Wire-based detectors in High Energy Physics experiments

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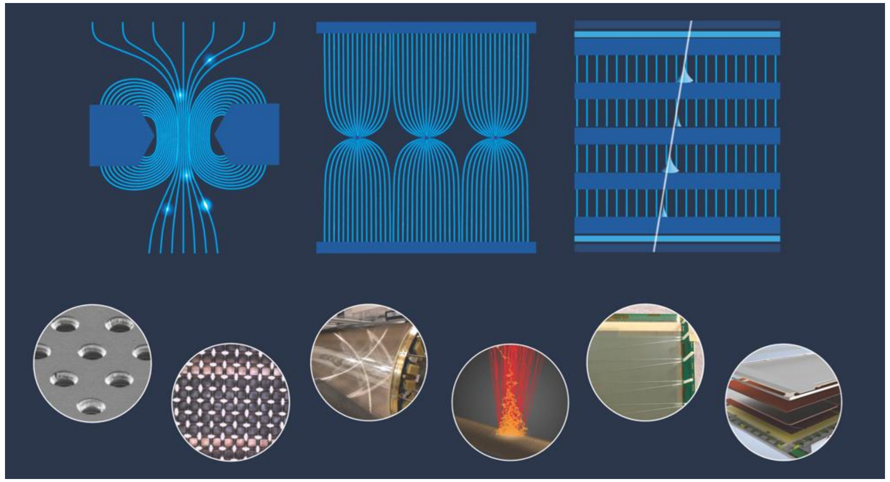
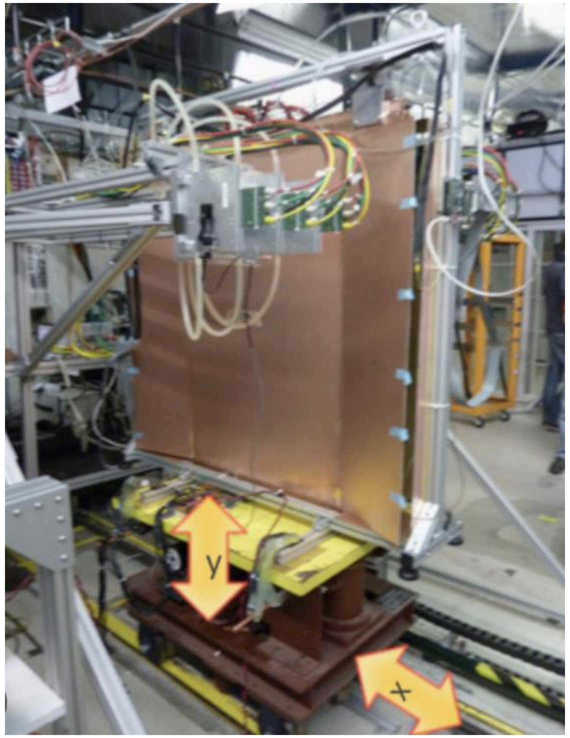


DRD1 Gaseous Detectors School 2024

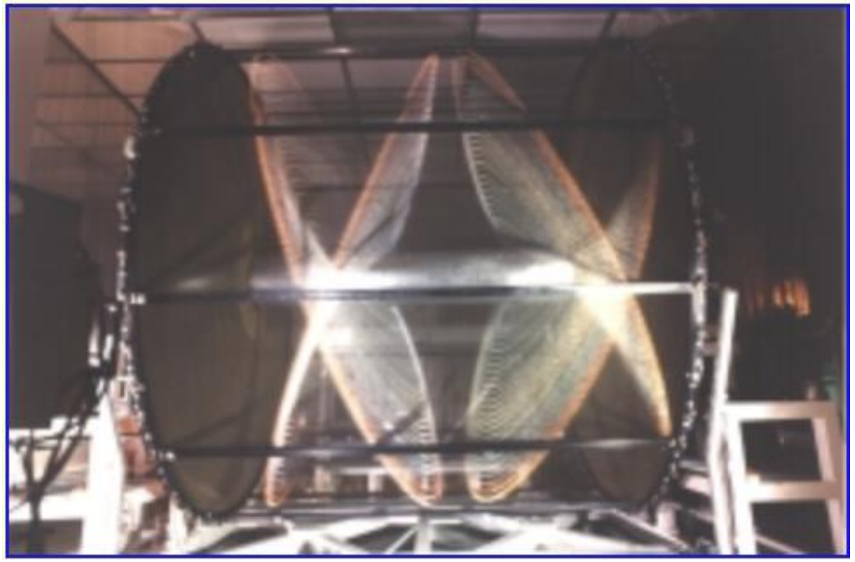
CERN, November 27th – December 6th 2024

Outline

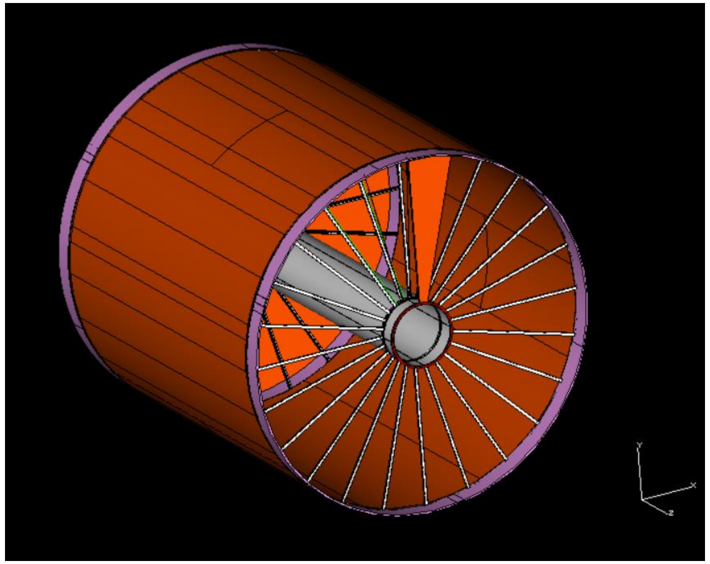
- Examples of current applications of MWPC, TGC, CSC
- Drift Tubes in LHC experiments
- Examples of past and current applications of Drift Chambers
- Drift Chambers in experiments at future lepton colliders



ATLAS sTGC


KLOE DCH


CMS DT


IDEA DCH

I assumed that now you know the main concepts related to gaseous wire-based detectors! → let's have a look to some applications of the wire-based detectors in HEP experiments!

→ Please note that (I apologize to be not exhaustive!):

- Only **few examples** for some technologies are shown here
- The choice of these examples is not driven by an **order of importance**
- ***Not covered here (but some of these subjects are discussed in other lectures in this School!): Time Projection Chambers (TPC), Time Expansion Chambers (TEC), Straw Tubes, Planar Drift Chambers, Radial Drift Chambers, …***
- ***Not covered here readout electronics!***
- ***Not covered here pattern recognition and track fitting techniques!***

- Wire-based detectors have been used in HEP experiments during the last ~50y, mainly for tracking, in some cases for trigger or Particle Identification (PId)

PAST (*,**)

Facility	Experiment	Detector type
SPEAR	MARK2 →	Drift Chamber
	MARK3	Drift Chamber
DORIS	PLUTO	MWPC
	ARGUS	Drift Chamber
CESR	CLEO1,2,3	Drift Chamber
VEPP2/4M	CMD-2	Drift Chamber
	KEDR	Drift Chamber
	NSD	Drift Chamber
PETRA	CELLO	MWPC + Drift Ch.
	JADE	Drift Chamber
	PLUTO	MWPC
	MARK-J	TEC + Drift Ch.
	TASSO	MWPC + Drift Ch.
TRISTAN	AMY	Drift Chamber
	VENUS	Drift Chamber
	TOPAZ	TPC
PEP	MARK2	Drift Chamber
	PEP-4	TPC
	MAC	Drift Chamber
	HRS	Drift Chamber
	DELCO	MWPC
BEPC	BES1,2	Drift Chamber
LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber

SpbarpS	UA1 UA2	Drift Chamber Drift Chamber
Hera	ZEUS H1	Drift Chamber Drift Chamber
Tevatron	CDF H1	Drift Chamber Fibers

(*) central trackers

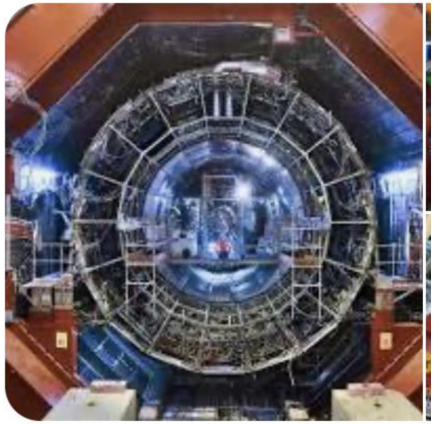
(**) not exhaustive list (e.g. no fixed target)

PRESENT and FUTURE (*,**)

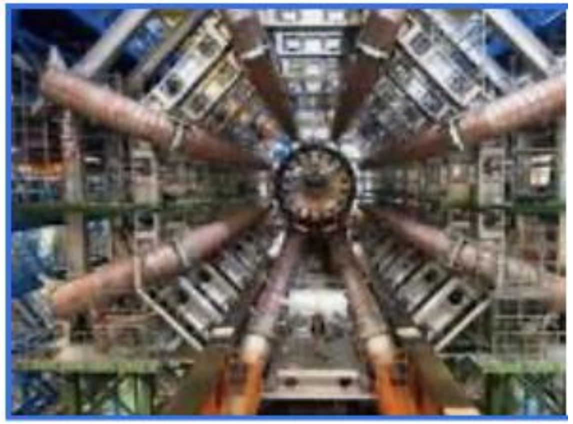
Facility	Experiment	Detector type
VEPP2000	CMD-3	Drift Chamber
	KEDR	Drift Chamber
BEPC2	BES3	Drift Chamber
S.KEKB	Belle2	Drift Chamber
LHC	ALICE	TPC
	ATLAS	Straw tubes
	LHCb	Straw tubes
CERN SPS	COMPASS	Drift Chamber + Straw
	NA35	TPC
	NA49	TPC
RHIC	STAR	TPC
	PHENIX	Drift Chamber
PSI	MEGII	Drift Chamber
ILC	ILD	TPC
	SiD	Si
FCC-ee	CLD	Si or TPC
	IDEA	Drift Chamber
	ALLEGRO	Drift Chamber, Straw
SCTF	BINP	Drift Chamber
	HIEPA	Drift Chamber

Examples of current applications of: MWPC, TGC, CSC

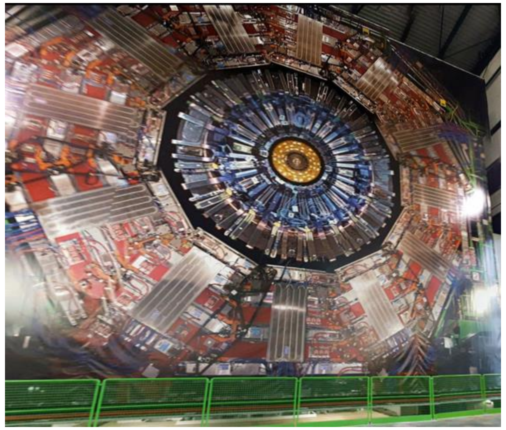
- MWPC, TGC, CSC have been used at LHC in the Muon Spectrometers of the experiments
- Detector challenges at LHC (and HL-LHC!!) → high rate capability, high detector longevity (aging), high space granularity, high time resolution!
- ATLAS and CMS → different technologies used for tracking/trigger in different $|\eta|$ ranges to cope with different conditions



ALICE
- CSC



ATLAS
- CSC (removed after Run2)
- TGC, sTGC



CMS
- CSC

LHCb
- MWPC

The LHCb MWPC

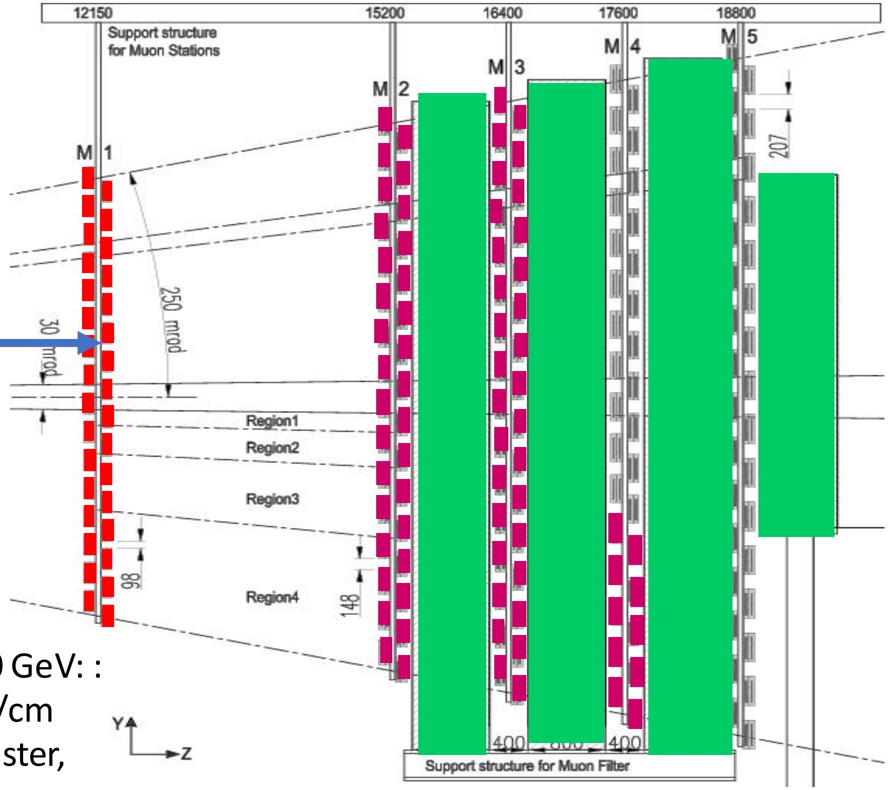
- **Muon spectrometer** → provide fast triggering and offline muon Identification for physics channels identified by clean muon signatures (CP violation, rare beauty and charm hadrons decays)

- 4 stations + 4 iron filters (M1 removed at the end of Run2). M2-M5 follow hadron calorimeter. Total absorber (including calorimeters): ~20 interaction lengths. Acceptance: ~50% of muons from inclusive b decays. ~1100 chambers.

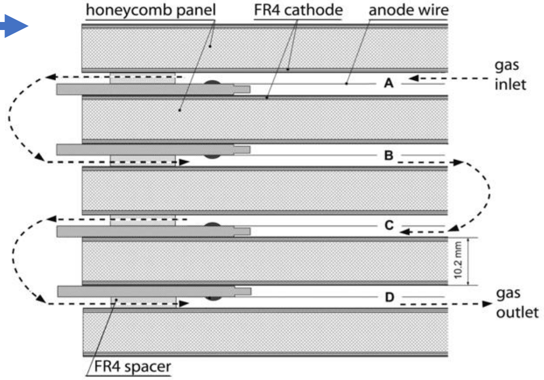
- Stations are divided in 4 regions at increasing distance from the beam axis, with ~same acceptance and granularity shaped according particle density in that region. Bending in the horizontal plane. Dipolar magnet.

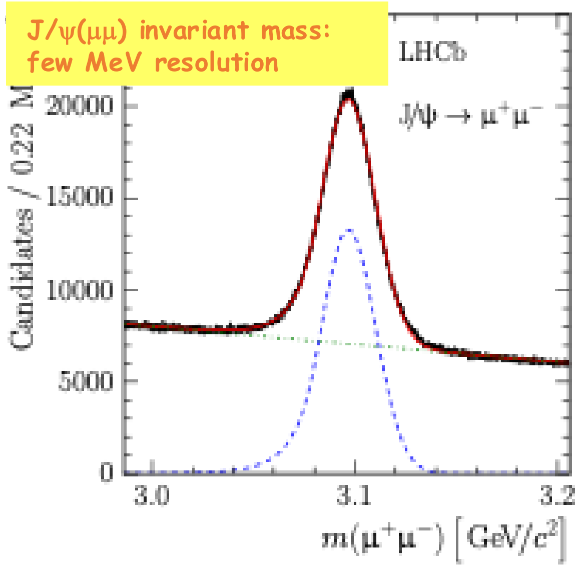
- **Muon detectors optimized for speed** (time window to address information is 20 ns)→ MWPC with 2mm wire spacing and small gas gap (5mm), fast gas mixture. Anode wires (30 μm W(Au)) and cathode pads are read. 4 gaps MWPC

- **Gas: 40% Ar + 55% CO_2 + 5% CF_4** (helps the cleaning of the electrod surfaces and prevents Malter Effects caused by silicone or organic films on the cathode surface). Drift velocity ~90-100μm/ns saturated → a small change in the electric field does not significantly perturb the drift velocity. Gas gain → 4-8 10^4



For muons with E =10 GeV: :
~40 clusters/cm
~2.38 e- /cluster,
~107 e- /cm



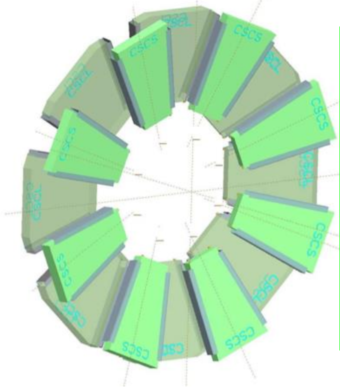


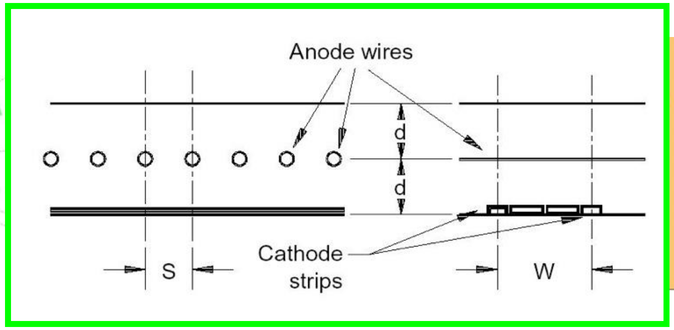
The ATLAS CSC

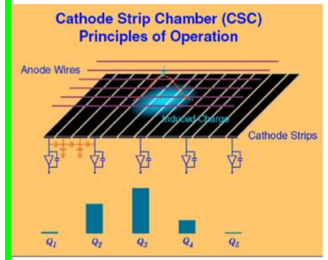
- **Precision Tracking in Muon Spectrometer End Caps (2.0<|η|<2.7):** the expected background rate at η=2.7 ~few KHz/cm^2 → MDT (see next slides) with large tube diameter and poor granularity cannot be used in such crowded environment.

  - 16 Cathode Strip Chambers (CSC) for each detector side.
  - 2 groups of 4 CSC layers per chamber.
  - Replaced in LHC Run3 by MicroMegas (MM)

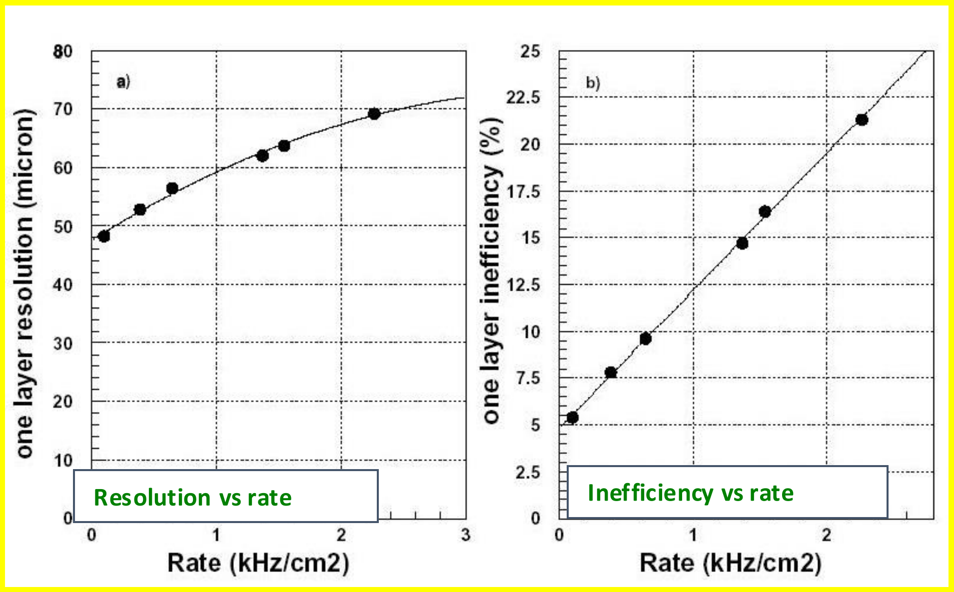
- **In CMS all endcap muon precision chambers are CSC**







- MWPC with symmetric cell where anode-cathode distance is equal to the anode wire pitch
- Anode diameter and pitch: **30 μm, 2.54 mm**
- Cathode read-out pitch: **5.08 mm**
- Very good spatial resolution: **~ 60 μm** per plane reading charge on the cathode strips ⊥ to wires
- Good time resolution: 7 ns due to short drift time (<30 ns)
- Second coordinate (ϕ) measured from the coarser strips // to the wires which form the second cathode (σ_ϕ < 1cm)



- The CSC System provided very good space resolution and track-separation
- CSC have low neutron sensitivity (no H in the gas)

Operating conditions

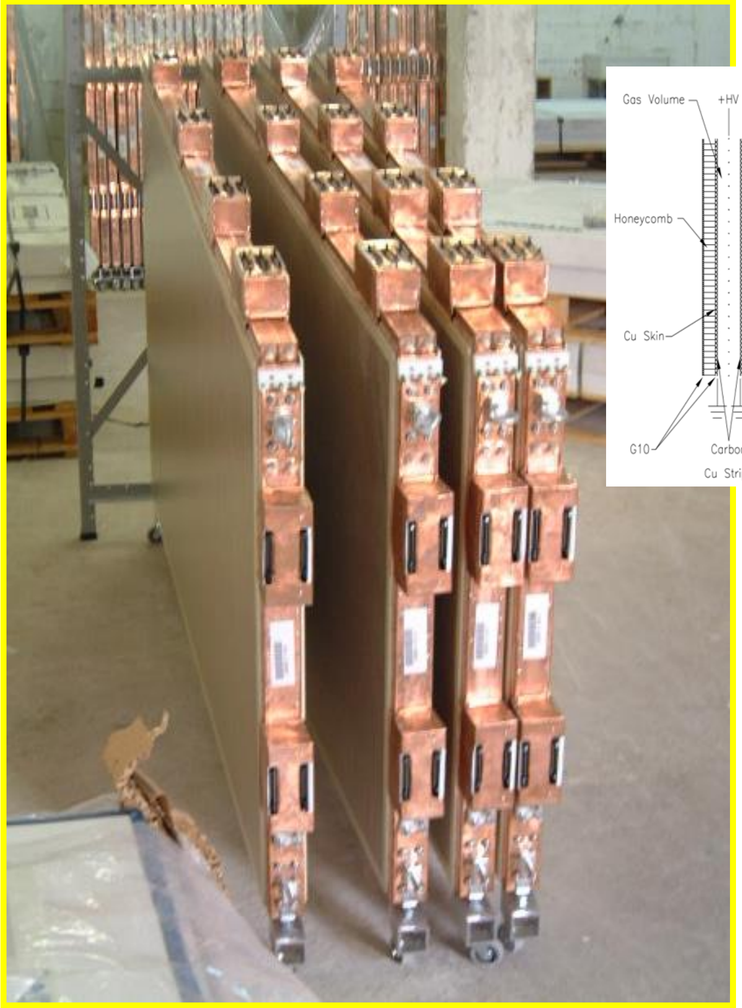
Gas : 30% Ar, 50 % CO_2 ,20 % CF_4 (supports detector longevity), high v_{drift} → 6cm/μsec

HV: 2.6 KV

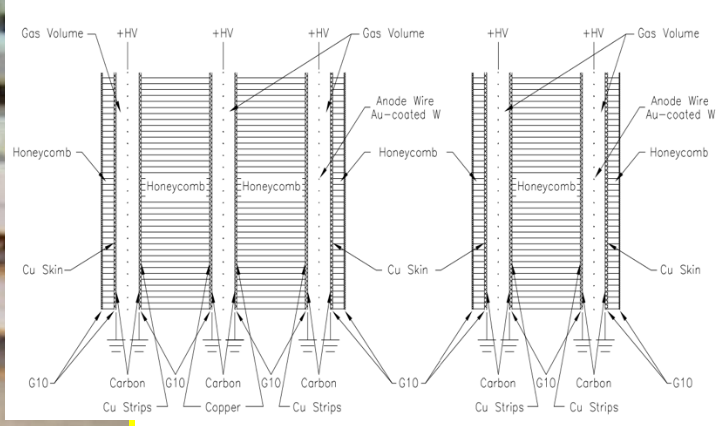
Gas Gain: 2x10^4

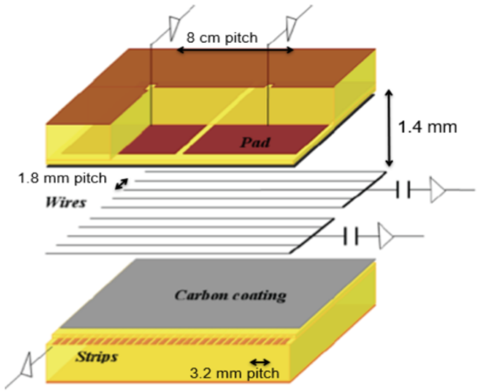
The ATLAS TGC

- **Trigger in Muon Spectrometer End Caps (1.05<|η|<2.4):** fine granularity is needed since trigger chambers are outside B and have a short lever arm → 2 double-gap TGC layers + 1 triple-gap TGC layer + 1 double-gap TGC layer in the innermost station (only measur.) for each detector side
- Small-strip TGC (sTGC) in the endcap muon spectrometer upgrade



Triplet Doublet





sTGC → strips with 3.2mm pitch, increased resolution to operate at high background rate reducing the muon fake rate

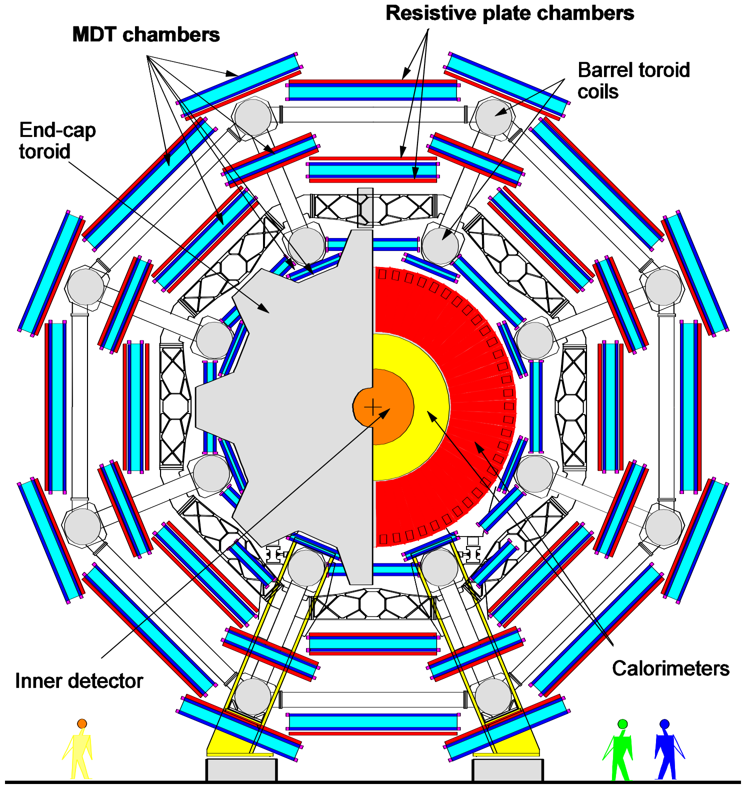
- MWPC with readout strips and small anode-cathode distance: less than anode pitch
- Anode wire pitch: **1.8 mm**
- Anode-Cathode dist: **1.4 mm**
- Cathode-Cathode dist: **2.8 mm**
- Read-out Strip pitch **20-30 mm**

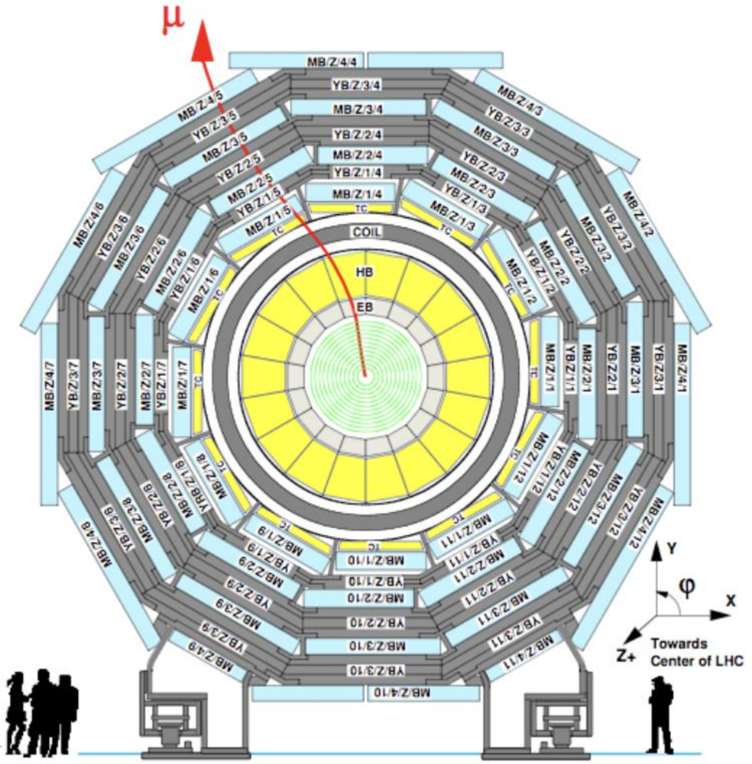
Operating conditions

- Gas : 55 % CO_2 , 45 % N-Pentane
- HV: 3.1 KV
- Saturated avalanche mode → less sensitivity to mechanical deformations (large detectors!)
- Very short drift time due to the thin gap → good time resolution needed for Bunch Crossing ID
- Wire (//to the MDT wires) signal used to provide the trigger, Cu strips (⊥ to the wires) signals used for the second coordinate ϕ
- Due to the small gap, high flatness is required to keep a uniform gain

Drift Tubes in LHC experiments

- ➢ MDT (DT) used in ATLAS (CMS) in the Muon Spectrometers





The ATLAS MDTs

➢ **Monitored Drift Tubes (MDT) → muon tracking in $|\eta|<2.0$**

➢ Muon spectrometer goal:

$\Delta p_T/p_T = 0.1$ @ p_T = 1TeV/c,

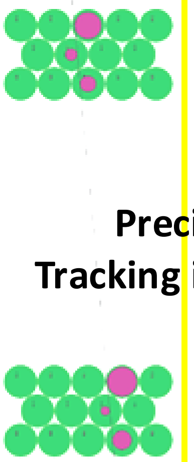
p_T = 1TeV/c -> 500μm sagitta; Δs=50μm

Tube Radius (*) :	15 mm
Tube thickness (Al)	400 μm
Wire (W-Re,Au) diameter	50 μm
Tube length:	1-6 m
Chamber mech. Precision	20 μm

- ❖ Chamber Spatial Resolution (per point) ~ 80μm
- ❖ Accurate calibration: time-to-distance relation within ~ 20μm
- ❖ Wire positioning inside tracking chambers within ~ 20μm
- ❖ Chamber Alignment within ~ 30-40μm (barrel - endcaps)
- ❖ Magnetic field knowledge @few permille

Operating Conditions

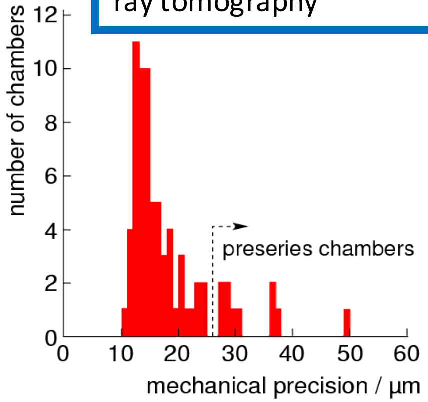
Gas Mixture:	93 % Ar-7%CO_2
Absolute pressure:	3 Bar
HV:	3080 V
Gas Gain:	2×10^4
Threshold:	25 electrons
Max drift time	~800 ns
Single tube average resol.	80μm
(precision measur. in the bending plane)	
Station resol.(6/8 meas.)	~50μm,~0.3mrad



Precision Tracking in $|\eta| < 2.$

- ❖ Precision measurements of z in the bending view (σ_z=80μm) with 3 MDT stations
- ❖ MDT station: 2 multilayers of 3 (4 in the inner station) layers of drift tubes
- ❖ (*) sMDT (1.5 cm tube diameter) installed in the detector feet during Run2

Wire position inside tube measured with X-ray tomography



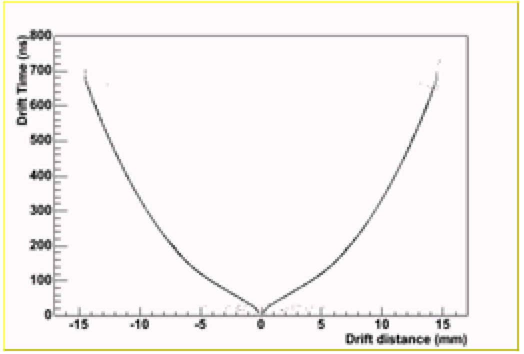
Time-to-distance (R-T) relation

Non linear, depends on:

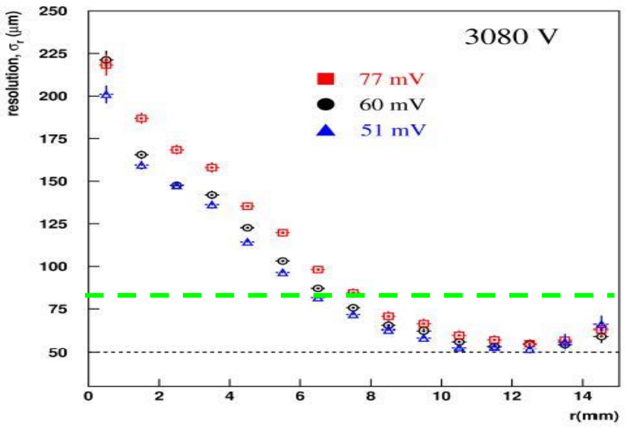
- ❖ Magnetic field
- ❖ Temperature
- ❖ CO_2 percentage

Known at the level of ~20μm over almost all distance from the wire

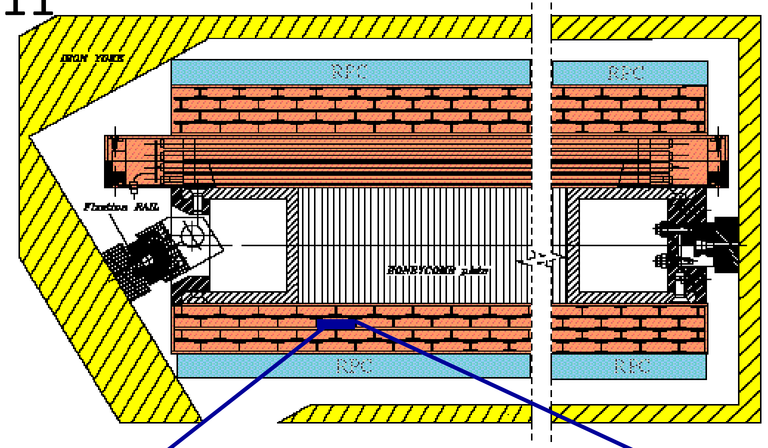
R-T relation



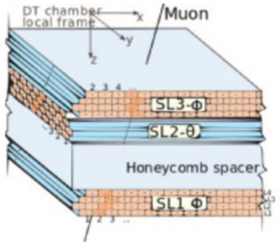
Resolution vs distance from wire

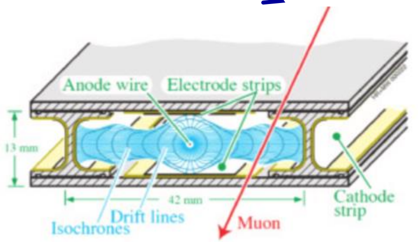


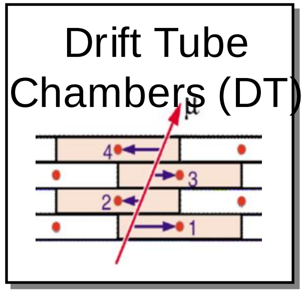
The CMS DTs



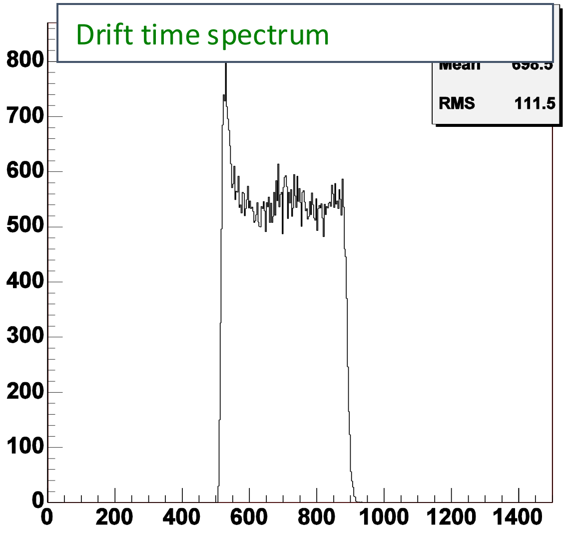
- **Muon Spectrometer Barrel (|η|<1.2):** Drift Tubes (DT) → ~172000 tubes, 250 chambers, 4 stations of DT, interleaved with the iron of magnet yoke

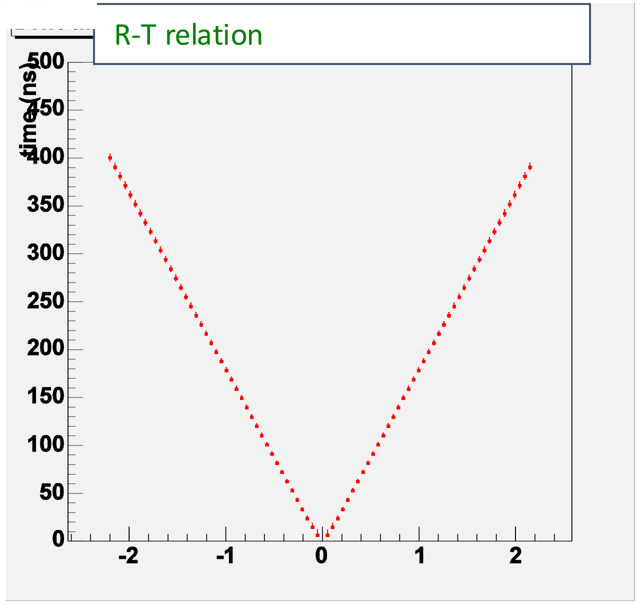






- Each station made of 3 SuperLayers (SL): 2 in r-ϕ (bending plane) and 1 in r-z (not in the 4-th station) separated by honeyconmb spacers
- Each SL made of 4 layers of staggered (of 1/2 cell) 4.2cm×1.3cm cells → allows auto-triggering and bunch crossing id, σ_t ~ 2ns
- Layer and SL alignment within O(10 μm)
- E field shaped in the cell to ensure very good linearity of the R-T relation (v_d~constant)
- Gas : 85% Ar - 15 % CO_2 ,atmosf. Pressure, max drift time ~400 ns
- Single point resolution : ~200 μm
- Very good chamber resolution: ~100 μm



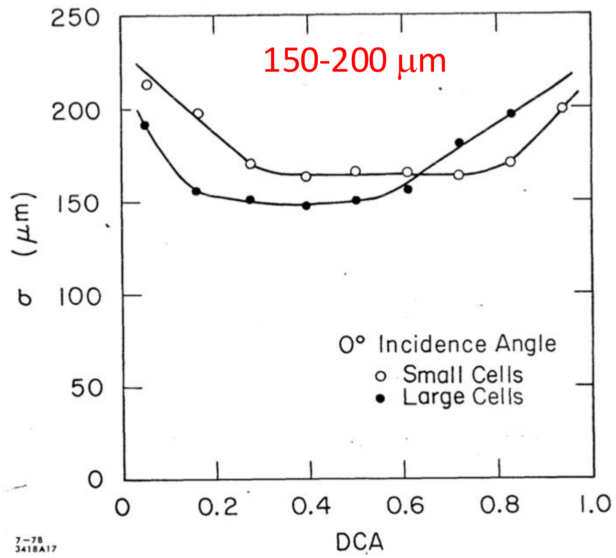


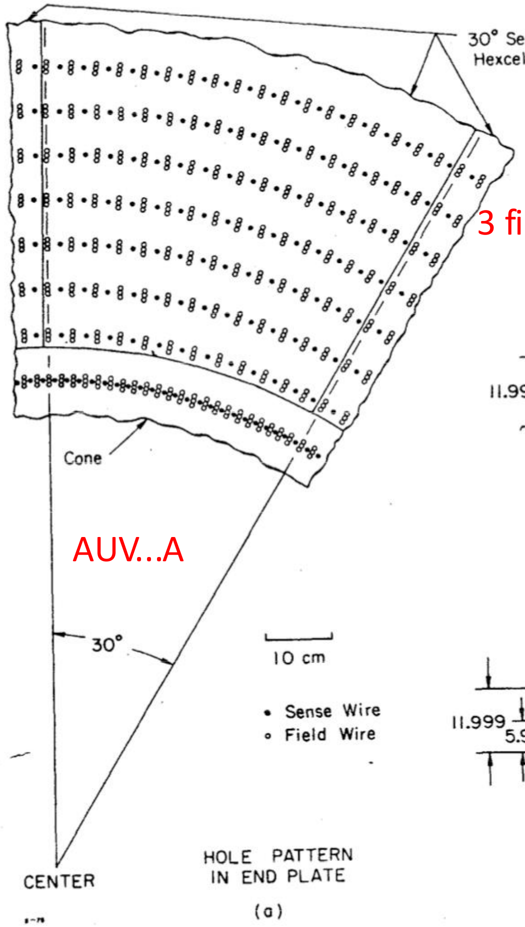
Drift Chambers: past and present

➢ A "generation" of cylindrical Drift Chambers started with MARK2@SPEAR, 1978 → *CLEO (1979), TASSO (1980), CELLO (1980), VENUS (1985)…*

MARK2→Single sense wire open cell

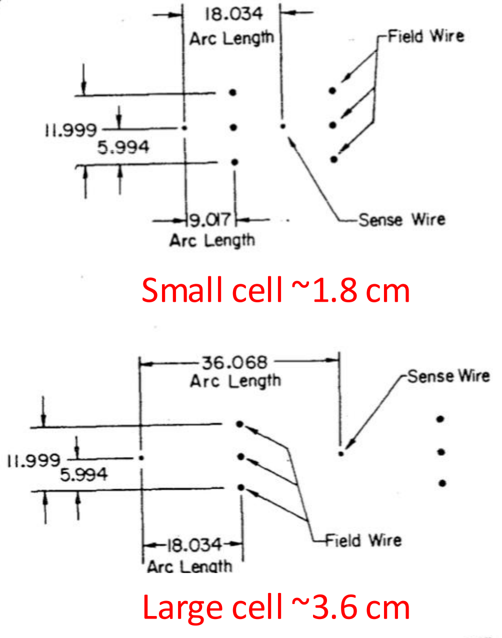
≈ 3 m diameter
≈ 2.7 m active length
0.41 Tesla B-field
max drift time 450 ns (780 ns BX)
16 layers → 6 axial + 10 stereo (±3°)
3204 drift cells (3:1)
22,000 wires
50% Ar – 50% C_2H_6
2% X_0 radial - 20% X_0 end plates

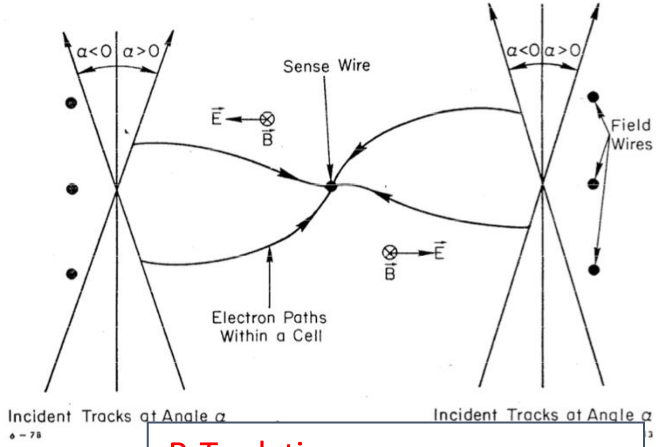


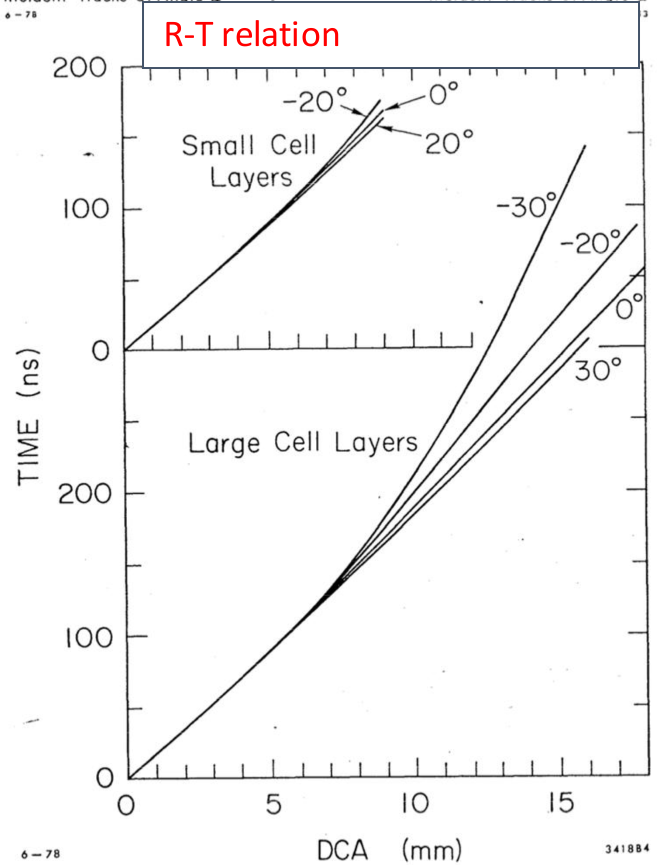


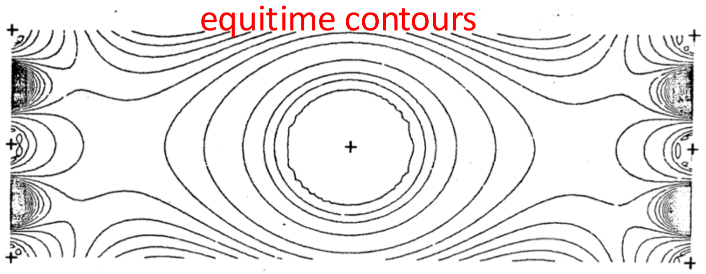
sense wires
40 μm CuBe (Ag)

field wires
150 μm CuBe (Ag)
3 field wires per sense wire (3:1)



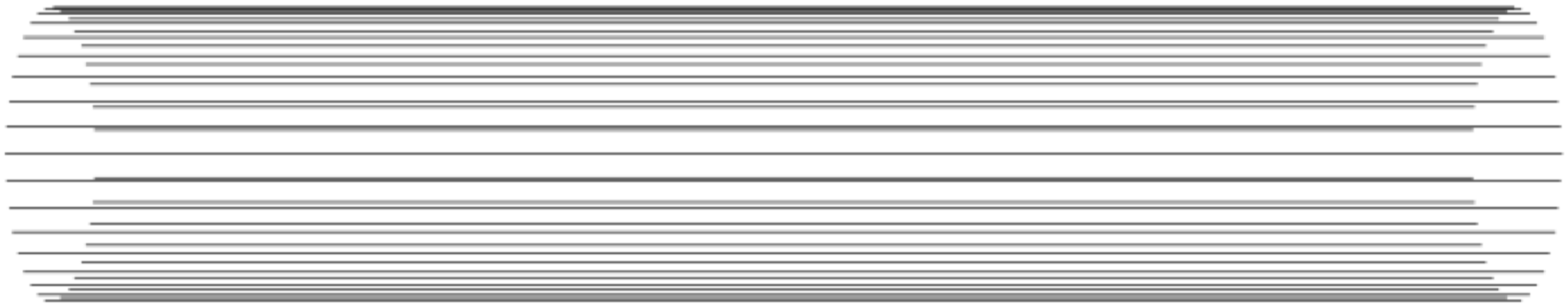






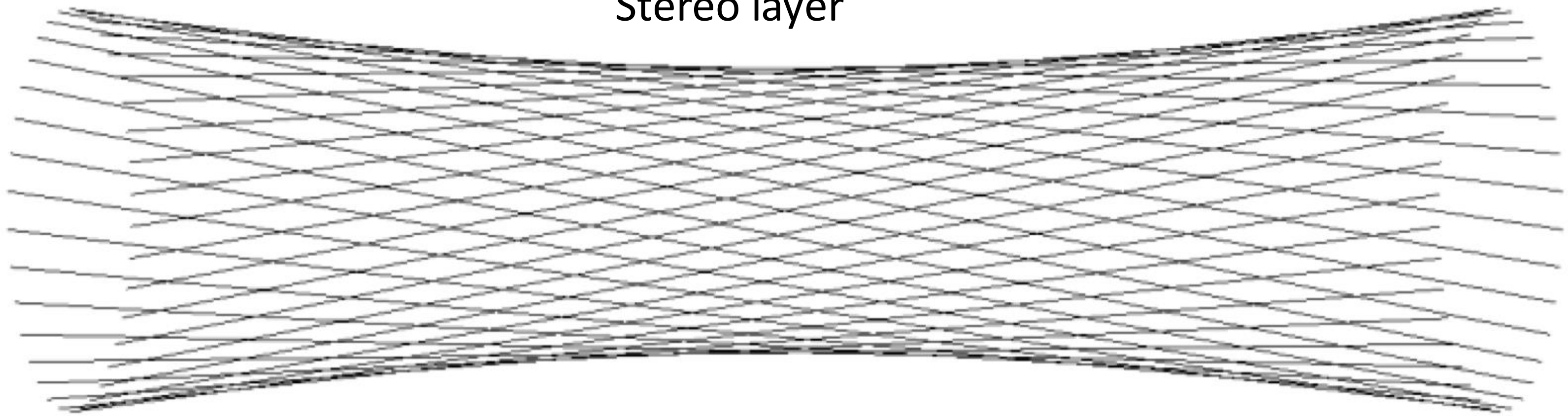
Axial and stereo layers

Axial layer



cylindrical envelope of axial wires

Stereo layer



hyperboloid envelope of stereo wires

Resolution in the measurement of the z coordinate in a stereo geometry: $\sigma_z = \sigma_{r\phi}/\sin(\varepsilon)$ with $\varepsilon =$ stereo angle

The MARK2 Drift Chamber

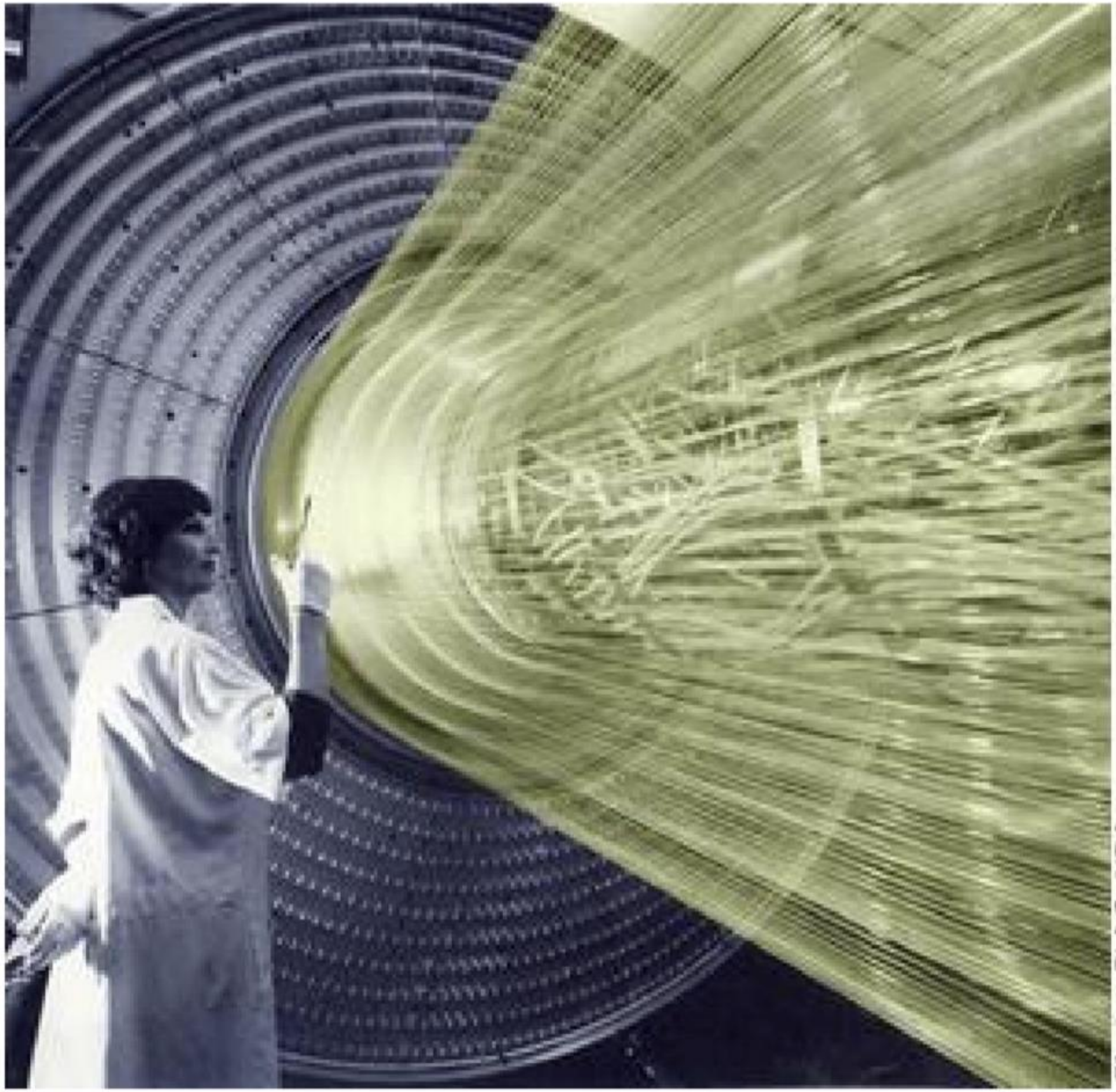
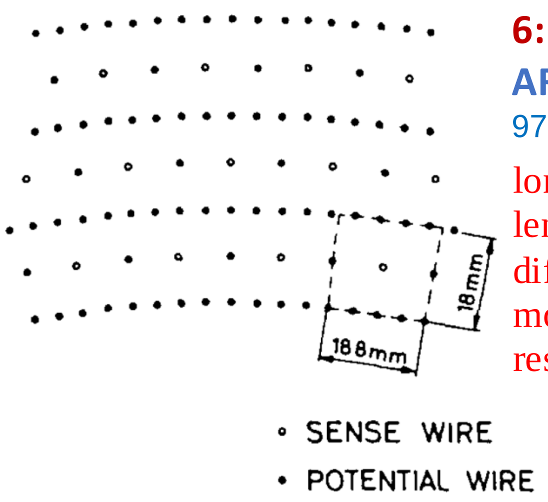


Photo: SLAC, USA

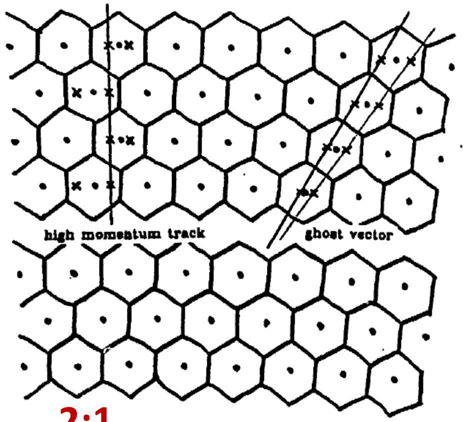
➢ … but the design of drift chambers went through **various stages of evolution:**

❖ from open to closed cells → ARGUS (1982), CLEO2 (1984), AMY (1984),…



6:1
ARGUS@DORIS
97 C_3H_6 / 3 methylal

long radiation length and small diffusion → good momentum resolution.



2:1
AMY@TRISTAN
50 Ne / 50 C_2H_6

Closed cells limit the very long tails in the drift time distribution, make the t-to-d (x-t) relations more uniform and less dependent from the track angle

A larger ratio of field to sense wires allows for thinner field wires and, therefore, for less multiple scattering contribution from the wires to the momentum measurement

Square cells make the time-to-distance relations more isotropic

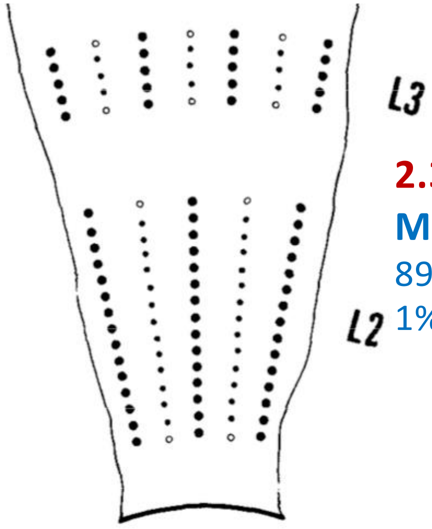
Small drift distance limits drift asymmetries due to Lorenz angle

However

Portions of **active volume** not sampled between the cylindrical envelope of axial wires and the hyperboloid envelope of stereo wires

some problems with **left-right ambiguity** and close tracks separation

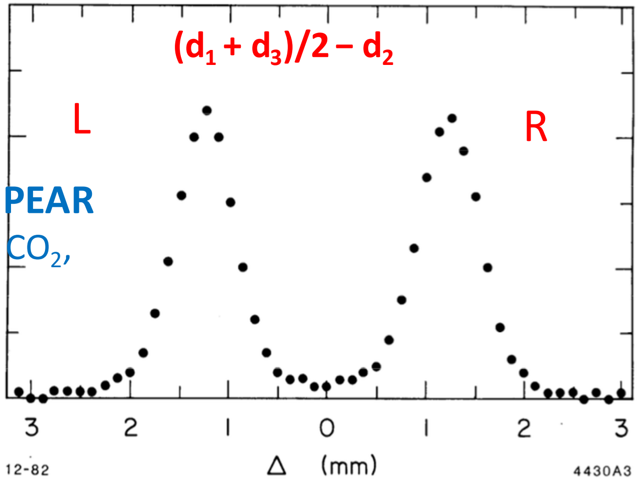
- from single sense wire cells to multi-wire and Jet-like cells → MARK3 (1980), JADE (1982), CMD2 (1985), SLD (1988), BES (1989), ZEUS (1992), CDF (1988, 2002), OPAL (1988), …



2.33:1

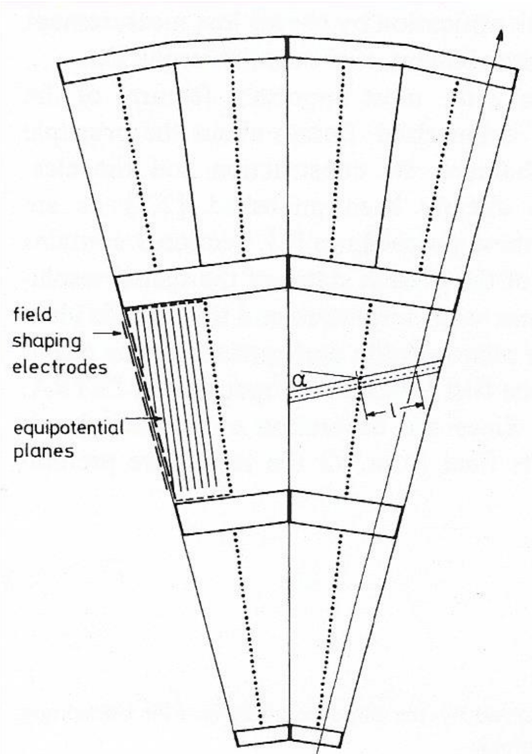
MARK3@SPEAR

89% Ar, 10% CO_2, 1%CH_4



4.25:1

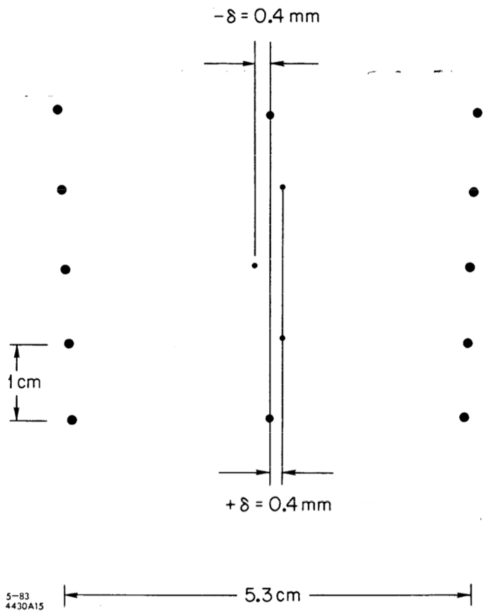
ZEUS@HERA



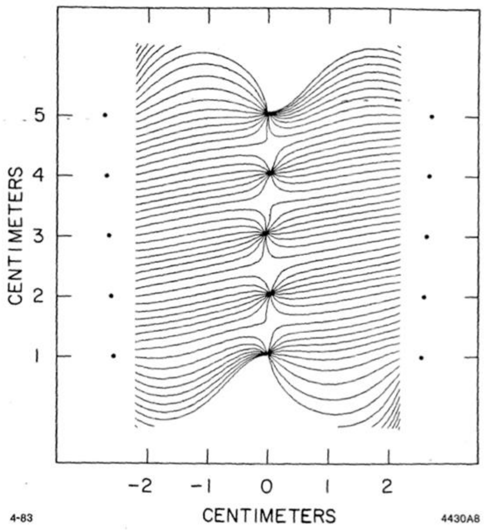
≈1:1

JADE@PETRA

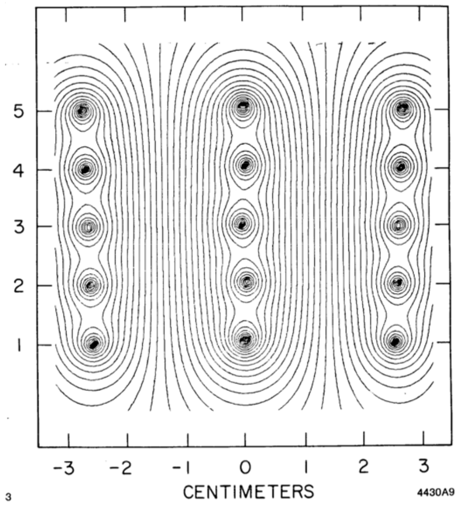
88.7 Ar / 8.5 CH_4 / 2.8 iC_4H_{10}



drift lines



equipotential lines



Track finding facilitated by the definition of a point and a vector within a single cell

Left-right ambiguity solved at the cell level

Double track resolution improved

However

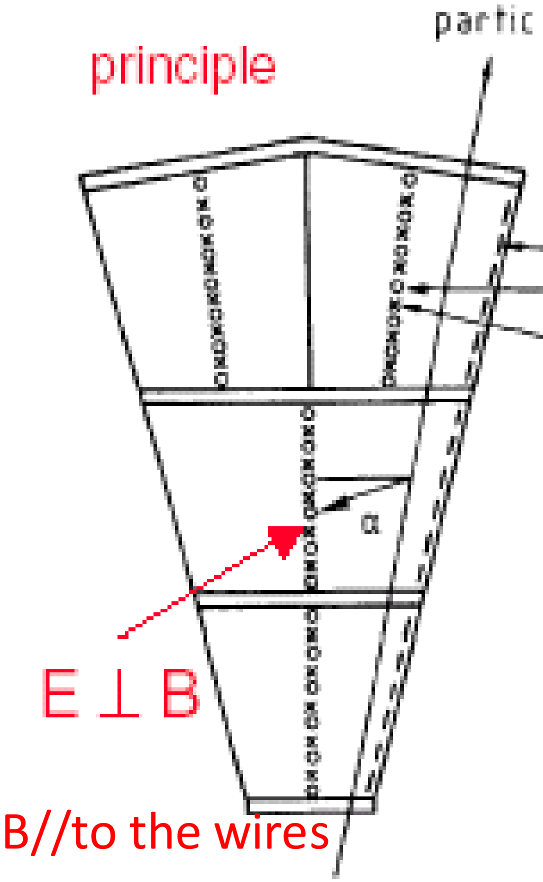
Only **limited stereo angles** allowed because of its radial dependence for long jet-like cells

Very long drift times

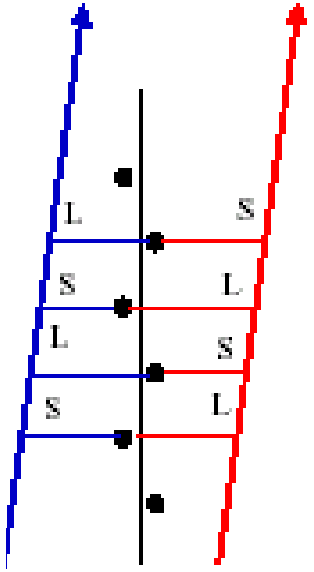
Portions of **active volume** not sampled between the cylindrical envelope of axial wires and the hyperboloid envelope of stereo wires

Need for extra (thick) wires to limit **cross-talk** between adjacent sense wires and for extra wires at cell boundary to limit long drifts

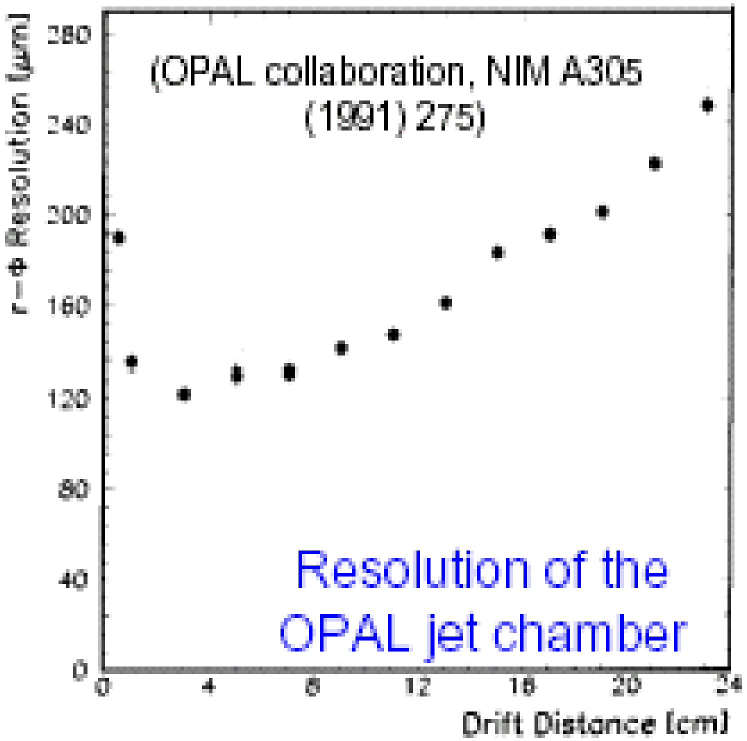
The OPAL Jet Chamber

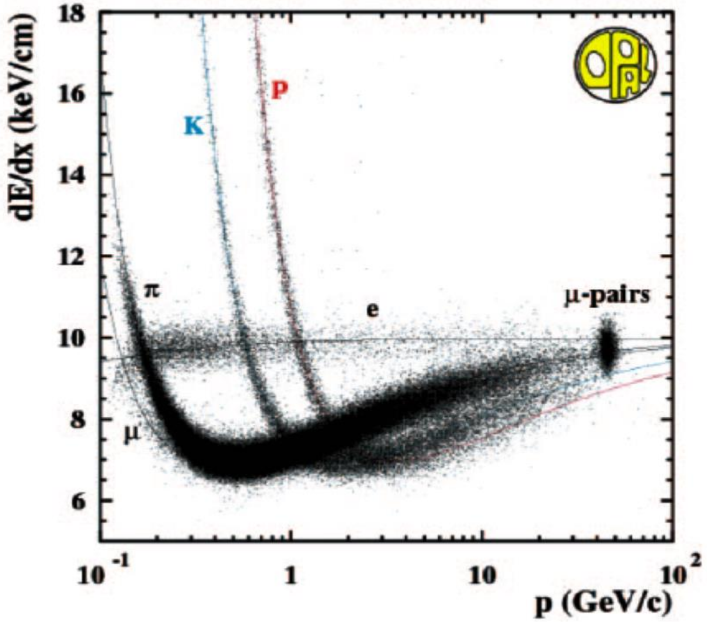


Left/right ambiguity solved with staggering the anode wires of ±100 μm.



Ø=3.7m, L=4m, 24 sectors with 159 sense wires (±100 μm staggered). 3 cm < l_{drift} < 25 cm





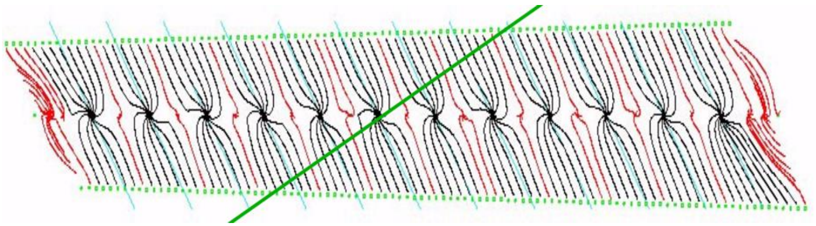
Gas: 88.2% Ar - 9.8% CH_4 – 2% Isobutane, v_{drift} ~ saturated at 53μm/ns
Oxigen content < 2ppm to minimize attachment over long drift distances

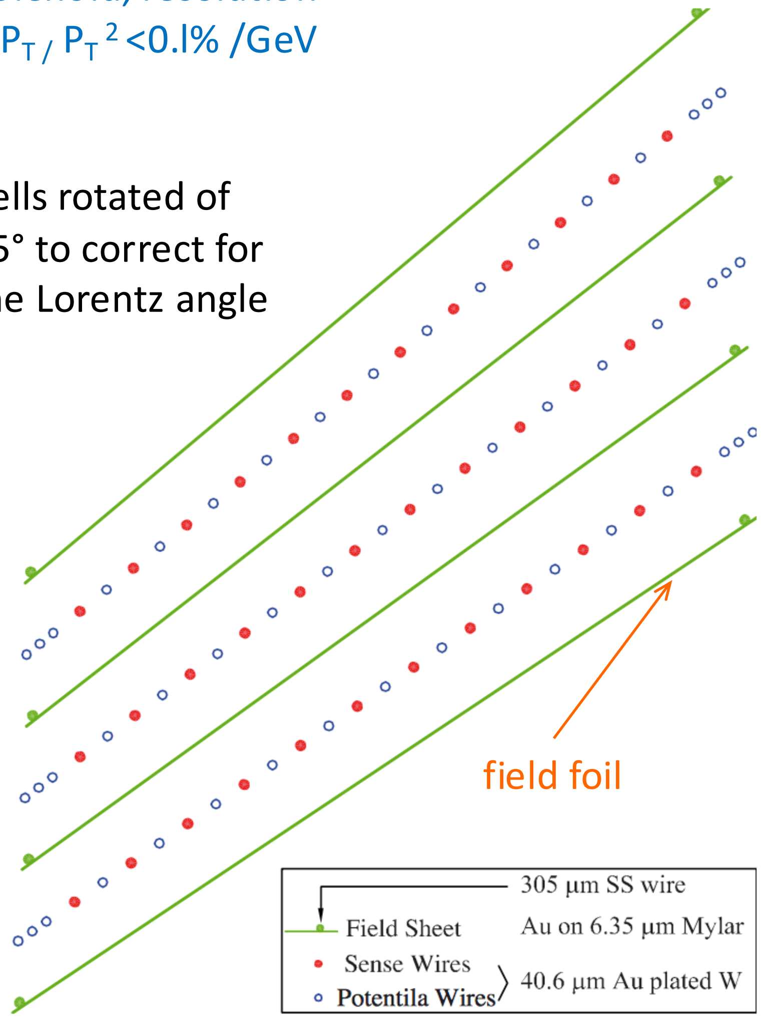
- dE/dx resolution improved operating the chamber at high pressure (e.g. 4 atm.) ➔ primary ionization fluctuations were suppressed
- However the pressure must not be too high, to avoid the density effect allows dE/dx to reach the Fermi plateau.
- Measurement of the z coordinate (// to the anode wires) performed with charge division

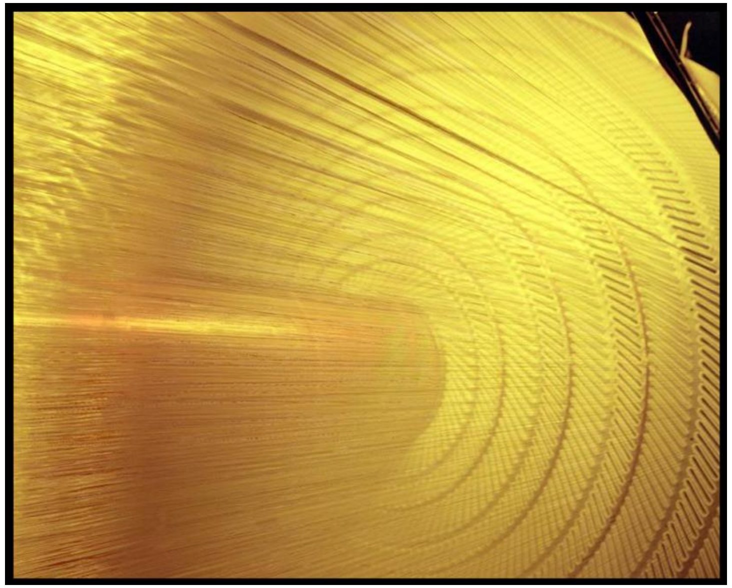
The CDF COT Drift Chamber

CDF II@Tevatron
tracks with P_T down to 400 MeV, B= 1.4 Tesla solenoid, resolution $\Delta P_T / P_T^2 < 0.1\%$ /GeV

Cells rotated of 35° to correct for the Lorentz angle







- 48 Axial layers, 48 Stereo layers
- 2520 sense, 2520 field slots

Field foil versus field wires:

- very effective solution to confine broken wires within a limited region
- very uniform field at the cell boundary
- larger cathode surface allows for running at higher gain
- radial symmetry wrt single sense wire cells
- azimuthal symmetry for axial wire layers but not for stereo layers
- Moreover:

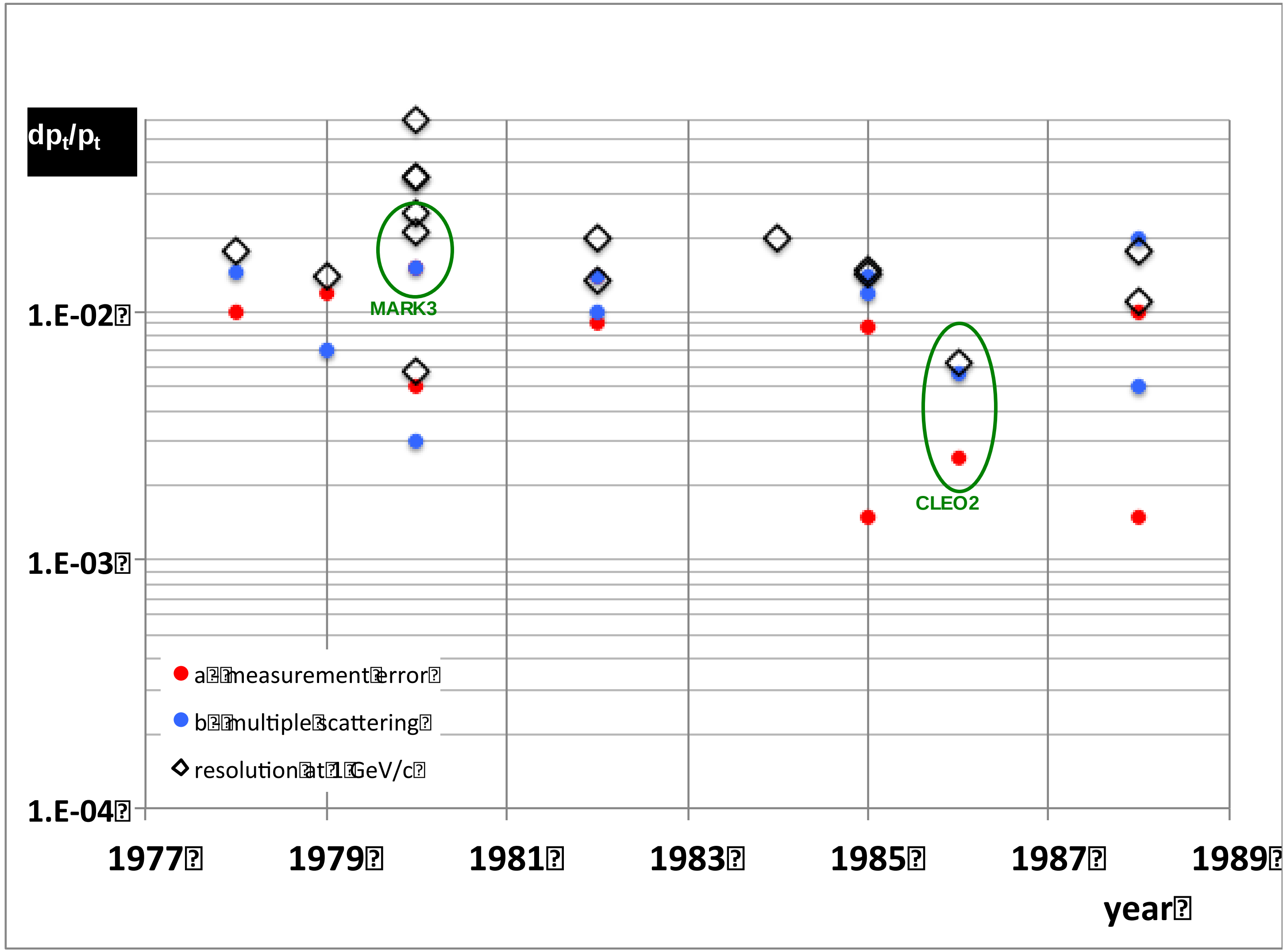
6.35 µm Mylar + 2×0.035 µm Au = 2.4×10^{-4} X_0

40 µm diameter Au plated W (4/cm) = 1.0×10^{-5} X_0

- Load on end plates: 560 g/cm of foil, 80 g for 4 wires/cm

- Gas: 50% Ar– 50% C_2H_6
(+ some ppm of O_2 to reduce aging effects)
- ~50 µm/ns drift velocity
(396 ns BX at Tevatron in Run II)
- Strong drift field to minimize space charge effects

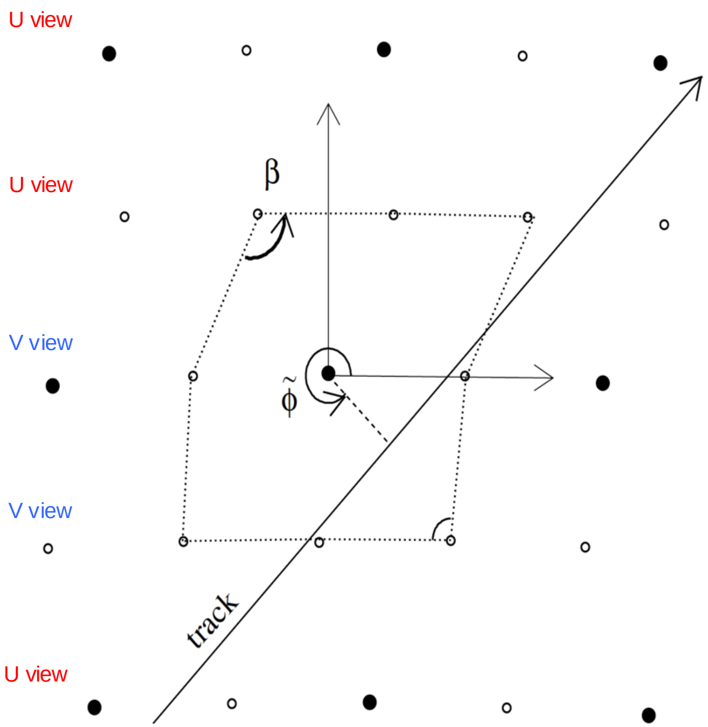
❖ Momentum resolution in early chambers



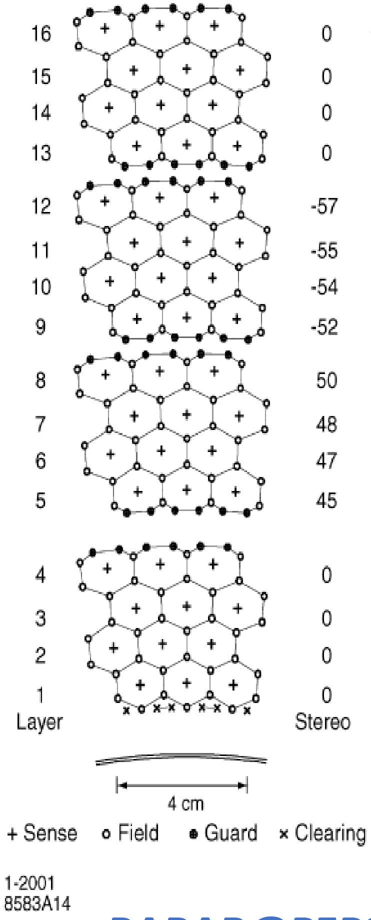
$$(dp_T/p_T)^2 = [8\sqrt{5}\sigma_{r\varphi}/(0.3BL^2\sqrt{N})]^2 p_T^2 + [5.4\times10^{-2}/BL\sqrt{(L/X_0)}]^2$$

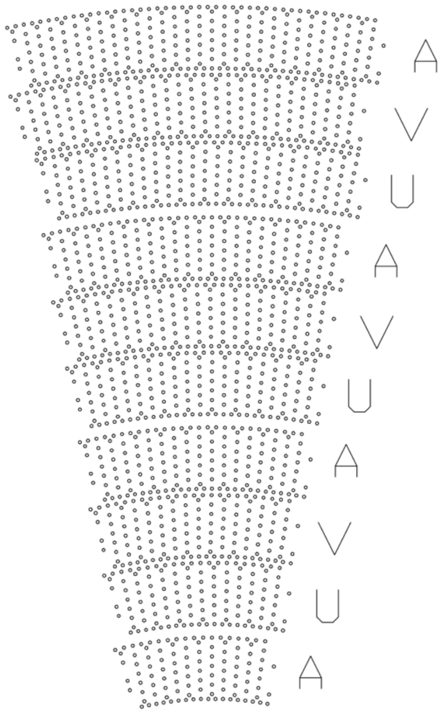
- ❖ Despite the large variety of different parameters involved, **momentum resolution** (at p=1GeV/c) clusters around **1-2%** for all chambers.
- ❖ Initially, resolution was dominated by the sagitta measurement error. With improved cell configurations, the dominant error became multiple scattering, requiring a significant change in the **gas mixture** and in the **wires**.

❖ Helium as Drift Chamber gas (@lepton colliders!), and back to single sense-wire cells! → KLOE (1998), CLEO3 (1998), BABAR (1998), BESIII (2008), BELLE2 (2017), …



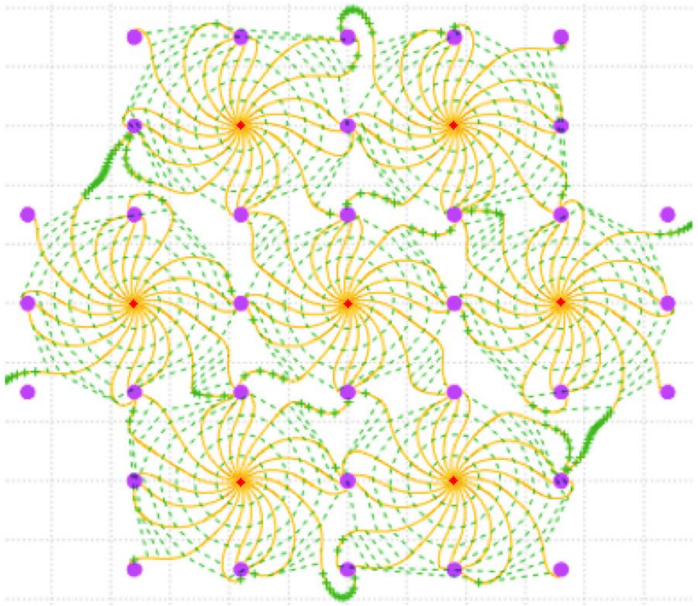
KLOE@DAPHNE
90 He/ 10 C_4H_{10}





BABAR@PEP2
80 He/ 20 C_4H_{10}

10 superlayers of 4 layers each,
Axial (A), stereo (U,V,~4°)



BELLE2@KEKB
50 He/ 50 C_2H_6

He **radiation length** 50× longer than Ar

Slower drift velocity in He→ smaller **Lorentz angle** for a given B-field

He has a **smaller cross section for low energy photons** than Ar

Small size cells limit the **electron diffusion** contribution to spatial resolution, reduces the accumulated charge→**slow down aging,** can provide **fast trigger signal at high luminosity**

Small size cells provide **high granularity** (improving occupancy) and allow for a larger number of hits per track, **improving spatial resolution** (more layers in the same space)

However

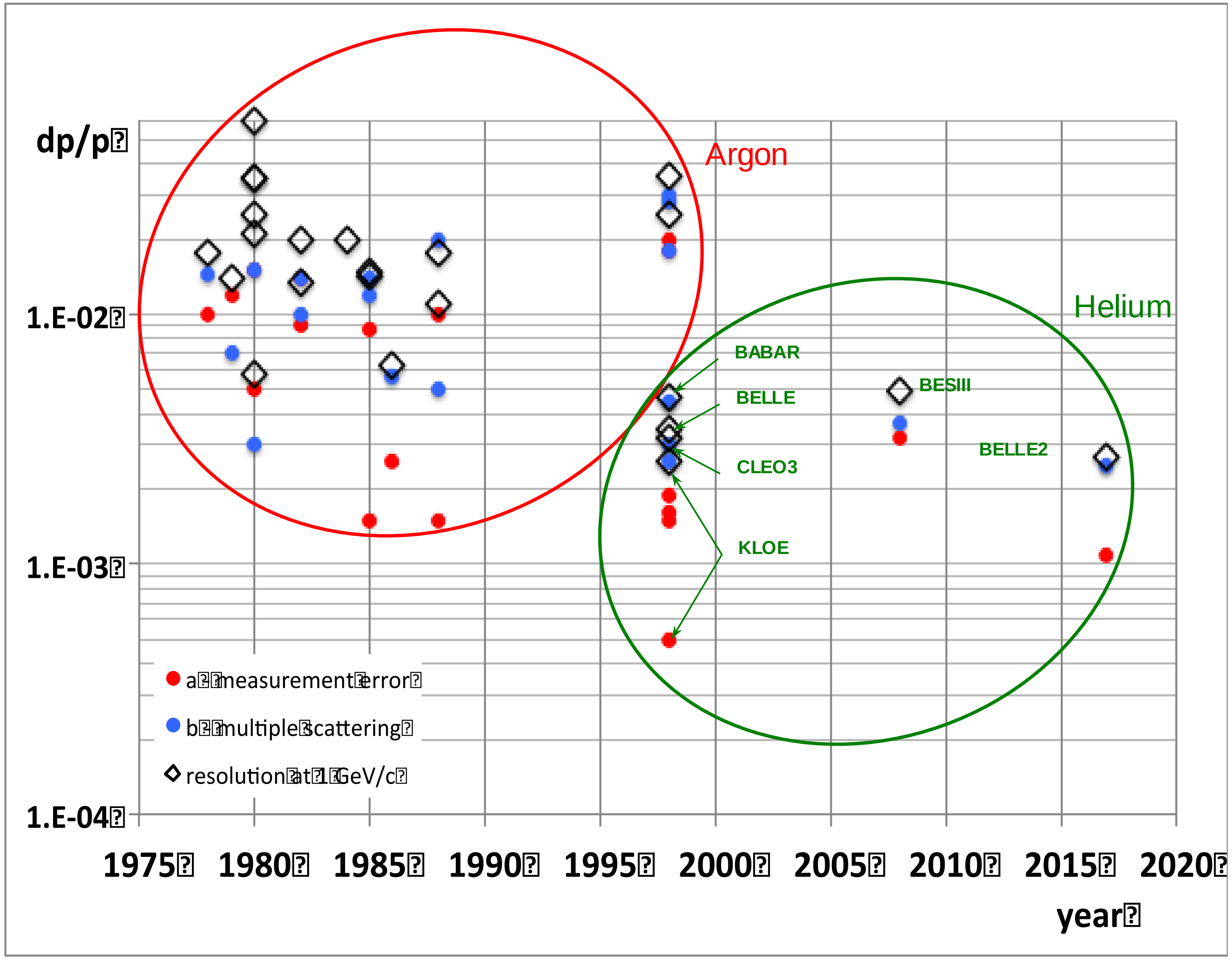
Portions of **active volume** not sampled between the cylindrical envelope of axial wires and the hyperboloid envelope of stereo wires

Spatial resolution dominated by ionization statistics for short drift distances → adding more quencher to compensate, mitigates the advantage of He

Accumulation of trapped electrons and ions in a region of **very low field**

Longitudinal **gain variation** at boundaries between axial and stereo layers

❖Momentum resolution in chambers operated with Helium-based mixture



$$(dp_T/p_T)^2 = [8\sqrt{5}\sigma_{r\varphi}/(0.3BL^2\sqrt{N})]^2 p_T^2 + \\ + [5.4\times10^{-2}/BL\sqrt{(L/X_0)}]^2$$

Momentum resolution ≤ a few $\times10^{-3}$

But too large amounts of quencher mitigate the advantages of the longer radiation length of Helium!!

- ❖ Helium as Drift Chamber gas, single sense-wire cells and full stereo configuration → KLOE (1998), MEG II (2017), IDEA (future FCCee), …

A configuration with **only alternating sign stereo layers (no axial layer)** fills the gaps occurring in a mixed stereo-axial configuration, making the chamber more isotropic and fully sampled, and increasing the number of hits on a track for a given cell size.

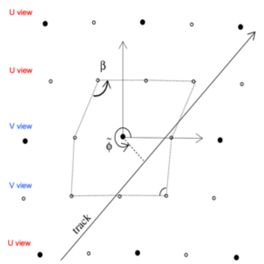
No gaps between axial and stereo layers which may trap electrons and ions in a region of very low field

Constant gain along the longitudinal coordinate for all layers

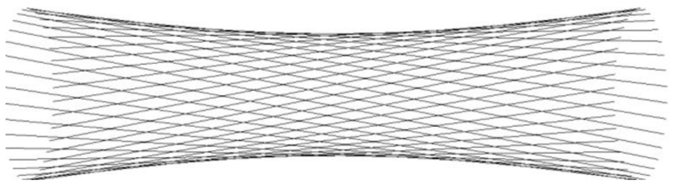
Larger number of hits on a track for a given cell size, maximize the number of measurements of the longitudinal coordinate

However

Open top cells cause a dependence of the time-to-distance relations from the track angle and from the cell-shape longitudinal periodicity



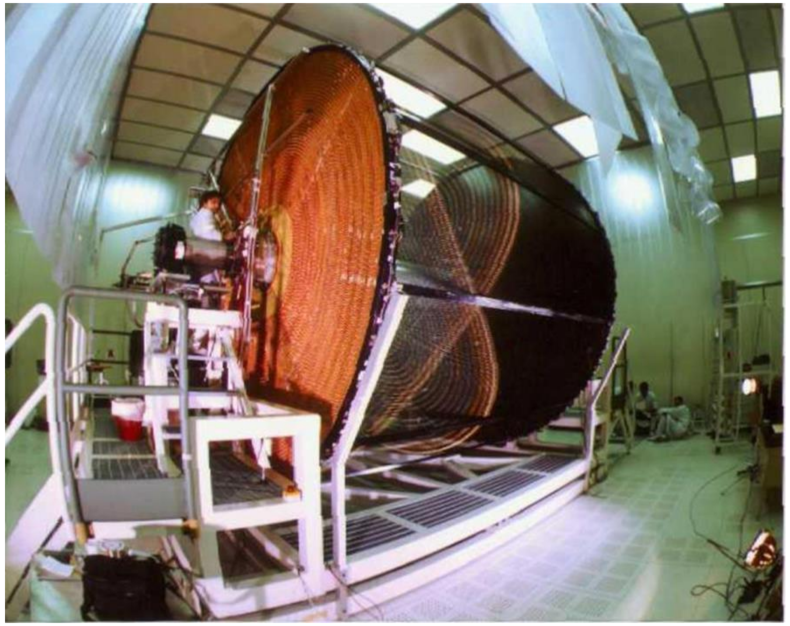
Constant stereo drop (e.g. KLOE) changes the cell aspect ratio along z → radial cell size constant but azimuthal width increased at end-plates,while **constant stereo angle** generates cell distortions for large stereo angles



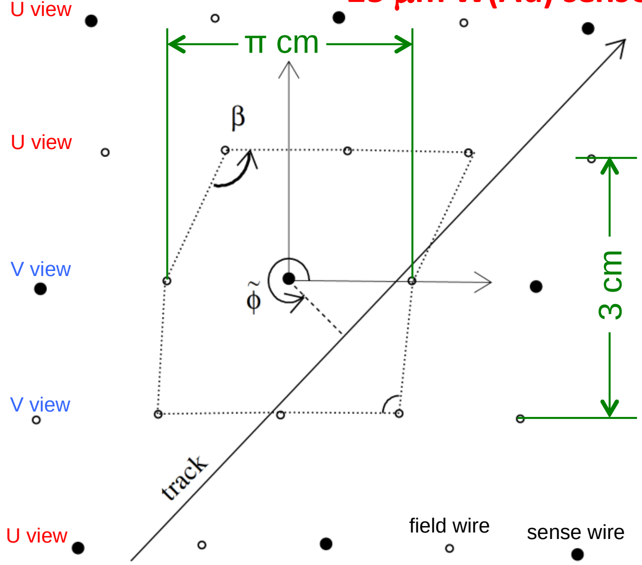
The KLOE Drift Chamber

All in C-fibers composites

Outer panels thickness	39 mm
Inner cylinder thickness	1.1 mm
End-plate thickness	9 mm (0:03X0)
C-fiber X_0	26.7 cm



25 μm W(Au) sense, 80 μm Al(Ag) field



- the field wires layer of the cell outer bound at a stereo angle of opposite sign w.r.t. the sense wire layer and to the field wires layer of the cell inner bound

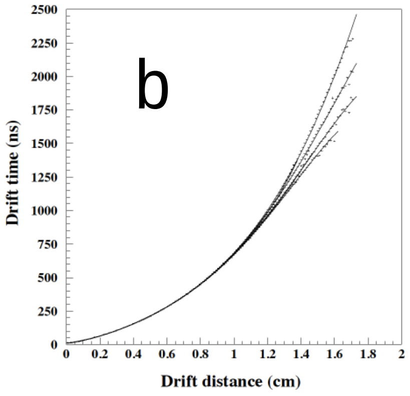
Requirements@KLOE:

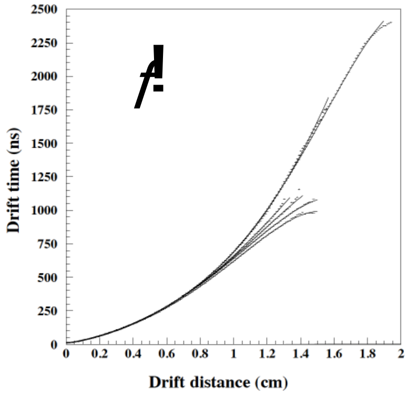
- Large volume, highly homogeneous detector (long K_L decay path and isotropic angular distribution of the charged decay products)
- High and uniform track reconstruction efficiency over all the volume
- Good momentum resolution (down to ~50 MeV)→ σ_{pT}/p_T ~0.5%
- Very high transparency (to minimize multiple scattering and K_S regeneration)
- Minimize the number of wires

Chamber design:

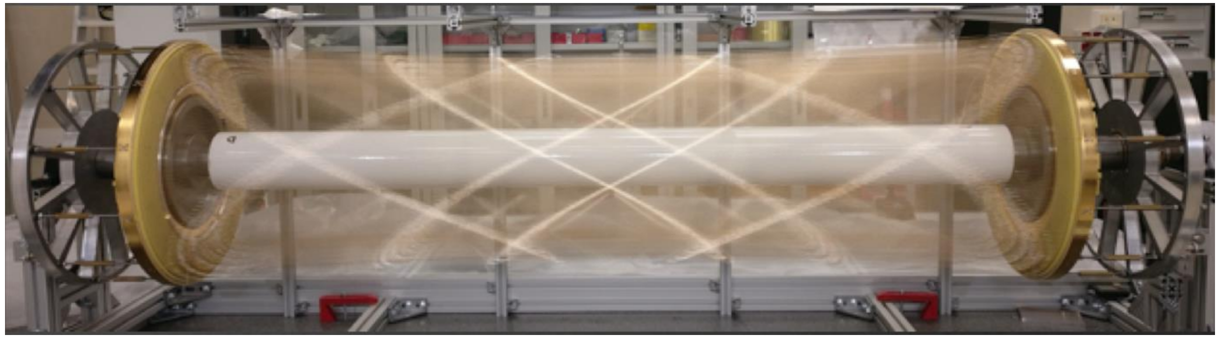
- Cylindrical (4m diameter, ~3.3m long) coaxial with B
- 58 layers of squared single sense wire cells (3:1), at alternating sign stereo angles (60-150 mrad)
- constant stereo drop at the middle transverse plane (1.5 cm) for all layers **(*)**
- 12 (inner) layers of (2x2π/3) cells, 46 layers of (3xπ) cells
- 12582 cells, **52140 wires in total**, 3.5 tons load on end plates
- 90% Helium-10% isobutane → **X_0 ~ 1300 m**

- **(*)** causes a small longitudinal variation of the cell aspect ratio → **time to distance relations depend on the track angle and on the cell periodicity in z.**





The MEG II Drift Chamber



- A unique volume, high granularity, all stereo, low mass cylindrical drift chamber, co-axial to B (1.27÷0.49 T).
- R_{in} =18 cm, R_{out} =30 cm,L ~ 2 m
- 10 co-axial layers, alternating sign stereo angles from 100 mrad to 150 mrad,
- Square cell size ≈7x7 mm^2
- Large field to sense wire ratio (5:1) → thinner field wires, reducing wire contribution to multiple scattering and total wire tension

  20 μm W sense, 40-50 μm Al field
- Hit resolution ~ 110 μm
- Operating gas: He ~90% - iC_4H_{10} ~10% (+ 1.5% isopropyl alcohol and 0.5% O_2 to keep current level stable)
- 1920 cells, 12678 wires in total

Reduced wire spacing → increased cell granularity

However

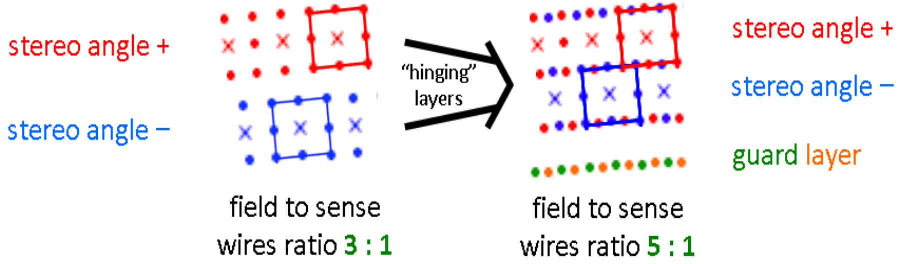
The wire density per cm² is high → Feed-trough-less wiring

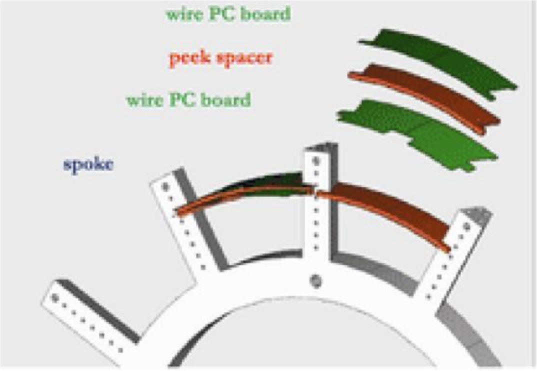
Gas containment

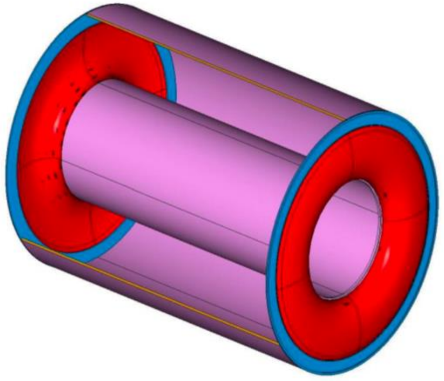
Gas vessel can freely deform → no impact on the internal wire position and mechanical tension.

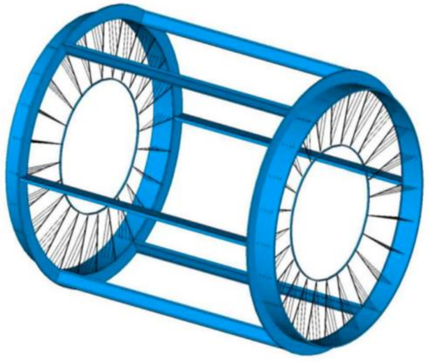
Wire cage

Wire support structure not subject to differential pressure can be light and feed-through-less





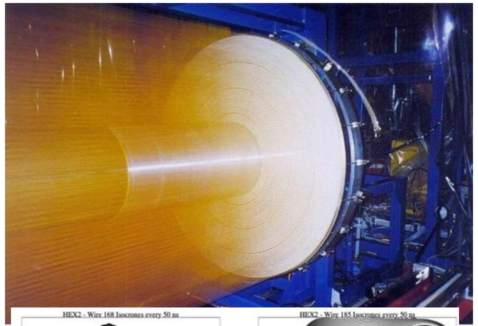


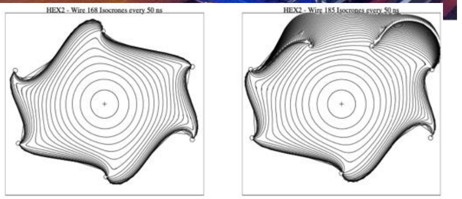


BABAR, BELLE2, BESIII, COMET Drift Chambers (for (very) low momenta charged particles expected!)

BABAR@SLAC

CP violation in B meson system

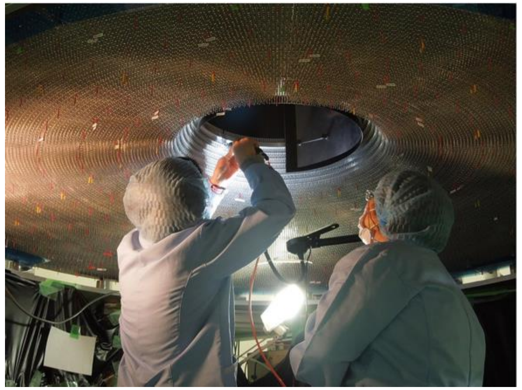




- R_{in} = 24 cm, R_{out} = 81 cm
  2.8 m length
- 10 superlayers of 4 layers each, Axial and stereo (~4^0)
- **Small hex cells, 1-2 cm**
- **Gas: He 80% - iC_4H_{10} 20%(+ water vapour+O_2)**
- Hit resolution ~ 125 μm
- $\sigma(p_T)/p_T$ =0.45%+0.13%p_T
- dE/dx resolution ~ 7.5%
- 28768 wires in total, **20 μm W-Rh (Au) sense, 120 μm Al (Au) field**

BELLE2@SUPERKEKB

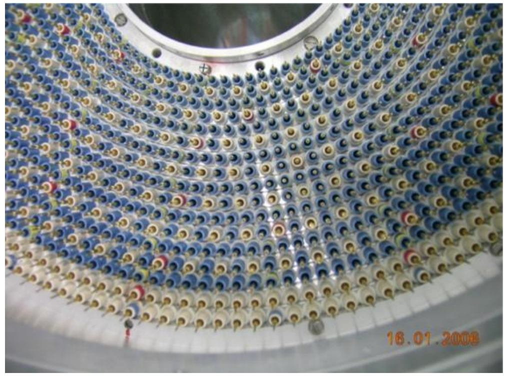
beauty and charm hadrons, tau physics



- R_{in} = 16.8 cm, R_{out} = 113 cm
  ~2.5 m length
- 9 superlayers of 6-8 layers each, 56 layers
- Axial and stereo (46-71 mrad)
- **Square cells (8:1), 0.6-1.8 cm**
- **Gas: He 50% - C_2H_6 50%**
- Hit resolution ~ 100 μm
- $\sigma(p_T)/p_T$ =0.2%+0.1%p_T
- dE/dx resolution ~ 5%
- 14336 sense wires, **30 μm W (Au) sense, 126 μm Al field**

BESIII@Beijing

charm, charmonium, tau, light hadron physics



- R_{in} = 6.3 cm, R_{out} = 81 cm
  ~2.3 m length
- 43 layers in 11 superlayers
- 19 Axial and 24 stereo (46-71 mrad) layers
- **Square cells (3:1),1.2-1.6cm**
- **Gas: He 60% - C_3H_8 40%**
- Hit resolution ~ 120 μm
- $\sigma(p_T)/p_T$ =~0.5%@1GeV
- dE/dx resolution ~ 5%
- 28680 wires in total, **25 μm W(Au) sense, 110 μm Al (Au) field**

COMET@J-PARC (Japan)

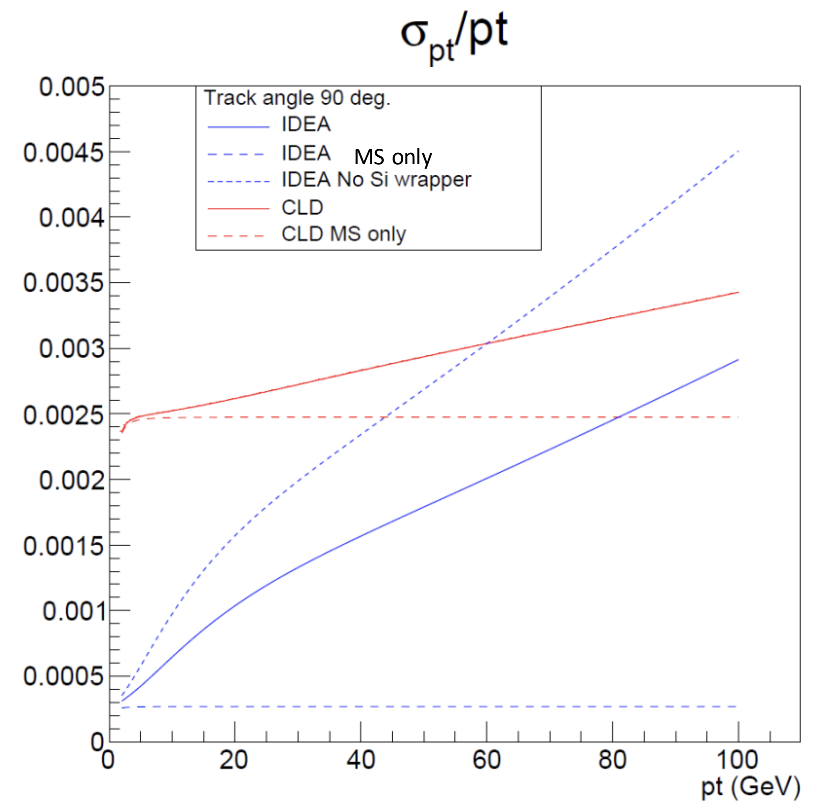
charged lepton flavor violating process of neutrino-less muon-to-electron

- R_{in} = 49.5 cm, R_{out} = 83.5 cm
  ~1.6 m length
- 20 layers
- All stereo (64-75 mrad)
- **Square cells (3:1),1.2-1.6cm**
- **Gas: He 90% - iC_4H_{10} 10%**
- Hit resolution ~ 150 μm
- $\sigma(p_T)/p_T$ =0.2%@100MeV
- 19548 wires in total , **25 μm W (Au) sense, 126 μm Al field**

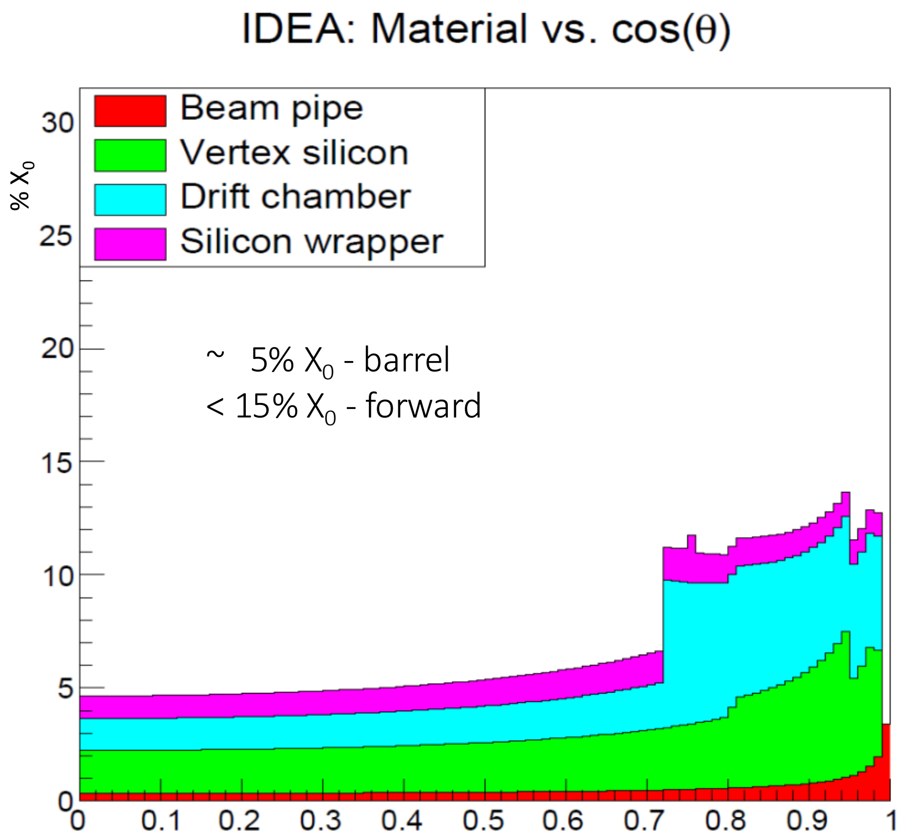
Drift Chambers at future colliders

The IDEA Drift Chamber/1

- ***IDEA*** **(→ Innovative Detector for Electron-positron Accelerators at FCCee)** detector concept → DCH designed to provide **efficient tracking, high precision momentum measurement and excellent particle identification** for particles of low and medium momenta (charged particle momenta@Z pole → few hundred MeV/c - several tens of GeV/c!). Main features:
  - Large tracking radius (to recover momentum resolution → magnetic field limited to ~ 2 T to contain the vertical emittance at Z pole)
  - High granularity
  - Transparency against multiple scattering
  - Cluster counting technique for PId



Particle momentum range far from the asymptotic limit where MS is negligible



The IDEA Drift Chamber/2

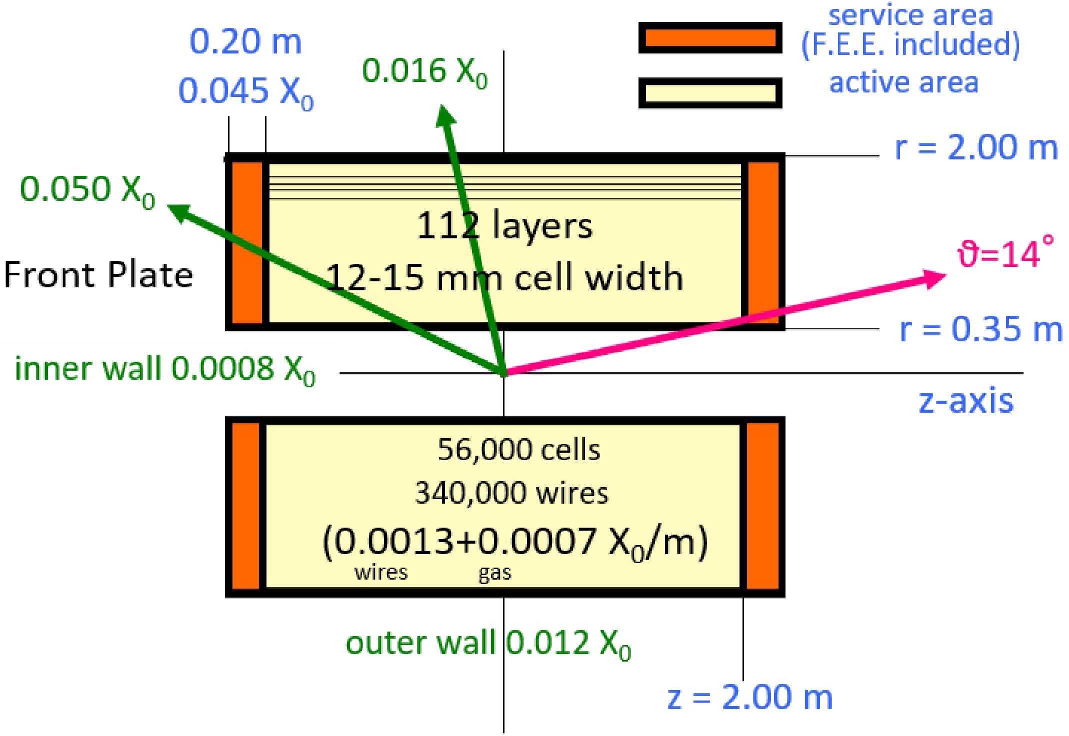
- Large volume: **R_{in} = 0.35 m, R_{out} = 2 m, Length= 4 m**, Inner wall = 200 µm thick Carbon fiber, Outer wall = 2cm thick composite material sandwich
- Operating gas: **He 90% - C_4H_{10} 10%**
- Full stereo: **112 co-axial layers**, arranged in 24 (15°) identical azimuthal sectors, at alternating-sign stereo angles **ranging from 50 to 250 mrad**
- Granularity: **12÷14.5 mm** (at z=0) wide square cells, **5 : 1 field to sense** wires ratio
- drift length ~1 cm, drift time ~350-400 ns
- Expected resolution **σ_{xy} < 100 µm, σ_z < 1 mm**
- **56,448 cells and 343968 wires** in total:

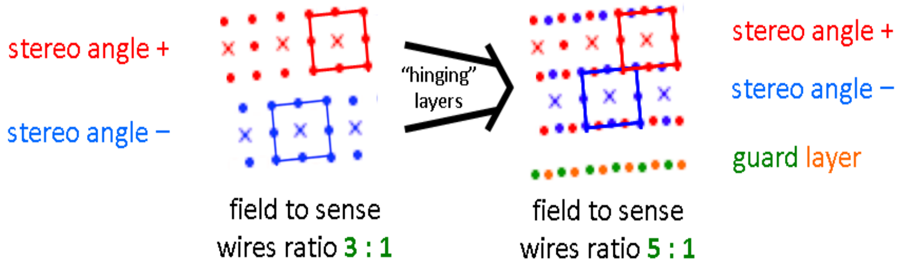
sense wires → 20 µm diameter W(Au) => 56448 wires
(thin!!) field wires → 40 µm diameter Al(Ag) => 229056 wires
Field between sense and guard wires → 50 µm diameter Al(Ag) => 58464 wires

combination of + and –wire orientation produces a more uniform equipotential surface → better E-field isotropy and smaller E×B asymmetries)

tracking efficiency ε ≈ 1
for ϑ > 14° (260 mrad)
97% solid angle

0.016 X_0 to barrel calorimeter
0.050 X_0 to end-cap calorimeter

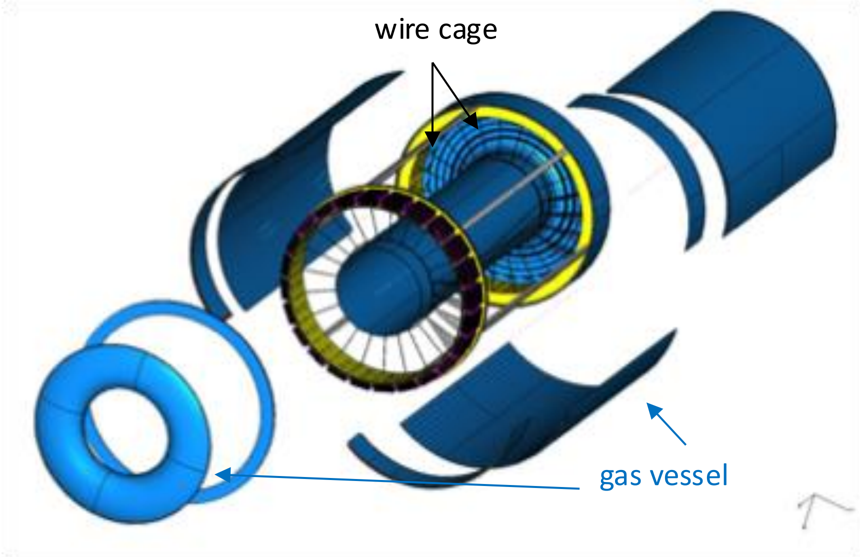




The IDEA Drift Chamber/3

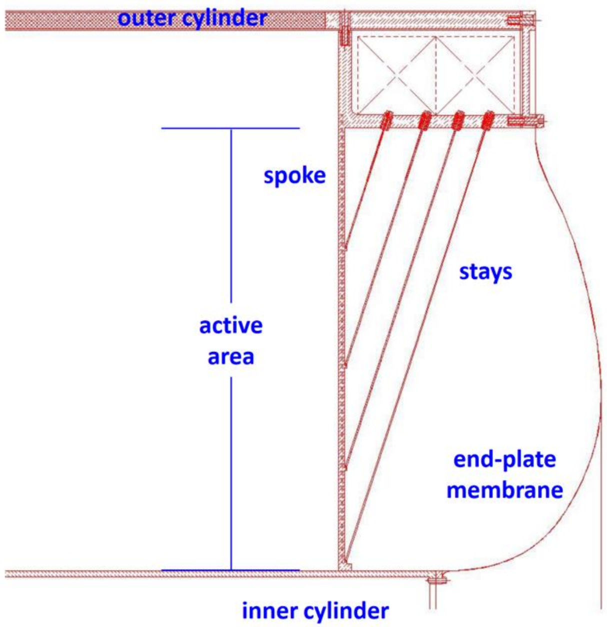
- ***Gas envelope and wire supporting structure separated*** → allows to reduce material to ≈ 10^{-3} X_0 for the inner cylinder and to a few 10^{-2} X_0 for the end-plates, including FEE, HV supply and signal cables.

- ***Feed-through-less wiring*** → allows to increase chamber granularity and field/sense wire ratio but reducing multiple scattering and total tension on end plates due to wires by using thinner wires (as in MEG II)

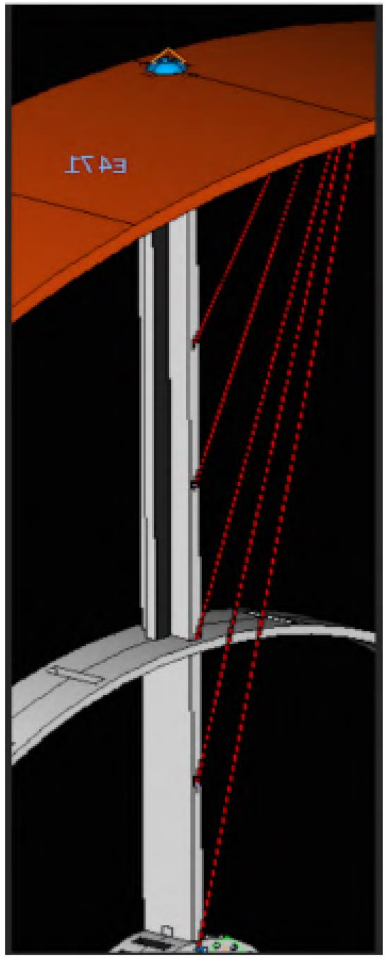


Inner cylinder and Outer cylinder connected with 48 Spokes (24 per Each side) forming 24 azimuthal sectors.

Each spoke supported by 15 Cables/Stays.
Spoke length = 160cm



Wire tension recovery scheme

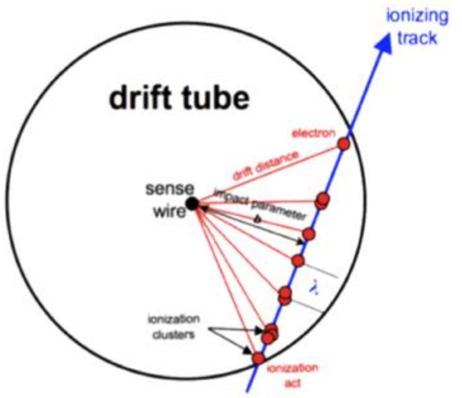


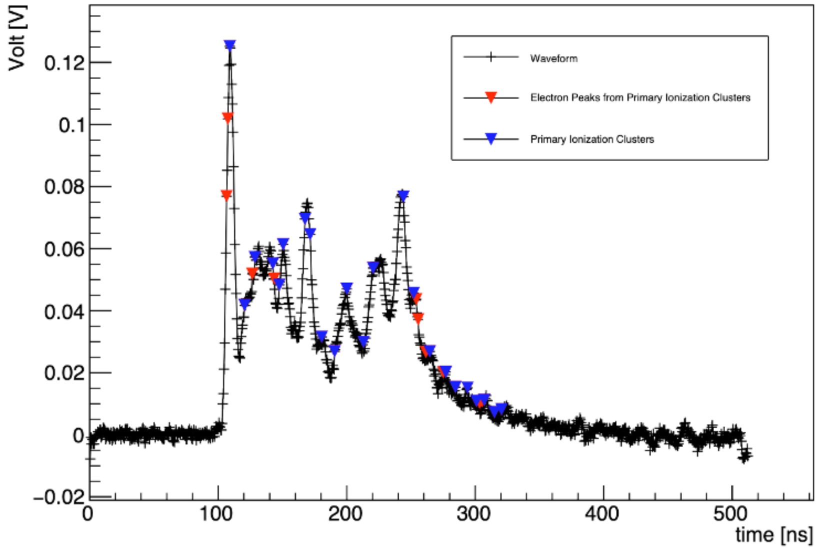
Material: Epoxy Carbon Prepeg for cylinders and spokes, Carbon fiber for the cables.

Main goal: limit the deformation of the spokes to 200 μm while ensuring the structural integrity

The IDEA Drift Chamber/4

- He based gas mixtures → signals from ionization acts are spread in time to few ns
- Fast read-out electronics (~GHz sampling) → efficiently identify them
- Counting dN_{cl}/dx (# of ionization acts per unit length) → make possible to identify particles (P.Id.) with a better resolution than dE/dx





- Collect signal and identify peaks
- record the arrival time of the clusters generated in every ionisation act (≈12cm^{-1})
- reconstruct the trajectory at the most likely position

Analytical calculations → predict excellent K/π separation over the full range of momenta except 0.85<p<1.05 GeV

dE/dx

- Requires high stability on HV and gas parameters and electronics calibration
- truncated mean cut (70-80%) reduces the amount of information. For n = 112 and a 2m track at 1 atm → **σ ≈ 4.3%**

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot N^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$

P. Reak and A.H. Walenta, IEEE Trans. Nucl. Sci. NS-27 (1980) 54

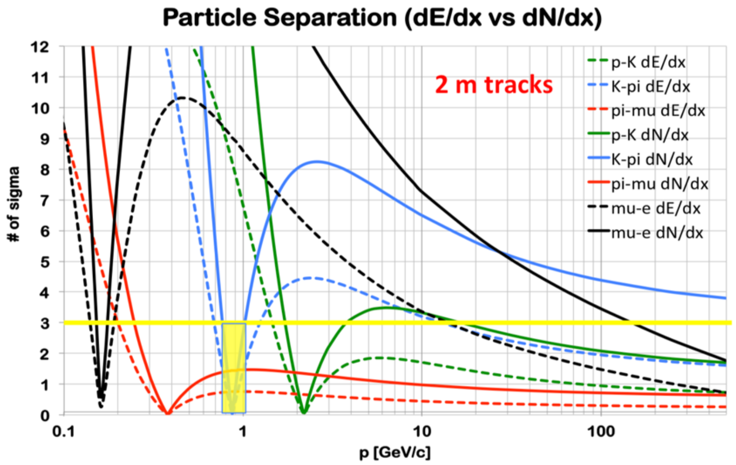
dN_{cl}/dx

- Requires fast electronics and sophisticated counting algorithms
- Less dependent on gain stability issues
- δ_{cl} = 12./cm for He/iC_4H_{10}=90/10 and a 2m track → **σ ≈ 2.0%**

Empirical parametrization

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2} = N_{cl}^{-1/2}$$

Poisson



The IDEA Drift Chamber challenges

- $\sigma_{xy} < 100\ \mu m$ → the position of the anode wire in space must be known with an accuracy better than 50µm at most
- the anodic and cathodic wires should be parallel in space to preserve the uniformity of the electric field
- a 20µm tungsten wire, 4m long, will bow about 400 µm at its middle point, if tensioned with a load of approximately 30gr → 30gr tension for each wire → **10 tons of total load on the endcap**

In addition:

- Given the requests on gas gain for cluster counting (~5x10[5]) and on the chamber length L, the electrostatic stability condition sets serious constraints on the cell width and on the wire materials

$$\frac{\lambda^2}{4\pi\varepsilon}\frac{L^2}{w^2} < wire\ tension < YTS \cdot \pi r_w^2$$

λ = linear charge density (gas gain)
L = wire length, r_w wire radius, w = drift cell width
YTS = wire material yield strength

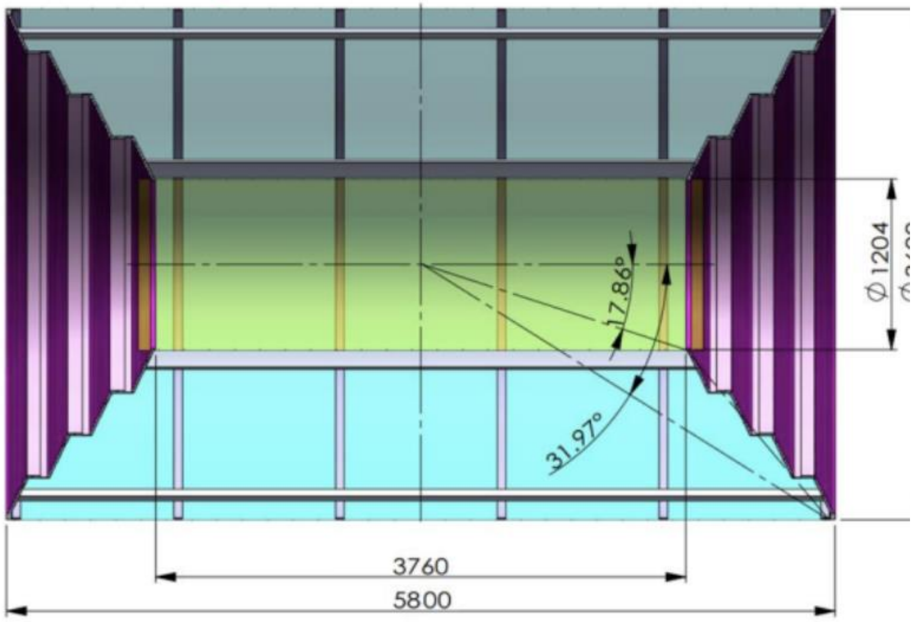
Yield Strength → the maximum load that a material can withstand without permanent deformation

- Safety requirements (ATEX) demands stringent limitations on flammable gases, continuous increase of the noble gases costs
- Large number of channels, high signal sampling rate and the high trigger rate at the Z pole at FCCee imply data transfer rates ~1TB/s

New wiring systems for high granularity/new end-plates/new materials

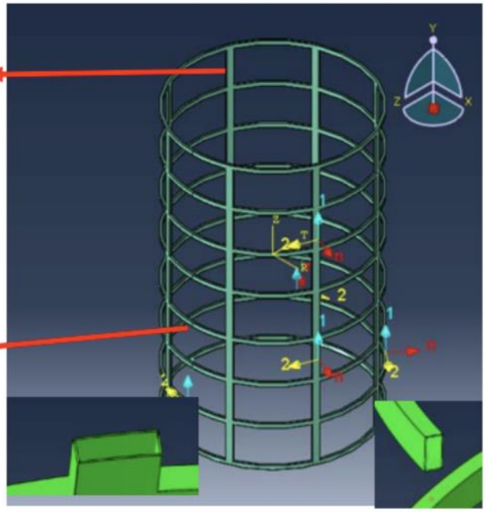
The CEPC (4th concept) Drift Chamber

End plates + CF frame structure



CF frame structure

Cross section of longitudinal HB：80mm*40mm，thickness: 3.2mm



Cross section of annular HB：40*10mm Thickness: 3.2mm

Preliminary design parameters

R extension	600-1800mm
Length of outermost wires（cosθ=0.85）	5800mm
Thickness of inner CF cylinder: (for gas tightness, without load)	200μm
Thickness of outer CF cylinder: (for gas tightness, without load)	300μm
Outer CF frame structure	Equivalent CF thickness: 1.8 mm
Thickness of end Al plate:	20mm
Cell size:	~ 18 mm × 18 mm
Cell number	27623
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC_4H_{10}=90:10

- CF frame structure: 8 longitudinal hollow beams + 8 annular hollow beams + inner CF cylinder and outer CF cylinder
  - Length: 5800 mm
  - Inner diameter: 1200 mm, Outer diameter: 3600 mm
- Each End plate: including 4 steps, thickness: 20 mm, weight: 880 kg

The R&D on wire detectors

- **Detector R&D areas and themes (I didn't discuss many of them)** which are required at the future facility:

- Drift Chambers → **Assembly techniques**: wiring strategy (**robots!!**), wire tensioning technique (with respect to the tolerances on the wire positions), wire anchoring procedure (soldering, welding, gluing, crimping, ...)

- Drift Chambers → **Mechanical structure**: design, materials (with respect to transparency, outgassing, aging, creeping, ...) and production procedures

- Drift Chambers → **Integration**: accessibility for repairing

- Wire detectors → **Wire materials** (uncoated Al, C monofilaments, Mo sense wires, …) to improve quality, transparency, to avoid corrosion

- Wire detectors → **Radiation hardness and long term stability**

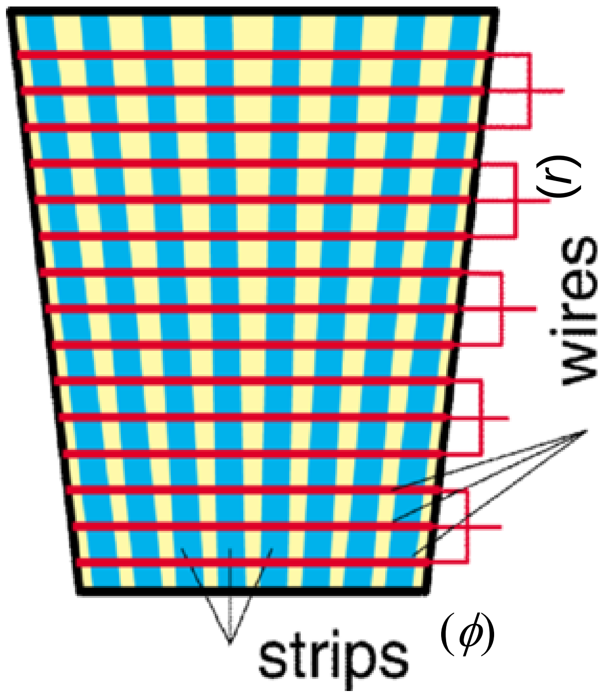
- Gases → **Sustainability**: eco-friendly gas mixture and mitigation of the issue related to the operation with high GWP (*global warming potential)* gas mixture, hydrocarbon-free gas mixture for long-term and high-rate operation

Thank you for your attention!! …

… and many thanks to F. Grancagnolo for his help in summarizing the drift chambers design evolution described in these slides

Backup slides

The CMS CSC

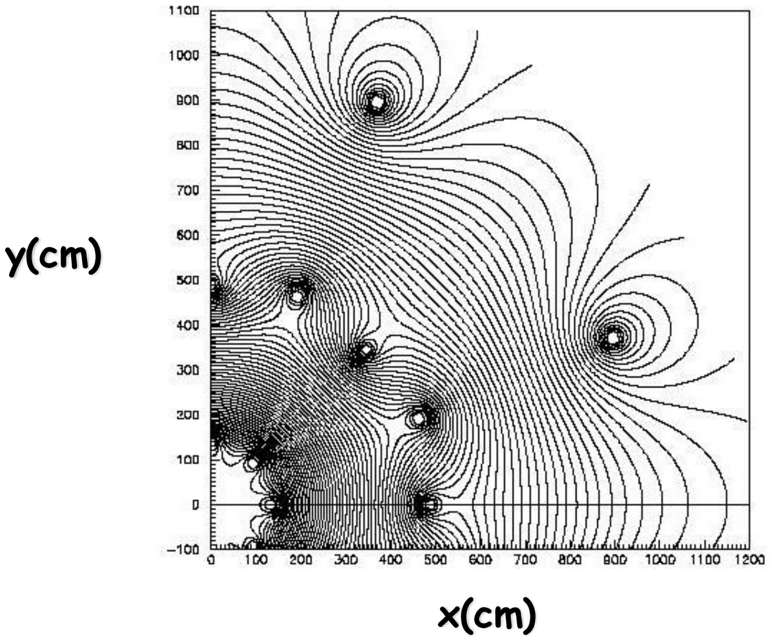


End cap: $1.2 < |\eta| < 2.4$
Cathode Strip Chambers (CSCs)

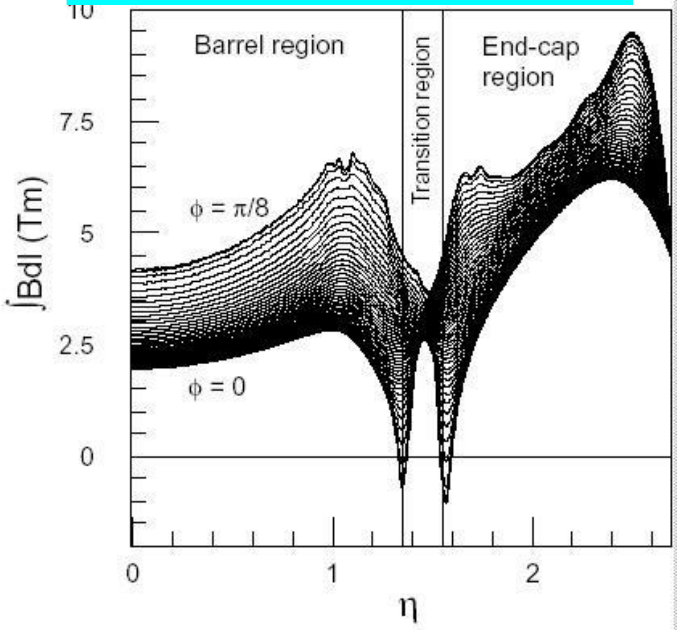
- Arranged in 4 stations (disks)
- Each chamber of trapezoidal shape, made of 6 layers
- Radial strips measure precisely the bending coordinate ϕ by interpolation of the induced charge on 3 contiguous strips $\rightarrow$ $\sigma \sim 100$-240 μm
- Orthogonal anode wires provide r coordinate, readout of 5-16 wires $\rightarrow$ $\sigma \sim 5$ mm
- Fast (closely spaced wires) for self-triggering
- Gas : 30%Ar - 50% CO_2 - 20% CF_4

ATLAS Toroidal Magnetic field configuration

Field map in the ECT median plane: field line are separated of 0.1 Tm



Field integral vs η for radial tracks



Field integral inhomogeneous in the tracking volume

Need to measure accurately the coordinate in the non bending plane

Need to take into account the differences in Lorentz angle for the calibration of the tracking chambers

More than a single time-to-distance relation per wire

Tracking requirements at future e^+e^- colliders

High Lumi e^+e^- colliders → Z, W^+W^-, ttbar and Higgs boson factories, flavor factories
Physics rates up to 100 kHz (at Z pole) → challenges for sub-detectors and DAQ systems

FCC-ee phase	Run duration (yr)	$\sqrt{s}$ (GeV)	L_{int} (ab^{-1})	Event statistics
Z^0	4	88–95	150	3×10^{12} hadronic Z^0 decays
W^+W^-	2	158–192	12	3×10^8 W^+W^- pairs
Z^0H	3	240	5	10^6 Z^0H events
$t\bar{t}$	5	345–365	1.5	10^6 $t\bar{t}$ and 6×10^4 $H\nu\bar{\nu}$ events
H (optional)	3	125	21	Optional run on H resonance

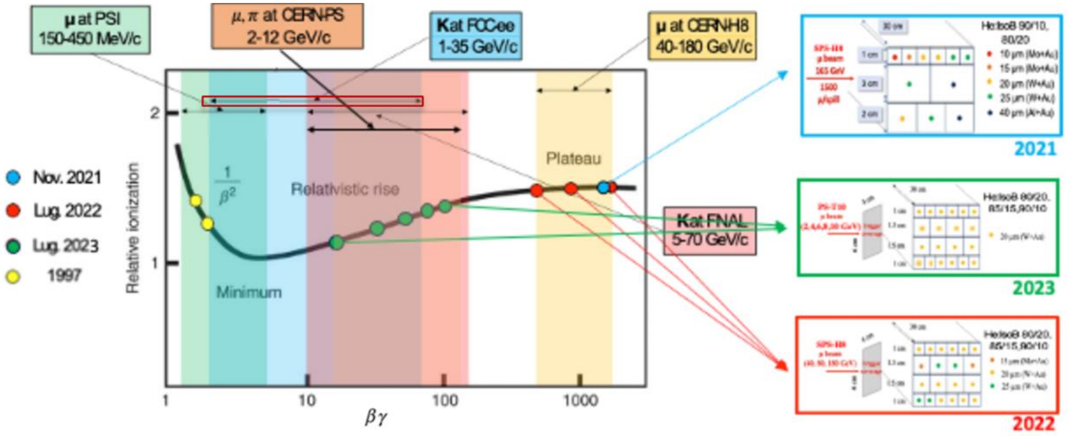
Central tracker:

Nature Physics 16, 402–407 (2020)

- *High momentum ($\delta p/p^2 \leq$ few x 10^{-5}) and angular resolution* ***$\Delta\vartheta \leq 0.1$ mrad*** (to monitor beam spread) for charged particle momenta ranging at the Z pole from a few hundred MeV/c to several tens of GeV/c
- ***Large angular coverage***
- *Large tracking radius* to recover momentum resolution, since magnetic field is limited to ~ 2 T to contain the vertical emittance at Z pole
- *High transparency* due to the (comparatively) low momenta involved in Z, H decays → Multiple Scattering (MS) contribution is not negligible!
- ***Particle identification*** mandatory to distinguish identical topology final states

DCH particle identification: new results

- New results from the 2021/2022 beam tests at CERN H8 ($\beta\gamma$ > 400) [ICHEP 2024]

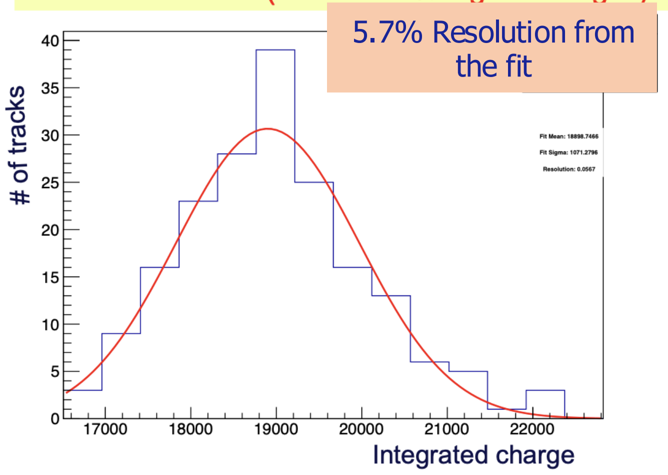


- Landau distribution for the charge along a track
- Selected the distribution with 80% of the charges for the dE/dx truncation to be compared with dN/dx. There is still margin for improvements in CC efficiency!

- Data analysis of the two test beams at CERN T10 performed in July 2023 and July 2024 with muons (1-12 GeV) ongoing

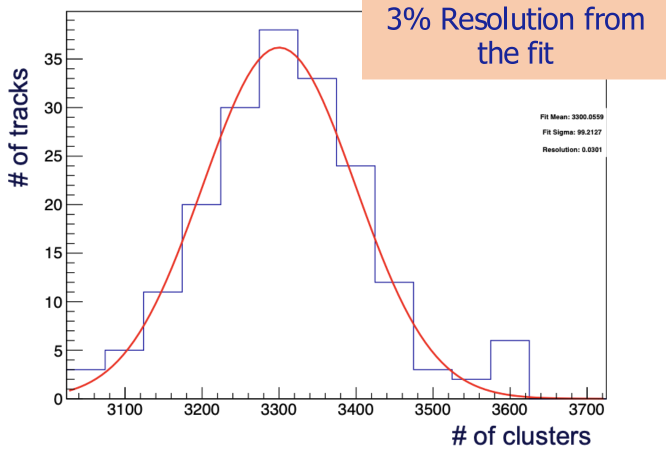
Study done using same tracks (2 m track length) made of the same hits. 180 GeV/c muons

dE/dx Resolution (remove 20% higher charges)



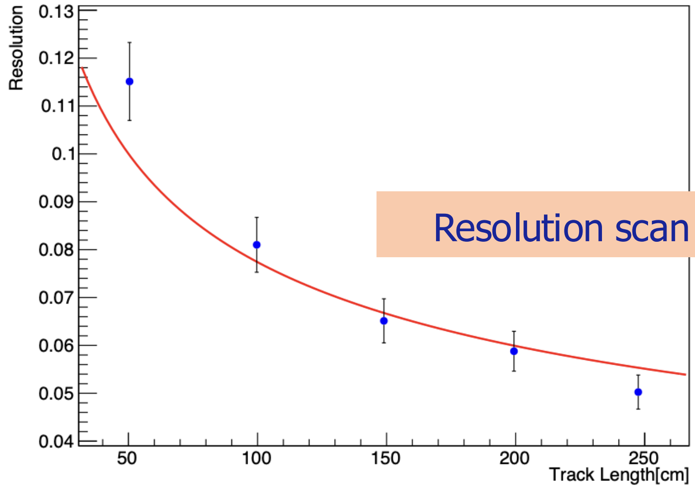
@2m long track we have dE/dx resolution 5.7%

dN/dx Resolution



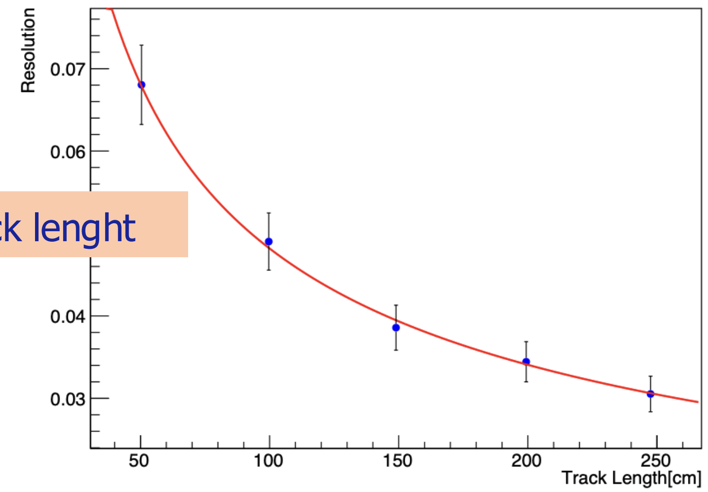
@2m long track we have dN/dx resolution 3%

dE/dx Resolution



Resolution scan vs track lenght

dN/dx Resolution



dE/dx resolution dependence on the track length $L^{-0.37}$ dN/dx resolution dependence on the track length $L^{-0.5}$

~ **2 times** improvement in the resolution using dN/dx method