UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

eRD18 - Precision Central Silicon Tracking & Vertexing for the EIC

FY18 Report and FY19 Proposal

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eRD18: Motivation

To develop a detailed concept for a central silicon vertex detector for a future EIC experiment, exploring the potential advantages of depleted MAPS (DMAPS) technologies

Science drivers

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

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

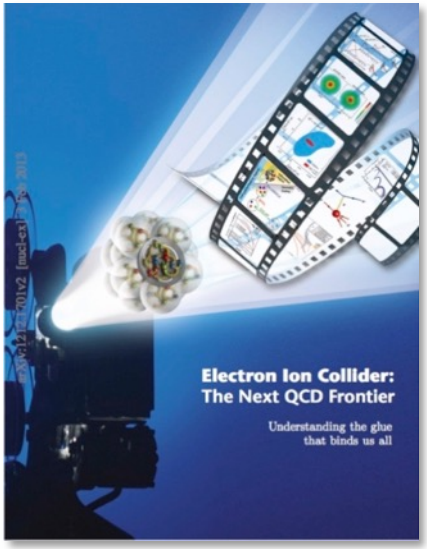
WP1: Sensor development

Exploiting on-going R&D in Birmingham into DMAPS to investigate potential solutions for the EIC

WP2: Silicon detector layout investigations

Specifications: numbers of layers, layout and spatial resolution to achieve required momentum resolution and vertex reconstruction

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

- Charm production 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
     - Quark mass dependence and nuclear modification

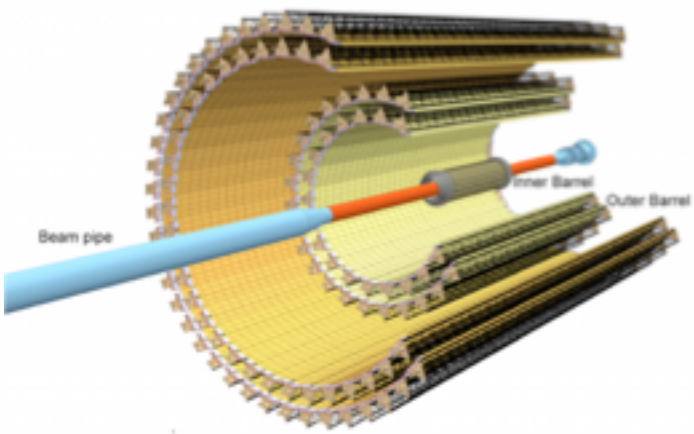
EIC promises **unprecedented precision** in charm observables in e-p/e-A

- Charm reconstruction requires identification of displaced vertices
  – Challenging due to decay lengths ~ 100 μm
  – Likely to place strongest constraints on the tracker design
  – Potential importance of low-p_T (standalone) tracking

MAPS Example: ALICE ITS Upgrade for LHC Run 3

- ALICE developed the ALPIDE monolithic active pixel sensor
  - Optimised for Pb-Pb collisions at the LHC
  - High spatial resolution (small pixels) and low power digital readout
  - Features a **small collection electrode** = small detector capacitance

    → low power, low noise, low crosstalk, fast readout
  - Partially depleted; charge collection by drift & diffusion

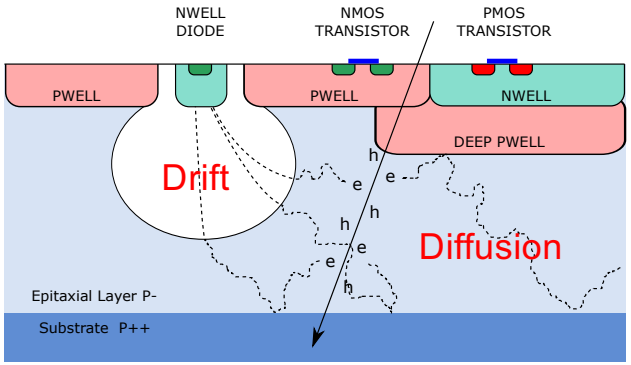


Inner Barrel = 0.3% X/X_0 per layer

Outer Barrel = 0.8% X/X_0 per layer

50 kHz interaction rate (Pb-Pb)

200 kHz interaction rate (pp)



0.18 μm CMOS TowerJazz

28 x 28 μm^2 pixel pitch

4 μs integration time

Power density < 50 mW cm^{-2}

WP1: Sensor development

- Towards an EIC-specific sensor
  - Explore ongoing developments toward (fully) depleted MAPS (DMAPS)
  - Aim for improved spatial resolution
    - Smaller pixels, low power
  - Consider readout requirements for the EIC
    - Integration time and time-stamping capability

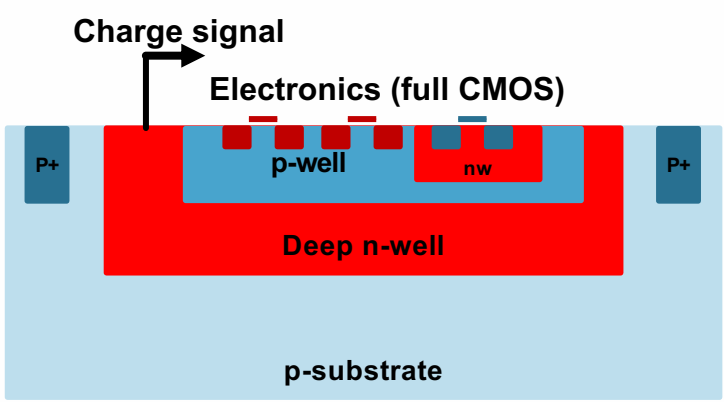
- Excerpt from EIC Detector Requirements and R&D Handbook

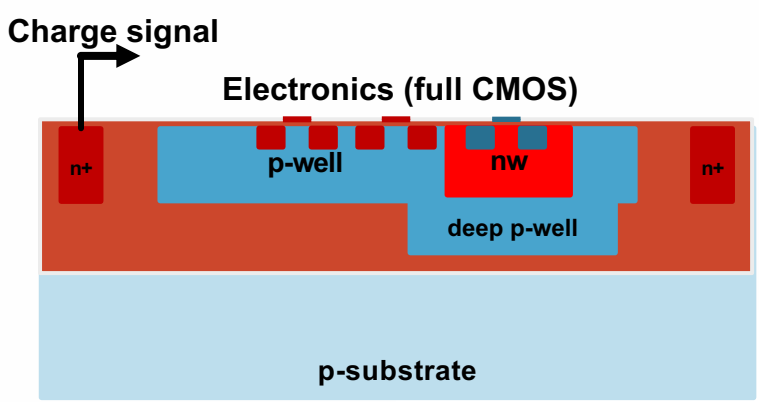
*"The EIC would certainly benefit in **improvements in the integration time** as well as in a further reduction of the energy consumption and material budget going towards **0.1-0.2% radiation length per layer**. Timing-wise the ultimate goal of this technology would be to **time stamp the bunch crossings** where the primary interaction occurred. […] Concerning spatial resolution the simulations indicate that a **pixel size of 20 microns** must be sufficient."*

Electron-Ion Collider Detector Requirements and R&D Handbook, v4

WP1: Depleted MAPS

- Main advantage is charge collection by drift
  - Achieved by full depletion of the substrate (HV/HR CMOS)
  - Faster and more complete charge collection
  - Less charge sharing between pixels (… also improved rad. hardness)
- Two approaches achieve to full depletion
  - Implement a **large collection electrode**
    - Approach followed in almost all technologies
    - Disadvantage: large capacitance
  - Introduce a **deep planar junction** (only in TJ modified process)
    - Advantage: small collection electrode (few μm^2)





WP1: Depleted MAPS technology survey

- State-of-the-art DMAPS prototypes
  - Mainly developed for application at the HL-LHC
  - Optimised for high particle fluences, radiation hardness and fast readout

DMAPS

	ALPIDE	MALTA	TJ-MONOPIX	LF_MONOPIX	ATLASpix_Simple
Experiment	ALICE ITS	ATLAS ITk pixel Phase II (outermost layers only)			
Technology	TJ 180 nm	Modified TJ 180 nm		LF 150 nm	AMS 180 nm
Substrate resistivity [kOhm cm]	> 1 (epi-layer 18-25 um)			> 2	0.08 - 1
Collection electrode	small	small	small	large	large
Detector capacitance [fF]		<5		Up to 400	
Chip size [cm x cm]	1.5 x 3	2 x 2	1 x 2	1 x 1	0.325 x 1.6
Pixel size [um x um]	28 x 28	36.4 x 36.4	36 x 40	50 x 250	40 x 130
Integration time [ns]	4×10^3	<25			
Particle rate [kHz/mm^2]	10	10^3			
Readout architecture	Asynchronous	Synchronous, column drain			
Analogue power [mW/cm^2]	5.4	< 120	~ 110	~ 300	N/A
Digital power [mW/cm^2]	31.5/14.8	N/A	N/A	N/A	N/A
Total power [mW/cm^2]	36.9/20.2	N/A	N/A	N/A	N/A
NIEL [1MeV n_{eq}/cm^2]	1.7×10^{13}	1.0×10^{15}			
TID [Mrad]	2.7	50			

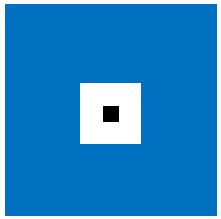
WP1: EIC-specific DMAPS specifications

- Preliminary specifications
  - Pixel pitch ≤ 20 μm
  - Interaction rate = 500 kHz
  - Integration time ≤ 2 μs
- To minimise power
  - Small collection electrode
  - Asynchronous readout
- Fast-timing capability
  - Timestamp each bunch crossing
  - Depends on facility
    - eRHIC = 9.38 MHz
    - JLEIC = 748.5 MHz
  - 100 ns – 1 ns resolution
  - Synergy with eRD3/6

	EIC DMAPS sensor	
Detector	Vertex and tracking	Outer timing layer
Technology	TJ or similar	
Substrate resistivity [kOhm cm]	> 1	
Collection electrode	small	
Detector capacitance [fF]	<5	
Chip size [cm x cm]	Reticule size [cm^2]	
Pixel size [um x um]	20 x 20	TBD
Integration time [ns]	<2 x 10^3	< 100 (eRHIC) <1 (MEIC)
Particle rate [kHz/mm^2]	TBD	
Readout architecture	Asynchronous	TBD
Analogue power [mW/cm^2]	TBD	TBD
Digital power [mW/cm^2]	TBD	TBD
Total power [mW/cm^2]	TBD	TBD
NIEL [1MeV n_{eq}/cm^2]	10^{10}	
TID [Mrad]	TBD	

WP1: TJ Investigator Chips

- Designed to study charge collection properties and detection efficiency
- Implemented in standard (v1) and modified process (v1 and v2)
- 134 matrices of 10 x 10 pixels
  - Different pitch, electrode size, electrode spacing
- TowerJazz investigator chip v2 has improvements for charge collection
  - Separate bias for p-substrate and the p-well
  - Faster readout
  - Reduced electrode spacing for large pitch pixels



Pixel: 28 x 28 μm^2
Electrode: 2 x 2 μm^2
Electrode spacing: 3 μm

Available pixel matrices

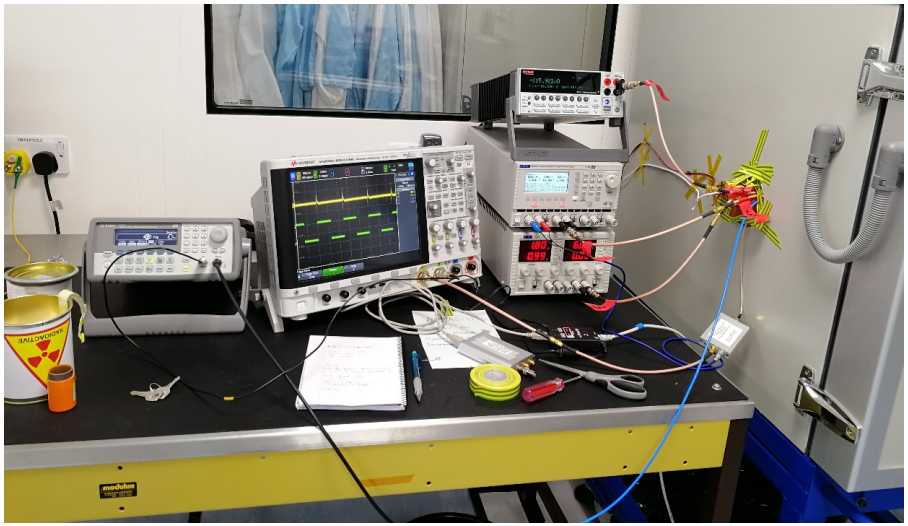
0-35:	20 x 20 μm^2
36-57:	22 x 22 μm^2
58-67:	25 x 25 μm^2
68-103:	28 x 28 μm^2
104-111:	30 x 30 μm^2
112-123:	40 x 40 μm^2
124-133:	50 x 50 μm^2

Electrode sizes
1-5 μm^2

Electrode spacing
1-5 μm typically
(except 50 x 50 μm^2 pixels in v1)

WP1: Ongoing work

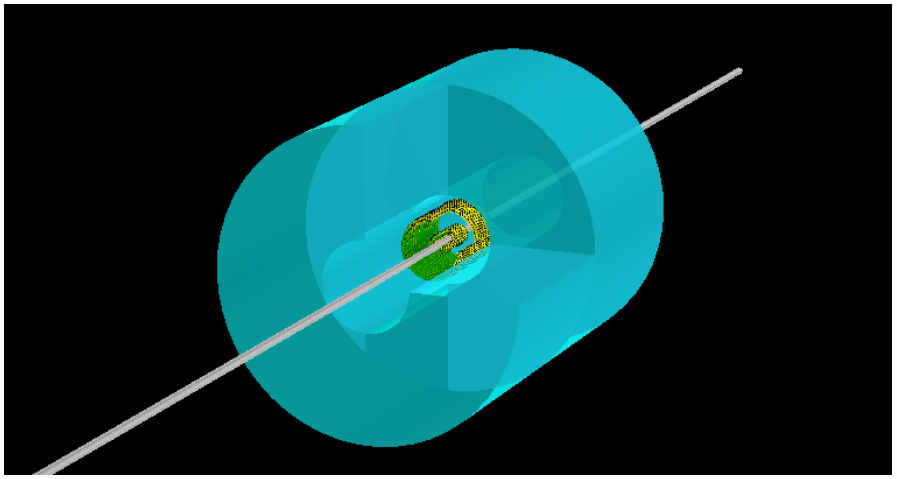
- Working with the TowerJazz investigator v2
  - Irradiations performed at MC40 cyclotron in Birmingham in February
  - 2 chips available irradiated to 2×10^{15} 1 MeV n_{eq}/cm^2
  - Setup almost ready to start testing (new carrier board)
  - Waiting to receive an un-irradiated chip for comparison

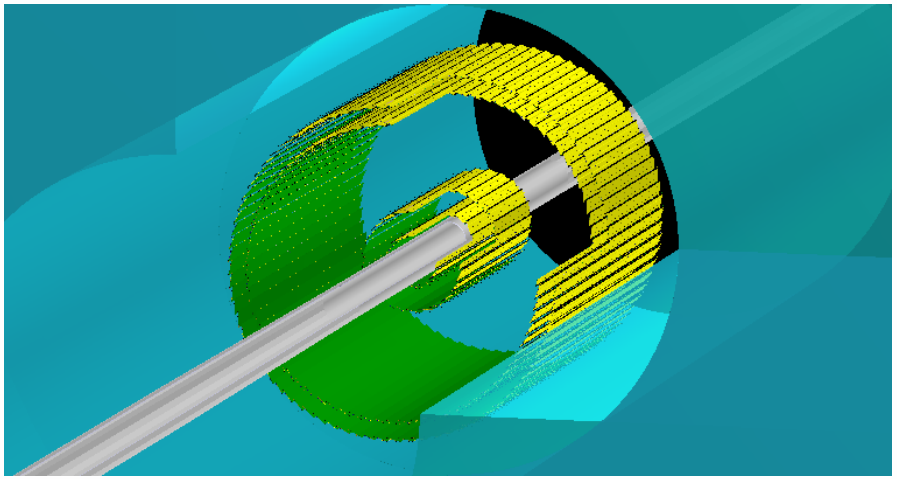


Reset signal provided by function generator
Amplifier is a CIVIDEC inverting 2 GHz / 20 dB C1-HV
Nitrogen flushed and cooled to -30 C

WP2: Simulations

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





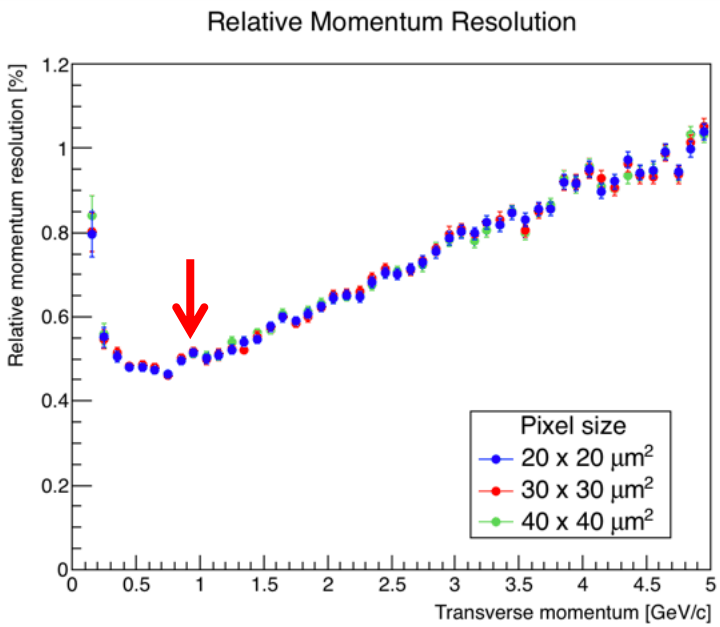
TPC parameters
Inner radius = 20 cm
Outer radius = 80 cm
250 μm position resolution

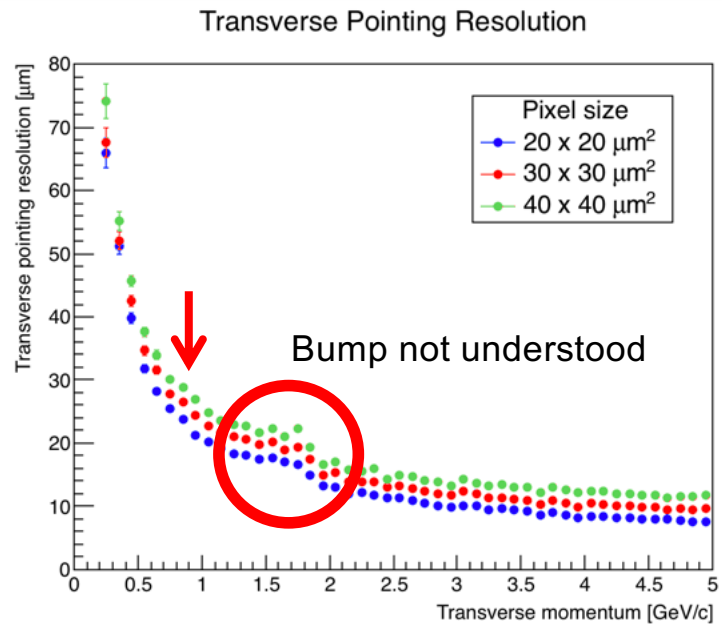
VST parameters
Layer #0 radius = 2.3 cm 0.3% X/X_0
Layer #1 radius = 4.6 cm 0.3% X/X_0
Layer #2 radius = 14 cm 0.8% X/X_0
Layer #3 radius = 16 cm 0.8% X/X_0
Layer #4 radius = 18 cm 1.6% X/X_0
20 x 20 μm^2 – 40 x 40 μm^2 pixels

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

WP2: Pixel size (spatial resolution)

- Simulation: TPC + 4 layer VST
  - Pions generated from (0,0,0) and $|\eta| < 1$

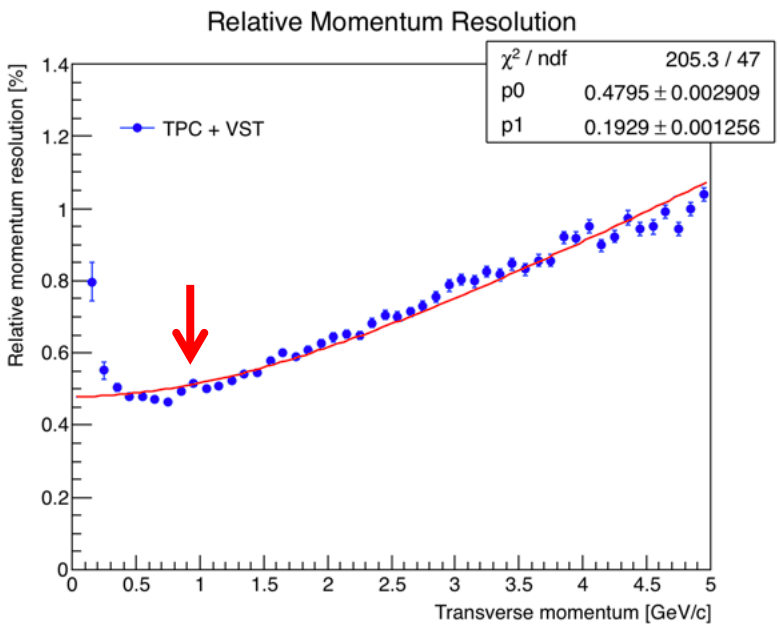


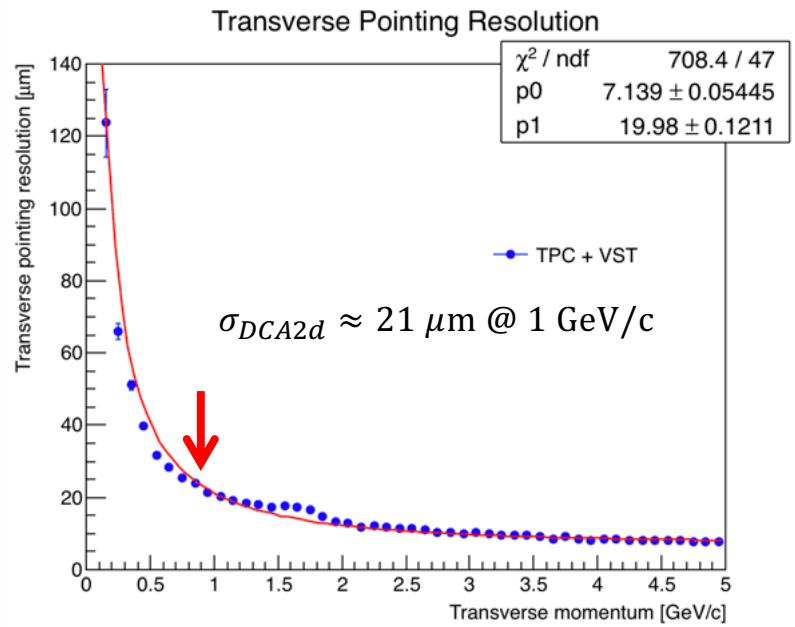


  - Momentum resolution is primarily a function of track length
  - Smaller pixels improve pointing resolution

WP2: Parameterisation

- Simulation: TPC + 4 layer VST (20 x 20 μm^2 pixels)
  - Pions generated from (0,0,0) and $|\eta| < 1$



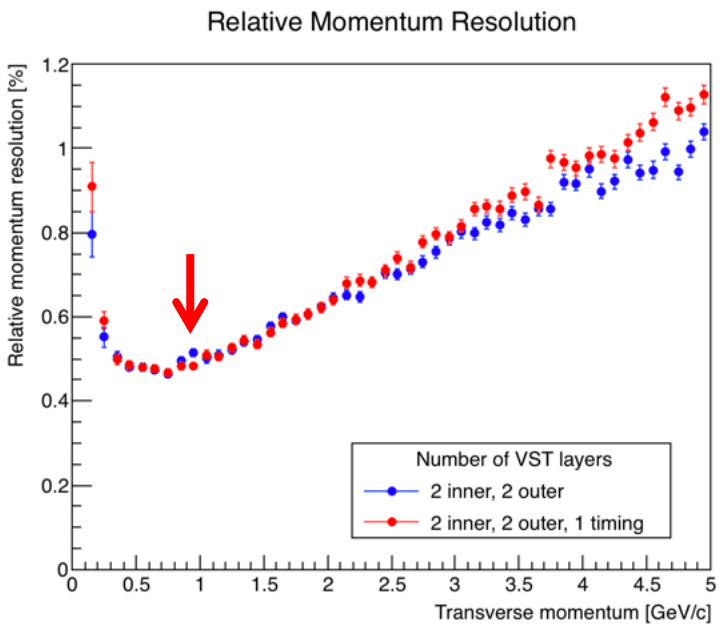


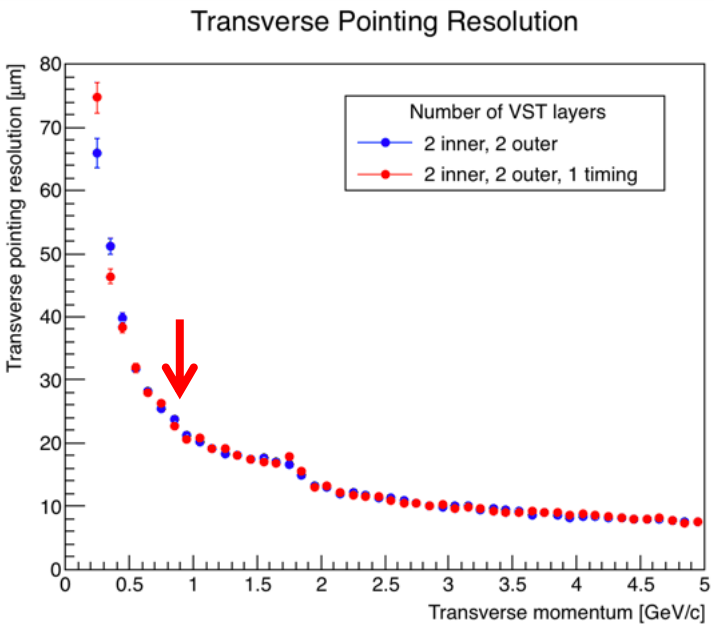
$$\frac{\sigma_{p_T}}{p_T} = \sqrt{p_0^2 + (p_1 . p_T)^2}$$

$$\sigma_{DCA2d}(\mu m) = \sqrt{p_0^2 + \left(\frac{p_1 . 1\ \mathrm{GeV/c}}{p_T}\right)^2}$$

WP2: Timing layer

- Simulation: TPC + 4 or 5 layer VST (20 x 20 μm^2 pixels)
  - Pions generated from (0,0,0) and $|\eta| < 1$

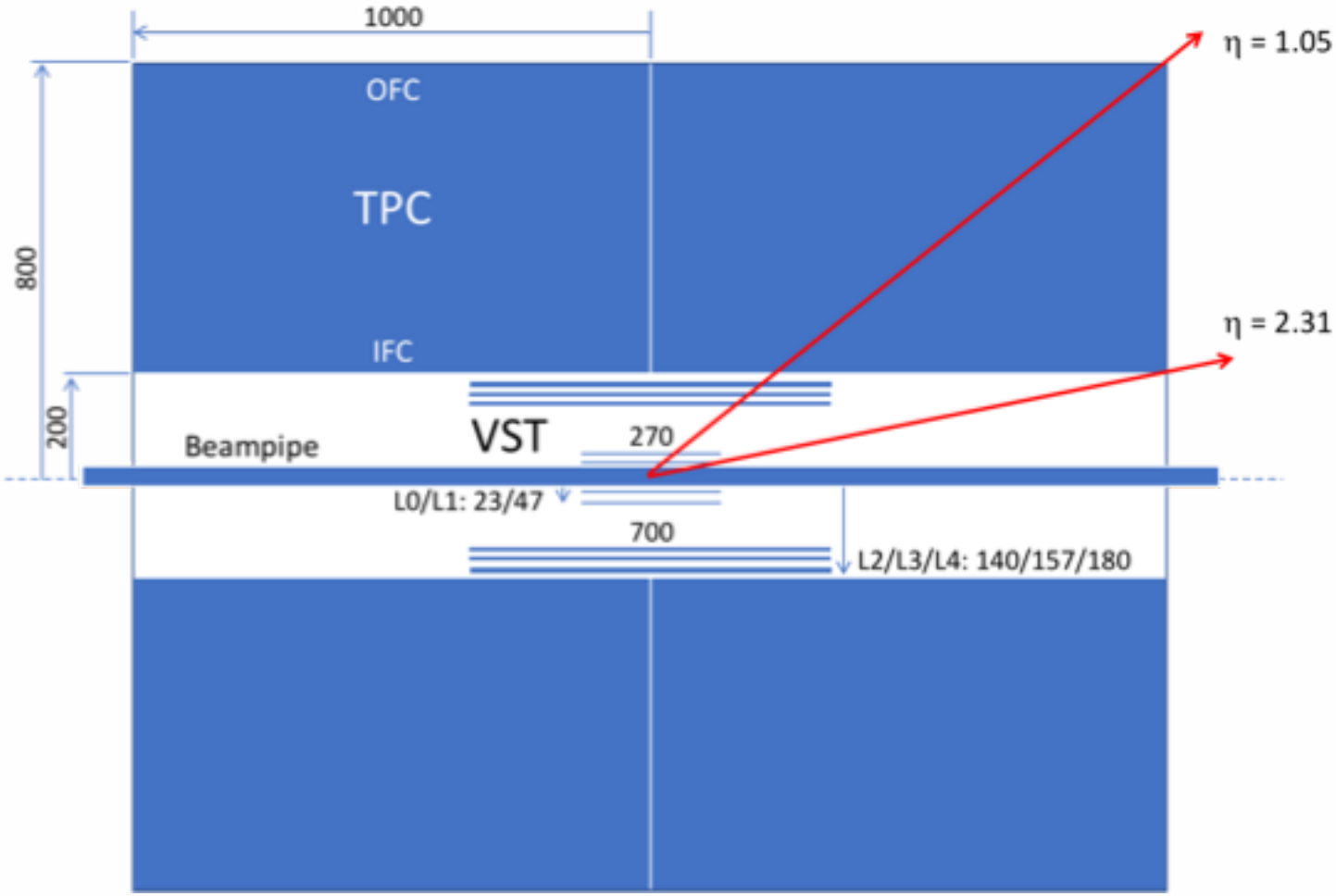




  - Added timing layer (1.6% X/X_0) has minimal impact on performance

WP2: Simulations

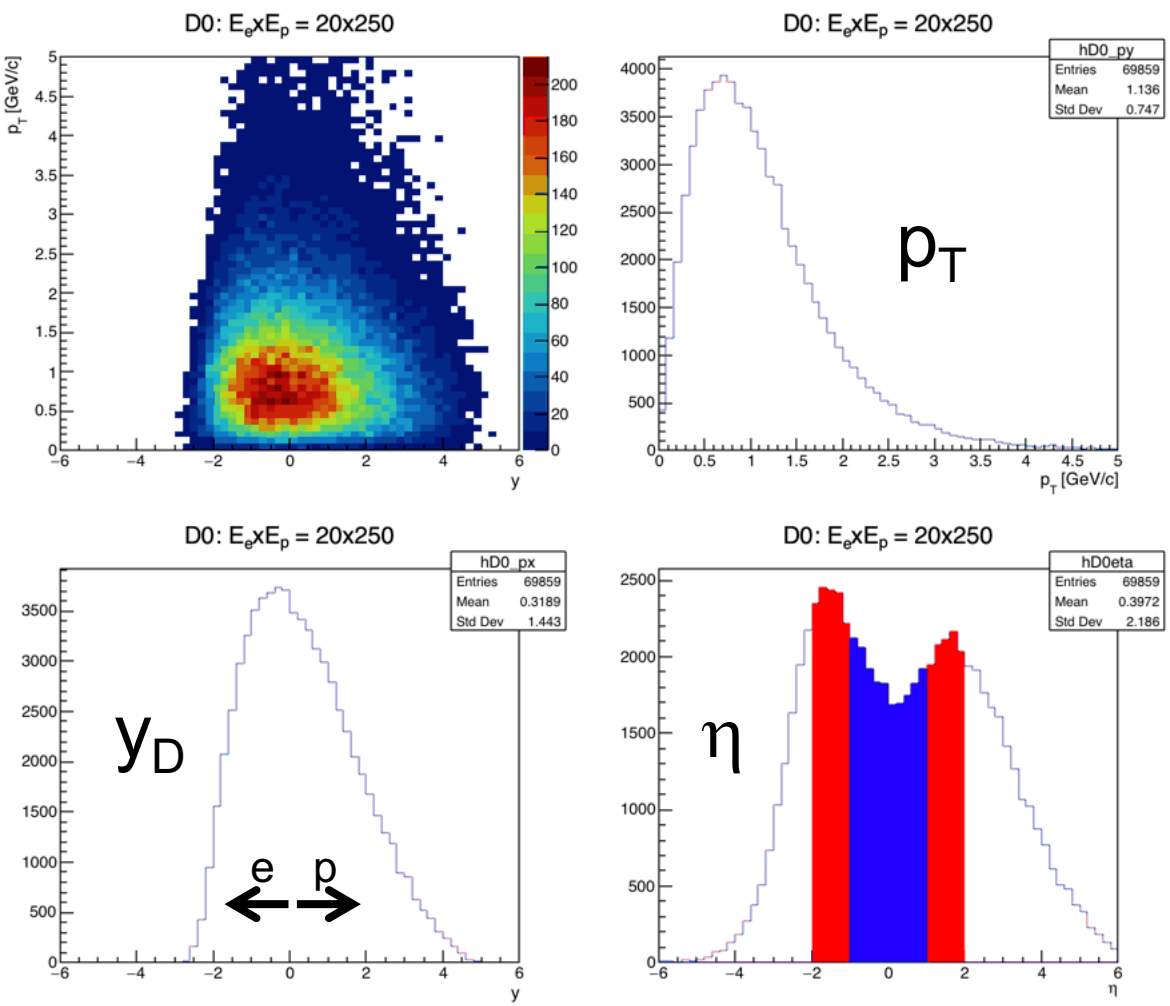
- Detector Geometry



Dimensions in mm

WP2: D^0 meson production in Pythia e-p collisions

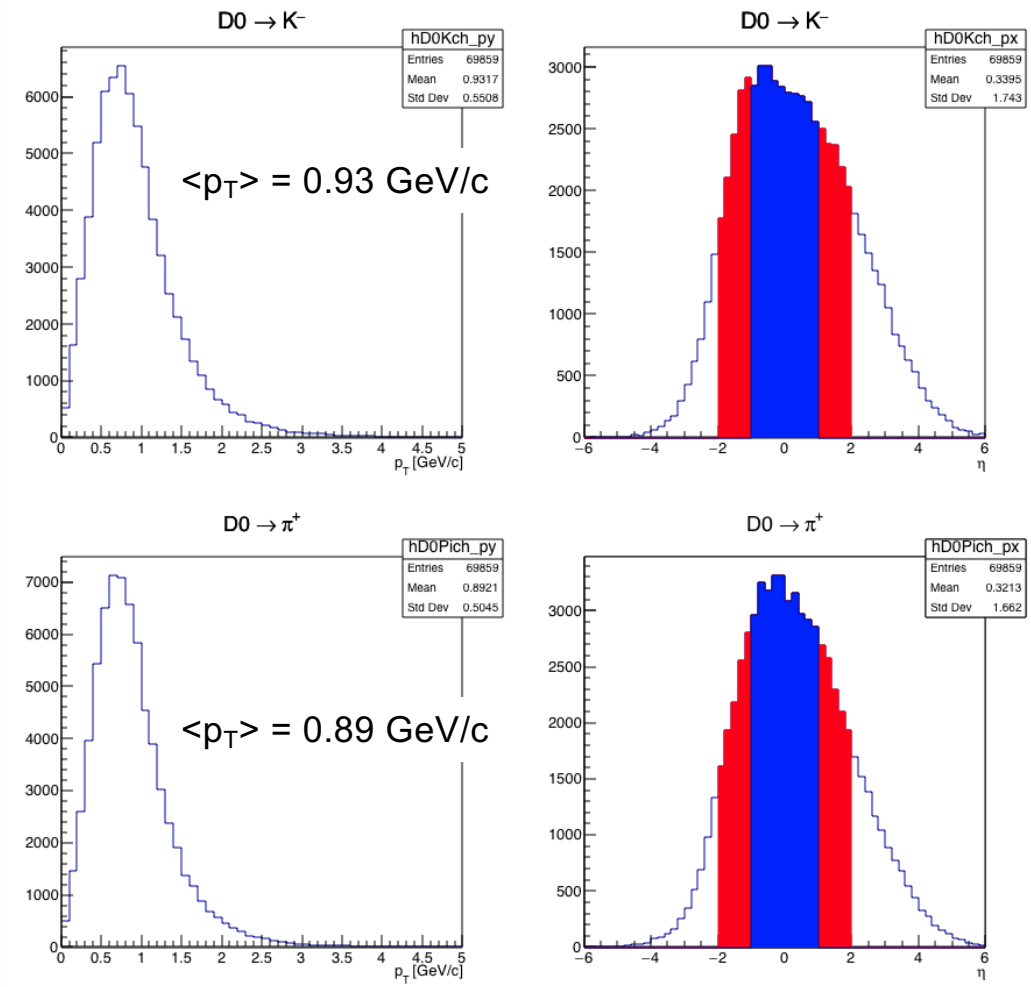
- Kinematic distributions (20 GeV x 250 GeV)



D^0 mesons	accept
$\|\eta\| < 1$	26.7%
$\|\eta\| < 2$	58.5%

WP2: D^0 decay daughters

- Kinematic distributions (20 GeV x 250 GeV)



$$D^0 \rightarrow K^- \pi^+$$

D^0 daughters	accept
Both central	22.2%
Both forward	11.2%
One central One forward	28.4%

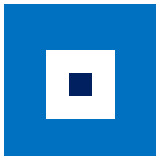
Central = $|\eta| < 1$
Forward = $1 < |\eta| < 2$

eRD18: FY19 Project Proposal

- WP1: Sensor development
  - Continue evaluation of TJ technology
    - CERN-TJ Investigator 2 chip
    - ATLAS MALTA chip
    - Additional designs will be available in the autumn
  - Work with chip designer at RAL
    - Simulate possible readout architectures
    - Explore tradeoff between power and pixel size
    - Provide realistic input into EIC DMAPS specifications
- WP2: Simulations
  - Explore interface with forward/backward disks (with eRD16)
  - Implement vertex fit in EicROOT
  - More detailed study of charm reconstruction
- WP1 & WP2: Collaboration with eRD16
  - Continue monthly Skype meetings and plan one face-to-face meeting
  - Also considering a silicon tracking workshop

eRD18: Comment on DMAPS strategy

- Only considering options in TJ modified process
  - For low power and fast readout require a single, small collection electrode



Pixel: 20 x 20 μm^2
Electrode: 3 x 3 μm^2
Electrode spacing: 3 μm

  - Fully depleted sensor + small collection electrode = TJ modified process
  - Evaluate **technologies and pixel layout configuration** with prototypes available through Birmingham involvement in DMAPS projects
  - Explore **readout architectures** for an EIC DMAPS sensor to optimize pixel size and power consumption against requirements from simulations

- No longer considering structures from our DECAL and RD50 projects
  - These achieve full depletion either using **multiple collection electrodes** or a **single large collection electrode** that would lead to higher pixel capacitance and higher power consumption

eRD18: FY18 Resources Summary

- FY18 expenditure
  - Awarded $98,611 (60% descope option)

Scenario	PDRA	Travel	Total (GBP)	Total (USD)
100%	£107,394	£10,000	£117,394	$164,352
80%	£83,915	£10,000	£93,915	$131,481
60%	£60,436	£10,000	£70,436	$98,611

  - Decided to use PDRA funds to consult with a chip designer
  - 4-6 months of designer time at RAL
  - Will be carried over into FY19 (Sep-Dec)
  - Needed to understand sensor requirements first

eRD18: FY19 Resources Summary

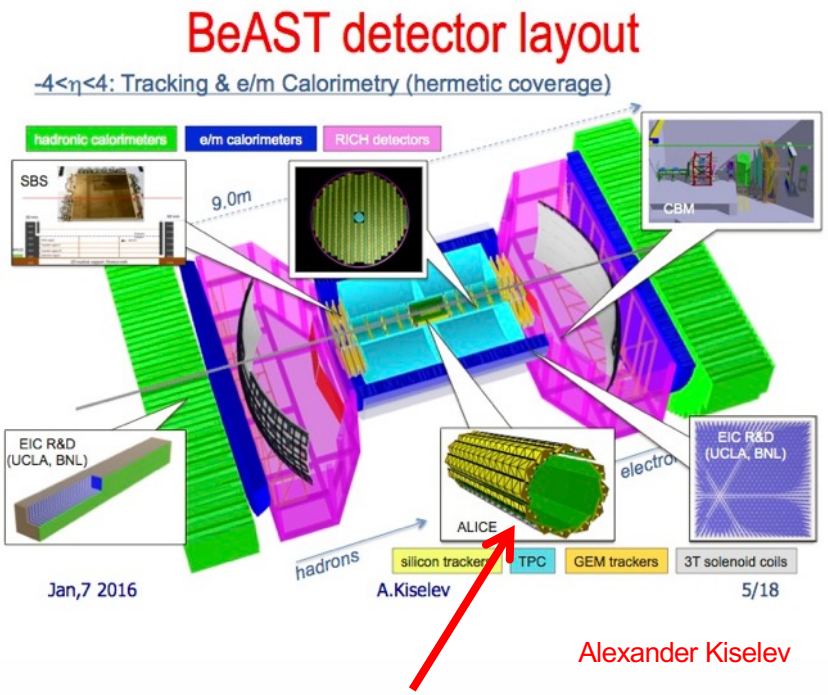
- Existing resources
  - Staff effort: Gonella (0.1 FTE), Jones (0.05 FTE), Newman, Allport
  - PhD student (Håkan Wennlöf) since October 2017
  - Access to technology investigators (CERN-TJ, ATLAS)
  - Access to MC40 cyclotron for irradiation studies
- FY19 funding request

1. Additional 3-4 months chip designer time at RAL	$60,000
2. Readout equipment for sensor tests	$6,000
3. Travel (4 x 2 x £1,250) = £10k	$14,000
Total	$80,000

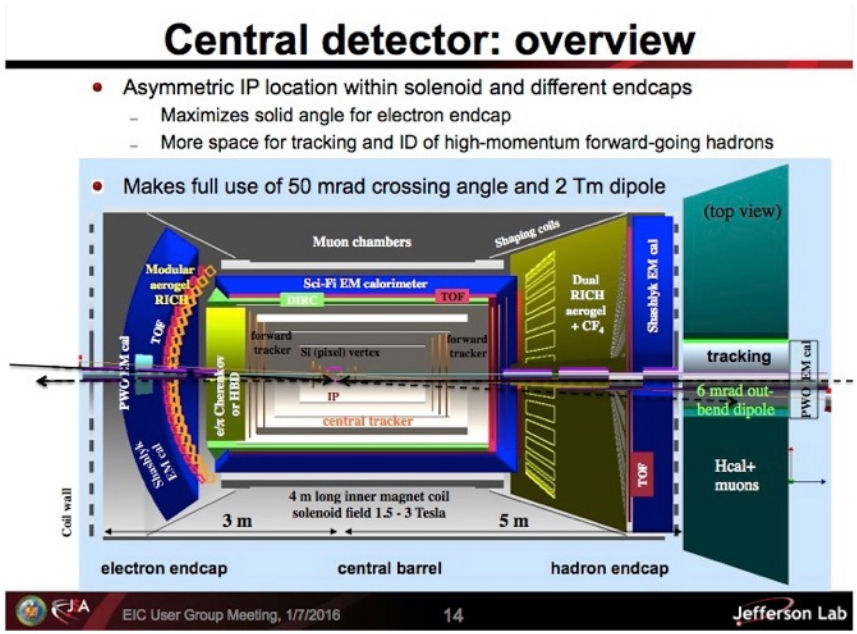
Scenario	Chip designer	Equipment	Travel	Total (USD)
100%	$60,000	$6,000	$14,000	$80,000
80%	$44,000	$6,000	$14,000	$64,000
60%	$24,000	$6,000	$14,000	$48,000

Backup Slides

EIC Detector Concepts



Alexander Kiselev



Pawel Nadel-Turonski

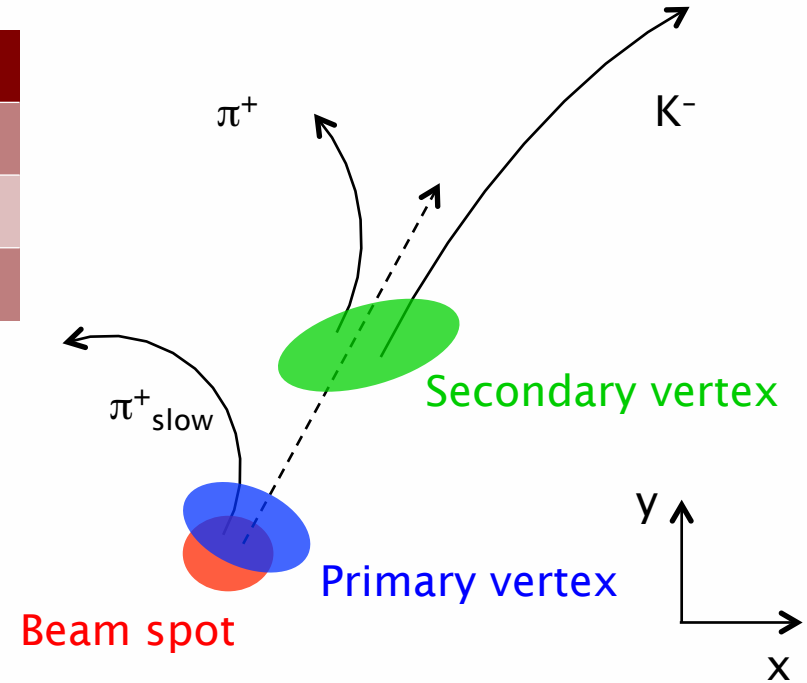
Based on **ALICE ITS** inner layer design

- Si vertex and tracker detectors in central and forward regions
- Seek high resolution, high s/n, low mass, low power solution
  - applicable to both eRHIC and JLEIC

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:

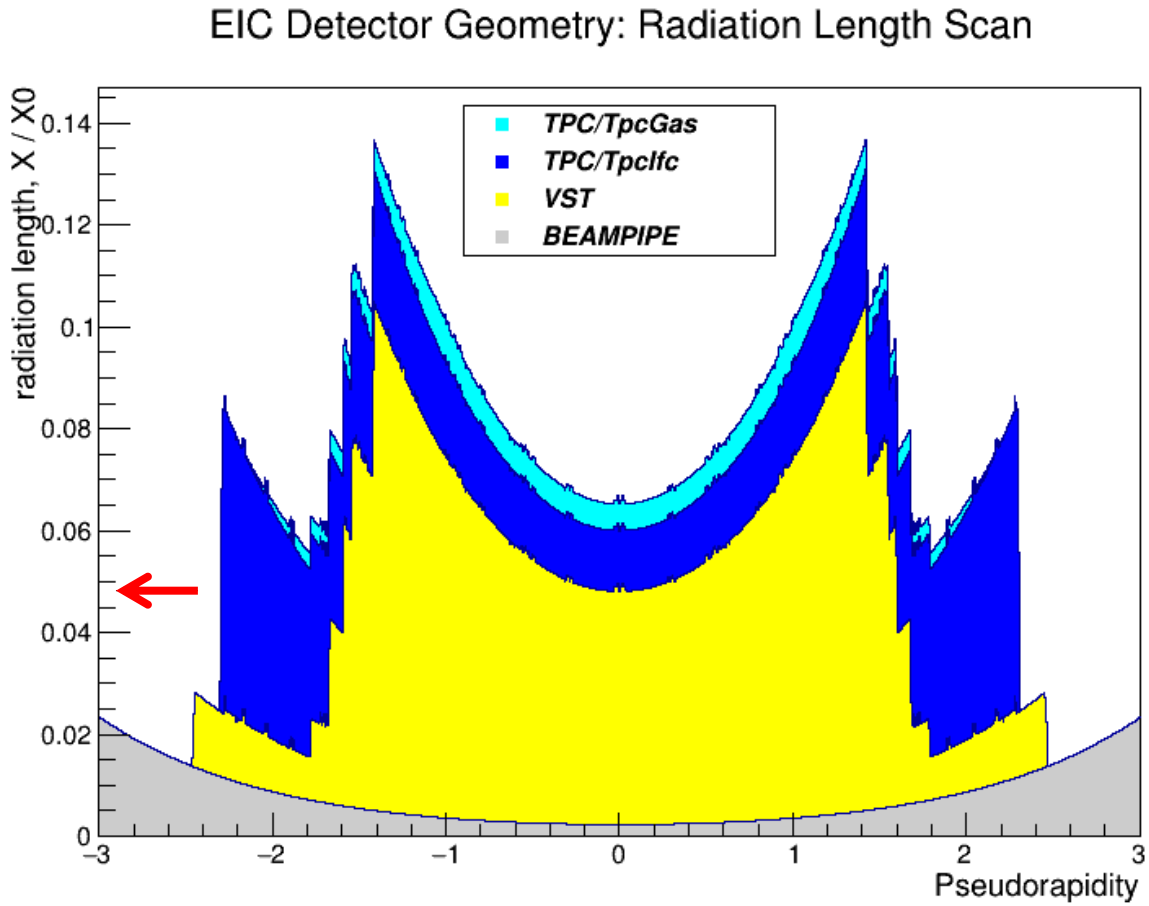
$$D^{*+} \rightarrow D^0\pi^+_{slow} \rightarrow \left(K^-\pi^+\right)\pi^+_{slow}$$

- 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: beam backgrounds)
    - Highest possible spatial resolution (small pixels)

WP2: Simulations

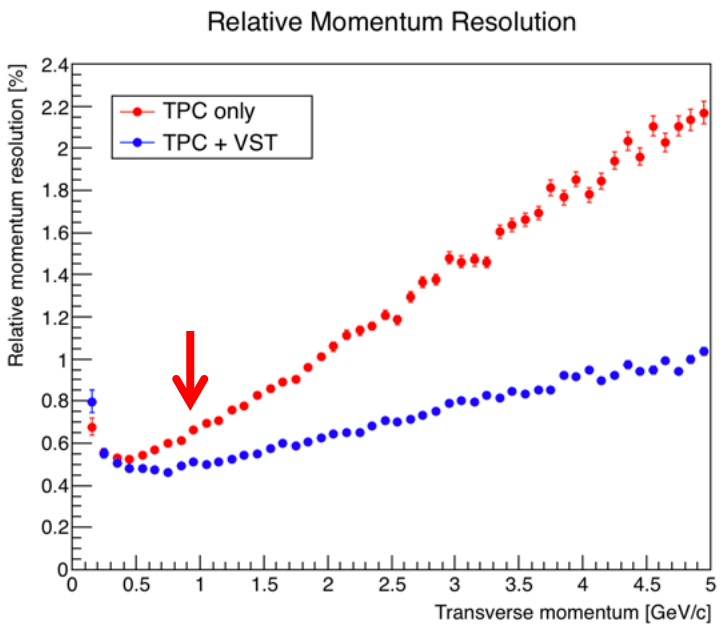
- Radiation length scan in EicRoot

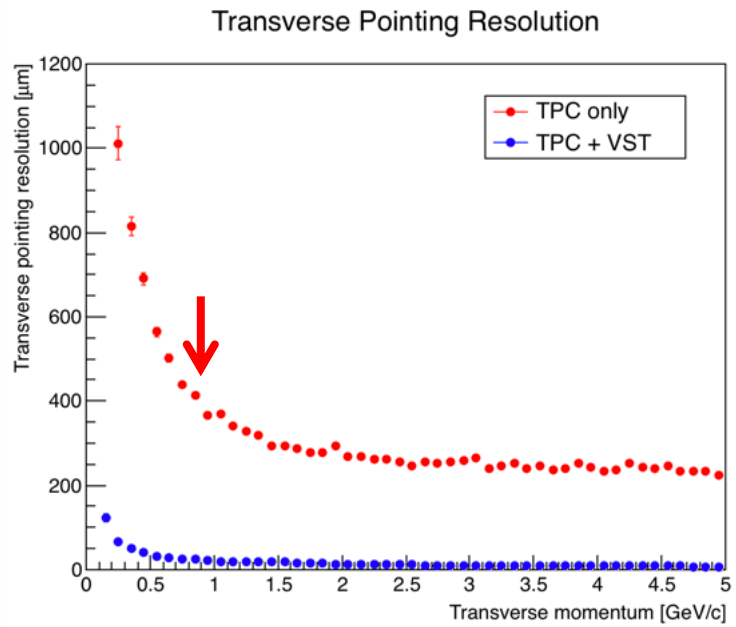
$\eta = 0$	X/X_0 [%]
Beampipe	0.2%
VST L0	0.3%
VST L1	0.3%
VST L2	0.8%
VST L3	0.8%
VST L4	1.6%
Total	4.0%



WP2: TPC+VST versus TPC only

- Simulation: TPC + 4 layer VST (20 x 20 μm^2 pixels)
  - Pions generated from (0,0,0) and $|\eta| < 1$





  - Momentum resolution is a function of track length
  - Pointing resolution is dominated by first layer of VST