Date: March 5, 2021

EIC Detector R&D Progress Report

Project ID: eRD29

Project Name: Precision Timing Silicon Detectors for a Combined PID and Tracking System at EIC

Period Reported: from 9/2020 to 2/2021

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Abstract

This report describes progress in the period between October 2020 and February 2021 on a new R&D program of precision timing silicon detectors for a combined particle identification (PID) and tracking system at EIC. The overall objectives are to establish the applicability of ultra fast silicon sensor technology (also known as low gain avalanche diodes, LGADs) for constructing a compact detector that is capable of providing both PID and tracking, and to provide a conceptual detector design that meets the EIC physics requirements via simulations.

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Past

What was planned for this period?

For this period, we planned to work on the first two proposed objectives in the proposal:

- R&D of ultra-thin LGADs sensors (10/2020–03/2021)
- Simulations of a LGADs-based TOF-tracker (10/2020–05/2021)

What was achieved?

Because of COVID-19, we have decided to re-shuffle the priorities and focus on completing the second objective of simulations and performance studies for a LGADs-based TOF and tracker in this period. This part of studies is in a very advanced stage and close to completion. Studies accomplished and preliminary conclusions are presented below.

The progress on the ultra-thin LGADs sensor R&D has been significantly delayed. We are still in the process of acquiring sensors for testing. In collaboration with eRD24, silicon wafers with thickness of 20 μm (active region) are purchased at BNL. Fabrication of LGADs will proceed as soon as COVID-19 situation allows. We have requested samples of 25-μm LGADs produced by FBK through collaborators in INFN Torino, and we have been working on the delivery of those sensors, hopefully ready for testing in the second period of the project. Meanwhile, we have acquired all other necessary components and equipment, such as testing readout boards.

All simulation studies are carried out in the Fun4All framework developed by the sPHENIX collaboration, based on the 1.5 T solenoid magnet and existing designs of all-silicon tracker, electromagnetic (EM) and hadronic calorimeters. However, designs and studies of LGADs-based detectors we developed can be easily adopted to other framework and full detector design. Main conclusions drawn are independent of specific simulation framework. Figure 1 shows a default detector design in Fun4All with LGADs timing layers we implemented. We simulate e$-$+p events at a collision energy of 10+250 GeV using PYTHIA6 (an example of simulated particles also shown in Fig. 1) with $p_{\mathrm{T}}^{\mathrm{hard}} > 5$ GeV/c. Details of dimensions and coverage of each LGADs-based

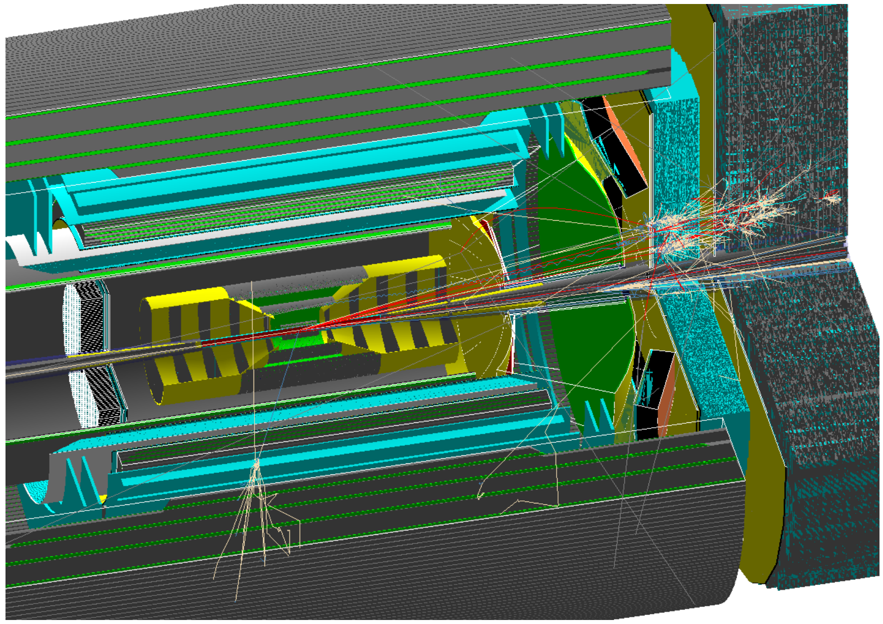

Figure 1: Illustration of detector design with LGADs-based timing-tracking layers using GEANT4 in Fun4All framework.

Timing-Tracking-Layers (TTL) are summarized in Table 1. Besides the default set up including all electron-going direction TTLs (ETTLs), central TTLs (CTTLs) and forward-going direction TTLs(FTTLs), two alternative designs by removing one CTTL and one FTTL either in front of or behind EMCal are also considered for cost considerations. The total detector areas of three scenarios are also summarized in Table 1.

The time resolution of each LGADs layer is assumed to be 20 ps, which is our R&D goal. Various options of LGADs spacial granularity are considered to guide our third R&D objective in this proposal. Our general design guideline is to place LGADs layers as far as possible to take advantage of longer flight distance for PID over a wider momentum range, especially in the forward region. In the forward region, there are two LGADs layers placed right behind the dRICH detectors and in front of EMCal, while a third one is placed in between EMCal and HCal. In the backward direction, two layers are placed right in front of EMCal, while the midrapidity region consists of two LGADs barrel layers, one before and after EMCal. We combine TTLs with two different all-silicon inner tracker designs in Fun4All from LBL [1] (shown in Fig. 1) and LANL. Performance in PID and track momentum resolution are evaluated. A strategy of determining the start time of particle TOF is developed.

	Default	R_{barrel}	Length	z location	$R_{endcap,in}$	$R_{endcap,out}$	η coverage	Area (m^2)
Backward	$ETTL_0$			-1.555	0.077	0.632	[-3.7,-1.6]	1.23
	$ETTL_1$			-1.585	0.078	0.62	[-3.7,-1.6]	1.19
Central	$CTTL_0$	0.92	3.6				[-1.34,1.34]	20.8
	$CTTL_1$	1.147	3.6				[-1.11,1.11]	25.9
Forward	$FTTL_0$			2.87	0.116	1.527	[1.3,3.9]	7.28
	$FTTL_1$			2.89	0.117	1.538	[1.3,3.9]	7.39
	$FTTL_2$			3.4	0.138	2.185	[1.1,3.9]	14.94
Default setup: $ETTL_0$ + $ETTL_1$ + $CTTL_0$ + $CTTL_1$ + $FTTL_0$ + $FTTL_1$ + $FTTL_2$								78.73
Alternative 1: $ETTL_0$ + $ETTL_1$ + $CTTL_1$ + $FTTL_0$ + $FTTL_2$								50.54
Alternative 2: $ETTL_0$ + $ETTL_1$ + $CTTL_0$ + $FTTL_0$ + $FTTL_1$								37.89

Table 1: Summary of key design parameters of LGADs-based timing-tracking layers. The unit for all lengths is meter.

1. Performance of TOF PID

The capability of particle identification via time-of-flight measured by TTLs is evaluated. The $1/\beta$ vs. momentum distributions from the default TTL setup are shown in Fig. 2, for the backward ($-3.0 < \eta < -1.5$), central ($-1.2 < \eta < 1.2$) and forward ($1.5 < \eta < 3.5$) regions. The hot spot at $\sim$10 GeV in the central region is predominantly from the scattered electron. The top row of Fig. 2 shows the results with only path length uncertainty, while the bottom row shows the results with both path length and time-of-flight uncertainties. For this plot, the start time (T_0) is assumed to have no uncertainty but a realistic T_0 determination will be presented later. Figure 3 presents similar results but for an alternative TTL design with one layer in front of the EMCal removed.

One can see that the uncertainty from path length of charged tracks alone is not negligible, even dominant over TOF resolution at low momentum range. This is mainly driven by the tracker design and is an important aspect to take into account for PID performance. In both scenarios of TTLs designs, excellent PID performance is shown, after combining uncertainties from both path length and TOF resolution. In the forward region, π/K separation for p from $\sim$ 0.1 to 4–5 GeV/c and K/p separation from $\sim$ 0.1 to p $\sim$7–8 GeV/c are achieved. Combined with the dRICH detectors, PID over the full momentum range in the forward region is covered. For backward and central regions, because of much shorter flight distance, the reach in high momentum range of PID is reduced but still sufficient as charged hadrons are generally produced with much lower momenta in this region of phase space. Therefore, high precision PID over the full phase space can be achieved with LGADs-based TTLs.

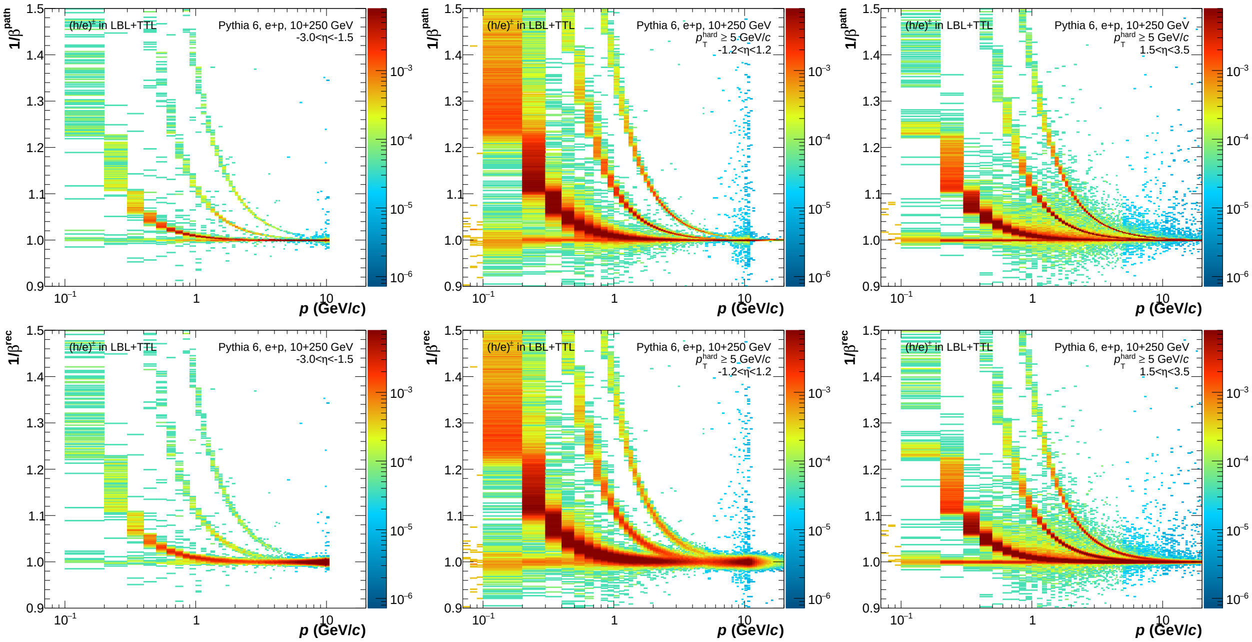

Figure 2: The $1/\beta$ vs momentum with only path length uncertainties (left) and with both path length and timing uncertainties (right) based on the default setup. The tracks were required to have at least 3 hits in the inner tracker based on the LBL design.

2. Performance of track momentum resolution

Besides providing PID capabilities, the impact of TTLs on tracking performance as an outer tracker is evaluated. Both inner tracker designs from LBL and LANL are evaluated. Charged particle tracks are reconstructed with a Kalman filter algorithm. Different granularity of TTLs are considered, which have direct impact on tracking performance. Track momentum, η, ϕ and impact parameter resolution are studied. Here, we focus on presenting the impact on track momentum resolution with TTLs.

Figure 4 shows the comparison of momentum resolution for all charged particles as a function of track momentum without TTLs and with the default TTL setup, for backward ($-2.5 < \eta < -2.0$), central ($-0.4 < \eta < 0.4$) and forward ($3.0 < \eta < 3.5$) pseudorapidity regions. The LBL design for inner tracking layers is used, where at least 3 hits are required for each track. Three scenarios of TTL granularity or pitch size of LGADs are assumed:

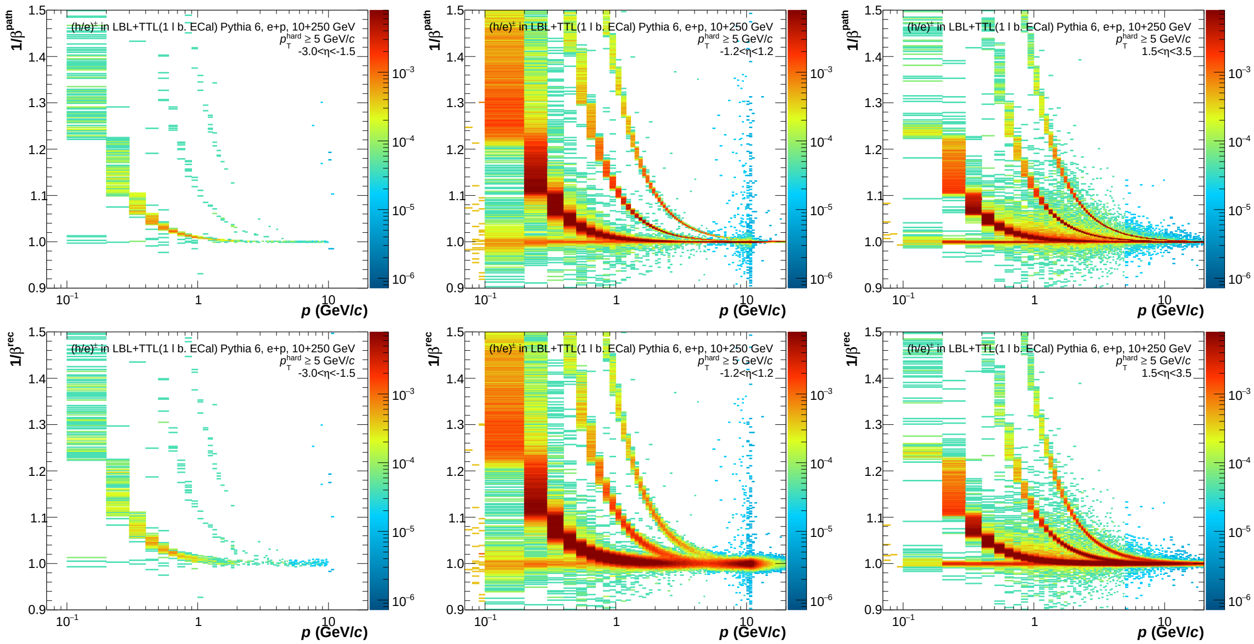

Figure 3: The $1/\beta$ vs momentum with only path length uncertainties (left) and with both path length and timing uncertainties (right) based on the default setup with only 1 layer in front of the ECal. The tracks were required to have at least 3 hits in the inner tracker based on the LBL design.

1. 1.3×1.3mm^2, the standard LGADs used by the CMS and ATLAS timing detectors for HL-LHC.

2. 0.5×0.5mm^2, which can be realized by trench-isolated LGADs sensors.

3. 0.5×0.5mm^2 AC-coupled LGADs with charge sharing among adjacent pads.

For scenarios 1 and 2, the single hit position resolution is assumed to be $1/\sqrt{12}$ of the pitch size, resulting 375 μm and 144 μm, respectively. For scenario 3, recent studies suggest that a position resolution of 30 μm or better can be achieved with AC-LGADs of 0.5 mm in pitch size [2], taking advantage of charge sharing.

The resulting momentum resolutions of reconstructed tracks with different TTL granularity are shown in Figure 4. For backward (Fig. 4, left) and central (Fig. 4, middle) regions, charged hadrons generally do not reach very high momentum region, up to $p \sim 5$ GeV/c. Tracks appearing from 6 to 30 GeV/c p range in the central region are primarily scattered electrons (most scattered electrons are ended up in the midrapidity region because of the $p_{\mathrm{T}}^{\mathrm{hard}} > 5$GeV/c requirement). Comparing to the scenario without TTLs, the addition of TTLs does not have a significant impact

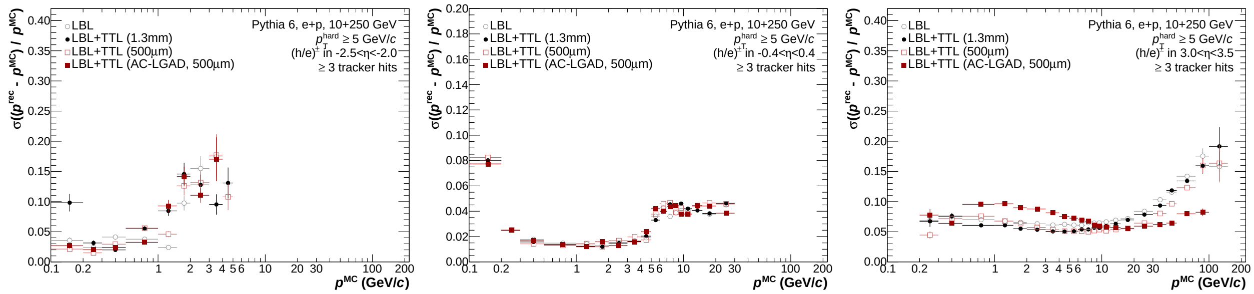

Figure 4: Comparison of the momentum resolution for different detector granularity of the TTL using the default geometry for all charged particles. For the inner tracking layers the LBL design is used at least 3 hits are required in those layers. The comparisons are shown for 3 different η regions.

or improvement on the momentum resolution in relatively low momentum ranges for the backward and central rapidity regions. However, in the forward proton going direction, high momentum charged hadrons are produced up to $p \sim 100$ GeV/c. With help of high granularity TTLs situated farther away behind the dRICH detectors, an improvement in momentum resolution up to 50% is achievable with 0.5 mm AC-LGADs. Even with 0.5 mm TL-LGADs (granularity scenario 2), an improvement of 25% in high momentum resolution can be achieved. For the low and intermediate momentum range in the forward region, a degraded resolution with the finest TTLs granularity (0.5 mm AC-LGADs) is observed, which is understood as an artifact of imperfect tracking. Work is in progress to optimize the tracking with combined inner tracker and outer TTLs over the full momentum range.

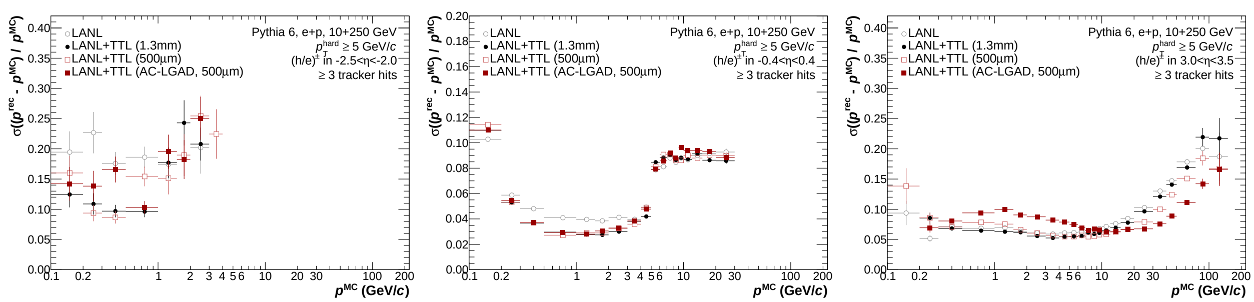

Figure 5: Comparison of the momentum resolution for different detector granularity of the TTL using the default geometry for all charged particles. For the inner tracking layers the LANL design is used at least 3 hits are required in those layers. The comparisons are shown for 3 different η regions.

Same studies of tracking performance in momentum resolution are shown for the LANL inner tracker design in Fig. 5. In general, the conclusion is similar to that with the LBL inner tracker design (and applied to any tracker design) that by adding LGADs-based TTLs with fine granularity, significant improvement in high momentum resolution can be achieved in the forward region. In addition, LGADs-based TTLs should also help determine the velocity/momentum of particles after exiting the dRICH detectors to facilitate its PID at very high momentum. This will be studied in future work.

Finally, we consider an alternative, lower-cost design of TTLs with one layer removed in all three regions. For central and forward regions, one layer before the EMCal is removed. Comparison of track momentum resolution without TTLs, with default TTLs and with one-layer-reduced TTLs is shown in Fig. 6, for backward, central and forward rapidity regions, respectively. The LBL inner tracker design is used here as an example but the conclusion is identical for other designs. As expected, reducing one TTL layer has no impact to the momentum resolution for the backward and central regions for relatively low momentum ranges. In the forward region at track high momenta, even the scenario of reduced TTL layers still provides significant improvement in momentum resolution. Therefore, there is a large degree of flexibility in designing TTL systems to accommodate both requirements of EIC physics and potential funding constraints.

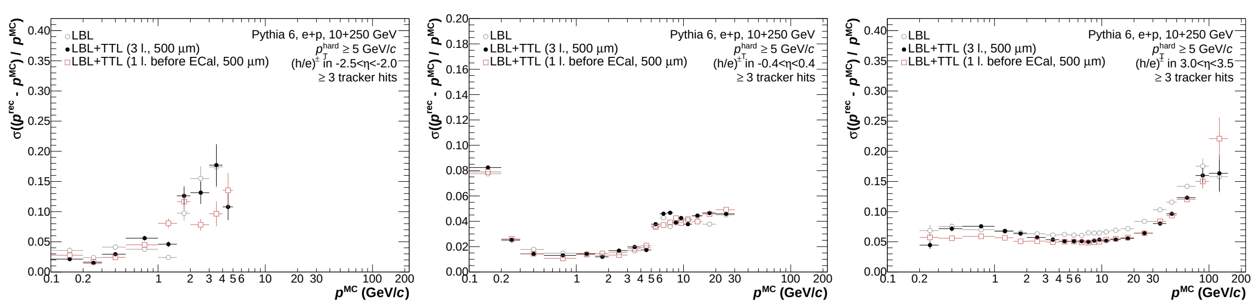

Figure 6: Comparison of the momentum resolution for different setups: without TTL (open circles), with default TTL (solid circles) and with reduced TTL (open squares). For the inner tracking layers the LBL design is used at least 3 hits are required in those layers. The comparisons are shown for 3 different η regions.

3. Strategy of start time (T_0) determination for PID

The determination of the start time (T_0) in particle time of flight is a universal issue for all TOF-based PID techniques. Here, we develop a generic strategy of T_0 determination and assess its impact on PID at EIC. For EIC, the duration of two bunches passing each other is about 30 ps, which is significantly larger than the time resolution of proposed TOF. Therefore, the beam crossing time cannot be used for T_0 determination but a strategy based on the TOF itself is needed. In relativistic heavy ion collisions, this is usually not an issue as the multiplicity of charged pions is large and T_0 can be well determined by assuming all particles are pions. This does not necessarily work for low multiplicity events at EIC.

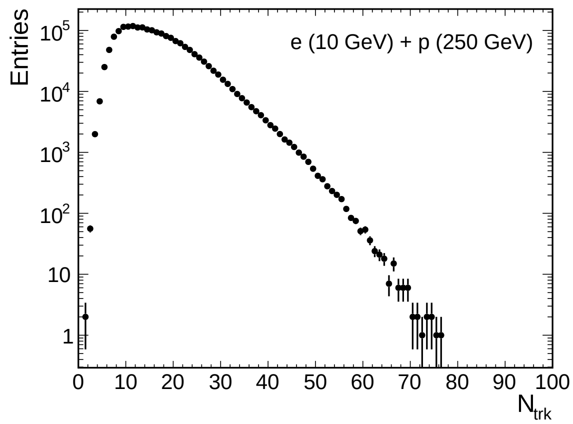

Figure 7: The particle multiplicity (including neutral particles) generated by PYTHIA 6 in e (10 GeV) + p (250 GeV) collisions within full phase space.

The T_0 determination is studied using the minimum bias events, generated by PYTHIA 6, in e (10 GeV) + p (250 GeV) collisions. The particle multiplicity distribution including neutral particles (N_{trk}) from PYTHIA 6, is shown in Fig. 7. The default TTL setup with the LBL inner (all-silicon) tracker design [1] is used in this study. Details of default TTL setup can be found earlier in the report. The timing resolution of each LGADs layer is still assumed to be at 20 ps. The procedure of T_0 determination is as follows,

- **Initial T_0 determination:** To determine the initial T_0 value, the scattering electron is firstly searched in the electron going direction. The scattering electron, which should be identified by ECAL in real data analysis, is treated to be found if falling into the ETTL acceptance in this study. Once the scattering electron is found, the initial T_0 is calculated only using the scattering electron, as shown in Fig. 8 (top). Otherwise, the initial T_0 is estimated with the assumption that all the charged particles are pions, as shown in Fig. 8 (bottom). The initial T_0 estimated by the scattering electron has no tail, while the initial T_0 estimated by charged particles has long tail because of the contamination from kaon, proton and other particle

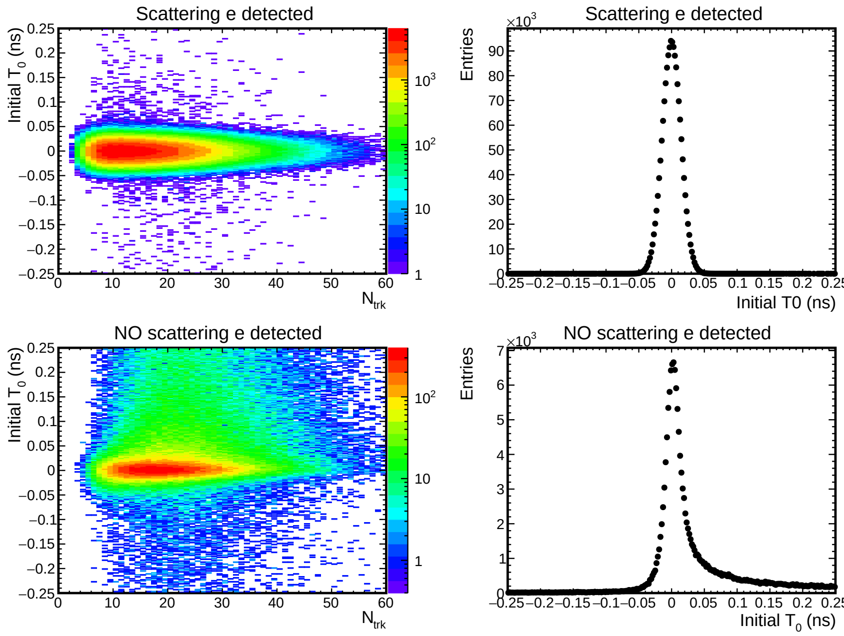

Figure 8: The initial T_0 distribution for the events with the scattering electron detected in which the initial T_0 is estimated only using the scattering electron. (Left) The initial T_0 distribution as a function of particle multiplicity including neutral particles. (Right) The overall initial T_0 distributions.

species.

- T_0 **optimization:** Once the initial T_0 is determined, particle identification is performed using $1/\beta - 1/\beta_{exp}$. $1/\beta$ is calculated by the trajectory length and time of flight while the $1/\beta_{exp}$ is calculated by the measured momentum and mass with a particle species assumption. T_0 is then re-calculated using the identified particles. For the events with the scattering electron detected, the scattering electron is always used to estimate T_0 besides the new identified particles. For the events with the scattering electron missing, the kaon and proton $1/\beta - 1/\beta_{exp}$ bands are washed out and biased to be negative values, because the initial T_0 is inaccurate caused by kaon and proton contamination, especially at low momentum. To solve this issue, an iterative procedure is employed to perform T_0 optimization, namely the newly generated T_0 is used to perform particle identification, and then generate a more optimal T_0. Figures 9 shows the $1/\beta - 1/\beta_{exp}$ distributions as a function of momentum for for the case of electron being detected, after several iterations until the T_0 becomes stable.

- T_0 **resolution:** The final T_0 distributions as a function of N_{trk} or N_{TTLHit} (number of timing

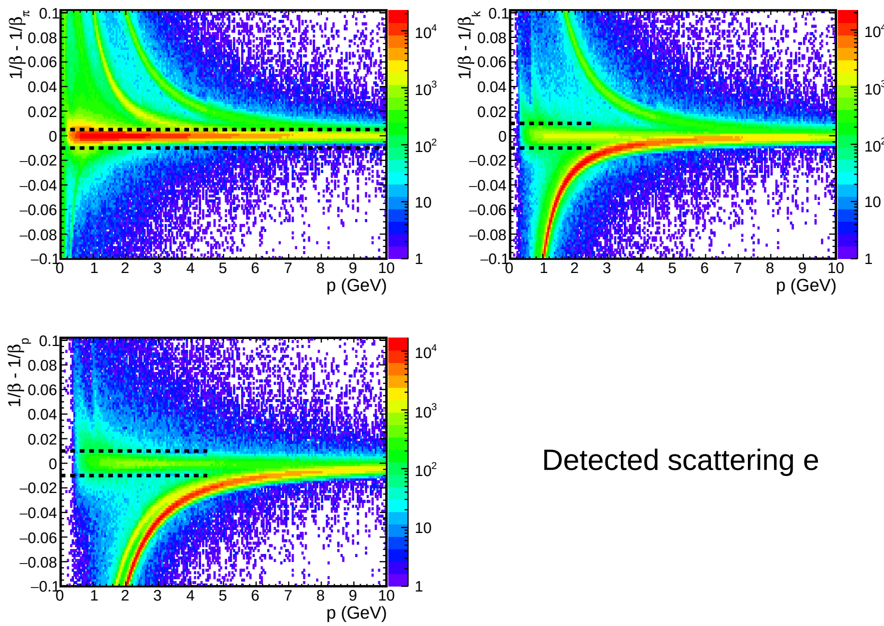

Figure 9: Particle identification is re-performed with the improved T_0, estimated using the identified particles in previous iteration, for the events with the scattering electron detected. The distributions of $1/\beta - 1/\beta_{exp}$ as a function of momentum are shown with pion (top left), kaon (top right), and proton (bottom left) assumptions, respectively. The black dashed lines indicate the $1/\beta$ difference cut and momentum range used for particle identification.

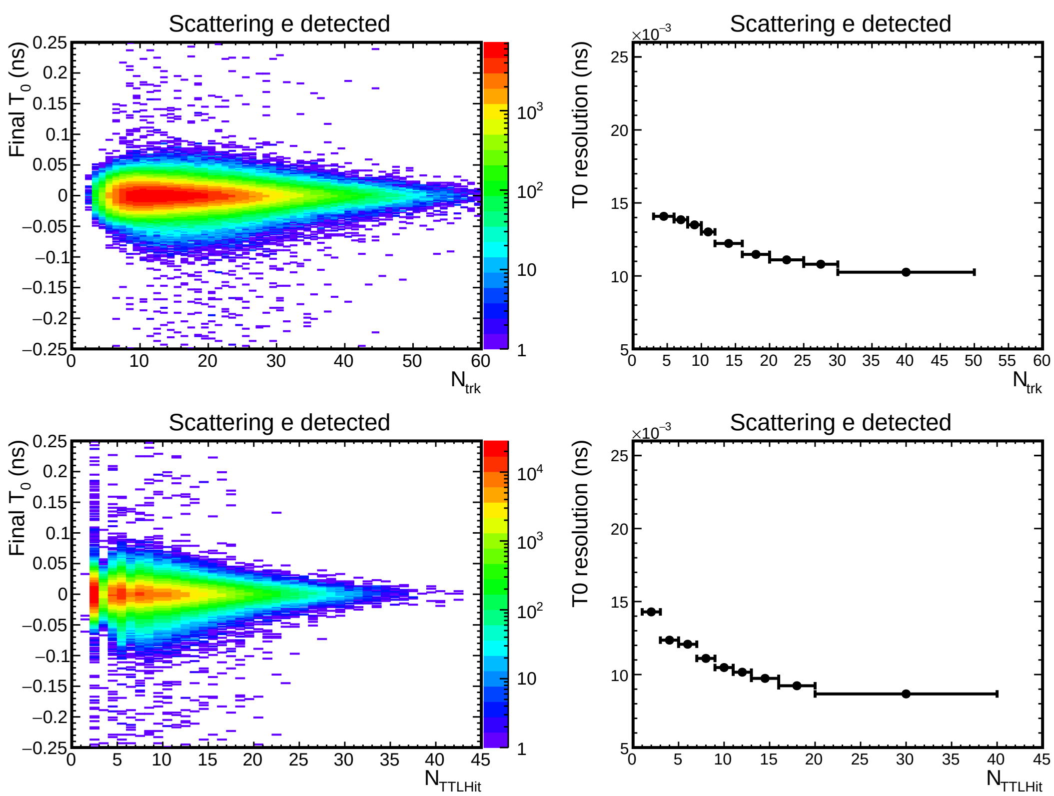

Figure 10: The final T_0 distribution for the events with (top) and without (bottom) scattering electron detected. (Left) The final T_0 distribution as a function of total particle multiplicity. (Right) The final T_0 resolution as a function of total particle multiplicity.

layer hit), are shown in Fig. 10. The overall T_0 resolution is ∼12 ps while the T_0 resolution with $N_{TTLHit} > 12$ is better than 10 ps, regardless the scattering electron detection.

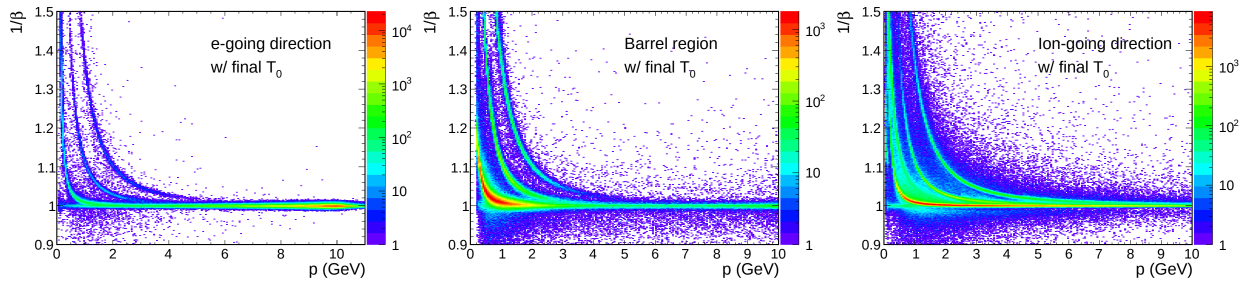

Figure 11: $1/\beta$ vs. momentum distribution from the default TTL setup in the backward ($-3.7 < \eta < -1.6$), central ($-1.4 < \eta < 1.4$) and forward ($1.1 < \eta < 3.9$) regions. The hot spot at ∼10 GeV is predominantly from the scattering electron.

Once the optimal T_0 is determined, β value is then calculated. The β value includes timing layer resolution, trajectory length uncertainty, momentum resolution, and T_0 resolution effects. Figure 11 shows the $1/\beta$ distributions for different particles in different η regions.

What was not achieved, why not, and what will be done to correct?

Because of COVID-19, most of our planned hardware activities on LGADs sensor characterization have been delayed. We have acquired sensors and testing readout boards needed but it has been difficult to access labs and proceed with planned activities. To mitigate the delay, we decided to shuffle the priority to focus on the proposed simulation tasks first and return to detector work in the second half of FY21, when hopefully labs and facilities will open and some travels are possible.

How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

See responses to the previous question. COVID-19 has a large impact on the progress of our project but we managed to mitigate it so far by re-shuffling priorities and focusing on simulation work first.

How much of your FY21 funding could not be spent due to pandemic related closing of facilities?

None. Most of our funding is only for a fraction of personnel salary and we expect to spend all.

Do you have running costs that are needed even if R&D efforts have paused?

None.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

For the next period of six months, the priority will focus on the planned LGADs sensor R&D, and at the meantime, wrap up simulation studies. We plan to study performance of thin 20 μm and 25 μm LGADs sensors to establish the expected time resolution of 20 ps or better. Next, we will collaborate with eRD24 team to fabricate thin AC-LGADs sensors and perform testing to qualify their performance as outer tracking layers. With this program completed, we anticipate to move onto addressing challenges in readout electronics and aim for developing a full technical design report.

Compared to the original plan, the ordering of planned work is re-shuffled to mitigate the impact of COVID-19 but the overall goal has not been changed.

What are critical issues?

Currently the most critical issues are delays due to COVID-19 and limited manpower to carry out lab work.

Additional information:

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.

All simulation work is carried out by groups at Rice University and ORNL. Work on LGADs sensor R&D is currently being set up by Rice University and will be joined later by ORNL and University of Kansas to perform the tests.

The Rice postdoc, Shuai Yang, is funded by the R&D fund at 0.33 FTE level. Shuai Yang is located at Rice University, supervised by Wei Li. He spends 50% of his time on EIC detector R&D project.

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

- All efforts from the ORNL group are supported by the ORNL internal fund.
- Efforts from the Rice University group are partially supported by the PI's internal university fund.

Publications

Please provide a list of publications coming out of the R&D effort.

This efforts just started about 5 months ago and there are currently no publications.