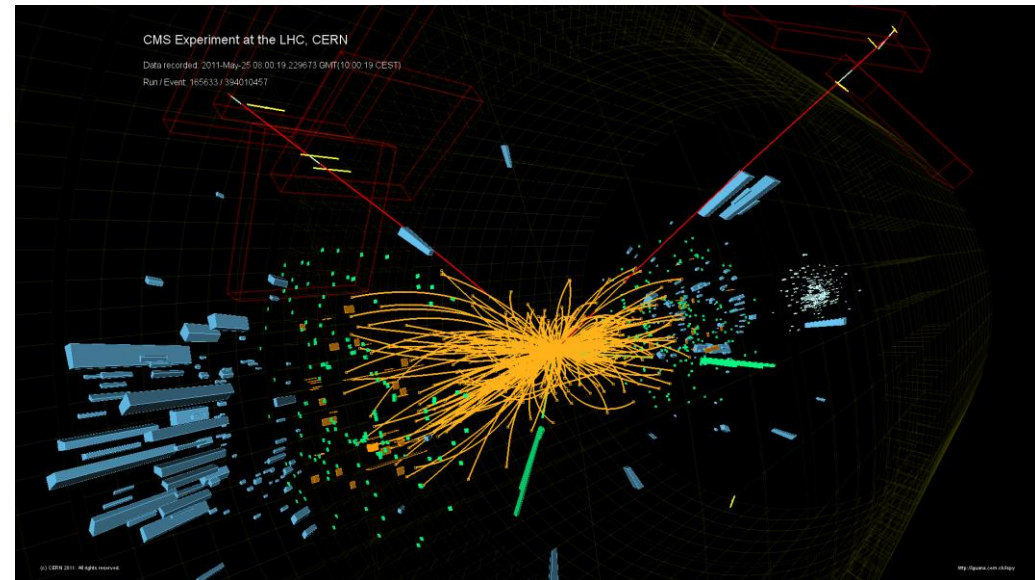
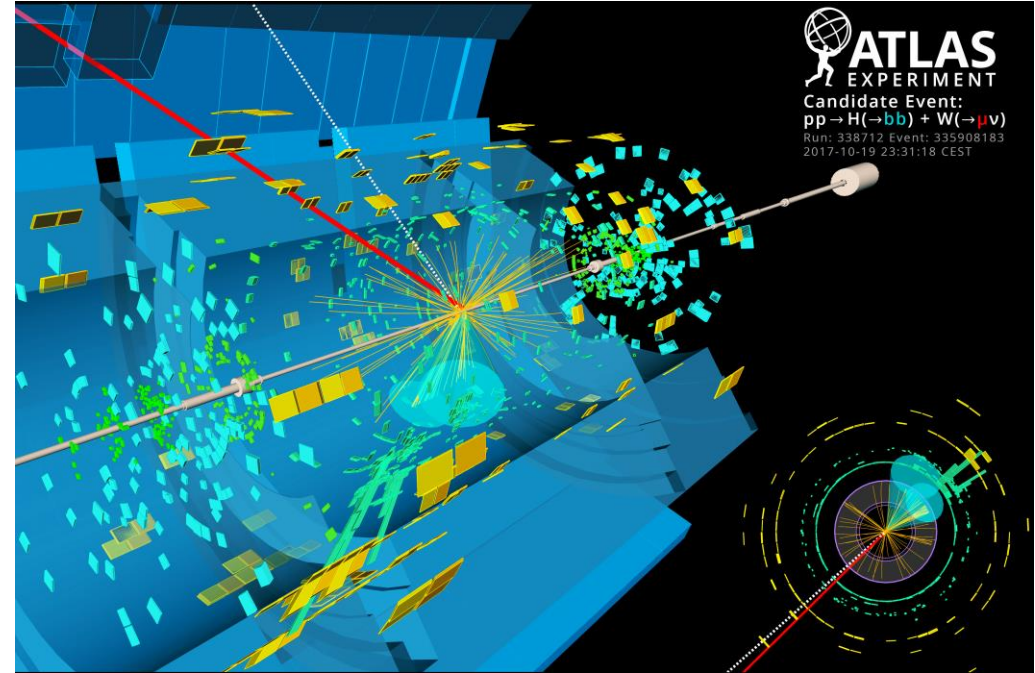
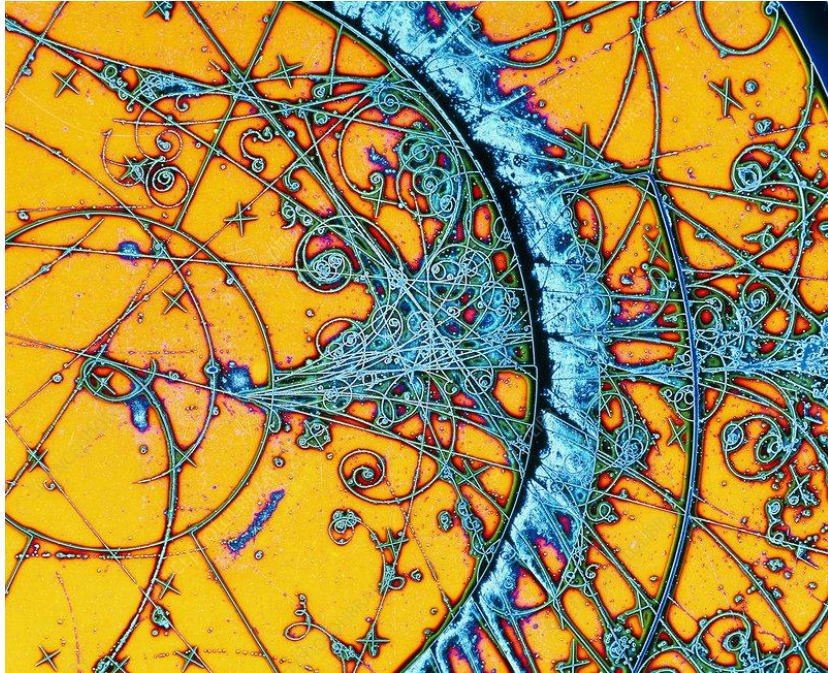
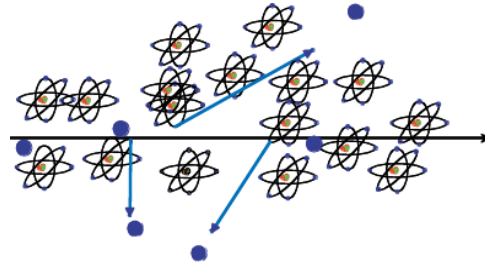


Въведение във физиката на детектори на елементарни частици



Creation of the Signal

Charged particles traversing matter leave excited atoms, electron-ion pairs (gases) or electrons-hole pairs (solids) behind.



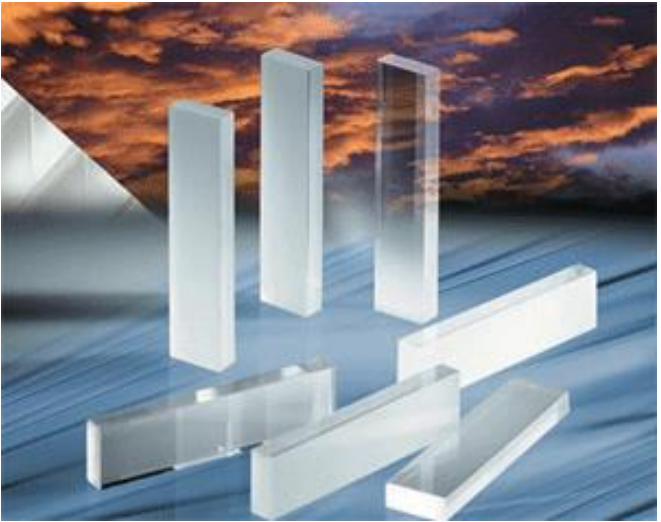
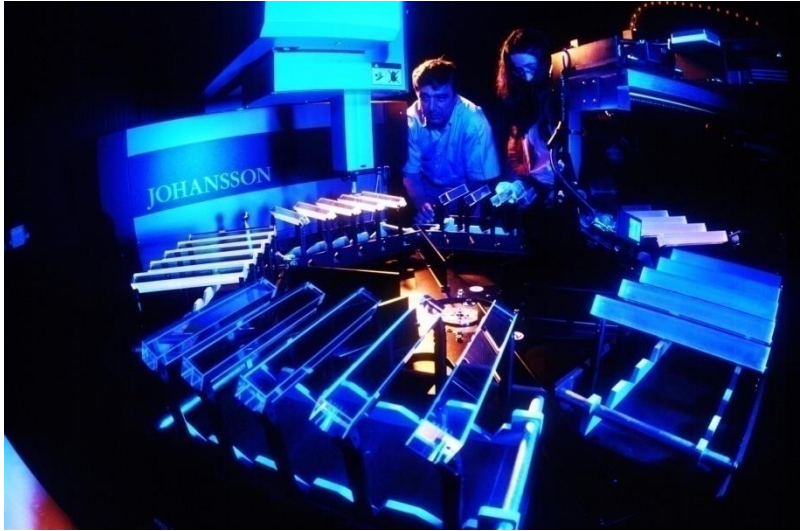
Excitation:

The photons emitted by the excited atoms in transparent materials can be detected with photon detectors like photomultipliers or semiconductor photon detectors.

Ionization:

By applying an electric field in the detector volume, the ionization electrons and ions are moving, which induces signals on metal electrodes. These signals are then read out by appropriate readout electronics.

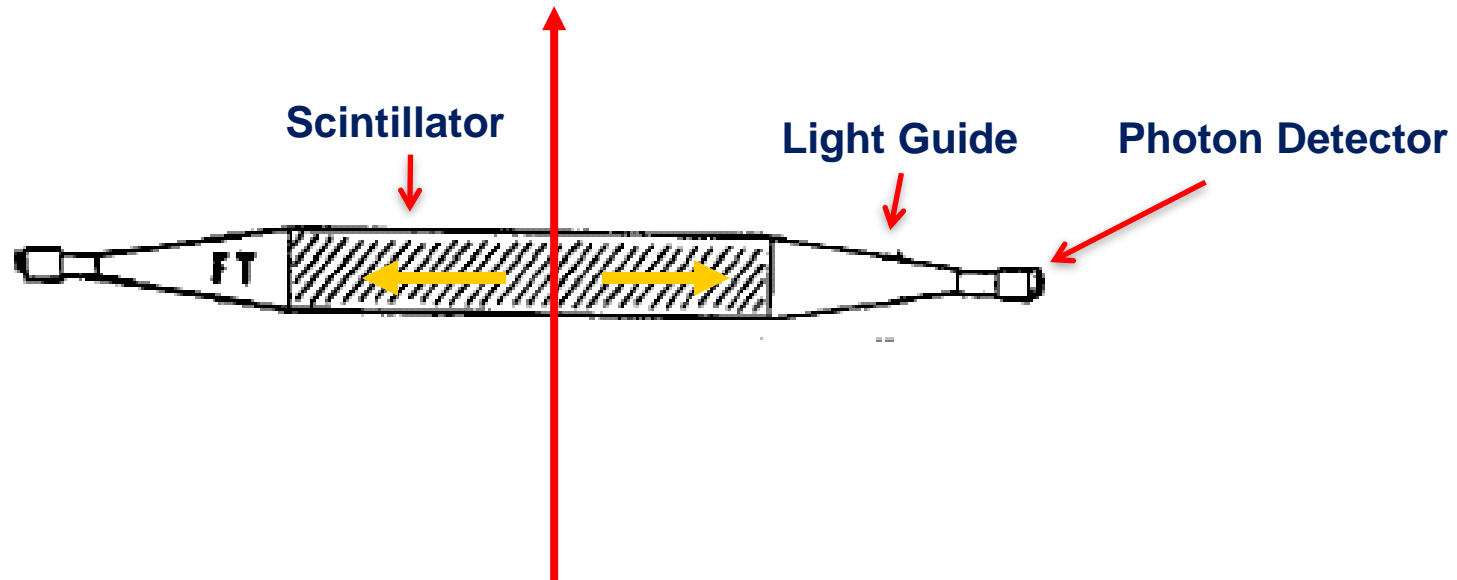
Detectors based on Registration of excited Atoms → Scintillators



Scintillators

Photons are being reflected towards the ends of the scintillator.

A light guide brings the photons to the Photomultipliers where the photons are converted to an electrical signal.



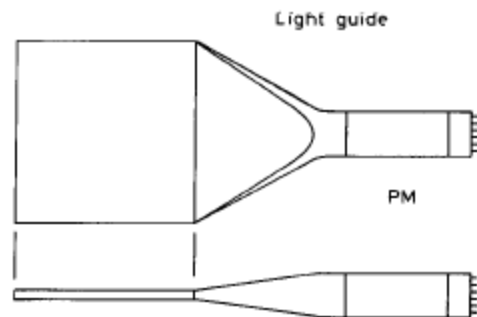
By segmentation one can arrive at spatial resolution.

Because of the excellent timing properties ($<1\text{ns}$) the arrival time, or time of flight, can be measured very accurately \rightarrow Trigger, Time of Flight.

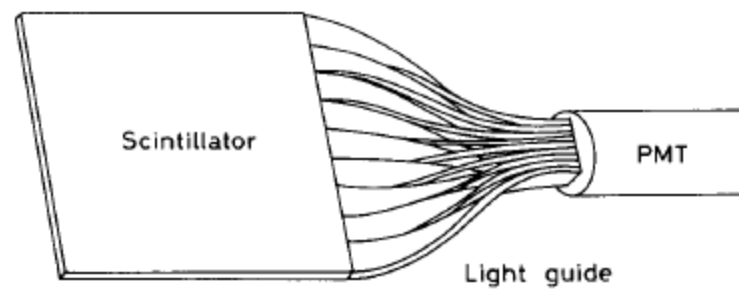
Scintillators

Typical Geometries:

- Light guides: transfer by total internal reflection (+outer reflector)

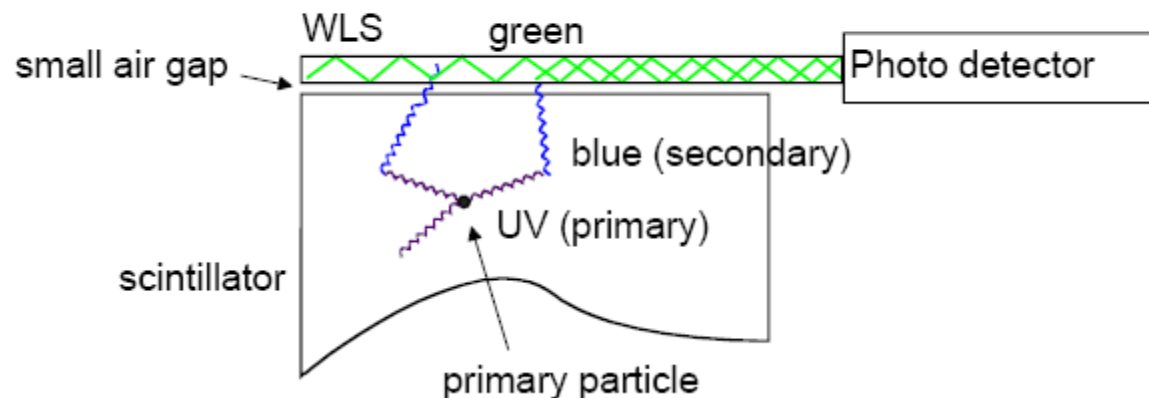


“fish tail”



adiabatic

- wavelength shifter (WLS) bars



UV light enters the WLS material
Light is transformed into longer wavelength
→ Total internal reflection inside the WLS material
→ ‘transport’ of the light to the photo detector

Photomultipliers

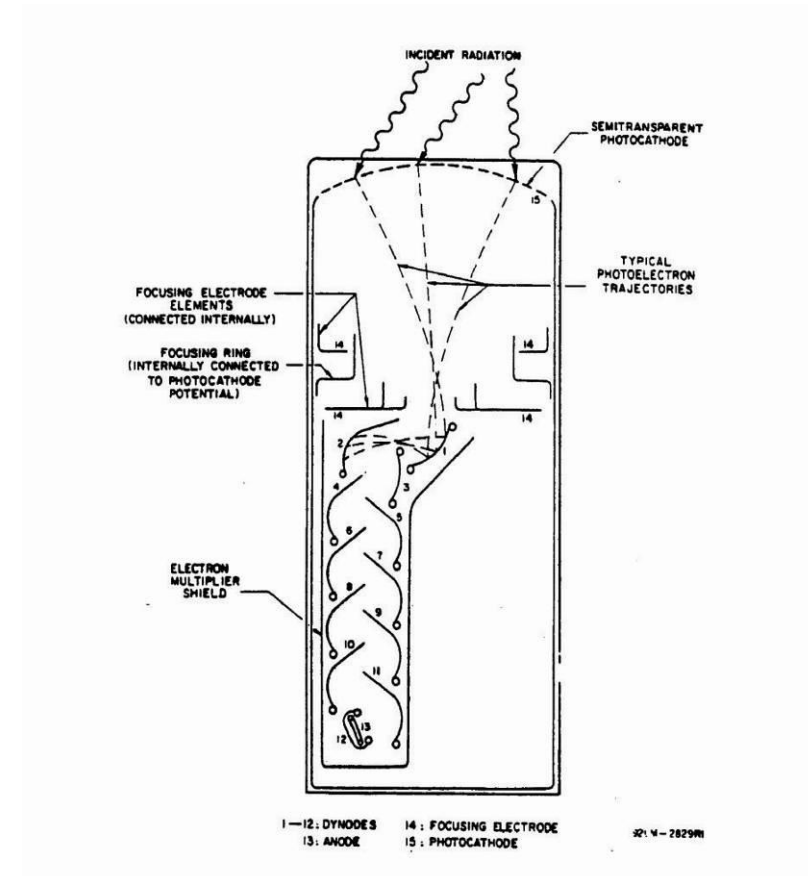
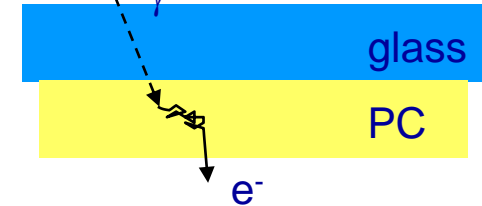
The frequent use of Scintillators is due to:

Well established, fast response time \rightarrow 1 to 100ns

Schematic of a Photomultiplier:

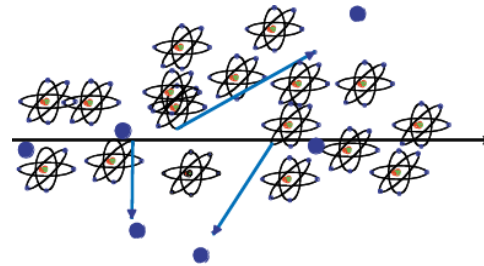
- Typical Gains (as a function of the applied voltage): 10^8 to 10^{10}
- Typical efficiency for photon detection: $< 20\%$
- For very good PMs: registration of single photons possible.
- Example: 10 primary Elektrons, Gain $10^7 \rightarrow 10^8$ electrons in the end in $T \approx 10\text{ns}$. $I=Q/T = 10^8 \cdot 1.603 \cdot 10^{-19} / 10 \cdot 10^{-9} = 1.6\text{mA}$.
- Across a 50Ω Resistor $\rightarrow U=R \cdot I = 80\text{mV}$.

Semitransparent photocathode



Creation of the Signal

Charged particles traversing matter leave excited atoms, electron-ion pairs (gases) or electrons-hole pairs (solids) behind.



Excitation:

The photons emitted by the excited atoms in transparent materials can be detected with photon detectors like photomultipliers or semiconductor photon detectors.

Ionization:

By applying an electric field in the detector volume, the ionization electrons and ions are moving, which induces signals on metal electrodes. These signals are then read out by appropriate readout electronics.

Principle of Signal Induction by Moving Charges

A point charge q at a distance z_0

Above a grounded metal plate 'induces' a surface charge.

The total induced charge on the surface is $-q$.

Different positions of the charge result in different charge distributions.

The total induced charge stays $-q$.

● q

● q

$-q$

$-q$

$V=0$

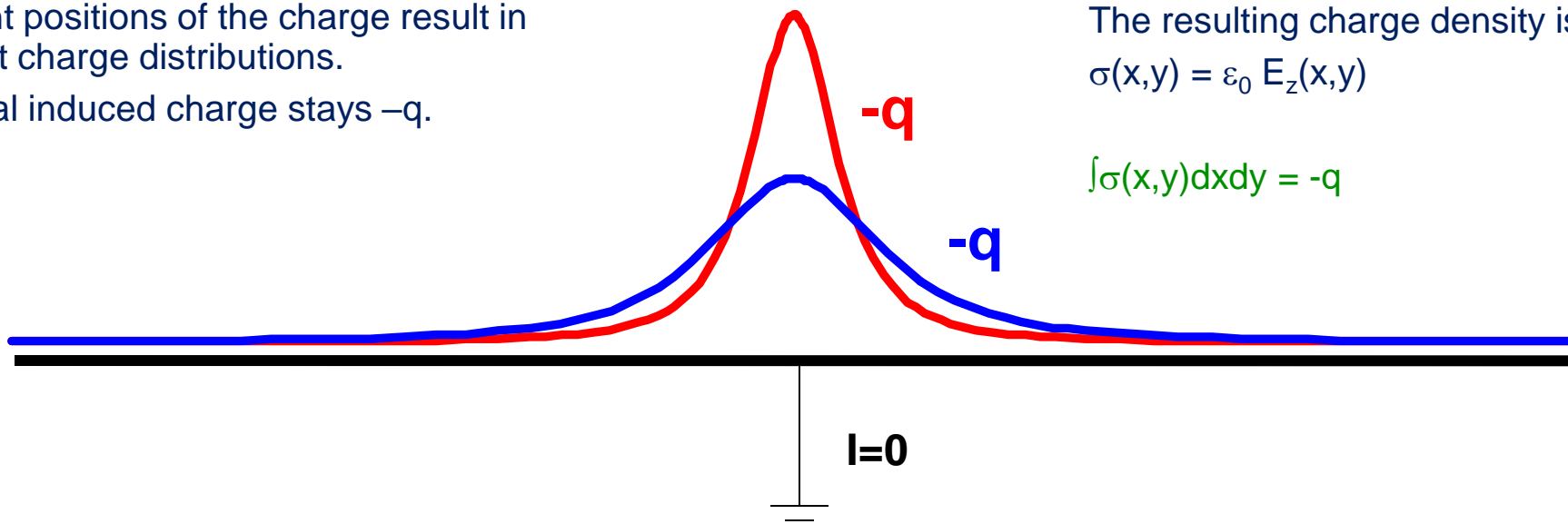
The electric field of the charge must be calculated with the boundary condition that the potential $\phi=0$ at $z=0$.

For this specific geometry the method of images can be used. A point charge $-q$ at distance $-z_0$ satisfies the boundary condition \rightarrow electric field.

The resulting charge density is

$$\sigma(x,y) = \epsilon_0 E_z(x,y)$$

$$\int \sigma(x,y) dx dy = -q$$



$$E_z(x,y) = -\frac{qz_0}{2\pi\epsilon_0(x^2 + y^2 + z_0^2)^{\frac{3}{2}}}$$

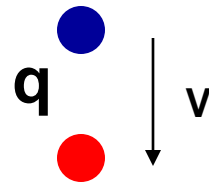
$$E_x = E_y = 0$$

$$\sigma(x,y) = \epsilon_0 E_z(x,y)$$

$$Q = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \sigma(x,y) dx dy = -q$$

Principle of Signal Induction by Moving Charges

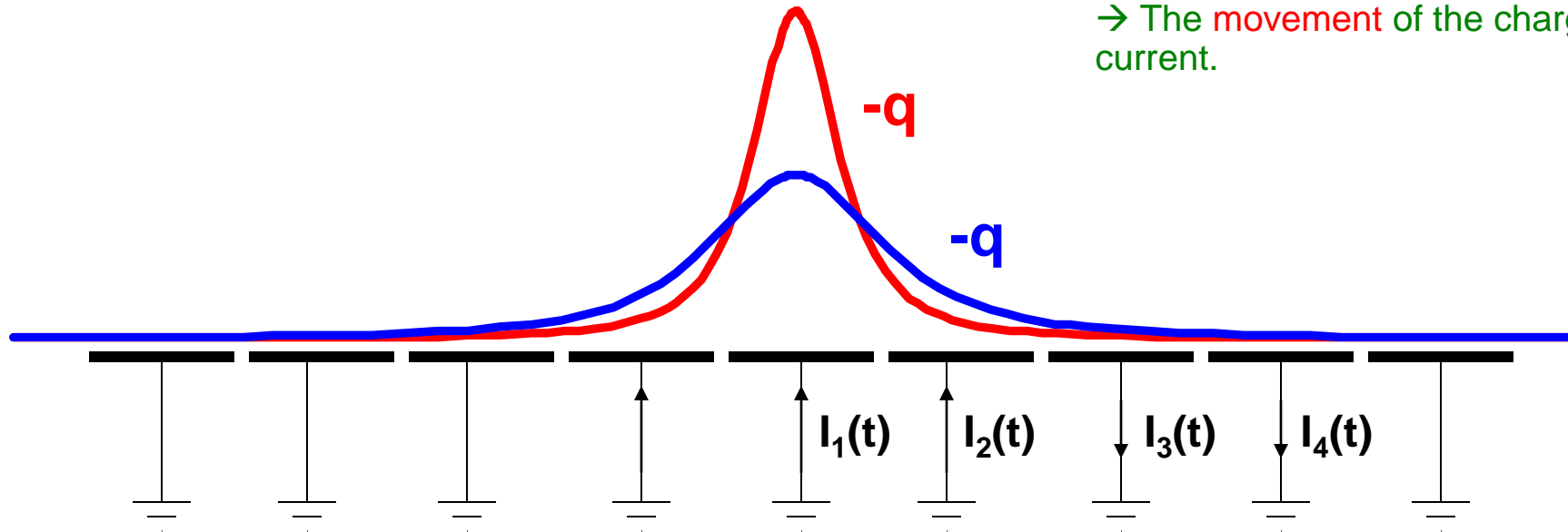
If we segment the grounded metal plate and if we ground the individual strips the surface charge density doesn't change with respect to the continuous metal plate.



The charge induced on the individual strips is now depending on the position z_0 of the charge.

If the charge is moving there are currents flowing between the strips and ground.

→ The movement of the charge induces a current.



$$Q_1(z_0) = \int_{-\infty}^{\infty} \int_{-w/2}^{w/2} \sigma(x, y) dx dy = -\frac{2q}{\pi} \arctan\left(\frac{w}{2z_0}\right)$$

$$z_0(t) = z_0 - vt$$

$$I_1^{ind}(t) = -\frac{d}{dt} Q_1[z_0(t)] = -\frac{\partial Q_1[z_0(t)]}{\partial z_0} \frac{dz_0(t)}{dt} = \frac{4qw}{\pi[4z_0(t)^2 + w^2]} v$$

Detectors based on Ionization

→ Gas detectors:

- Wire Chambers
- Drift Chambers
- Time Projection Chambers

Solid State Detectors

- Transport of Electrons and Holes in Solids
- Si- Detectors

Gas Detectors with internal Electron Multiplication

Principle: At sufficiently high electric fields (100kV/cm) the electrons gain energy in excess of the ionization energy → secondary ionization etc. etc.

$$dN = N \alpha dx$$

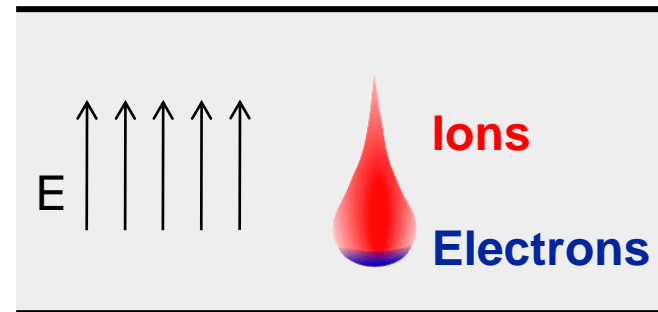
α ...Townsend Coefficient

$$N(x) = N_0 \exp(\alpha x)$$

$N/N_0 = A$ (Amplification, Gas Gain)

Avalanche in a homogeneous field:

Problem: High field on electrode surface
→ breakdown



In an inhomogeneous Field: $\alpha(E) \rightarrow N(x) = N_0 \exp [\int \alpha(E(x')) dx']$

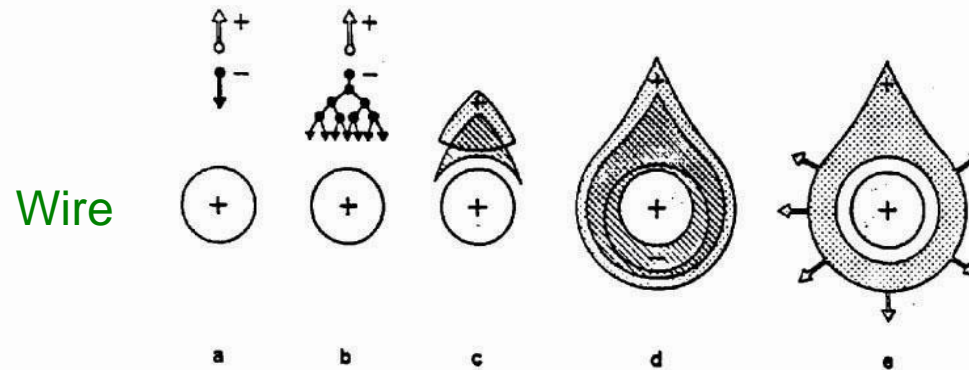
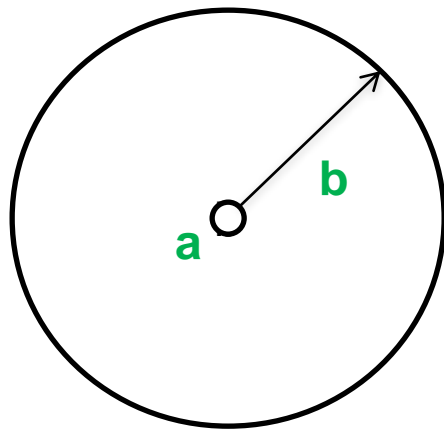
Wire Chamber: Electron Avalanche

Wire with radius (10-25 μm) in a tube of radius b (1-3cm):

$$E(r) = \frac{\lambda}{2\pi\epsilon_0 r} = \frac{V_0}{\ln \frac{b}{a}} \frac{1}{r}, \quad V(r) = \frac{V_0}{\ln \frac{b}{a}} \ln \frac{r}{a}$$

Electric field close to a thin wire (100-300kV/cm). E.g. $V_0=1000\text{V}$, $a=10\mu\text{m}$, $b=10\text{mm}$, $E(a)=150\text{kV/cm}$

Electric field is sufficient to accelerate electrons to energies which are sufficient to produce secondary ionization \rightarrow electron avalanche \rightarrow signal.



Multi Wire Proportional Chamber

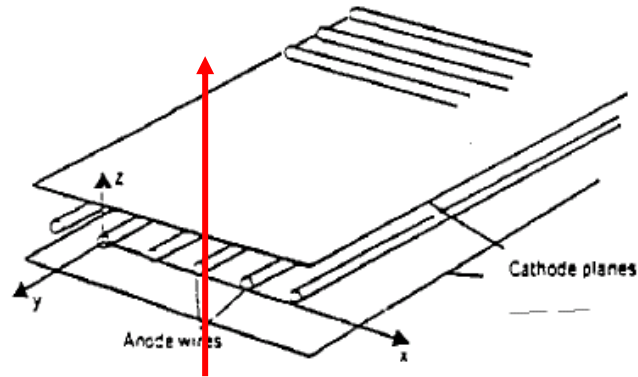
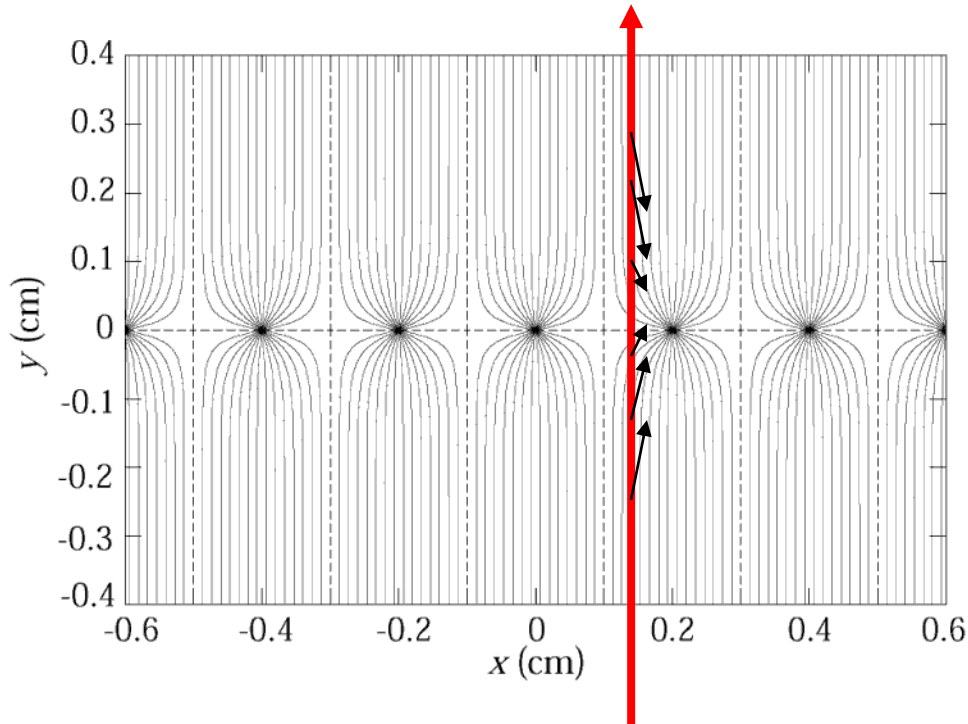


Abbildung 2.27: Vieldrahtproportionalkammer.



Classic geometry (Crosssection), Charpak 1968 :

One plane of thin sense wires is placed between two parallel plates.

Typical dimensions:

Wire distance 2-5mm, distance between cathode planes ~10mm.

Electrons ($v \approx 5\text{cm}/\mu\text{s}$) are collected within $\approx 100\text{ns}$. The ion tail can be eliminated by electronics filters \rightarrow pulses of $<100\text{ns}$ length.

For 10% occupancy \rightarrow every μs one pulse

\rightarrow 1MHz/wire rate capability !

\rightarrow Compare to Bubble Chamber with 10 Hz !

Multi Wire Proportional Chamber

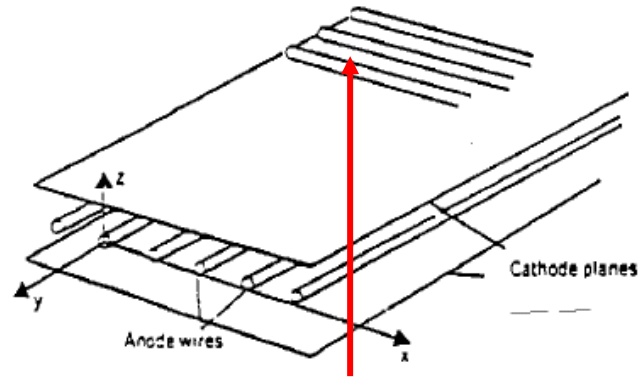
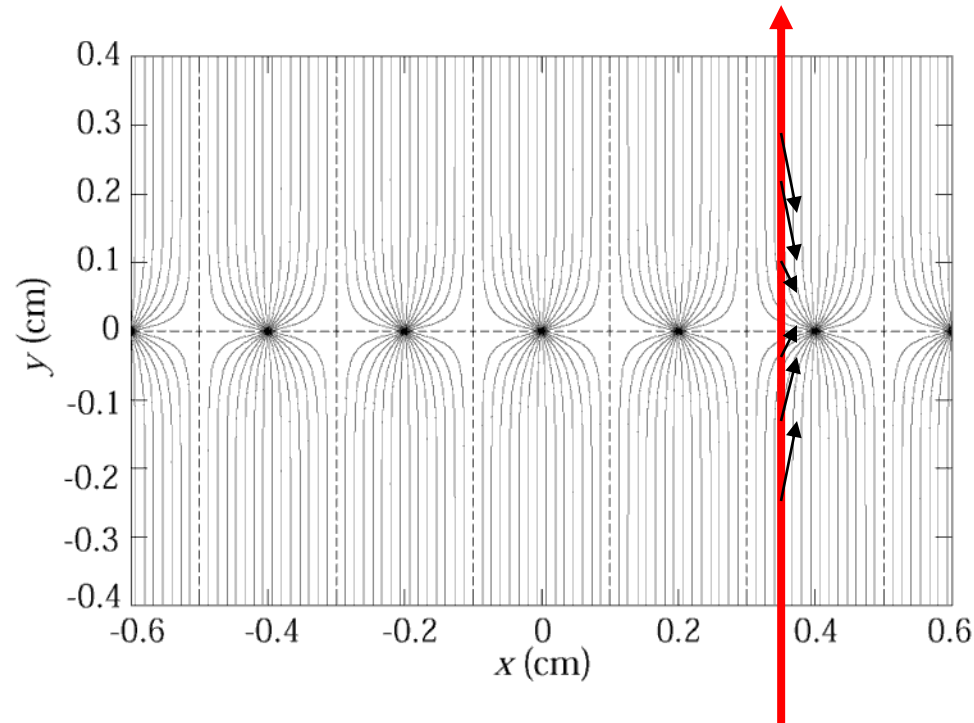


Abbildung 2.27: Vieldrahtproportionalkammer.



In order to eliminate the left/right ambiguities: Shift two wire chambers by half the wire pitch.

For second coordinate:

→ Another chamber at 90° relative rotation

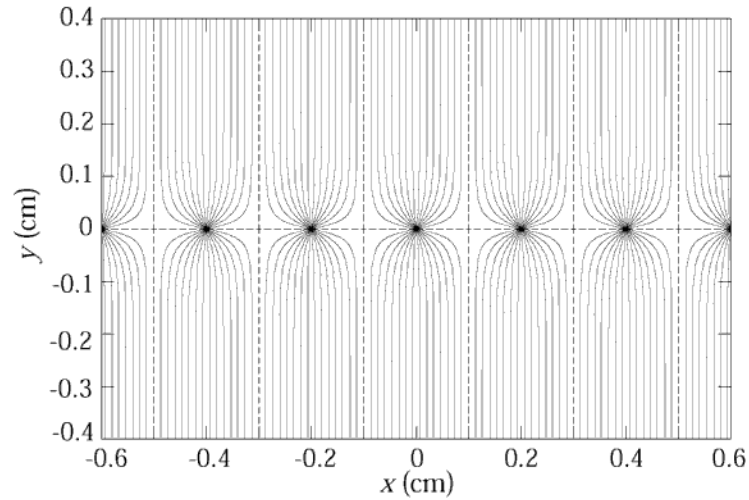
→ Signal propagation to the two ends of the wire.

→ Pulse height measurement on both ends of the wire. Because of resistivity of the wire, both ends see different charge.

Segmenting of the cathode into strips or pads:

The movement of the charges induces a signal on the wire AND on the cathode. By segmentation of the cathode plane and charge interpolation, resolutions of $50\mu\text{m}$ can be achieved.

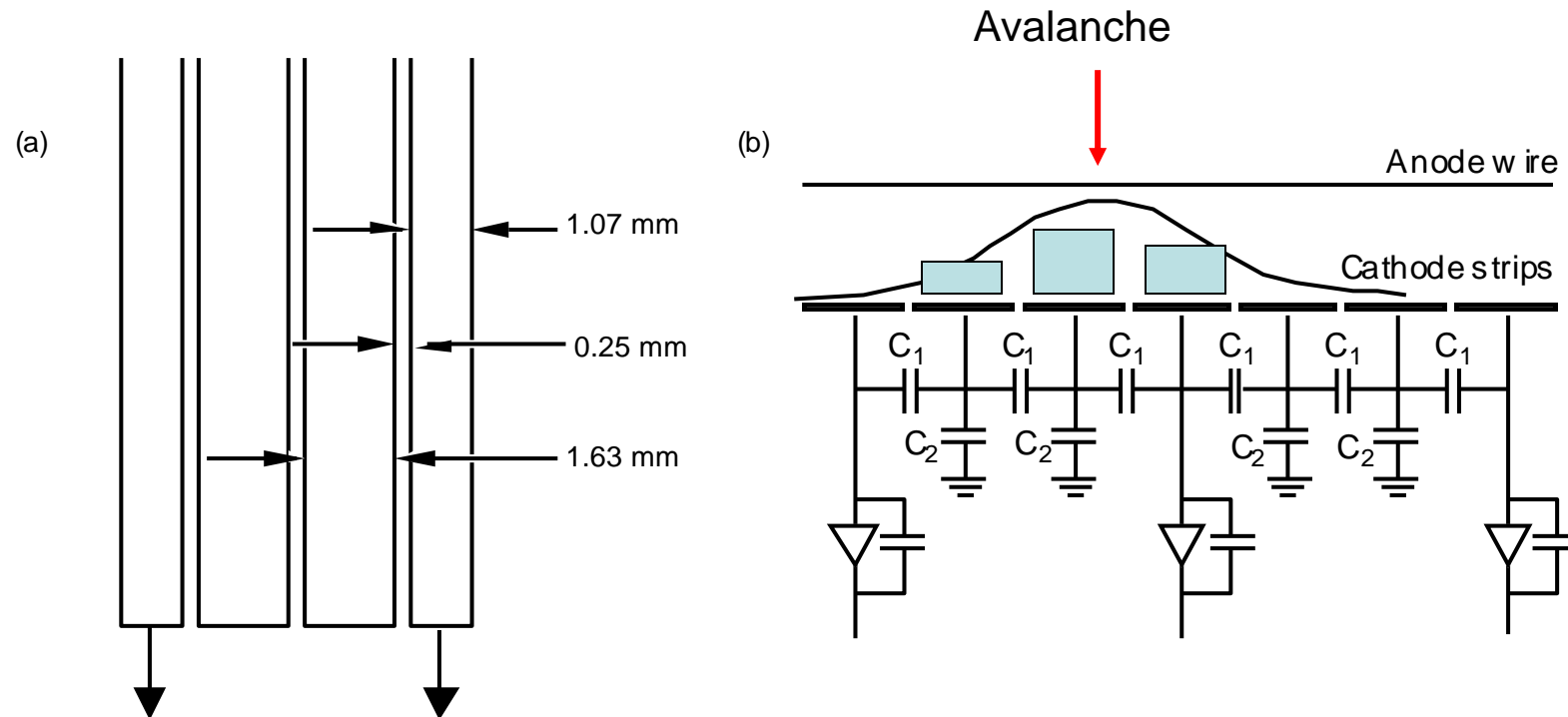
Multi Wire Proportional Chamber



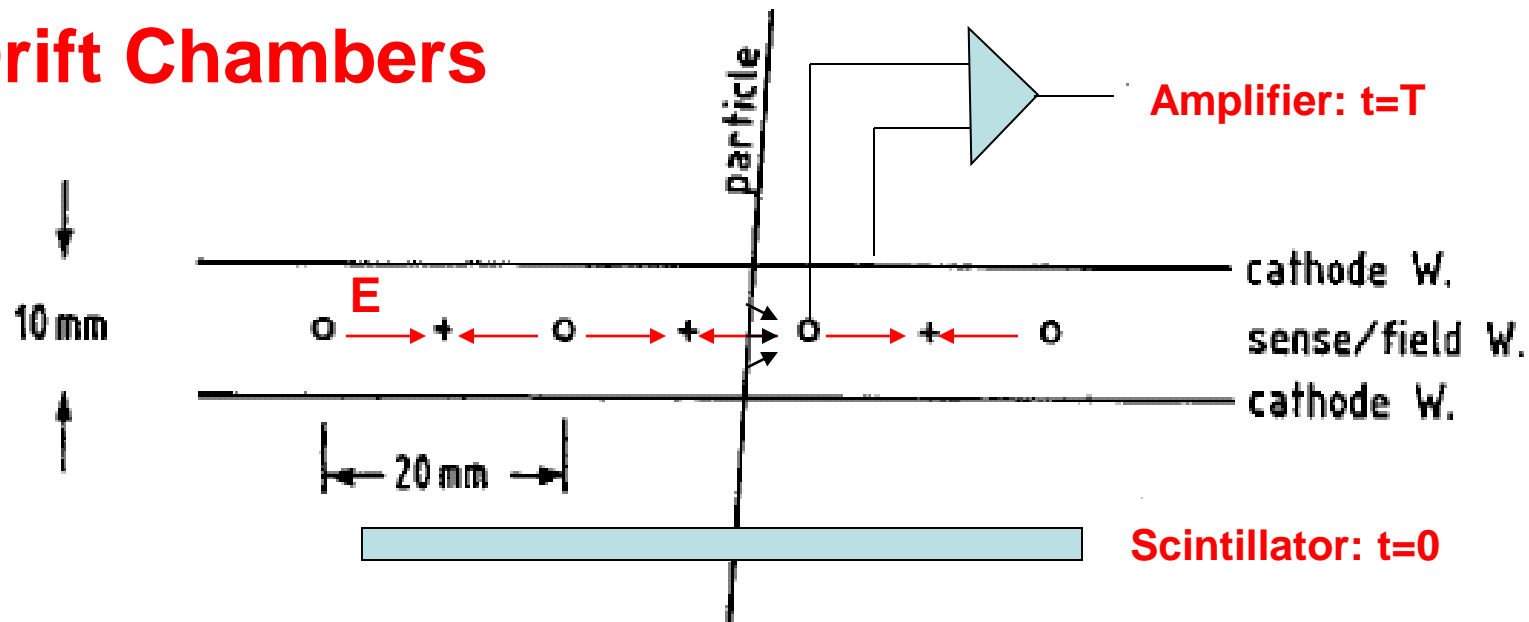
Cathode strip:

Width (1σ) of the charge distribution \approx distance between Wires and cathode plane.

'Center of gravity' defines the particle trajectory.



Drift Chambers



In an alternating sequence of wires with different potentials one finds an electric field between the 'sense wires' and 'field wires'.

The electrons are moving to the sense wires and produce an avalanche which induces a signal that is read out by electronics.

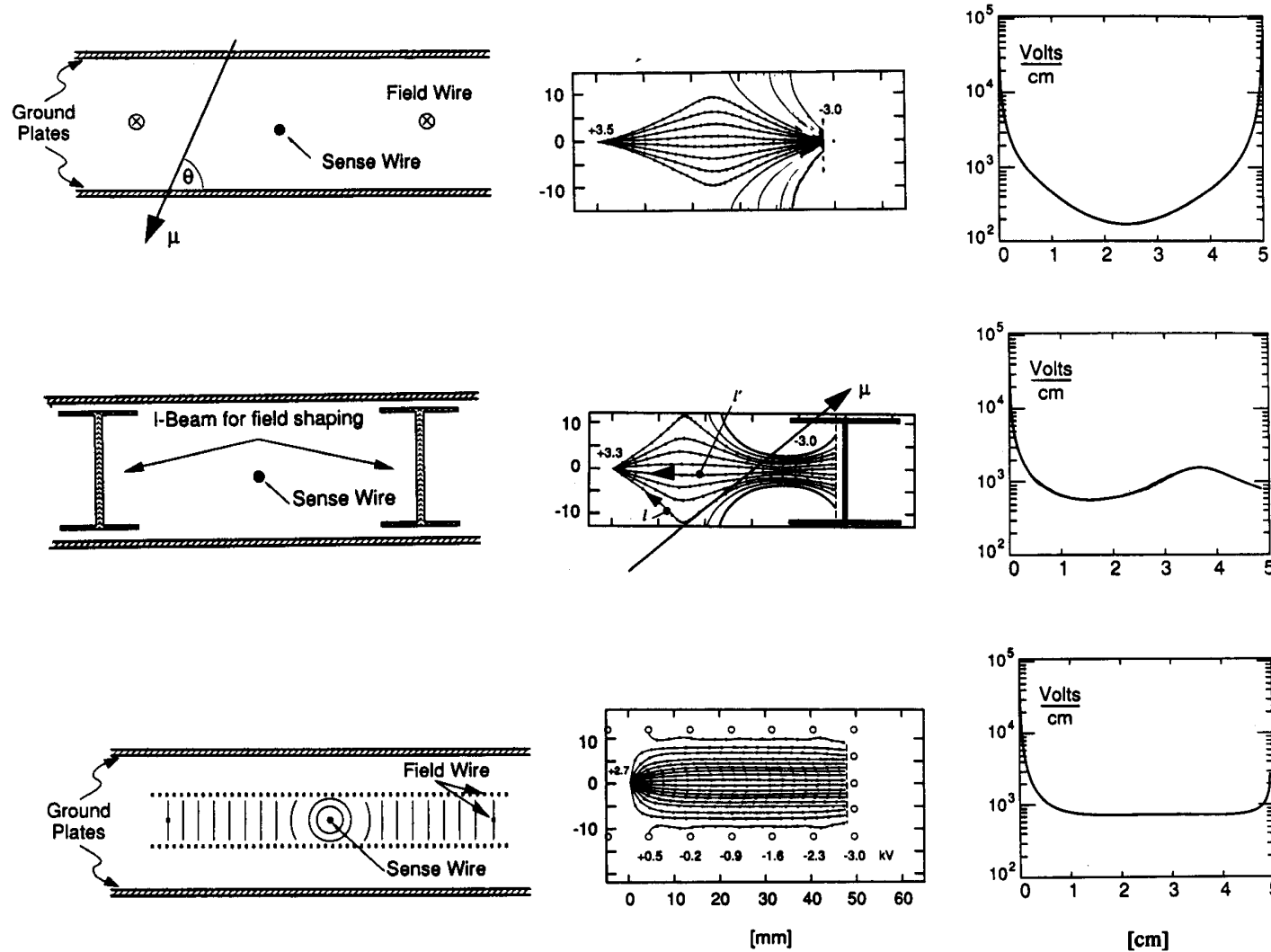
The time between the passage of the particle and the arrival of the electrons at the wire is measured.

The drift time T is a measure of the position of the particle !

By measuring the drift time, the wire distance can be increased (compared to the Multi Wire Proportional Chamber) → save electronics channels !

Drift Chambers, typical Geometries

Electric Field $\approx 1\text{kV/cm}$

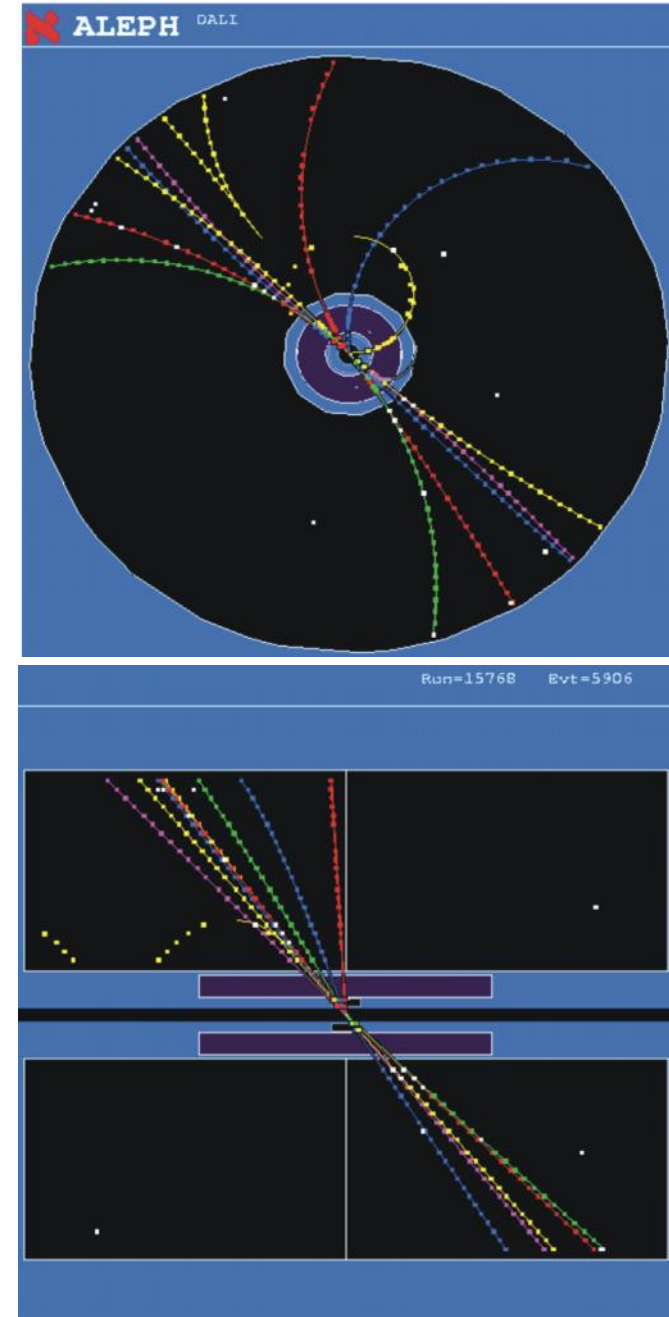
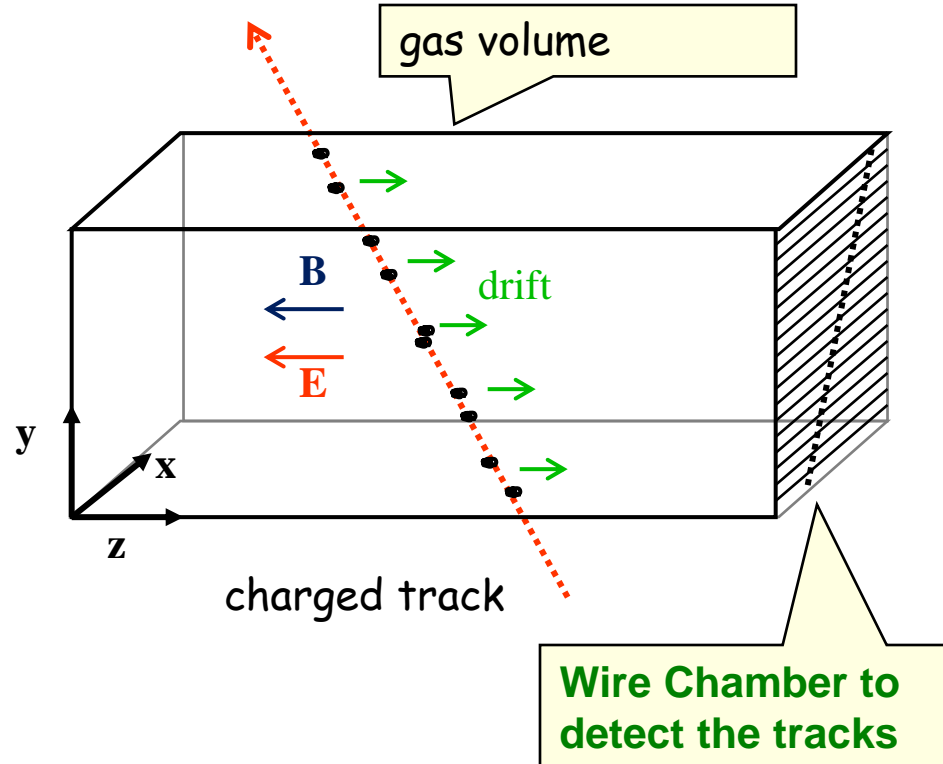


U.Becker Instr. of HEP, Vol#9, p516 World Scientific (1992) ed F.Sauli

Time Projection Chamber (TPC):

Gas volume with parallel E and B Field.
B for momentum measurement. Positive effect: Diffusion is strongly reduced by E//B (up to a factor 5).

Drift Fields 100-400V/cm. Drift times 10-100 μ s.
Distance up to 2.5m !

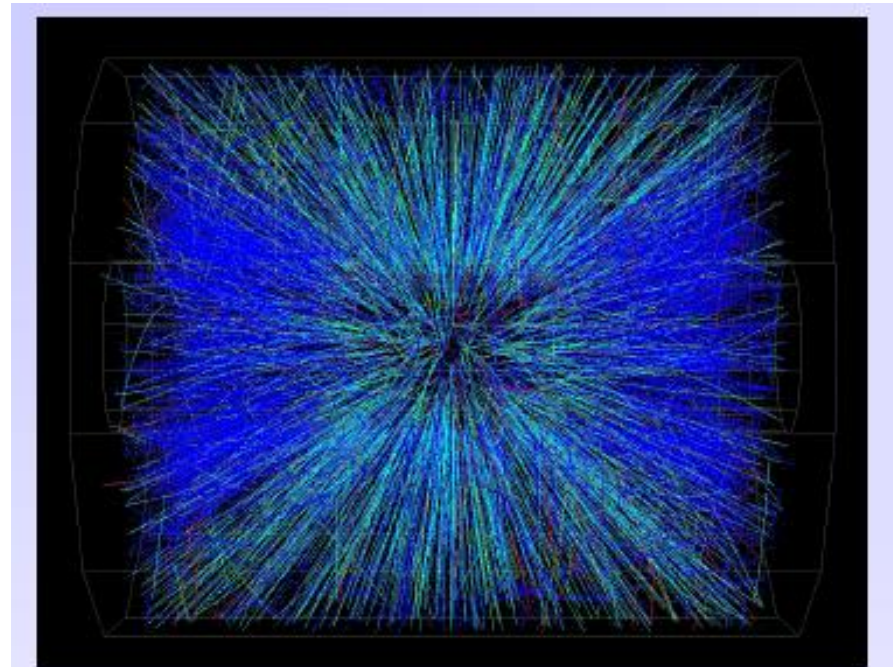
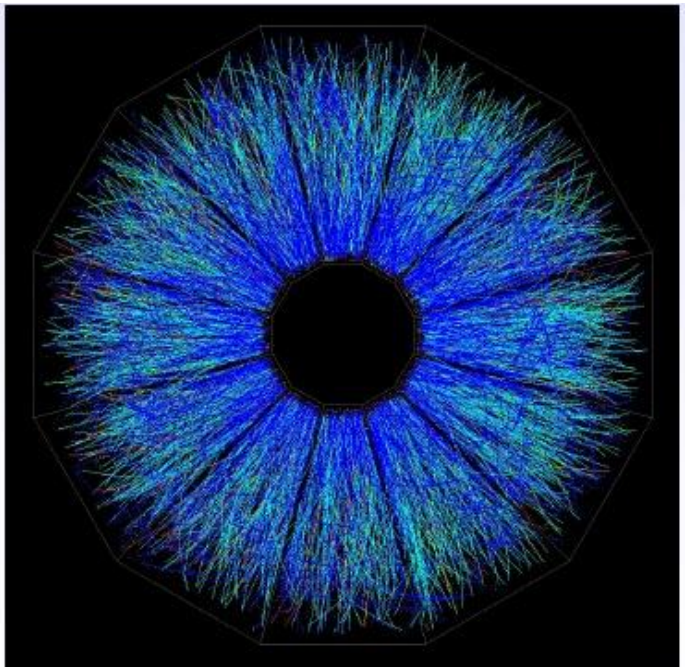


STAR TPC (BNL)

Event display of a Au Au collision at CM energy of 130 GeV/n.

Typically around 200 tracks per event.

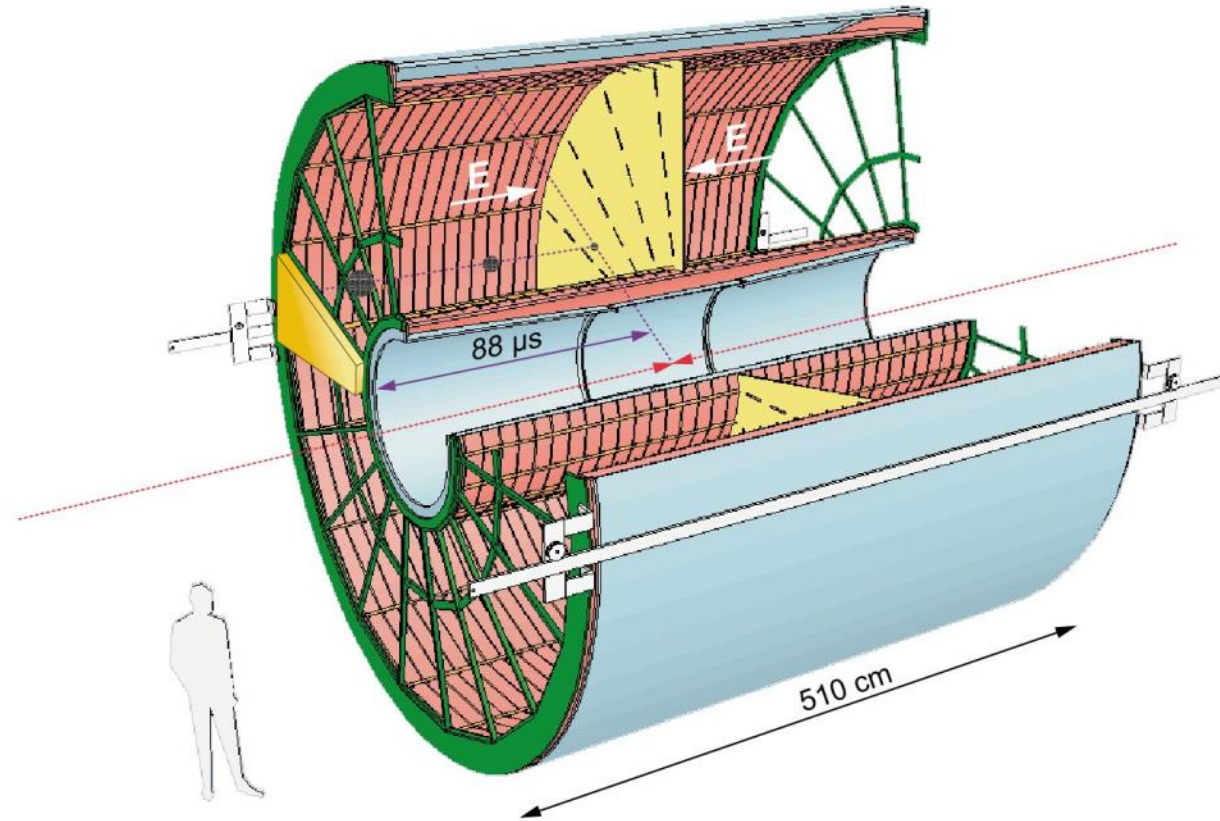
Great advantage of a TPC: The only material that is in the way of the particles is gas \rightarrow very low multiple scattering \rightarrow very good momentum resolution down to low momenta !



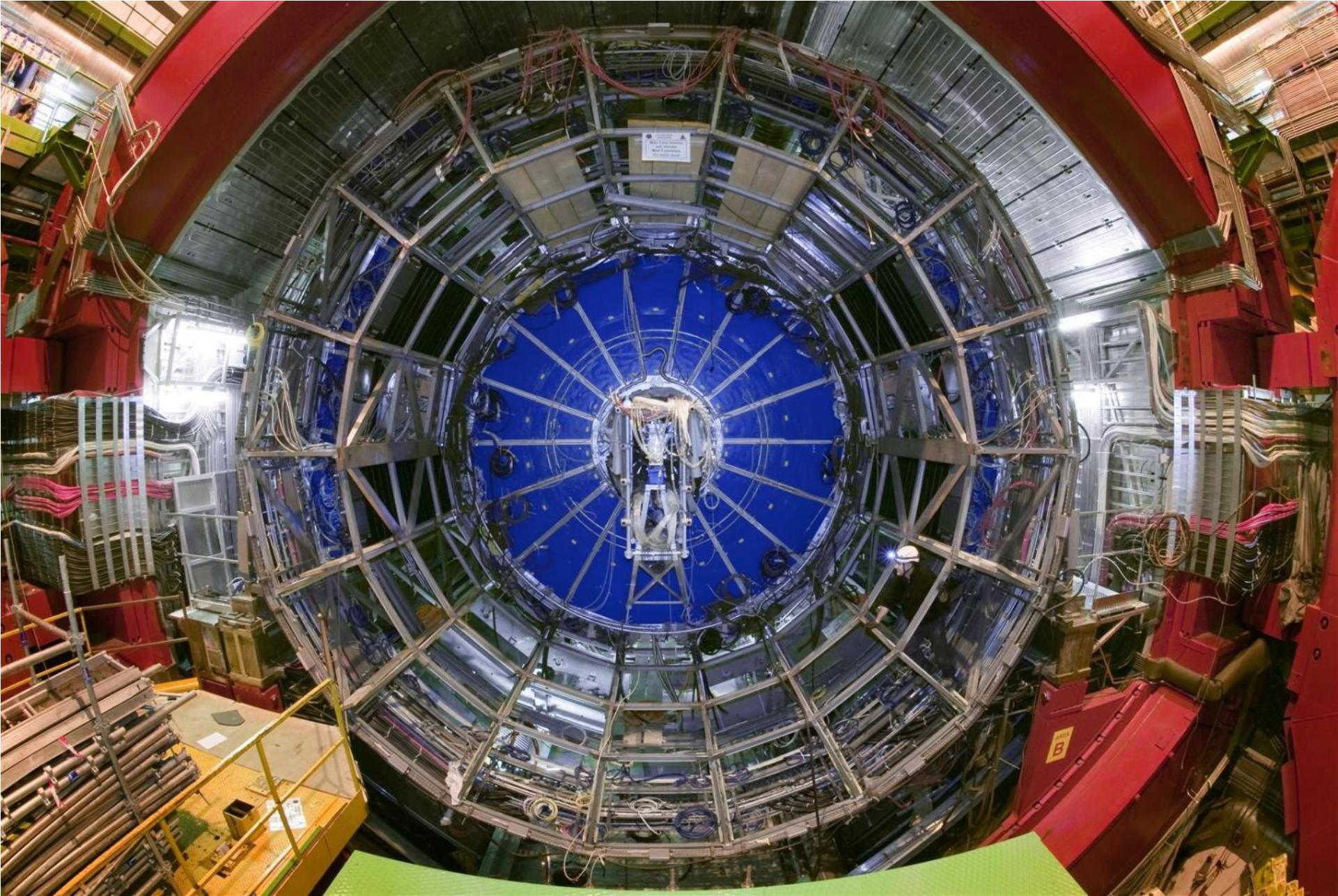
ALICE TPC: Detector Parameters

- Gas Ne/ CO₂ 90/10%
- Field 400V/cm
- Gas gain >10⁴
- Position resolution $\sigma = 0.25\text{mm}$
- Diffusion: $\sigma_t = 250\mu\text{m}$
- Pads inside: 4x7.5mm
- Pads outside: 6x15mm
- B-field: 0.5T
- Largest TPC:
 - Length 5m
 - Diameter 5m
 - Volume 88m³
 - Detector area 32m²
 - Channels ~570 000

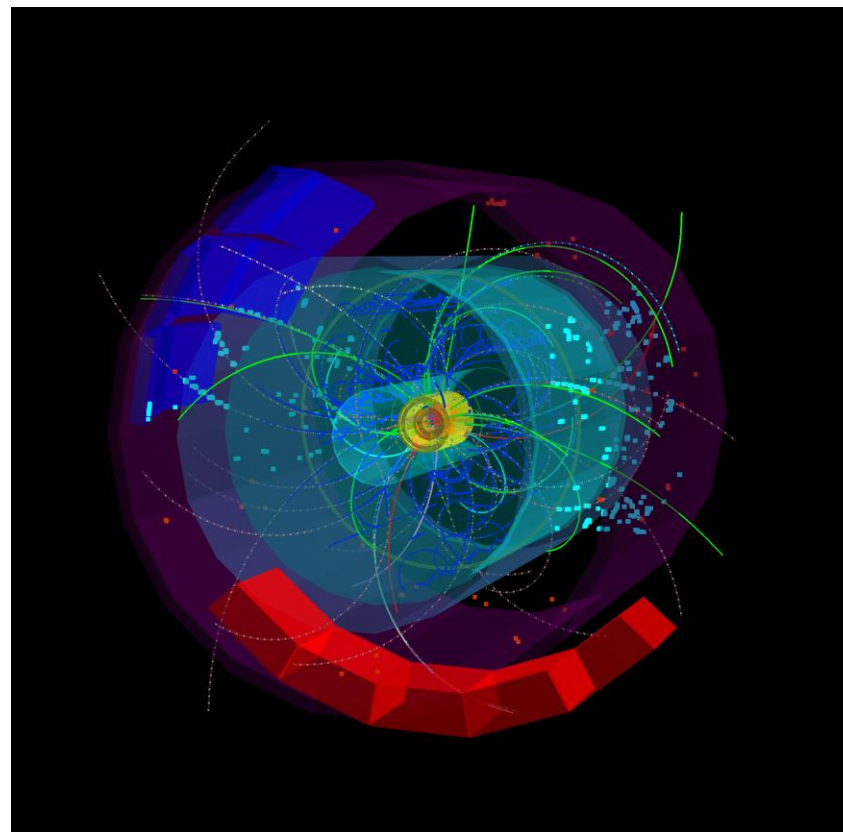
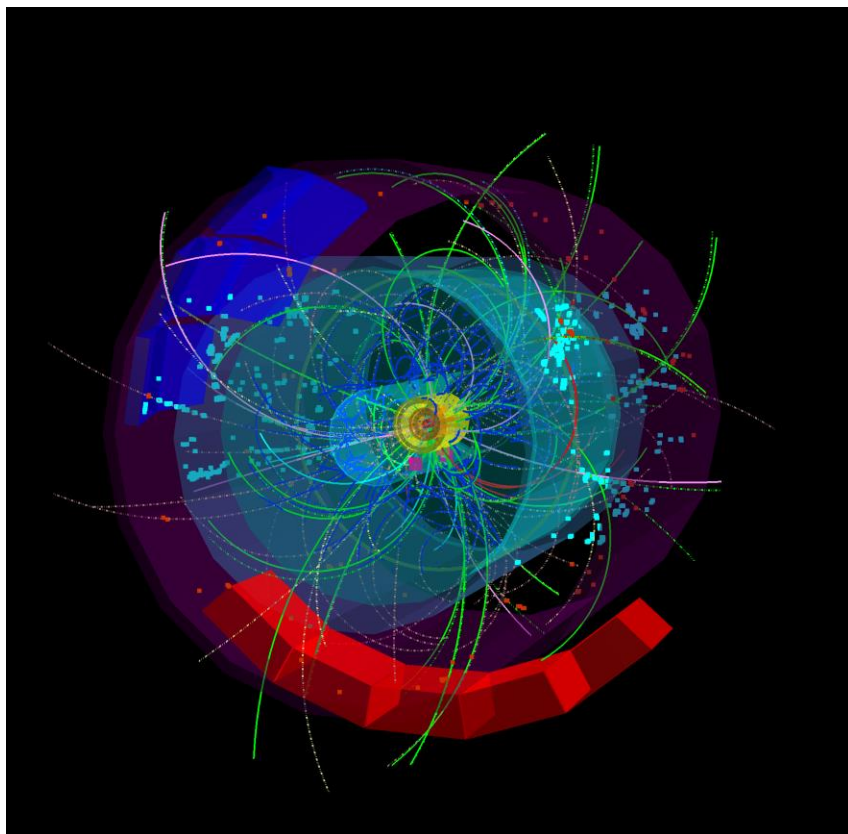
$\sqrt{\text{cm}}$



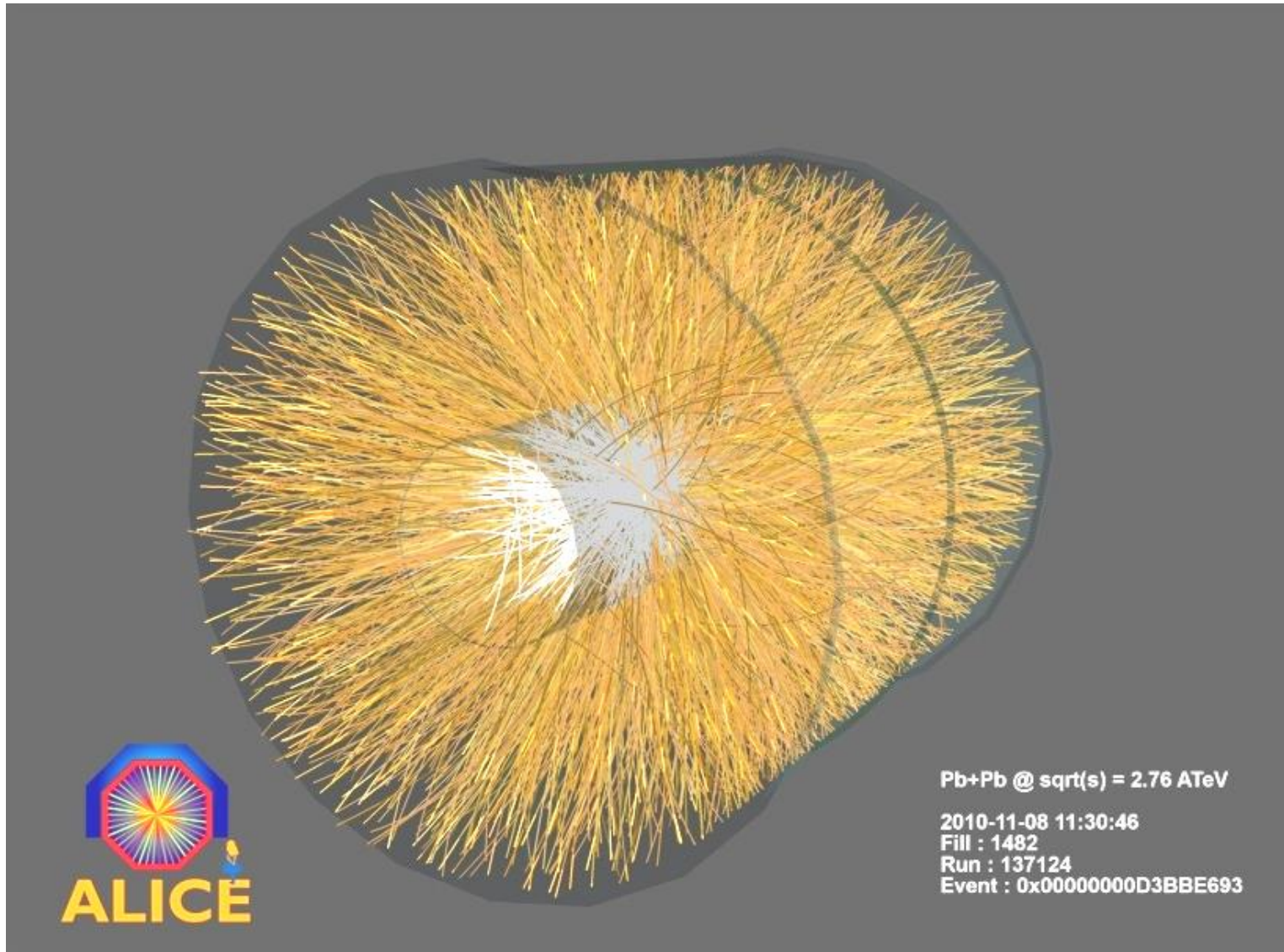
TPC installed in the ALICE Experiment



First 7 TeV p-p Collisions in the ALICE TPC in March 2010 !



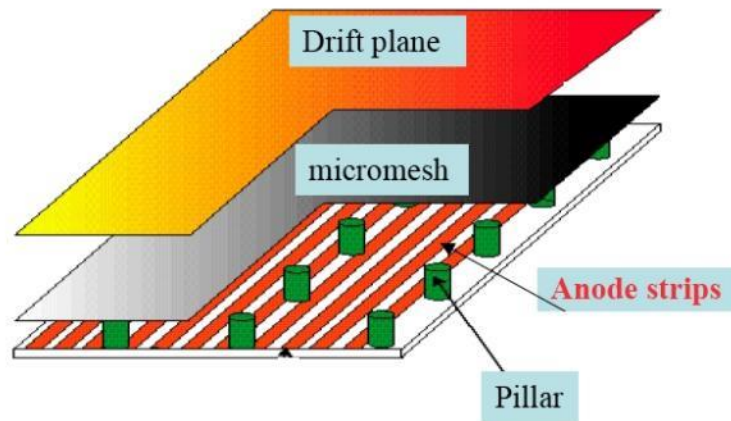
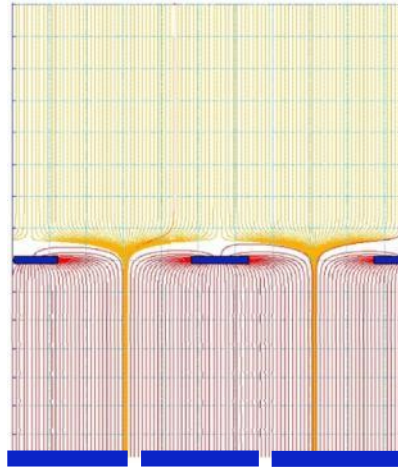
First Pb Pb Collisions in the ALICE TPC in Nov 2010 !



GEMs & MICROMEAS

MICROMEAS

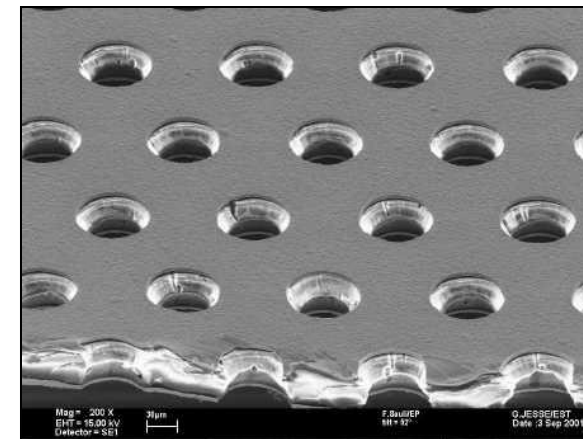
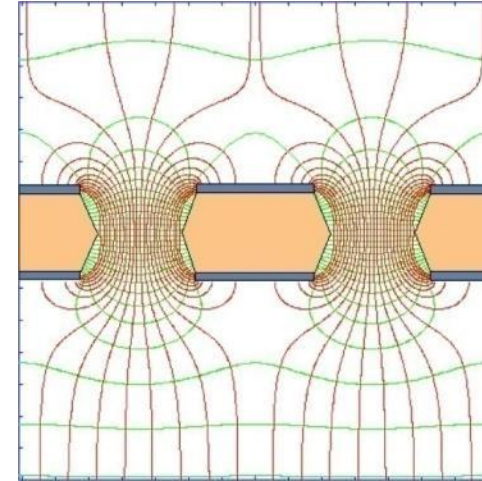
Narrow gap (50-100 μm) PPC with thin cathode mesh
Insulating gap-restoring wires or pillars



Y. Giomataris et al, Nucl. Instr. and Meth. A376(1996)239

GEM

Thin metal-coated polymer foils
70 μm holes at 140 μm pitch



F. Sauli, Nucl. Instr. and Methods A386(1997)531

Detectors based on Ionization

Gas detectors:

- Wire Chambers
- Drift Chambers
- Time Projection Chambers
- Transport of Electrons and Ions in Gases

Solid State Detectors

- Transport of Electrons and Holes in Solids
- Si- Detectors
- Diamond Detectors

Silicon Detector

Velocity:

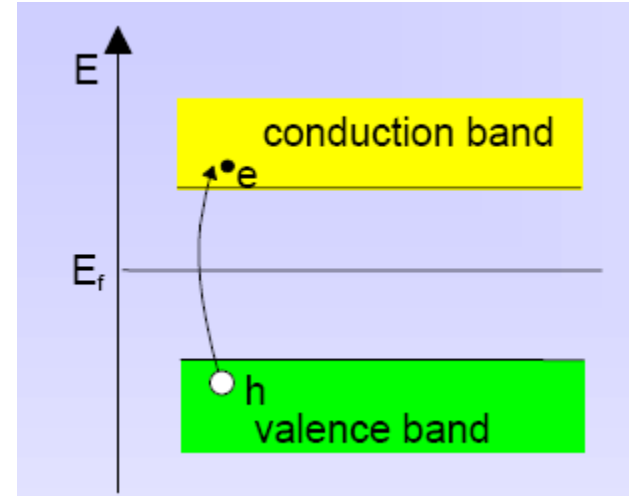
$\mu_e=1450 \text{ cm}^2/\text{Vs}$, $\mu_h=505 \text{ cm}^2/\text{Vs}$, 3.63eV per e-h pair.

~33000 e/h pairs in 300 μm of silicon.

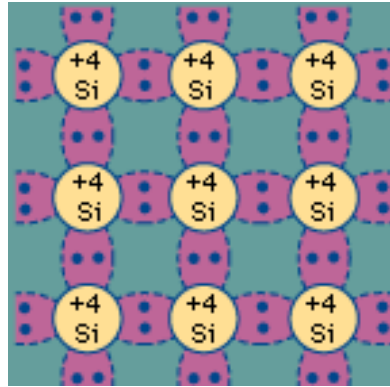
However: Free charge carriers in Si:

T=300 K: e,h = $1.45 \times 10^{10} / \text{cm}^3$ but only 33000 e/h pairs in 300 μm produced by a high energy particle.

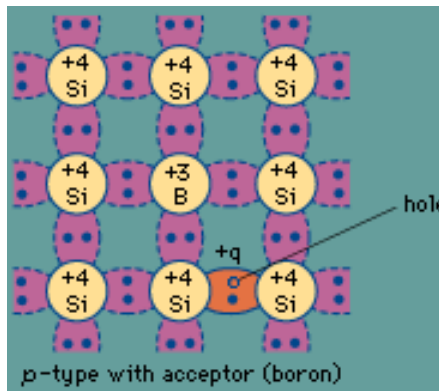
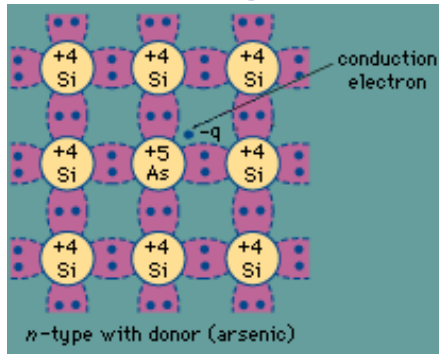
Why can we use Si as a solid state detector ???



Doping of Silicon



doping

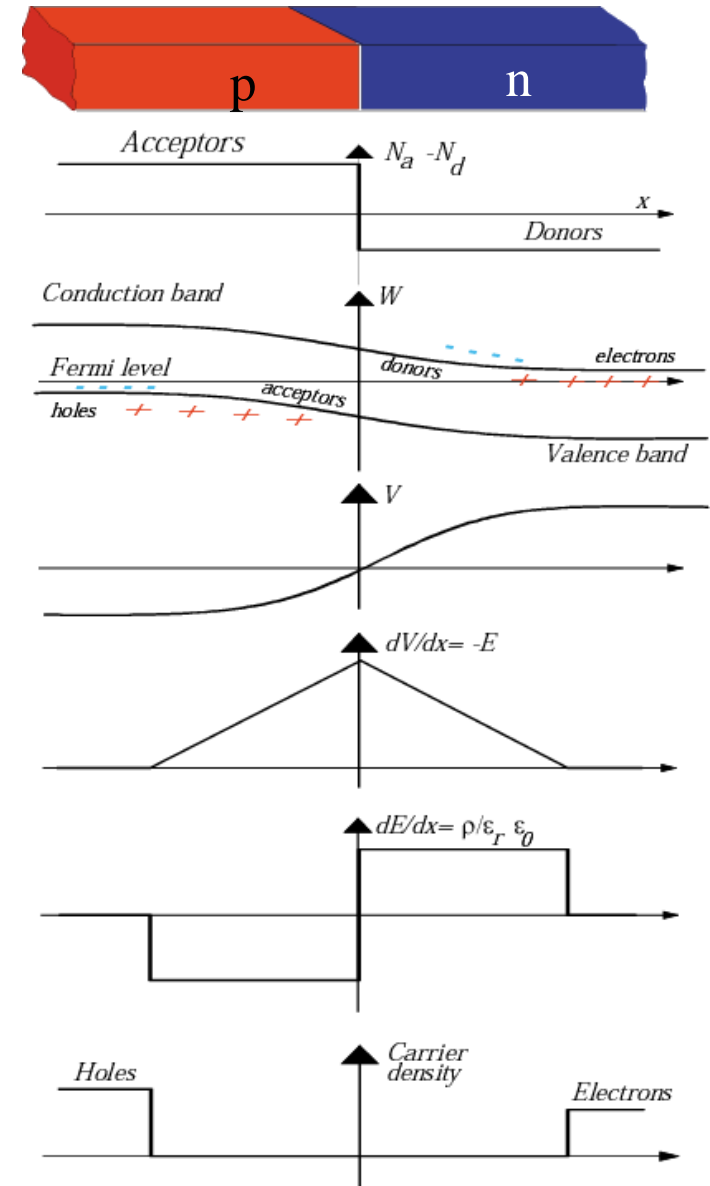


In a silicon crystal at a given temperature the number of electrons in the conduction band is equal to the number of holes in the valence band.

Doping Silicon with Arsen (+5) it becomes an n-type conductor (more electrons than holes).

Doping Silicon with Boron (+3) it becomes a p-type conductor (more holes than electrons).

Bringing p and n in contact makes a diode.



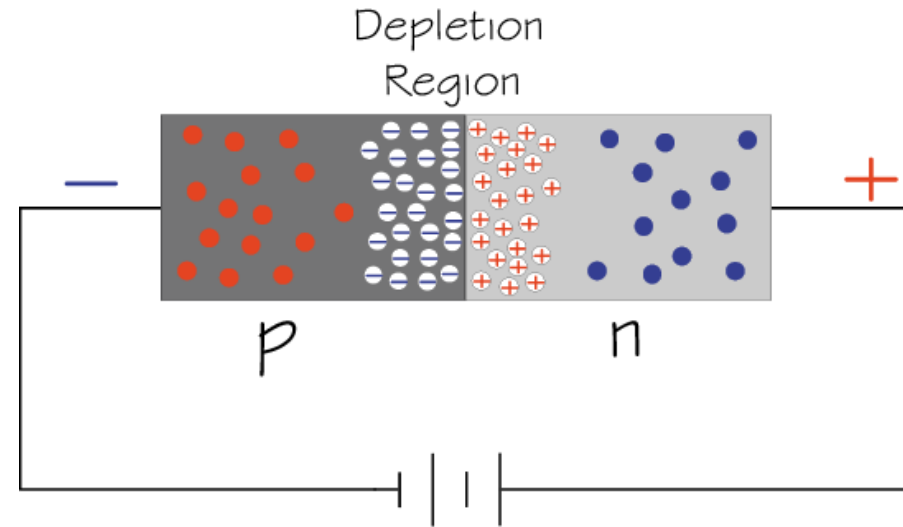
Si-Diode used as a Particle Detector !

At the p-n junction the charges are depleted and a zone free of charge carriers is established.

By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.

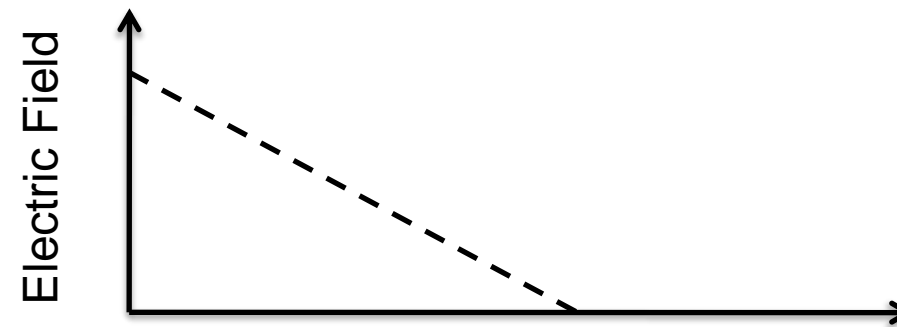
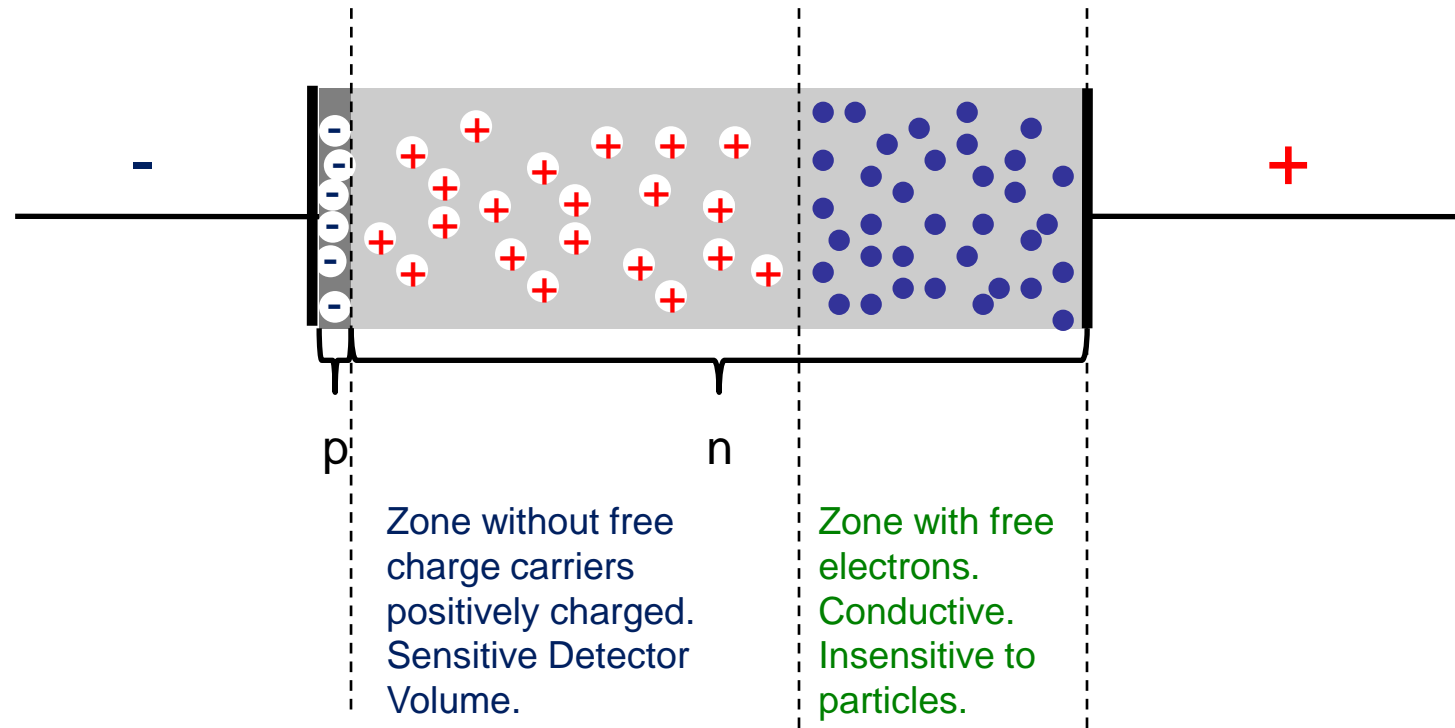
An ionizing particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal electrodes.

As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.

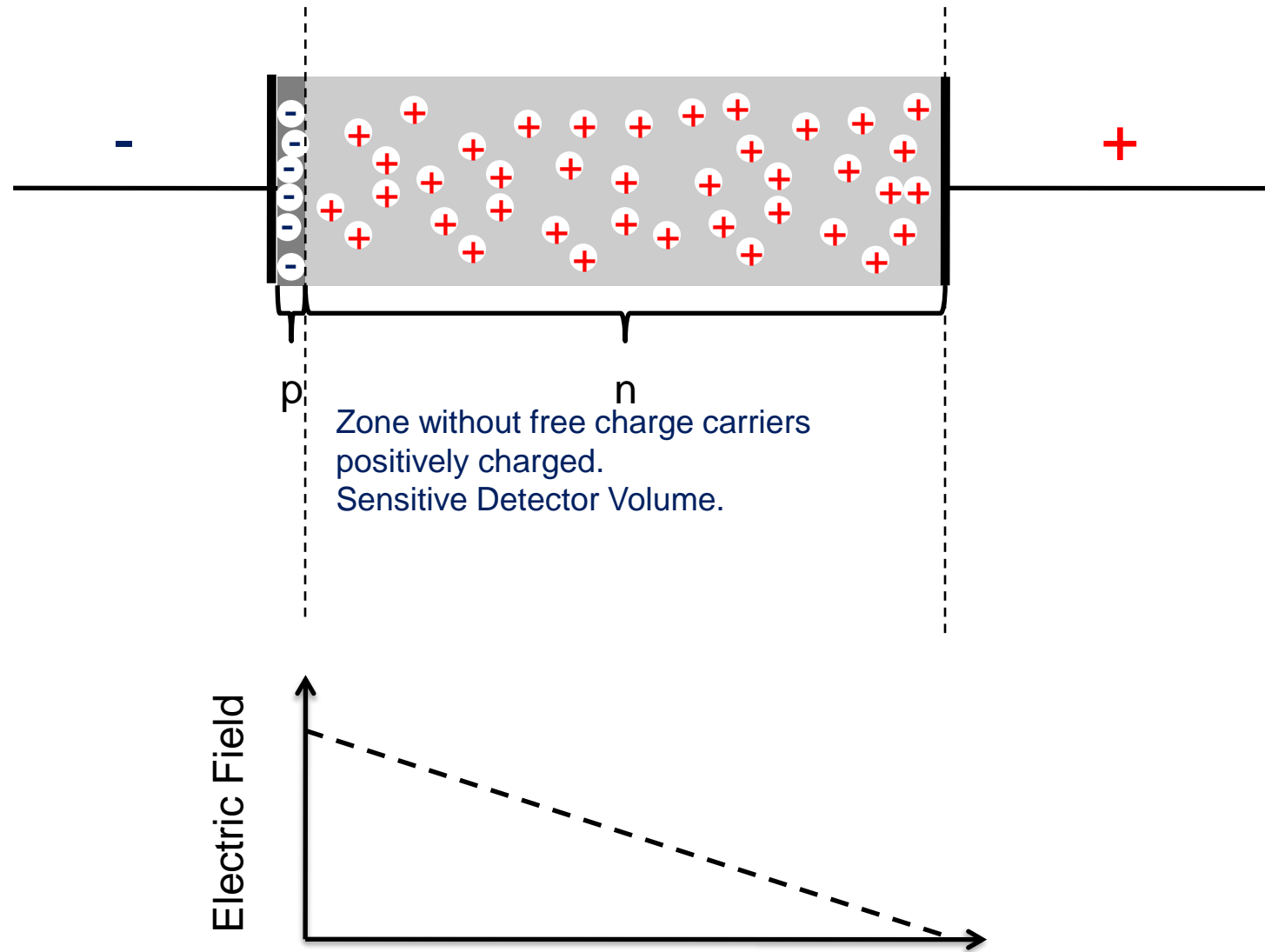


- Electron
- ⊕ Positive ion from removal of electron in n-type impurity
- ⊖ Negative ion from filling in p-type vacancy
- Hole

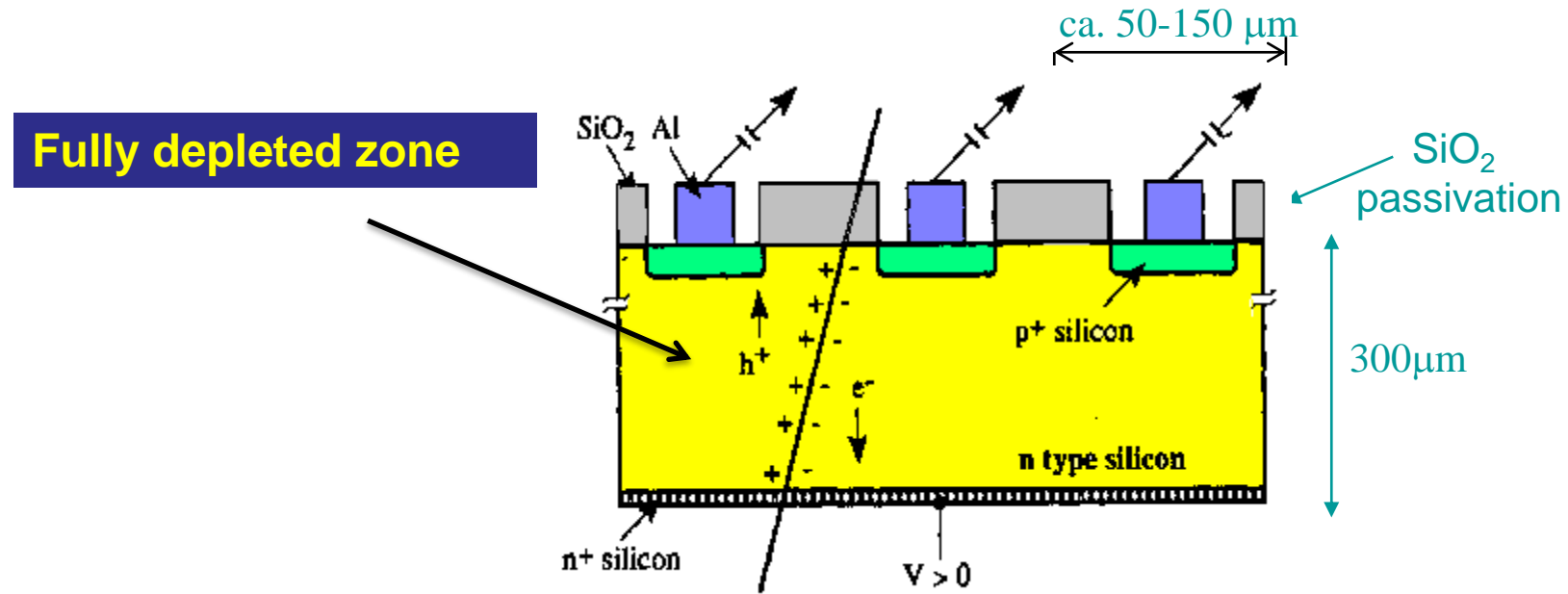
Under-Depleted Silicon Detector



Fully-Depleted Silicon Detector



Silicon Detector



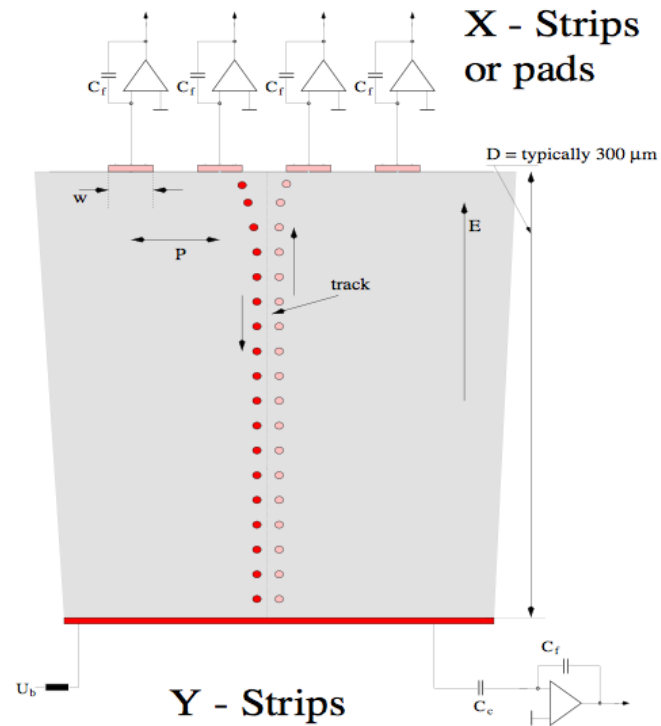
$N(e-h) = 11\ 000/100\mu\text{m}$

Position Resolution down to $\sim 5\mu\text{m}$!

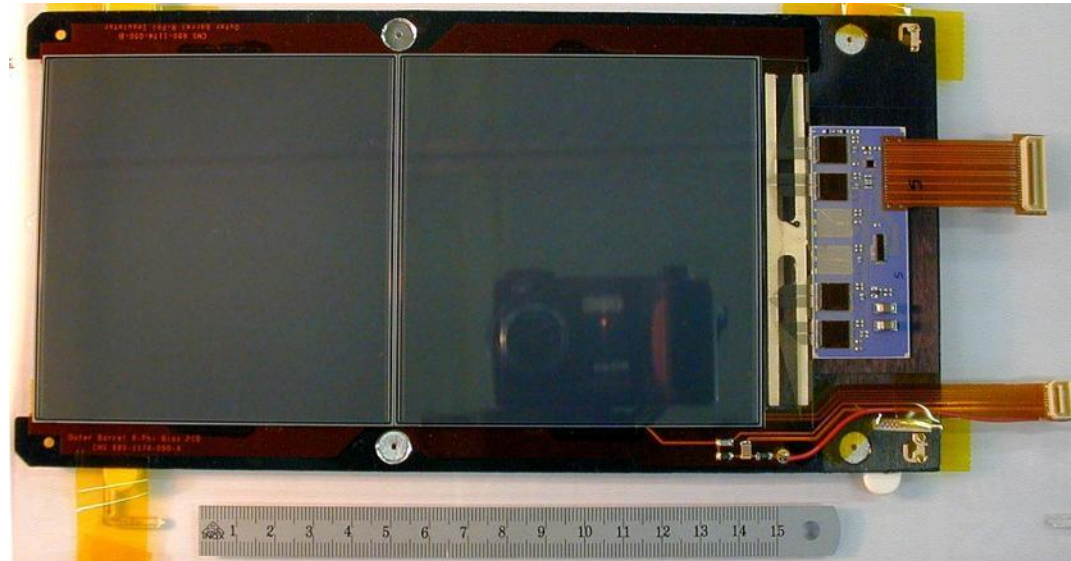
Silicon Detector

Every electrode is connected to an amplifier →
Highly integrated readout electronics.

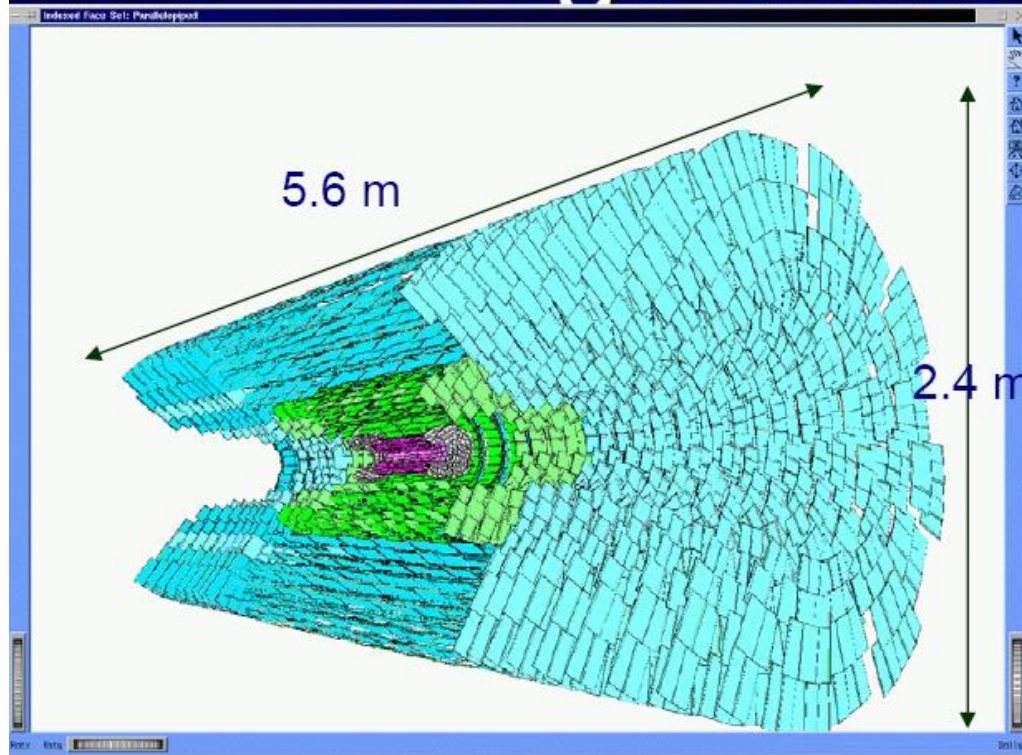
Two dimensional readout is possible.



CMS Outer Barrel Module



Large Silicon Systems



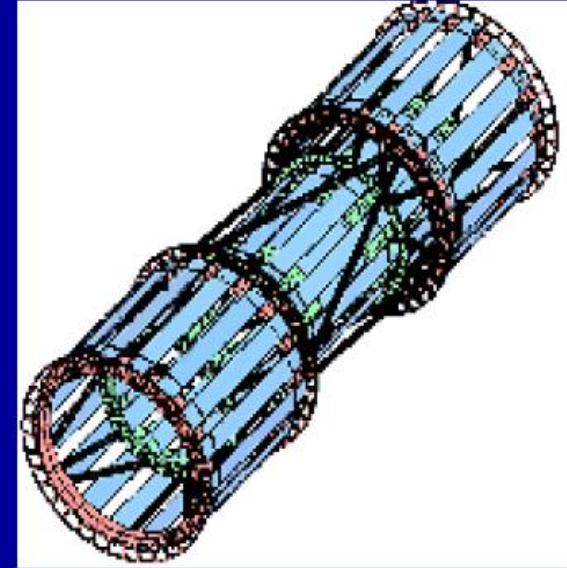
CMS tracker (~2007)

12000 modules

~ 445 m² silicon area

~ 24,328 silicon wafers

~ 60 M readout channels

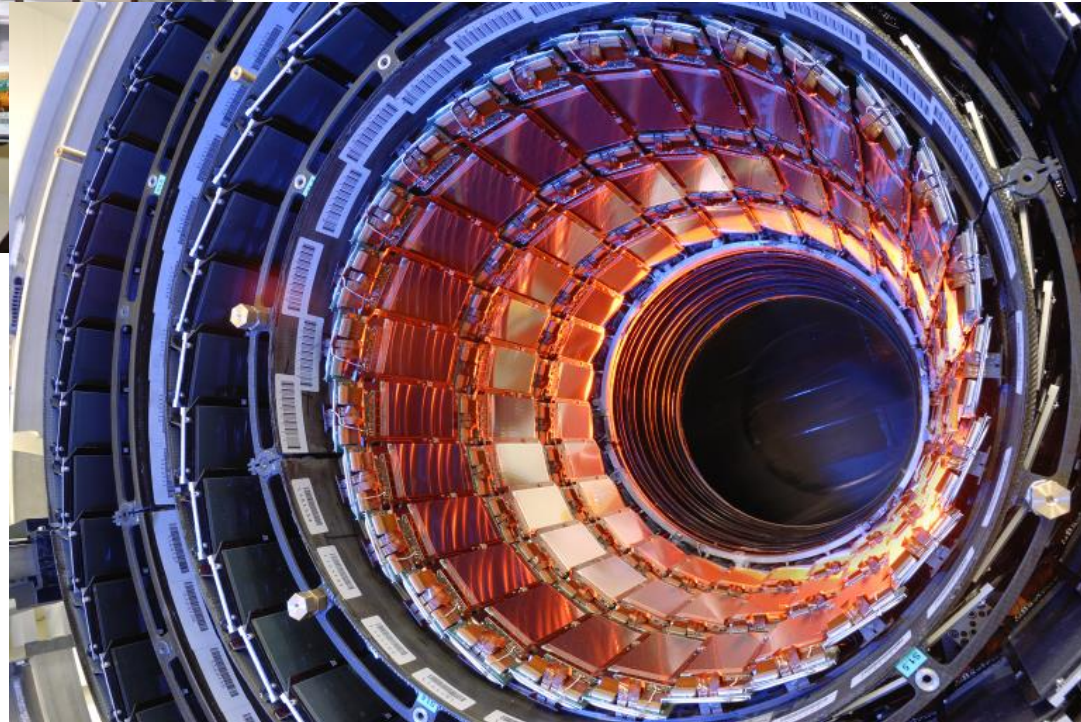


CDF SVX IIa (2001-)

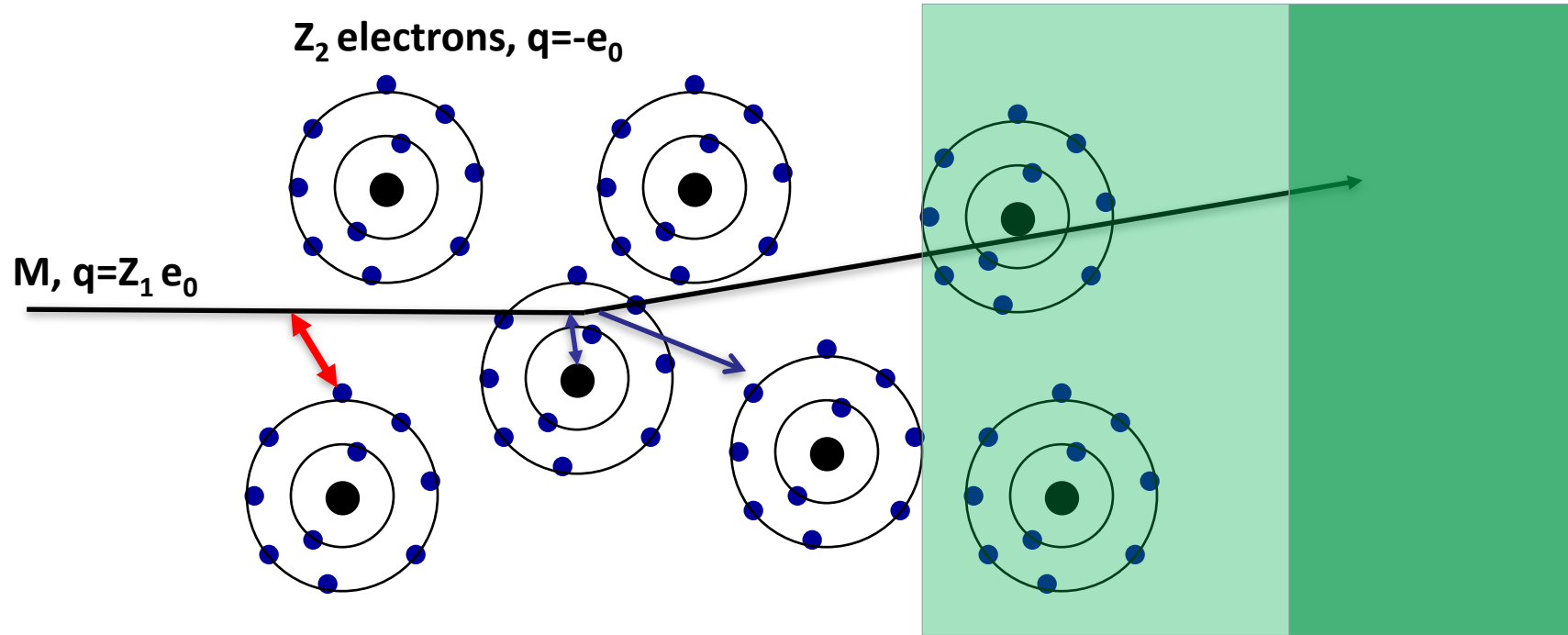
~ 11m² silicon area

~ 750 000 readout channels

CMS Tracker



Electromagnetic Interaction of Particles with Matter

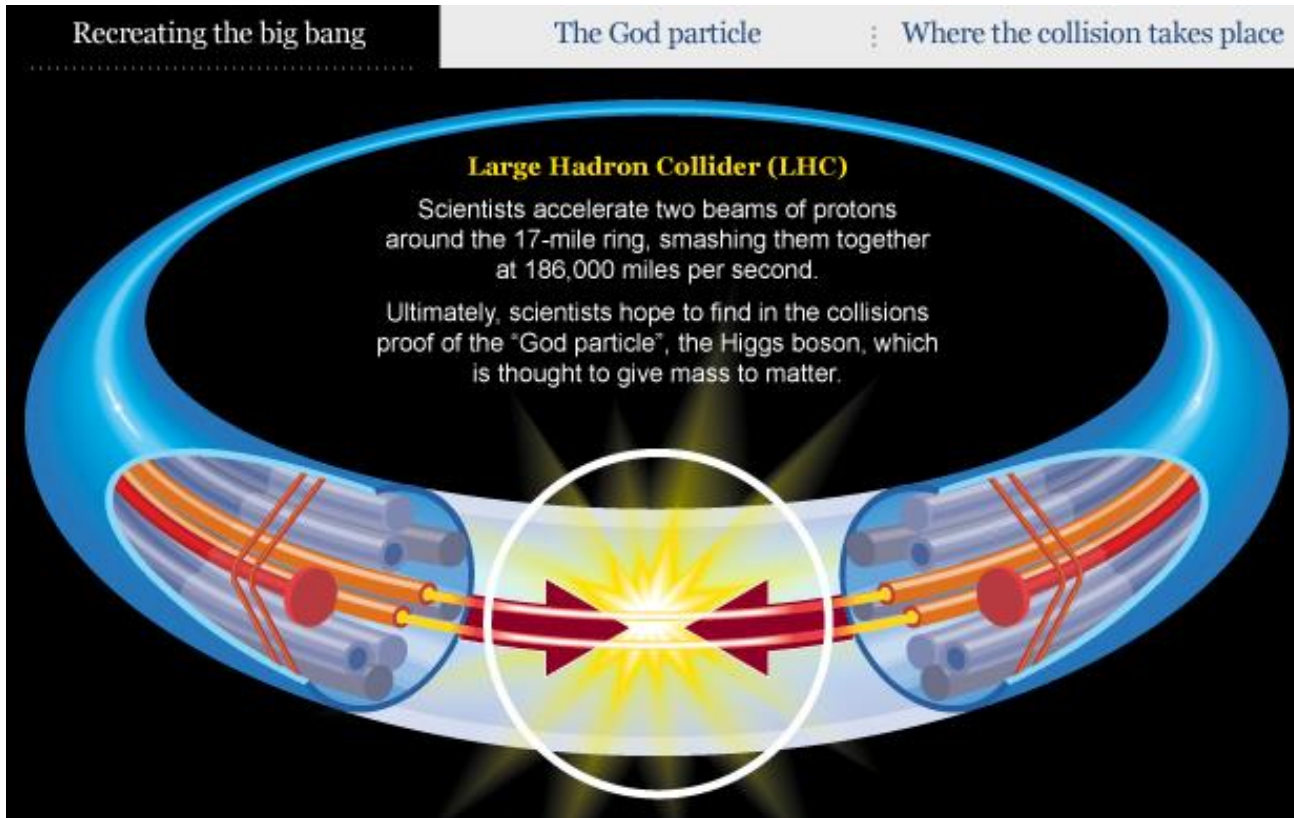


Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produce and X ray photon, called Transition radiation.

Детектори на Големия адронен ускорител на насрещни снопове



- Ускорител на заредени частици - в нашия случай протони
- Сблъскване на частици - енергия на взаимодействието:
 - $E = E(\text{сноп 1}) + E(\text{сноп 2})$
- Най-висока енергия на сблъсъците на LHC досега:
 - $E = 13 \text{ [TeV]} = 2 \times 6.5 \text{ [TeV]}$ (2015 - 2018 г.)
- Проектна енергия на LHC:
 - $E = 14 \text{ TeV}$

- Връзка (превръщане) между енергия и маса: $E = mc^2$
- При сблъсъка на сноповете от протони се раждат много нови частици.
- По-тежките частици са нестабилни и се разпадат бързо до по-леки частици, които можем да измерим.



Експериментът CMS

Експериментът CMS (Run1&2) (Компактен мюонен соленоид)

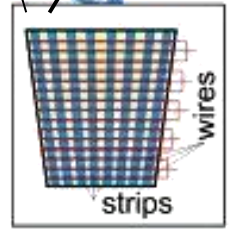
Соленоидален магнит
Суперпроводяща намотка
Магнитно поле:
3.8 Т във вътрешността,
затворена от магнита
~1.8 Т извън магнита

Електромагнитен
калориметър
Кристали от оловен
волфрамат

Адронен калориметър -
тип сандвич
Стомана(в централната част)
или месинг(в затварящите части)
и пластмасови сцинтилатори

Железен хамут на
детектора;
През него се затварят
магнитните силови линии.

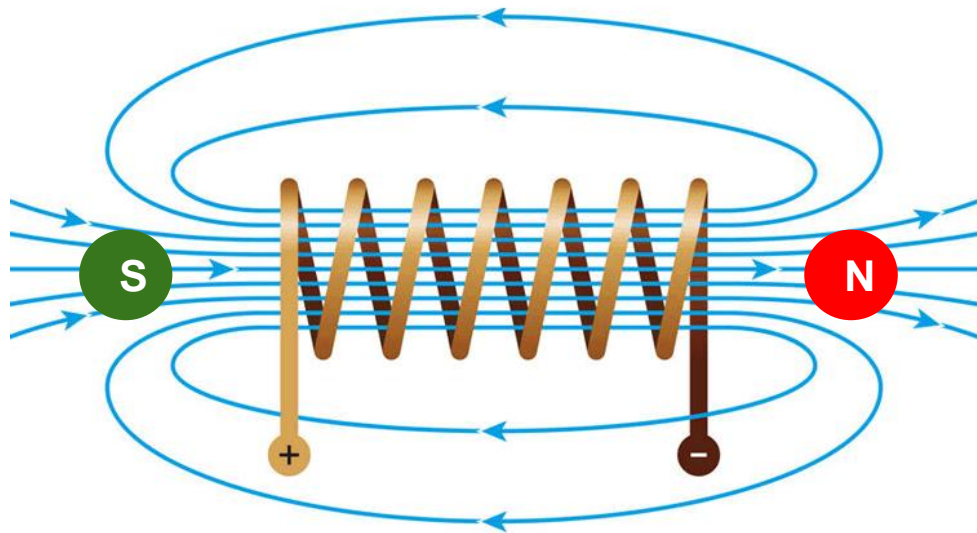
Вътрешен треков детектор – две основни
системи:
Силициев пикселов детектор
Силициев микрострипов детектор



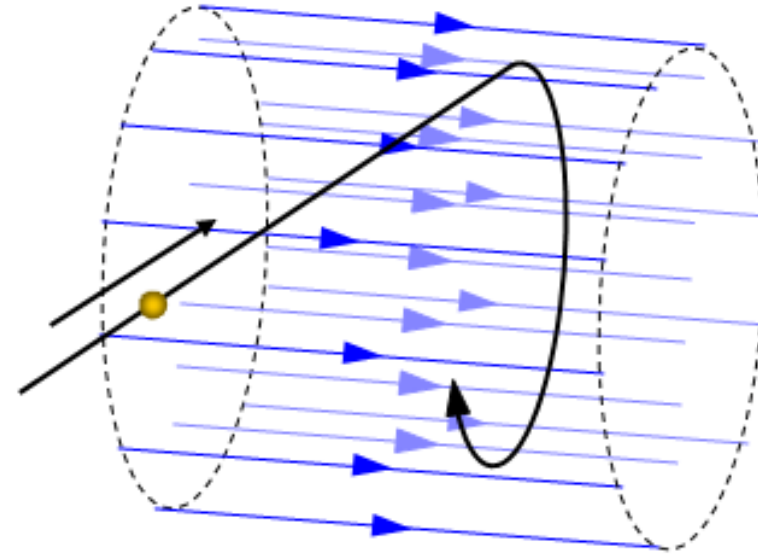
Мюонна система –
затварящи части:
Катодни стрипови
камери (CSC)
Камери със
съпротивителна
плоскост (RPC)

Тегло 12.5 t
Диаметър 15 m
Дължина 21.6 m

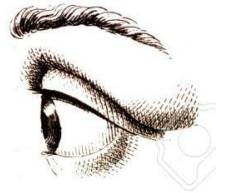
Движение на заредена частица в магнитно поле



Соленоидално магнитно поле



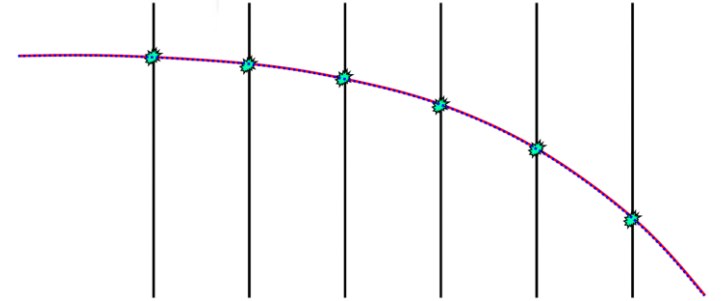
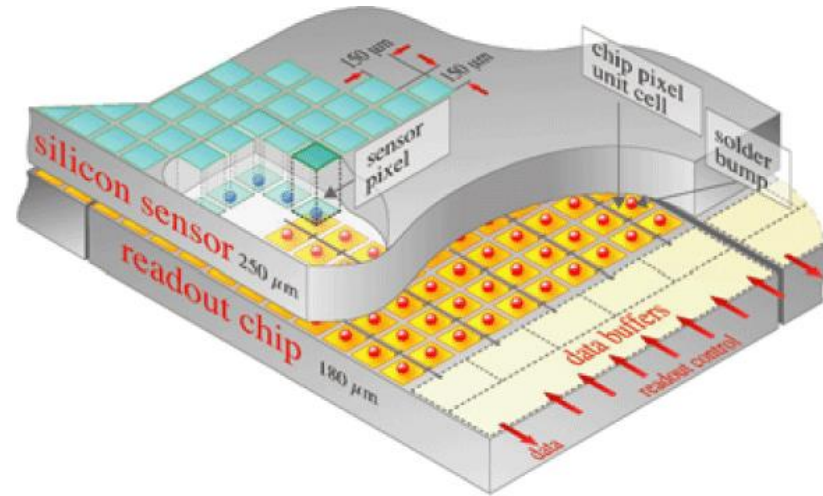
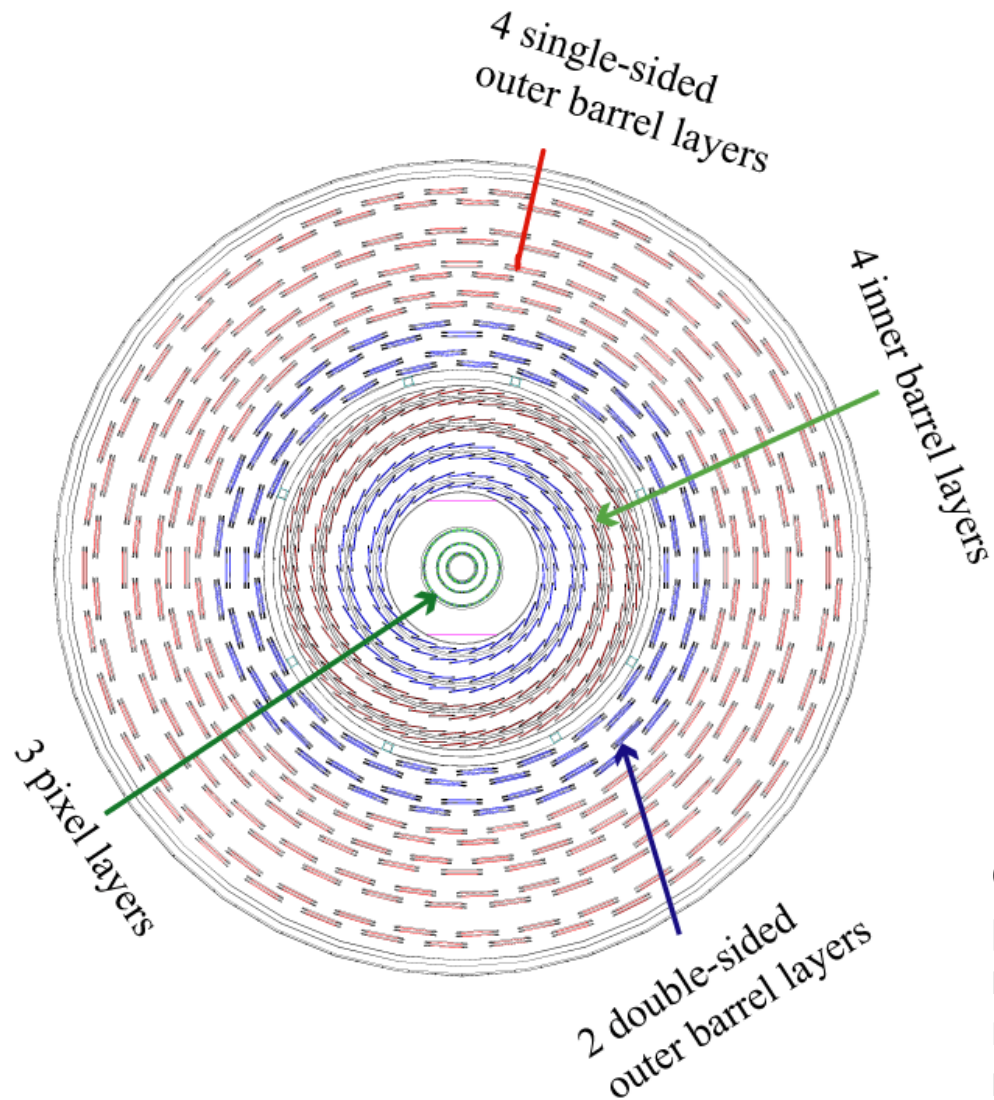
Траекторията на заредена частица се закривява в магнитно поле.



Ако гледаме срещу посоката на магнитното поле, положително заредените частици ще се отклоняват по посока на часовниковата стрелка, а отрицателно заредените в обратна посока.

В приложението iSpyWebGl, посоката на магнитното поле във вътрешността на магнита е по посока на оста Z. В основния ху изглед, оста z е насочена към наблюдателя.

Определяне на импулс и заряд - Вътрешен треков детектор



Сигналите от вътрешния треков детектор, позволяват да се реконструират техните траектории. Големината на закривяване на техните траектории позволяват определянето на техния импулс по формулата $r \sim p/B$, където r [m] е радиусът на кривината, p [GeV/c] – импулсът на електрона, а B [T] е магнитното поле.

Определяне на импулс и заряд - Вътрешен треков детектор



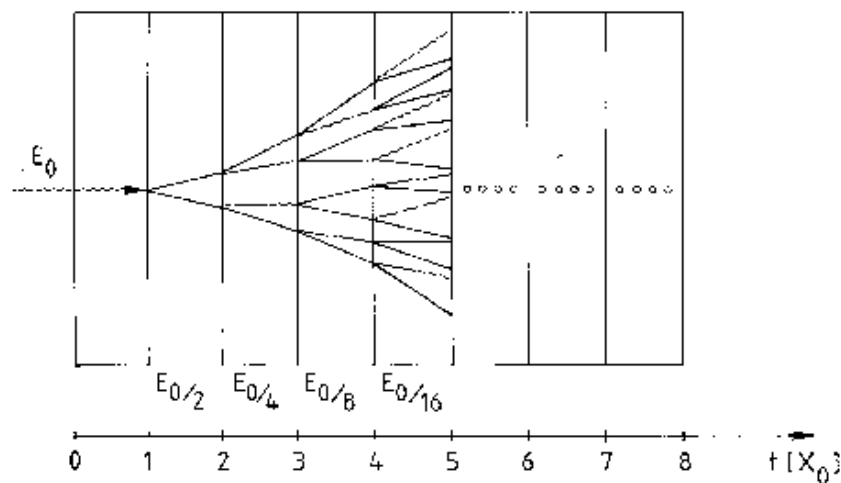
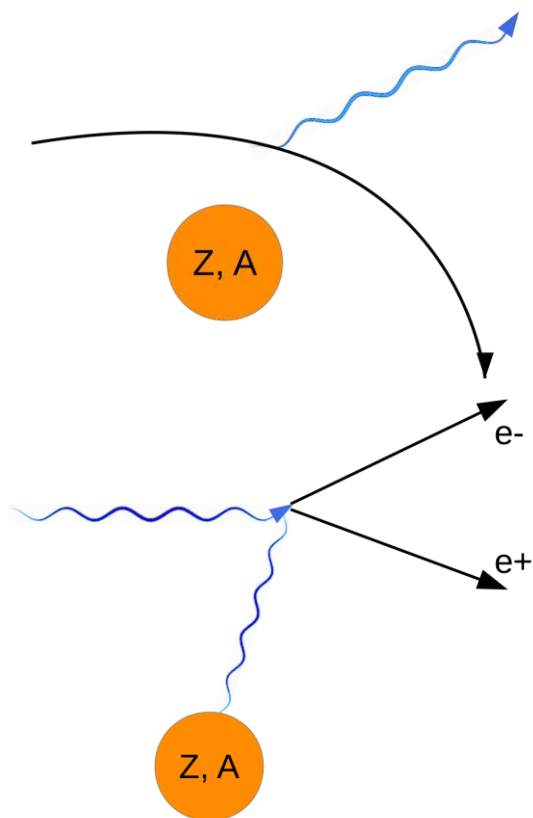
Измерване на енергия - калориметрична система

Детектиране на електрони, позитрони и фотони

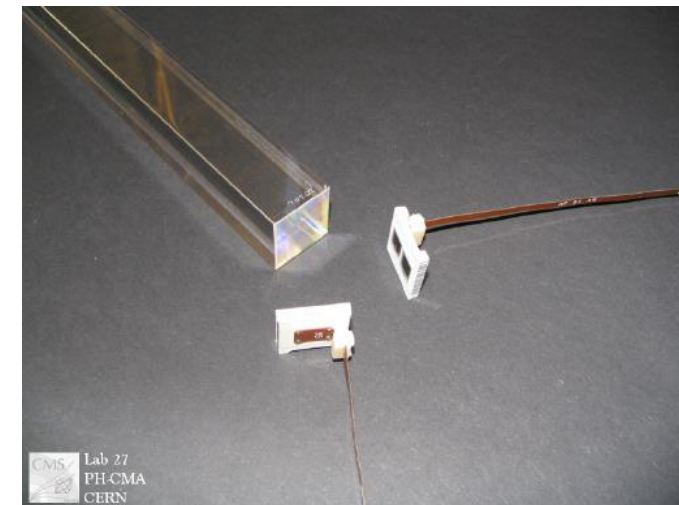
Електромагнитна лавина във вещество

Два процеса на загуба на енергия в плътна среда за e^\pm с $E > 1 \text{ GeV}$ или фотони:

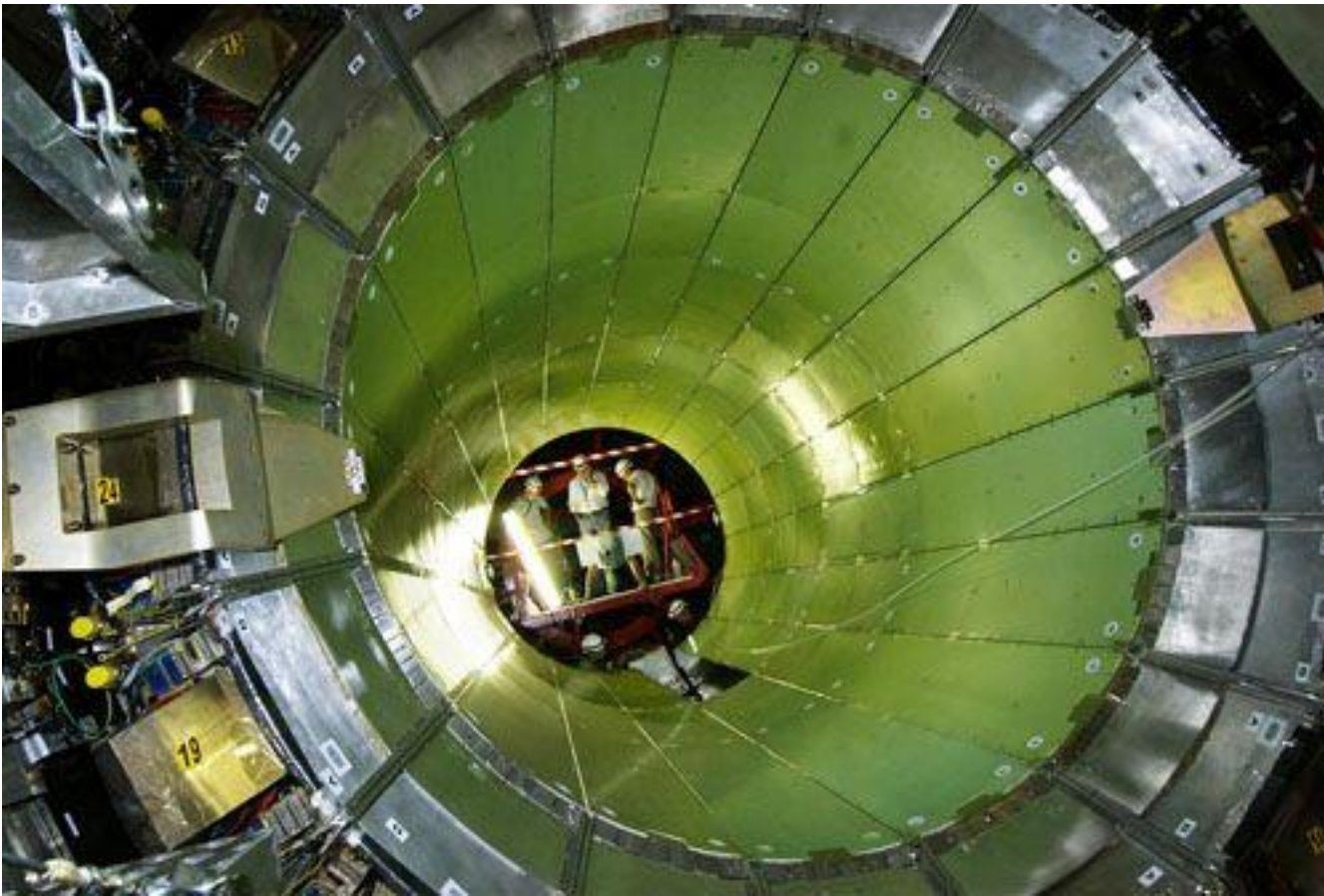
- излъчване на фотон от заредена частица (примерно e^+ или e^-) при движение в полето на ядро от средата
- раждане на e^+e^- двойки от фотон, в полето на ядро от средата



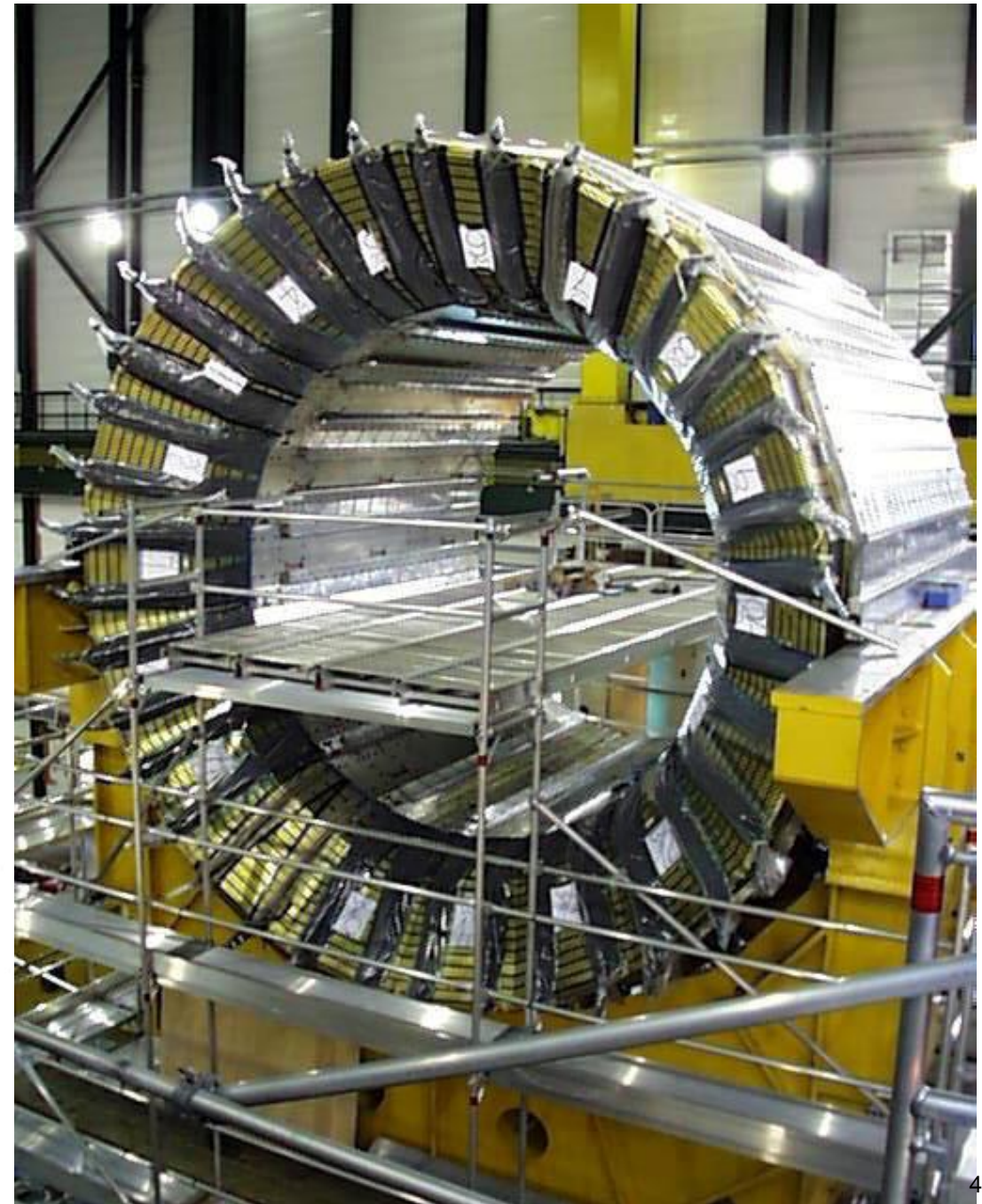
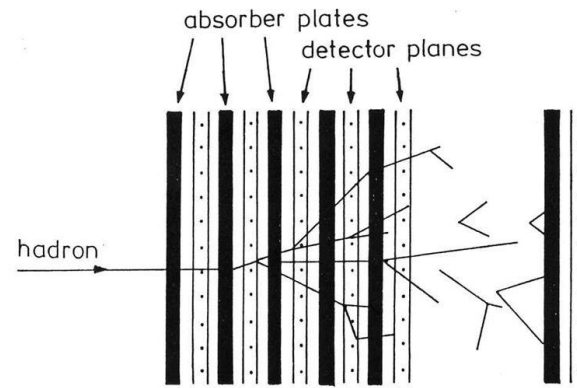
Енергията на частицата, инициирала лавината е пропорционална на броя изсветени фотони

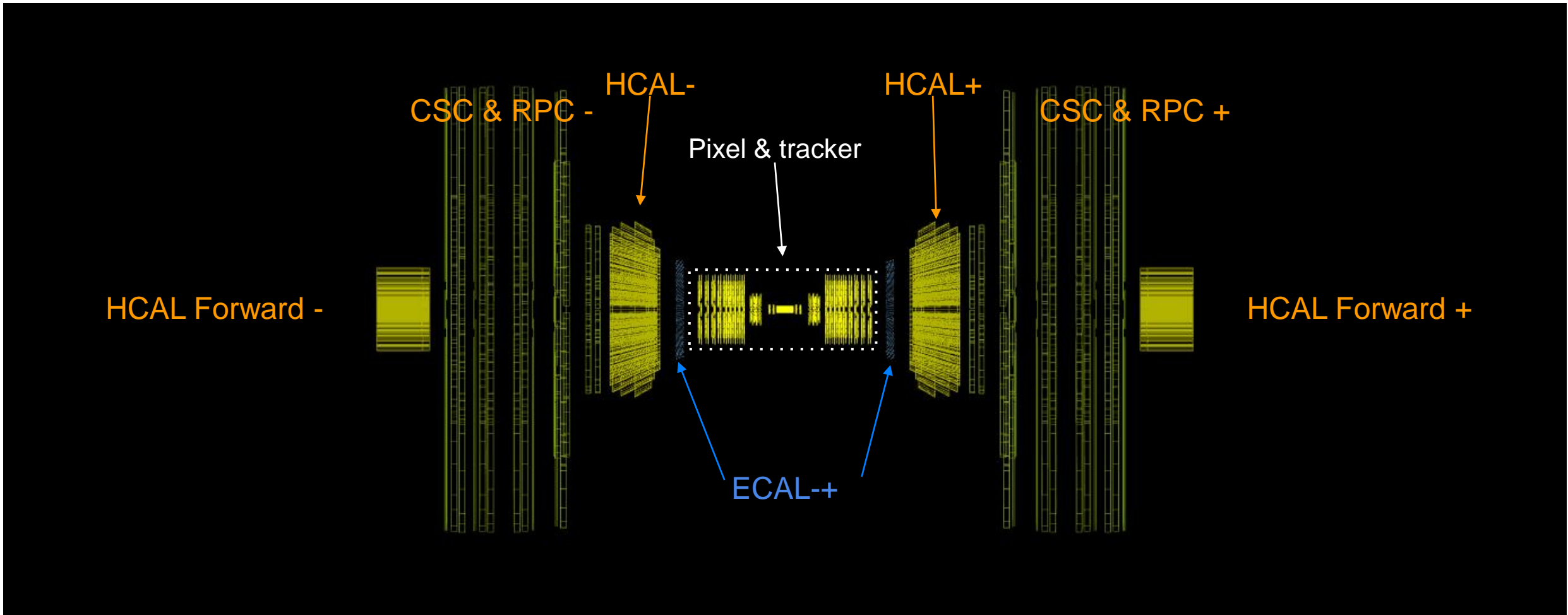


Кристал от оловен волфрамат и лавинни фотодиоди, използвани в ECAL на CMS



*ECAL - електромагнитен калориметър на CMS (в ляво)
 HCAL - адронен калориметър на CMS (в дясно)*

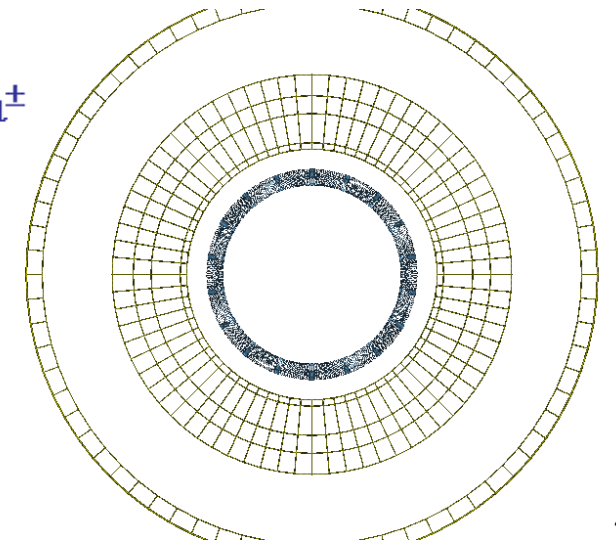
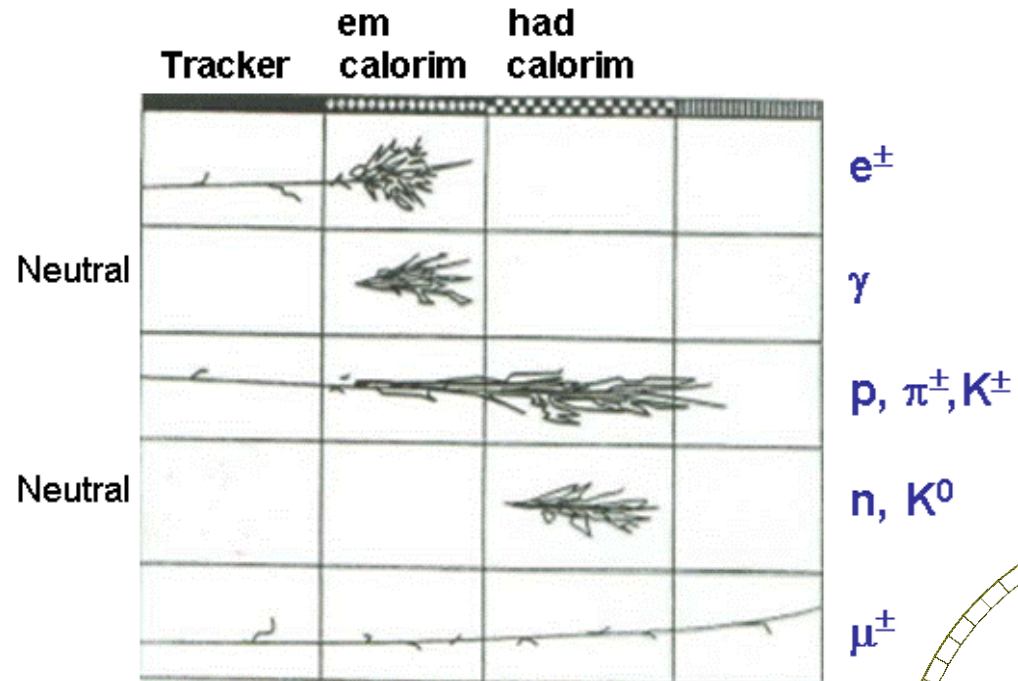
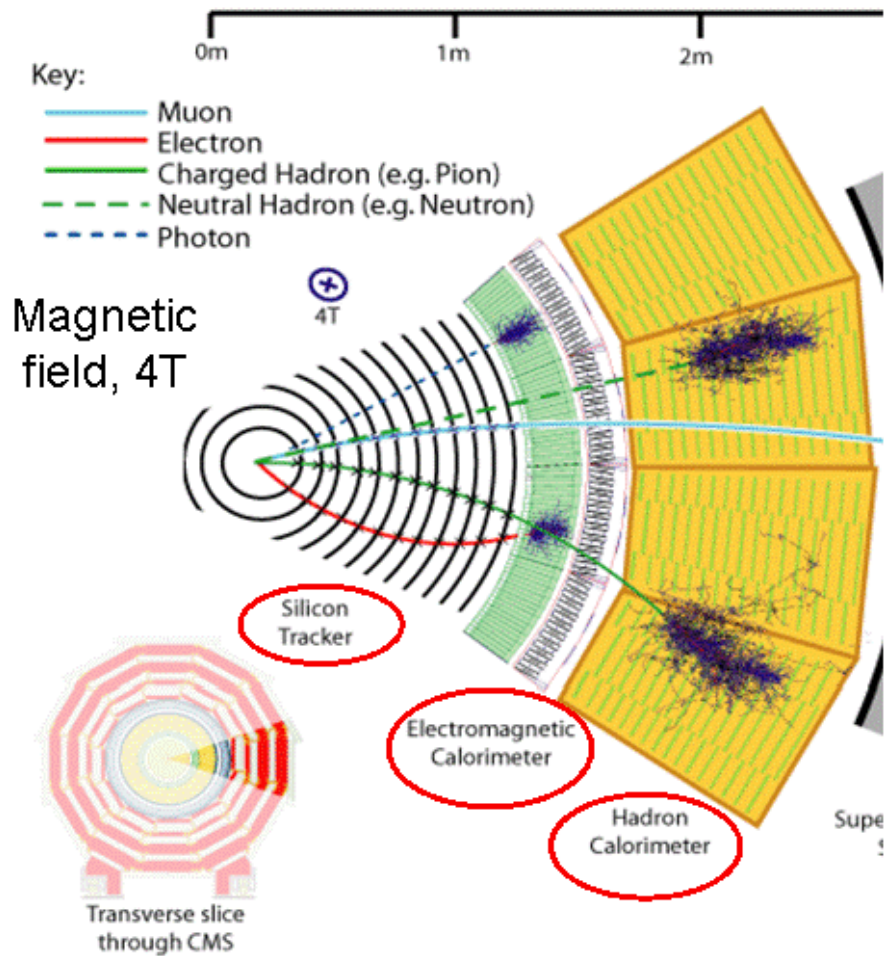




Забележка: не са показани всички детекторни слоеве, за да не се претрупва фигурата.

Калориметрична система

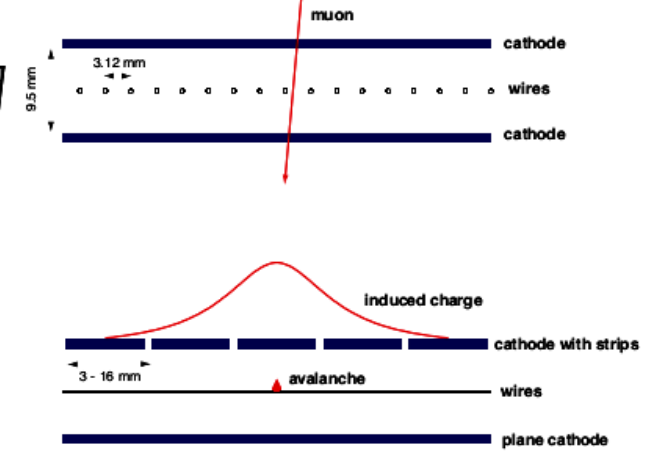
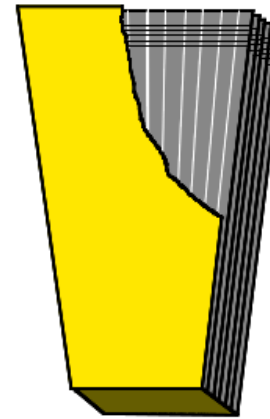
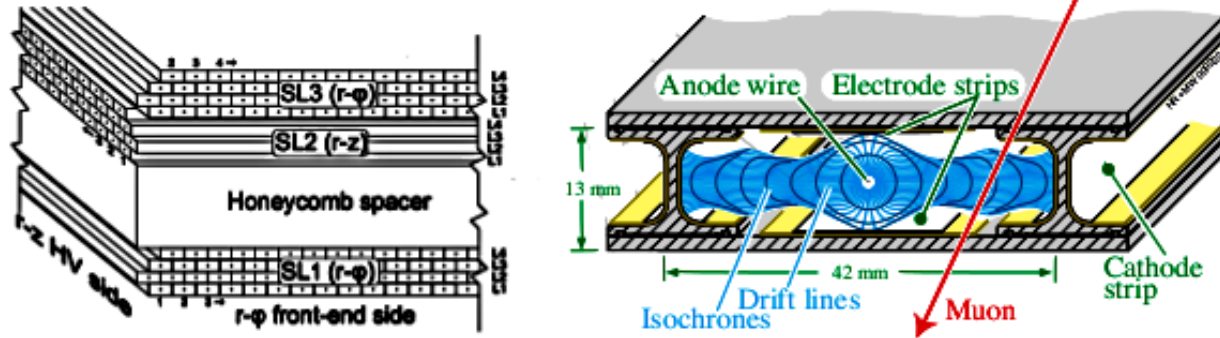
електромагнитен (ECAL) и адронен калориметър (HCAL)



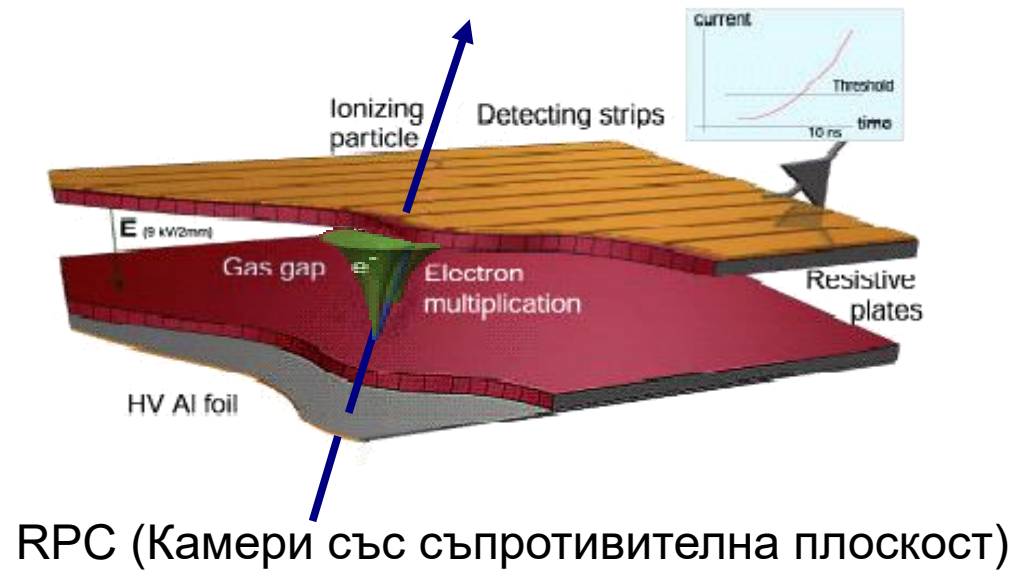
Мюонна система на CMS (Run1 & Run2)

Мюонна система на CMS (Run1 & Run2)

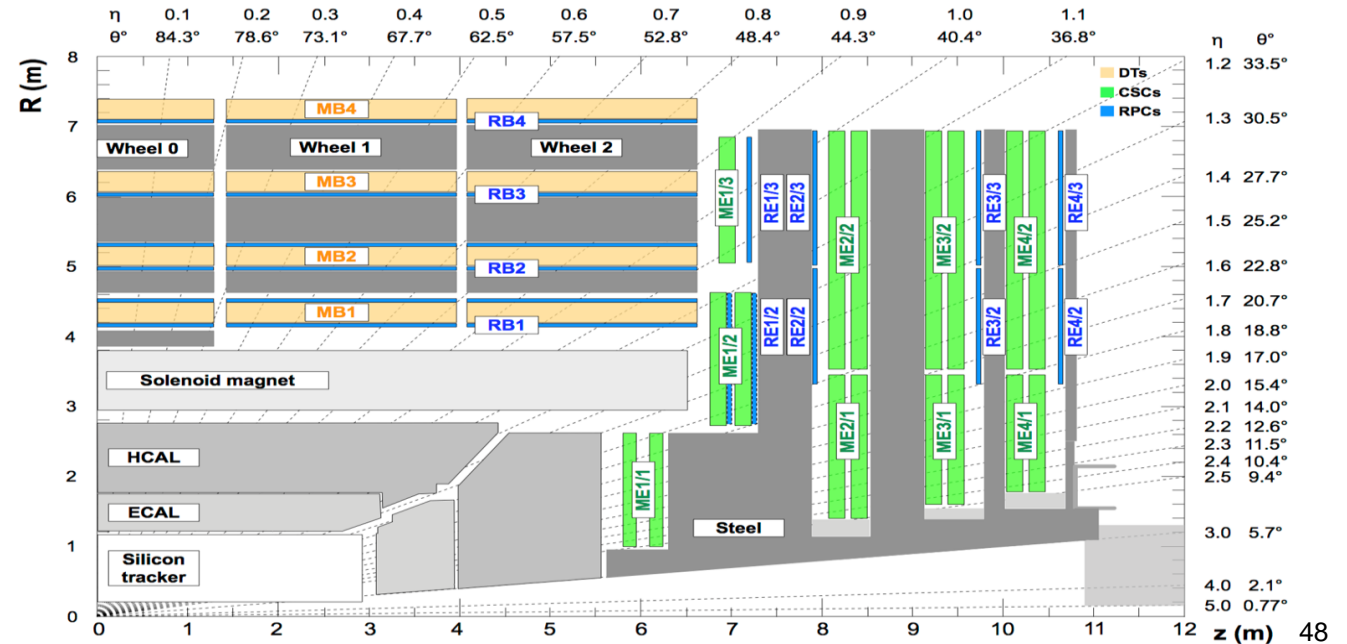
DT (Камери с дрейфови тръби)



CSC (Катодно стрипови камери)

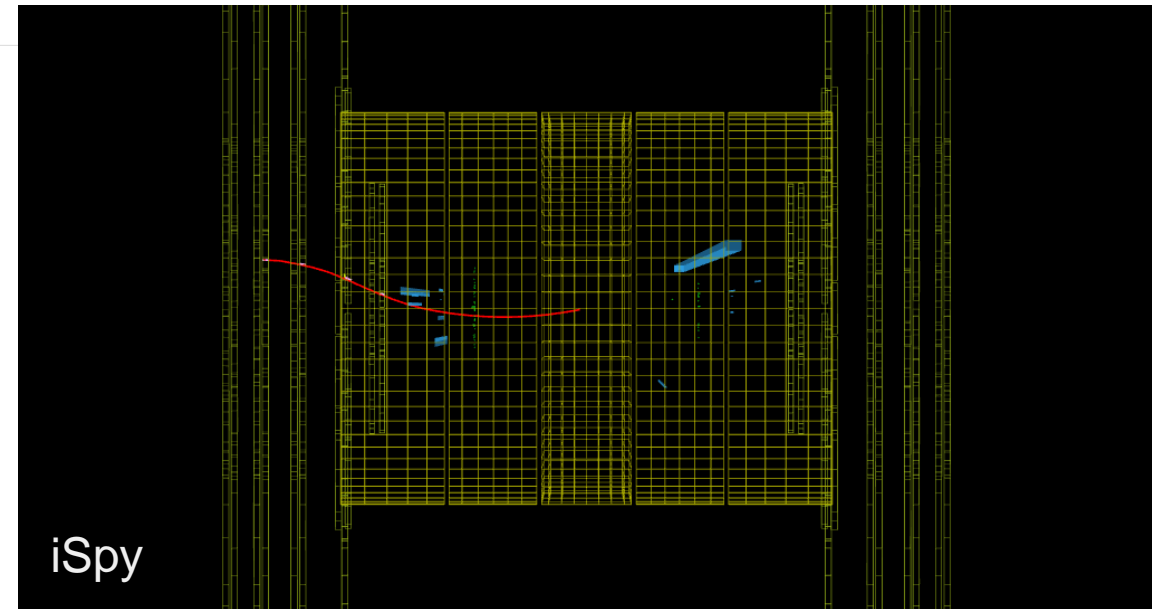
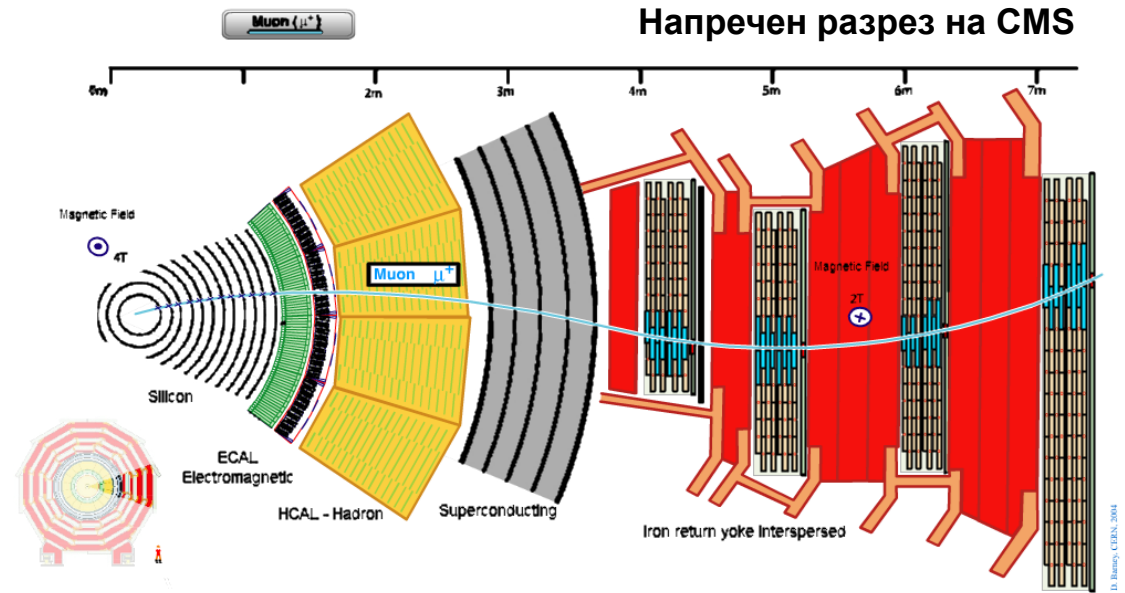


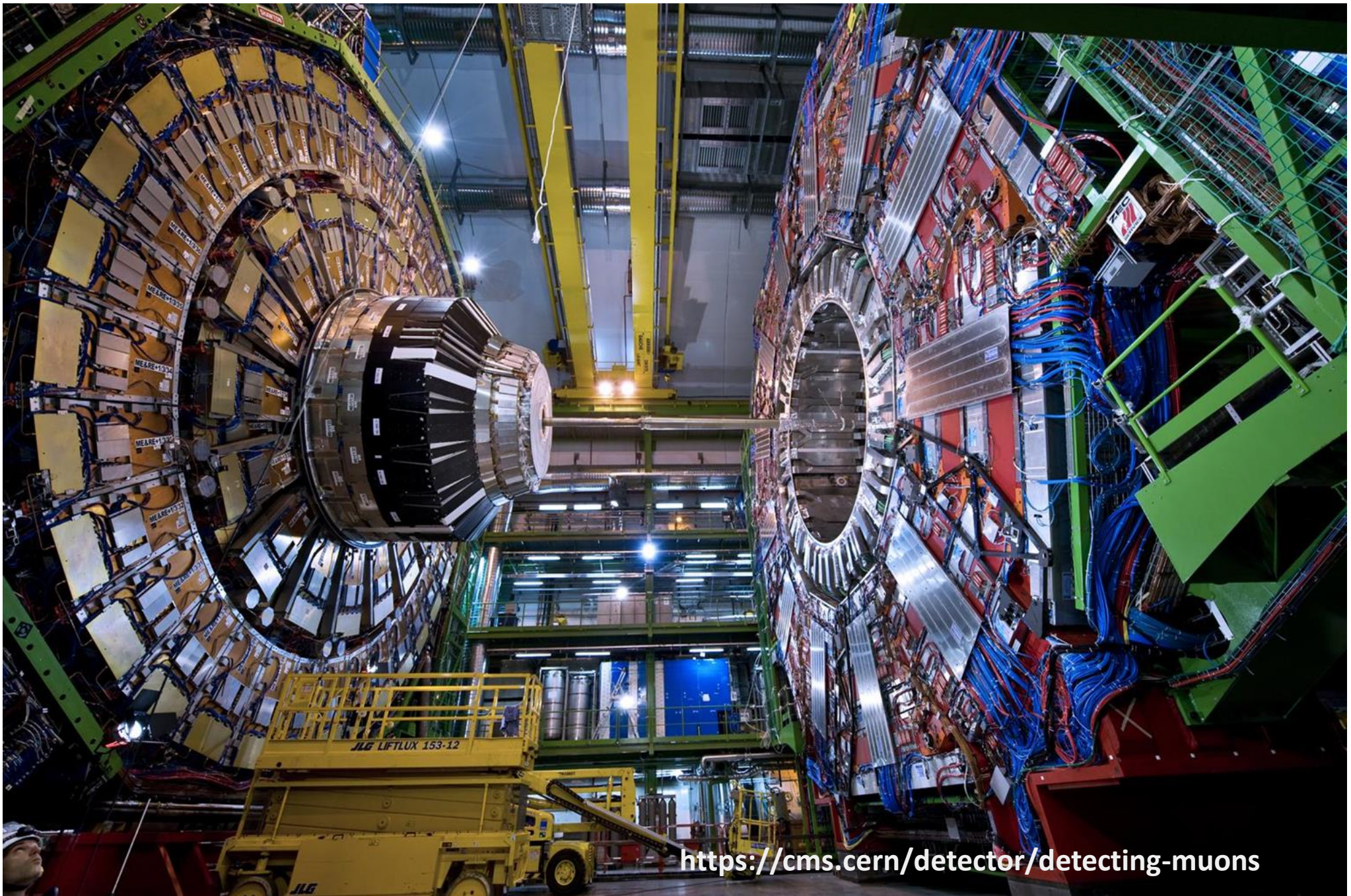
RPC (Камери със съпротивителна плоскост)



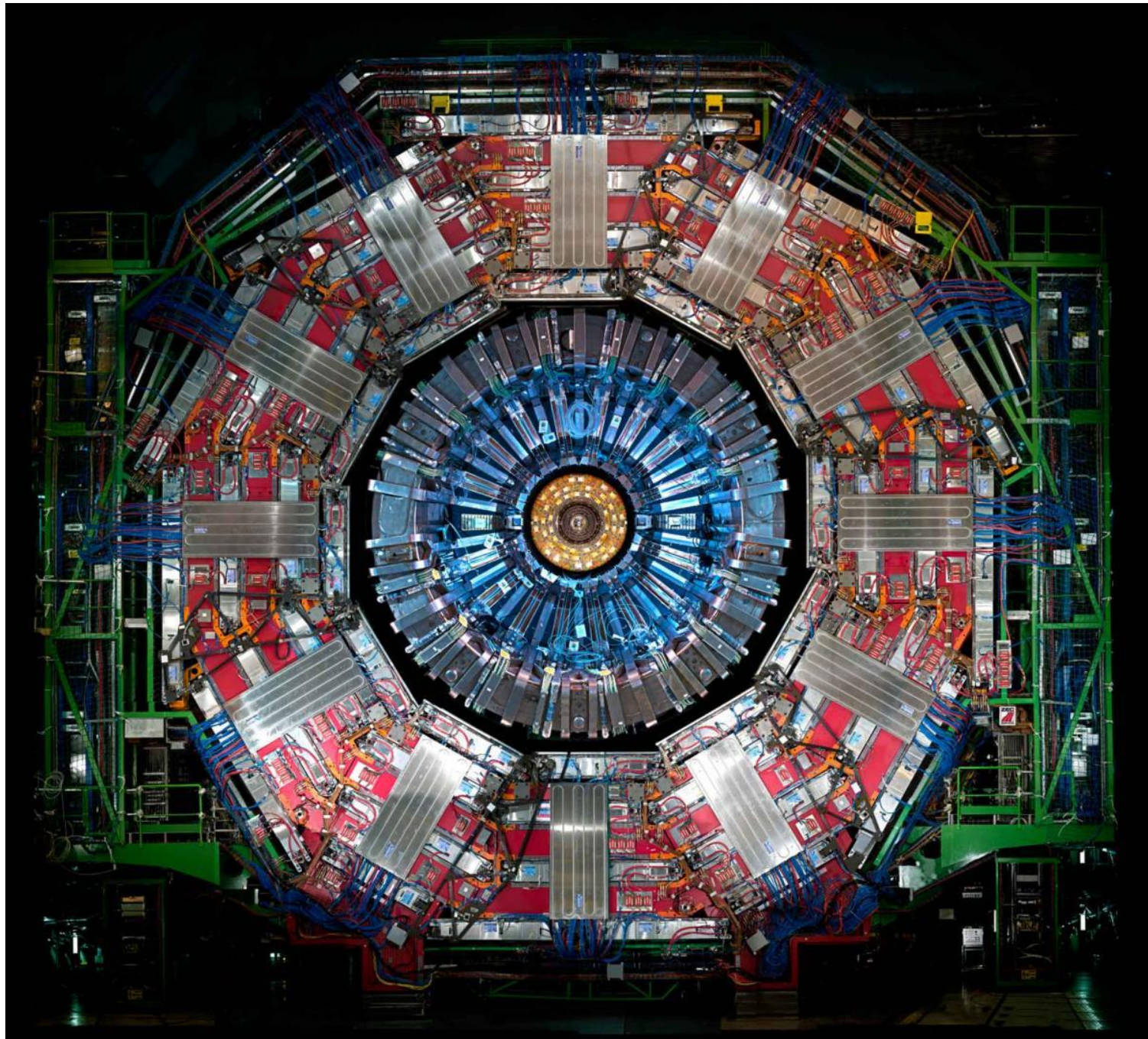
Регистриране на мюон

- Сигнали във вътрешния треков детектор и в мюонните камери;
- Почти не се наблюдават взаимодействия в калориметричната система;
- Имат електрически заряд и техните траектории се изкривяват в магнитното поле - измерване на импулс и определяне на заряд;
- Голяма проникваща способност, преминават през магнита и целия детектор;
- Раждат се в резултат от разпадането на по-тежки частици и носят информация за случването на интересни събития – примерно раждане и разпад на Хигс бозон.

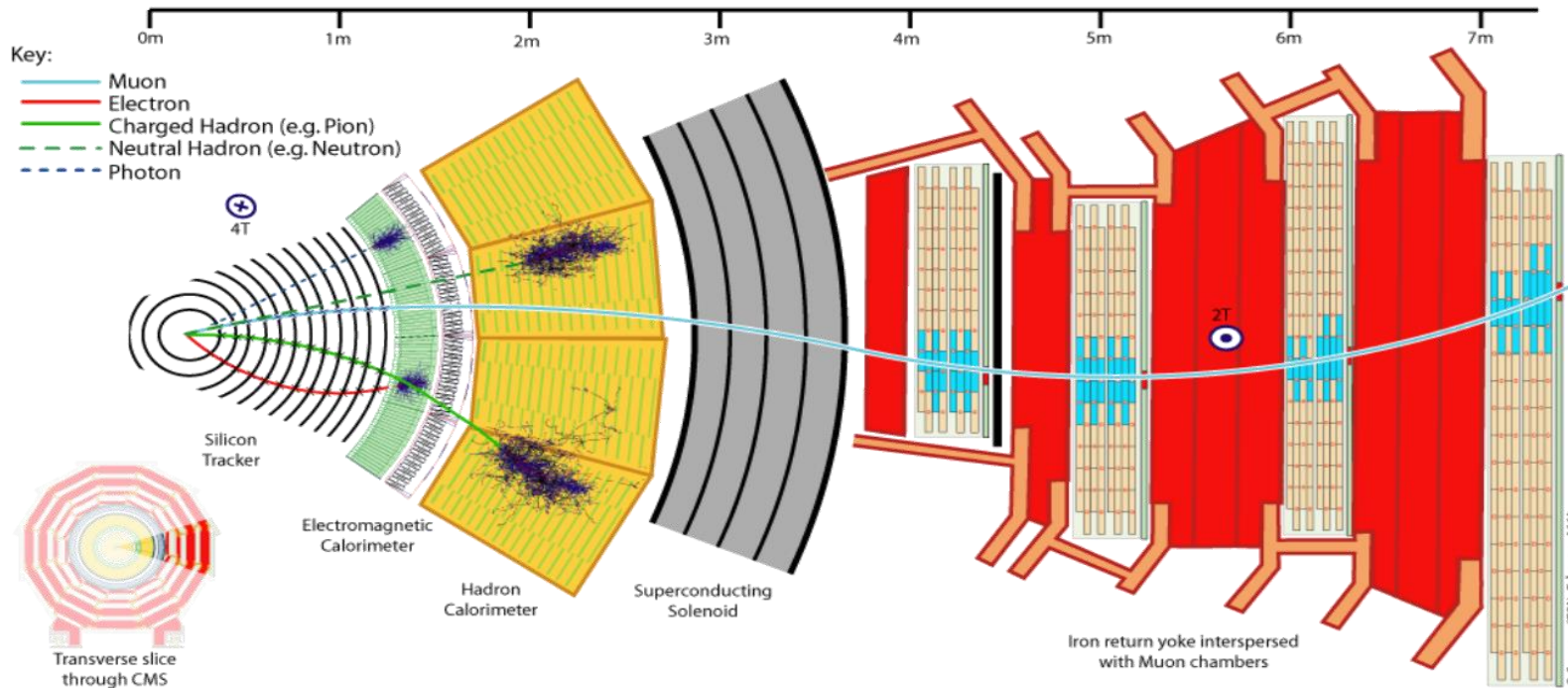




<https://cms.cern/detector/detecting-muons>



Как се регистрира частици със CMS



- Силициев детектор:
 - Регистрира попадения на електрически зарядени частици.
- Електромагнитен калориметър:
 - Регистрира електрони, позитрони и фотони
 - Те отлагат пълната си енергия в него
- Адронен калориметър
 - Регистрира адрони, които отлагат пълната си енергия в него

- Мюонна система:
 - Регистрира електрически зарядени частици, преминали през всички останали системи и магнита.
 - Ние предполагаваме, че такива могат да бъдат само мюоните.

Комбиниране информацията от отделните детекторни системи!

Липсваща енергия

- Частици, които не могат да бъдат регистрирани с нашия детектор
 - Неутрино - трябва ни много по-голям детектор
 - Частици, които не познаваме
- Но ние може да направим оценка какво количество енергия или импулс са отнесли тези частици!

Величината, който ще използваме в нашия анализ се нарича **Missing Energy** и съдържа в себе си сумата от енергиите, отнесени от всички частици, които не сме успели да регистрираме и измерим.

А също и информация за посоката, в която е отнесена тази енергия.

- Забележете, липсващата енергия може да е отнесена от повече от една частица!

Благодаря за вниманието!