Vertex and Tracking detectors

position and momentum measurement

Where do we stand

- What have we done so far:

Introduction to HEP detectors

Interaction of Particles with Matter

Physics of detection

Gaseous detectors

Scintillators detectors

Solid state detectors

Detection principles / materials

Introduction to Synchrotron Radiation detectors

Readout Electronics

We know how to detect particles
How do we build a detector for a specific meas.?

Vertex and Tracking

Calorimetry (electrons and photons)

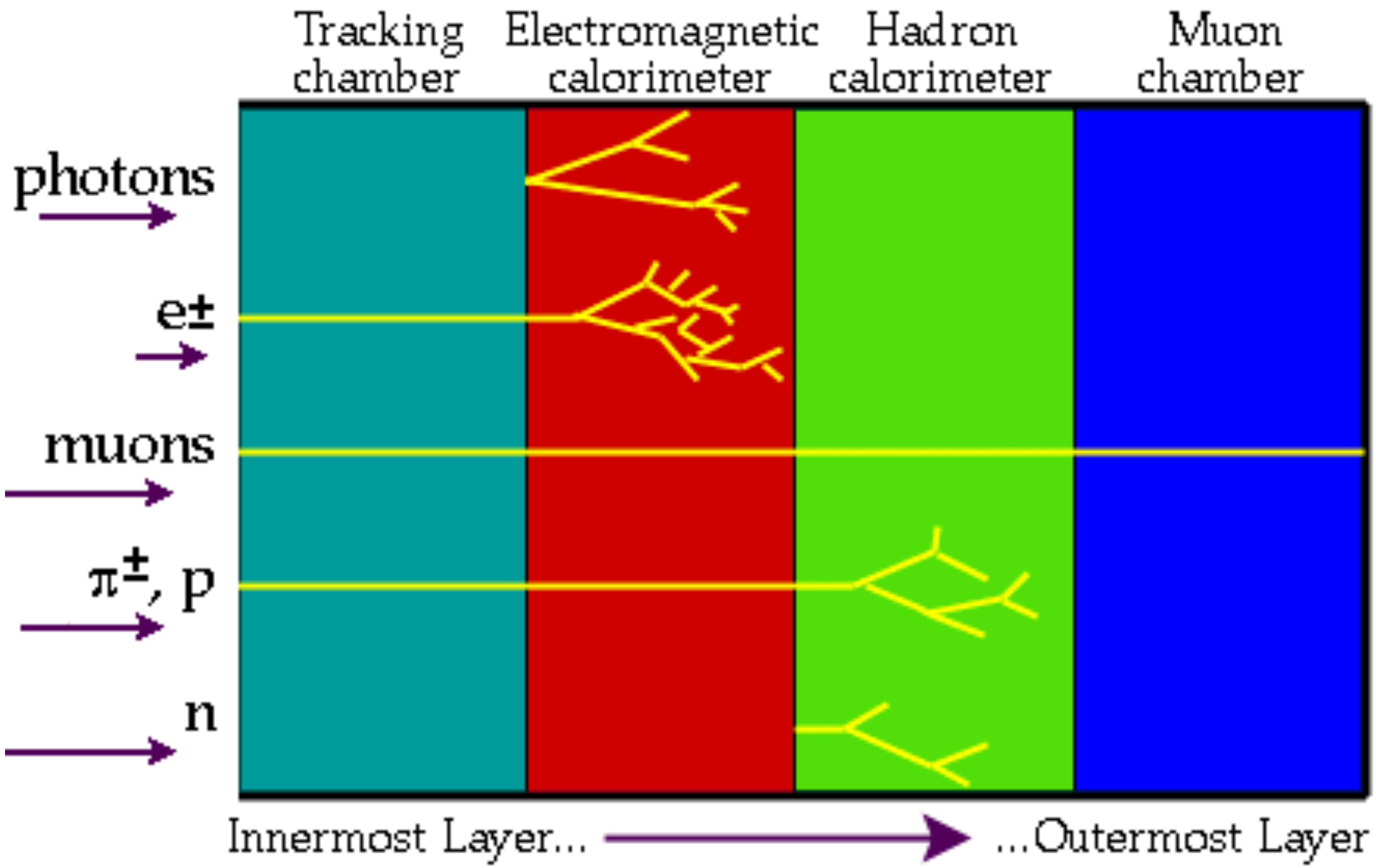
Calorimetry (charged hadrons and neutrons)

Particle Identification

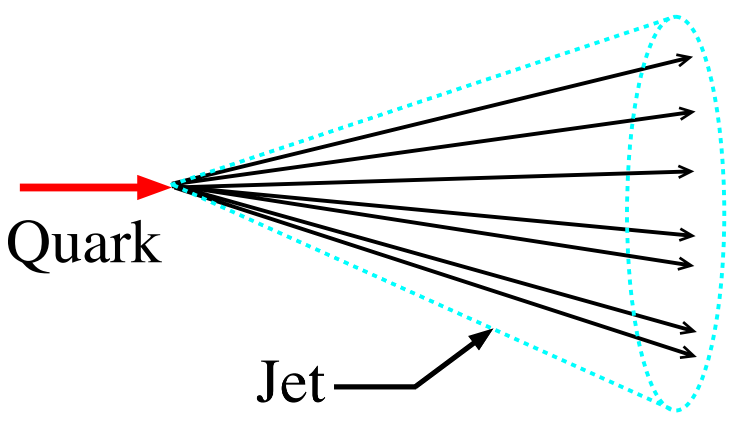
Detector systems

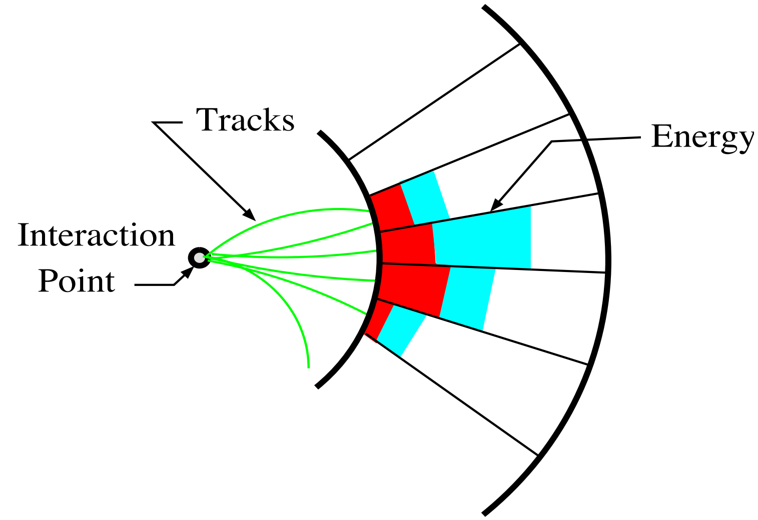
Measurements of specific particle observables

Brief recap on particles



“ jets ”

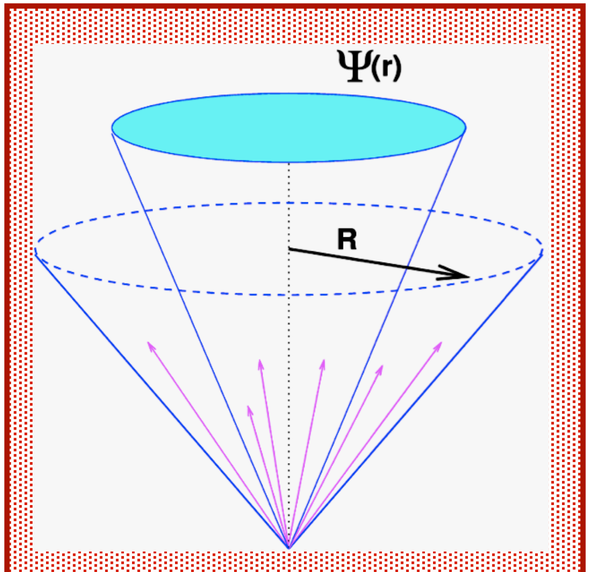




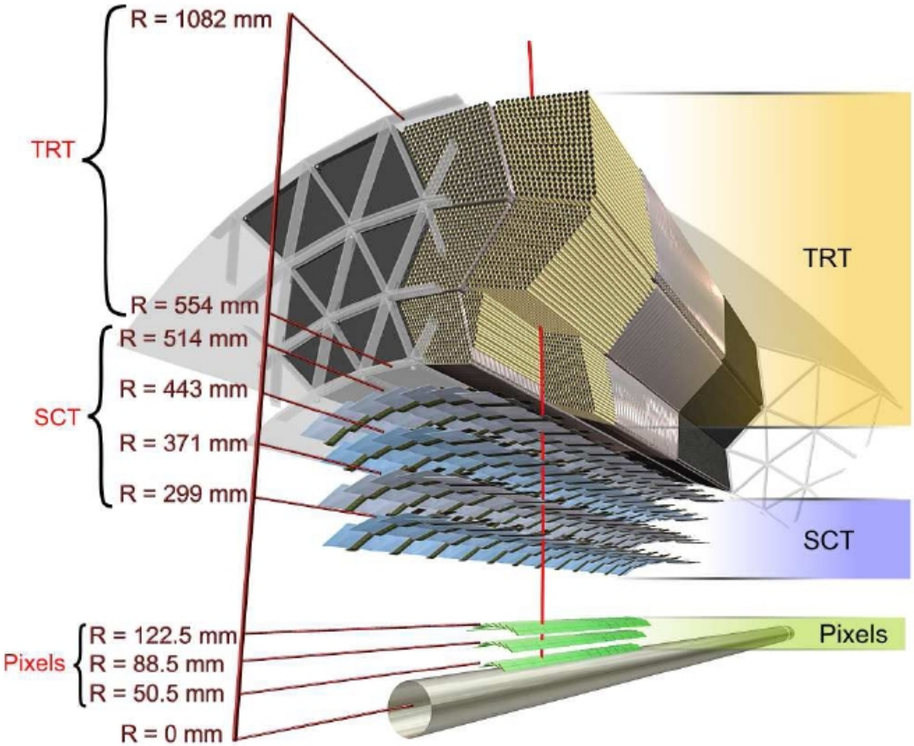
Jet (jet) *n.* a collimated spray of high energy hadrons

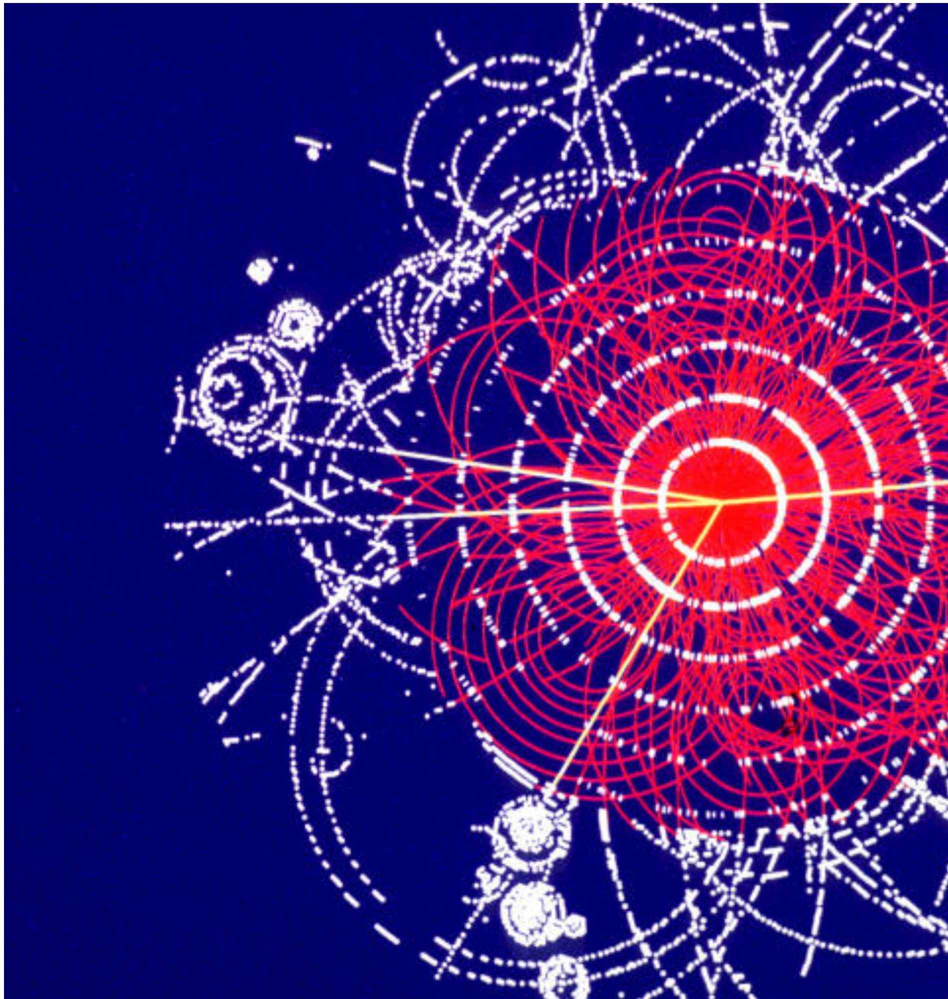
Quarks fragment into many particles to form a jet, depositing energy in both calorimeters.

Jet shapes narrower at high E_T.



Vertex and tracking detectors

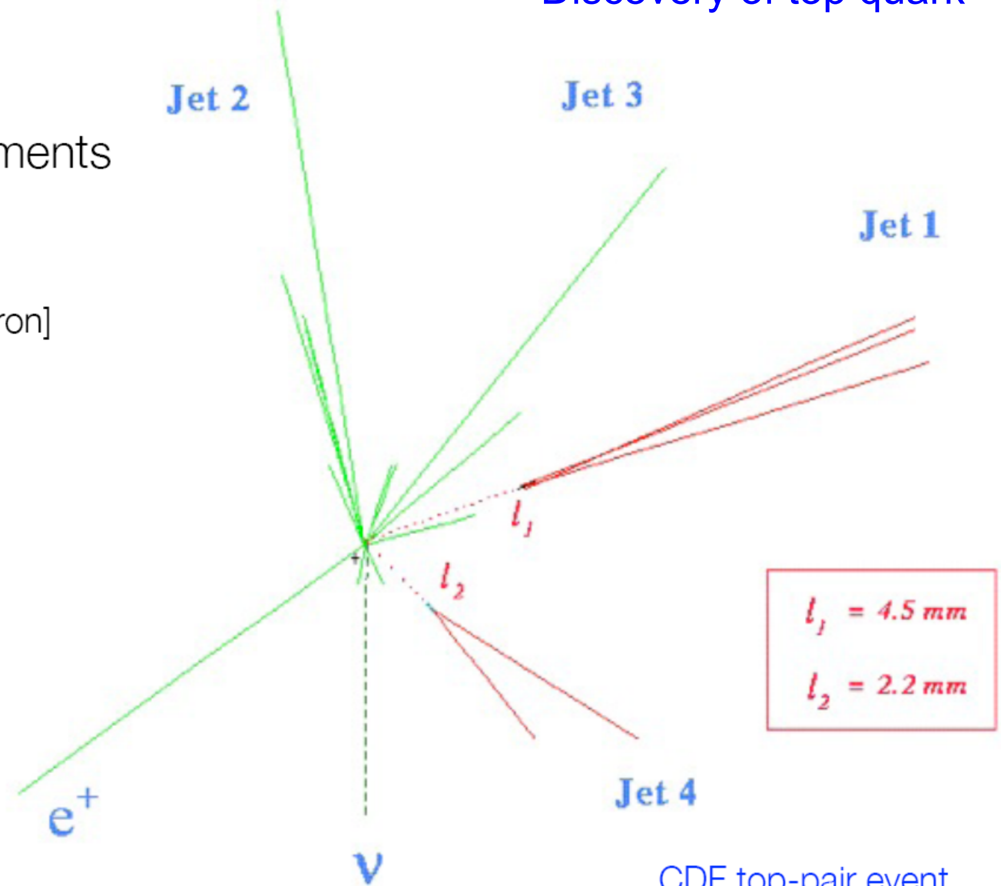




typical accuracy of:
~ 100-150 microns/straw
~ 20-30 micron/silicon strip
~5-15 micron/pixel

Position sensitive detectors

Discovery of top quark



Motivation:

b-Quark tagging & life time measurements
via secondary vertex finding ...

e.g.:

$$p\bar{p} \rightarrow t\bar{t} + X \qquad \text{[Tevatron]}$$
$$\hookrightarrow b\bar{b}W^+W^-$$

$$pp \rightarrow H + X \qquad \text{[LHC]}$$
$$\hookrightarrow b\bar{b}$$

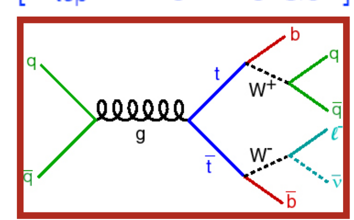
Typical lifetime: $\tau = 10^{-12} \ldots\ldots 10^{-13}$ s

$$\gamma c\tau = \gamma \cdot 3 \cdot 10^{10}\ \mathrm{cm/s} \cdot 10^{-13}\ \mathrm{s}$$
$$= \gamma \cdot 30\ \mu\mathrm{m} \qquad [\gamma \sim 100]$$
$$\sim 3\ \mathrm{mm}$$

Thus:

To measure lifetime in picosecond regime
one needs spacial resolution of the order of 5 - 30 µm ...

CDF top-pair event
[M_{top} = 170 ± 10 GeV]



Position sensitive detectors

Principle:

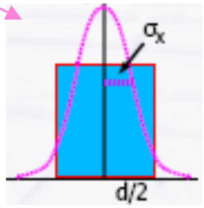
Segmentation
into strips, pads, pixels ...

Typical parameters:

Thickness: 150 - 500 µm
Strip separation (pitch): 20 - 150 µm
Resolution: 5 - 40 µm (pitch/√12)

Charge collection: 20 ns
Charge integration: 120 ns

Operation voltage: 160 V

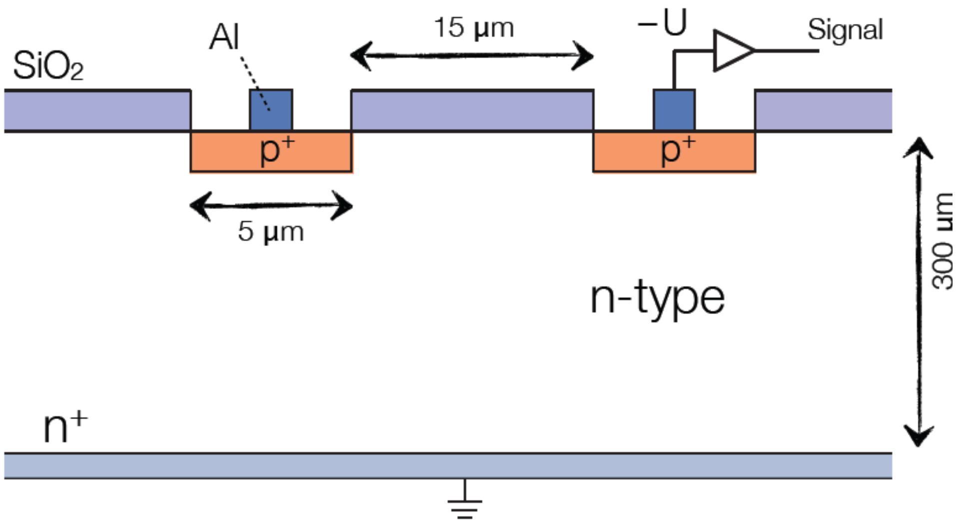


width of an Gaussian distribution equivalent to a "flat" probability distribution with 1mm pitch

Output signal:

Total charge: Q_{out} ~ 4 fC

Average energy loss of MIP: 300 eV/µm; Si: 3.6 eV/pair.
Thus 80 electron-hole pairs per µm;
300 µm thickness ➝ 25000 pairs/MIP



Schematics of
Silicon Strip Detector

[from 1983]

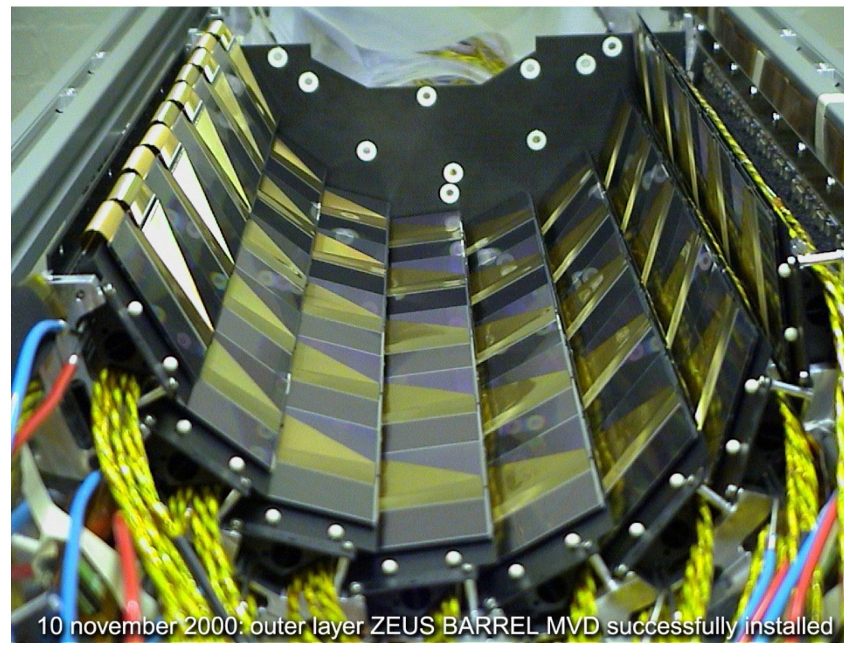
High resistive n-type silicon
onto which p^+ diode strips with
with aluminum contacts are implanted

ZEUS Silicon Micro-vertex Detector

- 3 layers (barrel) + 4 wheels (forward)
- silicon thickness: 330μm
- high resistivity n-type silicon with readout p+ strips, AC coupled to the readout electronics
- readout pitch: 120μm

- space resolution:
  expected = $120/\sqrt{12} = 8.3\mu m$
  measured = $7.5\ \mu m$

➔ improvement obtained adding five intermediate p+ strips between two readout strips by capacitive charge division



BaBar Silicon Vertex Tracker

- 5 layers
- two-sided silicon strip
- 300μm thick
- pitch: 50-200 μm

- space resolution: 10-30 μm

Pixel detectors

Pixel detectors:

Like micro-strips, but 2-dim. segmentation ...

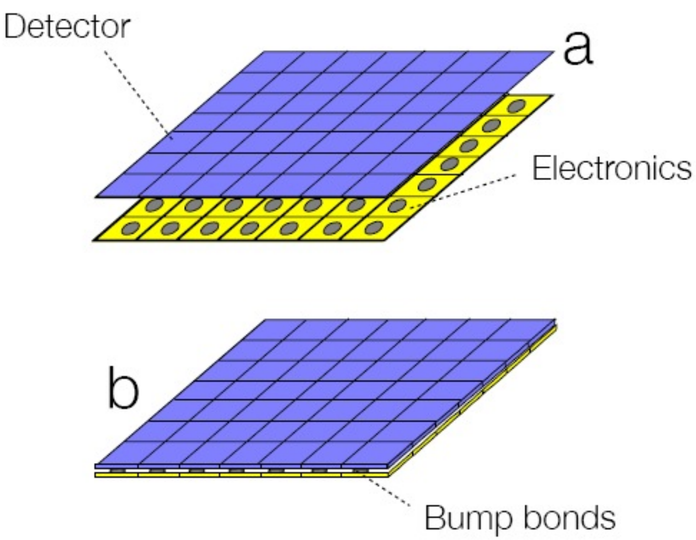
Advantage:

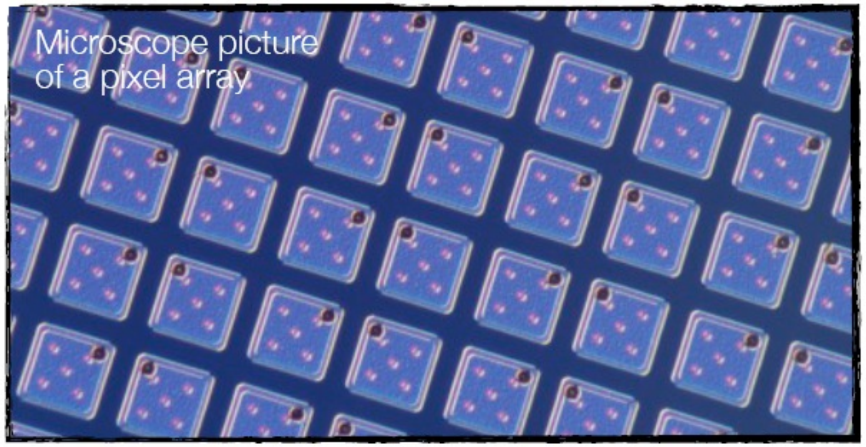
As for micro-strips 2-dim. information,
but higher occupancy allowed;

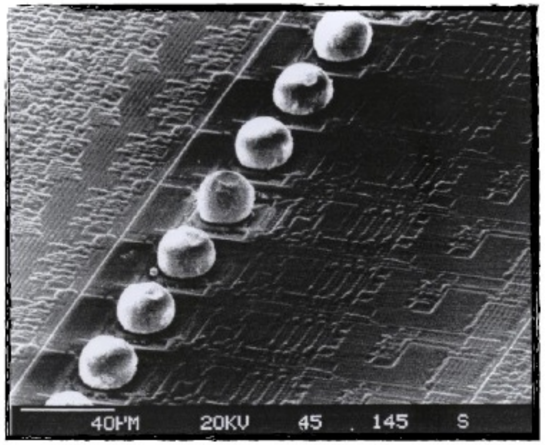
Lower noise due to lower capacitance ...

Disadvantage:

Huge number of readout channels;
Complicated technology ("bump bonding")
Requires sophisticated readout architecture ...







SEM Photograph
of solder bumps

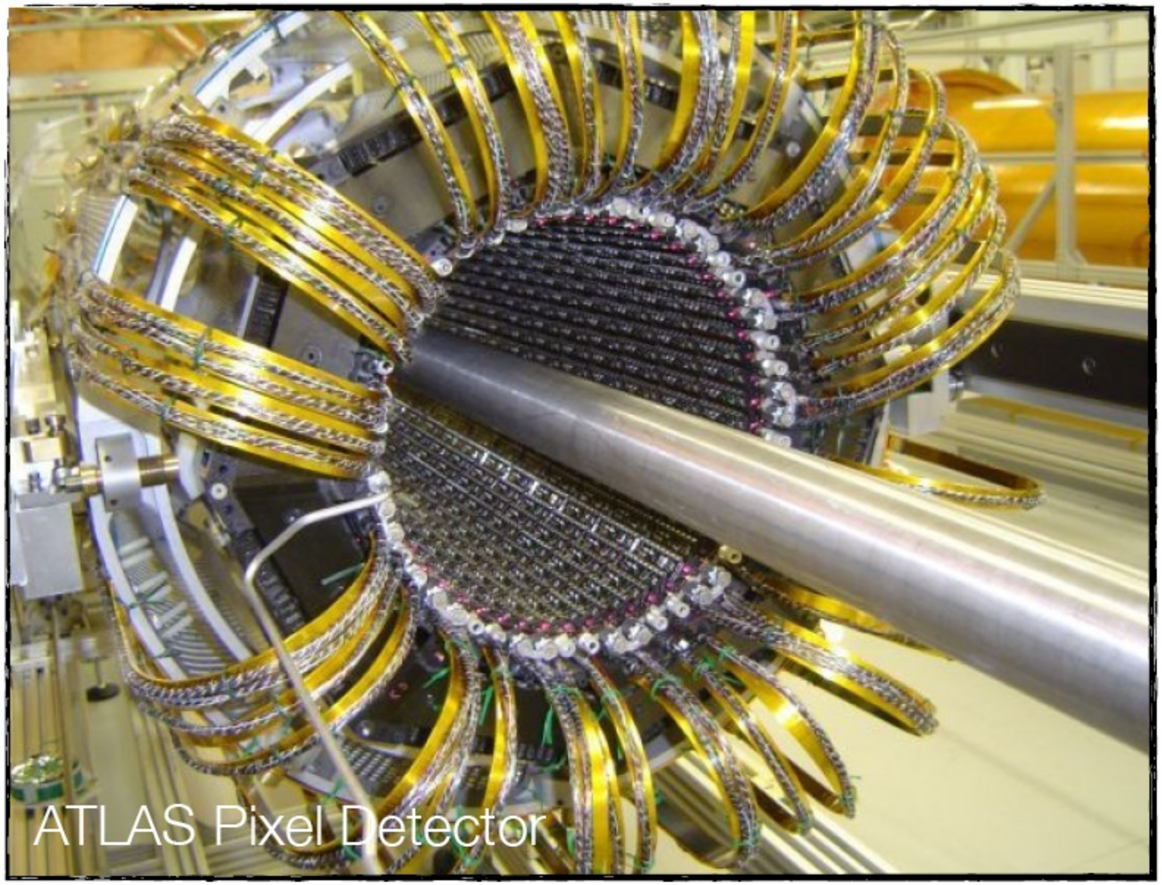
ATLAS Pixel Detectors

- 3 barrel layers + 3 disks
- pixels of 50μmx400μm
- 280 μm thick

- Total of 2.2M pixels

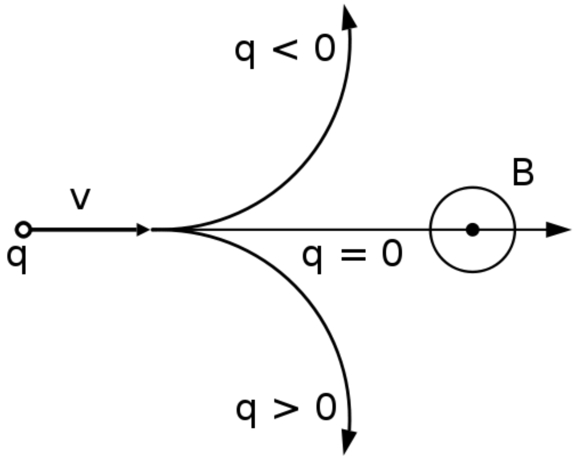
➔ largest assembly so far

- space resolution:
  ~8-14 μm



Tracking detectors

The determination of the momentum of charged particles can be performed by measuring the bending of a particle trajectory (track) in a magnetic field



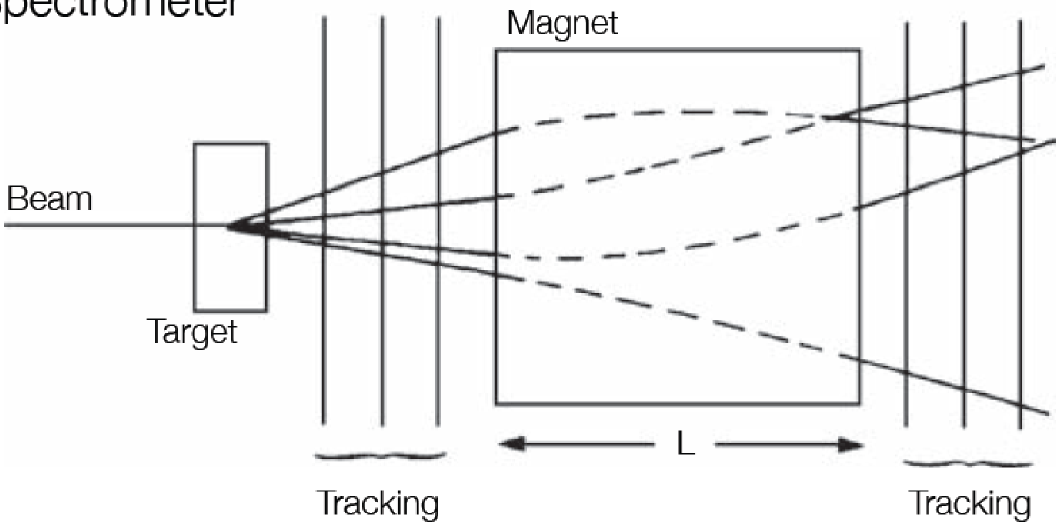
$$\vec{F} = q\vec{v} \times \vec{B}$$

Lorentz force: is the force on a point charge due to electromagnetic fields

$$\frac{mv^2}{r} = qvB$$

… for a particle in motion perpendicular to a constant B field

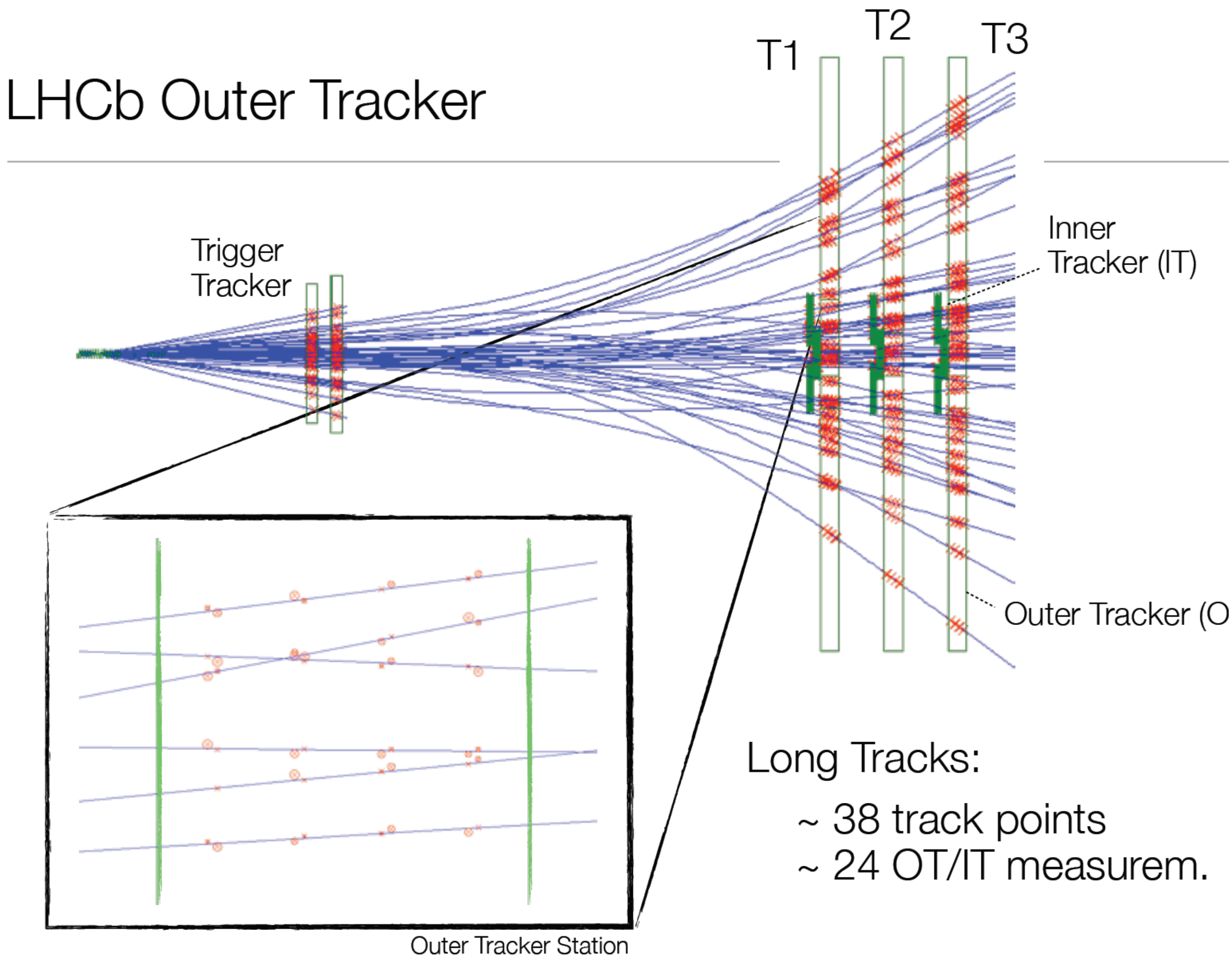
Schematics of a Spectrometer



In practice:

- use layers of position sensitive detectors before and after (or inside) a magnetic field to measure a trajectory
- determine the bending radius

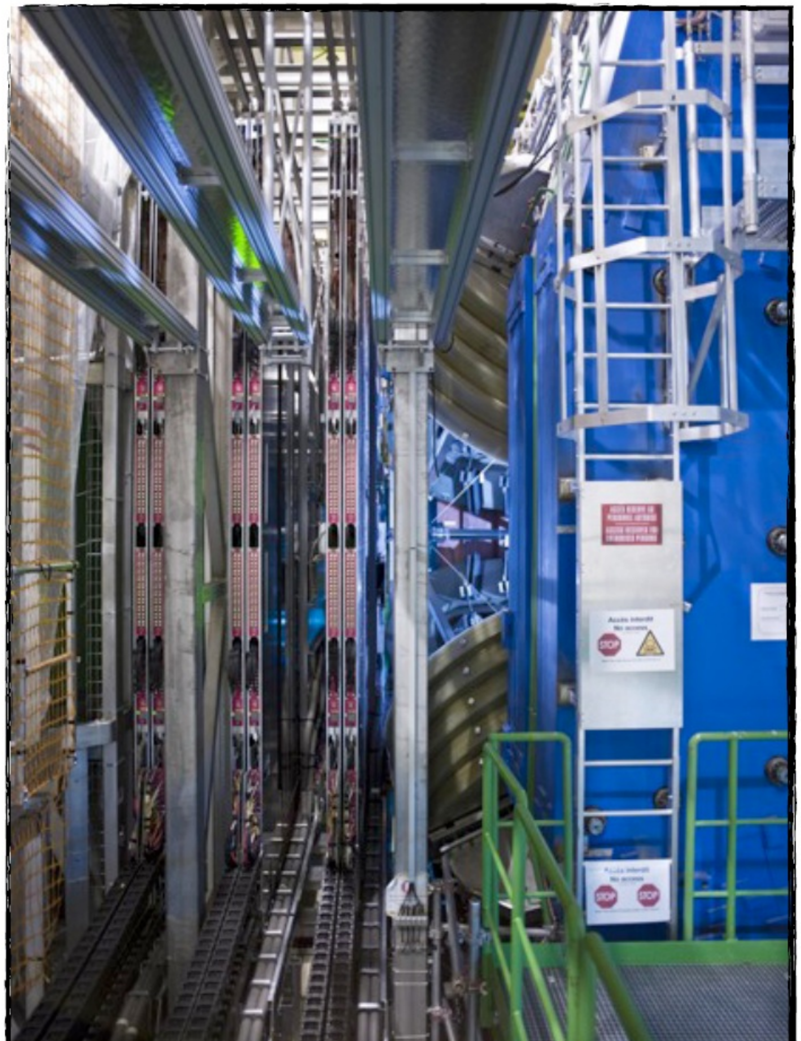
Tracking detectors

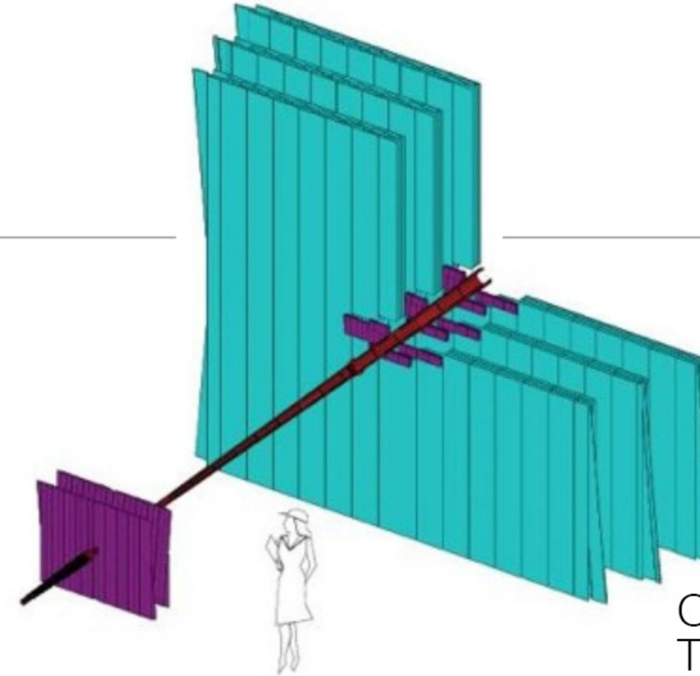


Long Tracks:

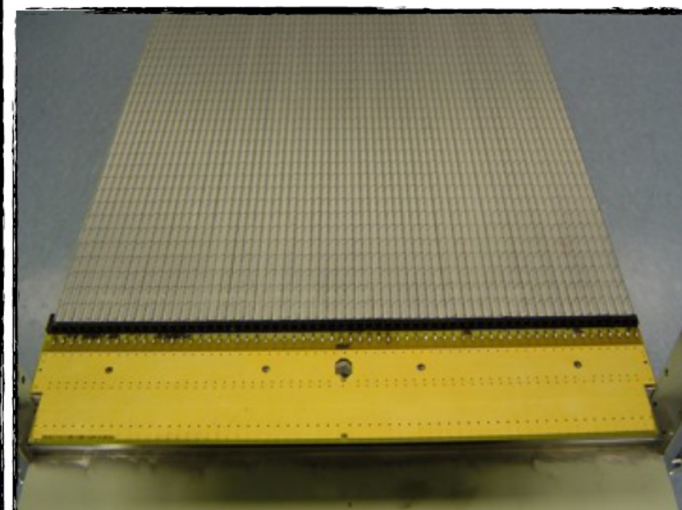
~ 38 track points
~ 24 OT/IT measurem.

LHCb Outer Tracker





Outer
Tracker

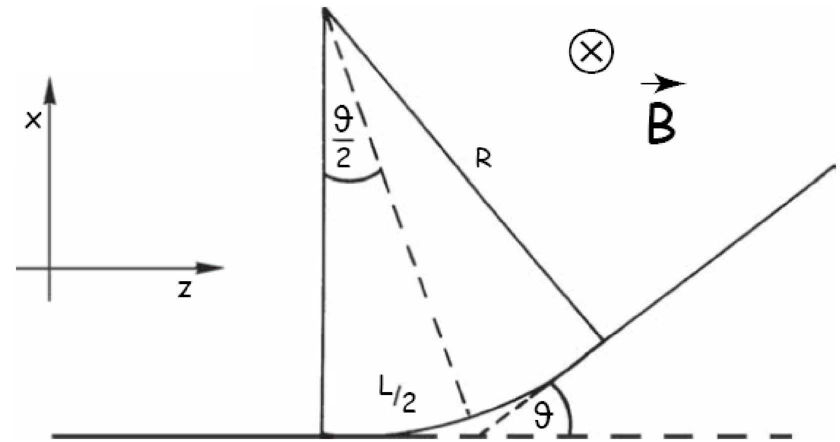


Straw Tubes
[double layers]

3 Chambers
[4 layers á 18 modules]

Tracking detectors

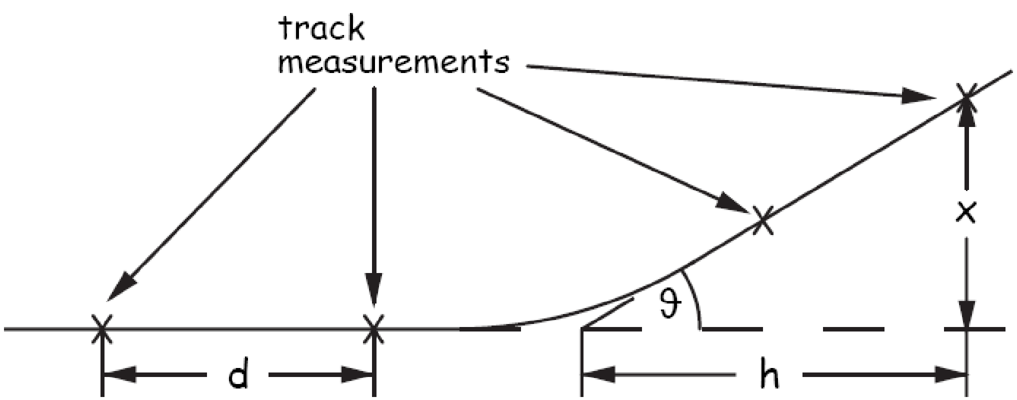
Momentum determination
in fixed target experiments ...



$$p = eRB \qquad \vartheta = {}^{L}/_{R}$$
$$= {}^{L}/_{p} \cdot eB$$

$$p = eB \cdot {}^{L}/_{\vartheta}$$

Momentum resolution: $\rightarrow \quad \dfrac{\sigma_p}{p} = \dfrac{\sigma_\vartheta}{\vartheta}$ with $\sigma_\vartheta \sim \sigma_x$



Determination of σ_p/p:

$$\vartheta = \frac{x}{h} \qquad \sigma_\vartheta = \frac{\sigma_x}{h}$$

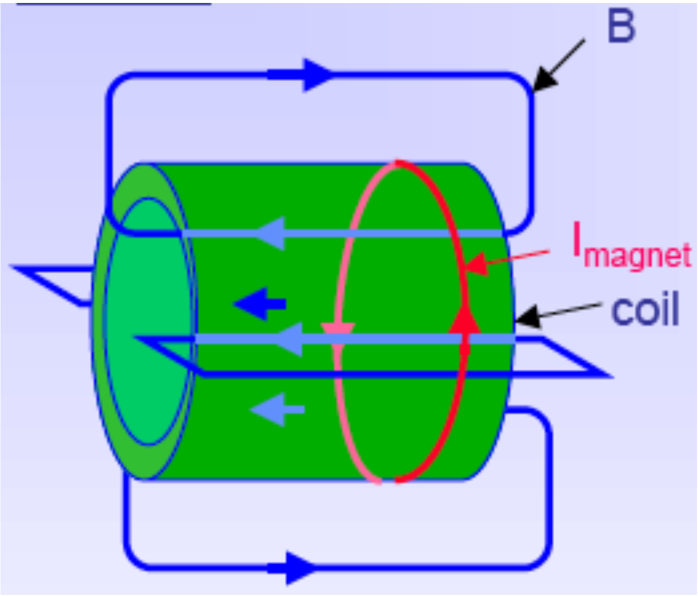
$$\frac{\sigma_p}{p} = \frac{\sigma_\vartheta}{\vartheta} = \frac{\sigma_x}{h} \cdot \frac{p}{eBL}$$

Long lever arm improves momentum resolution ...

Magnets for 4π detectors

<u>Solenoid</u>

+ Large homogeneous field inside
- Weak opposite field in return yoke
- Size limited by cost
- Relatively large material budget

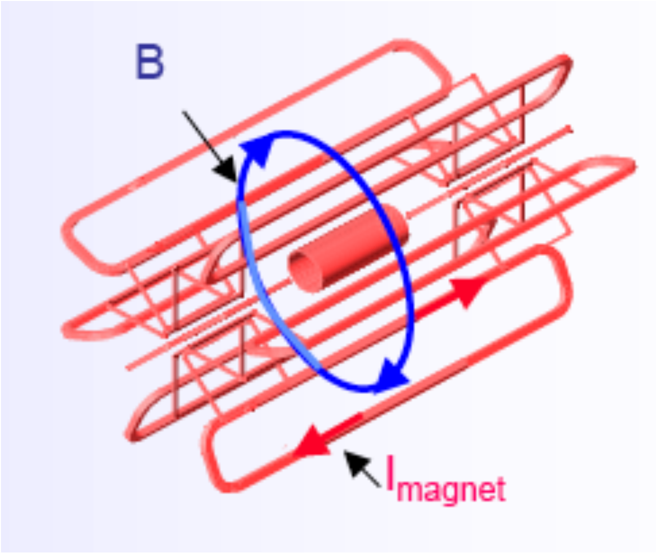


<u>Examples</u>:

•Delphi: SC, 1.2 T, 5.2 m, L 7.4 m
•L3: NC, 0.5 T, 11.9 m, L 11.9 m
•CMS: SC, 4 T, 5.9 m, L 12.5 m

<u>Toroid</u>

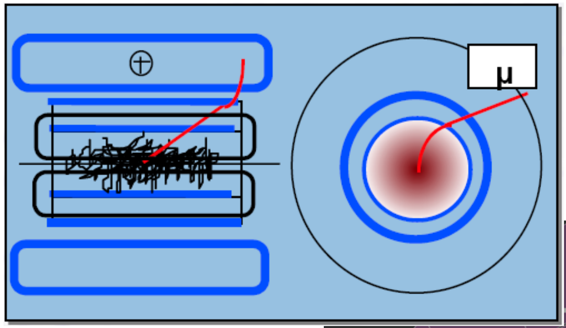
+ Field always perpendicular to p
+ Rel. large fields over large volume
+ Rel. low material budget
- Non-uniform field
- Complex structural design



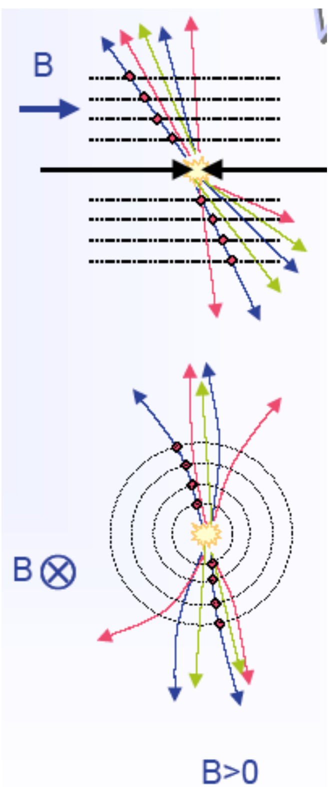
<u>Example</u>:

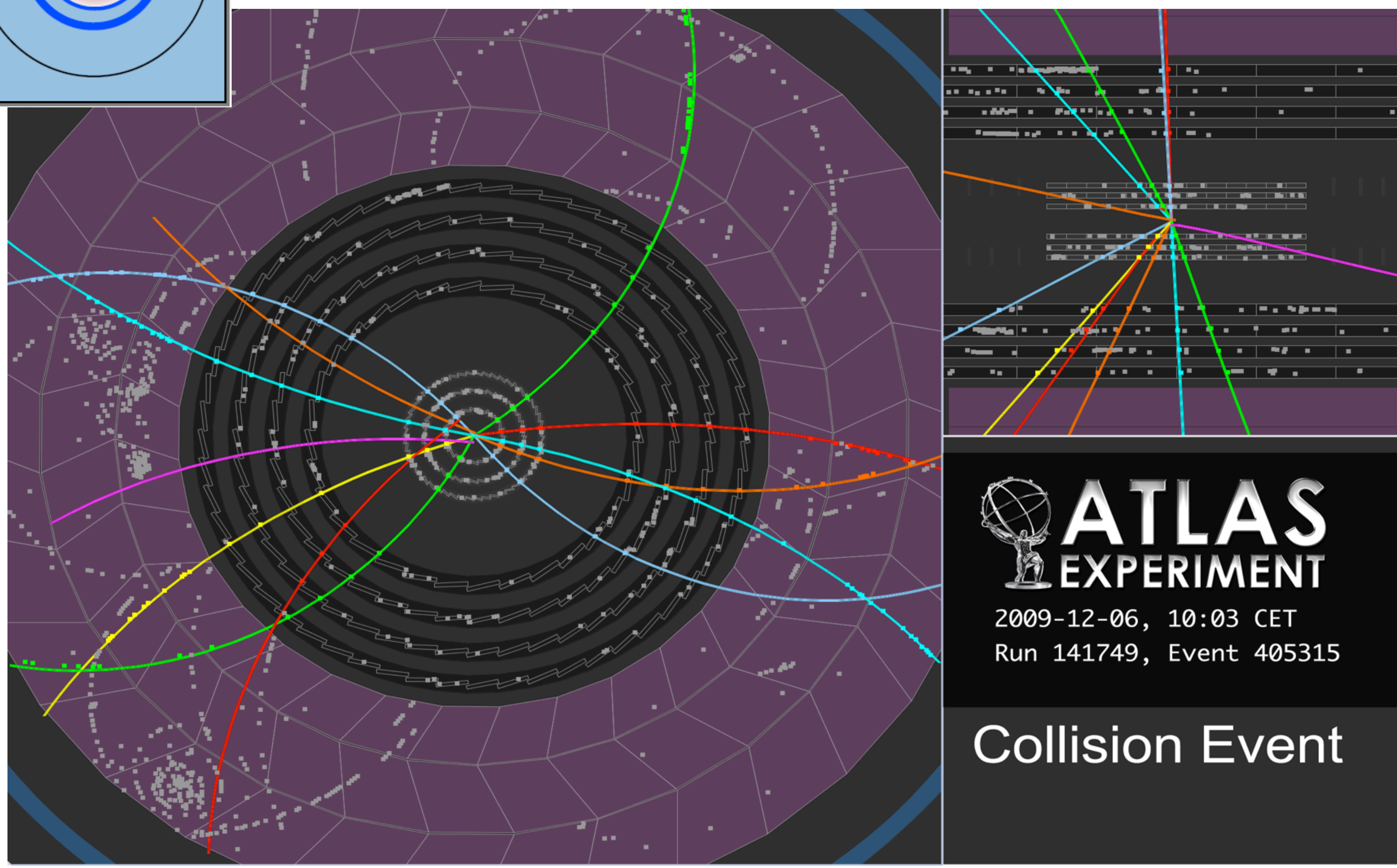
•ATLAS: Barrel air toroid, SC, ~1 T, 9.4 m, L 24.3 m

Tracking inside a magnetic field



ATLAS: (air-core) toroid magnet
+ inner solenoid





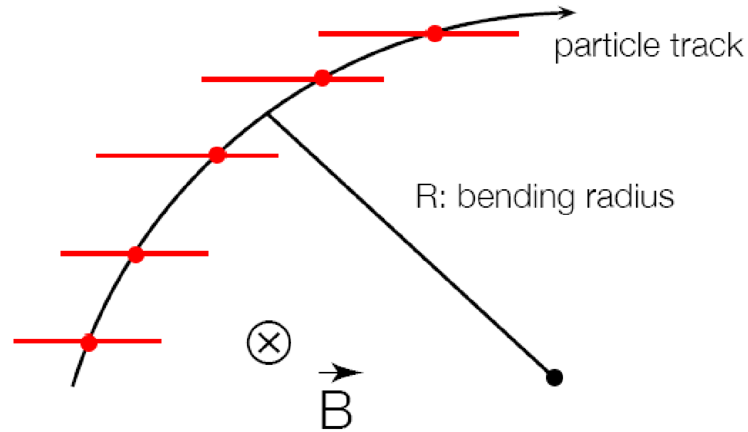
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Tracking detectors

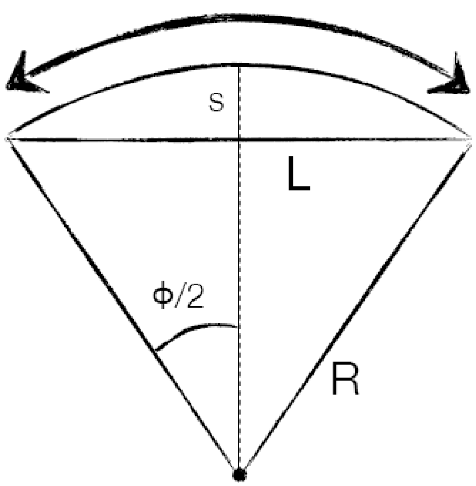
Momentum determination
in a cylindrical drift chamber ...

$$\frac{mv^2}{R} = evB \quad \rightarrow \quad p = eB \cdot R$$

$$\boxed{p\left[\frac{GeV}{c}\right] = 0.3\ \mathrm{B[T]\ R[m]}}$$



momentum component perpendicular to the B-field
transverse momentum p_t



For Sagitta s:

$$s = R - R\cos\frac{\phi}{2} \approx R\frac{\phi^2}{8} \qquad \text{with } \phi = \frac{L}{R}$$

$$s = R\frac{L^2}{8R^2} = \frac{L^2}{8R} \quad \text{and} \quad R = \frac{L^2}{8s}$$

$$\rightarrow \quad \frac{\Delta p}{p} = \frac{\Delta R}{R} = \frac{L^2}{8Rs} \cdot \frac{\Delta s}{s}$$

➔ radius is obtained by a circle fit through measurement points along the track with point resolution $\sigma_{r\phi}$

1T = 1kg/C/s^2
1eV/c = 0.535 10^{-27} kg m/s
1eV = 1.6 10^{-19} C

Some example number

$$p\left[\frac{GeV}{c}\right] = 0.3\ \mathrm{B[T]\ R[m]} \qquad s = \frac{\mathrm{L}^2}{8\mathrm{R}}$$

If we assume L=4m, B=1T and p=1TeV then:

R = p/(0.3 B) = 1000 / 0.3 = 3300 m, and

s ≈ 16/(8*3300) ≈ 0.6 mm

If we want to measure the momentum

with Δp/p ≈ Δs/s ≈ 10% (at p = 1 TeV) we need:

➔ Δs/s ≈ 60 μm

Momentum resolution

Momentum measurement uncertainty:

$$\frac{\sigma_p}{p} = \frac{L^2}{8Rs}\cdot\frac{\sigma_s}{s} = \frac{L^2}{8R}\cdot\frac{\sigma_s}{L^4/64R^2} = \frac{\sigma_s}{L^2}\cdot 8R = \frac{\sigma_s}{L^2}\cdot\frac{8p}{eB} \sim p\cdot\frac{\sigma_s}{BL^2}$$

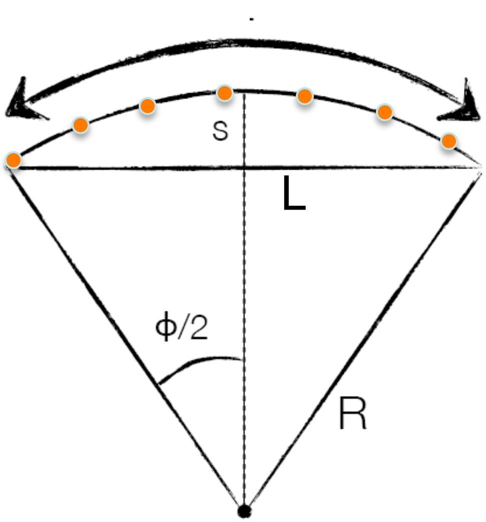
Uncertainty σ_s depends on number and spacing of track point measurements; for equal spacing and large N:

$$\sigma_s = \frac{\sigma_{r\phi}}{8}\sqrt{\frac{720}{N+5}}$$

see: Glückstern, NIM 24 (1963) 381 or
Blum & Rolandi, Particle Detection ...

Good momentum resolution:

- large path length L
- large magnetic field B
- good Sagitta measurement



For momentum p:

generally in experiment measure p_t

$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\frac{\sigma_{p_t}}{p_t}\right)^2 + \left(\frac{\sigma_\theta}{\sin\theta}\right)^2$$

multiple scattering term conts. in p_t

using $p = \frac{p_t}{\tan\theta}$

Examples:

Argus: $\sigma_{pt}/p_t = 0.009^2 + (0.009\ p_t)^2$

ATLAS: $\sigma_{pt}/p_t = 0.001^2 + (0.0005\ p_t)^2$

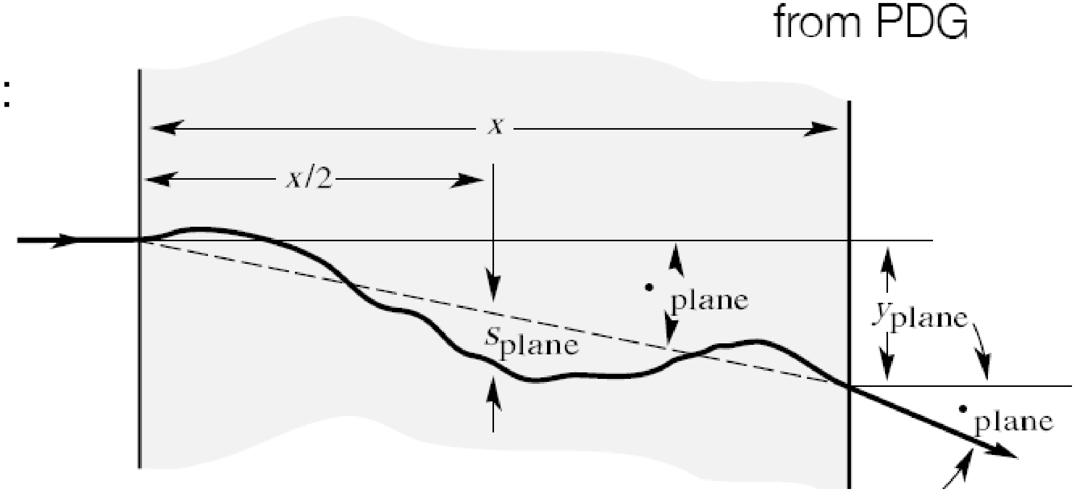
track uncertainty ≈ p_t

[ATLAS nominal; TDR]

Momentum resolution

from PDG

Multiple scattering contribution:



$$\sigma_\phi \approx \frac{14\ \mathrm{MeV}/c}{p}\sqrt{\frac{L}{X_0}}$$

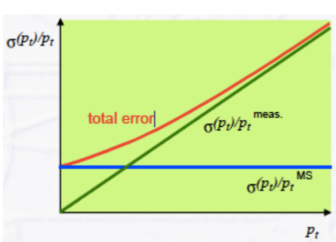
$$\frac{\sigma_p}{p} = \frac{\sigma_R}{R} = \frac{\sigma_\phi}{\phi}$$

as $R = \dfrac{L}{\phi}$

At small momenta this limits resolution of momentum measurement ...

momentum independent

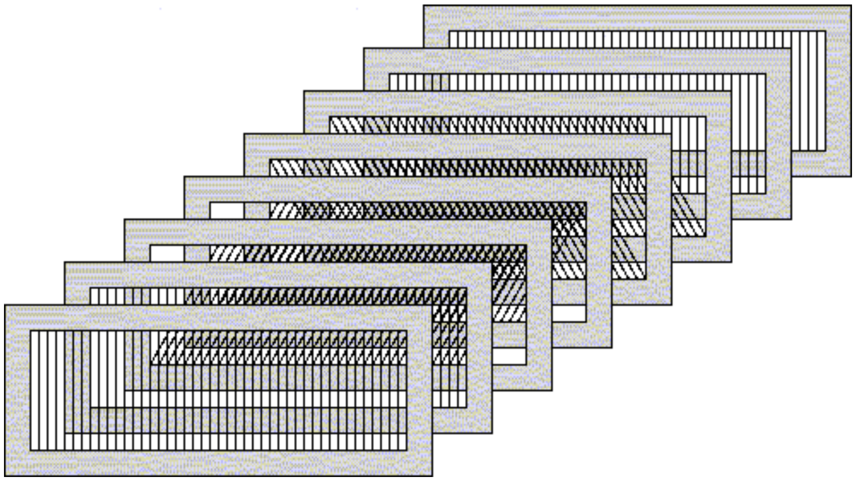
$$\frac{\sigma_p}{p} = \frac{\sigma_\phi}{\phi} = \frac{14\ \mathrm{MeV}/c}{p}\sqrt{\frac{L}{X_0}} \cdot \frac{R}{L} = \frac{14\ \mathrm{MeV}/c}{p}\sqrt{\frac{1}{LX_0}} \cdot \frac{p}{eB} \sim \frac{1}{\sqrt{LX_0}B}$$



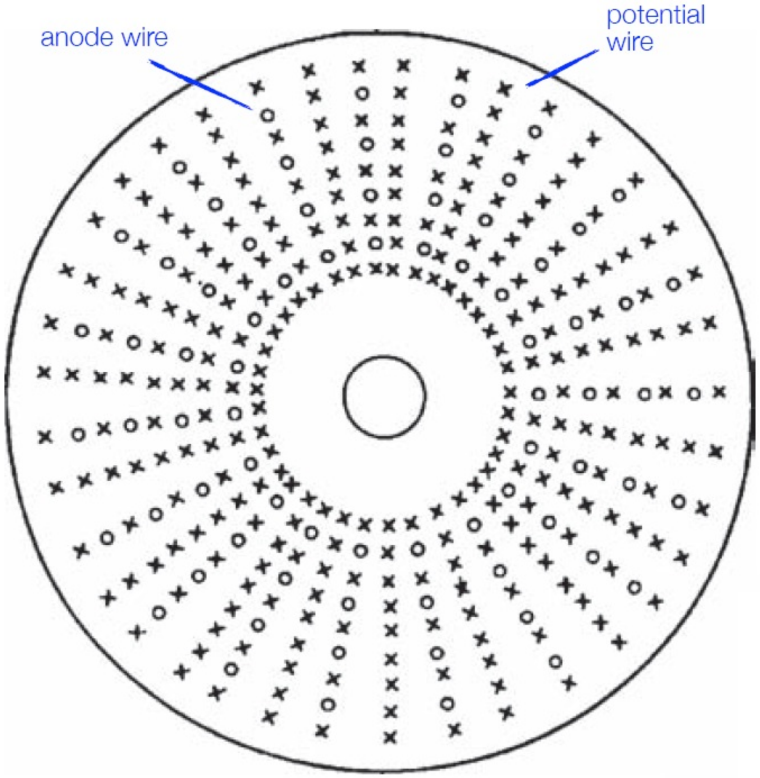
$$\left(\frac{\sigma_{p_t}}{p_t}\right)^2 = \boxed{\mathrm{const}\cdot\left(\frac{p_t}{BL^2}\right)^2} + \boxed{\mathrm{const}\cdot\left(\frac{1}{B\sqrt{LX_0}}\right)^2}$$

Tracking detectors

Tracking at fixed target experiments:
Multi-layer MWPC or drift chamber



Tracking at collider experiments:
cylindrical drift chamber



Drift chamber – spatial resolution

Resolution determined by
accuracy of drift time measurement ...

Influenced by:

Diffusion [$\sigma_{Diff.} \sim \sqrt{x}$]

see above: $\sigma^2 \sim 2Dt = 2Dx/v_D \sim x$ ...

δ-electrons [σ_δ = const.]

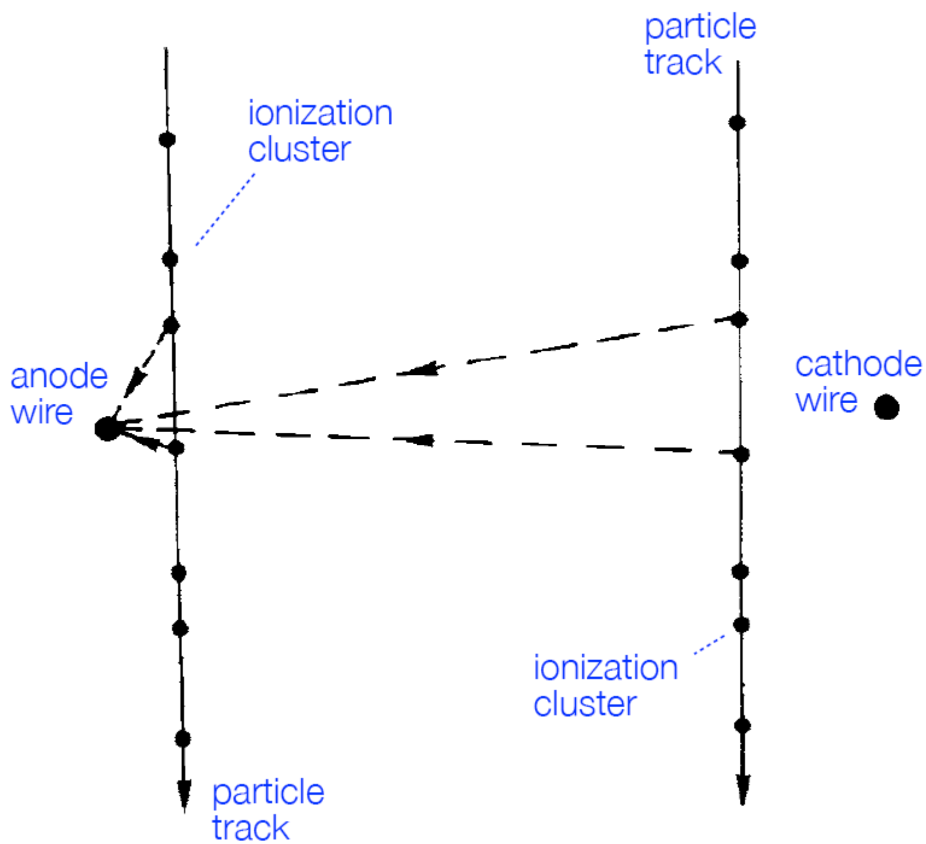
independent of drift length; yields constant
term in spatial resolution ...

Electronics [$\sigma_{electronics}$ = const.]

contribution also independent of drift length ...

Primary ionization statistics [$\sigma_{prim} = 1/x$]

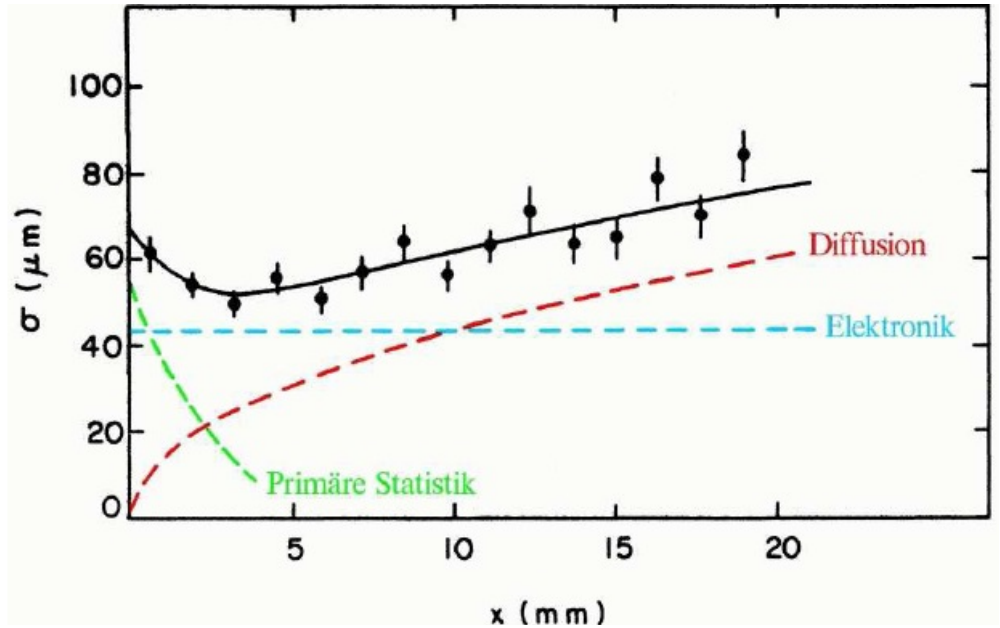
Spatial fluctuations of charge-carrier production result in
large drift-path differences for particle trajectories close to the anode ...
[minor influence for tracks far away from anode]



Drift chamber – spatial resolution

Typical resolutions: σ_x=50-150 μm depends on the length of the drift path

- primary ionization statistics: how many ion pairs, ionization fluctuations dominates close to the wire
- diffusion: diff. constant, drift length dominates for large drift length
- electronics: noise, shaping characteristics constant contribution, independent on drift length

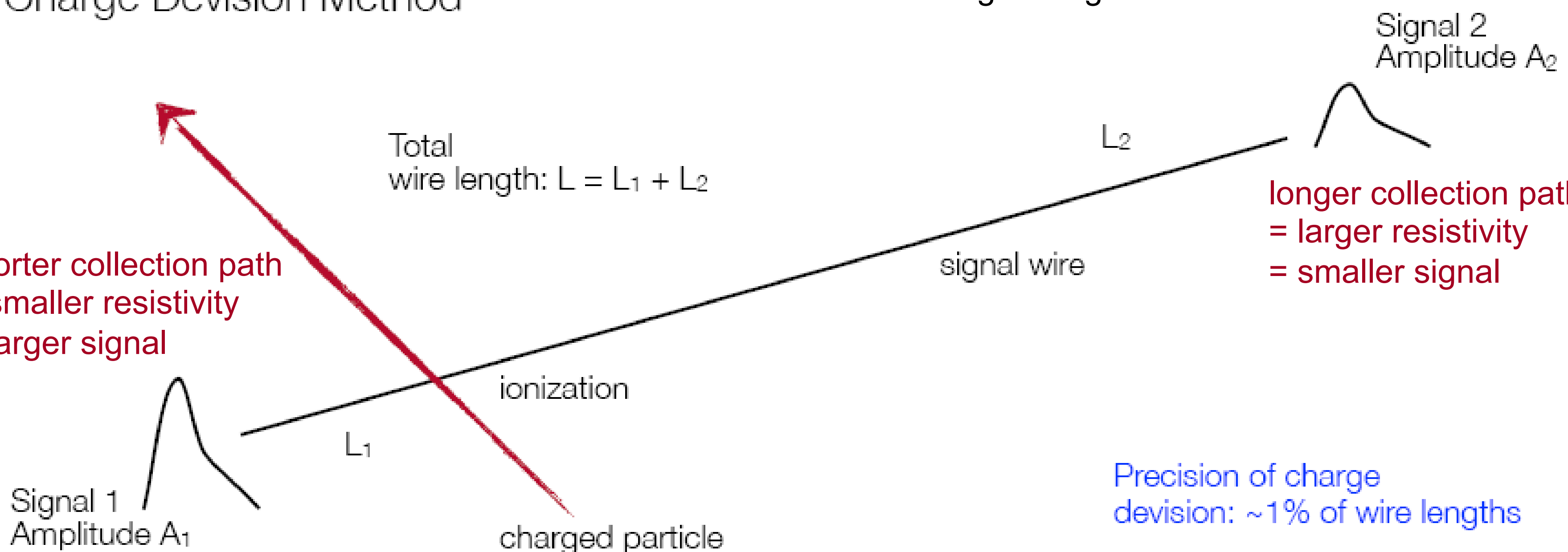


$$\sigma_x^2 = \underbrace{\left(\frac{1}{64N^2}\right)\cdot\frac{1}{x^2}}_{1^{\text{st}}\text{ ionization statistics}} + \underbrace{\frac{2D}{v_d}\cdot x}_{\text{diffusion}} + \underbrace{\sigma_{\text{const}}^2}_{\substack{\text{electronics}\\ \delta\text{-electrons}}}$$

Possible improvements:
Increase N by increasing pressure ...
Decrease D by increasing pressure ...

Drift chamber – z determination

Principle of
Charge Devision Method : measure the coordinate along the signal wire



shorter collection path
= smaller resistivity
= larger signal

longer collection path
= larger resistivity
= smaller signal

$$\boxed{\frac{A_1}{A_2} = \frac{L_2}{L_1}}$$

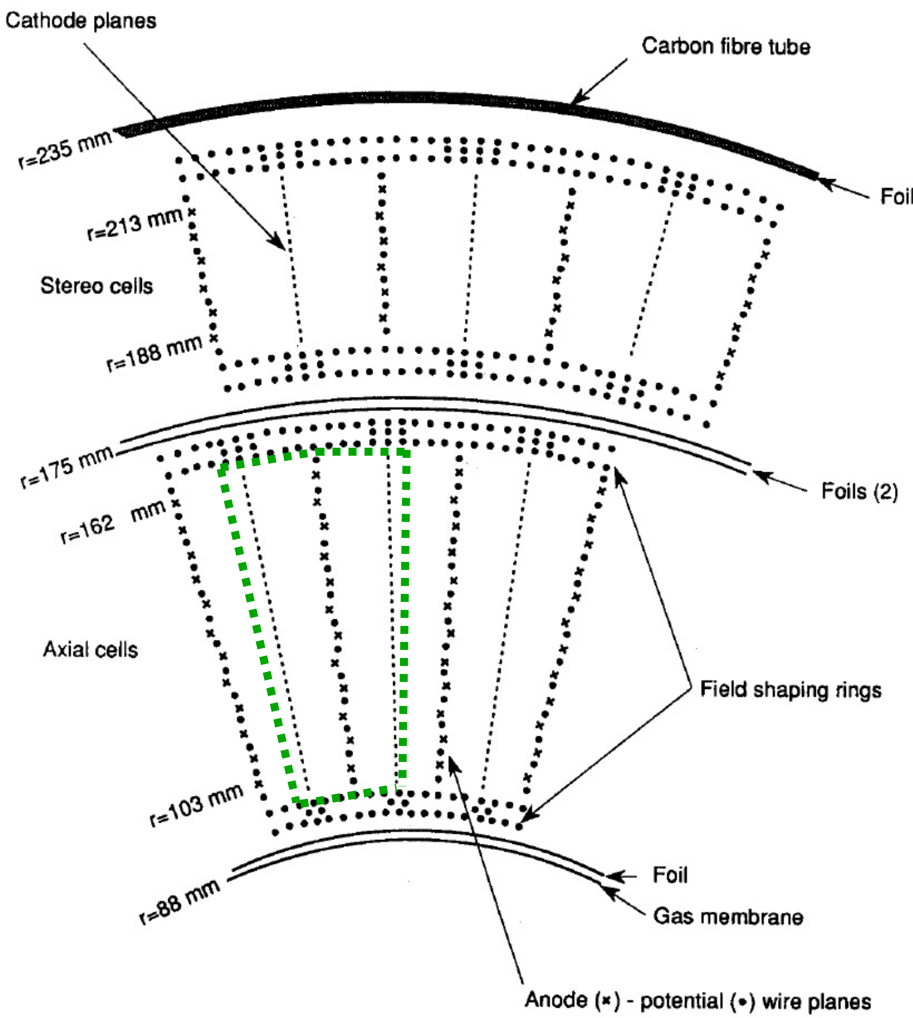
Precision of charge devision: ~1% of wire lengths

Also possible: time measurement on both ends

Determination of L_1, L_2:

$$L_2 = \frac{A_1}{A_1 + A_2} \cdot L \qquad L_1 = \frac{A_2}{A_1 + A_2} \cdot L$$

Jet drift chamber



Large volume drift chamber made of multiple independent cells, with a single wire plane in a moderate drift volume, often using drift on both sides of the wire.

precision along the drift is typically 100μm, and can be better than 50μm with pressurized gas, and precision by charge division along the wire is a few centimetres

very good two-track resolution using multi-hit electronics ➔ hence the name jet chamber

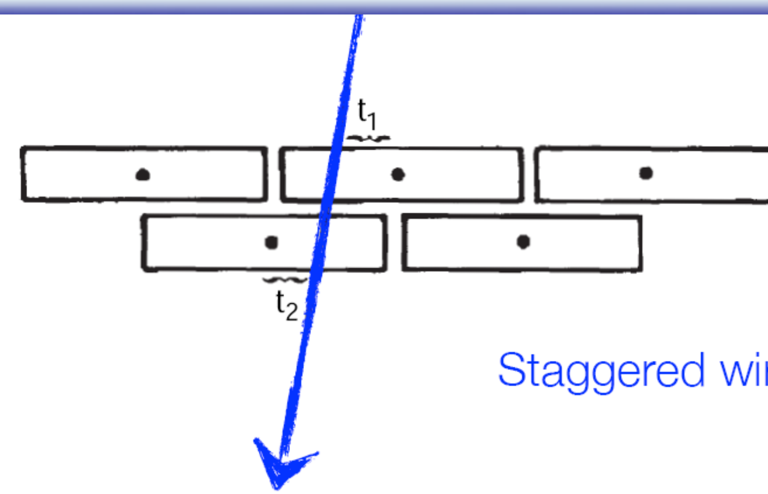
typical two-track resolution is 1-3 mm

Left right ambiguity

Difficulty:

Time measurement cannot distinguish whether particle has passed right or left from a wire ...

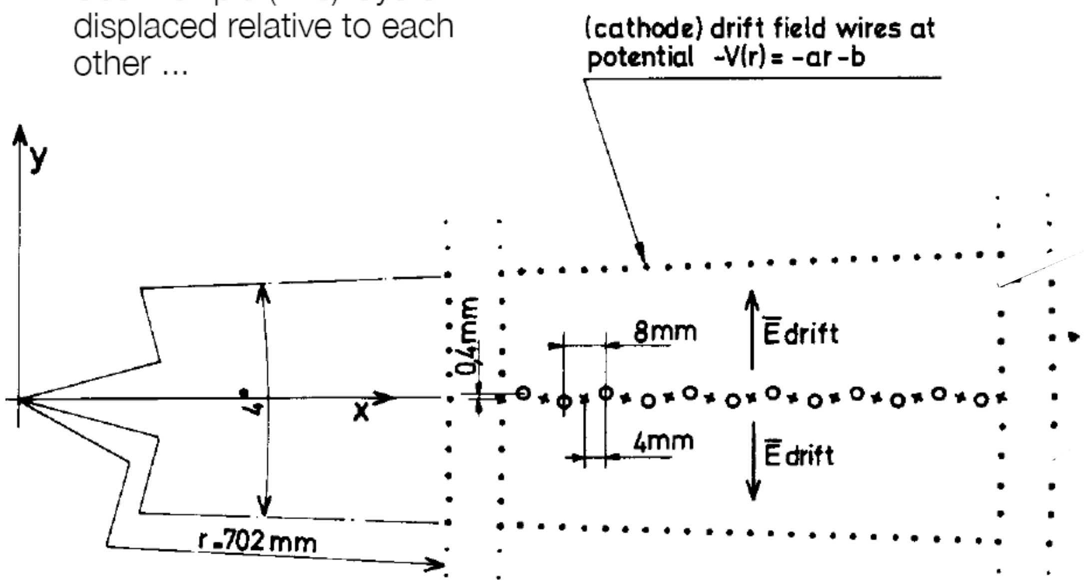
"Left-Right Ambiguity"

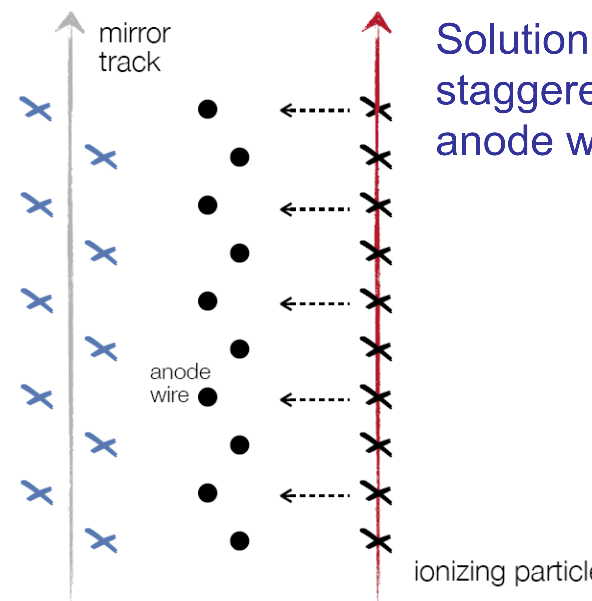


Staggered wires

Solution: "Staggered wires"

Use multiple (two) layers displaced relative to each other ...

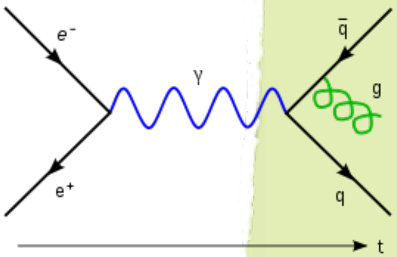


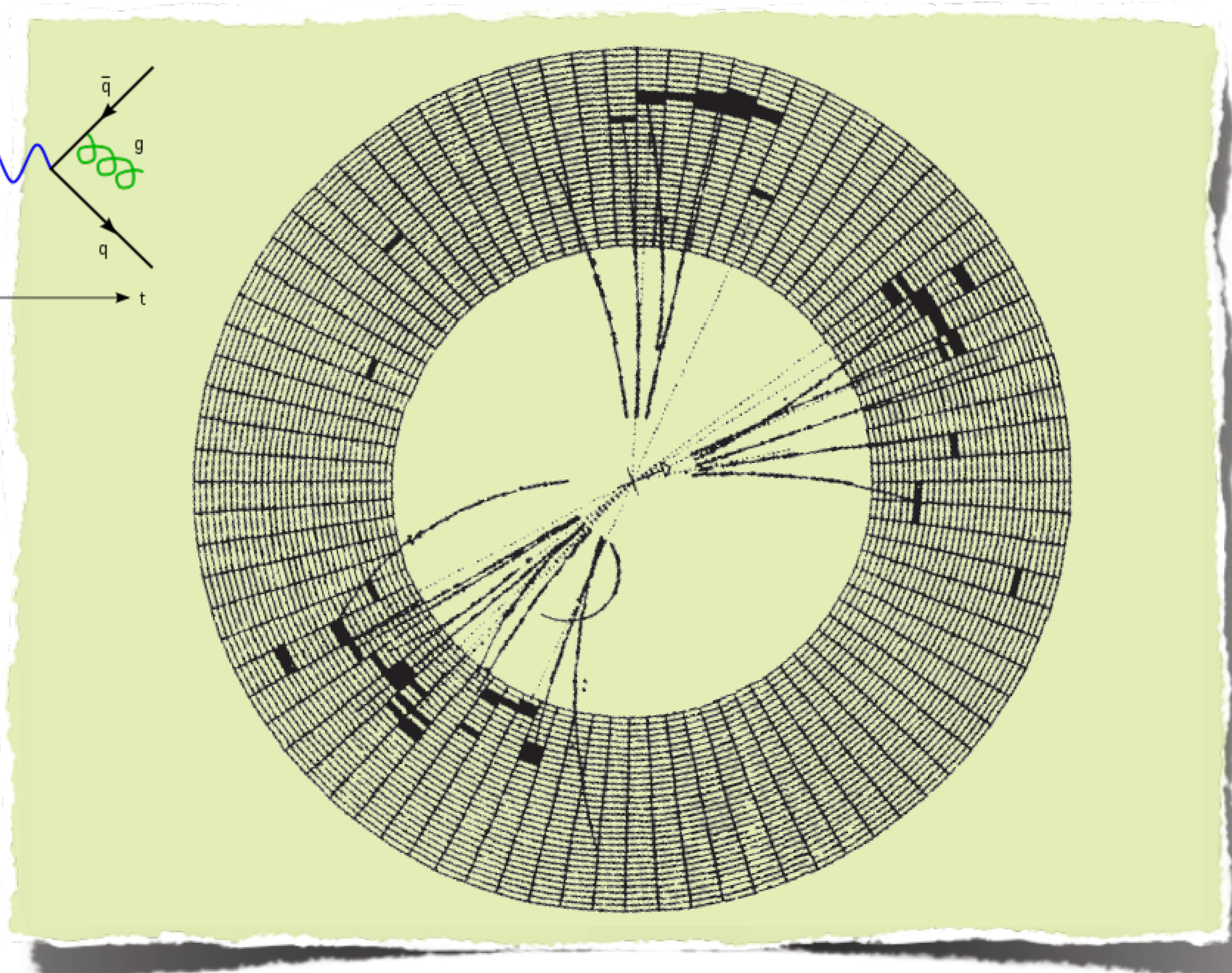


Solution: staggered anode wires

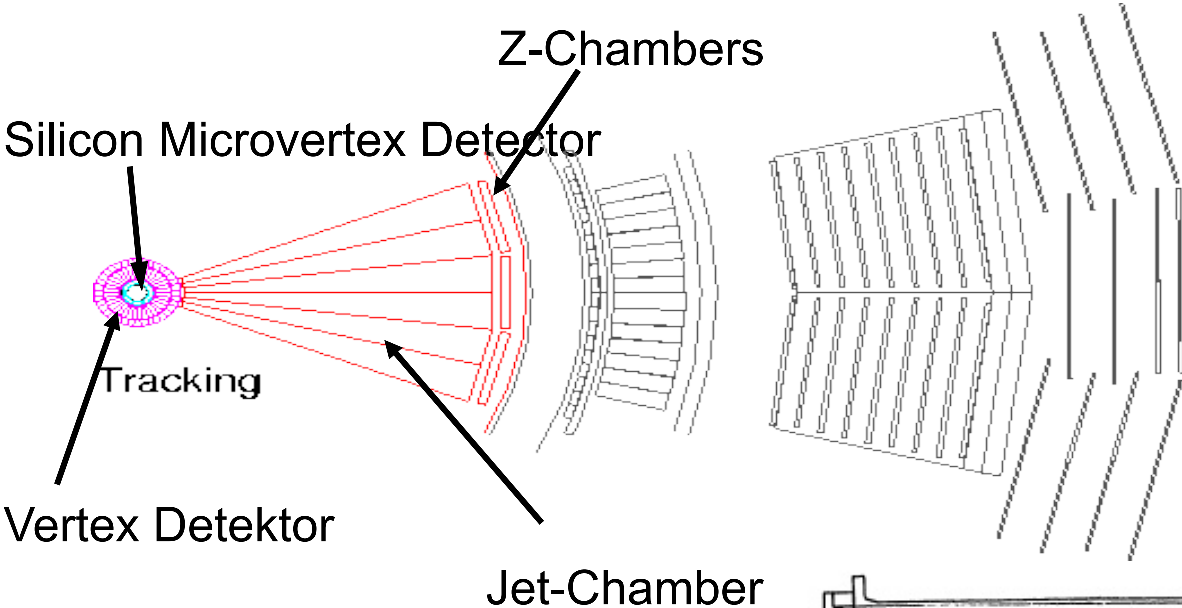
JADE - Jet drift chamber

1979: gluon discovery at PETRA (JADE, Mark-J, PLUTO) from 3-jets event

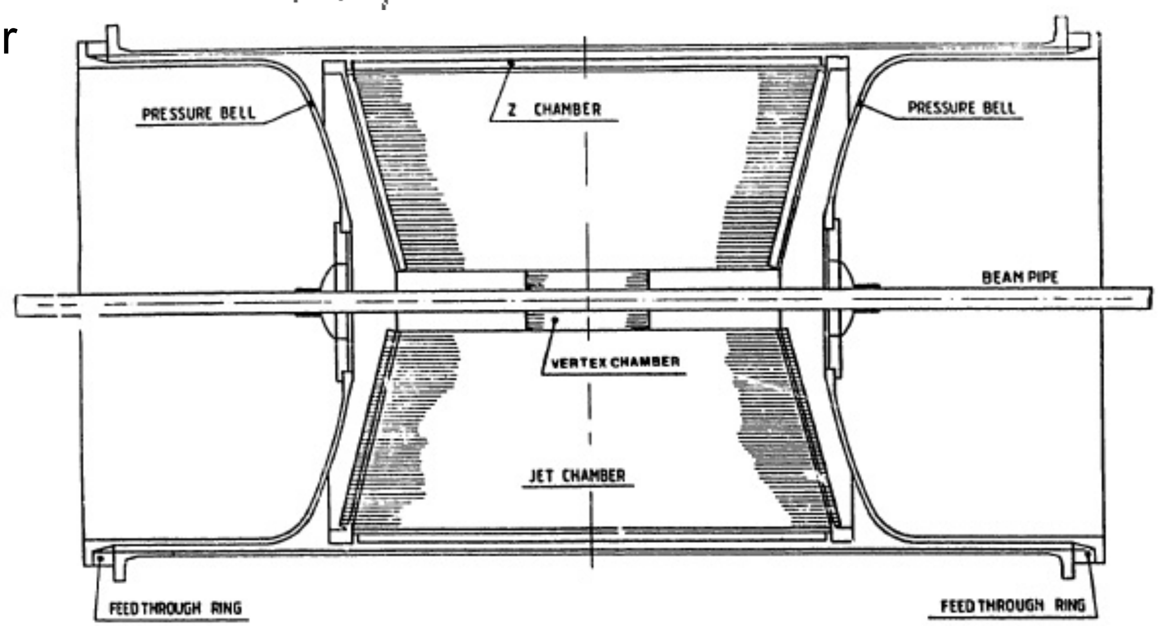




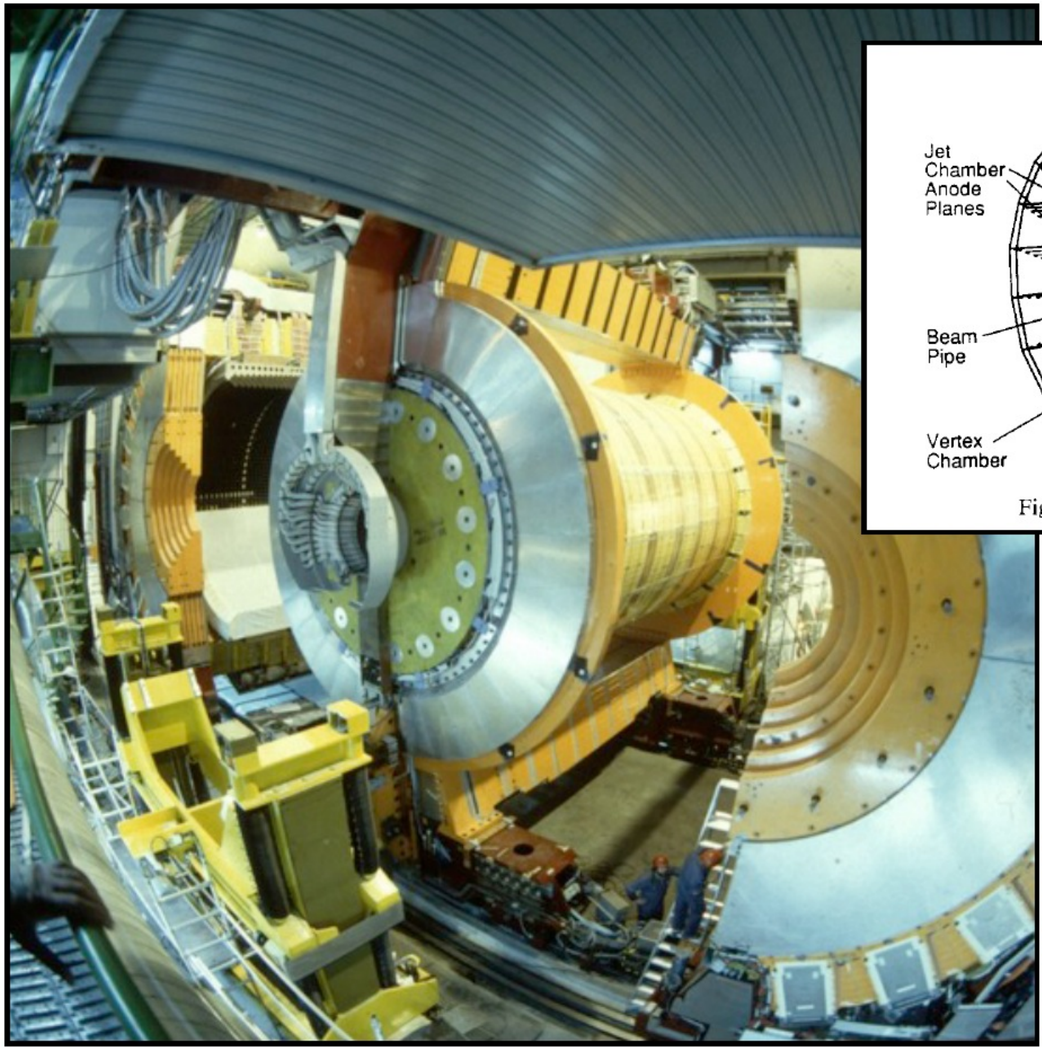
OPAL – Jet drift chamber



Jet drift chamber inside pressure vessel (P = 4 bar) and solenoid (B = 0.435 T)



OPAL – Jet drift chamber



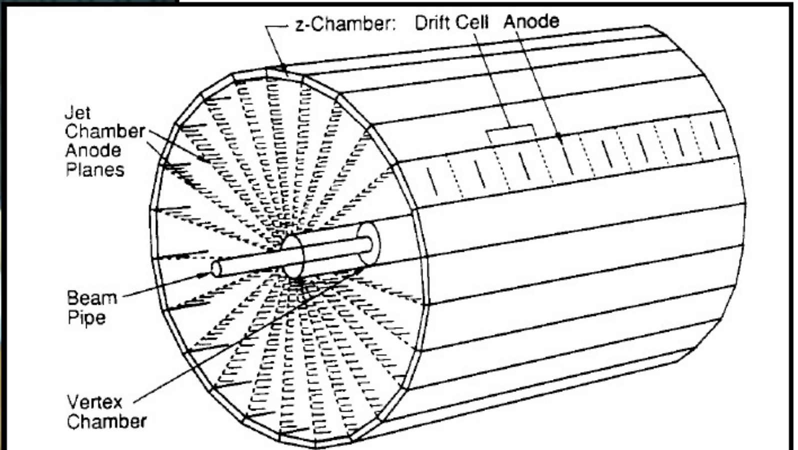
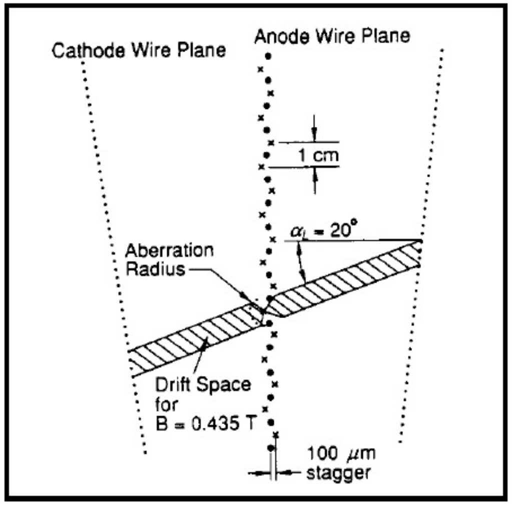


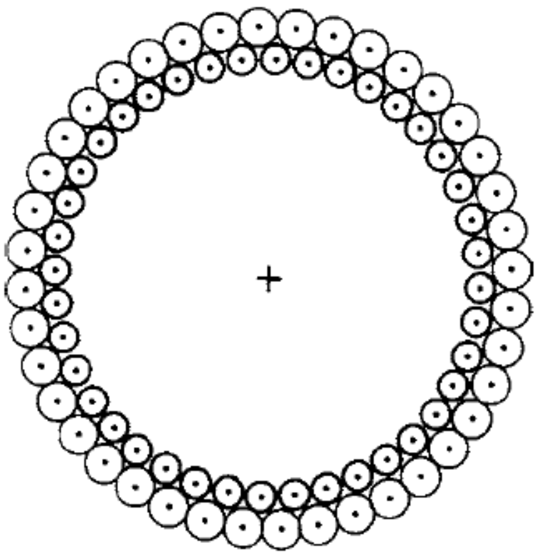
Fig. 1. Schematic view of the OPAL central detector.



OPAL – Jet drift chamber

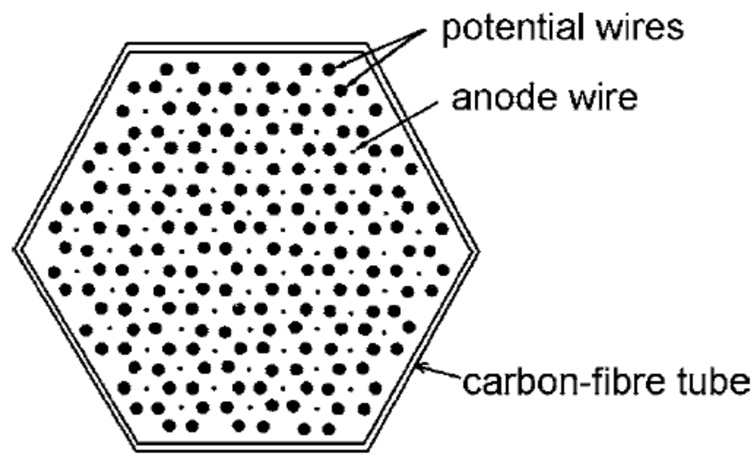
Alternative geometries for drift chambers

Cylindrical configuration of thin-wall straw-tube chambers or multi-wire drift module with 70 drift cells in one carbon-fibre container of 30mm diameter

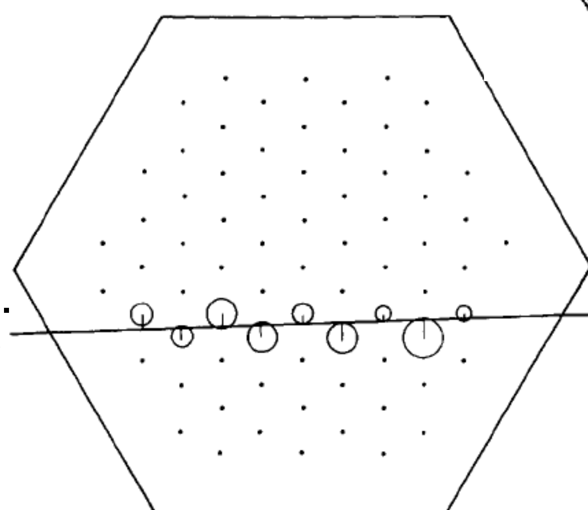


← advantage:
one broken wire =
one channel missing

one broken wire →
can kill a module

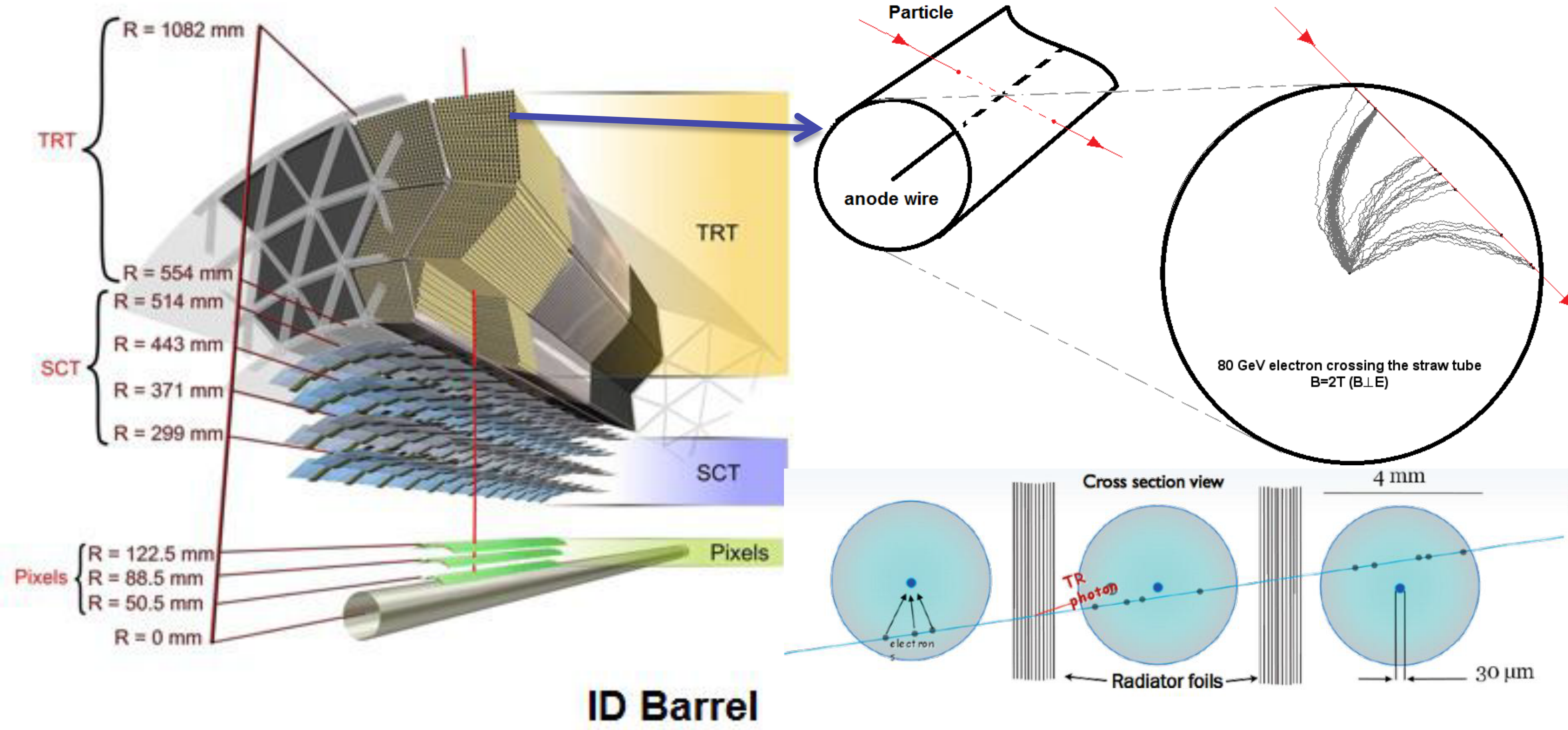


The straw tubes have diameters of 5-10mm and are frequently operated at overpressure. These detectors allow for spatial resolutions of 30μm



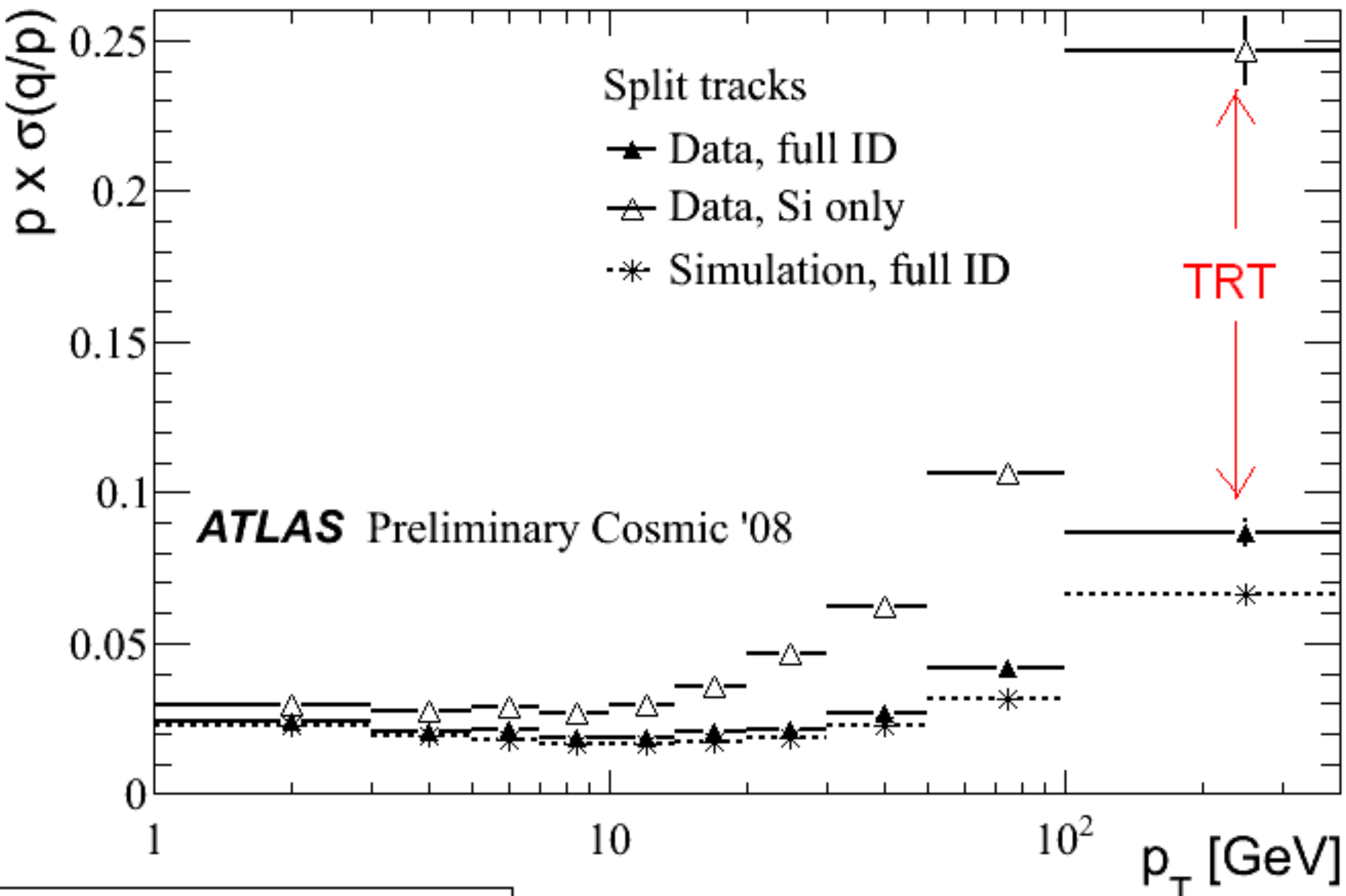
Reconstruction of a particle passage through a multi-wire drift module. The circles indicate the measured drift times of the fired anode wires. The particle track is a tangent to all drift circles

ATLAS: straw tubes (TRT)



Single point resolution: 120-130 um
Points per track: ~30 over a long lever arm (extend silicon tracker)
Momentum resolution: ➔

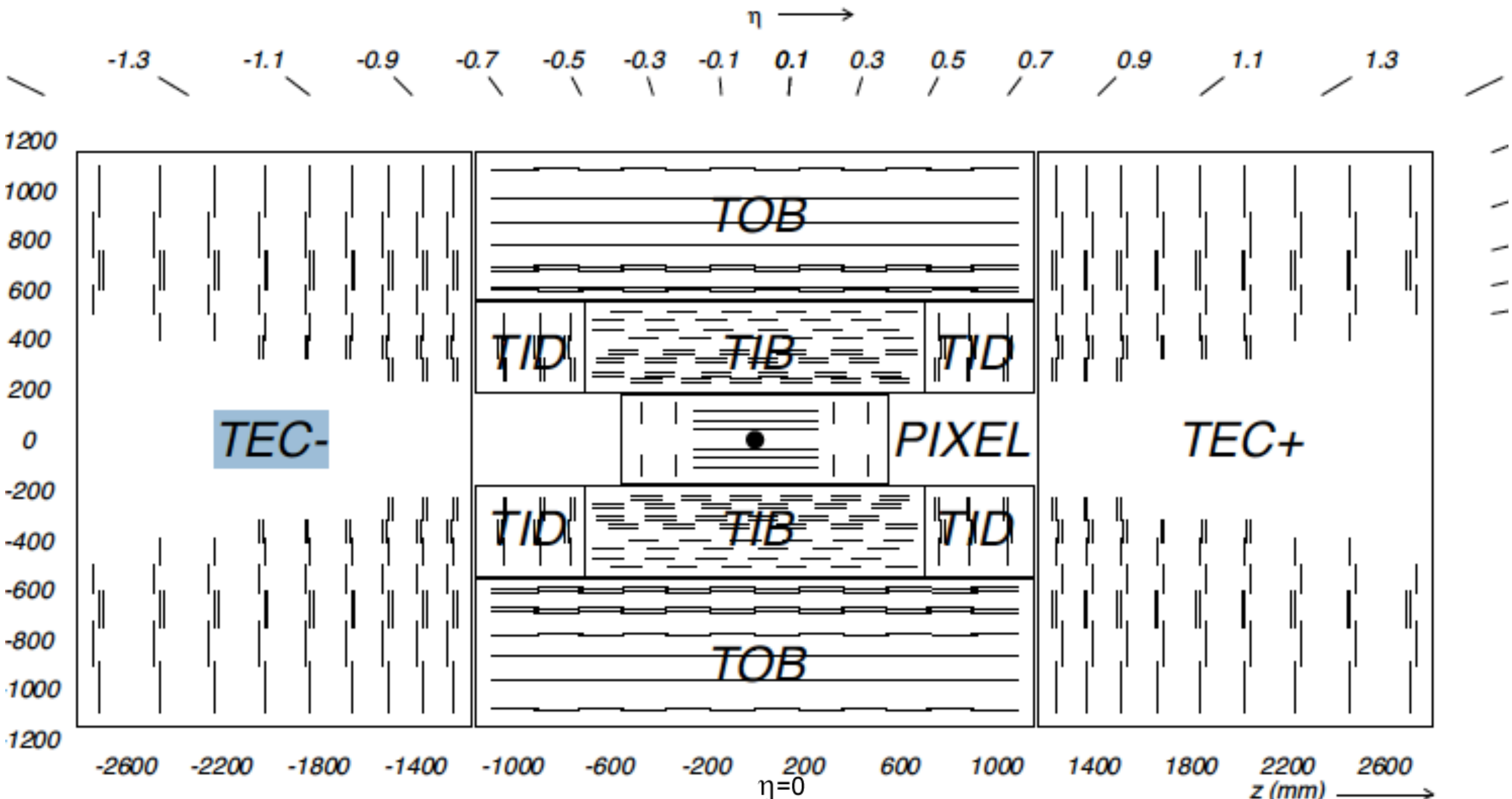
ATLAS: Momentum resolution



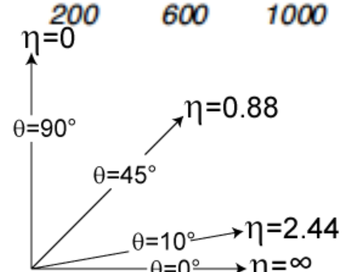
Momentum Resolution:

$\sigma(p_T)/p_T = 0.05\% p_T \oplus 1\%$

CMS: fully silicon tracker

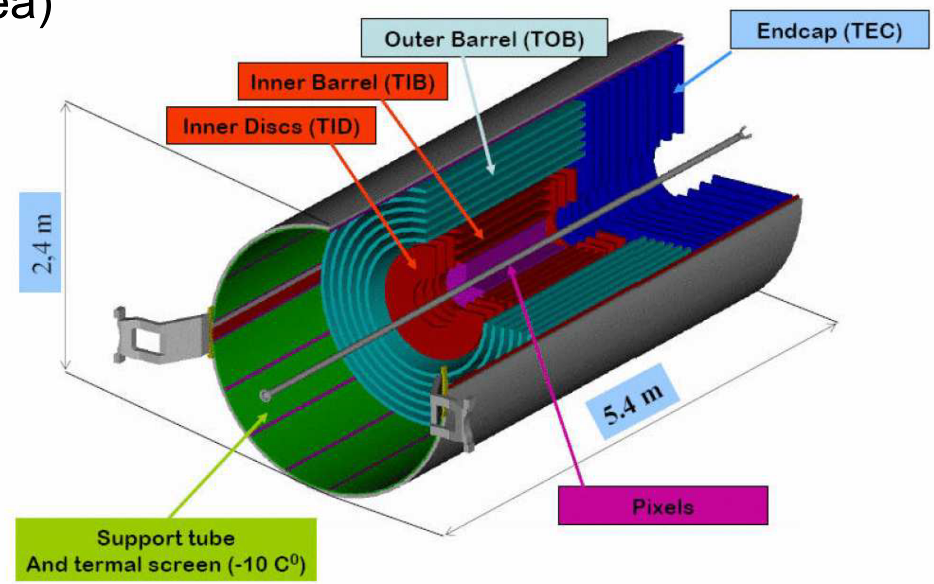


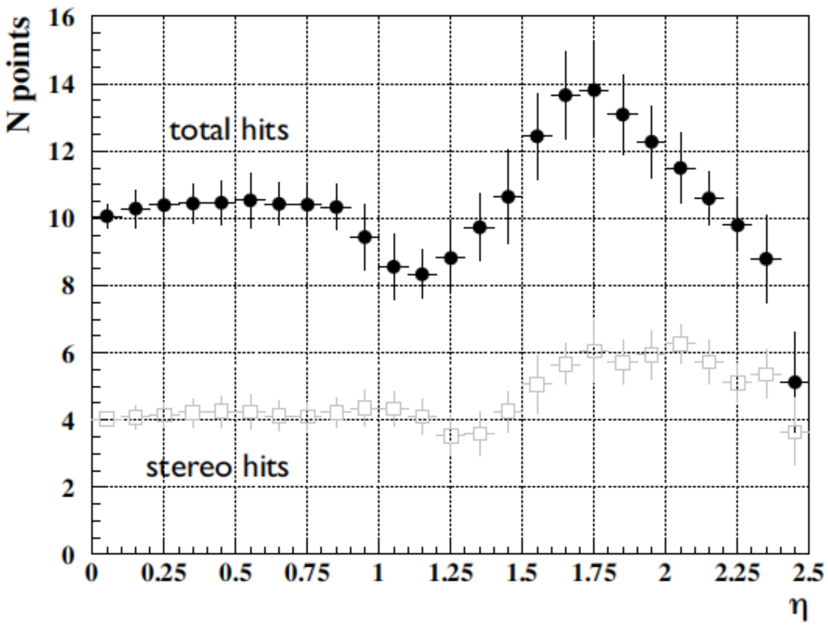
Pseudo-rapidity: $\eta = -\ln\left[tg\left(\frac{\theta}{2}\right)\right]$



CMS: fully silicon tracker

- Inner pixel detector (1 m^2 active area)
- Outer strip detector (200 m^2)
- Operated in a 4T magnetic field





multiple scattering due to the large amount of material (0.5 X_0 on average).

Single hit resolution: 8 - 64 μm.

Transverse momentum resolution: 0.7 - 5 %

Large number of hits per track

The error bars reflect the RMS of the distribution for many tracks with smeared primary vertices in the given η range.

Comparison

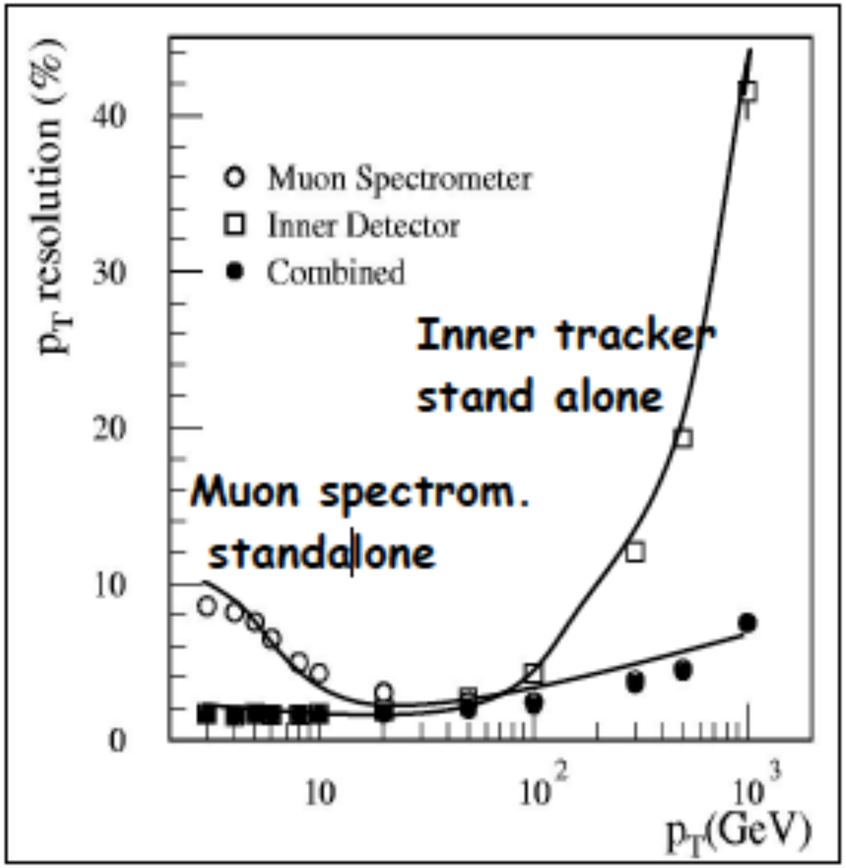
ATLAS / CMS barrel tracking

Charge sharing used to determine where charged particle passed through the detector. This way can get resolution much smaller than strip or pixel size

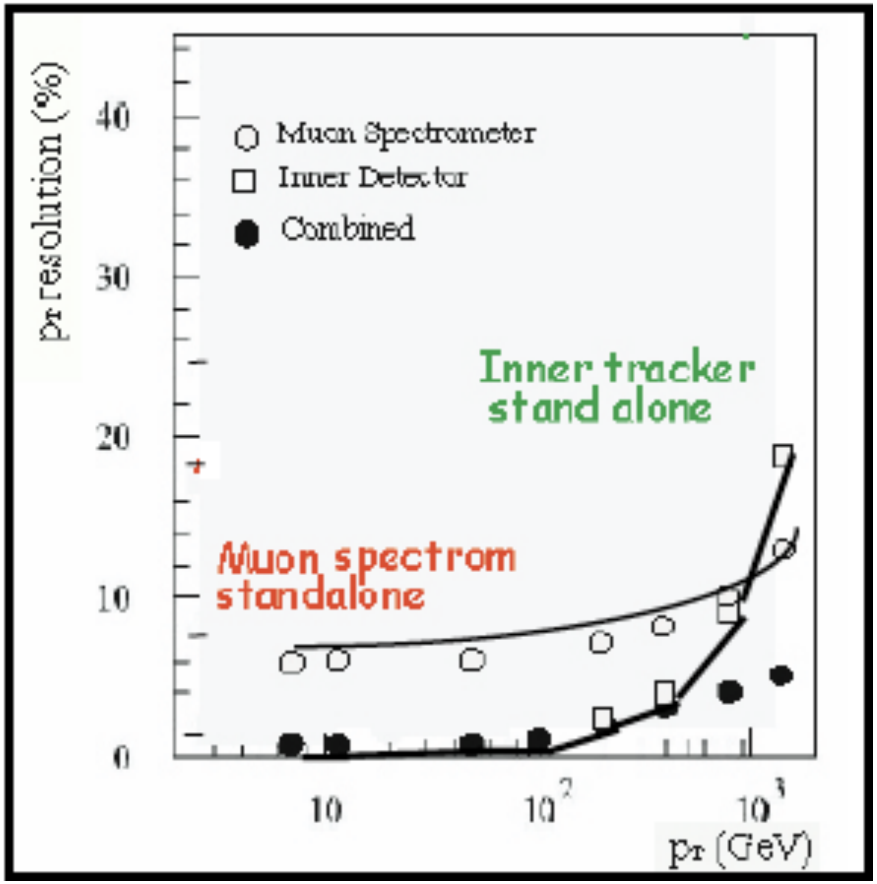
	ATLAS	CMS
Magnetic field (T)	2	4
Pixels:		
#hits	3	3
resolution (μm)	≈10	≈10
radius inner/outer	5.1/12.3	4.4/10.2
pixel size (μm^2)	50x400	100x150
channels	80 M	66 M
Silicon Microstrips:		
#hits	8	14
strip pitch (μm)	80	80/120
radius inner/outer (cm)	30/60	20/107
channels	6.2 M	9.6 M
Straw Tube Tracker		
#hits	35	
radius inner/outer (cm)	60/107	
cell size/strip pitch	4mm	
channels	0.35 M	

Muon momentum resolution (expected)

ATLAS



CMS



Transverse momentum resolution degrades with particle momentum