Fast timing silicon R&D for the future Electron-Ion Collider

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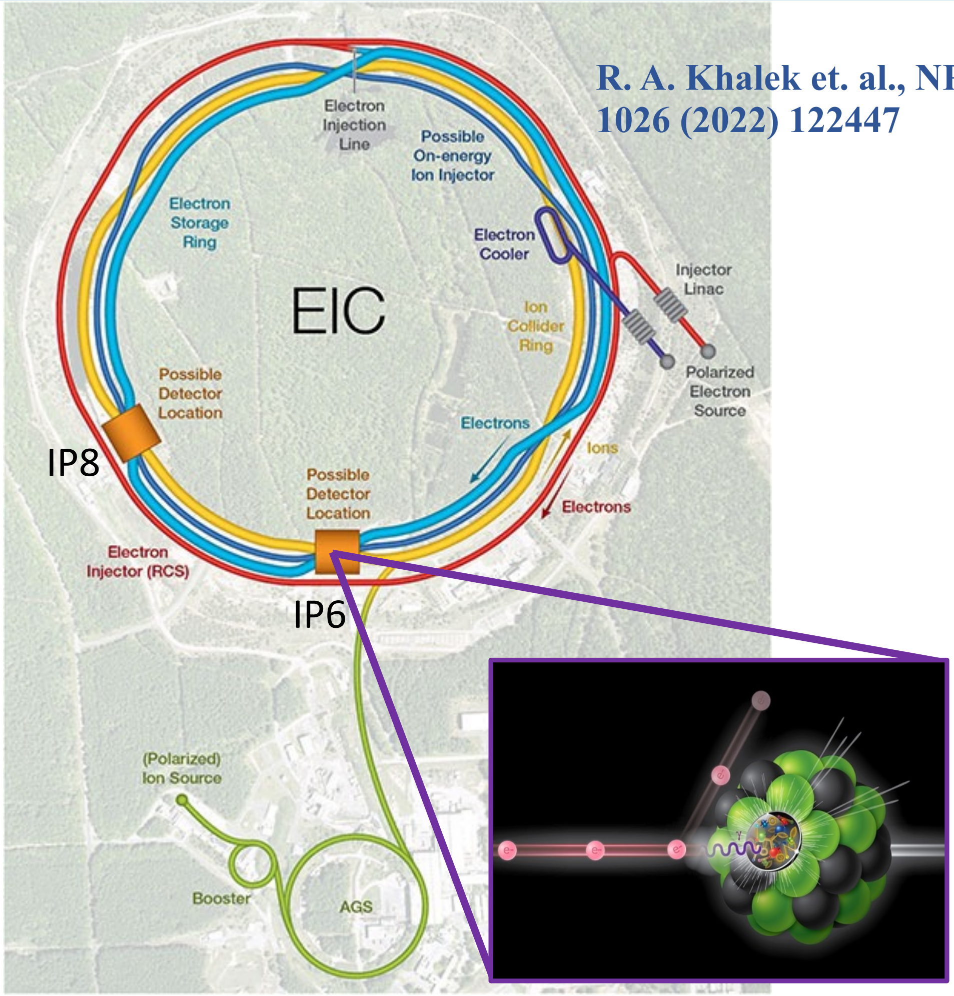
Outline

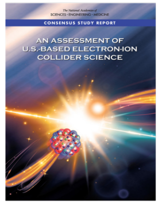
- Introduction to the Electron-Ion Collider (EIC) and the EIC detectors.
- Motivation of the proposed Fast MAPS Tracker (FMT) for the EIC.
- Fast MALTA2 R&D progress.
- Performance and impacts of the proposed FMT evaluated in simulation.
- Summary and Outlook.

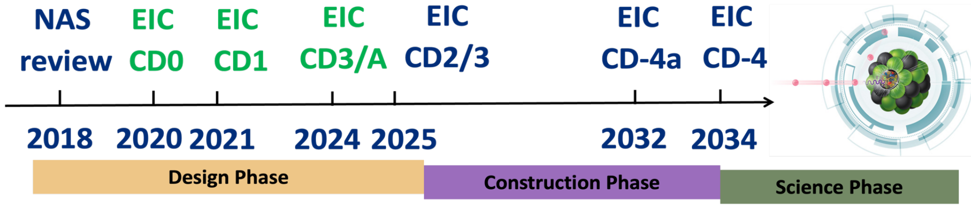
Introduction to the future Electron-Ion Collider (EIC)

- The future Electron-Ion Collider (EIC) will utilize high-luminosity high-energy e+p and e+A collisions to solve several fundamental questions in the nuclear physics field.
- The EIC project has received CD3/A approval from the US DOE in 2024 and is scheduled to start construction at BNL in 2025 and operation in early 2030s.
- The EIC will support up to two Interaction Points (IP6, IP8).
- The future EIC will operate:
  - (Polarized) p and nucleus (A=2-238) beams at 41, 100-275 GeV.
  - (Polarized) e beam at 5-18 GeV.
  - Instantaneous luminosity $L_{int} \sim 10^{33-34}$ $cm^{-2} sec^{-1}$. A factor of ~1000 higher than HERA.
  - Bunch crossing rate: 10.2 ns.
  - Beam crossing angle at IP6: 25 mrad.



R. A. Khalek et. al., NPA 1026 (2022) 122447

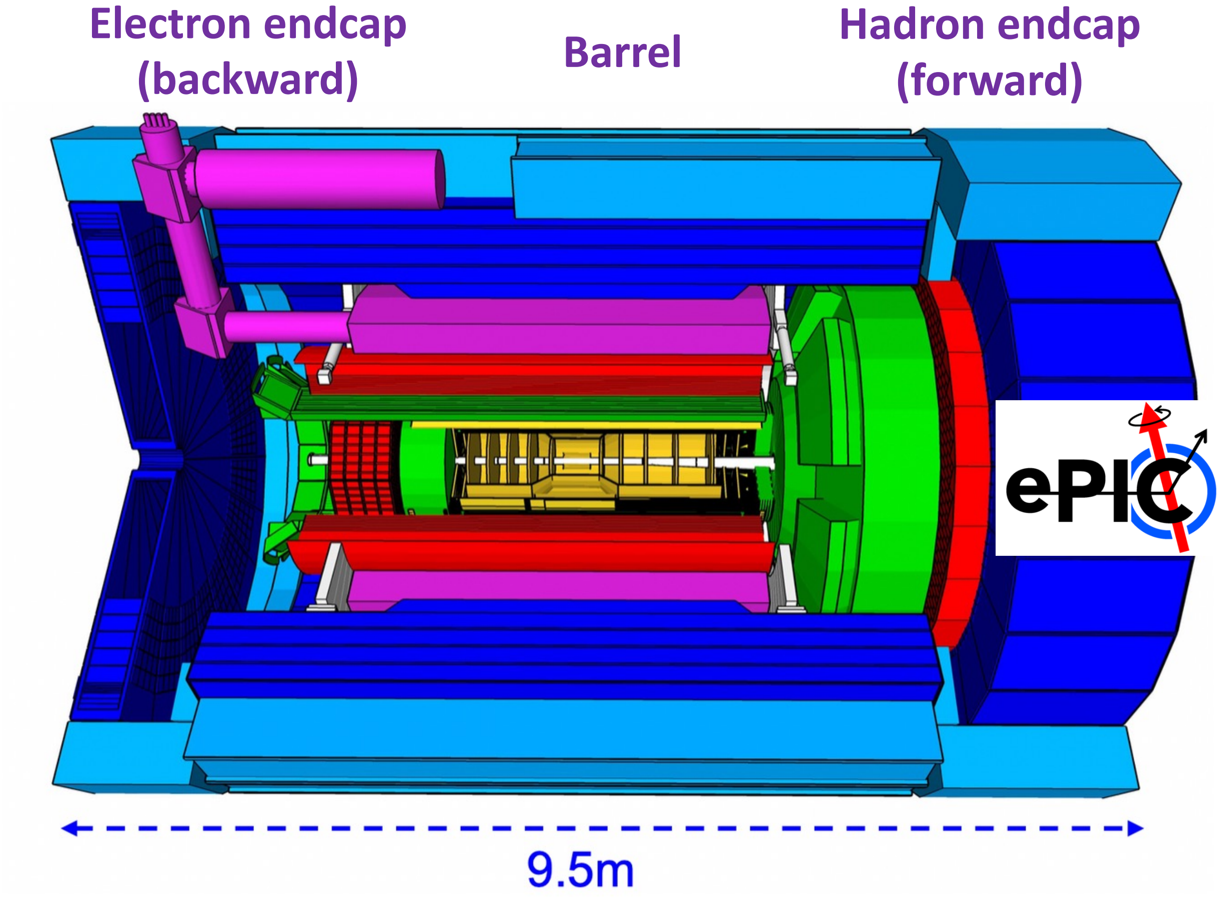




Current EIC project detector design by the ePIC collaboration

- The ePIC collaboration is leading the EIC project detector (at IP6) technical design towards the EIC CD2/3 approval (scheduled in April 2025).
- The 2nd EIC detector (at IP8) is to be designed.

More EIC details in C.M. Camacho's talk on Friday

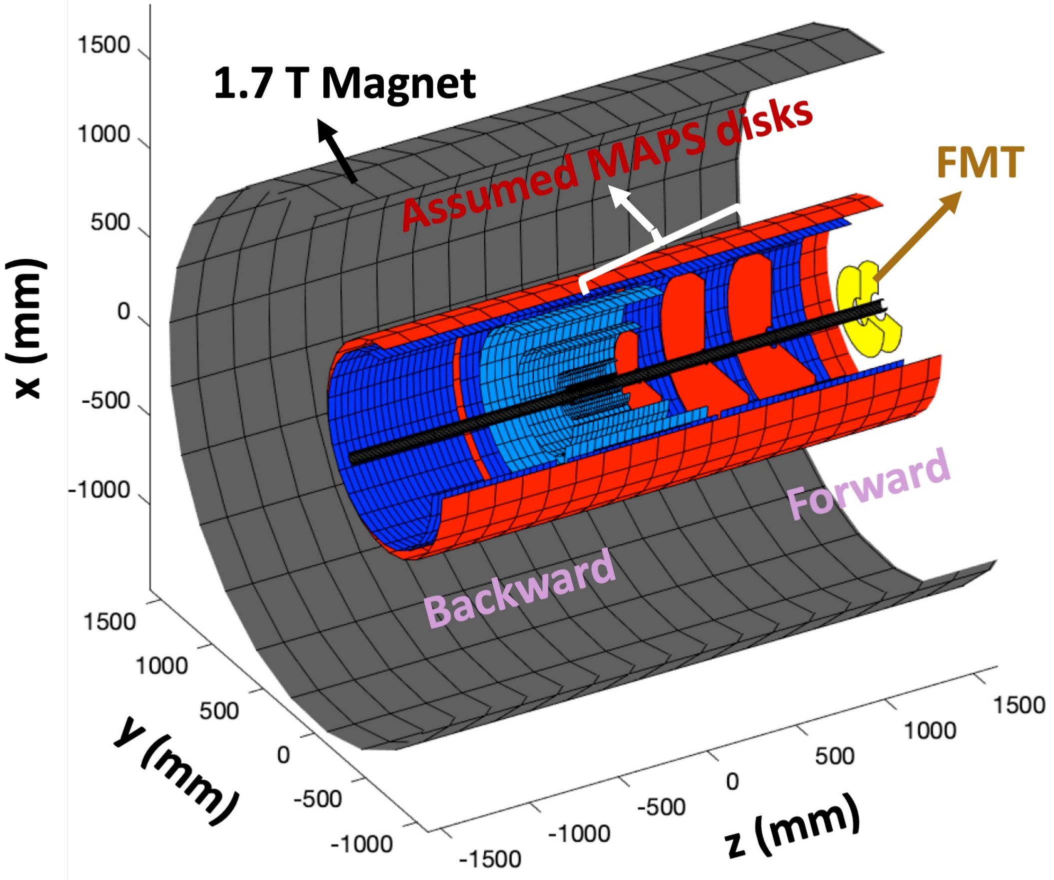


- The ePIC central detector (9.5m X 3.3m) consists of optimized vertex, tracking, PID, EMCal and HCAL subsystems and will utilize a new 1.7 T magnet.
- The high granularity ePIC vertex and tracking detector includes
  - 65 nm Monolithic Active Pixel Sensor (MAPS) vertex and tracking subsystems (innermost 5 layers).
  - Micro Pattern Gas Detector (MPGD) tracking subsystem (intermediate).
  - AC coupled Low Gain Avalanche Diode (AC-LGAD) layer/plane as the outer tracker.

The proposed 4D MAPS tracking detector for the EIC

- We propose a Fast MAPS Tracking detector (FMT) based on the Depleted Monolithic Active Pixel Sensor (DMAPS), i.e., MALTA2, technology, which could be used either for the ePIC detector upgrade or the 2nd EIC detector.

Standalone MC



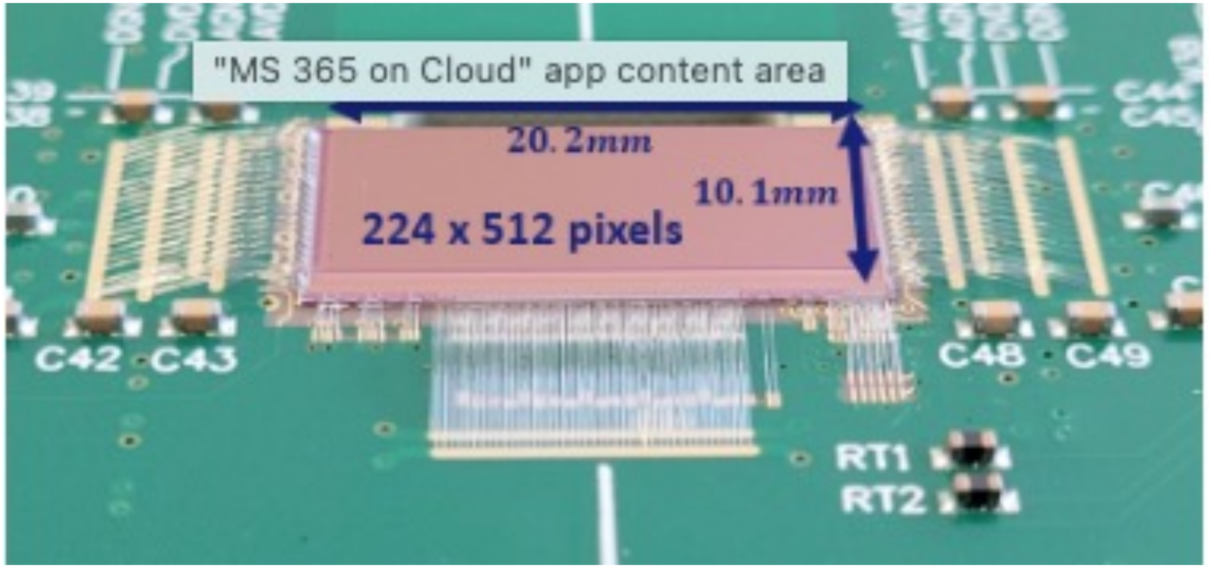
- The current design of the **proposed FMT** consists of 2 planes in the forward (hadron endcap) region and 2 planes in the backward (electron endcap) region, near the edge of the EIC central magnet. It aims to improve the track reconstruction in the $|\eta| > 2.5$ region.
- The **proposed FMT** can achieve 2 ns timing resolution and it helps separate backgrounds from DIS physics events in $2.5 < |\eta| < 3.5$.
- Further geometry optimization will be performed for detector integration purpose.

MALTA2 sensor technical feature

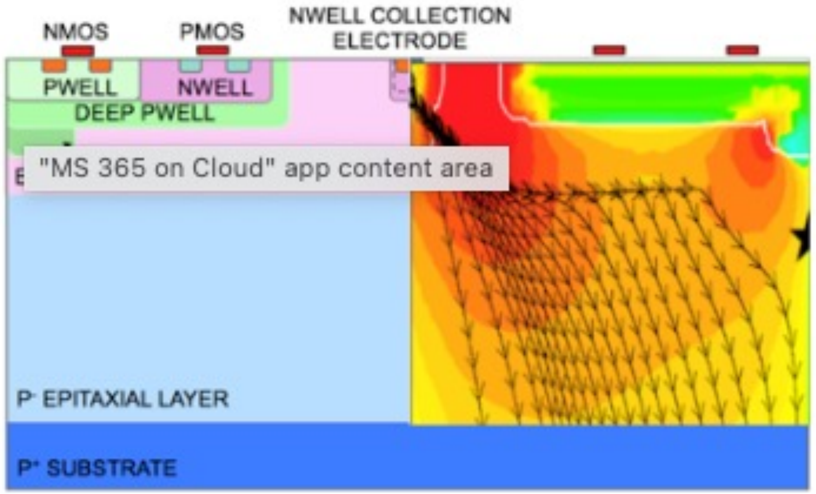
- The MALTA2 prototype sensors made of Tower 180 nm CMOS technology are under extensive bench and beam tests with well established readout chain.
- MALTA2 sensor has
  - 20 X10 mm^2 active area,
  - 224 X 512 pixels with 36.4 μm pixel pitch,
  - 10 mW/cm^2 digital power consumption, 70 mW/cm^2 analog power consumption.

IEEE Transactions on Nuclear Science, vol. 69, no. 6, pp. 1299-1309, 2022.

MALTA2 prototype sensor



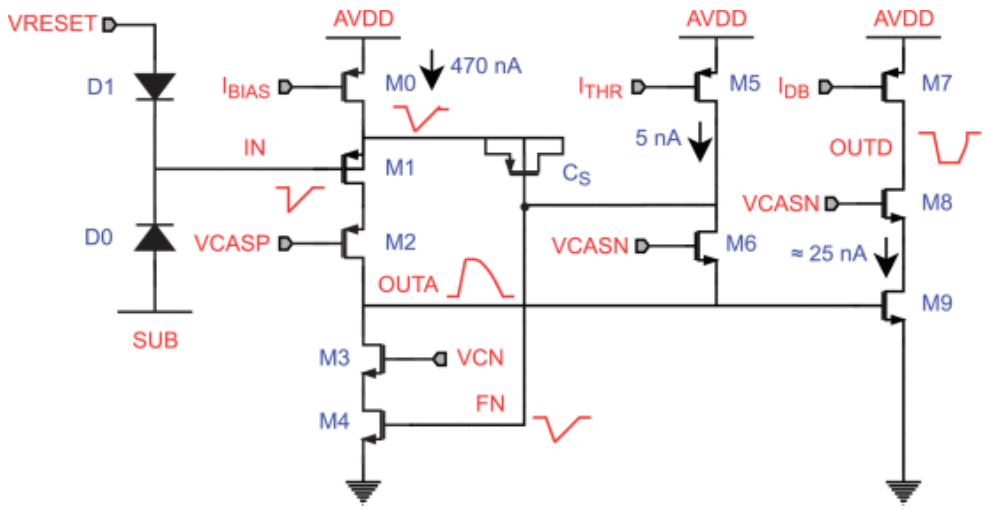
MALTA2 pixel design w/ improved charge collection in the pixel edge



MALTA2 readout scheme

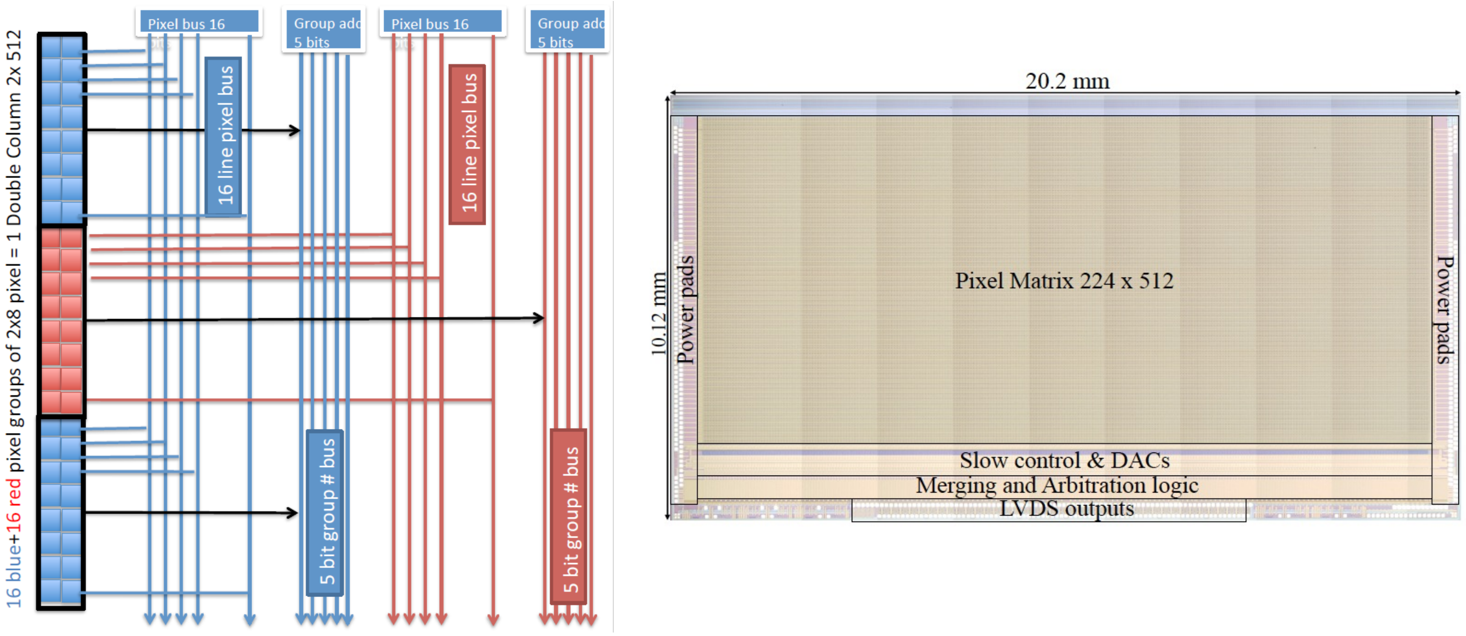
- At the periphery, arbitration and merging resolve timing conflicts of simultaneous signals.
- 40-bit wide data packet transmitted off chip by 5 Gbps LVDS drivers.
- Fully established front-end and back-end readout chain for MALTA2 prototype sensor characterization.

MALTA2 pixel front-end schematic w/ amplification, shaping and digitization



I Berdalovic et al. 2018 JINST 13 C01023

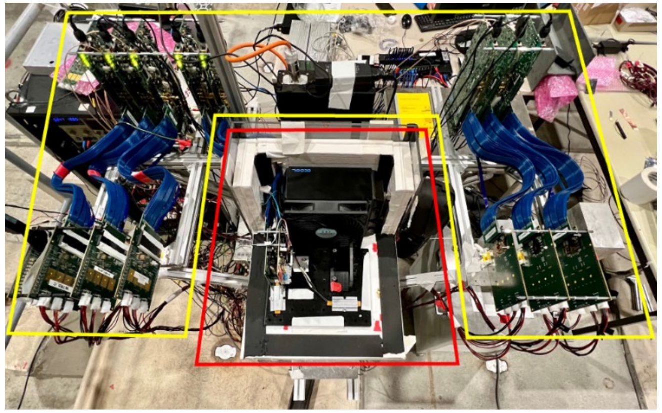
MALTA2 readout architecture



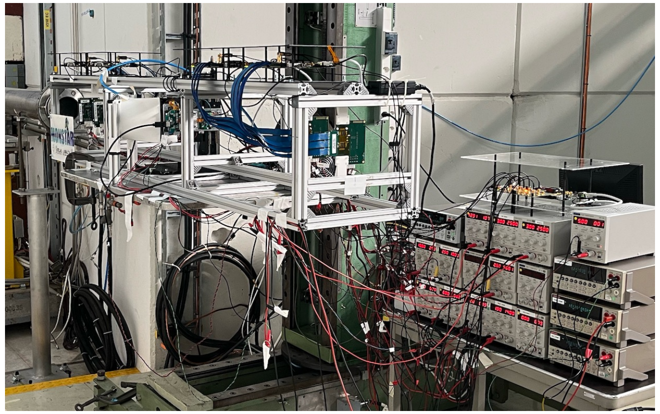
Latest MALTA2 R&D results (I)

- MALTA telescope beam tests have been performed at DESY, ELSA, SPS and PS from 2021 to 2023.

MALTA telescope in SPS H6

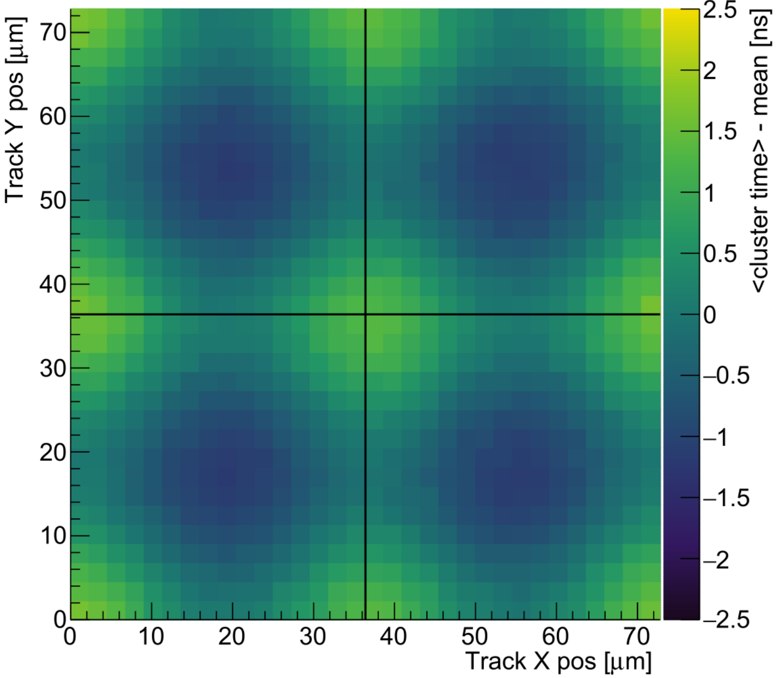


MALTA telescope in PS T9

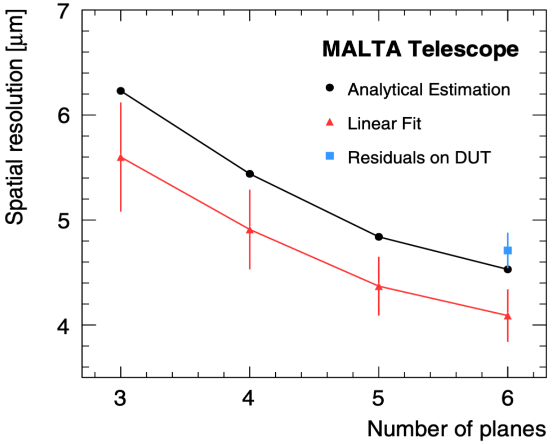


Eur. Phys. J. C 83(2023), 58

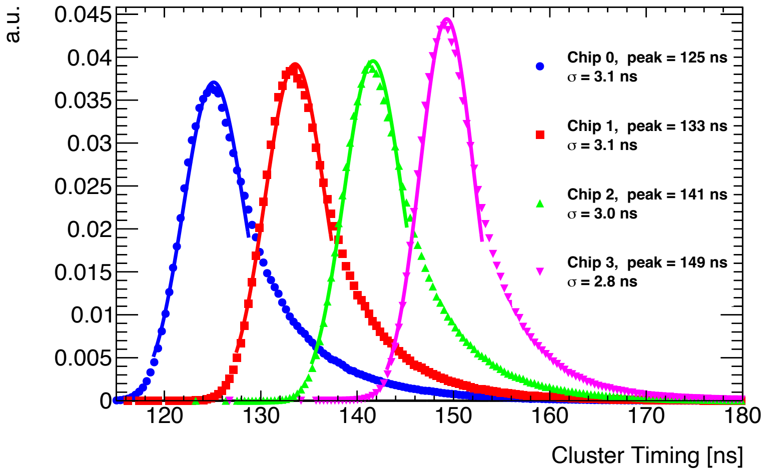
In-pixel timing projected in a 2x2 MALTA pixel matrix @SPS



Spatial resolution of MALTA telescope + MALTA2 DUT @SPS



Timing distribution of MALTA chips @SPS

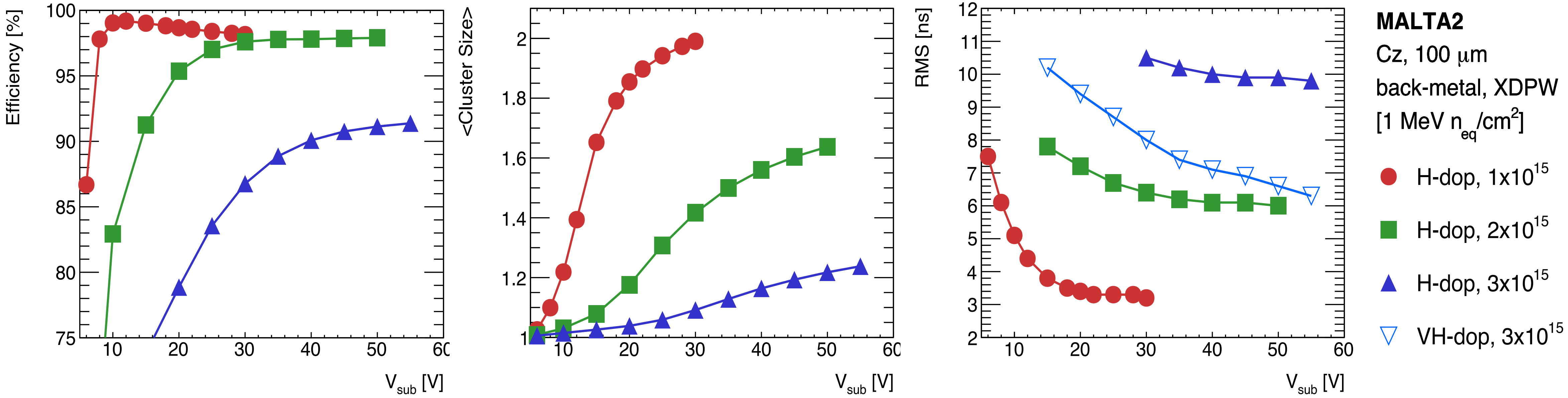


- Spatial resolution: ~4.1+0.2 μm
- Timing resolution: ~2.1 ns

Latest MALTA2 R&D results (II)

- MALTA2 Cz sensors can tolerate radiation dose up to 3×10^{15} n_{eq}/cm^2.

Eur Phys J. C 84 (2024) 251

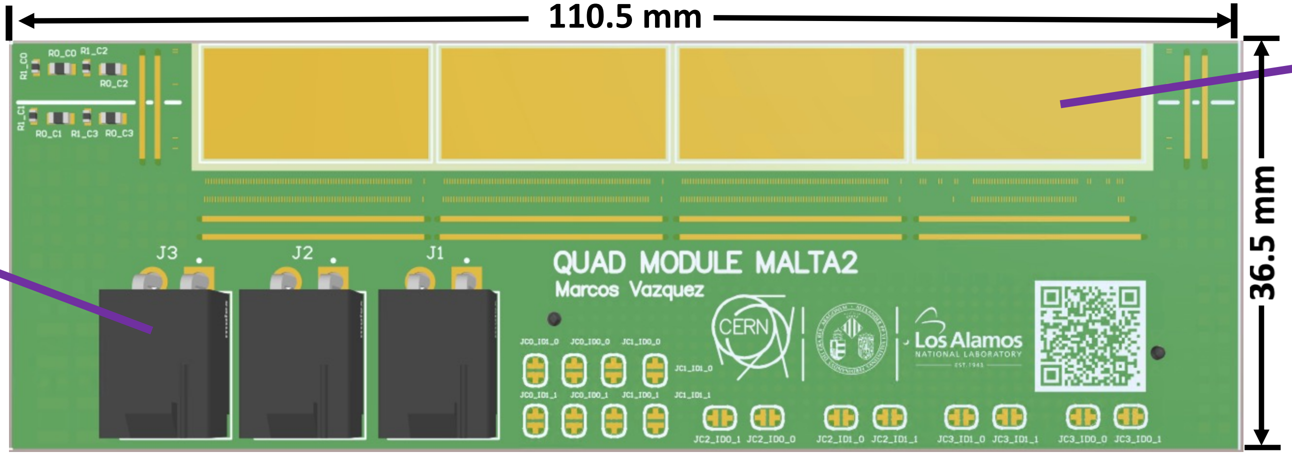


- No significant impacts on the hit efficiency, cluster size and timing RMS for irradiation dose at 1×10^{15} n_{eq}/cm^2. The current estimated irradiation dose at EIC is << 1×10^{14} n_{eq}/cm^2. Will use the characterization tests at 1×10^{15} n_{eq}/cm^2 (highlight in red) to evaluate the proposed FMT detector performance.

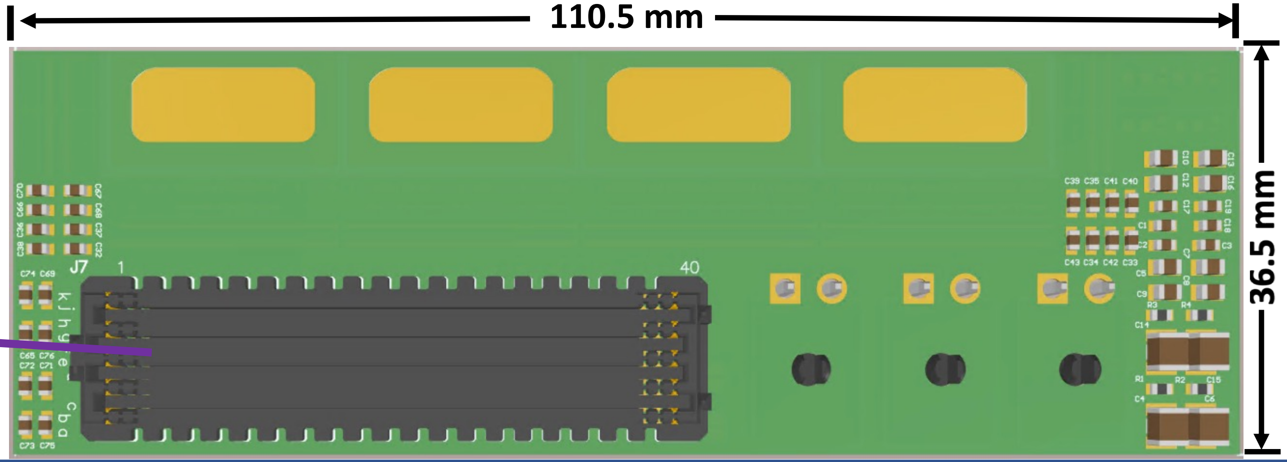
New MALTA2 quar-sensor stave design

- The first engineer design of the MALTA2 quad-sensor prototype module has been submitted for production. Utilize 100 μm thick silicon wafer and Cu-Al hybrid FPC.

Front view of the MALTA2 quad-sensor prototype module design



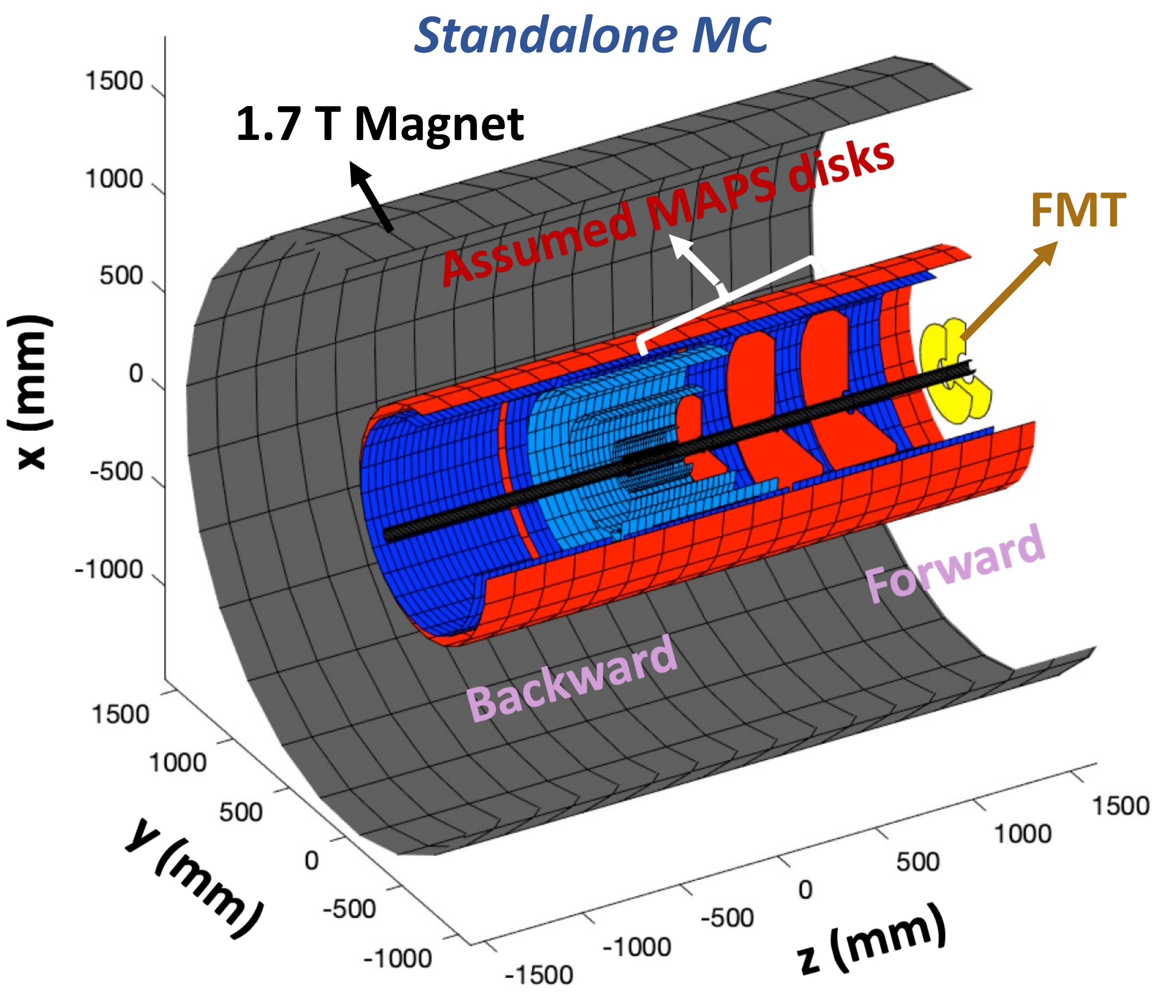
Back view of the MALTA2 quad-sensor prototype module design



- Plan to characterize the quad-sensor module performance in bench and lab tests.
- Will utilize air cooling.
- Average material budget per layer is 0.74% X/X_0, still have room to improve.

The proposed FMT detector geometry

- The proposed FMT is planned to be placed around the beam pipe near the edge of the magnet of the EIC.



- Use the design of the IP6 beam pipe, the 1.7T ePIC magnet and the ePIC central barrel detector as the reference.
- Assume three 65 nm MAPS based disks (z=25cm, 62.5cm, 100cm, maximum pseudorapidity η=2.5) to fill the gap between the central barrel and the forward region to be covered by the FMT. A symmetric design is applied in the backward region as well (not shown).
- The proposed FMT consists of 2 disks based on MALTA2 staves in the forward and backward region. Each MALTA2 stave will consist of 8 MALTA2 sensors or groups of two quad-sensor modules next to each other.

The proposed FMT detector performance (I)

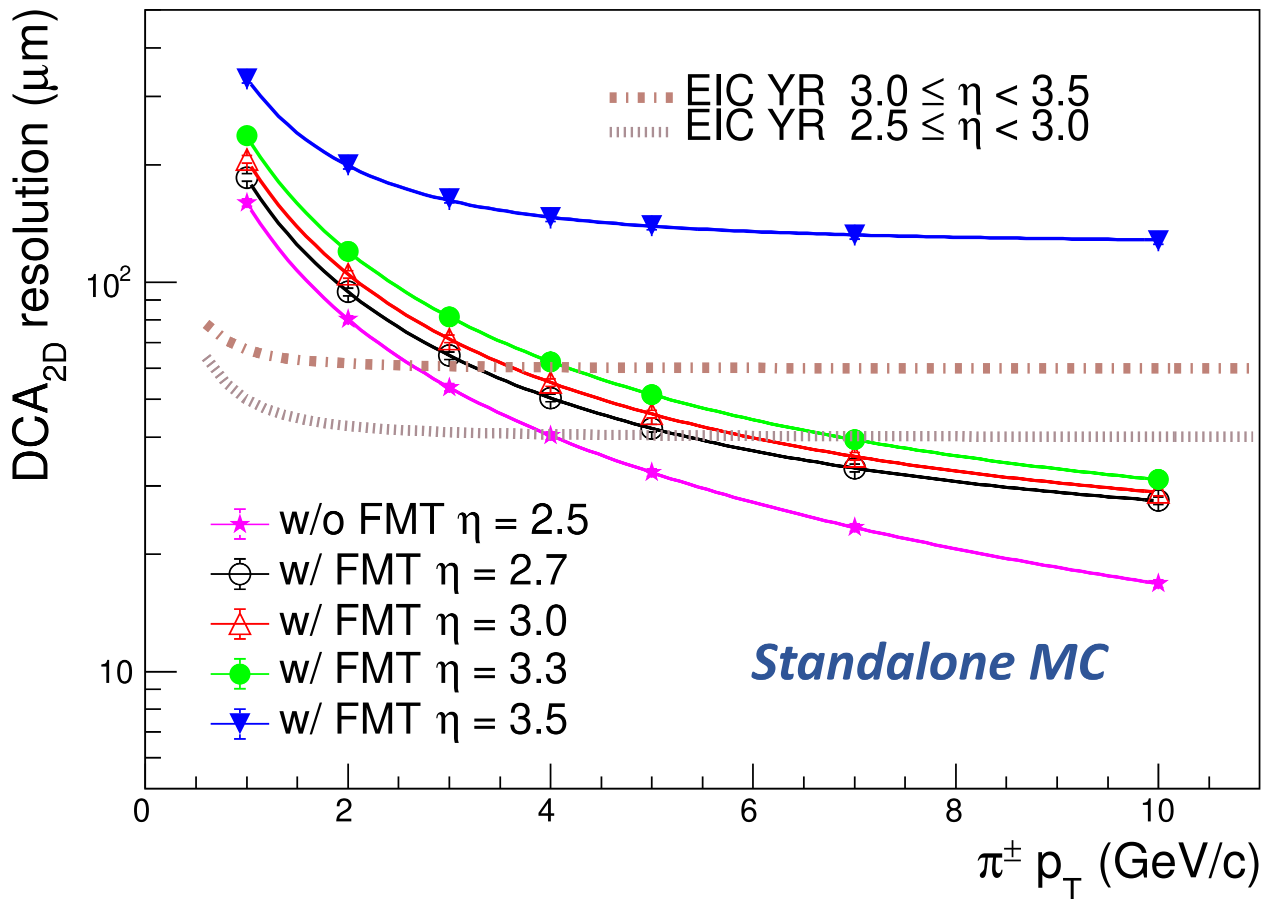
- Assume the FMT will utilize 8-sensor staves, or groups of two quad-sensor modules next to each other to assemble disks.

Hadron endcap FMT geometry (config 1)

Parameter	Disk 1	Disk 2
Inner Radius	7.014 cm	7.014 cm
Outer Radius	23.095 cm	23.095 cm
z location	150 cm	160 cm
Material budget	$0.74\%X/X_0$	$0.74\%X/X_0$
Average hit efficiency	98%	98%

DCA_{2D}: Distance of Closest Approach of tracks in the x-y plane at the primary vertex

Projected p_T dependent DCA_{2D} resolution

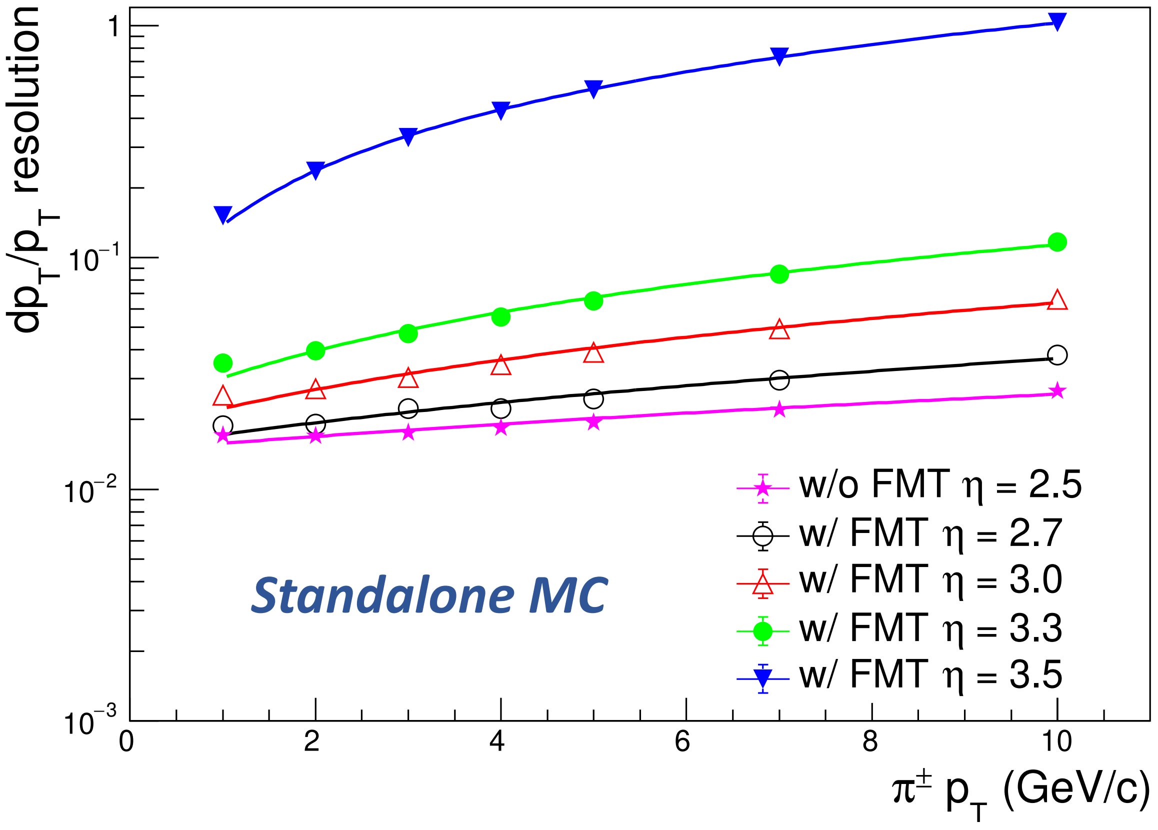


The proposed FMT detector performance (I)

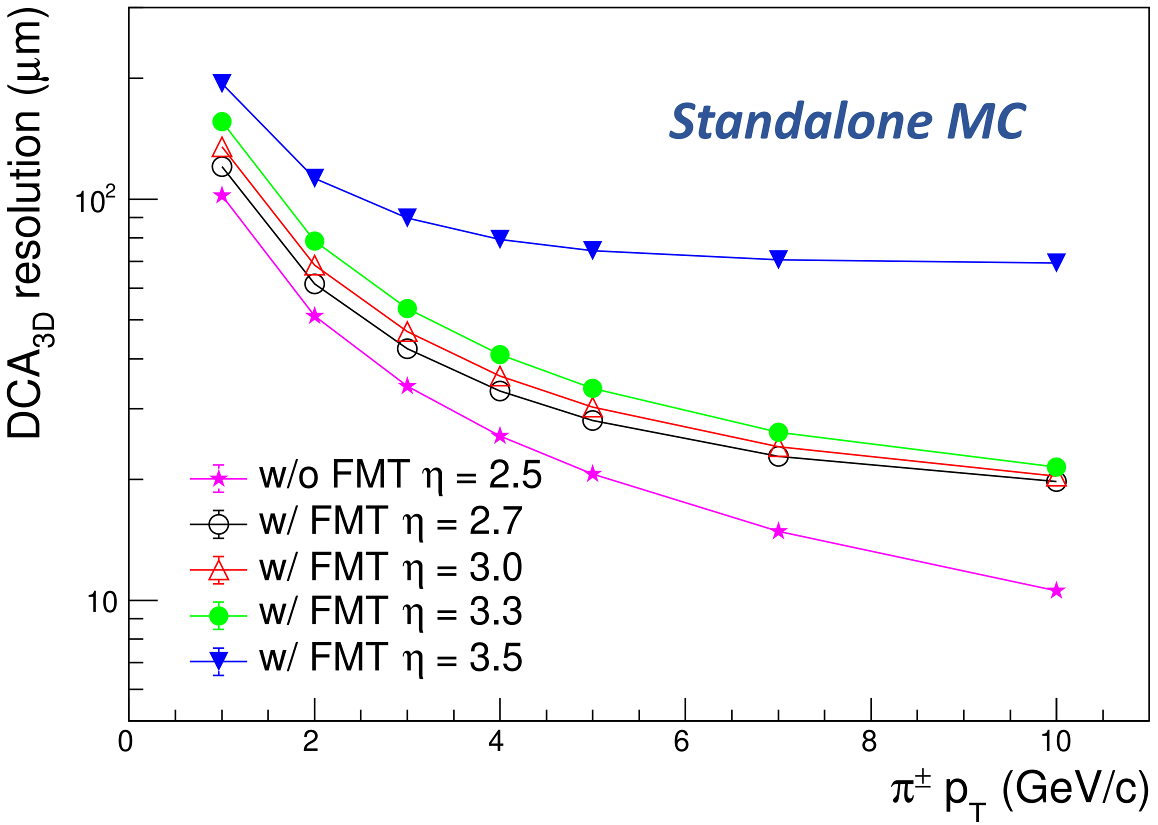
- Projected p_T dependent p_T resolution (left) and p_T dependent DCA_{3D} resolution w/ and w/o FMT.

Hadron endcap FMT geometry (config 1)

Projected p_T dependent $\Delta p_T/p_T$ resolution



Projected p_T dependent DCA_{3D} resolution



The proposed FMT detector performance (II)

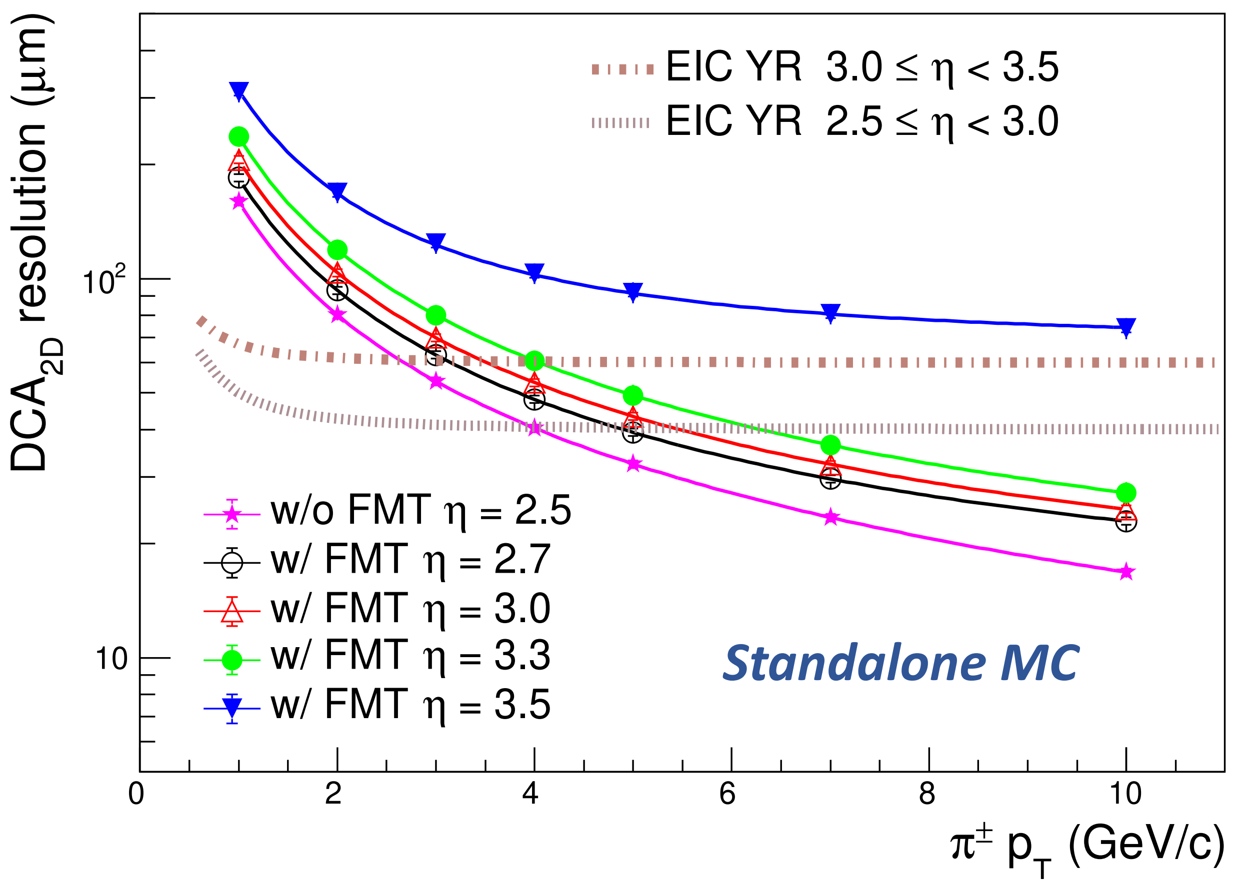
- Assume the FMT will utilize 8-sensor staves, or groups of two quad-sensor modules next to each other to assemble disks.

Hadron endcap FMT geometry (config 2)

Parameter	Disk 1	Disk 2
Inner Radius	7.014 cm	7.014 cm
Outer Radius	23.095 cm	23.095 cm
z location	145 cm	165 cm
Material budget	$0.74\%X/X_0$	$0.74\%X/X_0$
Average hit efficiency	98%	98%

DCA_{2D}: Distance of Closest Approach of tracks in the x-y plane at the primary vertex

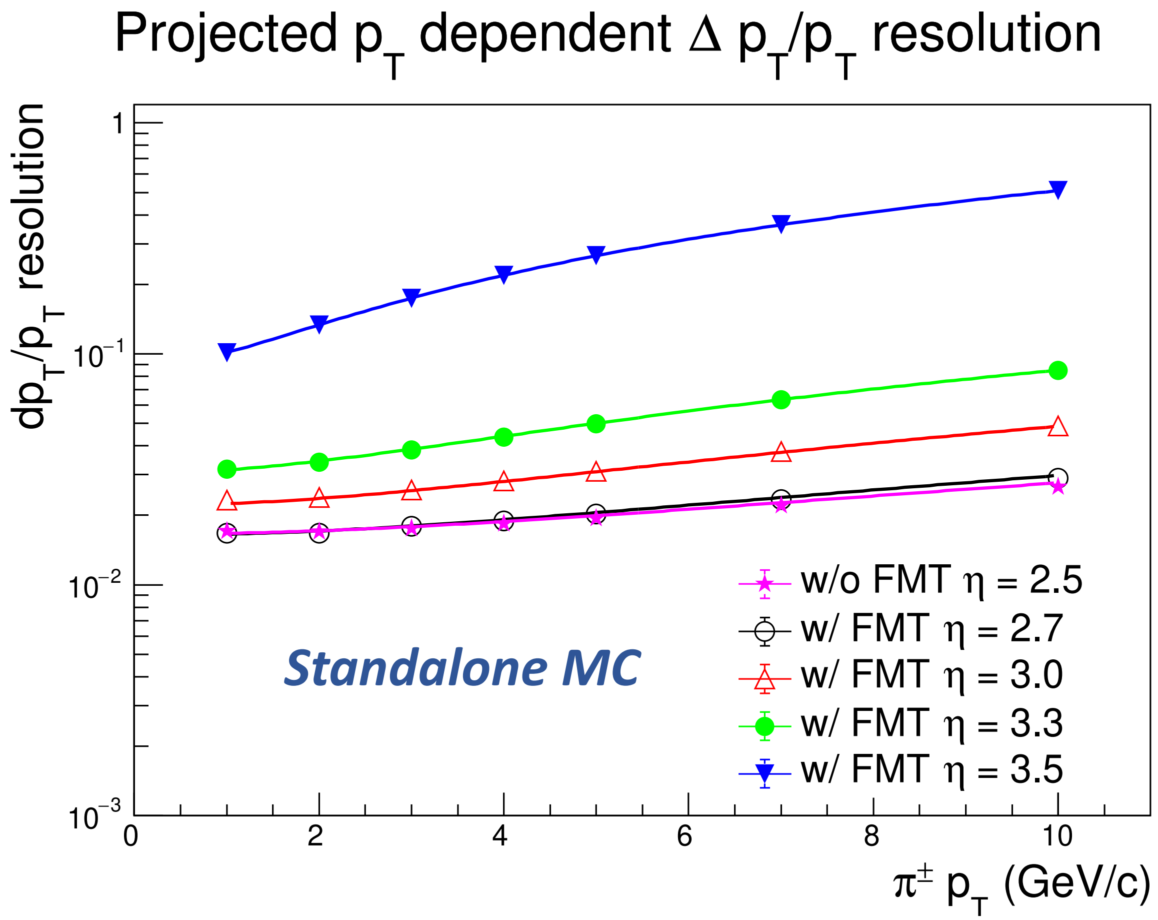
Projected p_T dependent DCA_{2D} resolution

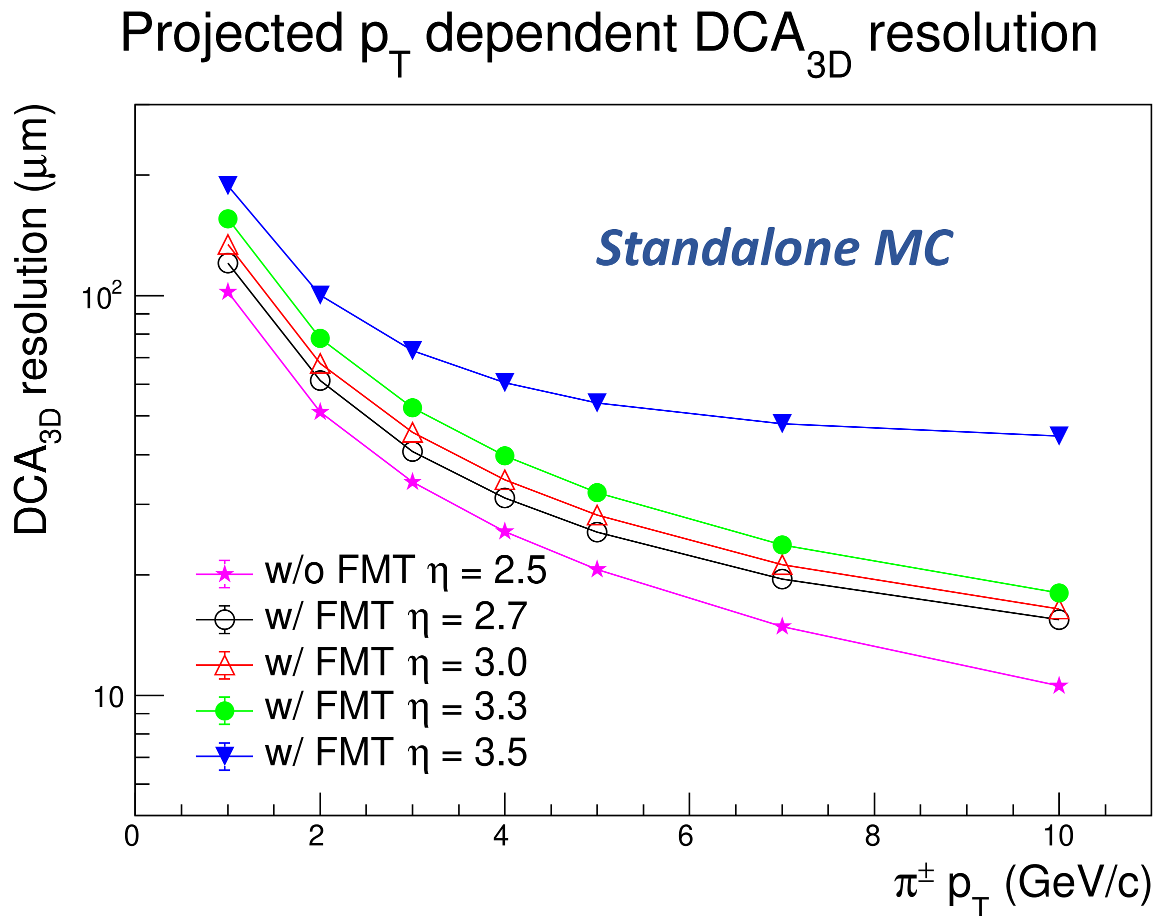


The proposed FMT detector performance (II)

- Projected p_T dependent p_T resolution (left) and p_T dependent DCA_{3D} resolution w/ and w/o FMT.

Hadron endcap FMT geometry (config 2)



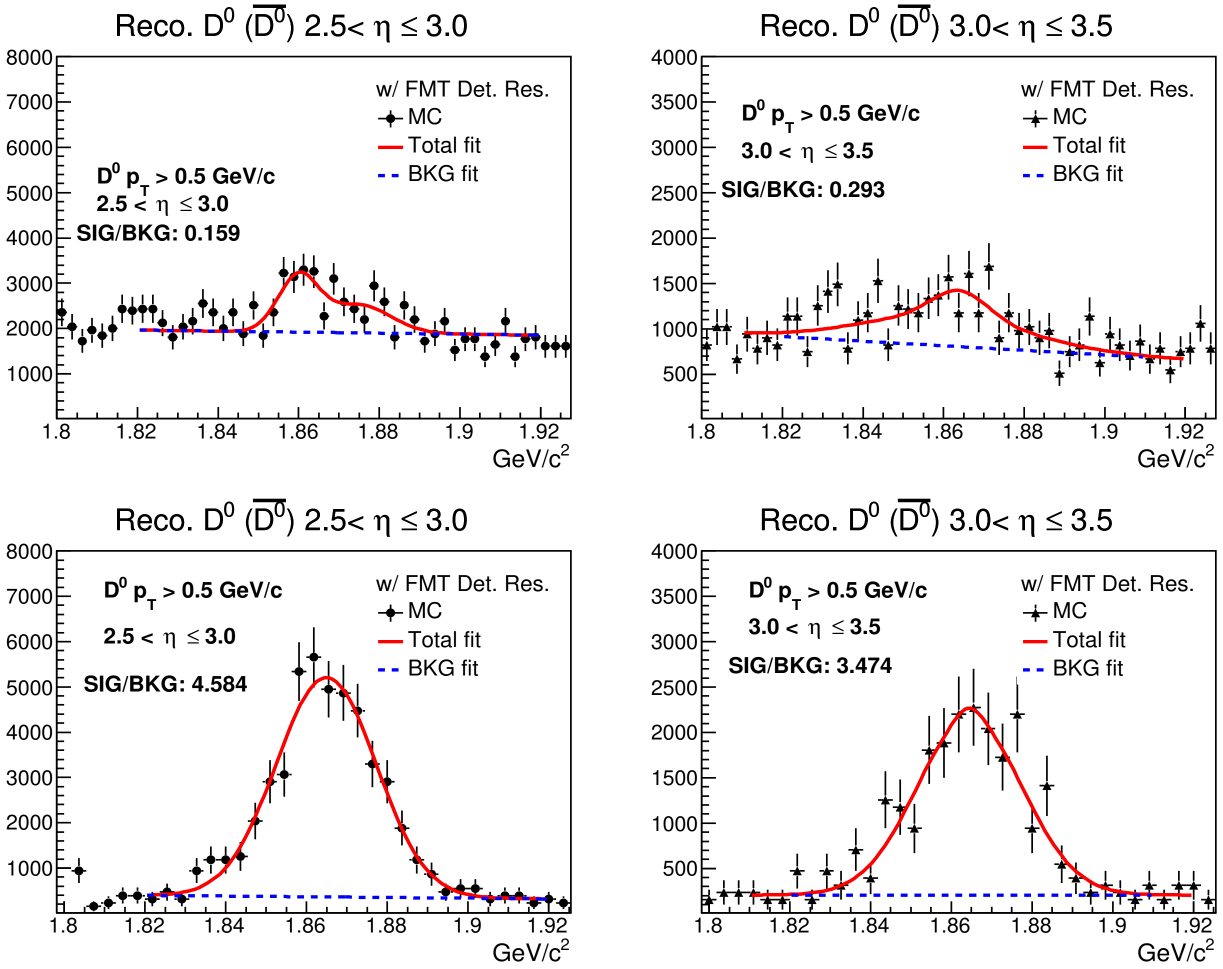


Forward D meson reconstruction w/ and w/o FMT timing

- On average, the EIC has one collision every 2 μs and its bunching crossing rate is ~10 ns.
- Reconstructed forward D^0 mass spectrums with the projected FMT performance (config 2) in 63 GeV e+p collisions.

5 pileup events
($10\mu s$ readout)

no pileup events
(2ns readout)

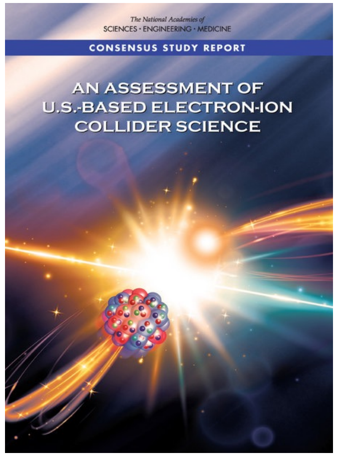


PYTHIA8 + FMT detector performance in standalone MC

- Need to add realistic EIC backgrounds for future studies.
- Faster readout provided by the proposed FMT can significantly reduce backgrounds from pileup events in forward heavy flavor reconstruction.

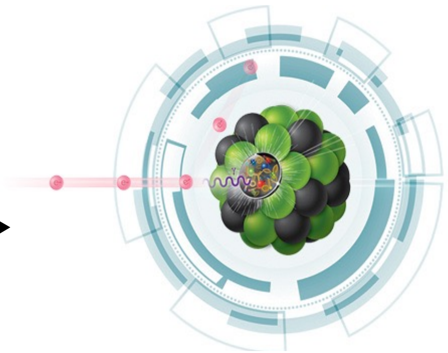
Summary and Outlook

- Good progresses have been achieved for the proposed MALTA2 based FMT detector R&D, module design and associated performance validation.
- New MALTA2 quad-sensor FPC design has been submitted for production. Will characterize the performance of new modules in bench and beam tests.
- The mechanical design of the FMT disk utilizing the MALTA2 quad-sensor modules is underway.
- More to come! ***Special thanks to the EIC generic R&D program @JLab!***



NAS review	2018
EIC CD0	2020
EIC CD1	2021
EIC CD3/A	2024
EIC CD2/3	2025
EIC CD-4a	2034
EIC CD-4	2036

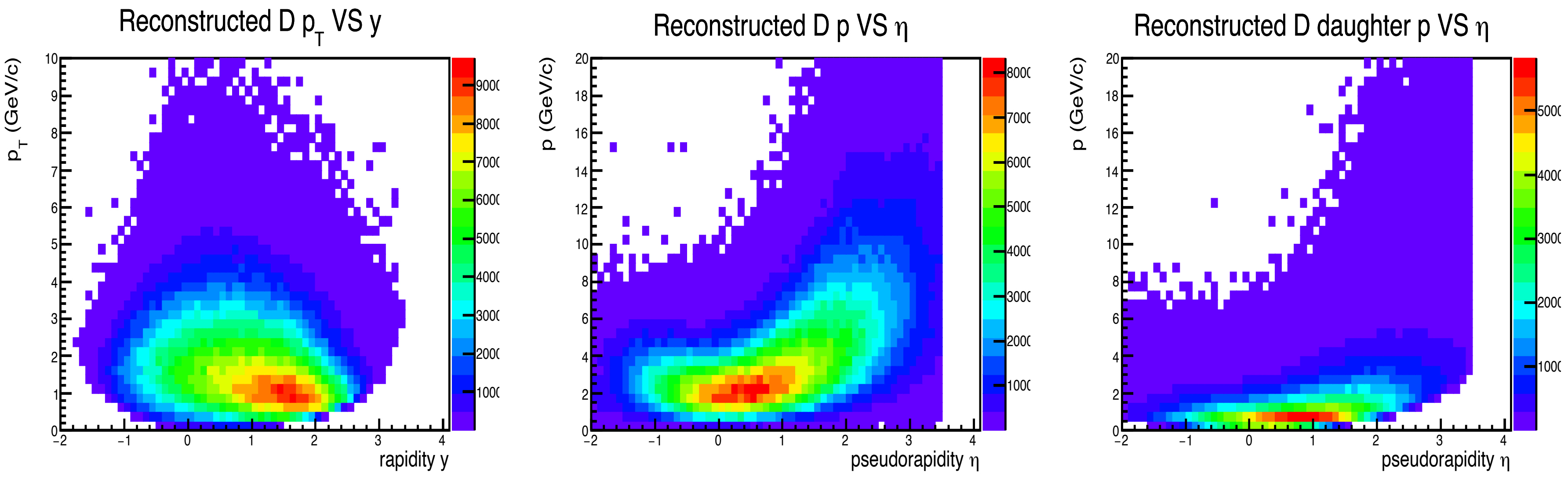
Design Phase | Construction Phase | Science Phase



Backup

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.

EIC Yellow Report requirement on tracking

- Estimated tracking requirement based on the 3T magnetic field.

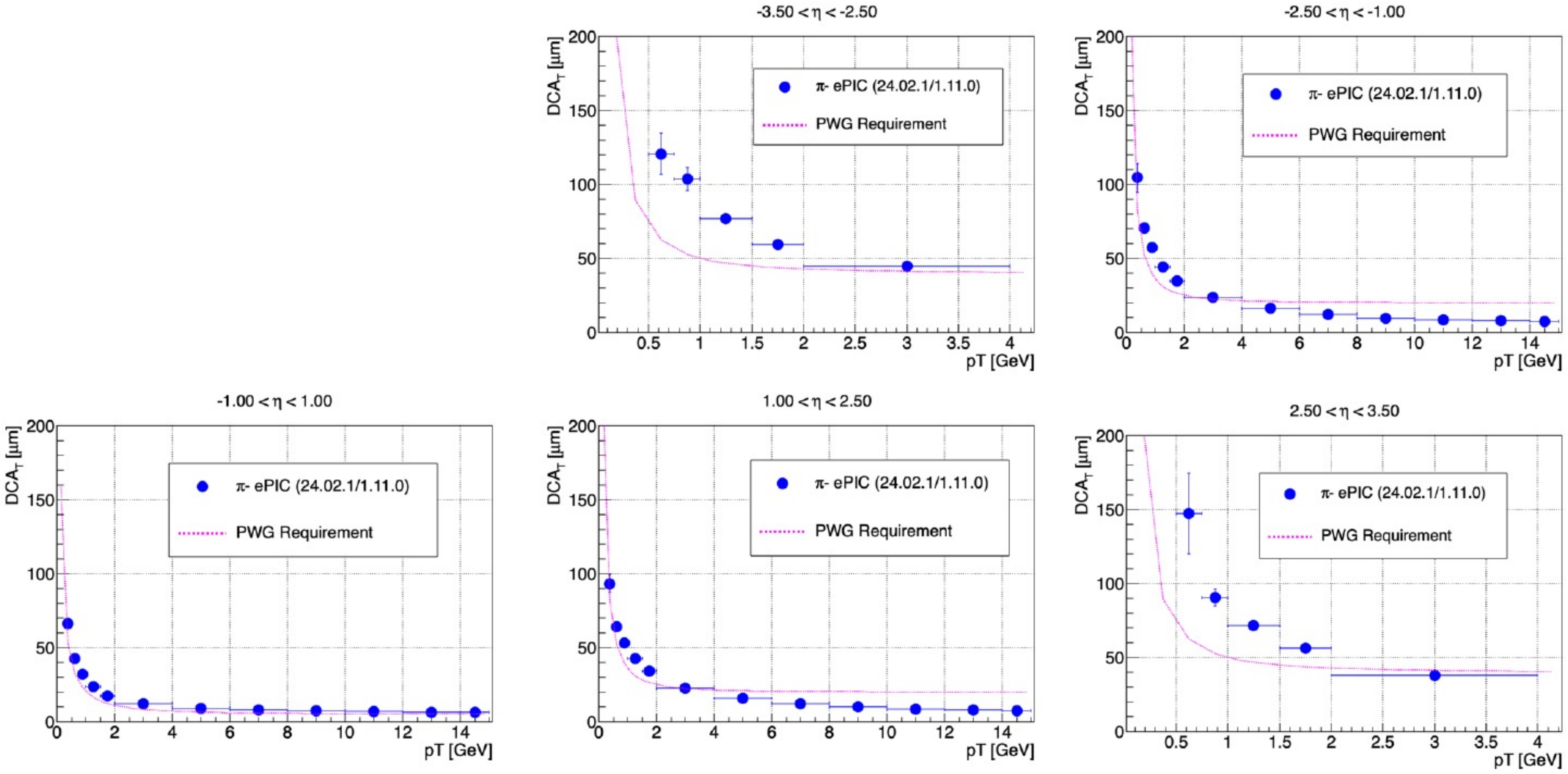
Nucl. Phys. A 1026 (2022) 122447

Table 11.2: Requirements for the tracking system from the physics groups.

Tracking requirements from PWGs						
			Momentum res.	Material budget	Minimum pT	Transverse pointing res.
η						
-3.5 to -3.0	Central Detector	Backward Detector	$\sigma p/p \sim 0.1\% \times p \oplus 0.5\%$	~5% X0 or less	100-150 MeV/c	
-3.0 to -2.5					100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 40 µm
-2.5 to -2.0			$\sigma p/p \sim 0.05\% \times p \oplus 0.5\%$		100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 20 µm
-2.0 to -1.5					100-150 MeV/c	
-1.5 to -1.0					100-150 MeV/c	
-1.0 to -0.5		Barrel	$\sigma p/p \sim 0.05\% \times p \oplus 0.5\%$		100-150 MeV/c	dca(xy) ~ 20/pT µm ⊕ 5 µm
-0.5 to 0						
0 to 0.5						
0.5 to 1.0						
1.0 to 1.5		Forward Detector	$\sigma p/p \sim 0.05\% \times p \oplus 1\%$		100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 20 µm
1.5 to 2.0					100-150 MeV/c	
2.0 to 2.5					100-150 MeV/c	
2.5 to 3.0			$\sigma p/p \sim 0.1\% \times p \oplus 2\%$		100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 40 µm
3.0 to 3.5					100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 60 µm

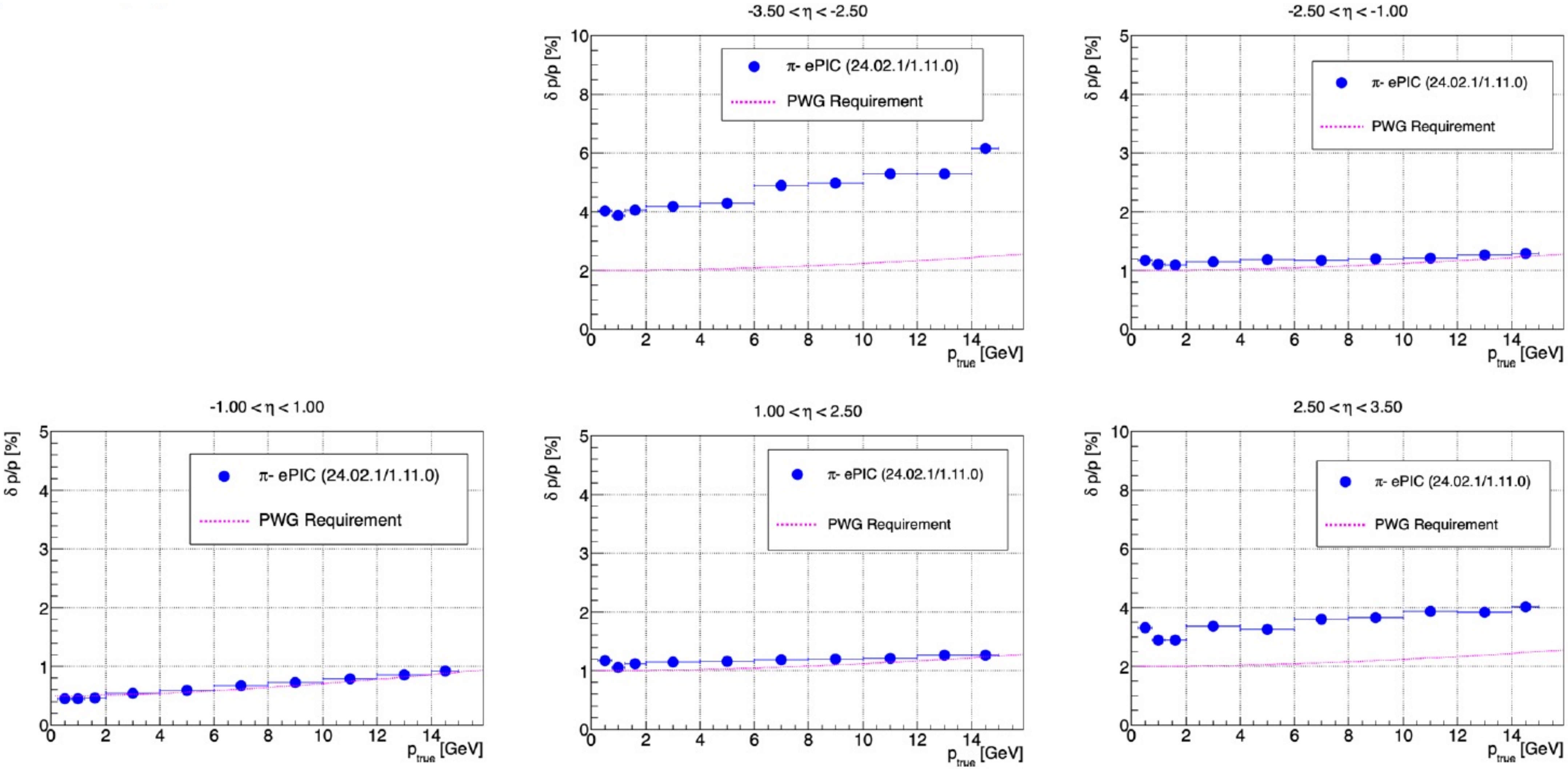
ePIC tracing performance

- Track p_T dependent DCA_{2D} resolution



ePIC tracing performance

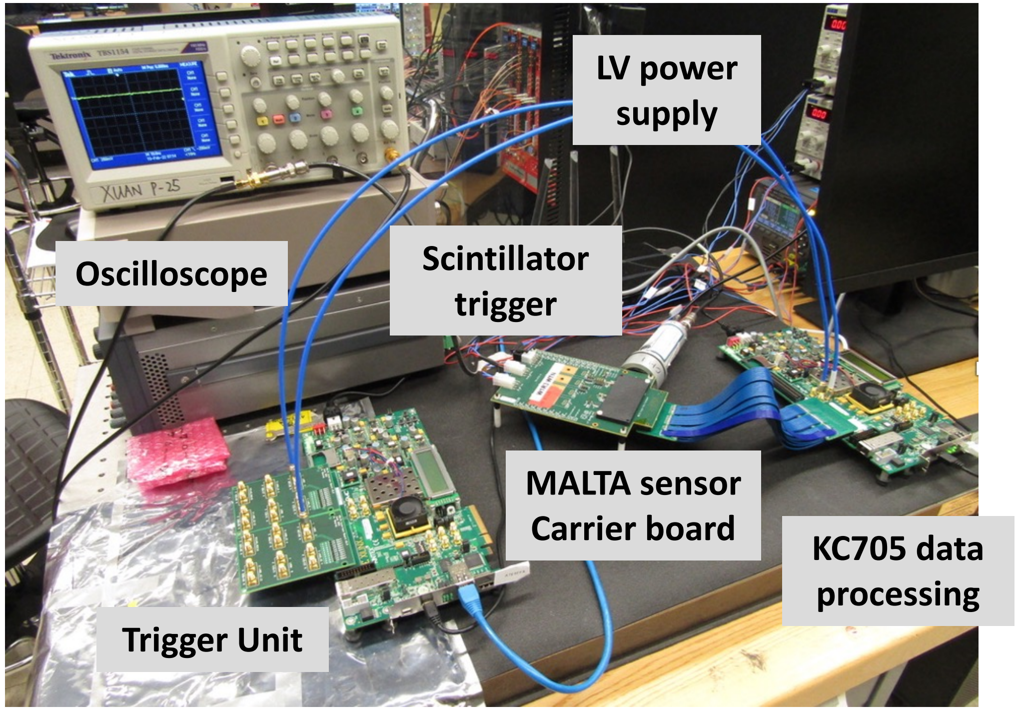
- Track p dependent momentum resolution



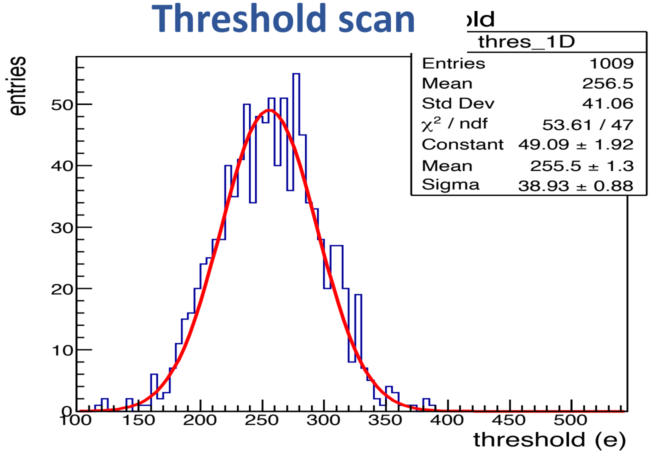
MALTA sensor R&D test results

- Threshold and noise scan has been performed.
- Successfully suppressing the noise hits with optimized DAC configuration and the hit occupancy has been studied with the ^{90}Sr source tests.

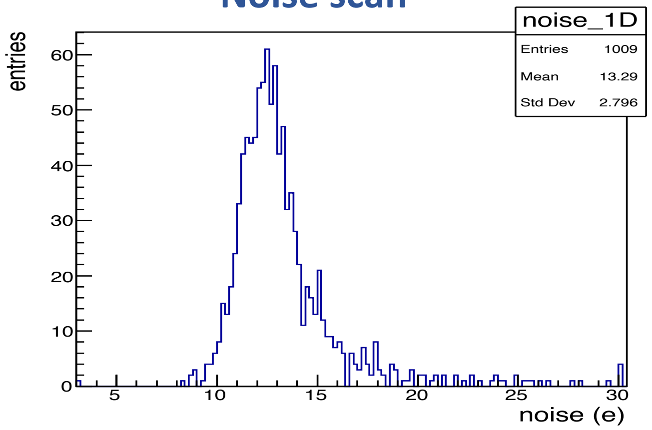
MALTA prototype sensor test setup



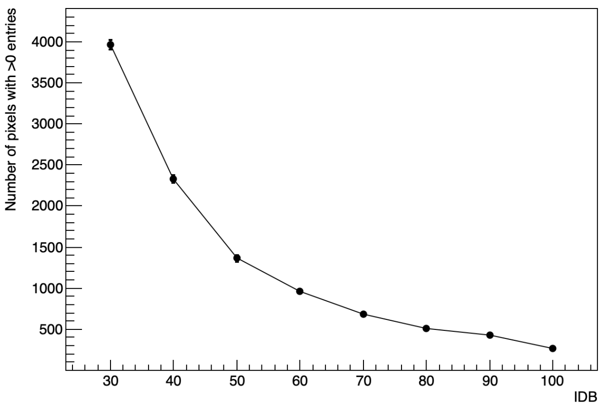
Threshold scan



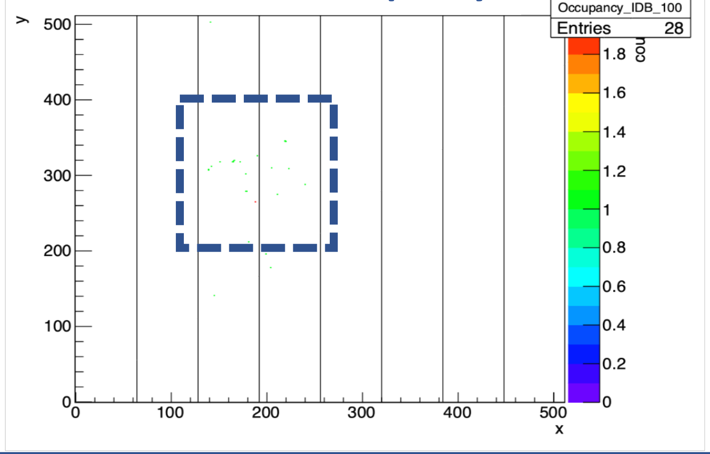
Noise scan



Noisy pixel rate VS IDB value



^{90}Sr source hit occupancy



The proposed FMT detector performance (III)

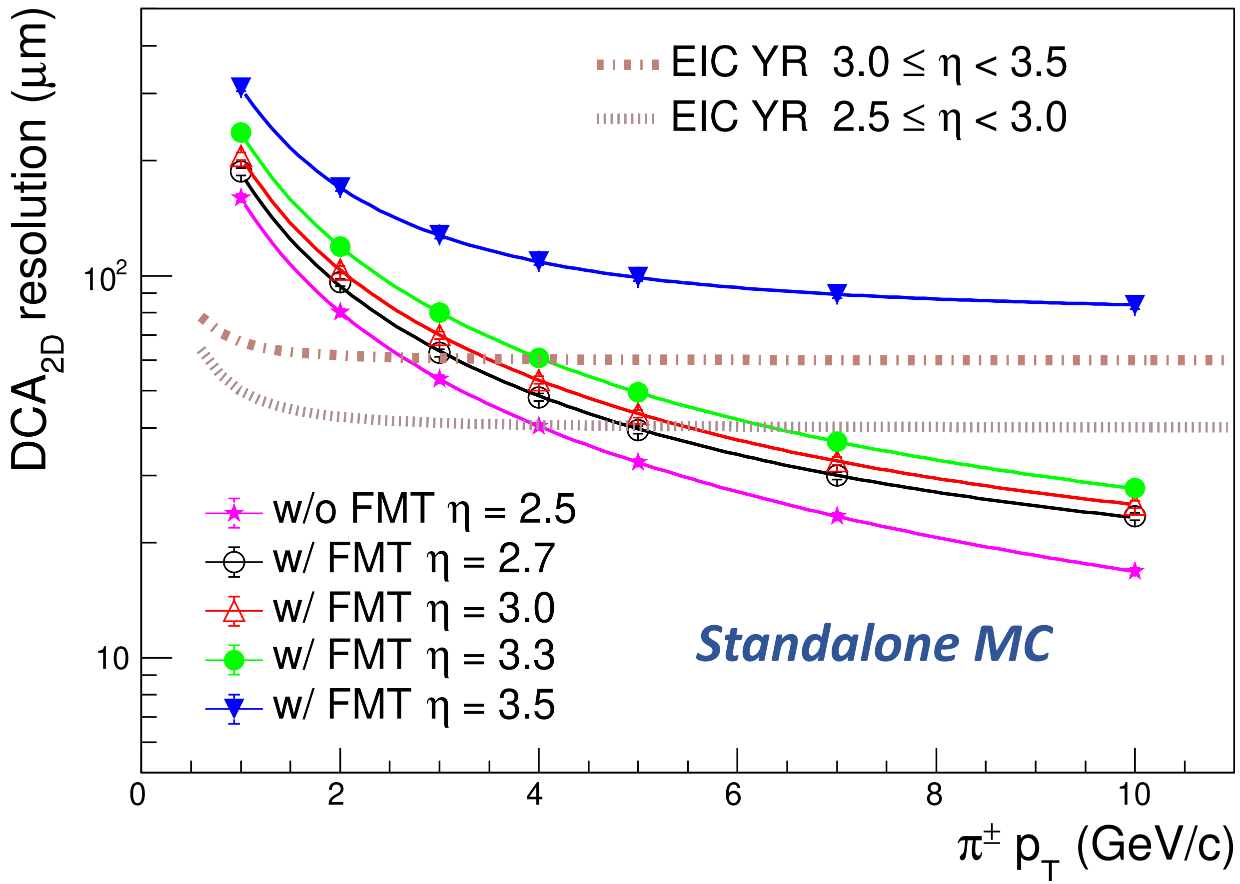
- Assume the FMT will utilize 8-sensor staves, or groups of two quad-sensor modules next to each other.

Hadron endcap FMT geometry (config 3)

Parameter	Disk 1	Disk 2
Inner Radius	7.014 cm	7.014 cm
Outer Radius	23.095 cm	23.095 cm
z location	155 cm	170 cm
Material budget	$0.74\%X/X_0$	$0.74\%X/X_0$
Average hit efficiency	98%	98%

DCA_{2D}: Distance of Closest Approach of tracks in the x-y plane at the primary vertex

Projected p_T dependent DCA_{2D} resolution



Simulation studies to evaluate w/ and w/o FMT timing

- Reconstructed $D^{\pm}$ and D^0 with projected FMT performance in 63 GeV e+p collisions w/ 20 pileup (40 μs timing) events. Need to add realistic EIC backgrounds for future studies.