Particle Detectors

A brief introduction with emphasis on high energy physics applications

TRIUMF Summer Institute 2006
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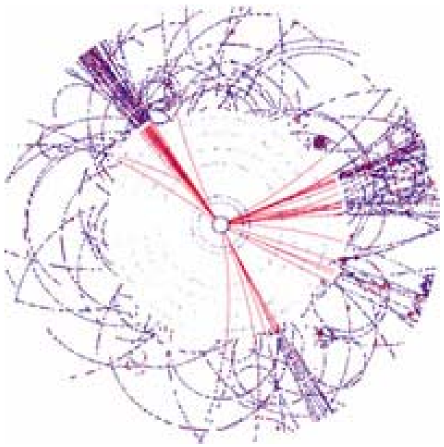

- Lecture I
  - measurement of ionization and position
- Lecture II
  - scintillation and photo detection
  - calorimetry
- Lecture III
  - particle identification
  - detector systems

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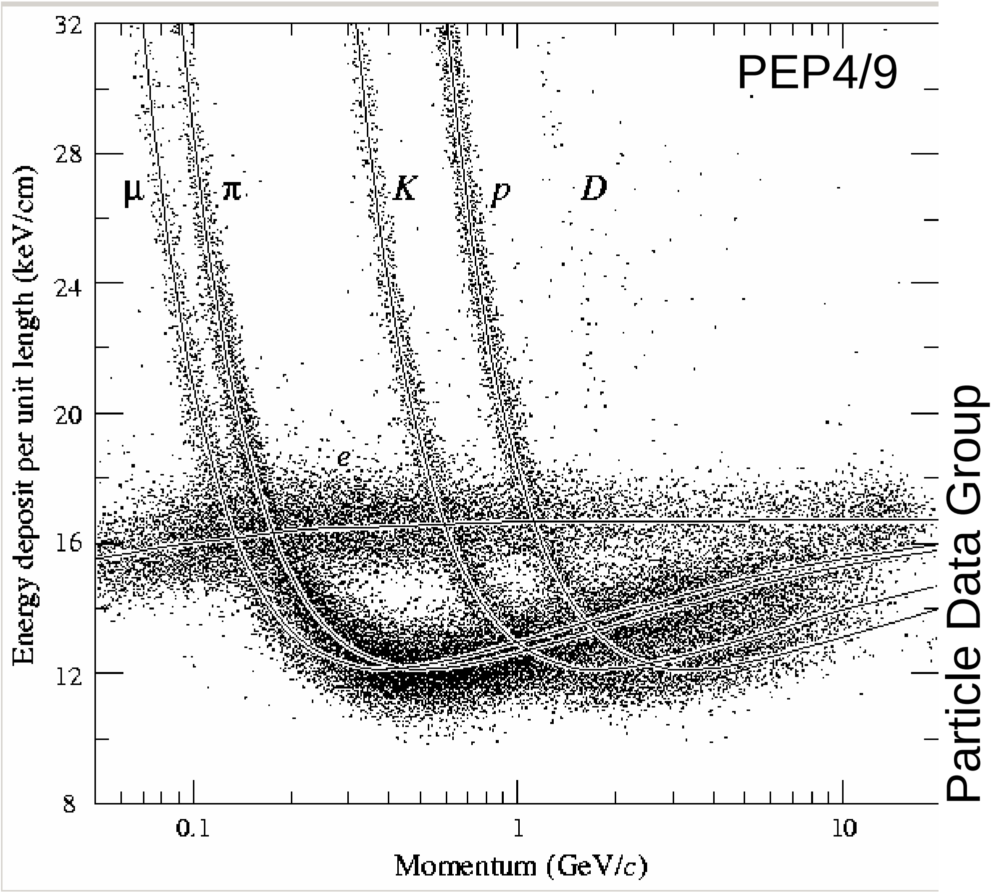
Lecture III

- Particle Identification
  - *dE*/*dx* measurement
  - Time of flight
  - Cherenkov detectors
  - Transition radiation detectors
- Detector systems

Particle ID with *dE/dx*

Particle ID using a TPC

- measure *dE/dx* many times along tracks
- measure momentum from curvature in B field



multihadron events in e^+e^- collisions.

muons from pion decays are separated at low momentum.

pions and kaons are separated almost in the whole momentum range

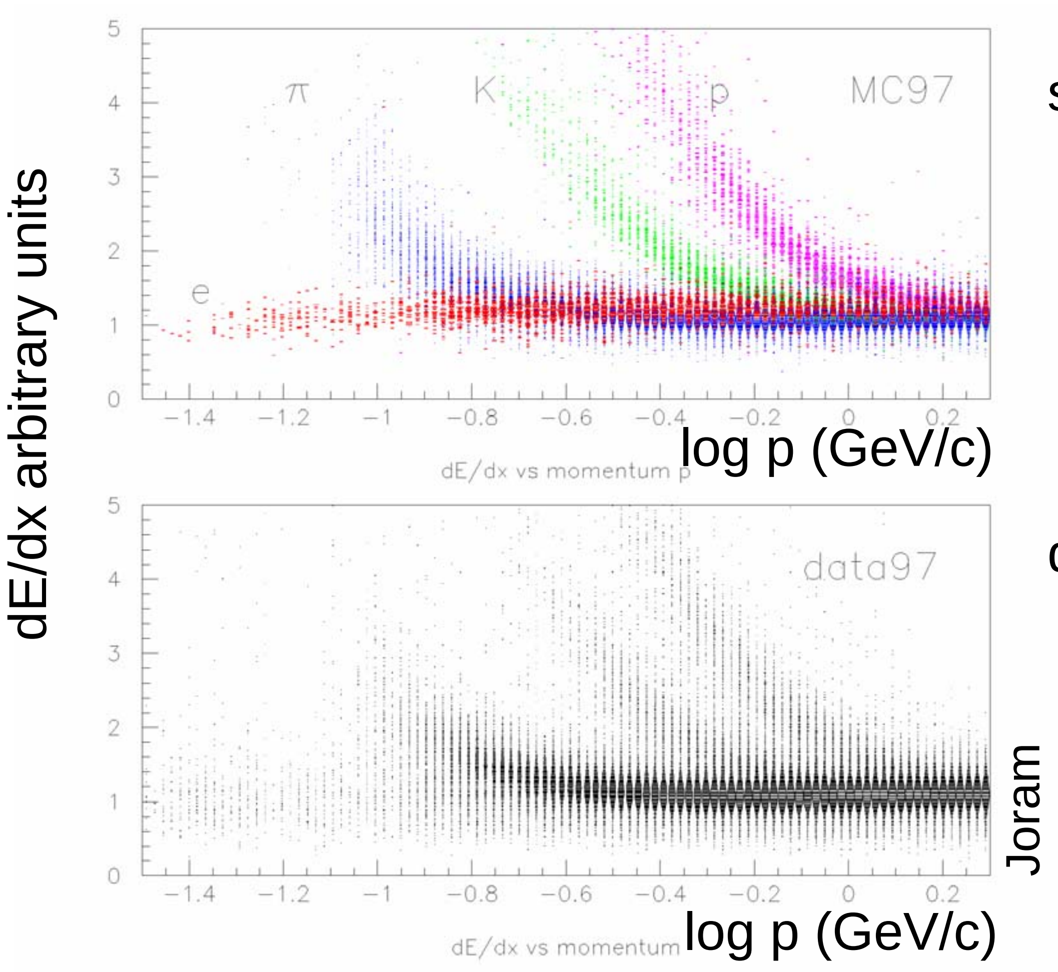
electrons reach Fermi plateau at 1.4 MIP

protons and deuterons come from hadron nucleus collisions in materials such as the beam pipe

Particle ID with *dE/dx*

Particle ID using a silicon detector

- DELPHI microvertex detector (3 × 300 μm Si)

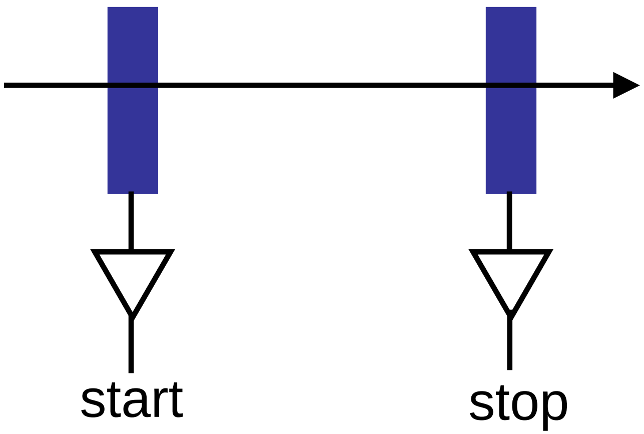


simulation

data

Particle ID with time of flight

- Combine TOF with momentum measurement



$$t = \frac{L}{\beta c} \qquad p = \gamma m \beta$$

$$m = \frac{p}{\gamma\beta} = p\sqrt{\beta^{-2} - 1} = p\sqrt{\left(\frac{ct}{L}\right)^2 - 1}$$

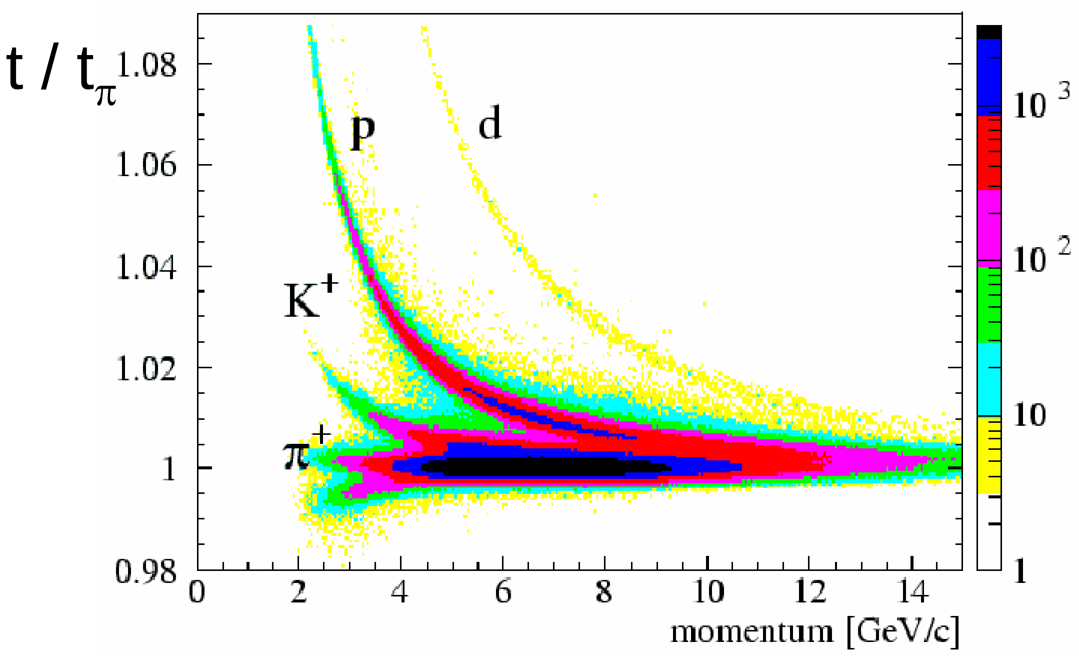
$$\left(\frac{\sigma_m}{m}\right)^2 = \left(\frac{\sigma_p}{p}\right)^2 + \gamma^4\left[\left(\frac{\sigma_L}{L}\right)^2 + \left(\frac{\sigma_t}{t}\right)^2\right]$$

  - Consider the TOF difference for two particles at a given momentum

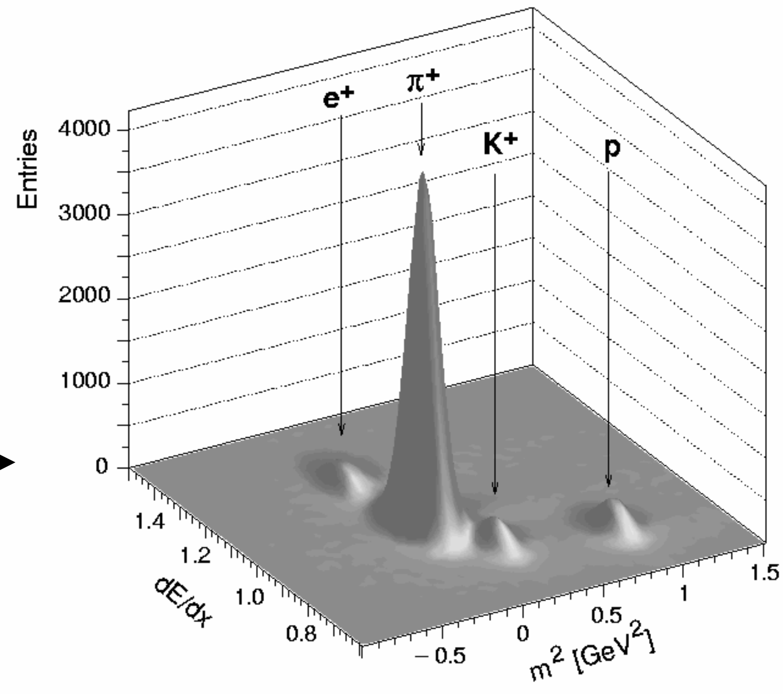
$$\Delta t = t_1 - t_2 = \frac{L}{c}\left[\sqrt{1 + \left(\frac{m_1 c}{p}\right)^2} - \sqrt{1 + \left(\frac{m_2 c}{p}\right)^2}\right] \xrightarrow{p \gg mc} \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

Particle ID with time of flight

- Example: CERN NA49 heavy ion experiment



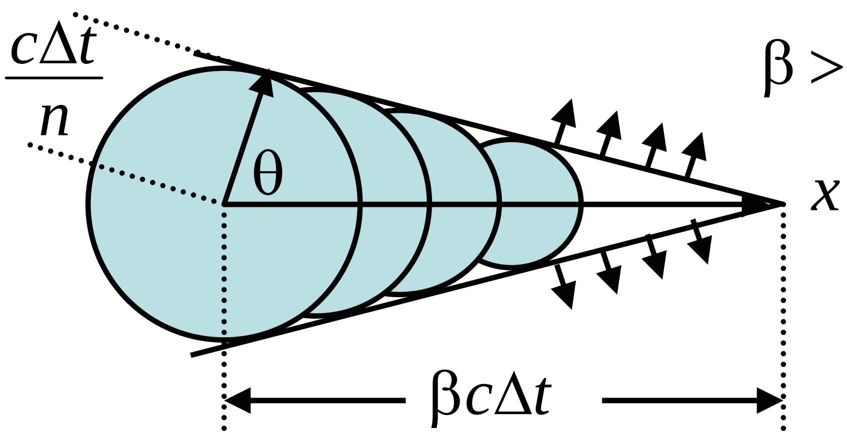
combine m^2 from TOF
and dE/dx of TPC!

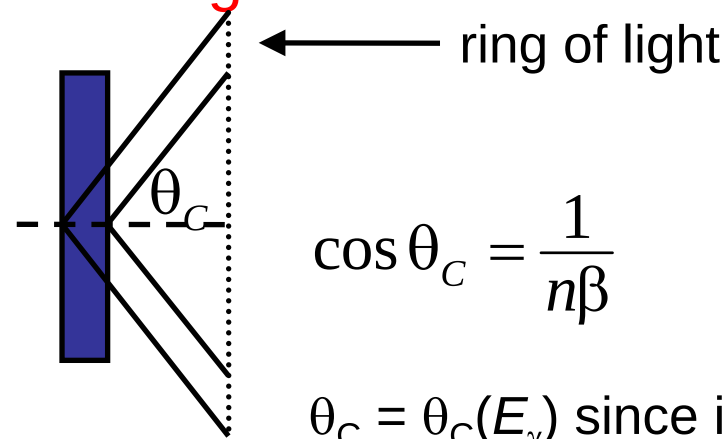


Particle ID with Cherenkov radiation

Cherenkov radiation

- charged particle travels faster than light in medium





$$\cos\theta_C = \frac{1}{n\beta}$$

$\theta_C = \theta_C(E_\gamma)$ since in general $n = n(E_\gamma)$

- number of photons emitted
  - energy loss small (~1%) compared to ionization

$$\frac{d^2N}{dE_\gamma dx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_C$$

$$\approx 370 \sin^2\theta_C\left(E_\gamma\right)\ \mathrm{eV}^{-1}\mathrm{cm}^{-1}$$

medium	n	θ_{max} (β=1)	N_{ph} (eV^{-1} cm^{-1})
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

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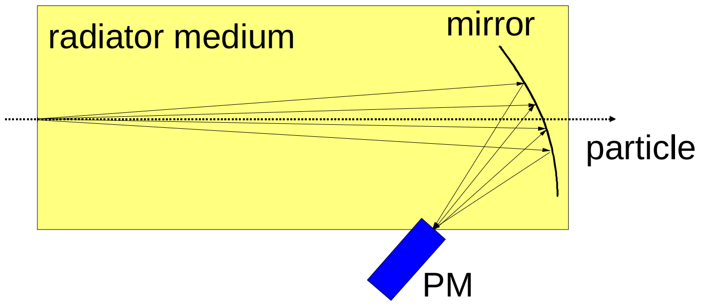
Particle ID with Cherenkov radiation

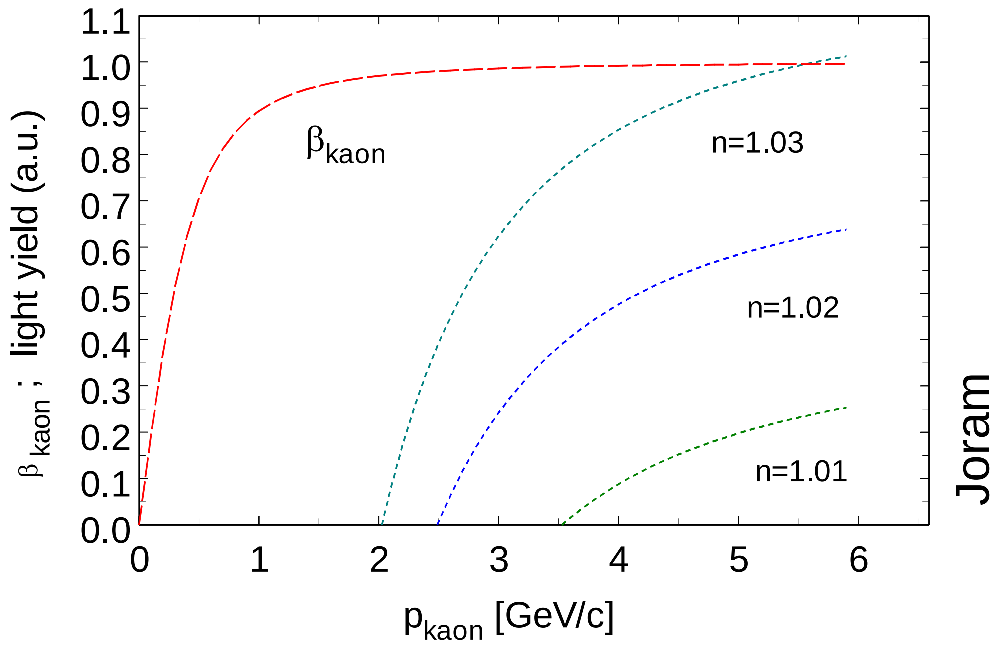
Threshold detector

$$N \propto 1 - \frac{1}{n^2\beta^2} = 1 - \frac{1}{n^2}\left(1 + \frac{m^2c^2}{p^2}\right)$$

$$\beta > \frac{1}{n}$$



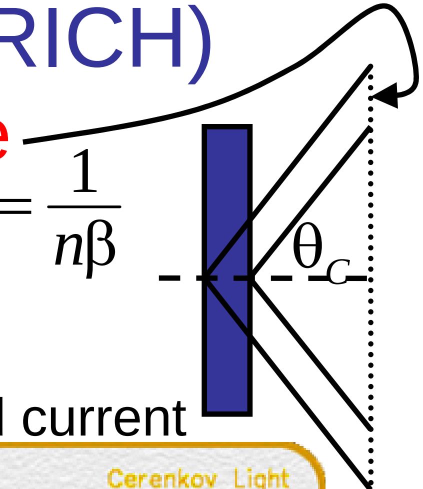
Study of an aerogel threshold detector for the BELLE experiment at KEK

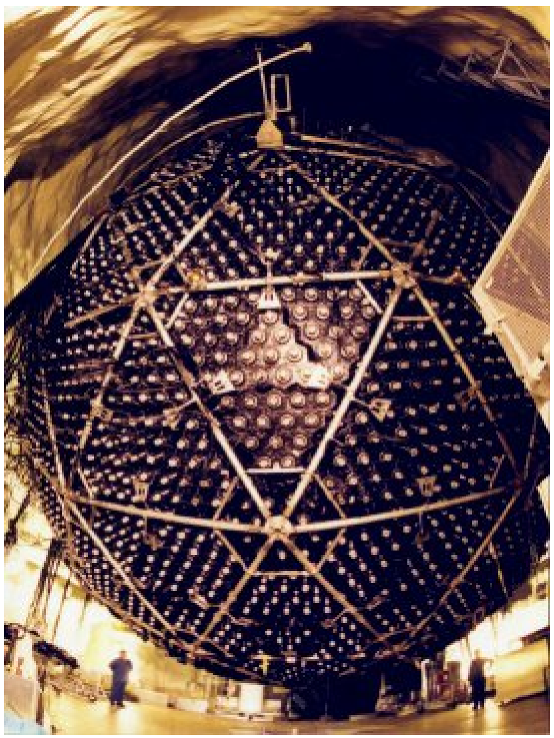


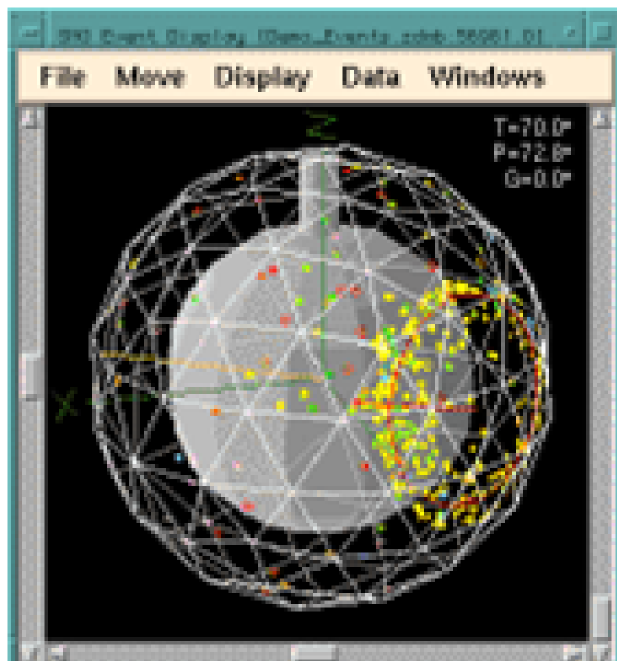
Particle ID with Cherenkov radiation

- Ring imaging Cherenkov detector (RICH)
  - mesure θ_C with a photosensitive plane
  - need large area photo detector
    - wire chambers with photosensitive gas
    - PMT arrays

$$\cos\theta_C = \frac{1}{n\beta}$$

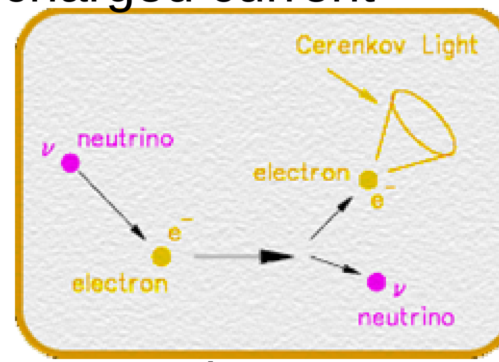




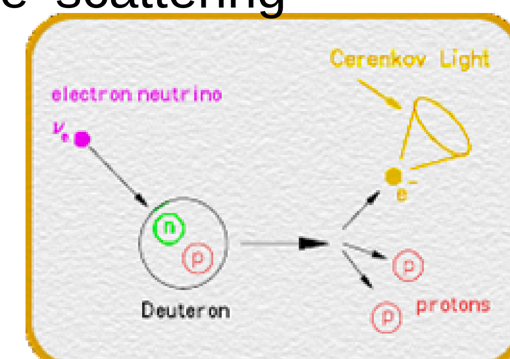


SNO has 10000 PMT's

charged current



e$^-$ scattering



Transition radiation detector

Transition radiation

- energy radiated when a *z* charged particle crosses the boundary between vacuum and a dielectric layer

$W = \frac{1}{3}\alpha\hbar\omega_p\gamma \propto \gamma$ only high energy $e^{\pm}$ will emit transition radiation

$\hbar\omega_p \approx 20$ eV for plastic radiators, ω_p is the plasma frequency

- number of photons emitted per boundary is small

$$N_\gamma\left(\hbar\omega > \frac{1}{10}\gamma\hbar\omega_p\right) = 0.59\%\ z^2$$

need many boundaries! For example you can build a stack with many foils with gas gaps

- photons are emitted close to the track $\theta \approx \frac{1}{\gamma}$
- typical energy is in the keV range

$$\hbar\omega \approx \frac{1}{4}\gamma\hbar\omega_p$$

Transition radiation detector

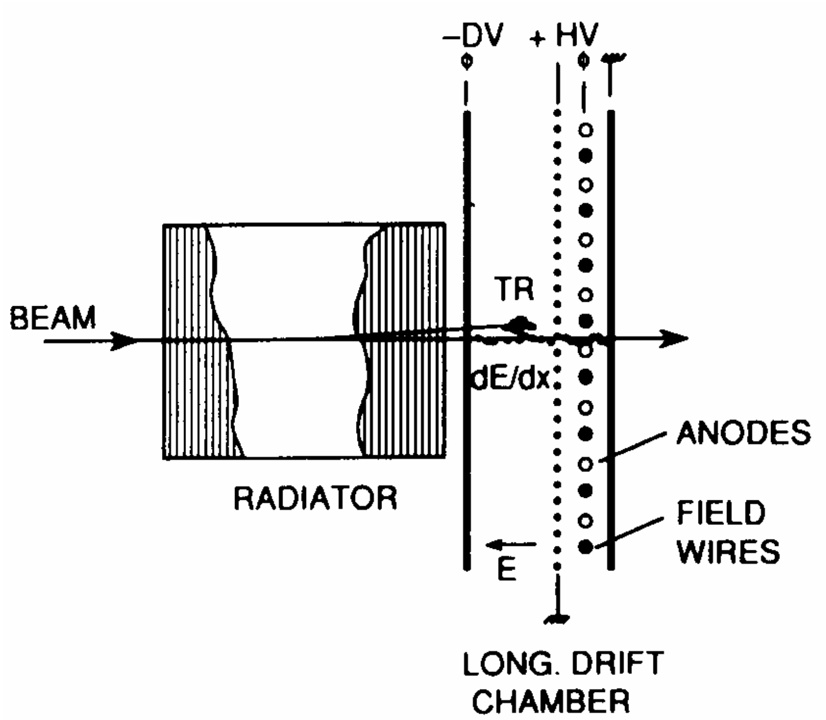
Transition radiation radiators

- low Z material preferred to keep re-absorption small ($\propto Z^5$)
  - stacks of CH_2 foils
  - hydrocarbon foam and fibre materials

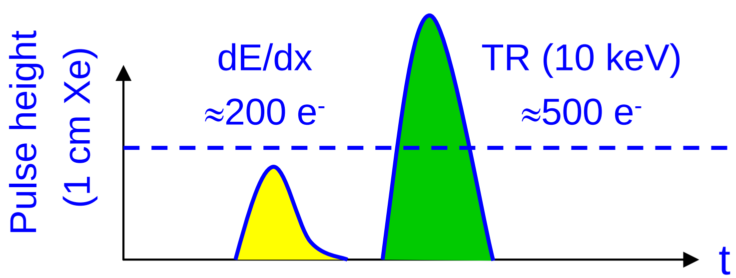
Transition radiation X-ray detectors

- should be sensitive for $3 \leq E_\gamma \leq 30$ keV
  - MWPC, drift chamber, straw tubes, etc.
  - gas with high Z to increase photoelectric effect ($\propto Z^5$)
    - for example Xe (Z = 54)

Transition radiation detector



ATLAS Transition radiation Tracker using about 400 000 straw tubes detectors with Xe based gas



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Discrimination
by threshold

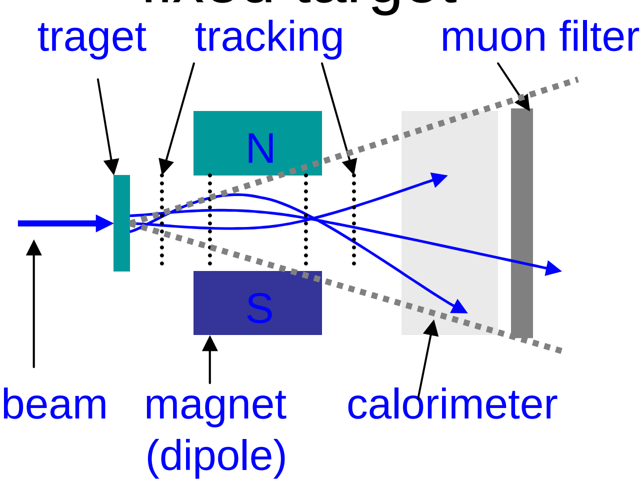
Detector systems

- Measure for each event
  - numbers of particles produced
  - particle identification
  - particle energy and/or momentum
  - event topology

  } detector system

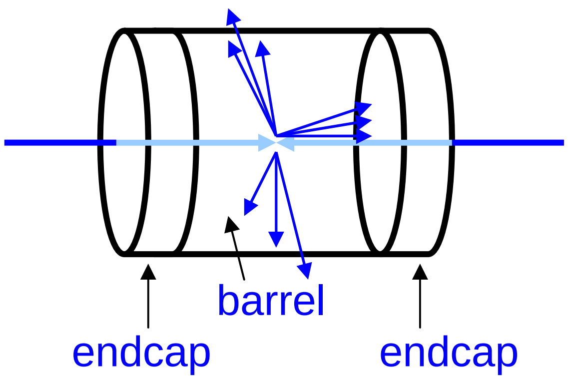
- Geometrical configurations

fixed target



- Limited solid angle dΩ coverage
- rel. easy access (cables, maintenance)

collider

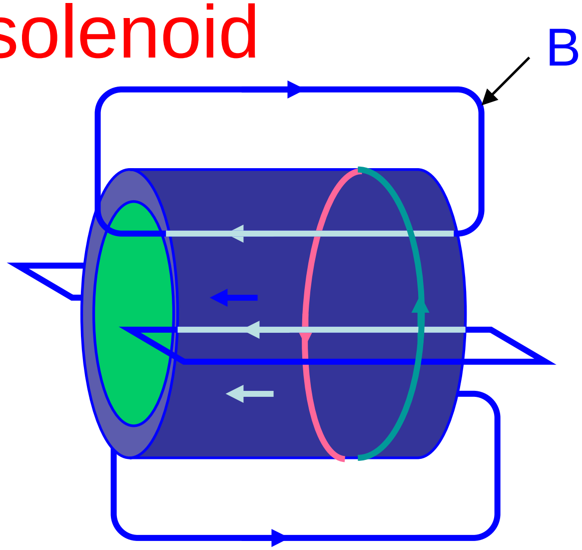


- “full” dΩ coverage
- very restricted access

Detector systems

Magnetic field configurations

solenoid



Large homogeneous field inside the coil

Week opposite field in the return yoke

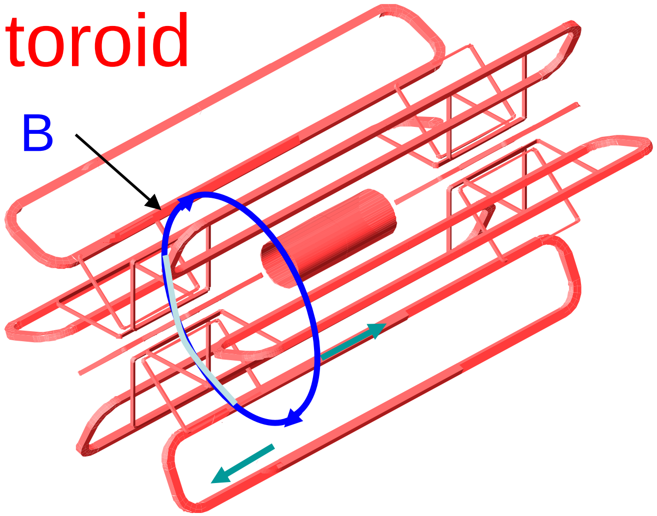
Cost limits the size

Relatively high material budget

Examples:

- DELPHI (SC, 1.2T)
- L3 (NC, 0.5T)
- CMS (SC, 4T)

toroid



Relatively large fields over large volume

Relatively low material budget

Non-uniform field

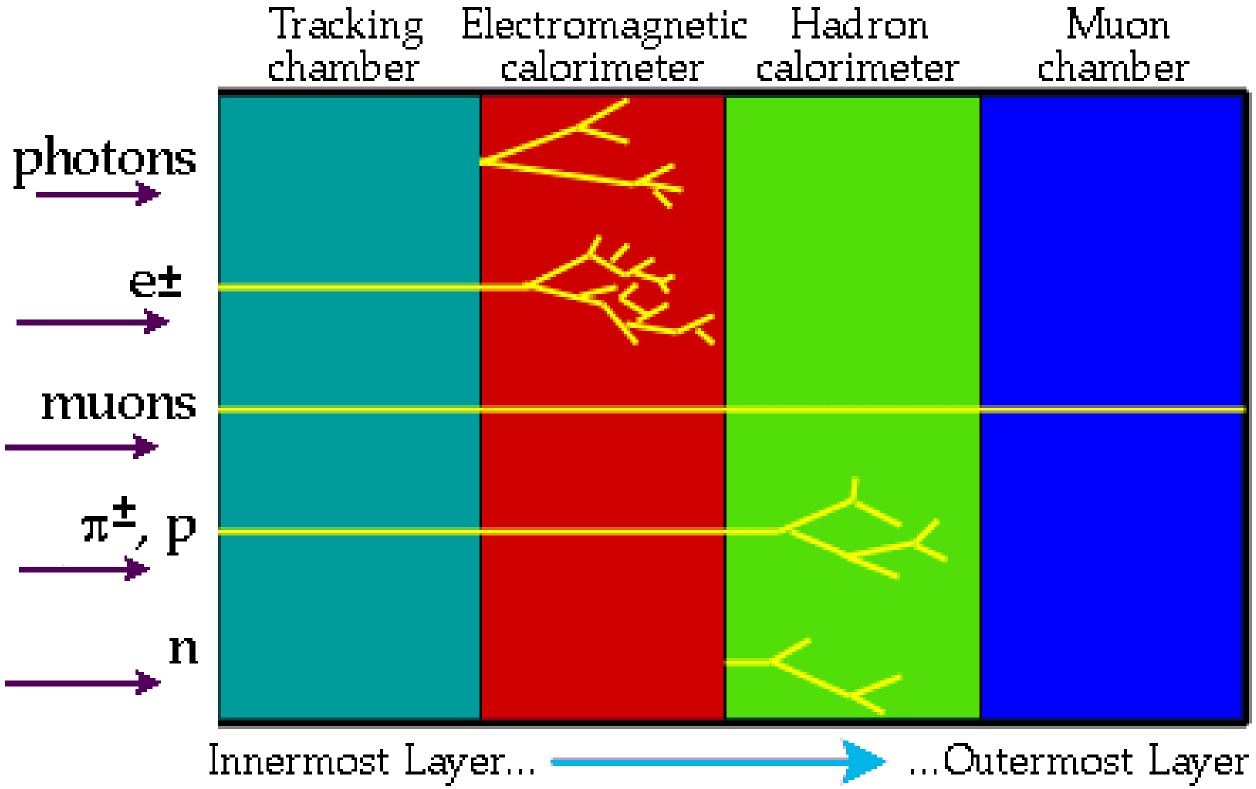
Complex structure

Example:

- ATLAS (Barrel air toroid, SC, 0.6T)

Detector systems

Typical detector components



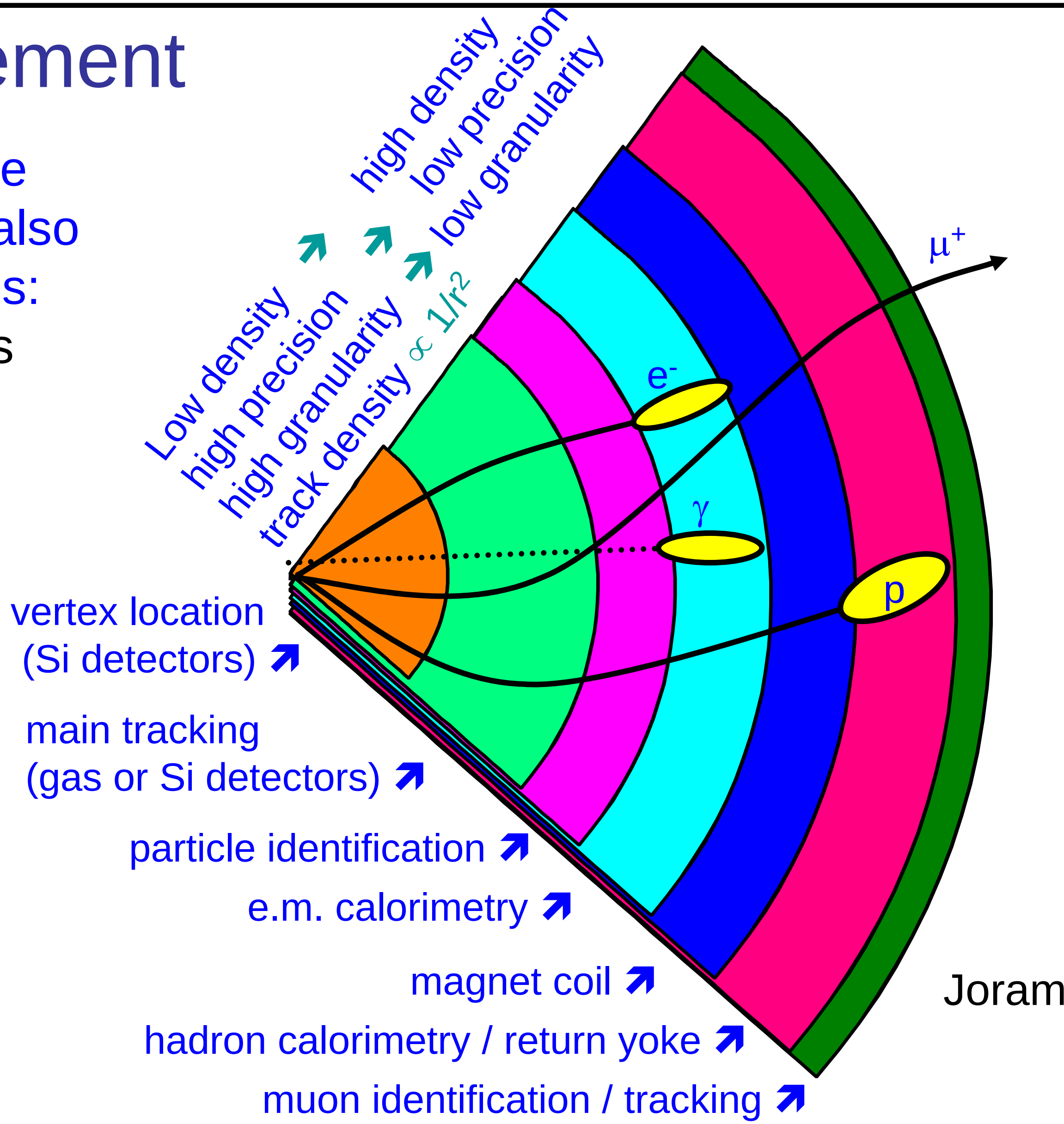
Need good e/γ, e/jet, γ/jet separation

Detector systems

■ Typical arrangement

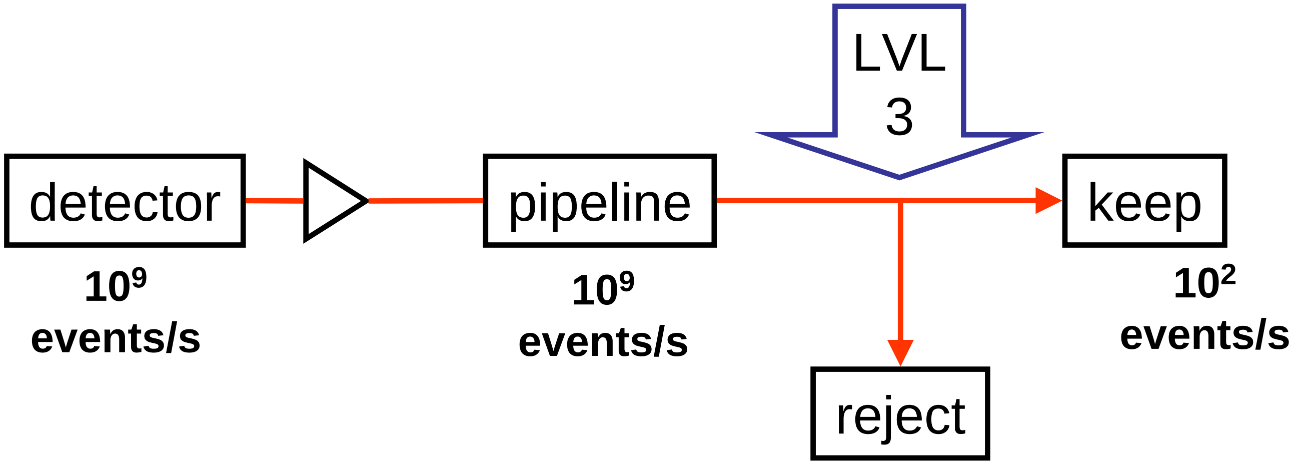
ATLAS and CMS require high precision tracking also for high energetic muons:

large muon systems with high spatial resolution behind calorimeters.



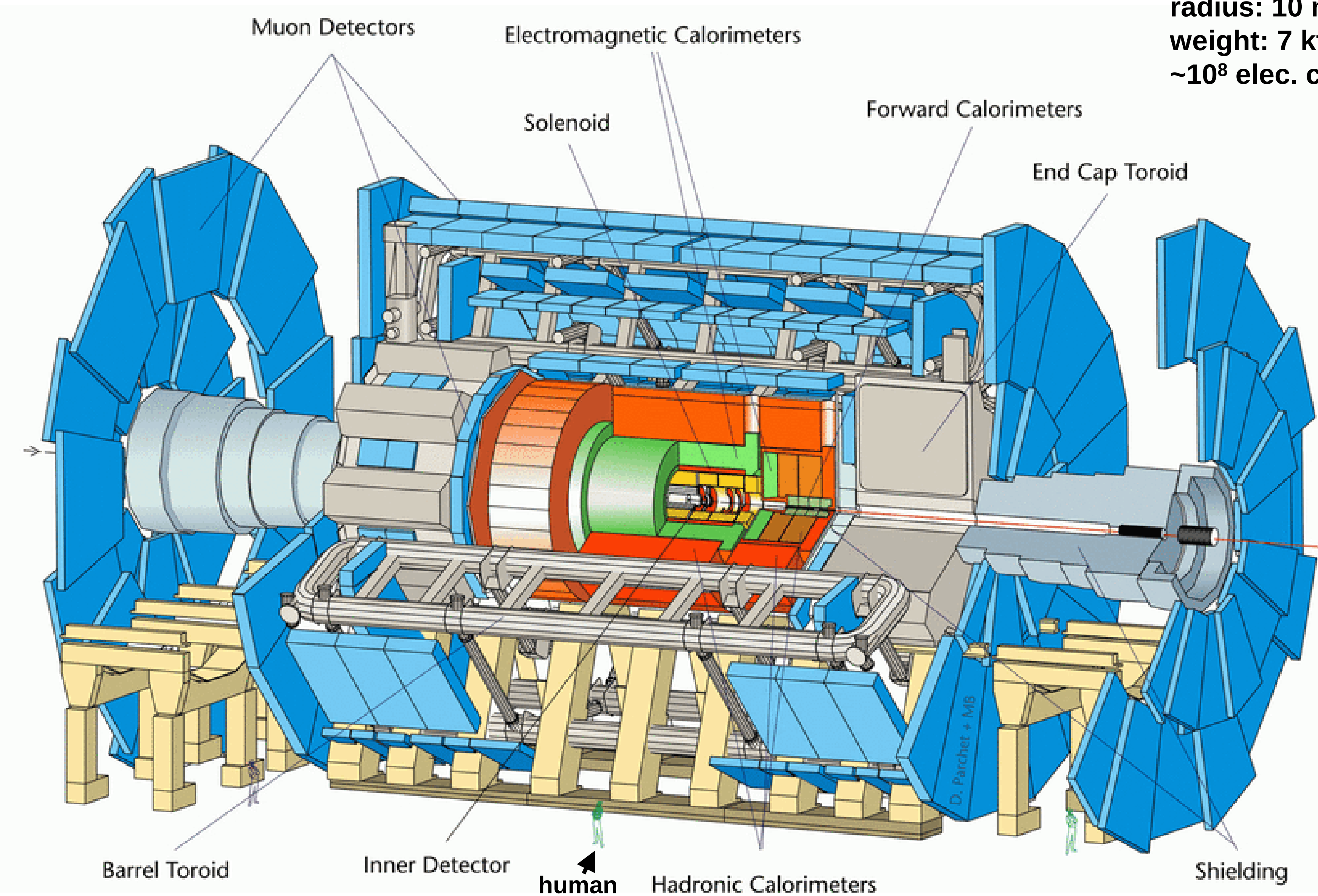
Event Triggering

- Much more difficult at LHC than at e^+e^- machines
- interaction rate ~ 10^9 events/s
- acquisition capacity ~ 100 events/s @ ~1MByte/event
- trigger rejection factor or ~ 10^7
- trigger decision time ~ 1 μs >> 25 ns
- need to store large amount of data in pipelines while the trigger performs calculations

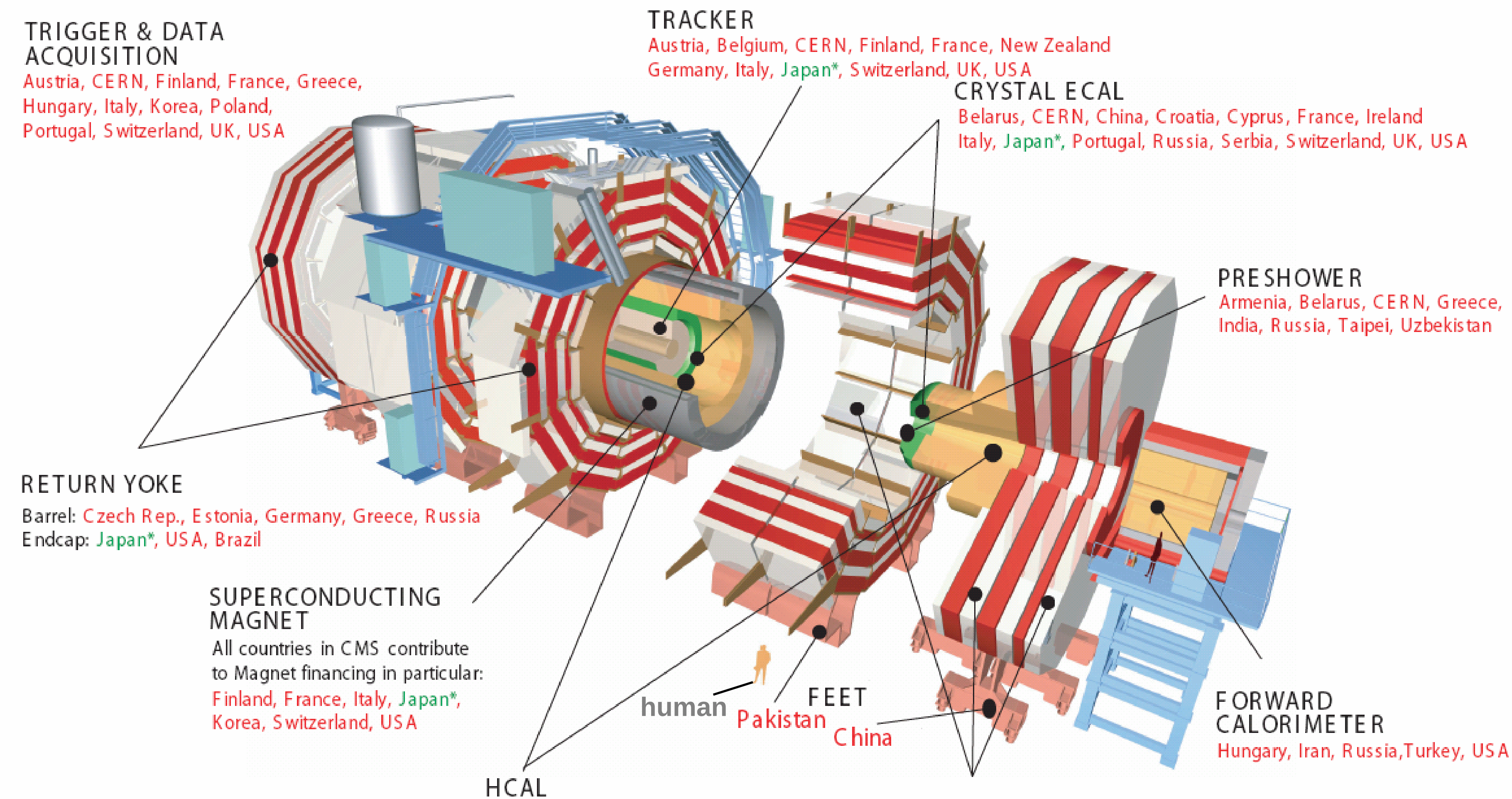


ATLAS Detector A Toroidal Lhc ApparatuS

length: 40 m
radius: 10 m
weight: 7 kt
~10^8 elec. ch



CMS Detector Compact Muon Solenoid



Total weight	:	12500 T
Overall diameter	:	15.0 m
Overall length	:	21.5 m
Magnetic field	:	4 Tesla

ATLAS and CMS

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels+ strips TRD → particle identification B=2T $\sigma/p_T \sim 5\mathrm{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\mathrm{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 70\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

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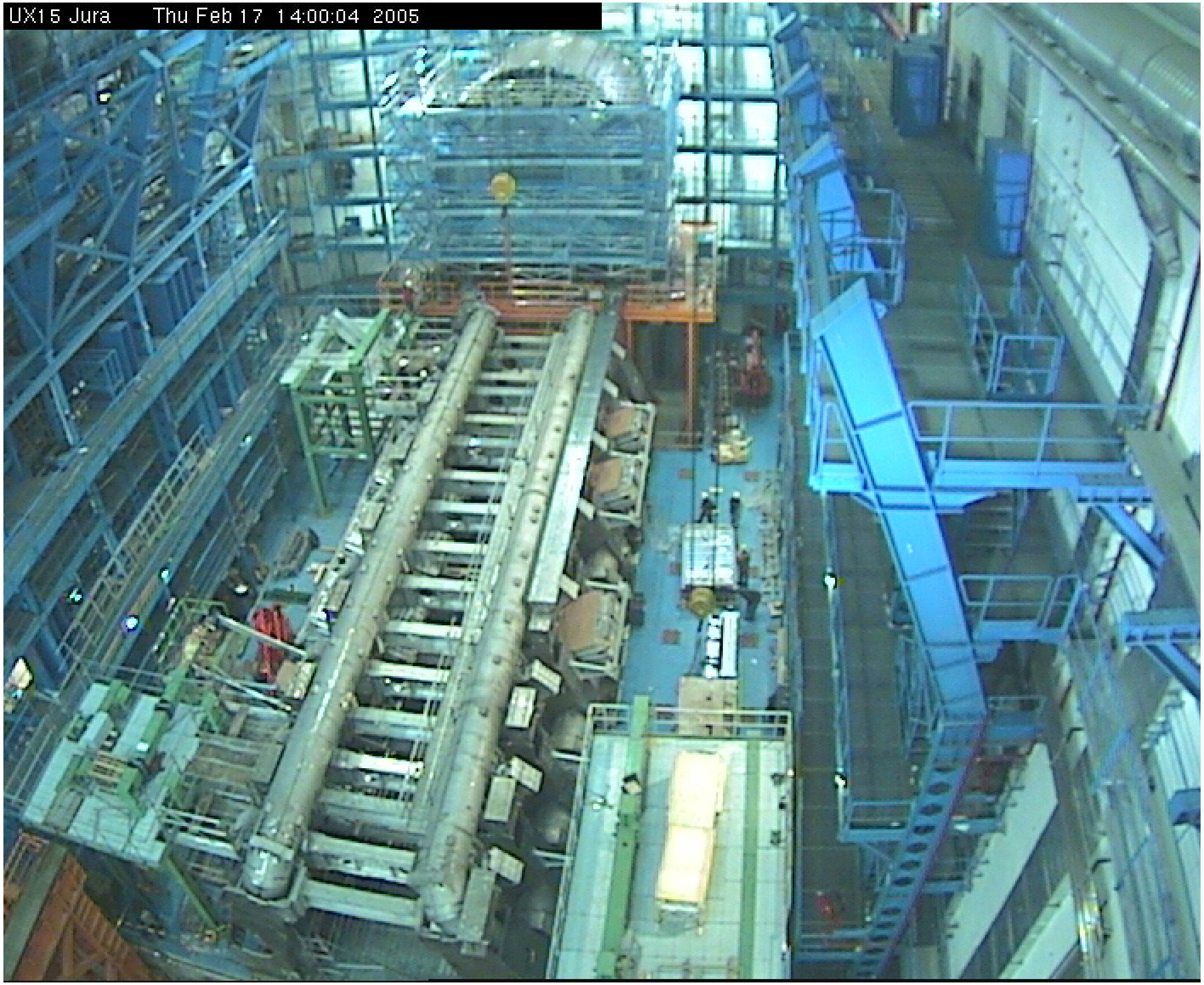
ATLAS web cam



ATLAS Detector Components

ATLAS barrel cryostat, containing the solenoid and the electromagnetic barrel calorimeter, being lowered in the pit

ATLAS Detector Components

Lecture III: Questions

- Question III.1
  - Obtain the result for the error on the mass given on slide III/5.
- Question III.2
  - Consider the separation of two particles using a time of flight detector. With a flight path of 1.0 m and a timing resolution of 200 ps, up to which momentum can you separate a π^+ from a K^+?

Acknowledements

- Christian Joram (CERN)
  - I have taken a lot of material from his very fine CERN summer Student Lectures 2003
- Steinar Stapnes
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- TSI06 organizing committee and TRIUMF hosts!