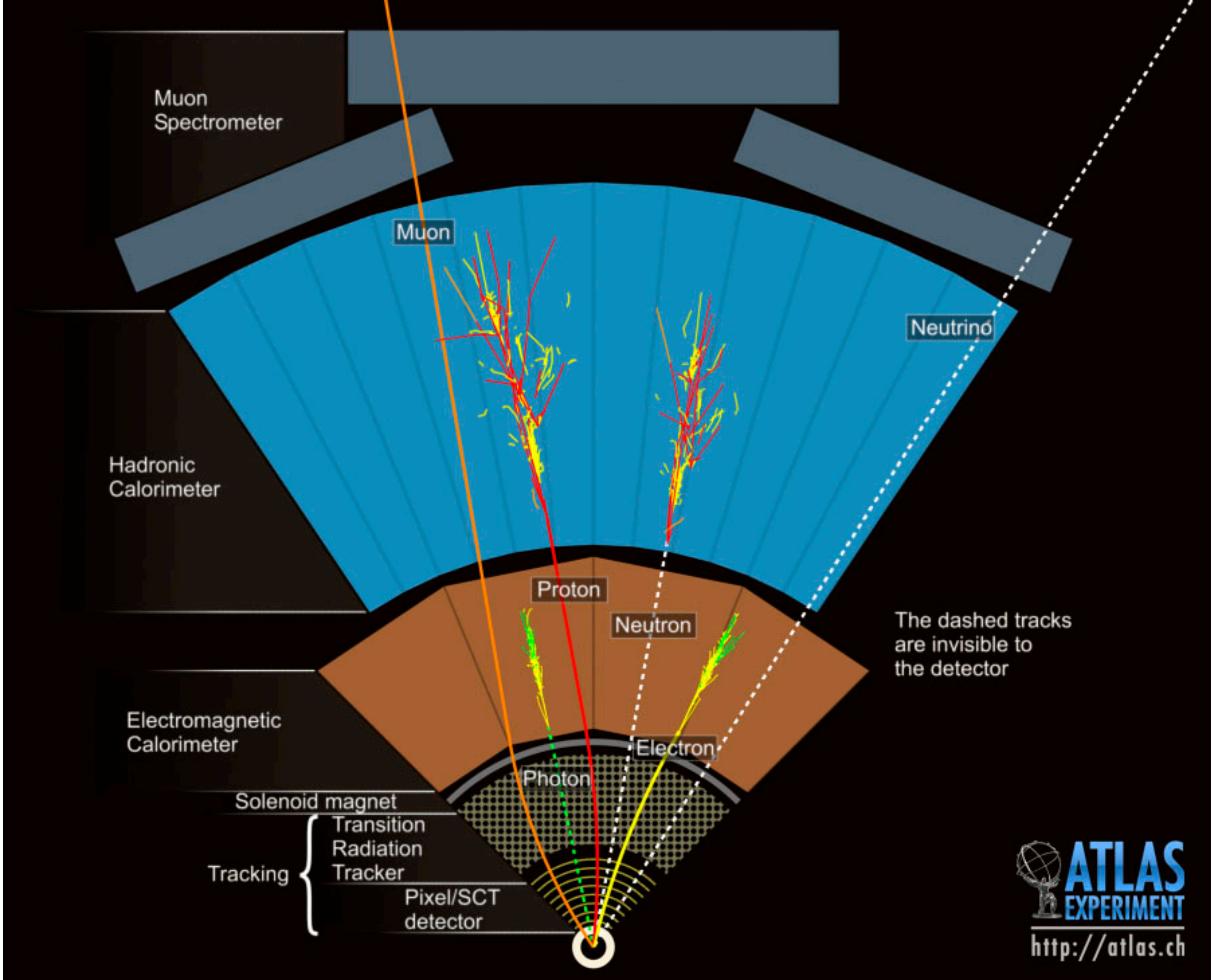
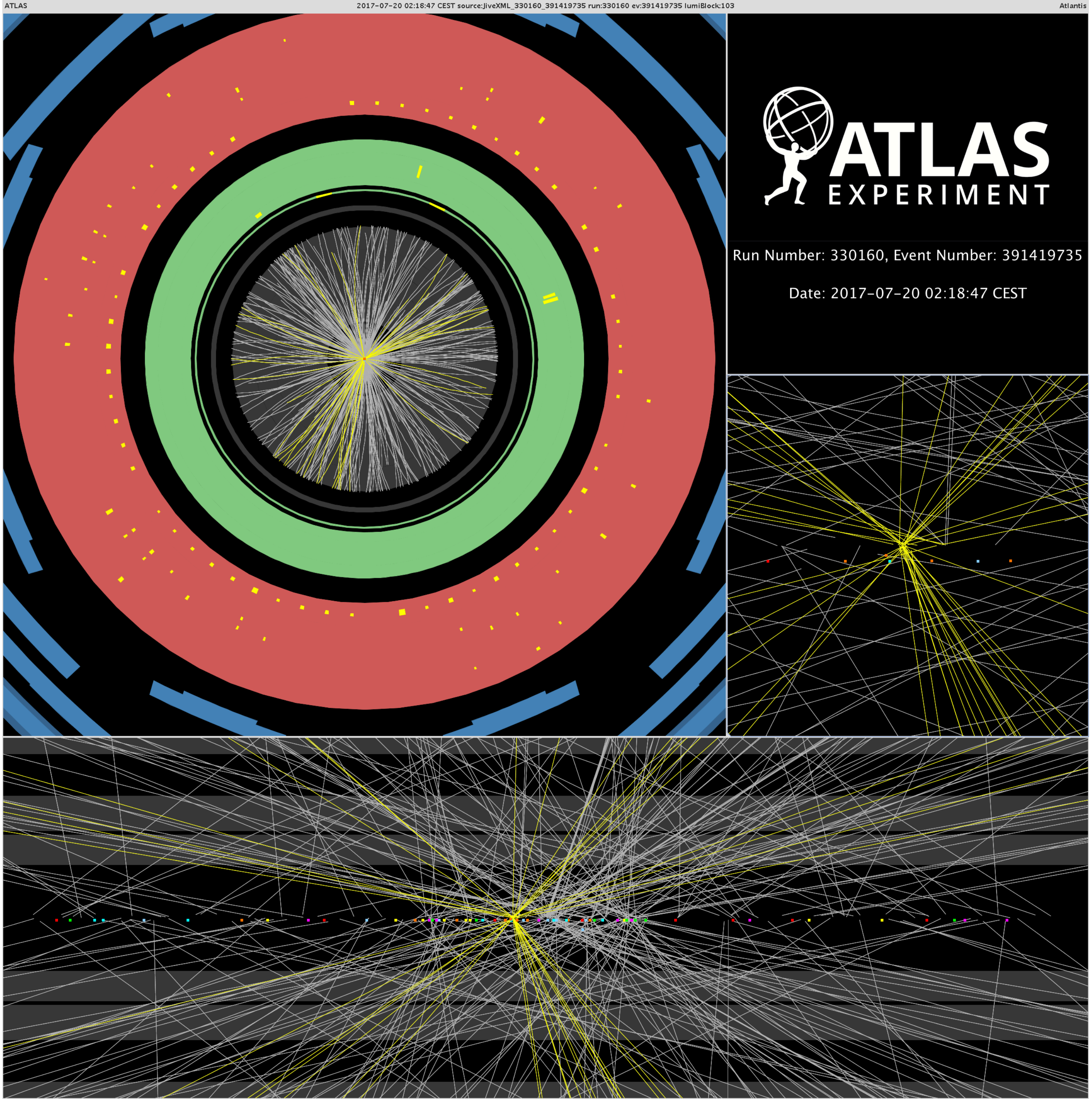
Lecture 21


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Proton
Neutron
Neutrino
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch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ATLAS
EXPERIMENT
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Date: 2017-07-20 02:18:47 CEST

Tracking

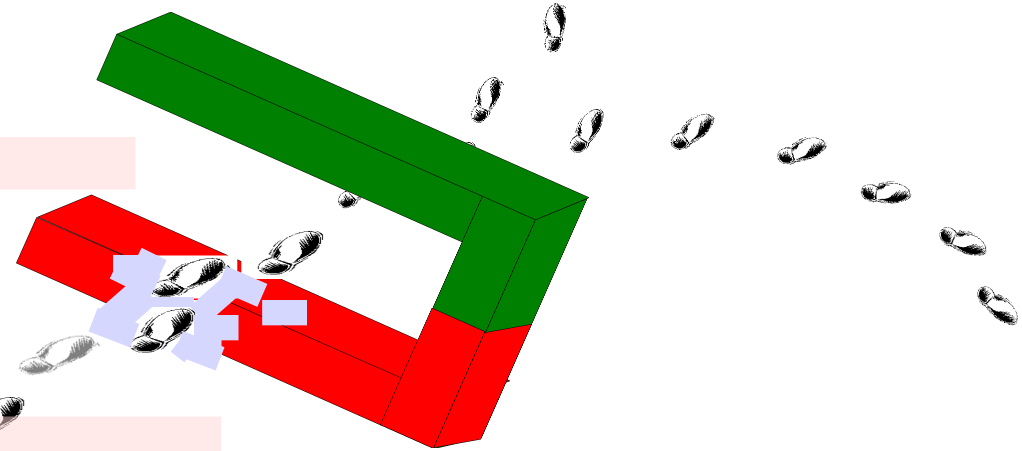
Momentum measurement

Multiple scattering

Bethe-Bloch formula
/ Landau tails

Ionization of gases

Wire chambers



Drift and diffusion in gases

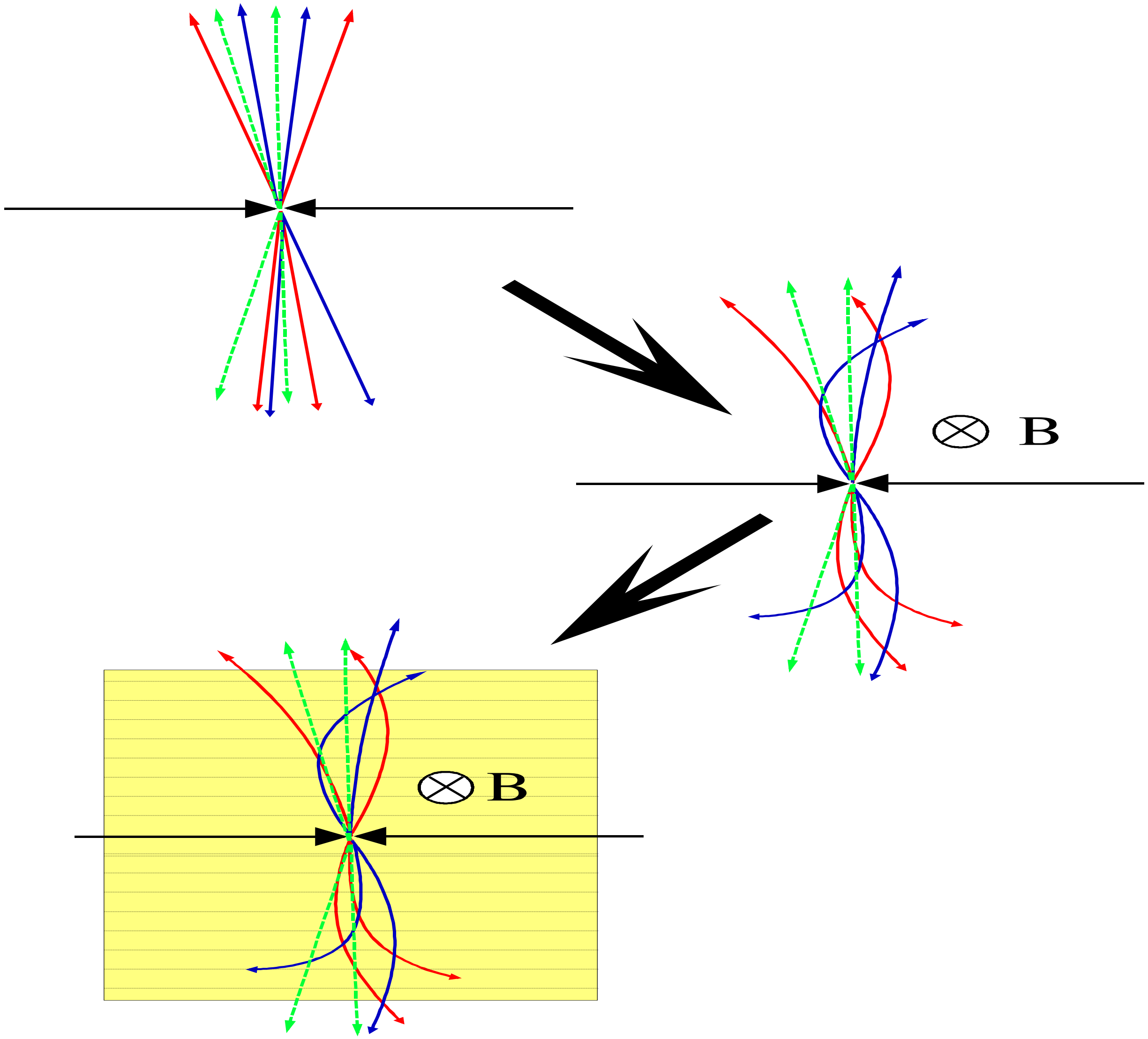
Drift chambers

Micro gas detectors

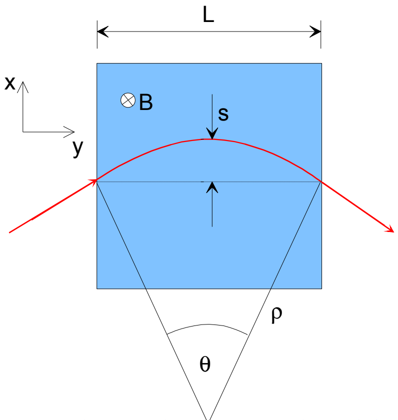
Silicon as a detection medium

Silicon detectors strips/pixels

Momentum measurement



Momentum measurement



$$\frac{mv^2}{\rho} = q(v \times B) \quad \rightarrow \quad p_T = qB\rho$$

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

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

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

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

Error on the sagitta $$s = x_2 - \tfrac{1}{2}(x_1 + x_3)$$

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

For N equidistant measurements (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)

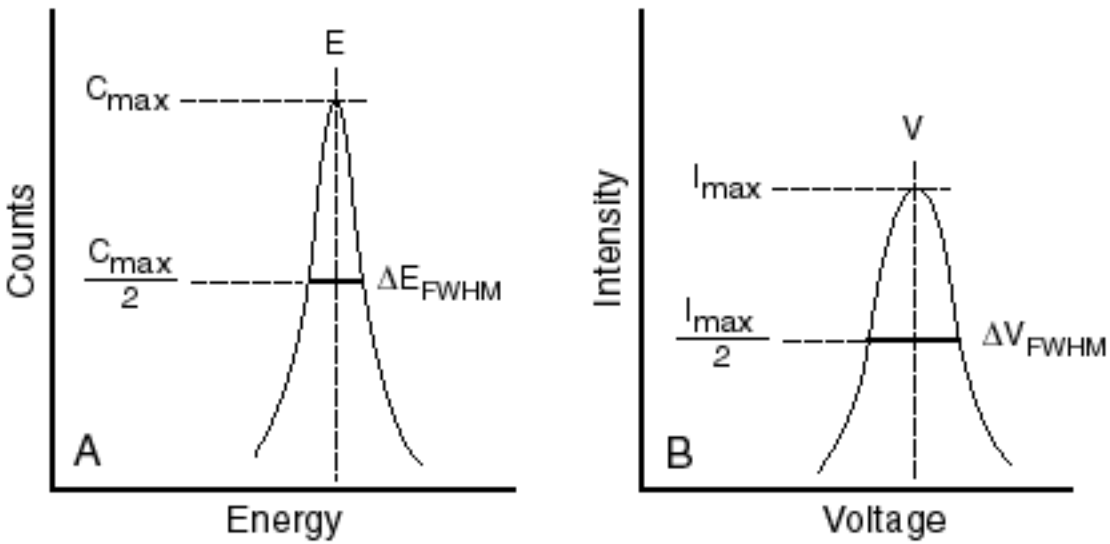
Example: $p_T = 1$ GeV/c, L = 1 m, B = 1 T, s(x) = 200 mm, N = 10

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

Momentum resolution

Resolution is generally defined as 1 standard deviation - 1σ – for a gaussian distribution dominated by Poisson fluctuations:

σ = "FWHM-full width at half-maximum"/2.36



E resolution = σ/E

For box distribution (uniform within an interval p): σ = p/√12

$$\sigma^2 = \frac{\int_{-\frac{p}{2}}^{\frac{p}{2}} (x_r - x_m)^2 D(x_r)\, dx_r}{\int_{-\frac{p}{2}}^{\frac{p}{2}} D(x_r)\, dx_r} = \frac{p^2}{12}$$

D(x) =1 uniform distribution of tracks

X_m=0 pixel centre

Can we distinguish curved track from the straight line ?

$$s = \rho - \sqrt{(\rho^2 - L^2/4)}$$

CLEO (electron-positron collider):

Maximum momentum p = 5 GeV/c, B field = 1.5 T

→ $\rho = p/(0.3\ B) = 11.11$ m

Track radius = 1.0 m

→ s = 0.011 m (1.1 mm) **EASY !!!**

ATLAS

Tracking length L = 1.15 m

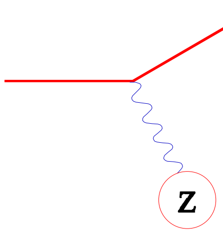
B field = 2 T

p = 50 GeV/c ρ = 144.9 m s = 0.0011m (1.1 mm)

p = 1000 GeV/c ρ = 1666.7 m s = 0.0001m (0.1 mm) !!!!

➡ **must consider measurement errors**

Scattering

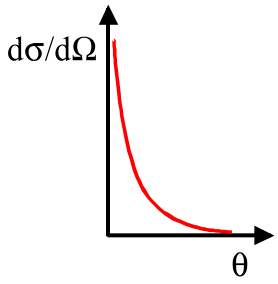


An incoming particle with charge z interacts with a target of nuclear charge Z via exchange of the virtual photon. The cross-section for this e.m. process is

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

Rutherford formula

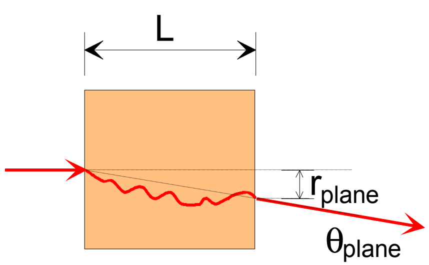
Depends on charge of the passing particle
and on the charge and density of the material

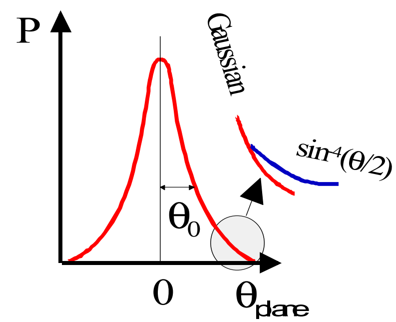


- Average scattering angle $\langle \theta \rangle = 0$
- Cross-section for $\theta \to 0$ is infinite !

Multiple Scattering

In sufficiently thick material layer the particle will undergo multiple scattering. Each individual scattering is independent of the previous one → statistical process in 3 dimensions





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

Approximation: $\theta_0 \propto \frac{1}{p} \sqrt{\frac{L}{X_0}}$ **X_0 is radiation length of the medium**

Contribution of multiple scattering to $\dfrac{\sigma(p)}{p_T}$

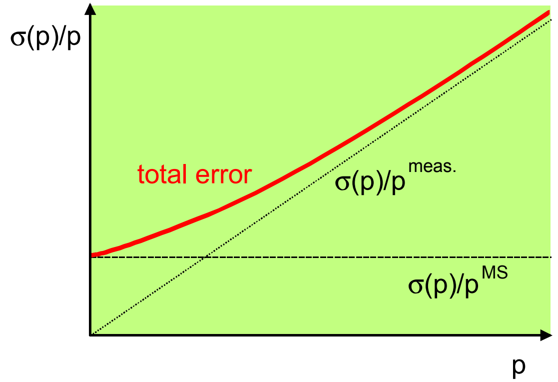
$$\frac{\sigma(p)}{p_T} \propto \sigma(x)\cdot p_T$$

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

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = \text{constant}$$

independent of p !

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



- example: Argon gas (X_0=110m), L=1m, B=1T $\left.\dfrac{\sigma(p)}{p_T}\right|^{MS} \approx 0.5\%$

The Helix Equation

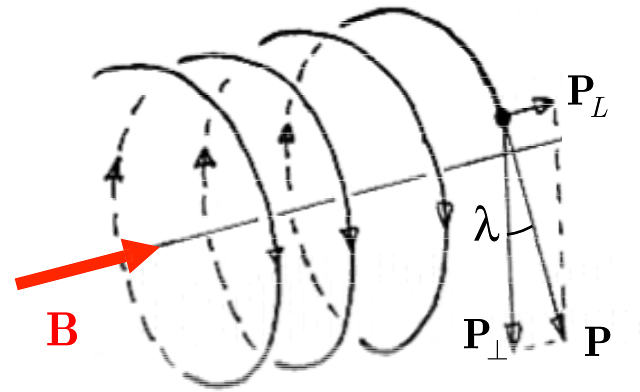
The helix is described in **parametric** form

$$R(m) = \frac{p_\perp(GeV)}{0.3B(T)}$$

$$x(s) = x_o + R\left[\cos\left(\Phi_o + \frac{hs\cos\lambda}{R}\right) - \cos\Phi_0\right]$$

$$y(s) = y_o + R\left[\sin\left(\Phi_o + \frac{hs\cos\lambda}{R}\right) - \sin\Phi_0\right]$$

$$z(s) = z_o + s\sin\lambda$$



λ is the **dip angle**

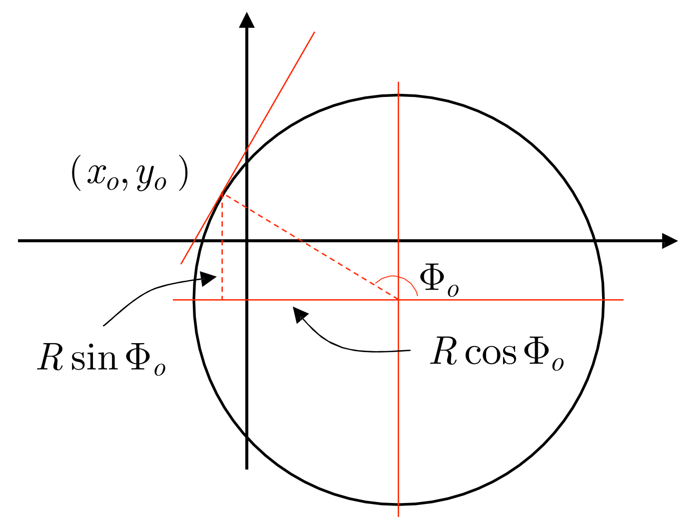
$h = \pm 1$ is the **sense of rotation** on the helix

The **projection** on th x-y **plane** is a circle

$$(x - x_o + R\cos\Phi_o)^2 + (y - y_o + R\sin\Phi_o)^2 = R^2$$

x_o and y_o the coordinates at $s = 0$

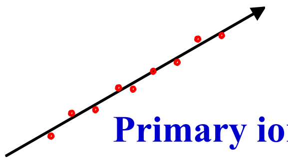
Φ_o is also related to the **slope** of the tangent to the circle at $s = 0$



right-handed system

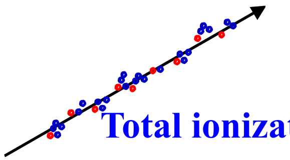
Gas detectors

Fast charged particles ionize the atoms of a gas. Often the resulting primary electron will have enough kinetic energy to ionize other atoms.



Primary ionization

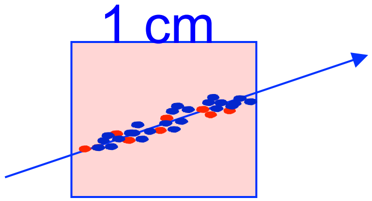
10 - 40 pairs/cm
ΔE/pair ~ 20 - 40 eV



Total ionization

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

Assume detector, 1 cm thick, filled with Ar gas:



~ 100 e-ion pair

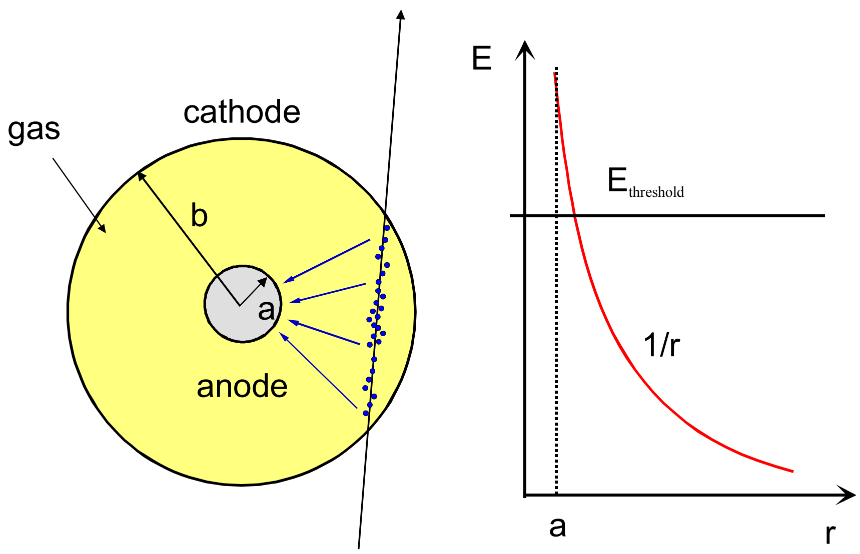
→ 100 electron-ion pairs are not easy to detect! (Noise of amplifier ~1000 e$^-$)

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

Gas amplification

Simplest case - cylindrical field geometry

Proportional Counter



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

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

***C* = capacitance / unit length**

<u>MECHANISM OF SIGNAL AMPLIFICATION</u>

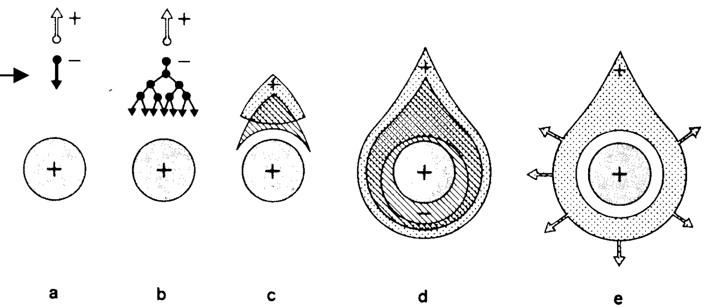
- **Electrons drift towards the anode wire.**
- **Close to the anode wire the field is high (~kV/cm)**
- **Electrons gain enough energy for further ionization → <u>exponential increase</u> of number of e^--ion pairs.**

Signal Formation

(F. Sauli, CERN 77-09)

electron

wire

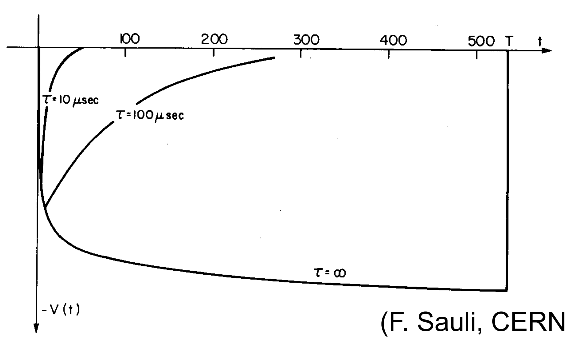


Avalanche formation within a few wire radii and within t < 1 ns!

Signal is induced by the moving charges both on anode and on cathode (electrons and ions).

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

Electrons collected by anode wire, i.e., *dr* is small (few μm)



(F. Sauli, CERN 77-09)

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

Need electronic signal differentiation to limit dead time.

Cross section for ionization by collisions of electrons with atoms of noble gasses

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

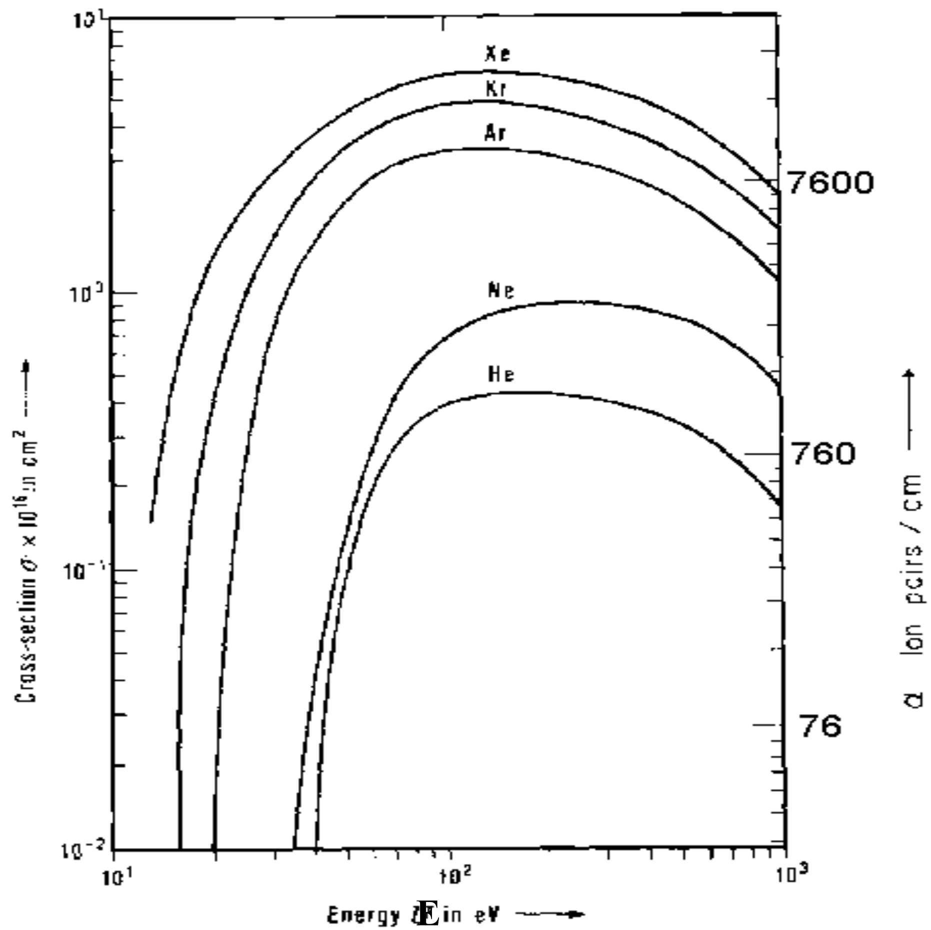
α: First Townsend coefficient (e⁻-ion pairs/cm)

λ: mean free path

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

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

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

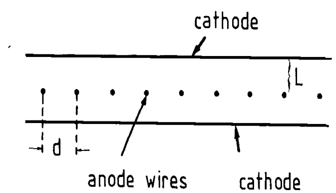


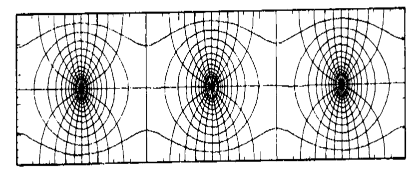
Total signal (number of collected electrons) is proportional to the total ionization generated by the passage of charged particle.

-> proportional chambers

Multi wire proportional chambers

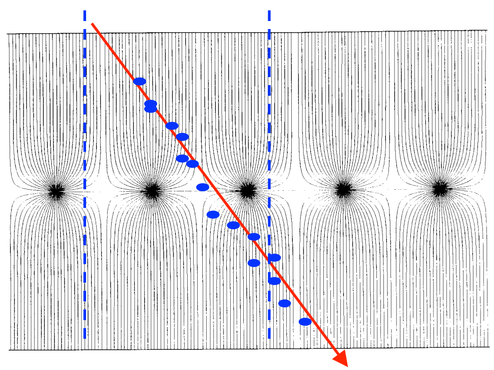
G. Charpak et al. 1968, Nobel prize 1992





field lines and equipotentials around anode wires

Negative signals on all wires.



Typical parameters:
L=5mm, d=1mm,
a_{wire}=20μm.

Digital readout:
spatial resolution limited to

$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

(d=1mm, s_x=300 μm)