Few Degree Calorimeter with SiPM-on-tile technology

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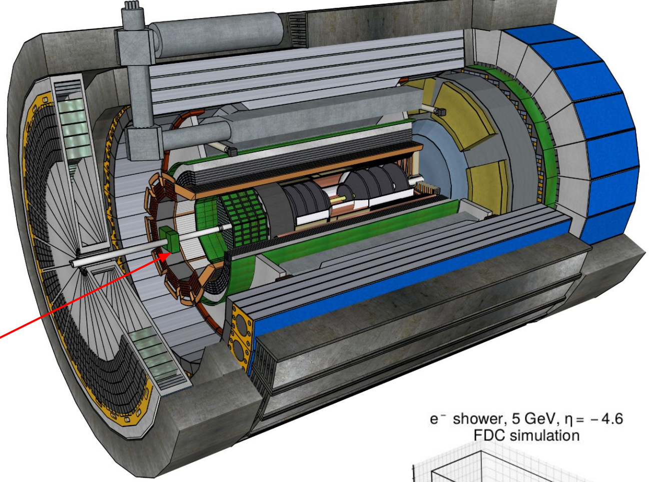
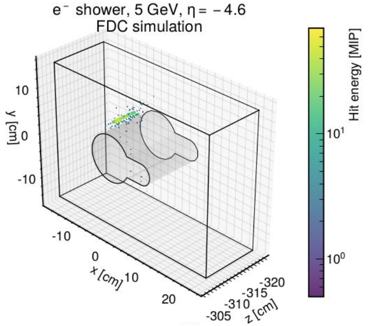
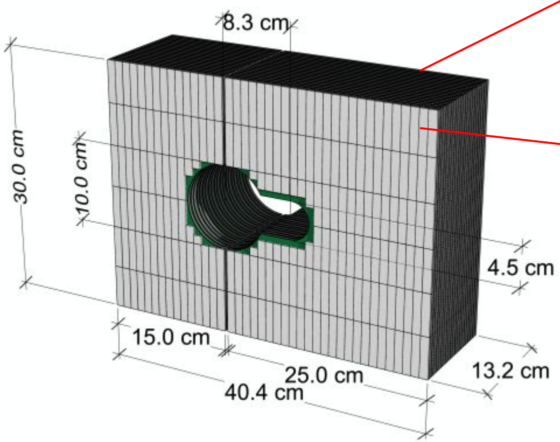
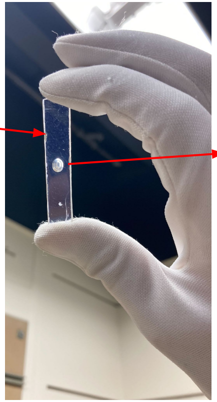
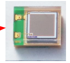
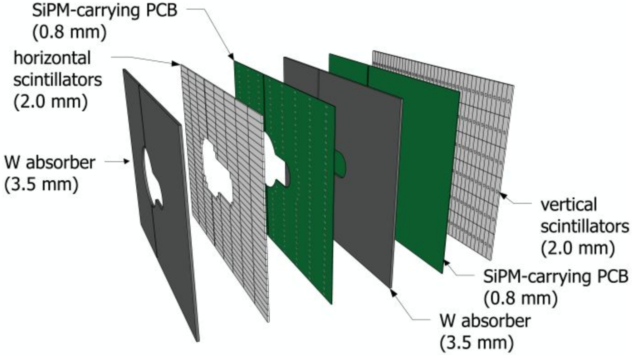












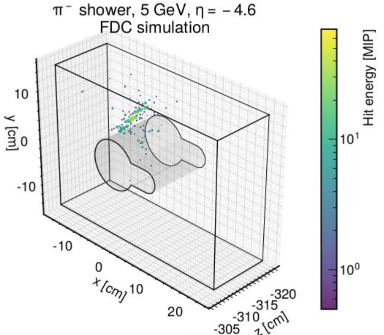
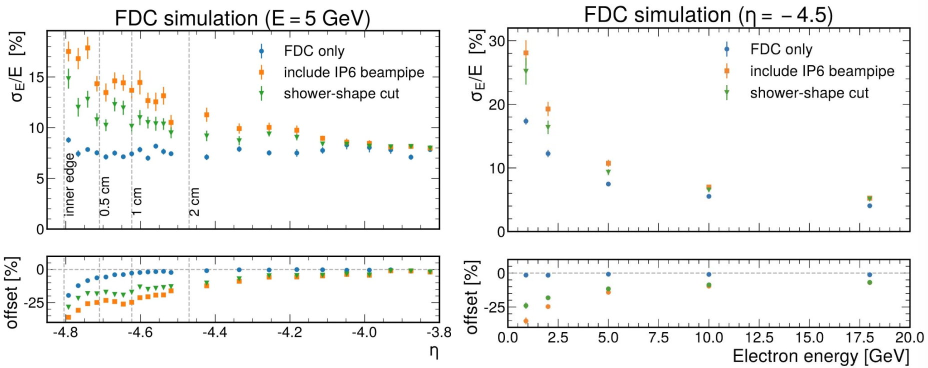


Figure 6 shows the amount of dead material as a function of pseudorapidity. Please show the effect on the energy resolution, (sigma/E) for these trajectories, and compare to the needed energy resolution.

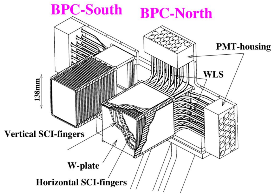
For a worse-case scenario of 2 mm Al pipe with IP6 layout, we indeed see a degradation of performance, see right. This can be mitigated with a simple shower shape cut (green).
Performance still would still be sufficient to perform measurements within fiducial region η>-4.6. We estimated a bin-migration purity and stability for 5 bins per decade in Q2 an x to be above 60%.

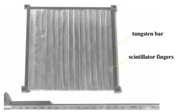
On the other hand, as we wrote in the proposal, we also seek to develop the FDC idea for an optimized detector-II layout, with Beryllium or exit window that would largely mitigate the material budget issues.

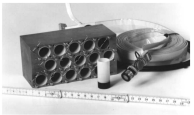


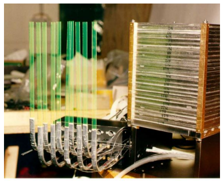
Could you comment on the construction details for the ZEUS BPC (section 2.3)?

See image on the right. ZEUS BPC used a neat design that minimizes number of channels, as photosensors and readout electronics were expensive back then. The situation changed drastically since then, given the advent of SiPMs & associated ASICs like the HGROC.









B. Surrow's slide

Page 9 section 2.5 mentions longitudinal and transverse segmentation for electron/hadron discrimination. The GAMS and L3 groups concluded transverse segmentation was enough, i.e. electron/hadron discrimination did not particularly improve by adding longitudinal segmentation. Have you studied this, and/or do you have any comments on this? It certainly seems reasonable to have a charged-particle tagger directly in front of the proposed calorimeter.

For high-granularity CALICE-style calorimeters like the FDC, longitudinal info is powerful, as has been shown explicitly for example in this recent paper: arXiv:2310.09489. See table 2 shown on the right, which shows longitudinal variables is the most-impactful variable in a BDT approach.

As we wrote in the proposal, a goal of this project is to quantify the FDC background rejection power using 5D showers across the EIC energy, using optimal reconstruction.

It's worth noting that the ePIC barrel ECAL features fine longitudinal segmentation, aimed at improving e/π separation across same energy range.

Table 2: Ranking of separation importance between electromagnetic showers and hadronic showe

Rank: Variable	Variable weight
1: Z depth	0.532
2: Shower radius	0.186
3: Shower layers	0.073
4: Fired layers	0.065
5: Shower density	0.370
6: Shower start	0.026
7: Shower layer ratio	0.022
8: FD_1	0.018
9: Hits number	0.013
10: FD_6	0.012
11: Shower end	0.009
12: Shower length	0.006

Table 3 in section 3.1 gives 20 radiation lengths as a proposed thickness. Have you studied shower leakage and effects on energy resolution, transverse position resolution, and e/hadron separation in choosing this number? I,e. is the proposed device "thick enough"?

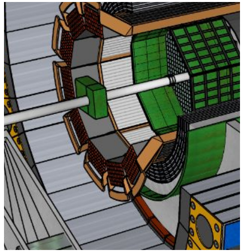
FDC design is subject to optimization. This will be done in the proposed project.

Are the proposed tests in section 4.4 at JLab Hall D to use tagged photons there? 1-8 GeV?

We will use positrons from Hall-D pair spectrometer. This can be run parasitically with GlueX, starting from ~Fall 2024.

Please provide some (preliminary) discussion of heat generated, and thus temperatures reached, in electronics and thus the SiPM area.

No problem, as we plan to use the same strategy as with the ePIC forward HCAL, Insert, and barrel HCAL. We will position the HGROC ASICs away from the SiPM, taking advantage of the ample space available in the adjacent area.



Please comment on the potential radiation damage to the detector:

- What is the expected range of radiation dose from collision and machine background?
- What is the expected per-tile zero-suppression threshold after the max dose accumulation of one EIC full luminosity run?
- What is the expected performance of the detector after the max dose accumulation of one EIC full luminosity run?

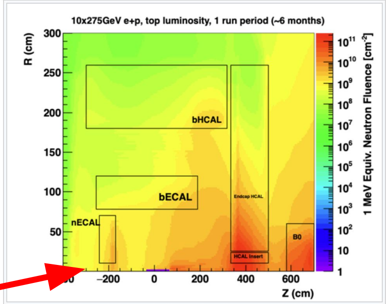


Figure 7: 1 MeV equivalent neutron fluence for minimum-bias PYTHIA e+p events at 10x275 GeV @ top machine luminosity for 6 months of running at 100% machine

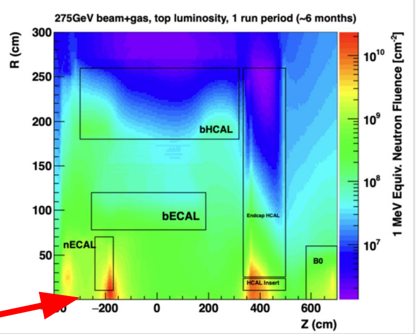


Figure 17: 1 MeV equivalent neutron fluence for 275 GeV hadron beam+gas events @ top machine luminosity for 6 months of running at 100% machine and detector

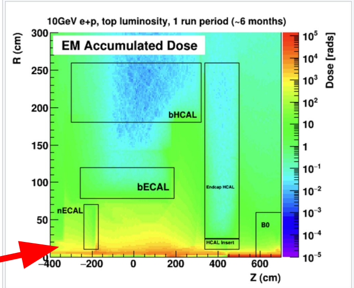


Figure 13: EM radiation dose for 10 GeV electron beam+gas events @ top machine

- https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses contains estimates for doses and neutron fluence from collisions, proton-gas and electron-gas interactions for ePIC. Taking that as estimate, we see that the FDC location is not a particularly high-radiation environment.
  Dose: ~1krad per year
  Neutron fluence: ~10e9 1 MeV n / cm2 per year
  Note that SiPM-on-tile tech will be used in areas with much higher dose and neutron fluence in ePIC (e.g. in the HCAL Insert or the ZDC), not to mention the LHC.

- Threshold will be ~0.5 MIP per tile, which will corresponds to ~10 pixel, yielding significant buffer so no rad damage is expected.

- The FDC performance is expected to not be significantly affected due to radiation damage under normal operating conditions.

Please discuss the expected hit rate with collision and beam gas interactions in the proposed FDC, and is there any concern for pile-up in the HGROC TOT/TOA TDCs ?

Such studies of hit rates / threshold studies are being completed in ePIC and we do not have numbers for FDC yet. We will study this when simulation frameworks needed to do so become established and available.

Please compare the proposed FDC with a potential PbWO4 FDC .

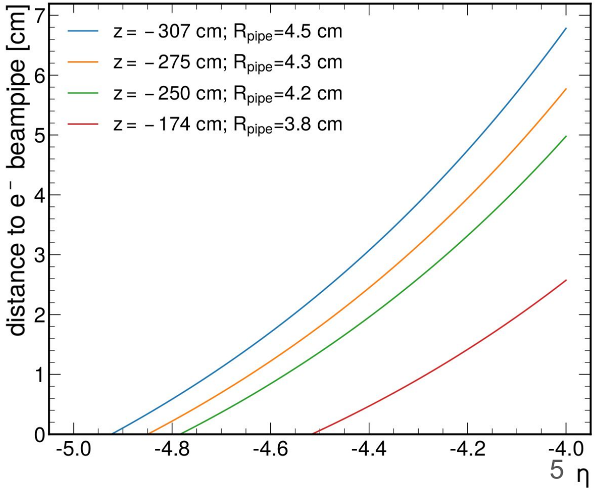
PbW04 without supporting momentum from tracking (thus without E/p cut to reject pions) is not very attractive for this application and likely would not deliver on the required pion rejection. It has a lot of cons with respect to Scintillator/Tungsten calorimeter:

Cons:

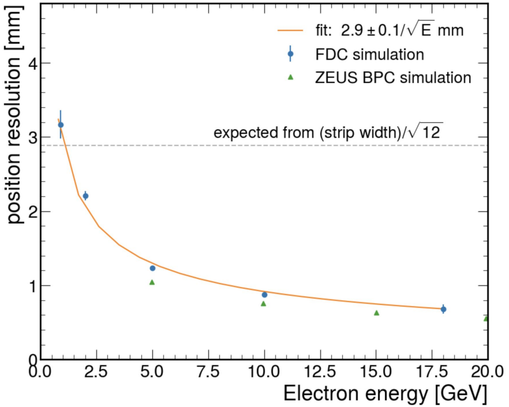
- Larger Moliere radius which reduces effective acceptance.
- Ratio of λ to X0 is ~20% higher than that of tungsten, i.e. more hadron background.
- Coarser transverse segmentation (Sc/W strips can yield effective ~5x5 mm2)
- Poorer timing measurements (both per-channel and per-shower).
- No longitudinal segmentation (decreasing background rejection power).
- Requires cooling.
- Less tolerance to radiation damage.
- Not self-supporting, so instrumenting complex shape effectively is not possible.

Pros:

- Better energy resolution



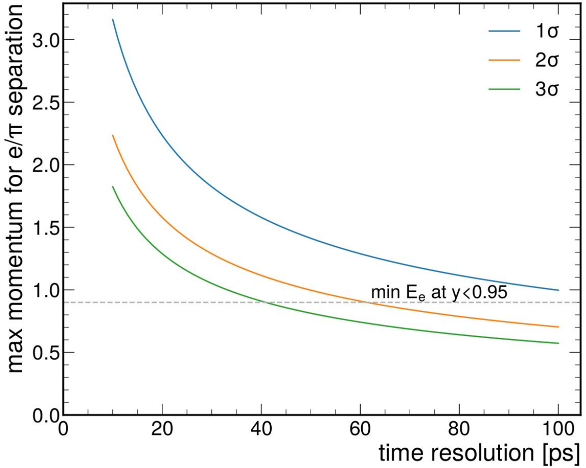
Please comment on the discrepancy between the position resolution requirement and the simulated performance.

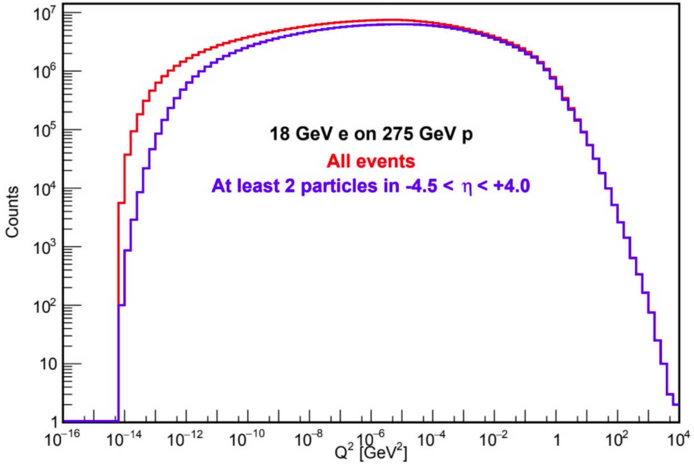


Was mainly due to tuning of cut off used in the log-weighting algorithm (updated on the right plot)
Remaining differences due to difference in width (10 mm vs 8 mm used in ZEUS BPC)
In any event, the FDC strip width is subject to optimization during the proposed project.

Please comment on the strategy to obtain T0 for the FDC TOF-based pi/e separation for the low-Q2 events under study.

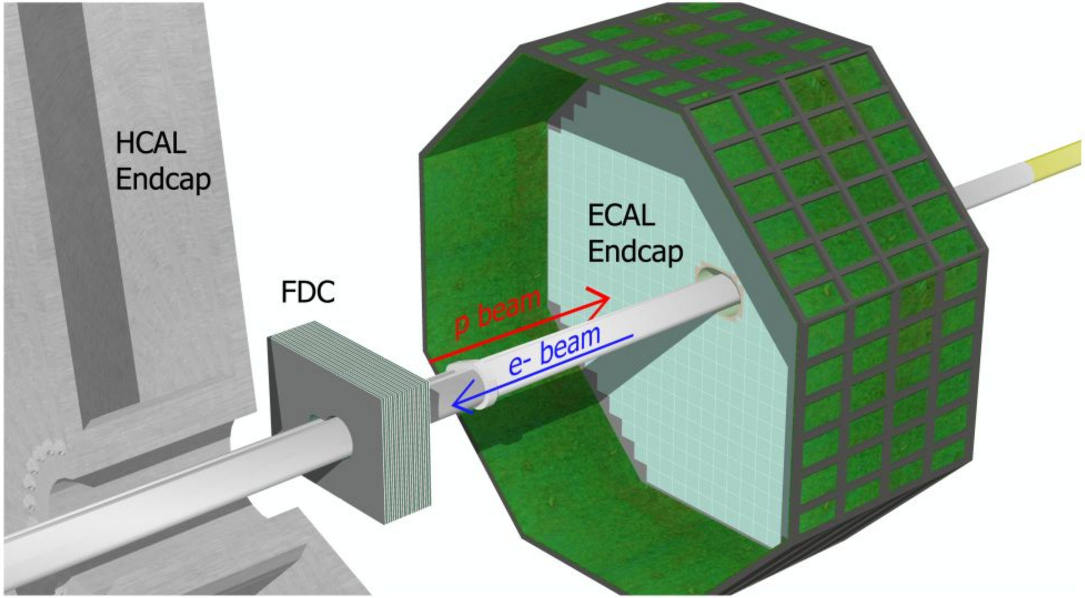
From other produced particles in the event that are measured in the central detector TOF systems and use their standard methods to get T0. Our studies using Pythia6 indicate that above 99% of events of interest for FDC have more than 2 particles, which can be measured from the TOF detectors.





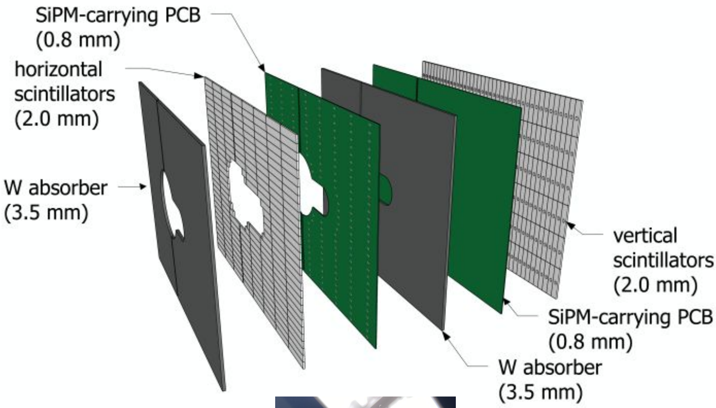
The FDC R&D proposal aims to develop:

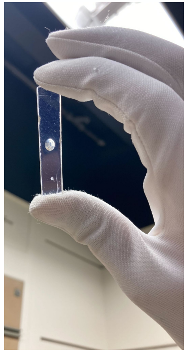
The Idea



"A Few-Degree Calorimeter for the future EIC" arXiv:2307.12531

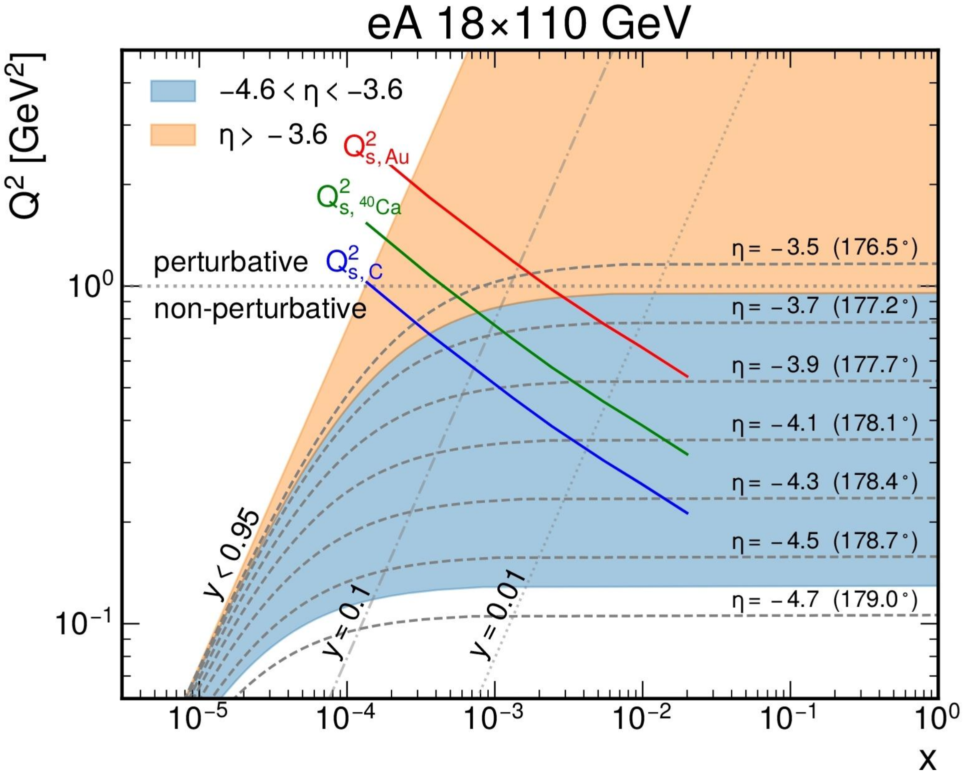
The Technology



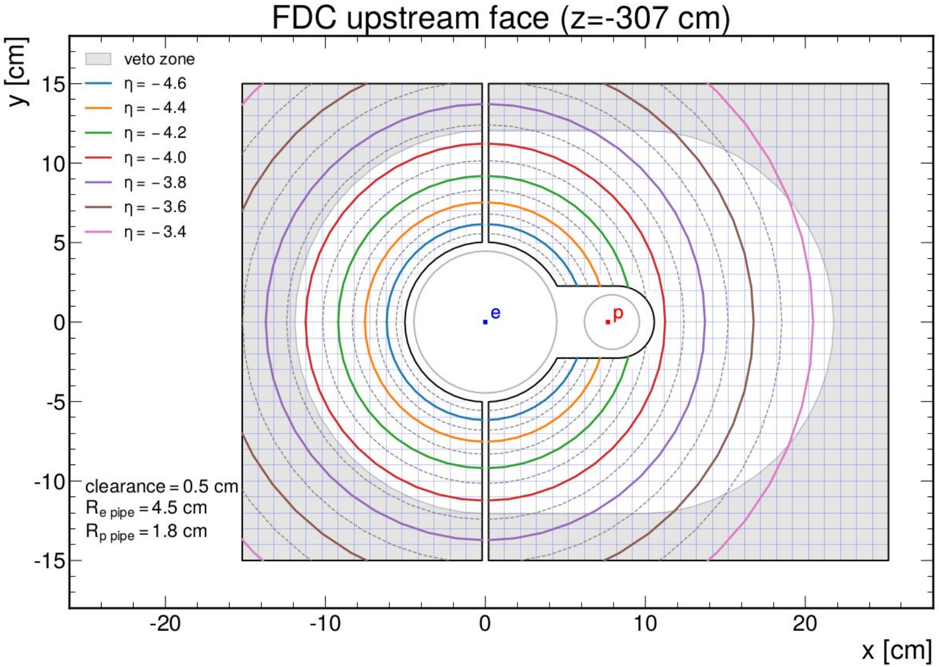


Motivation for a Few-Degree Calorimeter (-4.6<η<-3.6)

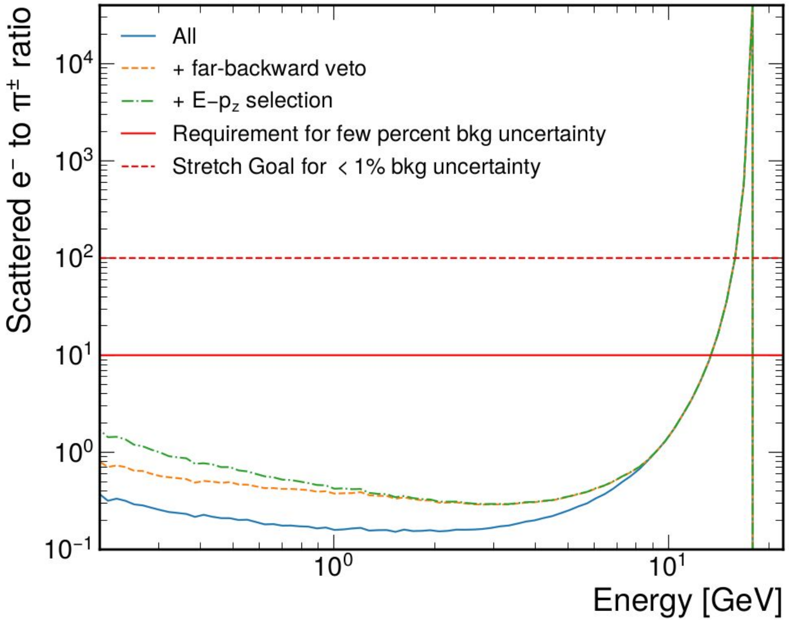
- Lepton Endcap ECAL cannot cover η<-3.6, given minimum radius and location.
- Covering lower angles is required to probe transition to perturbative regime and onset of Gluon Saturation, which requires measuring $0.1<Q^2<1.0$ GeV^2 at top energy.
- FDC is the first, and so far only, concrete proposal to solve the "Q^2 gap"



Challenges: acceptance & bkg rejection

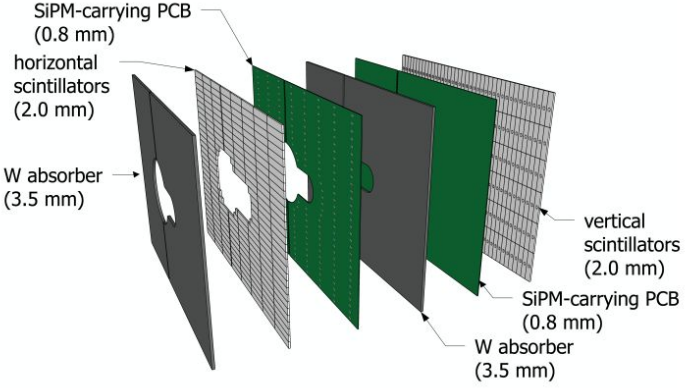


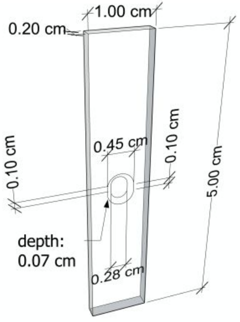
Reaching η=-4.6 demands small Moliere Radius

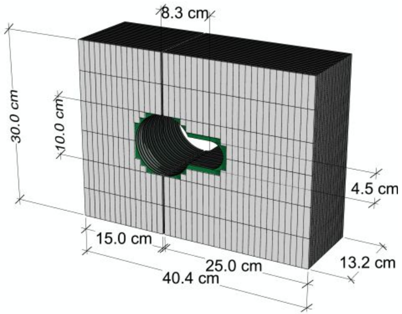


Standalone bkg rejection required (without momentum from tracking!)

FDC design is based on SiPM-on-tile technology







Proposed design, yet to be optimized, is a modern and improved version of ZEUS BPC

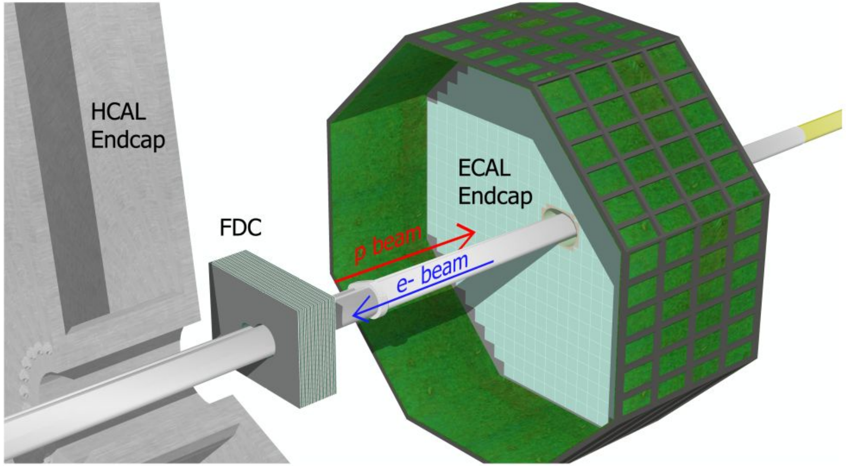
Table 3: Summary description of our proposed EIC FDC, the ZEUS BPC and the CEPC/CALICE ScECAL. The number of channels for CEPC/CALICE refer to the latest prototypes.

	ZEUS BPC	CEPC/CALICE	**EIC FDC**
Test beam	1994	2023	**2024 planned**
Depth	24 X_0	22 X_0	**20** X_0
W/Sc thickness	3.5/2.6 mm	3.2/2 mm	**3.5/2 mm**
Moliere Radius	13 mm	19 mm	**15 mm**
Optical readout	WLS bar+PMT	SiPM-on-tile	**SiPM-on-tile**
Trans. granularity	8×150 mm^2	5×45 mm^2	**10×50 mm^2**
Long. granularity	none	every strip	**every strip**
Readout channels	31	6720	**4500**
Electronic readout	FADC/TDC	SPIROC2E	**HGROC**
Readout location	outside	inside	**outside**
Position resolution	$2.2\ \text{mm}/\sqrt{E}$	—	$\mathbf{2.8\ mm}/\sqrt{E}$
Energy resolution	$\frac{17\%}{\sqrt{E}} \oplus 2\%$	$\frac{15\%}{\sqrt{E}} \oplus 1\%$	$\frac{17\%}{\sqrt{E}} \oplus 2\%$
Time resolution	400 ps	—	**<50 ps**

Possible FDC incarnations

ePIC

- Cost effective, small upgrade, but beampipe was not optimized for measurements at a few degree



Detector II

- IP8 will use larger crossing angle (bigger ECAL hole) so bigger need for it.
- Offers possibility of optimized layout, e.g extended Beryllium pipe or dedicated exit window.
- Potentially access even smaller Q^2 range.

FDC idea can foster complementarity. We will flesh it out during this project.

Research prongs

Test-Bench Measurements and Timing Studies
We will develop the design of the FDC by establishing a set of baseline measurements for its building blocks. Our main emphasis will be on timing studies and timing layer development, as this area is experiencing rapid development (work ongoing by CEPC/CALICE that aim O(10) ps).

Exploring the Potential of 5D High-Granularity for Background Rejection
We will perform detailed simulations for comprehensive evaluations of the FDC capabilities to quantify background rejection using 5D reconstruction algorithms.

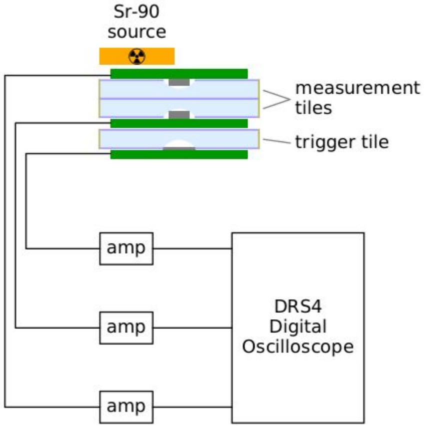
The First FDC prototype
We will construct an FDC prototype and conduct testing at JLab in Sep. 2024. The objectives of this test beam are to validate FDC simulations, and demonstrate the production capabilities, operation, and calibration of the SiPM-on-tile strip ECAL design.

Deliverables and Intermediate Milestones, part I

Fully characterize scintillator strips and SiPMs, and define design parameters

- Perform light yield measurements using cosmic rays and a Sr-90 source
- Characterize cell uniformity using a Sr-90 source
- Measure time resolution and its dependence on light yield using a picosecond laser.
- Iterate the above steps, varying strip geometry, width, and SiPM size.

We will use existing setups and expertise that we developed for Calorimeter Insert (different geometry and design).
We'll optimize a FDC "timing layer" by varying: cell geometry and size , SiPM size and number, tile-SiPM coupling, scintillator type.
Goal: ~100 ps for 100 p.e. per tile -> O(10) ps timing for shower. CEPC and CALICE are pursuing this too.



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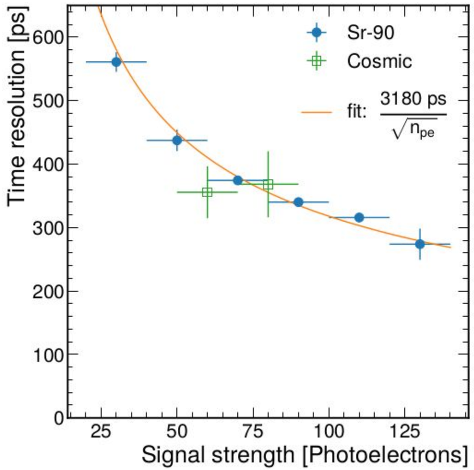
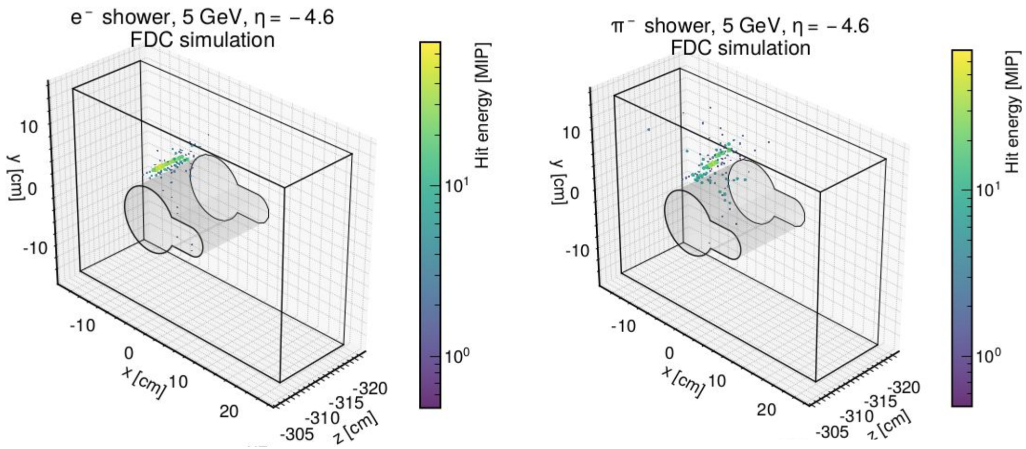


Deliverables and Intermediate Milestones, part II

Finalize the design of the FDC based on SiPM-on-tile technology, guided by full simulations.

- Define the tradeoff between sampling fraction (to improve energy resolution) and Moliere radius (to increase acceptance).
- Determine the optimal granularity per layer to enhance rejection of converted-photon, Hadron and beam-gas backgrounds
-Incorporate the design of the timing layer or pre-shower system into the FDC design.



Shown is effective granularity

Building upon our recent work (arXiv:2310.04442, arXiv:2307.04780 and arXiv:2308.06939), we will conduct studies of 5D regression employing state-of-the-art graph neural networks to fully quantify the potential of FDC.

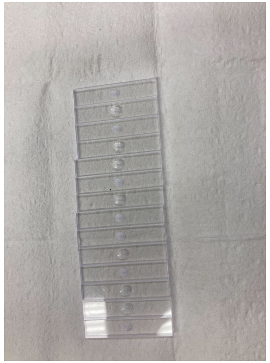
Deliverables and Intermediate Milestones, part III

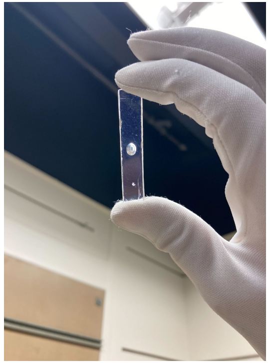
Construct a prototype of the detector that will be ready for beam testing.

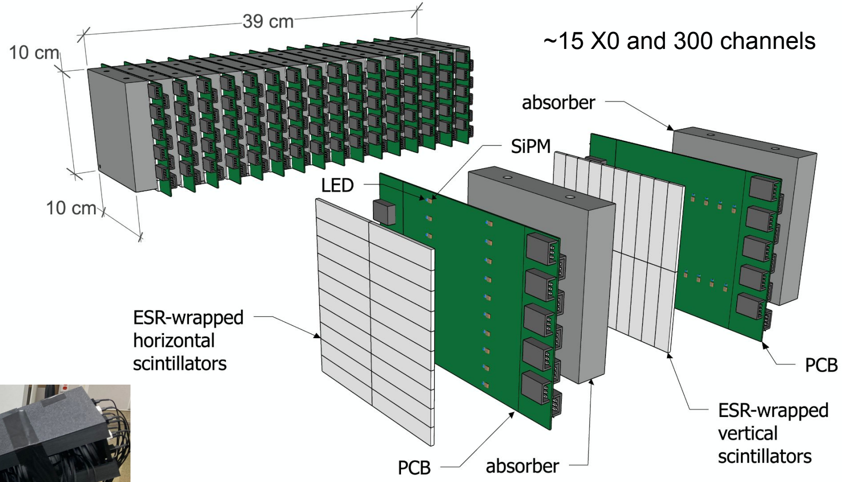
-Complete and test the procedure for scintillator strip machining.

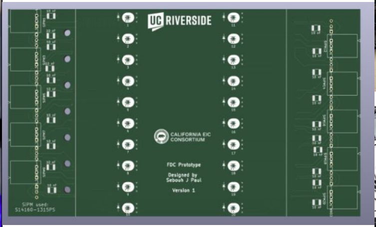
-Define the assembly procedure per layer, including ESR wrapping and SiPM soldering.

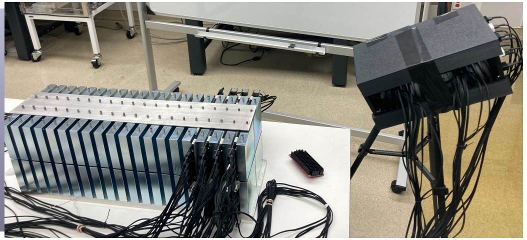
-Calibrate each layer using cosmic rays.











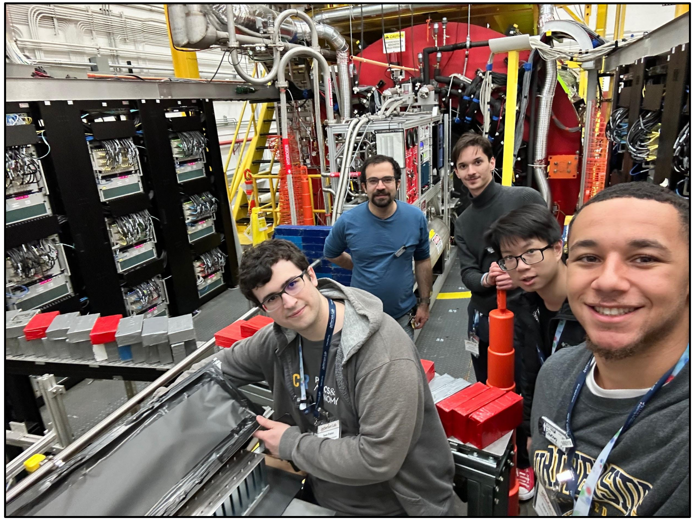
Deliverables and Intermediate Milestones, part IV

Our group has experience doing similar studies for ePIC Calorimeter Insert (HCAL)

Conduct a beam test of the prototype and analyze the results.

-Transport the prototype to JLab Hall-D for testing with positrons. Expected in ~September 24
-Complete beam test run.
-Analyze the collected data.

Submit a paper to journal and present the results at conferences.



The objectives of this test beam are to validate FDC simulations, and demonstrate the production capabilities, operation, and calibration of the SiPM-on-tile strip ECAL design.

"Beam Test of the First Prototype of SiPM-on-Tile Calorimeter Insert for the EIC Using 4 GeV Positrons at JLab" M. Arratia et al. (arXiv:2309.00818)

Budgets

Table 5: Budget with various scenarios. These numbers include the 55% UC overhead rate.

Material	Description	100%	80%	60%
Prototype materials	as per Table 4	$102k	$75k	$60k
UCR grad student	4 months FTE	$30k	$30k	$18k
UCR travel	Trip to JLab	$2.5k	$2.5k	$2.5k
Total		$135k	$108k	$81k

Table 4: Estimated Cost of the FDC Prototype. The quantities of SiPMs and scintillators include spare units.

Material	Description	Units	Cost per unit	Total cost	Info
Scintillator	EJ-212 $10 \times 10 \times 0.2$ cm	40	$80	$3.2k	Recent quote
SiPMs	S14160-1315PS	500	$22	$11k	Recent quote
ESR foil	26×26 in sheet	2	$2k	$4k	Recent quote
PCBs	0.8 mm from OSH-Park	20	$80	$1.6k	Recent quote
Bias and readout	CAEN FERS-5200	5	$8k	$40k	Recent quote
Supplies	Glue, wipes, gloves, etc	—	—	$3k	Educated guess
Fe blocks	$10\times10\times$ 3 cm^2	—	—	in kind	–
Machining	UCR machine shop	100 hr	$36	$3.6k	Educated guess
Total				$66k	

Summary

Idea: Our proposal addresses an emerging and urgent need recognized by the EIC community.
The FDC is the first, and so far only, concrete solution to bridge the Q^2 gap.

Technology: Our proposal aims to import and further develop the latest advances in SiPM-on-tile calorimetry to create a modern and improved version of the ZEUS BPC. The high-granularity 5D shower (position, time, and energy) measurements offers potential for improved background tagging.

Context: The SiPM-on-tile technology is a key pillar in global calorimetry R&D and is supported by an active community, including groups from ILC, CEPC, LHC, among others.
Its absence from the EIC's generic R&D portfolio would represent a missed opportunity.
Note that ePIC plans to implement SiPM-on-tile technology in the Insert HCAL, forward HCAL, backward HCAL, and ZDC HCAL, thereby highlighting its potential for EIC applications.

The Big Picture: A broad objective of this proposal is to import and further develop the SiPM-on-tile technology for electromagnetic calorimeters at the EIC.

Complementarity: While investigating the feasibility of integrating an FDC into either ePIC or Detector 2, the latter option offers more opportunities for optimization, i.e. extended Be pipe or exit window.

The Team: We first advocated for using SiPM-on-tile technology in ePIC,
and proposed and designed the HCAL Insert and ZDC HCAL.