LA-UR-21-22558

# Forward silicon tracking detector design and R&D for the future Electron-Ion Collider

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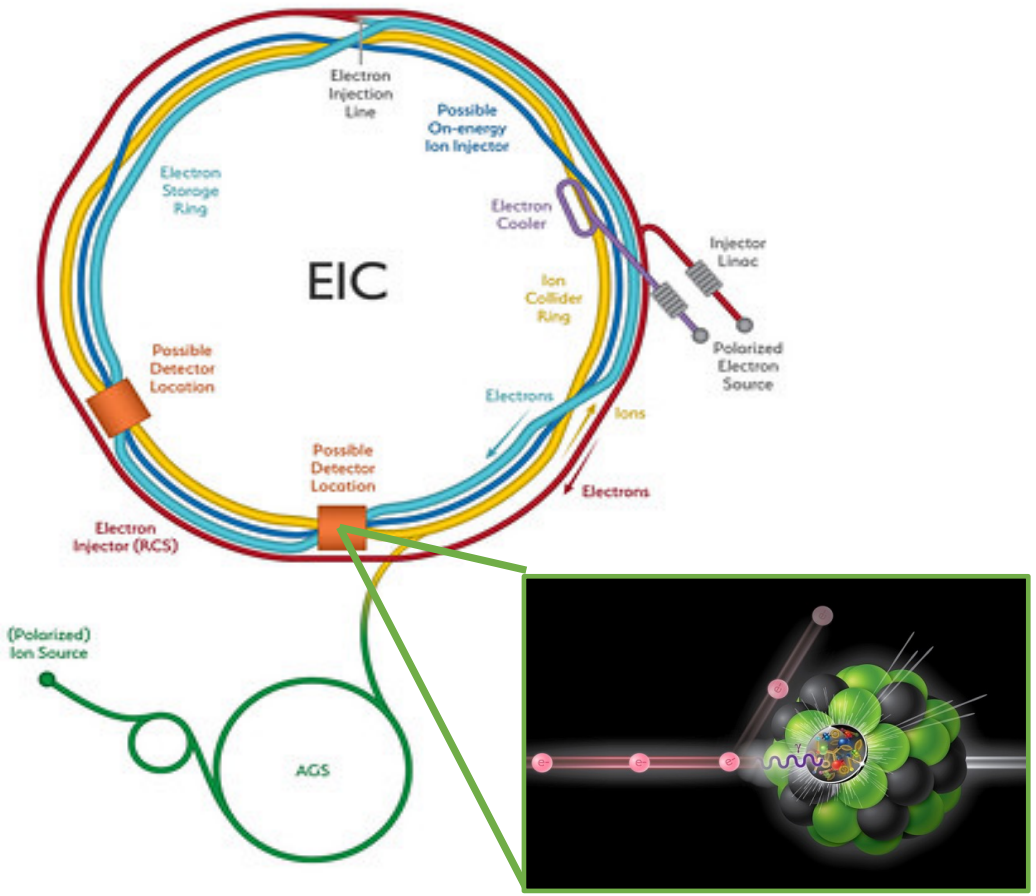
# Outline

- Motivation.
- The proposed forward silicon tracker design and performance for the Electron-Ion Collider.
- Results from the ongoing R&D for the silicon technologies.
- Summary and Outlook.

# Motivation

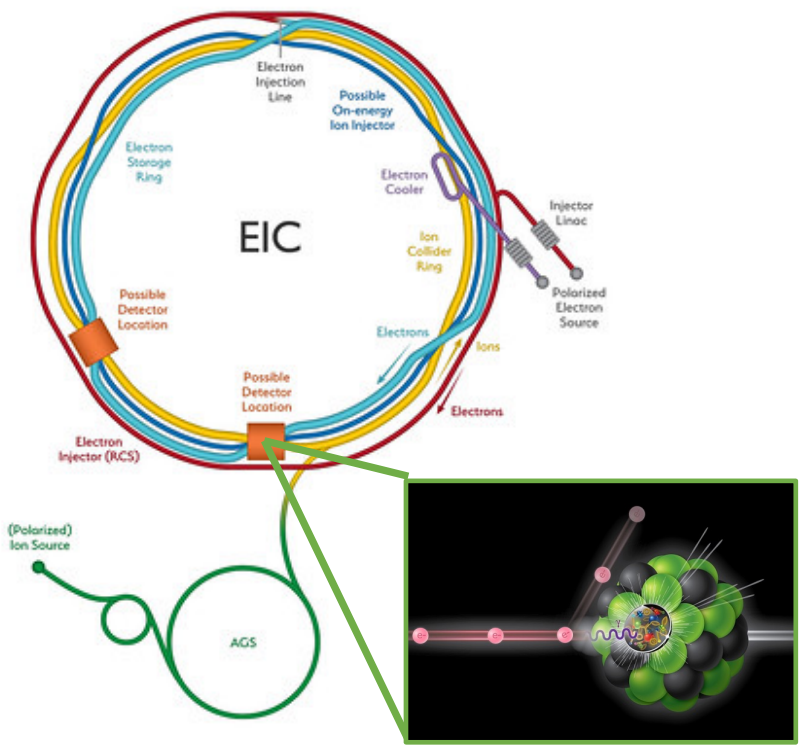
- The future Electron-Ion Collider (EIC) will utilize high luminosity high energy electron+proton and electron+nucleus collisions to solve several fundamental questions.




- e-p collisions at the EIC:
  - (Polarized) p, d/$^3$He beams at 40-275 GeV.
  - (Polarized) e beam at 2.5-18 GeV.
  - Instant luminosity $L_{int}$ ~ $10^{33\text{-}34}$ cm$^{-2}$sec$^{-1}$. A factor of ~1000 higher than HERA.
  - Bunch crossing rate: 1-10 ns.
- e-A collisions at the EIC:
  - Multiple nuclear species (A=2-208) and variable center of mass energies.
  - Instant luminosity $L_{int}$ ~ $10^{33\text{-}34}$ cm$^{-2}$sec$^{-1}$.
  - Bunch crossing rate: 1-10 ns.

# Motivation

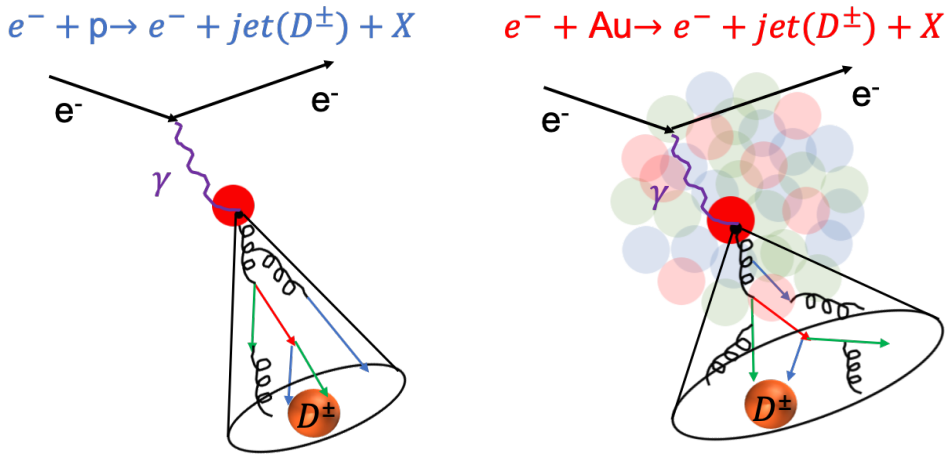
- The future Electron-Ion Collider (EIC) will utilize high luminosity high energy electron+proton and electron+nucleus collisions to solve several fundamental questions.




- Heavy flavor products such as $D^0$ meson at the EIC can provide further constraints on the initial nucleon/nuclear parton distribution functions and explore the final state hadronization process with better precisions.

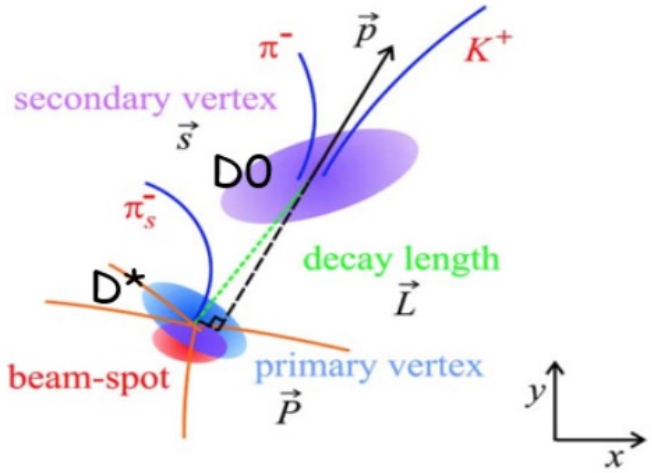
# How to measure heavy quarks at the EIC?

- At the EIC, hadrons or jets which contain heavy quarks can be identified by detectors using their unique lifetime and masses.



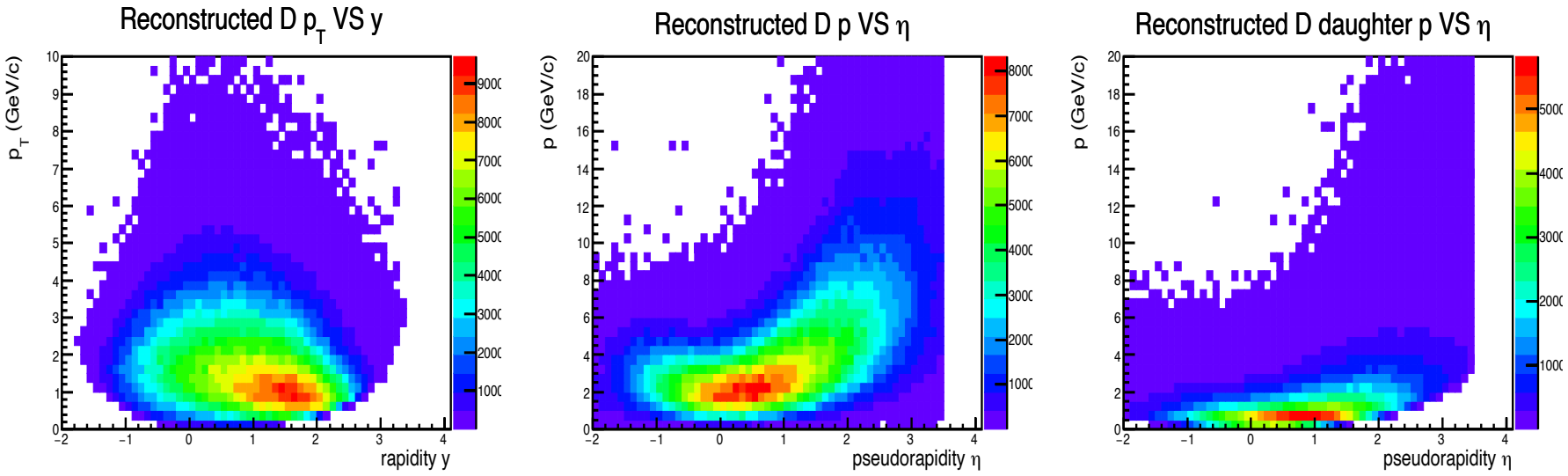

| Particle | Mass (GeV/c²) | Average decay length |
|---|---|---|
| $D^\pm$ | 1.869 | 312 micron |
| $D^0$ | 1.864 | 123 micron |
| $B^\pm$ | 5.279 | 491 micron |
| $B^0$ | 5.280 | 456 micron |

- Physics-driven detector performance requirements:
  - Fine spatial resolution (<100 μm) for displaced vertex reconstruction.
  - Fast timing resolution to suppress backgrounds from neighboring collisions.
  - Low material budgets to maintain fine hit resolution.



# EIC detector requirements for a silicon vertex/tracking detector

- To meet the heavy flavor physics measurements, a silicon vertex/tracking detector with low material budgets and fine spatial resolution is needed.
- Particles produced in the asymmetric electron+proton and electron+nucleus collisions have a higher production rate in the forward pseudorapidity. The EIC detector is required to have large granularity especially in the forward region.



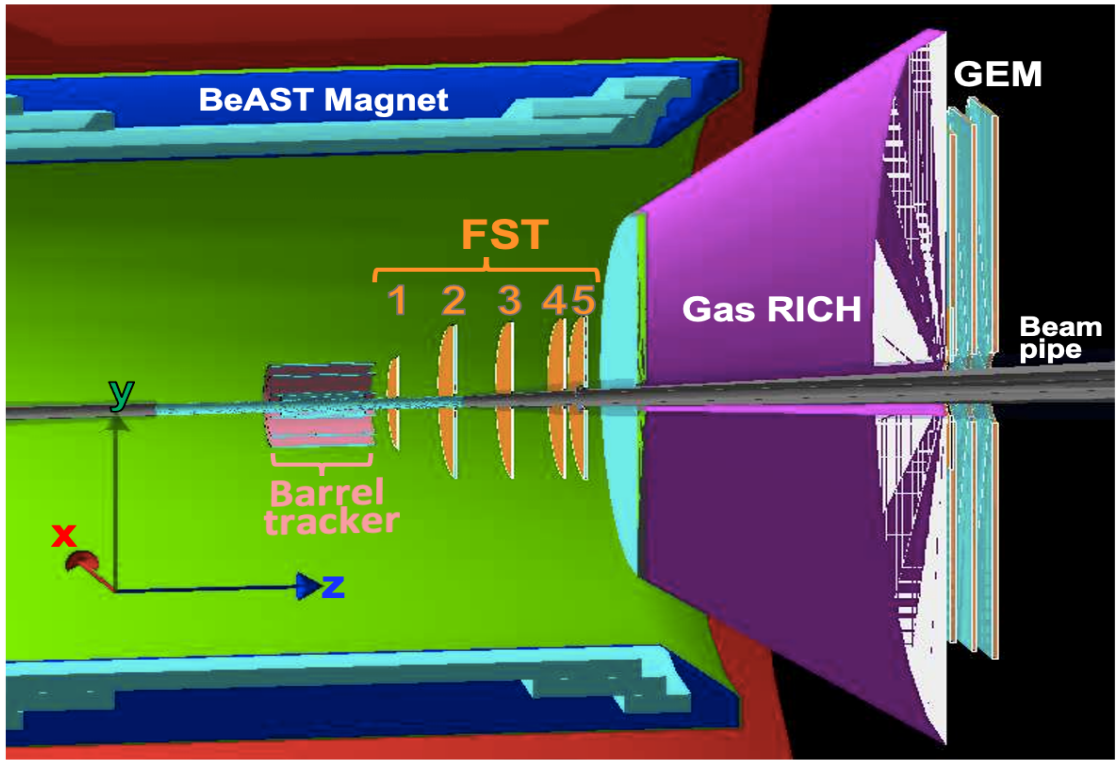

- Fast timing (1-10ns readout) capability allows the separation of different collisions and suppress the beam backgrounds.

# Conceptual design for a proposed forward silicon tracker at the EIC (I)

- GEANT4 simulation for the proposed Forward Silicon Tracker (FST) in the Fun4All framework:
  - The proposed forward-rapidity silicon tracking detector (FST) with $1.0 < \eta < 3.5$:

  3 planes of MAPS silicon detector and 2 forward planes of HV-MAPS silicon detector.

**LANL FST integrated inside the EIC**




**See more details in arXiv:2009.02888**

**LANL FST geometry parameters**

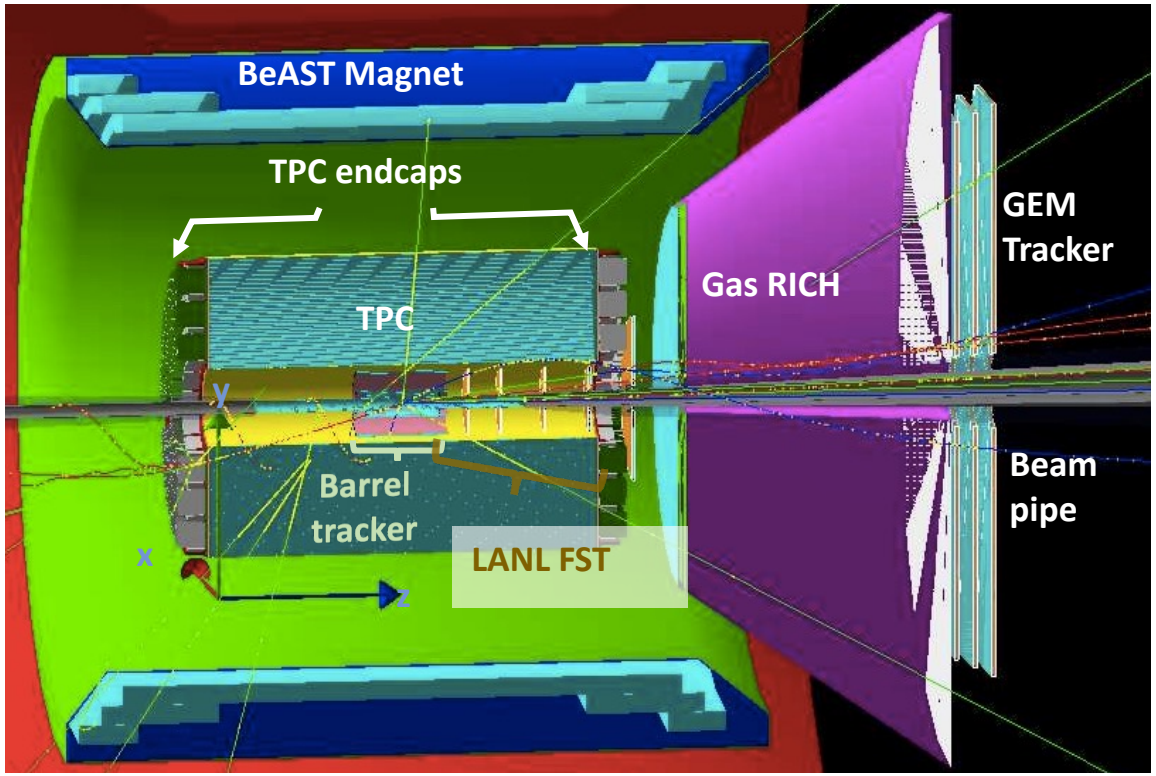
| Plane index | z (cm) | $r_{in}$ (cm) | $r_{out}$ (cm) | Pixel pitch (um) | Silicon thickness (um) |
|---|---|---|---|---|---|
| 1 | 35 | 4 | 25 | 20 | 50 |
| 2 | 62.3 | 4.5 | 42 | 20 | 50 |
| 3 | 90 | 5.2 | 43 | 20 | 50 |
| 4 | 115 | 6 | 44 | 36.4 | 100 |
| 5 | 125 | 6.5 | 45 | 36.4 | 100 |

# Conceptual design for a proposed forward silicon tracker at the EIC (II)

- GEANT4 simulation for the proposed Forward Silicon Tracker (FST) in the Fun4All framework:
  - The proposed forward-rapidity silicon tracking detector (FST) with $1.0 < \eta < 3.5$:

  3 planes of MAPS silicon detector and 2 forward planes of HV-MAPS silicon detector.

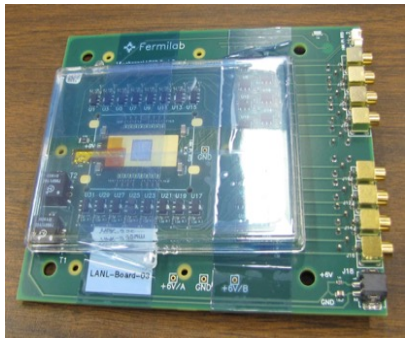
**Different geometries have been explored**



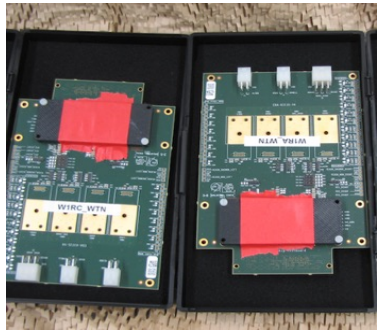

**Technology candidates**

**Monolithic Active Pixel Sensor (MAPS) sensor**


**LGAD/AC-LGAD sensor**



**DMAPS (MALTA) sensor**



# Conceptual design for a proposed forward silicon tracker at the EIC (II)

- GEANT4 simulation for the proposed Forward Silicon Tracker (FST) in the Fun4All framework:
  - The proposed forward-rapidity silicon tracking detector (FST) with $1.0 < \eta < 3.5$:

  3 planes of MAPS silicon detector and 2 forward planes of HV-MAPS silicon detector.

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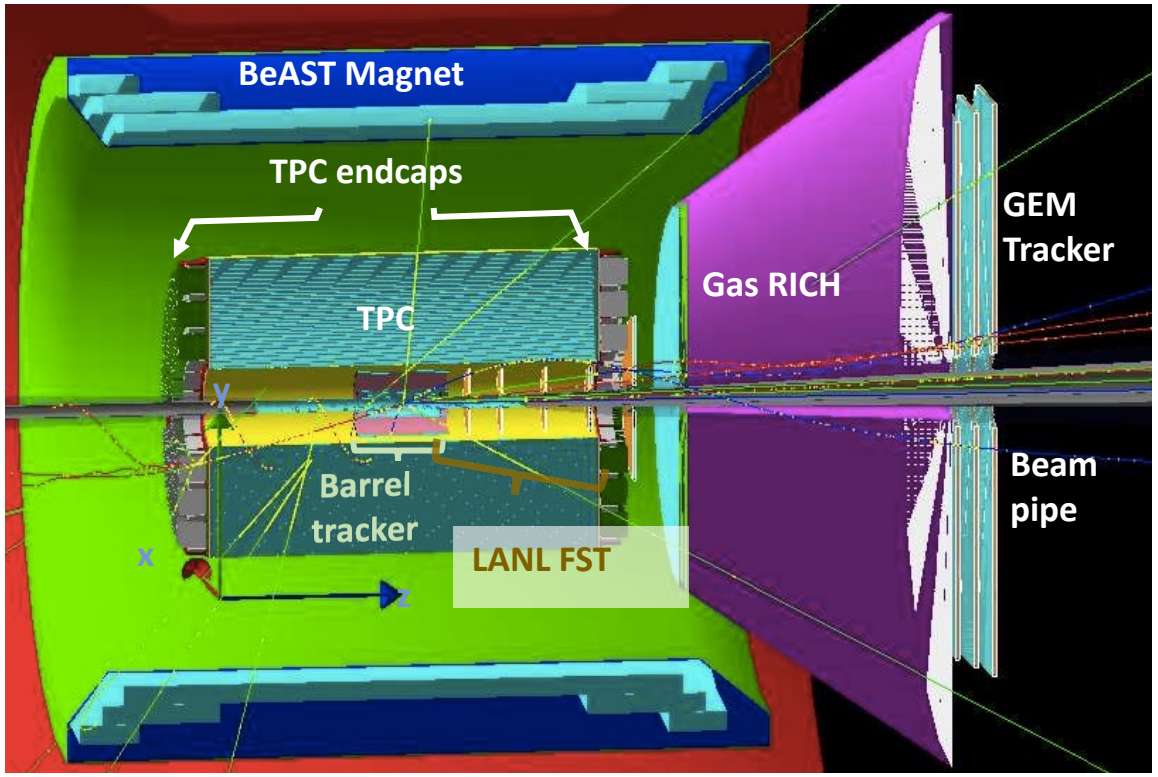
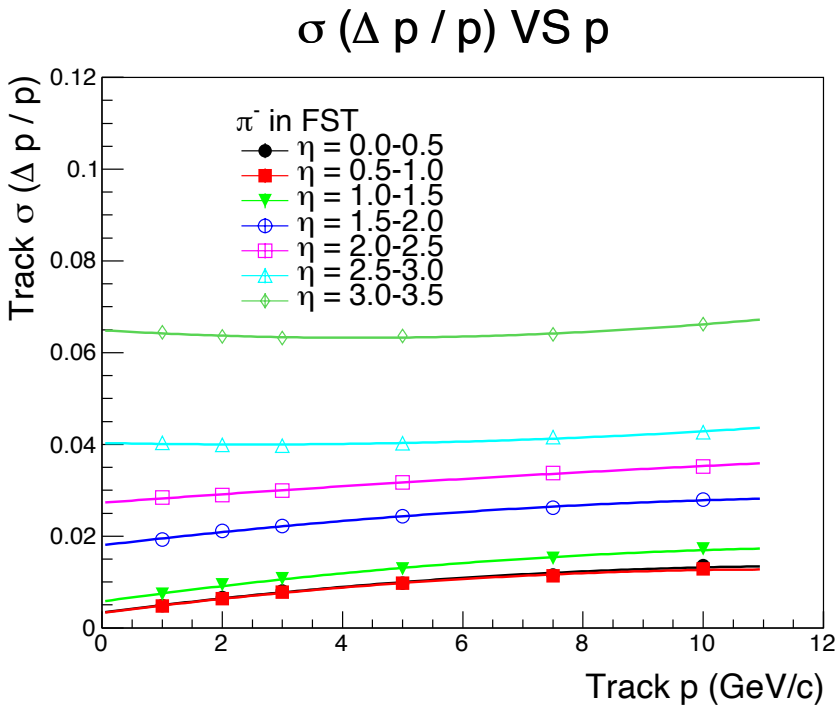


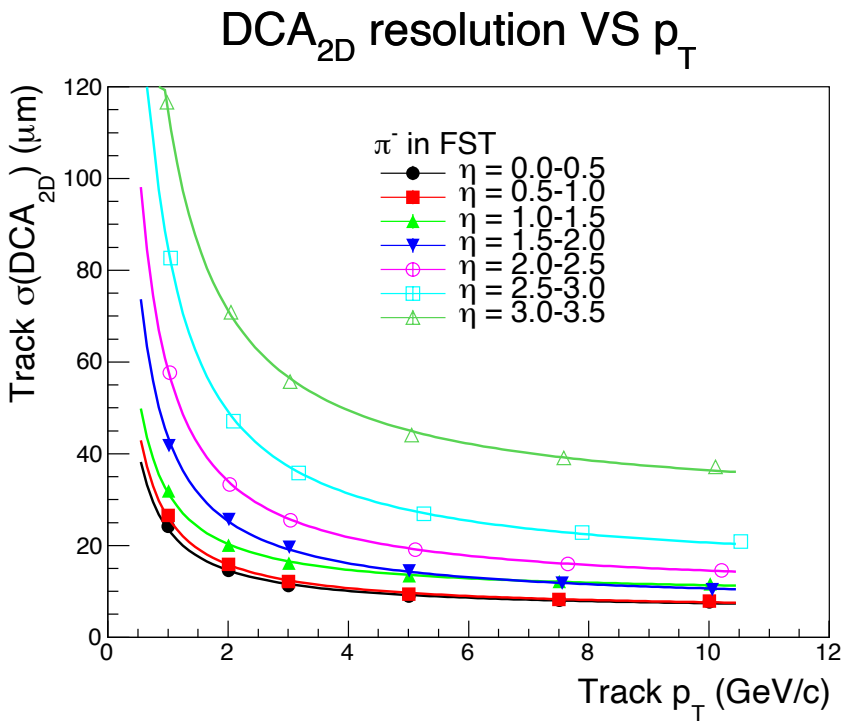

**Technology candidates**

| Name | Technique | Pixel Size | Integration Time | Thickness per layer |
|---|---|---|---|---|
| Monolithic Active Pixel Sensor (MAPS) | 180 nm (future 65 nm) Tower Jazz | ~ 20 X 20 $\mu m^2$ | ~ 100 ns | < 0.3%$X_0$ per layer |
| Radiation hard MAPS (MALTA) | 180 nm Tower Jazz | 36.4 X 36.4 $\mu m^2$ | < 5 ns | < 0.5%$X_0$ per layer |
| LGAD or AC-LGAD | Low Gain Avalanche Diode | 100 X 100 $\mu m^2$ | < 100 ps | < 1%$X_0$ per layer |

# Tracking performance of the proposed Forward Silicon Tracker (FST)

- Tracking performance of the proposed forward silicon tracker has been evaluated within the Fun4All framework.
- For example, the hybrid design of FST based on the MAPS and DMAPS technologies integrated inside the Time Projection Chamber (TPC) and the forward GEM tracker within the Beast magnet.

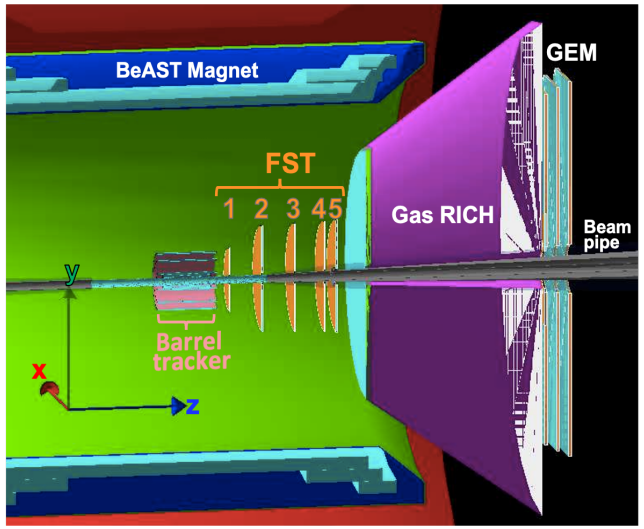


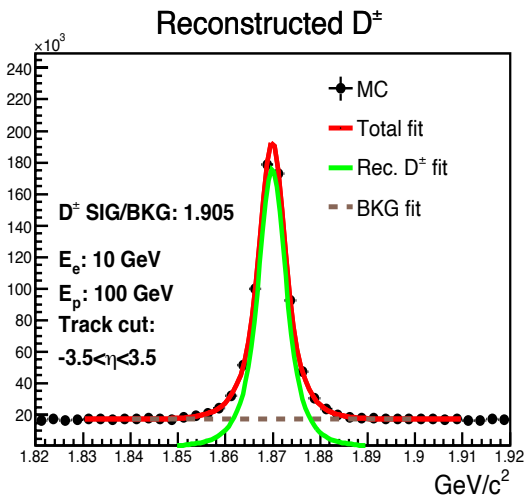
# Heavy Flavor signals enabled by the FST

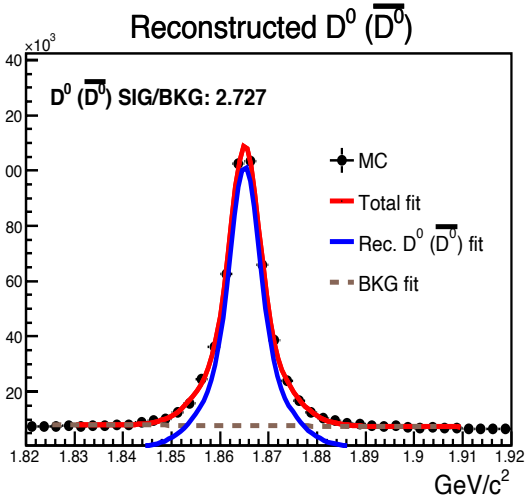
- The full analysis framework which includes the event generation (PYTHIA), detector response in GEANT4 simulation, beam remnant & QCD background, and hadron reconstruction algorithm have been setup.
- Mass distributions of reconstructed D-meson family in 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 $fb^{-1}$.

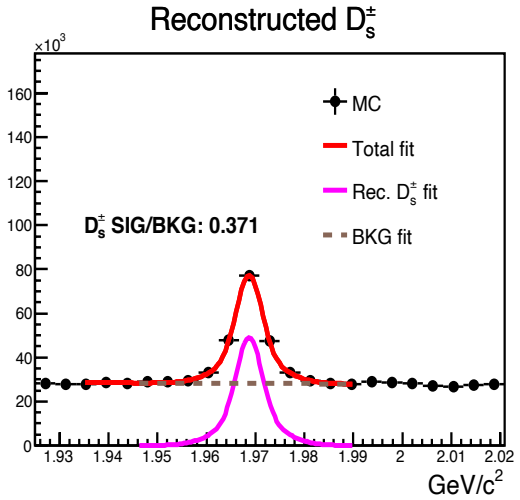
**Detector geometry**




**Reconstructed D-meson mass spectrum**



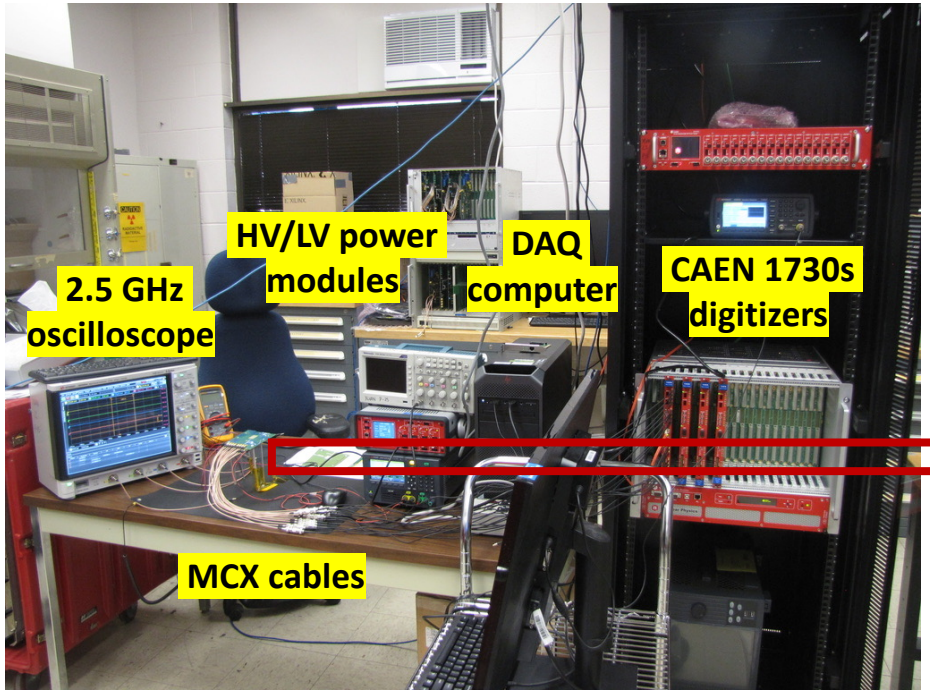




- Different detector geometries and magnet options have been studied. More details in **arXiv:2009.02888.**

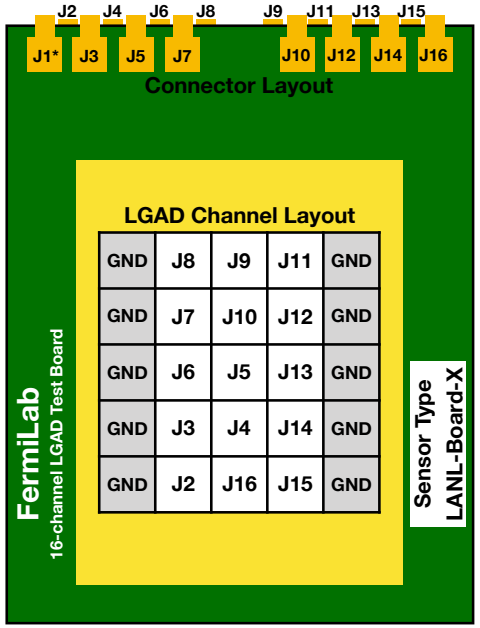
# R&D setup for the silicon technology candidates

- LGAD, AC-LGAD and MALTA sensors have been delivered to LANL (special thanks to colleagues at UCSC, FNAL and CERN).
- We start with the LGAD bench testing for a single LGAD sensor with a $Sr^{90}$ source. The data readout is processed by the CAEN 1730s digitizers.

**Front view of the Lab setup**

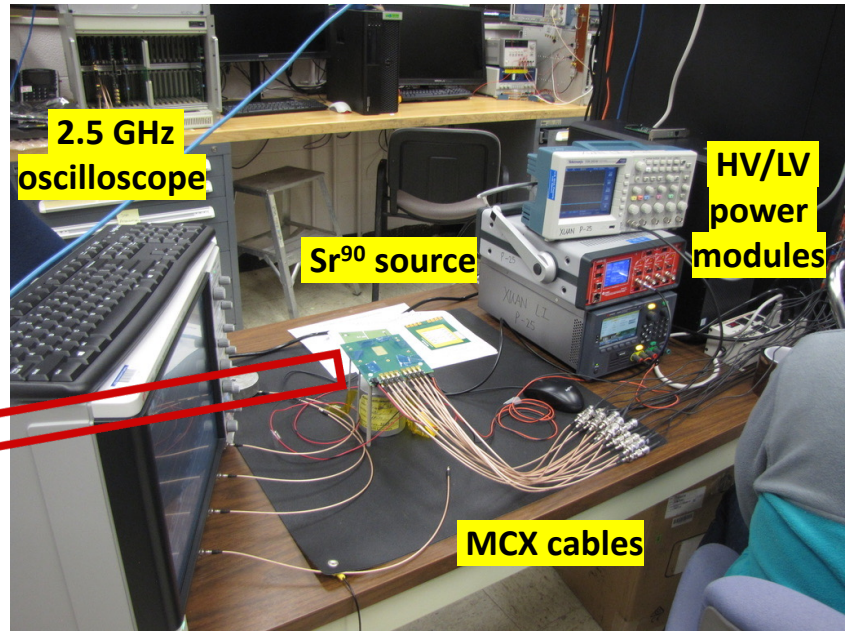



**LGAD pixel map**



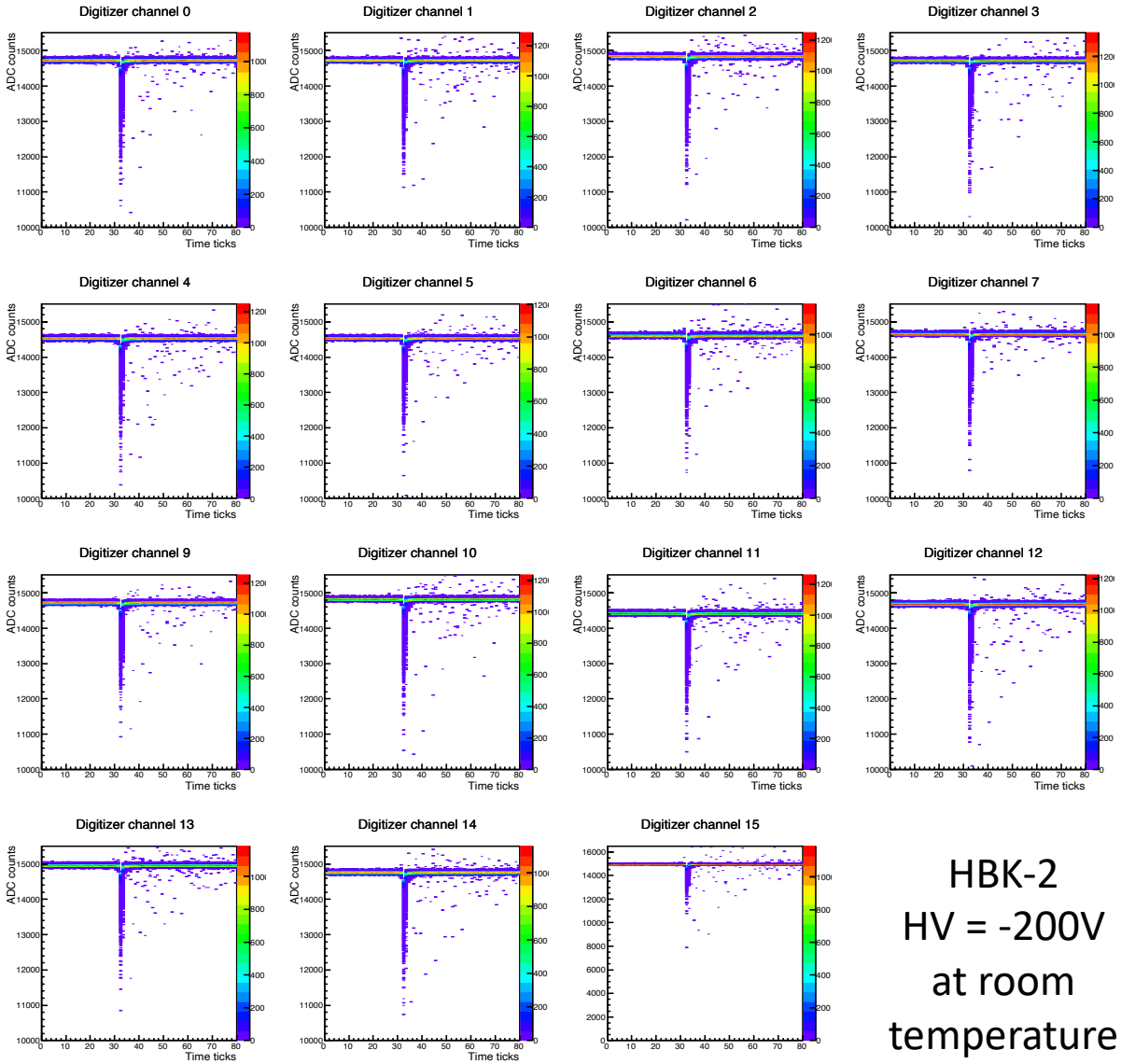

*Note that connector J1 is not bonded to a sensor pad.

**Side view of the Lab setup**



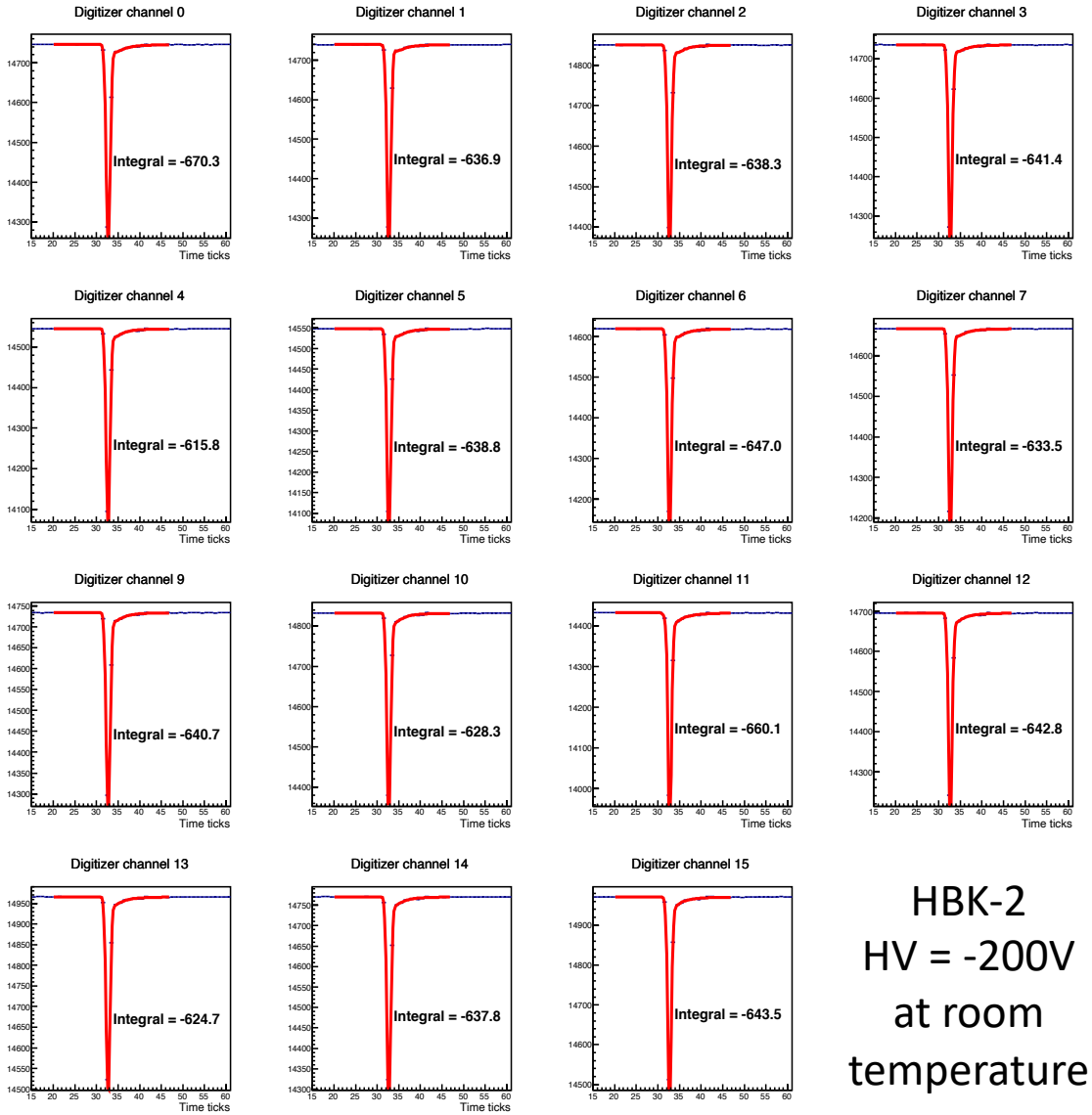
# Data analysis of the LGAD digitizer data

- Time dependent pulse distributions.




HBK-2
HV = -200V
at room
temperature

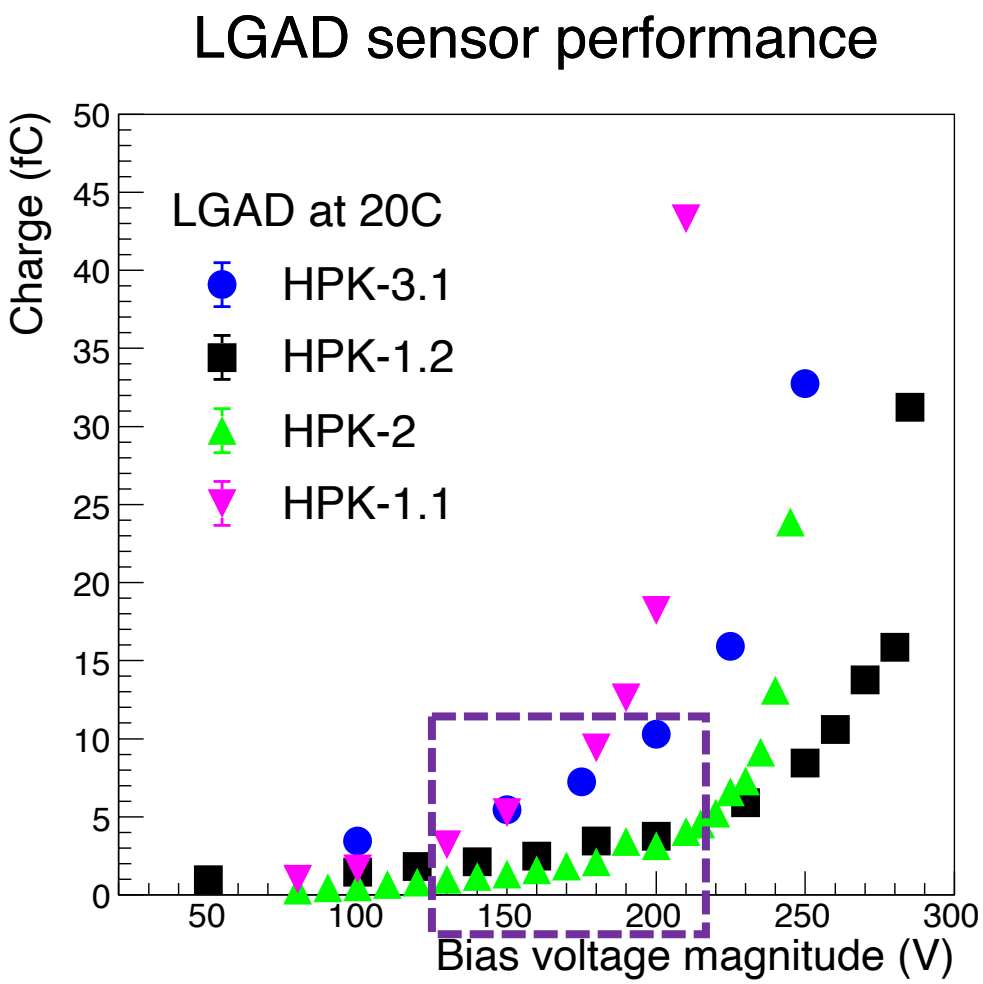
- Average pulse shape per pixel.



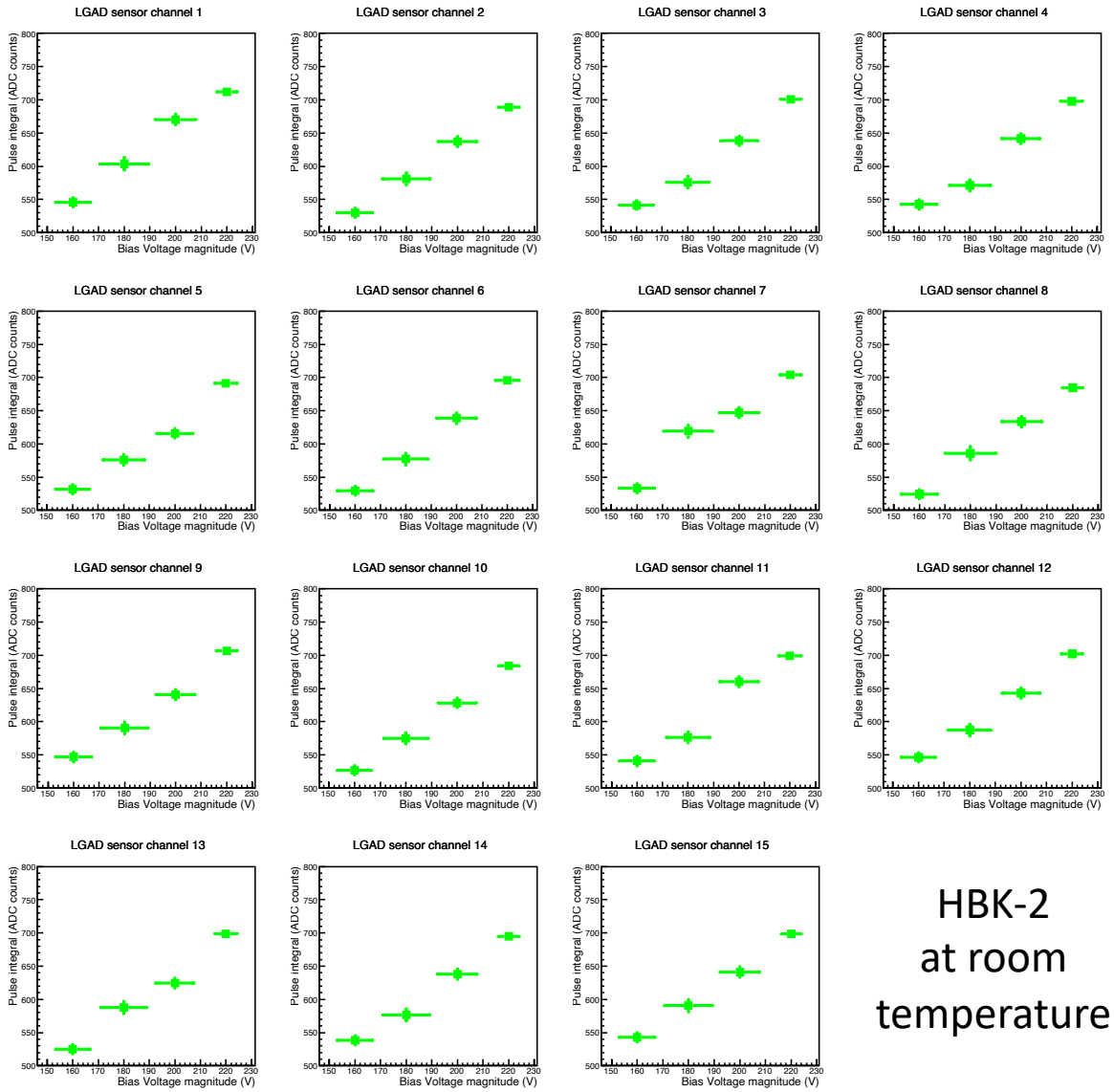

HBK-2
HV = -200V
at room
temperature

# Bias voltage dependent charge collection (I)

- Reference based on the laser scan tests.



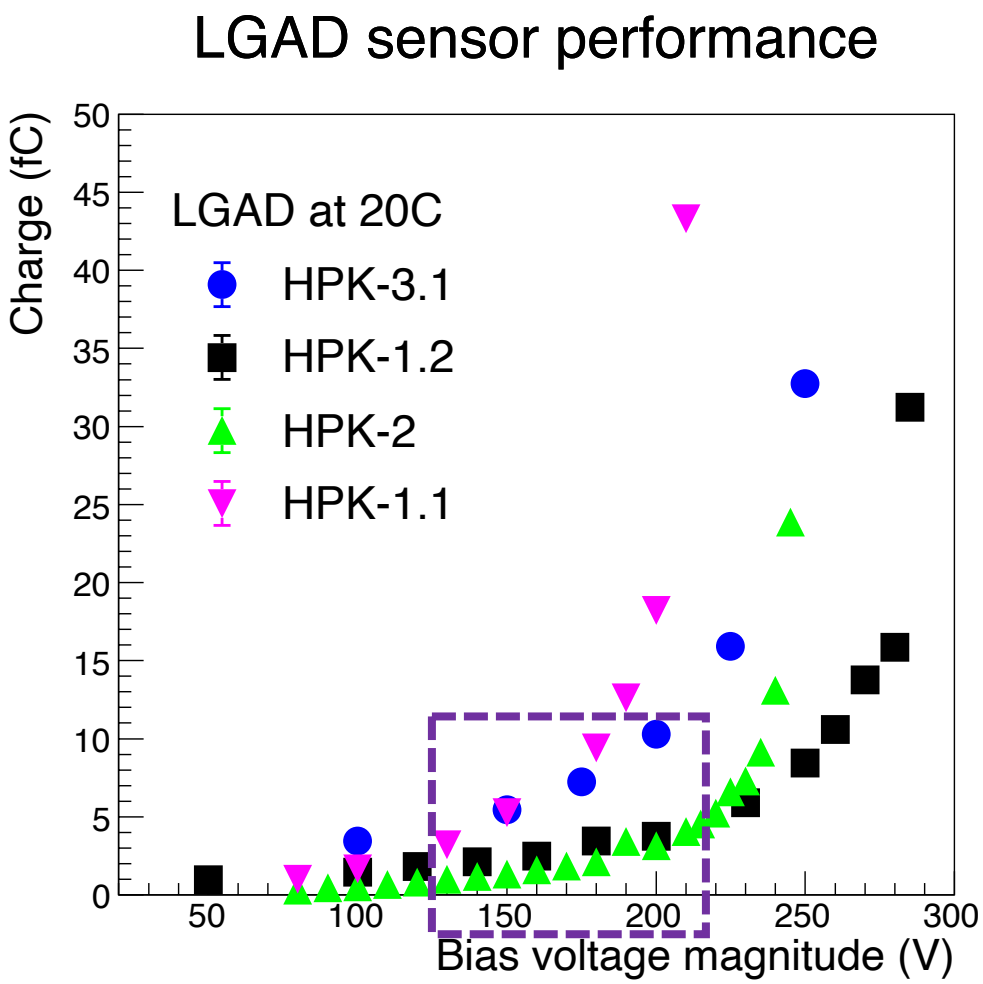

- Charge (ADC counts) VS Bias voltage.



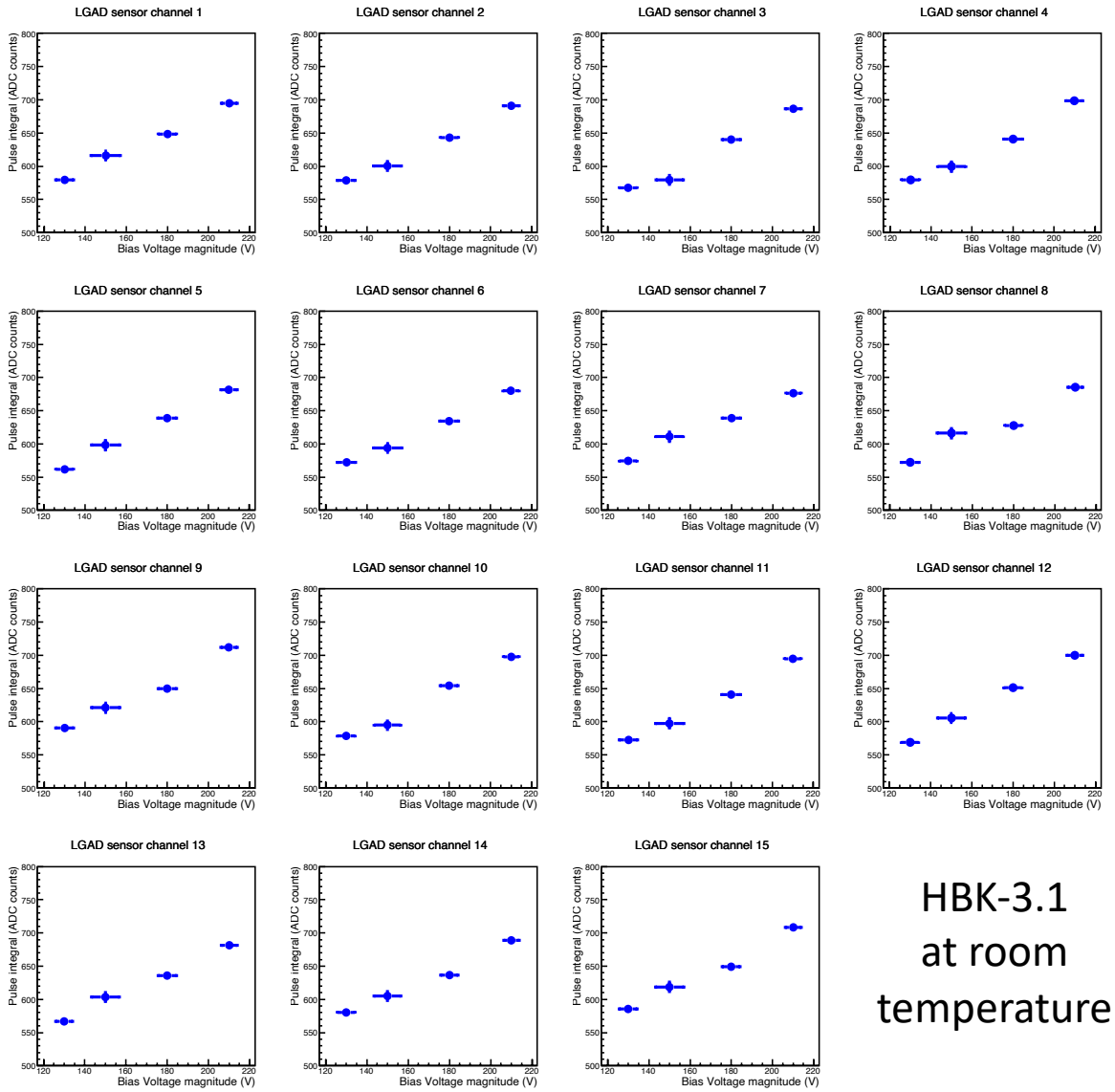

HBK-2
at room
temperature

# Bias voltage dependent charge collection (II)

- Reference based on the laser scan tests.




- Charge (ADC counts) VS Bias voltage.

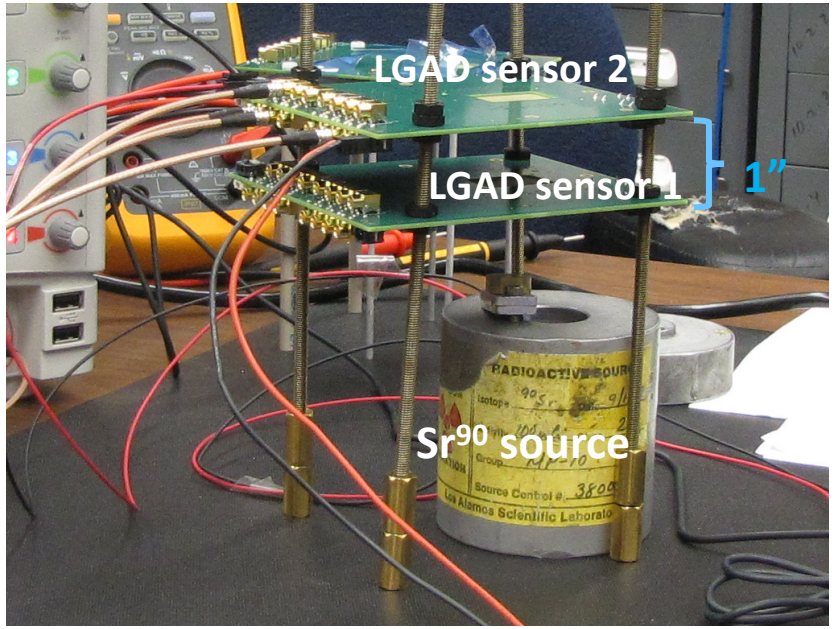



HBK-3.1 at room temperature

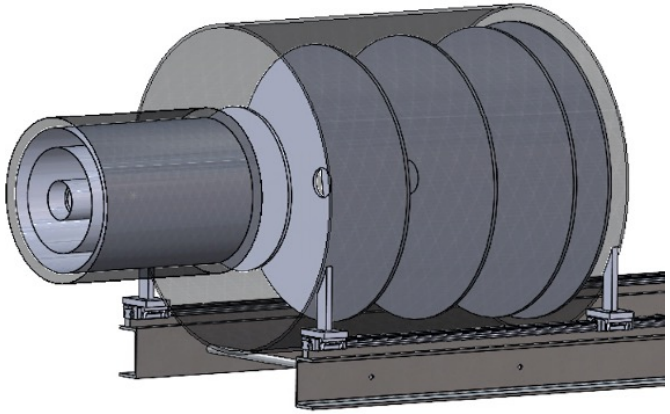
# Next steps

- LGAD test:
  - The telescope setup for $Sr^{90}$ source and cosmic ray tests is underway.
  - Plan to use a GHz laser scan system to test the timing resolution.
  - Will carry out the irradiation tests using the LANL LANSCE facility.
- MALTA test:
  - We're working on the setup and plan to carry out the $Sr^{90}$ source and cosmic ray tests.
- Detector conceptual design:
  - Will optimize the detector conceptual design and implement the service parts based on the R&D results.

**2-layer LGAD telescope setup**

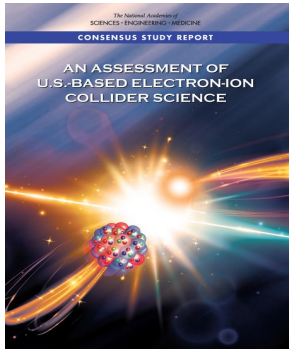



**Engineer drawing of the FST conceptual design**

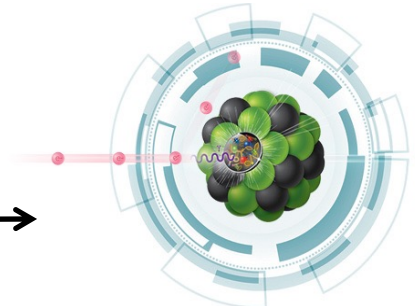


# Summary and Outlook

- The future EIC requires advanced silicon detectors to realize high precision particle tracking and identification measurements.
- The initial design of the proposed forward silicon vertex/tracking detector meets the EIC heavy flavor physics requirements.
- R&D work for one of the silicon detector candidates: LGAD has achieved the first test results.
- We look forward to collaborate with more institutions toward the detector developments and construction for the EIC.




| NAS review | EIC CD0 | EIC CD1 | EIC CD2 | EIC CD3 | EIC CD-4a | EIC CD-4 |
|---|---|---|---|---|---|---|
| 2018 | 2020 | 2021 | 2023 | 2024 | 2030 | 2033 |

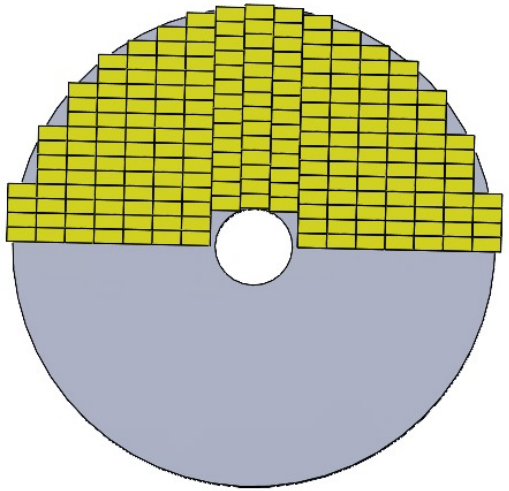


# Backup

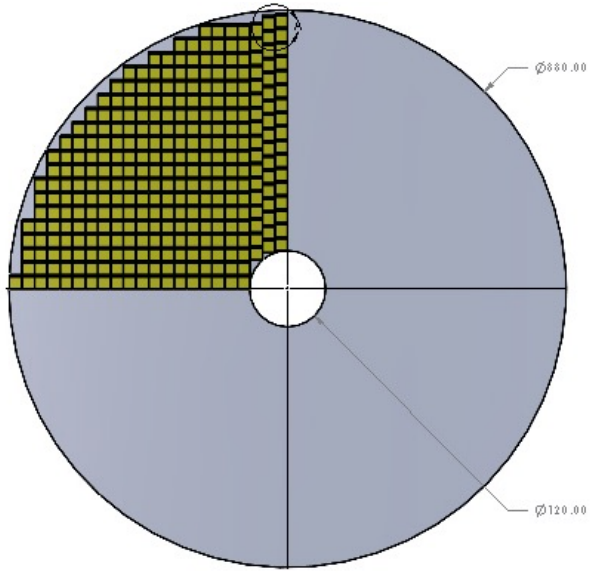
# Layout of the LANL FST

- The LANL FST is a hybrid design of ITS-3 type and MALTA Monolithic Active Pixel Sensor (MAPS) technology.
- The service parts and the initial concept for each technology has been developed. Optimization is underway.

1st disk layout (ITS-3)



4th disk layout (MALTA)




**LANL FST**