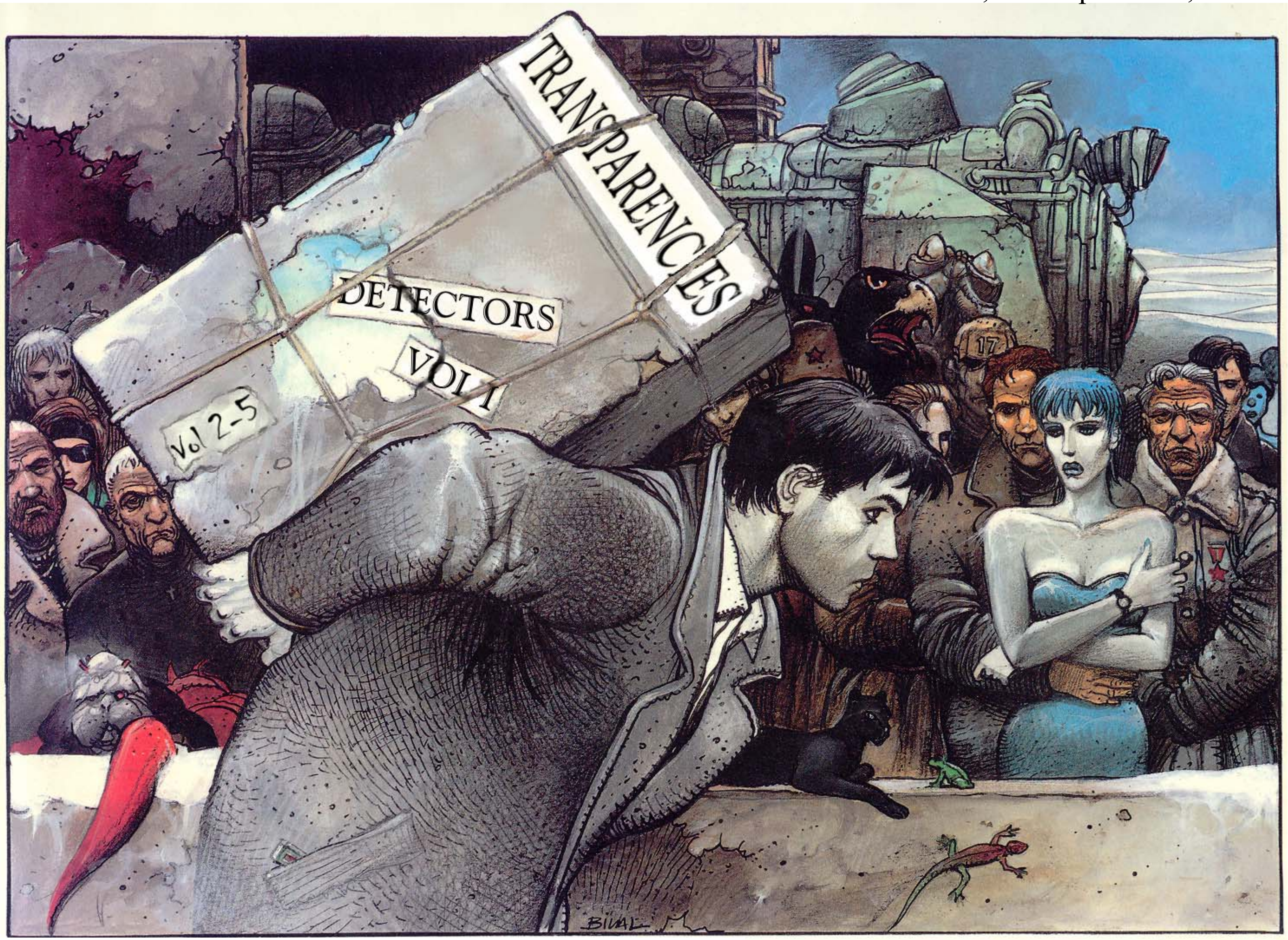
# CERN Summer Student Lectures 2006

## DETECTORS

Olav Ullaland, PH Department, CERN.




with all my excuses to Enki Bilal (b. 7/10/1951, Yugoslavia)

**These lectures in DETECTORS are based upon (and from time to time directly lifted from):**

| | |
|---|---|
| **John D. Jackson** | *Classical Electrodynamics* |
| **Dan Green** | *The Physics of Particle Detectors* |
| **Fabio Sauli** | *Principles of Operation of Multiwire Proportional and Drift Chambers* |
| **Richard Wigmans** | *Calorimetry* |
| **Christian Joram** | *Particle Detectors* |
| | Lectures for Postgraduates Students, CERN 1998 |
| | CERN Summer Student lectures 2003 |
| **C. Joram et al.** | *Particle detectors : principles and techniques* |
| | Academic Training Lectures , CERN 2005 |
| **H.P. Wellisch** | *Physics of shower simulation at LHC.* |
| | Academic Training Lectures, CERN 2004 |
| **R. Gilmore and G. P. Heath** | Particle Interactions University of Bristol |
| | http://wwwteach.phy.bris.ac.uk/Level3/phys30800/CourseMaterials/ |
| | http://wwwteach.phy.bris.ac.uk/Level3/phys30800/CourseMaterials/p308_slides_part2.ppt |

A good many plots and pictures from

http://pdg.web.cern.ch/pdg/

http://www.britannica.com/

Other references are given whenever appropriate.

Help from (former) friends is gratefully acknowledged.

Erich Albrecht,
Tito Bellunato,
Ariella Cattai,
Carmelo D'Ambrosio,
Martyn Davenport,
Marcella Diemoz,
Thierry Gys,
Christian Joram,
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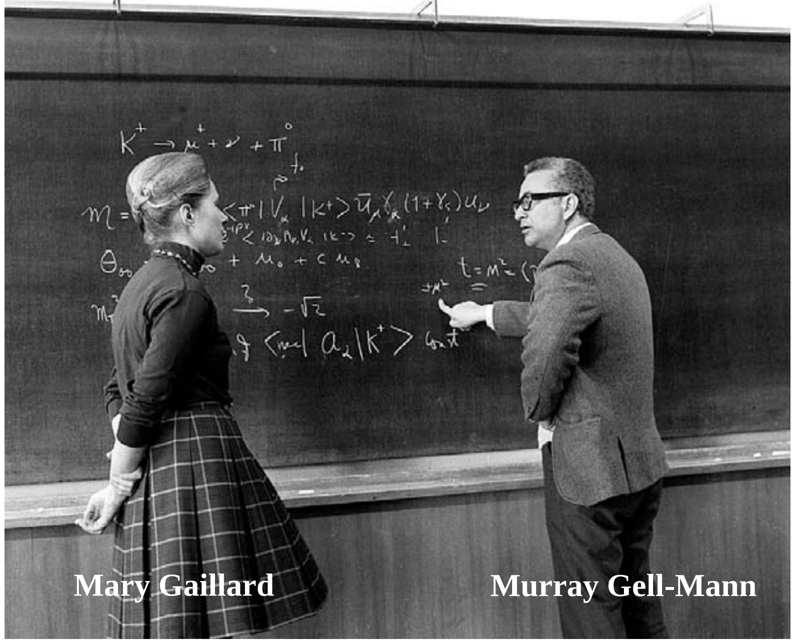
Stefan Koestner
Martin Laub,
Georg Lenzen,
Dietrich Liko,
Niko Neufeld,
Gianluca Aglieri Rinella,
Dietrich Schinzel
and
Ken Wyllie

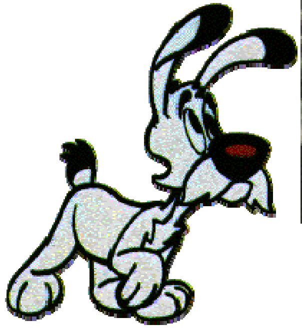
Disclaimer

The data presented is believed to be correct, but is not guaranteed to be so.

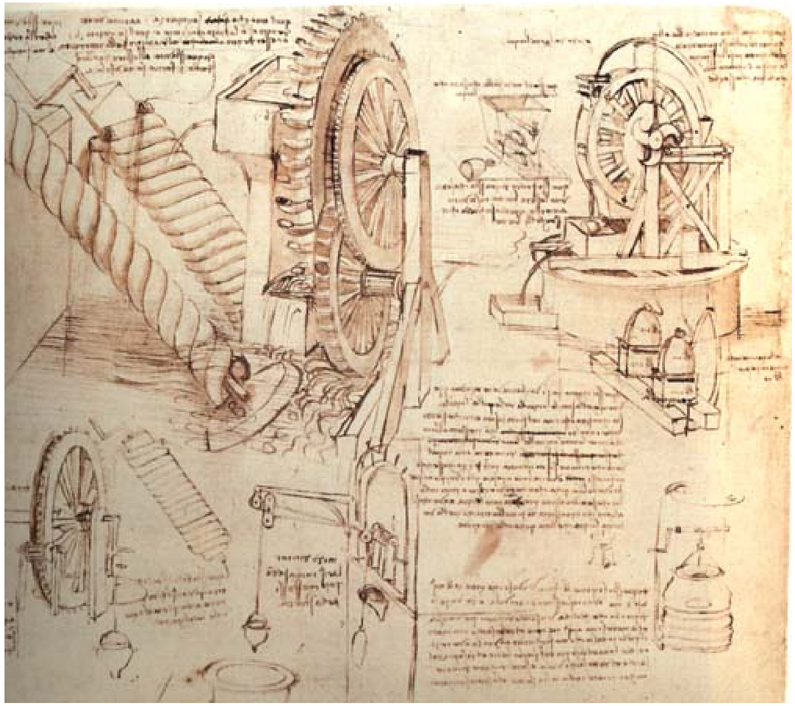
To do a HEP experiment, one needs:



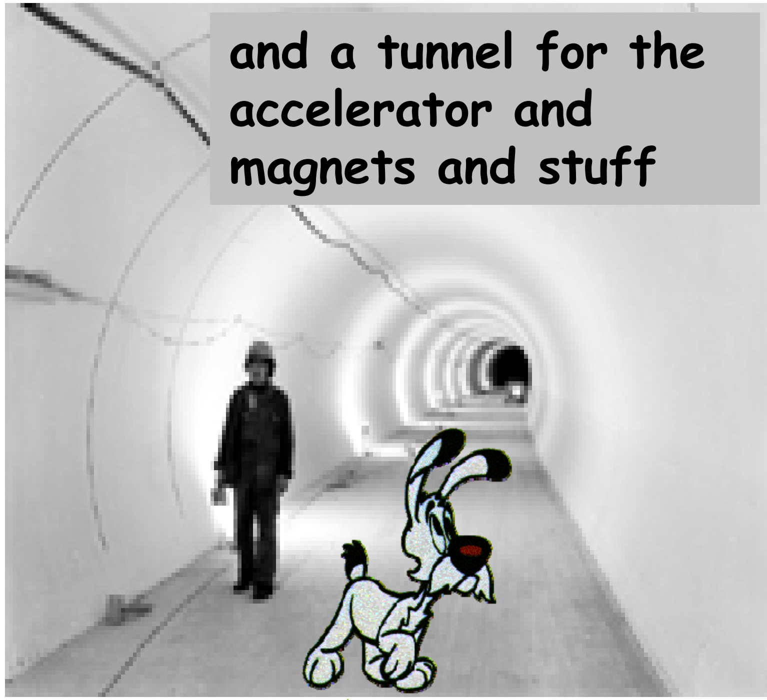

A theory,
an Idefix



and a cafeteria



Clear and
easy to
understand
drawings

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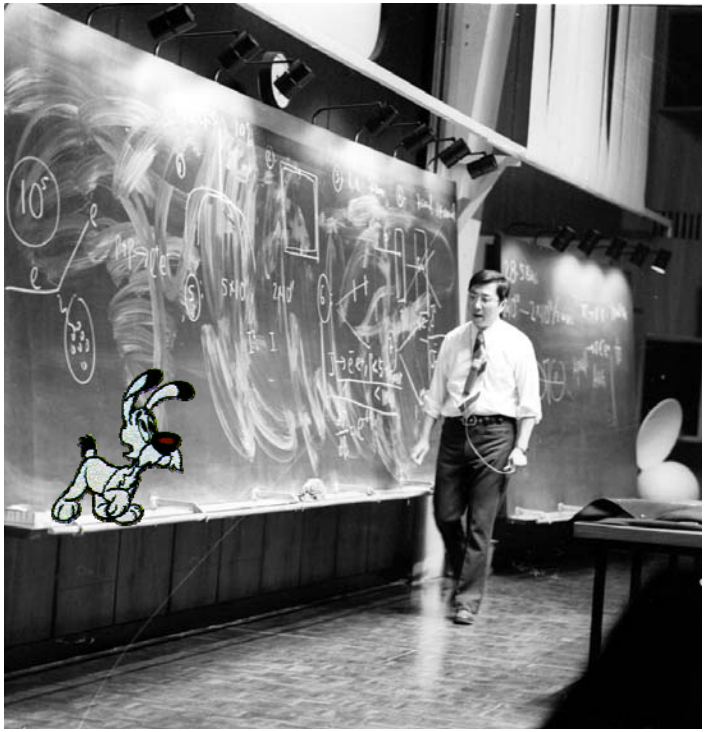
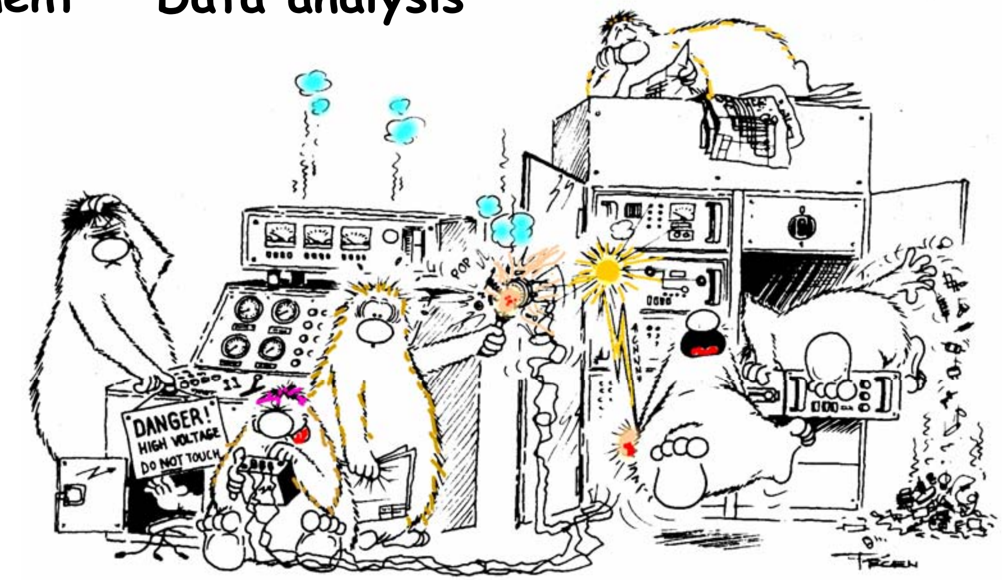
Easy access to the experiment

Data analysis



and a Nobel prize




We will just concentrate on the detectors

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## What I will try to cover:

- Particle interaction with matter
  and magnetic fields
- Tracking detectors
- Calorimeters
- Particle Identification

and some introduction to what it is all about.

## Some units which we will use and some relationships that might be useful.

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

energy $E$: measured in eV
momentum $p$: measured in eV/$c$
mass $m_0$ : measured in eV/$c^2$

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

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

1 eV is a small energy.

http://www.nature.com/news/2004/040105/images/bee_180.jpg

$1 \text{ eV} = 1.6 \cdot 10^{-19}$ J
$m_{\text{bee}} = 1\text{g} = 5.8 \cdot 10^{32}$ eV/$c^2$
$v_{\text{bee}} = 1$ m/s $\rightarrow E_{\text{bee}} = 10^{-3}$ J $= 6.25 \cdot 10^{15}$ eV
$E_{\text{LHC}} = 14 \cdot 10^{12}$ eV

However,
LHC has a total stored beam energy
$10^{14}$ protons $\times\ 14 \cdot 10^{12}$ eV $\cong 10^8$ J

or, if you like
One 100 T truck
at 100 km/h


from C. Joram, SSL 2003

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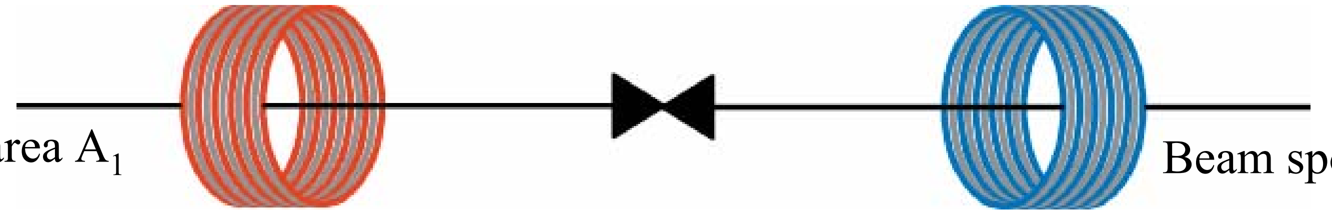
Cross section $\sigma$ or the differential cross section $d\sigma/d\Omega$ is an expression of the probability of interactions.

Beam spot area $A_1$



Beam spot area $A_2$

$\Phi_1 = N_1/t$

$\Phi_2 = N_2/t$

The interaction rate, $R_{int}$, is then given as:

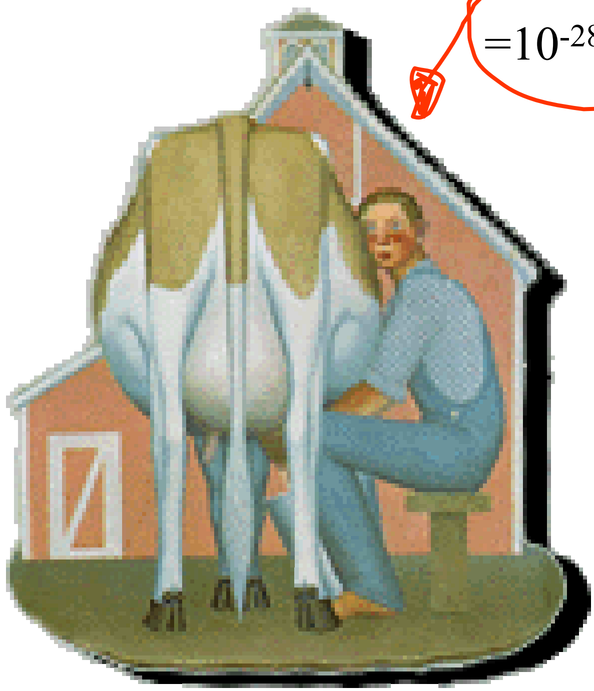
$$R_{int} \propto \frac{N_1 N_2}{A \cdot t}$$

$$= \sigma \mathcal{L}$$

$\sigma$ has the dimension area.

1 barn = $10^{-24}$ cm$^2$

$= 10^{-28}$ m$^2$



Grant Wood, Fruits of Iowa: Boy Milking Cow, 1932

The luminosity, $\mathcal{L}$, is given in cm$^{-2}$s$^{-1}$

from C. Joram, SSL 2003

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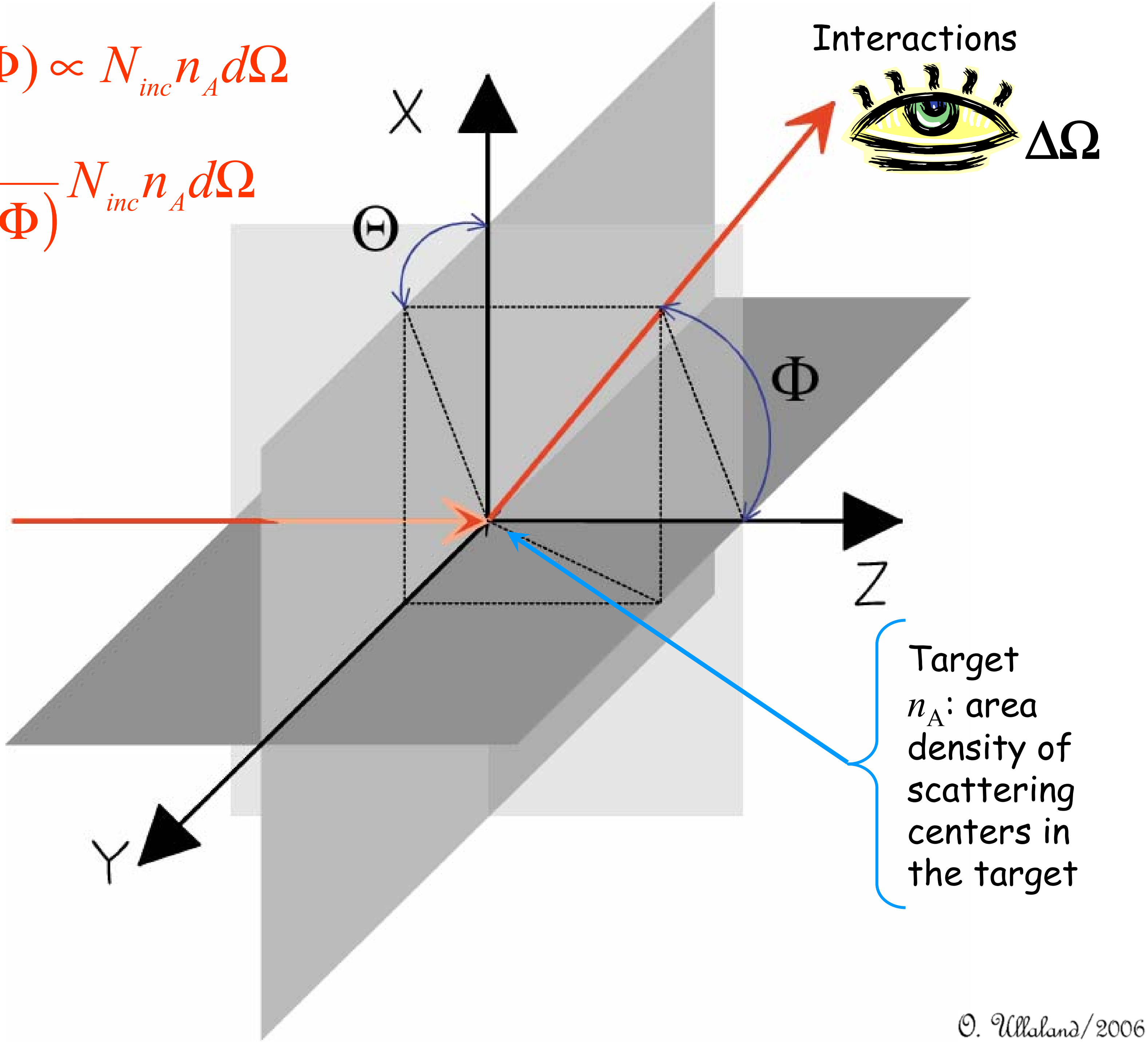
$$N_{scat}(\Theta,\Phi) \propto N_{inc} n_A d\Omega$$
$$= \frac{d\sigma}{d\Omega(\Theta,\Phi)} N_{inc} n_A d\Omega$$

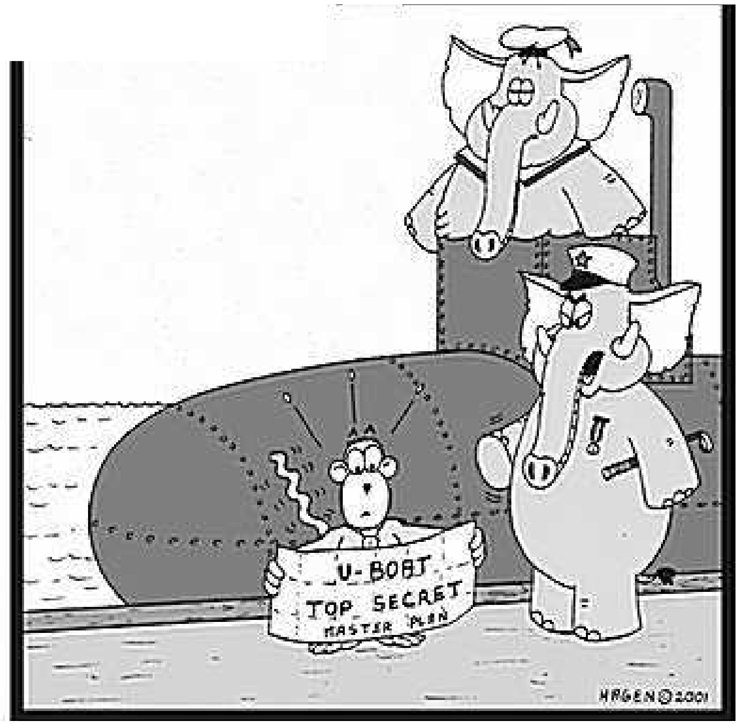


Of other more basic units, I will (try) to keep to definitions as given in the REVIEW OF PARTICLE PHYSICS, Particle Data Group like:

| | | |
|---|---|---|
| Atomic Number | $Z$ | |
| Atomic Mass Number | $A$ | |
| Electron Charge Magnitude | $e$ | $=1.602 \times 10^{-19}$ C |
| Permittivity | $\varepsilon$ | $\varepsilon_0=8.854 \times 10^{-12}$ F/m |
| Permeability | $\mu$ | $\mu_0=12.566 \times 10^{-7}\ N^*/A^2 \equiv 4\pi \times 10^{-7}$ henry/metre<br>$N^*$ denotes Neumann's integral for two linear circuits each carrying the current $I$. |

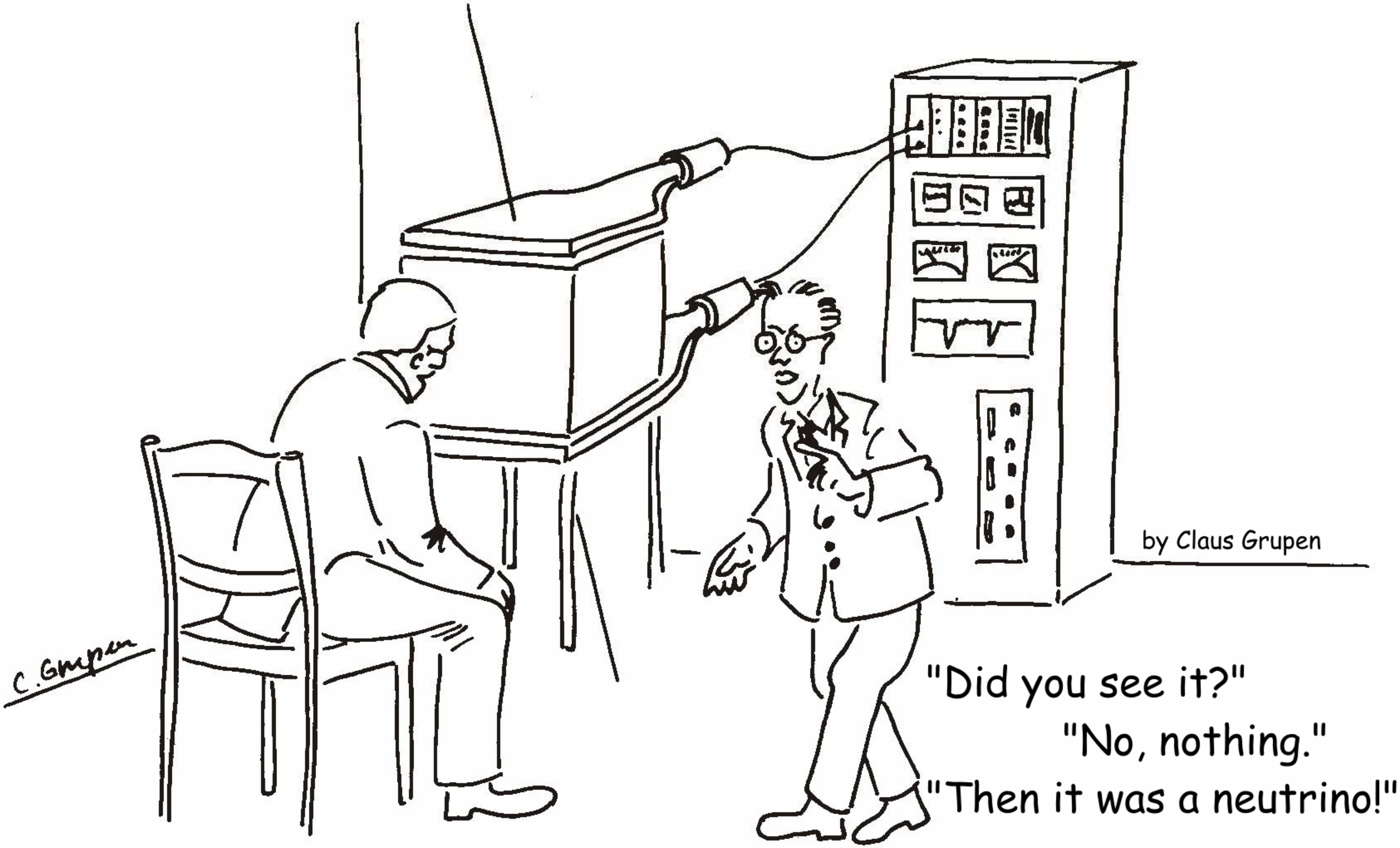
I will, from time to time when talking about pressure, use older units like
torr mmHg or mbar
and not the normal pascal=N/m$^2$
when showing original measurements.

I might even oscillate between
K and $^o$C.



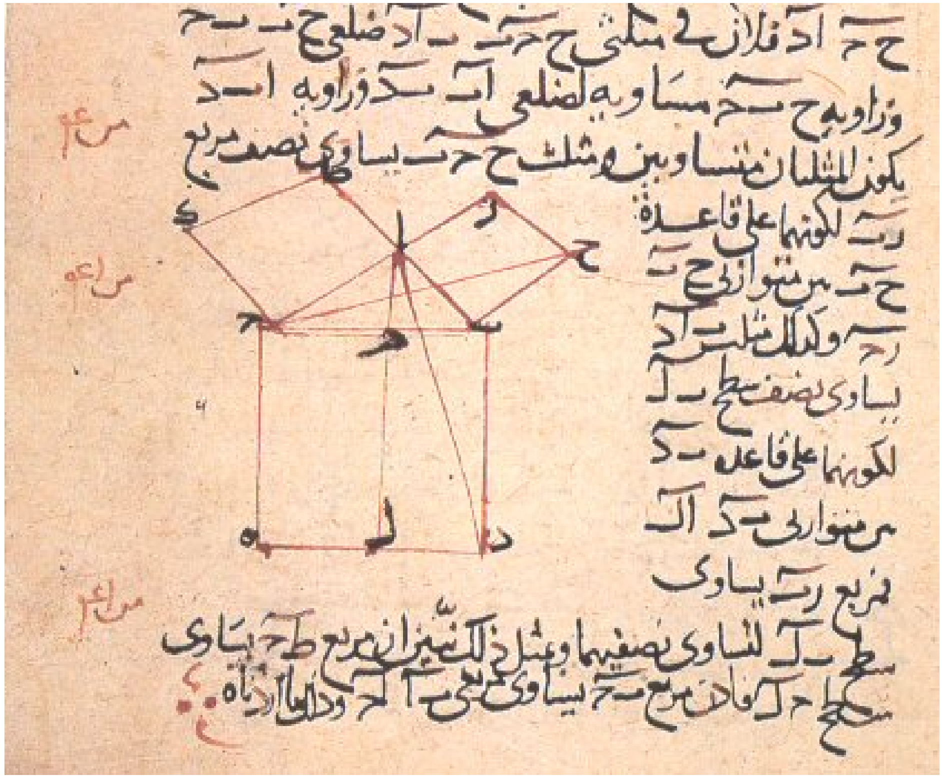
The unit in this plan is "metre", not "foot"!

# We can then start off________________




*Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8)*

Pythagoras (*ca*. 590-500 B.C.) invented the doctrine that the deep structure of ***reality resides in mathematical relations***.



Nasir al-Din al-Tusi's rendering (in A.D. 1258) of Euclid's (325-265 B.C.) proof of the Pythagorean Theorem.

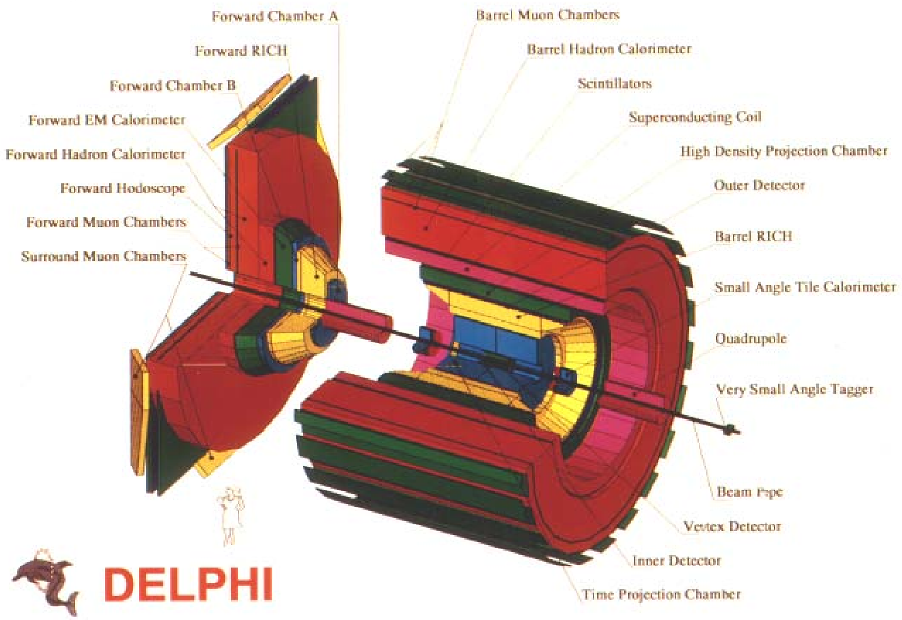
I will be less mathematical, there will be some, but I will mainly work with plots.

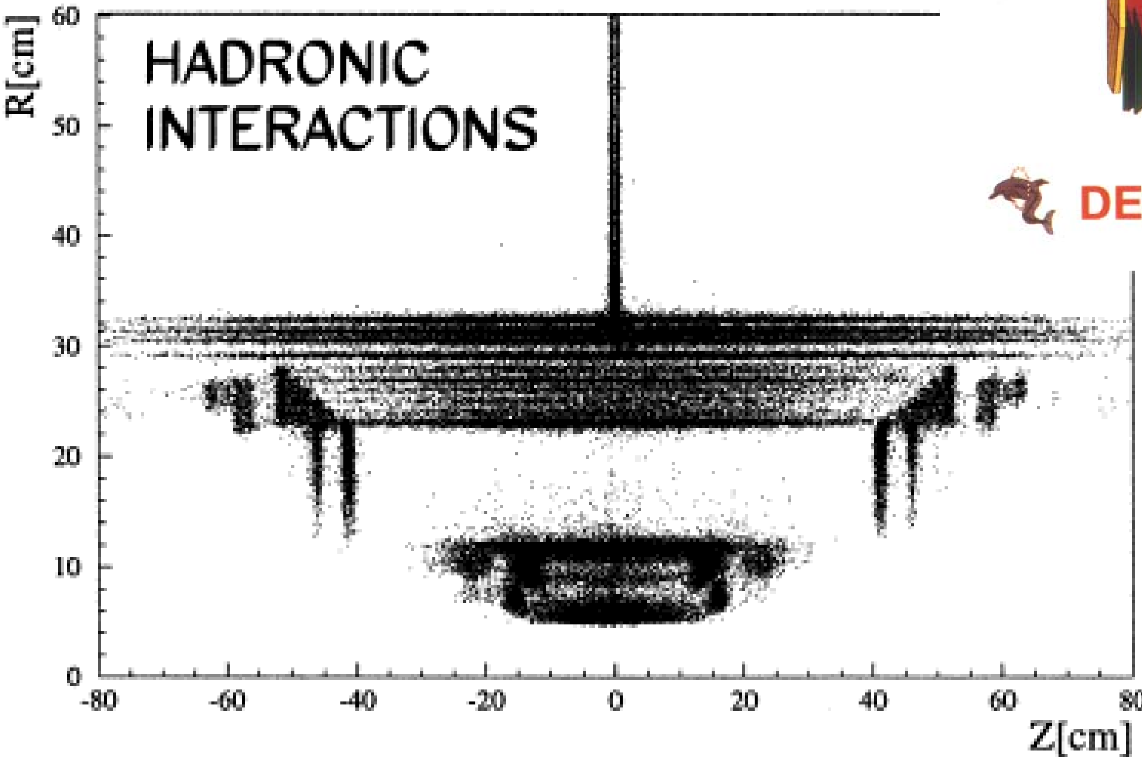
# 2006
# Summer Student Lectures
# Detectors

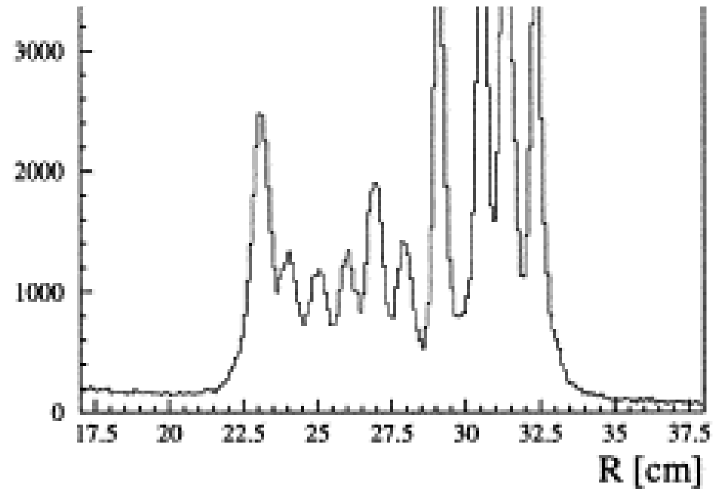
## Particle interaction with matter and fields.

### General (and nearly self evident) Statements

➔ Any device that is to detect a particle must interact with it in some way.
➔ If the particle is to pass through essentially undeviated,
this interaction must be a soft electromagnetic one.




Reconstructed hadronic interactions in the material of the DELPHI detector, used for the determination of the correction factor for the VD track efficiency.

Left: *Rz* view; Right: Radial projection.

Physics Letters B, Volume 475, Issues 3-4 , 2 March 2000, Pages 429-447

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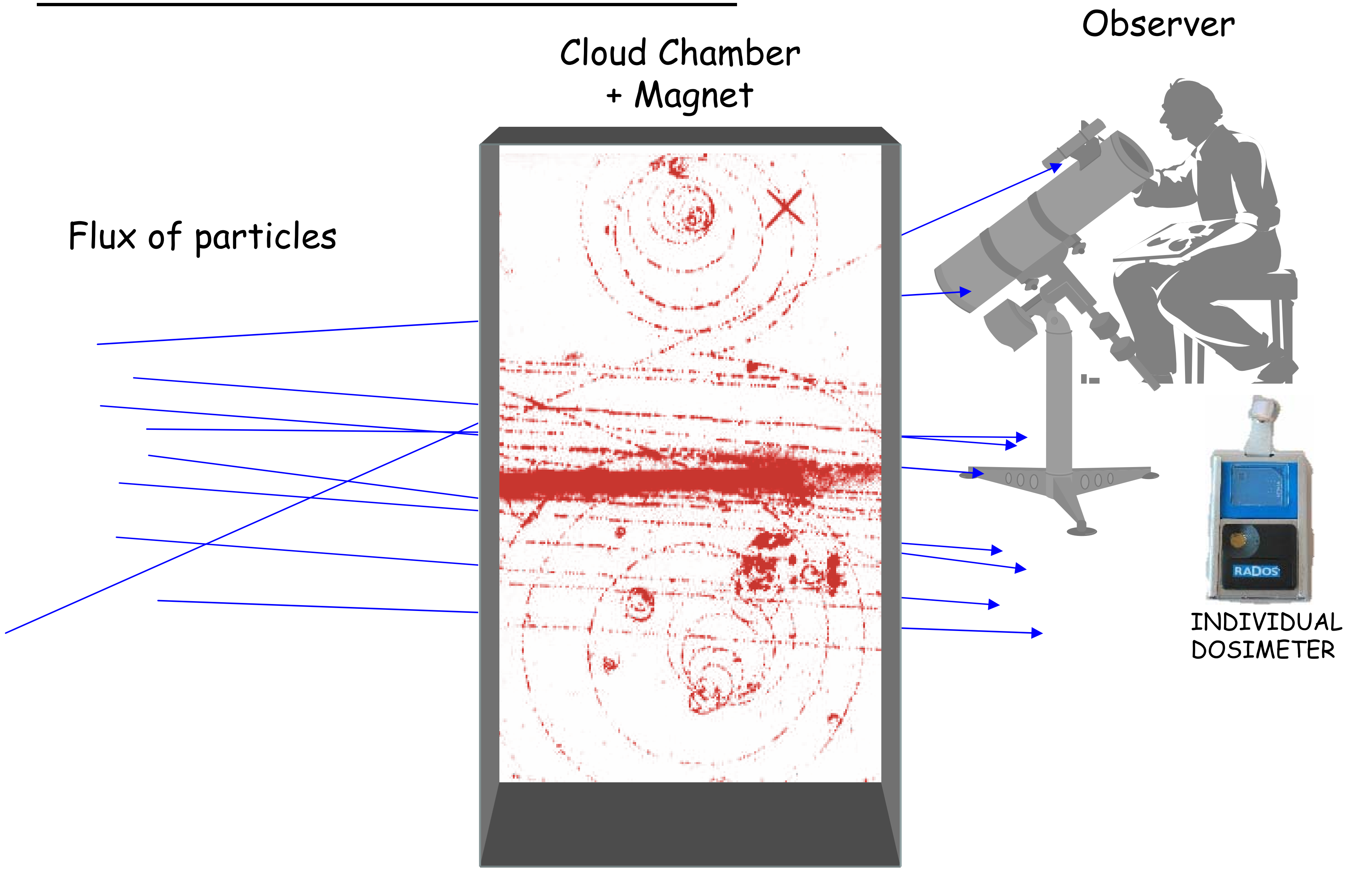
## To see the invisible:

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# Cloud Chamber design

C.T.R. Wilson described the new chamber in a paper to the Royal Society in 1912.

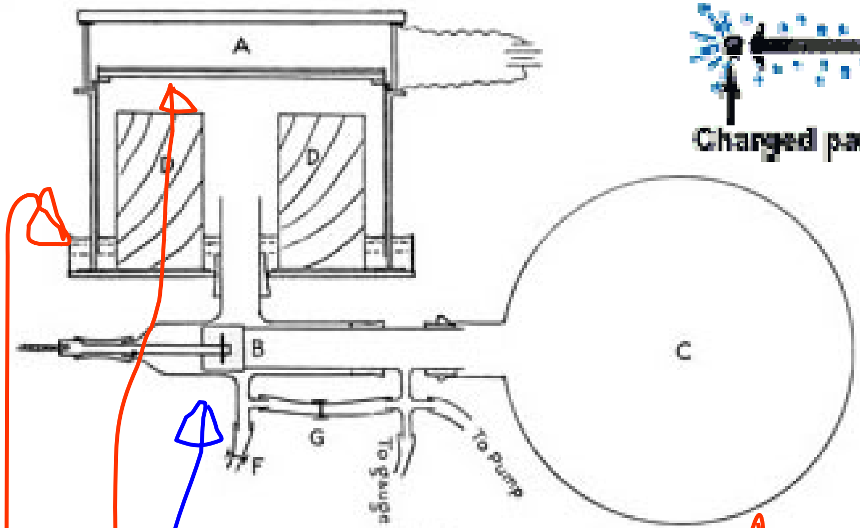



Fig. 1.

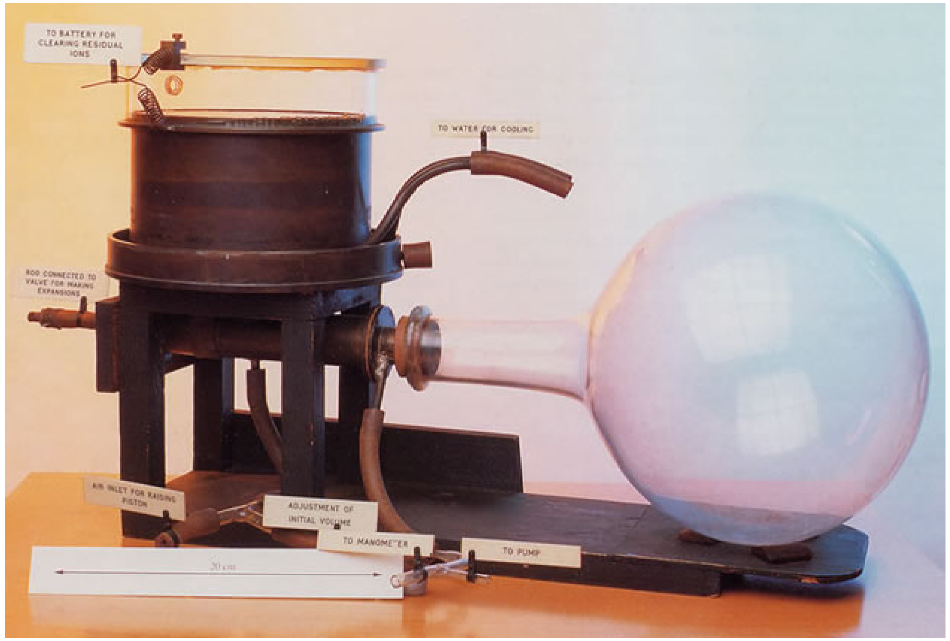
A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.


The floor of the chamber is fixed to the top of a brass plunger which can slide freely inside an outer cylinder.

A shallow trough of water that keeps the air in the chamber saturated with water molecules.

Vacuum chamber.

A valve can be opened to connect the bulb with the air beneath the plunger.

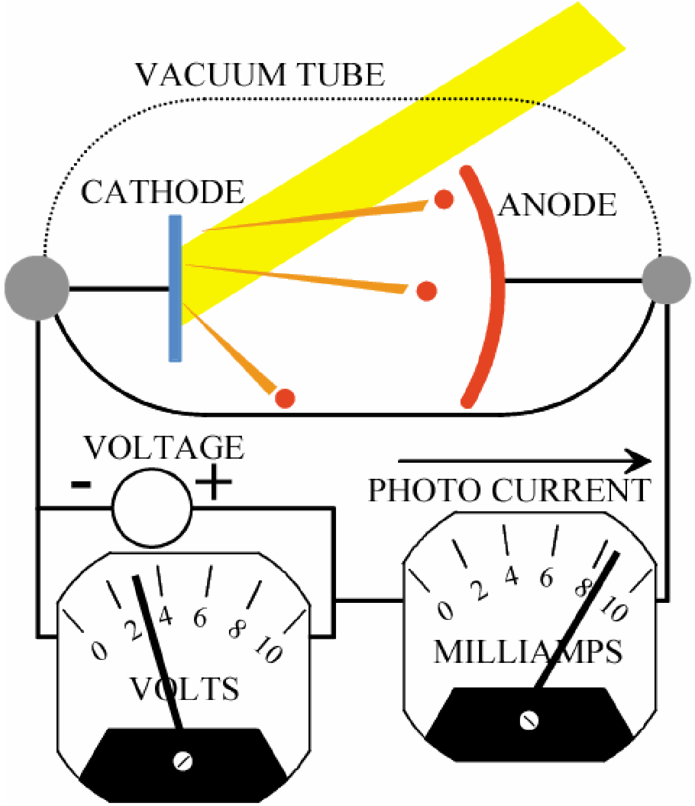


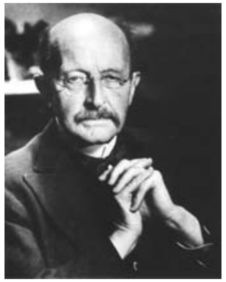

http://www.phy.cam.ac.uk/camphy/index.htm
and
http://www.bizarrelabs.com/cloud2.htm
for easy steps to build one in the kitchen

# The Photoelectric Effect

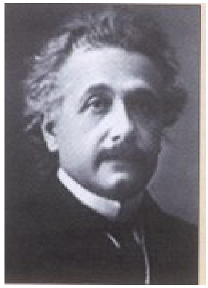
Über einen die Erzeugung und Verwanlung des Lichtes betreffenden heuristischen Gesisichtspunkt;
von A. Einstein; Bern, den 18. März 1905, Annalen der Physik 17(1905): 132-148 (ref. M. Planck, Ann. d. Phys. 4, p 562. 1902)

Only by reluctantly introducing a radical new assumption into his mathematics could **Planck** attain the correct formula. The assumption was that the energy of the radiation does not act continuously, as one would expect for waves, but exerts itself in equal discontinuous parcels, or "quanta," of energy. In essence Planck had discovered the quantum structure of electromagnetic radiation. But Planck himself did not see it that way; he saw the new assumption merely as a mathematical trick to obtain the right answer. Its significance remained for him a mystery.



Encouraged by his brief but successful application of statistical mechanics to radiation in 1904, in 1905 **Einstein** attempted to resolve the duality of atoms and waves by demonstrating that part of Planck's formula can arise only from the hypothesis that electromagnetic radiation behaves as if it actually consists of individual "quanta" of energy. The continuous waves of Maxwell's equations, which had been confirmed experimentally, could be considered only averages over myriads of tiny light quanta, essentially "atoms" of light. At first Einstein believed that the light-quantum hypothesis was merely "heuristic": light behaved only as if it consisted of discontinuous quanta. But in a brilliant series of subsequent papers in 1906 and 1907, Einstein used his statistical mechanics to demonstrate that when light interacts with matter, Planck's entire formula can arise only from the hypothesis that the existence of light quanta—not from waves.



From this,
the following equation results:

$$E_{kinetic} = hf - W$$

| | |
|---|---|
| $E_{kinetic}$ | maximal kinetic energy of an emitted electron |
| $h$ | Planck constant ($6.626 \times 10^{-34}$ Js) |
| $f$ | frequency |
| $W$ | work function |

David Cassidy, Einstein and Our World
http://www.physics.nwu.edu/new335/PDF/planck.pdf

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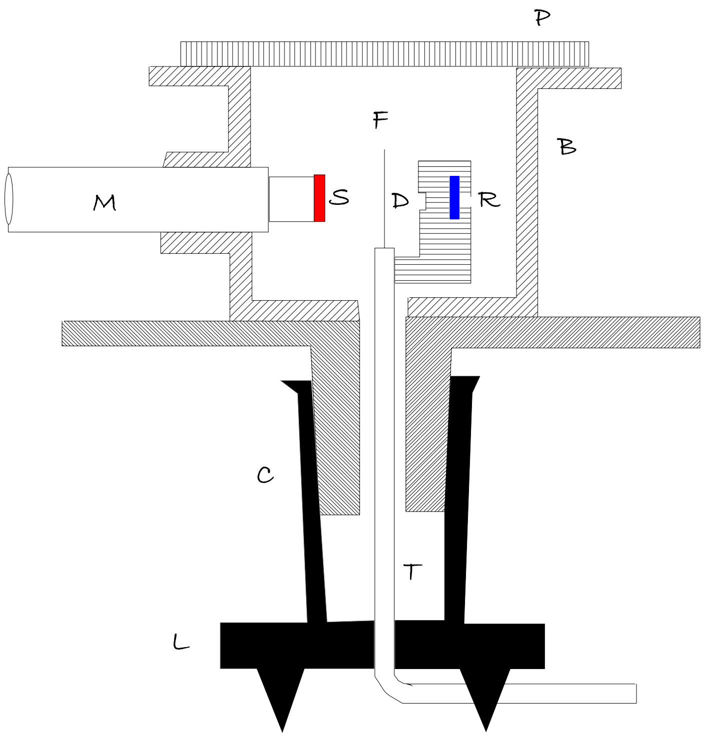
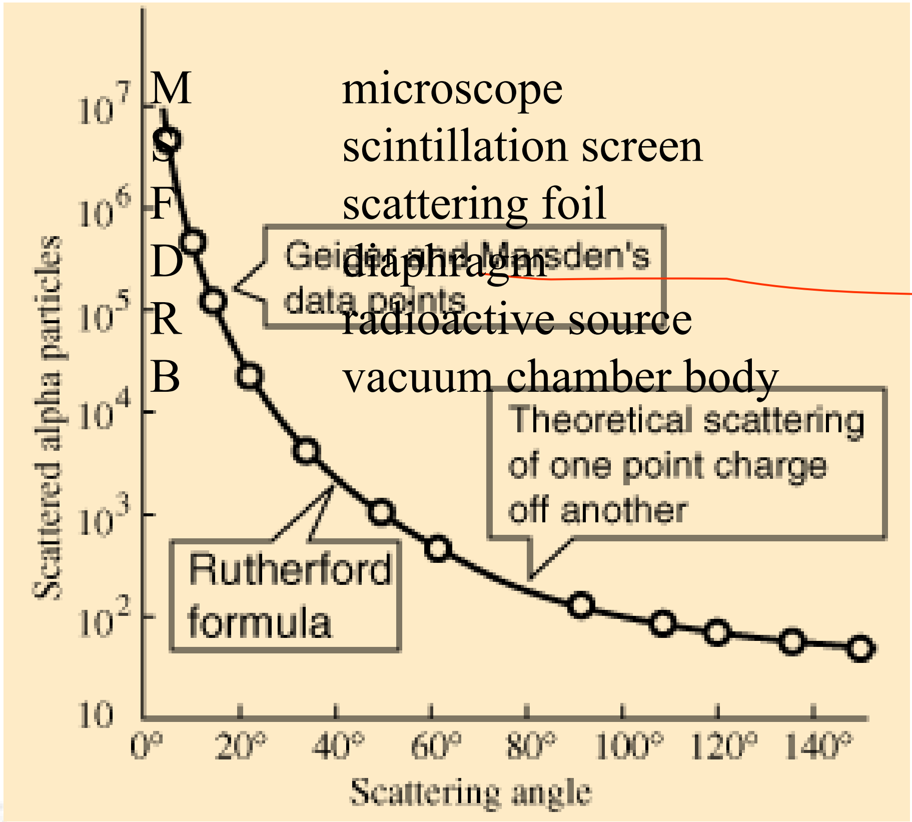
Figure 1




http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Ernest Rutherford and Hans Geiger with apparatus for counting alpha particles, Manchester, 1912

(Source: Science Museum)

1962

~50 years

Knight Bachelor in 1958

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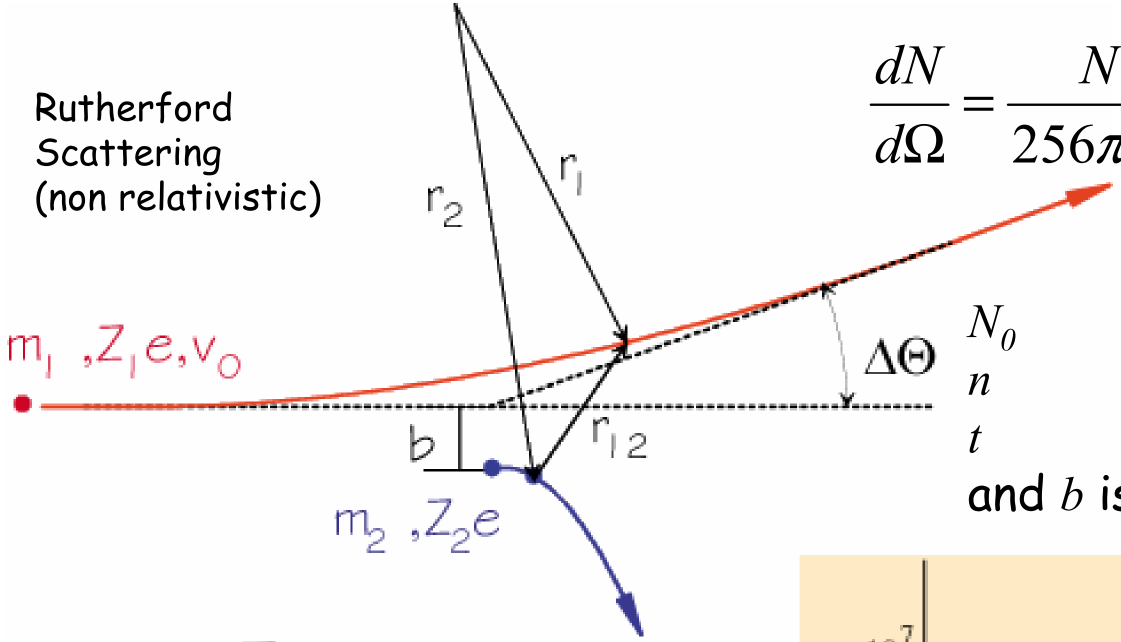
# Bethe-Bloch, energy loss dE/dx and tracking detectors.

Rutherford
Scattering
(non relativistic)

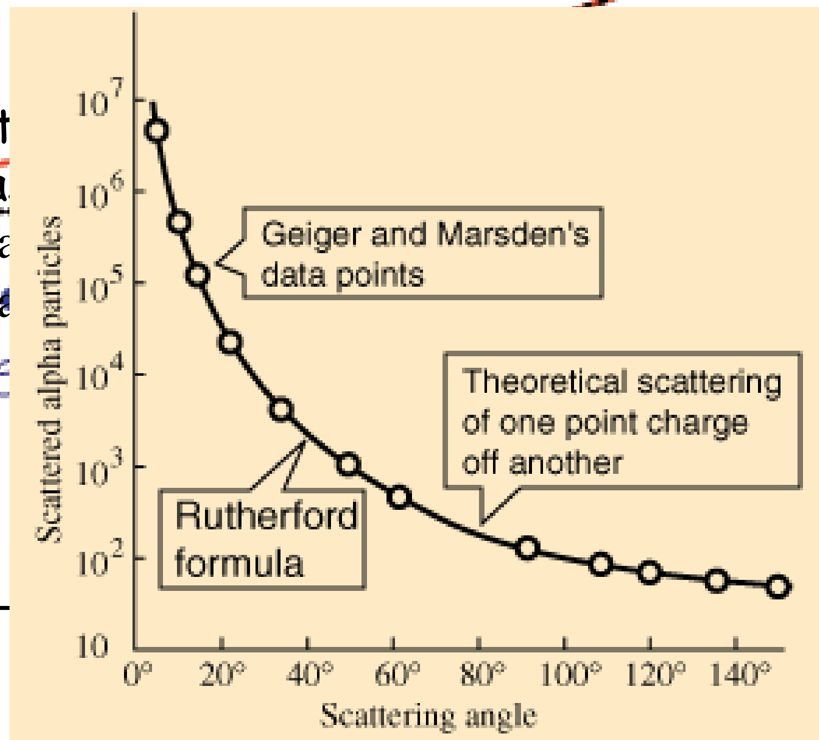



$$\frac{dN}{d\Omega} = \frac{N_0}{256\pi^2\varepsilon_0^2}[nt]Z_1^2 Z_2^2 e^4 \frac{1}{\left(\frac{1}{2}m_1 v_0^2\right)^2}\frac{1}{\sin^4\frac{\Theta_{CM}}{2}}$$

$N_0$ number of beam particles
$n$ target material in atoms/volume
$t$ target thickness
and $b$ is the impact parameter

Multiple Coulomb Scat
Energy Transfer = Cla
If Energy > Ioniza
Energy < Ioniza

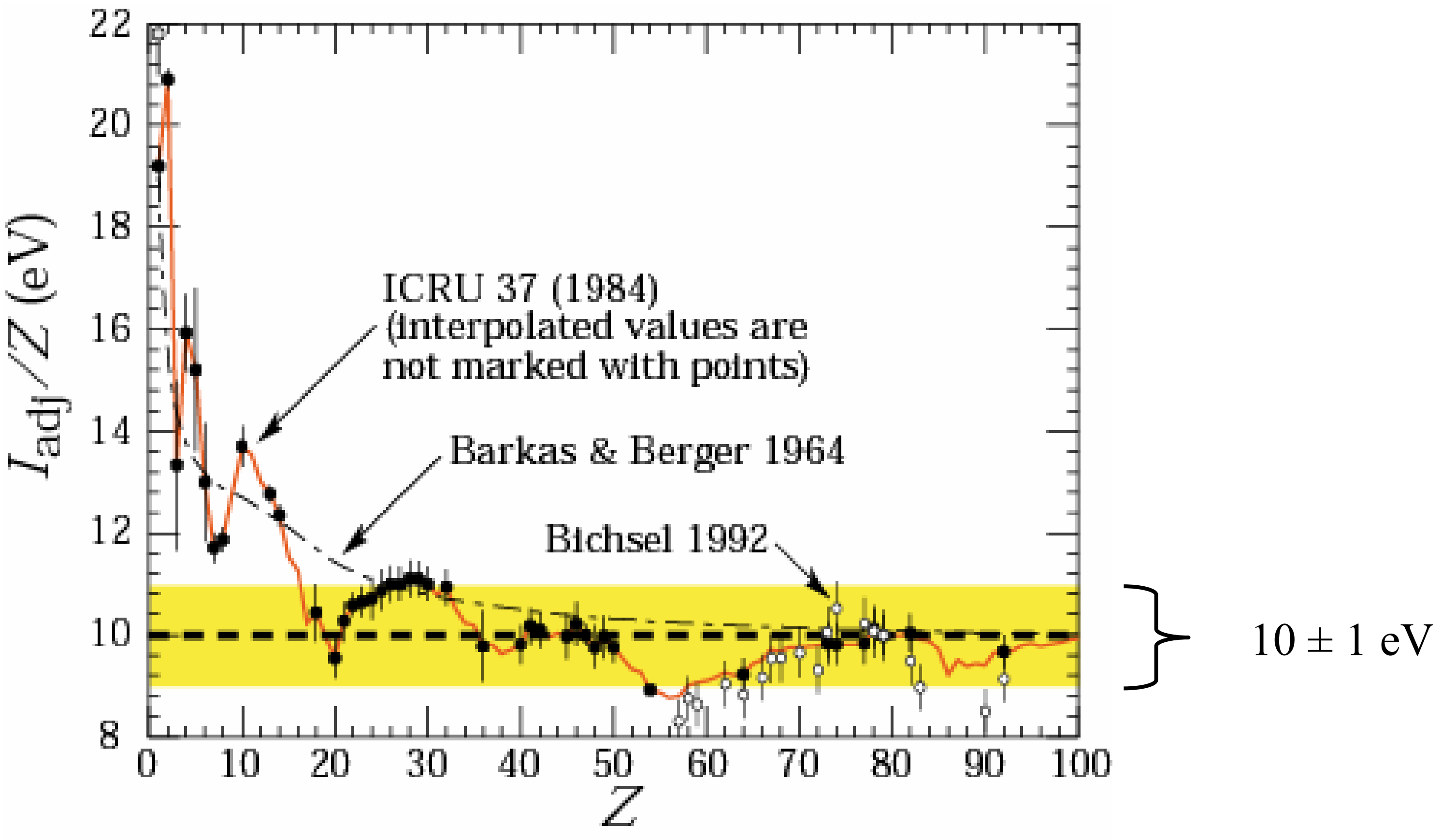
$$\frac{dE}{dx} = \frac{NZ_1^2 e^4}{8\pi\varepsilon_0^2 m_e v_0^2}\sum_{i=Z'}^{Z}\ln\frac{E_{max}}{I_i}$$




$$\ln\frac{2m_r^2 v_0^2}{m_e I_i}$$

Substituting in the maximum
(non relativistic) energy transfer:

ons in the atom
transfer is
rgy.

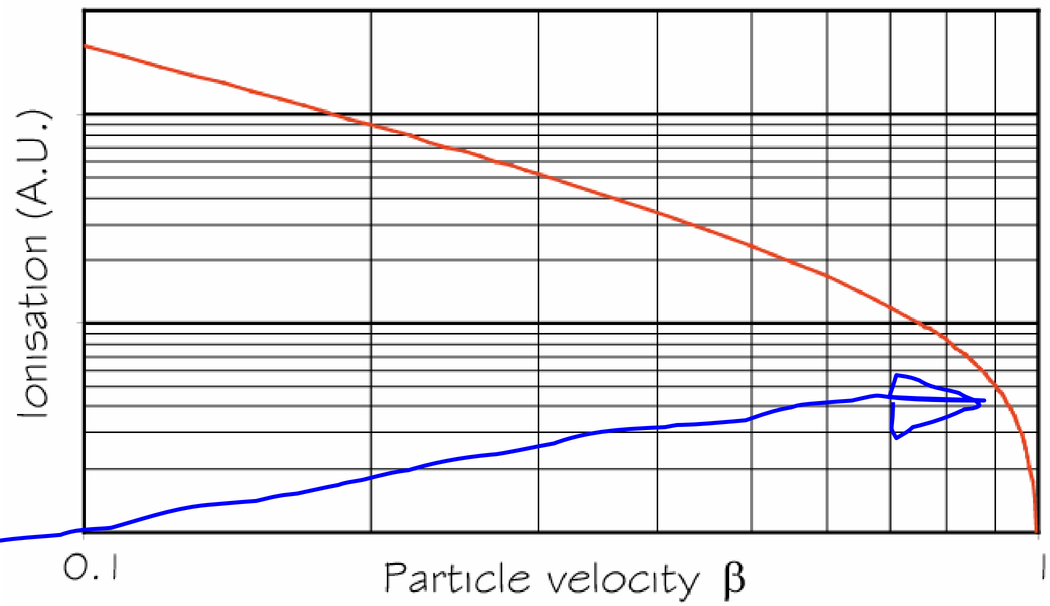



Mean excitation energies (divided by $Z$) as adopted by the ICRU [9]*. Those based on experimental measurements are shown by symbols with error flags; the interpolated values are simply joined. The grey point is for liquid $H_2$; the black point at 19.2 eV is for $H_2$ gas. The open circles show more recent determinations by Bichsel [11]. The dotted curve is from the approximate formula of Barkas [12] used in early editions of this *Review*.

* [Stopping Powers for Electrons and Positrons," ICRU Report No. 37 (1984)

http://pdg.lbl.gov/2004/reviews/passagerpp.pdf

Until now: $\frac{dE}{dx} \propto \frac{\ln(\beta^2)}{\beta^2}$




As $\beta \to 1$, the Rutherford formula becomes inaccurate.

Simplest modifications give Mott formula.
- First order perturbation theory
- Assumes no recoil of target
- No spin or structure effects.

$$\left.\frac{d\sigma}{d\Omega}\right|_{Mott} = \frac{z^2\alpha^2(\hbar c)^2}{4p_e^2\beta^2}\frac{1}{\sin^4\left(\frac{\theta}{2}\right)}\left[1-\beta^2\sin^2\frac{\theta}{2}\right]$$

and as

$$-\frac{dE}{dx} \propto \int_{\varepsilon_{cut}}^{\varepsilon_{\max}} \varepsilon \frac{d\sigma}{d\varepsilon} d\varepsilon$$

has now to be solved for

a) close interactions — the electrons are free

b) distant interactions — the electrons are not free

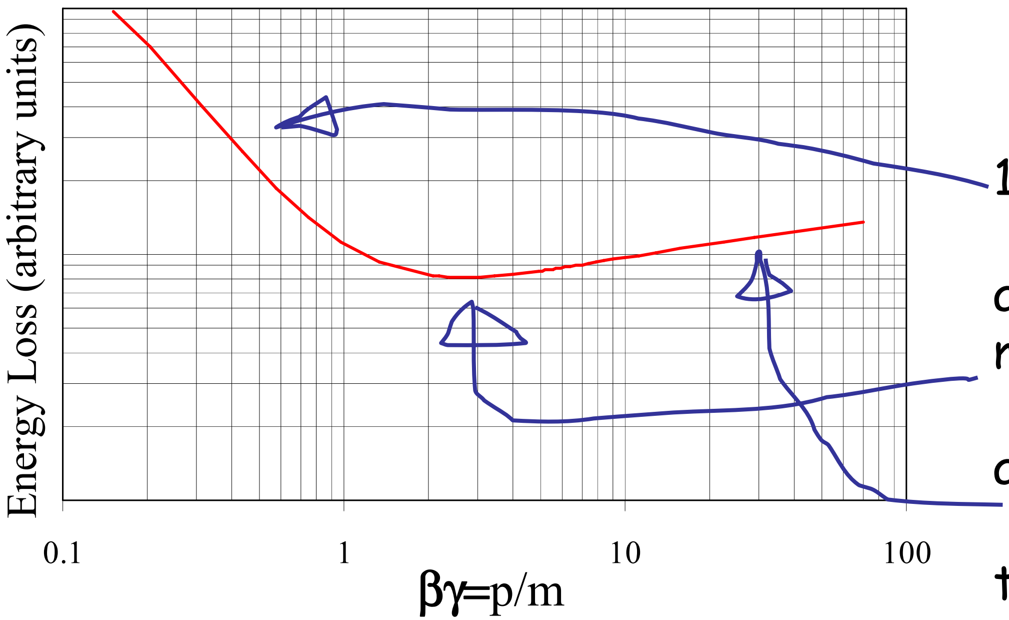
$$-\left(\frac{dE}{dx}\right)_{\text{close}} \propto \frac{1}{\beta^2}\left[\ln\left(\frac{\varepsilon_{\max}}{\varepsilon_{cut}}\right) - \beta^2\right]$$

for close interactions

$$-\left(\frac{dE}{dx}\right)_{\text{distant}} \propto \frac{1}{\beta^2}\left[\ln\left(\frac{2(\beta\gamma)^2 m_e \varepsilon_{\text{cut}}}{I^2}\right) - \beta^2 - \delta\right]$$

for distant interactions

The $\delta$ term models the density effect, the polarization of the medium.




What we would expect to see:

$1/\beta^2$ fall off

a minimum:
minimum ionizing particle: a MIP

a relativistic rise

the $\delta$ term should pull it down:
the Fermi plateau.

For all the missing steps:
see J.D. Jackson, Classical Electrodynamics, Section 13 or equivalent

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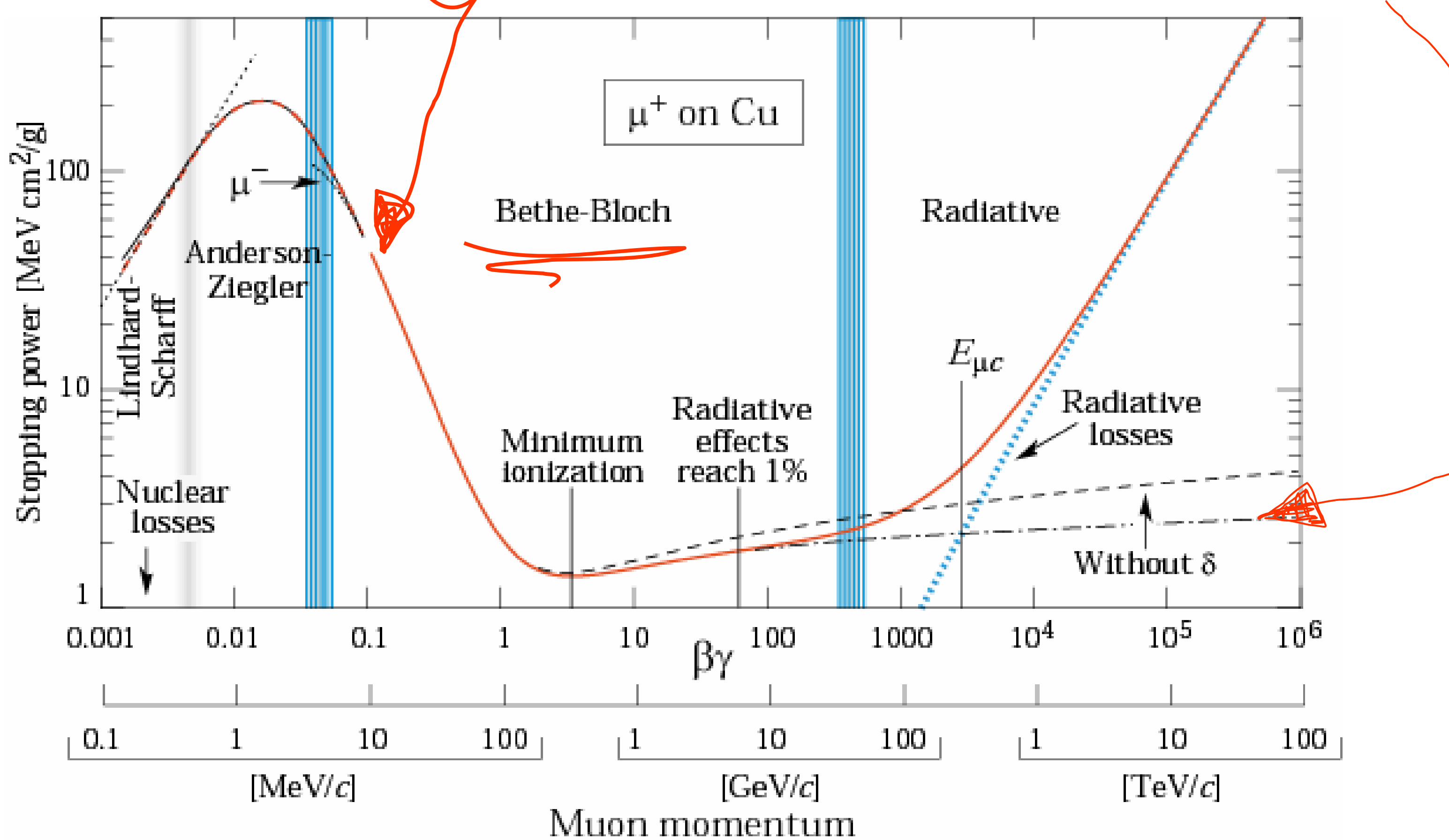
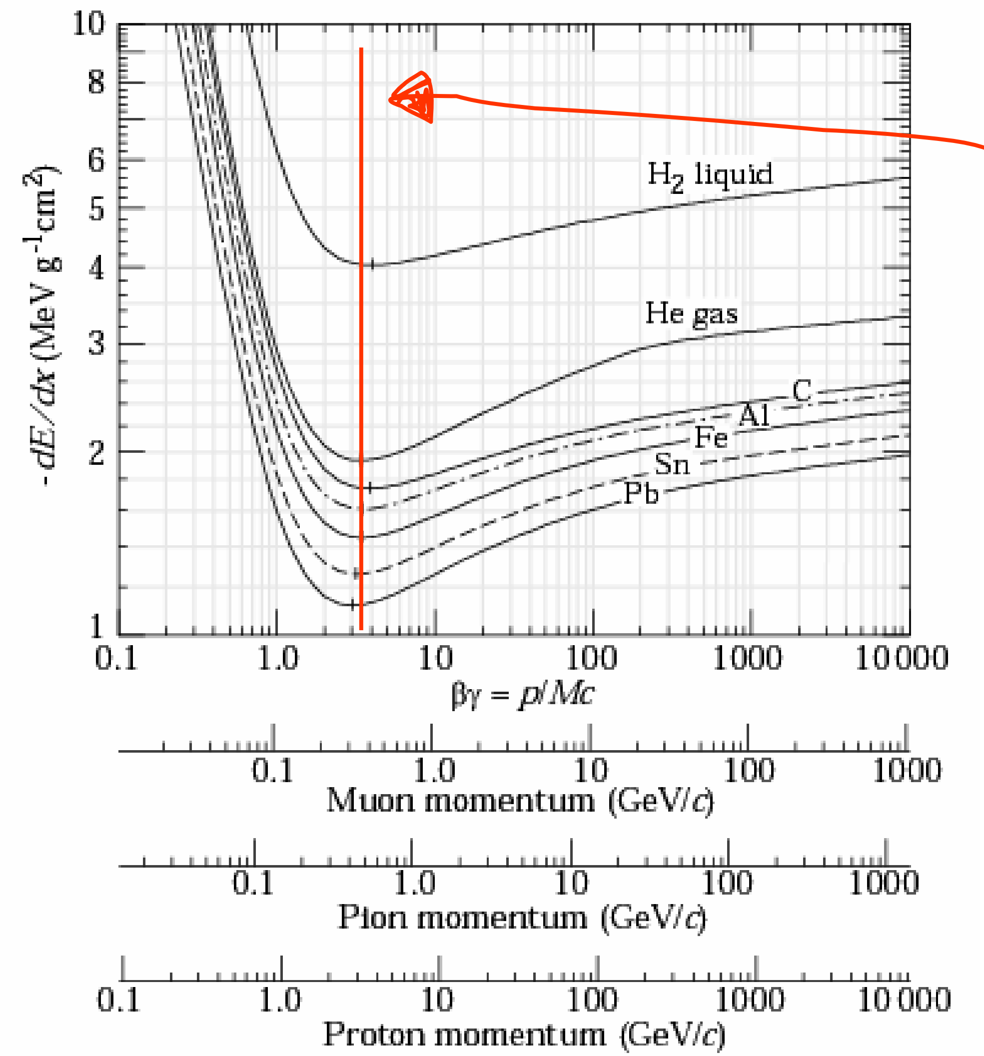
$$\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$




Stopping power ( ≡⟨dE/dx⟩) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power.

http://pdg.lbl.gov/2004/reviews/passagerpp.pdf

## The density effect.

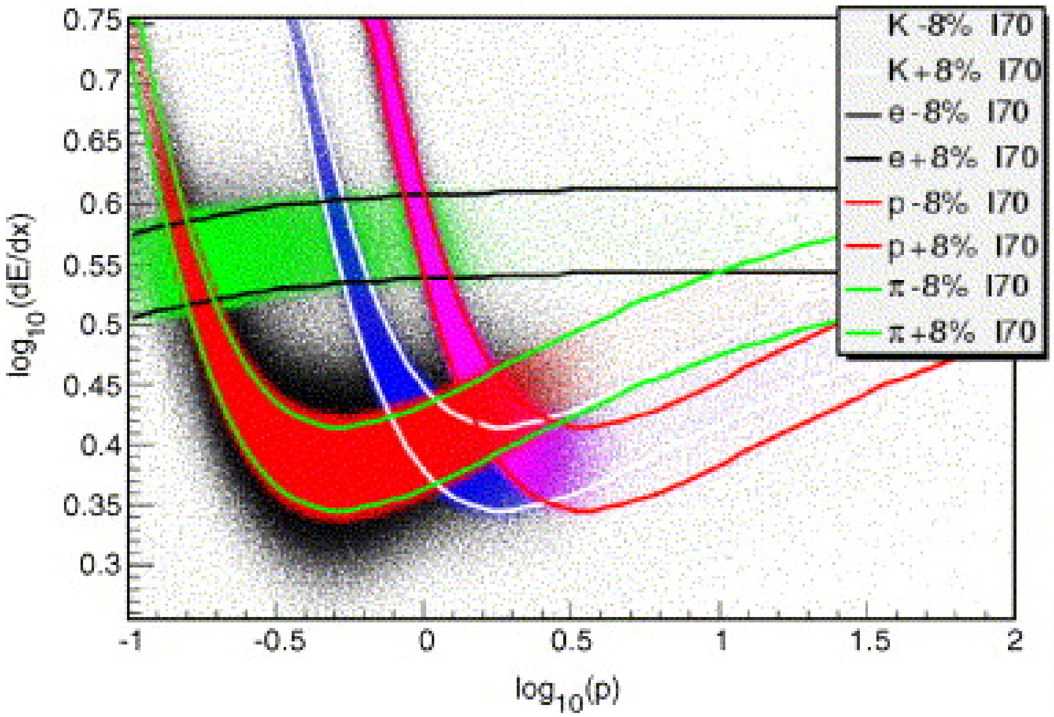



The minimum is approximately independent of the material.

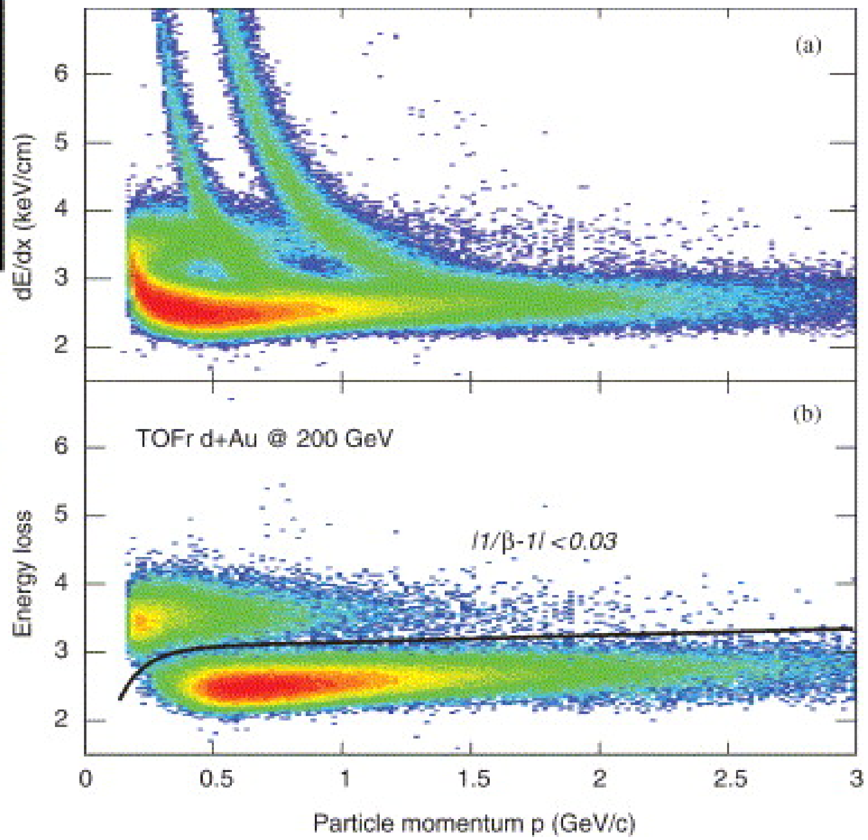
Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminium, iron, tin, and lead.

http://pdg.lbl.gov/2004/reviews/passagerpp.pdf

# the STAR experiment




Distribution of $\log_{10}(\mathrm{d}E/\mathrm{d}x)$ as a function of $\log_{10}(p)$ for electrons, pions, kaons and (anti-)protons. The units of d*E*/d*x* and momentum (*p*) are keV/cm and GeV/*c*, respectively. The colour bands denote within $\pm 1\sigma$ the d*E*/d*x* resolution.
*I*70 means Bichsel's prediction for 30% truncated d*E*/d*x* mean.



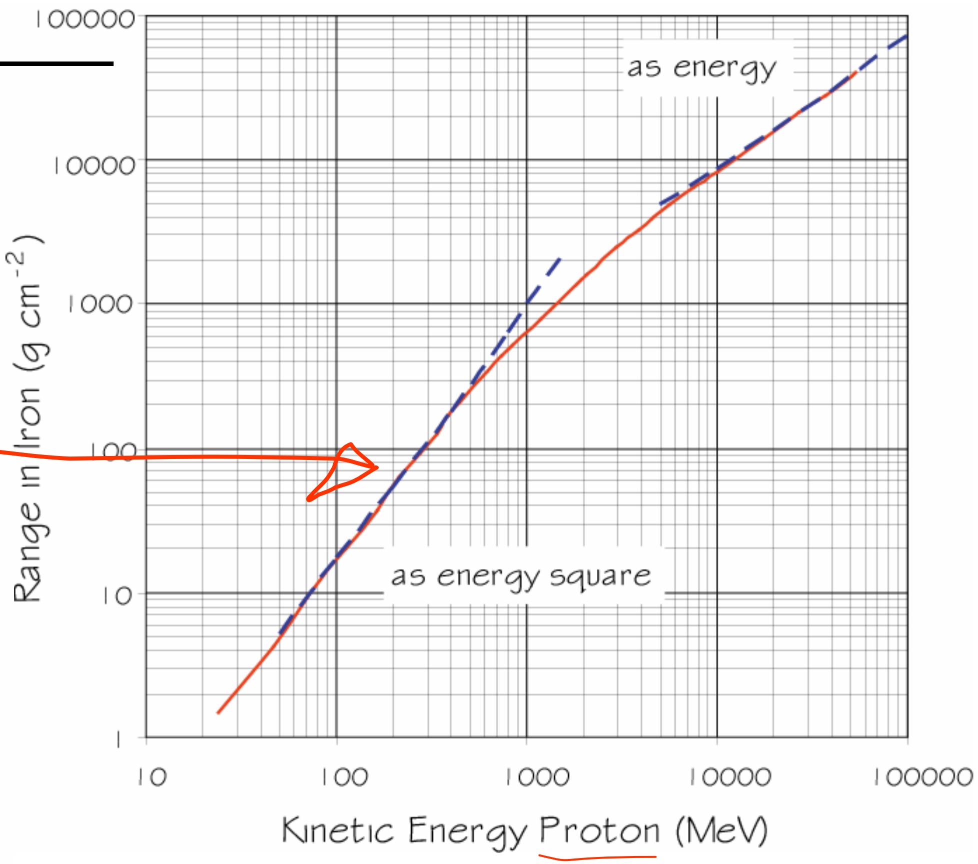

d*E*/d*x* in the TPC vs. particle momentum (*p*) without (upper panel) and with (lower panel) TOFr velocity cut of $|1/\beta - 1| < 0.03$.

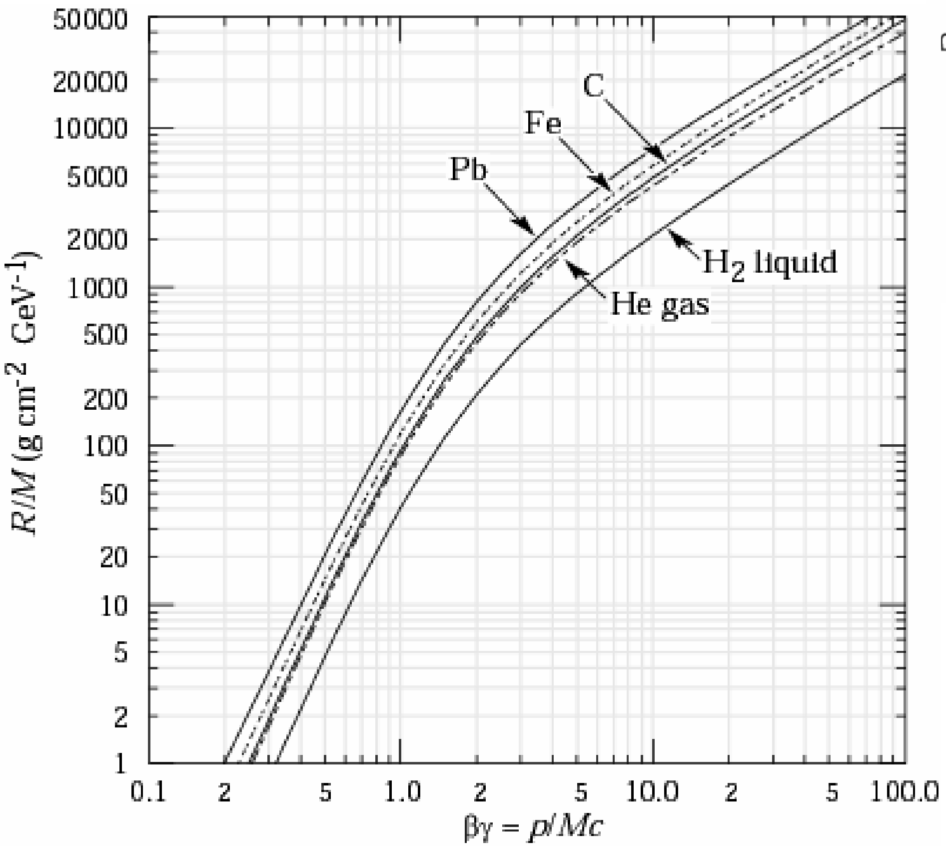
NIM Volume 558, Issue 2 , 15 March 2006, Pages 419-429

## Range of particles in matter.

Poor man's approach:
Integrating $dE/dX$ from Rutherford scattering and ignoring the slowly changing $ln(term)$.

$$Range = R \approx \frac{Const.}{Z_1^2 m_1^2} E_{Kinetic}^2$$




Range is approximately proportional to the kinetic energy square at low energy and approximately proportional to the kinetic energy at high energy where the $dE/dX$ is about constant.

http://pdg.lbl.gov/2004/reviews/passagerpp.pdf

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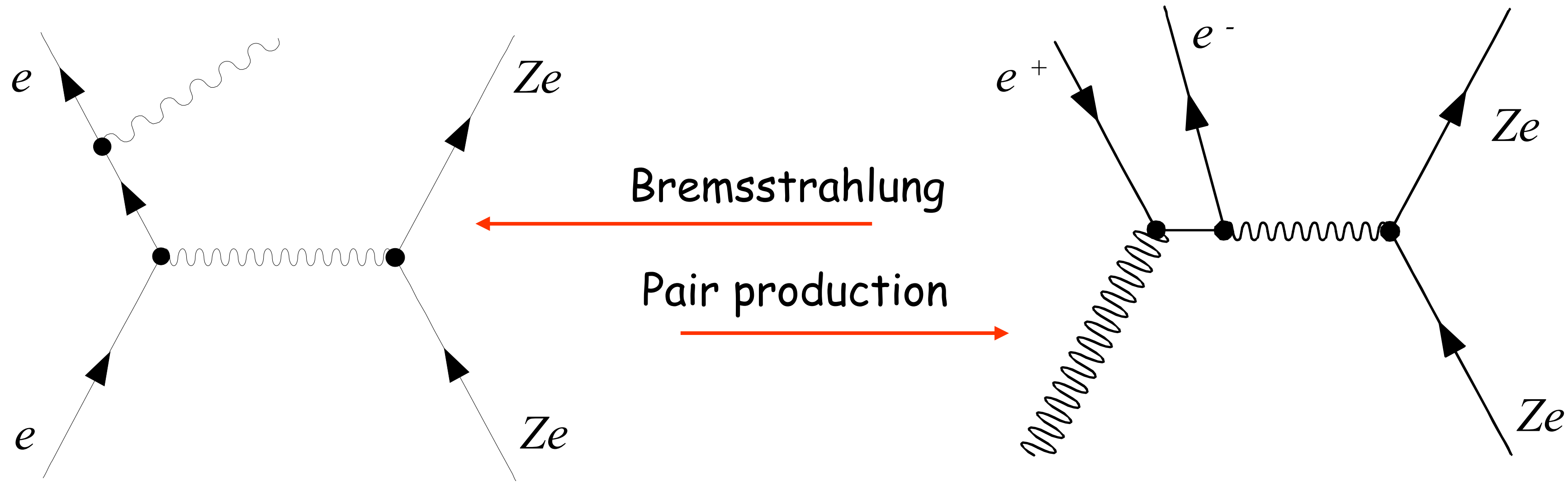
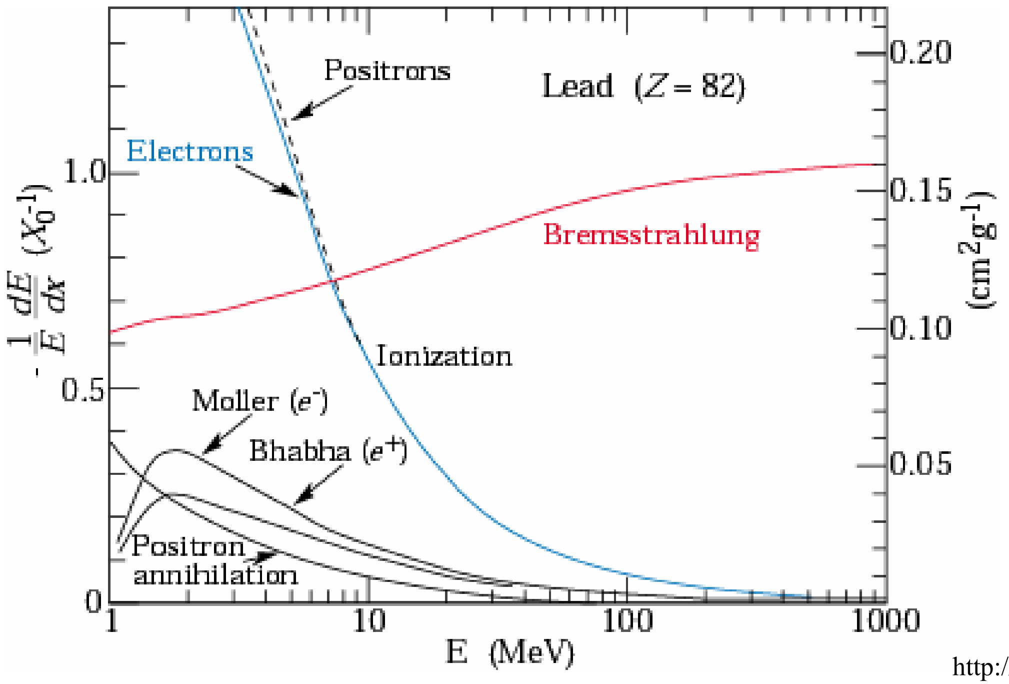
# Electrons (and positrons) are different as they are light.



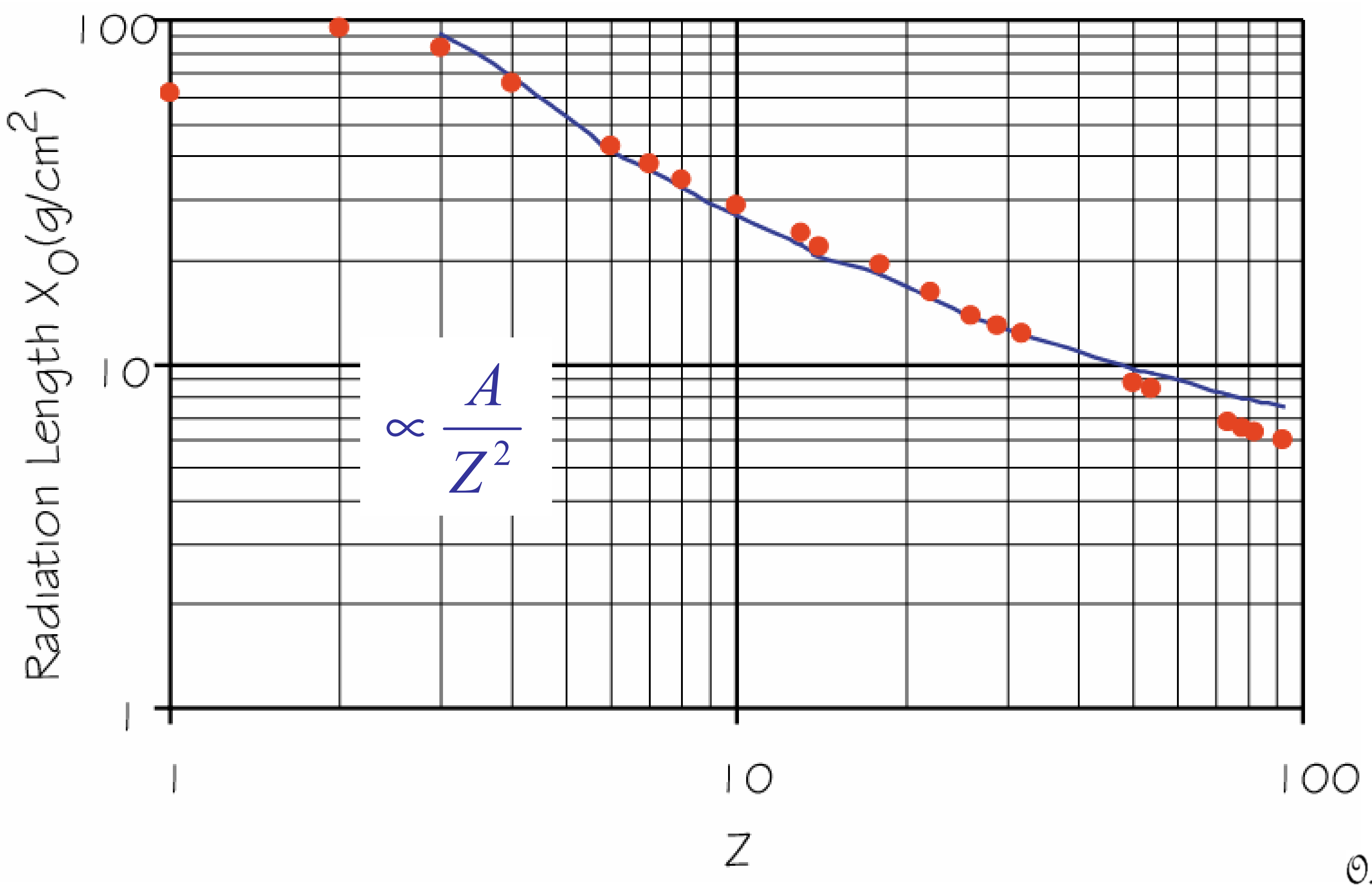

Fractional energy loss per radiation length in lead as a function of electron or positron energy.

http://pdg.lbl.gov/2004/reviews/passagerpp.pdf

Define $X_0$ as the Radiative Mean Path.
$X_0$ : Radiation Length

$$\frac{1}{X_0} \equiv \frac{1}{E}\frac{dE}{\rho dx}$$

$$\frac{1}{X_0} = \frac{16}{3} N_0 Z^2 \alpha (\alpha \bar{\lambda})^2 [\ln()] \frac{Z^2}{A} \Rightarrow X_0 \propto \frac{A}{Z^2}$$

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apart from a (nice) definition, what exactly is Radiation Length ?

1 $X_0$ is the distance over which an electron/positron looses 63.2% of it energy in Bremsstrahlung.
The energy loss probability across a path length $x$ → $P_{e^-e^+} = 1 - e^{-\frac{x}{X_0}}$

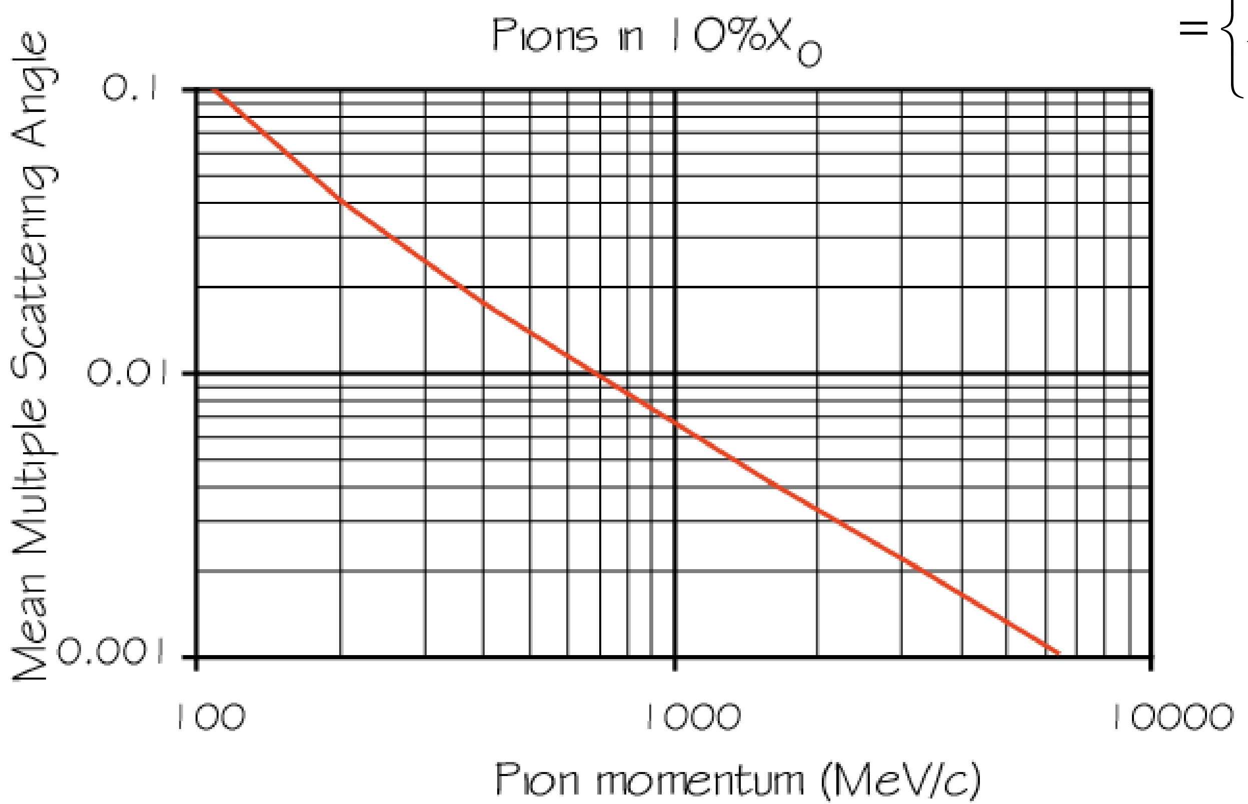
Pick up again

the Multiple Scattering $\langle \Theta^2_{MS} \rangle = N_{scatterings} * \langle \Theta^2 \rangle$

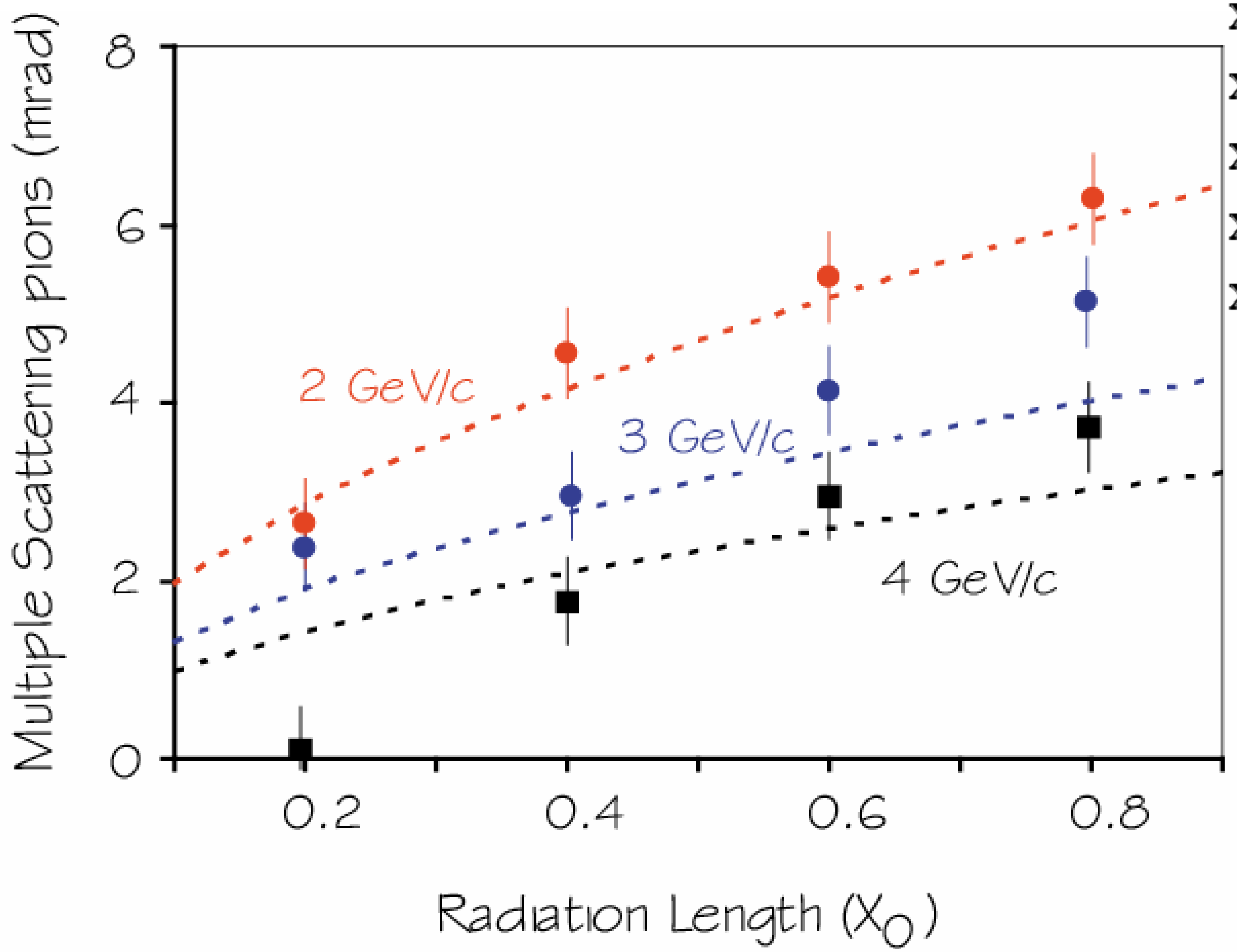
$$= \left\{ E_s \frac{1}{p\beta} \right\}^2 \frac{x}{X_0}$$

$$E_S \equiv m_e c^2 \cdot \sqrt{\frac{4\pi}{\alpha}} = 21.205 MeV$$

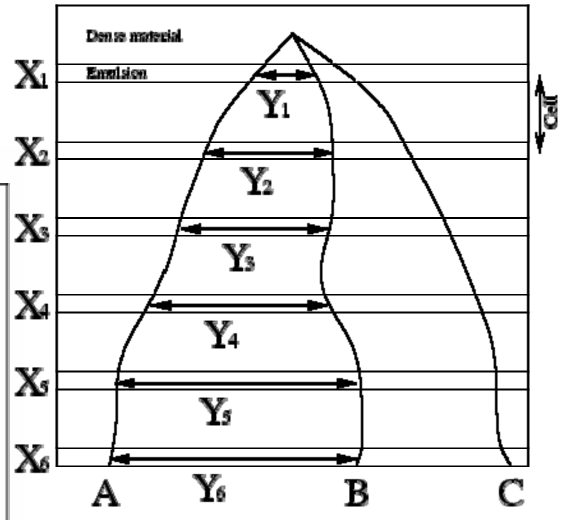
The characteristic energy



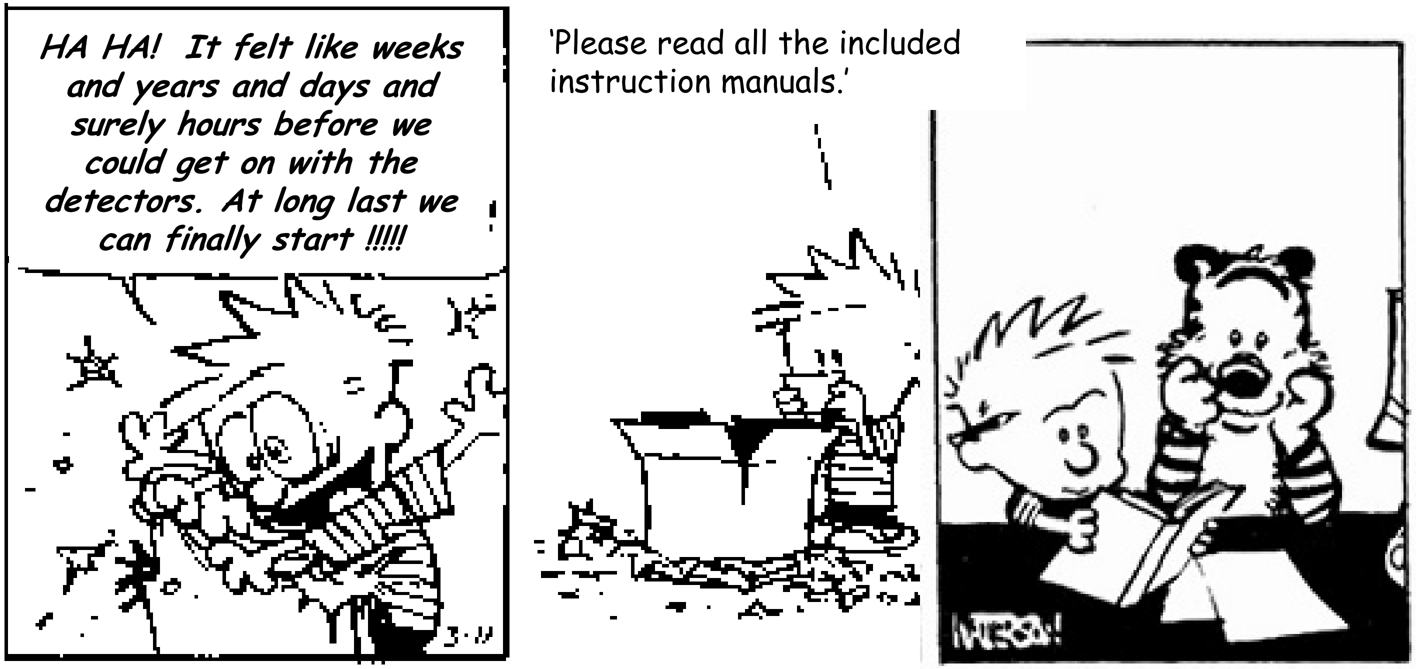
and (if you have no magnet) you can use it for
measuring momentum



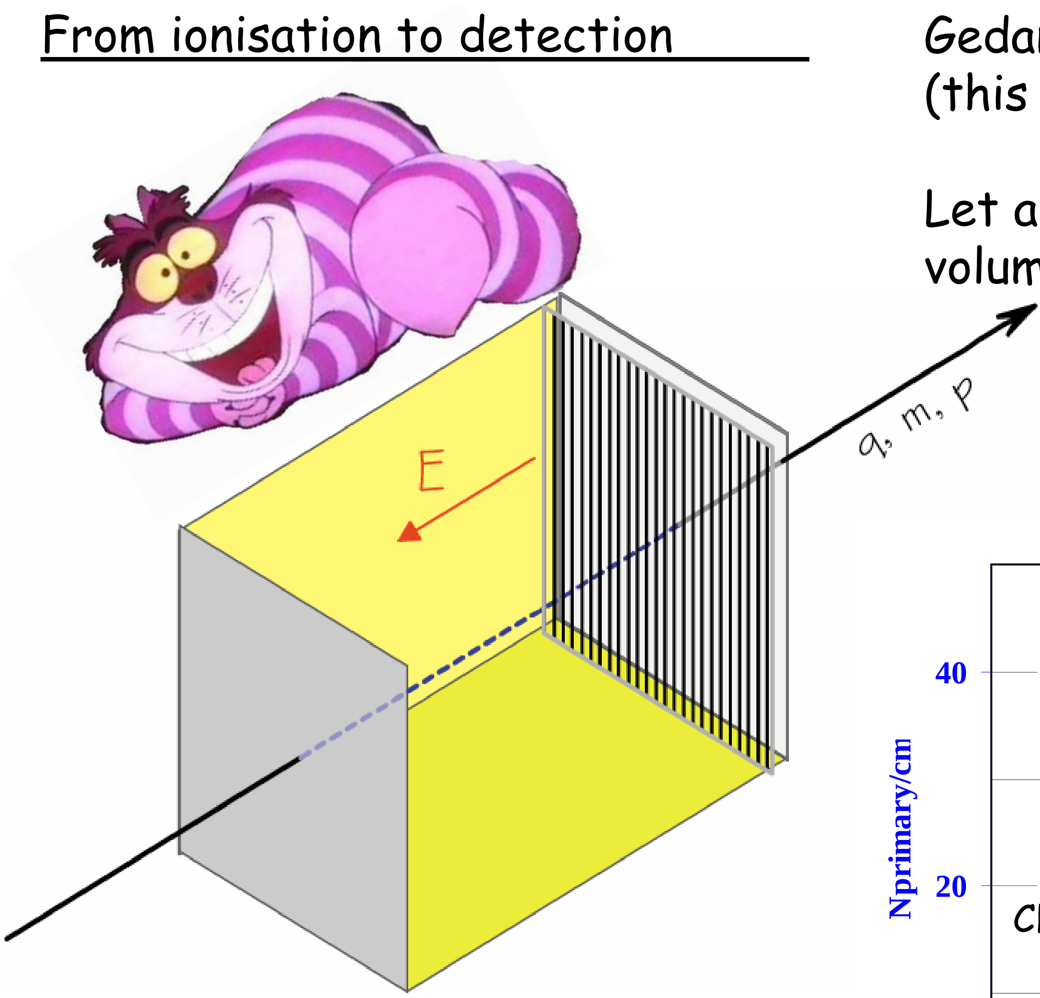

OPERA



We will now move on to detectors.

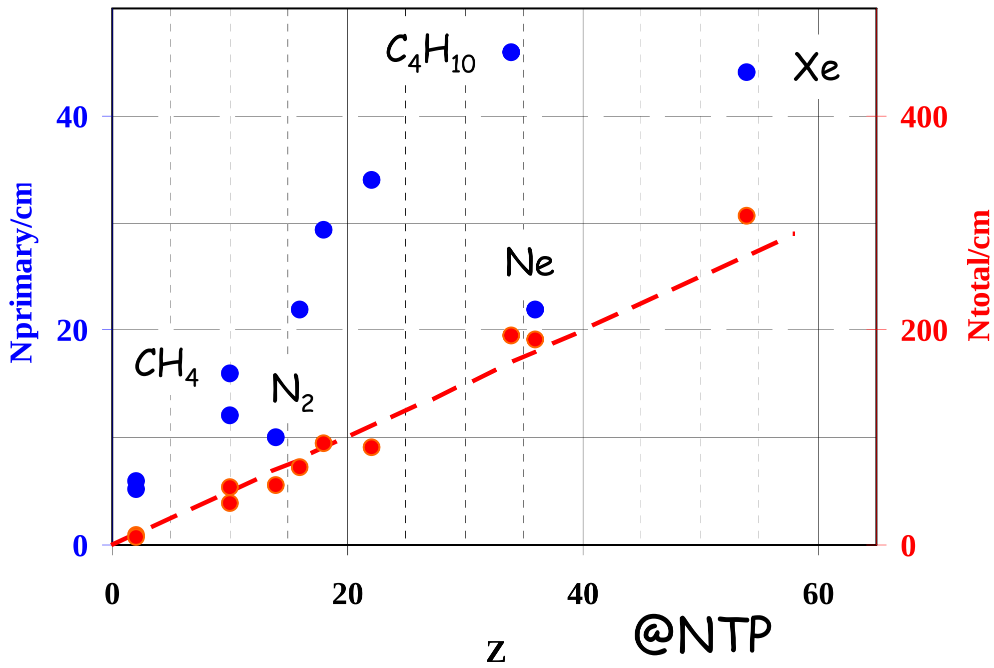


## From ionisation to detection




Gedanken experiment.
(this time leave the cat outside the box !)

Let a charged particle pass through a gas volume.




Primary and secondary ion pair production given at atmospheric pressure and for minimum ionizing particles.

$$N_{total} / cm \cong 5 \cdot Z$$

or, about $100\ e^{-}$ /cm in argon gas
$= 1.6\ 10^{-17}$ C

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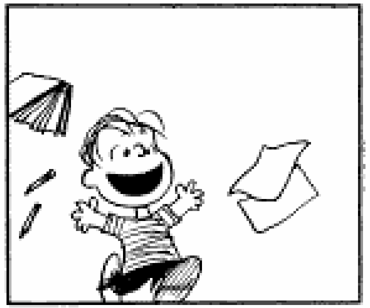
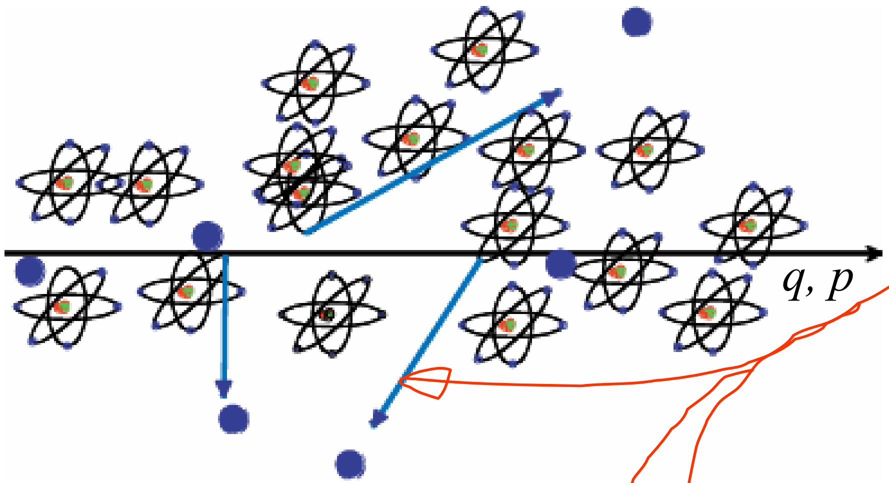
That was all planned for this lecture



## Some words on δ-electrons and other fluctuations.

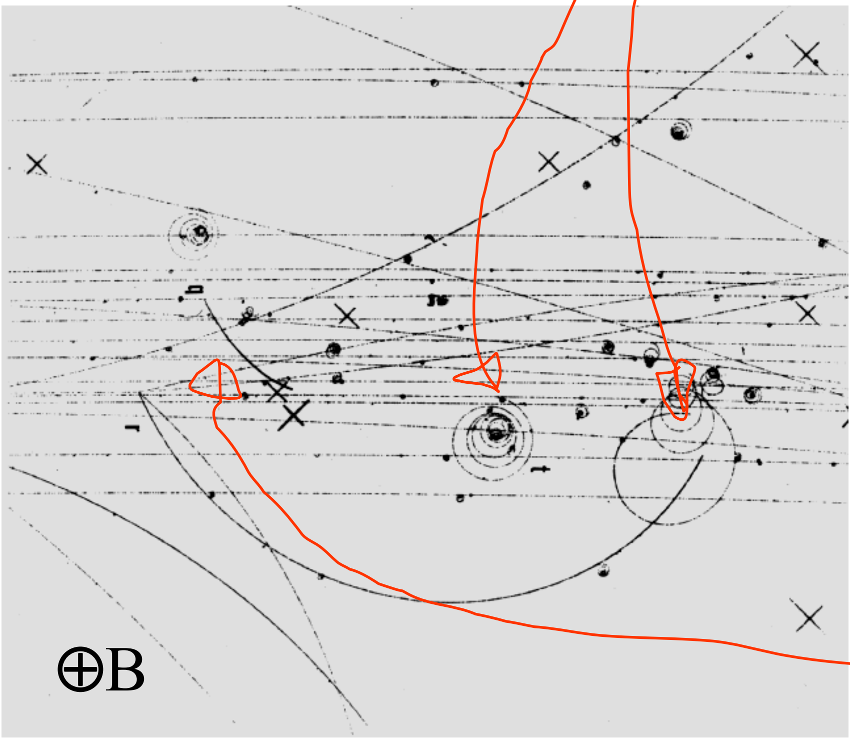



In the ionization, the ejected electron will have a kinetic energy: $0 \le T \le T_{max}$

A δ-ray with kinetic energy $T_e$ and corresponding momentum $p_e$ is produced at an angle Θ given by

$$\cos\Theta = \frac{T_e}{p_e}\frac{p_{max}}{T_{max}}$$

where $p_{max}$ is the momentum of an electron with the maximum possible energy transfer $T_{max}$.
This (knock-on) electron can therefore have enough energy to ionize (far) away from the primary track.




Knock on:

$K^- + p \rightarrow K^- + p$

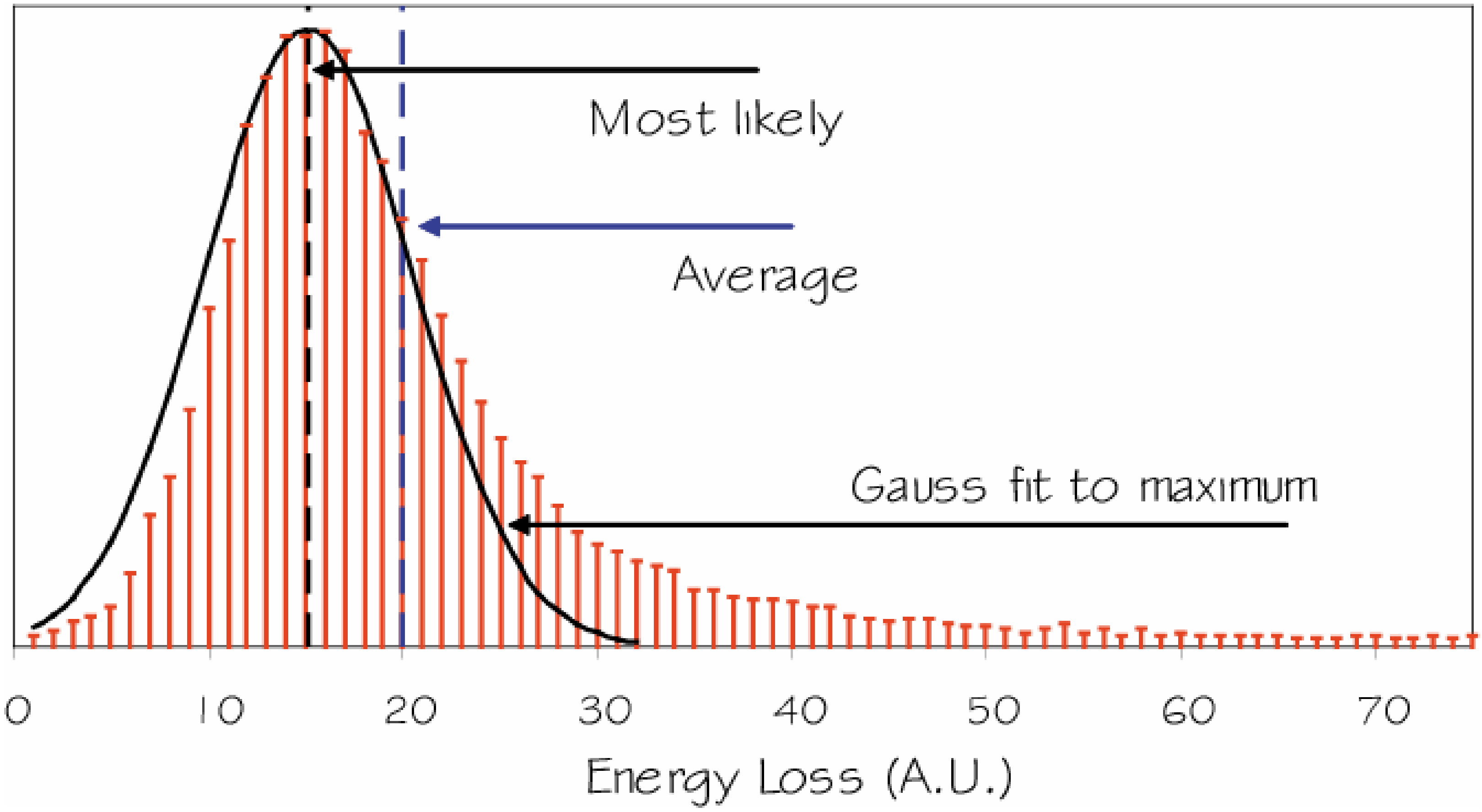
p slow
high ionisation

http://www.ep.ph.bham.ac.uk/user/watkins/seeweb/Bubble.htm
Written by Peter Watkins of Birmingham University. The web pages were produced by Tom Adams of Cheltenham College.

# Some more words on δ-electrons and other fluctuations.

This leads to large fluctuations in the measurement of the deposited energy:
Landau/Vavilov fluctuations.
(Normally) approximated by:

$$f(\lambda) = \sqrt{\frac{e^{-(\lambda + e^{-\lambda})}}{2\pi}}$$

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# My First Straw Tube

Cathode:

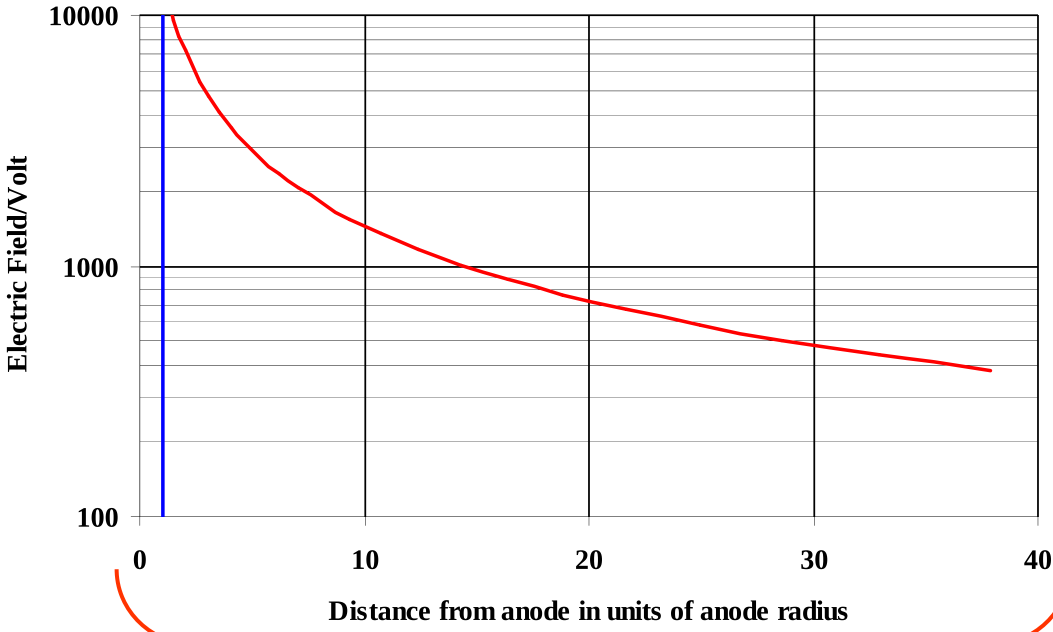
A metallic cylinder of radius R

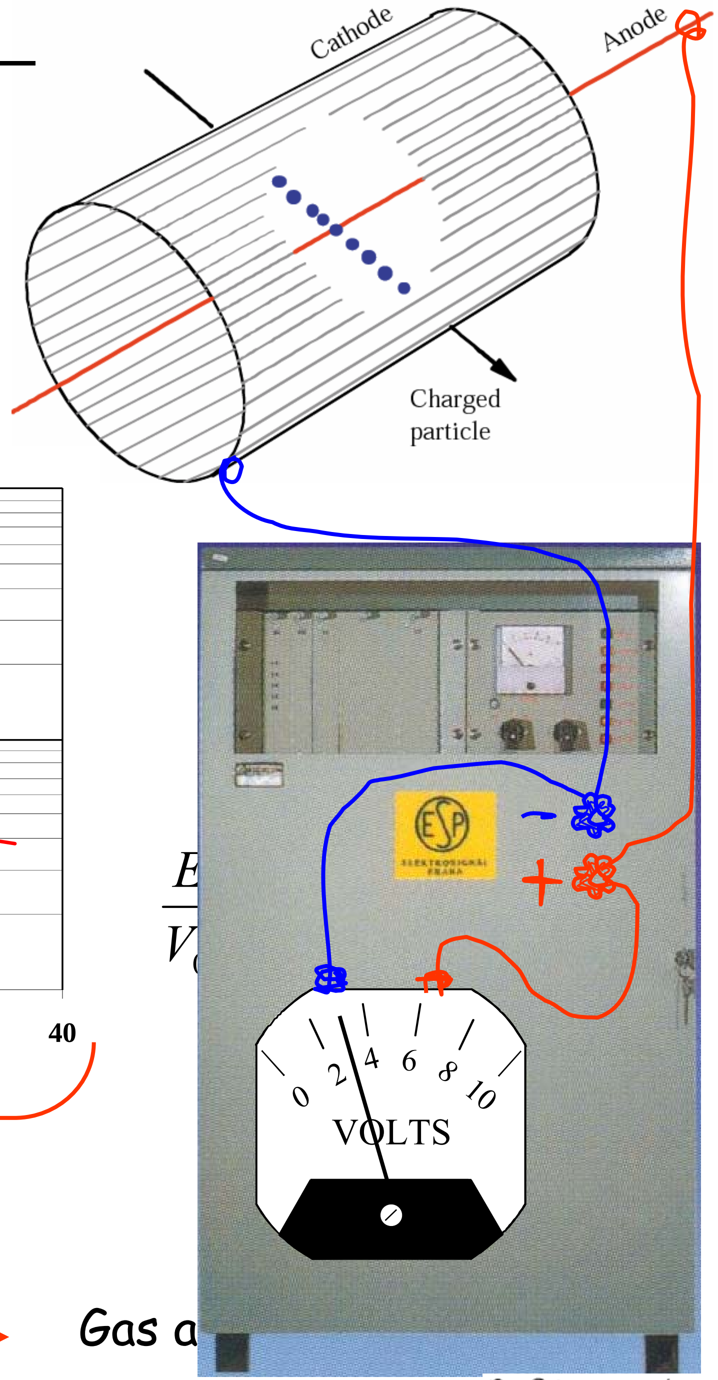
Anode:

A gold plated tungsten wire of radius $r_0$

$r_0 = 10\ \mu m$

$R/r_0 = 1000$




$$\sigma(ionization) = f(E, gas)$$

Gas a

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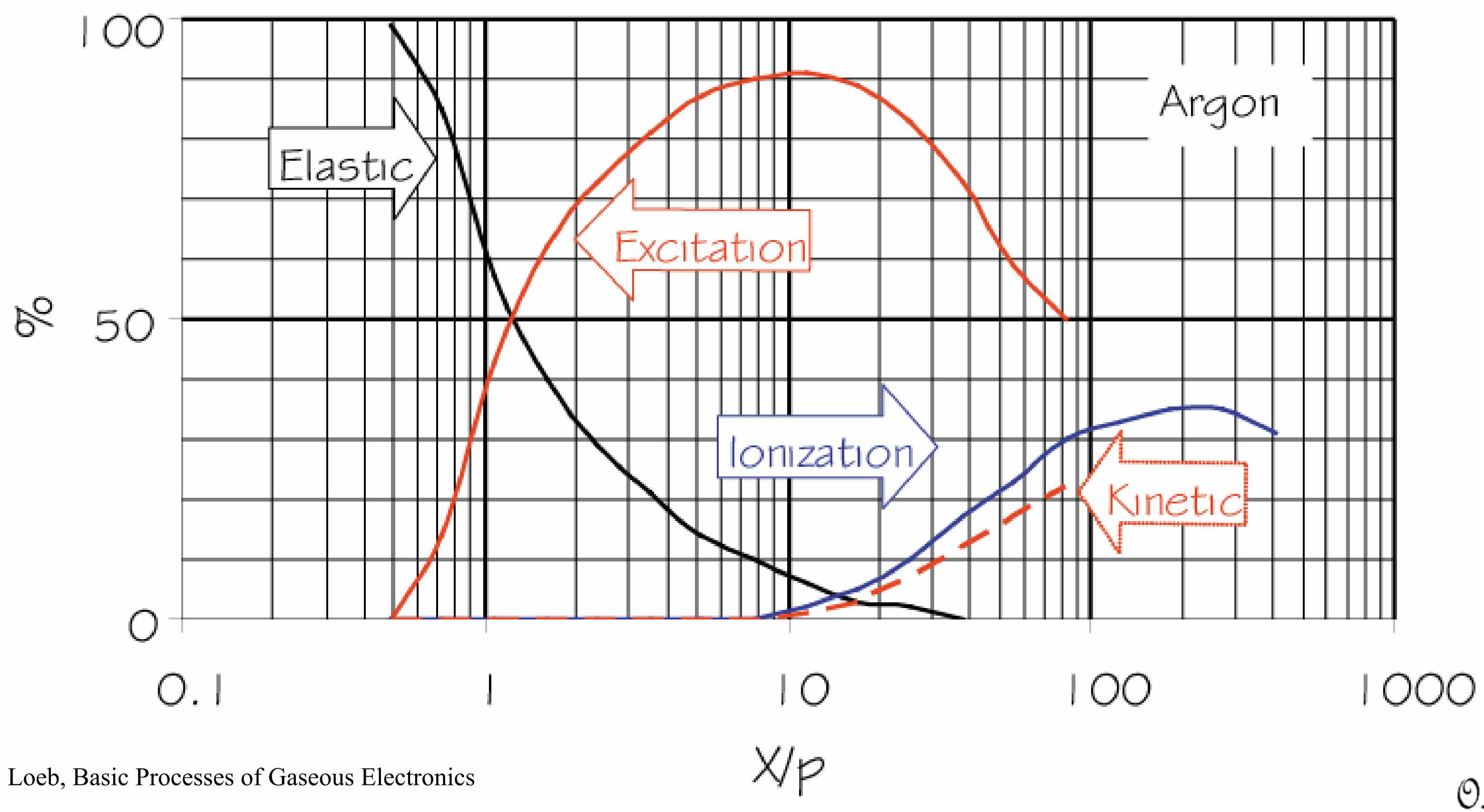
## From field to ionisation

Approximate computed curves showing the percentage of electron energy going to various actions at a given X/p (V/cm/mmHg)

- Elastic: loss to elastic impact
- Excitation: excitation of electron levels, leading to light emission and metastable states
- Ionization: ionization by direct impact
- Kinetic: average kinetic energy divided by their "temperature"
- Vibration: energy going to excitation of vibrational levels




L. B. Loeb, Basic Processes of Gaseous Electronics

# From ionisation to gas amplification.

Let $1/\alpha$ be the mean free path between each ionization

$\alpha = \alpha(E$, density, gas type)

temperature, pressure

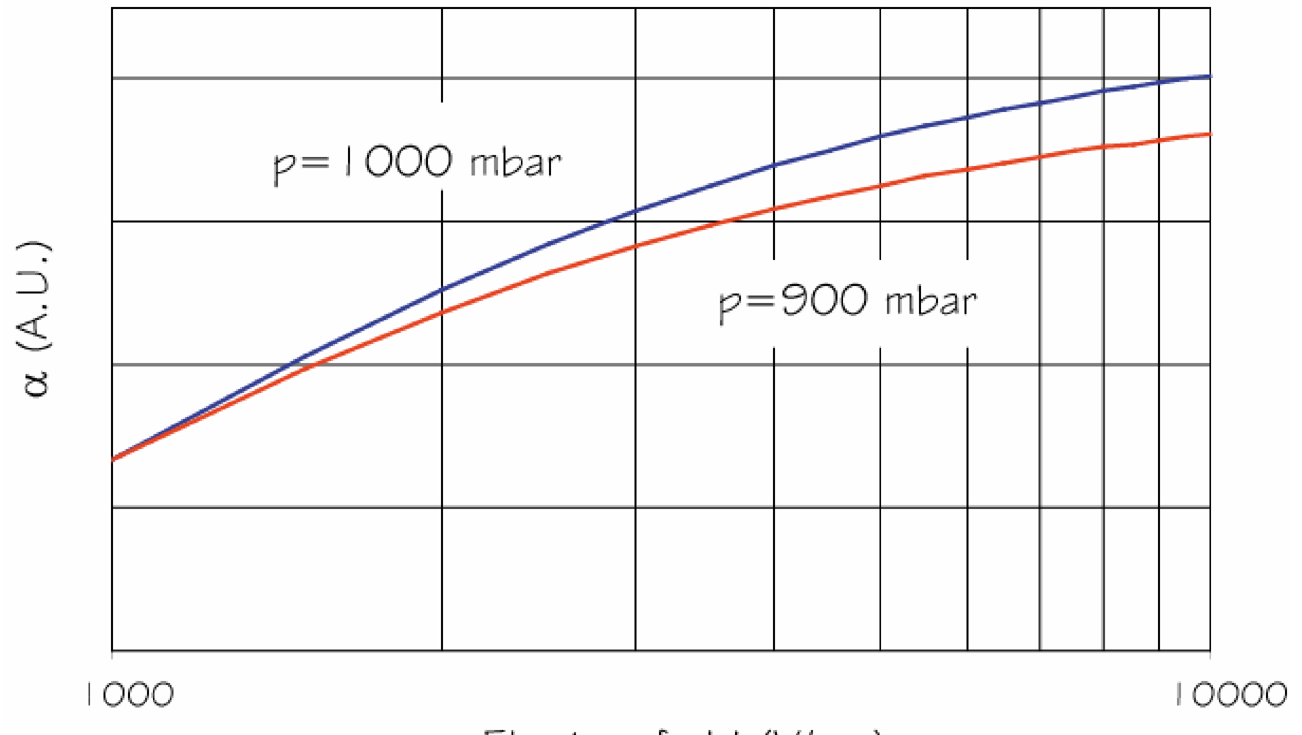
$E=E(r)$

The gas amplification, $M$, is then given by $$M = e^{\int_{r_1}^{r_2} \alpha(r)dr}$$

Korff's approximation:

$$\alpha = p \times A e^{-\frac{Bp}{E}}$$

Where $A$ and $B$ are gas dependent constants and $p$ is the pressure.

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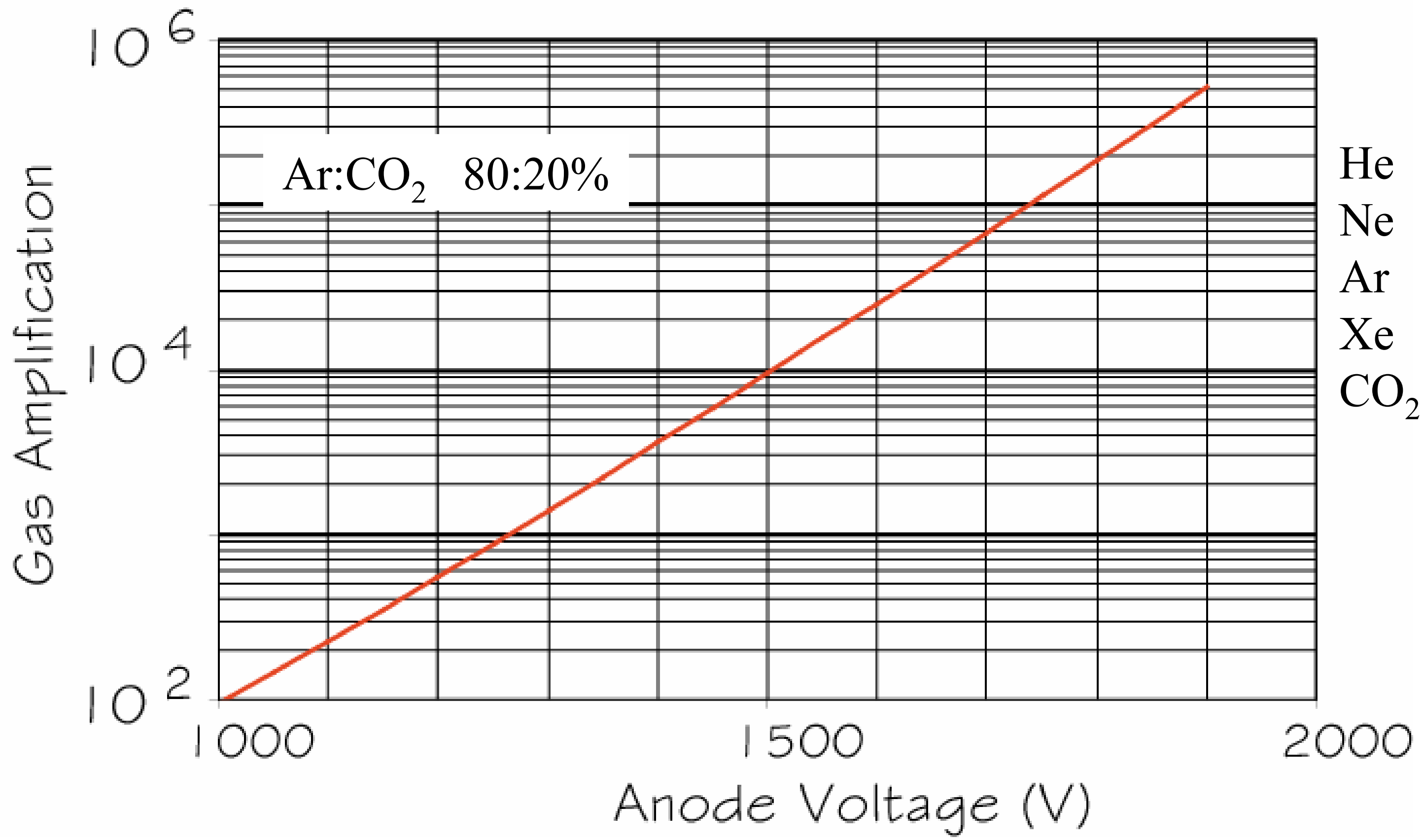
# From Korff's approximation to gas amplification.

$$\frac{E}{V_0} = \frac{1}{r}\frac{1}{\ln\left(\frac{R}{r}\right)}$$

$$M = e^{\int_{r_1}^{r_2}\alpha(r)dr}$$

$$\Rightarrow \quad M = \exp\left[\frac{A}{B}\frac{V_0}{\ln\frac{R}{r_0}} e^{-\frac{Bpr_0 \ln\frac{R}{r_0}}{V_0}}\right]$$

$\Downarrow$




| | $A$ Torr/cm | $B$ V/Torr/cm |
|---|---|---|
| He | 3 | 34 |
| Ne | 4 | 100 |
| Ar | 14 | 180 |
| Xe | 26 | 350 |
| $CO_2$ | 20 | 466 |

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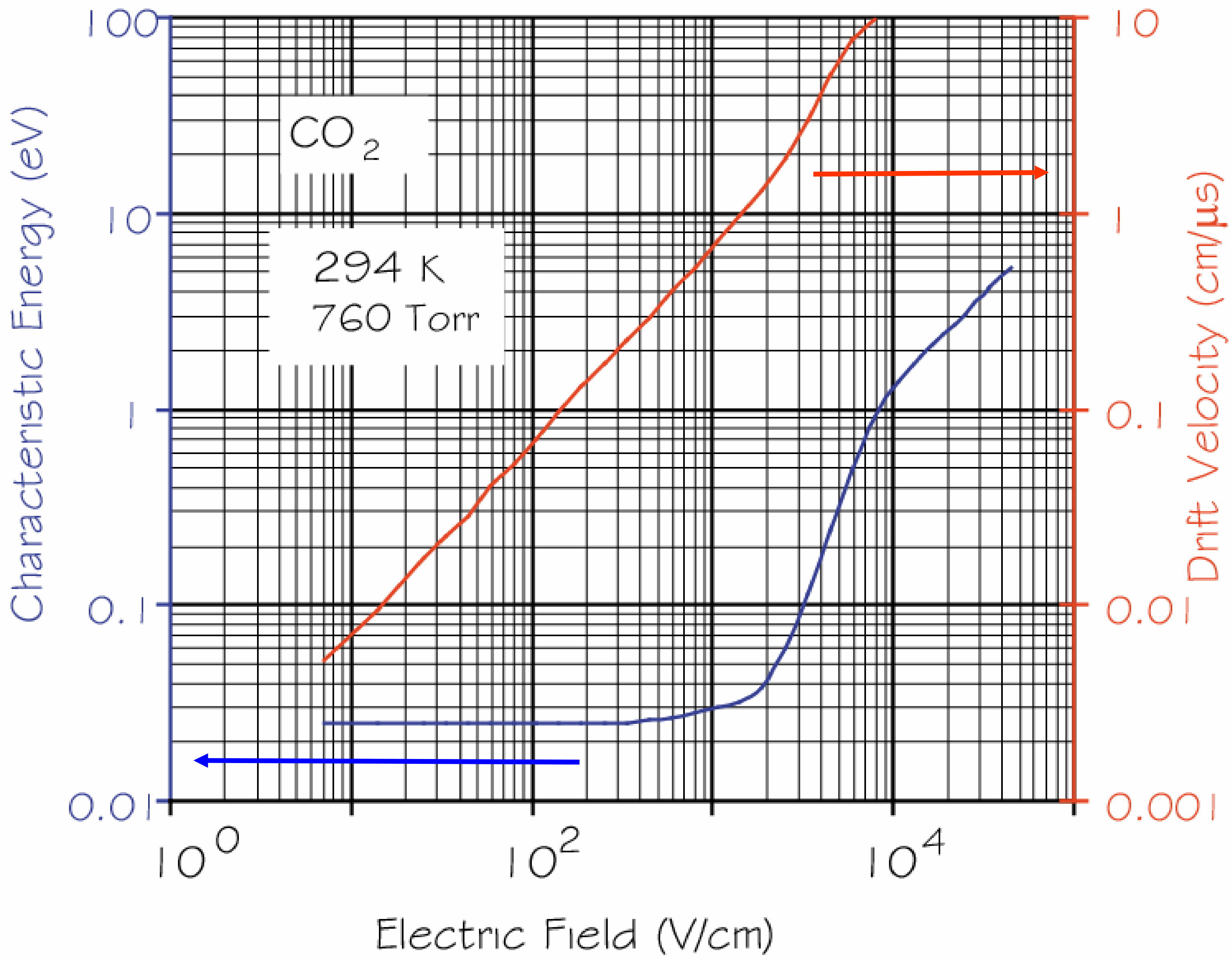
# Drift of electrons

under the action of the electric field.

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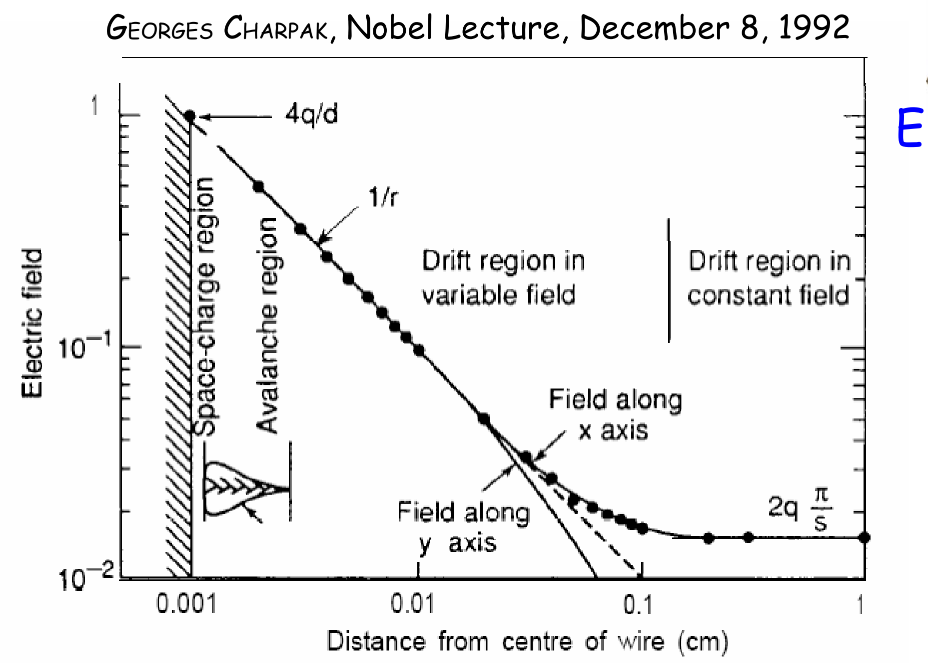
The drift velocity of the positive ions under the action of the electric field is linear with the reduced electric field up to very high fields.

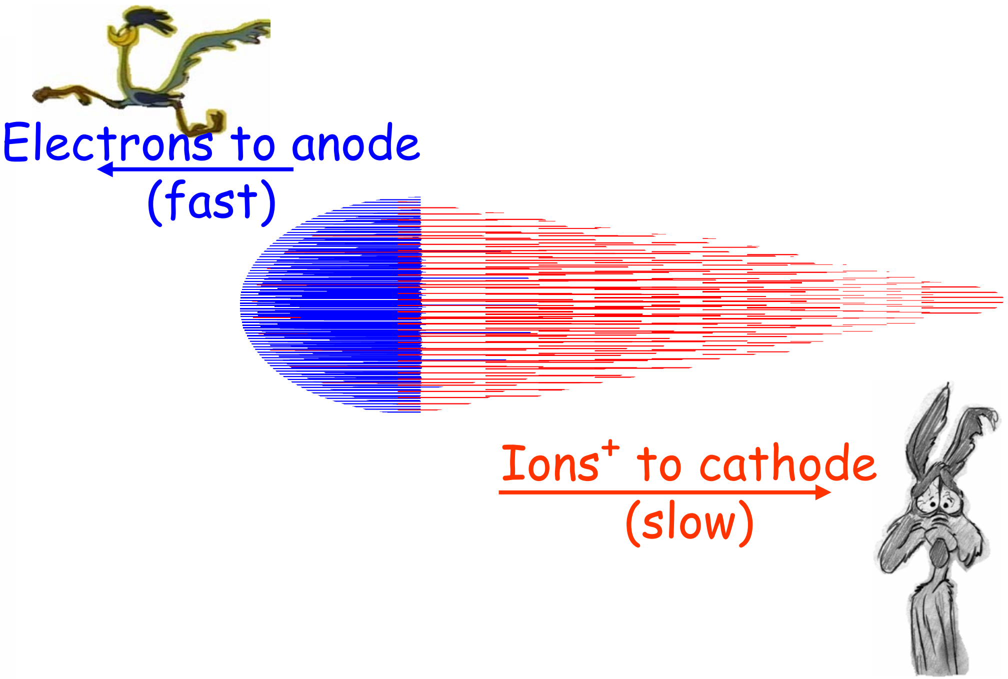
$v^{+ions} = \mu^{+ions} \times E$ where $\mu^{+} \propto 1/p$ and diffusion $D^{+ions} \propto T \times \mu^{+ions}$

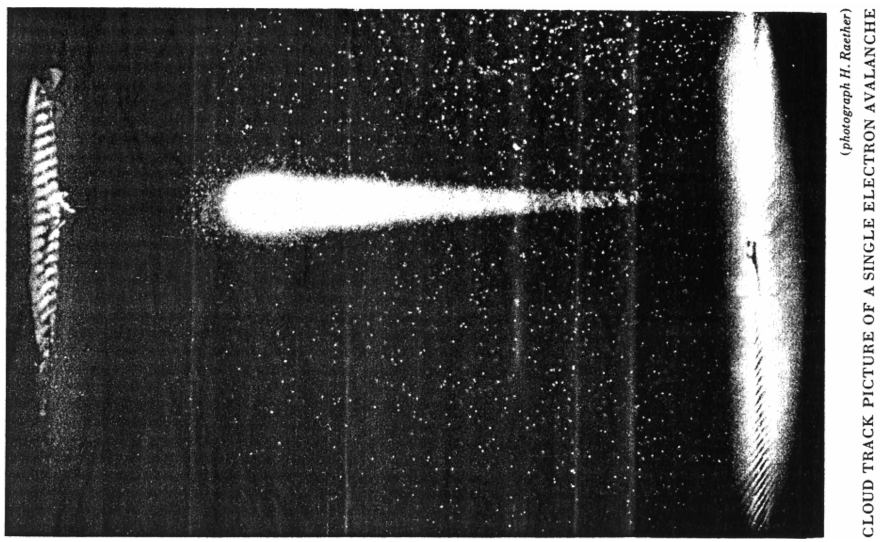
| | Ions | Mobility cm²/V/sec |
|---|---|---|
| Ar | $iC_4H_{10}+$ | 1.56 |
| Ar | $CH_4+$ | 1.87 |
| Ar | $CO_2+$ | 1.72 |
| $iC_4H_{10}$ | $iC_4H_{10}+$ | 0.61 |
| $CH_4$ | $CH_4+$ | 2.26 |
| $CO_2$ | $CO_2+$ | 1.09 |

$$\frac{v_{electron}}{v_{ion}} \approx 10^3$$

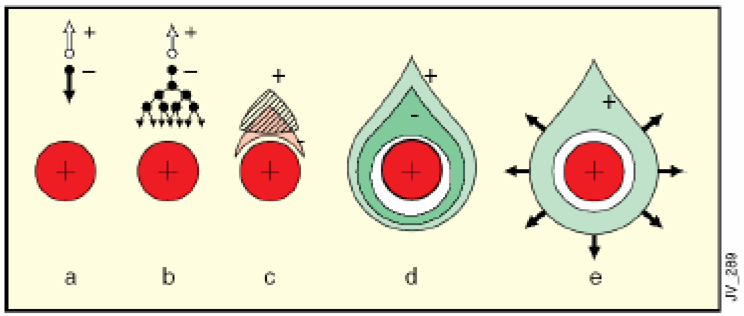
in $CO_2$ with $E = 10^4$ V/cm



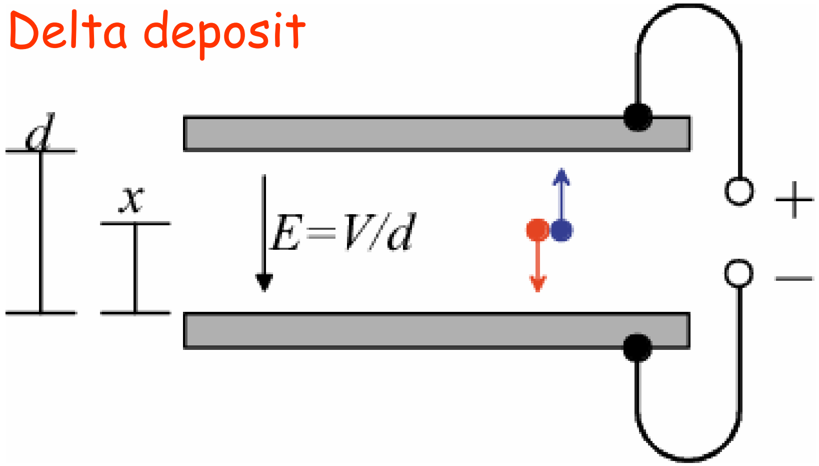

Cloud track picture of a single electron avalanche

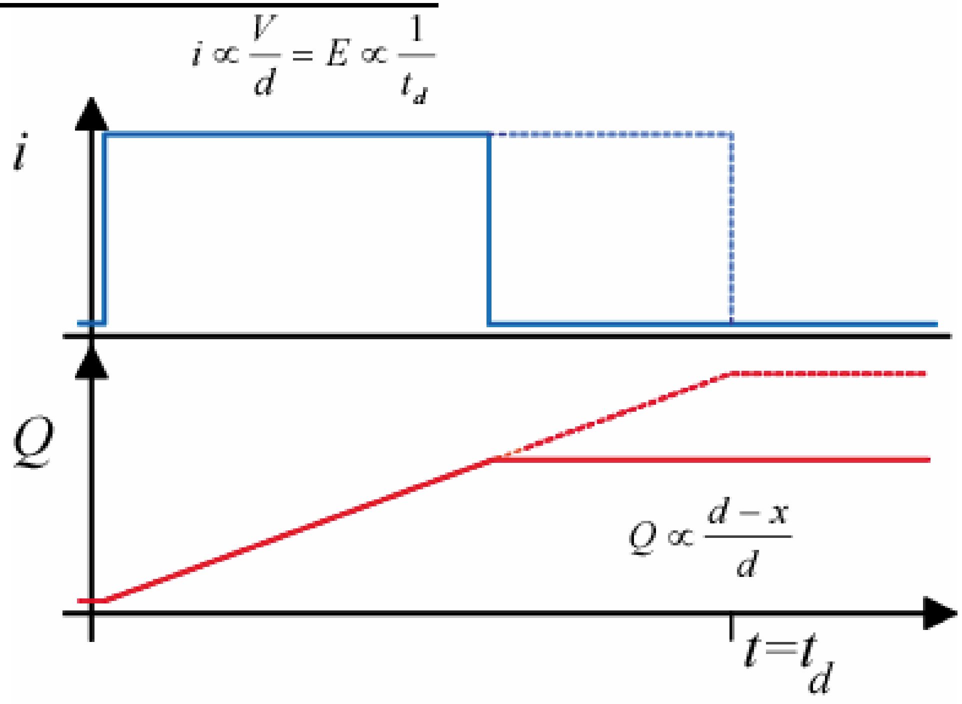



Different stages in the gas amplification process next to the anode wire.

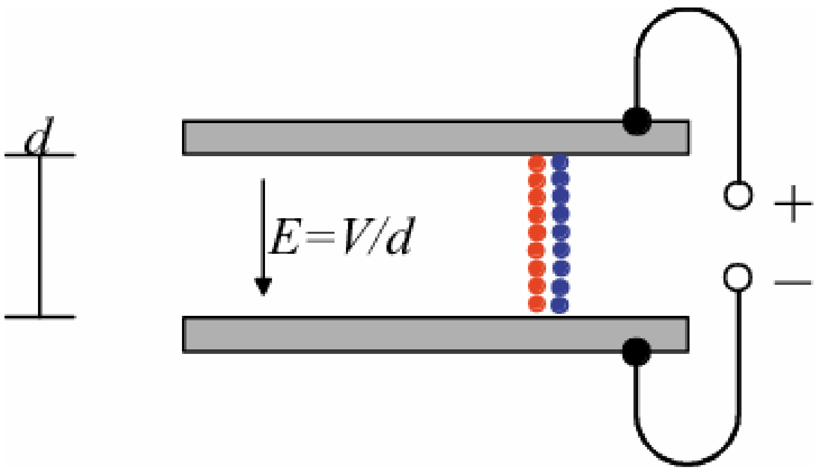
# Formation of Current and Charges in an Ionization Chamber

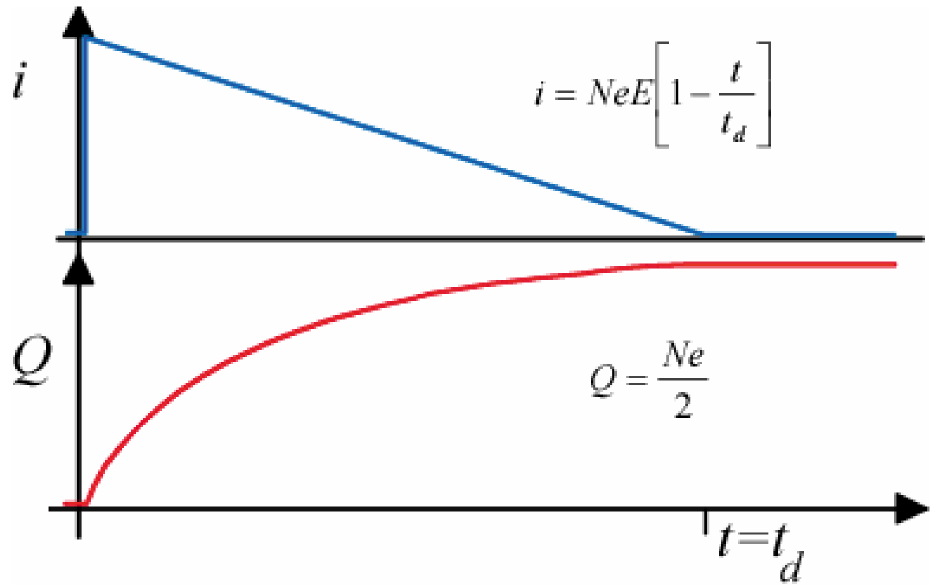
Delta deposit




Ionizing track




W.J. Willis, V. Radeka; NIM 120(1974)221

O. Ullaland/2006

# From movement of charges to signals.

Signal induced by (mainly) the positive ions moving in a high electric field.
Assume that all charges are created a distance λ from the anode.

$$V_{electron}^{signal} = -\frac{Q}{lCV_0}\int_{r_0}^{r_0+\lambda}\frac{dV}{dr}dr = -\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{r_0+\lambda}{r_0}$$

$$V_{ion}^{signal} = +\frac{Q}{lCV_0}\int_{r_0+\lambda}^{R}\frac{dV}{dr}dr = +\frac{Q}{2\pi\varepsilon_0 l}\ln\frac{R}{r_0+\lambda}$$

($lC$ is the total capacitance)

λ is of the order of a few μm $\rightarrow V_{electron} = V_{ion}/100$

*The basic fact in a wire proportional chamber is that if a negative pulse is obtained on a wire by the development of an avalanche, then positive pulses are obtained simultaneously on the neighboring wires.*

from
G. CHARPAK, EVOLUTION OF THE AUTOMATIC SPARK CHAMBERS,
ANNUAL REVIEW OF NUCLEAR SCIENCE, Vol. 20, 1970

230 CHARPAK

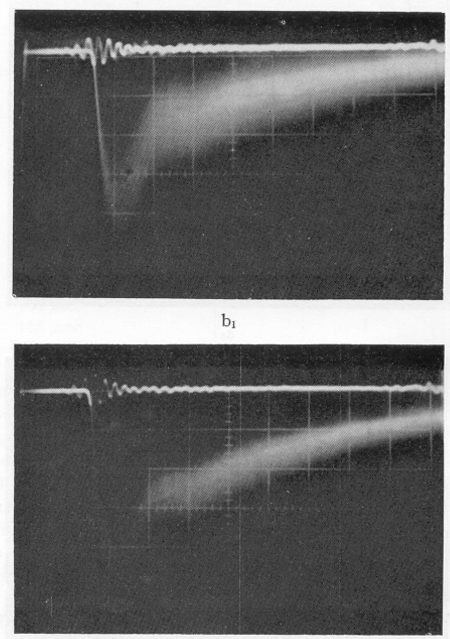
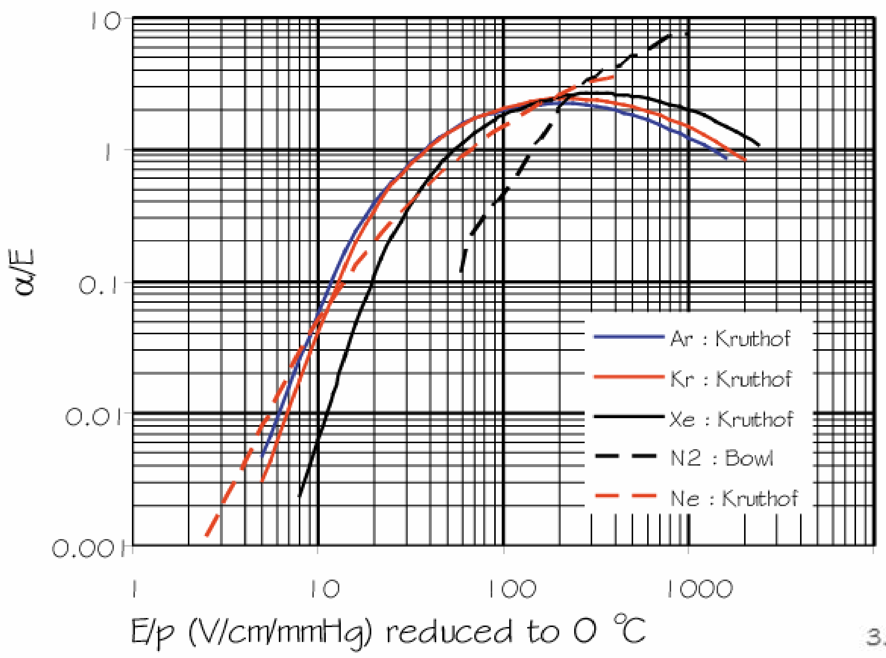



FIGURE 25. Proportional amplification at the limit of space charge saturation. Chamber with $L=8$ mm, $s=2$ mm, $d=20$ μm. "SFM magic mixture": argon+isobutane (80−20) and 0.4 percent freon 13 B1. 100 percent efficiency.

# Operation of proportional chambers.

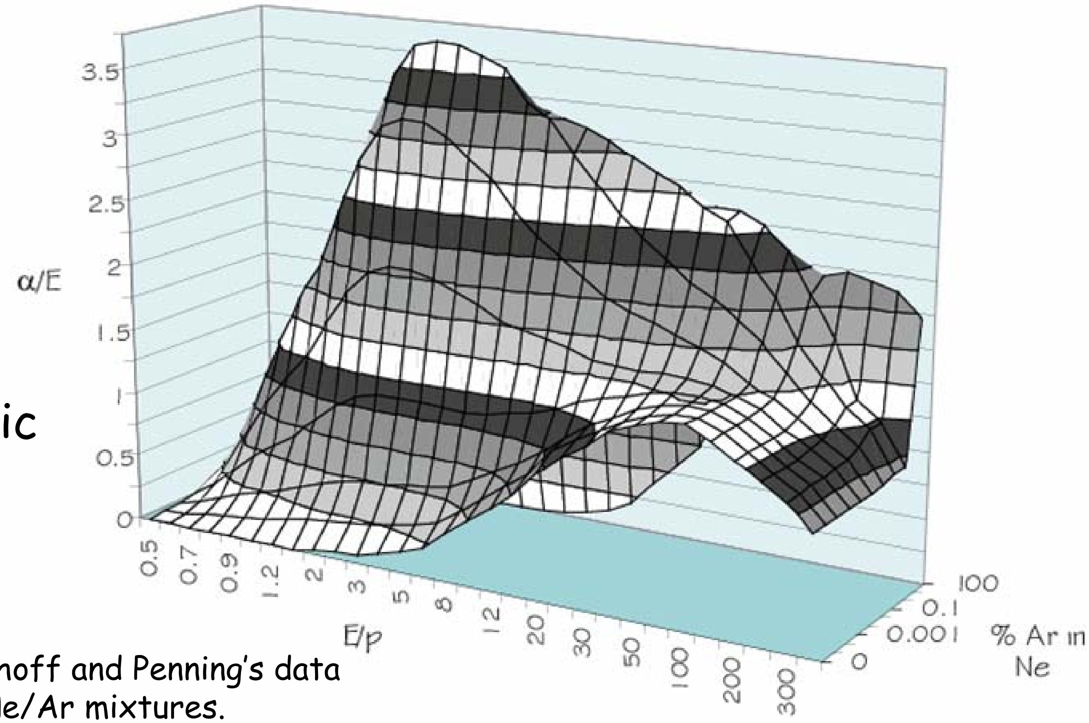



More or less any gas can be used.

$$M = e^{\int_{x_1}^{x} \alpha(x)dx}$$

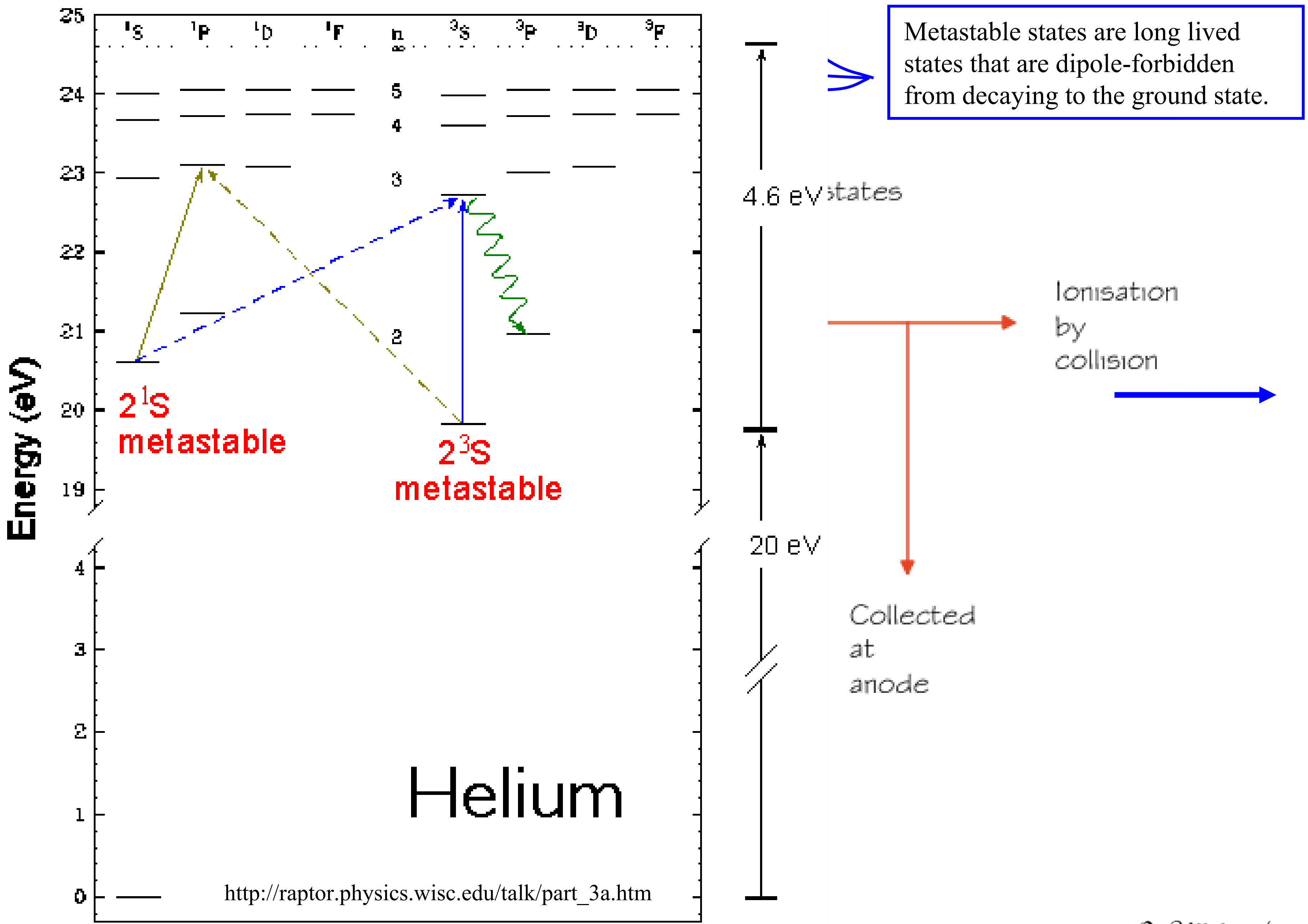
## The Penning effect.

The action of excited states in ionizing atoms of lower ionizing potentials is an example of inelastic impacts of second class.
The metastable states are responsible for the effect.




Kruithoff and Penning's data for Ne/Ar mixtures.

# a Life in an Excited State




Metastable states are long lived states that are dipole-forbidden from decaying to the ground state.

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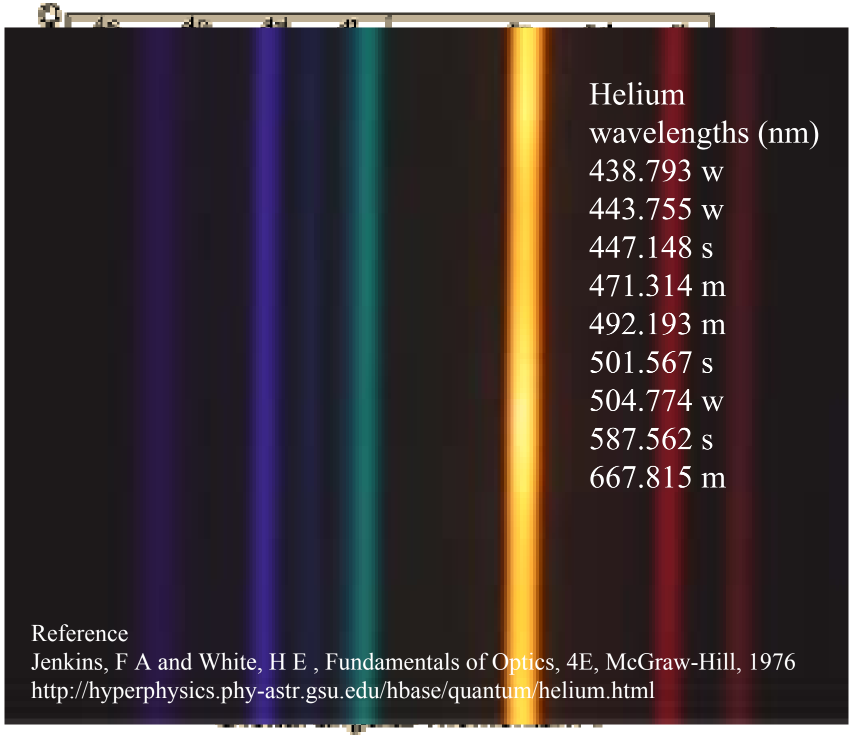
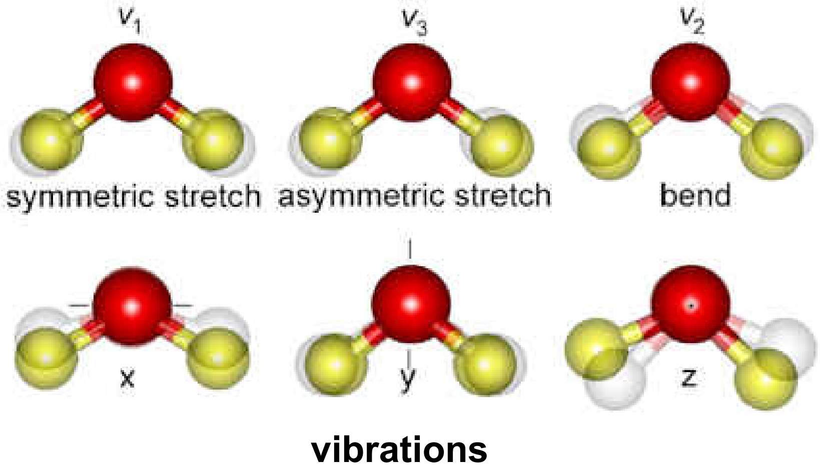
Nearly all gasses can be used. Noble gases.



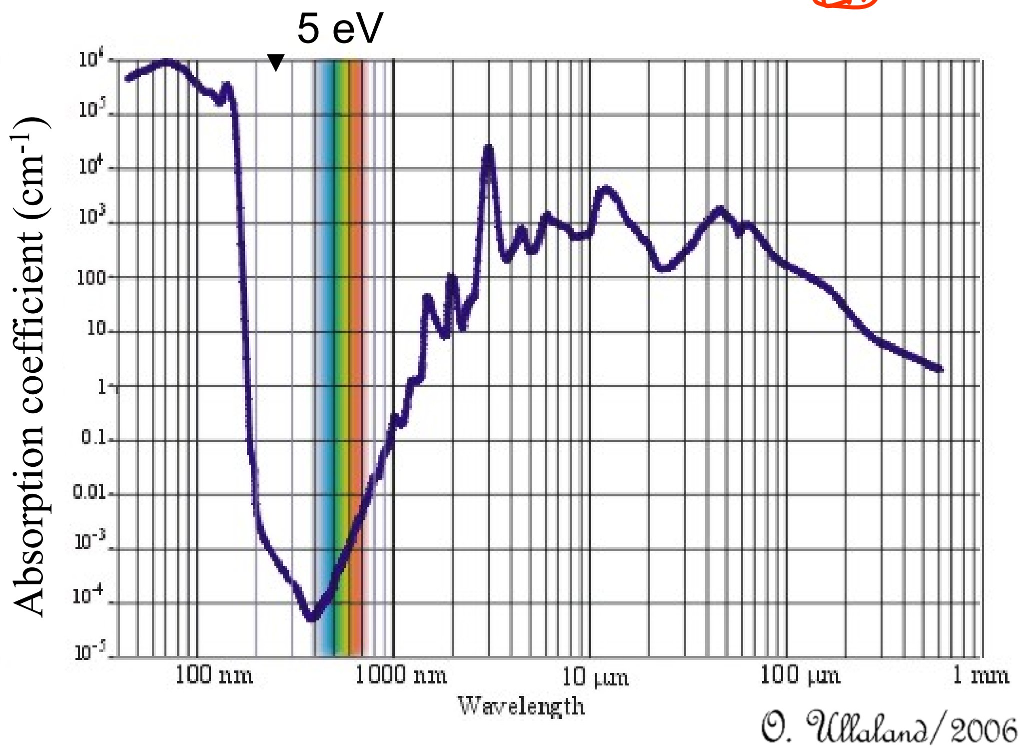

De-excitation of a noble gas is only possible via the emission of a photon.
If the photon energy is above the ionization threshold for other molecules in the set-up, new avalanches will be created.

→ Permanent discharges

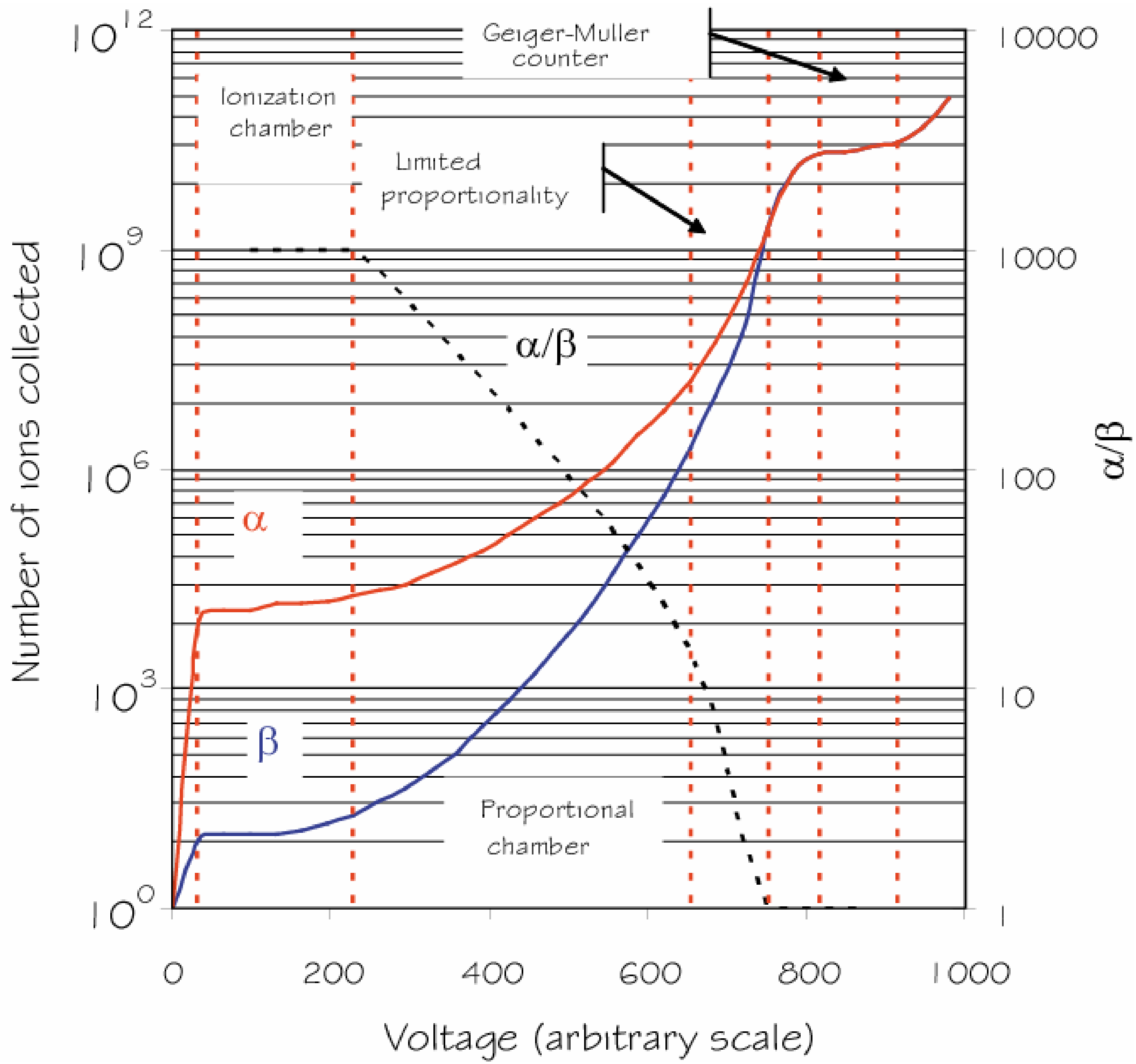
**Add poly-atomic gases as quenchers.**




What the water molecule can do.



## Gas amplification and the saturation effects.




α: alpha-particle =highly ionising particle

$^{241}_{95}Am$ : 5.443 MeV, 5.486 MeV

β: electron ~minimum ionising particle

cosmic ray or radioactive source like

$^{106}_{44}Ru$ : 39 keV

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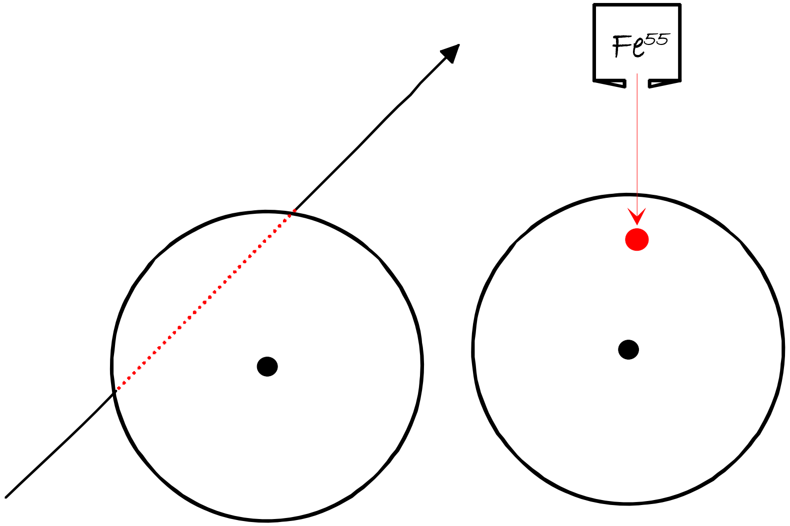
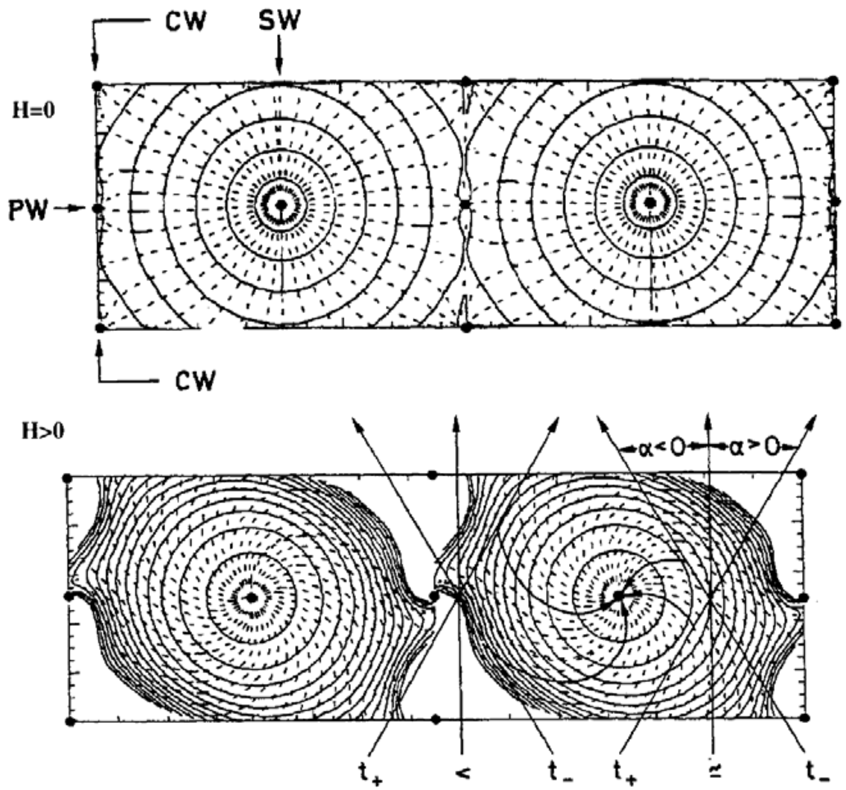
# (some) Additional effects

There will also be effects due to the way the electrons are collected at the anode.
The electric field of the chamber will be screened by the positive ions.

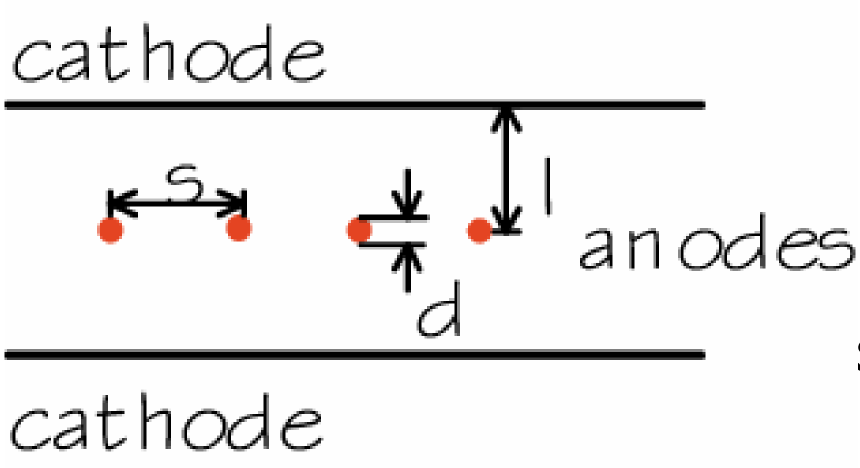
The gas amplification will therefore change as the angle between the electric field and the ionizing particle changes.


Other effects.
Drift velocity and diffusion of the electrons changes with the gas mixture.

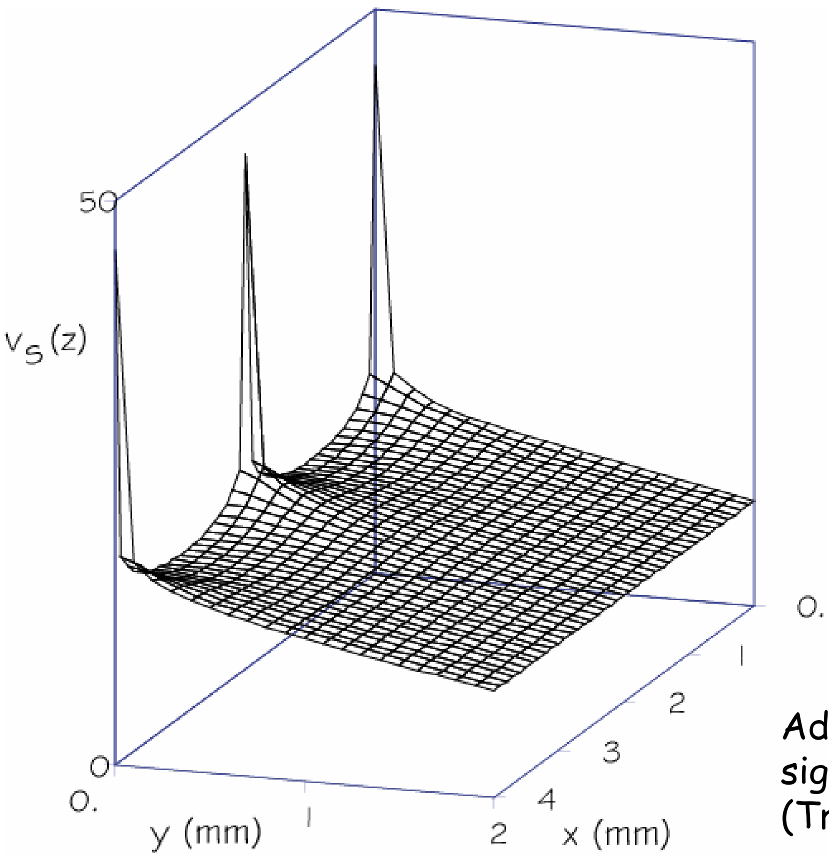
A magnetic field will change the drift path of the electrons as well as the diffusion.




Classic multi-wire proportional chamber
Typical parameters:

$l$ : 5 mm
$s$ : 2 - 4 mm
$d$ : 20 μm

Still possible to calculate by hand
(but straw tubes are easier)




$$V_s(z) \underset{d\to 0}{\approx} \frac{2\pi l}{s} - \ln\left\{4\sin^2\left(\frac{\pi x}{s}\right) + 4\sinh^2\left(\frac{\pi y}{s}\right)\right\}$$

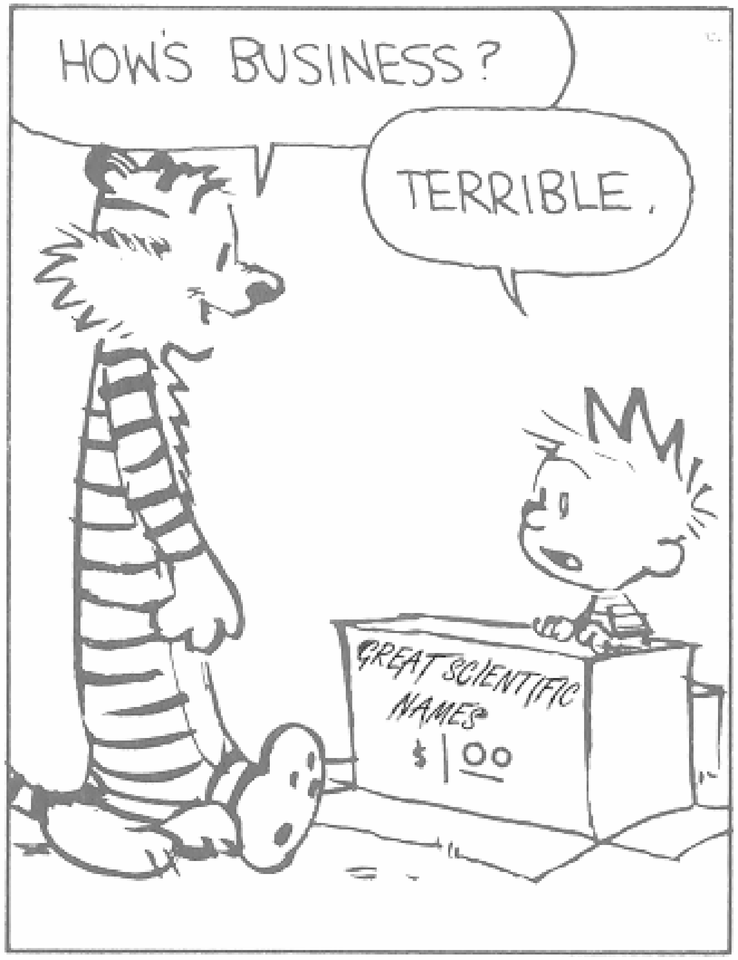
$$Q = \frac{V_0}{\frac{2\pi l}{s} - 2\ln\frac{\pi d}{s}}$$ and $$E_0 = \frac{sV_0}{\frac{\pi d}{2}\left[l - \frac{s}{\pi}\ln\frac{\pi d}{s}\right]}$$

The positive pulses induced by the positive ions onto the neighboring wires is much greater than the negative pulses induced electrostatically. The net effect is thereby positive.

Advanced calculations of electric field, drift, diffusion and signal formation can be done with programs like Garfield.
(Try first Ohm's Law.)

O. Ullaland/2006

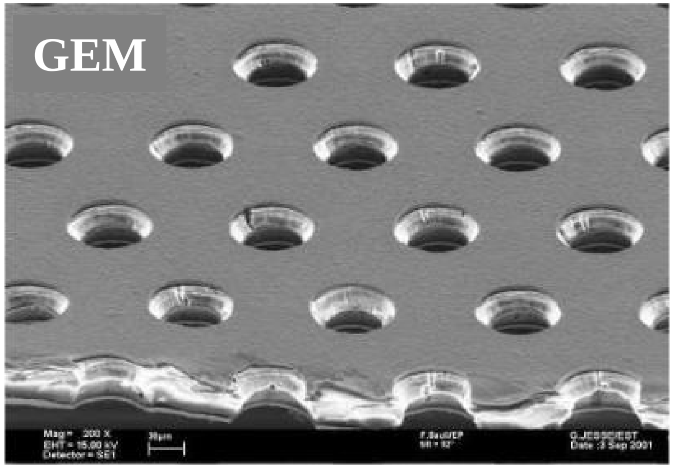
That is about all that is (really) needed to know about gas based tracking detectors. With these tools, we can now make:

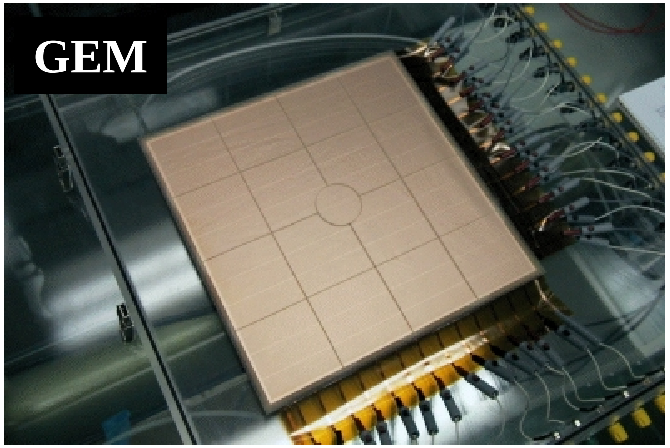


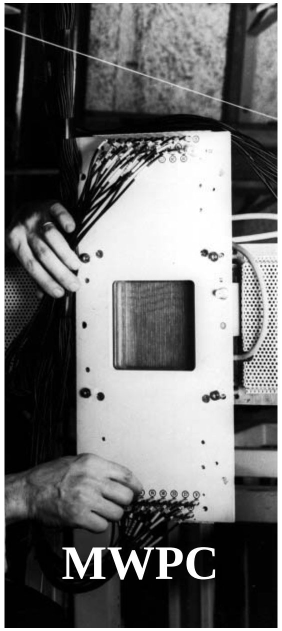

Multi Wire Proportional Chambers MWPC
Time Projection Chambers
Time Expansion Chambers
Proportional Chambers
Thin Gap Chambers
Drift Chambers
Jet Chambers
Straw Tubs
Micro Well Chambers
Cathode Strip Chambers
Resistive Plate Chambers
Micro Strip Gas Chambers
GEM - Gas Electron Multiplier
Micromegas – Micromesh Gaseous Structure

(and some I have surely forgotten.)

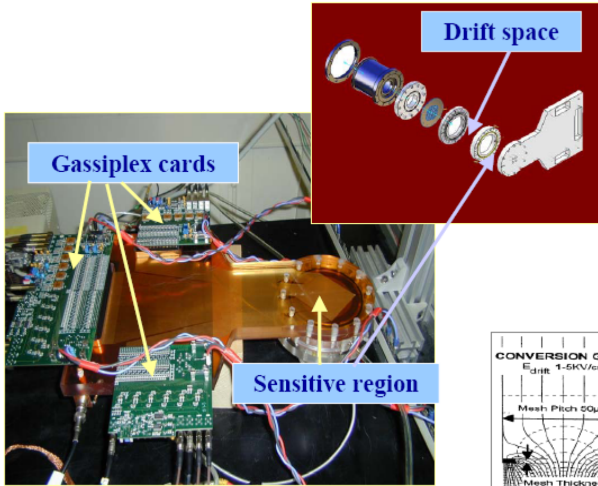
There are, though, some gory details that we will have a closer look at.



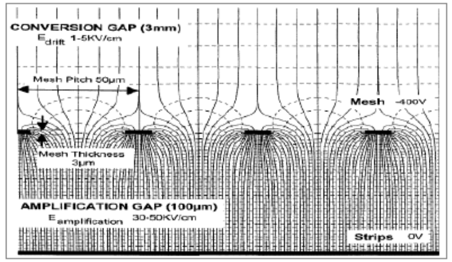




## CAST Micromesh gaseous detector

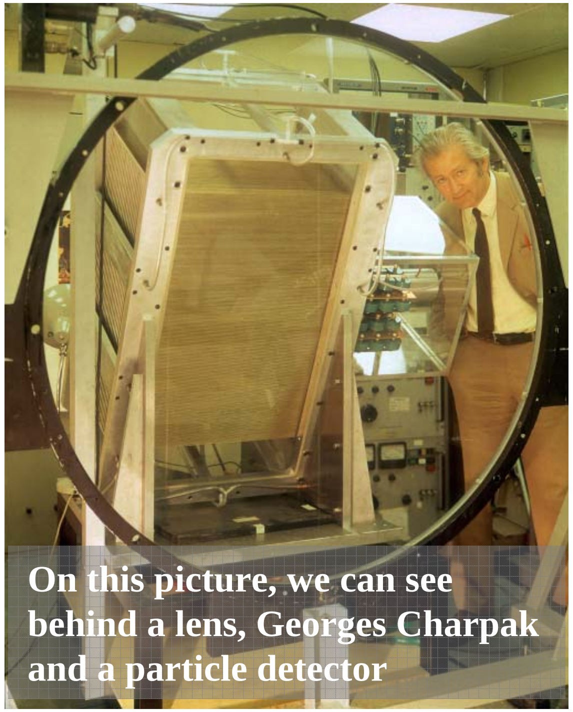


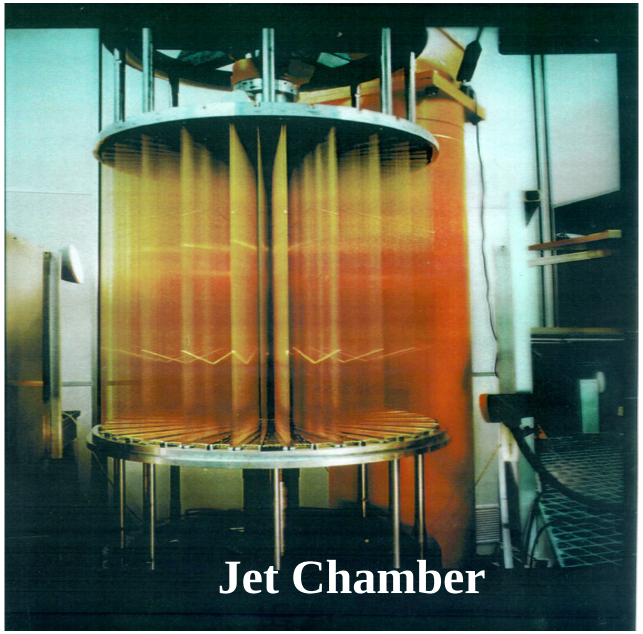

- ✓ Low background materials
- ✓ The operating gas is at atmospheric pressure.
- ✓ $10^4$ amplification is easily achievable.
- ✓ High field ratio: 100% electron transparency.
- ✓ No space charge effects due to fast collection of positive ions.




Development/construction/operation
Saclay-Demokritos-CERN

G. Fanourakis - Micropattern Gas Detectors - CERN – 20 Jan 2006



On this picture, we can see behind a lens, Georges Charpak and a particle detector

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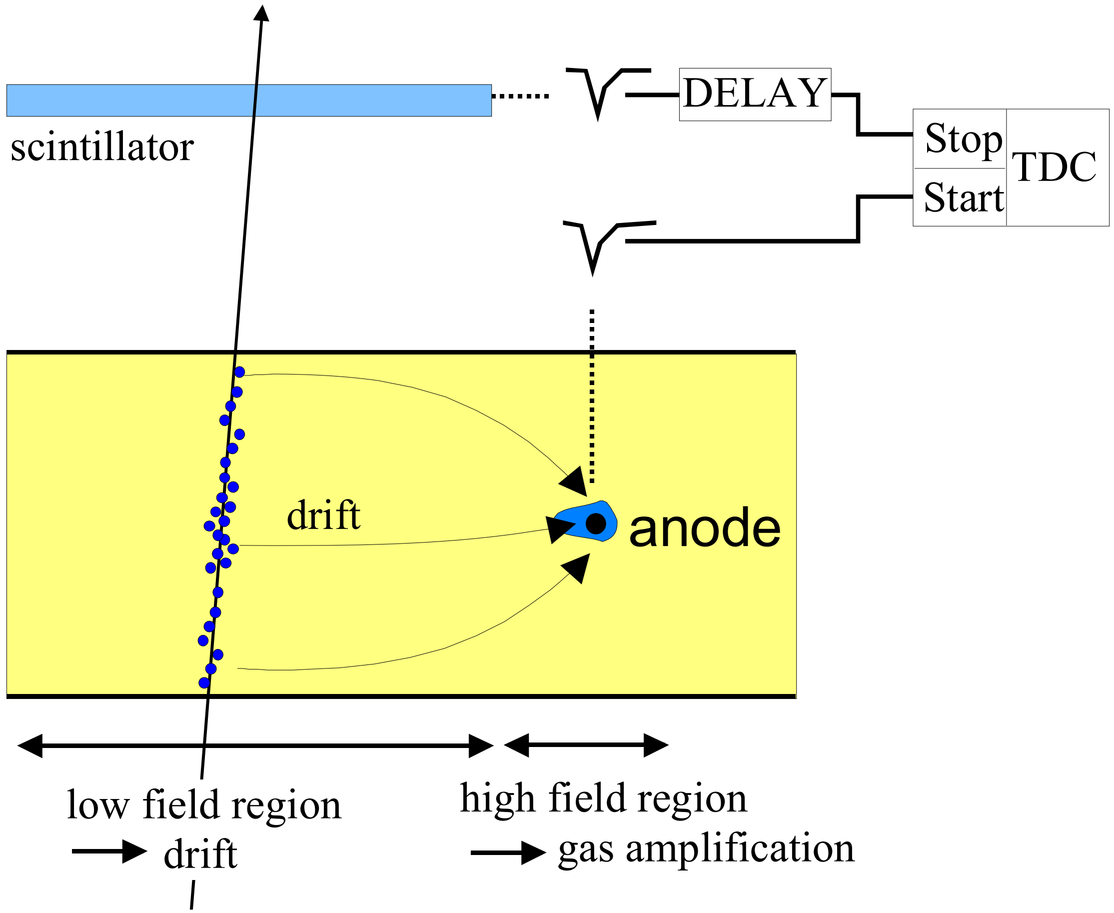
# Start with Drift Chambers



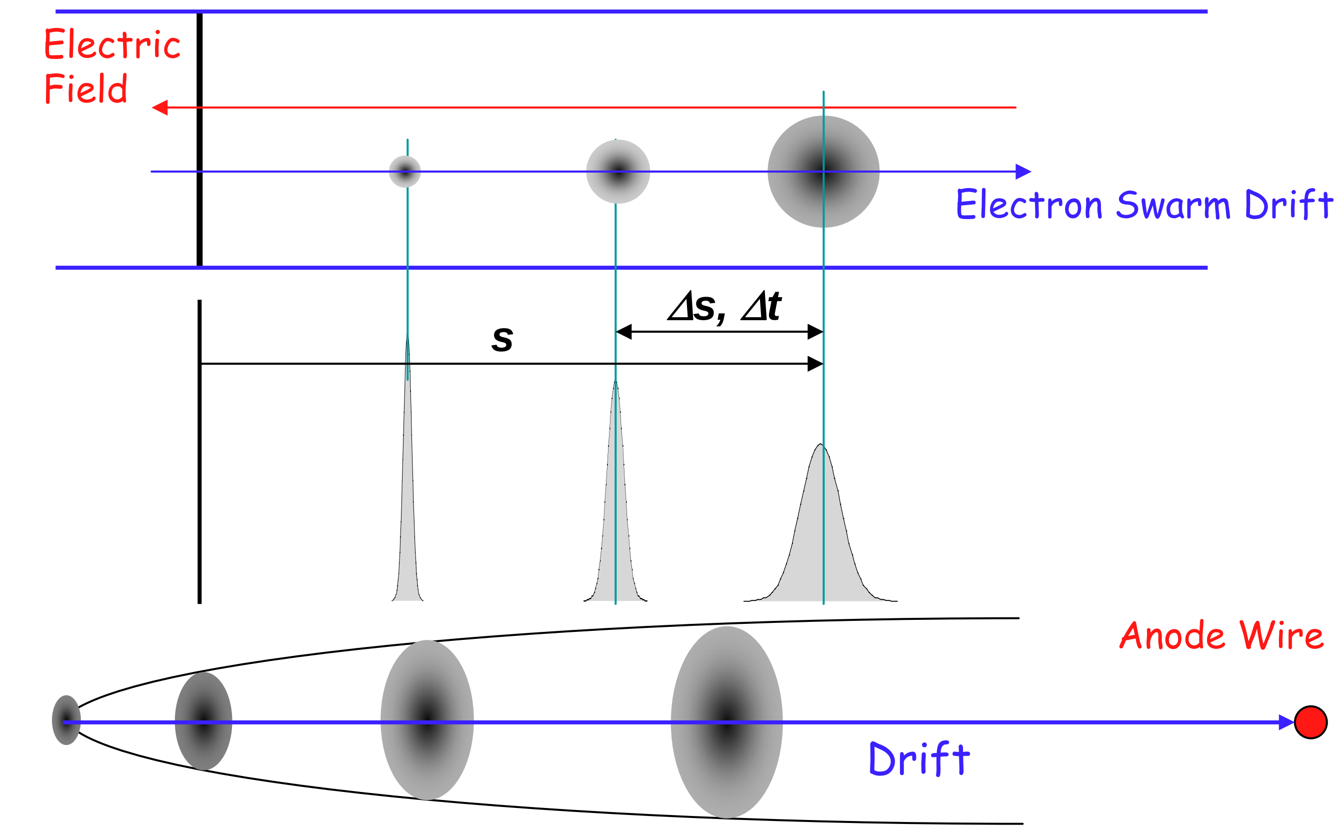

Measure the arrival time on wire

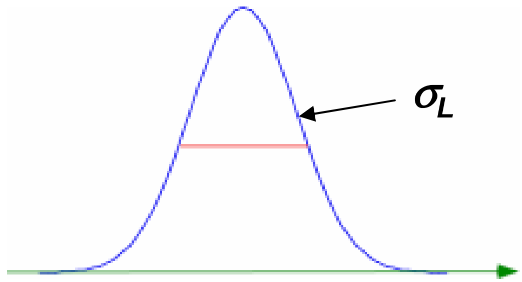
$$x = v_d (t - t_0)$$

To be solved:

Left-Right ambiguity

C. Joram, SSL 2003

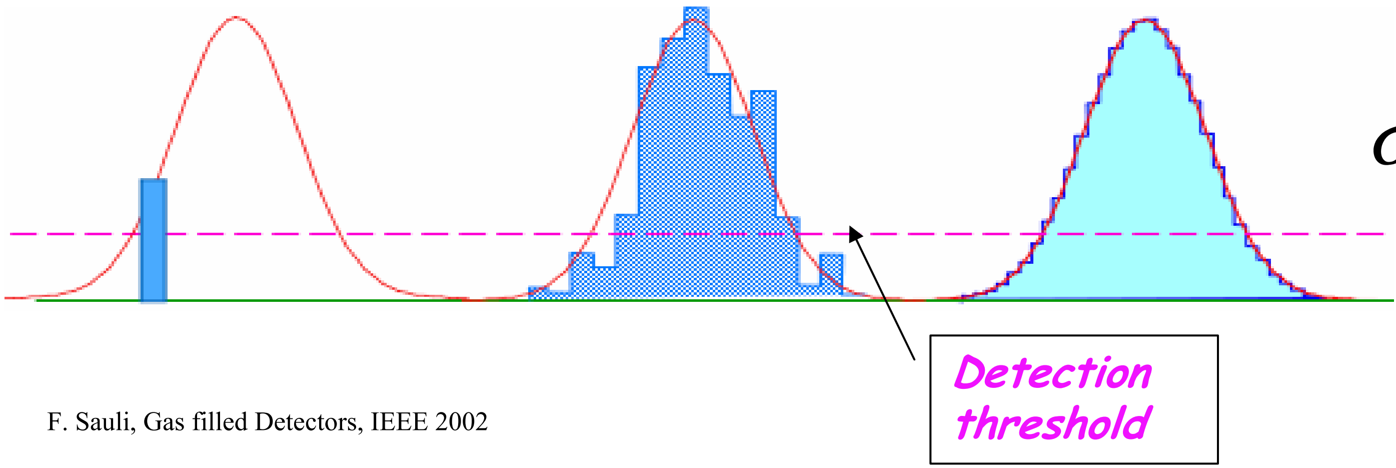



Single electron

Several electrons

Many electrons




Error on first electron :

$$\sigma_1 \sim \frac{\pi}{2\sqrt{3 \ln N}} \sigma_L$$

$N=100 \quad \sigma_1 \sim 0.4\, \sigma_L$

F. Sauli, Gas filled Detectors, IEEE 2002

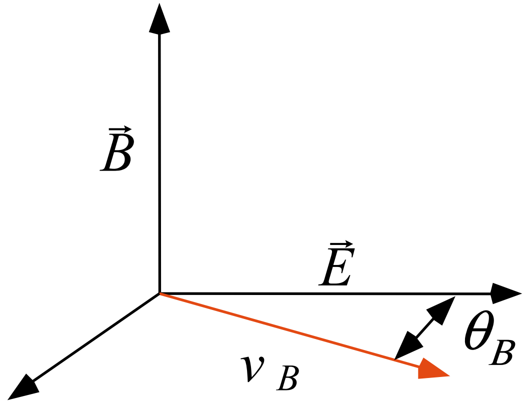
O. Ullaland/2006

## E and B fields

$\vec{E} \perp \vec{B}$

$$\tan\theta_B = \omega\tau$$

$$v_B = v_0 \frac{1+\omega\tau}{1+\omega^2\tau^2}$$




$\tau$ : mean collision time

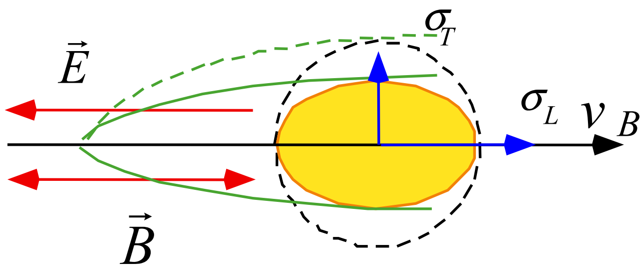
$\omega = eB/m$ Larmor frequency

$\vec{E} \parallel \vec{B}$

$$v_B = v_0$$

$$\sigma_L = \sigma_0$$

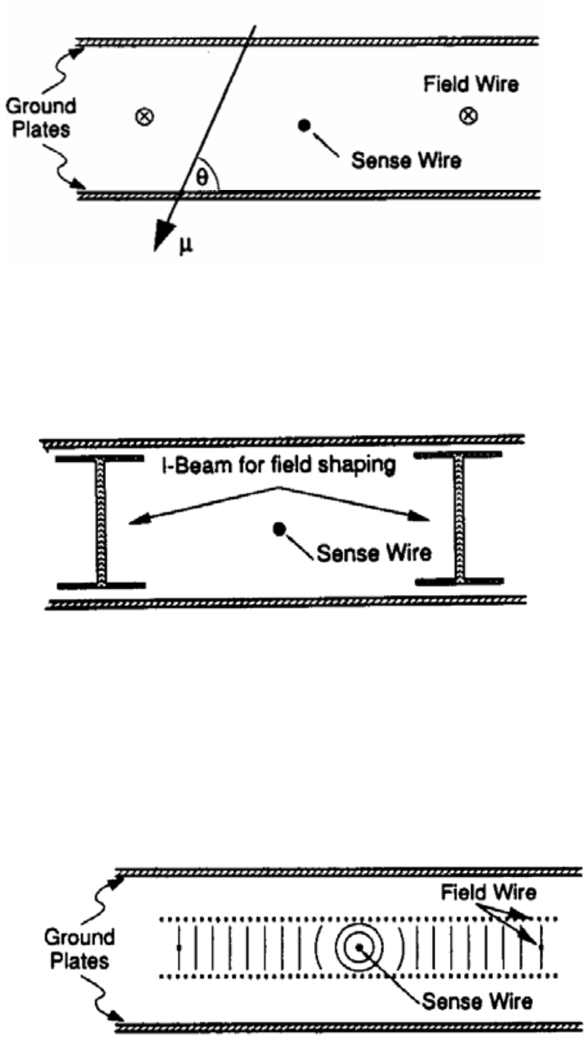
$$\sigma_T = \frac{\sigma_0}{\sqrt{1+\omega^2\tau^2}}$$

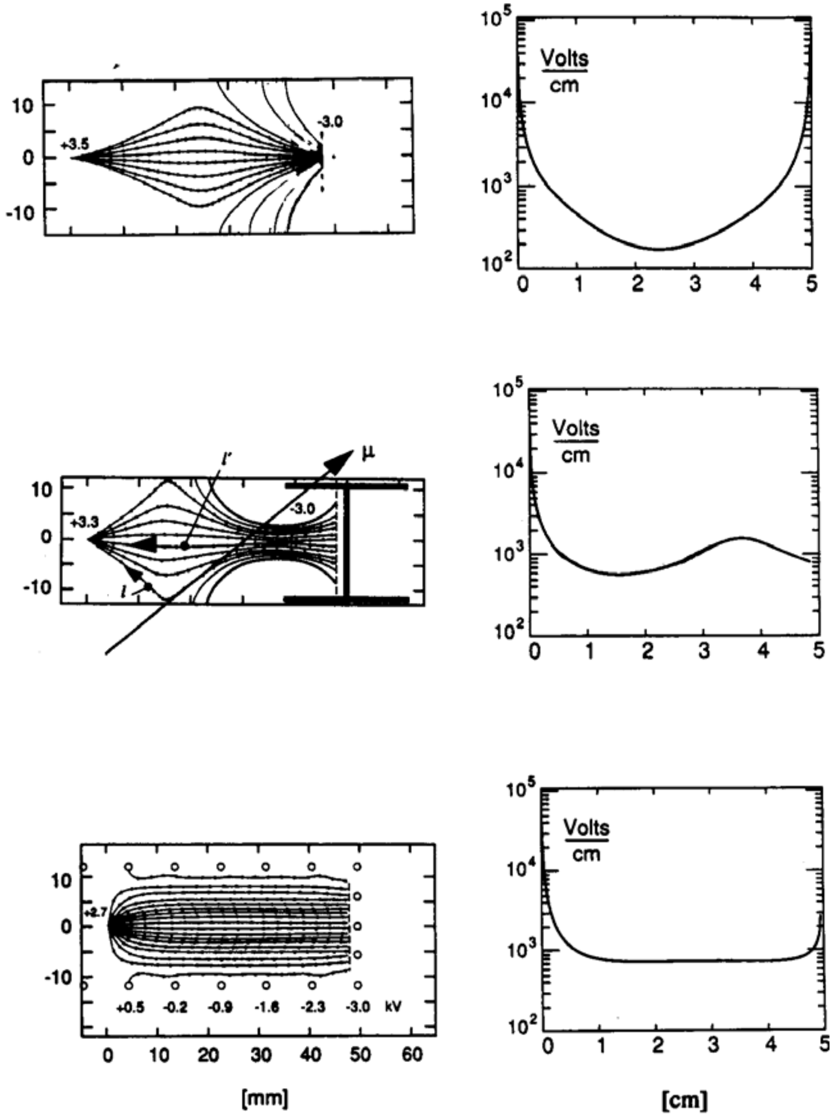



F. Sauli, Gas filled Detectors, IEEE 2002

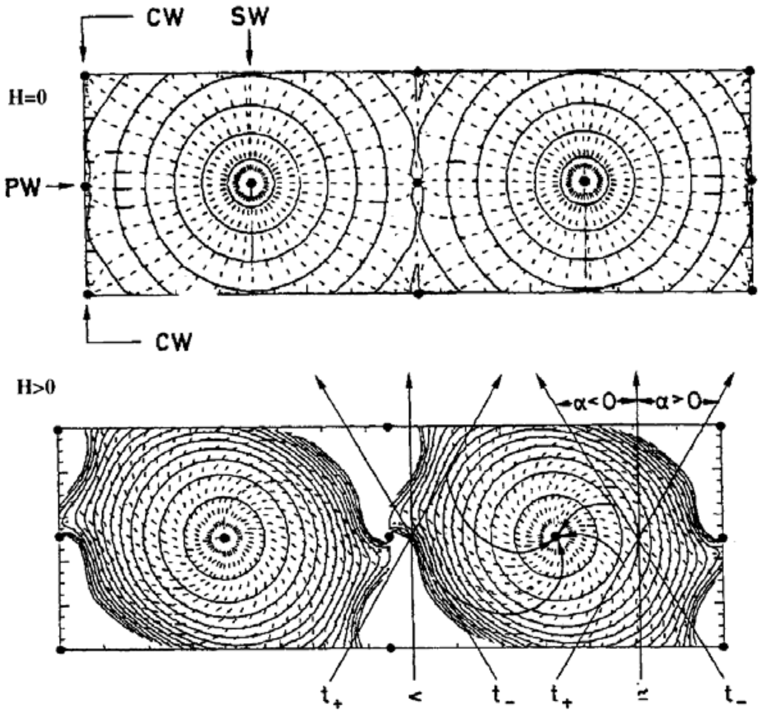
O. Ullaland/2006

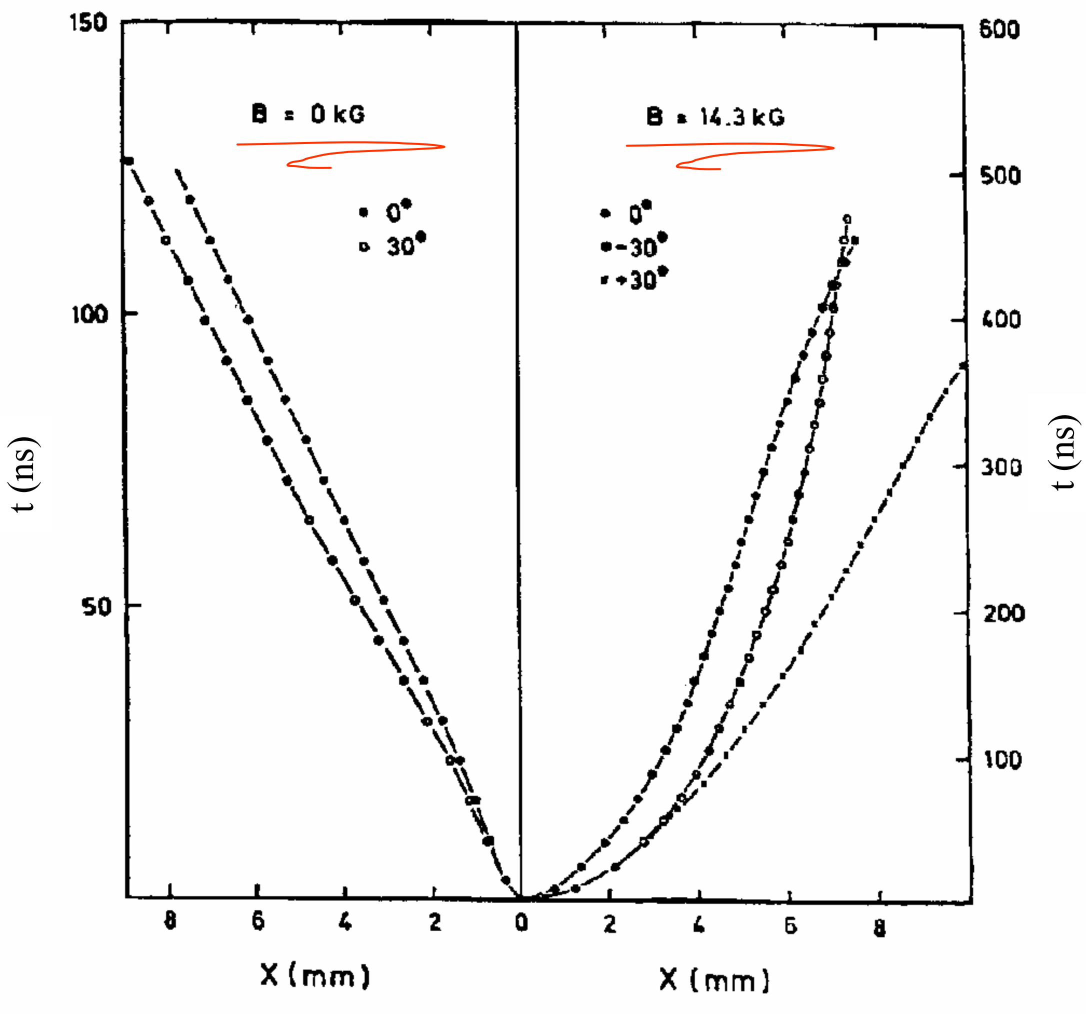
Some planar drift chamber designs
Optimize geometry → constant E-field
Choose drift gases with little dependence $v_D(E)$ → linear space - time relation r(t)



# MAGNETIC FIELD EFFECTS:
# DISTORSIONS IN DRIFT CHAMBERS




W. de Boer et al, Nucl. Instr. and Meth. 156(1978)249

O. Ullaland/2006

# Time Projection Chambers (TPC)

Large volume active detector.

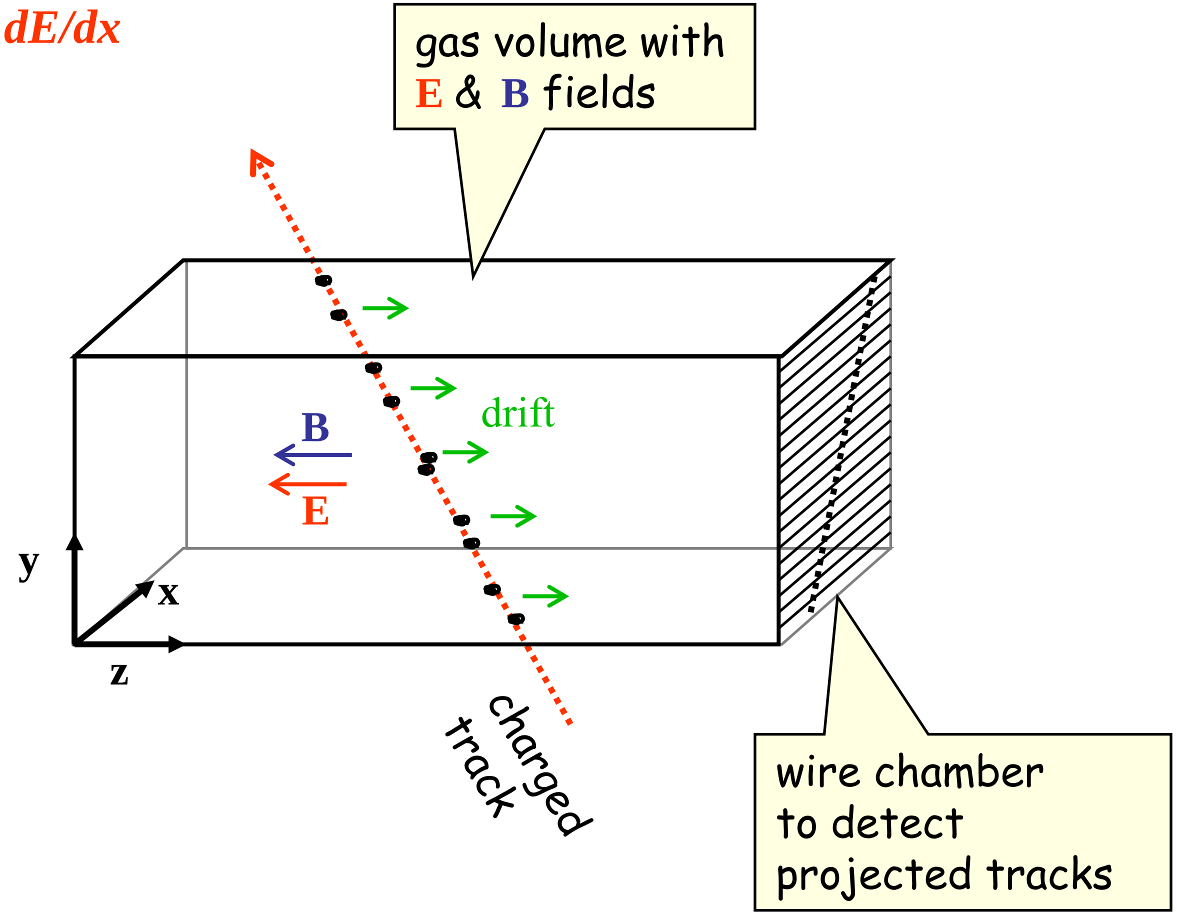
full 3-D track reconstruction

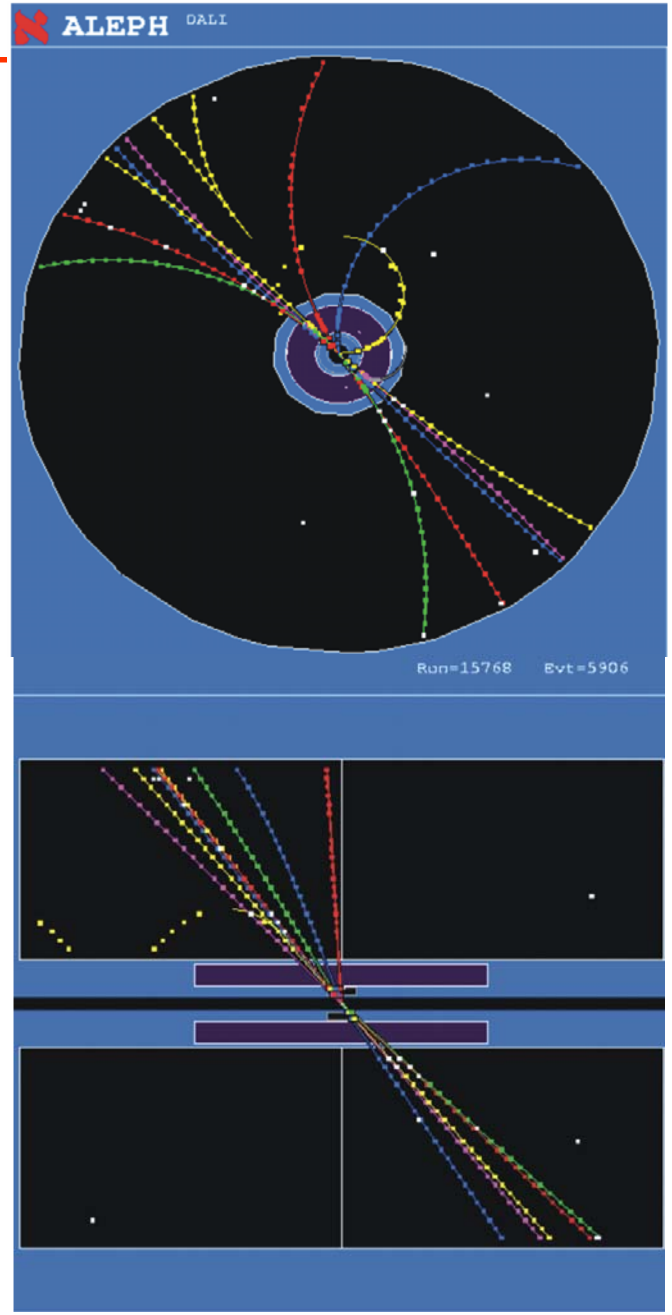
**x-y** from wires and segmented cathode of MWPC

**z** from drift time

and

***dE/dx***

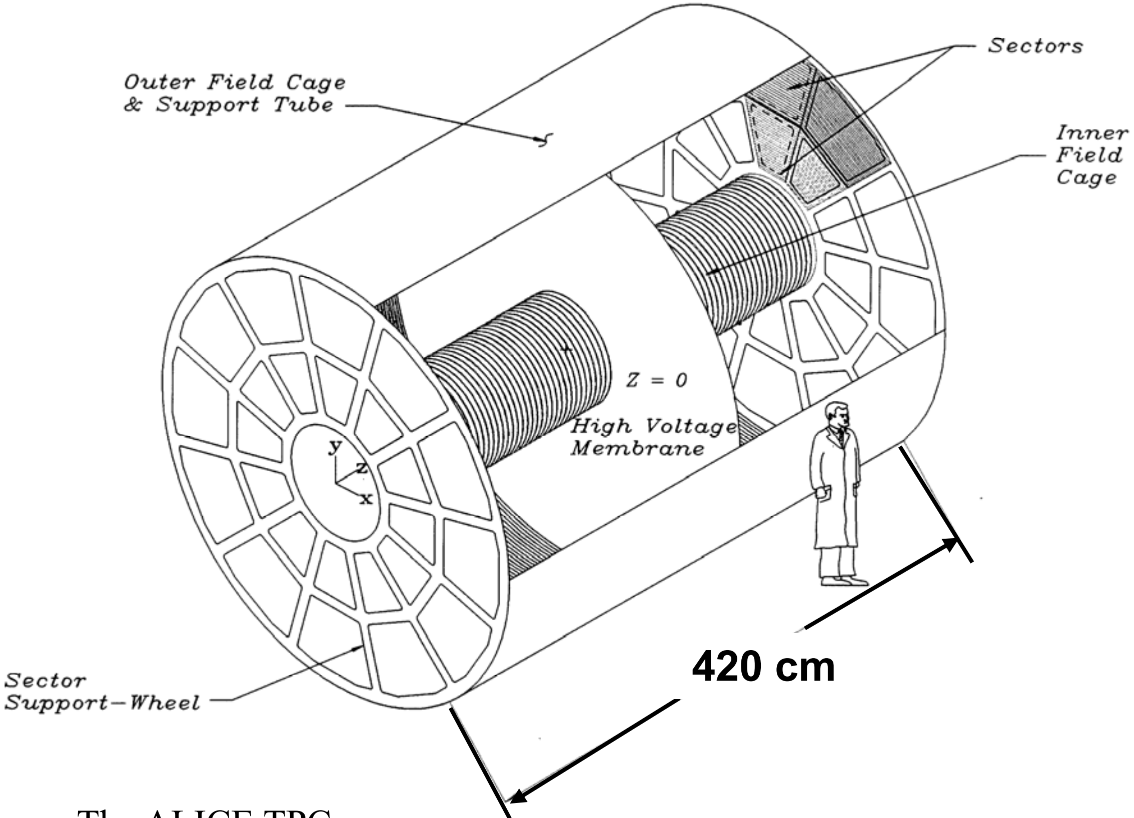


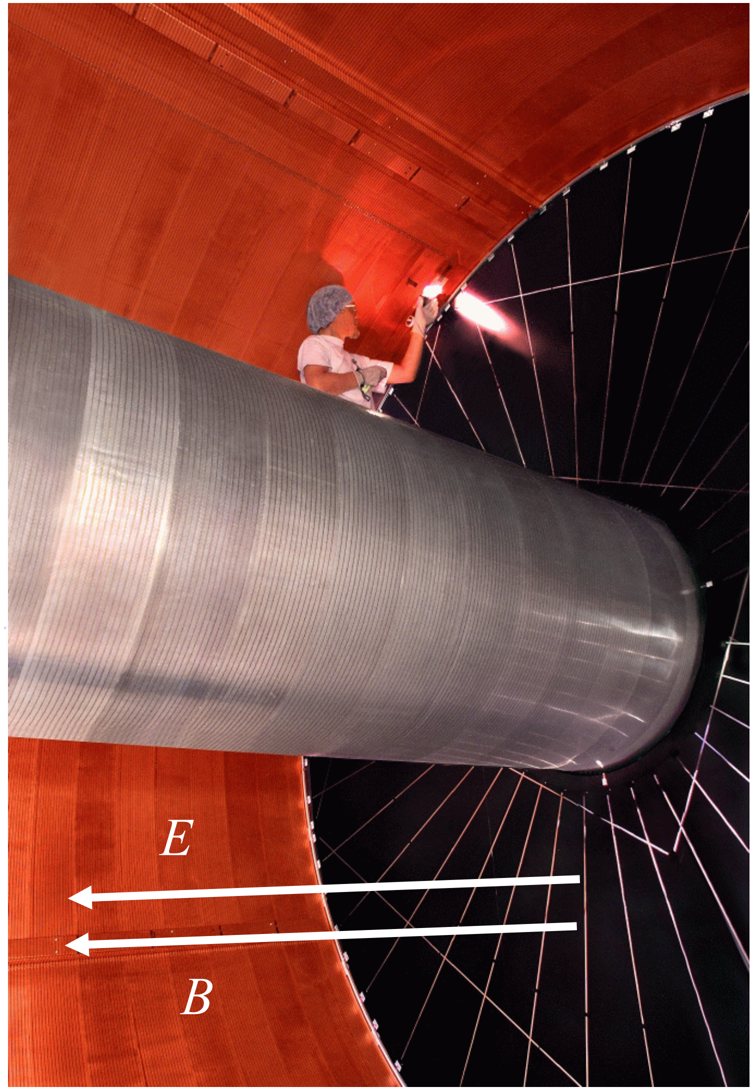
## More on TPCs

Usually $B \parallel E$ improvement of diffusion
Drift length $\geq 1\text{m}$
Rather (very) stringent requirement on homogeneity of $E$ and $B$ field
Space charge by ions
"Slow" detector

$$t_D \sim 10 \to 100\ \mu\text{s}$$

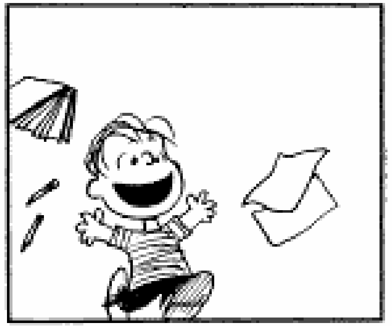



The ALICE TPC




O. Ullaland/2006

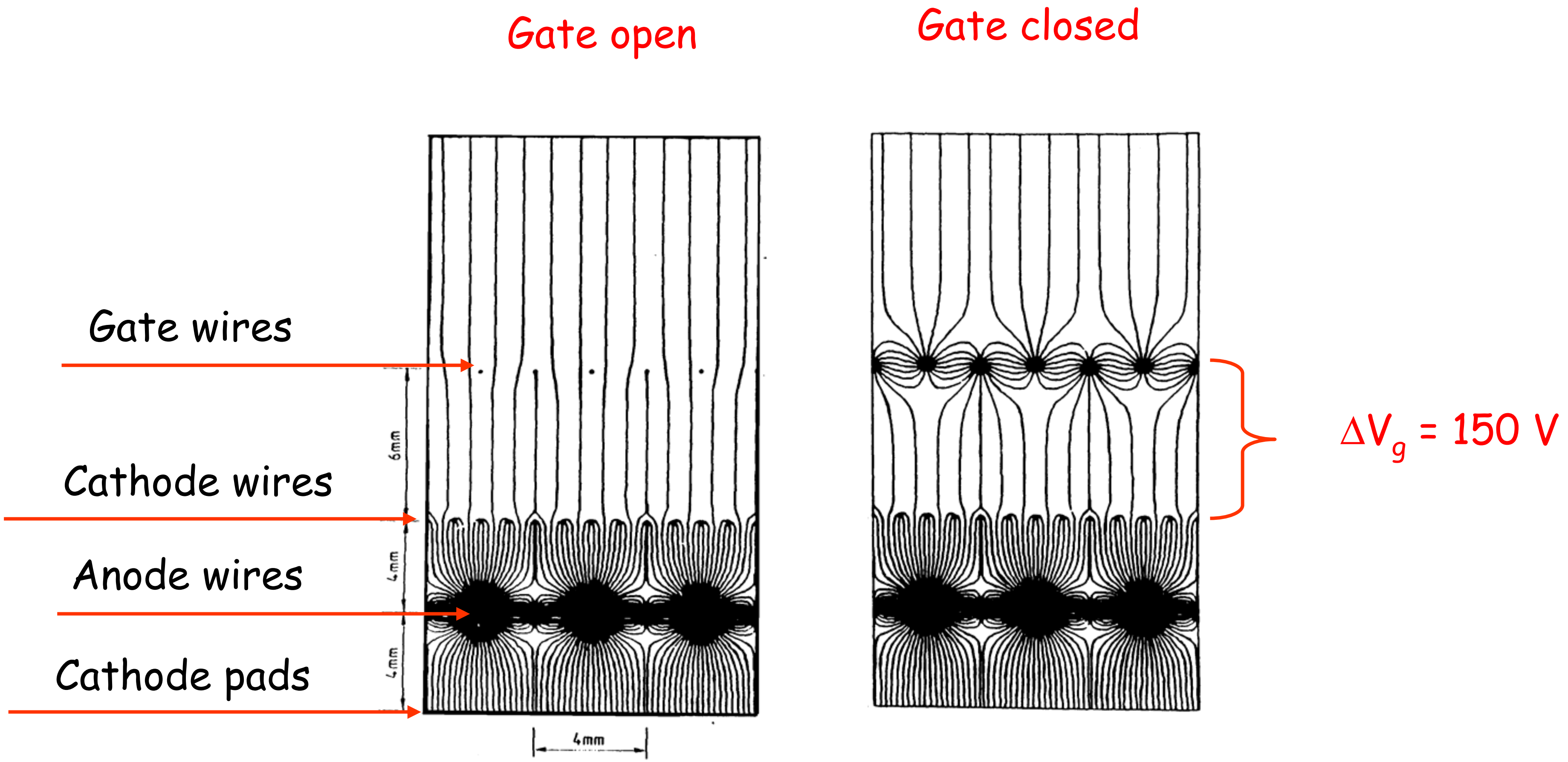
That was all planned for this lecture



## Space charge

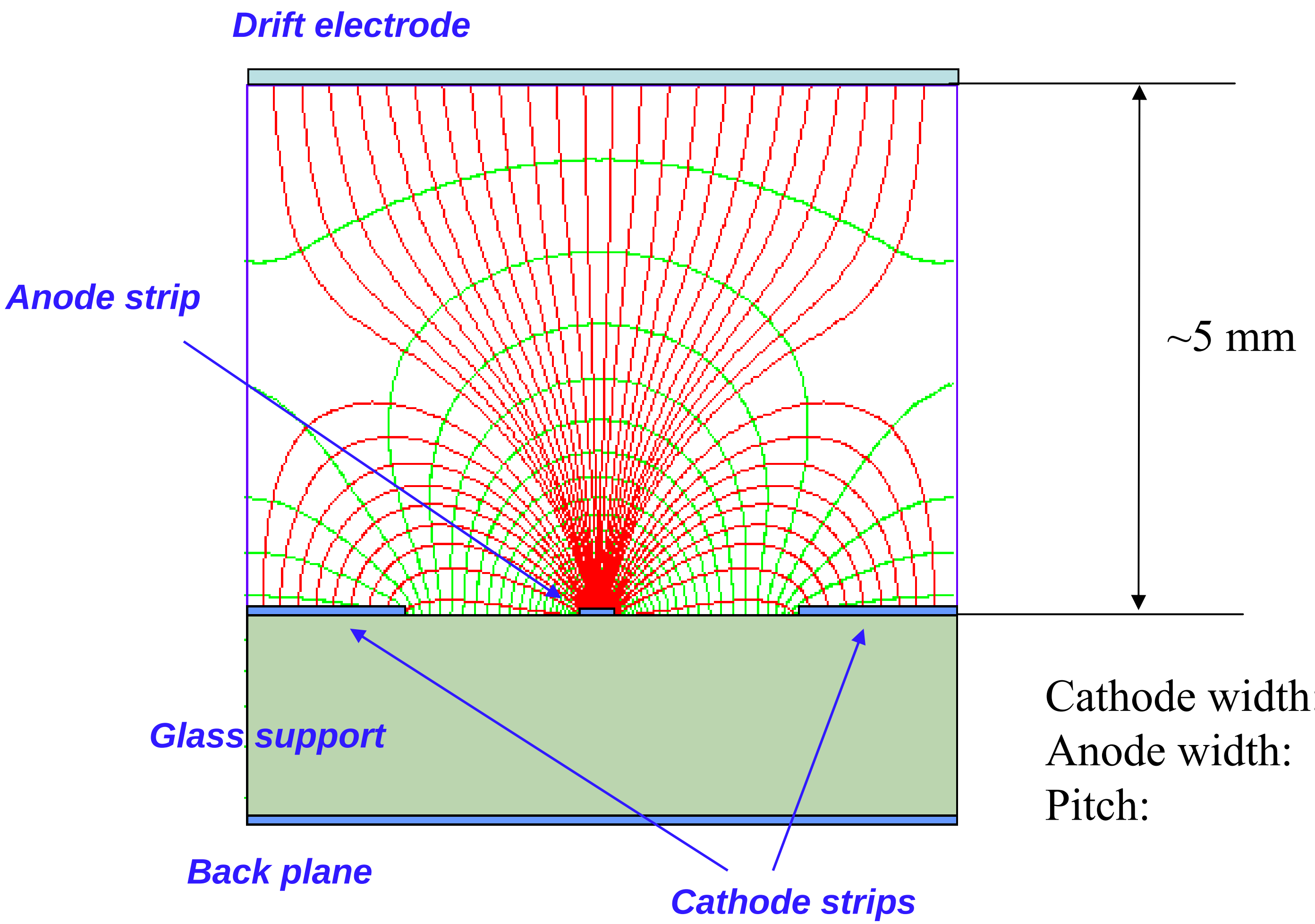
problem from positive ions, drifting back to medial membrane

→ gating



# MICRO-STRIP GAS CHAMBER (MSGC)

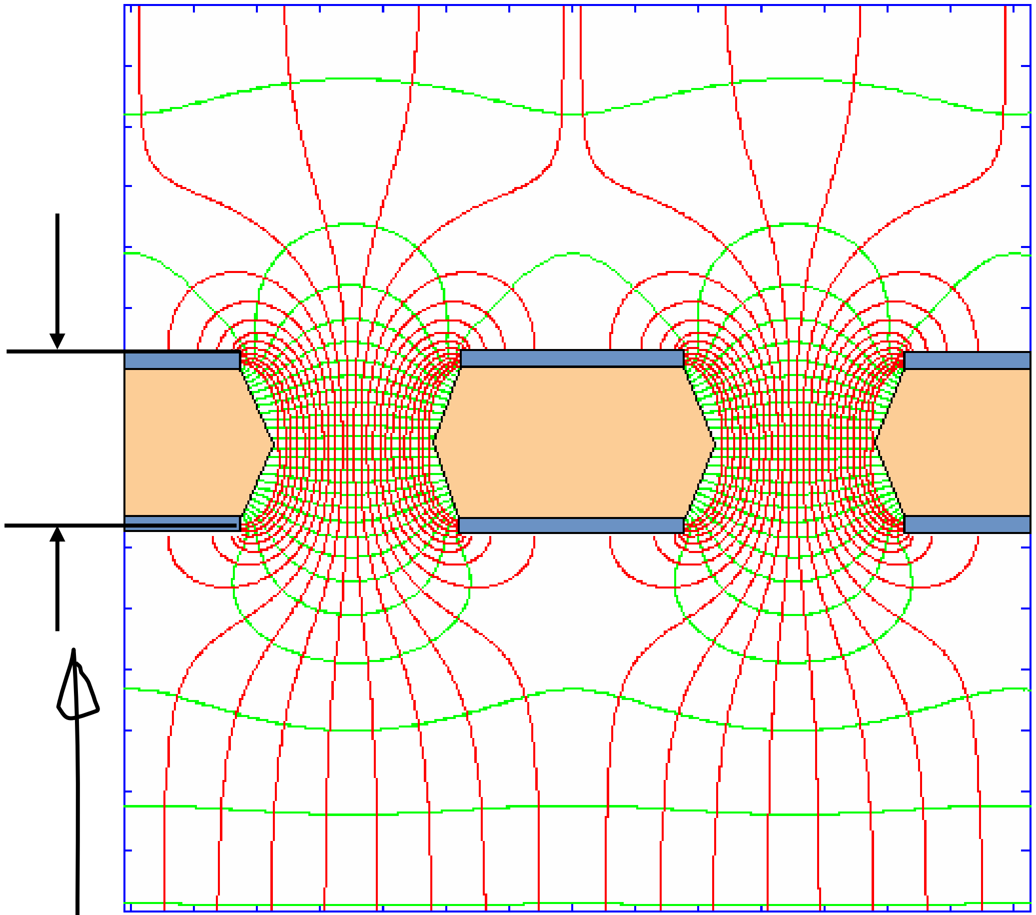
THIN ANODE AND CATHODE STRIPS ON AN INSULATING SUPPORT



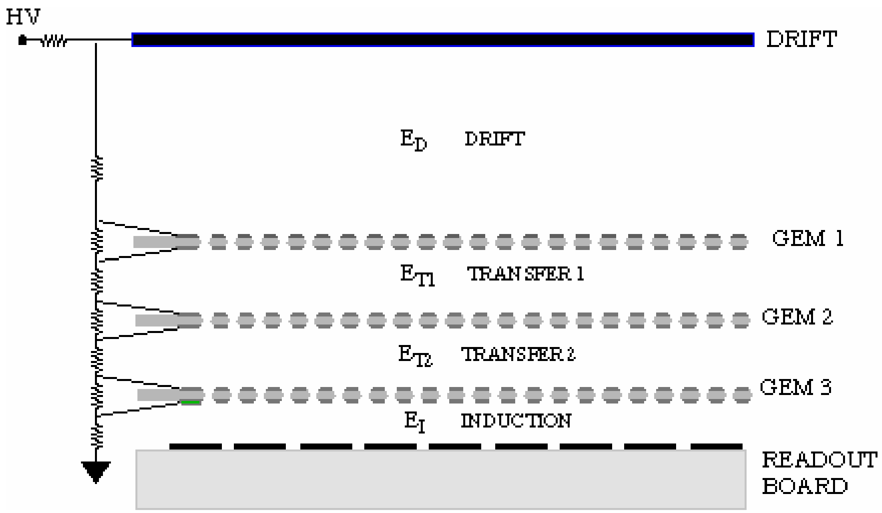

| | |
|---|---|
| Cathode width: | 90 µm |
| Anode width: | 10 µm |
| Pitch: | 200 µm |

J. van der Marel, Microstrip and Microgap Chambers

# Gas Electron Multiplier - GEM



Thin metal-coated polymer foil chemically pierced by a high density of holes.
On application of a voltage gradient, electrons released on the top side drift into the hole, multiply in avalanche and transfer the other side.
Proportional gains above $10^3$ are obtained in most common gases.

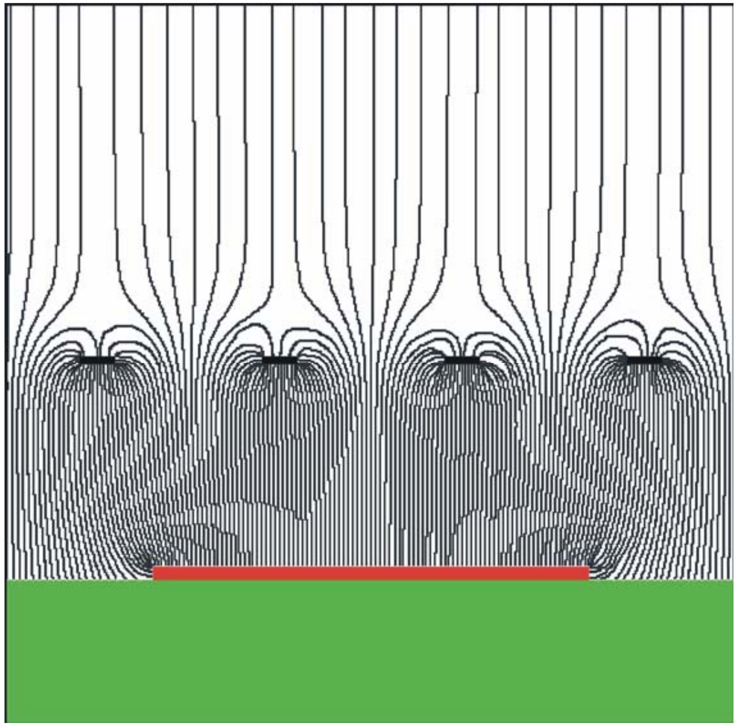


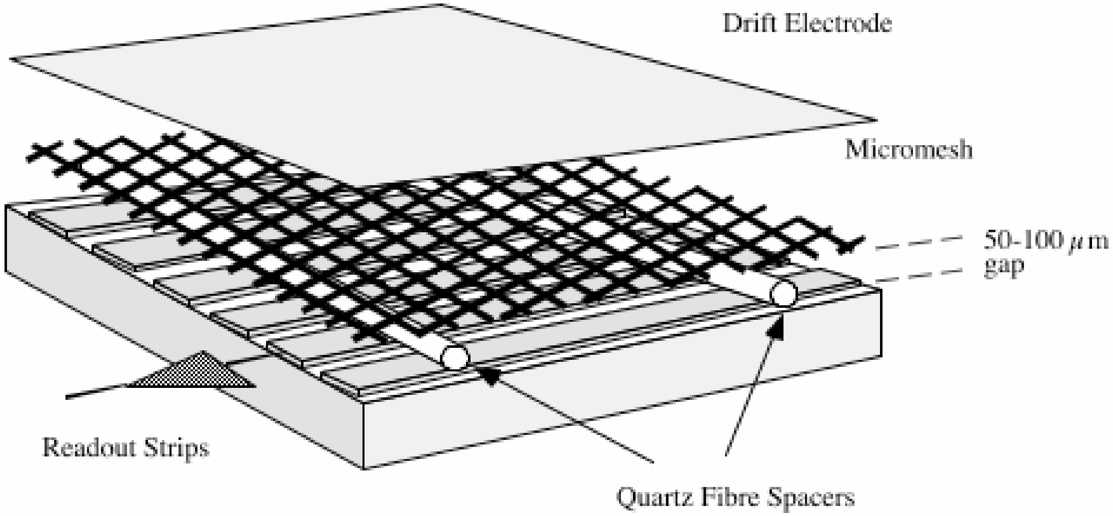

| | |
|---|---|
| Thickness: | ~ 50 µm |
| ΔV: | 400 – 600 V |
| Hole Diameter: | ~ 70 µm |
| Pitch: | ~140 µm |

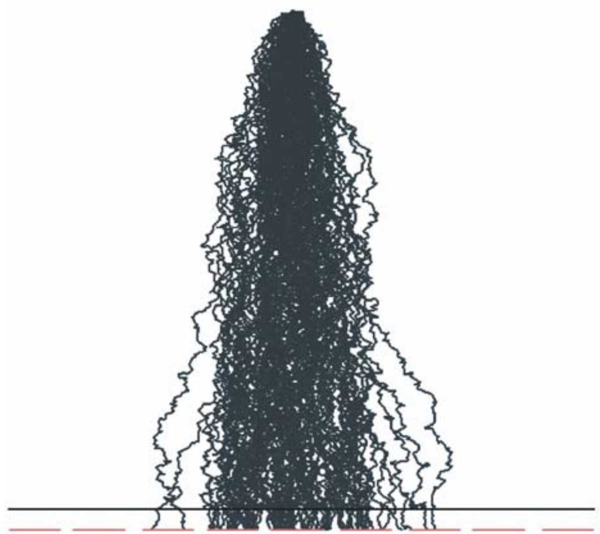
F. Sauli, Nucl. Instrum. Methods A386(1997)531
http://gdd.web.cern.ch/GDD/

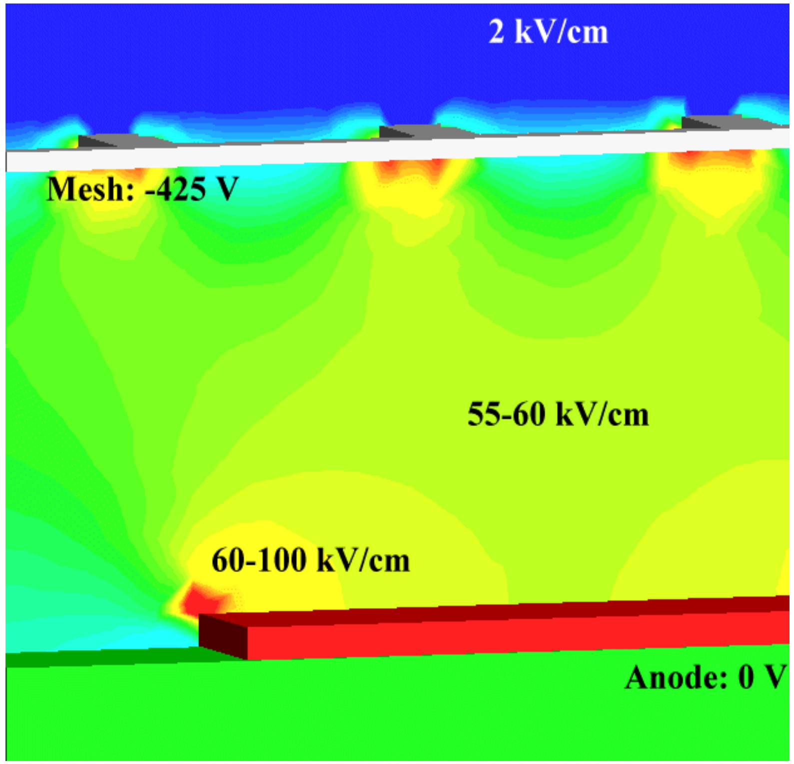
O. Ullaland/2006

# MICROMEGAS:
## Thin-gap parallel plate chamber





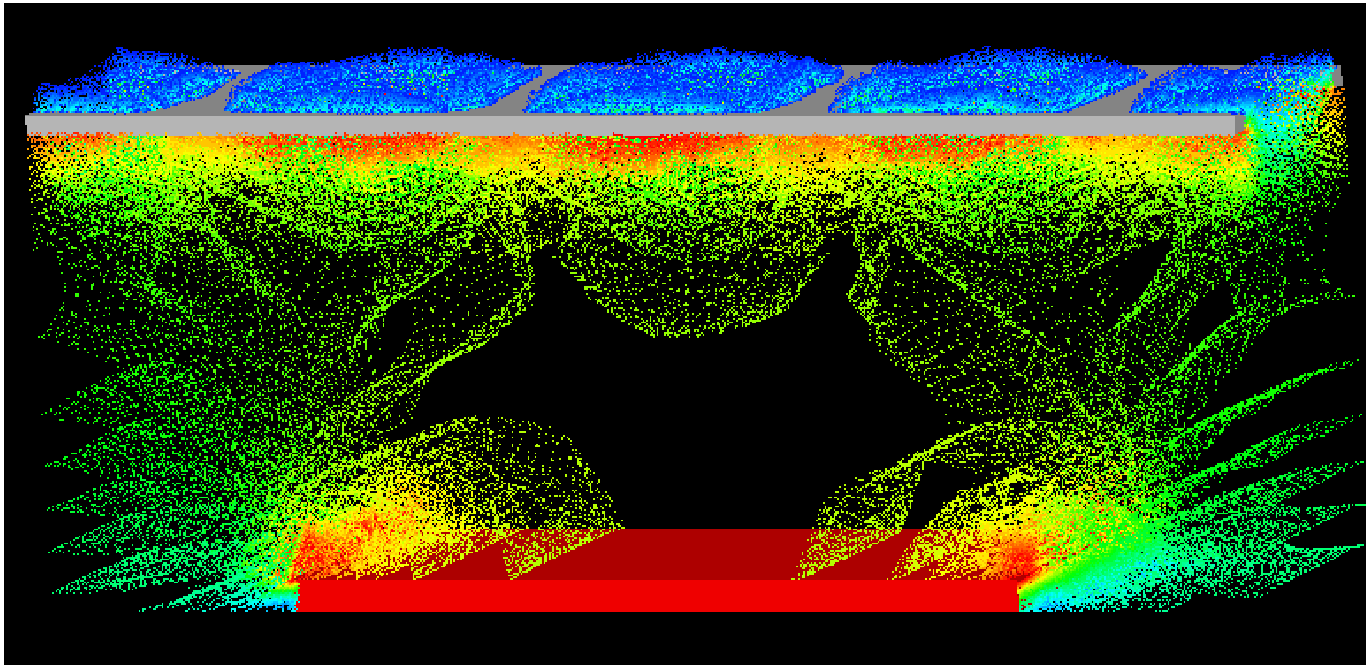






3ème Atelier Micromégas IPHE, Univ. Lausanne, March 9-10, 2000 by Peter Cwetanski

An example on the software tools available in the understanding of the detectors:

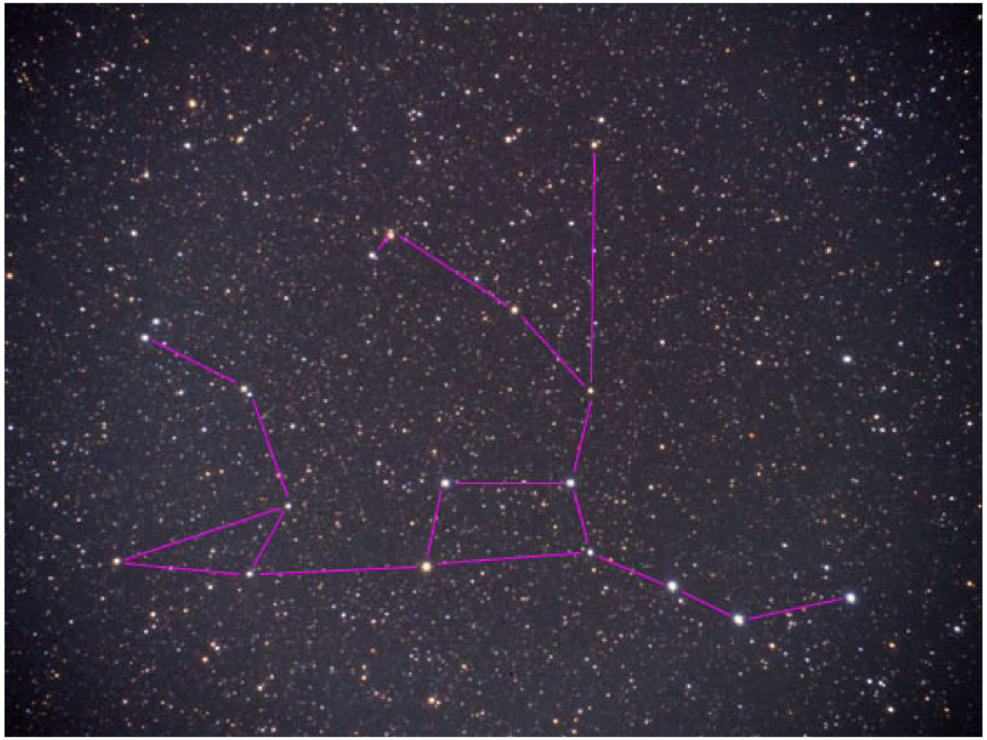
Micromegas 3D Simulations



- *Computation of field maps using 3D Finite Element Method. Software: Maxwell 3D Field Simulator ® (Ansoft Corp.)*
- *Obtain gas transport parameters for operating gas with Monte Carlo simulation using imonte 4.5 (author: Steve Biagi).*
- *Input of field maps and gas parameters in detector simulation software Garfield (author: Rob Veenhof).*

# Connecting the dots

to find the tracks and some properties
of the passing particles.



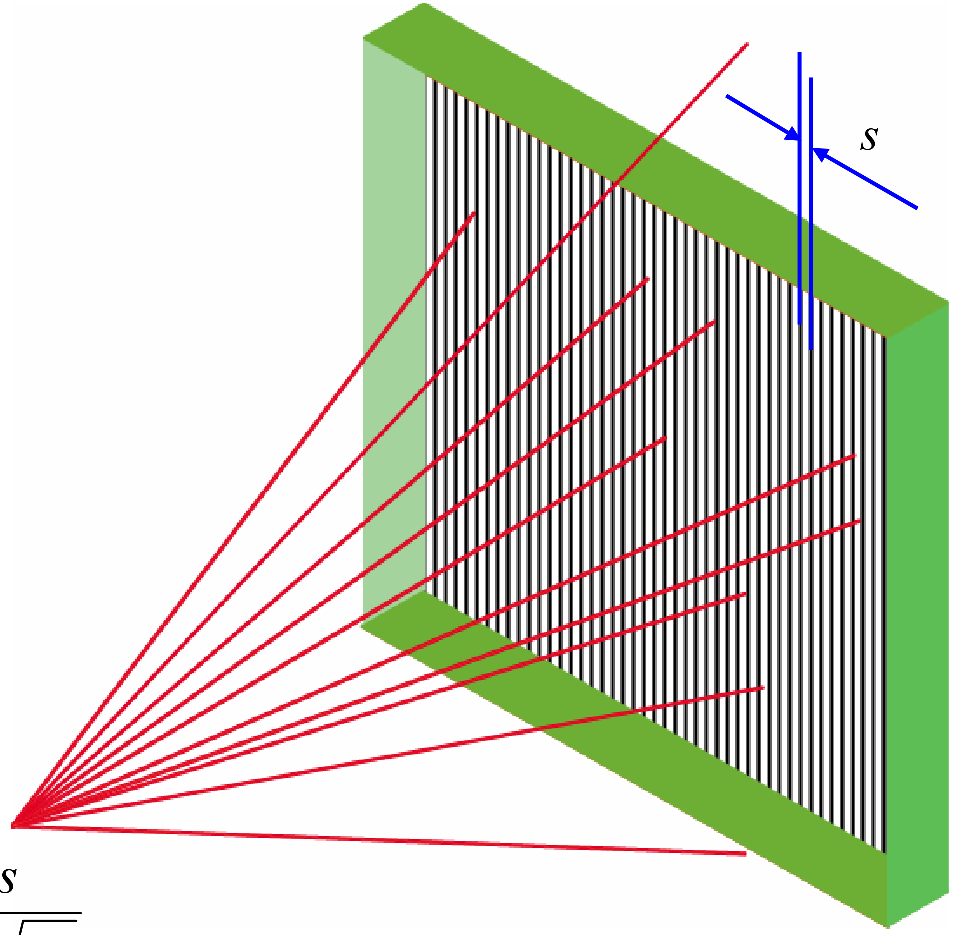
***The Big Bear, Ursa Major,*** is the third largest constellation in the skies, seen at northern sky in evening of spring. The constellation has no first magnitude stars, but the Big Dipper that forms the bear's tail is a rough guide on the clarity of the evening's sky. Though Ursa Major contains no bright celestial objects, it has plenty of galaxies in outer space.

Location: Ooizumi vil., Yamanashi prefecture, Honshu


http://www.ne.jp/asahi/stellar/scenes/english/seiza.htm

O. Ullaland/2006

# Position of the impact point.




One or several wires will be set depending on the particle orientation with respect to the chamber plane.

Let $s$ be the wire spacing.
The position of the impact point on the plane of wires is then given with a precision of about:

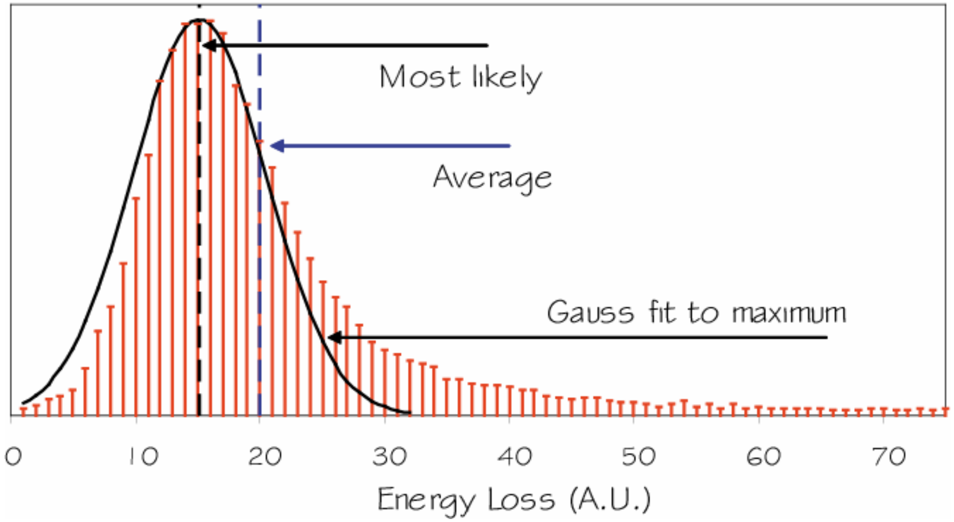
$$\sigma(x) \cong \frac{s}{\sqrt{12}}$$

The theoretical lower limit is:

$$\sigma(x) \cong \frac{s}{2 \cdot \sqrt{12}}$$

if we assume that a particle next to a wire will only set this wire and a particle passing between two wires will set these wires.

Further reading in
R. Frühwirth et al., Data Analysis Techniques for High-Energy Physics
Try also
A.G. Frodesen et al., probability and statistics in particle physics
or similar.

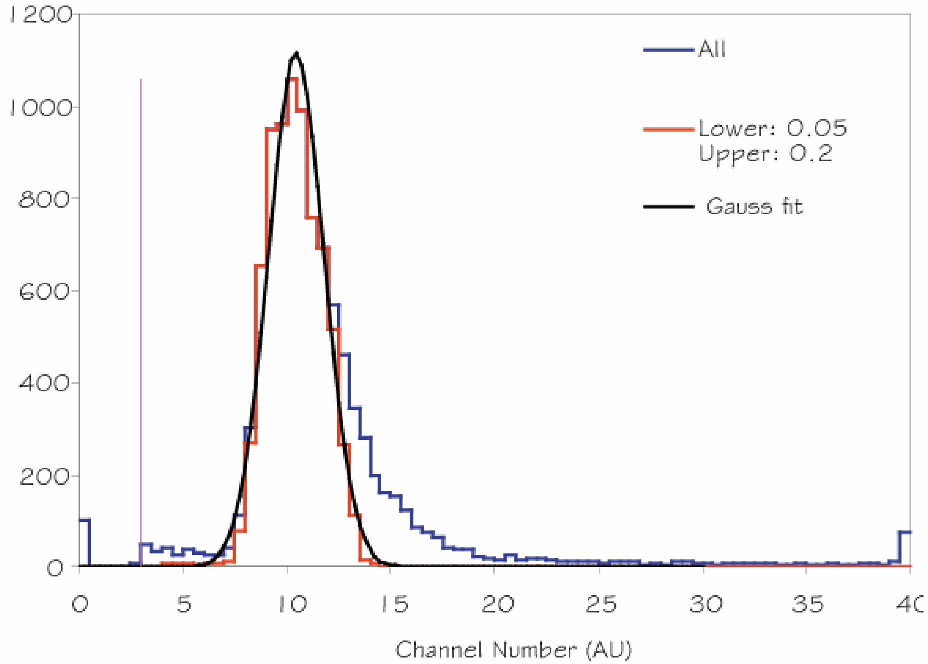


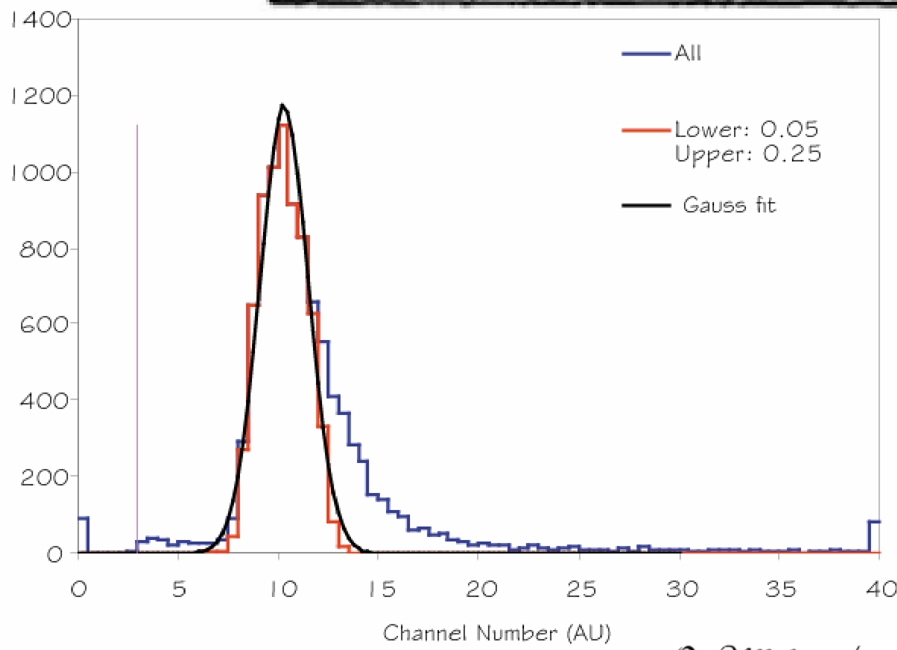


The challenge with $dE/dx$ measurements:

Long tails.

Do many measurements and build a truncated mean.

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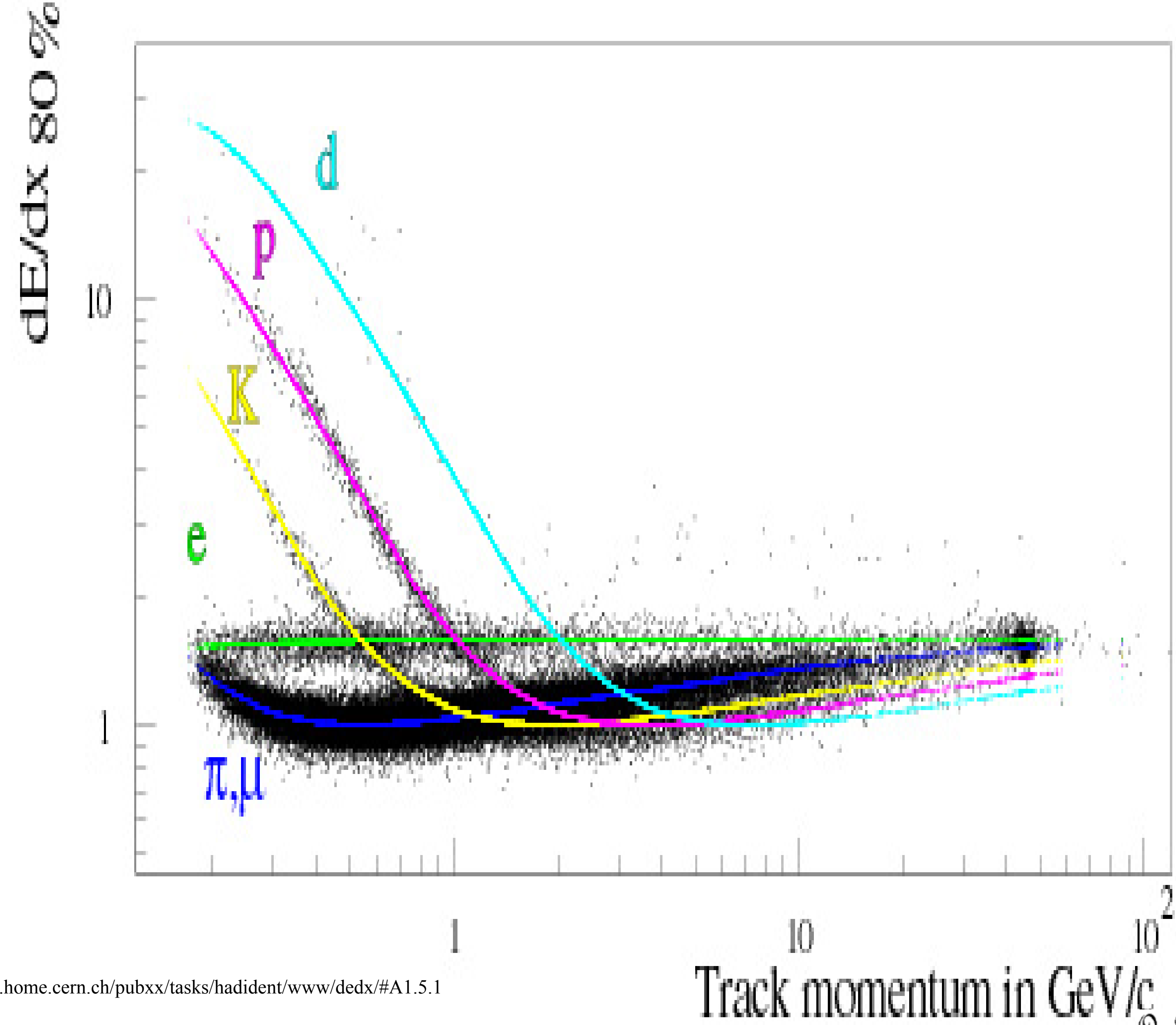
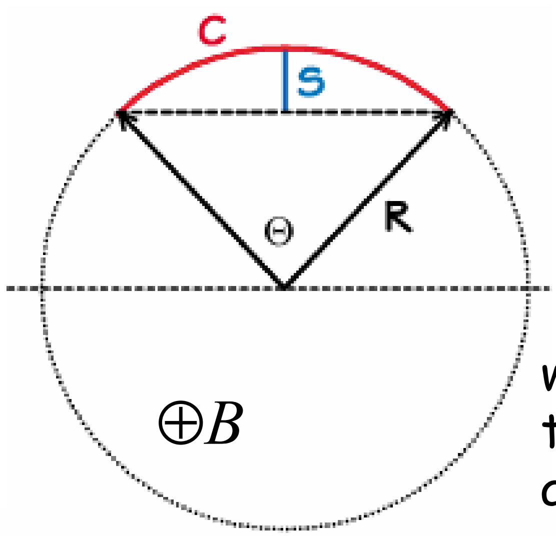
## *dE/dX* measurement from the DELPHI TPC




http://pubxx.home.cern.ch/pubxx/tasks/hadident/www/dedx/#A1.5.1

O. Ullaland/2006

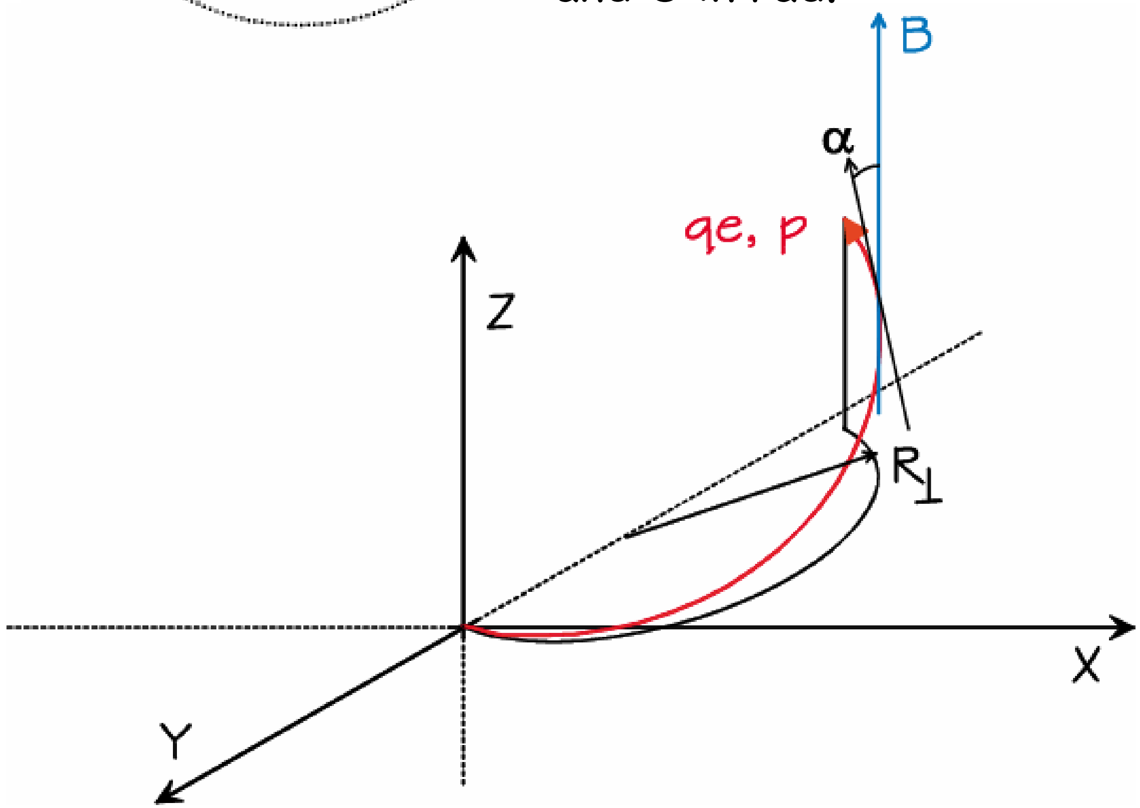
## Momentum measurement.




For a uniform magnetic field along the particle trajectory

$$p \cong 0.3q \frac{\int B_\perp dl}{\Theta} \cong 0.3qB\left(\frac{C^2 \sin\alpha}{8S} + \frac{S\sin\alpha}{2}\right)$$

where α is the angle between the trajectory and $B$. $B$ in tesla, $p$ in GeV/$c$, $q$ in electron charge, $C$, $S$ and $R$ in m and α and Θ in rad.




We can clearly also measure the charge, $q$, of the particle.

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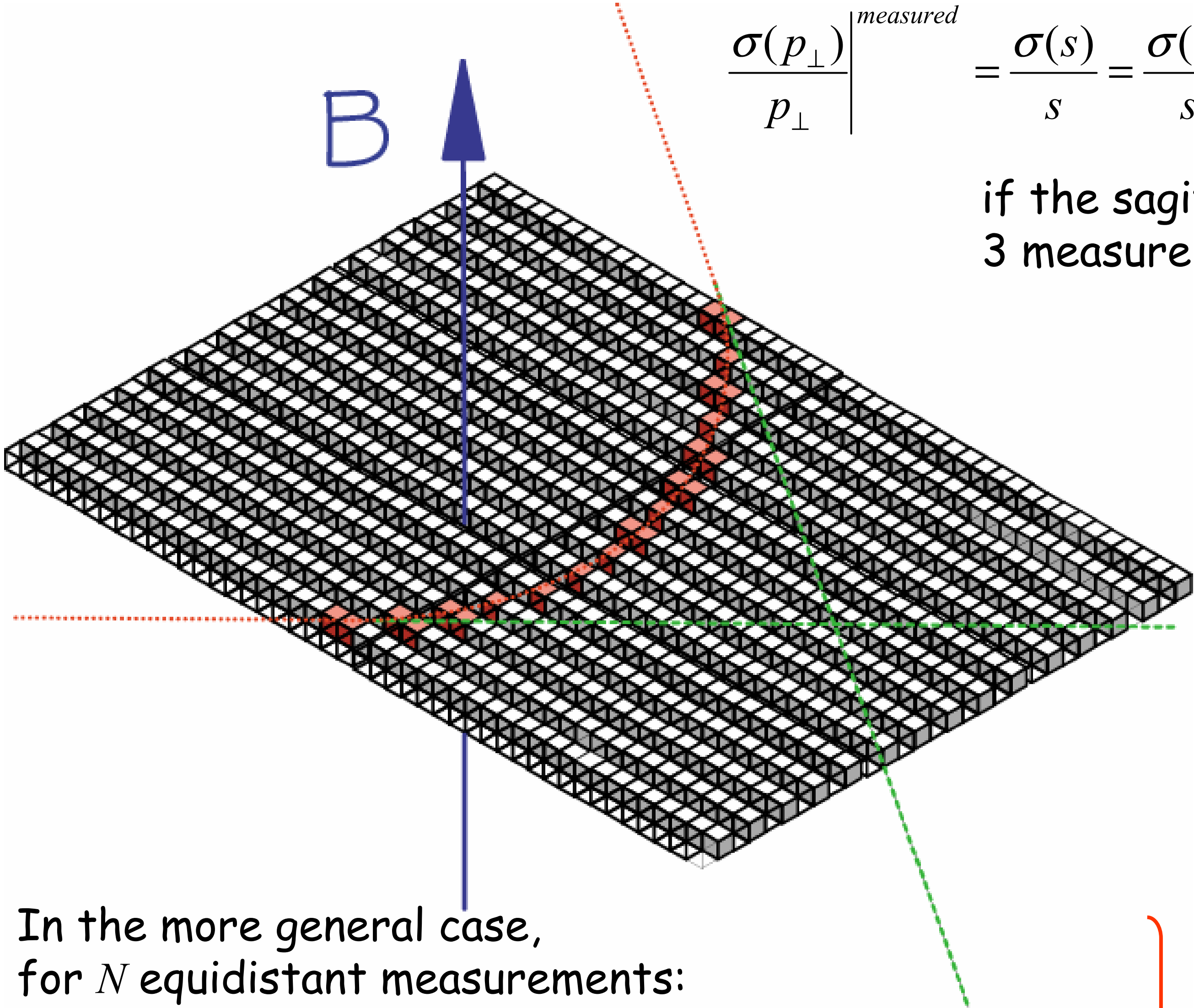
## Error in momentum measurement




$$\left.\frac{\sigma(p_\perp)}{p_\perp}\right|^{measured} = \frac{\sigma(s)}{s} = \frac{\sigma(x)}{s}\sqrt{\frac{3}{2}} = \frac{1}{0.3}\frac{\sigma(x)\cdot p_\perp}{BL^2}\sqrt{\frac{387}{2}}$$

if the sagitta, $s$, is determined by 3 measurements with error $\sigma(x)$

In the more general case, for $N$ equidistant measurements:

$$\left.\frac{\sigma(p_\perp)}{p_\perp}\right|_{measured} = \frac{1}{0.3}\frac{\sigma(x)\cdot p_\perp}{BL^2}\sqrt{\frac{720}{N+4}}$$

for $N \geq \sim 10$

In short → $\frac{\sigma(p_\perp)}{p_\perp^2} = const.$

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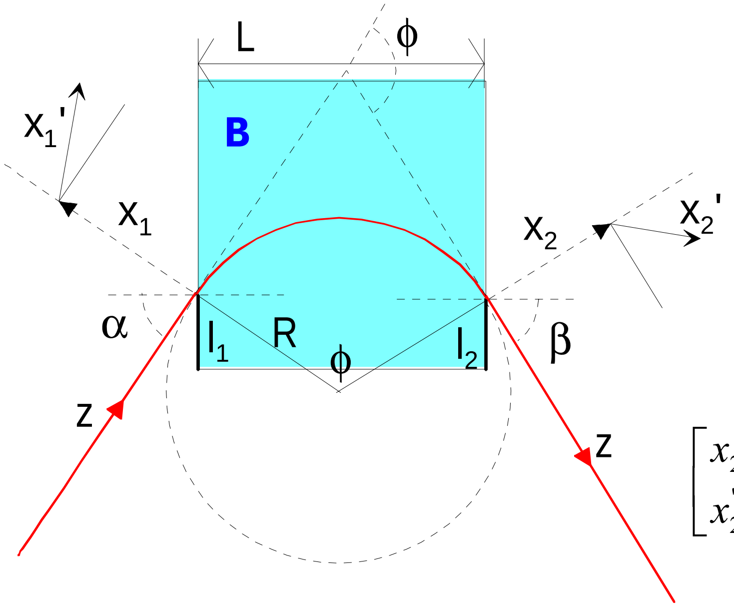
# (more on) Momentum measurement.




Rectangular bending magnet. The initial and final displacement and divergence $(x_1, x_1')$, $(x_2, x_2')$ is defined with respect to the central particle of the beam.

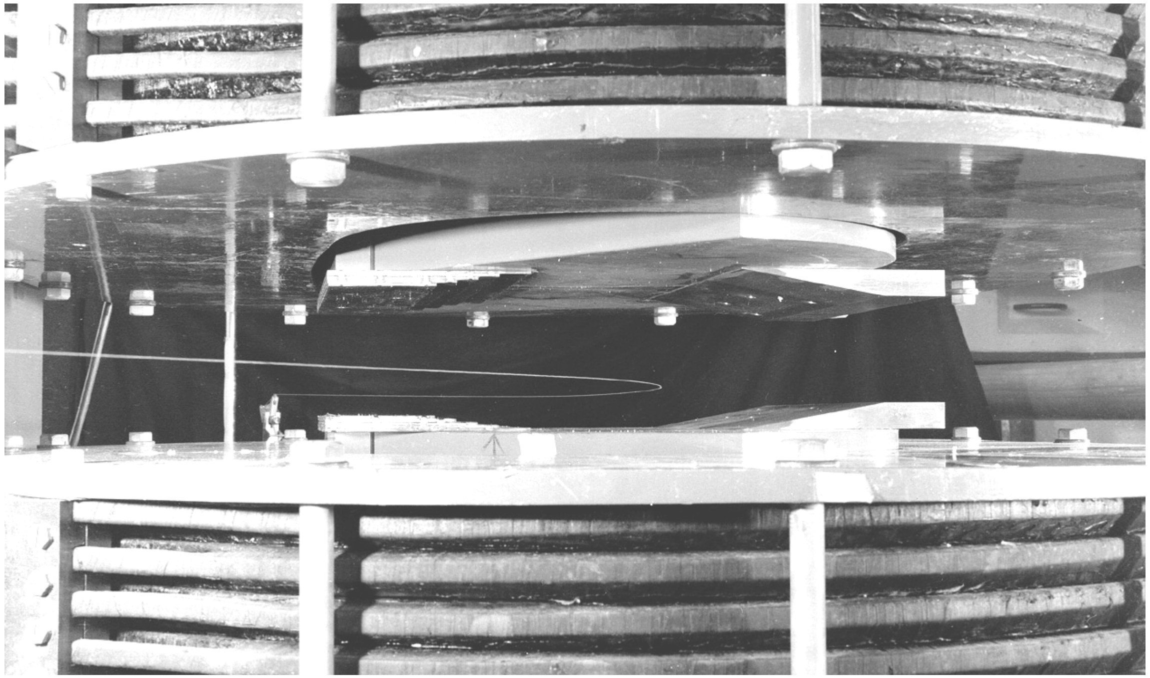
$(x_i' = dx_i/dz)$

It is usual to operate the magnet symmetrical:

$\rightarrow \alpha = \beta = \phi/2$

$$\begin{bmatrix} x_2 \\ x_2' \end{bmatrix} = \begin{bmatrix} \frac{\cos\beta}{\cos\alpha} & R\sin(\alpha+\beta) \\ 0 & \frac{\cos\alpha}{\cos\beta} \end{bmatrix} \begin{bmatrix} x_1 \\ x_1' \end{bmatrix} \Rightarrow \begin{bmatrix} x_2 \\ x_2' \end{bmatrix} \begin{bmatrix} 1 & R\sin\varphi \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_1' \end{bmatrix} \Rightarrow \varphi \cong 0.03 \frac{BL}{p}$$

kGm/GeV/$c$



The central momentum is given as

$p(\text{GeV}/c) \approx 3\ 10^{-3}\ M\ (\text{g})/i(\text{A})$

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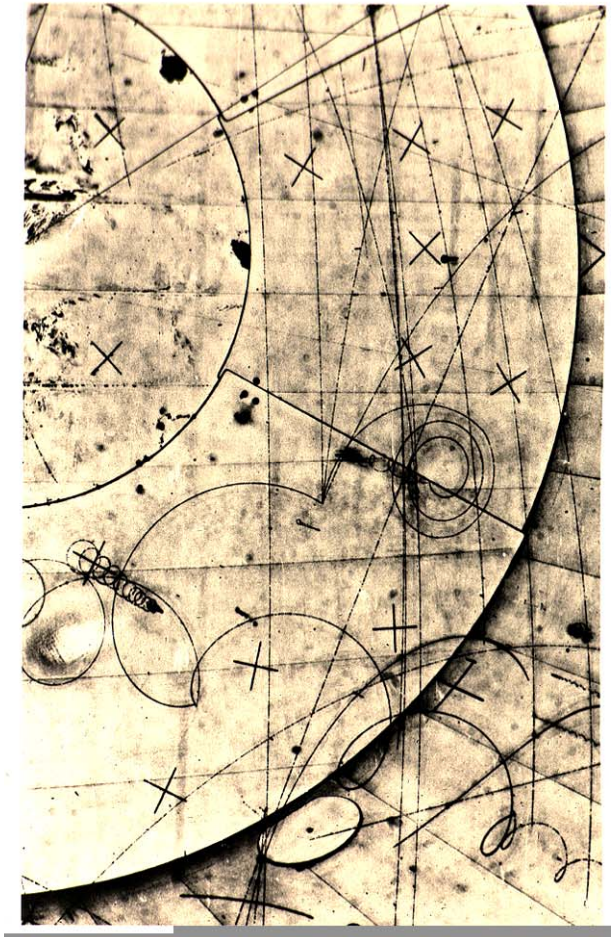
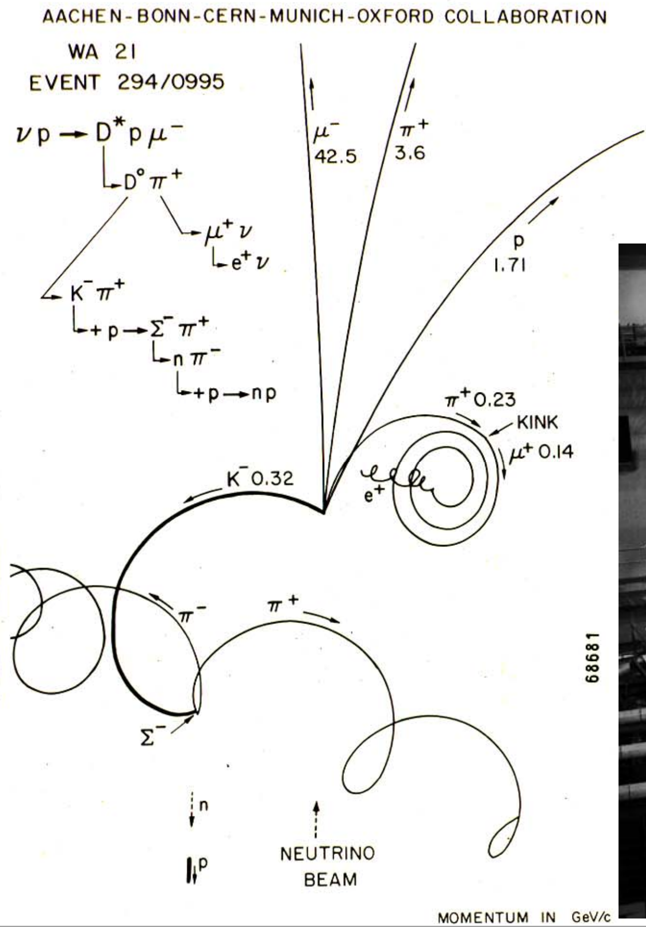




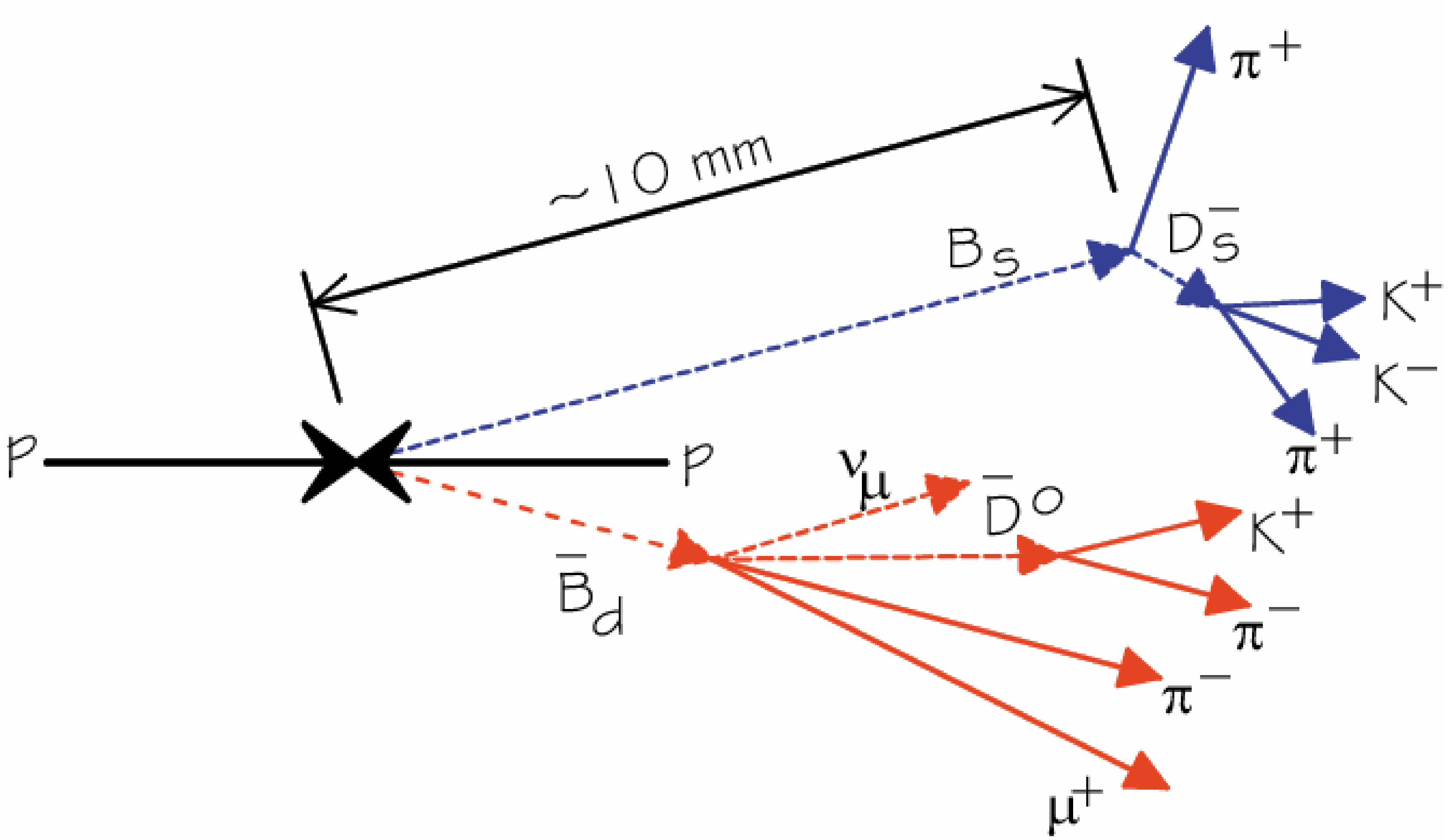

BEBC, equipped with the largest superconducting magnet in service at the time.

D* (excited D-meson, carrying the "charm" quantum number): production and decay during a wide band exposure in experiment WA21, in the BEBC liquid hydrogen bubble chamber.

Generic tracking issues.

Secondary vertices.

High spatial resolution.



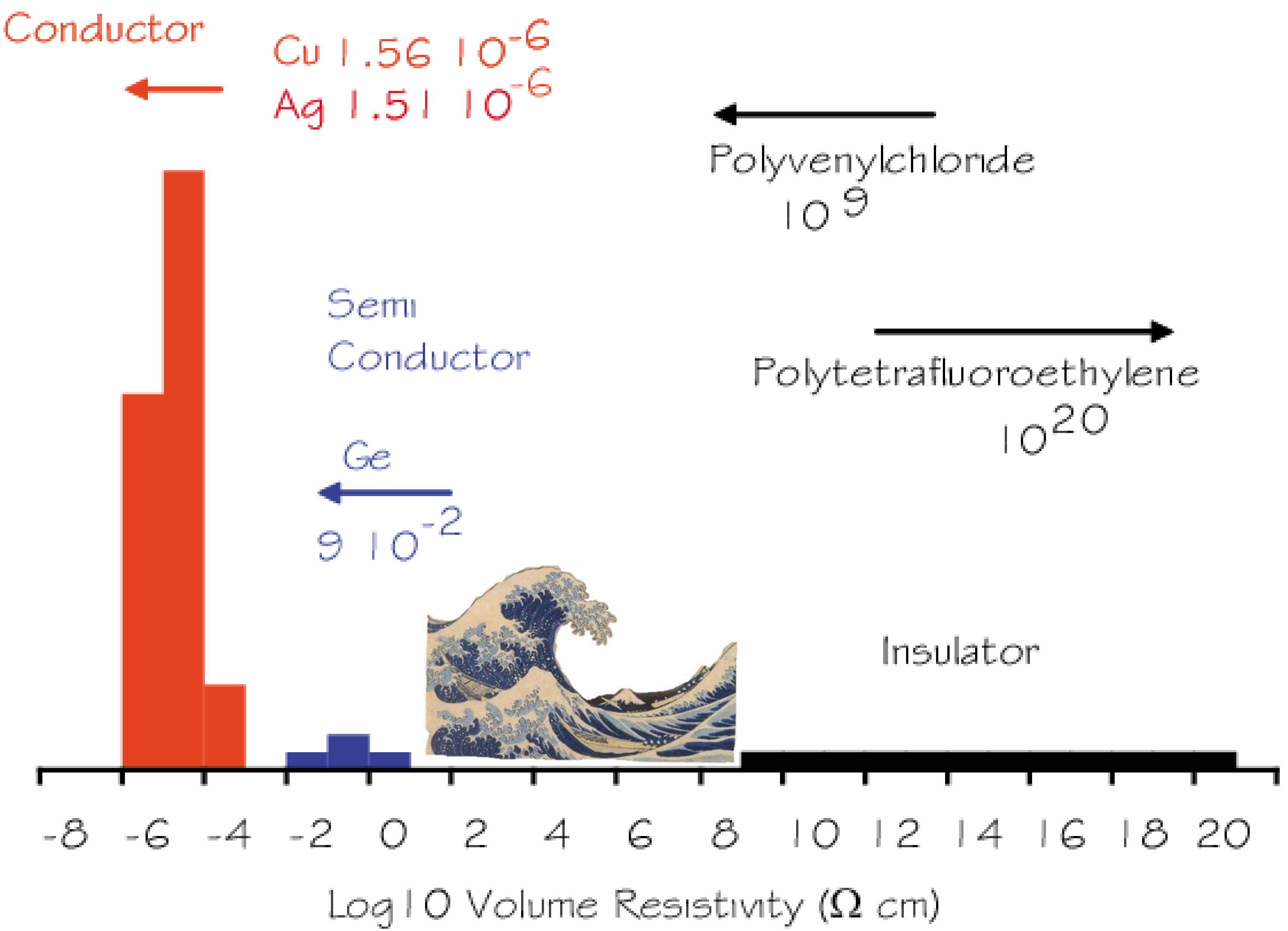

O. Ullaland/2006

2006
Summer Student Lectures
Detectors

# Solid State Detectors
# Scintillators
# and
# Photon Detectors

The Nuclear Spectroscopic Telescope Array (NuSTAR), which will take a telescope for focusing high-energy x rays into space and above the atmospheric interference. NuSTAR will fly 525 kilometres above Earth's surface and stay in orbit for 3 years. It will be the first hard x-ray focusing telescope in space and will observe energies from 10 to about 100 kiloelectronvolts, providing a 1,000-fold increase in sensitivity over previous missions.

The Nuclear Spectroscopic Telescope Array (artist's conception shown here) would be the first satellite mission with a high-energy x-ray focusing telescope in space and would provide a 1,000-fold increase in sensitivity over previous missions.

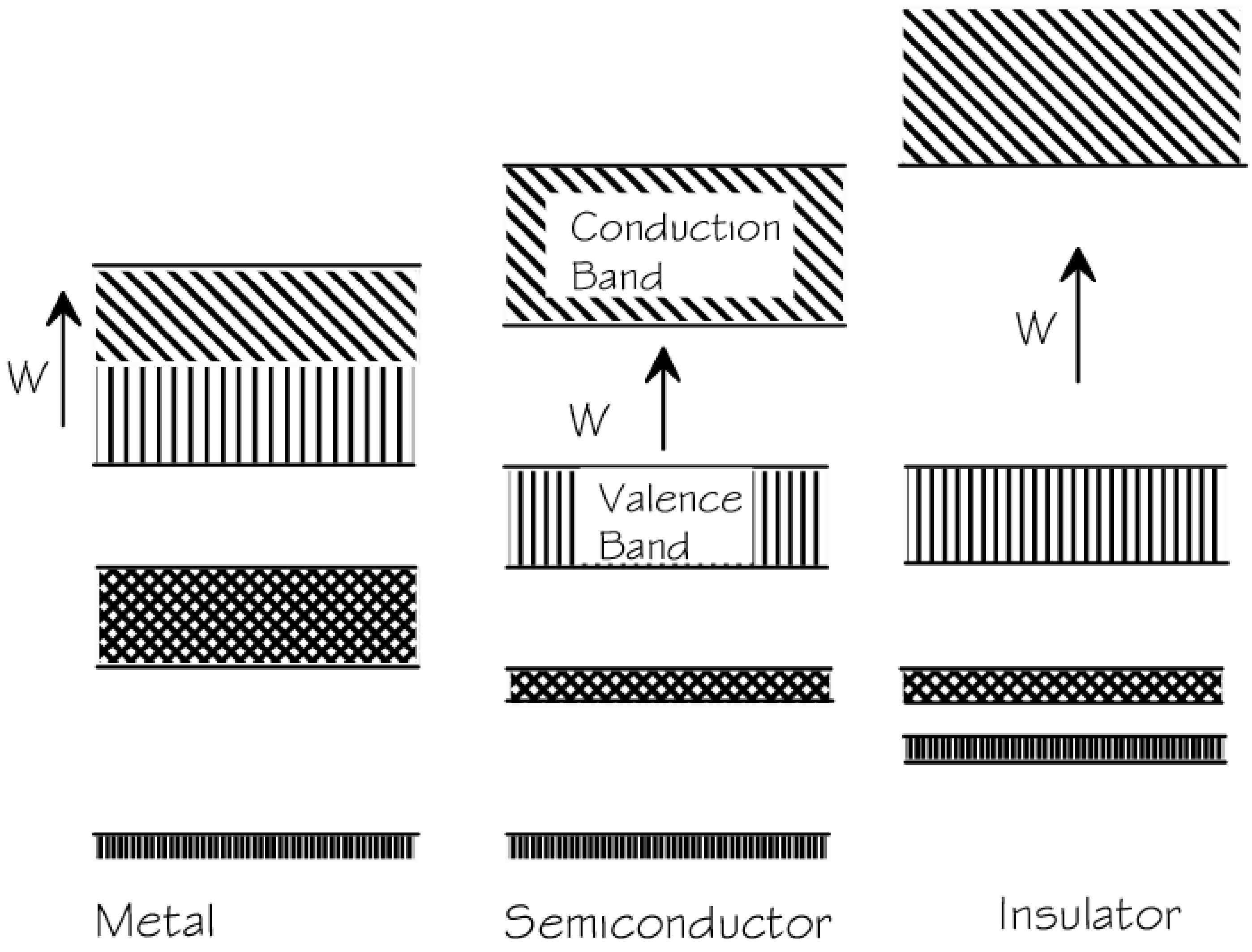



The Hollow of the Great Wave off Kanangawa (The Big Wave) by Katsushika Hokusai

O. Ullaland/2006

## Allowed and forbidden energy bands.

In metal one band is only partially filed.
In a semiconductor, the valence band is (nearly) filled
and the conduction band is (nearly) empty.

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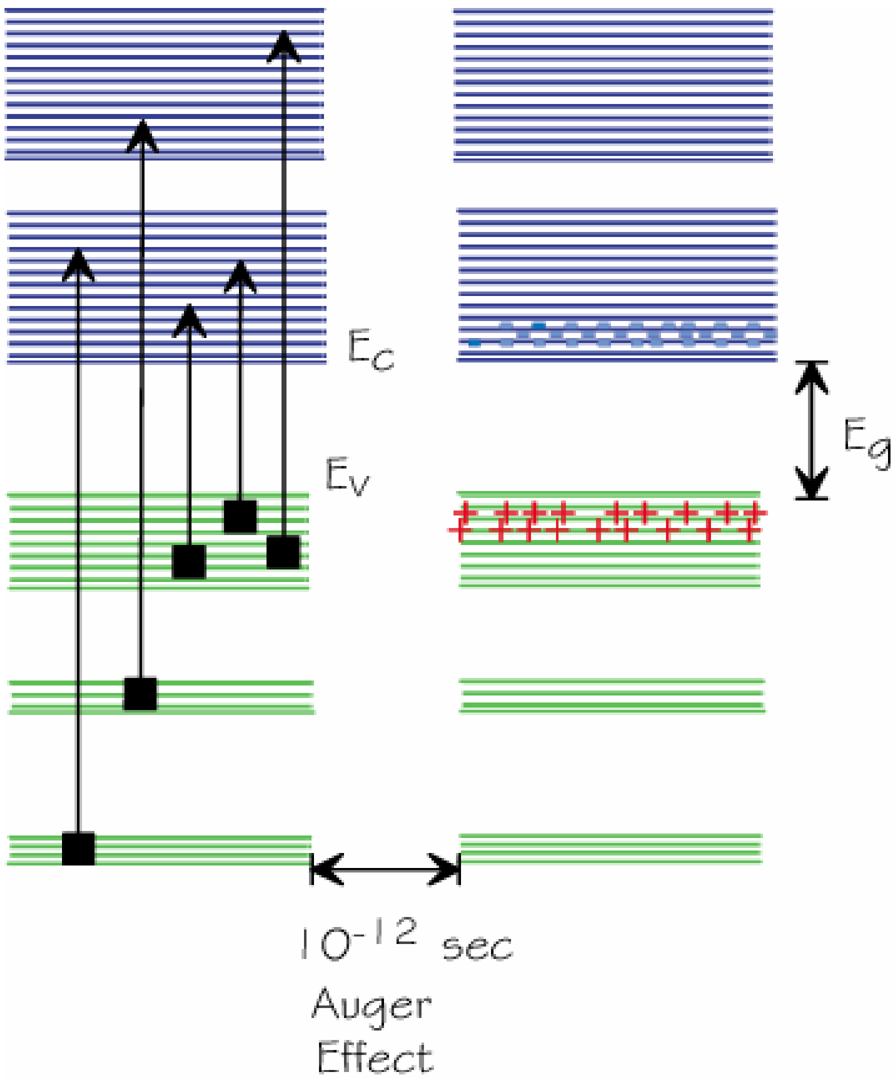
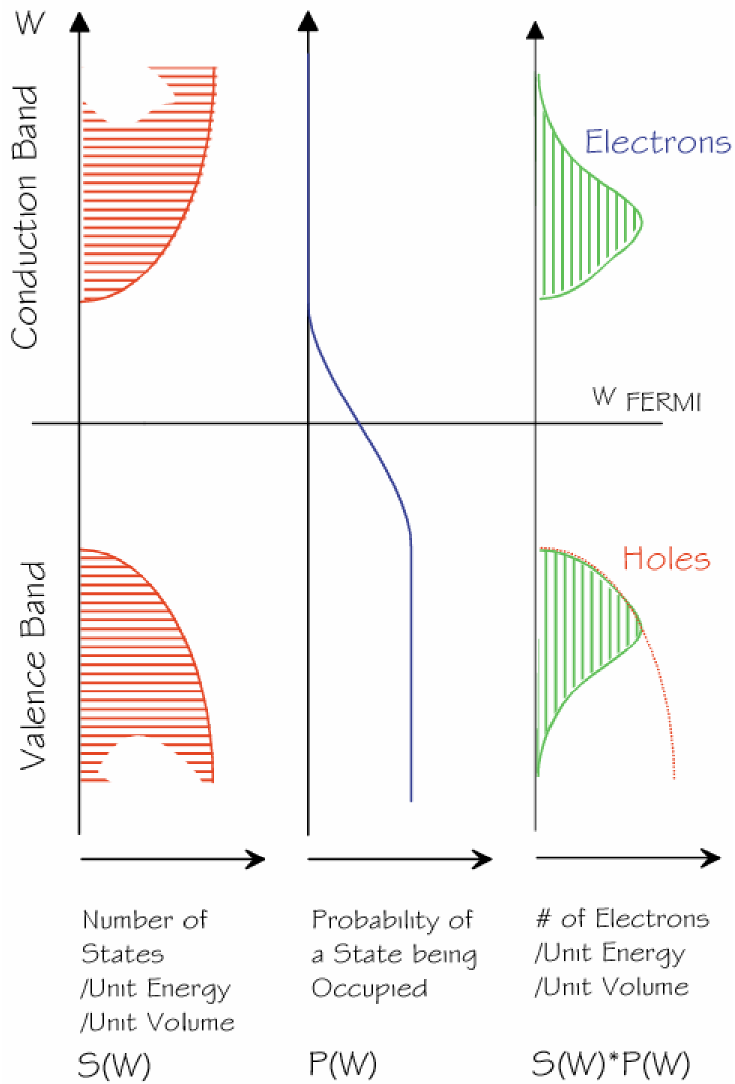
# Excitation of a semi conductor




Auger effect: an electron from a higher shell to a vacant electronic state and ejecting an electron from the same higher shell.

$$S(W) \propto \Delta W^{\frac{1}{2}} \quad P(W) \propto \exp\left[-\frac{W - W_F}{kT}\right]$$

$W_F$ = Fermi Level

= the Energy where $P(W)=1/2$

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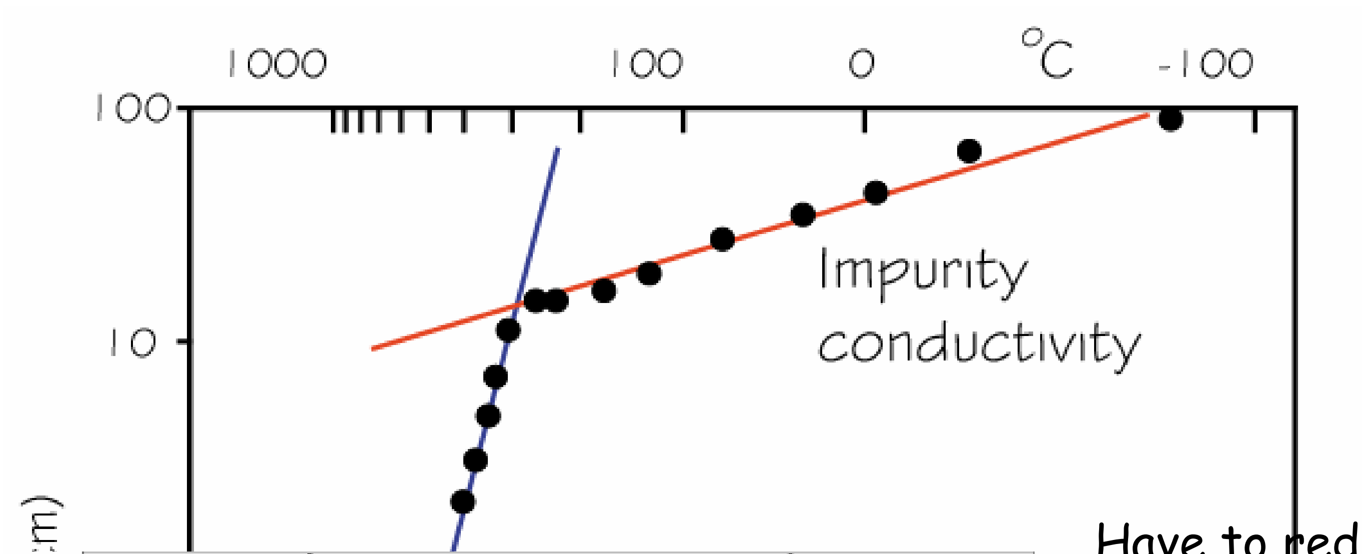
# Try to make a detector

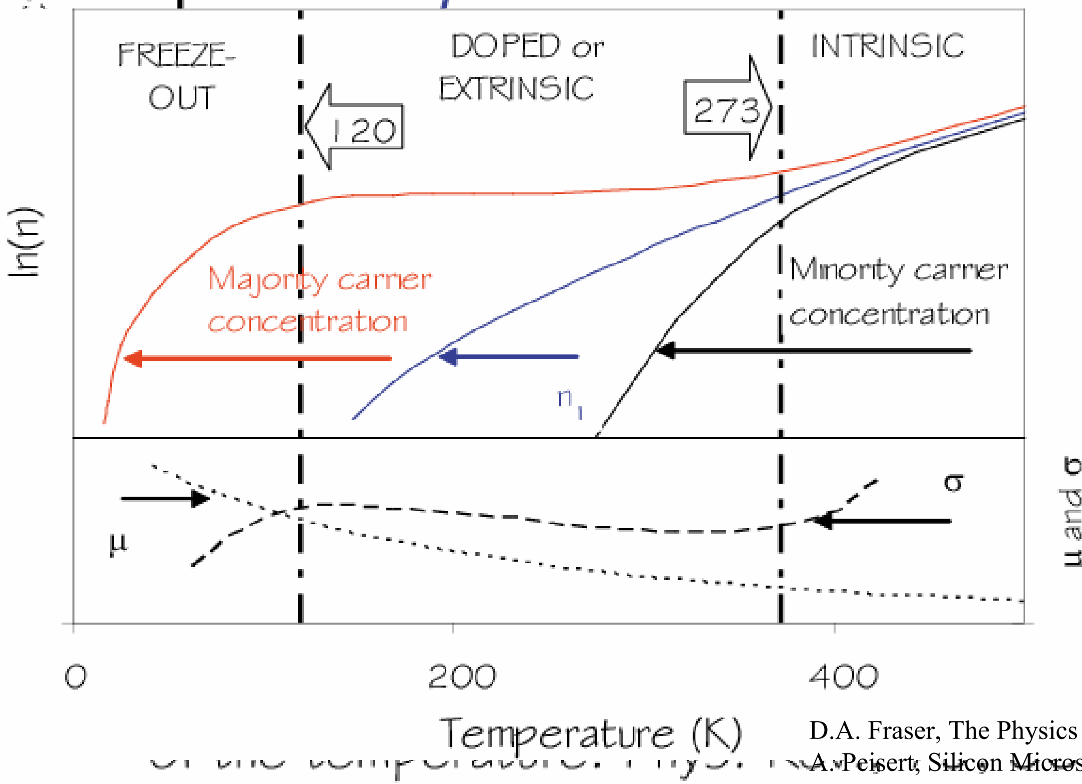



sistivity

m at 300K

m due to impurities

icle would produce




Have to reduce the number of free carriers. Freeze out:

Mobility, μ, conductivity, σ, majority [donors (*e*) acceptors (*holes*)] and minority [donors (*holes*) acceptors (*e*)] carrier concentration as function of temperature.

$n_i$ is the intrinsic carrier density.

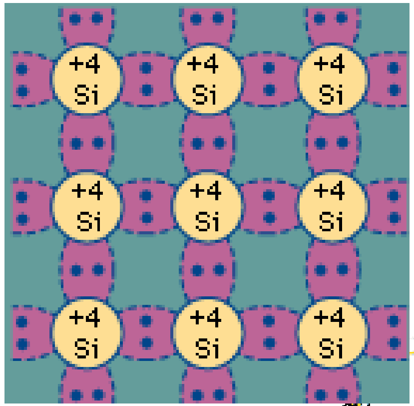
05 0.006

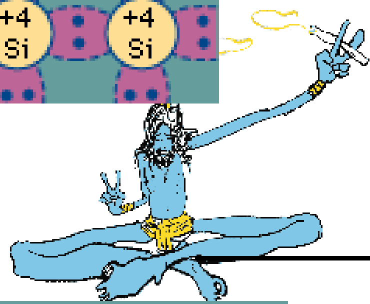
or depletion

ction

D.A. Fraser, The Physics of Semiconductor devices

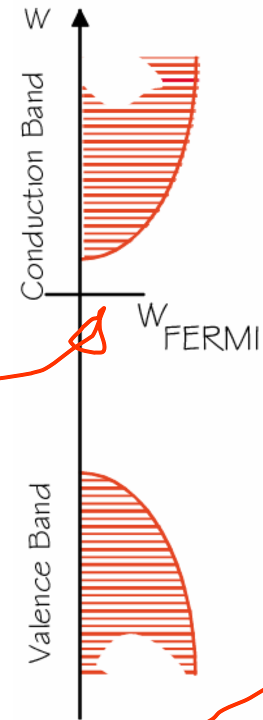
A. Peisert, Silicon Microstrip Detectors, Instrumentation in High Energy Physics



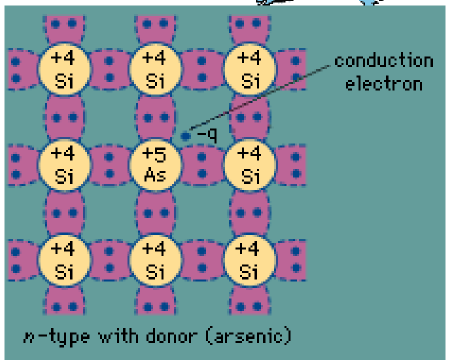



## Electron Configuration for Si:

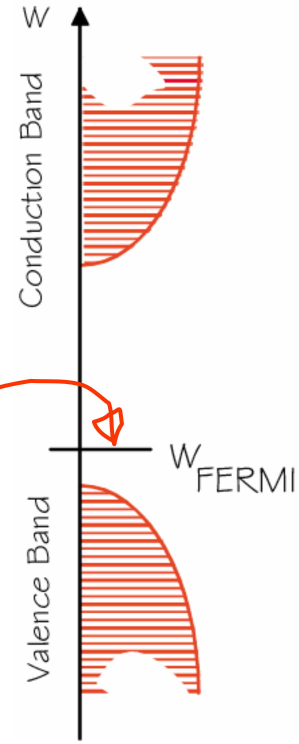
| | |
|---|---|
| K | 2 |
| L | 8 |
| M | 4 + 4 by bonding → 8 group |
| | $E_g \approx 1$ eV |

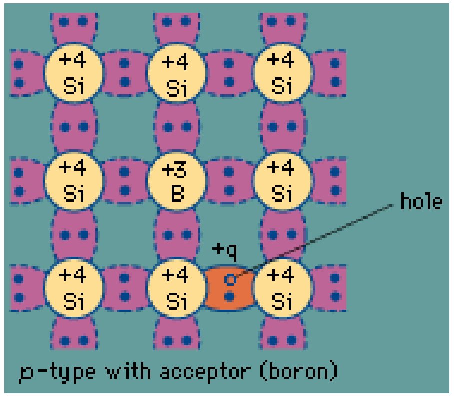



## Doping of semiconductors.




<u>n-Type</u>
P, As, Sb
5 electrons in the M-shell
→1 electron with binding energy 10-50 meV




<u>p-Type</u>
B, Al, Ga
3 electrons in the M-shell
→1 electron missing

http://phys.educ.ksu.edu/ for Visual Quantum Mechanics

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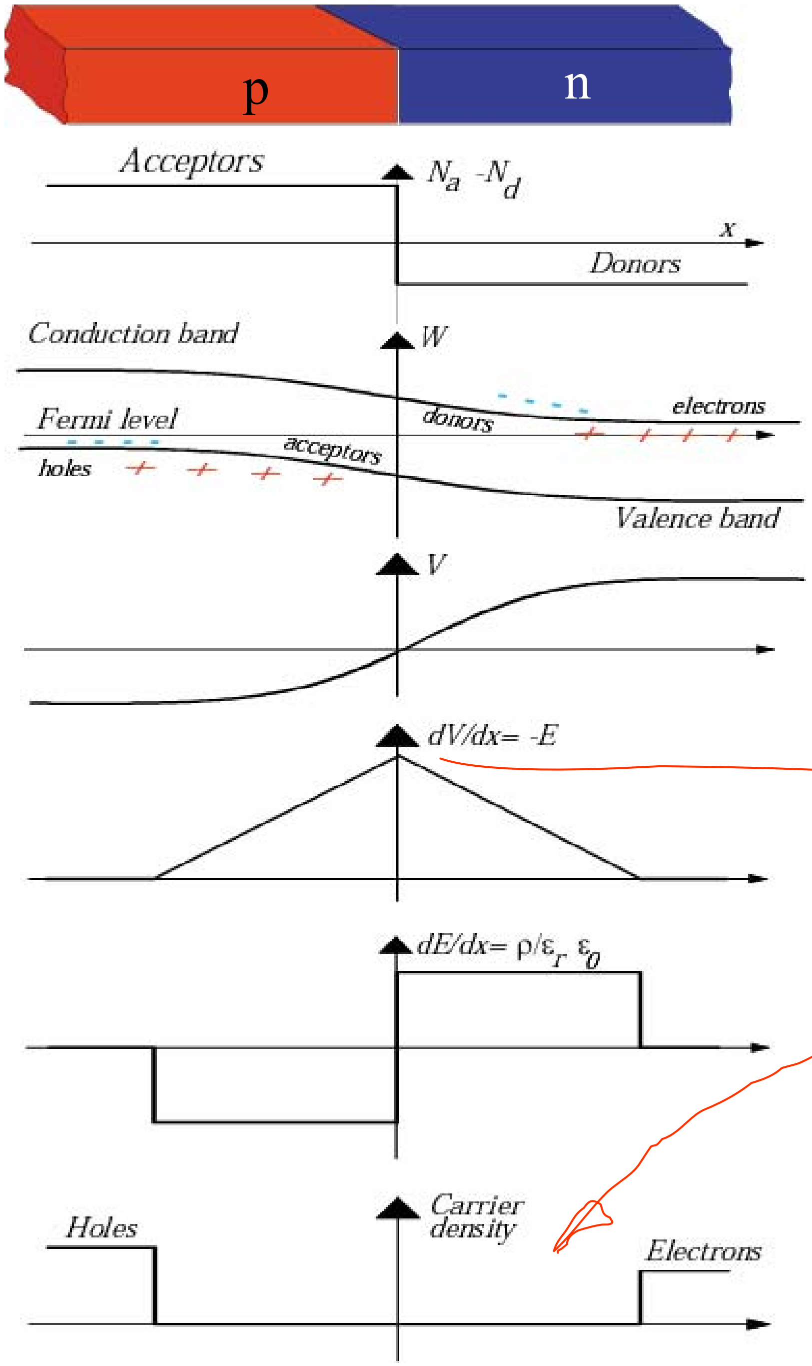
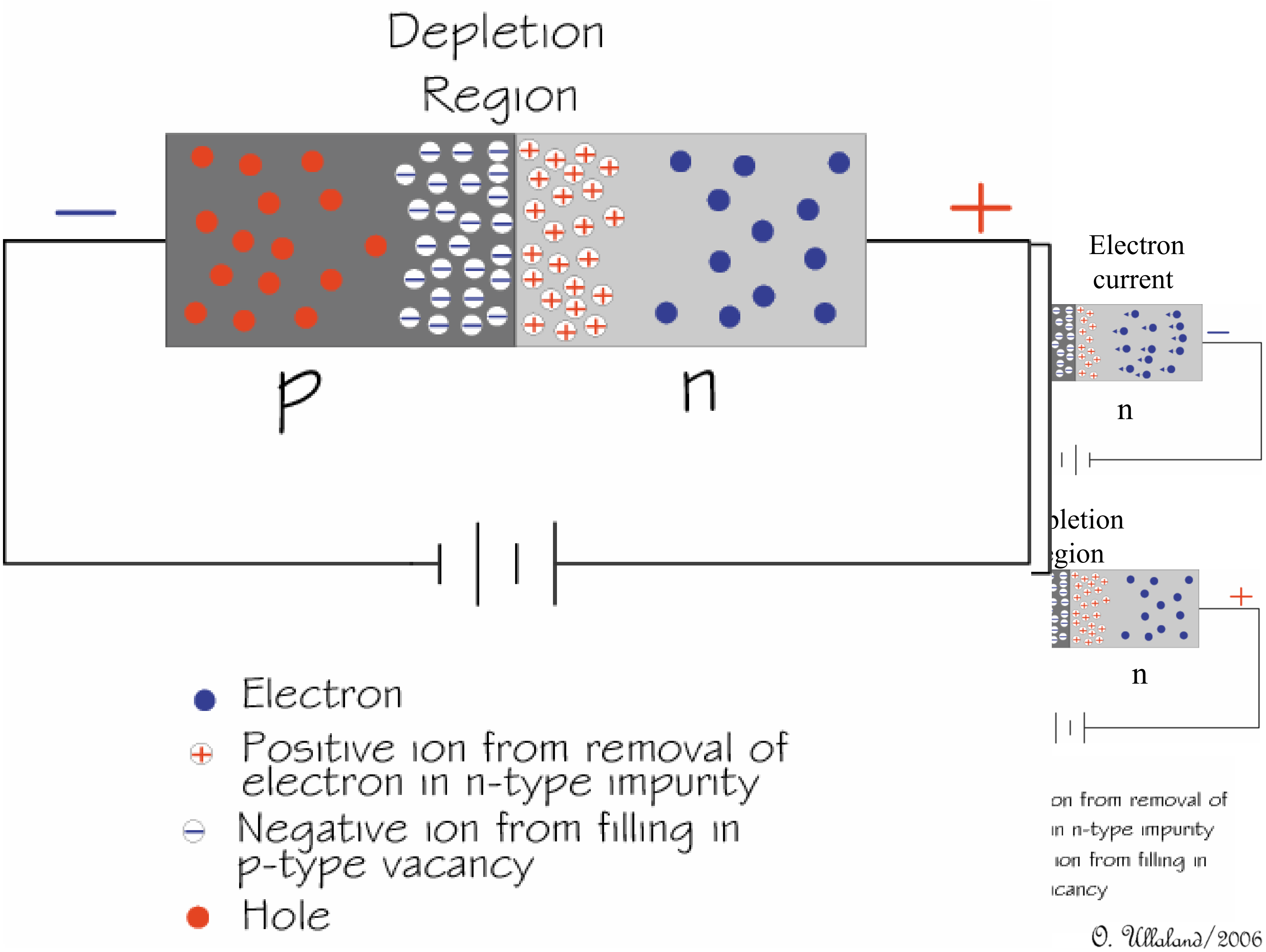



A p-n junction without bias:

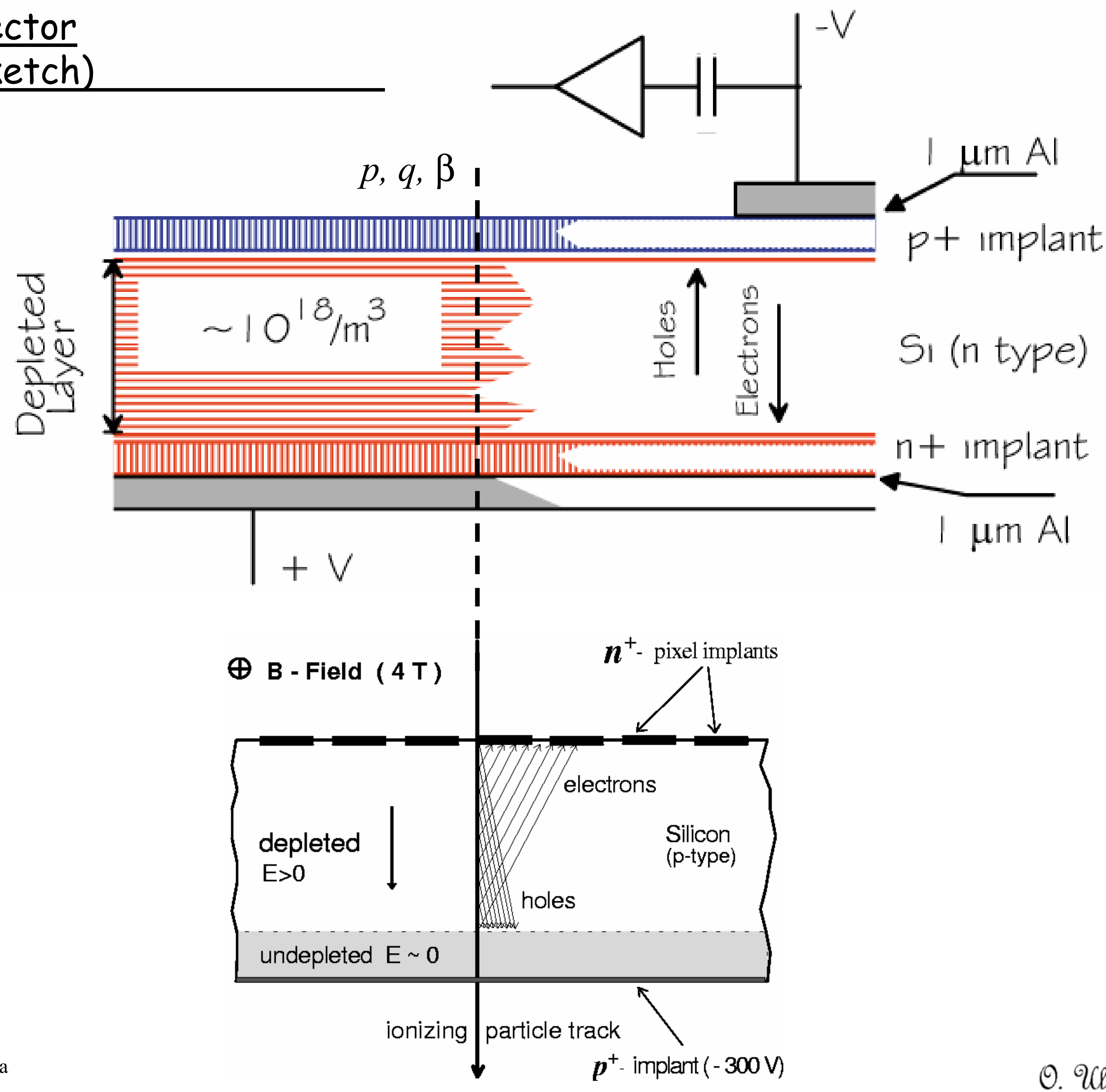
- Peak electric field at the boundary between the p and the n.
- Clear depletion layer.

D. A. Fraser, The physics of semiconductor devices

O. Ullaland/2006


Depletion Region
p
n
Electron current
n
n
Electron
Positive ion from removal of electron in n-type impurity
Negative ion from filling in p-type vacancy
Hole
O. Ullaland/2006

# Silicon Detector (principle sketch)

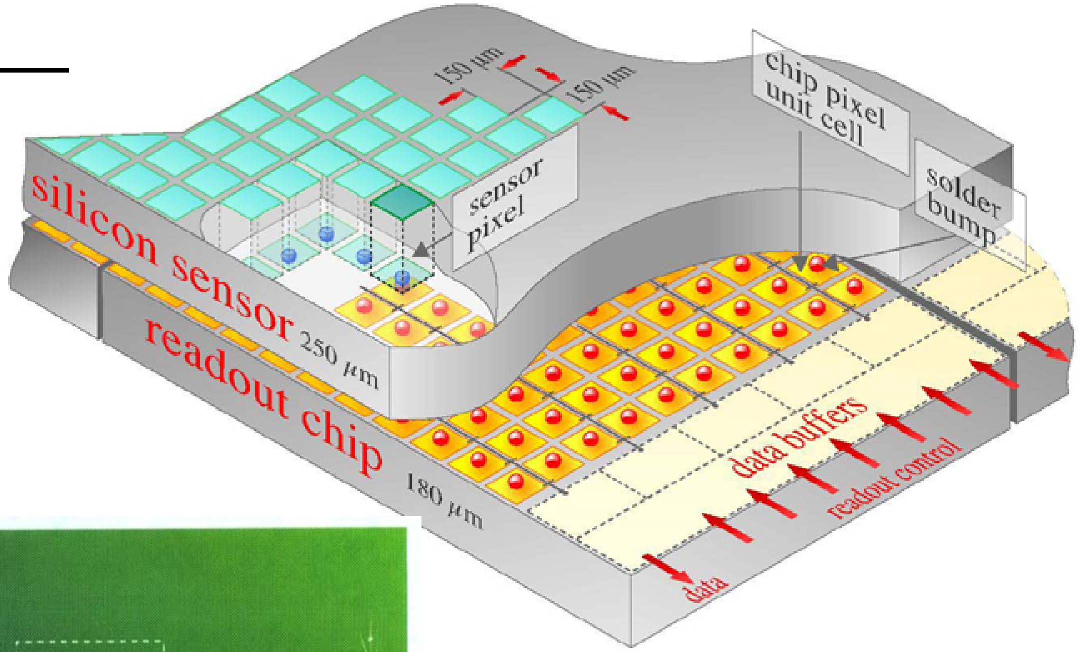


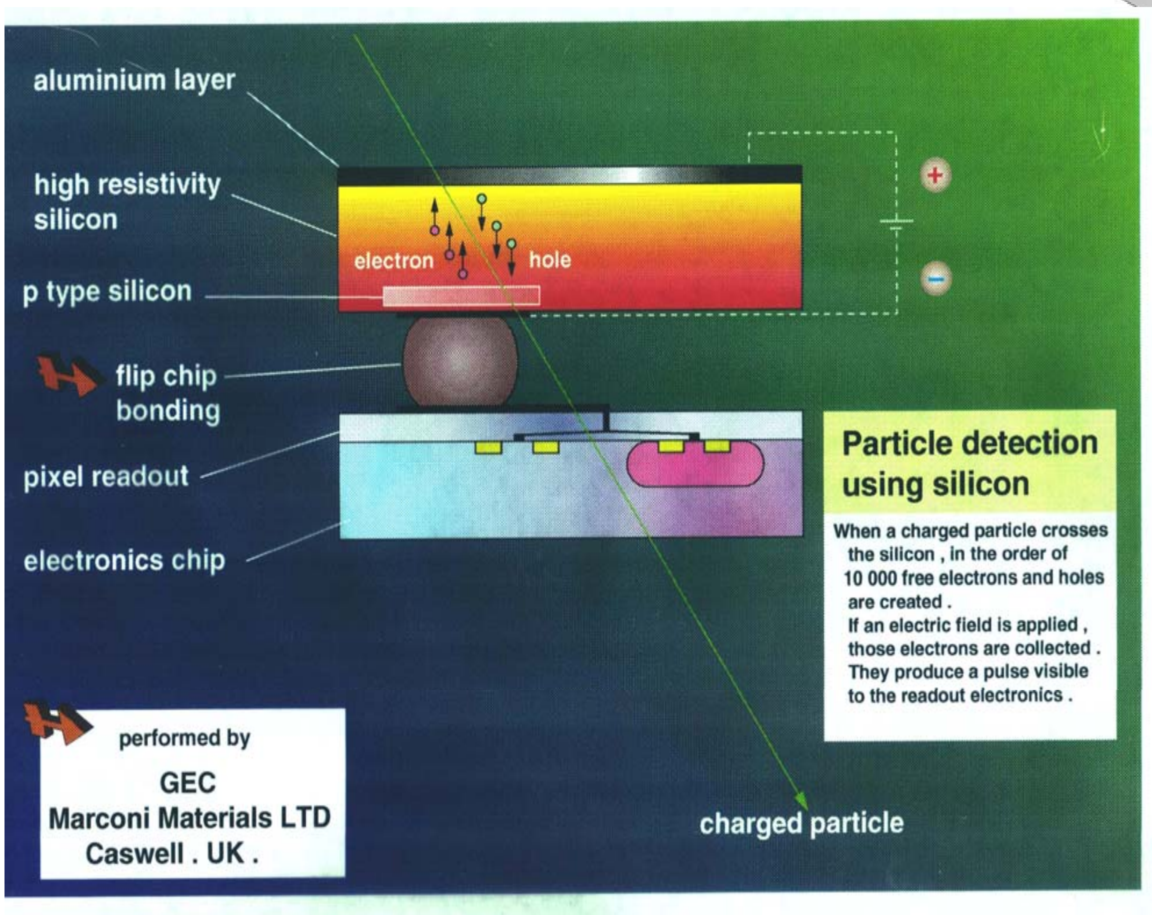

H. Pernegger - CERN
G. Bagliesi - INFN Pisa

O. Ullaland/2006

# Flip-chip assembly

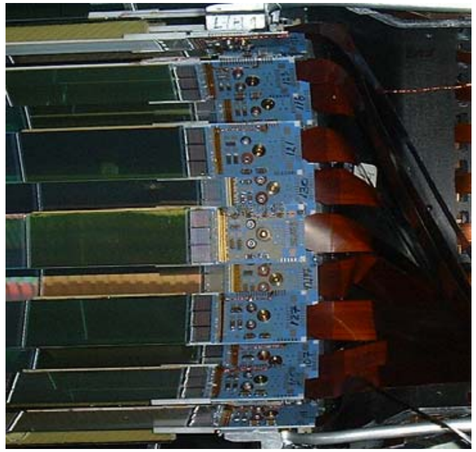
Pixel detector bump bonded to a read-out chip



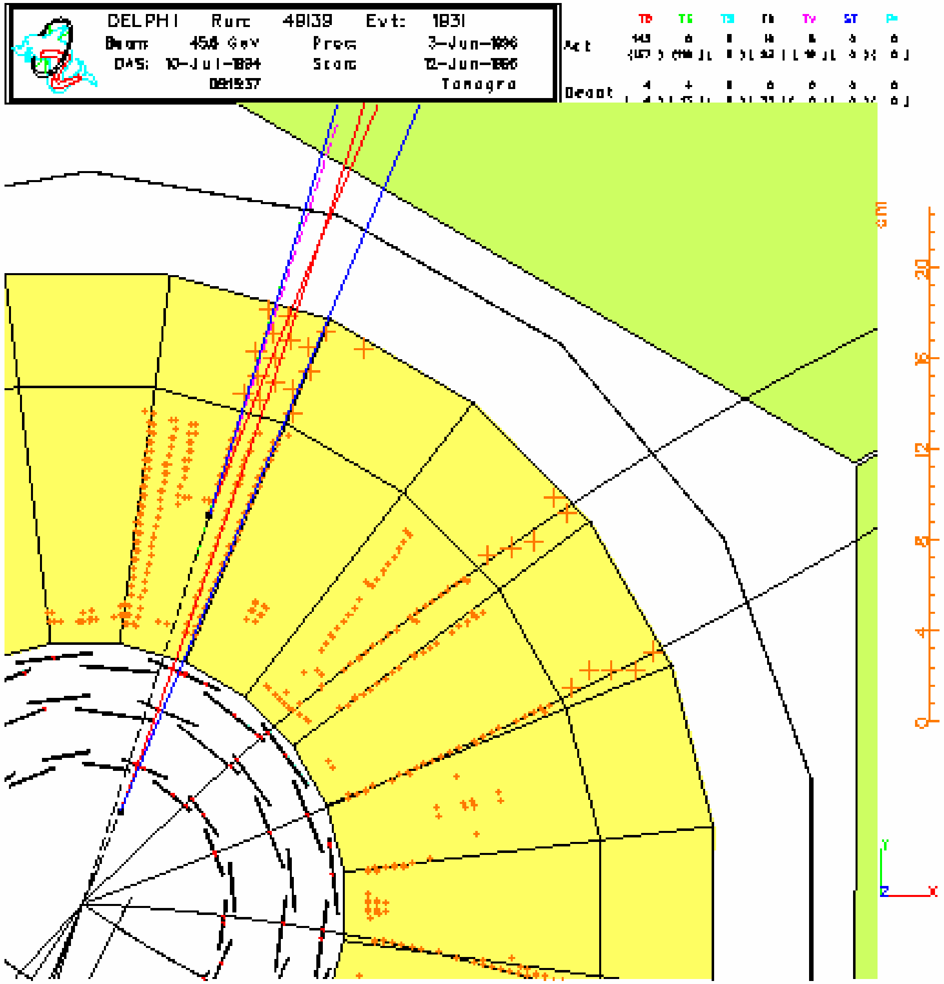



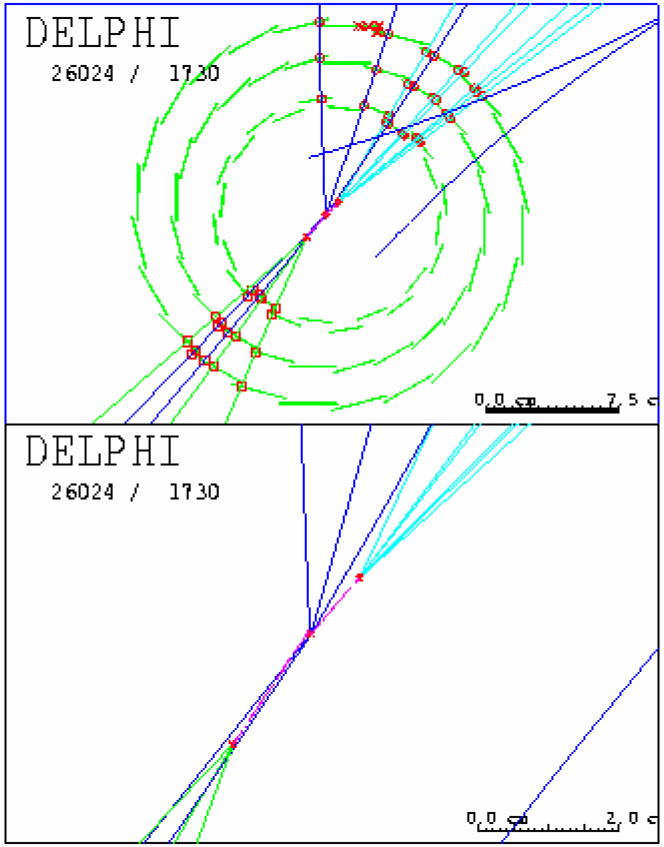

F.Riggi, ST-INFN-CERN Workshop, 23-24 October 2002

# The DELPHI Vertex Detector



$K_0$ and Lambda reconstruction




Reconstructed B decays

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# The beginning was:

EASY NEXT STEP:

SUBDIVIDE ONE ELECTRODE

SMALLER CAPACITY →

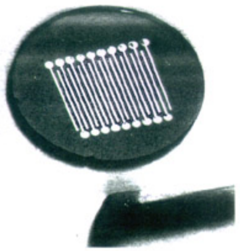


Fig. 2. The MESD after chemical stripping.

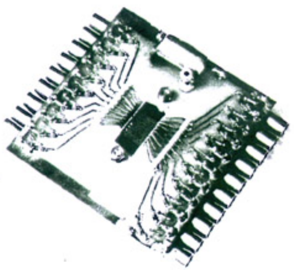
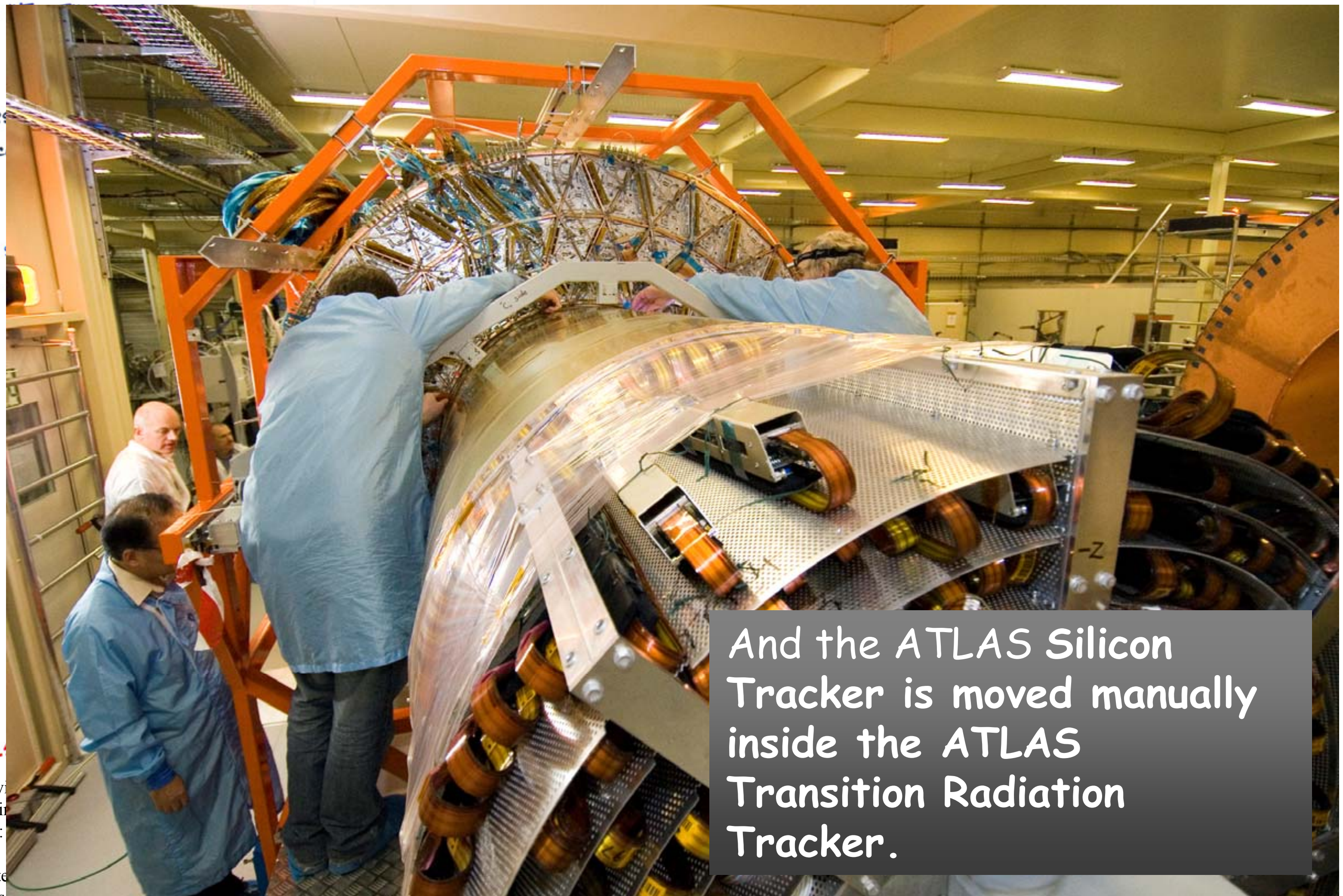


Fig. 3. General assembly of the MESD.




Capacitative charge division read-out w
England, J B A ; Hyams, B D ; Hubbeli
P ; Nucl. Instrum. Methods Phys. Res. :

.A silicon surface barrier microstrip dete
Heijne, E H M ; Hubbeling, L ; Hyams, B D ; Jarron, P ; Lazeyras, P ; Piuz, F ;
Vermeulen, J C ; Wylie, A ; Nucl. Instrum. Methods Phys. Res. : 178 (1980)

A multi electrode silicon detector for high energy physics experiments /
Amendolia, S R ; Batignani, G ; Bedeschi, F ; Bertolucci, E ; Bosisio, L ;
Bradaschia, C ; Budinich, M ; Fidecaro, F ; Foà, L ; Focardi, E ; Giazotto, A ;
Giorgi, M A ;Givoletti, M ; Marrocchesi, P S ; Menzione, A ; Passuello, D ;
Quaglia, M ; Ristori, L ; Rolandi, L ; Salvadori, P ; Scribano, A ; Stanga, R M ;
Stefanini, A ; Vincelli, M L ; IFUP-TH-80-2.

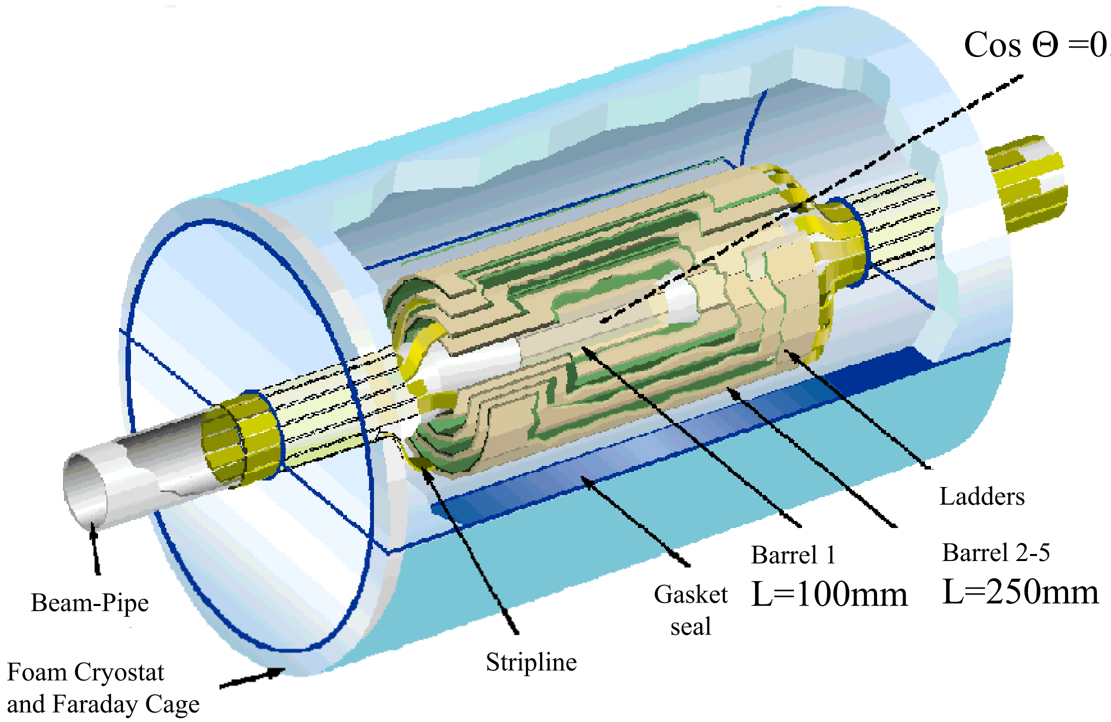
O. Ullaland/2006

## and the prophesy of what will come (and hit you): TESLA

**DEPFET features**

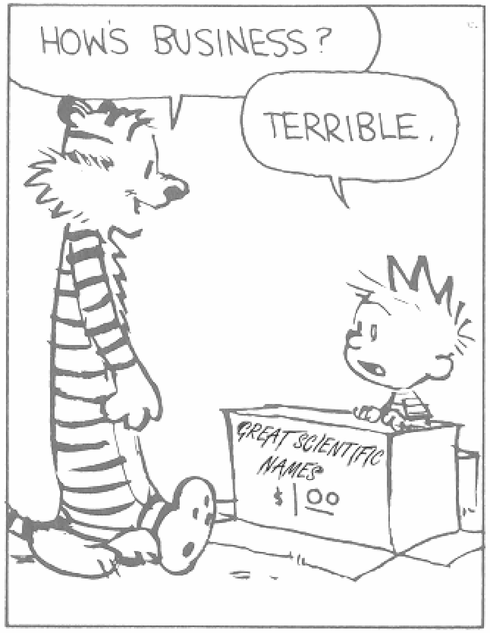
Thin (< 50 μm, 0.11% $X_0$)
Small cells (25 μm x 25 μm)
Fast (50 MHz/line, 25 kHz/frame ≈2 Mpix/module)
Low power (< 5W/full detector)

**Options**
CCD
MAPS
HAPS
DEPFET

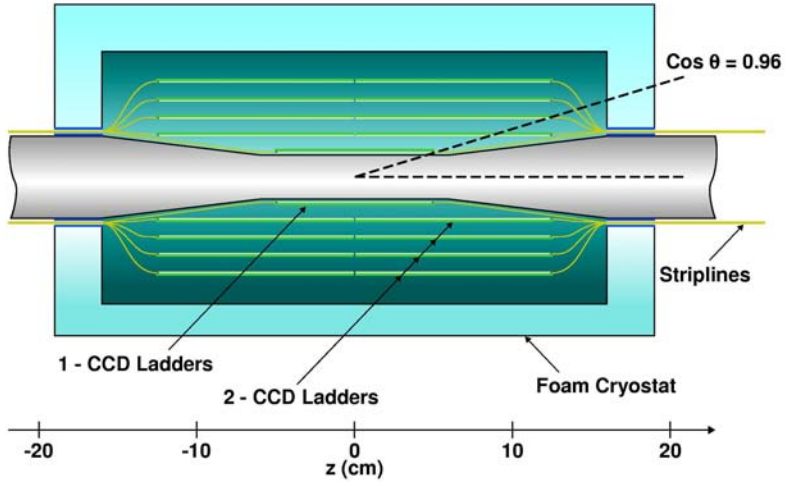



*translation of the three or four letter words:*

**CMOS** (Complementary Metal-Oxide Semiconductor)
**CCD** (Charge-Coupled Device)
**MAPS** (Monolithic Active Pixel Sensors)
**HAPS** (Hybrid Active Pixel Sensors)
**DEPFET** (DEPleted Field Effect Transistor)




Total > 500 MPixel (w. 25x25 μm cells)
tremendous hit rate (80 hits / mm² / bunch train)

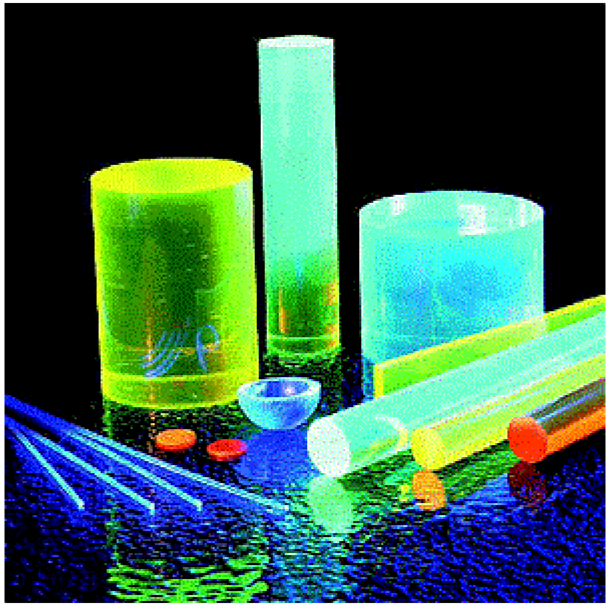



Some places to look
for additional information:

| | |
|---|---|
| HAPS | http://home.cern.ch/~caccia |
| MAPS | http://ireswww.in2p3.fr/ires/recherche/capteurs/index.html |
| | http://www.te.rl.ac.uk/med |
| CCD | http://hep.ph.liv.ac.uk/~green/lcfi/home.html |
| DEPFET | http://atlas.physik.uni-bonn.de/ |

**Vertex detectors web page**
**for the Linear Electron-Positron Collider project**
http://sbgat252.in2p3.fr/ires/recherche/capteurs/ECFA_vertex/

P. Jarron, Microelectronics and Nanoelectronics:
Trends and Applications to HEP Instrumentation
http://agenda.cern.ch/fullAgenda.php?ida=a036647



http://www.bicron.com.

# Scintillation

# Light Collection

# and

# Photon Detection

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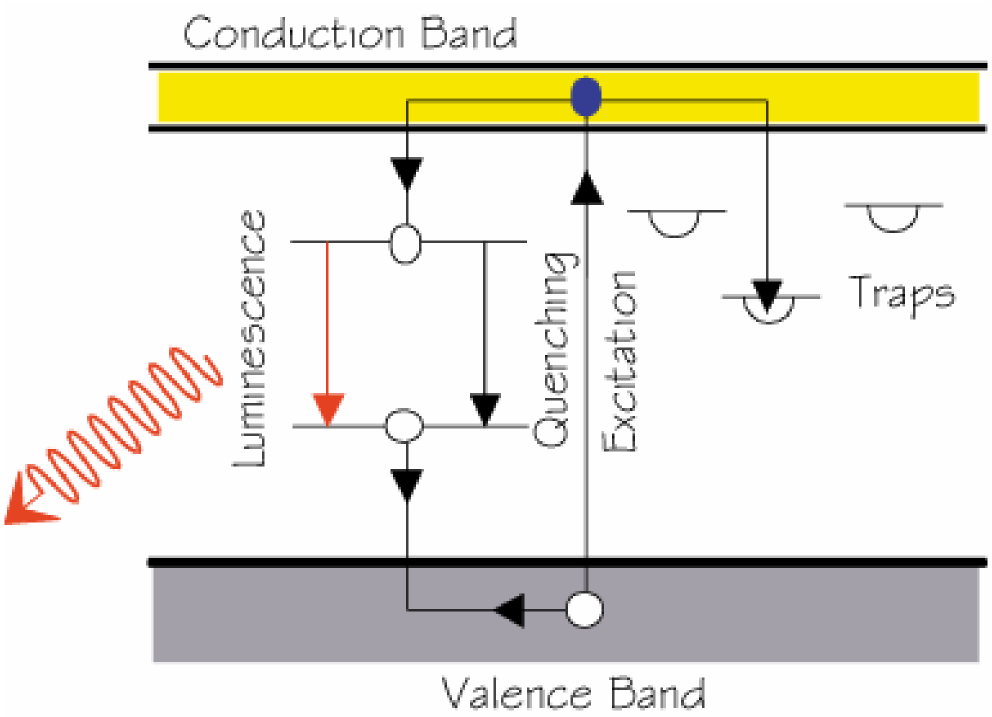
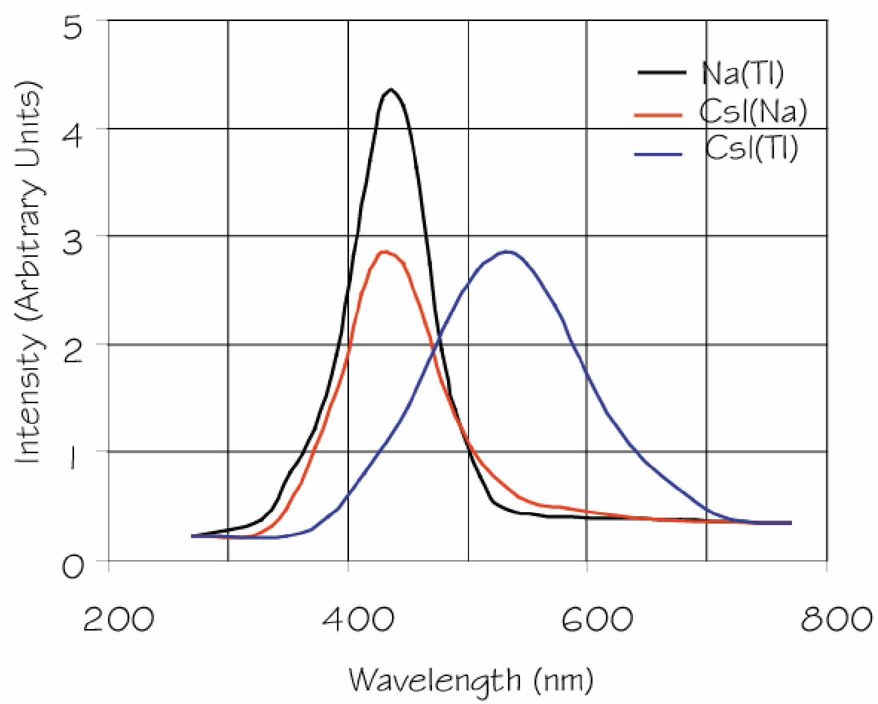
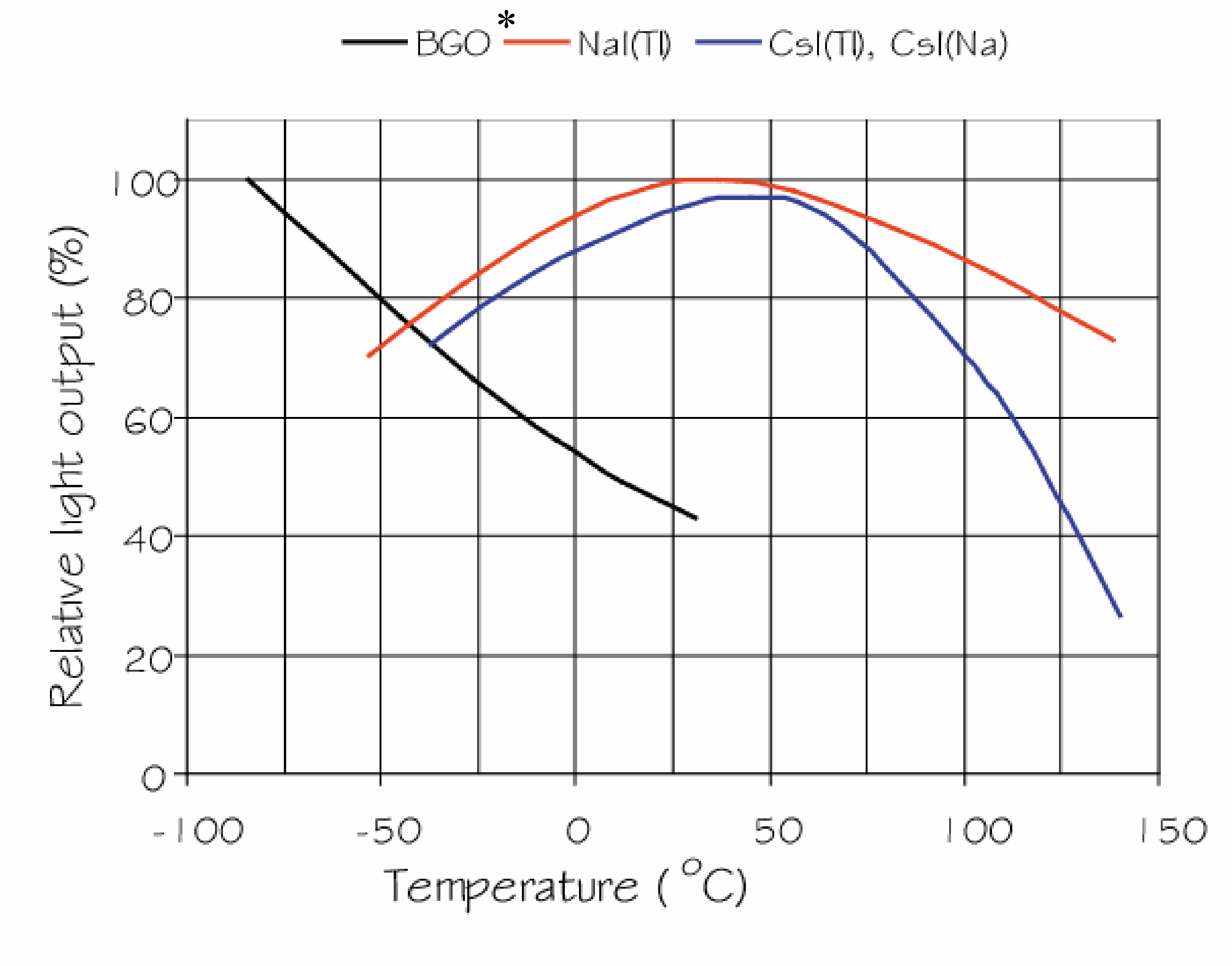
The most common inorganic scintillator is sodium iodide activated with a trace amount of thallium [NaI(Tl)].

Energy bands in impurity activated crystal



Strong dependence of the light output and the decay time with temperature.




* Bismuth germinate $Bi_4Ge_3O_{12}$ is the crystalline form of an inorganic oxide with cubic eulytine** structure, colourless, transparent, and insoluble in water.

** From the Greek eulitos = "easily liquefiable", in allusion to its low melting point.

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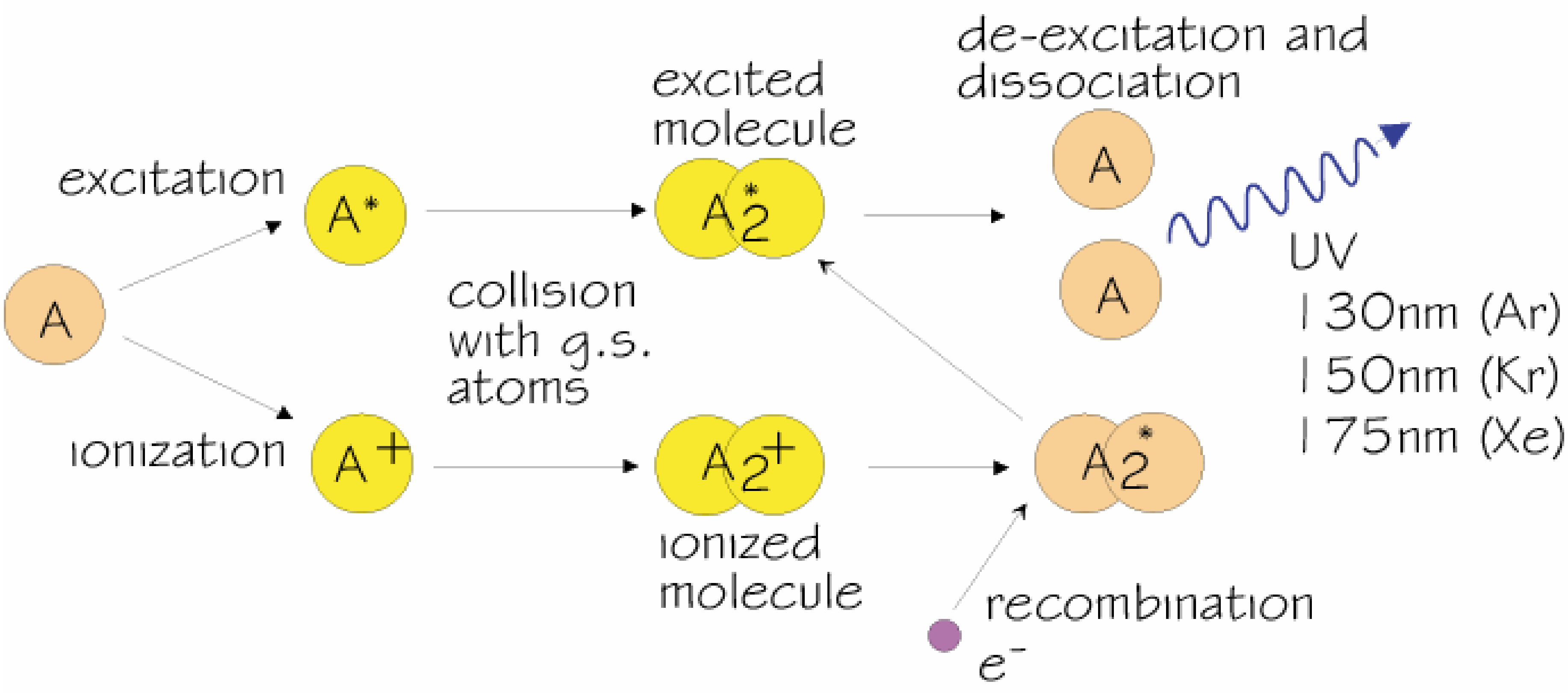
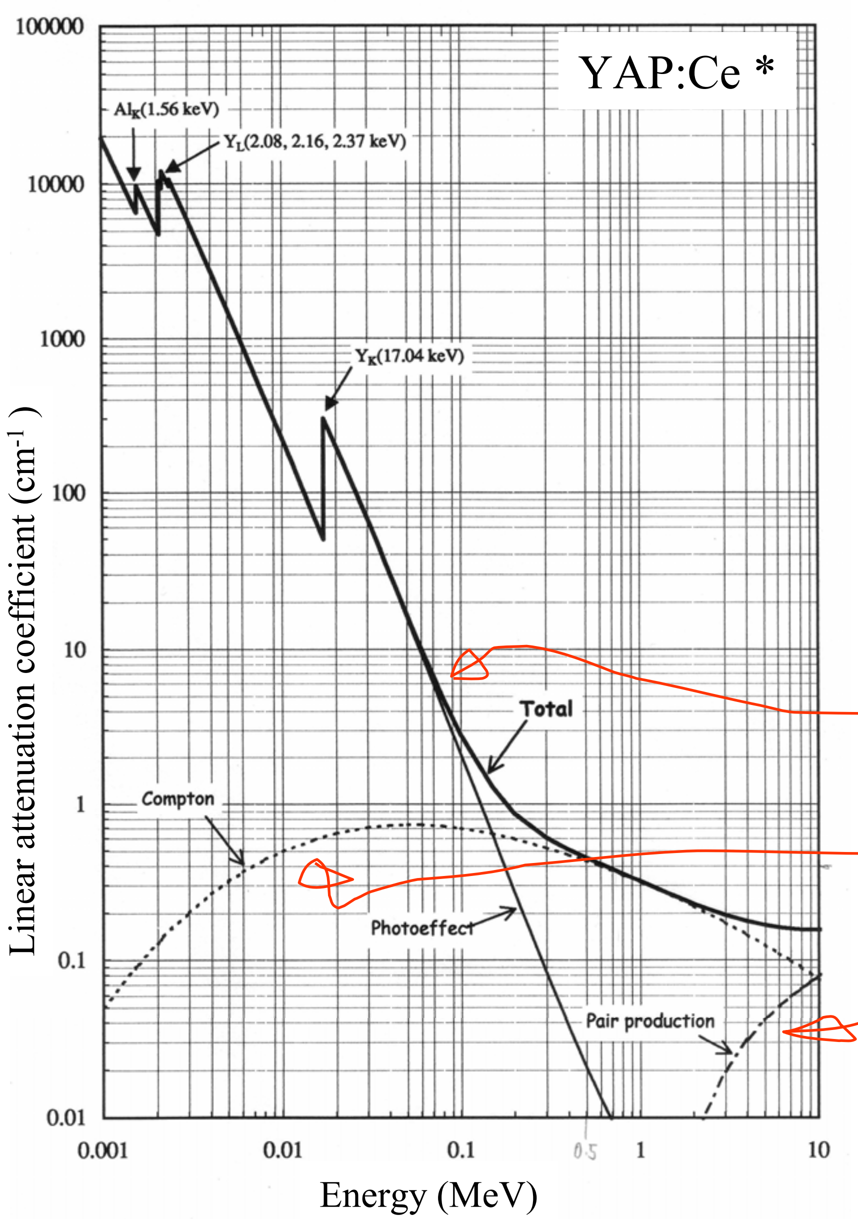
# Liquefied noble gases: LAr, LXe, LKr




Also here one finds 2 time constants: from a few ns to 1 μs.

from C. D'Ambrosio, Academic Training, 2005

## Photon Absorption




* YAP (Yttrium Aluminium Provskite $YAlO_3$ ) crystals

from C. D'Ambrosio, Academic Training, 2005

The intensity $I$ of a gamma beam traversing a target of thickness $d$ is

$$I = I_0 e^{-\mu d}$$

Where $\mu$ is the sum of three processes taking place in the material:

Photoel. Abs. $\rightarrow Z^4$ to $Z^5$

Compton scatt. $\rightarrow Z$

Pair production $\rightarrow Z^2$

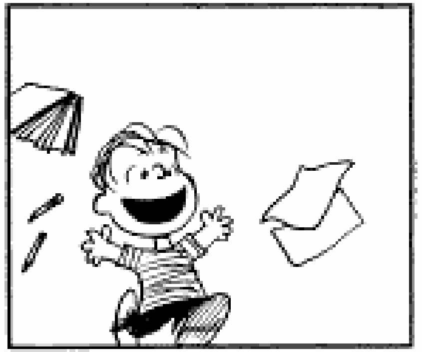
O. Ullaland/2006

| Scintillator composition | Density (g/cm³) | Index of refraction | Wavelength of max.Em. (nm) | Decay time Constant (µs) | Scinti Pulse height[1)] | Notes |
|---|---|---|---|---|---|---|
| NaI(Tl) | 3.67 | 1.9 | 410 | 0.25 | 100 | 2) |
| CsI | 4.51 | 1.8 | 310 | 0.01 | 6 | 3) |
| CsI(Tl) | 4.51 | 1.8 | 565 | 1.0 | 45 | 3) |
| $CaF_2$(Eu) | 3.19 | 1.4 | 435 | 0.9 | 50 | |
| $BaF_2$ | 4.88 | 1.5 | 190/220<br>310 | 0,0006<br>0.63 | 5<br>15 | |
| BGO | 7.13 | 2.2 | 480 | 0.30 | 10 | |
| $CdW0_4$ | 7.90 | 2.3 | 540 | 5.0 | 40 | |
| $PbWO_4$ | 8.28 | 2.1 | 440 | 0.020 | 0.1 | |
| $CeF_3$ | 6.16 | 1.7 | 300<br>340 | 0.005<br>0.020 | 5 | |
| GSO | 6.71 | 1.9 | 430 | 0.060 | 40 | |
| LSO | 7 | 1.8 | 420 | 0.040 | 75 | |
| YAP | 5.50 | 1.9 | 370 | 0.030 | 70 | |

1) Relative to NaI(Tl) in %; 2) Hygroscopic; 3) Water soluble

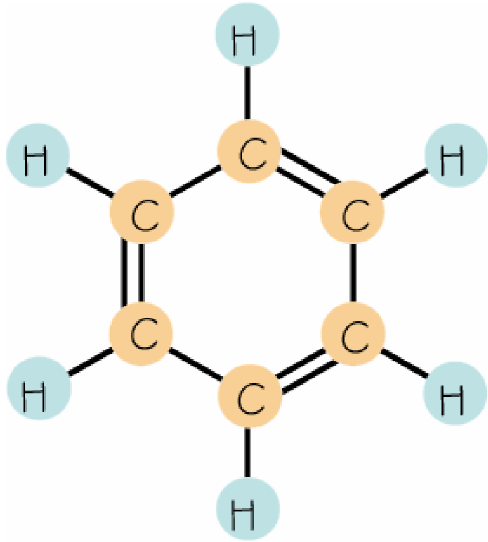
from C. D'Ambrosio, Academic Training, 2005

That was all planned for this lecture

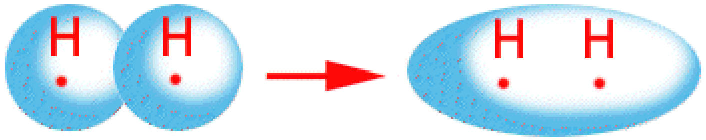


## Organic Scintillators

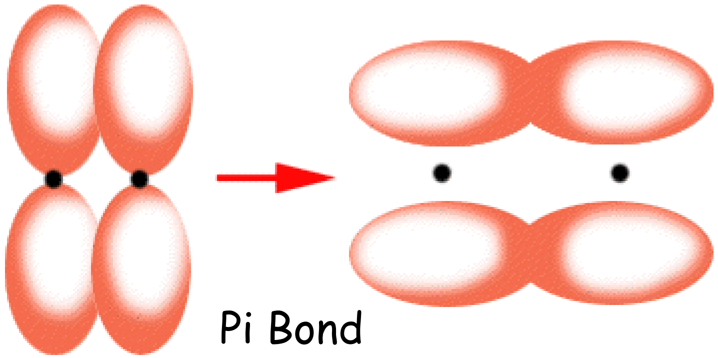
Benzene $C_6H_6$




a little bit of chemistry:




Single Bond = sigma Bond



Pi Bond

Double Bond = one sigma + one pi Bond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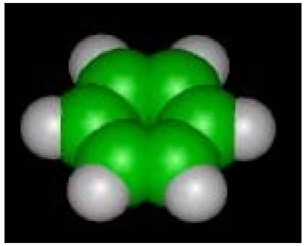
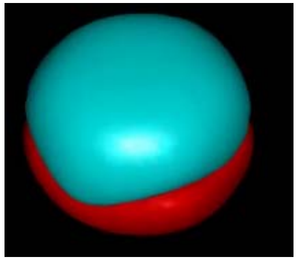
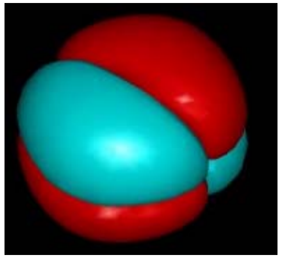
Many of the properties of organic molecules such as benzene can be attributed to molecular orbitals which are delocalized over the entire molecule and lead to increased stability of the molecule.

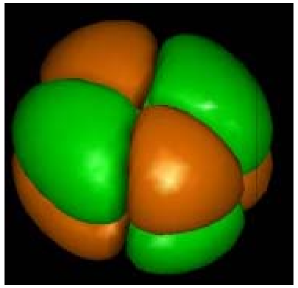


If we have atoms with parallel p atomic orbitals, we get more kinds of pi modes by adding and subtracting them.

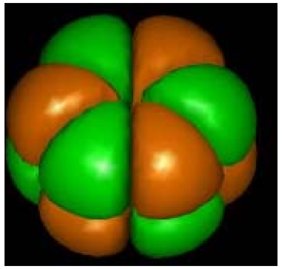


There are 6 pi electrons in benzene. These electrons fill 3 bonding pi molecular orbitals





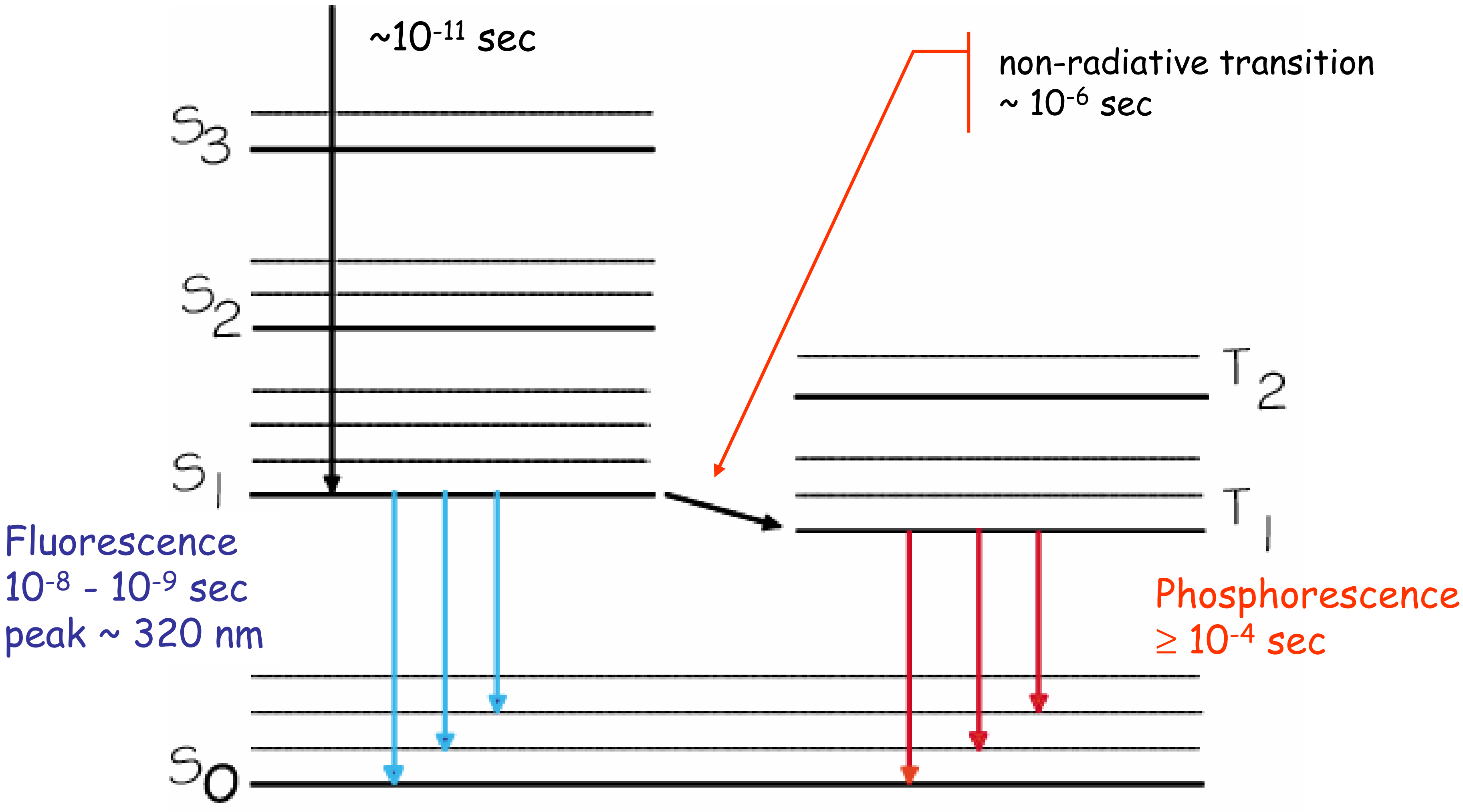
In addition, combining the carbon p orbitals, gives 3 antibonding molecular orbitals.



The pi electrons form the basis for the scintillation mechanism. They are quantized in a series of singlets $S_{ij}$ and triplets $T_{ij}$

http://bouman.chem.georgetown.edu/genchem.html
http://library.thinkquest.org/10429/low/geometry/geobody.htm

## Pi electron energy levels

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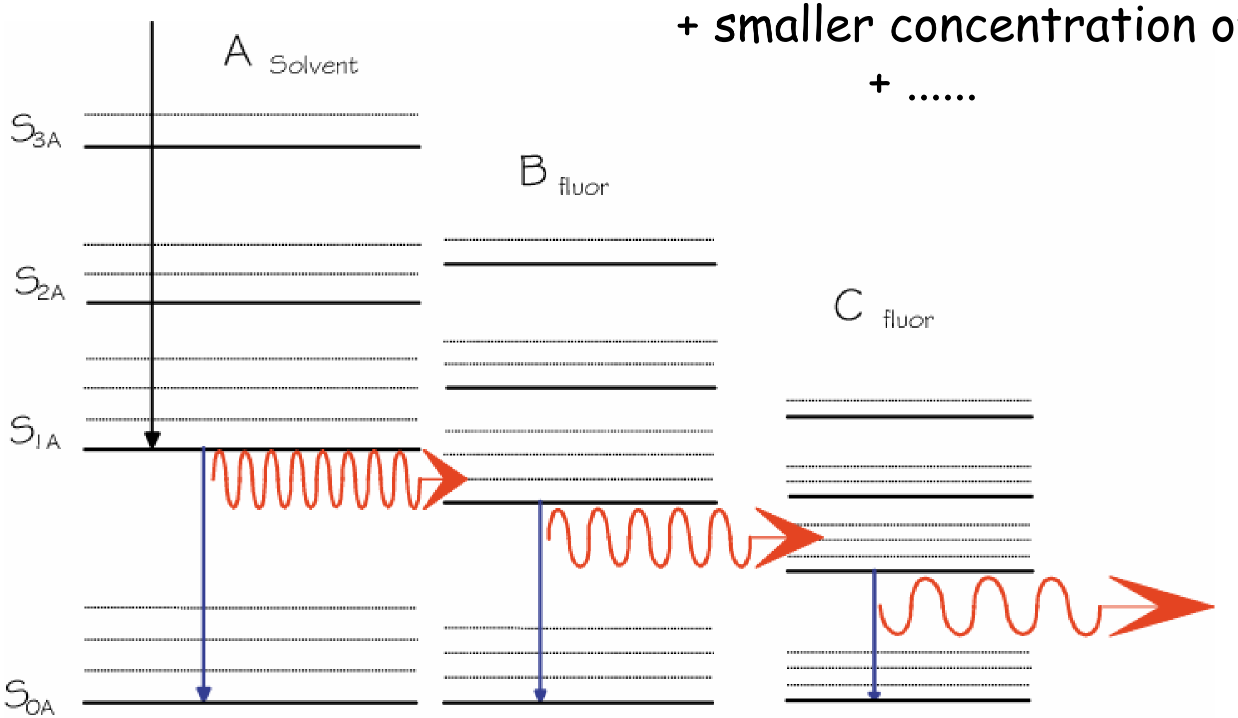
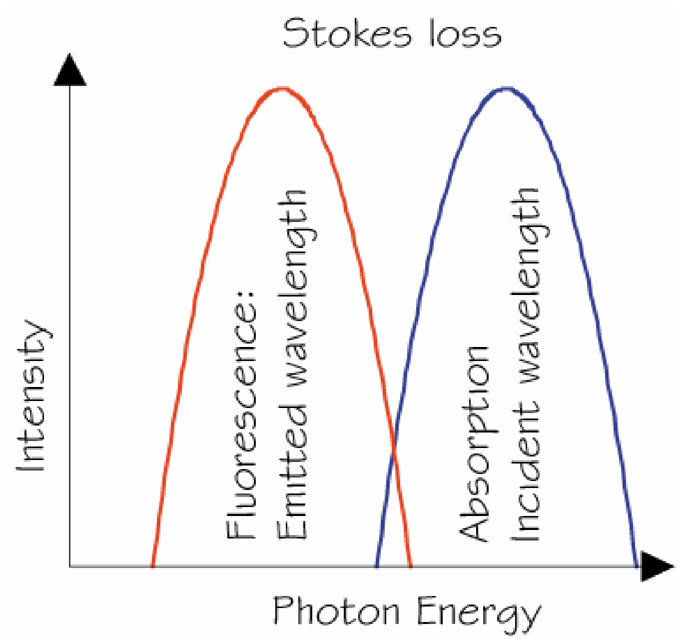
Practical organic scintillators uses
a solvent
+ large concentration of primary fluor
+ smaller concentration of secondary fluor
+ ......




The emitted wavelength is always longer or equal to the incident wavelength. The difference is absorbed as heat in the atomic lattice of the material.

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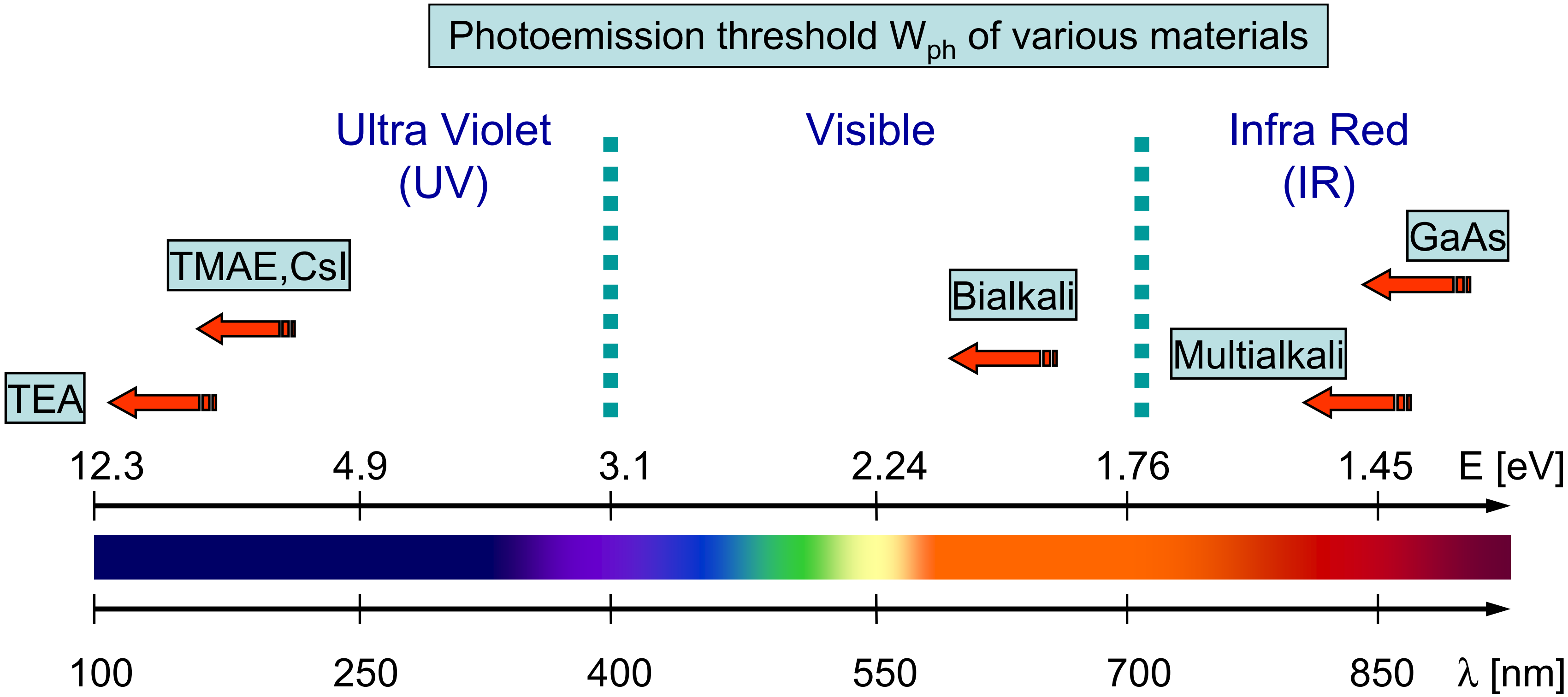
# Photon detectors

Main types of photon detectors:

- gas-based
- vacuum-based
- solid-state
- hybrid



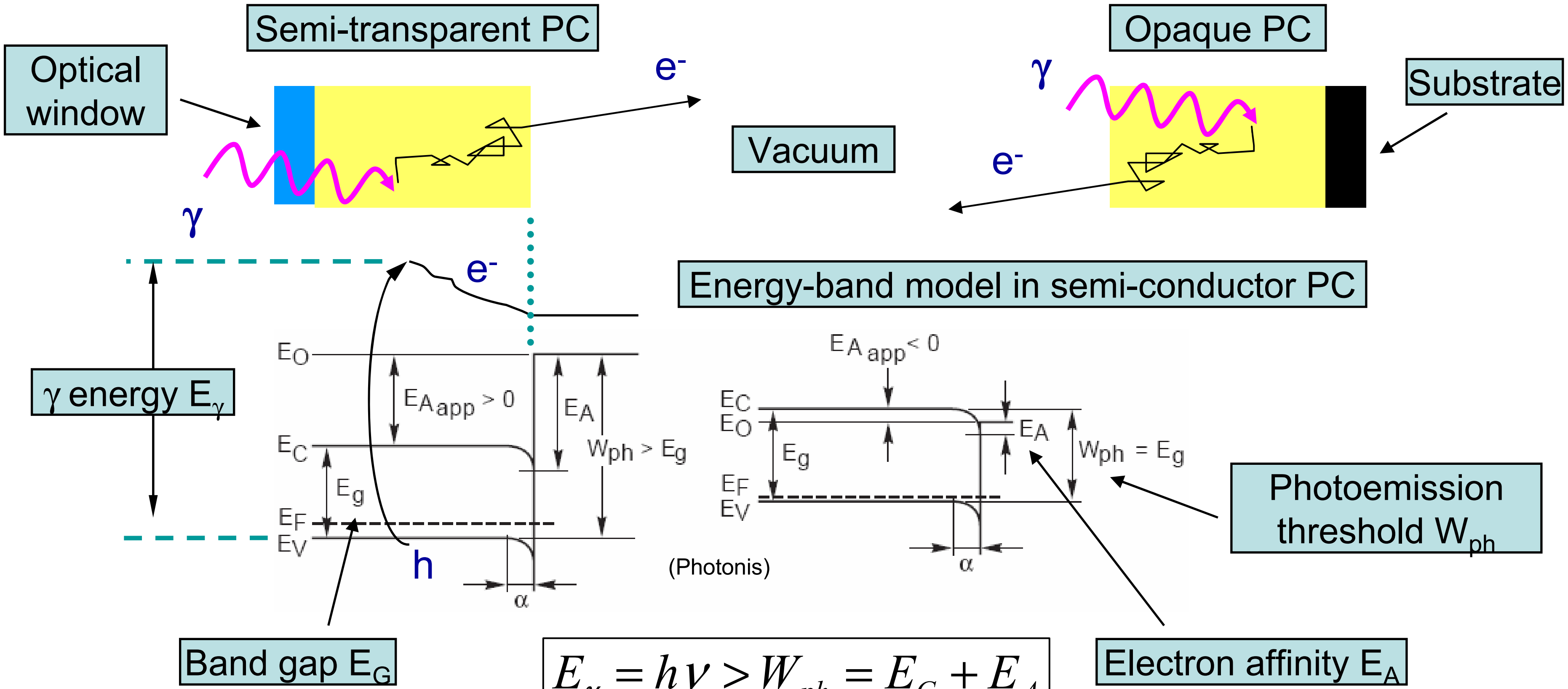

from T. Gys, Academic Training, 2005

# The photoelectric effect

3-step process:

- absorbed $\gamma$'s impart energy to electrons (e) in the material;
- energized e's diffuse through the material, losing part of their energy;
- e's reaching the surface with sufficient excess energy escape from it;

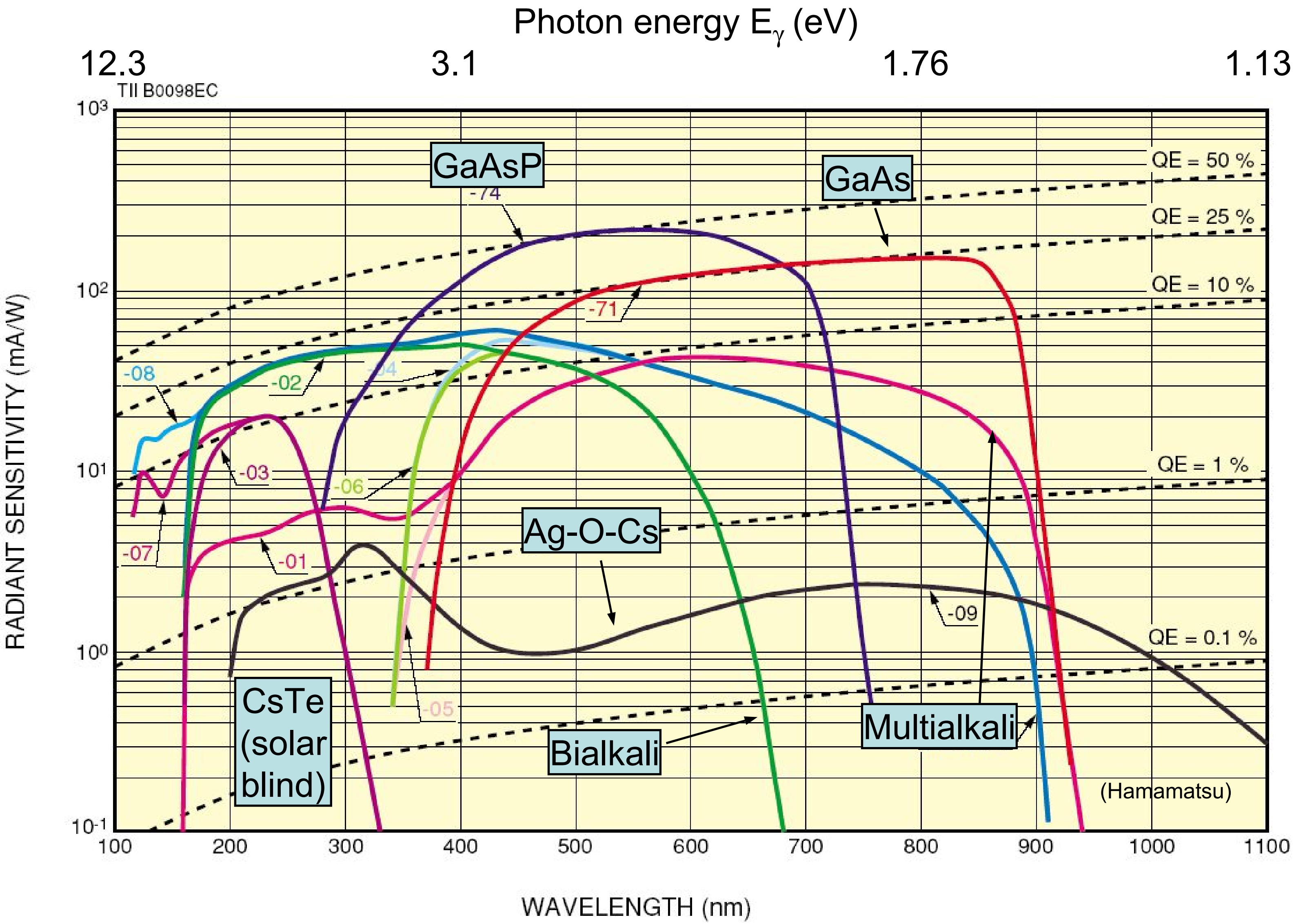
$\Rightarrow$ ideal photo-cathode (PC) must absorb all $\gamma$'s and emit all created e's




$$E_\gamma = h\nu > W_{ph} = E_G + E_A$$

from T. Gys, Academic Training, 2005

# QE's of typical photo-cathodes




Bialkali: SbKCs, SbRbCs  Multialkali: $SbNa_2KCs$ (alkali metals have low work function)

from T. Gys, Academic Training, 2005

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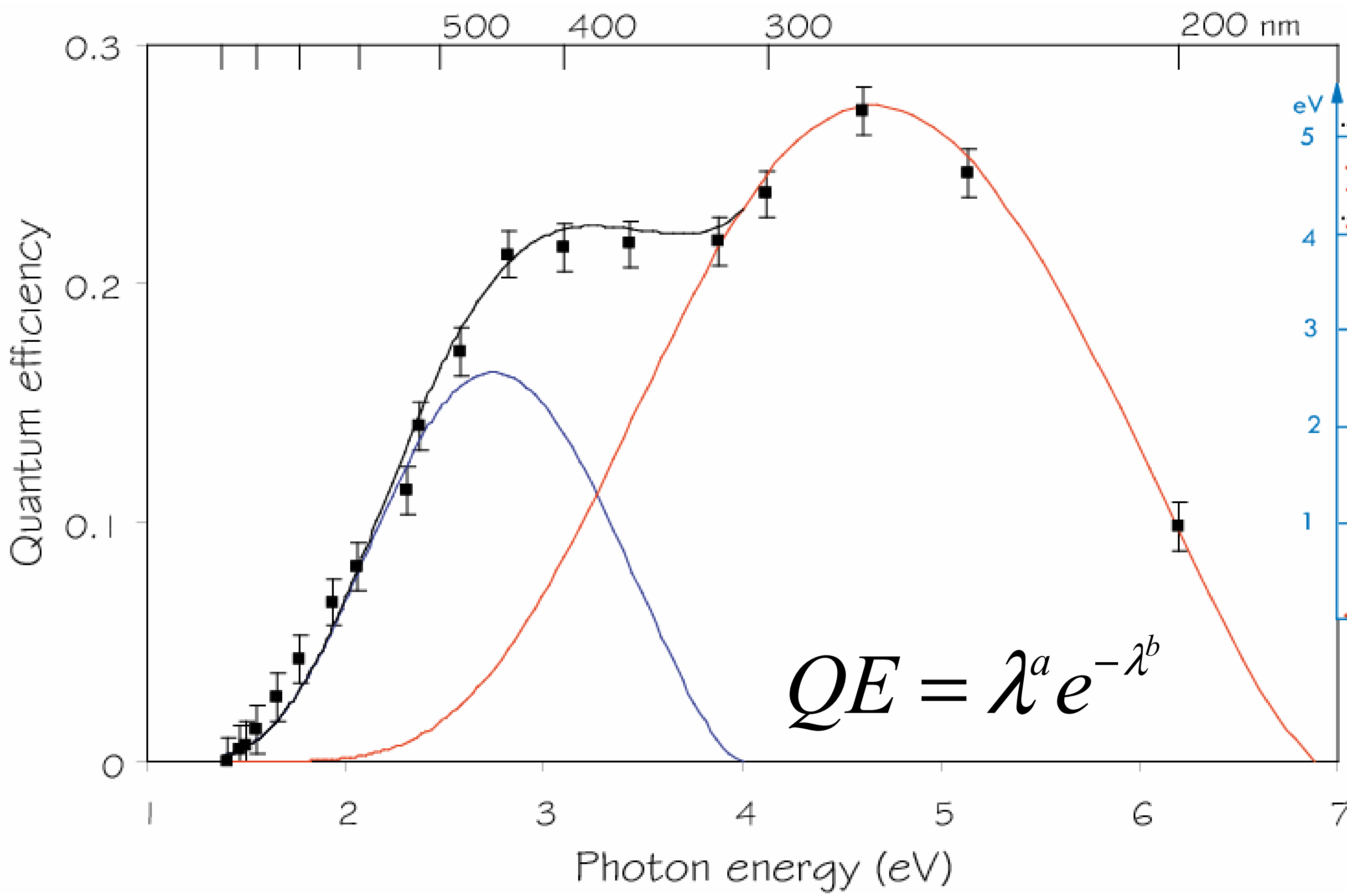
# S-20 (Sb-$Na_2$-K-Cs) tri-alkaline photo cathode with quartz window.

**Ionisation potential**

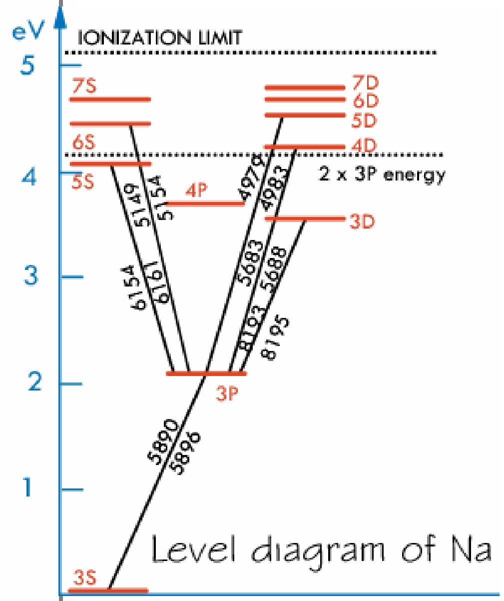
| Alkali | | bi-alkali | |
|---|---|---|---|
| Cs | 3.894 eV | Sb | 8.64 |
| K | 4.341 | | |
| Na | 5.139 | | |

**Photo-electric work function**

| | |
|---|---|
| Cs | 2.1 eV |
| K | 2.3 |
| Na | 2.8 |
| Sb | 4.8 |




$$QE = \lambda^a e^{-\lambda^b}$$




Other alkalis have essentially the same scheme.

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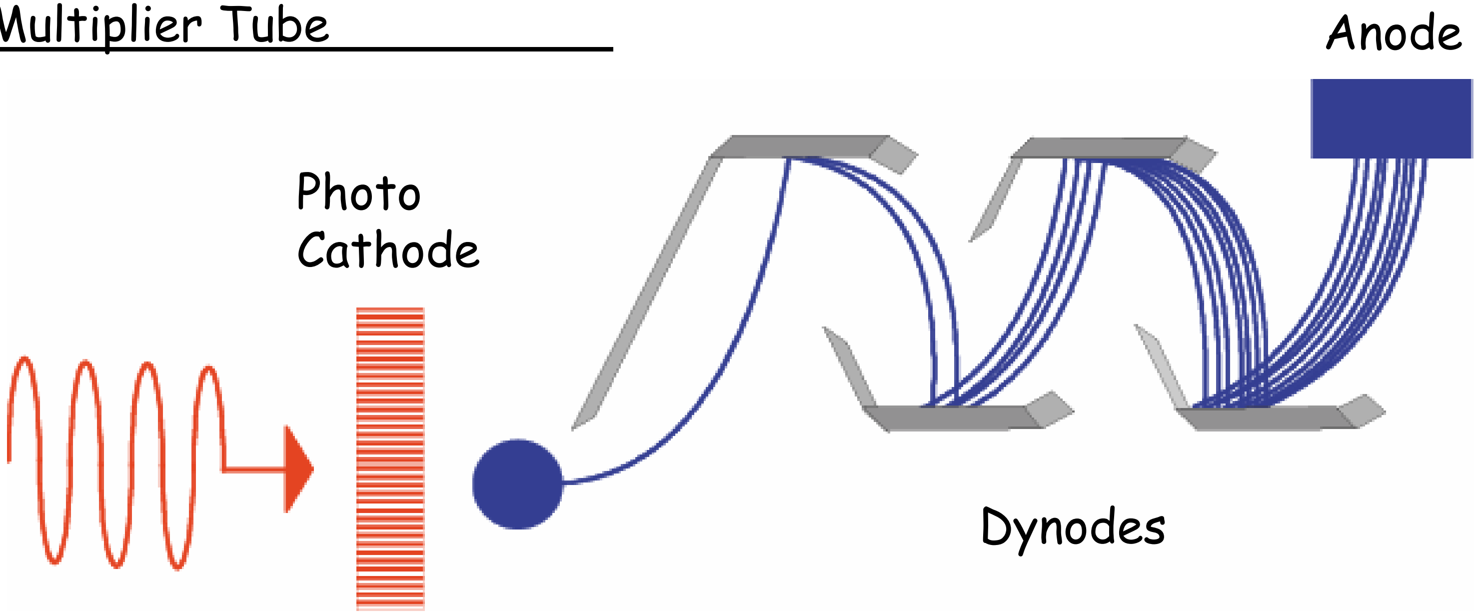
# Photo Multiplier Tube




Photon-to-Electron Converting Photo-Cathode

Dynodes with secondary electron emission

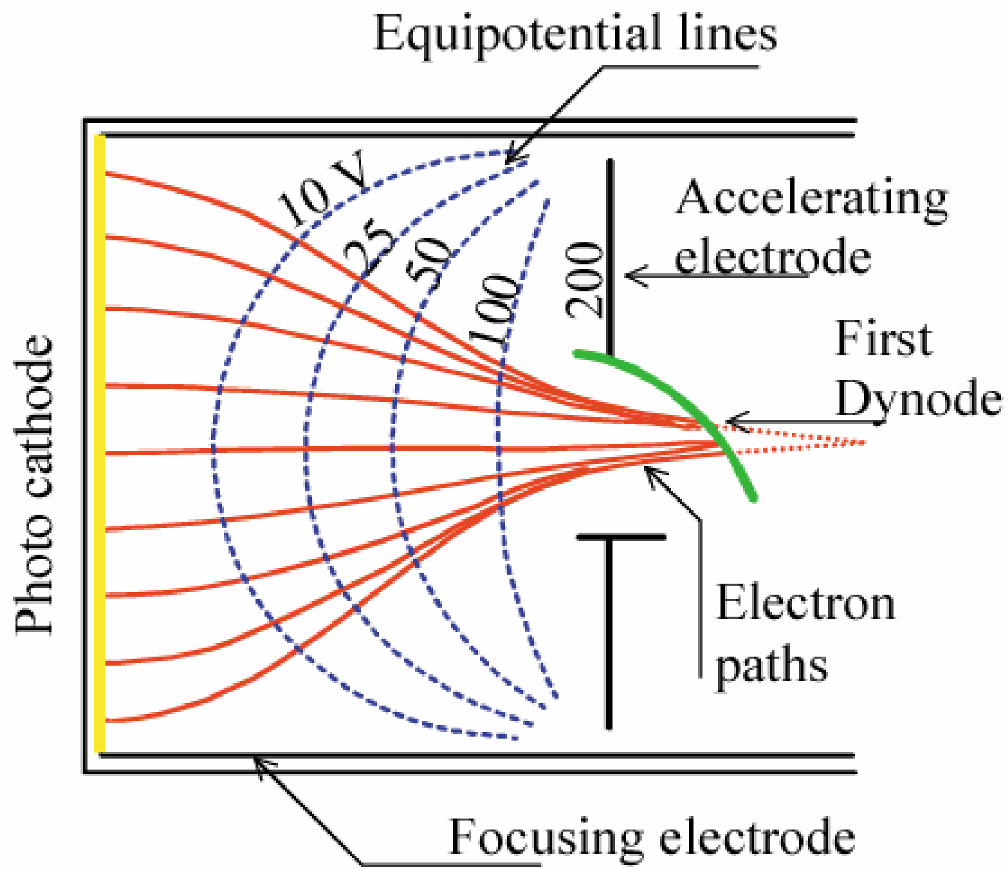
Typical gain $\approx 10^6$ . Transient time spread $\approx 200$ ps

What is ______ Secondary Electron Emission ______ ?

Approximately the same as the Photo Electric Effect.

______On electron impact, energy is transferred directly to the electrons in the secondary electron emission material allowing a number of secondary electrons to escape.

______Since the conducting electrons in metals hinder this escape, insulators and semiconductors are used.




Materials in common use are:
Ag/Mg, Cu/Be and Cs/Sb.

Use has also been made of negative affinity materials as dynodes, in particular GaP.

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# Gain fluctuations of PMT's

- Mainly determined by the fluctuations of the number m(δ) of secondary e's emitted from the dynodes;

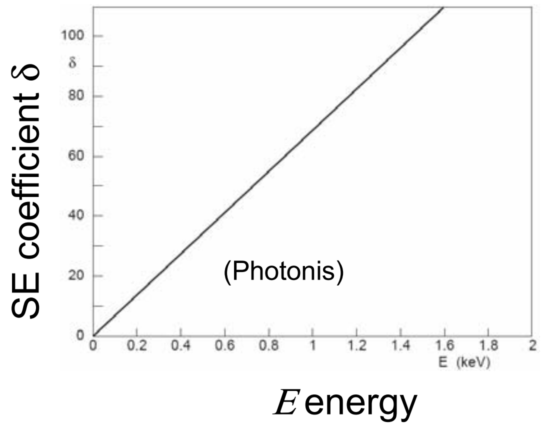
- Poisson distribution:

$$P_\delta(m) = \frac{\delta^m e^{-\delta}}{m!}$$

- Standard deviation:

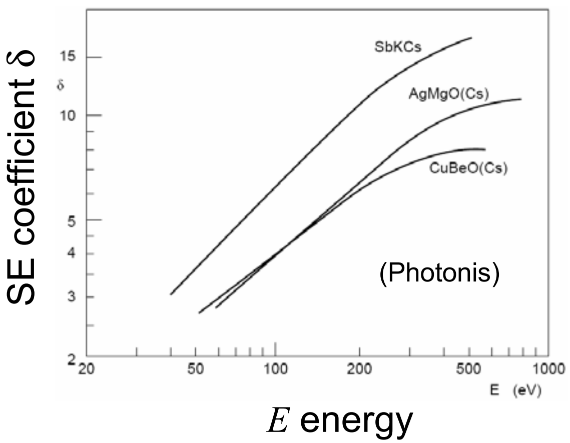
$$\frac{\sigma_m}{\delta} = \frac{\sqrt{\delta}}{\delta} = \frac{1}{\sqrt{\delta}}$$

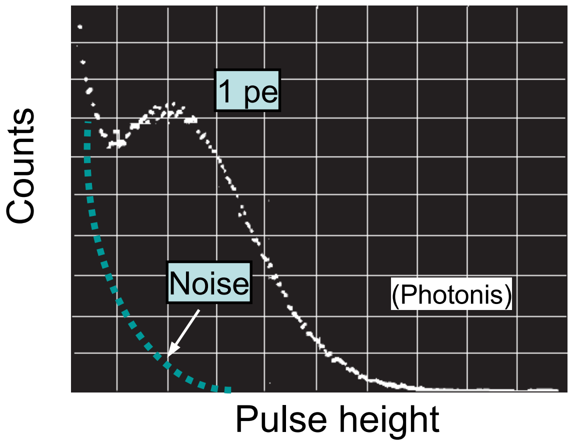
⇒ fluctuations dominated by 1st dynode gain;

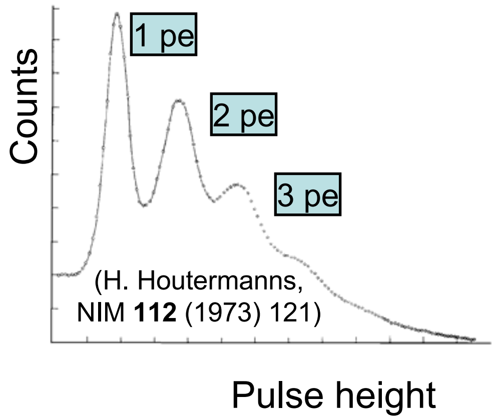



GaP(Cs) dynodes $E_A<0$

CuBe dynodes $E_A>0$




from T. Gys, Academic Training, 2005

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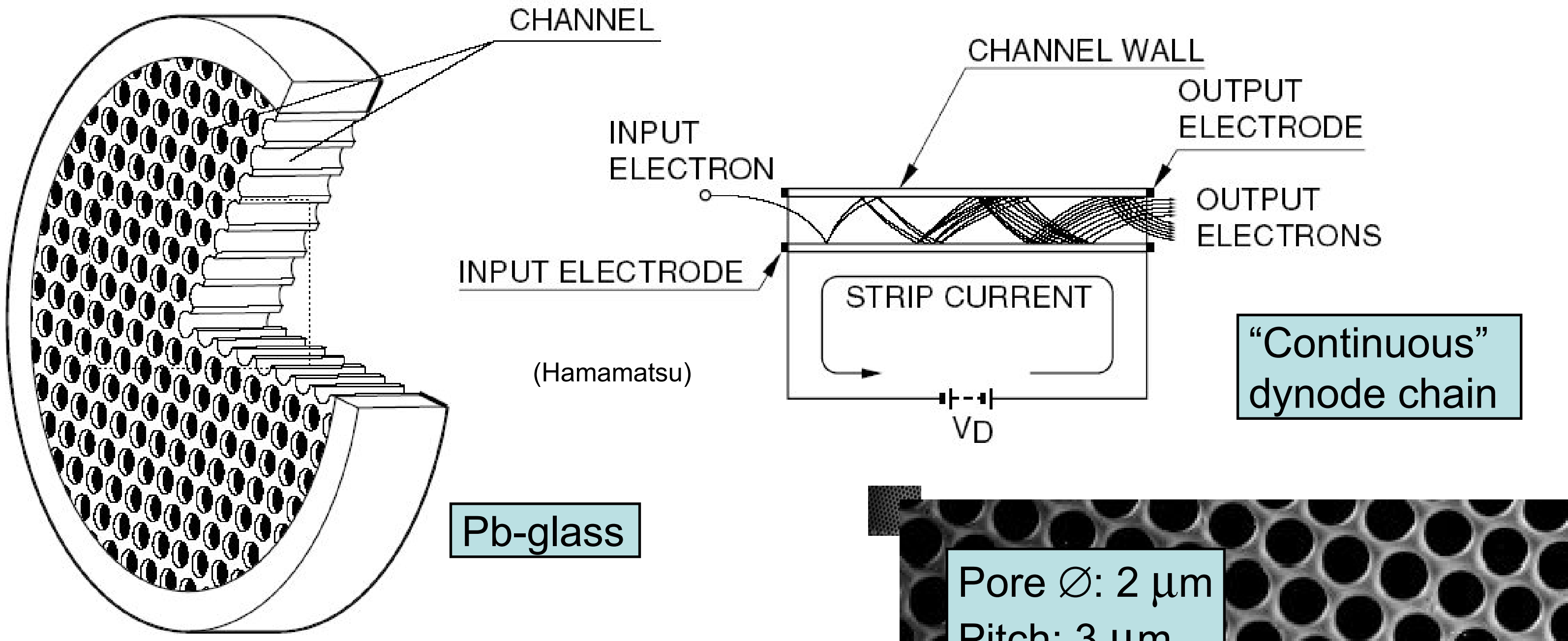
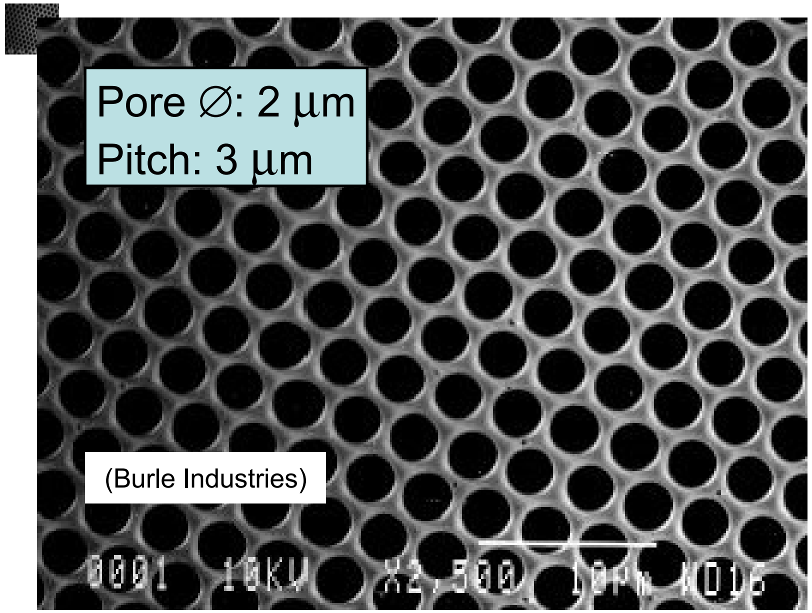
# The Micro Channel Plate (MCP)




Kind of 2D PMT:
+ high gain up to 5 $10^4$;
+ fast signal (transit time spread ~50 ps);
+ less sensitive to B-field (0.1 T);
- limited lifetime (0.5 C/$cm^2$);
- limited rate capability (µA/$cm^2$);

from T. Gys, Academic Training, 2005

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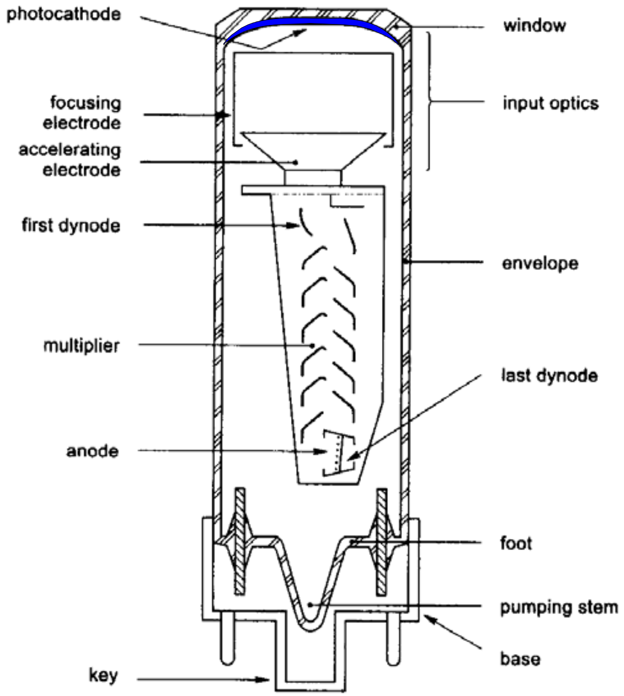
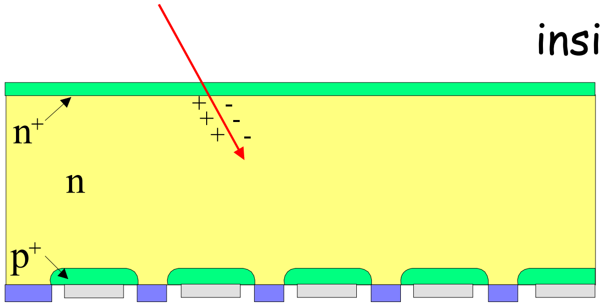
# Physical principles of **Hybrid Photo Detector**

Take one
Photo Multiplier Tube

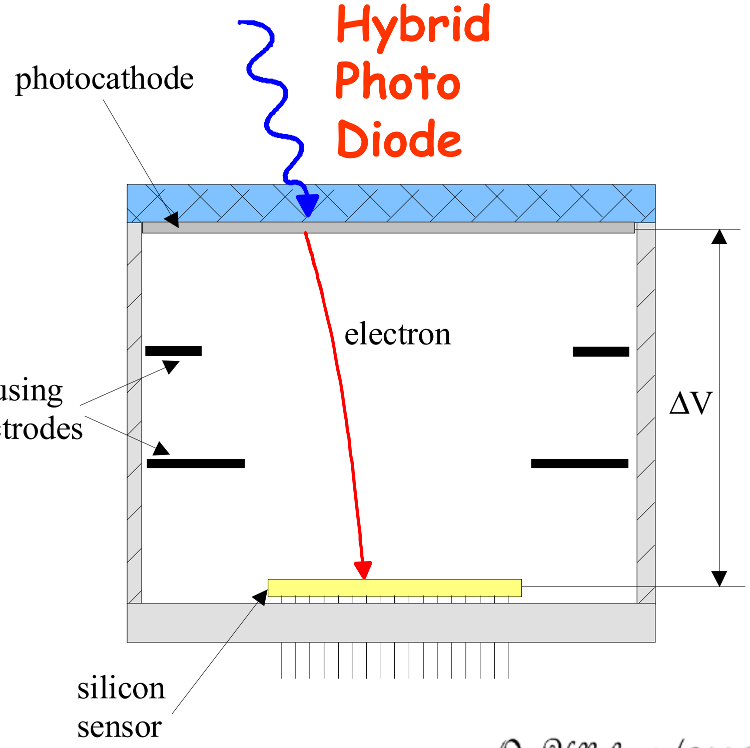



Remove dynodes and anode

Add
**Silicon Sensor**
inside tube




**Hybrid Photo Diode**




$$\text{Electron-hole pairs} = \frac{[\text{Kinetic energy of the impinging electron}] - [\text{work to overcome the surface}]}{[\text{Silicon ionization energy}]}$$

~ 4 - 5000 electron-hole pairs → Good energy resolution

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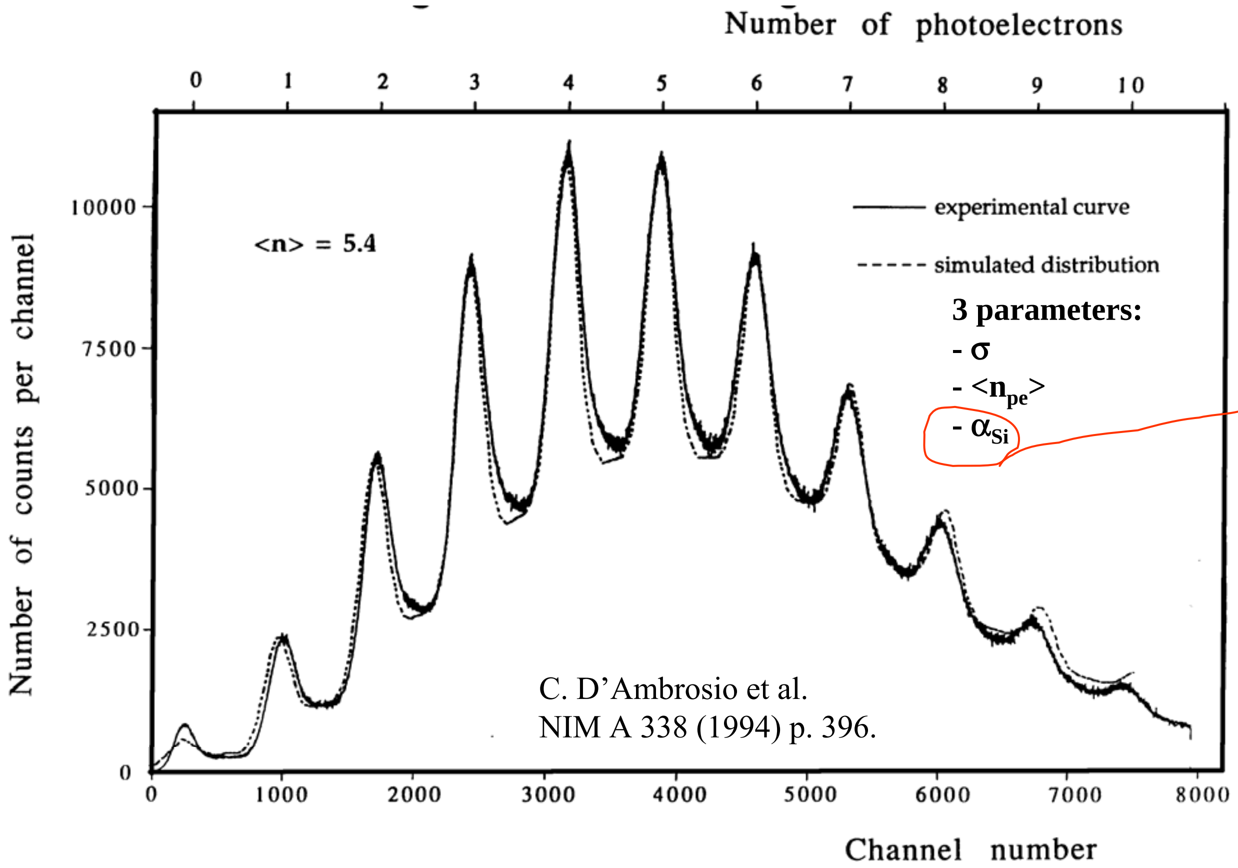
But…

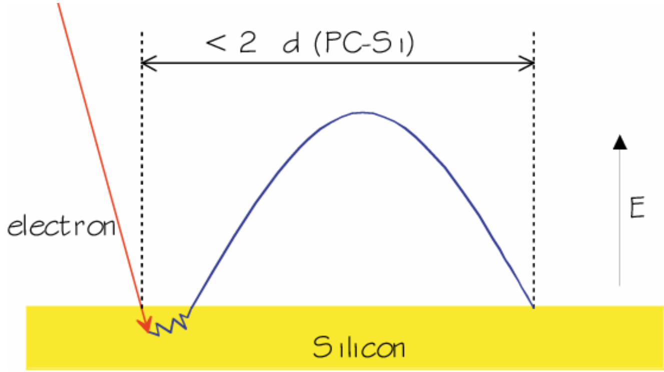
- Electronic noise, typically of the order of ≥ 500 $e$

$$\sigma^2_{total} = \sigma^2_{\text{int.}} + \sigma^2_{E_{loss}} + \sigma^2_{elec.} >> \sigma^2_{\text{int.}}$$

- Back scattering of electrons from Si surface

20% of the electrons deposit only a fraction $0 \leq \varepsilon < 1$ of their initial energy in the Si sensor .
→ continuous background (low energy side)




back scattering probability at E ≈ 20 kV

$\alpha_{Si} \approx 0.18$

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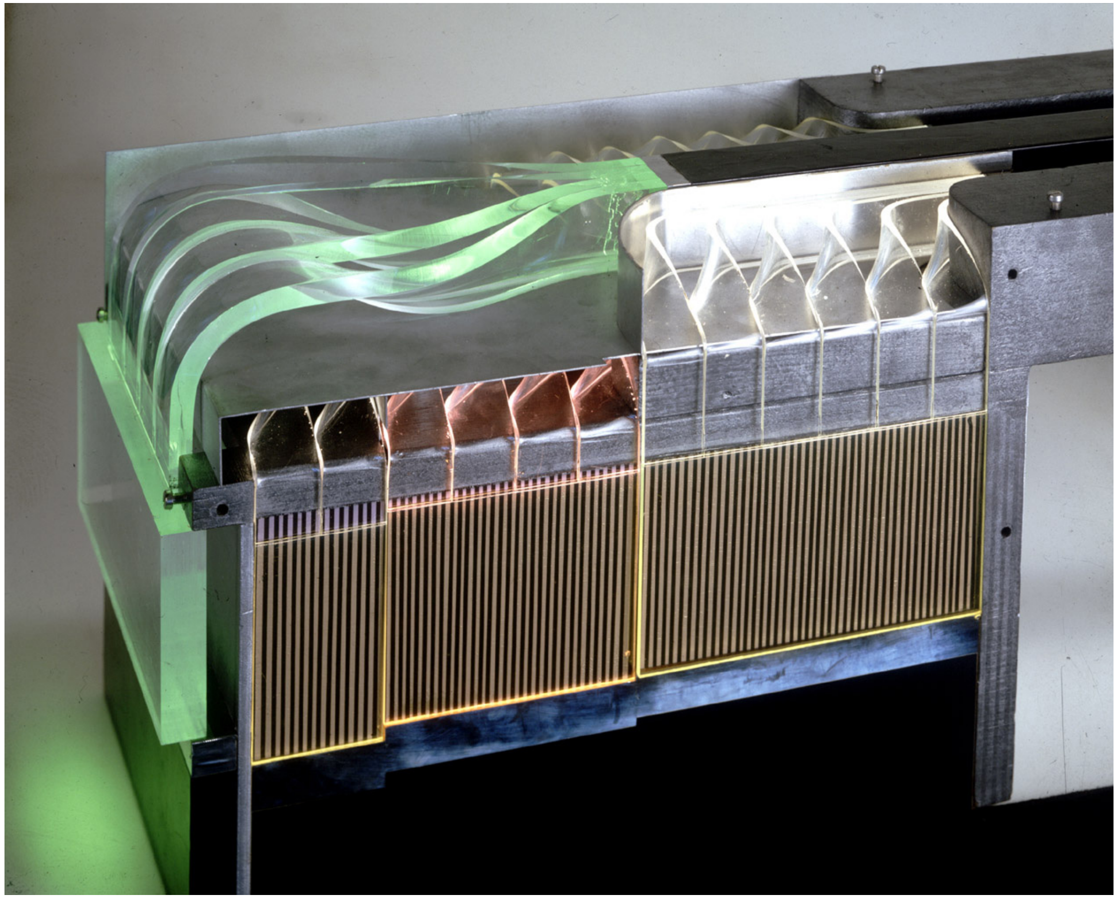
And we should now be ready to look at

Cherenkov radiation and Transition radiation

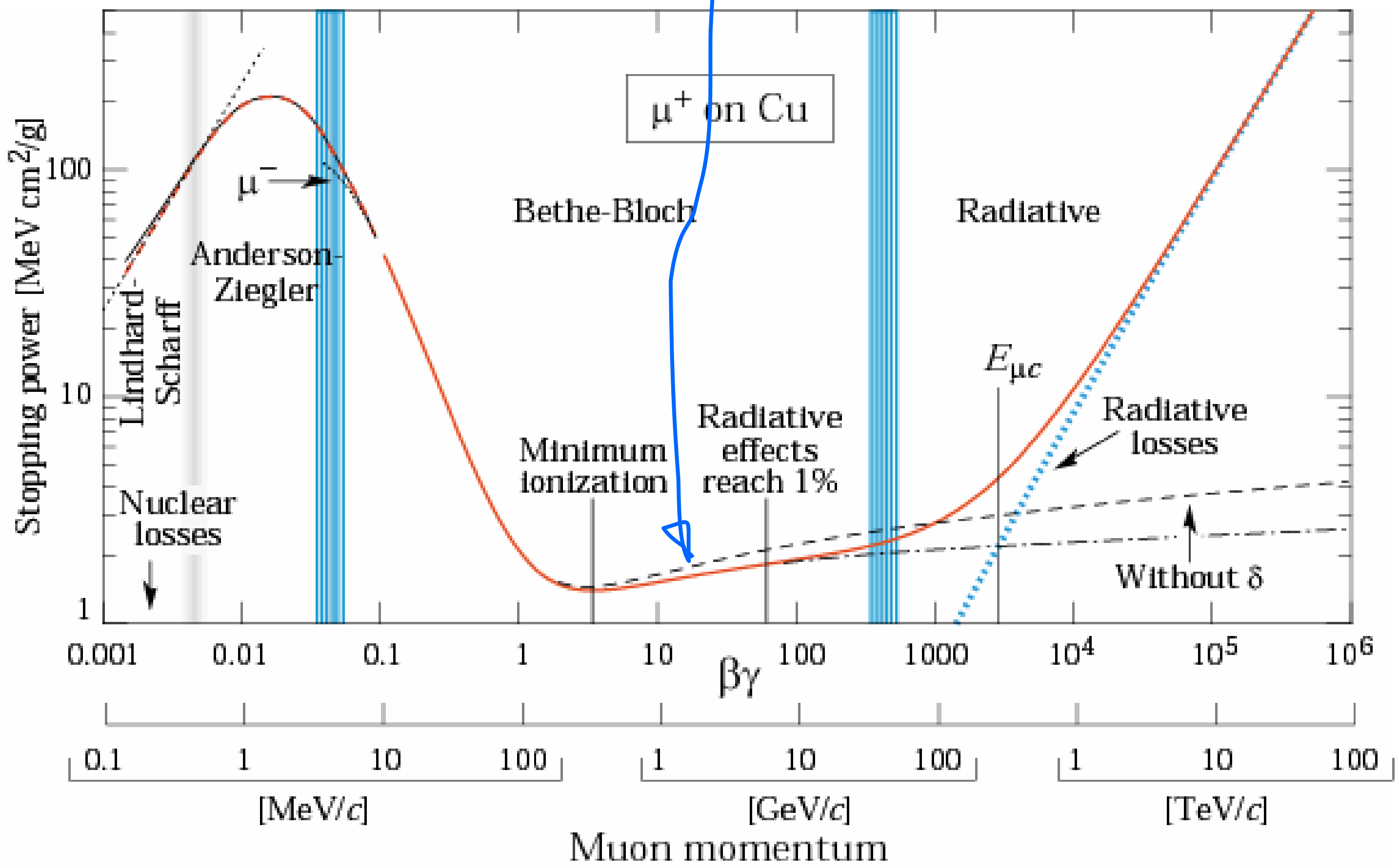
# Particle Identification

Cherenkov Radiation

Transition Radiation

Time-of-Flight

## Some of the processes at the Relativistic Rise



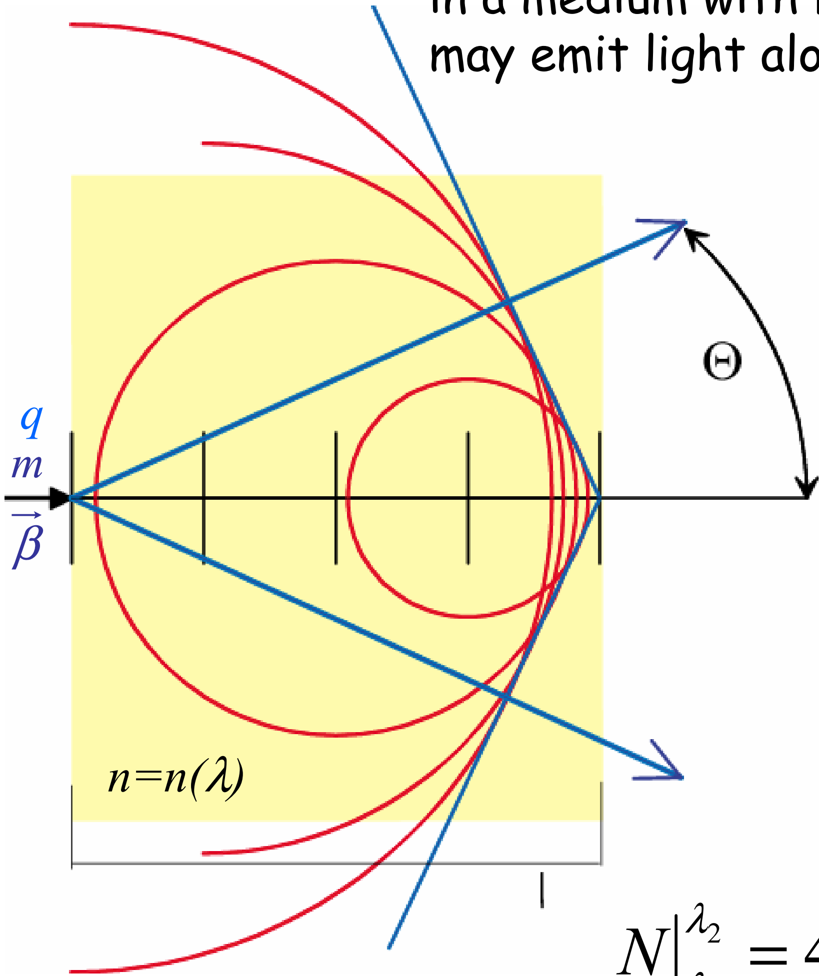

The density effect in the energy loss is intimately connected to the coherent response of a medium to the passage of a relativistic particle that causes the emission of Cherenkov radiation.

# Cherenkov Radiation with a classic twist:

A charged particle with velocity β in a medium with refractive index $n$ may emit light along a conical wave front.

$\beta = v/c$

$n = n(\lambda)$




**The angle of emission is given by:**

$$\cos\Theta = \frac{1}{\beta * n(\lambda)}$$

**and the number of photons by:**

$$\frac{dN}{d\lambda} = N_0 \cdot l \cdot \frac{\sin^2\Theta}{\lambda^2}$$

$$N\Big|_{\lambda_1}^{\lambda_2} = 4.6 \cdot 10^6 \cdot \left[\frac{1}{\lambda_2(A)} - \frac{1}{\lambda_1(A)}\right] \cdot l(cm) \cdot \sin^2\Theta$$

For some missing steps:
see J.D. Jackson, Classical Electrodynamics, Section 13 or equivalent

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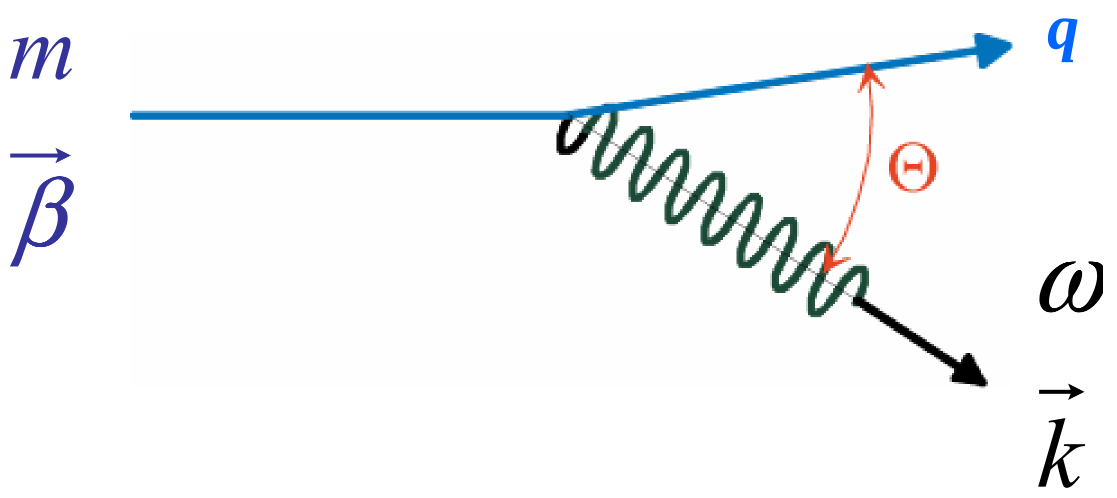
The same, but let us consider how a charged particle interacts with the medium




Conservation of energy and momentum → $\omega = \vec{\beta} \cdot \vec{k}$

The behavior of a photon in a medium is described by the dispersion relation → $\omega^2 - \frac{k^2}{\varepsilon} = 0$

If:

$\omega << \gamma m = E$

$k << \beta\gamma m = p$

then:

$$\cos\Theta = \frac{1}{\beta\sqrt{\varepsilon}}$$

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The Cherenkov radiation condition:

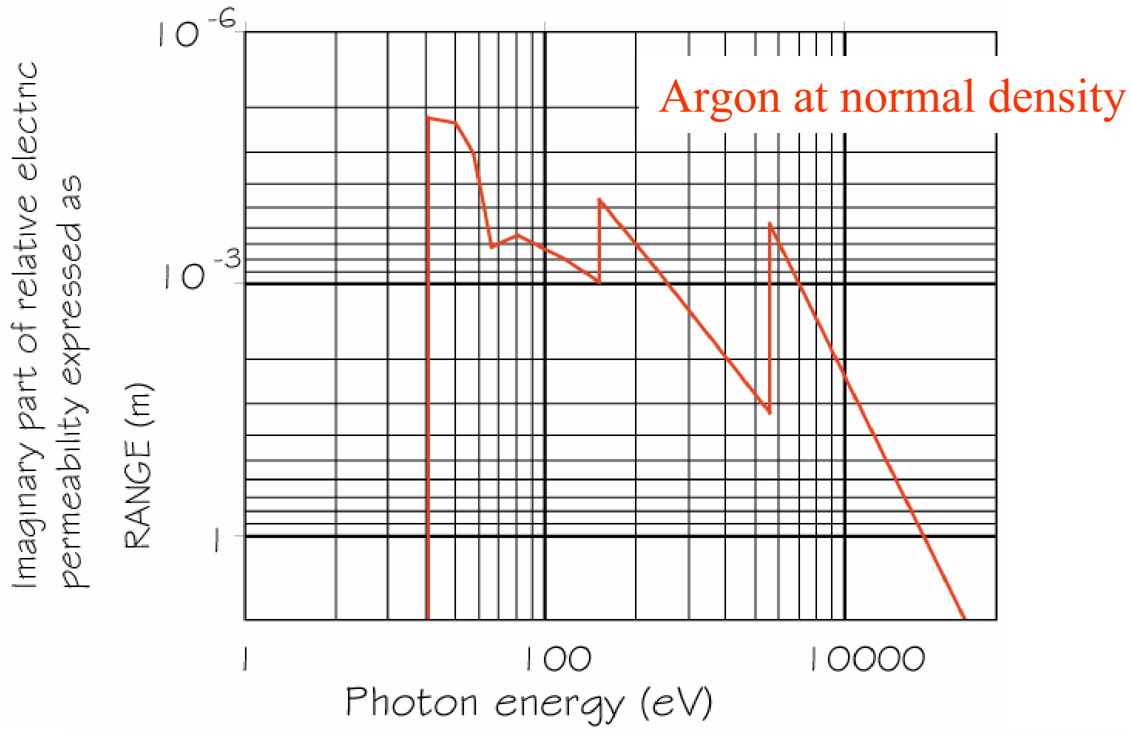
ε real ✓

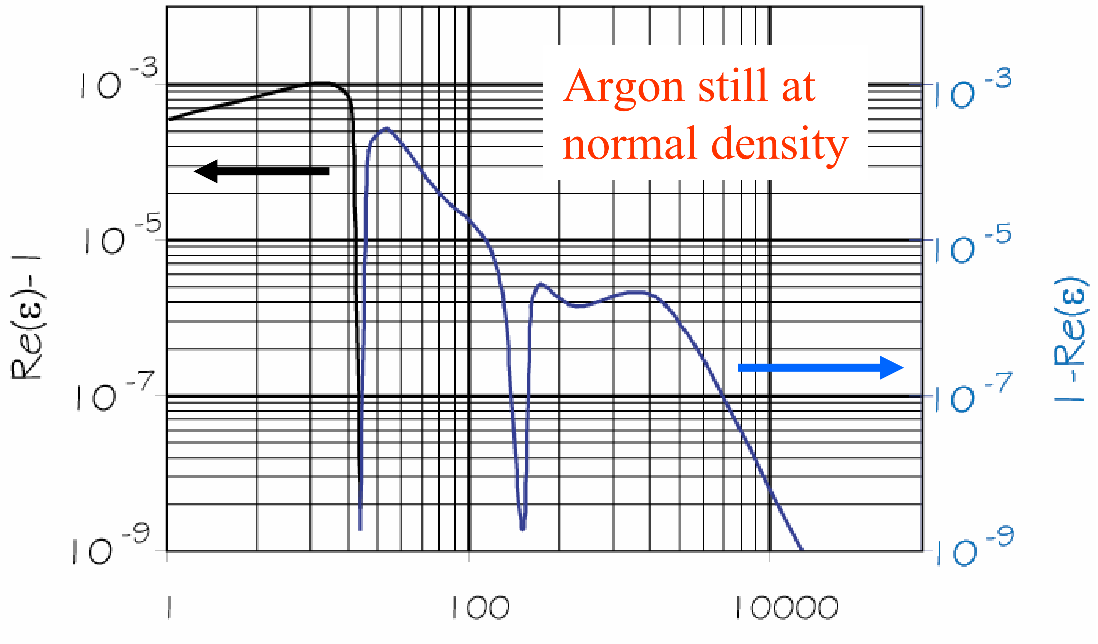
and

$0 \le \cos(\Theta) \le 1$ ✓

$$\cos\Theta_C = \frac{1}{\beta \cdot n}$$

where $n$ is the refractive index




W.W.M. Allison and P.R.S. Wright, RD/606-2000-January 1984

O. Ullaland/2006

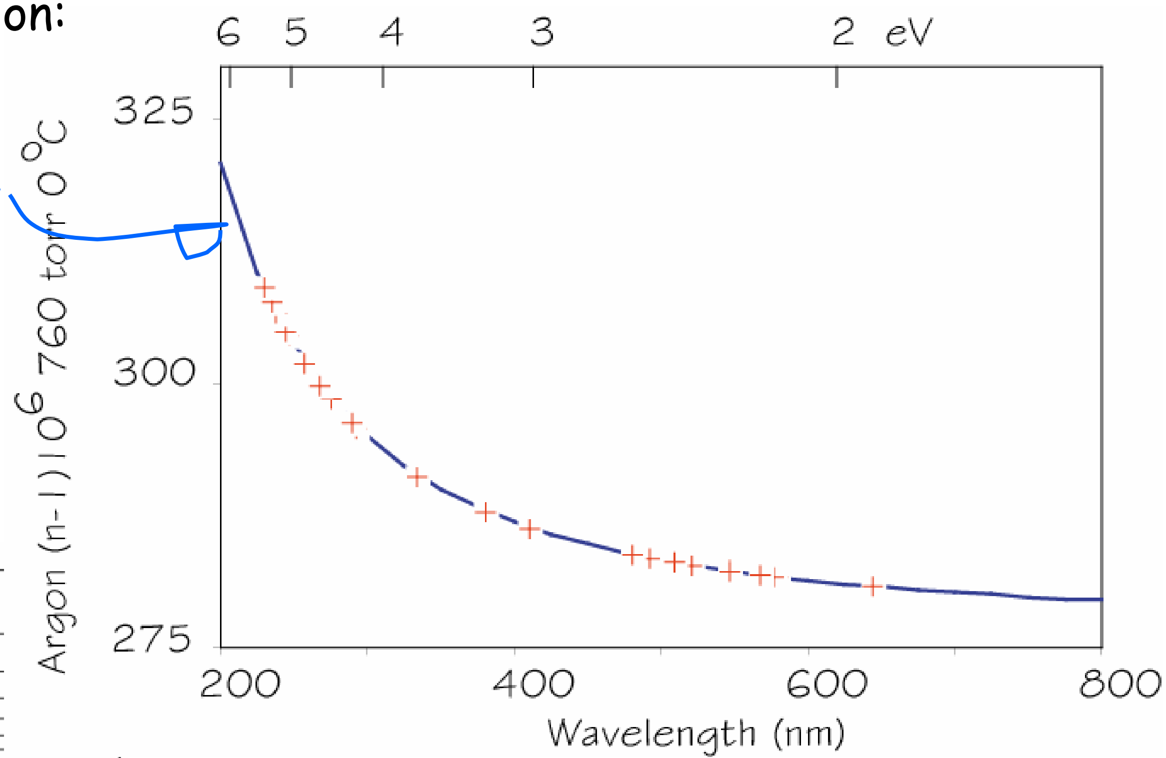
# Some words on refractive index

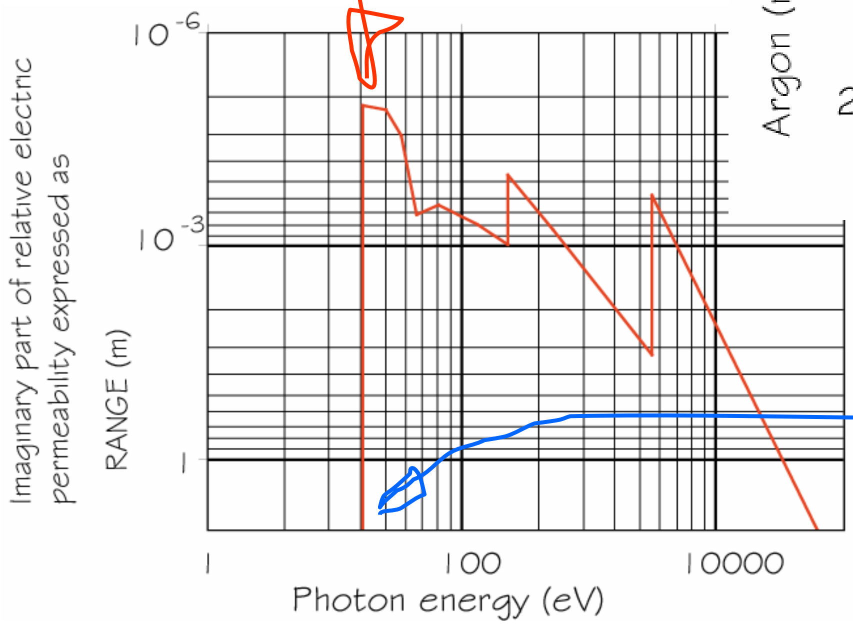
The normal way to express $n$ is as a power series.
For a simple gas, a simple
one pole Sellmeier approximation:

$$(n-1)\cdot 10^6 = \frac{0.05085}{\left(\frac{1}{73.8}\right)^2 - \left(\frac{1}{\lambda(nm)}\right)^2}$$

Argon

=16.8 eV




$\Rightarrow$ $\omega_0^2$=(plasma frequency)$^2$

$\propto$ (electron density)

For more on the plasma frequency, try Jackson, Section 7 (or similar) or go to sites like
http://farside.ph.utexas.edu/teaching/plasma/lectures/node44.html

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## A practical example

$$\cos\theta = \frac{1}{\beta n}$$

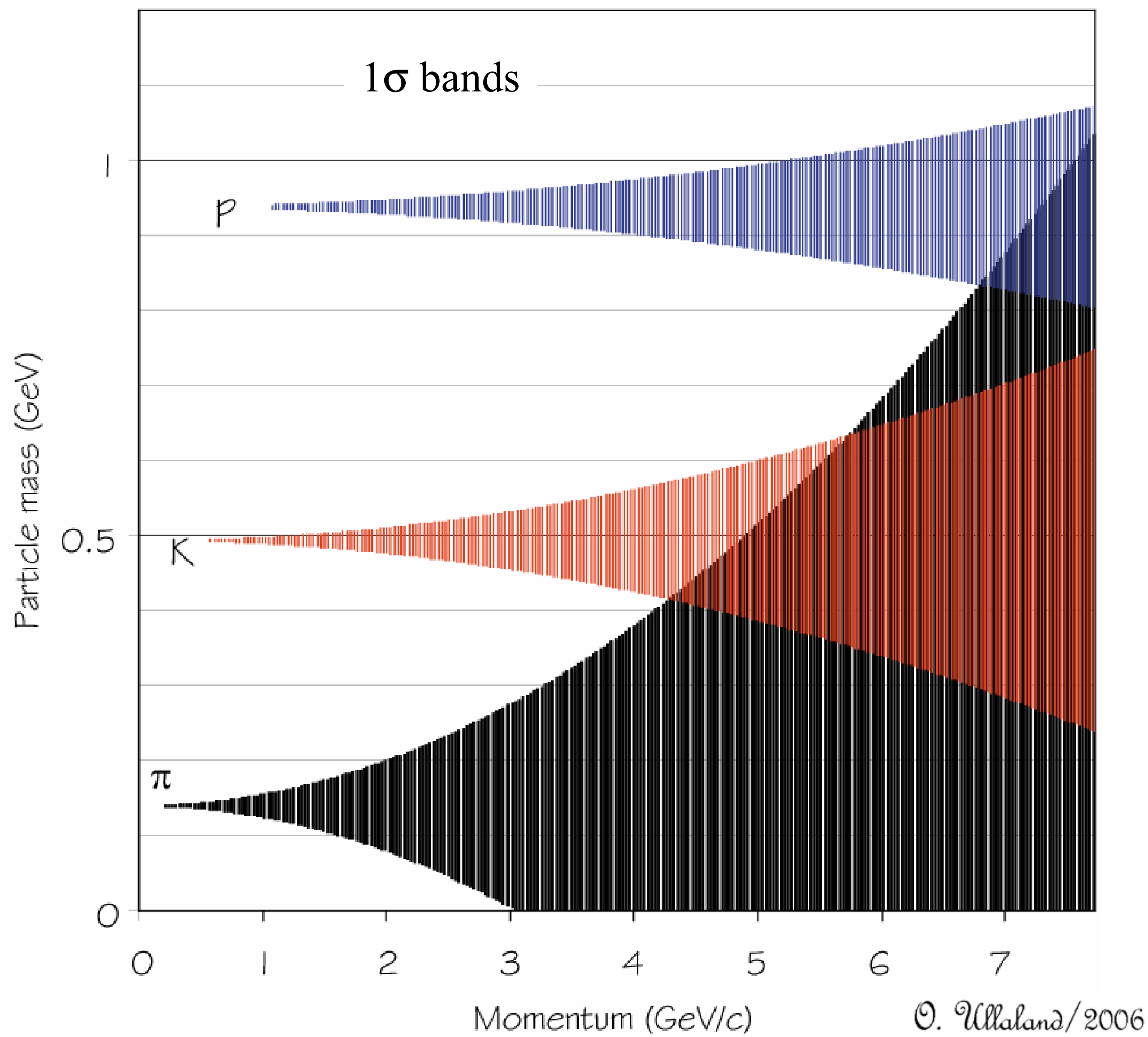
$$m = \frac{p}{\beta\gamma}$$

$$\frac{\Delta m}{m} = \sqrt{\left(\frac{\Delta p}{p}\right)^2 + \left(\gamma^2 \cdot tg\theta \cdot \Delta\theta\right)^2}$$

set :
$n$=1.333 ($H_2O$)

→ $\theta_{max} = 41.4^{o}$
$\beta_{min} = 0.75$

| | |
|---|---|
| $\Delta p/p^2$ | $5*10^{-4}$ |
| $\Delta\theta$ | 15 mrad |
| $l$ | 1 cm |



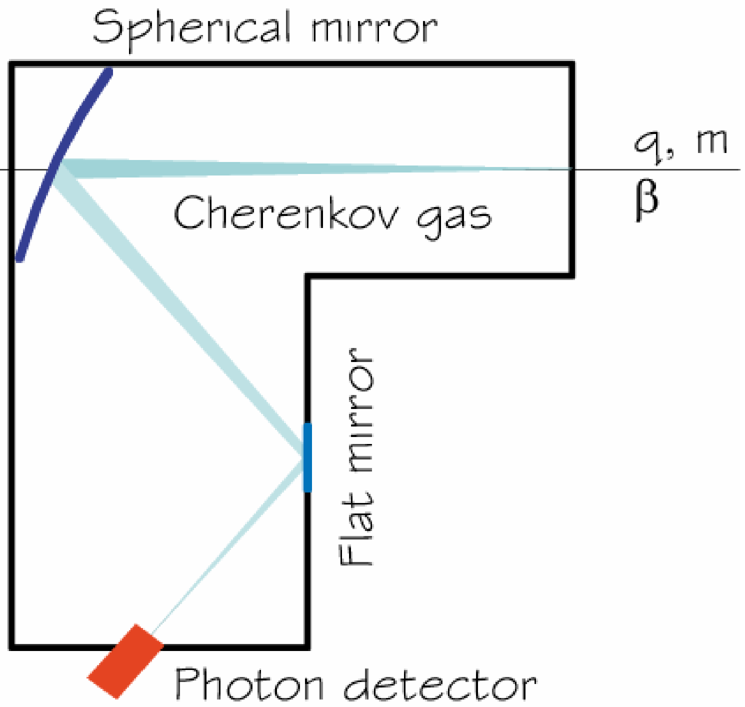
## Threshold Cherenkov Detector

To get a wider momentum range for particle identification, use more than one radiator.

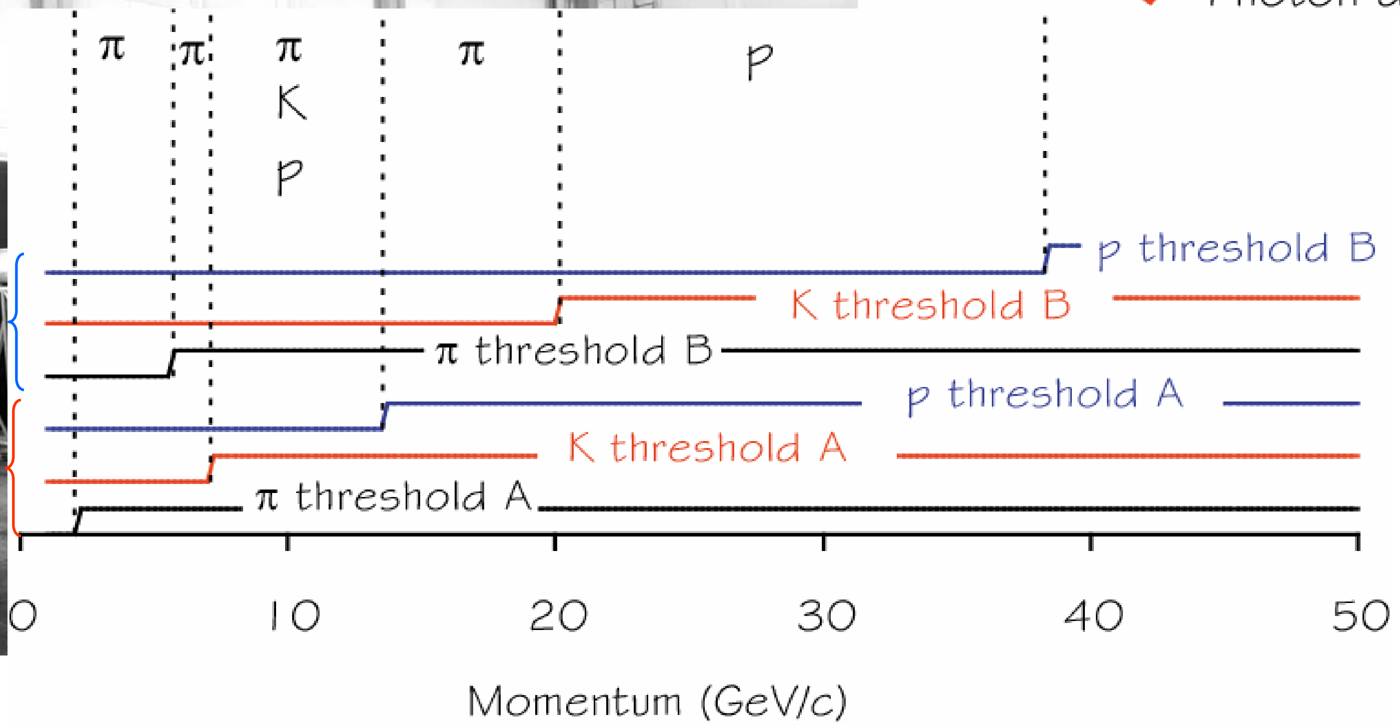
Assume

A radiator: $n$=1.0024

B radiator: $n$=1.0003




Positive particle identification:

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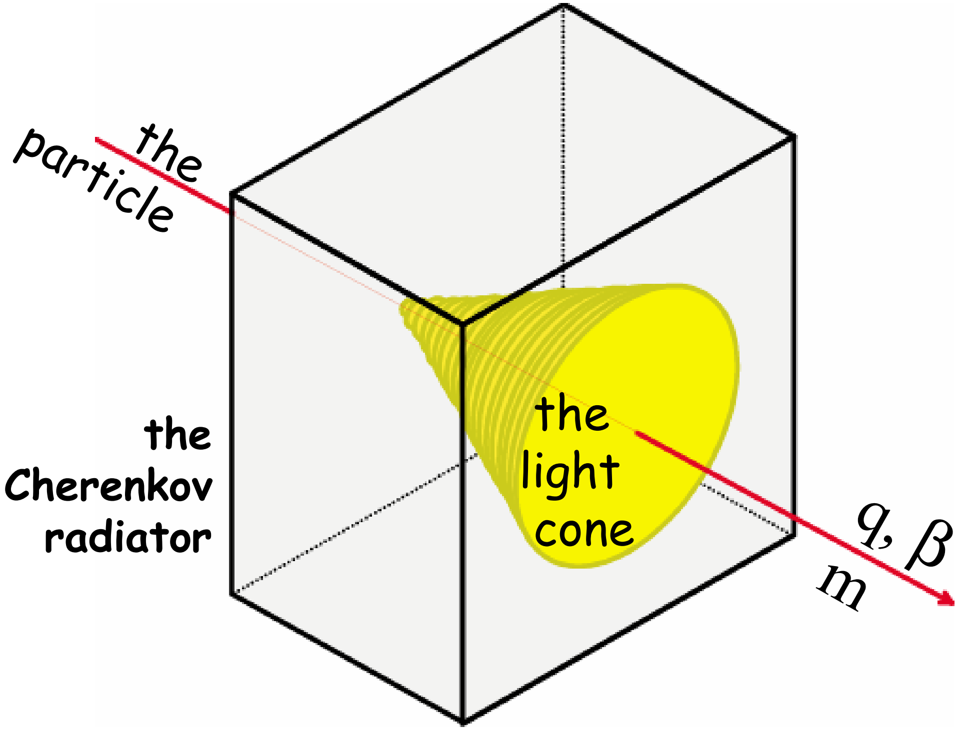
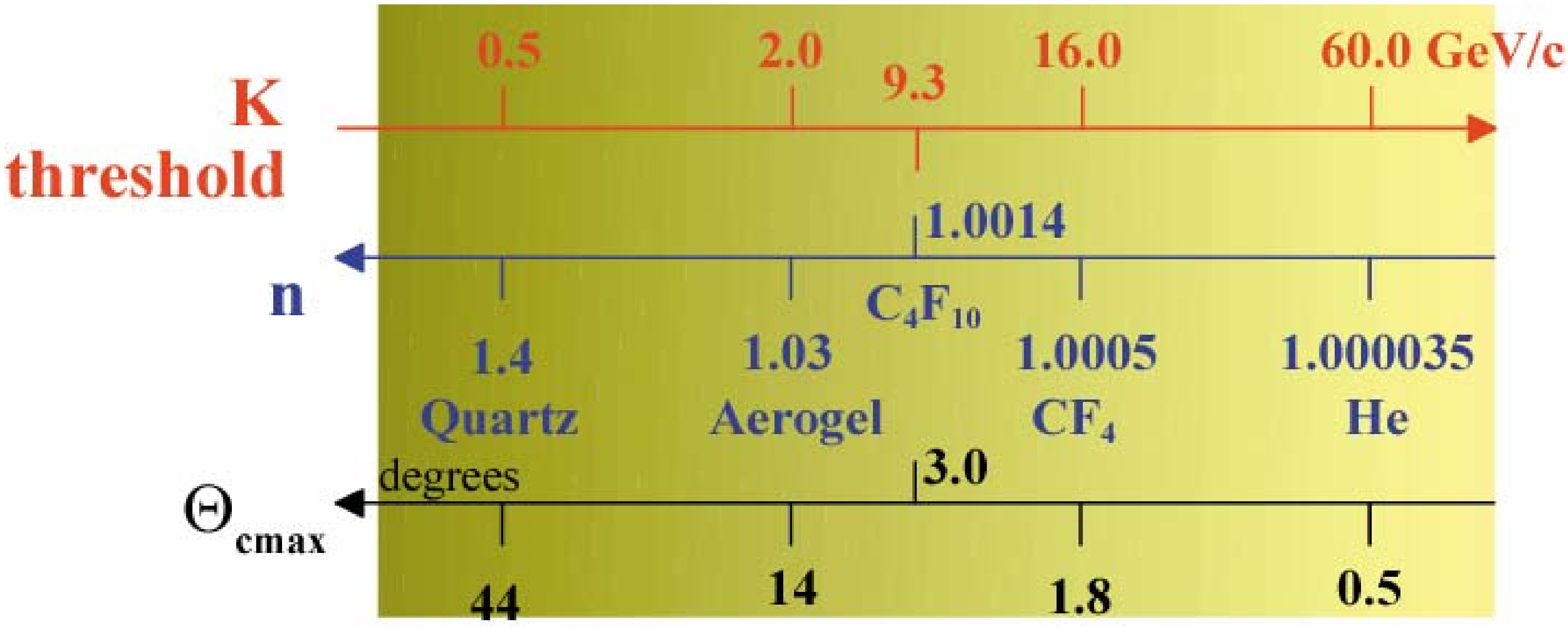
## A step back

$$n - 1 = \frac{A}{\lambda_0^{-2} - \lambda^{-2}}$$

$$\frac{dN_{ph}}{dLdE} = \frac{\alpha Z^2}{\hbar c} \sin^2 \Theta$$

$$\cos \Theta = \frac{1}{\beta n}$$

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Use all available information about the Cherenkov radiation:

________The existence of a threshold
________The dependence of the number of photons
________The dependence of Cherenkov angle on the velocity $\beta=p/E$ of the particle
________The dependence on the charge of the particle

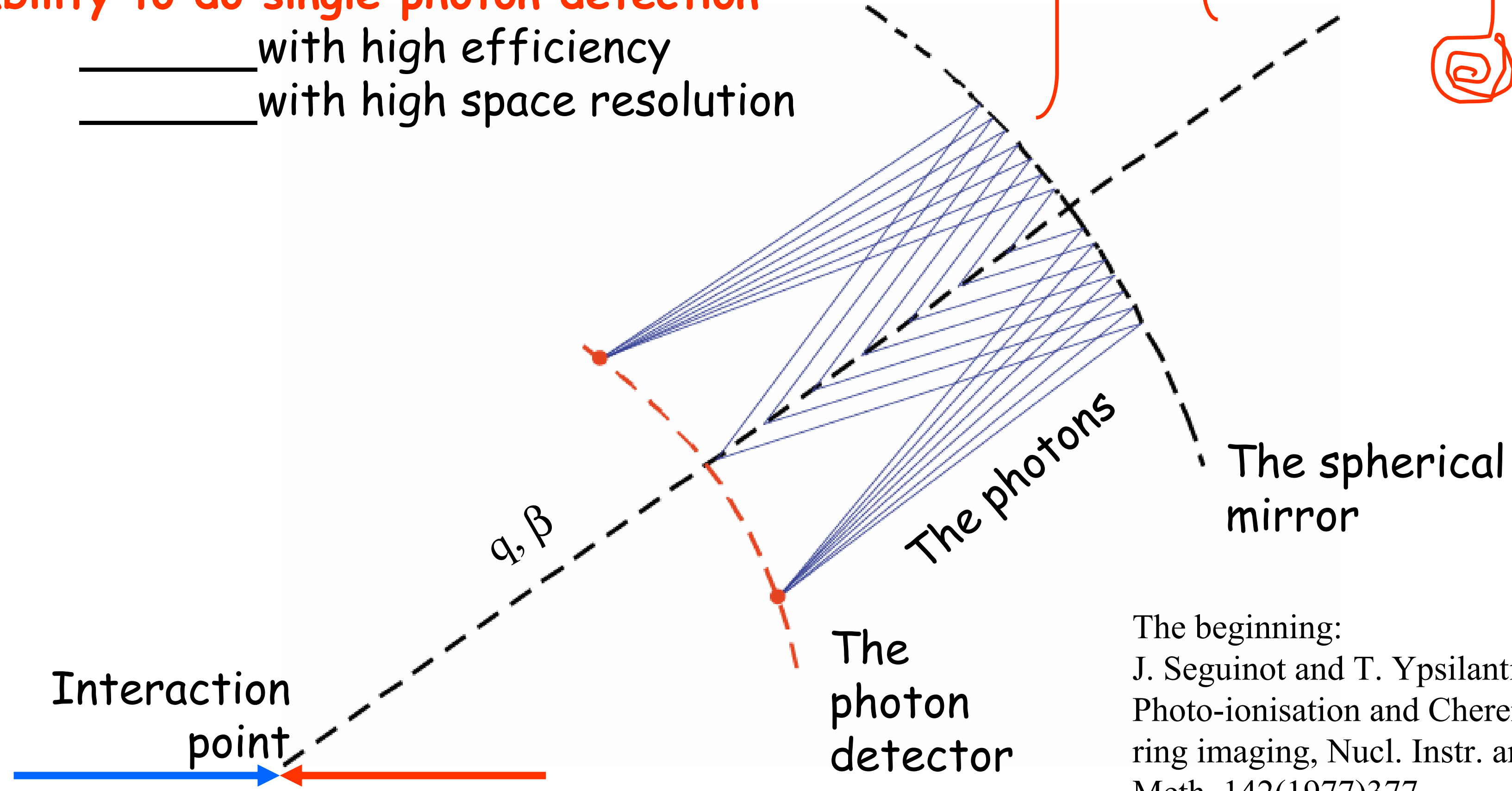
Ring Imaging Cherenkov detector

the RICH

**+**

**Capability to do single photon detection**

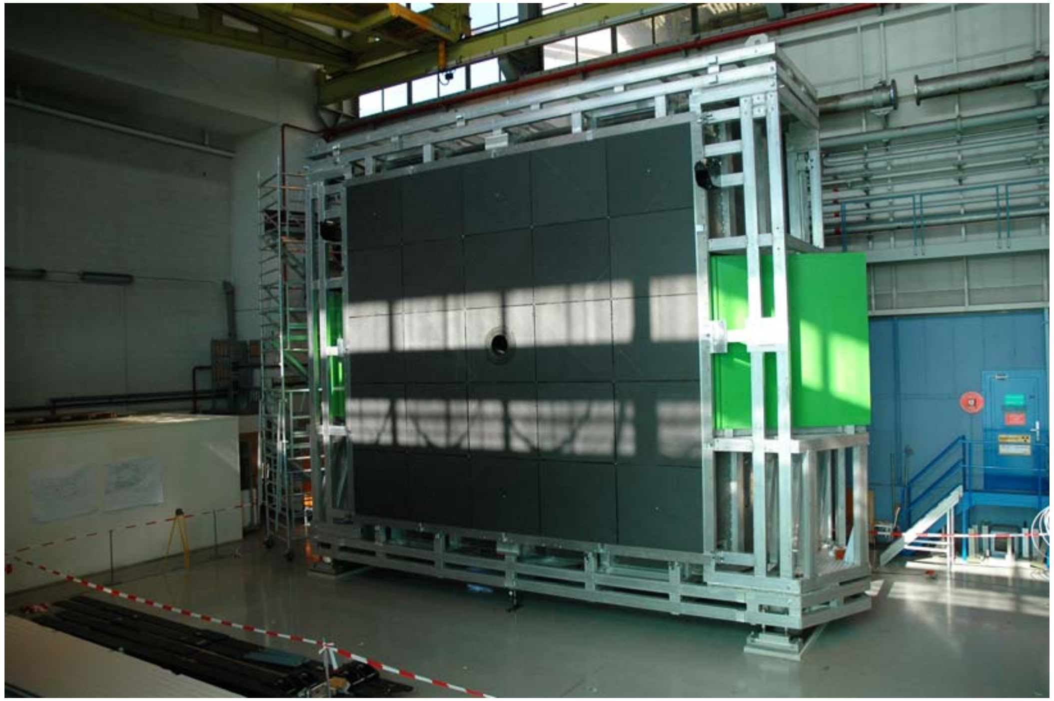
________with high efficiency
________with high space resolution




The beginning:
J. Seguinot and T. Ypsilantis, Photo-ionisation and Cherenkov ring imaging, Nucl. Instr. and Meth. 142(1977)377

O. Ullaland/2006

# LHCb RICH 2

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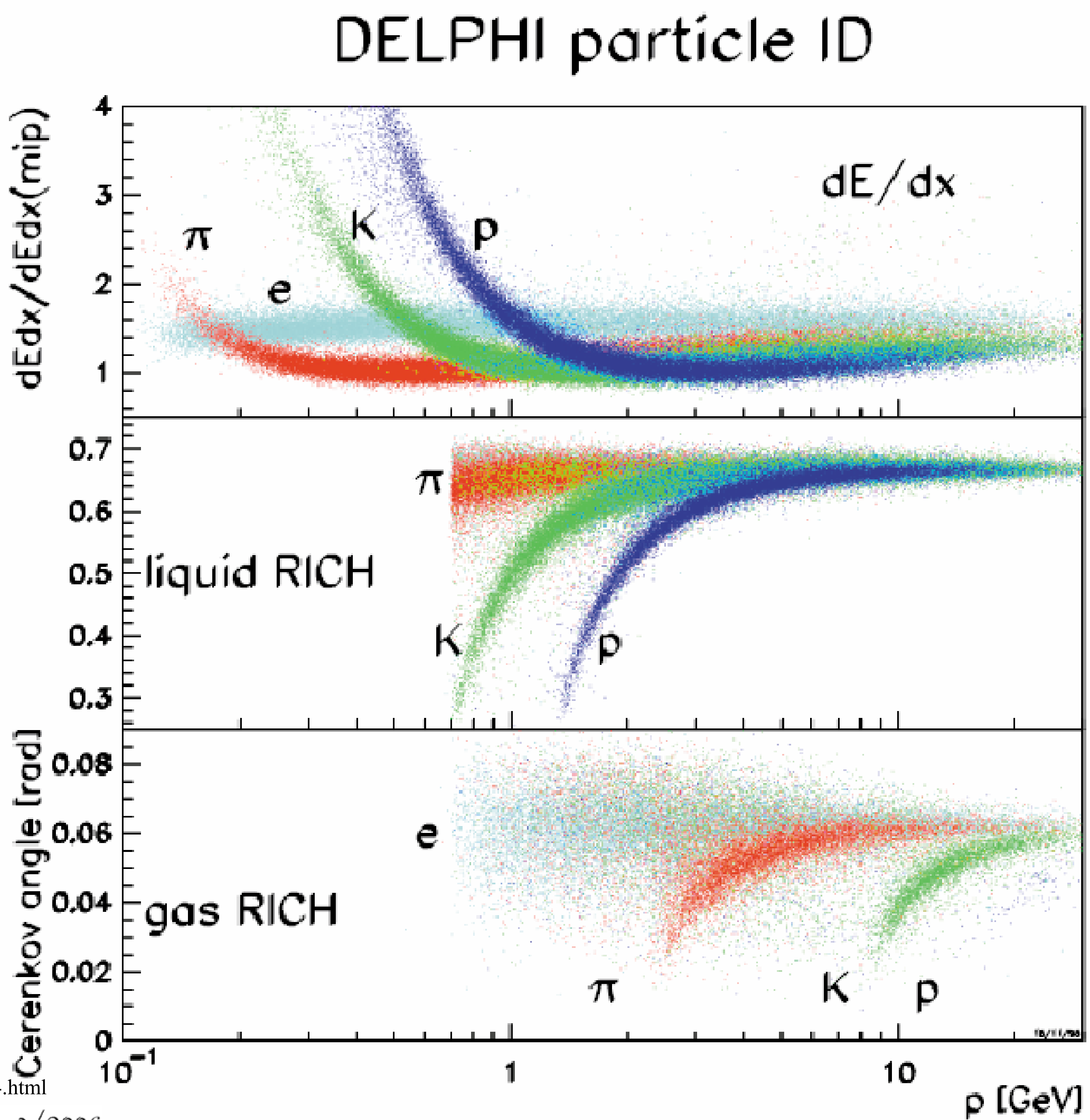
Particle Identification with the DELPHI TPC and RICHes

From data:

p from $\Lambda$

K from $\Phi$ $D^*$

$\pi$ from $K^o$




http://delphiwww.cern.ch/delfigs/export/pubdet4.html

DELPHI, NIM A: 378(1996)57

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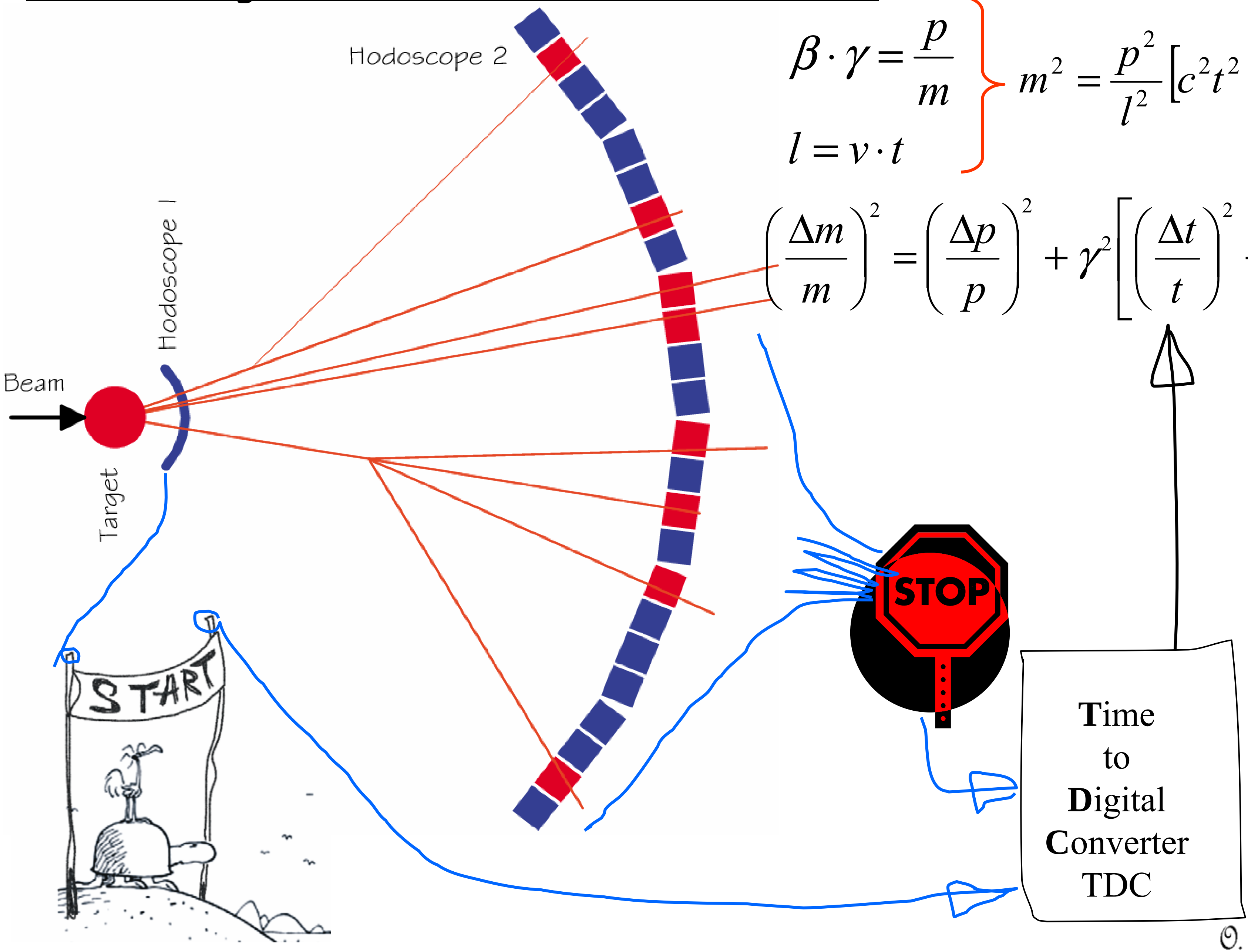
More beautiful pictures
(which has next to nothing to do with)
**Cherenkov radiation**

## and while we are at β-measurement
## Time-of-Flight (TOF) measurement

$$\beta \cdot \gamma = \frac{p}{m}, \quad l = v \cdot t \quad \Rightarrow \quad m^2 = \frac{p^2}{l^2}\left[c^2 t^2 - l^2\right]$$

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta p}{p}\right)^2 + \gamma^2\left[\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta l}{l}\right)^2\right]$$

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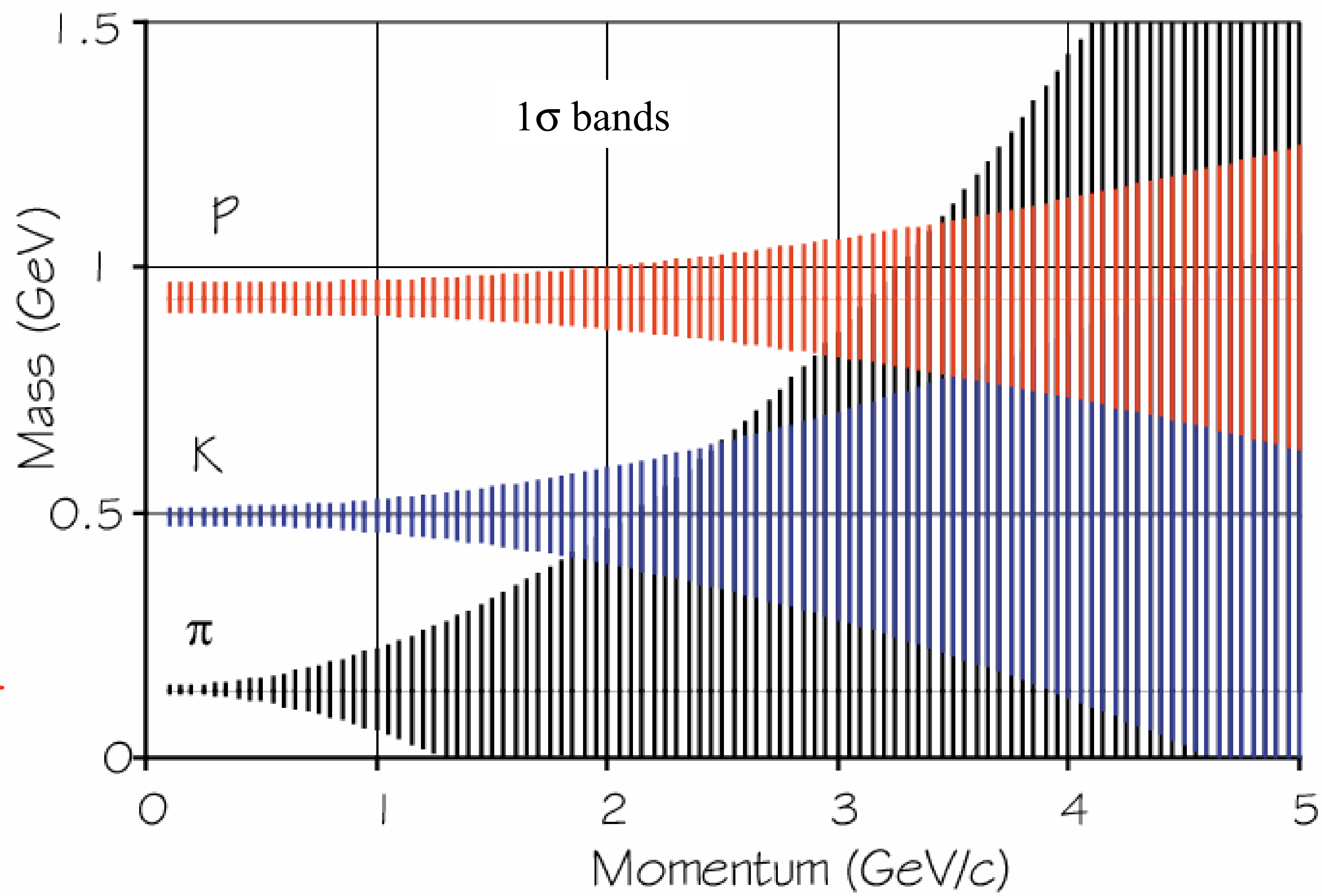
## A practical example: TOF




**For**

| | |
|---|---|
| $l$ | 12 m |
| $\Delta t$ | 150 ps |
| $\Delta p/p$ | 1 % |

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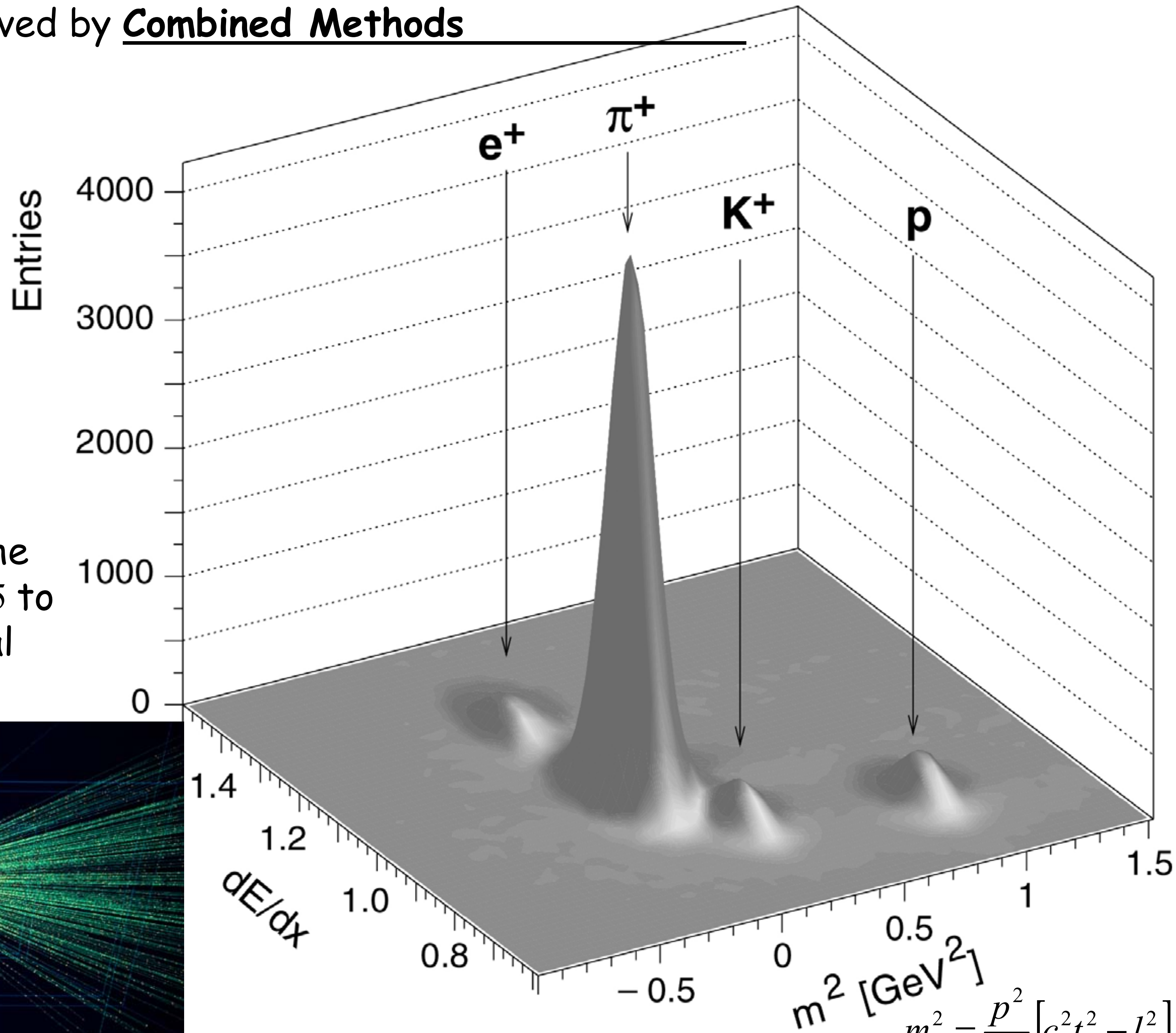
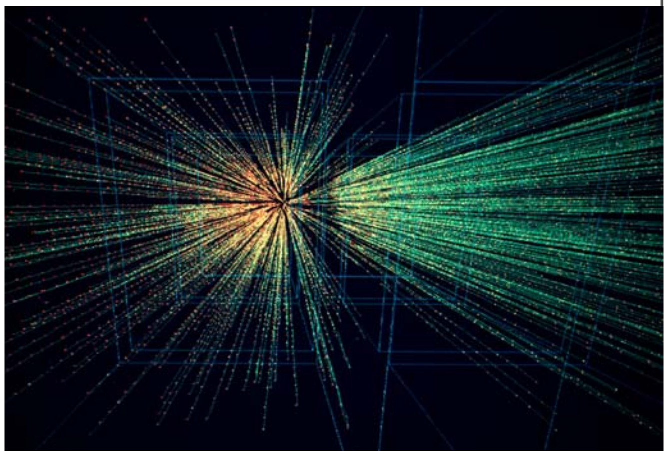
what can be achieved by **Combined Methods**

NA49

Particle identification by simultaneous *dE/dX* and TOF measurement in the momentum range 5 to 6 GeV/$c$ for central Pb+Pb collision




$$m^2 = \frac{p^2}{l^2}\left[c^2t^2 - l^2\right]$$



NA49, CERN-EP/99-001

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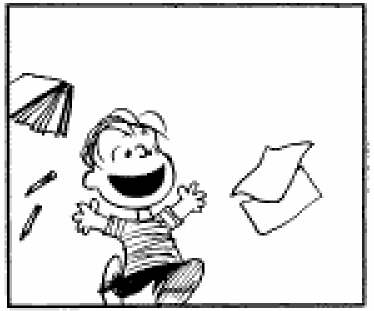
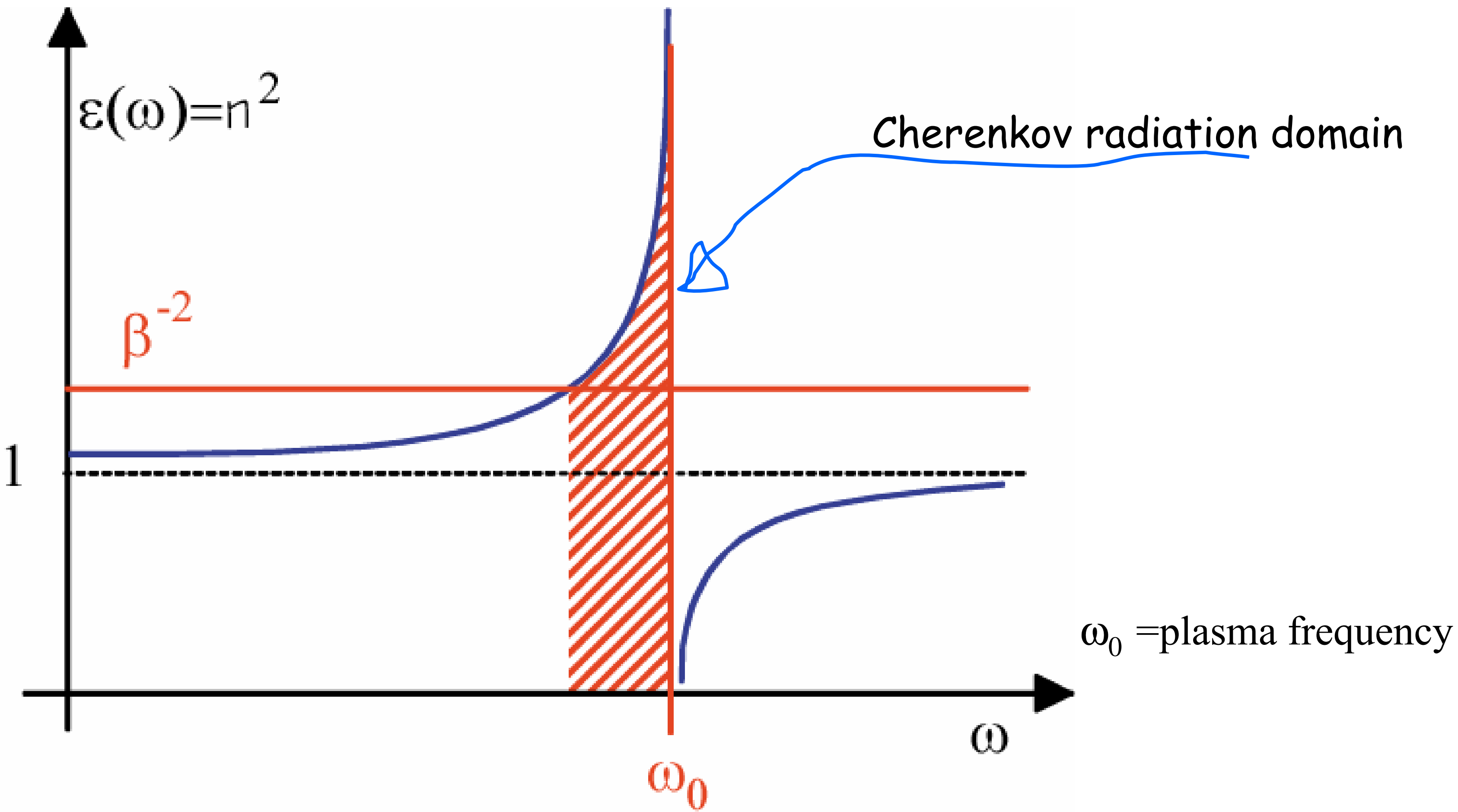
That was all
planned for this lecture



What is ______Transition Radiation__________?




If $\varepsilon<1$ no real photon can be emitted for an infinite long radiator. Due to diffraction broadening, sub-threshold emission of real photons in thin radiators.

This is transition radiation.

________________It is emitted when a charged particle passes suddenly from one medium to another.

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after "some missing" steps:

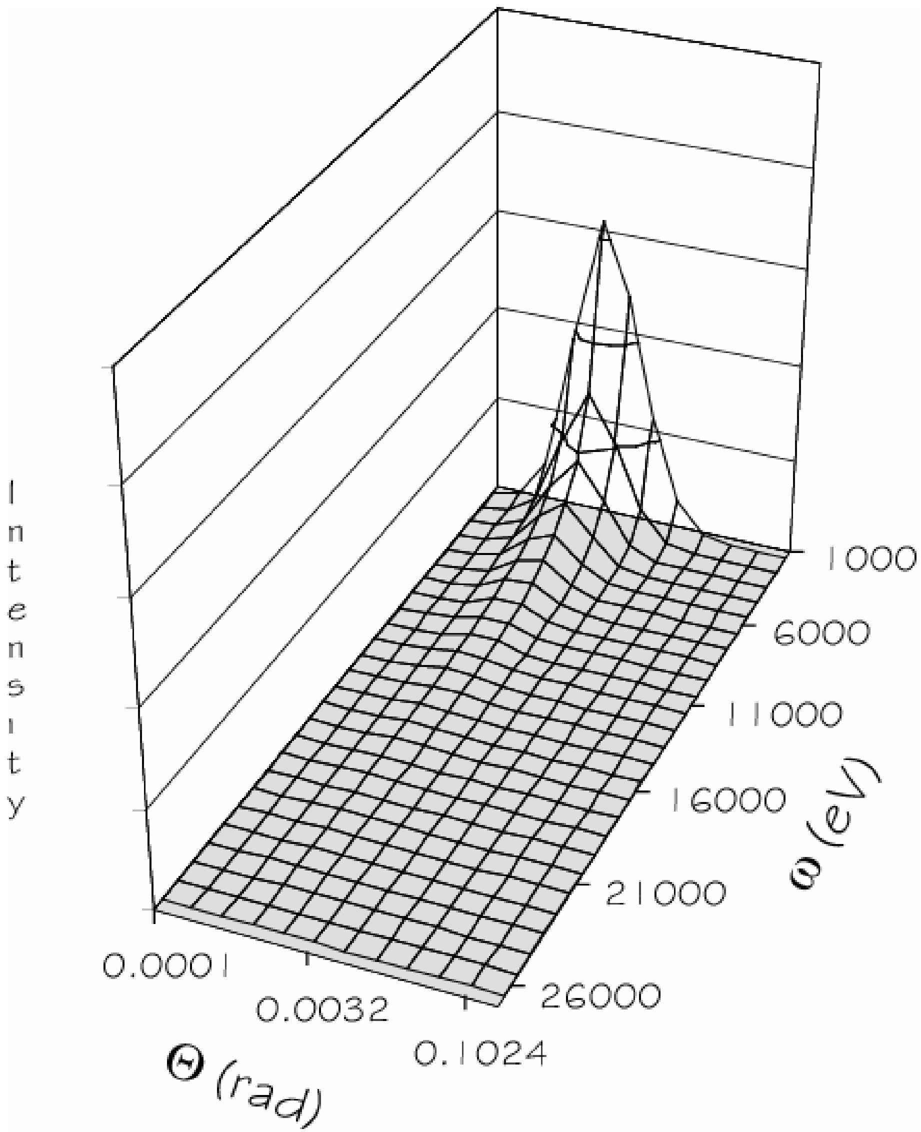
We will just take for granted, that if $\omega >> \omega_0$ then:

$$\frac{d^2 S_0}{d\Theta d\omega} = \frac{2\alpha\hbar\Theta^3}{\pi\omega}\left[\frac{1}{a_1} - \frac{1}{a_2}\right]^2$$

$$a_i = \frac{1}{\gamma^2} + \Theta^2 + \frac{\omega_i^2}{\omega^2}$$

for

| | |
|---|---|
| $\gamma$ | $10^3$ |
| $\omega_1$ | 20 eV |
| $\omega_2$ | 0 |




For all the missing steps:
see J.D. Jackson, Classical Electrodynamics, Section 13 or equivalent

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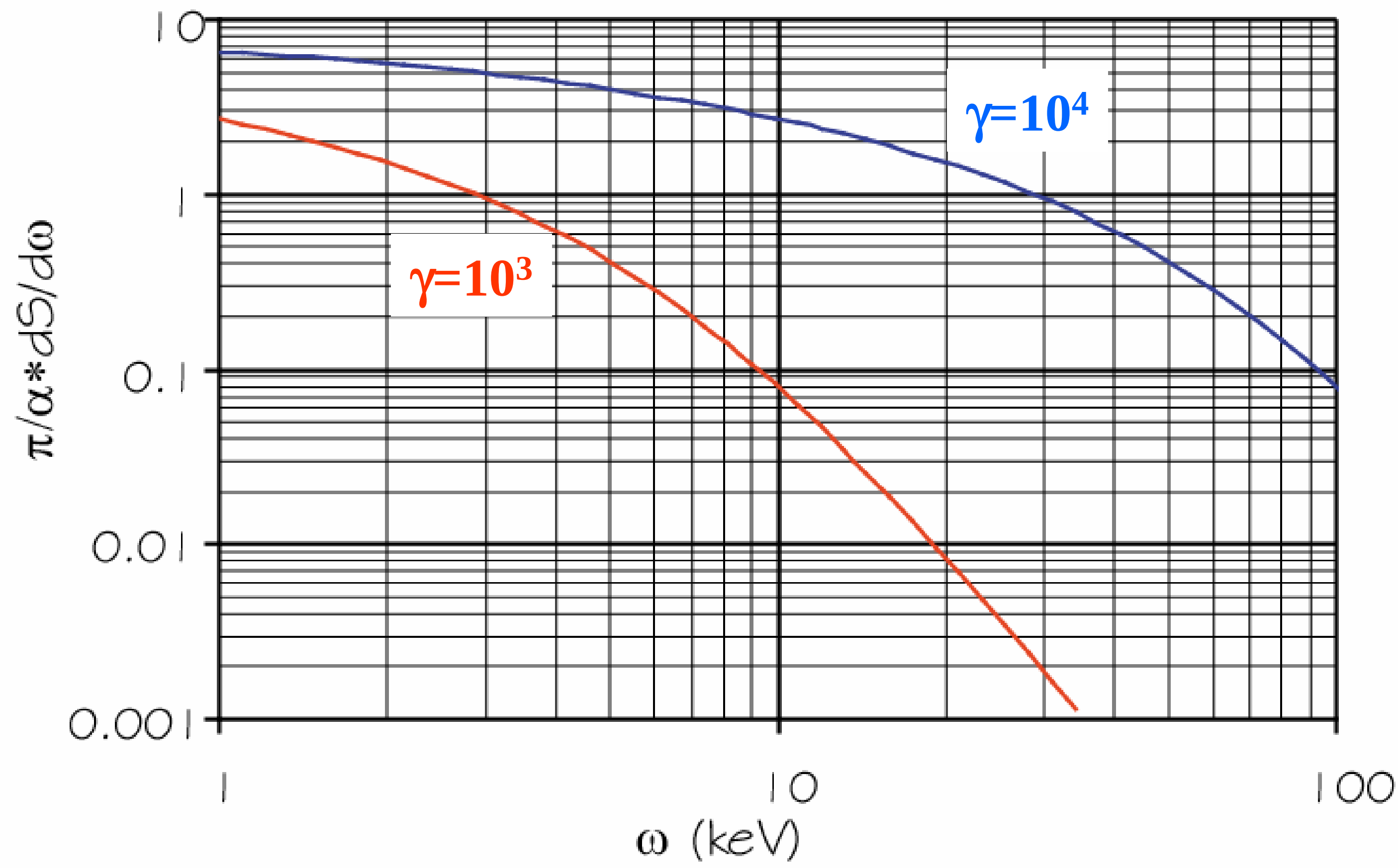
# Direction and magnitude of the radiated power




Total radiated power $S \approx 10^{-2}\,\gamma\,(eV)$

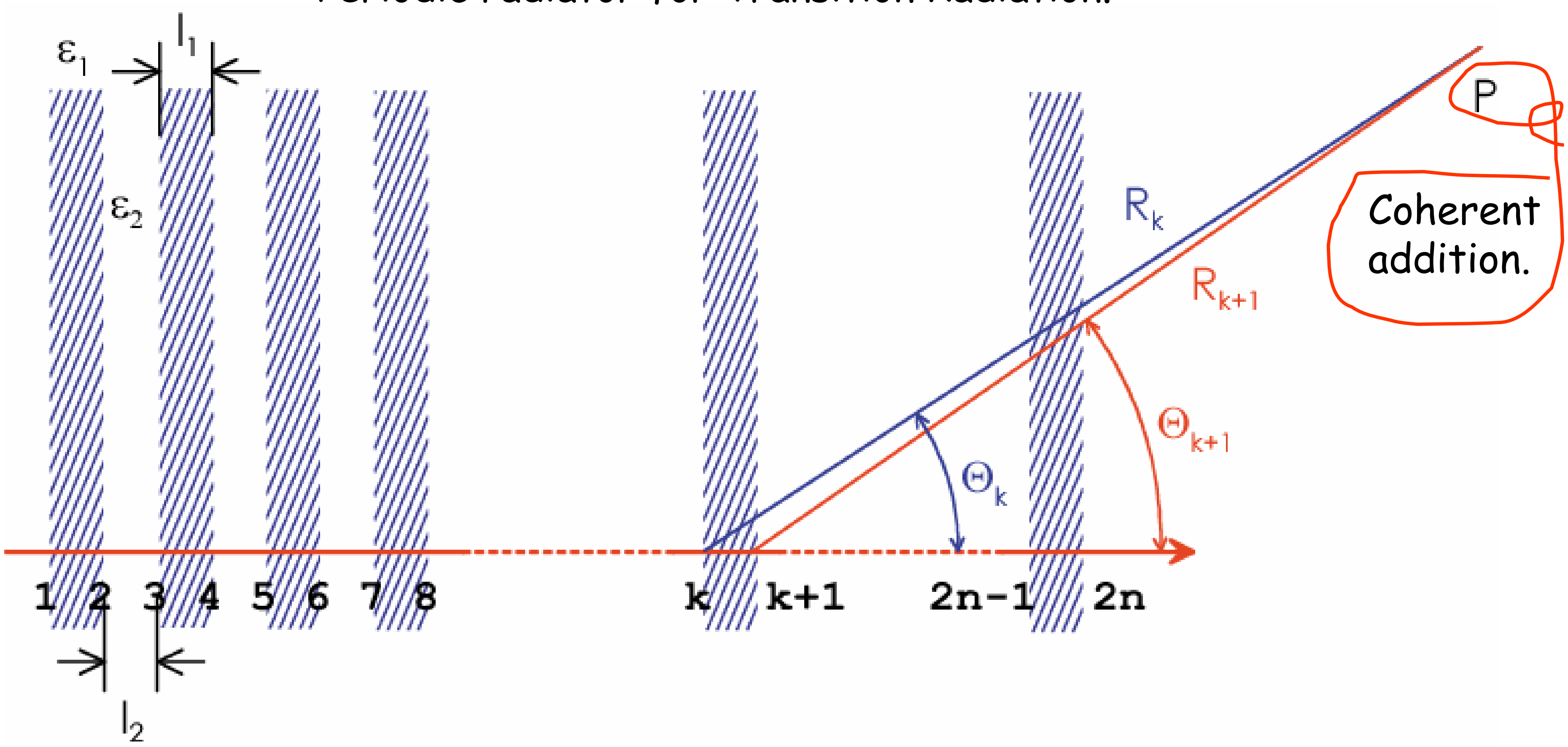
→ which is a small number

and if $\omega_{p2} > \omega_{p1}$ then $\Theta_{max} \approx \gamma^{-1}$

→ which is also a small number

from a small number to something that is detectable.

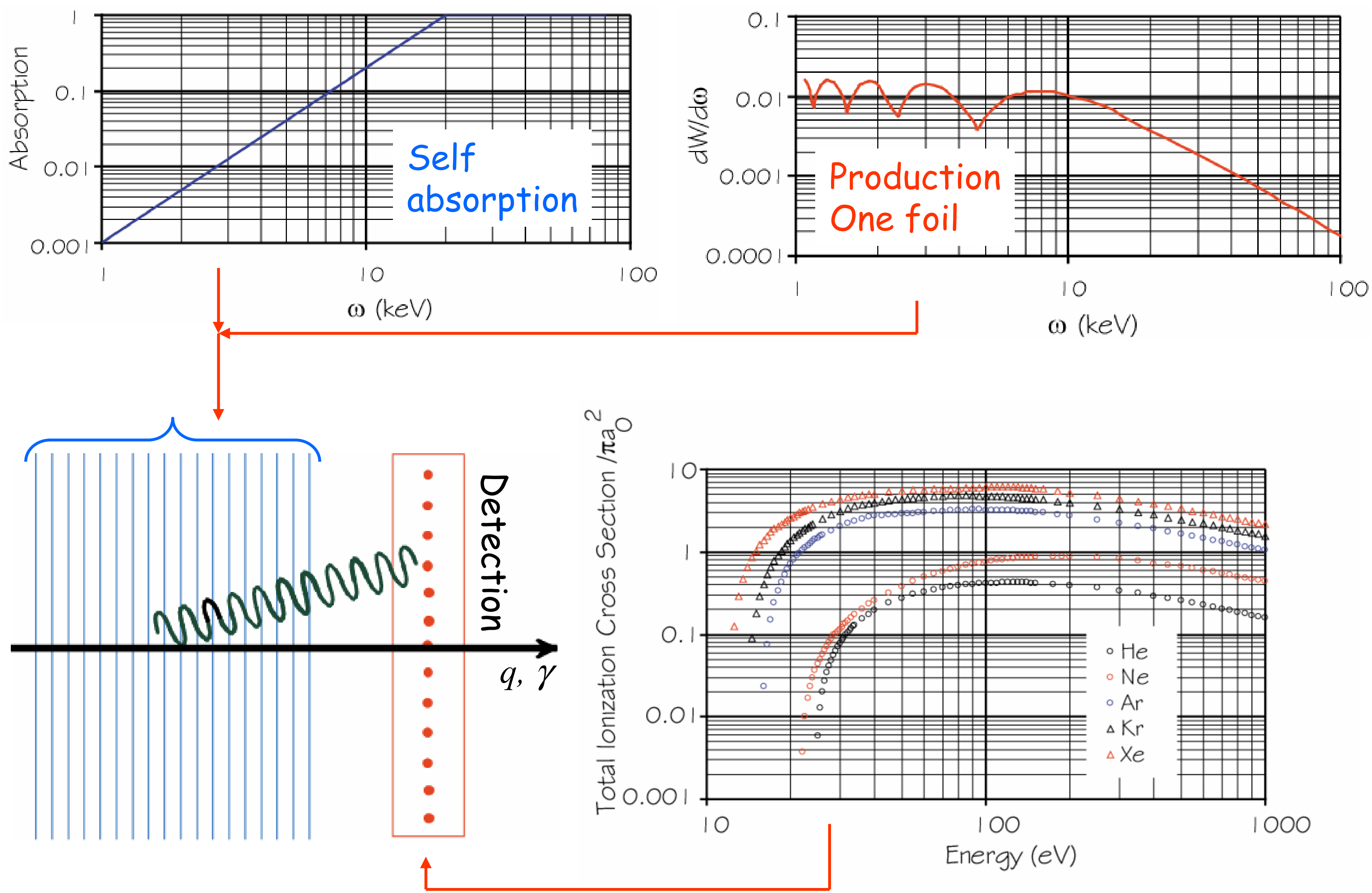
Periodic radiator for Transition Radiation.




a good place to start:

Egorytchev, V ; Saveliev, V V ;Monte Carlo simulation of transition radiation and electron identification for HERA-B ITEP-99-11. - Moscow : ITEP , 17 May 1999.

# Some ++ and some −− in the detection of Transition Radiation.

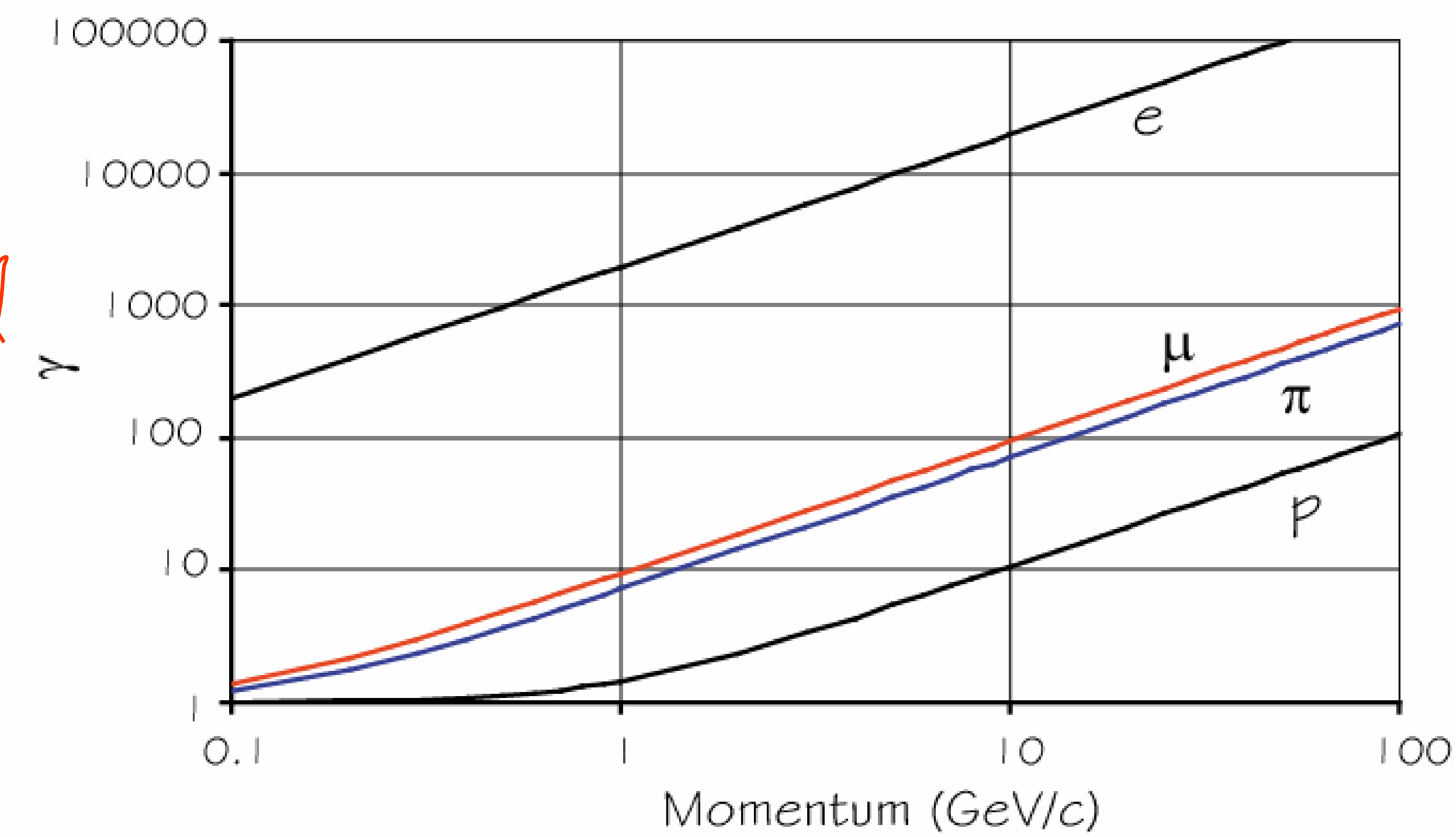



M.L. Cerry et al., Phys. Rev. 10(1974)3594

O. Ullaland/2006

$$\{\text{Total Radiated Power}\} \propto \gamma$$

$$\frac{\{\text{Ionisation}\} + \{\text{Detected Transition Radiation}\}}{\{\text{Ionisation}\}} \cong Z^{-7/2}$$




Transition radiation detectors are (normally) used for $e$ to $\pi$ separation

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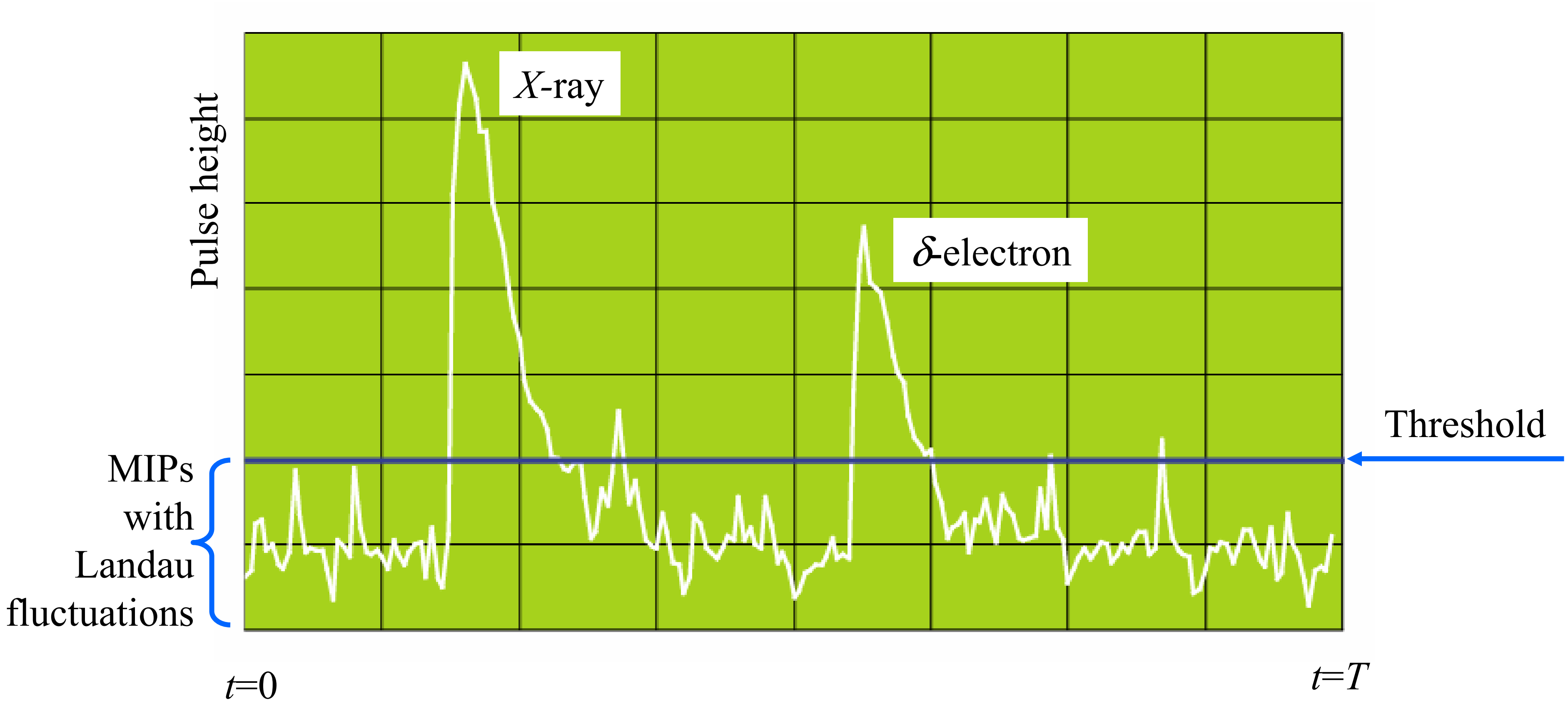
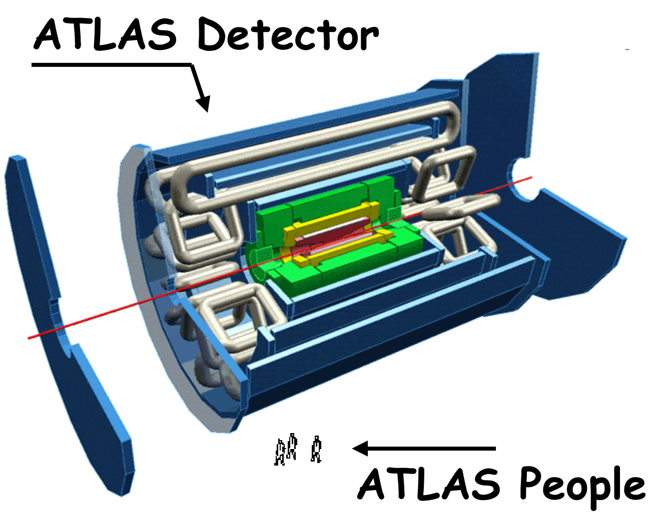
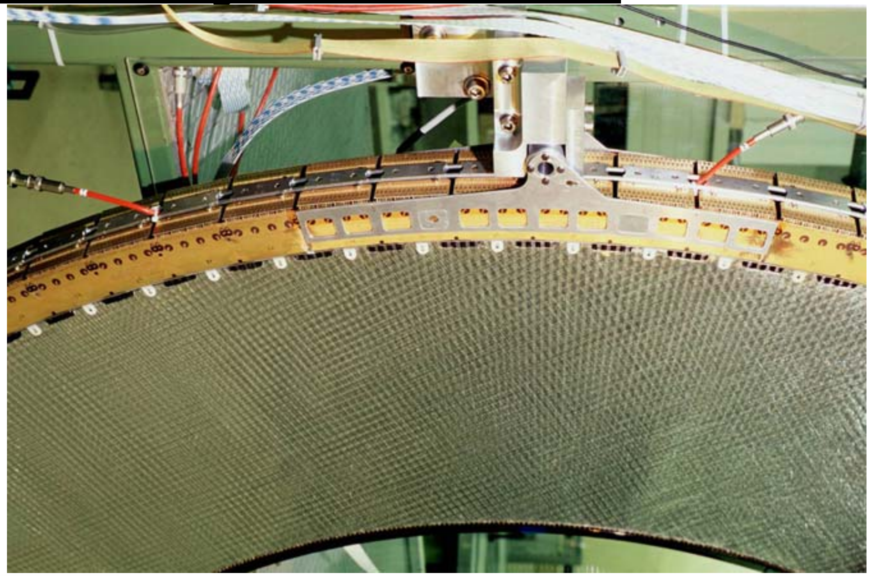
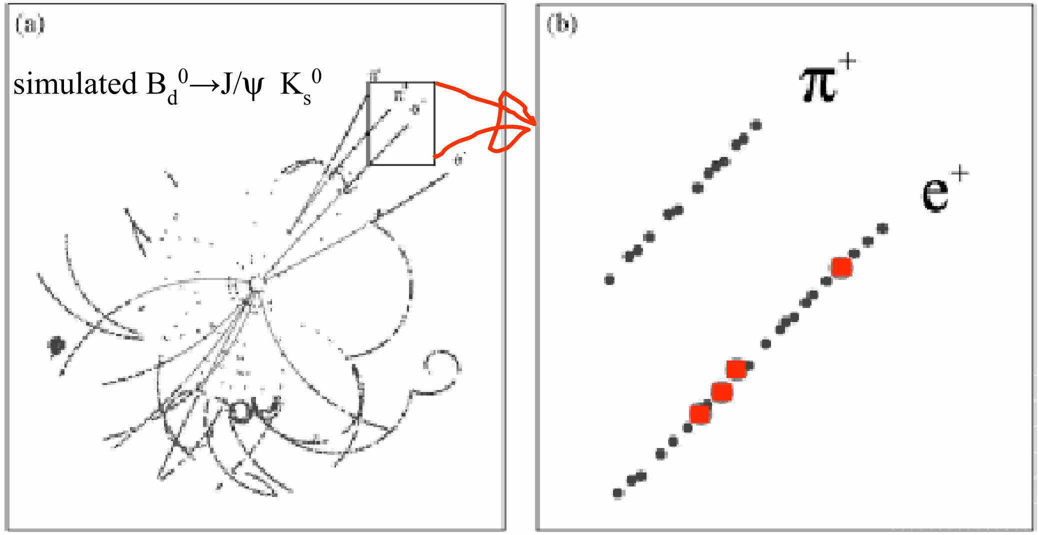
## The challenge:



## and just an example of one who pick up the challenge

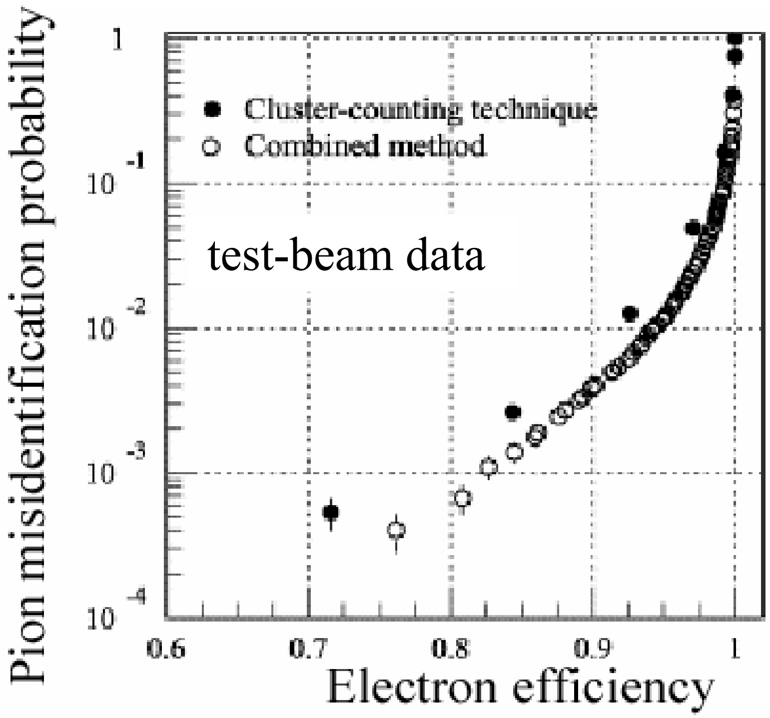




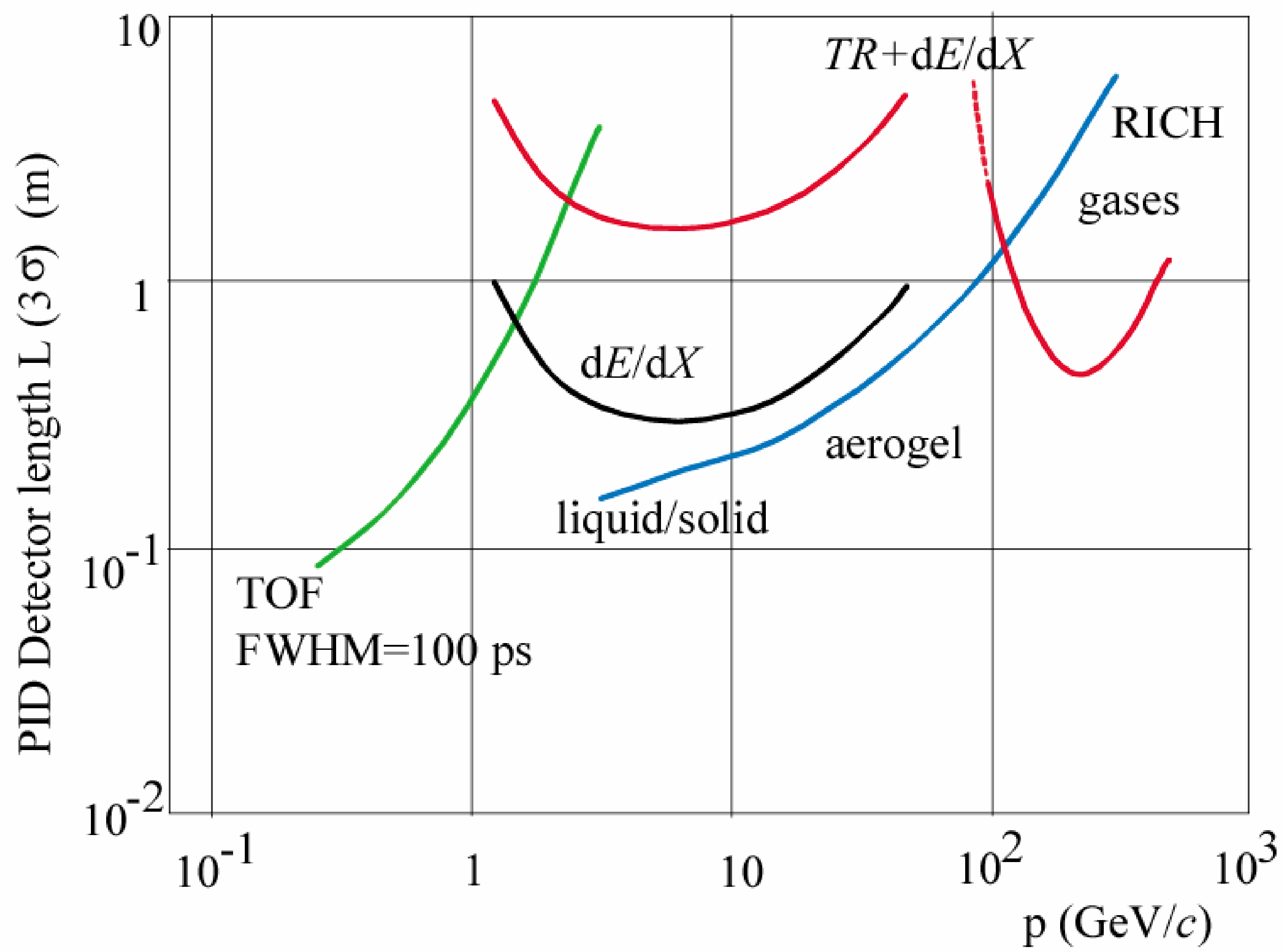

The small box selects a part of a pion track from the $K_s^0$ decay and of an electron track from a $J/\psi$ decay, shown in an enlarged frame.

NIM A 474 (2001) 172–187



A little summary about Particle Identification

**Pion-Kaon separation for different PID methods.**
**The length of the detectors needed for 3σ separation.**




Dolgoshein, NIM A 433 (1999)

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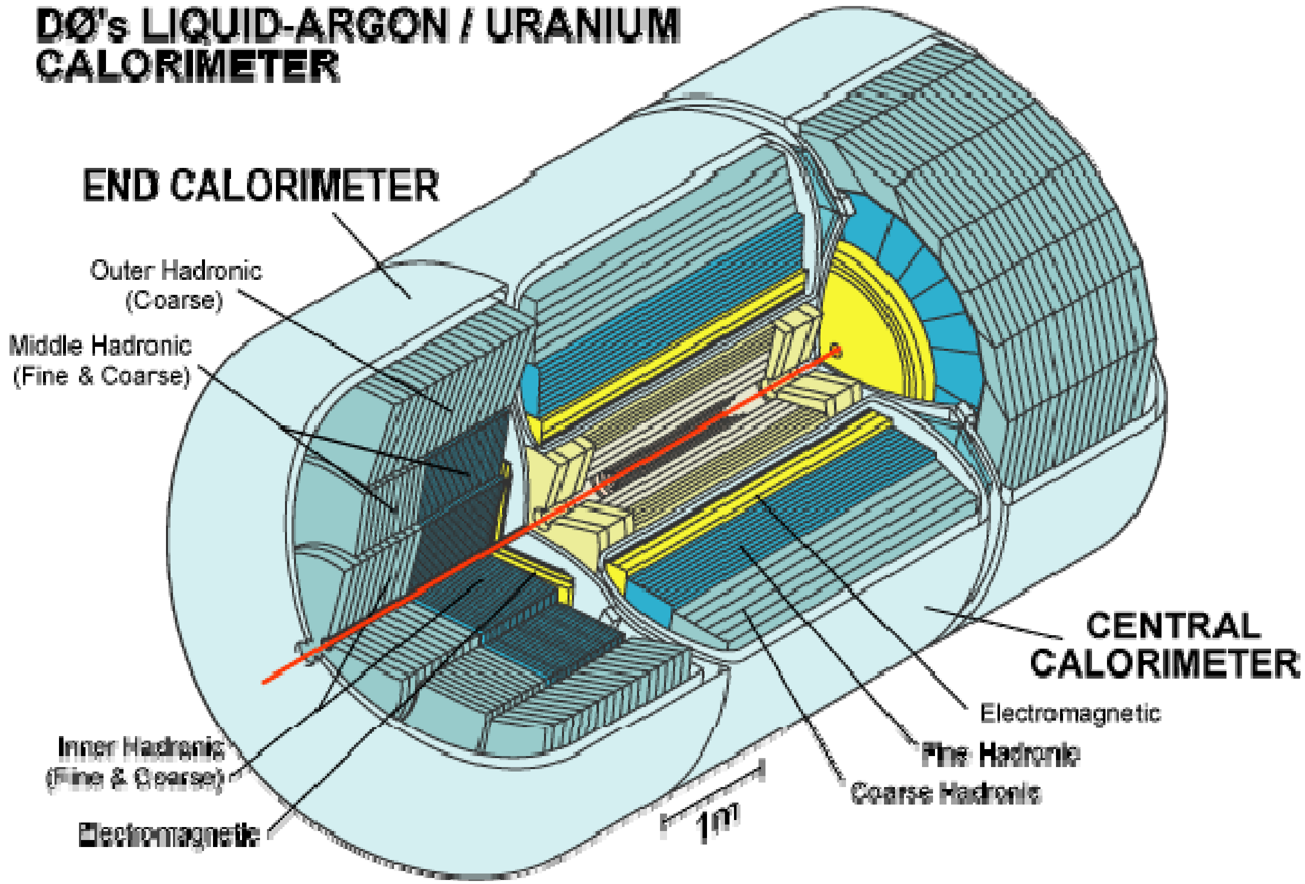
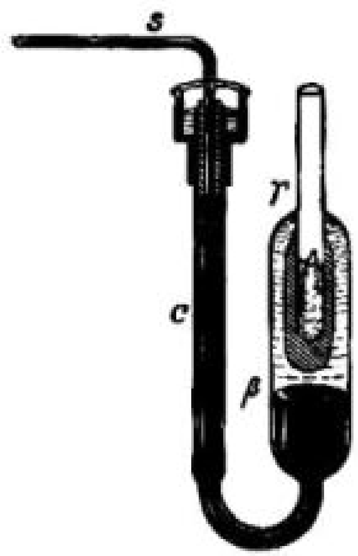
______Calorimeters
______Measurement of energy flow
______Measurement of neutral particle

**Electromagnetic Calorimeters______**
**Hadronic Calorimeters___________**

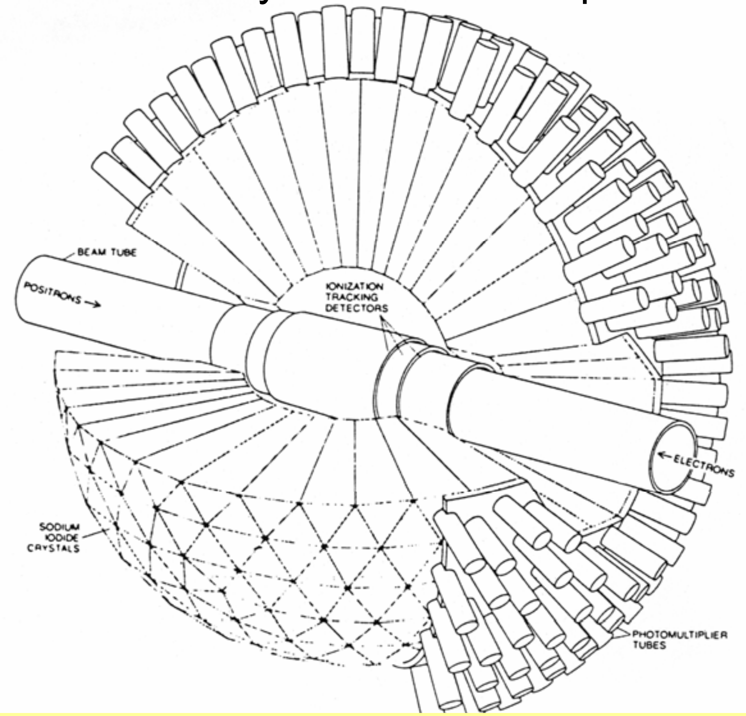


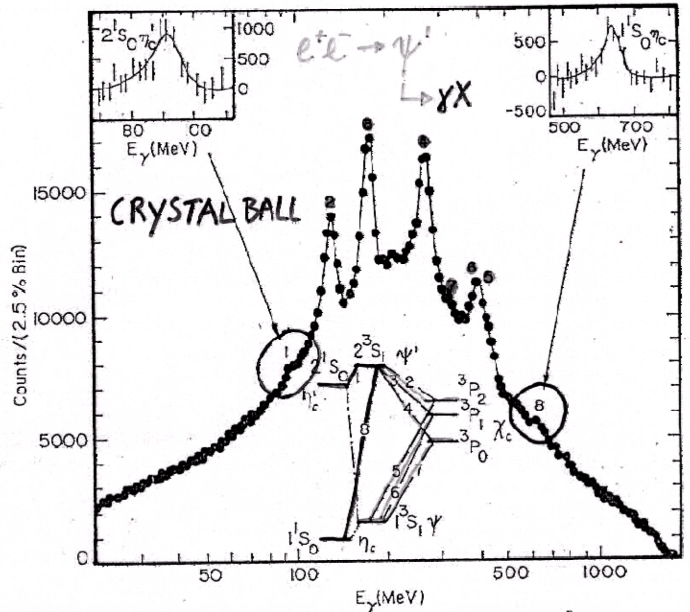




Bunsen's
ice calorimeter

# Crystal Ball @ SPEAR - Stanford

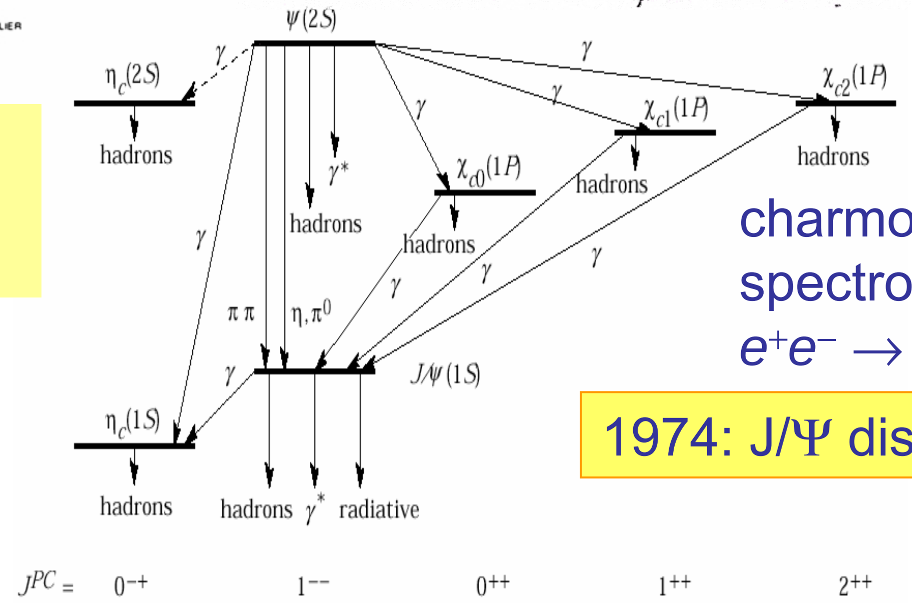
The first crystal calorimeter pioneering most of the features of modern barrel calorimeters




- 672 + 60 NaI(Tl) crystals
- PM read out
- $E_\gamma$ range 0.1→ 1 GeV

- **energy resolution:**
  **3.5% @ 300 MeV**
  **2.6% @ 1 GeV**
- **solid angle: 93% over 4π**

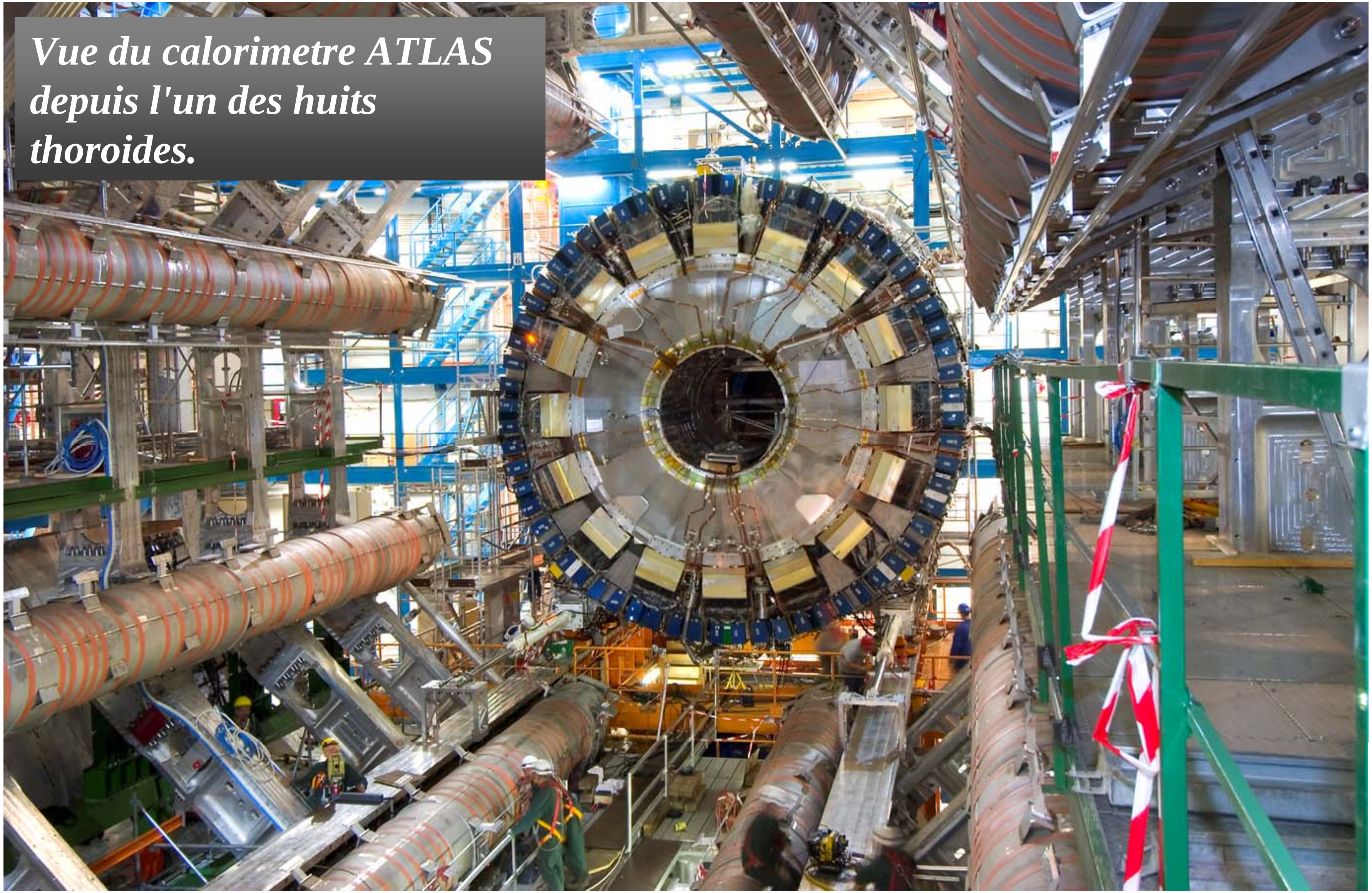



charmonium spectroscopy:
$e^+e^- \to \Psi' \to \gamma X$

1974: J/Ψ discovery

From M. Diemoz, Torino 3-02-05

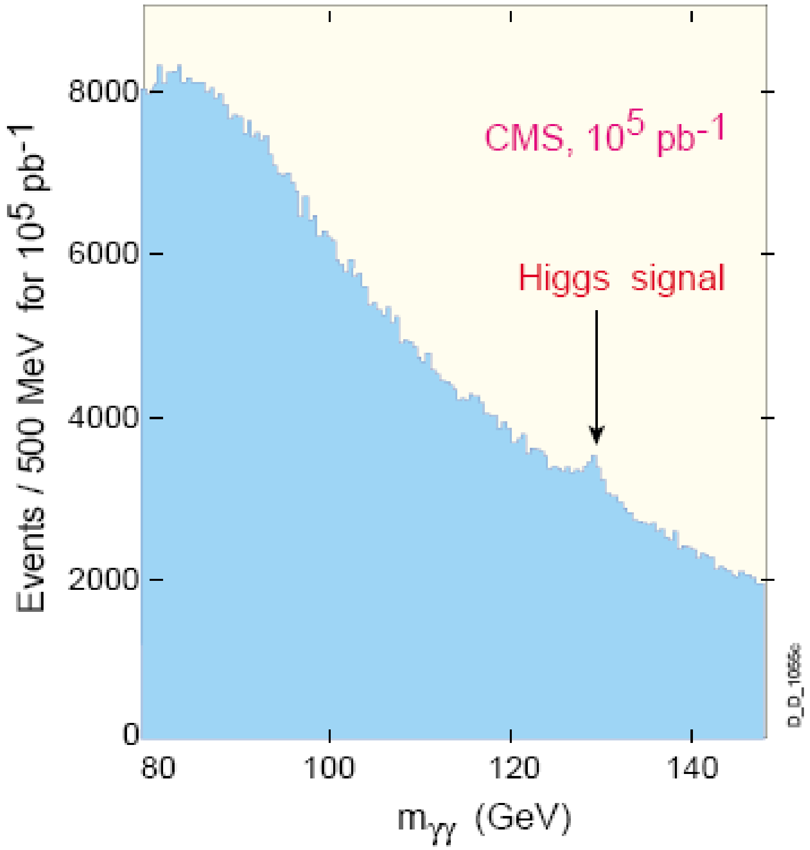
O. Ullaland/2006

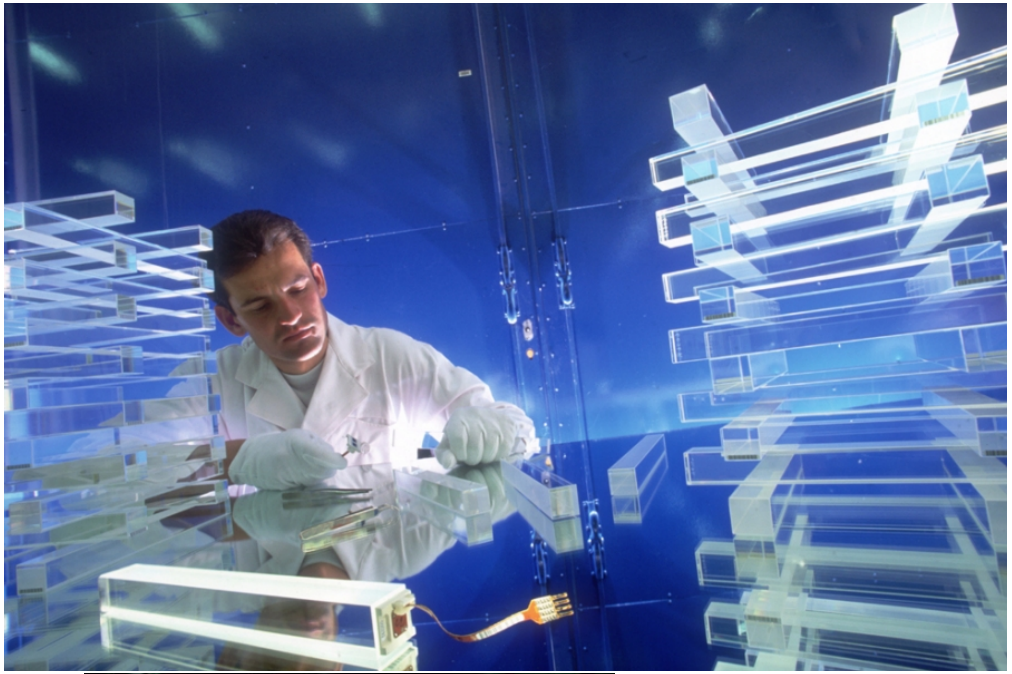


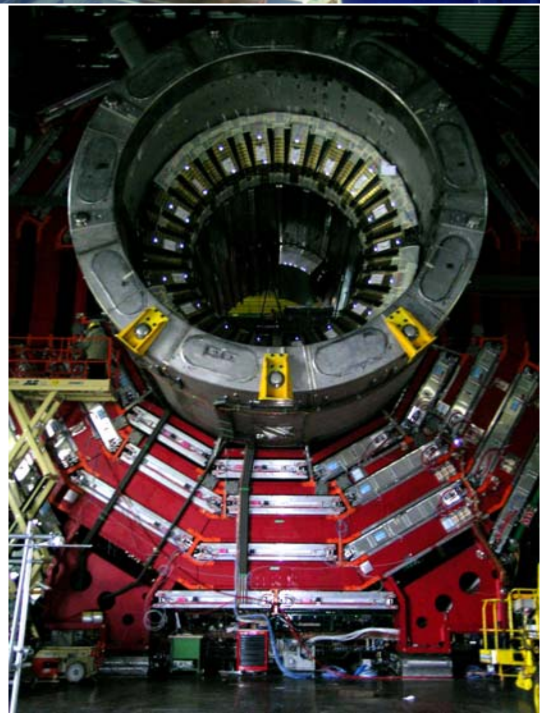
*Vue du calorimetre ATLAS depuis l'un des huits thoroides.*

O. Ullaland/2006

Simulated two-photon mass distribution for **SM Higgs** and expected background in the **CMS PbWO4** crystal calorimeter for an integrated luminosity of **$10^5$ pb$^{-1}$**, with detailed simulation of calorimeter response.



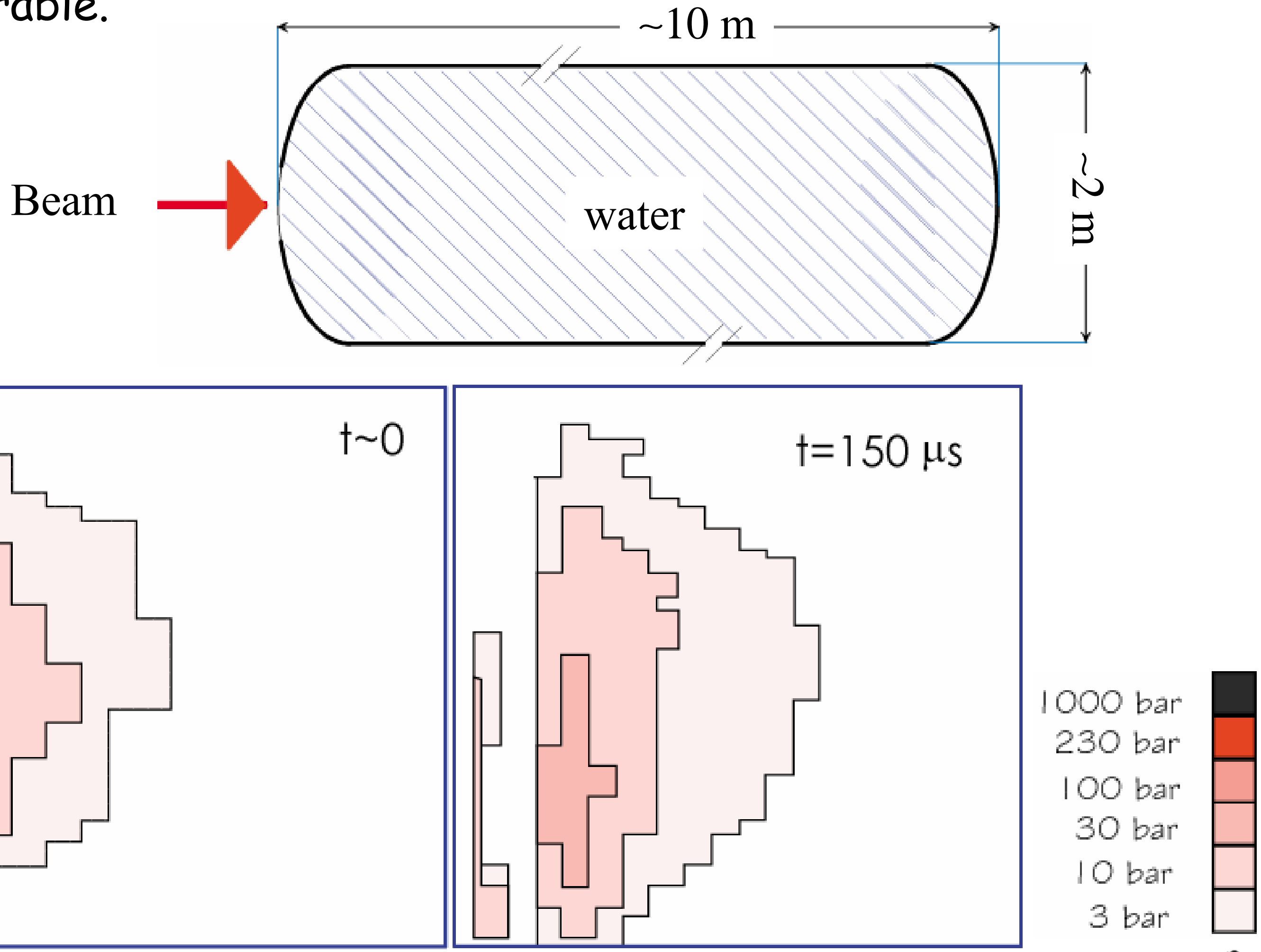


O. Ullaland/2006

The growth and the decay of a shower is a tremendously complex statistical process where several physical mechanisms participate.

The net result is however that the initiating particle is expanded in ionization and ultimately in heat.

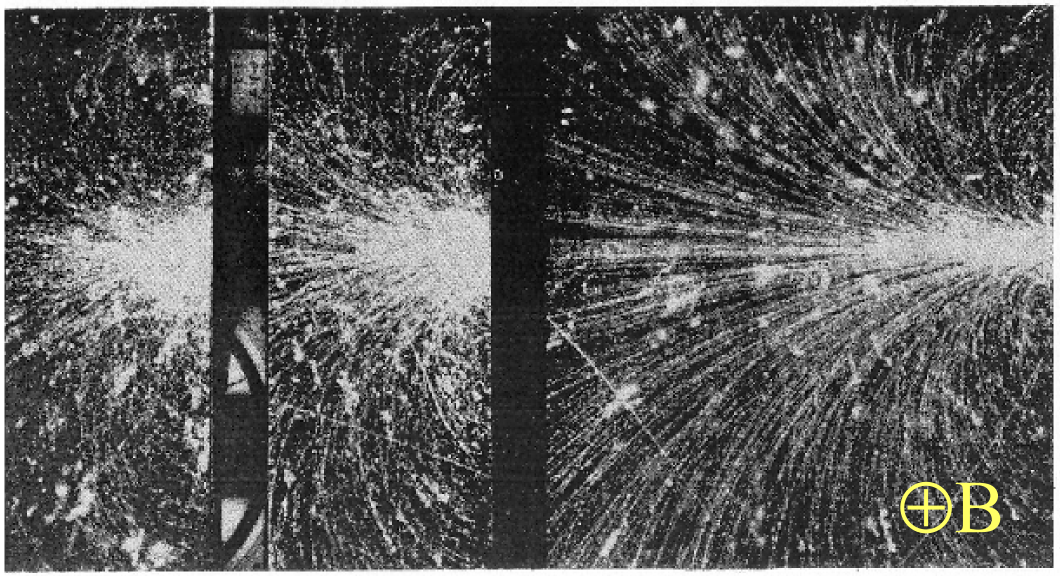
The temperature gradient and the shock wave accompanying is measurable.



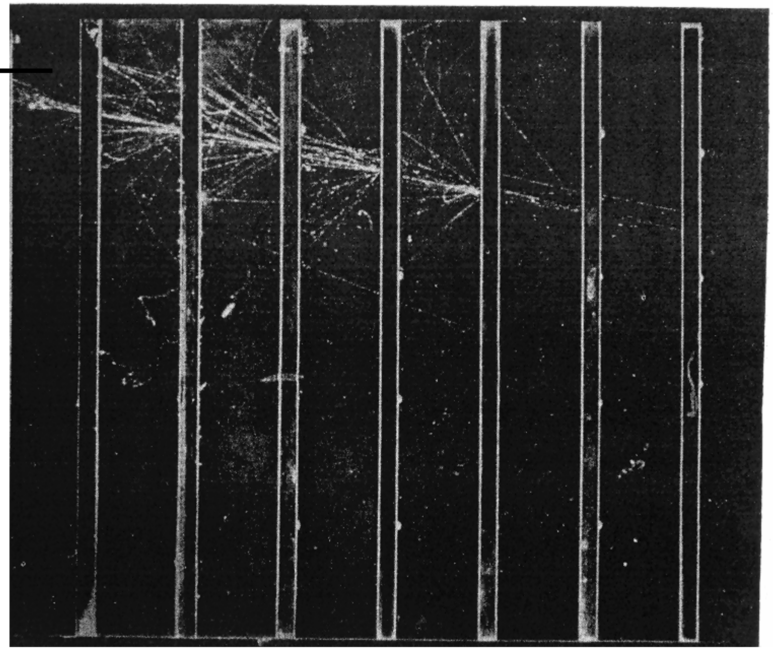

C. Hauviller, private communication, see also IEEE 26(1979)4134

O. Ullaland/2006

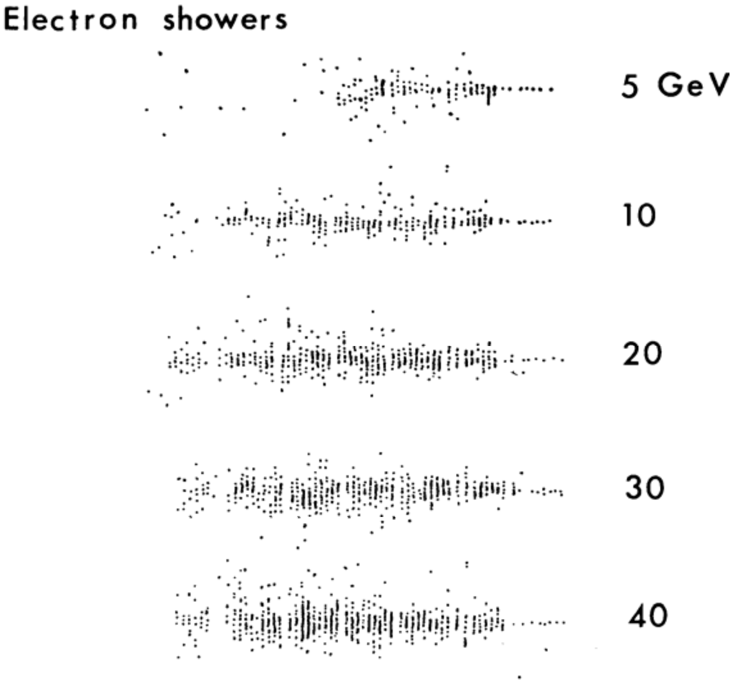
## How a shower looks like

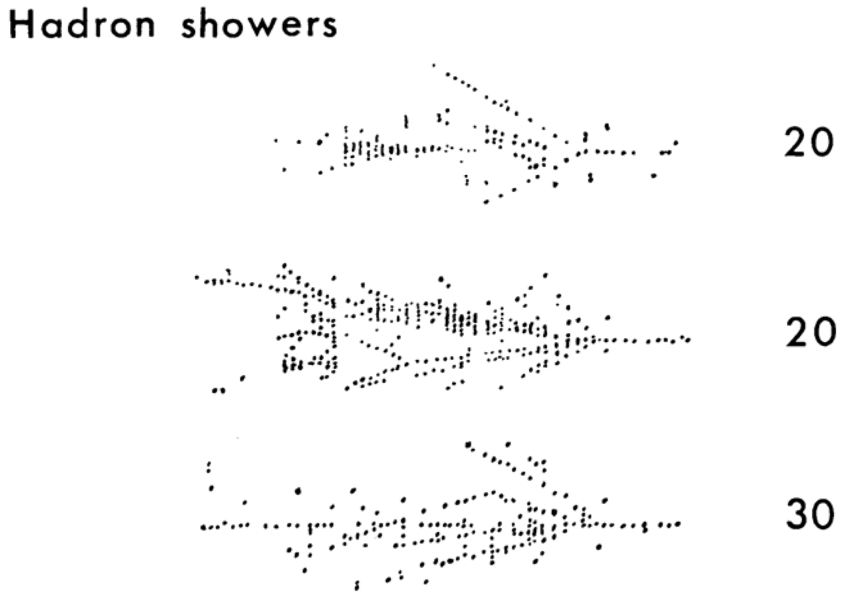



Electron shower in lead. 7500 gauss in cloud chamber. CALTECH



Electron shower in lead. Cloud chamber. W.B. Fretter, UCLA




F.E. Taylor et al., IEEE NS 27(1980)30

O. Ullaland/2006

## We will only look at some (very) basic processes.

For (more) interested people, look in:

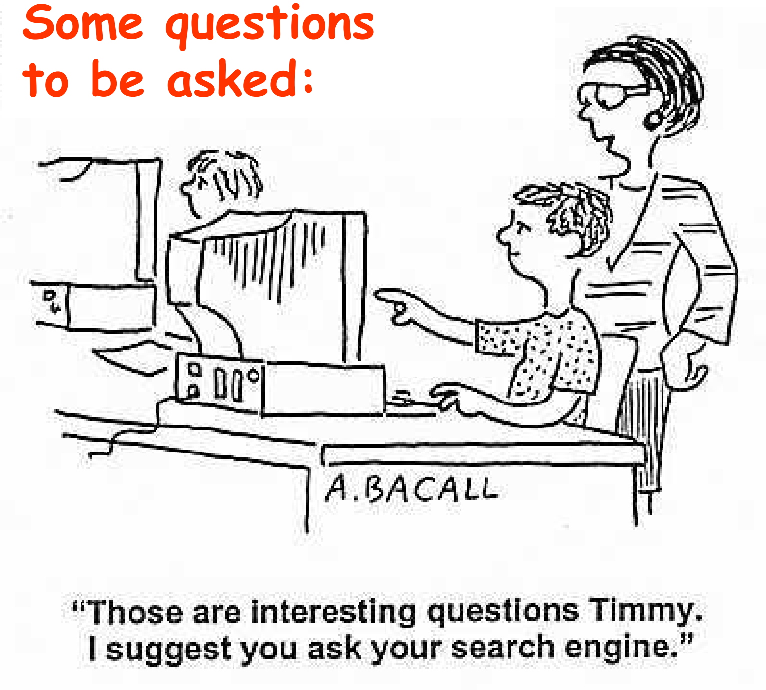
J.P. Wellisch, Physics of shower simulation at LHC, at the example of GEANT4.
http://agenda.cern.ch/fullAgenda.php?ida=a036558#2004-03-01

M. Diemoz, Calorimetri elettromagnetici a cristalli per la fisica delle alte energie.
http://www.gsr.unito.it/trasparenze2005.html

and then try

Richard Wigmans, Calorimetry, Energy Measurement in Particle Physics

**Some questions to be asked:**

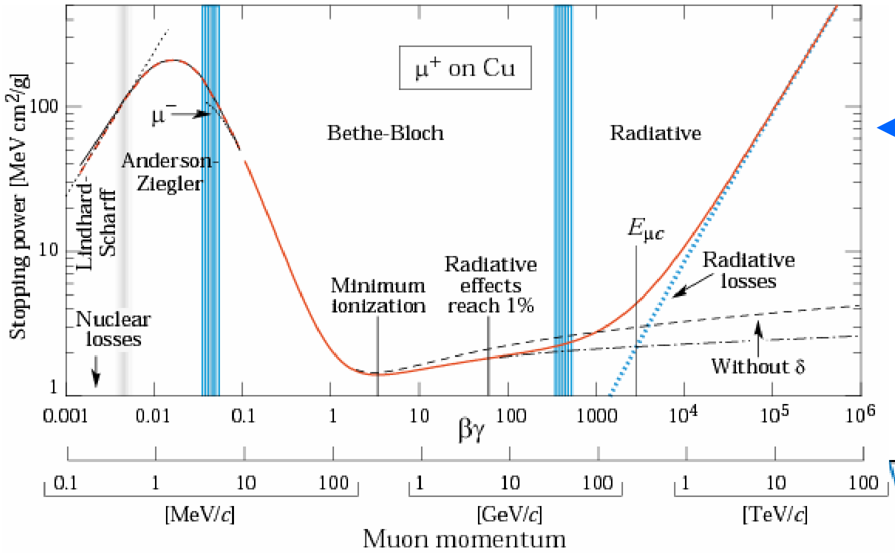



- What makes a signal
- What reacts
- What defines the shower topologies
- What processes are happening
- What defines the electromagnetic content in a hadronic shower
- What is invisible energy
- How different are different calorimeters

and so on

and so on ........

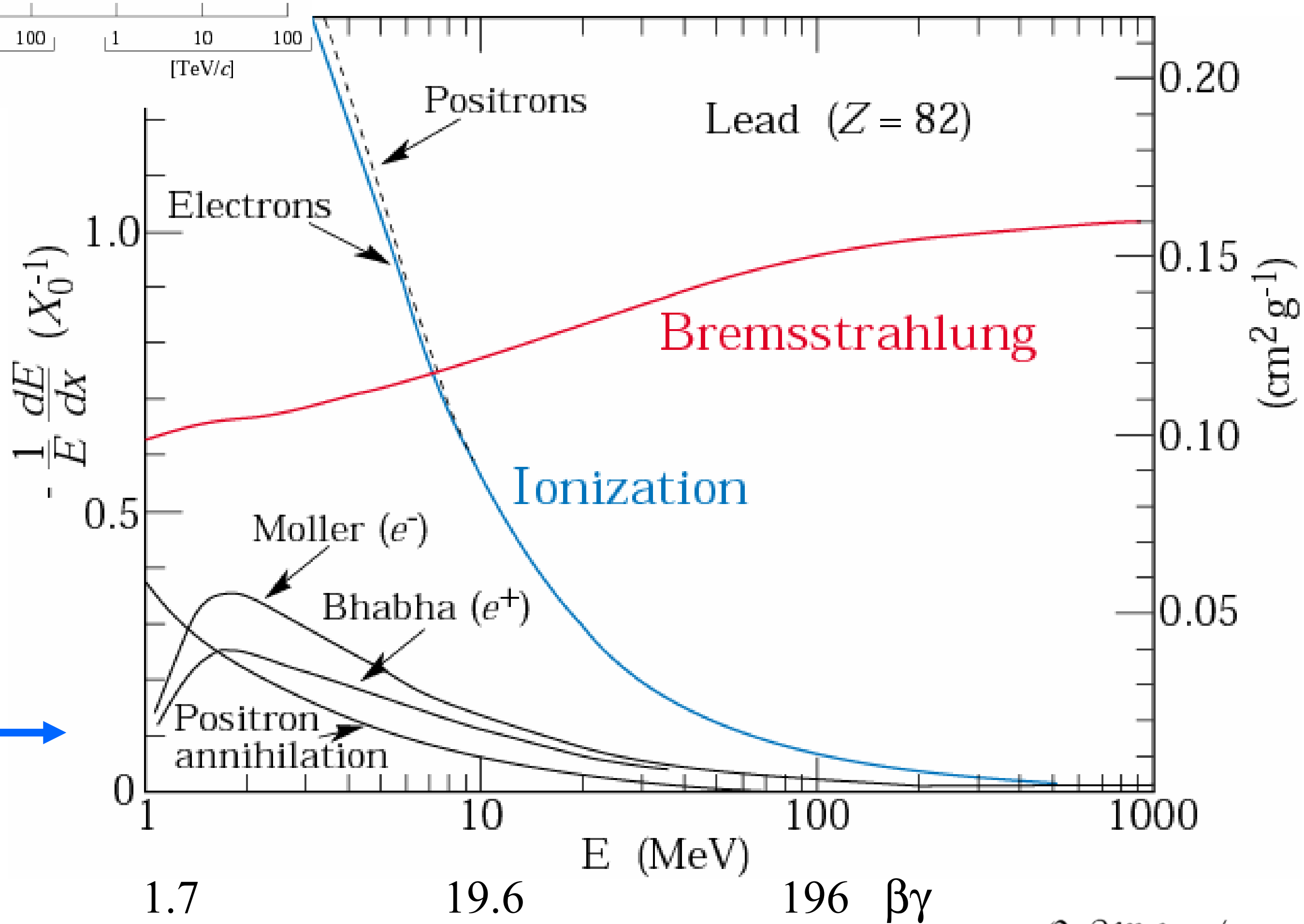
**We will start off with the electromagnetic shower.**




Bethe-Bloch for heavy particles.

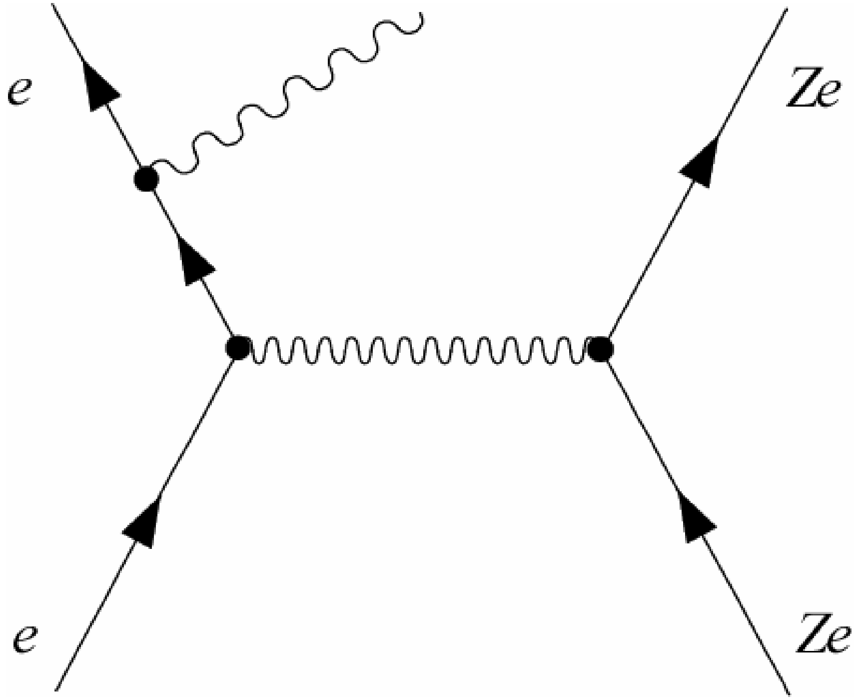
$$Stopping\ Power \equiv \frac{dE}{dx} \equiv E \cdot \rho \frac{1}{X_0}$$

Electron (positron) interaction with matter.




O. Ullaland/2006

## Bremsstrahlung




Bremsstrahlung is the emission of photons by a charged particle accelerated in the Coulomb field of a nucleus.

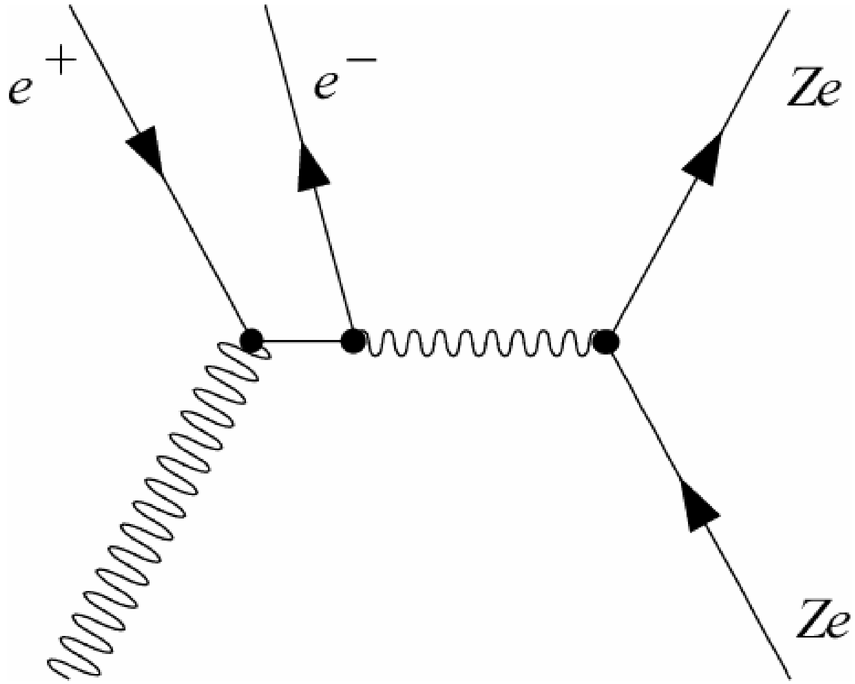
The radiative process is characterised by:

| | |
|---|---|
| Impact parameter : | $b$ |
| (non-relativistic!) | |
| Peak electric field prop. to | $e/b^2$ |
| Characteristic frequency | $\omega_c \propto 1/\Delta t \propto v/2b$ |

$$\frac{d\sigma_B}{d\omega} \propto \frac{Z^2}{\omega} \quad \rightarrow \quad \sigma_B \approx 0.58 \cdot Z^2 \ (mb)$$

We now have an additional photon.

# Pair production



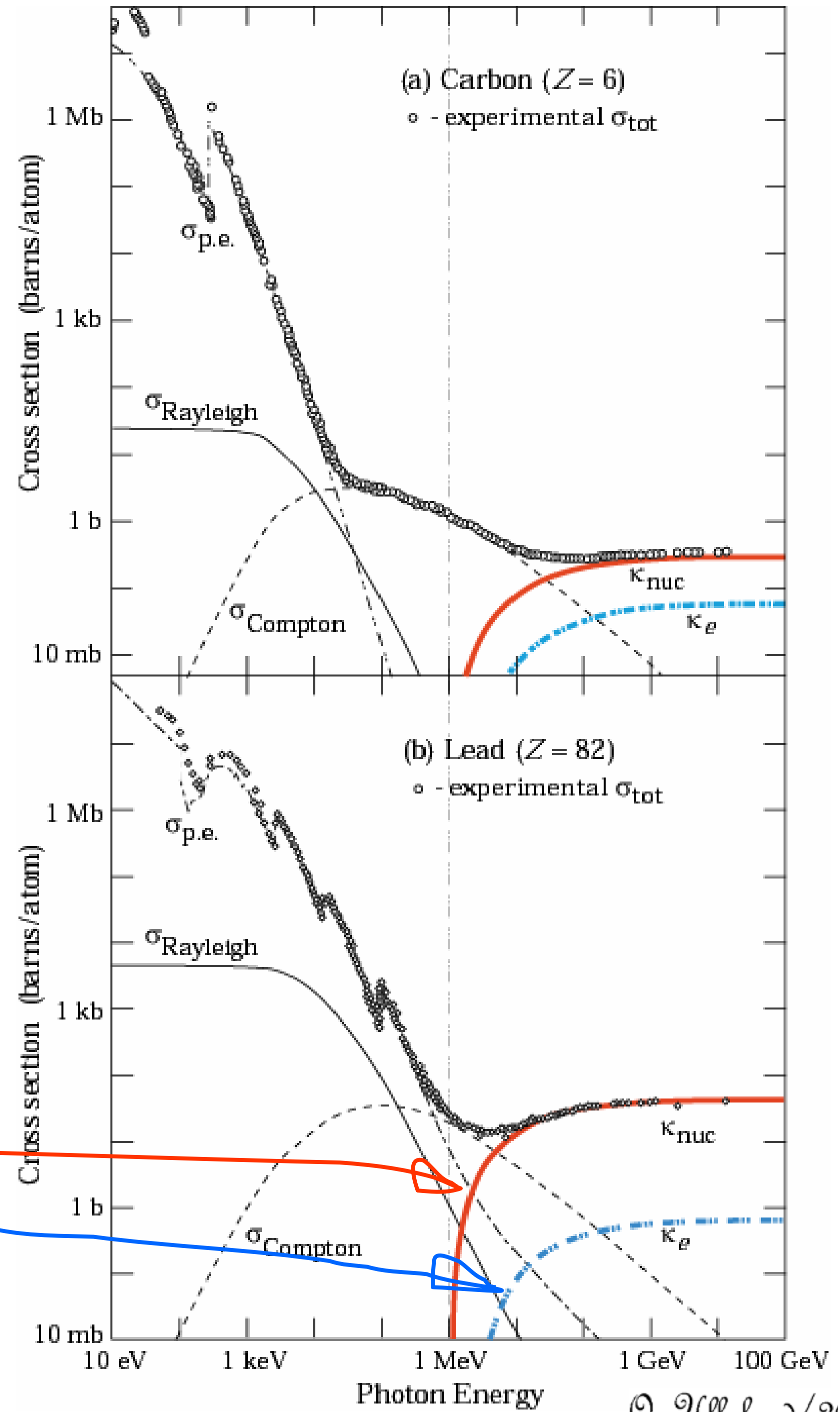

Creation of an electron/positron pair in the field of an atom.

As the two diagrams are more or less identical, we would expect the cross sections to be similar.

$$\sigma_{pair} = \frac{7}{9}\sigma_B \approx 0.45mb \times Z^2$$

## Photon total cross sections

as a function of energy in carbon and lead, showing the contributions of different processes.

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$\sigma_{pe}$ = Atomic photo-effect
(electron ejection, photon absorption)

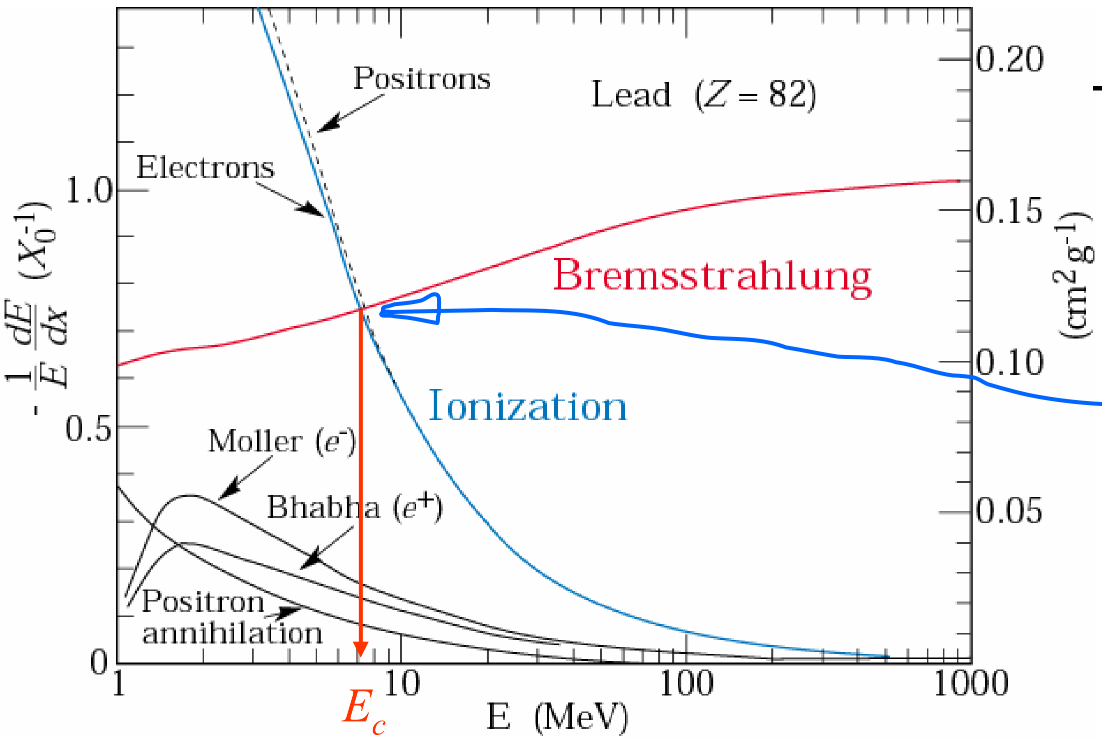
$\sigma_{Rayleigh}$ = Coherent scattering
(Rayleigh scattering-atom neither ionised nor excited)

$\sigma_{Compton}$ = Incoherent scattering
(Compton scattering off an electron)

$\kappa_n$ = Pair production, nuclear field

$\kappa_e$ = Pair production, electron field

## Critical Energy



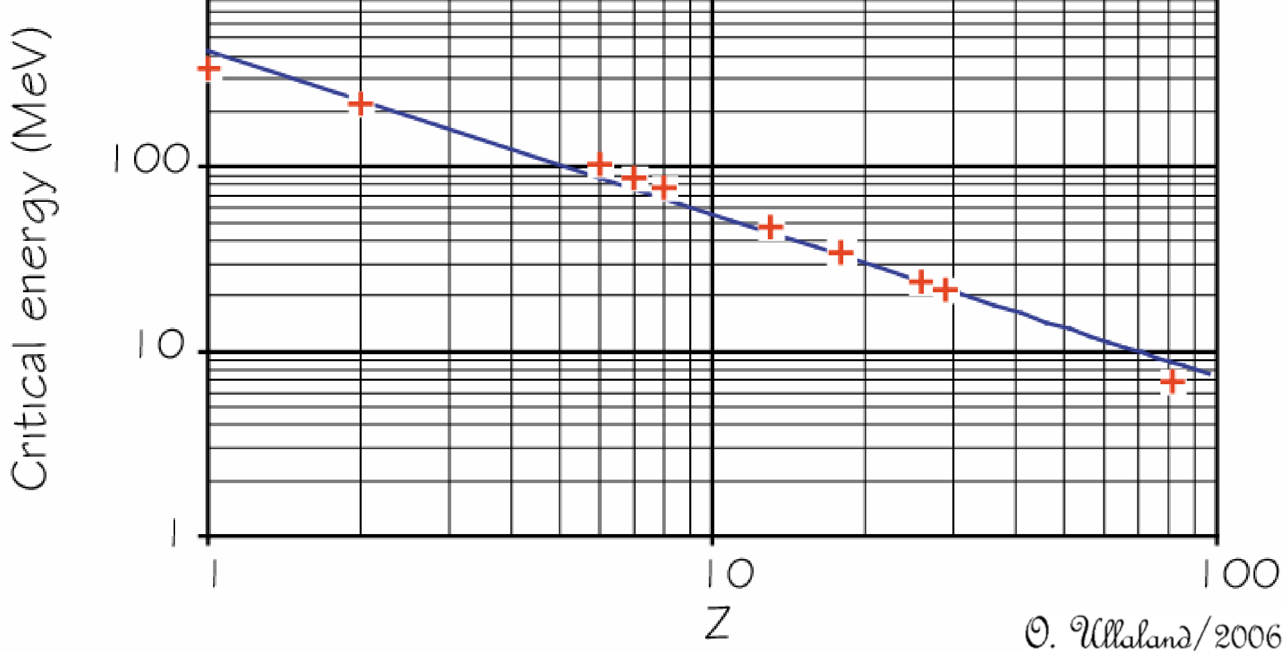

Electron (positron) interaction with matter.

Critical energy

$\boldsymbol{E_c}$

**Ionization = Bremsstrahlung**

$$E_c \propto Z^{-0.9}$$

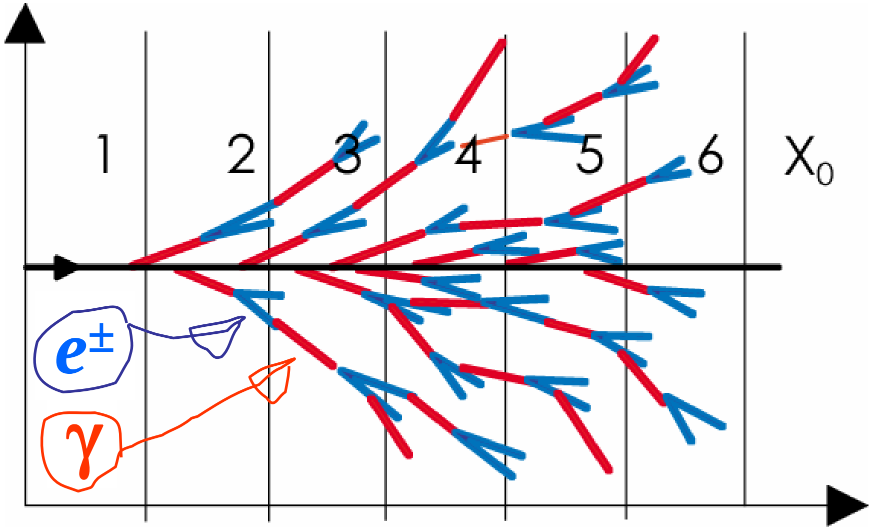


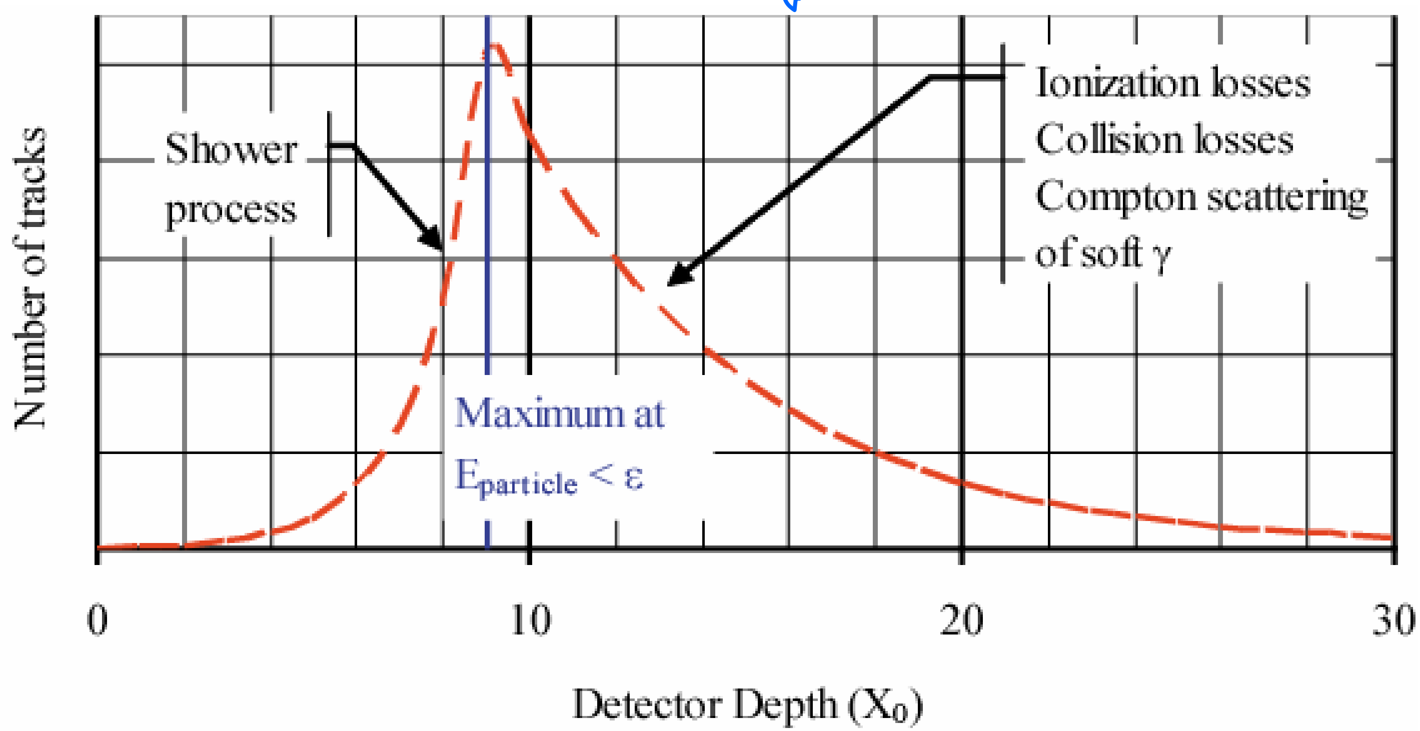
# My first Electromagnetic Calorimeter

Rossi B. Approximation to Shower Development.

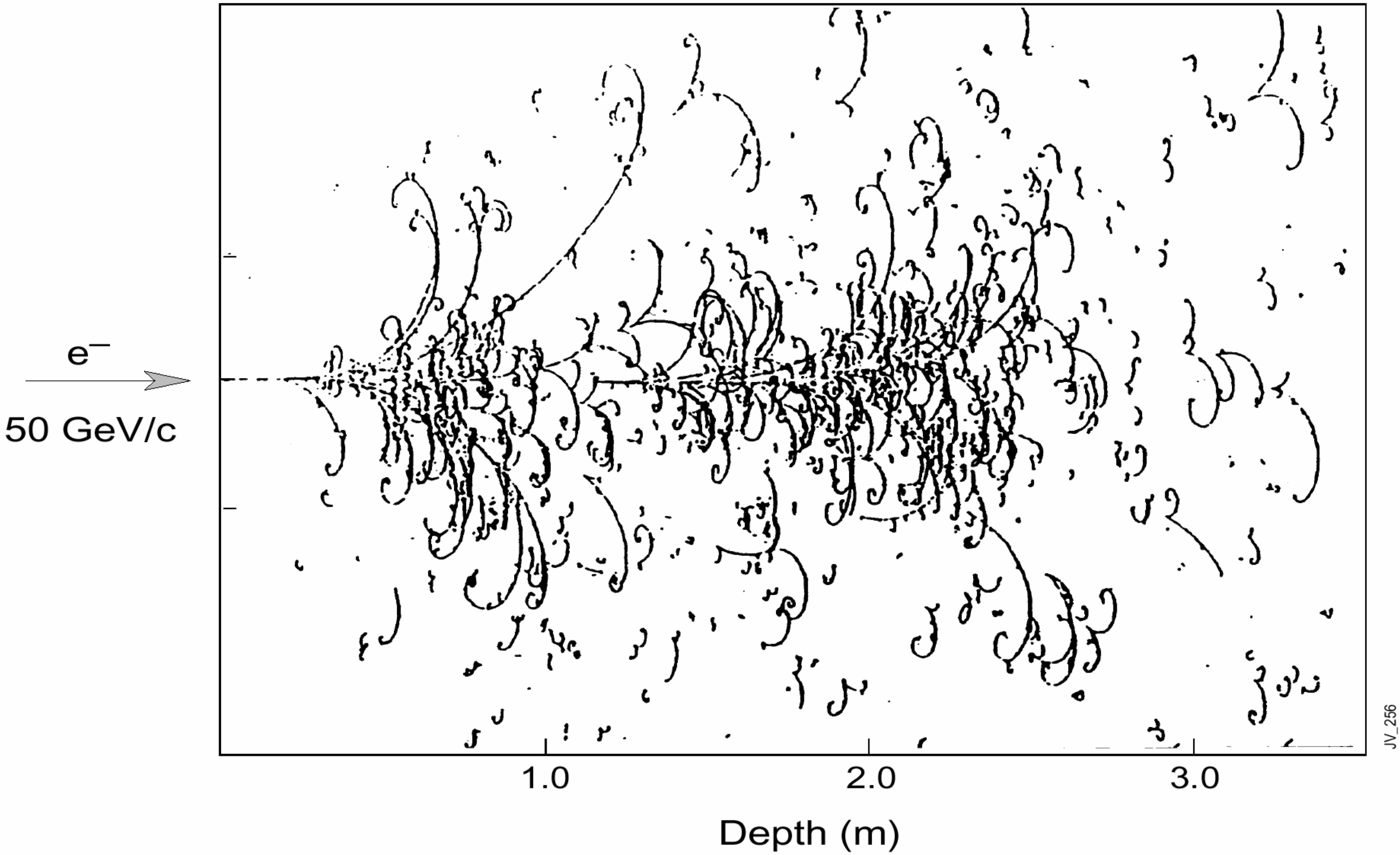
1) Electrons loses a constant amount of energy (ε) for each radiation length, $X_0$

2) Radiation and Pair production at all energies are described by the asymptotic formulae.




You can also use EGS4, FLUKA, GEANT4 ... but they are less easy to understand immediately.

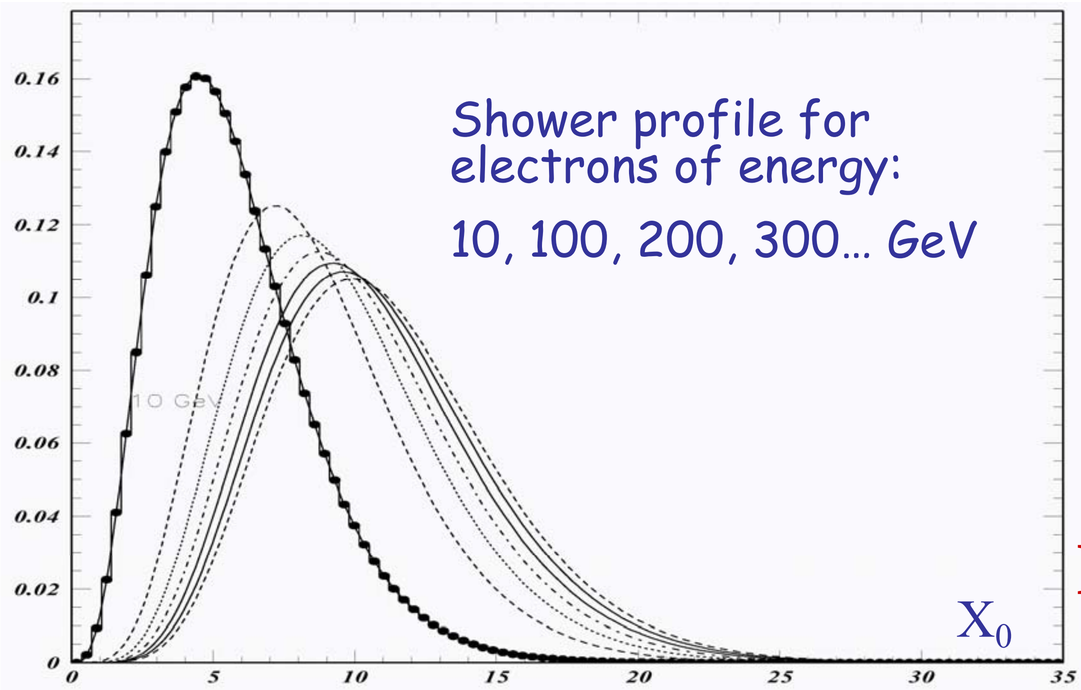



**Big European Bubble Chamber filled with Ne:$H_2$ = 70%:30%,**

**3T Field, L=3.5 m, $X_0 \approx 34$ cm, 50 GeV incident electron**

From M. Diemoz, Torino 3-02-05

# EM showers: longitudinal profile




$$t_{max} = 1.4 \ln(E_0/E_c)$$

$$N_{tot} \propto E_0/E_c$$

Longitudinal containment:

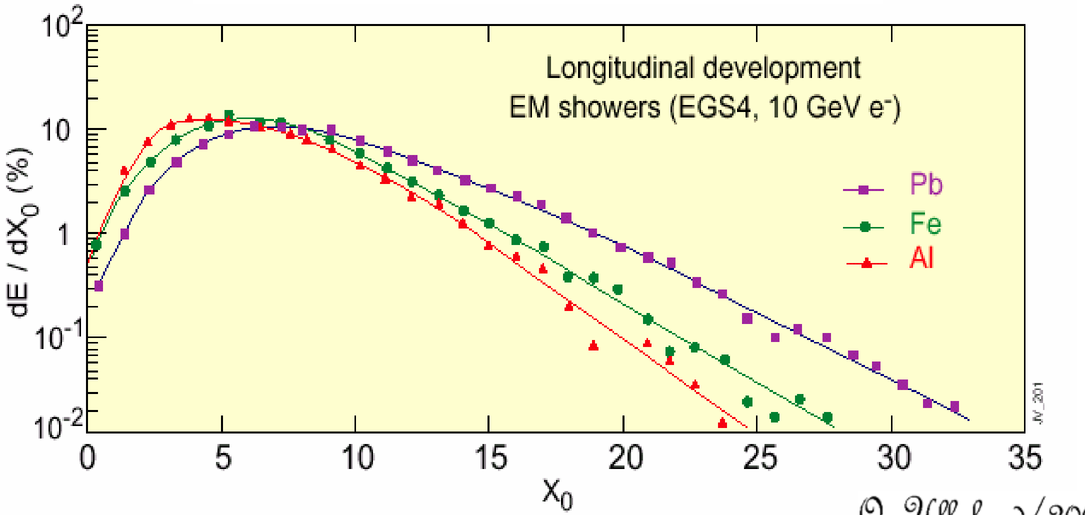
$$t_{95\%} = t_{max} + 0.08Z + 9.6$$

$E_c \propto 1/Z$ →

- shower max
- shower tail

Shower parametrization

$$\frac{dE}{dt} \propto t^{\alpha} e^{\beta t}$$




From M. Diemoz, Torino 3-02-05

O. Ullaland/2006

# EM showers: transverse profile

Transverse shower profile

- Multiple scattering make electrons move away from shower axis
- Photons with energies in the region of minimal absorption can travel far away from shower axis

Molière radius sets transverse shower size, it gives the average lateral deflection of critical energy electrons after traversing $1X_0$

$$R_M = \frac{21\text{MeV}}{E_C} X_0$$

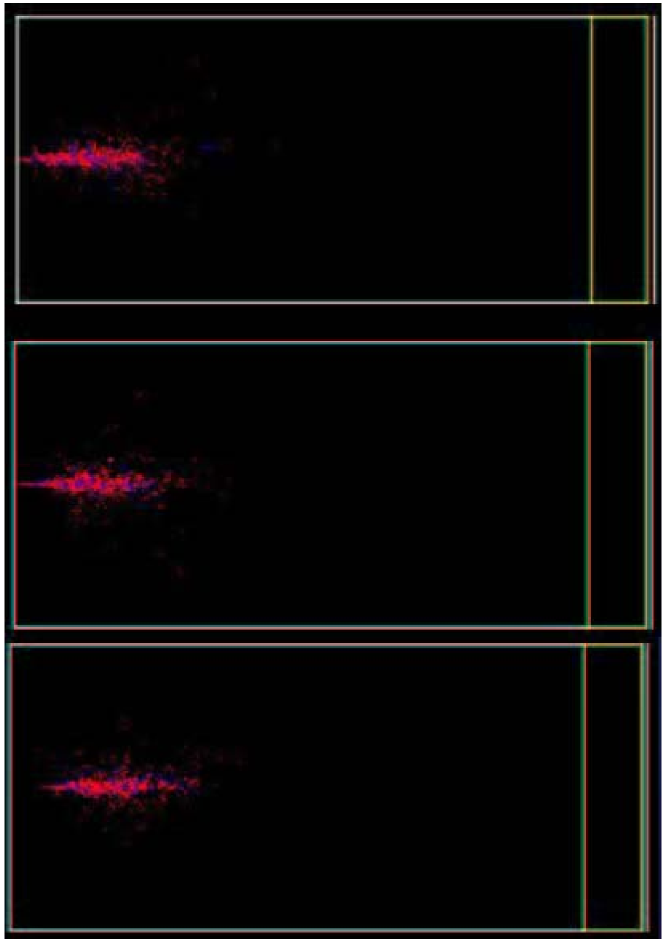
$$R_M \propto \frac{X_0}{E_C} \propto \frac{A}{Z} (Z >> 1)$$

75% $E_0$ within $1R_M$, 95% within $2R_M$, 99% within $3.5R_M$

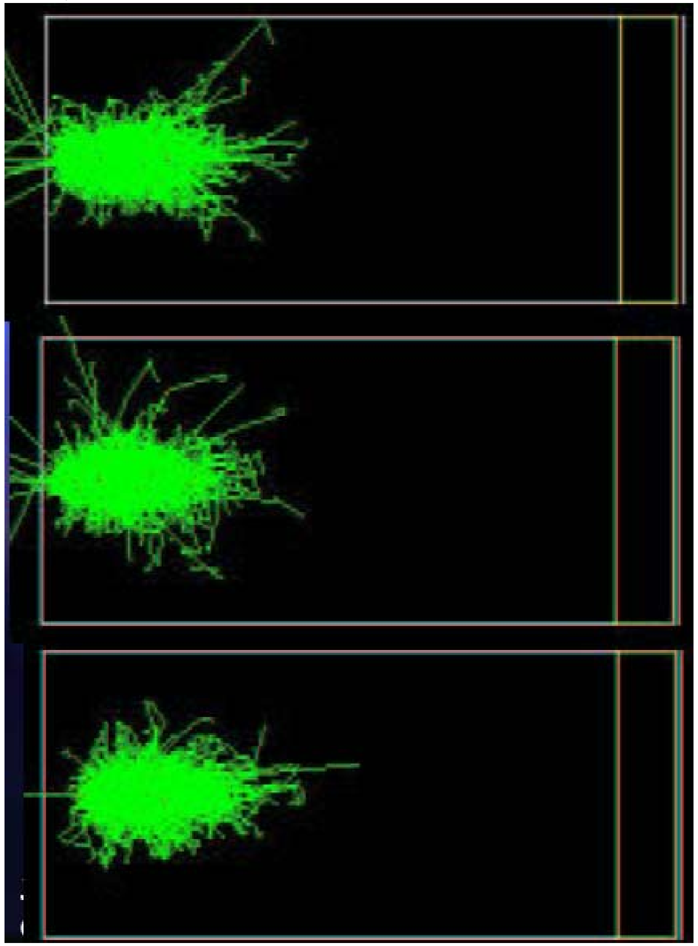
From M. Diemoz, Torino 3-02-05

# 20 GeV $\gamma$ in copper (simulation)

charged particles only



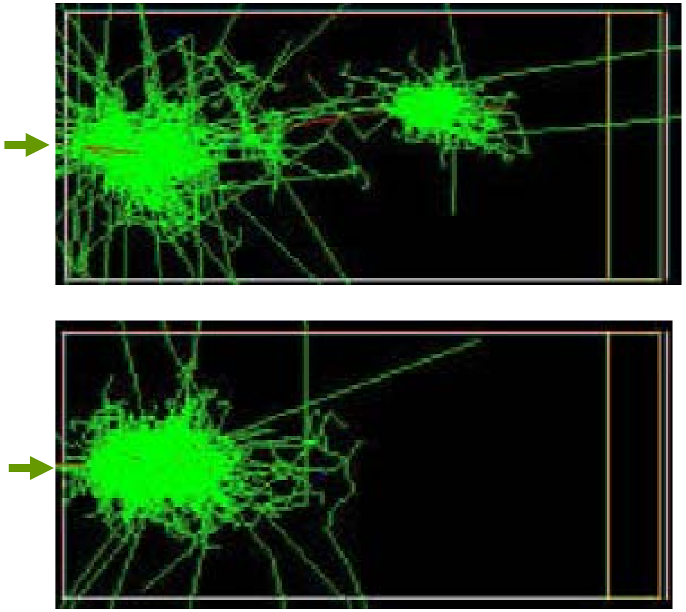
all particles



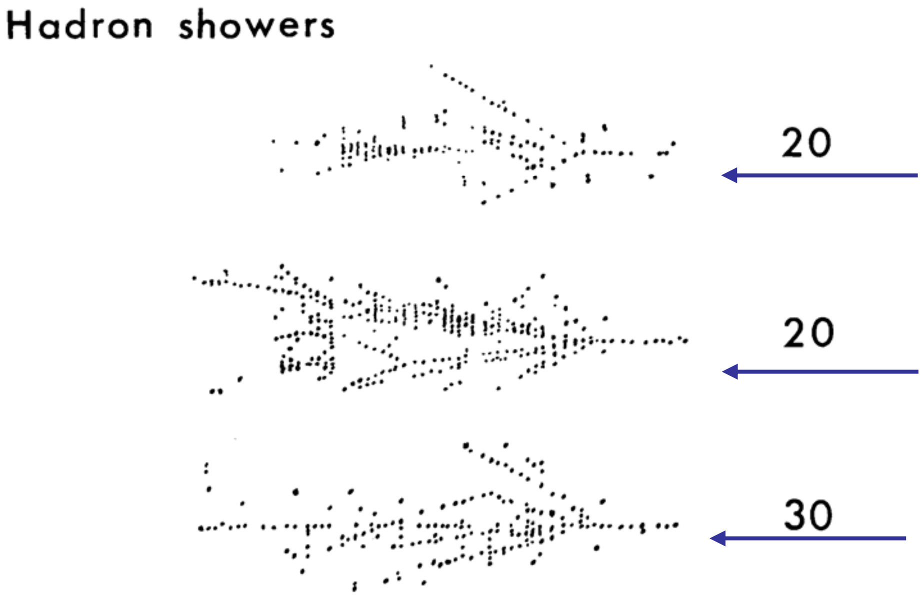
J.P. Wellisch

## Hadronic Calorimeters (are [very] difficult to model)

20 GeV π in copper (simulation)



J.P. Wellisch




Hadronic Showers (π, n, p, ...)

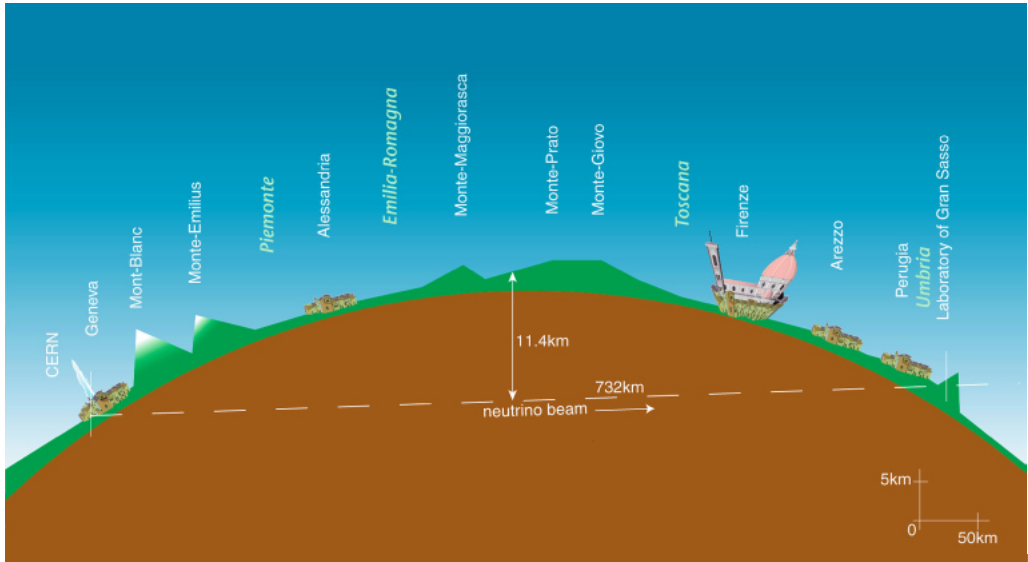
Propagation : inelastic hadron interactions
→ multi particle production
Nuclear disintegration

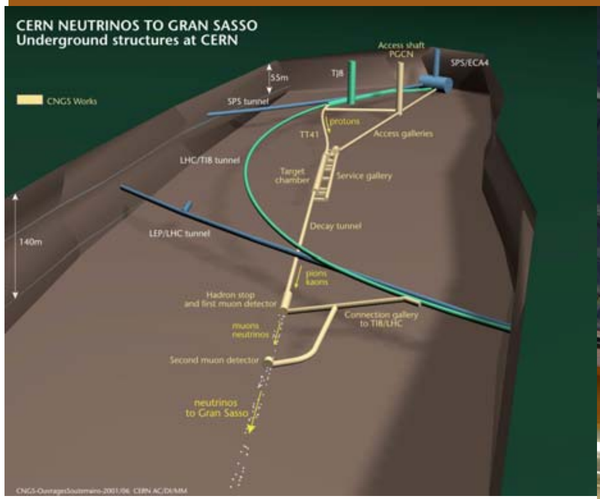
very LARGE

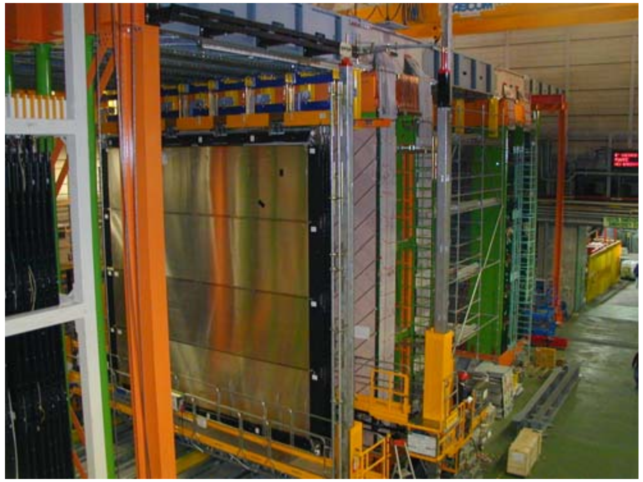
Neutrino

Weak interactions
secondaries : mostly hadrons

# Getting neutrinos to Gran Sasso and detecting them



OPERA detector installation in June 05:
- Second magnet and full mechanical structure installed.
- Started installation of the target in Super module 1: 8 planes of Target Tracker and Brick Wall installed out of 31.

Just for the record: **Description of hadronic showers.**

Energetic particles in a shower are close to the original axis
They define the shower core
The main part of the electromagnetic fraction of the shower
They define the longitudinal shower shape

The energy going towards secondary **proton** reactions is very small in hadronic showers
(In a sampling calorimeter, most secondary protons will not reach the active media)

There is a large number of **neutrons** in a hadronic shower
They spend a significant amount in invisible energy (excitation, break-up of nuclei ...)
They carry most of the transverse momentum

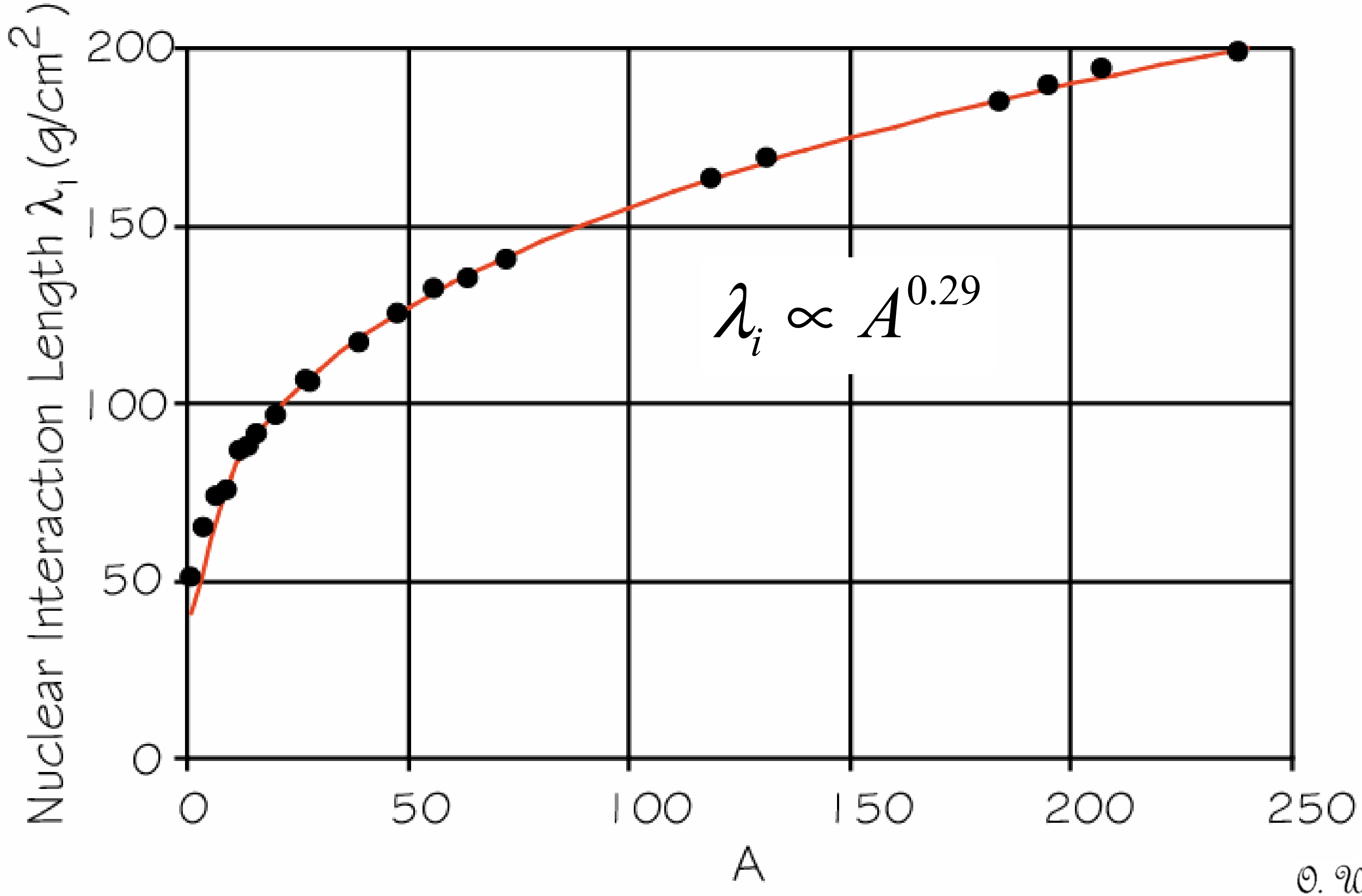
$\pi^0$'s carries a substantial fraction of the energy in a hadronic shower
They are created next to the shower core and they decay immediately, generating much of the electromagnetic content

O. Ullaland/2006

## Nuclear Interaction Length $\lambda_i$

is the average distance a high-energy hadron has to travel inside a medium before a nuclear interaction occurs.

Probability not to have interacted after a path $z$ $\quad P = e^{-z/\lambda_i}$

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back to

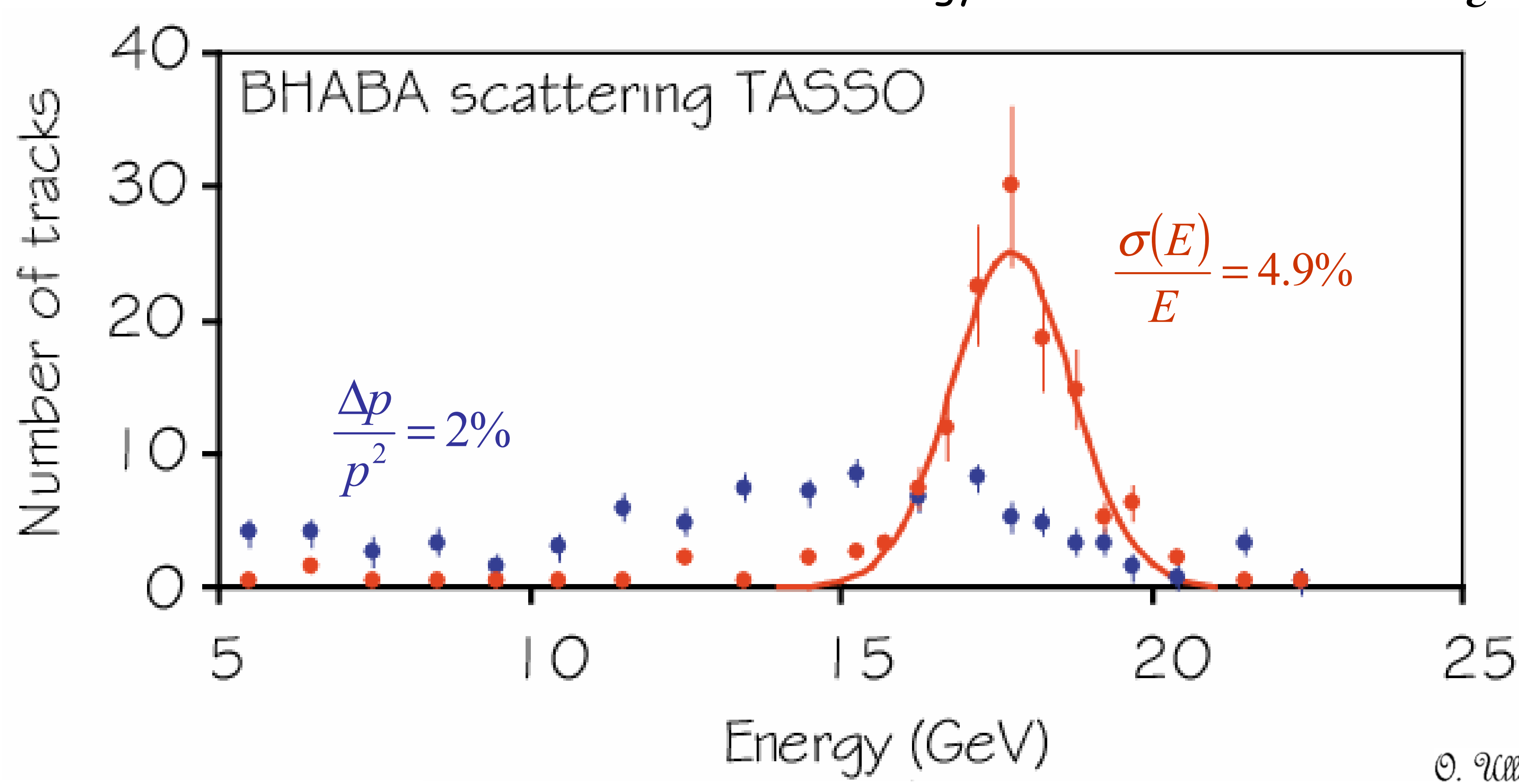
# Electromagnetic Calorimeters and fluctuations

The energy measurement of a shower is proportional to the energy deposit in the calorimeter and thereby to
the number of particles created in the shower

$$N_T = \frac{E}{\varepsilon} X_0$$

If the detector has
a lower energy cut-off

$$N_T^{'} = f(E_c)\frac{E}{\varepsilon} X_0$$




$\frac{1}{E}$

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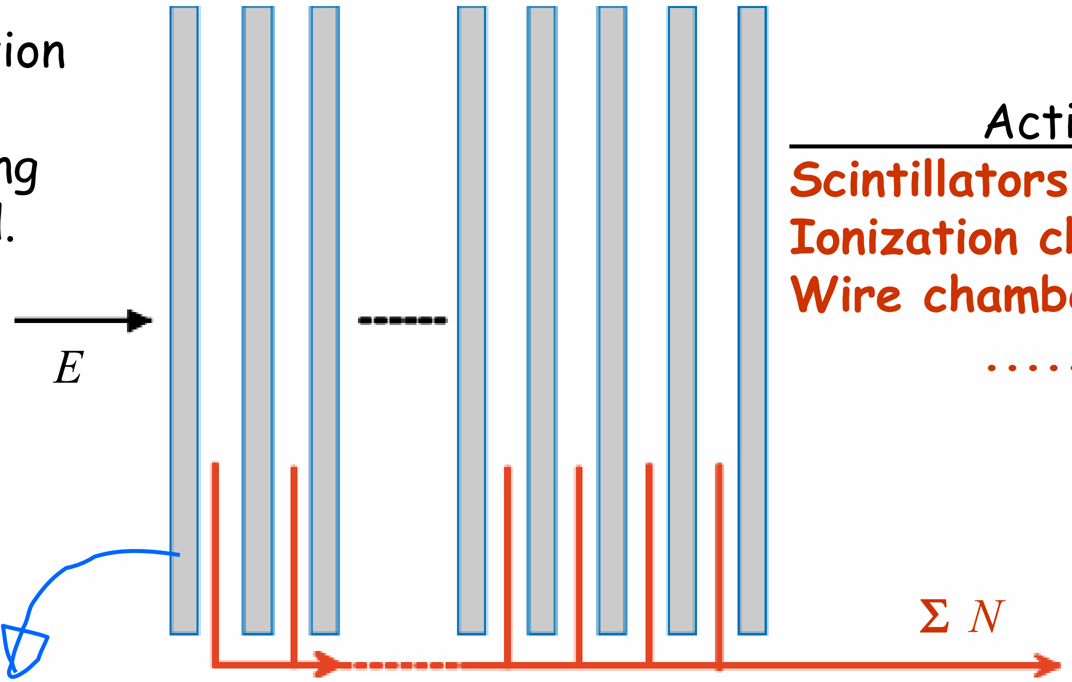
## what is a **Sampling Calorimeter** ?

A fraction of the total energy is sampled in the active detector

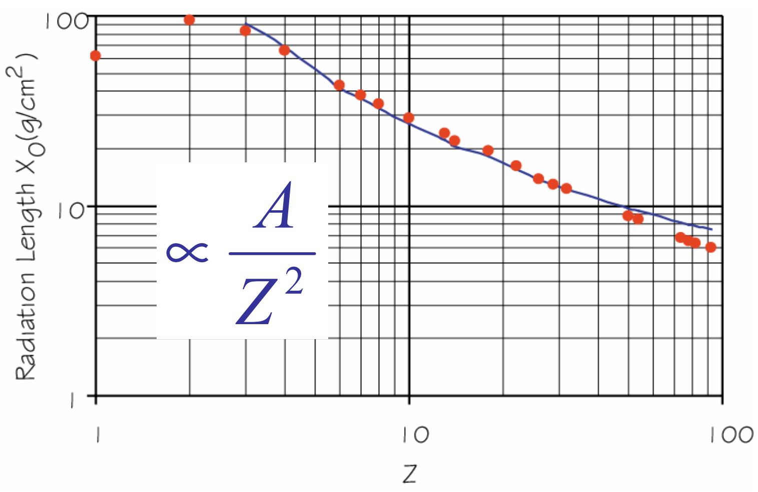
Particle absorption
and
Shower sampling
are separated.




Active detector:

**Scintillators**
**Ionization chambers**
**Wire chambers**
.......

Absorber:




$$\sum N \propto E \rightarrow \frac{\sigma(E)}{E} \geq 10\%$$

at 1 GeV

O. Ullaland/2006

# what is Homogeneous Calorimeter ?

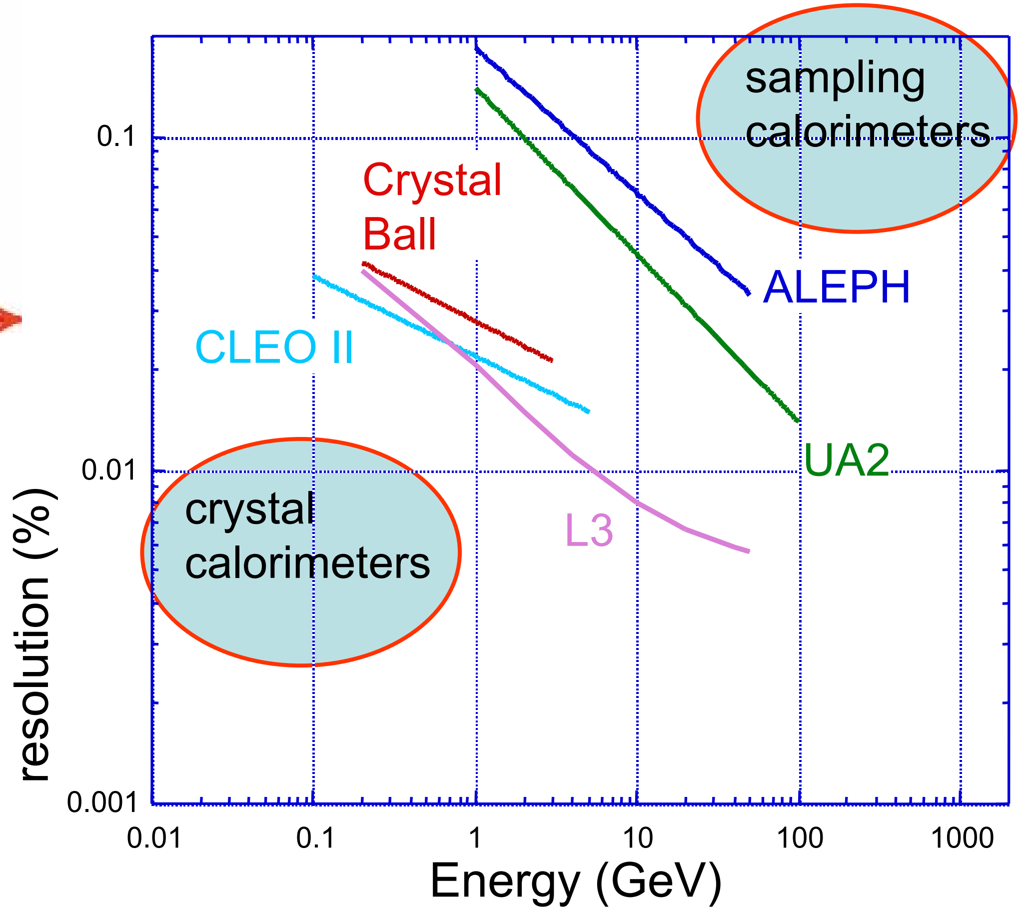
The total detector is the active detector.


$N \propto E$

$\sigma(E) \sim$ Limited by photon statistics

$$\frac{\sigma(E)}{E} \approx 1-2\% \text{ at 1 GeV}$$

The detector should (clearly) be transparent to photons.
Crystal scintillators
(Cherenkov light also works.)




From M. Diemoz, Torino 3-02-05

O. Ullaland/2006

How to: limit the fluctuations in sampling calorimeters **I**

Landau

Geiger
Streamer
Saturated avalanche
....
Liquid/Solids

Argon Gas 7 mm (proportional mode) → $\left.\frac{\sigma(E)}{E}\right]_{Landau} \cong 6\% \Rightarrow \left.\frac{\sigma(E)}{E}\right]_{Total} \cong 8.5\%$

Liquid Argon 3 mm ~ 300 times more ionization → $\left.\frac{\sigma(E)}{E}\right]_{Landau} \cong 0.4\% \Rightarrow \left.\frac{\sigma(E)}{E}\right]_{Total} \cong 6\%$

The energy resolution of a calorimeter is usually parameterized with the following terms:

$a$ is the stochastic term

$b$ is the constant term

$c$ is the electronic noise contribution

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

The difficult one ($b$)

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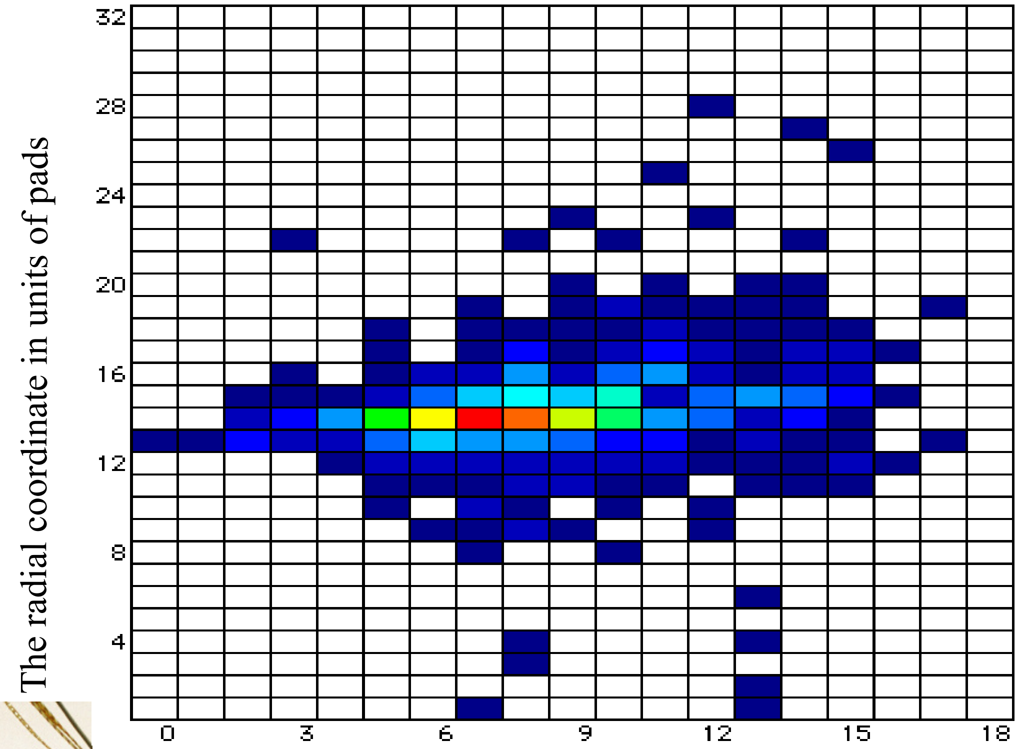
# How to: limit the fluctuations in sampling calorimeters II

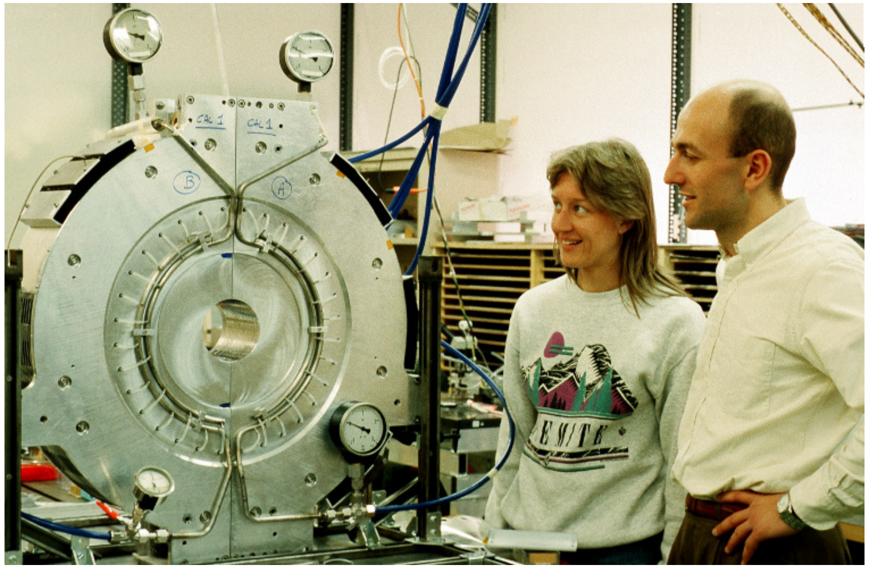
Something of the best we can do at the moment:

Silicon Tungsten calorimeters

(if you can afford it)




The depth within the calorimeter, numbered by detector layer

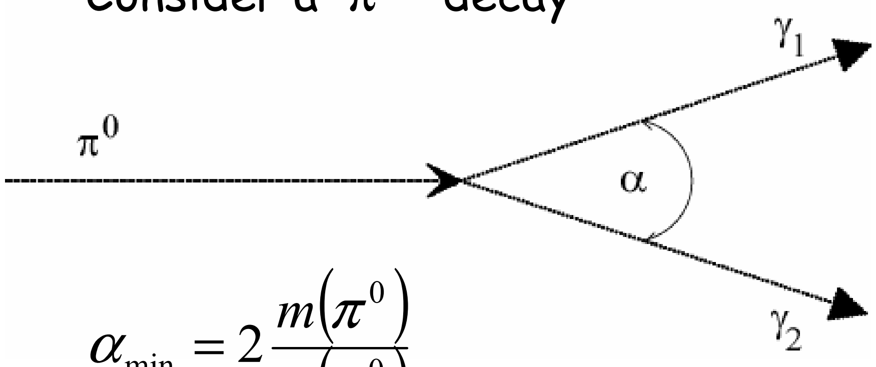


Excellent space and energy resolution!

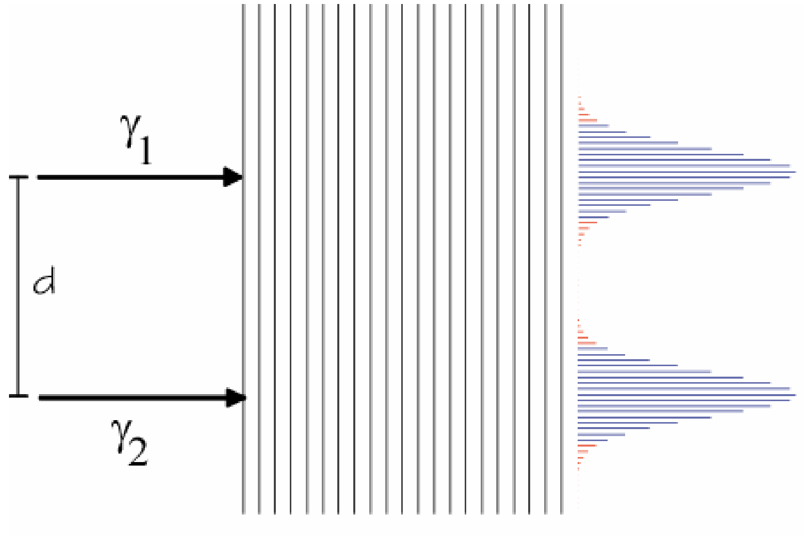
OPAL CERN-EP-99-13

Why is Space Resolution an issue in calorimeters ?

Consider a $\pi^0$ - decay




$$\alpha_{\min} = 2\frac{m(\pi^0)}{E(\pi^0)}$$

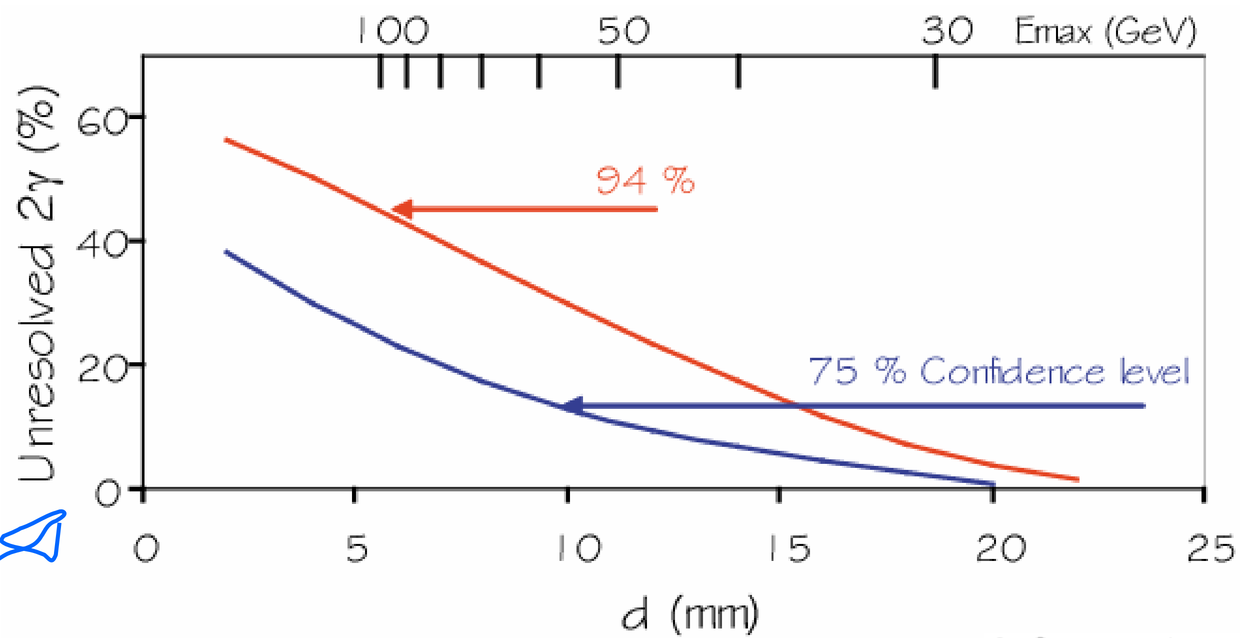



For a calorimeter with limited granularity, this would give:

$$\alpha_{\min} = 2R_M$$

$$\Rightarrow E(\pi^0)_{\max} = \frac{R \cdot m(\pi^0)}{R_M}$$

Set R=2 m

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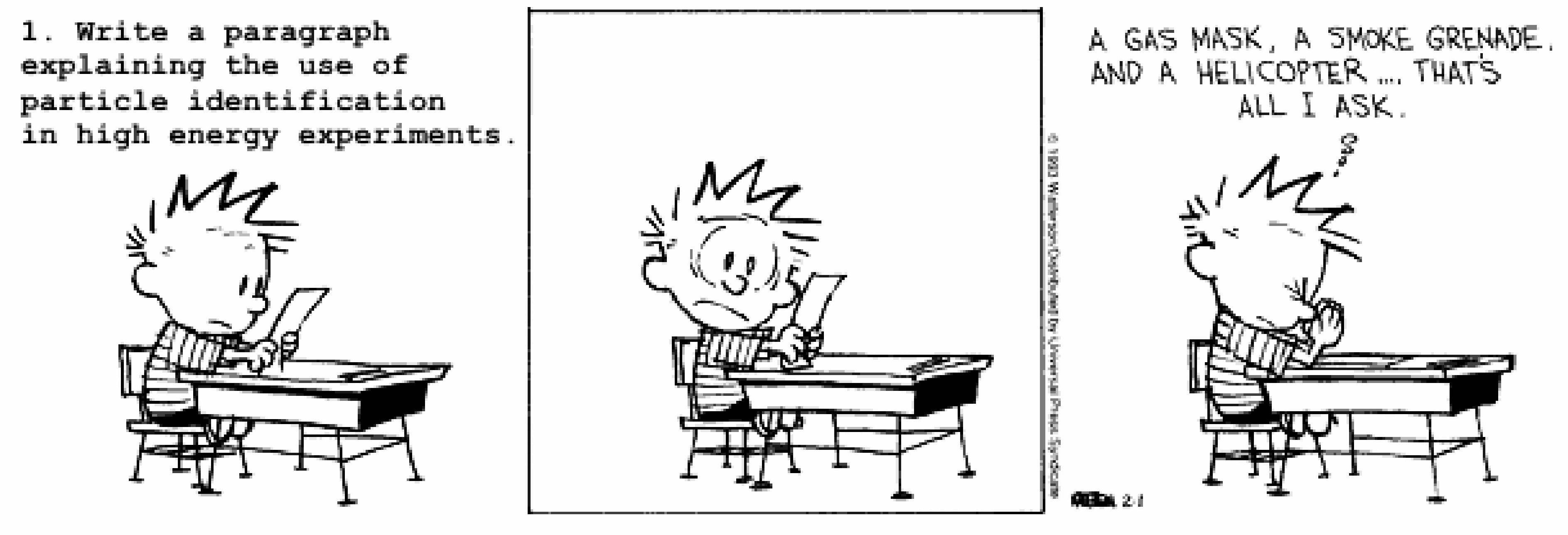
# That is all folks.

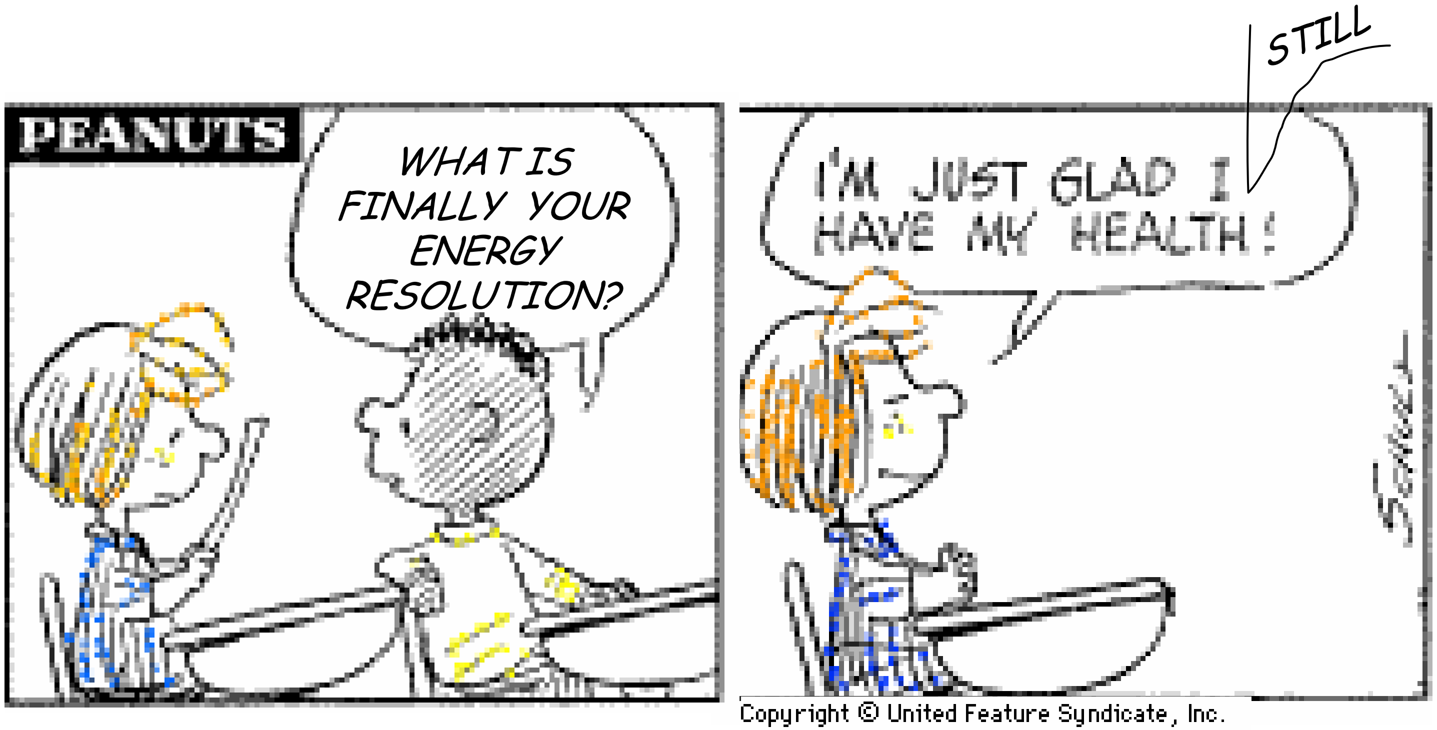
There is no exam.



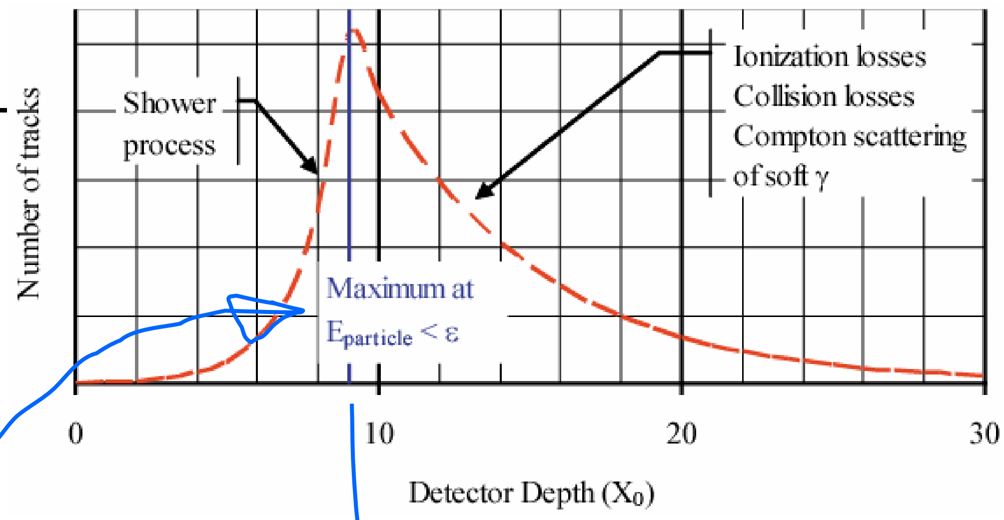

*Thank you for listening and for your questions.*

O. Ullaland/2006

back-ups


PEANUTS
WHAT IS FINALLY YOUR ENERGY RESOLUTION?
I'M JUST GLAD I HAVE MY HEALTH!
STILL
SCHULZ
Copyright © United Feature Syndicate, Inc.

## The shower maximum




Shower maximum $t = t(E, \varepsilon)$

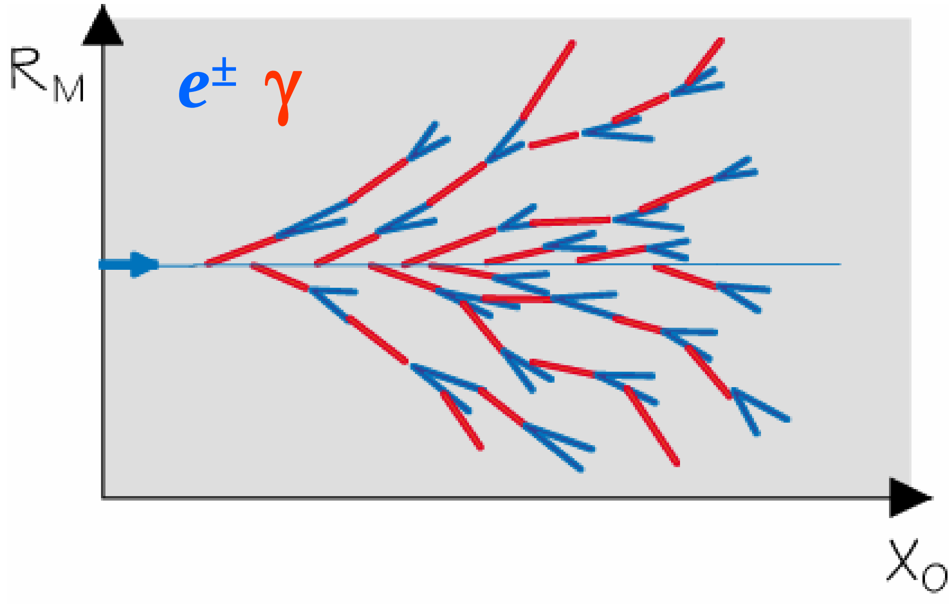
and there must be a difference between $e$ and $\gamma$

$$t(X_0) = \ln\left(\frac{E}{\varepsilon}\right) - 1.1 \quad \text{for } e$$

$$t(X_0) = \ln\left(\frac{E}{\varepsilon}\right) - 0.3 \quad \text{for } \gamma$$

U. Amaldi, Physica Scripta 23(1981)409

## Lateral shower development




The lateral spread of the shower is mainly governed by the multiple scattering of the electrons.

Define the Molière Unit:

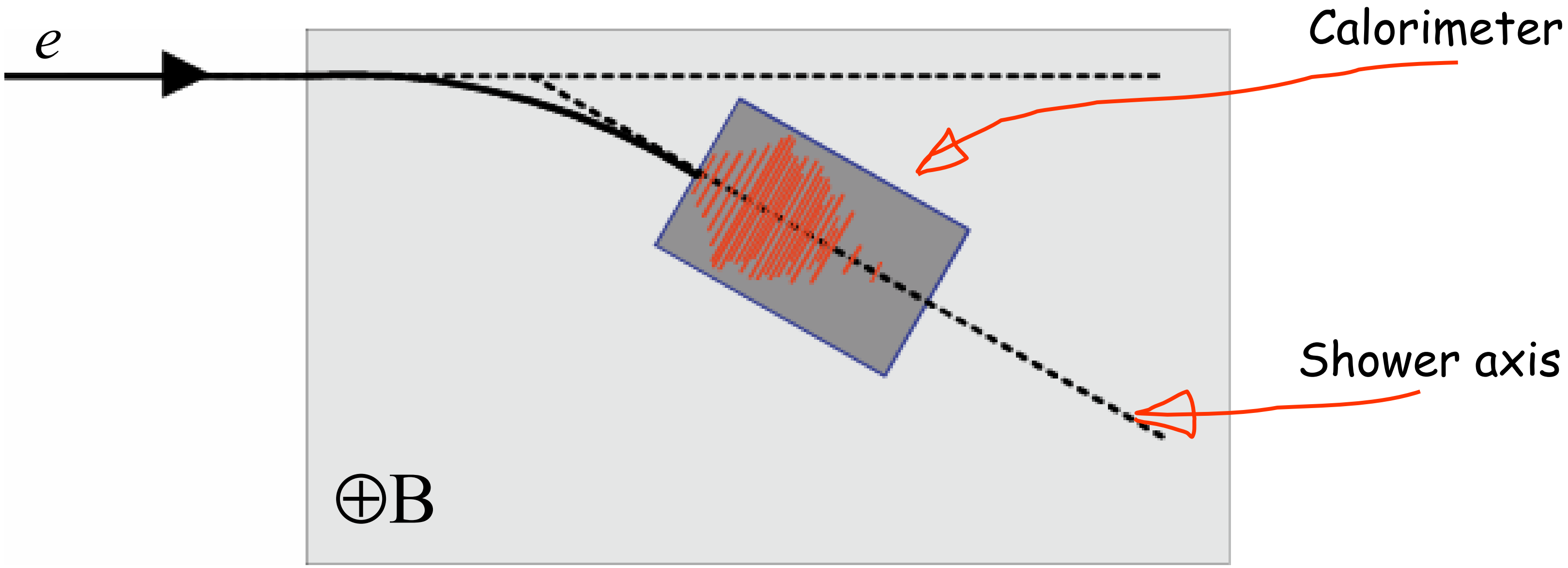
$$R_M = (\text{Characteristic Energy})\times(\text{Radiation Length}) / (\text{Critical Energy})$$
$$= 21\ \text{MeV} \times X_0 / \varepsilon \ \propto A/Z\ (\text{g cm}^{-2})$$

$$X_0 \propto \frac{A}{Z^2}$$

$$E_c = \varepsilon \propto Z^{-0.9}$$

95 % of the shower is contained inside a cone with radius $2R_M$

## Propagation of a Shower

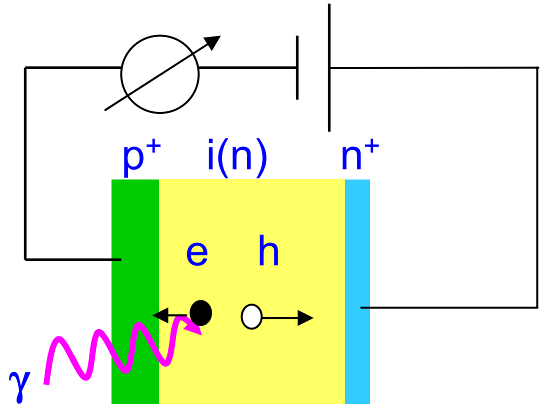


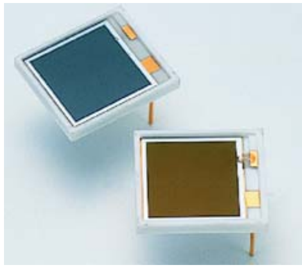

Electromagnetic Shower propagated by $\gamma$

# Solid-state photon detectors

Photodiodes:

- P(I)N type;
- p layer very thin (<1 mm), as visible light is rapidly absorbed by silicon;
- High QE (**80% @ $\lambda \approx$ 700nm**);
- No gain: cannot be used for single photon detection;



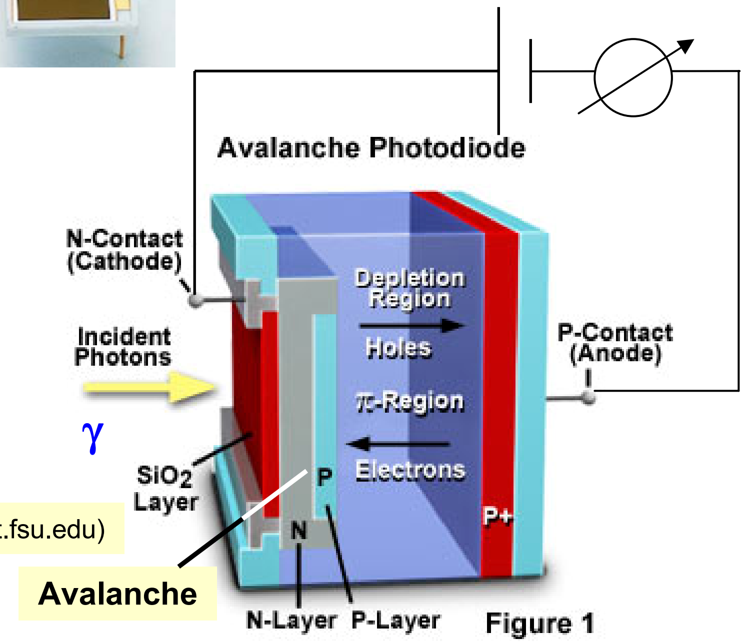



Avalanche photodiode:

- High reverse bias voltage: typ. 100-200 V

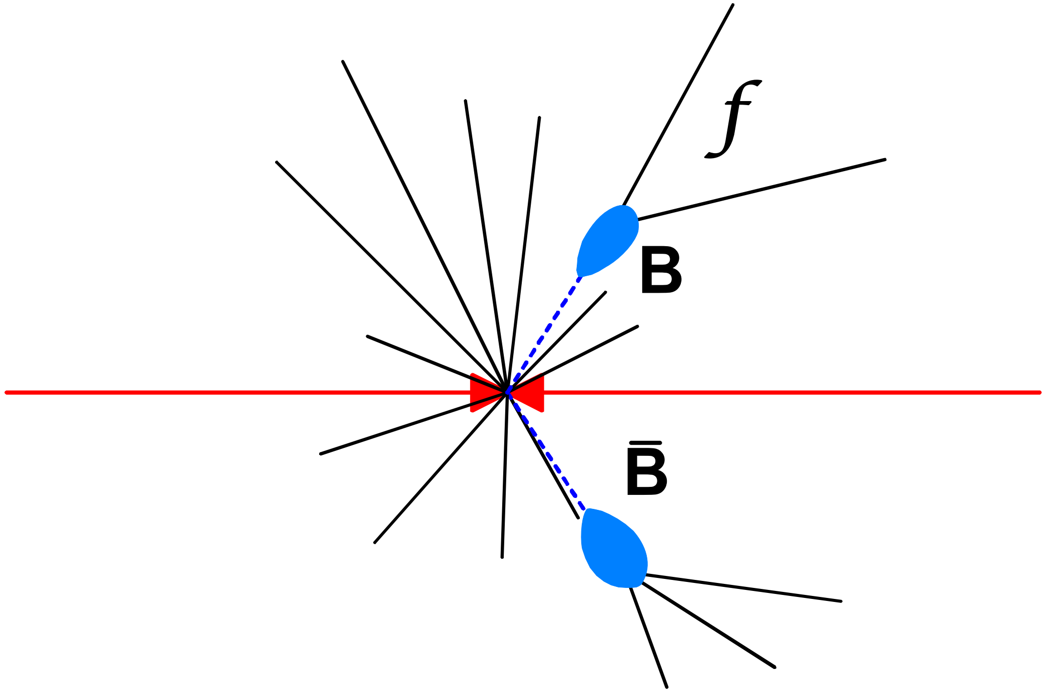
$\Rightarrow$ due to doping profile, high internal field and avalanche multiplication;

- High gain: typ. 100-1000;
- Used in CMS ECAL;

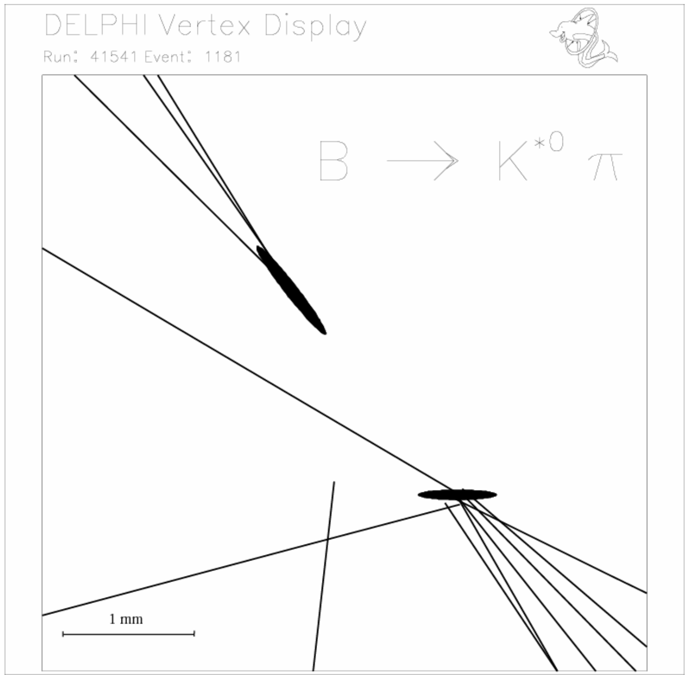



(http://micro.magnet.fsu.edu)

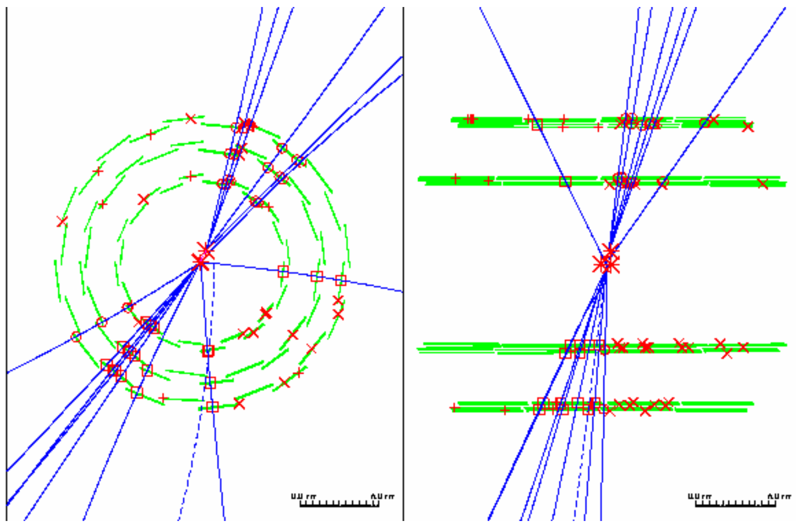
from T. Gys, Academic Training, 2005



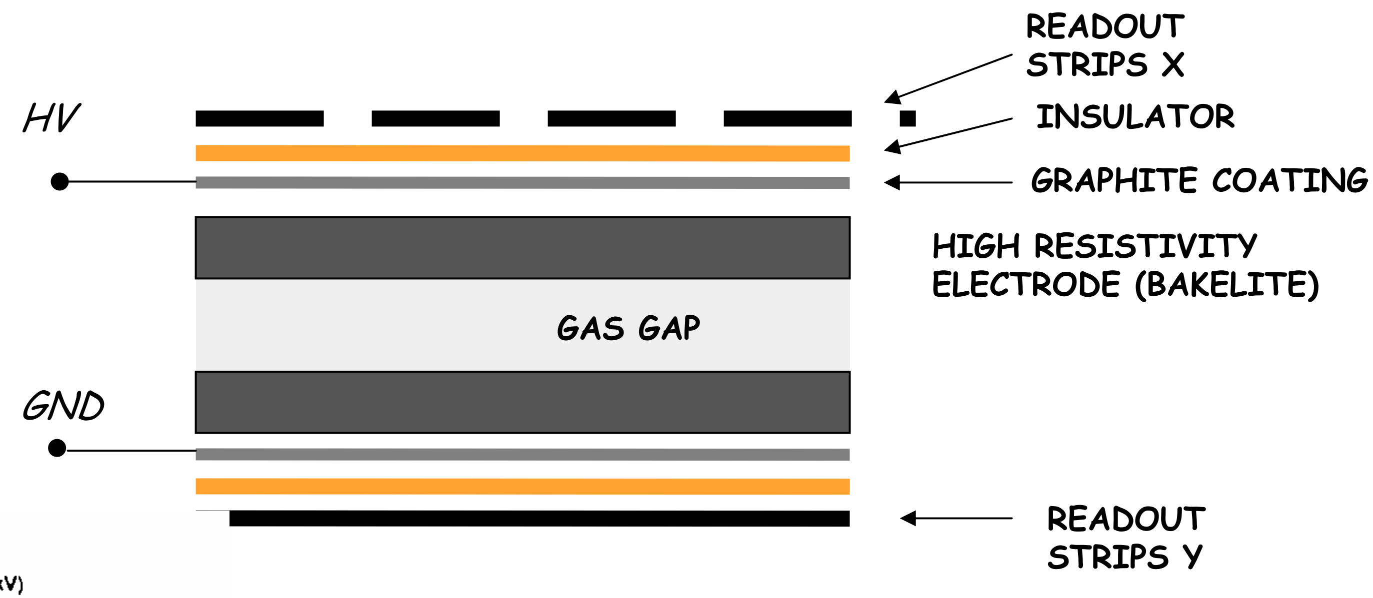

Generic tracking issues.
Secondary vertices.
High spatial resolution.

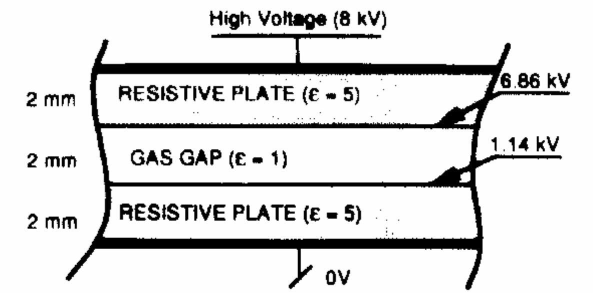



not shown



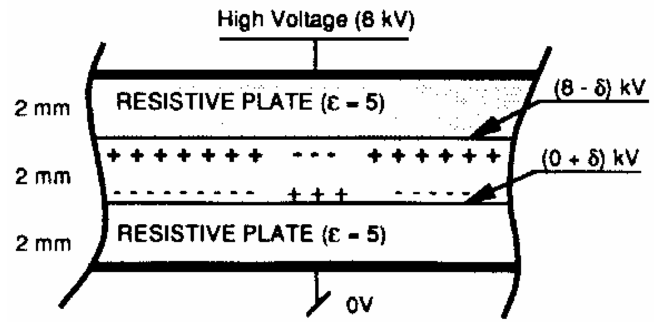
## and what is a Resistive Plate Chamber (RPC)?

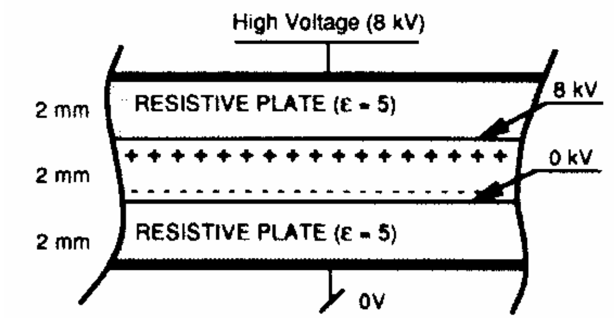



Initial condition after applying high voltage

After a discharge electrons are deposited on anode and positive ions on cathode



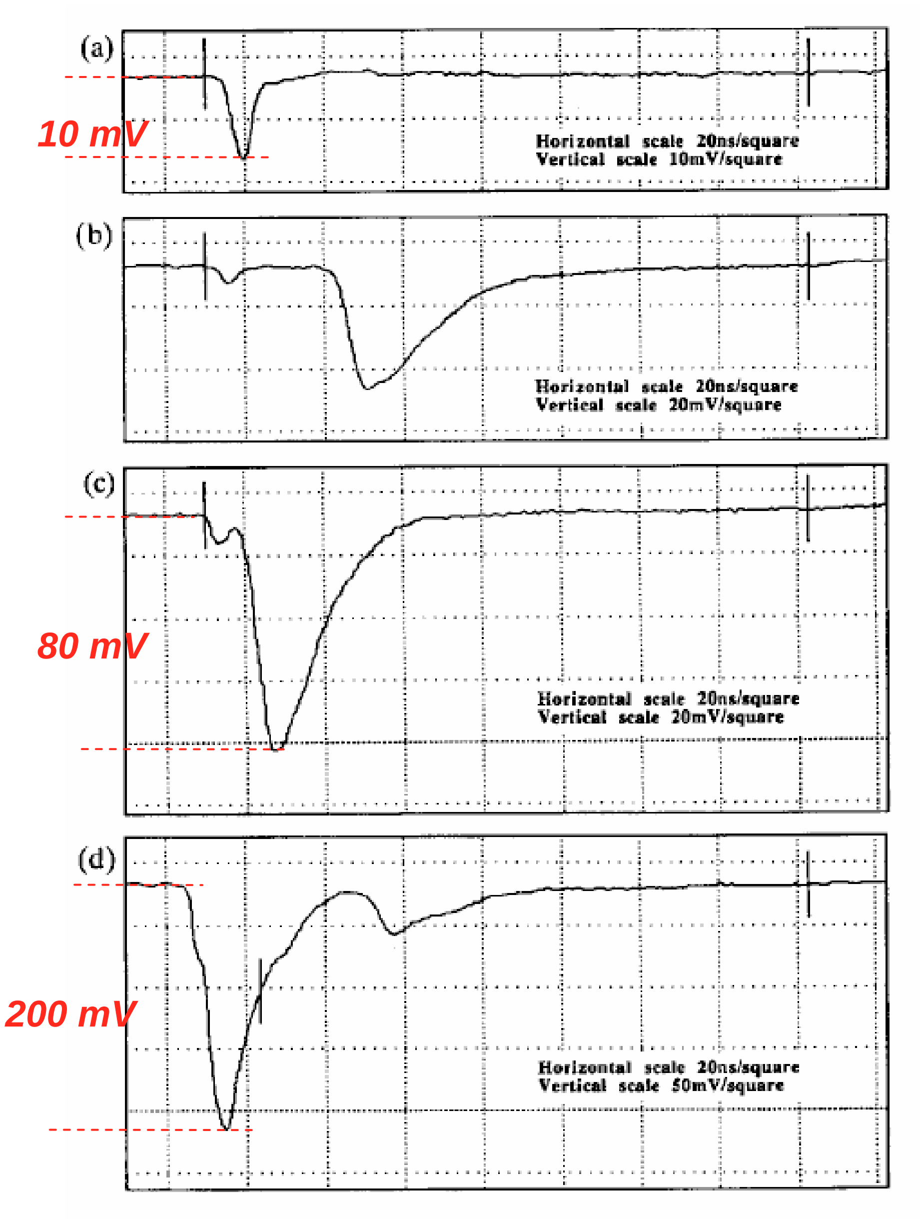



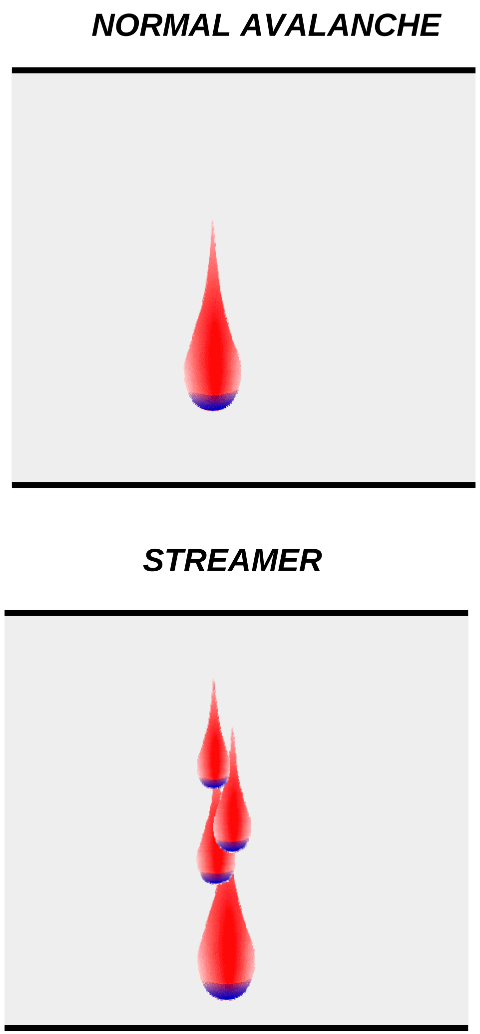

Surface charging of electrodes by current flow through resistive plates

I. Crotty et al, Nucl. Instr. and Meth. A337(1994)370

not shown

# TRANSITION AVALANCHE TO STREAMER

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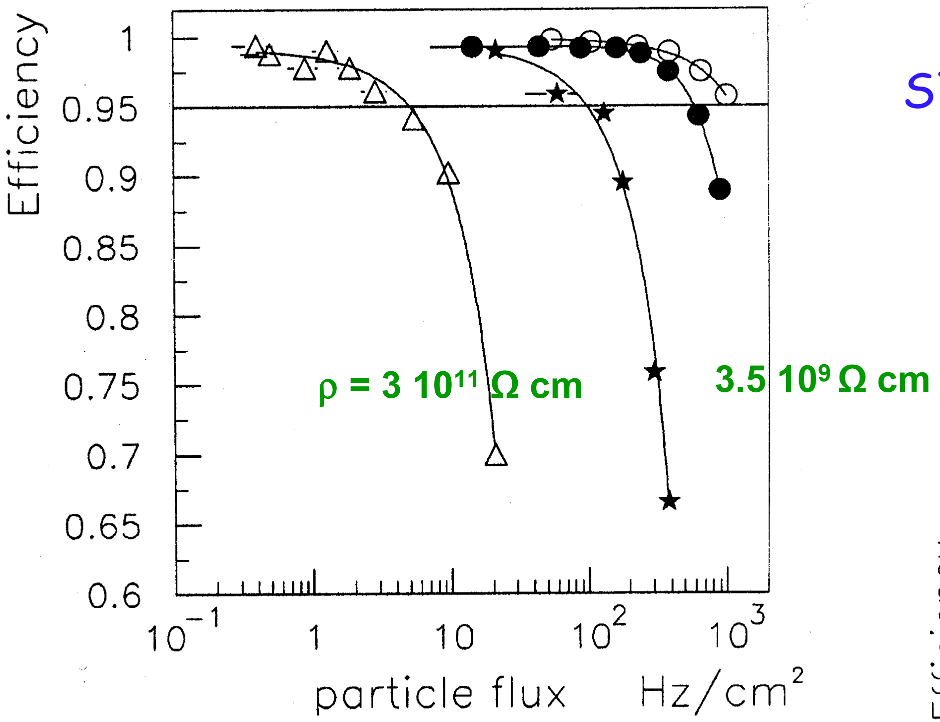
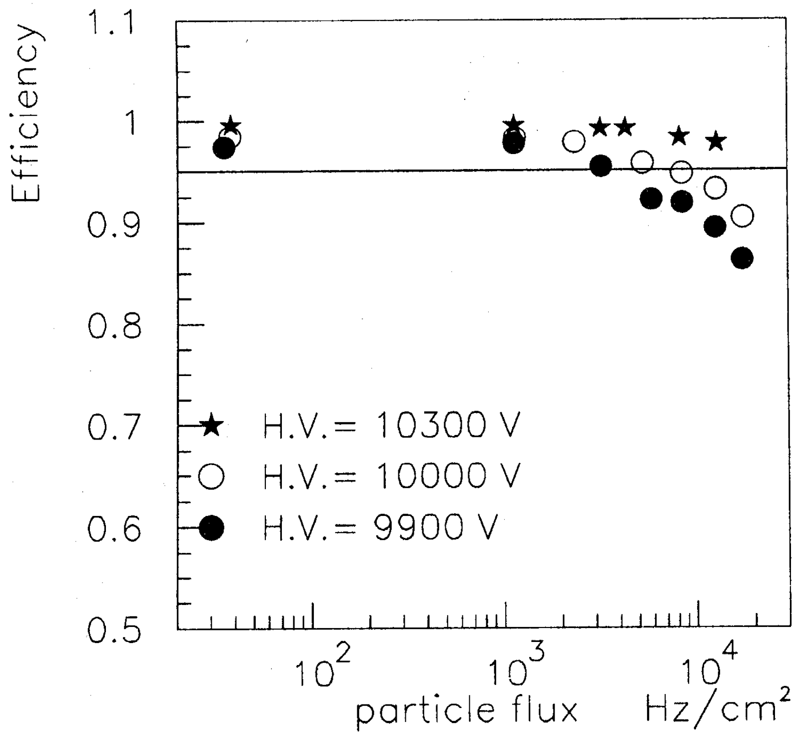
R. Cardarelli, V. Makeev, R. Santonico, Nucl. Instr. and Meth. A382(1996)470

# RPC RATE CAPABILITY: AVALANCHE VS STREAMER OPERATION




STREAMER MODE

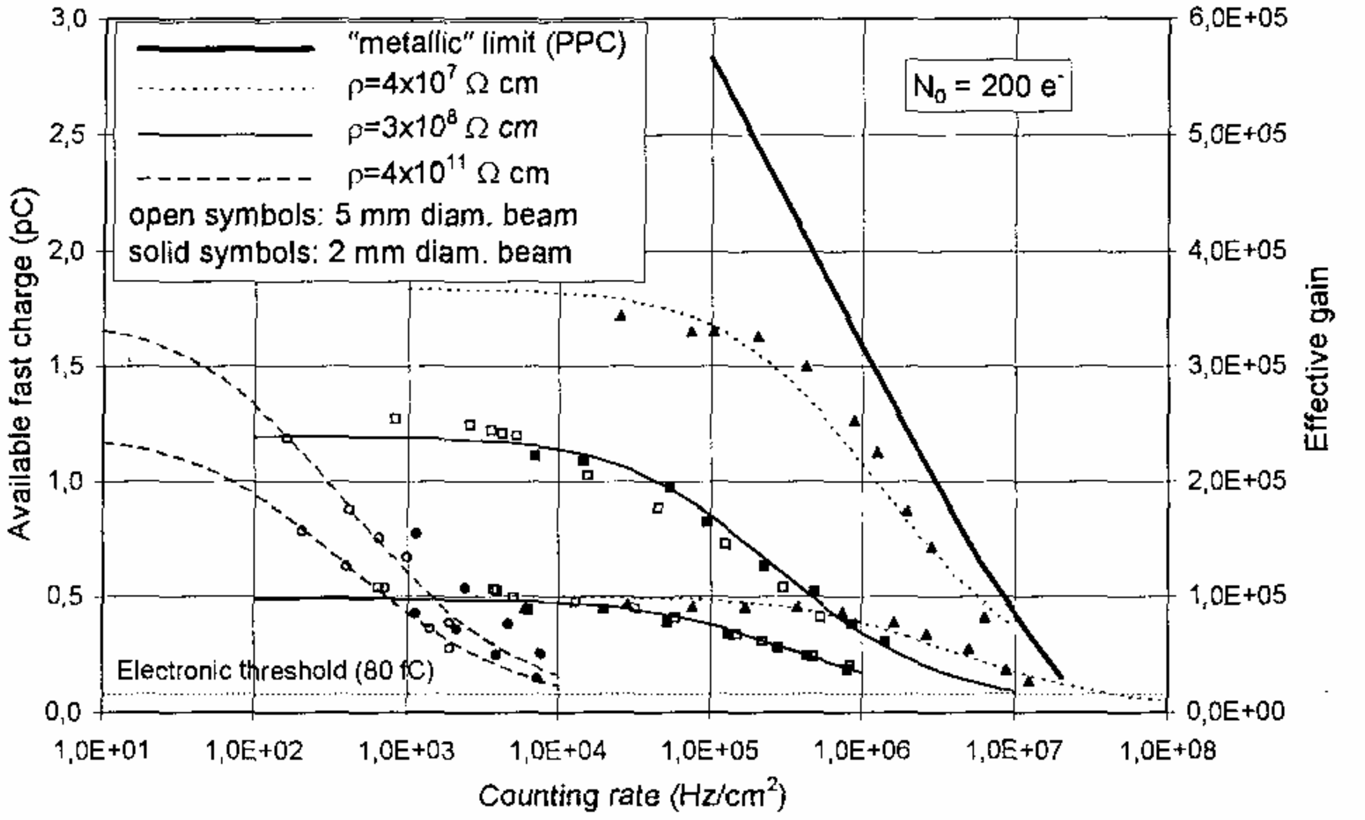



AVALANCHE MODE

not shown

# RPC RATE CAPABILITY:
# DEPENDS ON GAIN AND ELECTRODES RESISTIVITY

PROPORTIONAL (AVALANCHE) OPERATION:

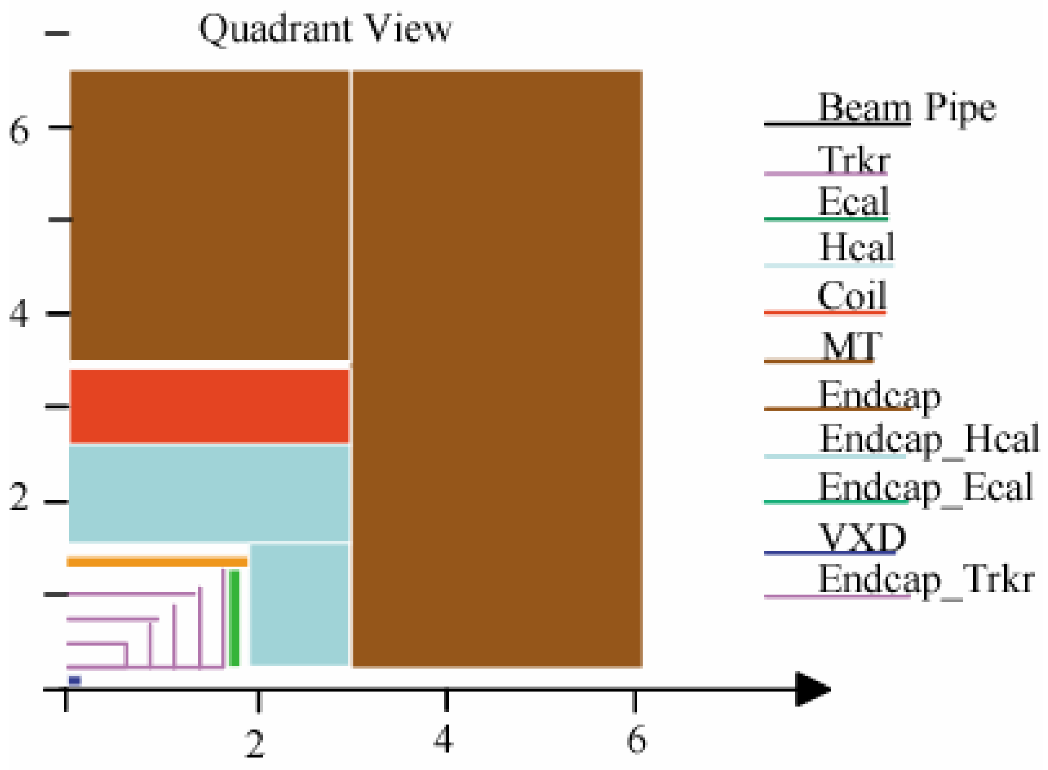



| MATERIAL | VOLUME RESISTIVITY (Ω.cm) |
|---|---|
| Pestov glass | $10^9$-$10^{10}$ |
| Phenolic (Bakelite) | $10^{10}$-$10^{11}$ |
| Cellulose | $5.10^{12}$ |
| Borosilicate glass | $10^{13}$ |
| Melamine | $2.10^{13}$ |

not shown

P. Fonte, Scientifica Acta XIII N2(1997)11

A word of encouragement before we start:




**This detector can't be built (without lots of work)**

*Breidenbach, M;*

Stanford, CA : SLAC, 30 Aug 2002 . - 4 p

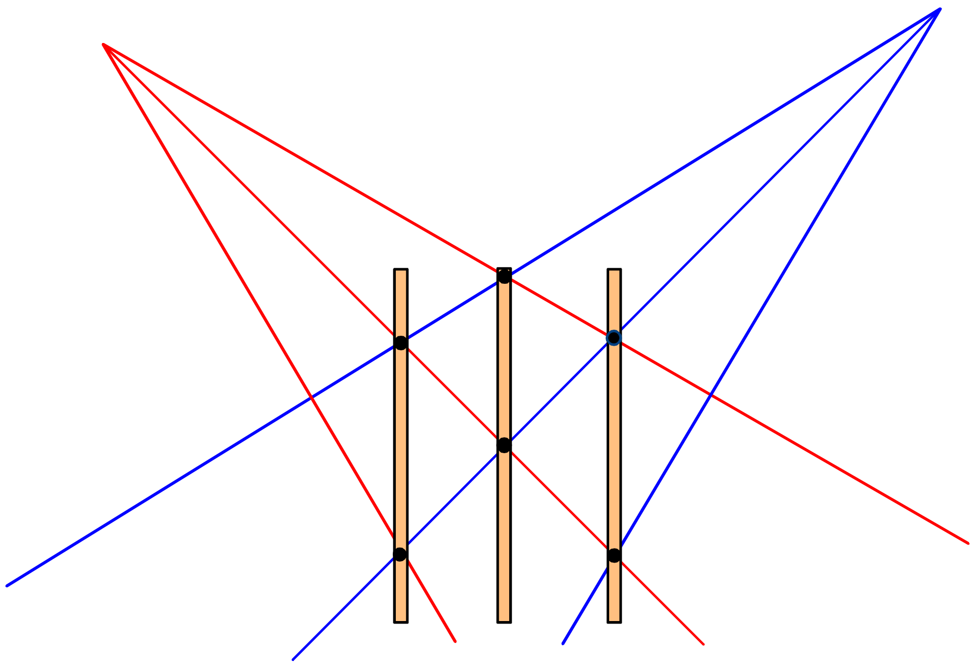
**Abstract:** *Most of us believe that $e^+ e^-$ detectors are technically trivial compared to those for hadron colliders and that detectors for linear colliders are extraordinarily trivial. The cross sections are tiny; there are approximately no radiation issues (compared to real machines) and for linear colliders, the situation is even simpler. The crossing rate is miniscule, so that hardware triggers are not needed, the DAQ is very simple, and the data processing requirements are quite modest. The challenges arise from the emphasis on precision measurements within reasonable cost constraints.*

# Connecting the dots

to find the tracks and some properties
of the passing particles.

Solution:

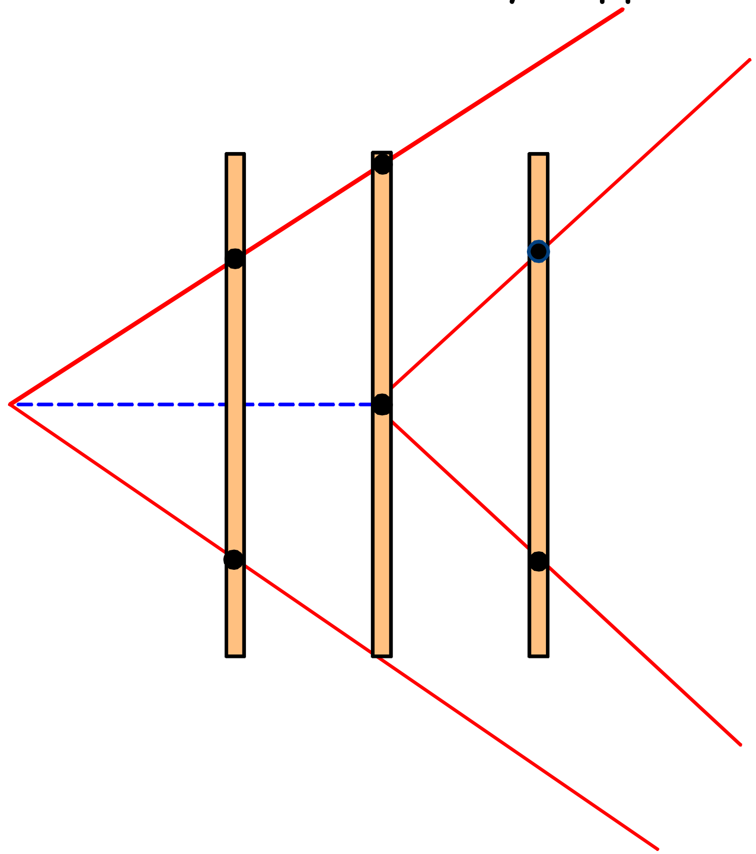
A



Guess:

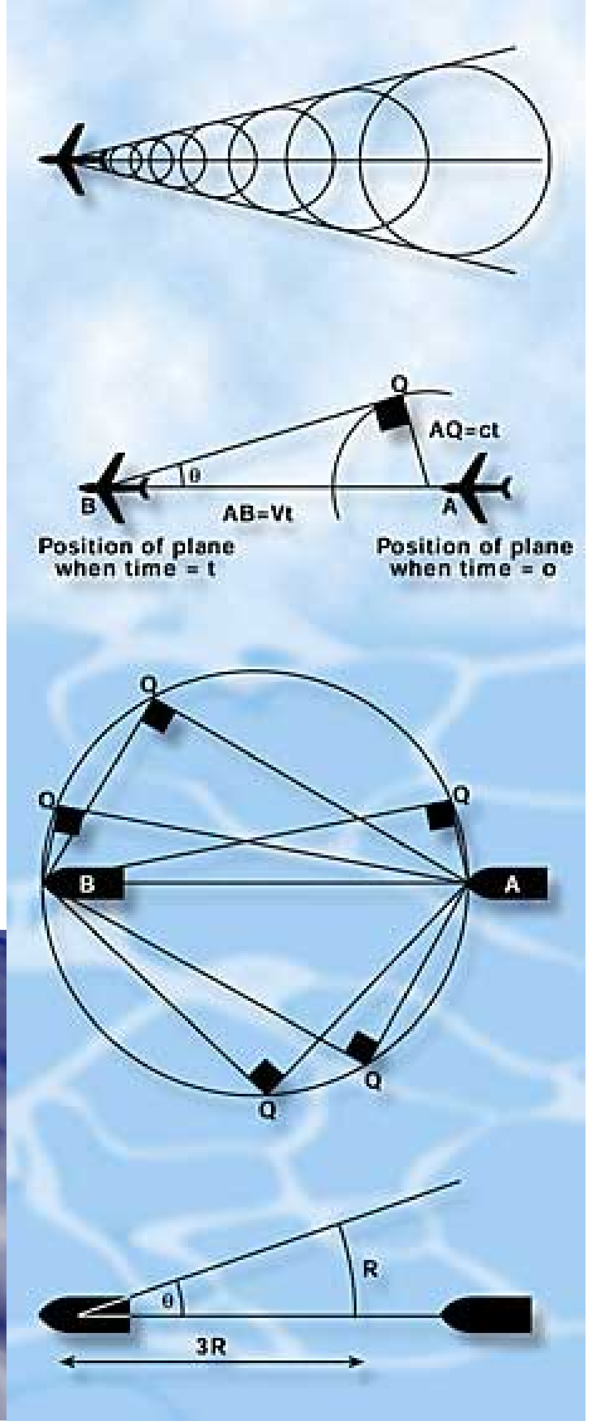
B

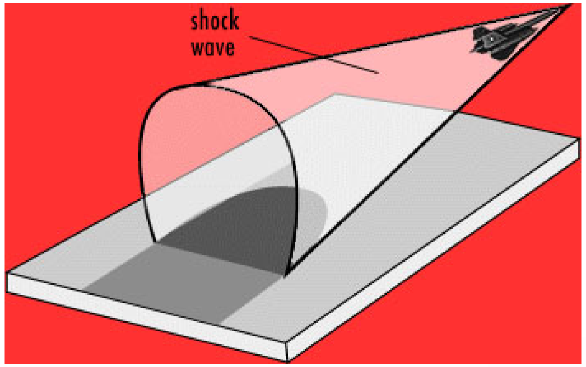
and what really happened



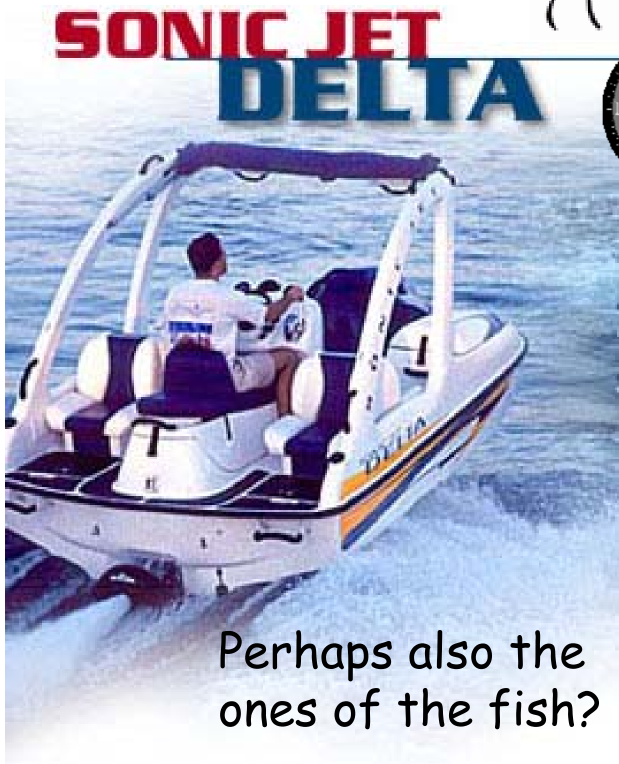
# Cherenkov Radiation

and other shocking waves.


Shock Waves May Confuse Birds' Internal Compass


http://www.newscientist.com/lastword/answers/lwa674bubbles.html
http://www.pbs.org/wgbh/nova/barrier/