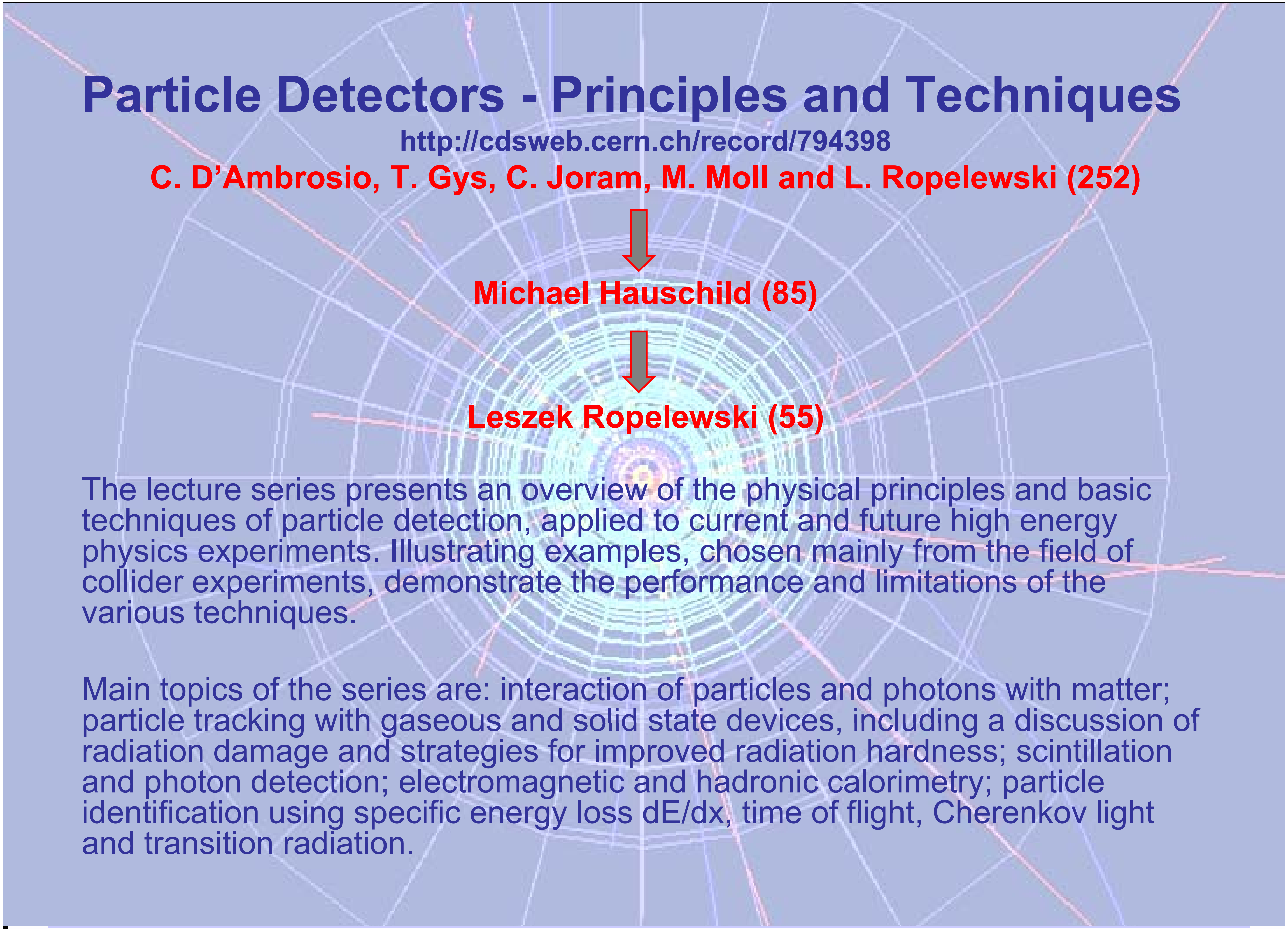


Particle Detectors - Principles and Techniques

http://cdsweb.cern.ch/record/794398

C. D'Ambrosio, T. Gys, C. Joram, M. Moll and L. Ropelewski (252)

↓

Michael Hauschild (85)

↓

Leszek Ropelewski (55)

The lecture series presents an overview of the physical principles and basic techniques of particle detection, applied to current and future high energy physics experiments. Illustrating examples, chosen mainly from the field of collider experiments, demonstrate the performance and limitations of the various techniques.

Main topics of the series are: interaction of particles and photons with matter; particle tracking with gaseous and solid state devices, including a discussion of radiation damage and strategies for improved radiation hardness; scintillation and photon detection; electromagnetic and hadronic calorimetry; particle identification using specific energy loss dE/dx, time of flight, Cherenkov light and transition radiation.

Outline

Lecture 1 - Introduction	C. Joram, L. Ropelewski
Lecture 2 - Tracking Detectors	L. Ropelewski, M. Moll
Lecture 3 - Scintillation and Photodetection	C. D'Ambrosio, T. Gys
Lecture 4 - Calorimetry, Particle ID	C. Joram
Lecture 5 - Particle ID, Detector Systems	C. Joram, C. D'Ambrosio

⇓

- **Detector Concepts (Experiments)**
- **Particle Interactions**
- **Tracking Detectors**
- **Photon Detectors**
- **Calorimeters**
- **Detectors R&D**

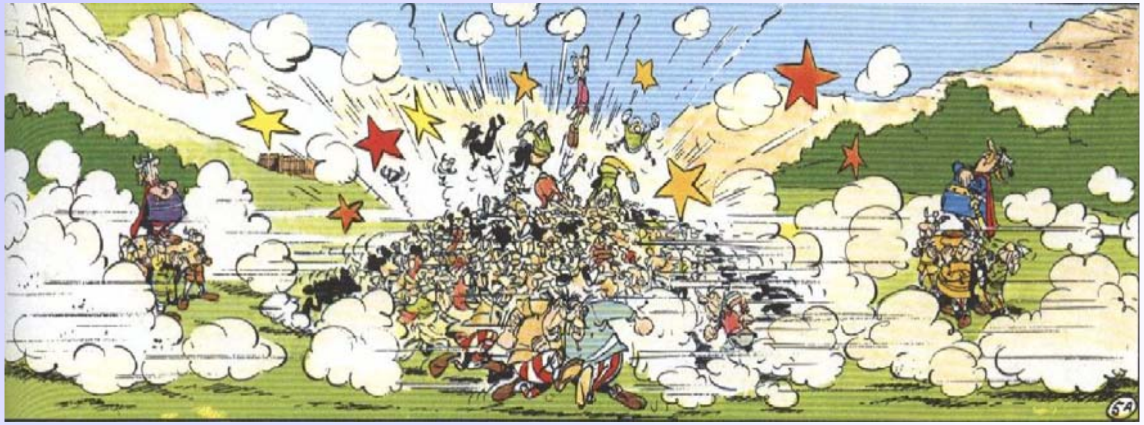
Literature

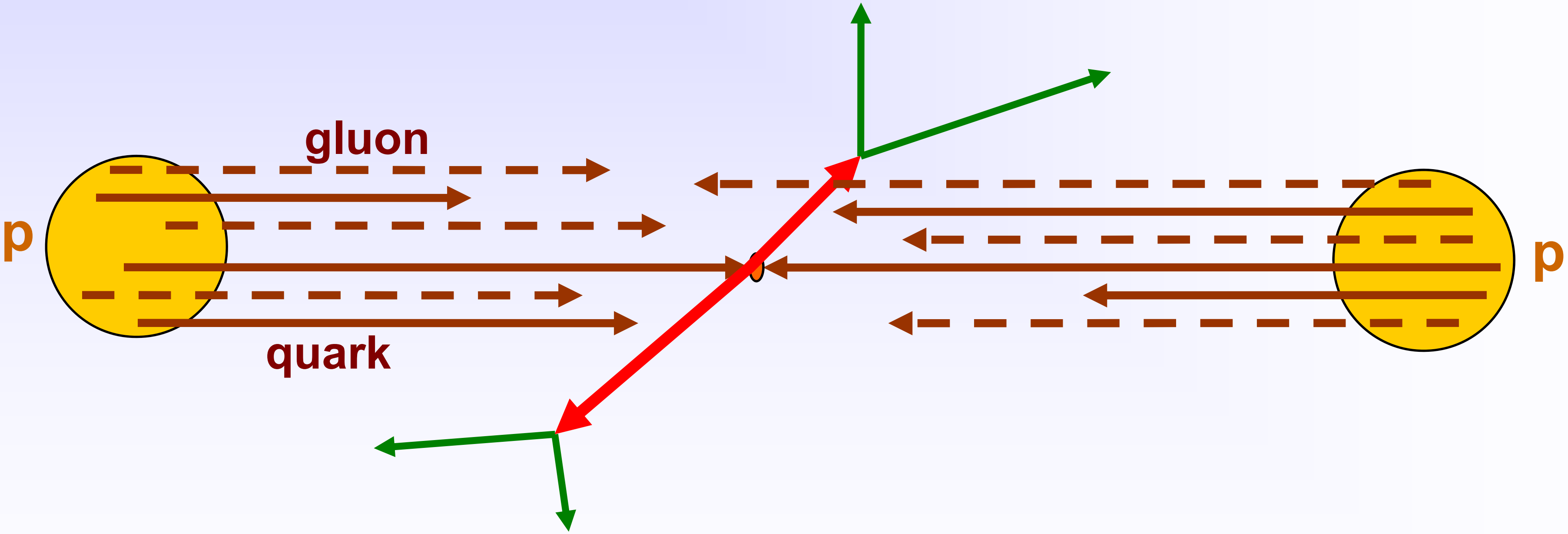
- **Text books** (a selection)
  - C. Grupen, Particle Detectors, Cambridge University Press, 1996
  - G. Knoll, Radiation Detection and Measurement, 3rd ed. Wiley, 2000
  - W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, 1994
  - R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992
  - K. Kleinknecht, Detectors for particle radiation , 2nd edition, Cambridge Univ. Press, 1998
  - W. Blum, L. Rolandi, Particle Detection with Drift Chambers, Springer, 1994
  - R. Wigmans, Calorimetry, Oxford Science Publications, 2000
  - G. Lutz, Semiconductor Radiation Detectors, Springer, 1999

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

- **Other sources**
  - Particle Data Book Phys. Lett. B**592**, 1 (2004) http://pdg.lbl.gov/pdg.html
  - R. Bock, A. Vasilescu, Particle Data Briefbook http://www.cern.ch/Physics/ParticleDetector/BriefBook/
  - Proceedings of detector conferences (Vienna CI, Elba, IEEE, Como)
  - Nucl. Instr. Meth. A

Large Hadron Collider





Detector Challenges

- Physics
  - Properties (way particles interact)
  - Particle Structure
  - Hunt for New Particles

→

- Measurements
  - Topology
  - Particle Momentum
  - Particle Velocity
  - Particle Energy
  - Particle Identification (mass)

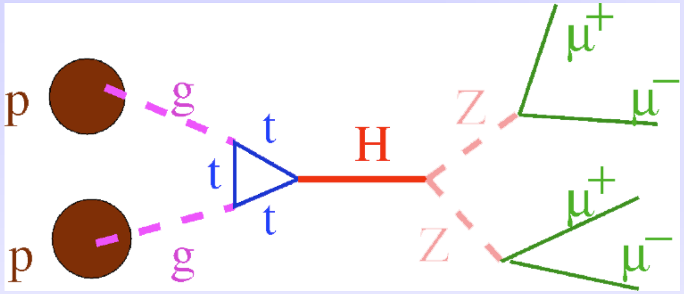
- Detector requirements
  - High energy collisions
    - sufficiently high momentum (position) resolution up to TeV scale
  - High luminosity
    - high rate capabilities and fast detectors because of high interaction rate
  - Large particle density
    - high granularity, sufficiently small detection units to resolve particles
  - At hadron colliders
    - radiation-hard detectors and electronics

      radiation mainly due to many protons/neutrons emerging from he interactions

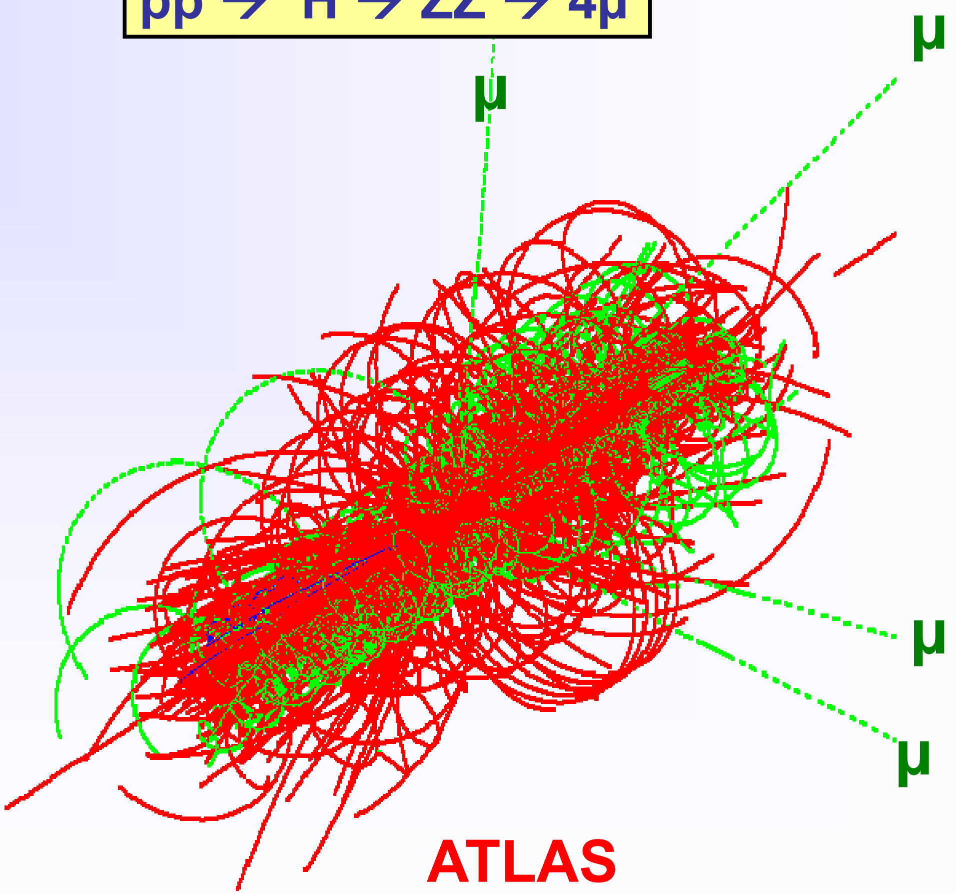
      not due to LHC machine backgrounds

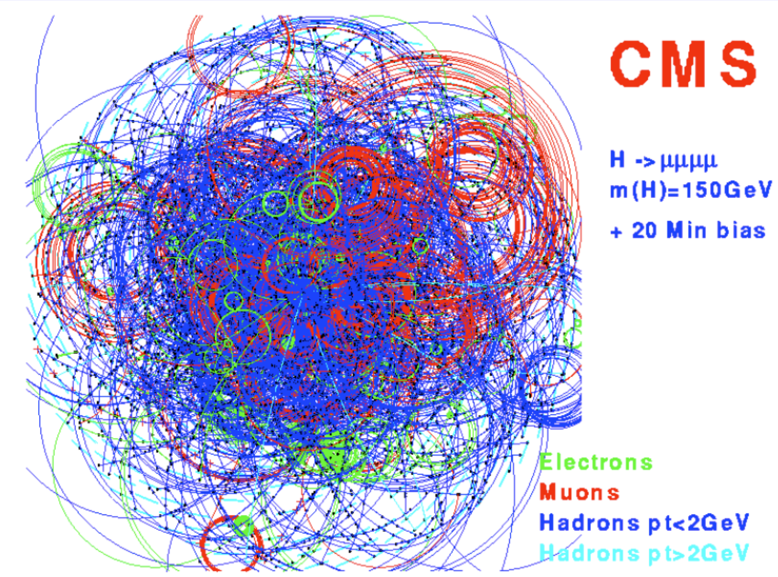
What we have to expect

- One bunch crossing every 25 ns with ~20 interactions
  - 1000 tracks per bunch crossing = $4 * 10^{10}$ tracks per second...
  - ...and very often you're interested in a few tracks only...



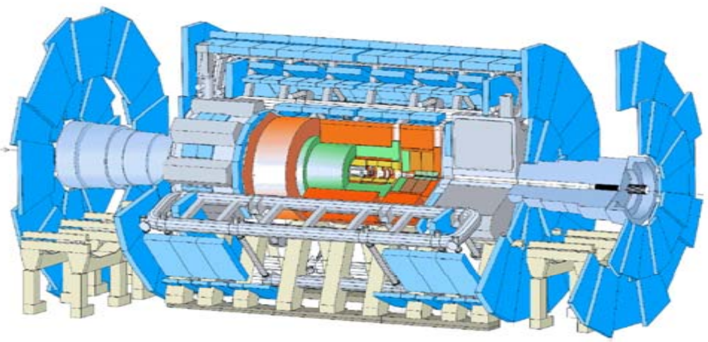
pp → H → ZZ → 4μ



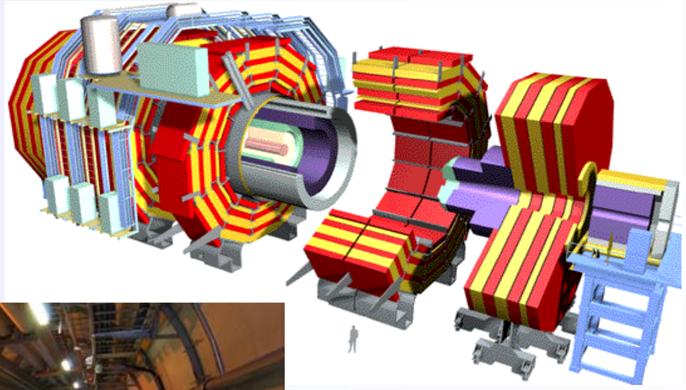


LHC Detectors

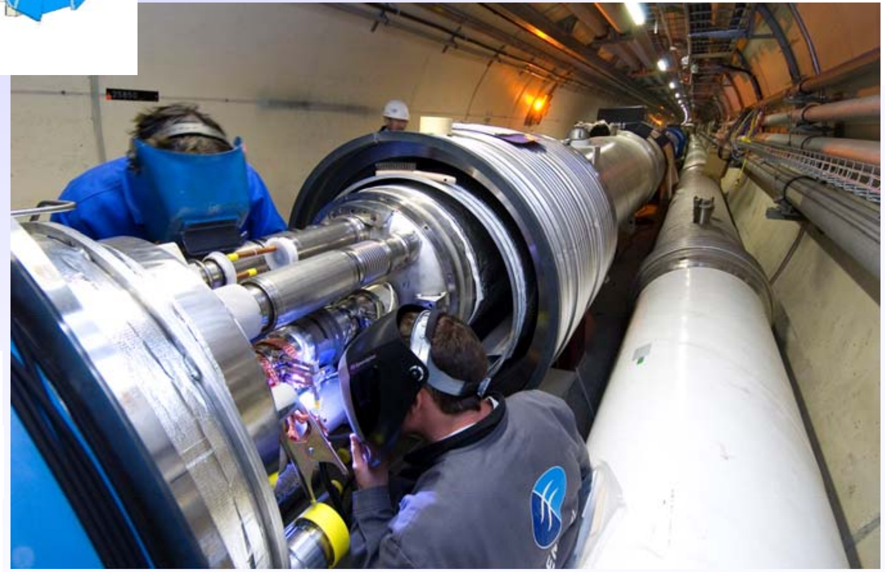
General purpose detectors (good for everything...)

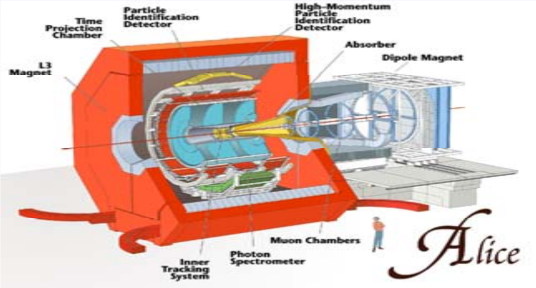


ATLAS



CMS

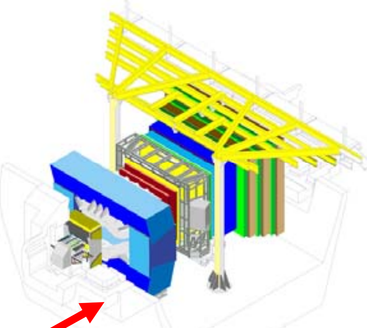




ALICE

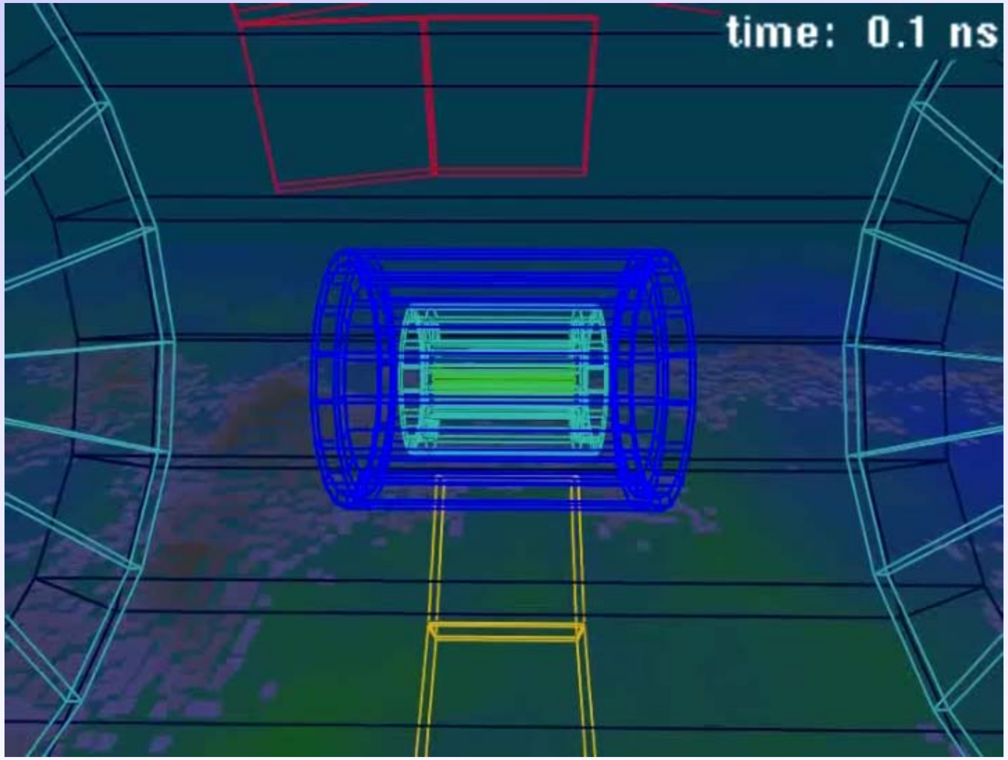
dedicated for Heavy Ion collisions

dedicated for b-physics



LHCb

Computer simulated event in ALICE



Particle	Life Time τ	$c \cdot \tau$
γ	∞	∞
e^-	∞	∞
ν	∞	∞
p^+	$>1.6\ 10^{33}$ y	∞
n	887 s	$2.7\ 10^{8}$ km
μ^-	$2.2\ 10^{-6}$ s	659 m
π^+	$2.6\ 10^{-8}$ s	7.8 m
K^+	$1.2\ 10^{-8}$ s	3.7 m
K^0_L	$5.2\ 10^{-8}$ s	15.5 m
K^0_S	$0.9\ 10^{-10}$ s	2.7 cm
$\Lambda^0\Sigma^+\Xi^{0-}\Omega^-\ldots$	$\sim 10^{-10}$ s	~3 cm
$D^{0+}B^{0+}\Lambda_c^+\ \Lambda_b^0$	$\sim 10^{-12}$ s	~300 μm
π^0	$8.4\ 10^{-17}$ s	25 nm
$\eta\ \psi\ldots$	$<10^{-19}$ s	–

In practice we detect only:

$$\gamma, e^{\pm}, p^{\pm}, n, \mu^{\pm}, \pi^{\pm}, K^{\pm}, K_L^0$$

The Perfect Detector...

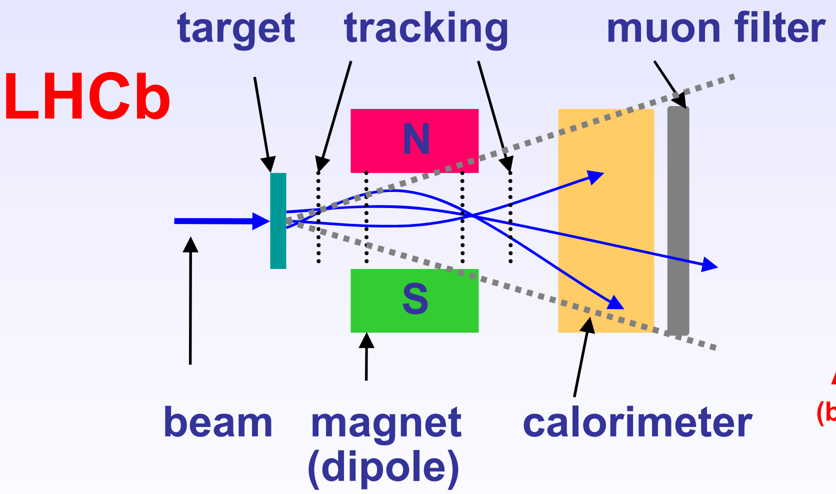
...should reconstruct any interaction of any type with 100% efficiency and unlimited resolution (get "4-momenta" of basic physics interaction)

efficiency:

not all particles are detected, some leave the detector without any trace (neutrinos), some escape through not sensitive detector areas (holes, cracks for e.g. water cooling and gas pipes, cables, electronics, mechanics)

Fixed target geometry

"Magnet spectrometer"

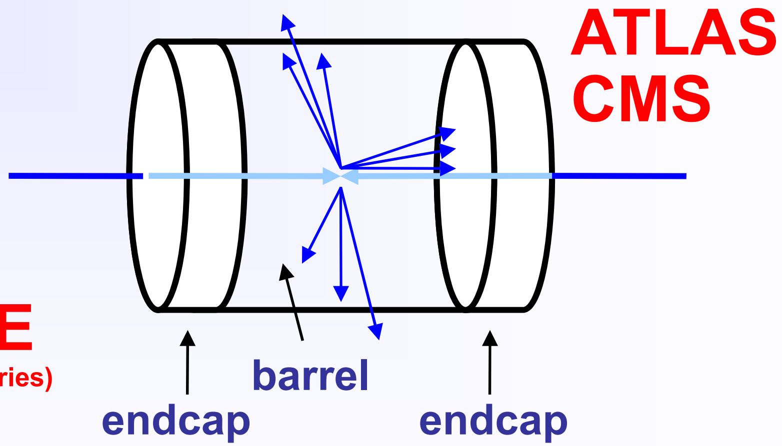


- Limited solid angle coverage
- rel. easy access (cables, maintenance)

ALICE
(both geometries)

Collider geometry

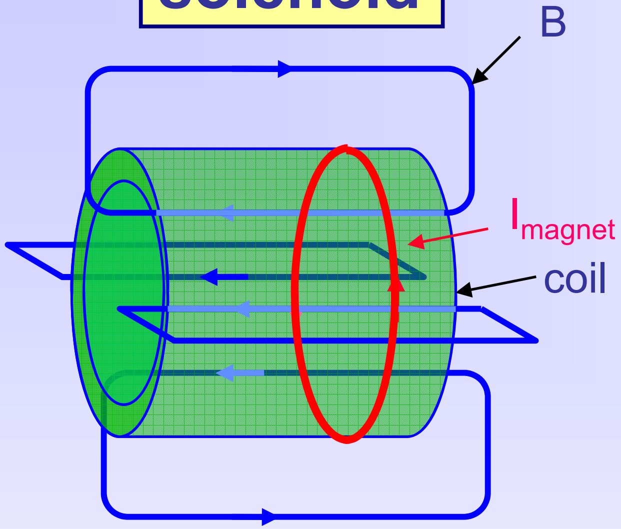
"4π multi purpose detector"



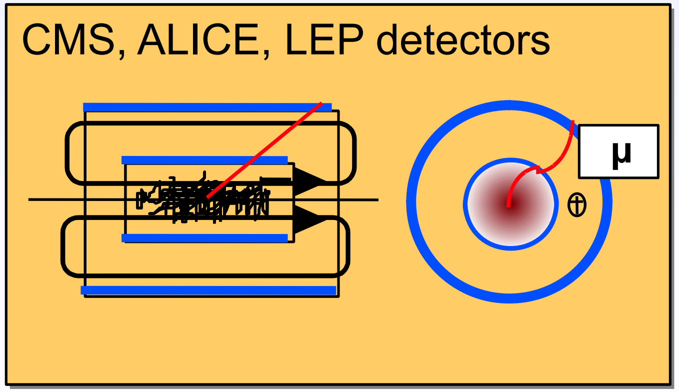
- "full" solid angle coverage
- very restricted access

Magnet Concepts at LHC experiments

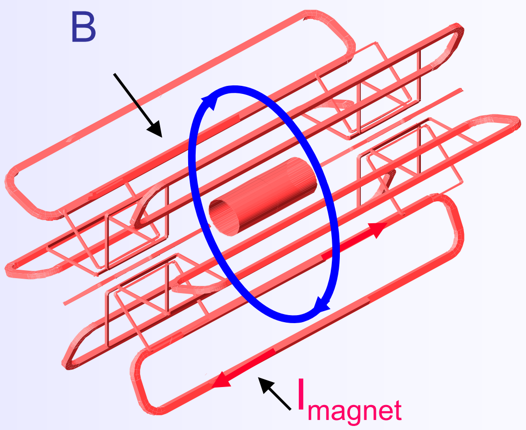
solenoid



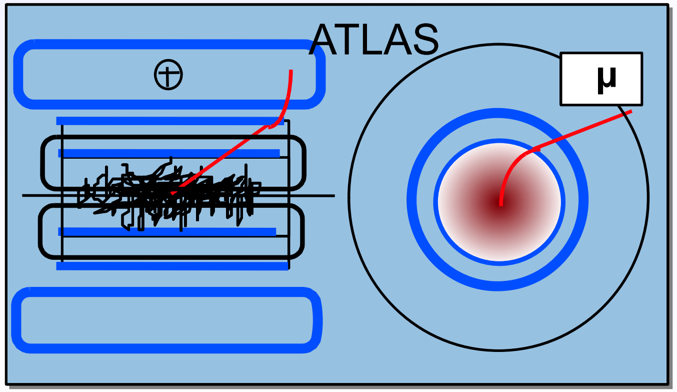
- \+ large homogenous field inside coil
- \- needs iron return yoke (magnetic shortcut)
- \- limited size (cost)
- \- coil thickness (radiation lengths)



(air-core) toroid

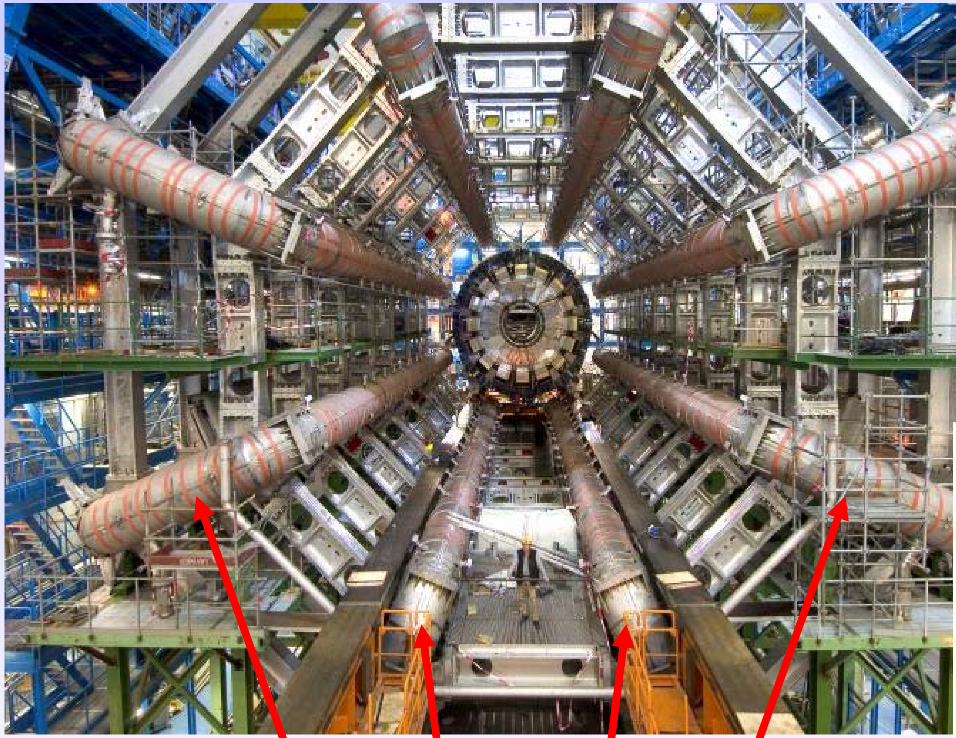


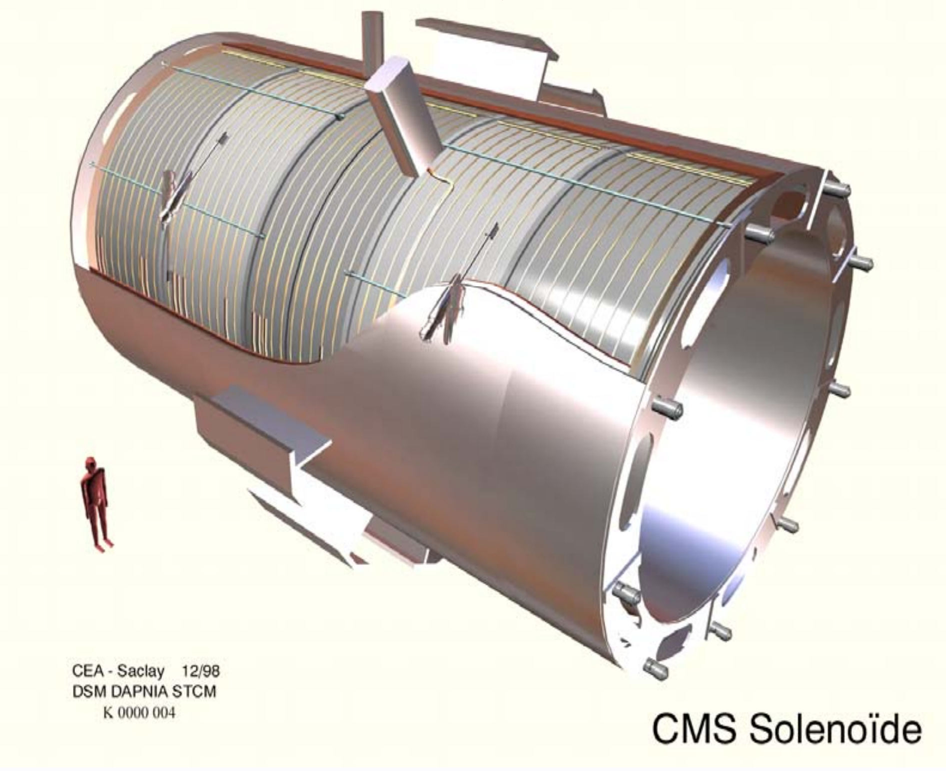
- \+ can cover large volume
- \+ air core, no iron, less material
- \- needs extra small solenoid for general tracking
- \- non-uniform field
- \- complex structure



ATLAS and CMS Coils

CMS solenoid (5 segments)





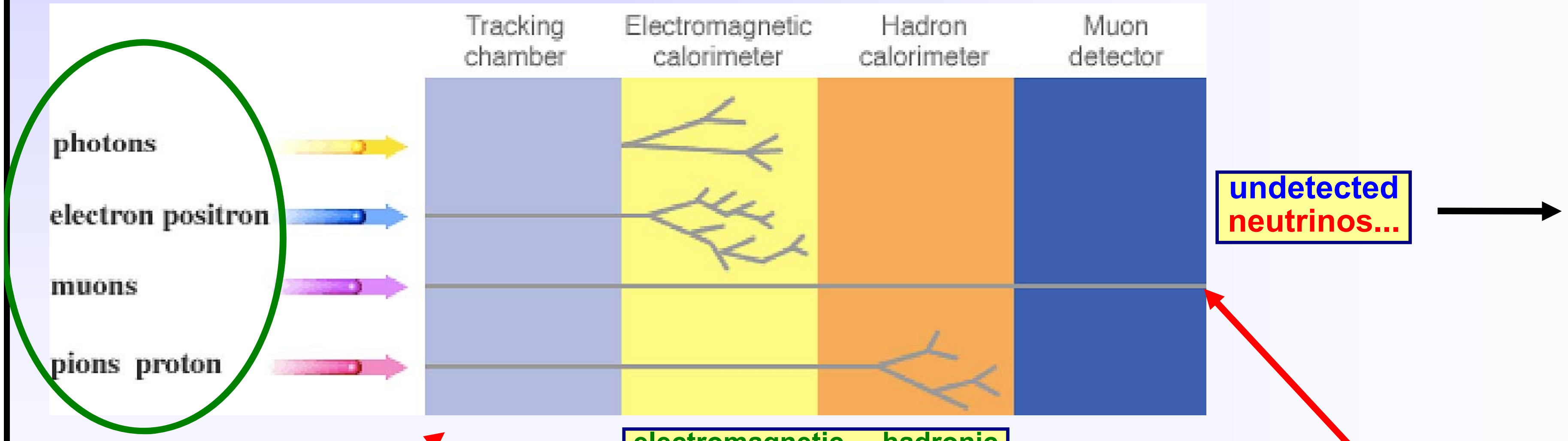
ATLAS toroid coils

Particle Interactions

- **Particles cannot be seen/detected directly, we only can observe the result of their interactions with the detector (material)**
  - **Interactions are mainly electromagnetic**

    exceptions: strong interactions in hadronic showers (hadron calorimeters)

    weak interactions at neutrino detection (not discussed here)



undetected neutrinos...

electromagnetic hadronic shower

momentum measurement by curvature in magnetic field

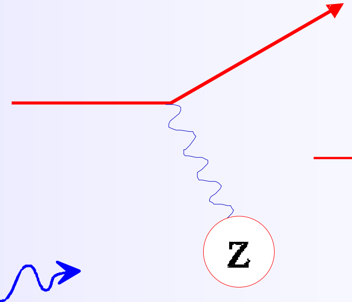
energy measurement by creation and total absorption of showers

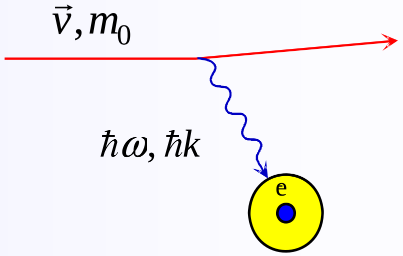
muon detection with improved momentum measurement (long lever arm)

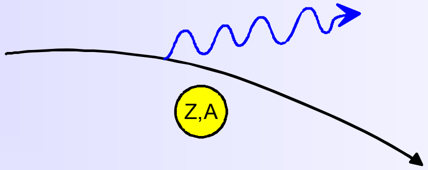
CERN Academic Training Programme 2004/2005

Particle Interactions

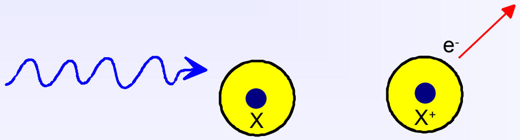
- Charged Particle Interactions
  - Scattering and Ionization
  - Photon Emission:
    - Bremsstrahlung
    - Čerenkov Radiation
    - Transition Radiation
    - Excitations (Scintillations)

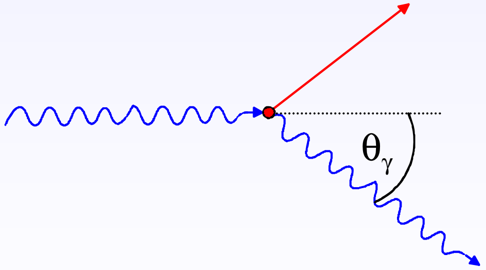


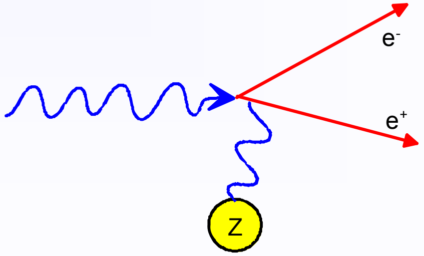




- Photon Interaction
  - Photo Effect
  - Compton Scattering
  - Pair Creation

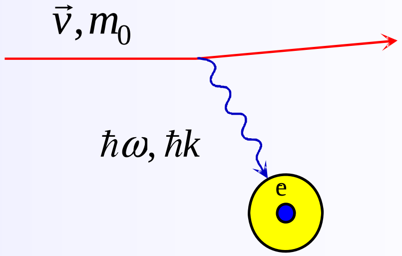




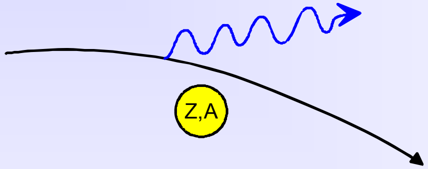


Charged Particle Interactions

- **(Multiple) elastic scattering with atoms of detector material**
  - **mostly unwanted, changes initial direction, affects momentum resolution**



- **Ionization**
  - **the basic mechanism in tracking detectors**



- **Photon radiation**
  - **Bremsstrahlung**

    initiates electromagnetic shower in calorimeters, unwanted in tracking detectors
  - **Čerenkov radiation**

    hadronic particle identification (ALICE),

    also in some homogeneous electromagnetic calorimeters (lead glass)
  - **Transition radiation**

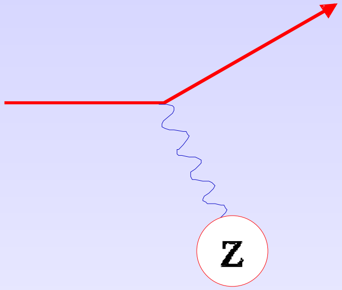
    electron identification in combination with tracking detector

- **Excitation**

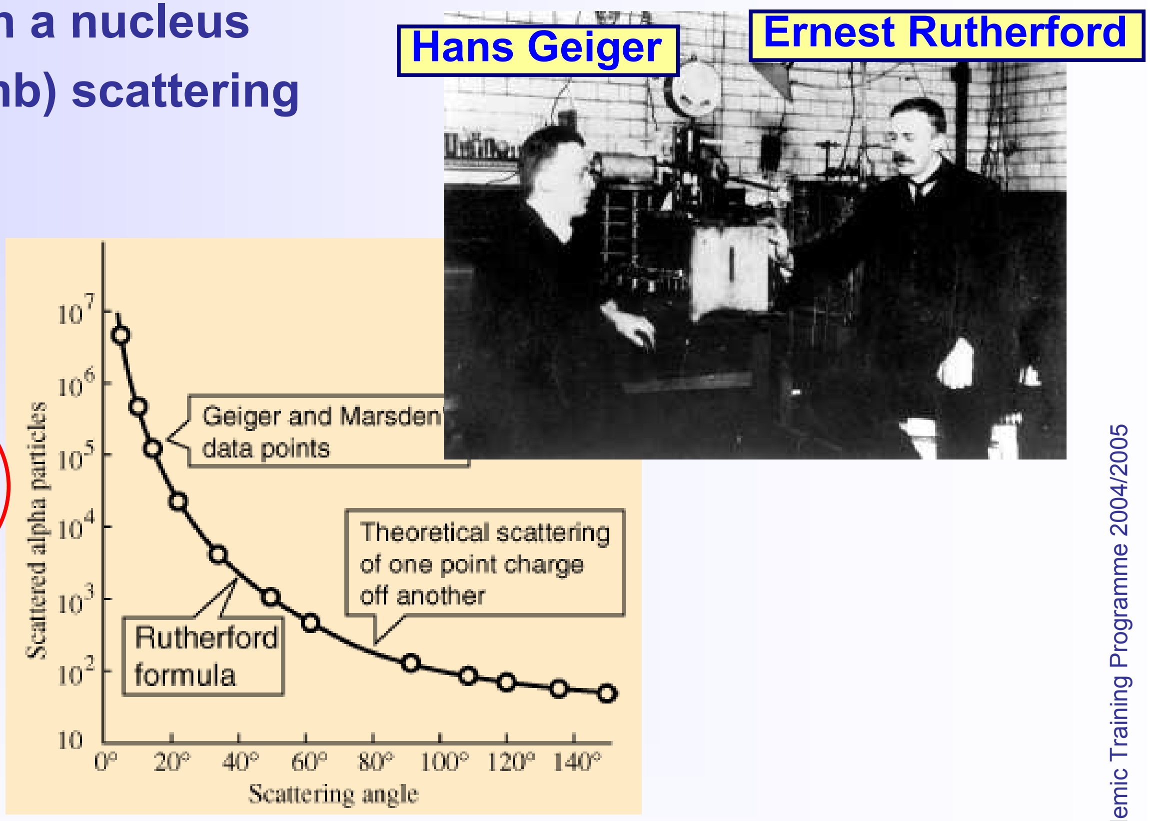
  Creation of scintillation light in calorimeters (plastic scintillators, fibers)

Elastic Scattering

- **Most basic interaction of a charged particle in matter**
  - **elastic scattering with a nucleus**
    = Rutherford (Coulomb) scattering



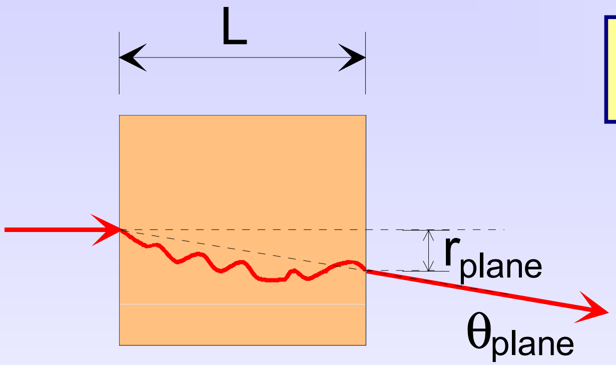
$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \Theta/2}$$



- **Approximations**
  - non-relativistic
  - no spins
- **Scattering angle and energy transfer to nucleus usually small**
  - No (significant) energy loss of the incoming particle
  - Just change of particle direction

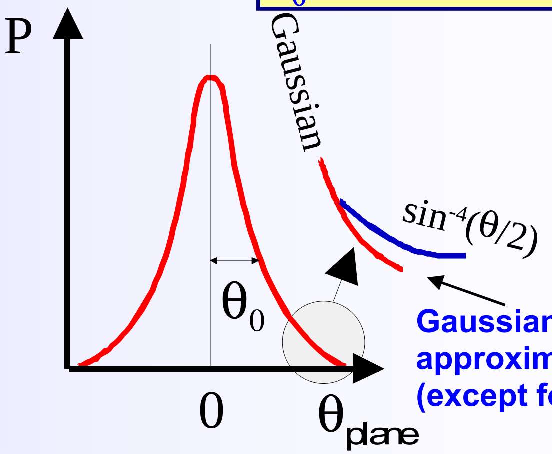
Elastic Scattering

- **If thick material layer: Multiple scattering**
  - **after passing layer of thickness L particle leaves with some displacement r_{plane} and some deflection angle Θ_{plane}**



distribution of deflection angle

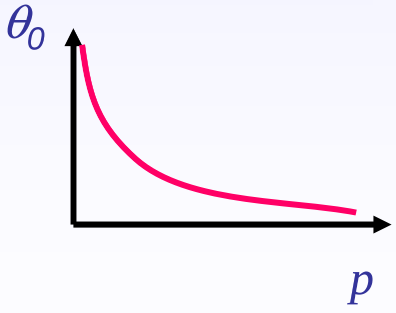
Θ_0= width of distribution

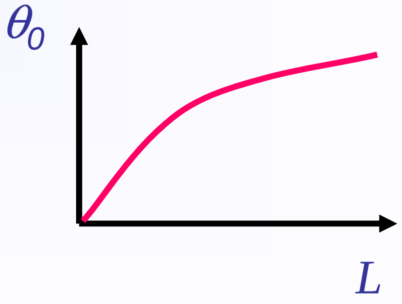


Gaussian is good approximation (except for tails)

- **Multiple scattering dominates momentum measurement for low momenta**

$$\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$





Momentum Measurement

- Charged particles are deflected by magnetic field
  - homogeneous B-field → particle follows a circle with radius r

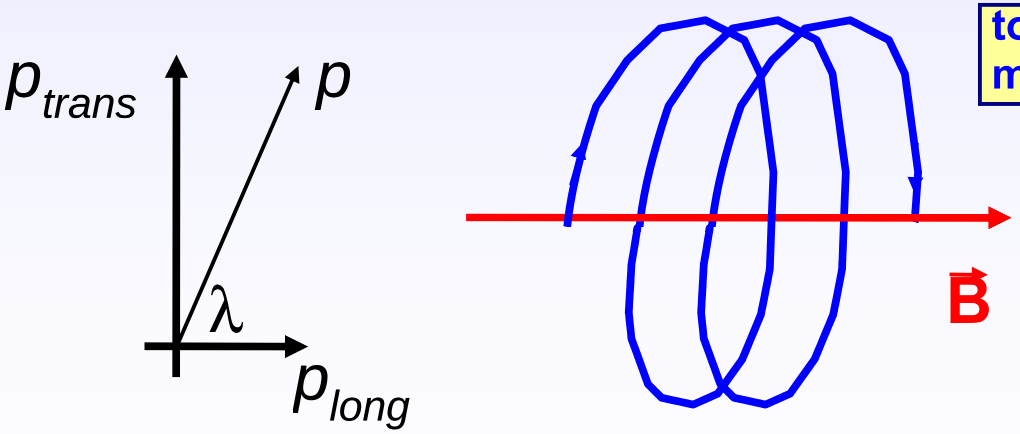
$$p_t\,[\mathrm{GeV/c}] = 0.3 \cdot B\,[\mathrm{T}] \cdot r\,[\mathrm{m}]$$

measuement of p_t via measuring the radius

  - this is just the momentum component ⊥ to the B-field

    transverse momentum p_t
  - no particle deflection parallel to magnetic field
  - if particle has longitudinal momentum component

    → particle follows a helix

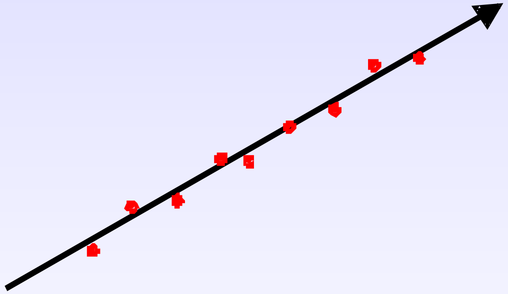


total momentum p to be measured via dip angle λ

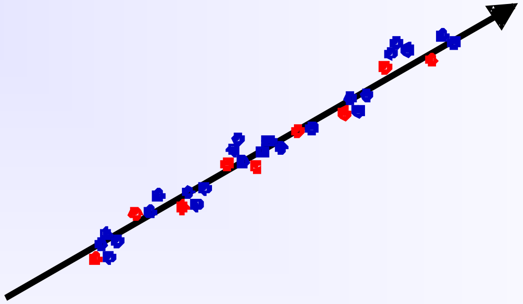
$$p = \frac{p_t}{\sin\lambda}$$

Ionization

- Primary number of ionizations per unit length is Poisson-distribute
  - typically ~30 primary interactions (ionization clusters) / cm in gas at 1 bar
- However, primary electrons sometimes get large energies
  - can make ionizations as well (secondary ionization)
  - can even create visible secondary track (“delta-electron”)
  - large fluctuations of energy loss by ionization



Primary ionization



Total ionization = primary + secondary ionization

- Typically: total ionization = 3 x primary ionization

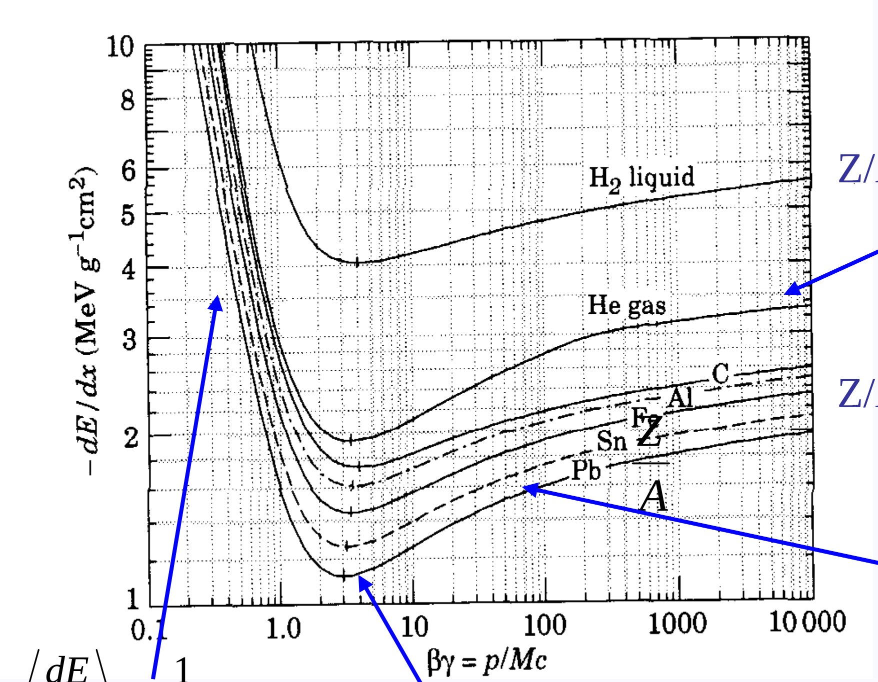
  on average ~ 90 electrons/cm

Ionization

Energy loss by Ionization only → Bethe - Bloch formula

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

- **dE/dx in [MeV g^{-1} cm^2]**
- **valid for "heavy" particles ($m \geq m_\mu$).**
- **dE/dx depends only on β, independent of m !**
- **First approximation: medium simply characterized by Z/A ~ electron density**



Z/A = 1

"Fermi plateau"

Z/A~0.5

$$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2 \gamma^2$$

"relativistic rise"

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

"kinematical term"

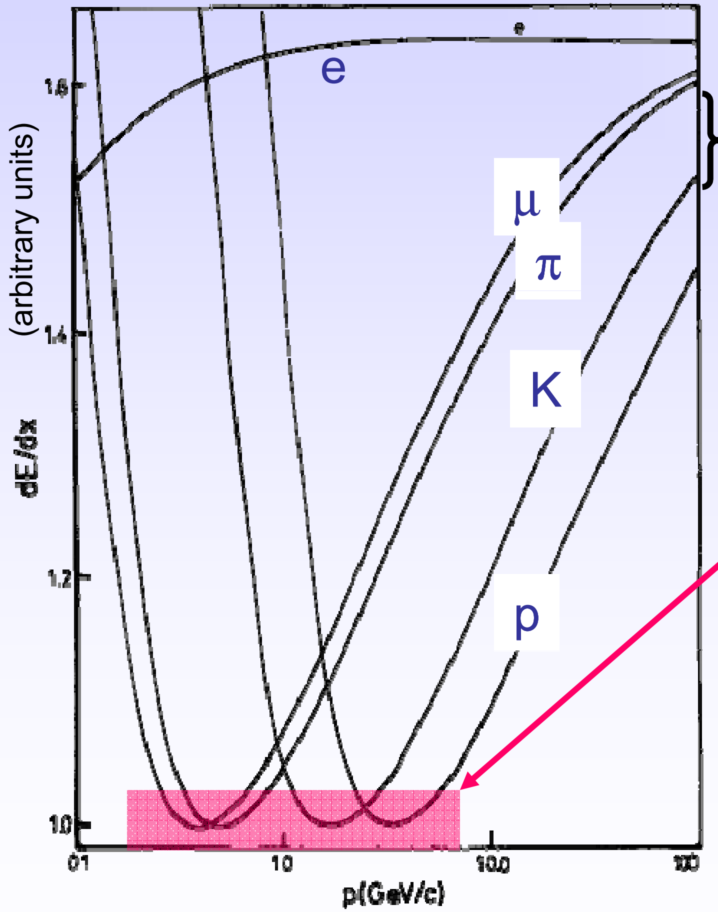
βγ ≈ 3-4
minimum ionizing particles, MIPs

Particle ID through dE/dx

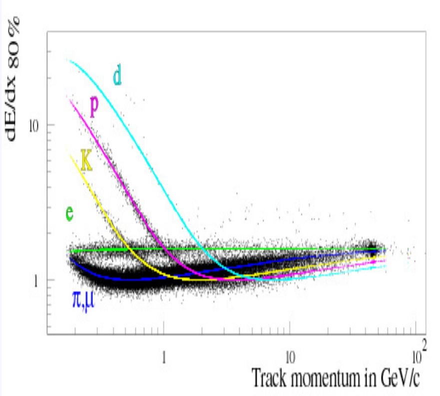
$$p = m_0 \beta \gamma c$$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \ln\left(\beta^2 \gamma^2\right)$$

Simultaneous measurement of *p* and *dE/dx* defines mass m_0, hence the particle identity



π/K separation (2σ) requires a *dE/dx* resolution of < 5%



Not so easy to achieve !

- **dE/dx is very similar for minimum ionizing particles.**
- **Energy loss fluctuates and shows Landau tails.**

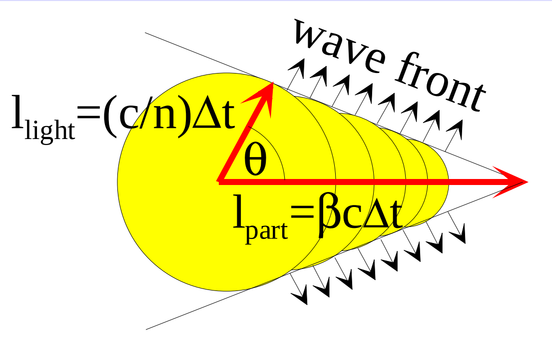
Average energy loss for e, μ, π, K, p in 80/20 Ar/CH_4 (NTP)
(J.N. Marx, Physics today, Oct.78)

Čerenkov Radiation

- Čerenkov radiation is emitted when a charged particle passes through a dielectric medium with velocity $\beta \geq \beta_{thr} = \frac{1}{n}$

speed of light in medium

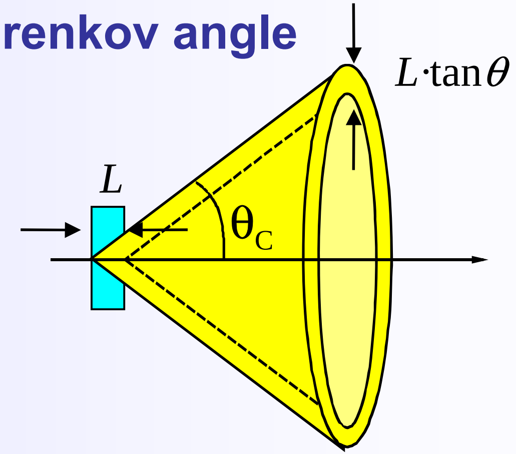
  - classical picture: wave front or cone under Čerenkov angle



continuous wave front emission from track

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

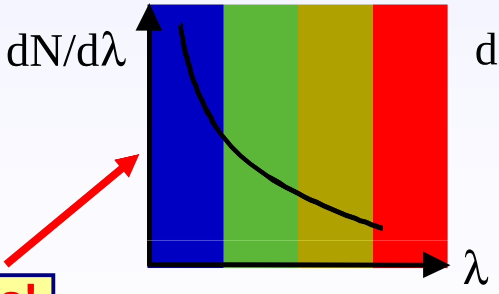
$$\text{with} \quad n = n(\lambda) \geq 1$$

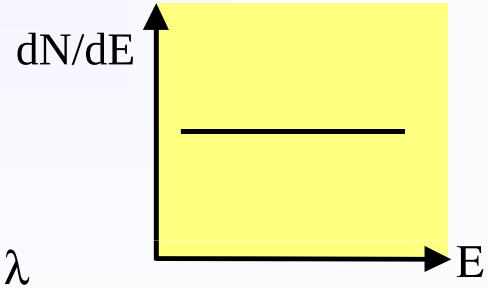


light cone emission when passing thin medium

  - number of emitted photons per unit length and unit wave length interval

$$\frac{d^2N}{dx\,d\lambda} \propto \frac{1}{\lambda^2} \qquad \frac{d^2N}{dx\,dE} = const$$

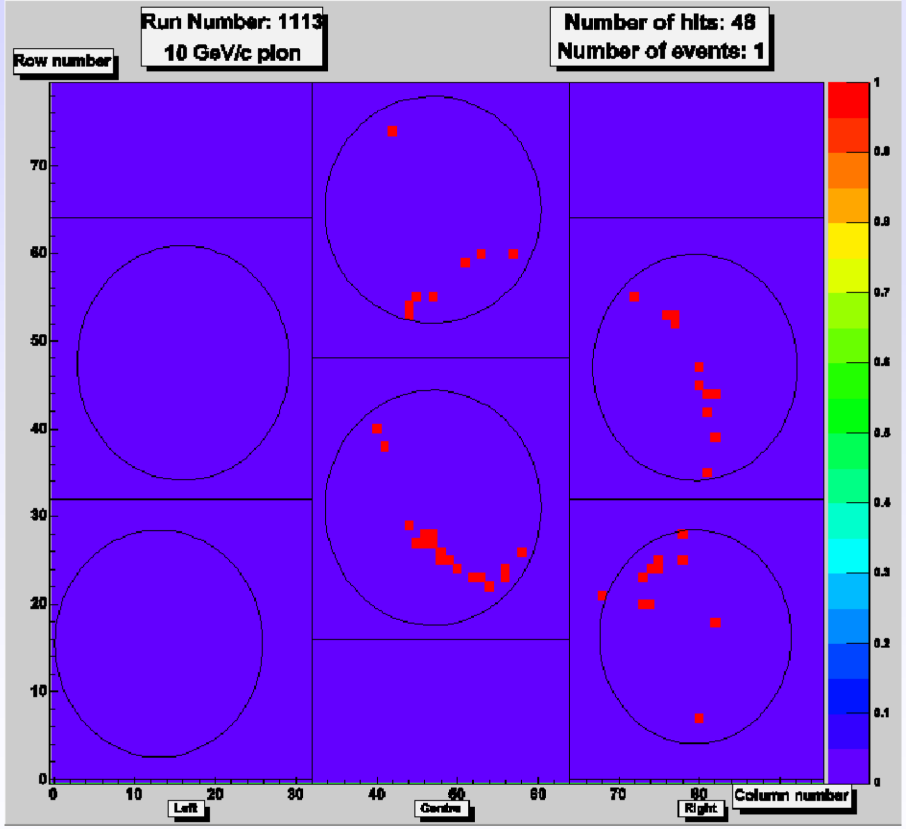




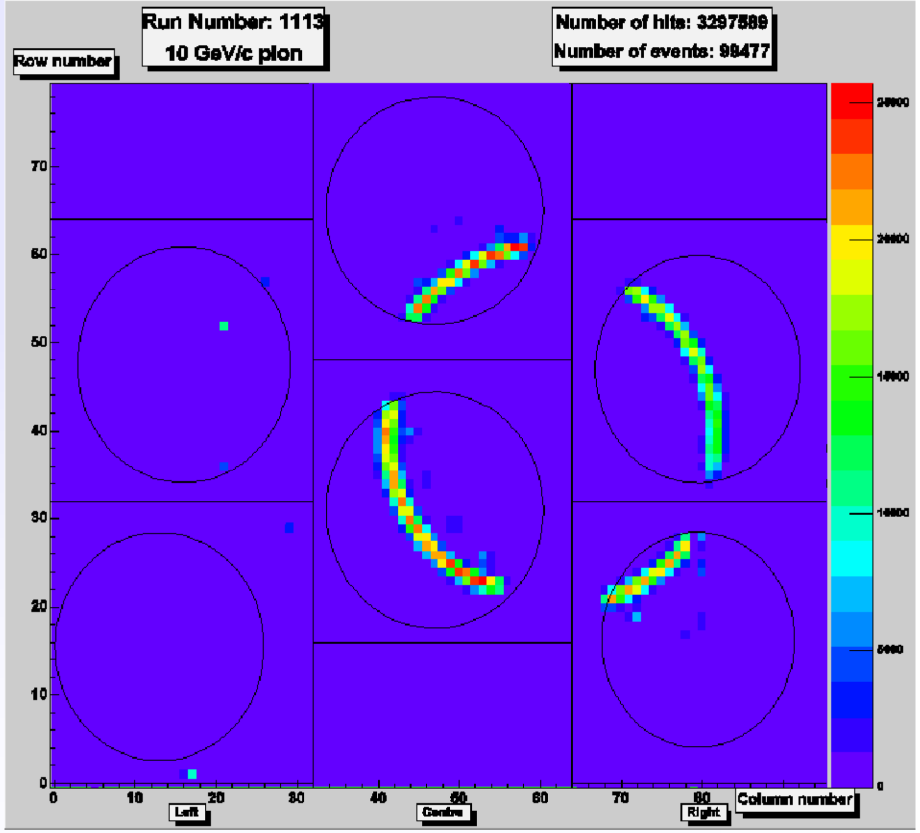
mainly UV photons!

Particle ID through Čerenkov Radiation

Single pion (10 GeV/c)

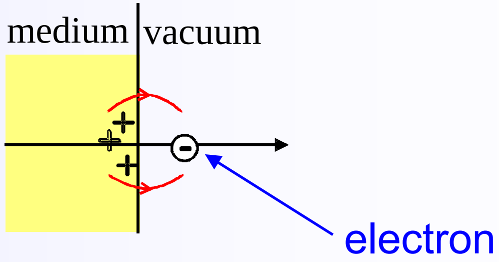


Superimposed events (100 k pions, 10 GeV/c)



Transition Radiation

- **Predicted by Ginzburg and Franck in 1946**
  - **emission of photons when a charged particle traverses through the boundary of two media with different refractive index**
  - **(very) simple picture**
    - charged particle is polarizing medium
    - polarized medium is left behind when particle leaves media and enters unpolarized vacuum
    - formation of an electrical dipole with (transition) radiation

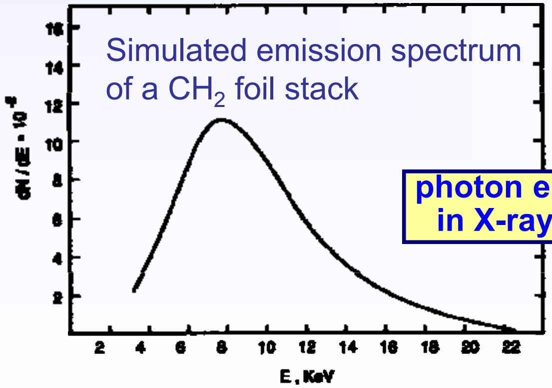


- **Radiated energy per boundary** $W \propto \gamma$
  - **only very high energetic particles can radiate significant energy**
    - need about $\gamma > 1000$

      in our present energy range reachable with accelerators only electrons can radiate but probability to emit photons still small

$$N_{photons} \propto \alpha_{EM} \approx \frac{1}{137}$$

→ **need many boundaries (foils, foam) to get a few photons**

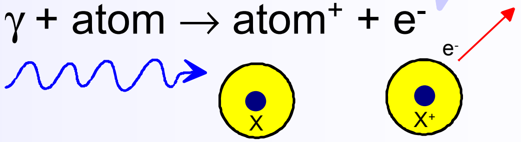

Simulated emission spectrum of a CH_2 foil stack

photon energy maximum in X-ray region (8 keV)

Particle Interactions – Photons

- **Photo effect**
  - **used at various photo detectors to create electrons on photo cathodes in vacuum and gas or at semi conductors (surface)**
    - Photo Multiplier Tubes (PMT)
    - photo diodes

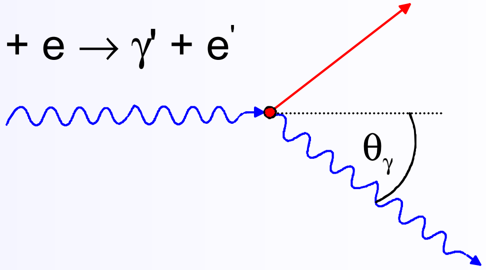
$\gamma + \text{atom} \rightarrow \text{atom}^+ + e^-$



$$\sigma_{photo} \propto Z^5$$

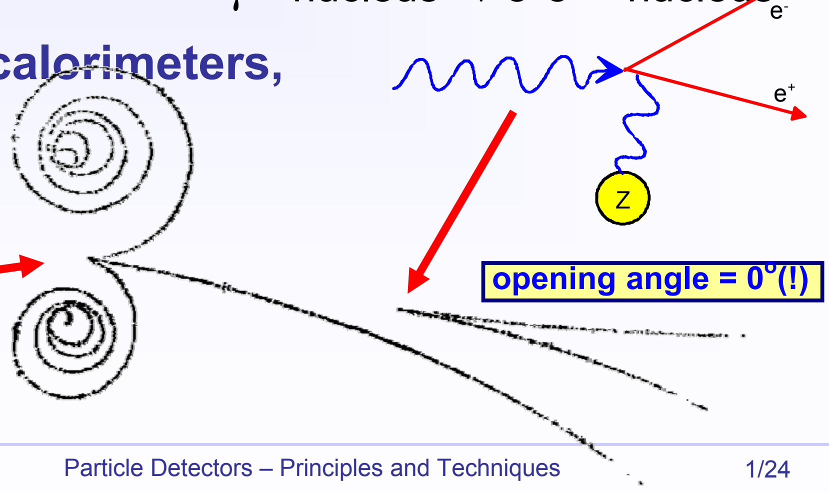
- **Compton scattering (e⁻γ scattering)**
  - **not used for particle detection**
    - but was/is used for polarization measurement of beams at e^+e^- machines and could be used to create high energy photons in a γγ - collider

$\gamma + e \rightarrow \gamma' + e'$



- **Pair production (γ → e^+e^-)**
  - **initiates electromagnetic shower in calorimeters, unwanted in tracking detectors**

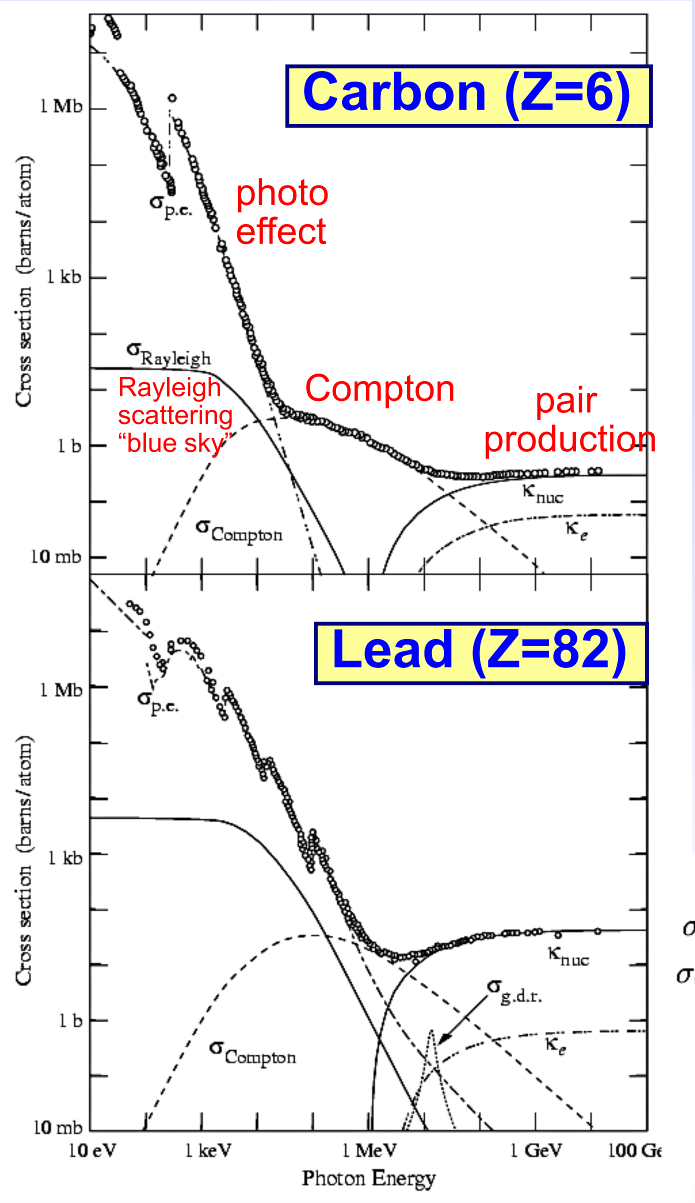
$\gamma + \text{nucleus} \rightarrow e^+e^- + \text{nucleus}$



opening angle = 0°(!)

$\gamma + e^- \rightarrow e^+e^- + e^- + \gamma$

Photon Interactions – Overview

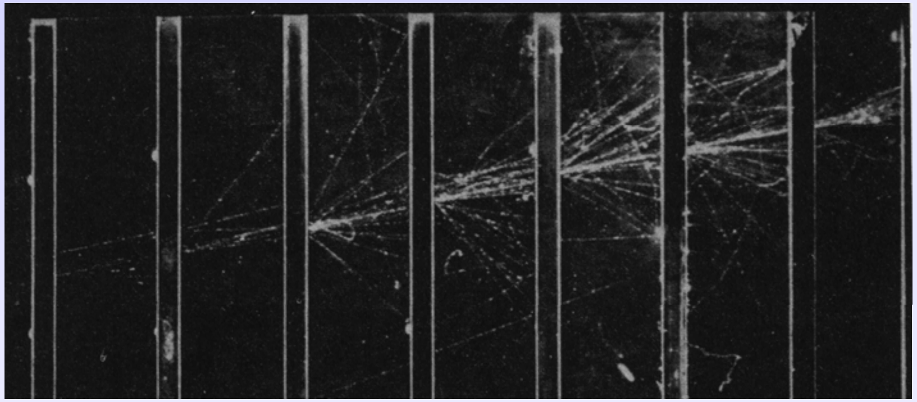


- **Photo effect dominates at low γ energies (< some 100 keV)**
- **Compton scattering regime ~some 100 keV up to ~10 MeV**
  - **exact energy domain depends on Z**
    - low Z: wide energy range of Compton scat.
    - large Z: small energy range of Compton scat.
- **Pair production dominates at high energies (> ~10 MeV)**

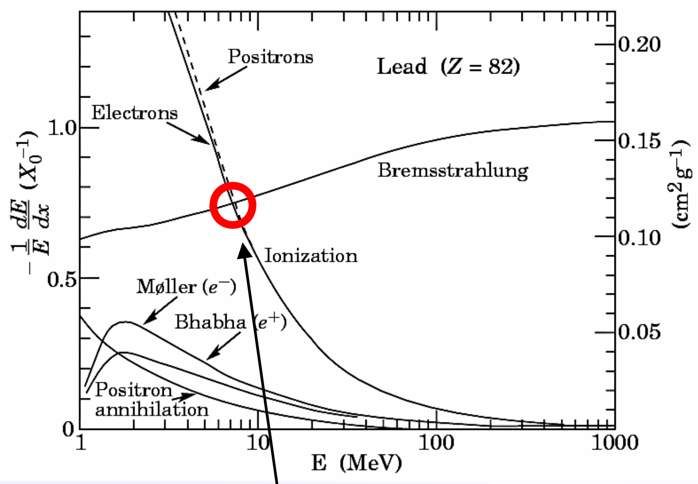
$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [4]. In these interactions, the target nucleus is broken up.

Electromagnetic Cascades

- **Starting from the first electron/photon an electromagnetic shower (cascade) develops in thick materials**



Electron shower in a cloud chamber with lead absorbers



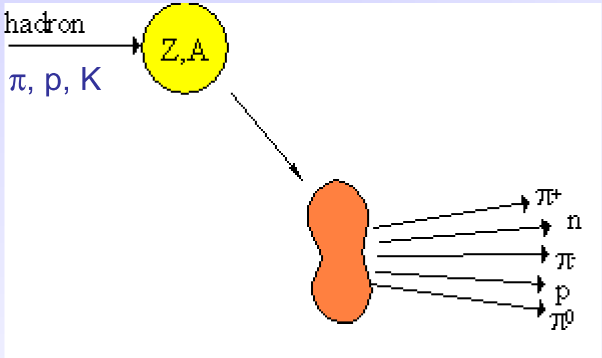
E_c = critical energy where energy loss (Ionization) = energy loss (Bremsstrahlung)

- Above E_c consider only Bremsstrahlung and pair production
- After the dominating processes are ionization, Compton effect and photo effect

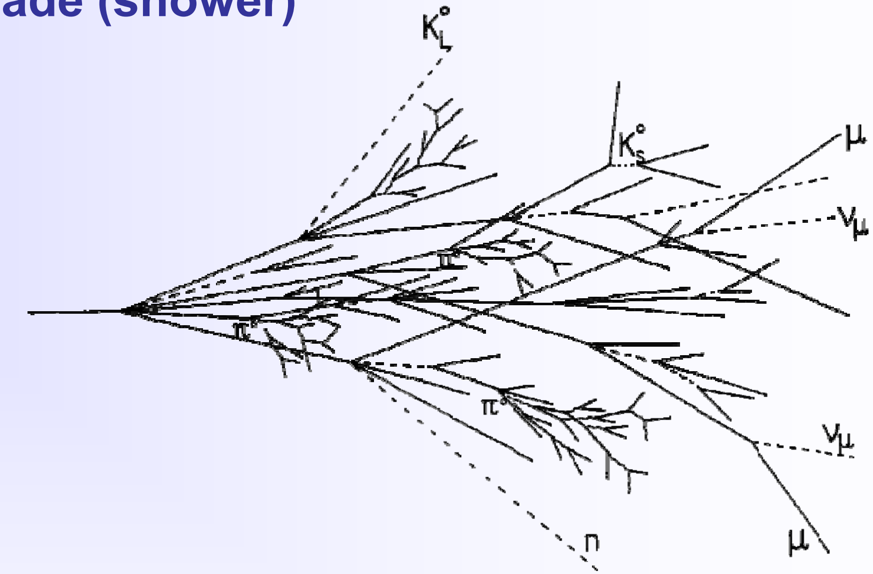
CERN Academic Training Programme 2004/2005

Hadronic Showers

- **Strong interaction of hadron with nucleus**
  - **Development of hadronic cascade (shower)**



Multiplicity ~ ln(*E*)



- **Hadronic showers have two main components**
  - **Hadronic**

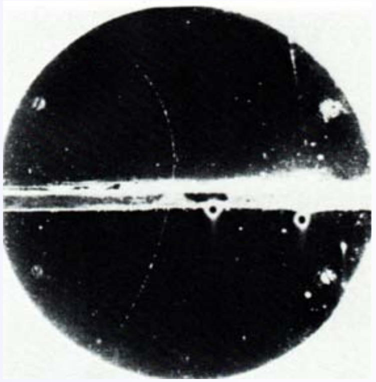
    charged hadrons, breaking up of nuclei (binding energy) nuclear fragments, neutrons
  - **Electromagnetic**

    decay of neutral pions: $\pi^0 \rightarrow 2\gamma$ (100% branching ratio)

“invisible” energy = large energy fluctuations

Tracking Detectors

- **“Classic” Detectors (historical touch...)**
- **Wire Chambers**
- **Silicon Detectors**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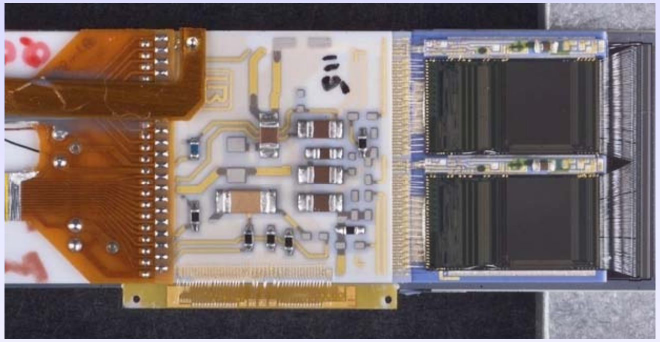
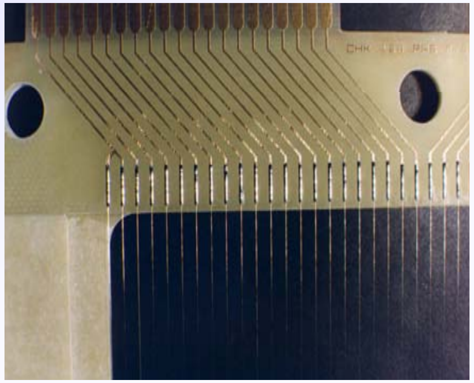
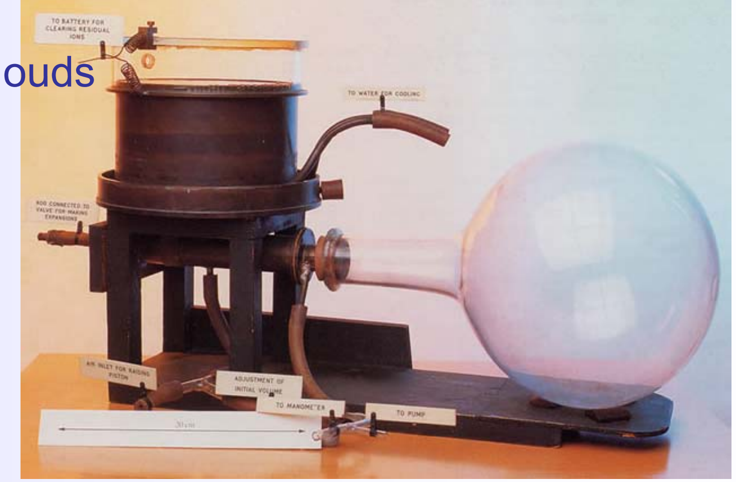
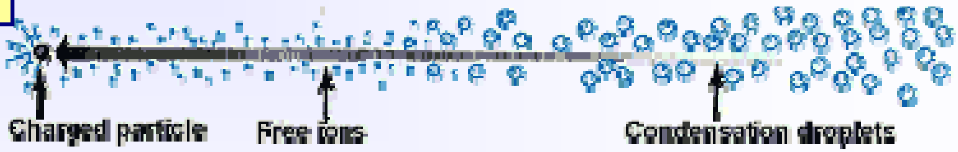


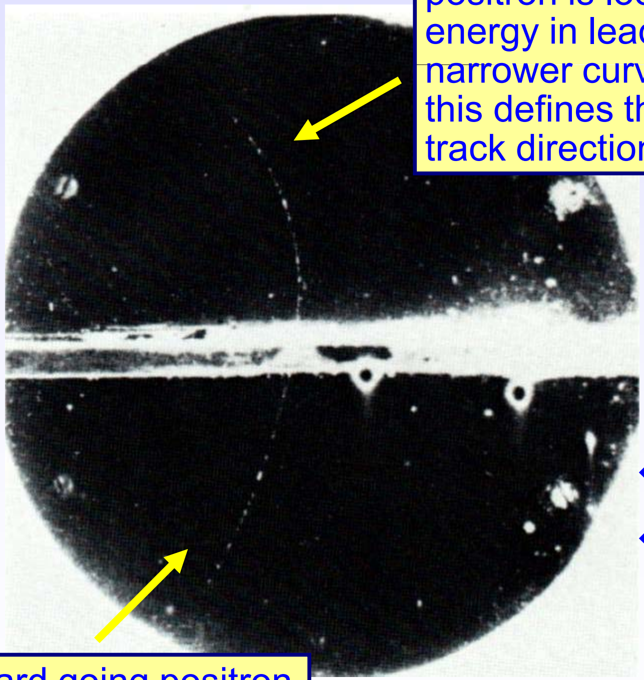


"Classic" Particle Detectors

- Cloud chamber (1911 by Charles T. R. Wilson, Noble Prize 1927
  - chamber with saturated water vapour
    - originally developed to study formation of rain clouds
  - charged particles leave trails of ion
    - water is condensing around ions
  - visible track as line of small water droplets







positron is loosing energy in lead: narrower curvature, this defines the track direction!

lead plate

⊗ **magnetic field**

upward going positron

LBNL Image Library

was used at discovery of the positron (1932 by Carl Anderson, Noble Prize 1936)

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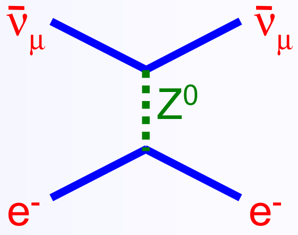
"Classic" Particle Detectors

- **Similar principle as cloud chamber:**
- **Bubble chamber (1952 by Donald Glaser, Noble Prize 1960)**
  - – **chamber with liquid (e.g. H2) at boiling point ("superheated")**
  - – **charged particles leave trails of ions**
    - formation of small gas bubbles around ions

was used at discovery of the "neutral current"
(1973 by Gargamelle Collaboration, no Noble Prize yet)

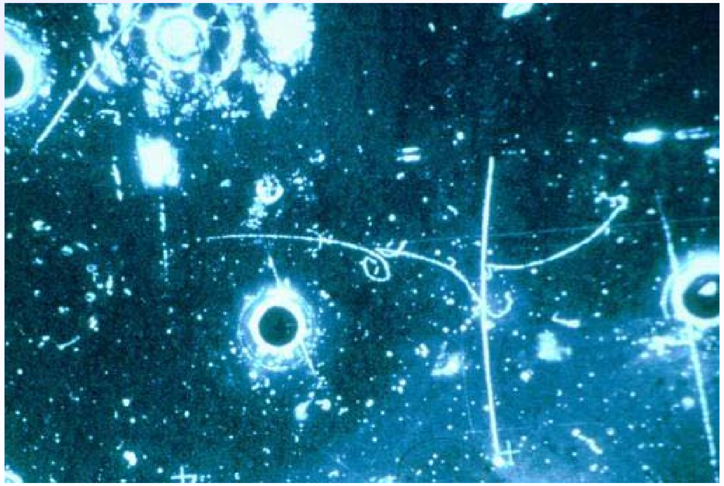
Donald Glaser

LBNL Image Library



Gargamelle bubble chamber

CERN

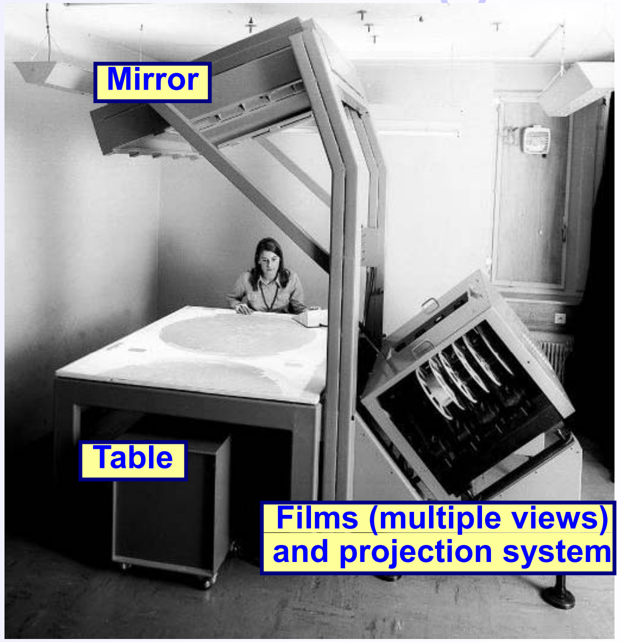


“Classic” Particle Detectors

- **Advantages of bubble chambers**
  - **liquid is**
    BOTH detector medium
    AND target
  - **high precision**
- **Disadvantages**
  - **SLOW!!!**
    - event pictures taken with cameras on film
    - film needs to be developed, shipped to institutes
    - and optically scanned for interesting events
  - **Need FASTER detectors (electronics!)**
- **However:**

Some important social side effects of bubble chamber era...

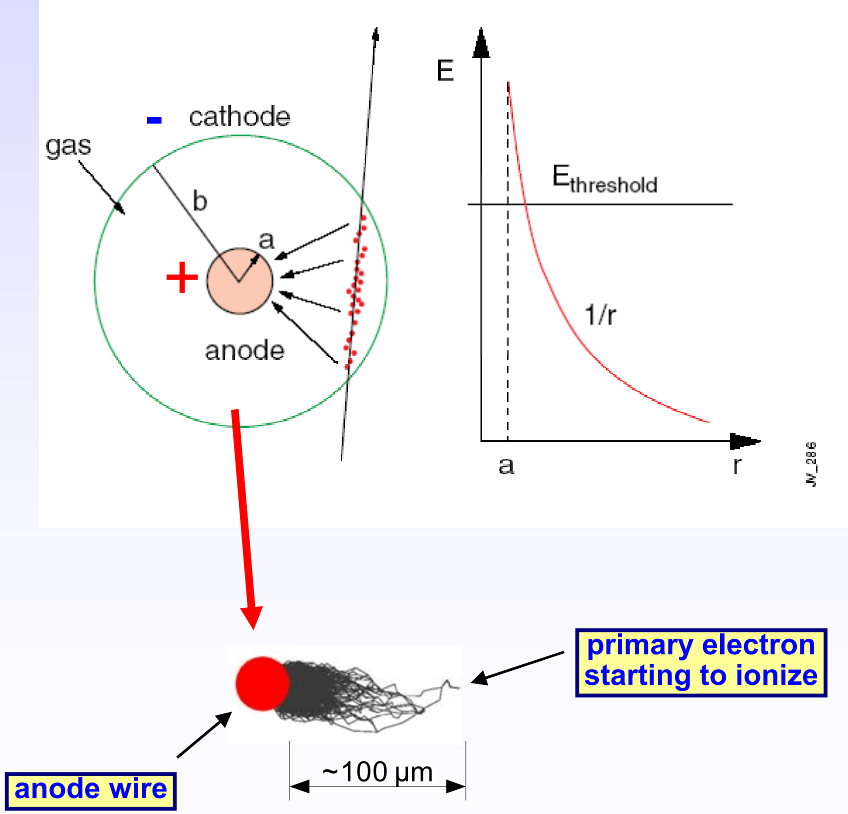
scanning often done by young “scanning girls” (students)...
...who later got married with the physicists...



Scanning table (1972)

“Classic” Particle Detectors

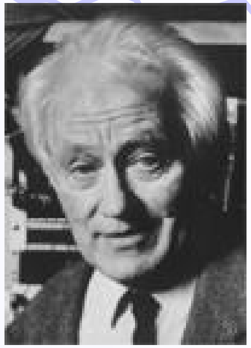
- **The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)**
  - **Tube filled with inert gas (He, Ne, Ar) + organic vapour**
  - **Central thin wire (20 – 50 µm ∅) , high voltage (several 100 Volts) between wire and tube**



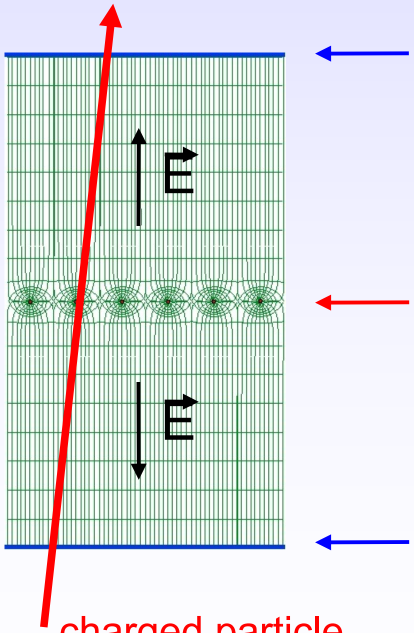
- **Strong increase of E-field close to the wire**
  - electron gains more and more energy
- **above some threshold (>10 kV/cm)**
  - electron energy high enough to ionize other gas molecules
  - newly created electrons also start ionizing
- **avalanche effect: exponential increase of # electrons (and ions)**
- **measurable signal on wire**
  - organic substances responsible for “quenching” (stopping) the discharge

“Classic” Particle Detectors

- **Geiger-Müller tube just good for single tracks with limited precision (no position information)**
  - **in case of more tracks more tubes are needed or...**
- **Multi Wire Proportional Chamber (MWPC)**
  (1968 by Georges Charpak, Nobel Prize 1992)
  - **put many wires with short distance between two parallel plates**



Georges Charpak

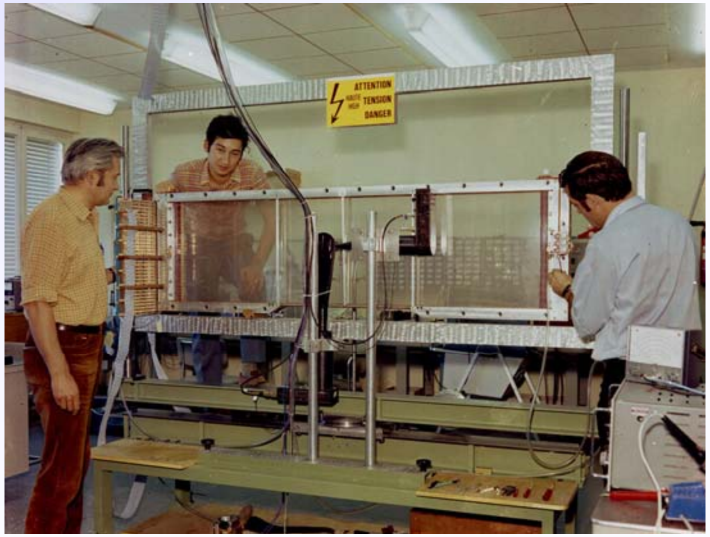


cathode plane (-)

anode plane (+),
many wires,
a few mm apart

cathode plane (-)

charged particle



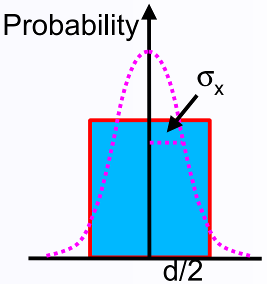
Georges Charpak, Fabio Sauli and Jean-Claude Santiard

Laboratorium 1993

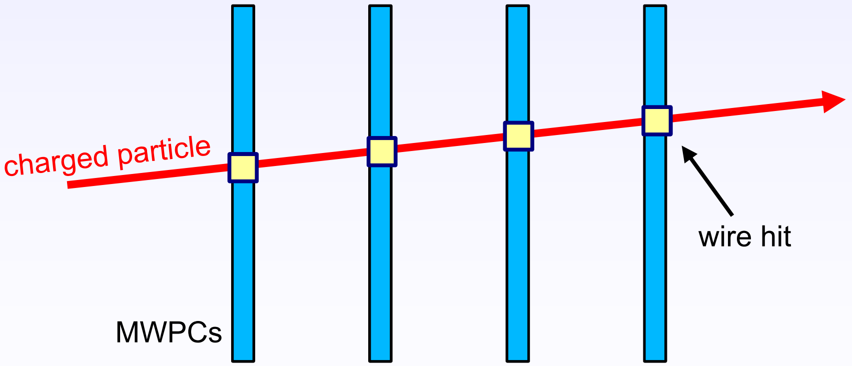
Wire Chambers - MWPC

- Multi Wire Proportional Chamber (MWPC)
  - was first electronic device allowing high statistics experiments
  - and with resonable resolution
- Typically several 100 – 1000 wires, ~ 1 mm spacing
  - if charged particle is passing the MWPC → one wire gives signal
  - resolution: $\sigma_x = \frac{d}{\sqrt{12}}$ e.g. for d = 1 mm → ~300 µm

we don't know where the particle went through within the 1 mm spacing = “flat” probability distribution, this is the width of an equivalent Gaussian distribution



- If many MPWCs are put one after each other
  - each particle creates one point per MWPC (~300 µm resolution per point)



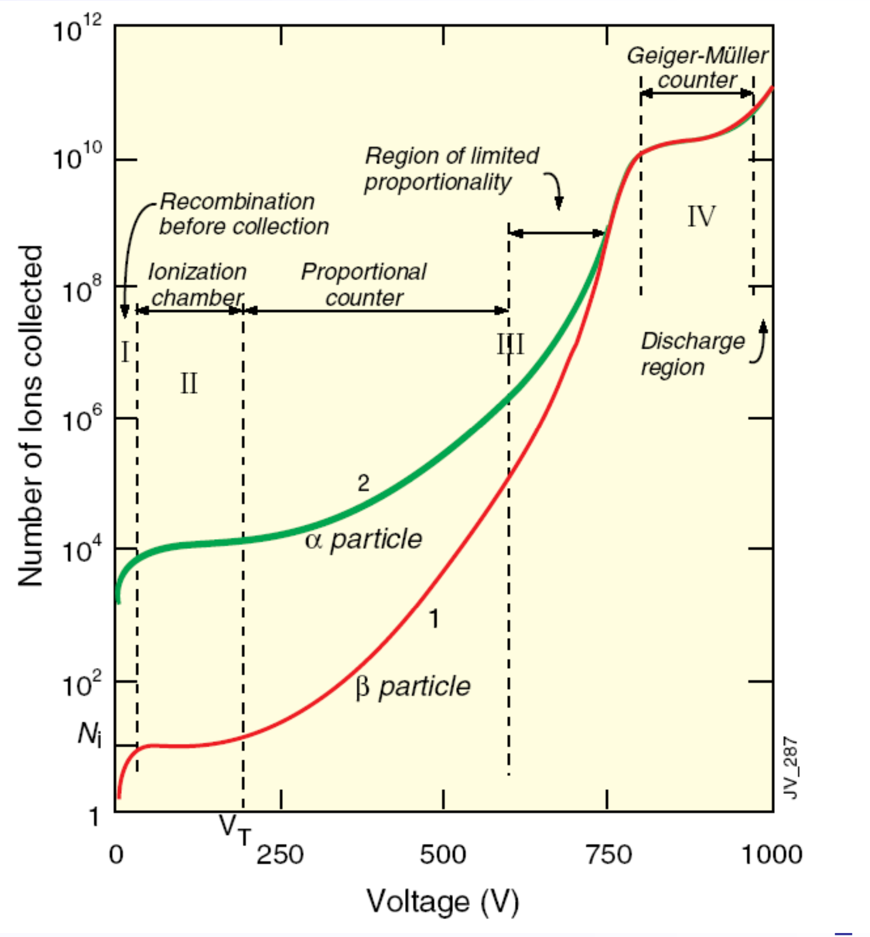
can reconstruct track with e.g. 4 points

one coordinate only, use additional MWPCs tilted by 90° to get other coordinate

Wire Chambers – Operation Modes

High Voltage

- **No collection (I)**
  - ions recombine before collected
- **Ionization Mode (II)**
  - ionization charge is fully collected, no charge multiplication yet
  - gain ~ 1
- **Proportional Mode (IIIa)**
  - gas multiplication, signal on wire proportional to original ionization
  - gain ~ 10^4
- **Limited Proportional Mode (IIIb)**
  - secondary avalances created by photoemission from primary avalances, signal no longer proportional to ionization
  - gain ~ 10^{10}
- **Geiger Mode (IV)**
  - massive photoemission + discharge, stopped by HV breakdown



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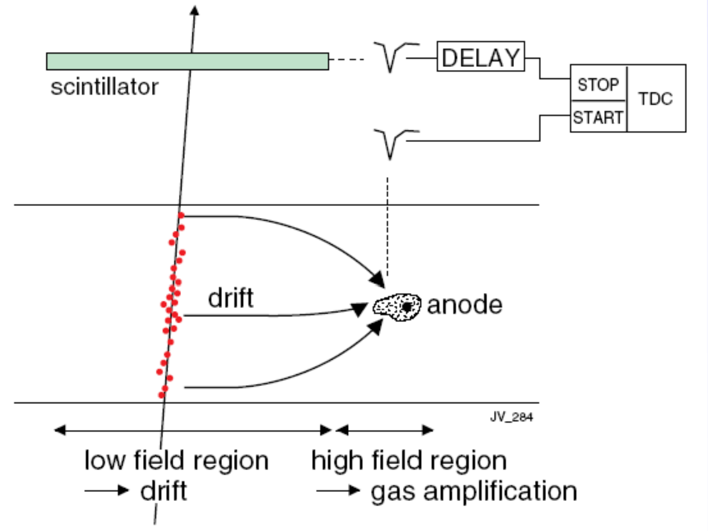
Wire Chambers – Drift Chambers

- **Resolution of MWPCs limited by wire spacing**
  - **better resolution → shorter wire spacing → more (and more) wires...**
    - larger wire forces (heavy mechanical structures needed)
    - (too) strong ionization and arrival on wire (signal formation)
    - electrostatic forces when wires too close to each other
- **Solution**
  - **obtain position information from drift time of electrons**
    - drift time = time between primary ionization and arrival on wire (signal formation)



start signal (track is passing drift volume) has to come from external source: scintillator or beam crossing signal

- **Need to know drift velocity v_D to calculate distance s to wire**

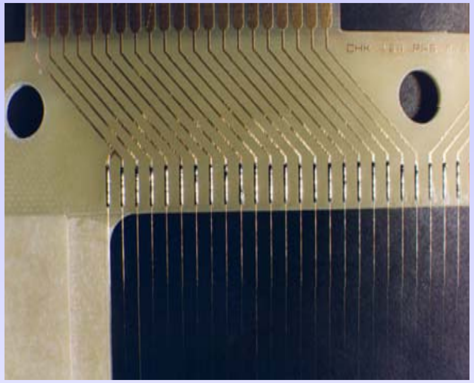
  (= track position within the detector)

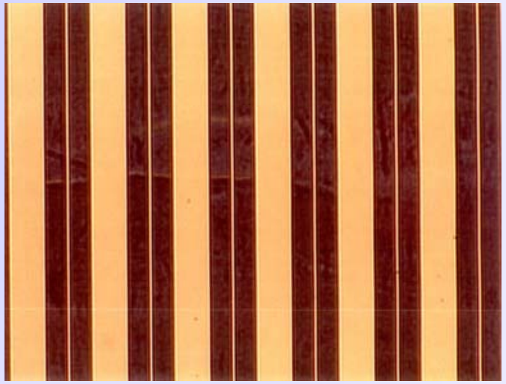
$$s = \int_{t_{start}}^{t_{stop}} v_D \, dt$$

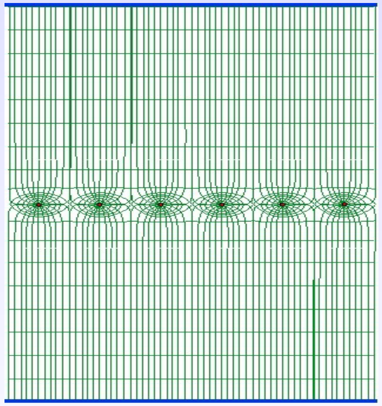
MicroStrip Gas Chamber

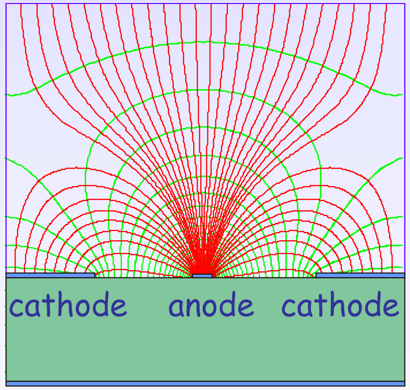
MWPC

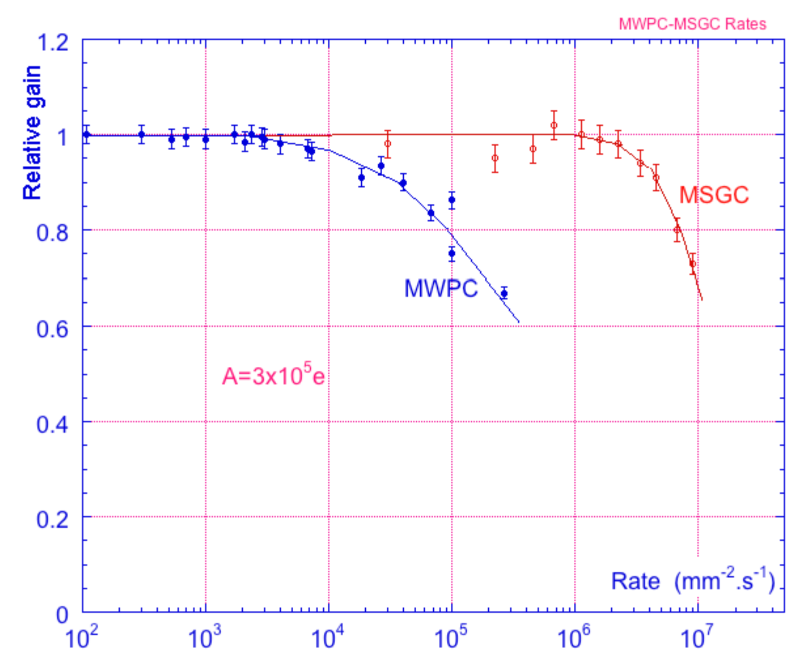
MSGC











Typical distance between wires limited to 1 mm due to mechanical and electrostatic forces

Typical distance between anodes 200 μm thanks to semiconductor etching technology

Rate capability limit due to space charge overcome by increased amplifying cell granularity

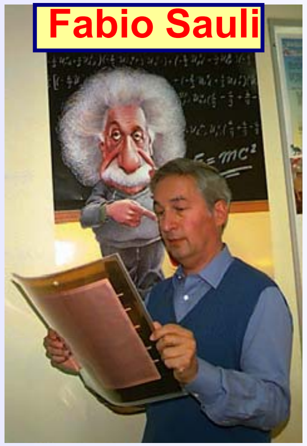
A. Oed
Nucl. Instr. and Meth. A263 (1988) 351.

Micropattern Gas Detectors Revolution

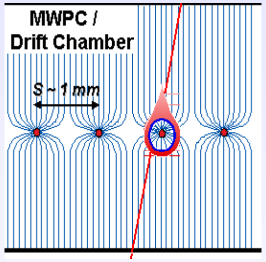
Semiconductor industry technology:

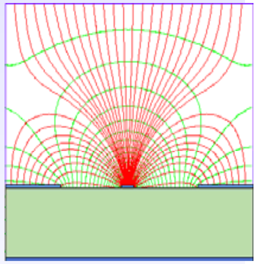
Photolithography
Etching
Coating
Doping

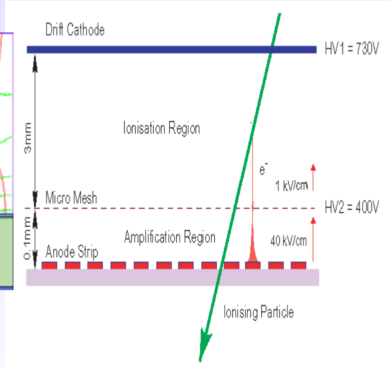

Anton Oed

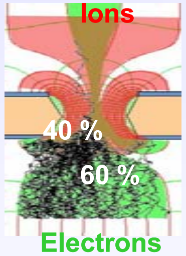

Fabio Sauli

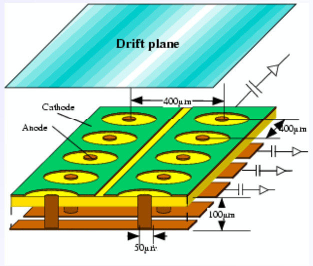

Ioannis Giomataris

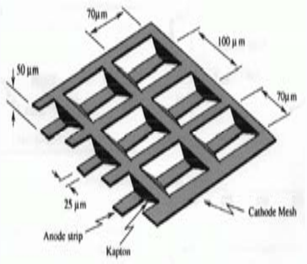


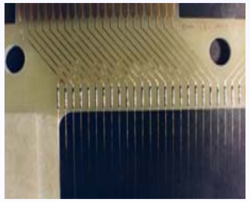


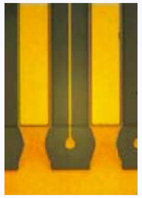


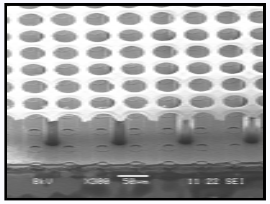


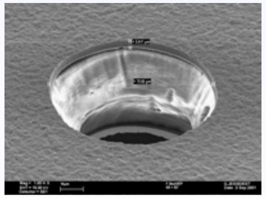


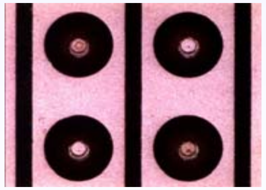


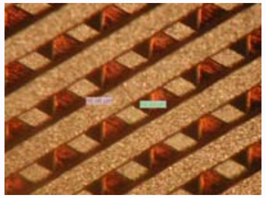




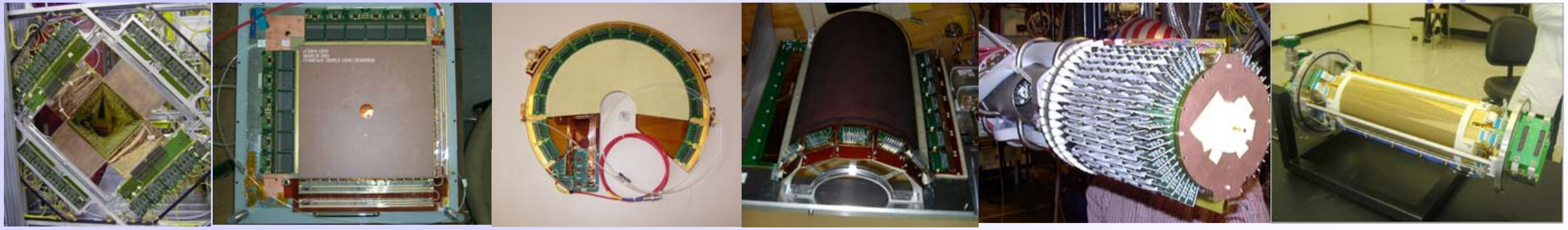


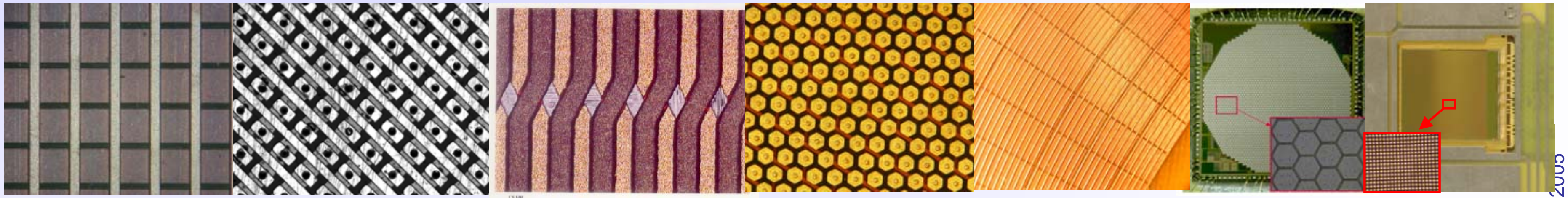


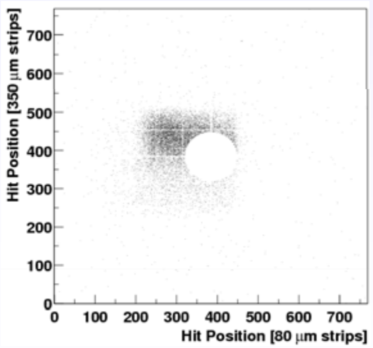


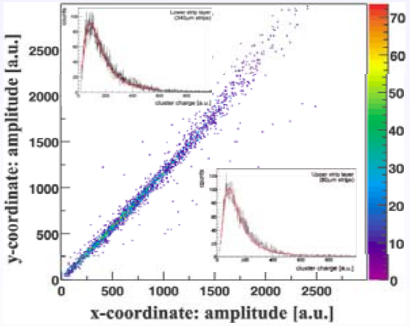


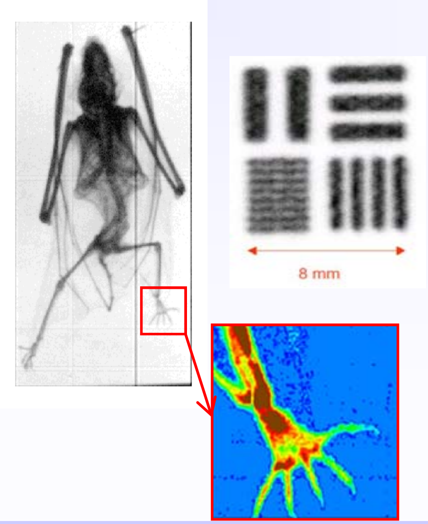
Micropattern Gas Detectors Technologies

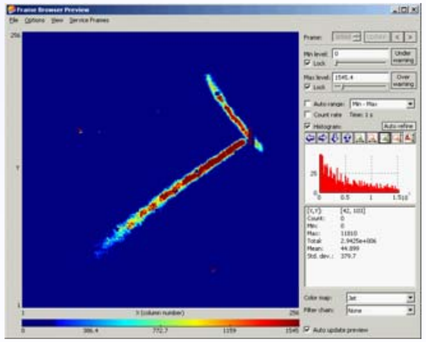








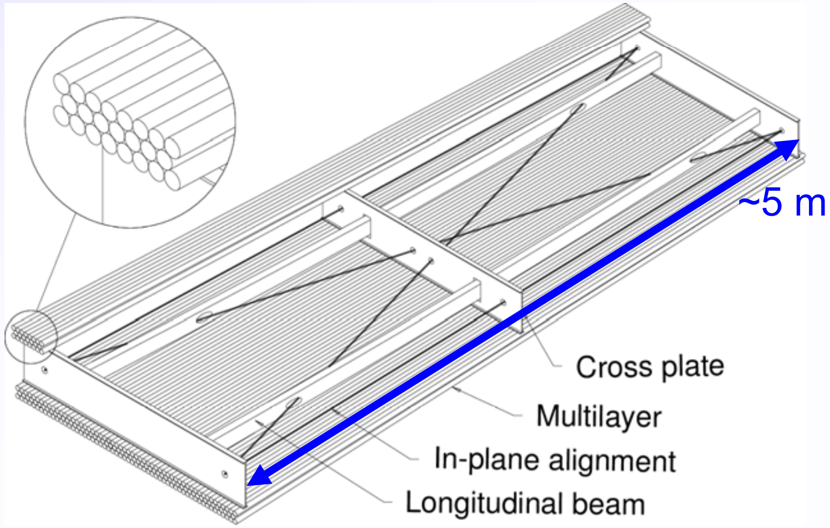




Muon Detectors

- Muon detectors are tracking detectors (wire chambers)
  - they form the outer shell of the (LHC) detectors
  - they are **not only sensitive to muons** (but to all charged particles)!
  - just by "definition": if a particle has reached the muon detector it's considered to be a muon
    - all other particles should have been absorbed in the calorimeters
- Challenge for muon detectors
  - large surface to cover (outer shell)
  - keep mechanical positioning stable over time
- ATLAS
  - 1200 chambers with 5500 m^2
  - also good knowledge of (inhomogeneous) magnetic field needed

ATLAS Muon Detector Elements



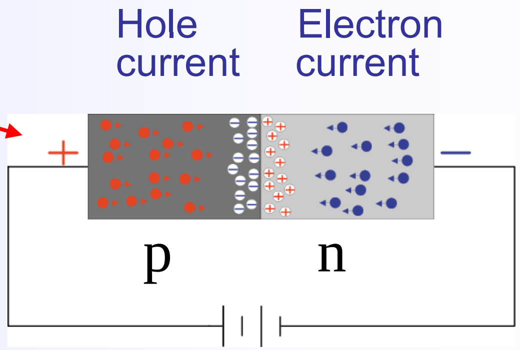
Aluminum tubes with central wire filled with 3 bar gas

Solid State Tracking Detectors

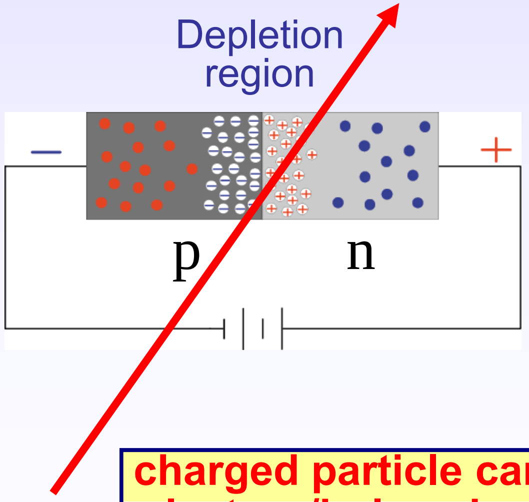
- Basic element of a solid state (silicon) detector is... a diode
  - p-type and n-type doped silicon material is put together

more holes **more electrons**

Current flow through diode if connects like this



  - for use as particle detector diode needs to be connected in opposite way



- Around junction of p- and n-type material depletion region is created
  - zone free of charge carriers
    - no holes, no electrons
    - thickness of depletion region depends on voltage, doping concentration

charged particle can create new electron/hole pairs in depletion area sufficient to create a signal

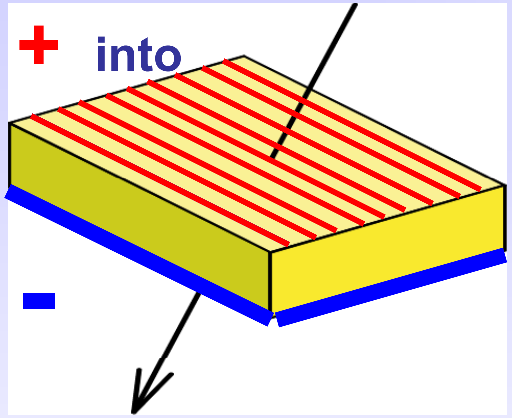
typically 20'000 – 30'000 electron/hole pairs in 300 μm thick material

Silicon Tracking Detectors

- **Now take a large Si crystal, e.g. 10 x 10 cm^2, 300 µm thick**

make bottom layer p-type

and subdivide the top n-type

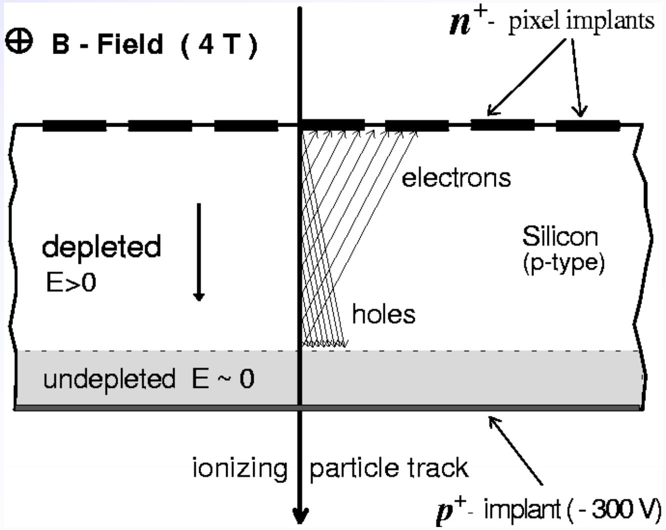


into

many strips with small spacing

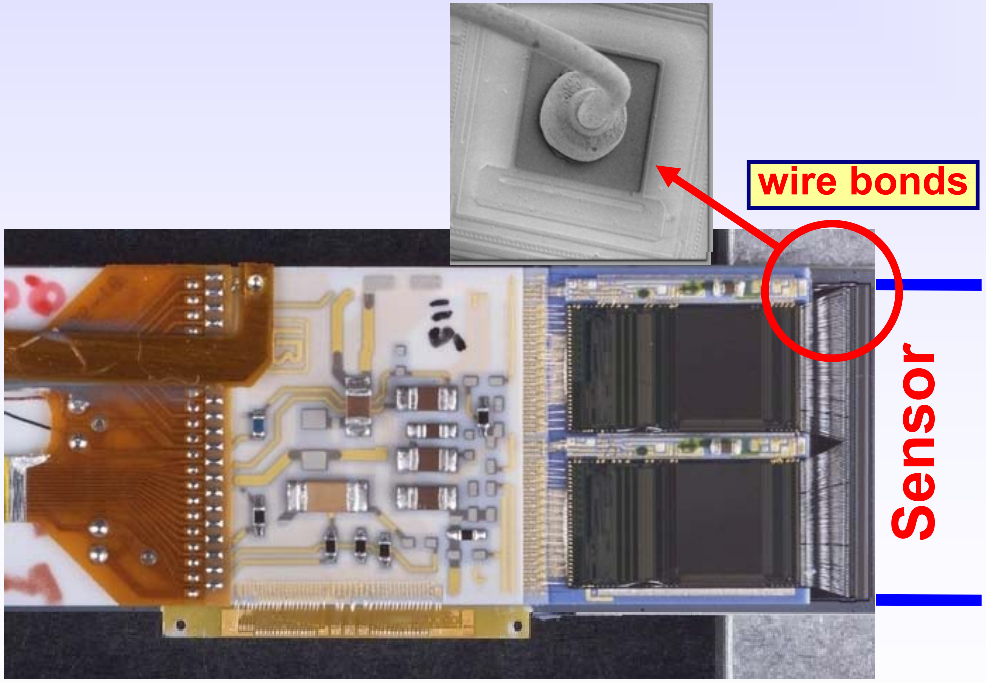
→ **many diodes next to each other (like MWPC at wire chambers) with position information**

- **Advantage compared to wire/gas detectors**
  - **strip density (pitch) can be rather high (e.g. ~20 µm)**
    - high position accuracy
    - but also many electronics channels needed

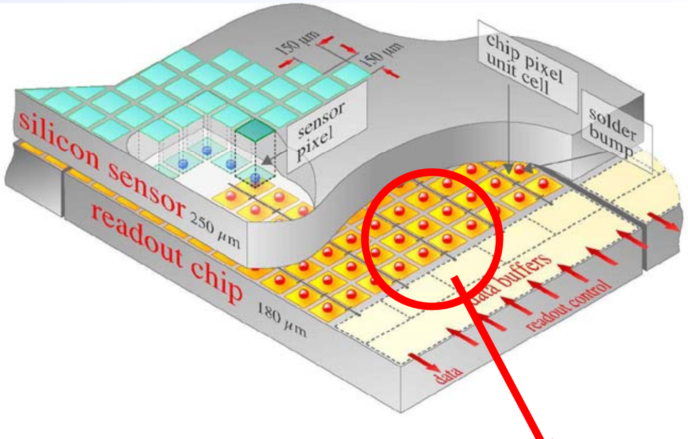


Si-Detector Electronics and Si-Pixels

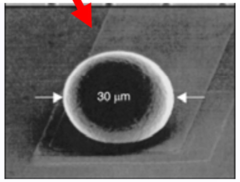
- **Silicon detectors have a laaaarge number of electronics channels, ~10^7 each for ATLAS and CMS Si trackers**
  - requires highly integrated chips for amplification, shaping, zero suppression (only information of strips with signals is read-out) and multiplexing (put all strip signals on a few cables only)
  - **electronics is directly connected to the sensor (the “multi-diode”) via wire bonds**



Si-strip detectors provide only 1 coordinate,
Pixel detectors are 2D detectors



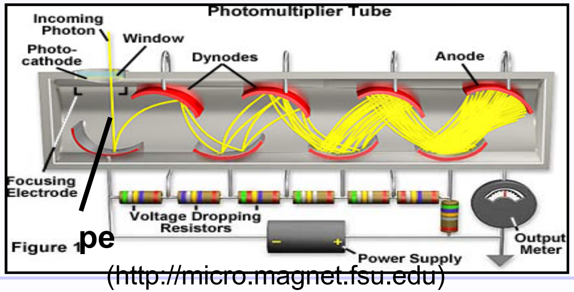
Pixel detector need “bump” bonding and have even more channels, ~10^8 - 10^9



CERN A

Photon Detectors

- We need to convert photons into an electronic signal
  - use photo effect
- Requirements
  - sometimes only a few photons available (Čerenkov radiation)
    - need high quantum efficiency (high efficiency to convert 1 $\gamma \rightarrow$ 1 e^-)
  - even with high(est) photon conversion efficiency
    - signal from a single electron after conversion is not sufficient
    - need multiplication mechanism to get signal well above noise level of electronics
      - typical noise level: O(100) electrons
- Main types
  - vaccum-based (classical Photo Multiplier Tube PMT)
  - gas-based
  - solid-state (solid state photo diodes)
  - hybrid (mixture of above types)

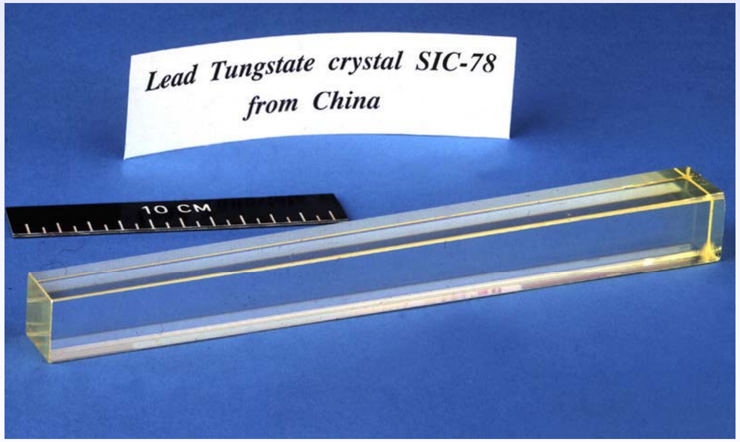


(http://micro.magnet.fsu.edu)

Calorimeters

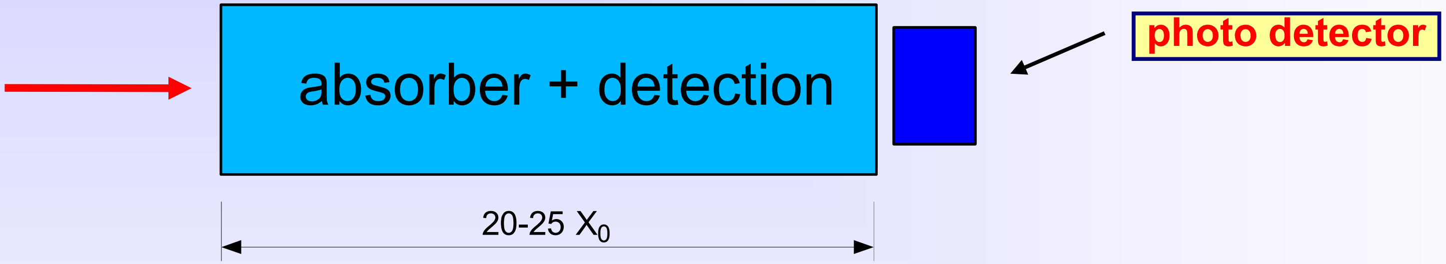
- **Homogeneous and Sampling Calorimeters**
- **Electromagnetic and Hadronic Calorimeters**

Calorimetry = Energy measurement by total absorption, usually combined with spatial reconstruction.

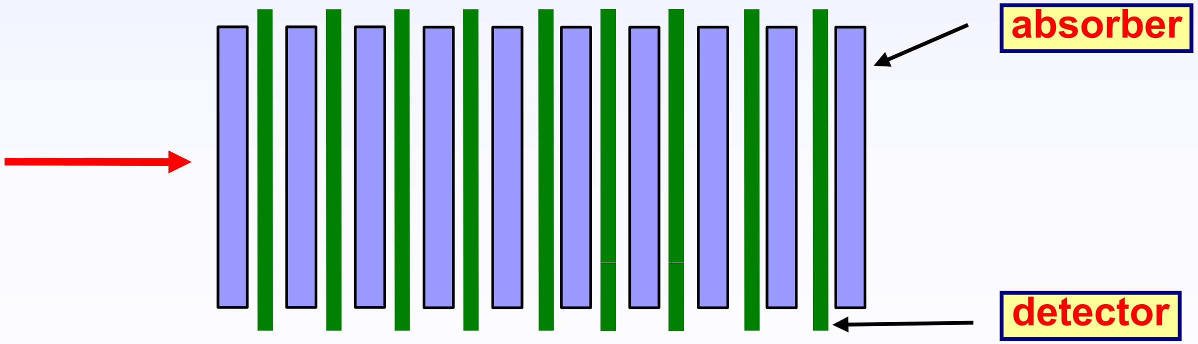


Calorimeter Concepts

- **Homogeneous calorimeters**
  - **absorber material (generation of the shower) = detector material**
    - typically an electromagnetic shower is created in an optical transparent absorber, photons created in the shower are collected and detected with some photo detector

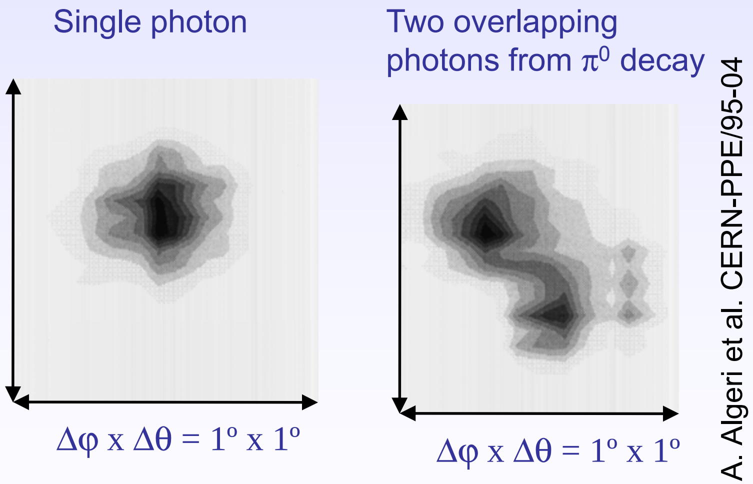


- **Sampling calorimeters**
  - **passive (heavy) absorber material (iron, copper, lead, tungsten, uranium) interleaved with active detector material**



Homogeneous Calorimeters

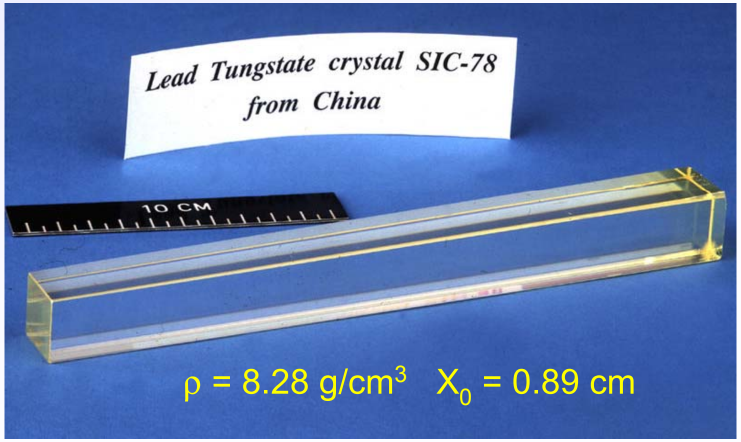
- **Clear advantage: good energy resolution**
  - **the entire shower is kept in active detector material**
    - no shower particle is lost in passive absorber
- **Disadvantages**
  - **limited granularity, no information on shower shape in longitudinal direction (along particle flight direction)**
    - position information is useful to resolve near-by energy clusters, e.g. single photons versus two photons from π^0 decay



A. Algeri et al. CERN-PPE/95-04

dense, transparent materials needed with short radiation length and high light yield

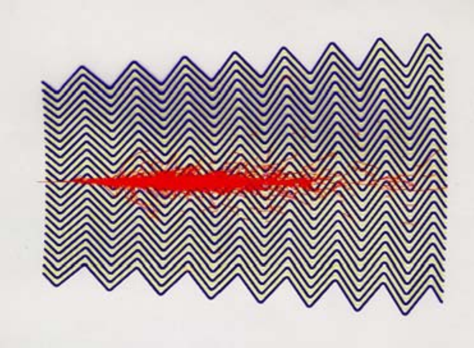
CMS $PbWO_4$ crystal



$\rho = 8.28\ \mathrm{g/cm^3}$ $X_0 = 0.89\ \mathrm{cm}$

Sampling Calorimeters

- **Typical sampling calorimeters use iron or lead absorber material, variety of detectors in between possible**
  - **gas detectors (MWPCs), plastic scintillators, liquid noble gases (LAr, LKr)**
- **ATLAS is using LAr with "acordeon" shaped steel absorbers**
  - **LAr is ionized by charged shower particles**
  - **Charge collected on pads**
    - ionization chamber, no "gas" amplification
    - pads can be formed as needed → high granularity
  - **acordeon structure helps to avoid dead zones (cables etc.)** →



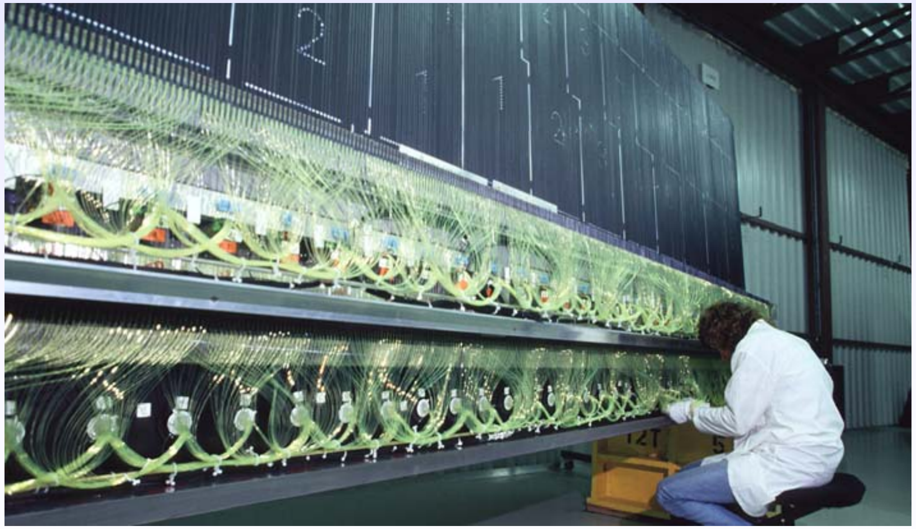
simulated shower

ATLAS LAr calorimeter

Hadron Calorimeters

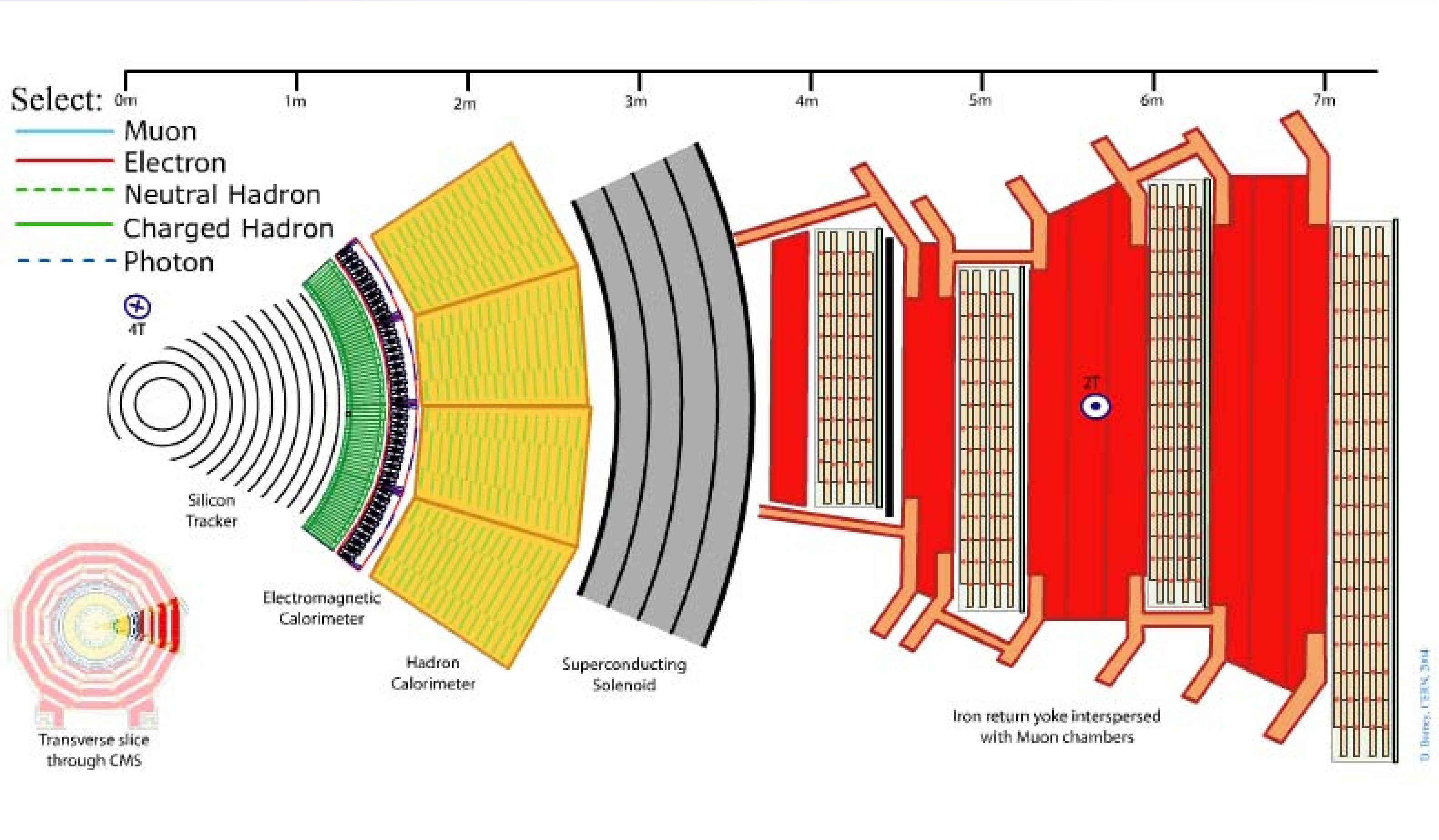
- **Energy resolution much worse than for electromagnetic calorimeters**
  - **larger fluctuations in hadronic shower**
- **Both ATLAS and CMS use scintillators as detector material**
  - **need many optical fibers to transport light from scintillators to photo detectors**

ATLAS

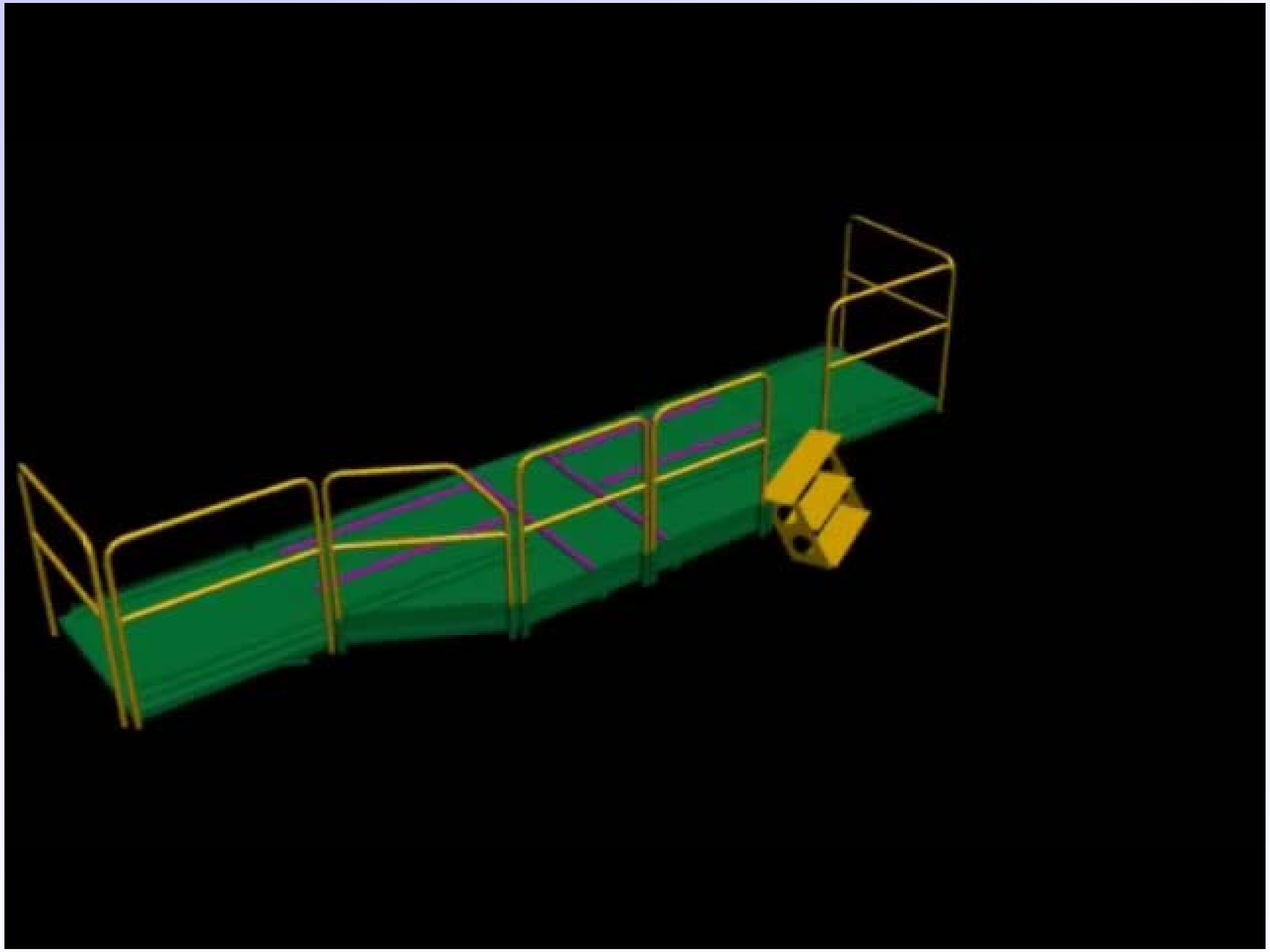


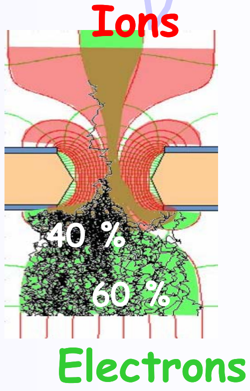
CMS

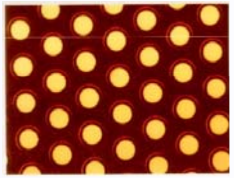
Transverse slice through CMS

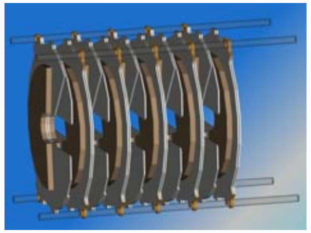


Detectors R&D







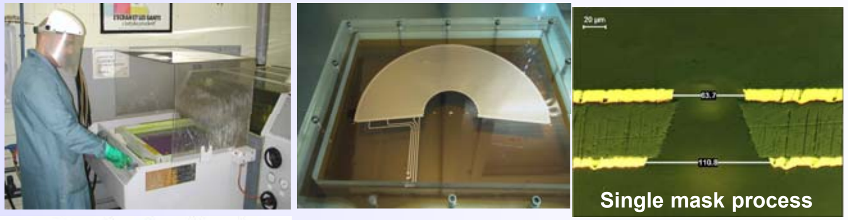


TOTEM T2 (GEM) Installation in CMS

Detectors Development at CERN

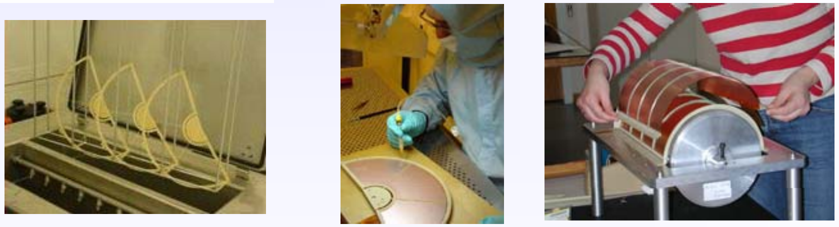
Detector Design & Development

Component Production

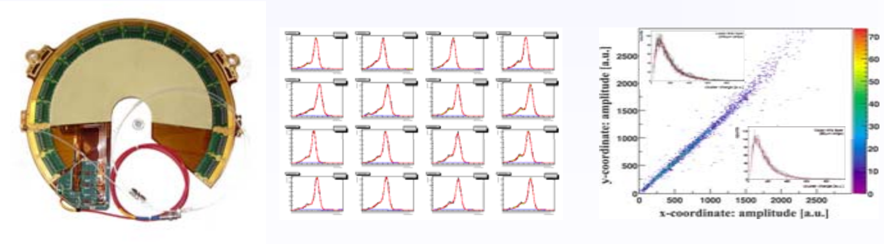


Component Quality Control

Detector Assembly

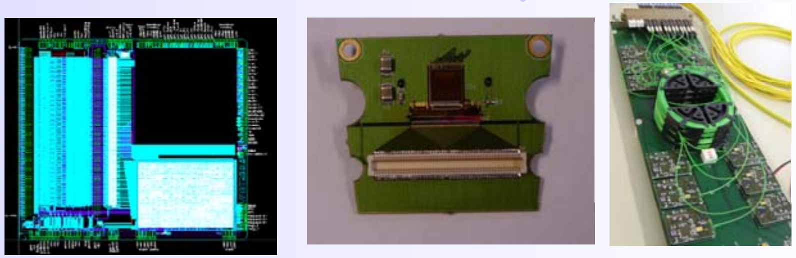


Detector Test



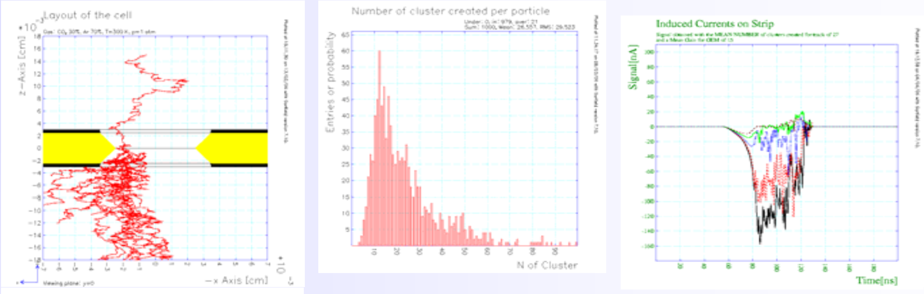
Detectors Development at CERN

Electronics



APV
VFAT
GP5
ALTRO
MEDIPIX

Detector Simulations

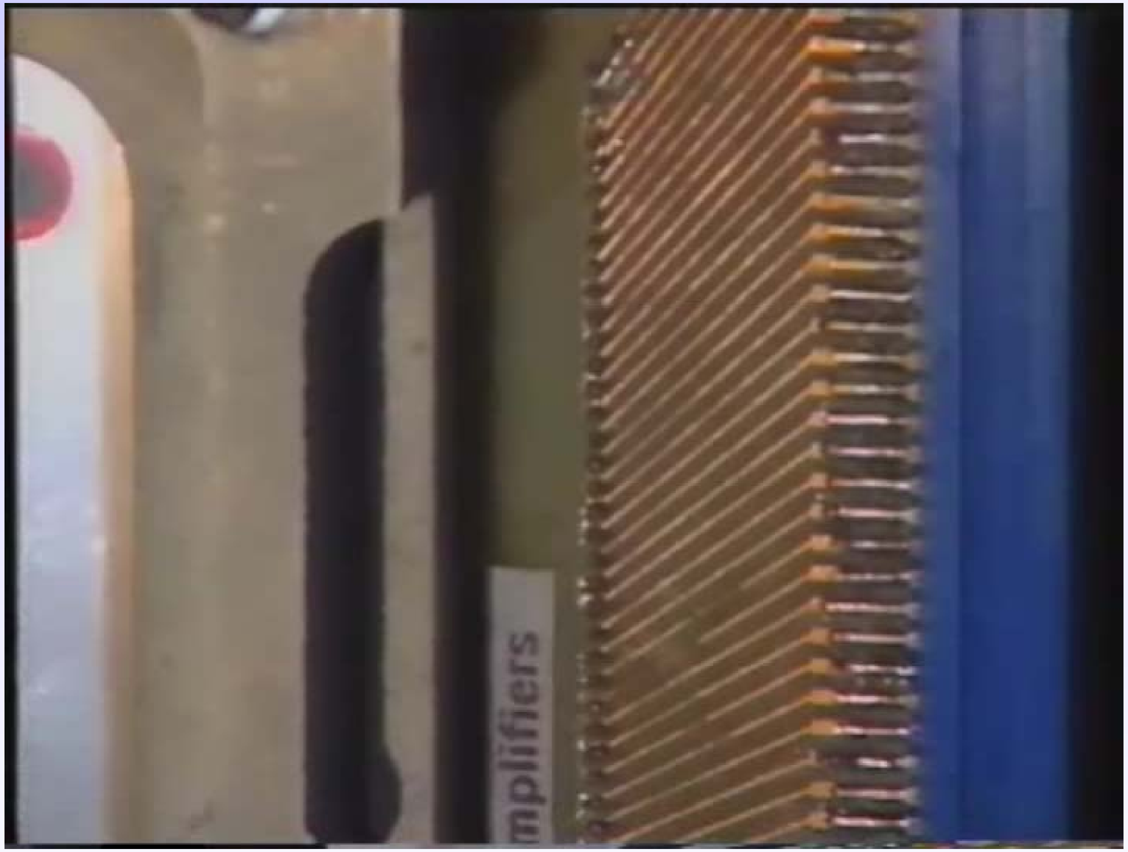


Garfield
Maxwell
Magboltz
Imonte
Heed

Technology Dissemination

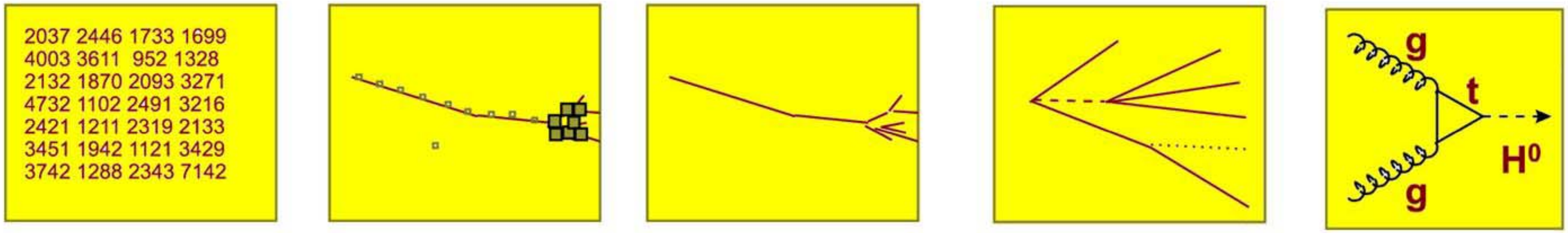
PANalytical
3M
TechEtch
Techtra
Centronic
G&A

Thank you



1982 !

From Raw Data To Physics



2037 2446 1733 1699
4003 3611 952 1328
2132 1870 2093 3271
4732 1102 2491 3216
2421 1211 2319 2133
3451 1942 1121 3429
3742 1288 2343 7142

Raw data

Convert to physics quantities

Detector response

apply calibration, alignment

Interaction with detector material

Pattern, recognition, Particle identification

Fragmentation Decay

Physics analysis

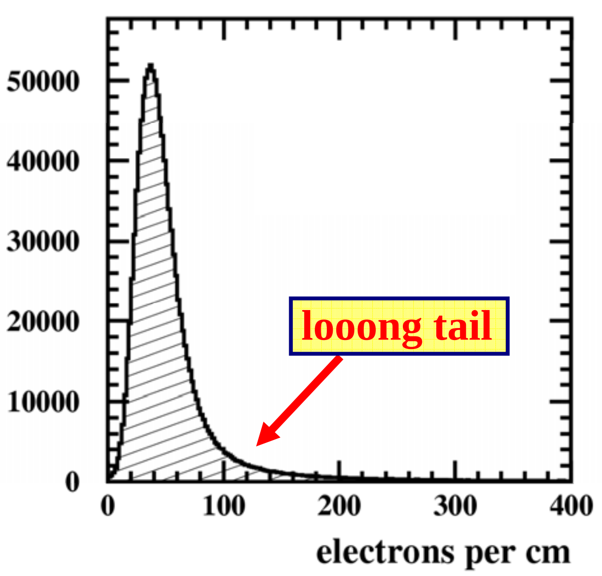
Basic physics

Results

- **Actually recorded are raw data with ~400 MB/s for ATLAS/CMS**
  - **mainly electronics numbers**
    - e.g. number of a detector element where the ADC (Analog-to-Digital converter) saw a signal with x counts...
- **We need to go from raw data back to physics**
  - **reconstruction + analysis of the event(s)**

Energy Loss Distribution

- **Cluster size fluctuations cause large variations of energy loss from track to track**
  - **Landau distribution**



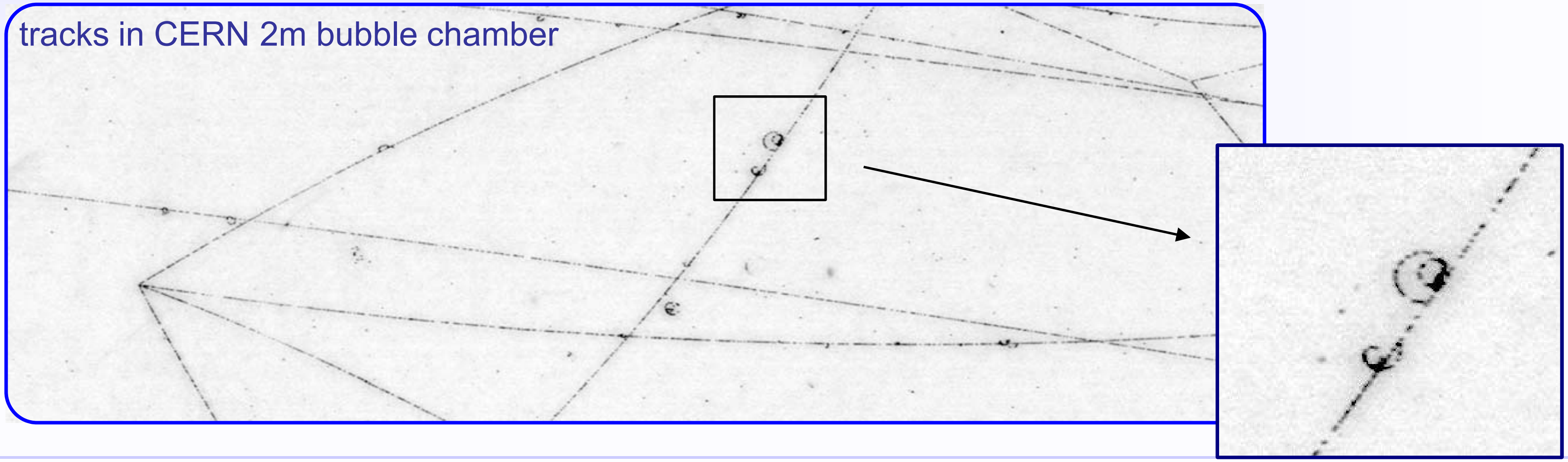
- **large broad peak (single or few el. clusters)**

  soft collisions, interaction with whole gas molecule

  small energy transfer
- **looong tail (multi el. clusters, δ-electrons)**

  hard collisions, semi-free shell electrons

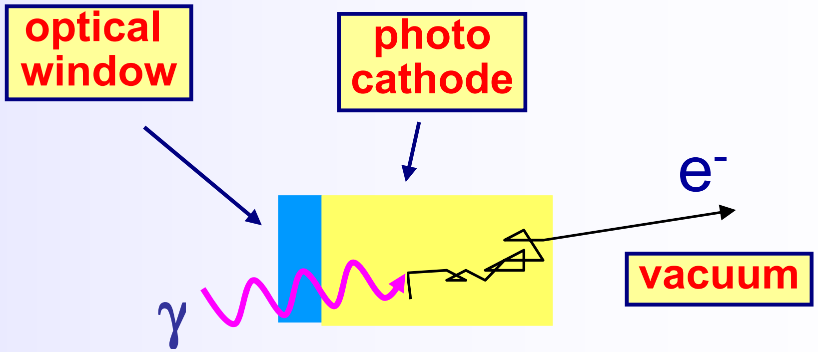
  large energy transfer



tracks in CERN 2m bubble chamber

Photo Cathodes

- **3-step process of photon to electron conversion**
  - **photon absorption**
    - photon is absorbed in photo cathode + creates electron with some energy by photo effect
  - **electron diffusion**
    - electron moves through photo cathode material, affected by multiple scattering with some energy loss
  - **electron emission**
    - electron reaches surface with sufficient energy (work function) to escape into vacuum

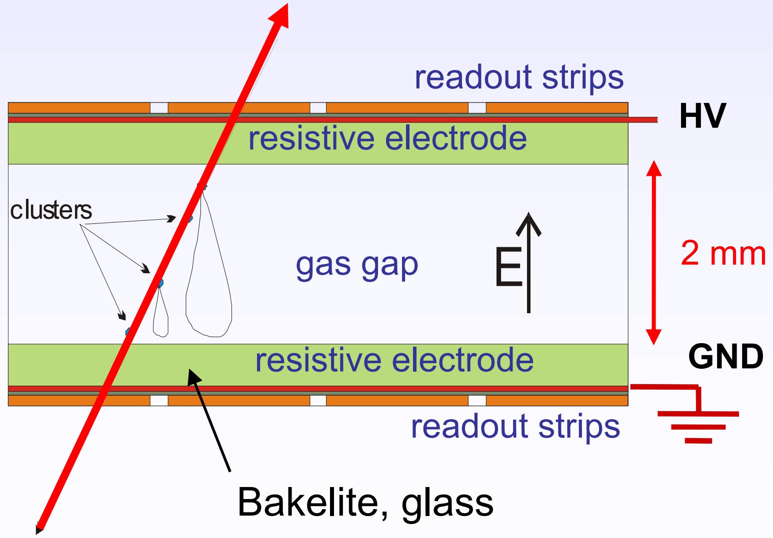


- **Typical losses**
  - photon already reflected/absorbed at/in optical window
  - photon passes through photo cathode layer without creating an electron
    - photo cathode layer too thin
  - electron is loosing too much energy before reaching surface
    - photo cathode layer too thick or work function too high

CERN Academic Training Programme 2004/2005

Resistive Plate Chambers (RPC)

- **There are also gaseous detectors without wires**
  - **two resistive plates (~10^9 Ω cm) with a small gas gap (2 mm) and large high voltage (12 kV) on outside electrodes**
  - **strong E-field: operation in “streamer mode”**
    - gas avalanche already starting in gas gap (no wires involved)
    - developing of “streamers” (blob with lots of charge, almost like a spark)
    - signal on external read-out strips via influence (segmented for position resolution)
    - streamer/discharge is “self-quenching”: stops when near-by resistive electrodes are locally discharged (E-field breaks down)



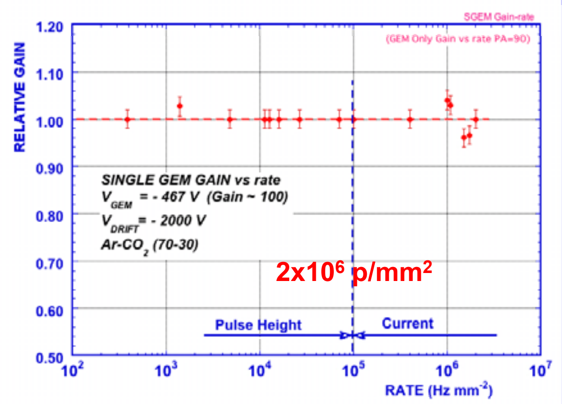
Advantages: simple device,
good to cover large areas,
VERY fast!!!

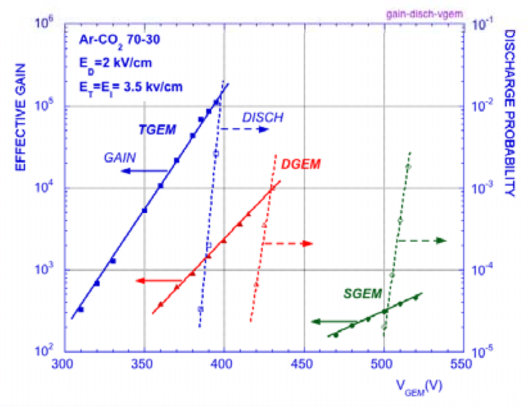
→ **used as trigger devices in LHC experiments, time resolution ~ 50 – 100 ps**

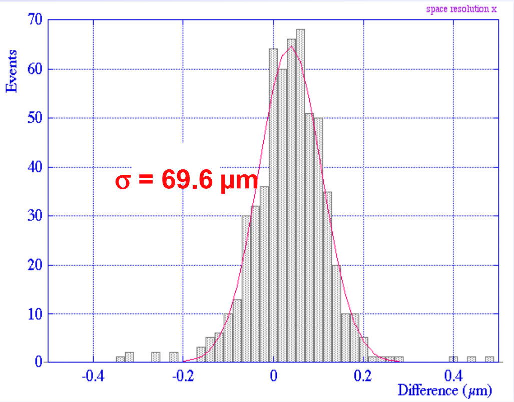
Disadvantages: Choice of resistive material + surface quality crucial, affects “dark” trigger rate

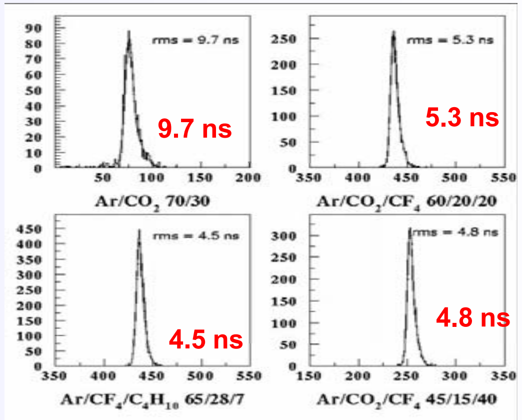
Micropattern Gas Detectors Properties

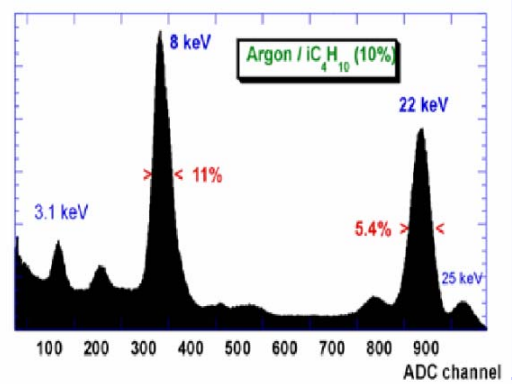
1. Rate Capability
2. High Gain
3. Space Resolution
4. Time Resolution
5. Energy Resolution
6. Ageing Properties
7. Low Material Budget
8. Geometrical Flexibility
9. Readout Structures
10. Ion Backflow Reduction
11. Photon feedback Reduction

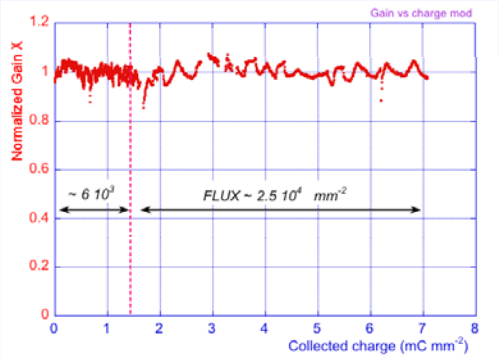


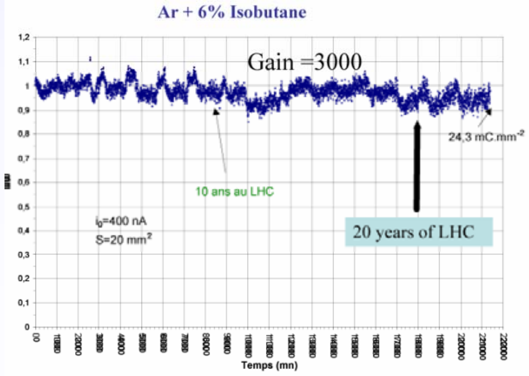












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