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Path to a hybrid tracker baseline and initial D^0 event studies

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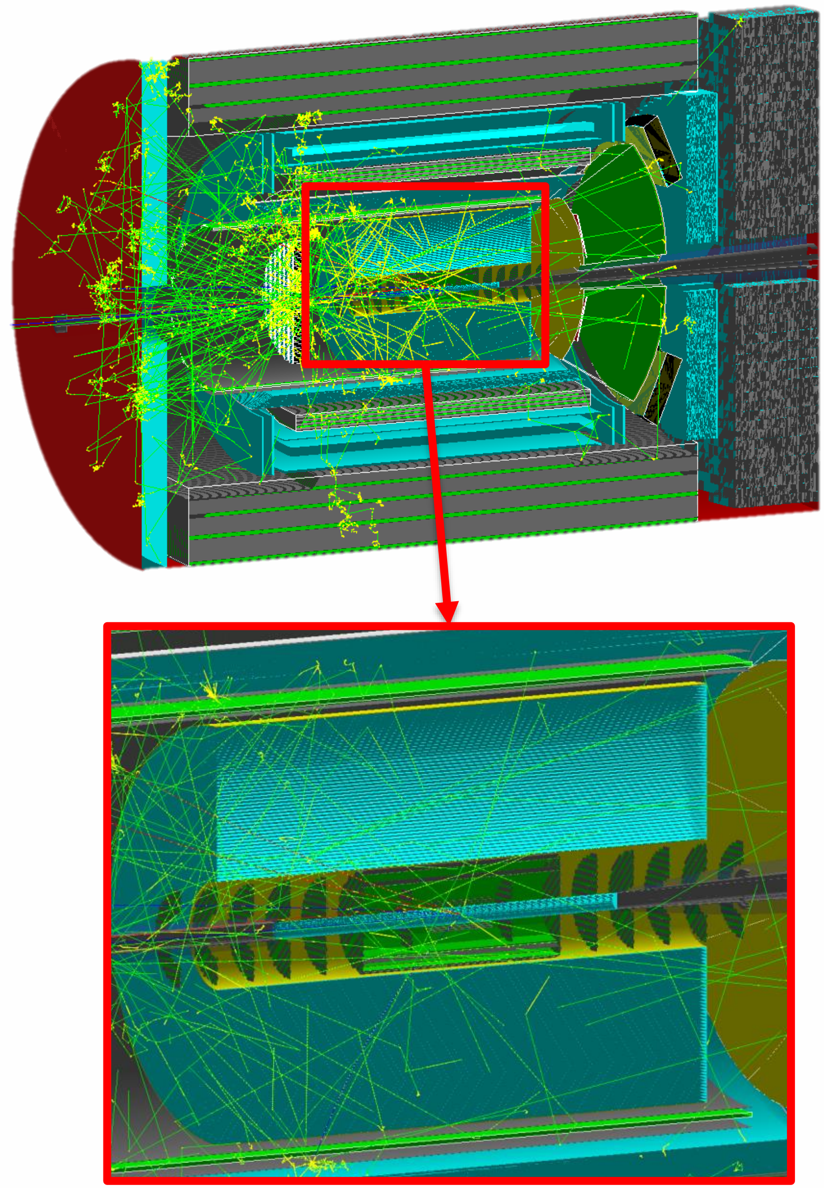
Outline

- Introduction
  - Motivation
  - Simulation tools used
  - Basic geometry description
- Baseline layout simulations
- Physics performance simulations
- Future work
- Conclusions



This work has been carried out as part of the Birmingham eRD18 project “Precision Central Silicon Tracking & Vertexing Detector for the EIC”, and eRD25 “Silicon Tracking and Vertexing Consortium” within the EIC Generic Detector R&D Programme

Motivation

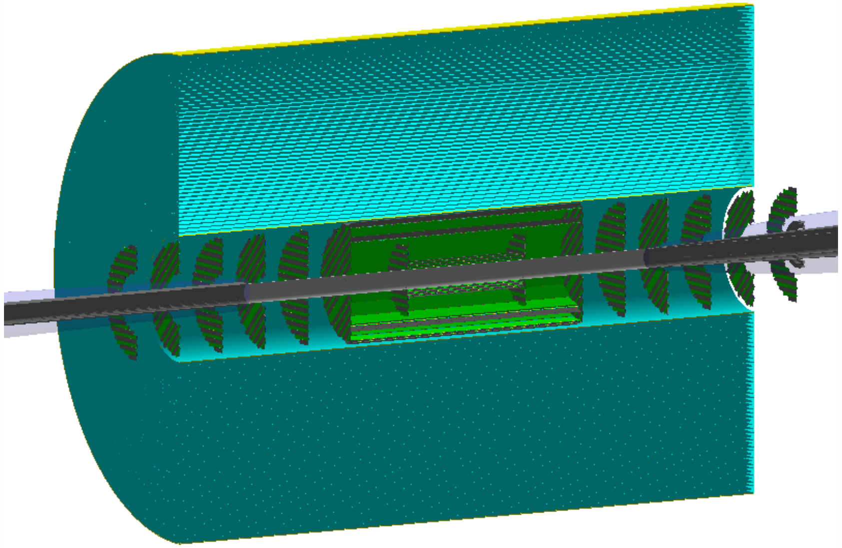
- Building on from initial technology investigations
  - Simulations make it easy to see performance impact of pixel size, material budget, magnetic field etc.
- Goal: developing and testing a silicon vertex tracker, taking technologies into account
  - Investigating performance of silicon vertex tracker concepts
  - Optimising SVT layout and parameters
  - Understanding constraints of detector on physics measurements
- **Two types** of simulations are run:
  - Baseline layout simulations using single particles
  - Physics performance simulations using generated collision events

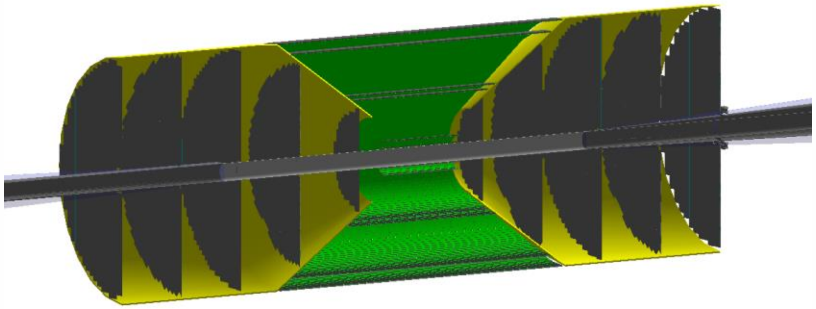
Simulation tools used

- EICROOT
  – For basic single-particle simulations
  – Developed at BNL, based on framework built for the FAIR lab and the PANDA experiment
  – GEANT-based, with single-particle gun input
- Pythia 8
  – For collision event generation
- Fun4All (used in sPHENIX simulations)
  – For propagation and reconstruction of the physics events
  – Developed for and used in the sPHENIX experiment
  – GEANT-based, with event generator input
- University of Birmingham BlueBEAR HPC service

Basic geometry description

Layout cross sections along the beam direction





Compact all-silicon design by R. Cruz Torres, see talk for details

- Two different designs are proposed and simulated; hybrid (silicon+gaseous detectors) and all-silicon
- Geometry components:
  - Beampipe runs through the centre
  - Silicon **barrel** layers in the central region
  - Silicon **disks** in the forward and backward regions
  - Gaseous detector or more silicon layers outside central barrel

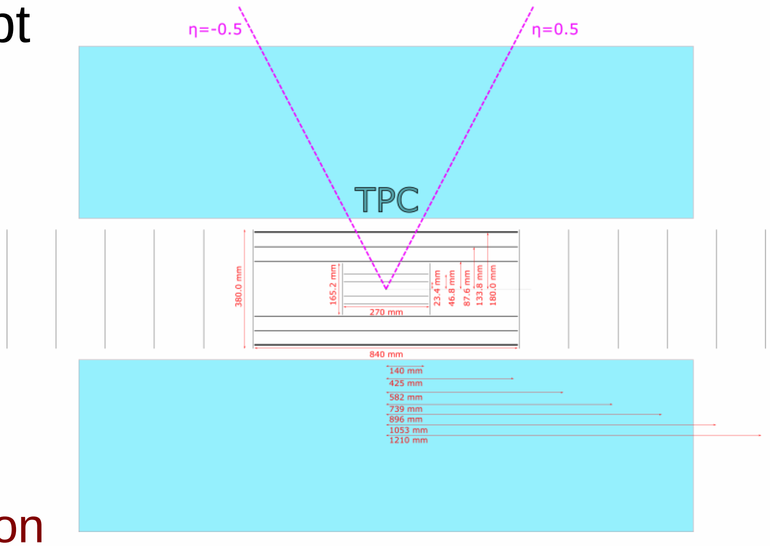
Baseline performance simulations in EICROOT

- Carried out for both silicon+TPC and all-silicon tracker designs
- Studies have covered:
  - Central and forward/backward regions
  - Interface region between barrel and disks
  - Si+TPC compared to all-silicon
- Figures of merit for studies:
  - Relative momentum resolution
  - Transverse and longitudinal pointing resolutions
- **Examples** shown in this talk. More studies and details in report http://cern.ch/go/xKk6

Contents

Initial design parameters

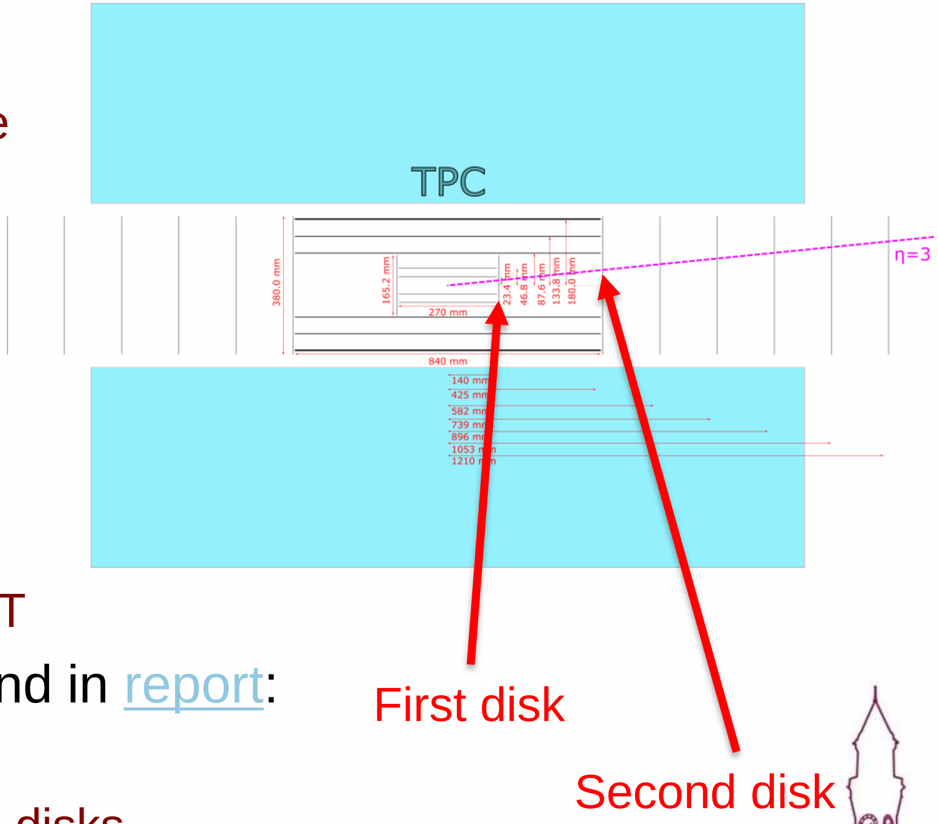
Cross section along beam direction



- Design based on modified BeAST concept
  - 2 inner barrel layers, 3 outer barrel layers
  - 7 disks in forward and backward directions
- Material budget;
  - Inner layers and disks: 0.3% X/X_0
  - Outer layers: 0.8% X/X_0
- Beampipe
  - Beryllium with 18 mm radius in central region
  - Aluminium with 20 mm radius further out
- Innermost barrel layer placed as close as possible to beampipe
- Innermost disk placed as close as possible to inner barrel layers (inside outer barrel layers)
- Default pixel size: 20x20 μm^2
- Default magnetic field: uniform 1.5 T
- Conservative TPC parametrisation

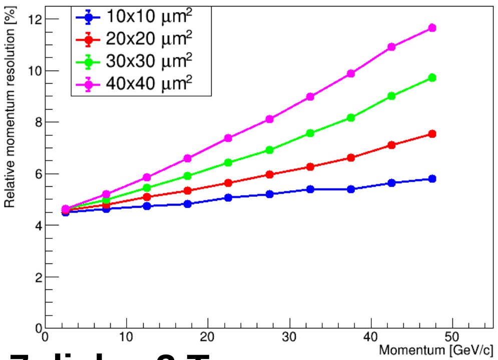
Example: Simulations of disks

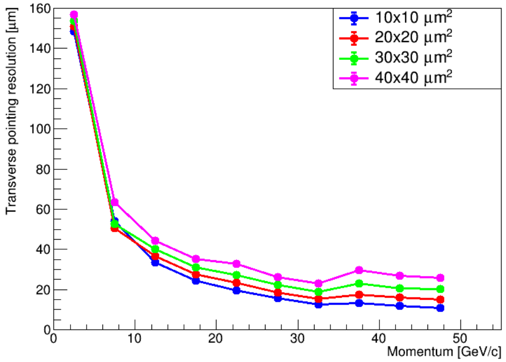
- Simulations have studied two configurations, with either 7 or 5 disks per side
  - First disk inside outer barrel layers
  - Remaining disks equidistant outside
- Study presented here:
  - Impact of disk pixel size and magnetic field
- Simulation parameters used:
  - Forward region studied; η = 3
  - Single electrons fired from centre
  - Magnetic field: uniform 1.5 T and 3 T
- Examples of other disk studies found in report:
  - Innermost disk position
  - Interface region between barrel and disks



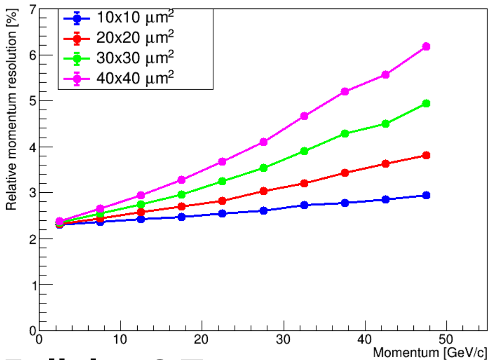
Disk pixel sizes - results

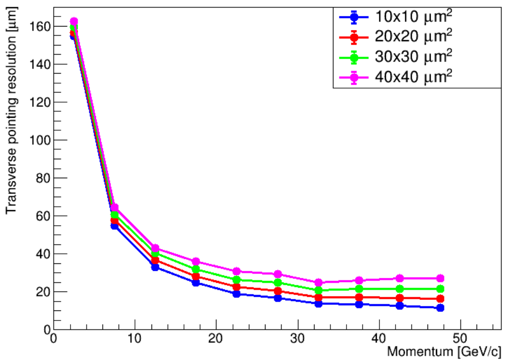
7 disks, 1.5 T



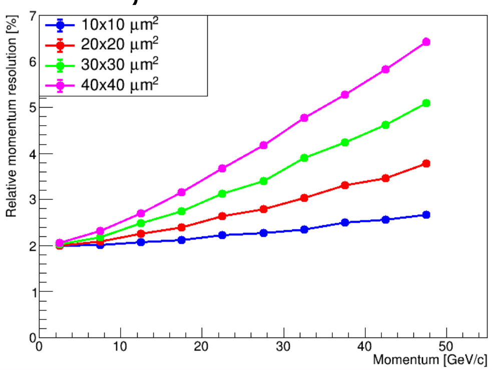


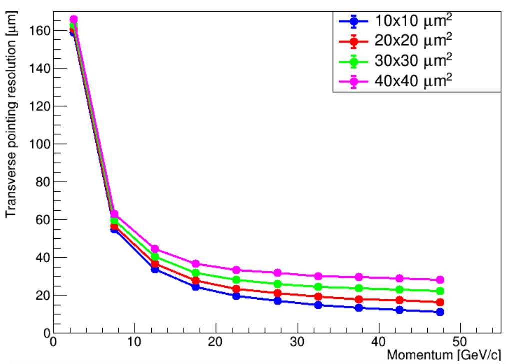
7 disks, 3 T





5 disks, 3 T

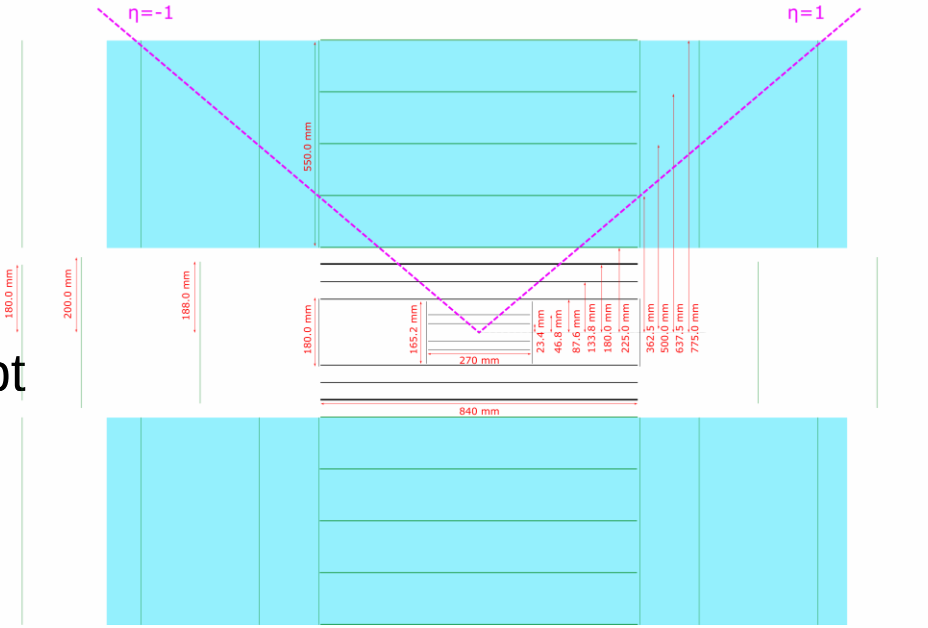




- Smaller pixel size improves **both relative momentum resolution and pointing resolutions**
- 3 T magnetic field improves momentum resolution by a factor of ~2, as expected from theory
- Not much difference between 7 or 5 disks
  - 5 slightly better momentum resolution due to lower material
  - 7 gives better coverage, however

Decreasing radius – comparing hybrid to all-silicon

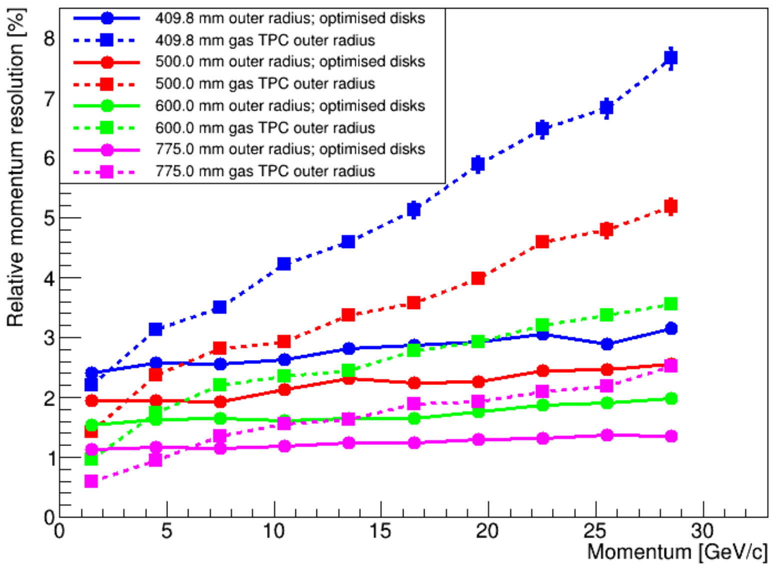
- Goal: investigate performance of Si+gas and all-Si when **outer radius is decreased**
- Potentially interesting for **detector complementarity** discussion
- Five-layer all-silicon layout used. Outer radius decreased, layers kept equidistant
- Simulation parameters used:
  - Central region studied, $|\eta| \leq 1$
  - Single electrons fired from centre
- Details, and study in forward regions, available in [report]
- **Note**: gas TPC provides more points for reconstruction, and gives some particle ID info. This does not factor into these simulations



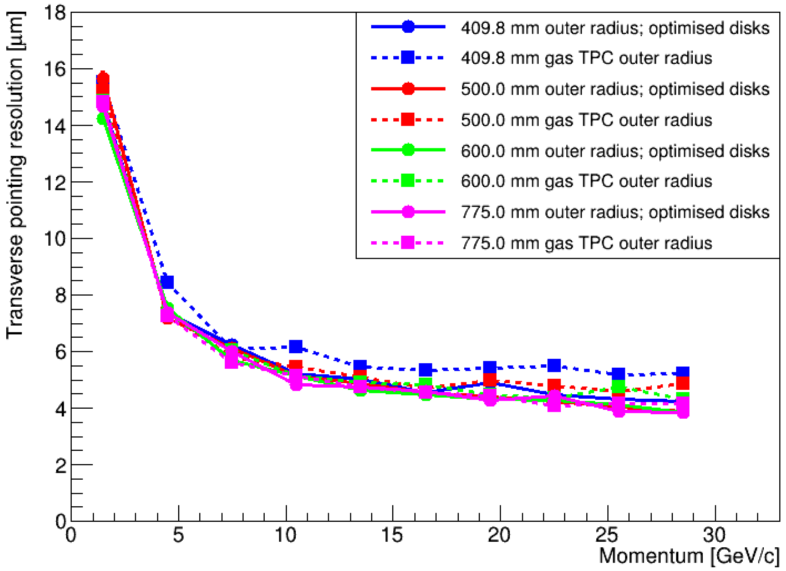
Pixel size used: 20x20 μm^2
Momentum range: 0 to 30 GeV/c
Magnetic field: uniform 1.5 T

Decreasing radius study - results

Relative momentum resolution



Transverse pointing resolution



- Colours correspond to radii. Solid line with circular markers indicates all-silicon, and dashed line with square markers indicates hybrid
- All-silicon layout relative momentum resolution deteriorates slower with increasing momentum
- The smaller the radius, the better the all-silicon compared to hybrid
- All-silicon layout **can outperform** Si+gas hybrid at p≥5 GeV/c

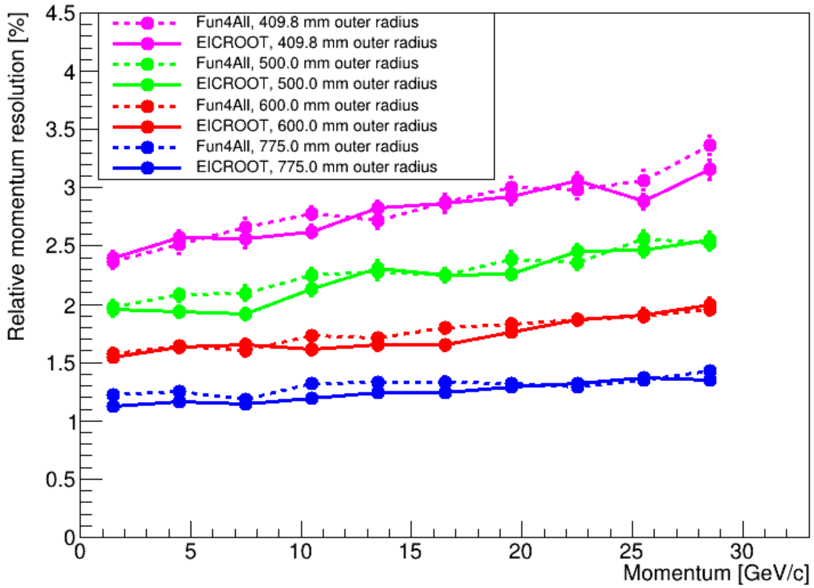
Physics performance simulations

- After CD-0 and site selection in January 2020, studies can be more focused
- Parameters are better known;
  - Beamline
  - Beampipe
  - Detector space constraints
  - Interaction rate
- Detector simulations can be more realistic, and study the impact of the parameters open for discussion (e.g. SVT radius, magnetic field, etc.)
- New layout based on new beampipe and ALICE ITS3 technology (see talks tomorrow morning)
  - Allows for **lower material** and **smaller pixel size**
- Investigations made into the detector physics performance, using realistic events and event reconstruction

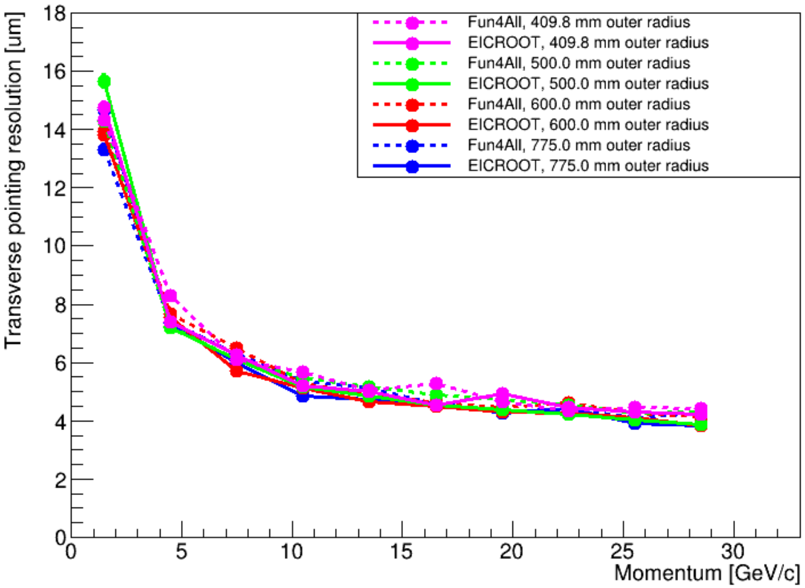
Framework benchmark study

- Moving into new simulation framework, a comparative study is first made
  - Exact same study made in EICROOT and Fun4All
- Generally very good agreement between the frameworks gives confidence that both old and new studies are relevant

Relative momentum resolution

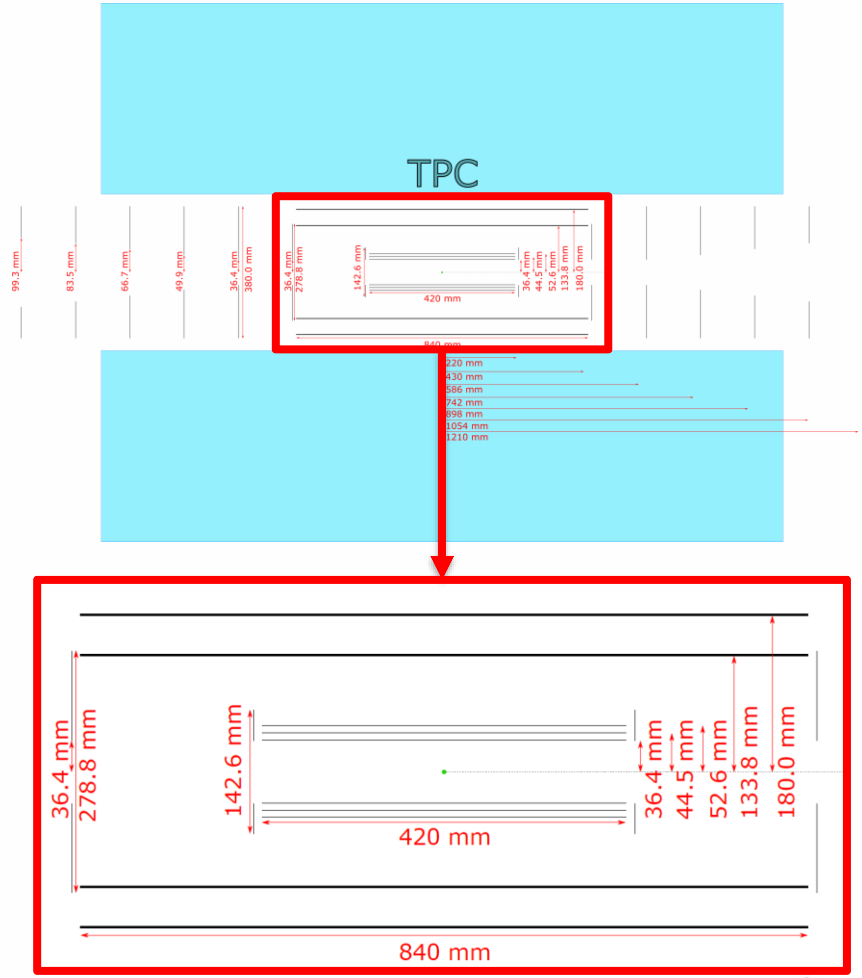


Transverse pointing resolution



New layout description

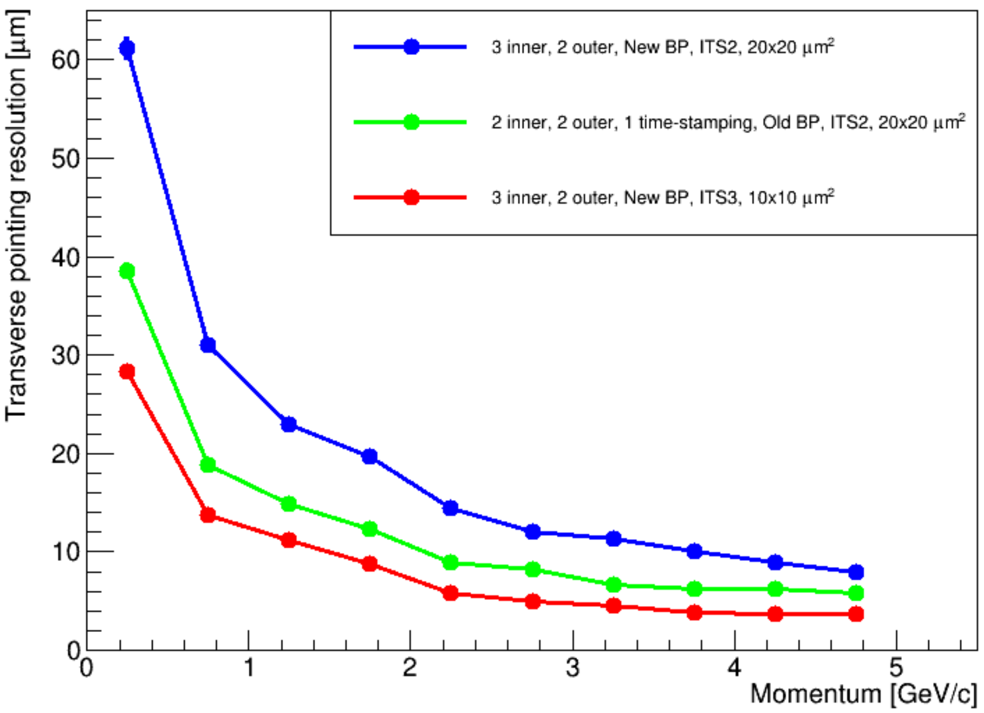
- Key part of simulations is to develop and test the performance of well-integrated, large-acceptance tracking concepts **based on the ITS3 technology**
- The EIC requires a larger beampipe than previously studied, so the innermost detector layers have to be shifted accordingly
- An extra inner layer added to better register low-momentum particles
  - Especially important at higher B-field
- A **new baseline** silicon vertex tracker is designed;
  - Three inner layers, two outer layers
  - Material budget: 0.05% X/X_0 inner layers, 0.55% X/X_0 outer layers
  - Pixel size: 10x10 μm^2



New layout performance

- Comparing old layout (green) with new layout using ITS2 technology (blue) and ITS3 technology (red)
- New layout using ITS2 technology performs worse due to larger beampipe radius
- The decline in performance is **overcome** by going to ITS3 technology
  - Smaller pixel size (10x10 μm^2)
  - Lower material (0.05% X/X_0)
- ITS3 technology **clearly worthwhile to pursue** to keep high vertexing performance

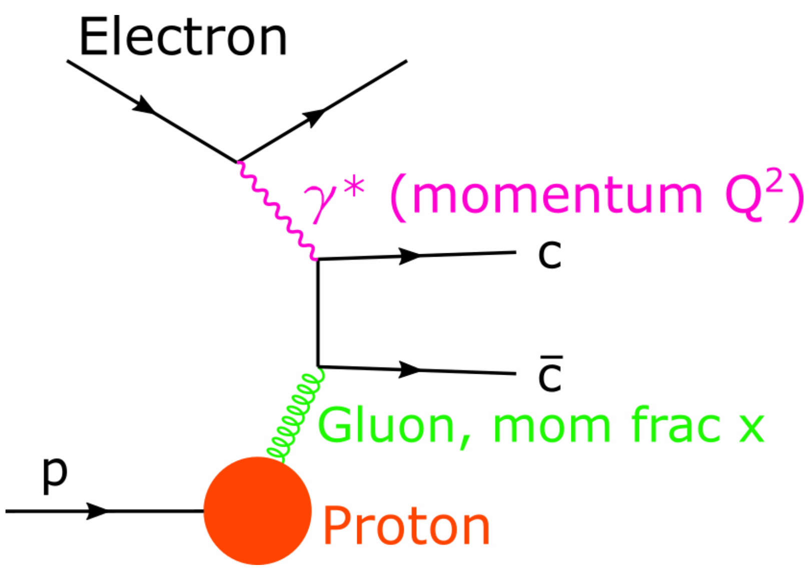
Transverse pointing resolution vs momentum

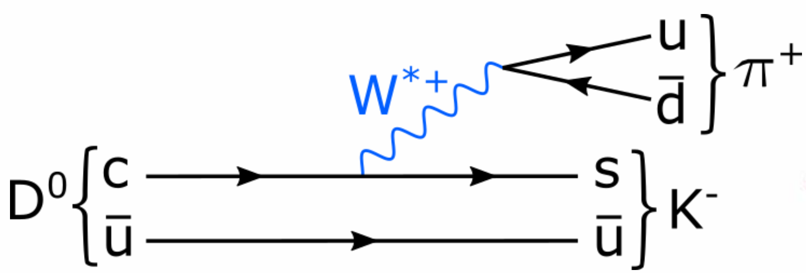


Particle: $\pi+$
Transverse momentum range: 0 to 5 GeV/c
Pseudorapidity: $-0.5 \leq \eta \leq 0.5$
Magnetic field: uniform 1.5 T

Physics performance simulations

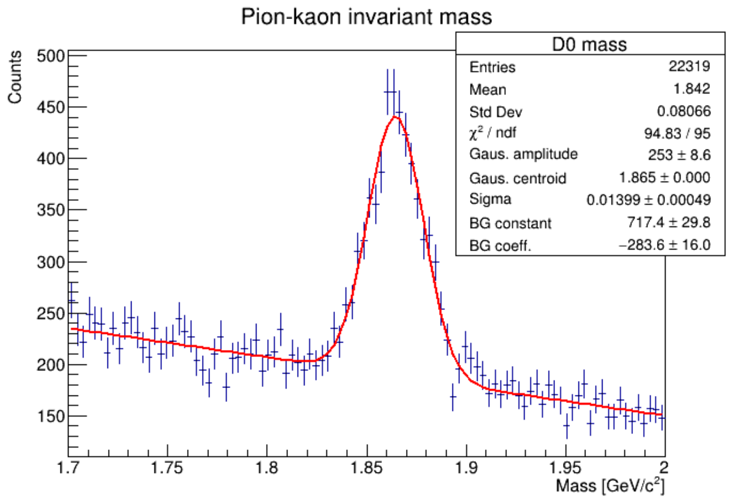
- Open charm events studied
- Pythia 8 used for event generation
  - Electron-proton collisions at a few different energies
  - Photon-gluon fusion to $c\bar{c}$ process
  - Allowed to hadronise freely
- Figure of merit: D^0 reconstructed mass, from hadronic decay to pion-kaon pair
- **Overall goal:** Finding detector kinematic range in x and Q^2, and precision of measurements in bins of x and Q^2, for varying layouts and parameters



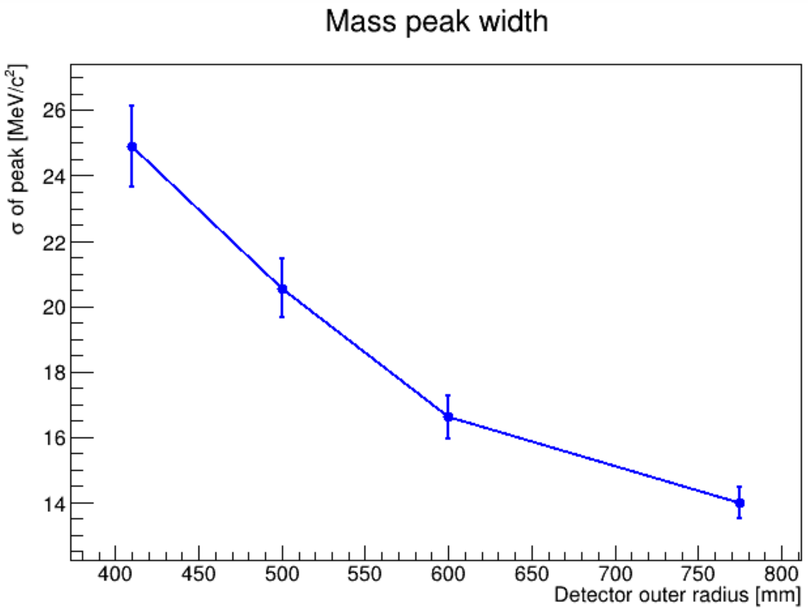


Initial all-silicon outer radius study

- All-silicon layout used, with varying outer radii
- Ideal particle ID assumed
- All pion-kaon pairings used in creating invariant mass spectrum
- Centroid value of D^0 peak (1865 ± 14 MeV/c^2) is within errors from PDG mass value (1864.84 ± 0.18 MeV/c^2)

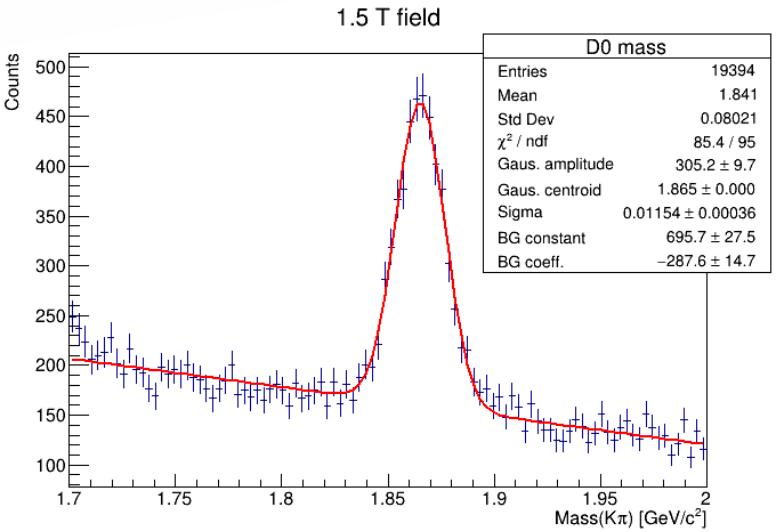


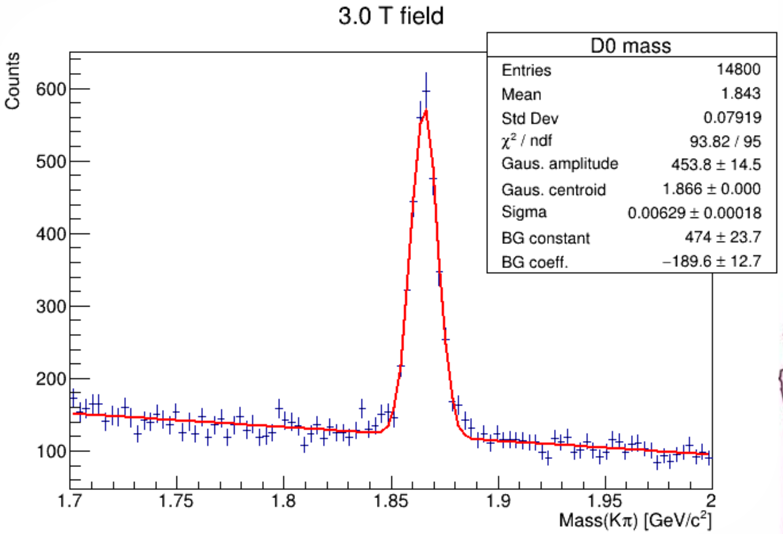
- Clear improvement in mass peak width as outer radius increases
  - Matches theoretical prediction for improved momentum resolution well



Initial magnetic field strength study

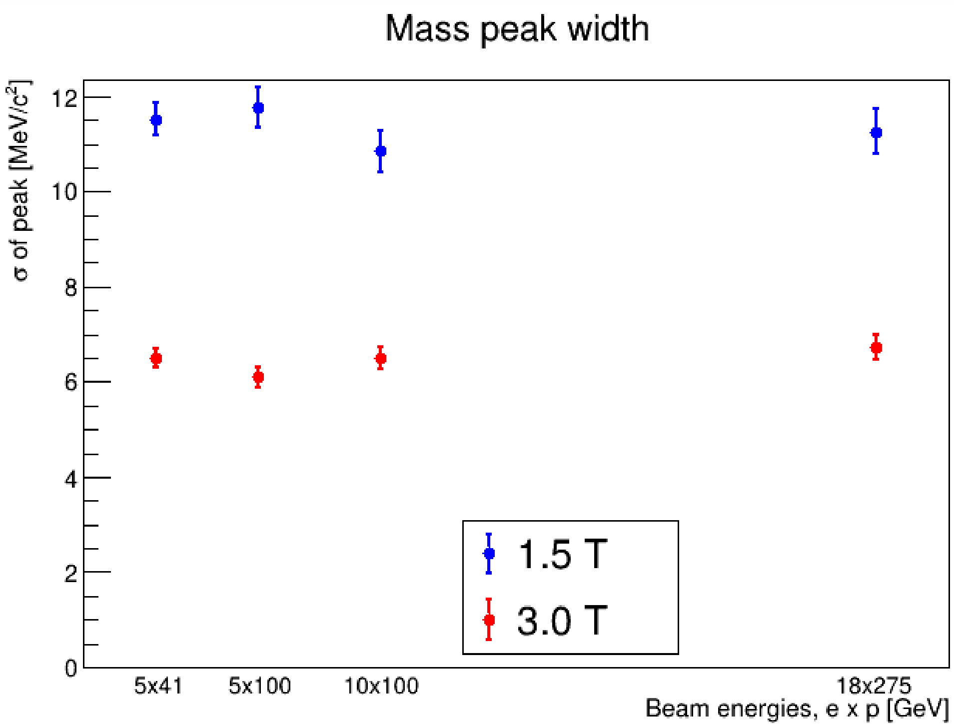
- All-silicon layout used, in ITS3-based design
- Magnetic field varied
  - 1.5 T
  - 3.0 T
- Initial results shown
  - Using 3.0 T **improves mass resolution** at this particular collision energy of $\sqrt{s} = 29$ GeV
  - Further studies ongoing
- Risk: higher field causes low-momentum particles to spiral before hitting the detector
  - This study made with ITS3-like and 3 inner layers to mitigate this risk





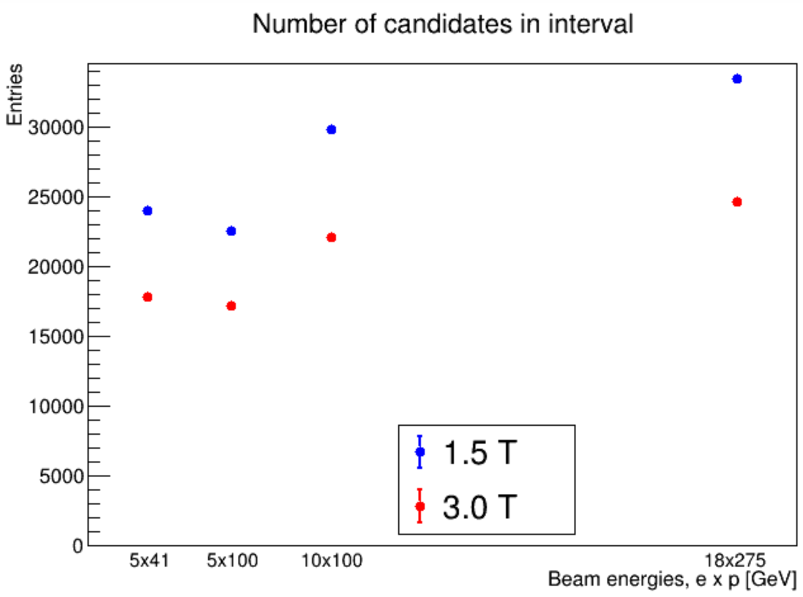
Initial magnetic field study

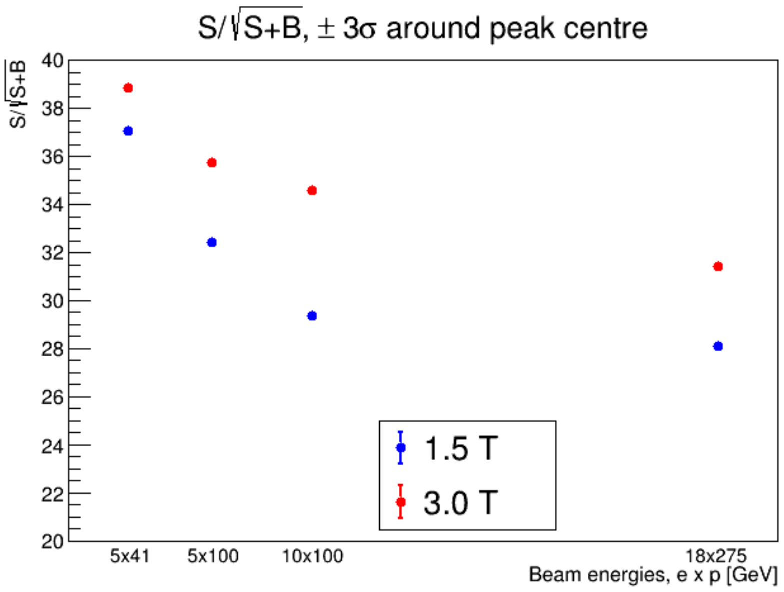
- Mass peak width for different e-p collision energies suggested by Physics WG;
  - 5x41 GeV
  - 5x100 GeV
  - 10x100 GeV
  - 18x275 GeV
- Mass resolution **improved** by higher magnetic field
- However, events are **lost** due to spiralling



Initial magnetic field study

- Number of events in mass interval **decreases with increased magnetic field**
  - ~25% decrease
- However, signal-to-noise ratio **increases**
  - Mass peak is sharper compared to background
- Study ongoing concerning the location of D^0 decay products for different fields
- Different cuts and their impact being investigated





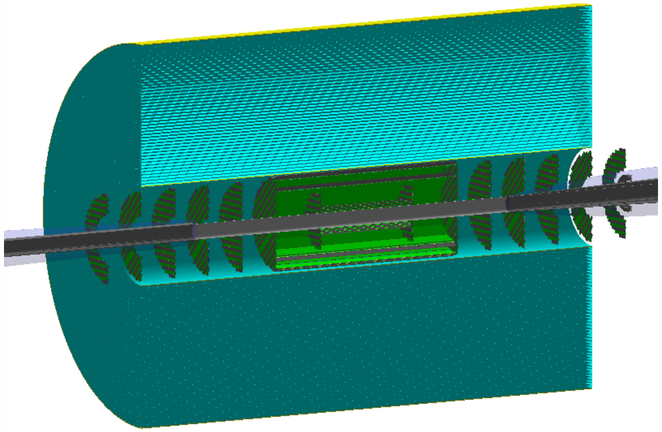
Future work

- Overall goal: Finding detector kinematic range in x and Q^2, and precision of measurements in bins of in x and Q^2, and **optimising layout and parameters**

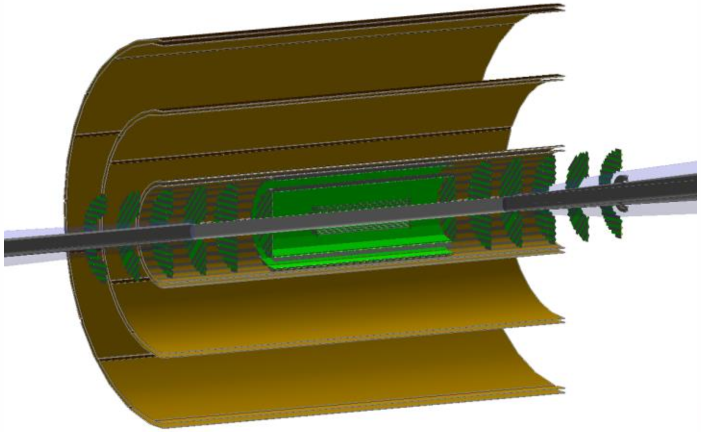
- Technical steps to get there:
  - Implementing realistic services in simulations (see talk by L. Greiner)
  - Further investigate impact of magnetic field for different collision energies
    - Higher magnetic field means better momentum resolution, **but** the lowest-momentum particles will not be detected
    - Investigate and quantify how ITS3-like design can improve performance
  - Using actual vertex reconstruction rather than simple distance of closest approach method
    - More realistic situation
  - Integrating SVT with other subdetectors to evaluate full detector performance
    - Work ongoing with gas detector groups to create full hybrid concept baseline

Future work – full hybrid concept

- Following work done by eRD16, eRD18, and eRD25, **baseline silicon layout determined** for the Yellow Report hybrid simulation effort
  - Details and implementation here. See also slide 14
  - Pixel size: 10x10 μm^2
  - Material budget: 0.05% X/X_0 inner layers, 0.55% X/X_0 outer layers, 0.24% X/X_0 disks
- Combining silicon vertex tracker baseline with gaseous outer detectors
- 2 possible designs;
  - TPC and large area MPGDs for end cap tracking
  - MPGD barrel and large area MPGDs for end cap tracking



Silicon and TPC layout



Silicon and MPGD layers layout, courtesy of Q. Huang, CEA Saclay

Conclusions

- A few concepts with high performance found from detector simulations, both in hybrid and all-silicon configurations
  - Simulations show that high granularity detectors and low material **essential** close to the interaction point
    - At most 20x20 μm^2 pixel size can be used, but **10x10 μm^2** needed to overcome disadvantages of large beampipe
    - Material budget below 0.1% X/X_0 **greatly improves** low-momentum position measurements
    - ITS3 technology gives best possible performance
- All-silicon layouts can match silicon+gas TPC hybrid layouts above a few GeV/c, and outperform them at higher momenta
  - If **smaller radius** is desired, it appears better to replace gas TPC with silicon layers
- A **baseline** has been determined for the silicon part of a hybrid tracker
- Simulations of physics performance ongoing
  - Evaluating the proposed ITS3-based concept and assess the improvements it brings
  - Simulation framework yields credible results

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Backup slides

Note: See report for summary of baseline layout simulations up until January 2020; http://cern.ch/go/xKk6

Tracking WG group meetings contain more recent studies

Baseline simulation parameters used initial studies

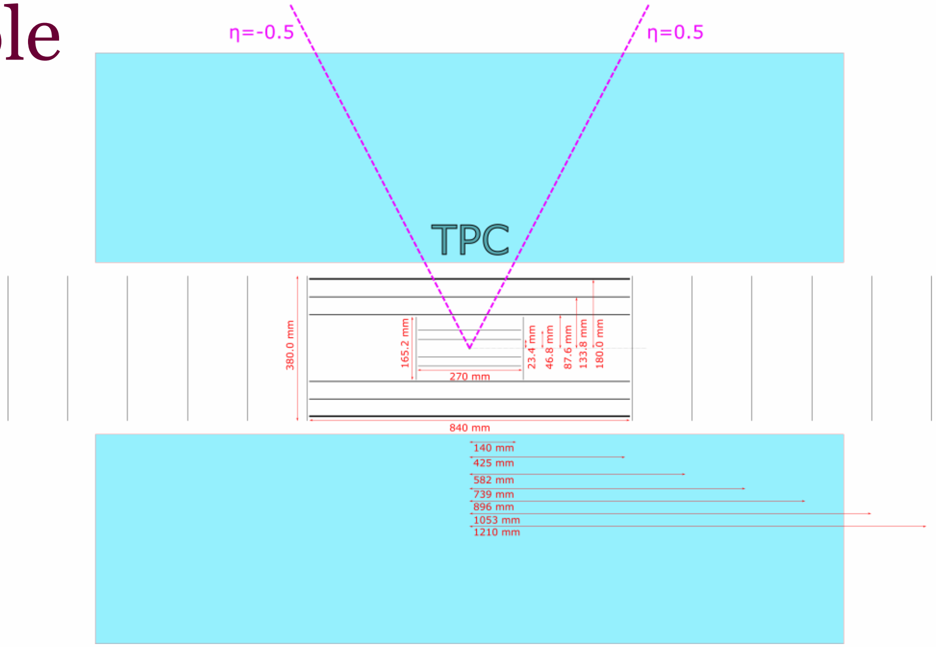
- Starting point: BeAST tracker
  - Radii of barrel layers adjusted to be consistent with ALICE ITS distances between layers (minimum distance between outer layers is 46.2 mm)

- Beampipe
  - 18 mm radius in central region (±400 mm), 0.8 mm thick beryllium
  - 20 mm radius aluminium further out

- TPC parametrisation default EICROOT one (conservative):
  - Transverse dispersion : 15.00 µm/√D[cm]
  - Transverse intrinsic resolution : 200.00 µm
  - Longitudinal dispersion : 1.00 µm/√D[cm]
  - Longitudinal intrinsic resolution: 500.00 µm
  - Vertical pad size : 0.50 cm

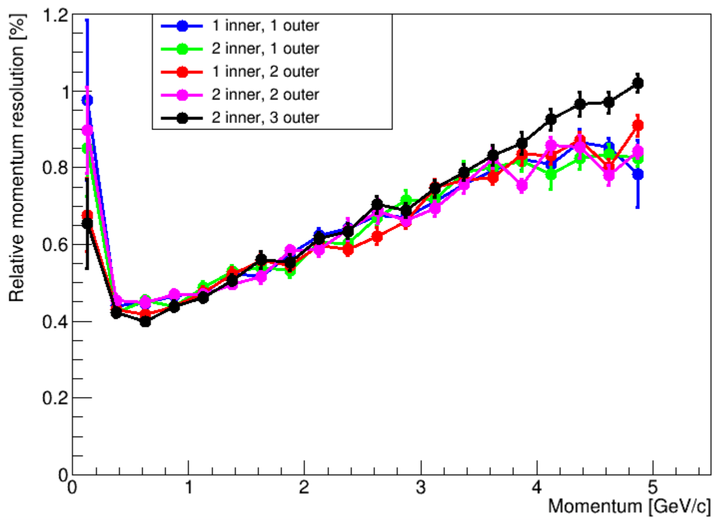
Barrel simulations example

- Carried out in the central region, |η| ≤ 0.5, using single pions fired from centre
- Results shown here for default parameters, varying the number of SVT layers
  - Full details and more studies in attached report

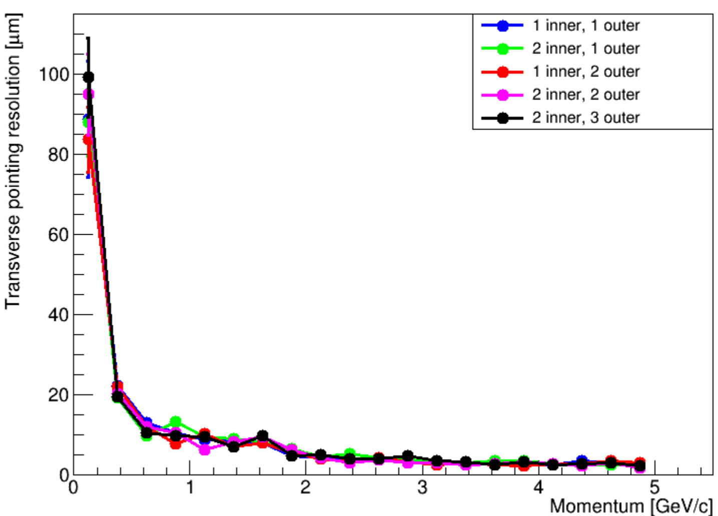


Momentum: 0 to 5 GeV/c

Relative momentum resolution



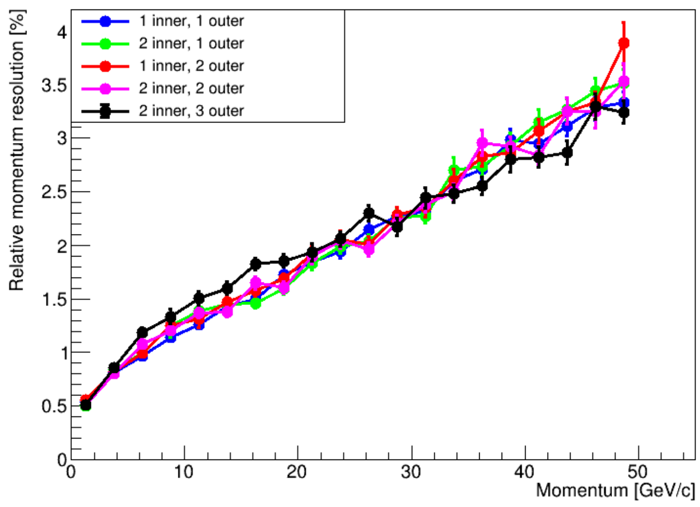
Transverse pointing resolution



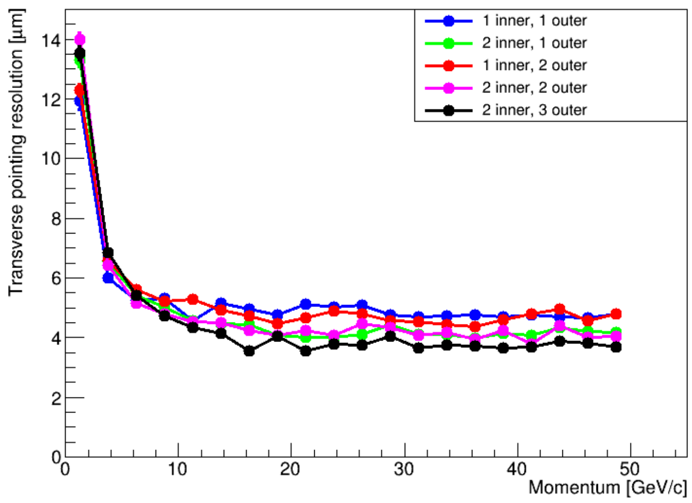
Barrel simulations example: number of layers

Momentum: 0 to 50 GeV/c

Relative momentum resolution



Transverse pointing resolution

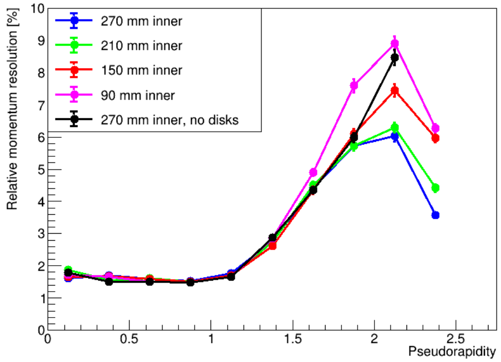


- Results as expected
  - Relative momentum resolution largely unchanged due to lever arm length being constant
  - 2 inner layers is the most important thing for pointing resolution at high momenta
- Want **as low material as possible** while keeping **redundancy and tracking efficiency**

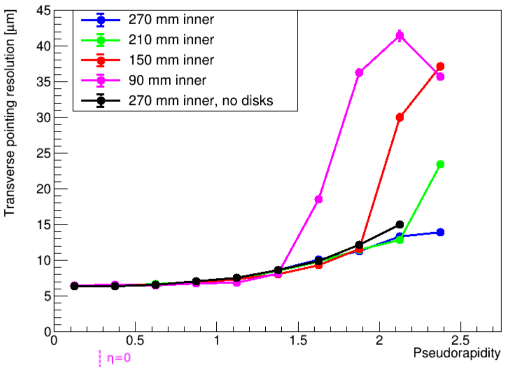
Barrel/disk interface region simulations

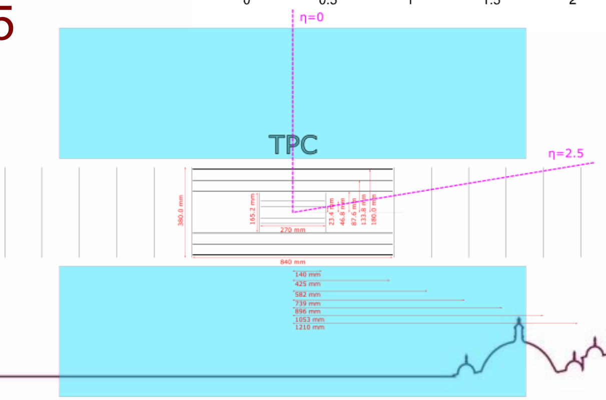
- Studies have looked at
  - Innermost disk position (at η = 3)
  - Length of inner barrel layers (at range of pseudorapidities)
- Length of inner barrel layer study presented here
- Innermost disk always 5 mm from inner barrel edge
- Parameters
  - Particle: e−
  - Momentum range: 0 to 50 GeV/c
  - Pseudorapidity range: $0 \leq \eta \leq 2.5$
  - Pixel size: $20 \times 20\ \mu m^2$
  - Magnetic field: 1.5 T
- Results show that 270 mm long inner barrel is best

Relative momentum resolution vs η



Transverse pointing resolution vs η

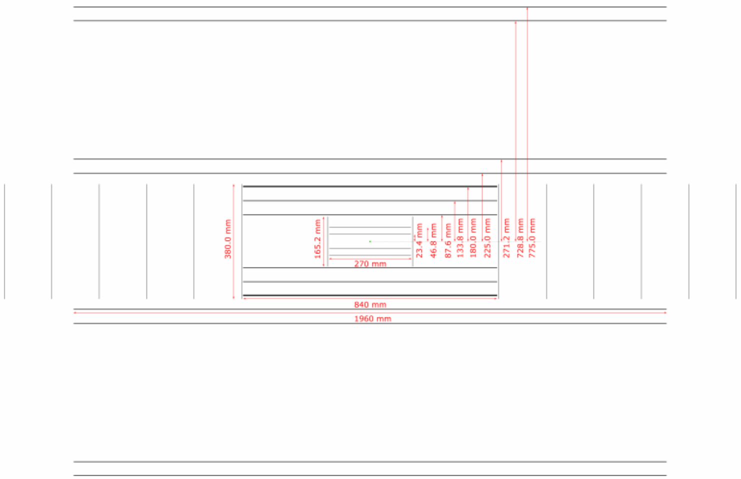




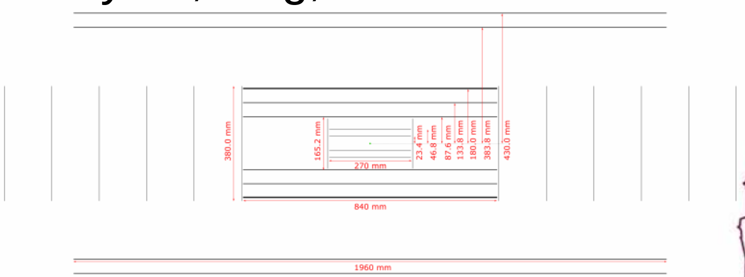
Silicon and gas TPC compared to all-silicon layouts

- "2+2 layers, long"
  - Naïve baseline
  - TPC replaced with long Si layers
- "2 layers, long, small radius"
  - Decreased outer radius

2+2 layers, long



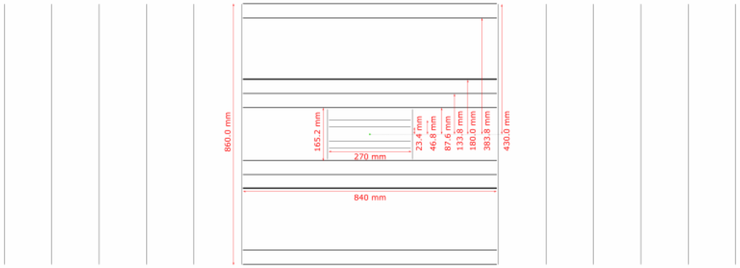
2 layers, long, small radius



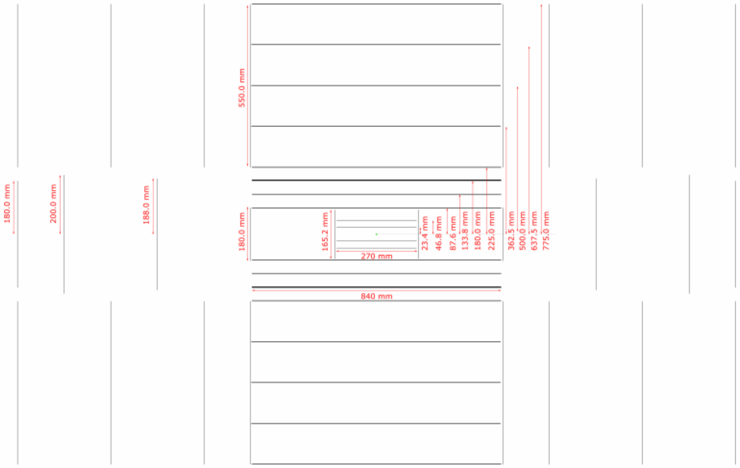
Silicon and gas TPC compared to all-silicon layouts

- "2 layers, short, small radius, large disks"
  - Shorter layers; more physically probable
  - Leaves room to increase disk size
  - Results indicate that good disk coverage is key to keeping resolution
- "5 layers, short, optimised disks"
  - Optimised design
  - Keeping parts physically viable
  - Filling gaps with disks and rings
  - 5 equidistant extra silicon layers, to aid in track reconstruction

2 layers, short, small radius, large disks

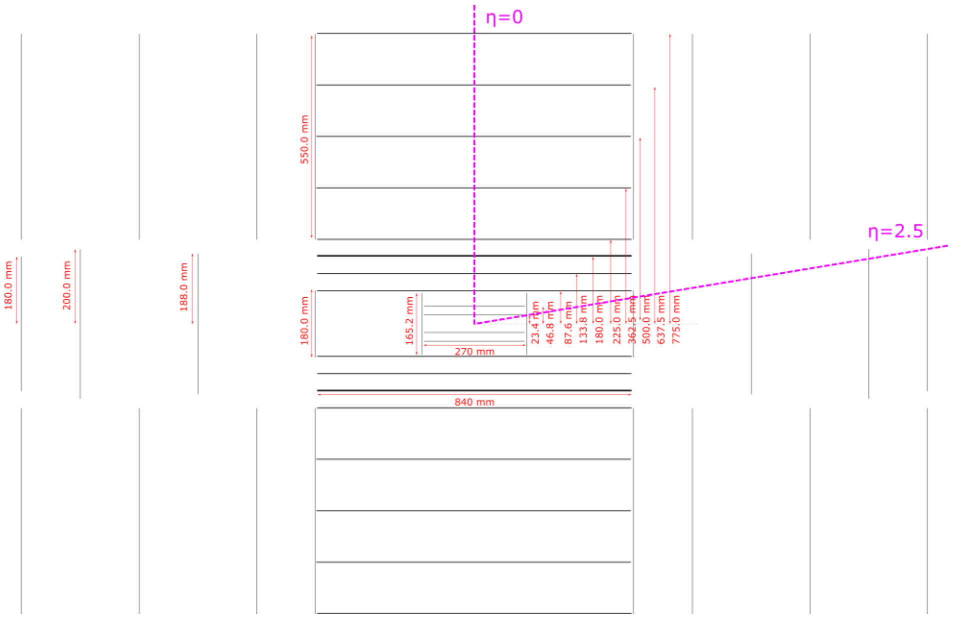


5 layers, short, optimised disks



Hybrid compared to all-silicon layouts

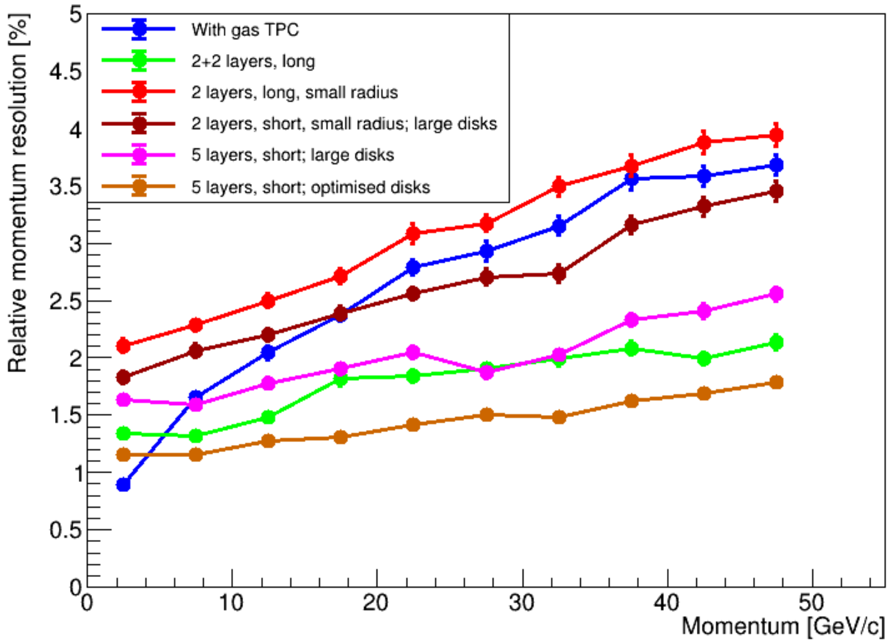
- Various all-silicon layouts tested
  - Only optimised layout shown here, more in backup slides and [report]
- Simulation parameters used:
  - Central and forward region studied, $0 \leq \eta \leq 2.5$
  - Single electrons fired from centre
  - Layer thickness in outer silicon layers: 0.8% X/X_0
- Optimised all-silicon layout:
  - Keeping parts physically viable
  - Filling gaps with disks and rings
  - 5 equidistant extra silicon layers, to aid in track reconstruction



Hybrid compared to all-silicon layouts - results

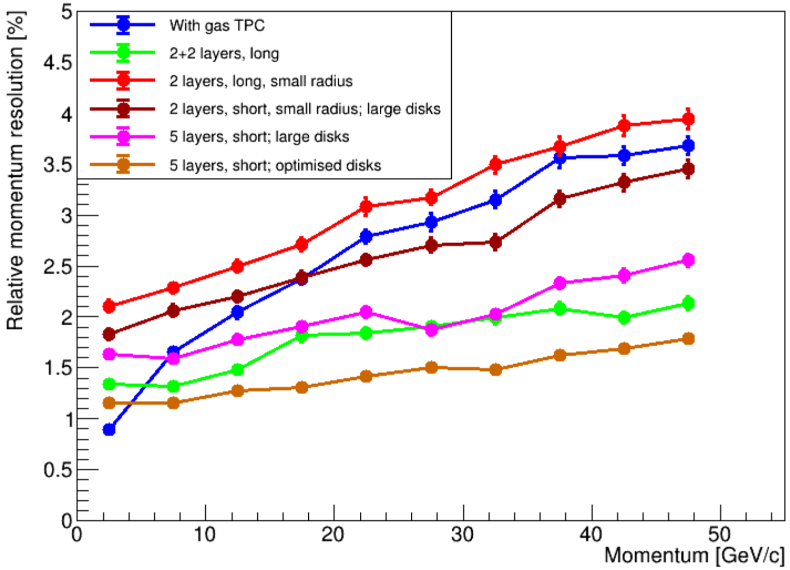
- Pointing resolutions do not change much between layouts, apart form where layers are missed
- Large disk coverage is important to keep resolution at higher η
- **Blue curve** in plot is hybrid layout, the others are all-silicon
- All-silicon layout **can outperform** Si+gas hybrid at p≥5 GeV/c
  - Note: gas TPC provides more points for reconstruction, and gives some particle ID info. This does not factor into these simulations

Relative momentum resolution vs p

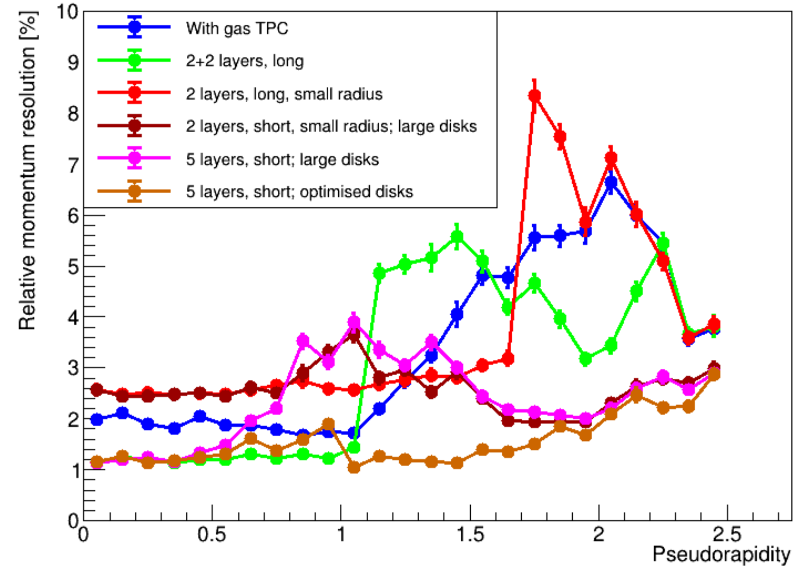


Silicon and gas TPC compared to all-silicon layouts - results

Relative momentum resolution vs p



Relative momentum resolution vs η

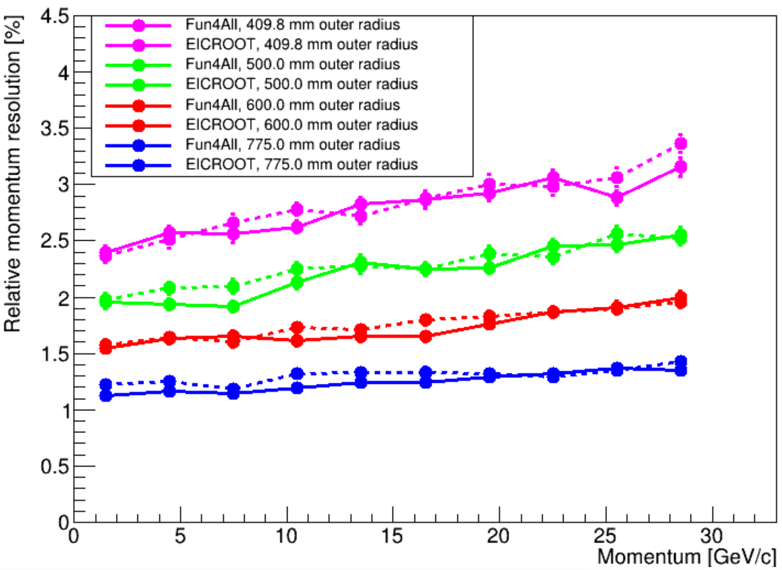


- Large disk coverage is important to keep resolution at higher η
- All-silicon layout **can outperform** Si+gas at p≥5 GeV/c
  - Note: gas TPC provides more points for reconstruction, and gives some particle ID info. This does not factor into these simulations
- Pointing resolutions do not change much between layouts, apart form where layers are missed

Framework benchmark study

- Moving into new simulation framework, a comparative study is first made
  - Exact same geometry used in an EICROOT study is imported into Fun4All framework
  - Single particles are generated in same parameter space
  - Same analysis code run on simulation results
- Generally very good agreement between the frameworks gives confidence that both old and new studies are relevant

Relative momentum resolution



Transverse pointing resolution