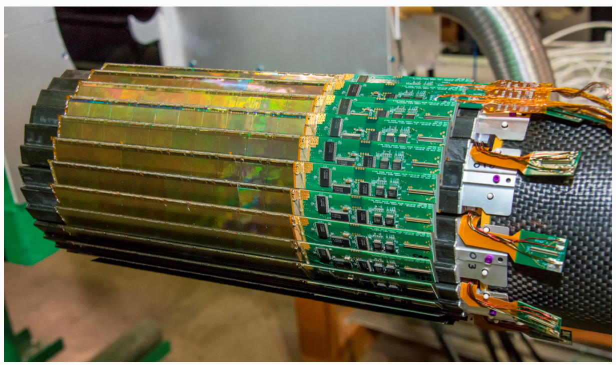
UNIVERSITY OF BIRMINGHAM
SCHOOL OF PHYSICS AND ASTRONOMY

Precision Central Silicon Tracking & Vertexing for the EIC

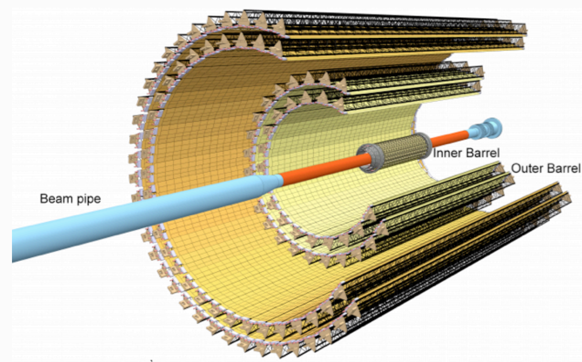
P. Allport, S. Bailey, L. Gonella, P. Jones, P. Newman

State-of-the-art MAPS

STAR Heavy Flavour Tracker (HFT) at RHIC (MIMOSA chip)

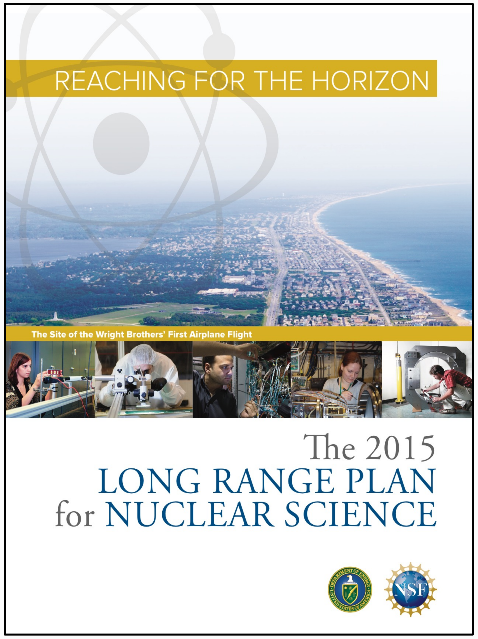


ALICE Inner Tracking System (ITS) Upgrade at LHC (ALPIDE chip)



- Key features of MAPS
  - Small pixel size (down to 20 µm x 20 µm)
  - Low power (< few hundred mW/cm^2)
  - Low material budget (~ 0.3% X_0 per layer)
  - Moderate radiation hardness (~Mrad, 10^{13} 1MeV n_{eq}/cm^2)

Electron Ion Collider



RECOMMENDATION III

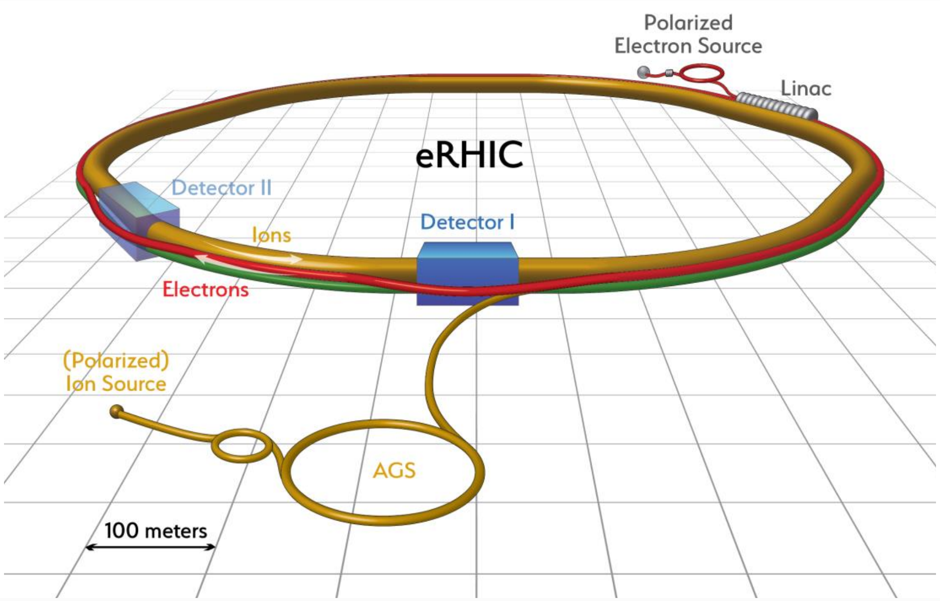
Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

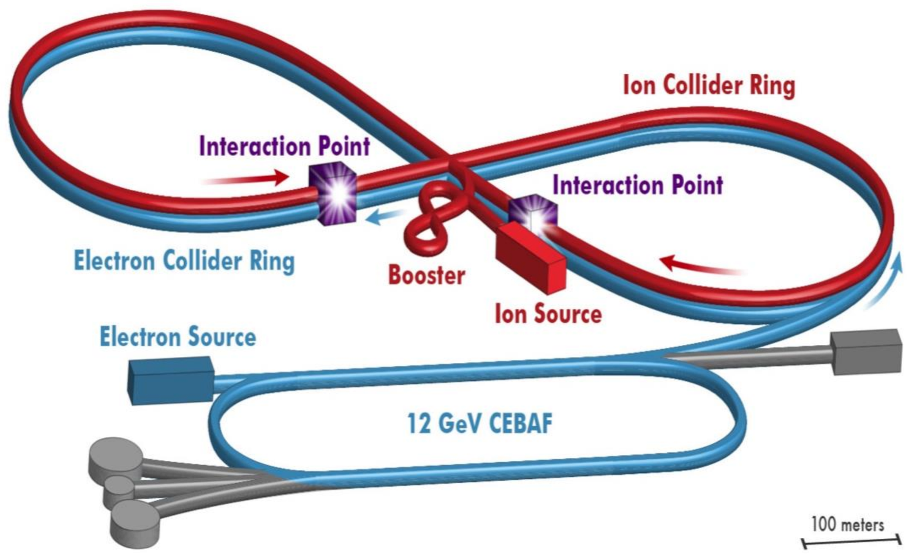
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

10 years time scale

- EIC physics goals
  - Nucleon spin, 3D structure and tomography
  - Saturated gluons density regime
  - Hadronization and energy loss in the nuclear environment
- Two proposals for realization of the science case
  - **eRHIC @ BNL**
  - **JLEIC @ JLAB**
  - Decision after CD0, around 2020

EIC accelerator design

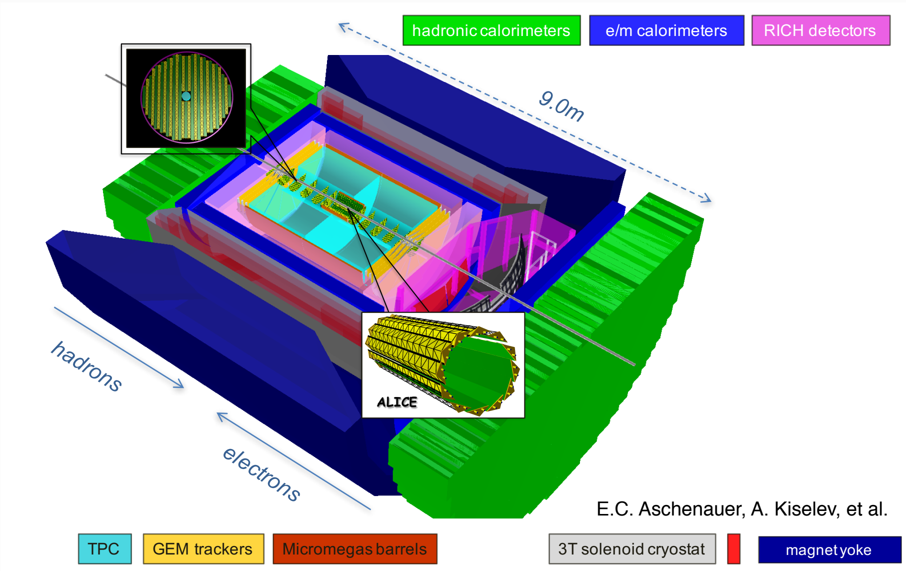




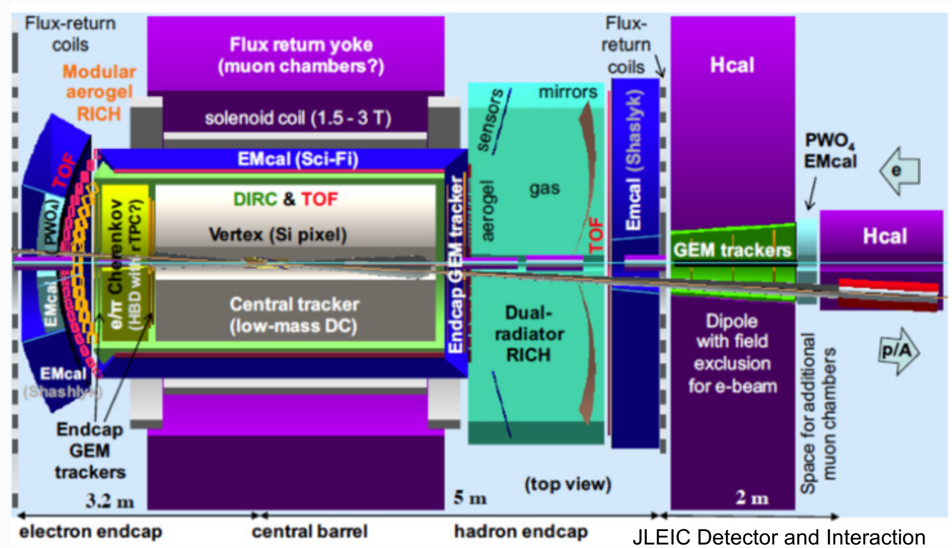
- World's first polarized electron-proton/light ion and electron-nucleus collider
  - E = 20-100 (140) GeV
  - E_e = 3-10(20) GeV
  - L = $10^{33\text{-}34}\text{cm}^{-2}\text{s}^{-1}$
  - Polarized electron and proton, and light ions beams
  - Wide range of nuclei

EIC Detector Concepts

eRHIC detector concept (BeAST)



JLEIC detector concept



JLEIC Detector and Interaction Region Study Group

- Advanced detector concepts for both BNL and JLAB
- Detector R&D supported by the EIC Generic Detector R&D program (DOE, 1M$/year)
- Si vertex and tracker detectors in central and forward regions
  - Seek **high position resolution and low mass**
  - ALPIDE for eRHIC, several technology options for JLEIC (e.g. Belle II DEPFET-based pixel SVD)

Silicon vertex and tracking at the EIC: eRD16 & eR18

eRD18: Birmingham

- **Central** region
- Detector simulations
- **MAPS** development
- Started in FY17

eRD16: LBNL

- **Forward/Backward** region
- Detector simulations
- **Engineering** developments
- Started in FY16

Precision Central Silicon Tracking & Vertexing for the EIC

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June 15, 2016

Abstract

We propose to develop a detailed concept for a central silicon pixel detector for an Electron-Ion Collider at BNL or JLab, exploring the advantages of using HV-CMOS or HR-CMOS MAPS technologies. The sensor development will exploit the newly created Birmingham Instrumentation Laboratory for Particle Physics and its Applications and will be closely coupled with simulations to optimise the basic layout, location and sensor/pixel dimensions. The design will be tested in full detector simulations to evaluate its performance with respect to the identification and precision measurement of heavy flavour processes and scattered electrons at high Q^2. A detailed evaluation of expected EIC performance for these processes will therefore be a key deliverable.

Forward/Backward Tracking at EIC using MAPS Detectors

G. Contin, X. Dong, L. Greiner, B. Jacak, P. Jacobs, S. Klein, C. Loizides, G. Odyniec, M. Ploskon, A. Schmah, E. Sichtermann, J. Thomas, H. Wieman, N. Xu

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Abstract:

We propose to develop a concept for a backward (electron-going direction) tracking station near the collision vertex. We focus on detection of the scattered electron, as the precision of this measurement defines the kinematics of the collision. Disks of thinned-silicon sensors (MAPS) detectors will be laid out, including conceptual design for the arrangement of services, including cooling, power, and readout. We will perform simulations to specify layout and sensors optimized for high priority early physics measurements, and eventually determine whether a copy of the same tracker should be used in the hadron-going direction. We will also perform R&D on low-mass cabling utilizing aluminum traces.

eRD18: Proposal

To develop a detailed concept for a **central silicon vertex** detector for a future EIC experiment, exploring the potential advantages of HV/HR-CMOS MAPS technologies

Physics motivation

Open heavy flavour decays – **high position resolution**

Precision tracking of high Q^2 scattered electrons – **low mass**

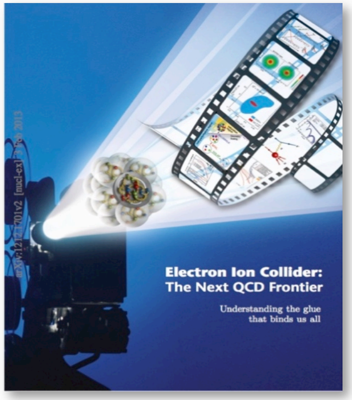
WP1: Sensor Development

Exploit on-going R&D in Birmingham into HV/HR-CMOS MAPS to investigate potential solutions for the EIC

WP2: Silicon Detector Layout Investigations

Performance requirements: numbers of layers, layout and spatial resolution of the pixel hits

Charm observables in the EIC White Paper



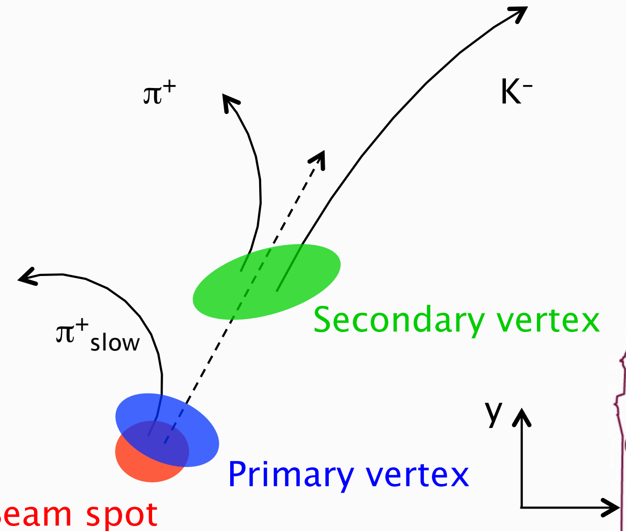
A. Accardi et al.,
Eur. Phys. J. A (2016) 52:268

- Leading order charm production process is γg fusion → provides sensitivity to main EIC physics goals

- A future EIC promises unprecedented precision in charm (and beauty)
  - Reconstruction challenging due to short decay lengths **~ 100 μm**
  - Likely to place strongest constraints on the tracker design

Example:

$$D^{*+} \to D^0\pi^+_{slow} \to \left(K^-\pi^+\right)\pi^+_{slow}$$



- Open charm reconstruction
  - Signature is displaced (secondary) decay vertex → Requires **excellent impact parameter resolution** in *r*-ϕ and *z*
  - Dominated by **position and resolution of innermost tracking layer**

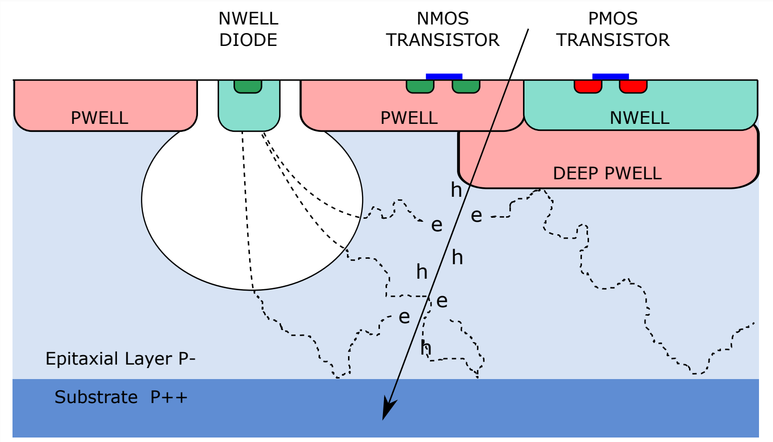
WP1: Sensor development

- Aim: to demonstrate *high spatial resolution* in a *fully depleted* sensor
  - Advantage of depletion = charge collection by drift → **larger charge**, fast collection, small cluster multiplicity, rad. hardness

- Starting point: ALPIDE sensor (ALICE ITS)
  - Partially depleted; charge collection in part by drift
  - Small collection electrode = **small detector capacitance** → low power, low noise, low crosstalk, fast readout

ALPIDE sensor
- 0.18 μm CMOS TowerJazz
- 28 x 28 μm^2 pixel pitch
- <2 μs time resolution
- Power density < 50 mW cm^{-2}
- 50 kHz interaction rate (Pb-Pb)
- 200 kHz interaction rate (pp)

ALICE- ITS
Inner layer thickness = 0.3% X_0
Outer layer thickness = 0.8% X_0



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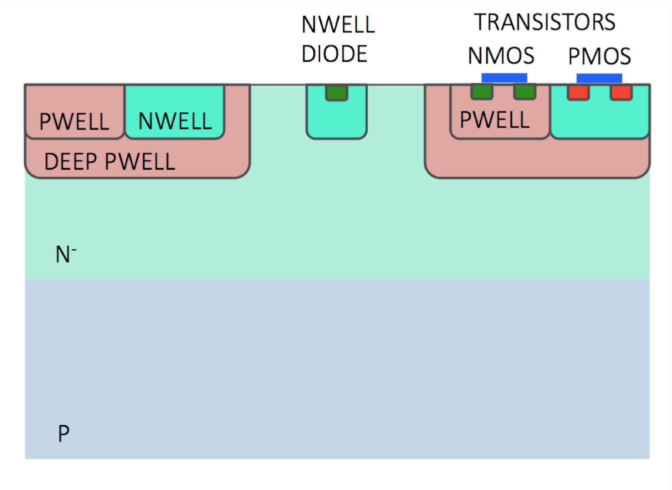
- R&D strategy
  - Investigate commercial **HV/HR-CMOS** technologies to achieve larger depleted volume (TowerJazz and LFoundry)
  - Explore configuration of **collection electrode and pixel size**

WP1: Sensor development

- TowerJazz “modified” process
  - CERN-TowerJazz (CERN-TJ) collaboration: 180 nm process with additional planar junction deep in the epitaxial layer
  - First results* indicate **full depletion**; larger signal with faster and more uniform charge collection wrt standard process
  - **Small collection electrode**, so low detector capacitance like ALPIDE



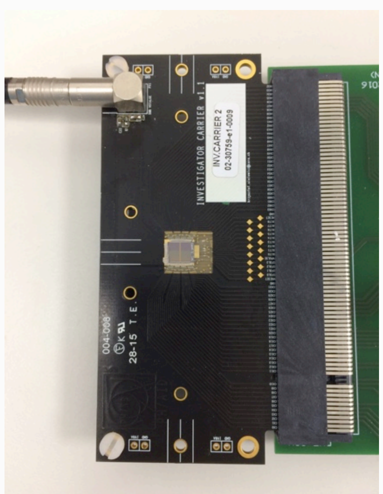
Modified pixel structure

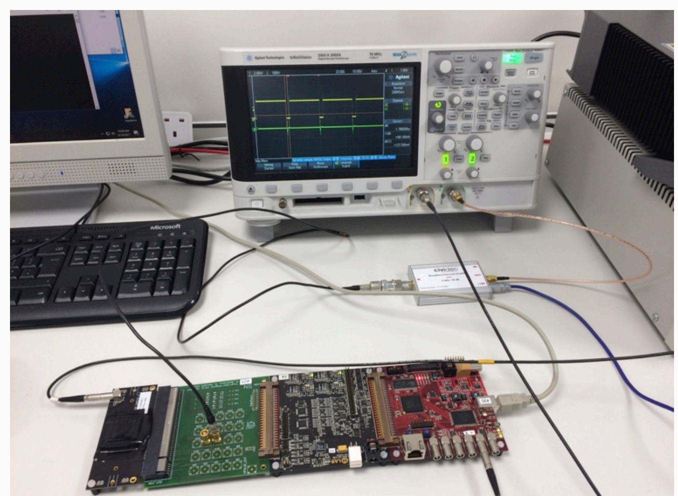
We believe this technology is a strong contender for a dedicated **EIC MAPS prototype**

*H. Pernegger et al., First tests of a novel radiation hard CMOS sensor process for Depleted Monolithic Active Pixel Sensors, 2017 JINST 12 P06008.

WP1: Sensor development

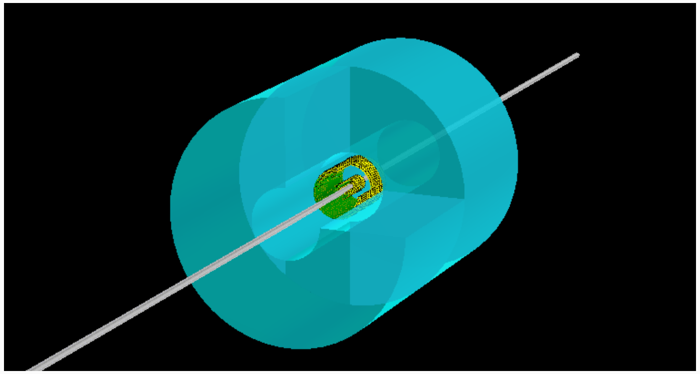
- CERN-TJ investigator chip now available for testing in Birmingham
  - Designed to study charge collection properties and detection efficiency
  - More than 100 pixel matrices (10 x 10 pixels)
  - Range of pixel sizes relevant to both EIC barrel and disks
    - **20 x 20 μm^2** to 50 x 50 μm^2 pixels
  - Simple follower-based (analogue-only) readout
  - Characterisation of the sensor will be our focus in FY18
    - Focusing on matrices with small pixels relevant for the EIC

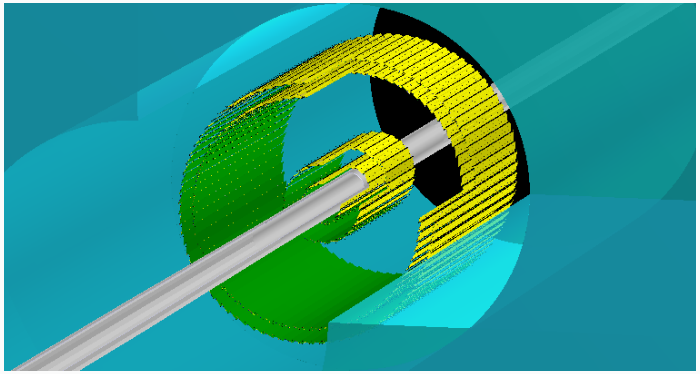




WP2: Simulations

- Default BeAST tracker geometry in EicRoot software framework
  - TPC + VST + beam pipe + magnetic field (B = 1.5 T)
  - 4 layers, 30 x 30 μm^2 pixels, 0.3% X0 per layer

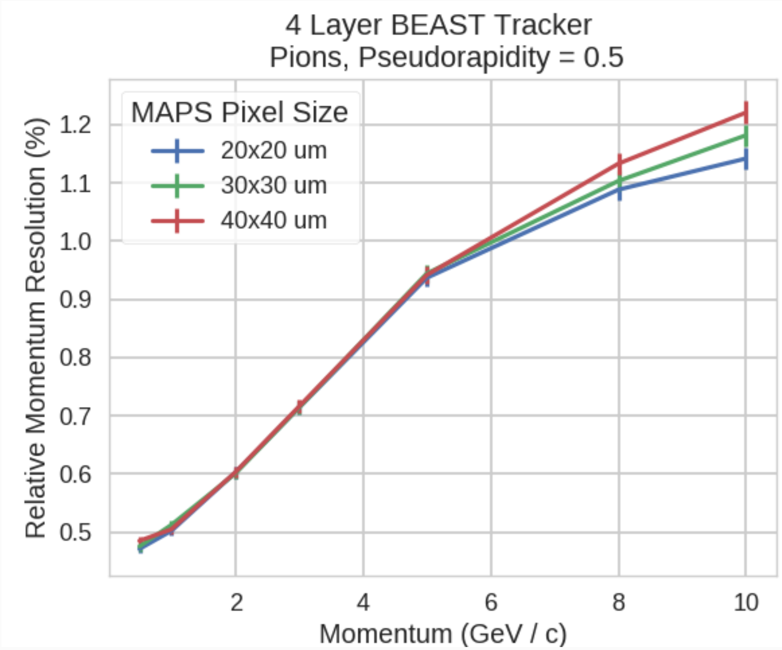




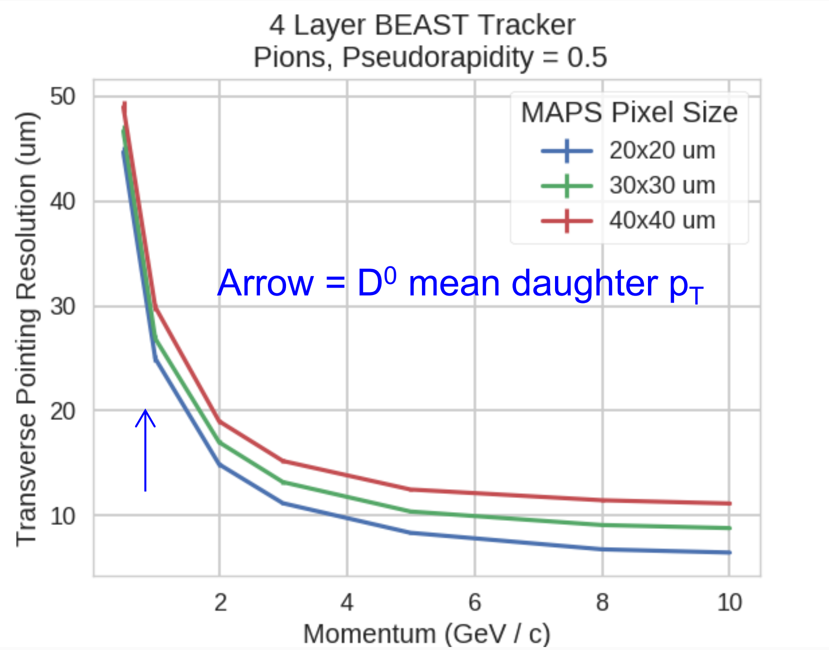
- Tests have focused on combined Si barrel plus TPC
  - Studied pions (kaons and protons) from 500 MeV/c to 10 GeV/c
  - Various barrel configurations plus default TPC specification
  - 4-layer barrel, default geometry, 20-40 μm pixels
  - 3, 4 and 5-layer barrels, 30 μm pixels
  - 4 and 5-layer barrels with 350 μm pixels in outer layer (on-going)

WP2: Simulations

- Results: pions; eta = 0.5; 3 pixel sizes: **20 μm, 30 μm and 40 μm**



Relative momentum resolution (%) versus momentum

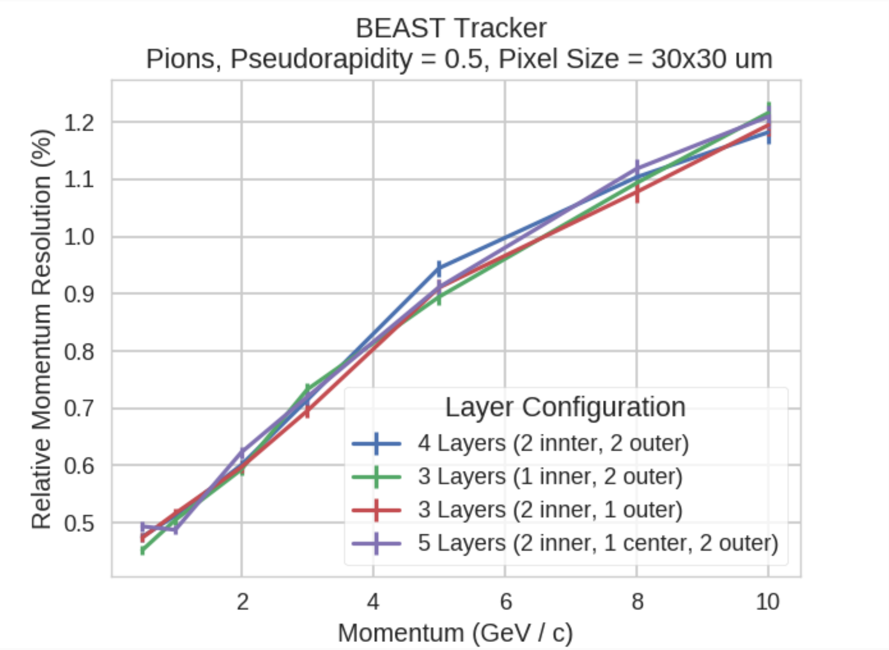


Impact parameter resolution (μm) in transverse (r-ϕ) plane versus momentum

- Modest improvement in impact parameter resolution for all p_T
  - Dominated by resolution of innermost layer

WP2: Simulations

- Results: pions; eta = 0.5; pixel size = 30 μm; **3, 4 and 5 layers**



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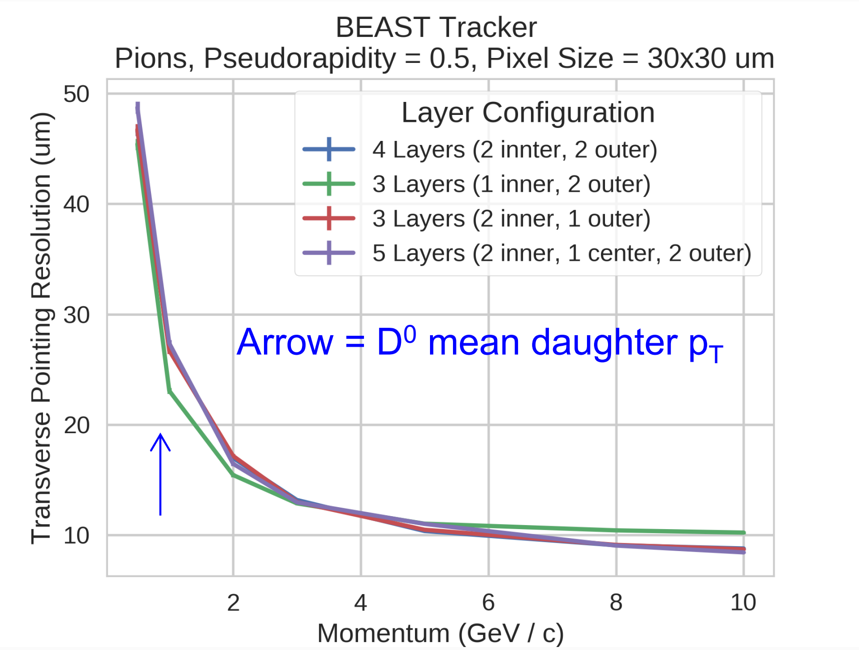


Impact parameter resolution (μm) in transverse (r-ϕ) plane versus momentum

- Little sensitivity to the number of layers
  - Slightly better impact parameter resolution with one inner layer

eRD18 and eRD16: Toward an EIC specific sensor

- Factors affecting readout architecture
  1. Interaction rate and hit occupancy
     - eRHIC: 28.2 MHz beam bunch repetition rate, or higher (35.5ns separation)
     - JLEIC: 476 MHz (2.1ns)
     - Interaction frequency = tens to hundreds kHz, few tracks/event
     - Background, bunch crossing tagging → tens of ns
  2. Time resolution
     - ALPIDE: <2 μs time resolution, 28 x 28 μm^2 pixel, analog power density: 5-6 mW/cm^2
     - Limited by pre-amp rise time (analogue power density) → important to have small detector capacitance
  3. Readout choices
     - Triggered versus untriggered readout, on-chip buffering, speed of output links, clock distribution – all drive digital power density

→ Time resolution and readout choices impact **mass and granularity**

eRD18 and eRD16: Toward an EIC specific sensor

- EIC sensor readout
  - Two possible scenarios – depending on required tracking performance
    1. Design sensor with required **spatial and time** resolution in all layers
    2. Develop a **faster, lower granularity sensor** for the outermost layer

- Future roadmap in collaboration with eRD16
  - Collaborating on layout simulations, using the same geometry descriptions
  - Divide work according to physics observable (electrons vs heavy flavour)
  - Placement of first disk layer(s) may have impact on barrel performance
  - Iterate toward a final set of requirements for barrel and disks in FY18
  - Work to define specifications for an EIC specific sensor prototype
  - **Aim to design and submit an EIC specific sensor prototype in FY19**

Conclusion

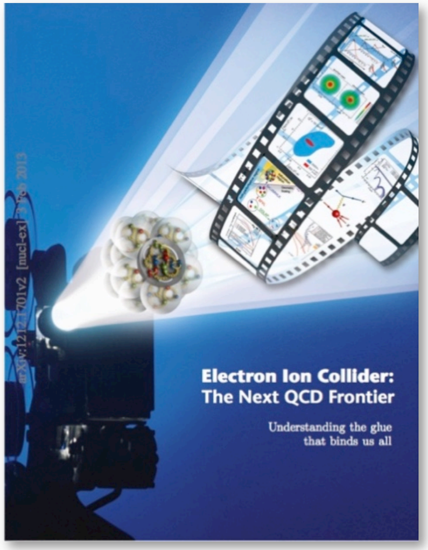
- Birmingham is working on an EIC silicon vertex and tracking detector using MAPS
- eRD18 is the only project led by an European institution and without a US partner supported by the EIC Generic Detector R&D funding
- Two years program to develop detailed central silicon tracker concept and define EIC MAPS specification
  - First year proposal funded at 50% of requested amount
  - Second year proposal positively received, funding recommended
- Collaboration with eRD16 (LBNL) towards a specific EIC MAPS prototype

Backup

Charm observables in the EIC White Paper

- Leading order charm production process is γg fusion

- Provides sensitivity to:
  I. The gluon contribution to spin of the nucleon
     - Charm sensitive to Δg in e-p scattering
  II. Physics of high gluon densities and low-x in nuclei
     - Measurement of F_2^{charm} sensitive to nuclear gluon density in e-A
  III. Hadronisation and energy loss in cold nuclear matter
     - Nuclear modification and quark mass dependence



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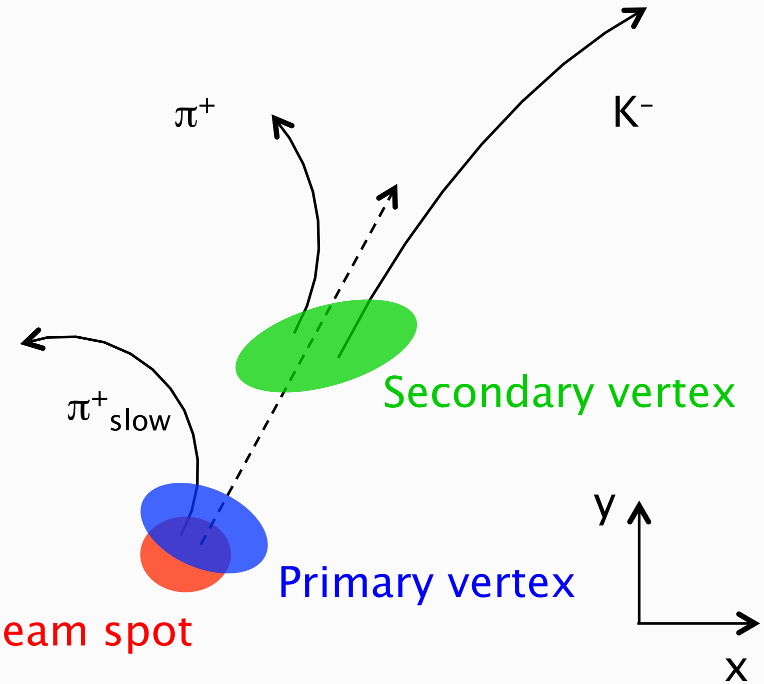
- A future EIC promises unprecedented precision in charm (and beauty)
  - Reconstruction challenging due to short decay lengths ~ 100 μm
  - Likely to place strongest constraints on the tracker design
  - Potential importance of low-p_T (standalone) tracking

Open charm reconstruction

- Signature is displaced (secondary) decay vertex

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



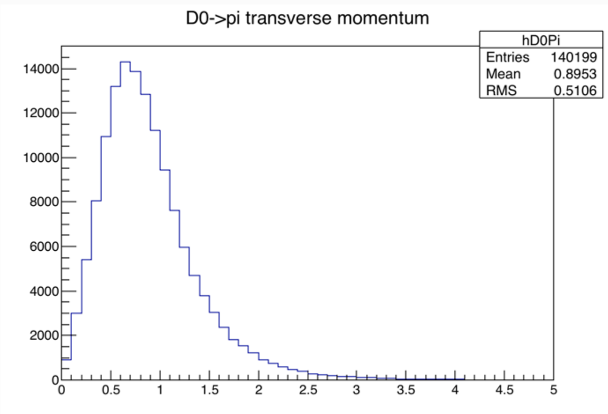
Example:

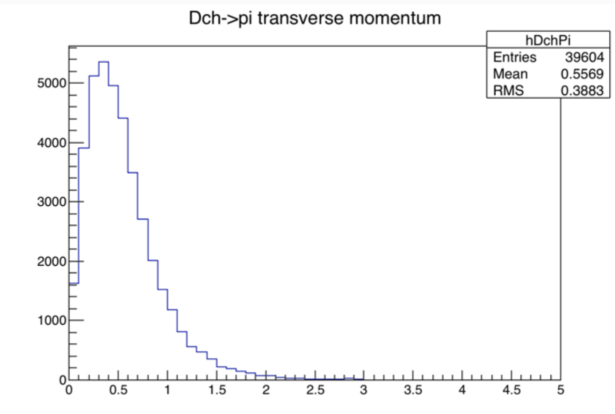
$$D^{*+} \rightarrow D^0\pi^+_{slow} \rightarrow \left(K^-\pi^+\right)\pi^+_{slow}$$

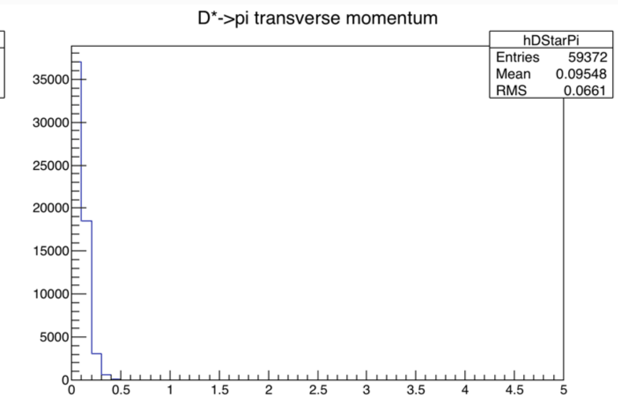
- Requires excellent impact parameter resolution in *r*-ϕ and *z*
  - Dominated by position and resolution of innermost tracking layer
    - Close as possible to beam pipe (caution: radiation environment)
    - Highest possible spatial resolution (small pixels)

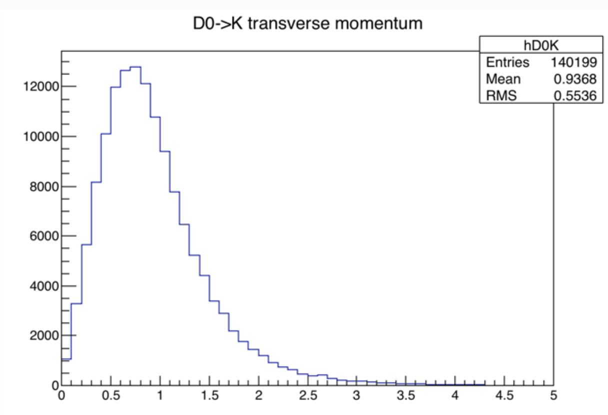
Pythia simulations

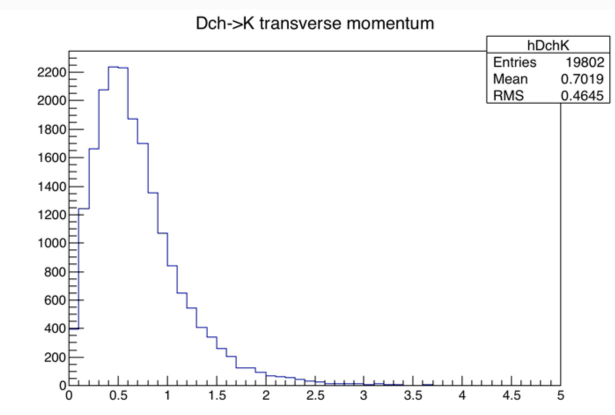
- Pythia e-p at √s = 145 GeV (21 GeV electrons + 250 GeV protons)











WP1: Sensor development

- Other developments
  - Submission of test structures in TowerJazz modified process
    - Multi-Project Wafer submission with CERN in July
    - Consists of larger pixels with multiple small collection electrodes (complementary to investigator chip structures)
  - RD50 LFoundry submission expected by end of the year
    - Matrices with **improved time resolution** (in-pixel TOA and TDC)
    - Test structures with pixels down to 20 x 20 μm^2
    - But, large electrode (electronics sits within the collecting n-well)

- These options are useful for evaluation purposes
  - Large Q, but also larger C than single small electrode

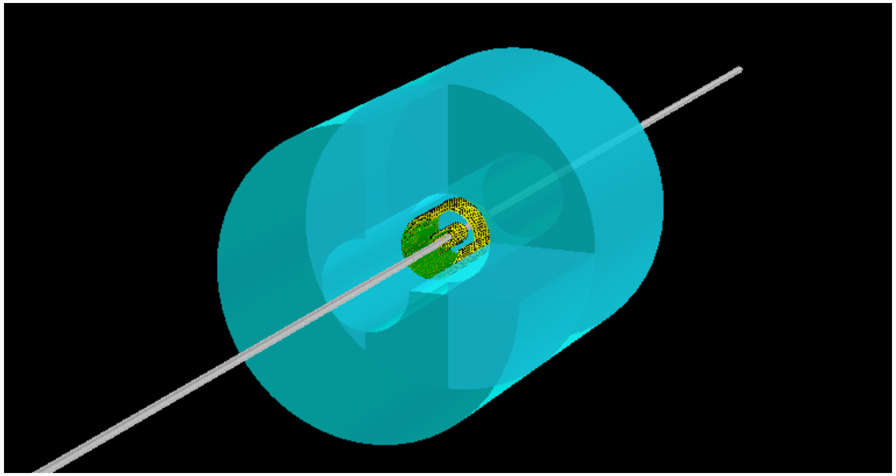
WP1: Sensor development

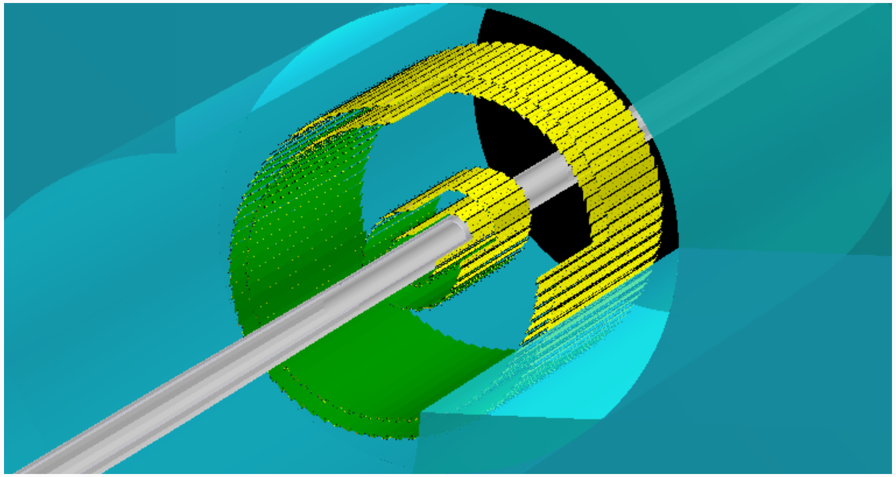
- Work plan for FY18
  1. Characterisation of the CERN-TJ investigator chip
     - Parameters to evaluate: signal amplitude and response time
     - Tests with radioactive sources (^{55}Fe and ^{90}Sr) and laser eTCT setup

       Calibration, measurement of depletion width, uniformity of charge collection between pixels
     - Irradiations at MC40 cyclotron with 28 MeV protons
     - Possible participation in test beam with colleagues at CERN to study detection efficiency
  2. TCAD simulations
     - Evaluate optimal electrode configuration, epitaxial layer resistivity, with inputs from results of characterisation
  3. EIC MAPS specifications and design
     - Define specifications for EIC specific sensor
     - Possibly start discussing design options with chip designer

WP2: Simulations

- Geometry: TPC + VST + beam pipe + magnetic field (B = 1.5 T)





TPC parameters
Inner radius = 20 cm
Outer radius = 80 cm
250 μm position resolution

VST parameters
Layer #1 radius = 2.3 cm
Layer #2 radius = 4.6 cm
Layer #3 radius = 14 cm
Layer #5 radius = 16 cm
30 x 30 μm pixels
0.3% X_0 per layer

Beam pipe parameters
Material = beryllium
Outer radius = 1.8 cm
Thickness = 0.8 mm

WP2 Simulations

- Work plan for FY18
  1. Tracker characterisation
     - Complete study of single track **momentum resolution** and **impact parameter resolution** based on different assumptions on **the pixel dimensions** and **number** and **thickness** of tracking layers
  2. Tracker optimisation
     - Optimise separation of tracking layers
     - Explore tradeoffs in scenarios with different **pixel sizes** and **layer thicknesses** in different layers

       e.g. fast timing layer
     - Study standalone tracking performance at low p_T