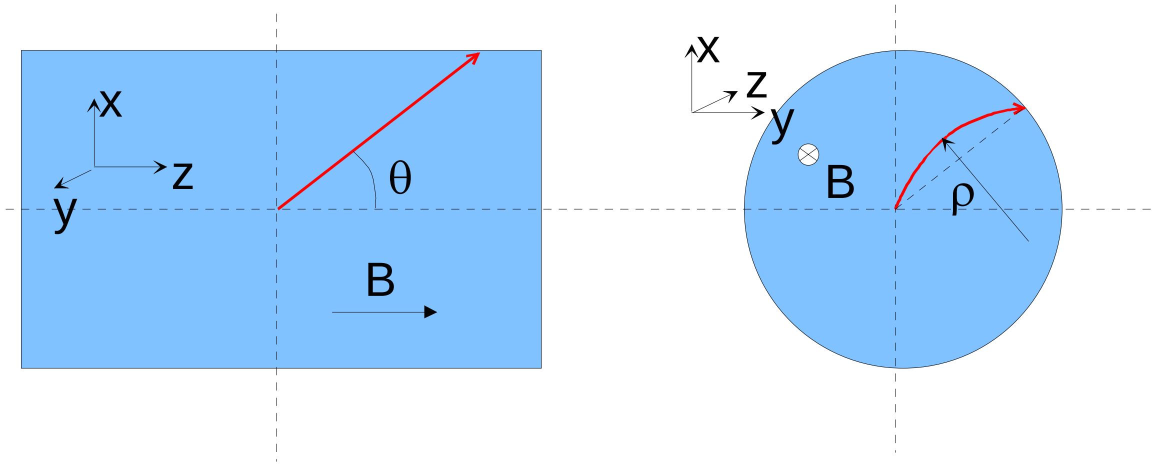
$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = \frac{\Delta p^{MS}}{\Delta p_T} = \frac{0.0136\sqrt{\frac{L}{X_0}}}{0.3BL} = 0.045\frac{1}{B\sqrt{LX_0}}$$

independent of p !



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

Momentum measurement in experiments with solenoid magnet:



$$p_T = p \sin\theta$$

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

N equidistant points with error $\sigma(z)$

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

\+ multiple scattering contribution…. } normally small

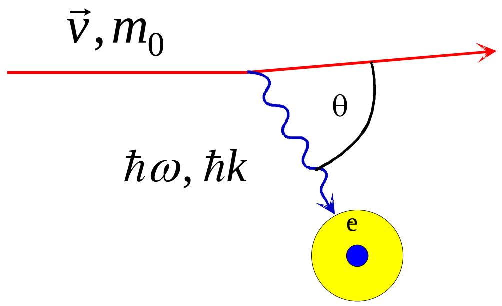
In practical cases: $$\frac{\sigma(p)}{p} \approx \frac{\sigma(p_T)}{p_T}$$

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

Detection of charged particles

How do they loose energy in matter ?

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



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

N : electron density

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

- If $\hbar\omega, \hbar k$ 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

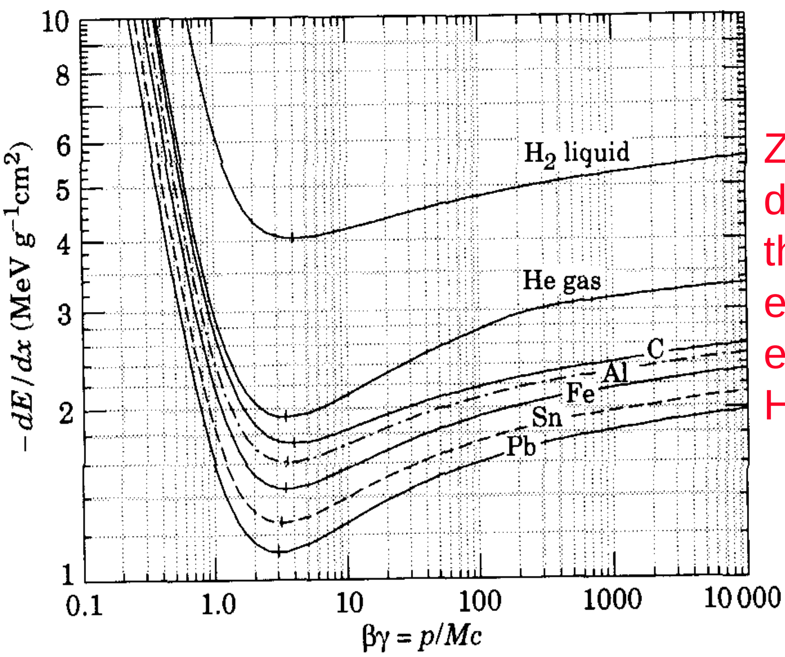
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} T^{max} - \beta^2 - \frac{\delta}{2} \right]$$

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

$I \leq dE \leq T^{max}$ $\quad$ I : mean excitation potential

$I \approx I_0 Z$ with $I_0 = 10$ eV $\quad$ (rough approximation, I fitted for each element)

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



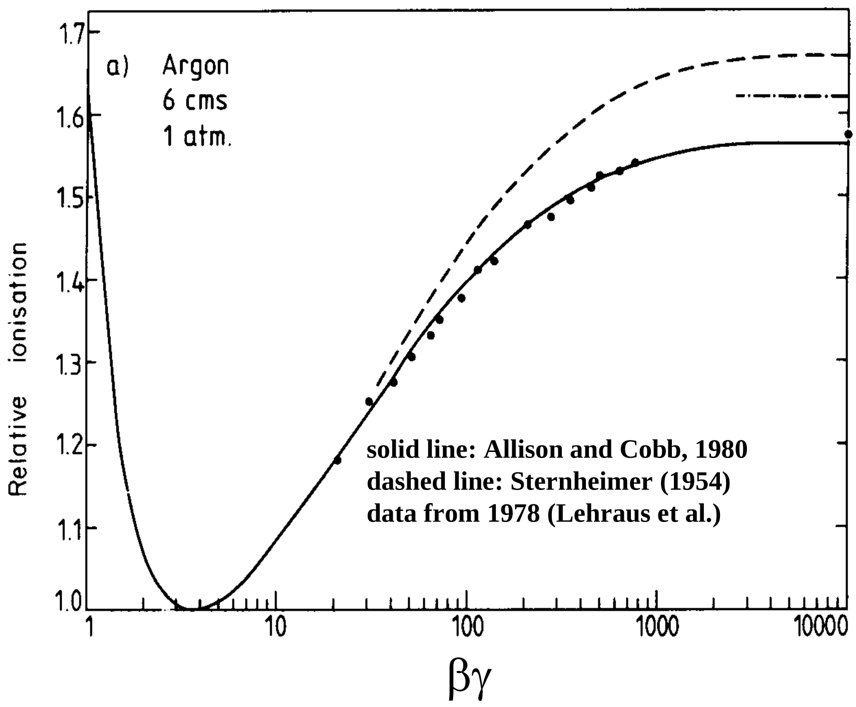
Z/A does not differ much for the various elements, except for Hydrogen!

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

- 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)

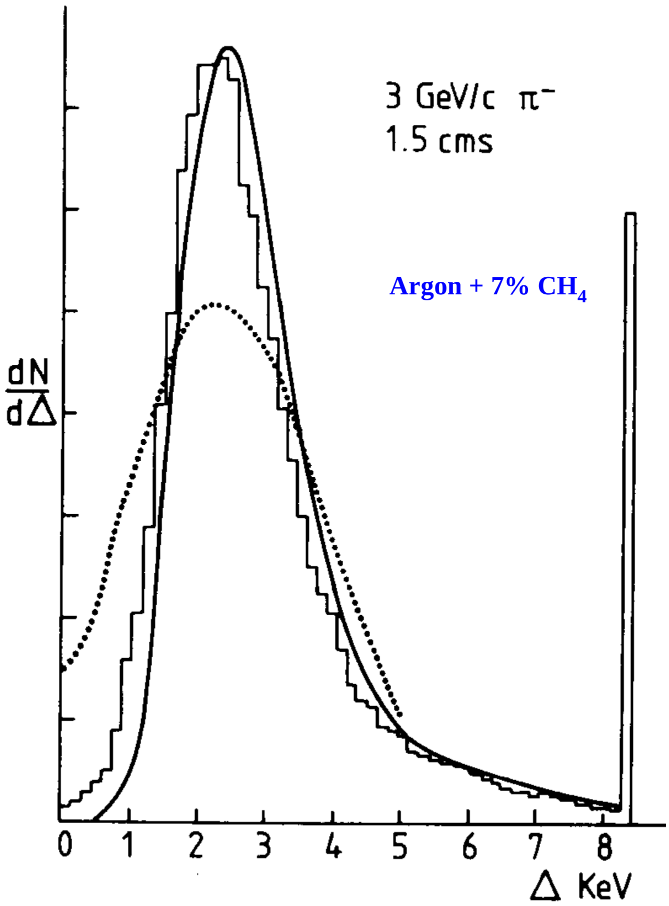
  (dE/dx $\approx$ 1 - 2 MeV g^{-1} cm^2)
- then again rising due to $\ln \gamma^2$ term, relativistic rise, attributed to relativistic expansion of transverse E-field $\rightarrow$ contributions from more distant collisions.
- relativistic rise cancelled at high γ by "density effect", polarization of 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):
→ Few collisions, some with high energy transfer.
→ Energy loss distributions show large fluctuations towards high losses: "Landau tails"

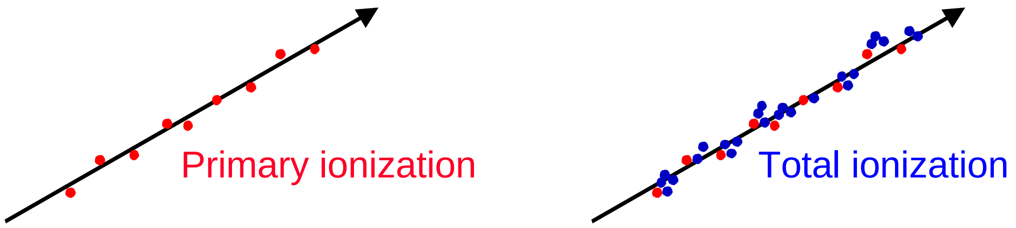


data: Harris et al. (1977)
dotted curve: Landau(1944)
solid curve: Allison and Cobb (1980)

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

Primary and total ionization

Fast charged particles ionize the atoms of a gas.



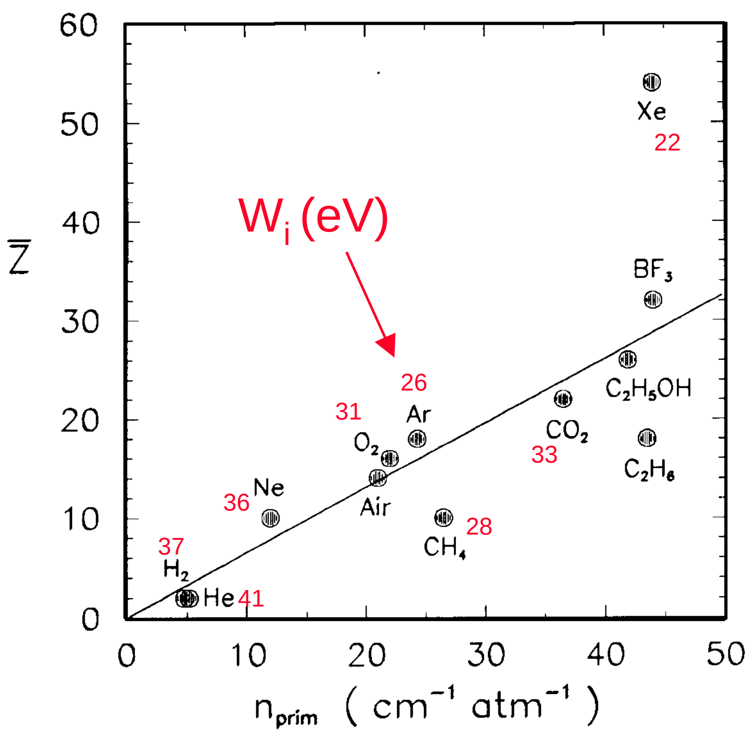
Often the resulting primary electron will have enough kinetic energy to ionize other atoms.

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

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

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)

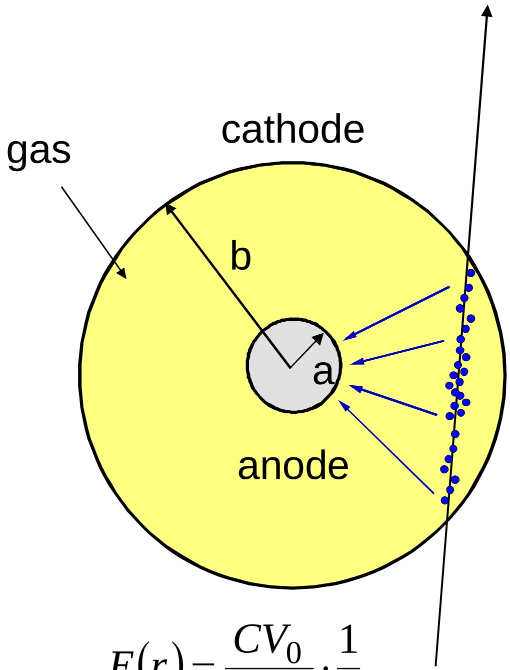
≈ 100 electron-ion pairs are not easy to detect!

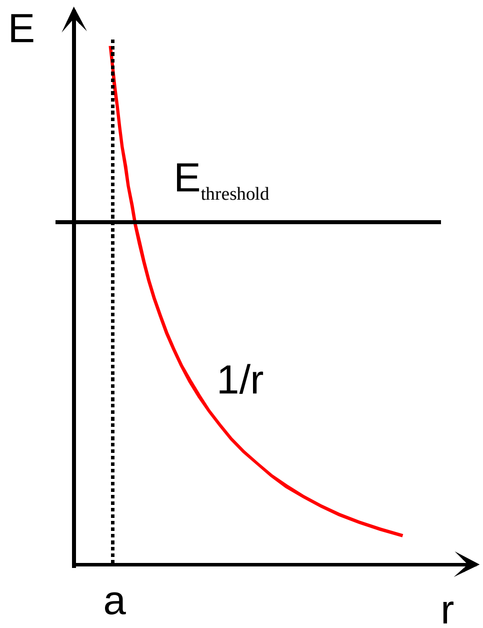
Noise of amplifier ≈1000 e^- (ENC) !

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

Gas amplification

Consider cylindrical field geometry (simplest case):





$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

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 → exponential increase 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)

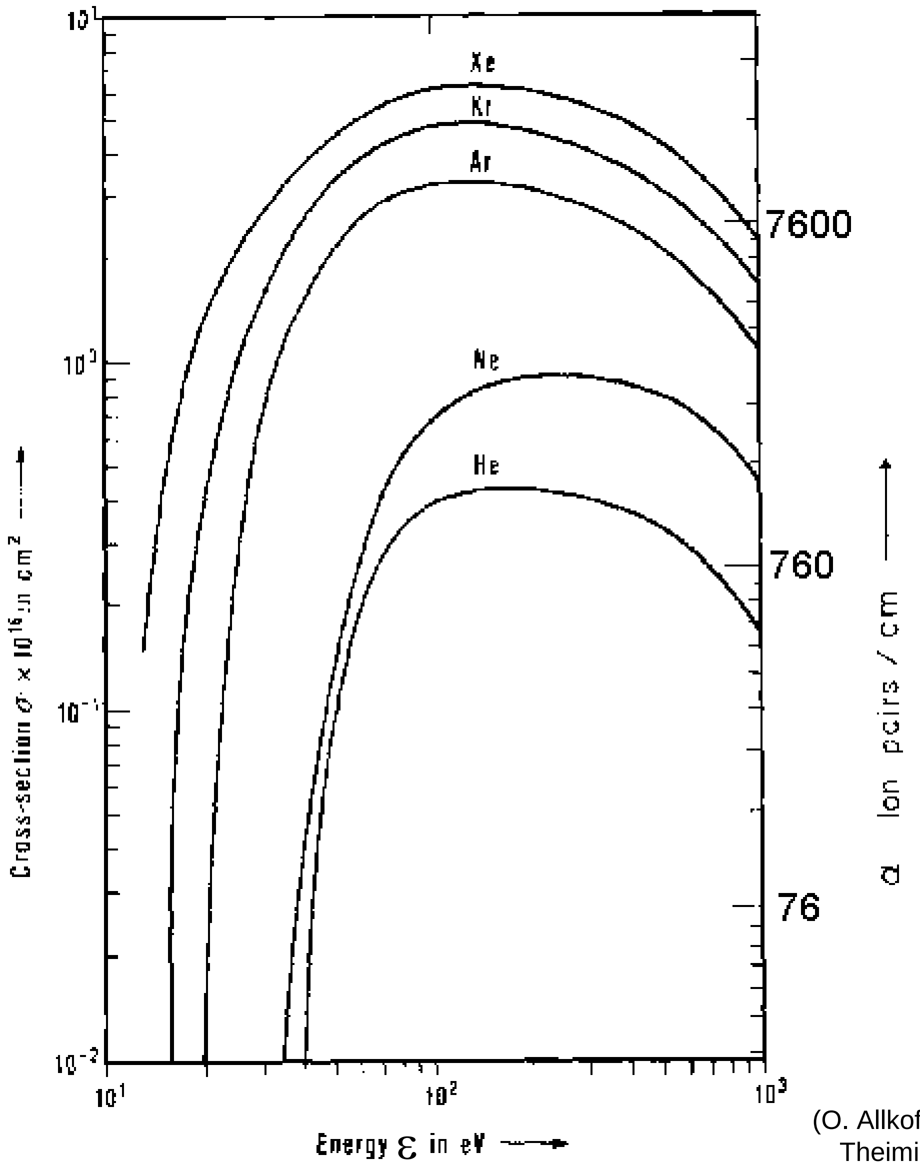
$$\alpha = \frac{1}{\lambda}$$

λ: mean free path

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

Gain

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

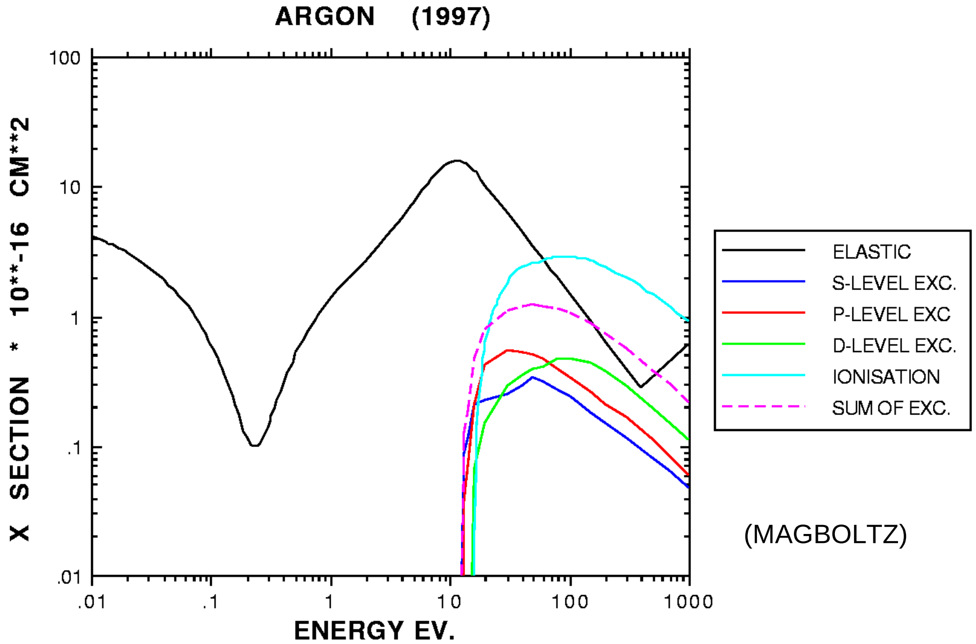


(F. Sauli, CERN 77-09)

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

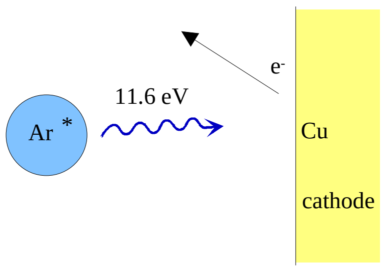
Choice of gas:

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.

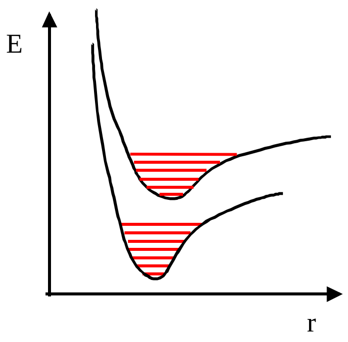
This is above ionization threshold of metals, e.g. Copper 7.7 eV.



→ new avalanches → permanent discharges !

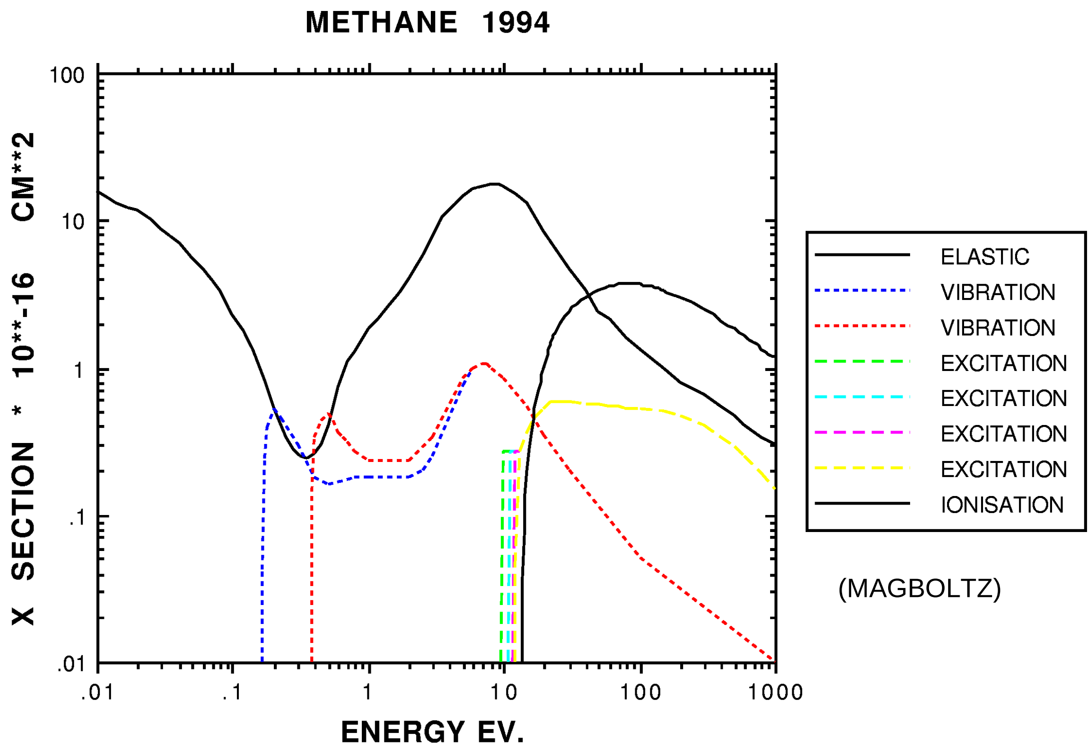
Solution: Add poly-atomic gases as quenchers.

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



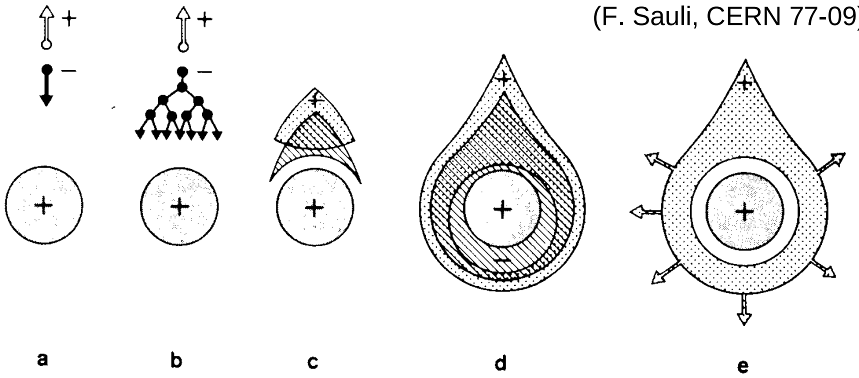
Energy dissipation by collisions or dissociation into smaller molecules.

Methane: absorption band 7.9 - 14.5 eV



Signal formation

(F. Sauli, CERN 77-09)

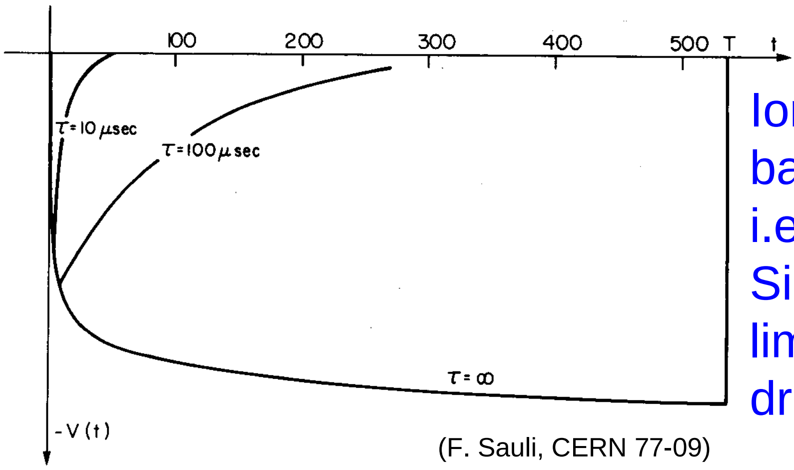


Avalanche formation within a few wire radii and within t < 1 ns!

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 %).



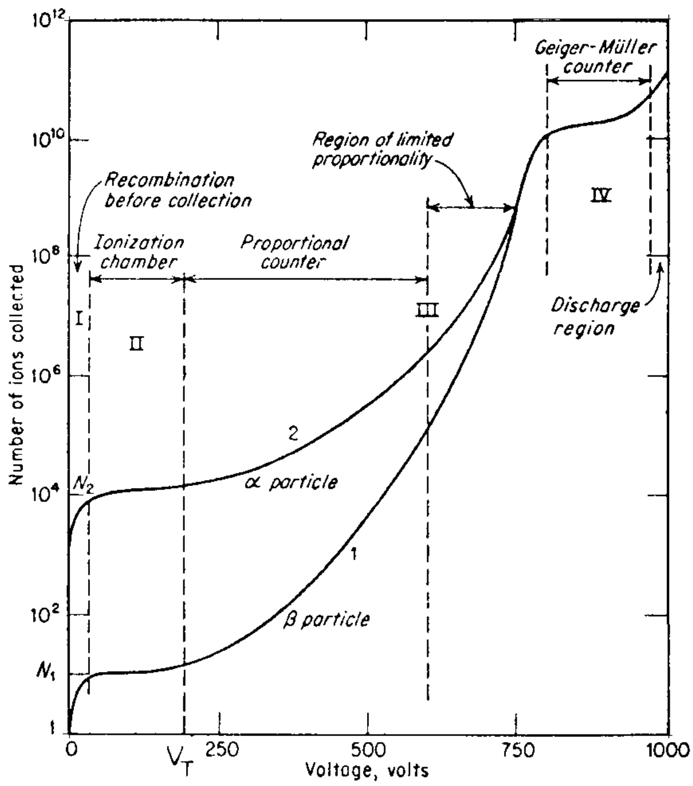
(F. Sauli, CERN 77-09)

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:

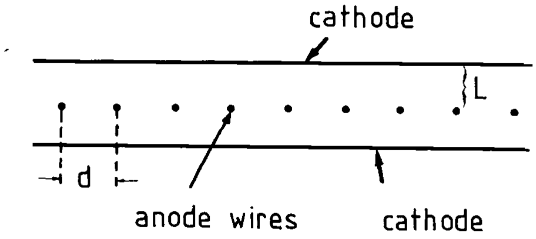
- ionization mode: full charge collection, but no charge multiplication.
- Proportional mode: above threshold voltage multiplication starts. Detected signal proportional to original ionization $\rightarrow$ energy measurement (dE/dx). Secondary avalanches have to be quenched. Gain 10^4 - 10^5.
- Limited Proportional $\rightarrow$ Saturated $\rightarrow$ Streamer mode: Strong photo-emission. Secondary avalanches, merging with original avalanche. Requires strong quenchers or pulsed HV. High gain (10^{10}), large signals $\rightarrow$ simple electronics.

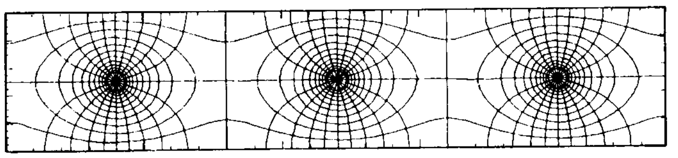


- Geiger mode: Massive photo emission. Full length of anode wire affected. Stop discharge by cutting down HV. Strong quenchers needed as well.

Multi wire proportional chamber (MWPC)

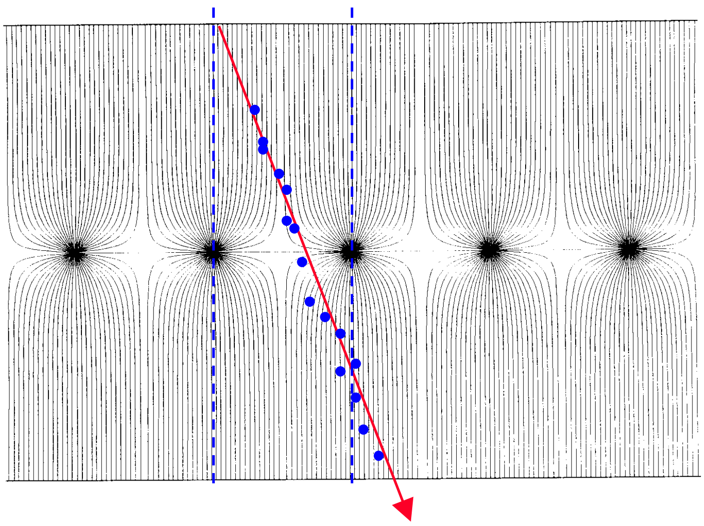
(G. Charpak et al. 1968, Nobel prize 1992)





field lines and equipotentials around anode wires

Capacitive coupling of non-screened parallel wires? Negative signals on all wires? Compensated by positive signal induction from ion avalanche.



Typical parameters:

L=5mm, d=1mm,

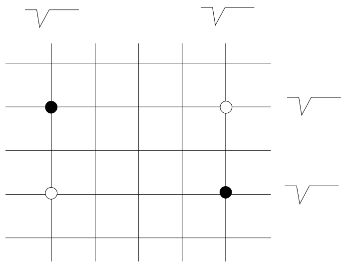
a_{wire}=20mm.

Normally digital readout:
spatial resolution limited to $\sigma_x \approx \frac{d}{\sqrt{12}}$ (d=1mm, σ_x=300 μm)

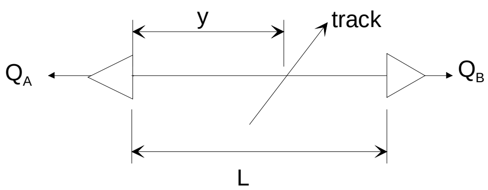
Address of fired wire(s) give only 1-dimensional information. Secondary coordinate ….

Secondary coordinate

- Crossed wire planes. Ghost hits. Restricted to low multiplicities. Also stereo planes (crossing under small angle).

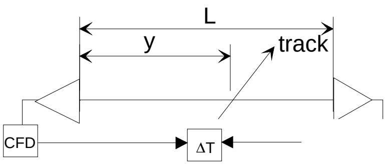


- Charge division. Resistive wires (Carbon,2kΩ/m).



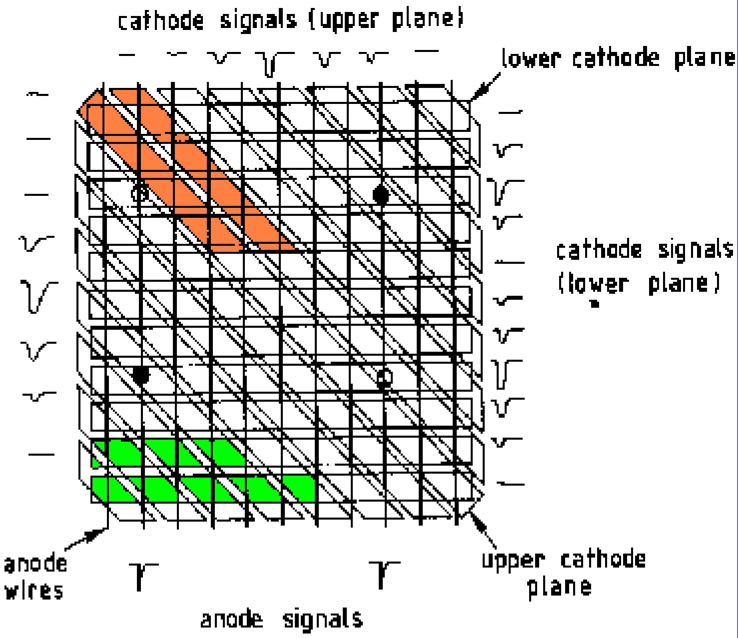
$$\frac{y}{L} = \frac{Q_B}{Q_A + Q_B} \qquad \sigma\left(\frac{y}{L}\right) \text{ up to } 0.4\%$$

- Timing difference (DELPHI Outer detector, OPAL vertex detector)



$$\sigma(\Delta T) = 100\,ps$$
$$\rightarrow \sigma(y) \approx 4cm \quad \text{(OPAL)}$$

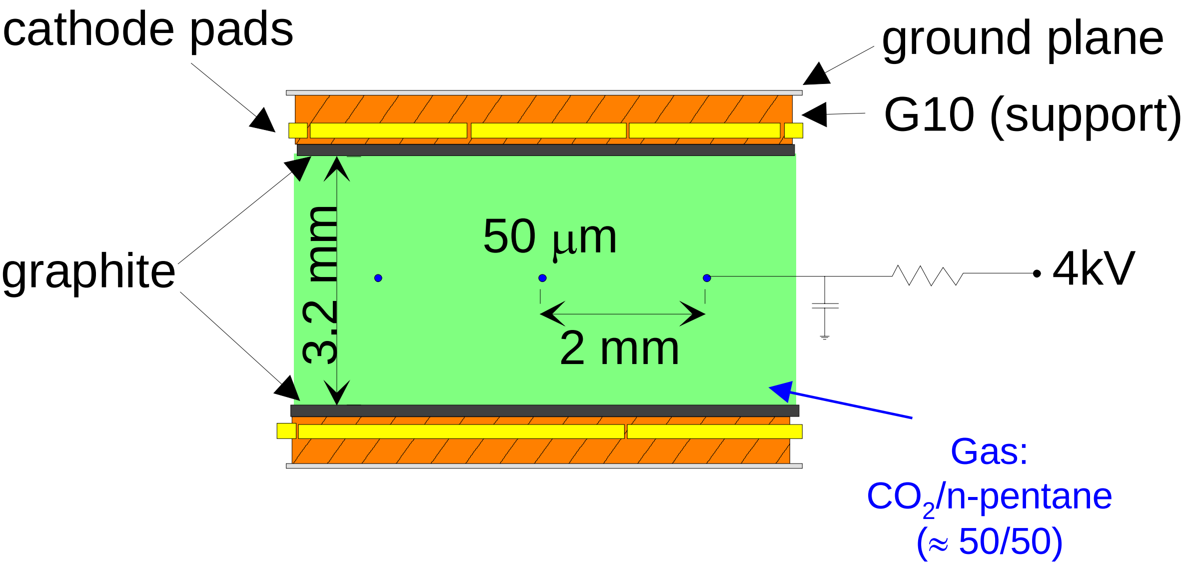
- 1 wire plane + 2 segmented cathode planes



Analog readout of cathode planes.
$\rightarrow \sigma \approx 100\ \mu m$

Some 'derivatives'

- Thin gap chambers (TGC)

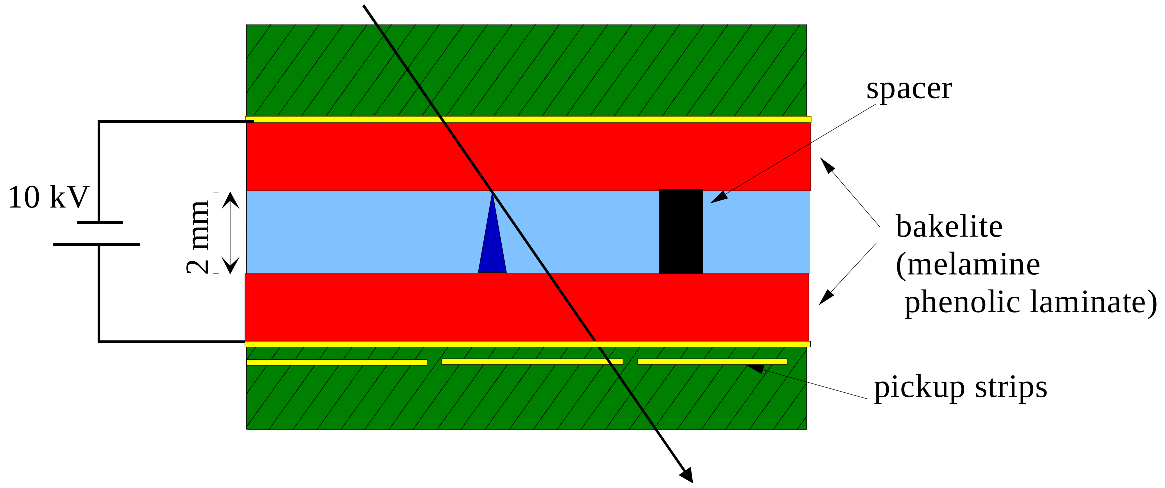


Operation in saturated mode. Signal amplitude limited by by the resistivity of the graphite layer (≈ 40kΩ/☐).

Fast (2 ns risetime), large signals (gain 10^6), robust

Application: OPAL pole tip hadron calorimeter.
G. Mikenberg, NIM A 265 (1988) 223
ATLAS muon endcap trigger, Y.Arai et al. NIM A 367 (1995) 398

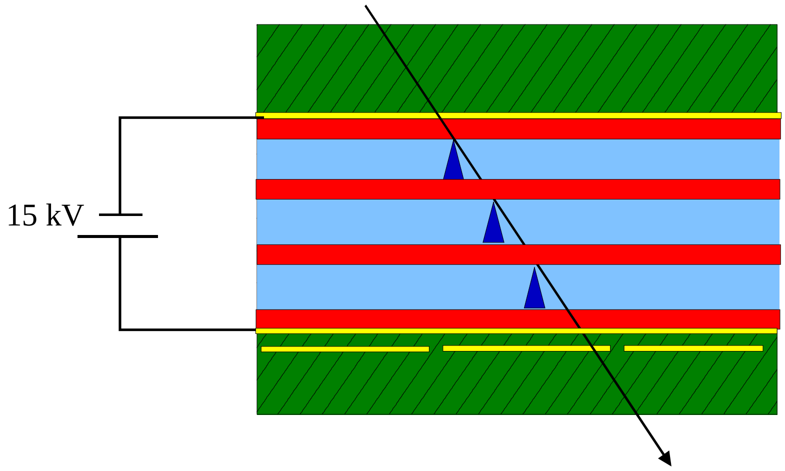
- Resistive plate chambers (RPC) No wires !



Gas: $C_2F_4H_2$, (C_2F_5H) + few % isobutane

(ATLAS, A. Di Ciaccio, NIM A 384 (1996) 222)

Time dispersion ≈ 1..2 ns → suited as trigger chamber
Rate capability ≈ 1 kHz / cm^2



Double and multigap geometries → improve timing and efficiency

Problem: Operation close to streamer mode.