ISOTDAQ XI

with DIY examples

Introduction to detectors and detector readout

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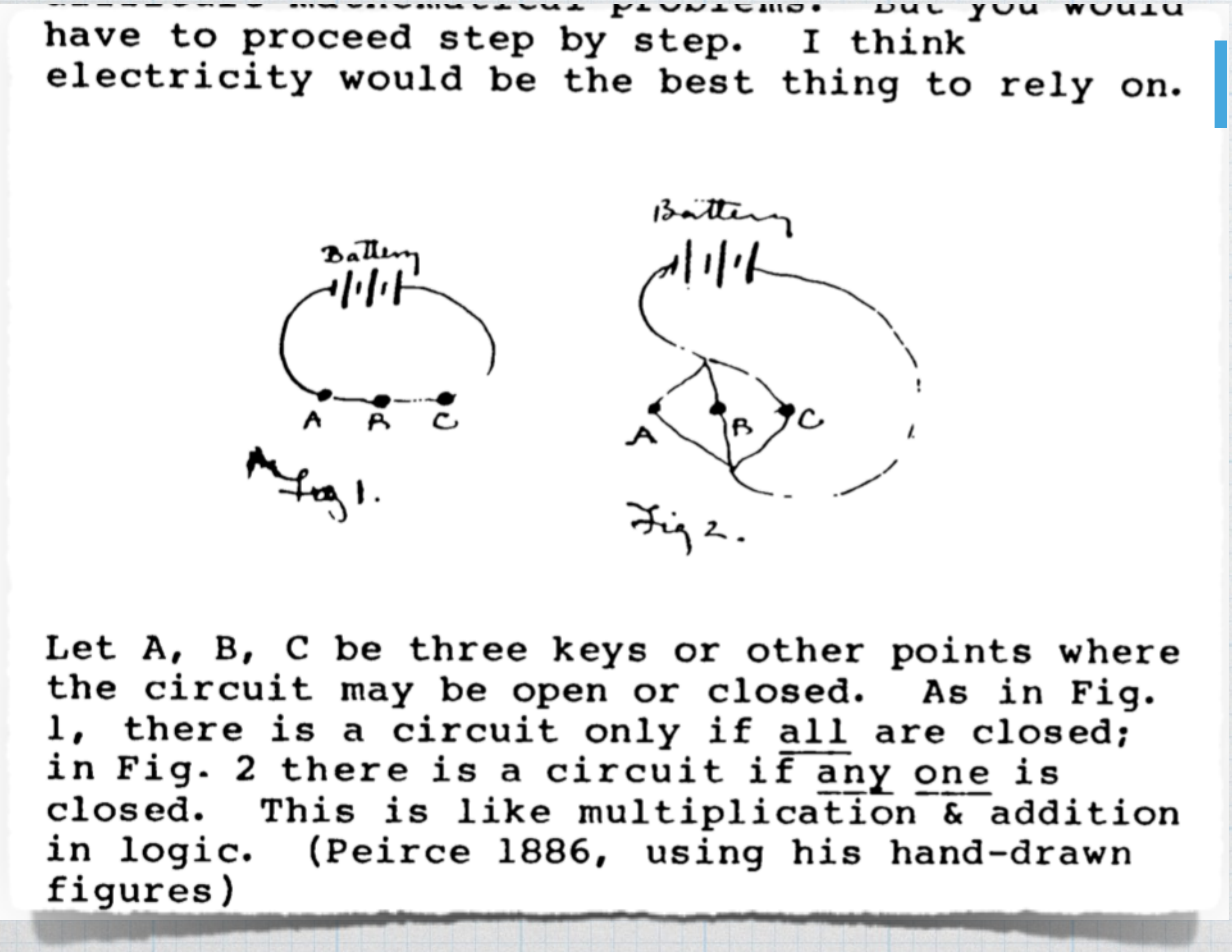


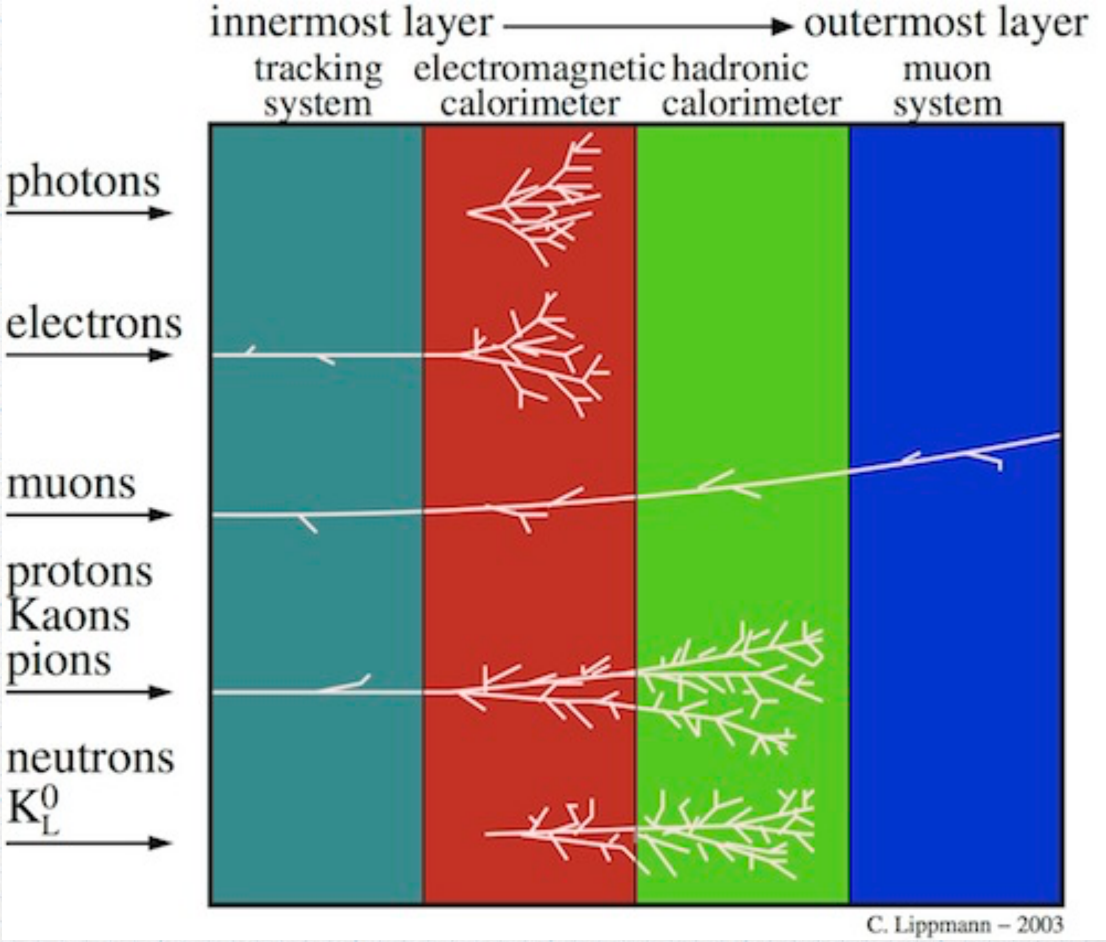
have to proceed step by step. I think electricity would be the best thing to rely on.

Let A, B, C be three keys or other points where the circuit may be open or closed. As in Fig. 1, there is a circuit only if all are closed; in Fig. 2 there is a circuit if any one is closed. This is like multiplication & addition in logic. (Peirce 1886, using his hand-drawn figures)

In an 1886 letter, Charles Sanders **Peirce** described how **logical** operations could be carried out by **electrical** switching **circuits**. ... Using this property of **electrical** switches to implement **logic** is the fundamental concept that underlies all electronic digital computers.

What do we detect & why

- Measure time
  - position, beam profile — **tracking**
  - Particle momentum, charge — spectrometer
- Measure charge
  - Faraday Cup
  - Energy — **calorimetry**
- Without forgetting
  - reading & routing signals
  - buffer, digitize, multiplex
  - Care for infrastructure
  - HV/LV PS, Gas and cables!

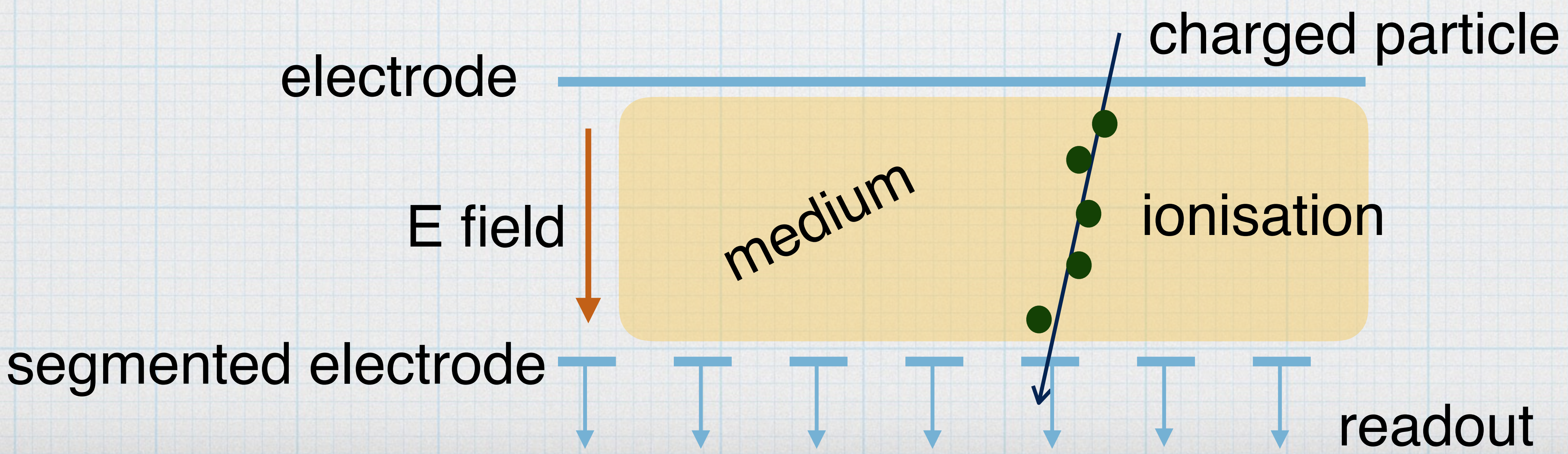


- Mostly electromagnetic interactions
- A bit of strong interactions
- Very little weak interactions

Particle 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

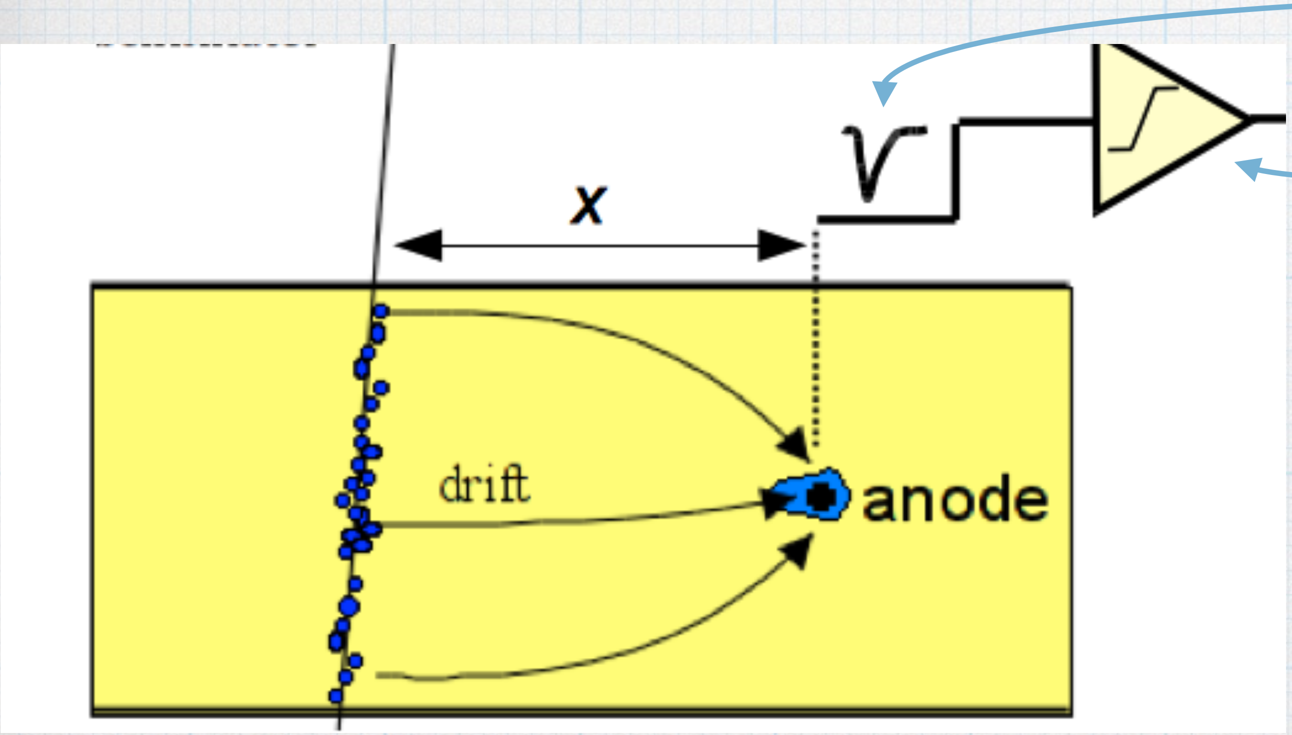


wire chamber as a tracker

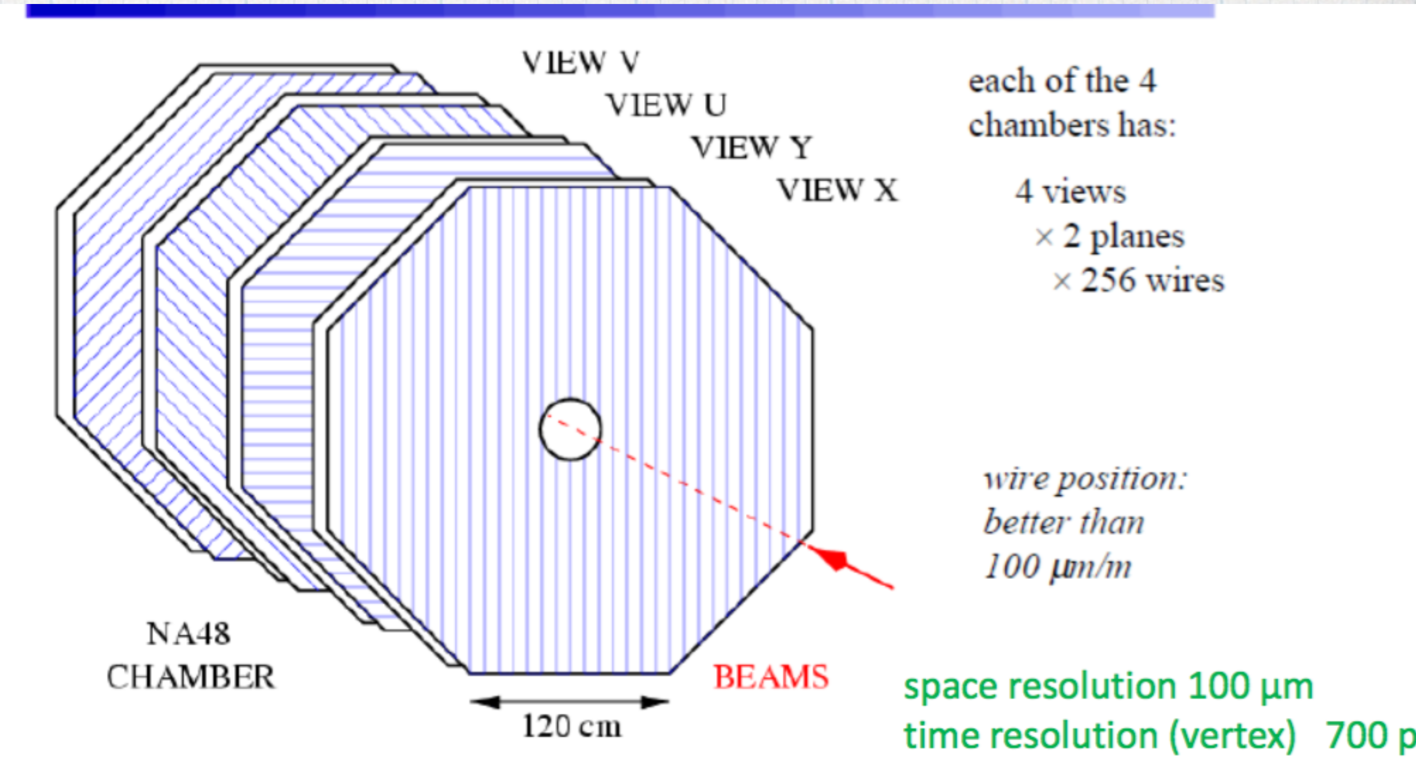
- Better positioning: electrode perpendicular to particle track
  - ➡position: $x = c_0 + c_1\Delta t + c_2\Delta t^2$....
  - ➡Δt: drift time of electrons to anode wire (under positive HV)
  - ➡We need a Time to Digital Converter: TDC
- Space resolution: 80 — 200 µm (small is good)
- "Low mass" (guess?) 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



each of the 4 chambers has:
4 views
× 2 planes
× 256 wires

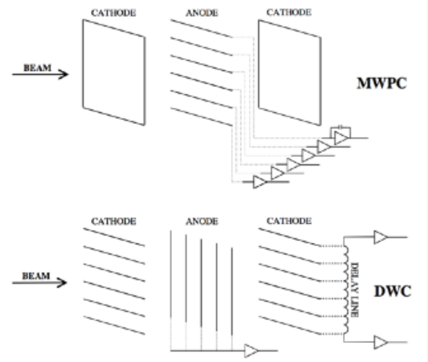
wire position: better than 100 µm/m

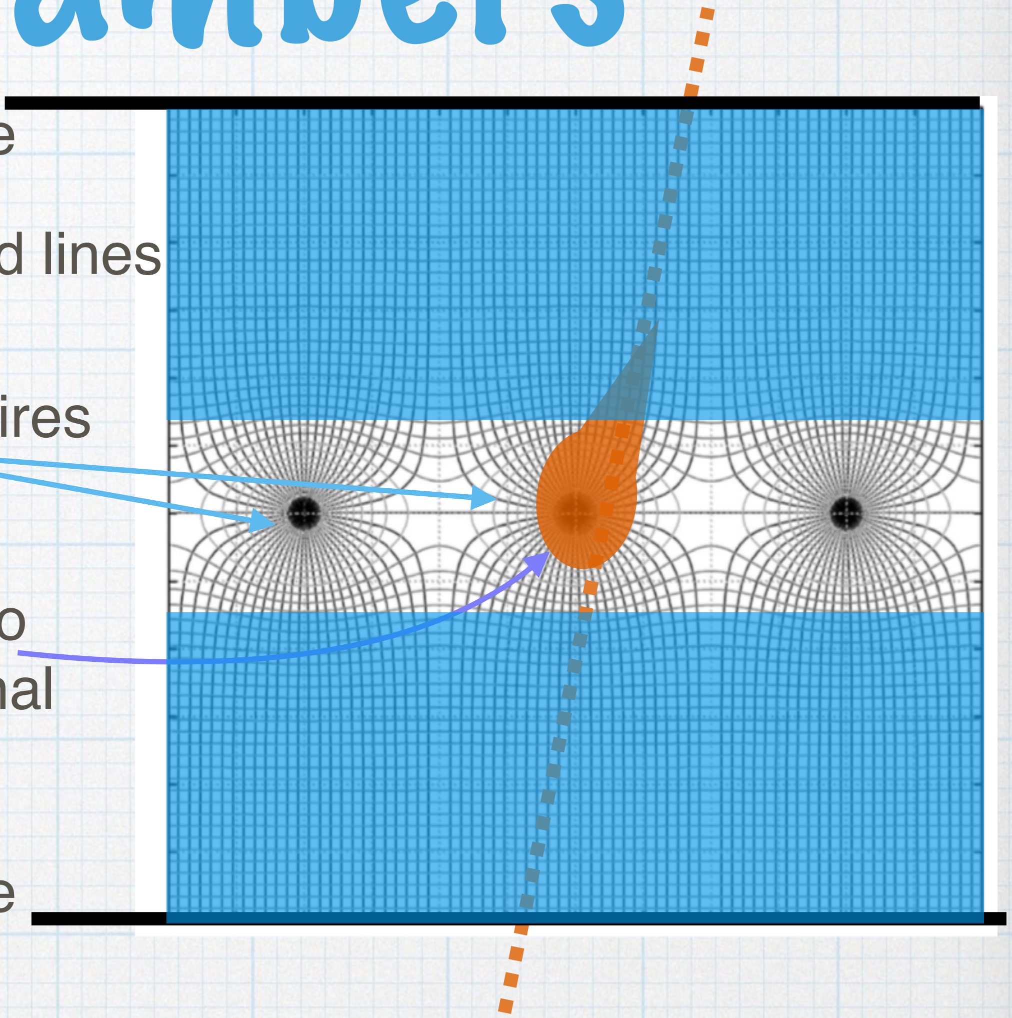
space resolution 100 µm
time resolution (vertex) 700 p

other “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

~3kV





Cathode plane

E Field lines

Anode (signal) wires

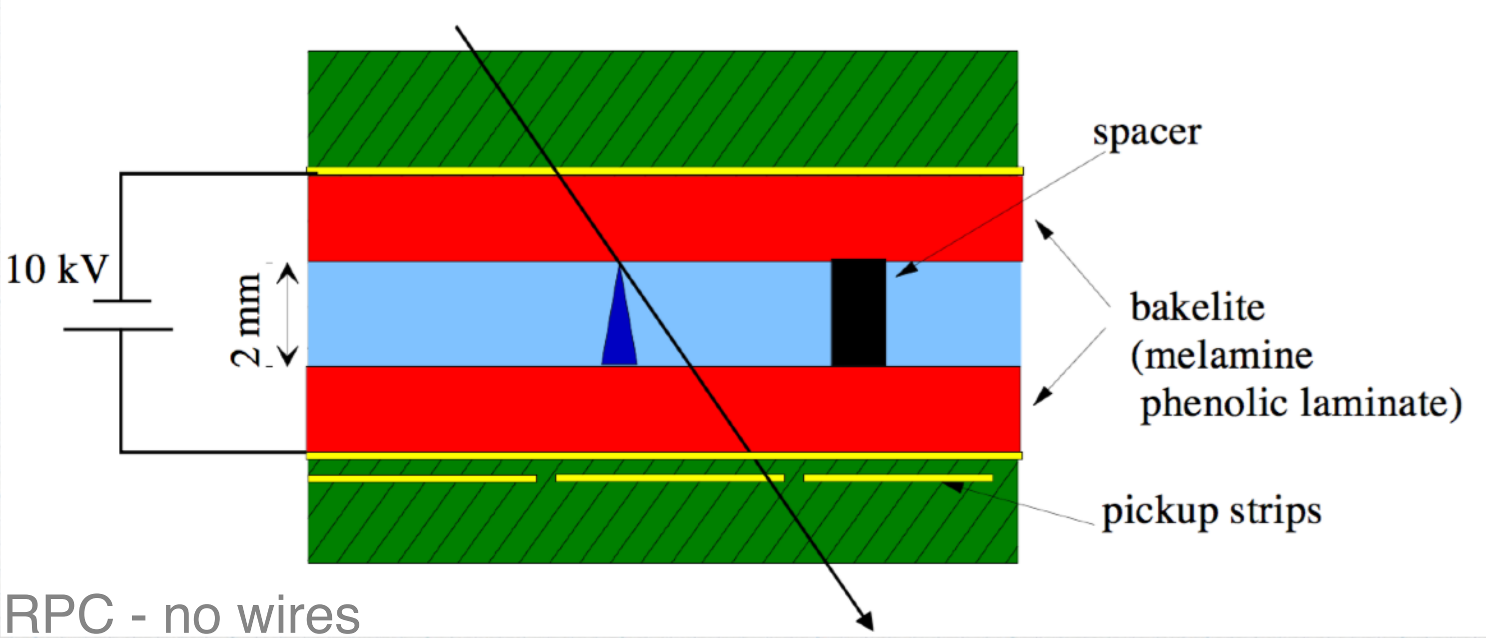
Avalanche region to produce a large signal

Cathode plane

charged particle track

- Resistive Plate Ch - Thin Gap Ch
  - supports a very high rate of 1 - 20 kHz/cm^2
  - Trigger chambers with 1cm resolution
    - RPC: $C_2F_4H_2$(97%) - i-C_4H_{10}
    - TGC: CO_2(55%)- i-C_5H_{12}
- Time Projection Ch
  - 3D tracking + Energy

d(a-c) < d(w-w)

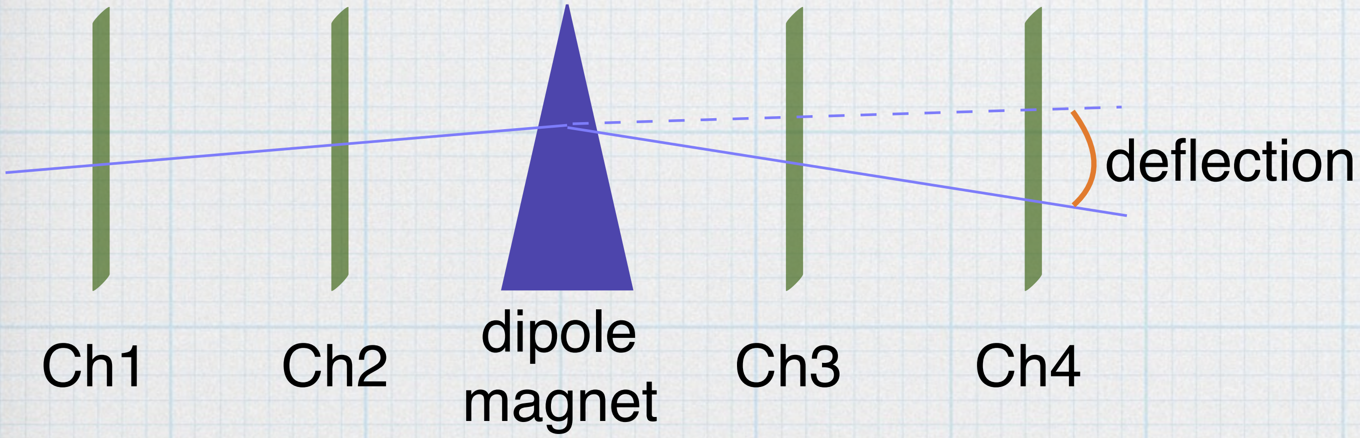


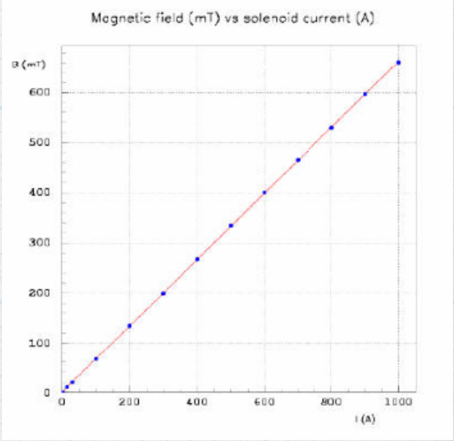
RPC - no wires

magnet + few DCW = spectrometer

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

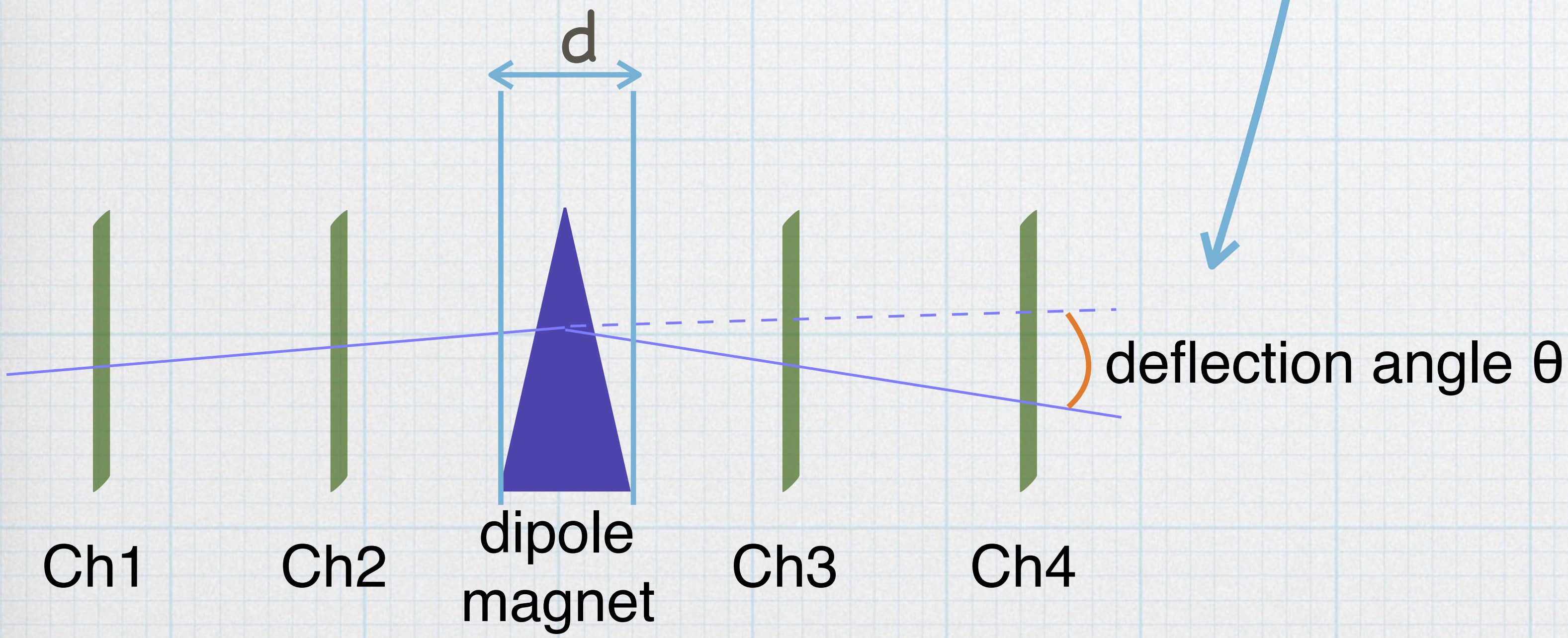
- In a fixed target experiment typically a dipole magnet is used. Bending power must be well known.

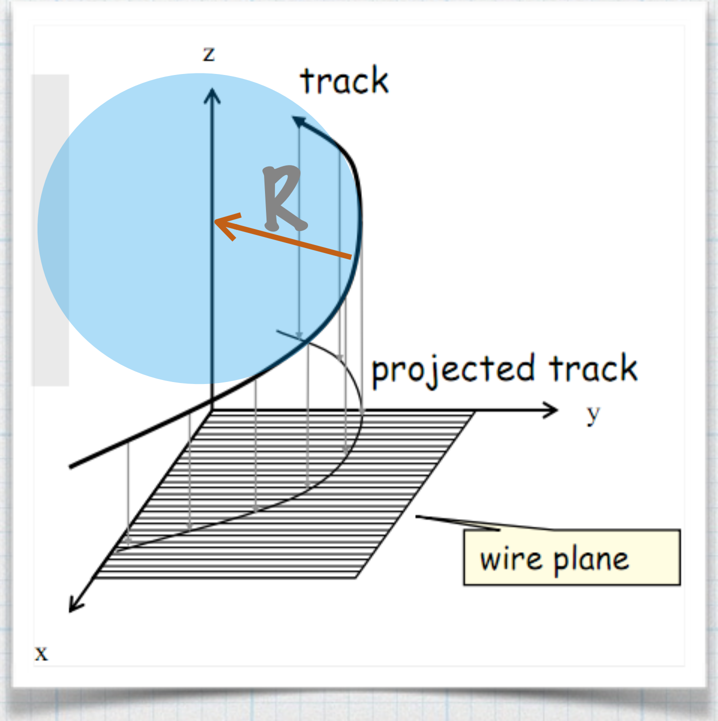




for a constant B field

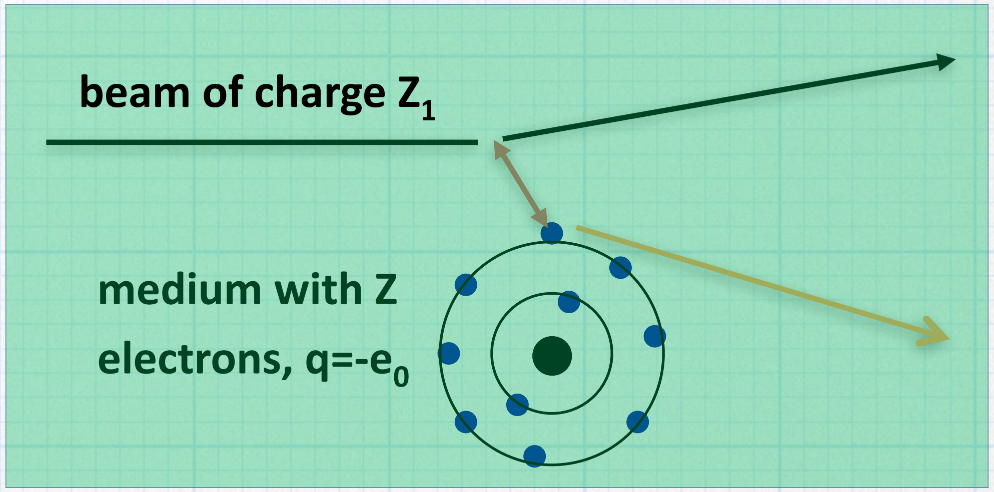
- measure deflection to find the momentum p perpendicular to the field
  - $p(\mathrm{GeV}) = 0.3\ Z\ B(\mathrm{T})\ R(\mathrm{m})$
  - $p(\mathrm{GeV}) = 0.3\ Z\ B(\mathrm{T})\ d(\mathrm{m}) / [2 \sin(\theta/2)]$
  - where
    - Z: Particle Charge
    - d: Field length
    - θ: Deflection angle
   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



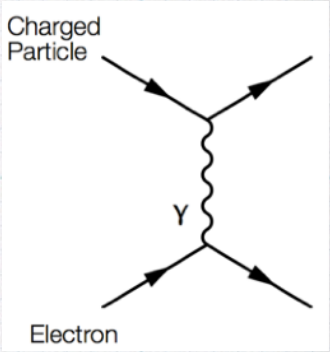


what about signal height?

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


beam of charge Z_1

medium with Z electrons, $q=-e_0$

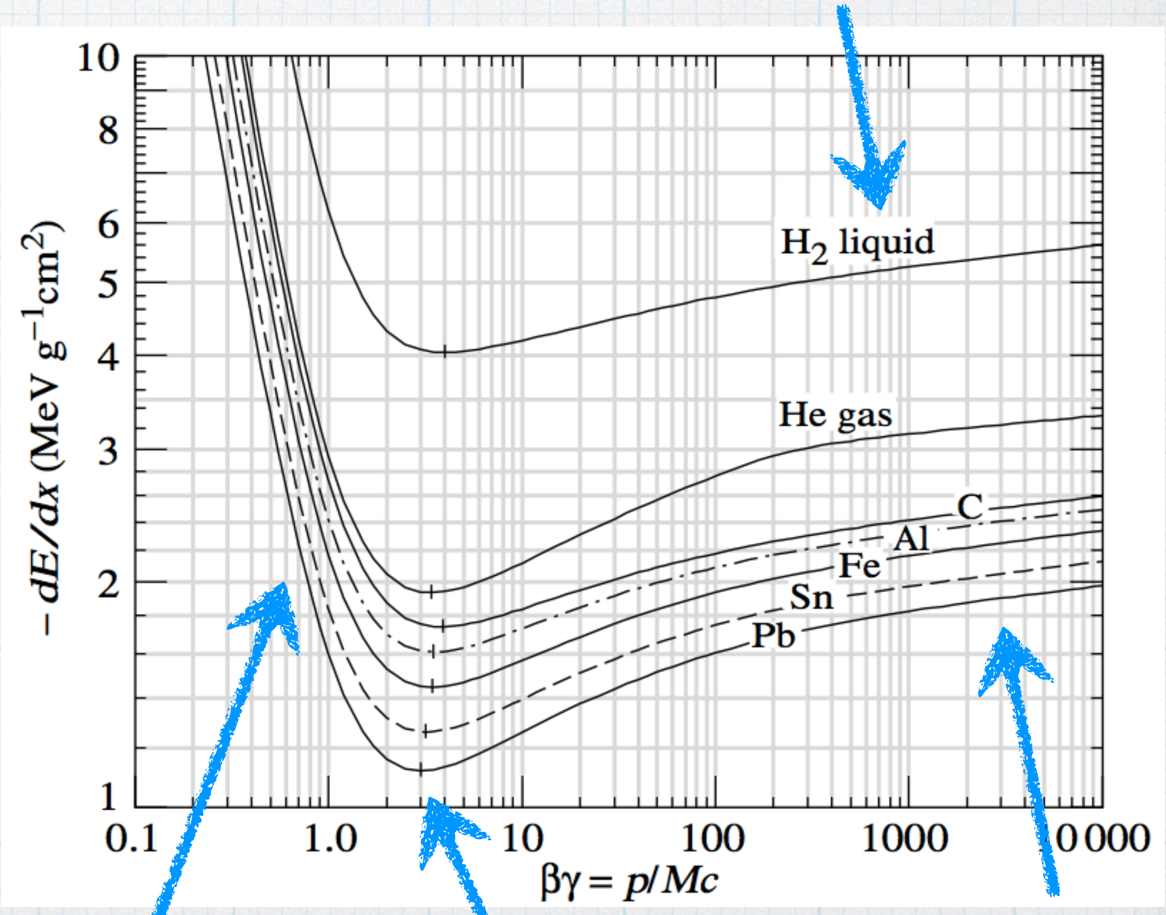


- <dE/dx>: mean energy loss per unit length of a particle which has
  - charge Z_1 and speed β
  - in a medium with atomic number Z and atomic mass A

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

- 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



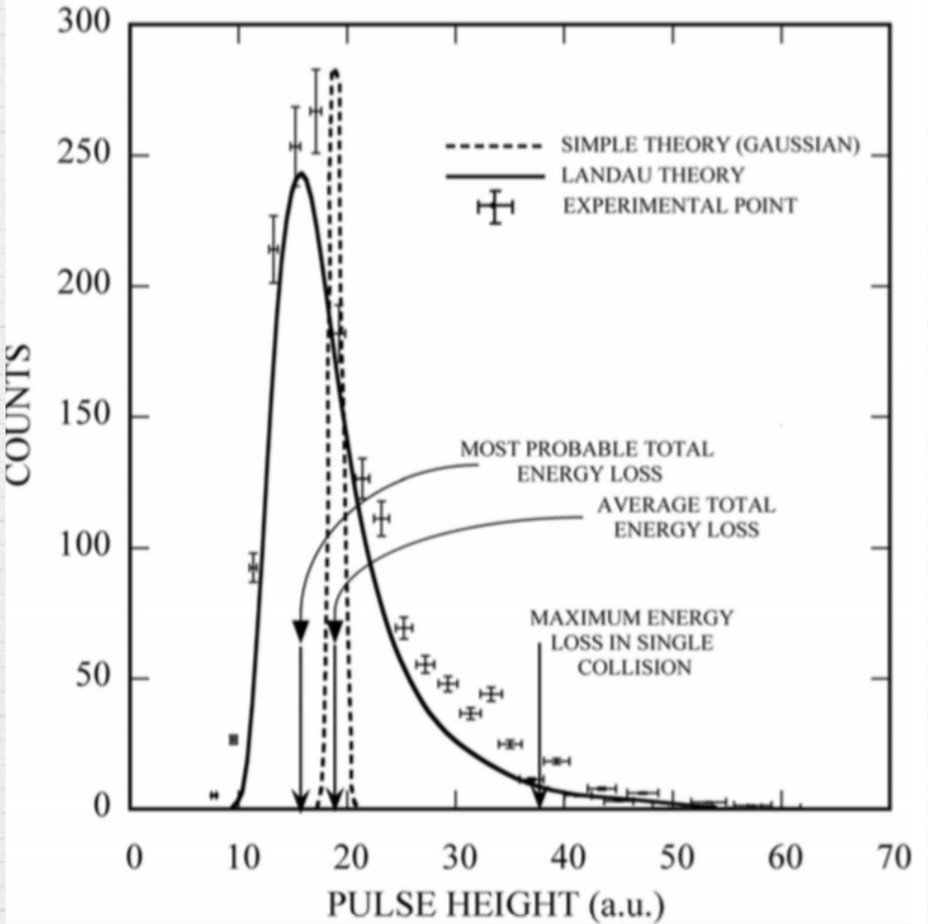
kinetic term: $\langle dE/dX\rangle \propto \beta^{-2}$

βγ ≈ 3-4 : minimum ionisation.

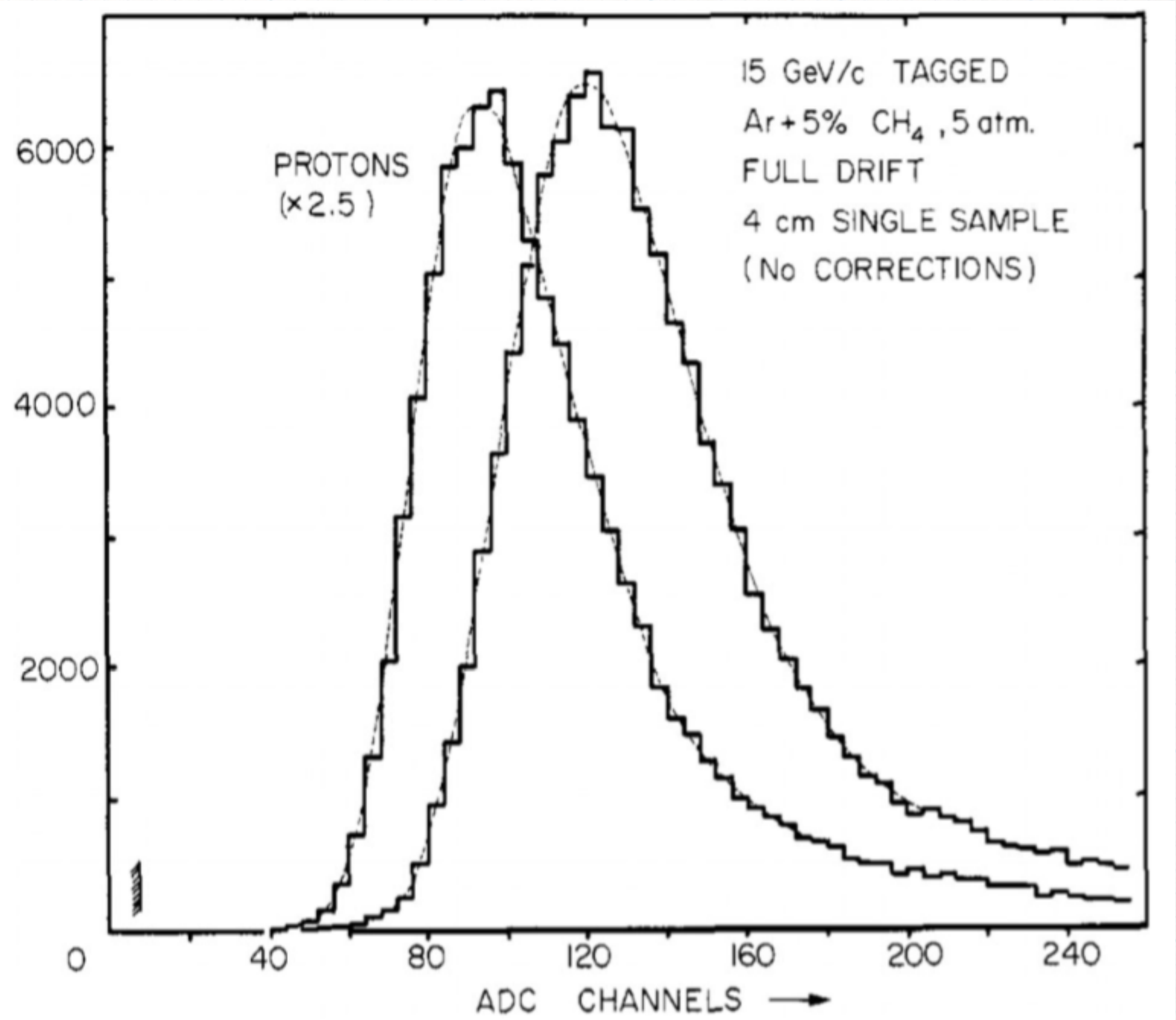
Fermi plateau

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



dE/dx



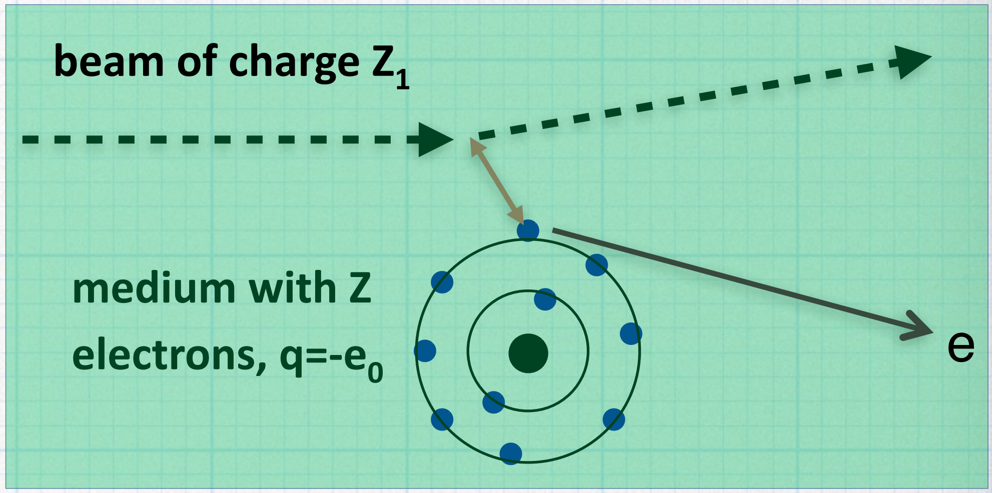
- Accurate measurement of primary ionization cloud is difficult, since the cloud can be quickly smeared by diffusion during its drift to a collecting electrode.

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

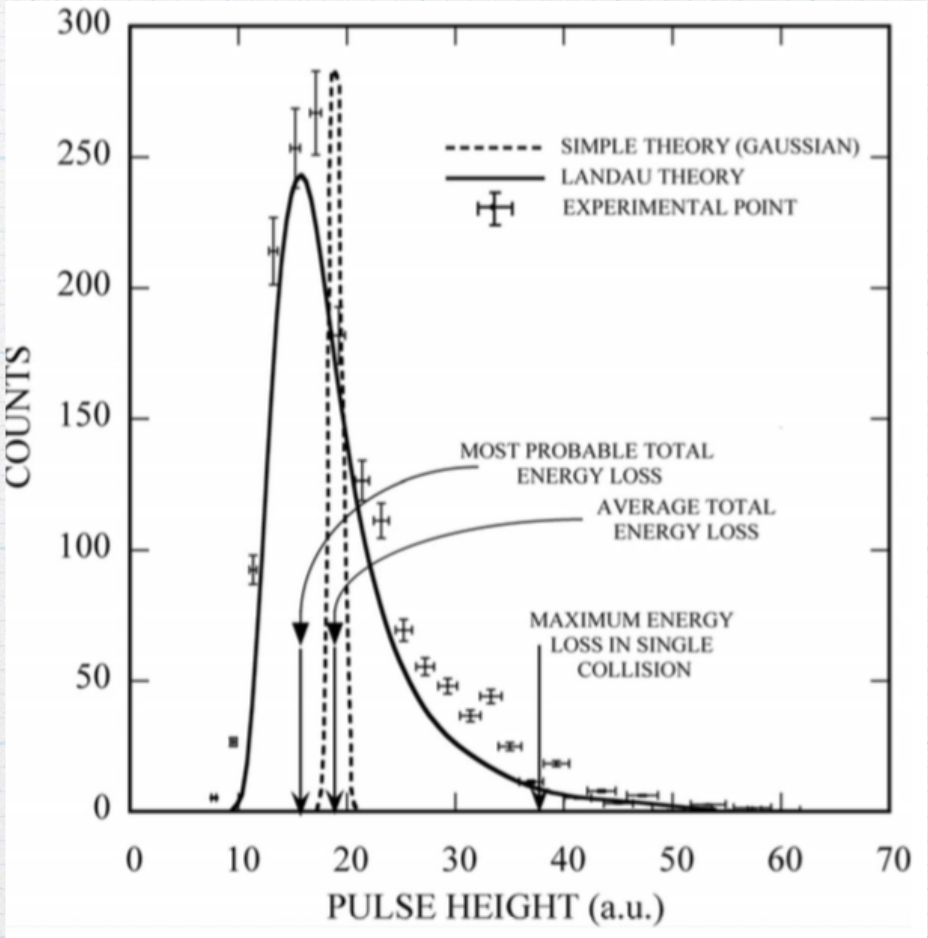
- need for detectors reading singal proportional to particle energy

what about signal height

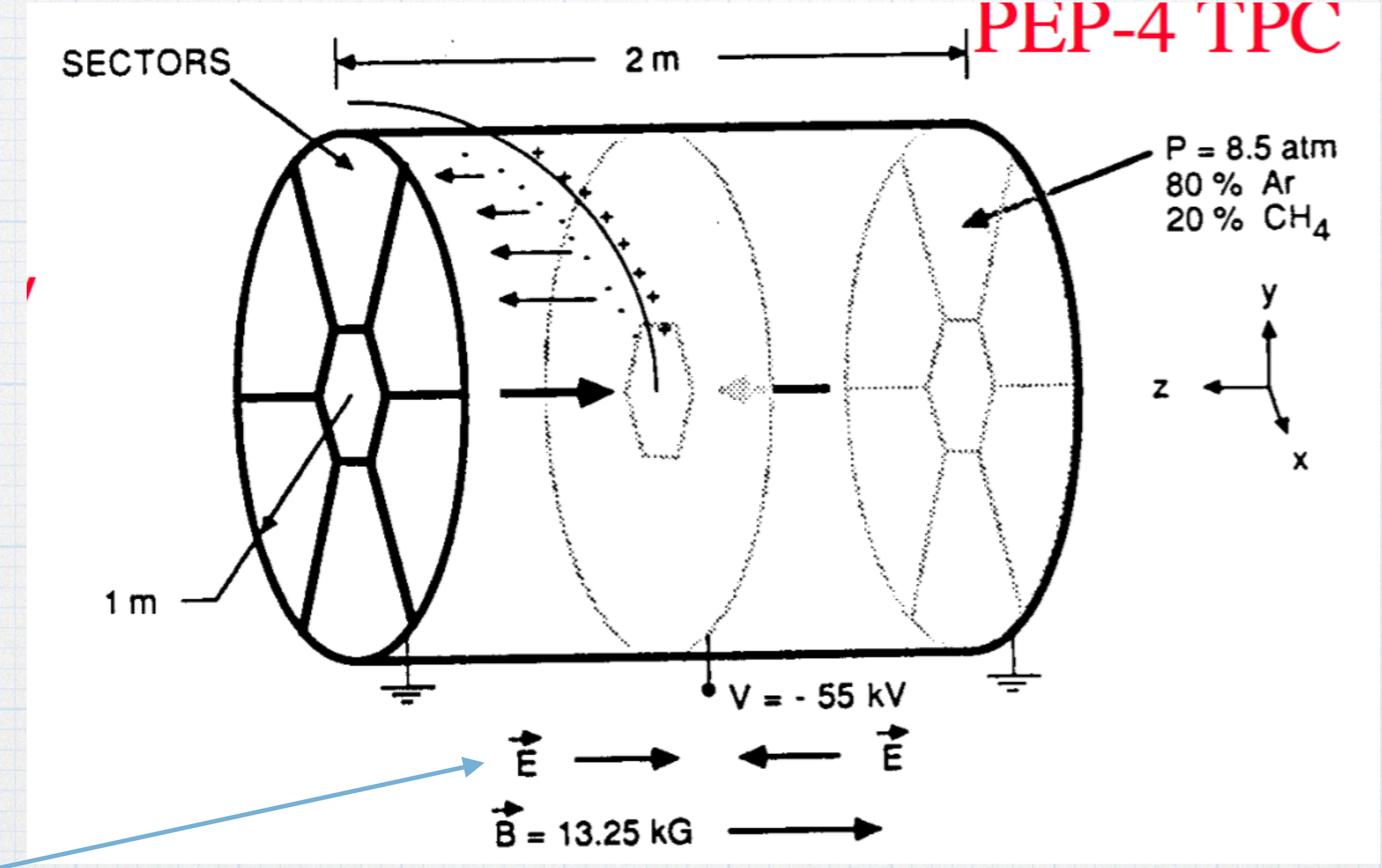
- mean Energy loss / unit length by ionisation was studied by Bethe, it depends on
  - beam charge Z_1 and speed β(=v/c)
  - medium's atomic number Z and atomic mass A
- After Bethe, Landau figured out most probable pulse height function
  - This is what we try to measure to find particle E energy by integrating the signal (measure charge)
  - find E and p —> You identify particle!



ionisation



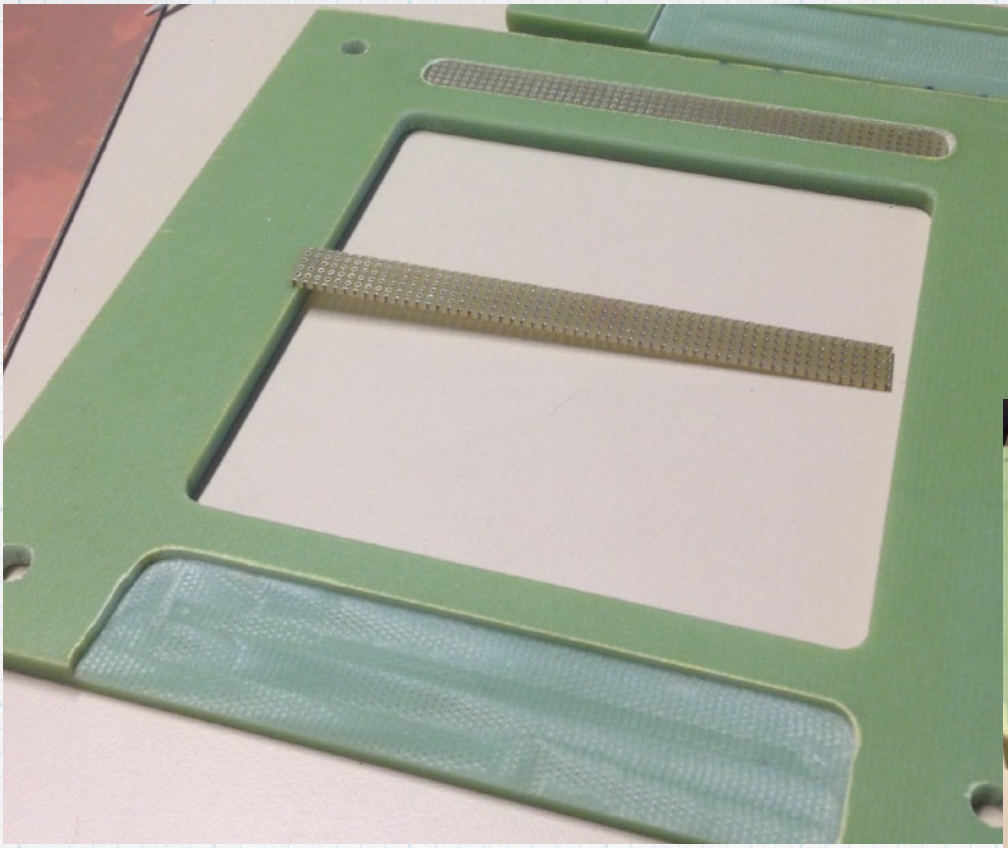
Time Projection Ch

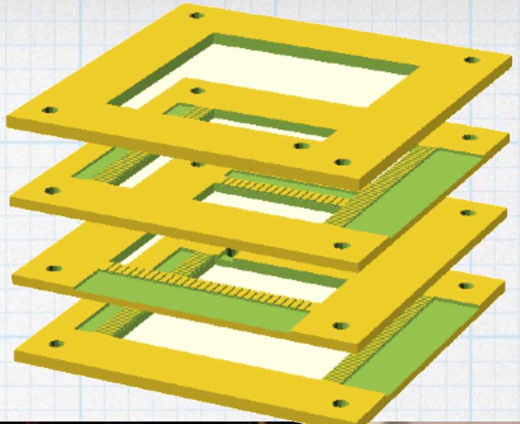


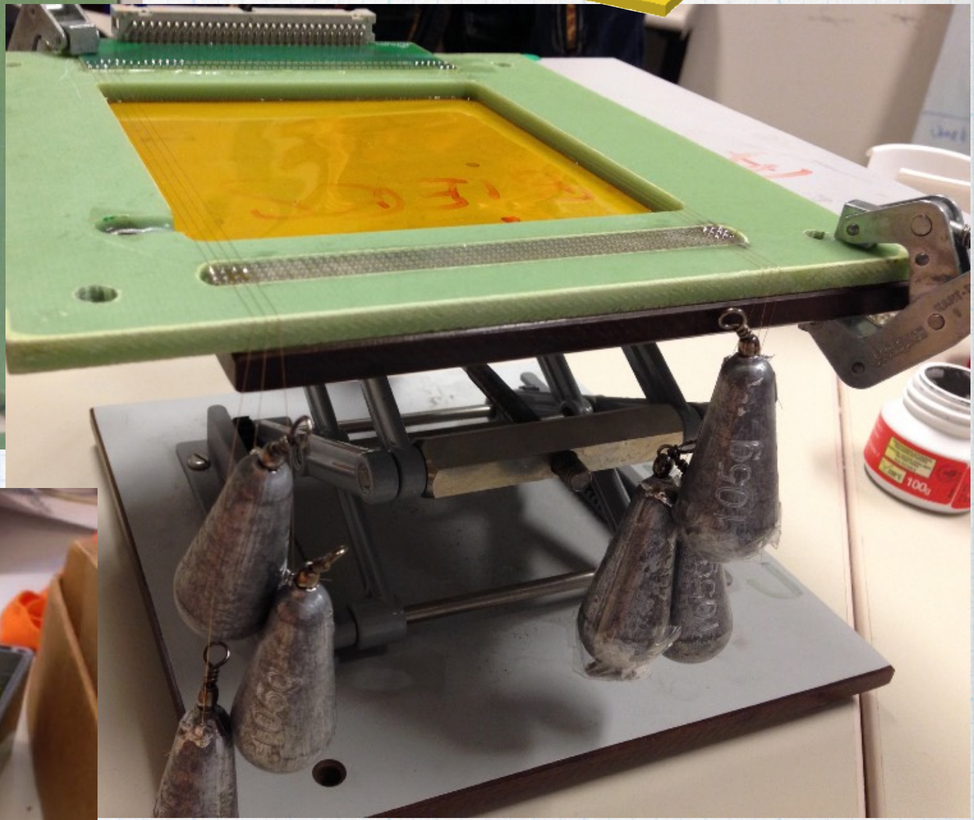
downside of TPC?

- 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

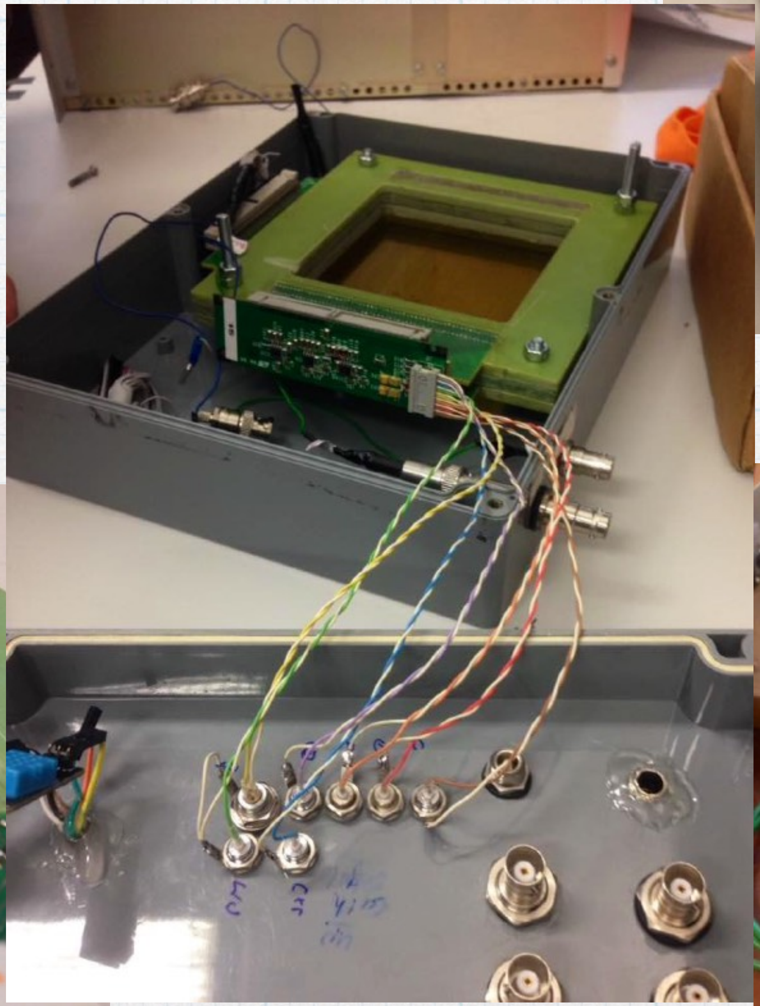
particle identification

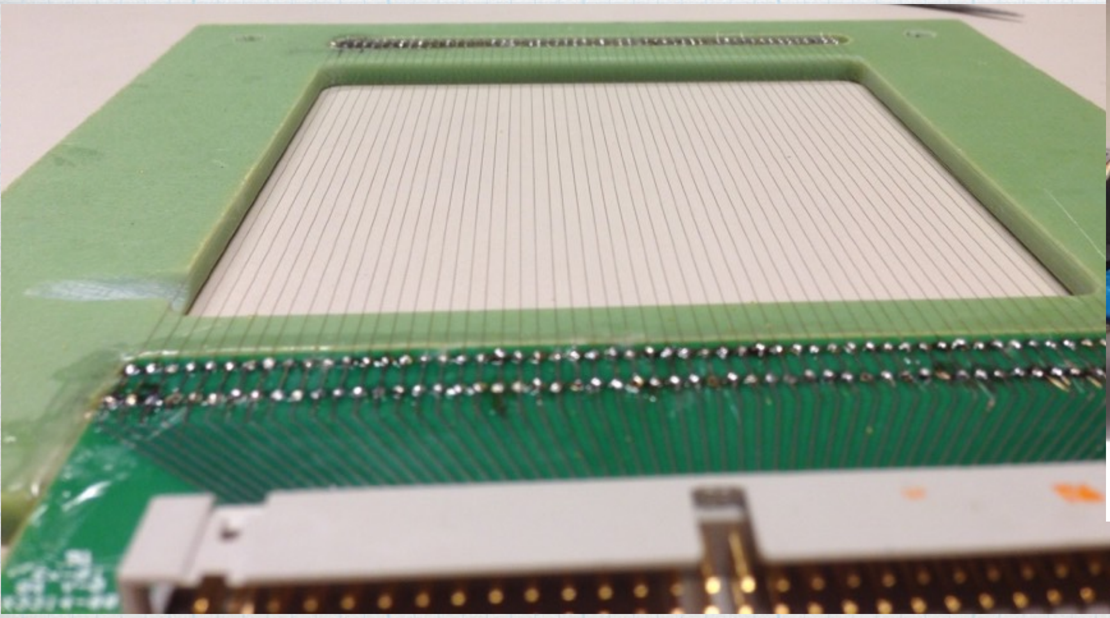




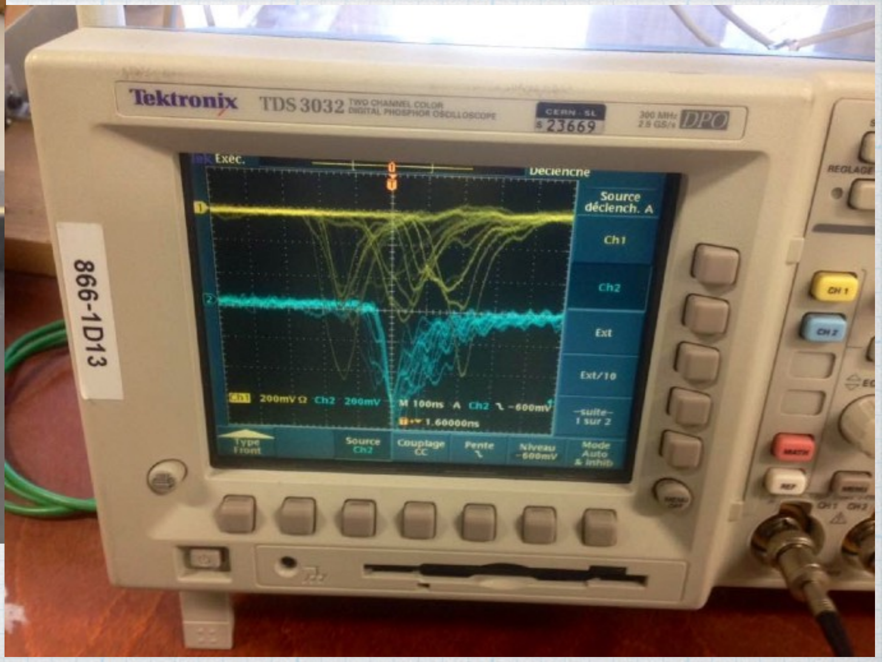


build your own DWC

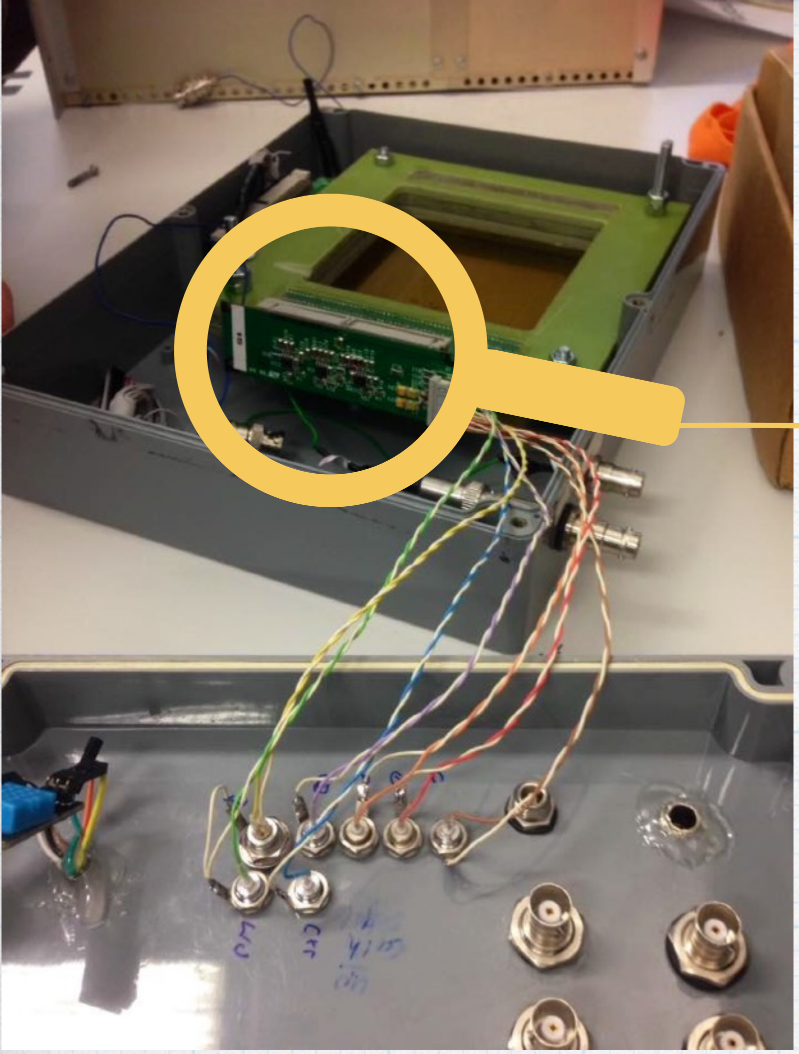




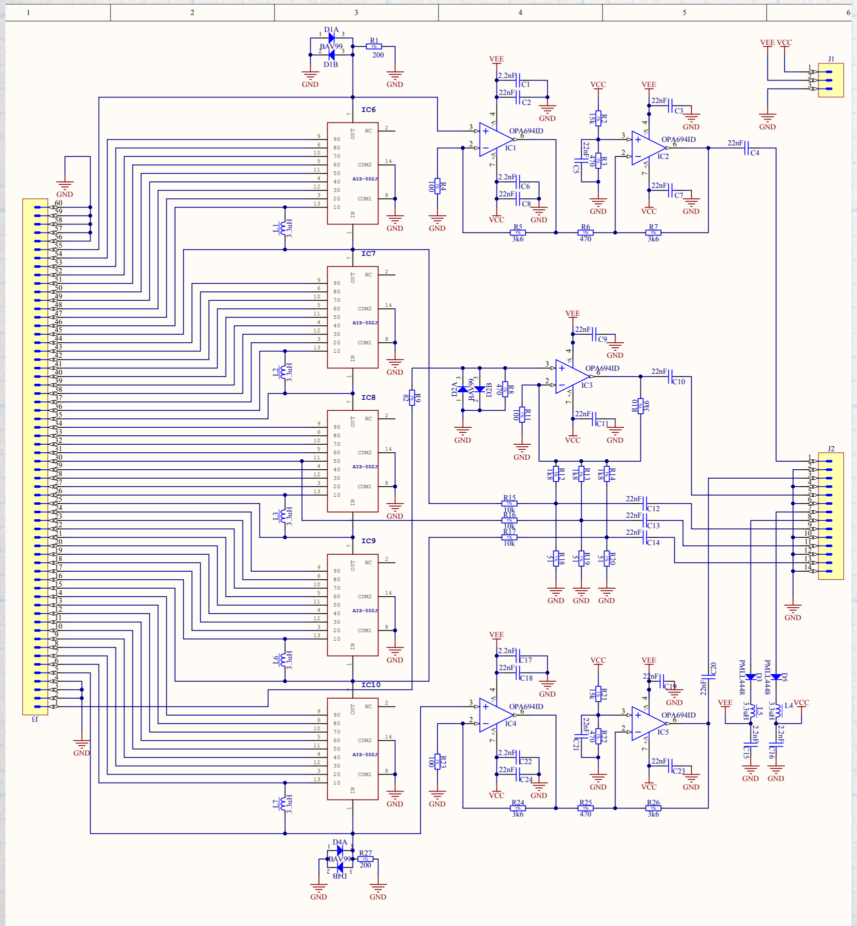
with Sr90 β source

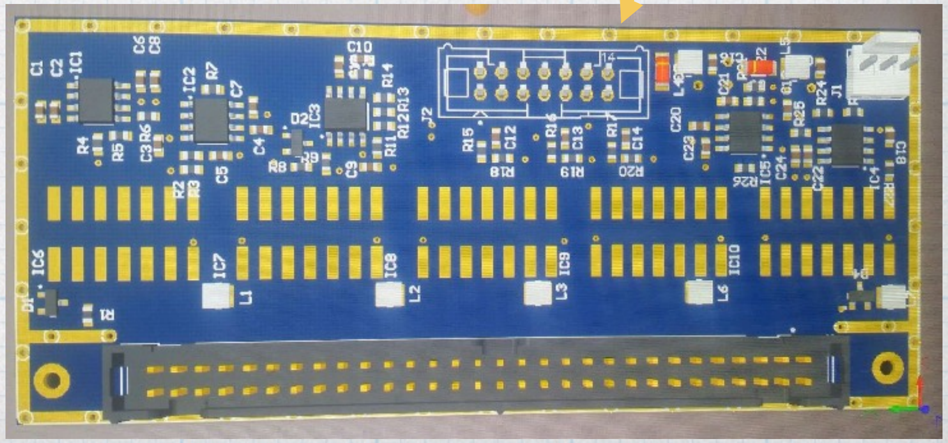


Read out electronics



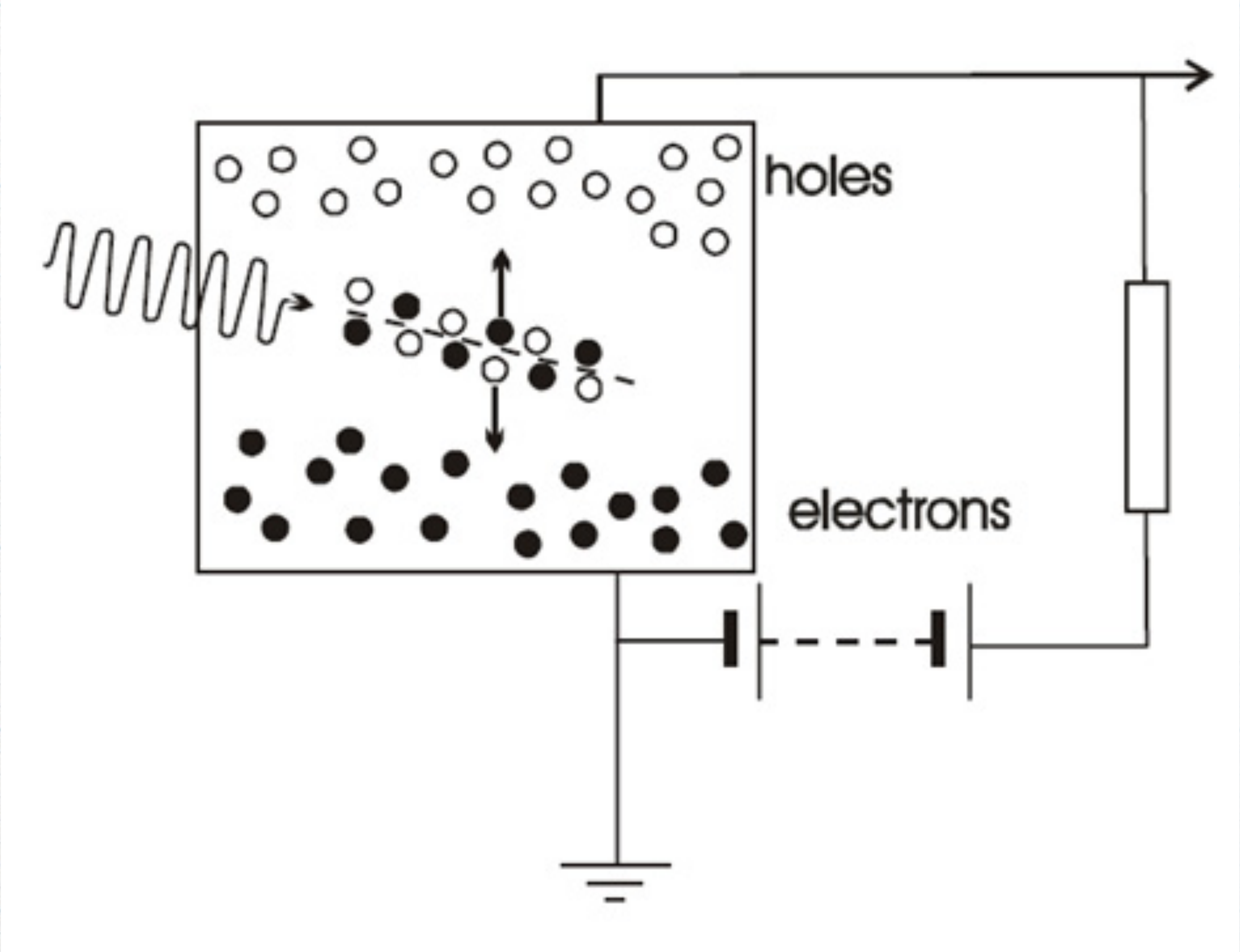
- Signals directly from the active sensors are seldom fit for reading out by generic (modular) electronics: We need to shape, (pre)amplify, invert the original signal.
- Items to consider for a good circuit
  - Input impedence, Output typically 50Ω
  - fast, low power, low noise components
  - grounding faraday-cage, twisted cable, ground plane etc. for noise reduction
  - multilayer PCB vs cost issues, SMD components
  - buy spares! (safety)
  - always prototpye
  - always simulate
  - learn spice, eagle,...



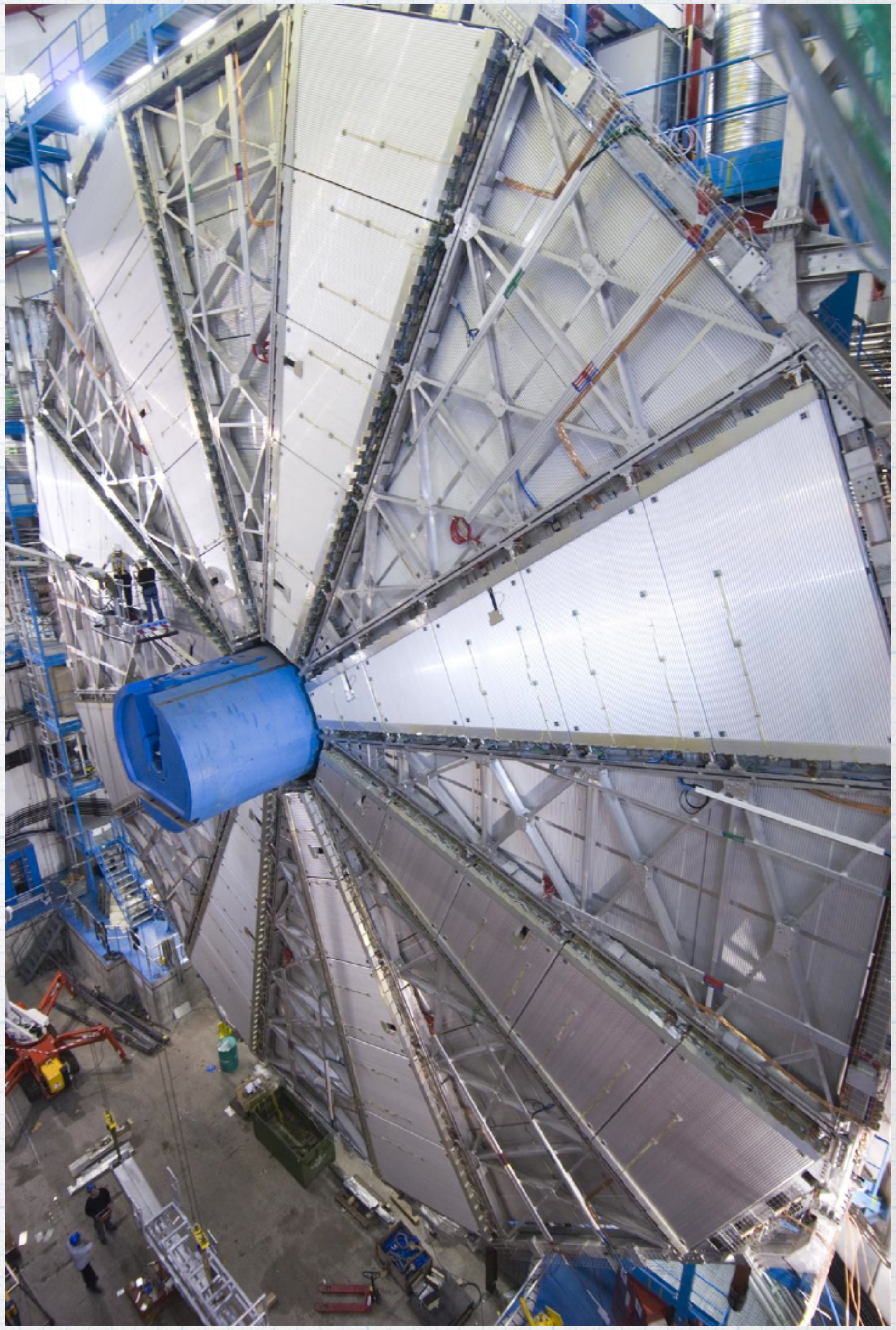


Silicon as the ionisation medium

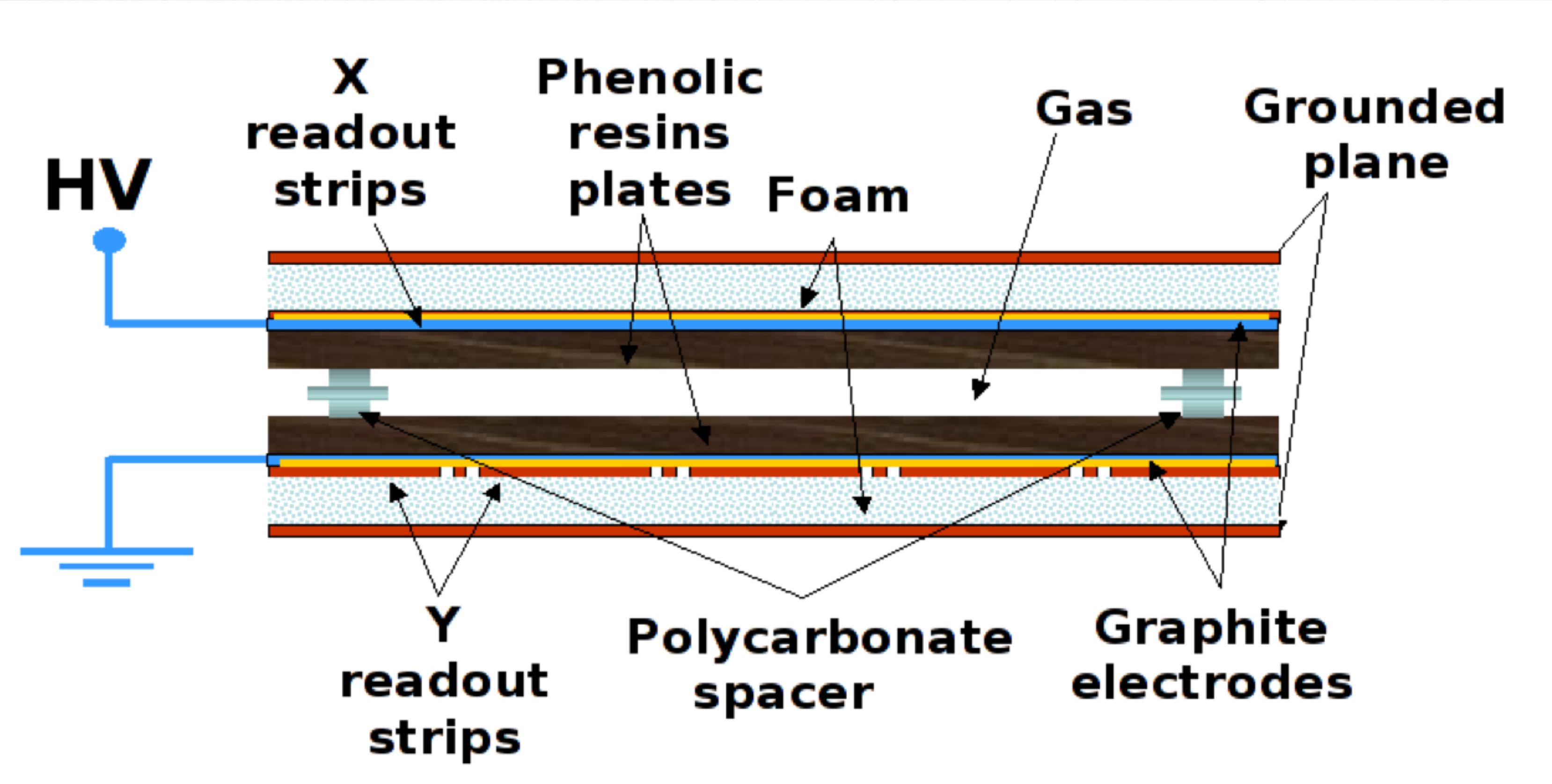
- Same working principle as the gaseous chamber
- Advantages
  - much smaller areas can be instrumented
  - smaller bias voltage needed (LV: 100V)
  - better resolution: about 10μm
- Disadvantages
  - Thermal noise can give fake signal
  - Cooling is necessary
  - Expensive detector
  - Many (100k) readout 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.



Scaling up

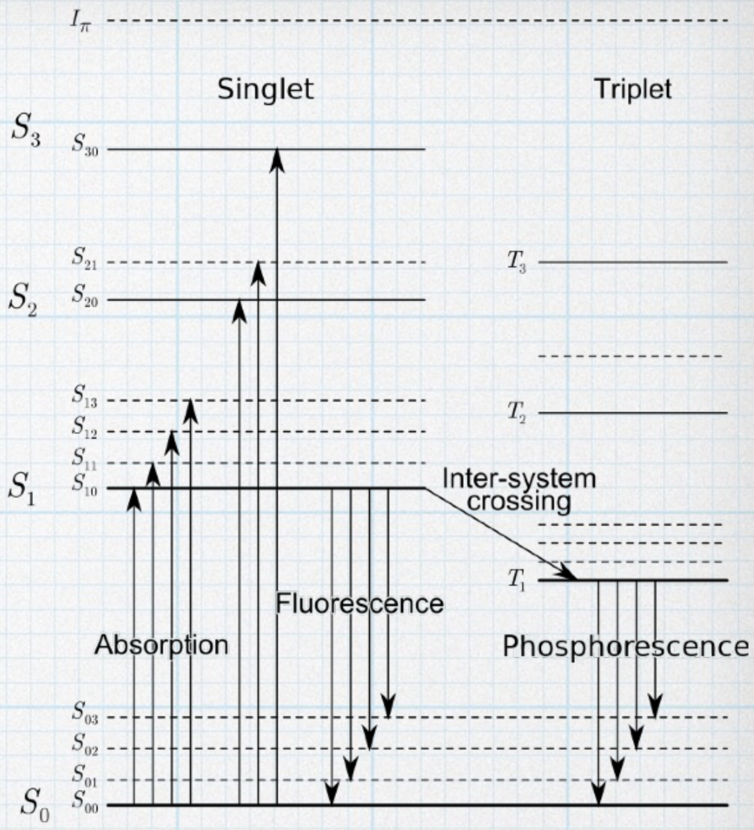


Remove the wire

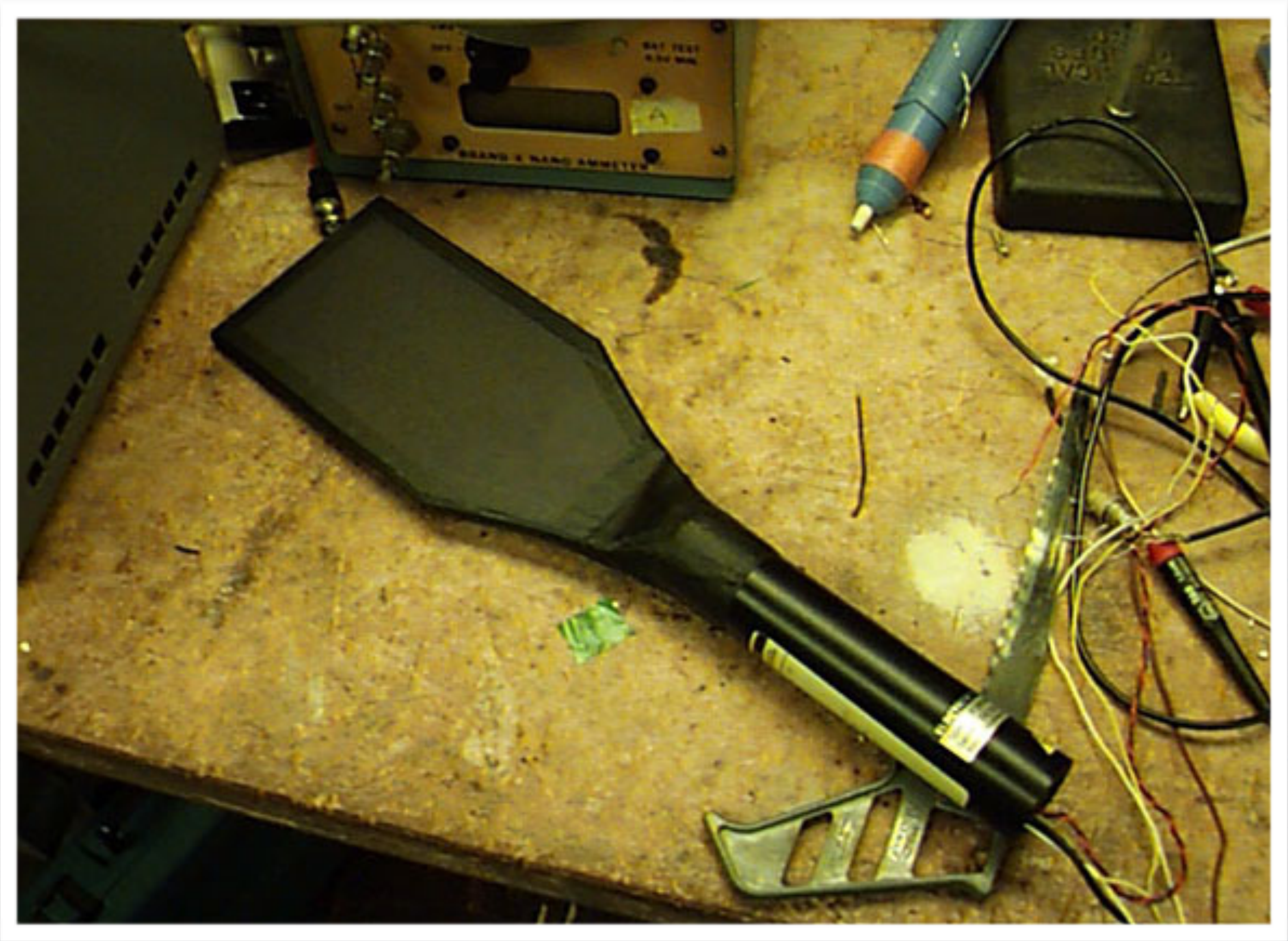


Scintillators

W. Crookes 1903, ZnS screen



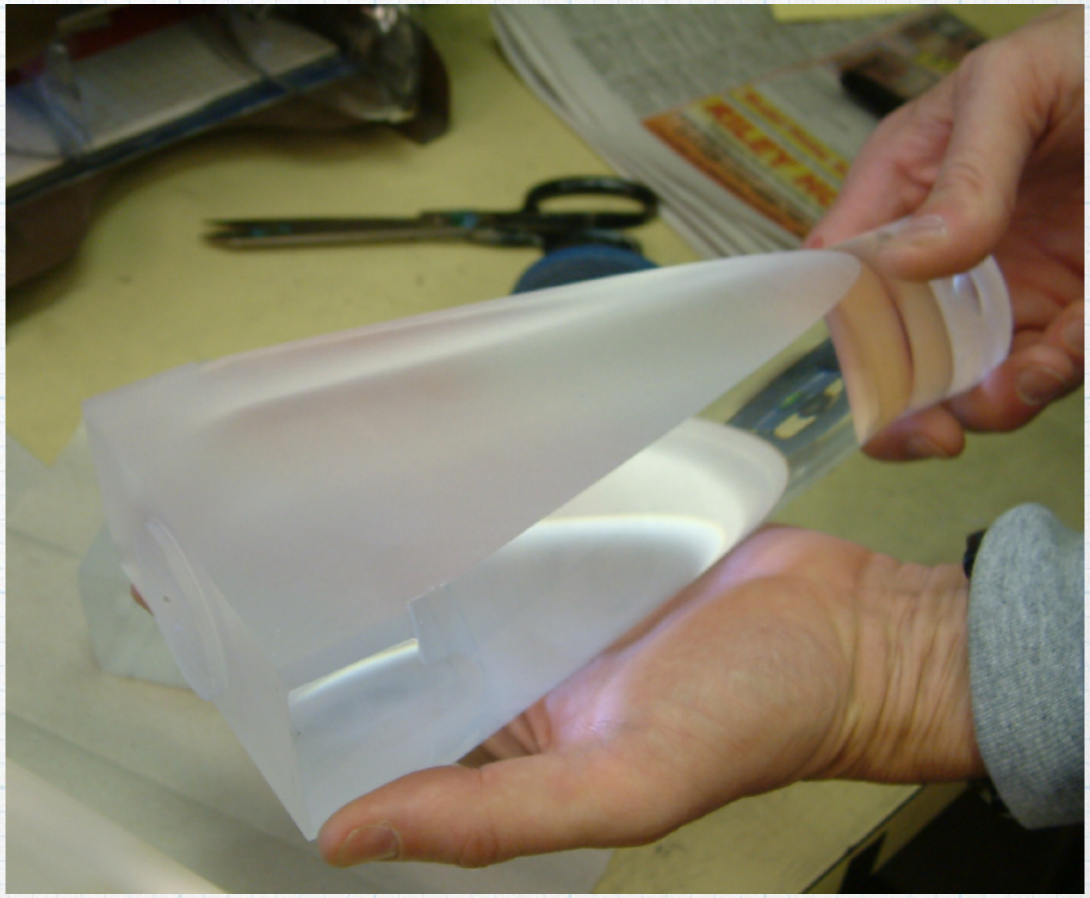
- Scintillation principle
  - energy absorbed by the atoms, and emitted as light "later on".
  - fast(fluorescence) and slow (phosphorescence) components.
- Converts the energy deposited by traversing particles into light: scintillation mechanism
  - ≈40 photons/keV NaI(Tl),
  - ≈10 photons/keV plastic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

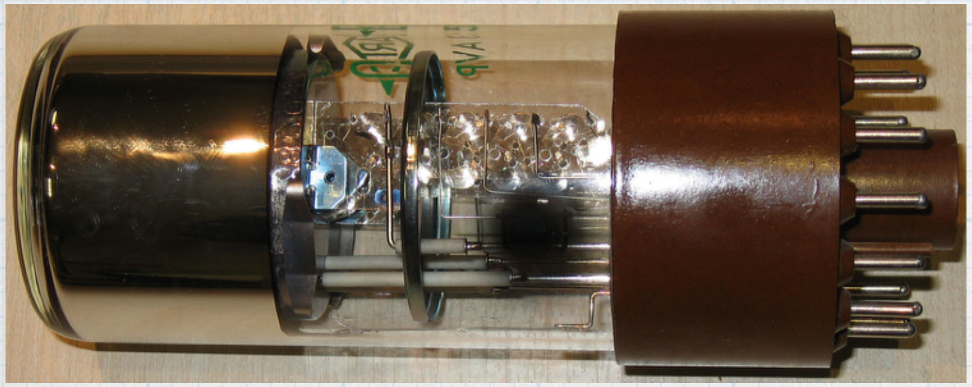


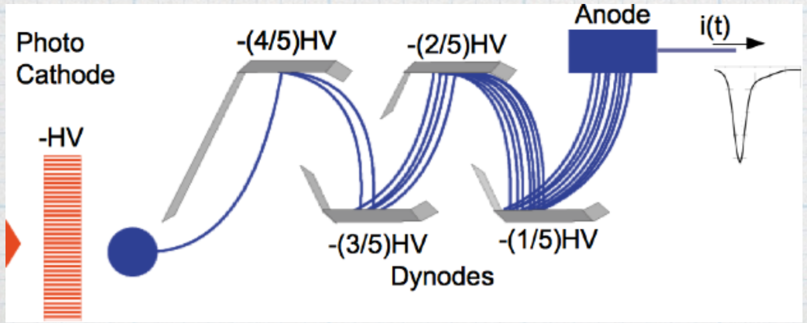
scintillator detector components

Polystyrene

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



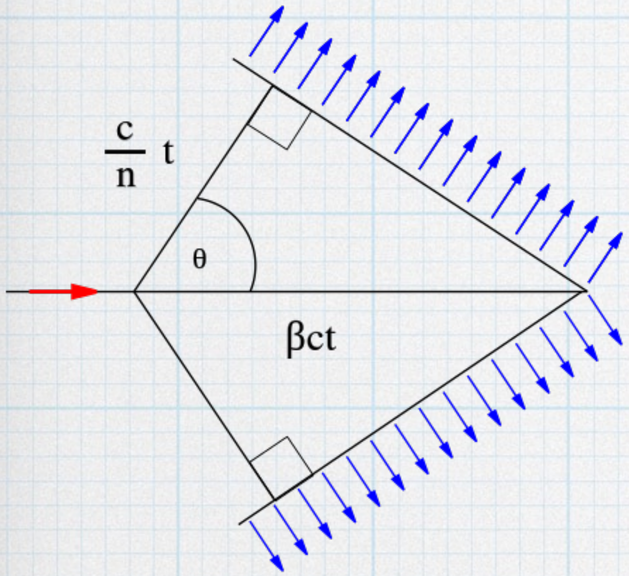


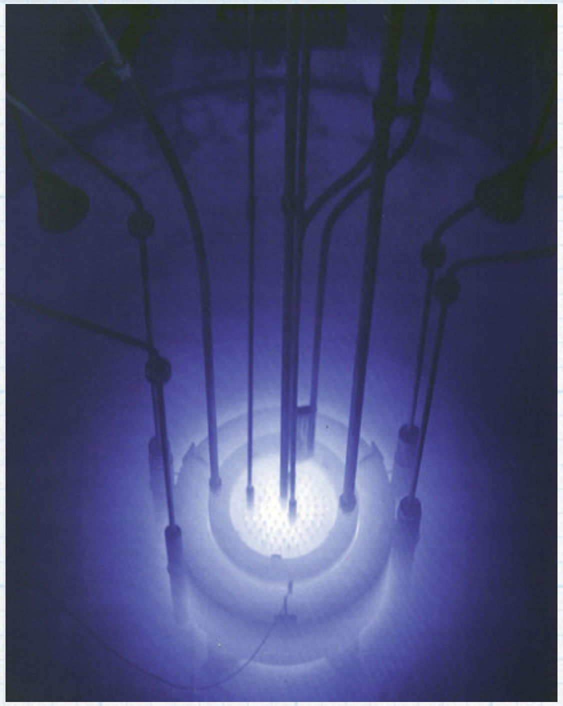


PMT

light guide

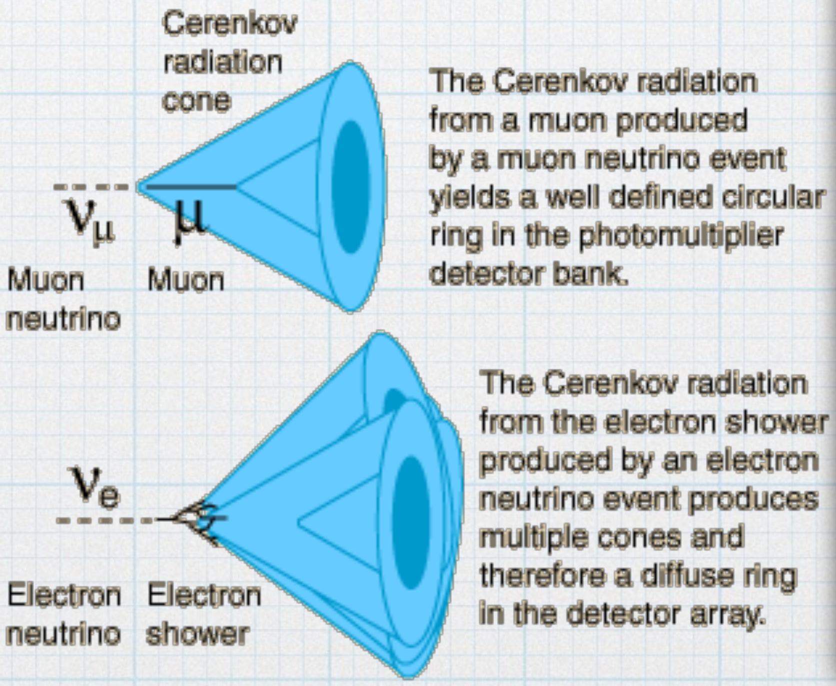
Using bigger PMTs for Cerenkov Radiation





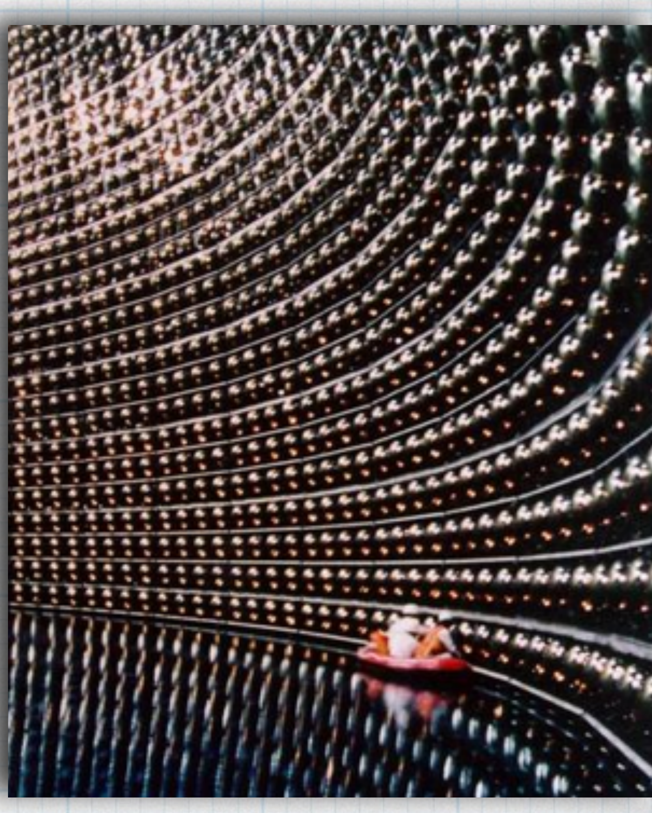
hamamatsu 50cm PMT

- ✦ 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.



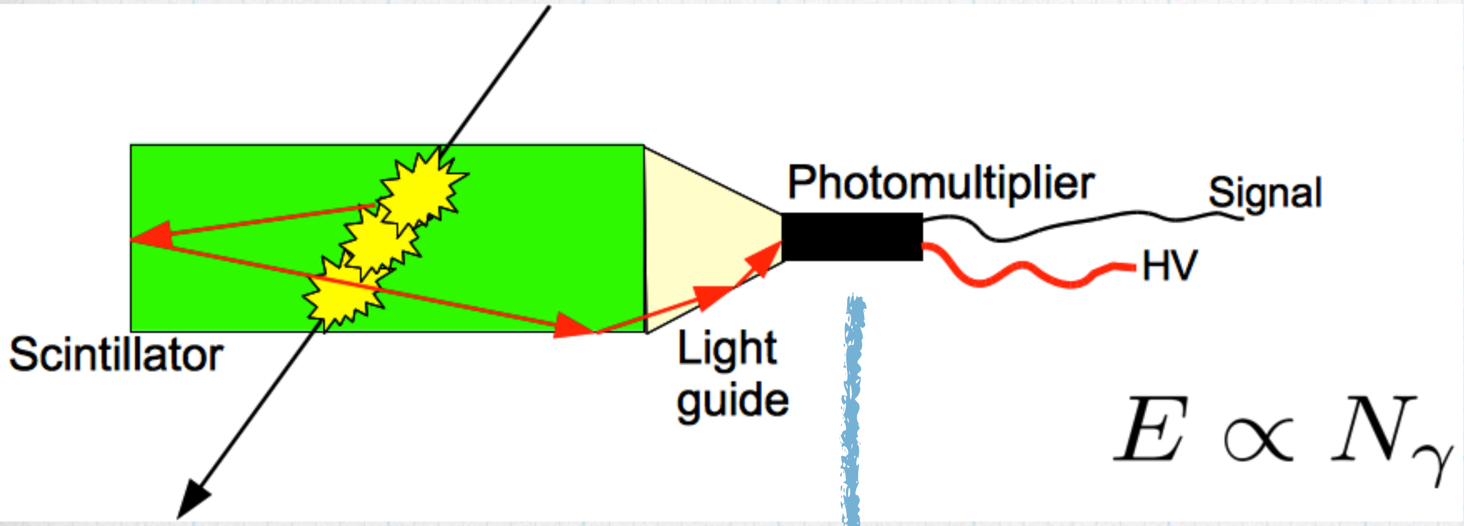
The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.



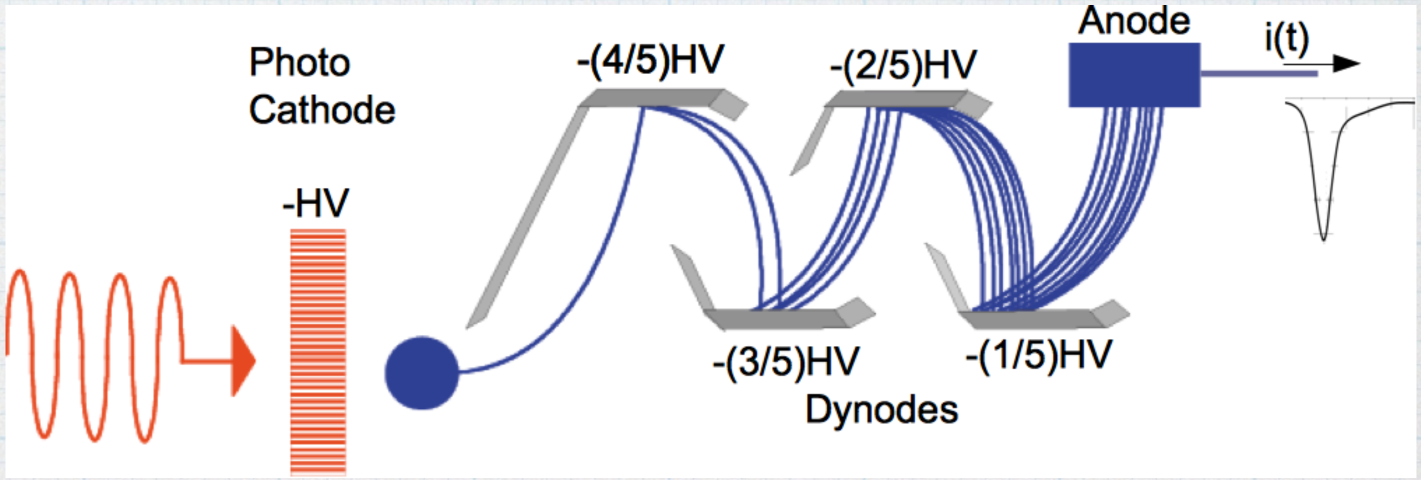
reading out a scintillator

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



— there are position sensitive PMTs (x-wire AND padded types)

— SiPM are "a la mode"
small sensitive area
uses silicon photodiode
bias voltage small (<100V)
can work under B field

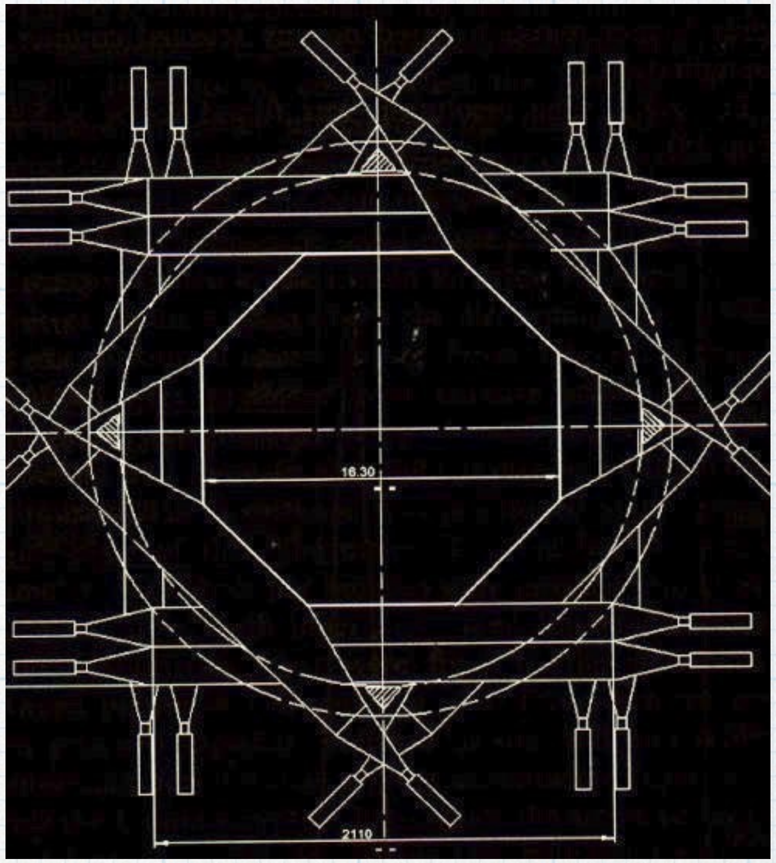


if signal is received without scintillation light: dark current

High gain: ~1M times

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.



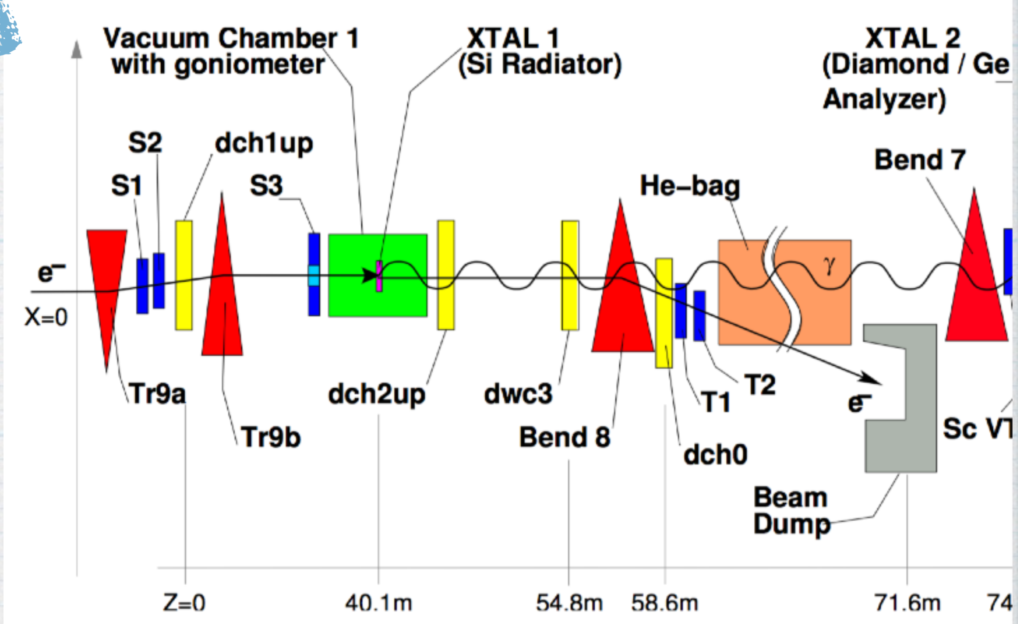


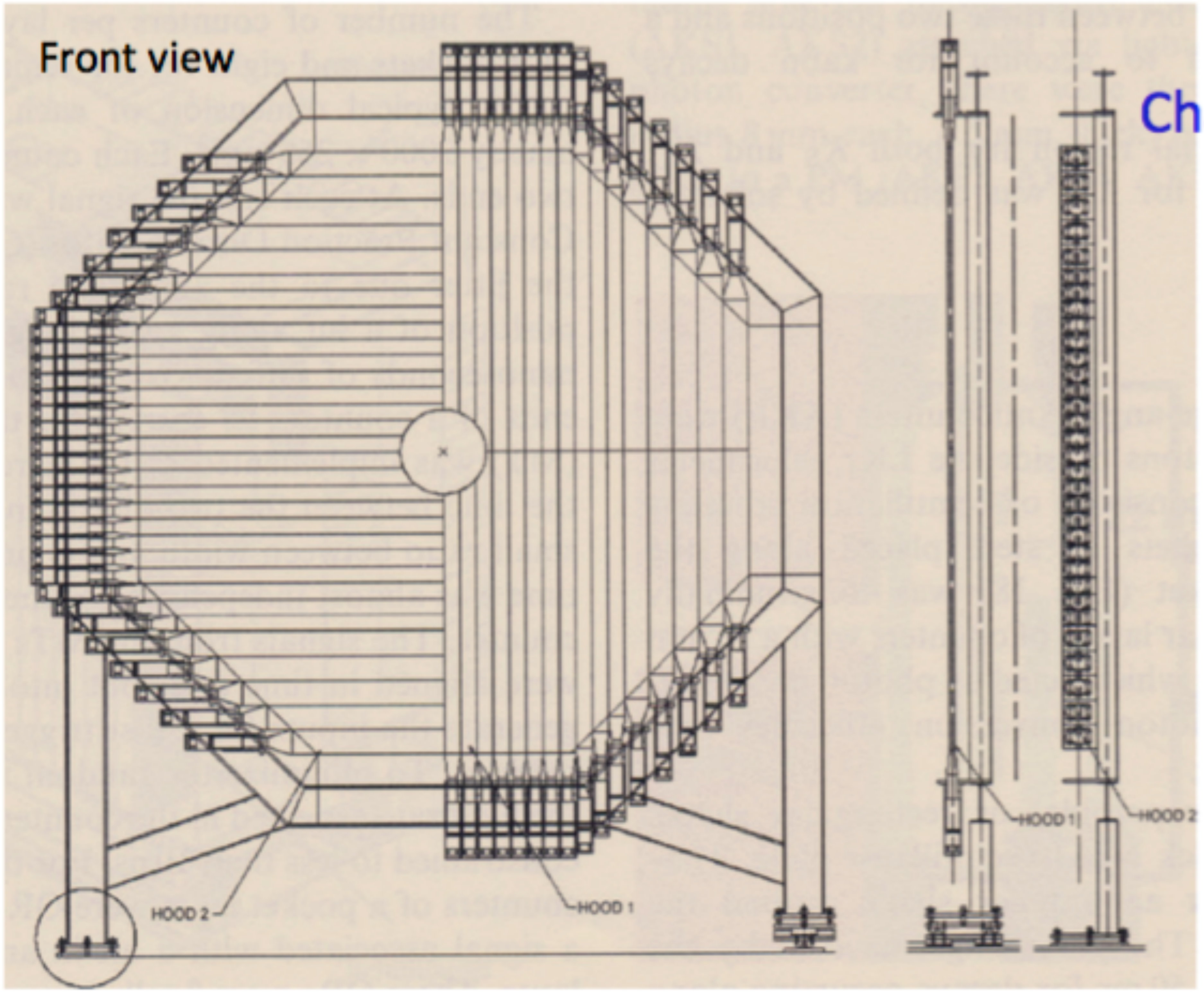
Fig. 1. Setup of the Na59 Experiment

Hodoscope

- Simple tracker: The beam has gone trough the scintillator that gives the signal.
  - ➡scintillators can be put in 2 directions to get both x and y information.

- OR
  - ➡Readout from both ends, let signal arrival times from left and right to be (t1, t2).
  - ➡t1=t2: beam at the center   t1>t2, closer to right   etc...

Na48 Hodoscope

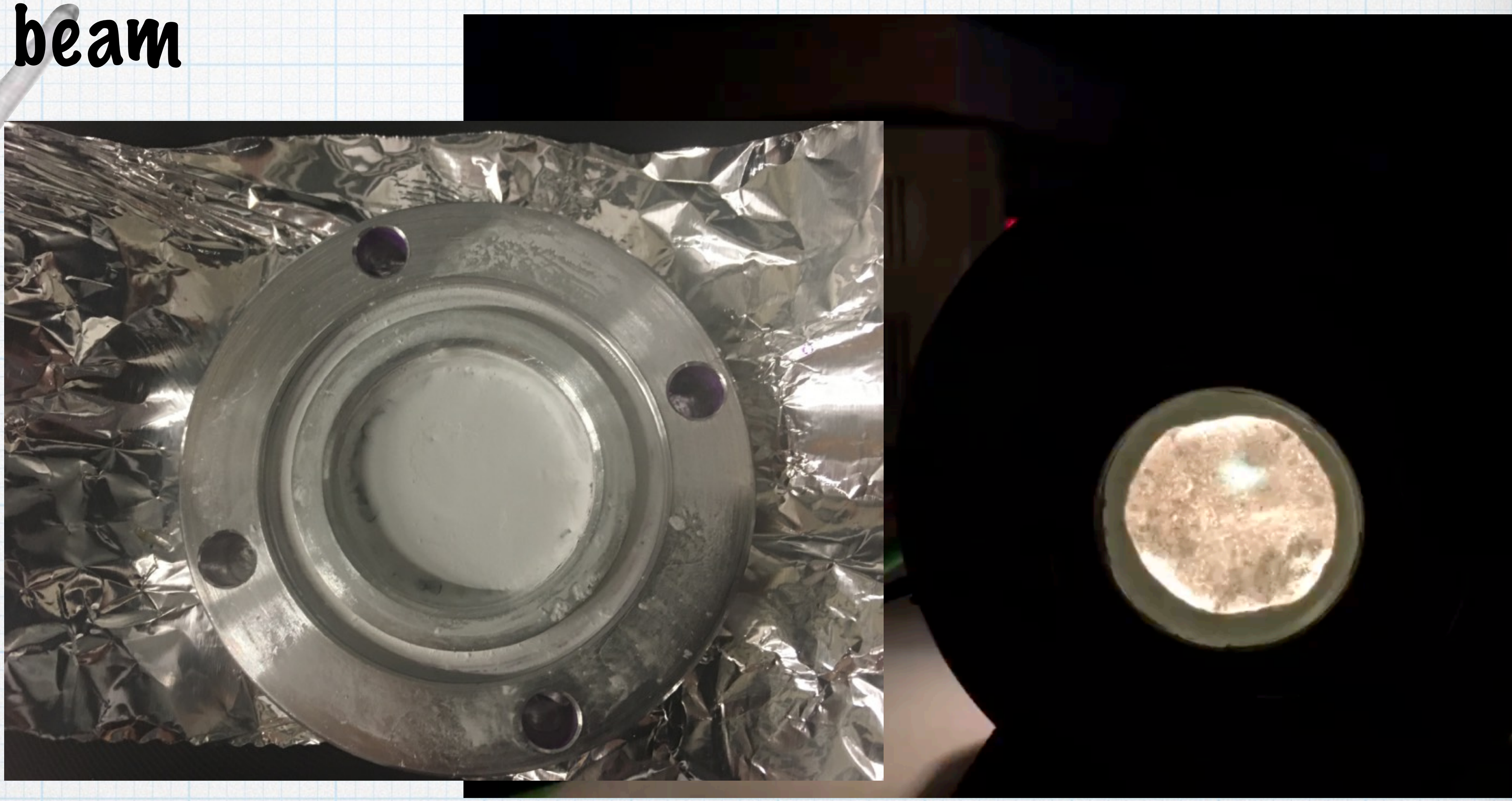


Charged hodoscope

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

Build your own scintillator

to see a particle beam



To use as a trigger

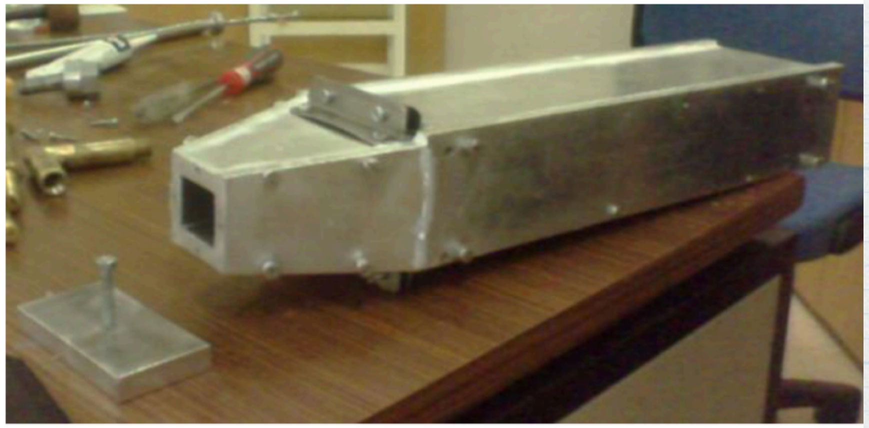
N2

Dow Styron 634 PS pellet + PPO + POPOP

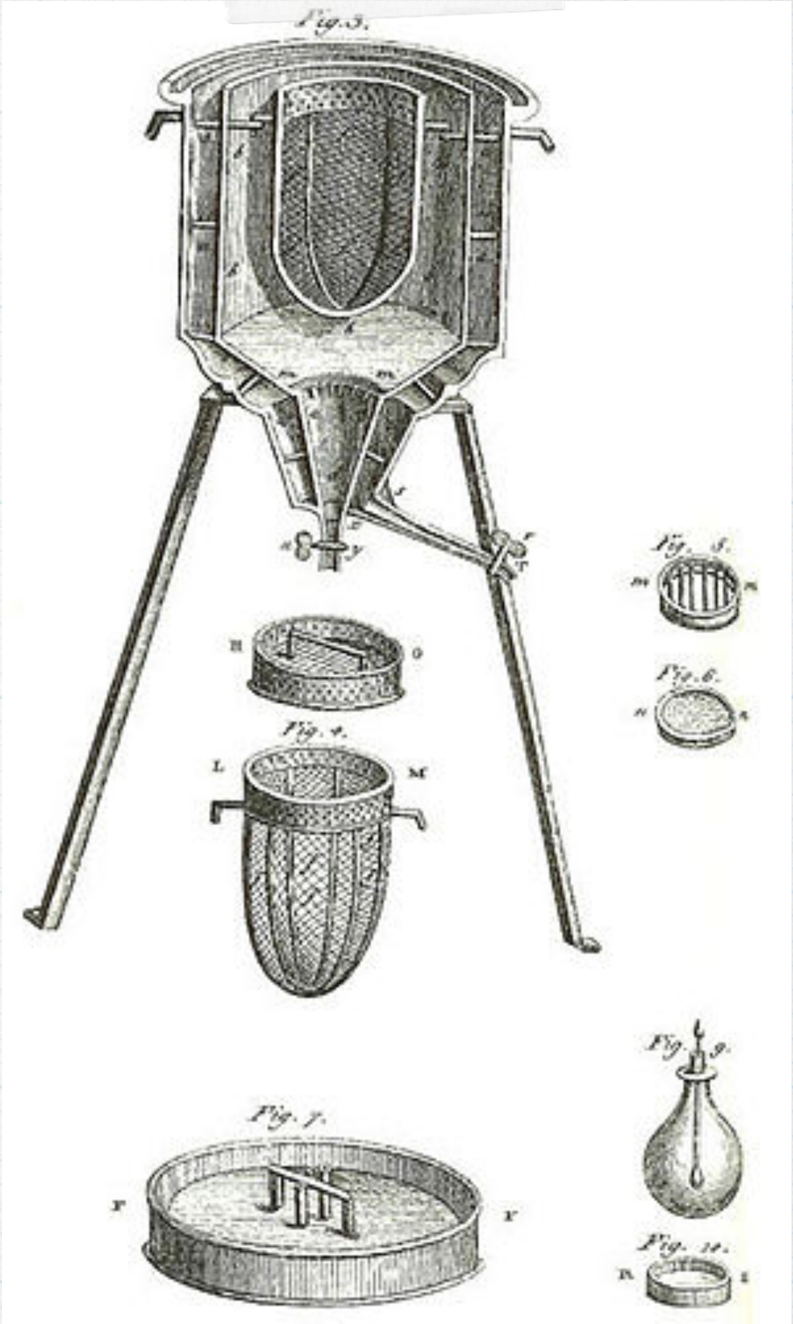
heater

extruder

final shape



Calorimetry

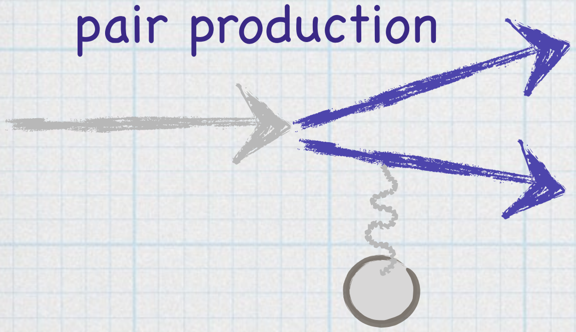


- The name calorimeter was made up by Antoine Lavoisier. In 1780, he used a guinea pig in his experiments with this device to measure heat production. The heat from the guinea pig's respiration melted snow surrounding the calorimeter, showing that respiratory gas exchange is a combustion, similar to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

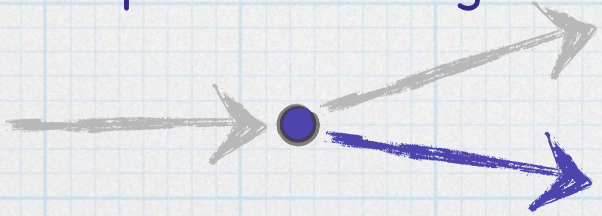
- calorimeters are "destructive" energy measurement devices.
  - the particle beam to be measured has to be absorbed.

- calorimeters benefit from many additional interactions:

pair production



compton scattering



bremmstrahlung

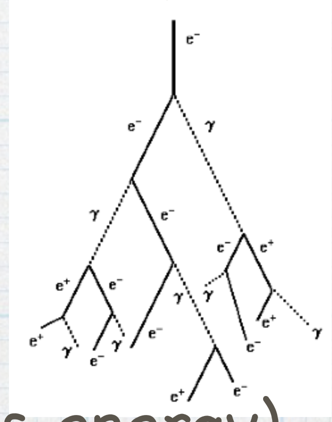
hadronization

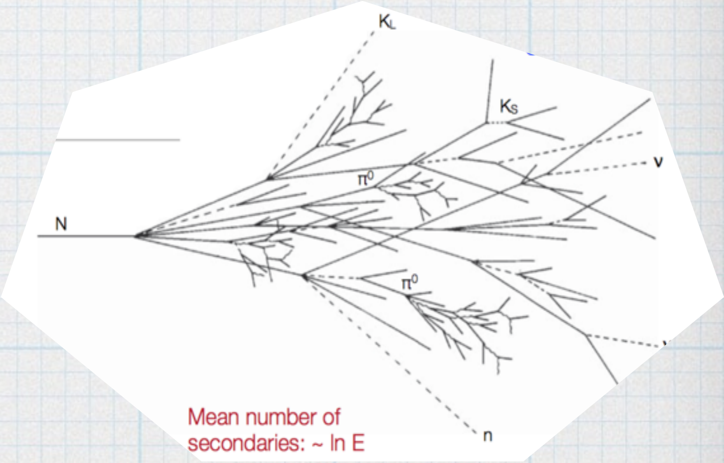
calorimeters in particle physics

- 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 $\lambda \approx 35\ \mathrm{g{*}cm^{-2}}\ A^{1/3}$ (# rel. particles drops to 1/e of its initial value)





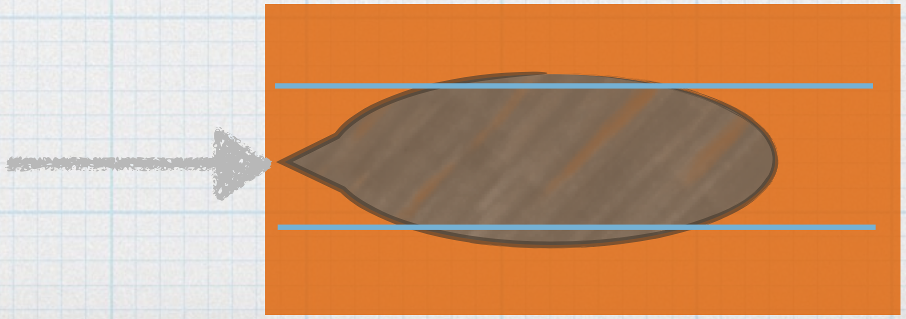
Mean number of secondaries: ~ ln E

EM calorimeters

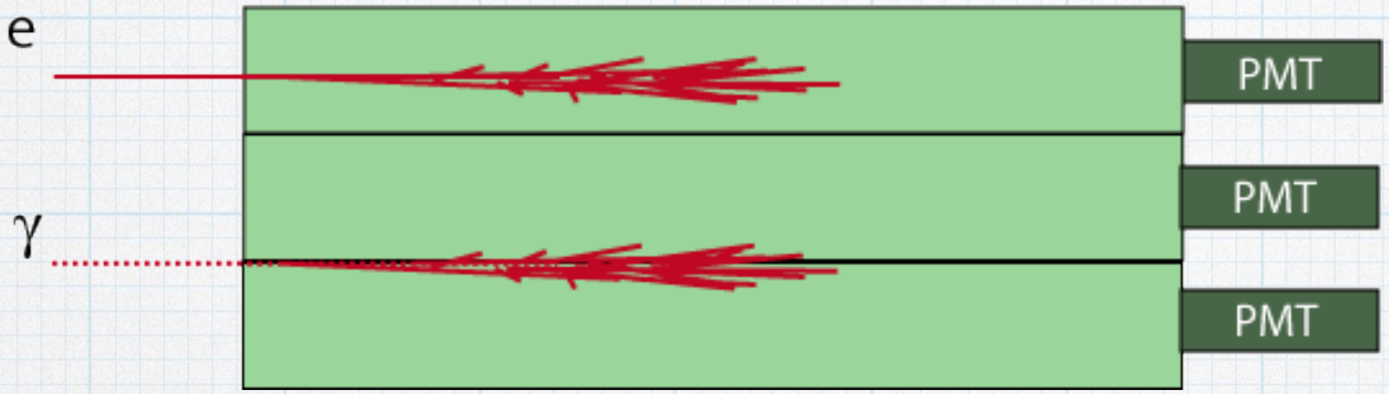
- Radiation length, X_0: the distance at which the particle energy drops down to 1/e of its initial value: $E(x) = E_0 e^{-x/X_0}$ $X_0 = \frac{716.4 \mathrm{cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$ ATLAS EMcalo: $22X_0$

- Critical Energy, E_c: The energy at which losses due to Bremmstrahlung and ionisation 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

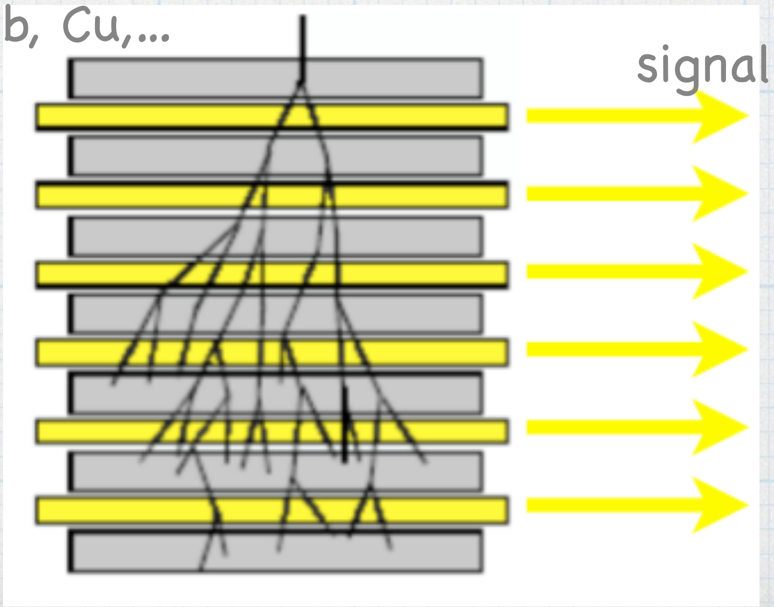
$\Delta E/E \sim 1\%/\sqrt{E}$

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 (~$1k/cm^3)
- 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: Scale at which secondary, tertiary particles are produced.
    - 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

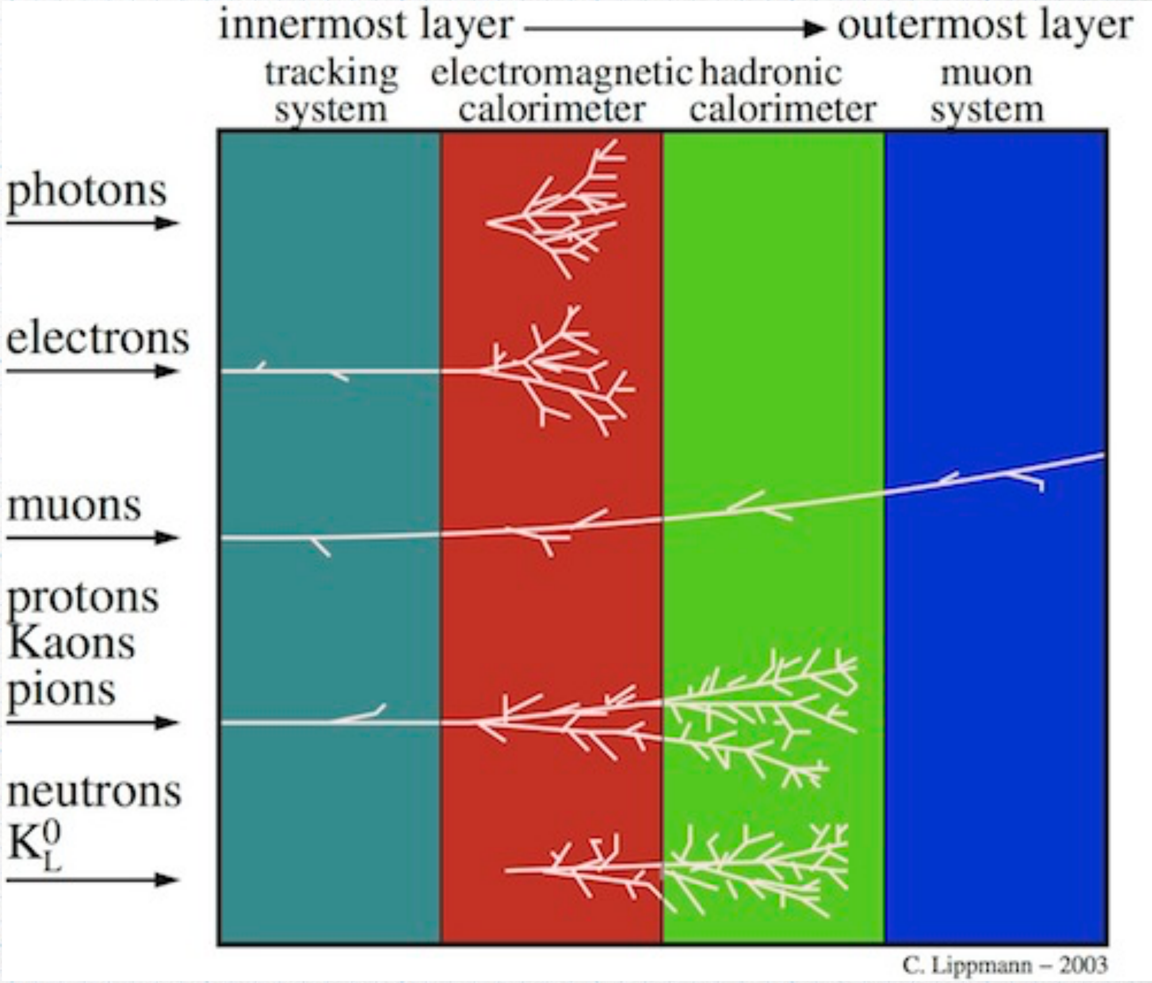
$E^2 = p^2 + m^2$

Measure E and p independently

- Energy from calorimeter
- p from magnetic spectrometer

Calculate E/p:

–E/p≈1 for electrons, <<1 for π

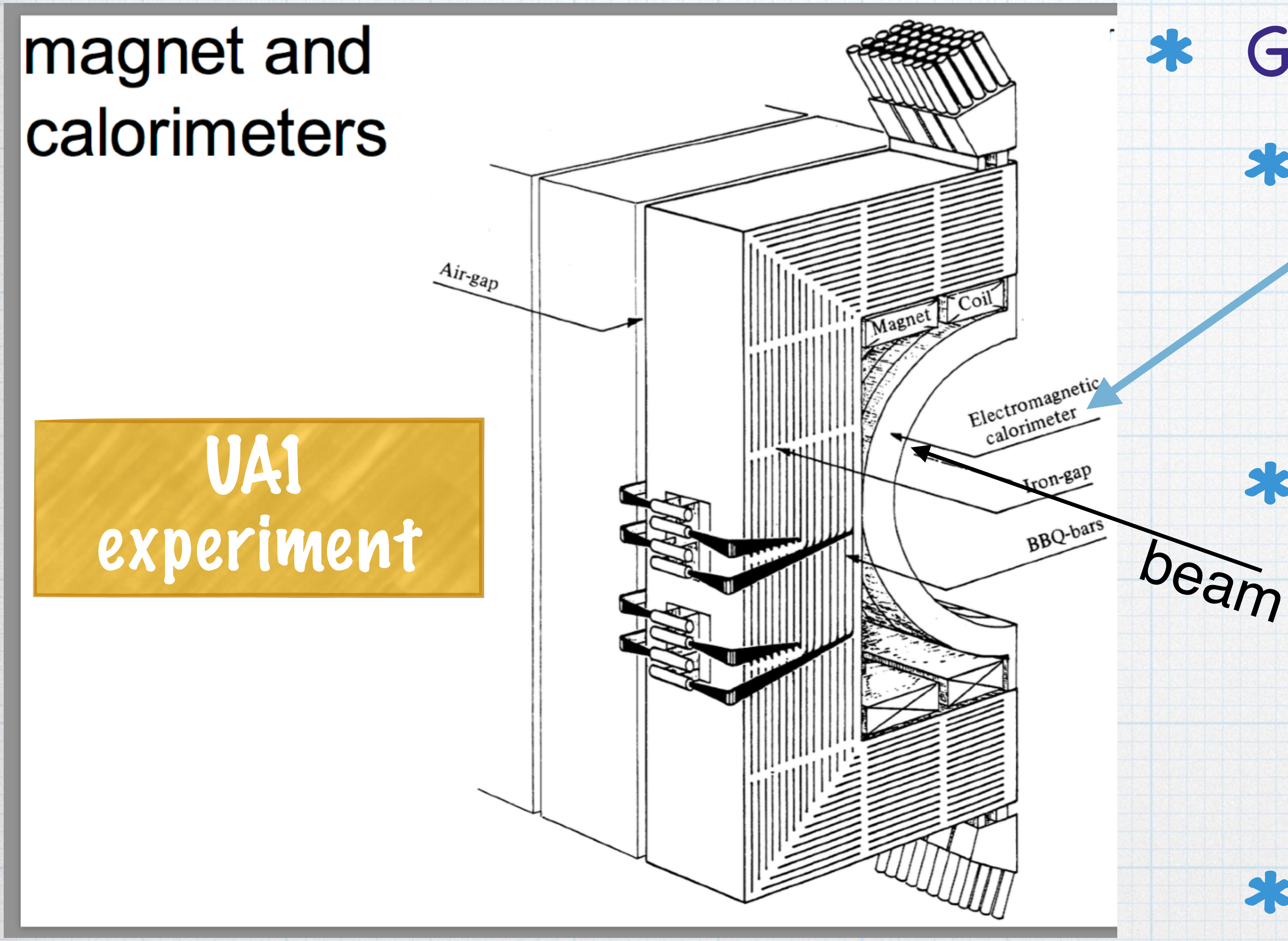


C. Lippmann – 2003

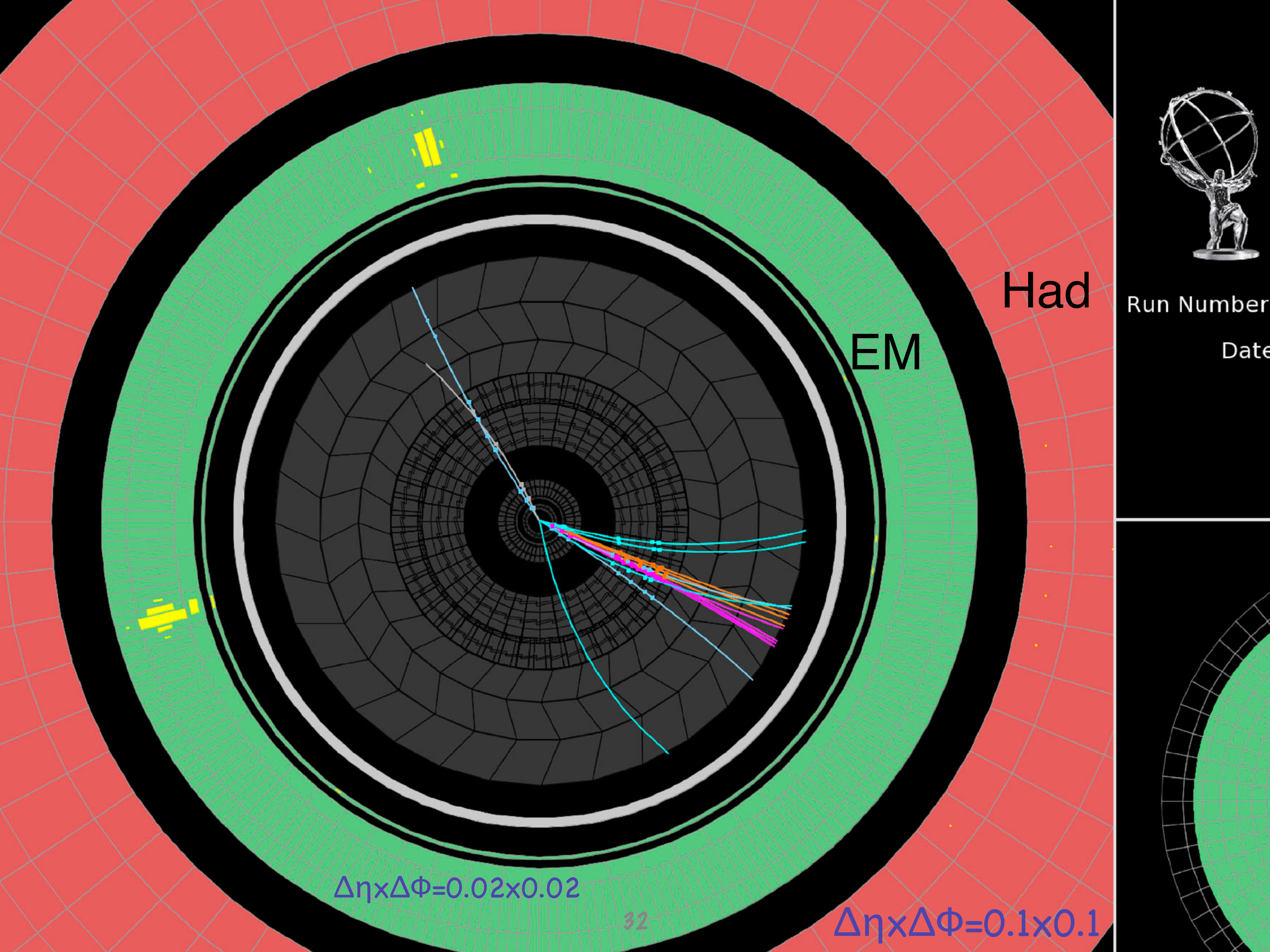
Only muons will be able traverse the calorimeters

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!..


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

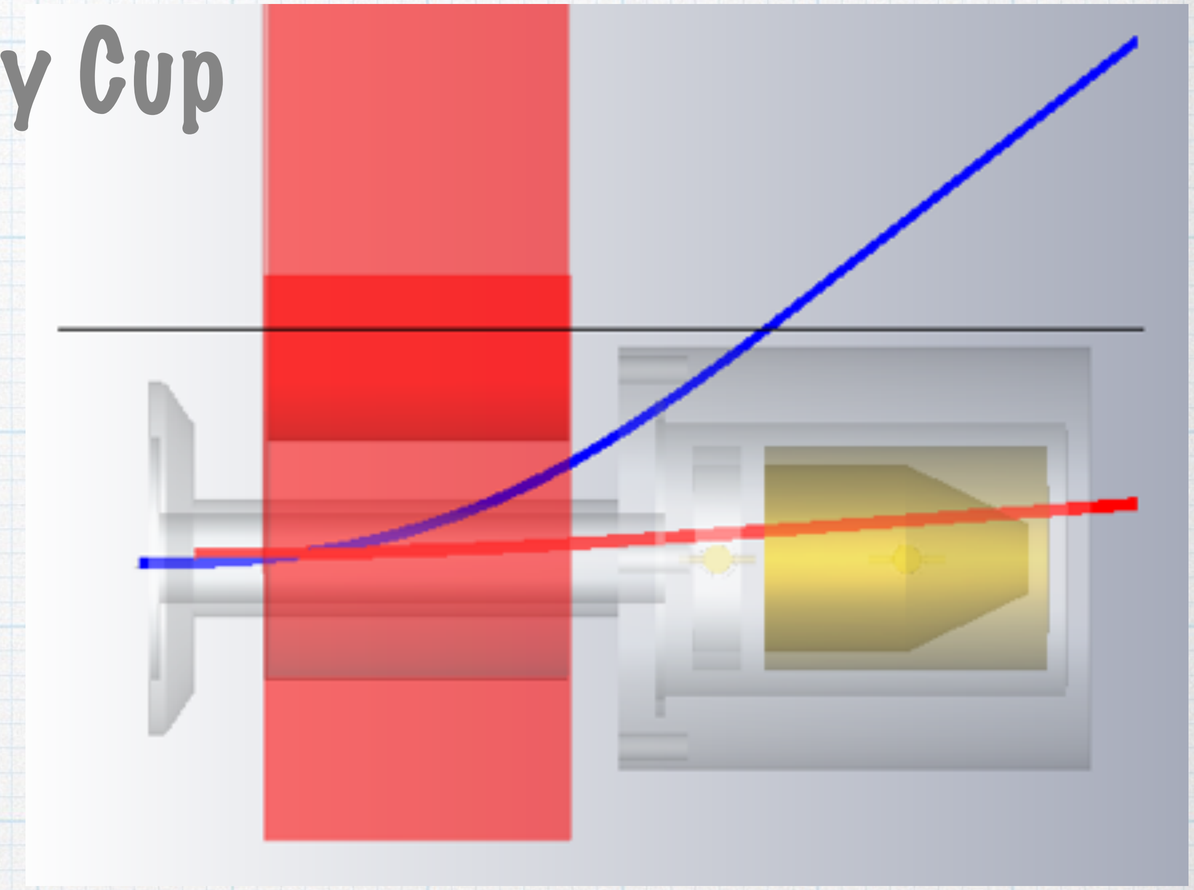
G.Turemen for simulation & photos

build your own beam monitor

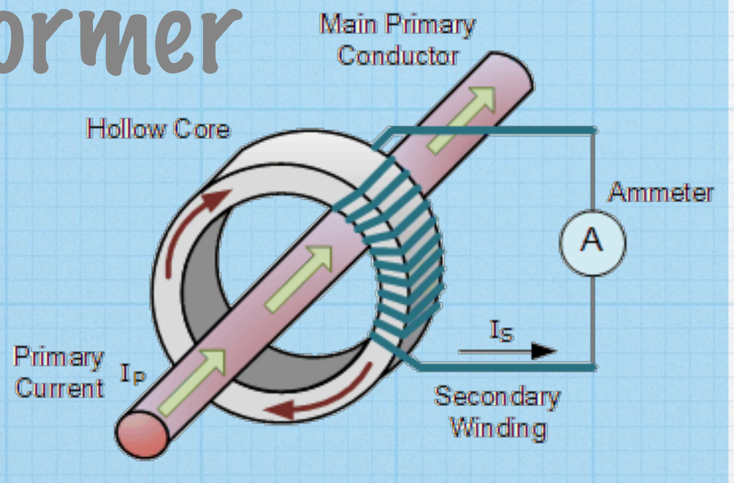
Measure Charge q

collect q in a Faraday Cup

measure q with an ampermeter



pick up passing q with a Current Transformer



Construction

q measured with a scope

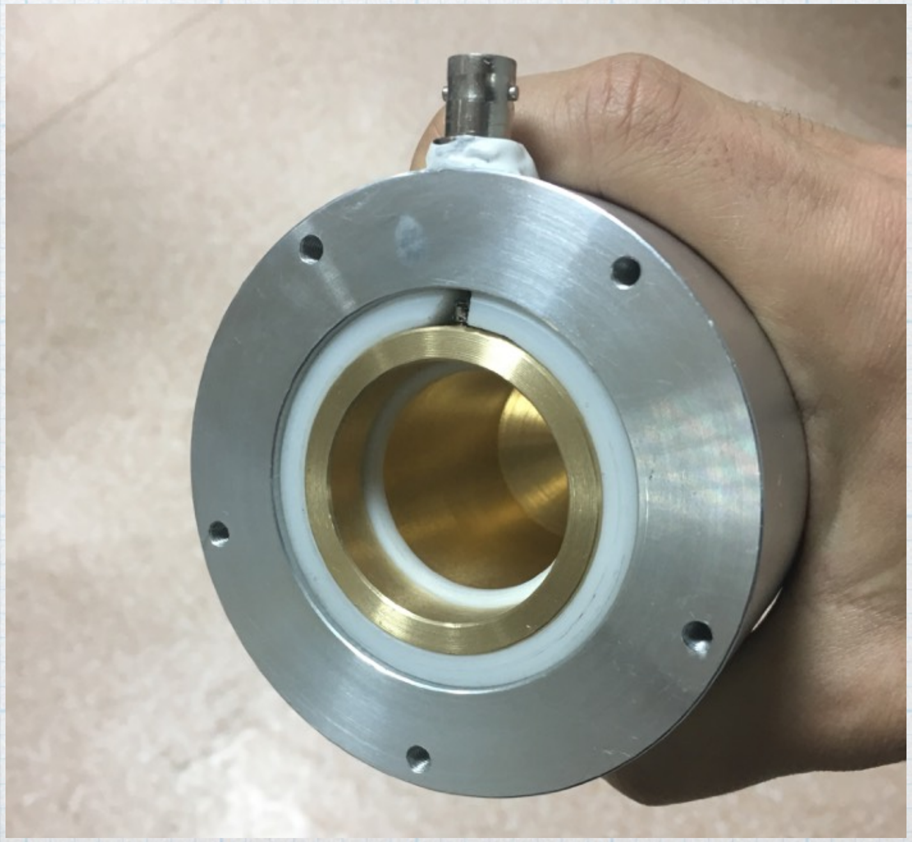
C1 4.0V/div 1MΩ B_W:500M
C3 400mV/div 1MΩ B_W:500M
C4 400mV/div 1MΩ B_W:500M

A' C1 ∫ 1.36V

2.0ms 5.0MS/s 200ns/pt
Run Sample
47 acqs RL:100k
Auto January 13, 2017 08:13:50

	Value	Mean	Min	Max	St Dev	Count	Info
C3 Pk-Pk	2.56V	1.9897658	96.0m	2.672	1.086	47.0	
C4 Pk-Pk	2.64V	2.6611988	2.608	2.72	23.39m	47.0	
C1 Ampl*	12.16V	12.192493	12.16	12.32	65.14m	47.0	

you can also have 2 such devices and do a time of flight (TOF) measurement to determine beam momentum



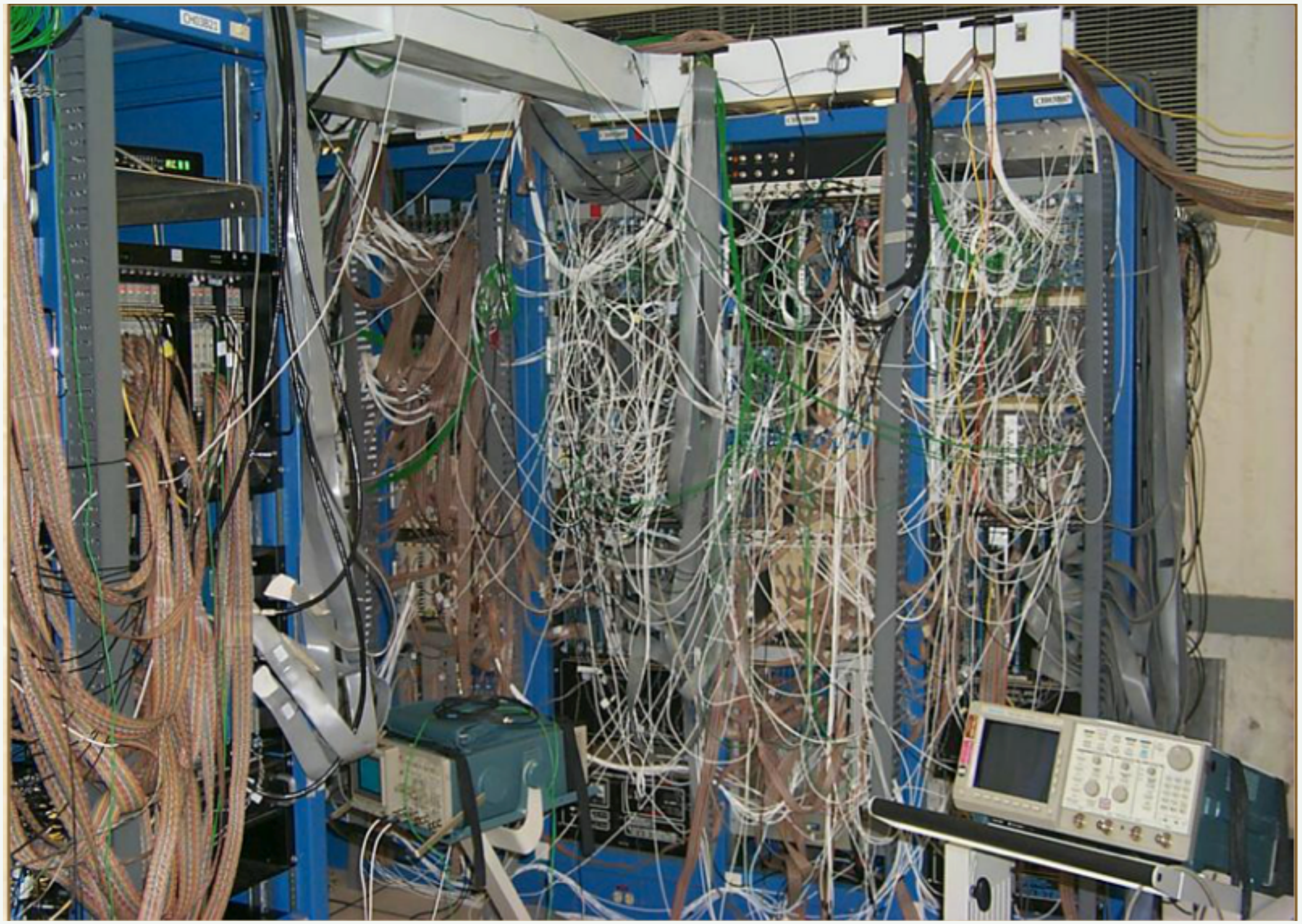
ReadOut Chain

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
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...

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

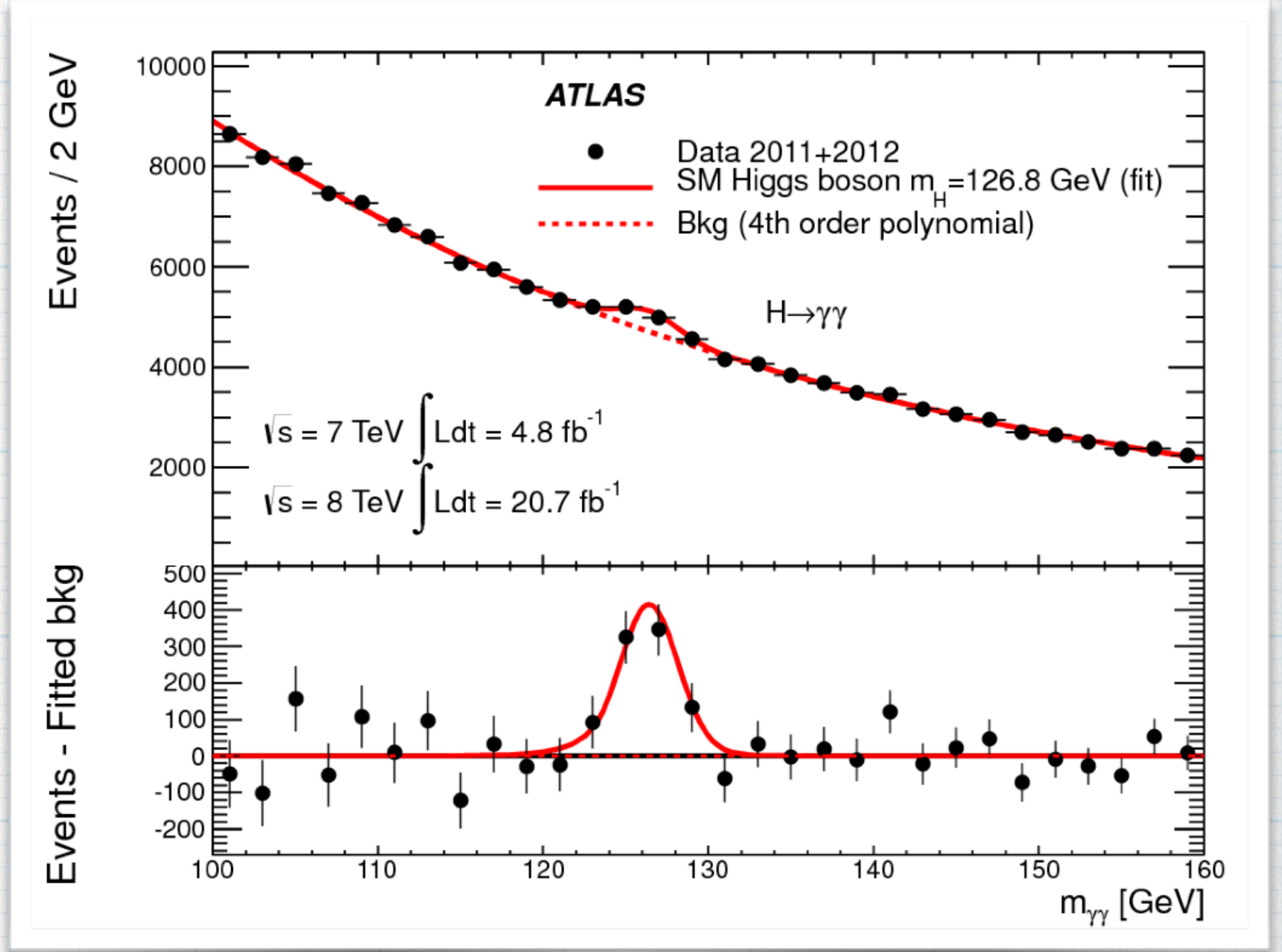
Infrastructure

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



your work as a TDAQ expert is **indispensible** for such successful results

Thank you for your attention

Thank you for your attention

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