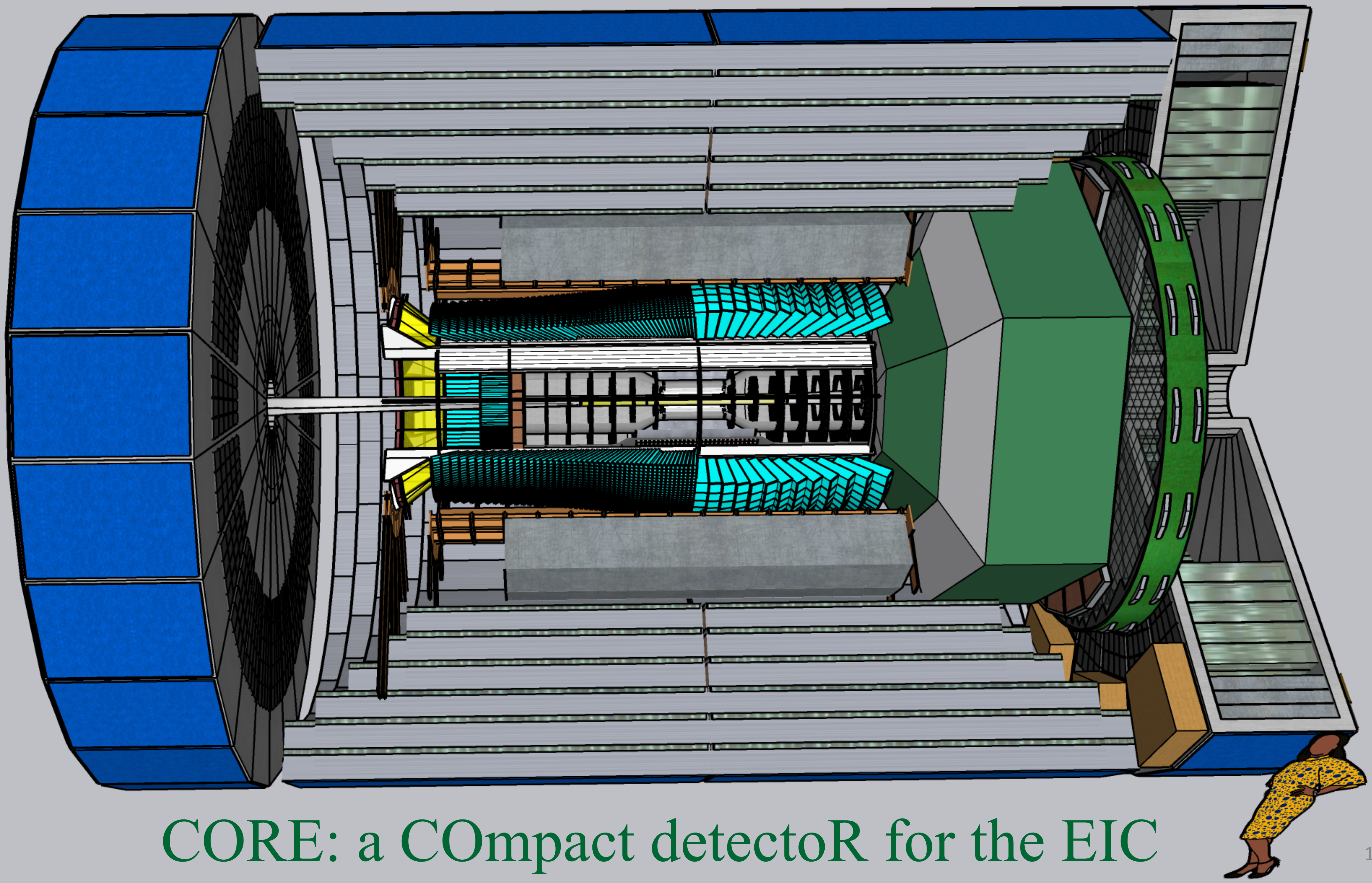


CORE: a COmpact detectoR for the EIC

Why a compact detector?

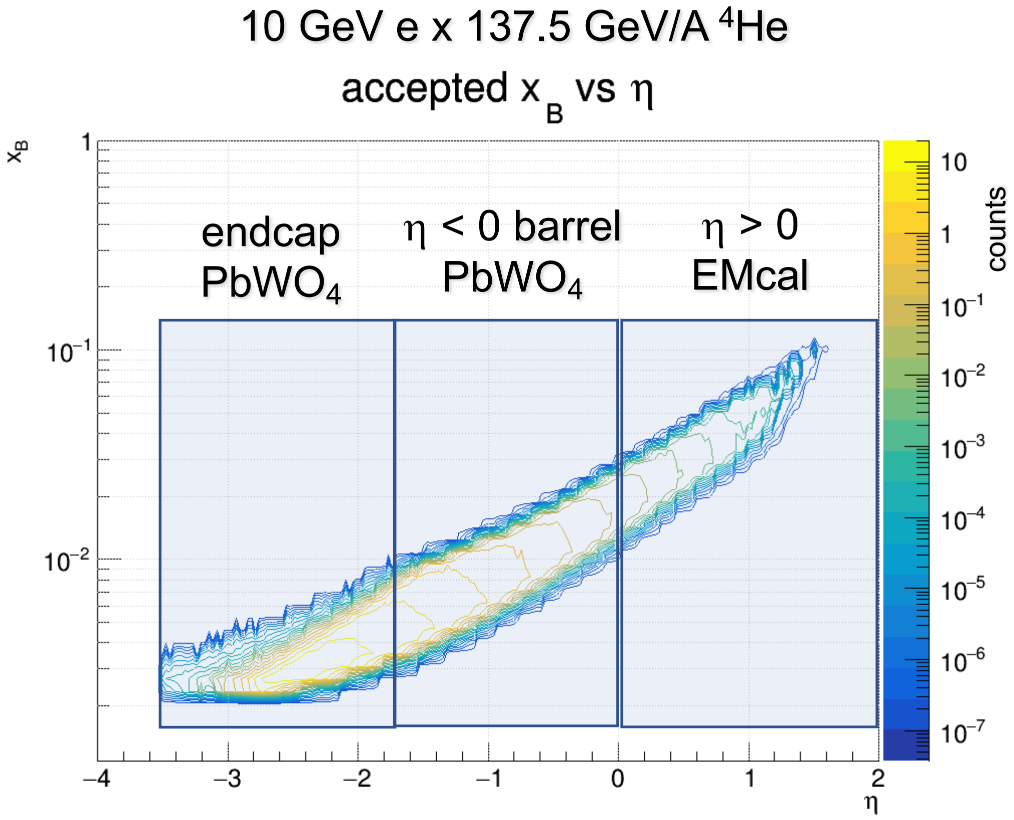
- Lower cost (without compromising any physics capabilities)
  - The performance of many subsystems (DIRC, EMcal, etc) does not depend on the overall system size or location. A compact detector simply has fewer modules, making it more cost-effective.

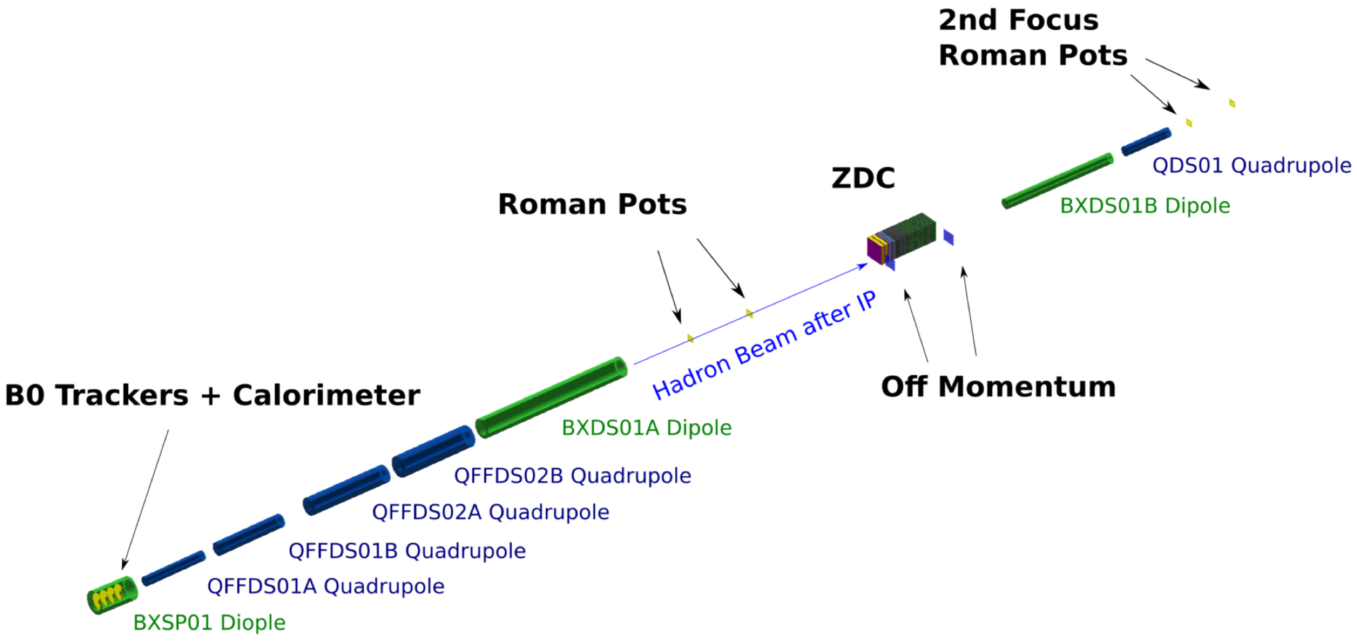
- Lower risk
  - A smaller new solenoid is not only less expensive but has lower technical and schedule risks.
  - A shorter detector is easier to integrate into the IR, as it leaves more space for accelerator infrastructure near the collision point and reduces challenges related to solenoid compensation.

- Synergies with IR8 (and the physics opportunities enabled by a secondary focus)
  - The lower cost equivalent subsystems makes it affordable to invest in key capabilities.
  - An example is a $PbWO_4$ EMcal for eta < 0, which makes it possible to reconstruct DVCS kinematics using the photon, while only tagging the proton or ion (fragments) in the Roman pots. in combination with the low-p_T acceptance with a 2nd focus, creating new opportunities for imaging of ions beyond He.

- Complementarity
  - A compact 3 T solenoid can in combination with an all-Si tracker provide excellent tracking resolution, and is technologically complementary to the hybrid tracker in a 1.5 T BaBar solenoid in Detector 1.

IR8 synergy: DVCS photon detection using $PbWO_4$





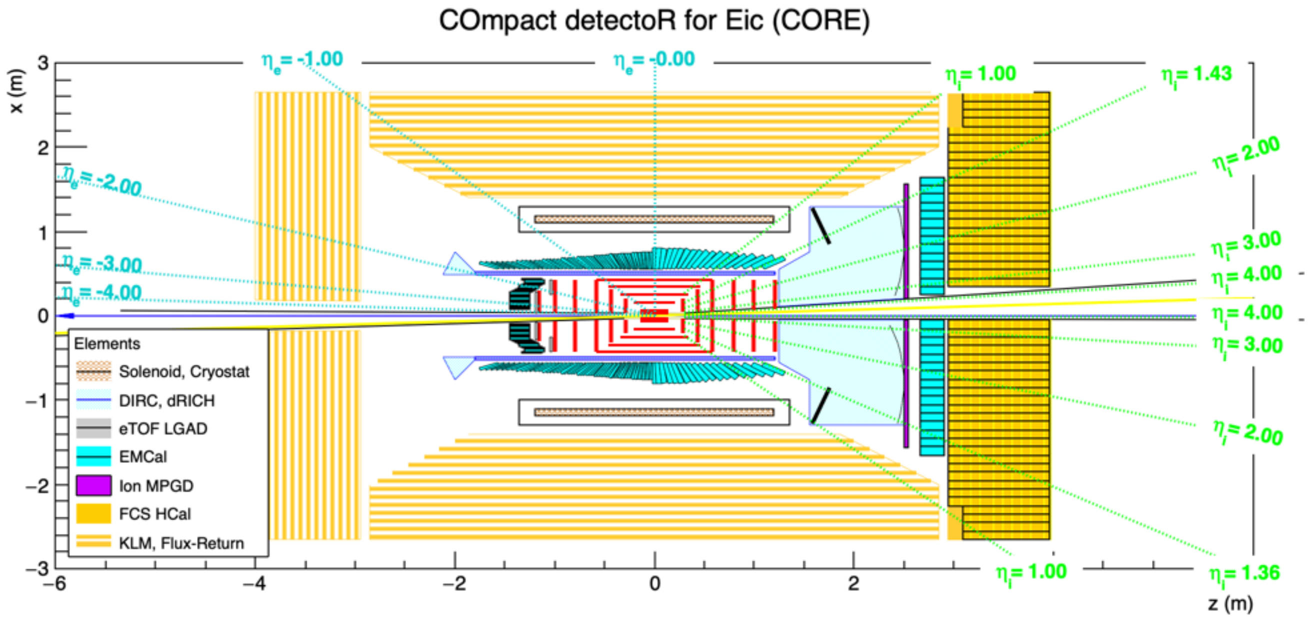
- A high-resolution $PbWO_4$ EMcal allows reconstruction of DVCS kinematics from the electron and photon, which is necessary for measurements on nuclei (tagging and veto of breakup).
- For protons, a 2^{nd} focus improves low-x acceptance, which is also of interest for di-lepton production (charmonium, TCS, and maybe double DVCS), for which muon ID is important.

CORE at a glance (systems of particular relevance for HF in red)

- Solenoid: compact 3 T

- Tracking:
  - silicon tracker (10 μm MAPS)
  - forward MPGD (μRWELL or GEM)

- Particle Identification:
  - dual-radiator RICH (hadron endcap)
  - high-performance DIRC (barrel)
  - AC-LGAD TOF (electron endcap)



- EM calorimetry:
  - $PbWO_4$ ($\eta < 0$)
  - W-shashlyk or equivalent ($\eta > 0$)

- Hadronic calorimetry:
  - Fe/Sci Hcal ($\eta > 1.2$)
  - KLM ($\eta < 1.2$)

CORE – overview

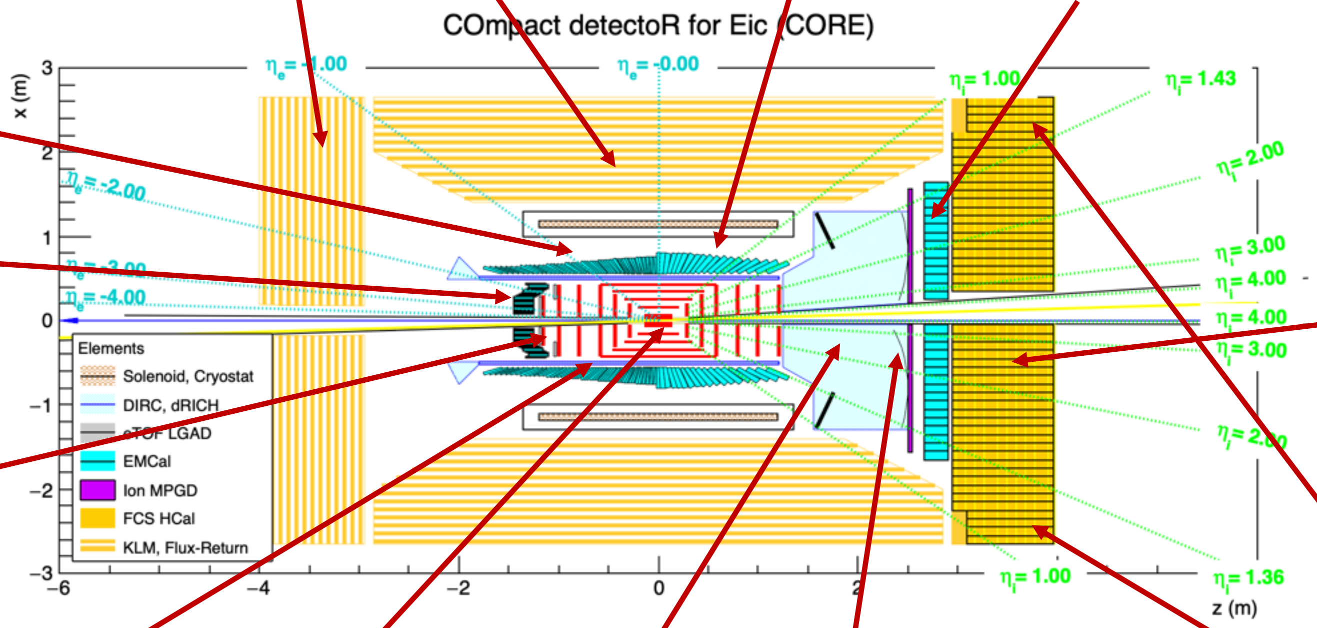
Neutral hadron and muon ID detector (KLM)

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

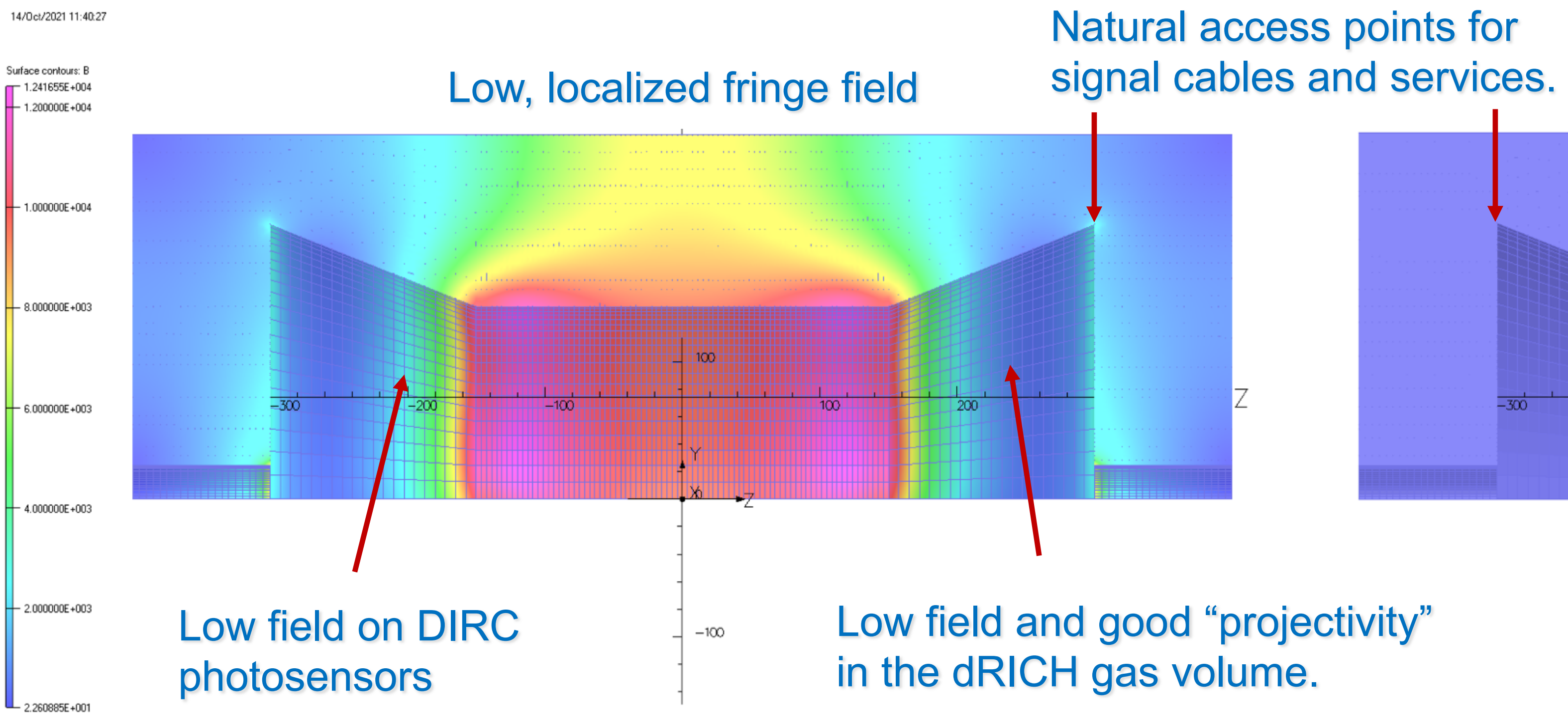
MPGD tracker

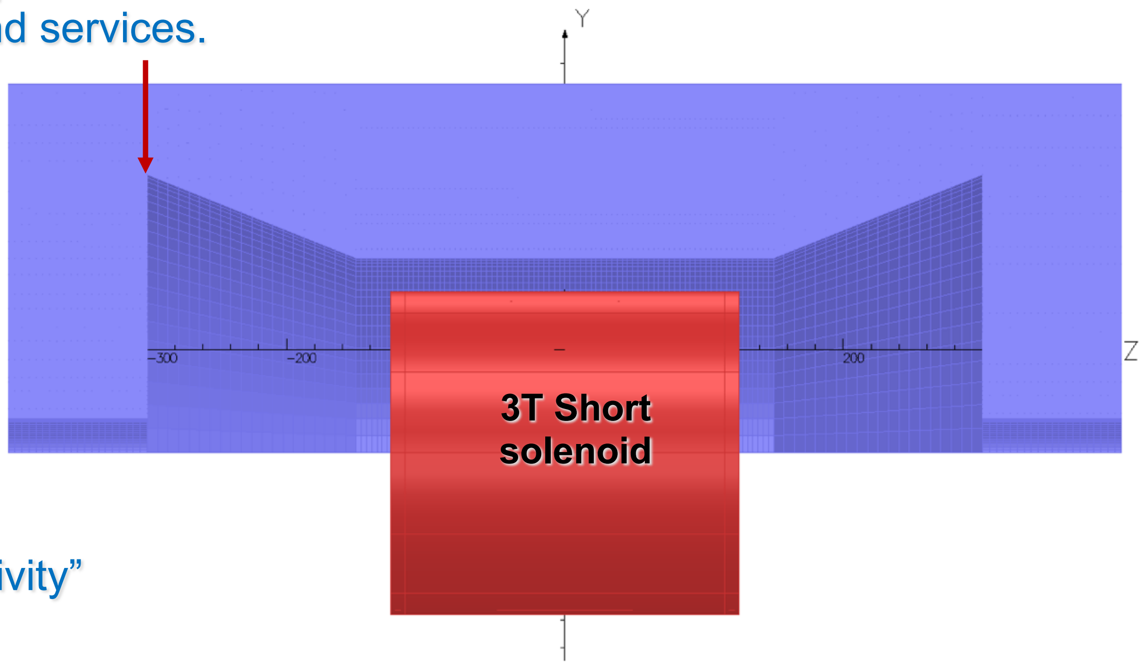
DIRC

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

Dual-radiator RICH

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)

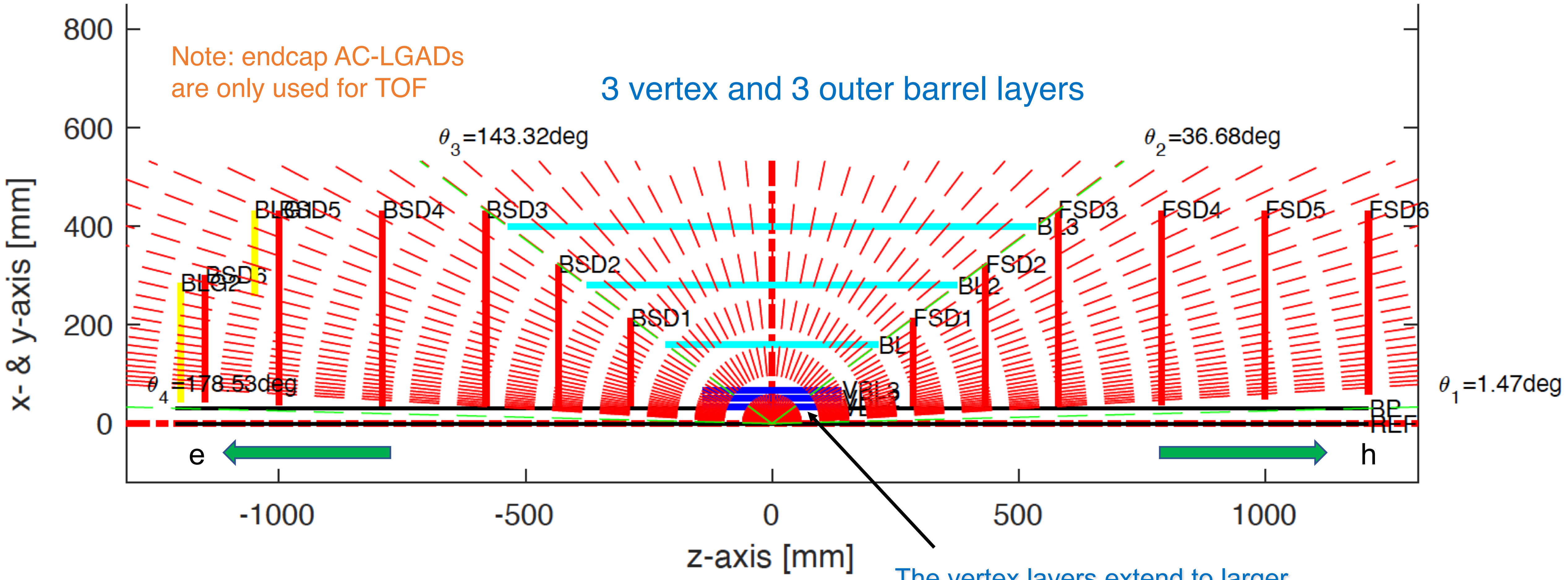
- Max field: 3 T @ 4,700 A/cm^2
- Coil length: 2.5 m
- Inner radius: 1 m
- Stored energy: 38.8 MJ

CORE all-Si tracker (based on eRD25)

ITS3 technology: MAPS (10 μm pixels)

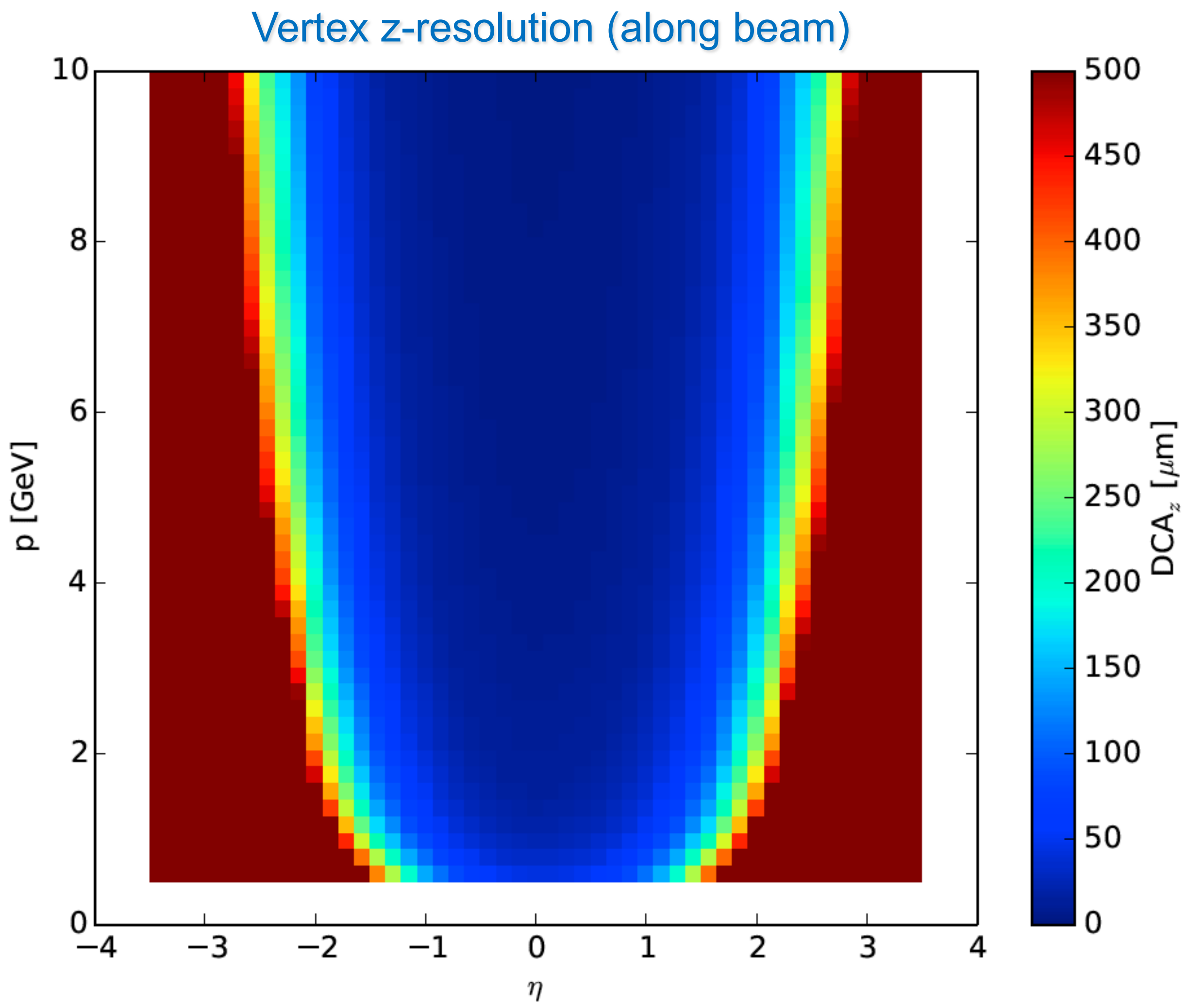
Layout: symmetric except for the last MAPS on each side

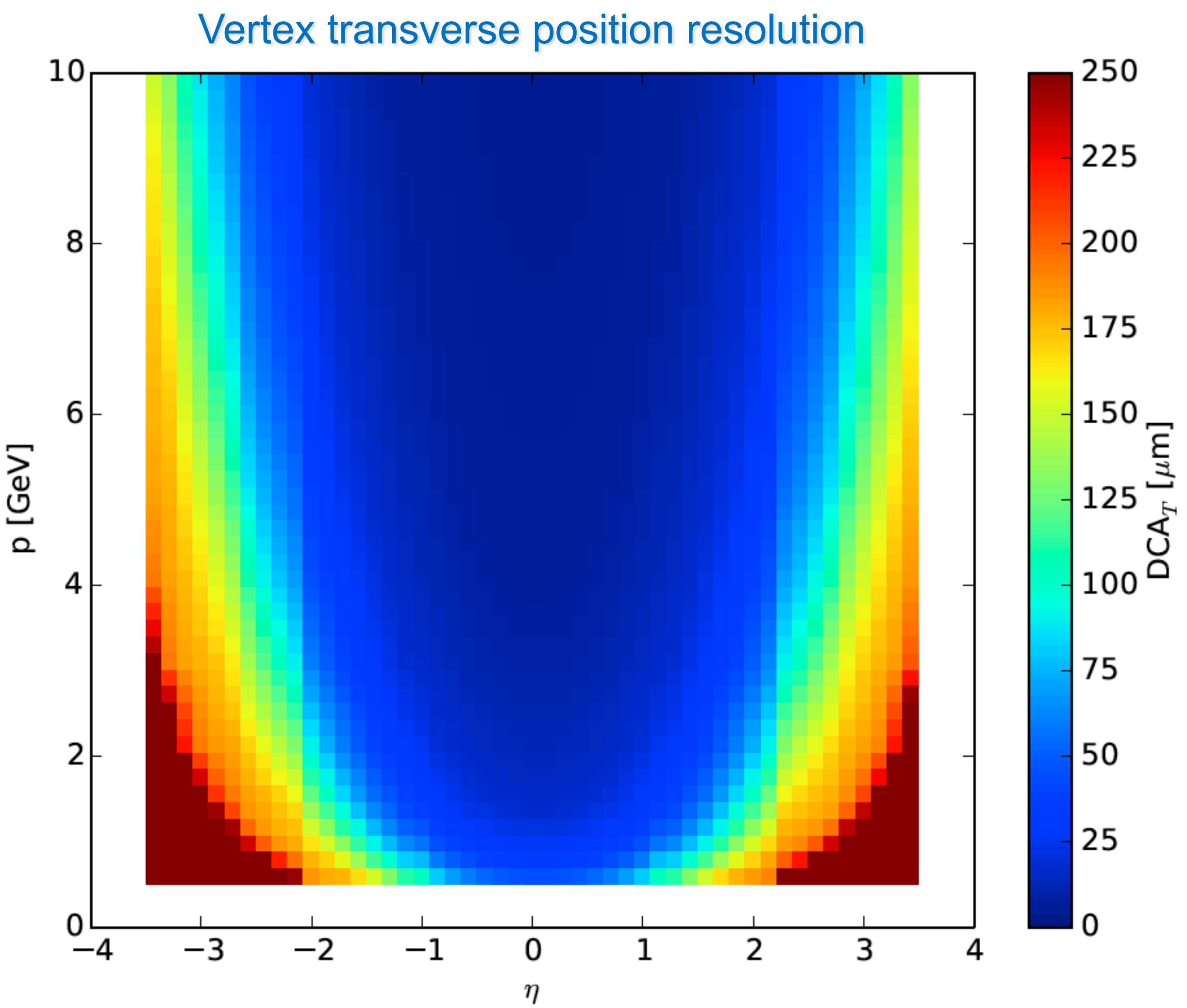
Goal: particles should cross six MAPS disks or barrel layers to minimize inefficiencies



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

Si-tracker: vertex position resolution

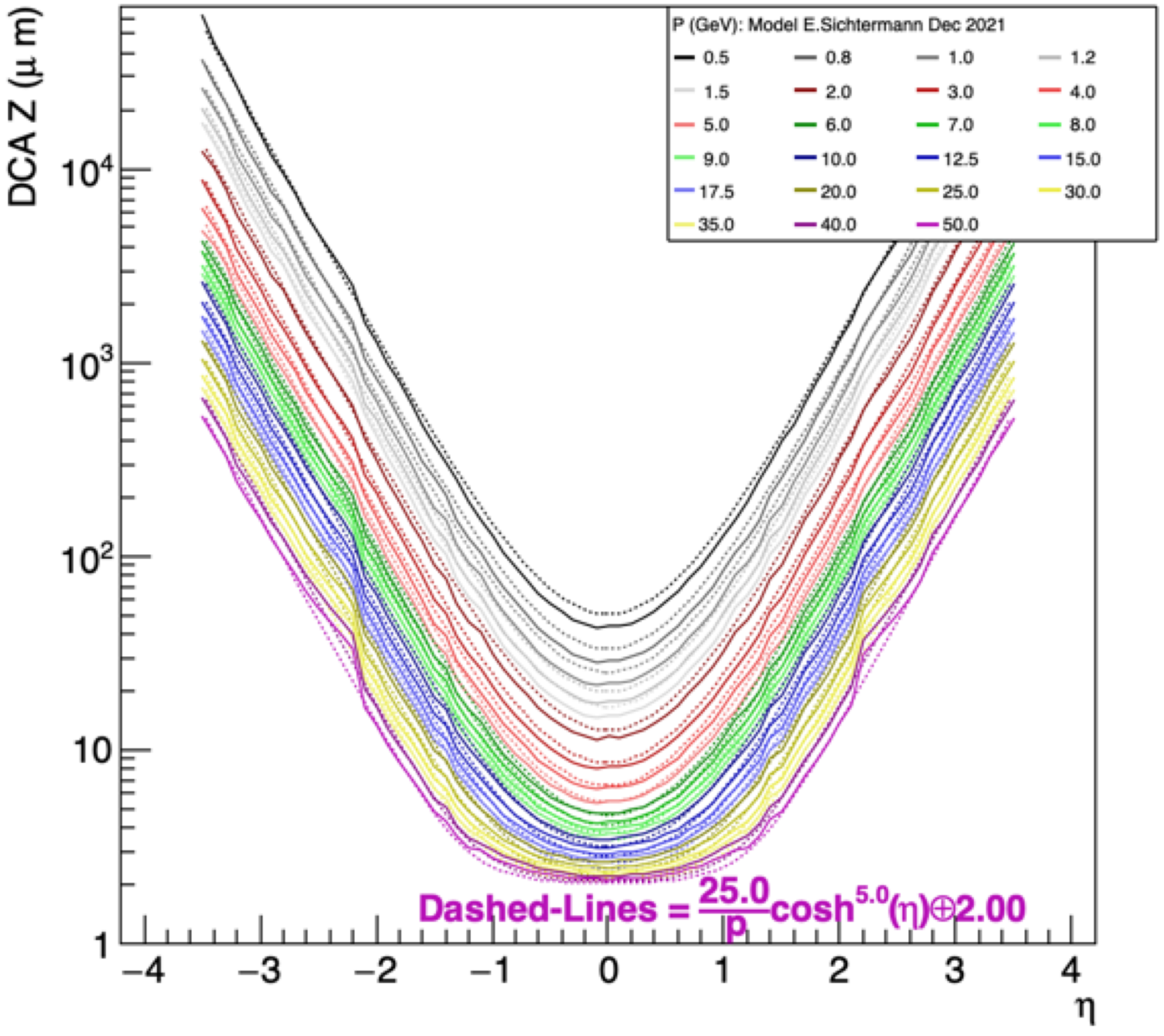




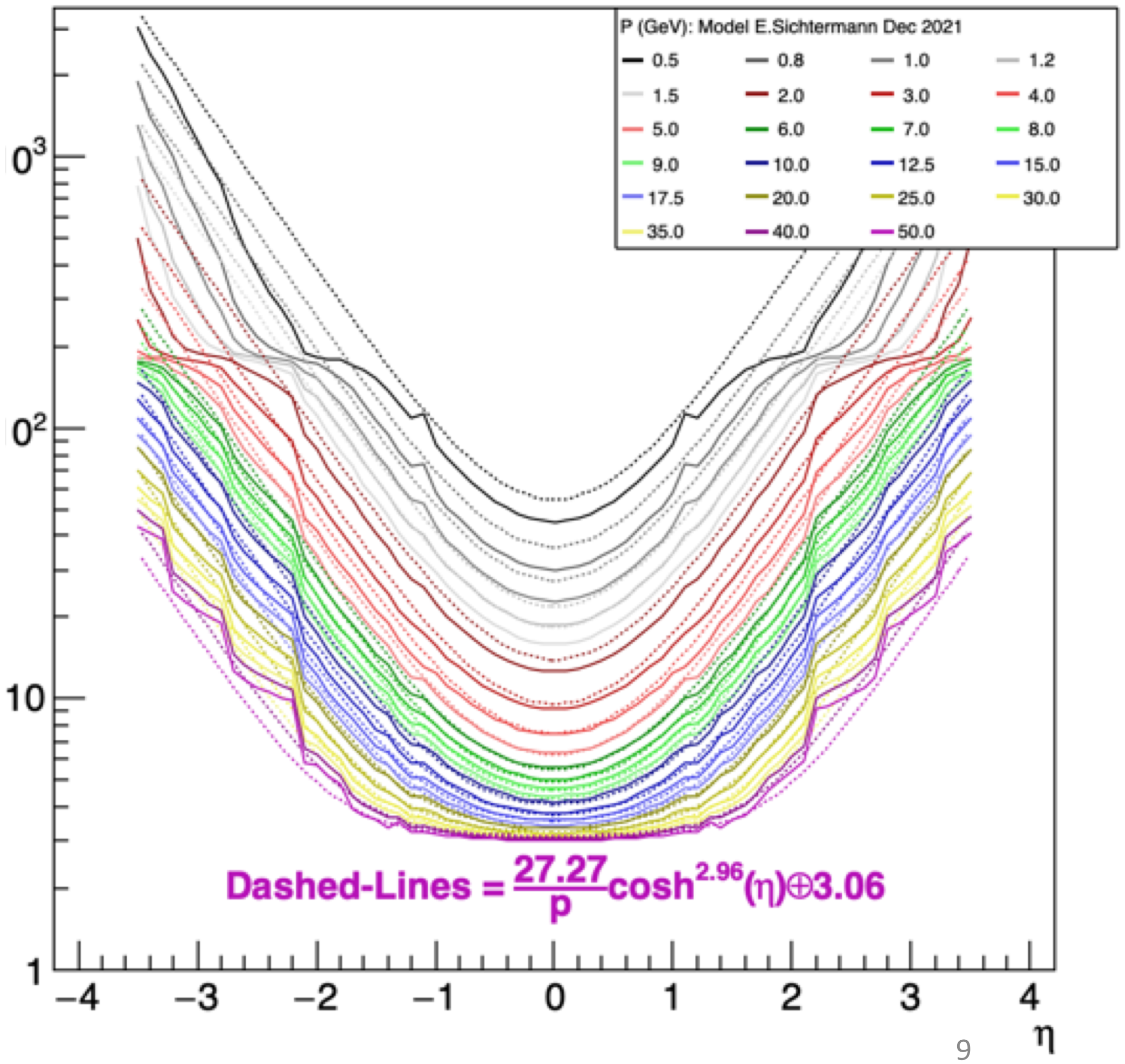
- The resolution is good for measuring detached vertices from, *e.g.*, open charm (D^0 cτ = 123 μm)

Si-tracker: vertex position resolution

Vertex z-resolution (along beam)

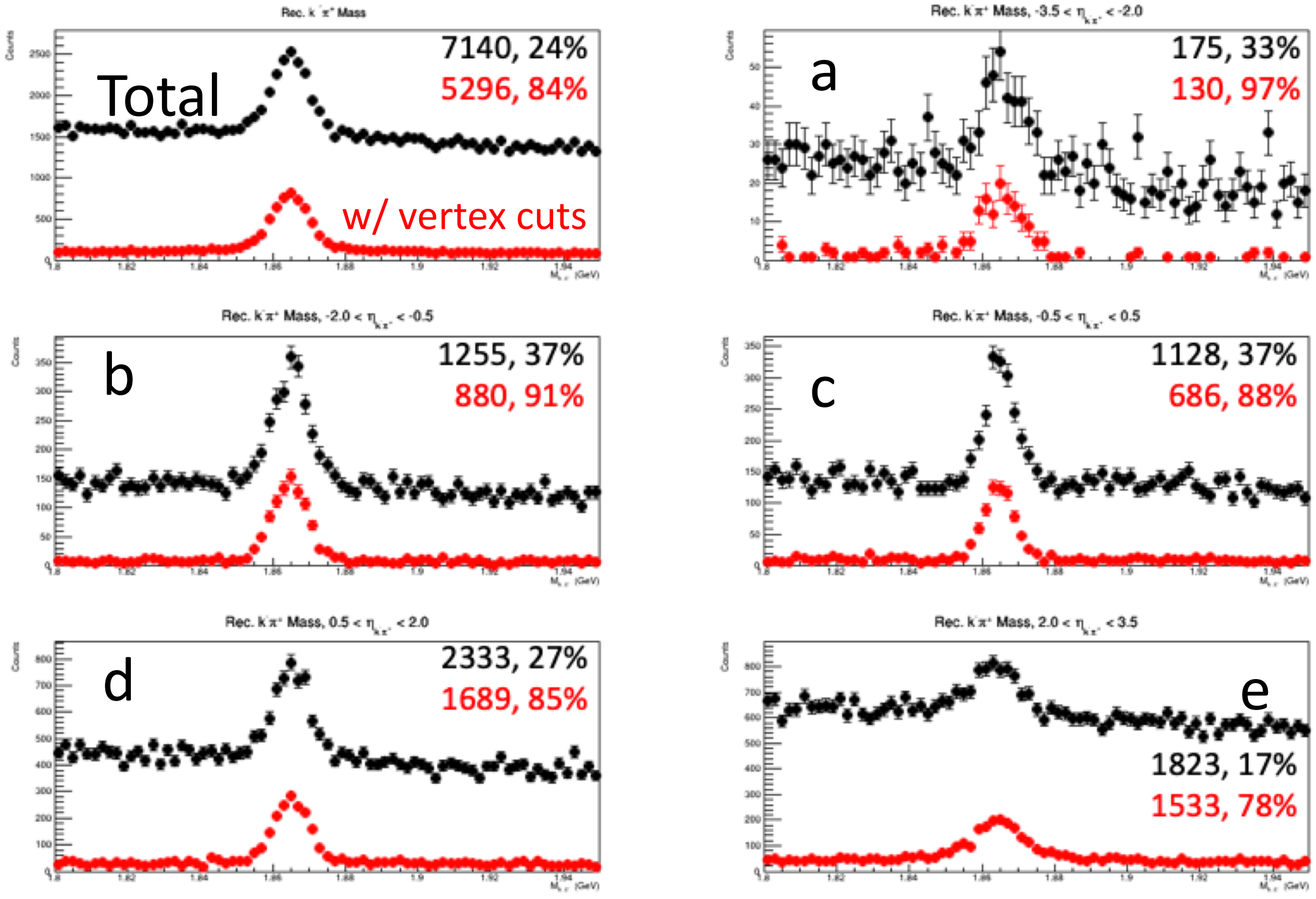


Vertex transverse position resolution



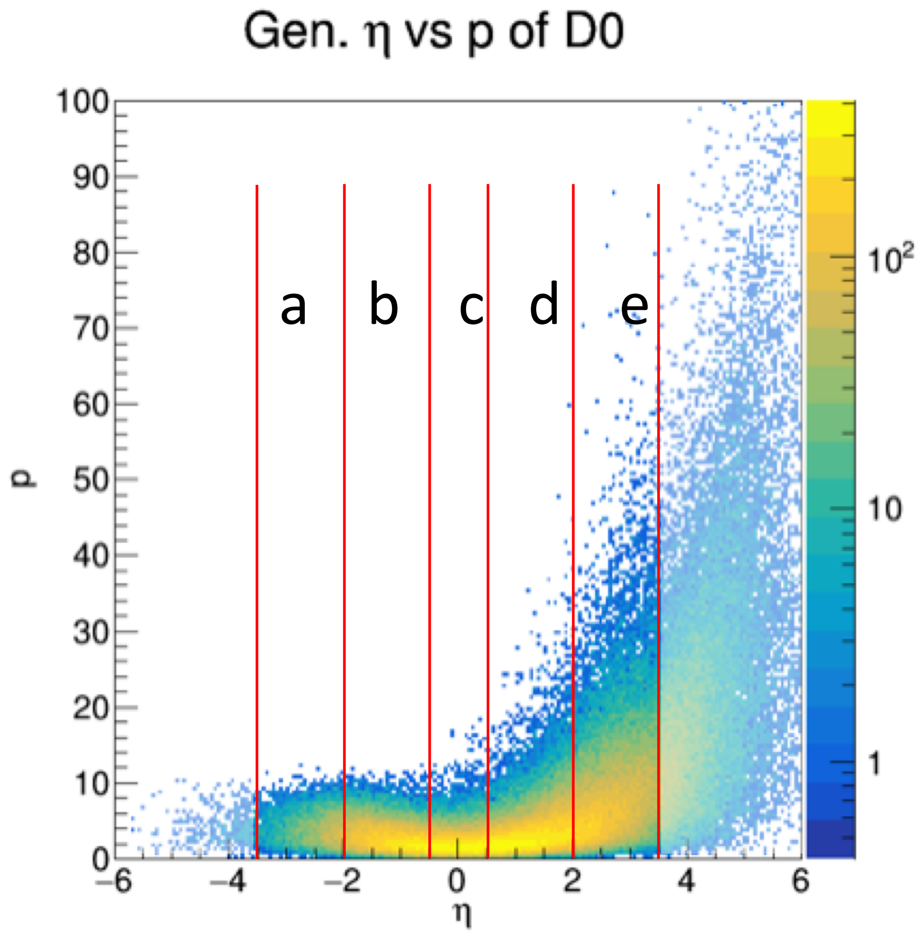
D^0 reconstruction (DPAP G-4)

18 x 275 GeV

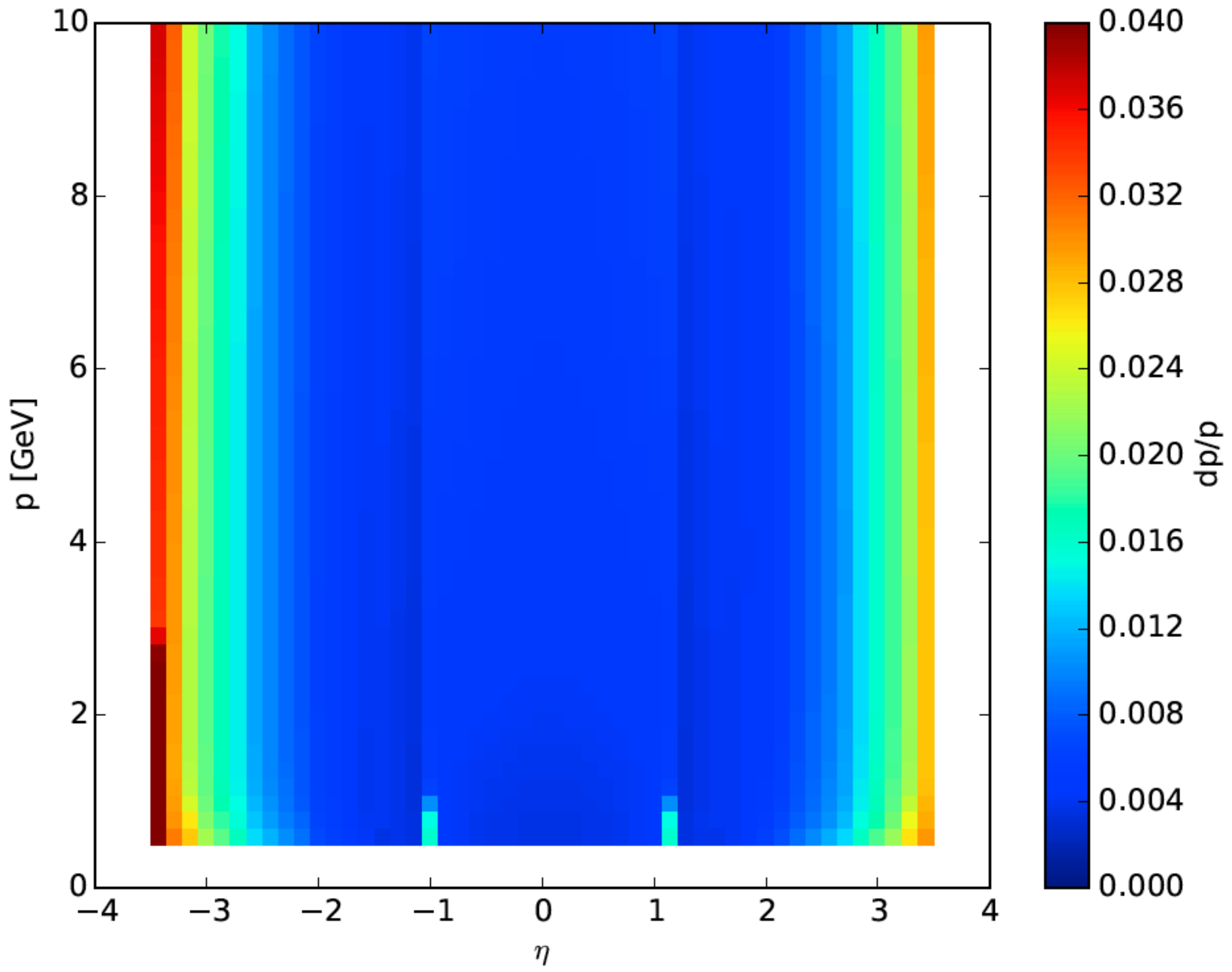


PYTHIA $D^0 \rightarrow K^- \pi^+$: invariant mass for total & 5 indiv. bins of D^0 pseudorapidity

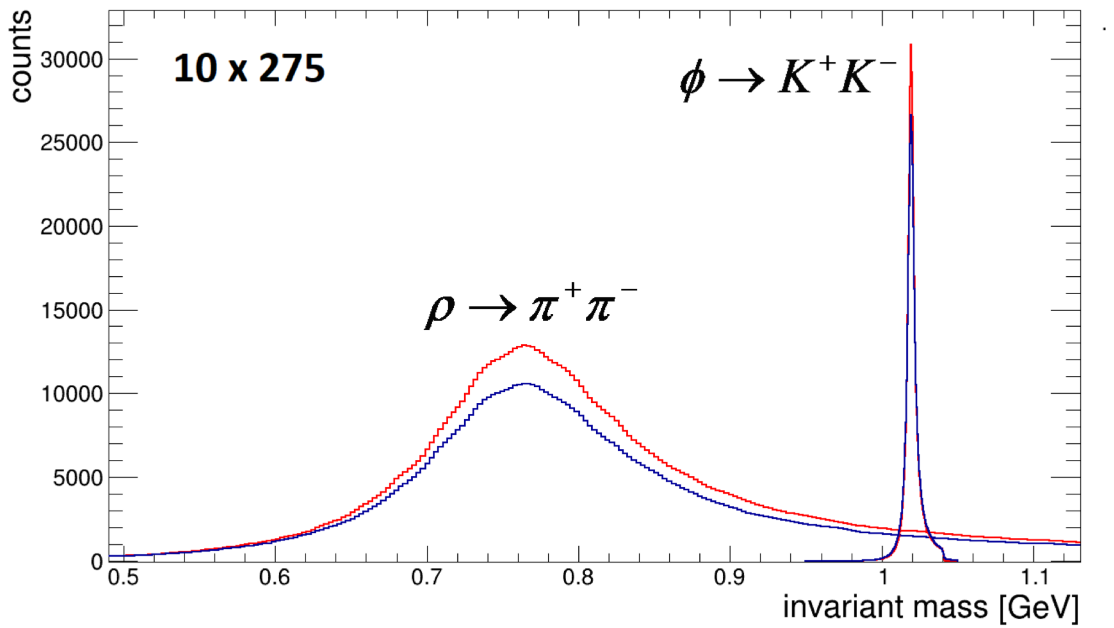
number of D^0, purity of D^0 sample before / after vertex constraints:



Si-tracker: momentum and invariant mass resolution



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

Tracking at large negative eta (DPAP G-1)

What is the physics impact of not meeting the Yellow Report (YR) tracking requirements at negative eta?

eta	1 GeV/c	3 GeV/c	7 GeV/c	10 GeV/c	15 GeV/c
-2	0.61%	0.62%	0.63%	0.64%	0.66%
-2.3	0.85%	0.81%	0.82%	0.84%	0.86%
-2.6	1.14%	1.09%	1.11%	1.13%	1.17%
-2.8	1.52%	1.49%	1.52%	1.56%	1.64%
-3	1.85%	1.81%	1.85%	1.90%	2.00%
-3.2	**2.25%**	2.22%	2.27%	2.32%	2.45%
-3.3	**2.77%**	**2.79%**	**2.92%**	3.05%	3.36%
-3.4	**3.05%**	**3.09%**	**3.22%**	**3.38%**	**3.72%**
-3.5	**4.58%**	**3.41%**	**3.56%**	**3.73%**	**4.11%**

The table shows the simulated CORE tracking resolution at large negative eta.

There is an optimum around 2-3 GeV/c.

Table 8.20 in the YR states a requirement for the tracking resolution in the -3.5 < eta < -2.5 bin as 0.1%*p + 2%, which is a factor 2 worse (both terms) than the requirement for the previous bin (-2.5 < eta < -1). In a bin-average sense, CORE thus not only fulfills, but in fact exceeds the YR tracking requirement for large negative eta.

Interpreted differentially, the tracking resolution for CORE does not fully meet the requirement at low momenta and very large negative eta (indicated in bold in the table above) - but by a very small margin. Even at 1 GeV/c and eta = -3.5 it is only a factor 2 worse than the requirement over the full eta bin. Thus, the physics impact is expected to be very small.

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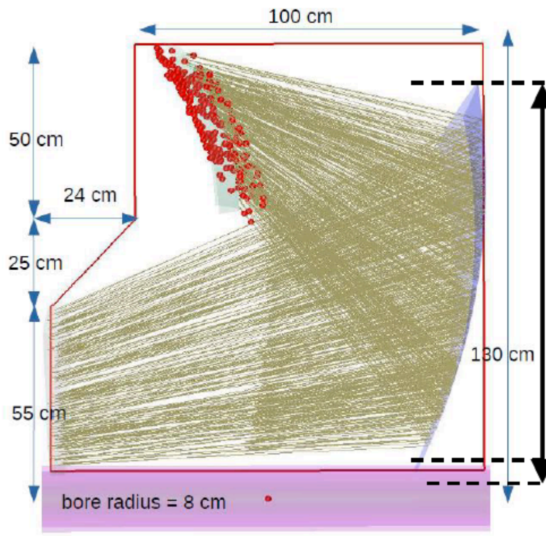
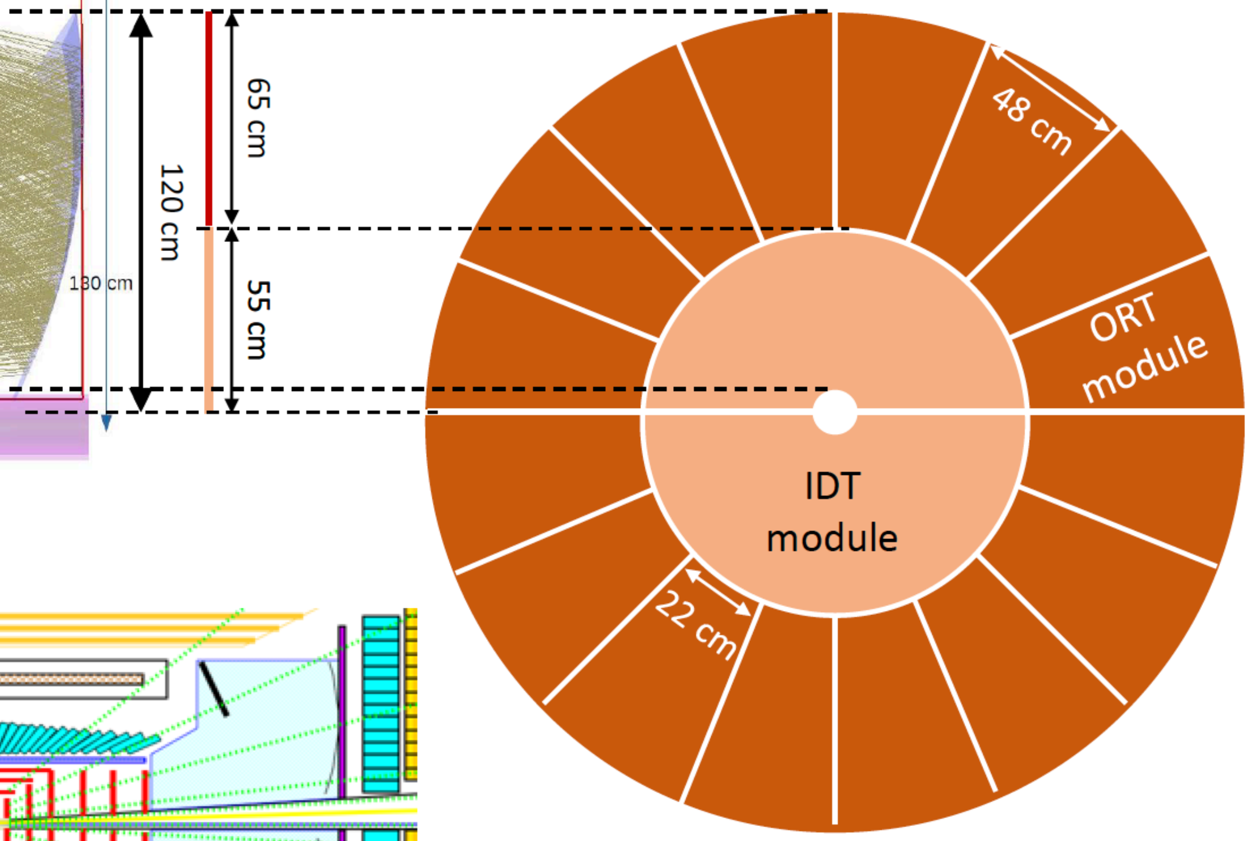
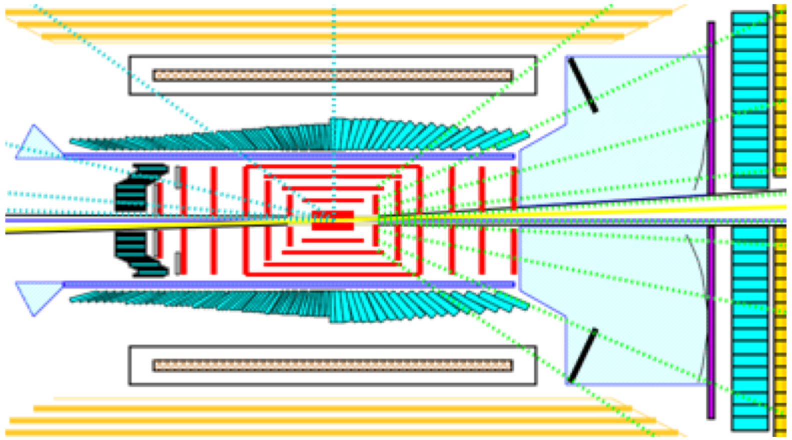
Forward MPGD

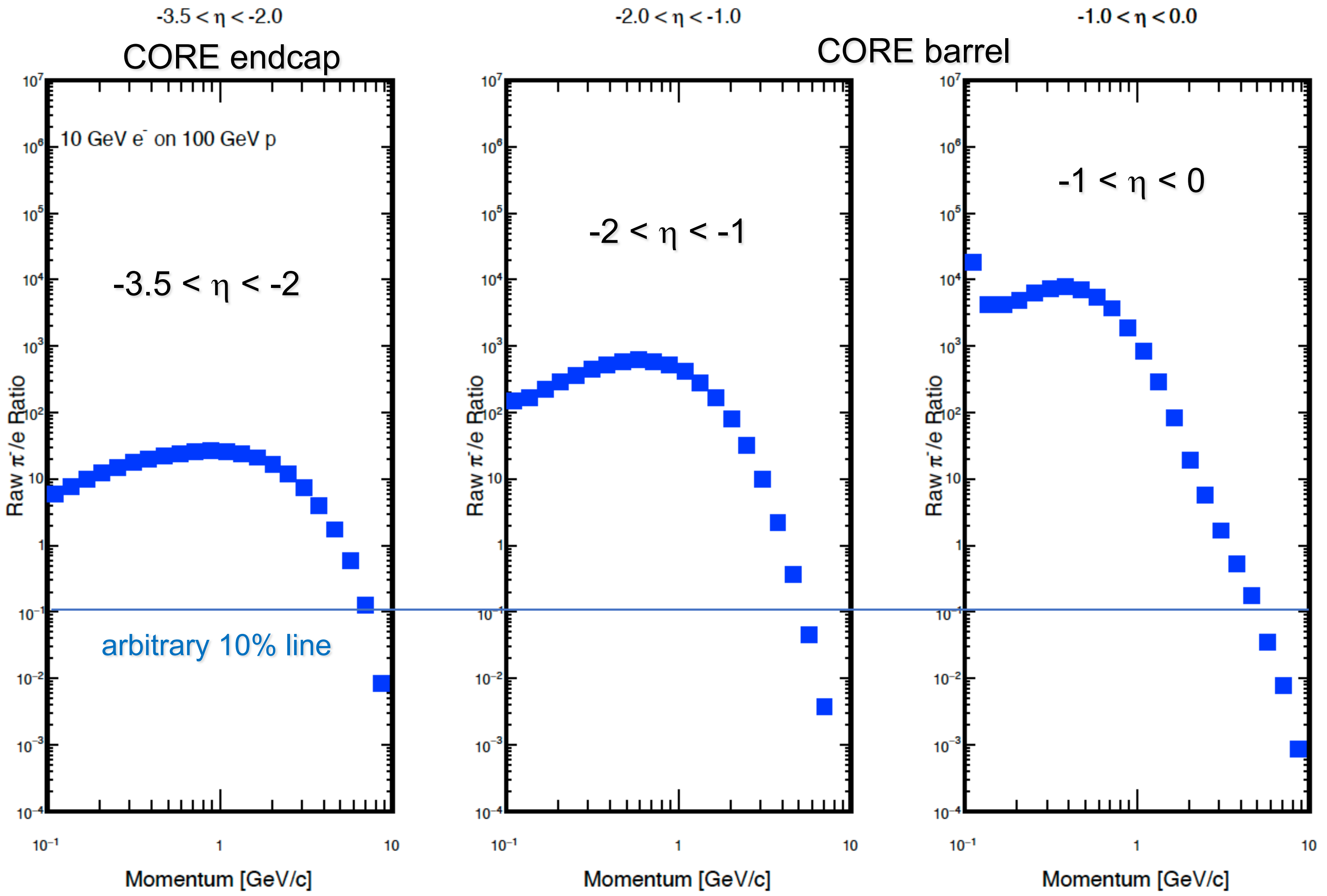
- The main purpose of the MPGD is to seed the ring finding for the dRICH.
- With a long lever arm and 50-100 μm resolution, it can also improve dp/p at large η.
- To optimize the acceptance at large η, it has an inner disk tracker (IDT) module that minimizes the dead area at the center.





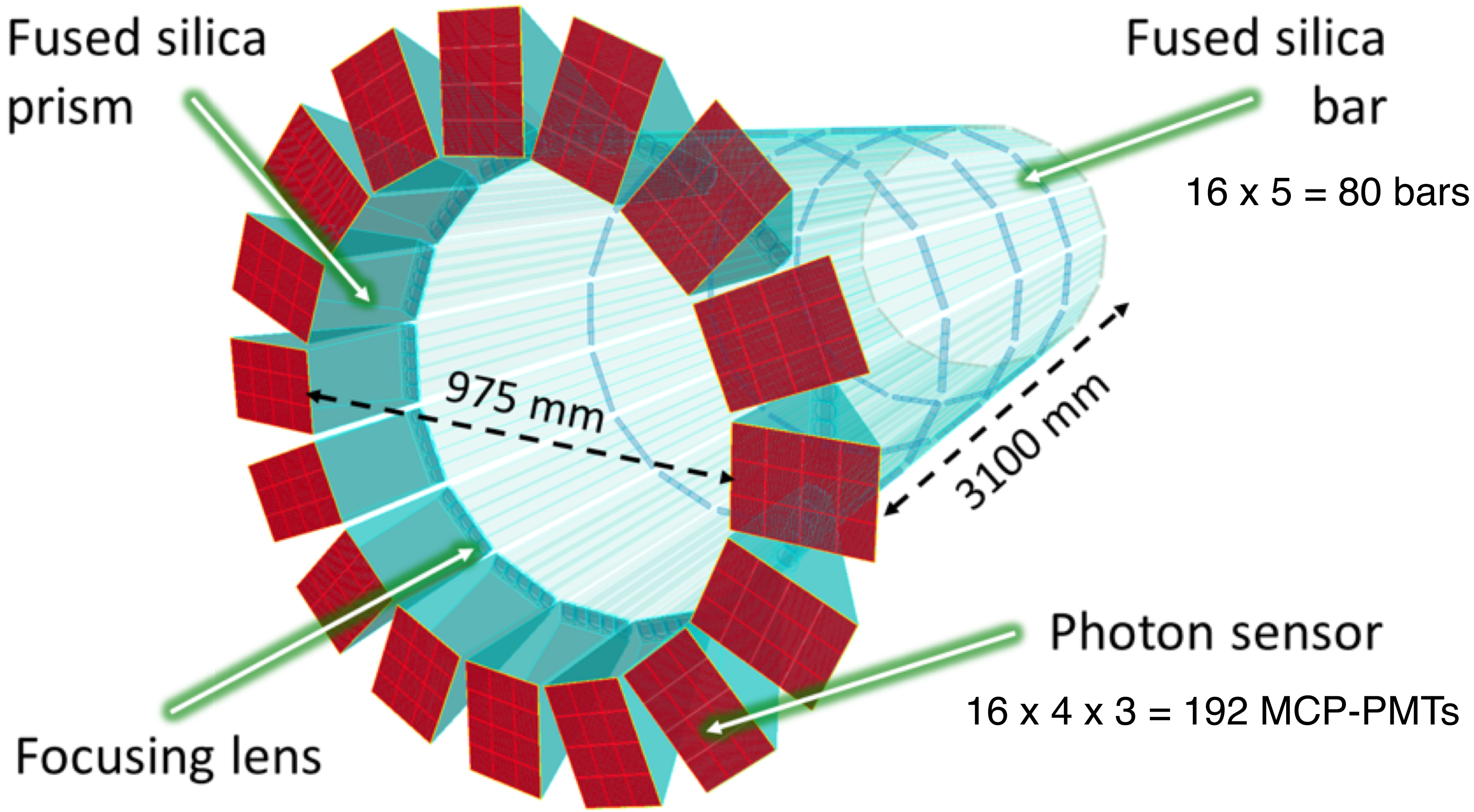


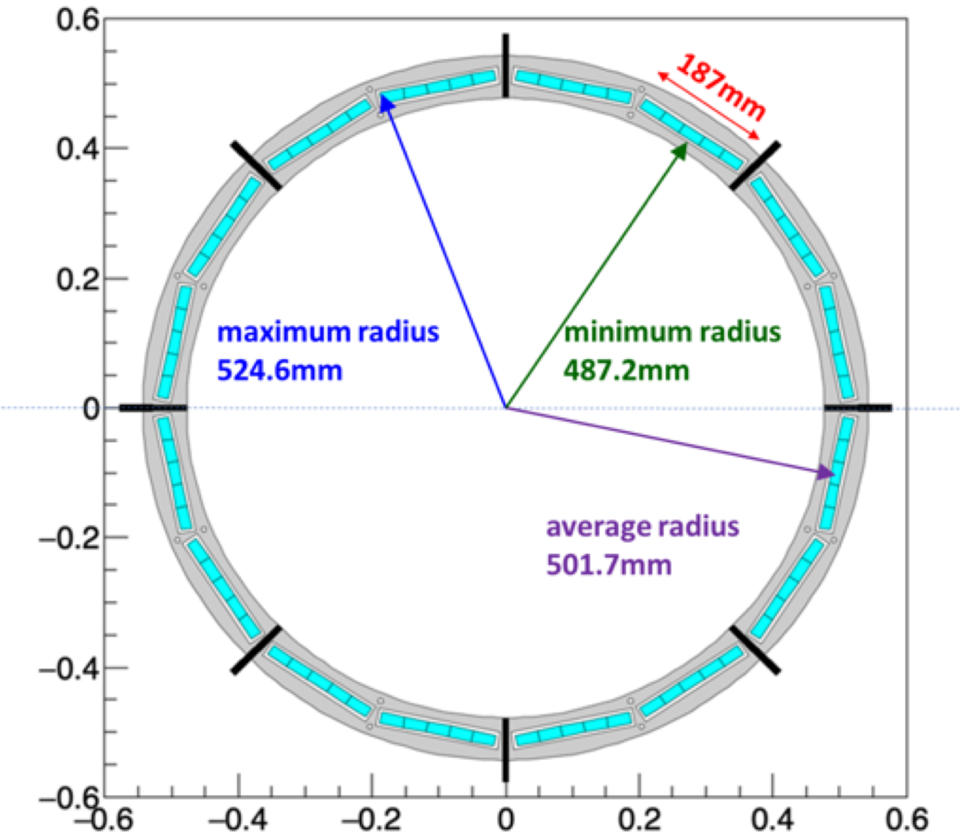
Electron ID - pion backgrounds (π/e ratios) for the scattered electron



- 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 η < 0 range.
- The DIRC provides additional e/π suppression around 1 GeV/c

PID in the barrel - a high-performance DIRC

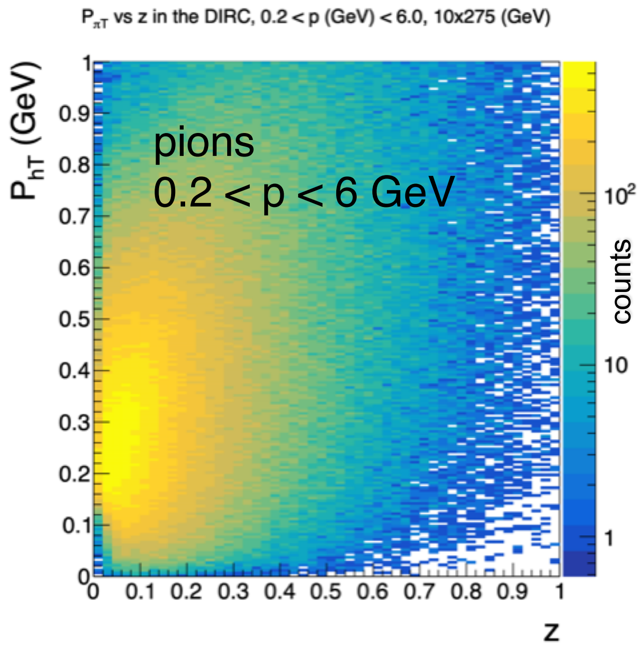


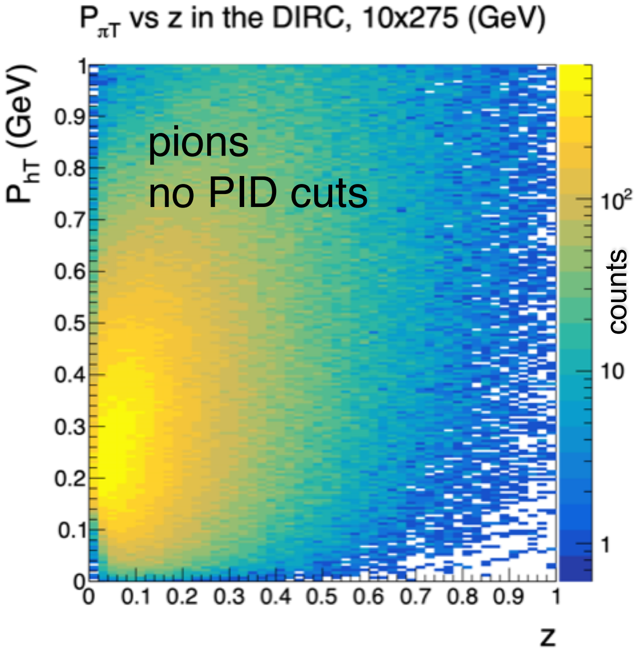


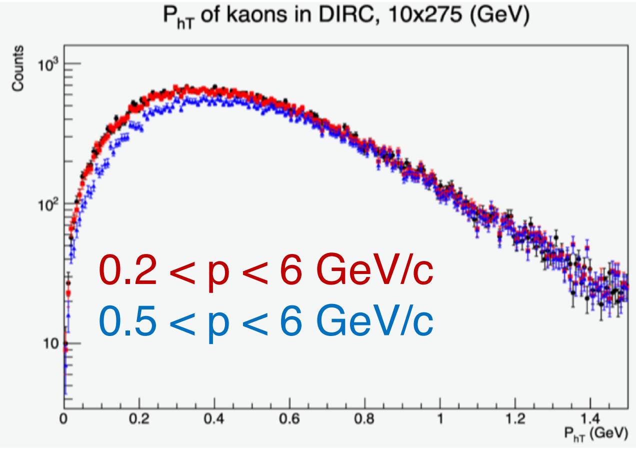
- The PID performance of a DIRC is largely independent of size
  - The small radius of the CORE DIRC improves low-momentum PID acceptance at high B-fields

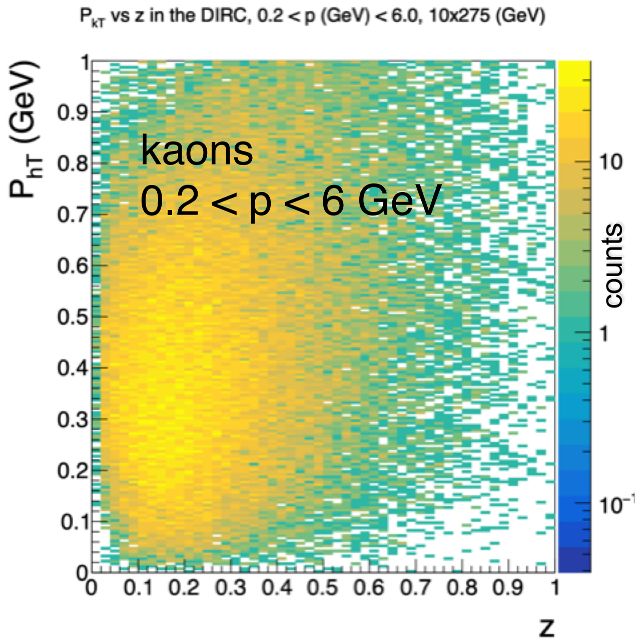
DIRC PID range - impact on TMDs

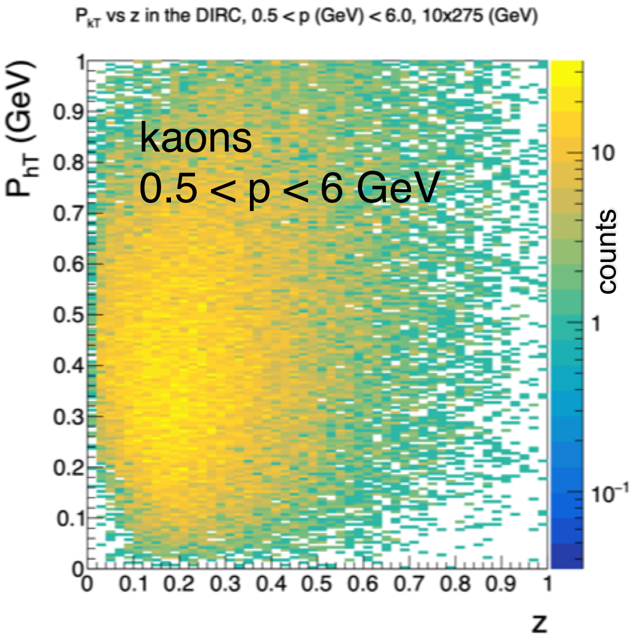
- In SIDIS, the transverse momentum P_{hT} is defined with respect to the virtual photon and not the beam direction.
  - Since the photon direction varies, the lower end of the PID range has little impact on the z-P_{hT} coverage (it adds statistics).
  - The PID range of the DIRC is ideal for TMD physics.

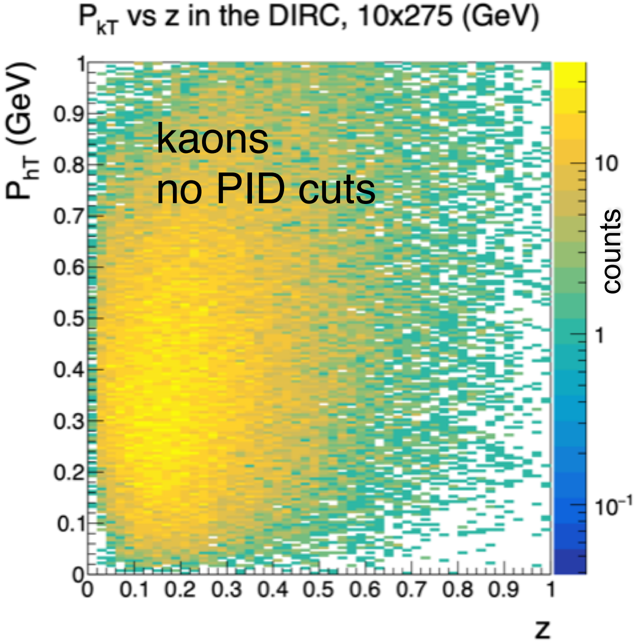




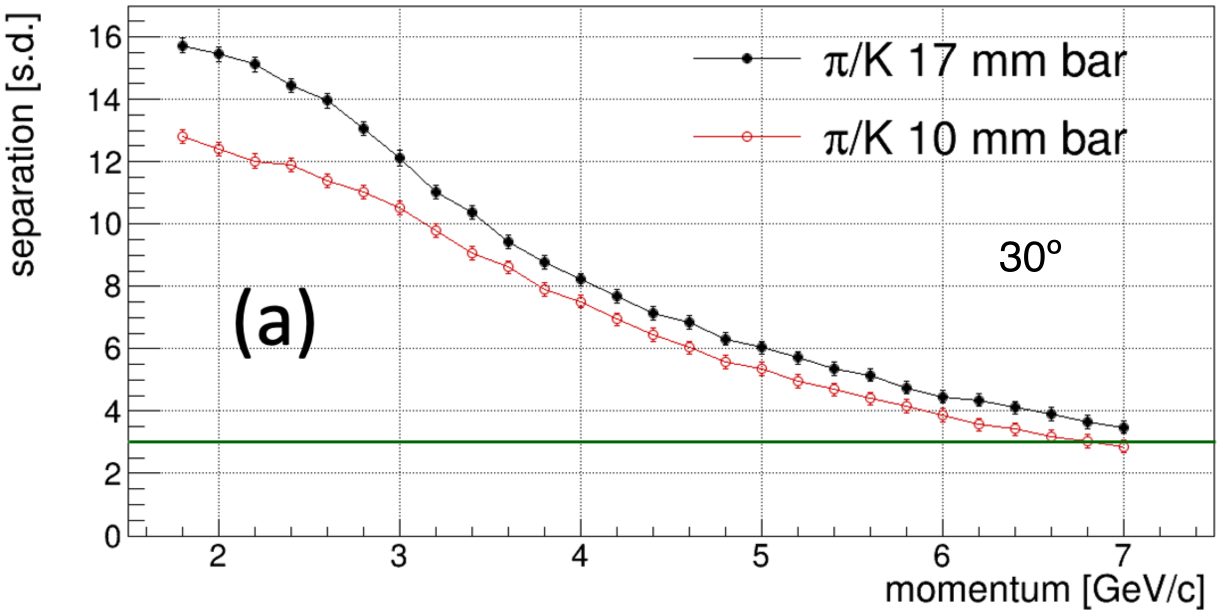


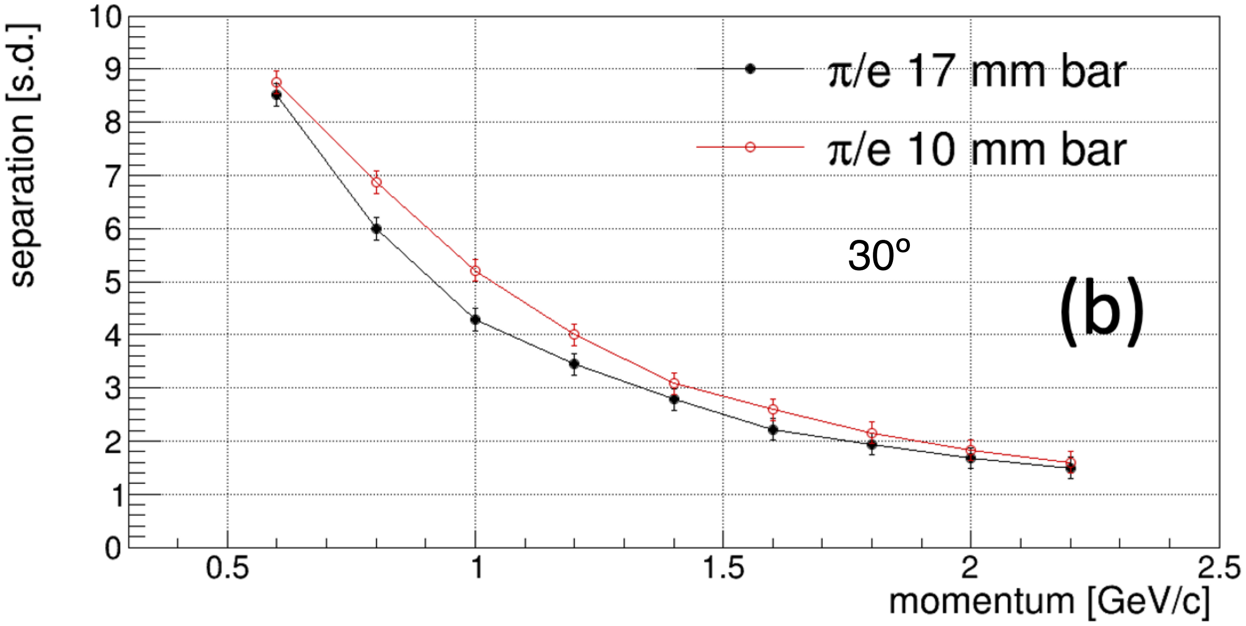






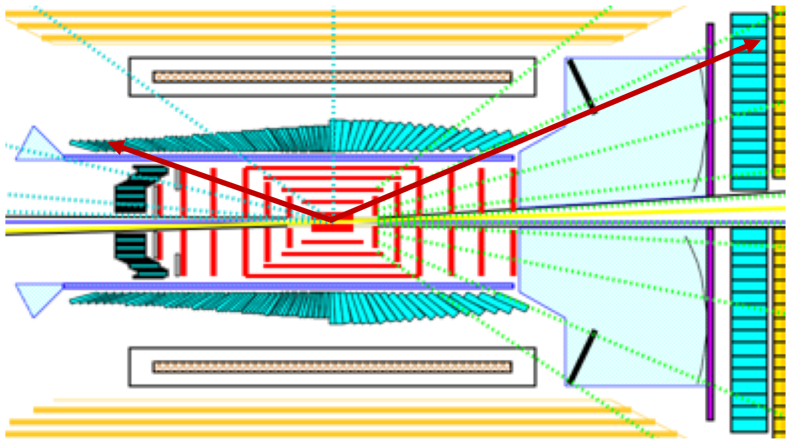
CORE DIRC performance

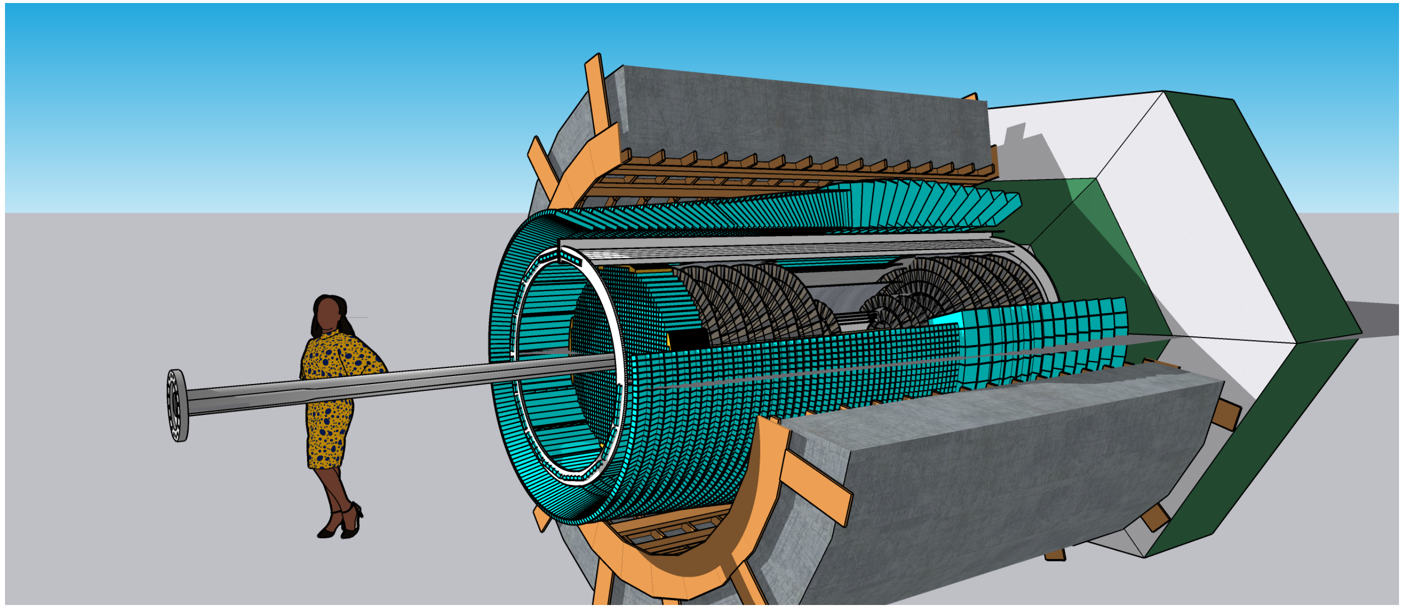




- The baseline choice for CORE is to re-use the (17 mm thick) BaBar DIRC bars
- Geant4 simulations for the CORE configuration show
  a) More than 3σ π/K separation up to 6-7 GeV/c
  b) Good e/π separation (pion suppression factor) around 1 GeV/c, where it is most important

4π EM calorimetry





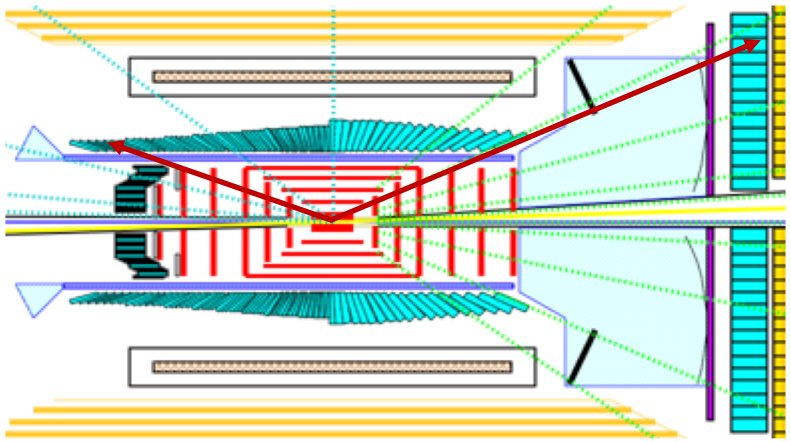
Electron hemisphere ($\eta < 0$)

- $PbWO_4$ ($2\%\, E^{-1/2} + 1\%$): 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

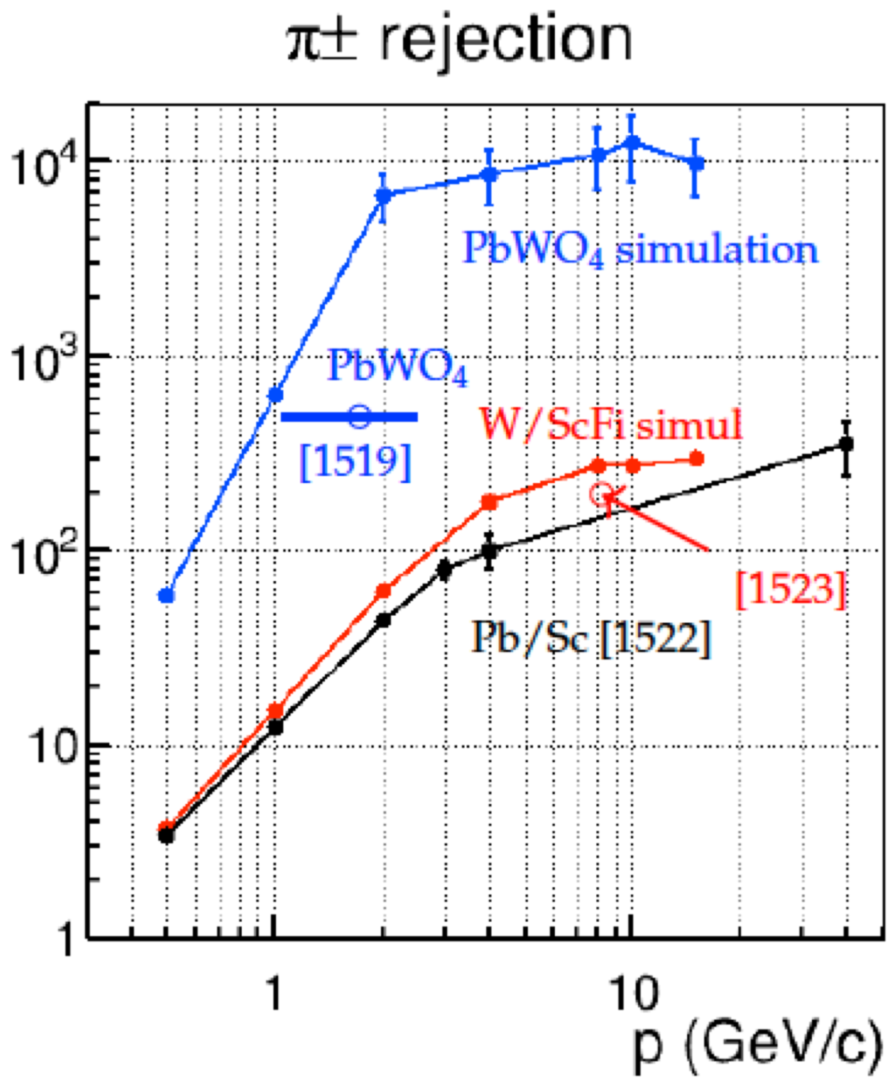
Hadron hemisphere ($\eta > 0$)

- 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

Why $PbWO_4$?

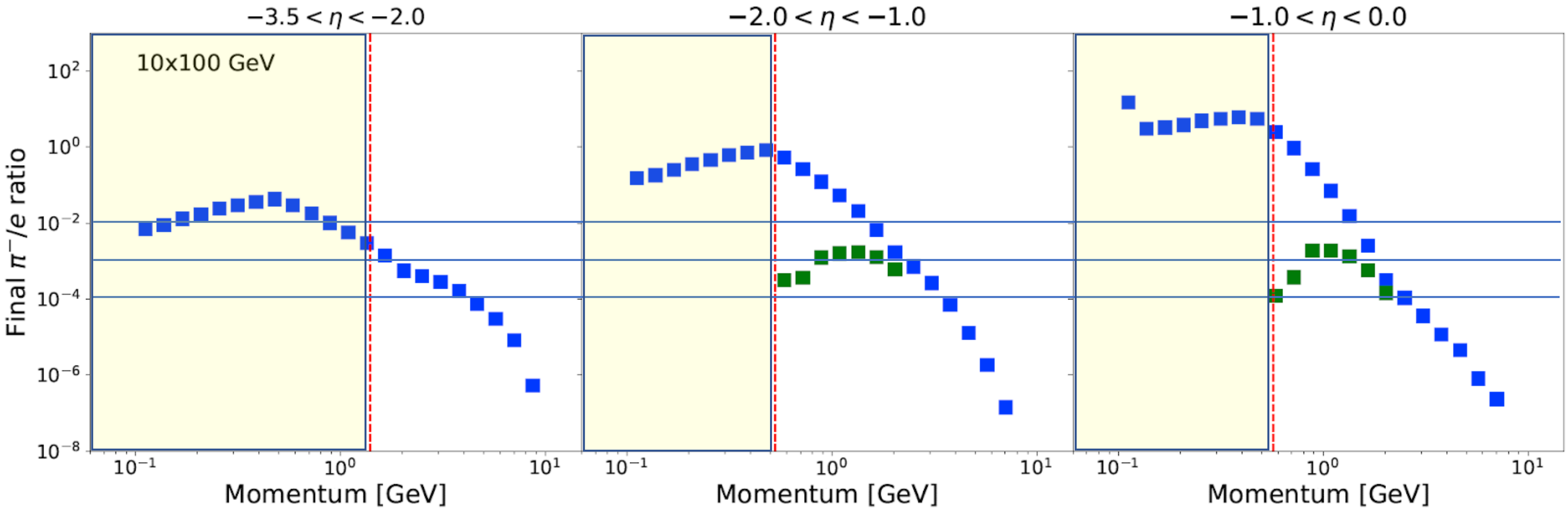


- Excellent energy resolution
  - Photon yield is an good match for photons and electrons in the GeV range
- Excellent pion rejection
  - In part due to favorable ratio between the radiation length the hadronic interaction length
- Excellent position resolution (Moliere radius)
- Compact size



From Yellow Report

pi- vs. e- rejection - combined plot for all sources (DPAP G-2)

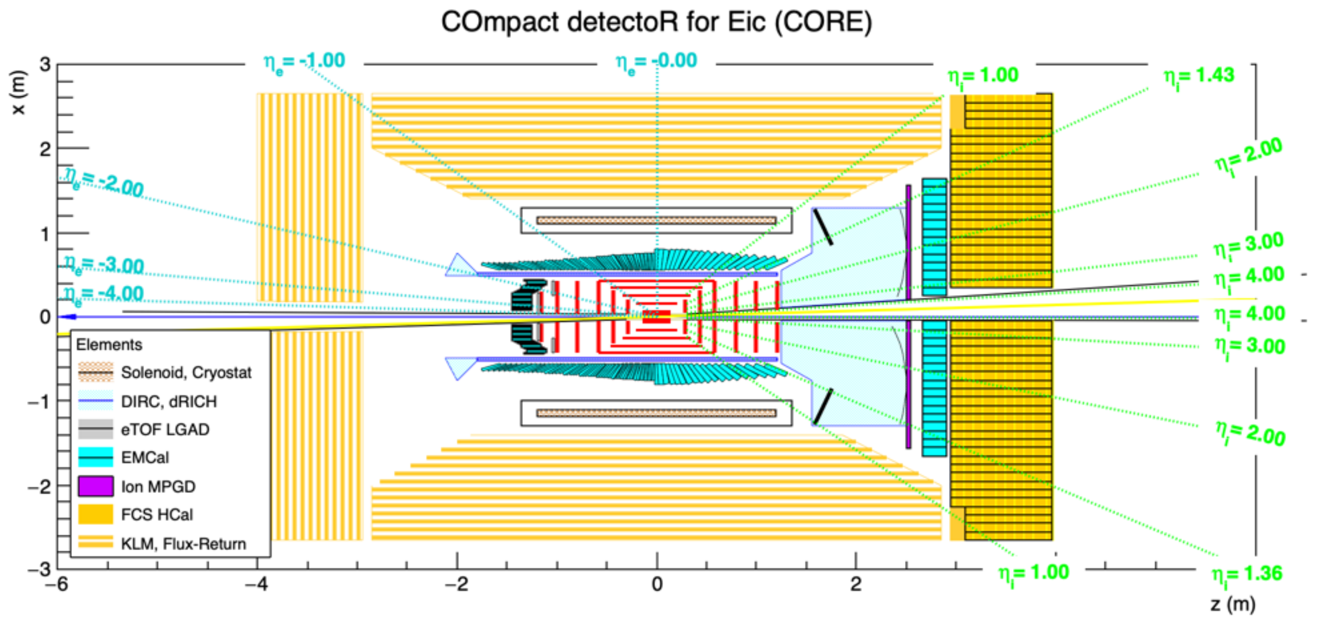


The plot shows the remaining pi contamination after applying the combined effects of all sources of discrimination.

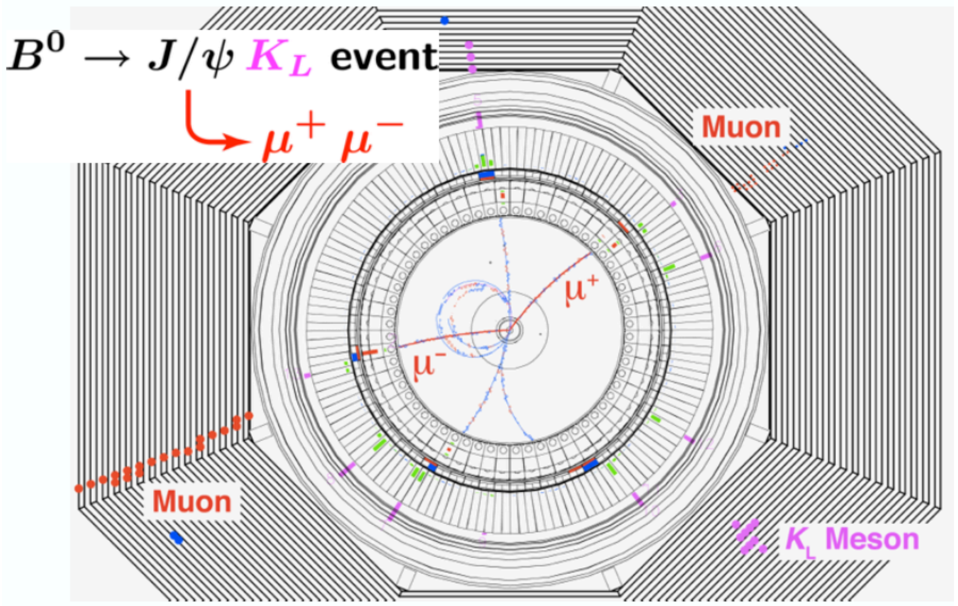
The blue points show the effect of the $PbWO_4$ EMcal and kinematic constraints. The green points show the total effect of also including the DIRC (in the momentum range where it is applicable).

The remaining pion / electron ratio is at the level of 0.1% or better for all kinematics (above the yellow area which is excluded by standard event selection cuts).

Hadronic calorimetry and muon ID



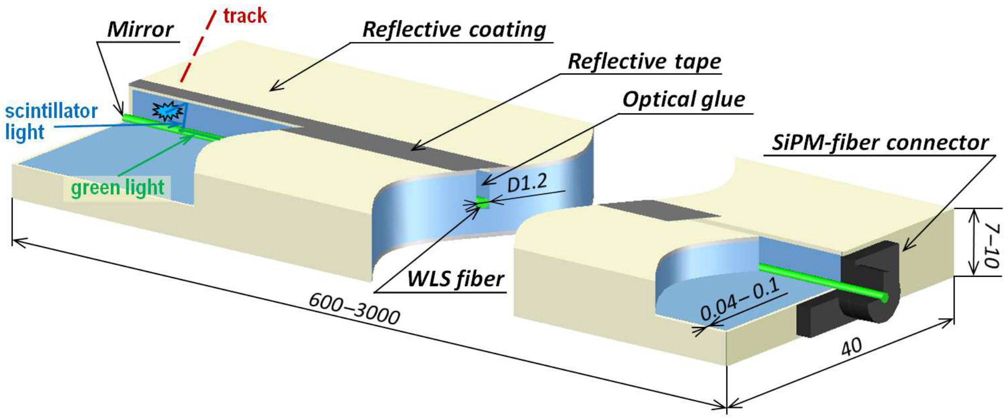
The Belle II K_L-μ (KLM) system



- 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

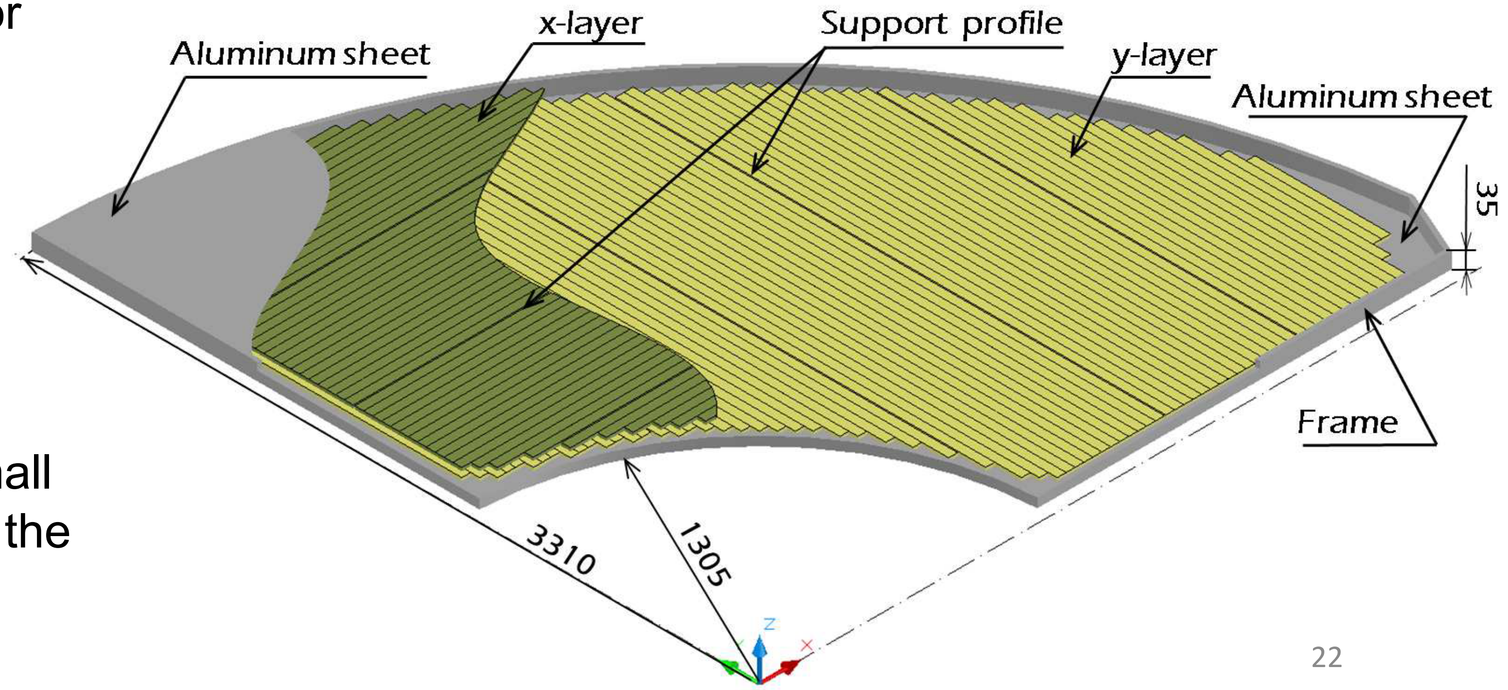
The CORE KLM

- The CORE KLM is in most respects similar to the one used in Belle II.
- Low mass in front of the muon system in combination with good depth segmentation Is needed to achieve good low-momentum muon ID.



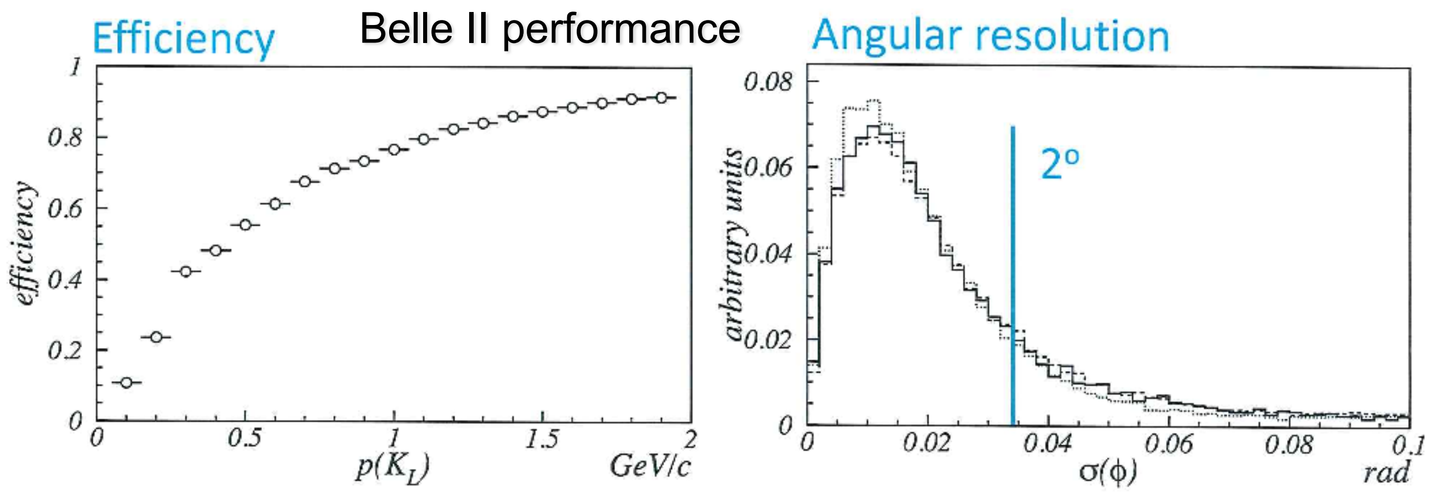
T. Aushev *et al.* arXiv:1406.3267v3 (2015)

- The CORE KLM the 14 double scintillator (x,y) layers, which are thinner than in Belle
  - 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. But the small solenoid makes it possible to use Cu for the coil matrix, significantly reducing risk.

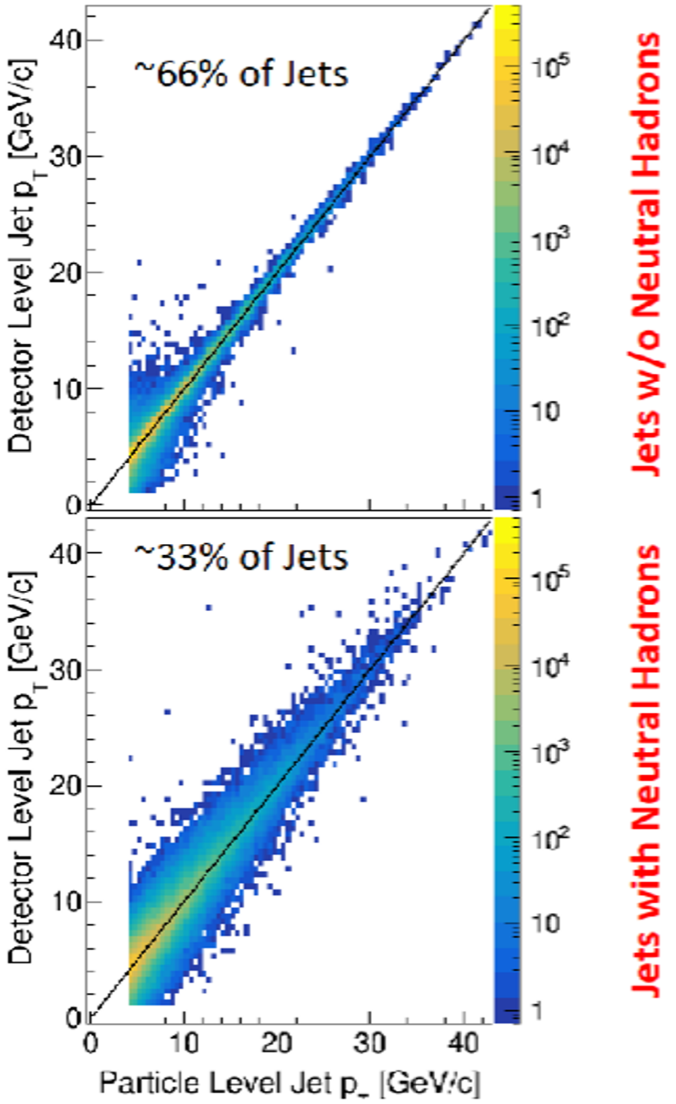


KLM – neutral hadron detection

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

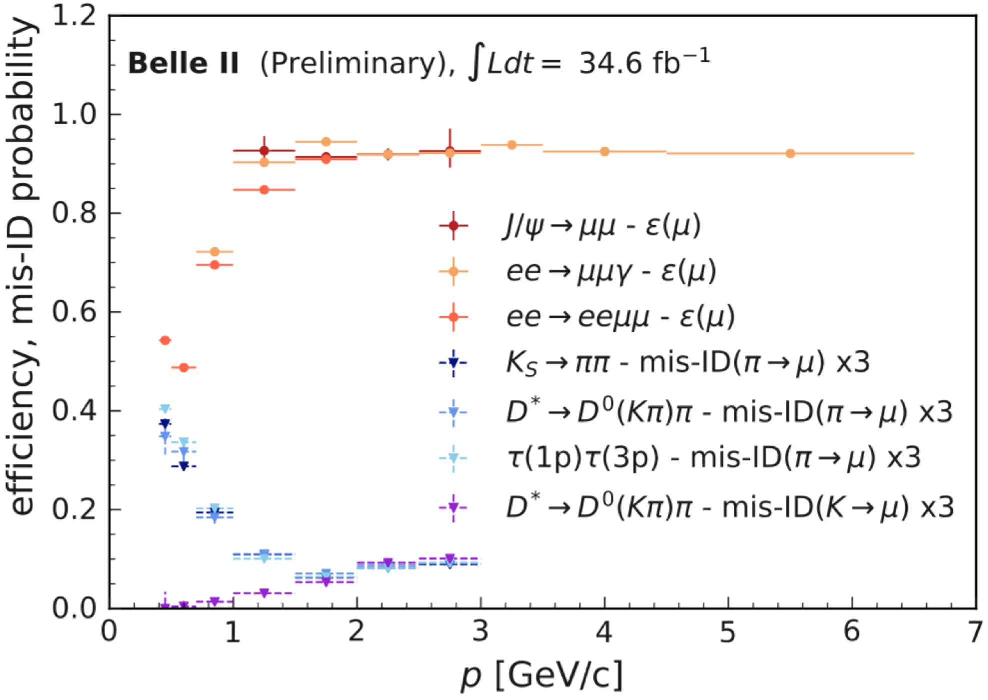


- For $\eta < 1$, jets are best reconstructed from individual particles, but the resolution will be poorer for jets with neutral hadrons
- Since the neutral hadron momenta are generally low, an Hcal measurement of the neutral hadron energy will have a large uncertainty and will not significantly improve 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.

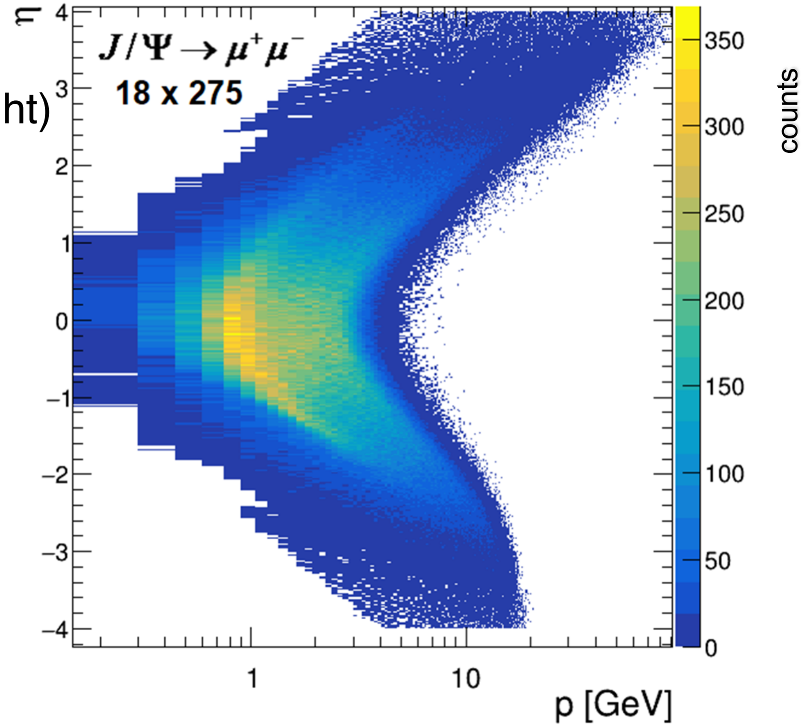


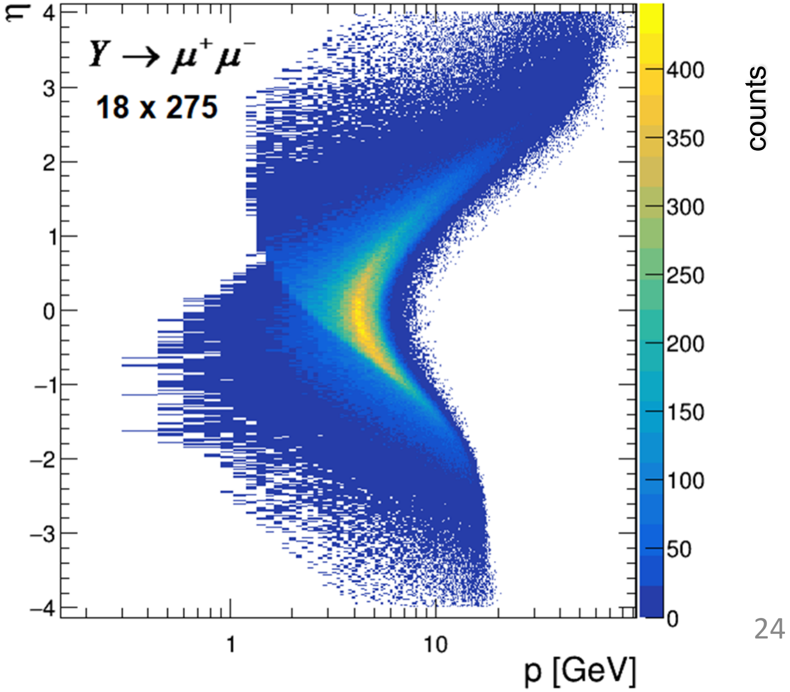
Note: the figure includes all jets, not just η < 1.2

KLM – muon ID



Exclusive production on the proton (Starlight)





- 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

Thank you!

CORE technologies

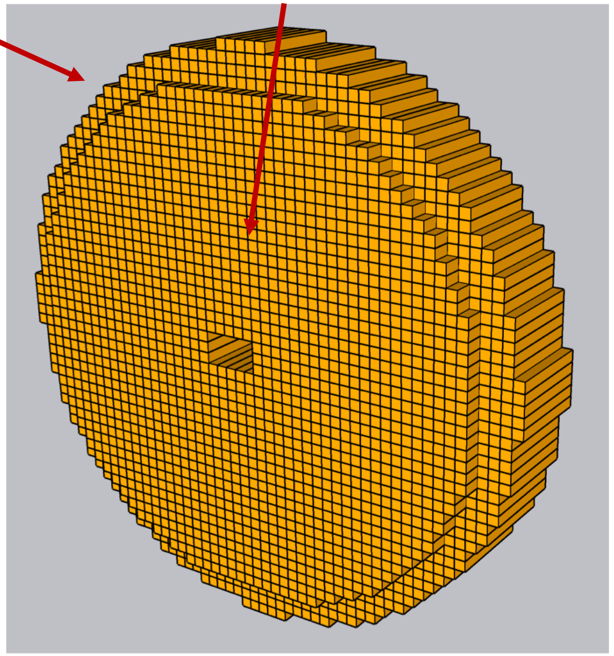
No high technical risk components .

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

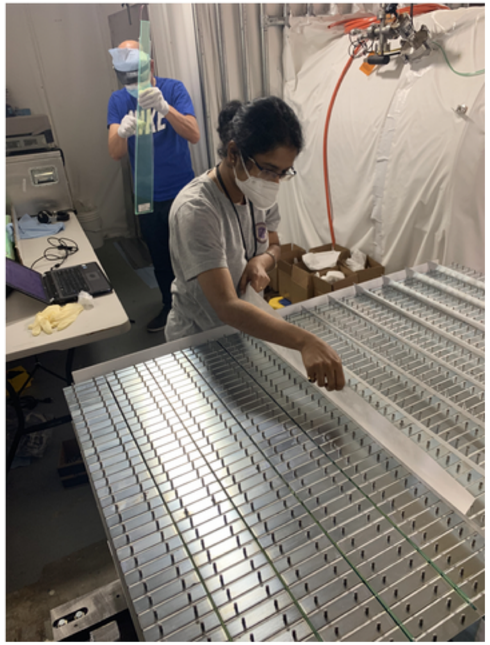
TABLE II. Summary of detector technologies.

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.

Hcal



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



Assembly of STAR FCS modules

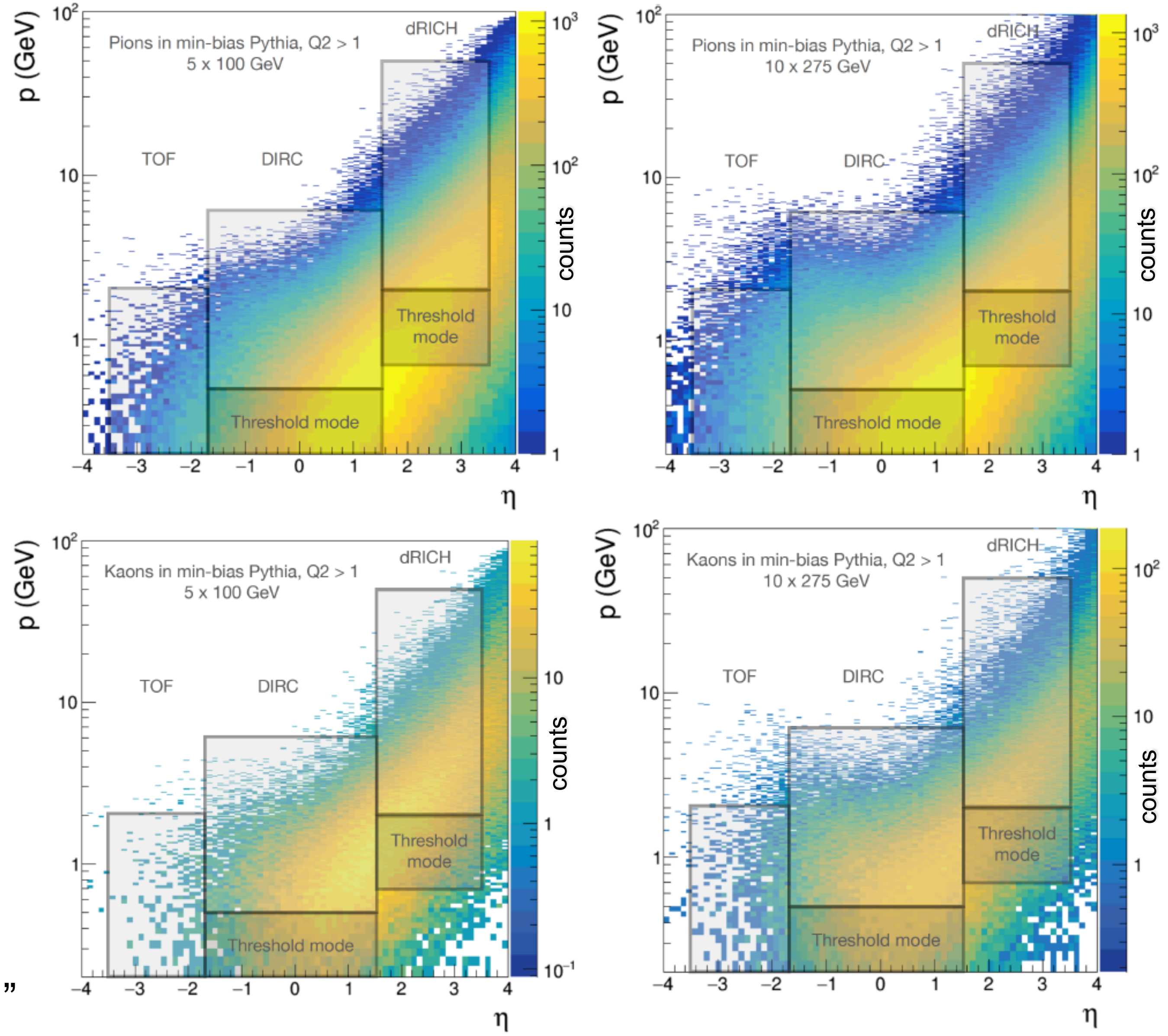
- The CORE Hcal is based on the STAR FCS and covers $\eta > 1.2$.
    - The 520 STAR FCS modules are re-used for the outer ring
- The non-projective endcap W-shashlyk EMcal is located directly in front of it, but on a separate frame attached to the barrel so that it does not interfere with the sideways motion during disassembly
- The original STAR FCS has 36 Fe/Sci layers (20+3 mm), while the new modules will have 44.

Hadron identification

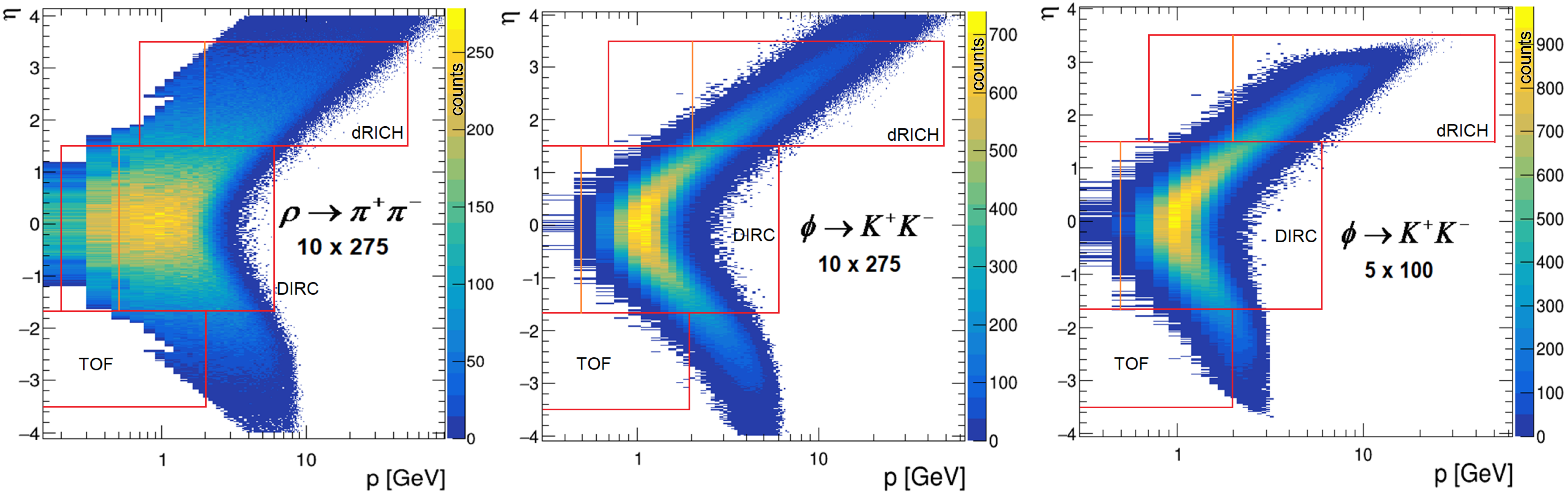
- Momenta of hadrons produced in DIS are strongly correlated with the beam energies, and generally decrease towards more negative values of η.
  - higher electron beam energies generate higher hadron momenta for η < -1.65

- 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.



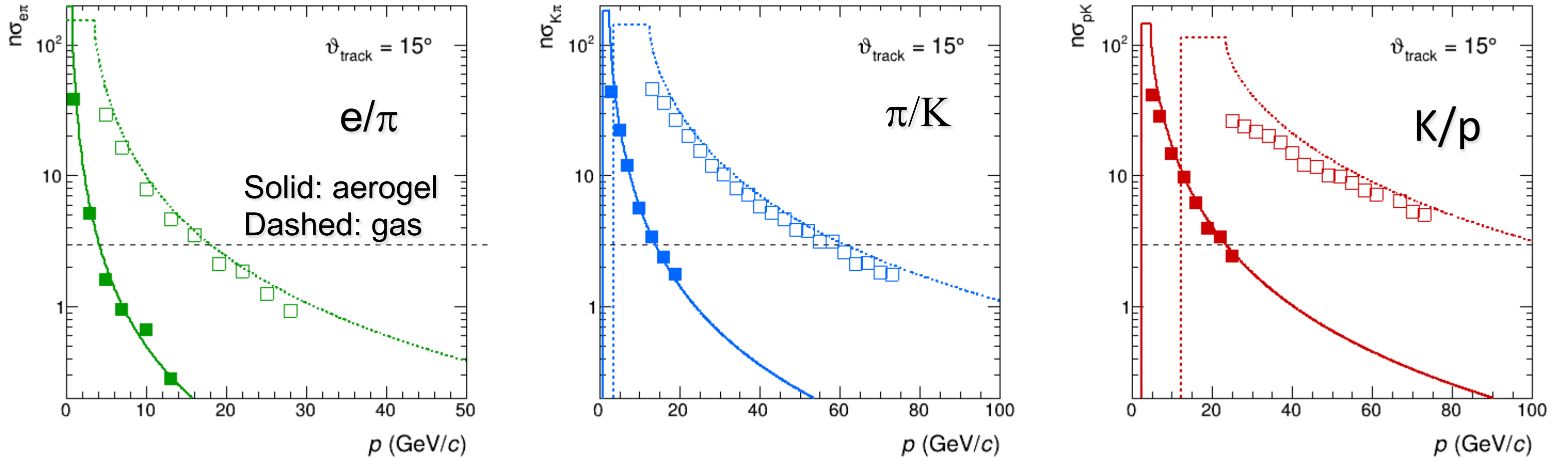
Particle identification in exclusive reactions

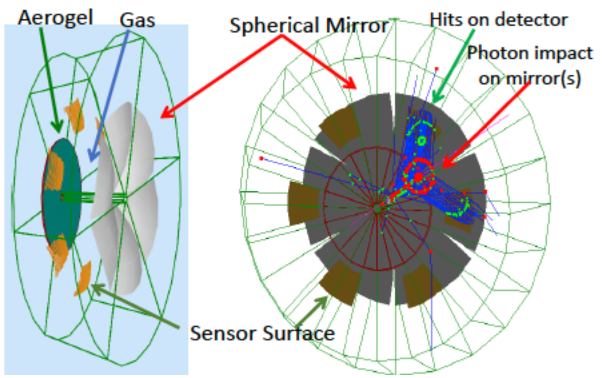


- In exclusive reactions, final-state hadron momenta are higher than in DIS.
  - In particular, kaons from ϕ decays are covered by the RICH modes of the DIRC and dRICH.
- In the electron endcap, the TOF covers the kaons only at the lowest electron beam energies, but with the excellent invariant mass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



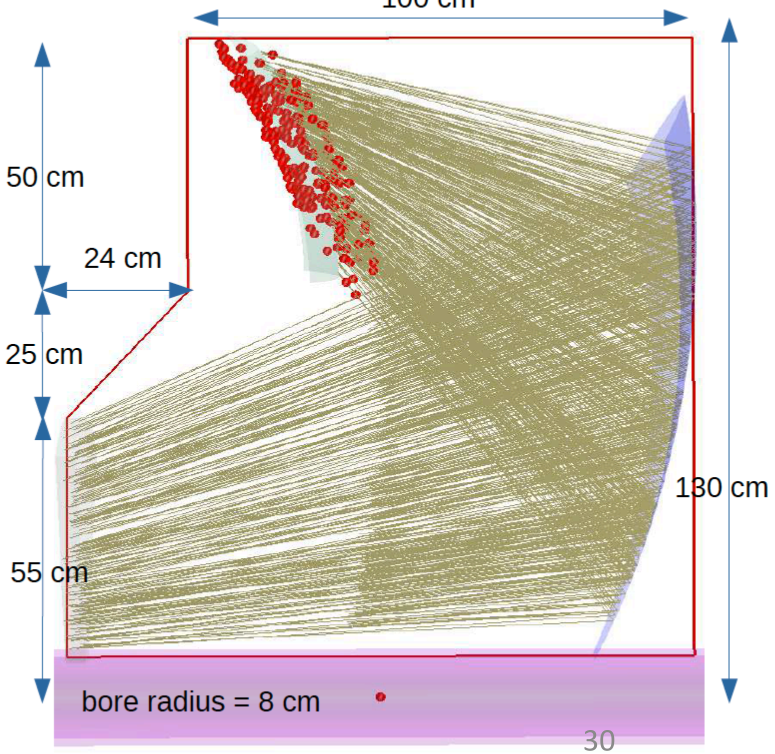


eRD14 dRICH

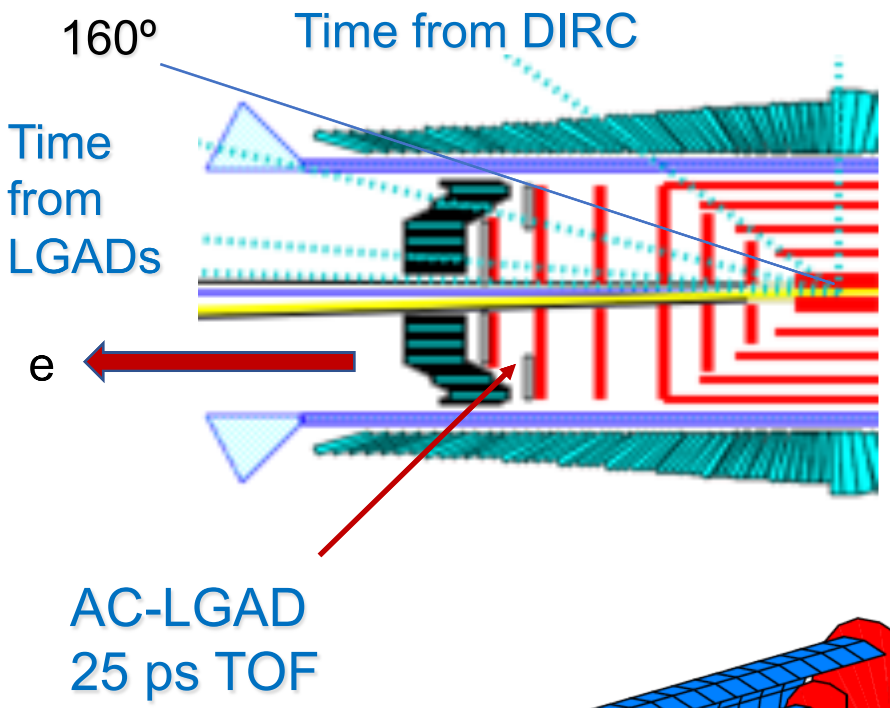
- The CORE dRICH is a smaller version of the eRD14 design
  - Most dimensions were scaled by a factor 2, but the length of the gas along the beam was only reduced from 1.6 m to 1.2 m (25%).
  - The resulting geometry provides a good match to the photosensor plane and a photon yield almost as high as the eRD14 dRICH
  - The 55 cm aperture matches the inner radius of the barrel EMcal

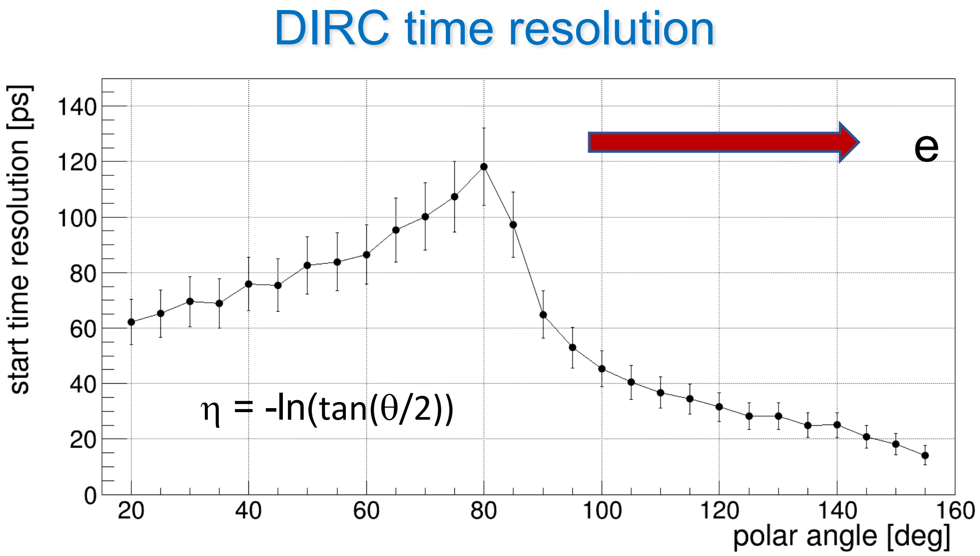
- The CORE dRICH performance should be close to that of the original eRD14 dRICH, with continuous π/K coverage in RICH mode for 2-50 GeV/c, and positive pion ID below kaon threshold.

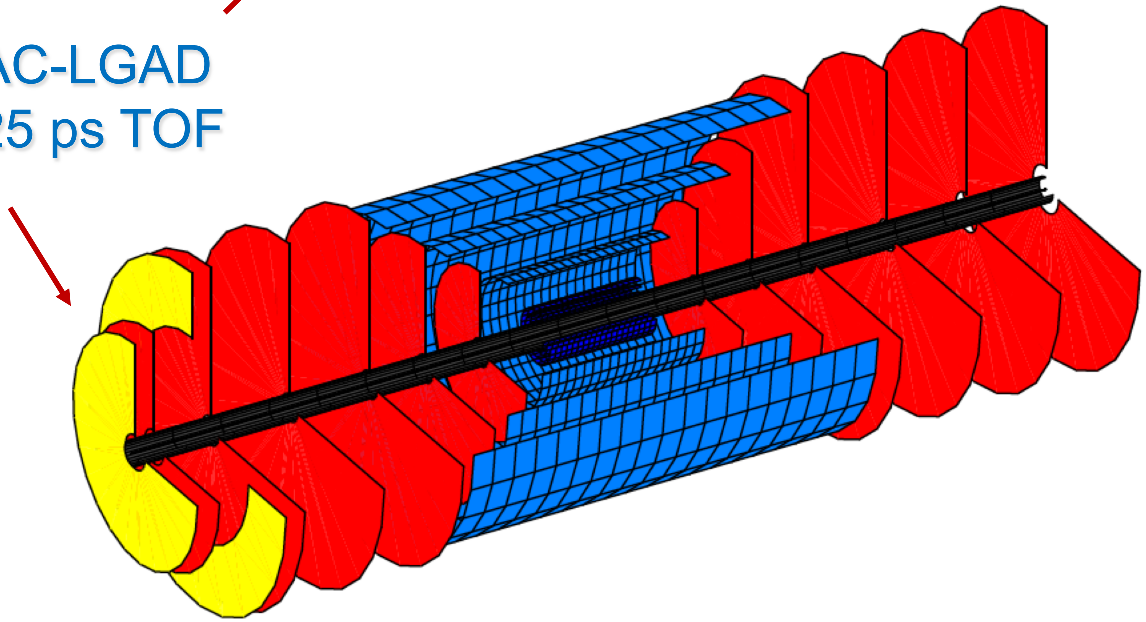
CORE dRICH



Time measurement in the electron endcap and barrel







- 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.