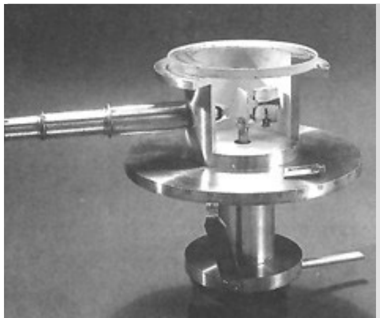
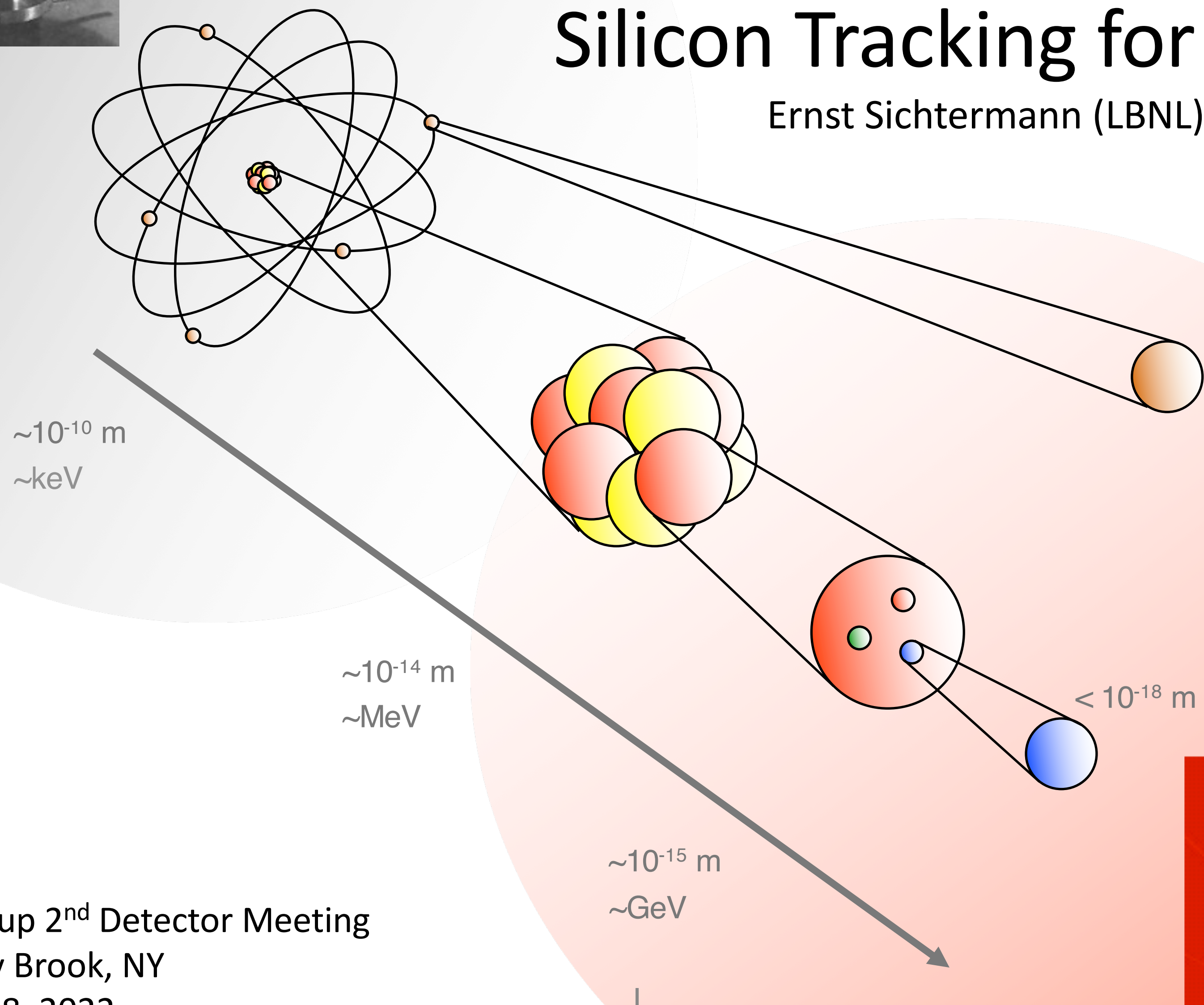
Funding support from:

Silicon Tracking for E(P)IC

Ernst Sichtermann (LBNL)



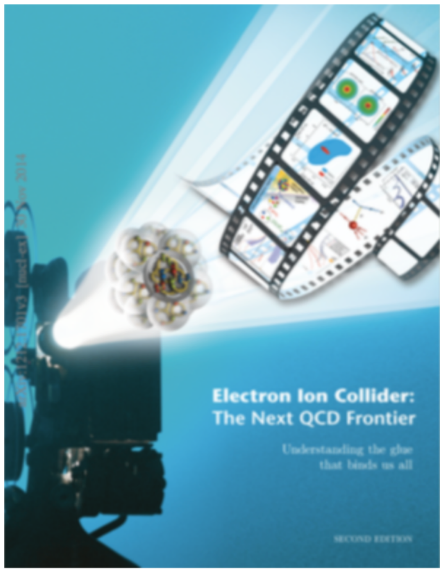


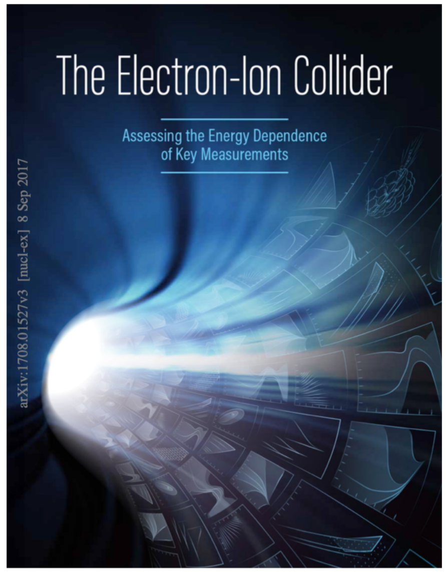
EIC User Group 2nd Detector Meeting
CFNS – Stony Brook, NY
December 6-8, 2022

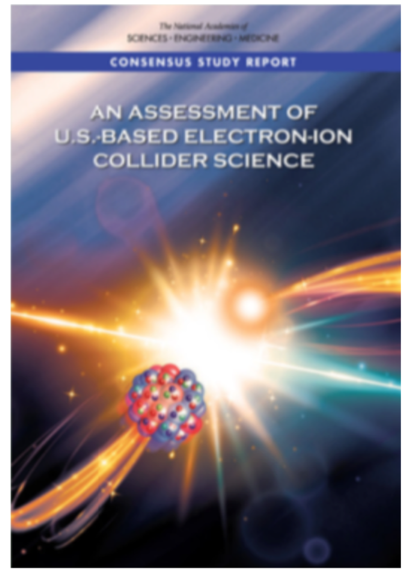
Outline

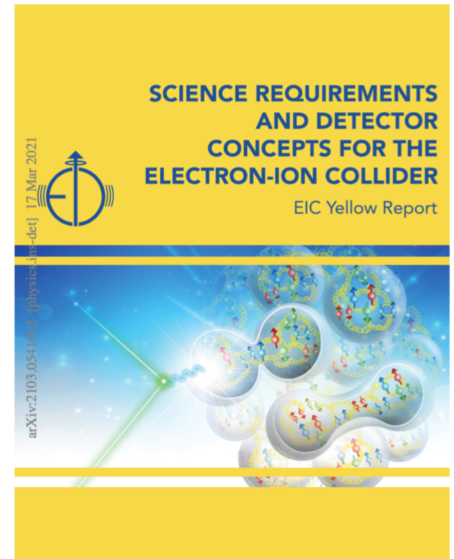
- Introduction
- EIC Detector(s)
- EIC Silicon Consortium
- Tracking
- ALICE ITS3 – EIC
- Project and generic R&D
- Closing comments

EIC Science









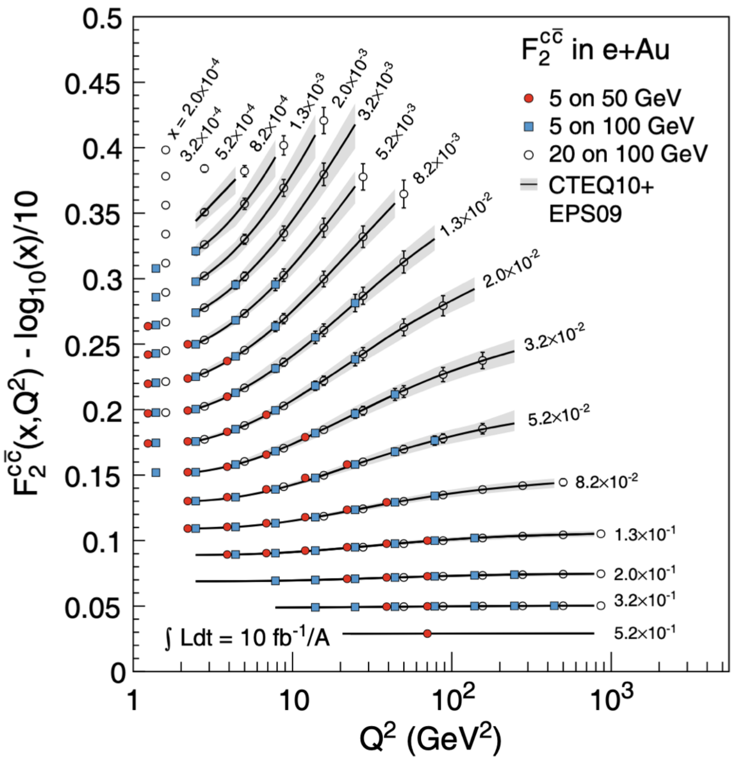
"An EIC can uniquely address three profound questions about nucleons – neutrons and protons – and how they are assembled to form the nuclei of atoms:

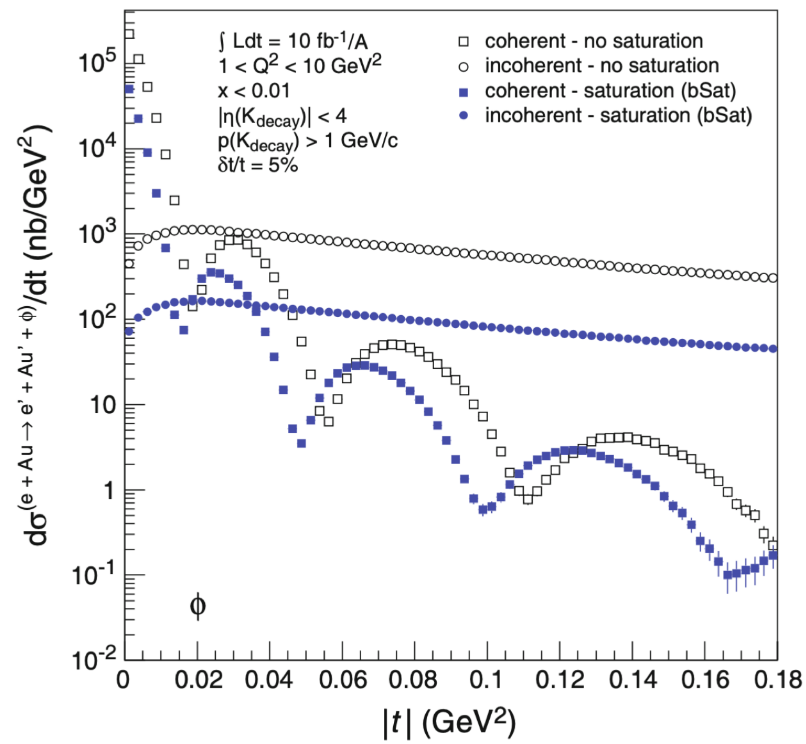
- *How does the mass of the nucleon arise?*
- *How does the spin of the nucleon arise?*
- *What are the emergent properties of dense systems of gluons?*

…

An EIC is timely and has the support of the nuclear science community." – 2018 NAS assessment of EIC science.

EIC Science – Just two examples

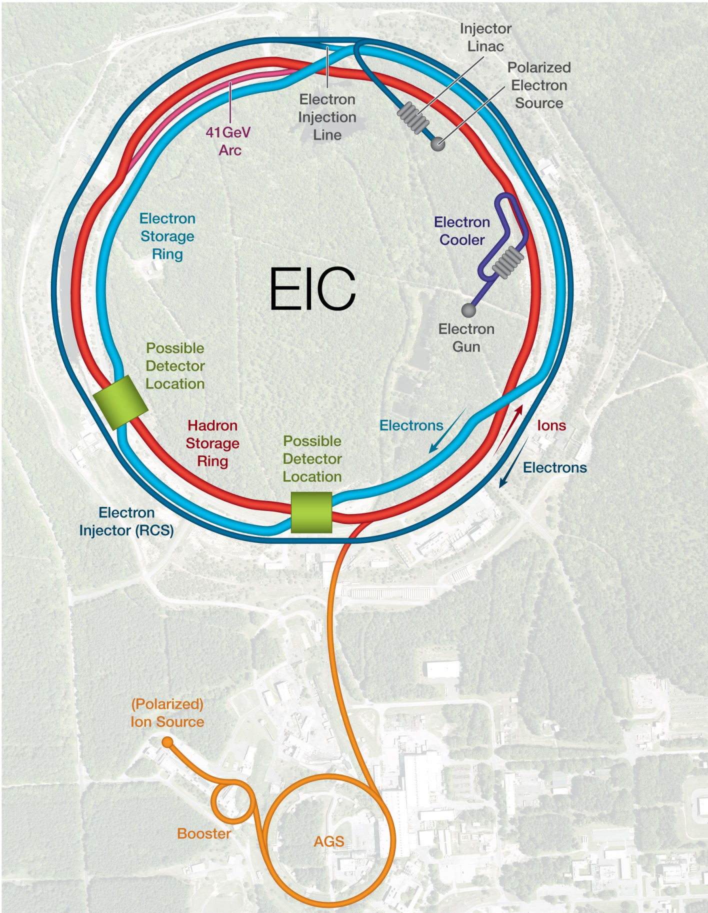




The study of gluons in polarized and unpolarized nucleons and nuclei is at the core of EIC science,

Drives detector requirements, including the need for large acceptance, low-mass, precision tracking and vertexing.

EIC Facility

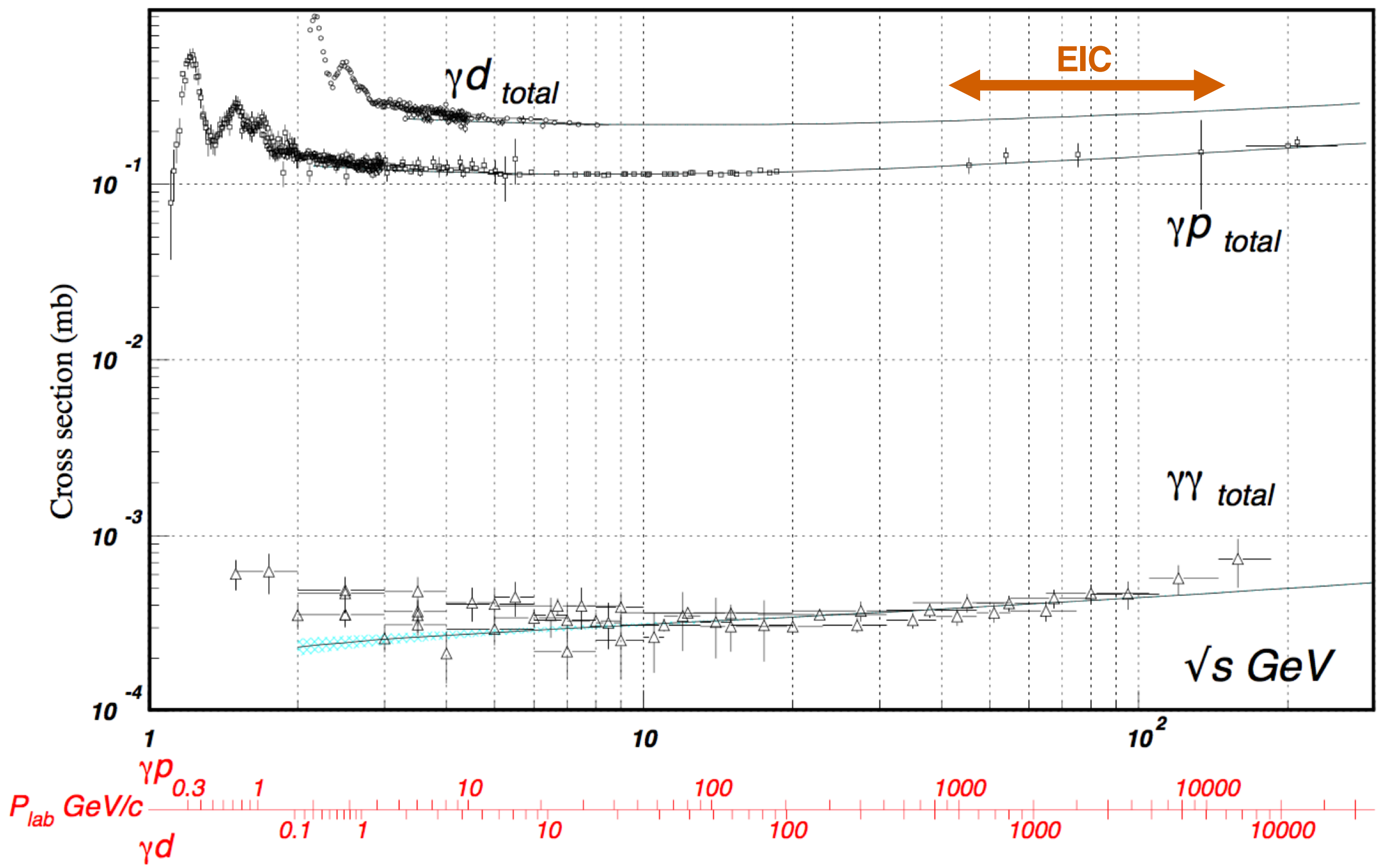


Design Goals:

- High Luminosity: L= $10^{33} – 10^{34} cm^{-2}s^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- *Possibility of a Second Interaction Region (IR) – why we are here today,*
- *Good to hear the "right words" for a 2^{nd} <u>instrumented</u> IR*

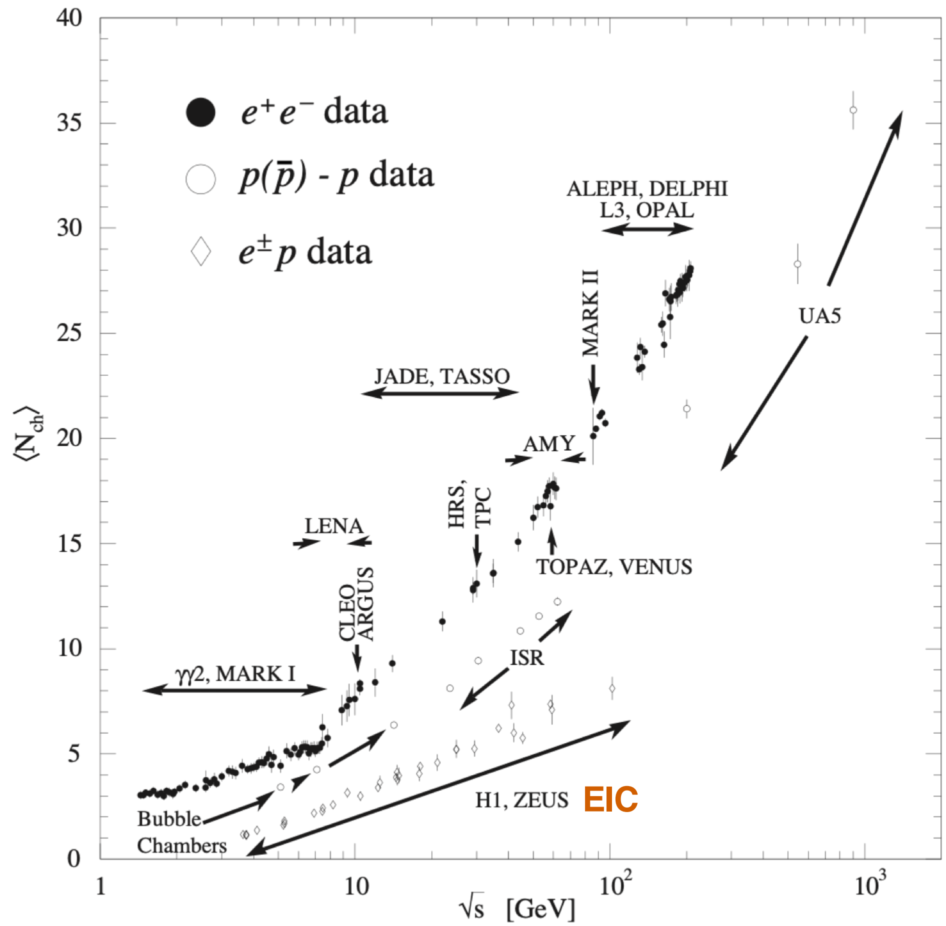
My personal take – right words are one of many steps towards a 2^{nd} instrumented IR; complementarity means different things for different colleagues; 2^{nd} collaboration/detector will (likely) need to balance timeliness and capability, and face formidable compromises.

EIC Collision Environment



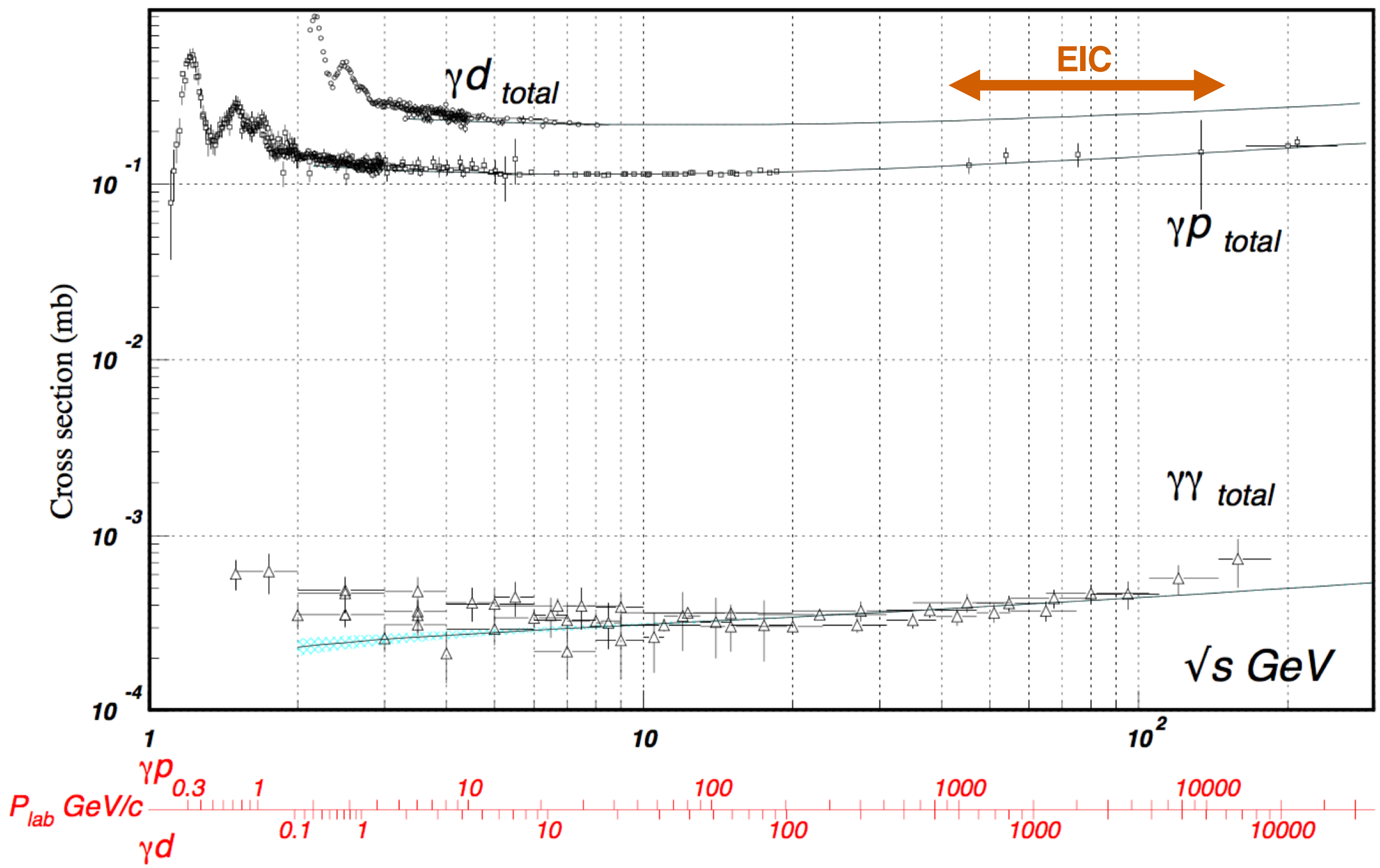
Photoproduction is the dominant cross-section; well known,
2 orders below RHIC, LHC

EIC Collision Environment



Likewise, particle multiplicities are known and well below those at the hadron colliders,

EIC Collision Environment

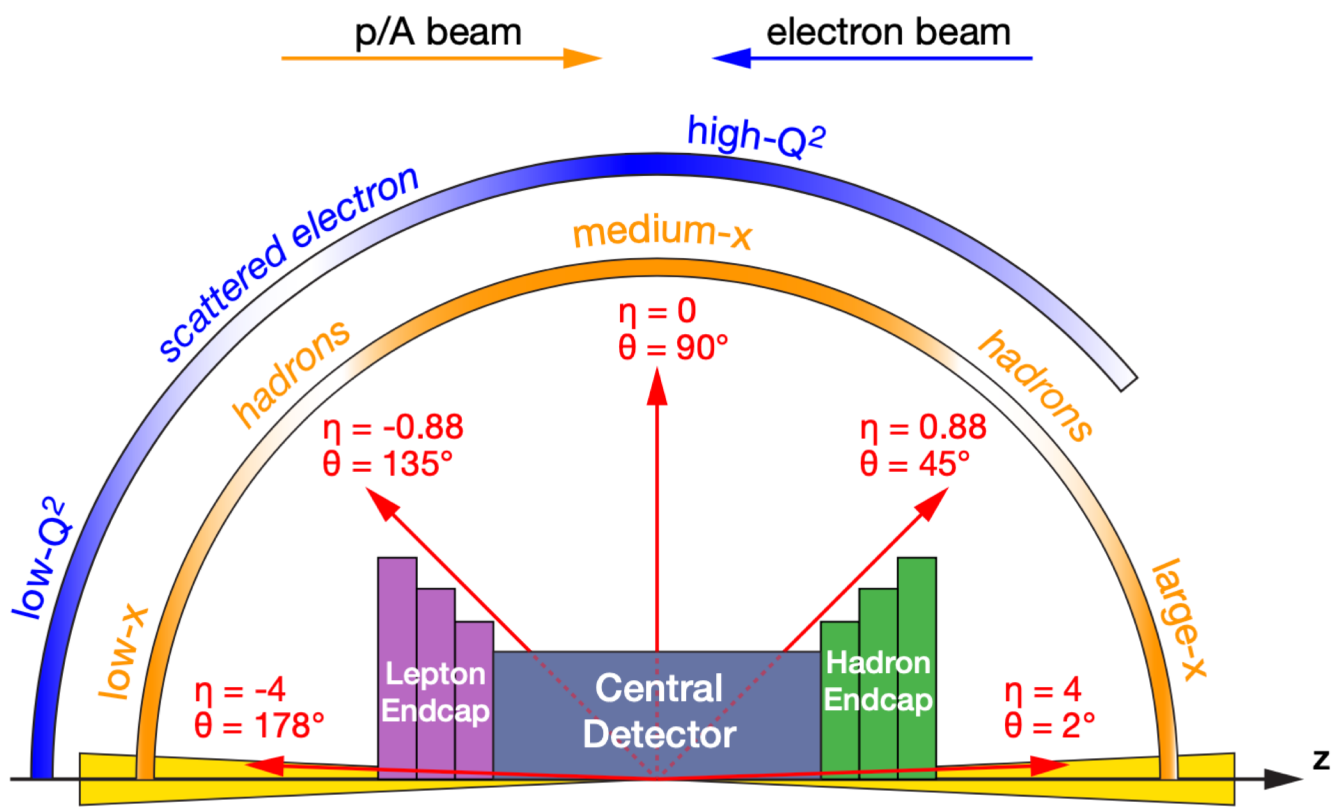


L ~ $10^{33(34)}$cm^{-2}s^{-1} implies a ~50 (500) kHz collision-event rate,

<< EIC bunch cross crossing rate

~ similar to μs integration times

EIC – Central Detector View



High luminosity drives the need for a compact device, ~ 9m along the beam axes,
Large acceptance required by the science drives the need for (very) careful integration,
Combination with calorimetry and PID drives the need for a *compact* tracking subsystem
(unless, say, PID and tracking capabilities are combined).

EIC – A bit of tracking history

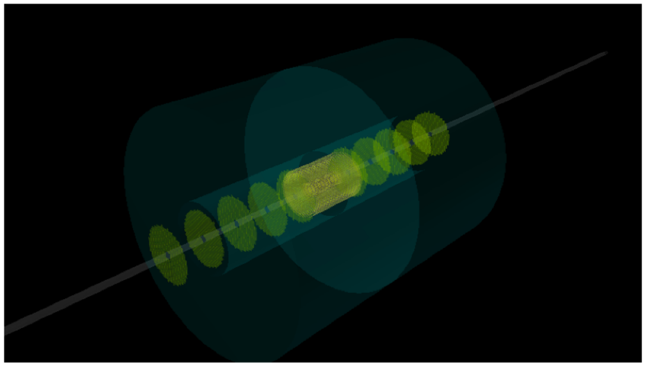
eRD16 - Simulations

- Past January, we reported our results from initial studies based on LDT fast simulations on an all-silicon tracker concept;

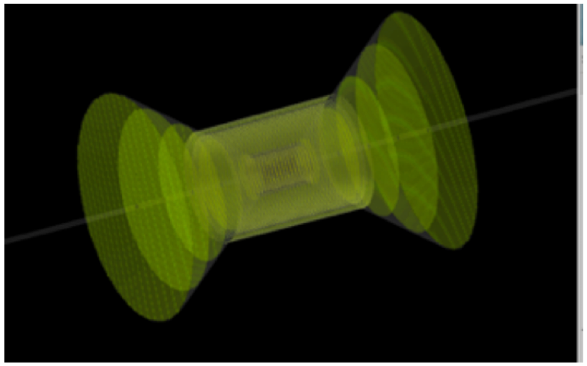
  The main outcome was that such a concept has potential to achieve similar momentum resolution and have smaller radius;

  This may be attractive: space for PID, non-uniform B-field, etc.

  We have now made a start in EICroot simulations of such a configuration, starting by reproducing the TPC+Si performance.



Beast(-like) TPC+Si configuration



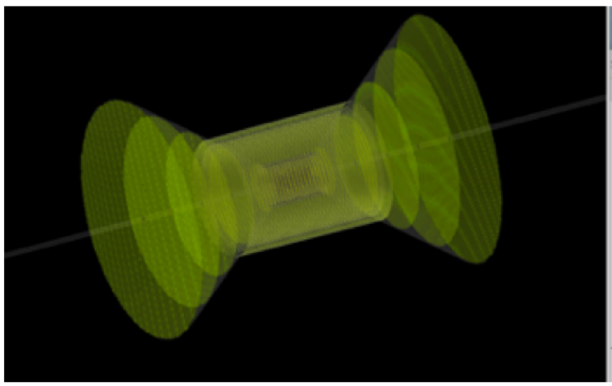
All Si configuration, same z-extent smaller barrel radius of ~43 cm.

EIC generic R&D program - https://wiki.bnl.gov/conferences/index.php?title=July_2019

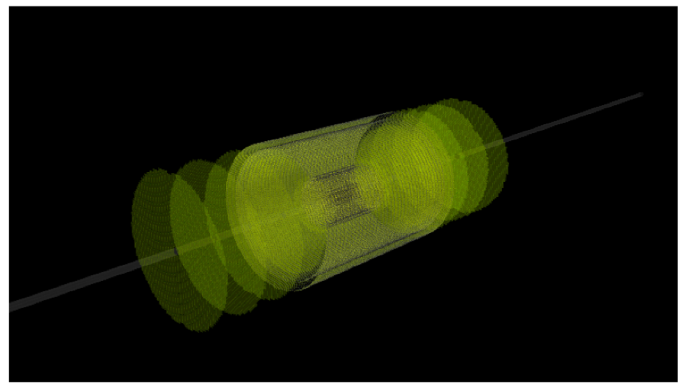
EIC – A bit of tracking history

eRD16 - Simulations

- Since radial compactness is potentially attractive, we considered also a variant with restricted outer disk radii, similar to the fast-simulation configuration reported past January (20 x 20um MAPS).



all-Si configuration



tapered all-Si configuration, r ~ 43cm

Identical barrel configurations, identical in length (*z*) to BeAST.

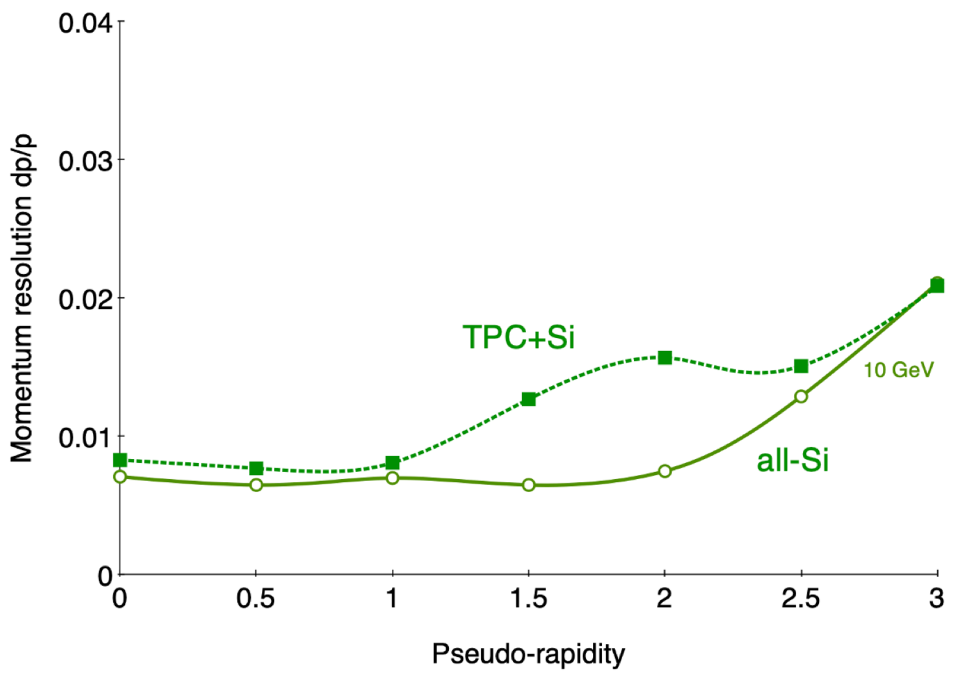
Material cones/cylinders surrounding the disks were implemented to make a start on the effects associated with support structures, read-out infrastructure, etc.; studies started/in progress.

EIC generic R&D program - https://wiki.bnl.gov/conferences/index.php?title=July_2019

EIC – A bit of tracking history

eRD16 - Simulations

- Resolution comparison with BeAST TPC+Si tracker



It seems worthwhile, to us, to investigate all-Si further.

20

EIC generic R&D program - https://wiki.bnl.gov/conferences/index.php?title=July_2019

EIC – A bit of tracking history

EIC Generic Detector R&D Program had an essential role in helping the community think and rethink tracking options for the EIC,

TPC-based option made a lot of sense, as long as it combined PID and tracking,

No “magic” in the ~0.4 m radius for the silicon-based tracking variant; it was simply tuned to provide similar or better resolutions than the larger TPC-based option; increase in B or size in r and/or z will improve performance.

Both options present challenges for services; services for tracking and basically all other subsystems present formidable challenges for detector design,

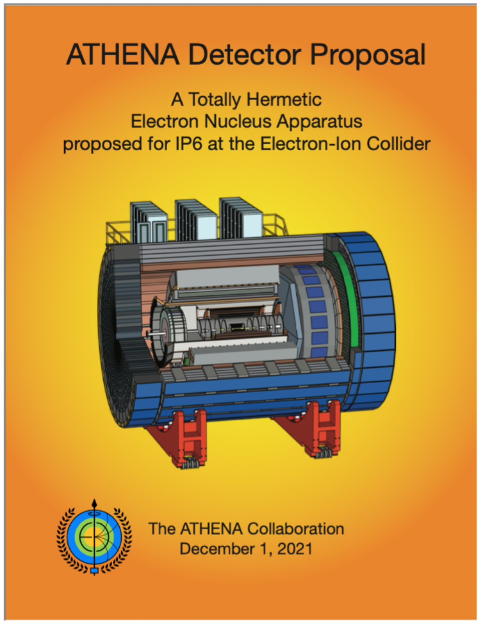
Subsequent detector proposals face these (and other) challenges in different ways,

---

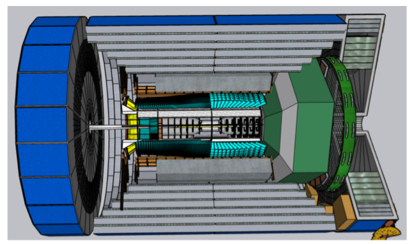
Generic R&D program has been restarted! - https://www.jlab.org/research/eic_rd_prgm

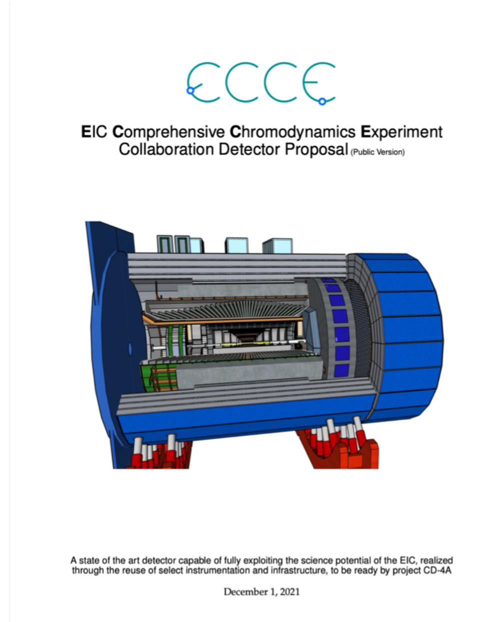
Endorsement of instrumentation for NP via the LRP would complement (likely) endorsements for theory, workforce development, and computing.

EIC Project Detector Environment



CORE





Detector Proposal Advisory Panel (DPAP) reviewed three proposals; ATHENA, CORE, and ECCE,

Finds that ATHENA and ECCE fulfill all requirements for a Detector 1, i.e. NAS science case,
none of the collaborations is strong or large enough to develop Detector 1 for Day 1

Recommended ECCE as Detector 1 in Spring 2022 – adopted by the EIC Project as Reference,

“Right words” for *a* Detector 2, but no language on an actual concept, technology, etc.

EIC SC – lead-up to YR and proposals

The EIC silicon consortium grew out of EIC generic detector R&D projects eRD16 and eRD18 → eRD25:

EIC silicon consortium is open and welcomes new collaborators,

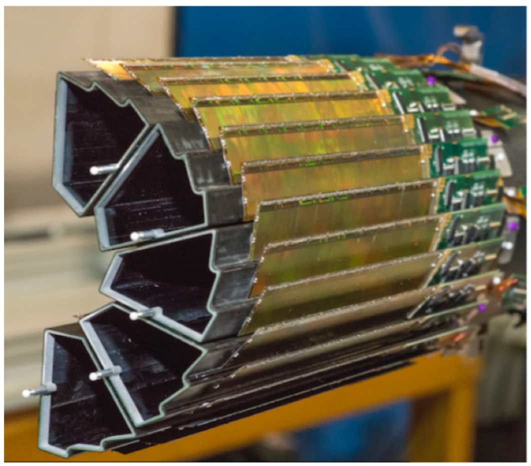
Main contacts: Laura Gonella of the University of Birmingham – l.gonella@bham.ac.uk
Giacomo Contin of INFN Trieste – giacomo.contin@ts.infn.it
Ernst Sichtermann of Berkeley Lab – epsichtermann@lbl.gov

Mailing list: https://lists.bnl.gov/mailman/listinfo/eic-rd-silicon-l

EIC SC – lead-up to YR and proposals

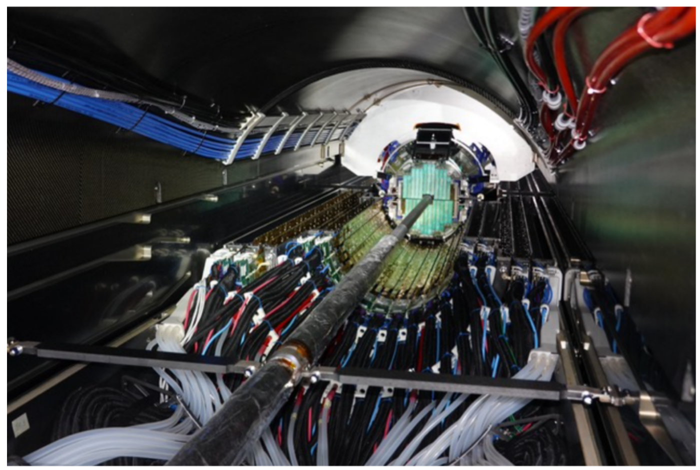
The EIC silicon consortium aims to bring together the expertise/experience and overall strength:

STAR HFT:



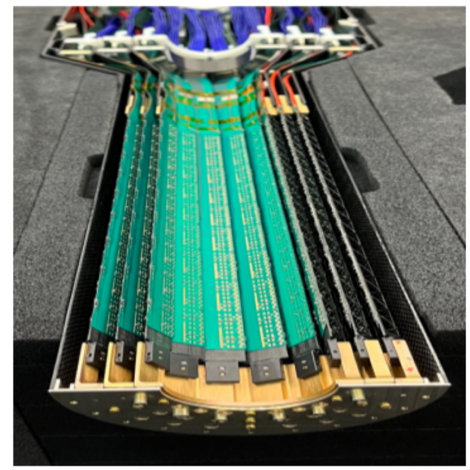
G. Contin et al NIM A 907 (2018) 60-80

ALICE ITS2:



J. Phys. G: Nucl. Part. Phys. 41 (2014) 087002

sPHENIX: MVTX



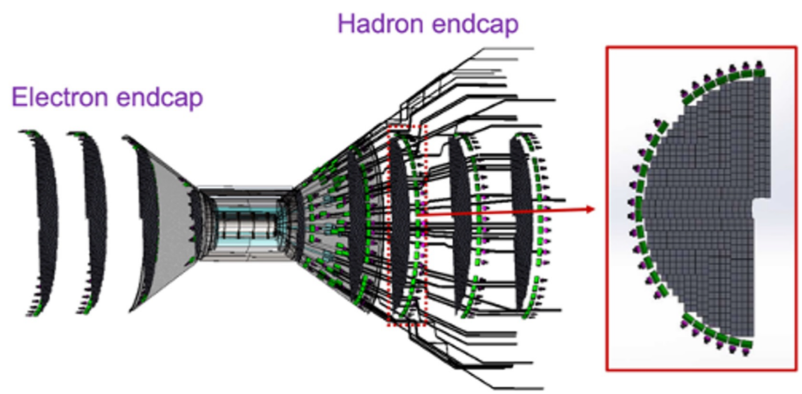
Ming Liu et al, sPHENIX coll.

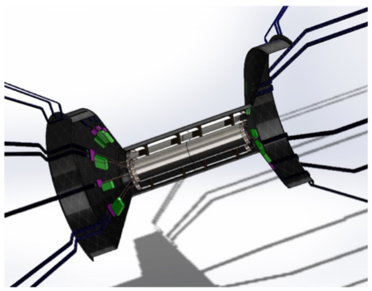
with the overarching goal to develop and construct a full tracking and vertexing detector subsystem for the EIC detector(s) based on 65nm MAPS sensors.

This technology choice and focus was a considered outcome from a broad survey, see e.g. L. Gonnella et al 1st YR workshop. Timeline presents challenges for new sensor development even for 2nd IR

EIC SC – lead-up to YR and proposals

- performed extensive simulations for the Yellow Report baseline tracking configurations; both the hybrid and the all-silicon options,
- surveyed and selected most suitable sensor technology – ITS3 65nm MAPS technology,
  - https://indico.bnl.gov/event/7449/contributions/35954/
  - https://indico.bnl.gov/event/7449/contributions/35955/
- joined / are joining the ITS3 effort,
- developed the initial CAD models for the ATHENA and ECCE proposals,





- investigated service options and model for simulations
- developed initial cost and schedule for the R&D phase to TDR,
- developed initial cost and schedule for all proposals,
  - Schedule works with multiple construction sites so construction proceeds in parallel – sites to be determined,
- predominantly joined the ATHENA proto-collaboration; since became founding members of EPIC,
- maintains an interest in tracking and vertexing solutions for *all* EIC detectors.

EIC Project Detector Reference

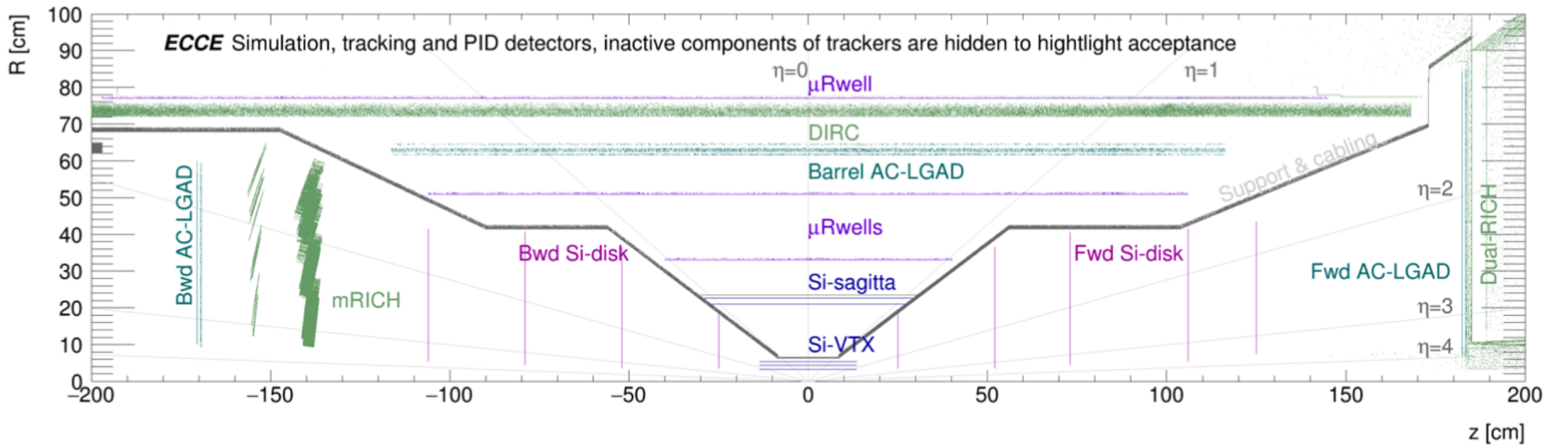


Figure 2.5: Schematic view of the ECCE tracker, including silicon, μRWELL, AC-LGAD, DIRC, mRICH and dRICH detector systems.

ECCE proposed re-use of the 1.4 T BaBar solenoidal field intrinsically limits the tracking performance compared to ATHENA 3T field (as is the case also compared to CORE),

Layout of the barrel relies on a combination of closely spaced vertex and sagitta MAPS layers and outer MPGD and AC-LGAD layers for momentum resolution; intrinsically very sensitive to assumptions on material in the sagitta layers as well as resolution in the MPGD and AC-LGAD layers.

EIC Project Detector Reference

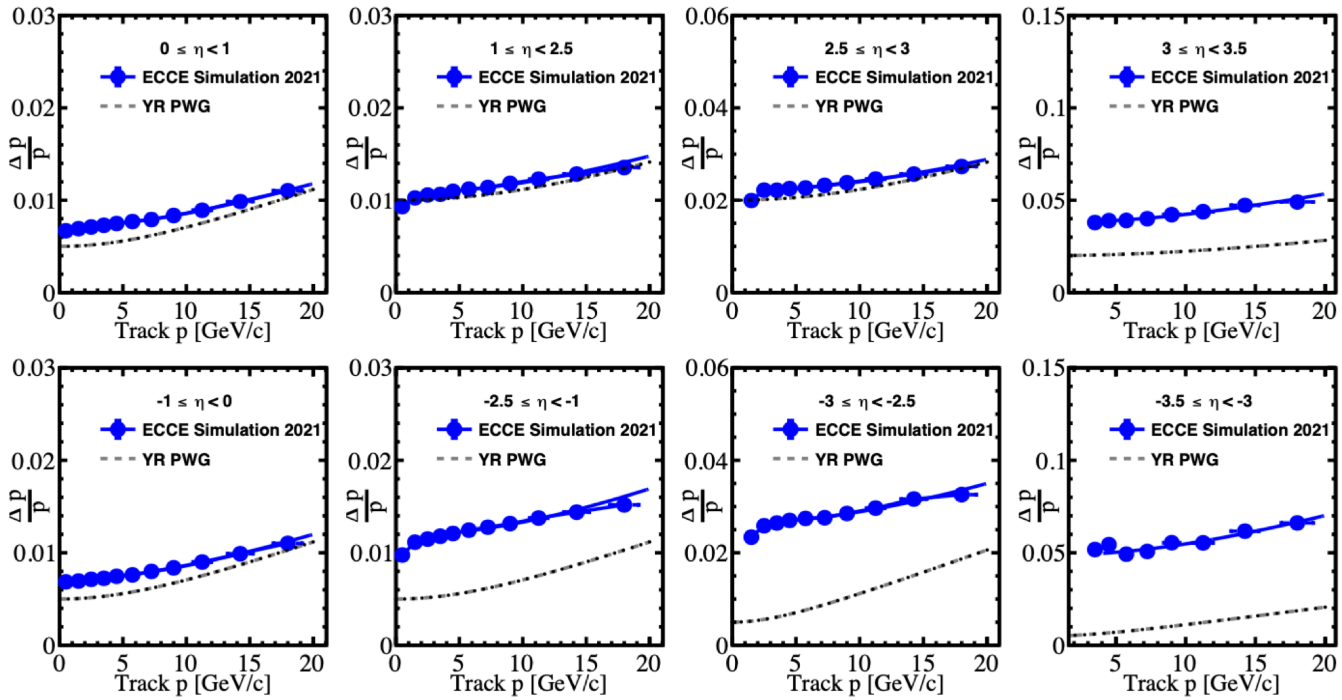


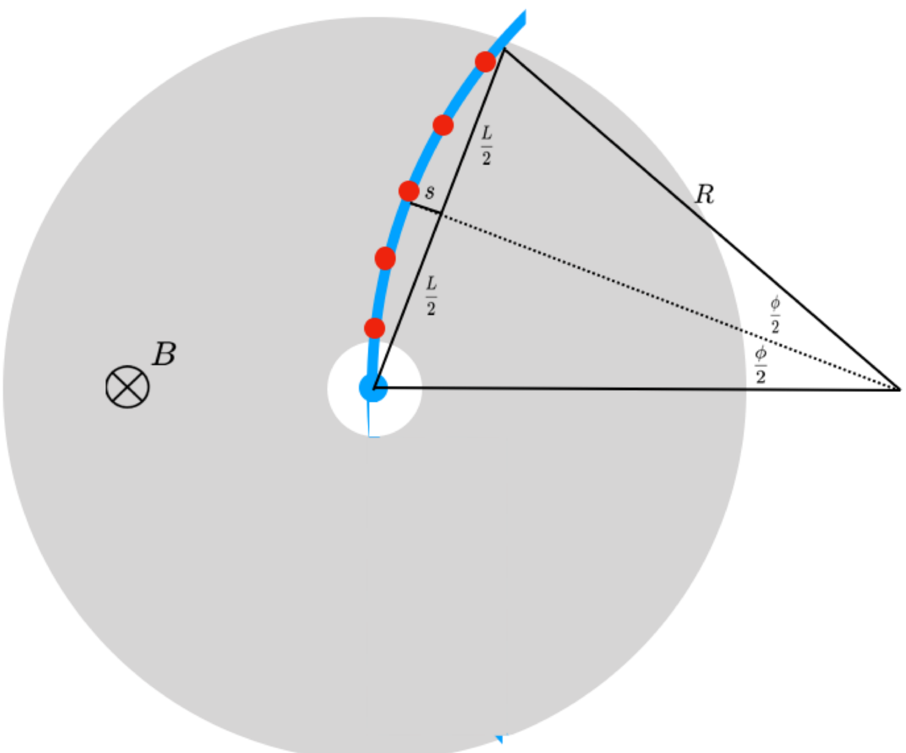
Figure 2.7: ECCE pion track momentum resolution (data points) with the EIC YR PWG requirements for the tracker indicated by the dashed lines. Note that the ECCE performance simulations take into account materials for readout and services. The impact of these can be observed most clearly in the bins covering the barrel/barrel endcap transition regions. As an integrated EIC detector with all subsystems operating in a complementary way, ECCE achieves the EIC physics goals as described in Chapter 3.

ECCE thus intrinsically relies on combined system performance, e.g. tracking and Emcal in the electron going direction, to accomplish its physics goals,

The ECCE assumptions on material budget in the sagitta layers have proven too optimistic.

Tracking 101 – apologies to experts

The basics can be captured by straightforward considerations. Imagine a view along the beam and a helical track model inside a solenoidal field. Then,



$$p_{\mathrm{T}}\,[\mathrm{GeV}] = 0.3B\,[T]\;R\,[m]$$

$$s = R - R\cos\frac{\phi}{2} \approx R\frac{\phi^2}{8} \qquad \phi = \frac{L}{R}$$

Hence,

$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} = \frac{\Delta R}{R} = \frac{\Delta\phi}{\phi} \approx \frac{\Delta s}{L^2}\cdot\frac{8p_{\mathrm{T}}}{B}$$

In other words, a good (transverse) momentum resolution requires:

- a large path length L (scales as L^2)
- a large magnetic field (scales as B)
- good Sagitta measurement.

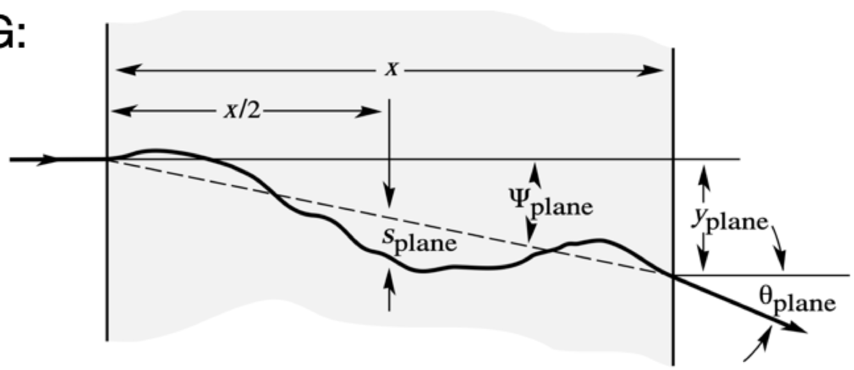
$$\Delta s = \frac{\Delta_{r\phi}}{8}\sqrt{\frac{720}{N+5}}$$ (Glückstern, 1963)

Note, however, that multiple scattering through the material of the disks matters.

Tracking 101 – apologies to experts

Regarding the multiple scattering contribution,

PDG:



$$\Delta\phi \approx \frac{14\,\mathrm{MeV}}{p}\sqrt{L/X_0}$$

$$p = \frac{p_\mathrm{T}}{\tan\theta}$$

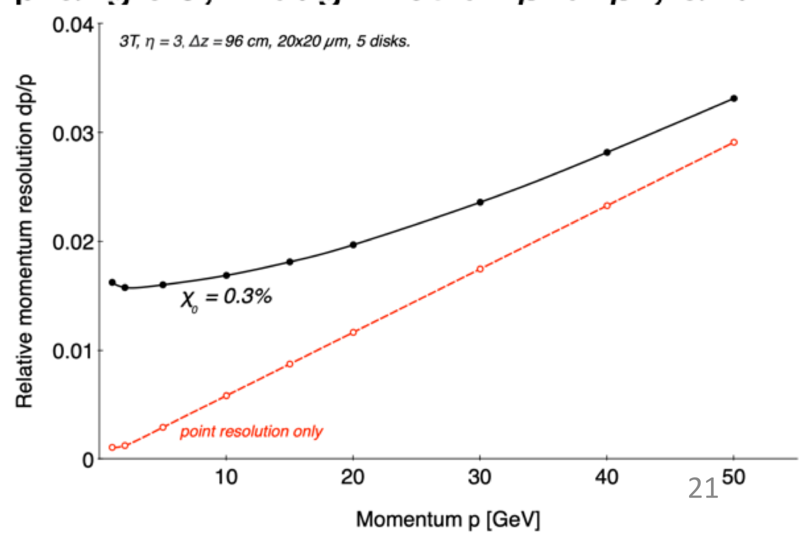
$$\left.\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}}\right|_{\mathrm{m.s.}} \approx \frac{14\,\mathrm{MeV}}{p}\sqrt{\frac{L}{X_0}}\cdot\frac{R}{L} = \frac{14\,\mathrm{MeV}}{p}\sqrt{\frac{1}{LX_0}}\frac{p_T}{eB}$$

Hence, the m.s. contribution depends on the dip-angle θ, though *not* on p or p_T, and

$$\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}} = a\cdot\frac{p_\mathrm{T}}{BL^2} \oplus b(\theta)\cdot\frac{1}{B\sqrt{LX_0}}$$

For forward angles, m.s. is the limiting component in d*p/p for much of the p range.*

There is, indeed, a subtle correlation of m.s. and the dip angle measurement (not explicitly considered in the arguments presented here).

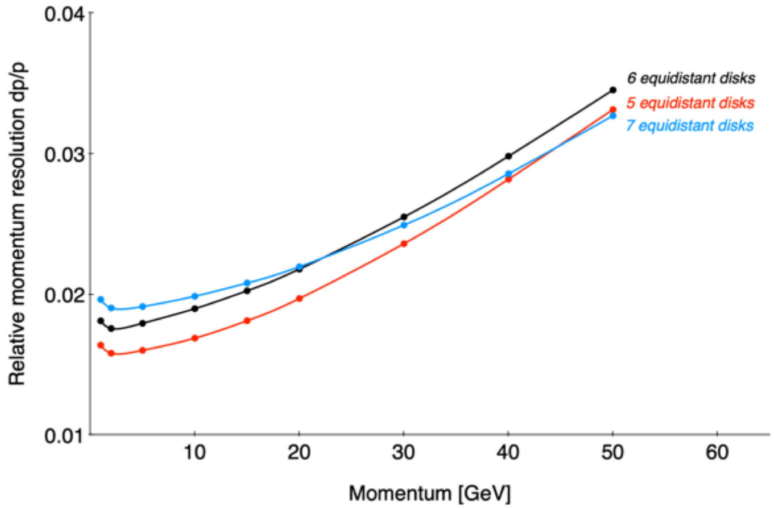


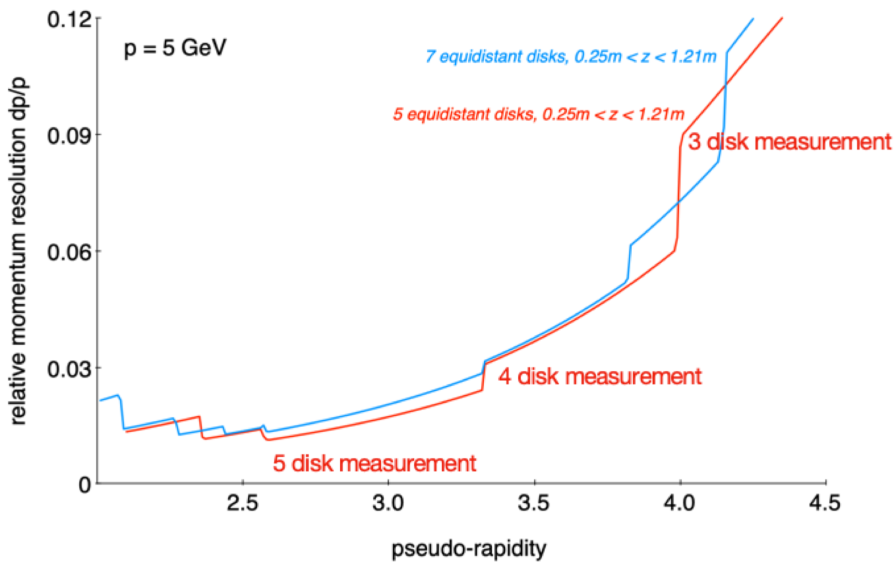
Tracking 101 – trade-offs for disks

Performance wise, $$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} = a \cdot \frac{p_{\mathrm{T}}}{BL^2} \oplus b(\theta) \cdot \frac{1}{B\sqrt{LX_0}}$$

n_{disk} increases measurement-points ***and*** material

We believe 5—7 disks presents a reasonable trade-off; an odd number tends to capture the Sagitta point and is thus preferred.



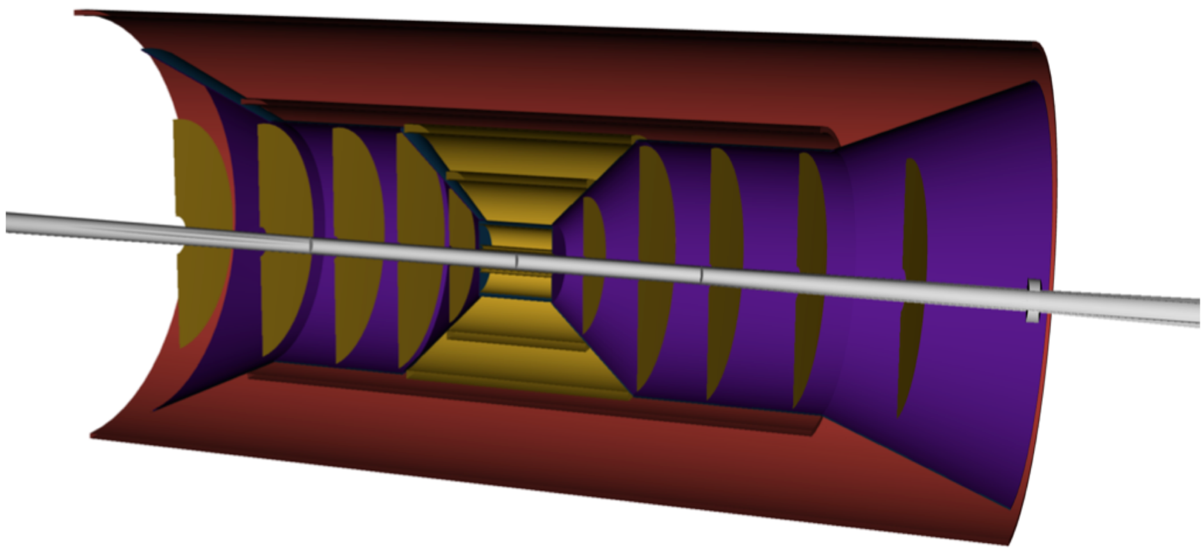


An equidistant configuration is *not* truly optimal in capturing the Sagitta, but avoids *acceptance issues* (illustrated on the left for 5—7 disks; details are geometry-dependent),

Viable ways to improve d*p*/*p* etc. are to increase *L* available for tracking and/or reduce material; increasing points within the same *L* or other technology are ***not***.

From Reference towards EPIC Baseline

Ways to recover YR performance, at least at mid-central and forward pseudo-rapidities,
- increase field strength, and/or
- reconfigure the barrel to introduce a precision point at outer radius (approx. 0.40 m), or
- pursue aggressive R&D to minimize material in the sagitta layers.



Barrel layers at radii r_{X0} of:

$r_{0.05\%}$ = 36, 48, 120 mm

$r_{0.25\%}$ = 270 mm,

$r_{0.55\%}$ = 420 mm

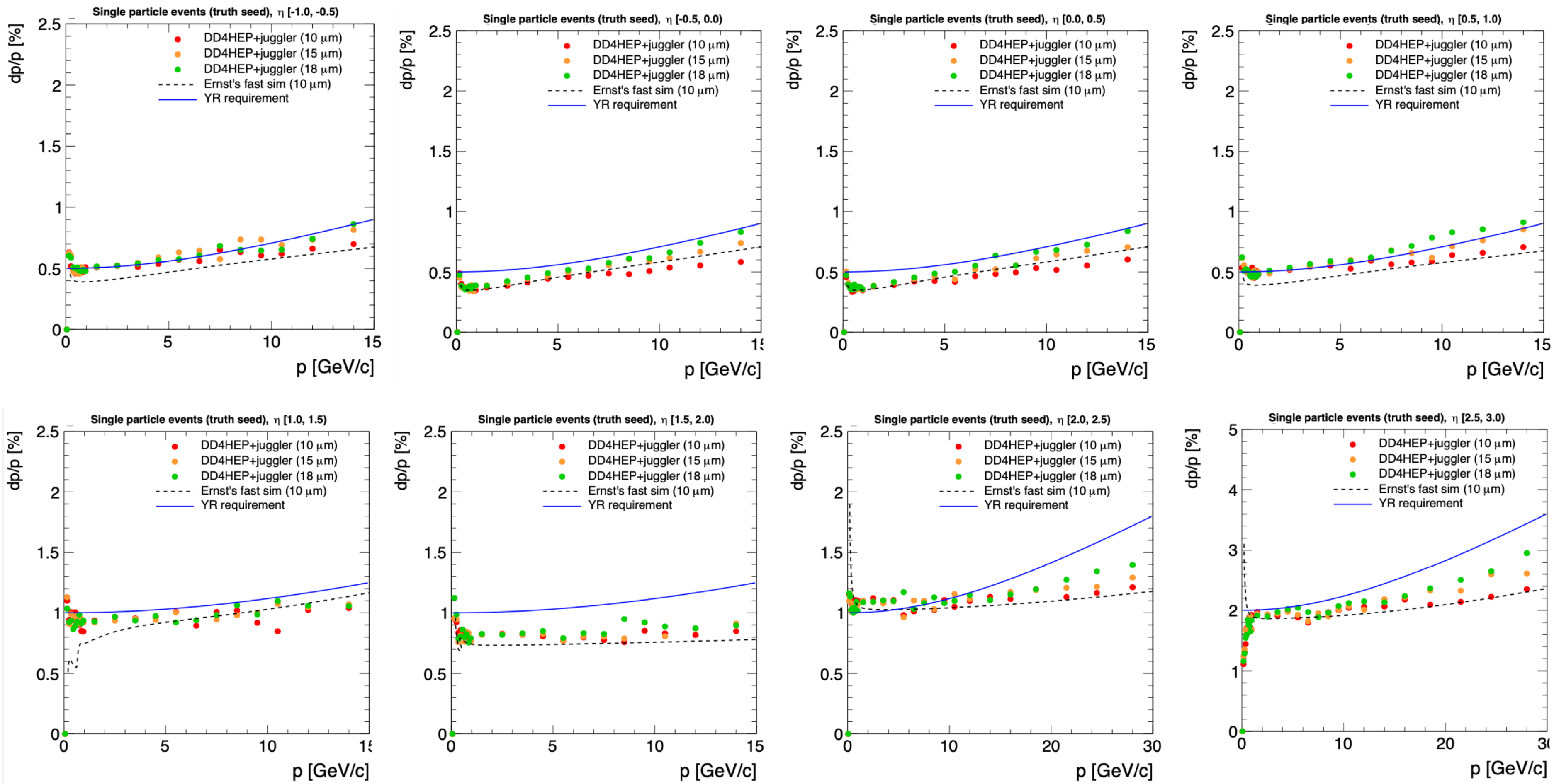
Extended disk arrays as space permits.

Project is proceeding with magnet design that can reach a 1.7T, possibly 2T, field of a identical (BaBar) geometry,

EIC silicon consortium has proposed kapton-embedded MAPS sensor R&D for FY23 *generic* R&D.

From Reference towards EPIC Baseline

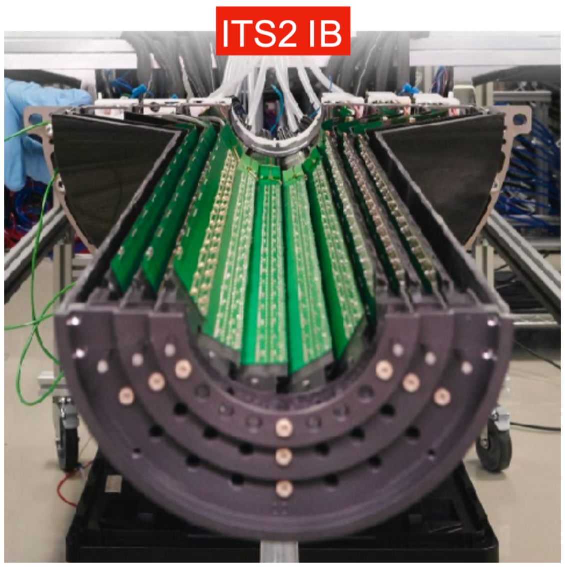
EPIC internal, courtesy Wenqing Fan (LBNL)

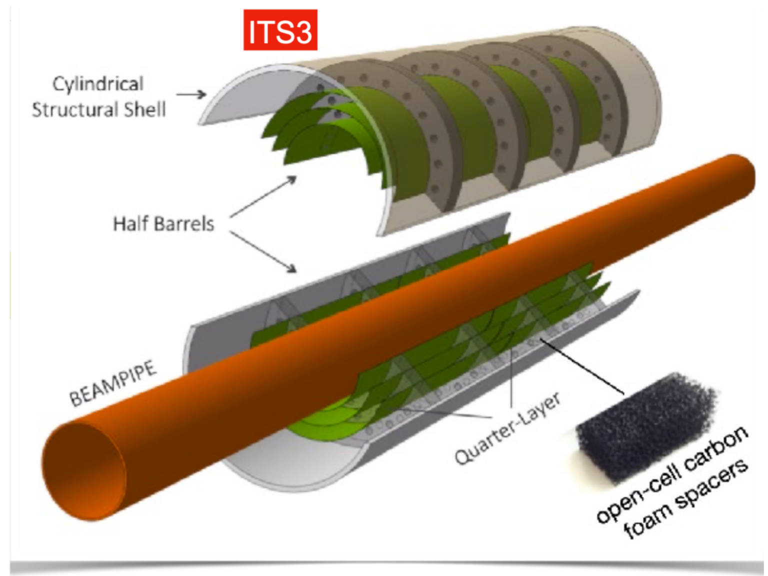


YR performance recovered with re-optimized barrel and forward disk configuration and new 1.7 field over the shown range (electron-arm performance is not recoverable and its envelope remains in flux), Performance is robust against pixel-sizes currently under consideration for ALICE-ITS3 sensor.

ALICE ITS3

The high-level basic goal is to replace the ITS2 vertexing layers with wafer-scale (280 by 100mm), thinned, bent silicon sensors of 1D stitched reticles during CERN LS3,



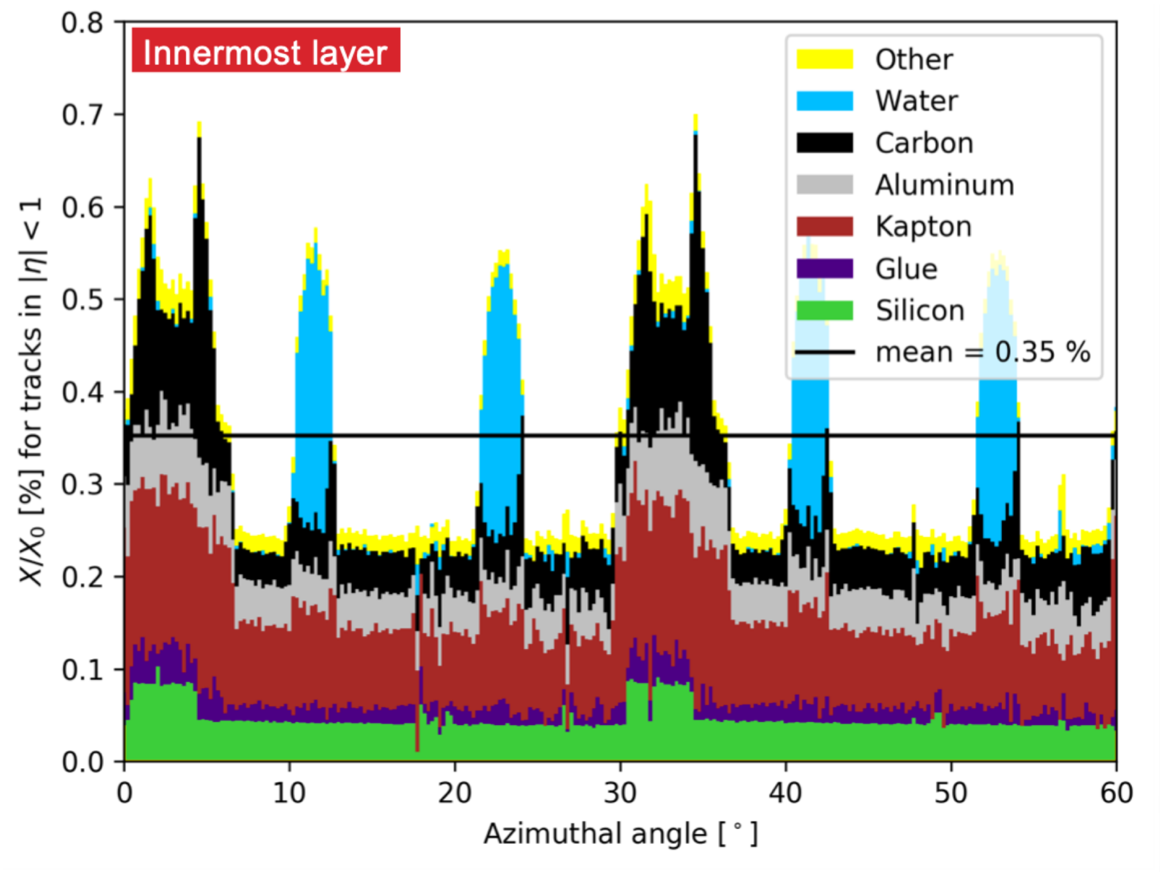


This will then result in improved vertexing performance at low p_T because of reduced power, services in the active area, mechanics, and proximity to the beampipe.

Note: O(0.1 m^2) area; the surrounding barrel layers are ITS2.

ALICE ITS2 to ITS3 - material

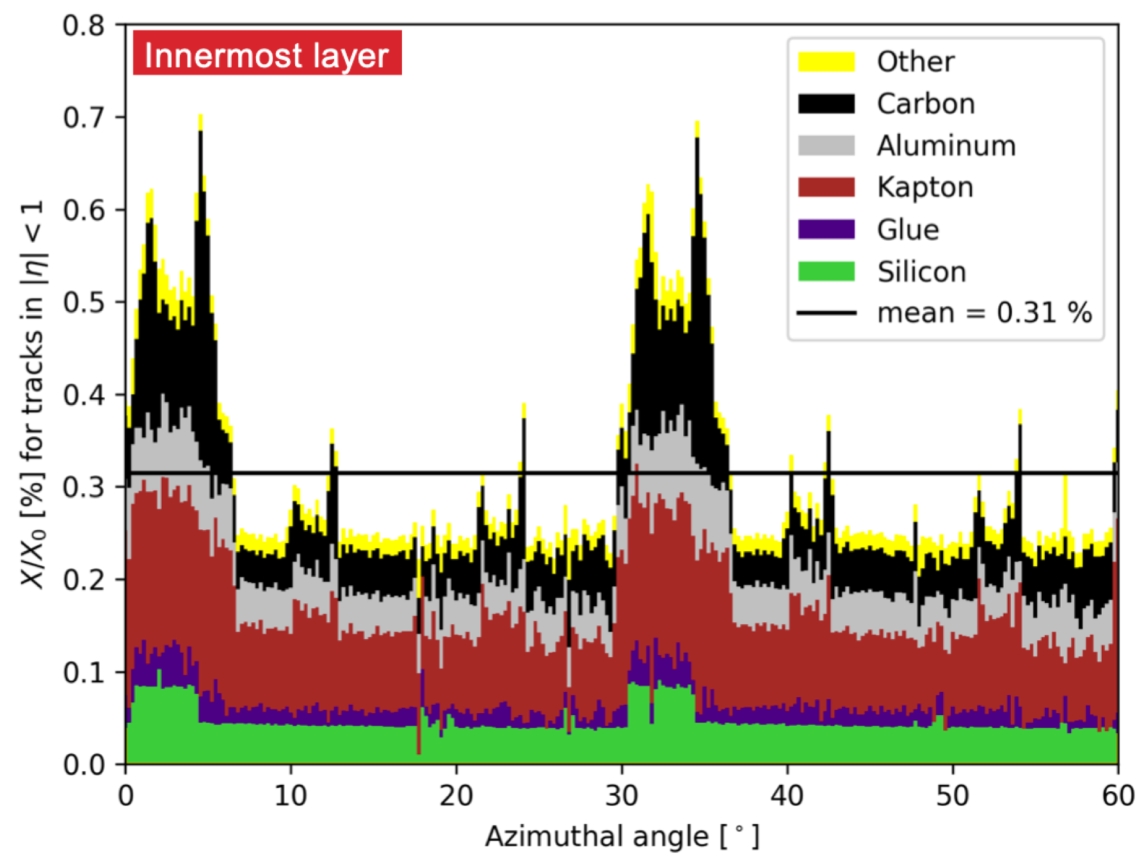
ALICE, courtesy Giacomo Contin (INFN)



- Observations:
  - Si makes only 1/7-th of total material budget
  - Non-uniformity due to support, cooling & overlaps

ALICE ITS2 to ITS3 - material

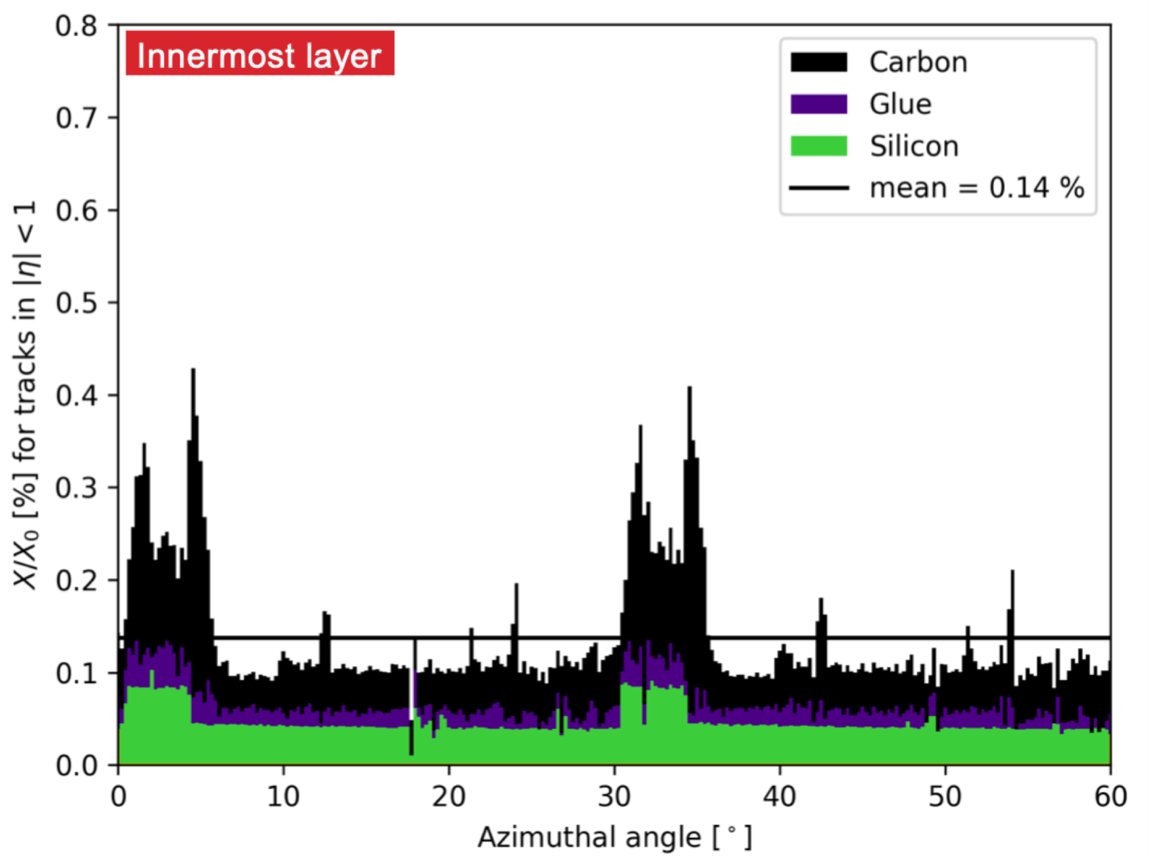
ALICE, courtesy Giacomo Contin (INFN)



- Observations:
  - Si makes only 1/7-th of total material budget
  - Non-uniformity due to support, cooling & overlaps
- Removal of water cooling:
  - If **power consumption < 20 mW/cm^2**

ALICE ITS2 to ITS3 - material

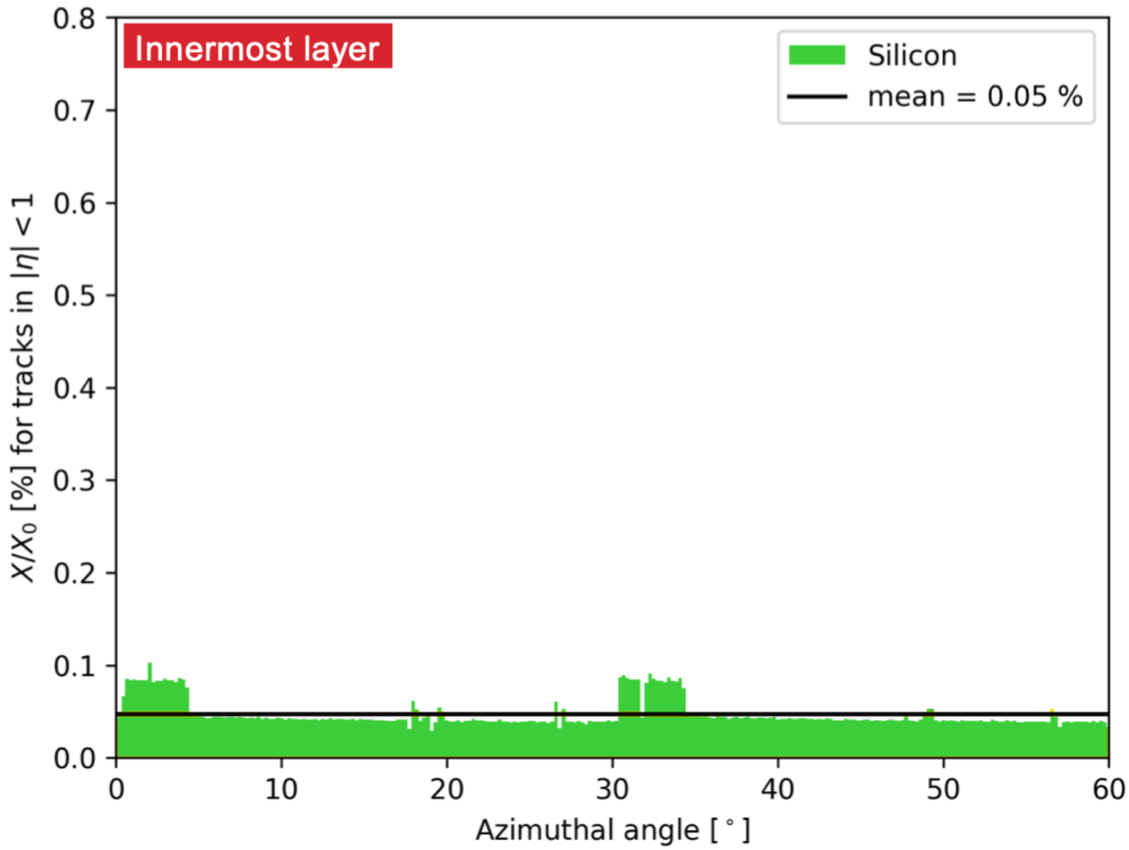
ALICE, courtesy Giacomo Contin (INFN)



- Observations:
  - Si makes only 1/7-th of total material budget
  - Non-uniformity due to support, cooling & overlaps
- Removal of water cooling:
  - If **power consumption < 20 mW/cm²**
- Removal of the circuit board for power & data:
  - If **integrated on chip**

ALICE ITS2 to ITS3 - material

ALICE, courtesy Giacomo Contin (INFN)



- Observations:
  - Si makes only 1/7-th of total material budget
  - Non-uniformity due to support, cooling & overlaps
- Removal of water cooling:
  - If **power consumption < 20 mW/cm²**
- Removal of the circuit board for power & data:
  - If **integrated on chip**
- Removal of mechanical support:
  - **Self-supporting arched structure**

ITS3 - EIC

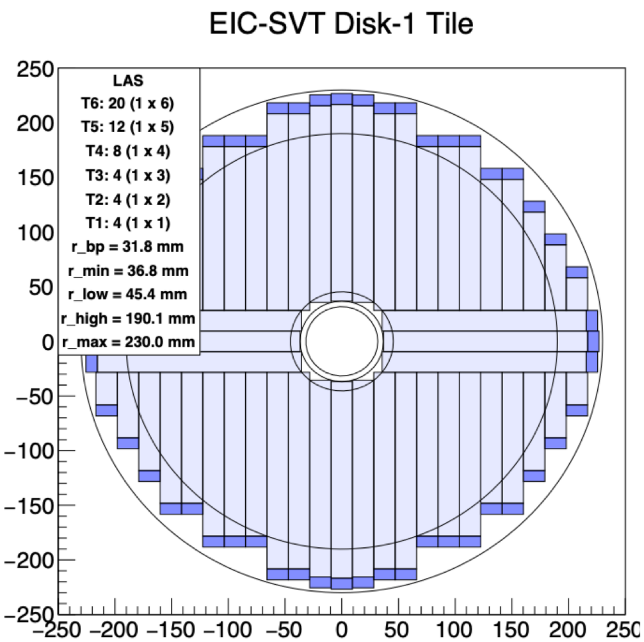
The path to an EIC detector based on 65nm MAPS technology thus requires us to develop:

- ITS3-like vertexing layers:
  - Re-use ITS3 sensor as is,
  - Adapt ITS3 subsystem concept to the EIC radii (R&D),

- EIC Large Area Sensor (LAS) variant(s) for the staves and disks,
  - EIC LAS, i.e. ITS3 sensor size optimized for high yield, low cost, large area coverage – O(10m^2),
  - EIC LAS will be stitched, but not to wafer scale. The functionality and interfaces are to stay the same as the ITS3 sensor,
  - Size(s) of the EIC LAS are to be defined based on the yield of the stitching process and requirements for full coverage,
  - Conventional carbon fiber support structures with integrated cooling.

EIC LAS – for staves and disks

Algorithms to lay out EIC LAS sensors to cover staves disks:



Example configurations for two of the disks; blue-colored and red-colored LAS could be mounted on alternate sides of the disks.

currently indeed favor a cross-pattern to accommodate the varying and offset EIC beam opening, complemented with a “picket fence” like arrangement to cover the disks,

Aim to keep the EIC-LAS peripheries at larger radii,

Ongoing studies to optimize / minimize the number of EIC-LAS variants.

EIC SC – a few words on R&D

Project R&D is of course focused (solely) on detector 1 – for FY23 specifically:

- eRD104 Services reduction – investigate methods to significantly reduce the services load for an EIC MAPS based tracking detector,
  - Powering system,
  - Readout system,

- eRD111 Si tracker – development of a full tracking detector solution compared of next generation 65 nm MAPS sensors,
  - Forming modules from stitched sensors,
  - Barrel and disks,
  - Mechanics, integration, and cooling,

- eRD113 Sensor – development of the EIC MAPS LAS senor(s)
  - Sensor design,
  - Sensor characterization.
- Recent DAC review: https://indico.bnl.gov/event/17159/

Generic R&D is a different matter – for FY 23 specifically:

- Kapton-embedding of sensors with additive manufacturing of electrical traces,
- Industrial production of *aluminum* flex cables,
- No generic sensor R&D

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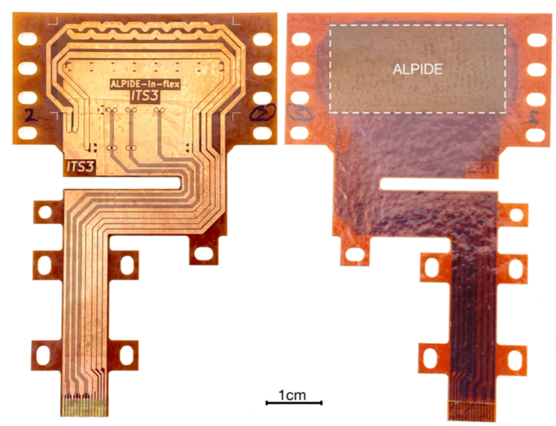
Courtesy ALICE-ITS2



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Closing comments

Tracking system of the EIC project detector (reference) is anticipated to be a combination of:

- A compact, large acceptance, highly granular, well-integrated, low-mass tracking and vertexing subsystem based on 65nm ITS3 MAPS technology,
- Outer MPGD layers and disks that remain to be optimized for track finding and angular resolutions into the PID subsystems – not covered in this talk,

EIC Silicon Consortium

- aims to bring together experience / expertise and strength with the overarching goal to develop and construct a full tracking and vertexing detector subsystem for the EIC detector(s) based on 65nm MAPS sensors,
- engaged in project R&D and generic R&D,
- is well-integrated into the EPIC collaboration (thus far) via the detector tracking working group,
- interested in MAPS-based tracking and vertexing for both IRs, welcome new collaborators,

Tracking

- Comparative compactness of MAPS-based tracking and vertexing is or was not a goal in and by itself; it does provide options to further improve resolutions (B, *r*, *z*) and for better detector integration by freeing space for other subsystems and services,
- Much of the present challenge is about scale, material budgets, and integration,
- Imaginative new sensor capability, e.g. O(20ps) timing, will be (too?) “far out”,
- Room for complementarity via B, *r*, *z* and, technologically, via hybrid-tracking solutions.