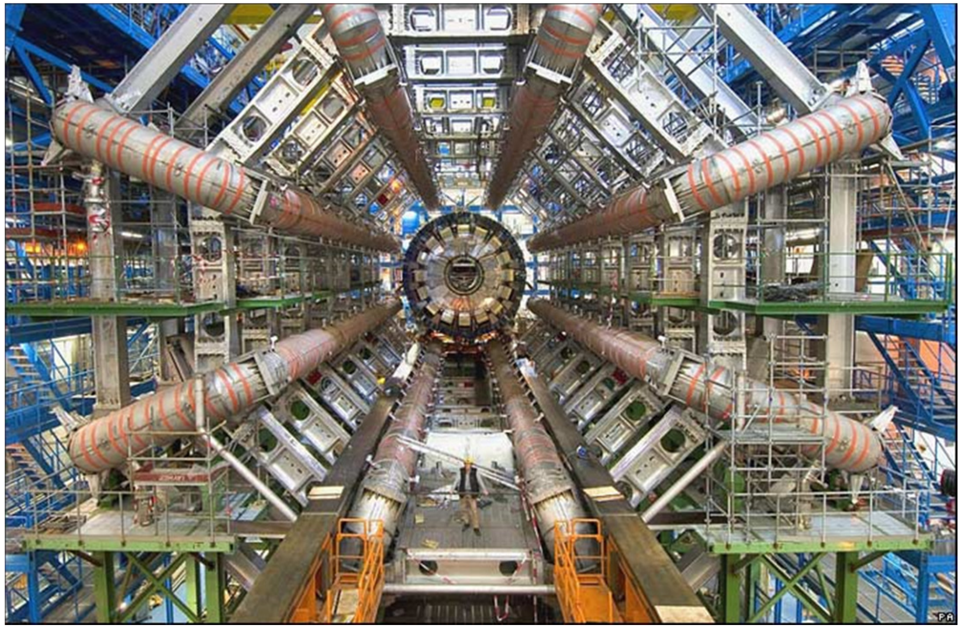
MUON DETECTION AT THE LHC

1. Basics: Muons and their interactions with matter
2. Principles of gas-filled detectors
3. Types of gas detectors
4. Implementations at the LHC



Kerstin Hoepfner
RWTH Aachen, III. Phys. Inst. A

THE BASICS

Muon properties

Why do muons have their own detection system?

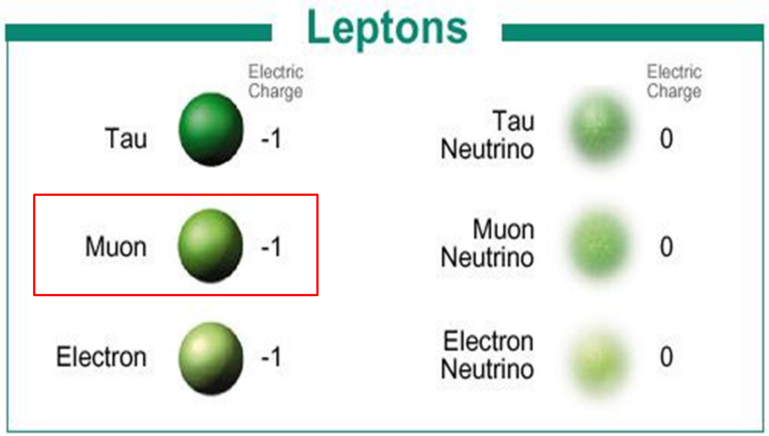
Interactions of muons with detector material

A Lepton Named „Muon“

Muon properties

- Lepton of 2. family
- Mass 105,6 MeV
- Muon charge: -1 or anti-muon charge: +1
- Spin: ½
- Discovered in cosmic rays 1937 by Anderson with a cloud chamber

- Muon is a heavy copy of electron, interacts electromagnetically, but not strongly
- Energy loss mainly due to ionization → can pass through a lot of material
- Mean life = 2.197 × 10^{-6} s → does not decay in the detector

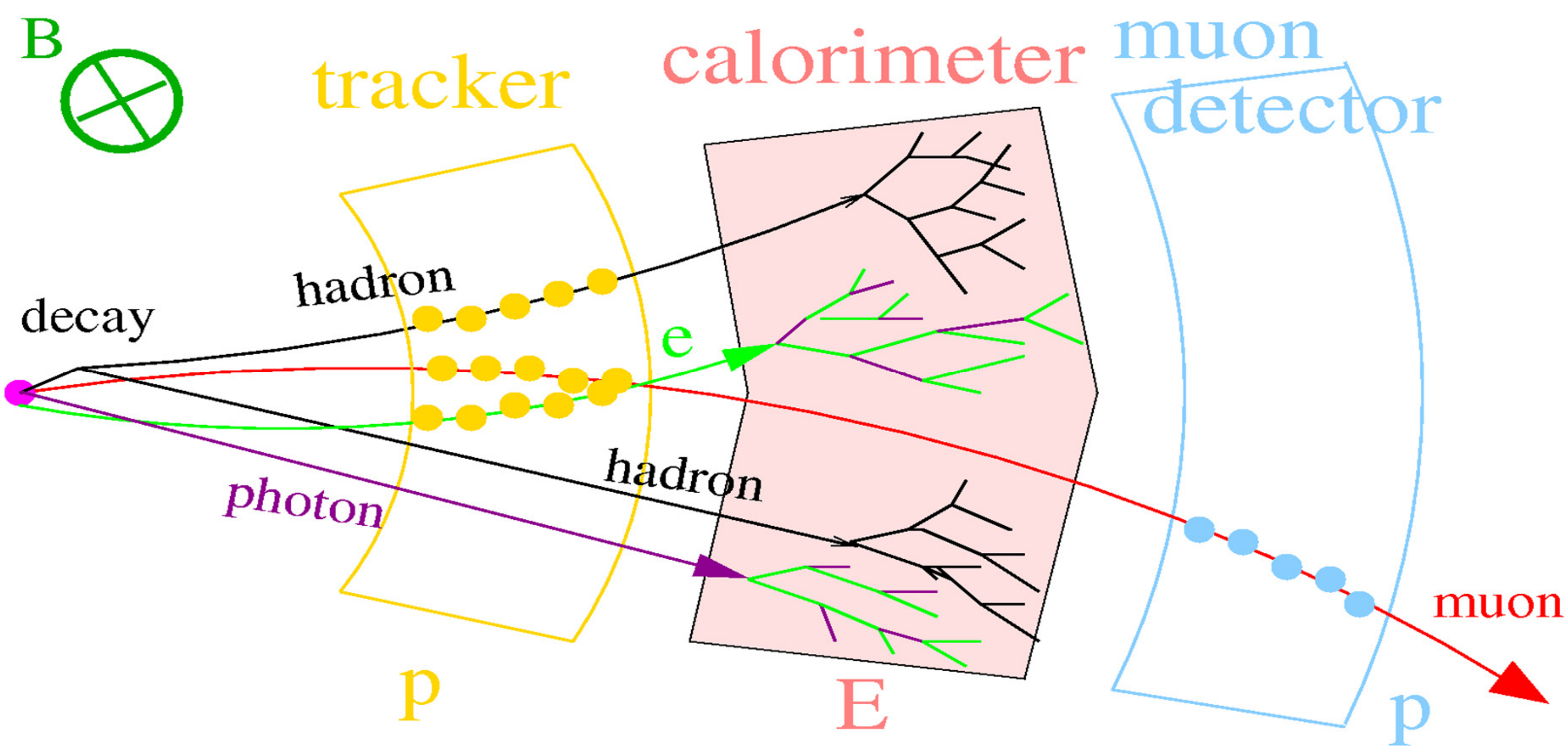


Anderson's cloud chamber to study cosmic rays (1937)

Particle Detection

Detection of particles through their interaction with matter → deposition of energy → electrical signal

- Ionization
- Bremsstrahlung (up to LHC energies mainly for electrons)
- Shower (electromagnetic for e/γ, strong for hadrons)



Neutrinos → Missing transverse energy

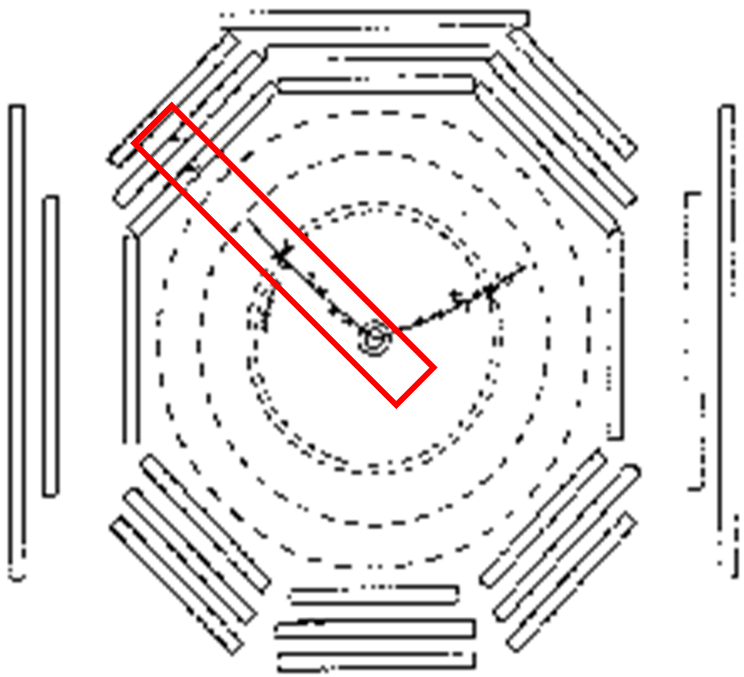
Important Discoveries with Muons

Tau Lepton:

SLAC 1975

Martin Perl et al.

$$e^+e^- \to \tau^+\tau^- \to \mu^- \, e^+ \, \nu' s$$



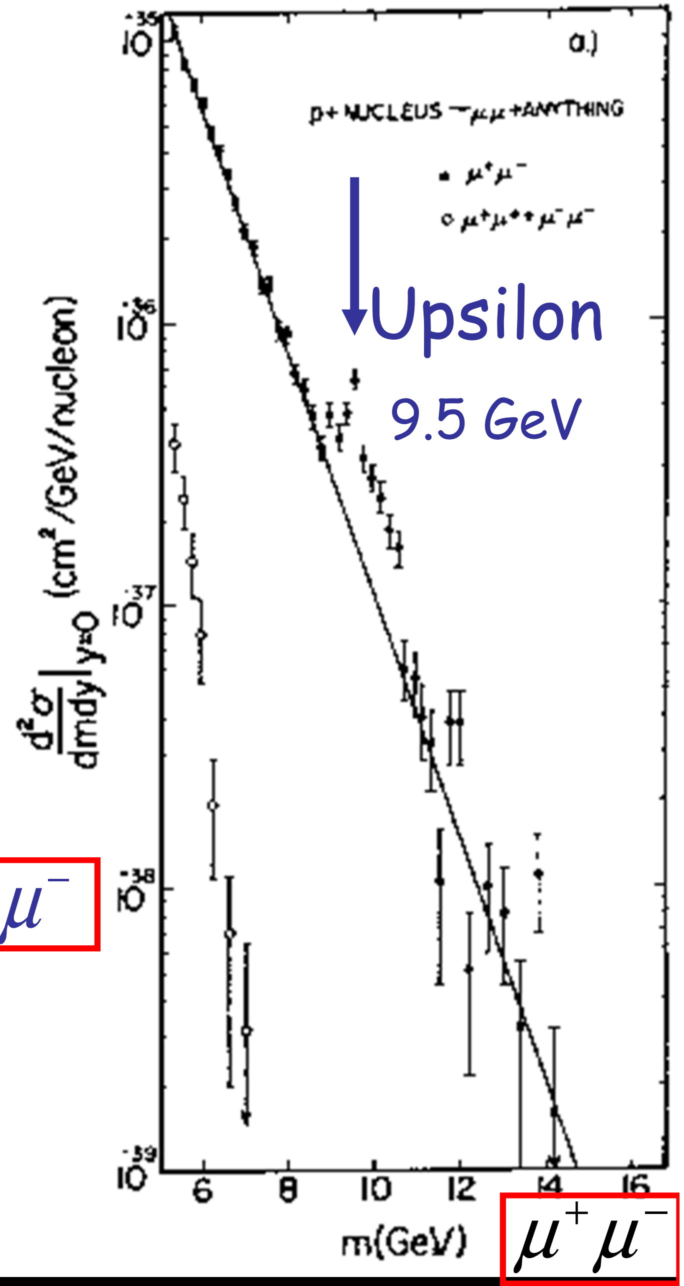
b-quark:

Fermilab 1977

Leon Lederman et al.

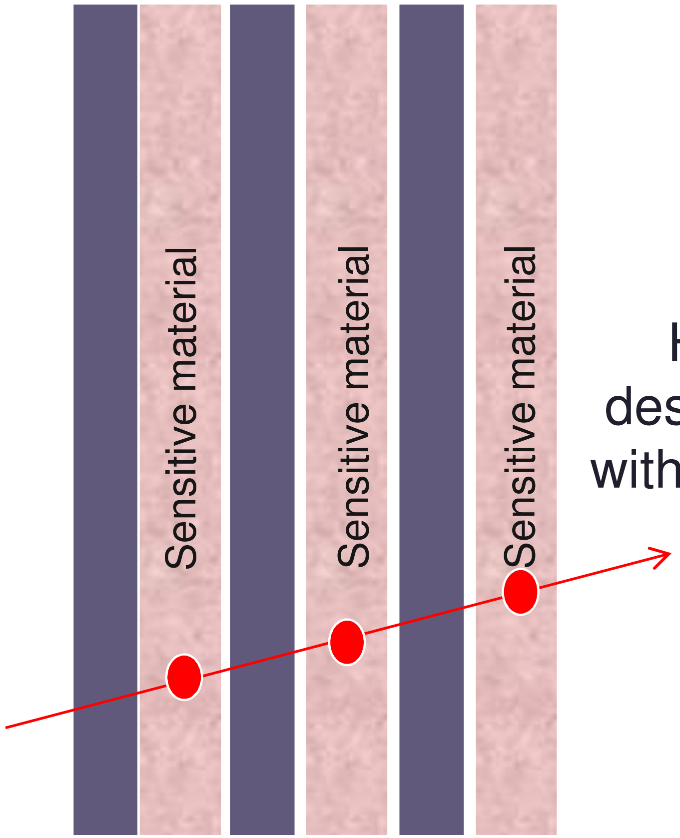
$$p + A \to \Upsilon \to \mu^+\mu^-$$

$$b\bar{b}$$



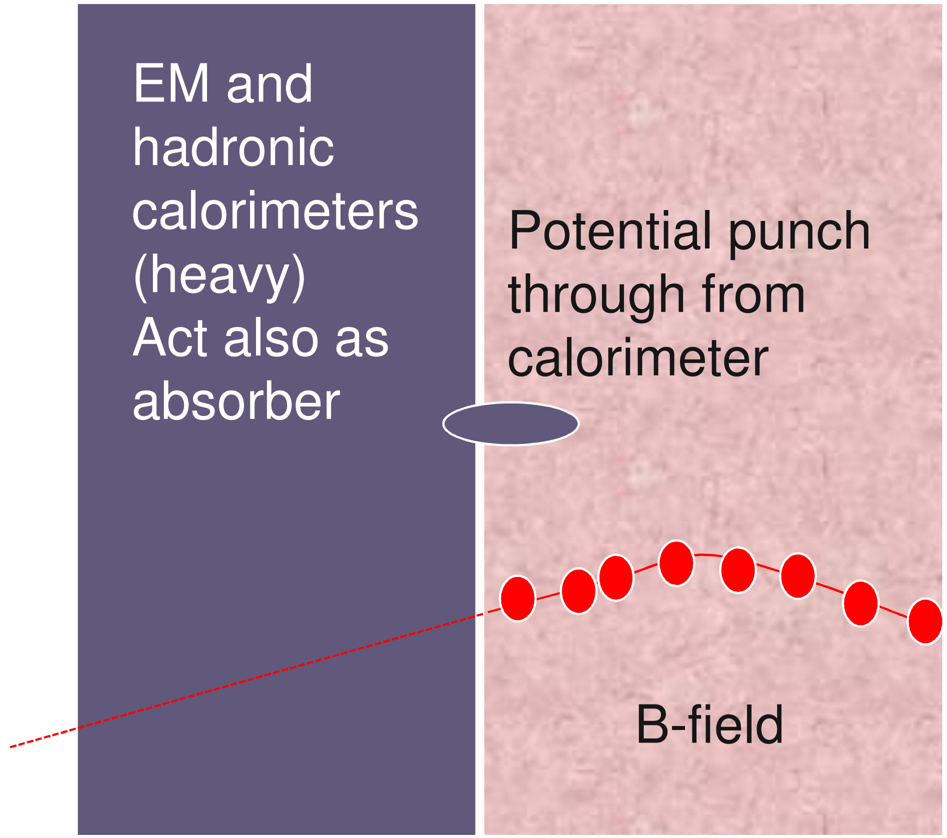
Basic Muon Detector

Material to absorb everything other than muons (thickness energy dependent)



Historic design, often without B-field

Today's design (very generic)



Because muons traverse the detector, signatures with muons in final states are relatively easy to detect → most golden channels are the ones with muons in the final state

Detectors for Muon Systems

Requirements for muon systems:

- Very large areas to cover O(100 m2)
- Low occupancy allows relatively large cell sizes O(mm)
- Low radiation levels

Main technologies:

- Planes of scintillator between absorber
- Gas-filled detectors in many different implementations ← Main technology

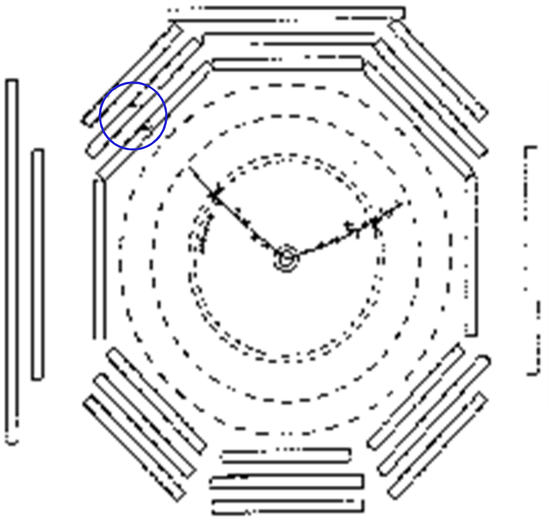
Advantages of gas detectors:

- Large radiation length X_0, multiple scattering proportional to $1/\mathrm{sqrt}(X_0)$
- Large volumes / areas possible, momentum resolution $\Delta p/p \sim 1/L^2$
- Can be segmented, multiple layers in a station
- Relatively inexpensive, mostly gas

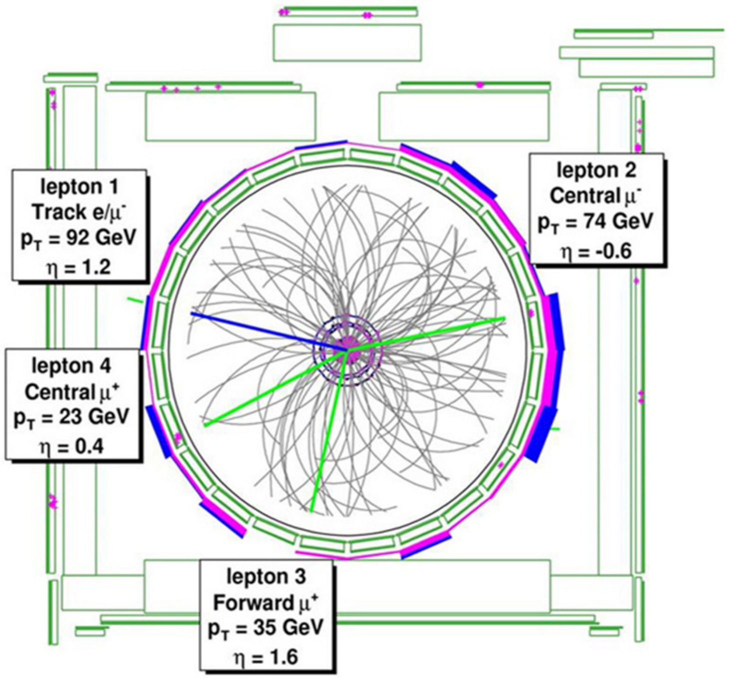
Historic Development

- In the past muon system concentrated on muon ID
- Today, at LHC, muon systems are full sized trackers

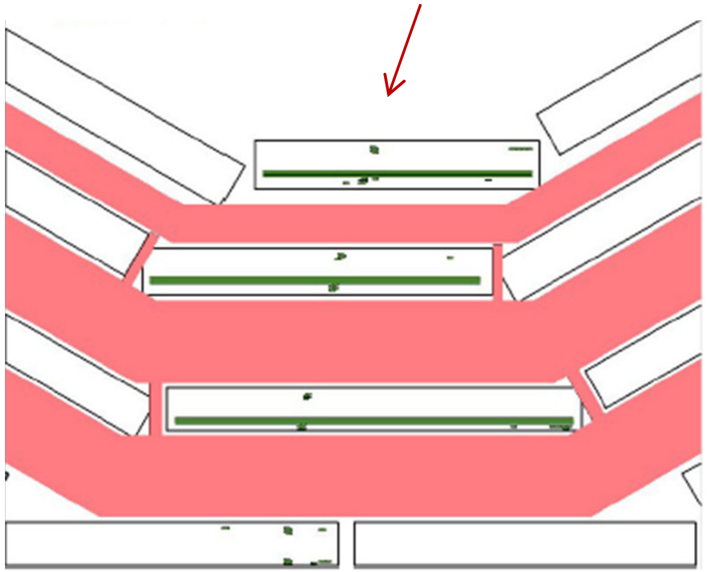
Hits in Mark-I detector at SPEAR



Muon detection in CDF at Tevatron



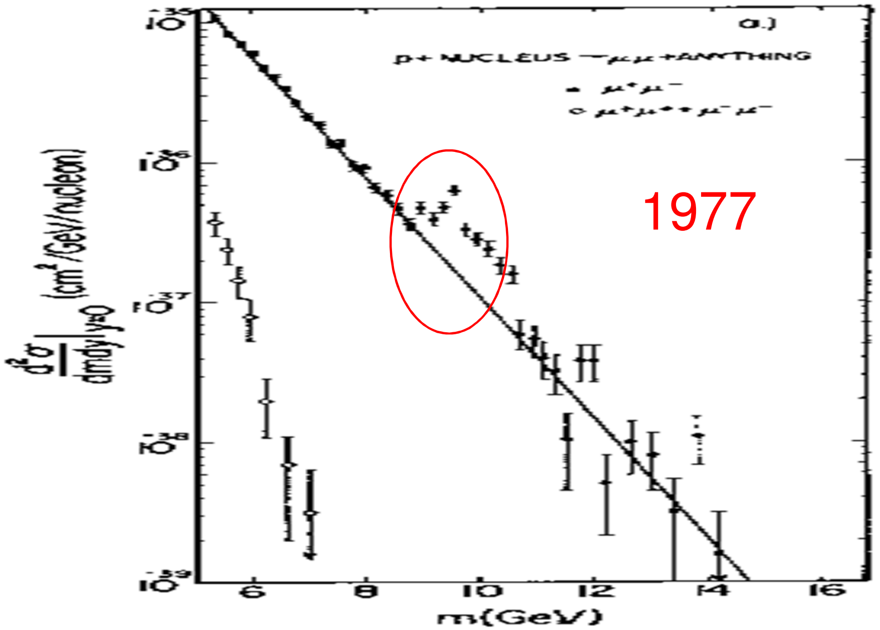
Muon track made up of O(40) hits at the LHC

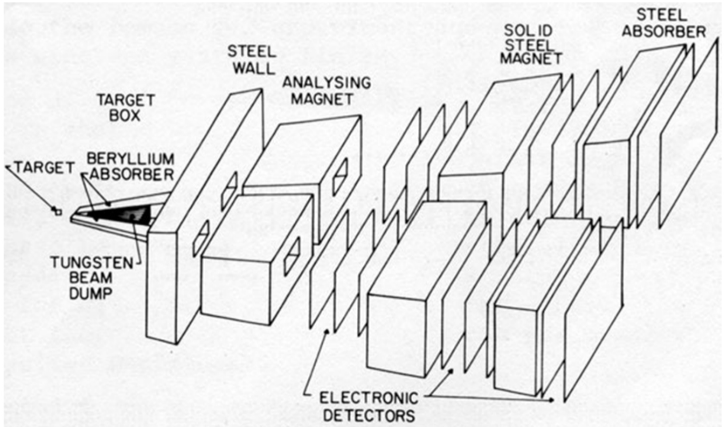


Muon system alone measures momentum and charge in addition to muon ID

Upsilon Signal at Discovery & Today

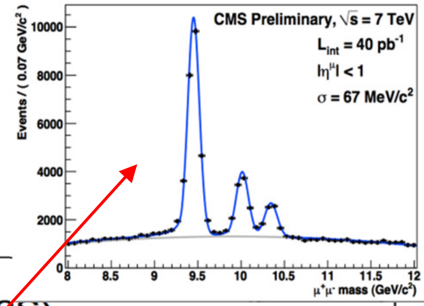
Discovery of the Upsilon 1977 at FNAL

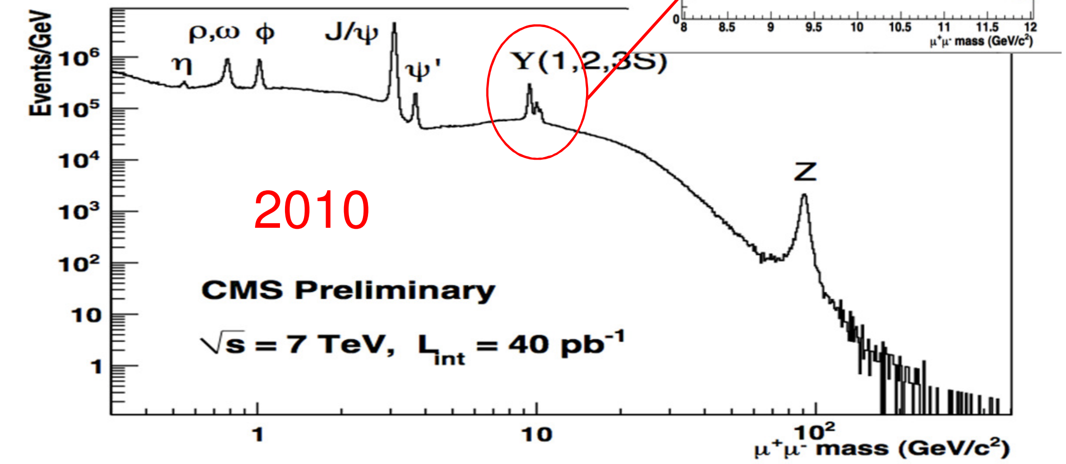


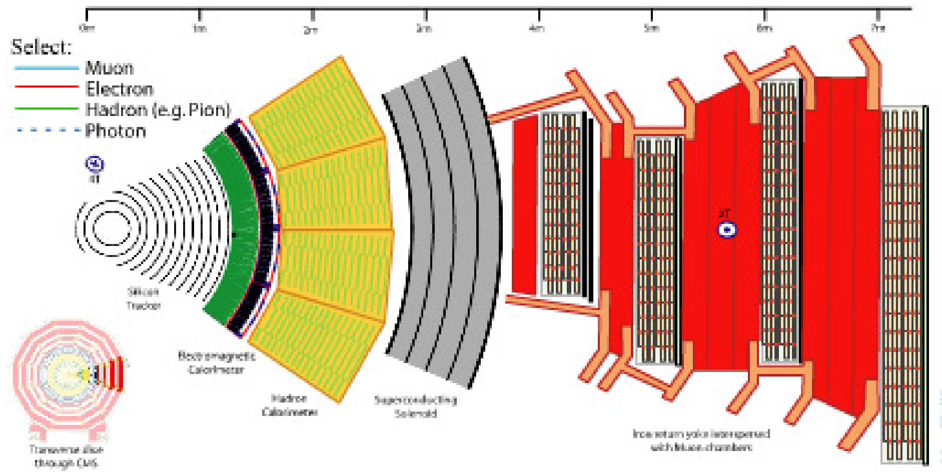


http://history.fnal.gov/botqrk.html

Observation of the Upsilon resonances Y(1,2,3S) in CMS 2010



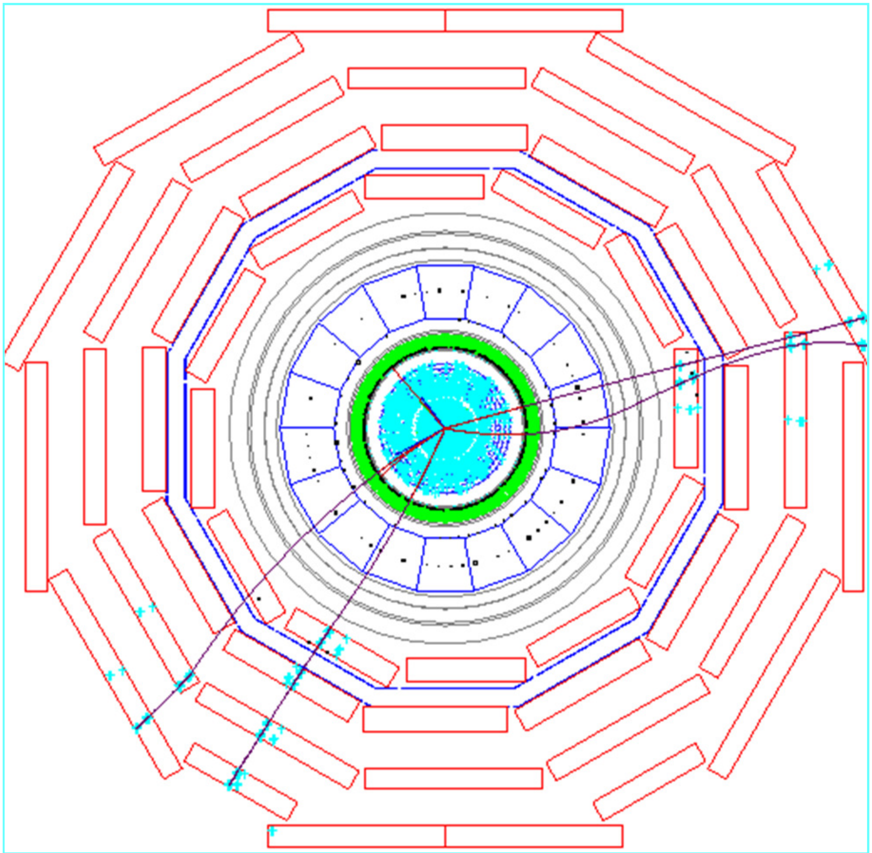




Example of Golden LHC Signature

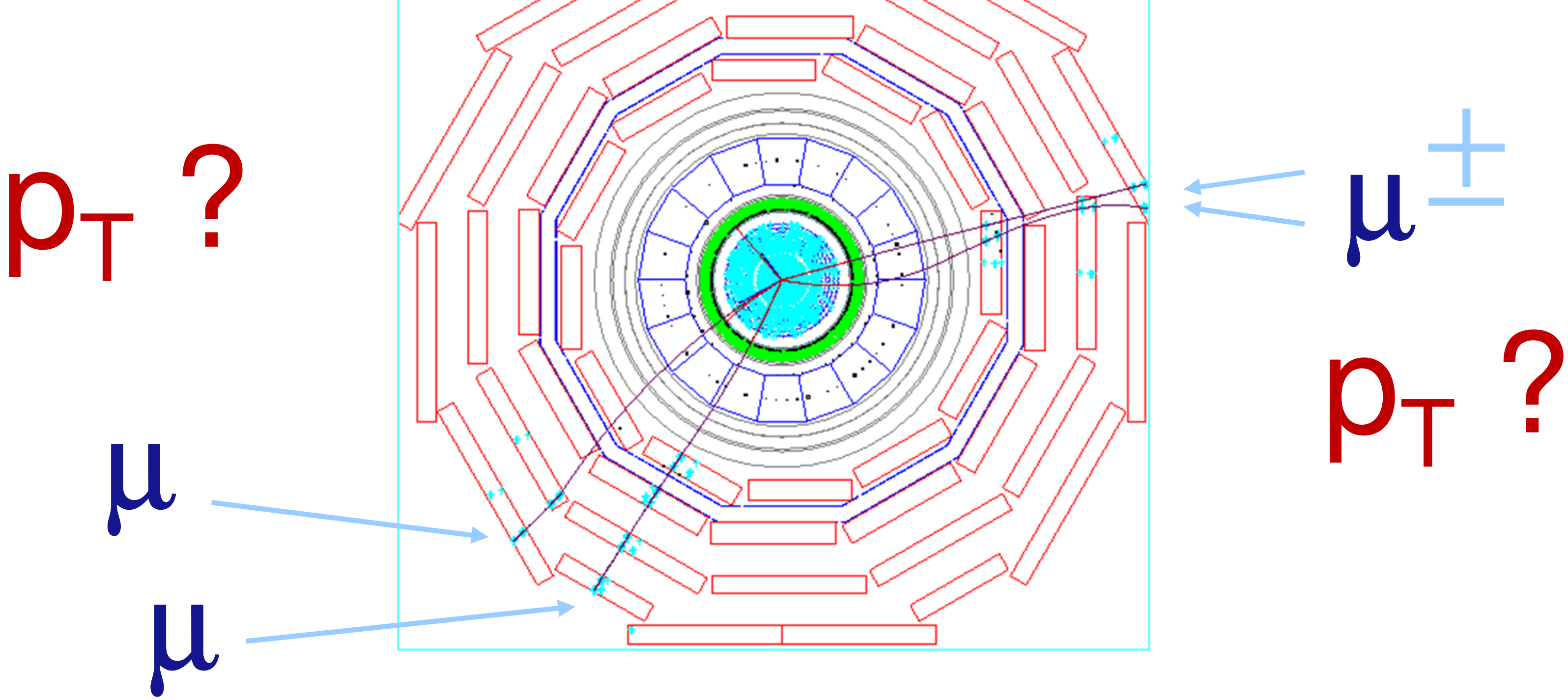
- Because muons fly so far, signatures with muons in final states are relatively easy to detect → most golden channels are the ones with muons in the final state
- Simulated Higgs event $H \rightarrow ZZ \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
- Guiding physics channel for the design of ATLAS & CMS muon systems

At high interactions rates of the LHC, high resolution measurements needed → muon SA track segments



How to Detect Muons?

$H \rightarrow ZZ \rightarrow \mu^+ \mu^- \mu^+ \mu^-$



- **Muon-ID** By Absorption and Tracking in the Muon System
- **Charge** Curvature in B-Field
- **Muon p_T** Bending of the track , to combine with tracker needs alignment
- **Acceptance** Tracker and Muon System
- **Efficiency** $\varepsilon_{Higgs} = \varepsilon_{\mu}^4$

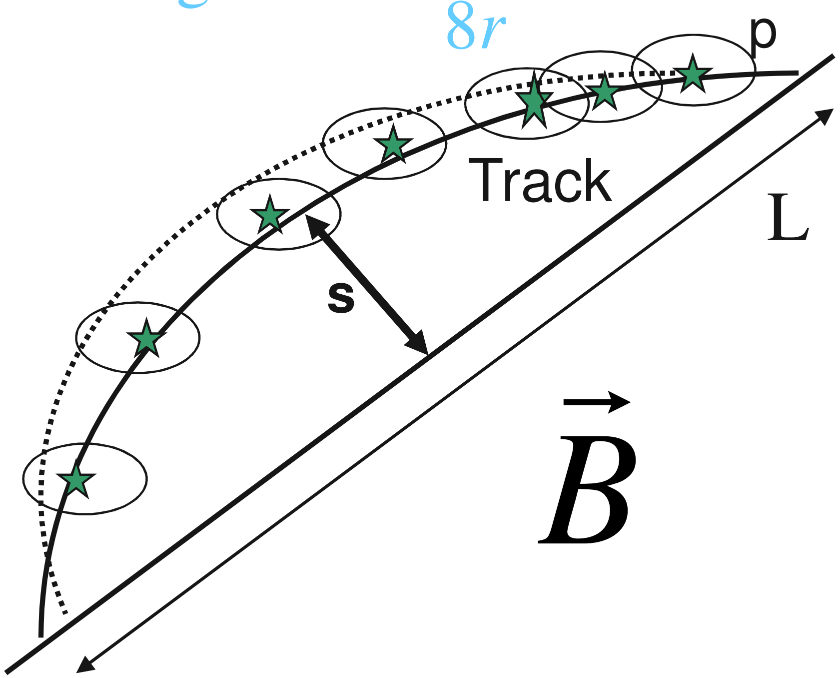
Precise Momentum Measurement

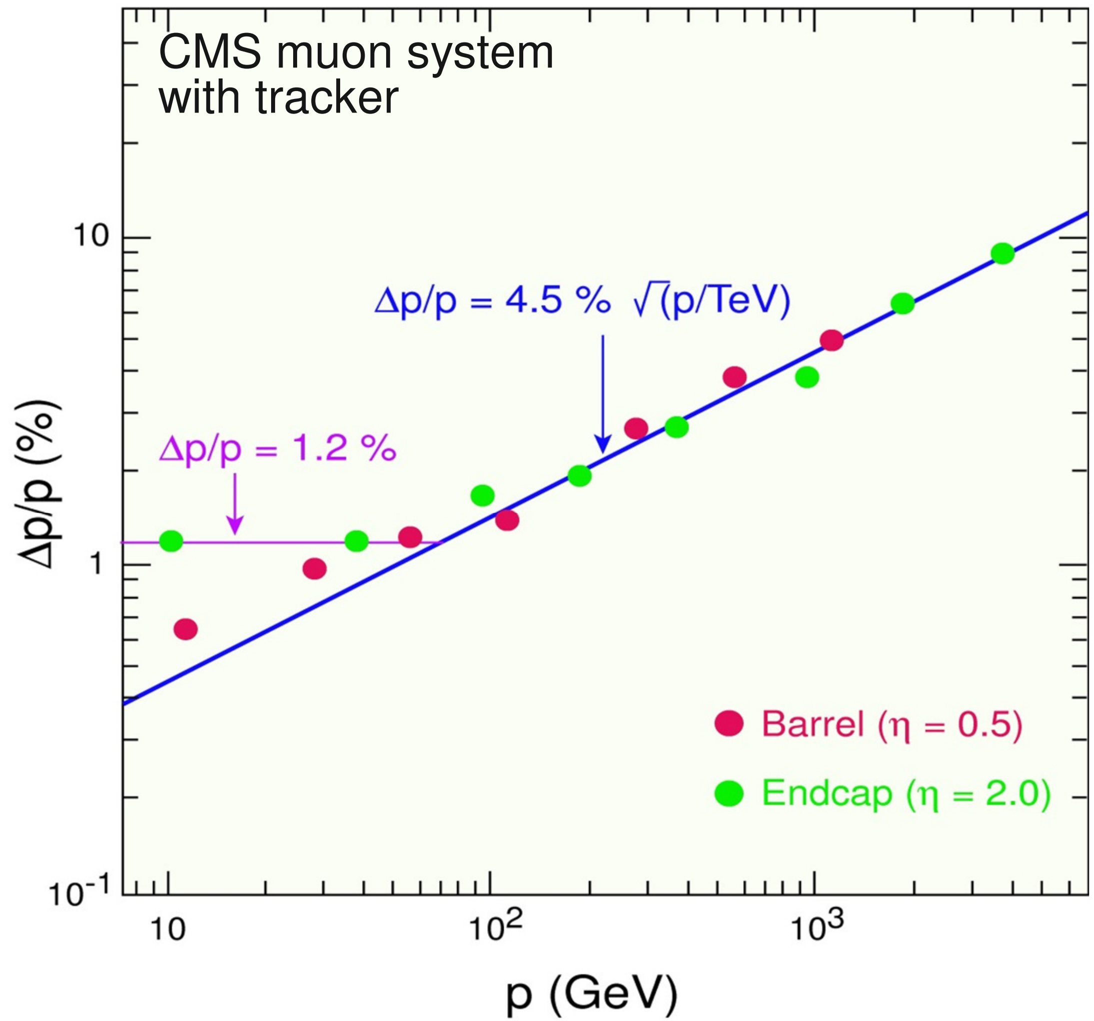
$$\frac{\Delta p}{p} \sim \frac{p}{L^2 B} \cdot \frac{\sigma_x}{\sqrt{N}}$$

See also Tracker lecture by Pippa Wells

Sagitta s of a 1 TeV track = 180 µm
→ Resolution 10% ~20 µm
Track length ~2m

Sagitta $s = \frac{L^2}{8r}$





Precision is a function of p
Increases with $1/BL^2$ and 1/sqrt(N)

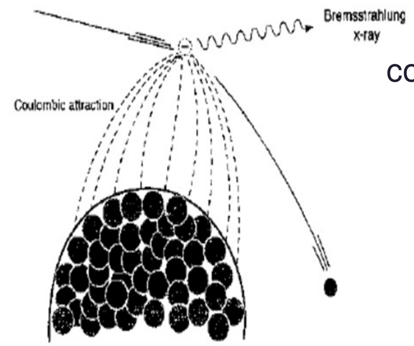
Bremsstrahlung of Muons

- Main energy loss due to ionization (Bethe-Bloch dE/dx)
- Additional energy loss through electromagnetic interaction in the coulomb field of the nucleus

$$-\left(\frac{dE}{dx}\right)_{brem} = 4\alpha \cdot N_A \left(\frac{e^2}{4\pi\varepsilon_0 c^2}\right)^2 \cdot \frac{Z^2}{A} \cdot \ln\frac{183}{Z^{1/3}} \cdot \frac{z^2}{m^2} E$$

Constant, independent on material and particle

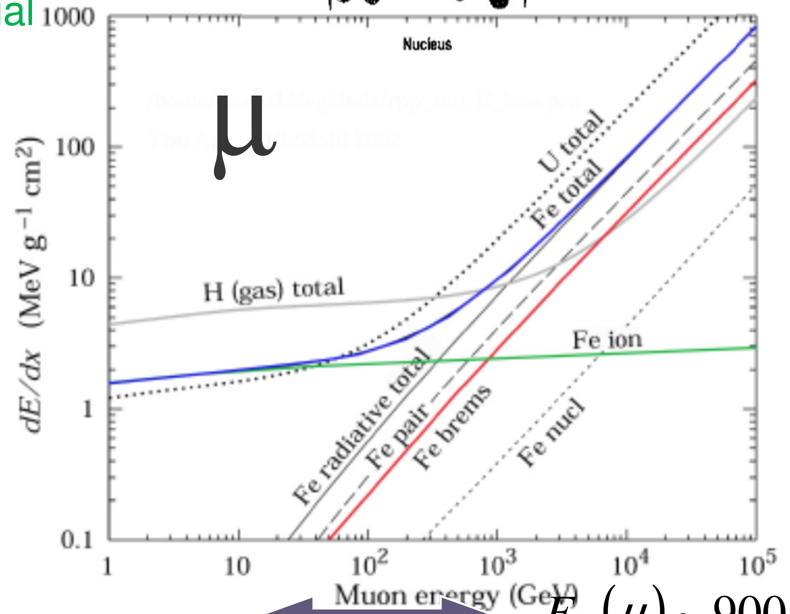
Properties of absorber material



Part of energy converted to photons

- Up to LHC energies, affected mainly electrons (Synch.radiation)

$$\left(\frac{dE}{dx}\right)_{\mu} \Big/ \left(\frac{dE}{dx}\right)_{e} \sim \frac{1}{40.000}$$



$E_C(\mu) \sim 900\ GeV$

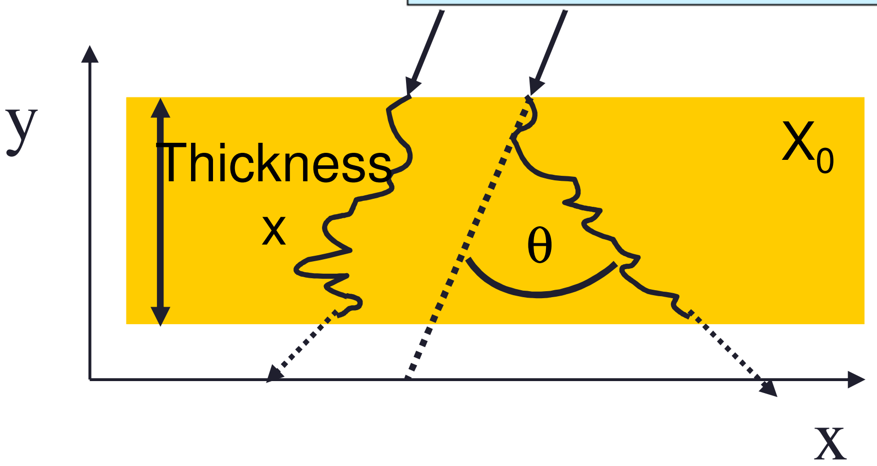
LHC muon energies

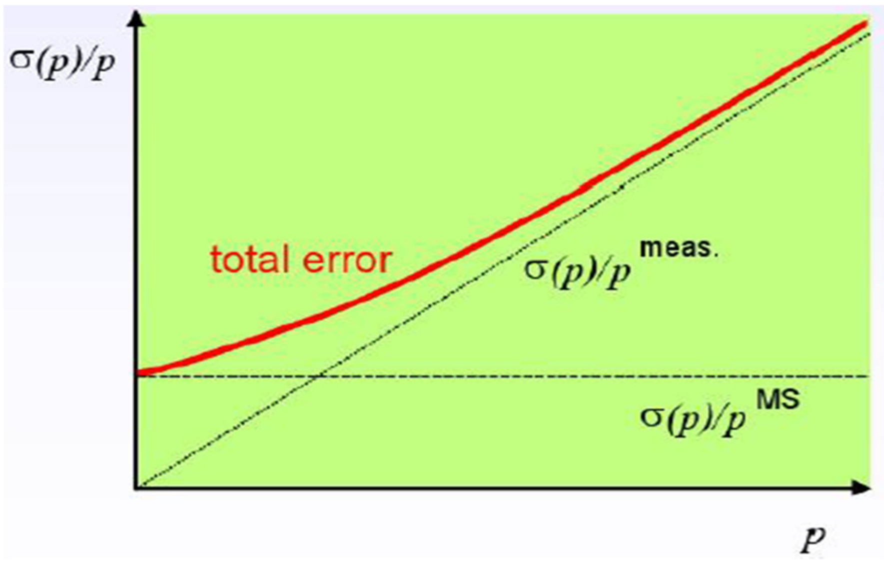
Multiple Scattering

Multiple Rutherford scattering with the nuclei of the detector material

- Small changes per collisions
- Many collisions → in the sum measurable deviation from trajectory

$$\sqrt{<\alpha^2>} = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$





Multiple scattering limits resolution

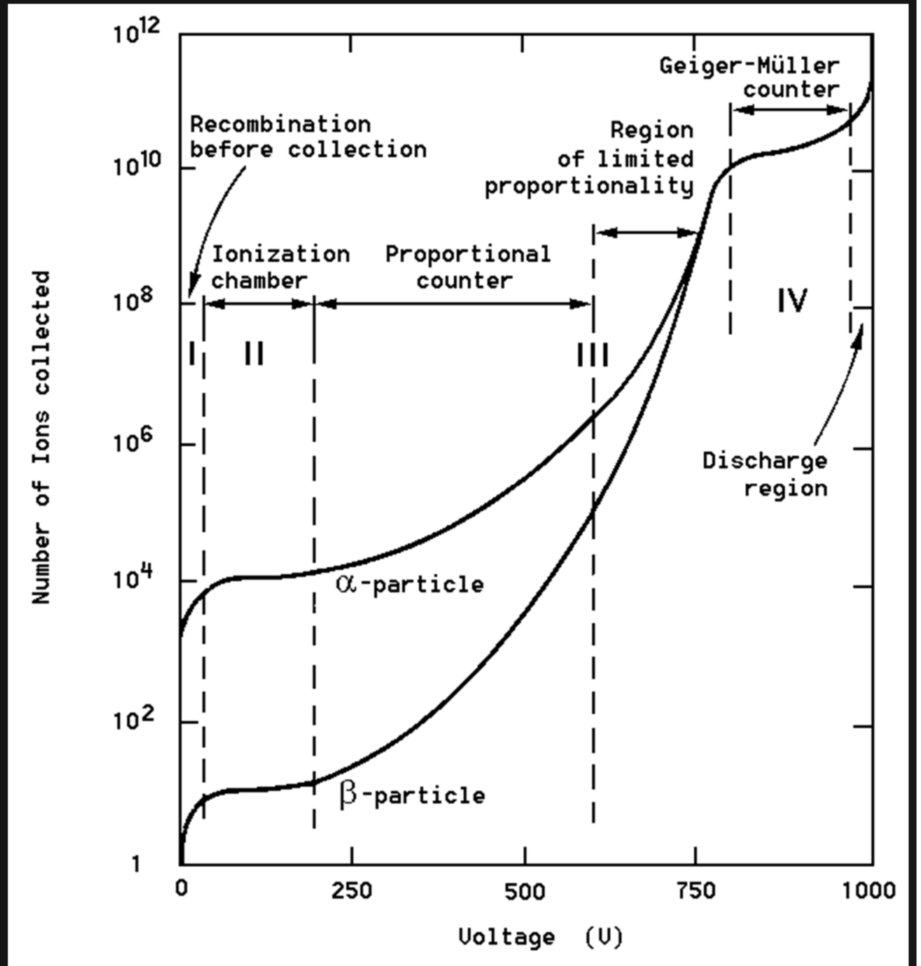
Example 100 GeV Myon:

1 m Iron = 4 mrad ~ 4 mm

1 m Air = 0.02 mrad ~ 20 μm

Independent on particle's momentum
At large momenta detector resolution dominating

Operational Principles of Gas-Filled Detectors



Main Processes in Gas

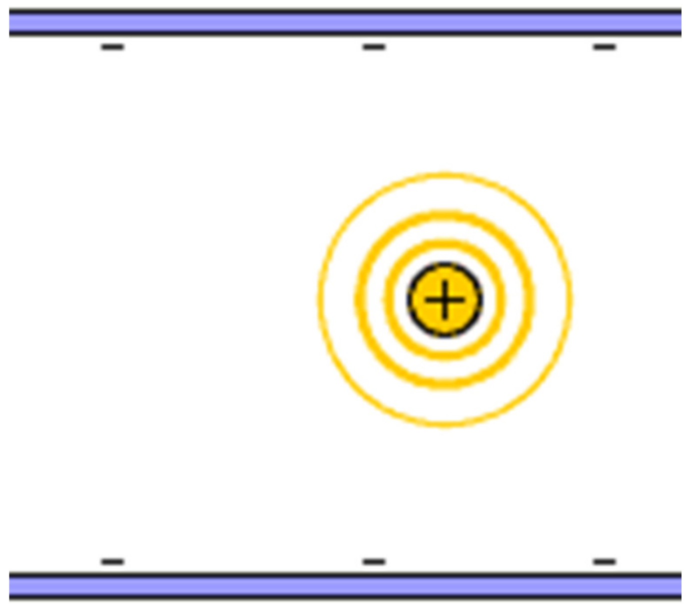
Particle detection based on ionization of gas

For gas detectors with an anode wire

1. Energy loss of charged particles, mainly through ionization
2. Energy loss transfered to gas and creation of electron-ion pairs, ionization threshold (Silicon ~3.6 eV, Gas ~20-100 eV), Statistics
3. Drift in electric field
4. Gas amplification (secondary process) in high E-field near the wire. Amplification strength → detector type. Number of primary electrons too small for direct detection

$$n_{total} = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx} \cdot \Delta x}{W_i} \approx (3-4) \cdot n_{primary}$$

5. Signal creation



Primary Ionization

Electron-Ion pairs created directly by the charged particle, along its trajectory of length L . Statistical process, depends on mean free path λ between collisions :

$$\lambda \propto \frac{1}{N\sigma_i} = \frac{1}{\alpha}$$

α = *1.Townsend-coefficient*

σ_i = ionisation cross section per electron

N = number of electrons

Collision frequency if Poisson distributed:

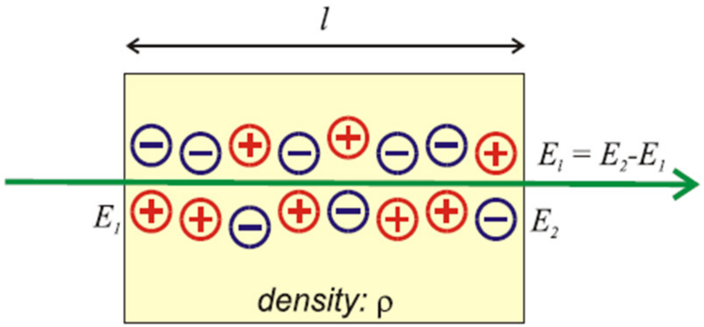
$$P(L/\lambda, k) = \frac{(L/\lambda)^k}{k!} e^{(-L/\lambda)}$$

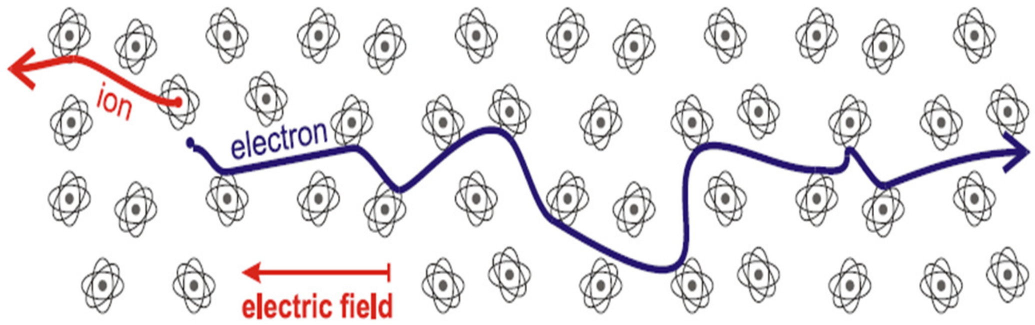
Typical values: N=10…100 e/Ion-Pairs per MIP (2 MeV/g cm^{-2}) in 1 cm gas.

Gas	σ_i (10^{-20} cm^2)	W (eV/e-Ion Pair)	dE/dx (keV/cm)	# collisions per cm (1 cm/λ) @ γ=4
He	18.6	41	0.32	~5
Ne	43.3	36	1.41	12.4
Ar	90.3	26	2.44	27.8
Xe	172	22	6.76	44
CO_2	132	33	3.01	n.n.

Ionization & Charge Separation

- Charges are distributed along the trajectory





- Electronic signal requires charge separation!

- Charge separation using electric fields, electrons and ions drift in opposite direction.

- Charge collection time → time resolution (separation of events)

Drift

Applying an electric field:

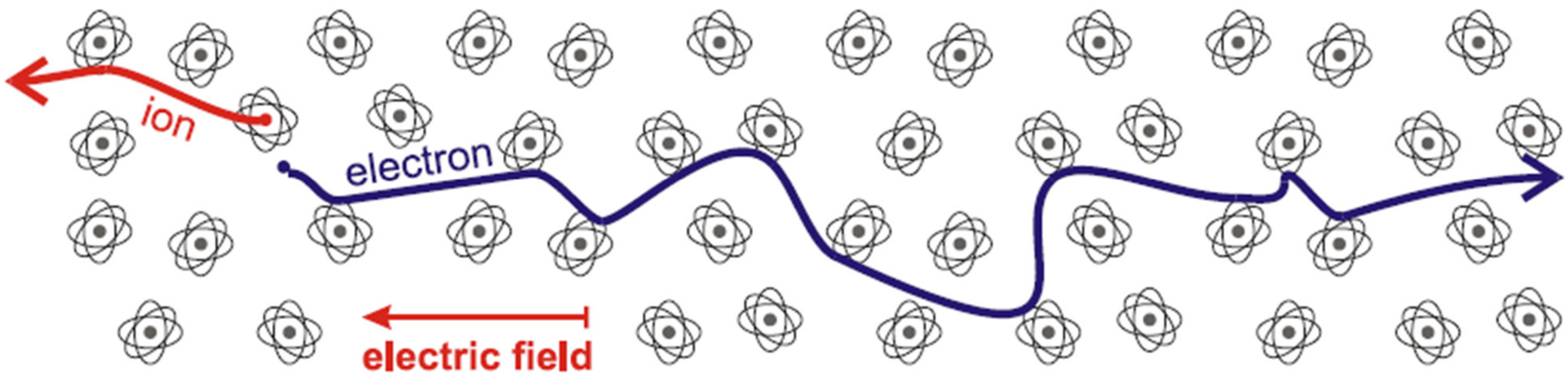
- Between the accidental collisions of the thermal movement (no particular direction) now directional acceleration due to the field
- Results in a macroscopic drift with velocity v_D

$$v_D = \mu \cdot \frac{p_0}{p} \cdot \vec{E} = \mu \cdot \frac{\vec{E}}{p}$$

P_0 = Standard pressure

P = gas pressure

μ = mobility



Drift Electrons and Ions

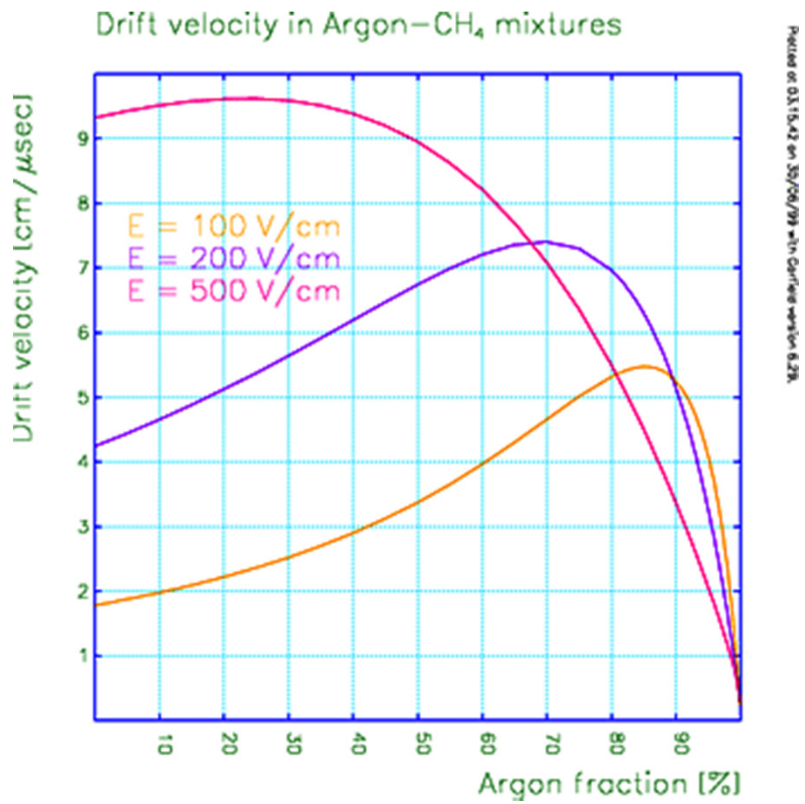
Drift of electrons

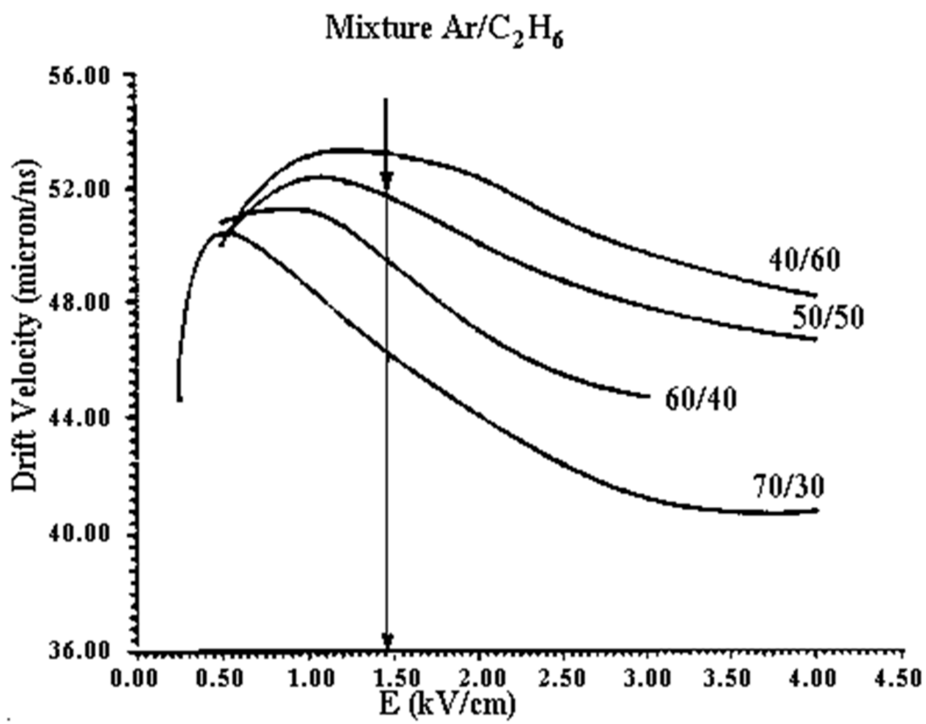
$$v_D = \mu_{Gas} \cdot \frac{p_0}{p} \cdot \vec{E}$$

Drift of ions: ions are much heavier, slower drift, less diffusion

$$v_D^+ = \mu^+ \cdot \frac{p_0}{p} \cdot \vec{E}$$

$$v_D \approx 10^3 \cdot v_D^+$$



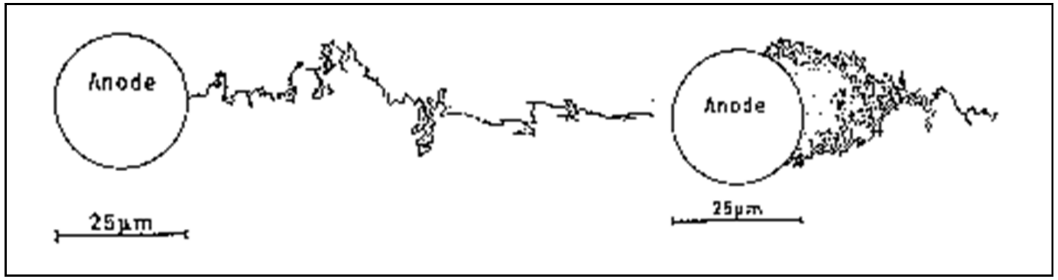


Gas Amplification

- Primary ionisation: typically ~100 e/Ion pairs per cm
- Electronics noise: ENC ~1000 e-

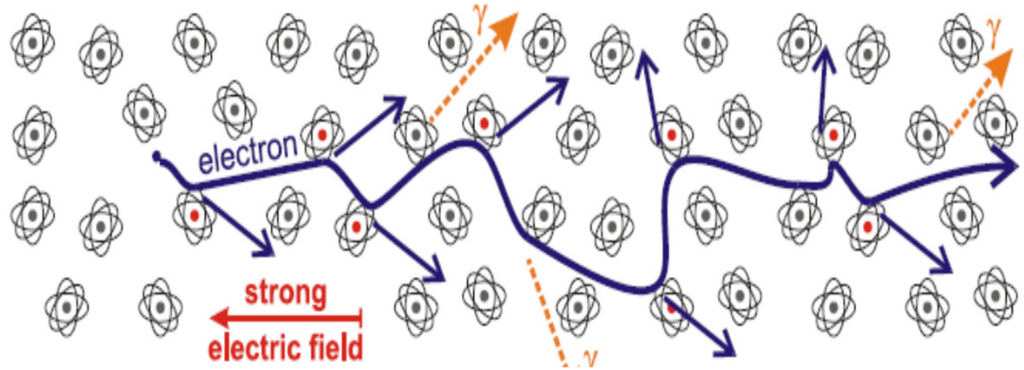
→ Signal needs to be amplified. Use high field strength near the anode wire (10^4-10^5 V/cm) → Avalanche

Drift



Amplification of the pulse by factor A

$$\Delta V_{\max} = A\frac{N \cdot e}{C} = A\frac{Q_{prim}}{C}$$

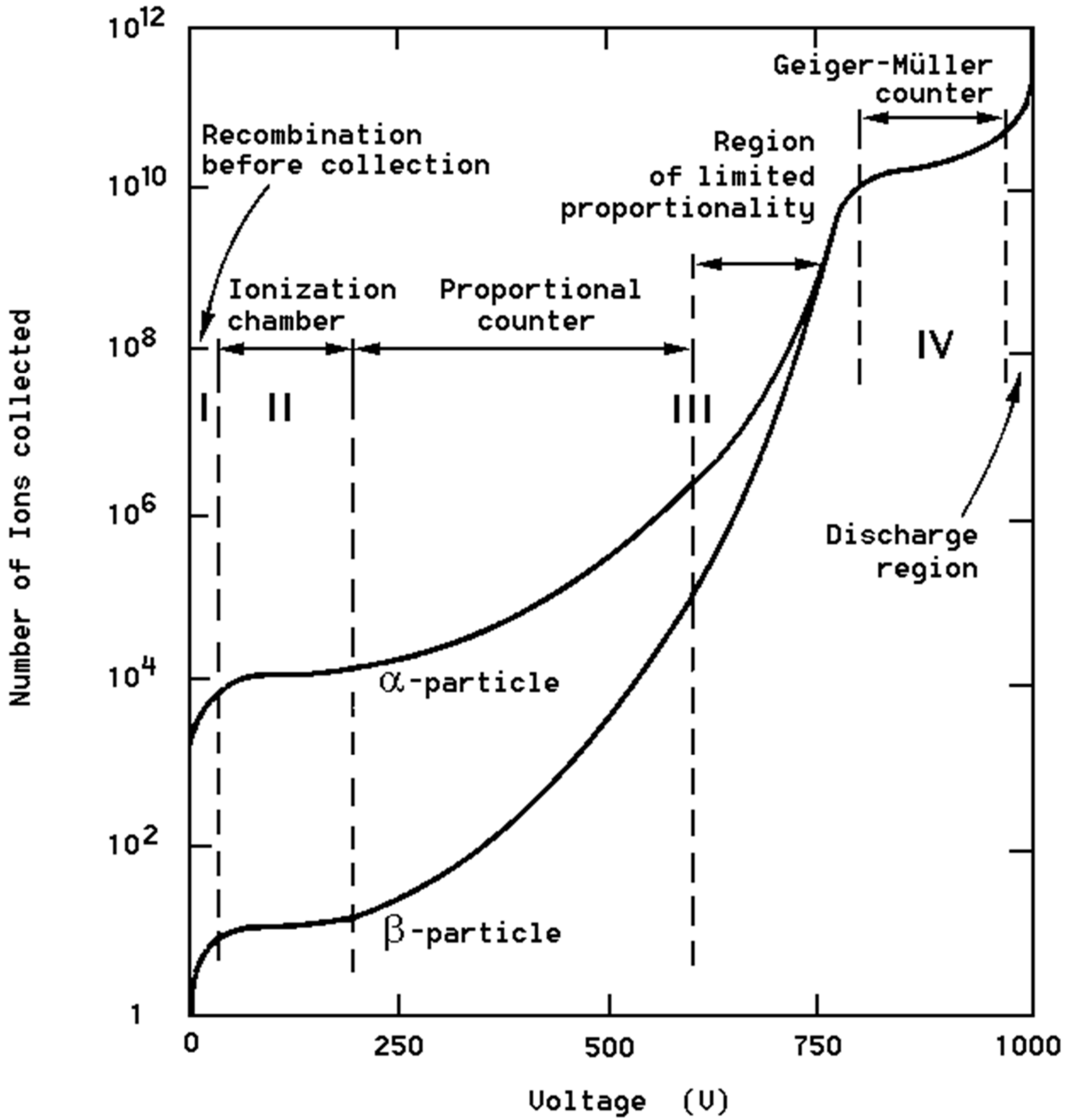


Amplified pulse can be electronically processed.

Amplification A depends on field strength E and pressure p. Region where $\Delta V \sim Q_{prim}$ (A=const) → Proportional region

Modes of Operation

Gas amplification depends on field strength (applied voltage)



I Recombination
II Ionization chamber
III Proportional counter
IV Geiger-Müller-counter
V Discharge region

proportional region prefered for most detectors

Amplification through Secondary Ionization

1. Collisions of primary electrons with further atoms (if sufficient energy)

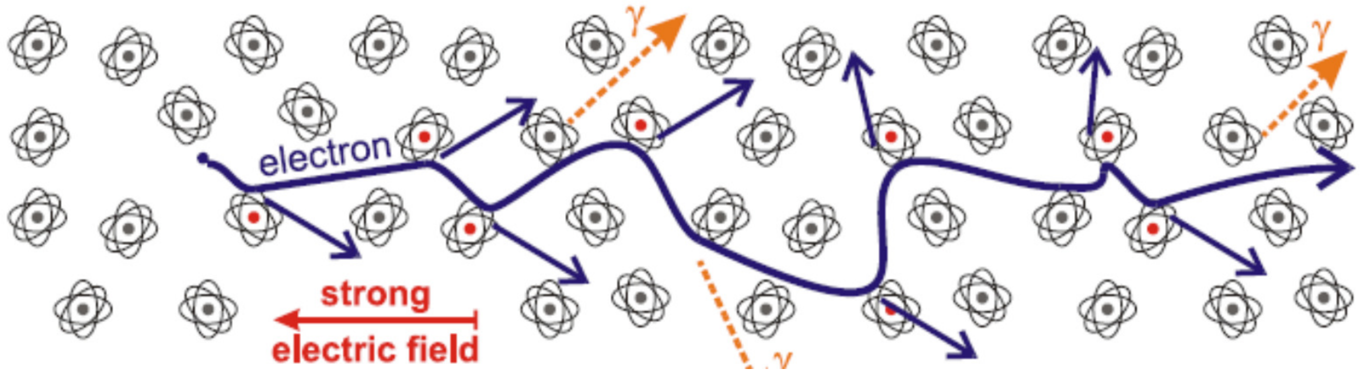
wanted

- Secondary amplification depends on Gas (α) and field strength
- Technically implemented with a thin wire (~50 μm) → $E \sim r^{-1}$
  → primary electrons gain sufficient energy for multiple secondary ionizations

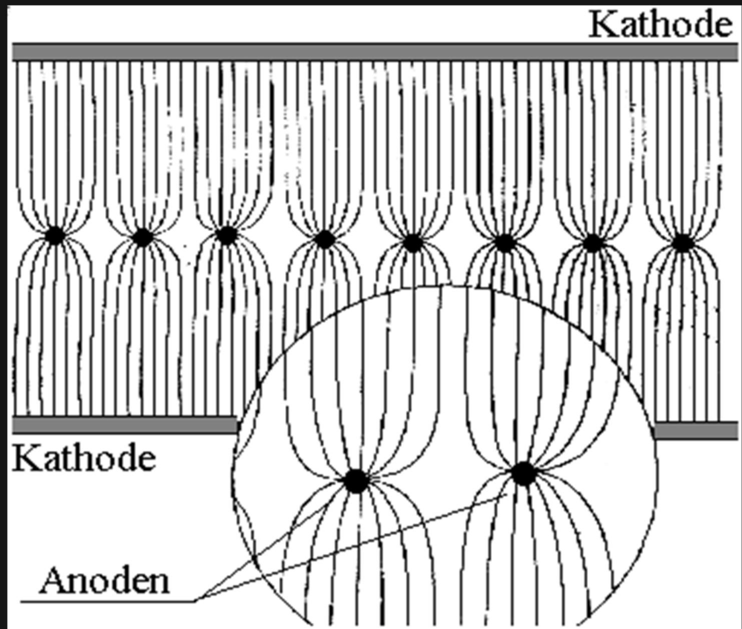
2. Energy released by atoms excited by collisions

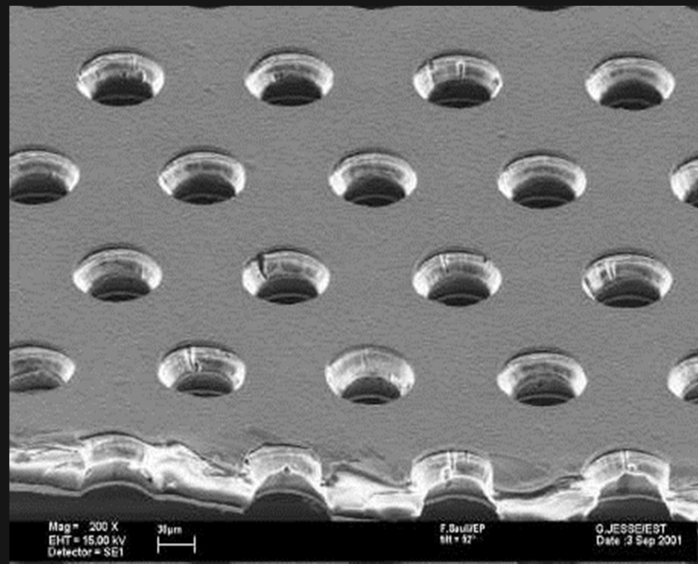
Not wanted

- Creation of UV-γ which can cause further ionization should be suppressed → reduced by addition of „quenchers“ which absorb photons
- Typical quench gases: organic molecules like CH_4, Isobutan C_3H_8, CO_2
- Note: addition of these gases modifies gas properties, like drift velocity (e.g. CO_2) and ageing (e.g. CF_4)



Types of Gas Detectors

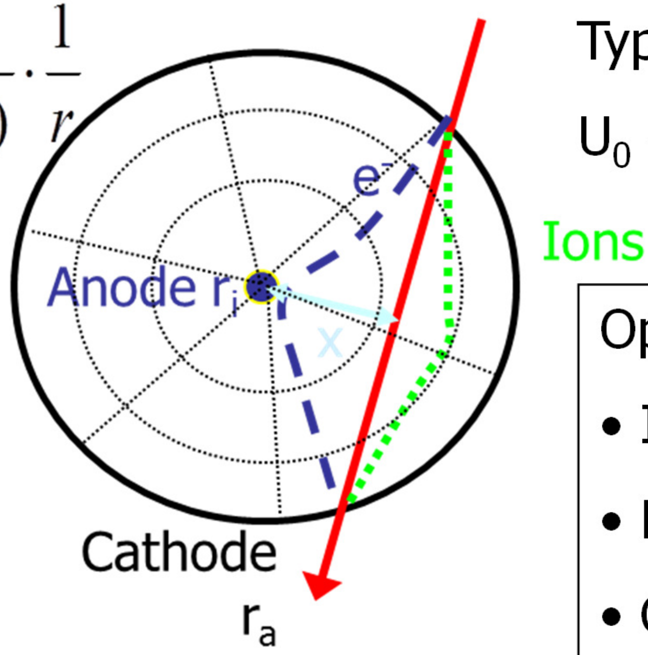




Drift Tubes (DT)

$$E(r) = \frac{U_0}{\ln(r_a/r_i)} \cdot \frac{1}{r}$$

Radiales
E-Feld



Typical parameters:

$U_0 \sim 2$ kV ; $r_a/r_i \sim$ cm/μm $\sim 10^{-5}$

Operational principle:

- Ionization along the particle's track
- Electrons drift to anode wire
- Gas amplification near the wire, $G \sim 10^3 \ldots 10^5$
- Charge collection, signal creation

Constant drift

Amplification near the wire

Applet

Resolution can be improved by:

Recording the drift time, Operation at overpressure

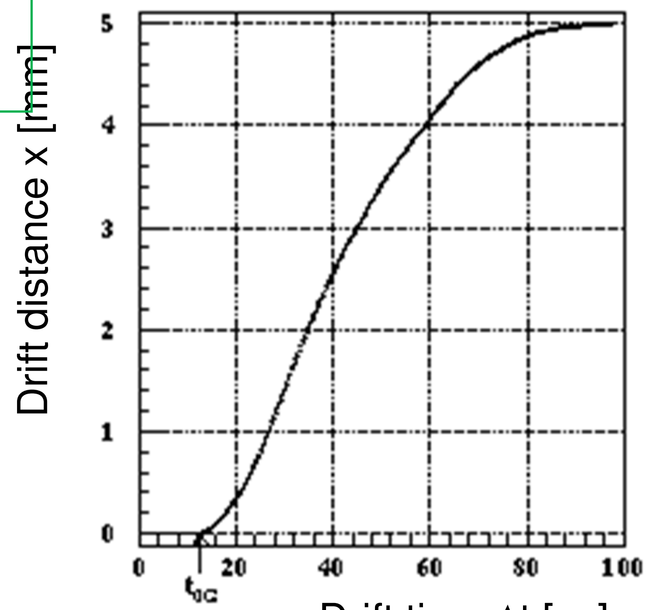
Improving the Resolution

1) Measurement of drift time Δt of electrons from location x (where particle passed) to the anode wire

Constant drift velocity v_D wanted (typically ~50 mum/ns, gas dependent)

Used by all experiments these days

$x = v_D \Delta t$

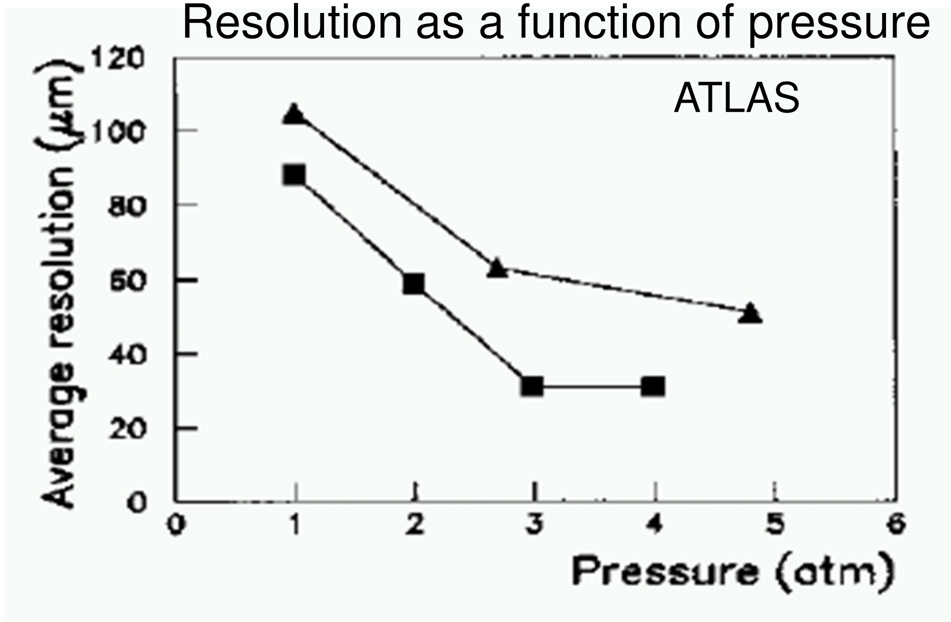


2) Application of overpressure

$$Diffusion\ \sqrt{D} \sim 1/\sqrt{p}$$

Only implemented by ATLAS

Resolution as a function of pressure



▲ ArC_2H_6 (70/30)%, d=3 cm, D_{Draht}=100 μm

■ $ArCO_2CH_4$ (45/45/10)%, d=2 cm, D_{Draht}= 50 μm

Resolution per cell (R-dependent) ~ 100 μm

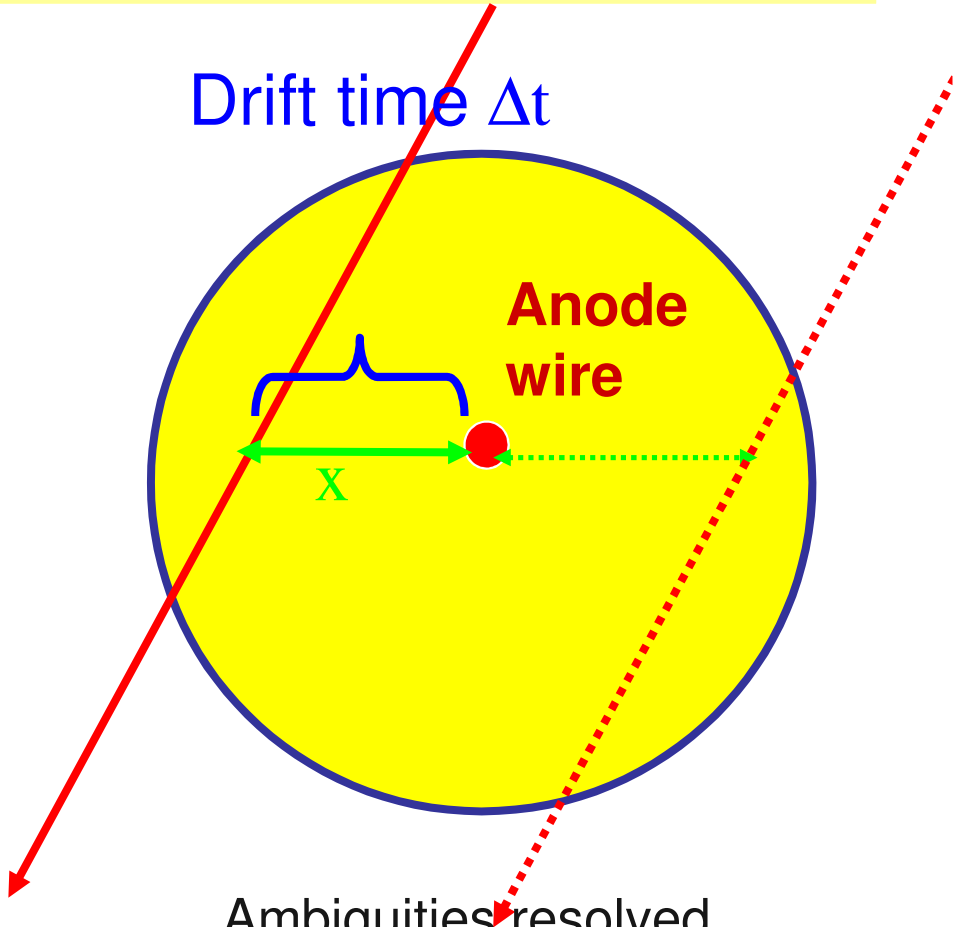
< 100 μm

Coordinate Reconstruction

Coordinate reconstruction: $\mathbf{x = v_D \Delta t}$ with v_D=const., t0 known (trigger)

Contributions to precision:

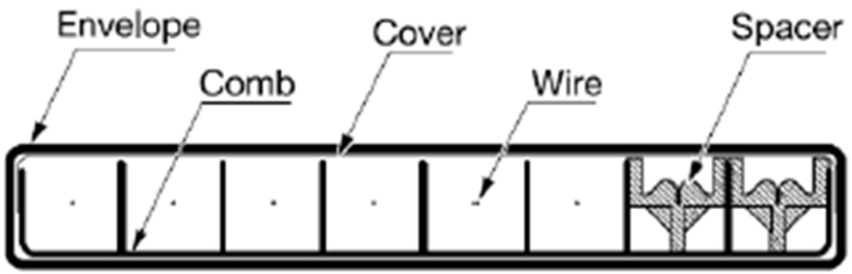
- Tolerances of drift distance:
  - mechanical precision,
  - wire positioning (~50 mum),
  - wire sag due to gravitation
- Inhomogeneities of electric field, variations of drift velocity
  - E-field,
  - gas purification
- Diffusion of drifting electrons (especially at large drift distances)
- Fluctuations in primary ionisation



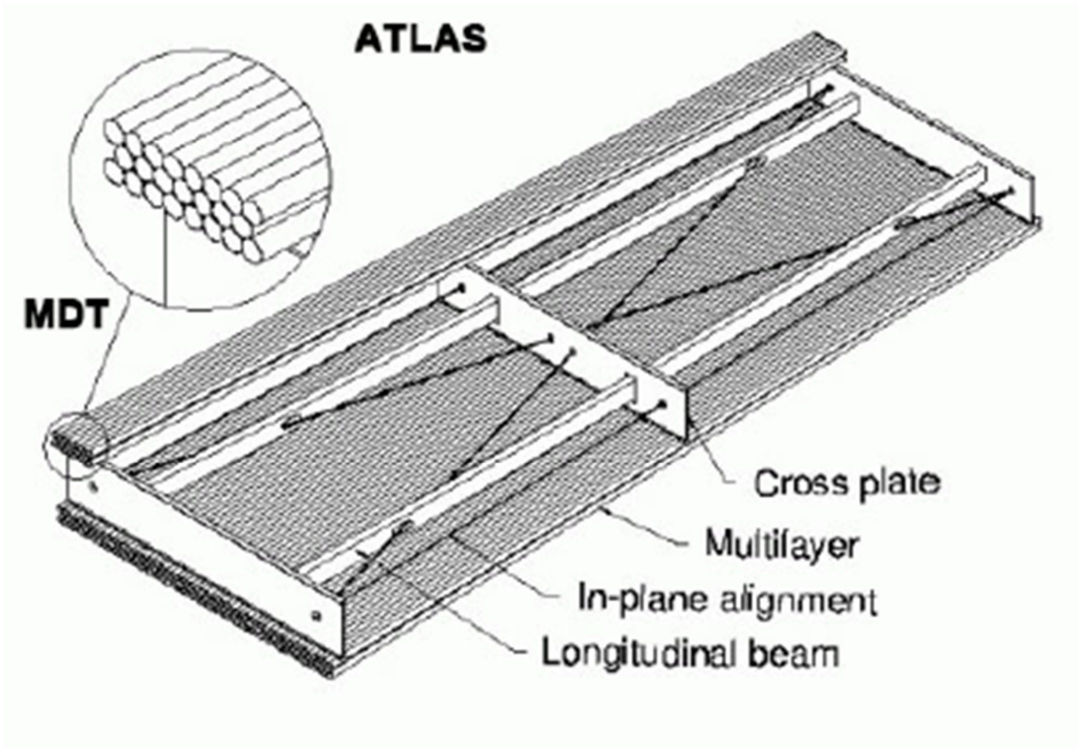
Ambiguities resolved by staggering cells

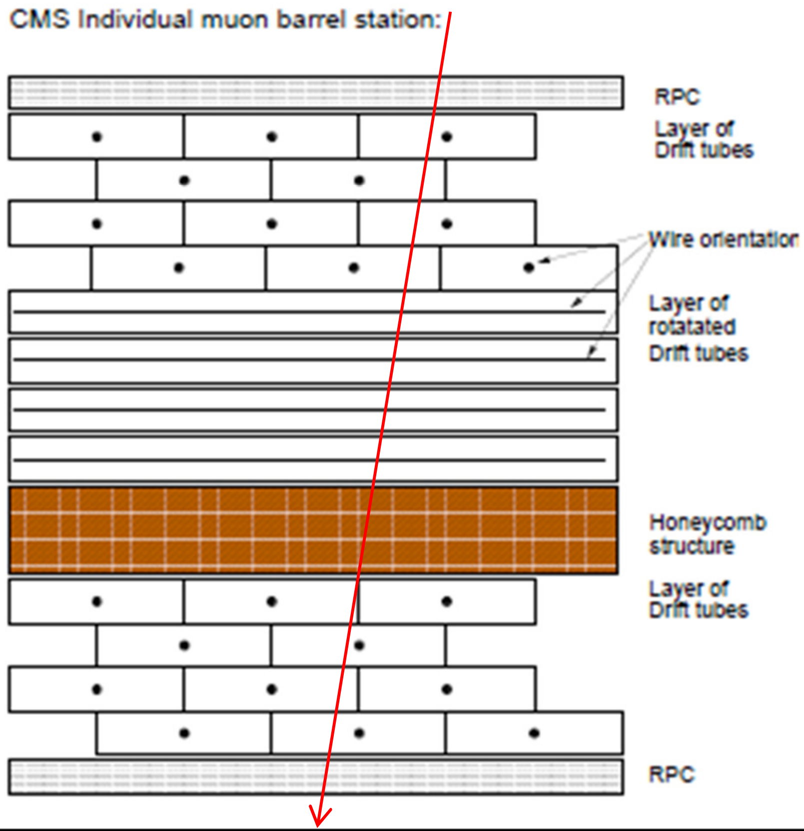
(Some) Implementations of DTs

+ many, many more implementations



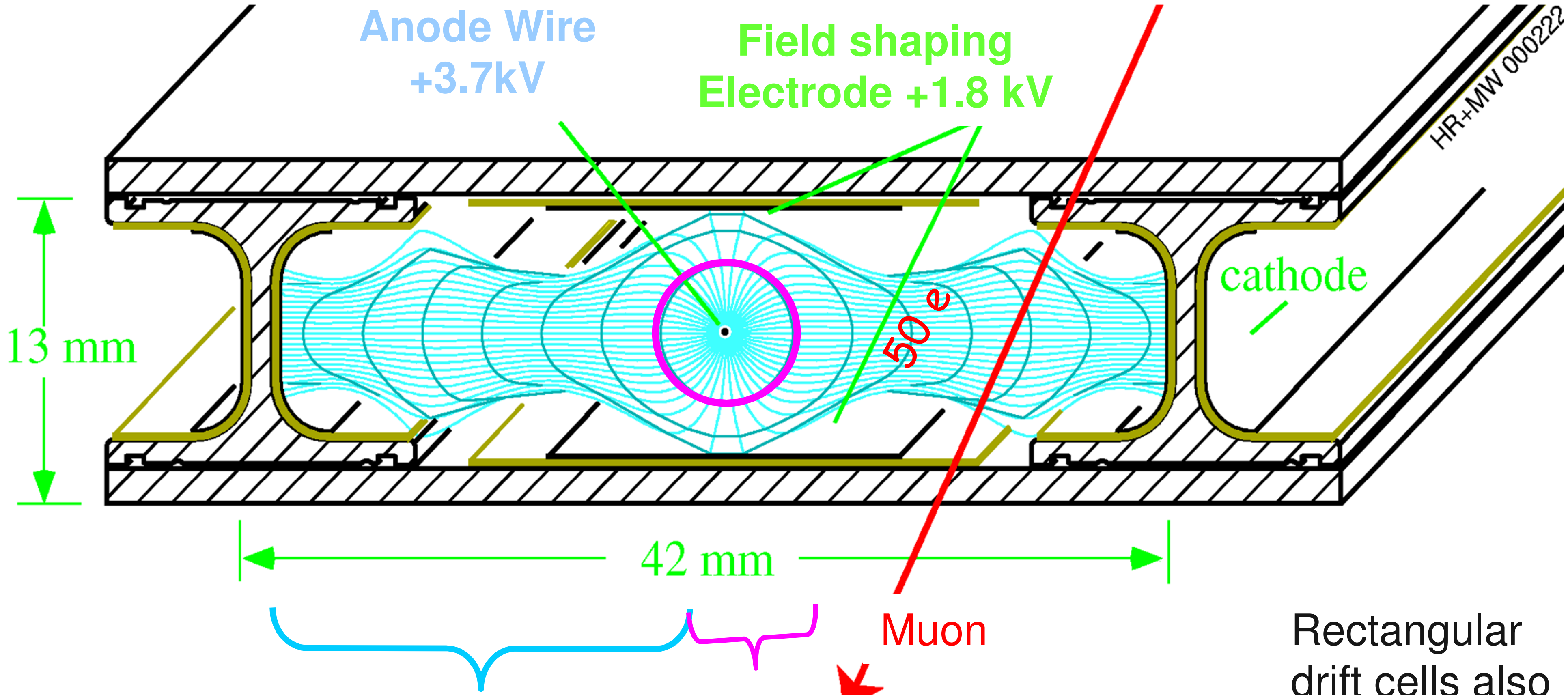
D0 mini drift tubes





CMS Drift Cell

$ArCO_2$ 85%-15%



<u>Constant Drift</u>

E ~ 2 kV/cm ~ const

v = 55 μm / ns ~ const

<u>Amplification</u>

E ~ 1/r -> 150 kV /cm

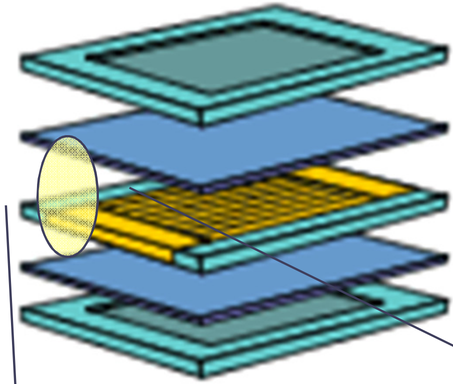
$A \sim 10^5$

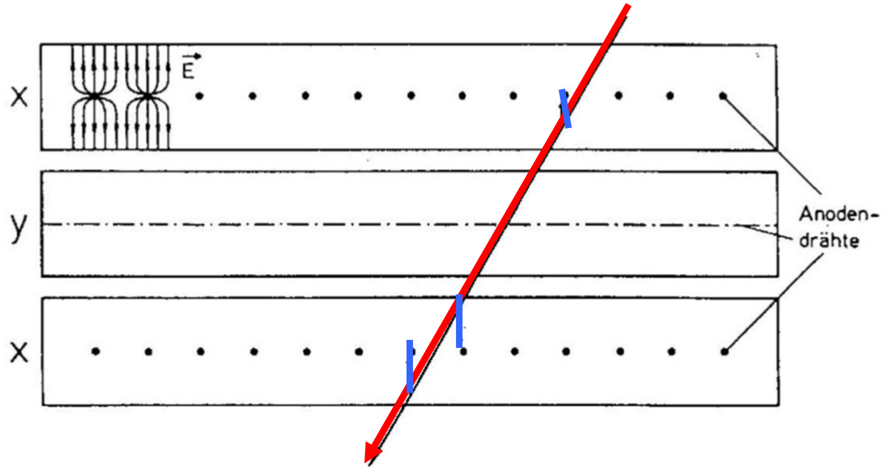
Rectangular drift cells also used in UA1 experiment, of larger size

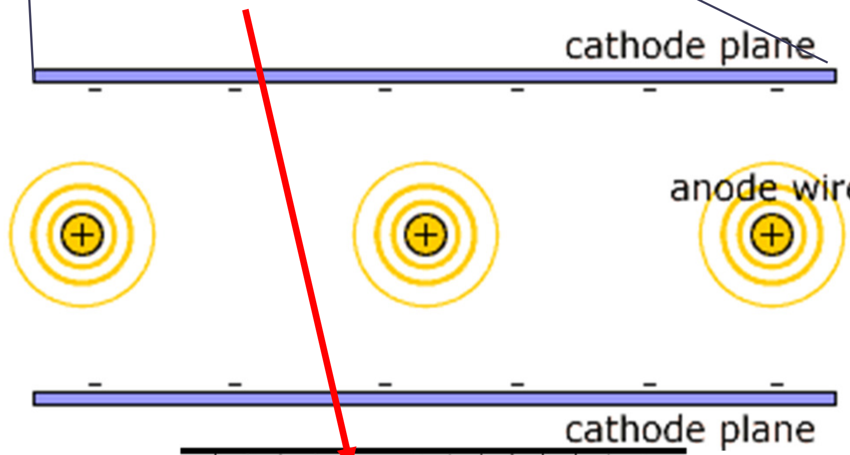
Multi Wire Proportional Chamber (MWPC)

Operational principle

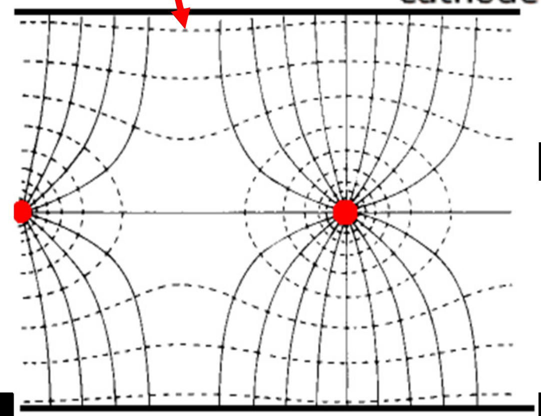
- Several wires between planar cathodes (Charpak Nobel prize)
- Operated in proportional mode
- Gas amplification G~$10^3 \dots 10^5$
- Resolution determined by wire spacing





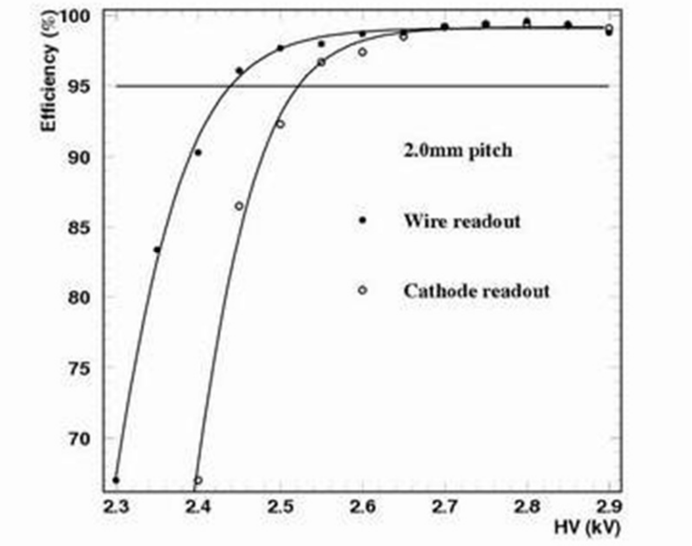


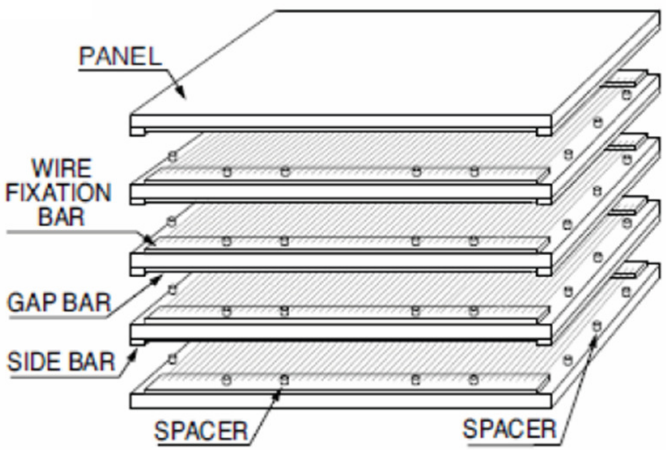
- Wire planes rotated by 90° allows reconstruction of 3D-coordinate
- Possible to measure dE/dx
- New, miniaturized version: Micro Strip Gas Chamber (MSGC)

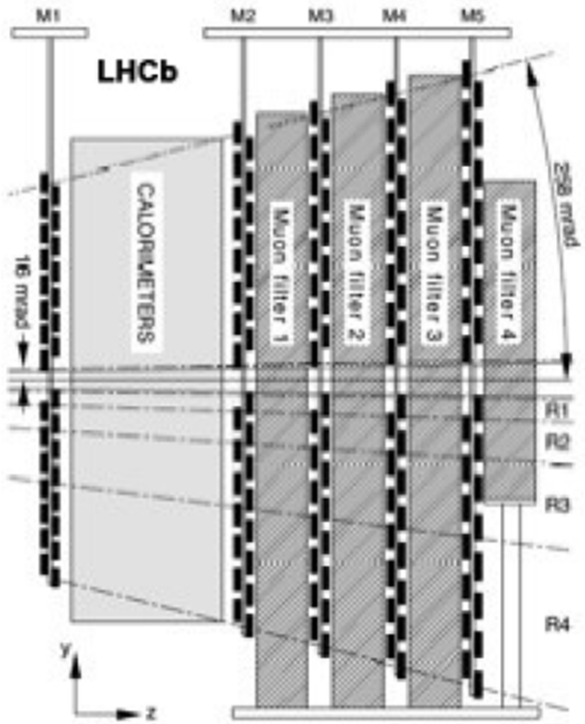


Implementation in LHCb

- 5 stations M1-M5 (total active surface of 435 m^2) separated by iron filters
- 1368 MWPC and 24 triple GEM detectors (in M1 close to beam) with spatial X-Y readout
- Most MWPCs (960) with anode-wire readout, others with cathode-pad or mixed (anode-wire + cathode-pad) readout
- To ensure efficiency and redundancy, all M1 detectors with two sensitive layers in OR, M2-M5 have four layers

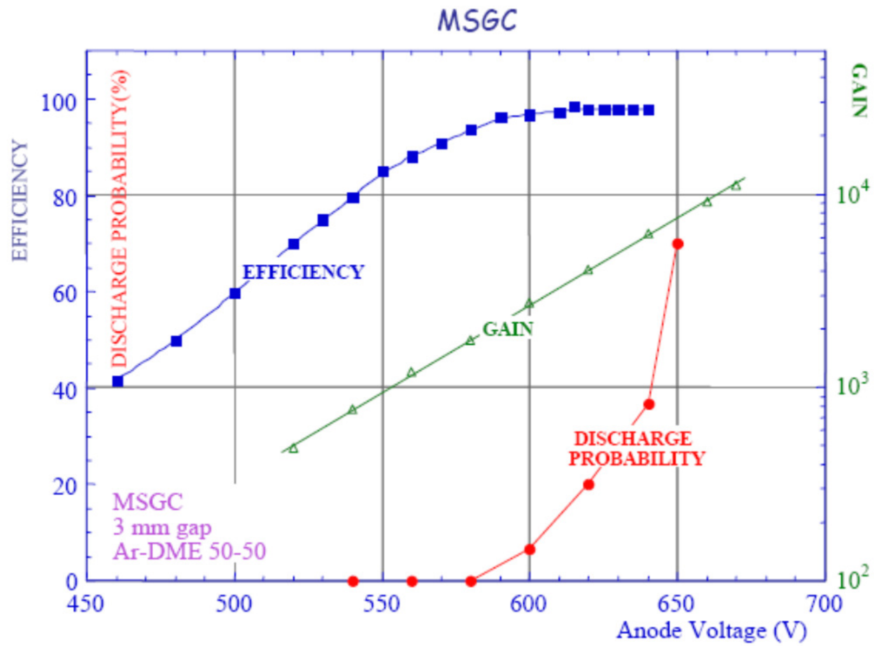


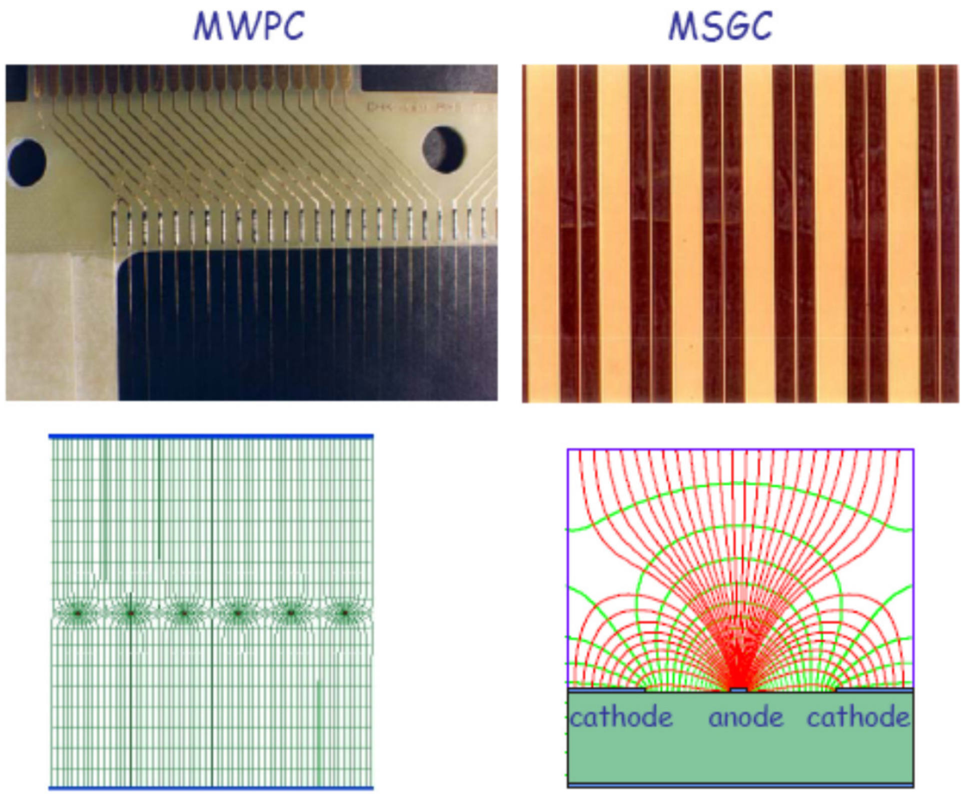




Micro Strip Gas Counters (MSGC)

- Minimized version of a MWPC without real wires
- Better resolution than MWPC
- Finer granularity to resolve high occupancies and provide faster signals (high rate environment)
- Amplification ~10^3, less than MWPC. High anode voltages → discharges can occur → structural damage

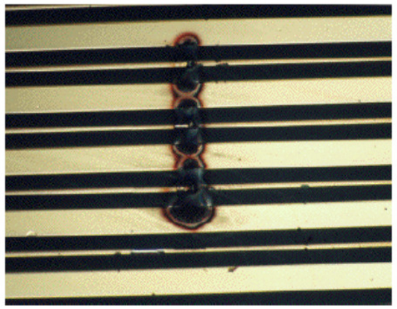




Typical distance between wires 1 mm

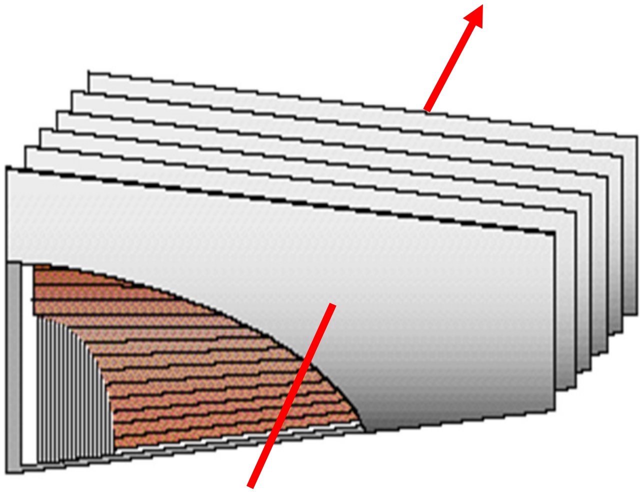
Typical distance between anodes 200 μm

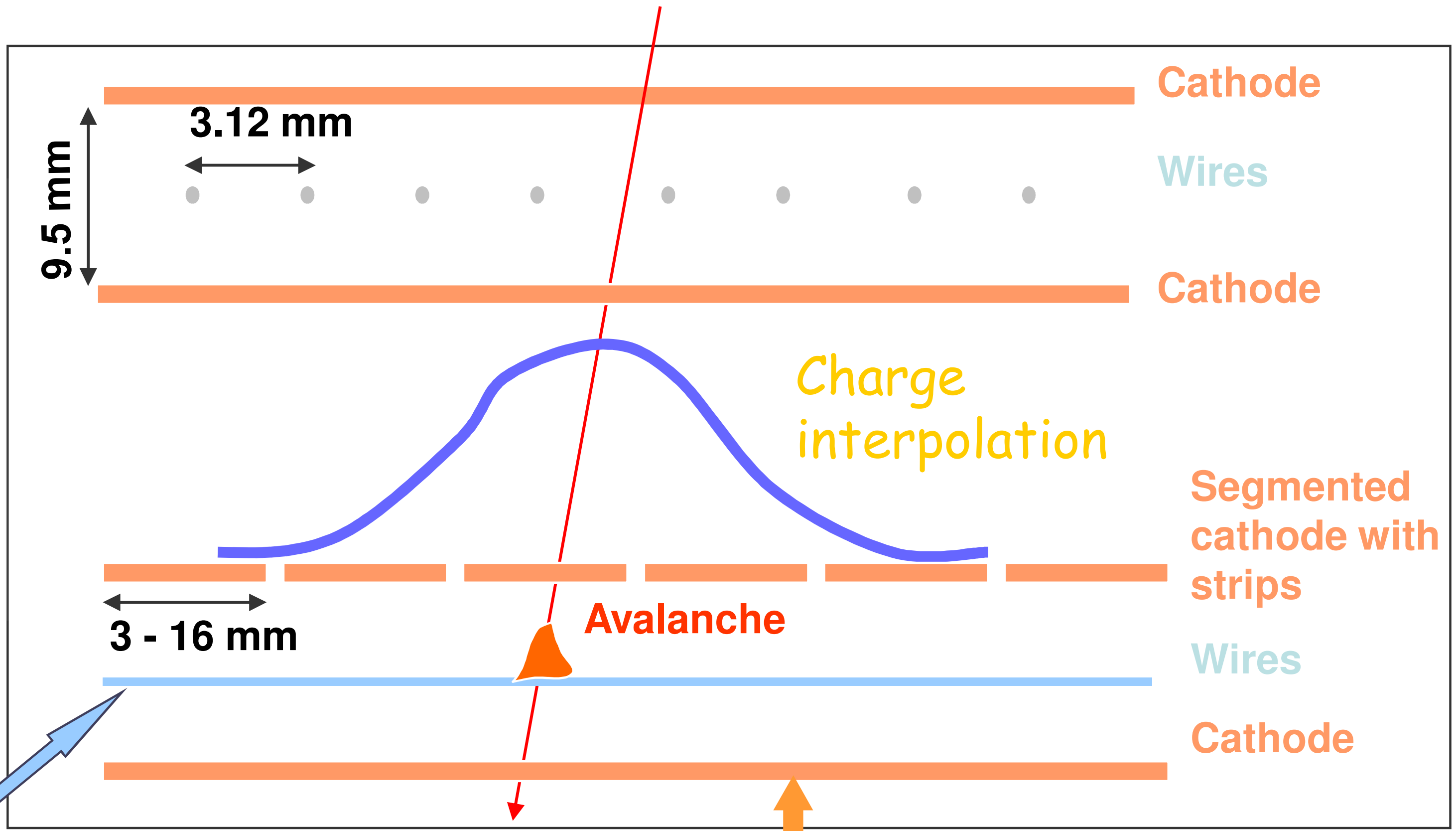
MSGC structure after several discharges → useless



Best operated in conjunction with GEMs to reduce voltage

Cathode Strip Chambers (CSC)





ANODE WIRES

Spatial resolution ~mm,

Time resolution (~4 ns)

CATHODE STIPS

Spatial resolution <100 μm

Timing resolution (t_D~100 ns)

Large CSC System (CMS & ATLAS)

CSC + RPC

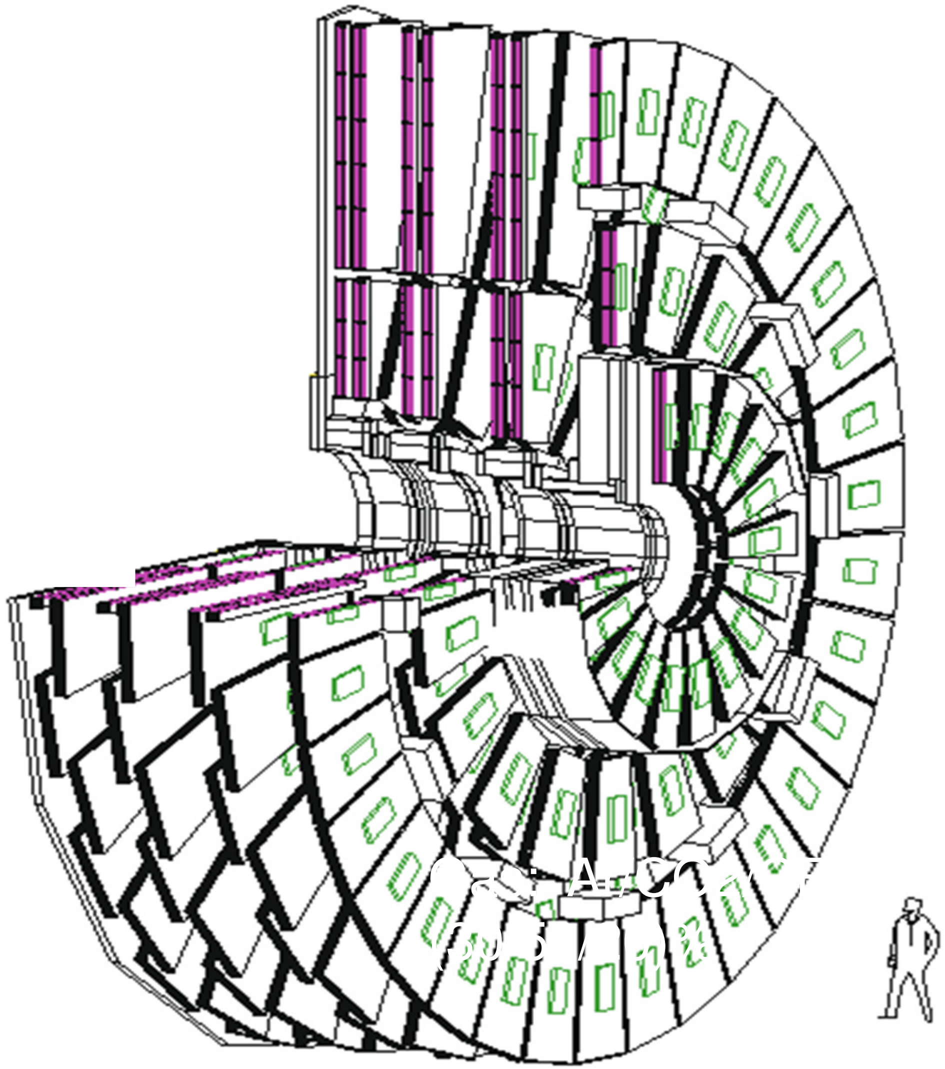
CMS conditions:

Gas: $Ar/CO_2/CF_4$ = (30/50/20)%
6 layers per station

Four stations per end-cap

CMS all of forward muon system,

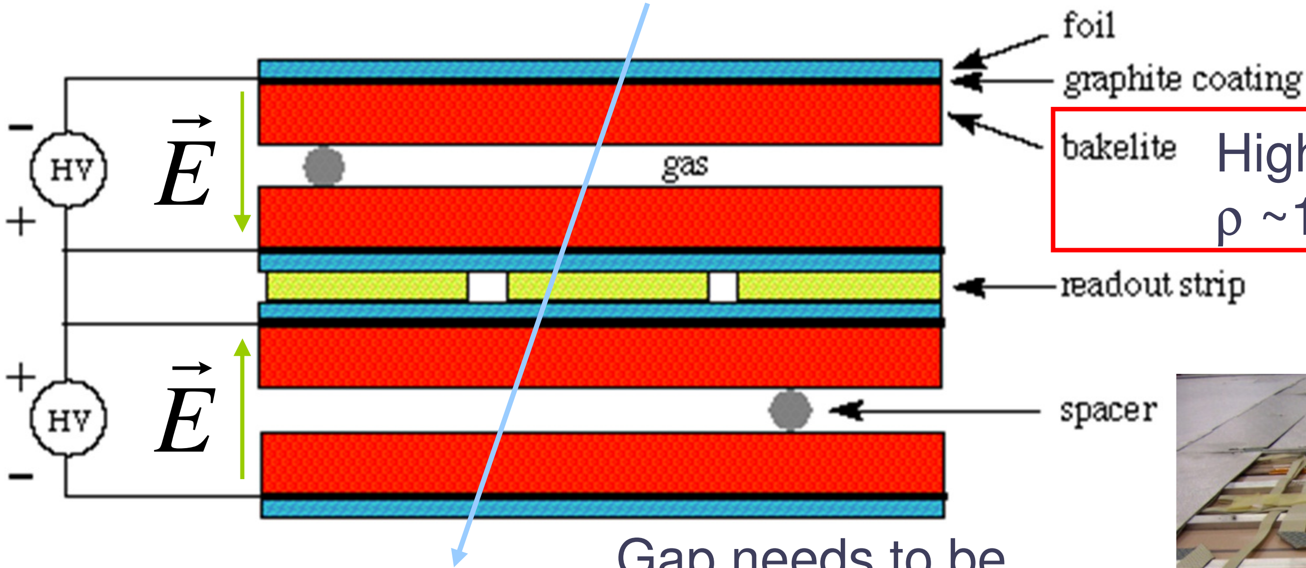
ATLAS at high eta



Detectors with short drift distances or no drift at all needed for environment with high rates or inhomogeneous B-field

Also possible: TGC as used by ATLAS

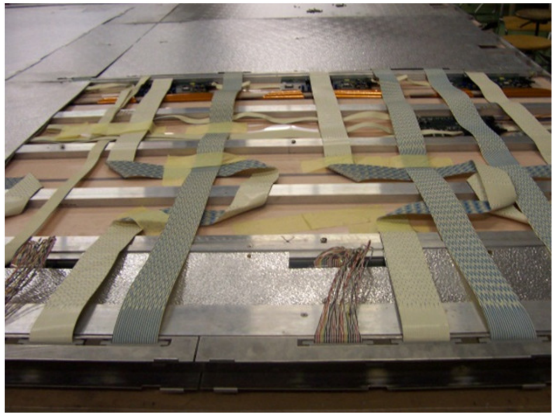
Resistive Plate Counter (RPC)



High resistivity
$\rho \sim 10^{10}\ \Omega$ cm

Gap needs to be constant

Signal in pick-up electrodes



Avalanche-Mode (Proportional)

Amplification $\sim 10^7\ e^-$

High rates ~10 kHz/ cm^2
(ATLAS, CMS, LHCb)

Streamer-Mode

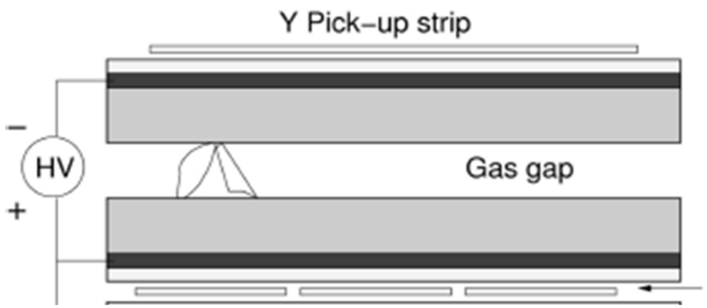
Higher amplification

Medium rates ~10 Hz/cm^2
(ALICE, BaBar)

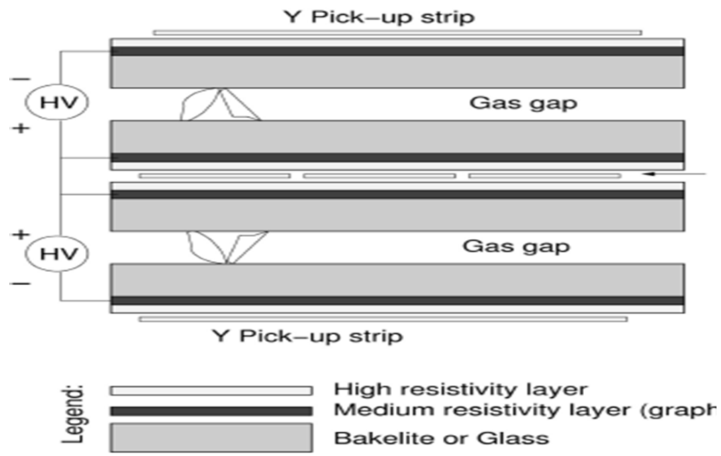
RPCs are Everywhere

- Implemented in all LHC experiments, mainly for triggering (fast time response) but also provide spatial information (example: third coordinate in ATLAS barrel)
- Need rather high voltage O(10 kV). Dark current increases with HV → careful tuning of parameters
- Noise needs to be controlled (HV, temperature, gas mixture)

Single gap



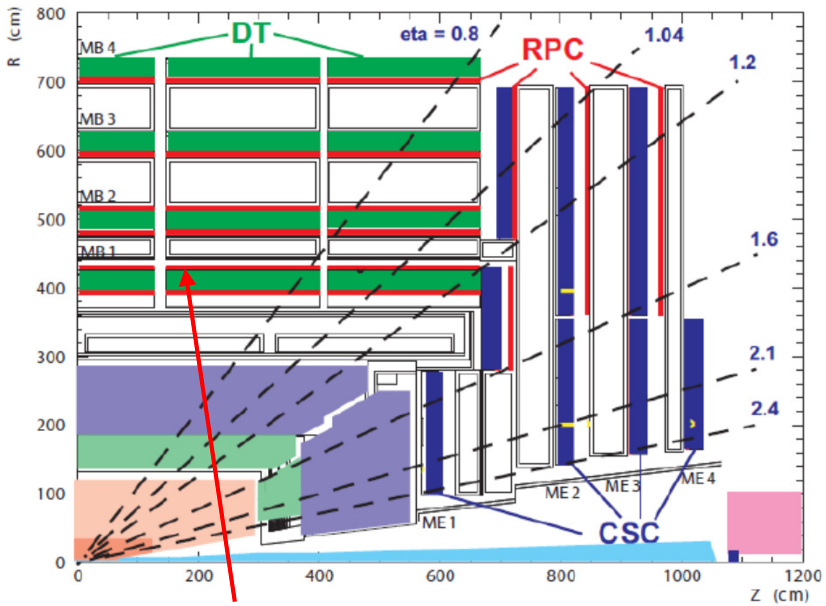
Double gap



Double gap: OR of both detectors → increases efficiency

CMS RPC System

1500 m^2 Forward RPCs



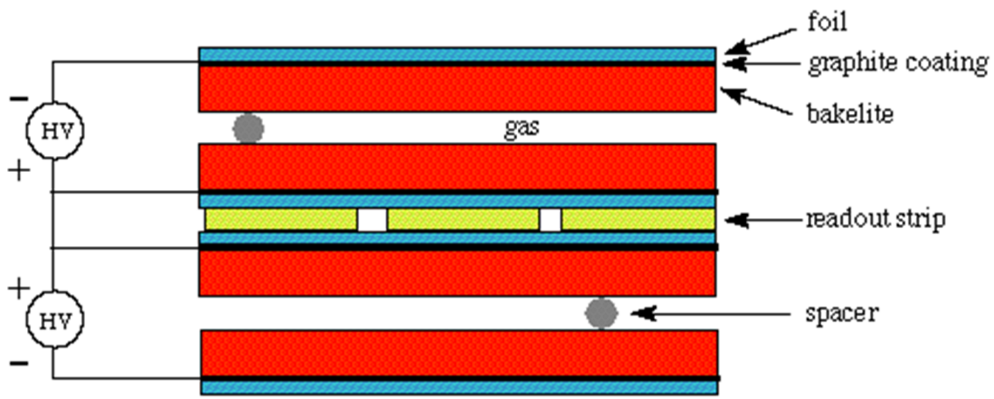
4000 m^2 Barrel RPCs

- 912 chambers with ~160 k channels
- Barrel with 6 stations (for softer muons), endcap with 3 stations up to $|\eta|<1.6$
- Double gap with single readout strip in OR
- **Avalanche mode to c**ope with hit rate up to 1 kHz/cm^2
- Gas: 96.2% C2H2F4, 3.5% Iso-Butane, 0.3% SF_6

Strips: measure bending coordinate, resolution ~1cm

Fast response (~2 ns) for unambiguous BX ID

Note: DTs integrate over several BXs (CMS & ATLAS)

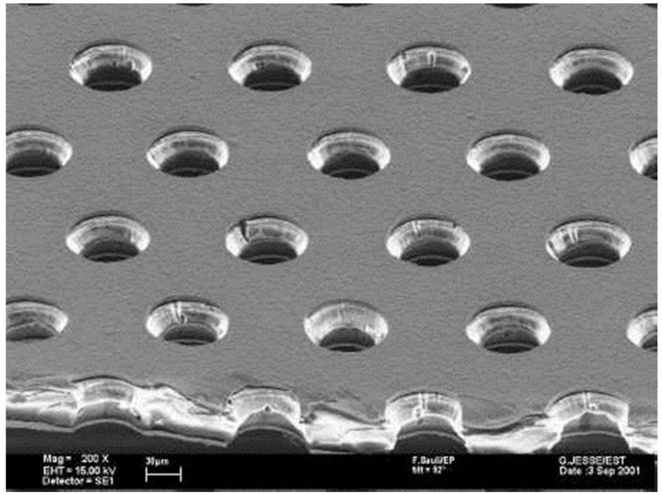


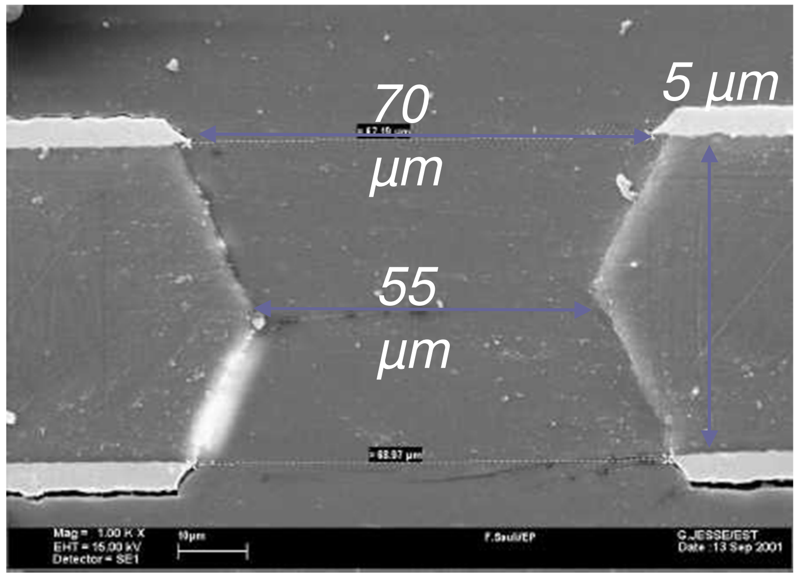
Gas Electron Multiplier (GEM)

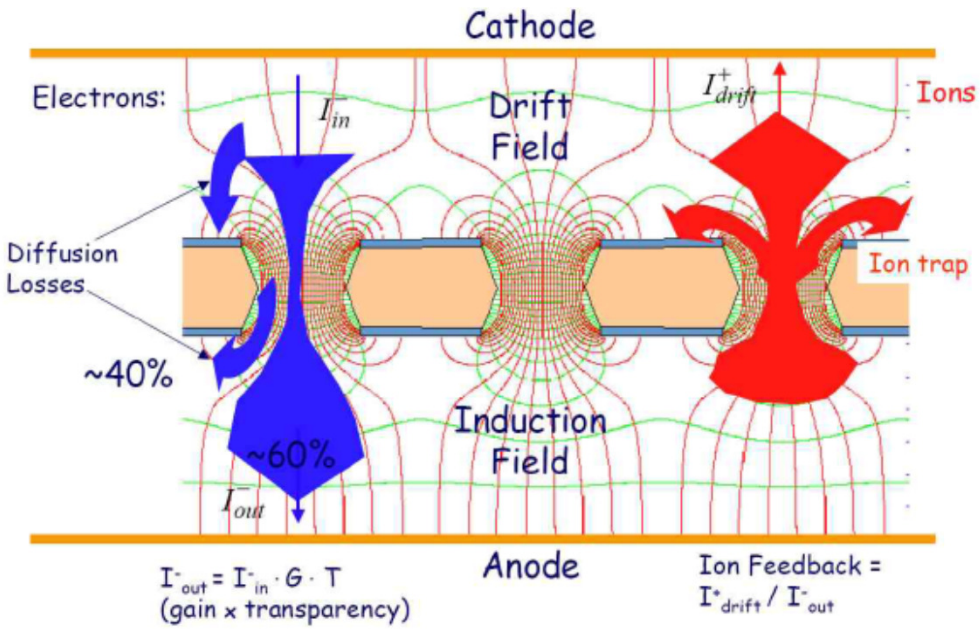
- Recent development (F.Sauli et al, CERN)
- Aim: separation of amplification and readout

Operational principle:

- Thin kapton foil with metalized surface and ~50-70 µm holes. ~140 µm separation
- In the holes high field strength, leads to amplification of the electron signal
- Amplification ~10^3 per GEM foil. Often several consecutive foils in a chambers (triple GEM)

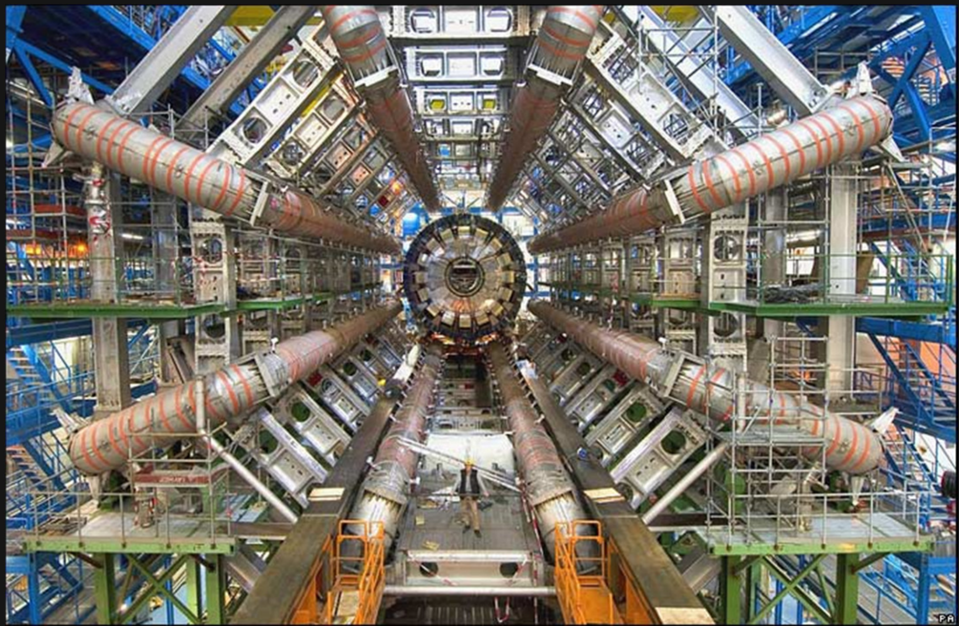


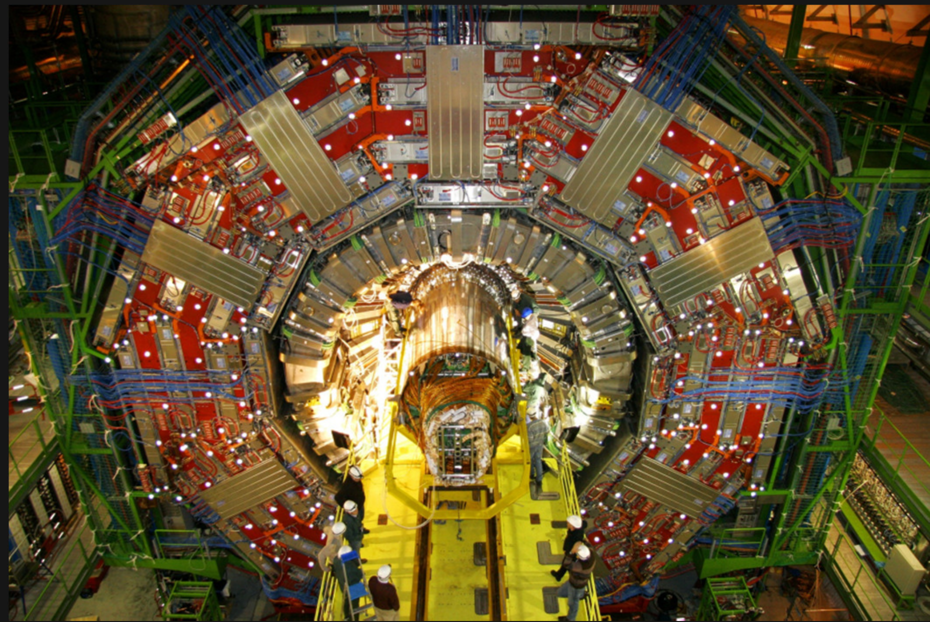




Implemented in LHCb

Implementations at the LHC





Overall Design Choices (Multipurpose Detectors)

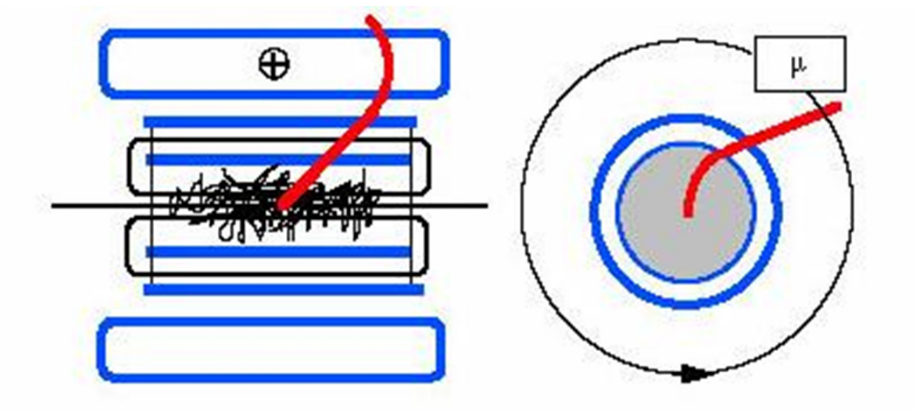
ATLAS and CMS: multipurpose experiments, need to detect muons over a large p_T range 3 GeV < p_T <3 TeV, muon systems are stand-alone trackers

- ATLAS
  - Air core toroid → no multiple scattering, good resolution
  - Toroidal B-field of 0.7 T → next slide for B-field
  - Three stations (min. number needed), very large area to be covered
  - Punch through from calorimeters to be treated
  - Technology choices: pressured DT, RPC, CSC, TGC

- CMS
  - Iron return yoke → resolution limited by multiple scattering
  - Less problems with punch through
  - Complementary technologies, high redundancy
  - 4 stations on muon track
  - Technology choice: DT, RPC, CSC

Impact of Magnet Design

ATLAS A Toroidal LHC ApparatuS



Main magnet = Toroid, B = 0.7 T

Bending in (r,z)

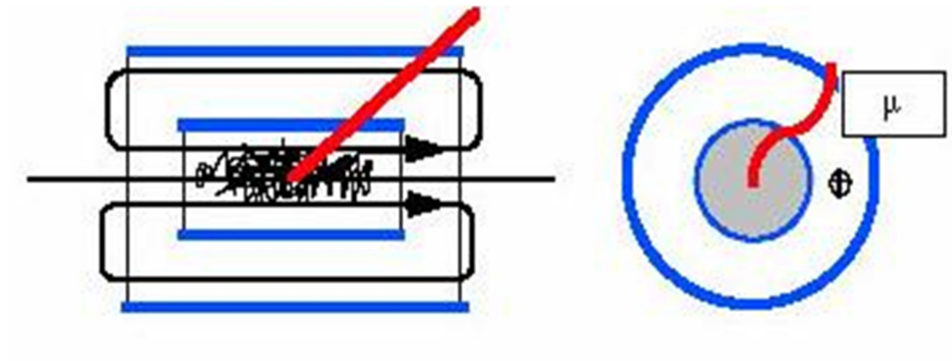
Straight track in (r,ϕ) → Extrapolation to z-coord. of the beam (~cm)

In tracker additional solenoid, B = 2 T, here bending in transversal plane (r,ϕ)

No iron in muon system

Homogeneous B-field

CMS Compact Muon Solenoid



Just one magnet, Solenoid B = 3.8 T

Bending in transversal plane (r,ϕ)

In (r,z) straight track → Extrapolation to beam (focused dimension) → Trigger on impact parameter

Requires return yoke in muon system

Inhomogeneous field at large η

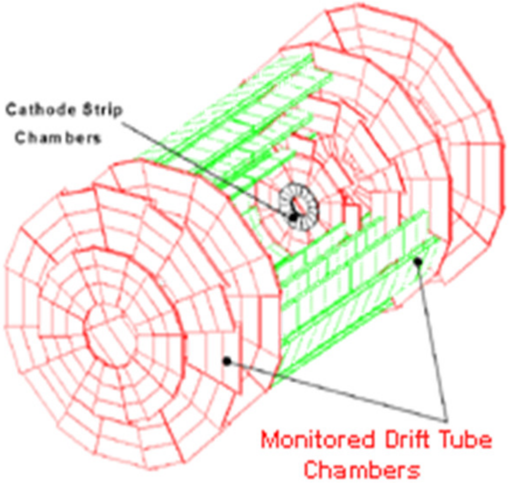
Momentum Resolution

ATLAS

B = 0.7 T

L ~ 5 m

N = 3 Stations * 8 Points



$$s = \frac{0.3 \cdot B[T] \cdot L[m]^2}{8 \cdot p[GeV]}$$

$$\frac{\Delta p_T}{p_T} \propto \frac{1}{s} \cdot \delta_{spatial} \cdot \sqrt{\frac{720}{N_{Stat}}}$$

s = 750 μm for 1 TeV Track

10% → σ = 75 μm

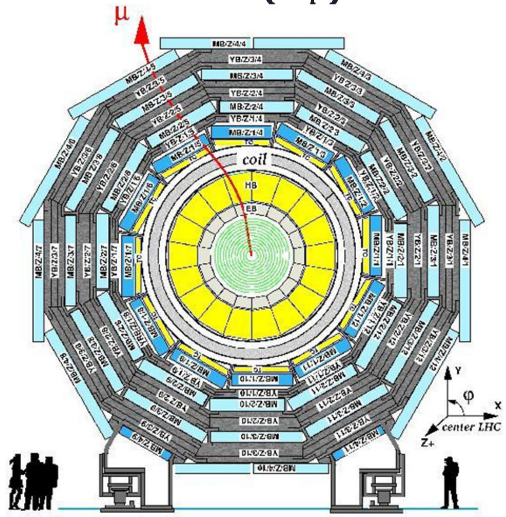
Δp/p ~ 6%

CMS

B ~ 2 T (B-Field in Fe)

L ~ 3.5 m

N = 4 Stations * 8 Points in (rϕ)



s = 900 μm for 1 TeV Track

10% → σ = 90 μm

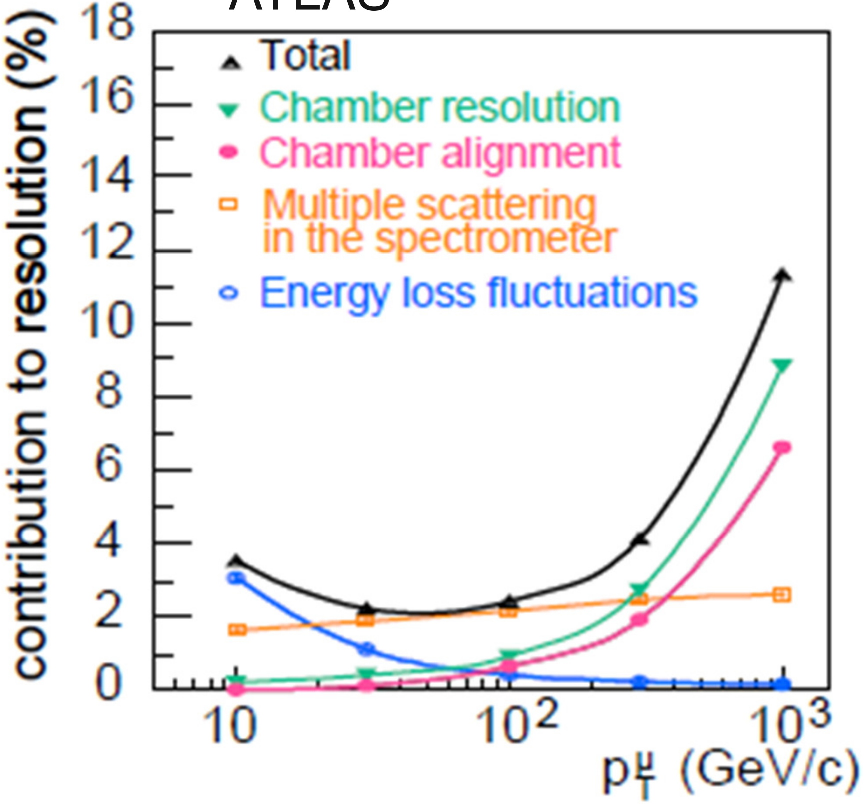
Δp/p ~ 12 %

(Multiple scattering in Fe ~100 μm)

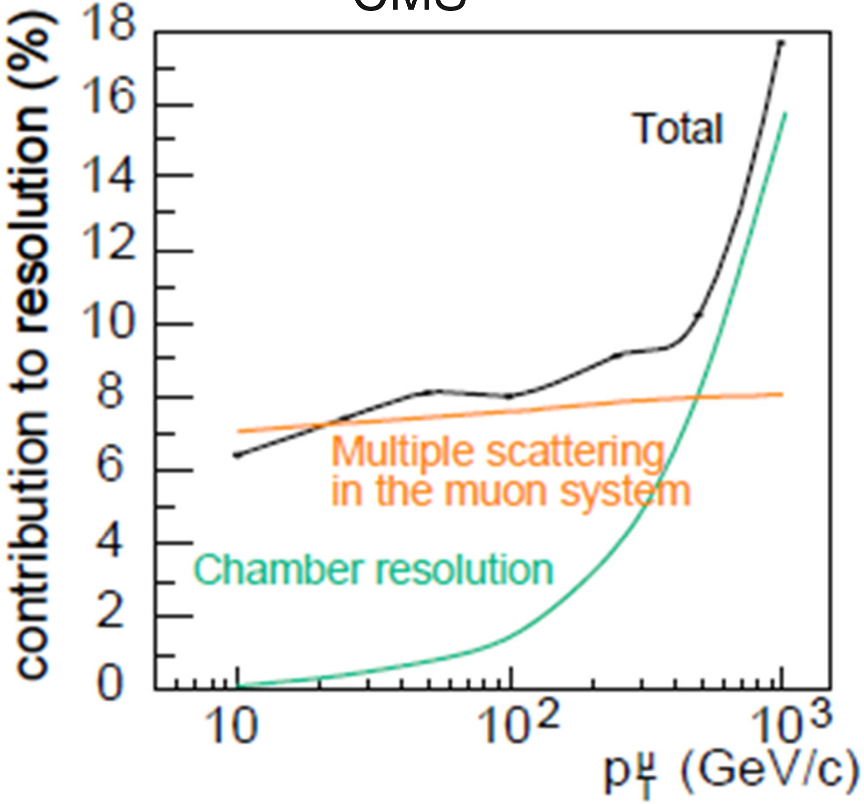
Combine with Tracker Δp/p ~ 2 %

Combined Resolution

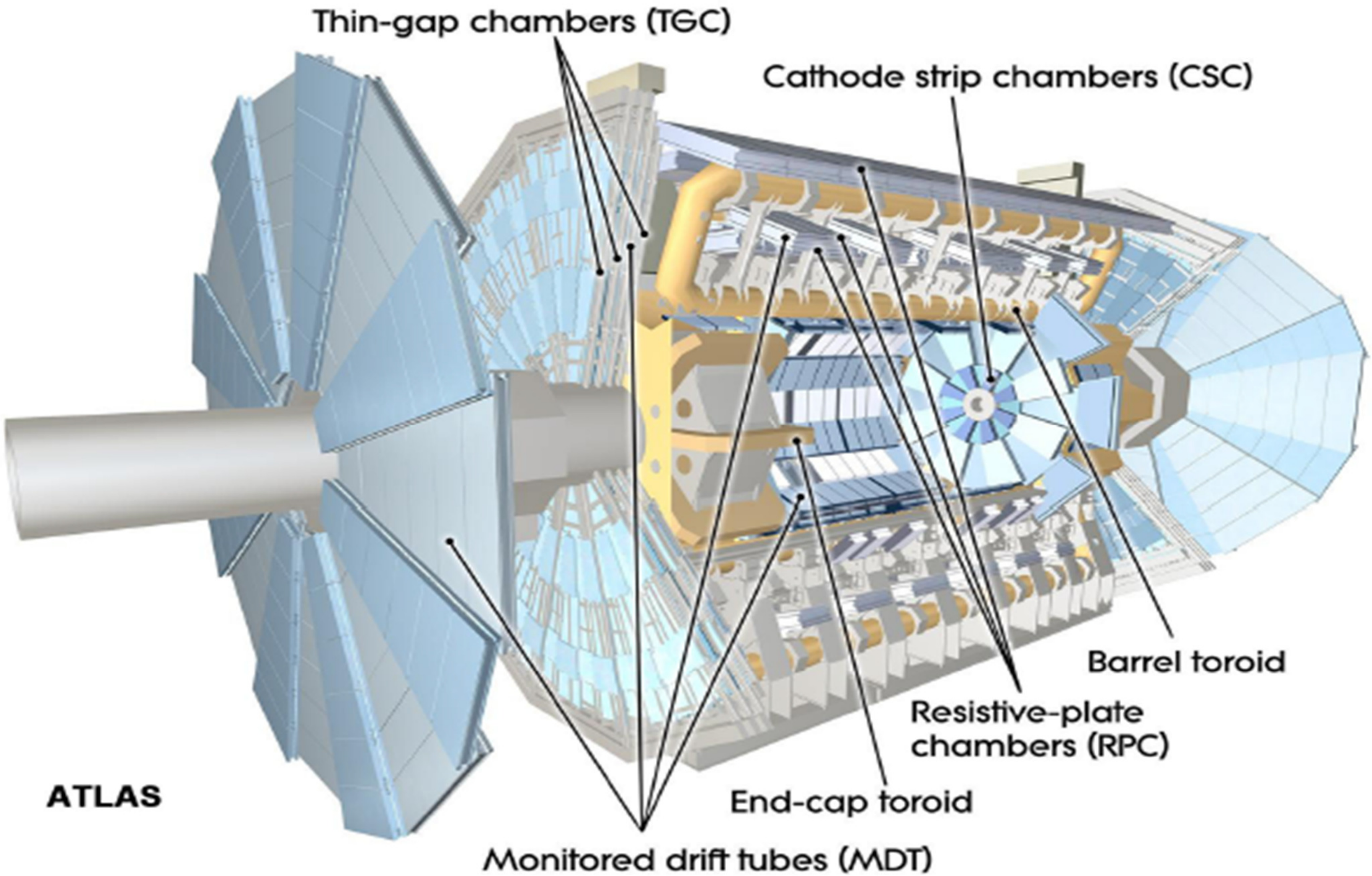
ATLAS



CMS



ATLAS

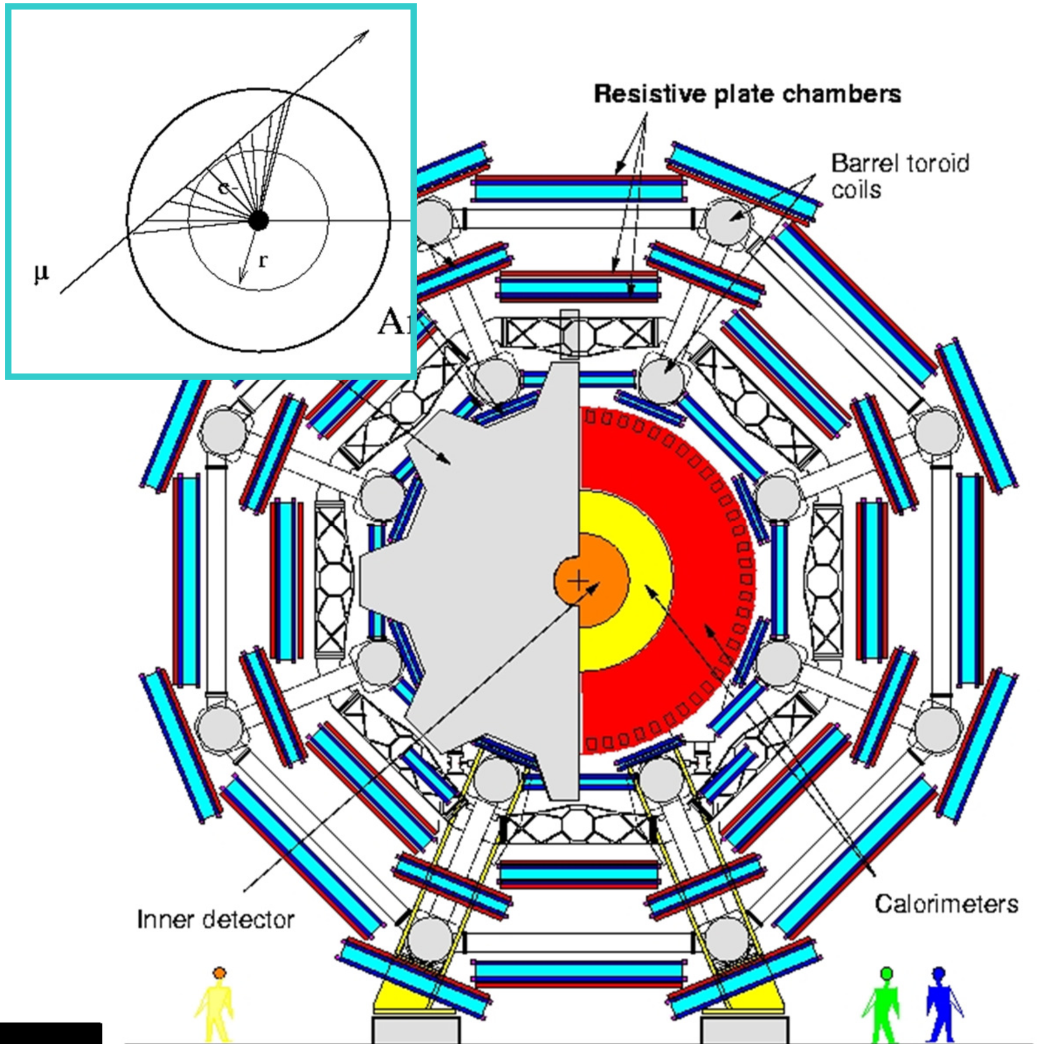


Thin-gap chambers (TGC)
Cathode strip chambers (CSC)
Barrel toroid
Resistive-plate chambers (RPC)
End-cap toroid
Monitored drift tubes (MDT)
ATLAS

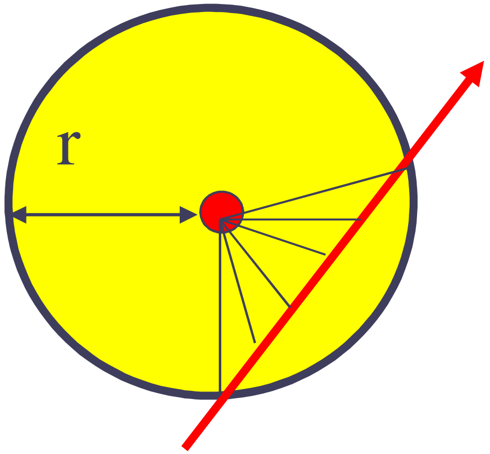
ATLAS Monitored DT System

- Little multiple scattering → high precision
- Less track bending → higher precision for measurement + alignment
  p_T=1 TeV/c has ~700 μm Sagitta → 10% Δp/p needs O(70 μm) precision
- Larger coverage in η

- **3 Muon Stations**
  ~1200 Chambers
  Outer diameter ~20m
  In barrel + endcap
- **1 Coordinate** measured with precision drift tubes, **(r,ϕ) Coordinate** provided by RPCs
- RPCs for triggering
- Alignment very important



ATLAS Drift Cell and Resolution with Overpressure



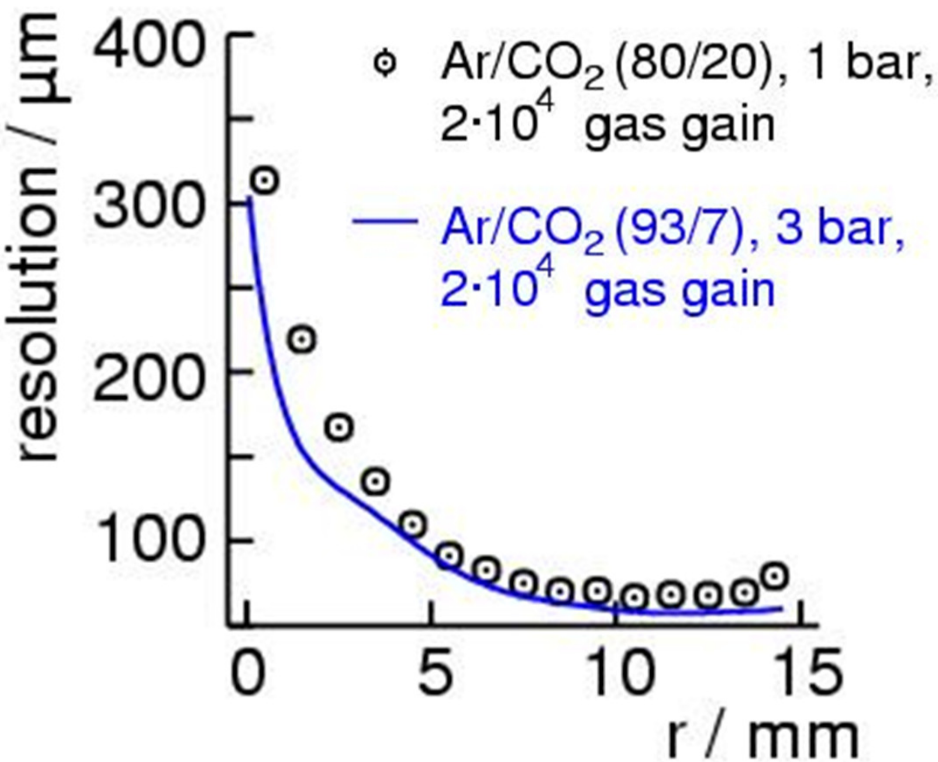
Radius = 1.5 cm

Gas mixture: Ar/CO_2 93/7

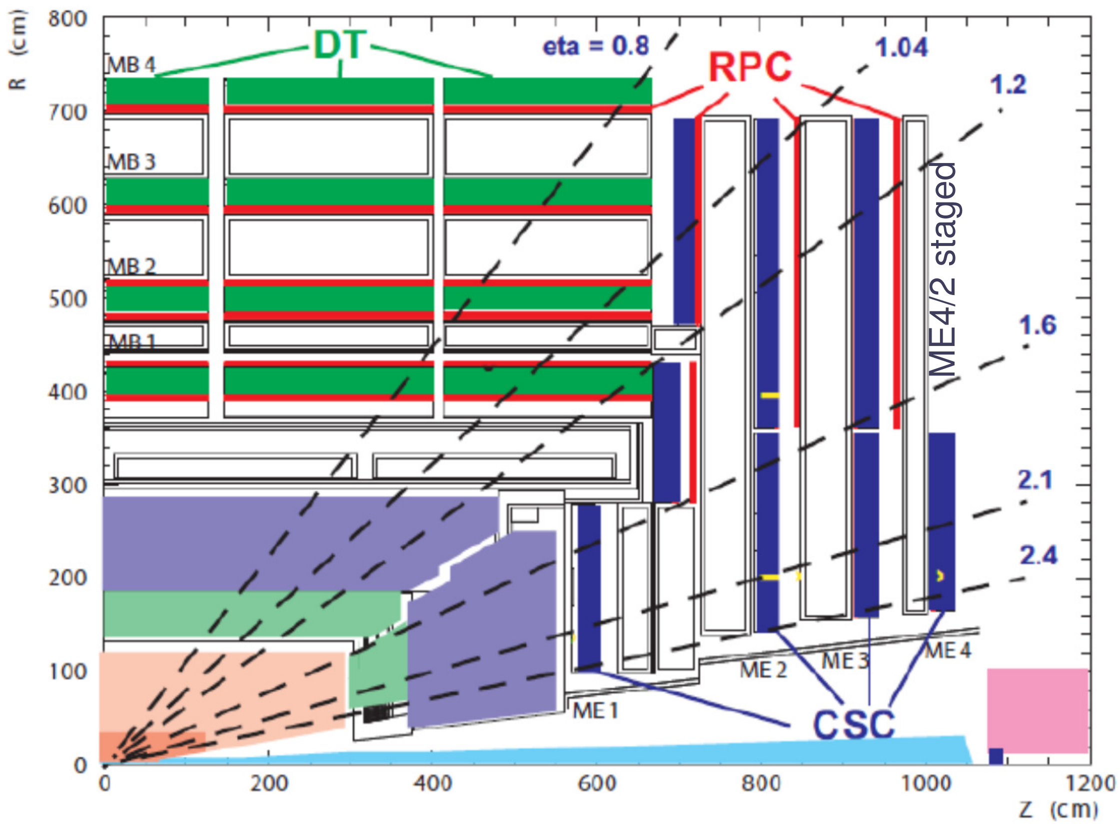
3 bar pressure

- Ionization: 100 cluster/cm with 2-3 e^- (3 bars Ar/CO_2 93/7)
- Electron drift: maximum Drift time ~800 ns for Ar/CO_2 93/7

Resolution per cell (r-dependent) < 100 μm



CMS Muon System



Muon Barrel 0 < |η| < 1.2

- 5 barrel wheels, iron return yoke for the solenoid magnet
- Almost no B-field at chamber positions
- 250 Drift Tube (DT) Chambers
- 480 Resistive Plate Chambers (RPC)

Forward Muon 0.9 < |η| < 2.4

- Arranged in 2 x 3 disks
- 4 muon stations in 2/3 rings
- Inhomogenous field with B<1.2 T
- 250 Cathode Strip Chambers (CSC)
- 483 Resistive Plate Chambers (RPC)

~0.5 M channels

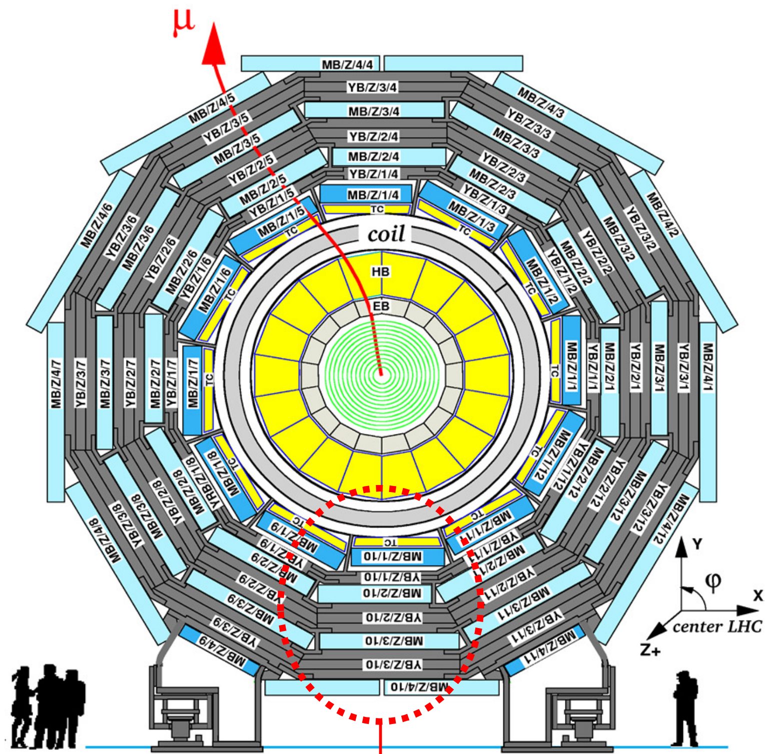
~10,000 m^2 instrumented

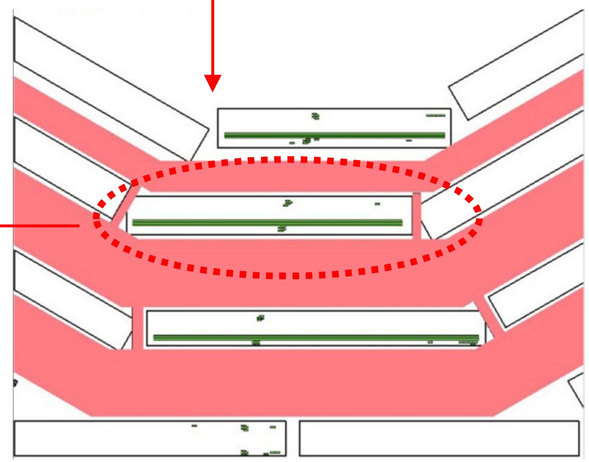
All detectors used for triggering and reconstruction

Barrel Drift Tube Chambers (DT)

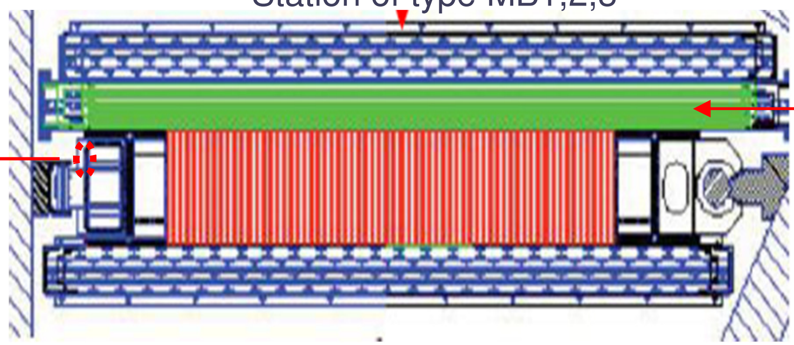
- 250 chambers arranged in 5 wheels, each with 4 stations forming concentric cylinders, 172 k readout channels

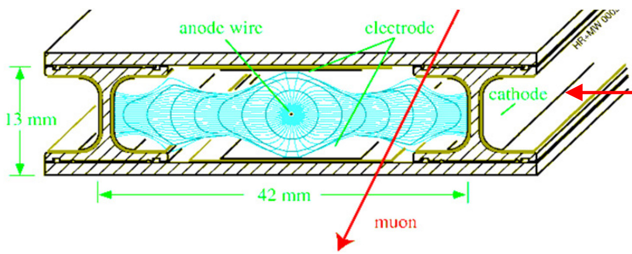
  CMS chambers interleaved with iron yoke
- B-field contained in the iron (B~1.9 T) except MB1 of outermost wheels
- B-field in iron for p_T measurement, track curvature flips in MB3
- Punch-through only in first station
- Cell resolution ~250 μm, station resolution ~100 μm (limited by multiple scattering)





Station of type MB1,2,3

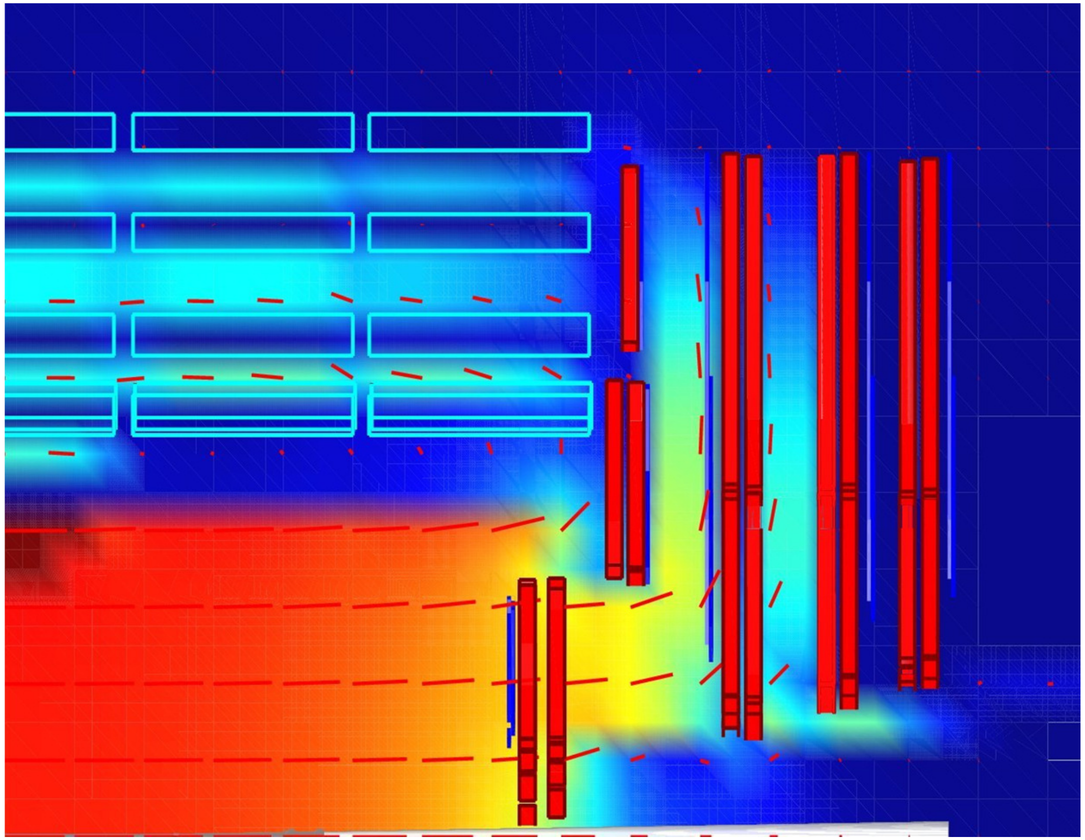




Operating Conditions of CMS Muon System

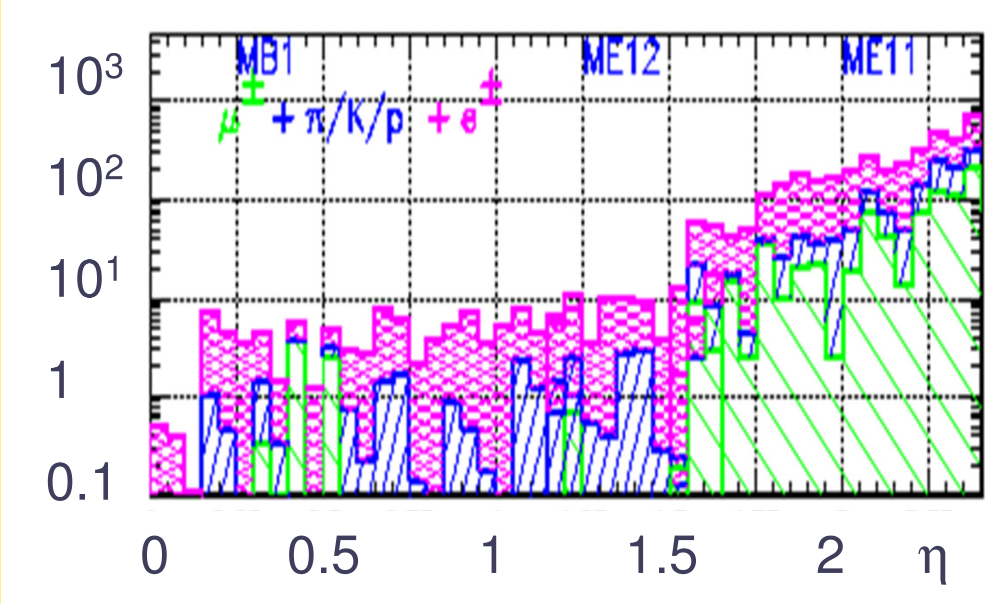
Magnetic Field

Uniform B-Field in central area.
Varying B-Field strength 1.5 T – 3.5 T in the end caps.

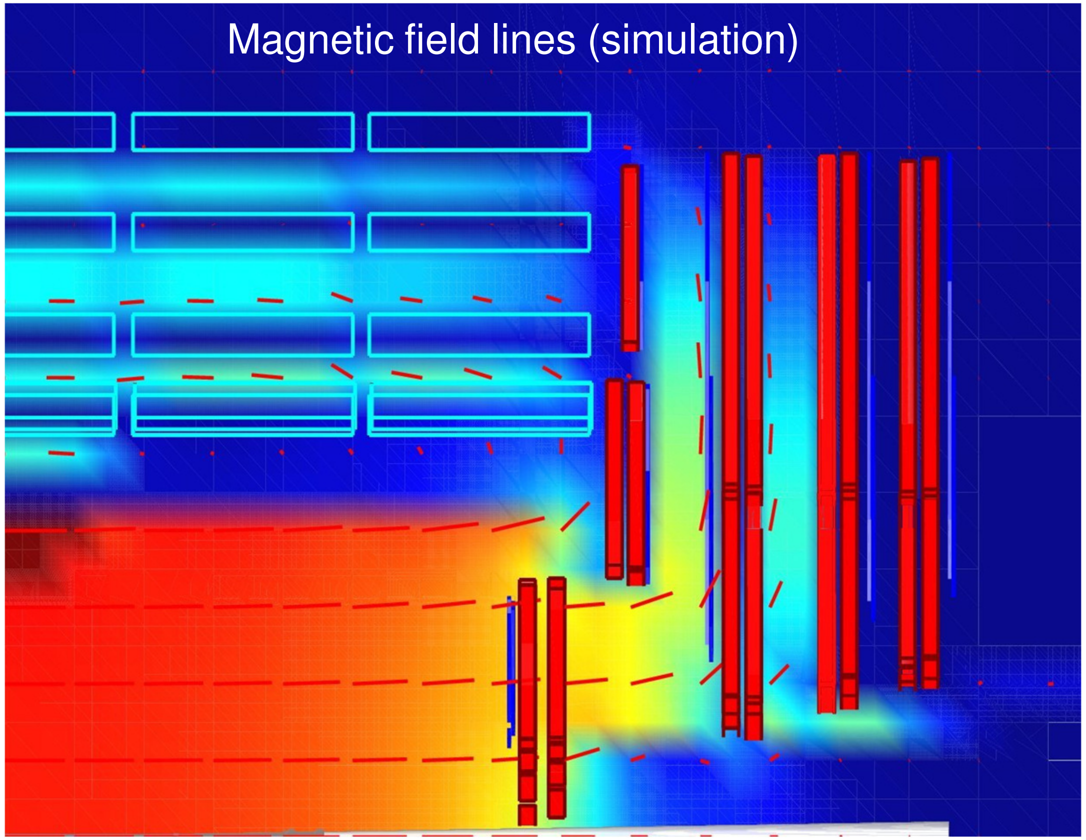


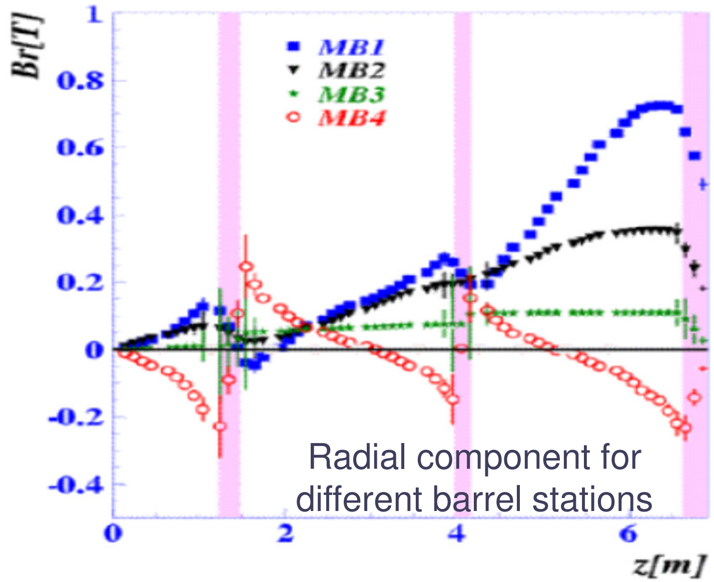
High Particle Flux

In the end caps 20 kHz/channel, 4x larger than MIP signal.
Maximum of 1 kHz/cm²

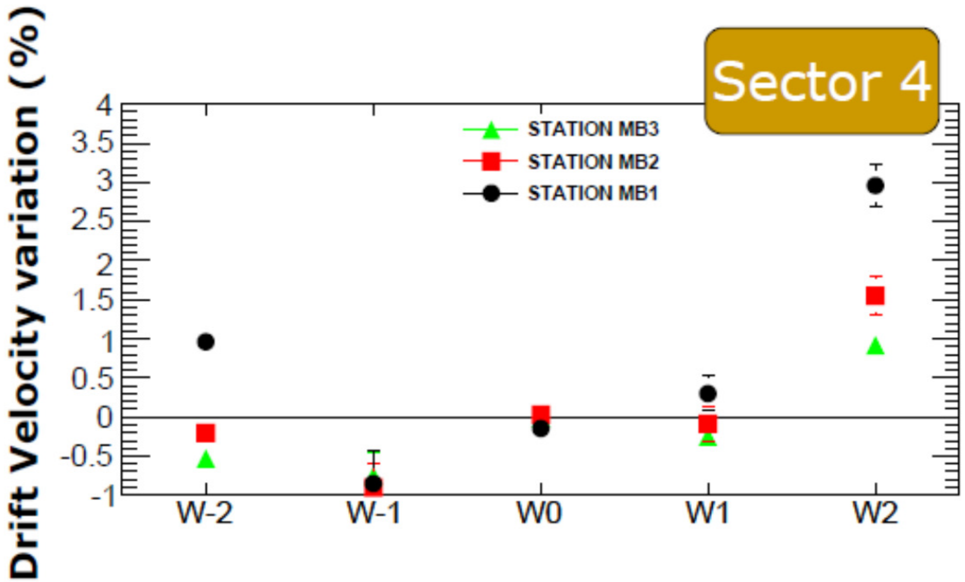


Drift and B-Field





CMS



Influence of B-field on drift behavior appears as change of drift velocity

In reality, drift distance changed

→ Correct for it with fixed drift velocity (external measurement)

Overall Design Choices (Dedicated exp)

- ALICE
  - Heavy ion experiment, very large track densities, medium pT
  - One-arm spectrometer with dipole magnet
  - Technology choice: RPC, cathode pad

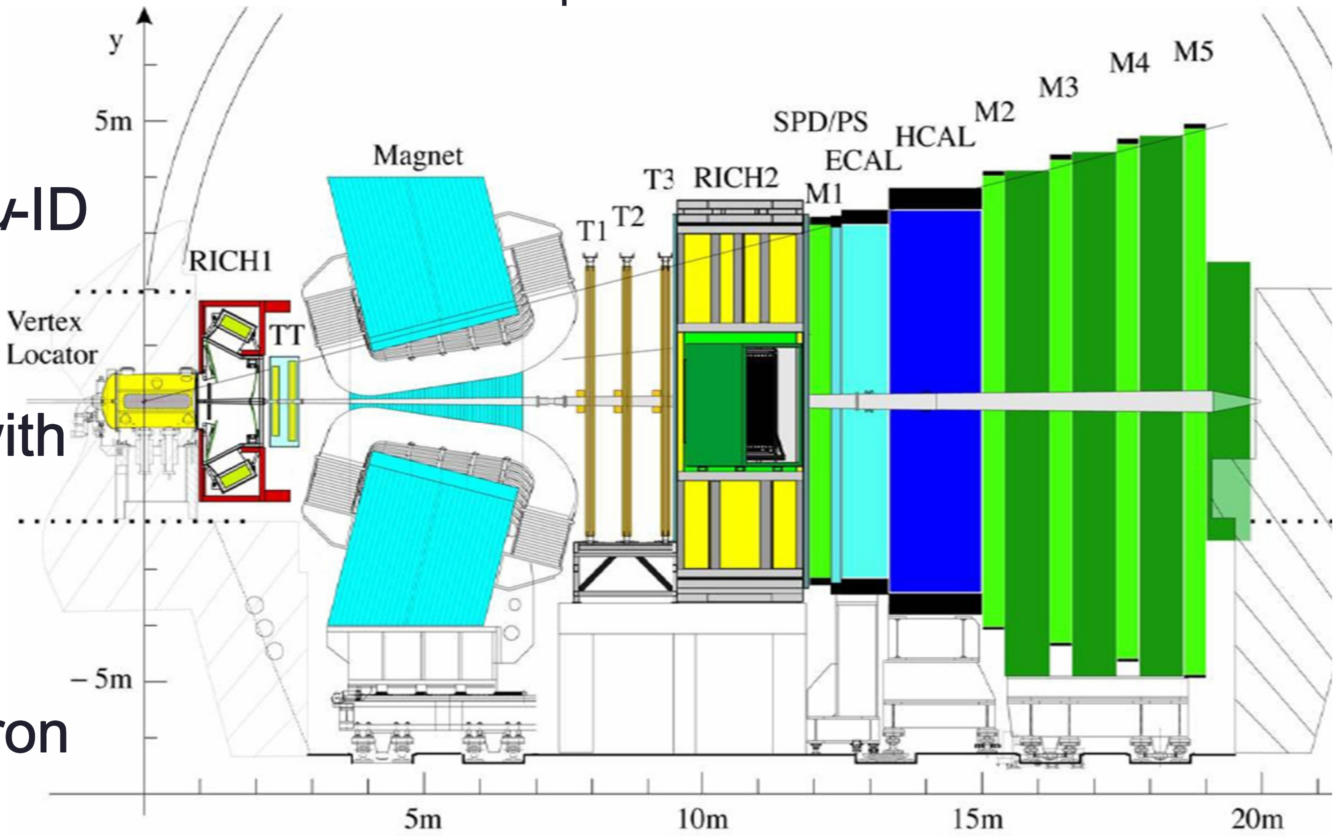
- LHCb
  - Forward spectrometer, fixed target geometry
  - Muons very important for b-physics
  - Four stations with high resolution chambers behind absorber, one additional station before absorber
  - Technology choice: MWPC, GEM

LHCb

Several key measurements rely on μ-ID: e.g. $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow K^{*0}\mu^+\mu^-$

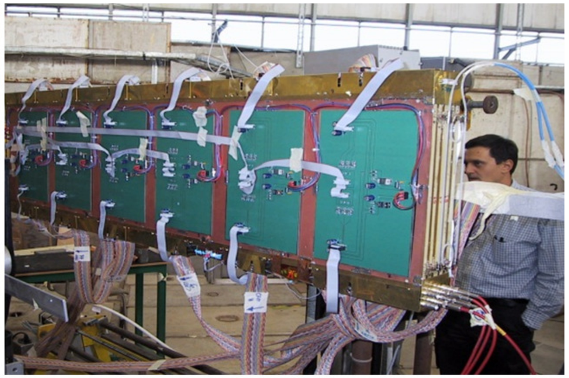
- Muon systems provides μ-ID to very high purity
- 5 tracking stations, each subdivided in 4 regions with different granularities
- Equipped with Multi Wire Proportional Chambers (MWPCs) and Gas Electron Multipliers (GEMs).
- Total thickness of LHCb hadron absorber (muon shield): ~ 23λ

Fixed target geometry
One arm spectrometer

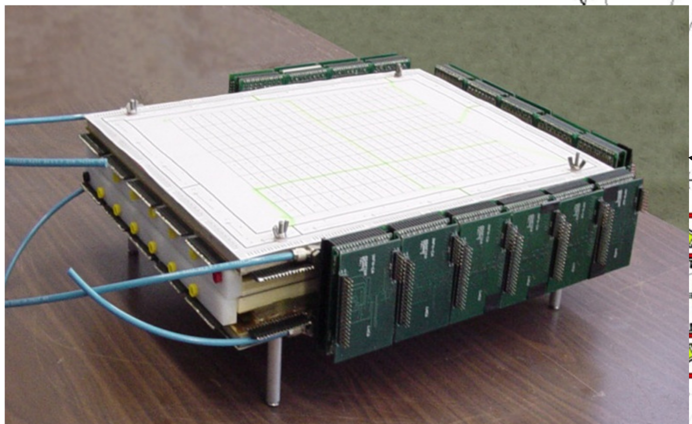


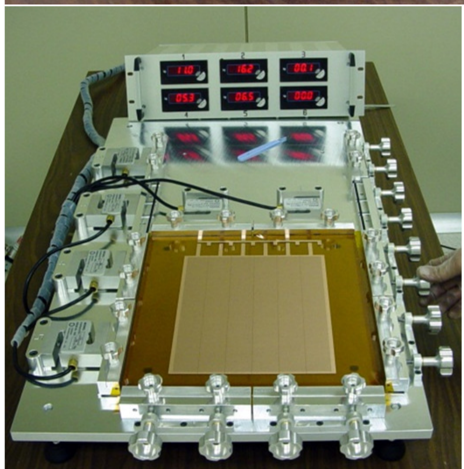
LHCb

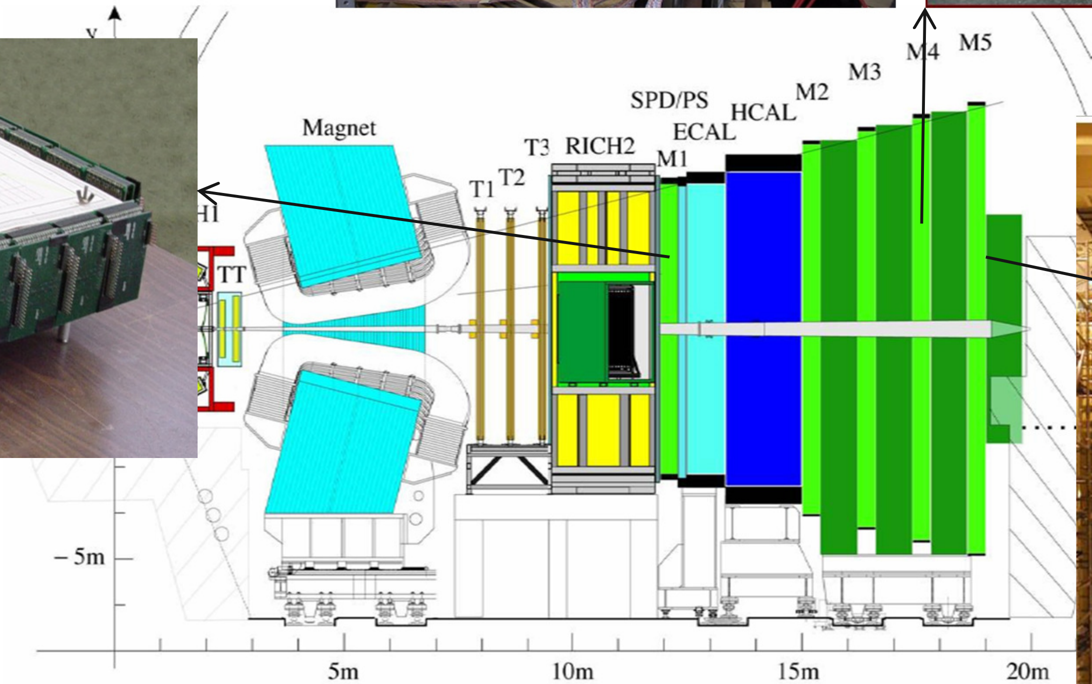
Parameter	Design value	
Gas Mixture	$Ar/CO_2/CF_4$ (45:15:40)	GEM
Gas Gain	$\simeq 6 * 10^3$	
Radiation Hardness	1.6 C/cm^2 in 10 years	
Chamber active area	20x24 cm^2	
Gas mixture	$Ar/CO_2/CF_4$ (40:55:5)	MWPC
Gas Gain	$\simeq 10^5$	
Gas Gap	5 mm	
Wire spacing	2 mm	
Wire Diameter	30 μm	



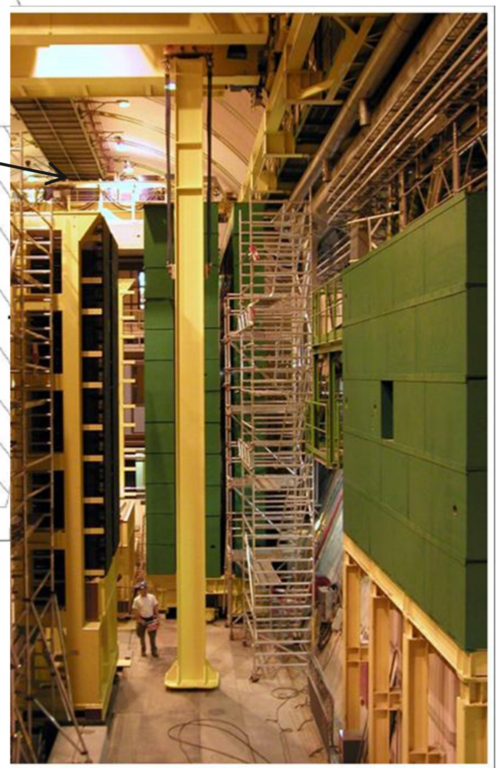
GEM detectors







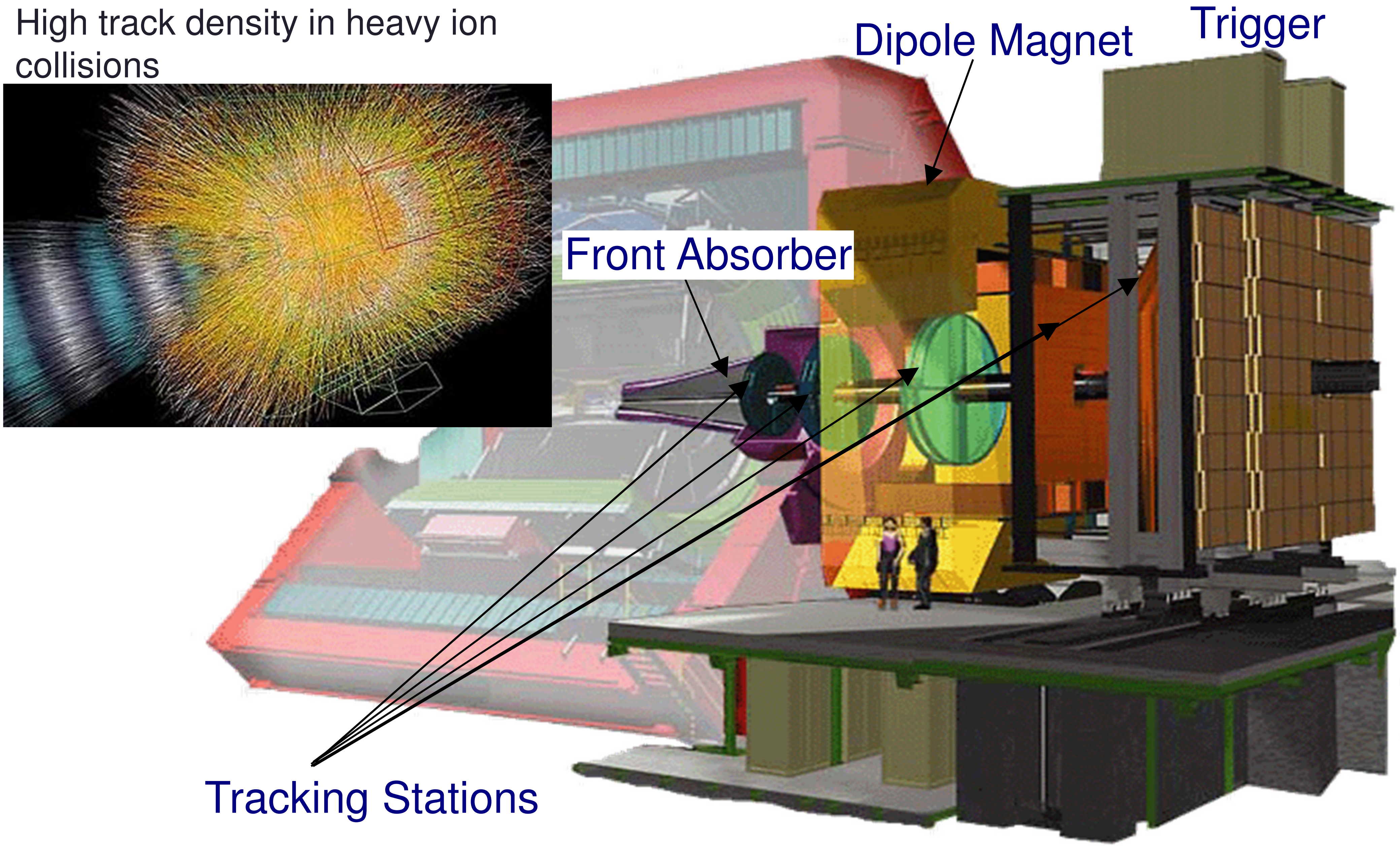
MWPC



Muon filter

ALICE Muon System

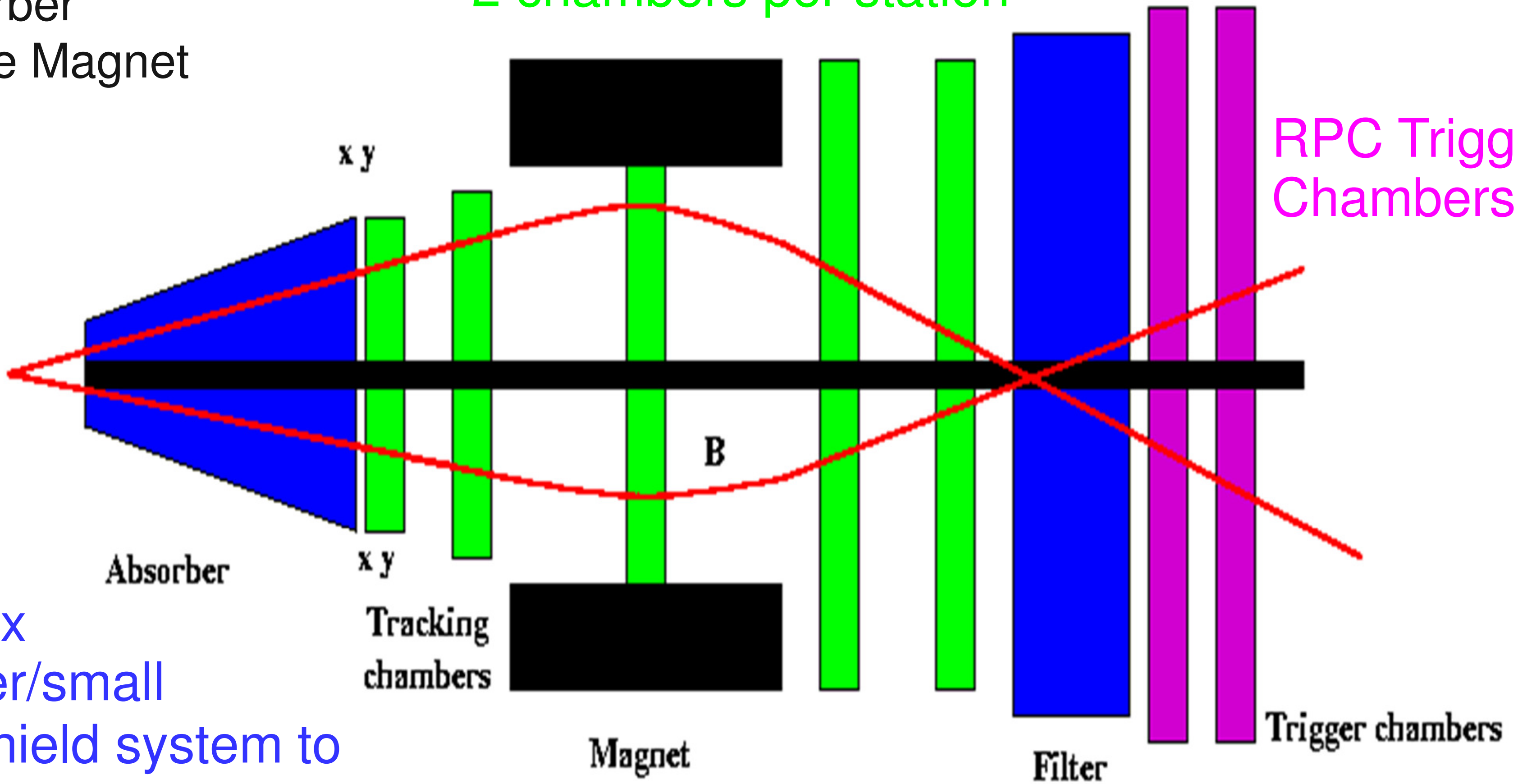
High track density in heavy ion collisions



ALICE Muon System

Components
- Tracking Chambers
- Trigger Chambers
- Absorber
- Dipole Magnet

- 5 stations of high granularity cathode pad tracking chambers (CPCs), over 1.1 M channels
- 2 chambers per station



RPC Trigger Chambers

Complex absorber/small angle shield system to minimize background (90 cm from vertex)

Dipole Magnet: bending power 3 Tm

Summary

- Their long lifetime and capability to pass material with minor energy loss (due to ionization) makes muons distinct for detection

- New physics was found in the past with muons. At the LHC, efficient detection of muons important for „golden channels“ in searches for new physics

- Muon detectors are based on gas detectors. Large variety of implementations. Most common are DTs, RPCs, CSCs and MWPCs.