Proposal for the GENERIC EIC-RELATED DETECTOR R&D PROGRAM

Tracking and PID with a GridPIX Detector

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We propose to investigate the low momentum PID & tracking capabilities of a GridPix-based gas detector configured as a mini-TPC. This device would be envisioned to be placed interstitially between layers of Silicon-based tracking in either the project detector (as an upgrade) or a second detector. This proposal describes the first year of what we anticipate to be a multi-year project and leverages the existence of equipment from prior R&D programs (namely sPHENIX-TPC and ILC-TPC) to be both cost effective and impactful in the very first year.

1 Motivation

The Electron-Ion Collider (EIC) will be an exceptional machine with a broad physics program. Both the beam collision energy and the beam species (electron on anything) can be rapidly changed and the machine's high luminosity will allow for investigation of phenomena with quite small cross section. Fittingly detector designs for the EIC strive to make a complete and unbiased sampling of events. The unbiased aspect stems from the fact that the EIC experiments plan to use a triggerless data acquisition for which every struck channel reports data regardless of some master decision. Completeness is achieved via an attempt to fully measure all characteristics of the debris from every collision and with high precision.

The Yellow Report [1] resulted from the community-wide effort to design a detector system capable of meeting these challenges and furthermore specifying the detector characteristics necessary to achieve the broadest range of currently sought physics goals. Among the most challenging aspects of the EIC is the particle ID task. Traditionally, difficulties in PID focus on the maximum momentum at which the three most common hadron ejectiles (pion, kaon, proton) can be distinguished from one another. Indeed, the Yellow Report in many ways advances the task of particle identification by pushing simultaneously upon the competing issues of PID reach and compactness of the detector. However, practical factors also complicate the PID task at the very lowest momenta.

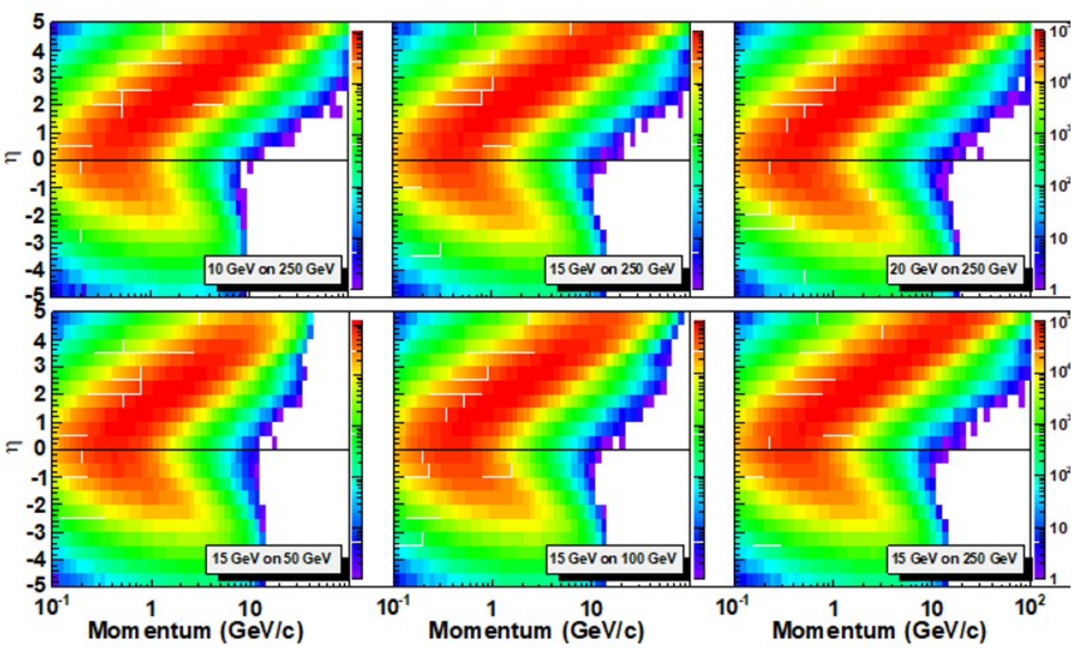

Figure 1: Pion yield as a function η and momentum for a variety of collision kinematics. The cases plotted span a significant range in both electron and ion momentum. Nonetheless, hadron yields near zero pseudo-rapidity all have the same character with the most yield below 1 GeV/c.

Figure 1 shows the yield of pions as a function of η and lab momentum for a variety of collision kinematics covering a range in both electron and hadron initial state energy. While the strong dependence of PID needs in the positive eta direction have a clear dependence on the collision kinematics, the regime near $\eta = 0$ remains largely unchanged. Not shown in the figure, but true nonetheless is that the pattern is similar for kaon and proton production. The characteristic is that near mid rapidity hadron spectra at the EIC are rather soft with the overwhelming flux of charged hadrons having momenta below 1 GeV/c.

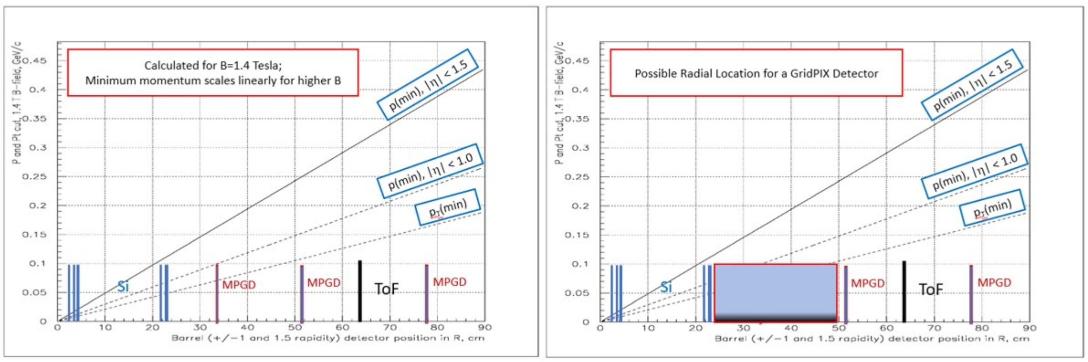

Figure 2: Low momentum particles will form tight spirals in a high magnetic field. As a result, there exists a linearly rising ”minimum” transverse momentum required for particles to reach a detector plane at any given radius. PID thereby acquires a minimum momentum due simply to the geometric placement of the first PID layer.

The characteristic of any magnetic spectrometer is that the highest resolution is achieved by selecting the highest possible magnetic field in combination with the most highly segmented position sensors having the least possible detector mass. All proposed EIC detector designs have featured the use of a superconducting magnetic (1.4 - 3 Tesla) combined with highly pixelated silicon sensors as the mainstay of the tracking system. This has a consequence upon the lowest momentum reach for all such detectors. This consequence illustrated in Figure 2.

In a uniform axial magnetic field there will be a linear relation between the radius at which any detector system resides and the minimum transverse momentum required for a charged particle to reach that detector. This relation even for the lowest field magnet considered for EIC (1.4 Tesla) will eliminate PID for any particle that does not reach the PID layer of the detector. Because the traditional display of particle yield uses momentum rather than p_T, additional lines have been added to the plot for particles produced at η = 1.0 and η = 1.5. As illustrated by the panel on the left, if the first PID layer were a TOF system located at a radius of roughly 65 cm, a substantial fraction of charged hadrons produced in the collisions have their momenta tagged, but their ID unknown.

The ATHENA proposal, (3 Tesla) chose to specifically address this issue by extending the capabilities of PID down to small radius. Although a TOF detector can indeed be placed at any radius, it loses its efficacy as the flight path becomes small. The natural alternative is to turn toward $\frac{dE}{dx}$ measurement to achieve PID near the beam pipe. Figure 3 shows the various technology options considered by ATHENA with the GridPIX TPC as the champion of low

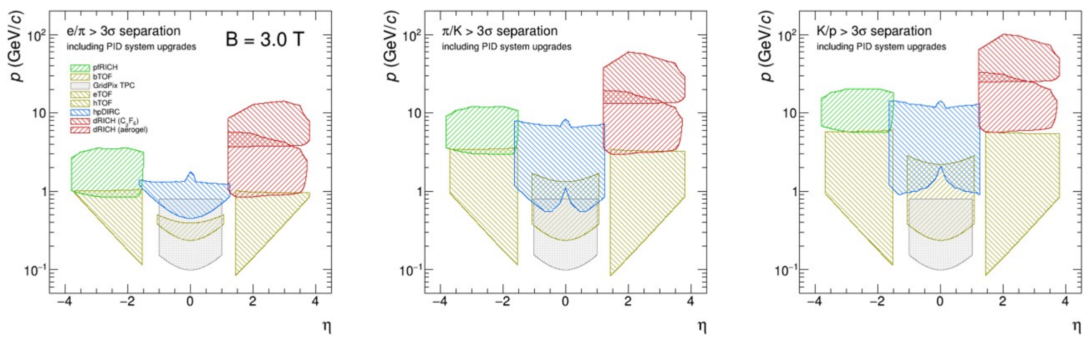

Figure 3: $\frac{dE}{dx}$ PID was thoroughly considered in the ATHENA proposal as a possible upgrade scenario. This plot shows the momentum and η coverage of each technology. Numerically $\frac{dE}{dx}$ identifies the largest number of particles in this detector design.

momentum at $\eta = 0$.

ATHENA decided that the concept of a GridPIX TPC, will attractive and likely rather effective, was no a mature enough technology to be included in the baseline. Instead, this technology was considered as an upgrade option that should be subject to further R&D. Additionally, as recently as July 2022, the newly forming ”Detector One” experiment requested an update on the status and plans for the GridPIX technology. Out status report to Detector One delivered the same message as our reports to ATHENA: [1]We are glad that you are interested in and recognize the promise of this technology. [2]We plan to pursue it as part of the EIC generic R&D program.

2 Implementation

2.1 Conceptual Design

The process of ionization in a gas is a multi-step phenomenon. First, interactions between the charged particle and the surrounding gas produce ionizations known as ”primary” electrons. The statistics of primary ionization are purely Poisson in nature and, if directly countable, would have a $\frac{dE}{dx}$ precision that scaled with $\sqrt{N_{primary}}$. Alas, nature is not so kind and each primary ionization also produces some number of secondary ionizations (2-4 typically). The fluctuations in the secondary yield generate the long high-side Landau tail which is the bane of the existence of all detectors that attempt to measure $\frac{dE}{dx}$ as a PID technique. The two basic approaches to fighting the Landau tail up to this point are:

- Truncated mean
  - Split the ionization trail into many small samples along the length.
  - Reject all measurements whose yield is a factor f higher than the mean of the others.
  - Average the remaining samples.

- Distribution Fit
  - Split the ionization trail into many small samples along the length.
  - Fit the probability distribution of all the samples to a Landau curve.
  - Use the most probable value from the fitted Landau function as $\frac{dE}{dx}$

Both of the traditional methods require the the ionization trail be divided into as many small samples as is practical. Macroscopic pads in a traditional pan plane are rather large as compared to the typical distance between ionizations and thereby always measure the integral of charge from a large but unknown number of primary ionizations. As sort of "Holy Grail" has been the concept to move from samples of many clusters each to so-called cluster counting [2]. This quest has been one of the driving factors in the development of the GridPIX chip, which is in many respects ideally suited for PID at low momentum at the EIC. Before discussion of the GridPIX chip and the appropriate R&D initiatives require to realize its potential at the EIC, we should briefly consider a few other aspects of how the detector would be envisioned and fit into an EIC detector.

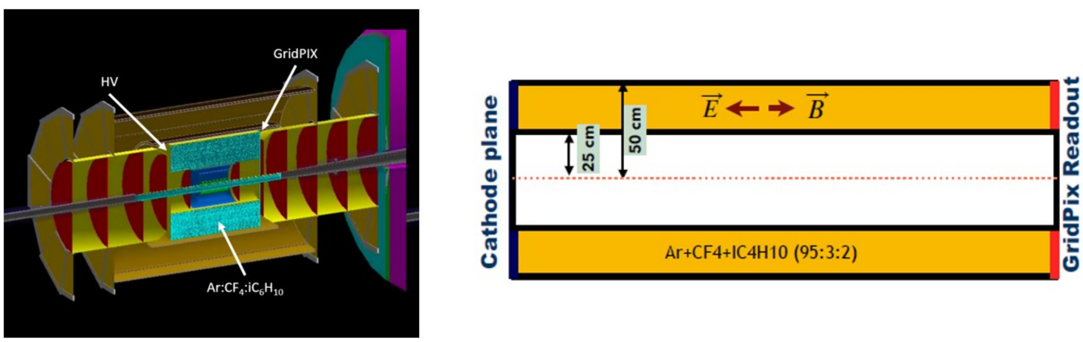

Figure 4: ATHENA studies included an implementation of the GridPIX tracking concept in GEANT. This detector positioning was selected strategically to fill the gaps between silicon layers. The basic layout, as shown in the panel on the right, implements a single-sided TPC volume with a negative cathode at negative η and a GridPIX readout plane at the positive eta end.

Figure 4 shows two panels. The leftmost panel is the GEANT4 implementation of the device into the ATHENA proposal. Different from a traditional TPC, the solution proposed here is a single ended TPC with a high voltage cathode at one end and all readout at the other end. The reasoning behind this choice is simple. Electron scattering experiments nearly always strive to measure the scattered electron with high precision as a means of determining the x and Q^2 of the collision at hand. The precision of the electron measurement (typically scatter into negative η) is of paramount importance. This single-ended TPC design effectively minimizes the material presented to the scattered electron.

We assume for now that the design of the field cage for the sPHENIX TPC can be mimicked at the EIC. That much larger device contributed only 1.5% of a radiation length from each field cage. Because the TPC here is much smaller, we conservatively assume that a thickness of only 1% of a radiation length is easily achievable.

Finally, the electrons terminate their drift by encountering the GridPIX chips where they are recorded.

2.2 The GridPIX Chip

Silicon pixel technology has seen explosive development in recent years and has become a mainstay of tracking detectors. In the typical configuration, charged particles traverse the silicon itself releasing enough ionization to be detectable with no or low avalanche again (LGAD). GridPIX is instead designed to collection the much less dense ionization trail coming from gas ionization. As such, the measurements will be dominantly none or one electron per pixel, a signal too small for detection using room temperature electronics. Thus, as it true for most gas detectors, an avalanche process is required to boost the signal size above the detection threshold.

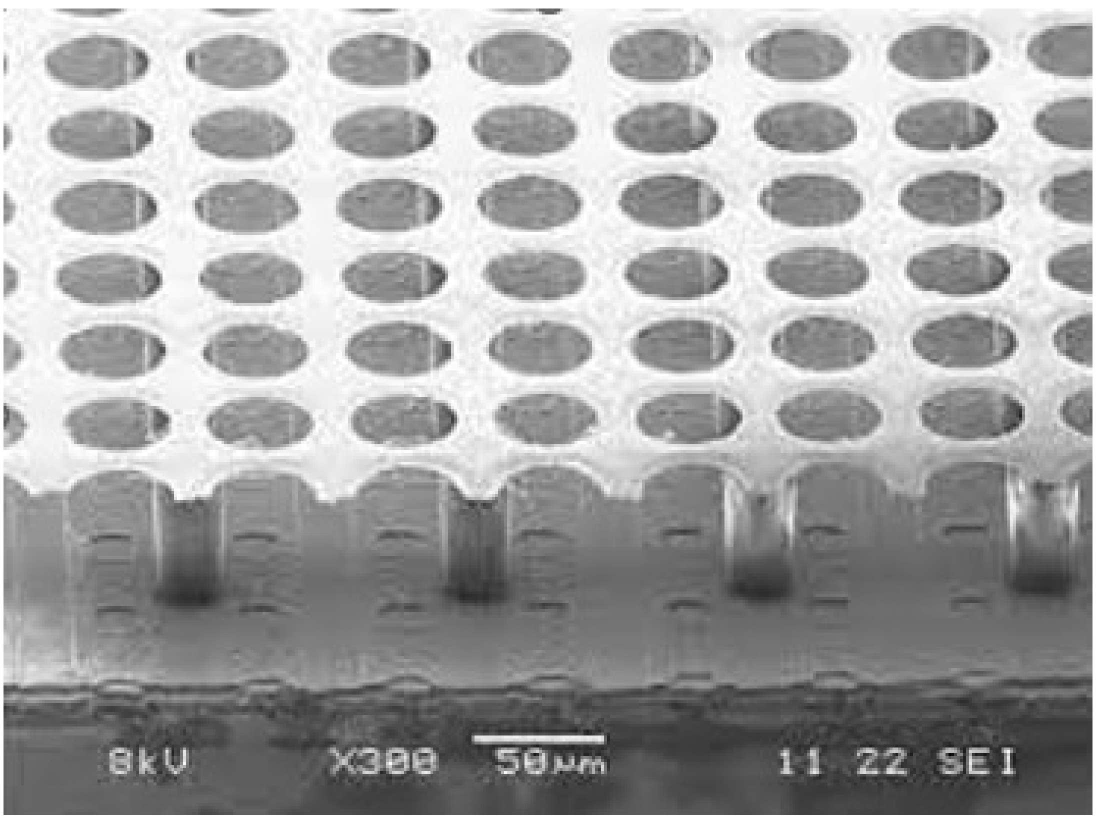

Figure 5: A magnified image of the GridPIX shows the basic operating principle of the chip. An avalanche mesh, similar conceptually to a μMEGAS, amplifies the electron signal across a small gap. Charge in then collected onto 55x55 μm^2 silicon pixels.

The GridPIX chip is the result of an extensive development campaign spanning many years,

[3] [4] [5][6][7][8][9][10] [11][12]. As shown in Figure 5, the GridPIX chip locates the pixels themselves below an etched aluminum grid. This grid yields sufficient gain that the post-avalanche signal from a single electron can be measured with higher than 90% efficiency. Below the grid is an array of $55 \times 55 \mu m^2$ pixels. Using typical Argon-based mixtures, diffusion is most often sufficient that each electron from a cluster lands in a different hole. In this way, the GridPIX detector technology promises a final realization of the long sought dream of cluster counting. Additionally, when coupled to a low diffusion gas, the GridPIX technology will act as a high resolution tracker competitive with all silicon systems.

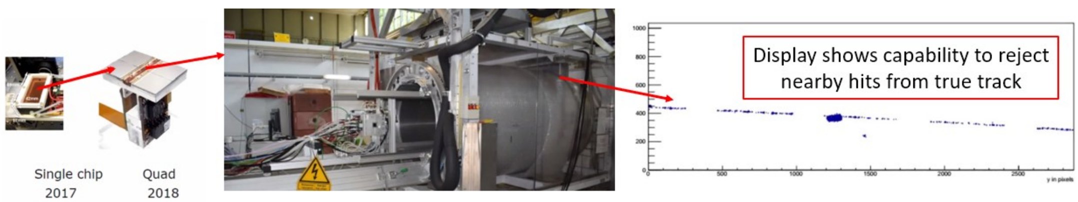

Figure 6: Building a set of chips into an array suitable for a test beam experiment.

GridPIX chips have already undergone multiple development stages, the most recent of which is GridPIX 4. The progression from the individual chip to the functioning tracker, is depicted in Figure 6. A single chip is mounter into a "quad" several of which make a "module" that is finally coupled to a gas volume to form a GridPIX tracker. The event show here is especially illustrative of the power of the high pixellation as applied to the PID task. A large "blob" that is possible a delta ray, is clearly visible near the center of the track. This can be removed topologically, thereby producing a substantial improvement in PID performance over conventional readout.

2.3 Anticipated Performance

As mentioned previously, the task of PID via $\frac{dE}{dx}$ is typically easiest at the lowest momenta. The reason for this fact is neatly summarized in Figure 7.

Notice that the axes of the figure are plotted logarithmically. The region to the left of the thick purple line indicates moment below 0.5 GeV/c the pion/kaon/proton separation is quite clear. We are not, however, proposing to build the STAR TPC with its 2 meter track length and roughly 100 samples along each track. Nonetheless, we can use the measured $\frac{dE}{dx}$ from STAR (which uses a dominantly Argon-based gas) and use known techniques to scale the resolution as a function of detector length.

Figure 8 shows in the left hand panel a so-called Lehraus plot. This analysis accumulates the measured $\frac{dE}{dx}$ for all known TPC experiments as a simple function of the length of the measured ionization trail. The world's TPC data indicates a ∼universal scaling of the energy resolution with path length. Using both the 1983 and the 2021 scaling laws, we can extrapolate the resolution prediction to our proposed detector length (25 cm) and thereby calculate with the STAR data the number of sigma separation we expect in the low momentum regime. The result

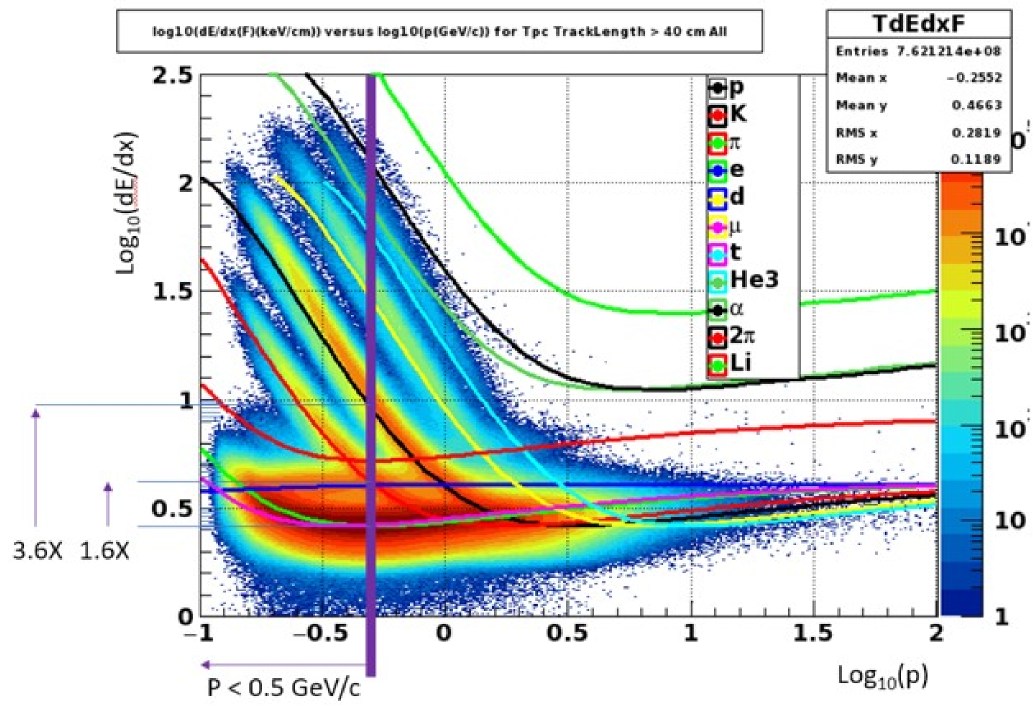

Figure 7: $\frac{dE}{dx}$ measured in the STAR TPC. The figure illustrates that the although $\frac{dE}{dx}$ measurements can be challenging in the region of the relativistic rise, the low momentum regime is comparatively simpler.

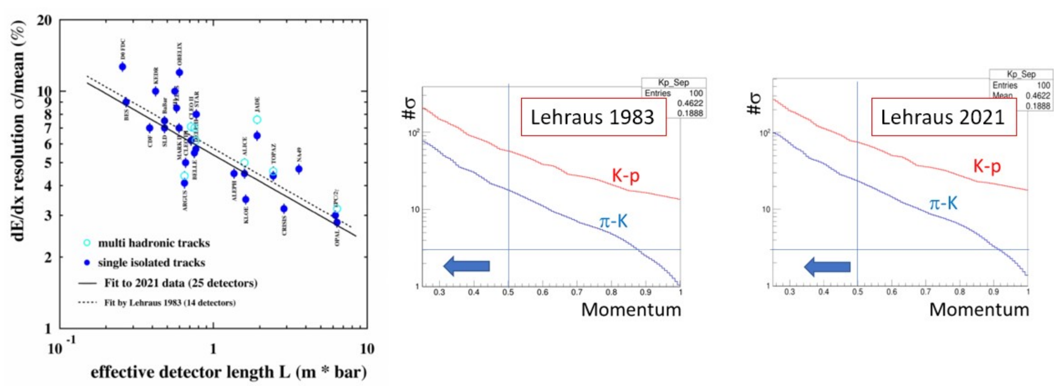

Figure 8: Lehraus has shown that all past TPC efforts lie along a universal curve correlating resolution with detector length. The parameterization of this performance allows one to extrapolate to a mini-TPC device to predict its efficacy.

is remarkable in the a worst case of 20 σ separation is observed. We take this rather optimistic result as a worst case since the Lehraus scaling applies to conventional TPC readout and the GridPIX should perform in a far superior manner. In any case, we can anticipate superb hadron

ID for all low momentum hadrons with only a 20 cm path length.

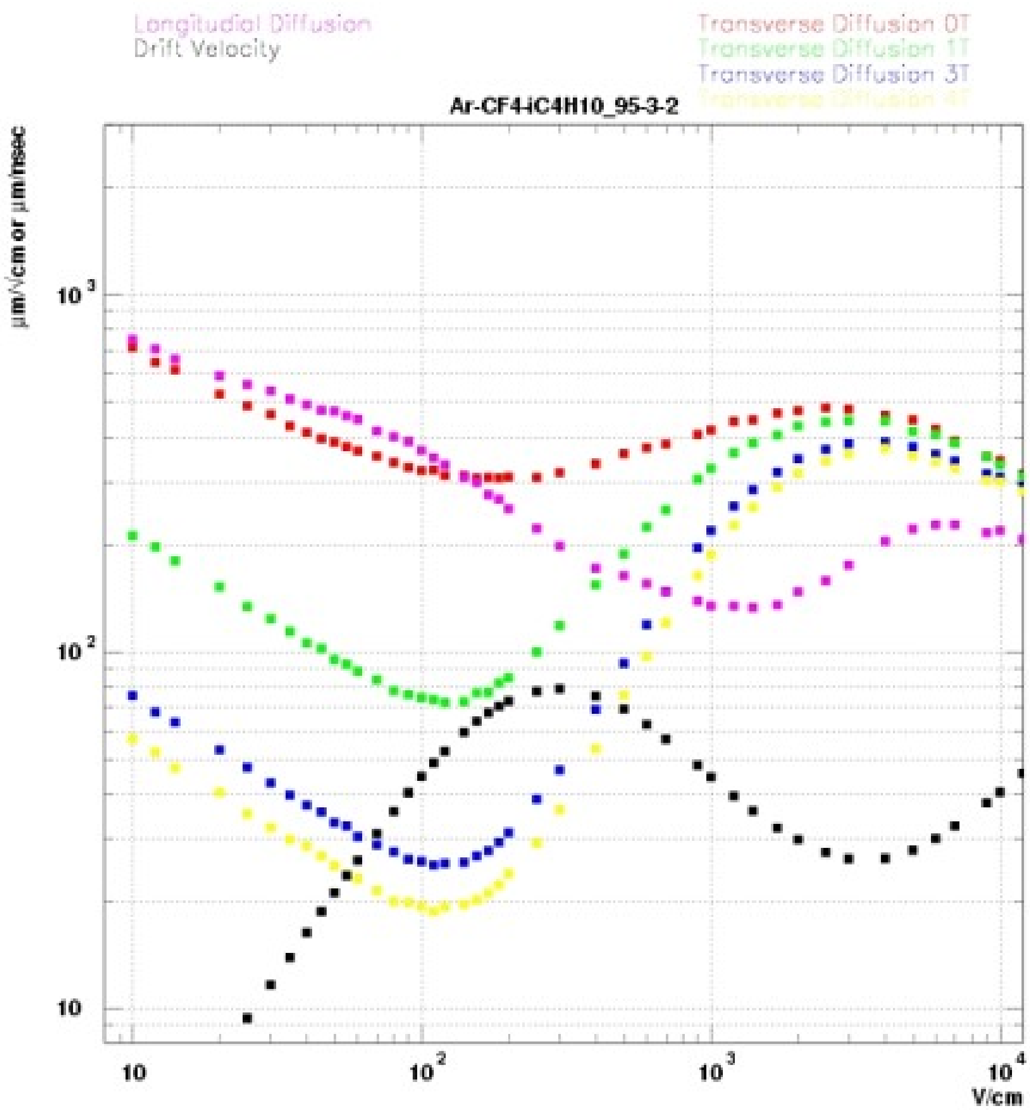

Figure 9: Transverse diffusion as a function of drift field for a variety of magnetic field values.

As a final note, Figure 9 shows the diffusion as a function of electric and magnetic fields for the gas mixture used in most GridPIX studies. This gas exhibits exceptionally low diffusion at high field and thereby makes a positive contribution to overall tracking resolution. For this reason, we anticipate that implementations wherein a GridPIX system were embedded into a silicon system like those considered by ATHENA and ECCE would overall likely have a positive impact on the momentum resolution. We note that it would certainly have a major positive impact on pattern recognition by providing thousands of points along each track. This latter consideration would certainly become more important as the machine luminosity increases over the years.

3 R & D Plans

The groups collaborating on the GridPIX project have varied and often complementary experience with detector R&D. Stony Brook has experience with gas cherenkov detectors for EIC and the sPHENIX TPC, Yale has experience in many technologies including state-of-the-art pad segmentation strategies, whereas Nikhef and Bonn are long time developers and users of the GridPIX. Our basic strategy would be to initiate our R&D efforts through reuse of existing parts from past R&D as we work our way toward new efforts. In particular, we would imagine combining the existing TPC prototype field cage from the sPHENIX studies with the quad GridPIX modules presently at Nikhef into a functioning single ended TPC.

3.1 Thermal Management Studies

Already at the time of the ATHENA proposal, we had undertaking studies of the thermal management of the GridPIX chips. Our first effort was to assume that we simply use conventional techniques with a flow of chilled water initially above the dew point in the hall.

The first result of these studies is shown in Figure 10. Here a maximum temperature of 35 C is observed with a conventional cooling block using only 4% of a radiation length in material. Further studies will be undertaking to see if more modern cooling strategies can yield a thinner electronics package.

3.2 Test Beam at FermiLab

In the US, the Fermilab test beam is the best source of mixed particle type beams at low momentum. This makes Fermilab the principle facility of interest for our initial run. Figure 11 shows the sPHENIX TPC prototype installed at the Fermilab Test Beam facility. The field cage and surrounding accoutrements would be reused for the initial GridPIX run. The major task will be to machine a new end plate for the TPC that accepts GridPIX grad modules instead of quad GEM stacks.

3.3 Cosmic Tests at Argonne

Unfortunately, the facilities at Fermilab do not feature a strong magnetic field. Thus, while Fermilab supplies ideal tests of PID capabilities, Argonne National Lab is the one that can supply studies of tracking resolution. Figure 12 shows the 5 Tesla user magnet facility at Argonne. SBU has experience using this facility for tests of the magnetic cloak from EIC R&D and has upcoming plans to place the TPC field cage into the magnet to study passive bipolar grids for

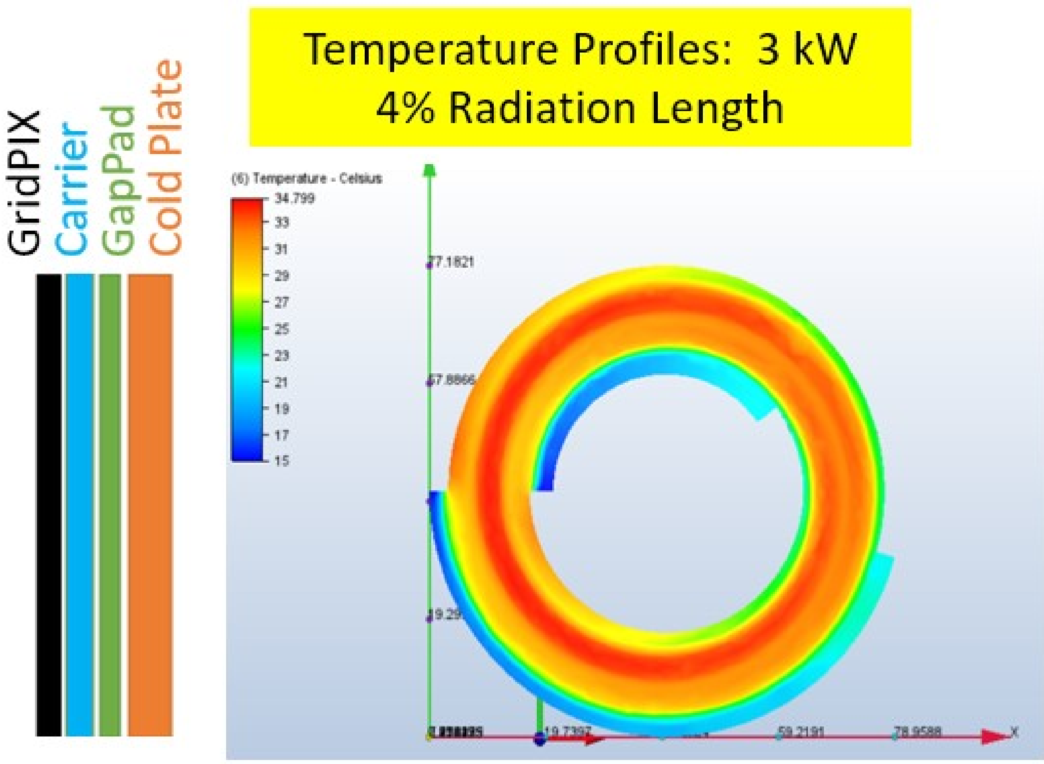

Figure 10: A simple model showing that conventional thermal management techniques would produce a detector end with $0.04\chi_0$ thickness. If funded, this proposal would pursue more advanced cooling methods to further reduce the material impact.

TPC gating. If outfitted with a pair of reference trackers, cosmics could be used at Argonne to study the tracking performance.

Presently, our highest priority is to student the PID capability and therefore we propose in the first year to run a test beam at Fermilab rather than Argonne.

3.4 Cost Effectiveness

Through the heavy reuse of existing equipment, the equipment costs of the proposal are rather low. It is dominated by mechanical modifications (new plate for quads), consumables (CF_4 gas is $5000 per bottle), DAQ (we must build from scratch a duplicate of the Nikhef DAQ) and travel.

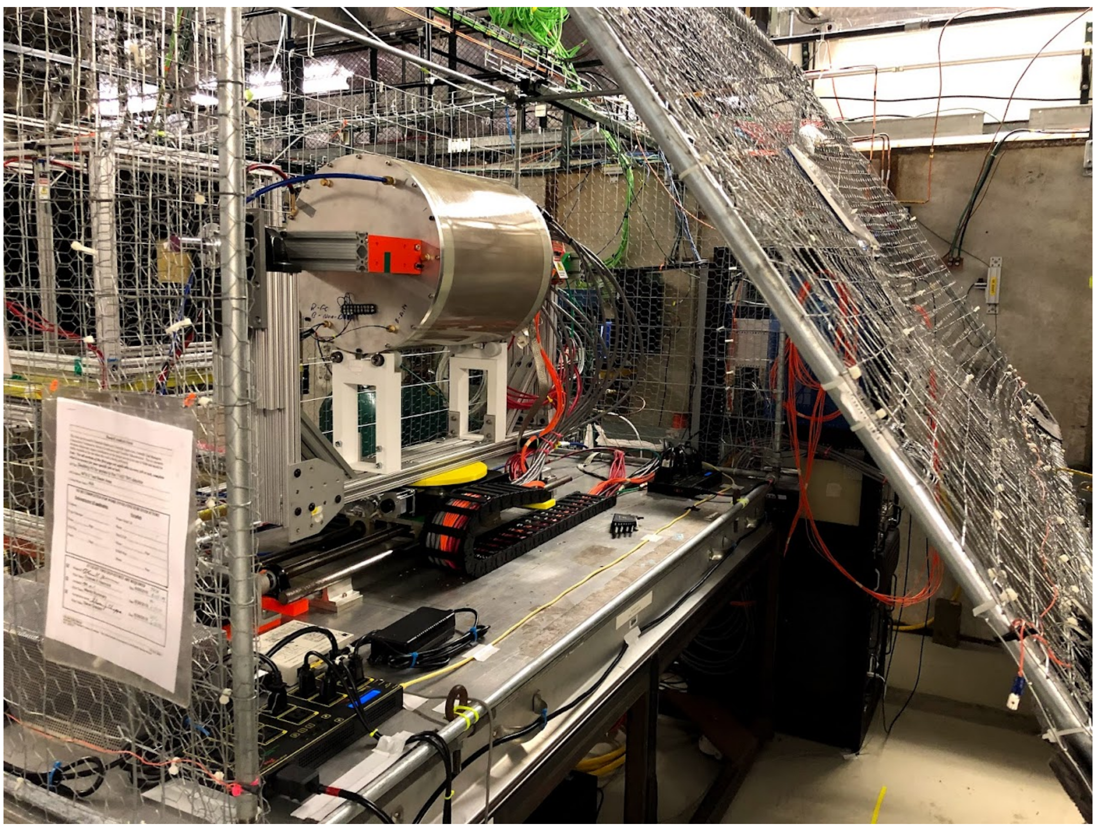

Figure 11: The sPHENIX TPC prototype set up in test beam in 2019. The field cage and all mechanical motion apparatus would be reused for the GridPIX experiment.

Figure 12: The magnetic solenoid at Argonne produces up to 5 Tesla for tracking resolution studies.

4 Budget

Table 2 shows our estimated costs for the first year of the project as well as a response to how we will continue in the case of reduced funding. To understand the scaling, it is important to understand the input assumptions. Because we have selected in our first year of effort a single test beam run with a marriage of the sPHENIX TPC prototype field cage with the existing quads from Nikhef, there is no way to scale down the costs of preparing the detector. This, to produce reduced cost scenarios, we have been forced to search elsewhere for savings. The only category for savings is that of the travel costs. These can be difficult to understand without a detailed explanation.

Item	Description	Nominal	20% down	40% Down
1	Mechanical	$ 8,000	$ 8,000	$ 8,000
2	Gas	$ 6,000	$ 6,000	$ 6,000
3	DAQ	$ 12,000	$ 12,000	$ 12,000
4	Travel (SBU)	$ 30,335	$ 24,735	$ 17,103
5	Travel (Yale)	$ 5,560	$ 2,780	$ 1,485
6	Travel (Nikhef)	$ 6,280	$ 3,140	$ 1,845
7	Travel (Bonn)	$ 6,380	$ 3,190	$ 1,895
	Total	$ 74,555	$ 59,845	$ 48,328
	Reduction		-19.7%	-35.2%

Table 1: Three funding scenarios are presented. Since the goal is a single test beam campaign, the hardware costs in all three scenarios are identical. The variations are whether we have a full or partial crew to run the experiment and how long the test beam campaign will last.

The ingredients into the budget are listed Table 2. The vehicle costs are difficult to understand without explanation. Figure 11 showed the TPC detector set up at Fermilab for a past beam test. This detector includes not only the field cage cylinder, but a remote control positioning apparatus allowing the detector to be re positioned for various drift distances, rotated around the vertical axis to simulate non-zero eta tracks, and around its own axis to simulate low momentum tracks. These are unusual motions and are not provided by the facility itself. Therefore, our apparatus stands directly on the floor, raises the detector to beam height, and is very heavy. The only method to transport the detector is via rented diesel truck (two one-way trips). We have made that same trip many times and have acquired fresh estimates of the charges as well as the diesel consumption and factored those into the travel costs.

Because we bring many young students to test beam (see Figure 13), we have found that having this crew drive a minivan or SUV from SBU is much more cost effective that buying plane tickets for the all. Finally, it is necessary when running 24 hour shifts to have two vehicles for ferrying people back and forth to the hotel. This we will have two rental cars (minivan driven from SBU and a second car rented in Chicago) for managing transportation to and from the hotel.

Item	Description	Cost
1	Vehicles and Fuel (14 day)	$ 10,945
2	Vehicles and Fuel (7 day)	$ 10,208
3	Hotel Rate per Room	$ 155
4	per diem	$ 30
5	Airfare/person (Yale)	$ 190
6	Airfare/person (Nikhef)	$ 550
7	Airfare/person (Bonn)	$ 600

Table 2: Assumed rates used to calculate expenses. Note that the vehicle and fuel costs are dominated by the truck rental and thus the length of the test beam does not have a major impact.

Table 3 shows how the reductions from the original estimate are calculated. To achieve a roughly 25% reduction in cost we must trim the personnel who travel for test beam.

Item	Description	Request	20% Down	40% Down
1	Test Beam Duration	14 days	14 days	7 days
2	SBU Senior Personnel	3	3	3
3	SBU Junior Personnel	7	4	4
4	Yale Senior Personnel	1	1	1
5	Yale Junior Personnel	1	0	0
6	Nikhef Senior Personnel	2	1	1
7	Nikhef Junior Personnel	0	0	0
8	Bonn Senior Personnel	2	1	1
9	Bonn Junior Personnel	0	0	0

Table 3: Scenarios for reduced budgets.

The final opportunity for cost reduction is to reduce the test beam duration from two to one week. Users who are familiar with the Fermilab test beam will recognize that runs are quantized by weeks. However, the available useful beam time does NOT scale linearly. The first few days of any run are dedicated to setup and safety inspection. The last days are dedicated to packing. Therefore the loss in running time by changing from a two week run (likely to be successful) to a one week run (risk of failure) is close to a factor of three. The savings, do not achieve the total loss of 40% and we do not see any further options to reduce the cost.

5 Diversity, Equity, and Inclusion

Stony Brook University has been engaged in diversity, equity, and inclusion practices since before the term came into common use. We are among the top few percent of school in the country for the high percentage of students who are first-in-family to attend college. We are also a university the strives to get undergraduates involved in research. Indeed, the general education curriculum requires every undergraduate to get a non-classroom experience before they may graduate. The result of these policies is shows pictorially in Figure 13.

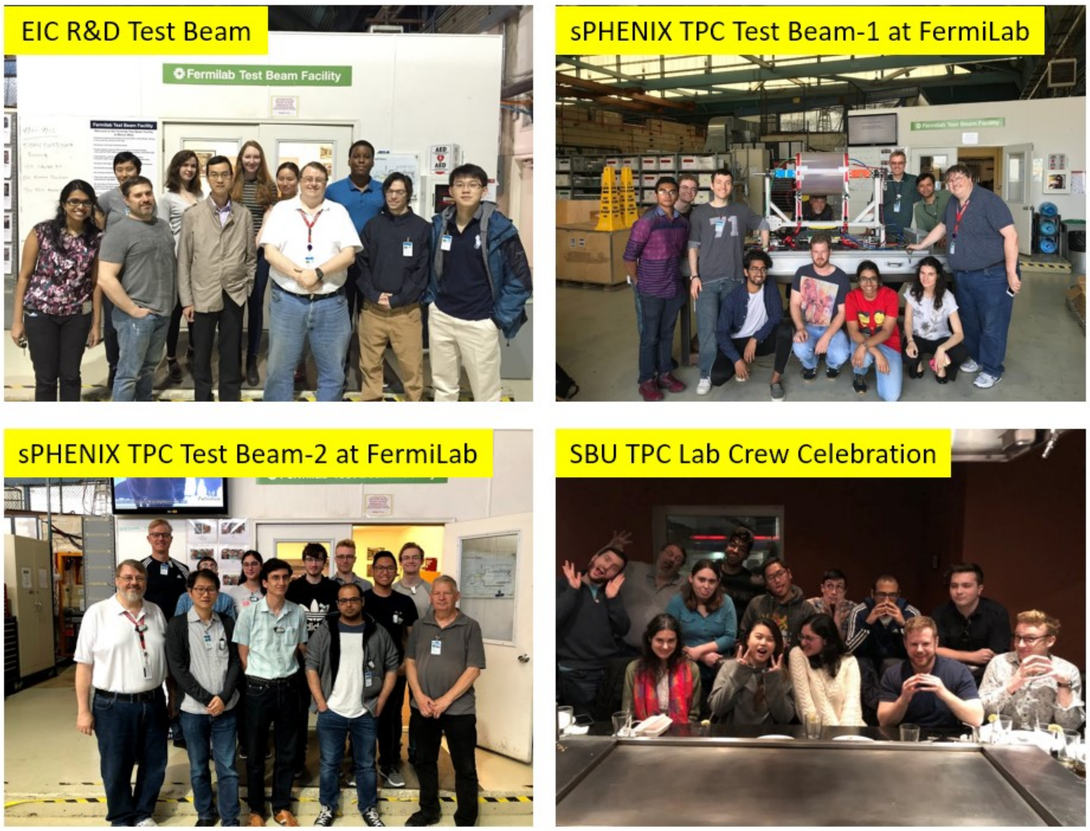

Figure 13: Stony Brook has a long tradition of supporting diversity, equity, and inclusion. These panels show the photos of the faculty, staff, and students present at our most recent three test beam campaigns. Additionally, the panel in the lower right shows the at home SBU crew celebrating a milestone in TPC construction.

Our test beam efforts have always included many young students with backgrounds as diverse as our undergraduate classes. Additionally, PI Hemmick was a member of the committee in ATHENA that wrote the ATHENA charter which included a lengthy and wise policy for nurturing DEI.

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