Detector design concept of the EIC

Tracking and Vertexing

Olga Evdokimov (UIC)

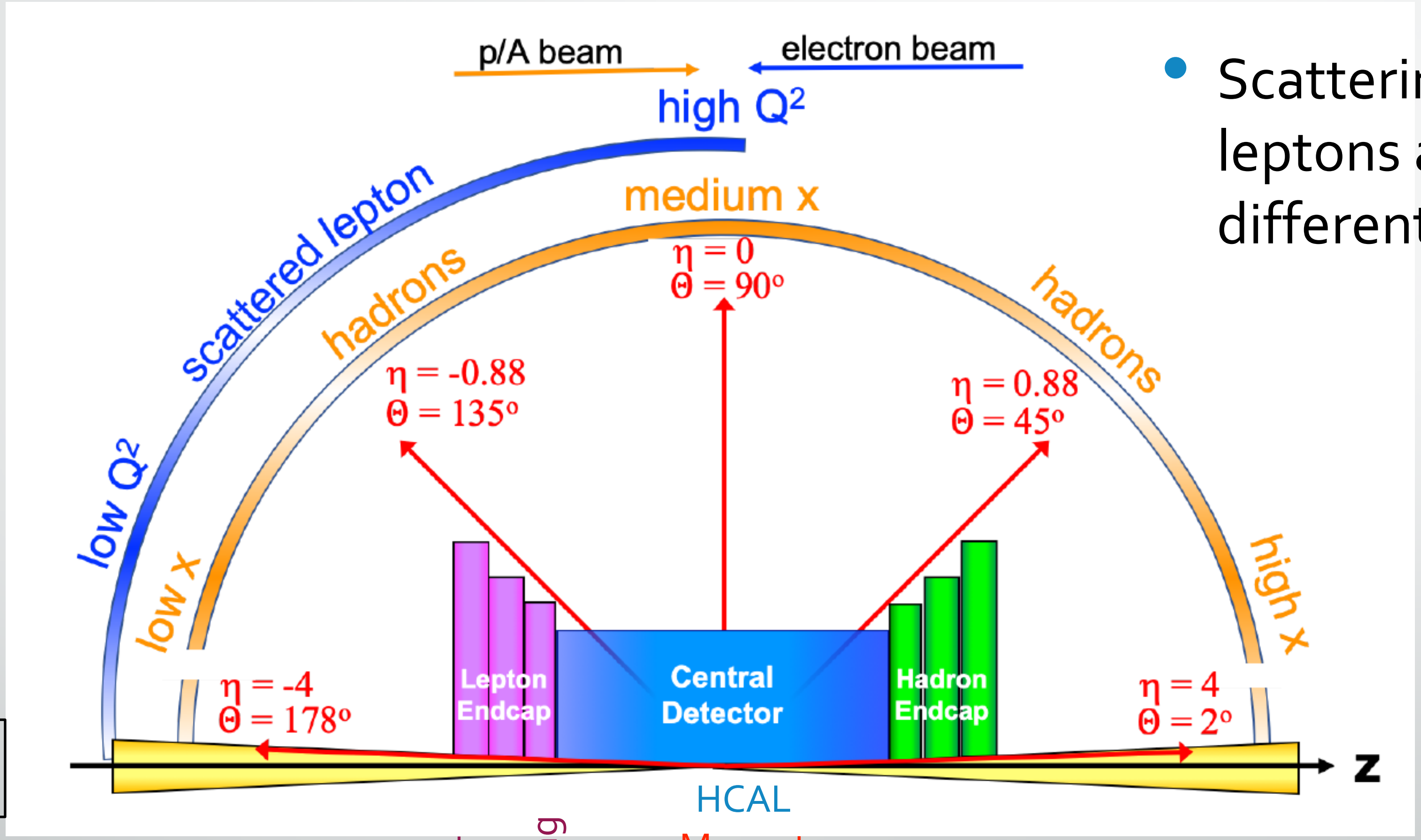
Inspired by presentations by Y. Furletova, A. Kiselev, B. Surrow, T. Ullrich, E. Sichterman

Outline

- Introduction
  - Foundations & motivation for the EIC program
  - Basics of Deep Inelastic Scattering and DIS kinematics
- EIC accelerator and detector requirements
- Building blocks of EIC multipurpose detector
  - Tracking detectors
  - Vertex reconstruction
  - Calorimeters
  - Detectors for Particle Identification
- Summary and Tutorial

★ *We are here!*

EIC General Purpose Detector Schematics



- Scattering patterns for leptons and hadrons for different x and Q^2

very low Q^2
scattered lepton

Bethe-Heitler
photons
for luminosity

Luminosity Detector

Low Q^2-Tagger

HCAL
EMCAL
PID
Tracking

HCAL
Magnet
EMCAL
PID
Tracking
Vertexing

Tracking
PID
EMCAL
HCAL

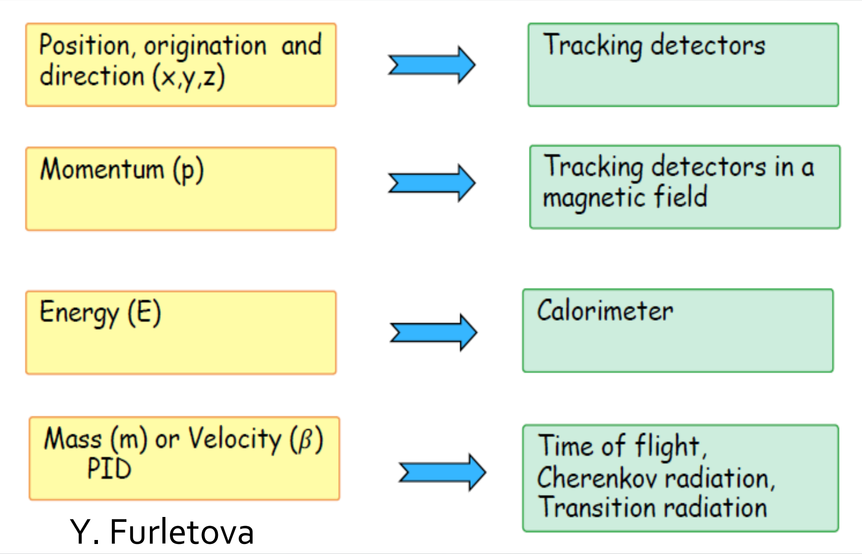
particles from nuclear
breakup and
from diffractive reactions

ZDC

Forward Tracking

Major Detector Classes

- "Trackers" provide momentum measurements
  - Closest to the interaction region are "vertex detectors;" measure/distinguish primary and secondary vertices
  - Main or "central" trackers measure momentum of charged particles in the magnetic field by the curvature. But also: direction, electric charge (direction of bend), dE/dx (energy loss per distance)
- "Calorimeters" provide energy measurements
  - Electromagnetic Calorimeters measure energy of light EM particles (electrons, positrons, photons) based on electromagnetic showers created by bremsstrahlung and pair production
  - Hadronic Calorimeters measure energy of heavier hadronic particles (pions, kaons, protons, neutrons) based on showers created by nuclear (and EM) interactions

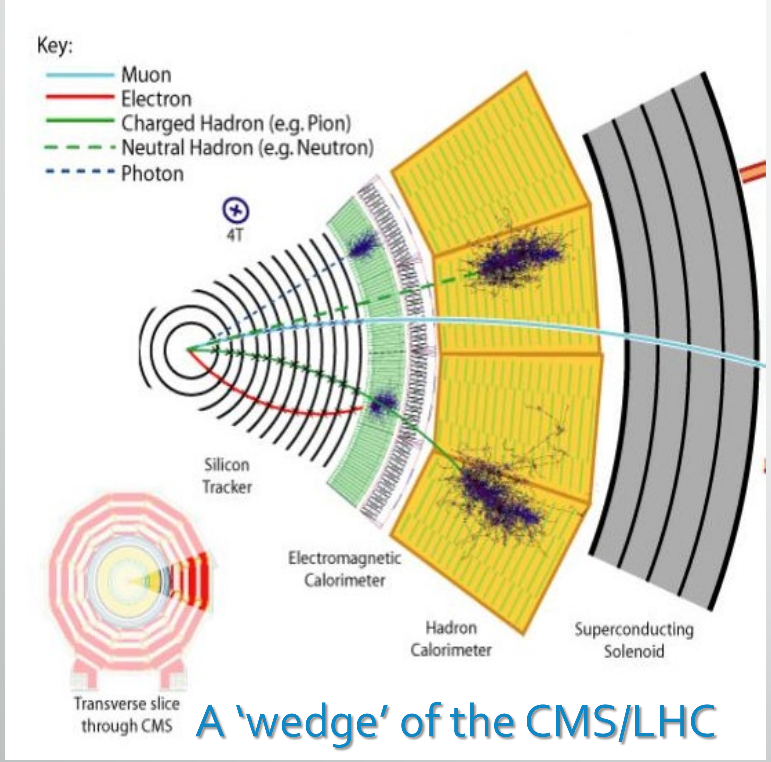


Position, origination and direction (x,y,z)	→	Tracking detectors
Momentum (p)	→	Tracking detectors in a magnetic field
Energy (E)	→	Calorimeter
Mass (m) or Velocity (β) PID	→	Time of flight, Cherenkov radiation, Transition radiation

Y. Furletova

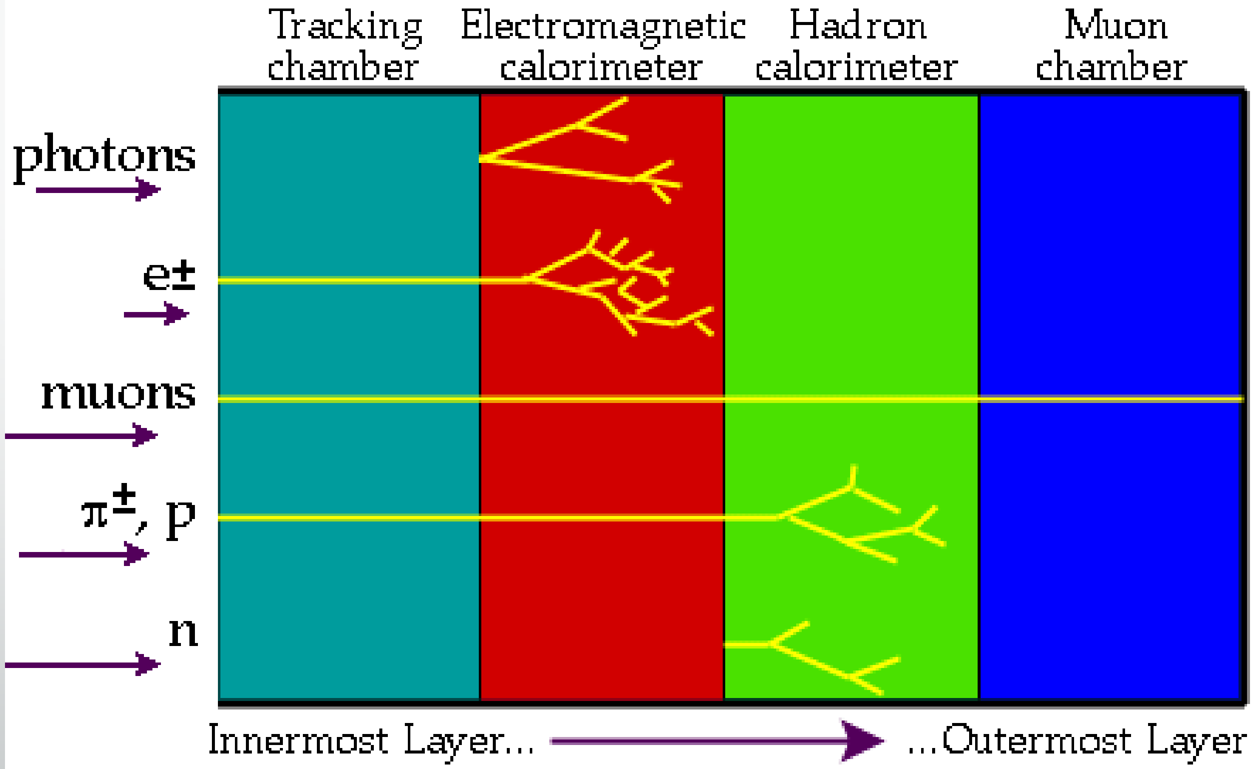
Central Region

- All “general purpose” collider detectors have similar “onion” structure in the central region



A ‘wedge’ of the CMS/LHC

“Stopping” location is the crude form of PID



- Trackers – the inner most layers; to avoid E_{loss} before calorimeters – minimal material budget

Outline: Trackers

- Introduction to tracking
- History
- Know your technology options:
  - Gaseous detectors
    - Multi-wire chambers
    - Time projection chambers
    - MPGDs
    - …
  - Silicon detectors

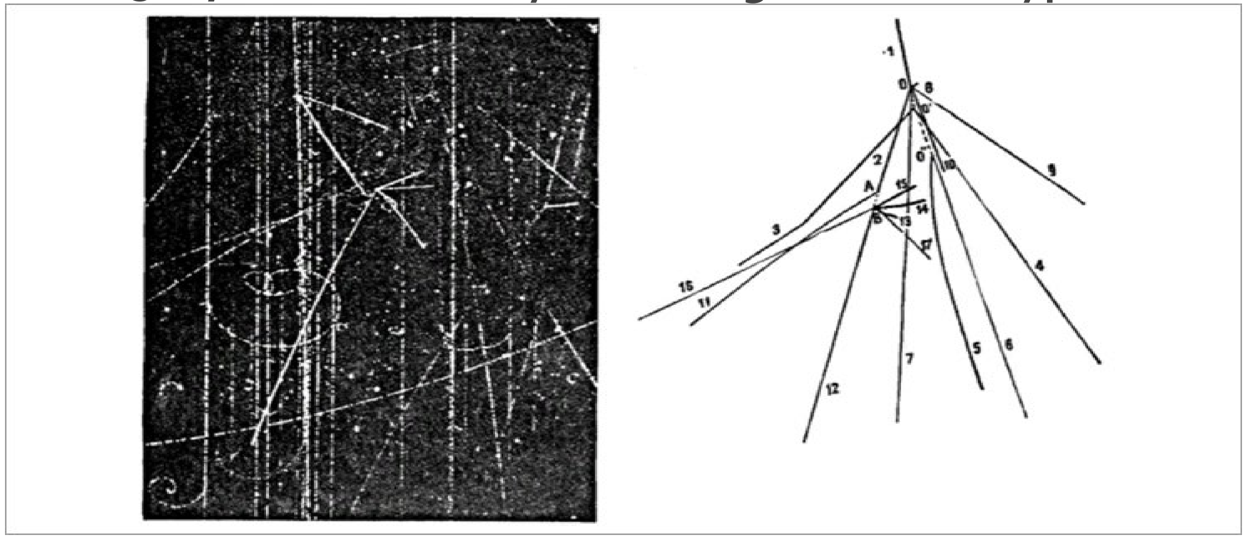
- Momentum measurements
  - Energy loss
  - Momentum reconstruction

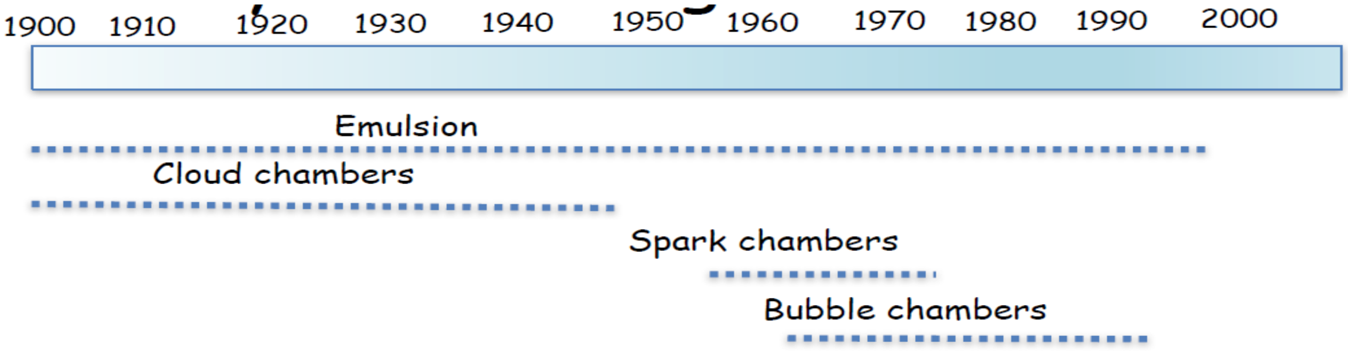
- Momentum resolution
  - Resolution for a measured track
  - Effects of multiple scattering

Trackers in HEP History

- Tracker is from “track,” as in trace left by particle
  - To leave a trace, particle must interact with detector material.
  - “Interact”↔ “leave energy”
- Earliest trackers:

1960, JINR: discovery of anti-sigma-minus-hyperon



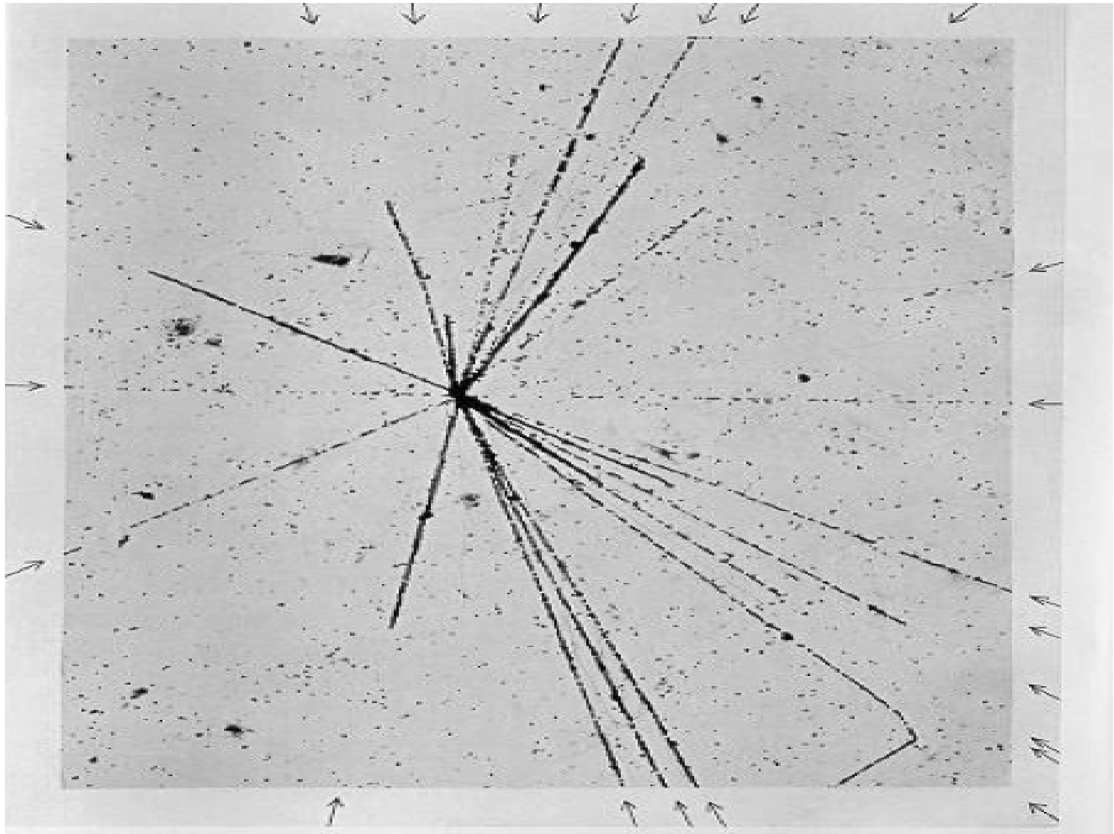


Trackers in HEP History

Emulsion

- Cosmic ray studies: high altitudes, long exposure (months)
- Advantages:
  - images are permanent and can be analyzed under microscope
  - high density- easier to see energy loss and disintegrations.

1937: Nuclear disintegrations

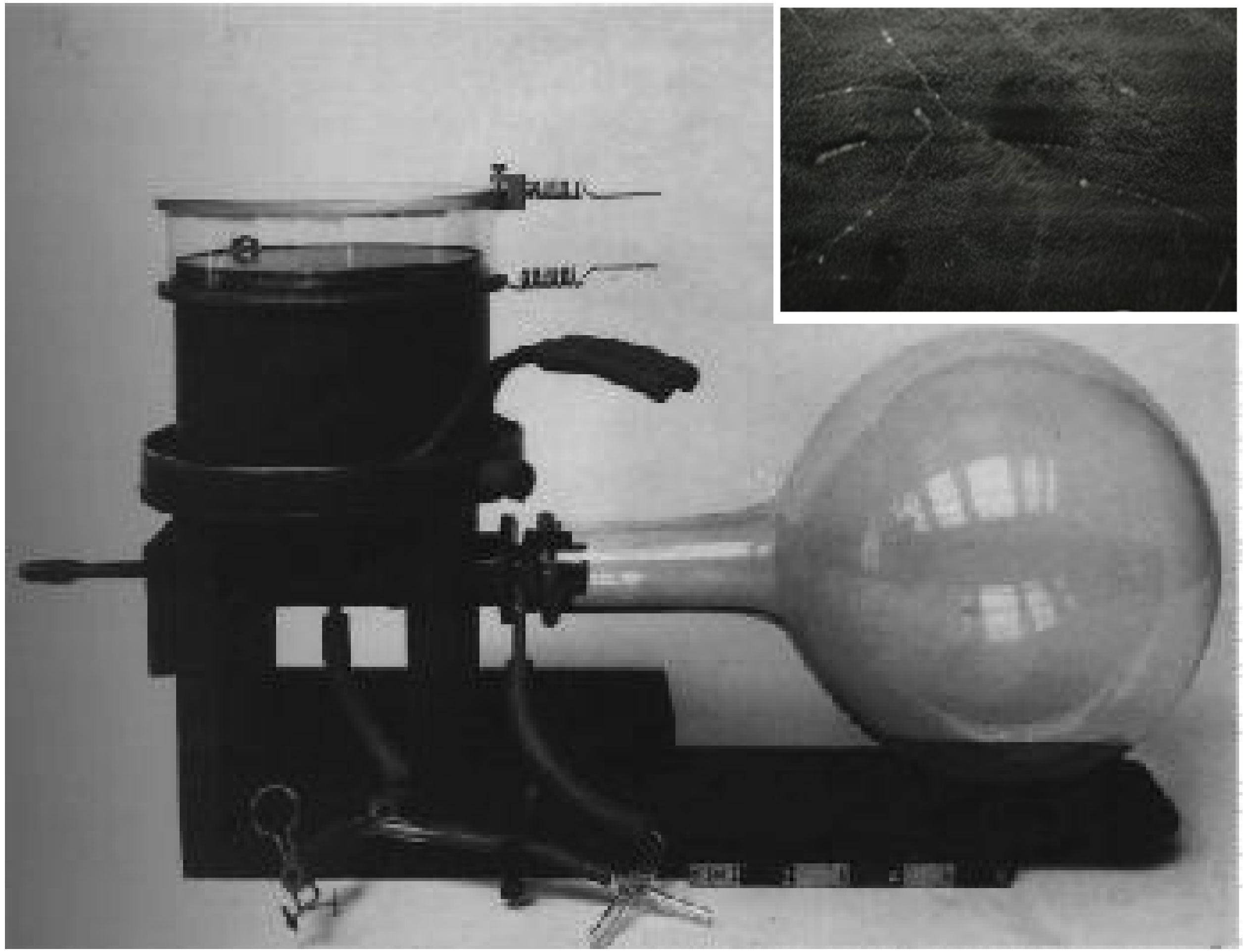


'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS

Trackers in HEP History

Cloud Chambers

- Ionizing particles are sent through a supersaturated vapor
- Radiation disturbs the vapor causing condensation
  - Track forms along the particle path
  - Tracks can be seen in real time

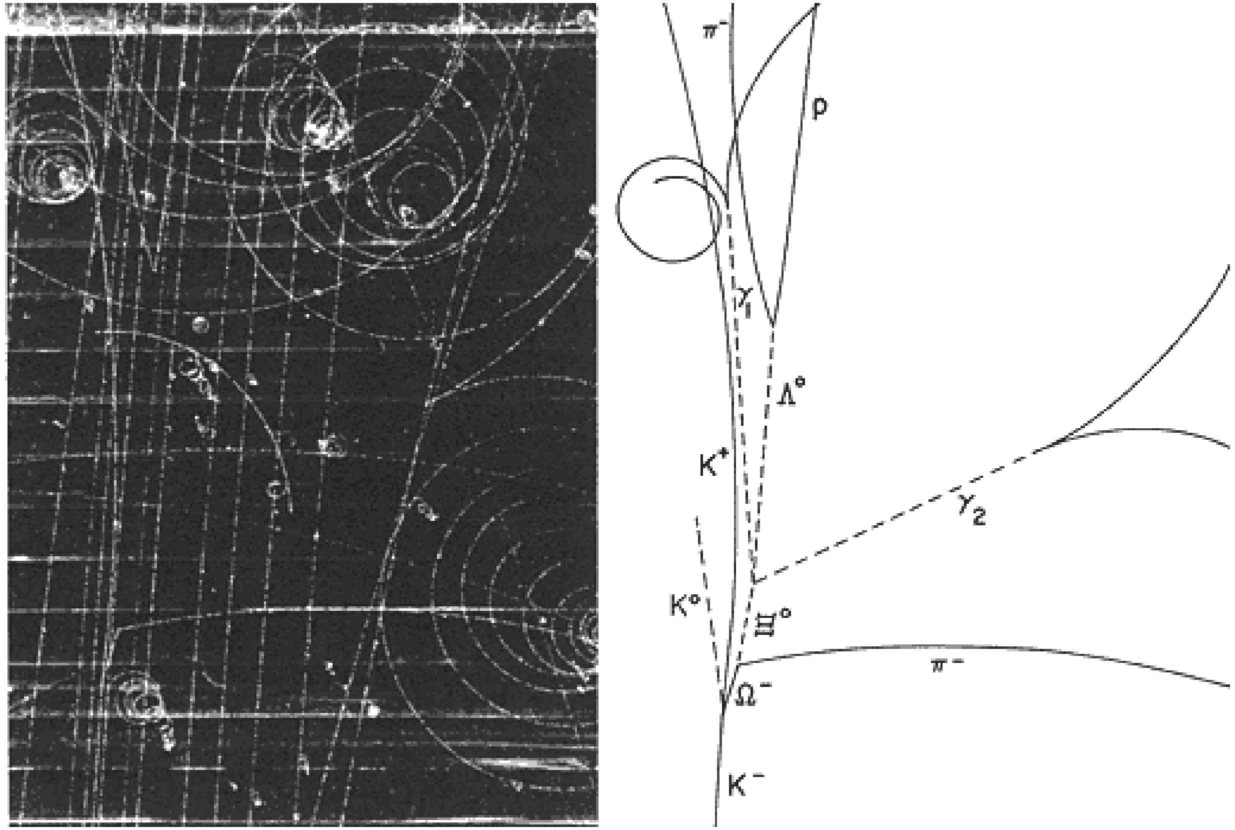


Trackers in HEP History

Bubble chambers:

- A vessel filled with a superheated transparent liquid used to detect electrically charged particles moving through
- But:
  - every interaction must be photographed
  - Error-prone manual “digitization”

1964, BNL: discovery of Omega baryon

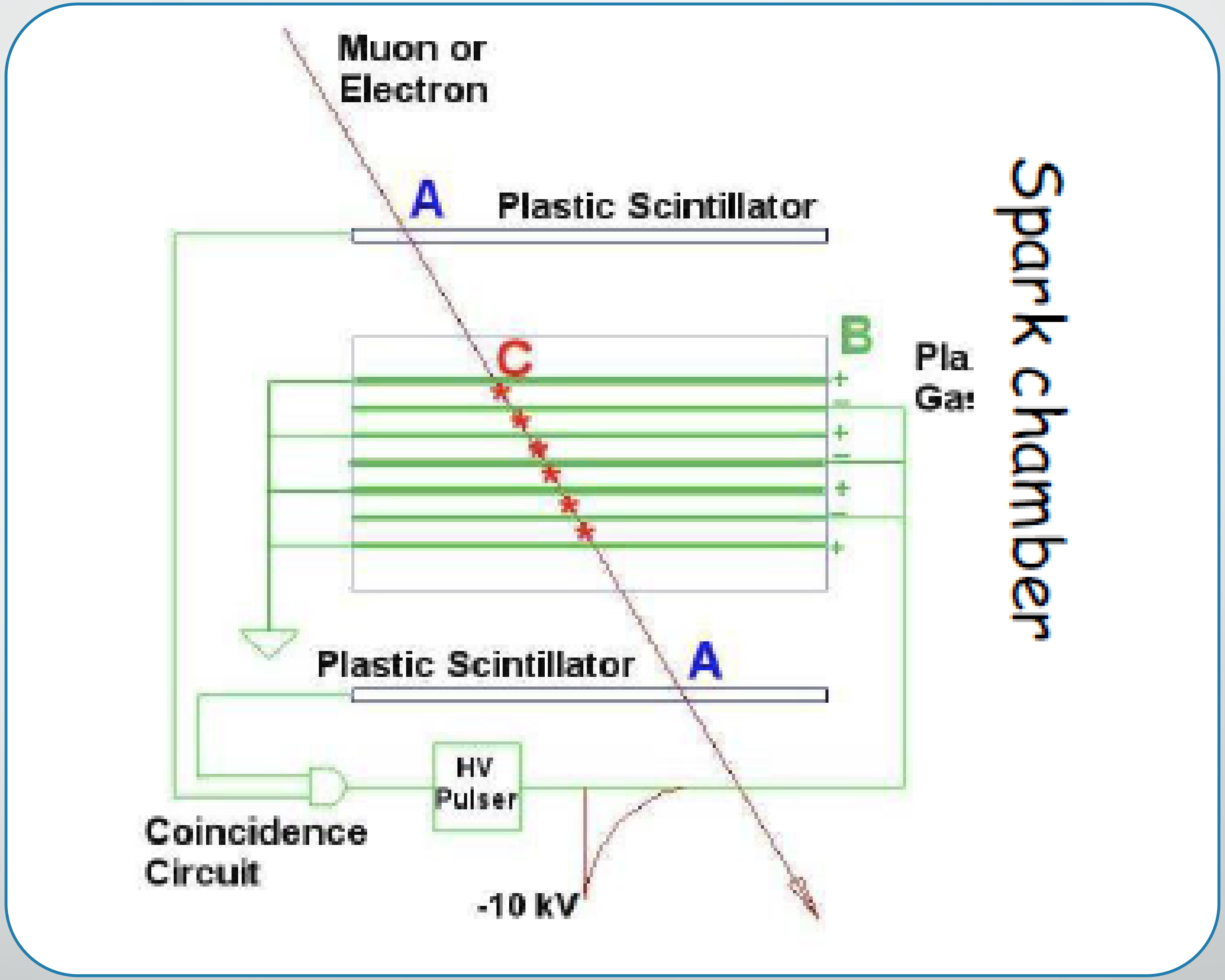


Trackers in HEP History

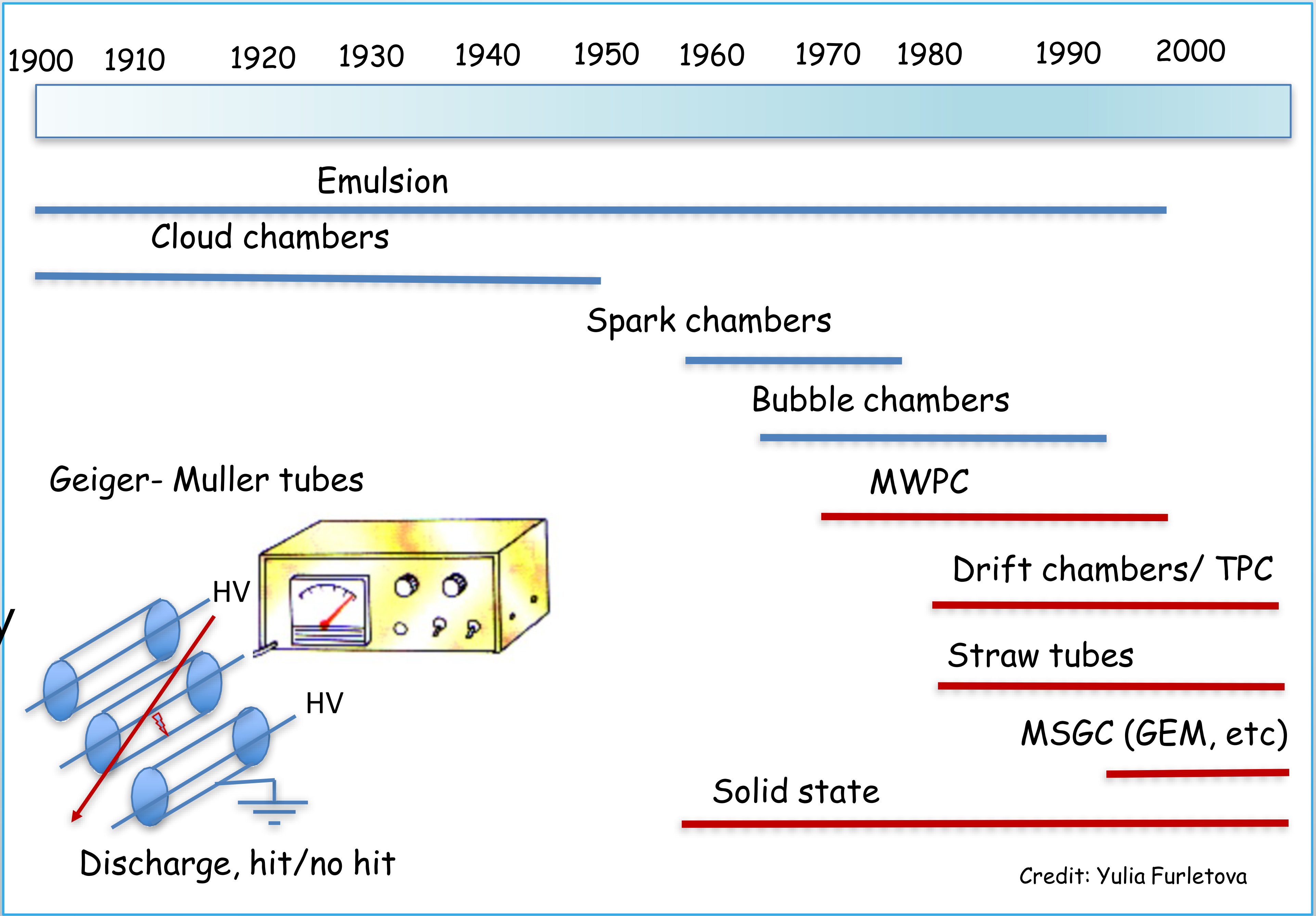
Spark Chambers

- Developed in ~1940ies.

- A stack of metal plates in a sealed box filled with a helium or neon
- Charged particle ionizes the gas between the plates
- Applied HV between the plates makes sparks visible along trajectory where ionization had happened



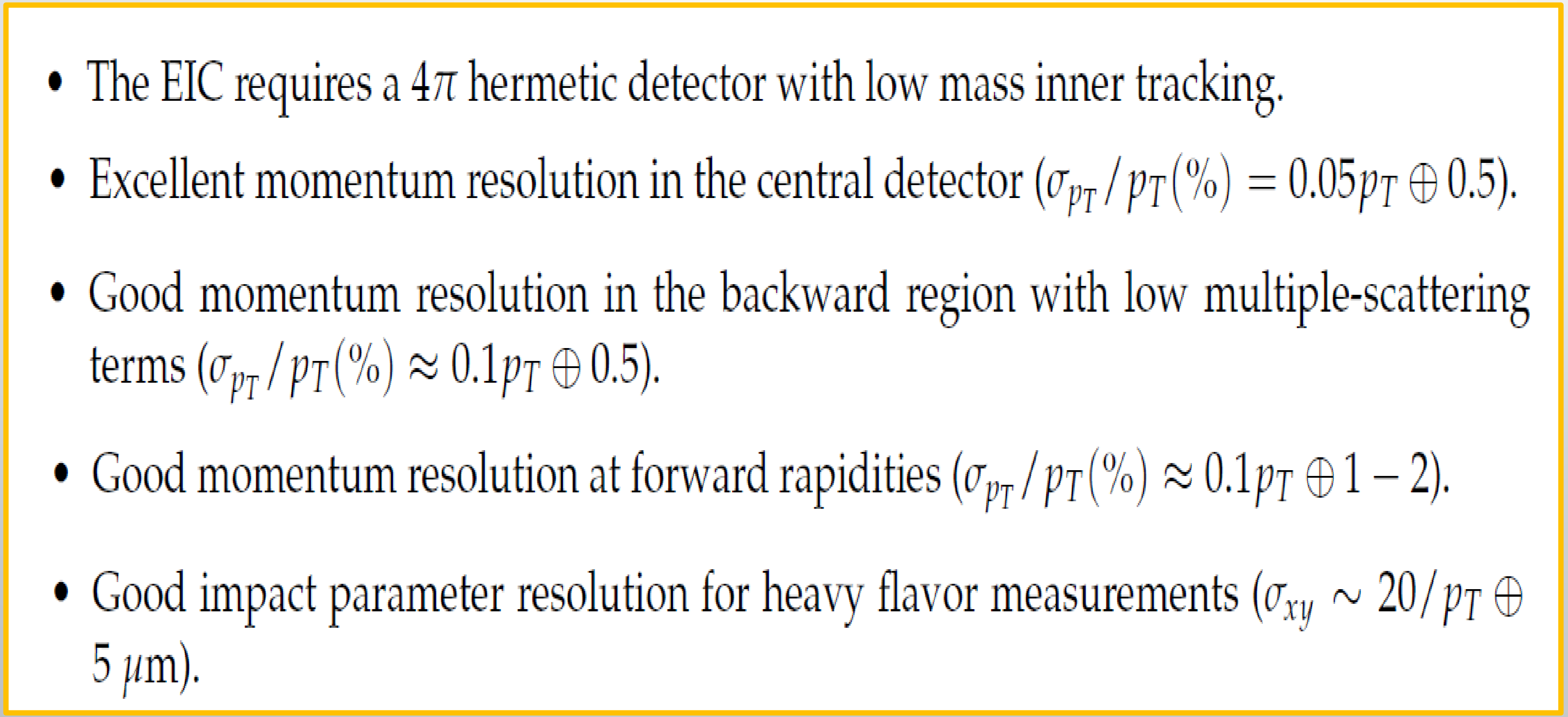
Tracking Technology Evolution



Credit: Yulia Furletova

Tracking for EIC

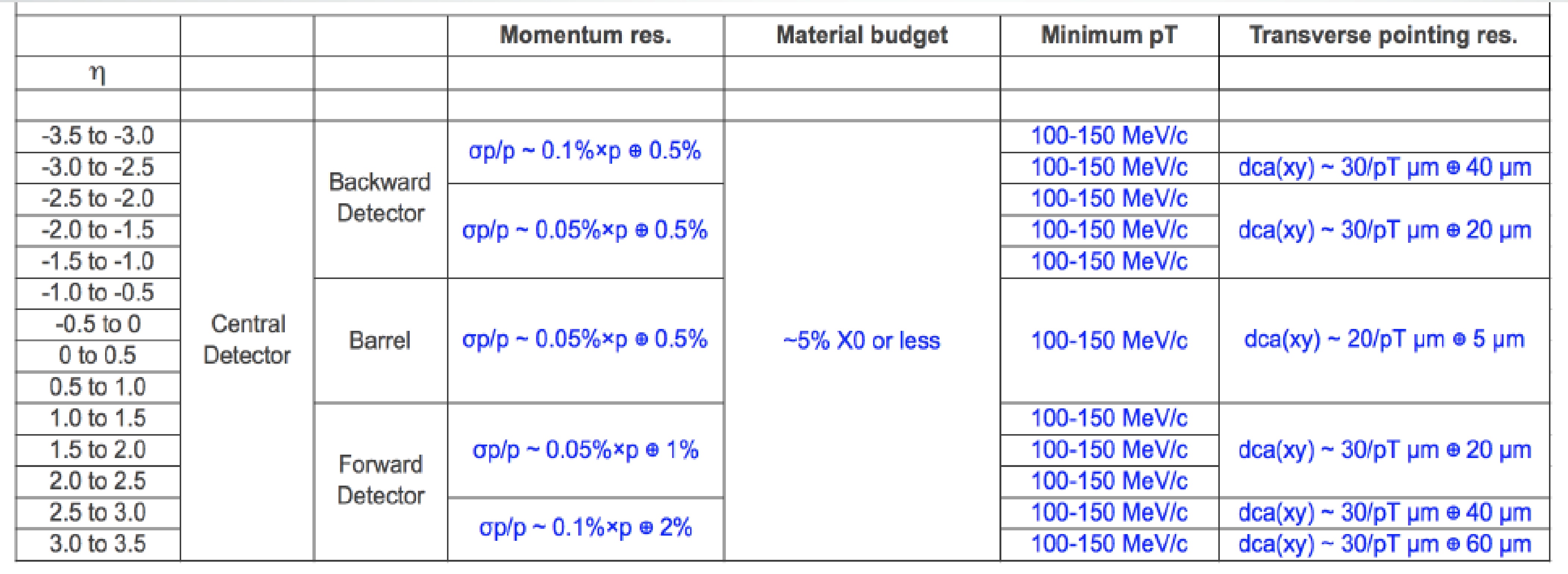
- Tracking requirements (YR):



- The EIC requires a 4π hermetic detector with low mass inner tracking.
- Excellent momentum resolution in the central detector ($\sigma_{p_T}/p_T(\%) = 0.05 p_T \oplus 0.5$).
- Good momentum resolution in the backward region with low multiple-scattering terms ($\sigma_{p_T}/p_T(\%) \approx 0.1 p_T \oplus 0.5$).
- Good momentum resolution at forward rapidities ($\sigma_{p_T}/p_T(\%) \approx 0.1 p_T \oplus 1-2$).
- Good impact parameter resolution for heavy flavor measurements ($\sigma_{xy} \sim 20/p_T \oplus 5\ \mu$m).

Tracking for EIC

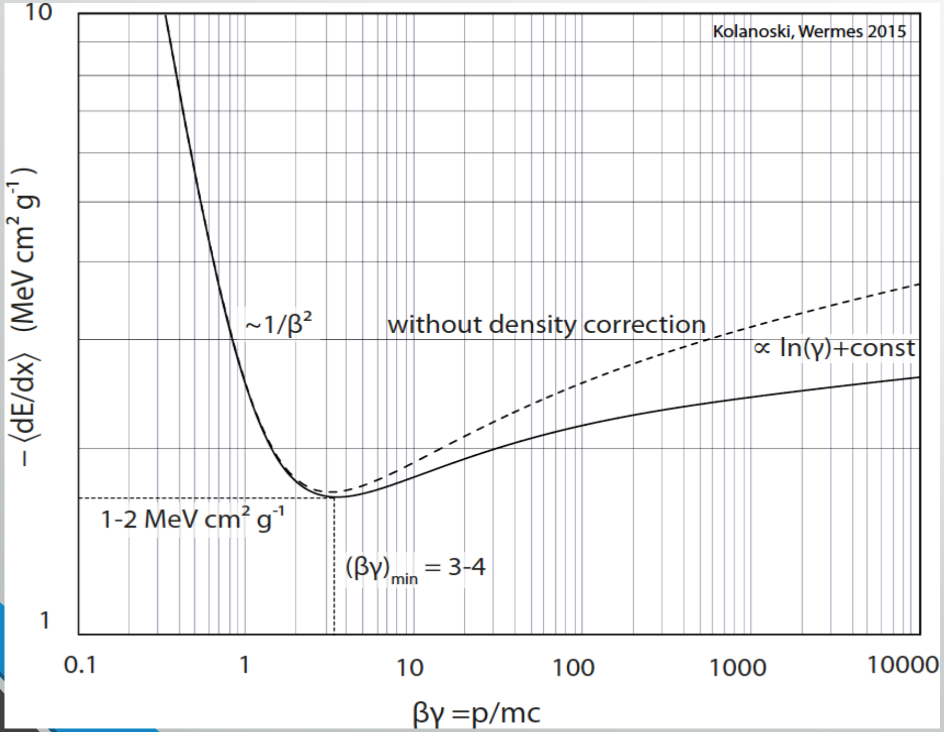
- For full details on tracking requirements see Yellow Report publication:



			Momentum res.	Material budget	Minimum pT	Transverse pointing res.
η						
-3.5 to -3.0	Central Detector	Backward Detector	σp/p ~ 0.1%×p ⊕ 0.5%	~5% X0 or less	100-150 MeV/c	
-3.0 to -2.5					100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 40 μm
-2.5 to -2.0			σp/p ~ 0.05%×p ⊕ 0.5%		100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 20 μm
-2.0 to -1.5					100-150 MeV/c	
-1.5 to -1.0					100-150 MeV/c	
-1.0 to -0.5		Barrel	σp/p ~ 0.05%×p ⊕ 0.5%		100-150 MeV/c	dca(xy) ~ 20/pT μm ⊕ 5 μm
-0.5 to 0						
0 to 0.5						
0.5 to 1.0						
1.0 to 1.5		Forward Detector	σp/p ~ 0.05%×p ⊕ 1%		100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 20 μm
1.5 to 2.0					100-150 MeV/c	
2.0 to 2.5					100-150 MeV/c	
2.5 to 3.0			σp/p ~ 0.1%×p ⊕ 2%		100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 40 μm
3.0 to 3.5					100-150 MeV/c	dca(xy) ~ 30/pT μm ⊕ 60 μm

Ionization Energy Loss

- Most trackers use ionization energy loss dE/dx by particle interacting with detector material (often, this can also be used for PID)



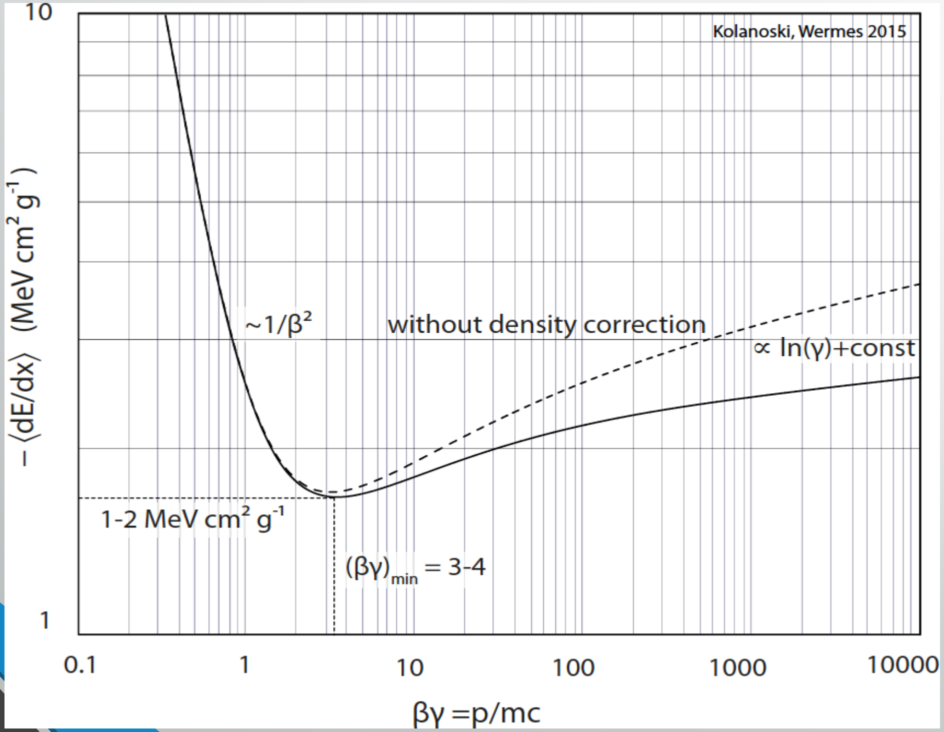
Bethe-Bloch formula:

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

- Z/A encodes material; but for most ~$1/2$
- Depends on $\beta\gamma = (p/E)(E/m) = p/m$
- Minimum at $\beta\gamma$ =3–4 ("MIP particle")
- Plateau at high $\beta\gamma$ (after "relativistic rise")

Ionization Energy Loss

- Most trackers use ionization energy loss dE/dx by particle interacting with detector material (often, this can also be used for PID)



Bethe-Bloch formula:

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

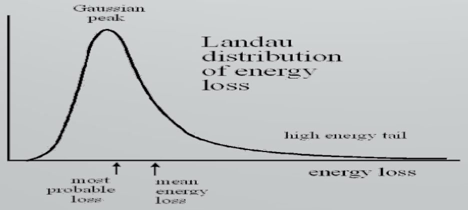
- Examples of typical energy loss at MIP:
  - ✓1 meter air: 0.22 MeV
  - ✓300μm Si: 0.12 MeV
  - ✓1mm iron: 1.1 MeV

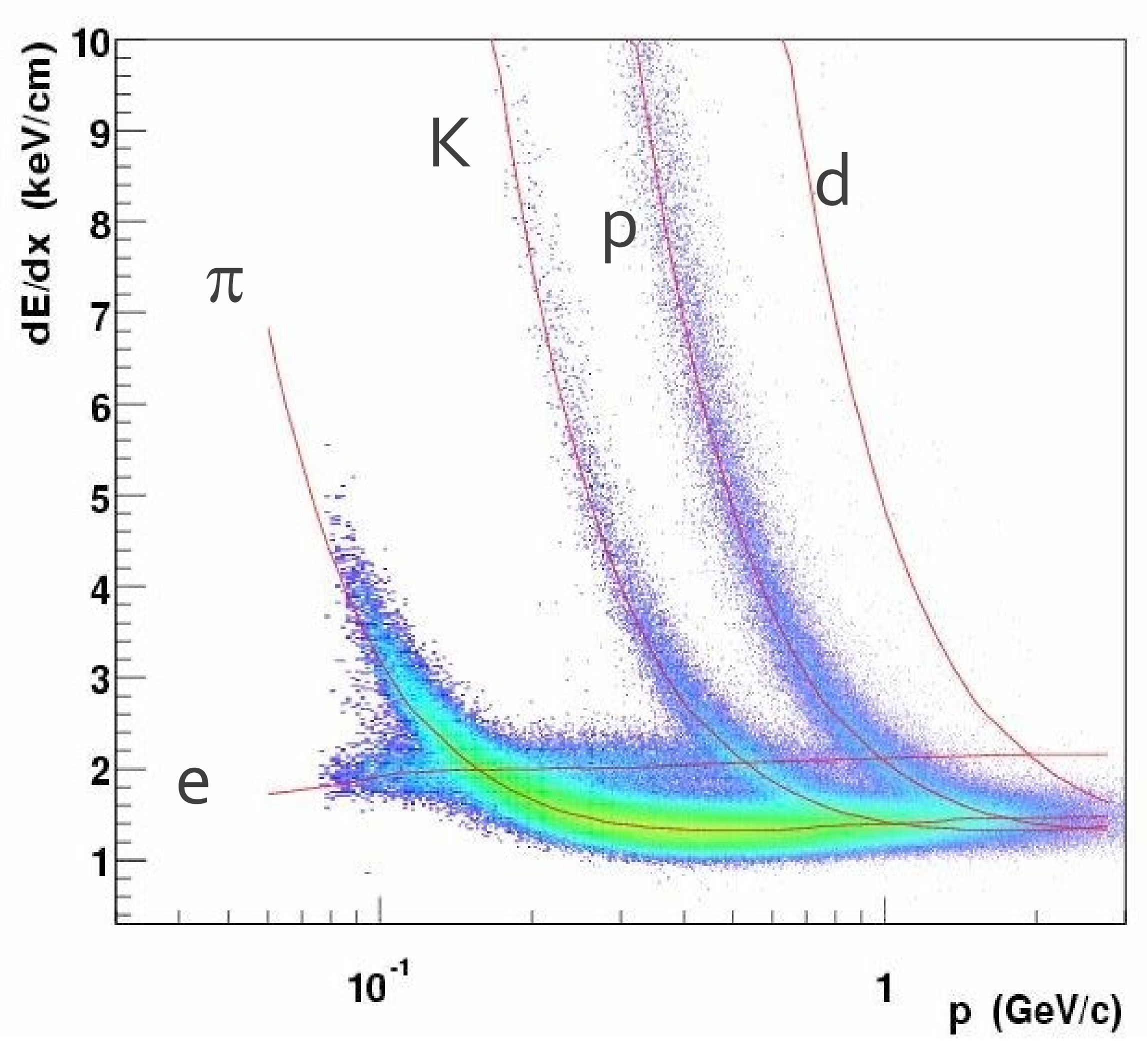
Ionization Energy Loss

- Since $p = mv = m_0 \beta\gamma c$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} ln(\beta^2\gamma^2)$$

- Simultaneous measurement of dE/dx and momentum provides PID
- Complication: "Landau tails" large fluctuations towards high losses
  - Remedies: truncated mean; log-scale



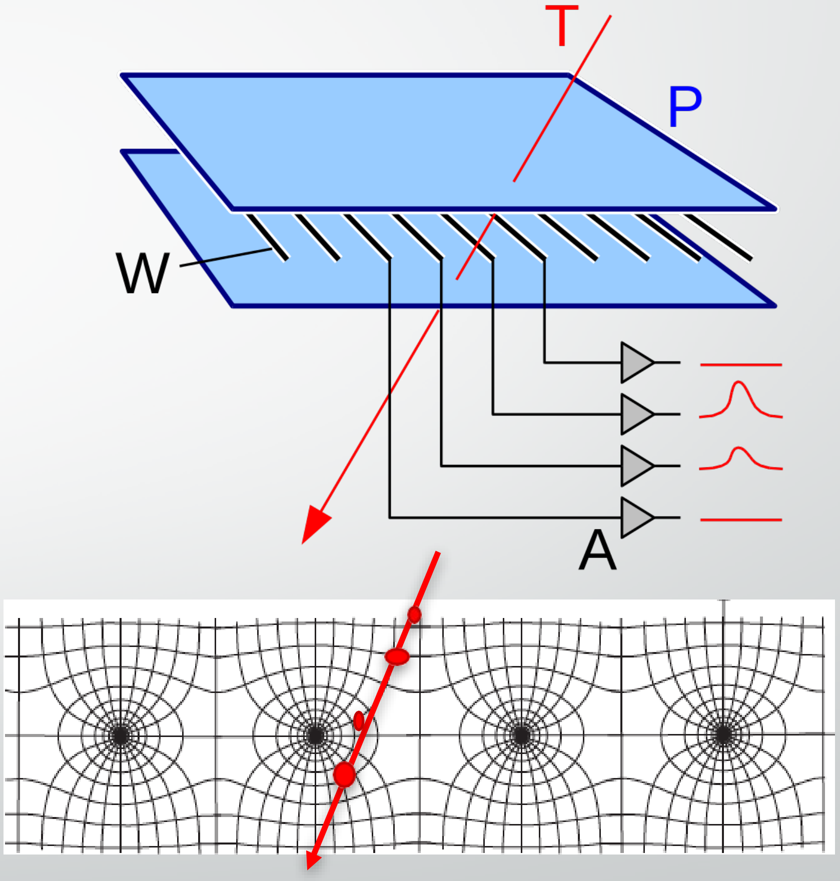


Multiwire Proportional Chambers

1992: George Charpak

"For his invention and development of particle detectors, in particular the multiwire proportional chamber"

- Technological breakthrough for trackers: signal is read-out electronically
- Ionization signal read by the nearest wire is proportional to the ionization energy loss by the ionizing particle
- Location of fired wire(s) gives 1D information



Equipotential line and field line in a MWPC

Time Projection Chambers

- Main “workhorse” subdetector for STAR and ALICE

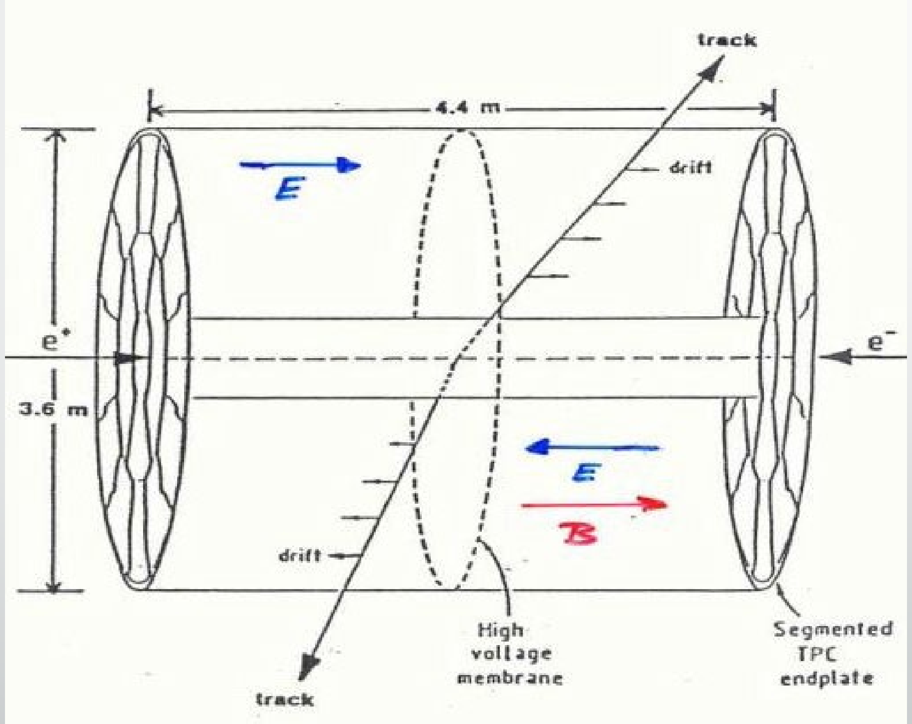
✓ Low material

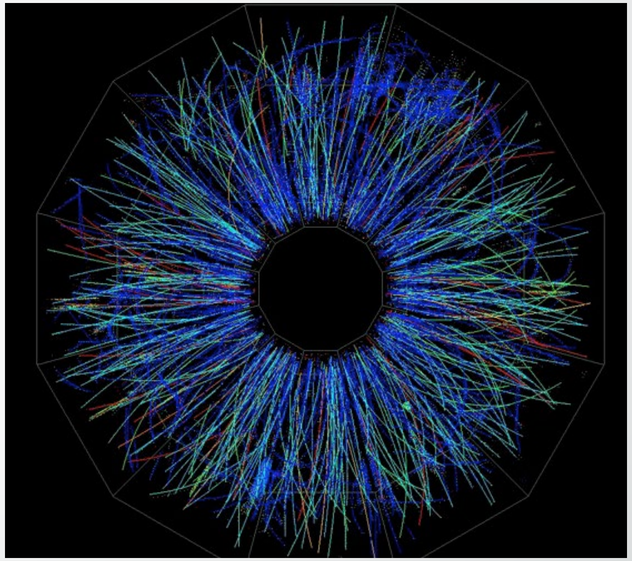
✓ 3D hit positioning

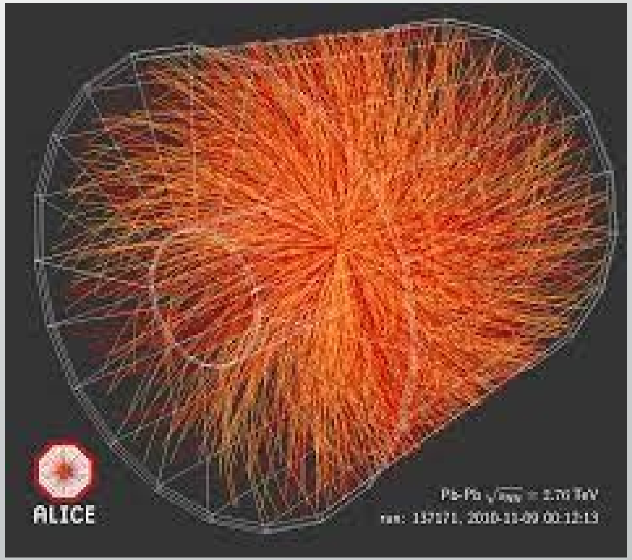
✓ PID capabilities

✓ Typical resolutions:

100-400μm (rφ), ≈mm (z)





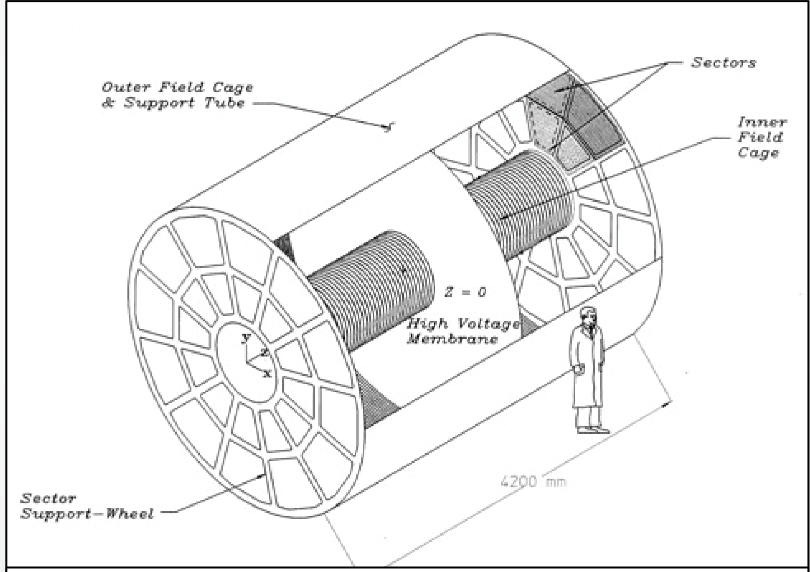


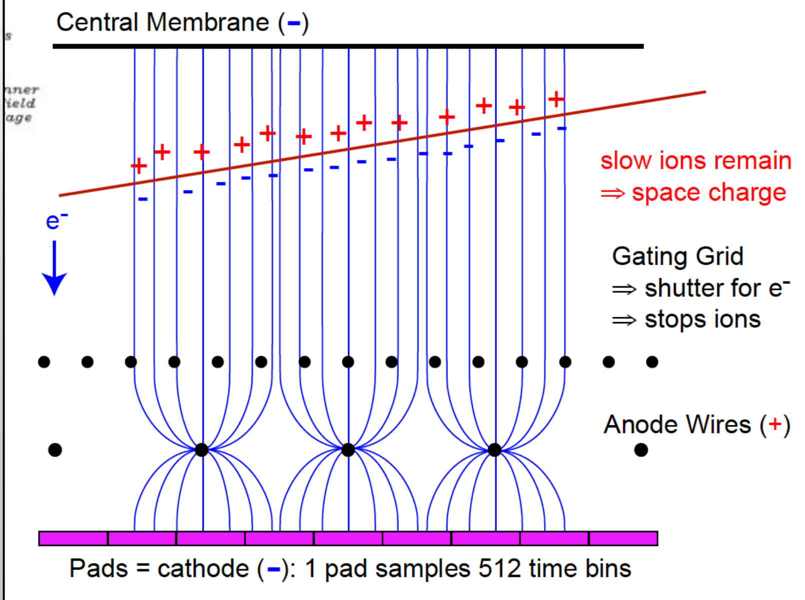
Time Projection Chambers

- Space-charge issue: MWPCs are used as gas amplification stages; ions produced in the avalanche drift back into TPC active volume “ion backflow.” Fast signal from elections and long tail coming from ion cloud

- Gating grid idea: to reduce ion backflow and positive space charge in TPC, gate is open by trigger for a few μs (STAR)

- Alternative:
  - using Gas Electron Multipliers (GEM) for signal amplification that naturally suppresses ion backflow (ALICE upgrade)
  - using a hybrid GEM+μMegas for amplification (sPHENIX)





Time Projection Chambers

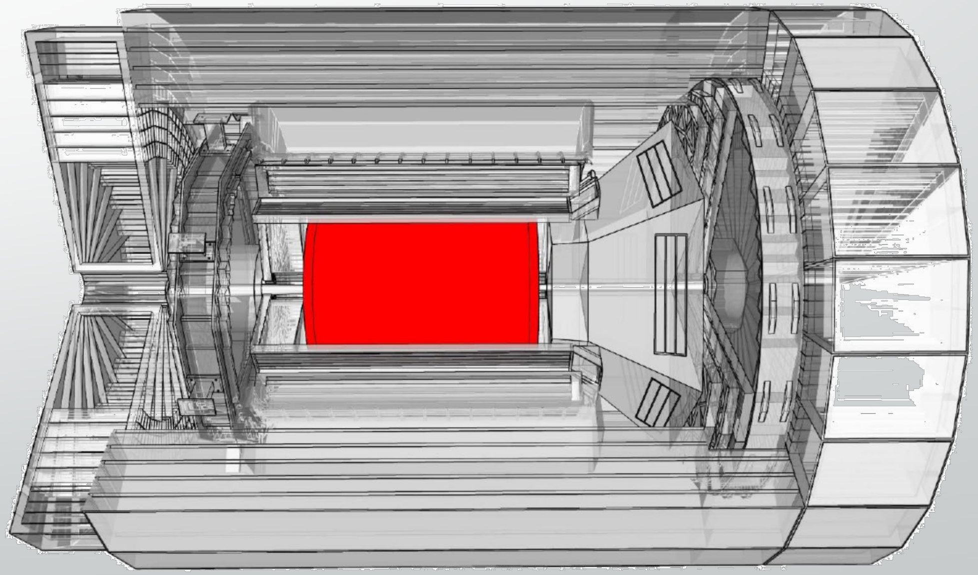
- Considered as one of the possible tracker contenders at the EIC for central region
  - Pros: very low mass, provides tracking and PID
  - Cons: need careful tuning of gas mixture; larger volume ;NOT a vertex detector

    long drift time → low rate

    large voltages → potential discharges

- Currently not under consideration by developing detector proposals (AFAIK)

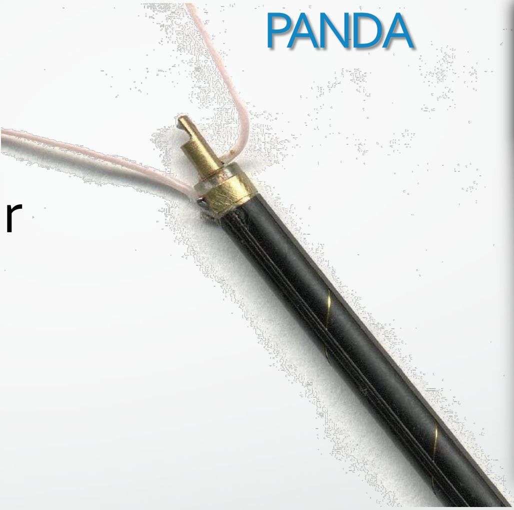
Possible TPC location in EIC Multipurpose Detector

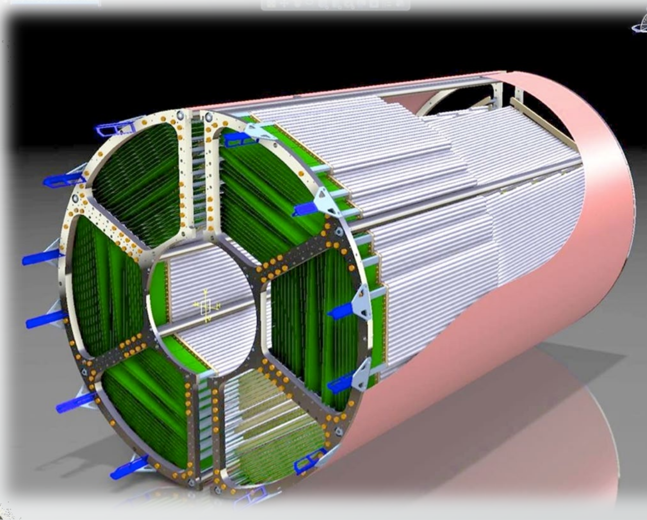


Straw Tube Tracker

- Instead of the large gas-filled volume – individual cathodes for each wire diameter 4-10mm
- Measures drift time (must know signal arrival time to extract distance)

PANDA





- Features: high spatial and momentum resolution, PID, low material budget
- Spatial resolution: $\sim 50 - 100\ \mu\text{m}$
- PANDA: $\sigma_p\ /p \sim 1 - 2\%$ (at $B = 2\ T$)

  $X/X0 \sim 1.25\%$

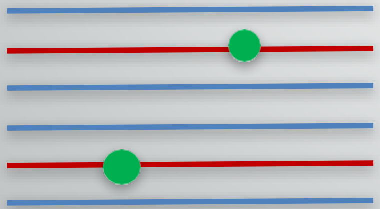
4636 self-supported straw tubes in 2 semi-barrels

23-27 radial layers in 6 hexagonal sectors

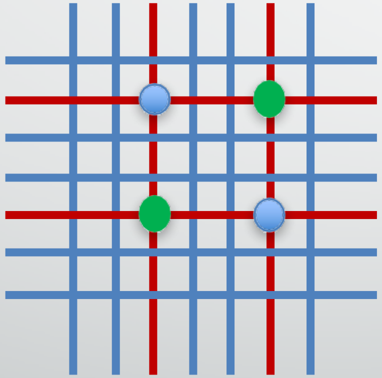
5-19 axial layers (green) in beam direction

Tracking with STT

- Reconstructing x-y position is trivial: tube locations; sufficient granularity
- The tube lengths are up to 4 m
- z-coordinate?



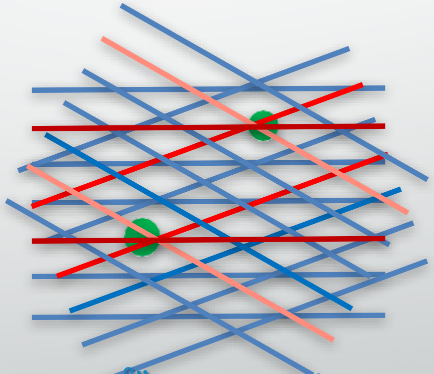
No z coordinate



90° “stereo”

Good: resolution

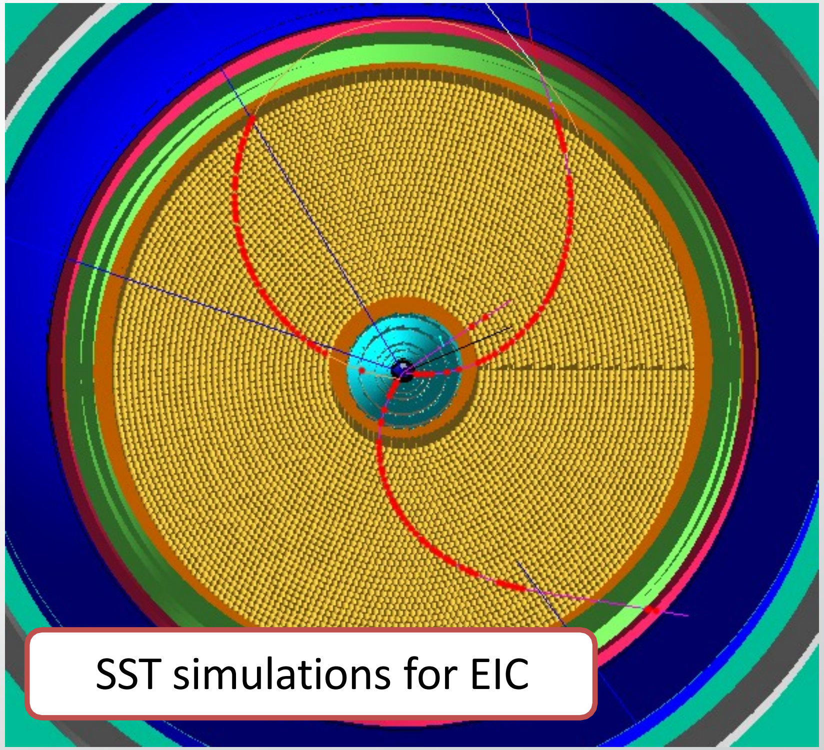
Bad: n² “ghost” hits



30°“ stereo” (3 layers)

Good: no ghosts

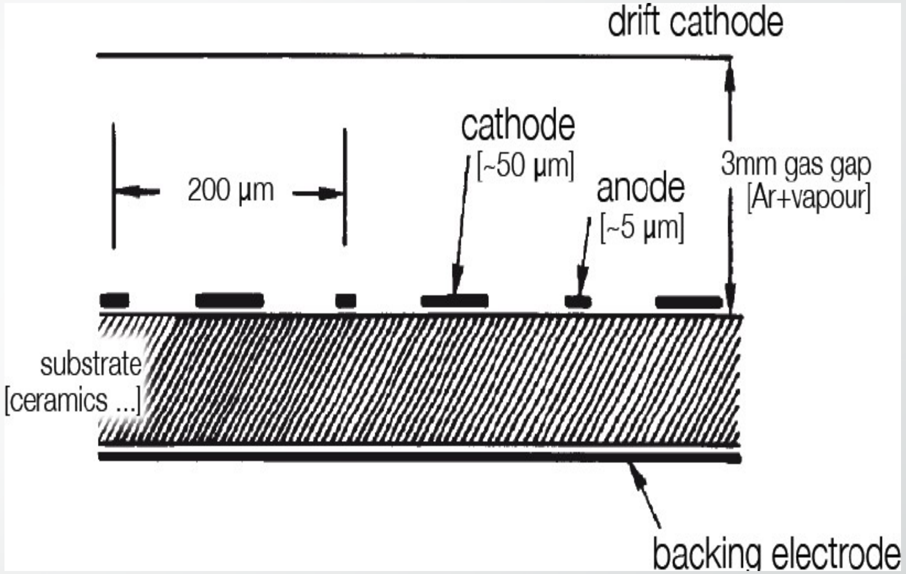
Bad: complicated pattern recognition



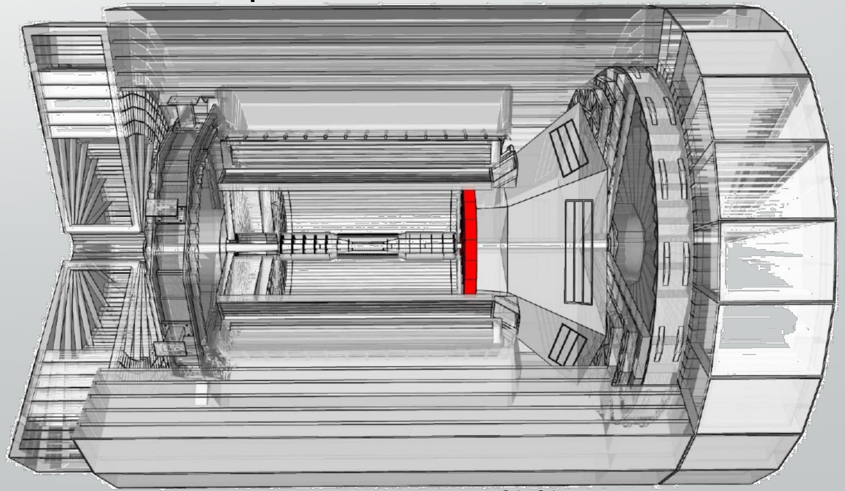
SST simulations for EIC

Micro Strip Gas Chambers (MSGC)

- MSGC is the "mother" of all Micro-Pattern Gaseous Detectors (**MPGD**s)
- The first MSGCs date back to 1990es
- The same (simple) general concept has later evolved into μMegas, GEM, and μRWellss
- All these are gas-filled for ionization by a passing charged particle; what is (somewhat) different is how the signal amplification is achieved



MPGD option in EIC Detector

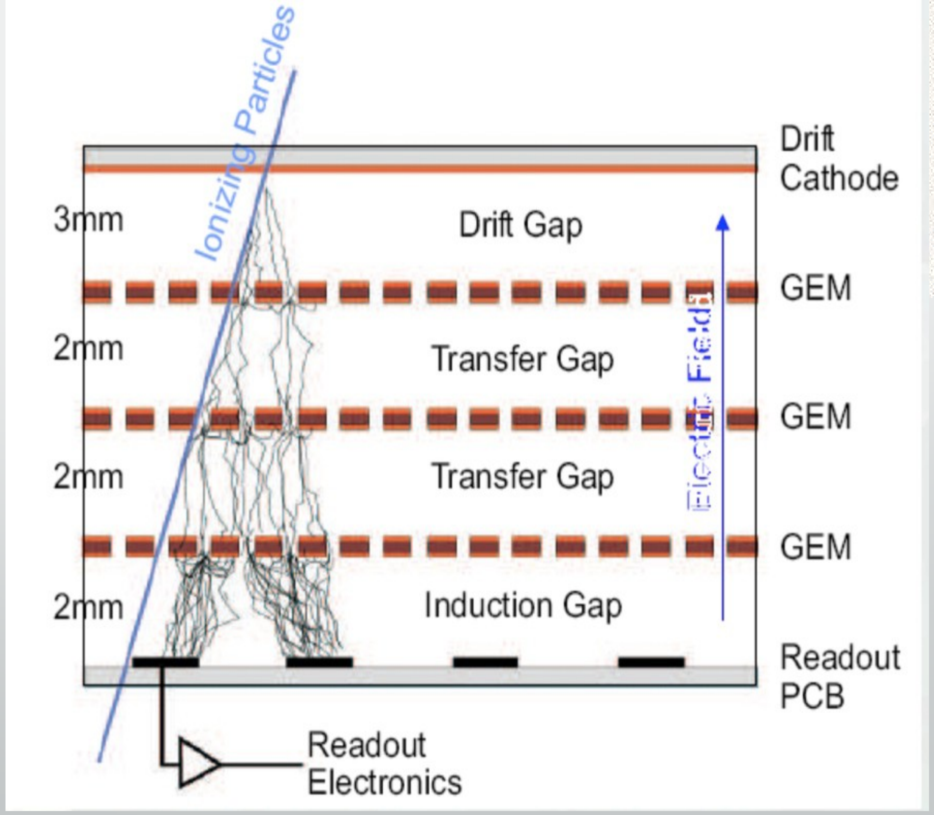


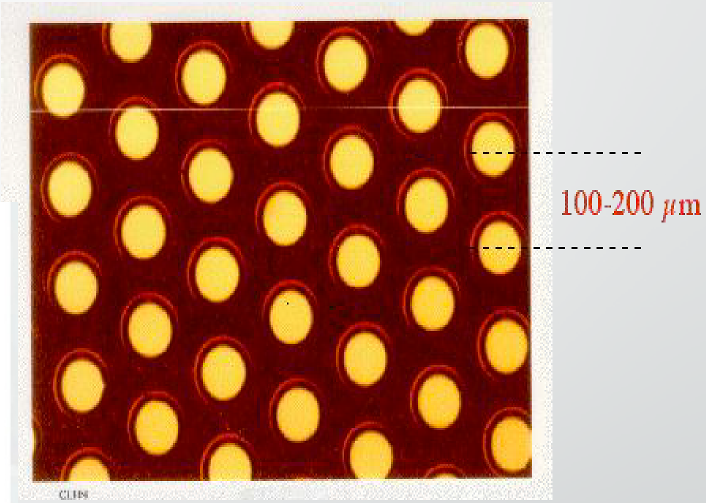
Gas Electron Multipliers (GEM)

- GEMs are gas-based trackers; novel design feature: a very thin metal-coated polymer film chemically pierced by a high density of holes.

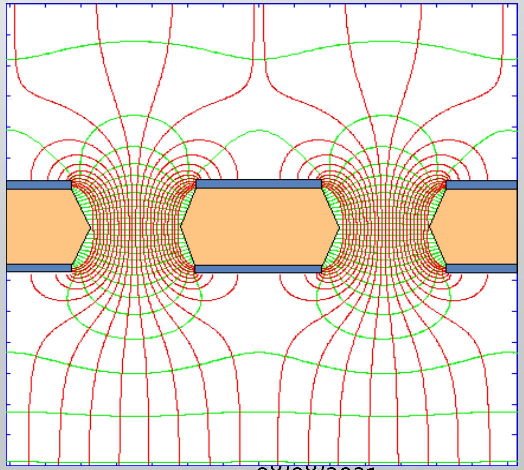
- Typical characteristics:
  - Drift gap: ~a few mm
  - Drift time: ~300ns
  - Spatial resolution ~50 μm

- Cons: film breakage





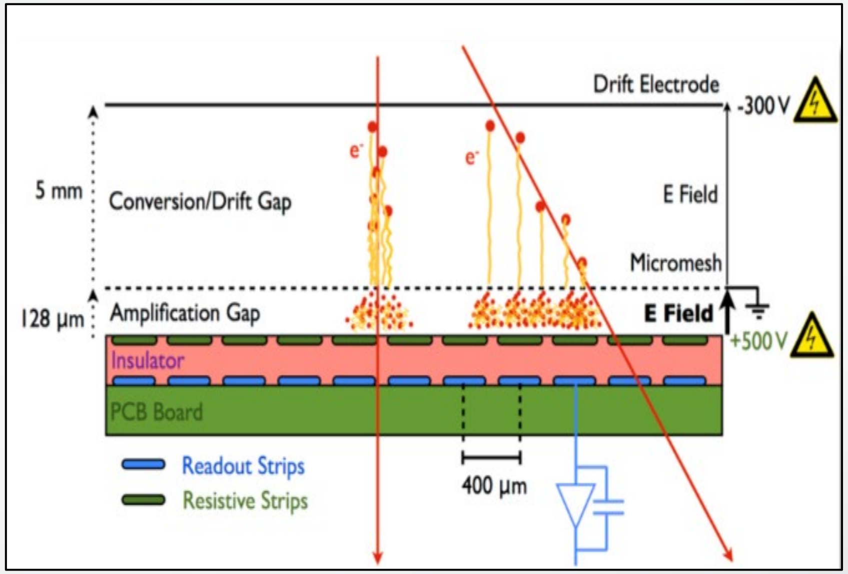
Field Map



Micro-Mega (μMega)

- Technology allows to make large planar detecting planes
- Metal micromesh creates high-field for avalanche signal amplification
- Spatial resolution: ~50 μm

- ATLAS design example:
  - Short drift gap (a few mm) for primary ionization
  - Single-stage amplification in a high field
  - Capacitive coupling to readout strips through the resistive layer
- CONS: stretching/breakage

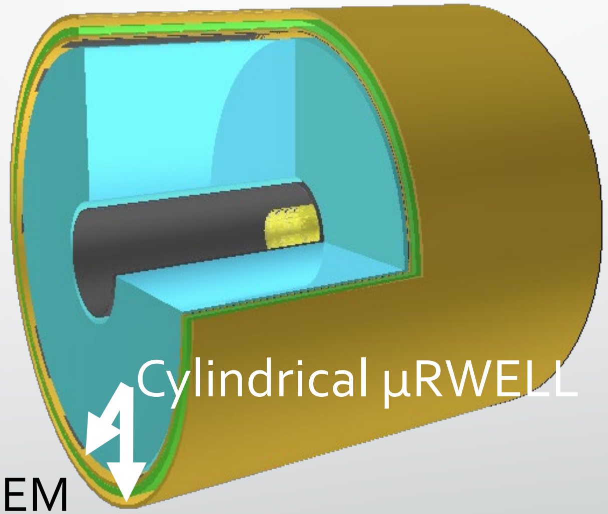


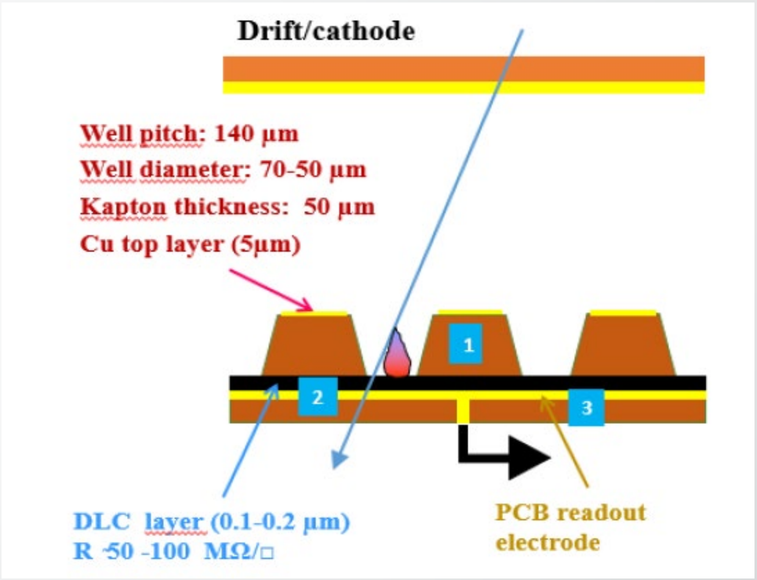
ATLAS New "Small Wheel"

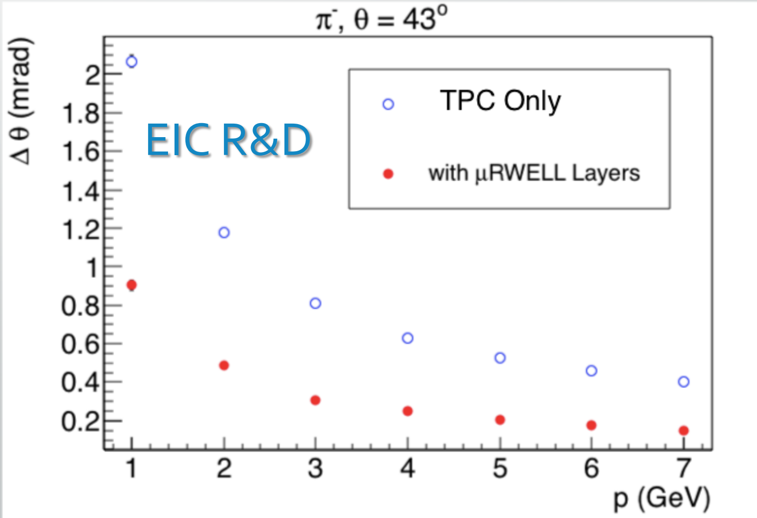
µRWELL Detectors

- Combines advantages of GEM and µMega, and needs no stretching

- Cylindrical layout (eRD6):
  - HV cathode
  - Drift gap: ~a few mm
  - Spatial resolution: ~50 µm
  - Micro-well layer (similar to a single GEM foil) mounted on a resistive readout board ("foil backed by ring")



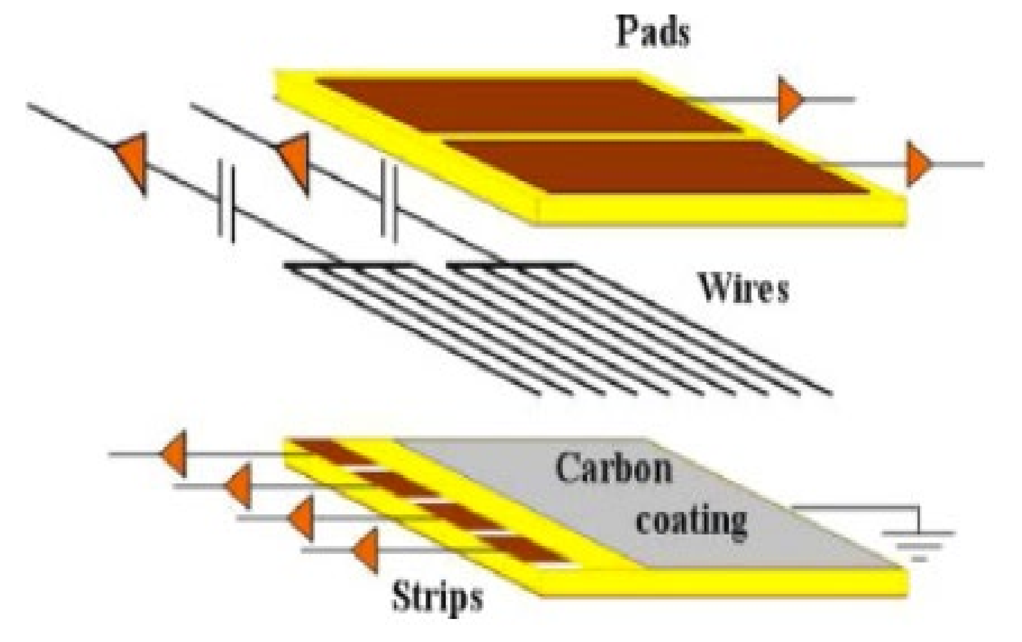




EIC R&D

Small-strip Thin Gap Chambers

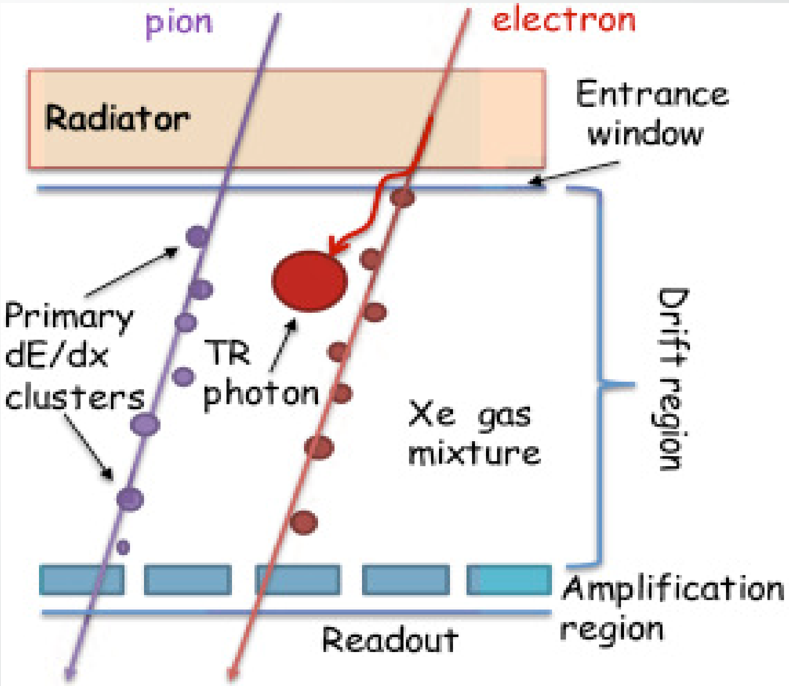
- STGS initially designed for ATLAS
  - Grid of wires in a gas mixture between two cathode plates
  - Dual (strip and pad) readout
- Suitable technology choice for large area planar tracking
- Typical characteristics:
  - Spatial resolution (~100μm)
  - Low material budget (~0.5%Xo per layer)
  - Low cost



Transition Radiation Detectors

- Transition radiation (TR) is produced by a charged particle crossing interface of two media with different dielectric constants
- The probability to emit one TR photon per boundary is of order $\alpha \sim 1/137$ → multilayer dielectric radiators are used(~ few hundreds of mylar foils)
- Energy of TR photons is 2 - 40 keV
- Spatial resolution: $\sim 100 - 200\ \mu\text{m}$
- Total TR energy is proportional to the γ factor with TR radiation onset at $\gamma \sim 1000$
  - electrons are measurable from ~1-2 GeV/c
  - pions – from a few hundred GeV/c

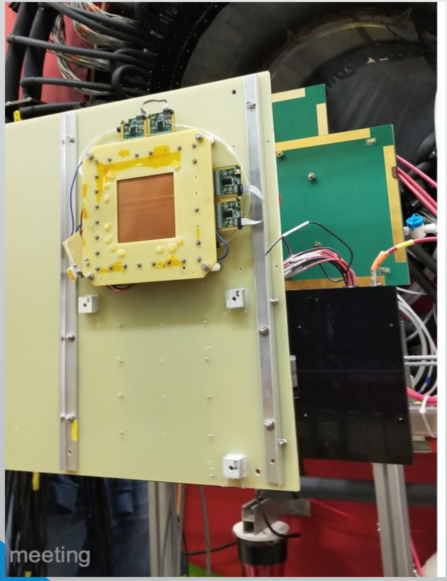
Example: ATLAS STT+TRD



TRD for EIC

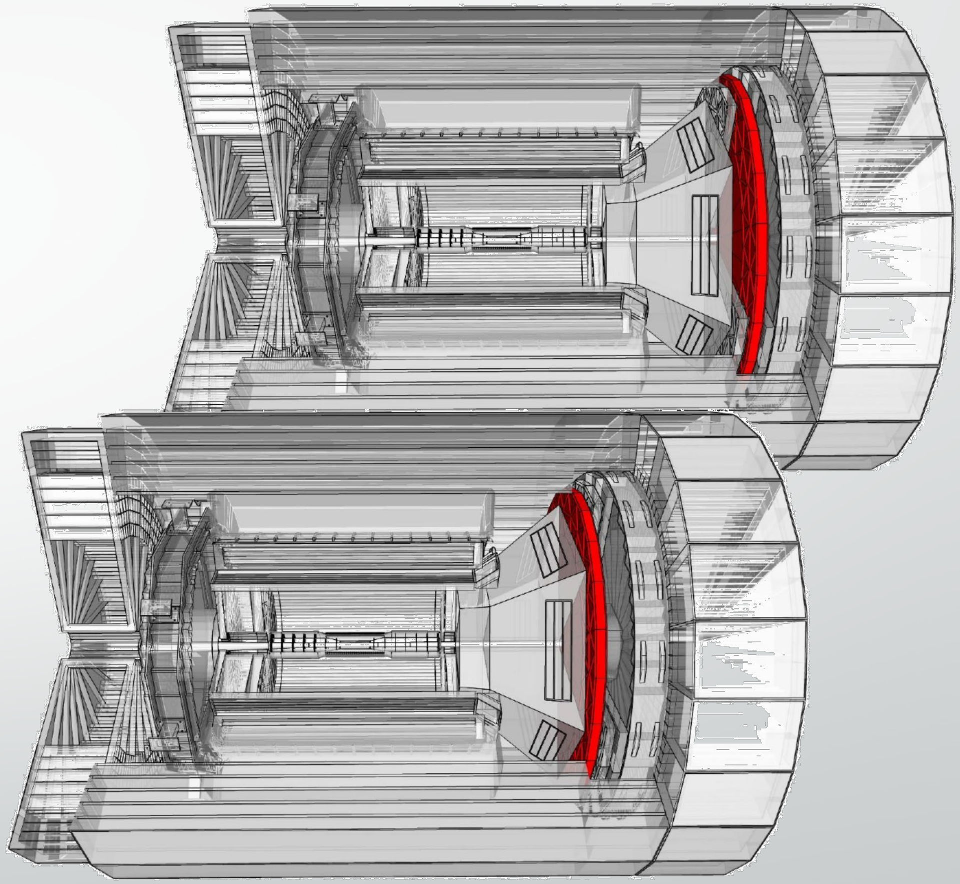
- TRD R&D goals for EIC: Electron identification (e/h separation) + tracking
- Convert a GEM tracker to TRD:

Test setup at GlueX@JLab



- Change from Argon to Xenon
- Increase drift region up to 2-3 cm
- Add a radiator in the front of each chamber
- Number of layers depends on needs: single layer e/π rejection of 10 with ~90% electron efficiency

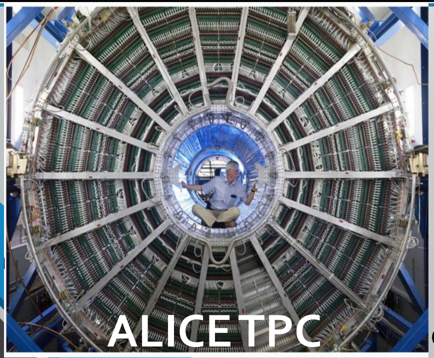
eRD22



Gaseous Tracker Options for EIC

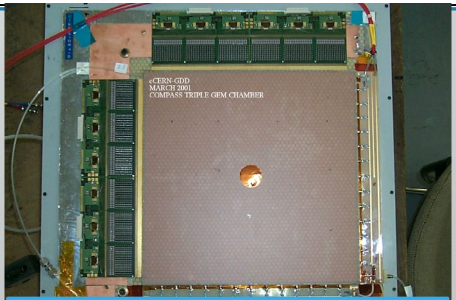
Barrel region

TPC + Fast MPGD Layer	Cylindrical MPGD (Micromegas, µRWELL)	Drift Chambers / Straw Tubes	Planar MPGDs (GEM, Micromegas, µRWELL)
Pros: - momentum res.; - additional dE/dx; - cost - Low material in barrel	Pros: - Space & angular res. - Time resolution (< 10 ns) - Low mat. in end cap - Cost & robustness	Pros: - momentum res.; - additional dE/dx; - cost - Low mat. in barrel	Pros: - Alternative to cylindrical MPGDs arrangement in polygons - Easier fabrication
Cons: - End cap material - calibration space charge distortion	Cons: - Momentum res. - Fabrication challenges - Material budget in barrel	Cons: - End cap material - calibration - Stability issues	Cons: - Momentum res. - Detector space barrel - Material budget in barrel


ALICE TPC

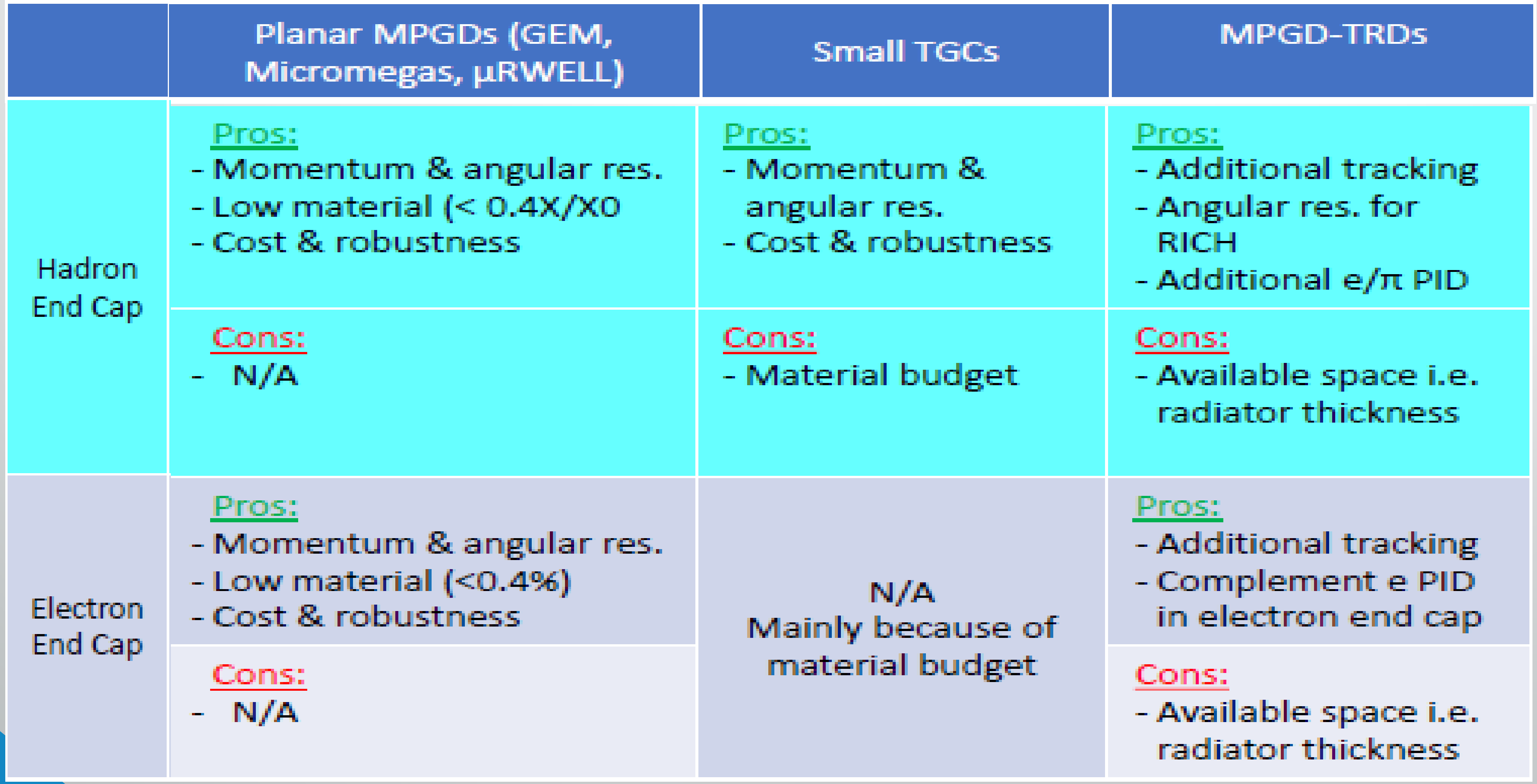

KLOE-II GEM


ATLAS Straw Tracker



COMPASS GEM

Gaseous Tracker Options for EIC



	Planar MPGDs (GEM, Micromegas, µRWELL)	Small TGCs	MPGD-TRDs
Hadron End Cap	Pros: - Momentum & angular res. - Low material (< 0.4X/X0 - Cost & robustness	Pros: - Momentum & angular res. - Cost & robustness	Pros: - Additional tracking - Angular res. for RICH - Additional e/π PID
	Cons: - N/A	Cons: - Material budget	Cons: - Available space i.e. radiator thickness
Electron End Cap	Pros: - Momentum & angular res. - Low material (<0.4%) - Cost & robustness	N/A Mainly because of material budget	Pros: - Additional tracking - Complement e PID in electron end cap
	Cons: - N/A		Cons: - Available space i.e. radiator thickness