Introduction to Detectors and Detector Readout

or
the ingredients of a particle physics experiment

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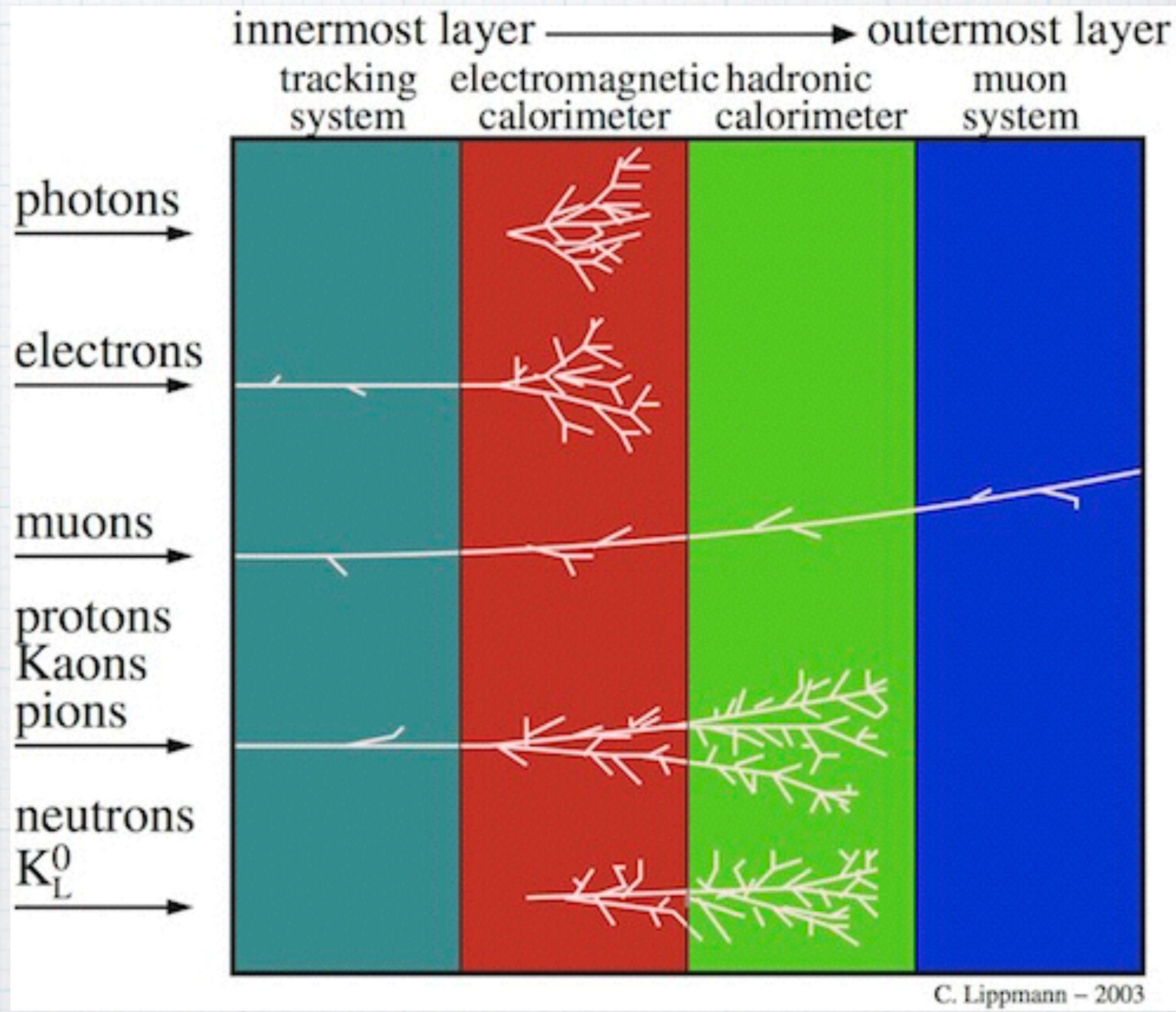
Rehovot - Israel

Lucas van Valckenborch, 1594, Louvre Museum

a failed experiment: babel tower

ingredients for a Particle Physics experiment

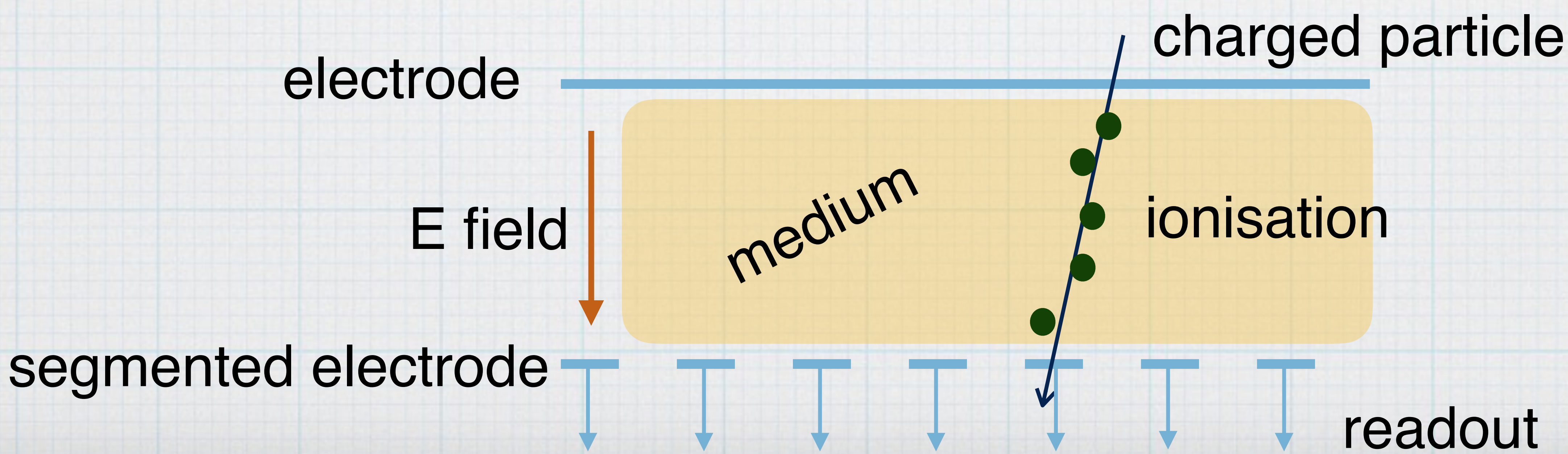
* Measure time
  * position, beam profile – tracking
  * Momentum, charge – spectrometer
* Measure Yes/No info
  * trigger, accept / veto
* Measure charge
  * Energy – calorimeter
* Readout Signals
  * buffer, digitize, multiplex
* Care for infrastructure
  * HV/LV PS, Gas and cables!



Tracking

* What happens?
  * Ionisation of a medium by a traversing particle.
    * medium: gas, semiconductor
  * HV (electric field) to transport charges to electrodes (few kV)
    * electrons move faster wrt ions (30-40 times)
  * Electrons accumulate on the electrodes

* How to read it out?
  * acquire signal from the segmented electrode to read position

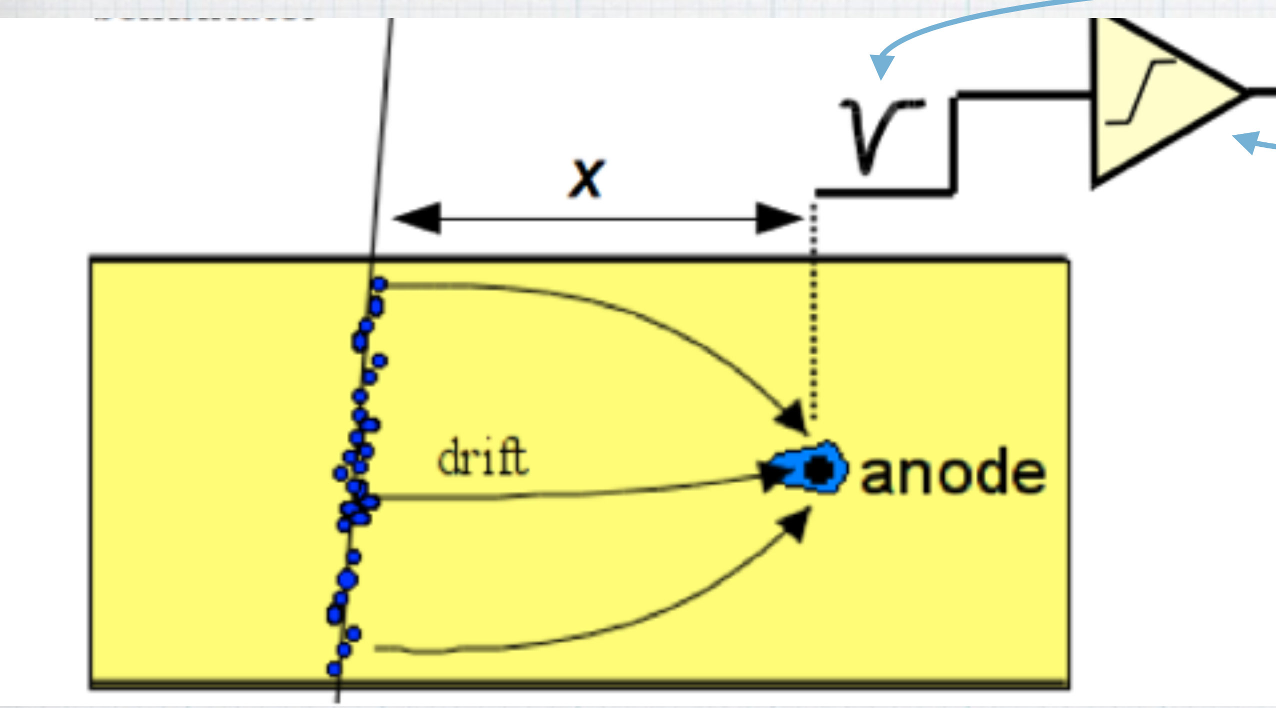


wire chamber as a tracker

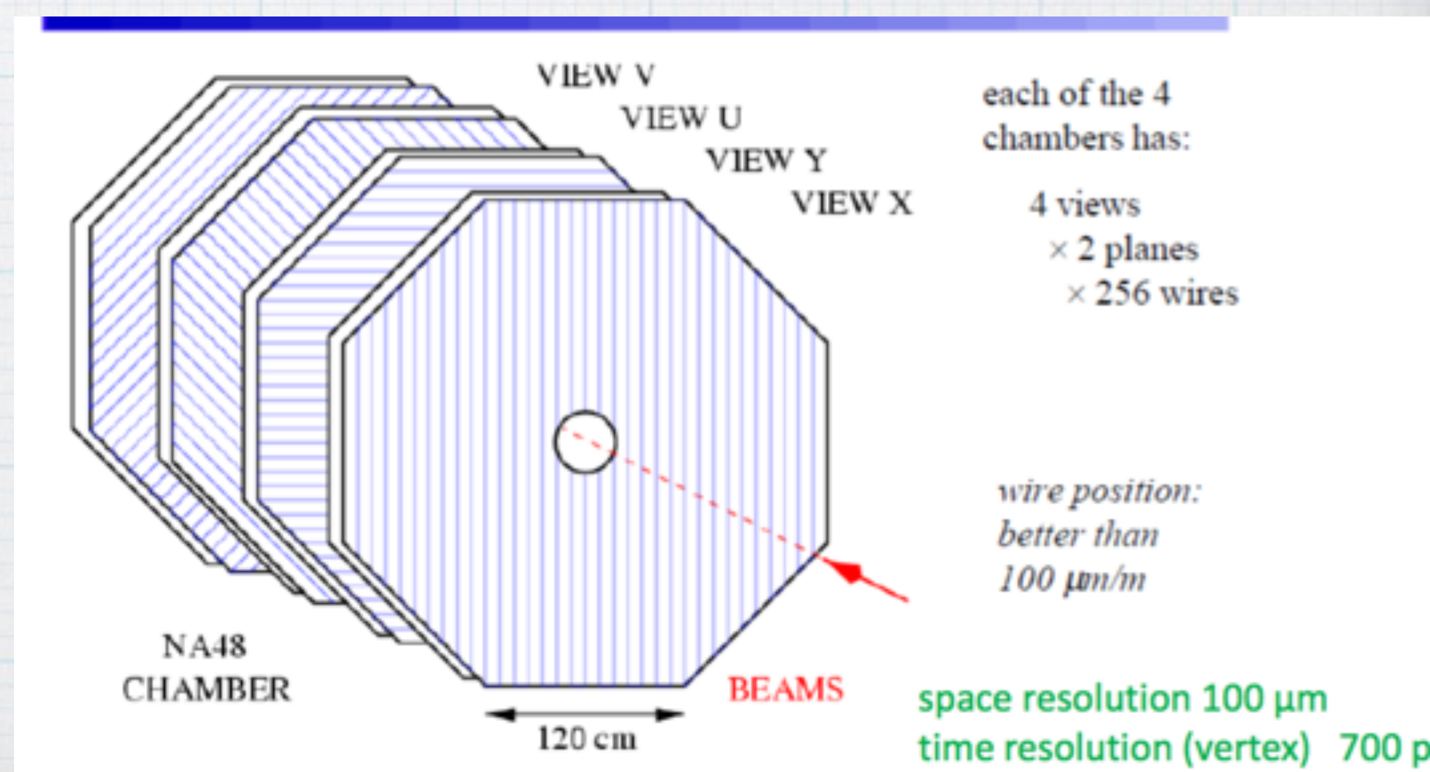
- Better positioning: electrode perpendicular to particle track
  - ➡ position: $x = c_0 + c_1\Delta t + c_2\Delta t^2 \ldots$
  - ➡ Δt: drift time of electrons to anode wire (under positive HV)
  - ➡ We need a Time to Digital Converter: TDC
- Space resolution: 80 — 200 µm
- "Low" mass detectors, can be big: 4m x 2m

typical signal shape.

need a discriminator to eliminate noise



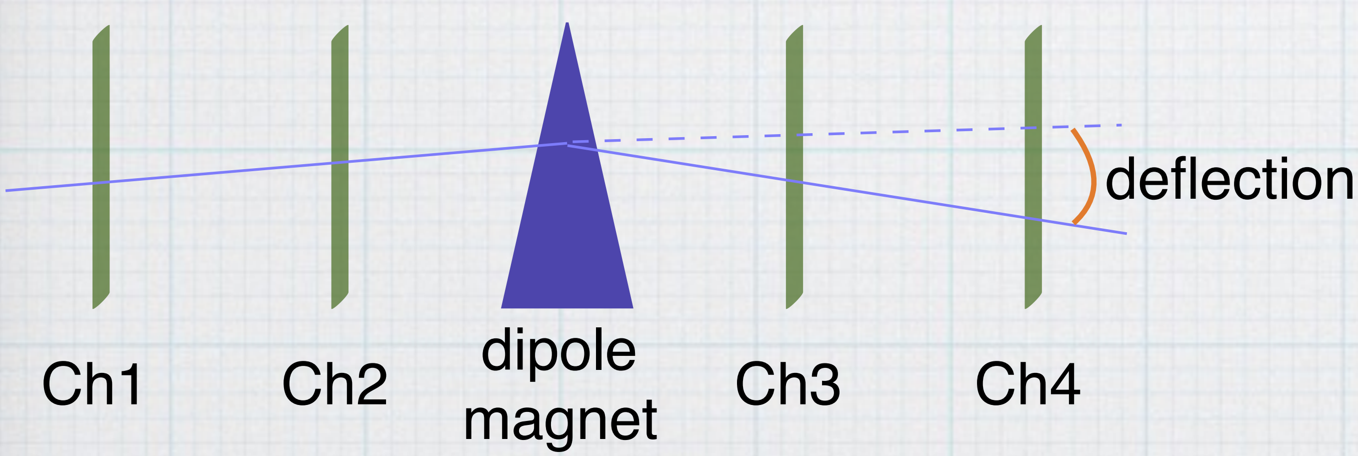
a "wire" chamber stationed at z(typically beam direction) with x-y planes to measure a point in space. u-v planes are often used for redundancy

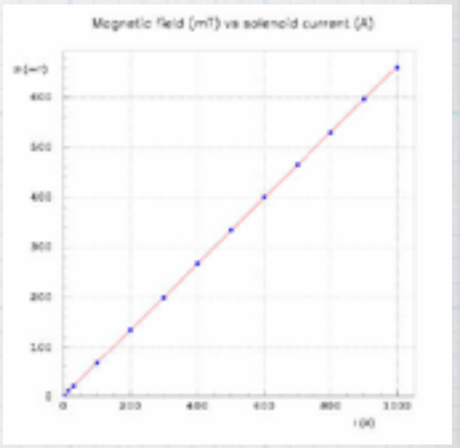


From tracker to spectrometer

* The principle: make the charged particle's track curve in a known magnetic field to find its
  * charge
  * momentum

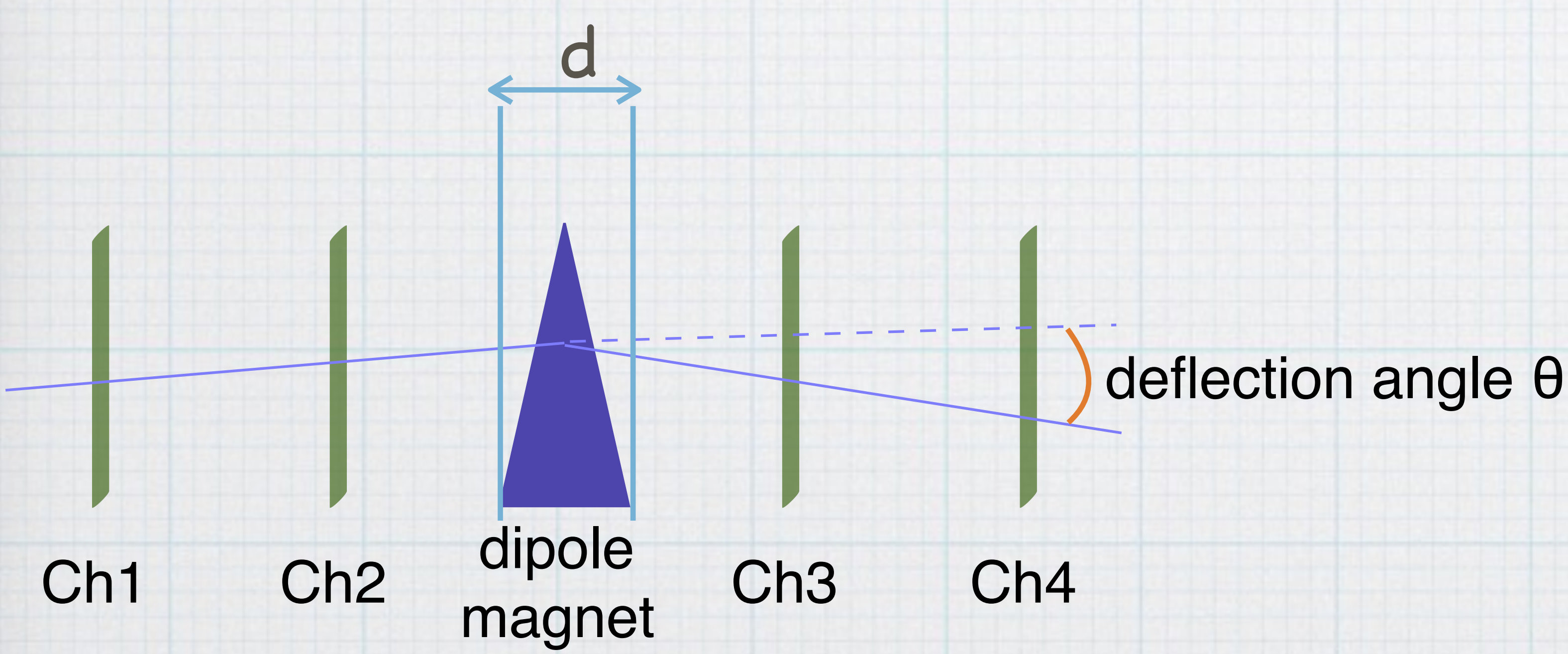
* In a fixed target experiment typically a dipole magnet is used. Bending power must be well known.

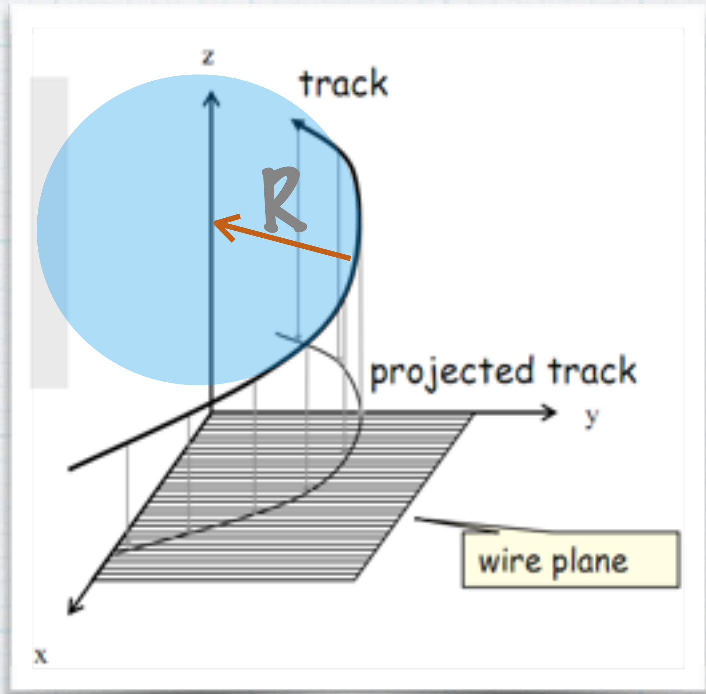




for a constant B field

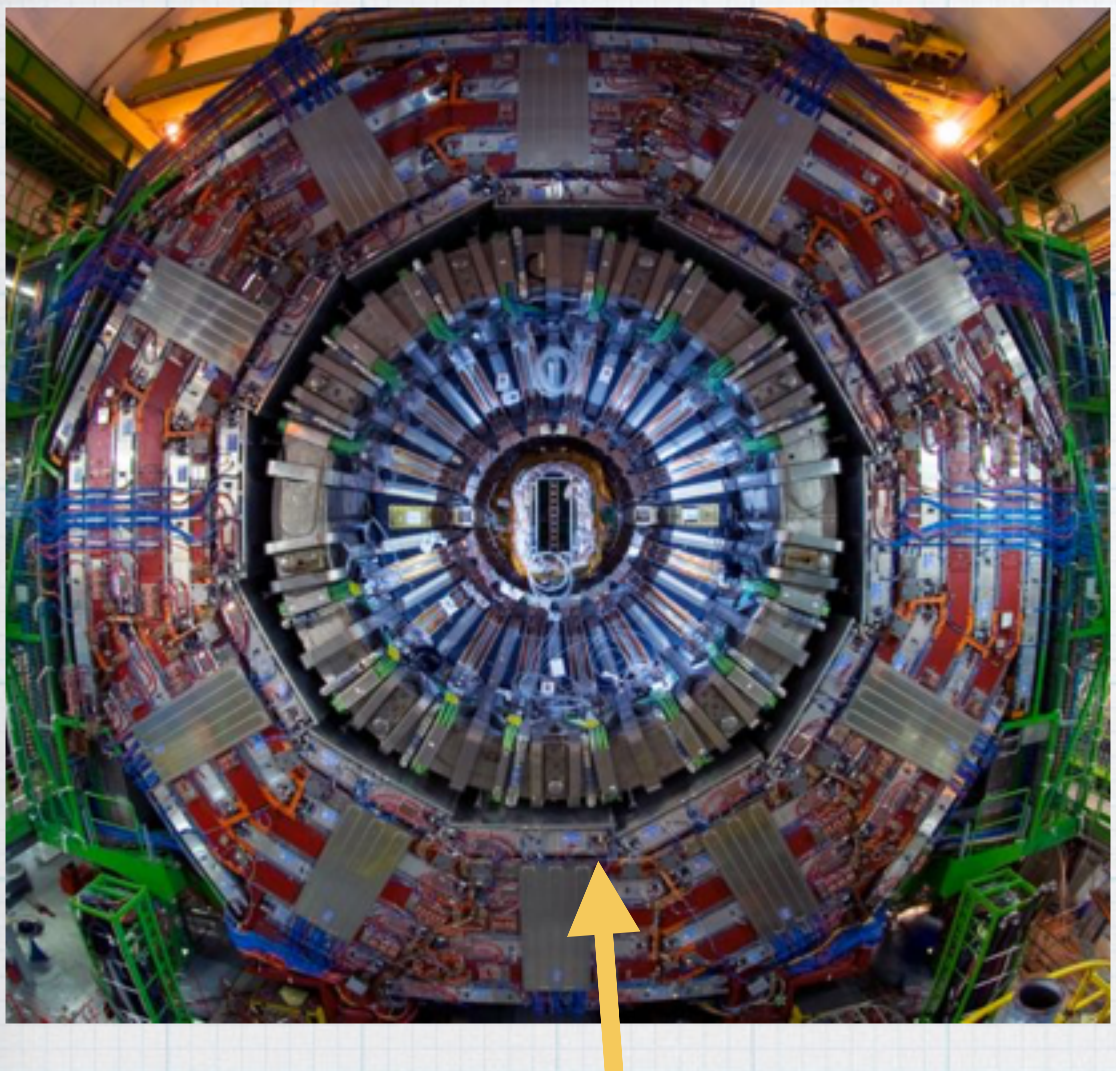
* measure deflection to find the momentum p perpendicular to the field
    * $p(GeV) = 0.3\ Z\ B(T)\ d(m) / [2 \sin(\theta/2)]$
    * $p(GeV) = 0.3\ Z\ B(T)\ R(m)$
    * where
        * Z: Particle Charge
        * d: Field length
        * θ: Deflection angle
        * R: Curvature Radius

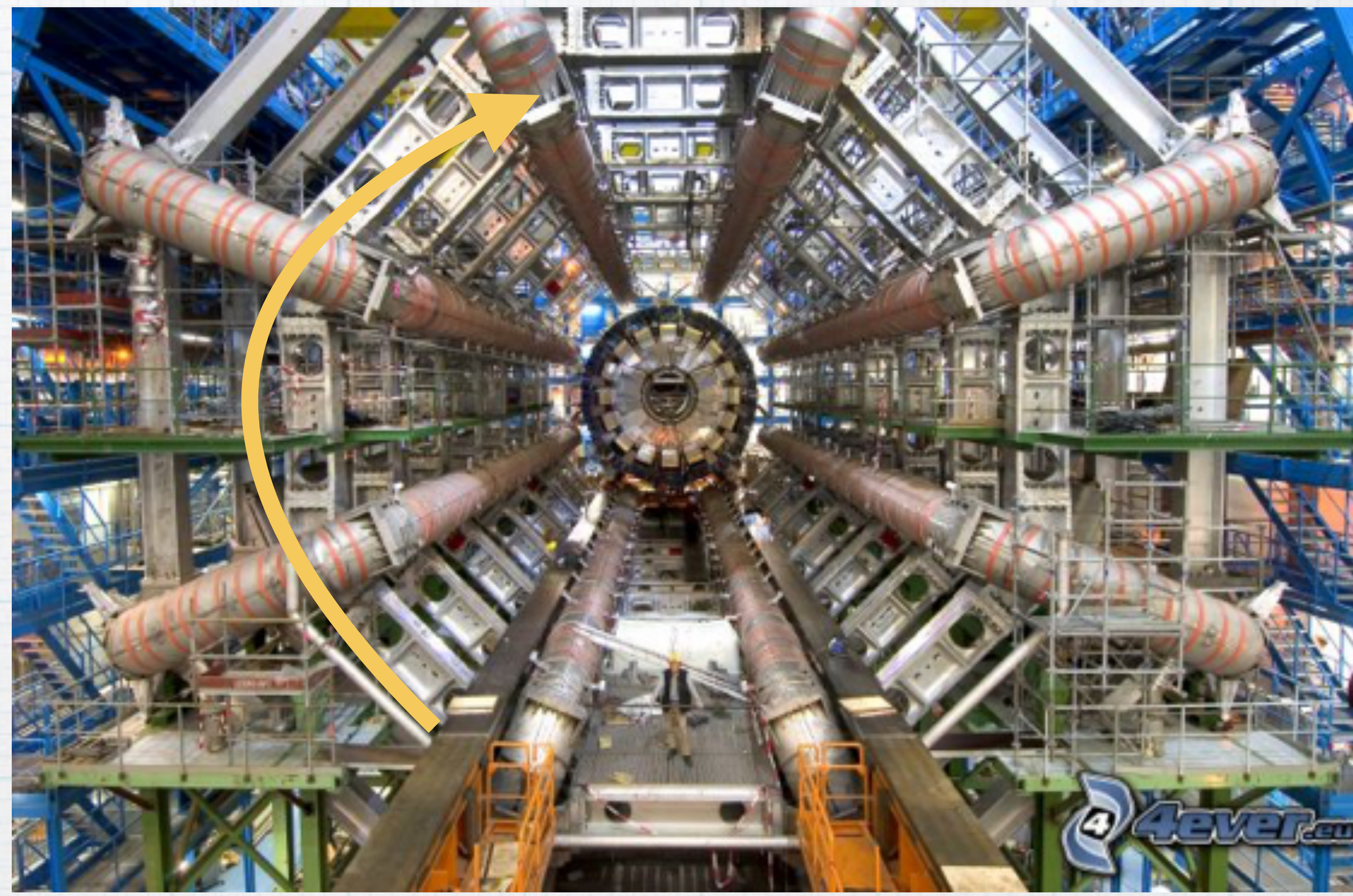




spectrometer for colliding beams

We use solenoid (CMS) and/or toroid (ATLAS) magnets

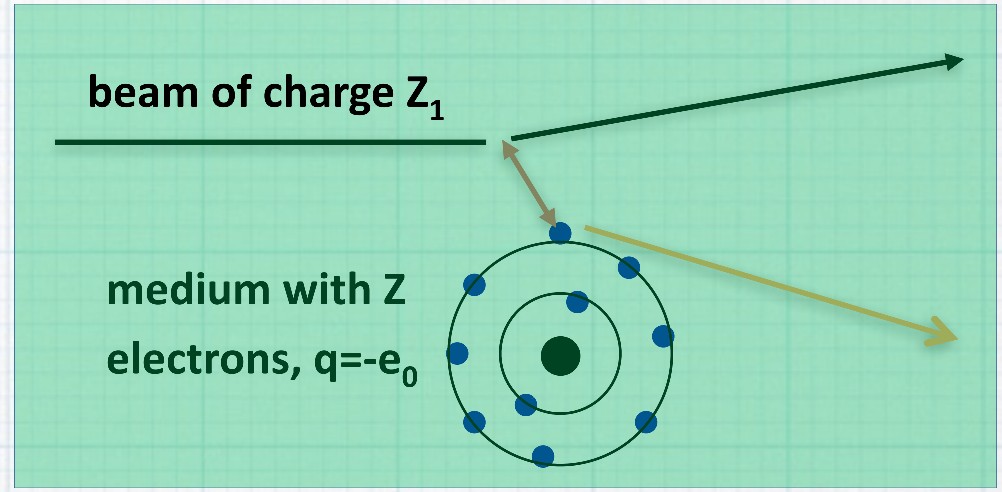


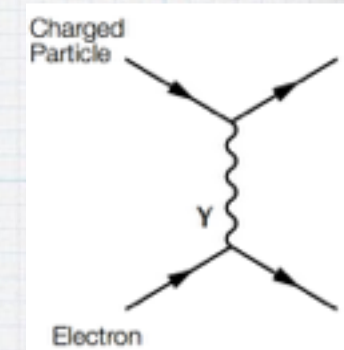


momentum resolution decreases with increasing particle momentum

what about signal height?

Energy loss by ionisation described by Bethe's formula in 1930s



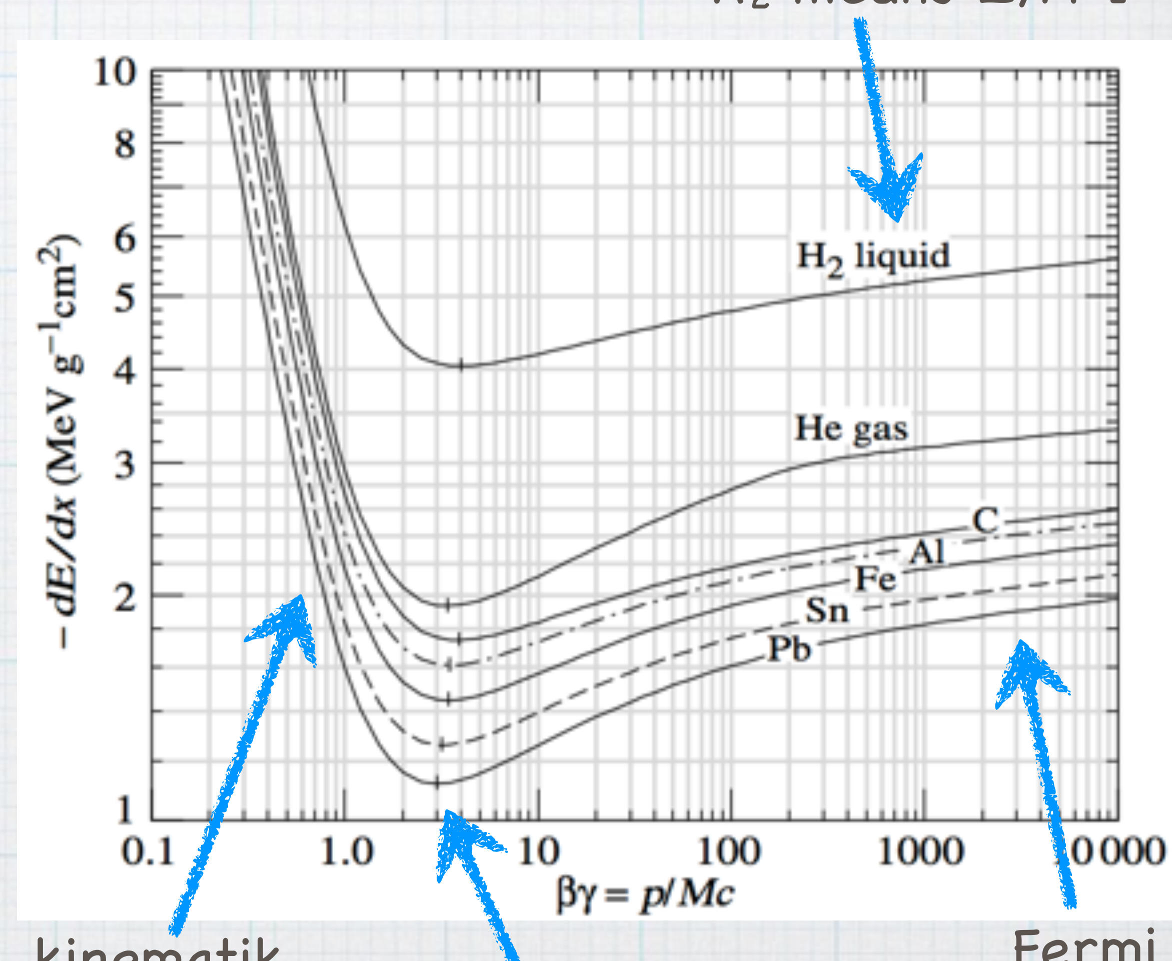


- <dE/dx>: mean energy loss per unit length of a particle which has
  - charge Z_1 and speed β
  - in a medium with atomic number Z and atomic mass A

$$\langle\frac{dE}{dx}\rangle = -4\pi r_e^2 m_e c^2 \frac{Z_1^2}{\beta^2} N_A \frac{Z}{A}$$
$$\times\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

- I = mean excitation energy of the medium
  T_{max} = maximum energy that can by transferred to the electrons of the medium
  δ(βγ) = polarization function of the medium

H_2 means Z/A=1



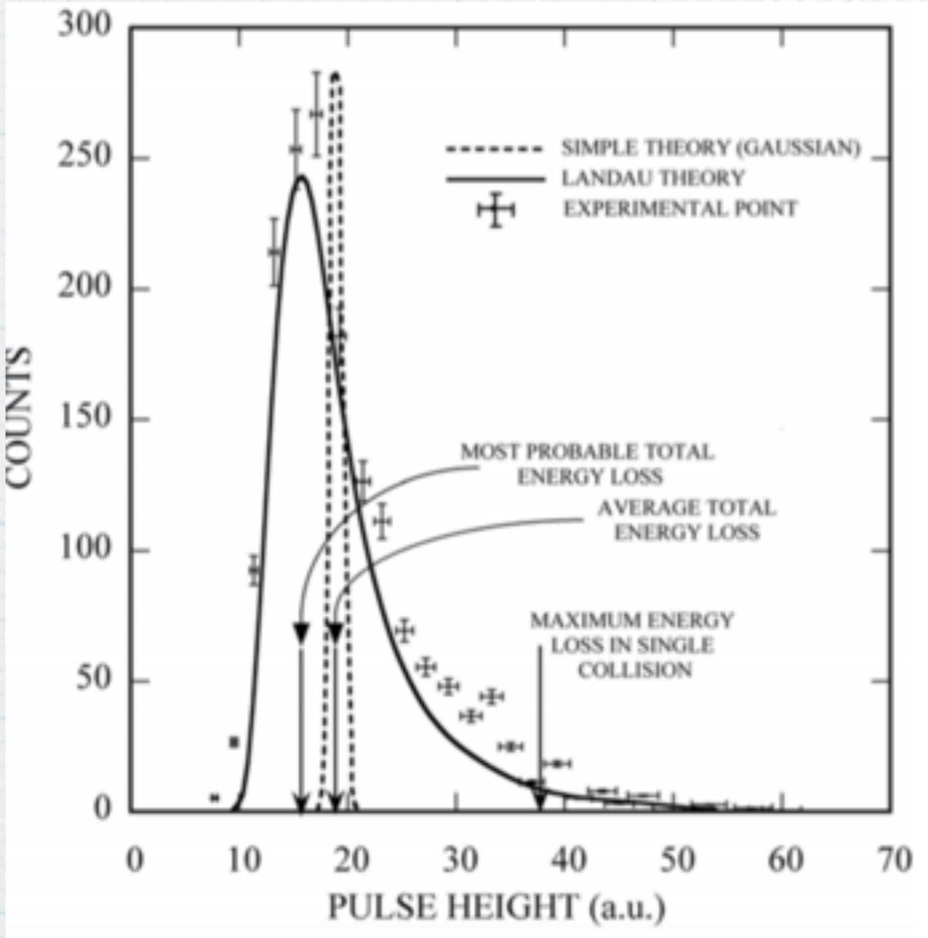
kinematik terim: $\langle dE/dX\rangle \propto \beta^{-2}$

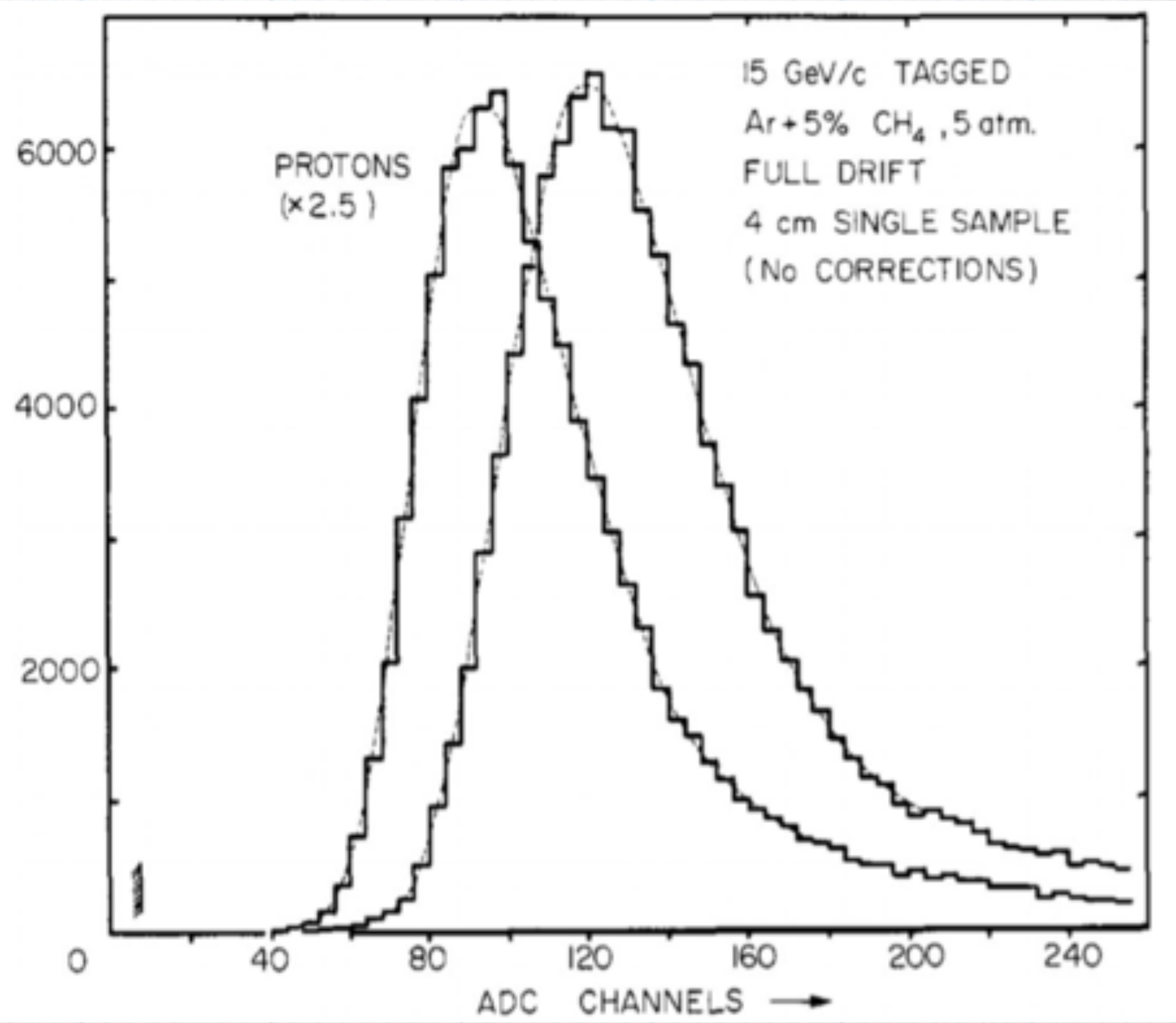
$\beta\gamma \approx$ 3-4 : minimum ionisation.

Fermi plateau

Bethe formula gives the average energy loss. Average, Most Probable Value and Shape Distributions define what happens in real life.

pulse shape can be calculated by Landau theory





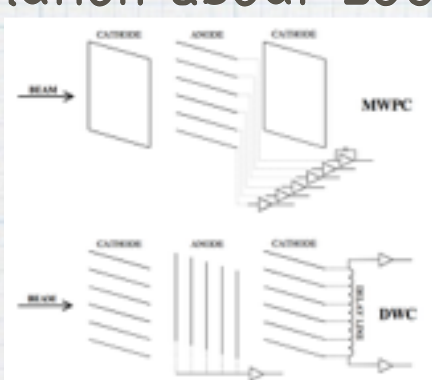
- Accurate measurement of primary ionization cloud is difficult, since the cloud can be quickly smeared by diffusion during its drift to a collecting electrode.

- if the signal height can be acquired, particle energy can be estimated.
  - then particle identification can be made.

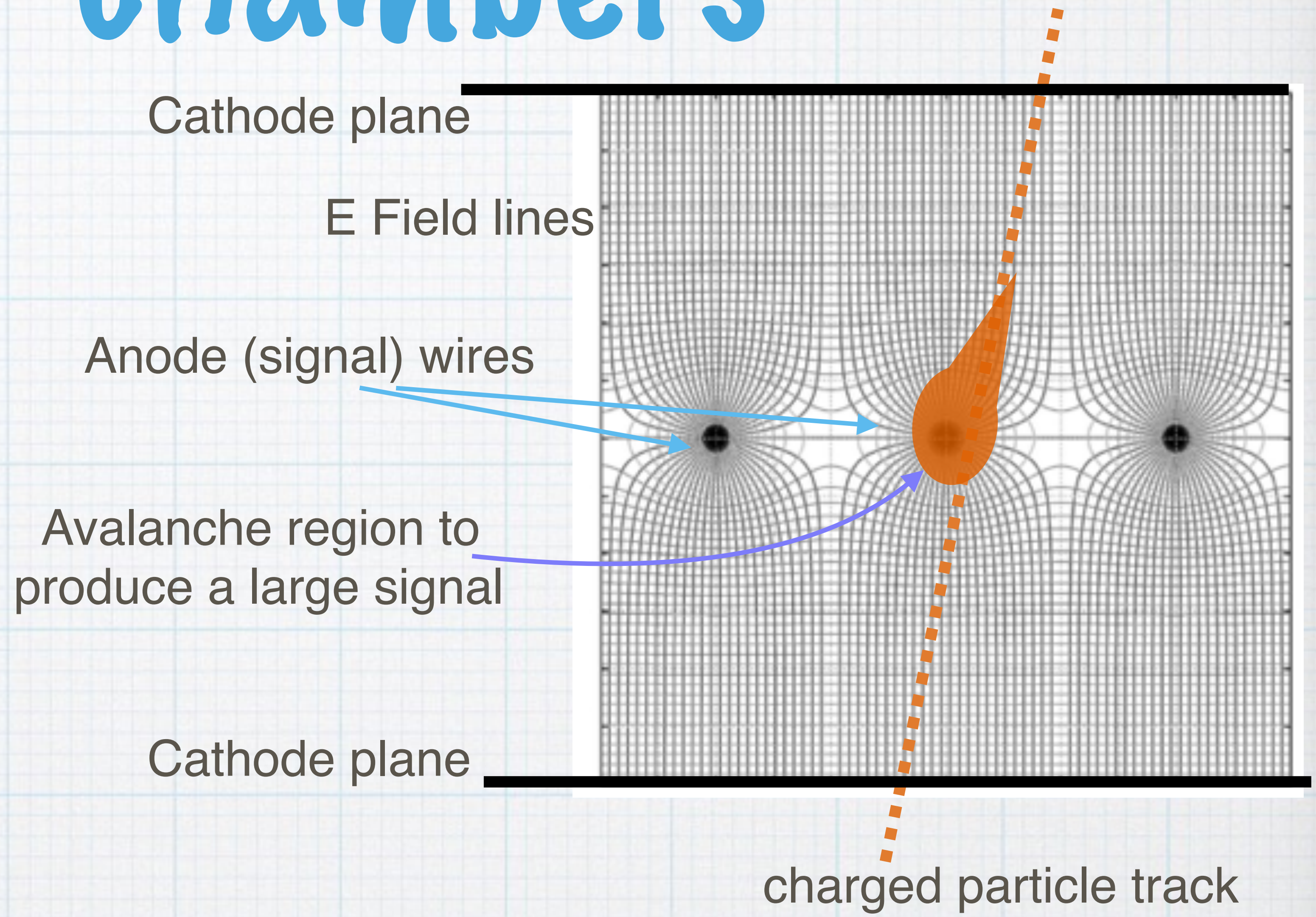
- need for detectors reading singal proportional to particle energy

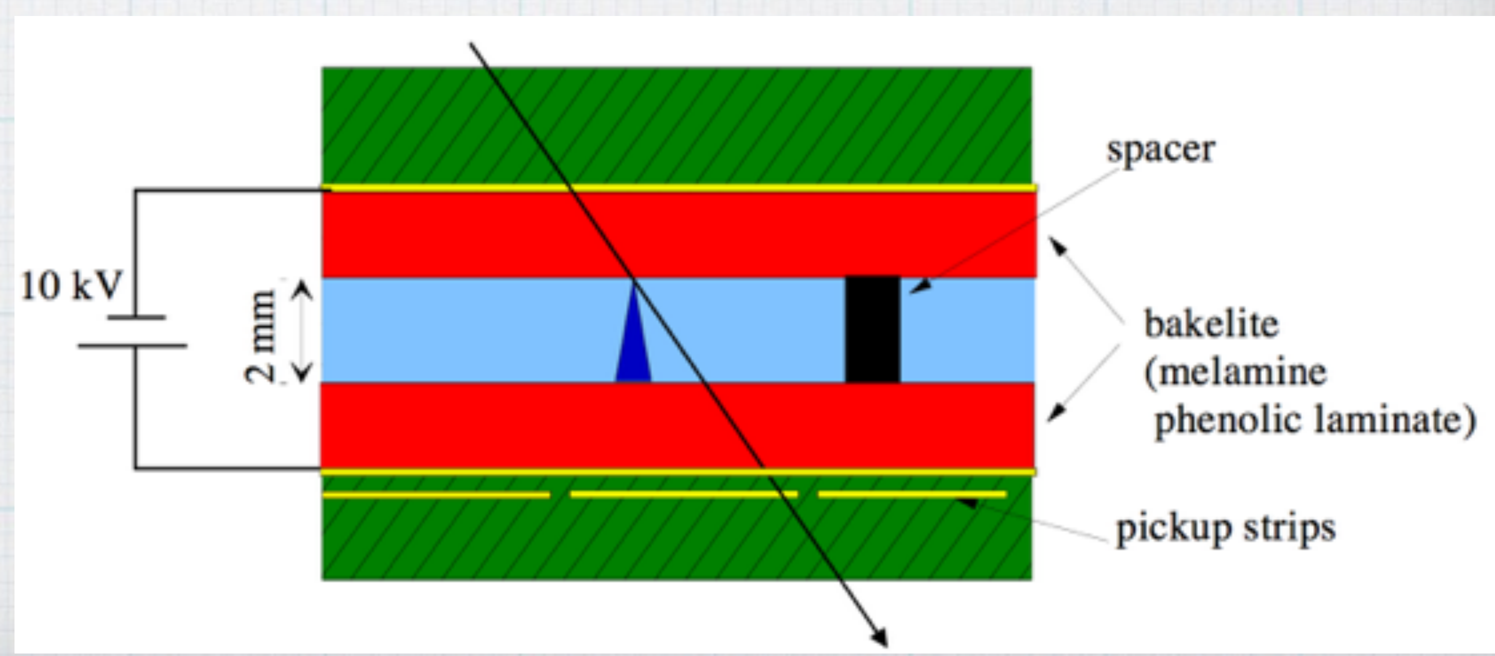
"wire" chambers

- MWPC/ DCh
  - #signal wires = #readout chs
  - precision chamber 80um
- DWC - only 2 ch/plane
  - analog signal delayed & compared - position only
  - resolution about 200um

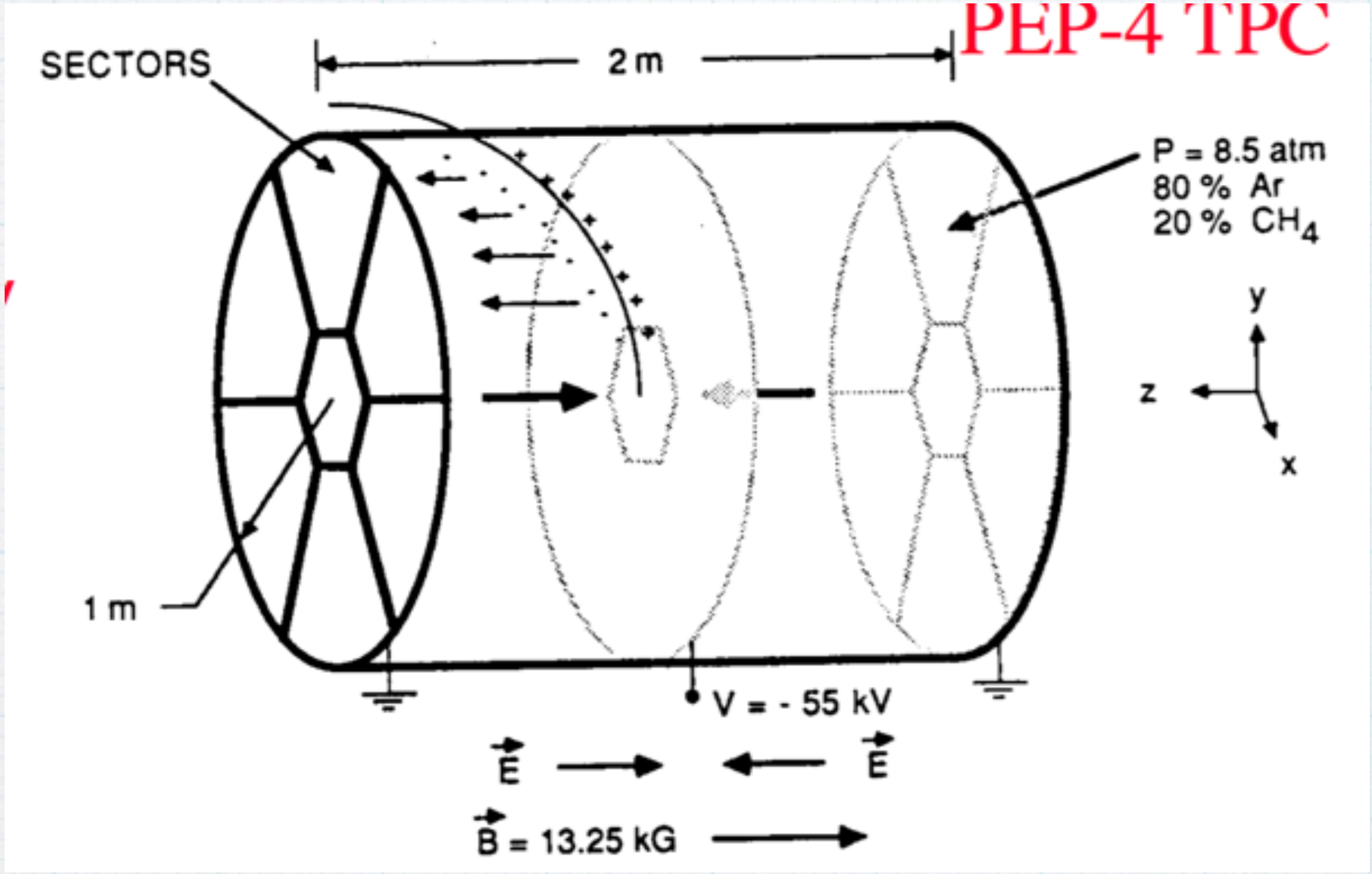


- Thin Gap Ch/ Resistive Plate Ch
  - supports a very high rate of 1 kHz/cm^2
  - Trigger chambers with 1cm resolution
  - RPC: no wires!
- Time Projection Ch
  - 3D tracking + Energy



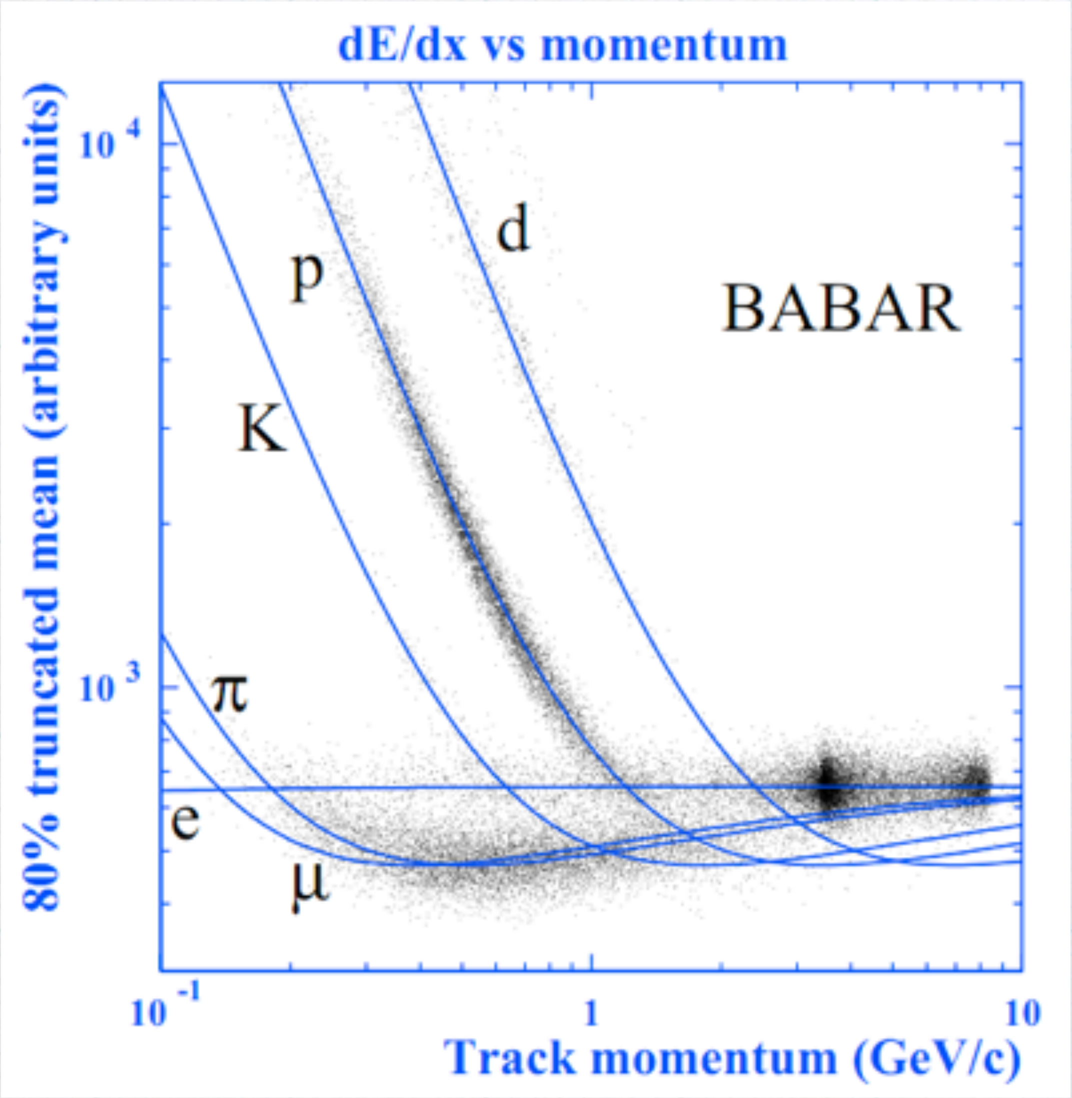


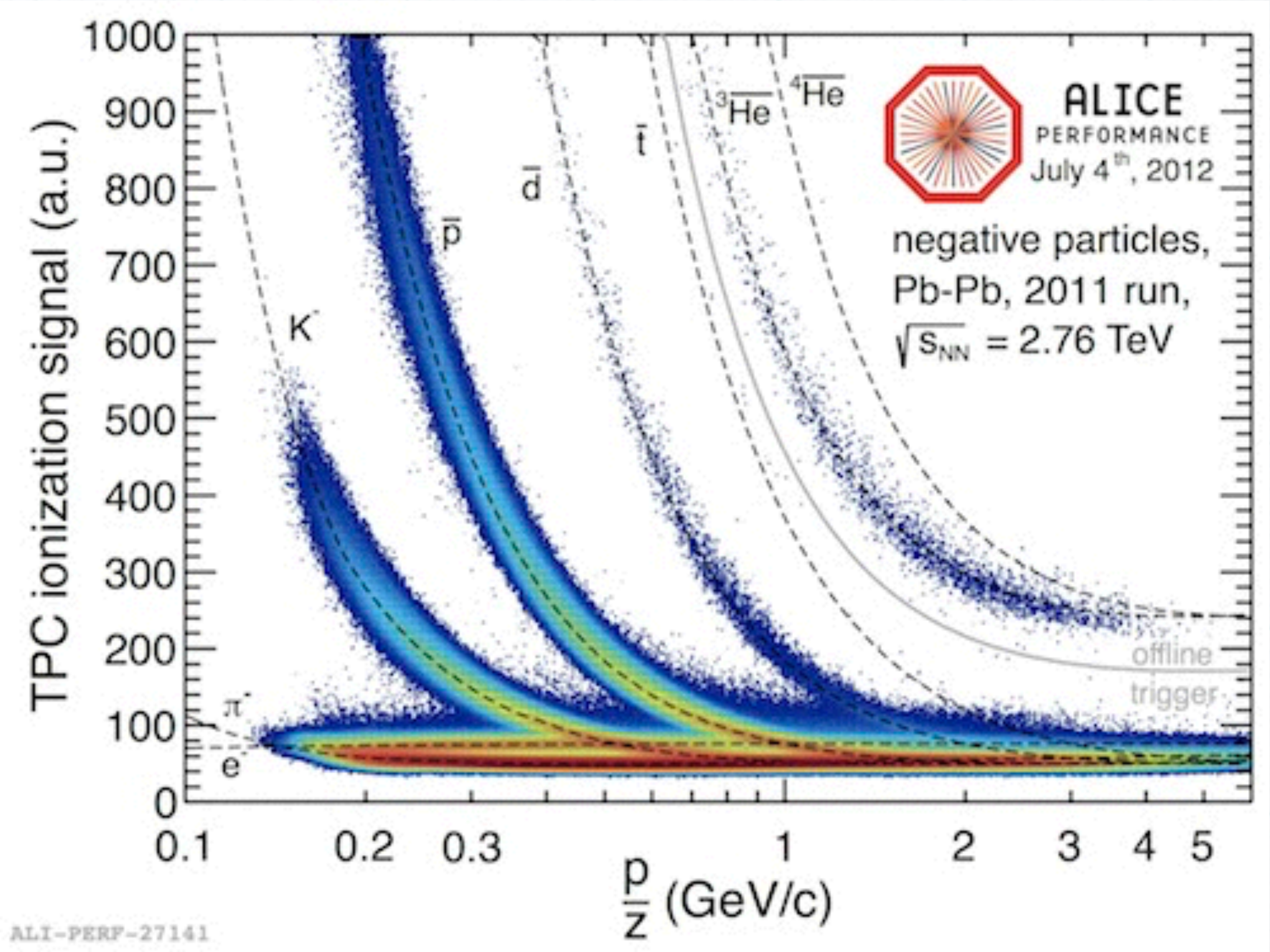
TPC



- E field to drift electrons towards the MWPCs at the both ends of the cylindirical volume.
  - wire coordinates give x-y positions of the track
  - signal timing gives z position of the track
  - signal amplitude gives dE/dx —> energy information
- B field parallel to E field curves the ionization track
  - momentum infomation can be extracted

particle identification

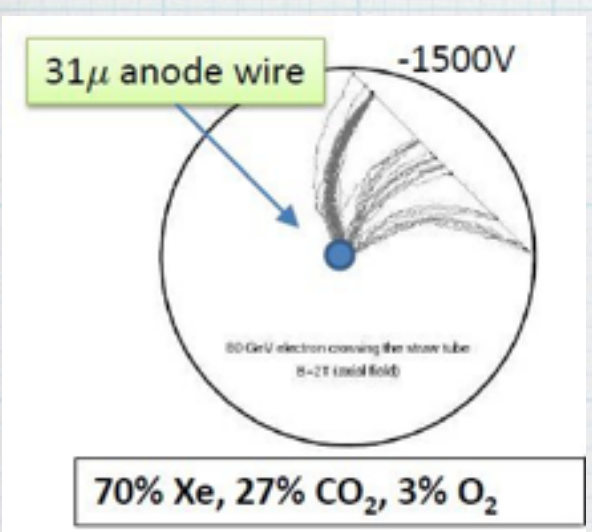


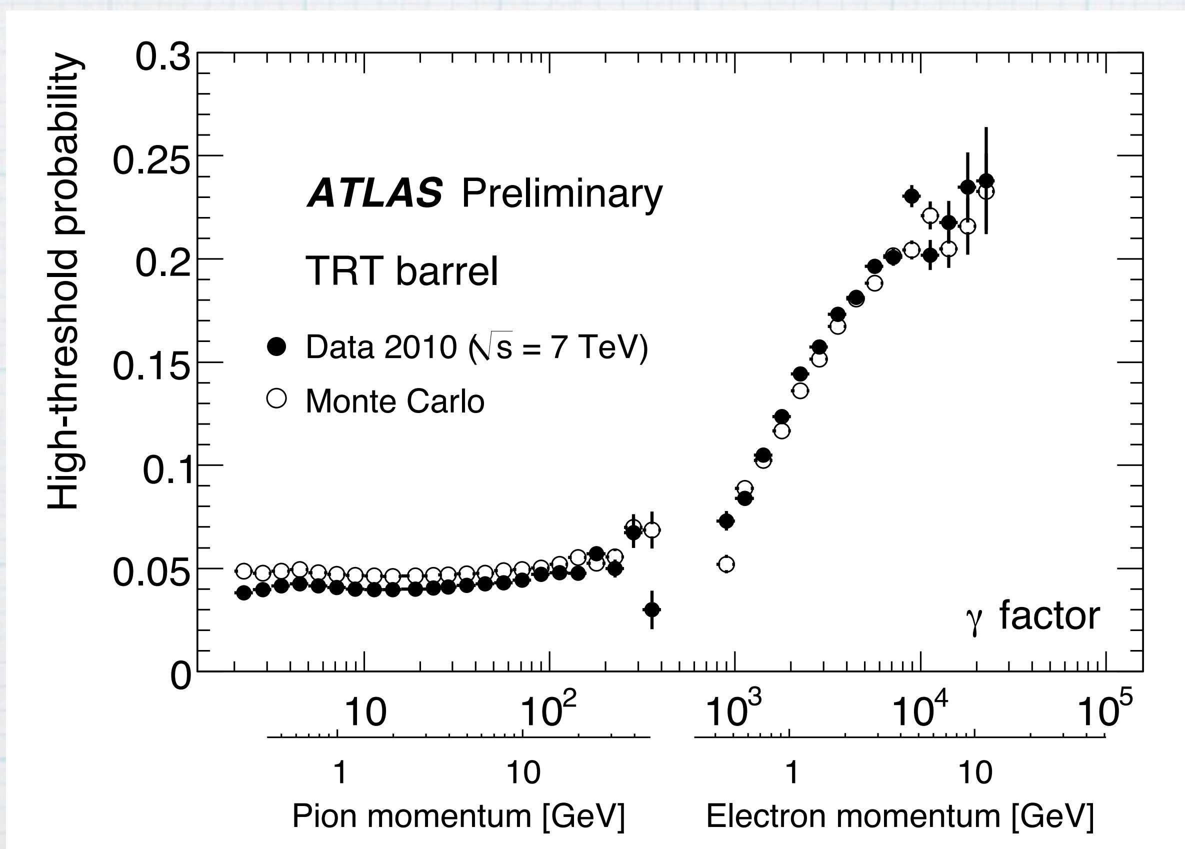


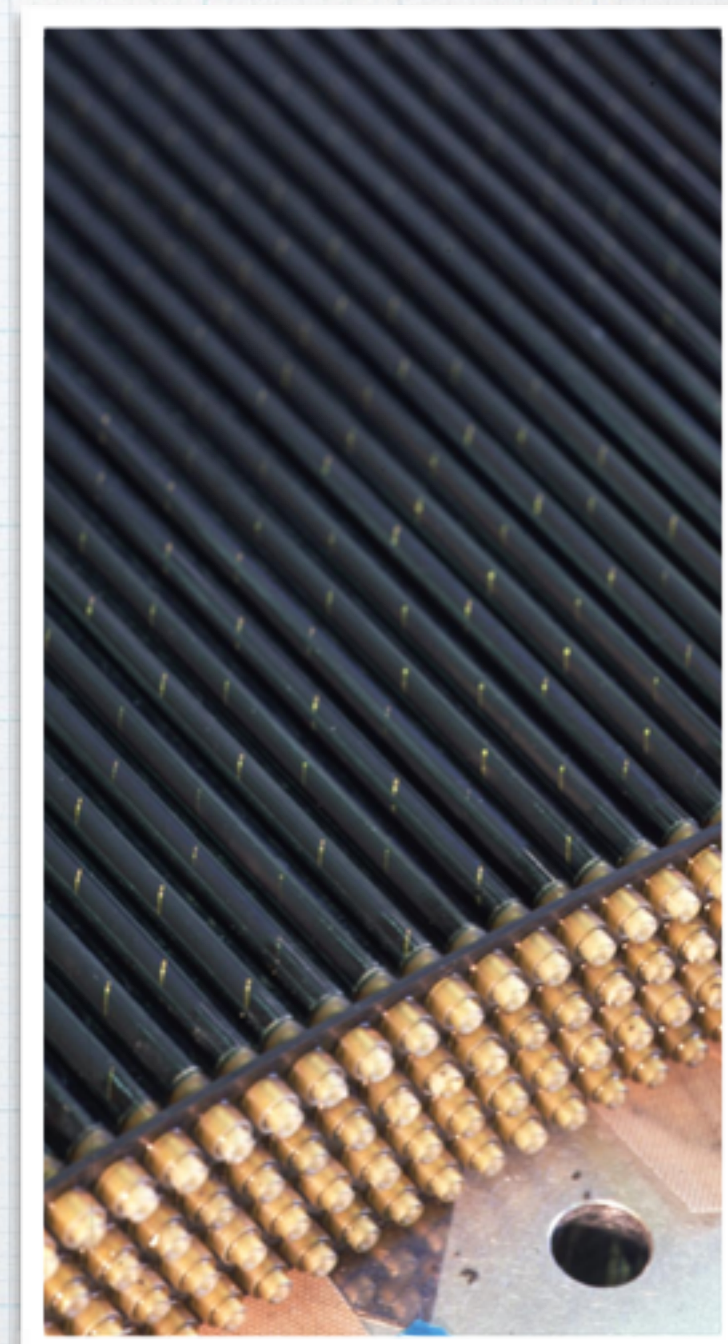
TPC particle identification examples

Transition Radiation

- A charged high energy particle travelling between two media with different dielectric constants emits EM radiation.
  - $E_r \propto \gamma$ and $\theta_r \propto 1/\gamma$
- ATLAS TR Tracker uses 370k tubes of L=144cm & d=4mm filled with gas mixture ionized by TR x-rays. This improves e-π separation.

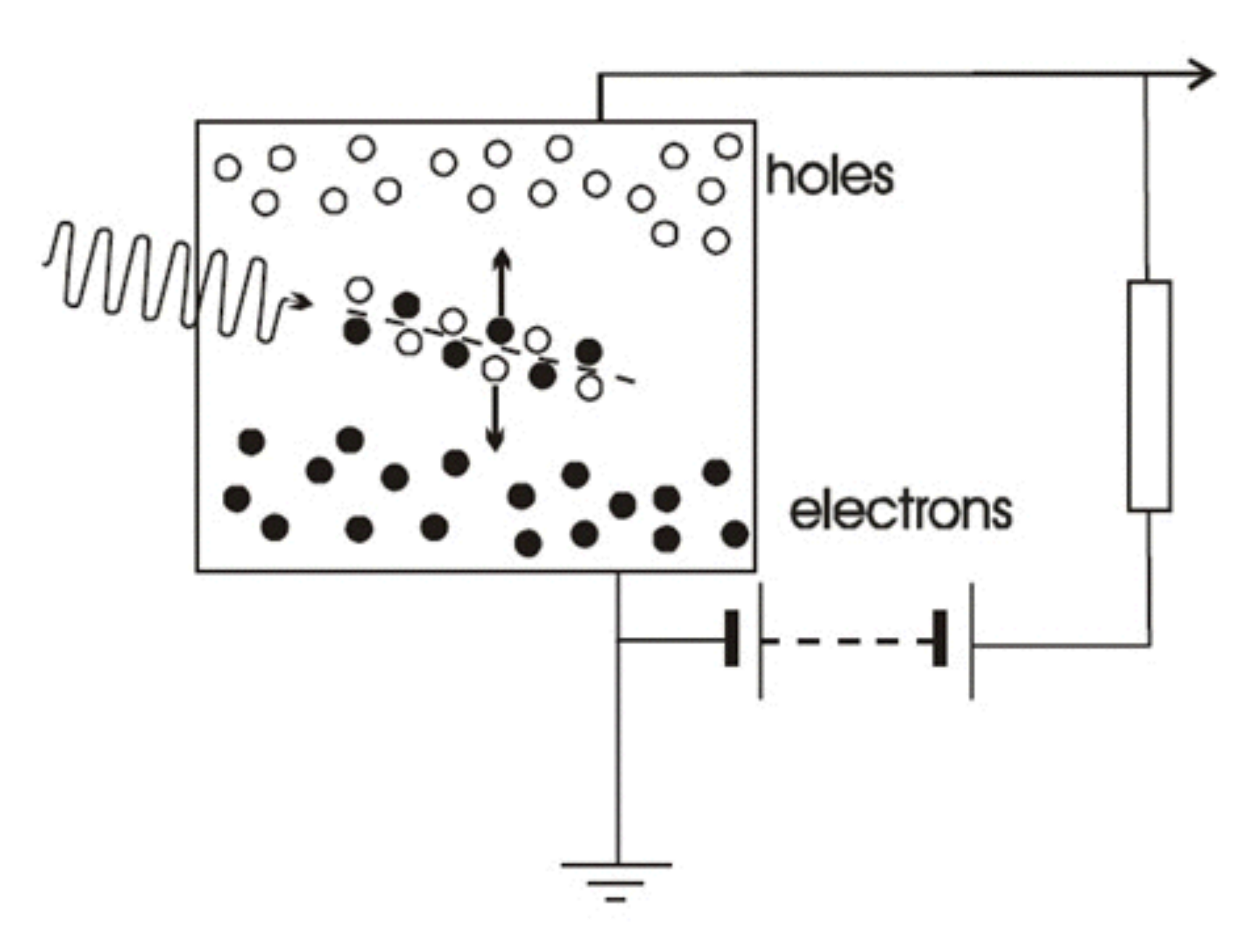




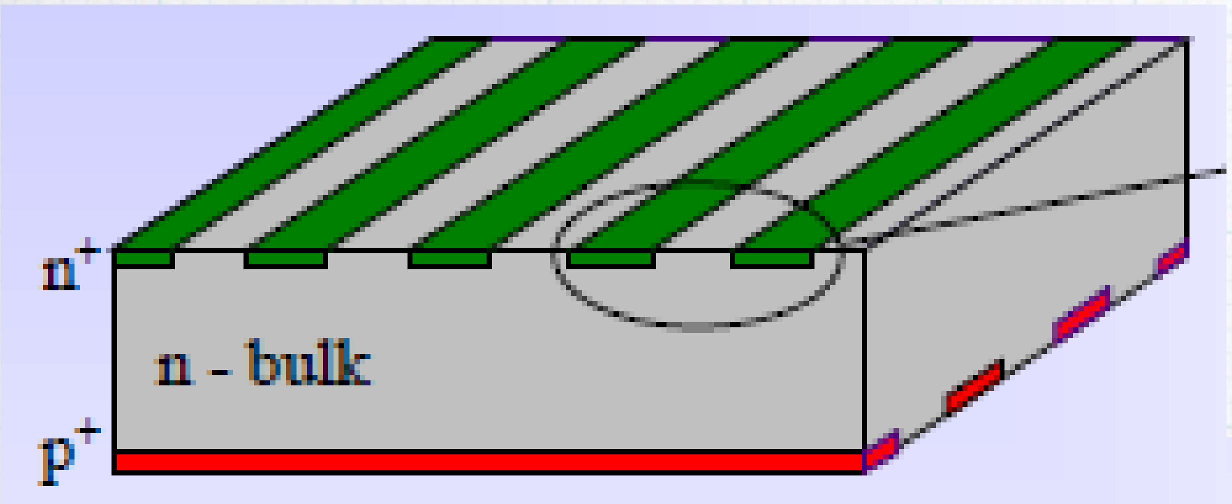


Silicon as the ionisation medium

* Same working principle as the gaseous chamber
* Advantages
  * much smaller areas can be instrumented
  * smaller bias voltage needed (LV: 100V)
  * better resolution: about 10μm
* Disadvantages
  * Thermal noise can give fake signal
  * Cooling is necessary
  * Expensive detector
  * Many (100k) readout channels
* Typical utilisation
  * Pixel: x,y information
    * Many channels, expensive
  * Strip: only x or y information
    * But I can use two or more strips at an angle to get x-y information.

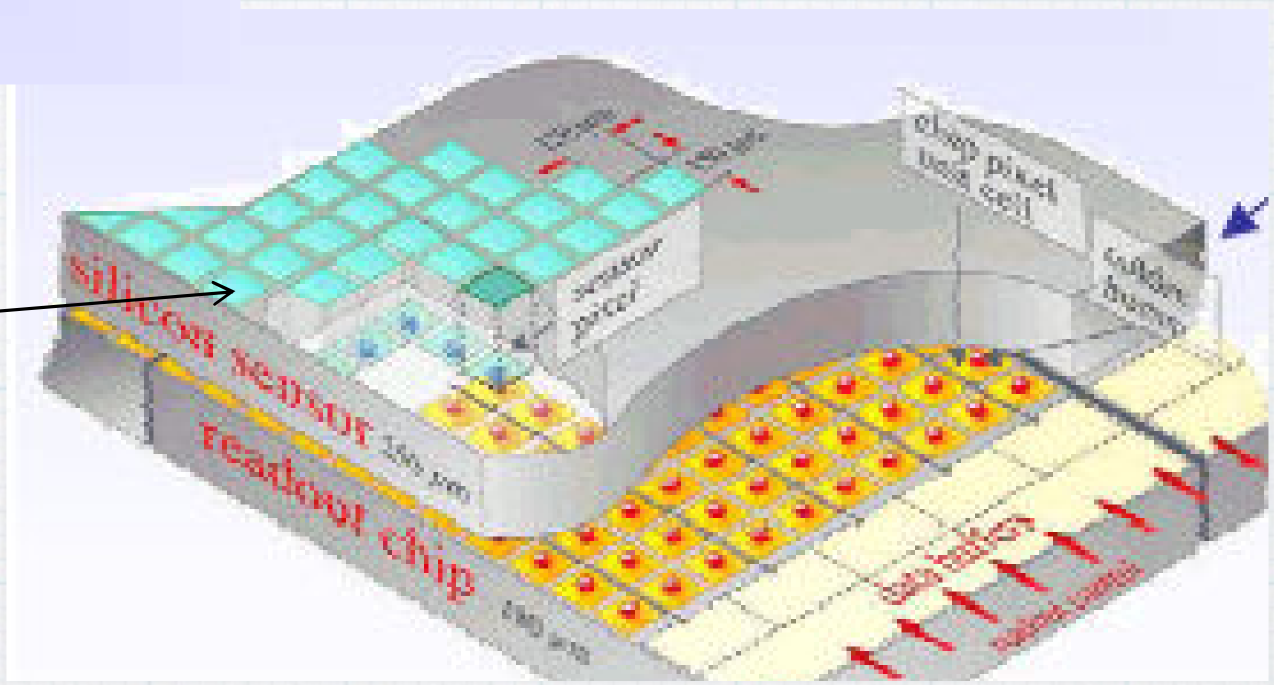


Strip or Pixel, that is the question...



Strip detector,
Readout strips

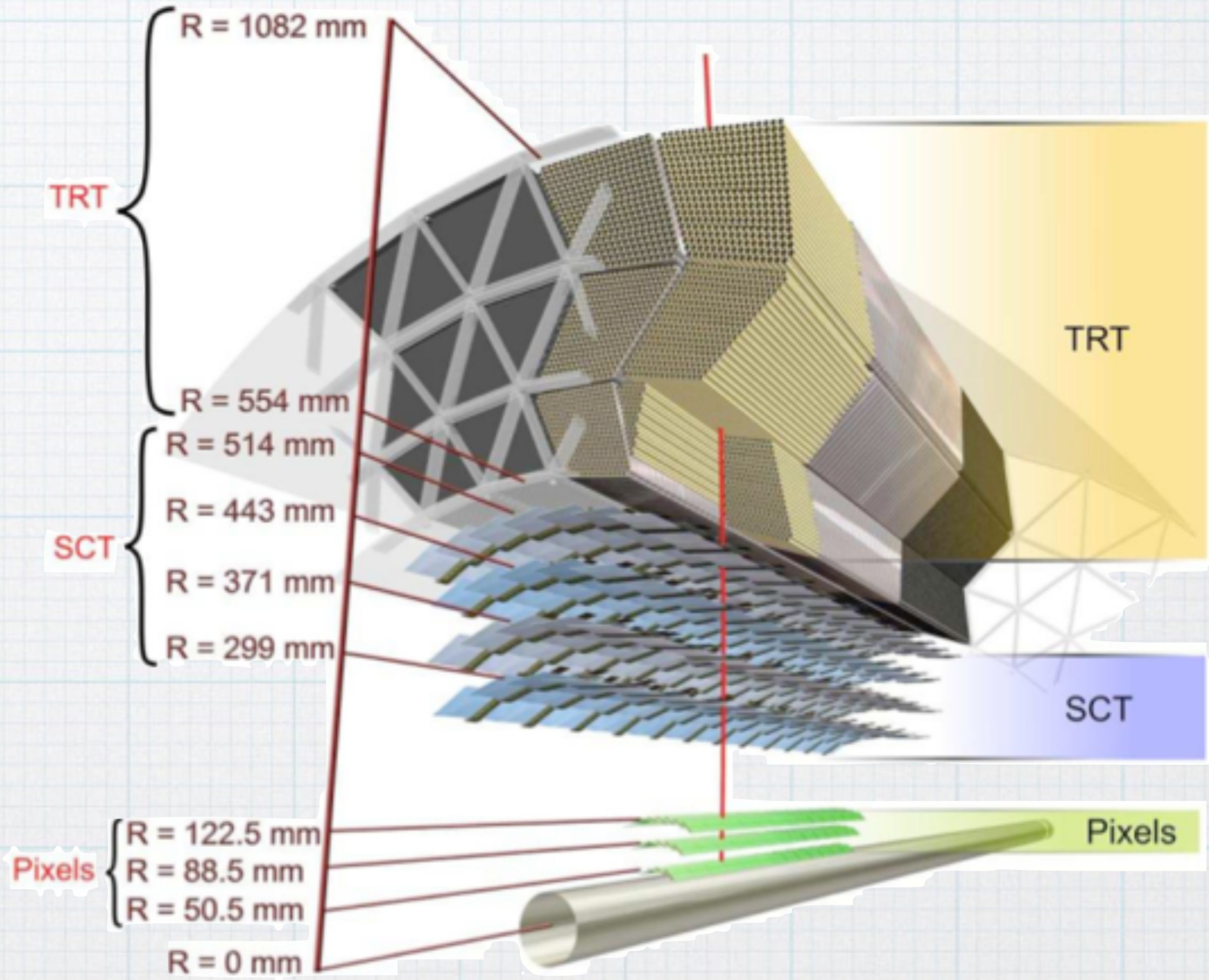
Pixel detector,
Pixel



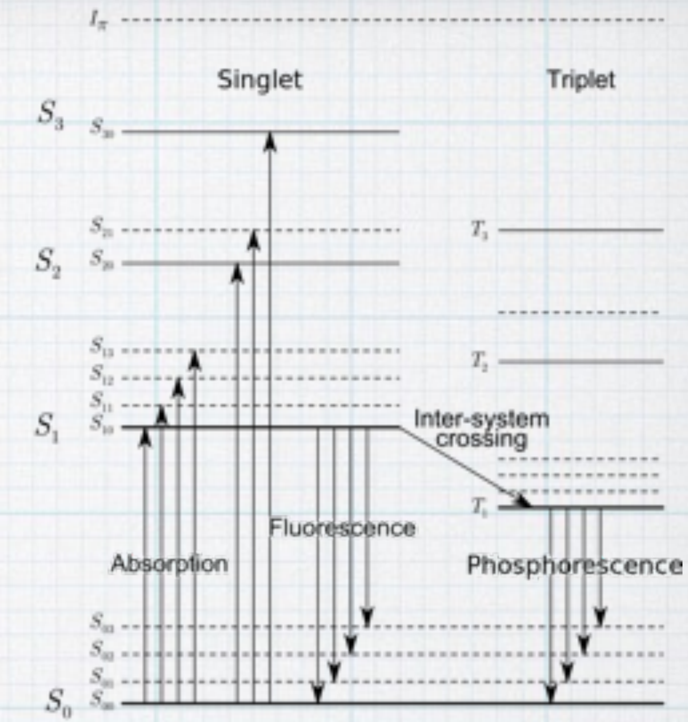
strips and pixels, use them all...

ATLAS Inner detector

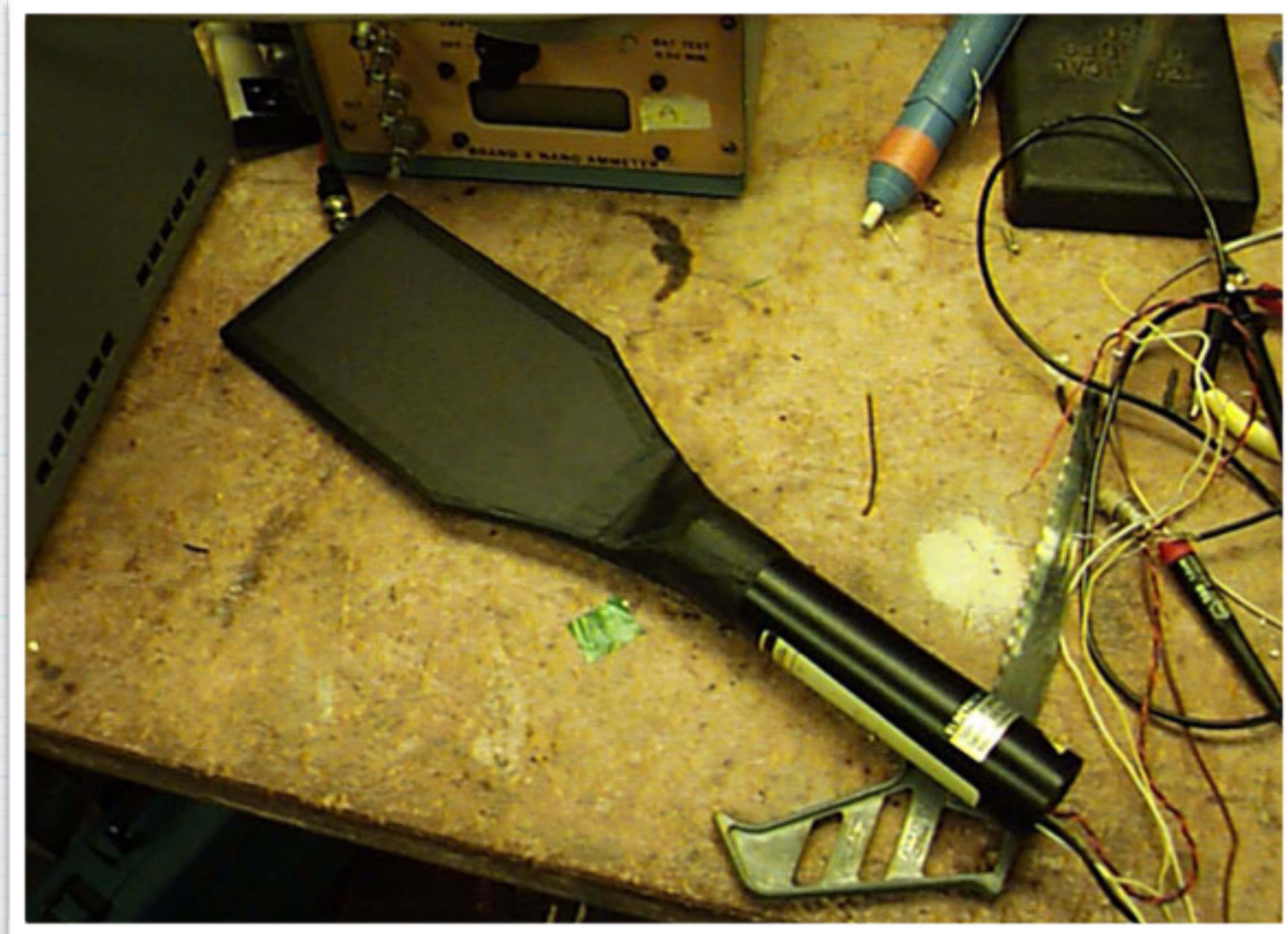
- Silicon system
  - Pixel : R=12.3cm
    - ideal 16μm, using cosmics 24μm
  - SCT : R=51.4cm
    - ideal 24μm, using cosmics 30μm
- TRT Detector R=108.2cm
  - ideal 130μm, using cosmics 187μm



Scintillator

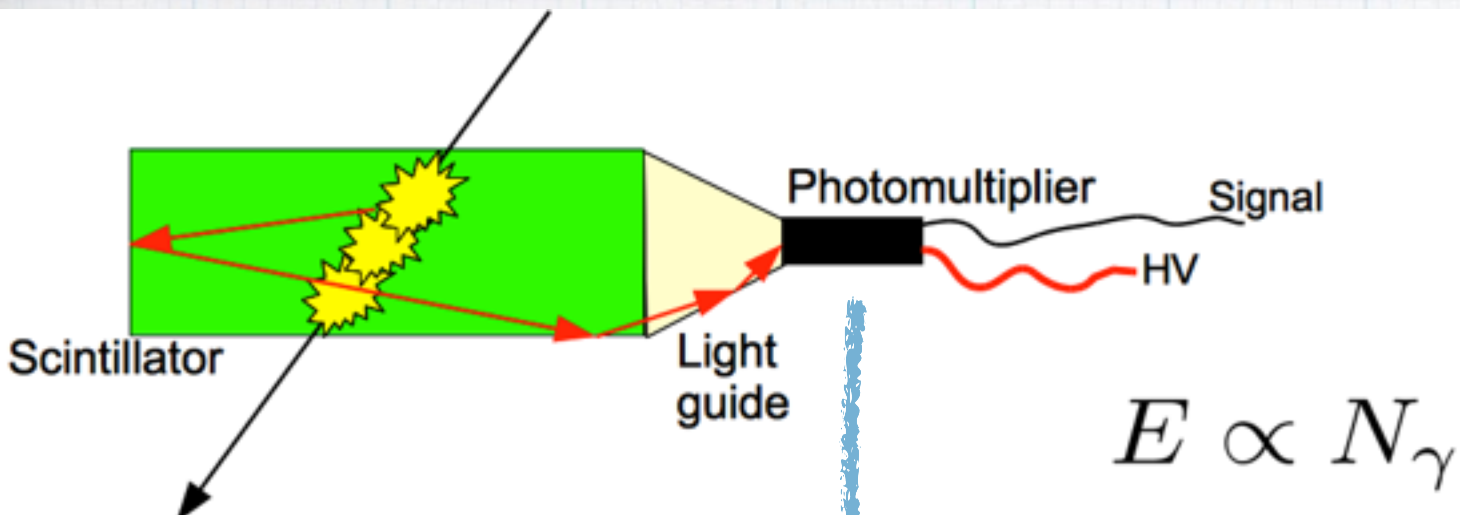


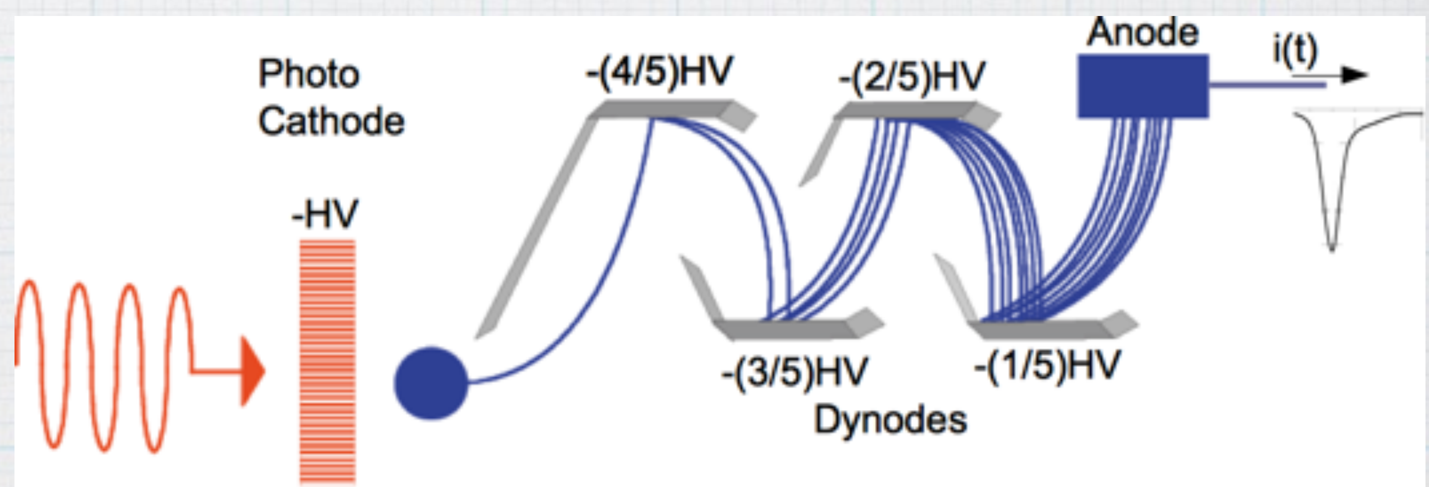
- New interaction mechanism!
  - energy absorbed by the atoms, and emitted as light later on.
  - fast(fluorescence) and slow (phosphorescence) components.
- Converts the energy deposited by traversing particles into light: scintillation mechanism
  - ≈40 photons/keV NaI(Tl),
  - ≈10 photons/keV plastic scintillator,
  - ≈4 photons/keV BGO
- Transparent to its own light.
- Plastic or Crystal Scintillator - W. Crookes 1903, ZnS screen



reading out a scintillator

- Digitizing the scintillation light
  - ➡ Converting light to charge: photoelectric effect
- Photomultiplier tube does the job
  - ➡ An electric signal is readout —> need to convert analog to digital: **ADC**
    - Total charge: Q = k E (+k'E^2)

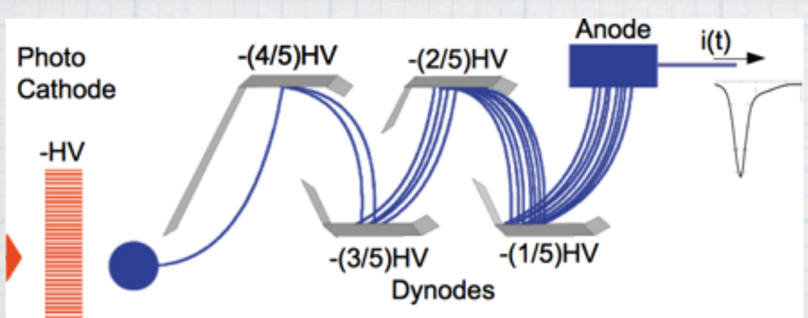




scintillator auxilaries

Polystyrene

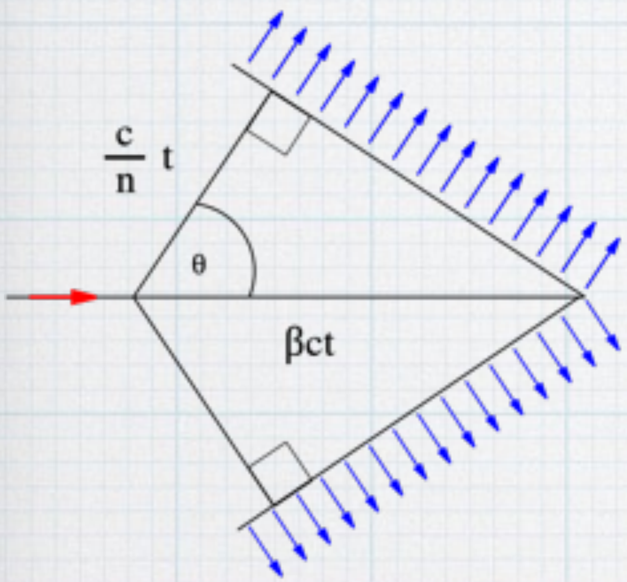
PbWO4 Crystal
LYSO(Ce) Crystal
BGO Crystal
CsI Crystal
NaI(Tl) Crystal
CdWO4 Crystal
YSO(Ce) Crystal

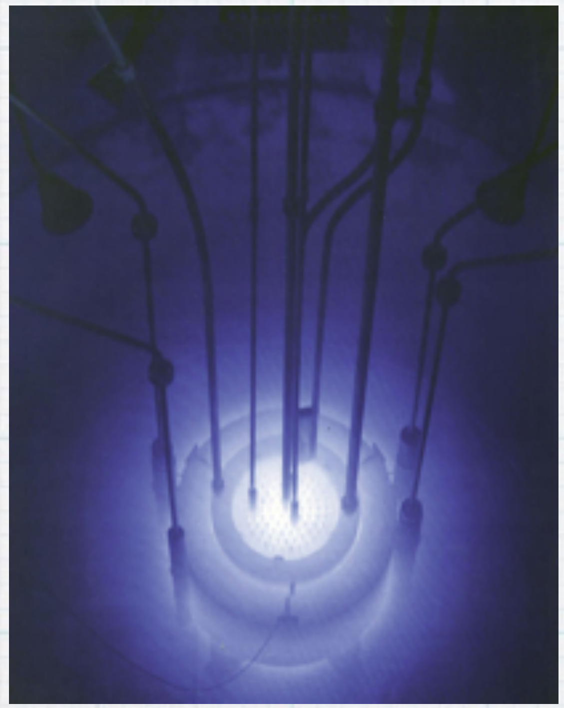


PMT

light guide

Çerenkov Radiation

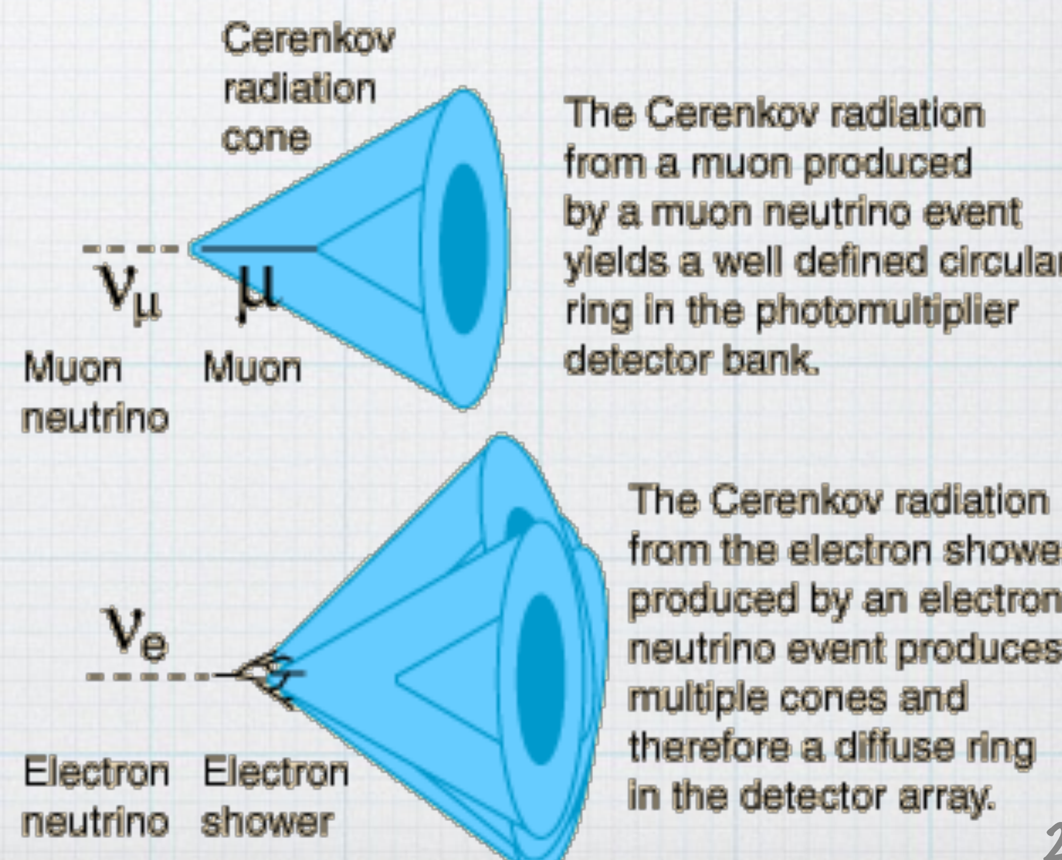




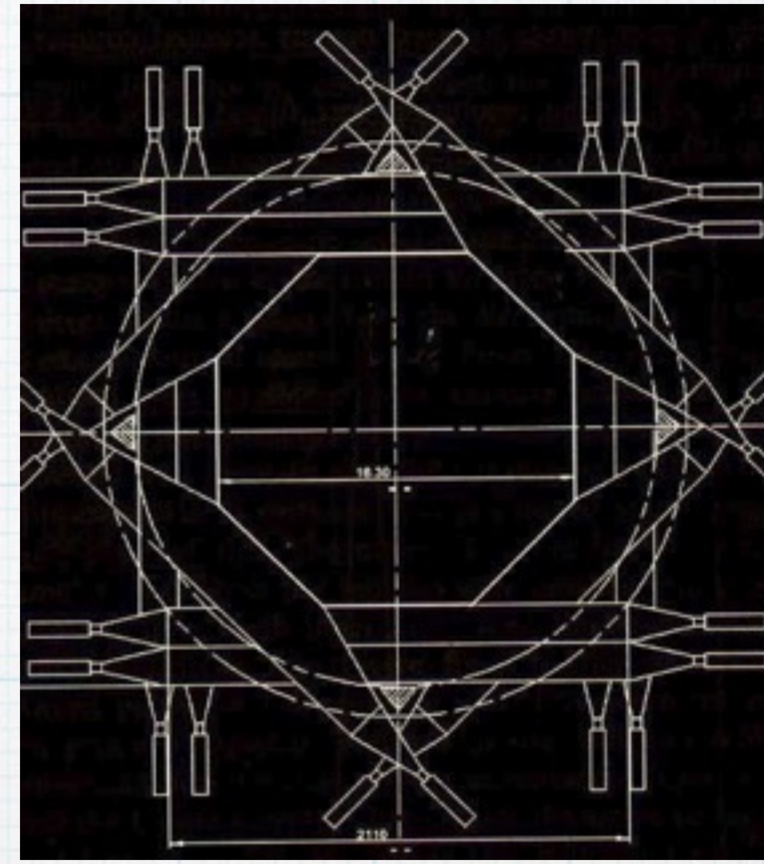
hamamatsu 50cm PMT

- If a charged particle's speed inside a medium ($\beta = v/c$), is greater than the speed of light in that medium ($\beta_{thr} = 1/n$, $n \equiv$ medium's refractive index, $n \geq 1$), the particle emits EM radiation at an angle $\cos\theta_C = 1/(n\beta)$

- This light read by large PMTs can be used for particle identification if momentum can be independently measured.



Using scintillators in a beamline



* As veto
  * reject events from beam halo
* As trigger
  * simple way to count event types
  * $N1 = s1.s2.\overline{s3}$
  * $N2 = N1.(T1 \,||\, T2)$
* As a crude tracker: hodoscope
  * read a long scintillator from both ends and compare the arrival times of signals to PMTs. Time difference can be converted to positon information.

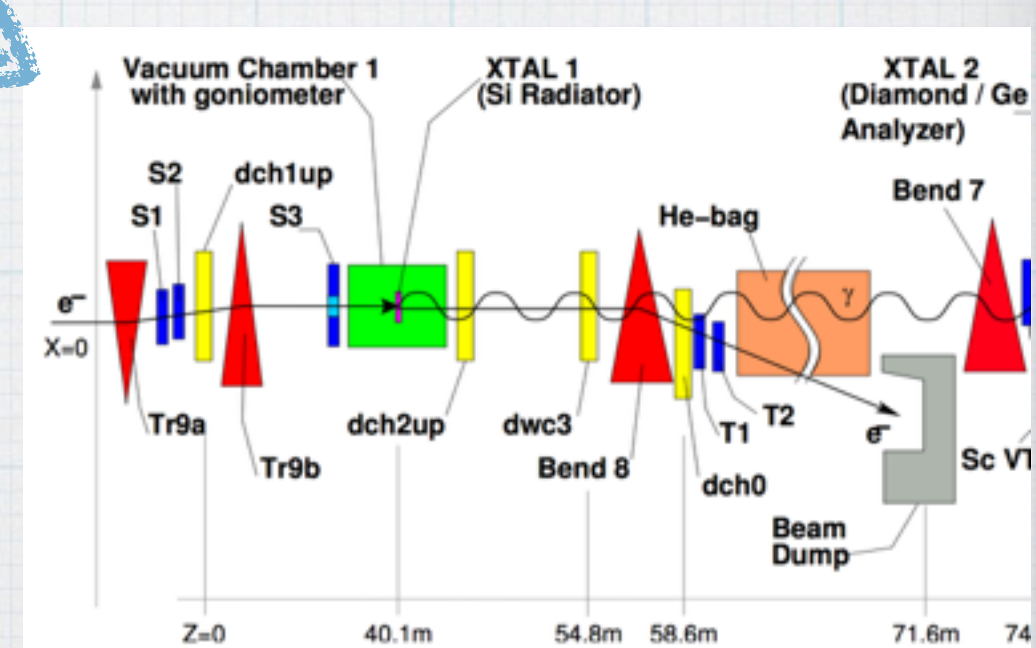
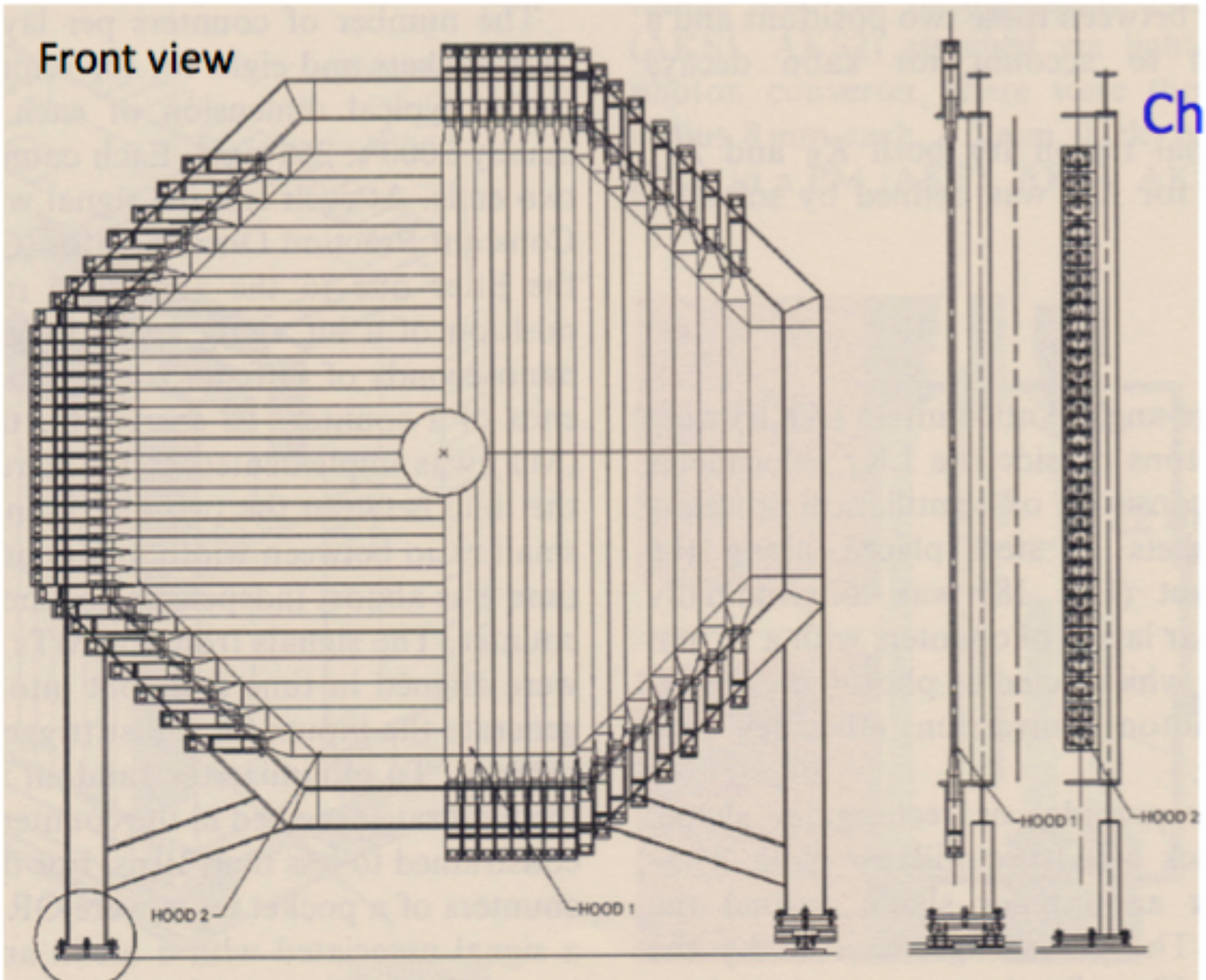


Fig. 1. Setup of the Na59 Experiment

Na48 Hodoscope

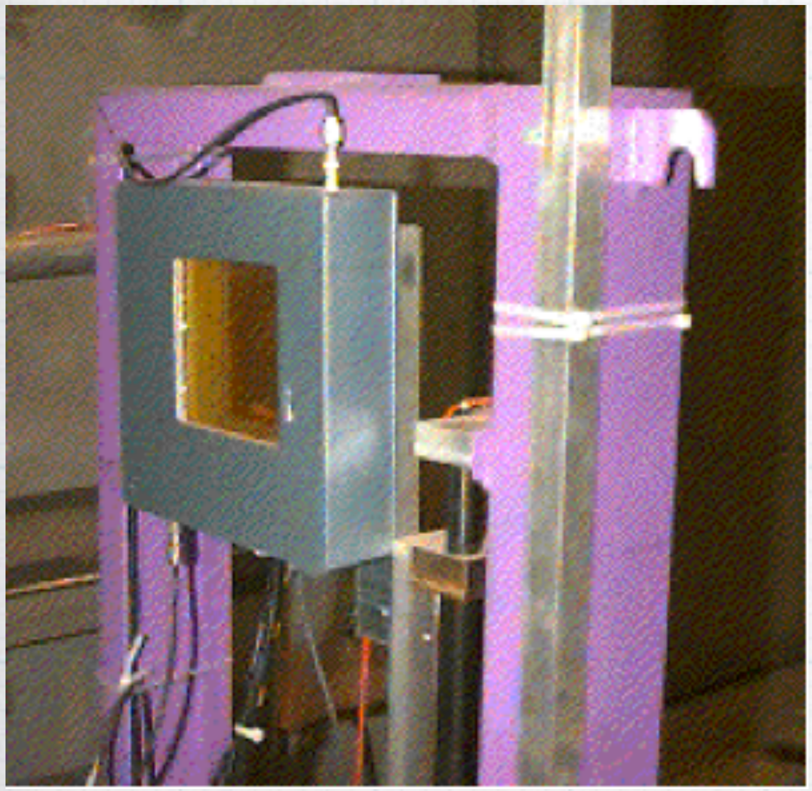


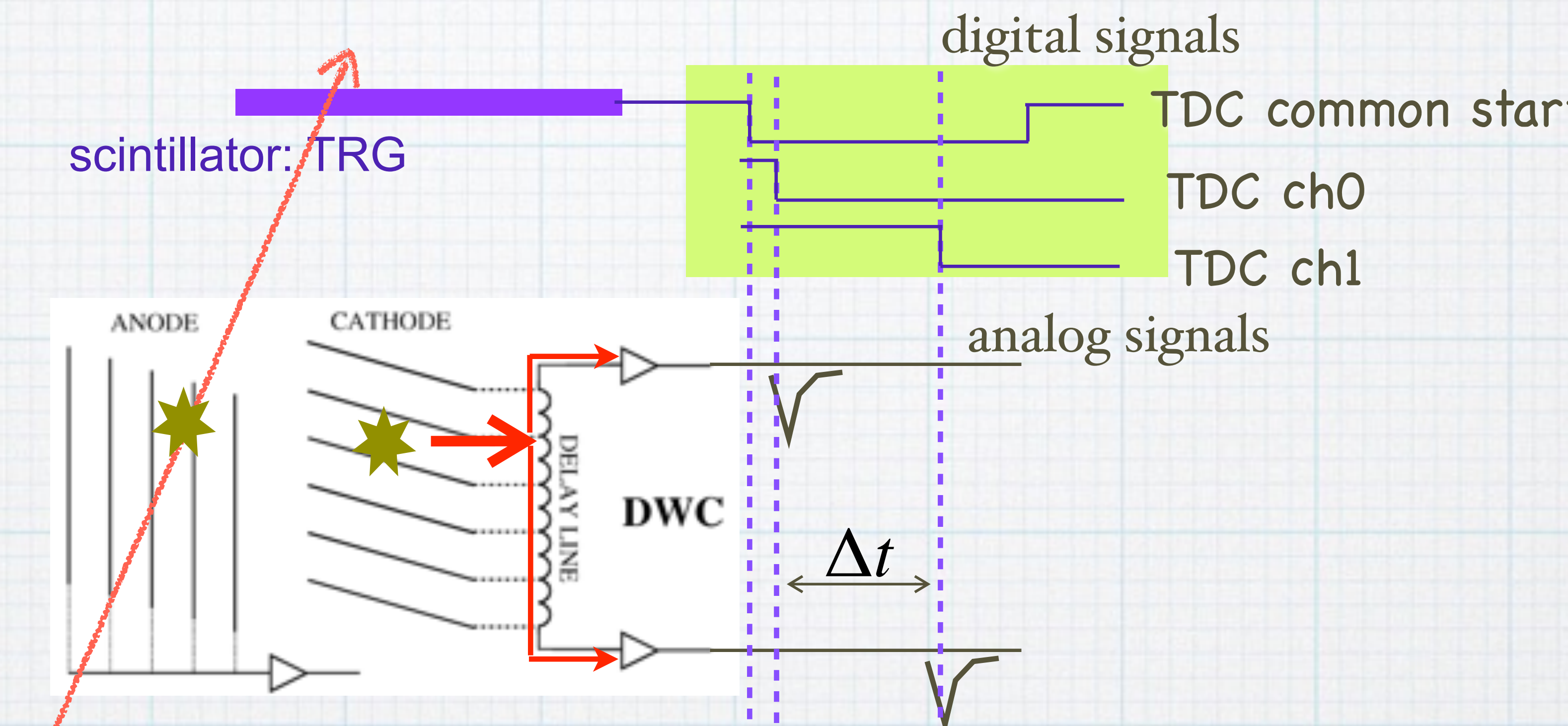
Charged hodoscope

- 2 planes of scintillation counters
- 2 orientations
- Time resolution 260 ps
- In front of Kr calorimeter
- Time difference between planes gives direction of particles

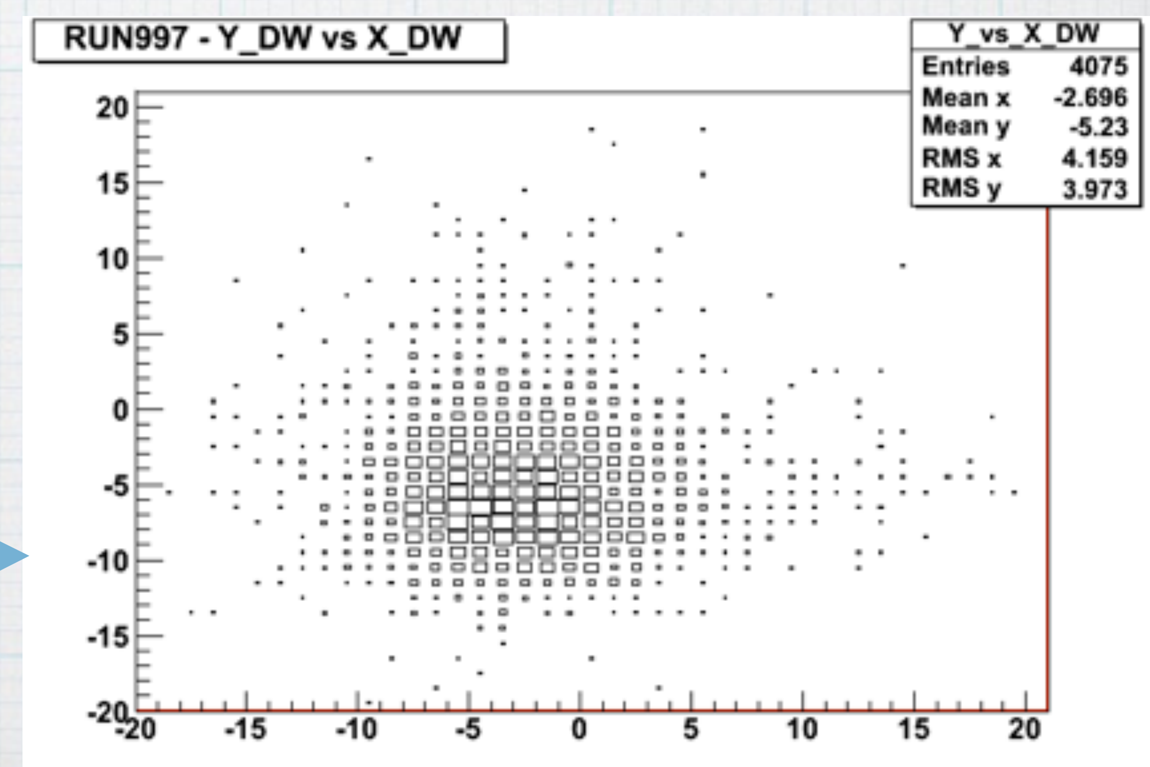
Side view

triggering a delay wire chamber by a scintillator





$$y = \alpha \cdot \Delta t + \beta = \alpha \cdot (t_{top} - t_{bottom}) + \beta$$

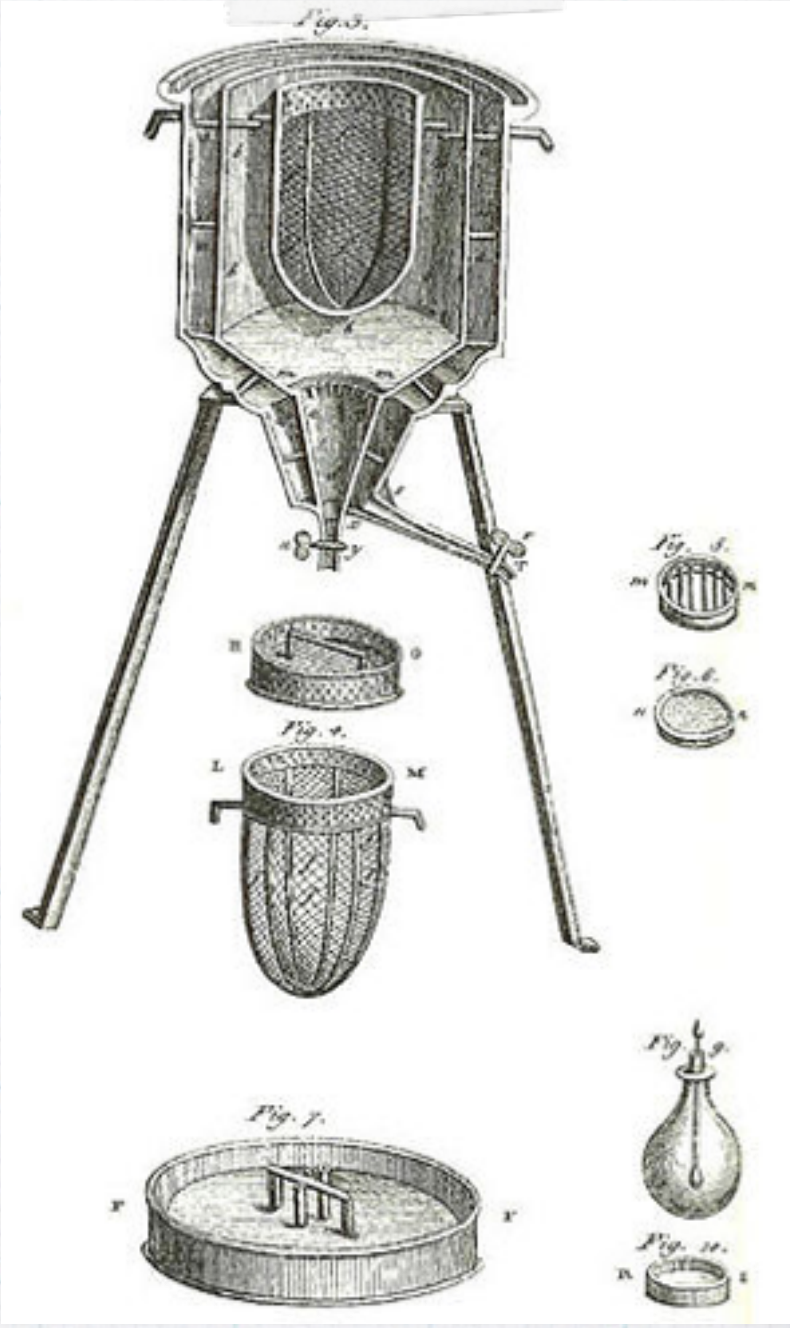


- DWC: Delay Wire Chamber
  - ➡ Simple detector to typically measure the beam profile on fixed target experiments.
  - ➡ gaseous & multiwire
  - ➡ TDC readout: 2CH /plane.

Notes on Triggering

* Select interesting events
  * Do it as early as possible
  * Do it as efficiently as possible
  * Do it as rapidly as possible
  * Use all the available information
* May have to trigger in stages
  * low level: use hardware, be quick and crude
  * high level: use software, be thorough
* more in TRG lecture by F.P.

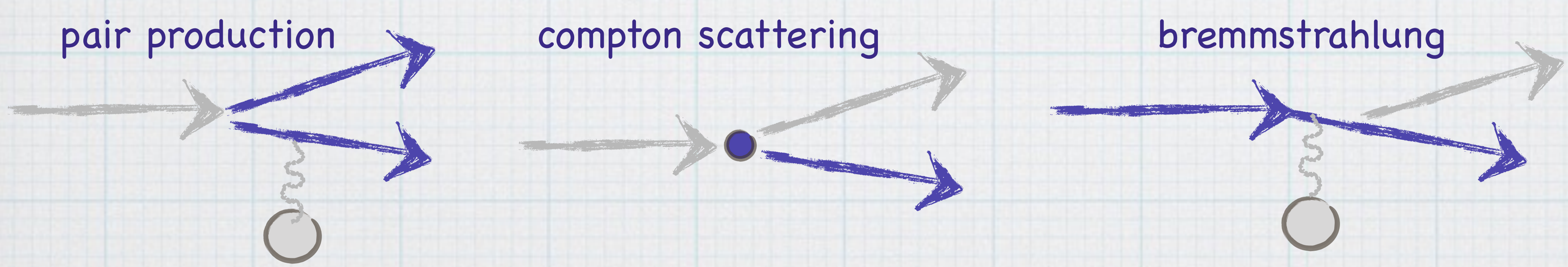
Calorimeter



* The name calorimeter was made up by Antoine Lavoisier. In 1780, he used a guinea pig in his experiments with this device to measure heat production. The heat from the guinea pig's respiration melted snow surrounding the calorimeter, showing that respiratory gas exchange is a combustion, similar to a candle burning.

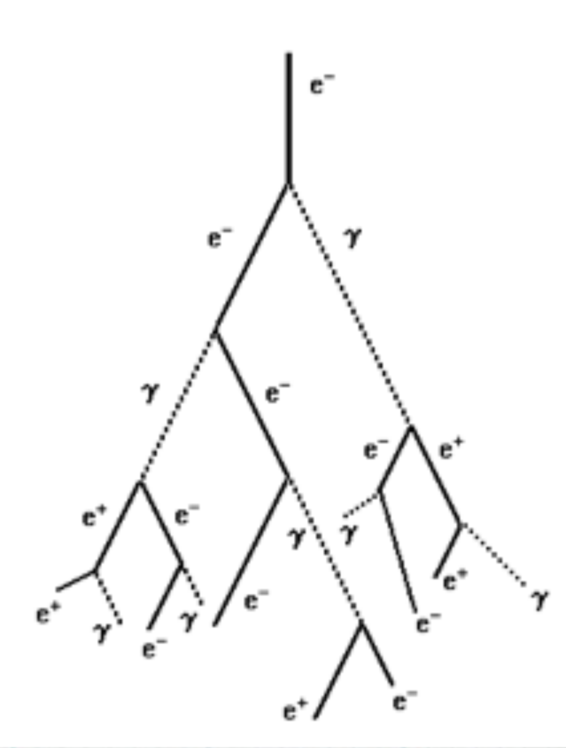
* PP calorimeters are "destructive" energy measurement devices.
    * the particle beam to be measured has to be absorbed.

* PP calorimeters benefit from many additional interactions:



PP calorimetry

* Particle interactions determine calorimeter type
  * material choice, size
* Incoming particle interacts with calorimeter material
  * it generates a “shower” of secondary particles
  * These particles excite, ionize the material of the calorimeter
  * Incoming particle can be neutral or charged
* Two flavors
  * Electromagnetic (photons, electrons)
    * Radiation length (electron loses 1/e of its energy)
  * Hadronic (strongly interacting particles)
    * Nuclear interaction length $\lambda \approx 35$ g*cm-2 A1/3

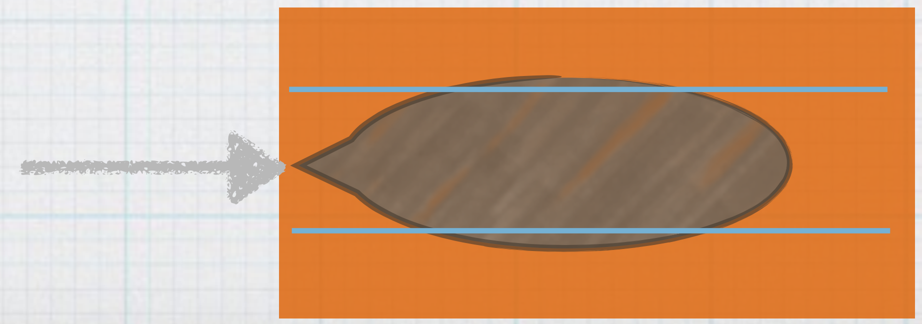


EM calorimeters

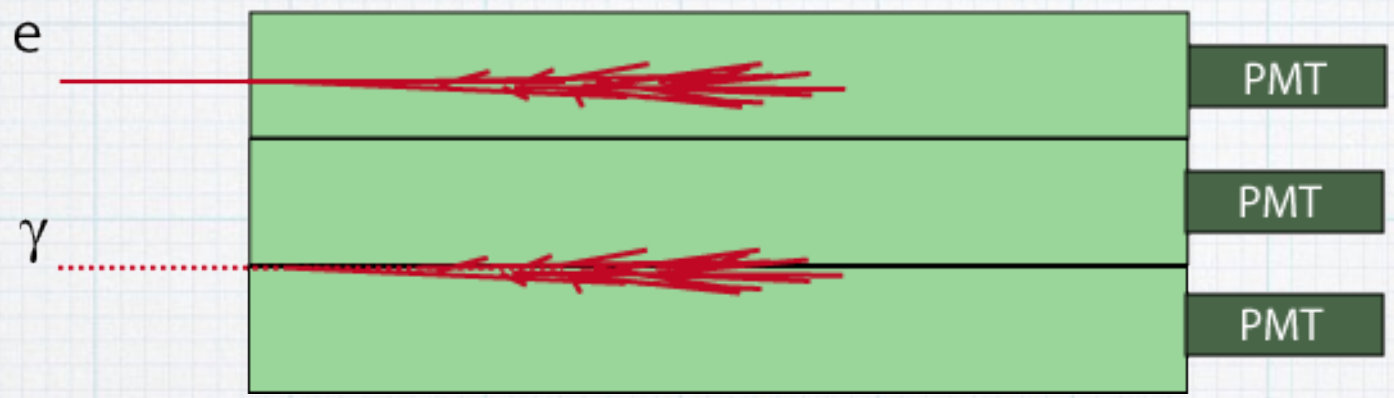
* Radiation length, X_0: the distance at which the particle energy drops down to 1/e of its initial value: $E(x) = E_0 e^{-x/X_0}$ $X_0 = \frac{716.4\text{cm}^{-2}\, A}{Z(Z+1)\ln(287/\sqrt{Z})}$ ATLAS EMcalo: $22X_0$

* Critical Energy, Ec: The energy at which losses due to Bremstrahlung and ionization are equal. $E_c = \frac{580 MeV}{Z}$

* Moliere Radius, R_m: The radius of a cylinder containing on average 90% of the shower's energy deposition.
  - $R_m = 0.0265\ X_0\ (Z + 1.2)$
  - $R_m = 21X_0\ /\ Ec$



Homogeneous vs Sampling Calorimeters



dense medium

$\Delta E/E \sim 1\%/\sqrt{E}$

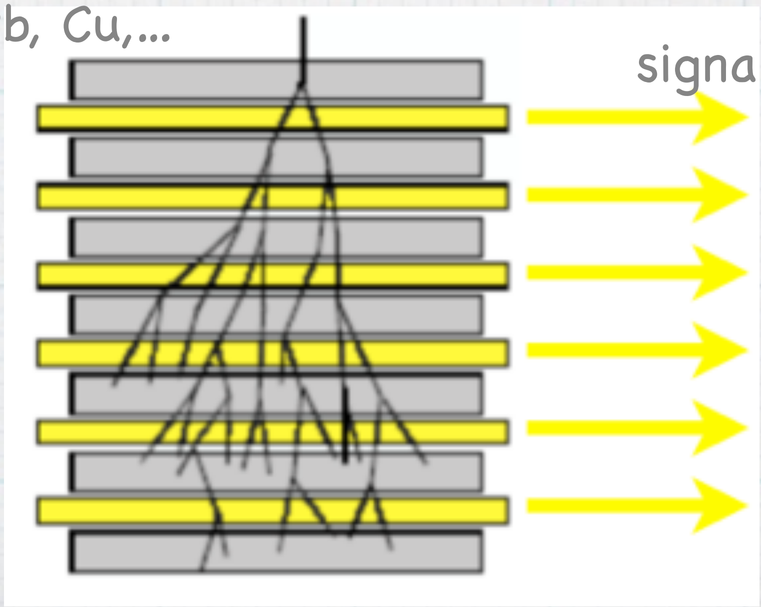
The dense medium may be "active" or "passive" :

- Homogeneous calorimeters: CsI(Tl), BGO, Pb-glass, PWO, Xe(liq)...
- Sampling calorimeters: Pb-scintillator, Fe-scintillator, Pb-Ar(liq)...

shashlik

şiş kebap

High Z passive material
e.g. Pb, Cu,...



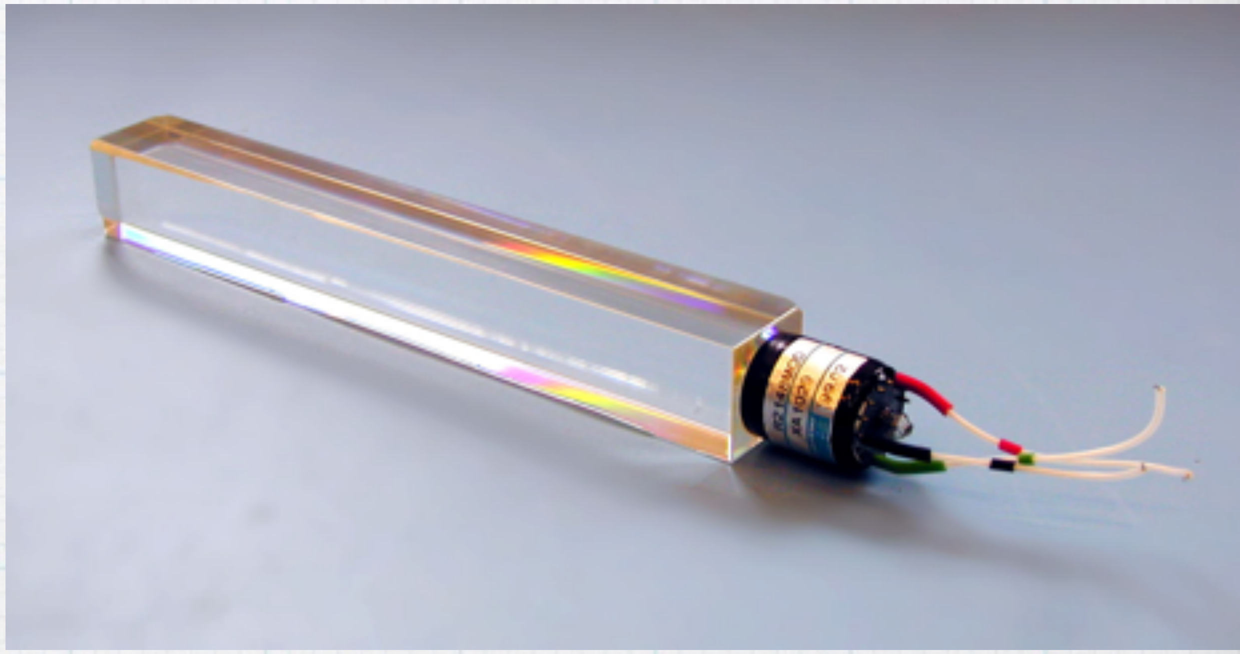
signal from sandwiched scintillators

readout by PMTs

$\Delta E/E \sim 20\%/\sqrt{E}$

Calorimeter Materials

* Crystal calorimeter
  * Measure produced light
  * Full containment in depth difficult
  * Response stability limited
* Semiconductors (Ge)
  * Only small devices feasible
* Liquid noble gas calorimeter
  * Intrinsically stable
  * Easy calibration
  * Complication of cryogenics
  * Slow collection time



Hadronic Calorimeters

* High Energy strongly interacting particles, interact with the nucleons of the medium.
  * A hadronic shower: cascades of mesons (K,π...) and hadrons(p,n...) similar to EM case
  * Absorbtion length, λ: distance where the intensity of the beam has dropped to 1/e of the initial value.
    * Typically 9-10λ are needed for longitudinal containment and 1λ for lateral. Hcal depth > EMcal.
* Most common type: Sampling Calorimeter
  * High Z material (Fe, Pb,..) and Sensor (Scintillator, LAr)

particle ID revisited

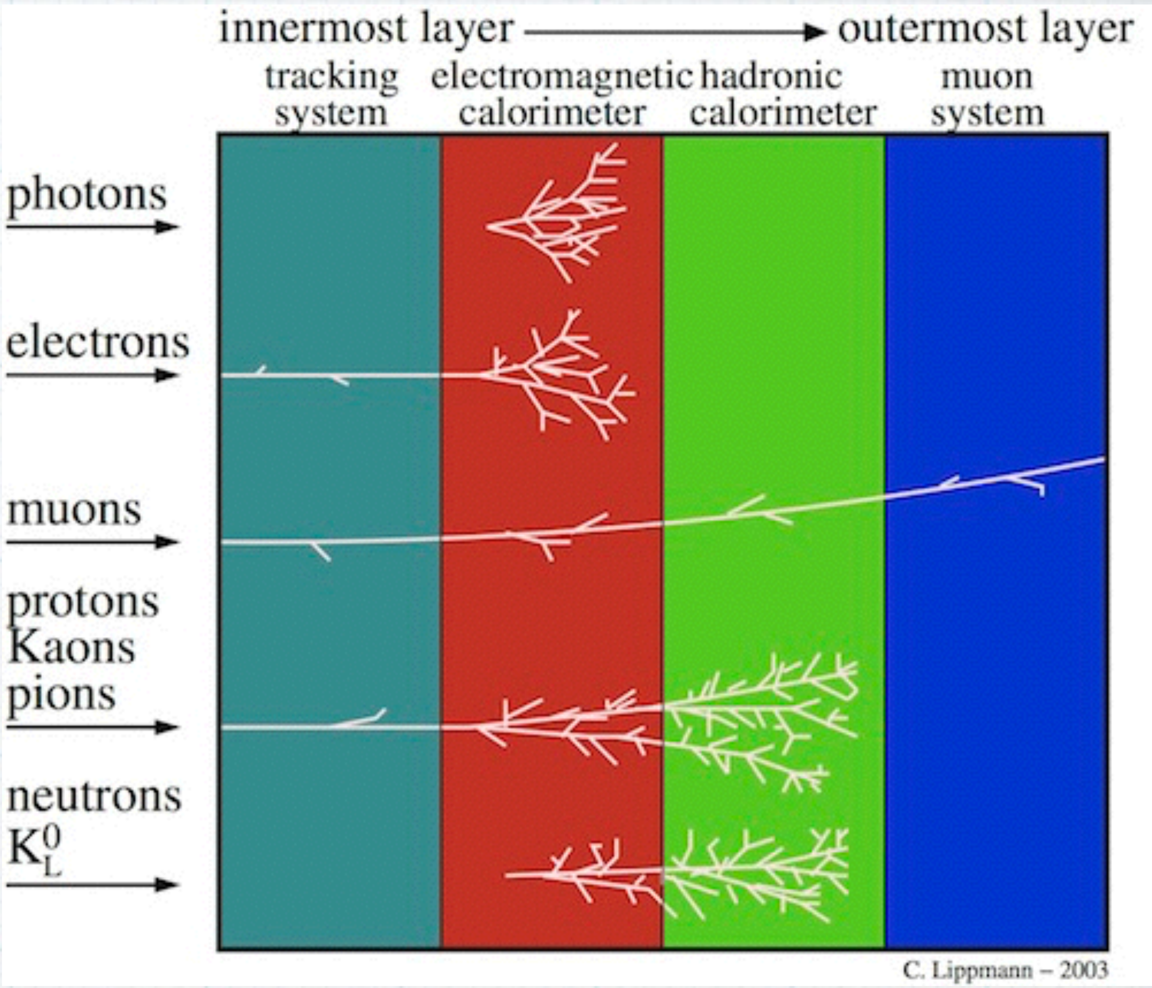
$E^2 = p^2 + m^2$

Measure E and p independently

- Energy from calorimeter
- p from magnetic spectrometer

Calculate E/p:

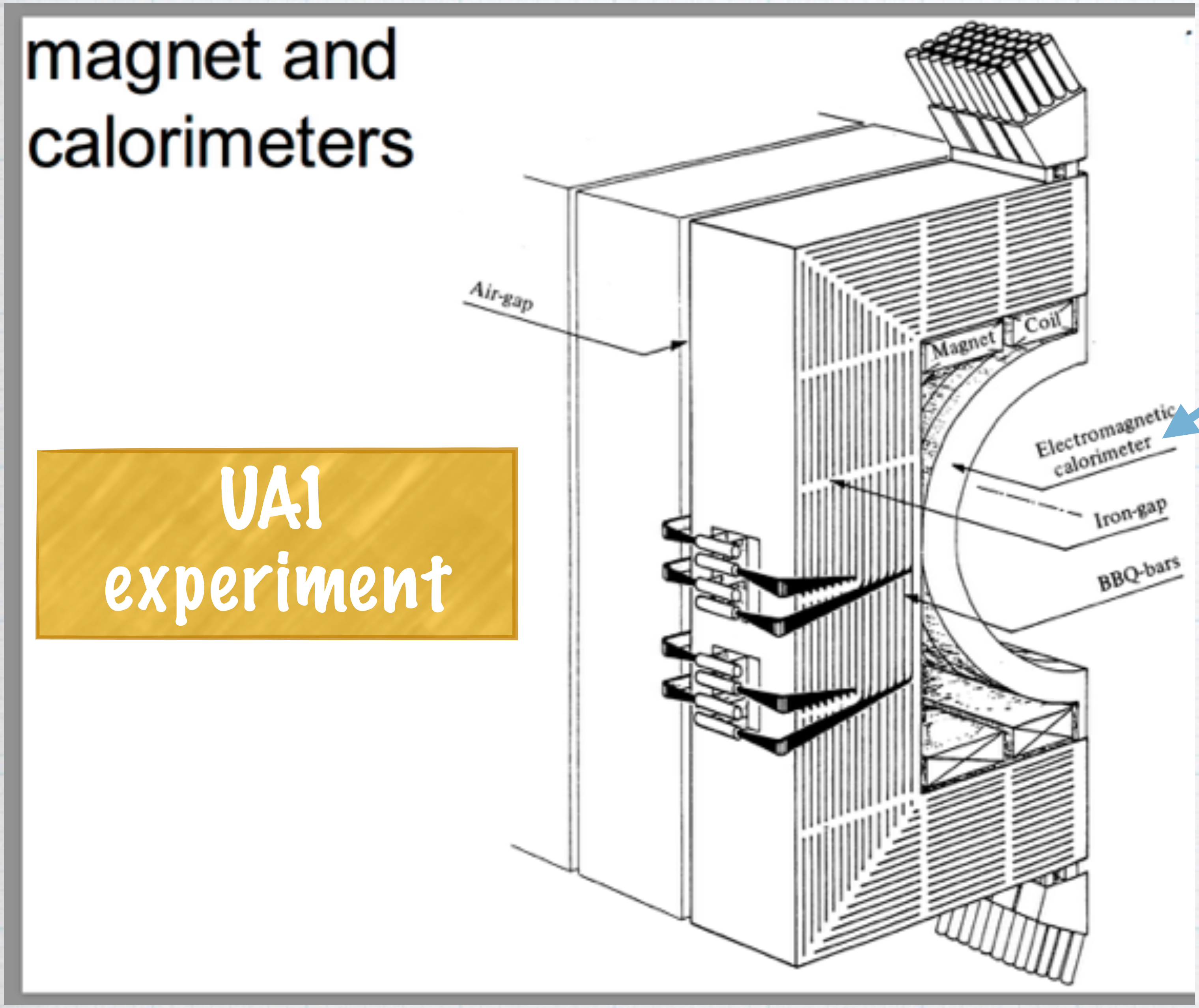
–E/p≈1 for electrons, <<1 for π



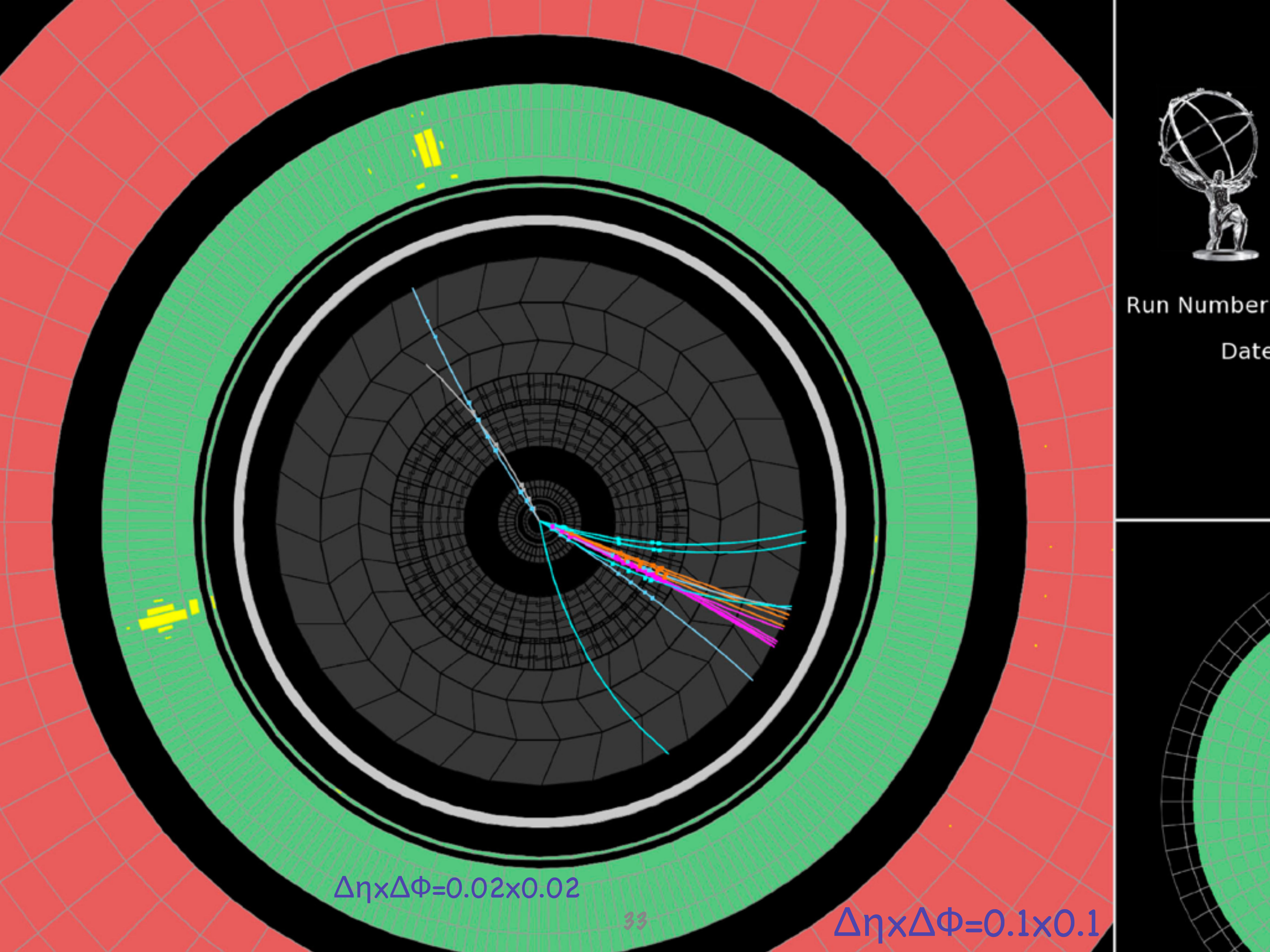
Only muons will be able traverse the calorimeters

Balance the momentum in transverse plane to find hints for neutrino(s). Denoted as MET.

Segmentation



- Gondola Calorimeters
  - What is the problem here?
  - No radial segments! momentum balance in x-y not possible.
  - A good calorimeter should do some crude tracking!..


Run Number
Date
ΔηxΔΦ=0.02x0.02
ΔηxΔΦ=0.1x0.1

ReadOut Chain

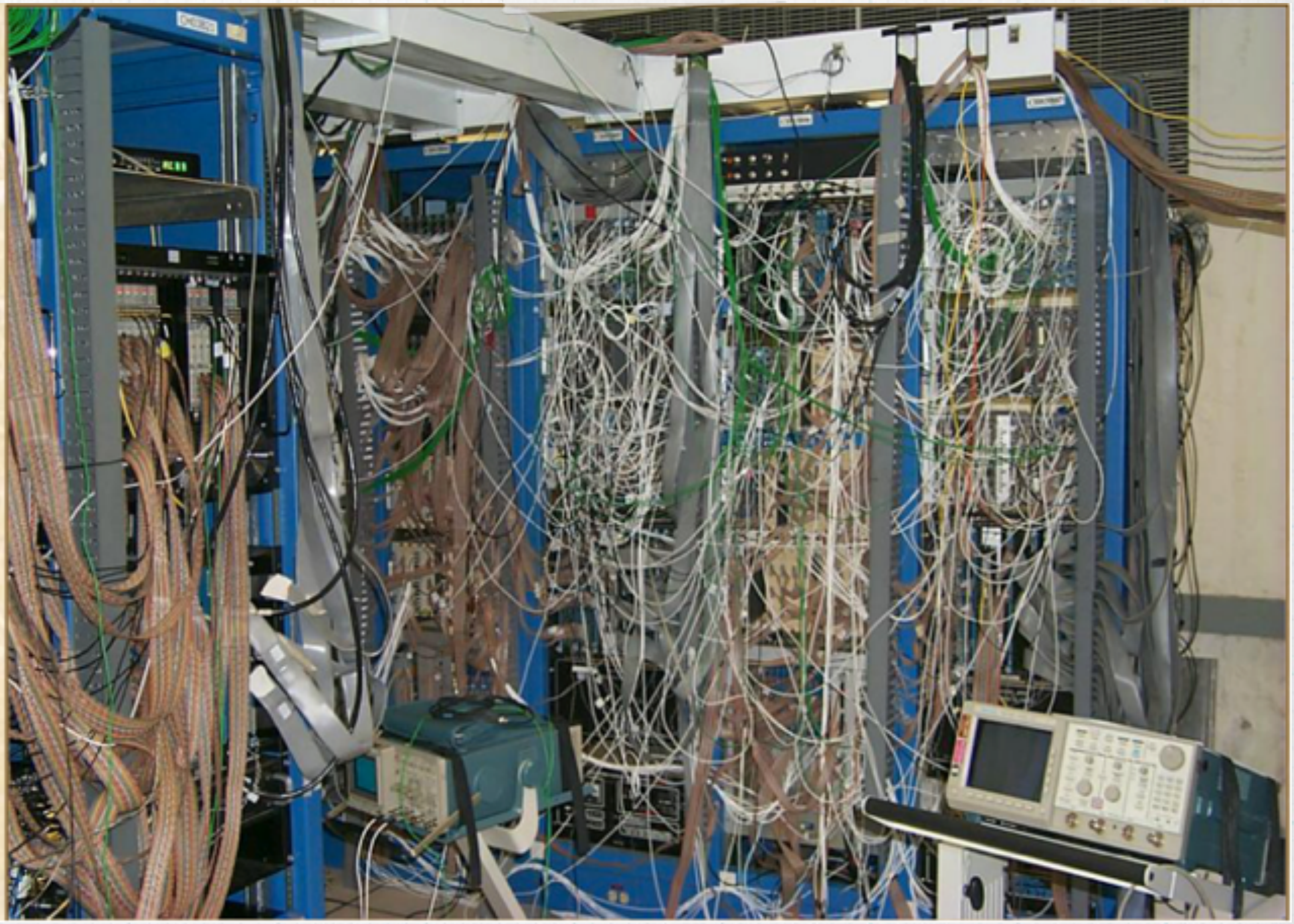
1. pre-amplifer — Strengthen the initial signal to a measureable level
2. discriminator - filter — Reduce noise.
3. buffer (analog) — Used when ADC is not fast enough or an ADC should be shared across channels. Reduces the readout electronics dead-time.
4. digitiser — Convert analog info to digital using standard electronics

In practice achieved using ASICs made by and for HEP exps: low level Front End design.

5. zero-suppression and digital buffering — No need to send channels with 0, but event format should contain channel ID. Alternative: data compression algorithms. Buffering can also be done in RAM.
6. multiplexer — single data path can be shared (in time) between multiple senders and receivers. Beware of synchronization issues.
7. network — Gigabit to infiniband many network solutions are available.
8. storage — Disk servers, tape robots, custom solutions... many choices...

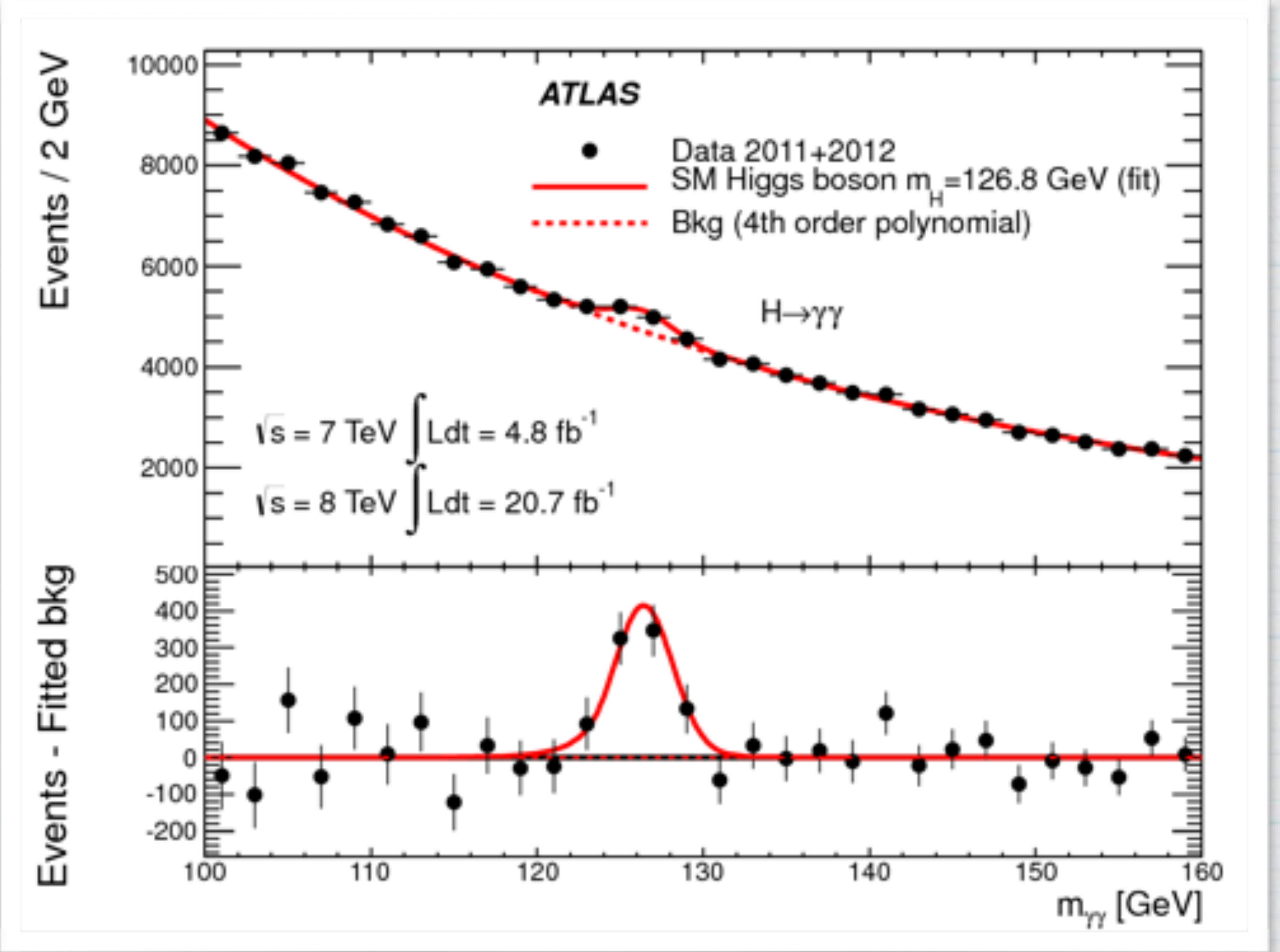
Infrastructure

- Cables (fibers) for power, data, controls
- Pipes for gases, cooling
- Access to the detector
- Mounting tools
- Control room
- Storage of supplies (gas, cooling, spares)



outlook

* Building an experiment requires very diverse competences:
  Physics, detectors, computing, networking, infrastructure, management,...
  * These requirements are technically challenging.
  * Exp. physics needs a broad knowledge in many areas.
* To become a TDAQ person means talking to various experts: one needs at least to know the jargon.
  * Enjoy the rest of the school, especially the exercises.



a successful experiment: Higgs discovery

further reading & references

1. W. R. Leo, “Techniques For Nuclear And Particle Physics Experiments”, Springer-Verlag, 1994

2. F. Sauli “Gaseous Radiation Detectors” Cambridge Univ. Press, 2014

3. C. Grupen & B. Shwartz “Particle Detectors” Cambridge Univ. Press, 2008

4. R Wigmans “Calorimetry: Energy Measurement in Particle Physics”, Clarendon Press, 2000

5. ATLAS, CMS, BaBar, LHCb, D0 etc. TDR reports (various dates)

6. CERN Summer Student Lectures on Particle Detectors 2002