Experimental methods in particle physics

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Webpage of lecture:
http://atomfizika.elte.hu/rfkm/rfkm2019.html

Calorimeter types and processes

- Homogeneous (EM) calorimeters: full volume sensitive (contributes to the signal)
  - Usually inorganic (high density, high Z) crystal scintillators or non-scintillator Cherenkov-radiators (e.g. lead-glass)
  - Excellent energy resolution, but expensive and high quality mass-production challenging
  - E.g. CMS lead-tungstate EM calorimeter:

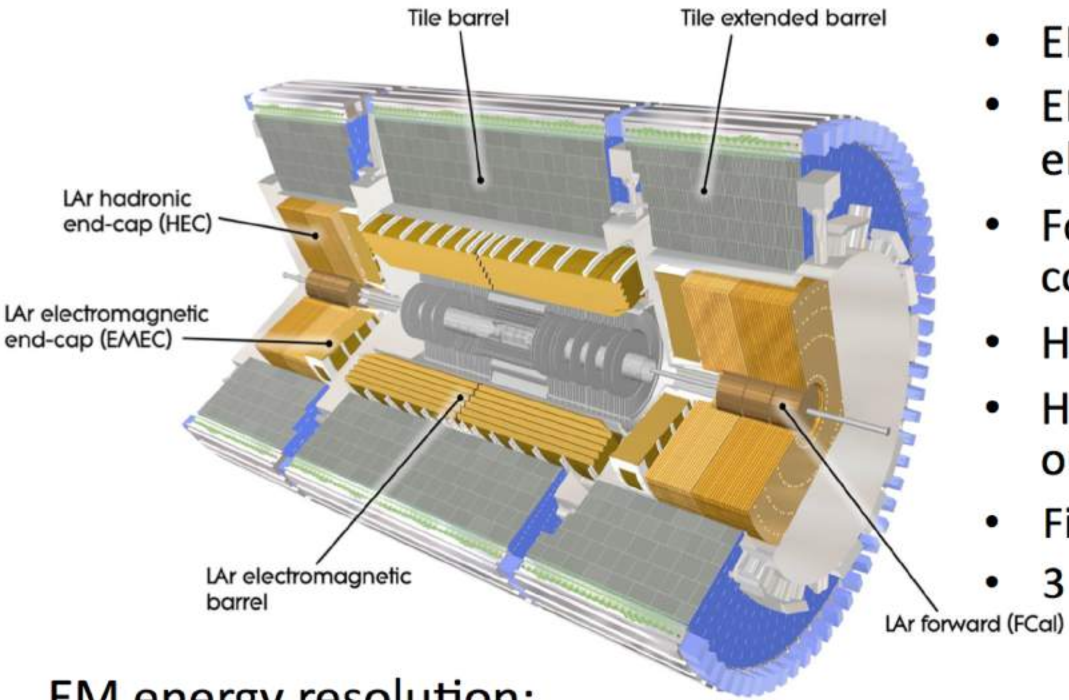
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997

- Sampling (EM or hadron) calorimeters: absorber metal layers, pl. Fe, Cu (hadron) and Pb (EM), alternate with active detector layers
  - Active material could be scintillator, ionizing liquid noble gas, Cherenkov-radiator, semi-conductor or gas detector
  - Cheap, provides fine segmentation (better vertex determination precision, more e/γ identification information), but not whole shower visible (worse energy resolution)
  - E.g. ATLAS EM calorimeter:

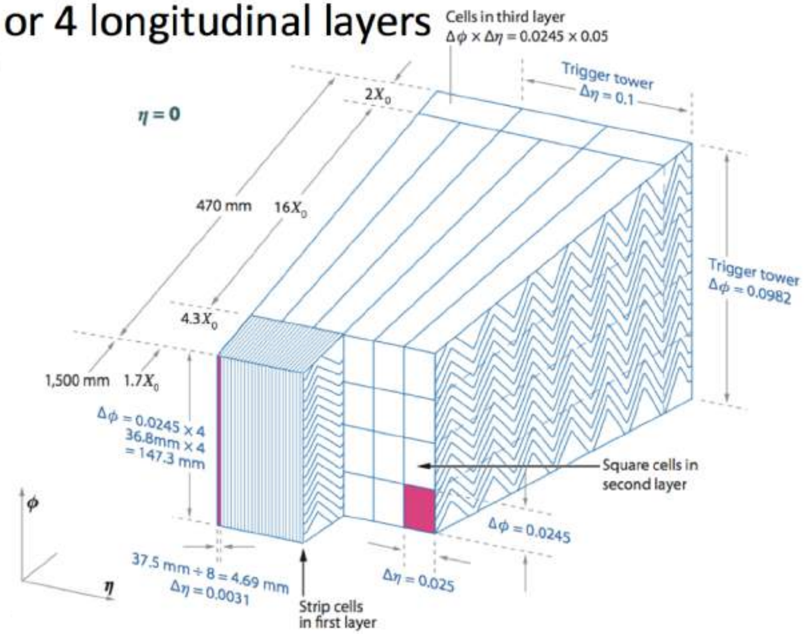
Liquid Ar/Pb accordion	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

- Energy resolution: $(\sigma_E / E)^2 = (a/E)^2 + (b/\sqrt{E})^2 + c$ b: stochastic (sampling) term
  - Fluctuation of first interaction point   a: noise term,   c: constant term (→ Calo quality)
  - Sampling fluctuations
  - Fluctuation of energy leakage in longitudinal direction
  - crystal non-uniformity
  - Electronic noise
  - …
- Spatial resolution

The ATLAS Calorimeter System



- EM presampler, |η|<1.8: active LAr layer
- EM calorimeter, |η|<3.2: accordion shaped electrodes and lead absorbers in LAr
- Forward calorimeter, 3.1<|η|<4.9: copper/tungsten-LAr
- Hadronic end-cap, 1.5<|η|<3.2: copper/LAr
- Hadronic tile calorimeter, |η|<1.7: outside LAr cryostats
- Fine lateral segmentation
- 3 or 4 longitudinal layers



EM energy resolution:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

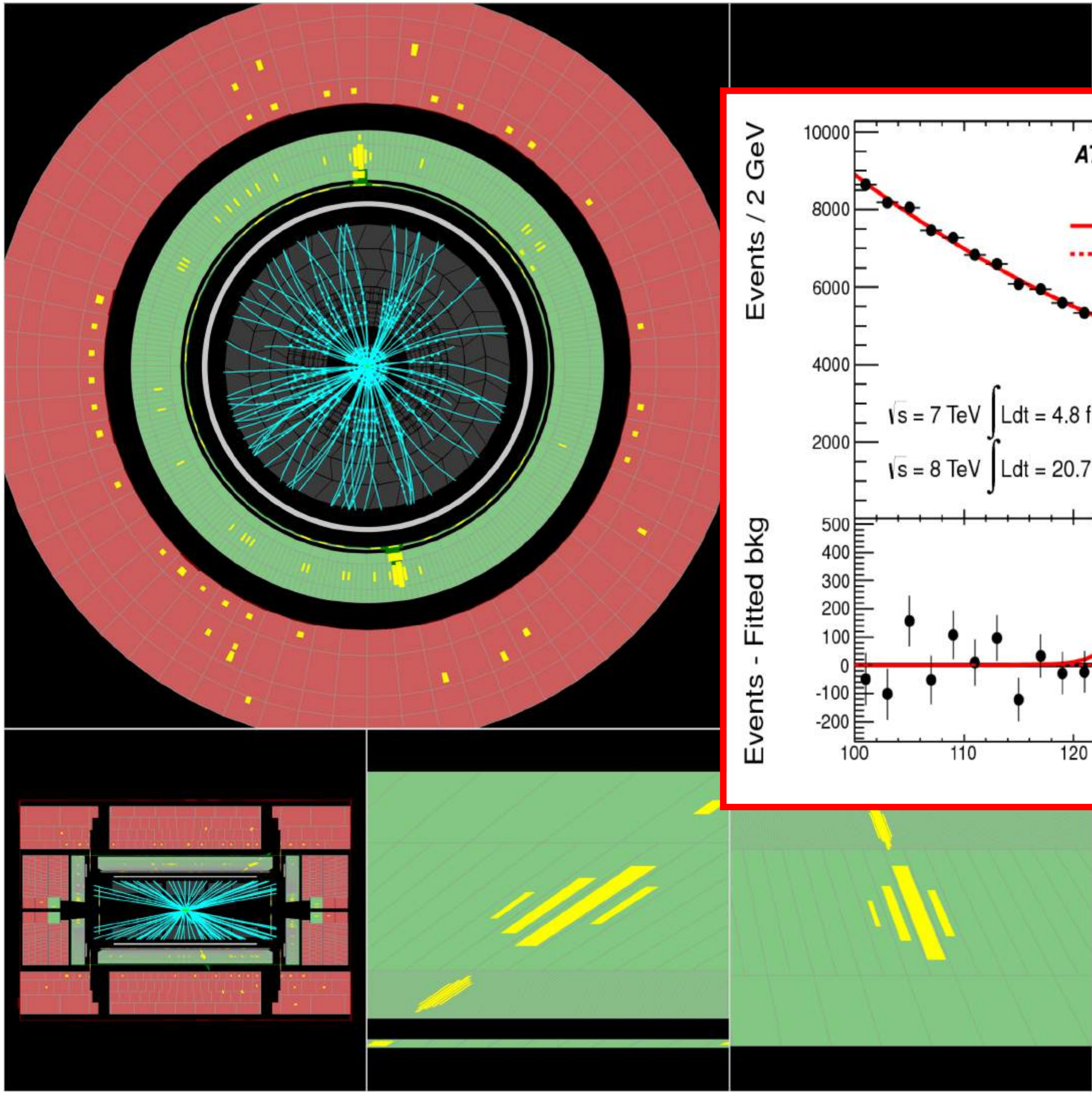
a≈10%, b≈170 MeV, c≈0.7%

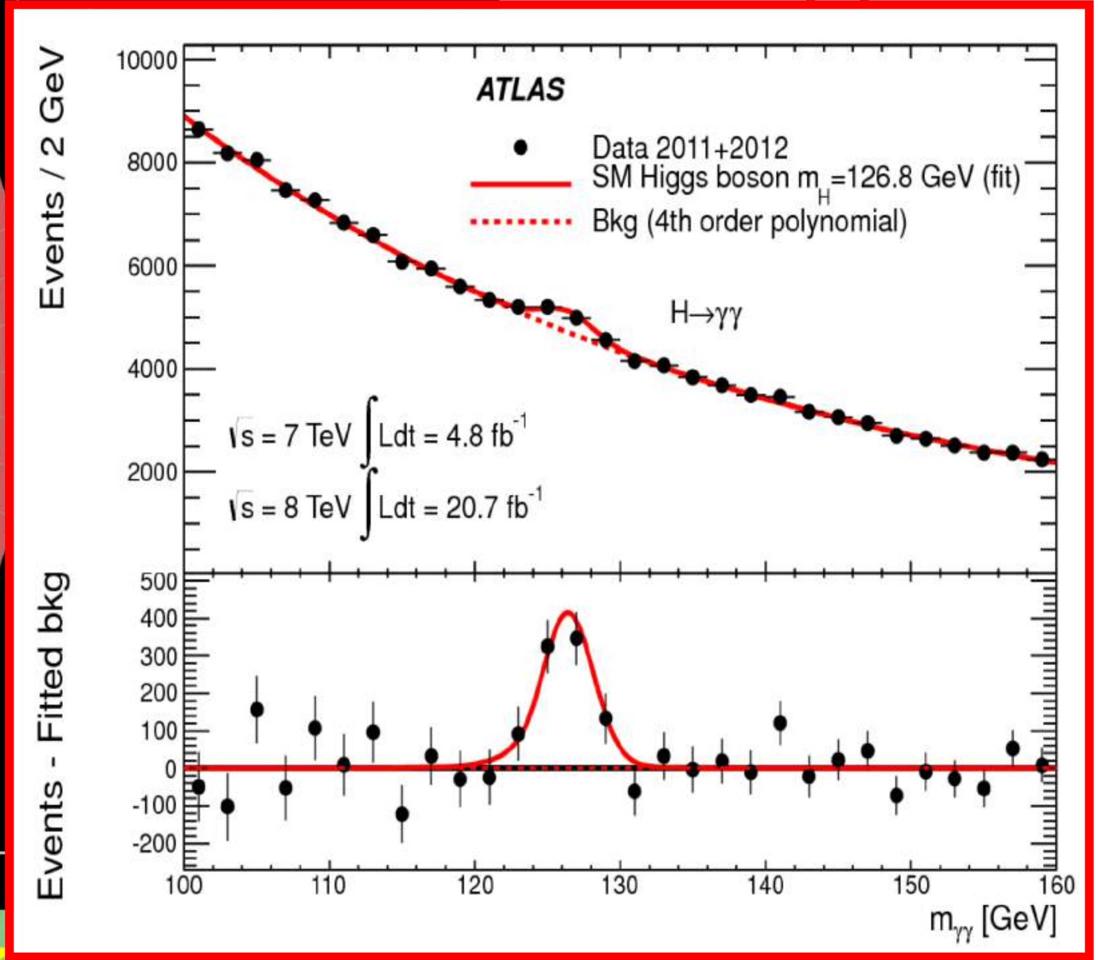
Hadronic energy resolution:

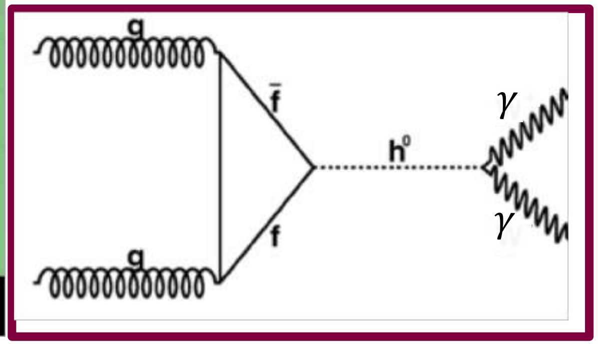
a≈50%, c≈3%

Compare with CMS crystal size:
22 x 22 x 230 mm^3 (1 R_M x 1 R_M x 26 X_0) (barrel),
30 x 30 x 220 (endcap)

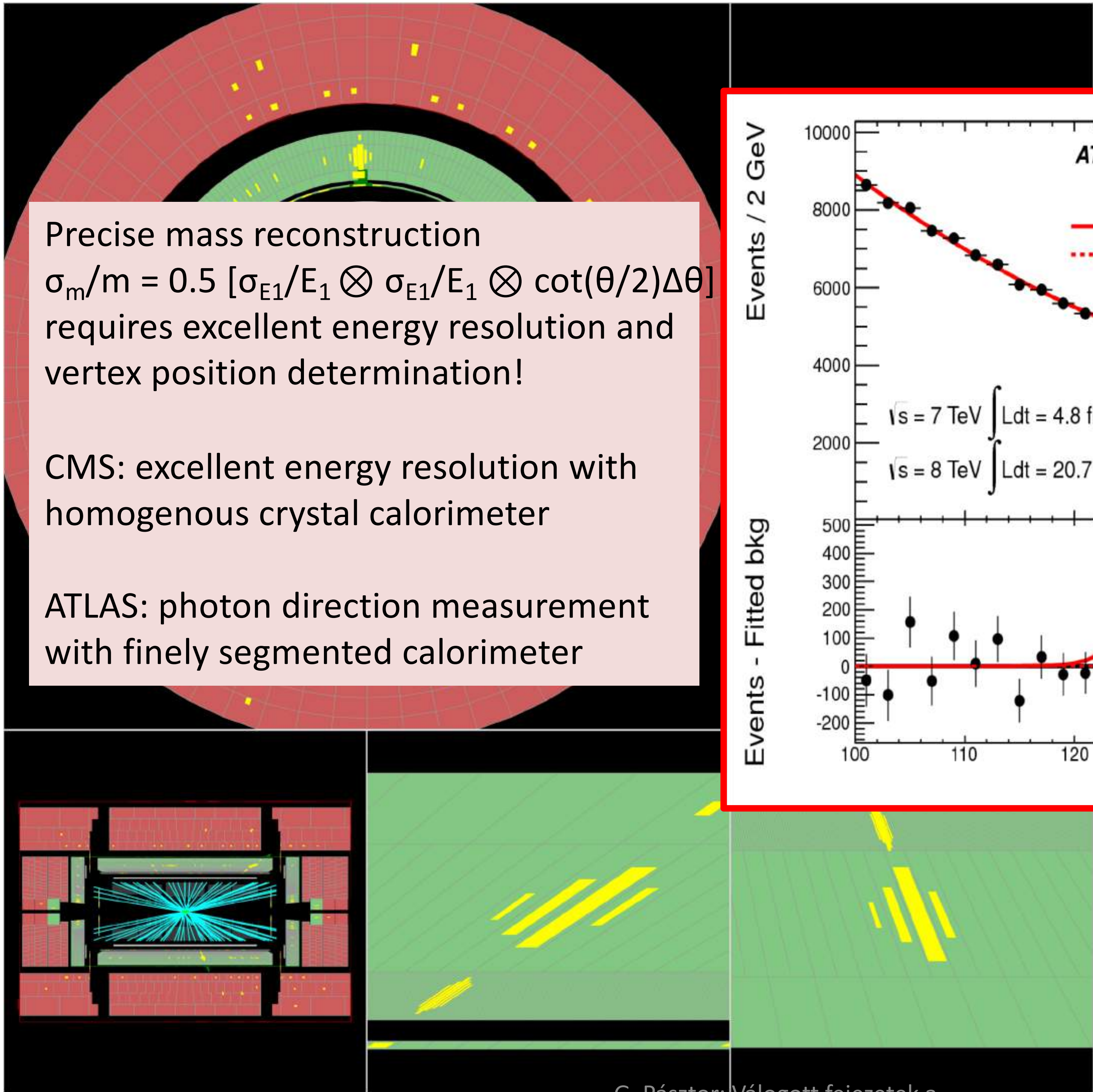
H→$\gamma\gamma$







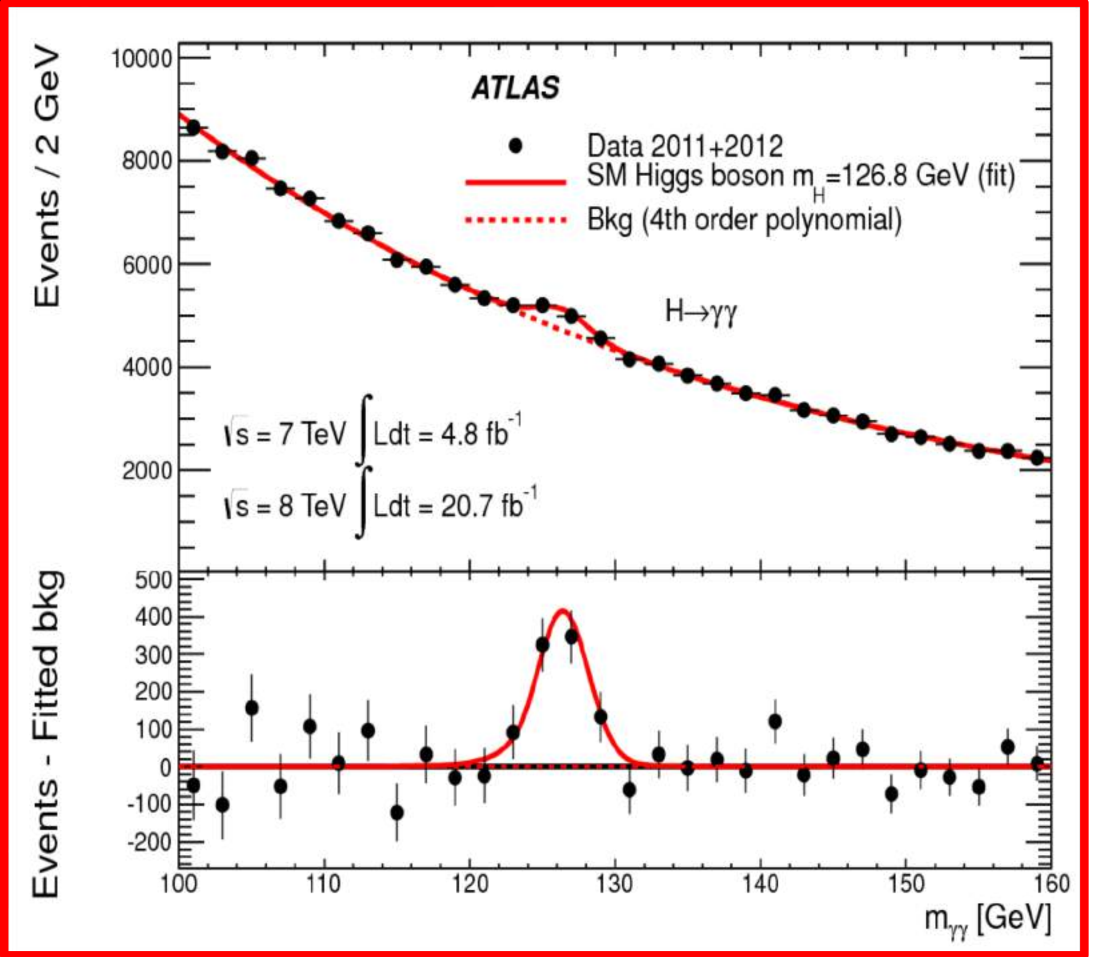
$H \to \gamma\gamma$

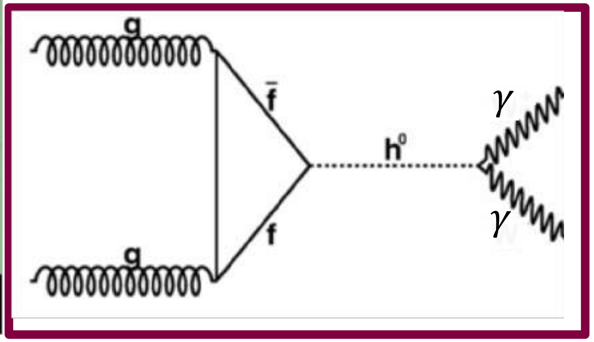


Precise mass reconstruction
$\sigma_m/m = 0.5\ [\sigma_{E1}/E_1 \otimes \sigma_{E1}/E_1 \otimes \cot(\theta/2)\Delta\theta]$
requires excellent energy resolution and vertex position determination!

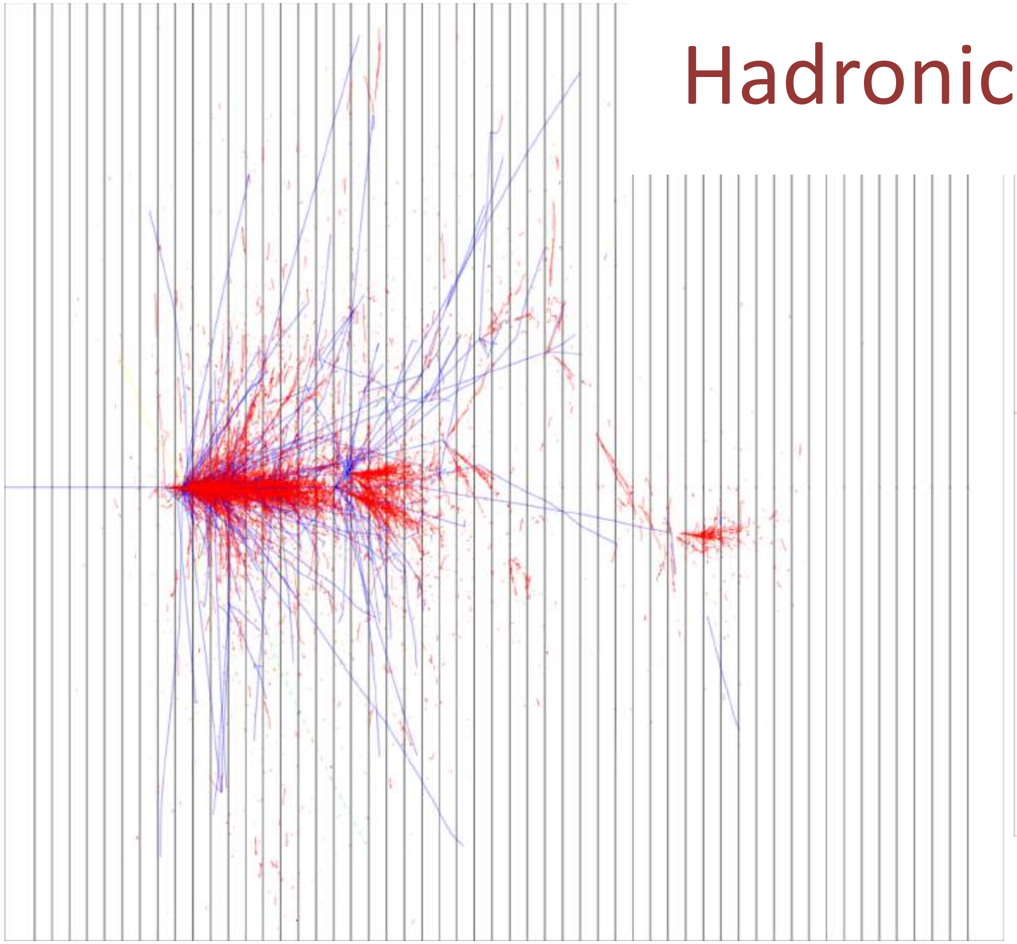
CMS: excellent energy resolution with homogenous crystal calorimeter

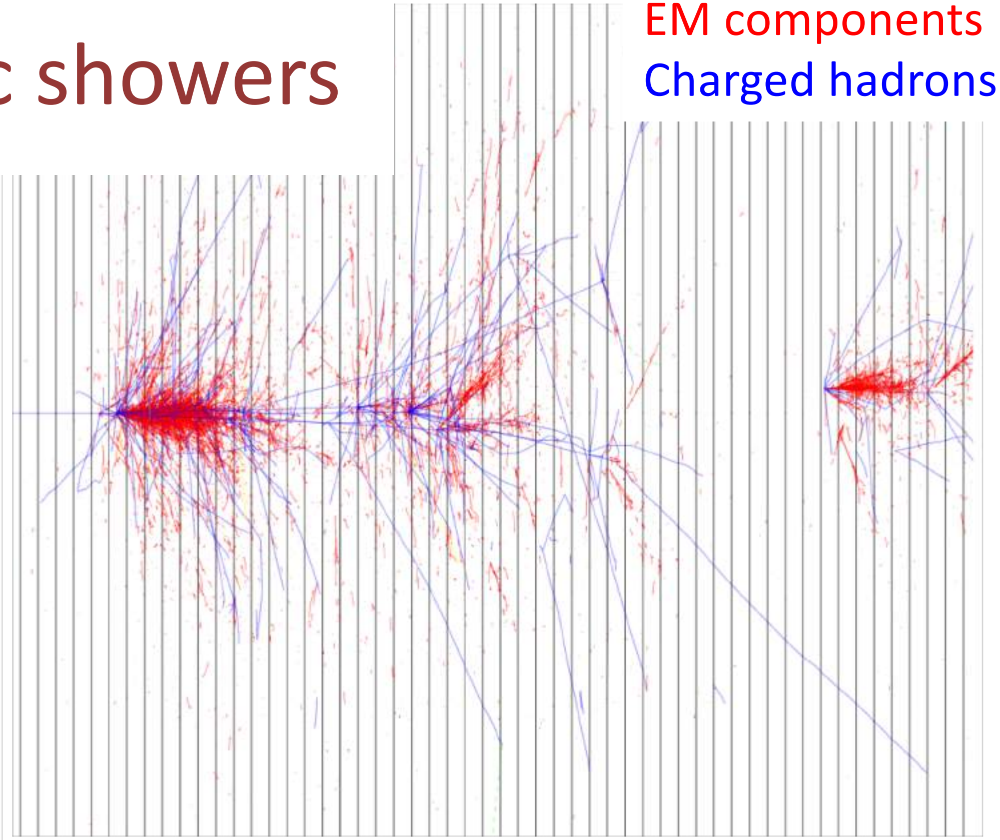
ATLAS: photon direction measurement with finely segmented calorimeter





Hadronic showers





Electromagnetic and hadronic component

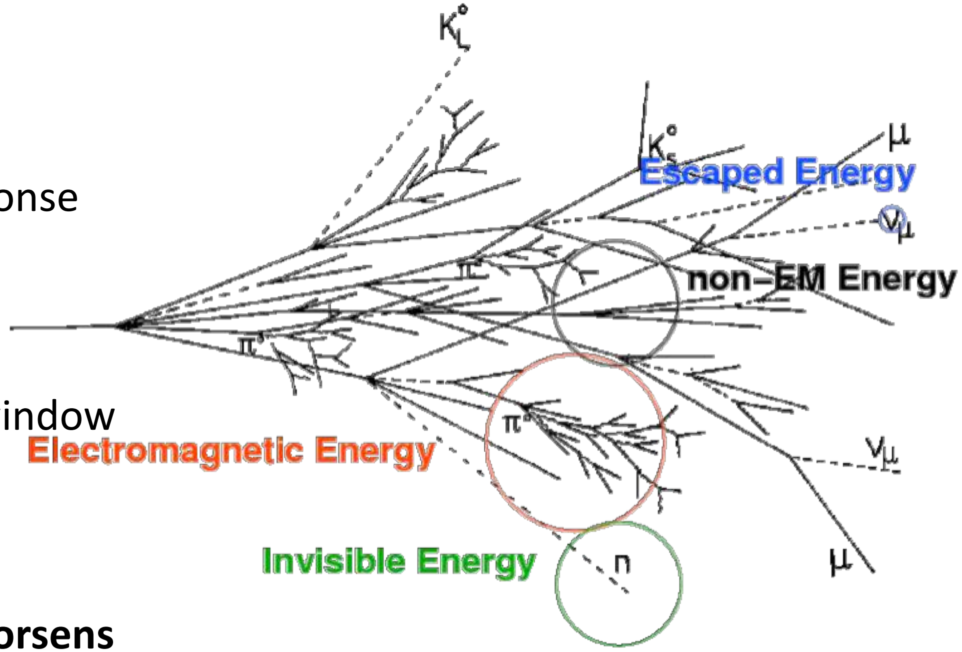
- EM component grows with energy → non-linear response

Energy loss in hadron calorimeters

(energy that is not observable as an ionisation signal):

- Nuclear fission, spallation, excitation
- Late energy deposit outside the measurement time window (e.g. late photons)
- Low energy neutrons
- Particles escaping the detector

Large event-by-event fluctuation→ energy resolution worsens



Hadron calorimeters

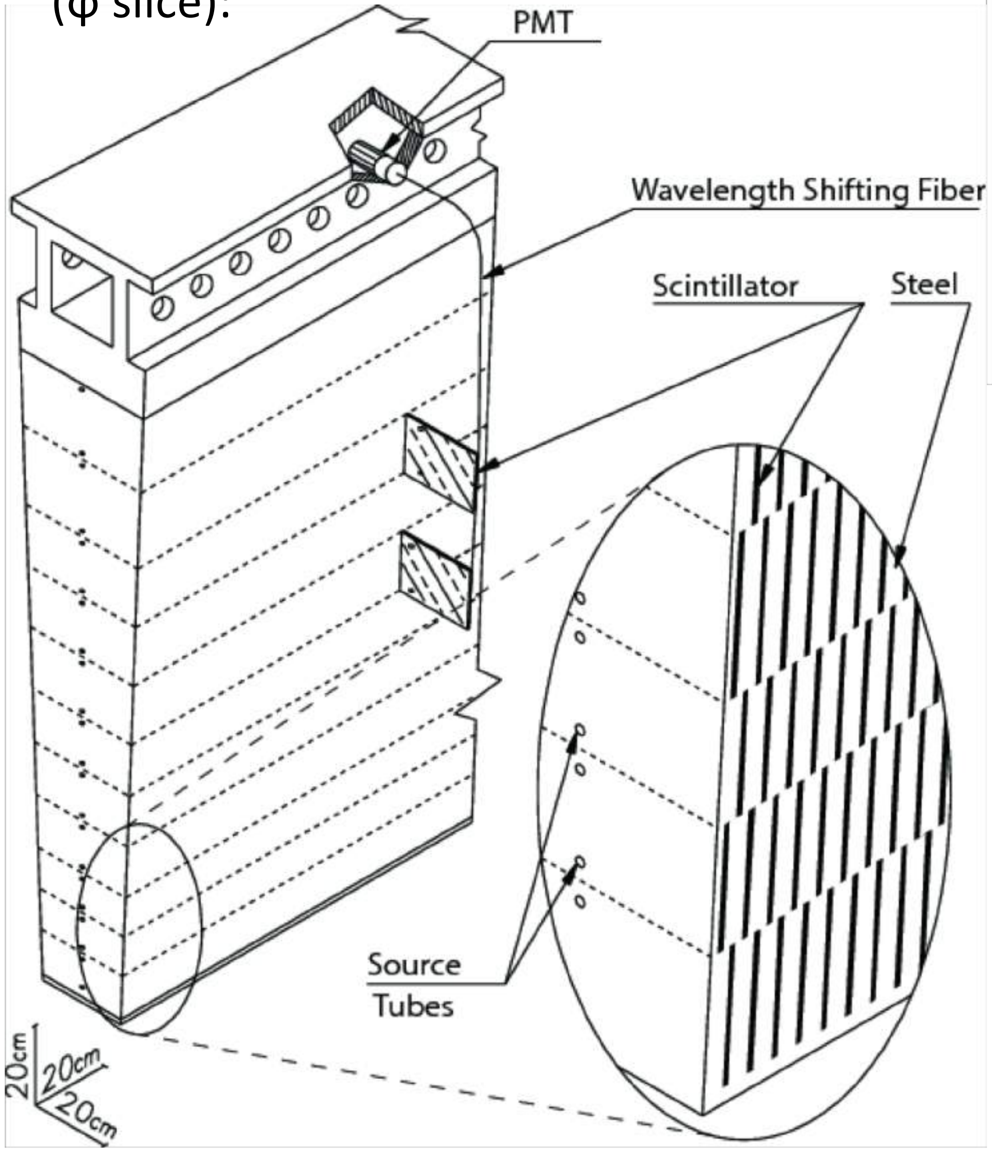
- Operation similar to sampling EM calorimeters but interaction length $\lambda_I \approx 35\ g/cm^2 \cdot A^{1/3}$ takes over the role of X_0
- Hadron calorimeters are much larger
- **Shower not only longer but also wider than EM shower**
  - EM: multiple scattering
  - Hadron: large transverse momentum transfer in nuclear interactions
- **Large non-visible energy fraction: 30-40%**
  - Energy to open nuclear bonds
  - Very short lifetime nuclear remnants, absorbed before reaching the active region of the sampling calorimeter
  - Long lifetime and stable particles (K_L^0, n) might escape the calorimeter
  - Muons from pion decay could also escape

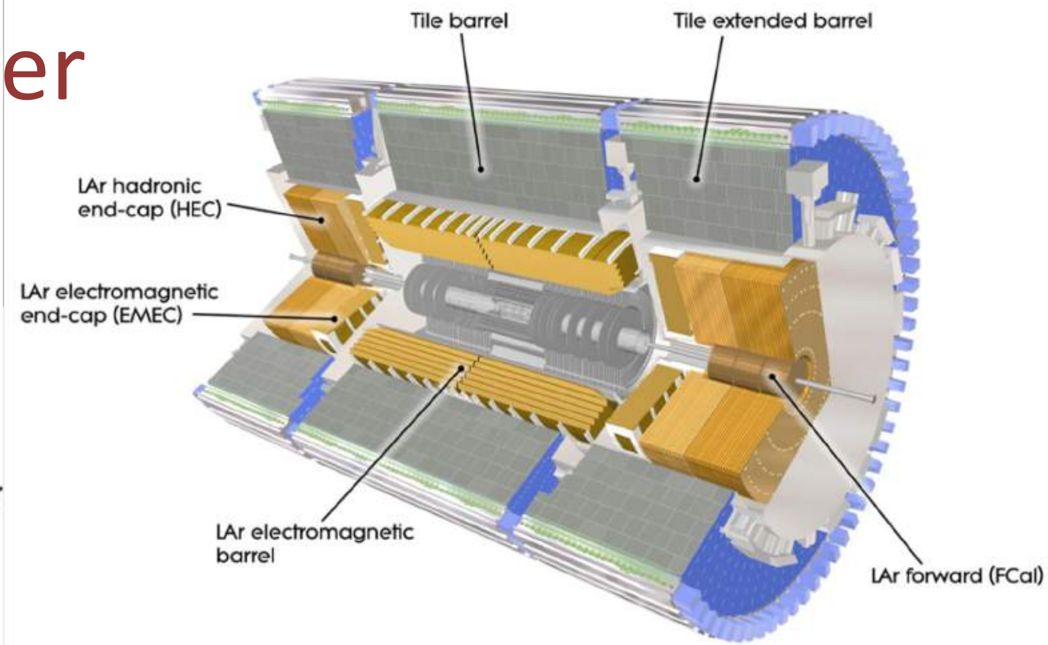
Only the EM energy and the energy of charged particles can be measured in the calorimeter!

- Compensating calorimeters try to get back this energy loss and to equalize the response for electrons and hadrons
  - If Uranium absorber used, neutrons are also produced, which can induce nuclear fission in the material of the absorber, creating more neutrons and high energy photons
  - By measuring the energy of these neutrons and γ's, the hadron shower signal increases
  - With appropriate U/LAr, U/Cu/scintillator mixtures for multi-GeV hadrons compensation is achievable
  - For very large energies (>100 GeV) overcompensation could manifest
- **Best hadron calorimeters achieve $\sigma_E / E = 35\% / \sqrt{E}$ [GeV] resolution**
  - Dominant term : sampling fluctuations

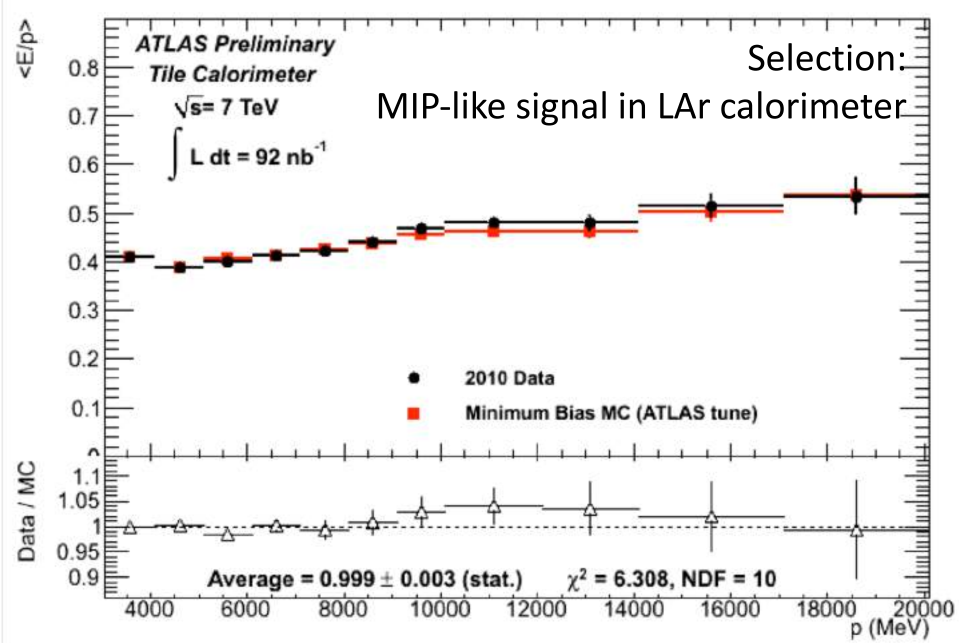
ATLAS Tile calorimeter

Mechanical structure and optical readout (φ slice):



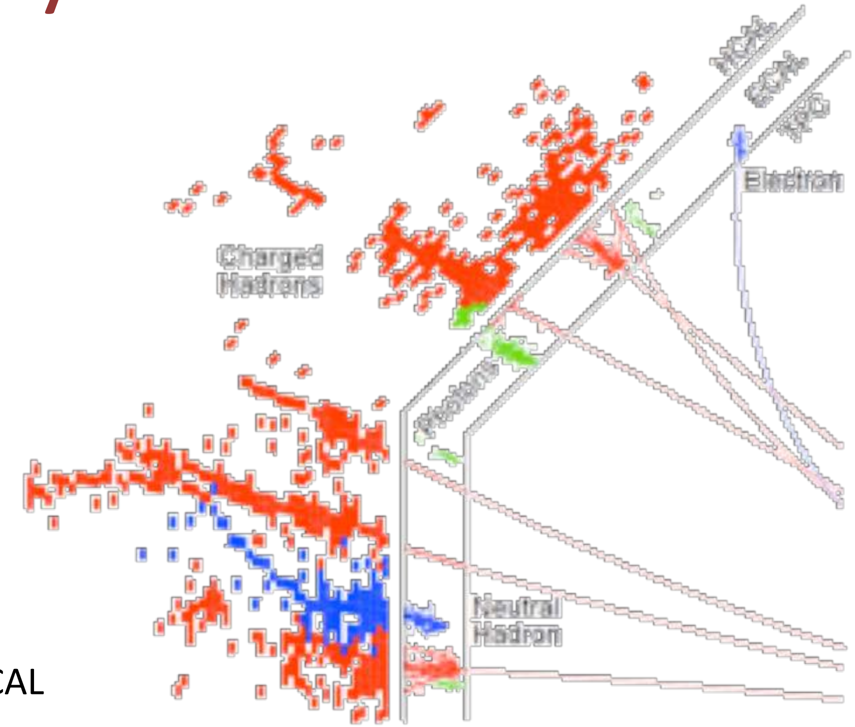


Isolated hadron response



Future of calorimetry

Typical event topology:
Photons, electrons, charged and neutral hadrons



Typical jet:

- 60% of jet energy in charged hadrons
- 30% in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
- 10% in neutral hadrons (mainly n and K_L)

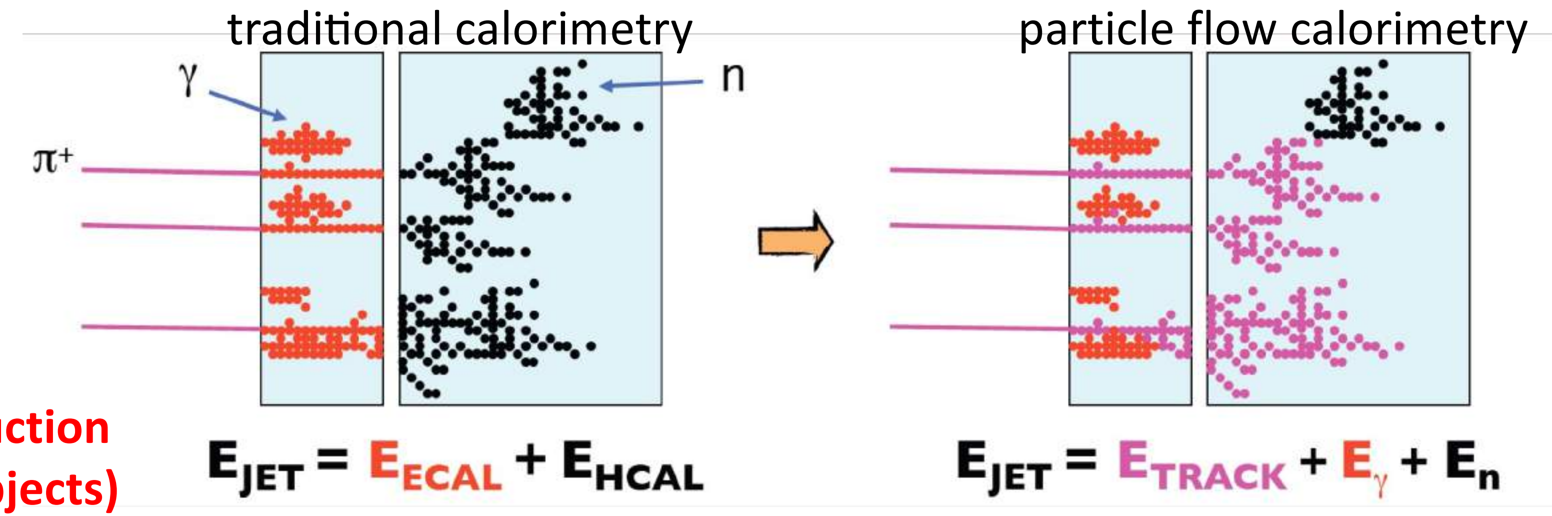
Traditional calorimetric approach:

- Measure all components of jet energy in ECAL/HCAL
- Approx. 70% of energy measured in HCAL: $\sigma_E/E \approx 60\% / \sqrt{E(\mathrm{GeV})}$

Fine granularity Particle Flow Calorimetry reconstructing individual particles:

- Charged particle momentum measured in tracker (essentially perfectly)
- Photon energies measured in ECAL: $\sigma_E/E < 20\% / \sqrt{E(\mathrm{GeV})}$
- Only neutral hadron energies (10% of jet energy) measured in HCAL

→ much improved resolution



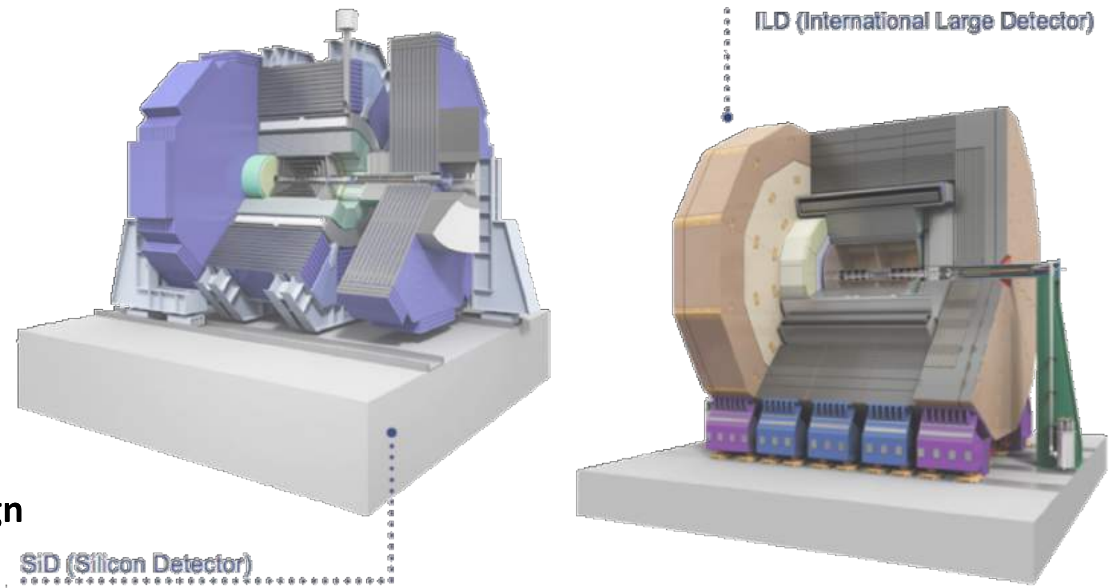
Particle flow plays already a major role at LHC event reconstruction (CMS uses PF for all objects)

Particle flow calorimetry: reconstruct the particle track
→ greatly improved energy resolution for charged hadrons

From Cambridge Linear Collider Group Home Page

Particle Flow Calorimetry (PFCal)

- **Hardware** needs to be able to resolve energy deposits from different particles:
  → **highly granular detectors** (as studied by CALICE for ILC)
- **Software** needs to be able to identify energy deposits from each individual particle:
  → **sophisticated reconstruction** software to deal with complex events, containing many hits
- Fine granularity Particle Flow must be studied in context of whole detector:
  → detailed GEANT4 simulations of potential detector designs, e.g. ILC detector concepts
- **Silicon Detector design**
  • tracker radius 1.2m
  • B-field: 5T
  • Tracker: Silicon (5 layers)
  • Calorimetry : fine granularity particle flow
  • ECAL + HCAL inside large solenoid
- **International Large Detector**
  • tracker radius 1.8m
  • B-field: 3.5 T
  • Tracker: TPC (220 layers)
  • Calorimetry: fine granularity particle flow
  • ECAL + HCAL inside large solenoid

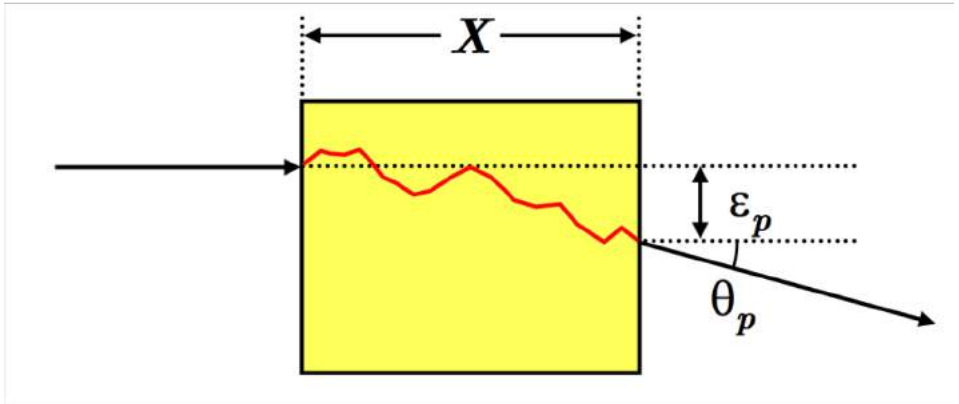


- **PFCal puts requirements on ECAL and HCAL design**
- ECAL requirements:
  • Minimise transverse spread of EM showers: small Molière radius & transverse segmentation
  • Longitudinally separate EM/Hadronic showers: large ratio λ_I/X_0
  • Identification of EM showers: longitudinal segmentation
- HCAL requirements:
  • Fully contain hadronic showers: small λ_I
  • Resolve hadronic shower structure: longitudinal and transverse segmentation
  • HCAL will be rather large: cost and structural properties important

Tracking detectors

Multiple scattering

- Particles along their path in the medium scatter multiple times loosing energy and changing direction
- Dominant process: small-angle Coulomb scattering
- In case of hadrons, strong interaction also plays a major role
- Direction change is random, contributes to position measurement error → Gaussian distribution
- Non-Gaussian tail from rare "hard" (large momentum transfer) scatterings
- Lateral displacement (ε) proportional to material thickness, for thin (~300-500 μm) Si detectors negligible



$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0} \left[1 + 0.038 \ln(x/X_0)\right]$$

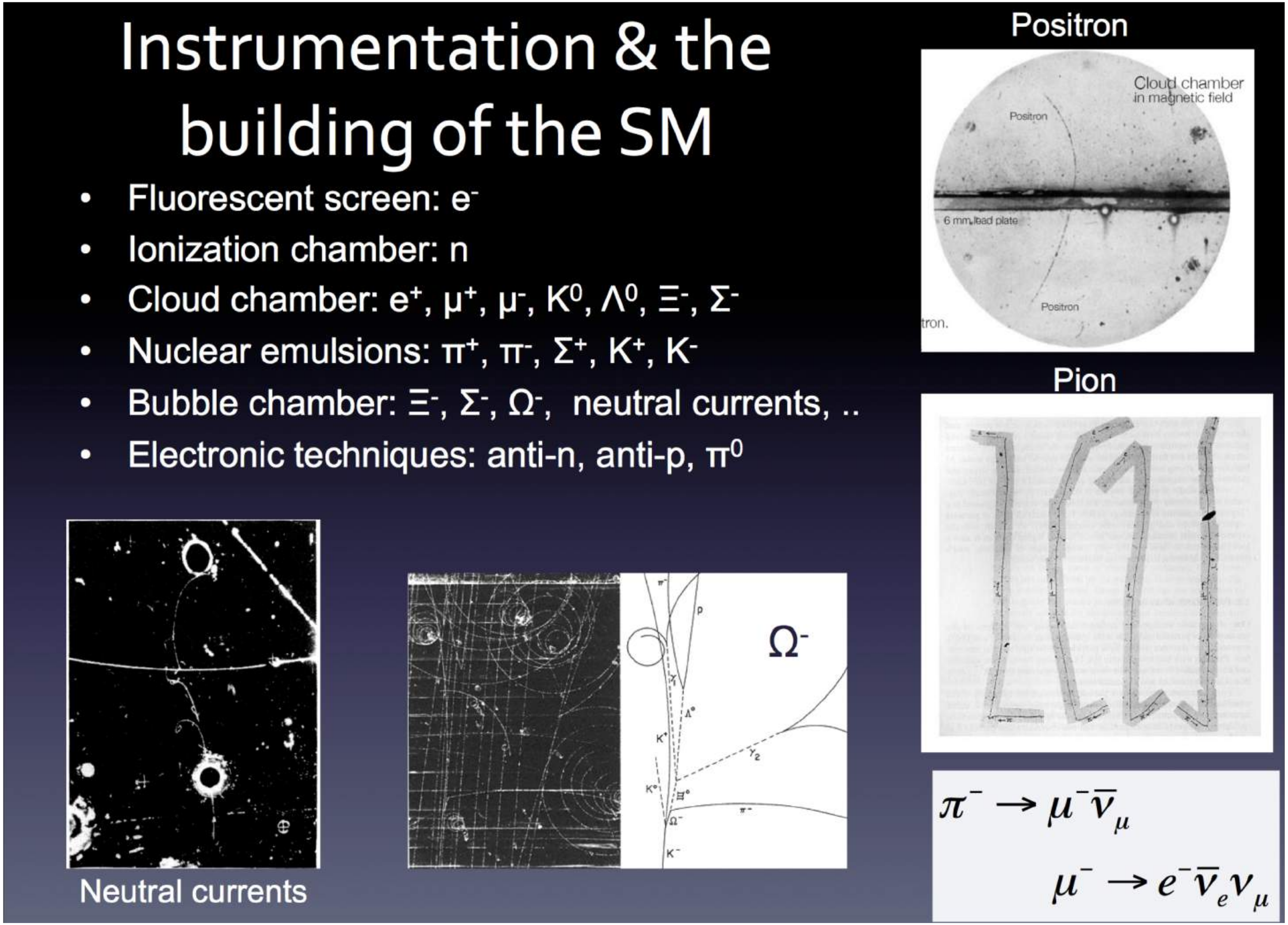
Particle charge

Material thickness in radiation length

Example:

300 micron Si	: RMS = 0.9 mrad / βp
1 mm Be	: RMS = 0.8 mrad / βp

Particle discoveries – detection techniques



New particles in cosmic rays

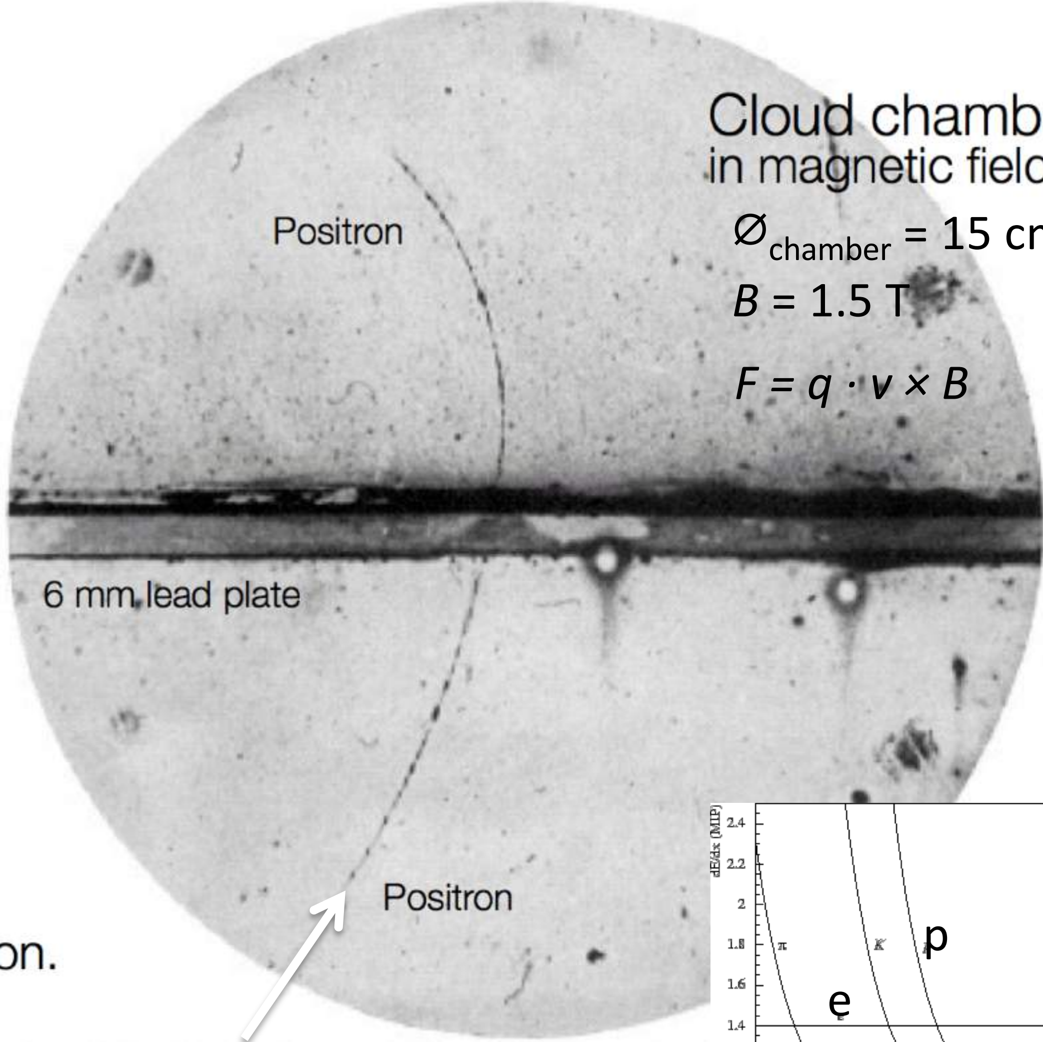
Positron discovery in cosmic rays using a cloud chamber in a strong magnetic field

Discovery of antimatter

[Anderson 1932; Nobel prize 1936]

$$\rho = \frac{p_T}{q|B|} = \frac{\gamma m_0 \beta c}{q|B|}$$

Axiális mágneses térben:
p [GeV/c] = 0.3 B [T] ·ρ [m]

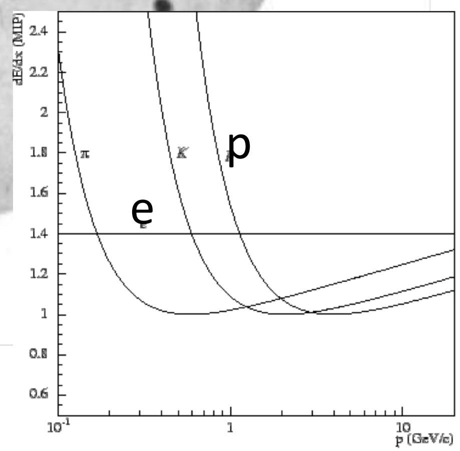


Cloud chamber in magnetic field

$\varnothing_{chamber}$ = 15 cm

B = 1.5 T

$F = q \cdot v \times B$



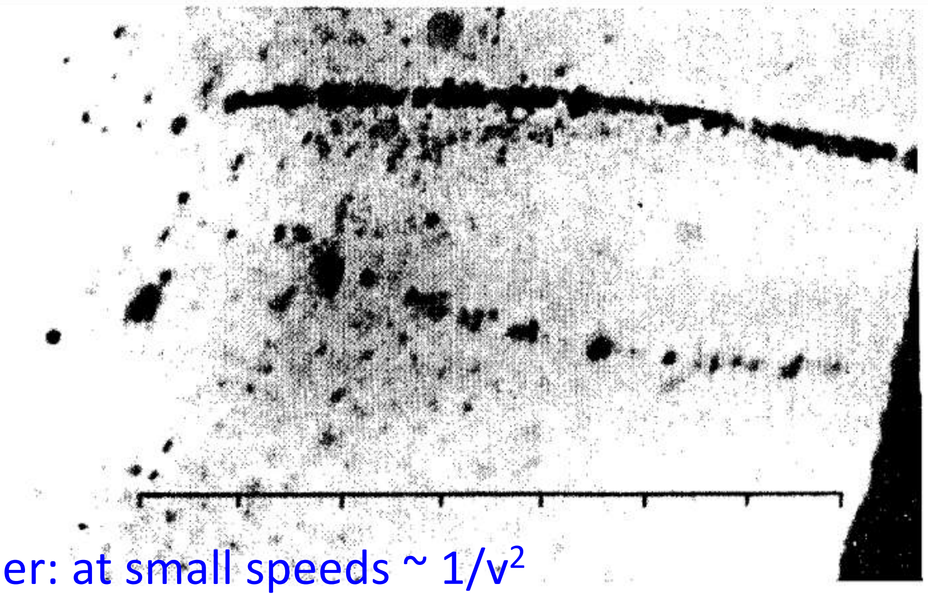
63 MeV positron passing through lead plate emerging as 23 MeV positron.

The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

http://journals.aps.org/pr/abstract/10.1103/PhysRev.43.491

A muon discovery

http://journals.aps.org/pr/pdf/10.1103/PhysRev.51.884
http://journals.aps.org/pr/pdf/10.1103/PhysRev.52.1003

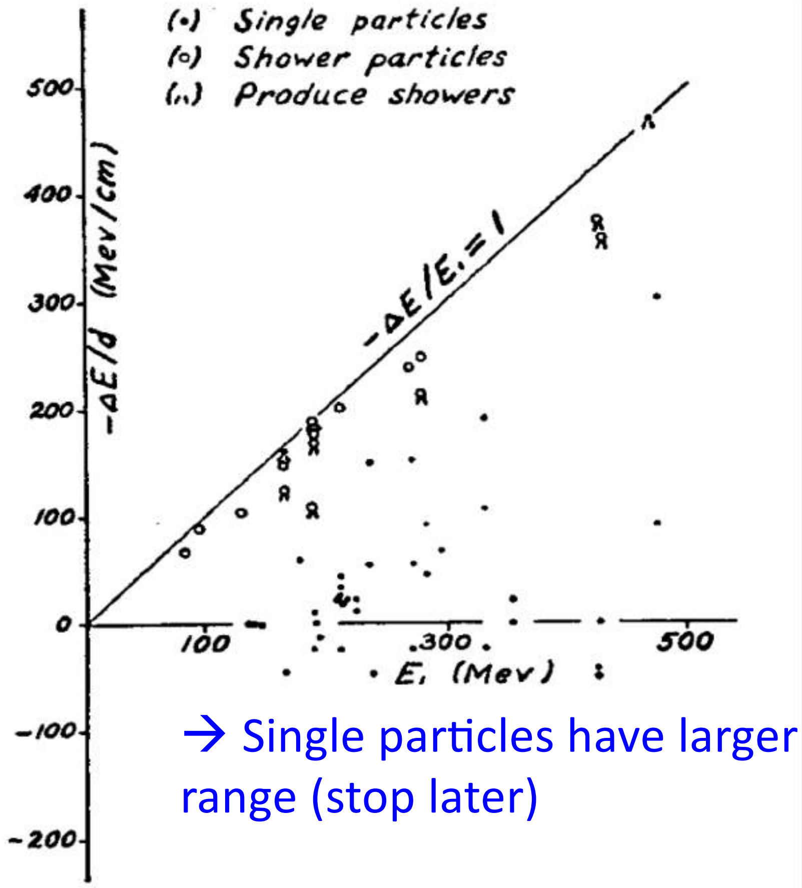


Reminder: at small speeds ~ $1/v^2$

"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

http://link.springer.com/article/10.1007/BF01331088

Kunze, P., Z. Phys. 83, (1933) 1



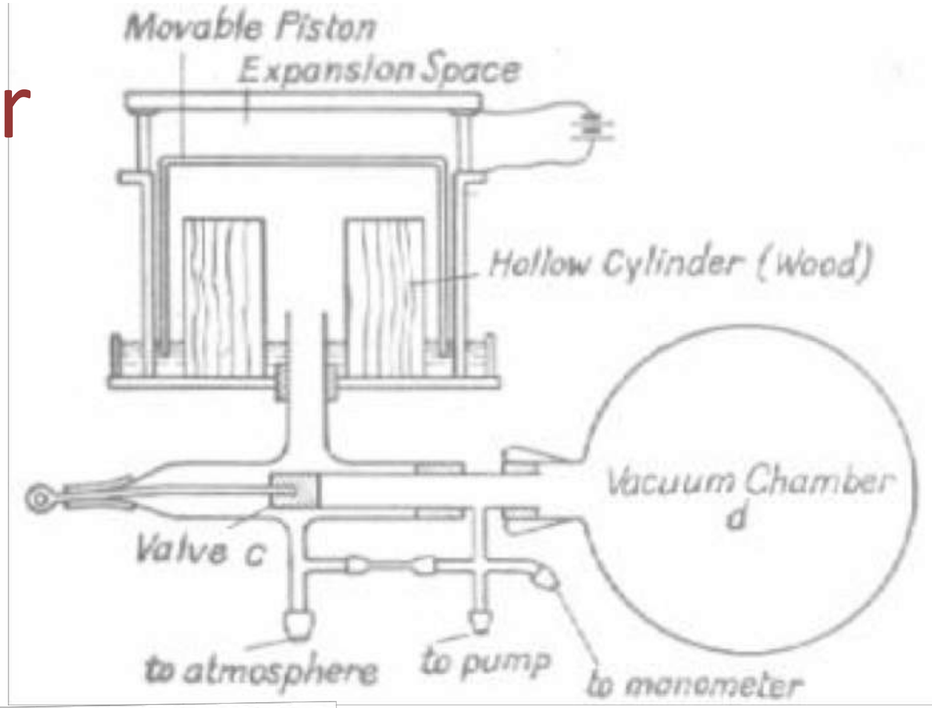
→ Single particles have larger range (stop later)

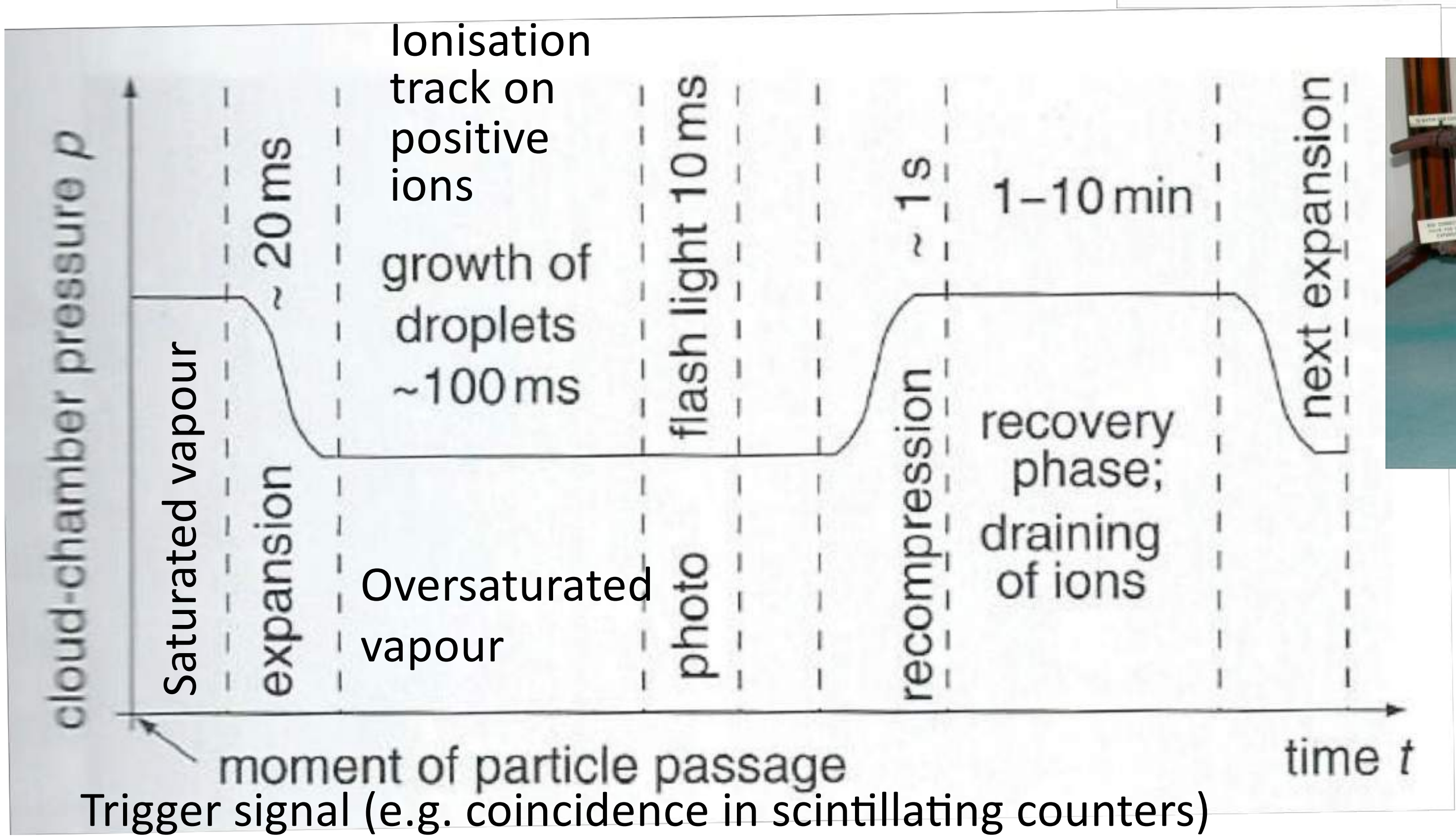
Figure 1: Energy loss in 1 cm of platinum.

- 1932 Paul Kunze: first muon track in cosmic rays (almost fully forgotton)
- 1936 Carl D. Anderson, Seth Neddermeyer (Caltech)
  - Measure energy loss of single and shower particles in dense materials
  - Bending in magnetic field → momentum
  - **New particle that is heavier than an electron but lighter than a proton → mesotron**
- 1937 J.C. Street and E.C. Stevenson proves it
- Initially believes to be the pion, predicted by Yukawa in 1935 as mediator of nuclear force

Cloud or Wilson chamber

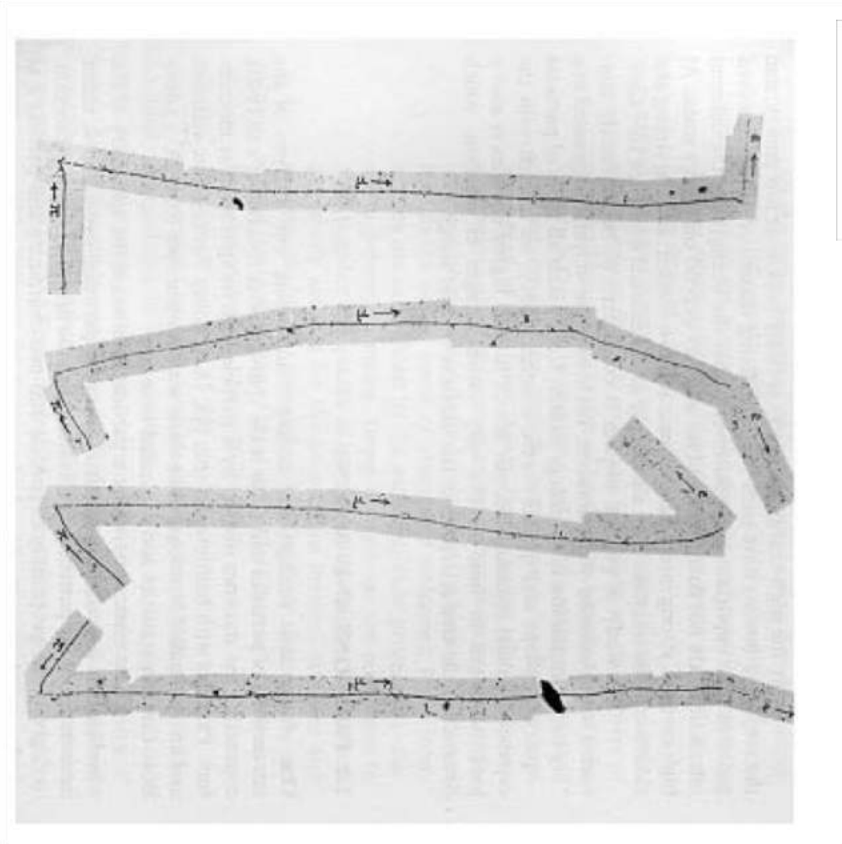
- Oldest tracking detector
- Volume filled with oversaturated vapour (e.g. air – water, Ar – alcohol)
- Quick adiabatic expansion
- Charged particle ionise mixture, we see the droplets that condensate on the ions





C.T.R. Wilson: meteorologist, studying originally cloud
Later in the Cavendish Laboratory, worked with J.J. Thomson, E. Rutherford

New particles in cosmic rays

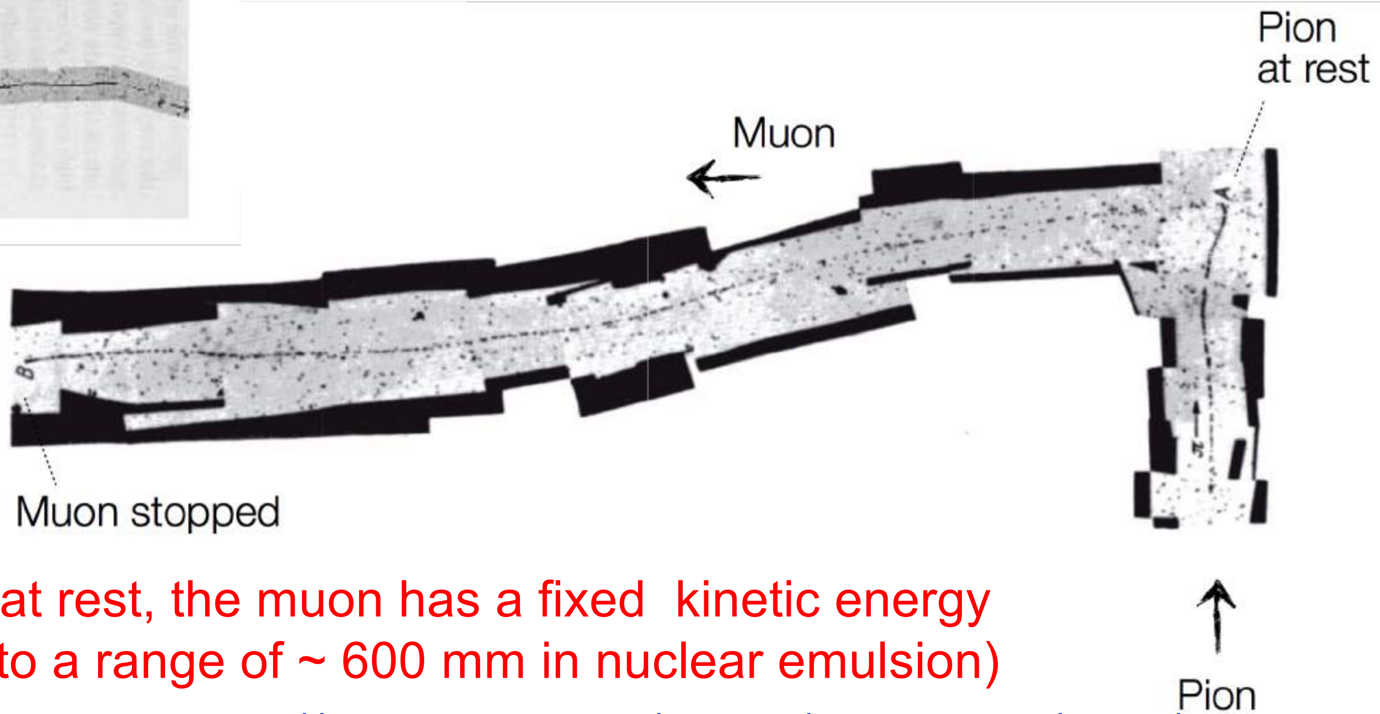


Discovery of the pion
Nuclear emulsion technique
[Powell 1947; Nobel prize 1950]

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Nuclear emulsion: a detector sensitive to ionization with **~1 µm space resolution** (AgBr microcrystals suspended in gelatin)

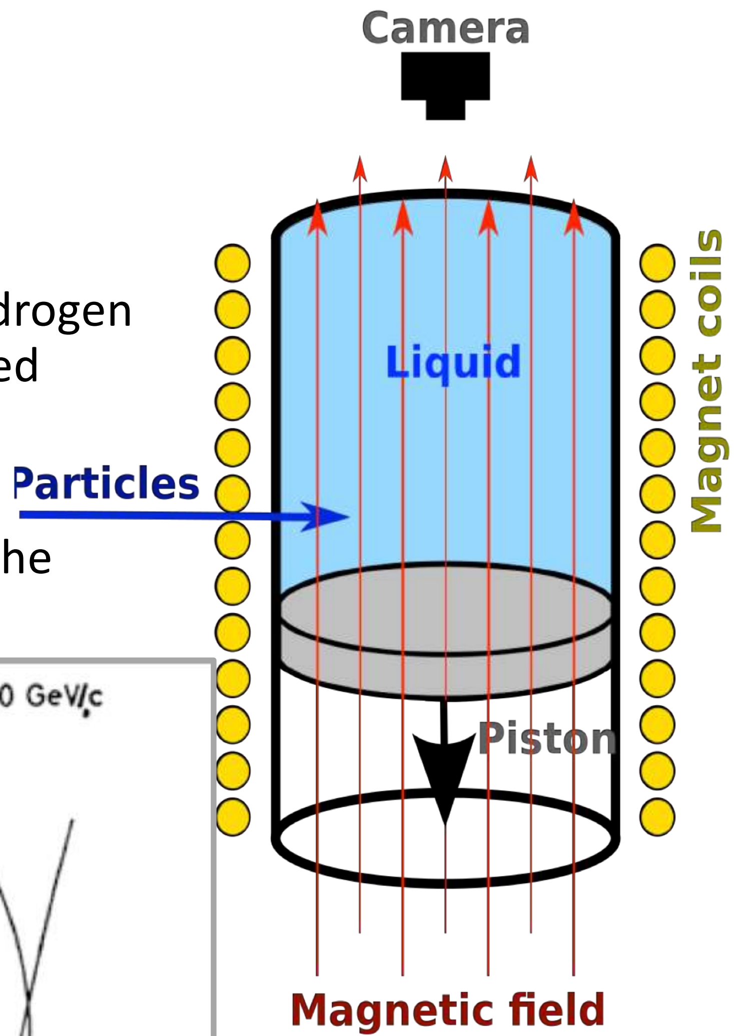


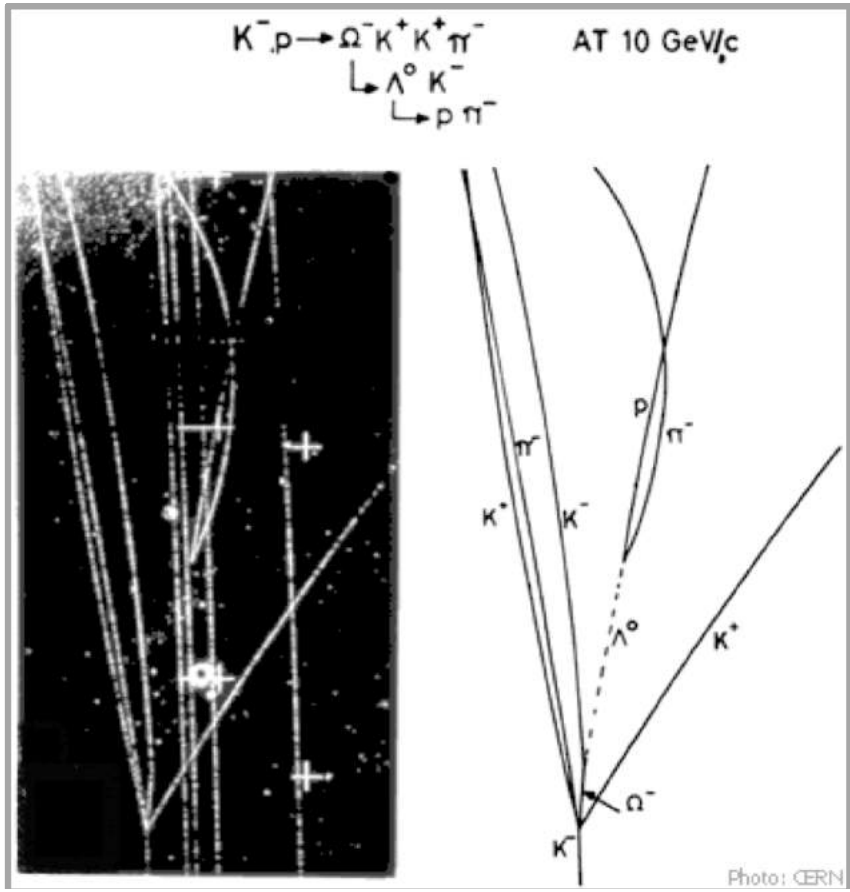
In all events pion decays at rest, the muon has a fixed kinetic energy (4.1 MeV, corresponding to a range of ~ 600 mm in nuclear emulsion)
$\Rightarrow$ two-body decay

http://www.nature.com/physics/looking-back/lattes/lattes.pdf

Bubble chambers

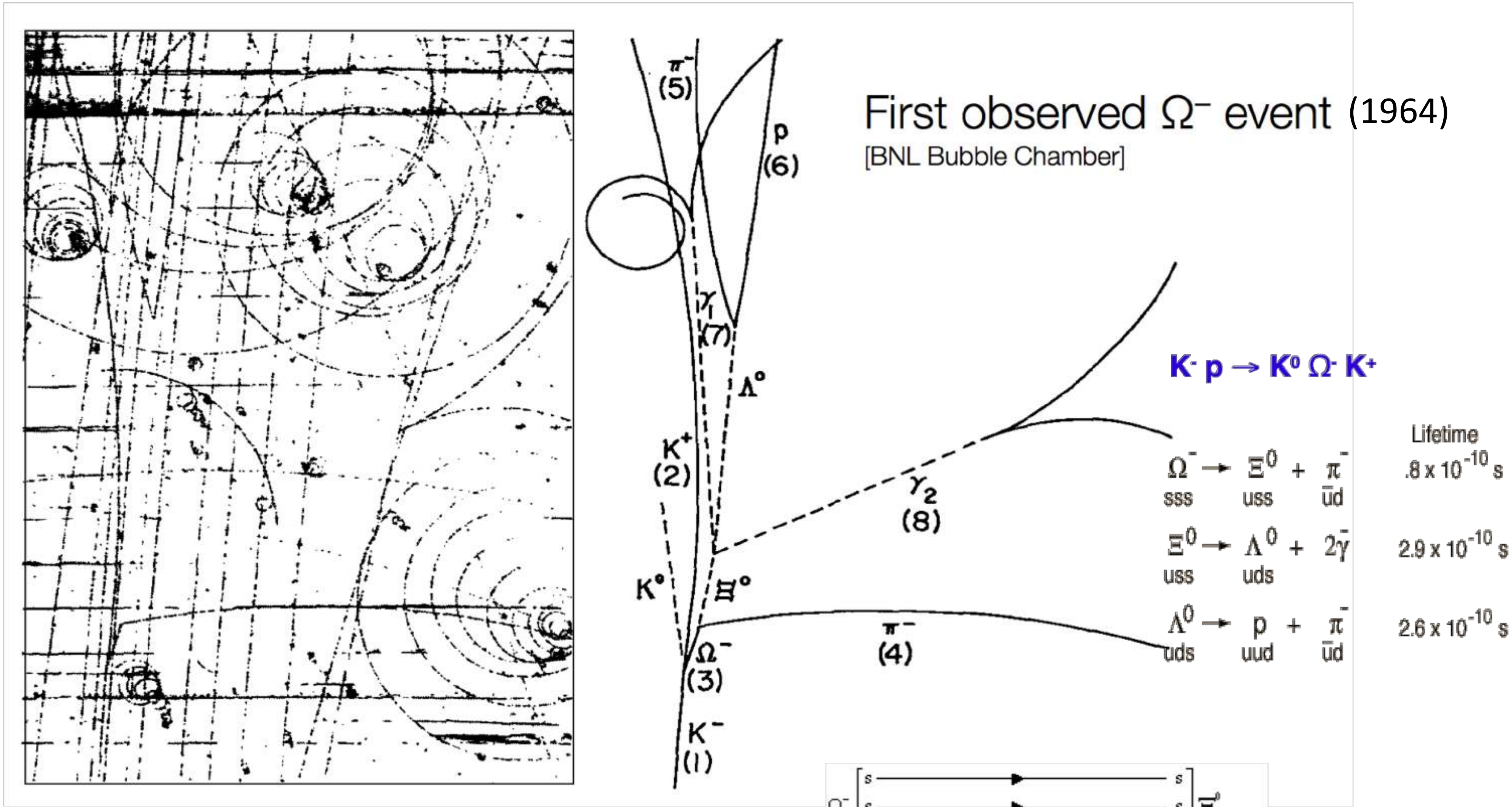
- 1952, Donald A. Glaser (1960 Nobel prize)
- An overheated, transparent liquid (e.g. liquid Helium, hydrogen @ T = 30.K) in a large cylindrical volume: incoming charged particle causes the liquid to boil
- 3D image with many cameras, a few μm resolution
- Bubble density proportional to ionisation energy loss of the particle dE / dx: it can be used for particle identification
- Trigger is not possible (Lifetime of positive ions ~ 10^{-10}-10^{-11} s)
- Collider experiments, timing to arrival of beam / collisions
- Repetition frequency: ~ 0.1 - 50 Hz
- Lifetime measurement precision can reach ~$2 \cdot 10^{-14}$ s (σ_x~6 μm)

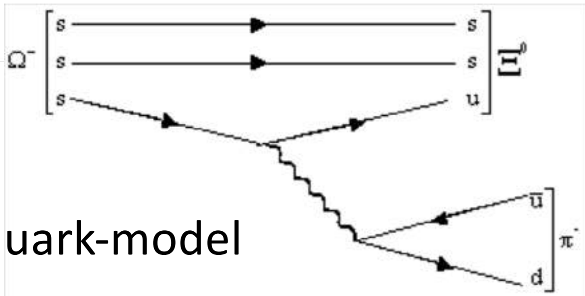




Today: Dark matter (WIMP) search, e.g. COUPP experiment

Particle factories: accelerator experiments





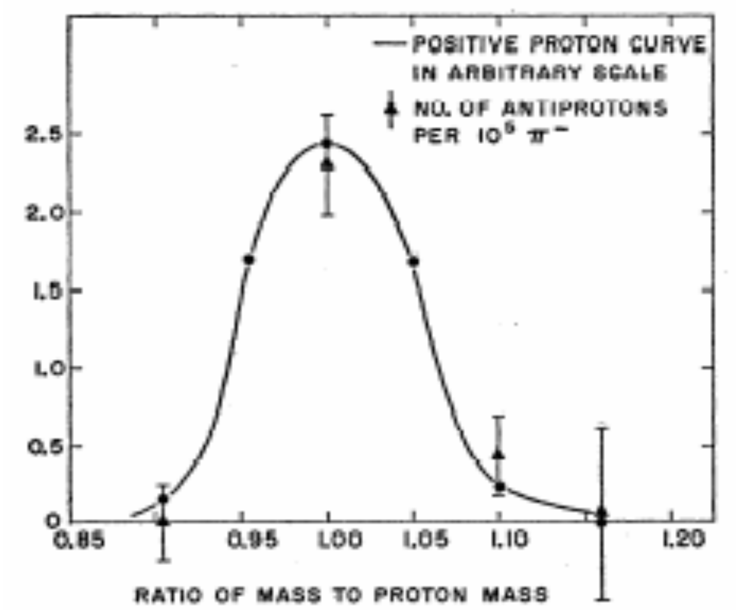
Proof of the quark-model

Antiproton discovery (1955)

Threshold energy for antiproton ($\overline{p}$) production in proton – proton collisions
Baryon number conservation $\Rightarrow$ simultaneous production of $\overline{p}$ and p (or $\overline{p}$ and n)
Example: $p + p \rightarrow p + p + \overline{p} + p$
Threshold energy $\sim$ 6 GeV
"Bevatron": 6 GeV proton synchrotron in Berkeley (initiated by Ernest Lawrence)

Need to measure two quantities (decided to be velocity and momentum)

- build a beam line for 1.19 GeV/c momentum
- select negatively charged particles (mostly π^-)
- reject fast π^- by Čerenkov effect: light emission in transparent medium if v > c/n
  antiprotons have v < c/n $\Rightarrow$ no Čerenkov light
- measure time of flight between counters S_1 and S_2
  (12 m path): 40 ns for π^-, 51 ns for antiprotons
- **Time of flight gives the particle velocity,
  hence for known momentum the particle mass**



1959 Nobel Prize in Physics
Emilio Segrè and Owen Chamberlain
University of California, Berkeley

http://journals.aps.org/pr/pdf/10.1103/PhysRev.100.947

Antiproton discovery

Velocity measurement:

- Time-of-flight measurement
  S1 - S2 distance: 12 m → Δt(p–π) = 11 ns
- Cherenkov radiation
  C1: π, K veto
  C2: β = 0.77±0.15 particle selection

Beam momentum filtering:
p=1.19 GeV/c (β = 0.78) beam

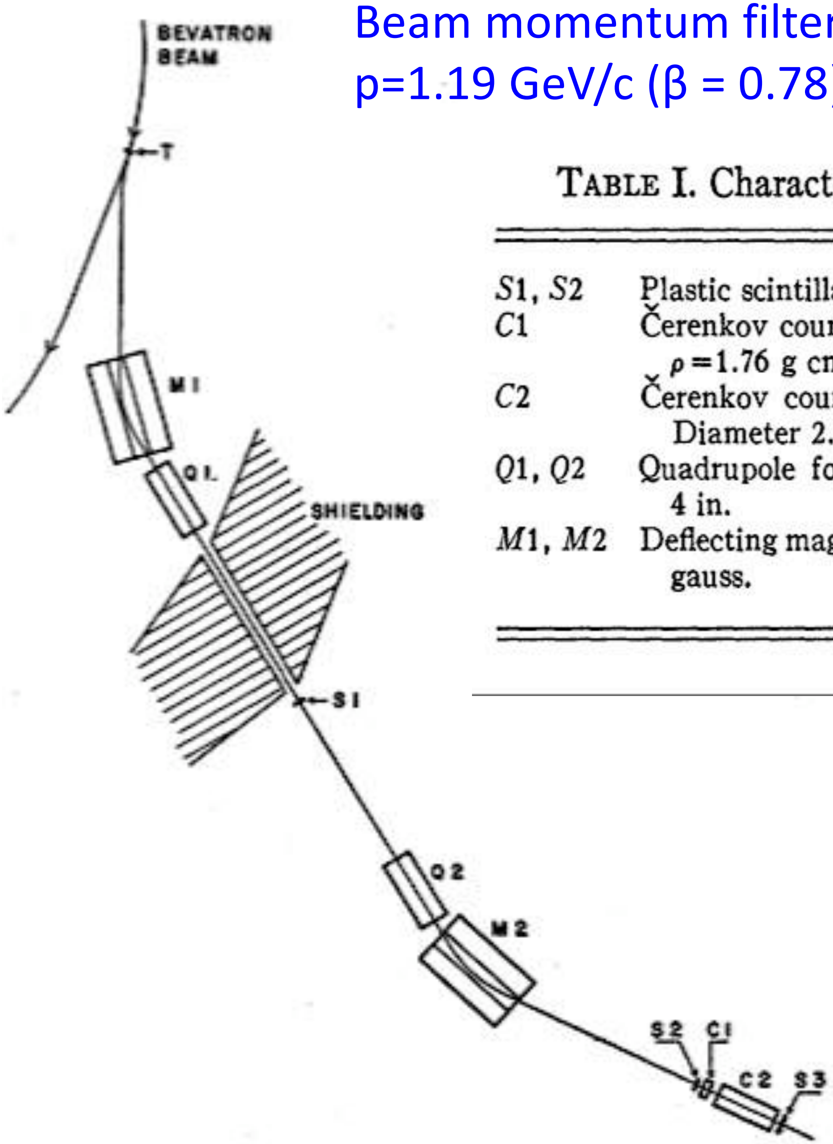
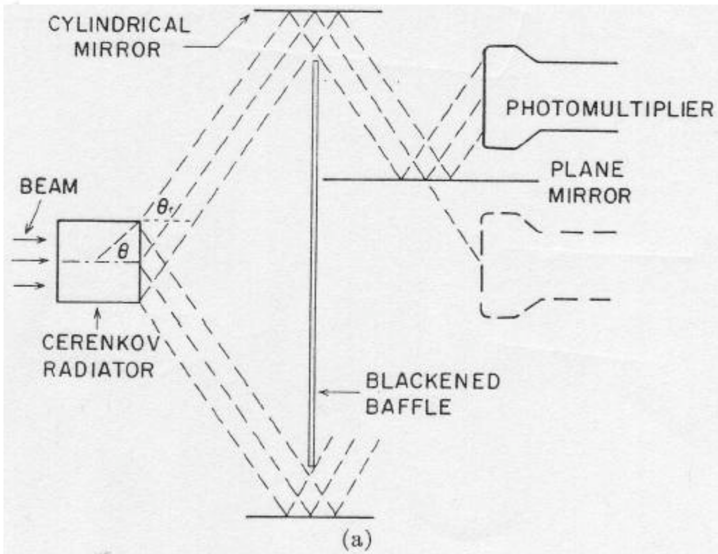
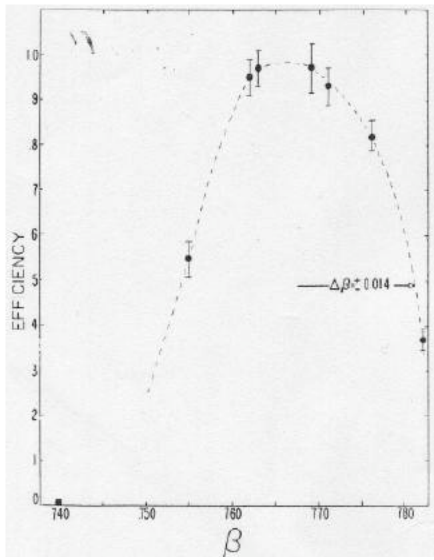


TABLE I. Characteristics of components of the apparatus.

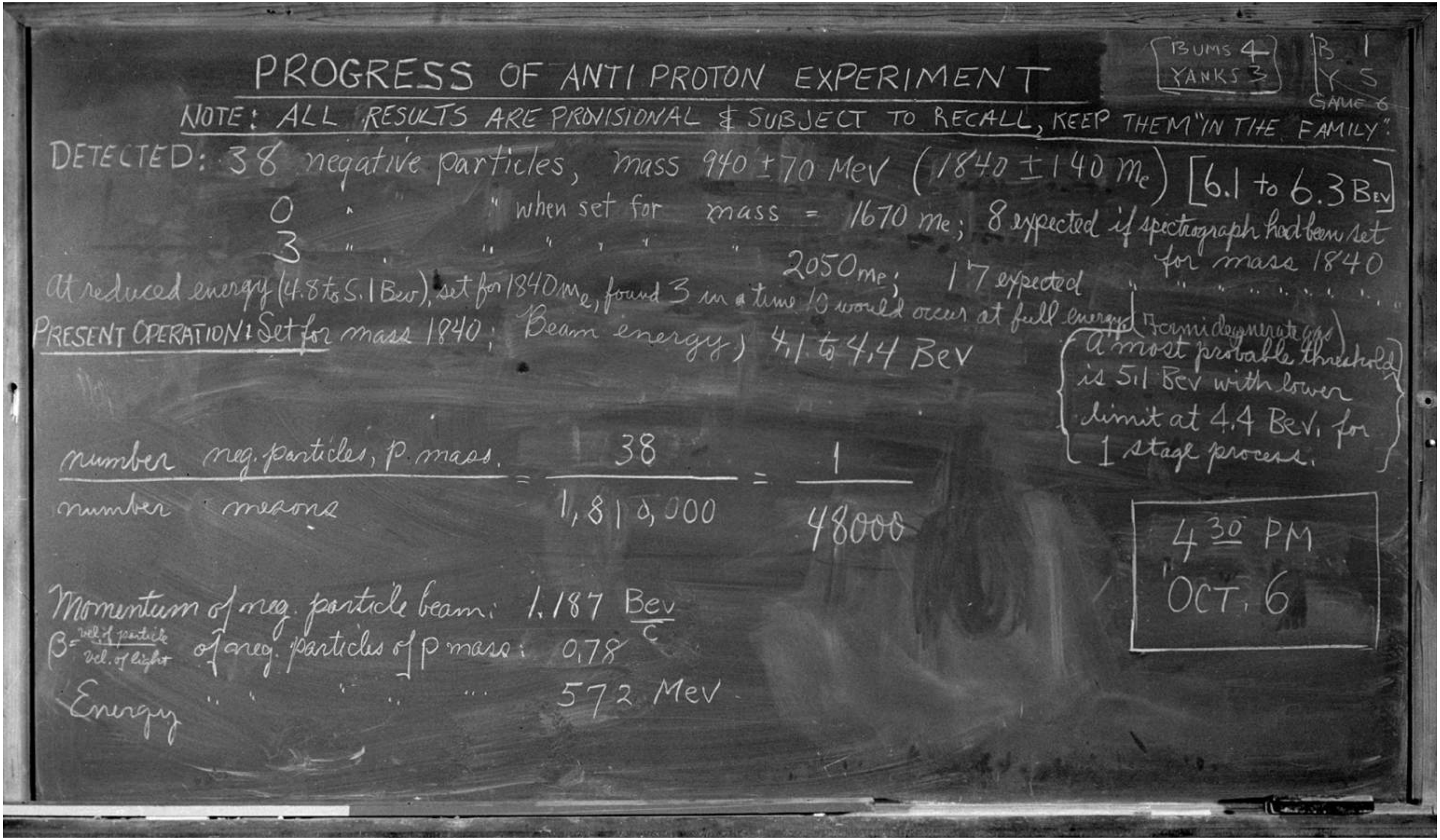
$S1$, $S2$	Plastic scintillator counters 2.25 in. diameter by 0.62 in. thick.
$C1$	Čerenkov counter of fluorochemical 0–75, ($C_8F_{16}O$); $\mu_D=1.276$; $\rho=1.76$ g cm^{-3}. Diameter 3 in.; thickness 2 in.
$C2$	Čerenkov counter of fused quartz: $\mu_D=1.458$; $\rho=2.2$ g cm^{-3}. Diameter 2.38 in.; length 2.5 in.
$Q1$, $Q2$	Quadrupole focusing magnets: Focal length 119 in.; aperture 4 in.
$M1$, $M2$	Deflecting magnets 60 in. long. Aperture 12 in. by 4 in. $B\cong 13\,700$ gauss.



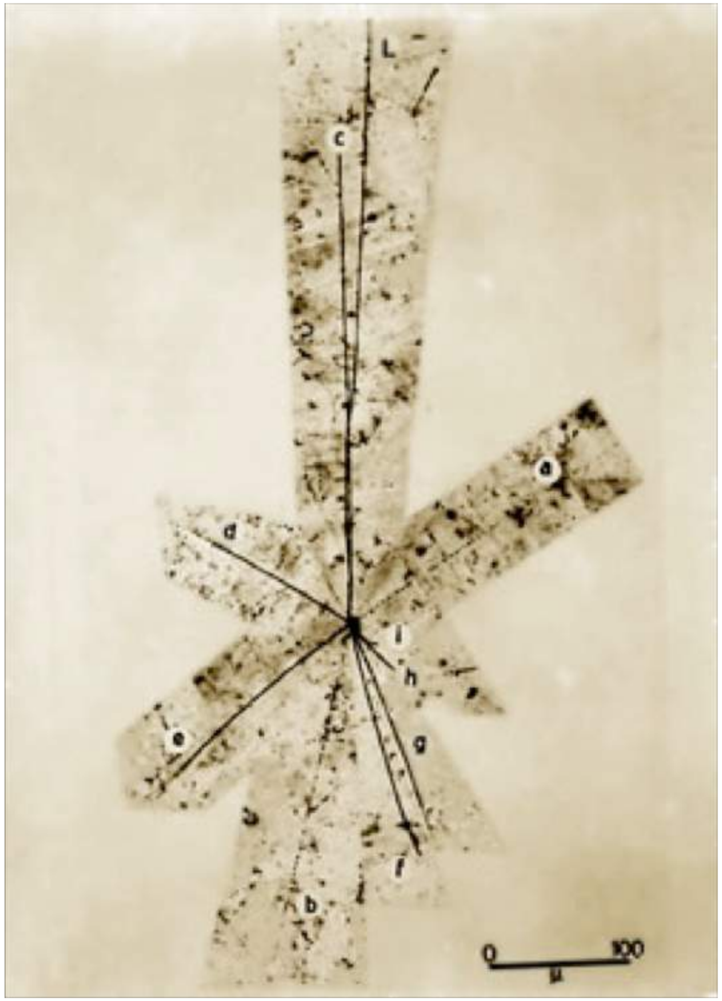


Owen **Chamberlain**, Emilio **Segrè**
1959 Nobel Prize

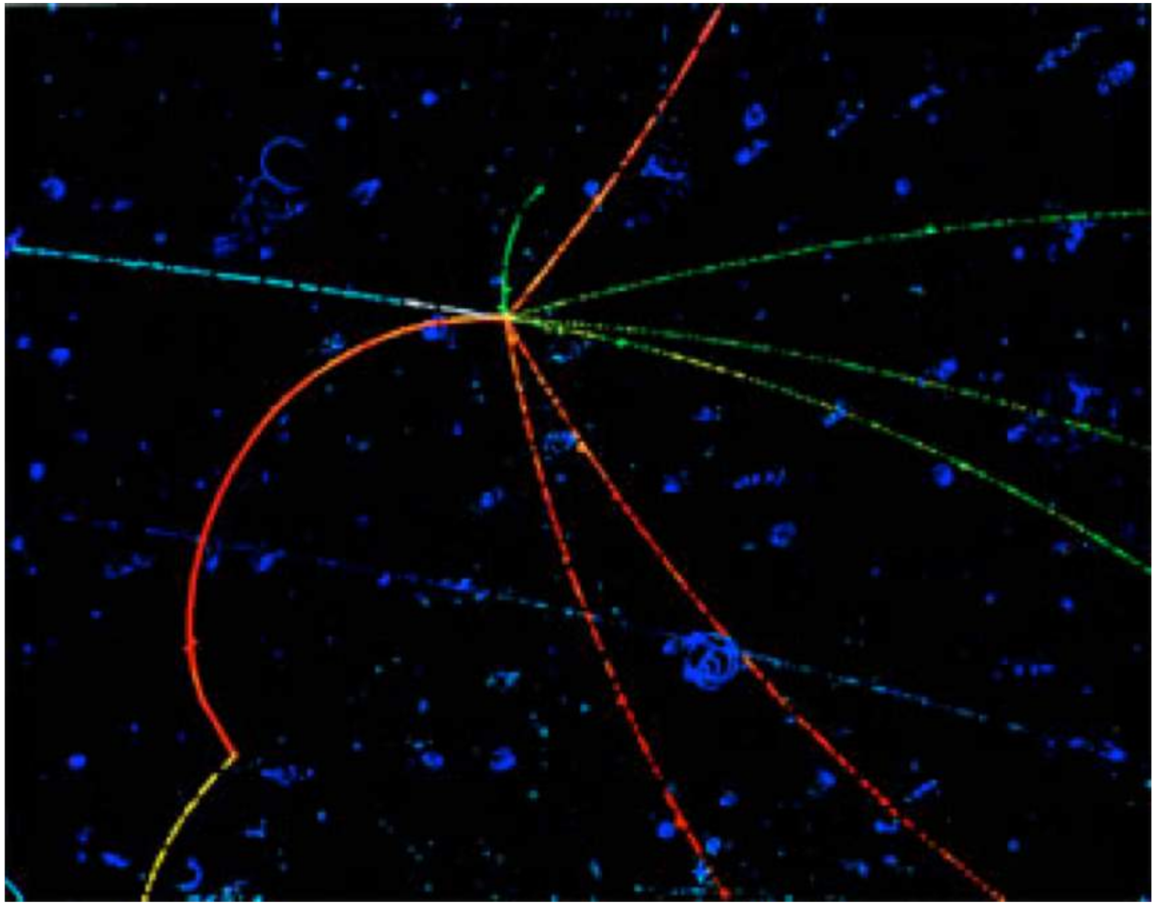
Pre-Twitter blackboard



Antiproton discovery (1955)

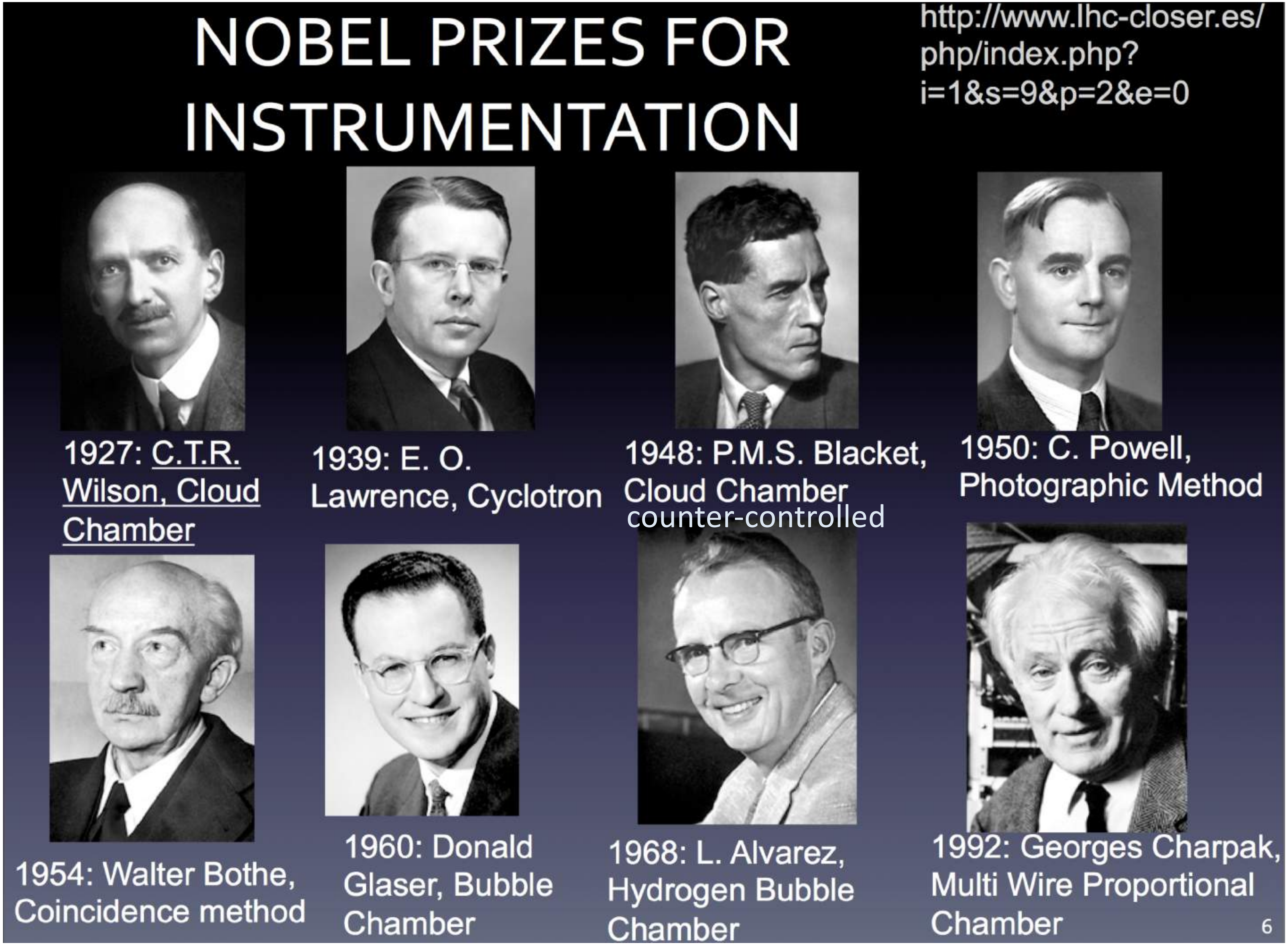


This first image of an annihilation star, found in the photographic emulsion stack experiments led by Gerson Goldhaber of the Segrè group, confirmed the discovery of the antiproton. An antiproton enters from the top of the image and travels about 430 micrometers before meeting a proton. Nine charged particles emerge from their mutual annihilation.



Evidence based on momentum and velocity: An antiproton (blue) enters the bubble chamber from bottom left and strikes a proton. The released energy creates four positive pions (red) and four negative pions (green). The yellow streak at the far right is a muon, a decay product of the adjacent pion. (The dark blue curlicues are low-energy electrons knocked from atoms, not involved with the antiproton.)

The way to discoveries



Homework #7

- Calculate the full width at half maximum relative energy resolution for the mono-chromatic gamma-ray emission of ^{137}Cs line of a NaI(Tl) scintillator with a mean excitation energy of 22 eV read out by a PMT with a quantum efficiency of 0.3%.
- Estimate how much the particle flow technique can improve the jet energy resolution for a typical high-energy physics experiment.
- For charged particle (eg. charged hadron, muon, ...) tracking usually the so-called Kalman filter method is used in collider experiments to take into account random process noise in the tracking. For electrons, however, a different technique is necessary (such as Gaussian Sum Filter method). Why and how electron tracks differ from other charged particle tracks?
- The anti-proton was discovered in the process p + p → p + p + p + anti-p by shooting a proton beam to a proton target at rest. What is the minimal center-of-mass energy for this process to happen? What is the minimal proton beam energy in the laboratory system?
- In the anti-proton discovery, the few anti-p produced had to be efficiently separated from the more numerous pions and kaons. Discuss how the collaboration of Chamberlain and Segrè achieved this task based on the setup of the Nobel prize winning experiment.