EIC Detector Design

Alexander Kiselev

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Outline

- **Introduction**
- **EIC detector concepts**
- **Tracking**

Wednesday

- **Calorimetry**
- **Particle identification**
- **Summary**

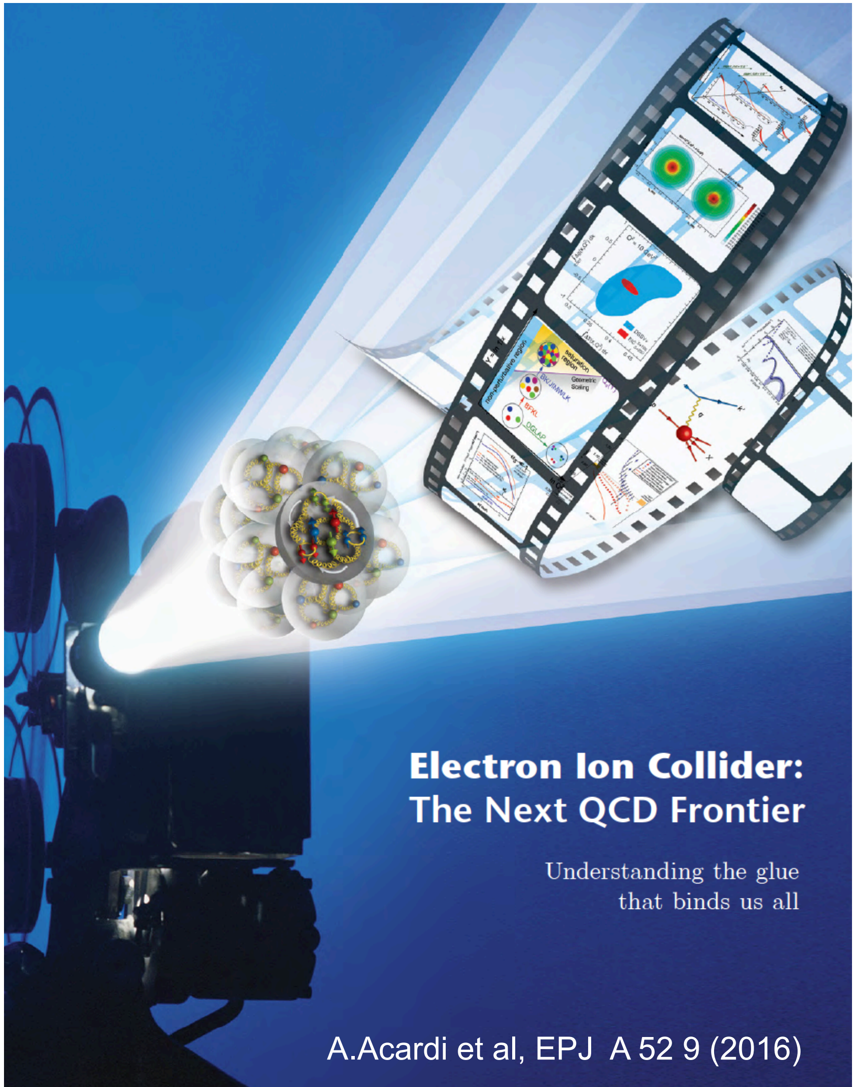
Thursday

*Input from E.Aschenauer, M.Chiu, R.Erbacher, Y.Furletova, K.Gnanvo, T.Horn, U.Langenegger, V.Manzari, P.Nadel-Turonski, B.Page, D.Pitzl, J.Repond, L.Ruan, F.Sefkow, M.Stanitzki, B.Surrow, M.Vandenbroucke, H.Wennloef, P.Wintz, C.Woody, R.Yoshida and other colleagues used in this lecture

Introduction

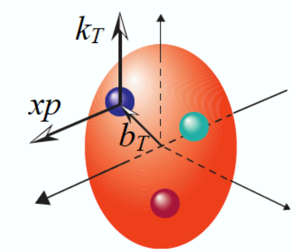
EIC Physics

Precision study of quark and gluon dynamics inside nucleon and nuclei

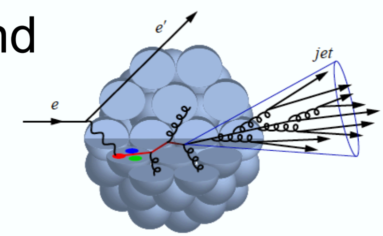


Key questions:

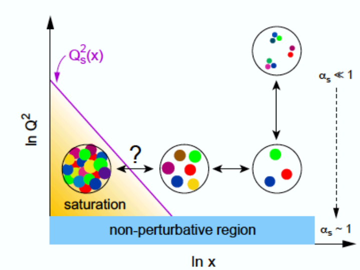
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?



- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?



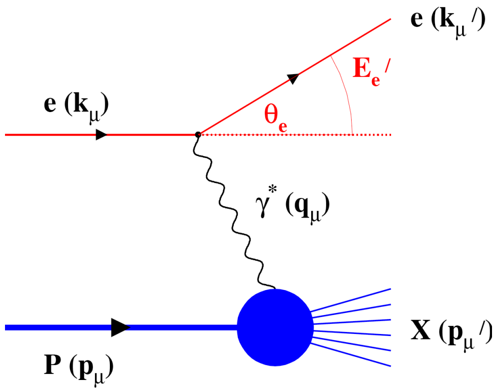
- Where does the saturation of gluon densities set in? Does this saturation produce matter with universal properties?



Typical EIC experimental measurements

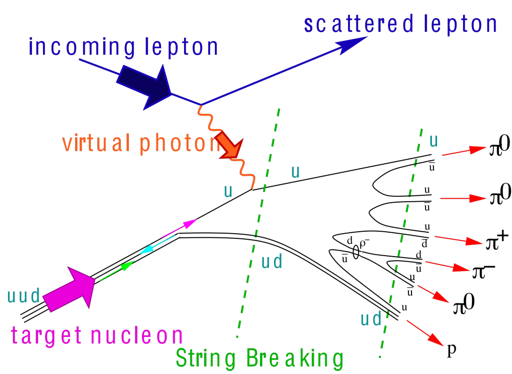
(A) Inclusive Reactions in ep/eA:

- Structure Functions: g_1, F_2, F_L



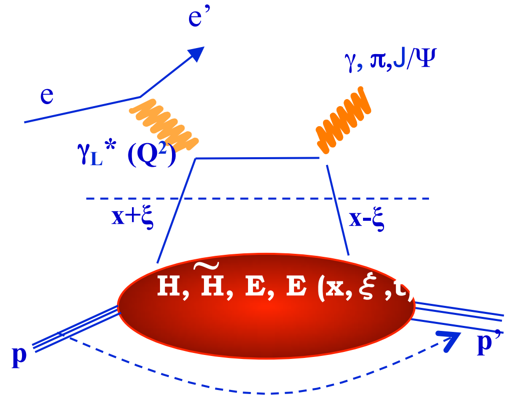
(B) Semi-inclusive Reactions in ep/eA:

- TMDs, Helicity PDFs, FFs (with flavor separation); di-hadron correlations; Kaon asymmetries, cross sections

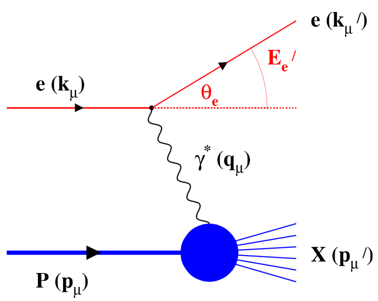


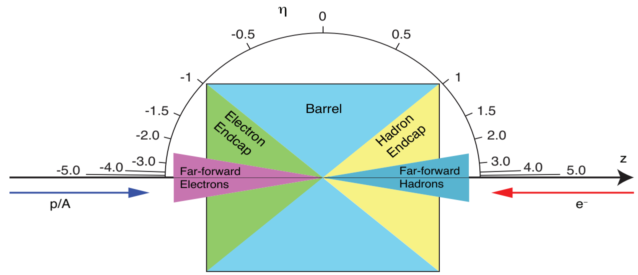
(C) Exclusive Reactions in ep/eA:

- DVCS, exclusive VM production (GPDs; parton imaging)



Example (A): scattered e⁻ acceptance



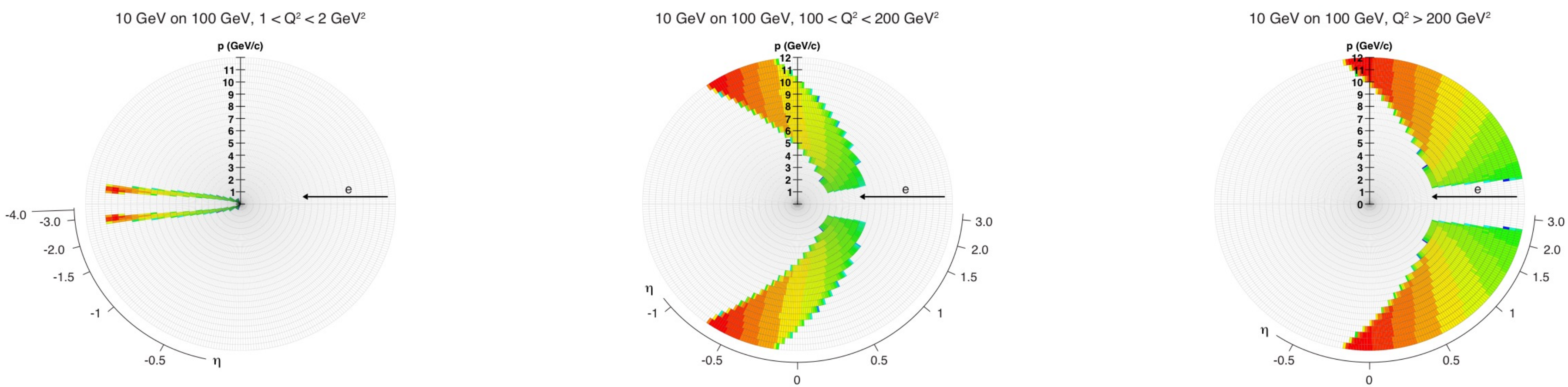


$\eta=4 \sim 2^0$

$\eta=0 \sim 90^0$

Typically use pseudo-rapidity $\eta = -\ln(\tan(\theta/2))$ rather than θ

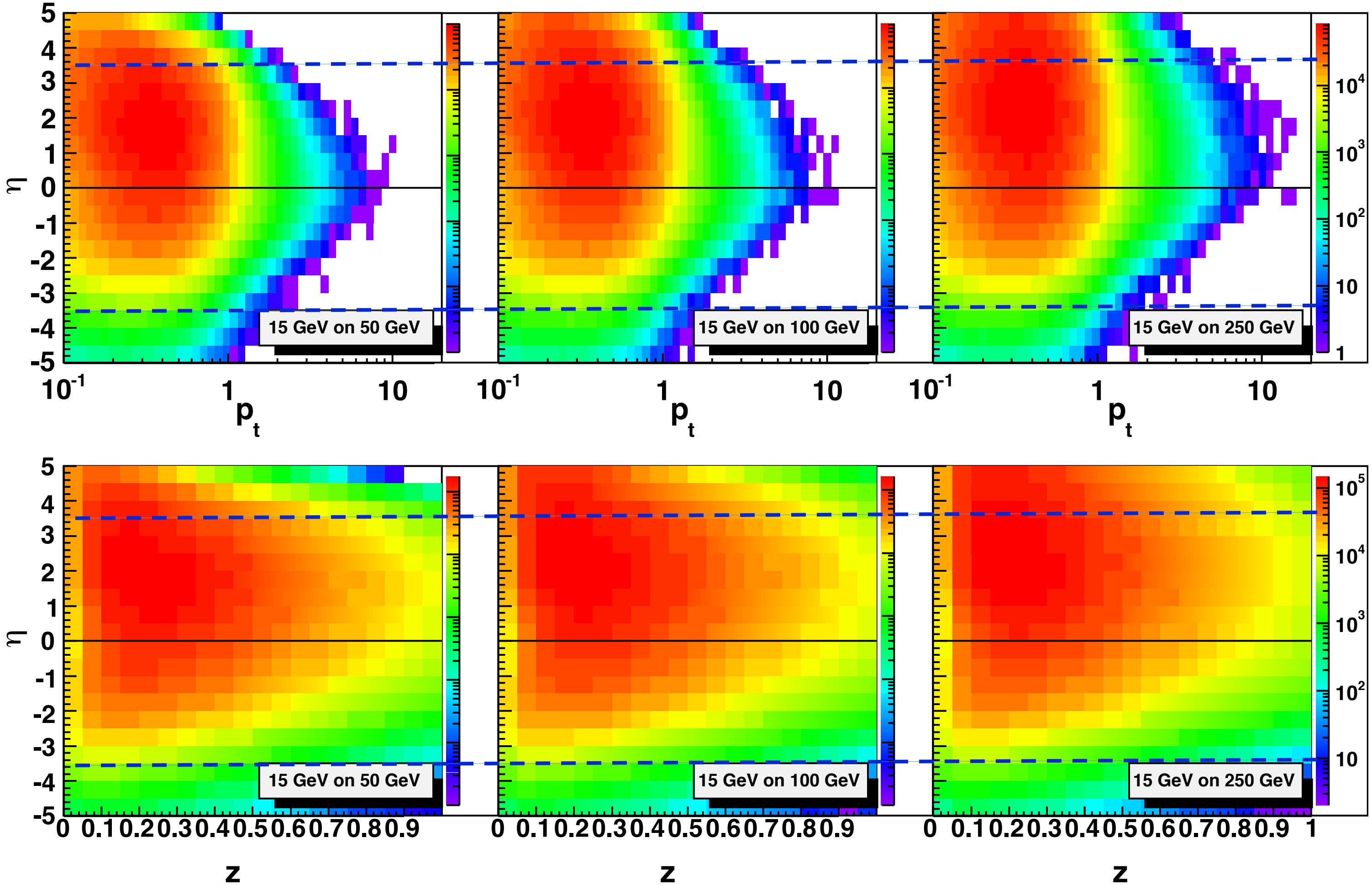
Scattered electron {η,p} for various Q² ranges at the same set of beam energies



- In principle need to cover at least $-4 < \eta < 2$ range with appropriate tracking and e/m calorimetry

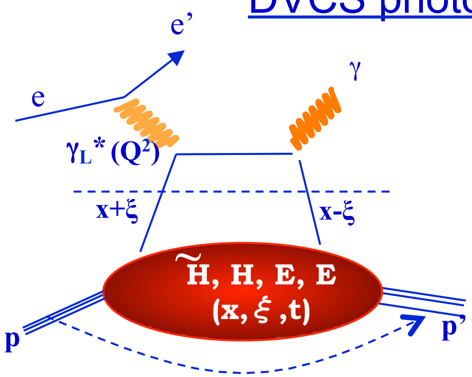
Example (B): kinematics of SIDIS pions

Cuts: Q^2>1 GeV^2, 0.01<y<0.95, p>1GeV (no difference between $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$)

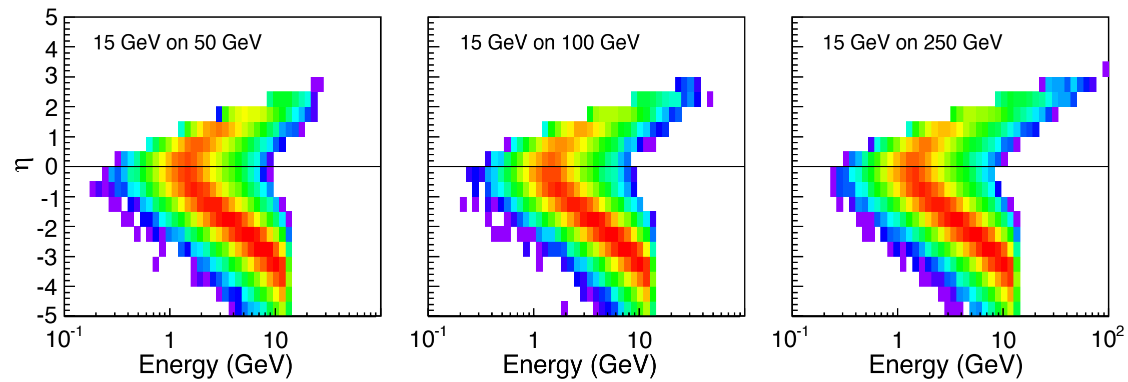


-> -3.5 < η < 3.5 covers entire kinematic region in hadron p_t (transverse momentum) and z (virtual photon energy fraction), which are important for physics

Example (C): DVCS photons & protons

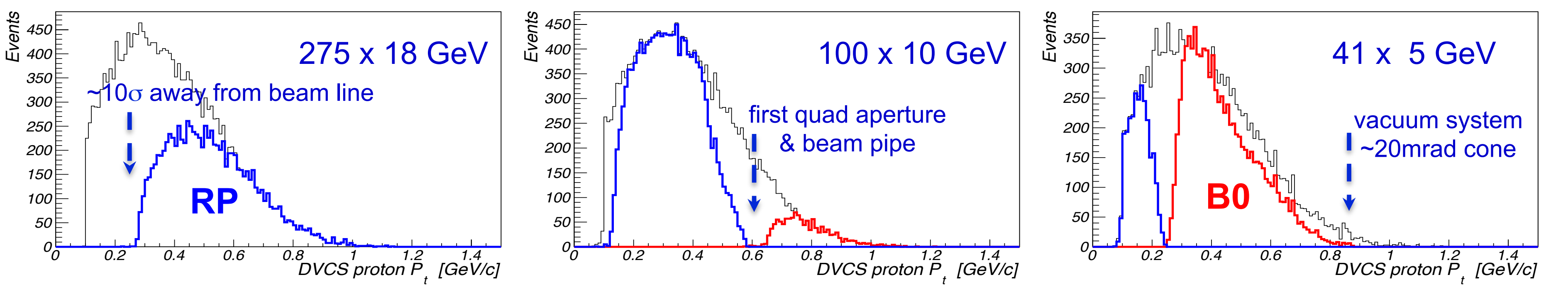


DVCS photon {η,E} for 10 GeV electrons and various proton beam energies



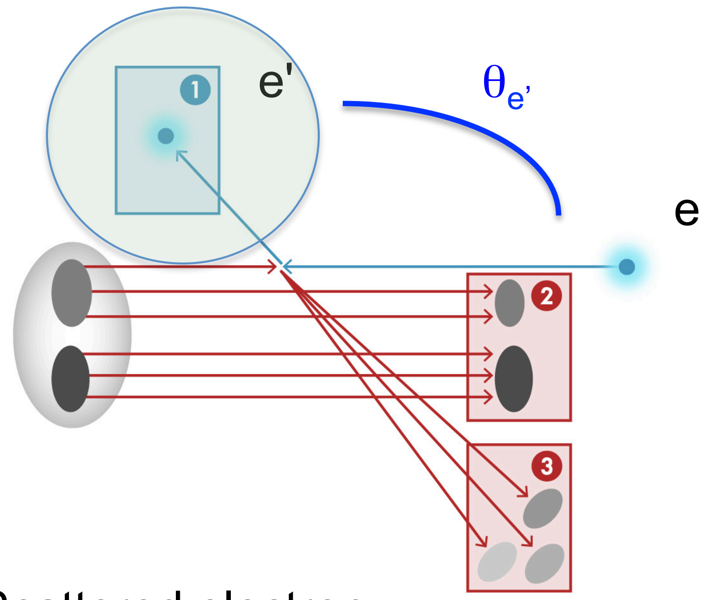
- Need e/m calorimetry coverage in $-4 < \eta < 2$ range

DVCS proton P_t (by far forward spectrometers B0/RP); range up to ~1.3 GeV/c required by physics



- 20mrad vacuum system cone opening from IP to B0 magnet suffices, except for the lowest energy combination

DIS kinematics reconstruction basics



(1) Scattered electron
(2) Proton (ion) remnants
(3) Struck quark fragmentation products

Electron method

-> only scattered electron information is used

$$Q^2_{\text{EM}} = 2E_e E_{e'}\,(1 + \cos\theta_{e'})\,,$$

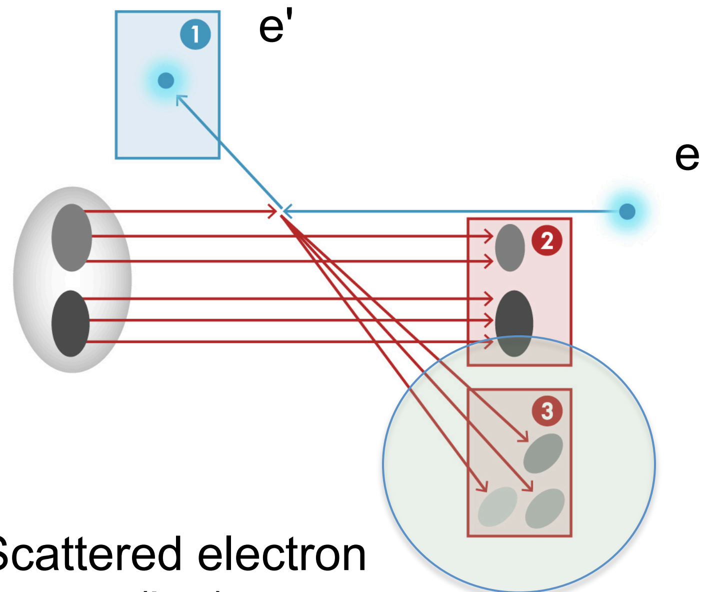
$$y_{\text{EM}} = 1 - \frac{E_{e'}}{2E_e}(1 - \cos\theta_{e'})\,,$$

$$x = \frac{Q^2}{4E_e E_{\text{ion}}}\boxed{\frac{1}{y}}$$

"Classic" way to determine $\{x, Q^2\}$

Obviously diverges at small *y*

DIS kinematics reconstruction basics



(1) Scattered electron
(2) Proton (ion) remnants
(3) Struck quark fragmentation products

Jacquet-Blondel method

-> only hadronic final state information is used

$$y_{JB} = \frac{1}{2E_e} \sum_h (E_h - p_{z,h}),$$

$$Q^2_{JB} = \frac{1}{1-y_{JB}} \left[\left(\sum_h p_{x,h} \right)^2 + \left(\sum_h p_{y,h} \right)^2 \right].$$

Relatively poor resolution (yet better than nothing)

The only way to reconstruct {x,Q^2} for charged current events (since neutrino in the final state can not be detected)

-> FYI: “mixed” reconstruction methods exist as well (see e.g. next slide)

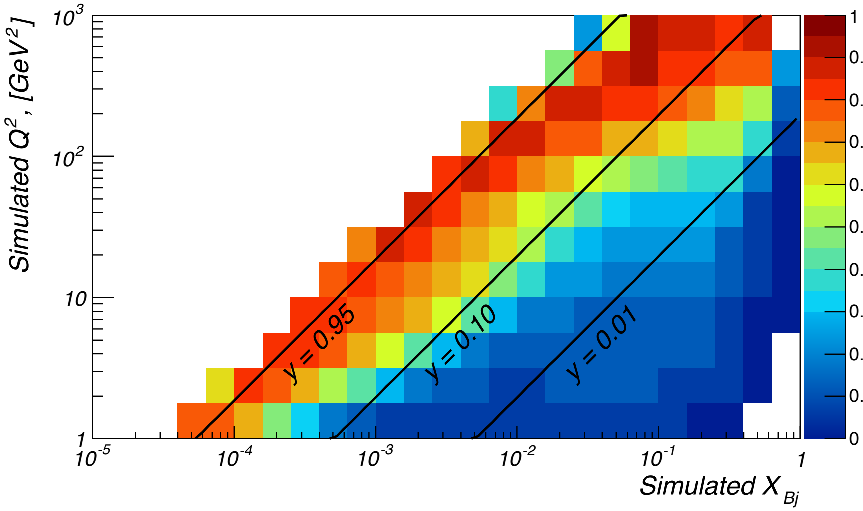
DIS kinematics reconstruction example

$$Purity = \frac{N_{gen} - N_{out}}{N_{gen} - N_{out} + N_{in}}$$

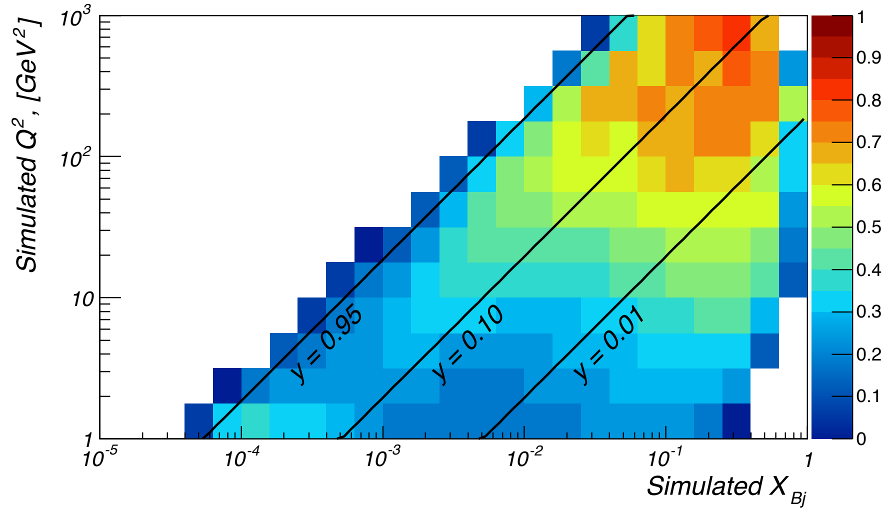
- Describes migration between kinematic bins
- Important to keep it close to 1.0 for successful unfolding

- {PYTHIA events 20x250 GeV} -> {BeAST detector; full GEANT simulation} -> {Kalman filter track fit}
- Bremsstrahlung turned on here (and it matters even for detector with ~5% X/X_0!)

Lepton tracking only



Double-angle method



- "Straightforward" lepton tracking can hardly help at Y<0.1
- Hadronic final state accounting allows to recover part of the high Q^2 range

EIC detector concepts

Detector requirements: ideal vs real life

- **The "ideal" detector (for a given process):**
  - Detect all *final state* particles of interest with 100% efficiency
  - Determine their type (PDG) with high confidence level
  - Measure all 4-momenta precisely

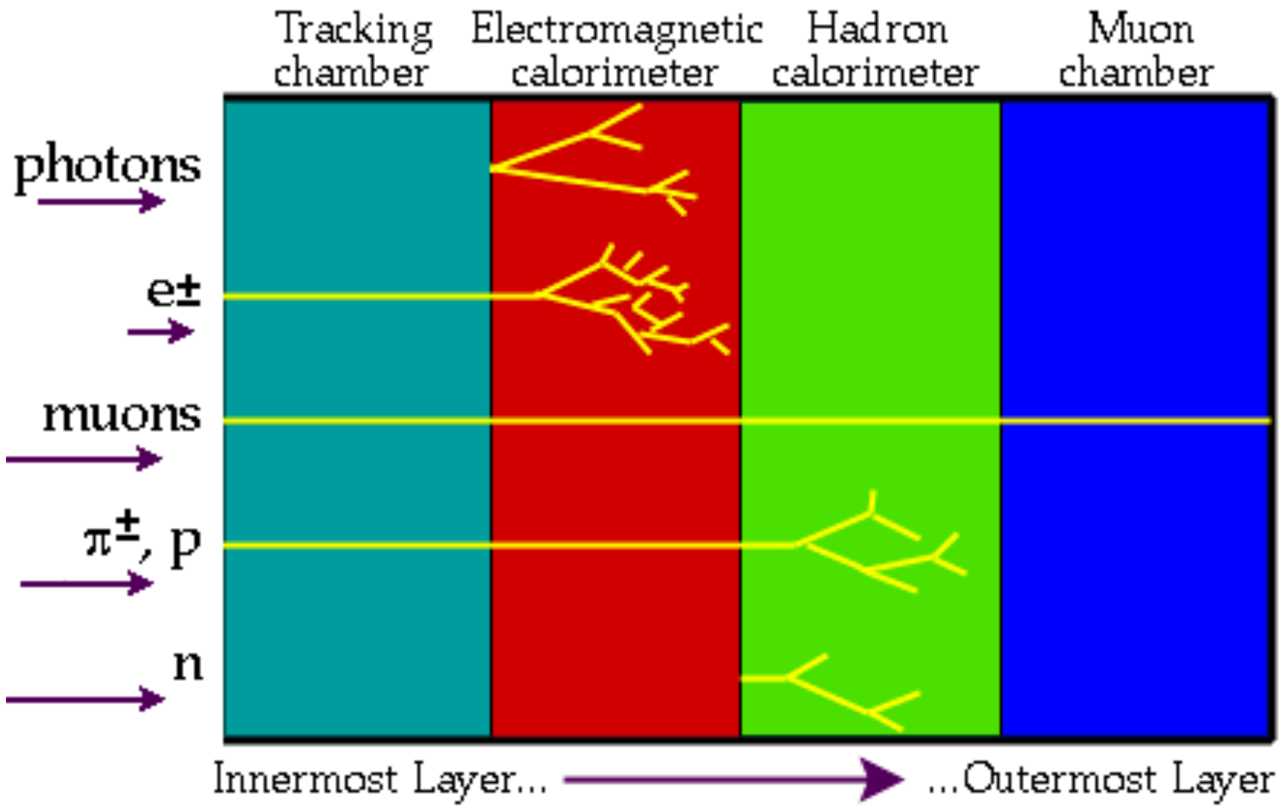
- **Real life:**
  - Only 13 particle species have $c\tau$ > 500μm -> have to deal with the *decay products*, secondary vertices, invariant mass peaks
  - Never get 100% efficient acceptance (cracks, support system, beam pipe, sub-detector frames, ...)
  - Never get 100% detection efficiency (detector imperfectness, reconstruction algorithms, DAQ limitations, ...)
  - Particle identification is never perfect
  - Have to deal with the finite detector resolutions (detector size and technology limitations, costs, ...)
  - Background processes spoil the picture

How do we detect particles?

- Long-lived: through their interaction with the detector material
  - Tracking (“gentle” measurement)
  - Calorimetry (destructive measurement)
  - & PID detectors
- Short-lived: through measuring their decay products

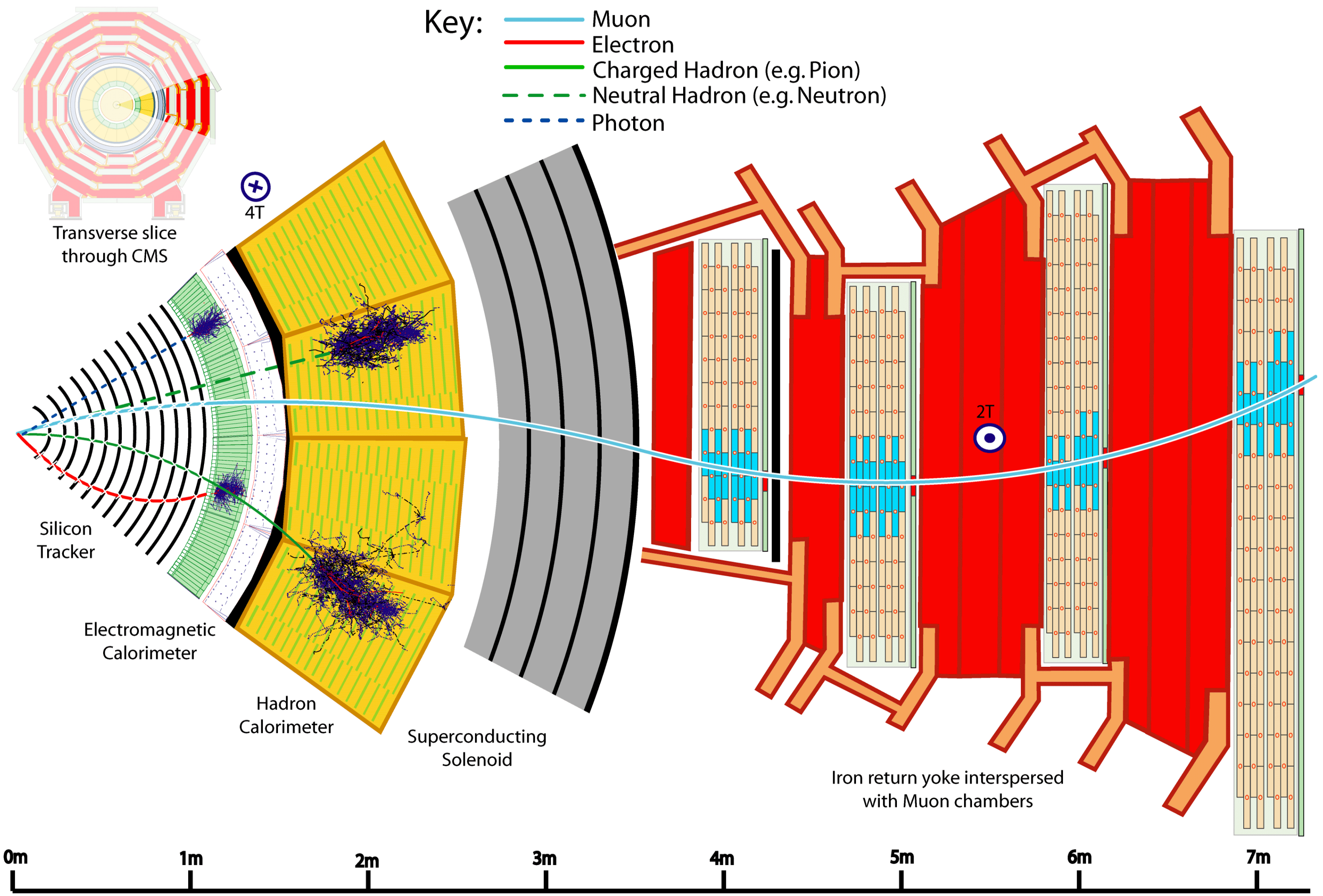
neutrinos	none	Missing energy
electrons	Ionisation, electromagnetic	Track and EM shower
muons	Ionisation	Penetrating track
p, K, π	Ionisation, hadronic	Track and hadron shower
photons	electromagnetic	EM shower
neutrons, K^0_L	hadronic	hadron shower
B, D	Weak decay	Secondary vertex
J/ψ, Υ, W, Z, H, t	prompt decay	Invariant mass

Emerging practical implementation

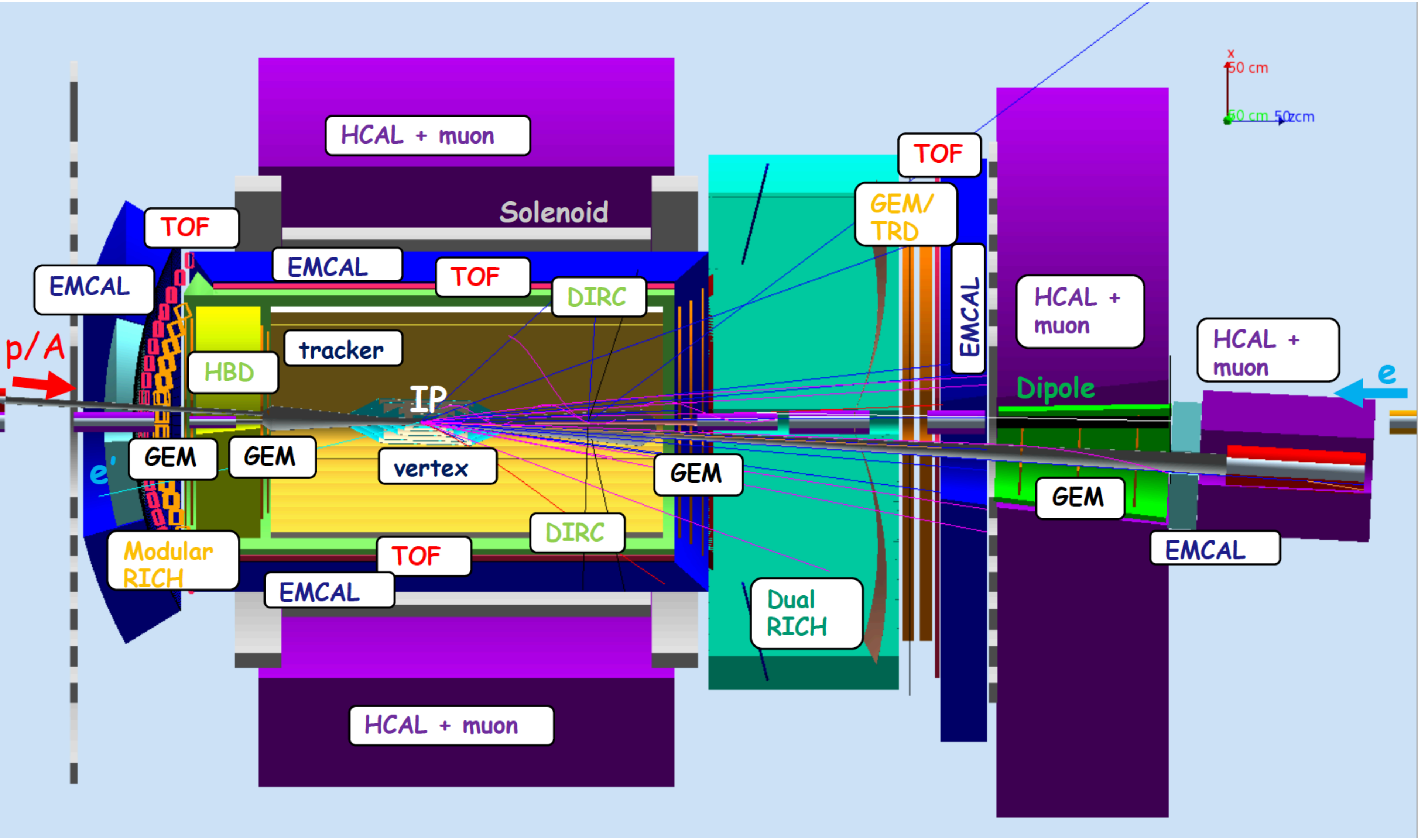


- **Caveats:**
  - Calorimetry measurement is destructive, therefore tracking system should be the closest to the IP
  - EIC physics also requires hadron species π/K/p identification!

Illustration: CMS detector at LHC

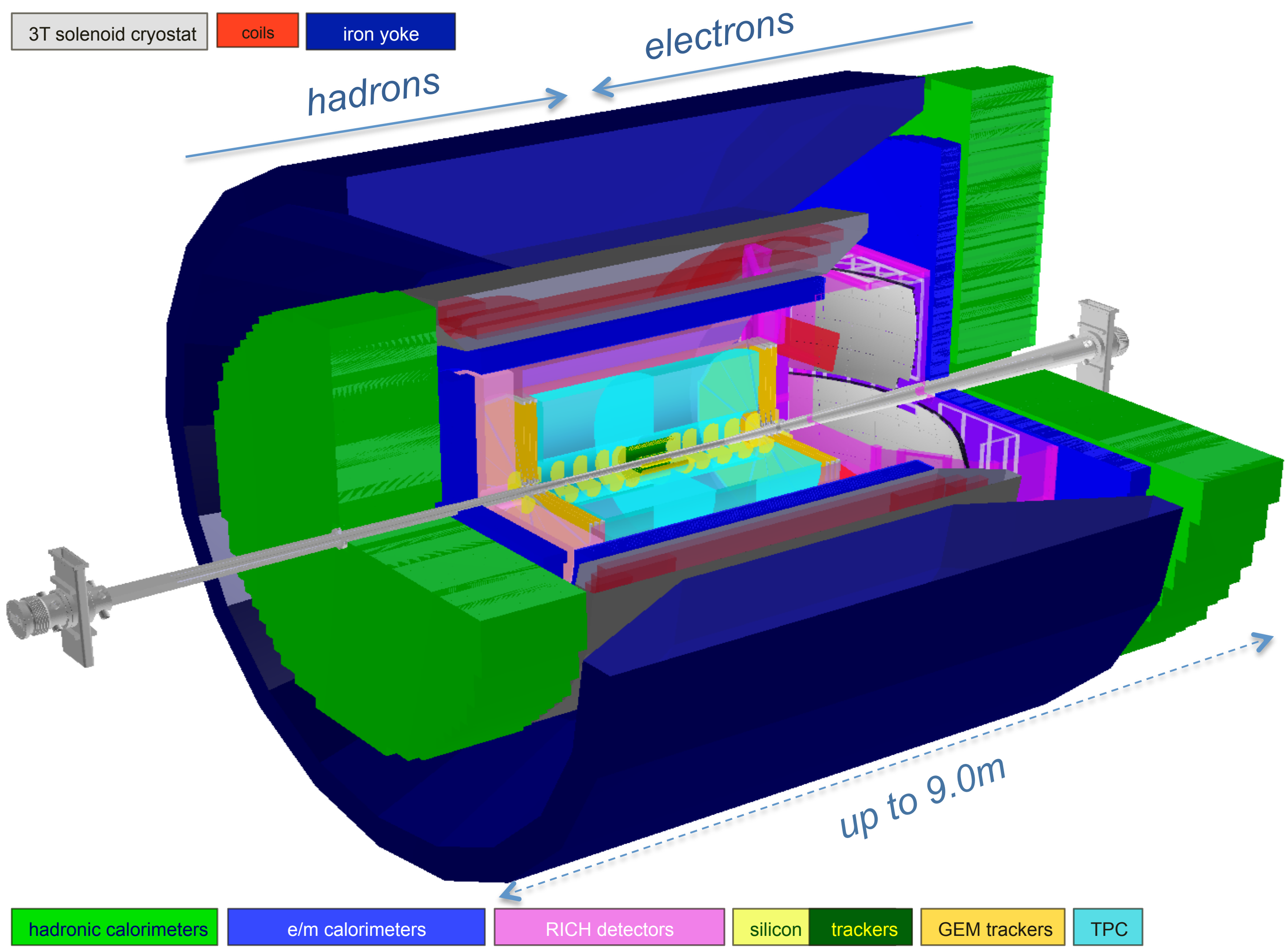


EIC detector concept: JLEIC



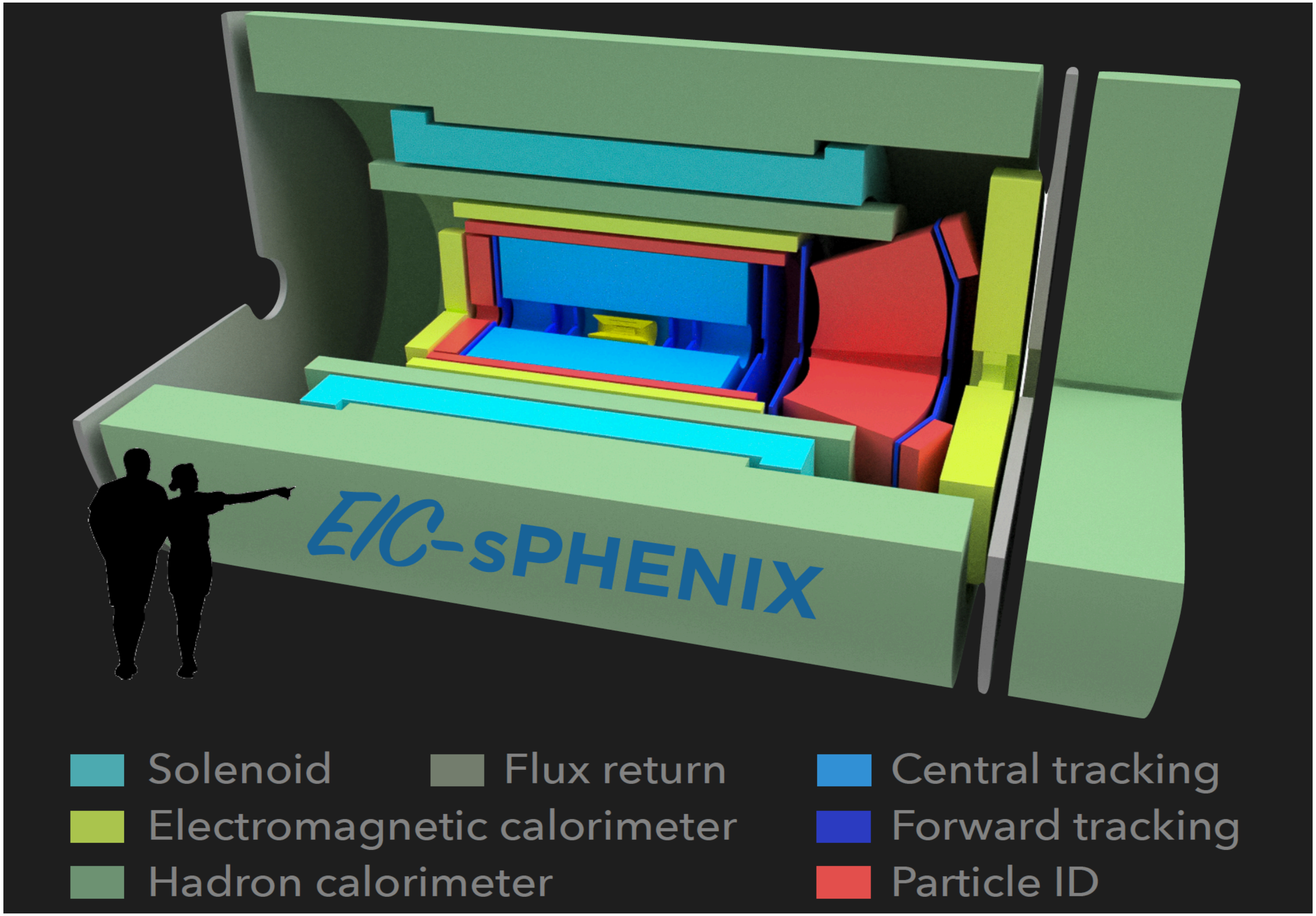
- **Jefferson Laboratory (JLab) "green field" detector**

EIC detector concept: BeAST



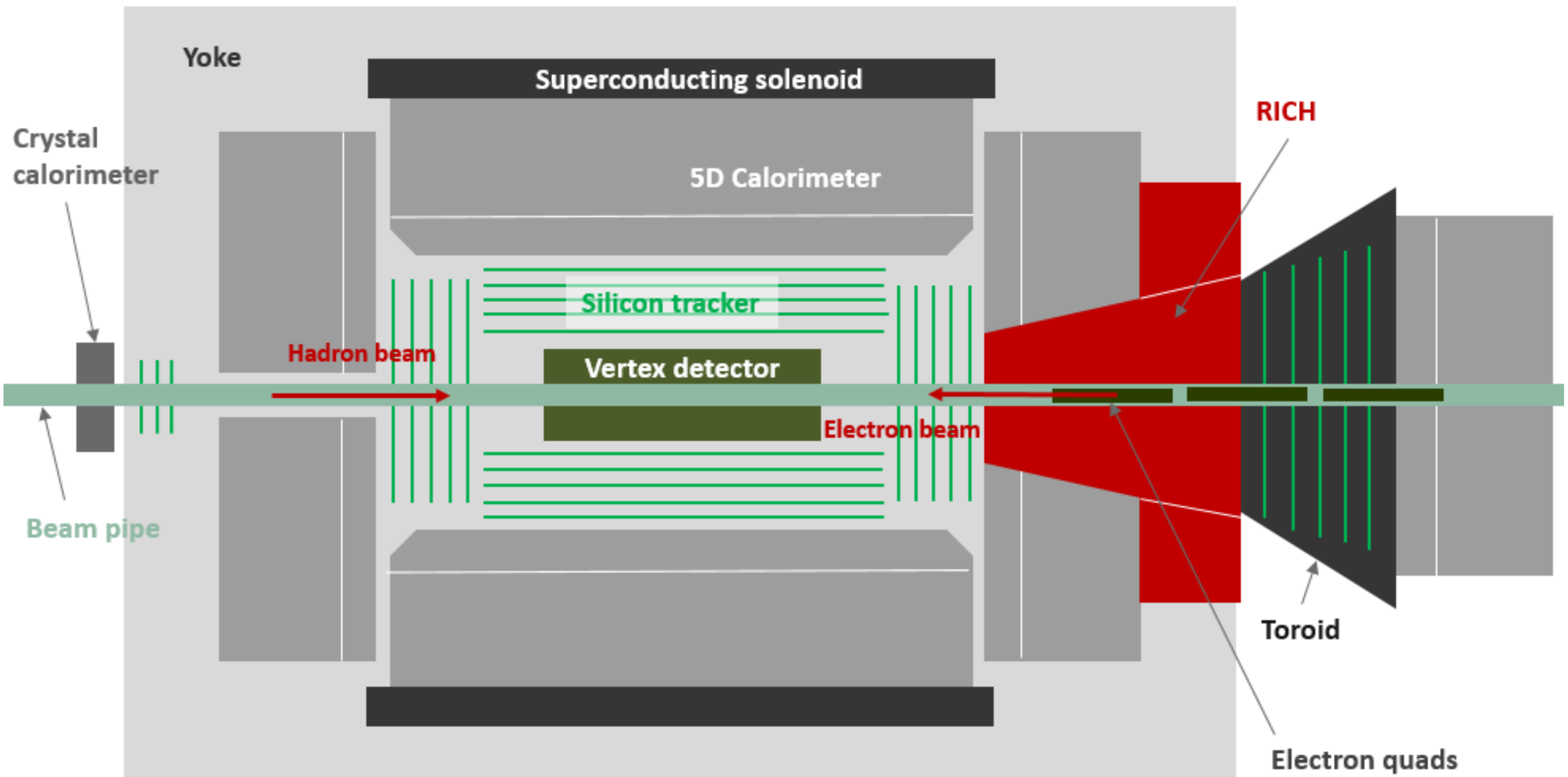
- **Brookhaven Laboratory (BNL) “green field” detector**

EIC detector concept: ePHENIX



- **Brookhaven Laboratory sPHENIX-based implementation**

EIC detector concept: TOPSiDE



- **Argonne Laboratory (ANL) all-silicon implementation**

EIC Detector Concepts

- **Common features:**
  - Compact design
  - (Almost) 4π hermetic acceptance in tracking/calorimetry/PID
  - Vertex + central + forward/backward + far forward tracker layout

  - Low material budget in the tracker volume
  - Strong central solenoid field

  - Moderate momentum resolution (~1% level)
  - Moderate EmCal and HCal energy resolution

- **Note:**
  - Community wants ***two*** general-purpose detectors

Tracking

Tracking basics: idea

- **Charged particles lose energy via ionization when passing through media (a gas volume, a silicon layer, …):**

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

Bethe-Bloch formula

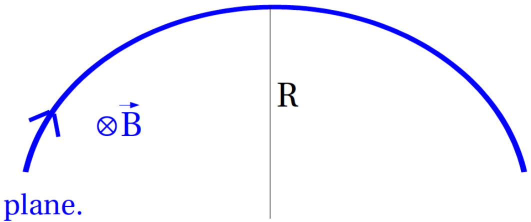
- **Tracking detector:**
  - Amplify this "electron signal" if needed
  - Discretize it according to the detector design
- **Track fitting algorithm:**
  - Use the resulting N discrete "space points", their respective covariance matrices (error estimates) and knowledge about the underlying dynamics (magnetic field, material distribution) in order to estimate track parameters at the detector location
  - Extrapolate to the interaction point and build vertices

Tracking basics: momentum measurement

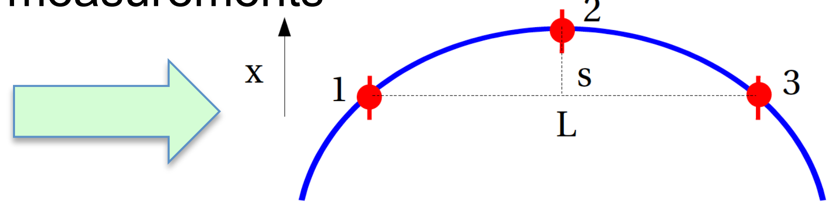
Lorentz Force:

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

For B = constant:
circular motion in the transverse plane.



add 3 measurements



$$cp_t\,[GeV] = 0.3\,R\,[m]\,B\,[T]$$

Sagitta: $s = x_2 - \dfrac{x_1 + x_3}{2}$

$$\Rightarrow \sigma_{p_t}/p_t = \sigma_s/s = \sqrt{96}\,\sigma_x\,p_t/qBL^2$$

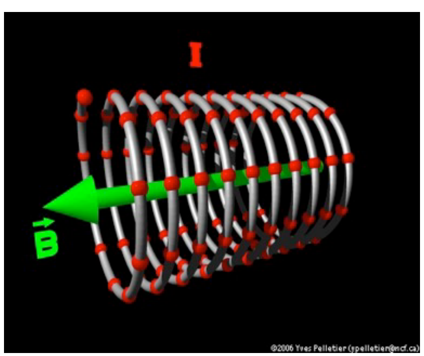
- 3 points

$$\sigma_{p_t}/p_t = \sqrt{720/(N+4)}\,\sigma_x\,p_t/qBL^2$$

(Glückstern 1964)

- N equidistant points

solenoidal field



- **Important observations:**

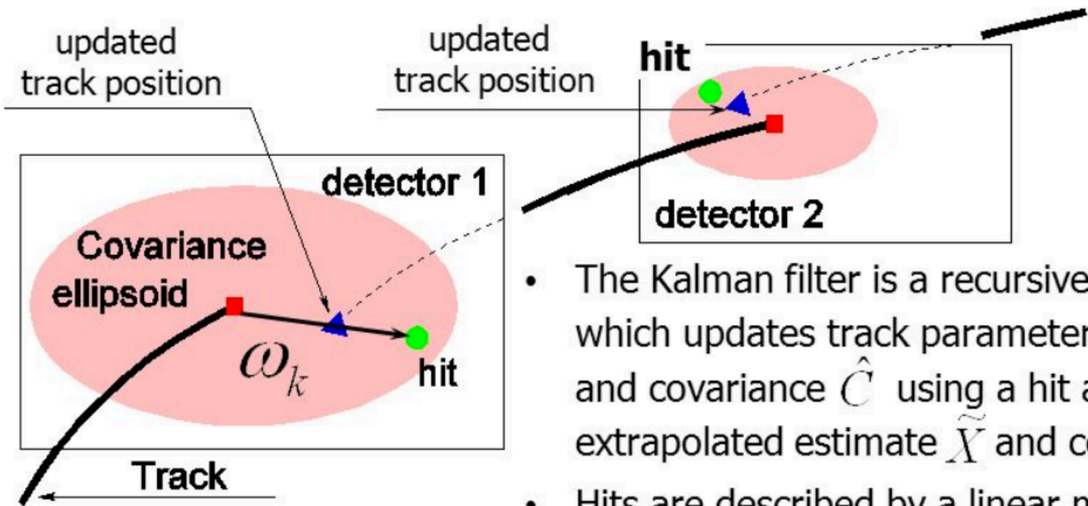
$$\sigma_{p_t}/p_t \sim p_t$$

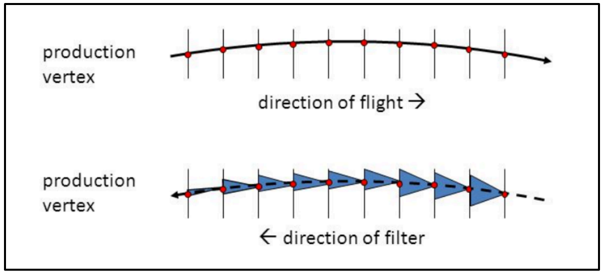
-> resolution becomes worse with increasing momentum

$$\sigma_{p_t}/p_t \sim \sigma_x/BL^2$$

-> want high single point resolution, large field and large size

Tracking basics: Kalman filter algorithm





- The Kalman filter is a recursive algorithm which updates track parameter estimate $\hat{X}$ and covariance $\hat{C}$ using a hit and the extrapolated estimate $\widetilde{X}$ and covariance $\widetilde{C}$
- Hits are described by a linear model:

$u_k = HX + \eta_k$, u_k – hit coordinates, H – measurement matrix, η_k – gaussian noise with zero mean and covariance V_k

- The track parameter and covariance update by the Kalman filter:

$$\hat{X}_k = \widetilde{X} + K_k \omega_k \qquad \hat{C}_k = \widetilde{C} - K_k H \widetilde{C}$$

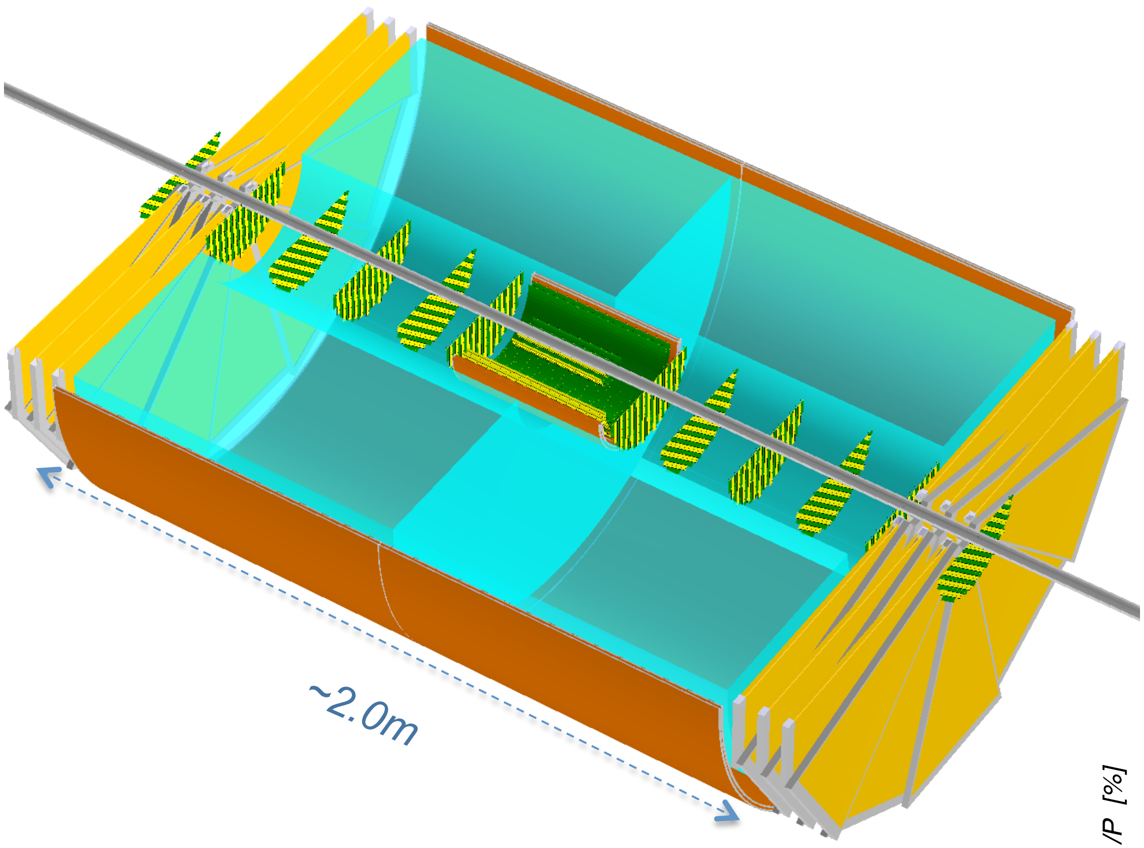
- K_k – the Kalman gain matrix, ω_k – "hit-track "residual: $\omega_k = u_k - H\widetilde{X}$

- Originally developed by R.Kalman in 1960 for spacecraft radar applications
- Formulated for charged particle tracking and vertex fitting by R.Fruehwirth in 1987

EIC detector tracking: systems & options

- **Vertex detector**
  - MAPS
- **Central tracker**
  - TPC (+ MM)
  - All-silicon tracker
  - A set of MM cylinders
  - Drift chamber
  - Straw tube tracker
- **Endcap trackers**
  - Large-area GEMs (MM, μRWELL, GEM-TRD, sTGC)
- **Forward & backward trackers**
  - MAPS
  - (Very) high resolution GEMs
- **Close-to-beamline instrumentation**
  - Roman Pots, B0 magnet tracker, low-Q^2 tagger, …

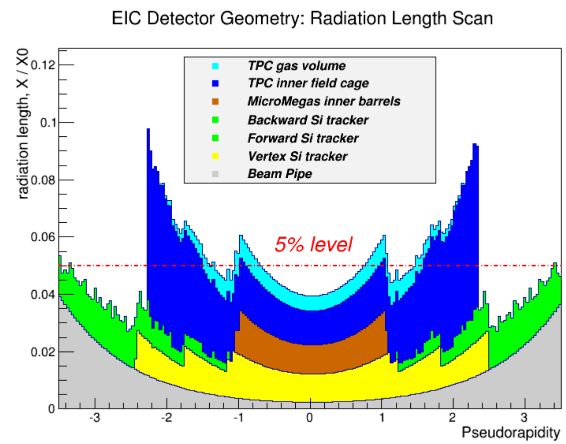
Expected "typical" EIC tracker performance



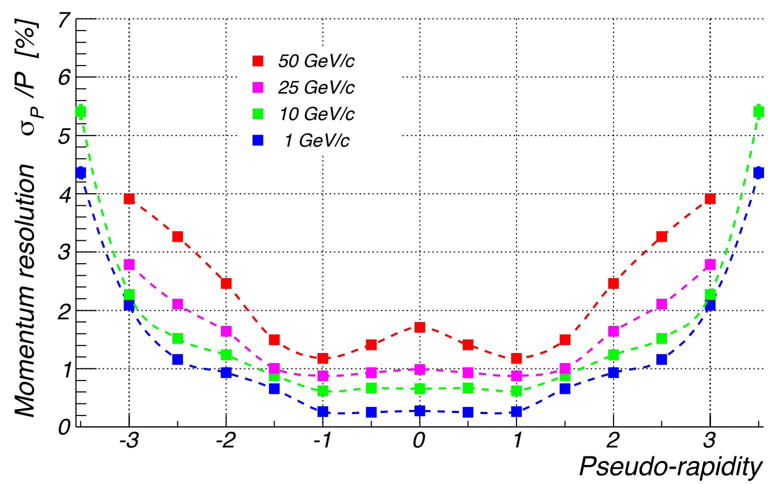
$\rightarrow$ H1 : $0.6\% * P_t + 1.5\%$

$\rightarrow$ ZEUS : $0.5\% * P_t + 1.5\%$

Radiation length scan



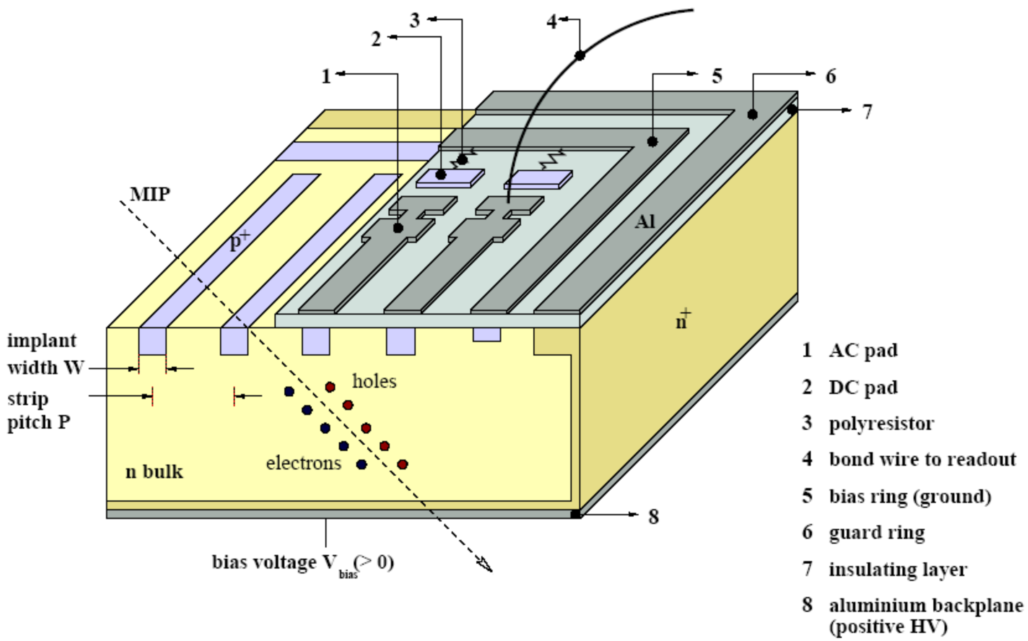
Momentum resolution

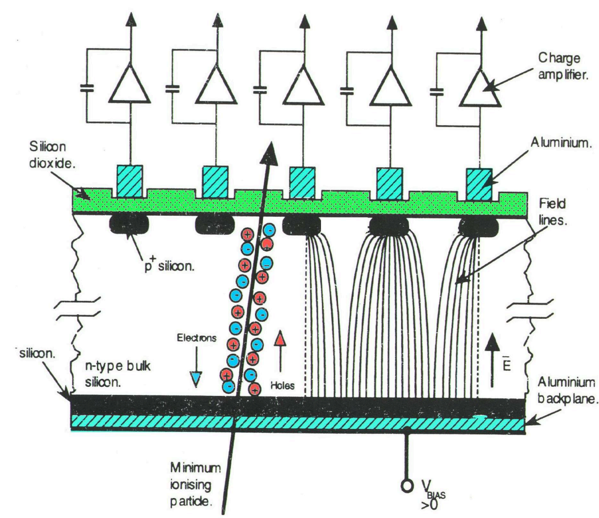


"Traditional" Si detectors (here: CMS strips)

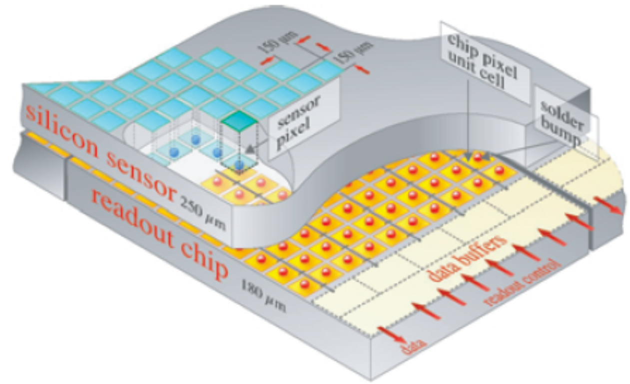
- Planar sensor from a high purity silicon wafer (here n-type).
- Segmented into strips by implants forming pn junctions.
- Strip pitch 20 to 200 μm, high precision photolithography.
- Bulk is fully depleted by a reverse bias voltage (25-500V).
- Ionizing particle creates electron-hole pairs (25k in 300 μm; 3.6eV/pair).
- Electrons and holes are separated by the electric field and collected on the implanted strips

- High spatial resolution (dozens of microns, pitch-dependent)
- Fast (~10ns collection time)

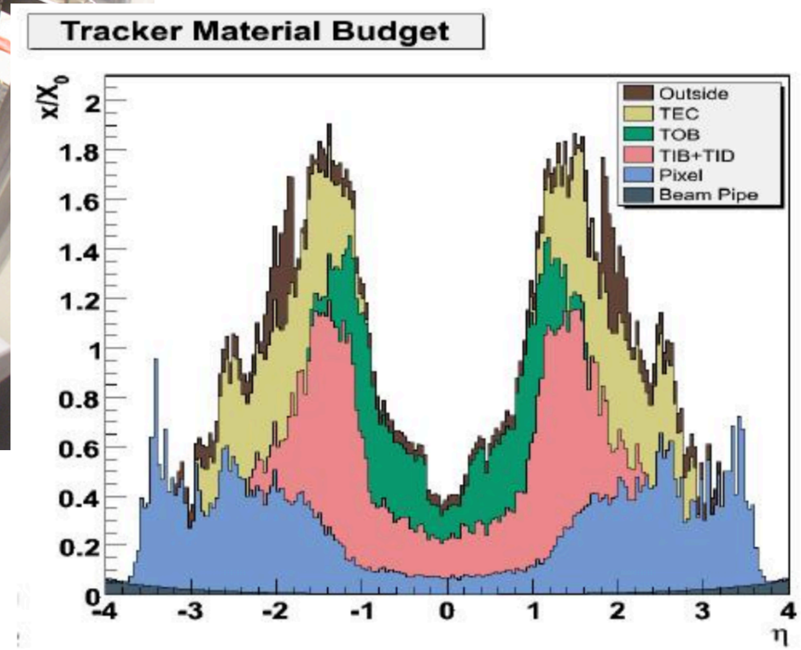




"Traditional" Si detectors (CMS)



Bump-bonding to a (separate from sensor) readout chip …

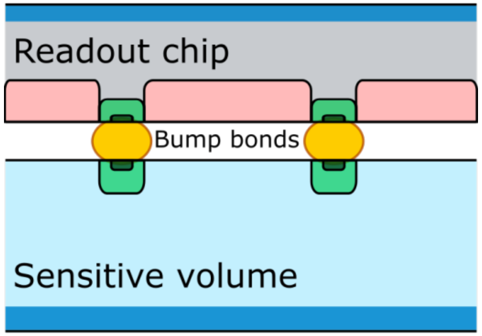


Impressive system: 10^7 channels; 200 m^2!

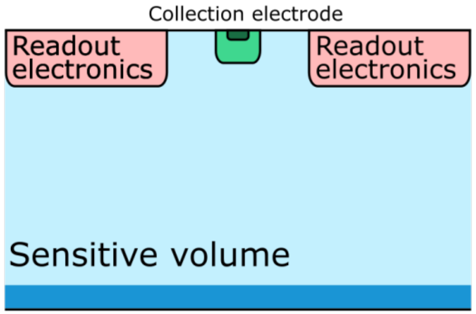
- … this blows up the material budget (no good for EIC)!

Monolithic active pixel sensors

- Hybrids
  Sensitive volume and readout electronics on separate chips
  Most commonly used in silicon vertex trackers
  Radiation tolerant and fast

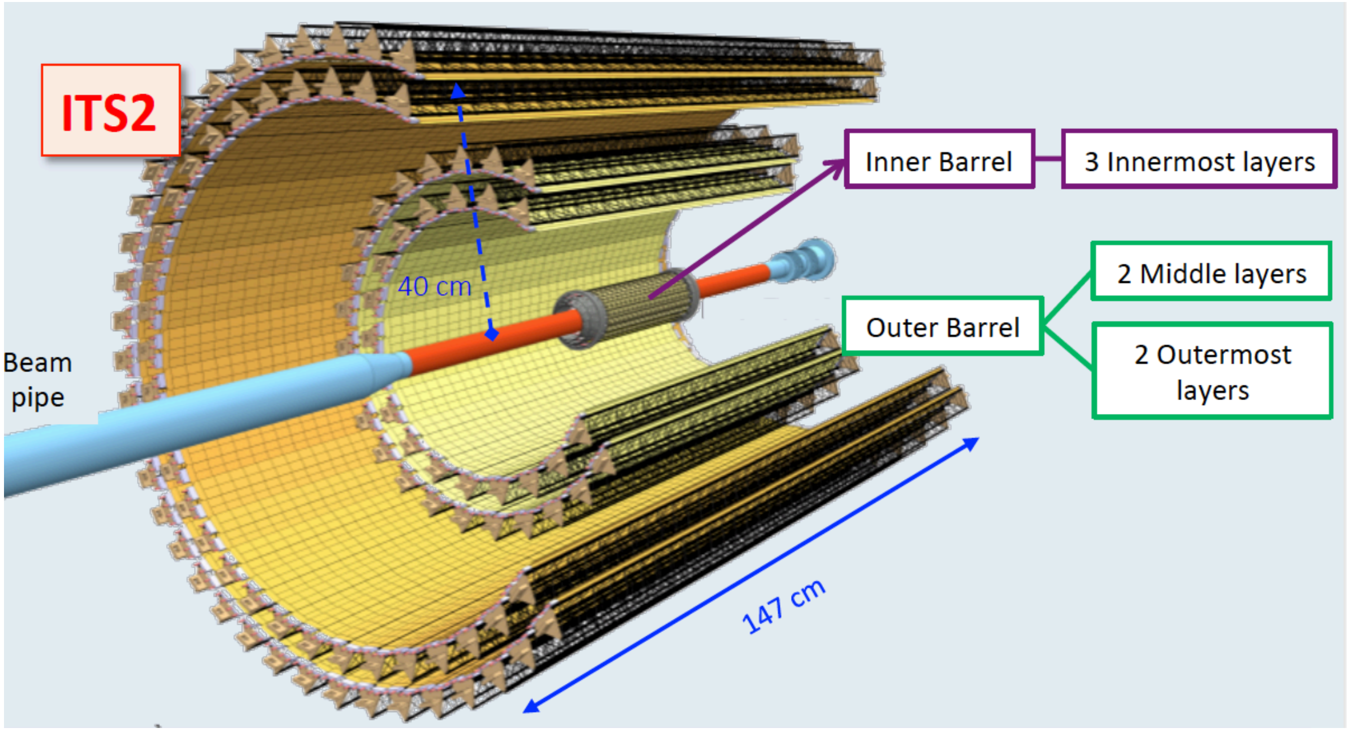


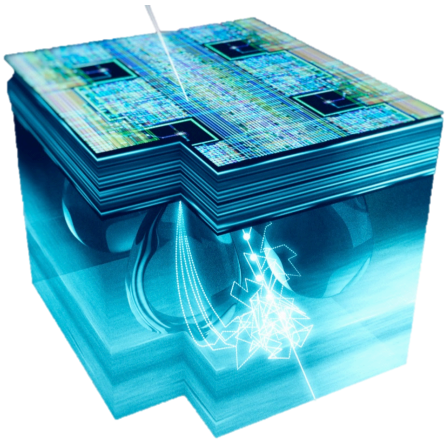
- Monolithic Active Pixel Sensors (MAPS)
  Sensitive volume and readout electronics on same chip
  Made using commercial CMOS technology
  Thin and fine granularity
  Slow (charge collection partly via diffusion)



Monolithic active pixel sensors (ALICE)

Upgraded ALICE Inner Tracker System (ITS2)



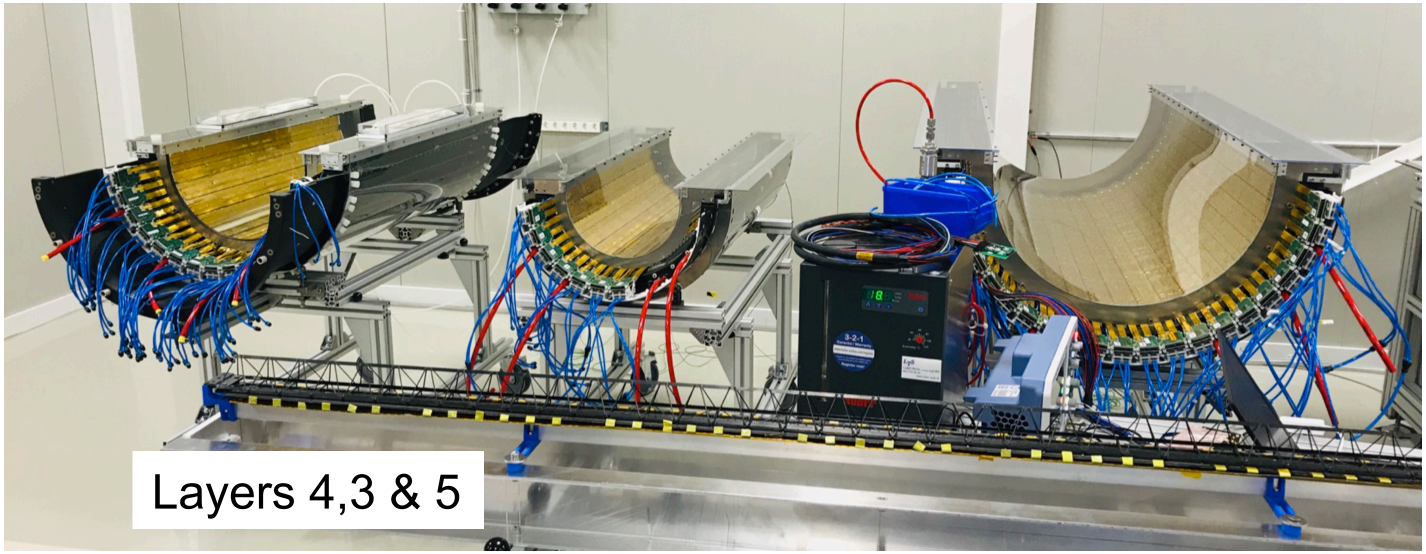


artistic view of charge collection process

- Based on novel MAPS ALPIDE (vs ITS1)
- 10 m^2 active silicon area, 12.5 G-pixels
- Smaller pixels: ~5 μm in rφ and z directions (vs 12 μm and 100 μm)
- Power density < 40mW / cm2
- Less material: ~0.3% X0 for Inner Barrel (vs 1.1% X0)
- Faster readout: 100 kHz Pb-Pb (vs 1 kHz)

Monolithic active pixel sensors (ALICE)

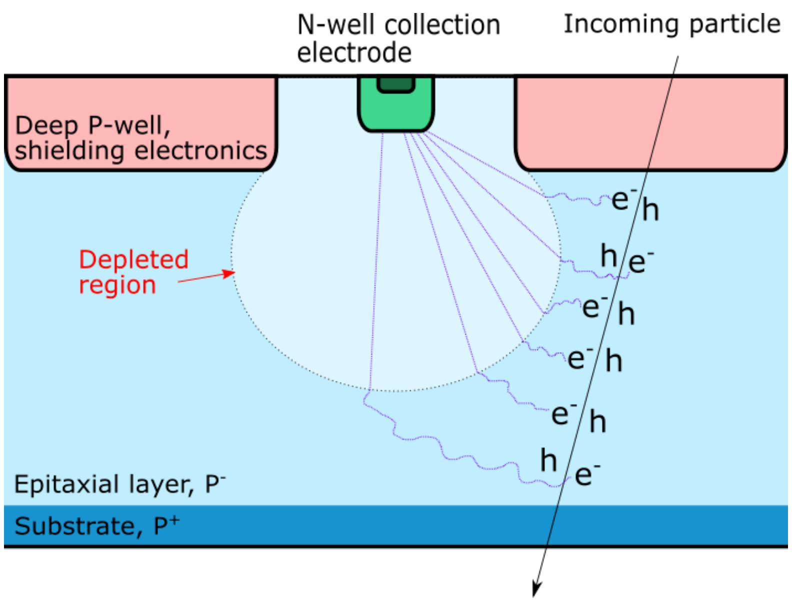
Upgraded ALICE Inner Tracker System (ITS2)



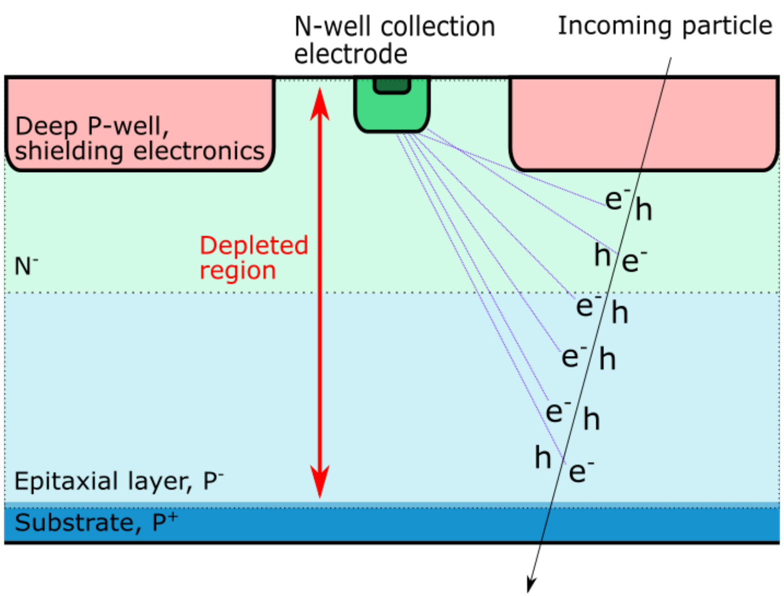
Depleted monolithic active pixel sensors

- Depleted Monolithic Active Pixel Sensors (DMAPS)
  Utilizing high voltage/high resistivity CMOS technology
  Depleted volume intended to be as large as possible

Depletion gives **faster** (drift mode) and **more uniform** charge collection compared to standard MAPS



Standard process (MAPS)

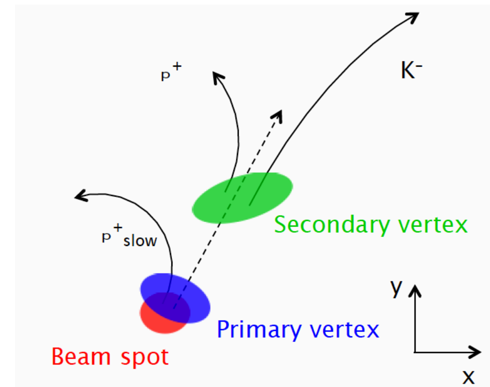


Modified process (DMAPS)

Why small pixels are required?

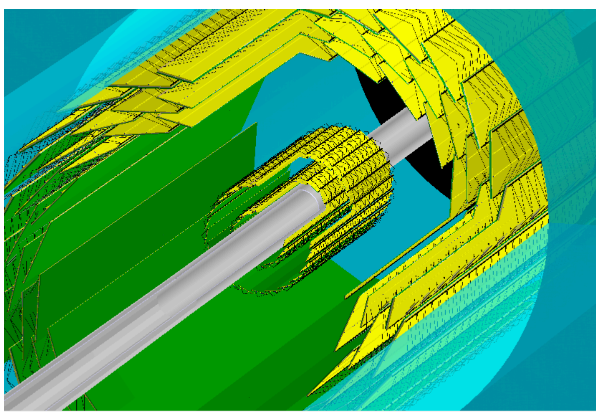
Open charm reconstruction

Particle	Decay	Branching	cτ [μm]
D^0	$K^-\pi^+$	3.9%	123
D^+	$K^-\pi^+\pi^+$	9.5%	311
D^{*+}	$D^0\pi^+_{slow}$	67.7%	

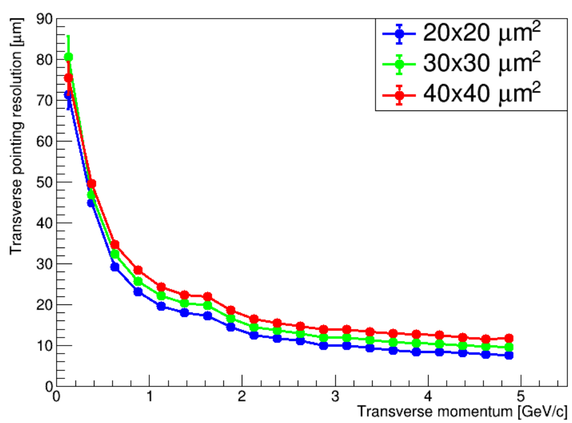


Signature: displaced Kπ vertex

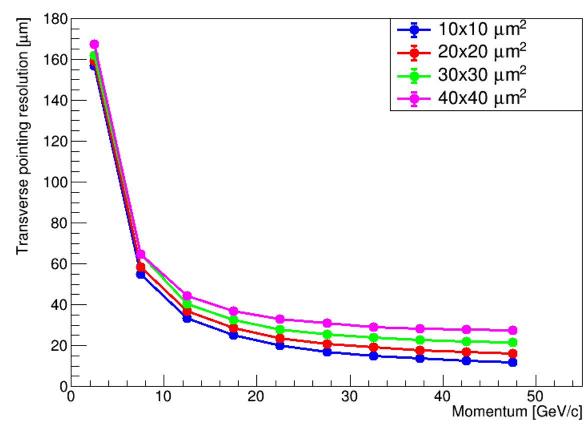
Pointing resolution plots



Simulated vertex tracker



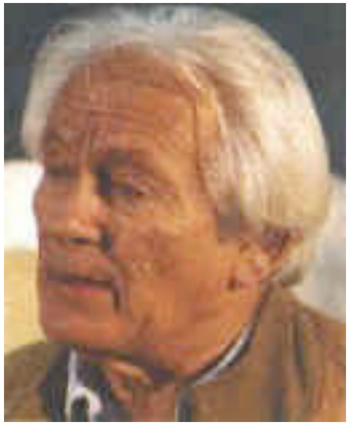
|η| < 0.5 (barrel region)



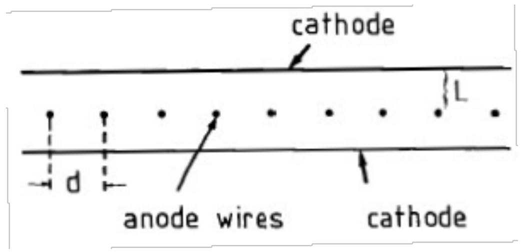
η = 3 (forward region)

- Smaller pixels provide better pointing resolution …

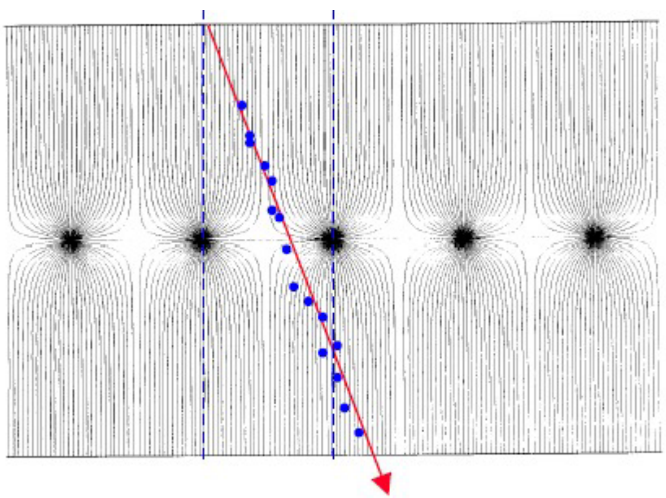
Central tracker: Drift Chamber

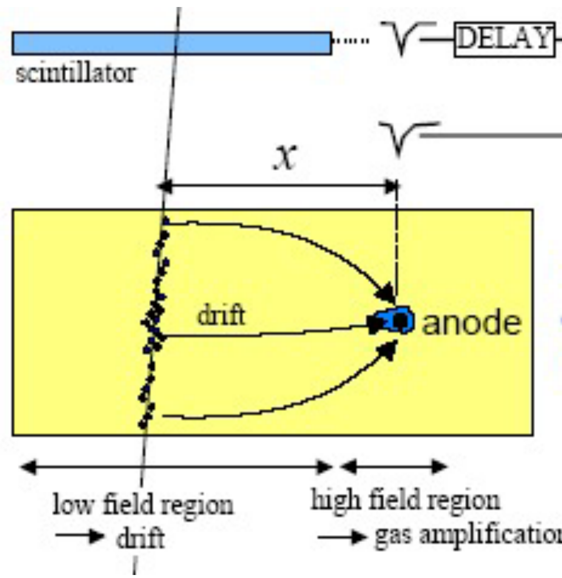


Multi Wire Proportional Chamber (MWPC)
G.Charpak 1968, Nobel prize 1992



Typical parameters: L=5~8 mm, d=2mm, anode wire diameter =20 μm.





Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t)dt$$

- MWPC: address of fired wire(s) give one dimensional information and $\sigma_x \approx d/\sqrt{12}$
- Drift chamber: use drift length time information, typical resolution ~200 μm
- Resolution limits: drift and diffusion effects

Central tracker: Drift Chamber (issues)

Remember, error of momentum measurement: $$\frac{\sigma(p_T)}{p_T} \propto \frac{\sigma(x) \cdot p_T}{B \cdot L^2}$$

⇒ L has to be large ⇒ detector has to be wide (small Rin, large Rout)
Also: want large η coverage ⇒ z dimension has to be large ⇒ detector has to be long

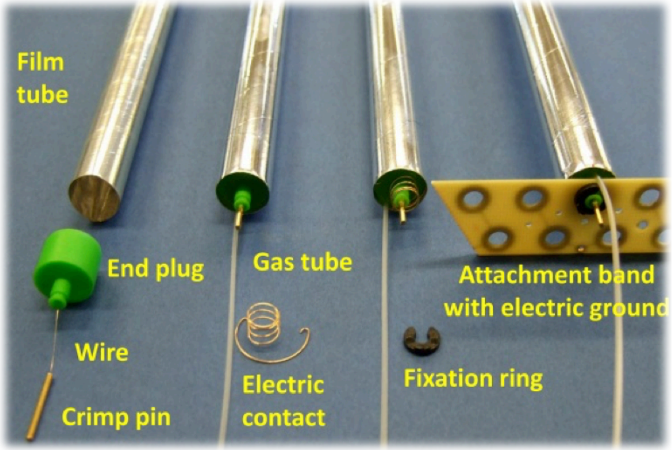
-> a drift chamber with several thousand long wires
-> problems with both construction and maintenance

Solution#1: encapsulate each anode wire in a separate cylindrical volume ⇒ straw tracker

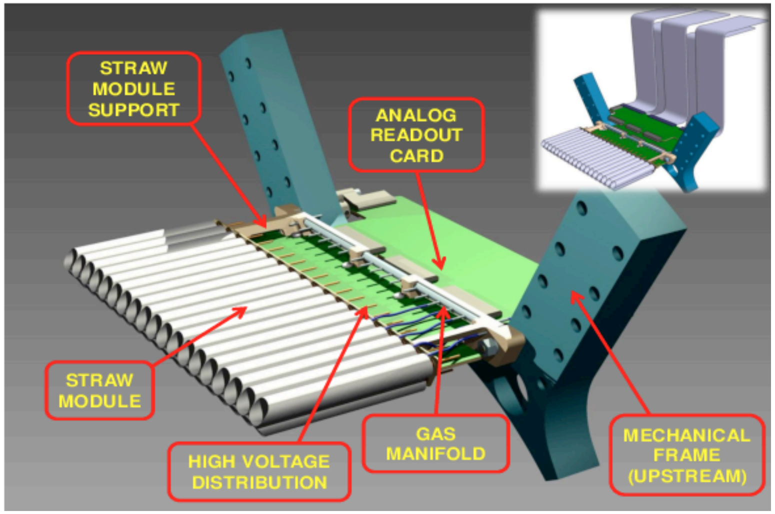
Solution#2: let the electrons drift over long distances
⇒ TPC: essentially a huge gas filled box

Central tracker: Straw Tubes (PANDA)

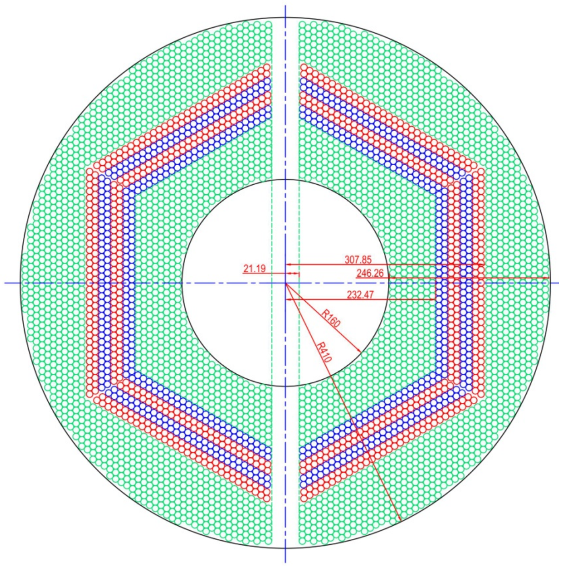
- 4636 straw tubes in 2 separated semi-barrels
- 23-27 radial layers in 6 hexagonal sectors
  - 15-19 axial layers (green) in beam direction
  - 4 stereo double-layers: ±3° skew angle (blue/red)
- Volume: R_{in} / R_{outr}= 150 / 418 mm, L~ 1650 mm
  - Inner / outer protection skins (~ 1mm Rohacell/CF)
- Ar/CO_2 (10%), 2 bar, ~ 200ns drift time (2 T field)

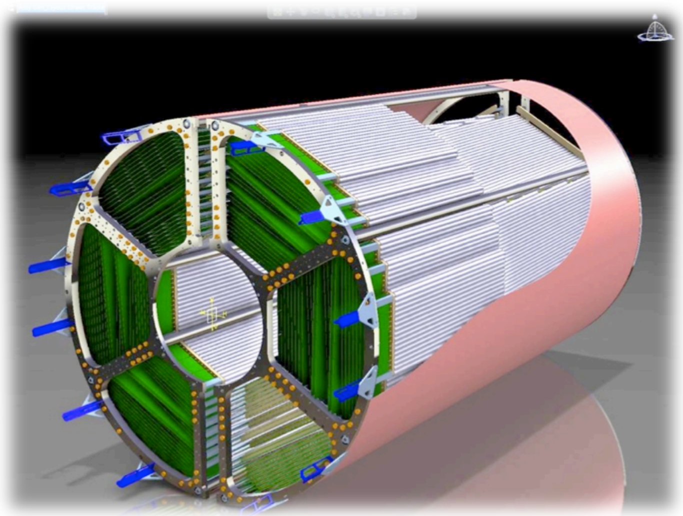


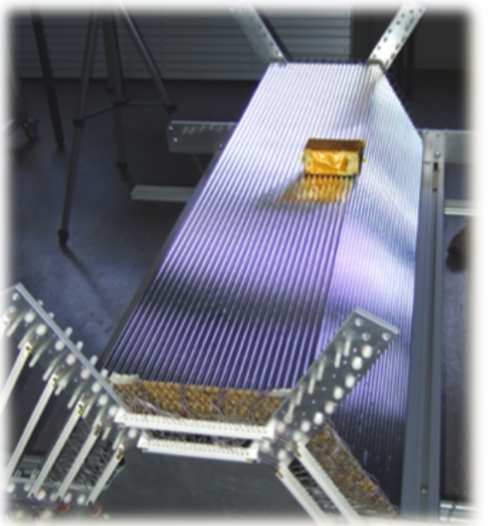
- Time & amplitude readout
  - $\sigma_{r\varphi}$ ~ 150 µm, σ_z ~ 2-3 mm (isochrone)
  - σ(dE/dx) < 10% for PID (p/K/π < 1 GeV/c)
- σ_p /p ~ 1-2% at B=2 Tesla (STT + MVD)
- X/X_0 ~ 1.25% (~ $^2/_3$ tube wall + $^1/_3$ gas)



Central tracker: Straw Tubes (PANDA)



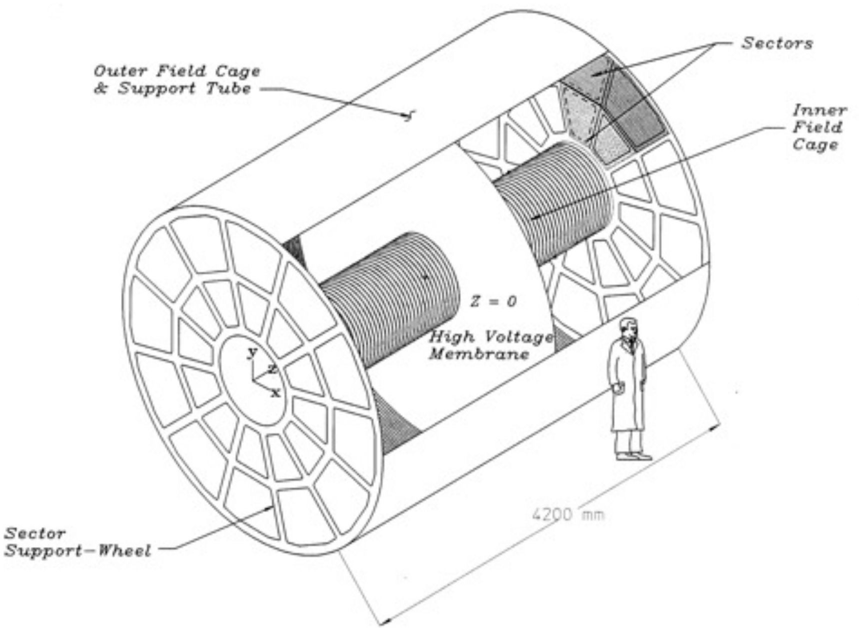


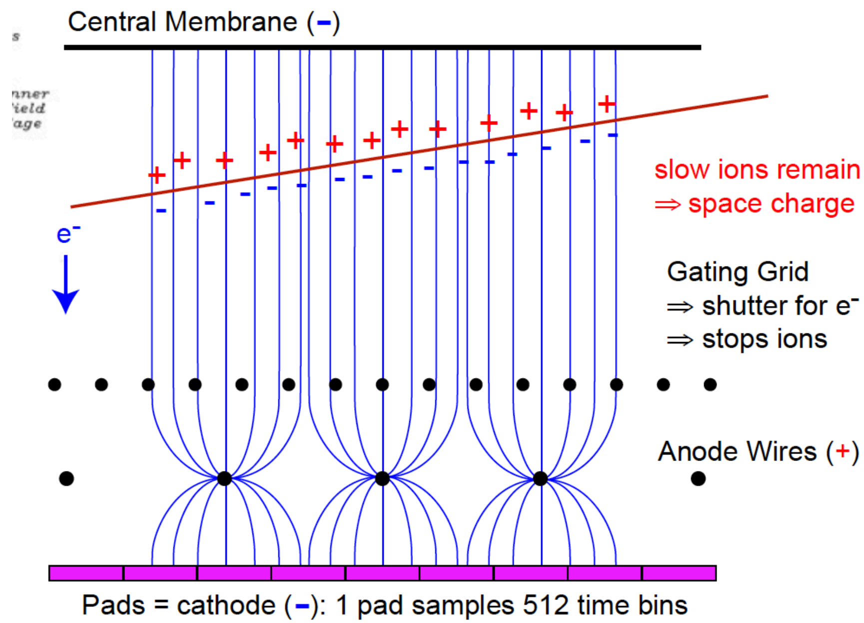


- Material budget at lowest limit (2.5 g per assembled straw)
- thinnest Al-mylar film, d=27μm, ∅=10mm, L=1400mm

- thin wall endcaps, wire fixation (crimp pins), radiation-hard
- self-supporting modules of pressurized straws (Δp=1bar)
  - close-packed (~20 μm gaps) and glued to planar multi-layers
  - replacement of single straws in module possible (glue dots)
- strong stretching (230kg wires, 3.2tons tubes)*, but no reinforcement needed

Central tracker: Time Projection Chamber





STAR TPC

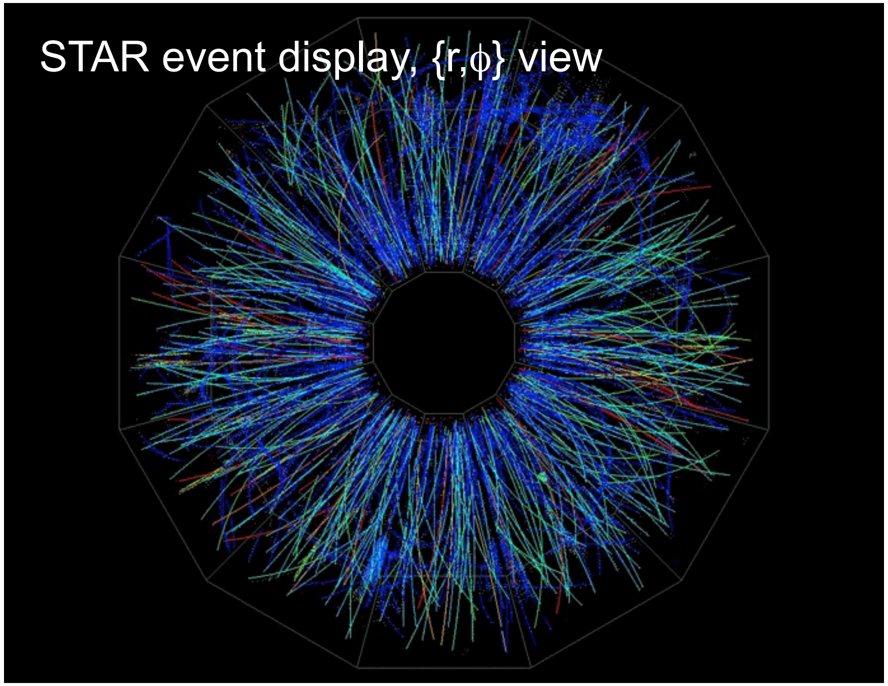
- 140,000 electronics channels (pads)
- 512 time bins
- 140,000 x 512 = 72 million 3D "pixels"

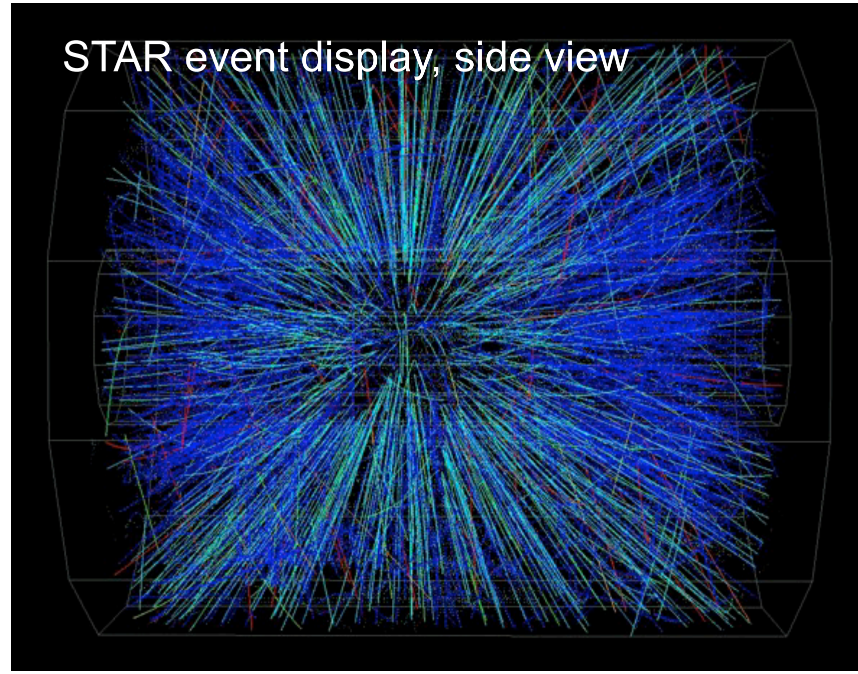
- Inner sectors were instrumented in 2019

Gating Grid concept:

- Designed to reduce Ion Back Flow (IBF) from the amplification stage, and respective space charge of positive ions in the TPC volume (gate open by trigger only for the time needed to collect all electrons – several μs only)

STAR TPC, legacy pictures





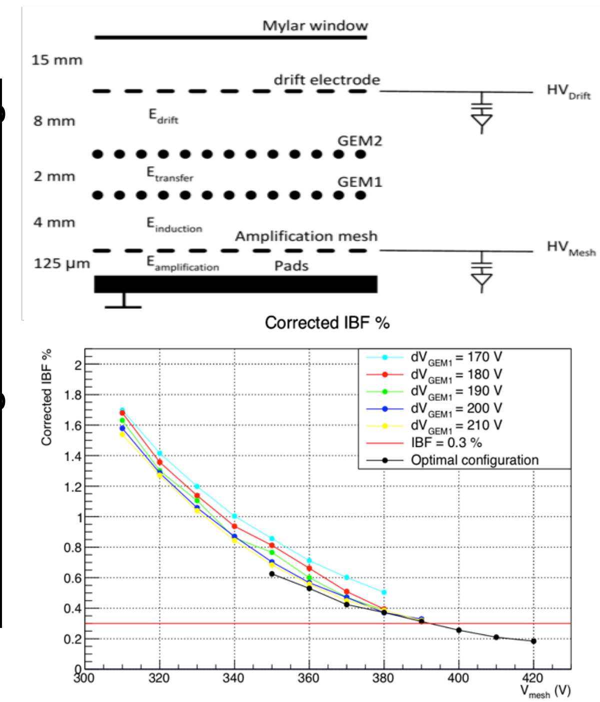
“New generation” TPCs: attack IBF problem

MWPC-based TPC drawbacks

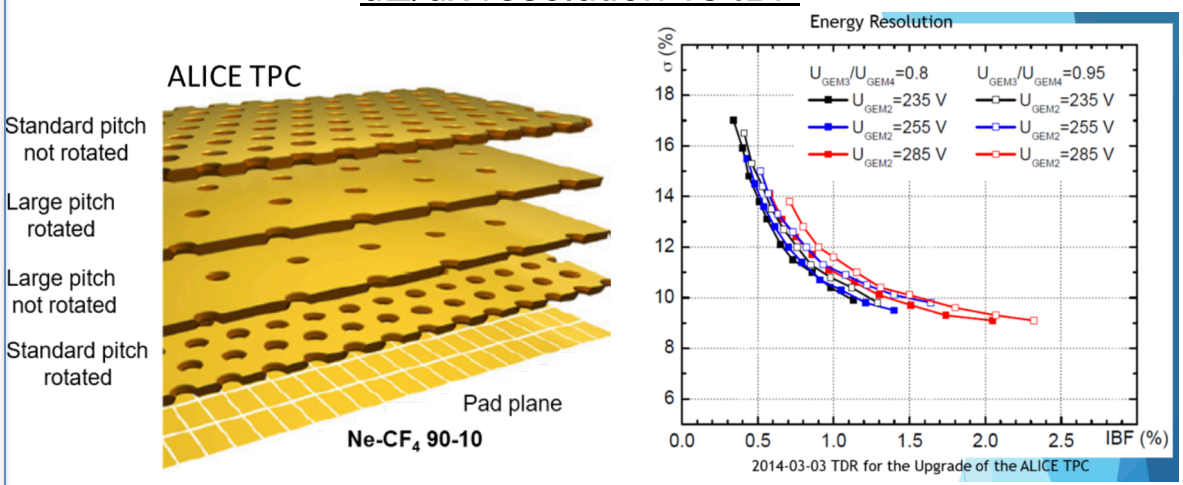
- No other means to suppress IBF other than gating grid
- This in particular excludes TPC usage in a continuous readout mode (and in a high luminosity environment)

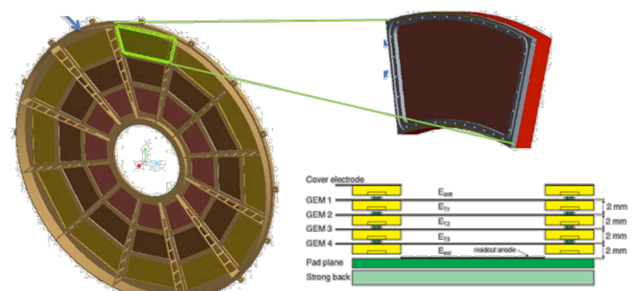
Solution: replace MWPC amplification stage by either quadruple GEM (ALICE upgrade & sPHENIX TPC) or a GEM+μMegas hybrid; carefully tune gas mixture, GEM foil configuration & HV

IBF vs uMegas mesh voltage



dE/dx resolution vs IBF



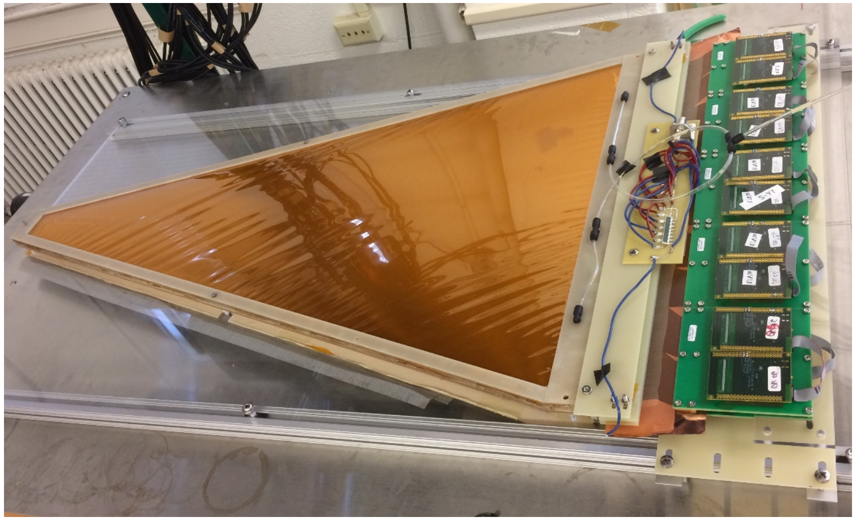


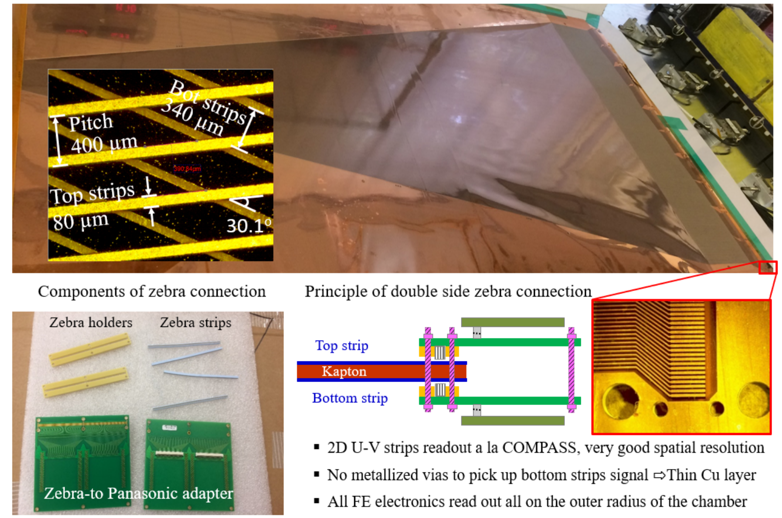
72 modules
2(z), 12(ϕ), 3(r)

Quad-GEM Gain Stage
Operated @ low IBF

sPHENIX TPC: ALICE approach

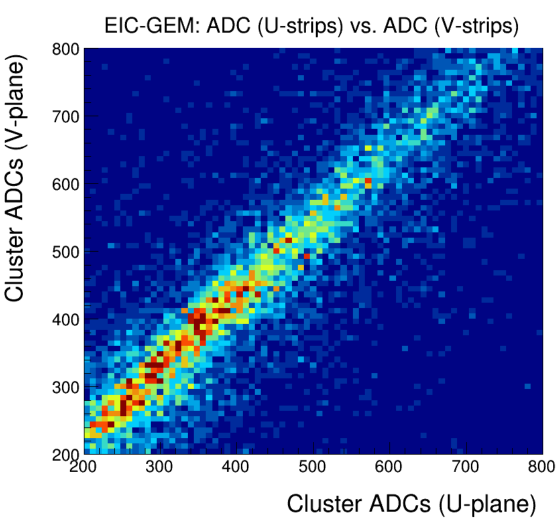
Large (here 2D) planar detectors: GEM





- 2D U-V strips readout a la COMPASS, very good spatial resolution
- No metallized vias to pick up bottom strips signal ⇨Thin Cu layer
- All FE electronics read out all on the outer radius of the chamber

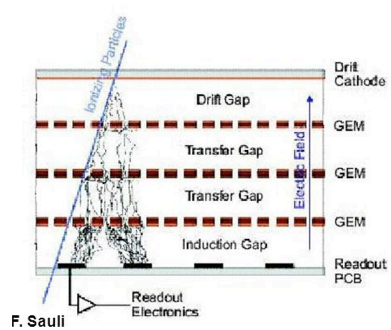
EIC Detector R&D program

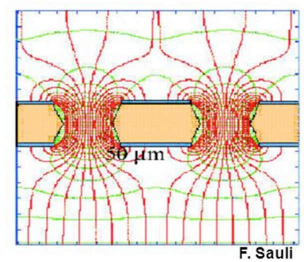


U-V strips charge sharing

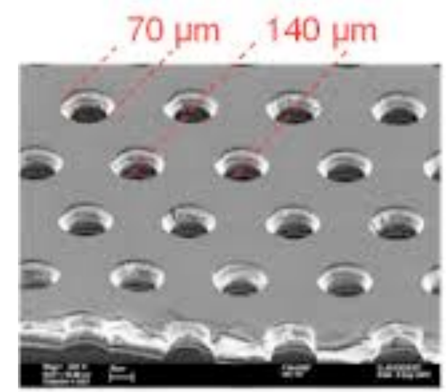
GEM Foils

- Potential Difference across each GEM foil (300 V – 500 V)



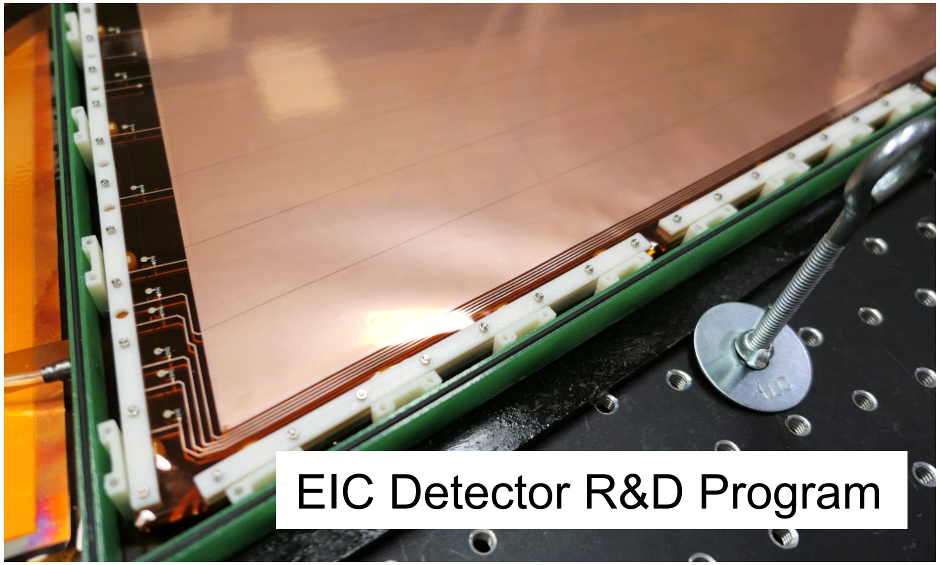


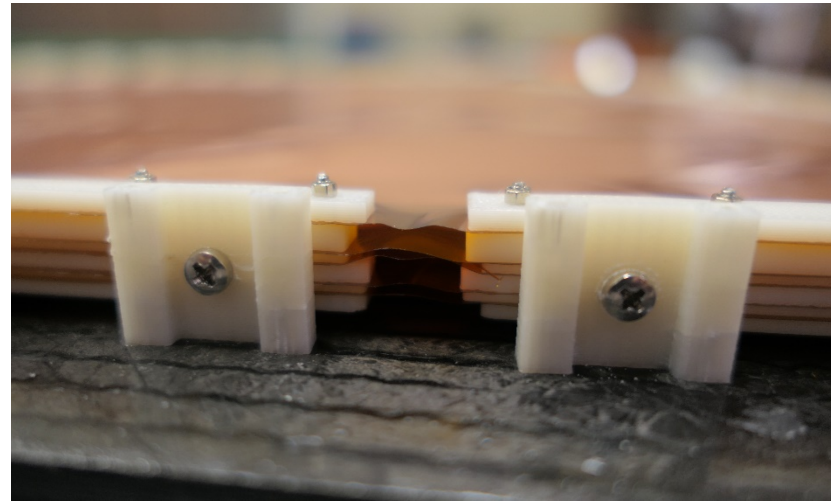
- High energy particles ionize the gas inside the detector which drift to the GEM foil
- Electric field through the holes causes the electrons to cascade

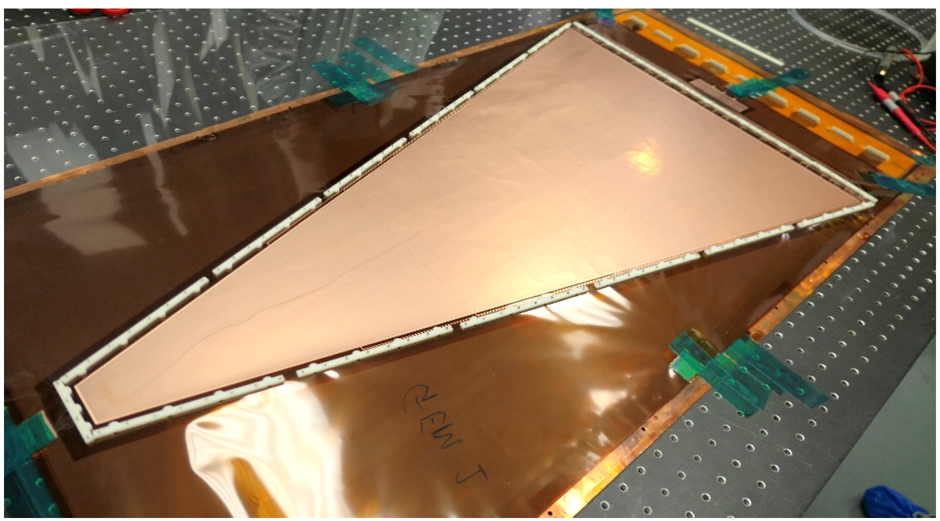


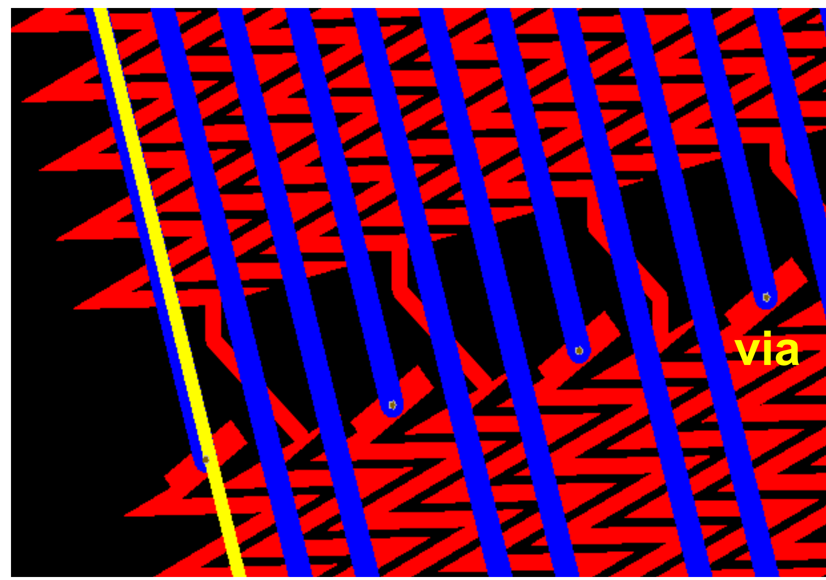
- GEM: Gas Electron Multiplier
- Primary ionization in a short (few mm) drift gap
- Multi-stage (3-5 50µm thick foils) amplification in a high field
- Direct coupling to readout strips (or pads)

Large (1D) planar detectors: GEM





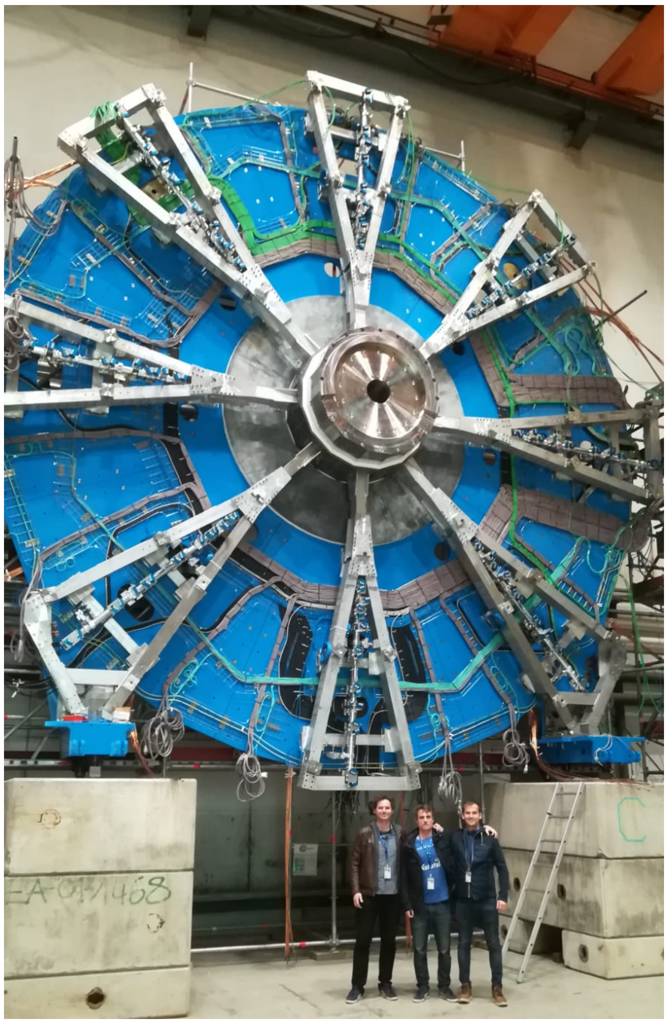


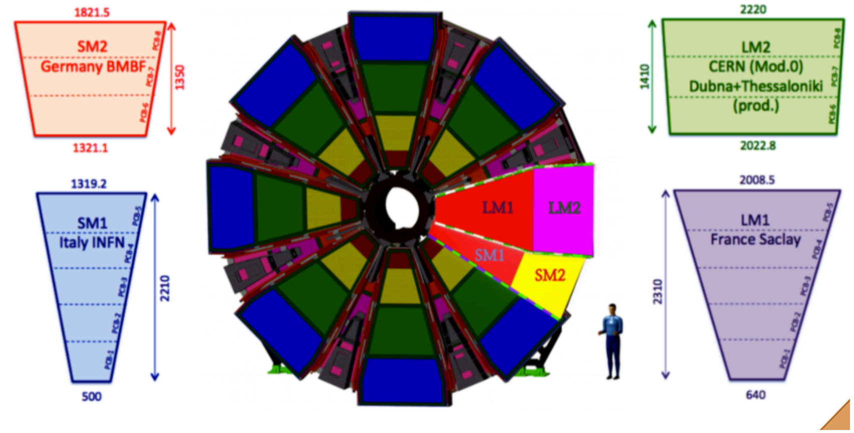


- Low mass, stretched carbon fiber frames
- High spatial resolution & low channel count zigzag charge sharing readout

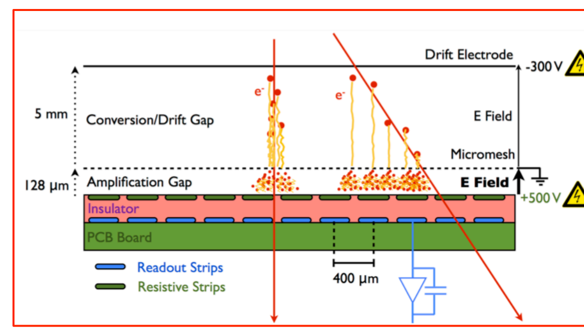
Large planar detectors: μMegas

ATLAS New Small Wheel





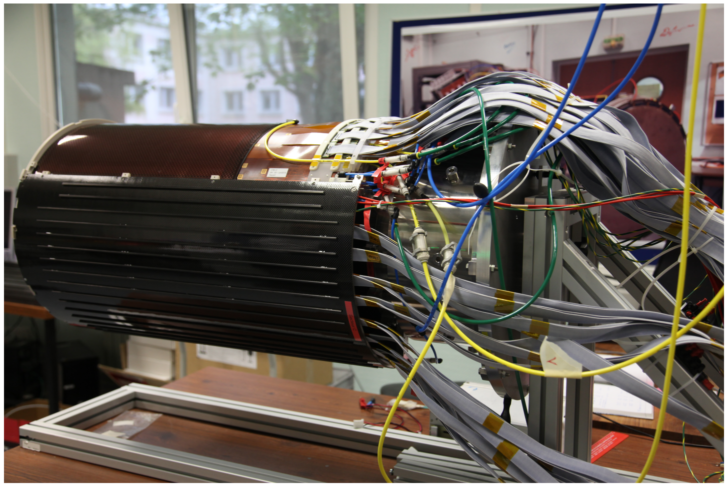
- 4 Types of detectors => 4 constructions sites
- Technology: 1200 m^2 of resistive Micromegas
- 2M channels

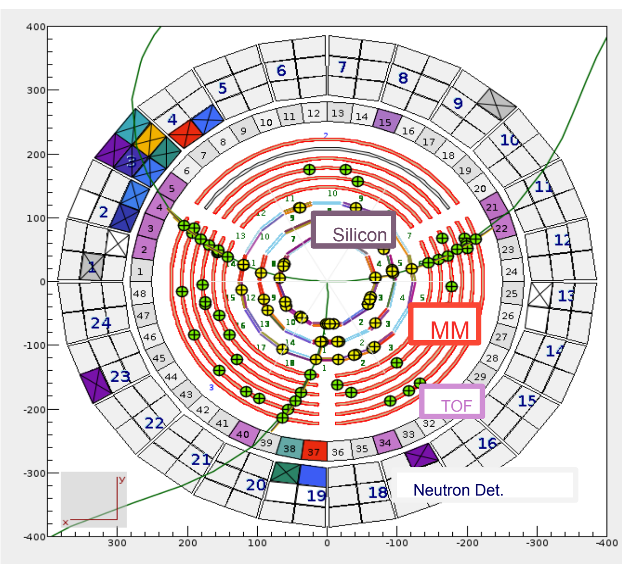


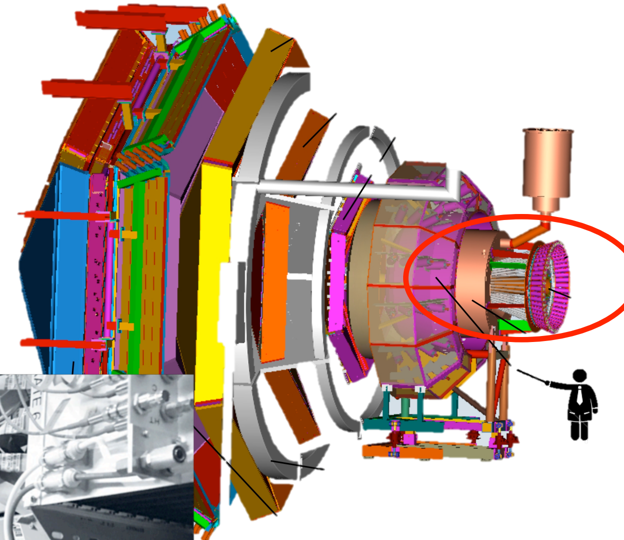
- Primary ionization in a short (few mm) drift gap
- Single-stage amplification in a high field 128μm gap
- Capacitive coupling to readout strips through the resistive layer

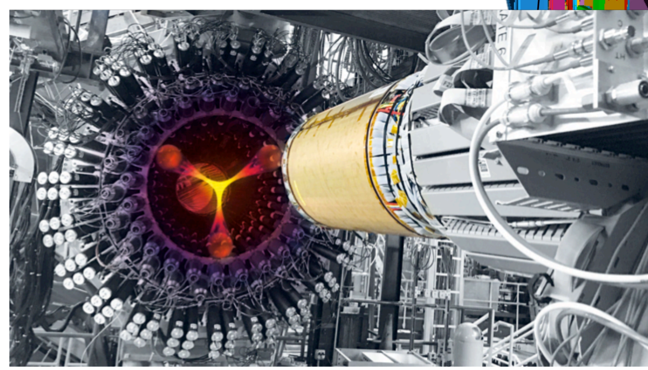
Medium-size cylindrical tracker: μMegas

CLAS12 vertex tracker upgrade







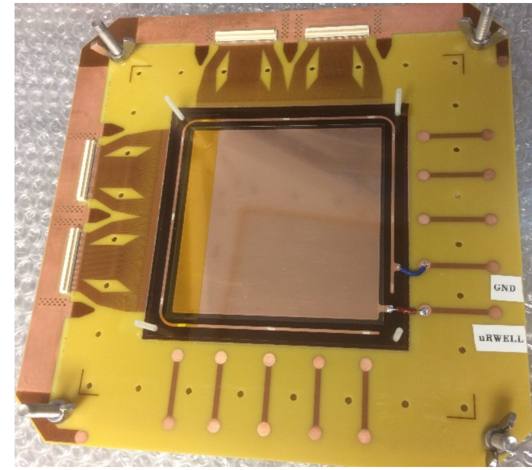


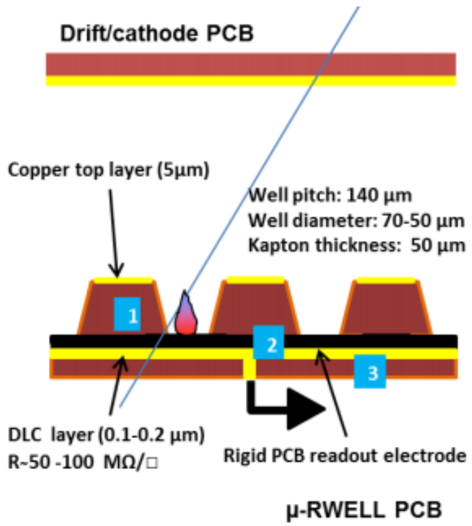
- Same technology: 4 m² of μMegas detectors
- Light-Weight Detectors (~0.5% of X_0 per layer)
- Limited space (~10 cm for 6 layers)
- High magnetic field (5T)
- Variable geometry (6 Layers with different R)
- High enough spatial resolution (~100μm)

μRWELL trackers

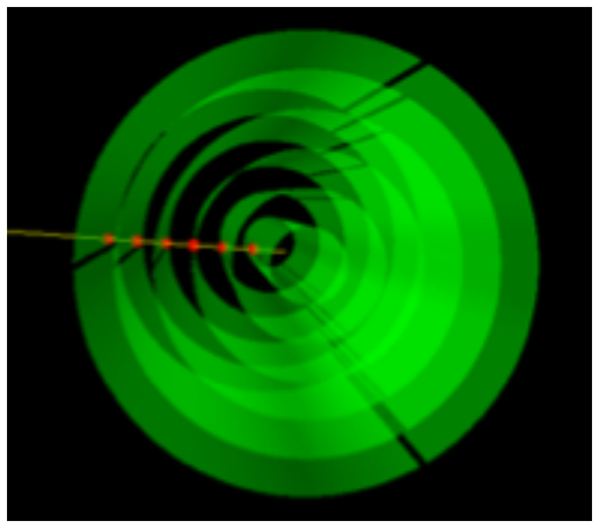
- Modern technology, competing with GEM & μMegas:
  - Simple, low mass, no stretching, low cost
  - 1D & 2D configurations, flat & cylindrical

μRWELL with 2D X-Y readout

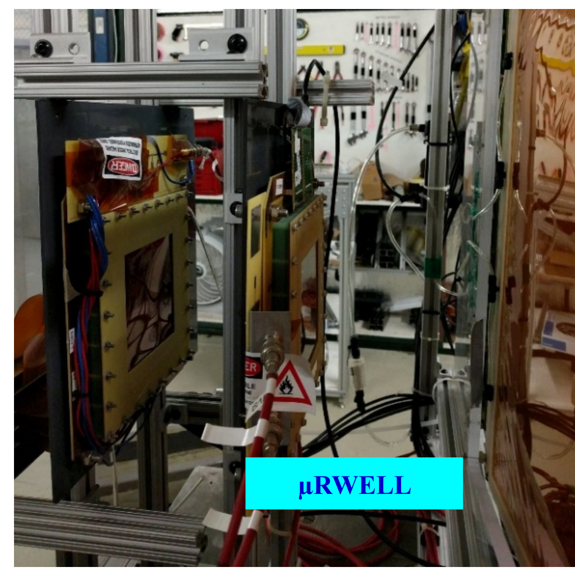




G. Bencivenni et al., 2015_JINST_10_P02008



μRWELL in FNAL Test Beam



- Primary ionization in a short (few mm) drift gap
- Single-stage amplification in a high field 50μm gap (foil)
- Capacitive coupling to readout strips through the resistive layer

End of day one!