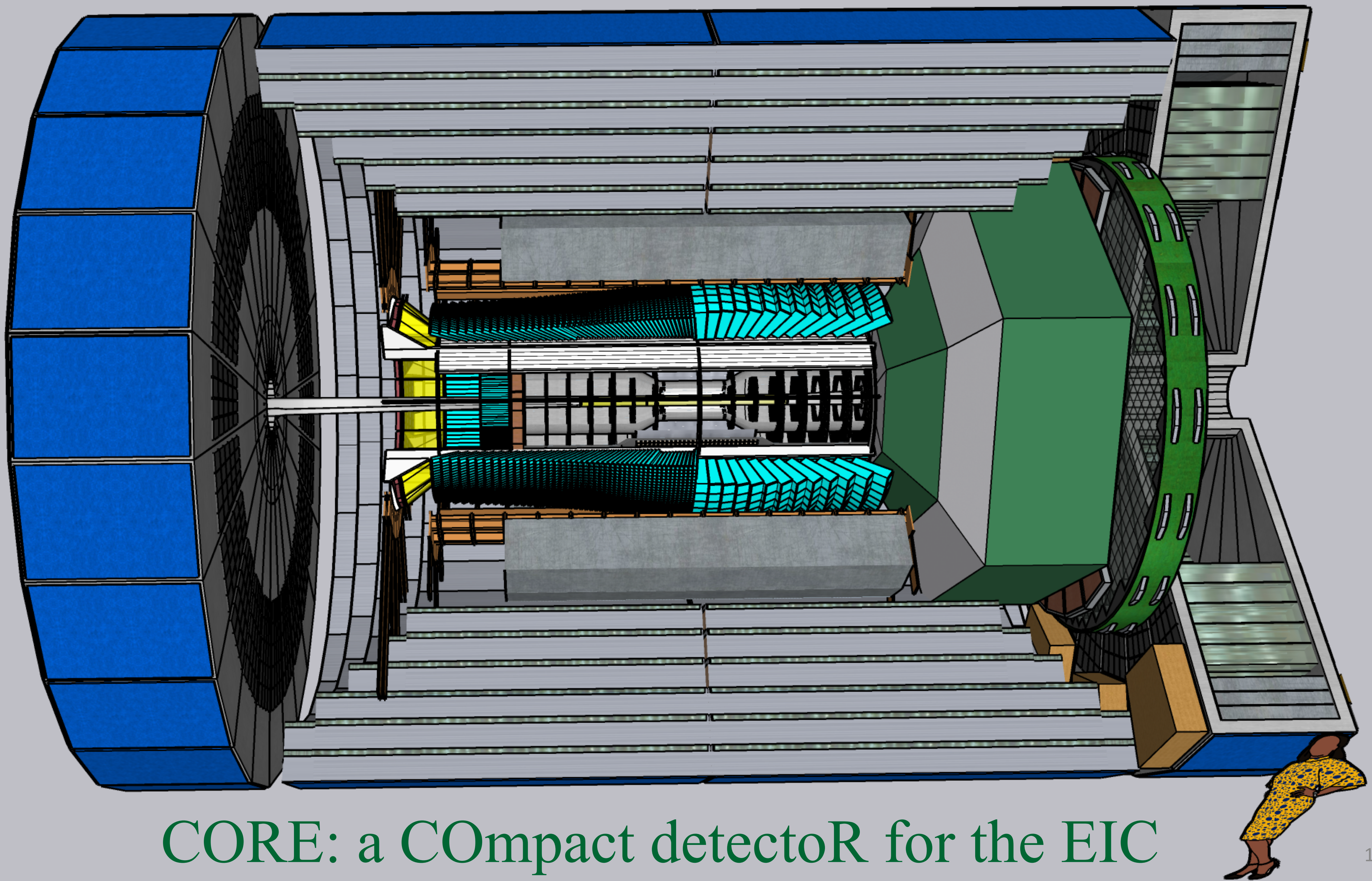


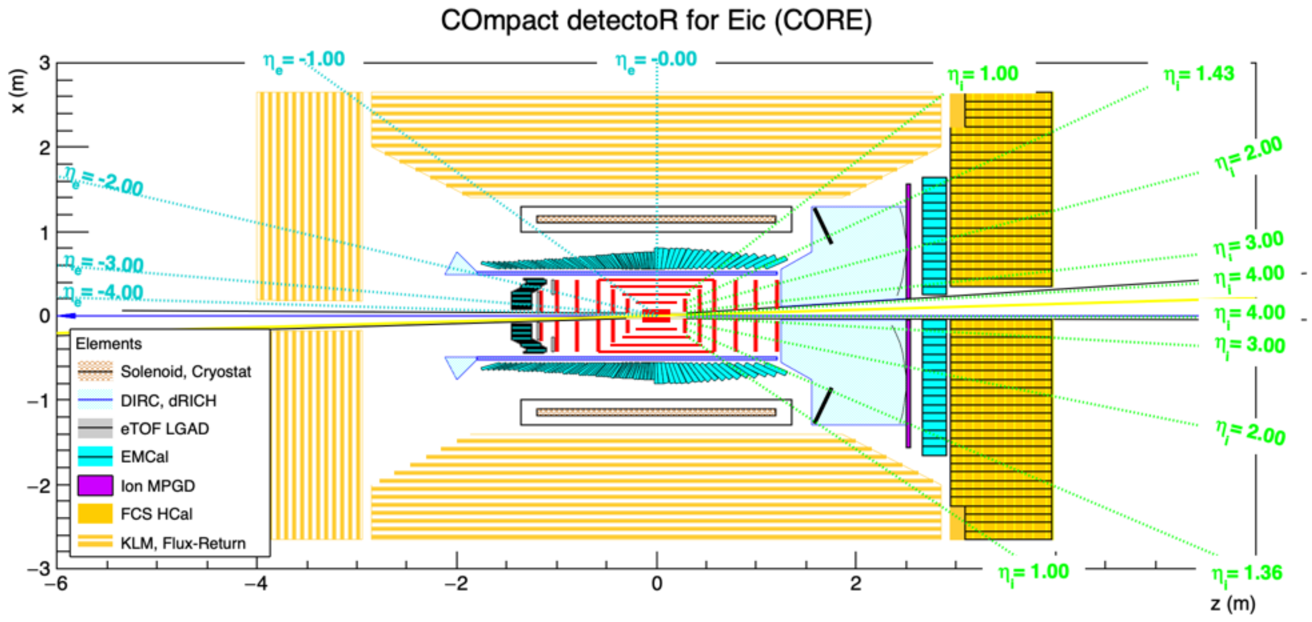
CORE: a COmpact detectoR for the EIC

Outline

- Technologies and technology choices
  - EIC R&D
- Tracking
  - Silicon tracker, fwd MPGD tracker
- Particle Identification
  - Dual-radiator RICH, DIRC, LGAD TOF
- EM calorimetry
  - $PbWO_4$, W-shashlyk
- Hadronic calorimetry
  - fwd Hcal, KLM
- Electronics

CORE design philosophy

- A short 3 T solenoid enables high-resolution tracking and a higher luminosity
  - Synergetic with an IR with a 2nd focus, which provides the best far-forward acceptance at the lowest β^*



- A compact core of subsystems around a high-resolution all-silicon tracker inside a spacious flux return, makes the detector cost-effective and provides ample space for supports and services.

- In particular, the compact core makes it affordable to use the best possible EM calorimetry in the barrel, enabling new physics (*e.g.*, tomography of nuclei).

- CORE is a fully hermetic detector with 4π tracking, calorimetry, and PID.

- Since EIC jets generally have low energies and multiplicities, and are best reconstructed from the individual particles, the KLM in the barrel and electron endcap of CORE emphasizes measurement of the position of neutral hadrons and identification of muons.

CORE – overview

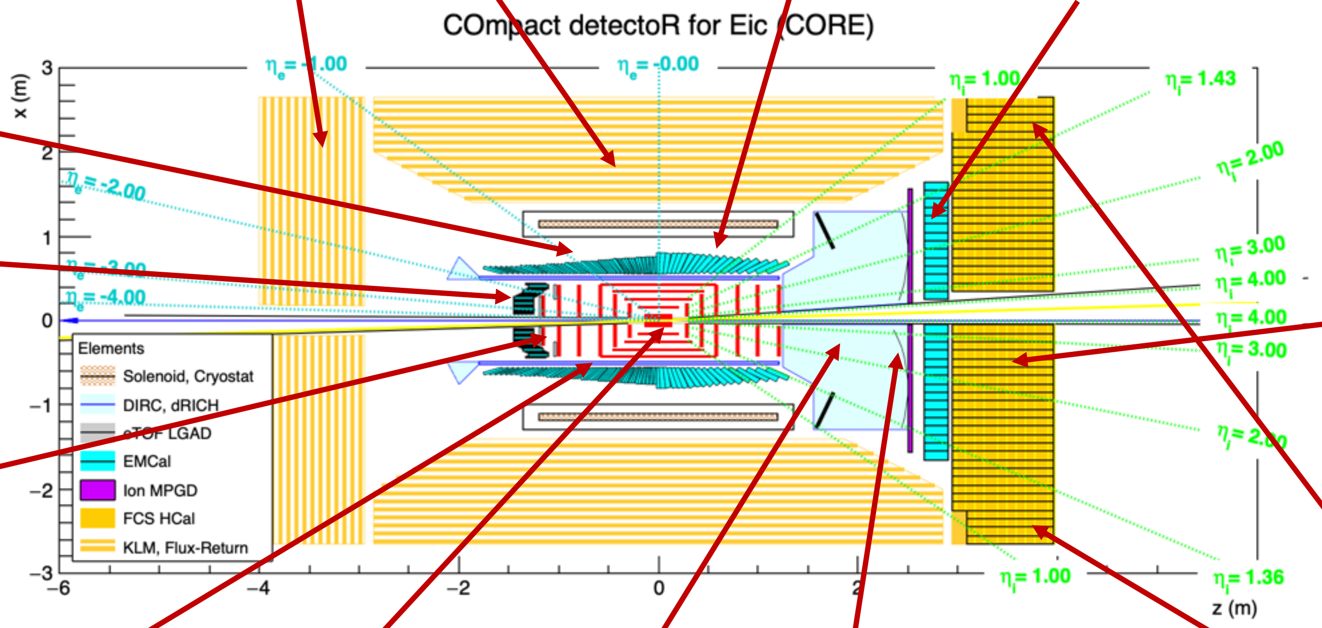
Neutral hadron and muon ID detector (KLM)

Projective W-shaslik EMcal

Non-projective W-shaslik EMcal

Projective $PbWO_4$ EMcal

Non-projective $PbWO_4$ EMcal



Hcal, new Fe/Sci modules (44 layers)

LGAD TOF

Silicon tracker

MPGD tracker

Hcal, outer rings: re-used STAR FCS modules (36 layers)

DIRC

Dual-radiator RICH

CORE technologies

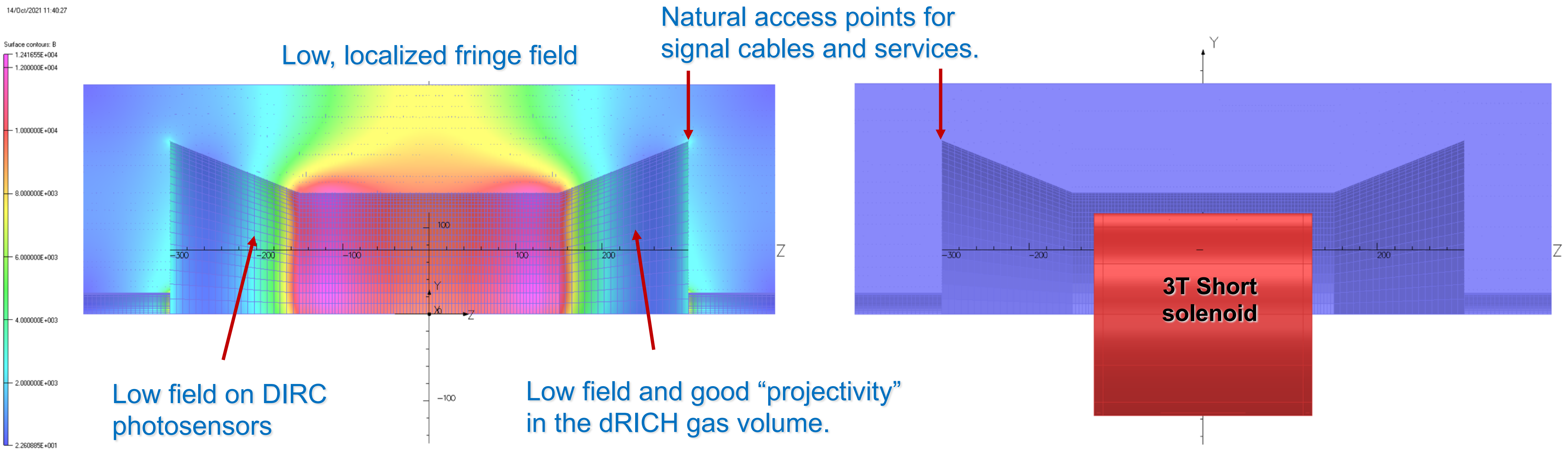
No high technical risk components .

Component	Baseline Technology	Basis for Tech.	Risk	Alternative	Alternative seen as
compact solenoid	NbTi	widespread use	medium	lower field	fallback
silicon tracker	MAPS (10 μm pixels)	ITS3, eRD25	medium	as for ALICE	fallback
MPGD tracker	μRWELL	eRD6	medium	GEM	fallback
LGAD TOF	AC-LGAD	eRD112	medium	resistive LGAD	lower fill factor
dRICH PID	gas + aerogel	eRD14, HERMES	medium	non-CFC gas	eco friendly
DIRC PID	hpDIRC	eRD14, PANDA, BaBar	low	thin bars	improved e/π ID
EMcal $\eta < 0$	$PbWO_4$	PANDA, CMS, etc	low	W-shashlyk	fallback
EMcal $\eta > 0$	W-shashlyk	similar to Pb-shashlyk	low	W/SciFi	fallback
HCal $\eta > 1.2$	Fe/Sci towers	STAR FCS, eRD1, etc	low	eRD107 compensation	improved resolution
KLM $\eta < 1.2$	Fe/Sci 2D layers	Belle II	low	sPHENIX HCal	traditional HCal

TABLE II. Summary of detector technologies.

Note: The decade-long Generic R&D for an EIC program was very successful in bringing forth many technologies that are suitable for use in an EIC detector. Most of the CORE subsystems are adaptations of these technologies made in collaboration with the respective R&D consortia.

The short 3 T solenoid designed for CORE



- A symmetric distribution of iron minimizes coil forces
- Variable field – iron far from saturation even at 3 T
  - 75% iron fraction assumed for the barrel flux return
- Cryostat integrated with barrel instrumentation (KLM)

- Max field: 3 T @ 4,700 A/cm^2
- Coil length: 2.5 m
- Inner radius: 1 m
- Stored energy: 38.8 MJ

Support cradle

- The cradle at IP8 could be used to support CORE, which has an outer diameter similar to sPHENIX.

- Some general adaptations would be needed in the transition from RHIC to EIC.
  - The detector has to be aligned with the electron beam, but the angle is different and does not match the old rails.
  - The endcaps have to be supported separately so that they can be moved directly sideways as required by the project.

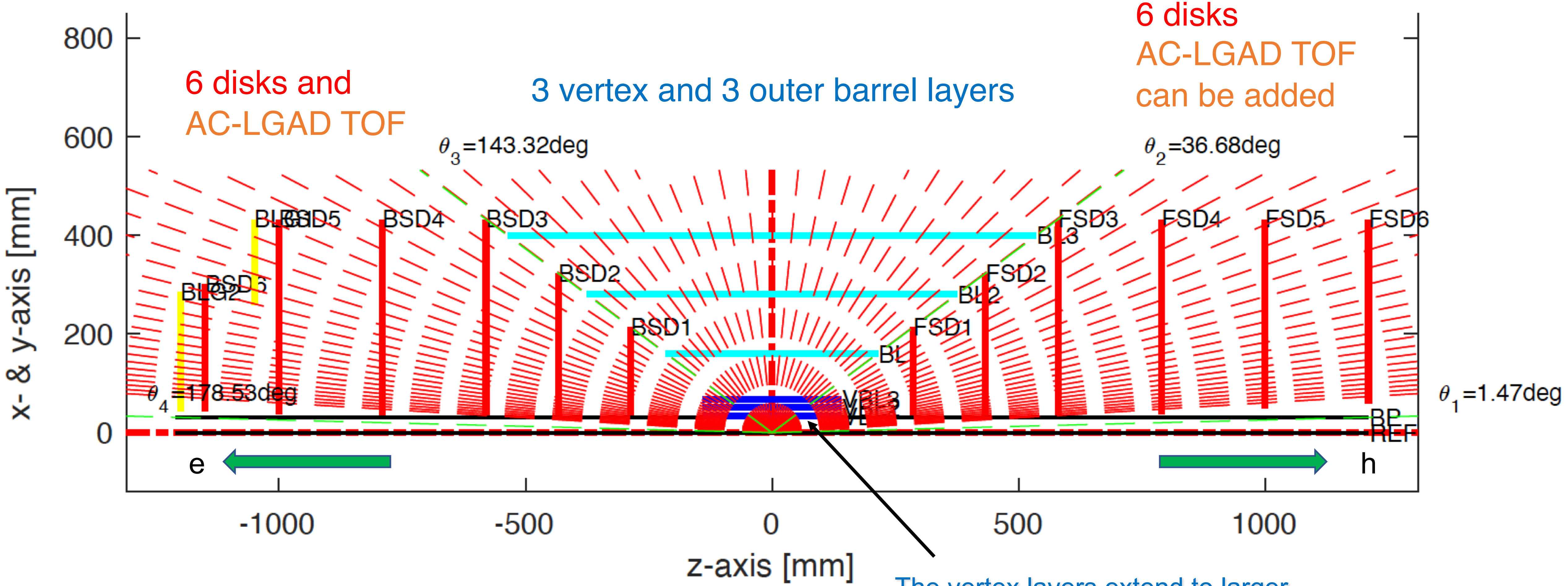
- To address this, a new platform could be built re-using elements from the old one, with the correct length and angles for the ”inverted arches” - or the old platform could be adapted.

Si-tracker: simulation

ITS3 technology:
MAPS (10 μm pixels)

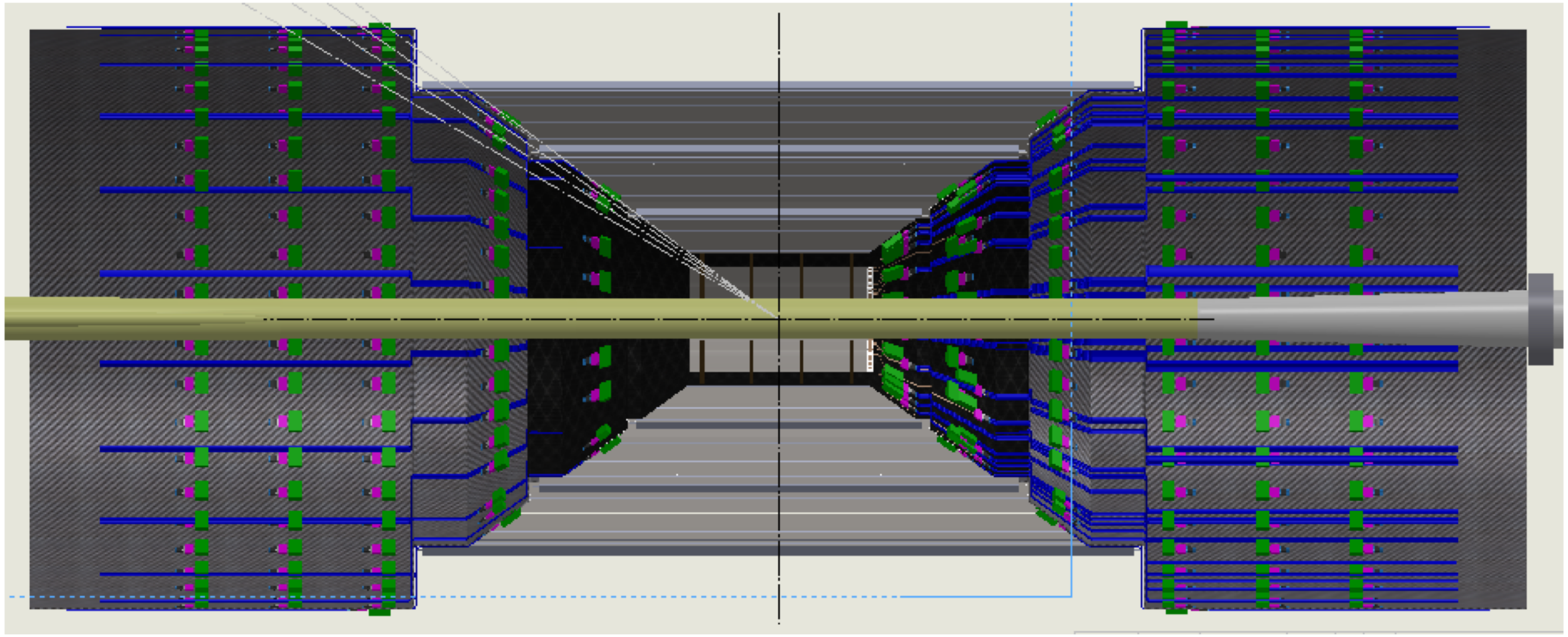
Layout: symmetric except for the last MAPS on each side

Goal: particles should cross six disks or barrel layers to minimize inefficiencies



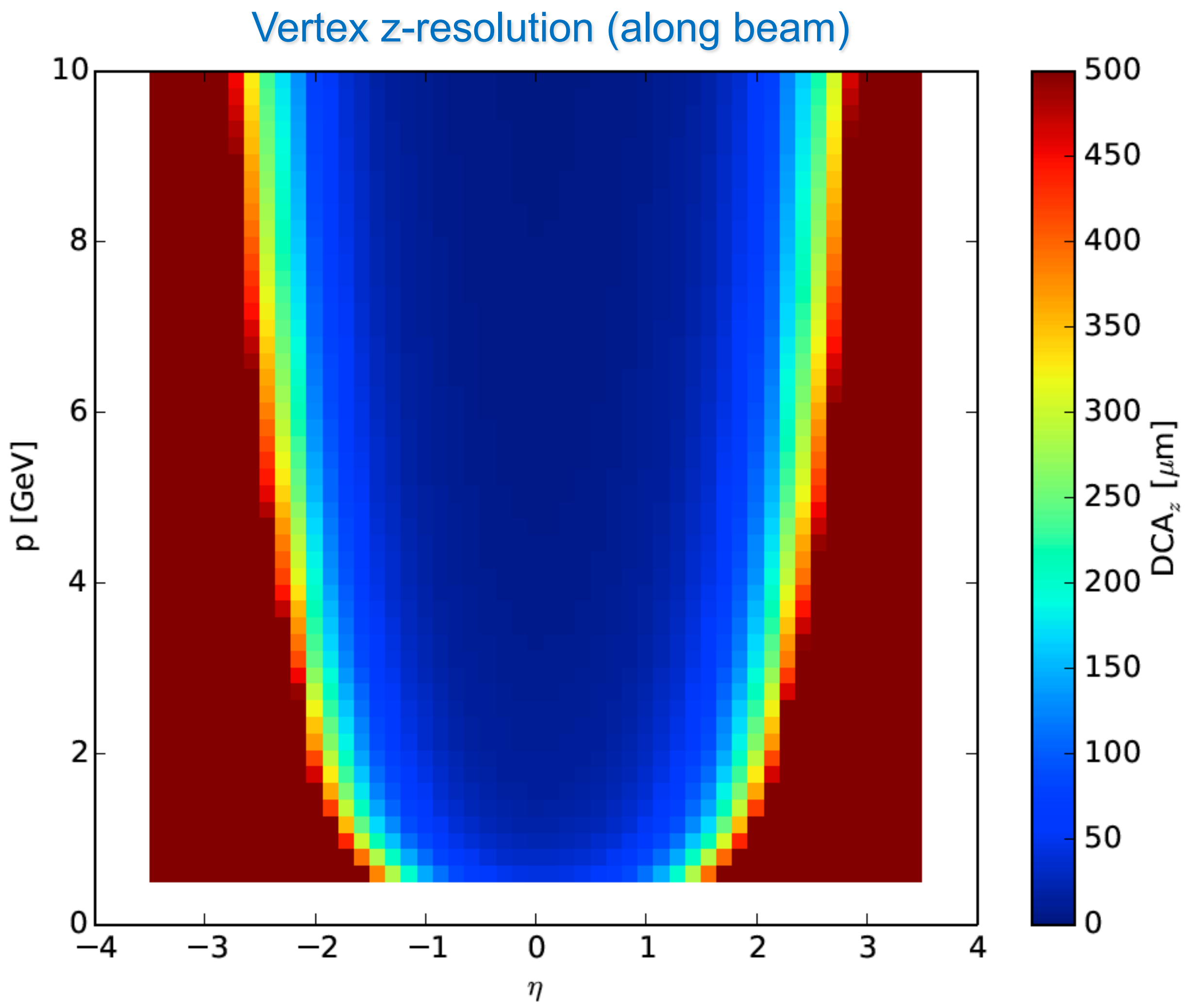
The vertex layers extend to larger rapidities than the outer barrel layers.

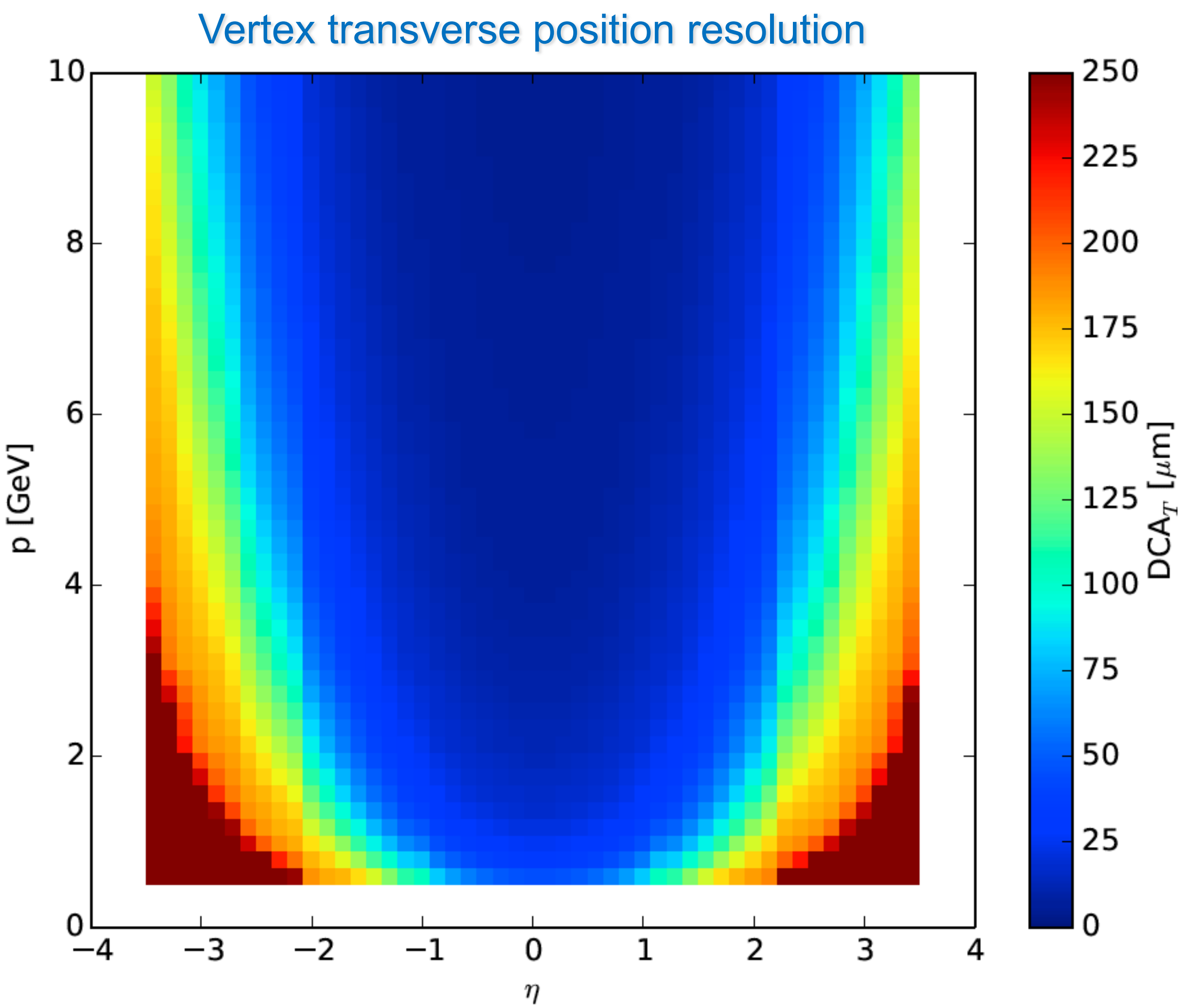
Si-tracker: realistic implementation



- A realistic implementation of the CORE tracker, including supports, electronics, and services, demonstrates the feasibility of the concept.

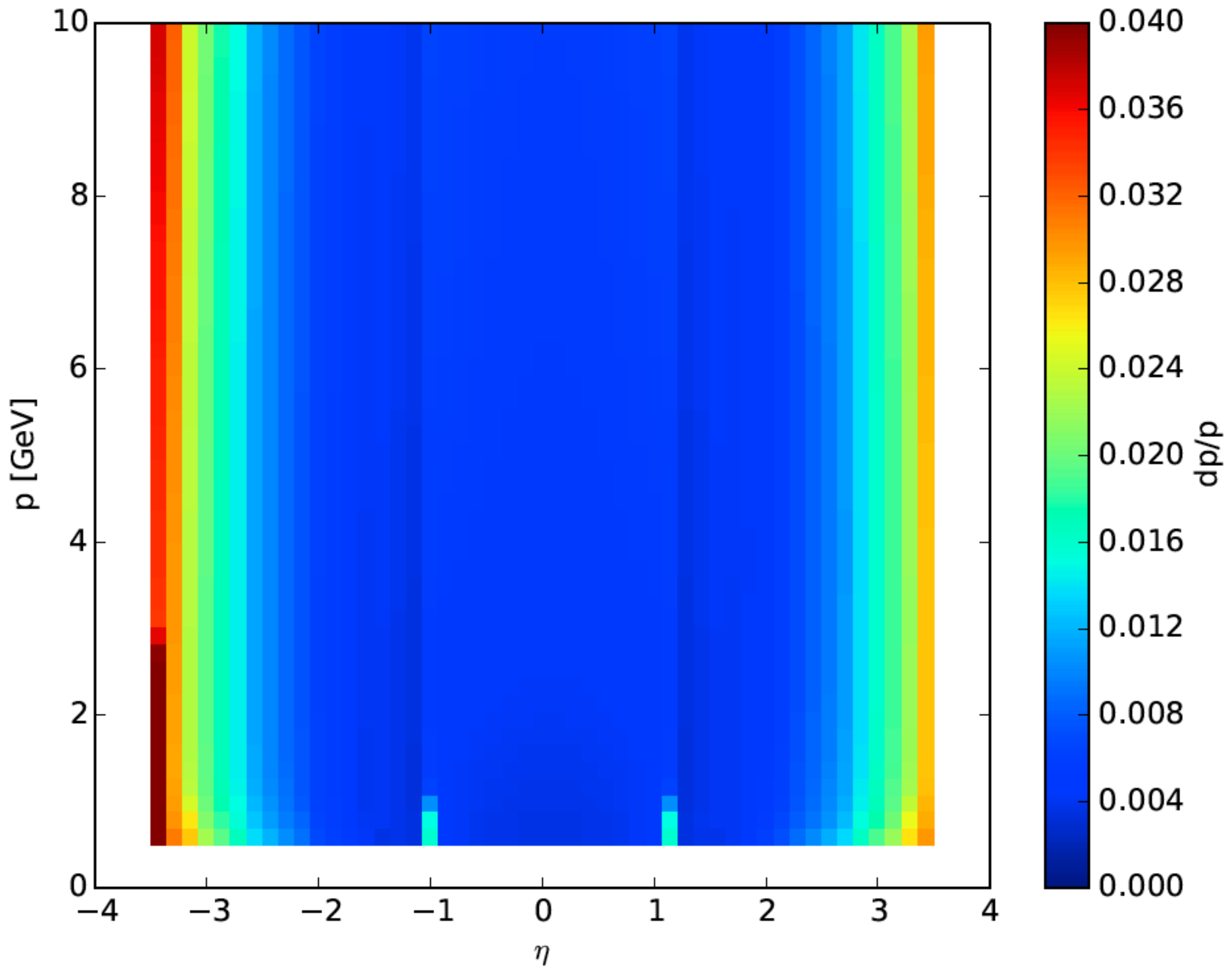
Si-tracker: vertex position resolution



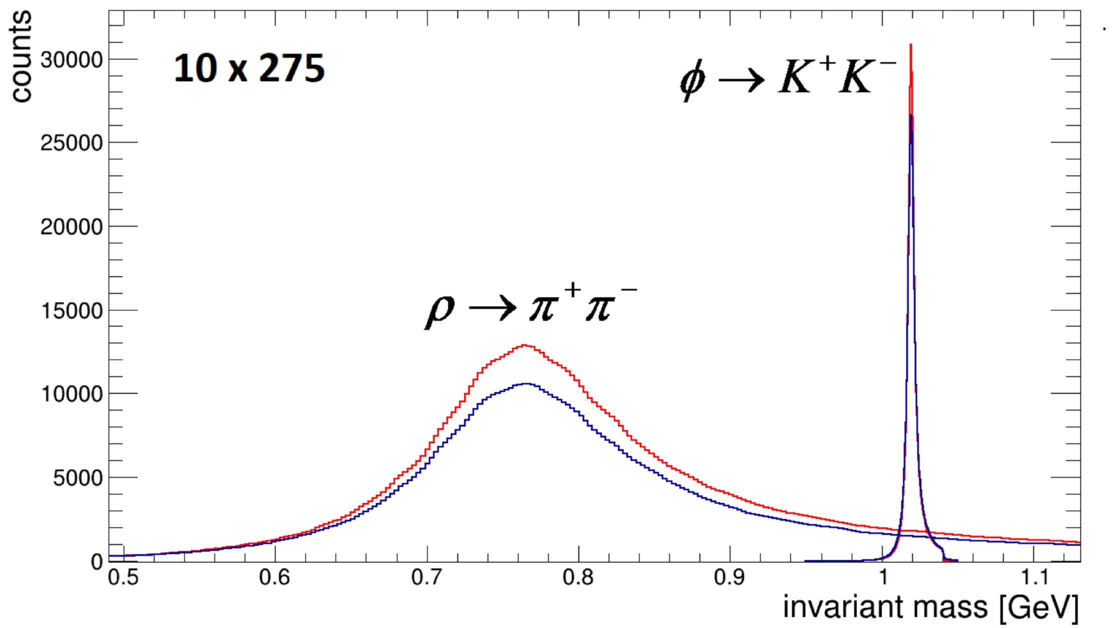


- The resolution is good for measuring detached vertices from, *e.g.*, open charm (D^0 $c\tau$ = 123 μm)

Si-tracker: momentum resolution (at 3 T)



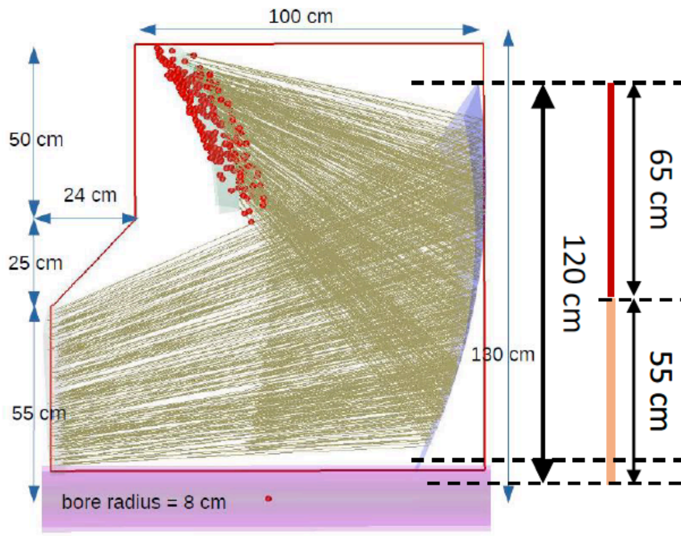
Note: adding the MPGD will improve the resolution at forward rapidities.

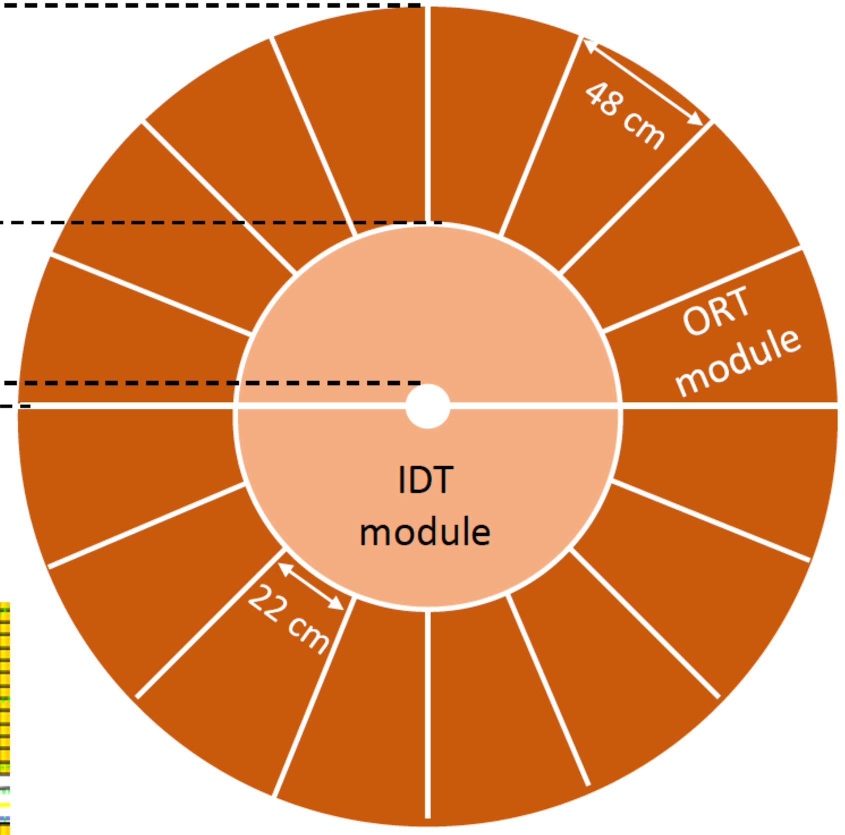


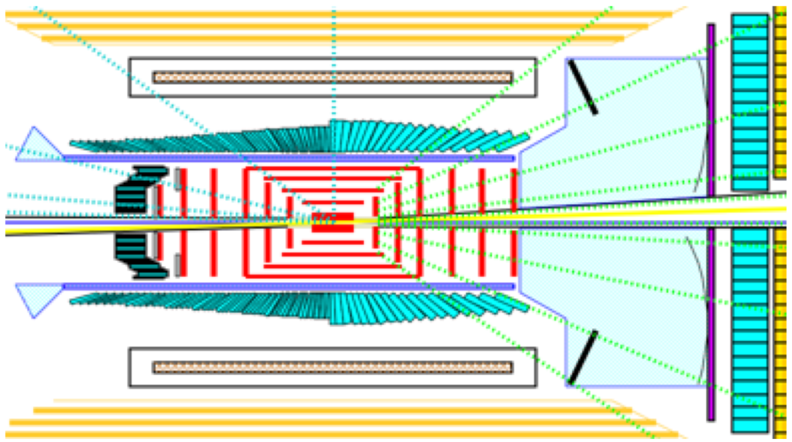
- The invariant mass resolution for the ϕ is 0.37 MeV when integrated over the full angular range
  - Straightforward to analyze even without PID

Forward MPGD (μRWELL)

- The main purpose of the MPGD is to seed the ring finding for the dRICH.
- With a long lever arm and 50-100 μm resolution, it can also improve dp/p at large η.
- To optimize the acceptance at large η, it has an inner disk tracker (IDT) module that minimizes the dead area at the center.
- The baseline technology is μRWELL.

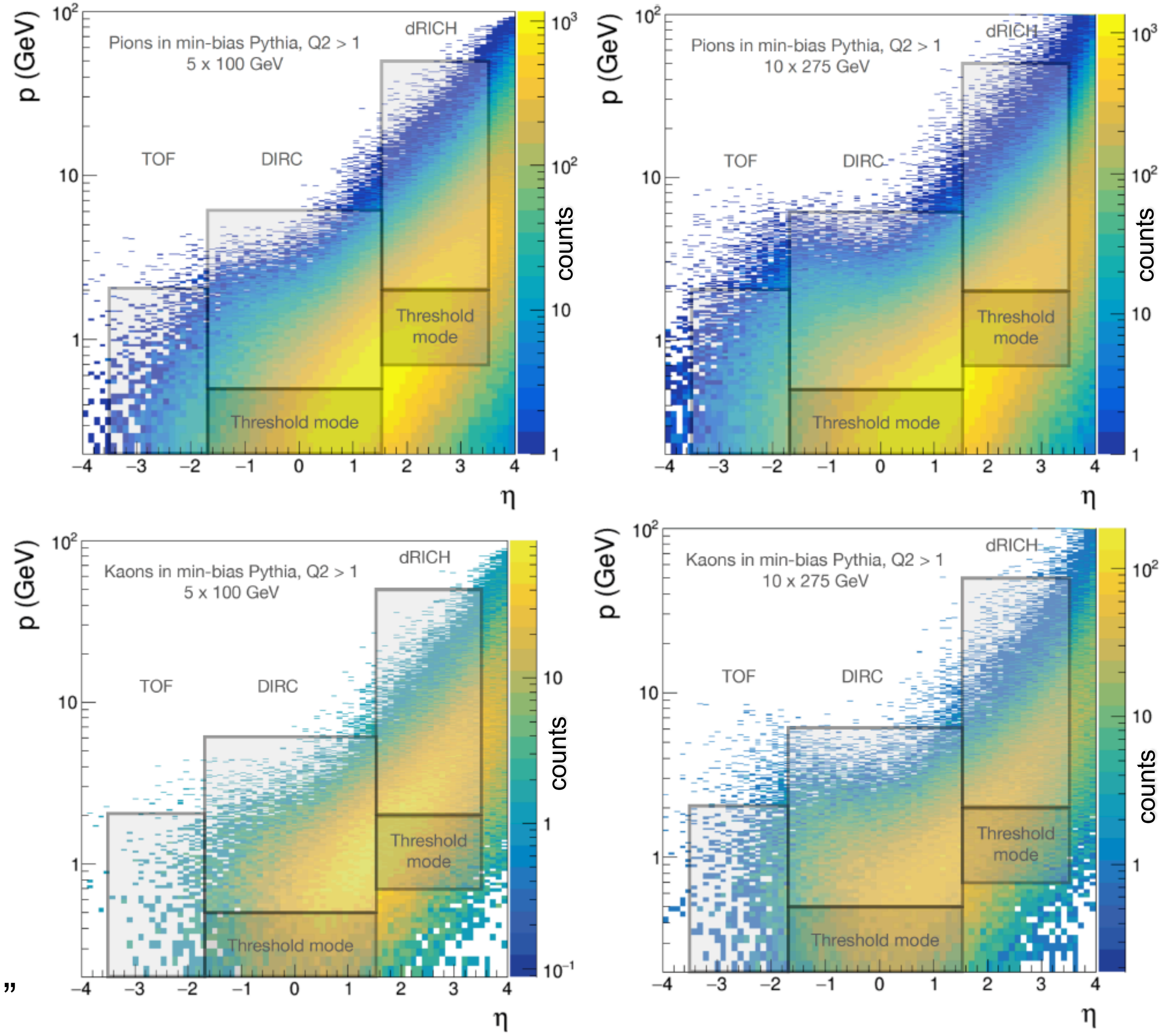




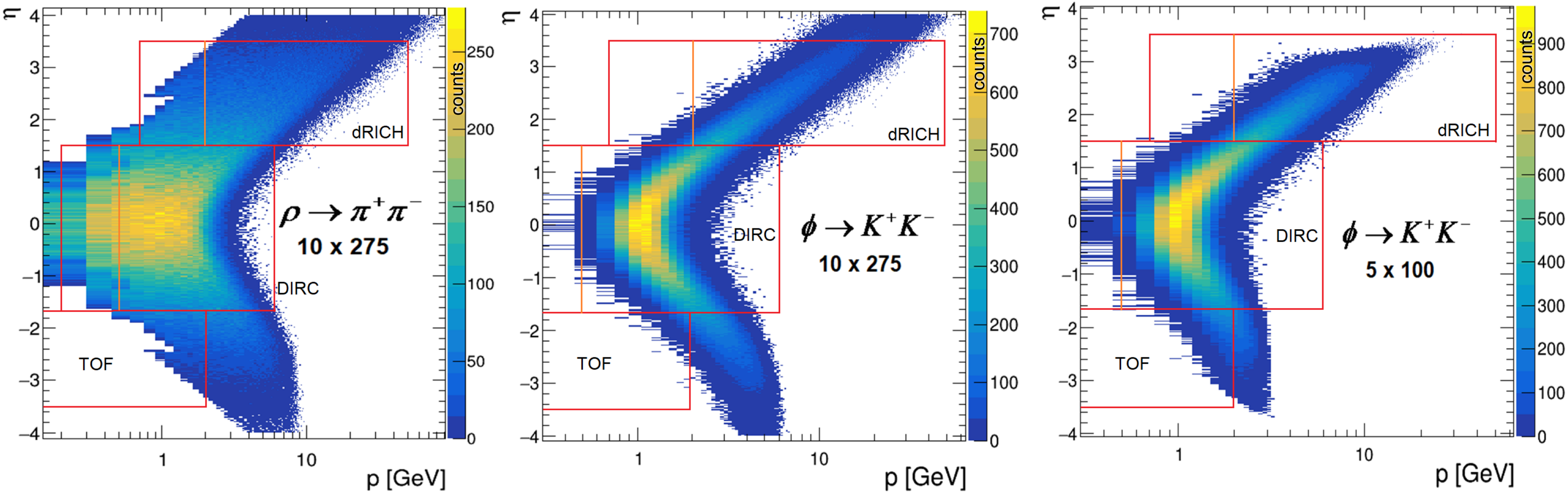


Hadron identification

- Momenta of hadrons produced in DIS are strongly correlated with the beam energies, and generally decrease towards more negative values of η.
  - higher electron beam energies generate higher hadron momenta for $\eta < -1.65$
- The distributions for pions (top) and kaons (bottom) are shown for typical beam energies of 5x100 (left) and 10x275 GeV (right).
- A conservative estimate of the (3σ) coverage for the PID systems is superimposed.
  - For the Cherenkov detectors, the threshold mode indicates that pions produces a “ring,” but kaons and protons are below threshold.



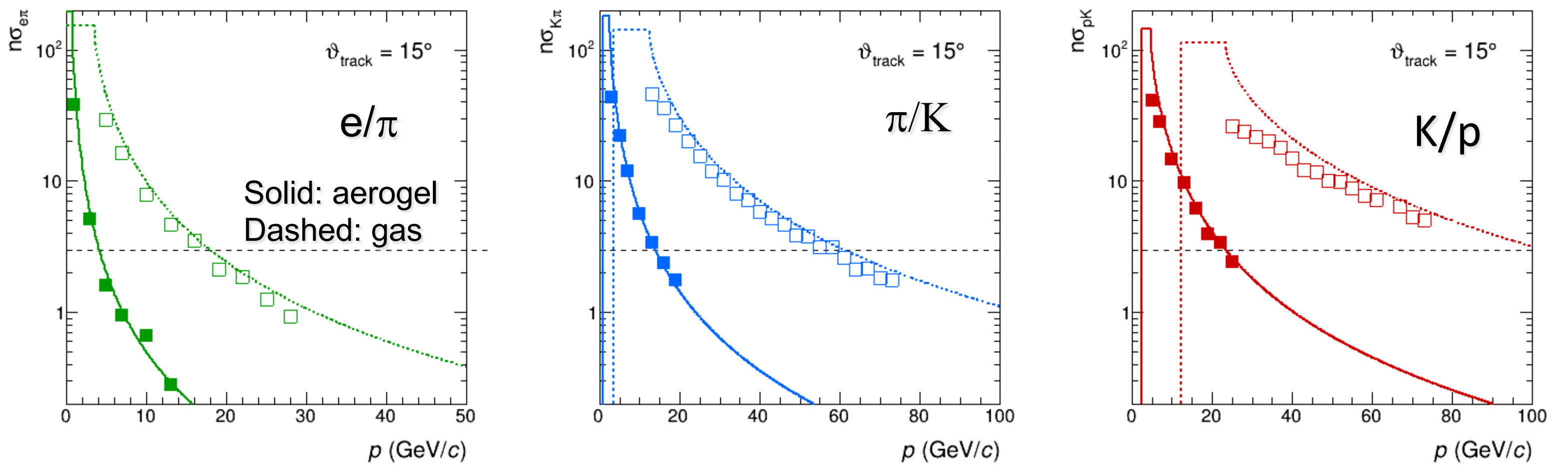
Particle identification in exclusive reactions

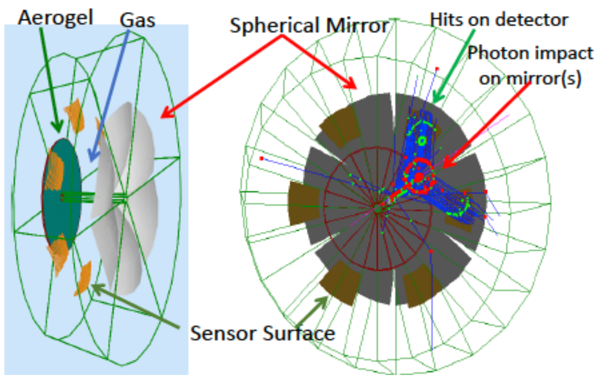


- In exclusive reactions, final-state hadron momenta are higher than in DIS.
  - In particular, kaons from ϕ decays are covered by the RICH modes of the DIRC and dRICH.
- In the electron endcap, the TOF covers the kaons only at the lowest electron beam energies, but with the excellent invariant mass resolution of the tracker, the ϕ yield can be extracted using sideband subtraction.

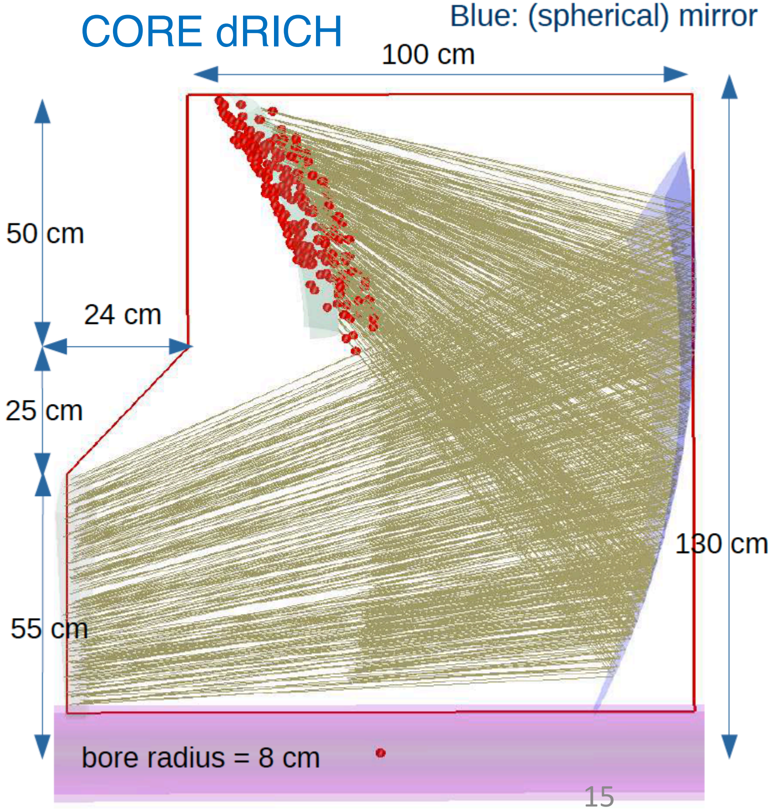
PID in the hadron endcap – dual-radiator RICH

Performance of the dRICH developed by the EIC PID consortium (eRD14)



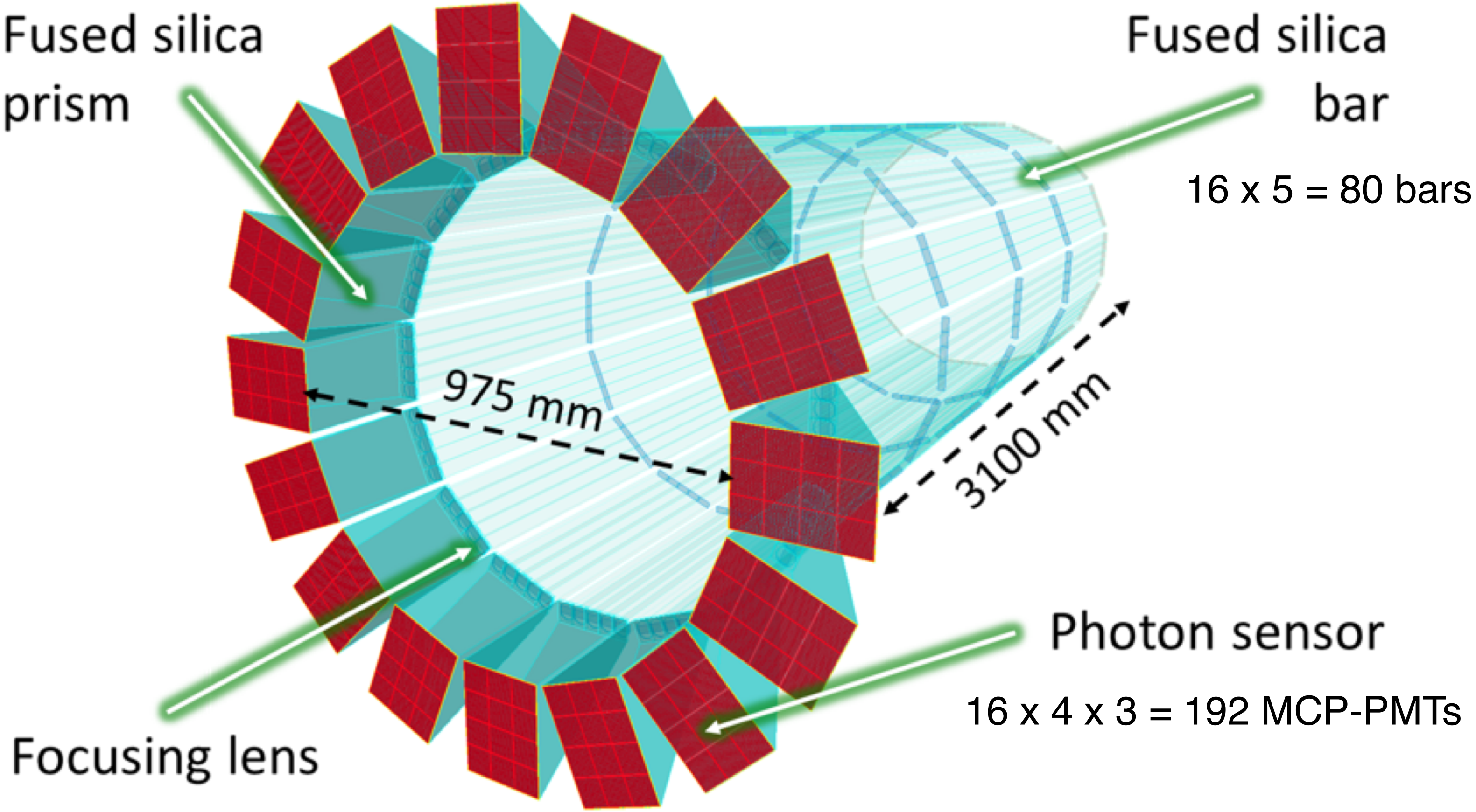


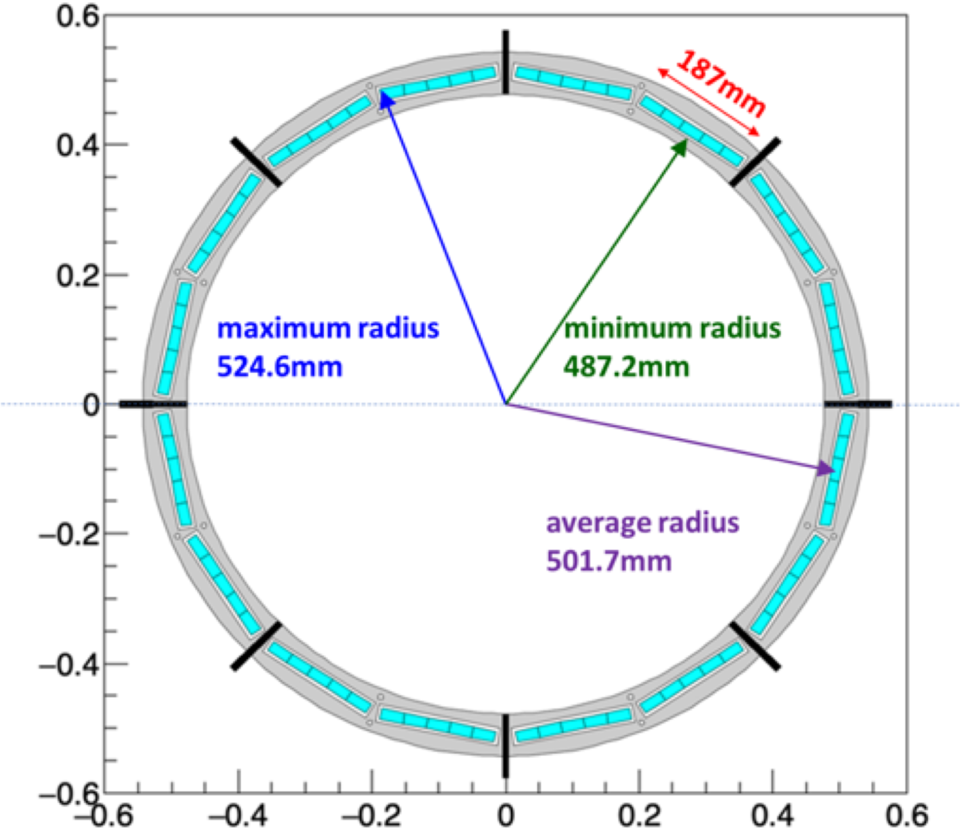
eRD14 dRICH



- The CORE dRICH is a smaller version of the eRD14 design
  - Most dimensions were scaled by a factor 2, but the length of the gas along the beam was only reduced from 1.6 m to 1.2 m (25%).
  - The resulting geometry provides a good match to the photosensor plane and a photon yield almost as high as the eRD14 dRICH
  - The 55 cm aperture matches the inner radius of the barrel EMcal
- The CORE dRICH performance should be close to that of the original eRD14 dRICH, with continuous π/K coverage in RICH mode for 2-50 GeV/c, and positive pion ID below kaon threshold.

PID in the barrel - a high-performance DIRC

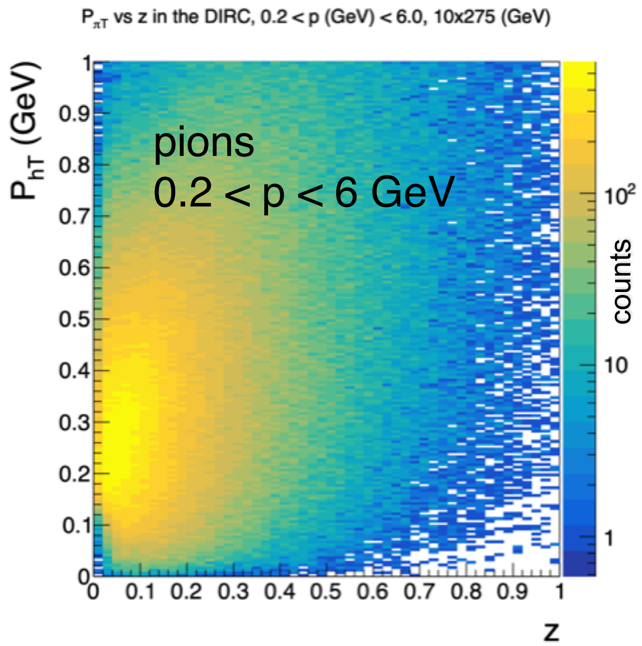


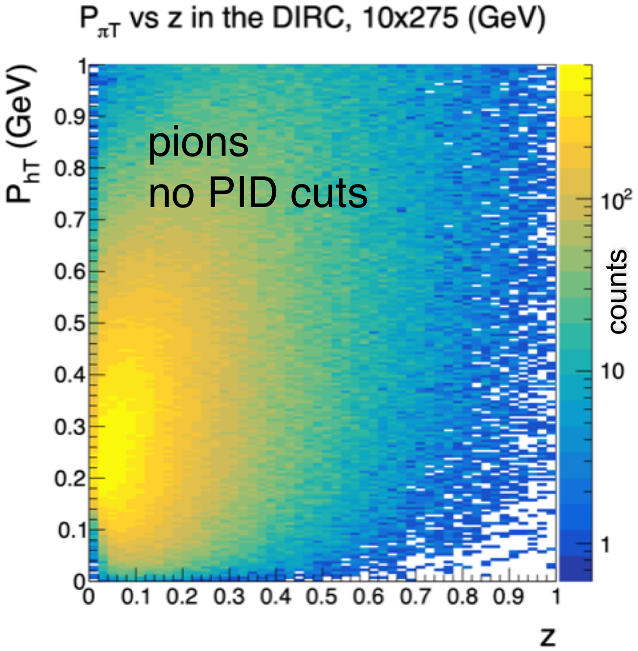


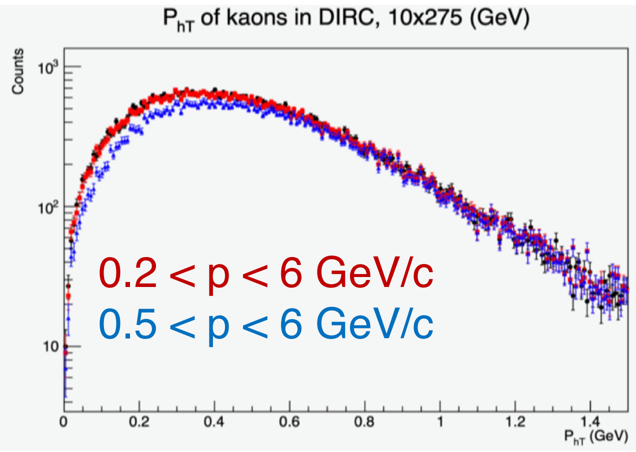
- The PID performance of a DIRC is largely independent of size
  - The small radius of the CORE DIRC improves low-momentum PID acceptance at high B-fields

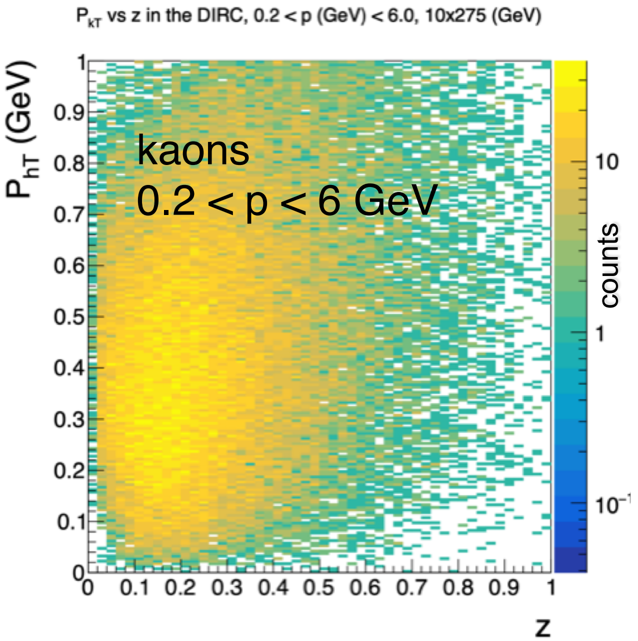
DIRC PID range - impact on TMDs

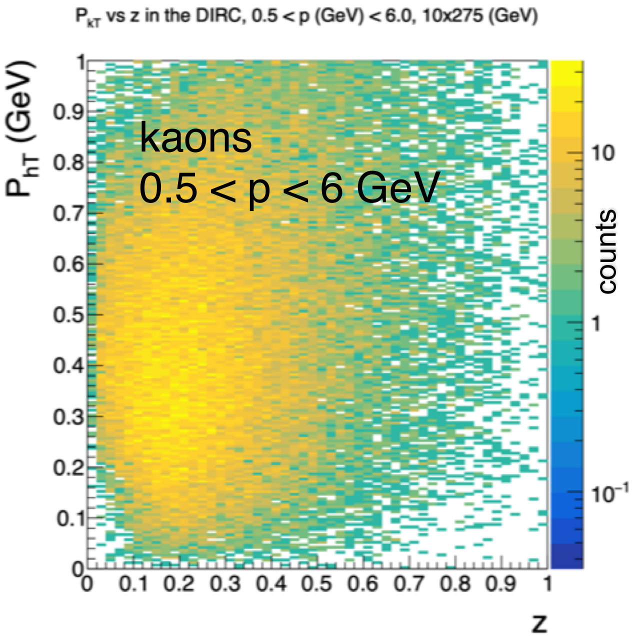
- In SIDIS, the transverse momentum P_{hT} is defined with respect to the virtual photon and not the beam direction.
  - Since the photon direction varies, the lower end of the PID range has little impact on the z-P_{hT} coverage (it adds statistics).
  - The PID range of the DIRC is ideal for TMD physics.

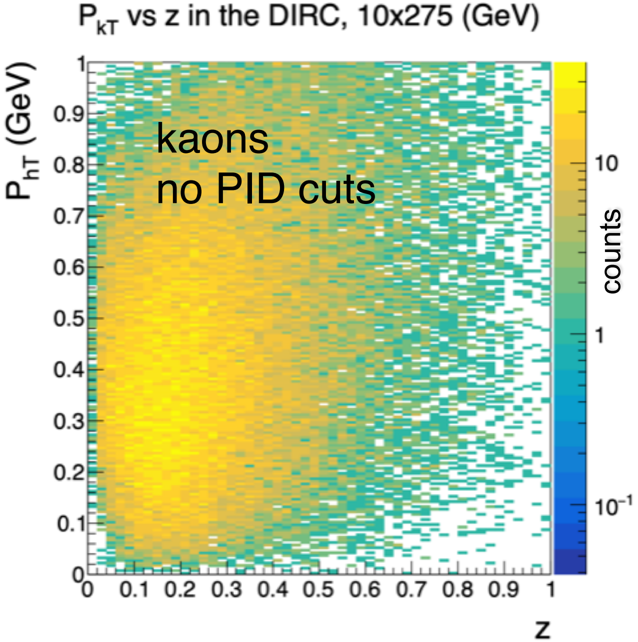




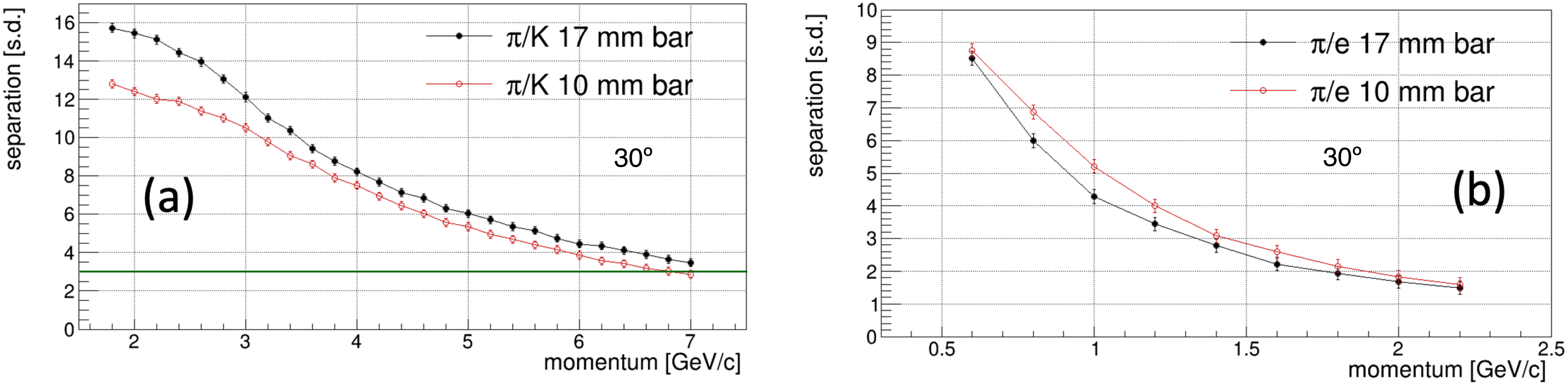






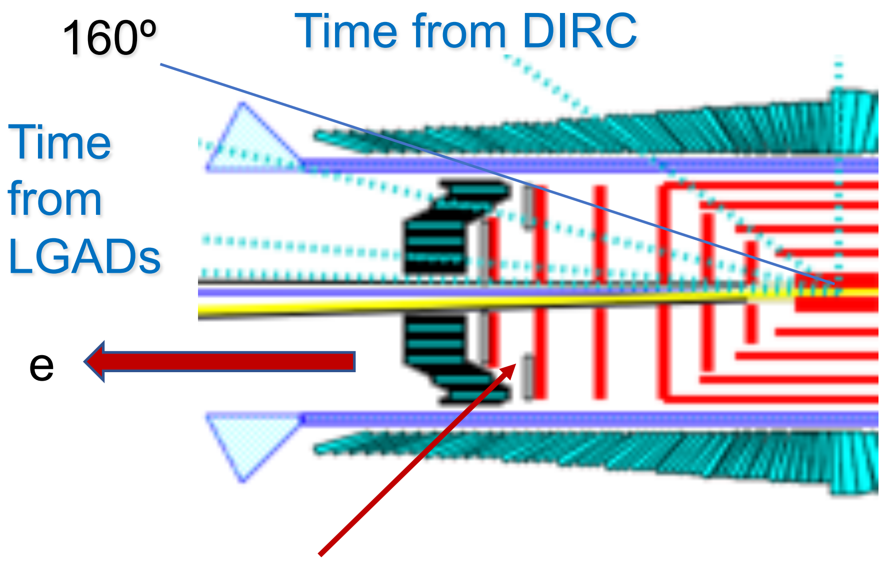


CORE DIRC performance

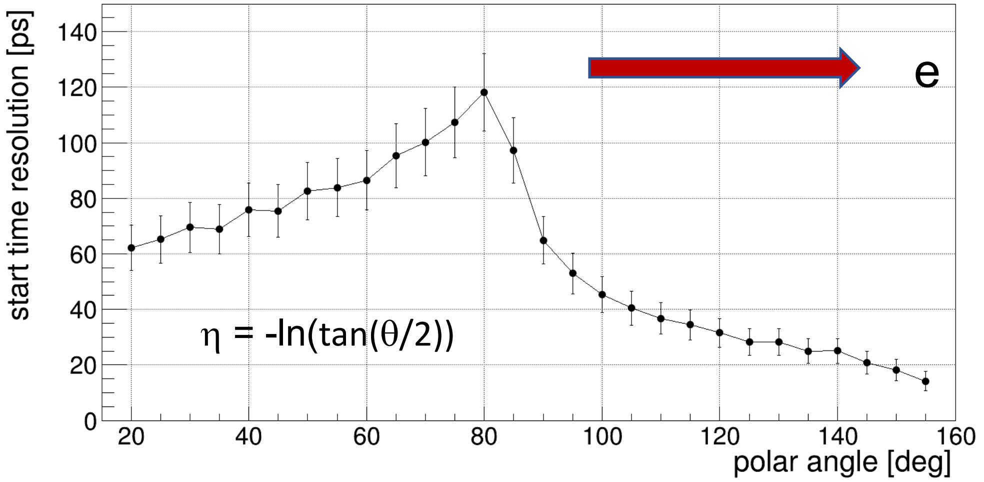


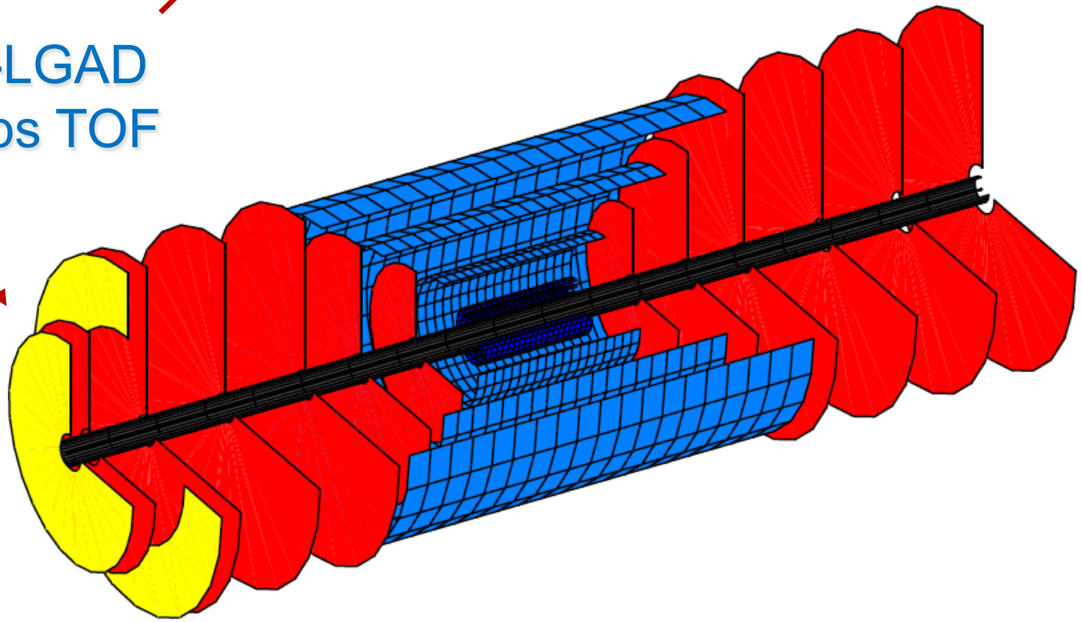
- The baseline choice for CORE is to re-use the (17 mm thick) BaBar DIRC bars
- Geant4 simulations for the CORE configuration show
  a) More than 3σ π/K separation up to 6-7 GeV/c
  b) Good e/π separation (pion suppression factor) around 1 GeV/c, where it is most important

Time measurement in the electron endcap and barrel



DIRC time resolution





- The combination of the AC-LGAD in the electron endcap and DIRC in the barrel provide a high-resolution time measurement in the electron hemisphere
  - electrons are always above the Cherenkov threshold in the DIRC

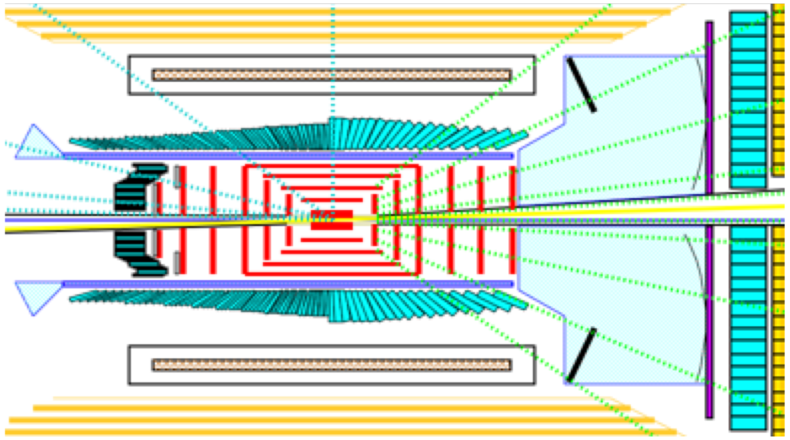
TOF - determination of t_0

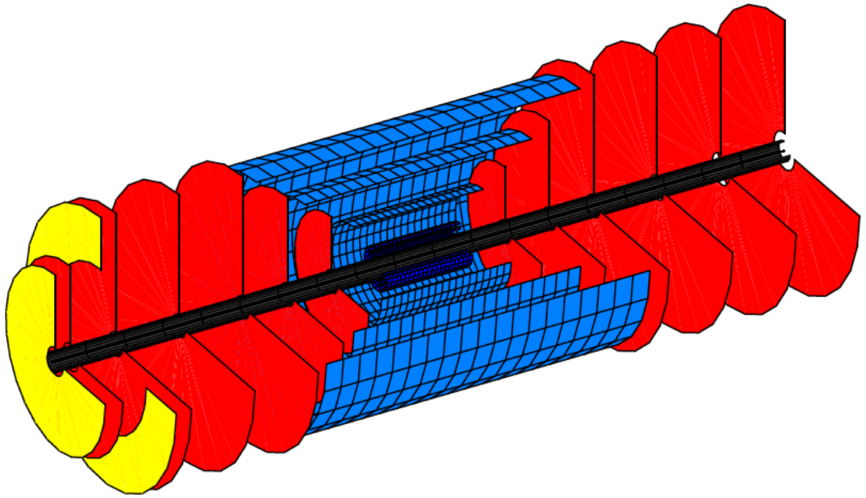
- A well-established method for t_0 determination is to measure the arrival time of an identified electron, which is a β=1 particle.

- The path length traveled by the electron is determined using the tracker. Knowing the time of arrival, β, and the path length, one can calculate the start time at the vertex (t_0).

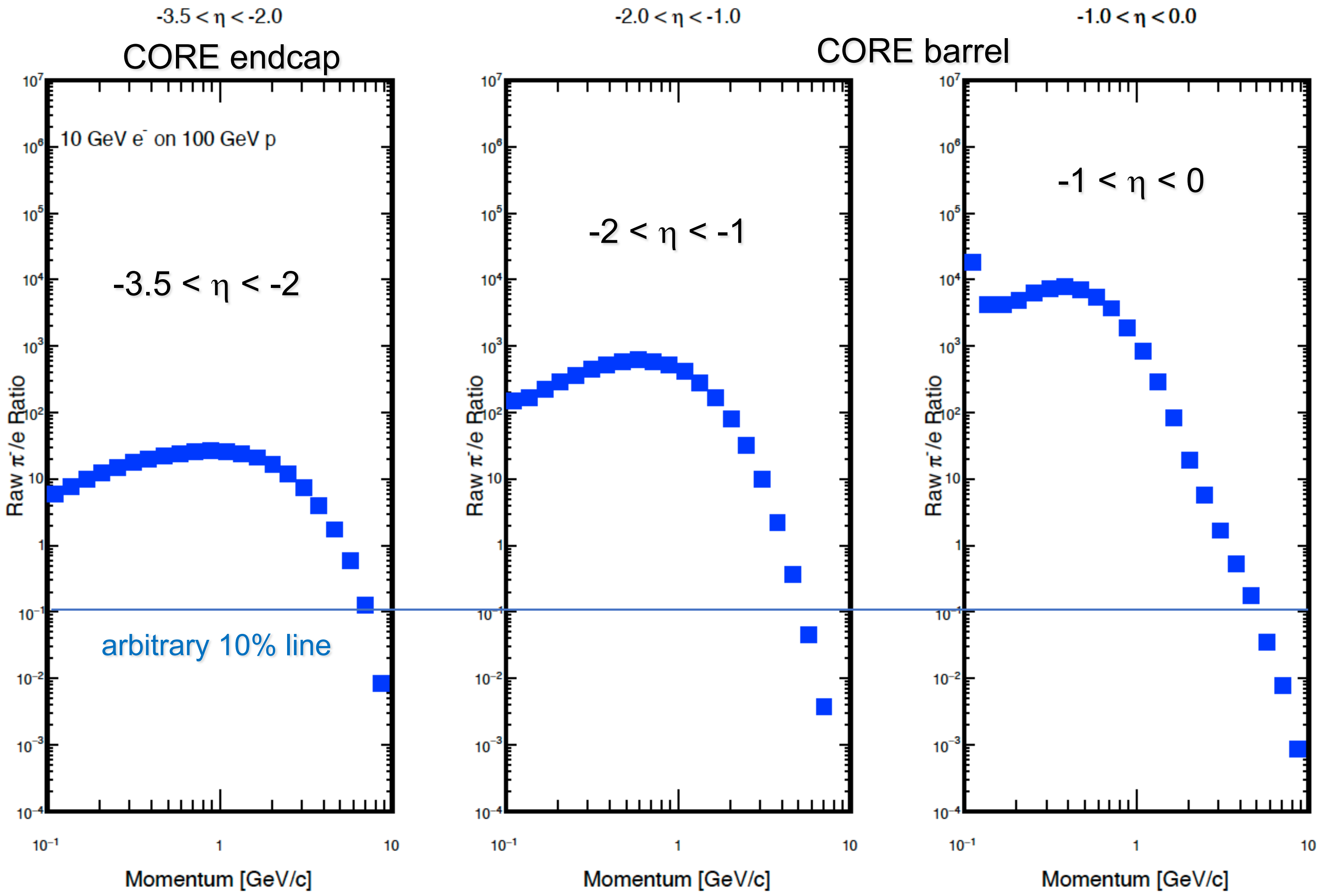
- The time of arrival at the LGAD TOF detector, the t_0, the path length, and the momentum, can then be used to identify the hadron (β vs p).

- This "electron" method was used successfully for over a decade in the CLAS detector, and is also employed for the upgraded CLAS12.



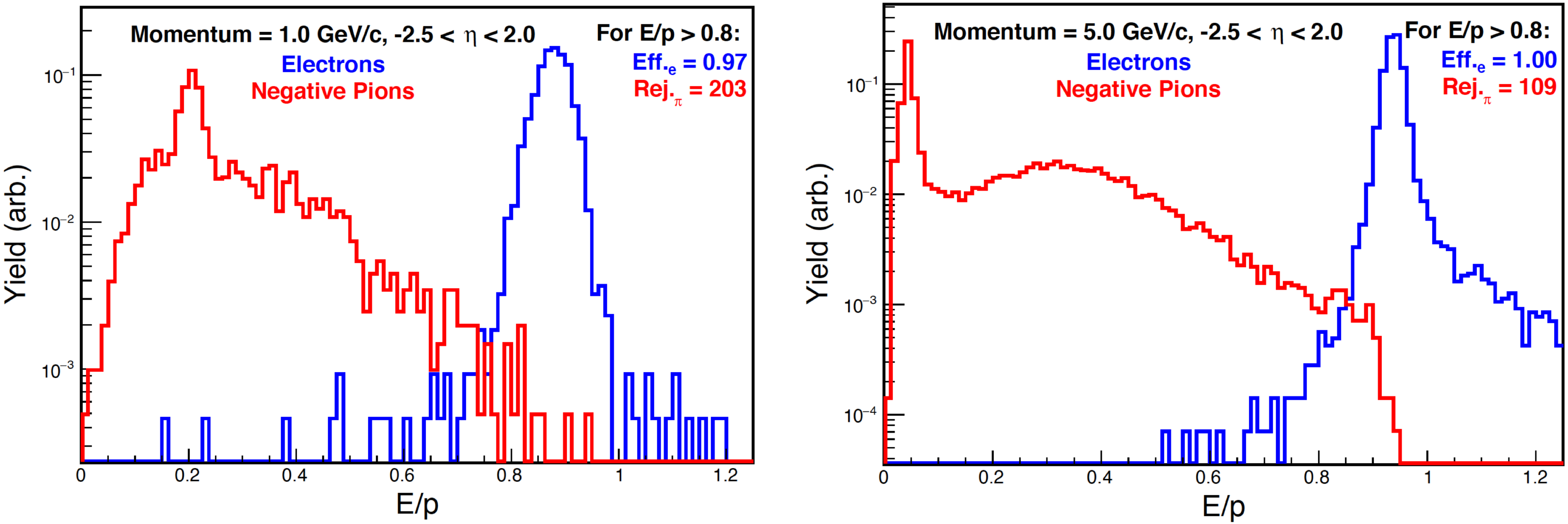


Electron ID - pion backgrounds (π/e ratios) for the scattered electron



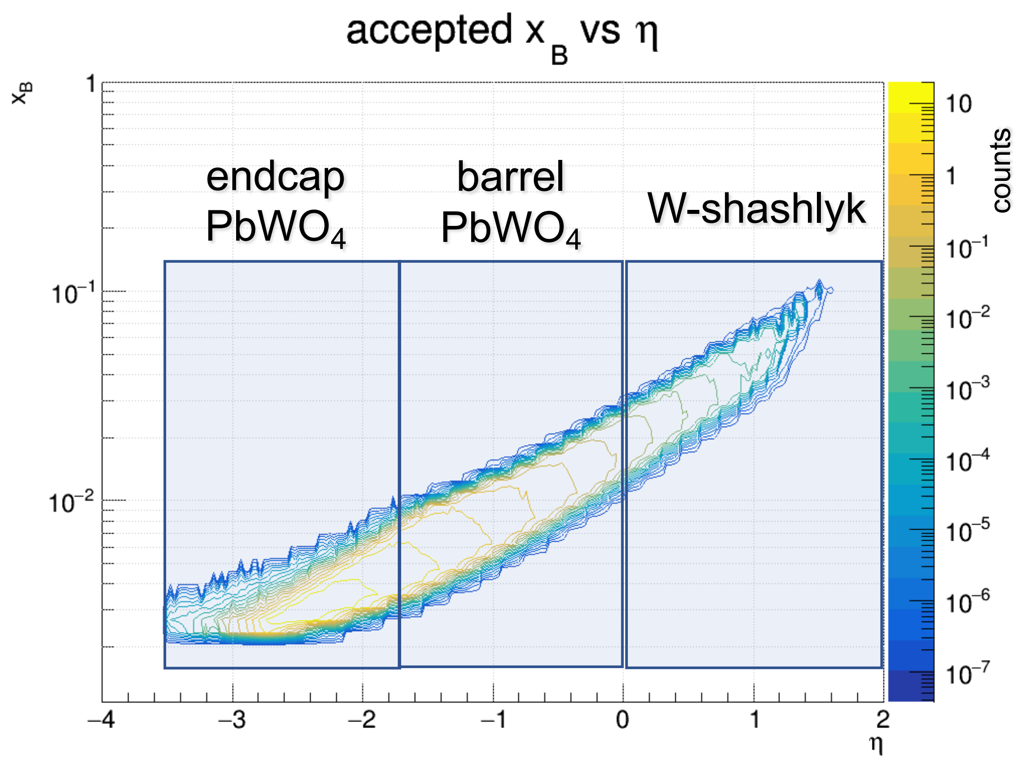
- A clean identification of the scattered electron is essential for the EIC.
- The π/e ratios get worse at larger (less negative) η.
  - The barrel region is the most challenging.
- The best EMcal for e/π ID is $PbWO_4$, which in CORE covers the full $\eta < 0$ range.
- The DIRC provides additional e/π suppression around 1 GeV/c

Electron ID - suppression pion backgrounds using a $PbWO_4$ EMcal

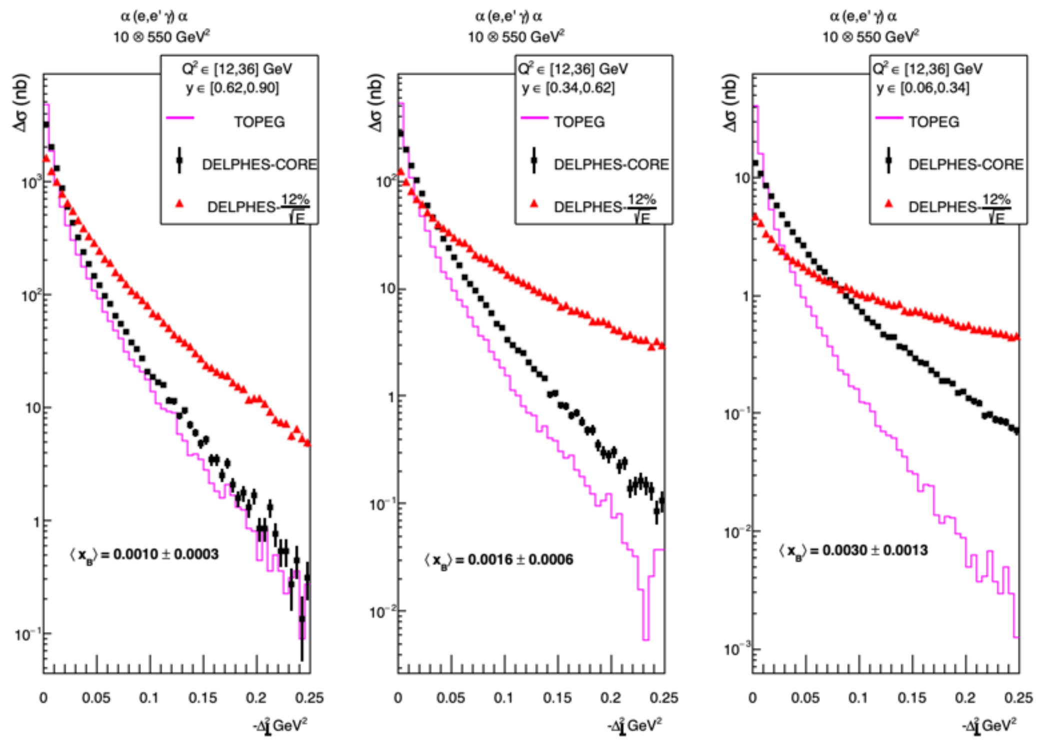


- A high-resolution $PbWO_4$ EMcal offers good pion suppression and a high detection efficiency
  - E is measured by the $PbWO_4$ and p by the si-tracker
- In combination with kinematic constraints (an order of magnitude suppression) and a DIRC in the barrel (possibly with thin bars), the $PbWO_4$ provides CORE with high-purity electron ID.

DVCS photon detection using $PbWO_4$ - coverage and impact

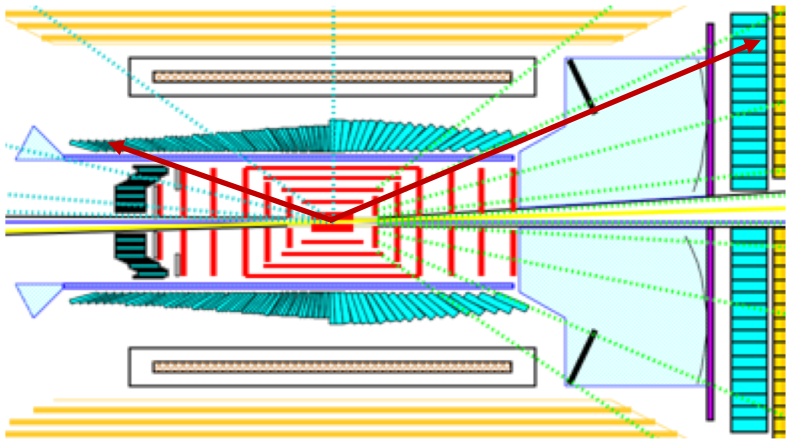


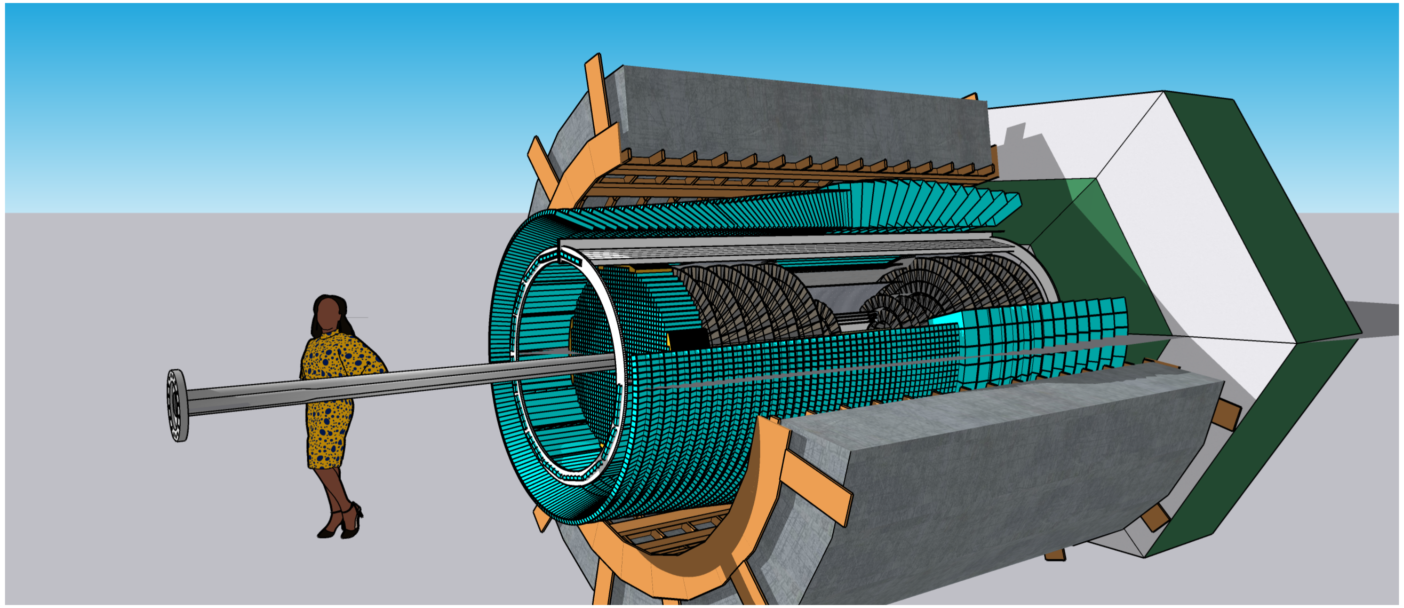
10 GeV e x 137.5 GeV/A ^{4}He



- A high-resolution $PbWO_4$ EMcal is essential for reconstruction of DVCS kinematics from the electron and photon, which is necessary for measurements on nuclei.
- For protons, which are easier to detect in the Roman pots than nuclei are, this method will provide an important cross-check since it does not rely on the unfolding of hadron beam effects

4π EM calorimetry





Electron hemisphere ($\eta < 0$)

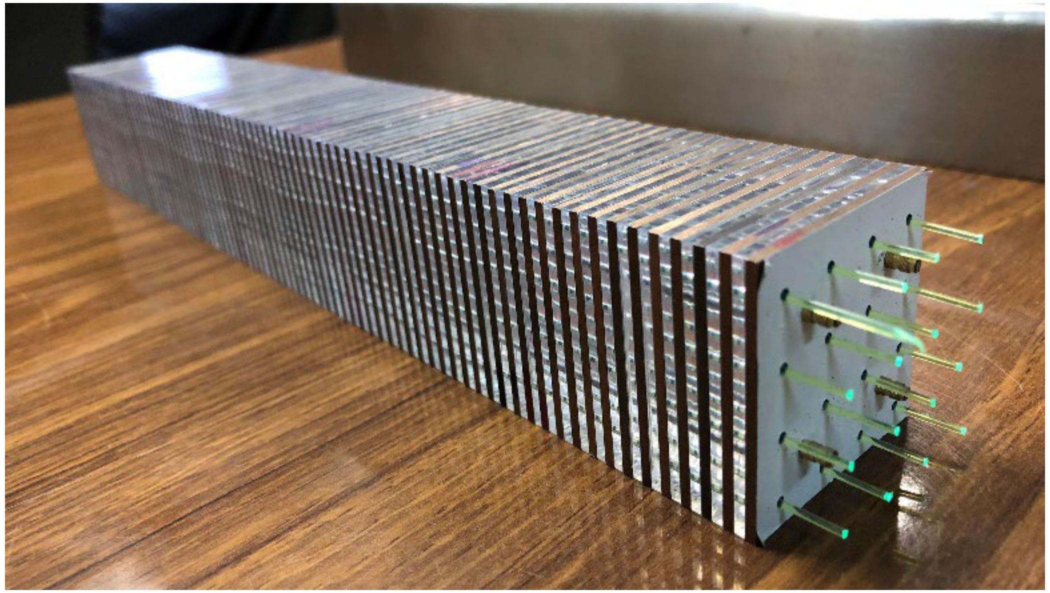
- $PbWO_4$ (2% $E^{-1/2}$ + 1%): 2x2x20 cm^3 temperature-controlled crystals (22 X_0, 1 λ_{int})
  - electron endcap: non-projective
  - backward part of the barrel: projective
- The endcap EMcal is small (0.6 m^2) and light. It can be cantilevered from behind to reduce supports, improving hermeticity

Hadron hemisphere ($\eta > 0$)

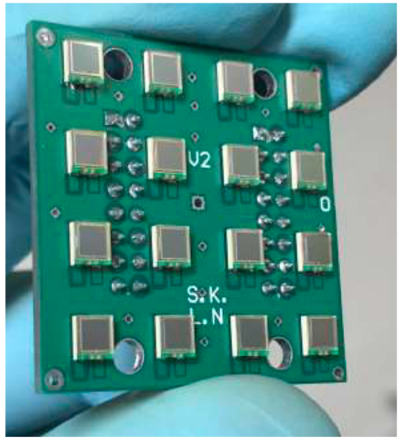
- W-Shashlyk (6% $E^{-1/2}$ + 2%): 12x12 cm^2 modules
  - hadron endcap: 20 X_0 non-projective
  - forward part of the barrel: 25 X_0 projective
- Excellent position resolution (γ/π^0 at high energy)
- The barrel-endcap transition minimizes partial showers in the edge of the barrel

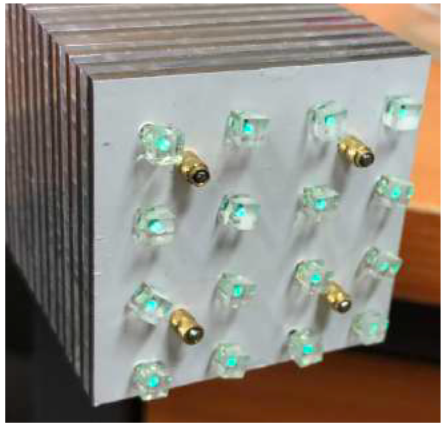
W-shashlyk EMcal

- The CORE W-shashlyk has interleaved layers of:
  - 1.25 mm W/Cu alloy (80% / 20%)
  - 2 mm scintillator
- The readout is done by WLS fibers 14 mm apart, each attached to a small SiPM.
  - The area of each CORE module is 12x12 cm^2
- Both projective and non-projective modules can be made.
- Drilling holes in W/Cu plates is more demanding (but more environmentally friendly) than drilling in Pb. A company like Uniplast LLC can do it quickly and affordably.
  - The Uniplast quote is for fully assembled modules

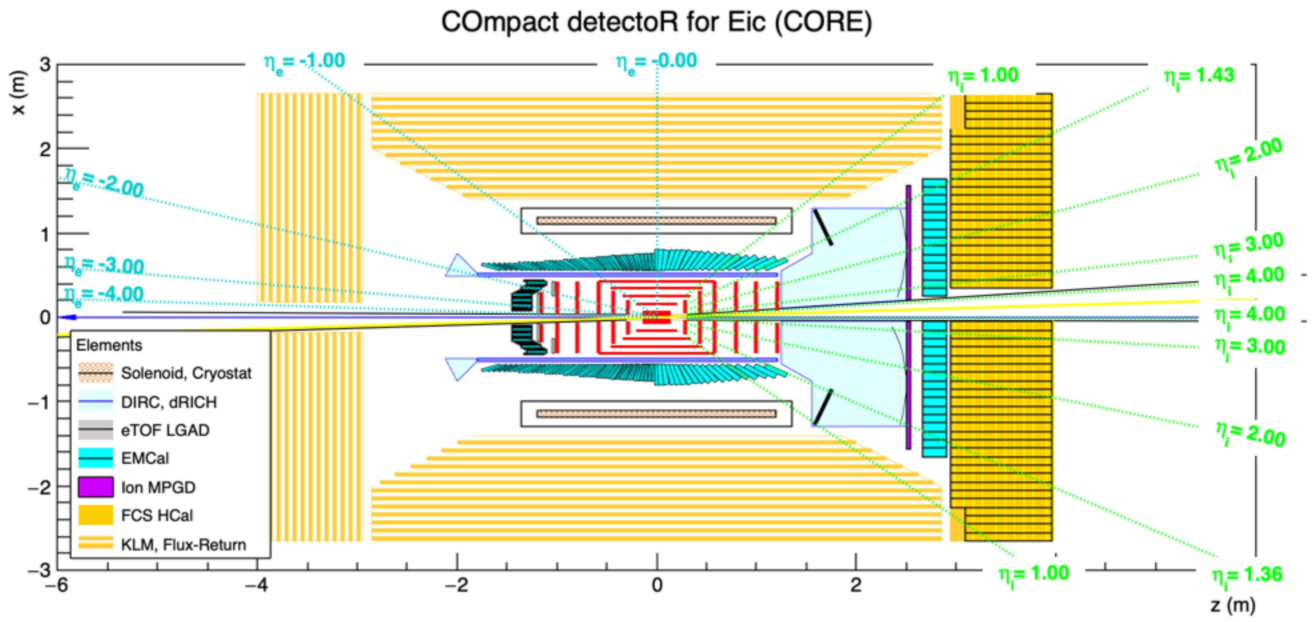


W-shashlyk module (not made for CORE, but illustrating some of the key features)

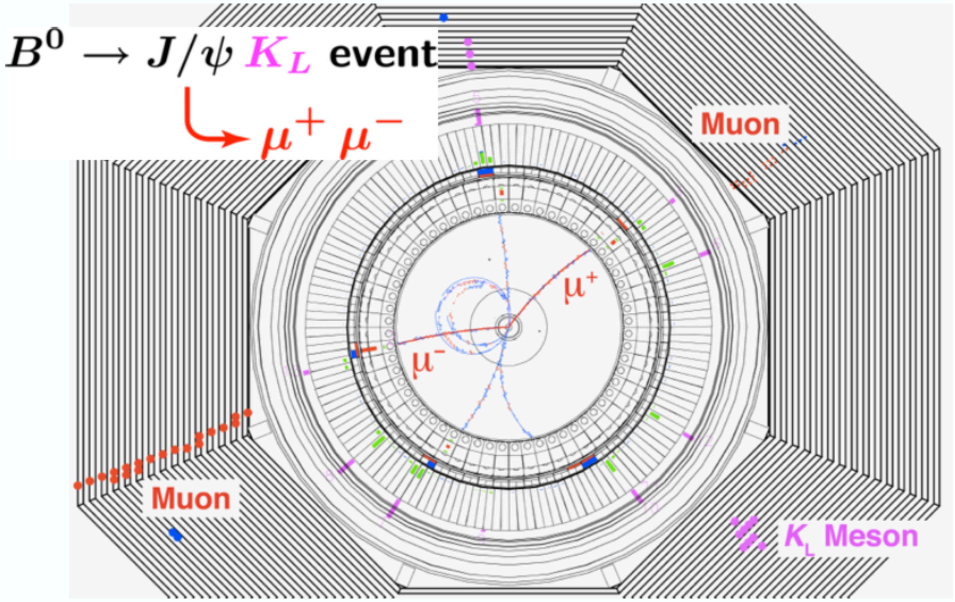




Hadronic calorimetry and muon ID



The Belle II K_L-μ (KLM) system



- At the EIC, jets are generally best reconstructed from individual particles (tracking, EMcal, PID)
- The exception are large-rapidity jets, since momenta in the hadron going direction are large and the tracking resolution starts to deteriorate in the $2.5 < \eta < 3.5$ range.
  - For $\eta > 1.2$ CORE has a traditional Hcal based on the STAR FCS
  - Important for high-x jets, J-B and DA methods for reconstruction of event kinematics, etc.
- For $\eta < 1.2$, CORE has a neutral hadron and muon ID detector based on the Belle II KLM
  - Layers of orthogonal scintillator readout strips interleaved with the solenoid return steel

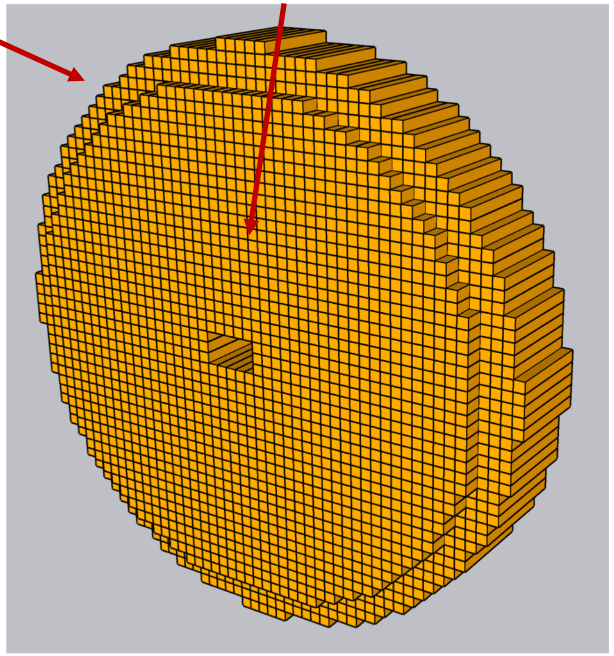
Hcal

- The CORE Hcal is based on the STAR FCS and covers $\eta > 1.2$.
  - The 520 STAR FCS modules are re-used for the outer ring

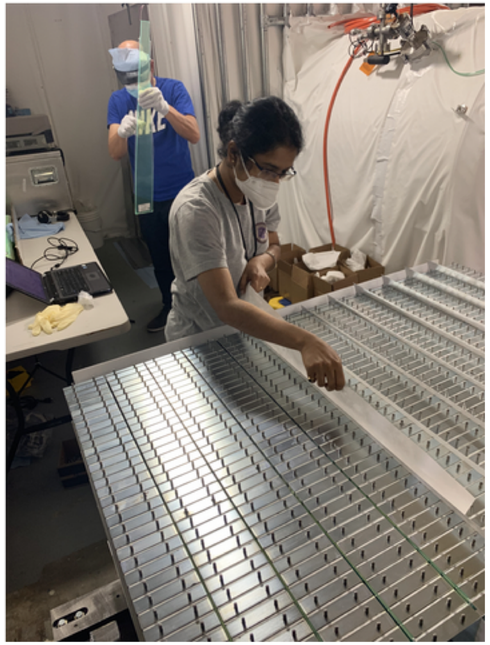
- The non-projective endcap W-shashlyk EMcal is located directly in front of it, but on a separate frame attached to the barrel so that it does not interfere with the sideways motion during disassembly

Outer ring of STAR FCS modules

New modules



The Hcal is divided into two parts that be moved out to the sides.



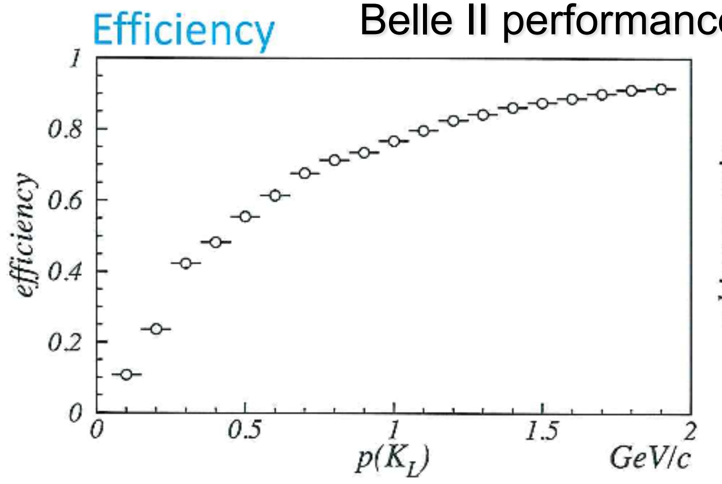
Assembly of STAR FCS modules

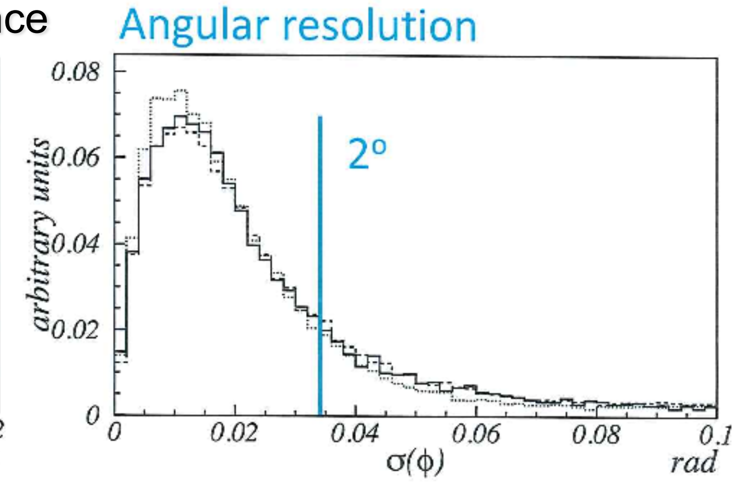
- The original STAR FCS has 36 Fe/Sci layers (20+3 mm), while the new modules will have 44.

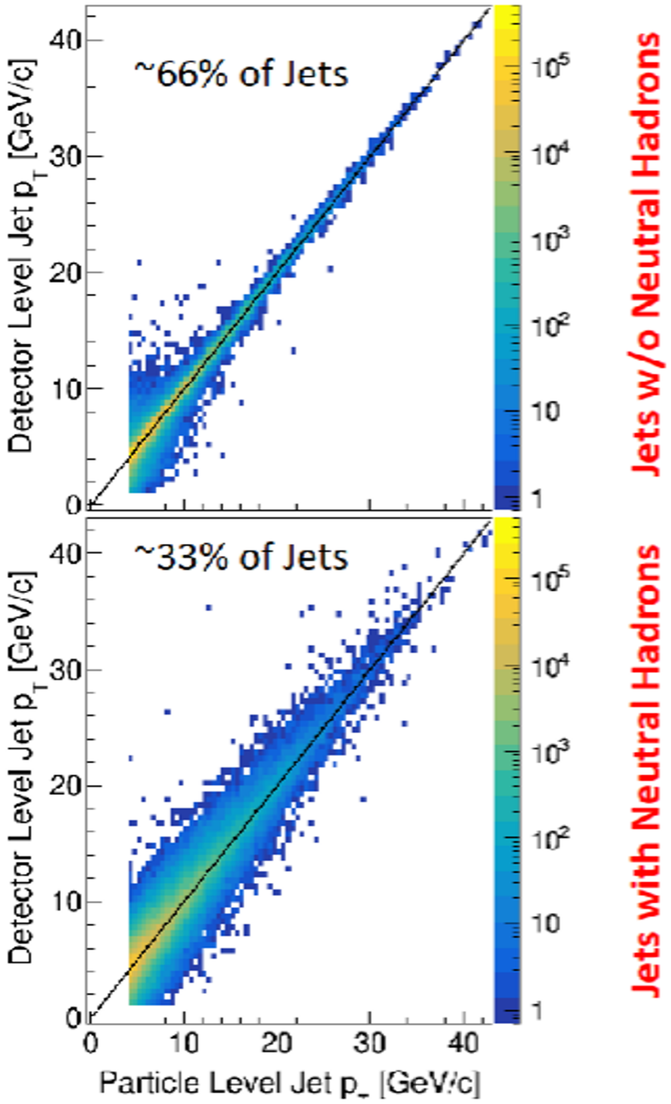
KLM – neutral hadron detection

B.S. Page *et al.*, arXiv.1911.00657
“Jet Physics at a Future EIC“

Belle II performance



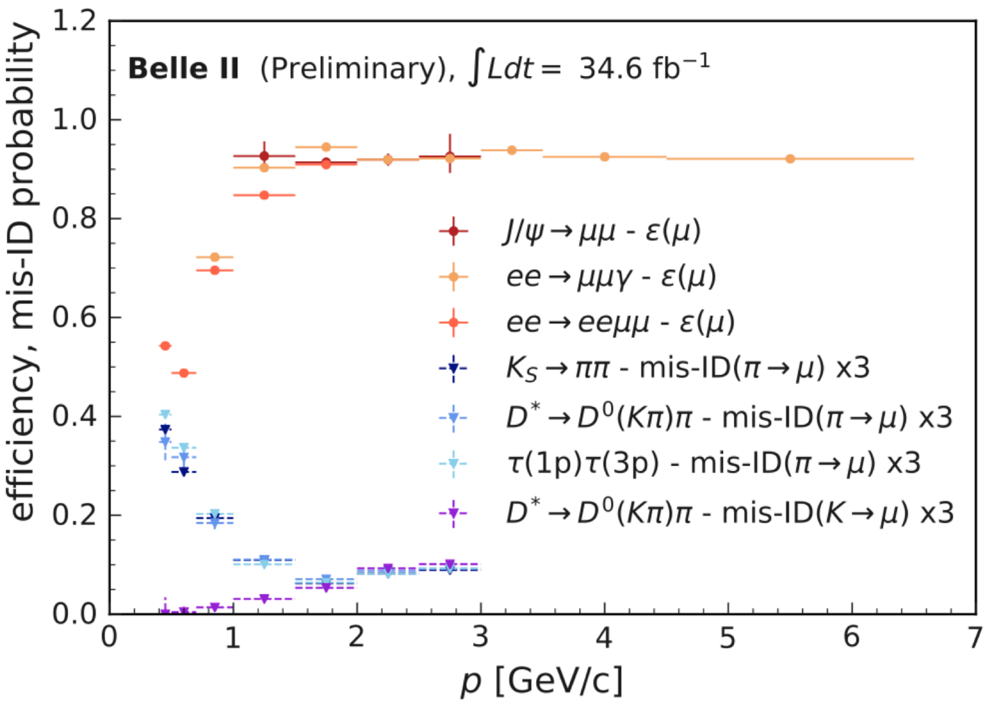


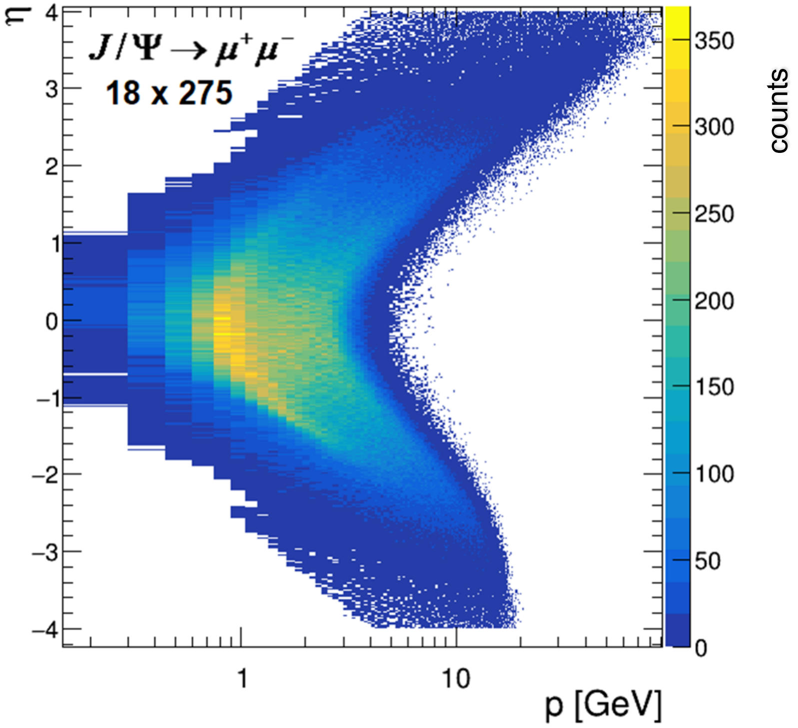


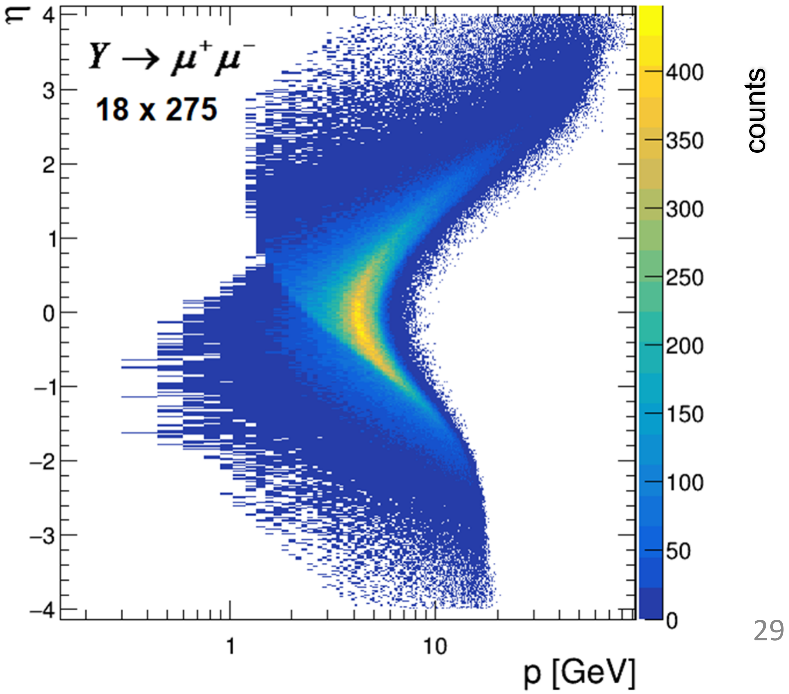
- For $\eta < 1$, jets are best reconstructed from individual particles, but the resolution will be poorer for jets with neutral hadrons
- Since the neutral hadron momenta are generally low, an Hcal measurement of the neutral hadron energy will have a large uncertainty and will not significantly improve the resolution
- The KLM provides a high detection efficiency and good angular resolution, making it possible to determine if there were neutral hadrons within the jet cone.

Note: the figure includes all jets, not just $\eta < 1.2$

KLM – muon ID



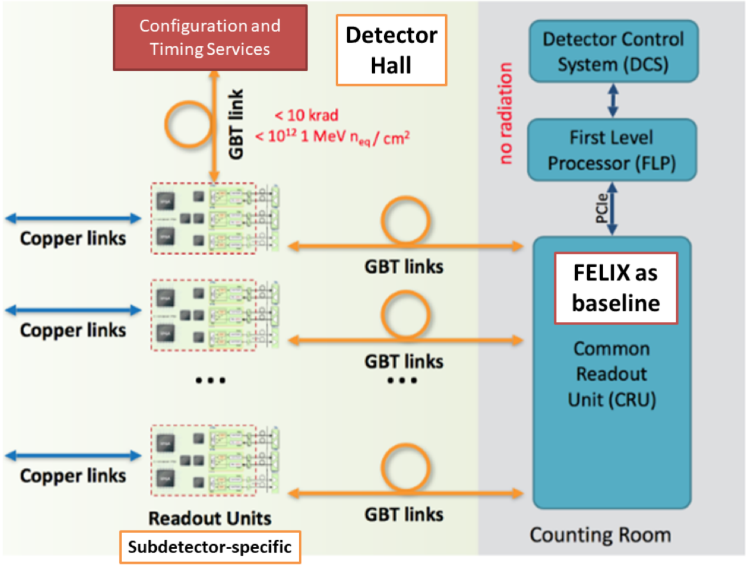




- The performance of the Belle II KLM is indicative of what could be achieved at the EIC
- The KLM coverage is a good match for muon momenta from both J/ψ and Y meson decays in both the barrel and electron endcap

Electronics

Detector Subsystem	Sensor Type	Digitization ASIC/ADC	# of Channels	# of RU	# of FELIX	basis
Si-Tracker	MAPS	ITS3	30 G	~500	12	eRD25
hpDIRC	MCP-PMT	AARDVARC	49 k	~120	4	eRD14, Nalu
Dual RICH	SiPM	ALCOR	65 k	~190	4	eRD14, INFN
TOF (eEndcap)	AC-LGAD	ALTIROC	2 M	~150	8	
EMCal: PBWO4	MAPS	COTS ADC	20 k	~150	2	
EMCal: W-shashlyk	MAPS	COTS ADC	30 k	~150	3	
Ion HCal	MAPS	COTS ADC	50 k	~150	4	eRD1
KLM (mu/Hcal)	SiPM	HDSoC	38 k	~270	7	Belle II, Nalu
Far-FWD/BWD	AC-LGAD	ALTIROC	TBD	TBD	2?	

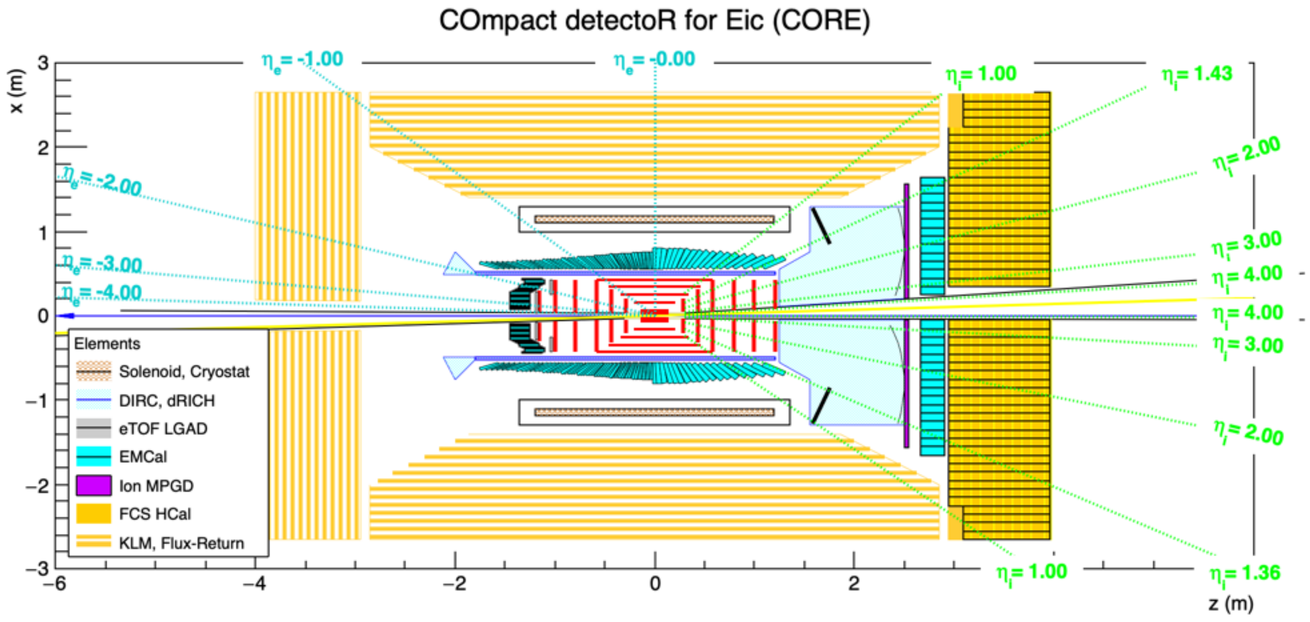


Overview of readout with in-situ digitization and back-end data collection/event building

- Front-end electronics are integrated as close to the detector as feasible, to reduce cabling and associated performance, cost, and space penalties.
- The CORE electronics are well-suited for streaming readout.
- All ASICs are already available or are at an advanced stage of development.

CORE at a glance

- Solenoid: compact 3 T
- Tracking:
  - silicon tracker (10 μm MAPS)
  - forward MPGD (μRWELL)
- Particle Identification:
  - dual-radiator RICH (hadron endcap)
  - high-performance DIRC (barrel)
  - AC-LGAD TOF (electron endcap)

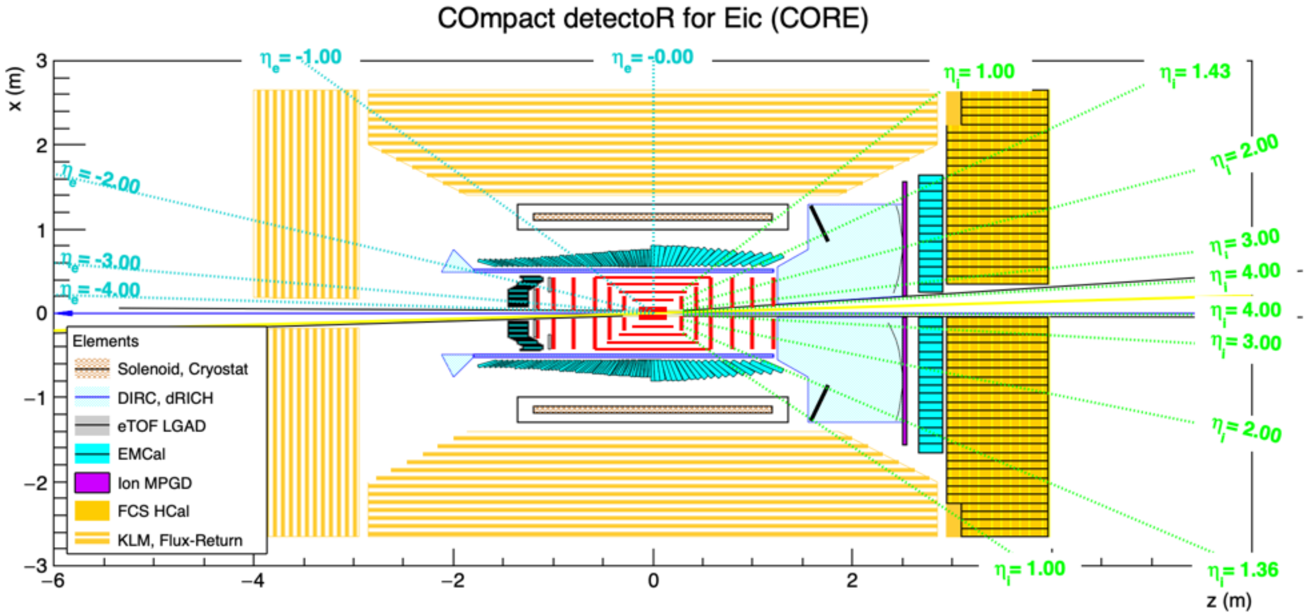


- EM calorimetry:
  - $PbWO_4$ ($\eta < 0$)
  - W-shashlyk ($\eta > 0$)
- Hadronic calorimetry:
  - Fe/Sci Hcal ($\eta > 1.2$)
  - KLM ($\eta < 1.2$)

CORE detector summary

- The interaction region design is consistent with the accelerator design as detailed in the CDR, with some interaction region optimization. The latter includes
  - a shorter detector length to enable a higher luminosity
  - a layout with a secondary focus, which greatly improves the far-forward acceptance and is currently implemented for IR8.
- CORE addresses science goals described in the EIC White Paper (WP), with a particular focus on the Physics Deliverables of the EIC described in section 1.3 of the WP (2014, v3).
  - CORE also extends these goals to the tomography of nuclei, leveraging a key capability of the EIC to accelerate (almost) all nuclei form Deuterium to Uranium.
  - Other new opportunities that would require a second focus include a possibility to study excited states of rare isotopes.
- CORE also addresses the broader science case of the NAS report
- Completion of detector construction can be achieved by CD-4A. The estimated construction schedule is also compatible with achieving detector completion by CD-4 on Detector 2 timeline.

CORE detector summary

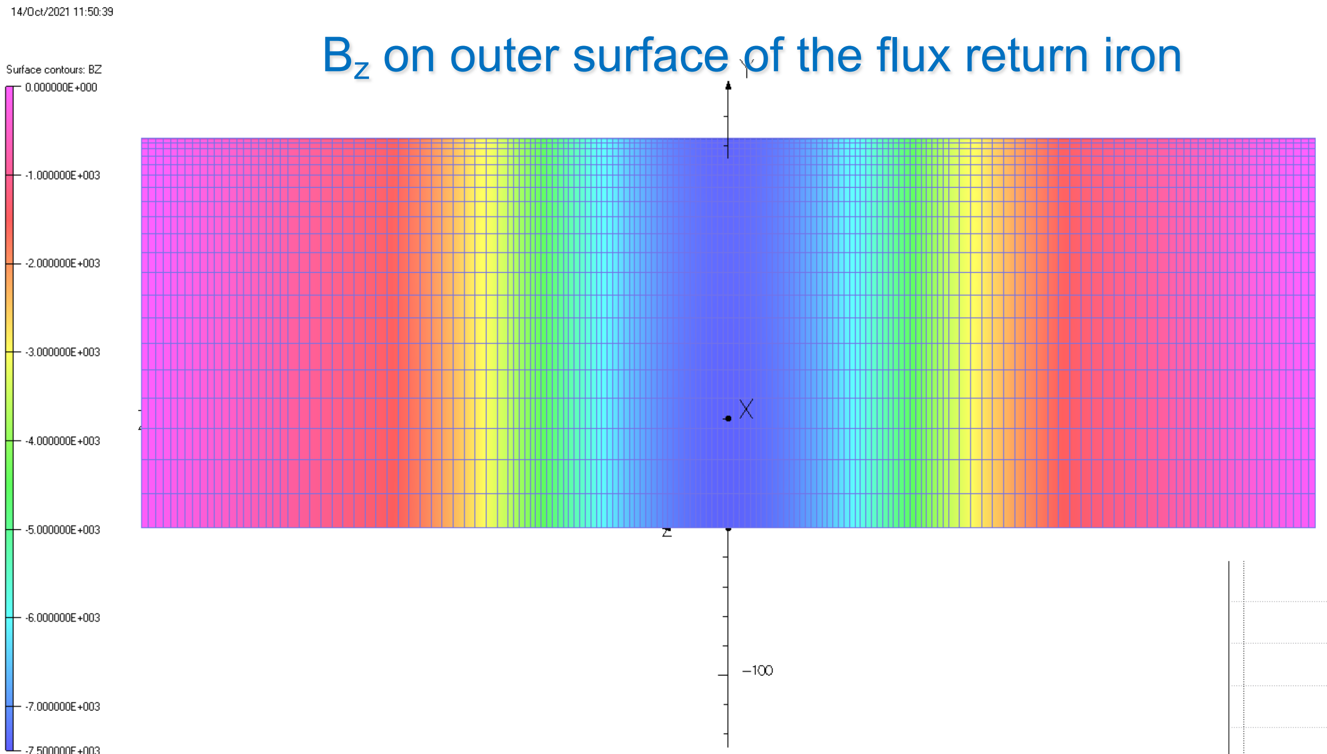


- CORE meets the general performance requirements described in the EIC CDR and the Yellow Report (YR).
- Both CORE and the YR reference detector are hermetic, have a 3 T solenoid and a high-resolution tracker, 4π EM calorimetry and PID, and an Hcal in the hadron endcap.
- CORE has a higher luminosity, higher resolution EM calorimetry, and a neutral hadron and muon detector in the barrel and electron endcap instead of a traditional Hcal. By not including an aerogel detector on the electron side, it has little material in front of the EMcal.
  - CORE is naturally synergetic with an IR with a second focus
- Thus, while the capabilities of CORE meet the general performance requirements outlined in the YR, it is also in many important ways complementary to the “YR detector,” providing additional physics opportunities.

Thank you!

Short 3 T solenoid – B_z

B_z on outer surface of the flux return iron

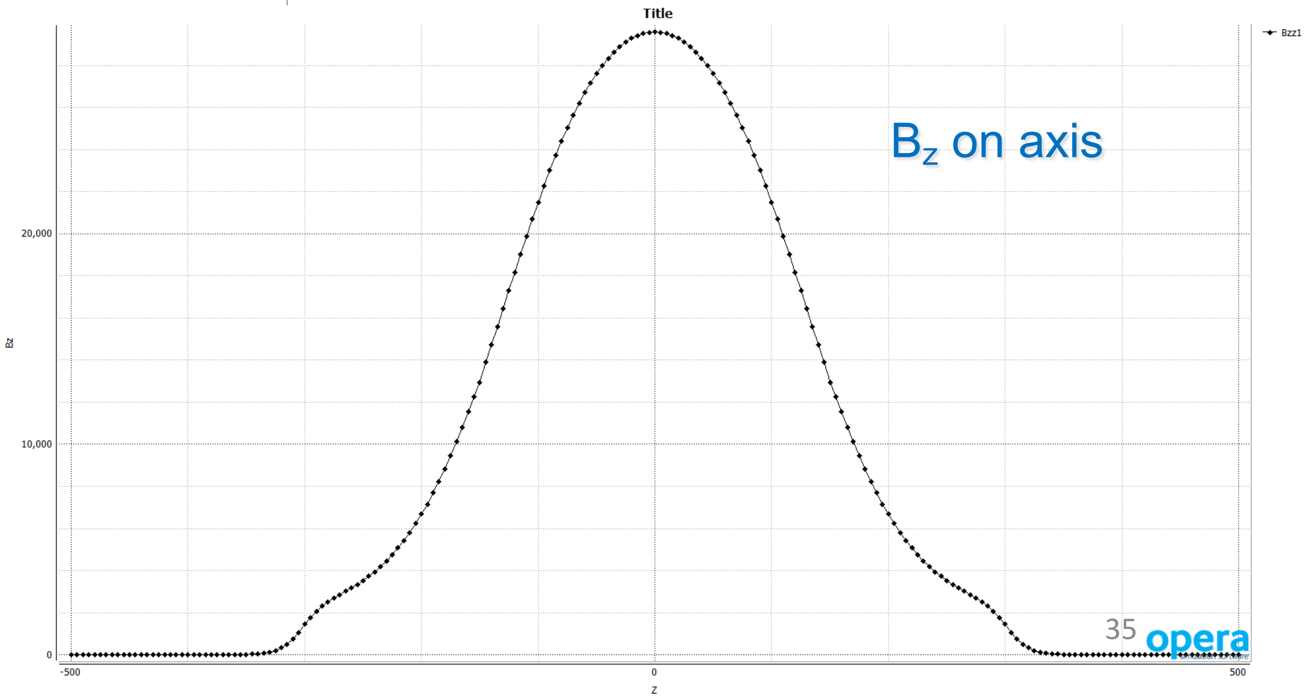


UNITS
Length cm
Magn Flux Density gauss
Magnetic Field oersted
Magn Scalar Pot oersted cm
Current Density A/cm²
Power W
Force N

MODEL DATA
core40.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
784000 elements
826421 nodes
3 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in YZ plane (X field=0)
Reflection in ZX plane (Y field=0)

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Line LINE (nodal) 201 Cartesian
x=0.0 y=0.0 z=-500.0 to 500.0

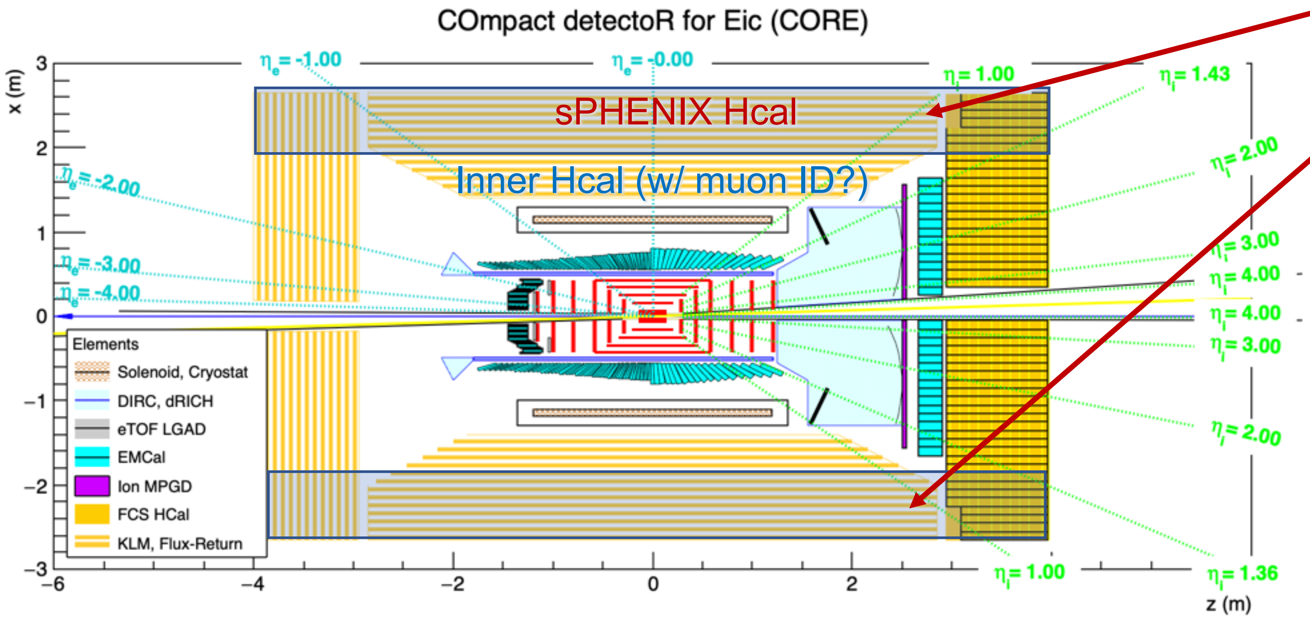


- The short solenoid allows for an efficient transition from a high central field to a low field on the DIRC photosensors and provides a good “projectivity” for the dRICH

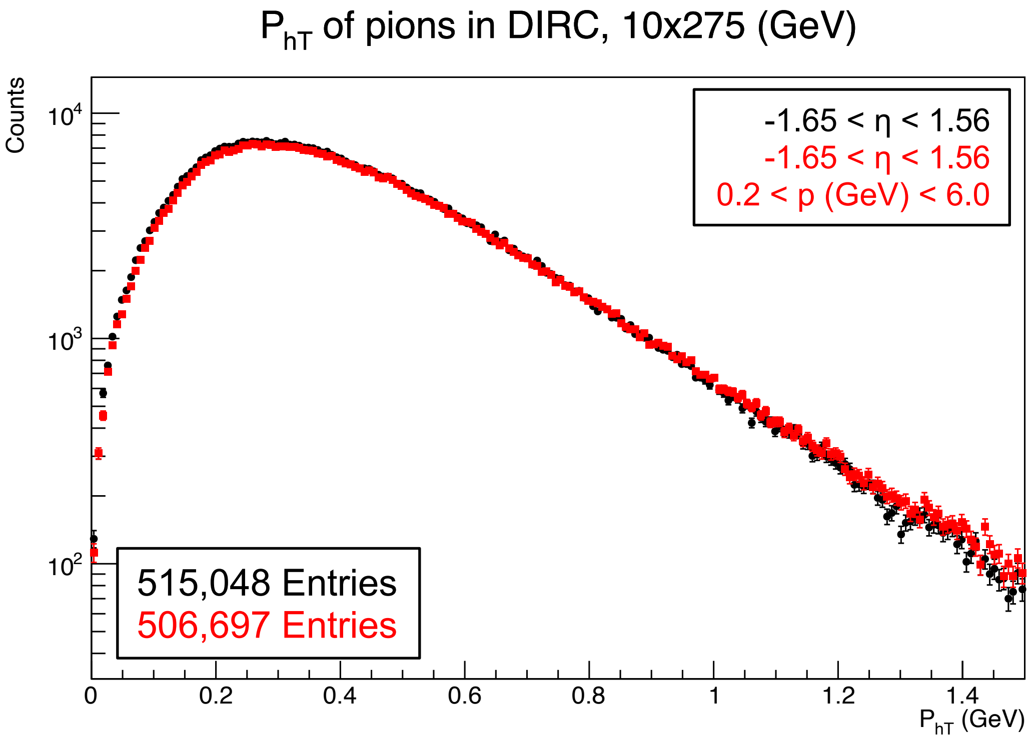
OPTION: re-use of the sPHENIX Hcal

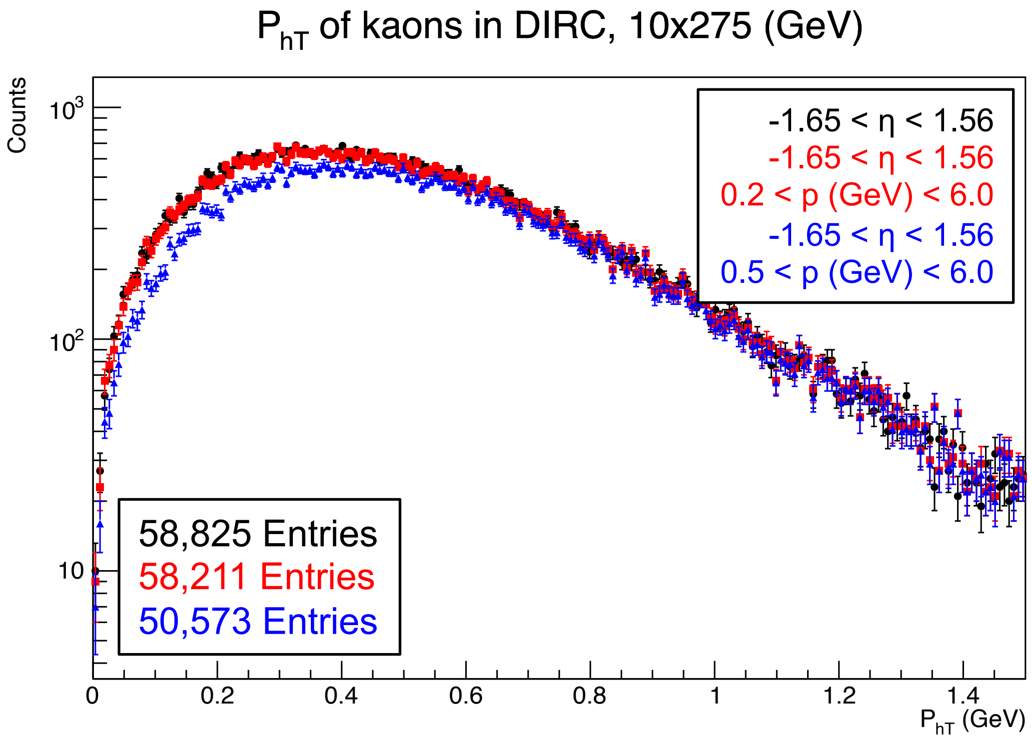
- The sPHENIX Hcal could be used to house the smaller CORE solenoid and its internal detectors
  - It would be accompanied by an inner Hcal.

- This possibility emphasizes that CORE can be seen as a natural upgrade path for sPHENIX.



P_{hT} coverage in the DIRC





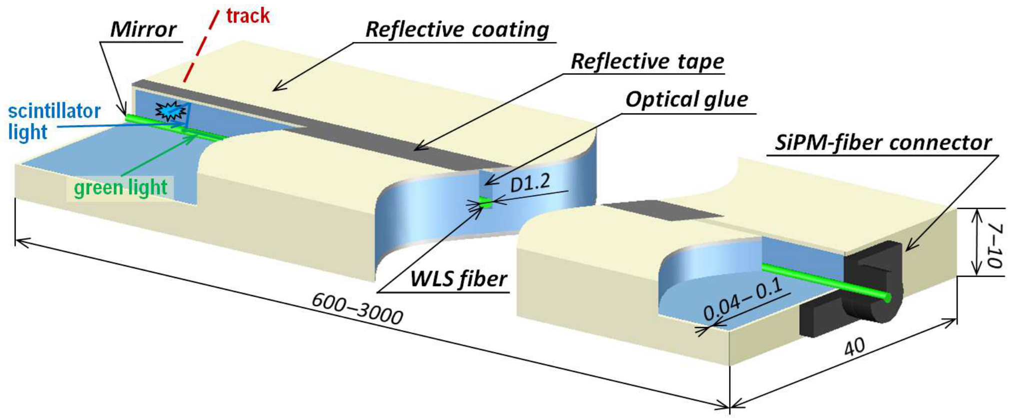
- Kaons in the 0.2-0.5 GeV range give no signal (pions do). The only effect of adding this ”threshold” mode to the kaon distribution is a slight increase in statistics.

The CORE KLM

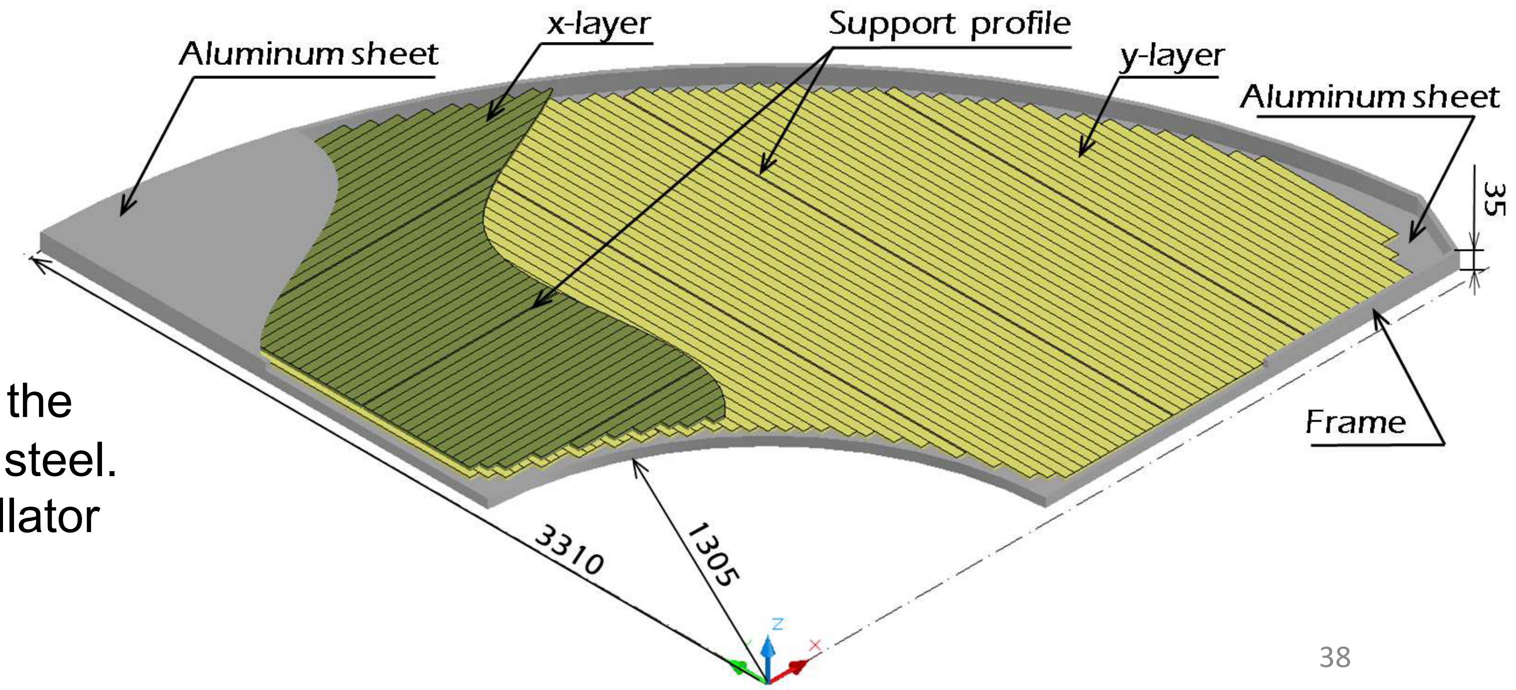
- The CORE KLM is in most respects similar to the one used in Belle II – although further optimizations could be made before initiating construction.

- The main differences is that the 14 scintillator double (x,y) layers in CORE are thinner than in Belle II to increase the average iron fraction of the flux return
    - The Belle spacing was driven by RPCs that are replaced in the various Belle II upgrades

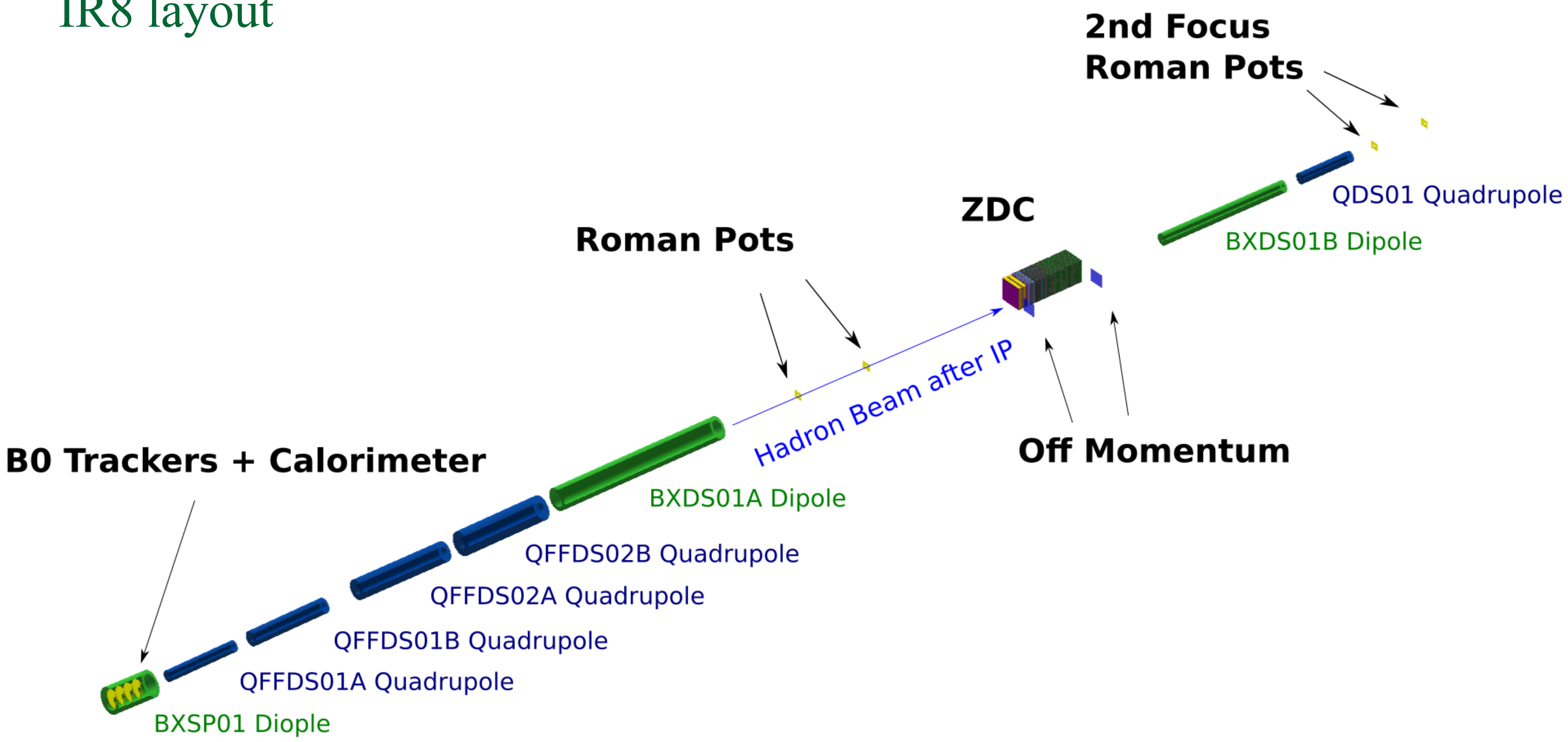
- The CORE KLM is integrated with the cryostat, which is made of Al except for the outer vessel, which is 5 cm of stainless steel. This is directly followed by a KLM scintillator layer.



T. Aushev *et al.* arXiv:1406.3267v3 (2015)



IR8 layout



2nd Focus
Roman Pots
QDS01 Quadrupole
ZDC
BXDS01B Dipole
Roman Pots
Hadron Beam after IP
Off Momentum
B0 Trackers + Calorimeter
BXDS01A Dipole
QFFDS02B Quadrupole
QFFDS02A Quadrupole
QFFDS01B Quadrupole
QFFDS01A Quadrupole
BXSP01 Diople