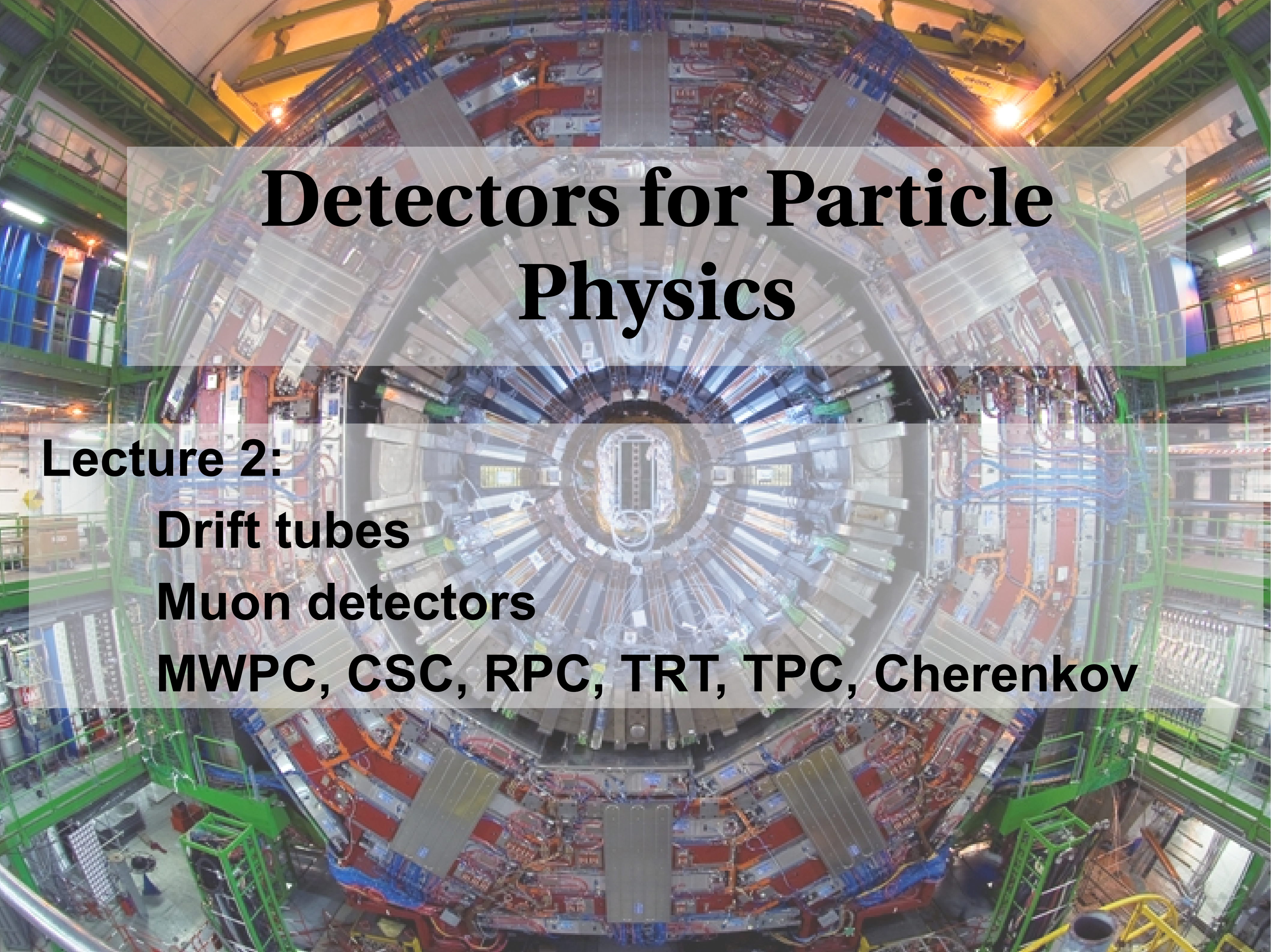


Detectors for Particle Physics

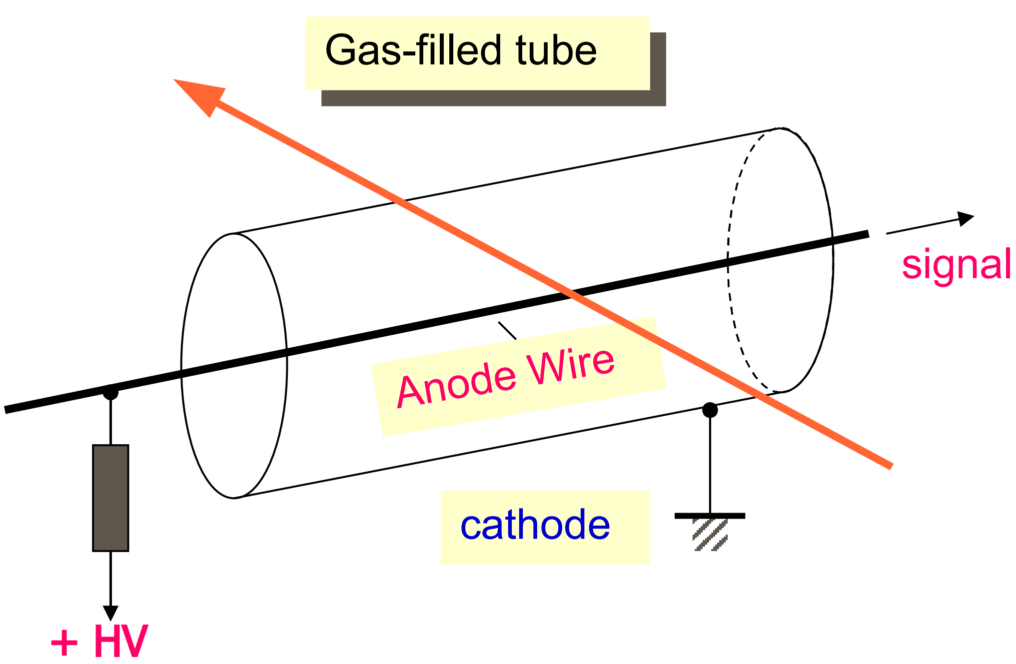
Lecture 2:

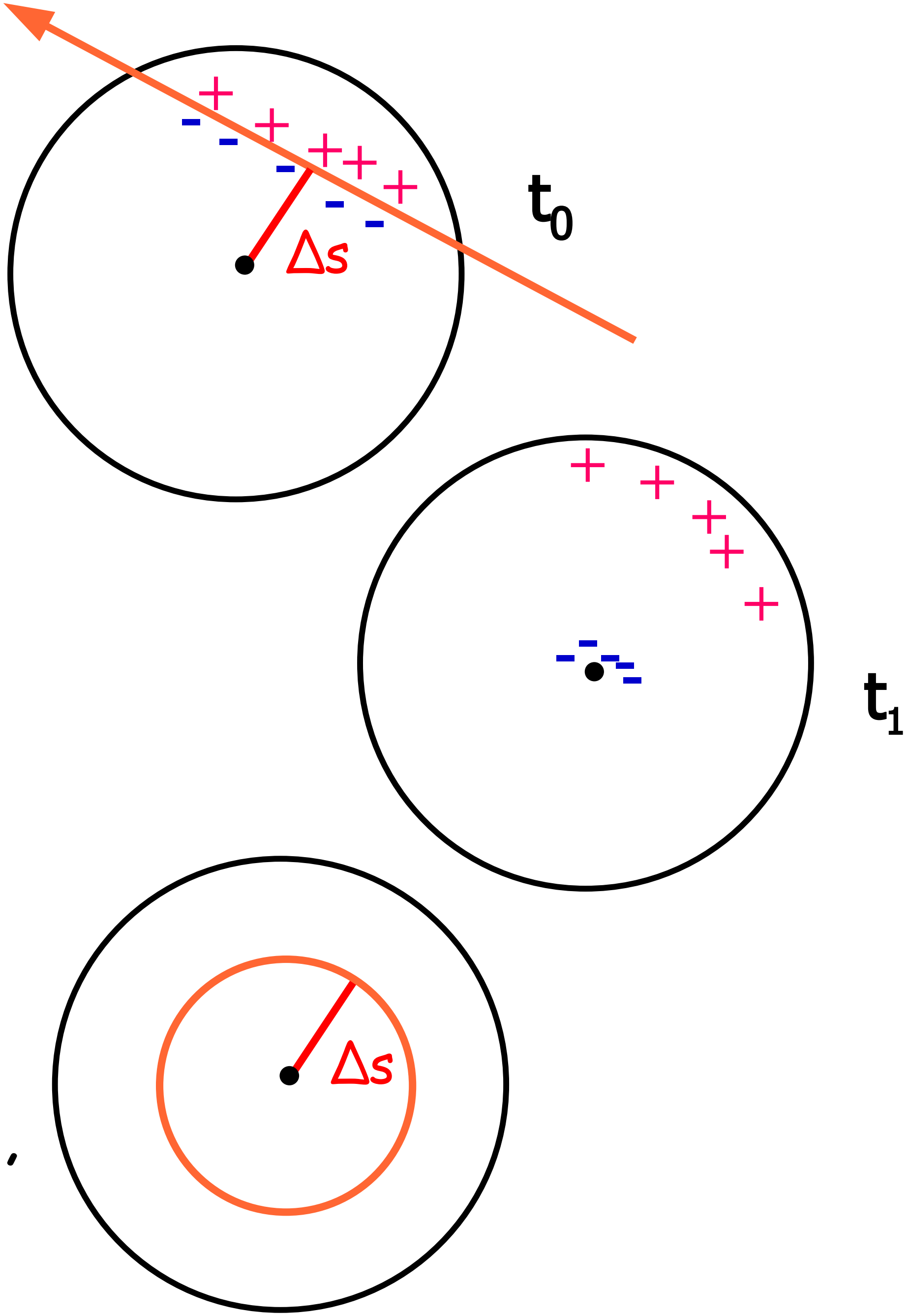
- **Drift tubes**
- **Muon detectors**
- **MWPC, CSC, RPC, TRT, TPC, Cherenkov**

Outline

- Lecture 1:
  - Collider detectors
  - Charged particles in a magnetic field
  - Silicon detectors
- Lecture 2:
  - Drift tubes
  - Muon systems
  - MWPCs, CSCs, RPCs, TRTs, TPCs, Cherenkovs
- Lecture 3:
  - Electromagnetic showers and calorimeters
  - Photon detectors
  - Hadronics showers and calorimeters
  - Particle flow technique
- Discussion session:
  - Your questions, please

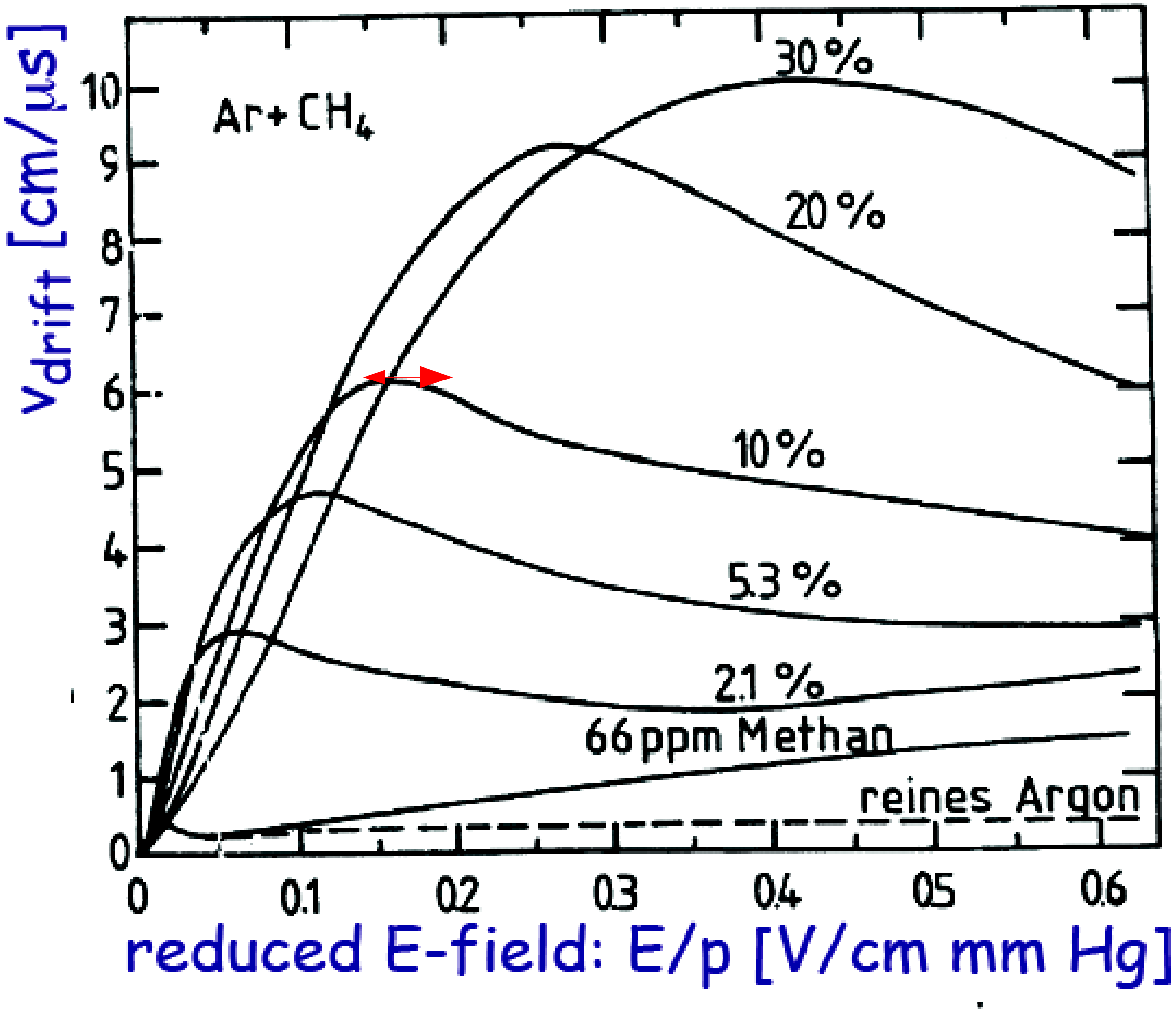
Principle of drift detectors





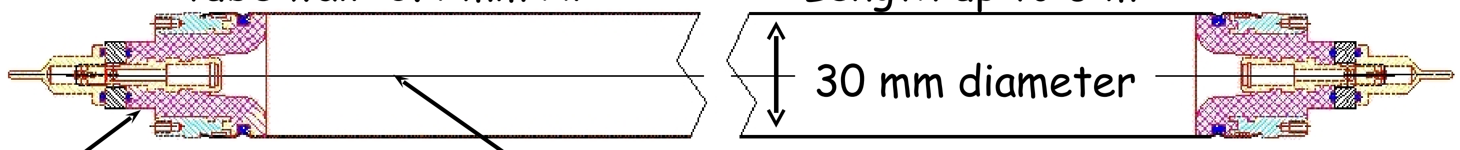
- Track ionises gas atoms
- electrons drift towards anode: v_D
- Amplify
- Measure drift time: $\Delta t = t_1 - t_0$
- Reconstruct radius: $\Delta s = v_D \, \Delta t$.
- vD depends on gas, voltage, pressure, temperature, field: need calibration.

Drift velocity



- Drift velocity depends on electric field, pressure, gas, temperature, magnetic field.
- Want stable operation point: just above maximum.
- tradeoff:
  - slower gas = higher resolution.
  - faster gas better in a high-rate environment.

ATLAS drift tubes



tube wall: 0.4 mm Al

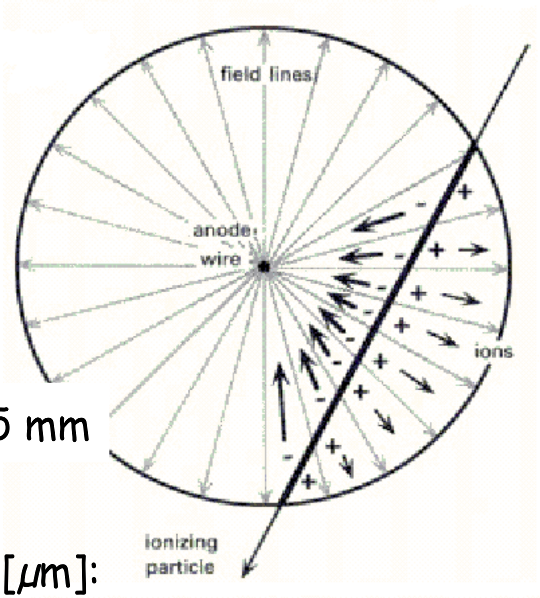
Length up to 6 m

30 mm diameter

endplug

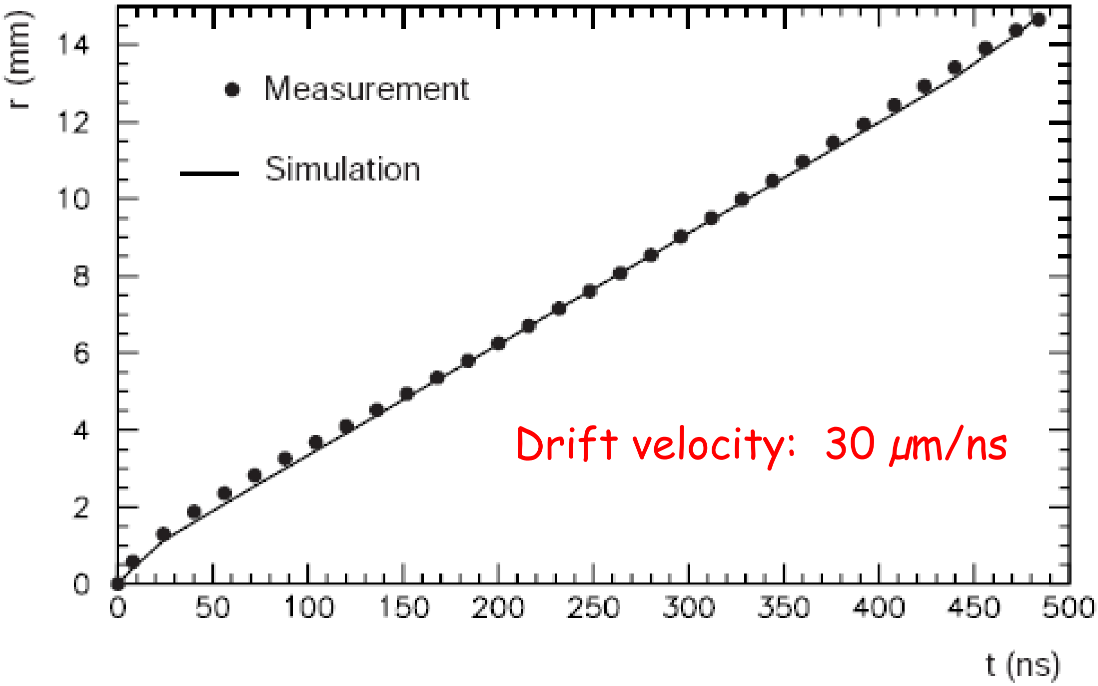
wire: 50 μm W-Re at +3300V

Gas: Ar (91%) CH4 (5%) N2 (4%) at 3 bar



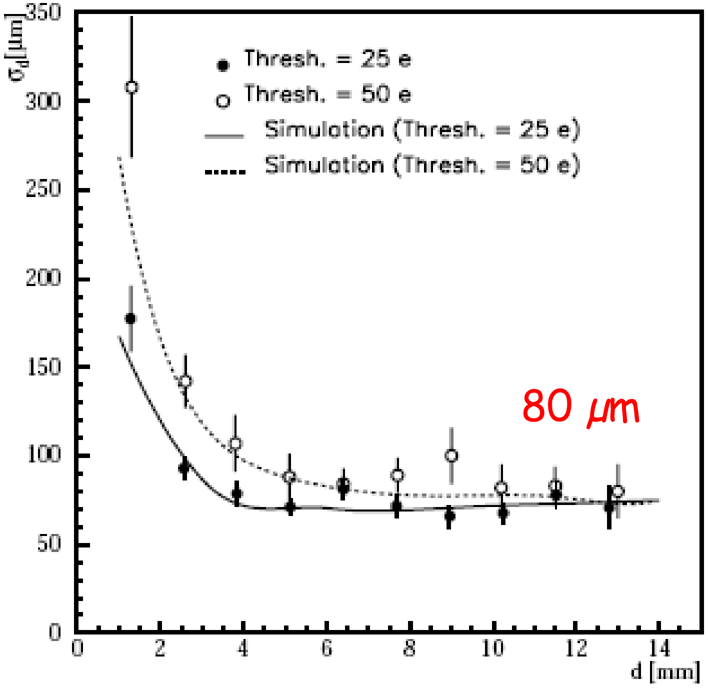
R=15 mm

Distance from time:



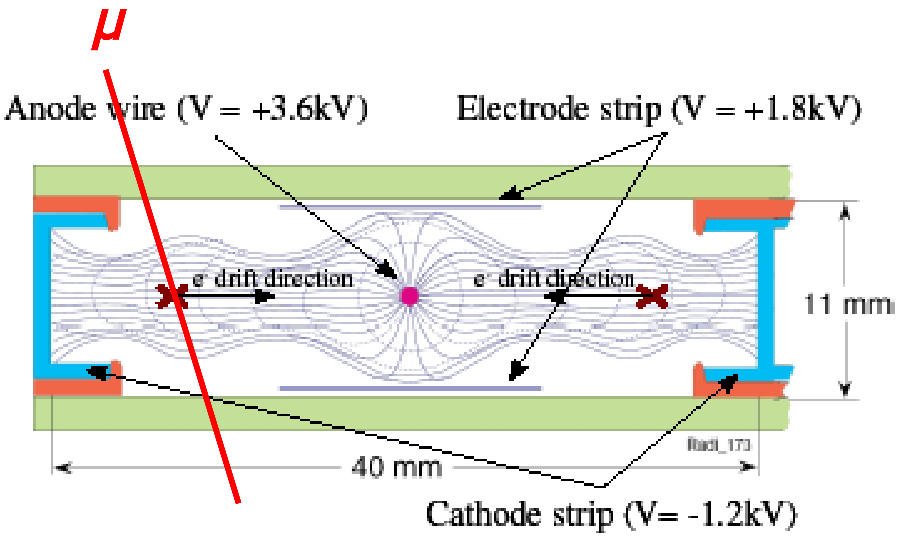
Drift velocity: 30 μm/ns

Resolution [μm]:



80 μm

CMS drift cells

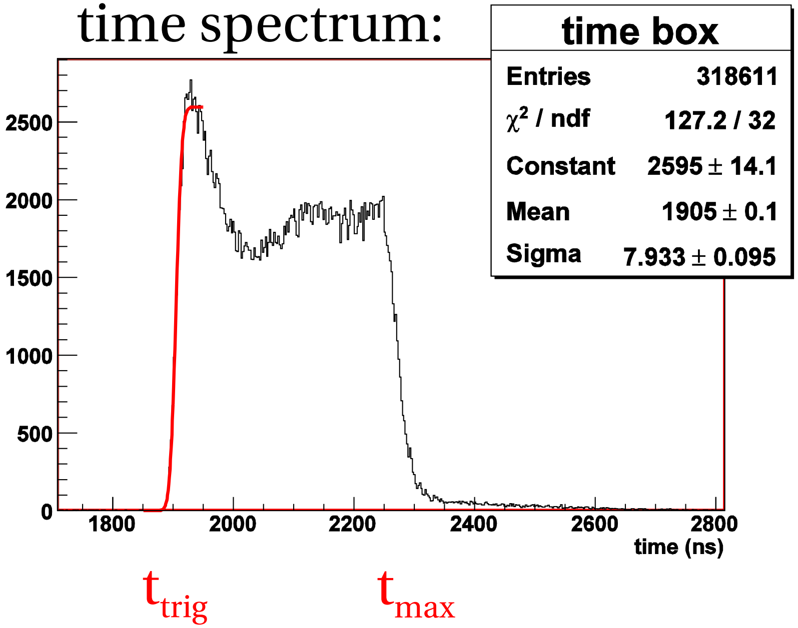


Extra electrode for field shaping:
more uniform drift.
Left/right ambiguity remains.

- **time synchronization:**

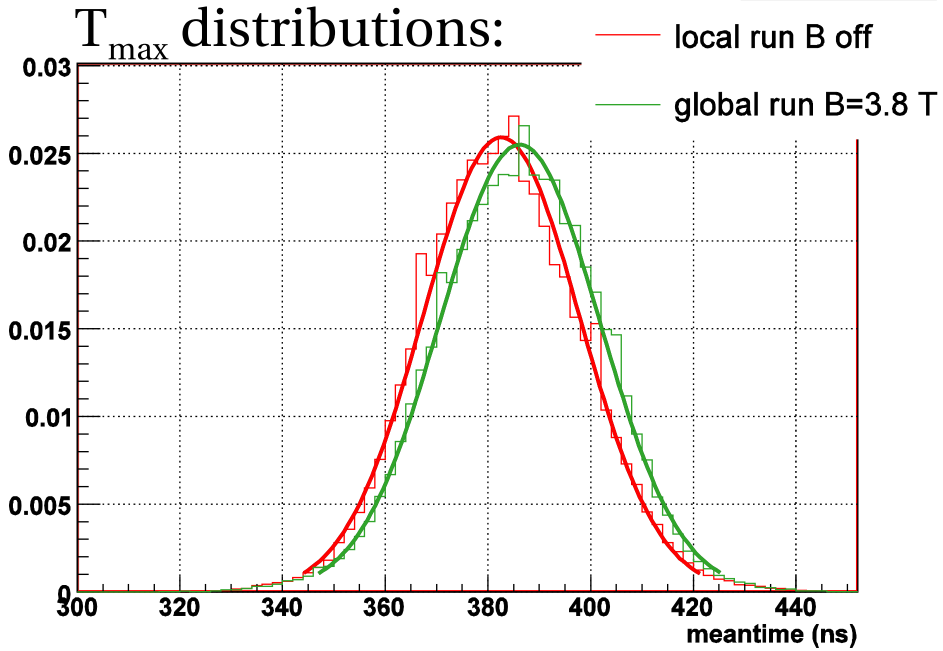
$$t_{meas} = \underbrace{t_{electr} + t.o.f. + t_{prop}}_{\text{time pedestal } (t_{trig})} + t_{drift}$$

time spectrum:



time box	
Entries	318611
χ^2 / ndf	127.2 / 32
Constant	2595 ± 14.1
Mean	1905 ± 0.1
Sigma	7.933 ± 0.095

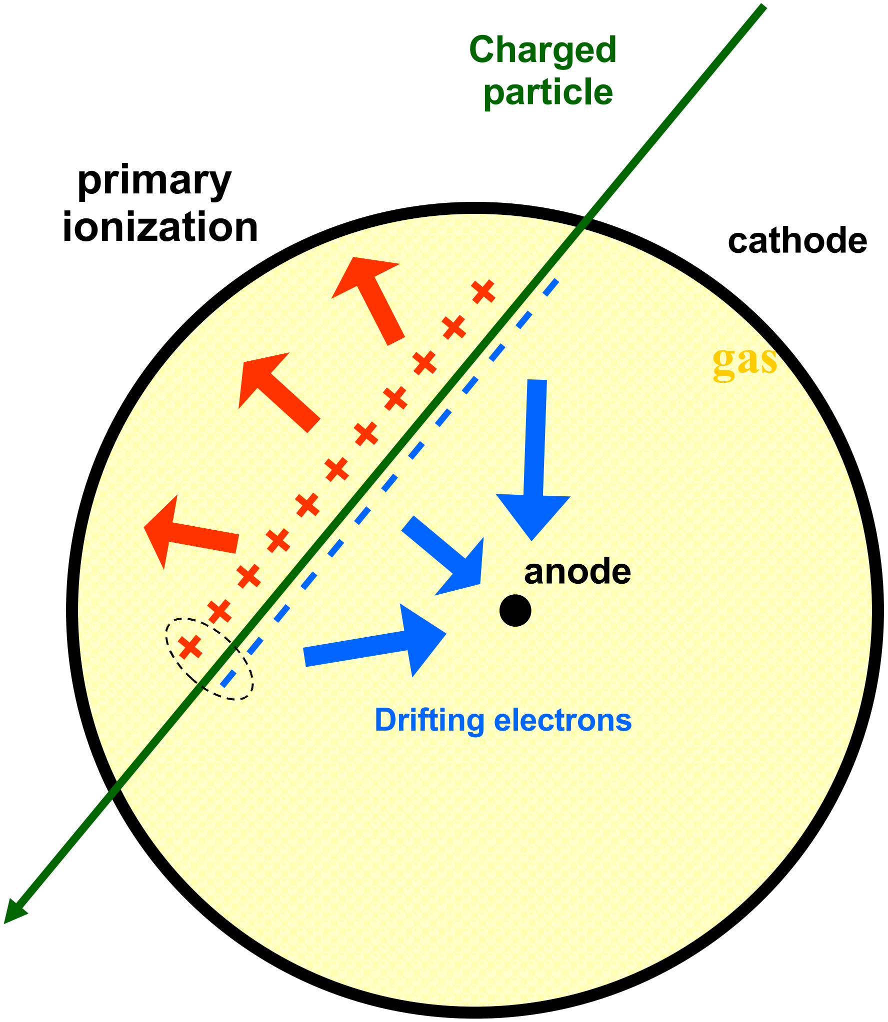
- **drift velocity calibration:**


T_{max} distributions:

$$v_{drift} = L / (2 \times \langle T_{max} \rangle)$$

$$\text{resolution} = v_{drift} \times \langle \sigma_{Tmax} \rangle$$

Choice of Gas 1: ionization and drift



- Drifting electrons should not be trapped:
  - Use noble gas, e.g. Ar.
- Want large primary ionzation yield:
  - Ar gives 25 ions/cm at normal T, p for a minimm ionizing particle.
- The primary electrons may ionize further atoms:
  - $\times 3$ or $\times 4$ increase.
- Xe and/or higher pressure are even better (and more expensive).

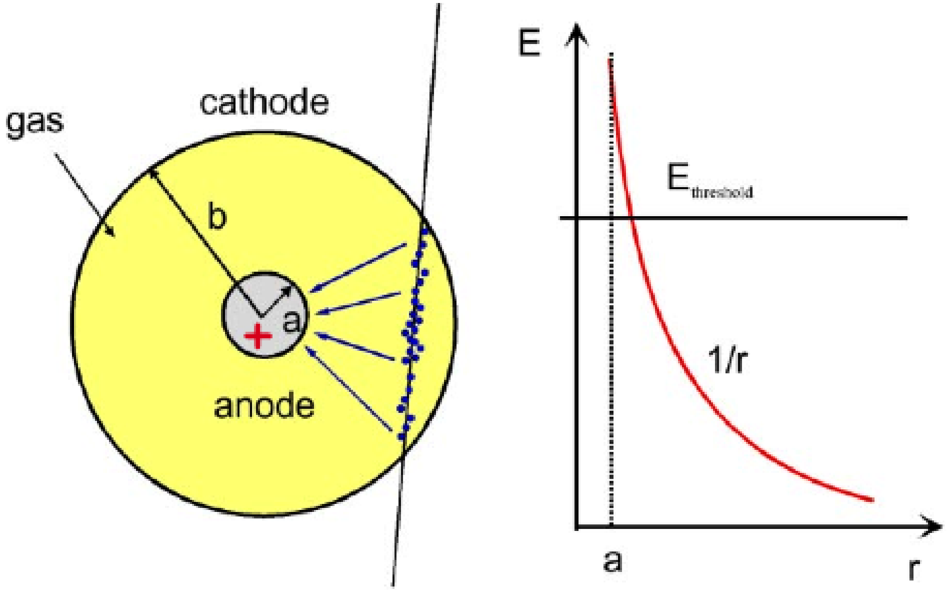
Signal amplification near the wire

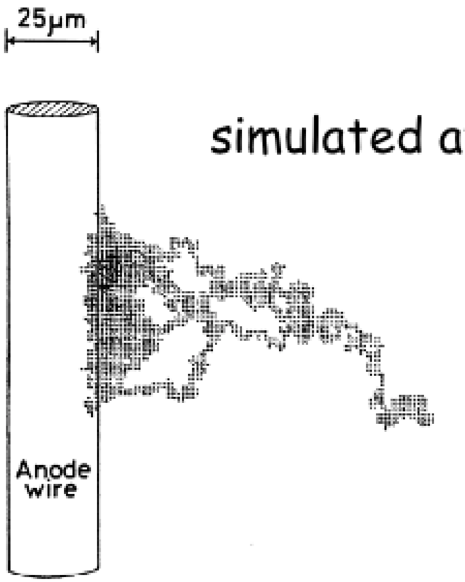
For cylindrical geometry:

$$E(r) \propto \frac{1}{r} \quad \text{and} \quad V(r) \propto \ln\frac{r}{a}$$

- the primary electrons drift towards the positive anode
- due to 1/r dependence the electric field close to very thin wires reaches values of E > kV/cm
- ⇒ in between collisions with atoms electrons gain enough energy to ionize further gas molecules
- ⇒ exponential increase in number of electron-ion pairs very close (few μm) to the wire

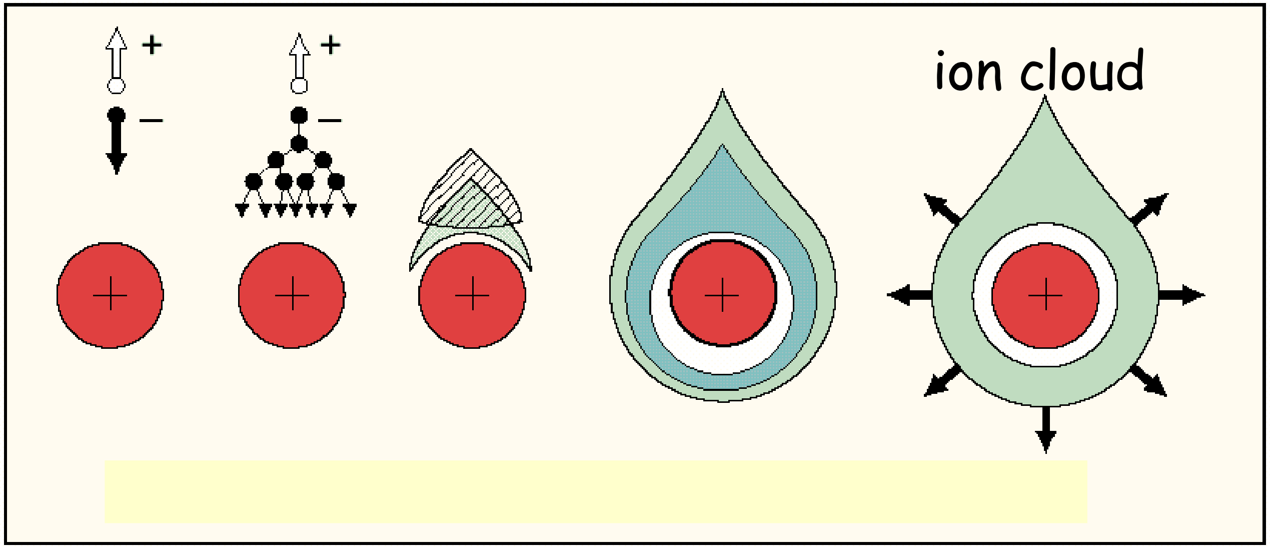
Amplification by 10^4 possible





simulated avalanche

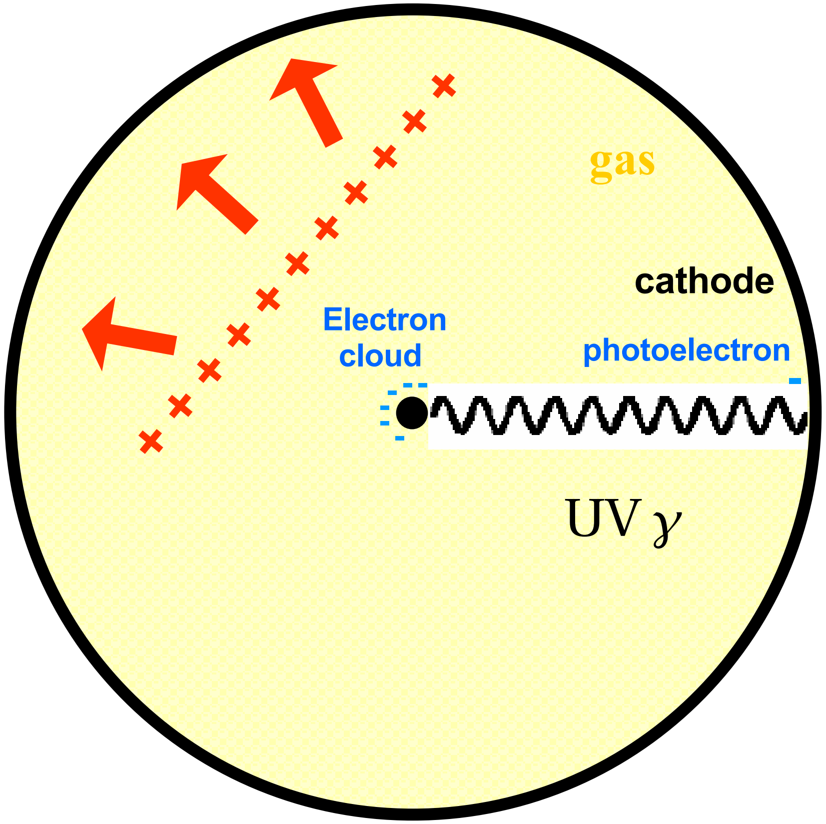
The Avalanche



- Amplification depends on:
  - Anode voltage
  - Wire radius
  - Gas composition
  - Pressure
  - temperature

Receeding ion cloud
induces signal on the wire

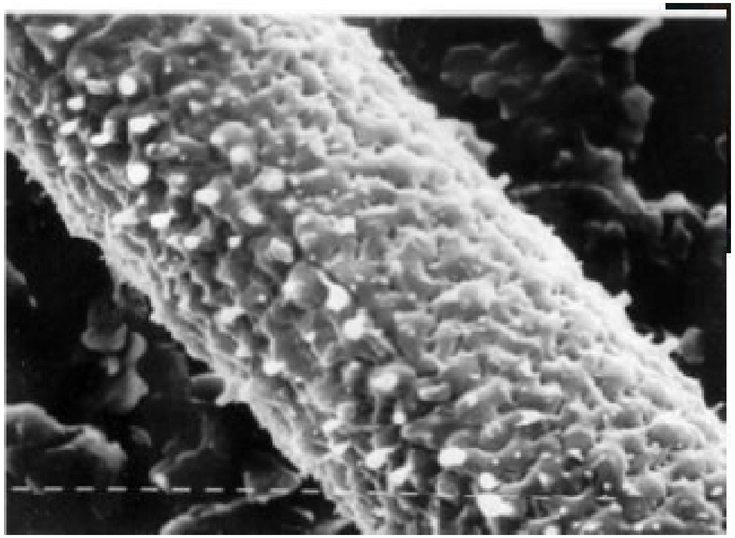
Choice of Gas 2: high gain, stable operation



- Want large gain at low voltage:
  - Ar is monoatomic gas
  - No vibrational or rotational modes, only excitation and ionization.
- Excited Ar atoms may emit UV photons (11.6 eV):
  - UV photons may reach the cathode and produce photoelectrons.
  - Photoelectrons drift back towards the wire and may start a new avalanche
  - Continous discharge!
- Need 'quencher' molecules that absorb UV photons without creating photoelectrons:
  - CH_4, C_2H_6, CO_2, ...

Choice of Gas 3: prevent ageing

deposits on the wire:



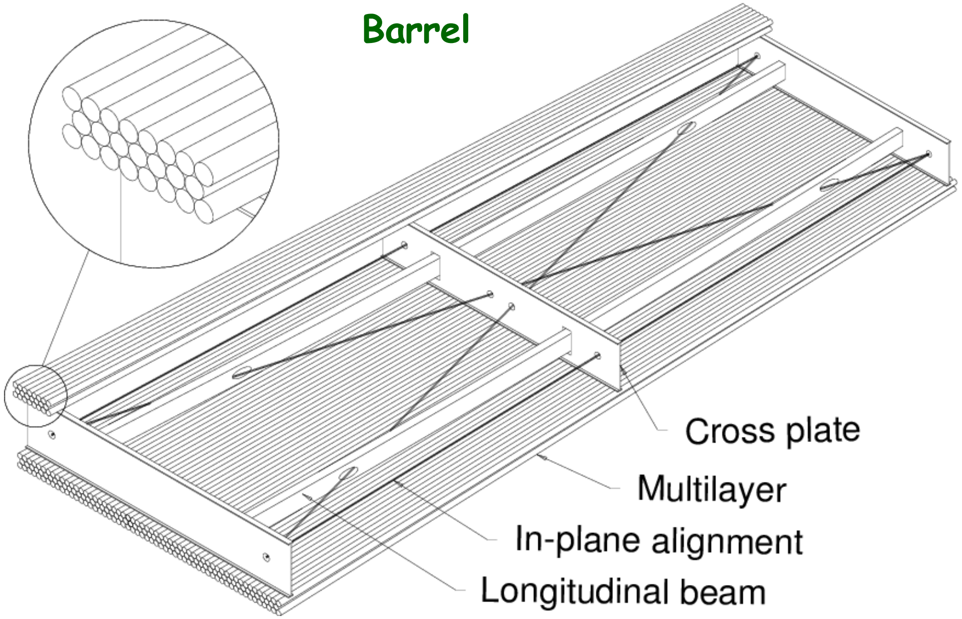
'whiskers':

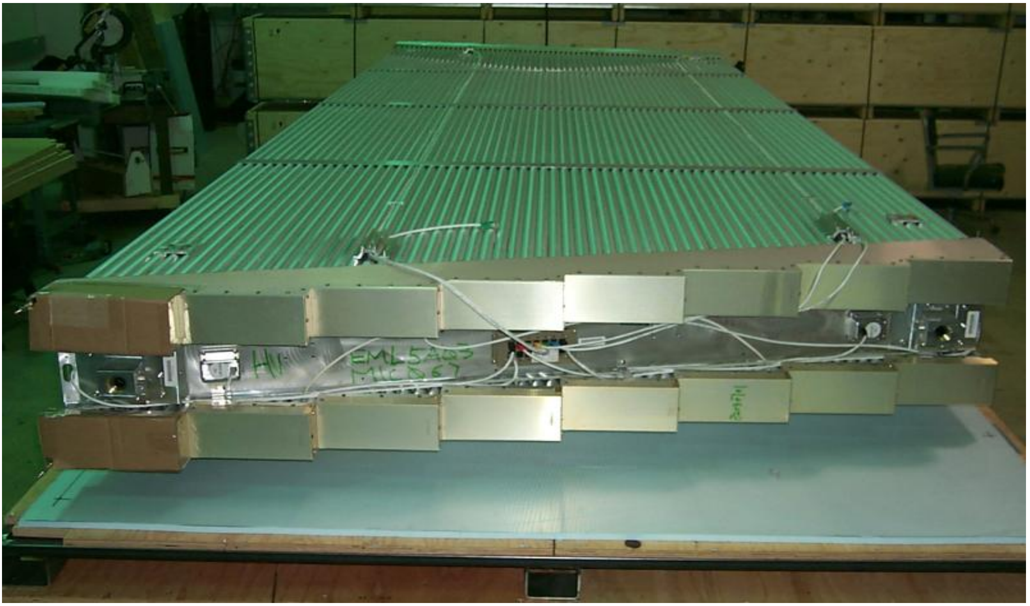
- Impurities in the gas (or in the chamber) may form deposits on the wire and reduce the gain.
- 'Whiskers' lead to HV instabilities.
- Prevention:
  - Build chamber in a clean room.
  - Use clean gas.
  - Add ~1% alcohol, water, or oxygen.

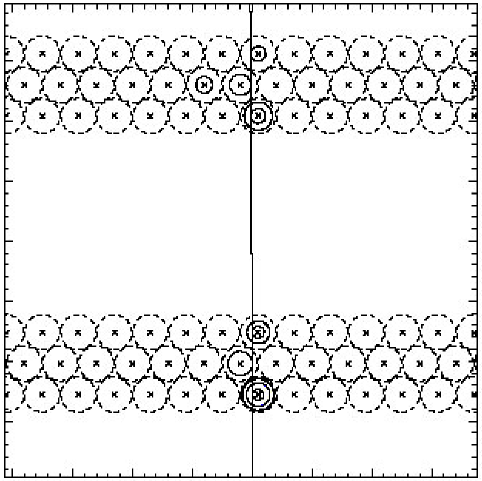
ATLAS Drift Tube Chambers

- 6 drift tube layers, arranged in 2 multilayers glued to a spacer frame
- length: 1 – 6 m, width: 1 – 2 m
- optical system to monitor chamber deformations
- gas: Ar:CO_2 (93:7) to prevent aging, 3 bar

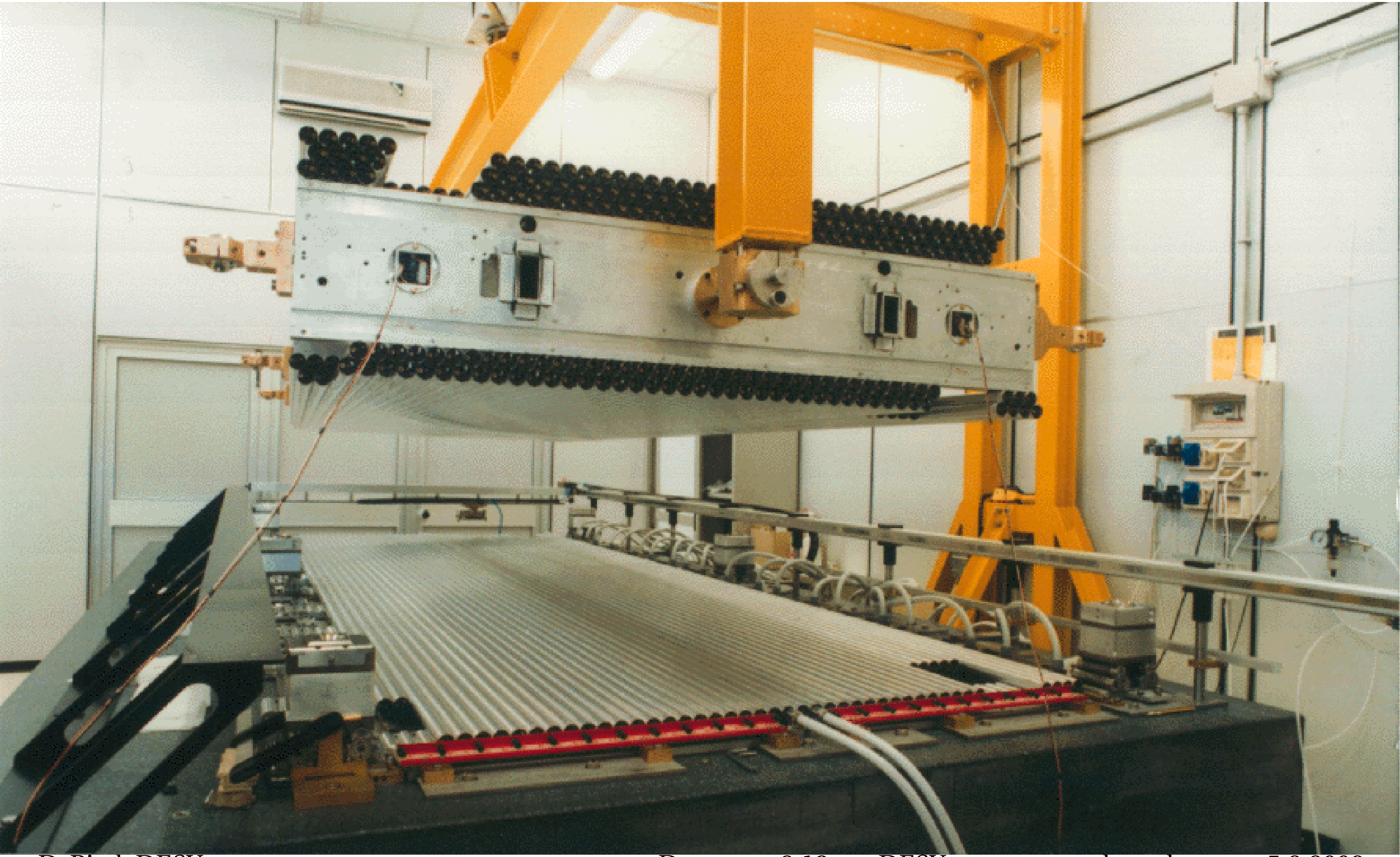
- chamber resolution: 50 µm
    - ➔ single tube resolution: 100 µm
    - ➔ required wire position accuracy: 20 µm



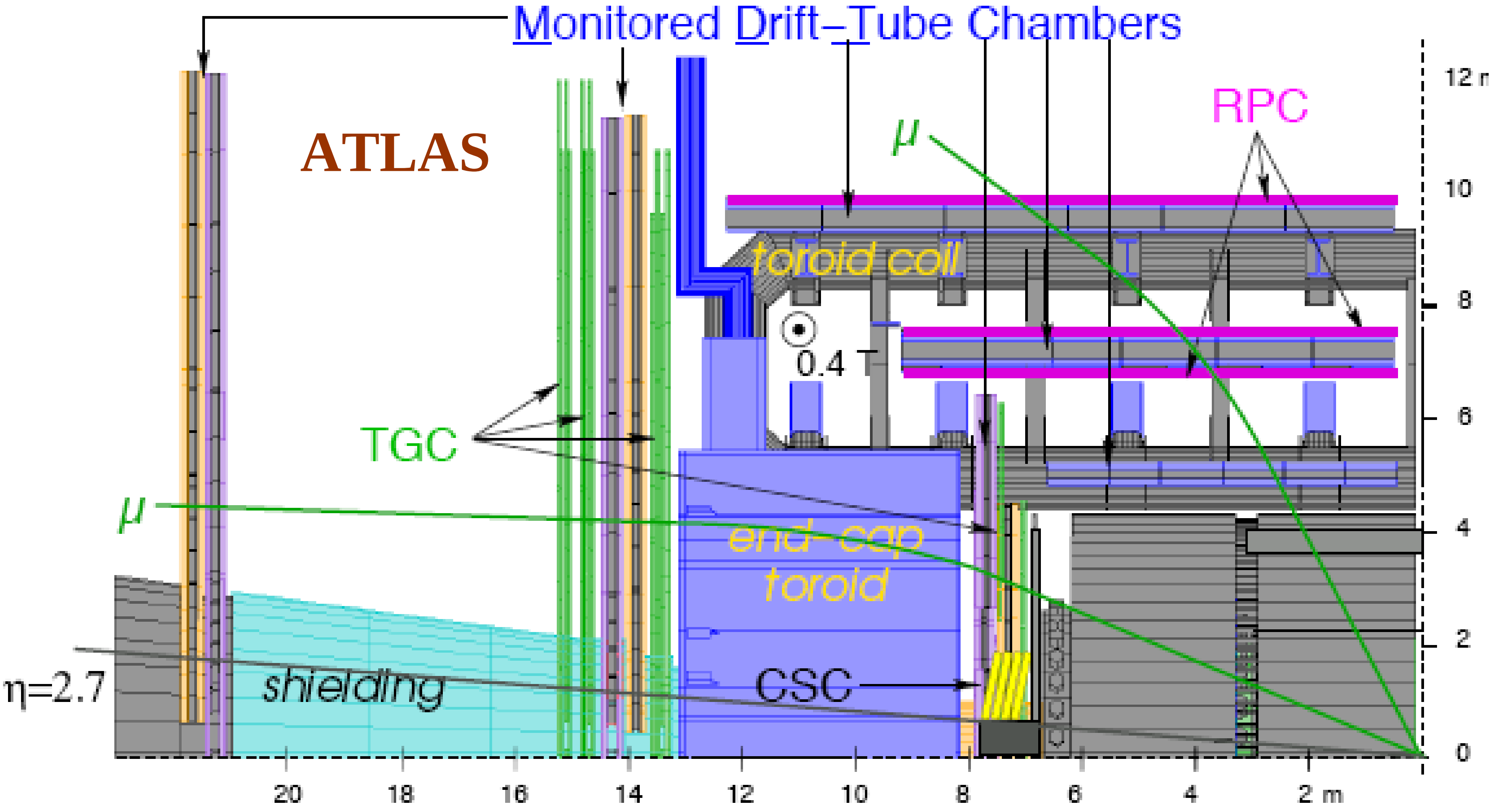




Assembly of MDT Chambers (Frascati, IT)



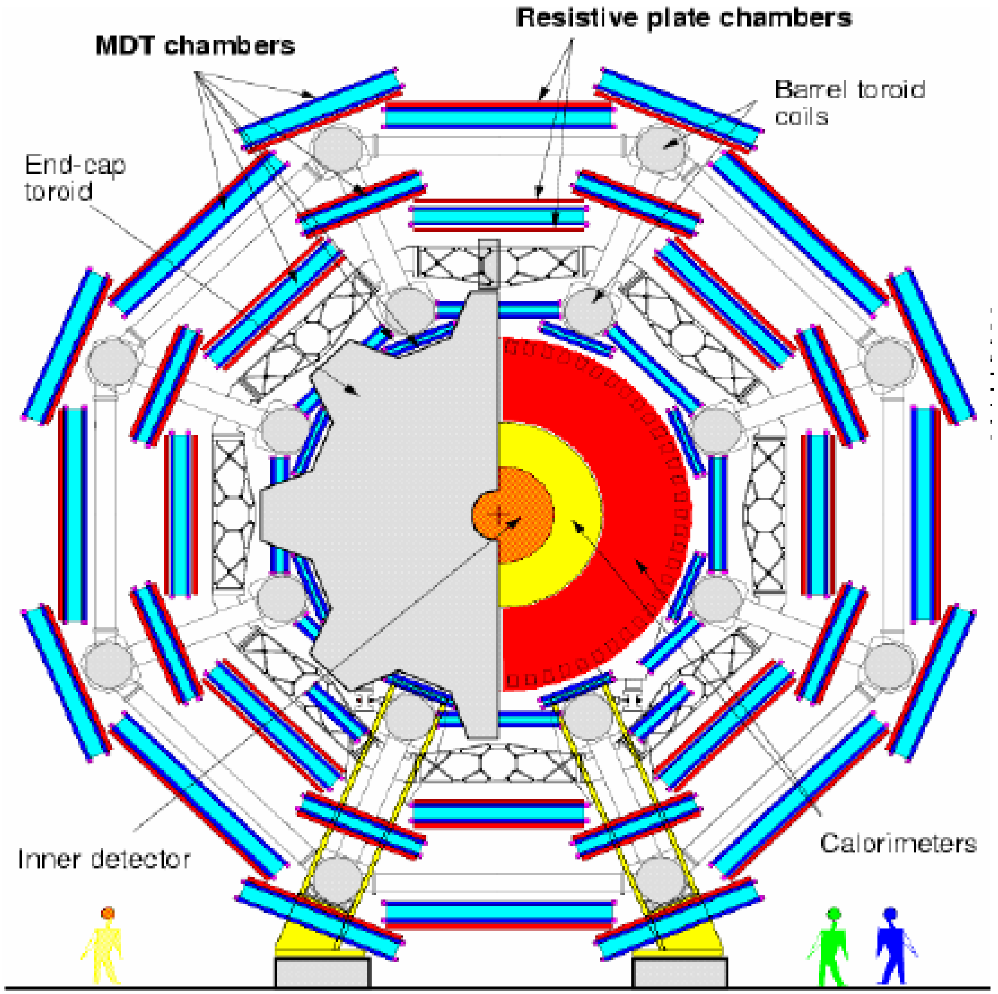
ATLAS muon system

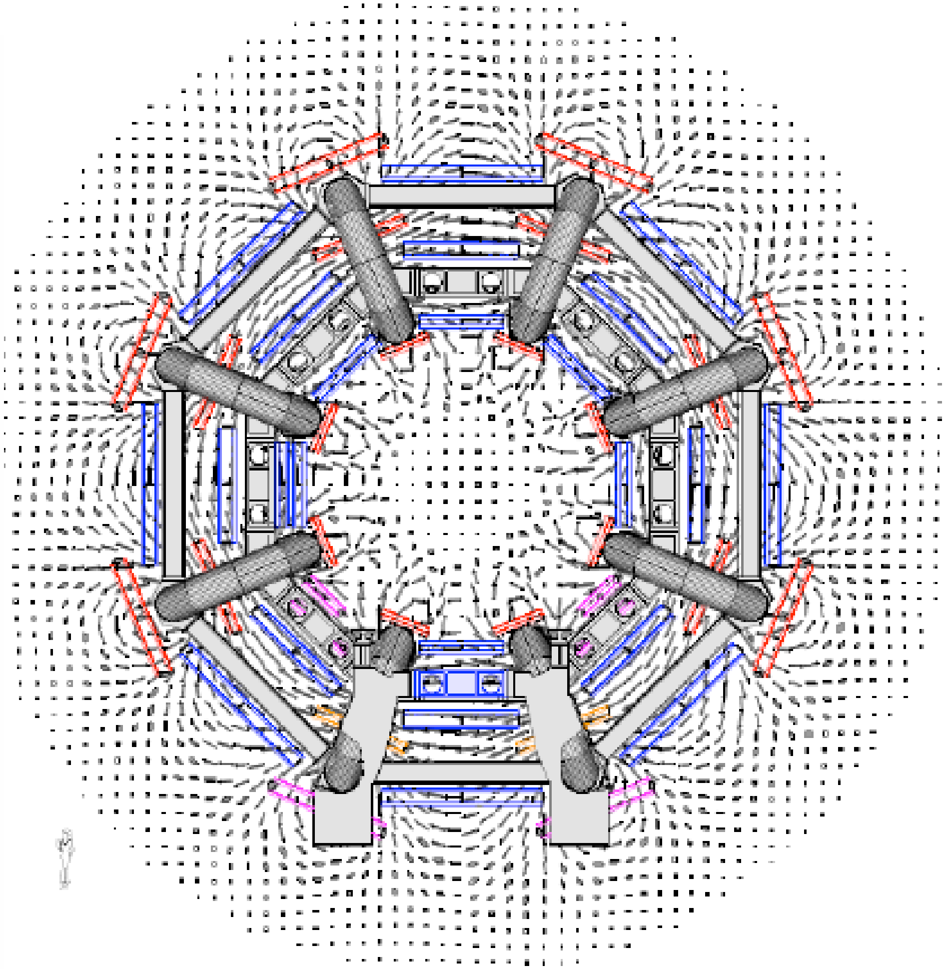


ATLAS muon spectrometer

- **Excellent stand-alone capabilities and coverage in open geometry**
- **Complicated geometry and field configuration (large fluctuations in acceptance and performance over full potential $\eta \times \varphi$ coverage ($|\eta| < 2.7$)**

ATLAS Barrel muon system in the toroid field

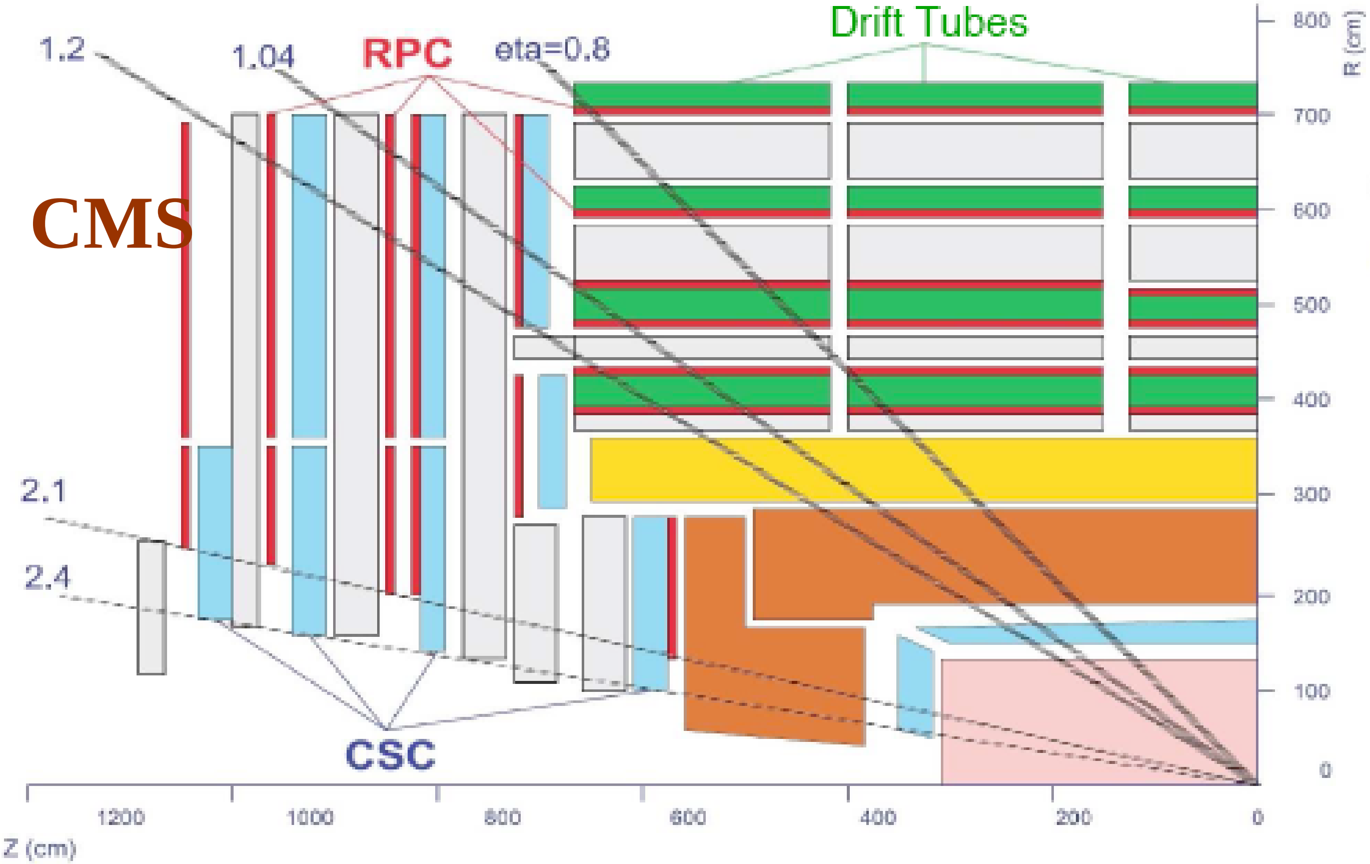


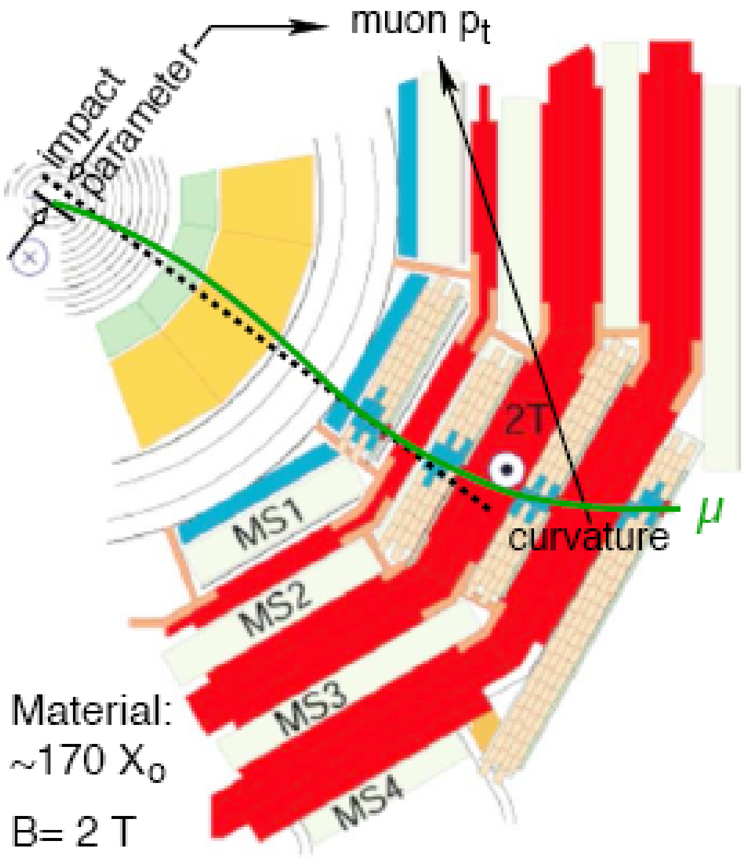


Detailed field map needed!

CMS muon system

CMS

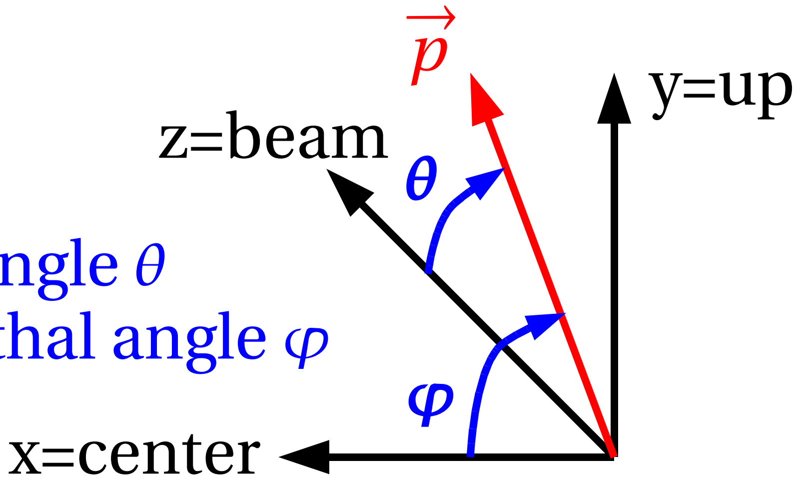




CMS muon spectrometer

- Superior combined momentum resolution in the central region with silicon tracker.
- Limited stand-alone resolution and trigger (at very high luminosities) due to multiple scattering in iron
- Degraded overall resolution in the forward regions ($|\eta| > 2.0$) where solenoid bending power becomes insufficient

Pseudo-rapidity



Polar angle θ
Azimuthal angle φ

$$p_t = \sqrt{p_x^2 + p_y^2}$$

$$p = \sqrt{p_x^2 + p_y^2 + p_z^2}$$

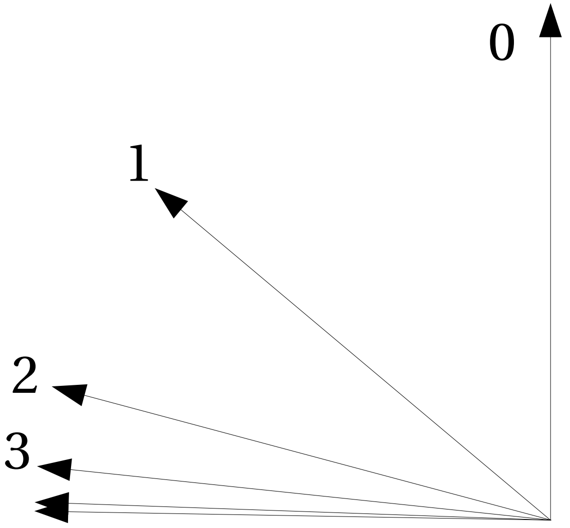
$$\varphi = \arctan(p_y / p_x) \in [-\pi, \pi]$$

$$\theta = \arccos(p_z / p) \in [0, \pi]$$

pseudo-rapidity: $\eta = -\ln(\tan(\theta/2))$

(soft hadron production: $dn/d\eta \approx$ const. 'central rapidity plateau')

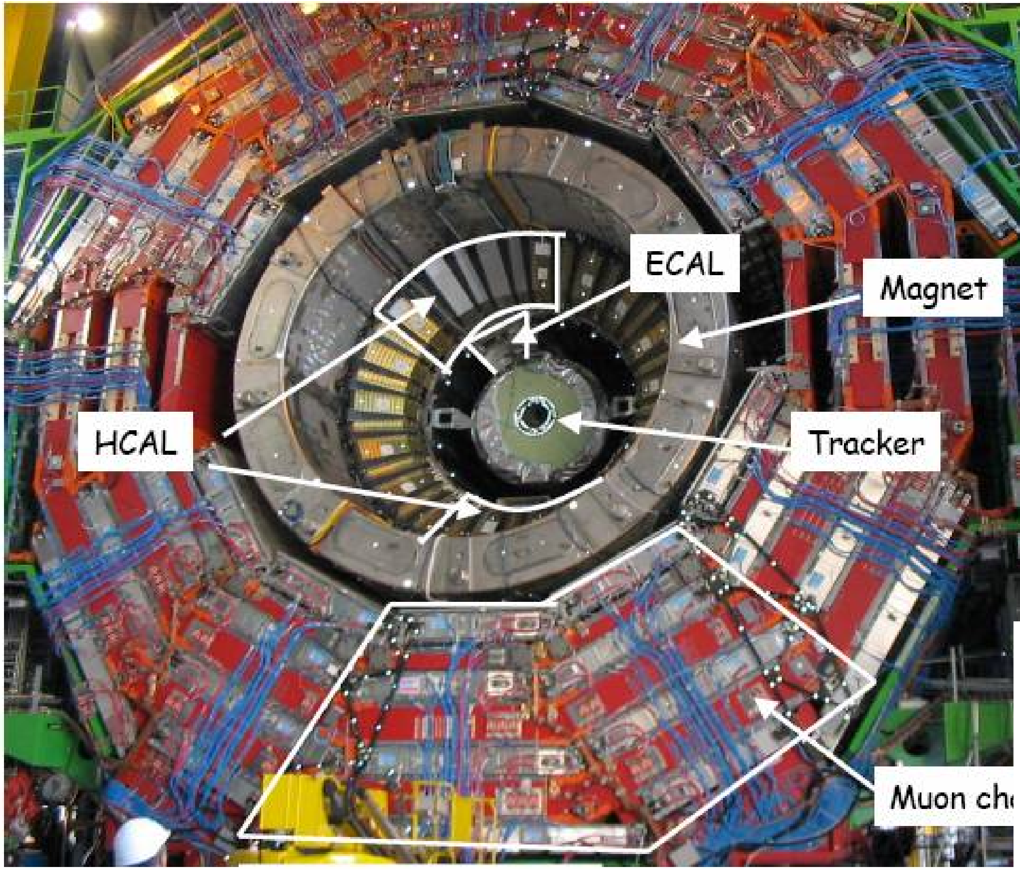
η	θ
0	90°
±1	±40°
±2	±15°
±3	±6°
±4	±2°
±5	±1°

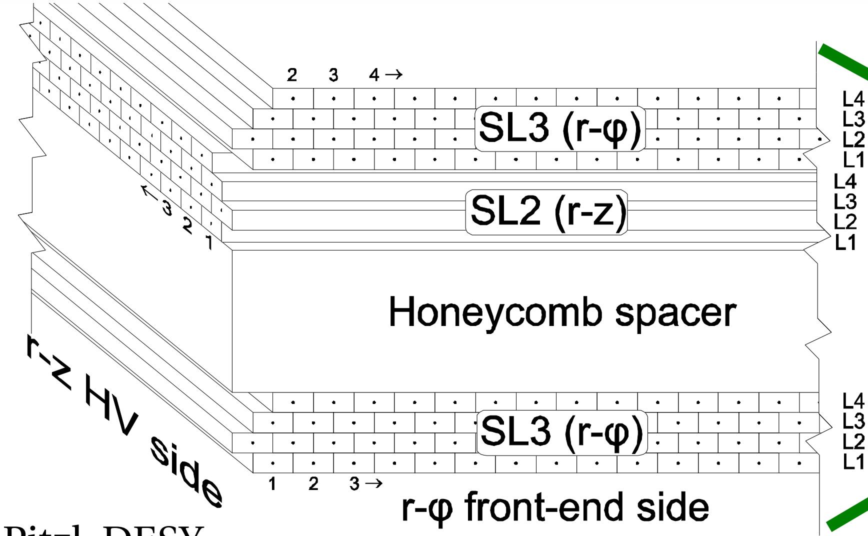


rapidity: $y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right)$

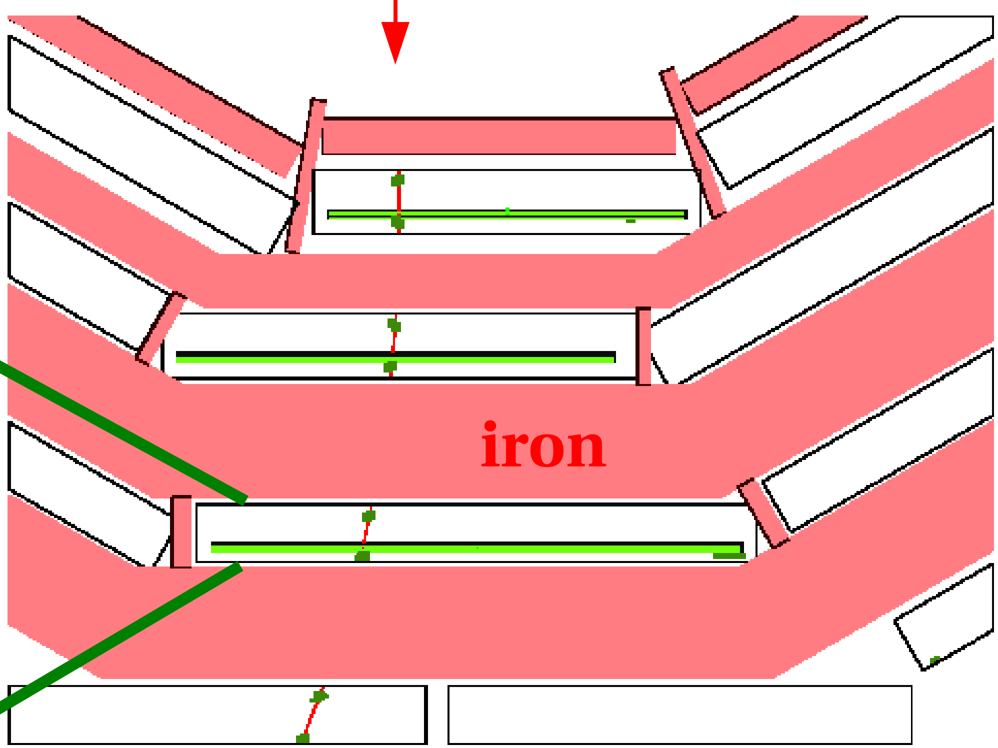
$y \approx \eta$ for $p \gg m$

CMS Muon chambers

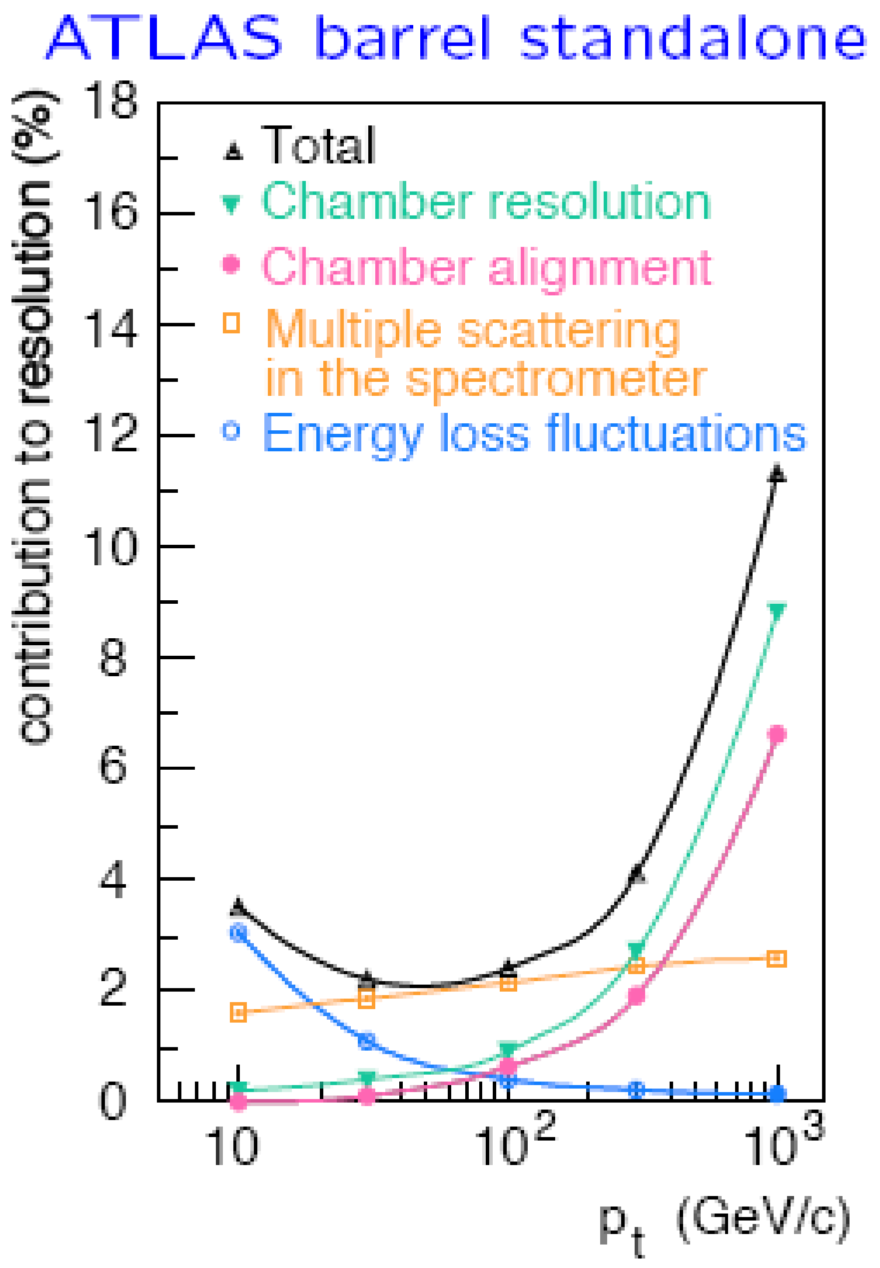


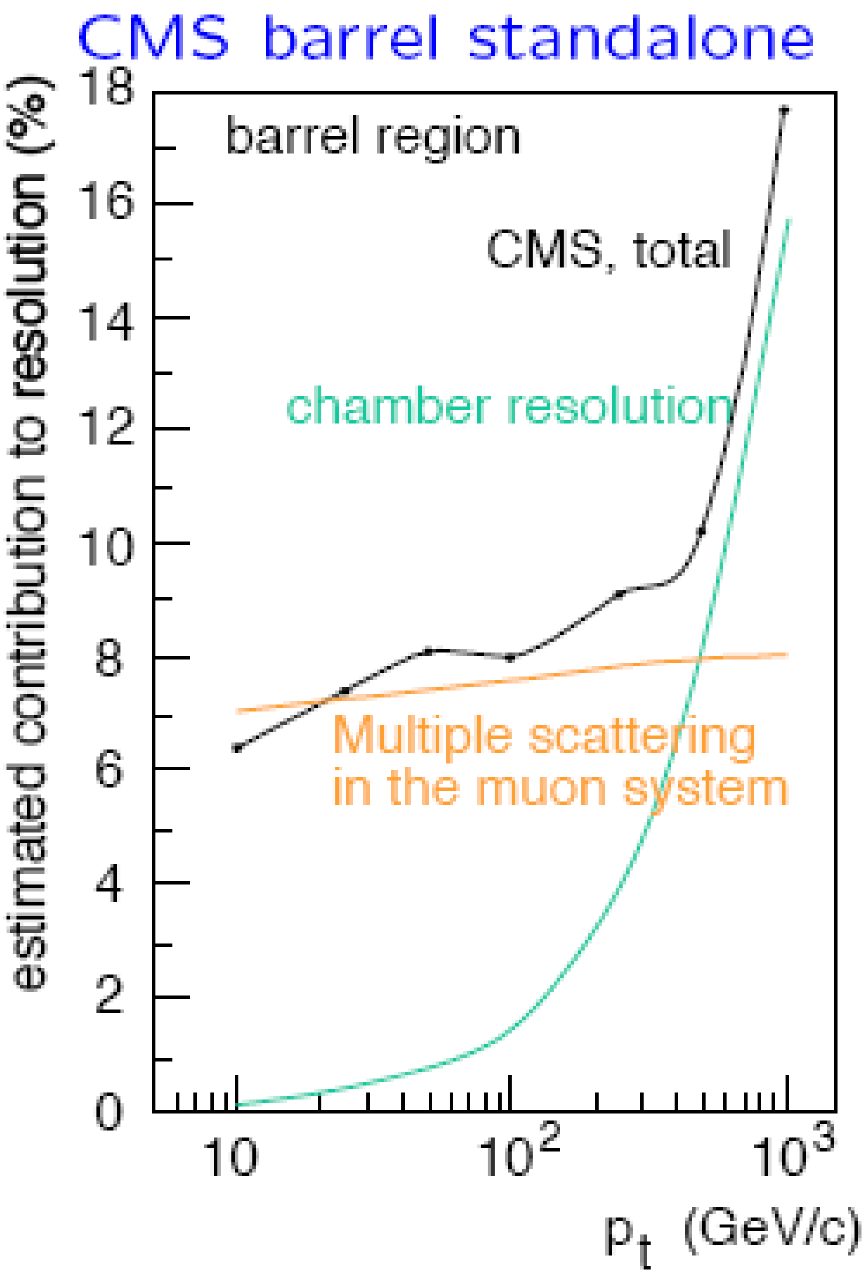


cosmic ray
muon track



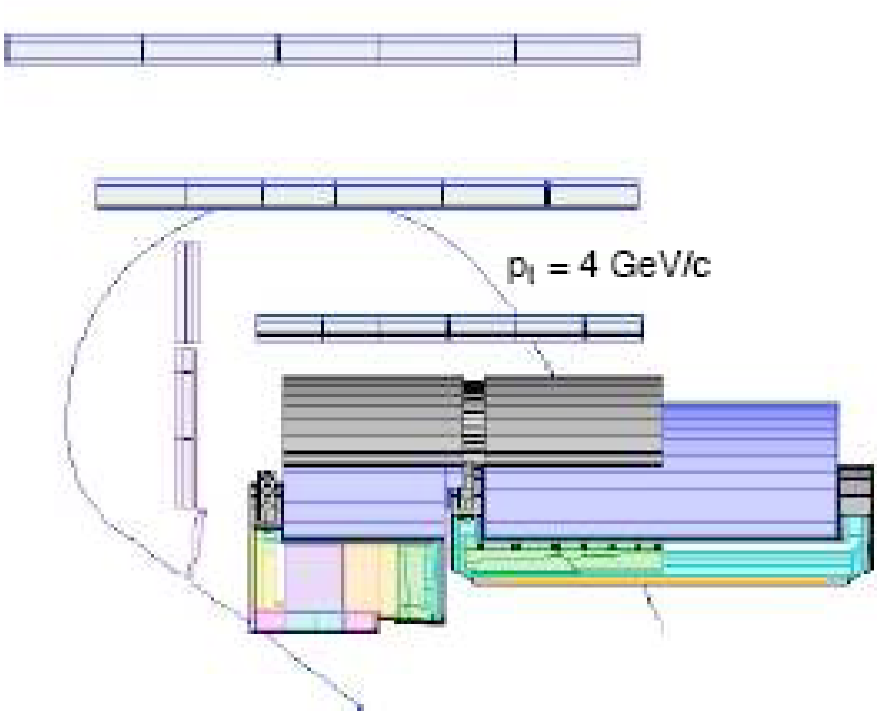
ATLAS and CMS: muon momentum resolution



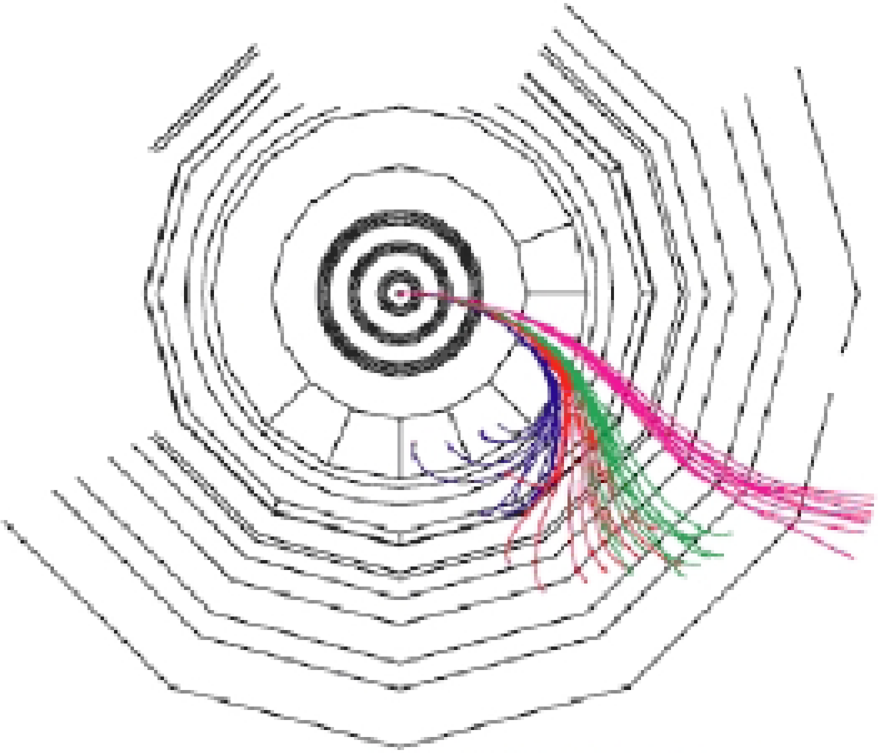


low-p_T muons

ATLAS



CMS

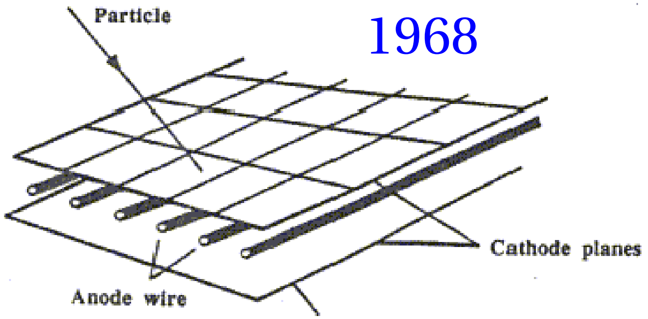


Requirements for muon identification and reconstruction at low p_T

- **Identify track stub in first layer of muon system**
- **Check for minimum ionising signals in last layers of hadron calorimeter**
- **Match as precisely as feasible (within limitations due to large MS and energy loss in calorimetry) measured track in inner detector with track stub in muon system**

Multi-wire proportional chambers MWPCs

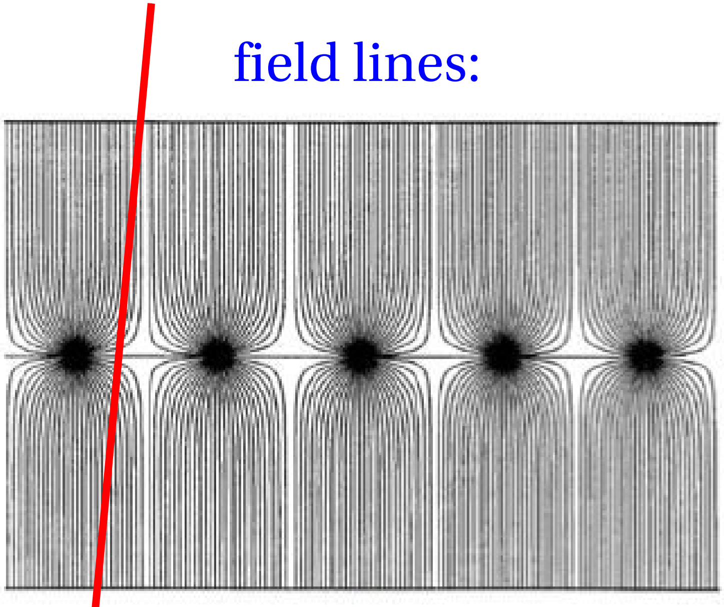
string many anode wires between cathode planes:



1968

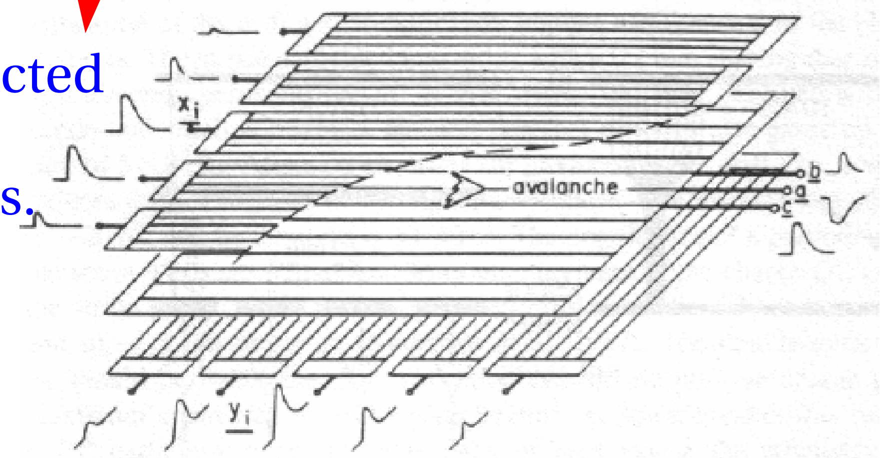
field lines:

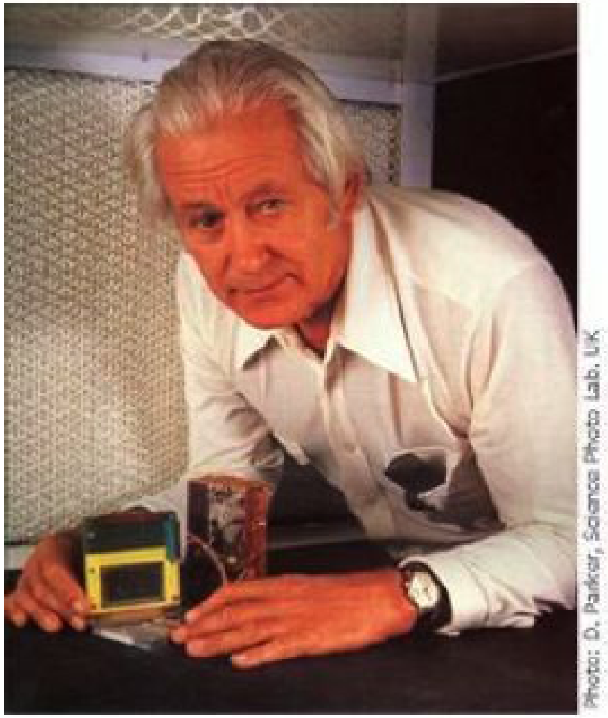
±3 mm. max. drift time can be < 50 ns. Fast!



2 mm wire spacing
resolution ~ 0.5 mm

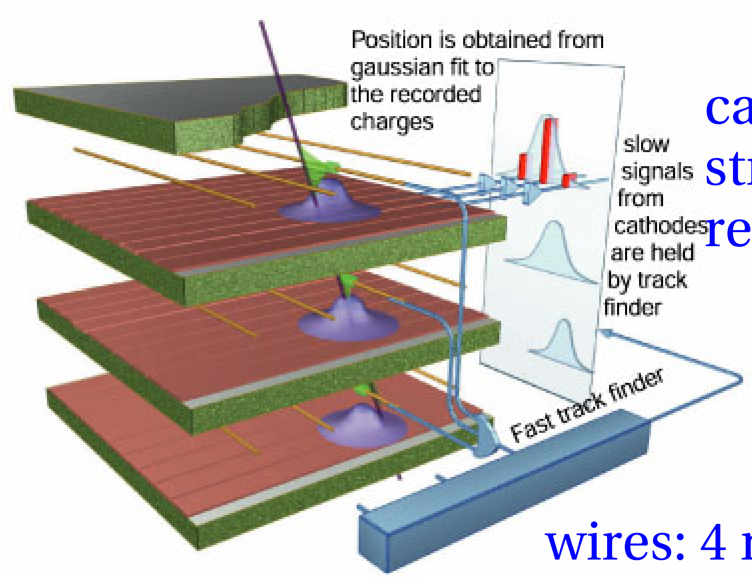
signals can be extracted from the wire and both cathode planes. Cathodes can be segmented.





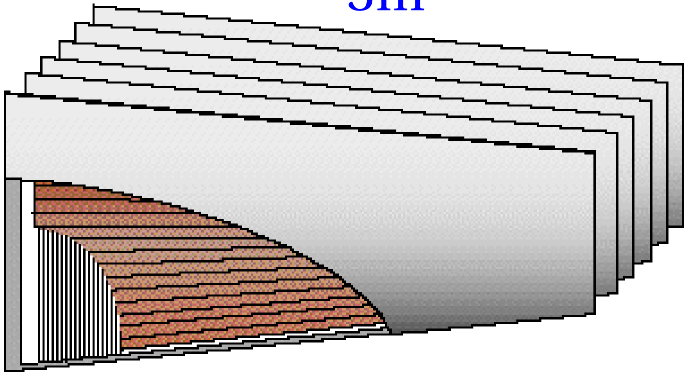
Georges Charpak, CERN
Nobel prize 1992

CMS Cathode Strip Chambers



cathode strips: 0.1 mm resolution.

wires: 4 ns timing for the trigger

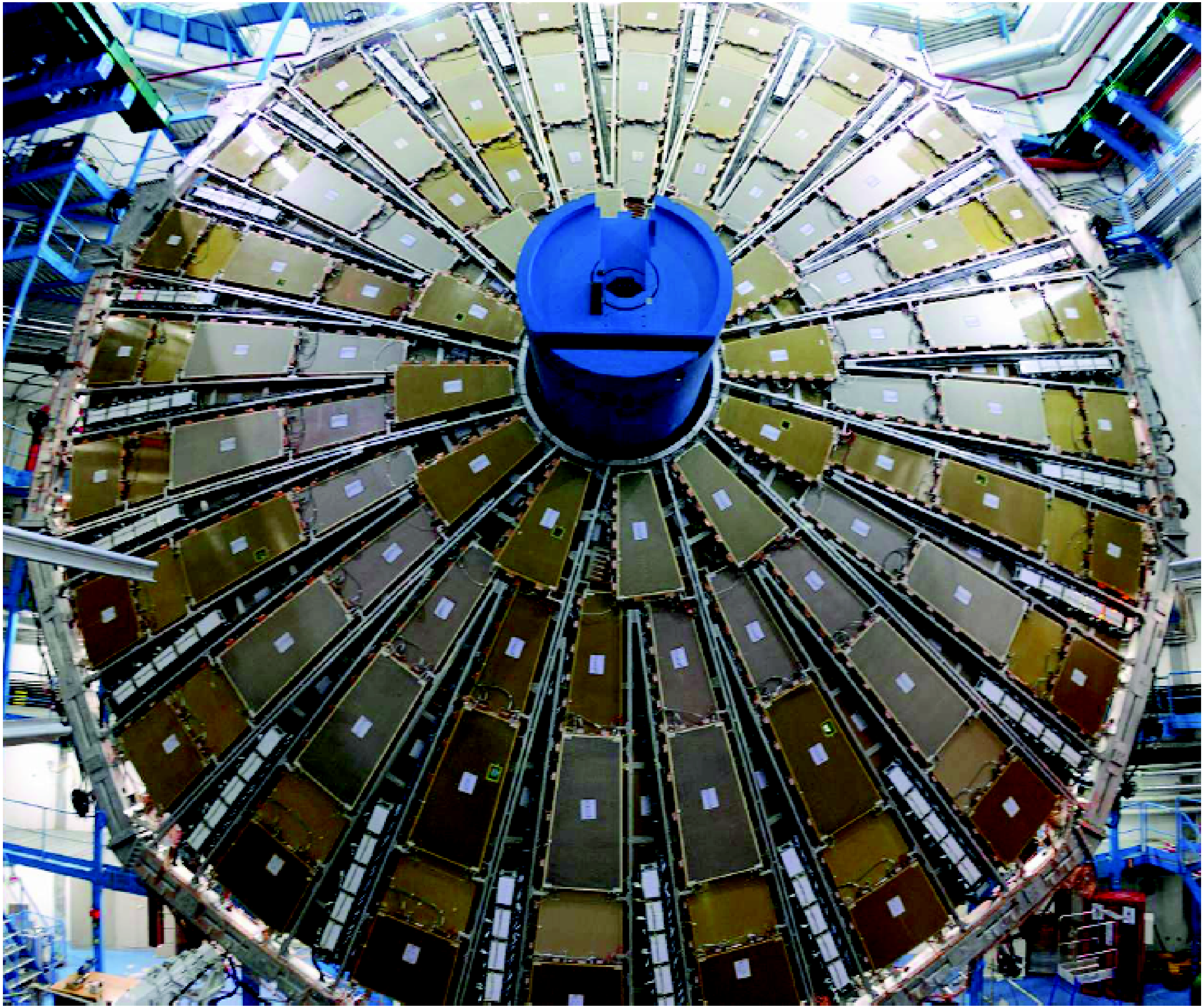


6 planes/chamber
468 chambers

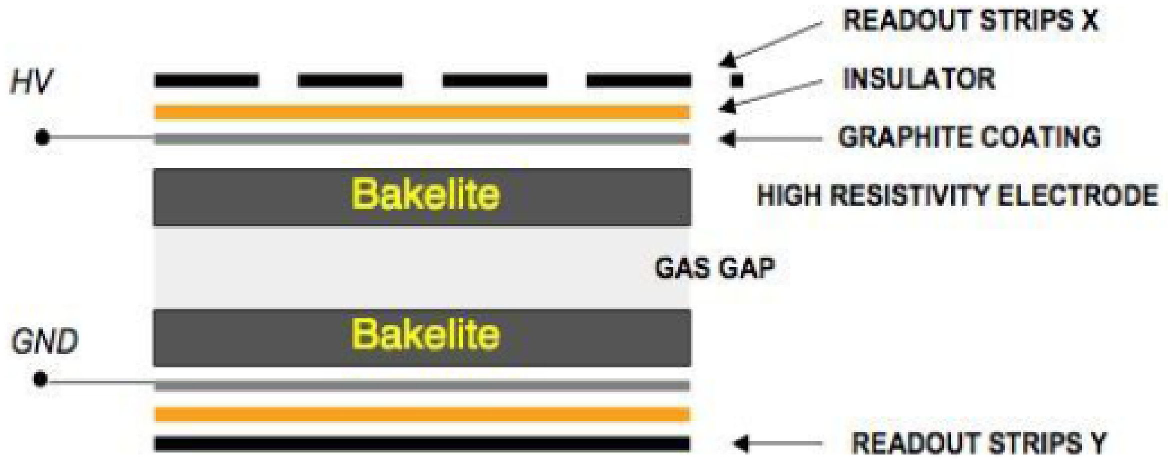
6000 m^2
450k channels

ATLAS muon chamber wheel

Ø25m

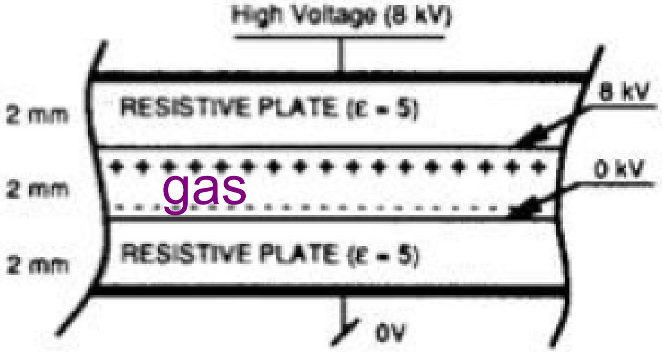


RPC Resistive plate chambers

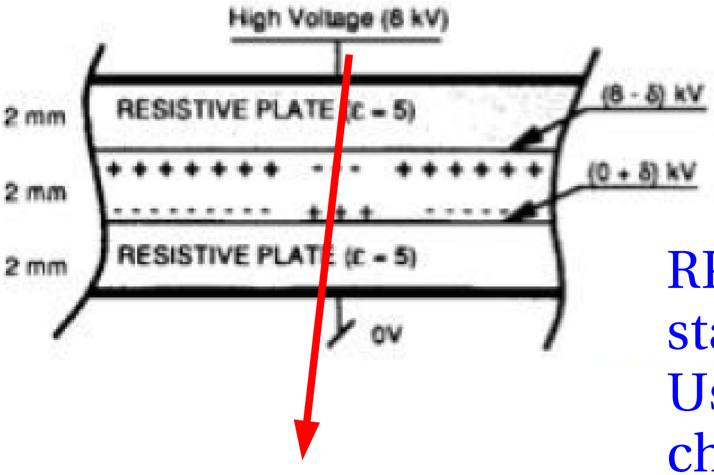


no wires!
2 Bakelite plates separated by a gas gap and 8kV.

Surface charging of electrodes by current flow through resistive plates



a particles causes local discharge which induces signals in the readout strips.



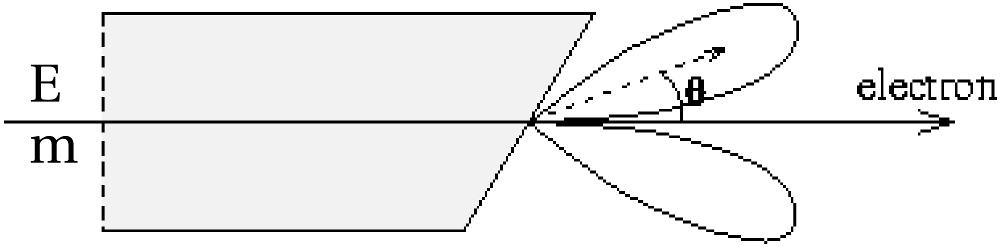
RPCs are fast and stable at high rate.
Used as trigger chambers.

Transition Radiation

- Relativistic particles passing through an interface radiate.

polypropylene
$(C_3H_6)_x$
$\hbar\omega_P = 20$ eV

air
$\hbar\omega_P = 0.7$ eV

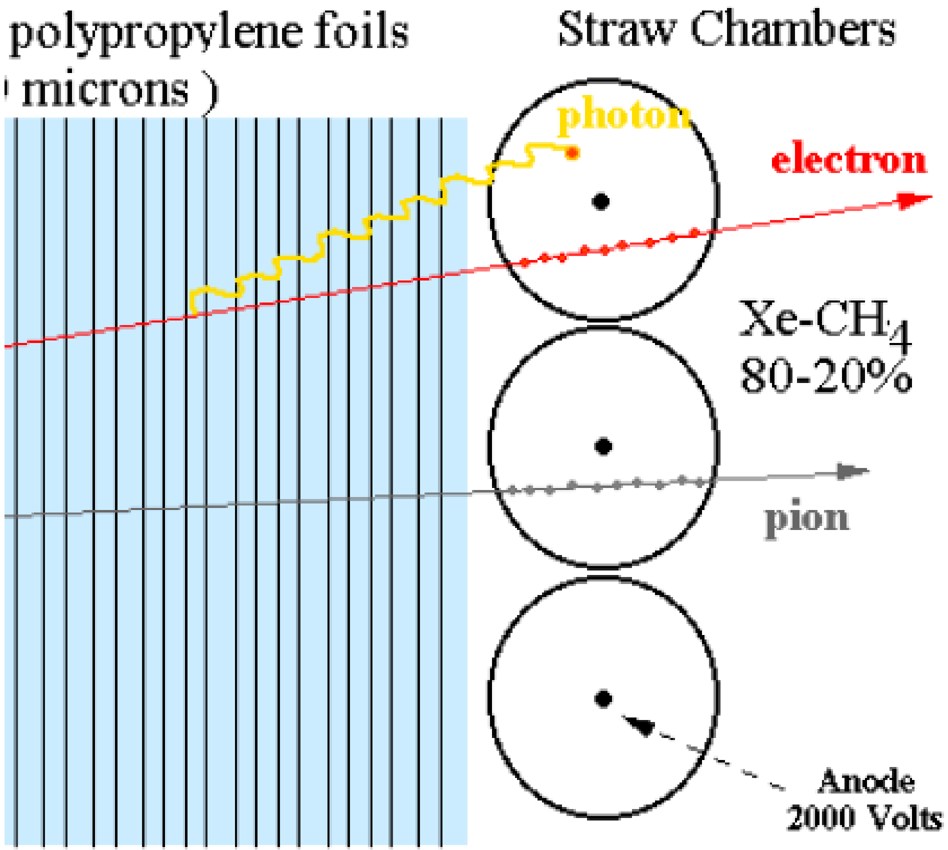


$\gamma = E/m$

$\theta \approx 1/\gamma$

$\hbar\omega \approx$ 10-30 keV
for $\gamma \approx$ 10'000
$N \sim \gamma\ \hbar\omega_P$
depends on particle!

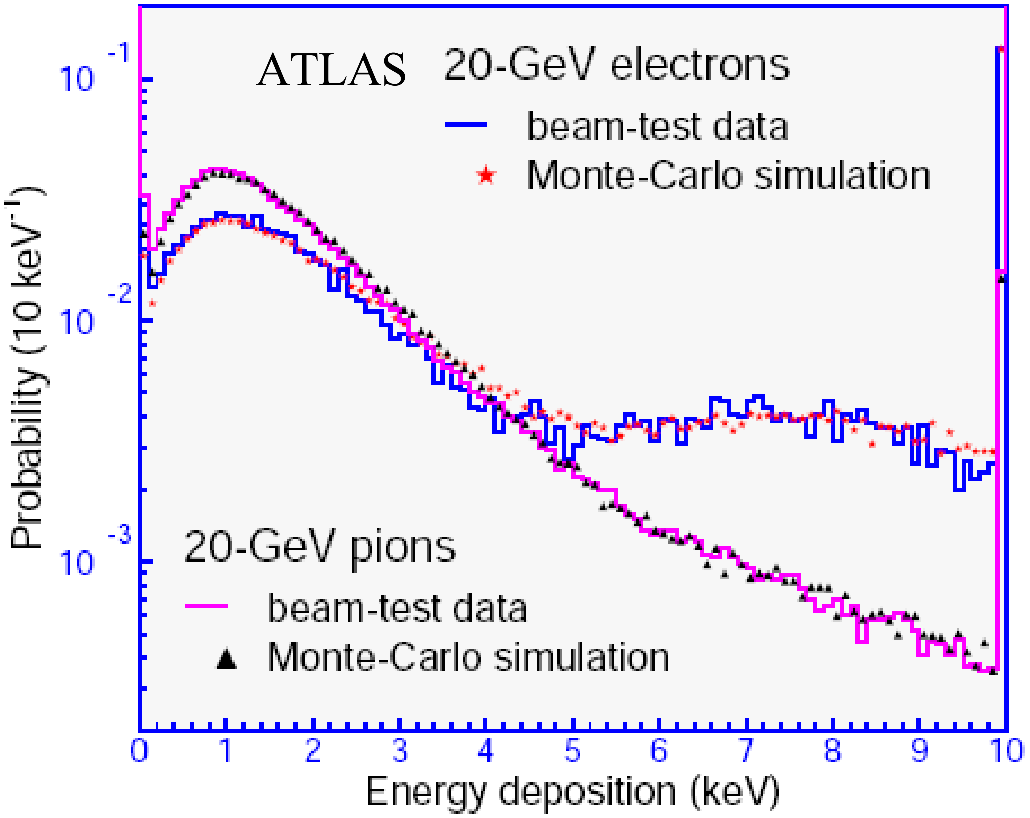
$$\frac{d^2W}{d\omega d\theta} = \frac{2\alpha\theta^3}{\pi}\left(\frac{1}{\frac{1}{\gamma^2}+\theta^2+\frac{\omega_1^2}{\omega^2}} - \frac{1}{\frac{1}{\gamma^2}+\theta^2+\frac{\omega_2^2}{\omega^2}}\right)^2$$

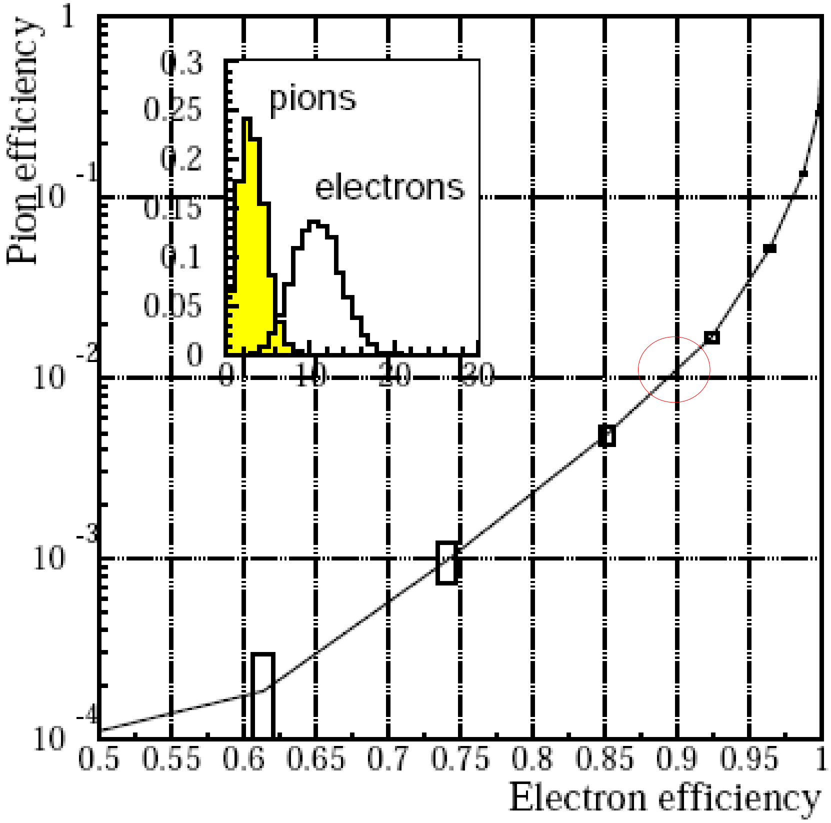


1% probability per foil

Xe gas to absorb X-ray.

e/π separation using TRT

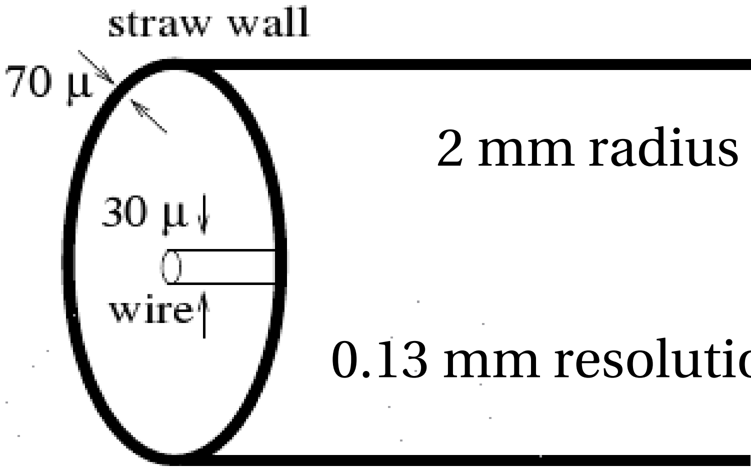




pion reduction by factor 75
for 90% electron efficiency

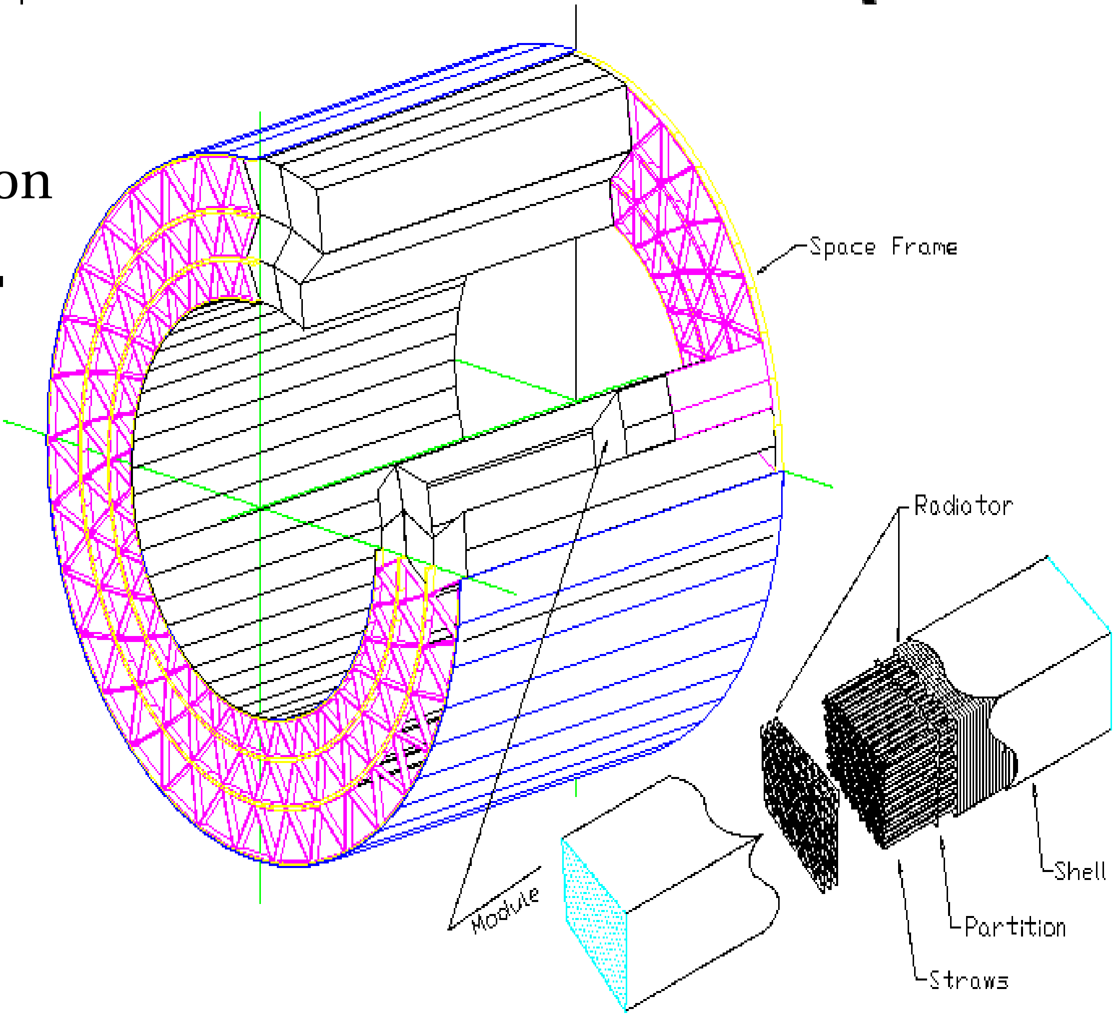
ATLAS Transition Radiation Tracker

built from straw tubes:



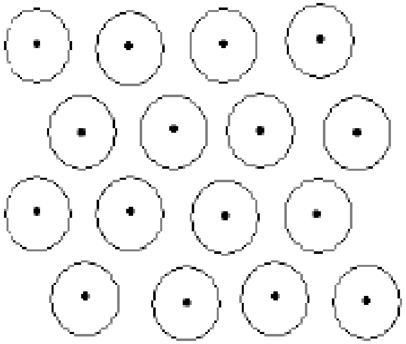
2 mm radius

0.13 mm resolution



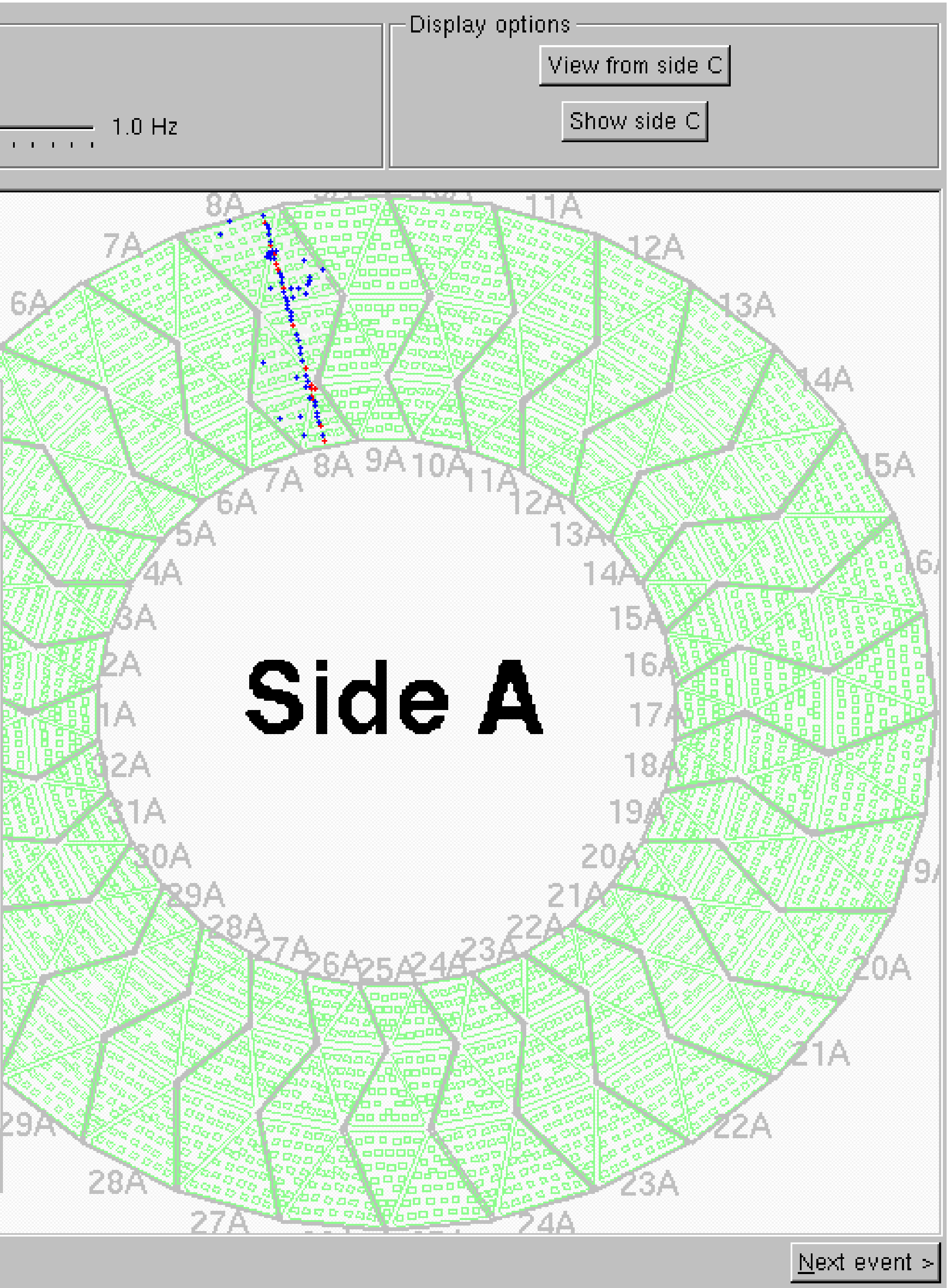
Straw gas mixture :

Xe(70%) CO2(27%) O2(3%)



Radiator foils are placed between the straws

First cosmic ray event seen in the Barrel TRT!



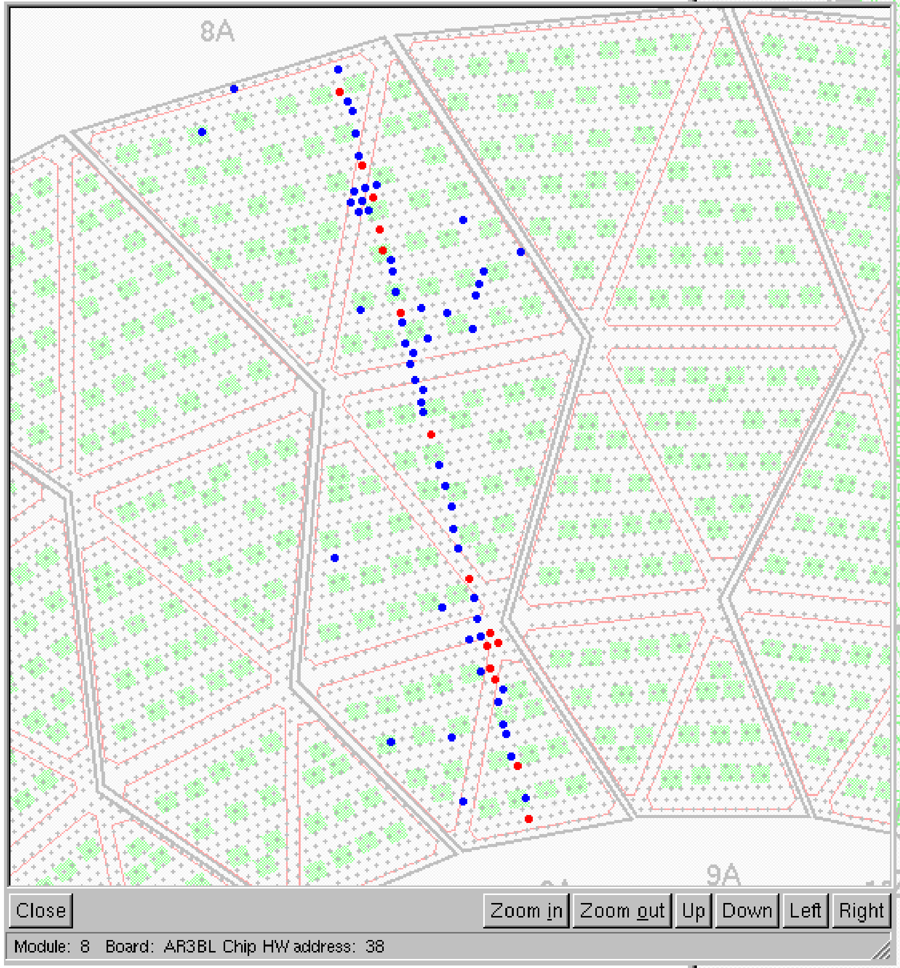
Refresh mode

● By event

○ Rate

1.0 Hz

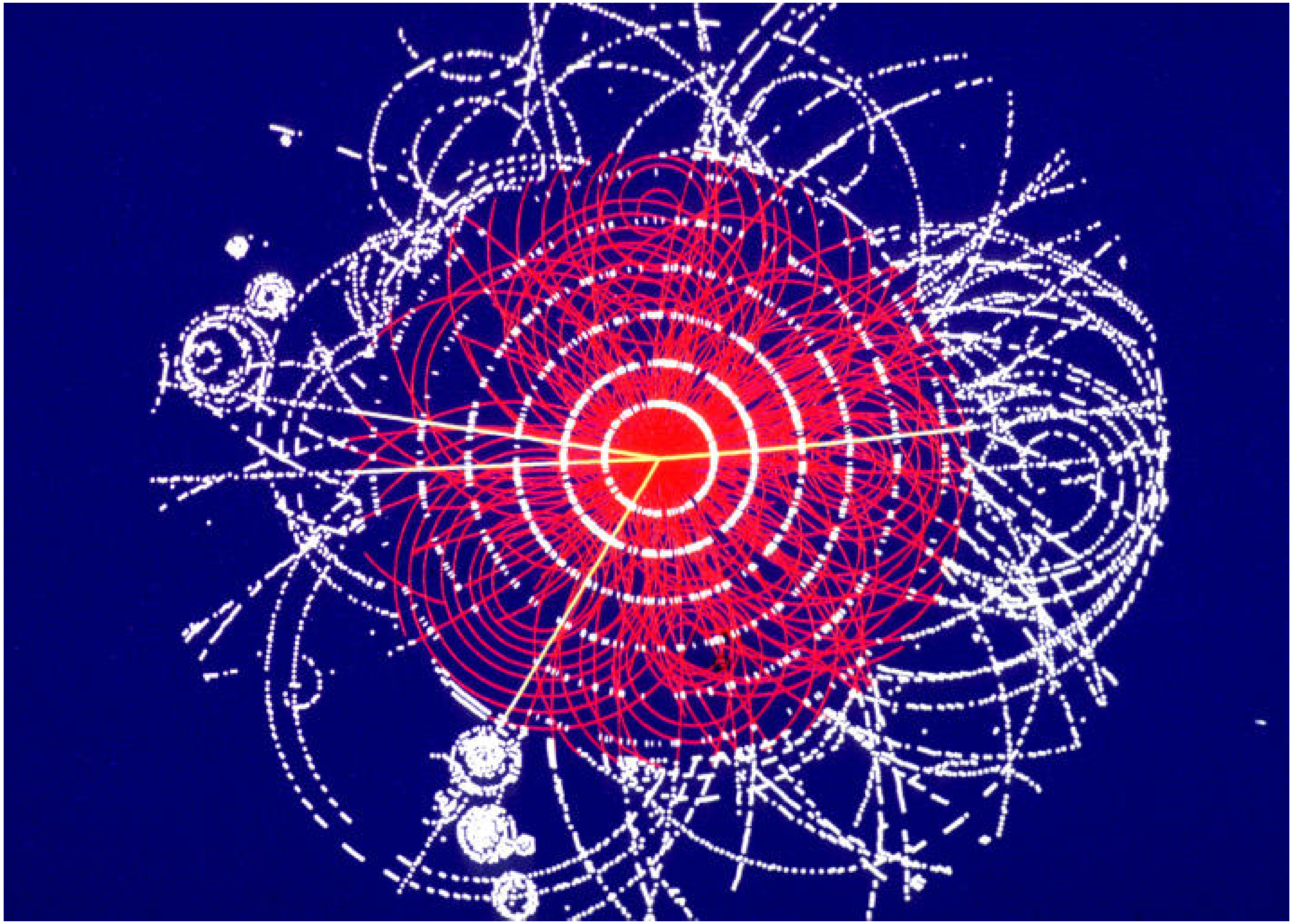
Display options



Module: 8 Board: AR3BL Chip HW address: 38

D. Pitzl, DESY

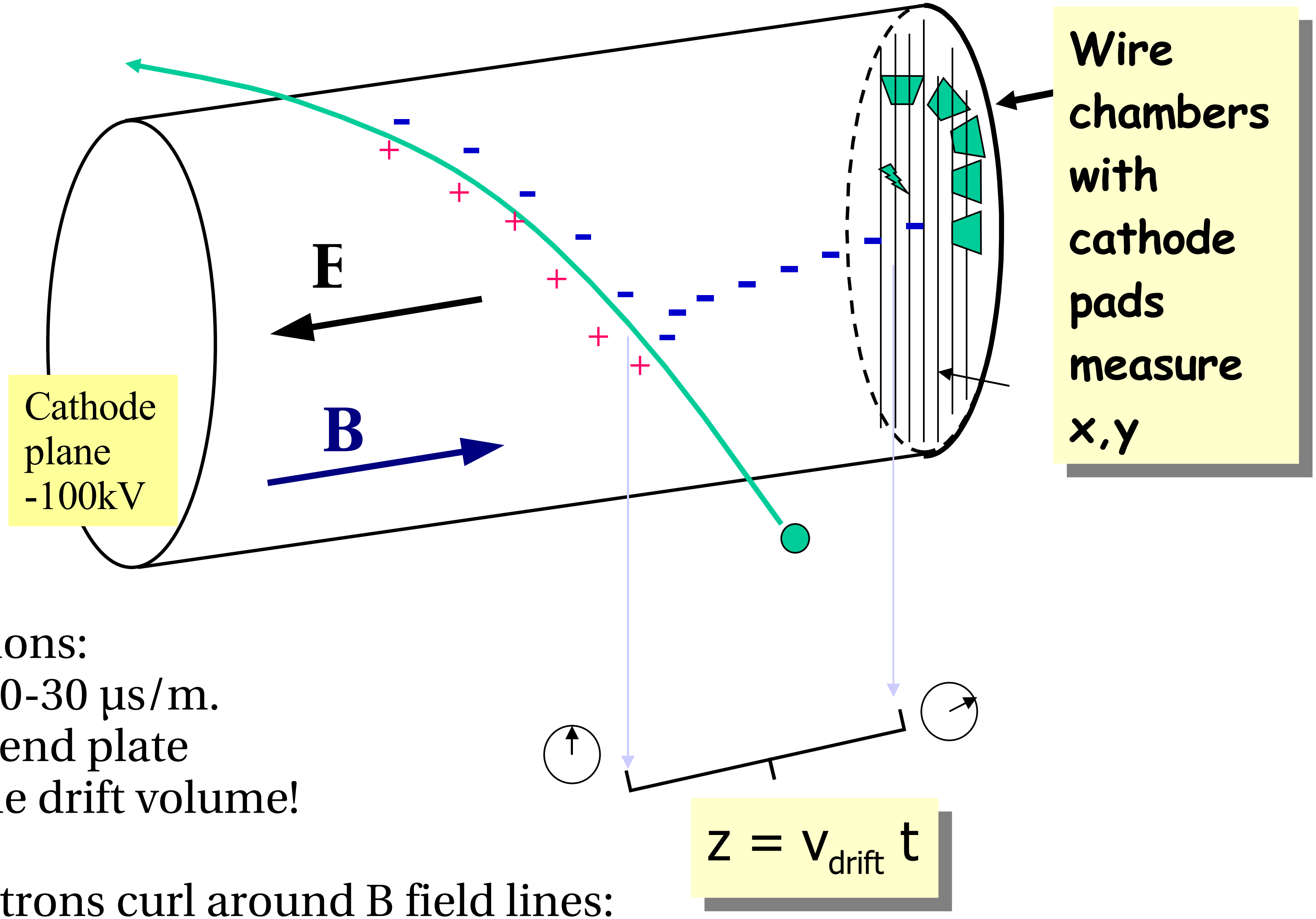
ATLAS inner tracking: silicon and straws



red = tracks found in the silicon layers.

white = hits in the straw tubes.
36 hits/track:
good for pattern recognition.

Time Projection Chamber in a solenoid field



Cathode plane -100kV

Wire chambers with cathode pads measure x,y

$z = v_{drift}\, t$

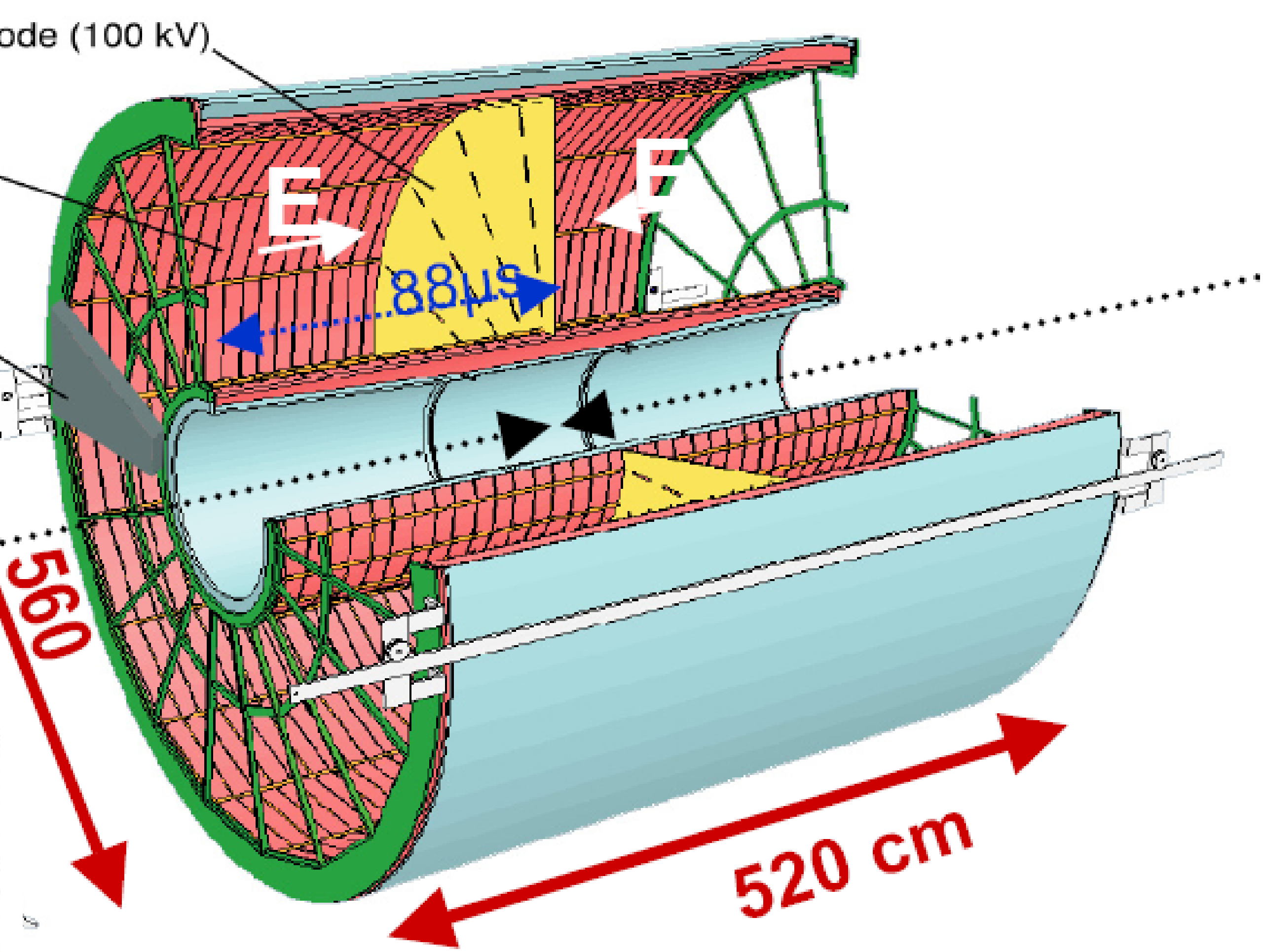
Separate two regions:

- ☐ Drift along z: 20-30 µs/m.
- ☐ Amplify at the end plate

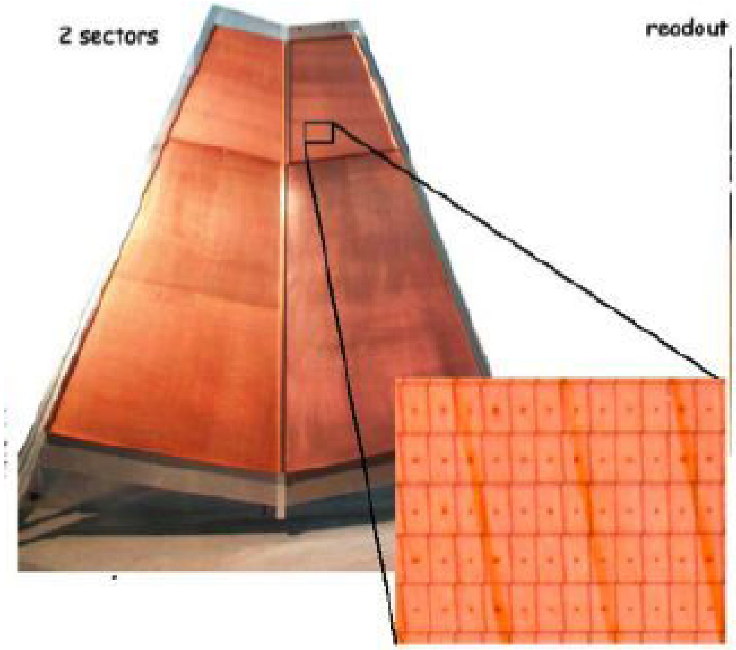
No material inside drift volume!

E||B: drifting electrons curl around B field lines: limited spread.

ALICE TPC

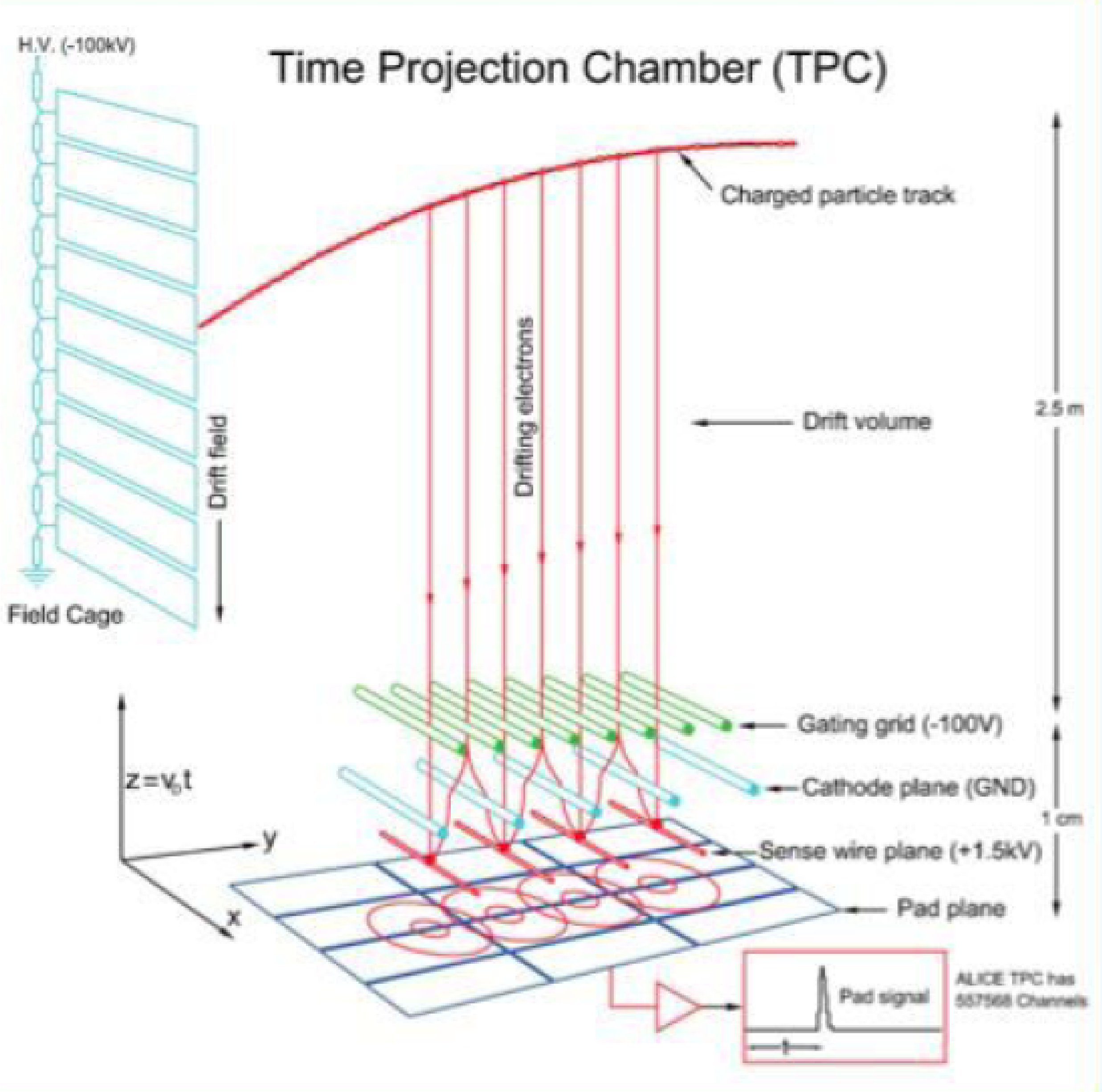


readout:



max. drift time 88 µs.
LHC operates with low luminosity
at ALICE (pp and PbPb).

TPC


H.V. (-100kV)
Time Projection Chamber (TPC)
Charged particle track
Drifting electrons
Drift field
Drift volume
2.5 m
Field Cage
Gating grid (-100V)
Cathode plane (GND)
$z=v_D t$
y
x
1 cm
Sense wire plane (+1.5kV)
Pad plane
Pad signal
t
ALICE TPC has
557568 Channels

Energy loss of charged particles in matter

- Charged particles loose energy in collisions with electrons in matter:

Bethe-Bloch:

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

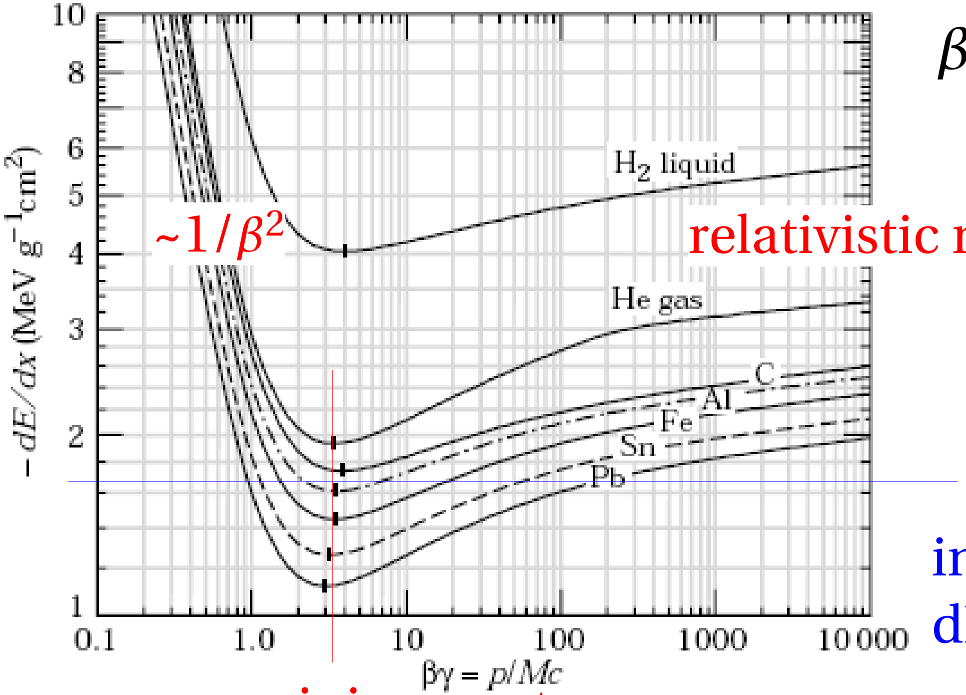
medium

particle

ionisation potential

density correction

dE/dρx



~$1/\beta^2$

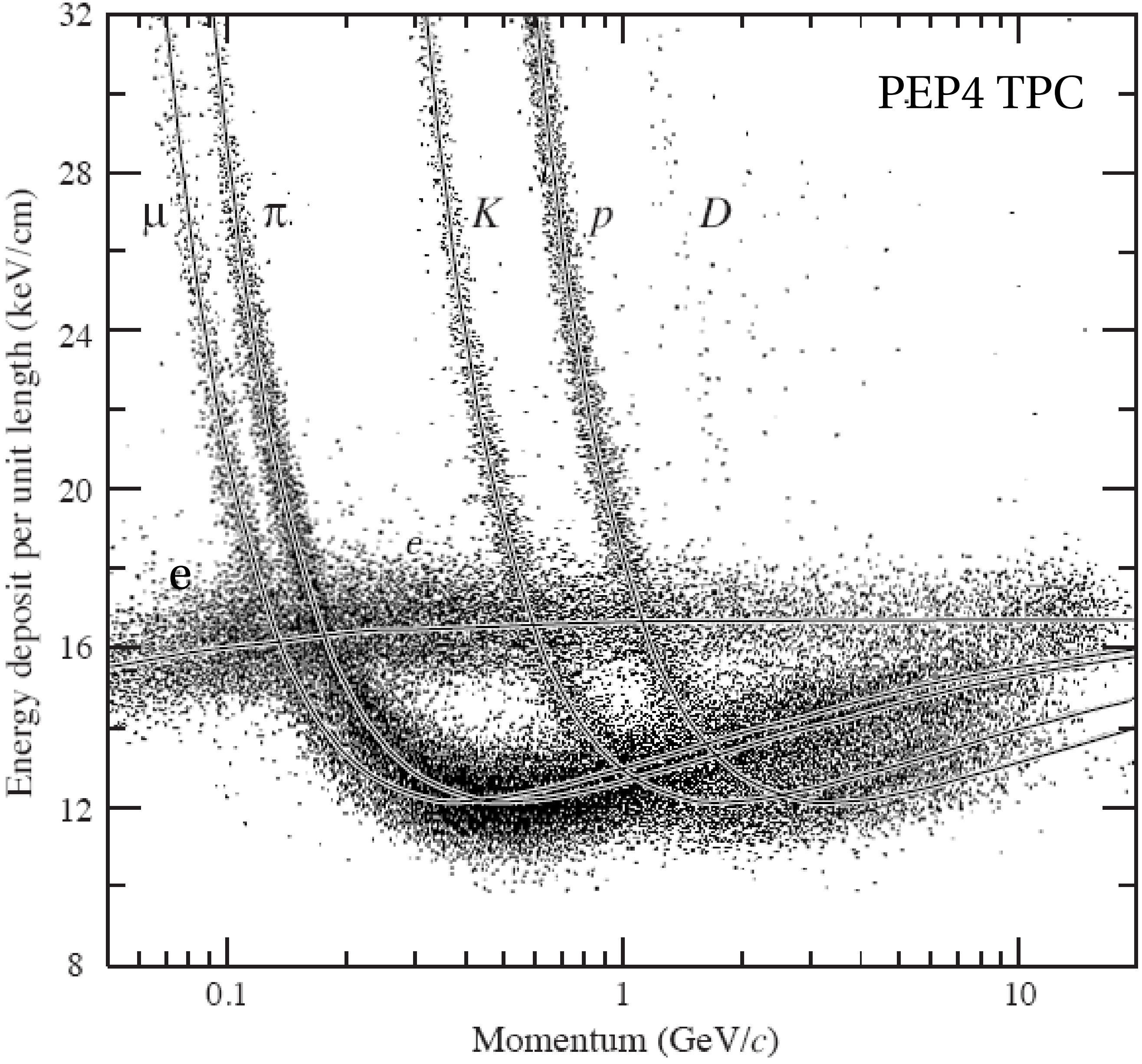
relativistic rise ~ln(γ)

minimum at
p/m ≈ 3.5 for all particles

$$\beta = \frac{v}{c} = \frac{cp}{E}, \gamma = \frac{E}{mc^2}, \ \beta\gamma = \frac{cp}{mc^2}$$

in iron (ρ=7.9 g/cm^3):
dE/dx = 1.3 GeV/m.

dE/dx Data



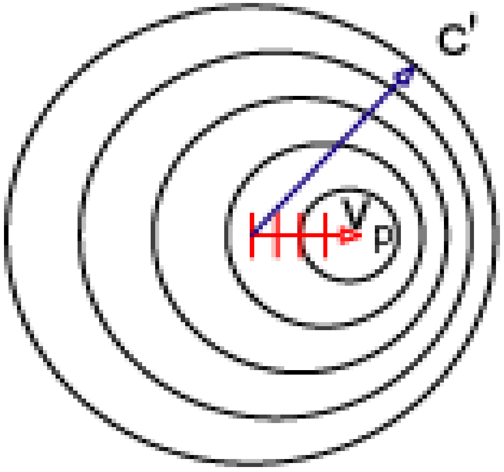
<dE/dx> averaged over many samplings: $\sigma \sim \sqrt{N}$.

good for particle identification at low momenta.

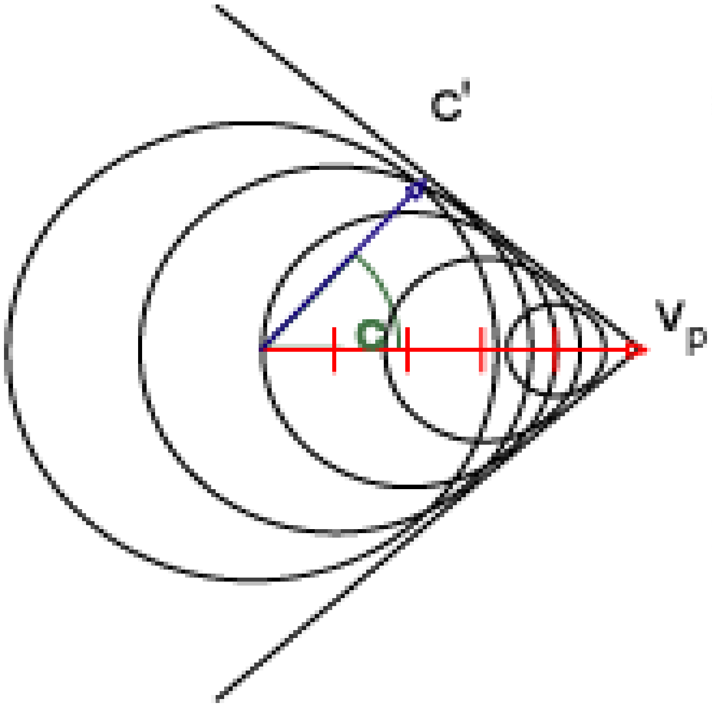
Cerenkov Radiation

Cherenkov-Effect:
A charged particle moving faster than the speed of light in a medium $v > c/n$ emits Cherenkov radiation.

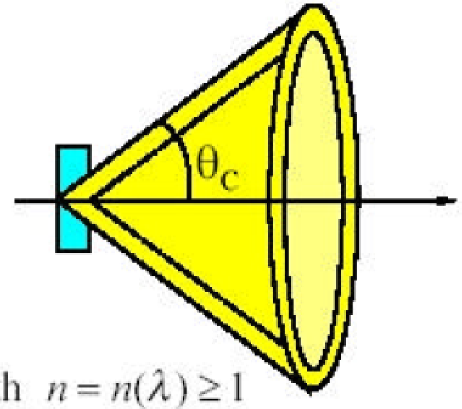
Emission of a coherent wave front: $\cos\theta_C = 1/(\beta n)$



$v_p < c'$



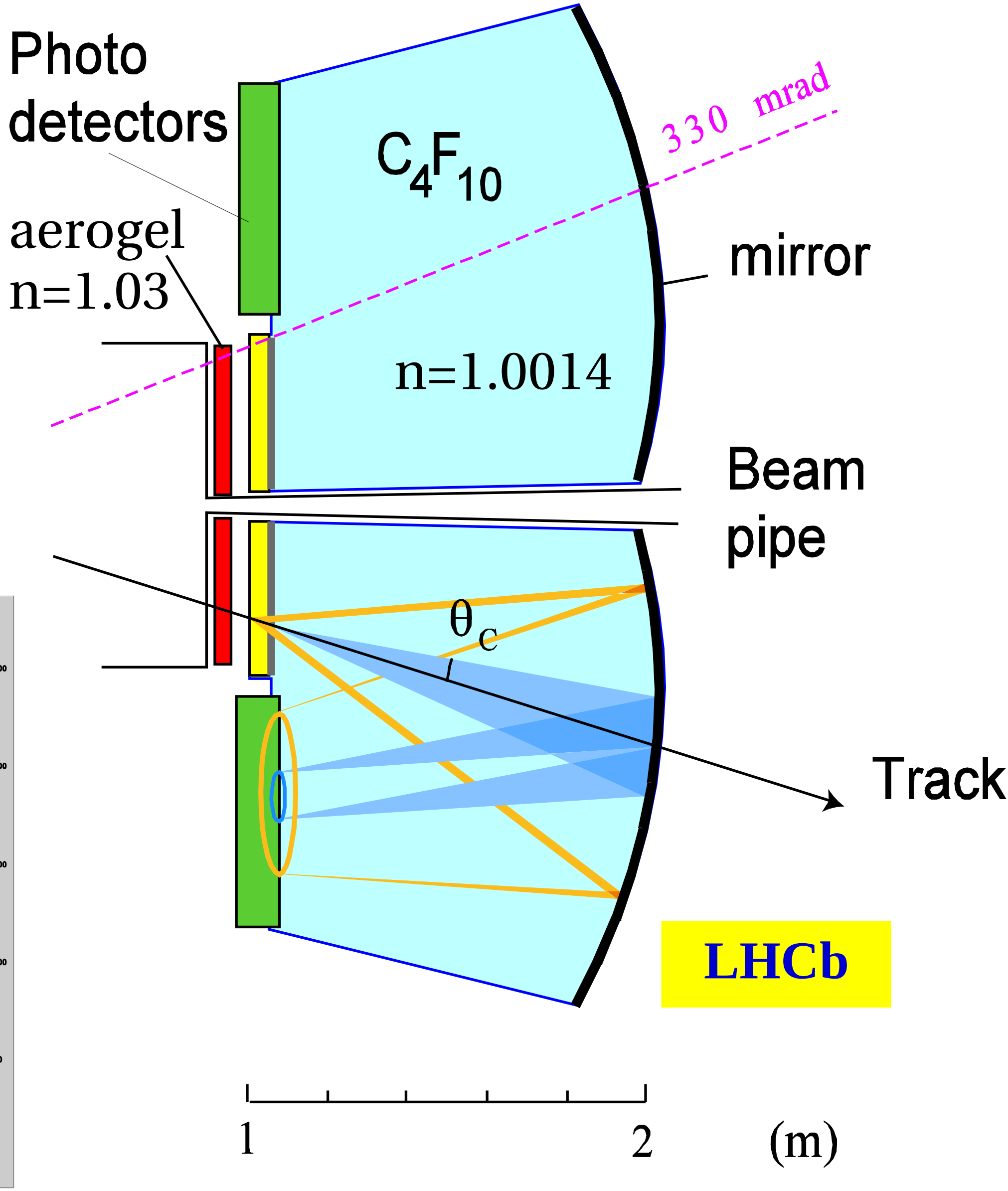
$v_p > c'$

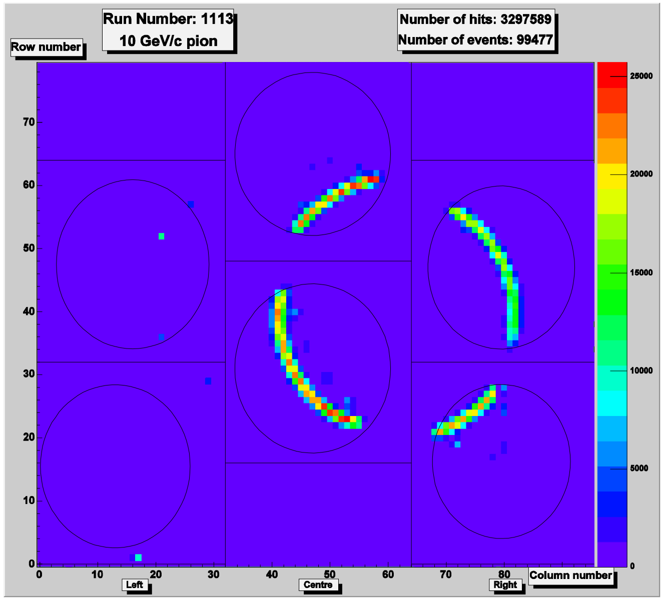


with $n = n(\lambda) \geq 1$

LHCb Cerenkov Detector

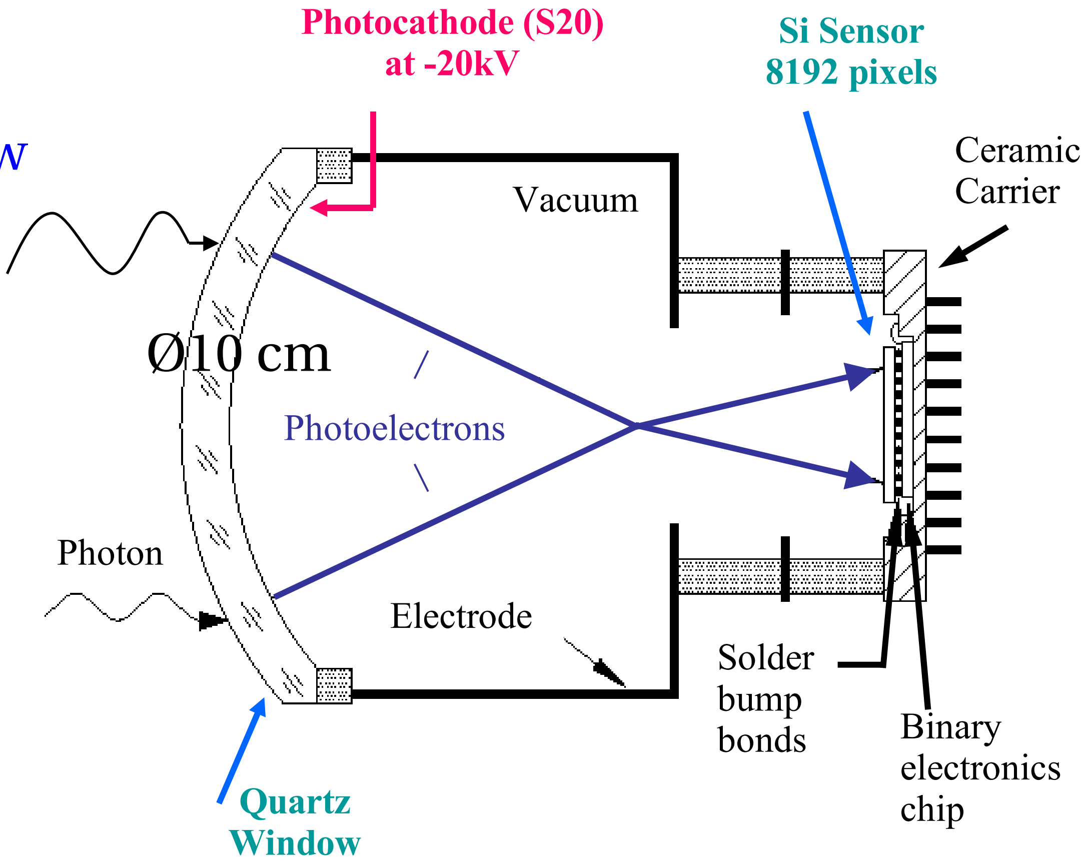
The Cherenkov cone is imaged into a ring at a position-sensitive photon detector.
Ring radius -> Cherenkov angle
-> particle velocity.
Together with momentum measurement:
determine particle mass.
Good for π – K- p separation.

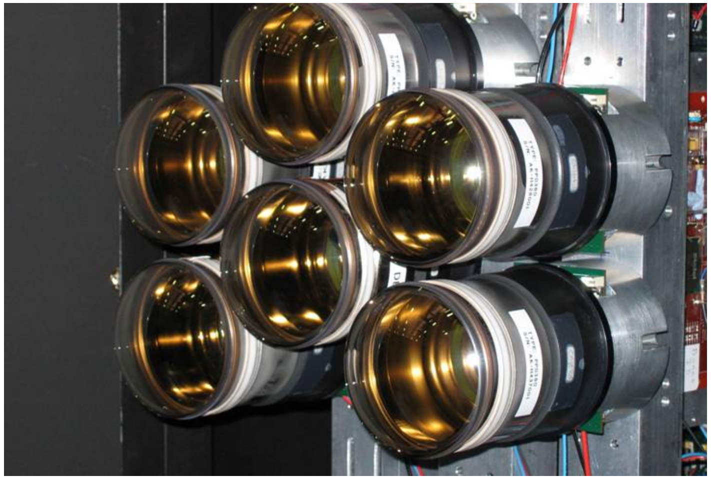




Hybrid photon detector HPD

- A Cherenkov photon reaches the multialkali-coated quartz window of an HPD.
- A photoelectron is released, and is accelerated toward the silicon array by a 20kV potential.
- The photoelectron creates around 5,000 electron-hole pairs in the silicon.
- The silicon array has 1024 pixels for position measurement.
- Readout is by a bump-bonded amplifier and discriminator chip.





Summary

- Drift detectors
- muons systems
- MWPC, CSC, RPC
- transition radiation
- TPCs
- Bethe-Bloch dE/dx
- Cherenkov and HPDs