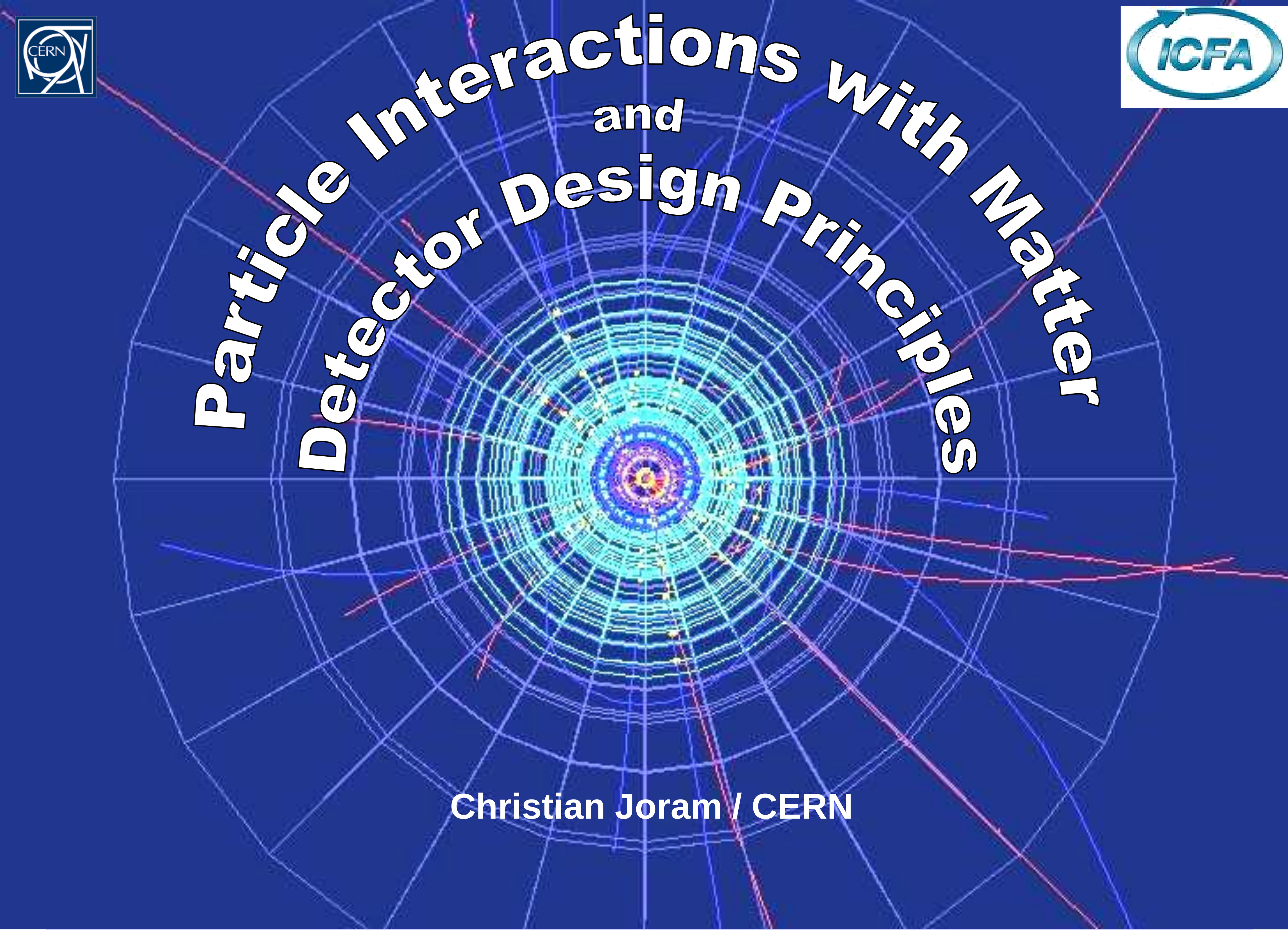
Particle Interactions with Matter
and
Detector Design Principles



Christian Joram / CERN

Outline

- Lecture 1 – **Interaction of charged particle**
- Lecture 2 – **Gaseous Detectors**
- Lecture 3 – **More interactions: electrons, photons, neutrons, neutrinos. Cascades.**
- Lecture 4
  - Organic scintillators
  - Scintillating fibres
  - Detector testing (cosmic rays, radioactive sources)
  - Detector systems
  - Magnetic field geometries
  - Some practical considerations
  - Brief tour through the 4 LHC experiments

Detector testing

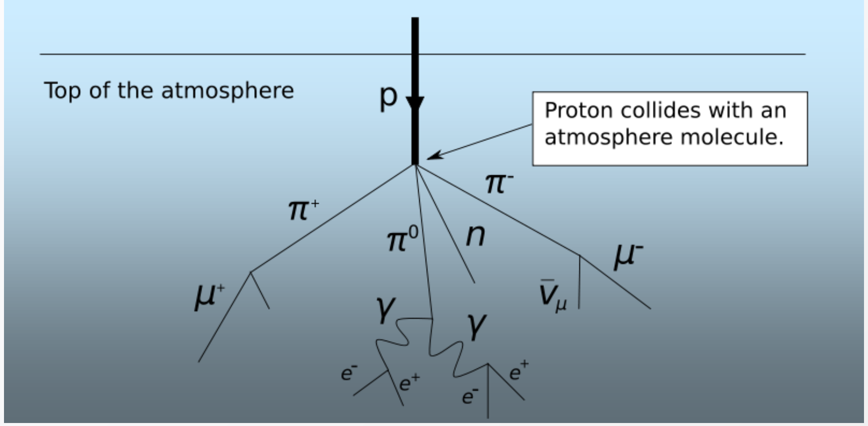
- what do you want to measure ?
  - does it work at all ?
  - resolution (time, space)
  - detection efficiency
  - rate capability
  - variation of parameters (HV, thresholds, gas mixtures, …)

- Preferred option: particle (test) beam
  - a test beam is a controlled source of particles (particle type, energy, rate, beam spot size, angular divergence)
  - but…
    - o you need to reserve the beam time long (many months) ahead
    - o difficult to postpone when your detector isn't ready
    - o expensive (operation of accelerator ~k$/hour)
    - o lots of restriction (access, radiation safety, transport, crane, …)

- What are the alternatives ?
  - cosmic radiation: everywhere available, but relatively low rate
  - Radioactive sources: lots of choices, but only low energy particles

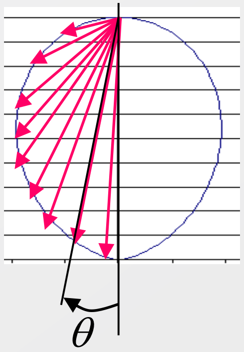
Detector testing with cosmic radiation

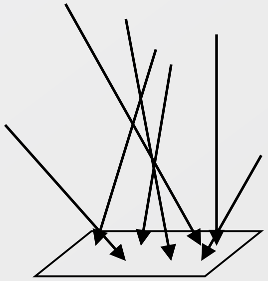
- **Cosmic radiation** are energetic particles originating from outer space that impinge on Earth's atmosphere. Almost 90% of all the incoming cosmic ray particles are protons, almost 10% are α-particles), and slightly under 1% are heavier elements.
- The origins of these particles range from energetic processes on the sun to yet unknown events in the far universe. Cosmic rays can have energies of over 10^{20} eV !



Proton collides with an atmosphere molecule.

The atmosphere of the earth acts like a calorimeter. Hadronic showers form, generating lots of secondary particles. On the ground level, we find mainly muons (and neutrinos). They follow roughly a $\cos^2\theta$ angular distribution.





horizontal detector

Detector testing with cosmic radiation

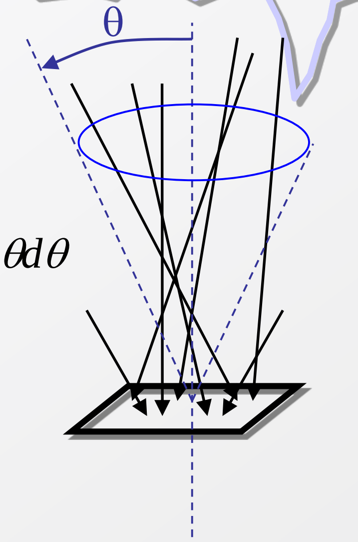
- The integral intensity of ‘vertical’ muons with $p_\mu \geq 1$ GeV/*c* at sea level is

$$\frac{N_\mu}{\Delta t \cdot A \cdot d\Omega} \approx 70\,\mathrm{s}^{-1}\mathrm{m}^{-2}\mathrm{sr}^{-1}$$

- For horizontal detectors: dΩ ~ 1-2π sr ~ 3 – 6 sr

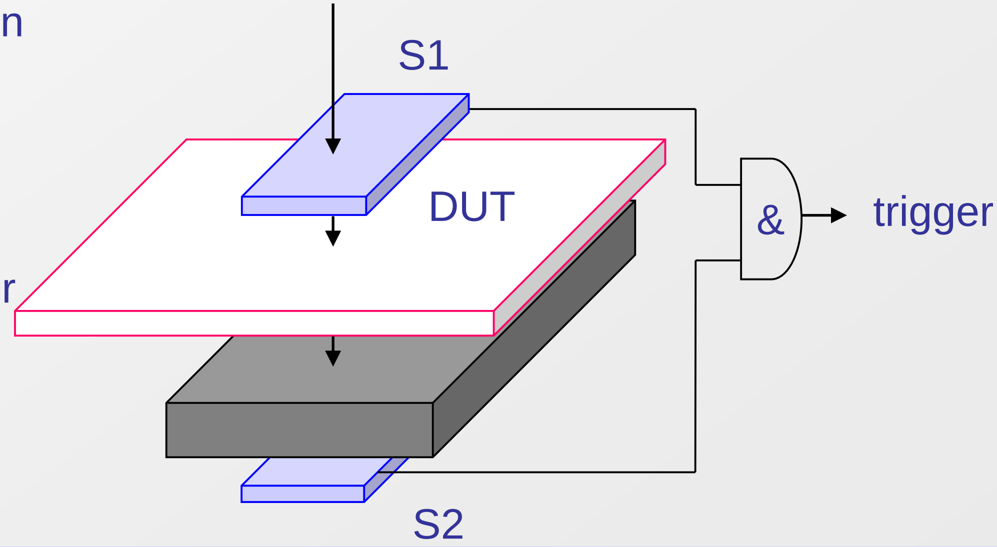
$$\frac{N_\mu}{\Delta t \cdot A} \approx 1\,\mathrm{min}^{-1}\mathrm{cm}^{-2}$$

$$d\Omega = 2\pi\int_0^\theta \sin\theta\, d\theta$$



Typical arrangement for detector testing: take two plastic scintillators (e.g. 10 mm thick) in coincidence as trigger for the readout of your detector under test (DUT).

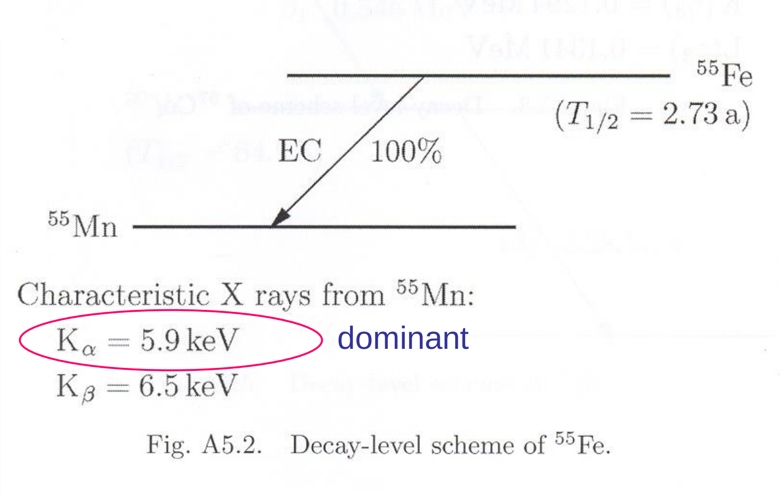
Option for cleaner conditions: add a lead layer (>5 cm) to filter away low energy particles.



Radioactive sources

Some examples of frequently used radioactive sources

Fe-55

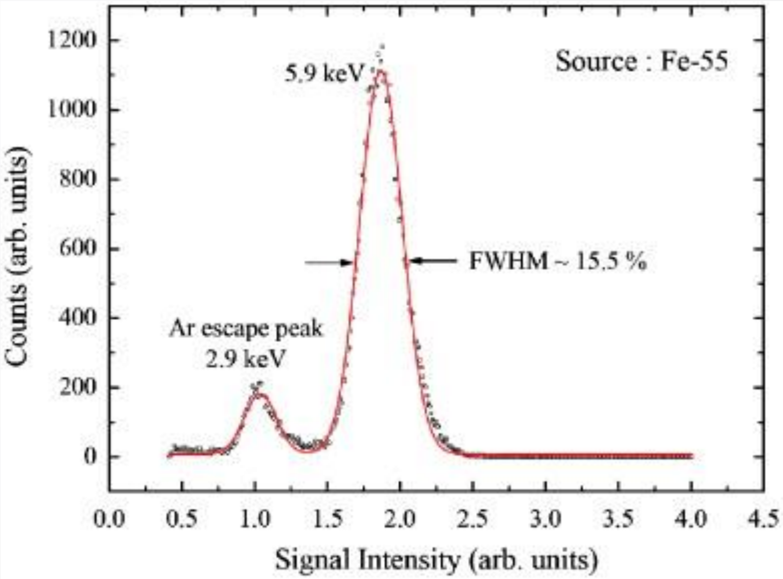


Characteristic X rays from ^{55}Mn:

$K_\alpha = 5.9\text{ keV}$ dominant

$K_\beta = 6.5\text{ keV}$

Fig. A5.2. Decay-level scheme of ^{55}Fe.

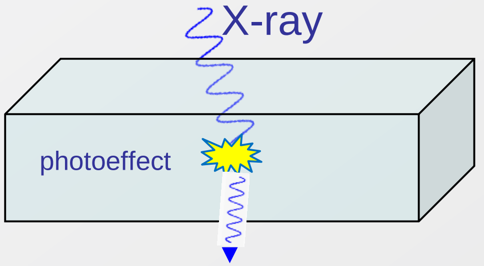


S. Park et al., Applied Radiation and Isotopes, Vol 67(2009) 1476-1478

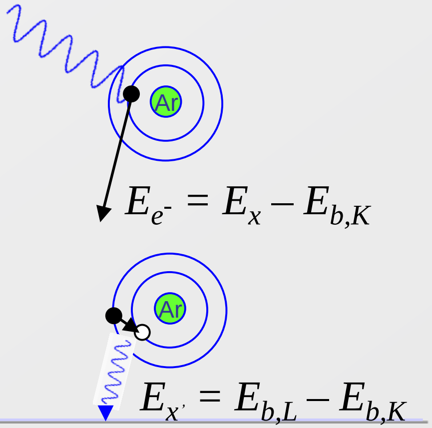
Often used to test gas detectors.

X-ray produces a well-defined energy deposition in detector

→ measure gain, stability, energy resolution.



Ar x-ray may escape undetected



$$E_{e^-} = E_x - E_{b,K}$$

$$E_{x'} = E_{b,L} - E_{b,K}$$

Radioactive sources

Na-22

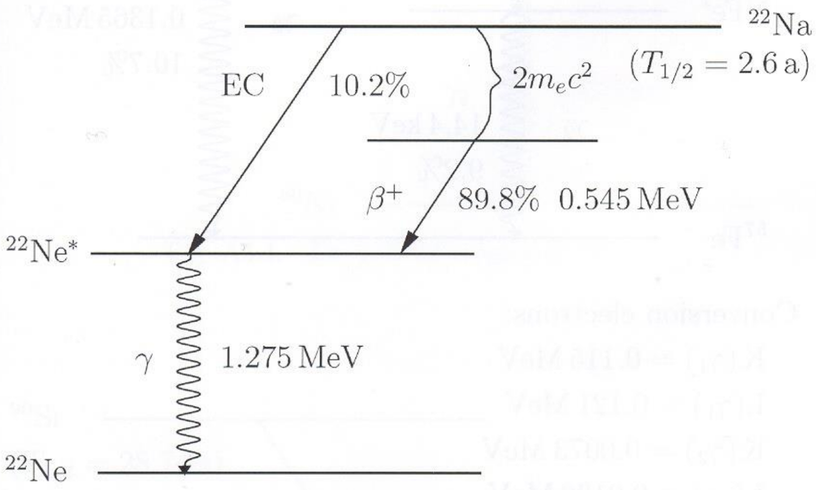
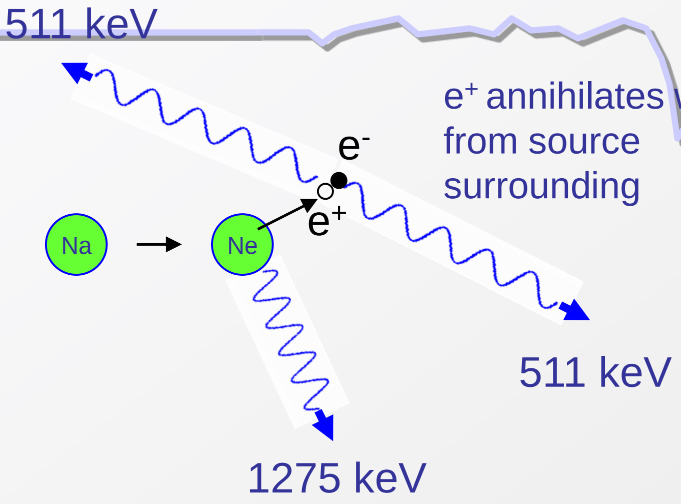
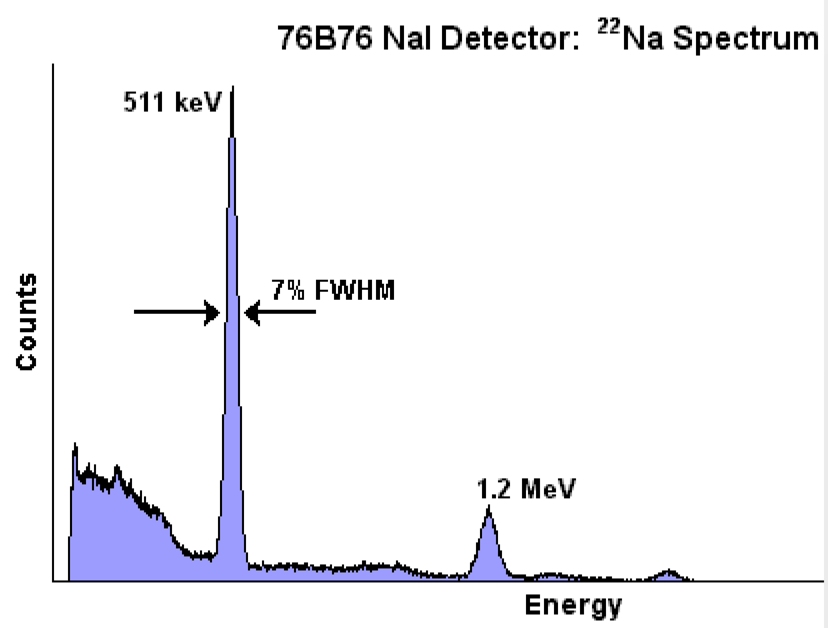


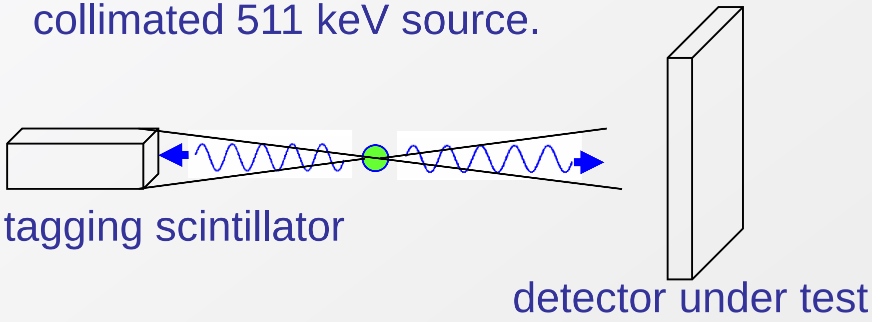
Fig. A5.1. Decay-level scheme of ^{22}Na.



e^+ annihilates with e^- from source surrounding



Tagging 1 of the 511 keV gammas with a small scintillator gives a nicely collimated 511 keV source.



Radioactive sources

Sr-90

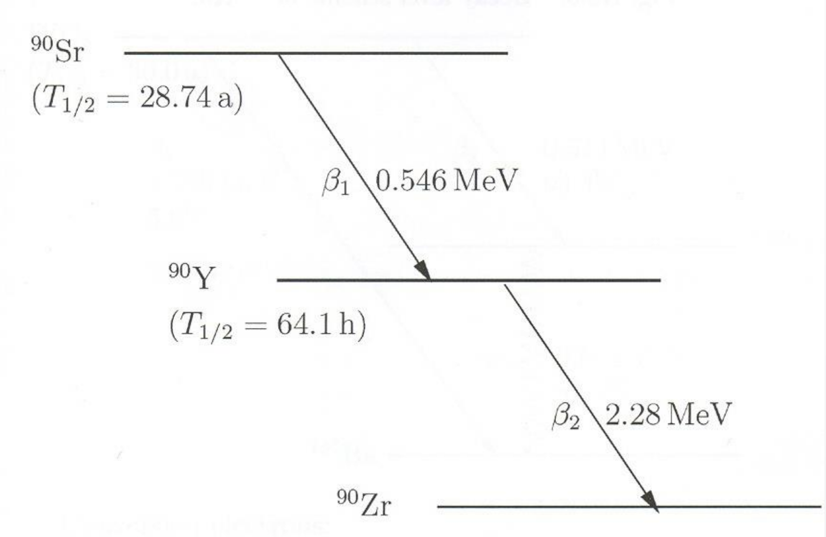
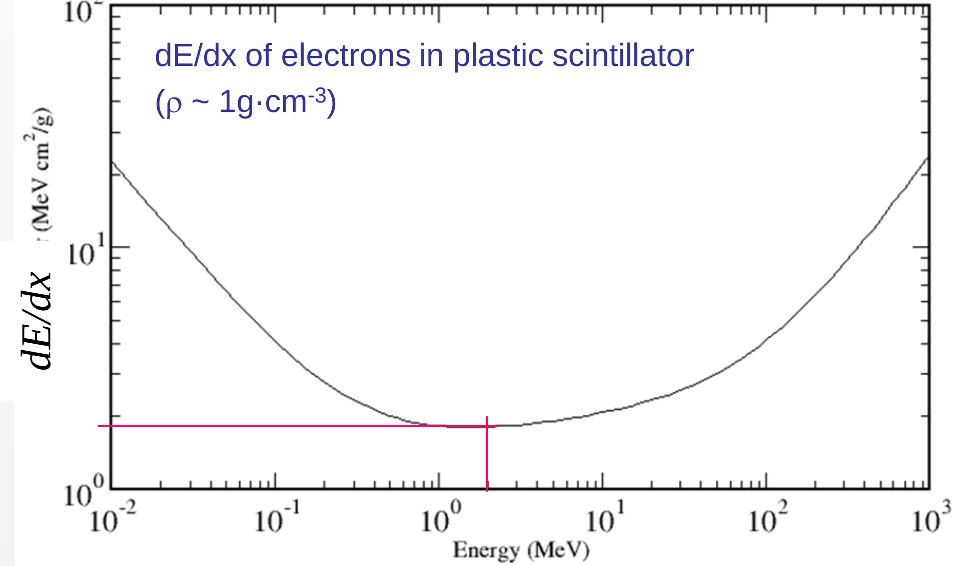


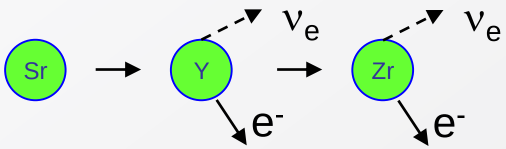
Fig. A5.5. Decay-level scheme of ^{90}Sr.

http://physics.nist.gov/PhysRefData/contents-radi.html



dE/dx of electrons in plastic scintillator
($\rho \sim 1\,\mathrm{g \cdot cm^{-3}}$)

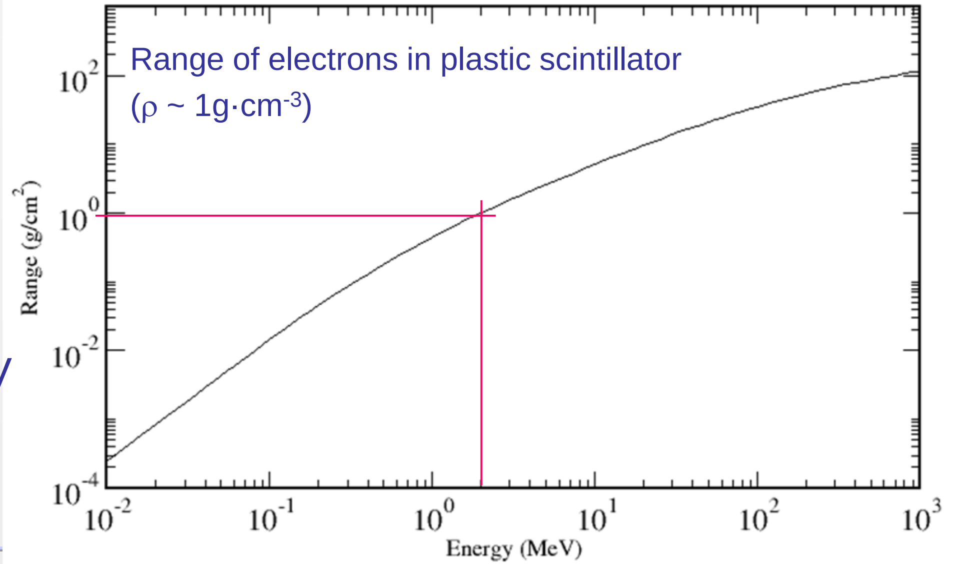
3-body decays (neutrinos unobserved)



→ continuous e- spectrum. E_{max} = 2.28 MeV

→ comes close to a MIP (minimum ionizing particle)

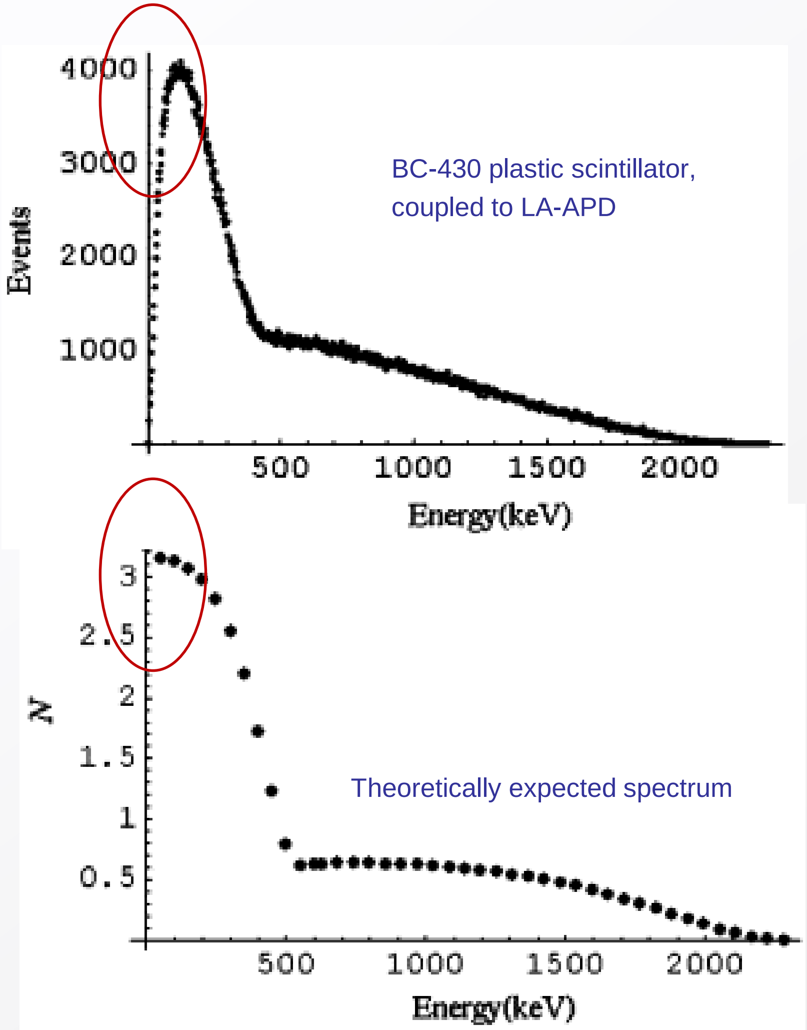
http://physics.nist.gov/PhysRefData/contents-radi.html



Range of electrons in plastic scintillator
($\rho \sim 1\,\mathrm{g \cdot cm^{-3}}$)

Radioactive sources

Example of detection of electrons from Sr-90 with a thick scintillator

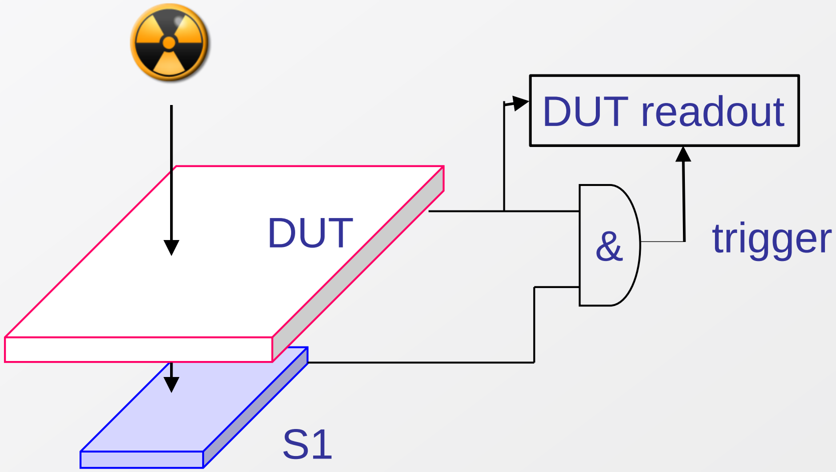


BC-430 plastic scintillator, coupled to LA-APD

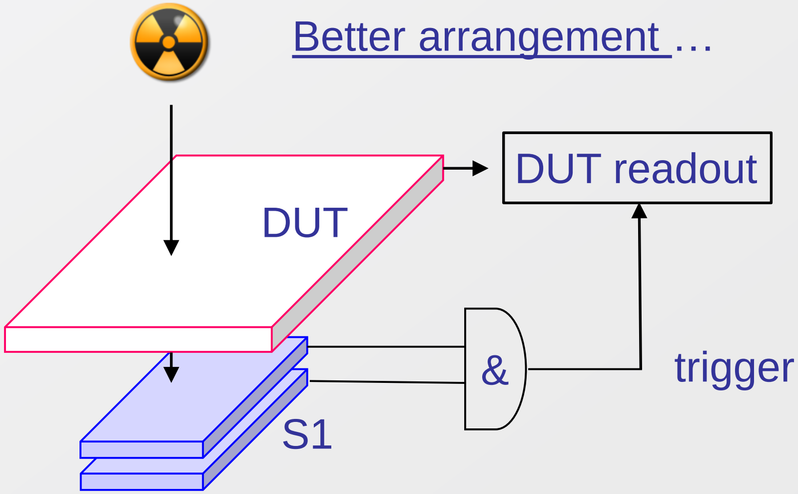
Theoretically expected spectrum

A.A. Kriss et al., NIM A525, (2004) 553-559

Simple arrangement for detector testing: take a thin scintillator (e.g. 3 mm) in coincidence with your detector under test (DUT)



Better arrangement …

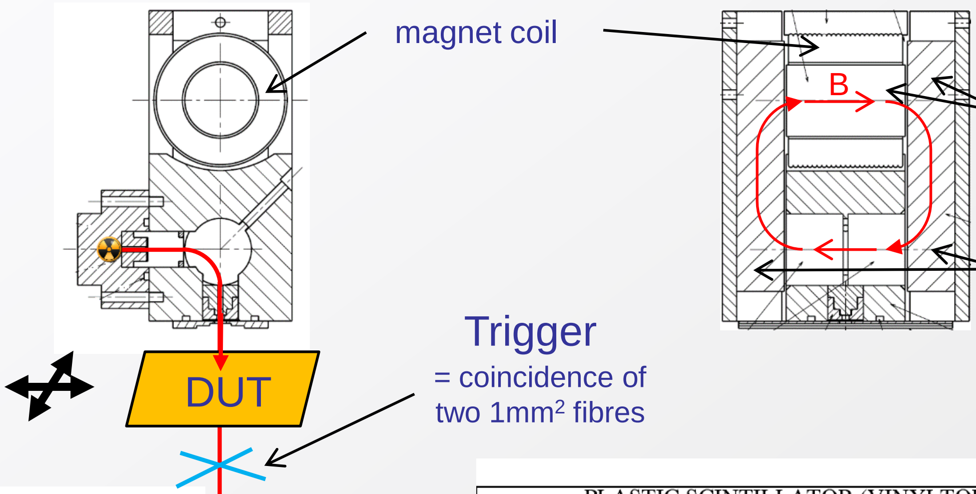


Radioactive sources

Deluxe arrangement …

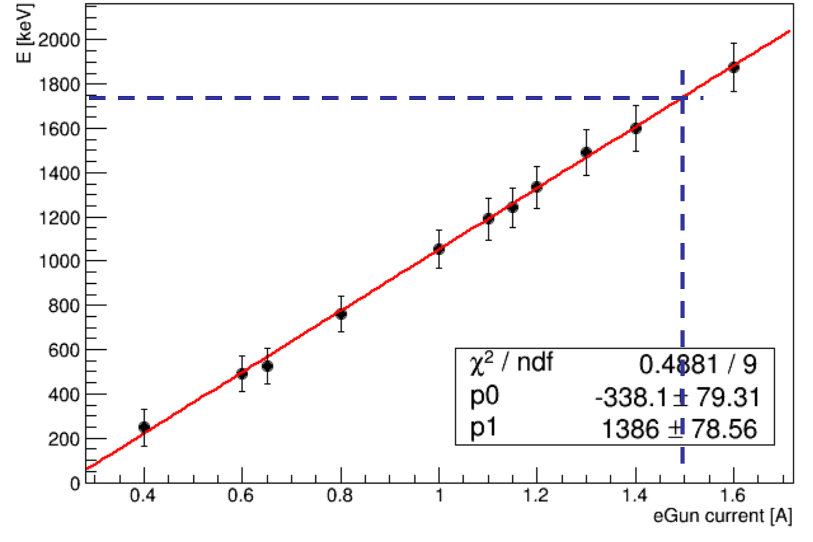
= a quasi mono-energetic source of minimum ionizing electrons

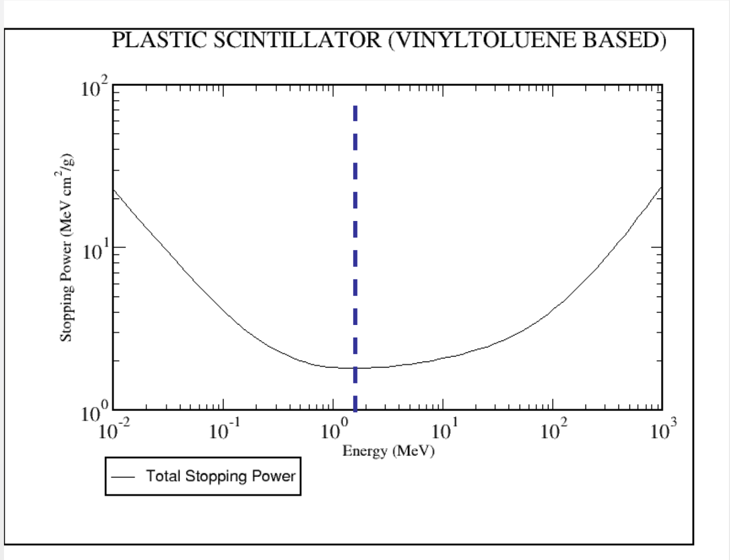
Energy filtered
Sr-90 source



Soft iron pieces for efficient B-field guidance

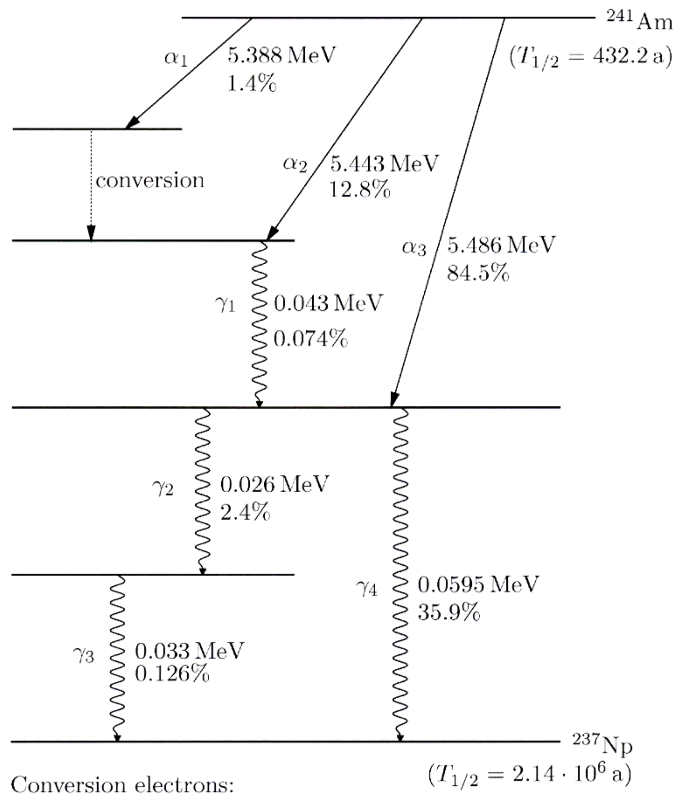
Trigger
= coincidence of two 1mm^2 fibres





Radioactive sources

Am-241



Conversion electrons:

K (γ_i) kinematically not possible
L $(\gamma_1) = 0.0210$ MeV
L $(\gamma_2) = 0.0039$ MeV
L $(\gamma_3) = 0.0108$ MeV
L $(\gamma_4) = 0.0371$ MeV

Fig. A5.10. Decay-level scheme of ^{241}Am.

α-particles ($z = 2$, $m_\alpha = 3.7$ GeV) have a very high energy loss (dE/dx ~GeV/cm or ~0.1 MeV/μm).

Their range in matter, e.g. plastic scintillator, is very short ($E_\alpha = 5$ MeV, $R = 36$ μm)

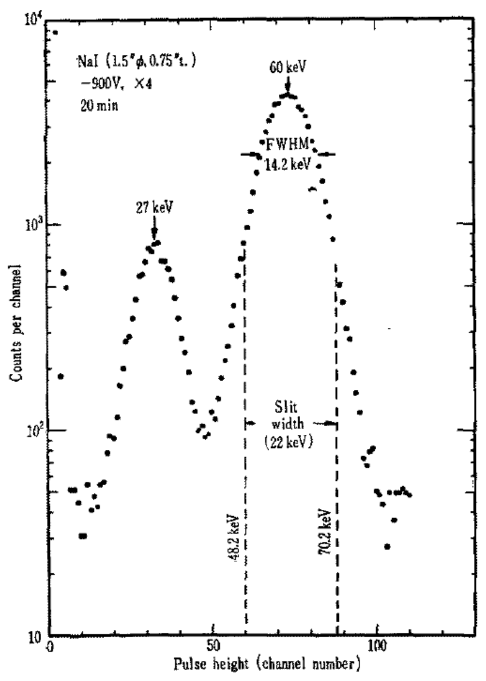


Fig. 6 Gamma-ray Spectrum of ^{241}Am

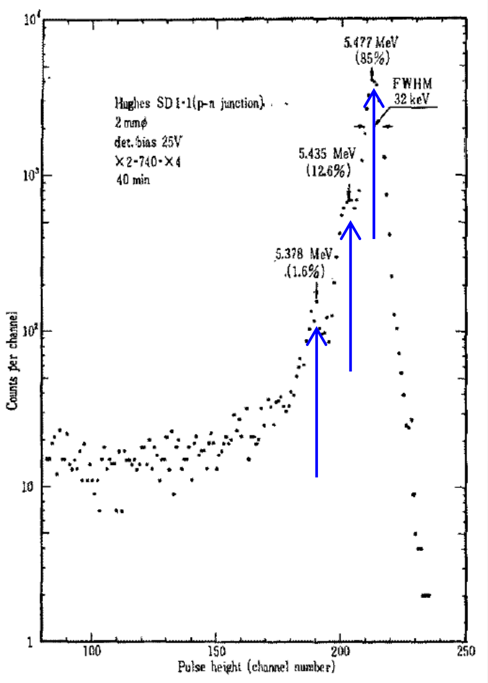


Fig. 5 Alpha Particle Spectrum of ^{241}Am

E. SAKAI et al. Journal of Nuclear Science and Technology Vol.1 , No.3 (1964)pp.101-109

Both, alpha and gamma lines can be used to test / calibrate detectors

Detector Systems

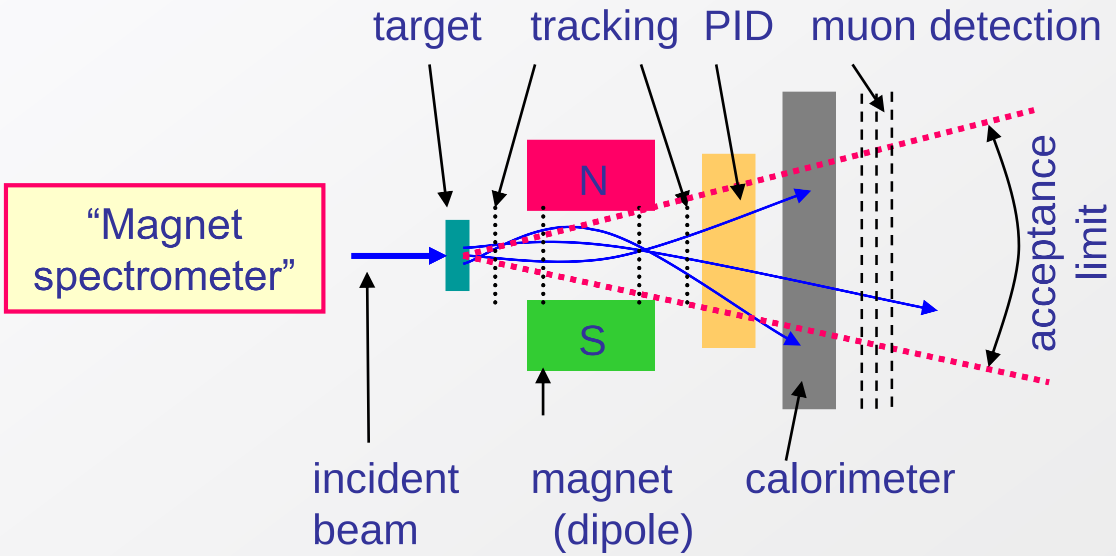
What do we want to measure in a HEP experiment ?

- number of particles
- event topology
- momentum / energy
- particle identity
- jets
- missing energy/momentum

Can't be achieved with a single detector ! → integrate detectors to detector systems

Geometrical concepts

Fixed target geometry



- Limited solid angle $d\Omega$ coverage
- rel. easy access (cables, maintenance)

Magnets

‘Warm’ Dipole Magnet of the LHCb experiment

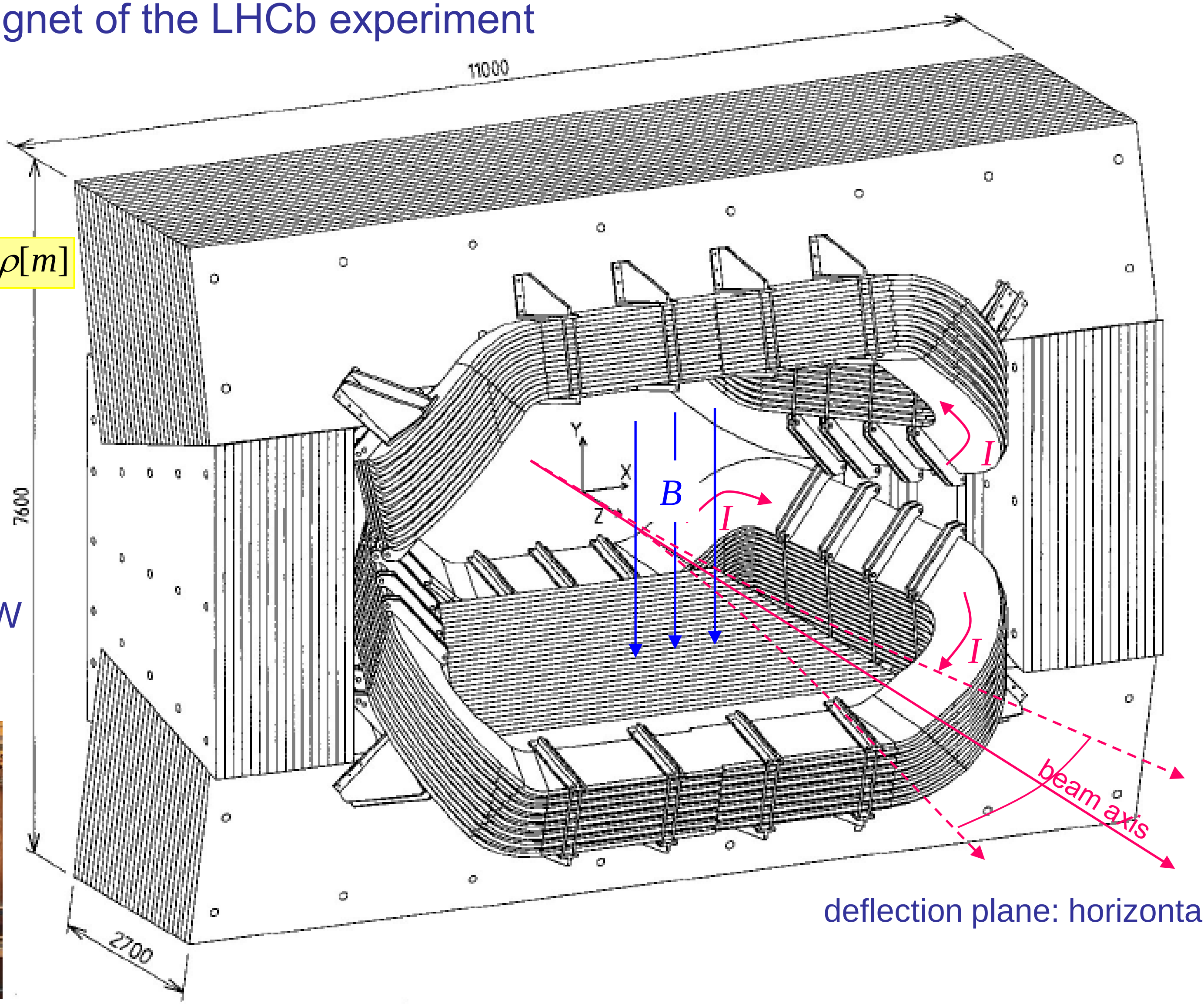
- $\int B\cdot dl = 4$ Tm

Remember ...

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

$$\alpha \approx \frac{0.3L\cdot B}{p_T}$$

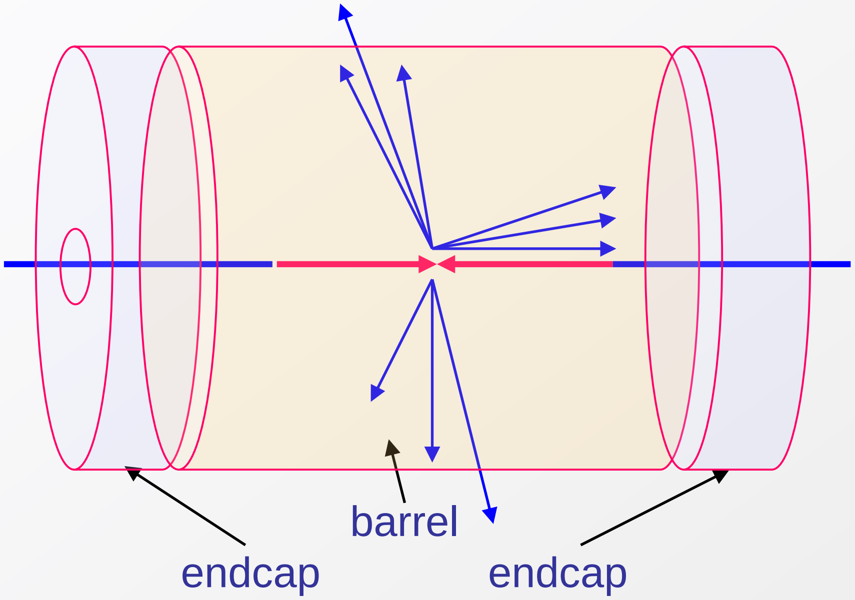
- B_{max} ~ 1 T
- I = 5.8 kA
- R = 125 mΩ
- $P_{el} = R\cdot I^2$ = 4.2 MW
- W_m = 32 MJ



deflection plane: horizontal

Collider Geometry

“4π multi purpose detector”



- “full” dΩ coverage
- very restricted access
- barrel + endcaps

Detector Systems

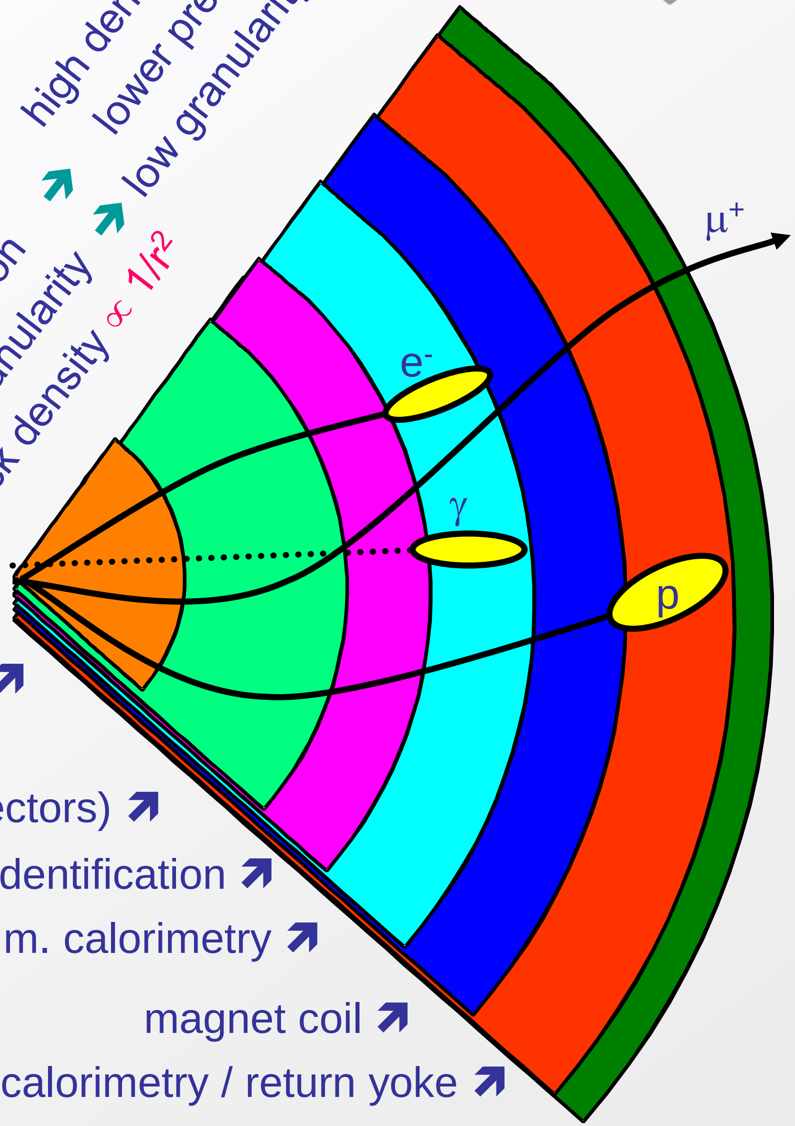
‘Typical’ arrangement of subdetectors

Low density ↗ high density

high precision ↗ lower precision

high granularity ↗ low granularity

track density $\propto 1/r^2$



vertex location (Si detectors) ↗

main tracking (gas or Si detectors) ↗

particle identification ↗

e.m. calorimetry ↗

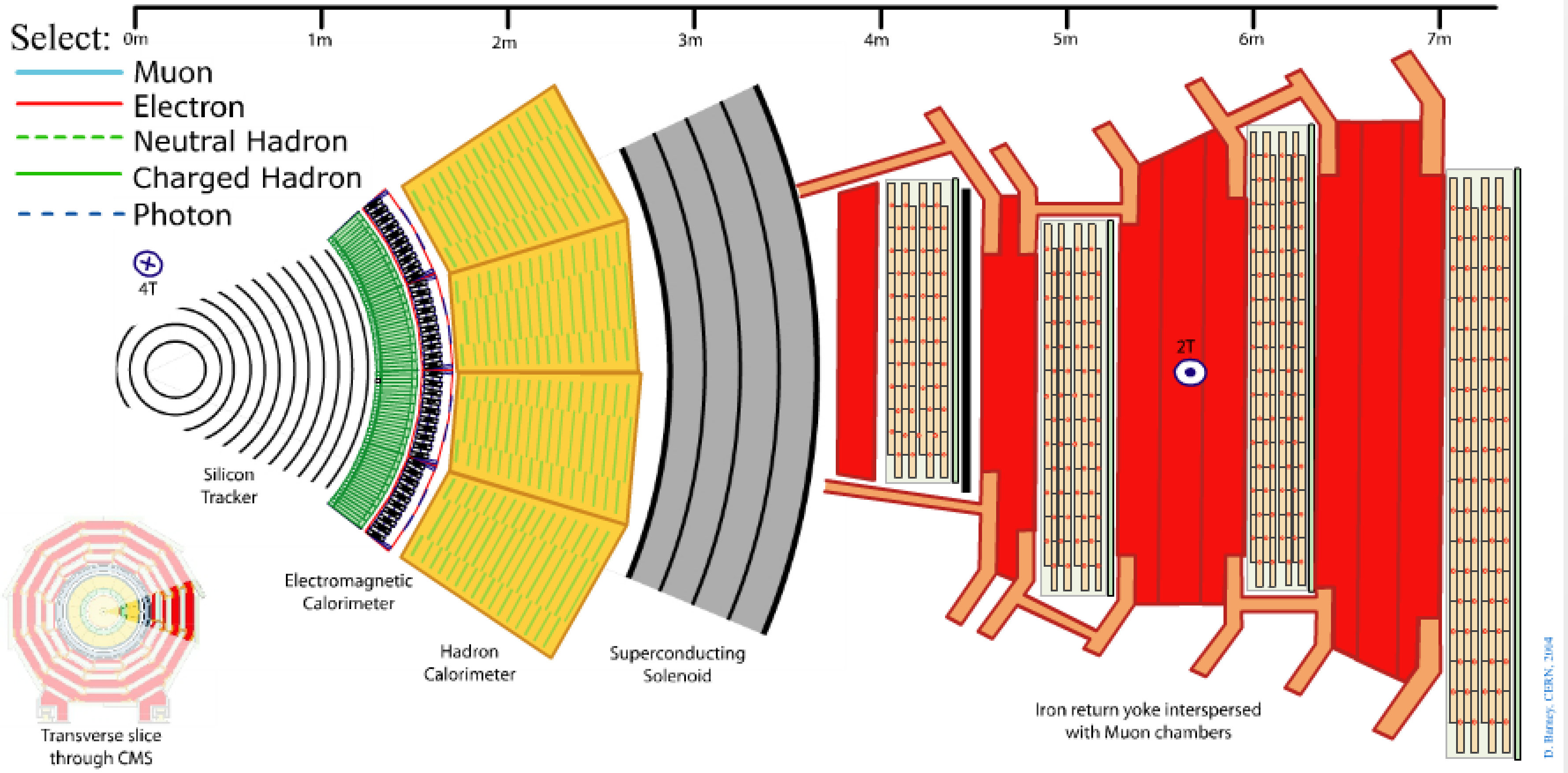
magnet coil ↗

hadron calorimetry / return yoke ↗

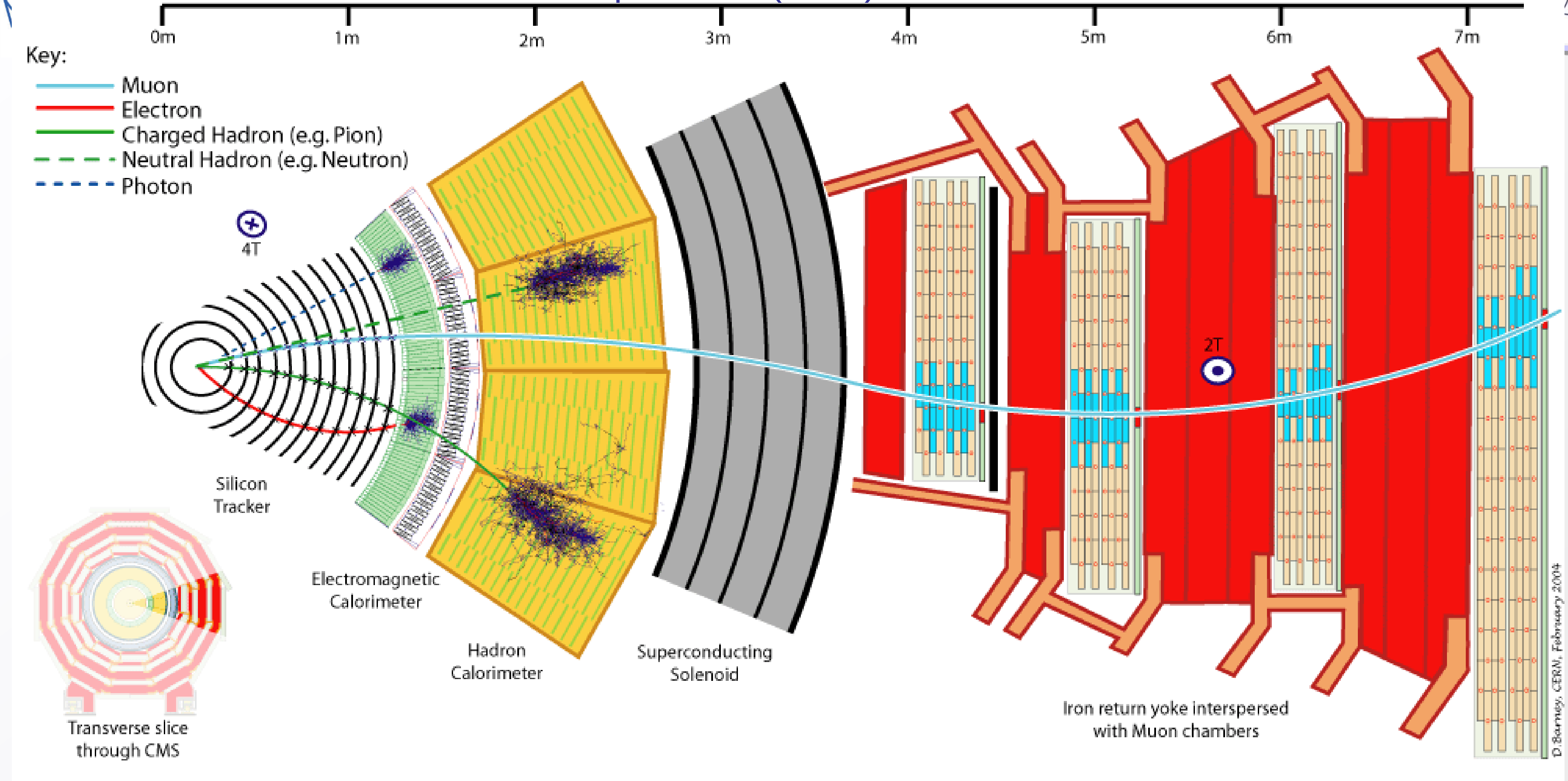
muon identification / tracking ↗

ATLAS and CMS require high precision tracking also for high energetic muons ➔ large muon systems with high spatial resolution behind calorimeters.

A radial sector of a LHC experiment (CMS), animated



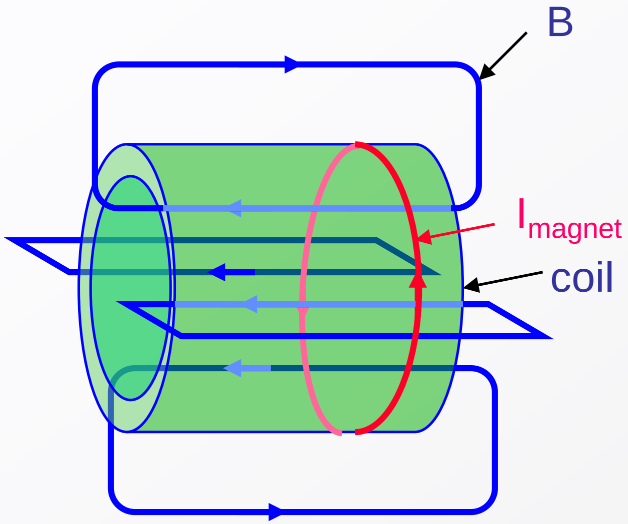
A radial sector of a LHC experiment (CMS)



- Measurement of particle track space points with 10-50 μm precision
- Inner tracking systems in strong magnetic field (superconducting solenoid, B = 4T)
- Calorimeters, both electromagnetic and hadronic, inside magnet coil.
- High performance muon system. Many detector planes, magnetic field still high (2T).
- High requirements in terms of relative alignment and stability.

Magnet concepts for 4π detectors

solenoid

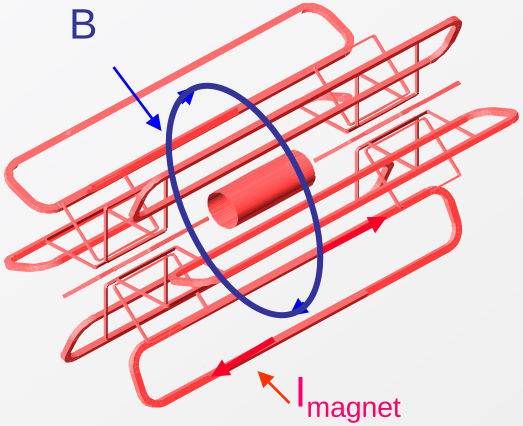


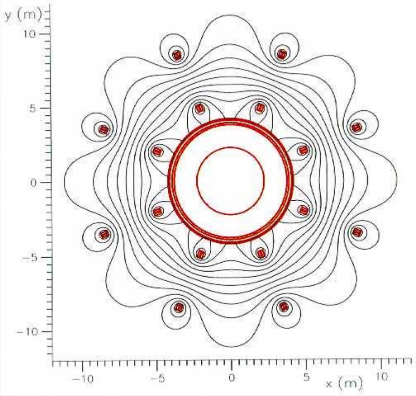
- \+ Large homogenous field inside coil
- \- weak opposite field in return yoke
- \- size limited (cost)
- \- rel. high material budget

Examples:

- DELPHI: SC, 1.2T, Ø5.2m, L   7.4m
- L3: NC, 0.5T, Ø11.9m, L 11.9m
- CMS: SC, 4.0T, Ø5.9m, L 12.5m

toroid



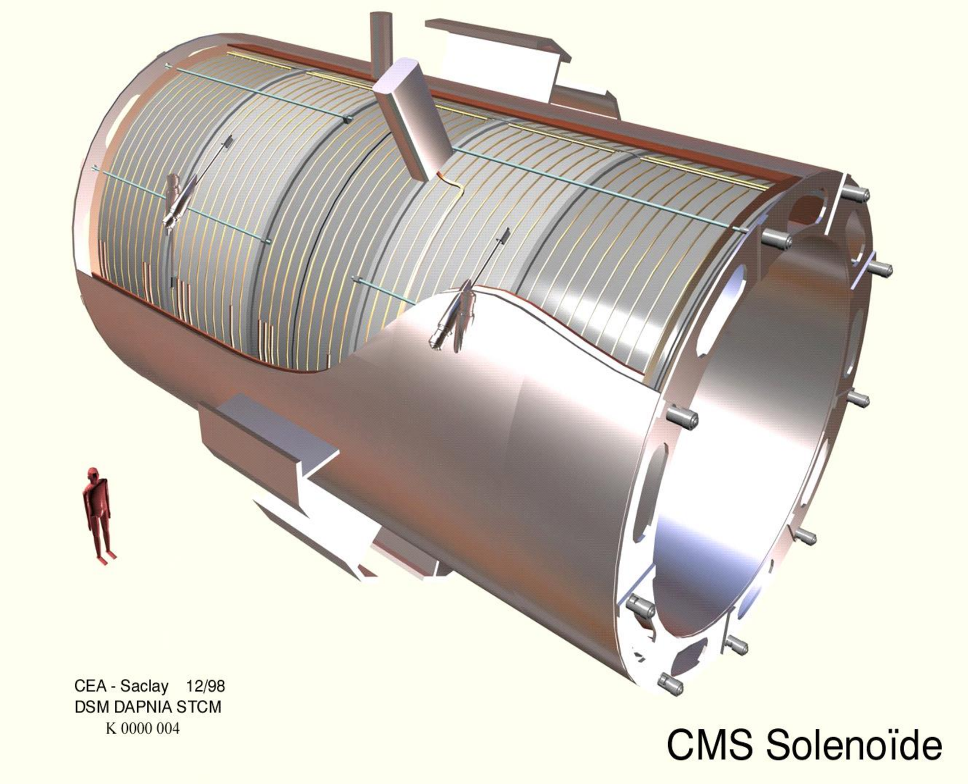


- \+ Field always perpendicular to $\vec{p}$
- \+ Rel. large fields over large volume
- \+ no return yoke needed
- \+ Rel. low material budget
- \- non-uniform field
- \- complex structure

Example:

- ATLAS: Barrel air toroid, SC, ~1T, Ø 9.4 -20.1 m, L = 25.3m

Artistic view of CMS coil

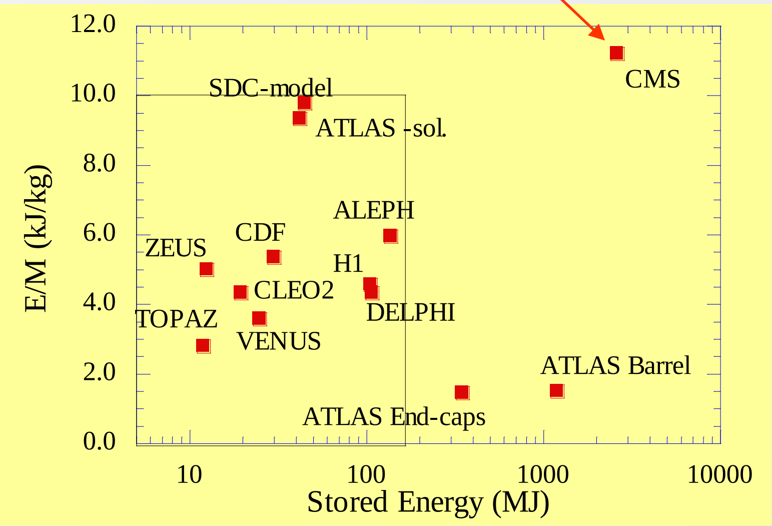


- Length = 22 m
- Diameter = 15 m
- Mass = 12500 t

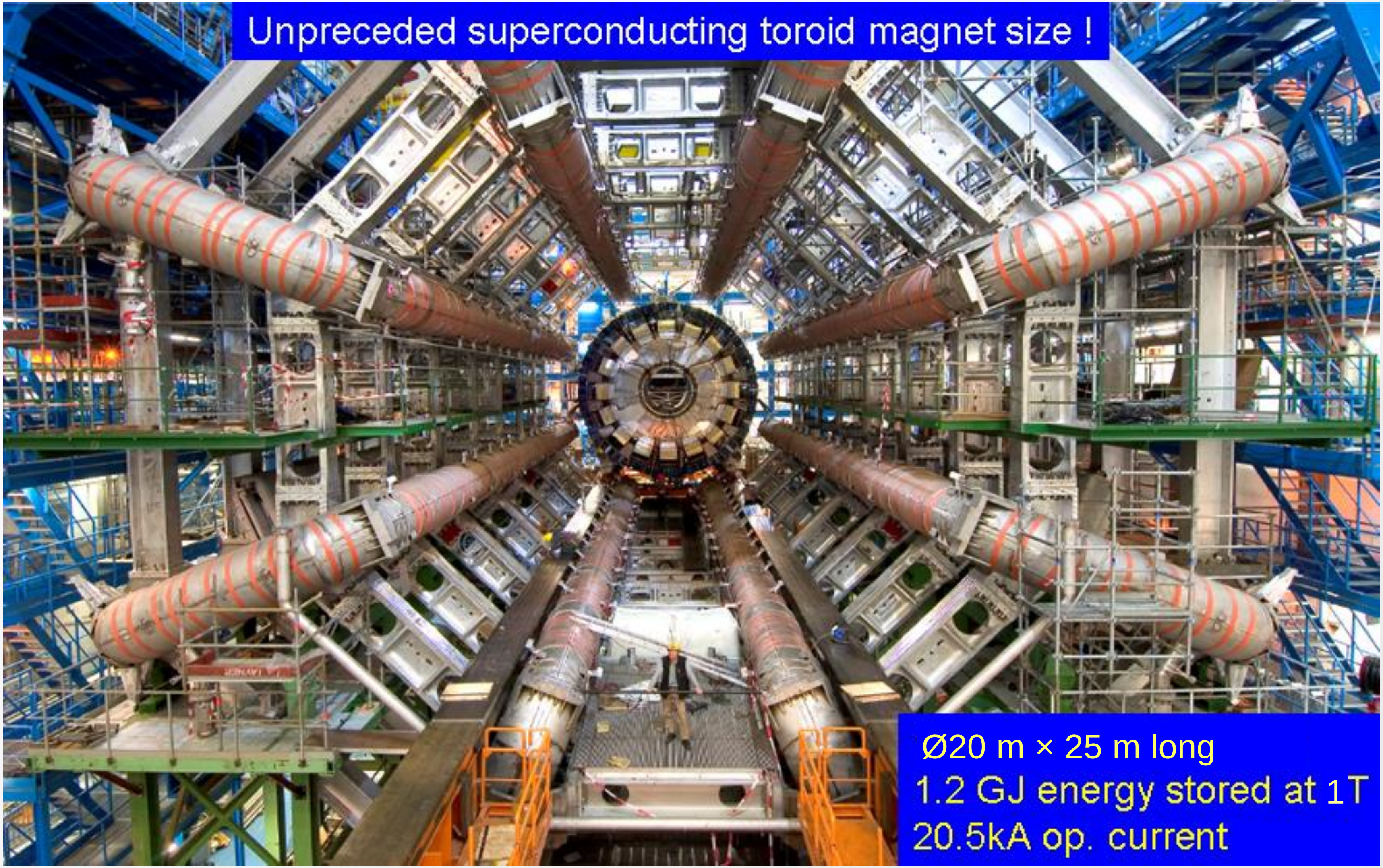
} incl. yoke!

m_{coil} = 220T

- I = 19.2 kA
- W_m = 2.6 GJ



ATLAS toroid coils



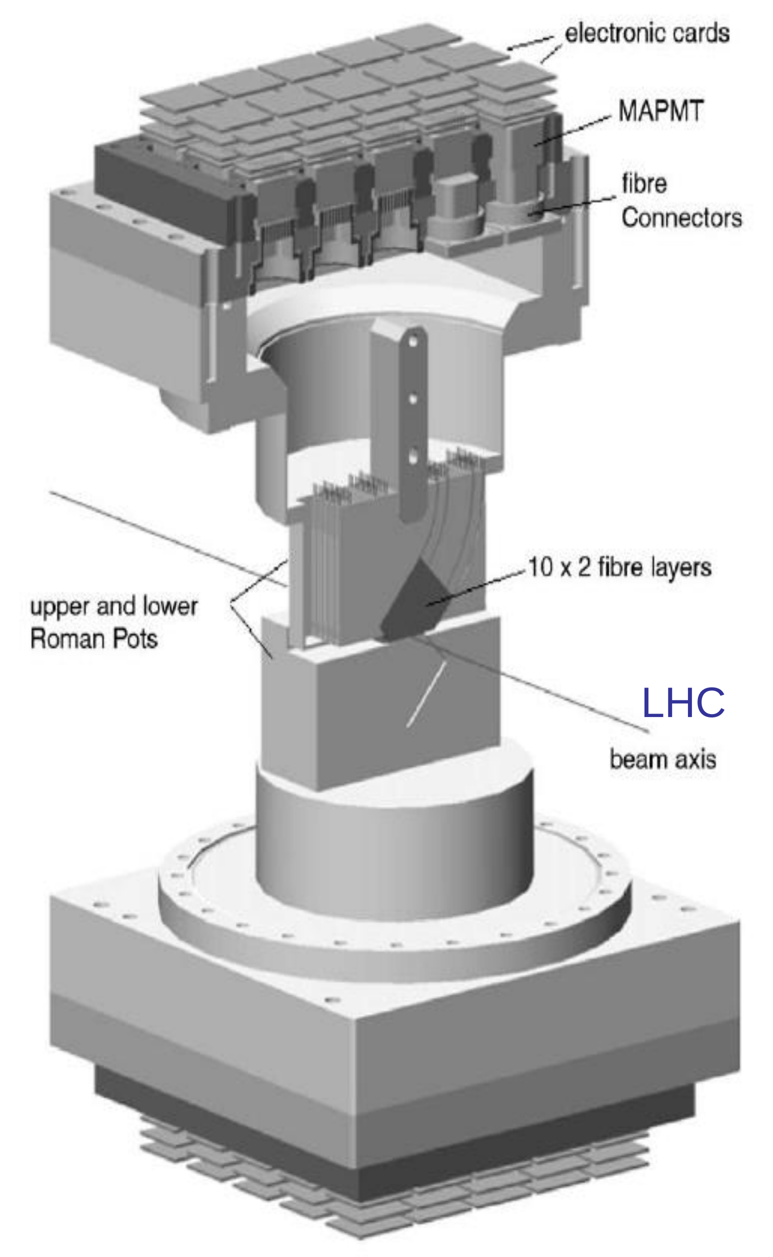
Unprecedented superconducting toroid magnet size !

Ø20 m × 25 m long

1.2 GJ energy stored at 1T

20.5kA op. current

4 such «Roman Pot» stations are located at ± 240 m from ATLAS in LHC tunnel



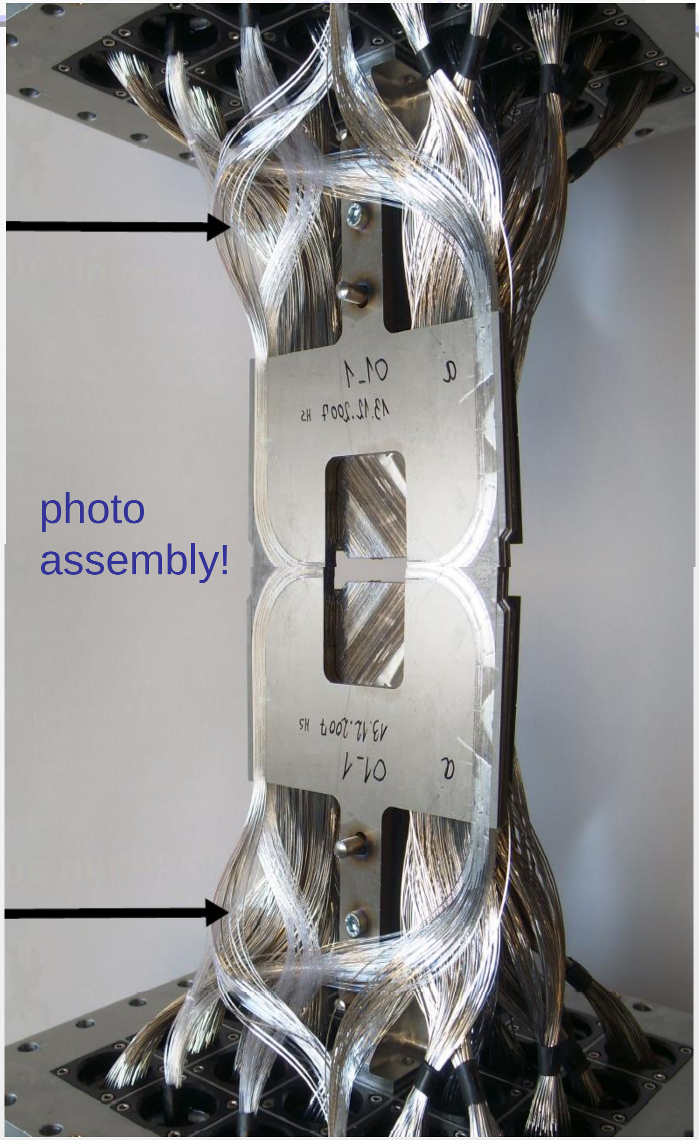
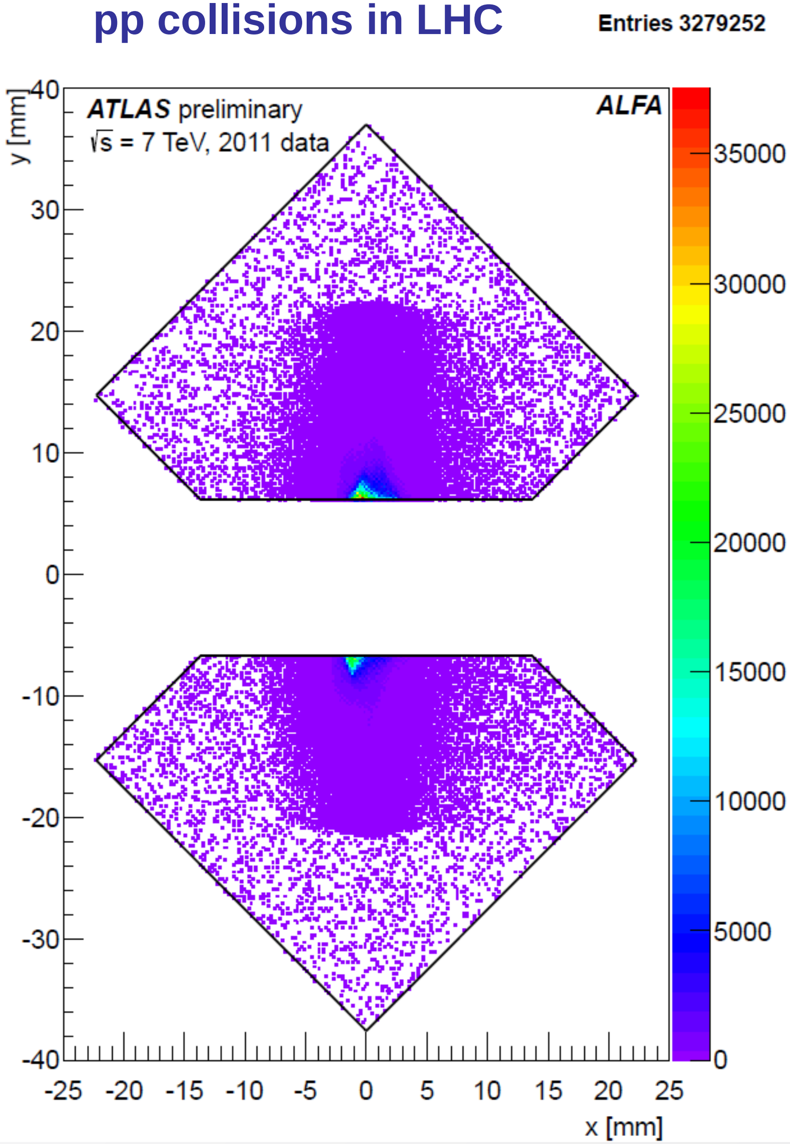


photo
assembly!

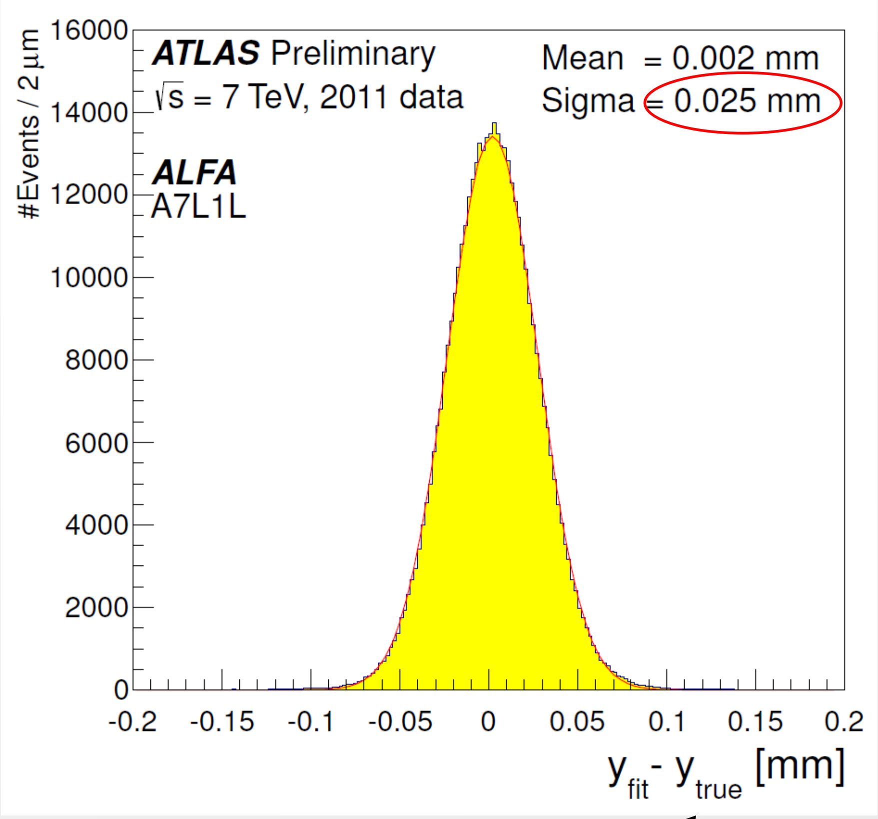
~2 x 1400 fibres

ATLAS ALFA

pp collisions in LHC

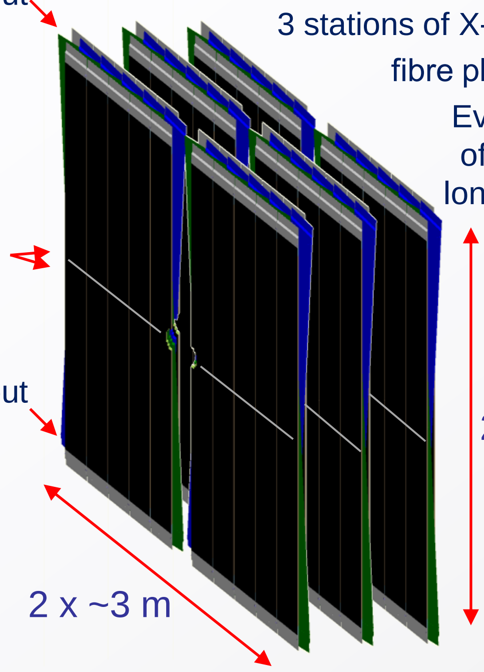


Residuals plot

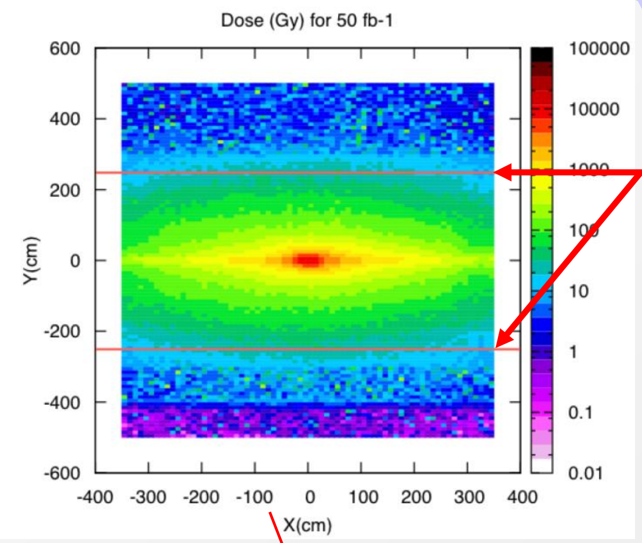


3 ALFA stations predict the track position at the 4th station.

LHCb SciFi A very large fibre tracker for LHCb upgrade (2019)

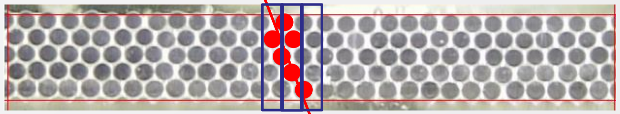


3 stations of X-U-V-X scintillating fibre planes (≤5° stereo). Every plane is made of 5 layers of 2.5 m long Ø250 µm fibres.

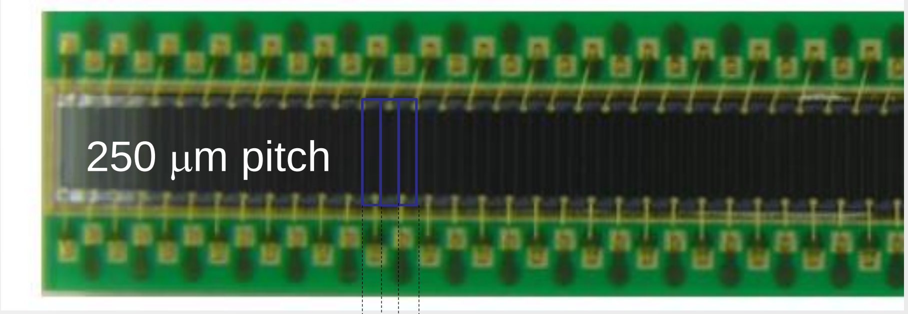


SiPM location

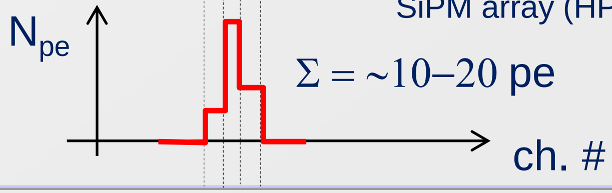
$F_n = 6 \cdot 10^{11}\ \mathrm{cm}^{-2}$



5 layer proto fibre mat



SiPM array (HPK)



Benefits

- Fibres generate and transport signal
- Low and uniform mass distribution

Challenges

- Large size – high precision
- O(10’000 km) of fibres
- Operation of SiPM at -40°C (radiation damage)

Birk’s law

The response of a plastic scintillator is found to be non-linear for high ionization densities (i.e. non MIP) → Birk’s law

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}.$$

Recombination and quenching effects between the excited molecules and the surrounding substrate reduce the light yield.

k_B is 0.126 mm/MeV for polystyrene-based scintillators

$dE/dx = 2 \cdot dE/dx_{MIP}$ → $dL/dx = 1.96\ dL/dx_{MIP}$

Light yield can also be (indirectly) affected by magnetic field → curling of low momentum tracks at the same location → large effective dE/dx.