EIC Detector Overview

Alexander Kiselev

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Outline

- Introduction
- EIC detector concepts

- Tracking
- Calorimetry
- Particle identification

- Interaction Region
- Backgrounds

EIC experimental program in one slide

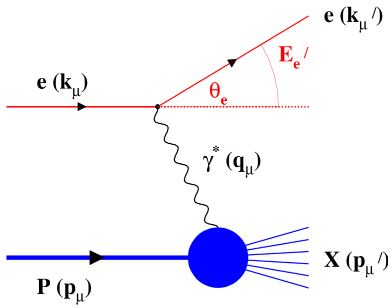
Parton Distributions in nucleons and nuclei

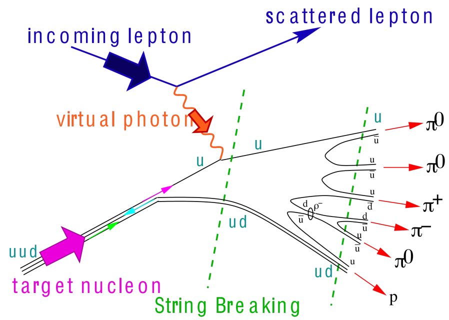
Spin and Flavor structure of nucleons and nuclei

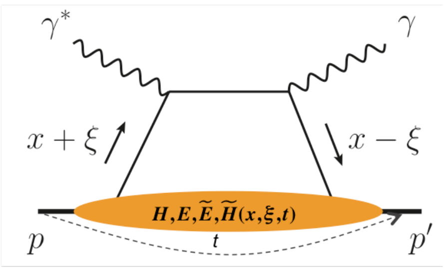
Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging







inclusive DIS

- measure scattered lepton
- two-dimensional binning: $\{x, Q^2\}$

→ reach to lowest x, Q^2 impacts Interaction Region design

~1 fb^{-1}

semi-inclusive DIS

- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: $\{x, Q^2, z, p_T, \Phi\}$

→ hadron identification over entire acceptance is critical

~10 fb^{-1}

exclusive processes

- measure all particles in event
- multi-dimensional binning: $\{x, Q^2, t, \Phi\}$
- proton p_t: 0.2 - 1.3 GeV/c

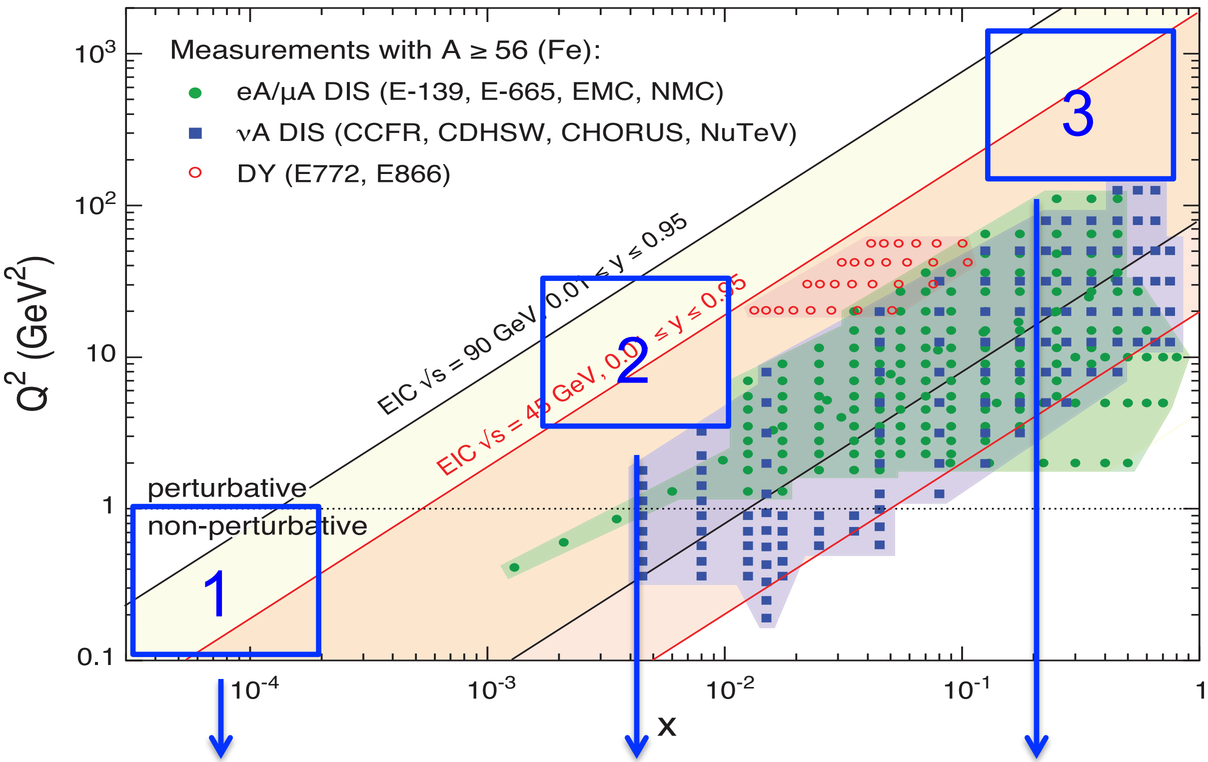
→ cannot be detected in main detector

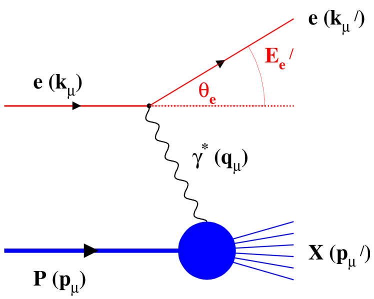
→ strong impact on Interaction Region design

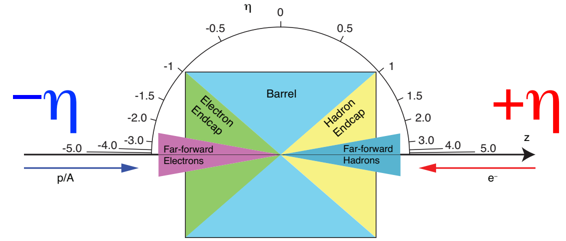
10-100 fb^{-1}

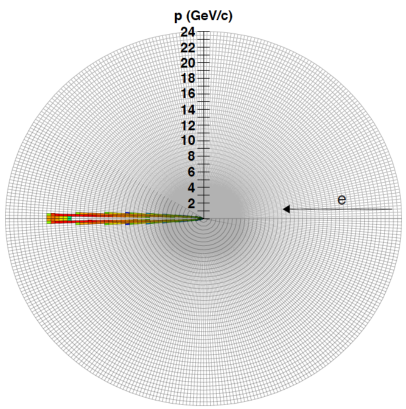
Inclusive DIS

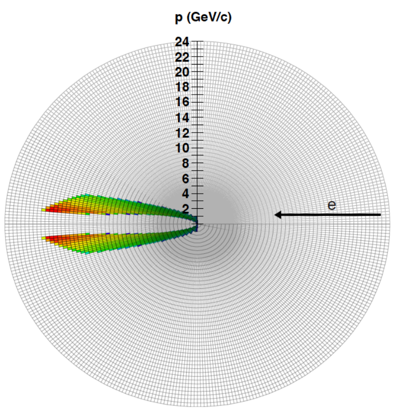
Scattered electron kinematics is very different depending on $\{x,Q^2\}$

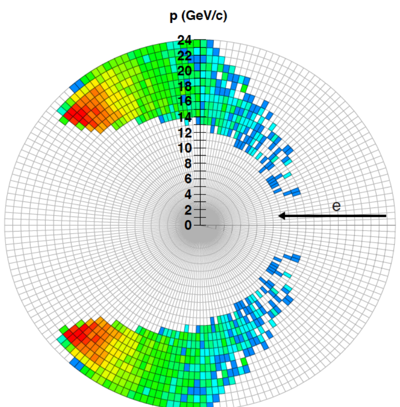










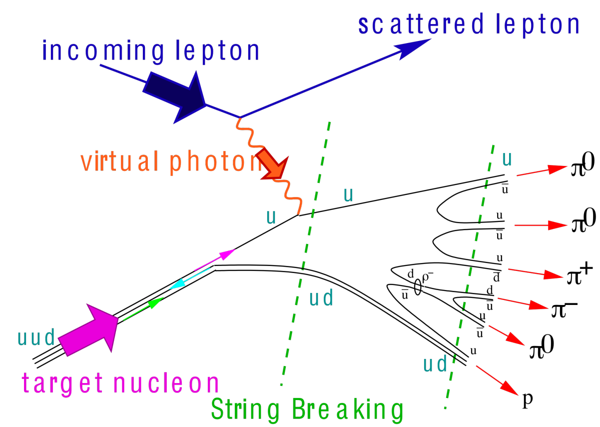


$-4<\eta<4 \sim [2^0 .. 178^0]$

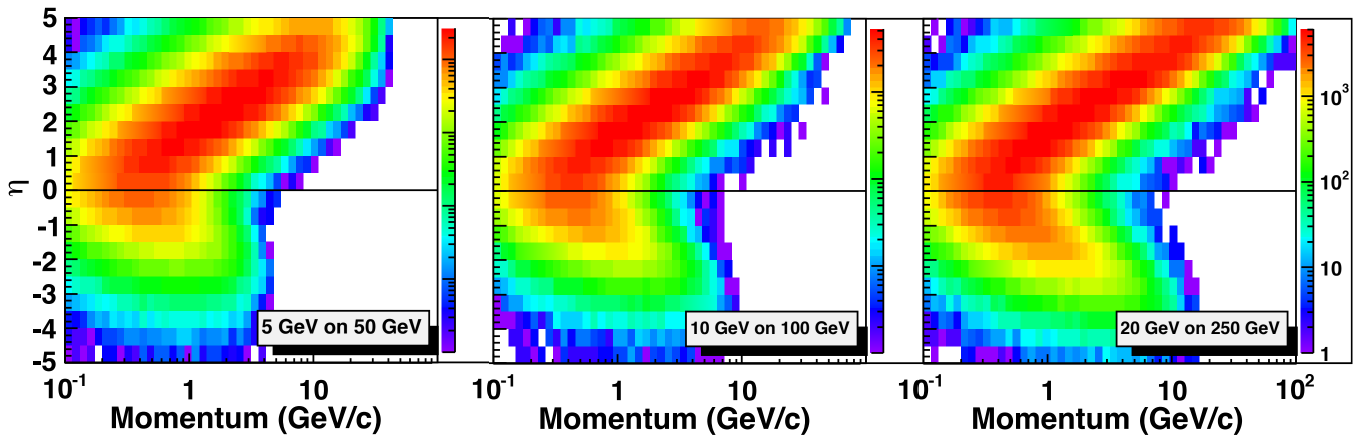
- Need excellent electron ID in a wide range of energies and polar angles
  - → equal rapidity coverage for tracking and e/m calorimeter
  - → low material budget to reduce bremsstrahlung
- Momentum (energy) and angular resolution of scattered electron is critical

Semi-inclusive ep/eA scattering

- $\pi^{\pm}$,$K^{\pm}$,$p^{\pm}$ separation over a wide range $|\eta|$<~3.5
  - → excellent hadron identification
  - → excellent momentum resolution, also at forward rapidities
- need to cover entire kinematic region in p_t & z
- need full Φ-coverage around γ^*
- charm and bottom tagging
  - → excellent vertex resolution



Semi-inclusive hadron kinematics



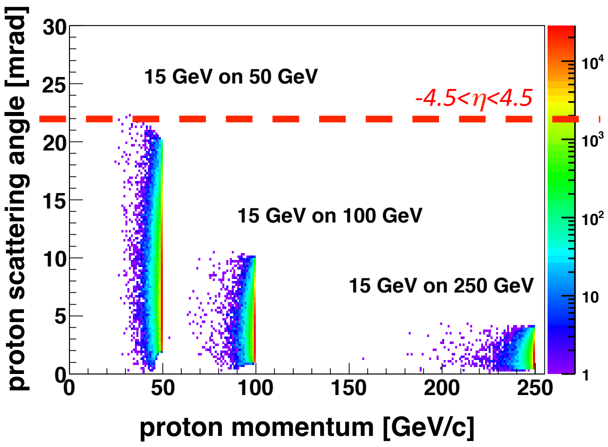
Cuts: Q^2>1 GeV, 0.01<y<0.95, z>0.1

- with increasing $\sqrt{s}$ hadrons are boosted to negative η
- very strong η−momentum correlation

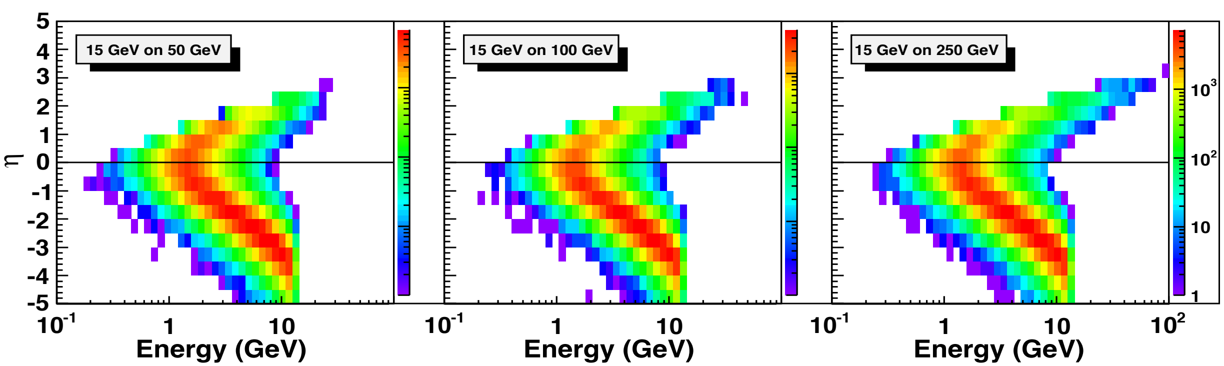
Exclusive reactions in ep/eA

- Exclusivity criteria:
  - eA: large rapidity coverage → rapidity gap events
    - HCal for $1<\eta<4.5$
  - ep: reconstruction of all particles in event
    - wide coverage in t ($=p_t^2$) → Roman pots
- eA: large acceptance for neutrons from nucleus break-up
  - Zero Degree Calorimeter
    - veto nucleus breakup
    - determine impact parameter of collision

scattered protons

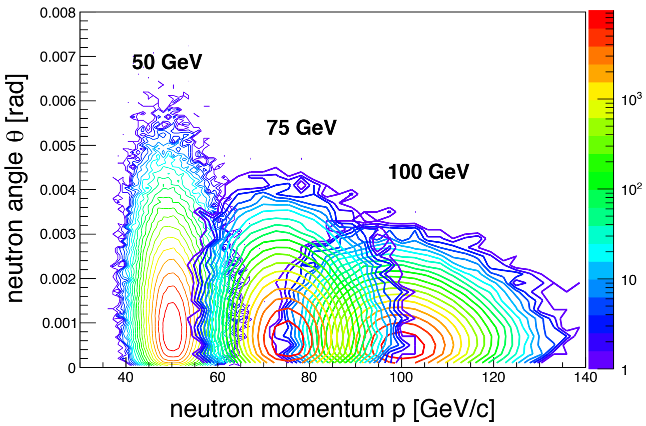


DVCS photon kinematics



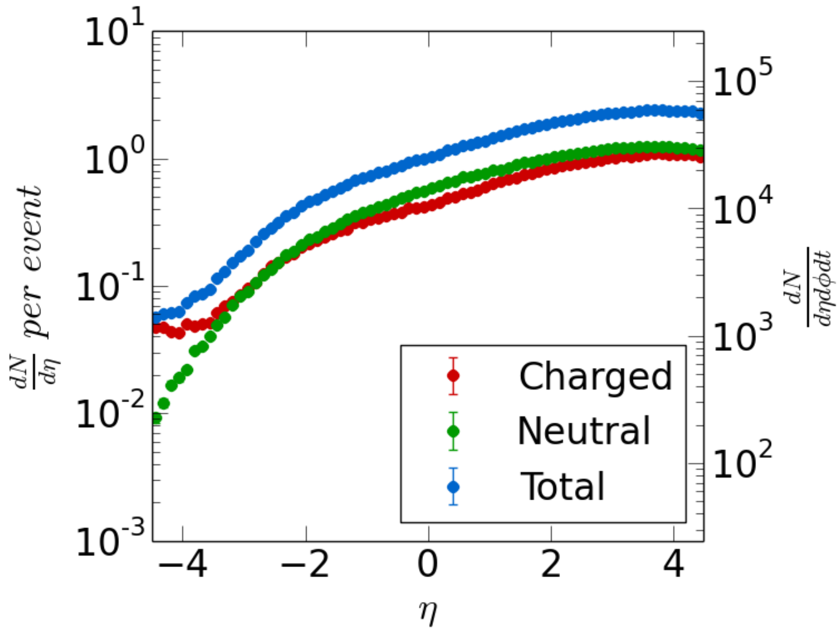
Cuts: $Q^2>1$ GeV, $0.01<y<0.85$

break-up neutrons

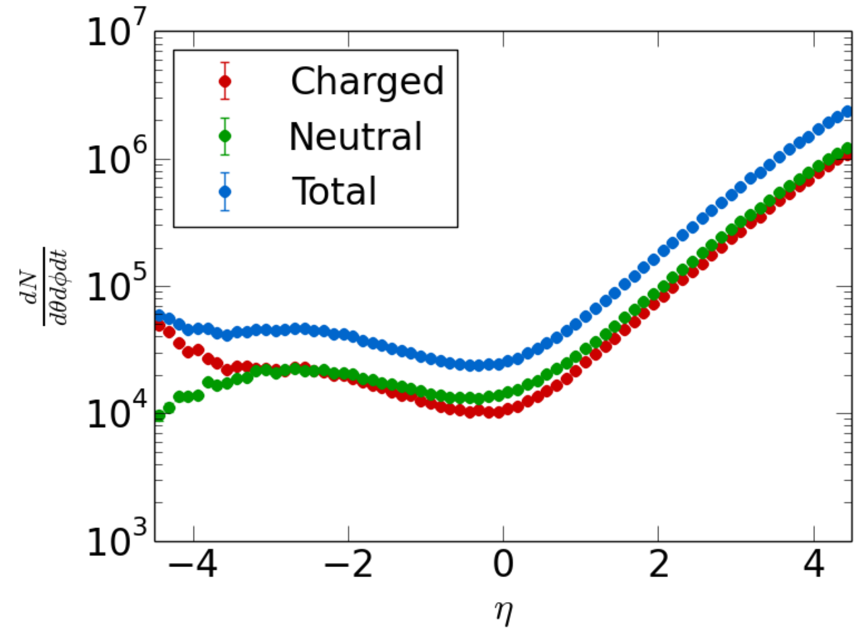


Interaction rate & absolute yields

PYTHIA 20x250 GeV configuration; absolute particle yields for L=10^{33} cm^{-2} s^{-1}



Per unit of {η,ϕ}



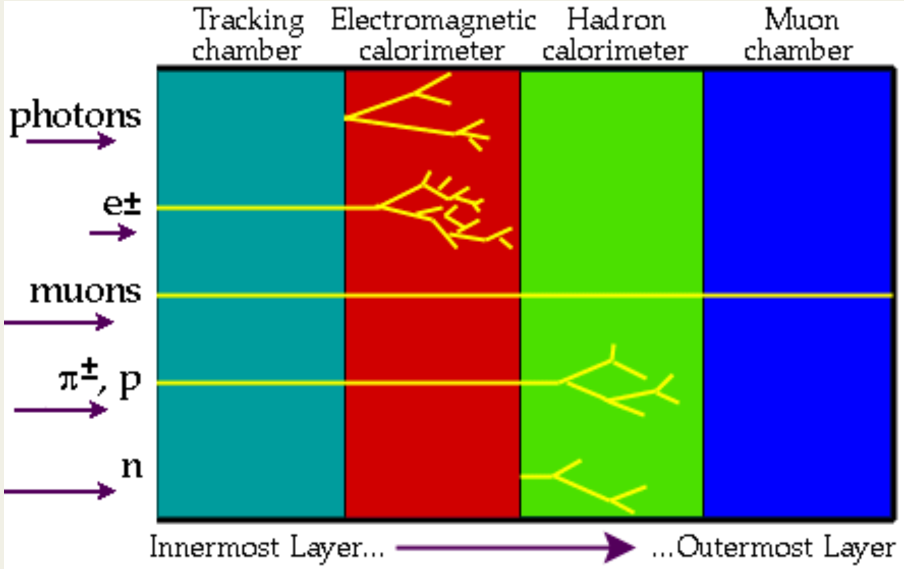
Per unit of {θ,ϕ}

- Interaction rate ~50kHz @ 10^{33} cm^{-2} s^{-1}
- At most few particles per unit of η per event
- Correspondingly low particle fluxes per unit of time

Particle detection in a typical NP/HEP setup

- Long-lived particles: through their interaction with the detector material
  - Tracking ("gentle" measurement)
  - PID detectors
  - Calorimetry (destructive measurement)
- Short-lived particles: 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



- **"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!

EIC Detector Concepts

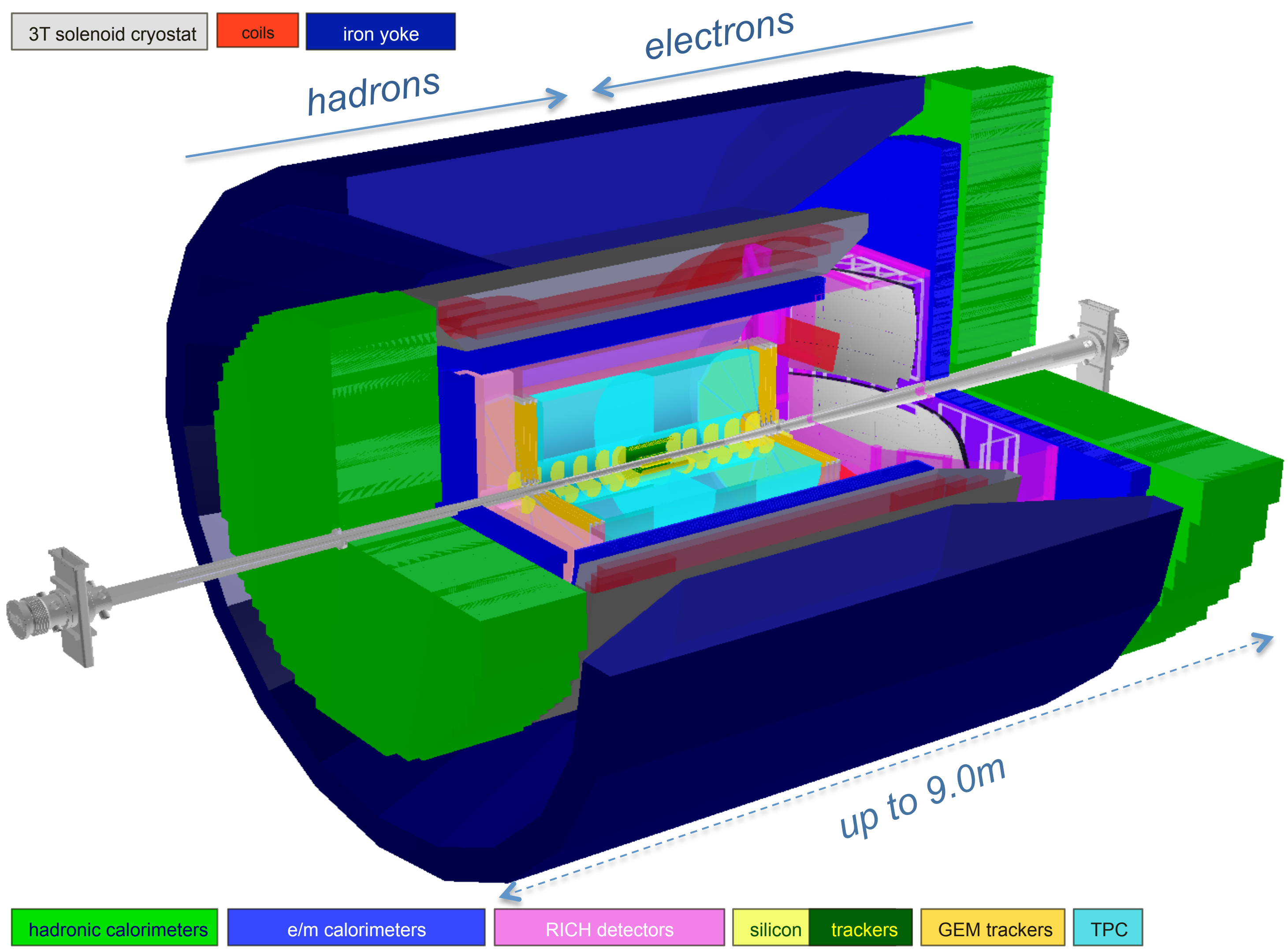
- **Common features:**
  - Compact design, driven by strong beam focusing at the IP
  - (Almost) 4π hermetic acceptance in tracking/calorimetry/PID

  - Vertex + central + forward/backward + far forward tracker layout

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

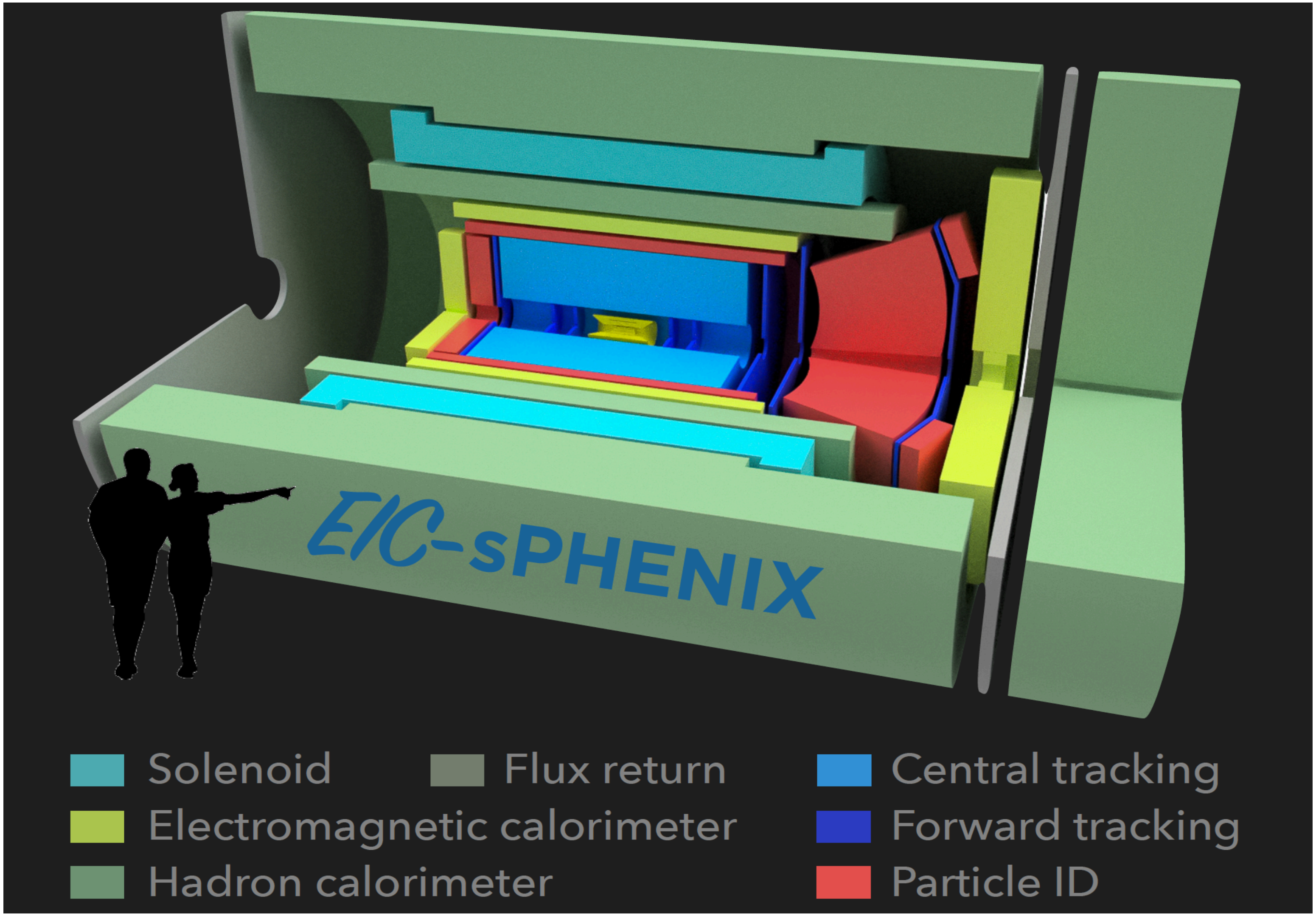
  - Moderate momentum resolution (~1% level)
  - Moderate EmCal and HCal energy resolution

BeAST



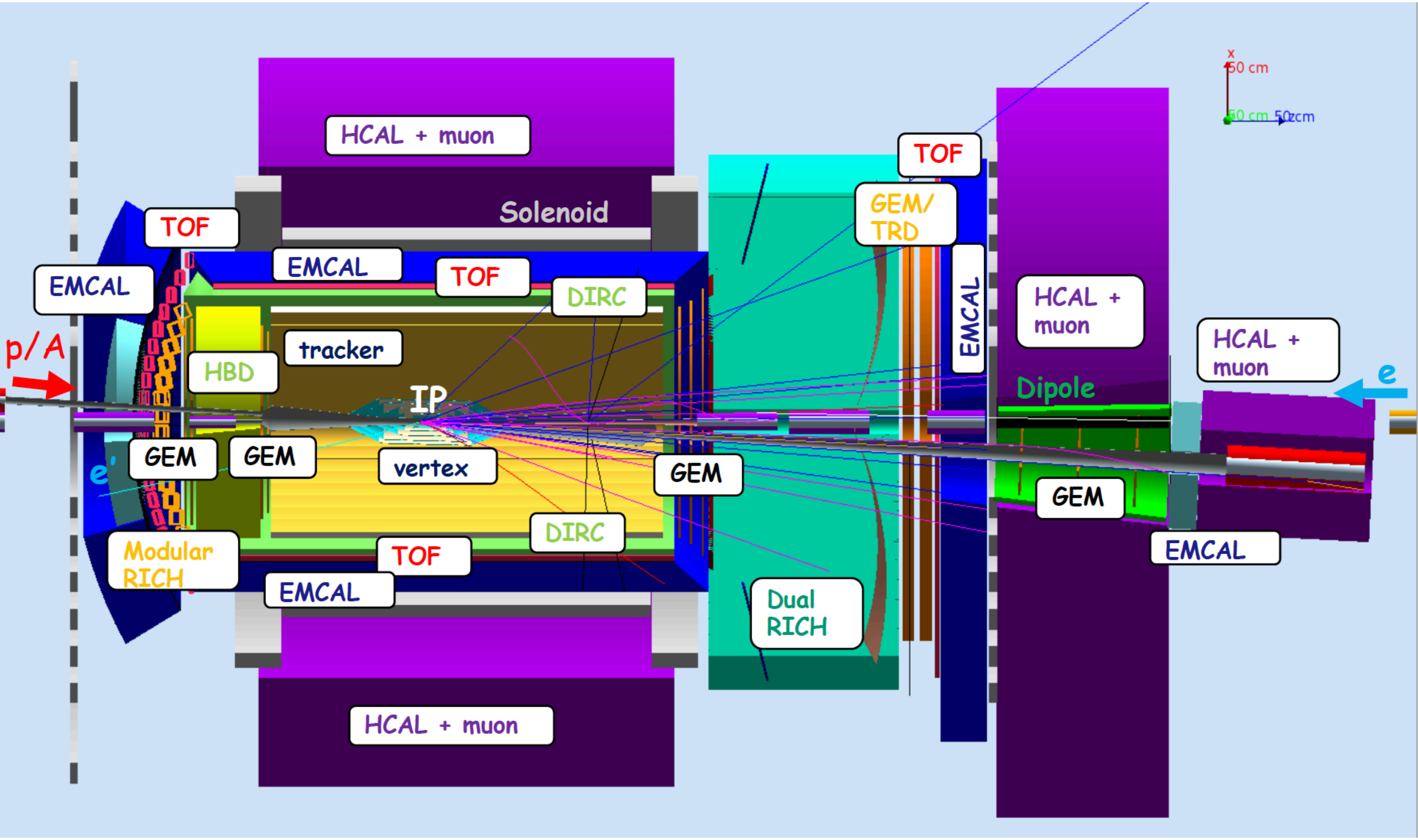
- **Brookhaven Laboratory (BNL) "green field" detector**

ePHENIX



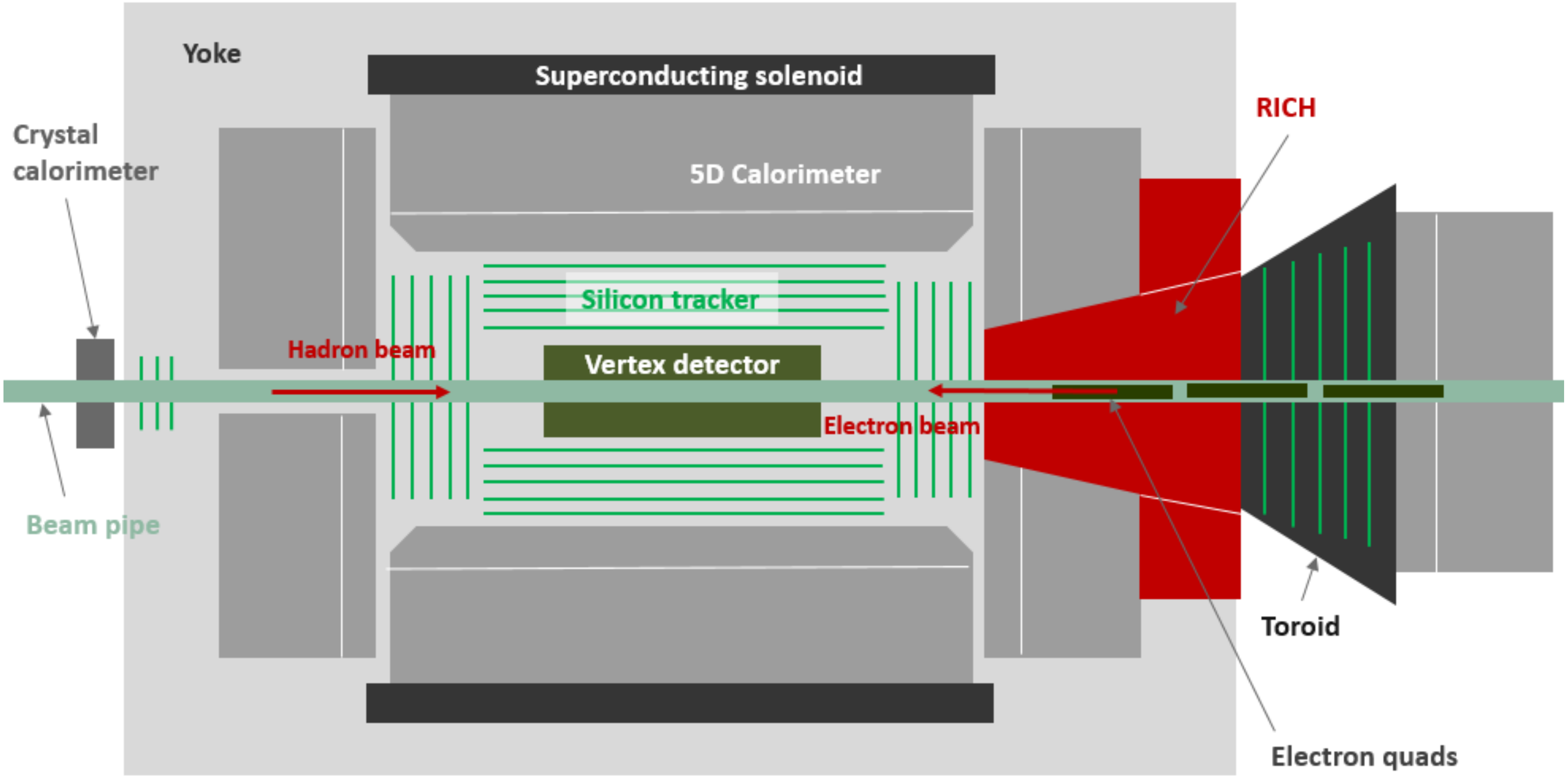
- **Brookhaven Laboratory sPHENIX-based implementation**

JLEIC



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

TOPSiDE



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

EIC Detector R&D Program

- In January 2011 BNL, in association with JLab and the DOE Office of NP, announced **a generic detector R&D program** to address the scientific requirements for measurements at a future EIC

Goals:

- Enable successful design and timely implementation of an EIC experimental program
  - Quantify the key physics measurements that drive instrumentation requirements
  - Develop instrumentation solutions that meet realistic cost expectations
- Stimulate the formation of user collaborations to design and build experiments

EIC Detector R&D Program

- Hardware-oriented projects:

Project	Description
eRD1	Calorimeter consortium
eRD6	Tracking consortium (gaseous detectors) & RICH
eRD14	PID consortium (RICH, DIRC, Time of Flight, sensors)
eRD16	Forward/Backward Tracking using MAPS Detectors
eRD18	Precision Central Silicon Tracking & Vertexing
eRD21	EIC background studies
eRD22	GEM TRD
eRD23	Streaming readout
eRD24	Roman Pots for EIC

-> Work in progress, with participation of both US and European groups

Tracking trivia

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

- **Tracking detector:**
  - Amplify this "primary 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 detectors location
  - (Momentum estimated by degree of bending in the magnetic field)

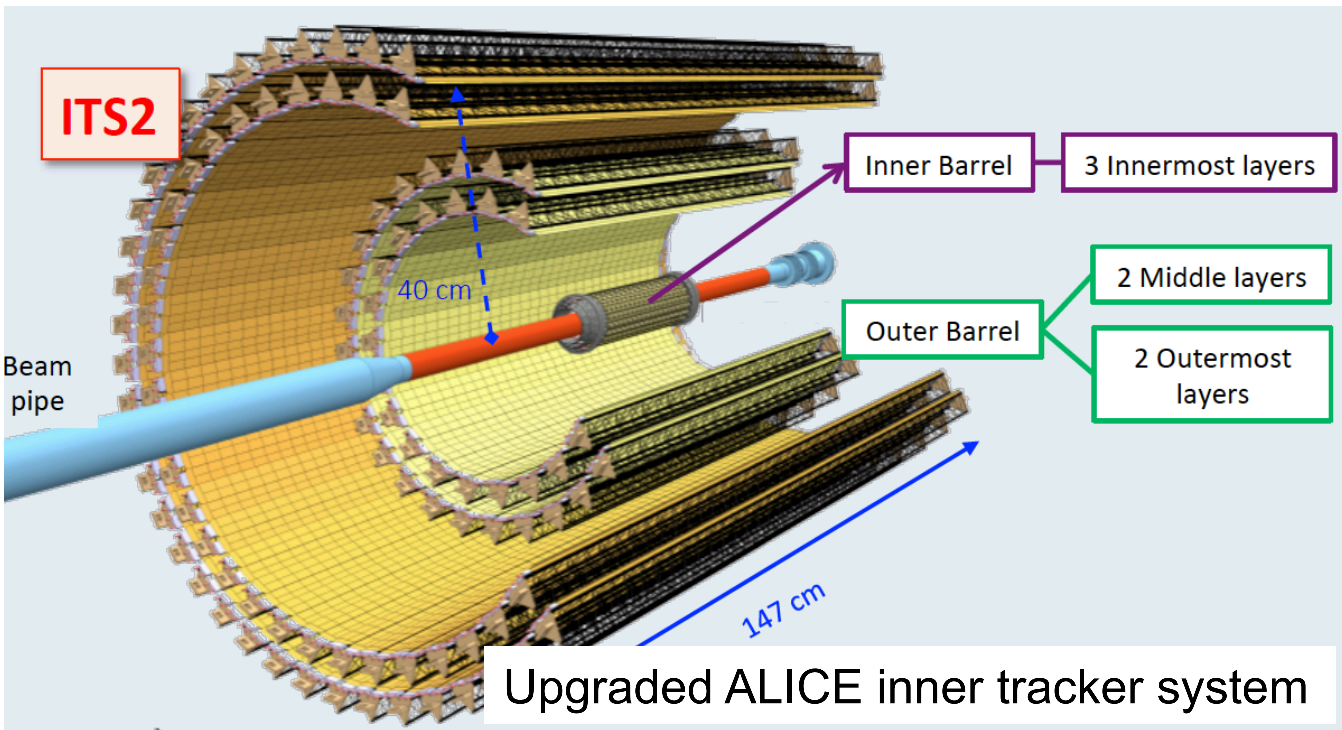
  - Extrapolate to the interaction point and build vertices

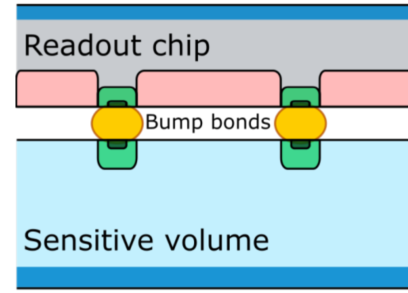
EIC detector tracking: systems & options

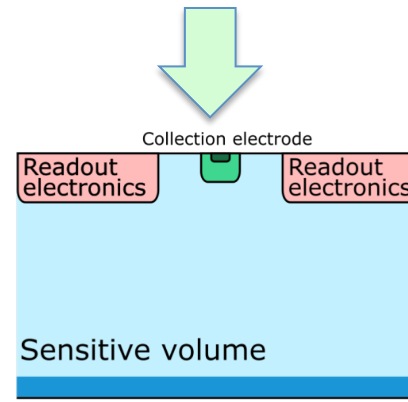
- **Vertex detector, forward & backward trackers**
  - MAPS (Monolithic Active Pixel Sensors)
- **Central tracker**
  - TPC (+ MM)
  - All-silicon tracker
  - A set of Micromegas (MM) or μRWELL cylindrical layers
  - Drift chamber
  - Straw tube tracker
- **Endcap trackers**
  - Large-area flat modules: GEMs, MM, μRWELL, GEM-TRD, sTGC
- **Close-to-beam-line instrumentation (all Si-based technology)**
  - Roman Pots, B0 magnet tracker, low-Q^2 tagger tracker

Monolithic Active Pixel Sensors (MAPS)

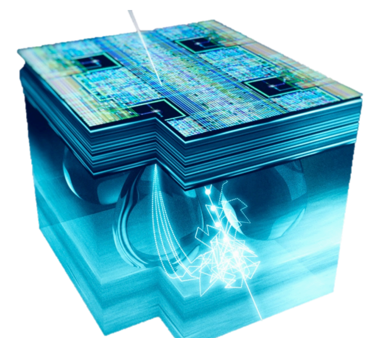
- Sensitive volume and readout electronics on same chip
- Made using commercial CMOS technology
- Thin and fine granularity
- Slow (charge collection partly via diffusion)





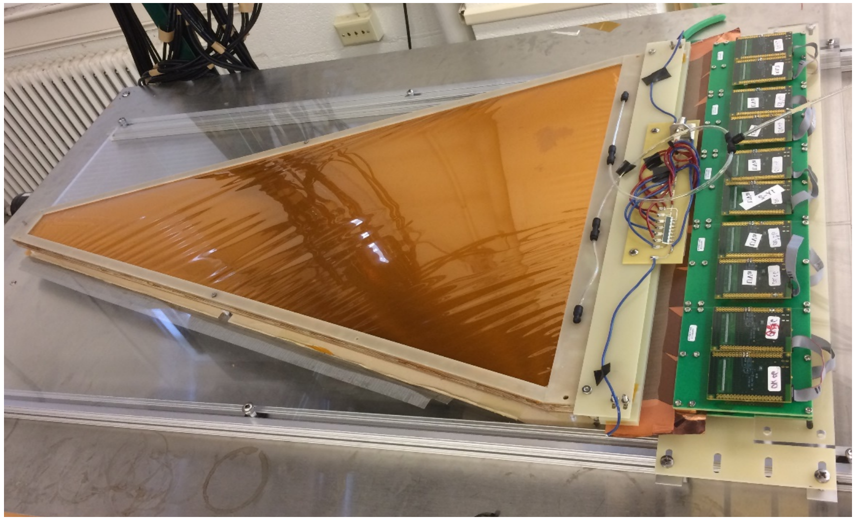


- 10 m^2 active silicon area, 12.5 G-pixels
- Material budget: ~0.3% X0 for Inner Barrel
- Faster readout: 100 kHz Pb-Pb (vs 1 kHz)

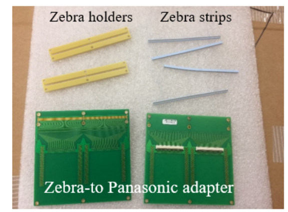


artistic view of charge collection process

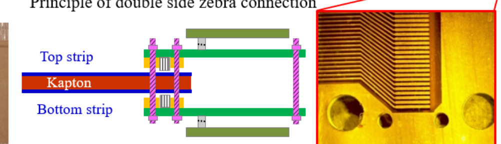
Large planar GEM detectors



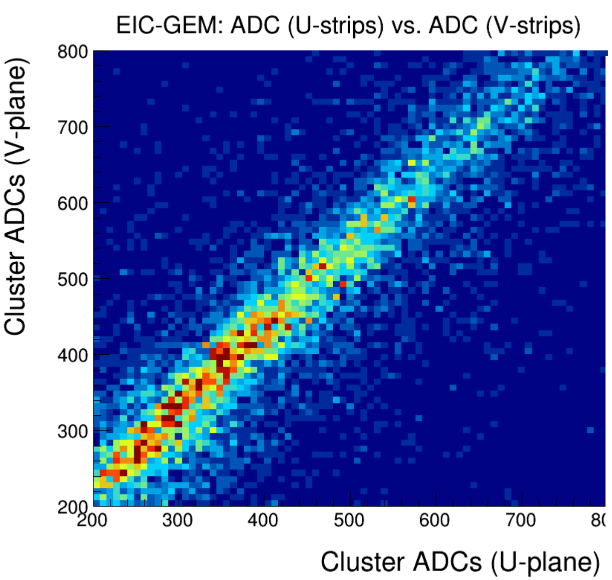
Components of zebra connection



Principle of double side zebra connection



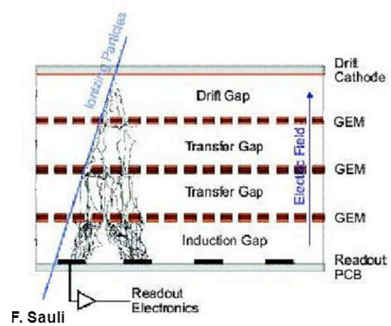
- 2D U-V strips readout a la COMPASS, very good spatial resolution
- No metallized vias to pick up bottom strips signal ⇨Thin Cu layer
- All FE electronics read out all on the outer radius of the chamber

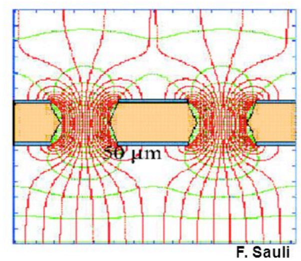


U-V strips charge sharing

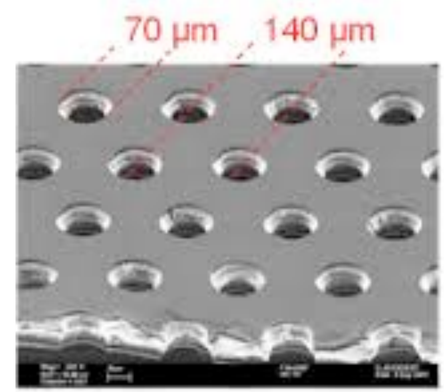
GEM Foils

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



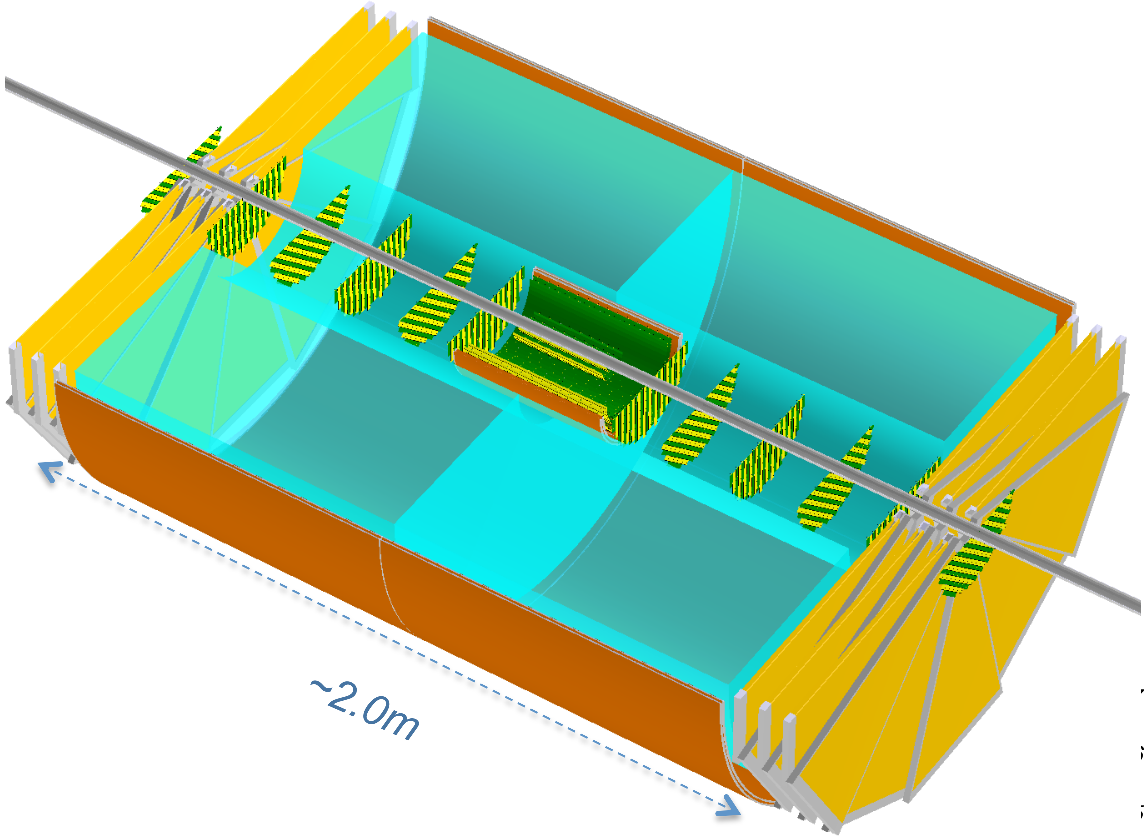


- High energy particles ionize the gas inside the detector which drift to the GEM foil
- Electric field through the holes causes the electrons to cascade

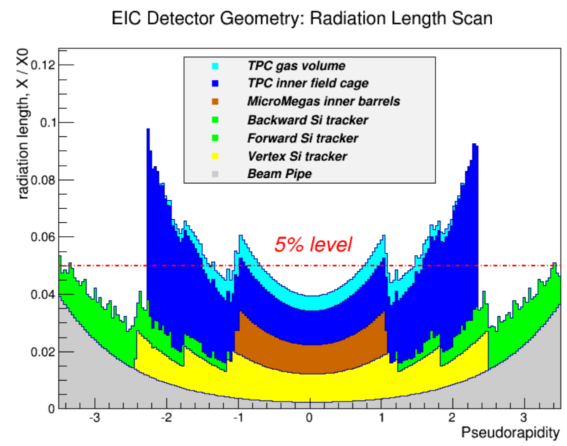


- GEM: Gas Electron Multiplier
- Primary ionization in a short (few mm) drift gap
- Multi-stage (3-5 50μm thick foils) amplification in a high field
- Direct coupling to readout strips (or pads)

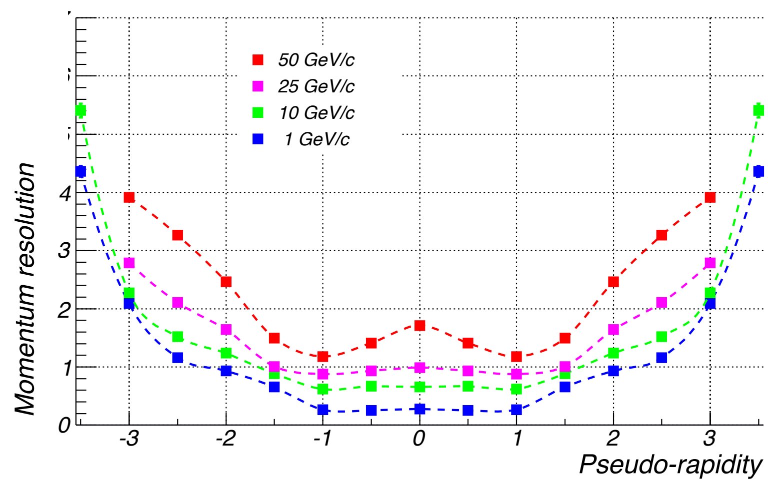
Si-TPC-GEM EIC tracker



Radiation length scan



Momentum resolution

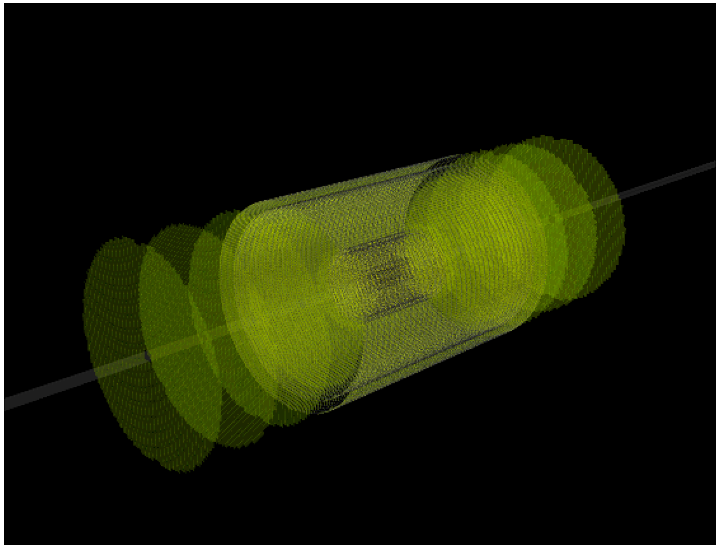


- Favorably compares to the performance of HERA collider experiments:

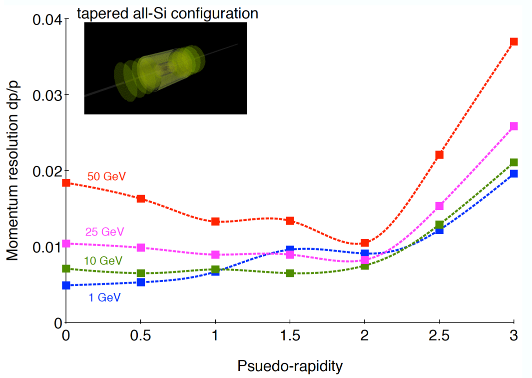
  → H1 : $0.6\%*P_t + 1.5\%$

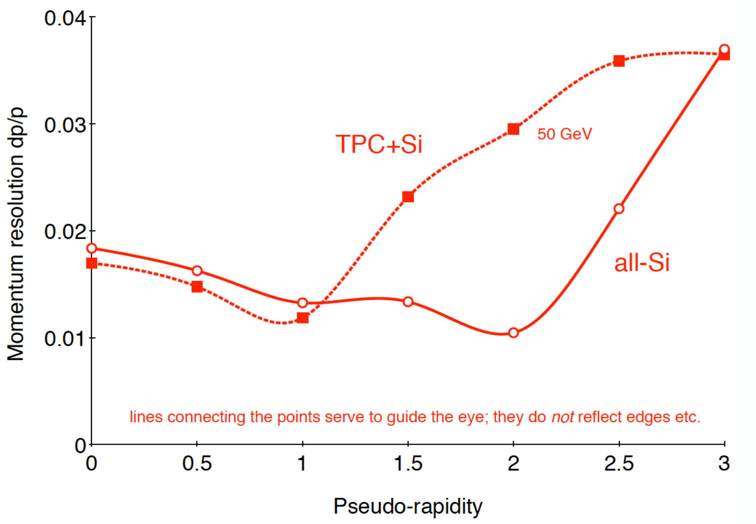
  → ZEUS : $0.5\%*P_t + 1.5\%$

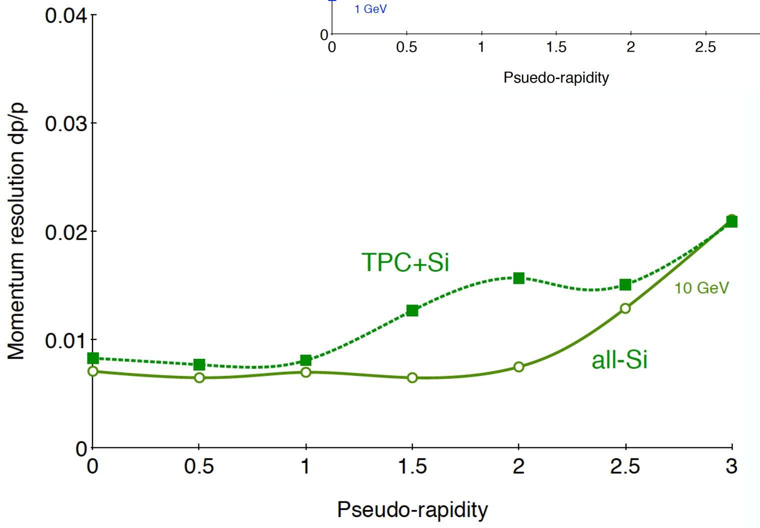
All-silicon EIC central tracker



- MAPS 20μm pixel layers
- Compact design: R ~ 43cm …
- … therefore more radial space for PID detectors



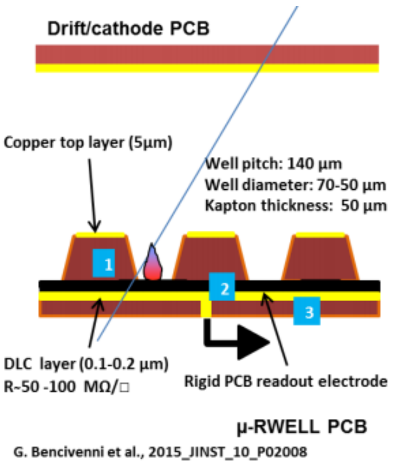


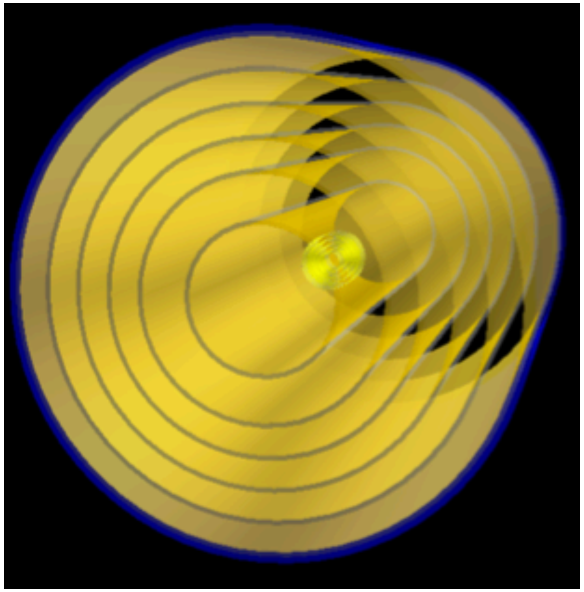


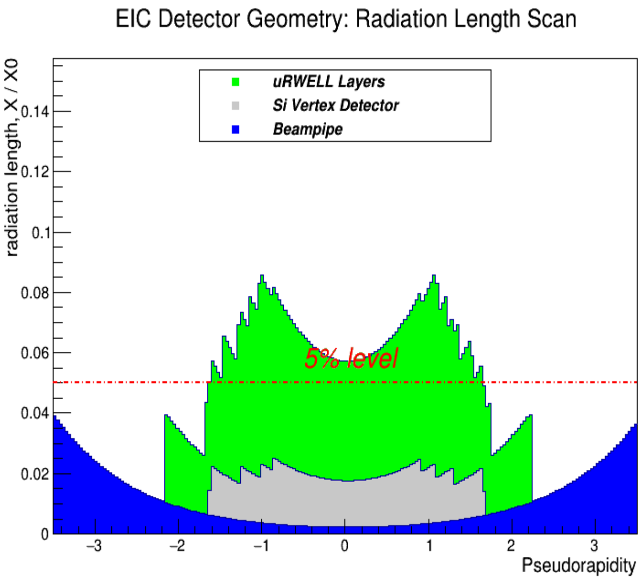
Momentum resolution comparison against the TPC+Si (BeAST) at 50 GeV and 10 GeV

μRWELL-based tracker

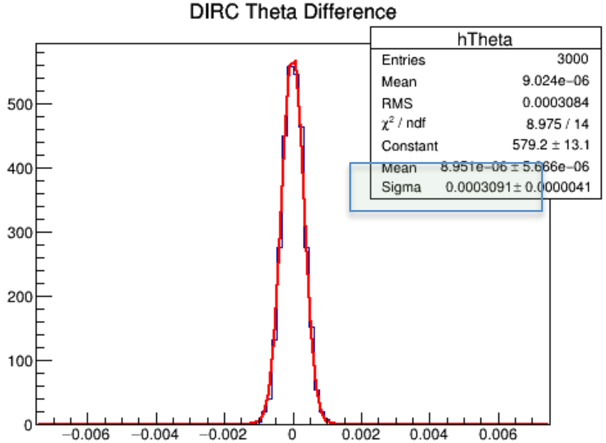
- Modern technology, competing with GEM & Micromegas:
  - Simple, low mass, no stretching, low cost
  - 1D & 2D configurations, flat & cylindrical
  - Favorably compares to a TPC in terms of tracking performance …
  - … but lacks dE/dx measurement capability







~0.4mrad polar angle resolution at DIRC radius for 6 GeV particles



-> may become a viable option for EIC!

Calorimetry trivia

- **Calorimeter measures *energy* of incoming particle**
  - Stopping the particle
  - Converting the energy into something detectable (light, charge)
  - Basic mechanism: e/m and hadronic showers
  - The measured output is proportional to the particle energy

- **It also measures the location of energy deposit**
  - Showers are relatively well localized
  - Calorimeter readout is segmented
  - Therefore (provided primary vertex location is known) one can determine *directional information* for neutral particles (photons, neutrons)

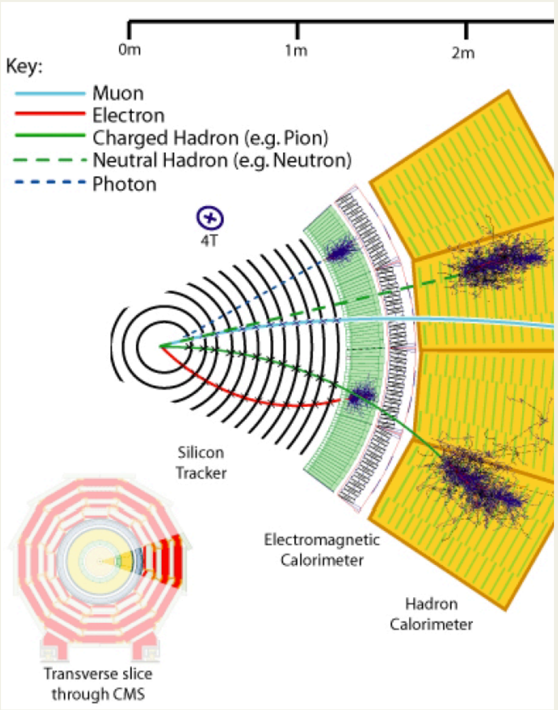


Illustration by CMS setup

- **Electrons**
  - Track & e/m shower
- **Photons**
  - e/m shower
- **Charged hadrons (π, K, p)**
  - Track & hadronic shower
- **Neutral hadrons (n, K_L)**
  - Hadronic shower

EIC e/m calorimetry: systems & options

- **Inner EmCal at backward (η < -2) rapidities**
  - PWO crystals; energy resolution ~1.5%/√E + 0.5% required to measure scattered electron energy; radiation hardness!

- **Electron-going endcap at -2 < η < -1**
  - As tracker takes over the scattered electron momentum measurement, modest energy resolution ~7-10%/√E suffices
- **Barrel (-1 < η < 1) and Hadron-going endcap (1 < η < 4)**
  - Photons from exclusive reactions, π^0 decay; modest energy resolution ~10-12%/√E may suffice; limited radial space in the barrel!
- **Technology**: sampling W/SciFi spaghetti or W/Cu/SciTile shashlik

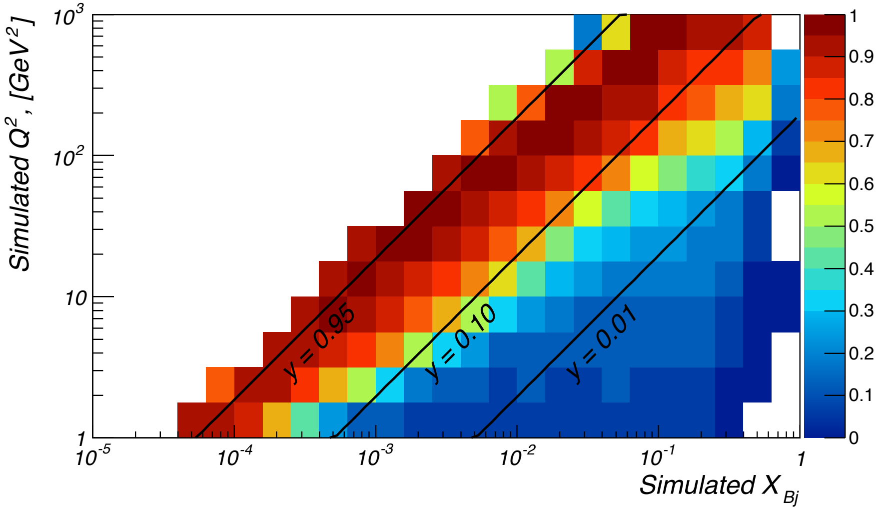
- **Close-to-beam-line instrumentation**
  - Low-Q^2 tagger, Luminosity monitor: radiation hardness!

Scattered electron kinematics reconstruction

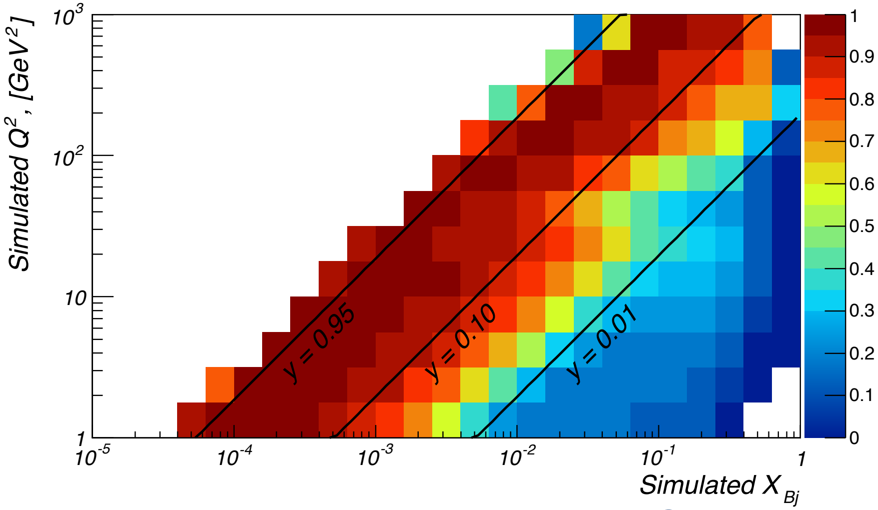
$$Purity = \frac{N_{gen} - N_{out}}{N_{gen} - N_{out} + N_{in}}$$

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

- A possible way to increase ***y*** range: use e/m calorimeter in addition to tracking
  - ~2%/√E energy resolution (and ~0 constant term) for η < -2 (PWO crystals)
  - ~7%/√E energy resolution for -2 < η < 1 (W/SciFi sampling towers)



Lepton tracking only



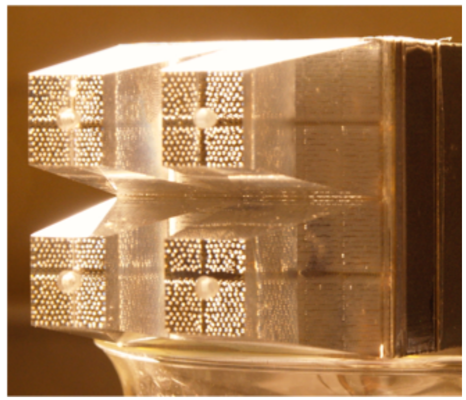
Lepton tracking + EmCal

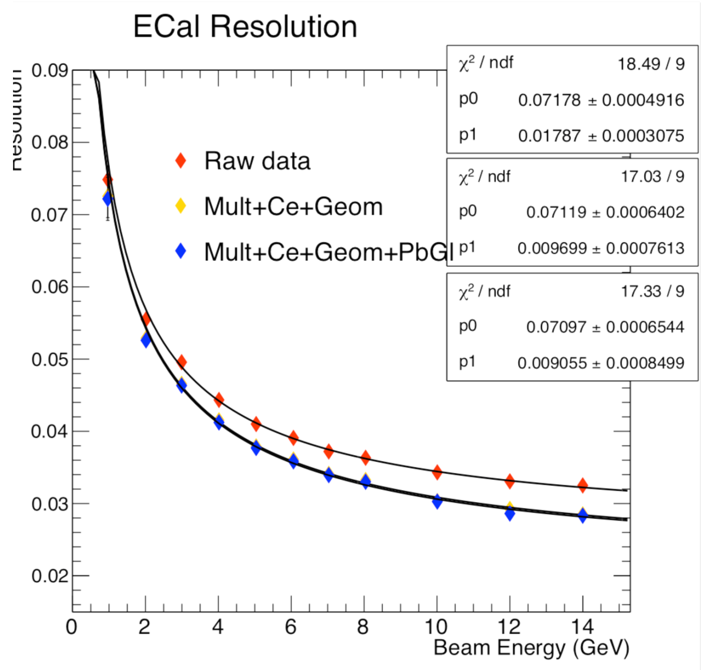
- Apparently, the high-resolution crystal EmCal at very backward rapidities can help increasing the available ***y*** range ...
- ... but only if it has a very small constant term and is “radiation hard”

W/SciFi e/m calorimeter

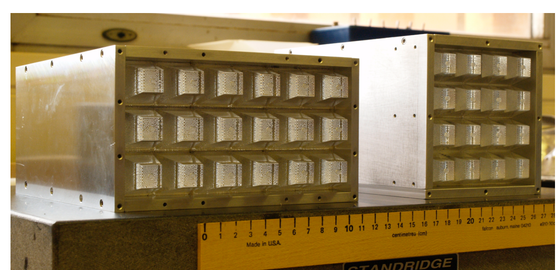
- Scintillating fibers embedded in a composite absorber (tungsten power + epoxy)
- Round and square fibers tested

Detector	Fibers SCSF 78	Absorber
"Old" High sampling frequency	Round, 0.4mm	75% W 25% Sn
"Square" High sampling fraction	Square, 0.59 x 0.59 mm^2	100% W





- Several test beam campaigns in 2012 .. 2016
- Achieve 7-12%/√E (variable by design), with ~1% constant term at 10°, ~3% at 4°
- PMT and SiPM implementations
- Implemented in sPHENIX



EIC hadronic calorimetry: systems & options

- **Hadron-going endcap (1 < η < 4)**
  - High-performance system required for forward jet measurements, energy resolution <40%/$\sqrt{E}$ with a small constant term

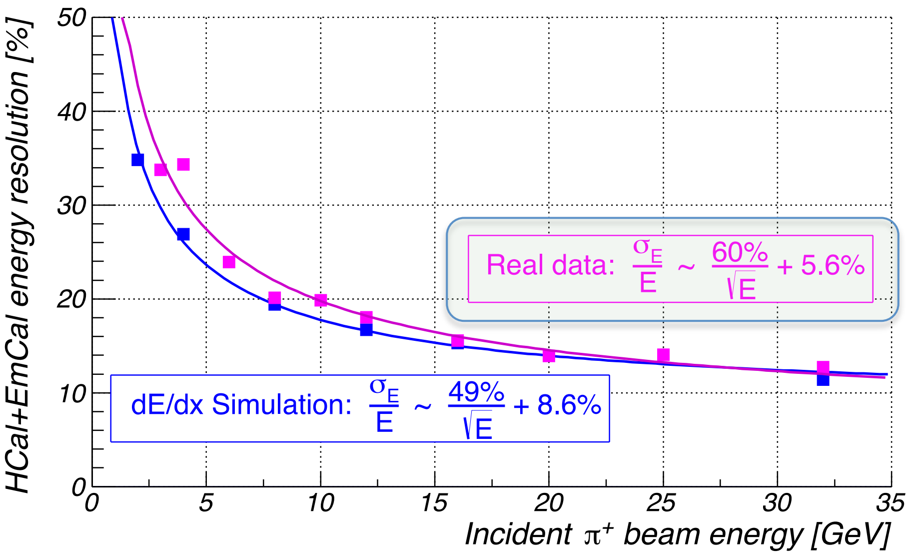
- **Electron-going endcap and barrel (-4 < η < 1)**
  - Case needs to be justified; modest energy resolution may suffice

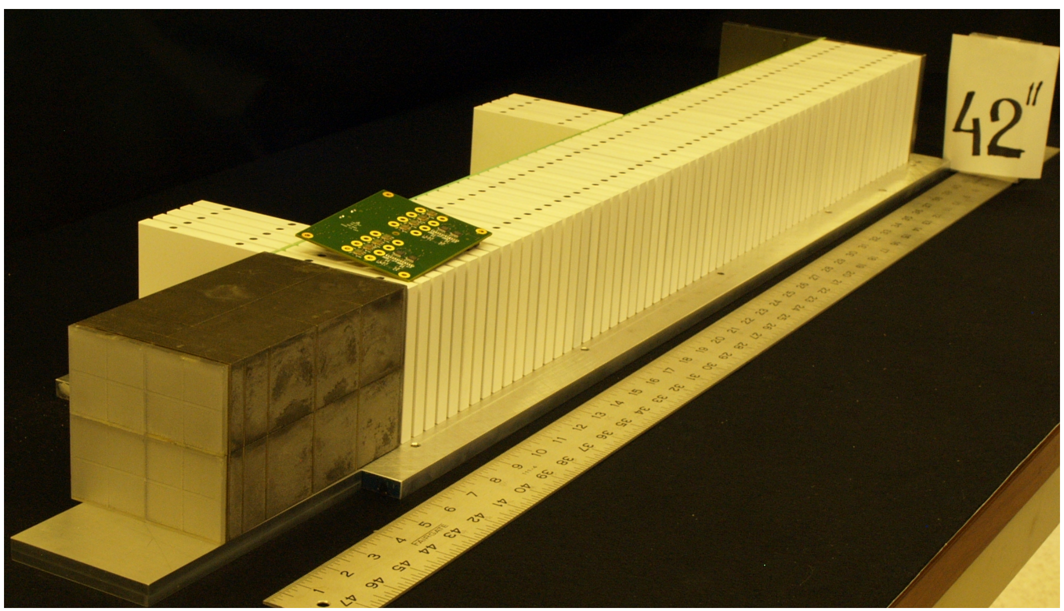
- **Close-to-beam-line instrumentation**
  - Zero Degree Calorimeter: high-performance system with a good transverse position measurement is required

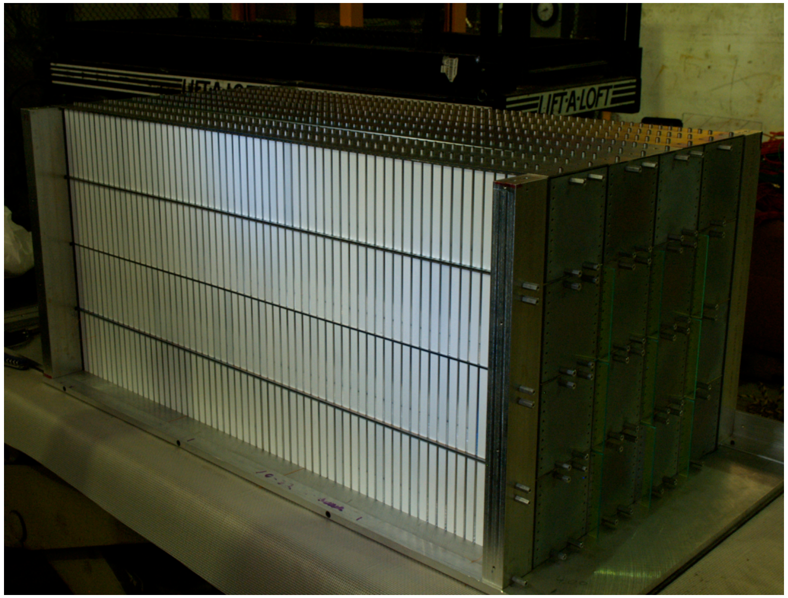
- **Possible implementations**
  - Pb/Sci tile compensated sandwich design
  - High granularity calorimetry?
  - Dual readout (Scintillation/Cerenkov) or dual gate (late neutrons)?

Pb/SciTile hadronic calorimeter

- Compensated design
- Scintillating tiles interleaved with Pb absorber plates
- Wavelength shifter for light collection
- SiPM readout
- Several test beam campaigns







Particle ID for an EIC detector

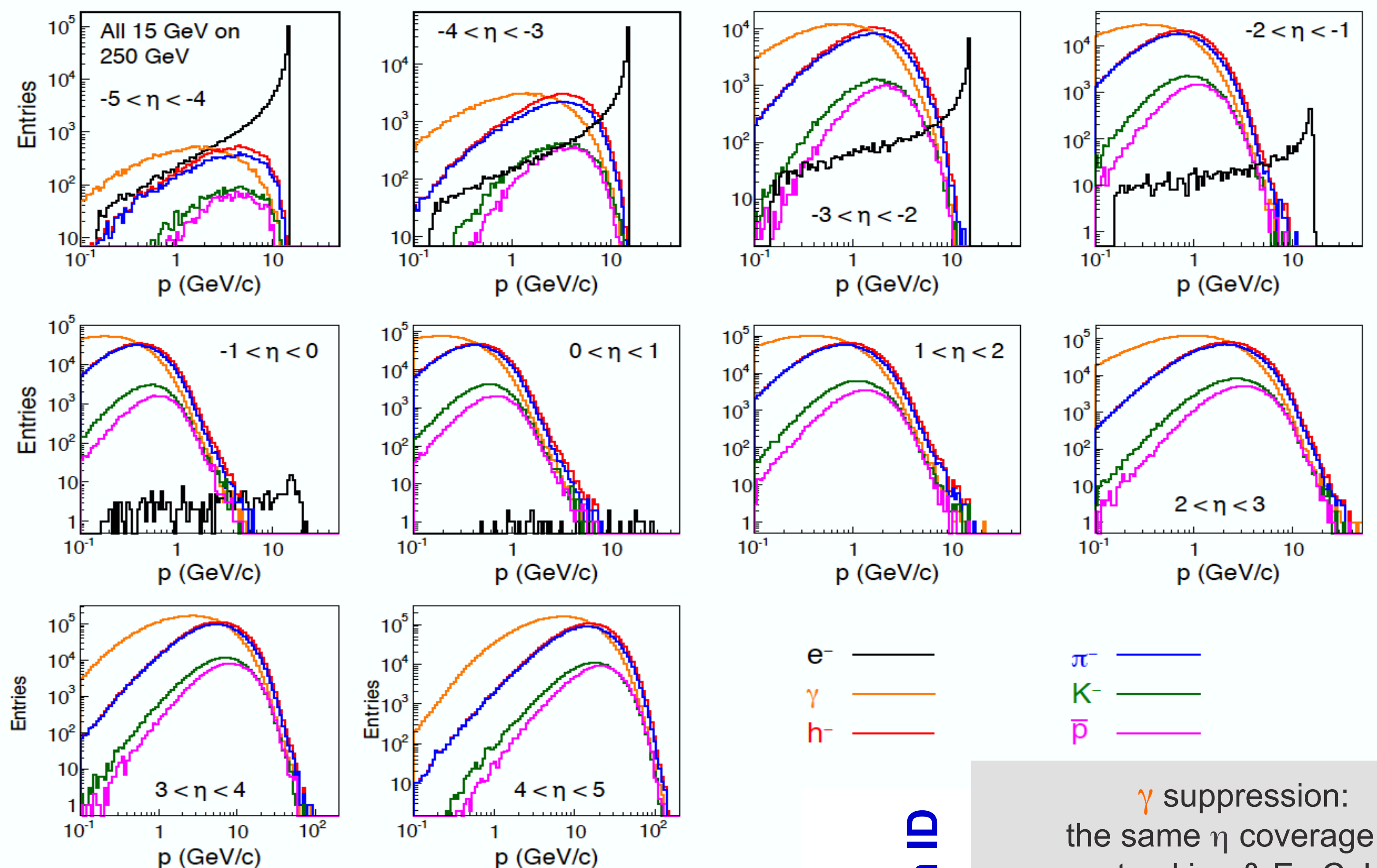
In this talk focus on electron and charged hadron identification

- **In general, need to separate:**
  - Electrons from photons
  - Electrons from charged hadrons
  - Charged pions, kaons and protons from each other

- **Use available physics processes and the detector arrangement(s) to do so:**
  - Cerenkov radiation
  - Transition radiation
  - Time of flight
  - Energy loss (dE/dx)

  - Longitudinal segmentation of the calorimeter setup (EmCal + HCal)

Relative particle yields



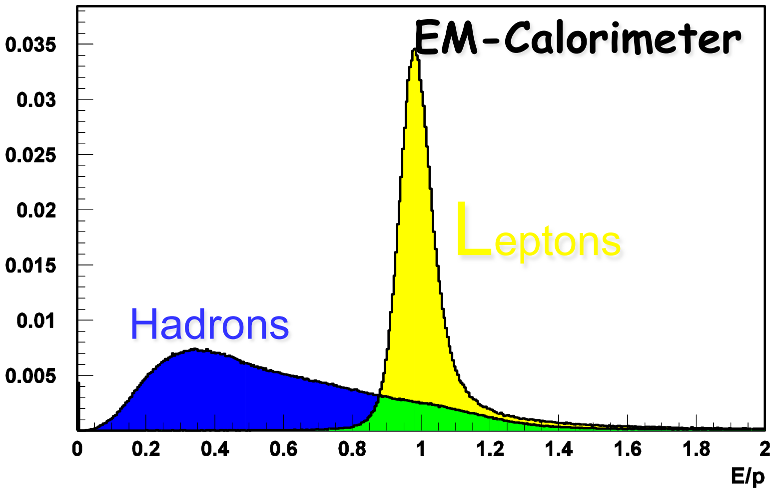
- π/K/p distributions at the same η look similar ...
- … and p/K ratio is about 3:1

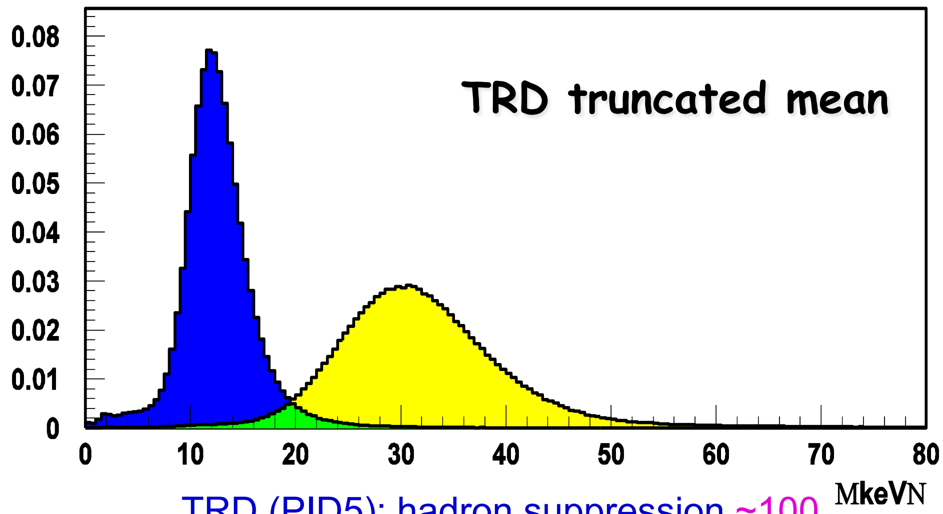
Electron ID

γ suppression:
the same η coverage for
tracking & EmCal

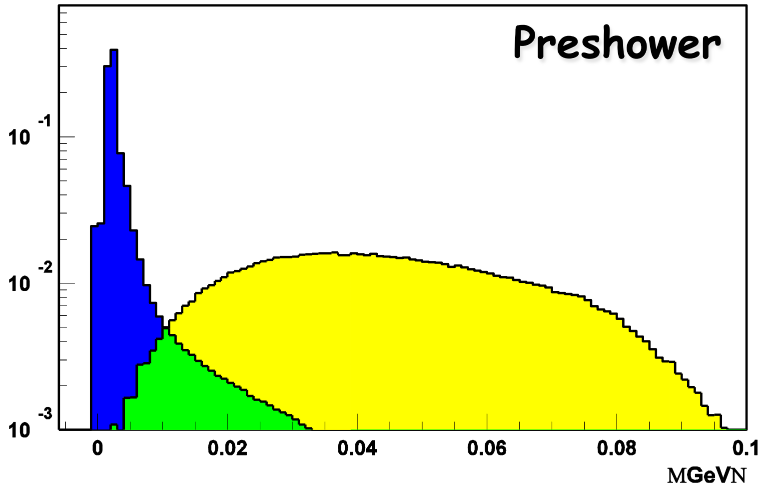
h^- suppression: through E/p and
a combination of other
technologies, η range dependent

EmCal + TRD + preshower e⁻ ID @ HERMES

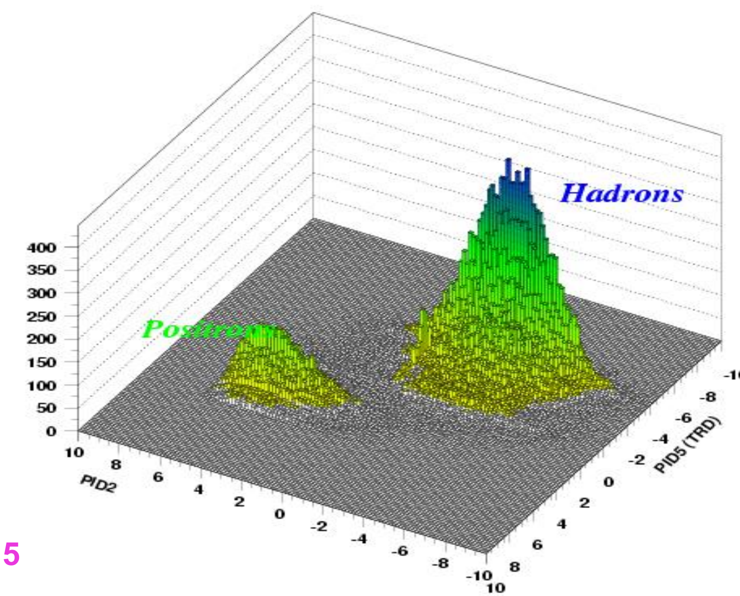




TRD (PID5): hadron suppression ~100

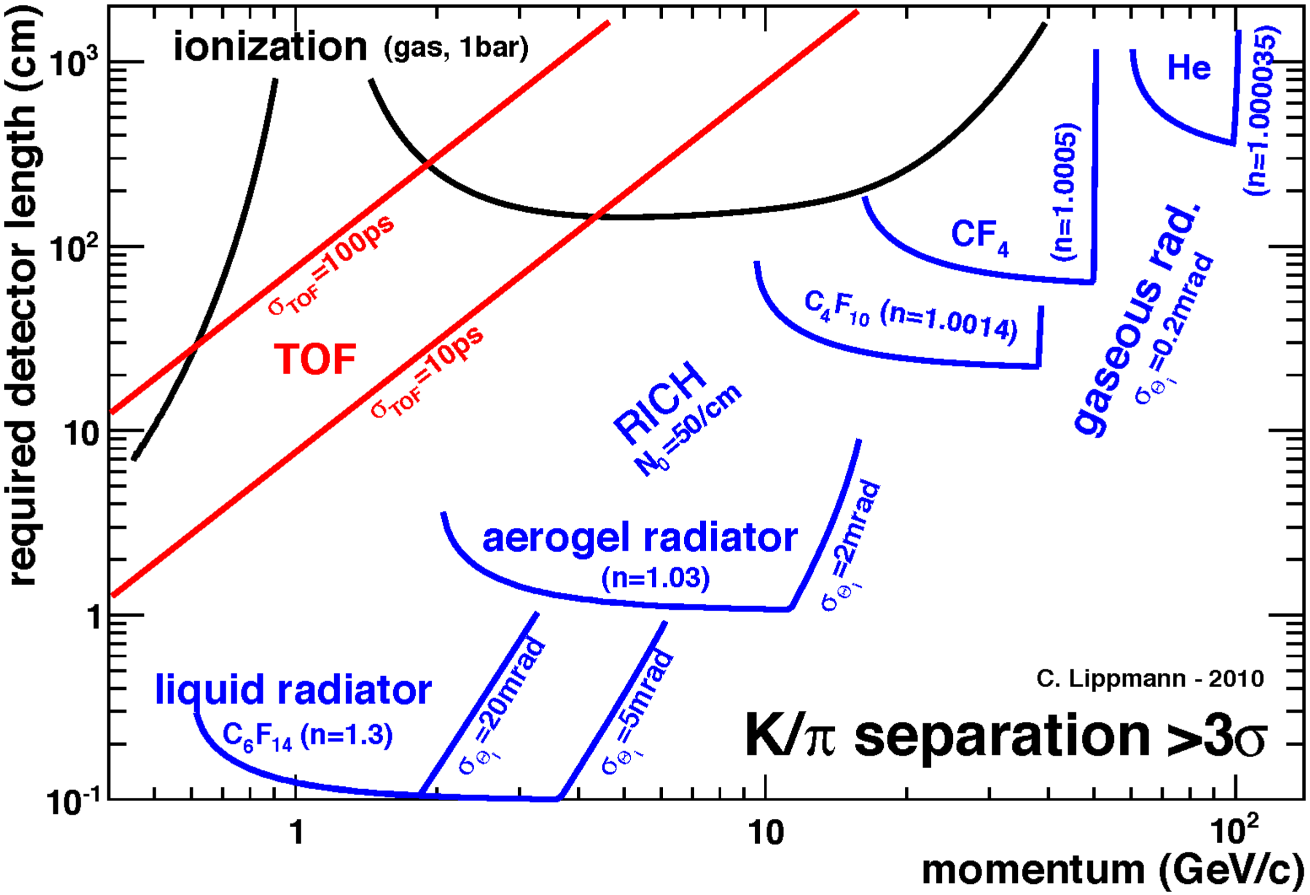


Both together (PID2): hadron suppression ~1000



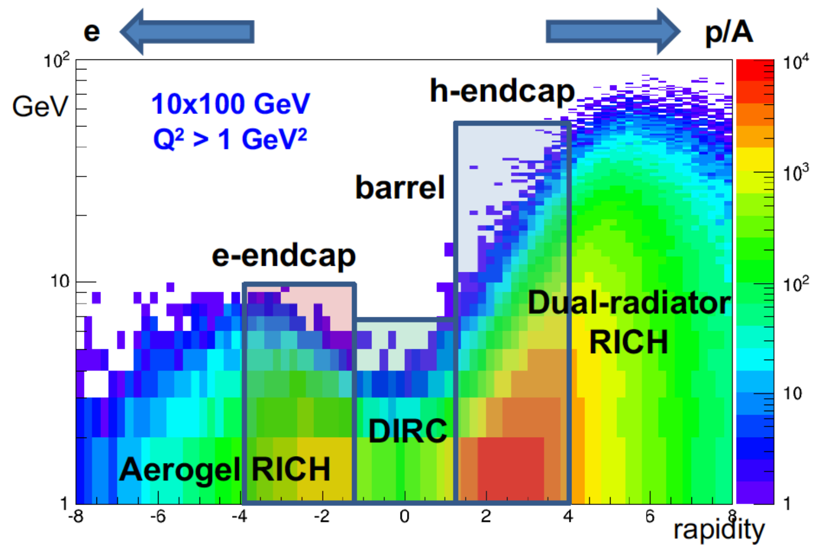
-> Note: overall pion suppression up to ~10^5

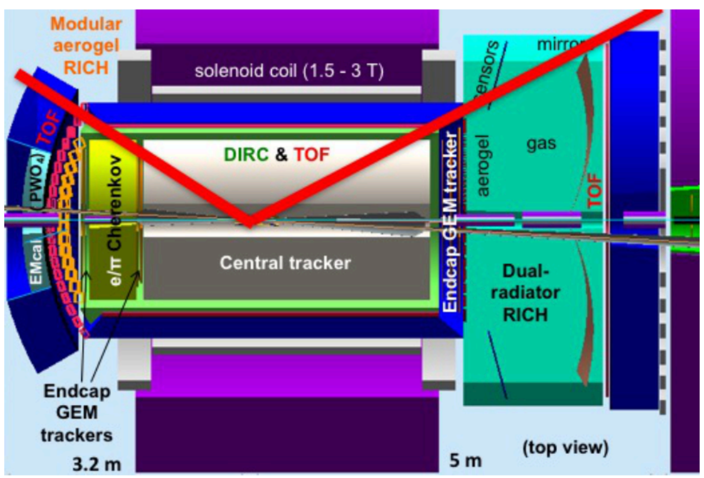
Hadron identification



- An EIC detector will apparently need more than one technology to cover the required momentum range in the whole η acceptance, …
- … a definitive particle type assignment on 4-5σ level may be desired …
- … therefore in general the PID requirements are much more demanding than for a typical collider experiment

Hadron PID solution for EIC



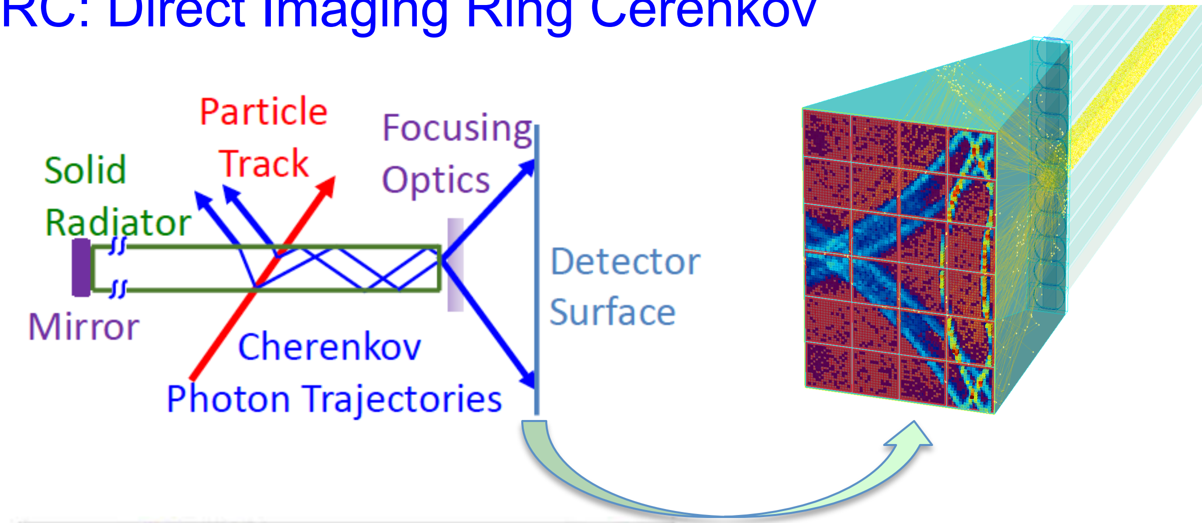


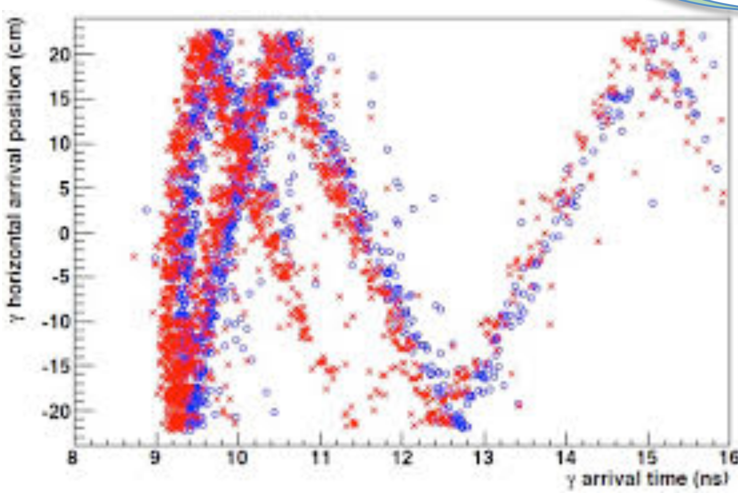
- **h-endcap:** a RICH with two radiators (gas + aerogel) is needed for π/K separation up to ~50 GeV/c
- **e-endcap:** A compact aerogel RICH with π/K separation up to ~10 GeV/c
- **barrel:** A high-performance DIRC provides a compact and cost-effective way to cover the area with π/K separation up to ~6-7 GeV/c
- TOF and/or dE/dx in a TPC can cover lower momenta

-> Note: RICH detectors are assumed to be the main hadron PID tool

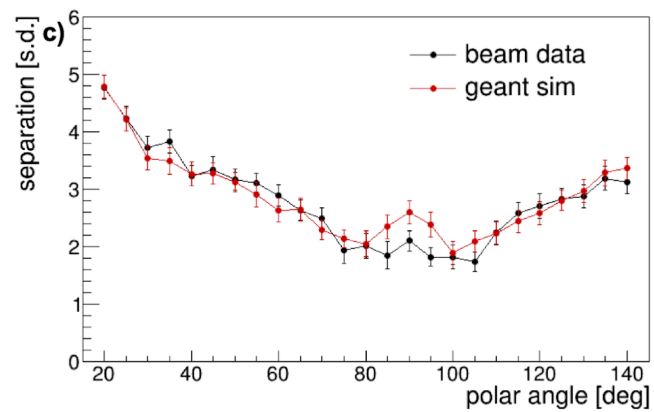
EIC barrel: DIRC with high resolution timing

DIRC: Direct Imaging Ring Cerenkov





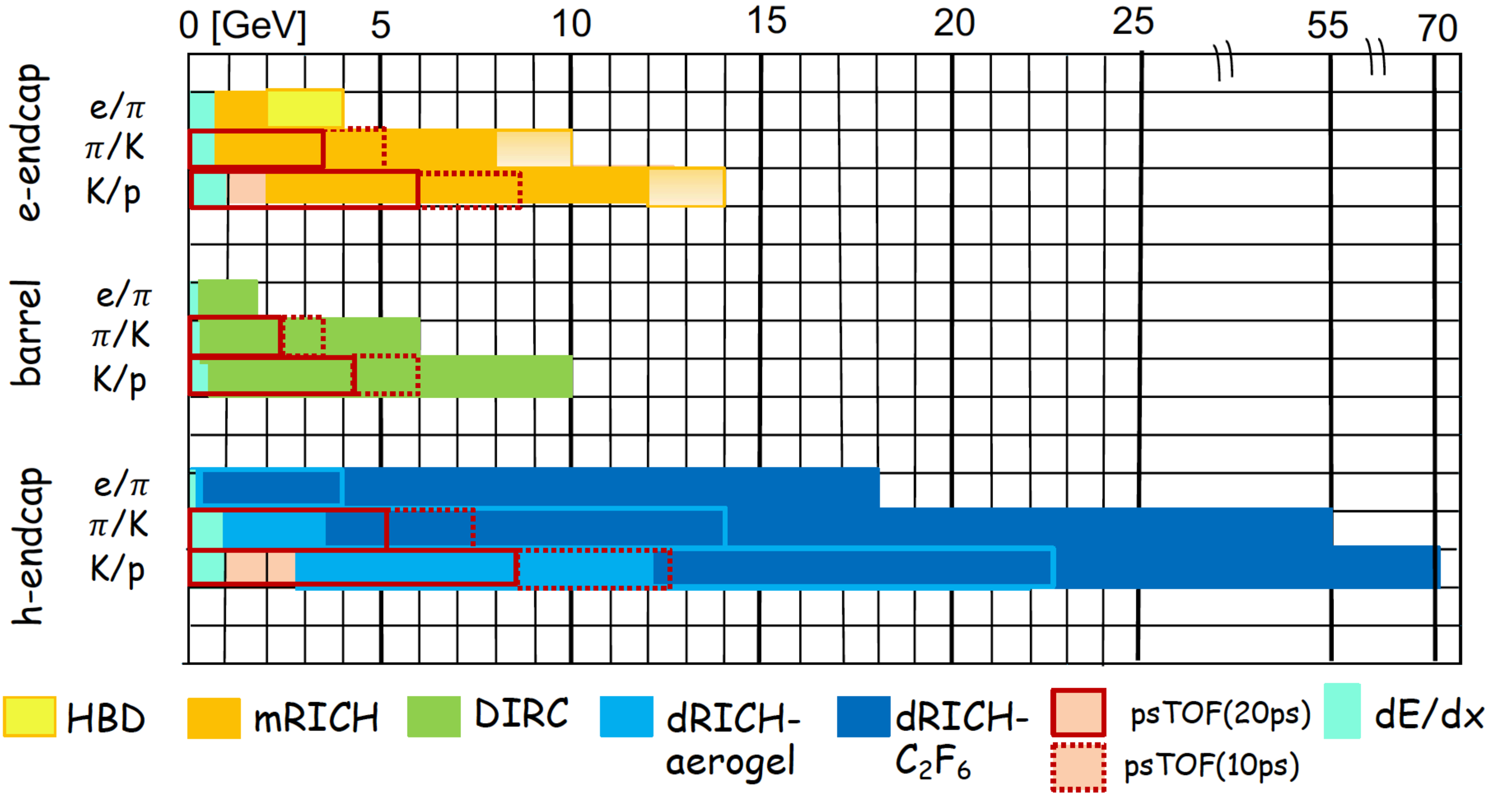
Correlation between photon coordinate and arrival time for Belle II barrel DIRC



Projected π/K separation at 7 GeV/c for EIC barrel DIRC

-> Note: modeling suggests that by using high-resolution timing one can extend π/K 3σ separation range to up to ~6 GeV/c, sufficient for EIC needs

Expected particle ID performance



-> Note: electron/pion separation will be mostly provided by e/m calorimetry (and possibly Transition Radiation Detectors)

- **Caveat:** 3σ separation is listed in this table

Interaction Region (IR) design goals

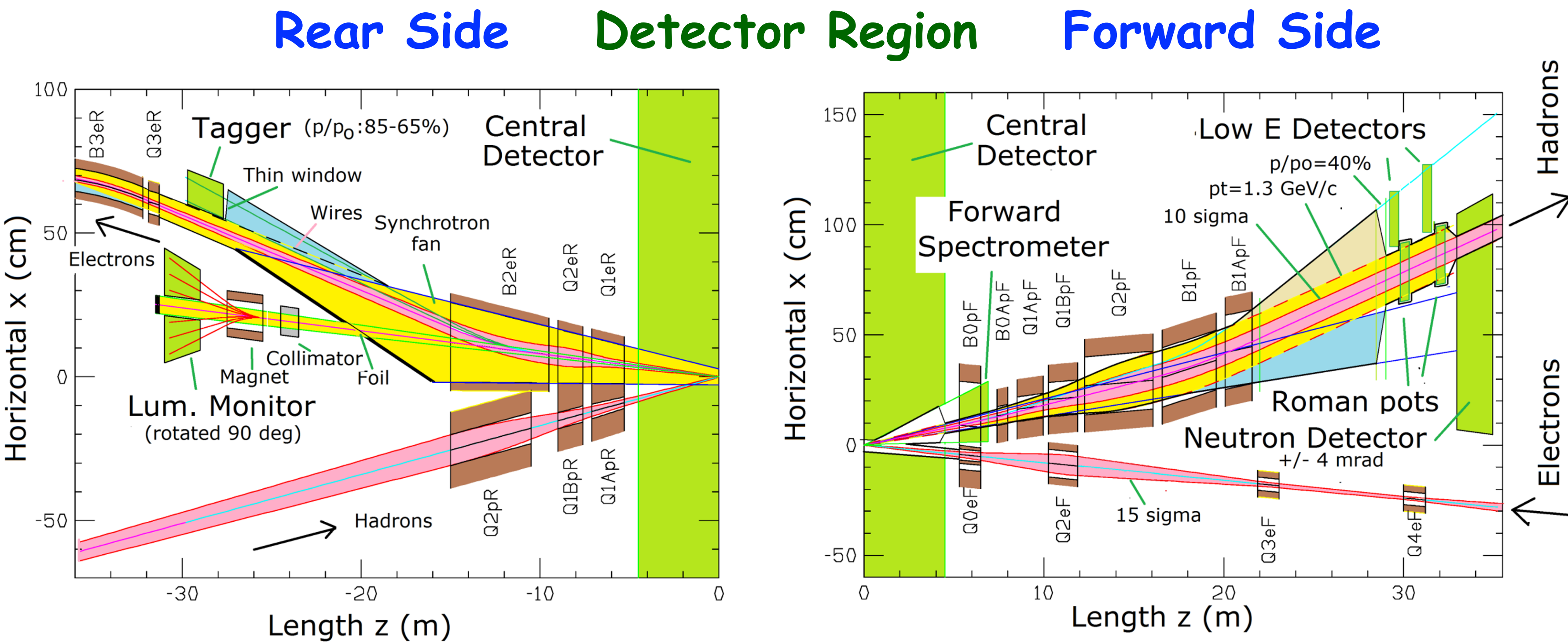
- Focus both beams to small spot sizes for maximum luminosity
  - Deal with a very confined machine-element-free region around the IP
- Minimize beam divergence as it is equivalent to P_t smearing
  - This is in conflict with maximizing the luminosity
- Run with a high collision frequency to increase the luminosity
  - Bunch-by-bunch luminosity and polarization measurements become challenging

- Provide early beam separation and minimize synchrotron radiation
  - Use crossing angle -> introduce crabbing to recover the luminosity
- Pass synchrotron radiation through the detector with minimal losses
  - Have to increase the diameter of the beam pipe at the IP & find space for masks

- Provide clear close-to-beam-line acceptance and separation for several types of secondary particles
  - This causes numerous conflicts between the IR subsystems

-> Need to find a working compromise between mutually exclusive requirements

eRHIC Interaction Region design



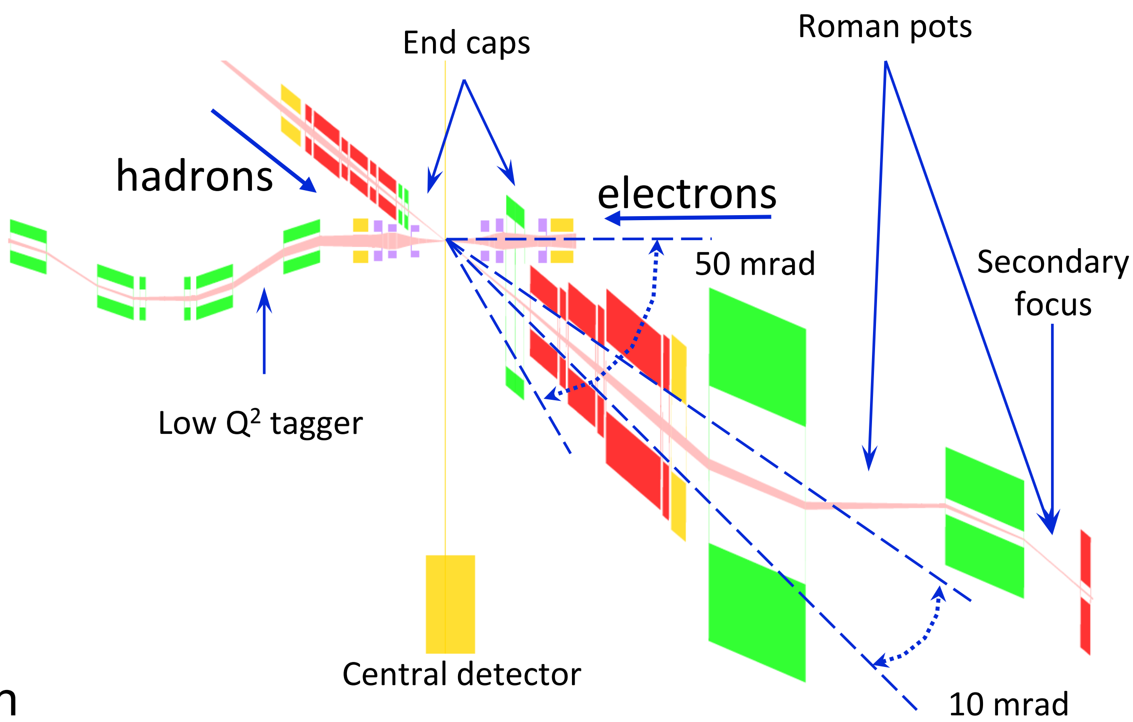
25mrad total crossing angle to separate beams
and avoid synchrotron radiation from dipoles

- Spectrometer dipole (B0) with ~20mrad acceptance adjacent to central detector
- 2nd dipole to separate hadrons from ±4mrad neutron cone to ZDC
- Sufficient aperture to transport forward-scattered particles to Roman Pots; goal: 0.2-1.3 GeV/c

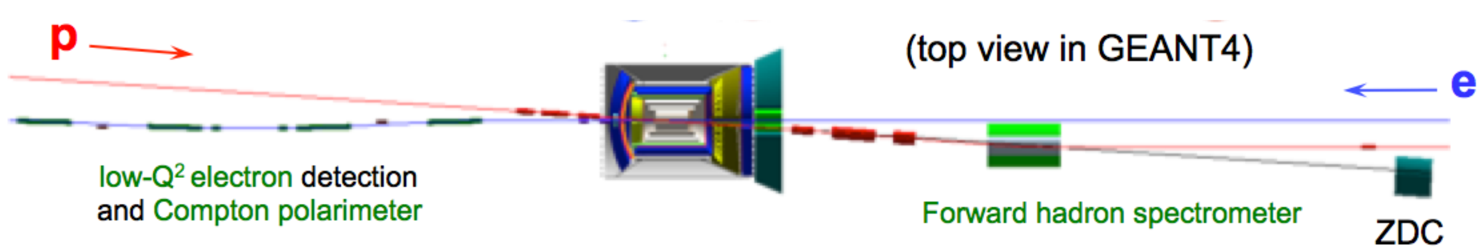
- Sufficient aperture to the Luminosity Monitor & Low-Q^2 tagger
- Separate BH photons from beam, low-Q^2 electrons from beam and lepton beam from SR-fan

JLEIC Interaction Region Design

- 50 mrad crossing angle
- Forward hadron detection in three stages
    - Endcap
    - Small dipole covering angles up to ~3°
    - Far forward, ~10 mrad, for particles passing through accelerator quads
- Low-Q2 tagger
    - Small-angle electron detection

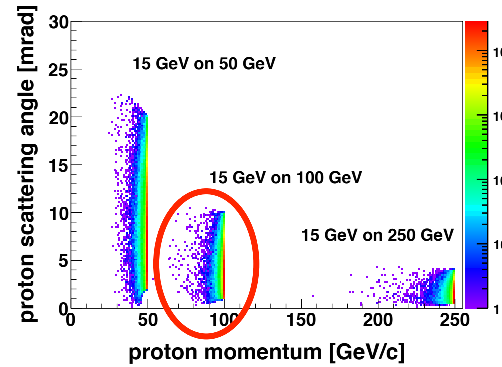


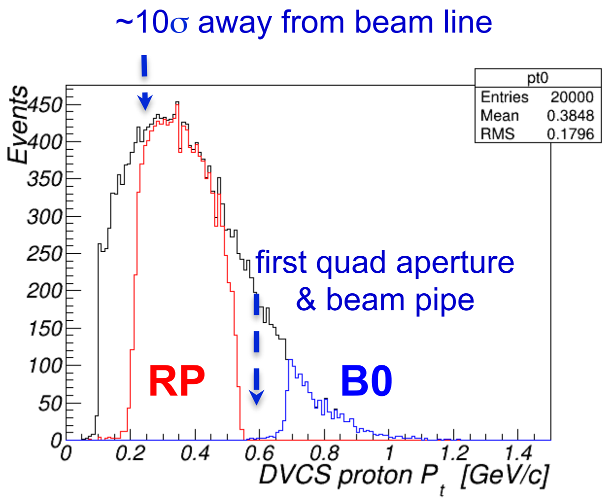
- Large beta functions in the IR up to 4 km, but manageable dynamic aperture

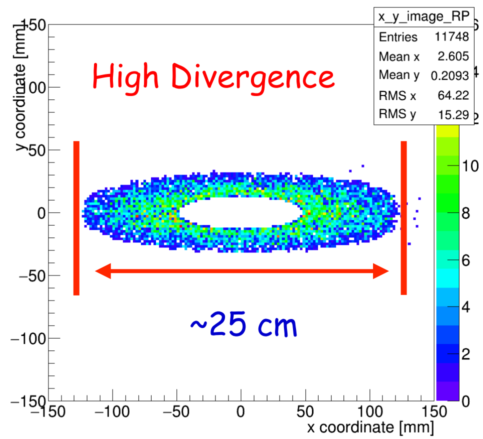


Far forward acceptance (Roman Pots & B0)

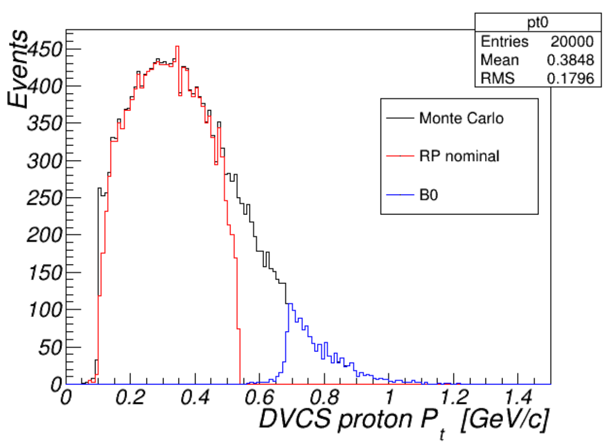
→ GEANT simulation of DVCS events
→ BeAST geometry; 15 x 100 GeV

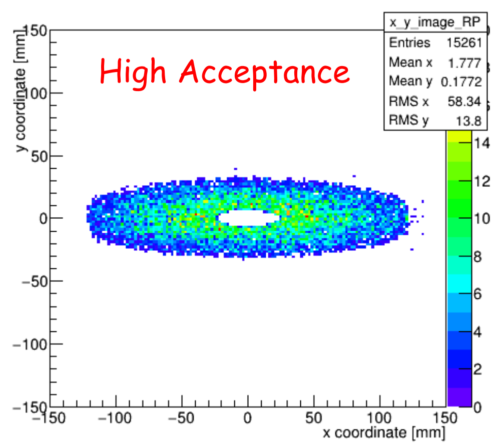






The high divergence configuration reduces low p_t acceptance (stronger focusing), but gives maximum luminosity

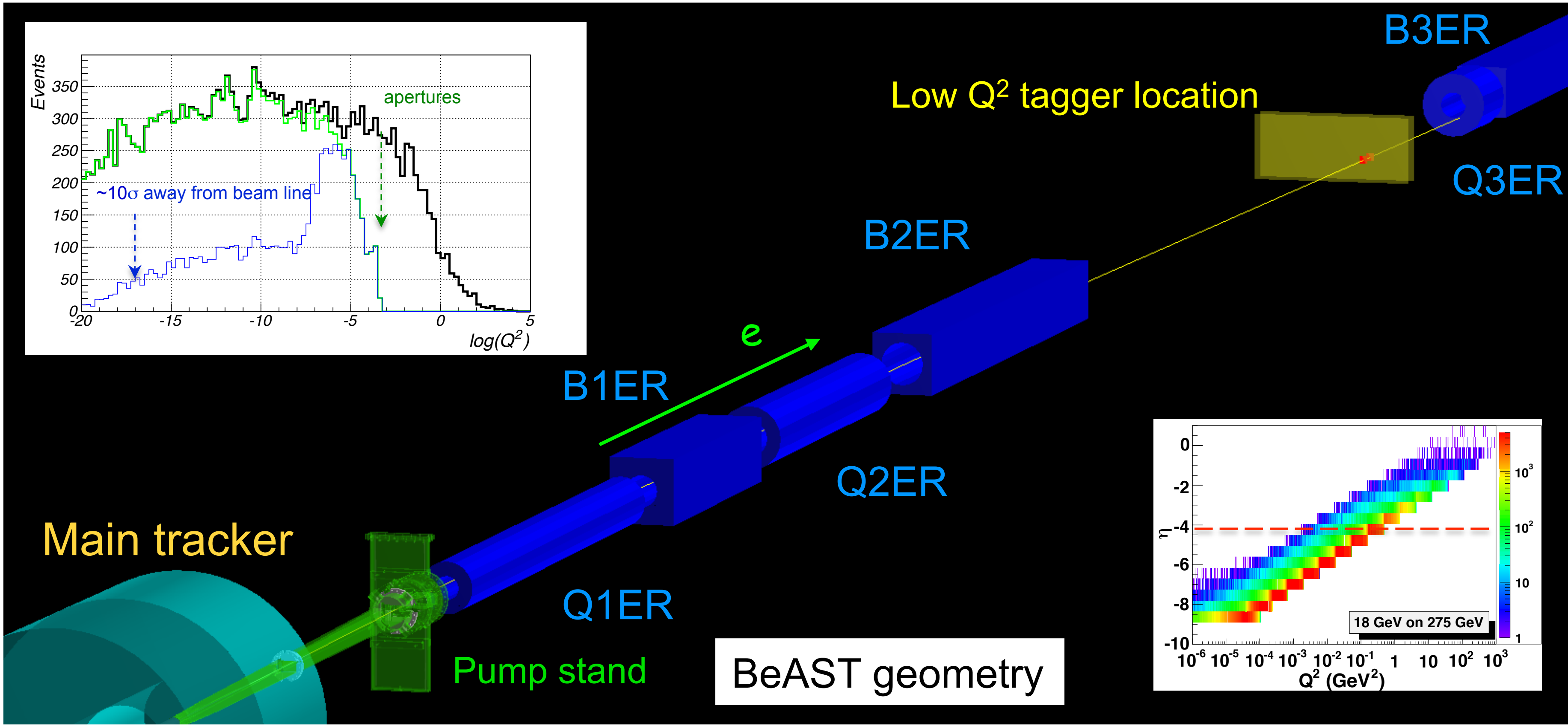




The high acceptance configuration improves low p_t acceptance, but at a cost of ~10% luminosity

Low-Q^2 tagger acceptance

→ GEANT simulation of Pythia events; 18 x 275 GeV



- Main spectrometer can not measure below η ~ -4 -> need a separate device
- A combination of silicon planes and e/m calorimeter is anticipated

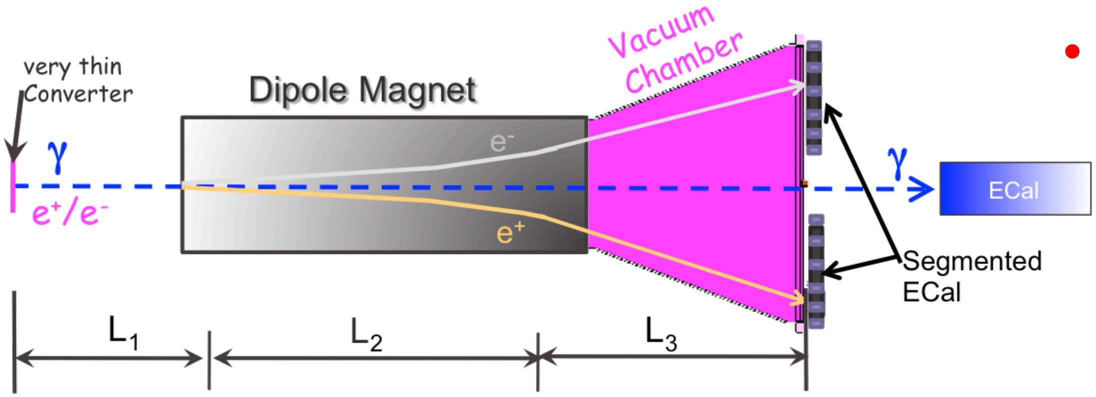
- Beam optics and magnetic element apertures taken into account

Luminosity Monitor

- Concept: use bremsstrahlung ep -> epγ as a reference cross-section
- HERA: reached 1-2% systematic uncertainty

- EIC challenges:
  - With $10^{33}cm^{-2}s^{-1}$ luminosity (and 10MHz bunch crossing frequency) one gets on average 23 bremsstrahlung photons per bunch
  - Z^2-dependence with the nuclei beams

-> this clearly challenges single photon measurement at 0°



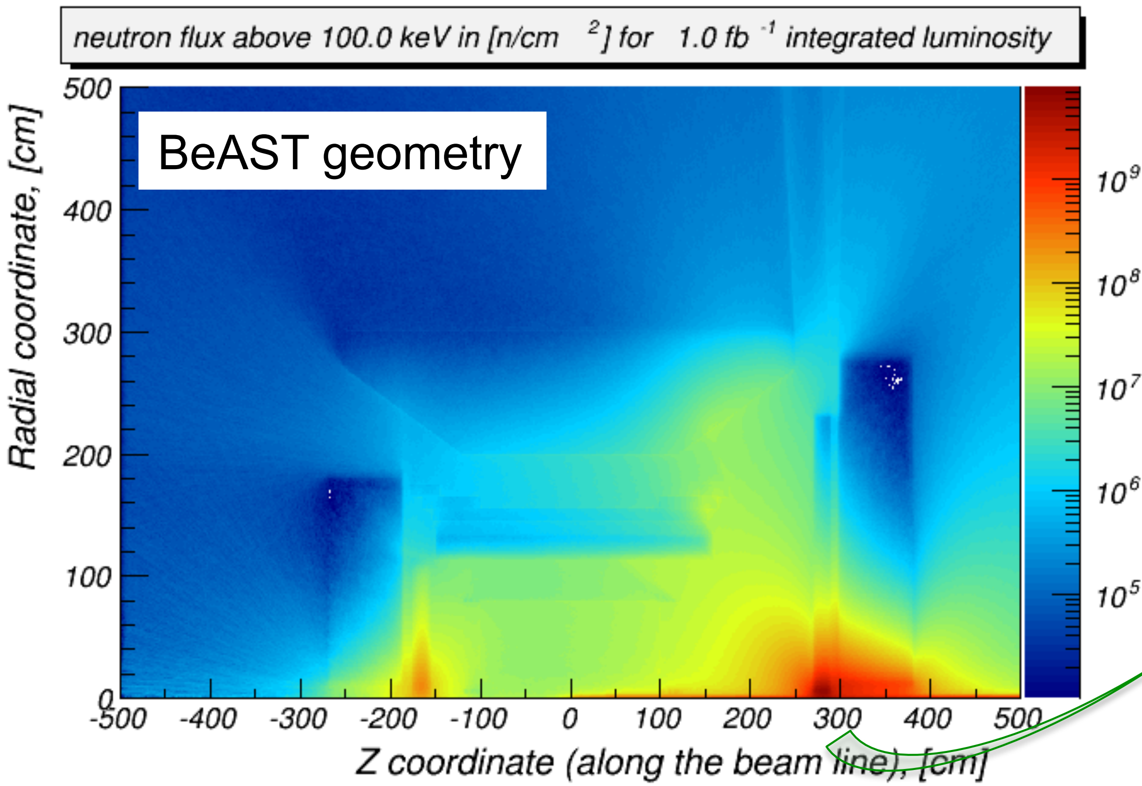
- Zero degree photon calorimeter
  - Excellent fast luminosity monitor
  - Subject to synchrotron damage

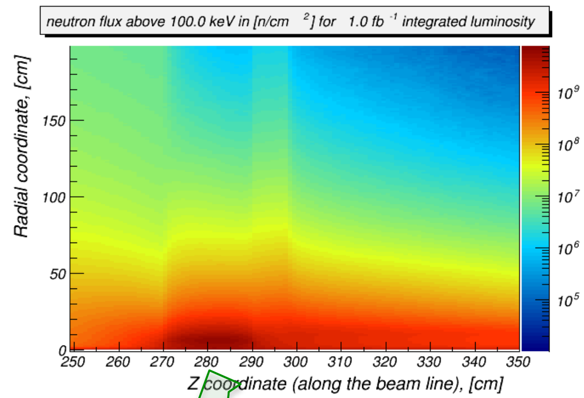
- Pair spectrometer
  - Low rate (tunable by the exit window thickness)
  - Calorimeters are outside of the primary synchrotron fan

-> modeling and adaptation to a particular IR design required; but no showstoppers identified so far

Neutron fluence from primary interactions

<u>The quantity</u>: Fluence = "a sum of neutron path lengths"/"cell volume" for N events





-> forward EmCal: up to ~5*10^9 n/cm^2 per fb^{-1} (*inside the towers*); perhaps ~5 less at the SiPM location;

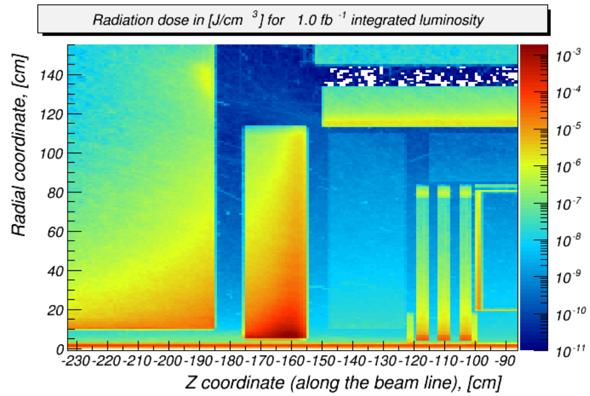
NB: "standard" EIC run at ~10^{33} cm^{-2}s^{-1} luminosity is 10 fb^{-1}

<u>The numbers look OK, but:</u>

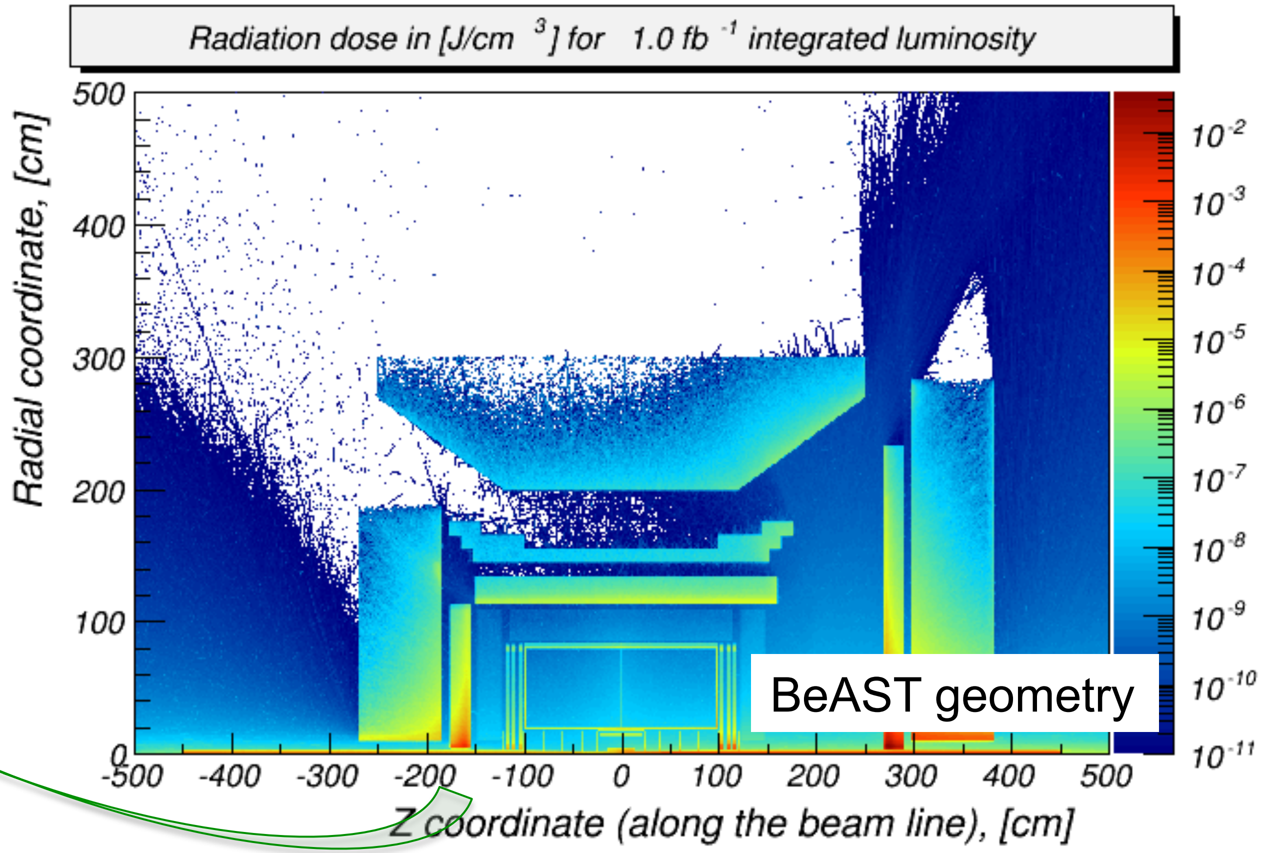
- Beam line elements not incorporated in the simulation
- Thermal neutrons are not accounted
- Close to beam line: ~10^{34} cm^{-2}s^{-1} over ~10 years would exceed ~10^{11} n/cm^2

Radiation dose from primary interactions

The (primary) quantity: E_{sum} = "a sum of dE/dx"/"cell volume" for N events



-> crystal EmCal: up to $\sim 2*10^{-3}$ J/cm^3 per fb^{-1} (close to beam line)



1 rad = 0.01 Gy & [Gy] = [J/kg] & PWO density ~8g/cm^3 -> ~250 rad/year

(at "nominal" luminosity $\sim 10^{33}$ cm^{-2} s^{-1})

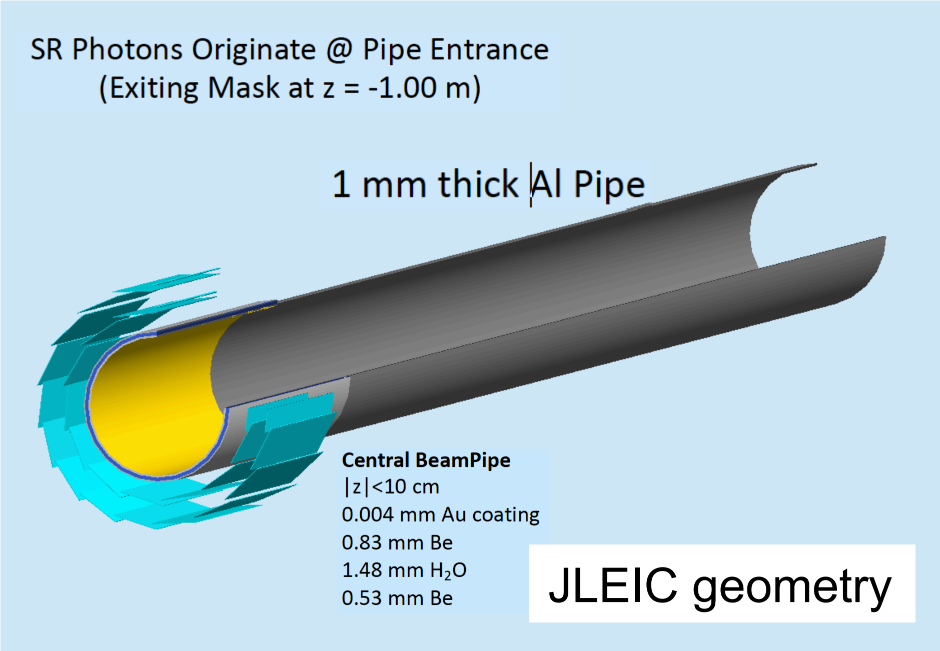
-> looks OK?

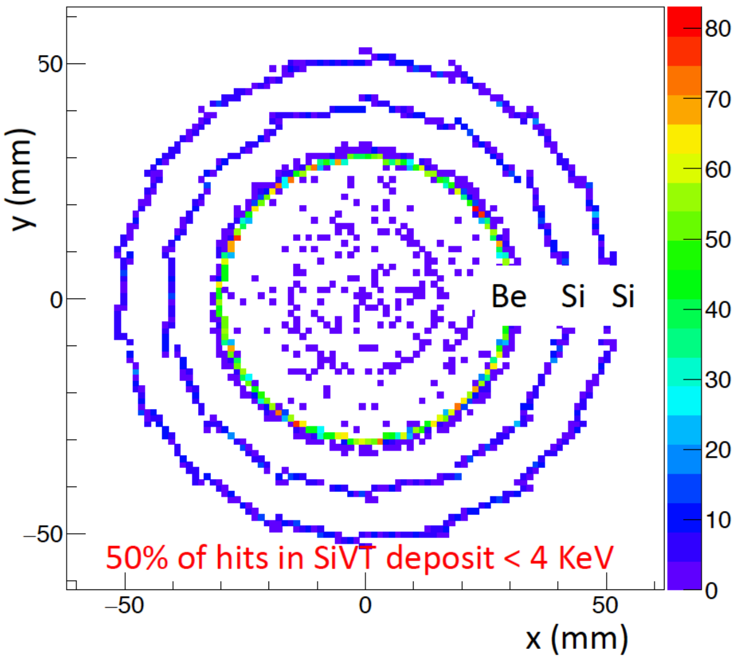
Synchrotron radiation

- Crossing angle (no strong electron bending at the IP) does not solve the synchrotron radiation problem completely ...
- ... because of the bending in Final Focusing Quads (FFQs)

- Need either to increase the beam pipe diameter at the IP or install masks or both

Synchrotron fan induced in FFQs hitting JLEIC SVT tracker after passing 24mm diameter mask at Z=-1m





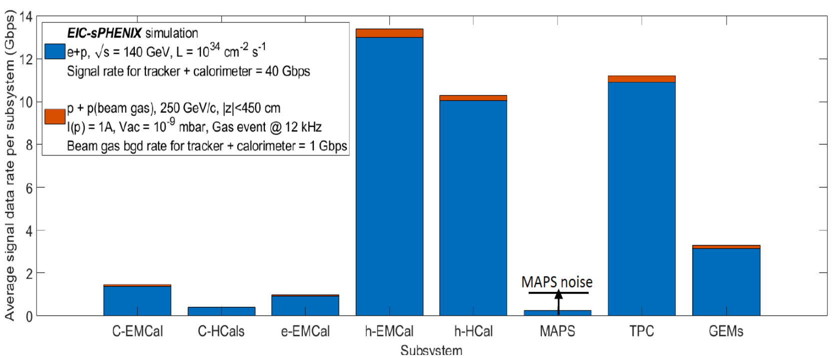
-> tedious optimization work is ongoing for both JLAB and BNL EIC designs

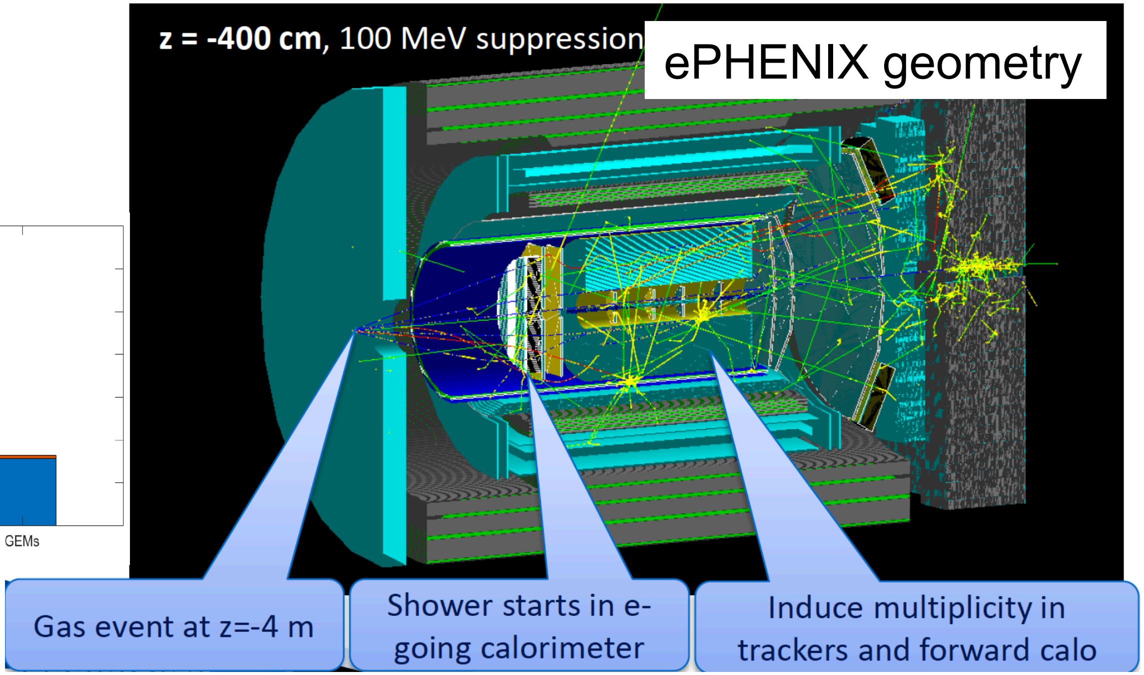
Beam-gas interaction

- Produced by hadron beam particles scattered off residual gas (mostly H_2) in the vacuum system
- Dynamic vacuum problem: synchrotron radiation heats the IR vacuum chamber walls, this causes outgassing, and subsequent hadronic scattering in a “fixed target” fashion, which floods the detector with secondary particles -> very hard to model!

Vacuum pressure	10^{-9} mbar
Beampipe temperature	Room temperature
Average atomic weight of gas	Hydrogen (H^2)
Molecular density (for 10 m pipe)	2.65×10^{10} molecules/cm^2
Luminosity (Ring-Ring)	10.05×10^{33} cm^{-2}s^{-1}
Bunch intensity (R-R) (e/p)	15.1 / 6.0 x 10^{10}
Beam Current (R-R) (e/p)	2.5 / 1 A
Bunch spacing (Ring-Ring)	8.7 ns → 1320 bunches
ElectronxProton beam energy	10 GeV x 275 GeV

Beam-gas events effect on the streaming readout @ EIC





Summary

- **Various EIC detector concepts developed already**
- **Design optimization work is ongoing**

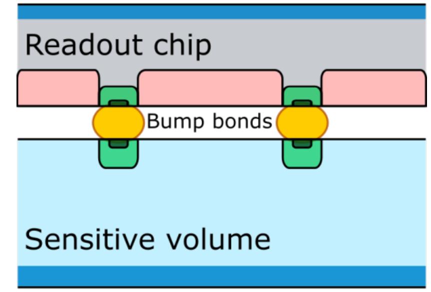
- **To first order both physics- and accelerator-driven requirements are defined and taken into account**

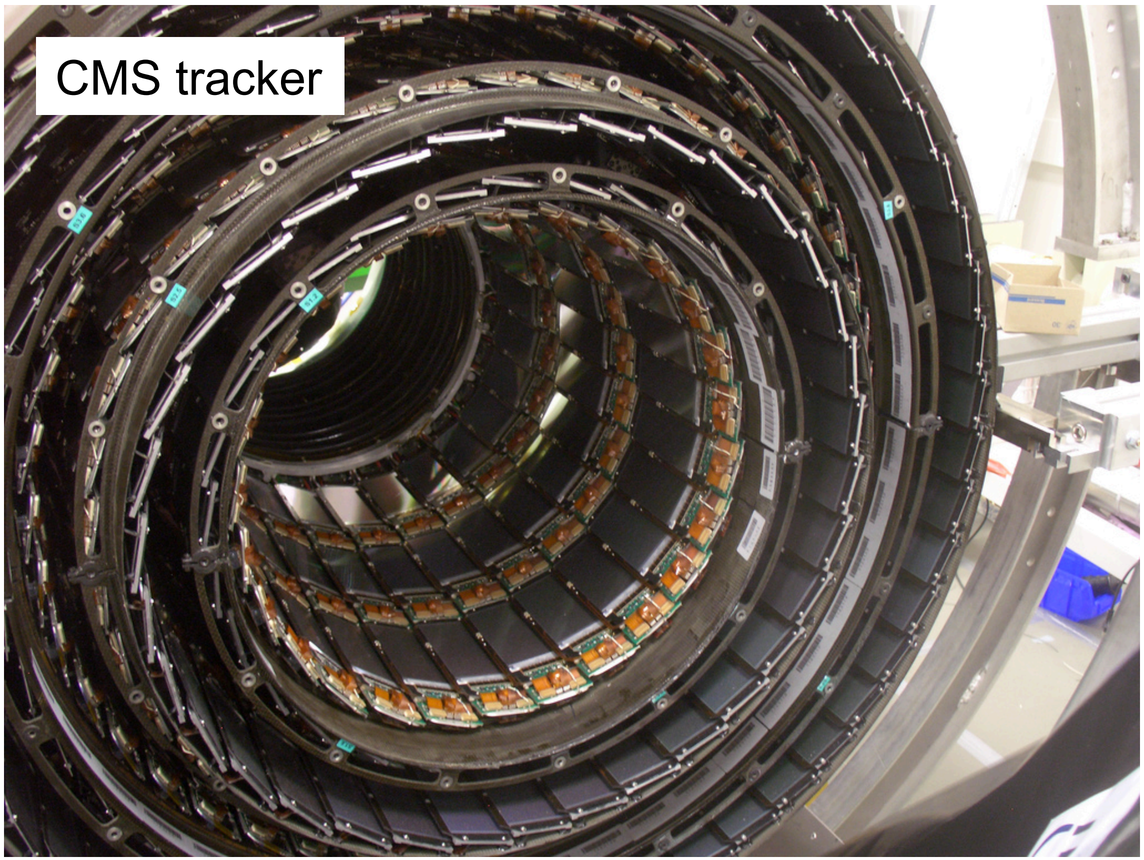
- **Manpower to join modeling and detector R&D effort is more than welcome!**

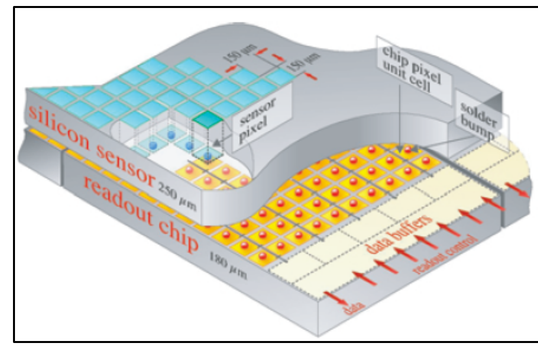
Backup

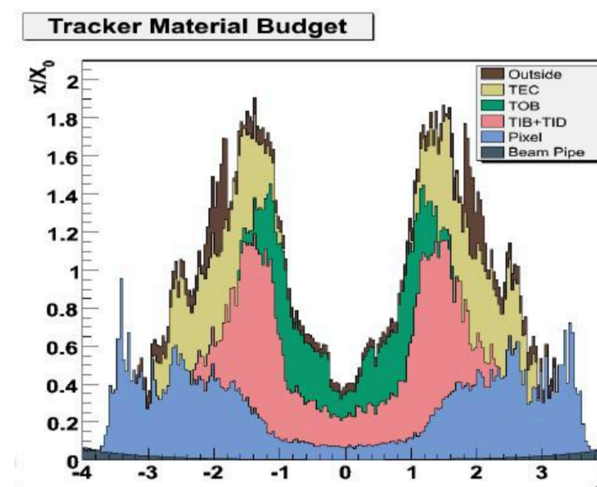
Hybrid silicon sensors

- Sensitive volume and readout electronics on separate chips
- Most commonly used in silicon vertex trackers
- Radiation tolerant and fast
- Material budget is an issue though







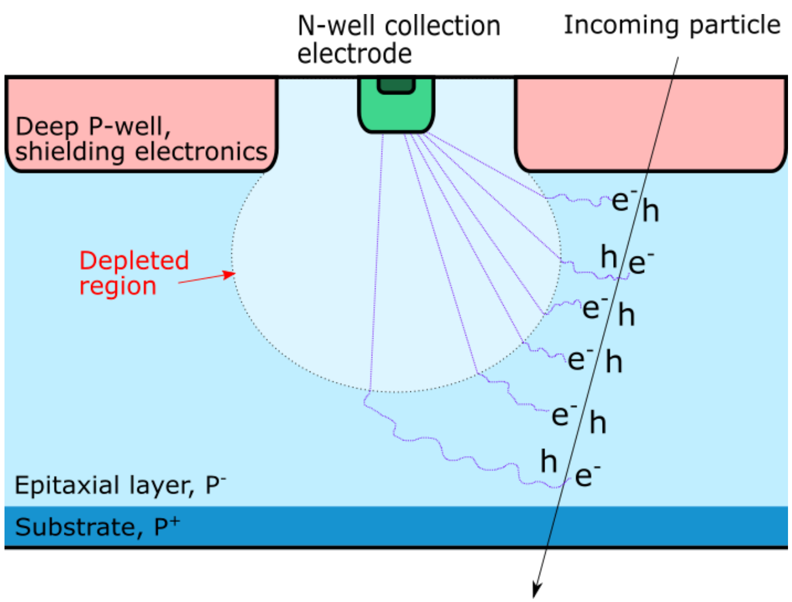


Impressive system: 10^7 channels; 200 m^2!

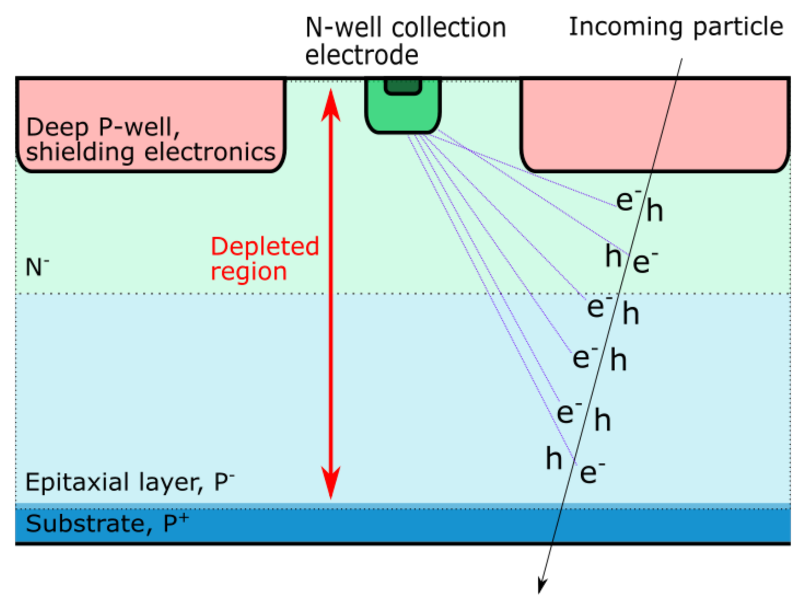
eRD18: depleted MAPS (DMAPS)

- 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



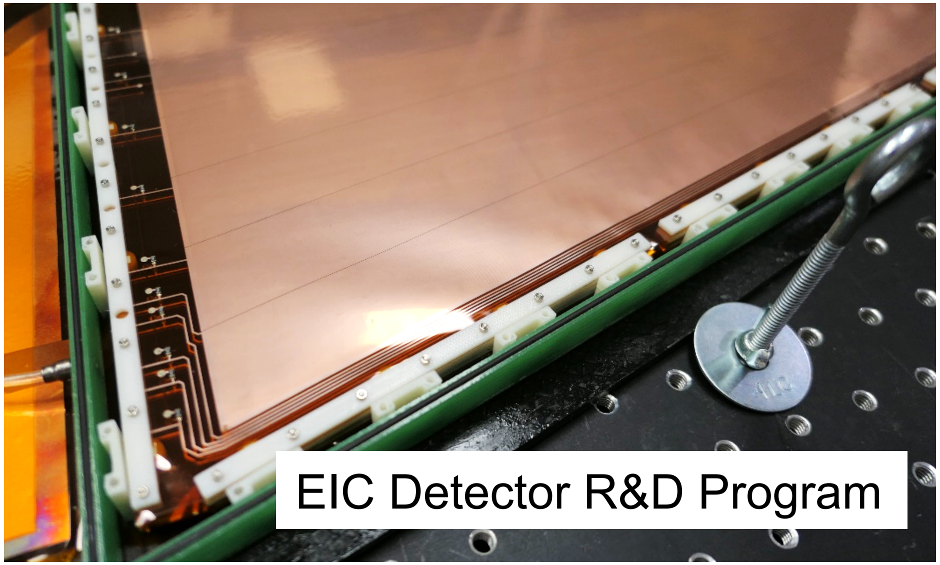
Standard process (MAPS)

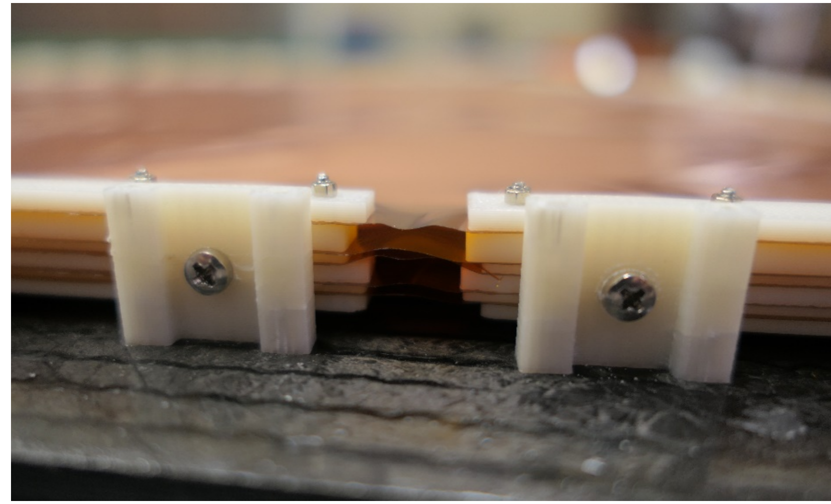


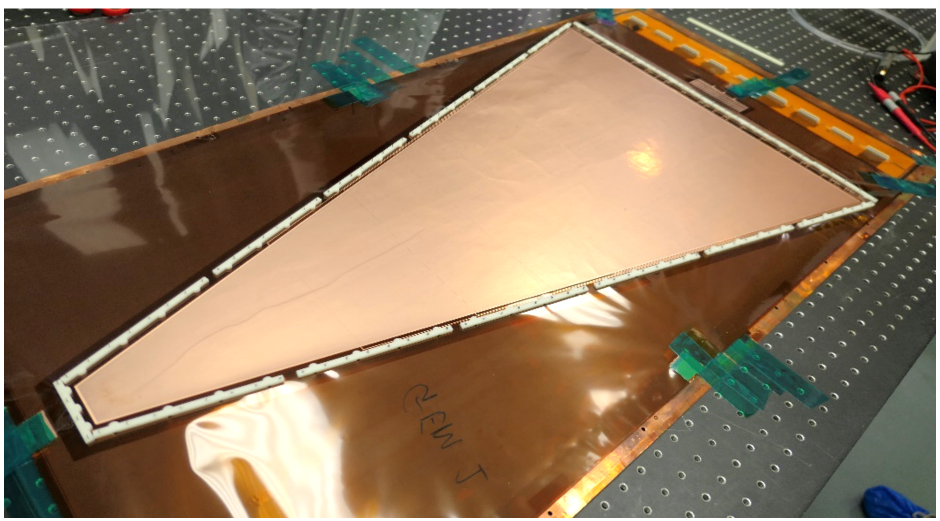
Modified process (DMAPS)

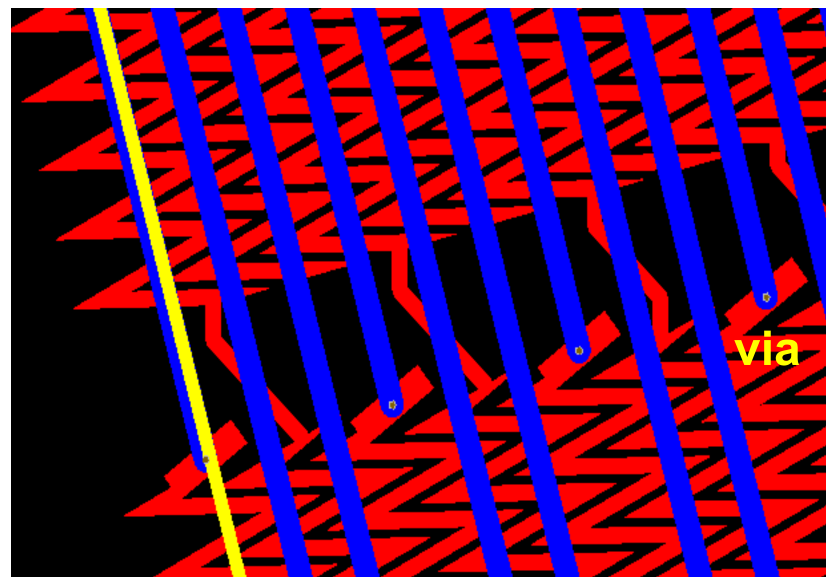
-> An EIC-detector-specific compromise between pixel size, material budget, power consumption and timing resolution needs to be found

eRD6: large (1D) planar GEM detectors





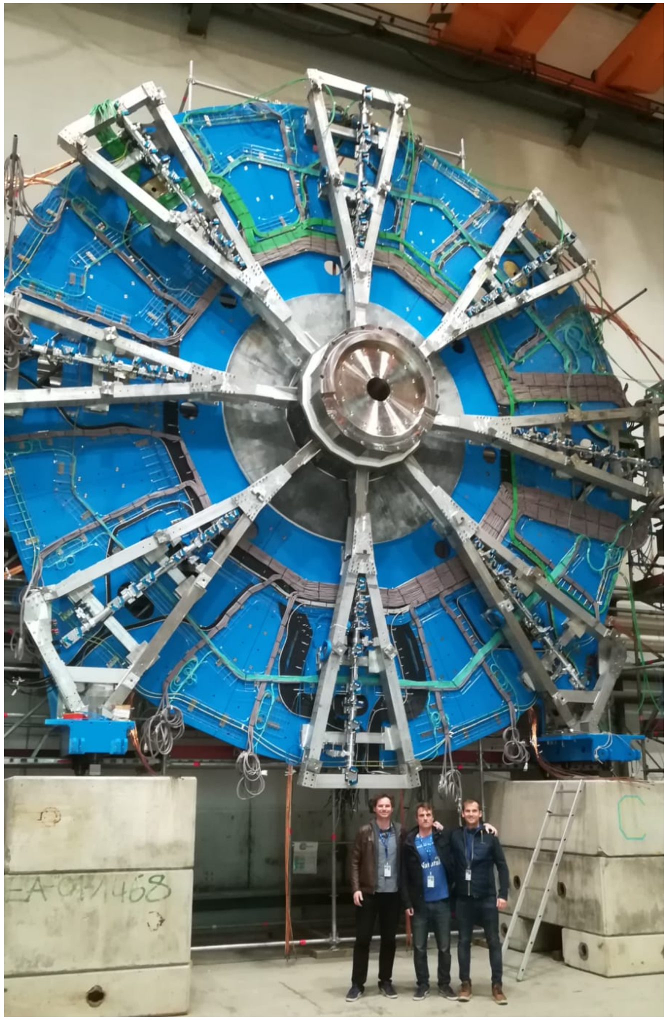


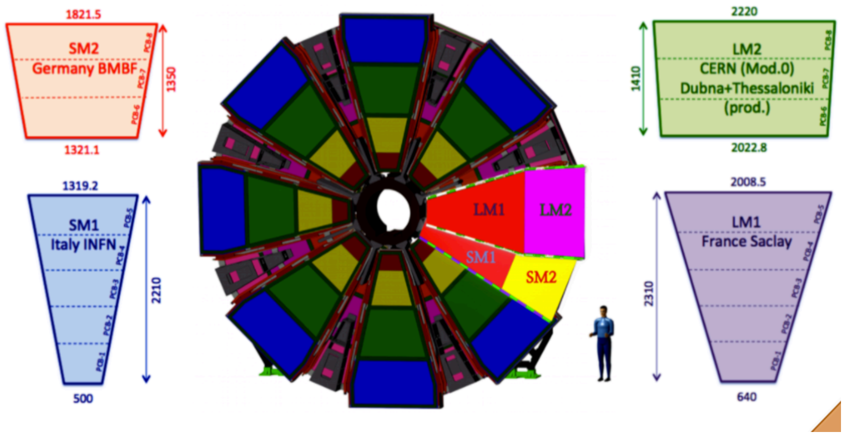


- Low mass, stretched carbon fiber frames
- High spatial resolution & low channel count zigzag charge sharing readout

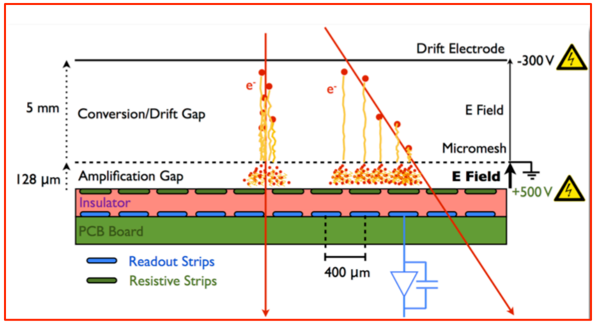
Planar Micromegas detectors

ATLAS New Small Wheel





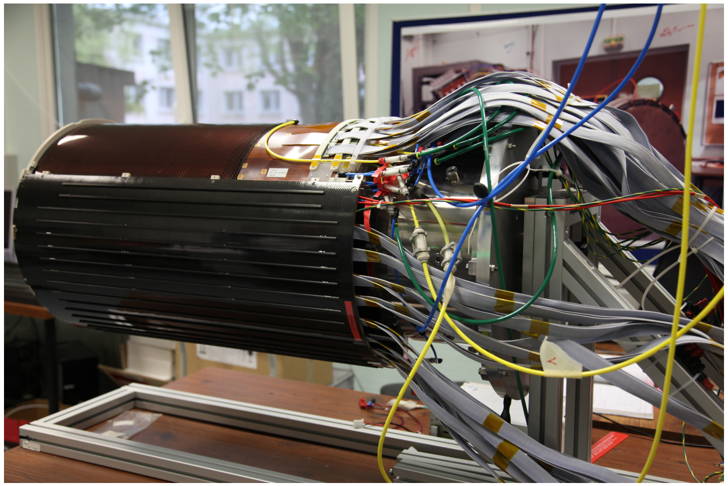
- 4 Types of detectors => 4 constructions sites
- Technology: 1200 m^2 of resistive Micromegas
- 2M channels

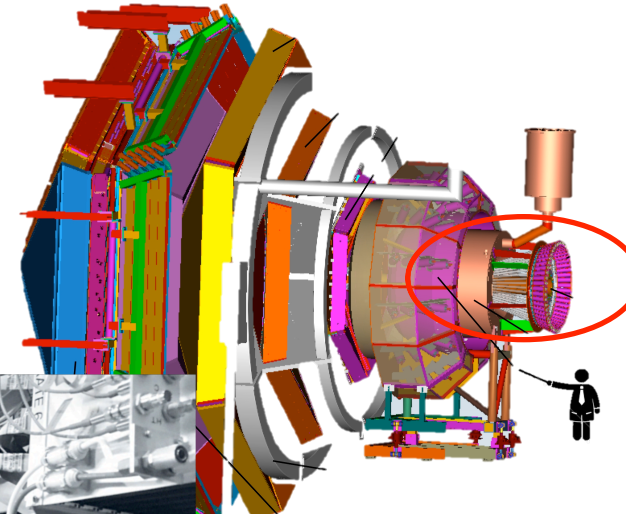


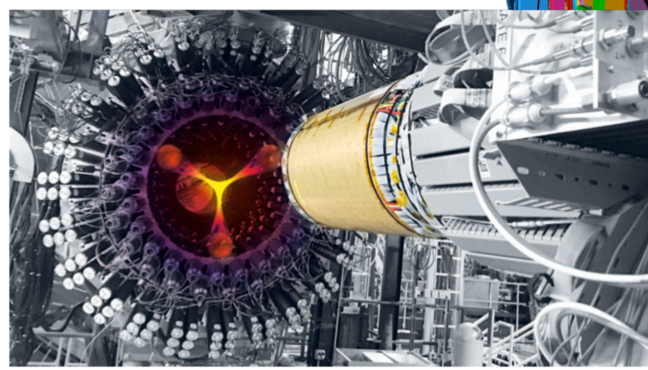
- Primary ionization in a short (few mm) drift gap
- Single-stage amplification in a high field 128μm gap
- Capacitive coupling to readout strips through the resistive layer

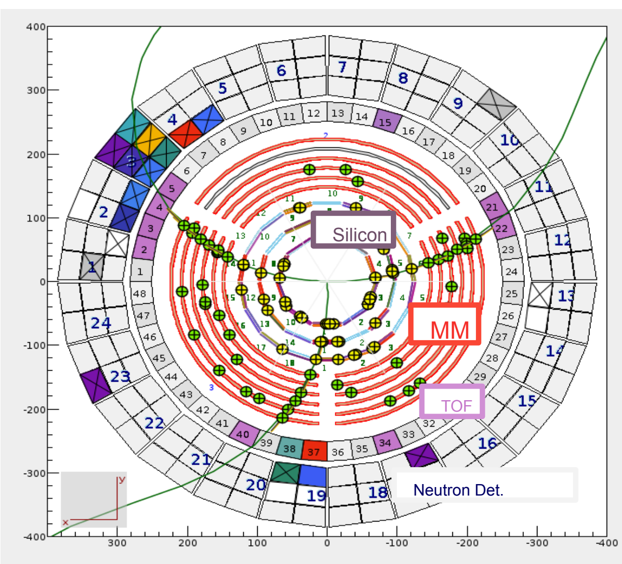
Curved Micromegas tracker

CLAS12 vertex tracker upgrade





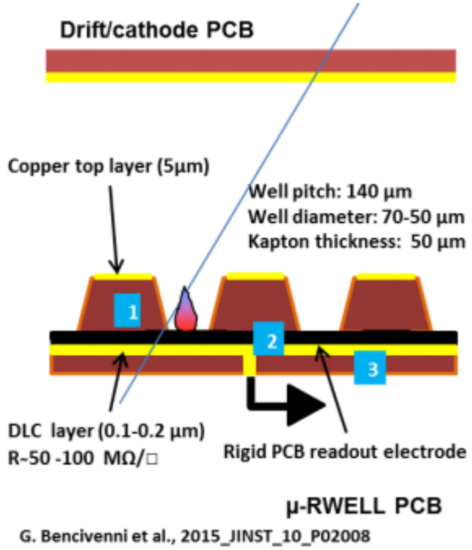


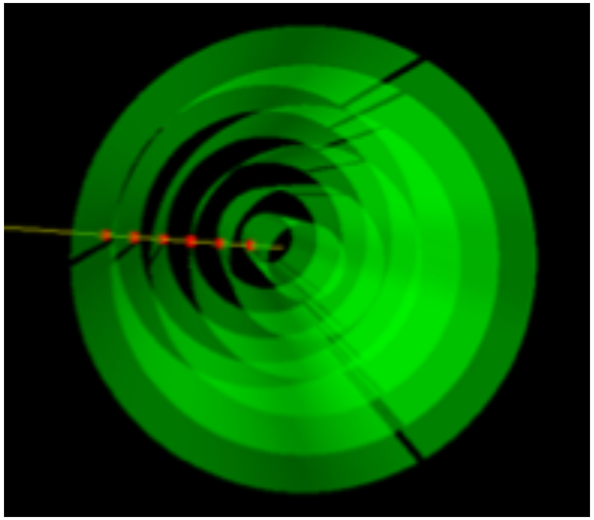


- 4 m² of Micromegas detectors
- Light-Weight Detectors (~0.5% of X_0 per layer)
- Limited space (~10 cm for 6 layers)
- High magnetic field (5T)
- Variable geometry (6 Layers with different R)
- High enough spatial resolution (~100μm)

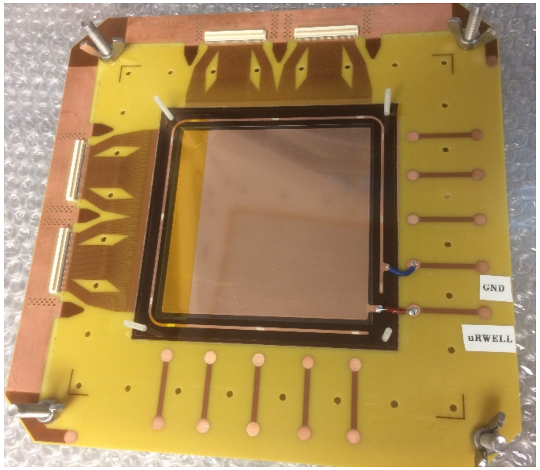
μRWELL trackers

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

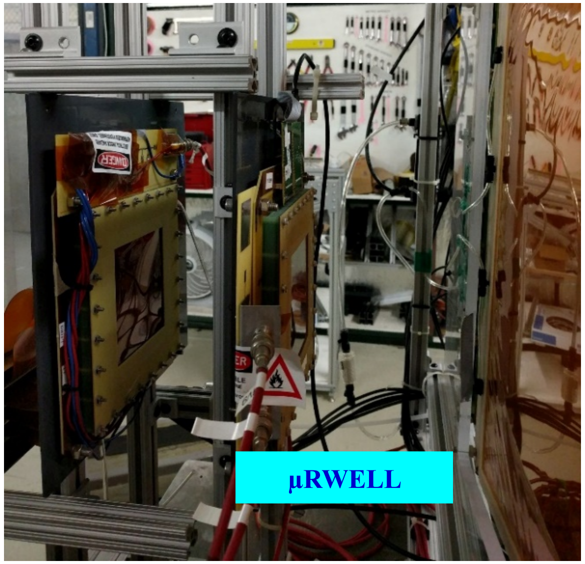




μRWELL with 2D X-Y readout



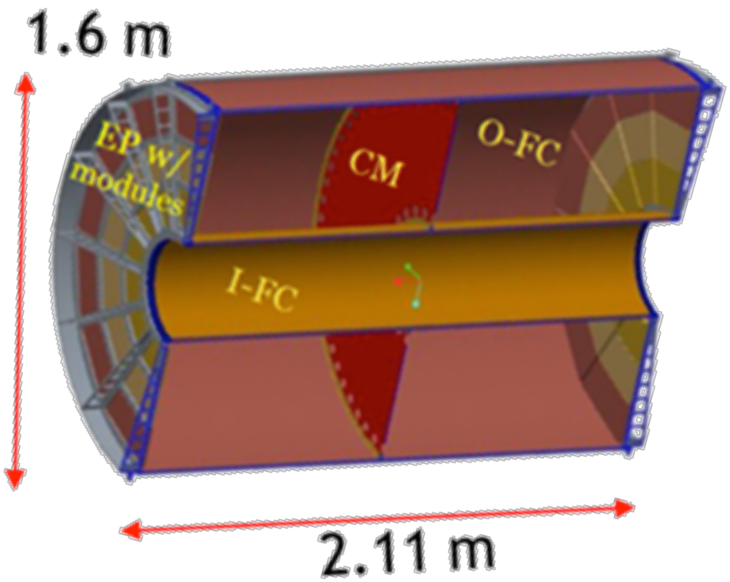
μRWELL in FNAL Test Beam



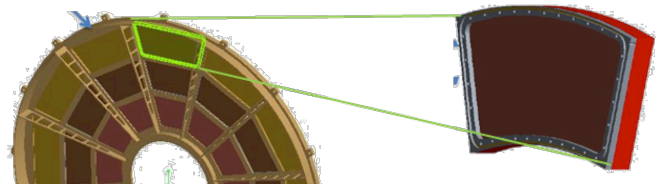
- Primary ionization in a short (few mm) drift gap
- Single-stage amplification in a high field 50μm gap (foil)
- Capacitive coupling to readout strips through the resistive layer

sPHENIX TPC as an EIC central tracker

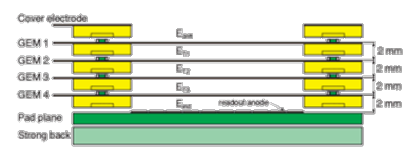
- Compact size, matching BaBar magnet
- High enough spatial resolution



- No gating grid, therefore usage in a continuous readout mode (and in a high luminosity environment)

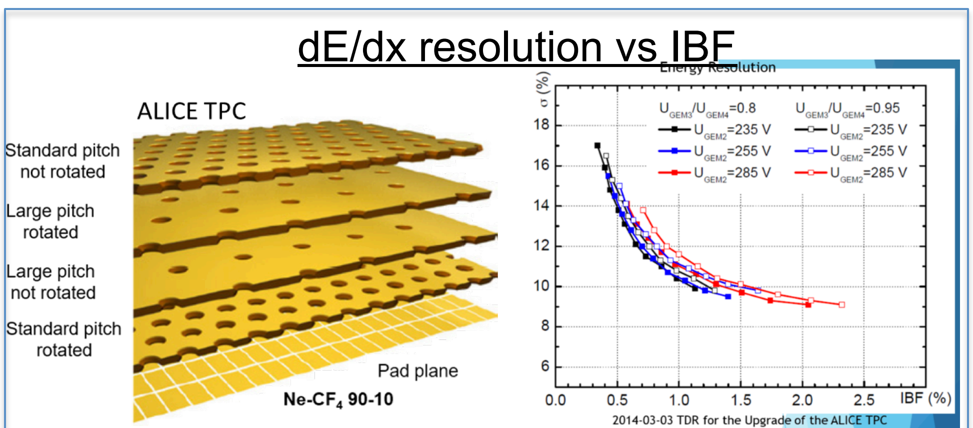


72 modules
2(z), 12(ϕ), 3(r)



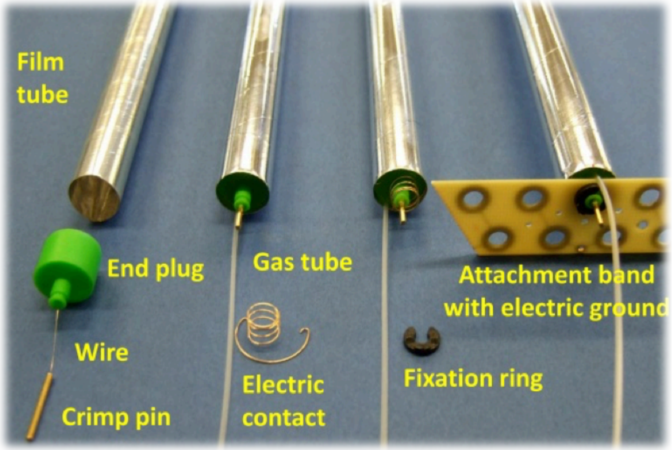
Quad-GEM Gain Stage
Operated @ low IBF

- **Caveats**
  - EIC will most likely need optimal dE/dx performance rather than small Ion Back Flow ...
  - ... which will require a different gas and a different HV setting ...
  - ... and in general the dE/dx resolution for such a small TPC yet needs to be demonstrated

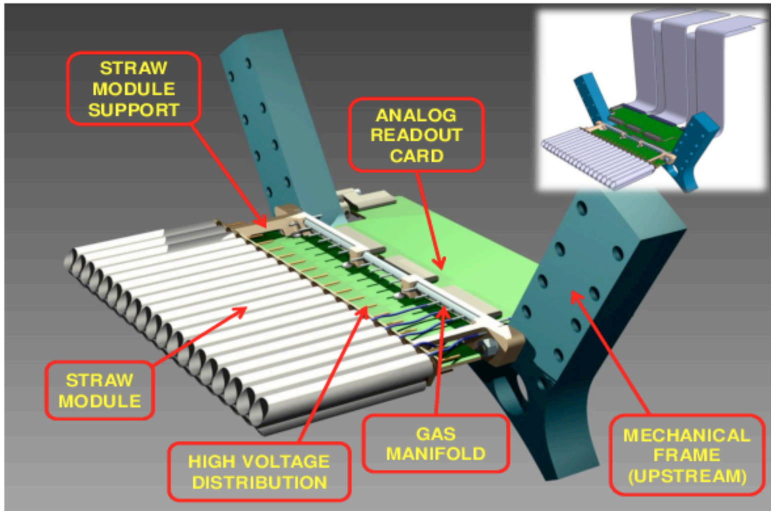


Central tracker: Straw Tubes (PANDA)

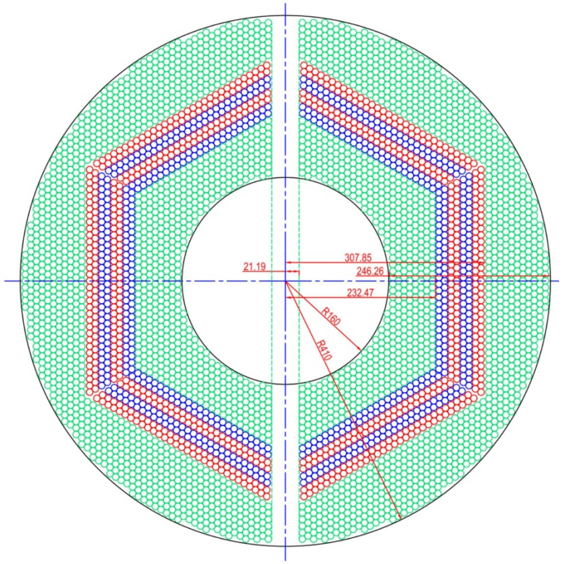
- 4636 straw tubes in 2 separated semi-barrels
- 23-27 radial layers in 6 hexagonal sectors
  - 15-19 axial layers (green) in beam direction
  - 4 stereo double-layers: ±3° skew angle (blue/red)
- Volume: R_{in} / R_{outr}= 150 / 418 mm, L~ 1650 mm
  - Inner / outer protection skins (~ 1mm Rohacell/CF)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

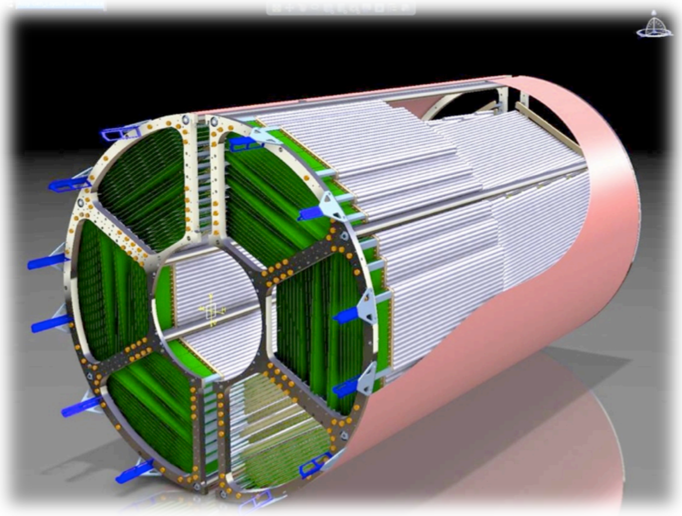


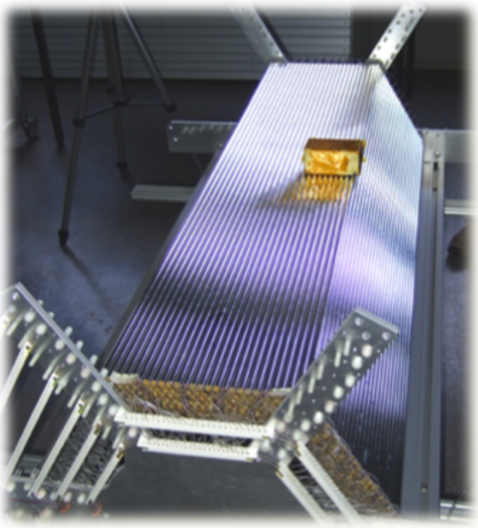
- Time & amplitude readout
  - $\sigma_{r\varphi}$ ~ 150 µm, σ_z ~ 2-3 mm (isochrone)
  - σ(dE/dx) < 10% for PID (p/K/π < 1 GeV/c)
- σ_p /p ~ 1-2% at B=2 Tesla (STT + MVD)
- X/X_0 ~ 1.25% (~ $^2/_3$ tube wall + $^1/_3$ gas)



Central tracker: Straw Tubes (PANDA)



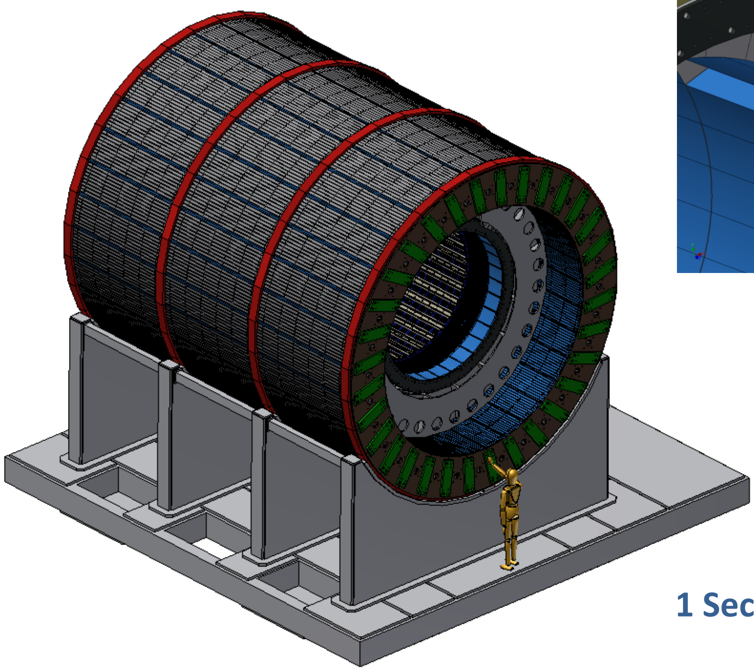


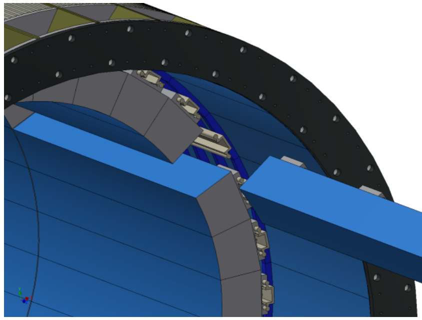


- Material budget at lowest limit (2.5 g per assembled straw)
- thinnest Al-mylar film, d=27µm, ∅=10mm, L=1400mm
- thin wall endcaps, wire fixation (crimp pins), radiation-hard
- self-supporting modules of pressurized straws (Δp=1bar)
  - close-packed (~20 µm gaps) and glued to planar multi-layers
  - replacement of single straws in module possible (glue dots)
- strong stretching (230kg wires, 3.2tons tubes)*, but no reinforcement needed

W/SciFi design: sPHENIX implementation

2(±η) x 32 (ϕ) = 64 Sectors

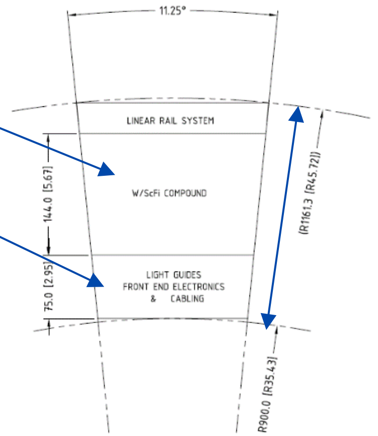


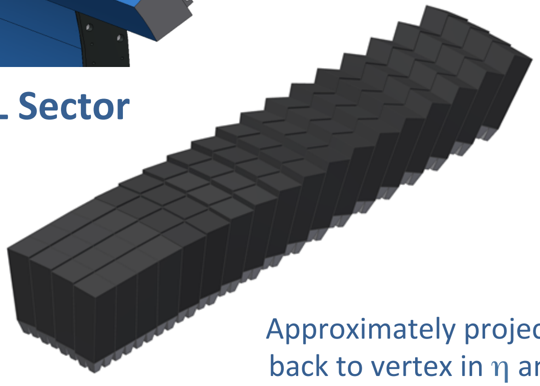


EMCAL Sector

~14 cm absorber (η=0)

7.5 cm readout

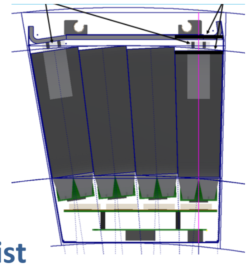




Approximately projective back to vertex in η and ϕ

1 Sector = 72 Blocks
= 288 towers

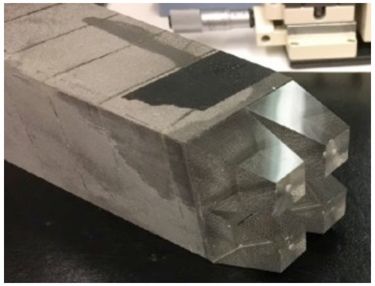
Module = Block/Reflector/Light Guides/SiPMs

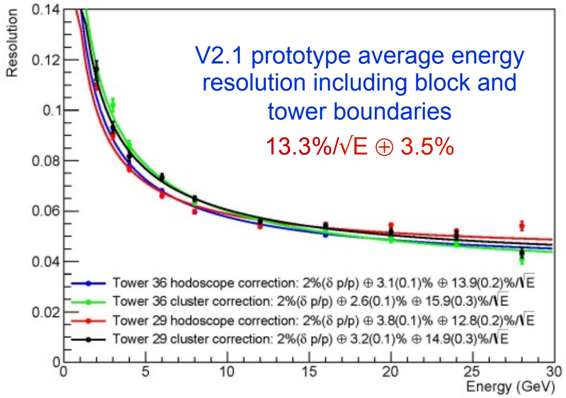


Blocks consist of 2x2 towers

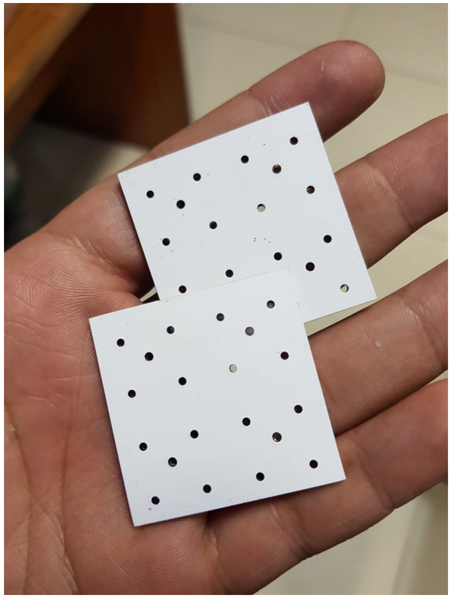
- Coverage: ± 0.85 in η, 2π in ϕ
- Segmentation: $\Delta\eta \times \Delta\varphi \approx 0.025 \times 0.025$
- Readout channels (towers): 72x256 = 18432
- Energy Resolution: $\sigma_E/E < 16\%/\sqrt{E} \oplus 5\%$
- Provide an e/h separation > 100:1 at 4 GeV
- Approximately projective in η and ϕ

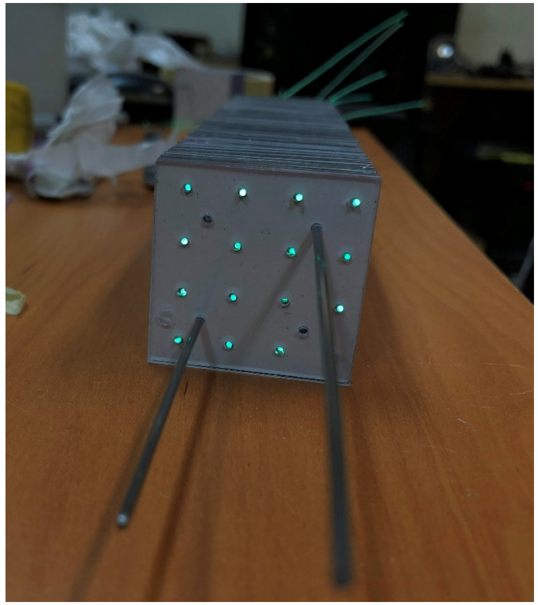
Light Guides
4 towers/block

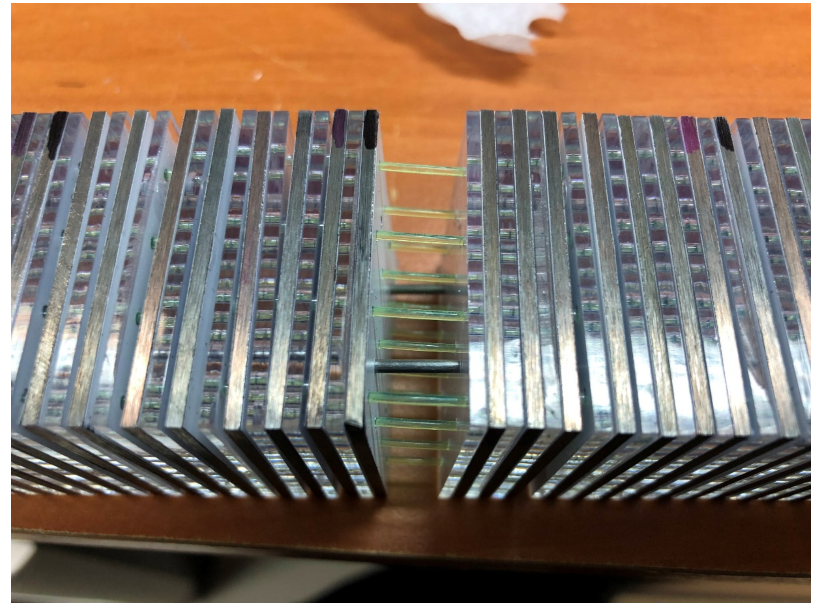




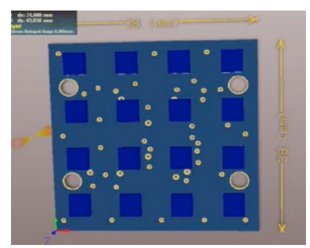
eRD1: W/Cu/SciTile shashlik e/m calorimeter

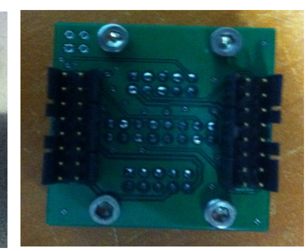






- Use W80/Cu20 alloy as absorber
- Read out each WLS fiber with an individual SiPM

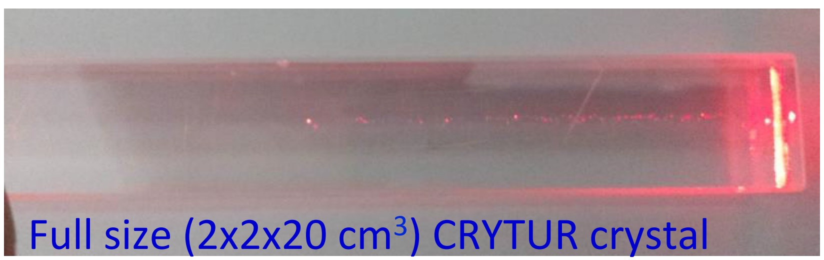




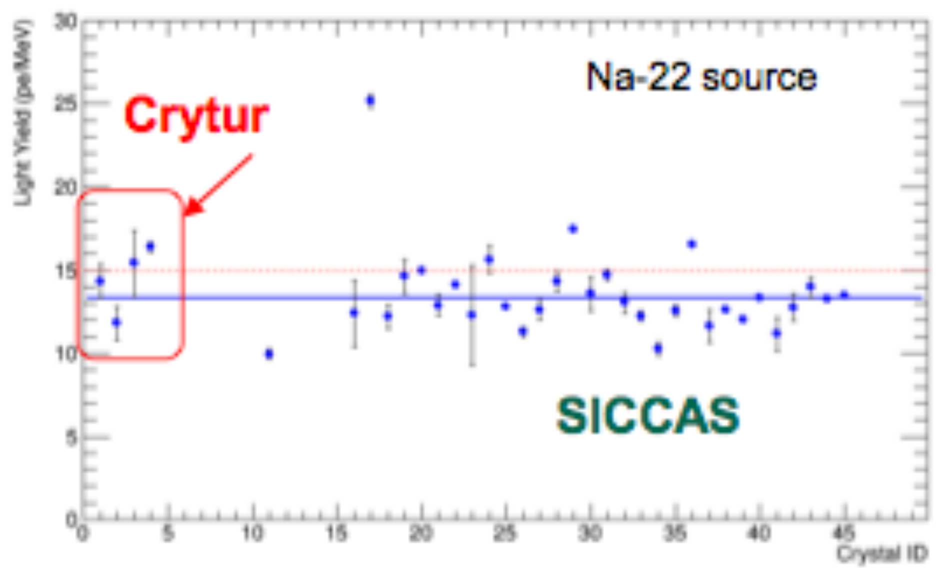
- A viable alternative solution to W/SciFi calorimeter ...
- ... potentially with a better light collection uniformity in a compact design

eRD1: Crystal Calorimetry

- e-going direction needs high precision calorimetry (~2%/√E)
- PbWO calorimeter option for this role, extensively used for high precision calorimetry (CMS, JLab, PANDA…) because of its excellent energy and time resolutions and its radiation hardness
- BTCP (Russia) produced high quality crystals in the past but out of business
- SICCAS (China) has difficulties maintaining good crystal quality
- Collaborative effort with PANDA to qualify CRYTUR (Czech Republic)


Full size (2x2x20 cm^3) CRYTUR crystal

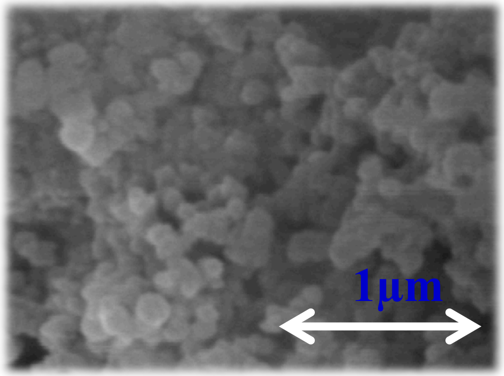
Light Yield for Crytur and SICCAS



- 2017: chemical analysis ongoing
- CUA: growing crystals for faster turnaround time?

New materials for EIC calorimetry

- **Ceramic glass as active calorimeter material:**
  - More cost effective that PWO
  - Easier to manufacture
  - Better optical properties (?)



SEM image of recrystallized $BaO*2SiO_2$ at 950°C

  - Technology: glass production combined with successive thermal annealing (800 – 900°C)

Material/ Parameter	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Interact Length (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
(PWO)$PbWO_4$	8.30	0.89 0.92	2.00	20.7 18.0	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
$(BaO*2SiO_2)$:Ce glass	3.7	3.6	2-3	~20		440, 460	22 72 450	>100	10 *(no tests >10krad yet)*	Scint.	51
$(BaO*2SiO_2)$:Ce glass loaded with Gd	4.7-5.4	2.2		~20		440, 460	50 86-120 330-400	>100	10 *(no tests >10krad yet)*	Scint.	58

Also: $(BaO*2SiO_2)$:Ce shows no temperature dependence

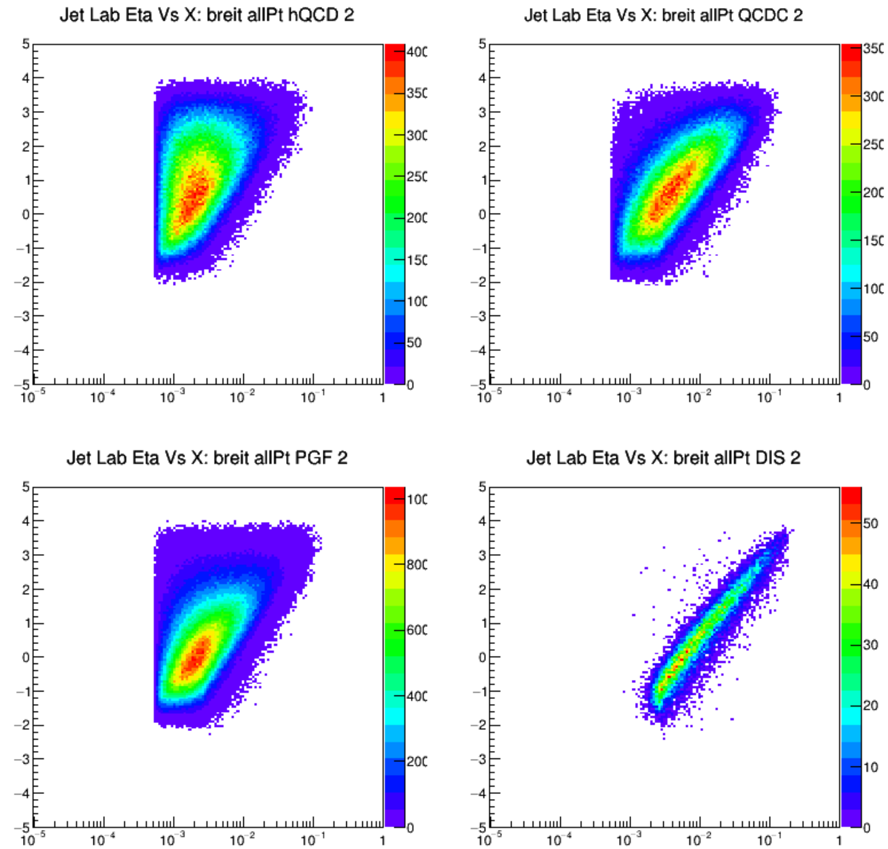
Hadronic calorimetry for EIC

- Hadronic energy resolution, especially in the forward endcap, is important for several EIC physics measurements

- Requirements:
  - Compactness
  - Immunity to the magnetic field
  - High (enough) energy resolution
  - Reasonable cost
  - Other (minimal neutron flux, etc)

- Pending questions:
  - Should one stick to the compensated calorimeter design (which by the way never showed high energy resolution for jets) or consider other options (dual-readout or dual-gate concepts, high-granularity calorimetry)?
  - How at all one can get a decent performance out of a 5-7λ deep HCal?

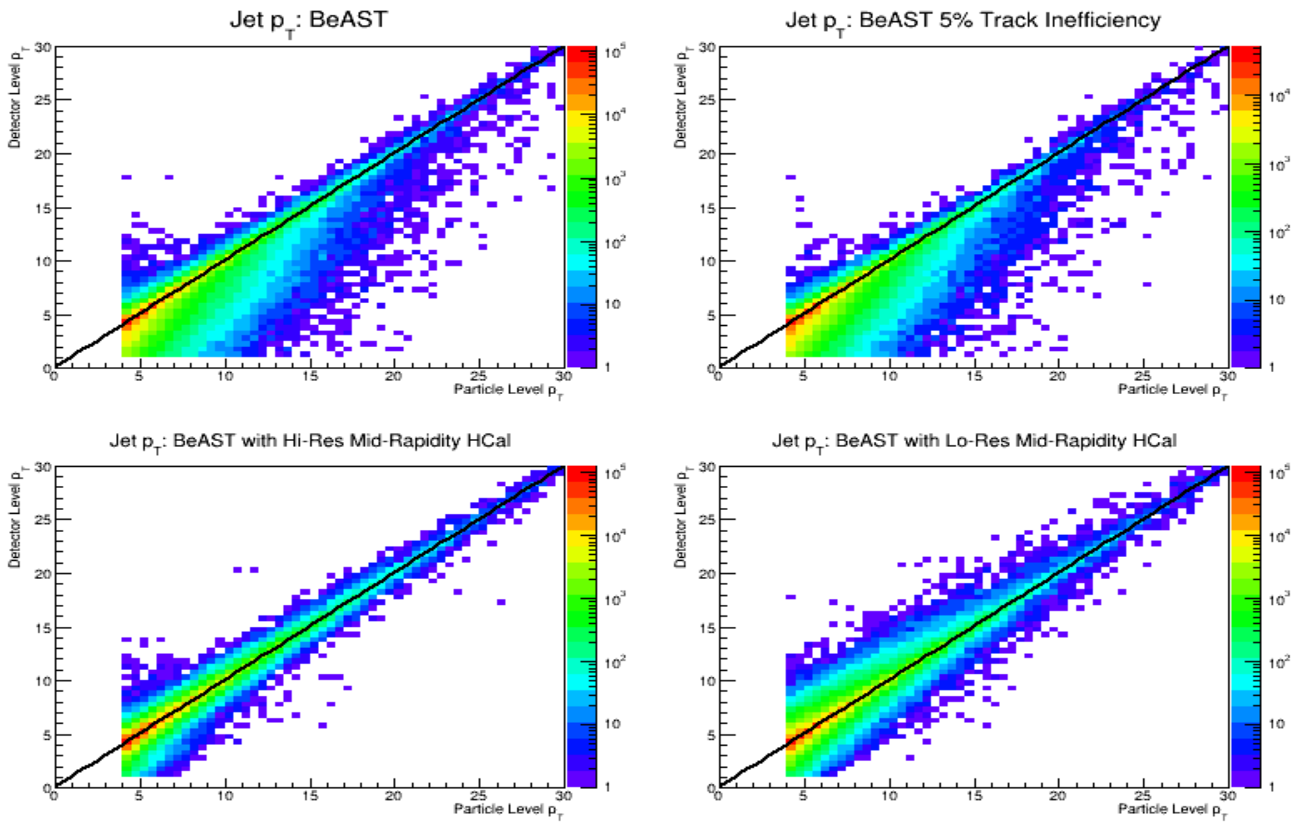
[Jet kinematics for various MC processes]



Hadronic calorimeter in the barrel

Jet study for BeAST: ep-events, 20 x 250 GeV, 10 < Q^2 < 100 GeV^2

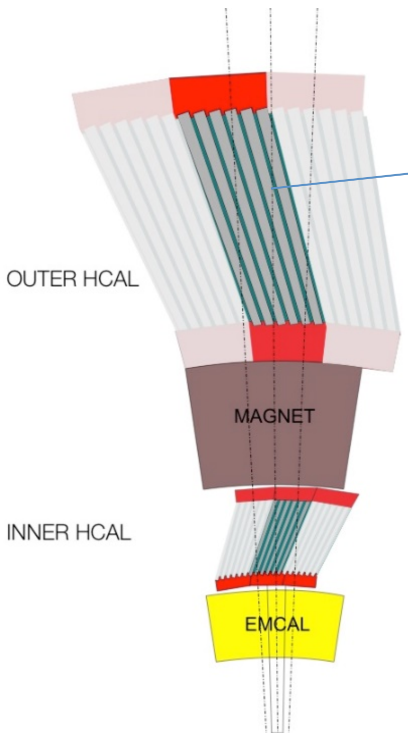
- eic-smear pass in a PFA-like fashion (check P_t reconstruction quality)

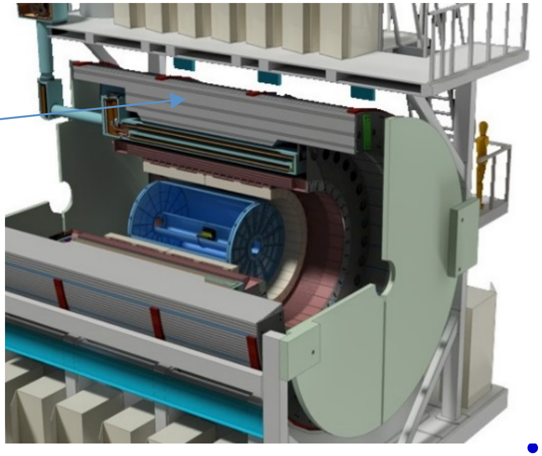


- Here Hi-Res HCal is ~35%/√E + 2% (ZEUS) ...
- ... and Lo-Res HCal is ~85%/√E + 7% (CMS)

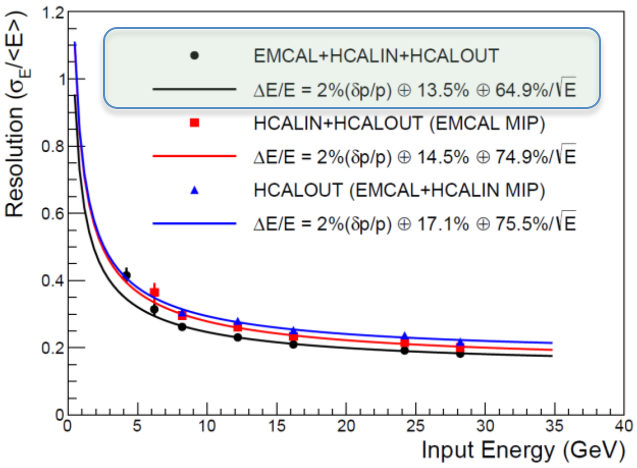
-> So it does make a difference

sPHENIX Hadron Calorimeter





- HCAL steel and scintillating tiles with wavelength shifting fiber
  - **Outer HCal (outside the solenoid)**
  - **$\Delta\eta \times \Delta\varphi \approx 0.1 \times 0.1$**
  - **1,536 readout channels**
- SiPM Readout
- Uniform fiducial acceptance $-1<\eta<1$ and $0<\varphi<2\pi$; extended coverage $-1.1<\eta<1.1$ to account for jet cone

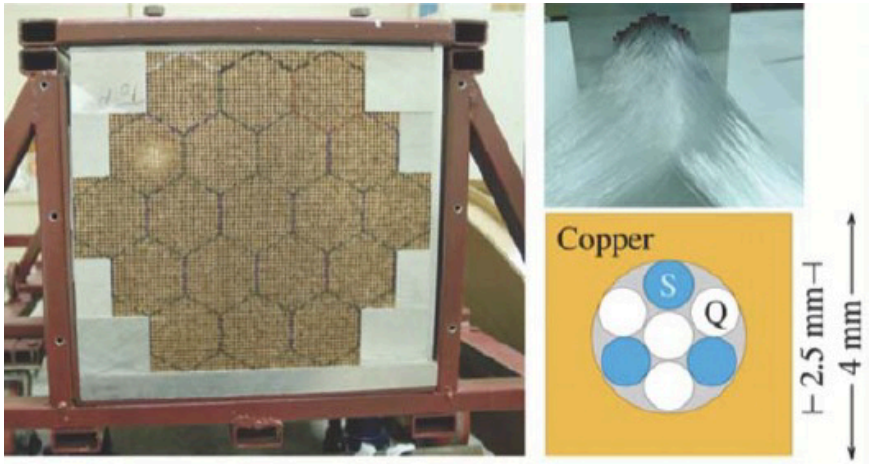


- Outer HCAL $\approx 3.5\lambda_I$
- Magnet $\approx 1.4X_0$
- Frame $\approx 0.25\lambda_I$
- EMCAL $\approx 18X_0 \approx 0.7\lambda_I$

Dual readout hadronic calorimetry?

The idea:

- Abandon built-in compensation (and raise sampling fraction)
- Use two types of fibers as active media (scintillating and clear ones)
- Measure Cherenkov light in addition to the scintillation one and use the ratio of two to correct for the f_{em} fluctuations on event-by-event basis

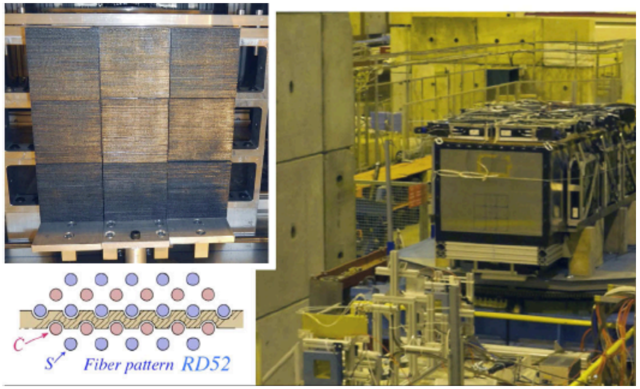


Performance attained so far:

- DREAM (Cu/fiber): ~65%/√E + 0.6%
- RD52 (Pb/fiber): ~70%/√E

Applicability at EIC is problematic:

- Cumbersome construction process
- So far only a PMT configuration (although a small prototype with SiPMs was tried out already)



Dual-gate hadronic calorimetry?

- Large fluctuations in ‘invisible’ energy (nuclear binding energy) main cause of poor resolution
- Main mechanism of production of **n** is spallation (except for U), can be thought as evaporating nucleons from excited nuclei
- Kinetic energy of **n** correlated with ‘invisible’ energy

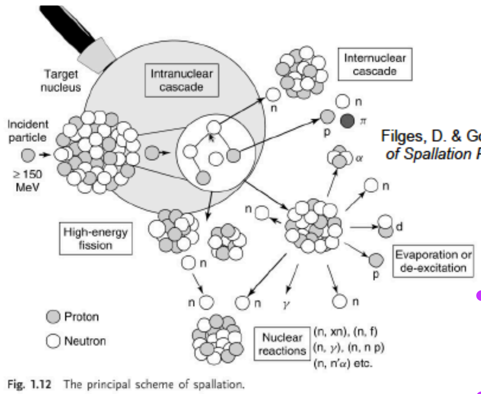
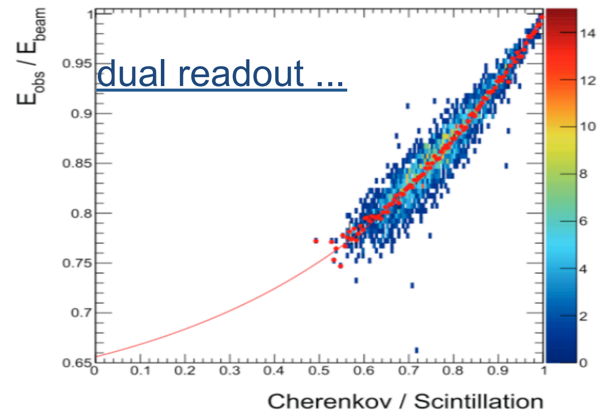


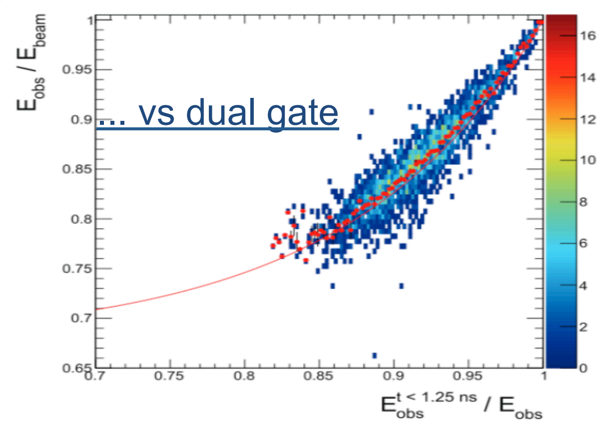
Fig. 1.12 The principal scheme of spallation.

Filges, D. & Goldenbaum, *Handbook of Spallation Research*, Wiley, 2010

90% between 0.1 and 10 MeV

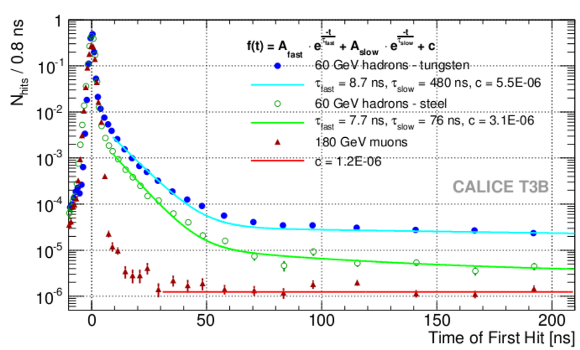
- Thermalization is mainly due to elastic scattering on hydrogen
- Mean free path ~ 20 cm, t ~ 15ns





First measurements by ZEUS in the 90-th; Recently repeated by

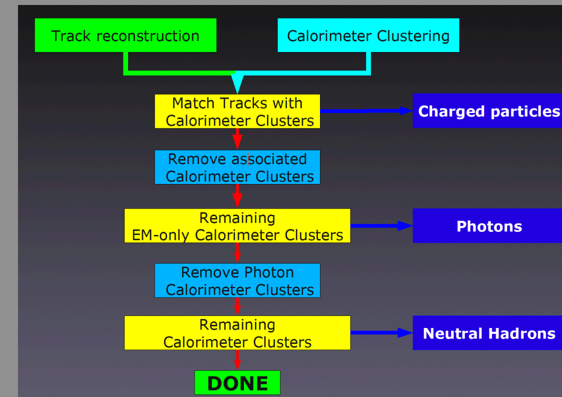
- DREAM
- RD52 Collaboration
- CALICE Collaboration



CALICE (Fe/Sc; ~8ns fall-down)

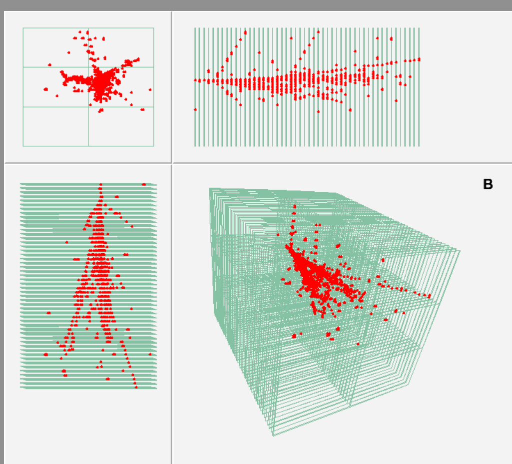
High granularity calorimetry & PFA?

Attempt to measure the energy/momentum of each particle in a hadronic jet with the detector subsystem providing the best resolution



The idea

Replace the traditional tower structure with very fine granularity
Few 1,000 channels → few 10,000,000 channels
Option to reduce resolution on single channels to 1 – 2 bits (digital readout)



Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion	If goal is to achieve a resolution of 30%/√E →		**$\leq 0.24^2\ E_{jet}$**

18%/√E

EIC environment: particularly suited for PFAs, due to low particle multiplicity and low momenta

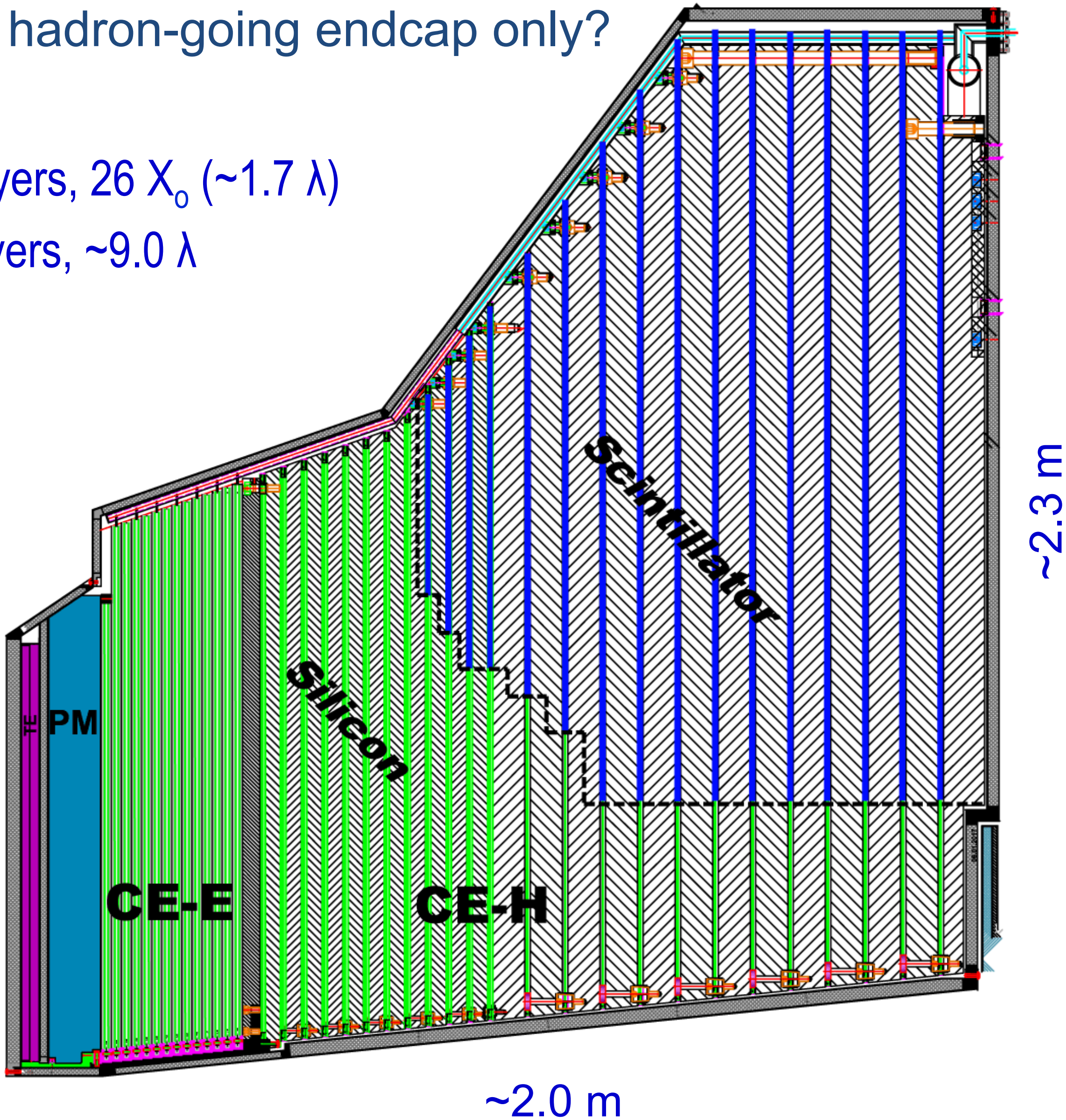
CMS forward calorimeter upgrade

- Use this technology in the hadron-going endcap only?

- **CE-E**: Si and Cu/CuW/Pb, 28 layers, 26 X_o (~1.7 λ)
- **CE-H**: Si+Scint and Steel, 24 layers, ~9.0 λ

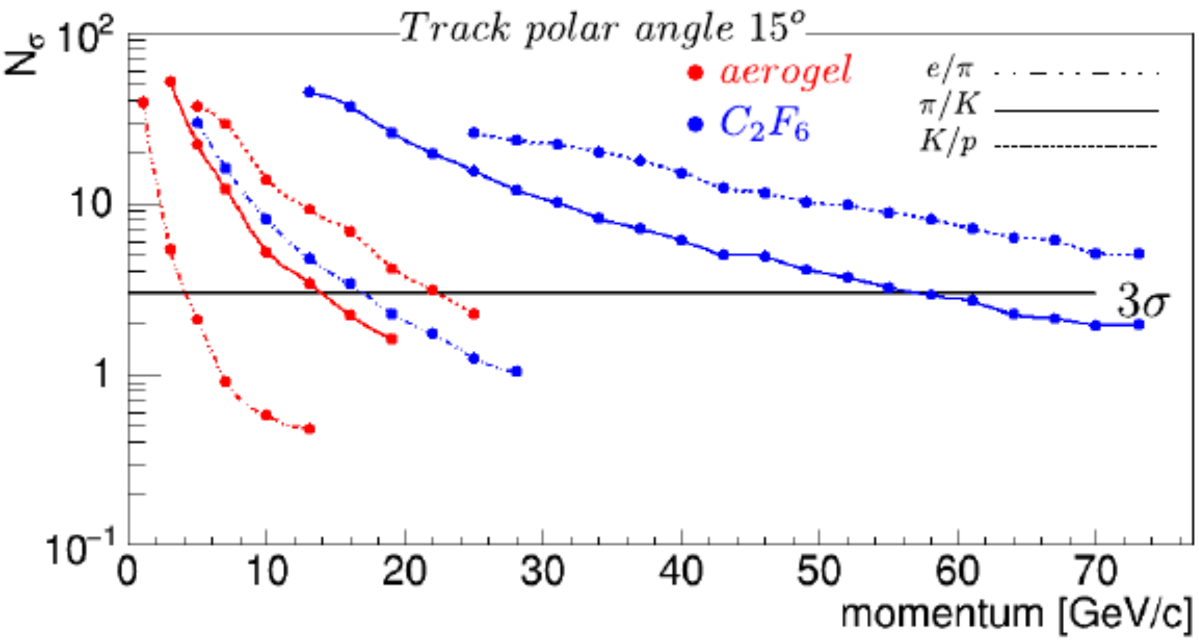
- 1.5 < η < 3.0
- ~600 m^2 of Si,
- ~500 m^2 of scintillator
- ~6M Si channels

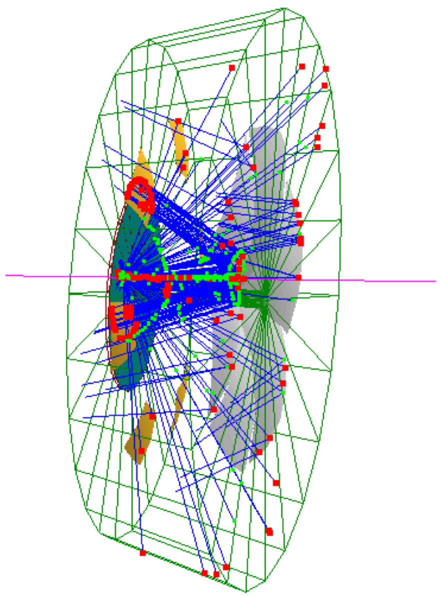
-> this would be pretty much the size of the EIC “ideal” endcap calorimeter!



EIC hadron endcap: dual radiator RICH

dRICH: use a very successful HERMES-like configuration with two radiators (here: n=1.02 aerogel and C_2F_6 gas) in order to provide continuous coverage with >3σ π/K separation in the whole required EIC hadron-going endcap momentum range, so from lowest momenta up to ~50 GeV/c



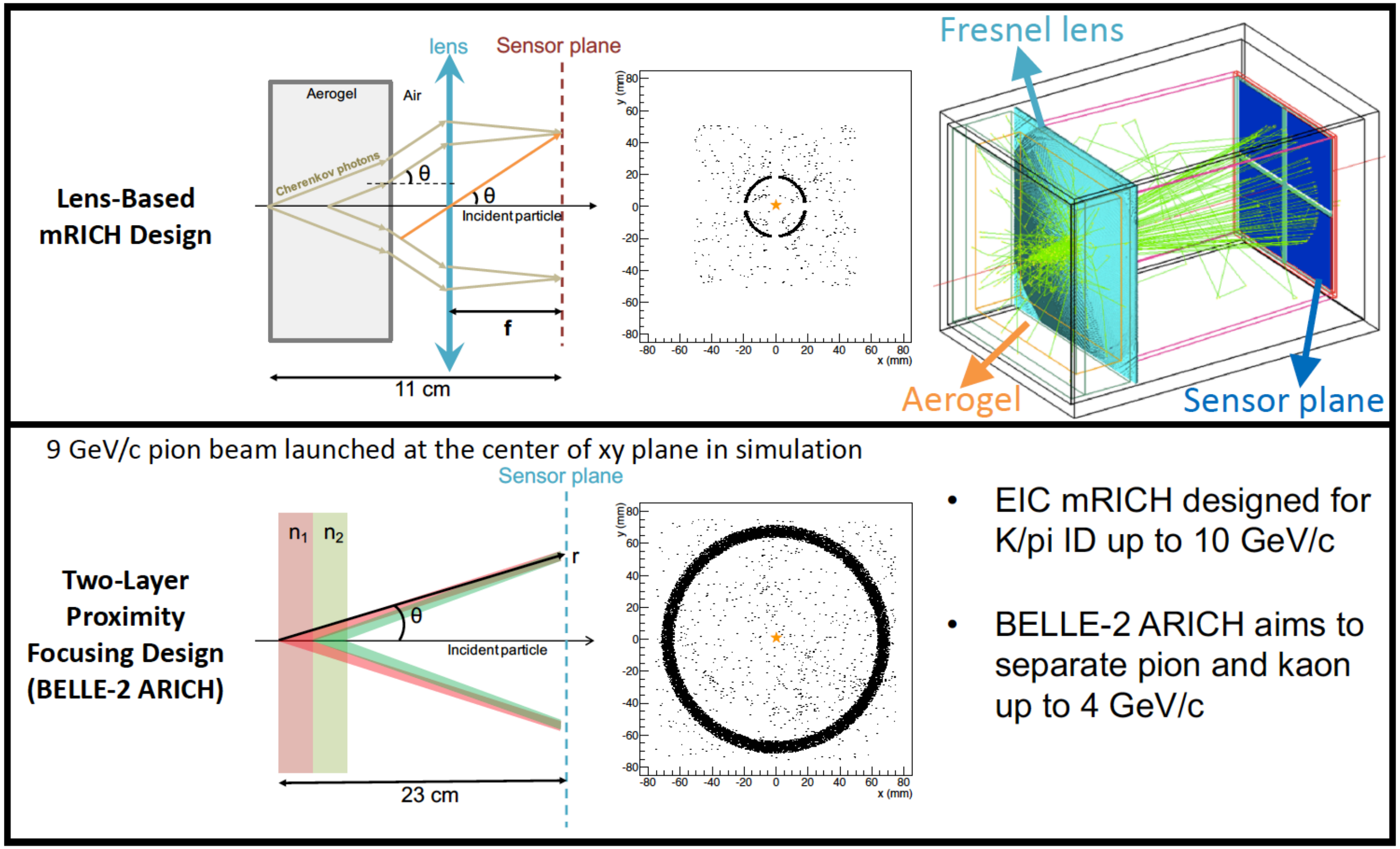


-> Note: one can also consider a pair of independent RICH detectors, where gaseous RICH may then also work in UV range

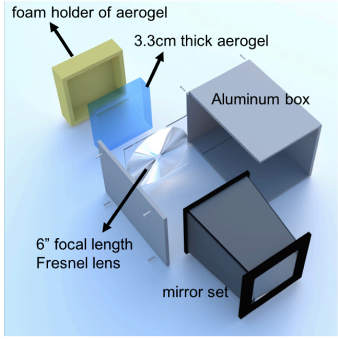
- **Caveats**
  - At most ~1m of “linear” space is available (relatively short radiator -> lower photon yields)
  - Strong solenoid fringe field (tracks are bent -> blurry rings -> less separation power)

EIC electron endcap: modular RICH

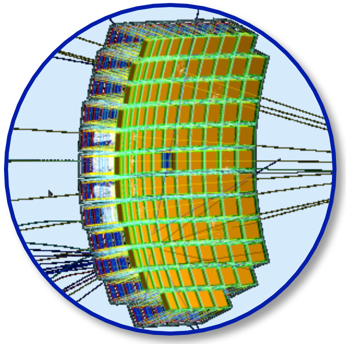
mRICH: use aerogel in a configuration with a Fresnel lens instead of the "Belle II – like" proximity focusing configuration



- EIC mRICH designed for K/pi ID up to 10 GeV/c
- BELLE-2 ARICH aims to separate pion and kaon up to 4 GeV/c



Single module



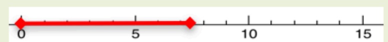
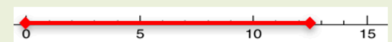
EIC endcap matrix

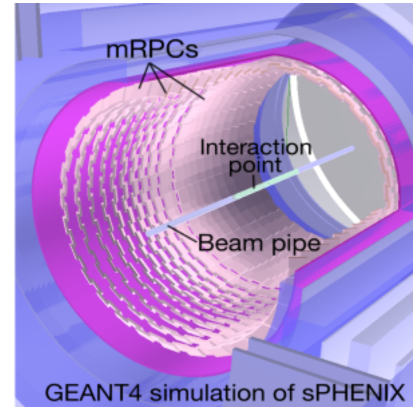
-> Note: this approach allows one to extend the momentum range, save linear space as well as minimize the size of the photosensor assembly

- **Caveat:** performance strongly depends on particle-to-detector relative position/orientation

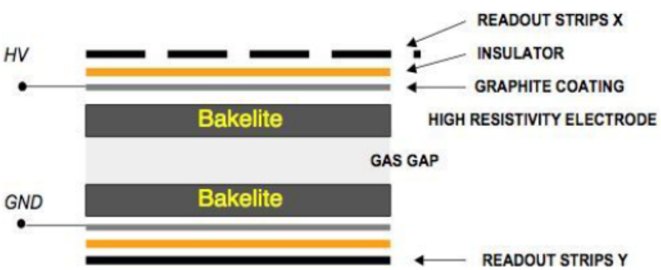
Time of Flight

In “sigma” units, for 10ps timing: **pion/kaon** & **kaon/proton** separation

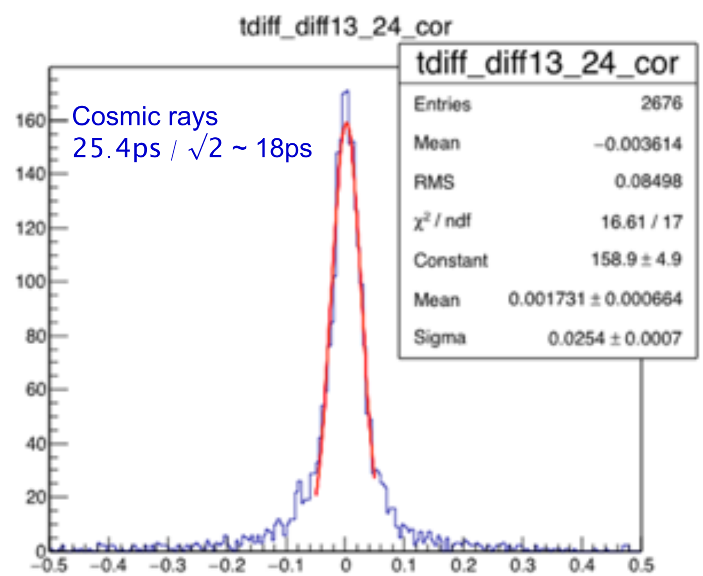
		pion/kaon	kaon/proton
σ_{tot}=10 ps	1m (Barrel)		
σ_{tot}=10 ps	4m (Hadron)		



Multi-gap Resistive Plate Chamber (MRPC) R&D: achieved ~18 ps resolution with 36x 105 μm gaps



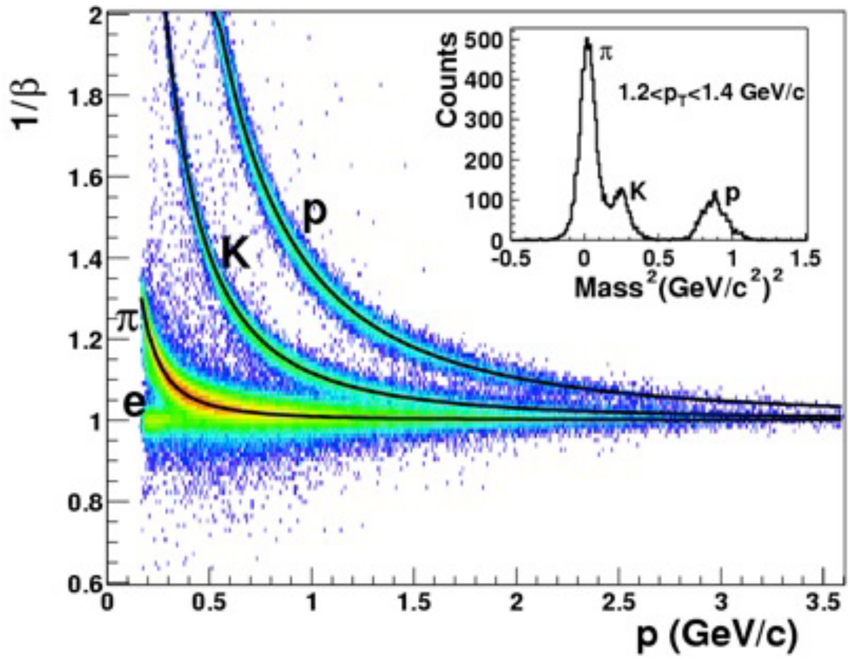
a charged particle passing through causes local discharge which induces signals in the readout strips



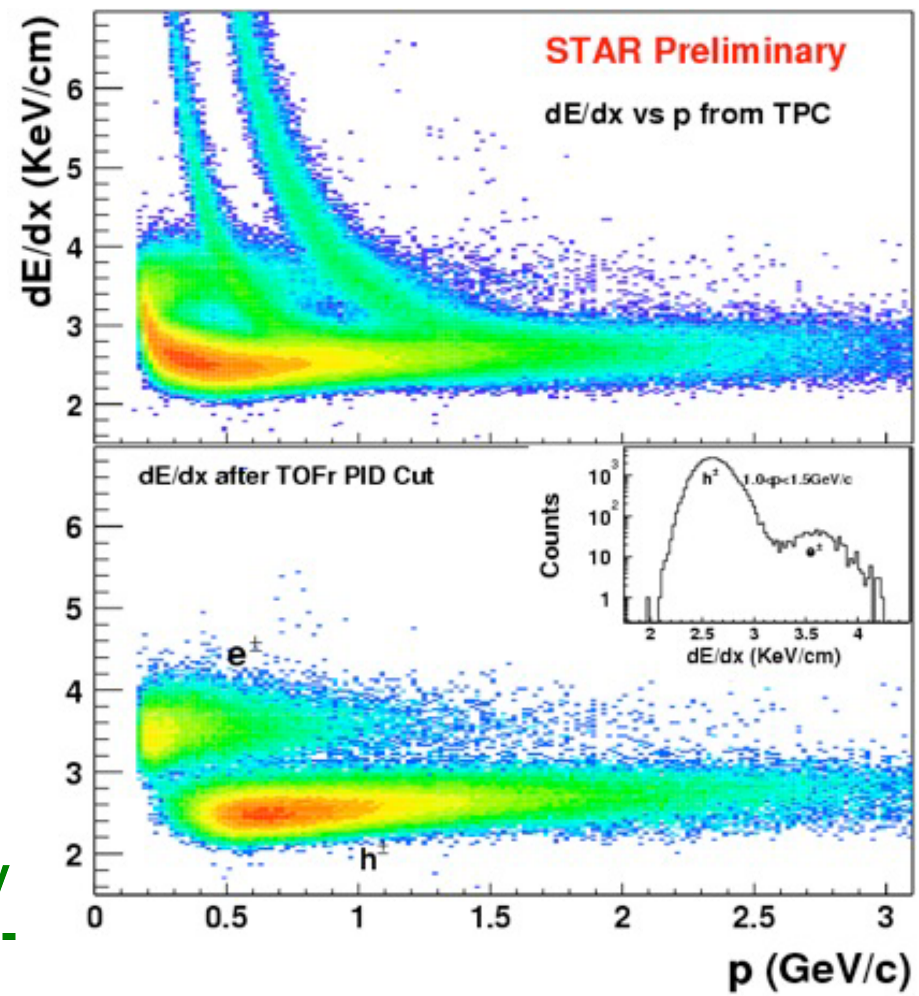
- **Caveat**
  - Providing a high resolution T_{start} measurement is not trivial at an EIC (electron bunches have finite, ~1cm length; installing ~10ps timing detectors around IP would add material, etc)

Time of flight + dE/dx @ STAR

Time of Flight alone



dE/dx alone

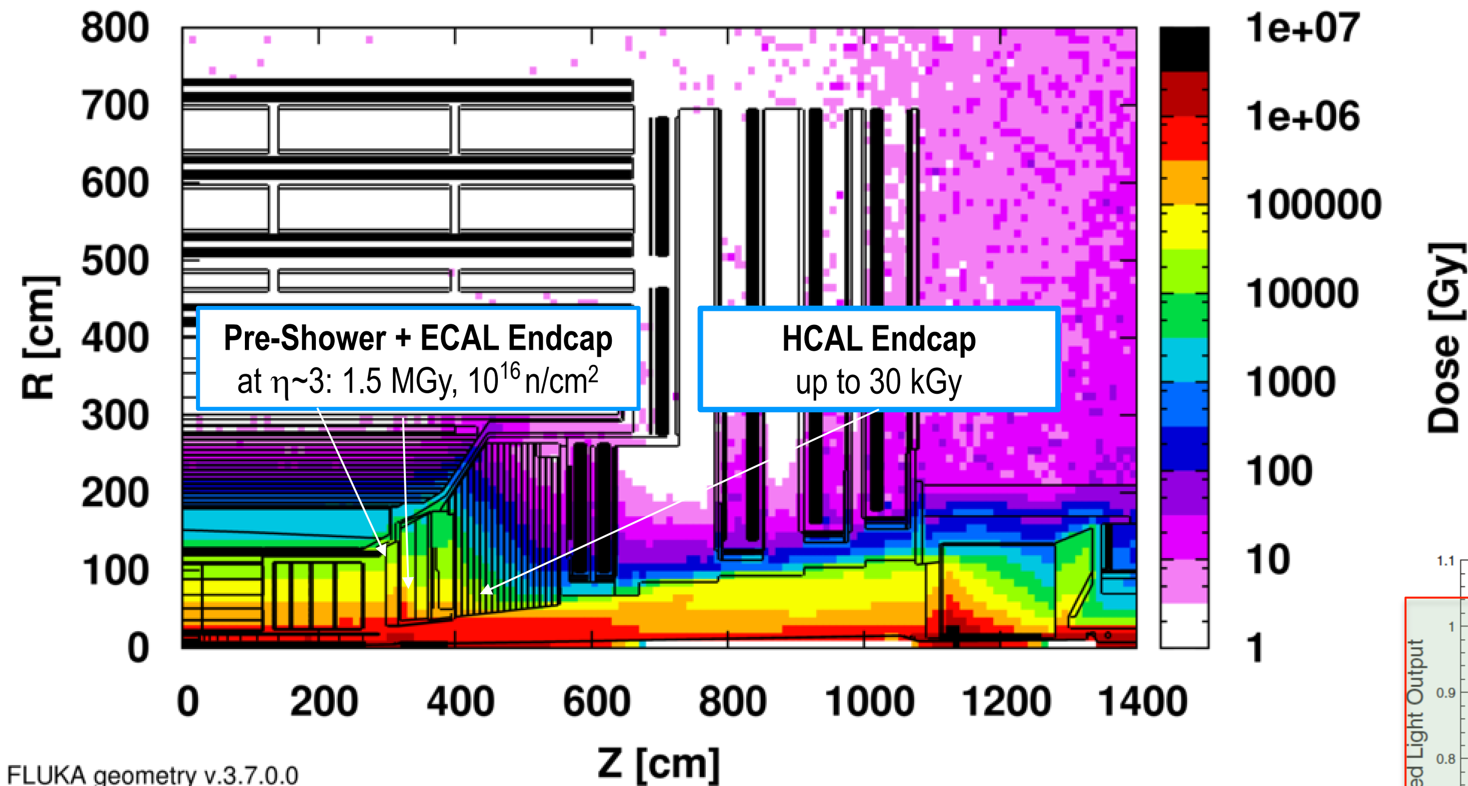


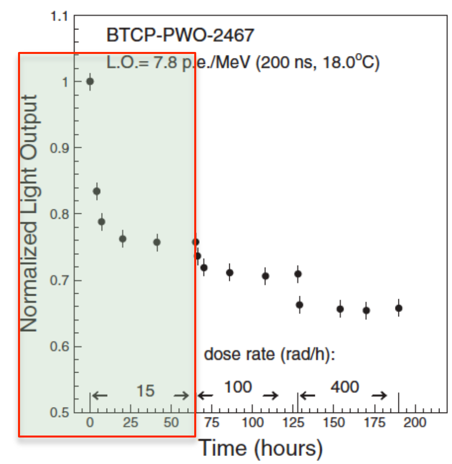
dE/dx with a hard ToF cut

-> Note: combining information from several independent PID detectors can drastically improve the selection quality (in this example provides clear electron-hadron separation up to ~3 GeV/c)

Comparison to CMS

3000 fb-1 Absolute Dose map in [Gy] simulated with MARS and FLUKA





clearly our numbers are orders of magnitude smaller

-> however integrated flux of ~10^{11} n/cm^2 is already harmful for SiPMs

-> and PWO crystals show reduction in light output at relatively small doses