Overview of the ePIC Low-Q^2 Tagger

Exotic Heavy Meson Spectroscopy and Structure with EIC
CFNS Stony Brook

Gary Penman*
University of Glasgow
17th April 2025

*gary.penman@glasgow.ac.uk

WORLD CHANGING GLASGOW

A WORLD TOP 100 UNIVERSITY

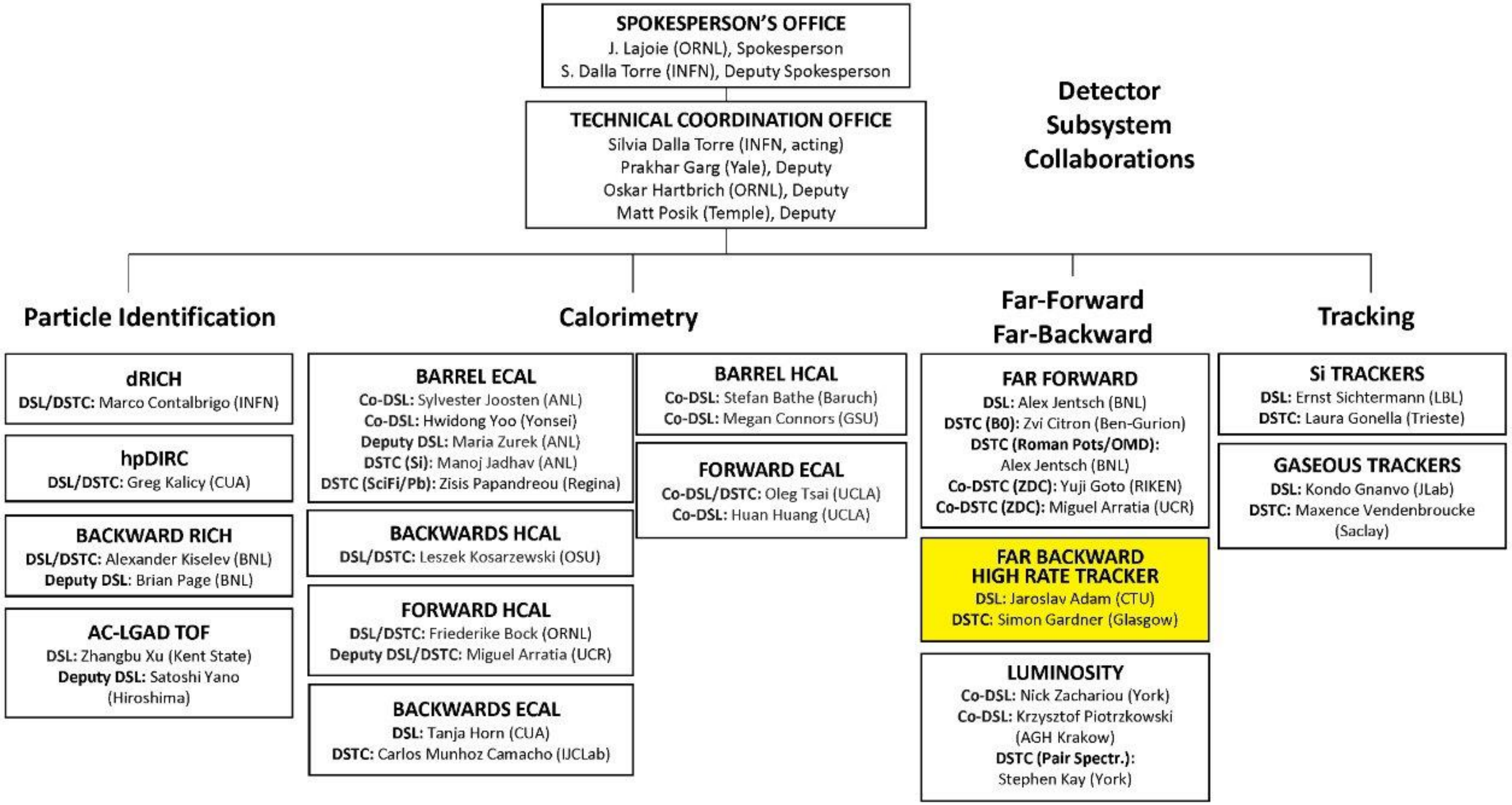
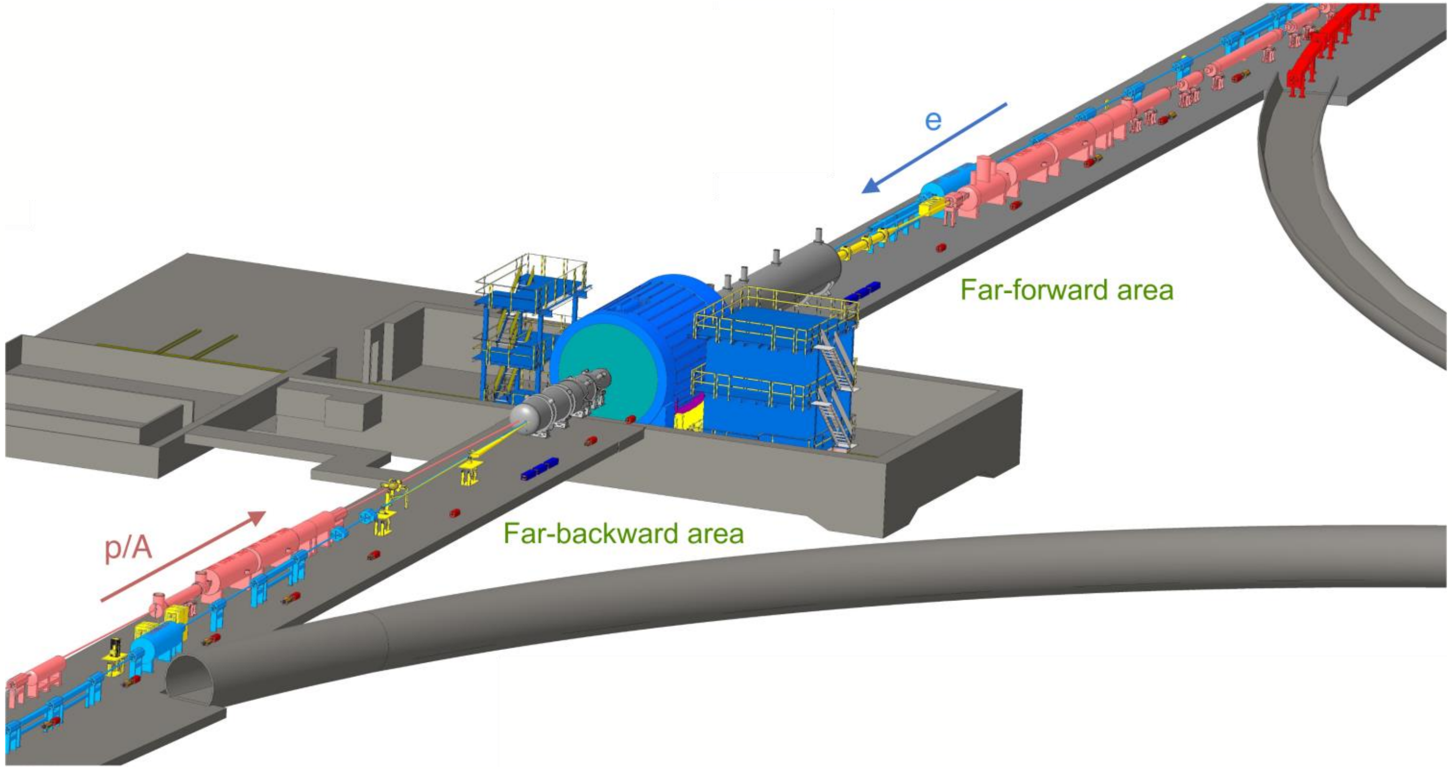


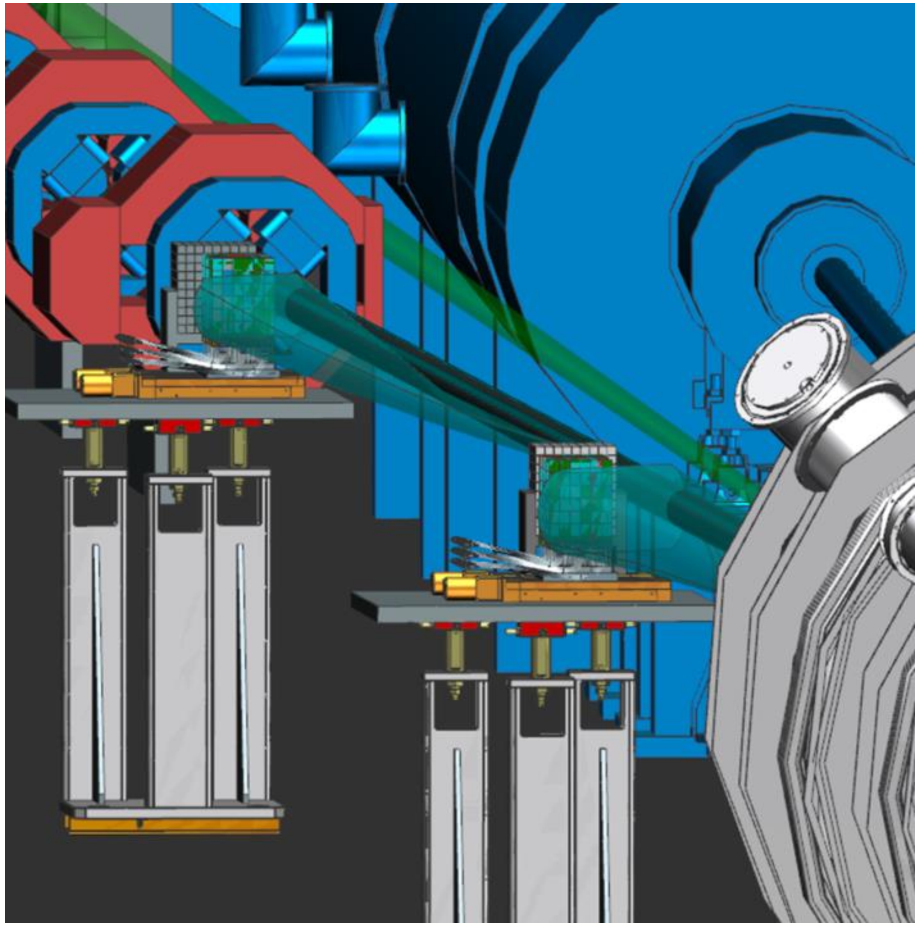
Figure 1: Organisation of the ePIC collaboration DSCs.

Jarda (Jaroslav Adam) - DSC Lead

Simon Gardner - DSC Technical Lead

- Introduction
- ePIC Low Q^2 Tagger Design and Simulation
- Mainz Beam Test Results (Feb 2025)
- Status and Plans
- Conclusion





Introduction

ePIC Detector

- ePIC will be the first detector of the future Electron Ion Collider (EIC).
- EIC will collide electrons and protons/ions, at the central interaction point (IP6) of ePIC.
- This will enable a fantastic physics regime, with measurements of Structure, Spin Structure functions, Gluon density, GPDs, TMDs, Nuclear PDFs... and more!
- However, many of the detection requirements of the physics processes which provide access to these topics are limited by only a central hermitic detector – forward hadron / backward electron detection required!
- This has motivated the development of the far backward and far forward detector packages.

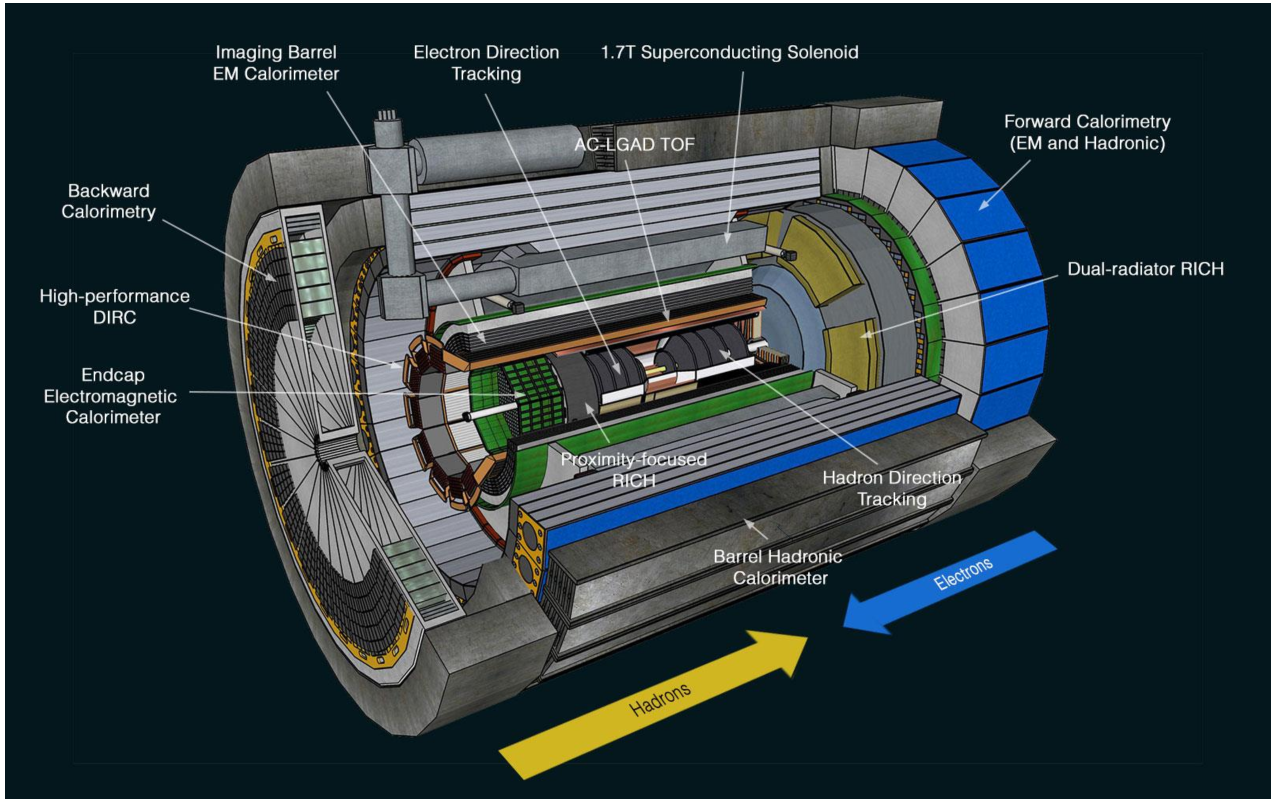


Figure 2: Cutaway view of the ePIC detector.

Introduction

ePIC Far Backward Region

- B2eR Magnet - bends beam away from synchrotron radiation, provides spectrometer for Low-Q^2 tagger.
- Luminosity Monitor – detects flux of BH gamma to provide a measure of Luminosity. Crucial for cross section measurements!
  - Direct Photon Calorimeter
  - Pair Spectrometer
- Low-Q^2 tagger – track electrons out of Low-Q^2 reactions in order to tag the produced photon. Currently being developed by Glasgow University.

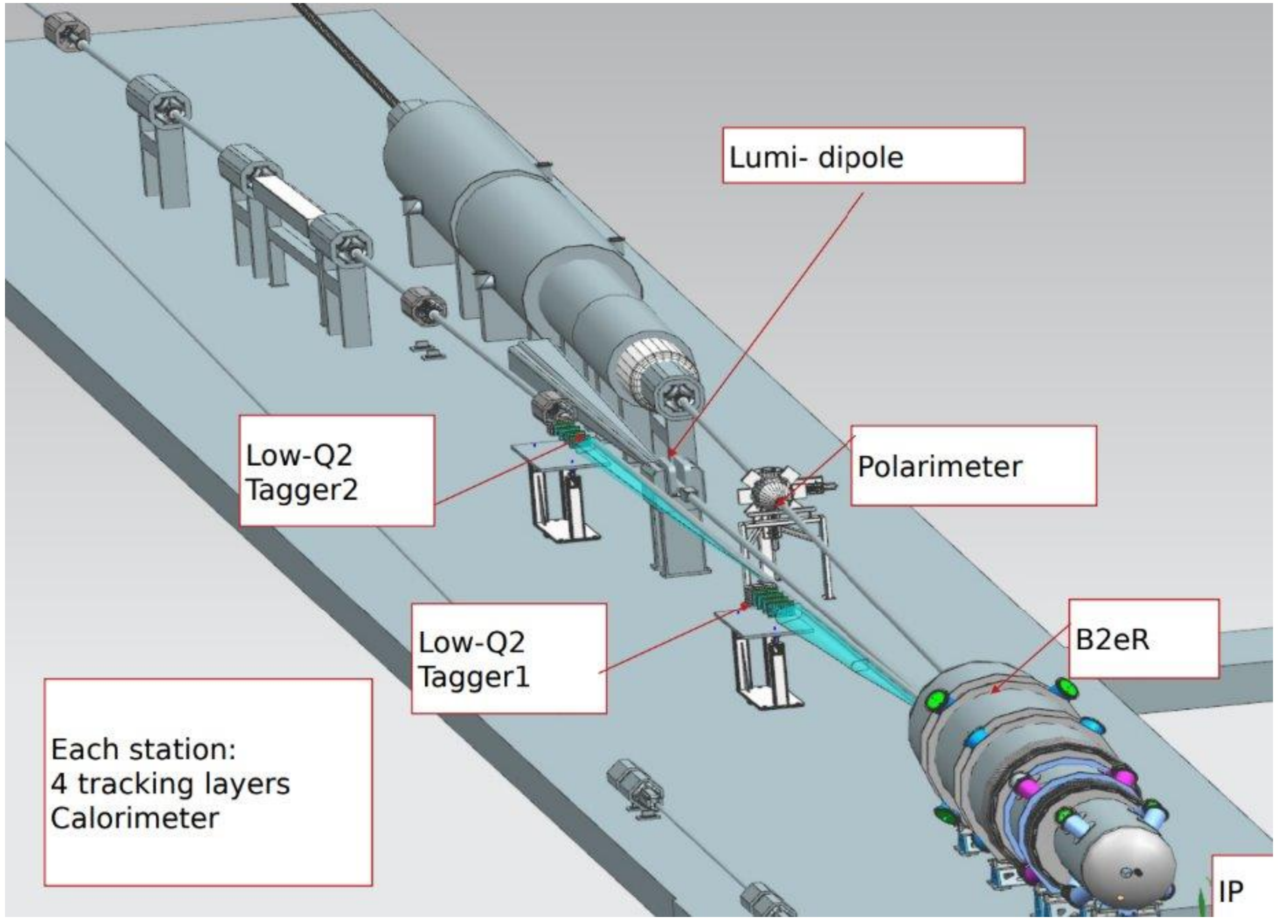


Figure 3: CAD Image of the far backward region of ePIC.

Photon Tagging at Glasgow

Glasgow group have a long history with photon tagging, spanning decades since the construction of the 300 MeV Synchrotron in the 1950's.

Experience in using Timepix3 detectors to develop pair spectrometer/polarimeter in Mainz

Recent role in developing Low-Q^2 tagger for CLAS12 – NIM A. 2020 163419, NIM A. 2020 163475.

Figure 4: Rochester Conference, first operation of synchrotron, 1954.

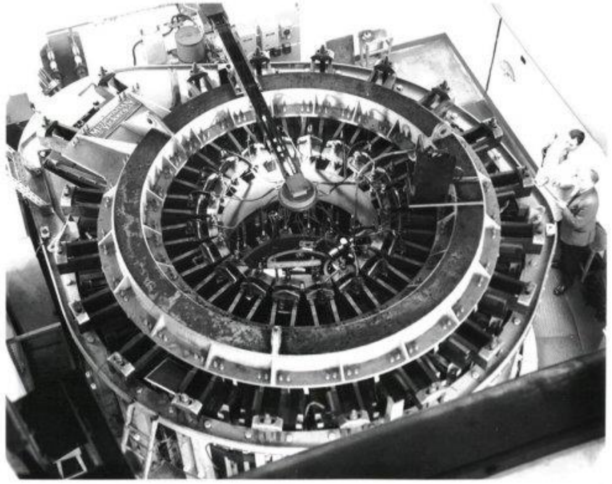


Figure 5: 300 MeV Synchrotron in the Kelvin Building Basement.

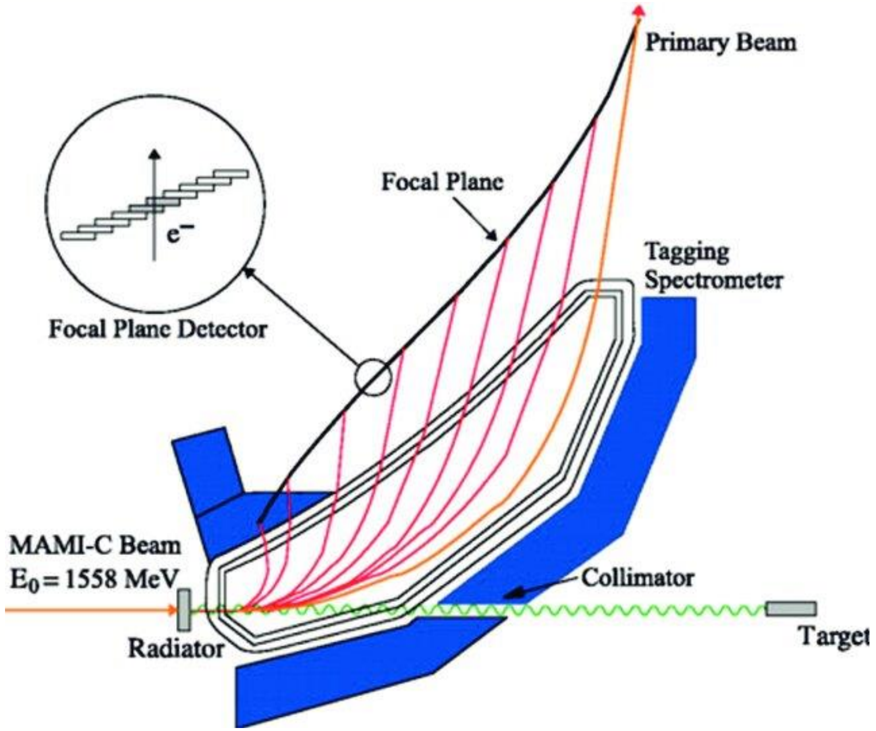


Figure 6: The Glasgow-Mainz photon tagging spectrometer at MAMI – EPJConf 20147200024.

ePIC Low-Q^2 Tagger

Future EIC Tagger Concept

ePIC Low-Q^2 Tagger

- For precise measurements of photoproduction and vector mesons.
- The ePIC Low-Q^2 Tagger extends the reach of the central detector down to effectively $Q^2 = 0$ GeV^2.
- Located after the first group of beamline steering and focusing magnets.
- Scattered electrons follow a unique path through the magnetic optics, resulting in a unique measured electron vector.
- Electrons with reduced energy are steered away from the main beam.
- Transforming the vector back through the magnetic optics accesses the original scattered vector.
- 4-momentum of the virtual photon interaction can be inferred.

Figure 7: ePIC Low-Q^2 Tagger in Far Backward region.

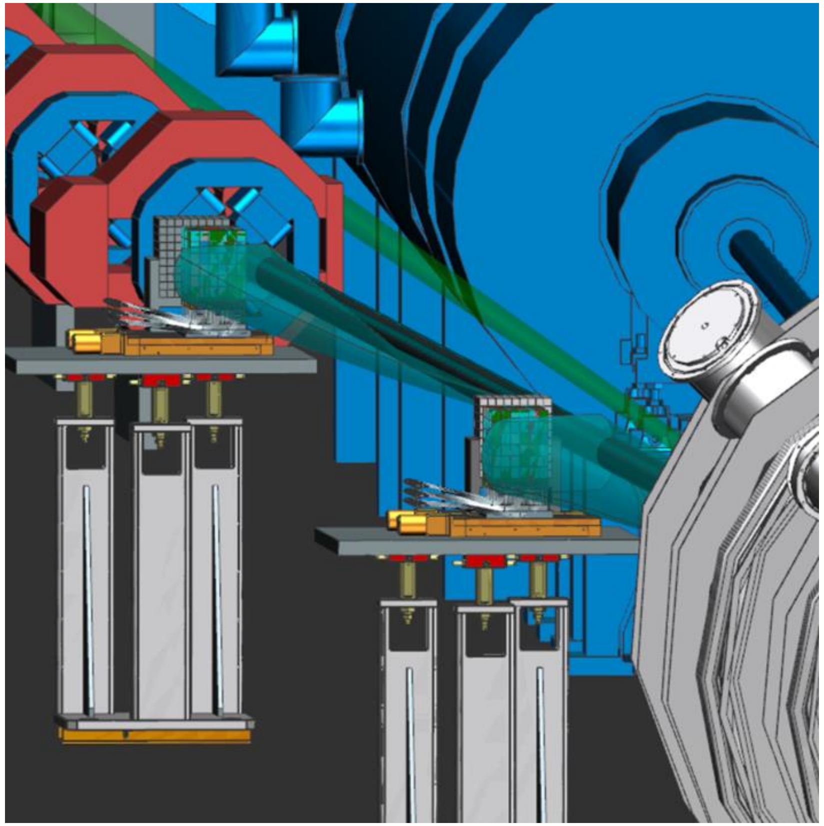


Figure 8: 2 Low-Q^2 Tagger stations placed beside the outgoing electron beamline.

Requirements - Rates

We expect a high bremsstrahlung background (10-20 brem tracks per bunch cross @ peak luminosity) with a non-uniform distribution.

Maximum Rates

Pixal (P1)	70 kHz
2 Column (C1)	8 MHz
Tpix4 (T1)	600 MHz, 38 Gb/s
Board (B1)	1500 MHz, 96 Gb/s
Layer (L1)	2500 MHz, 160 Gb/s

Total Integrated Rates

Tagger 1	2 GHz, 140 Gb/s
Tagger 2	7 GHz, 480 Gb/s
Total	**9 GHz, 600 Gb/s**

Data Buffered & Filtered (Hadron in main Det)

Trigger rate	500 kHz, 99.4% rejection (brem only)
Data rate (signal)	4 Gb/s
Data Rate (incl BG and rand)	**<20 Gb/s to tape**

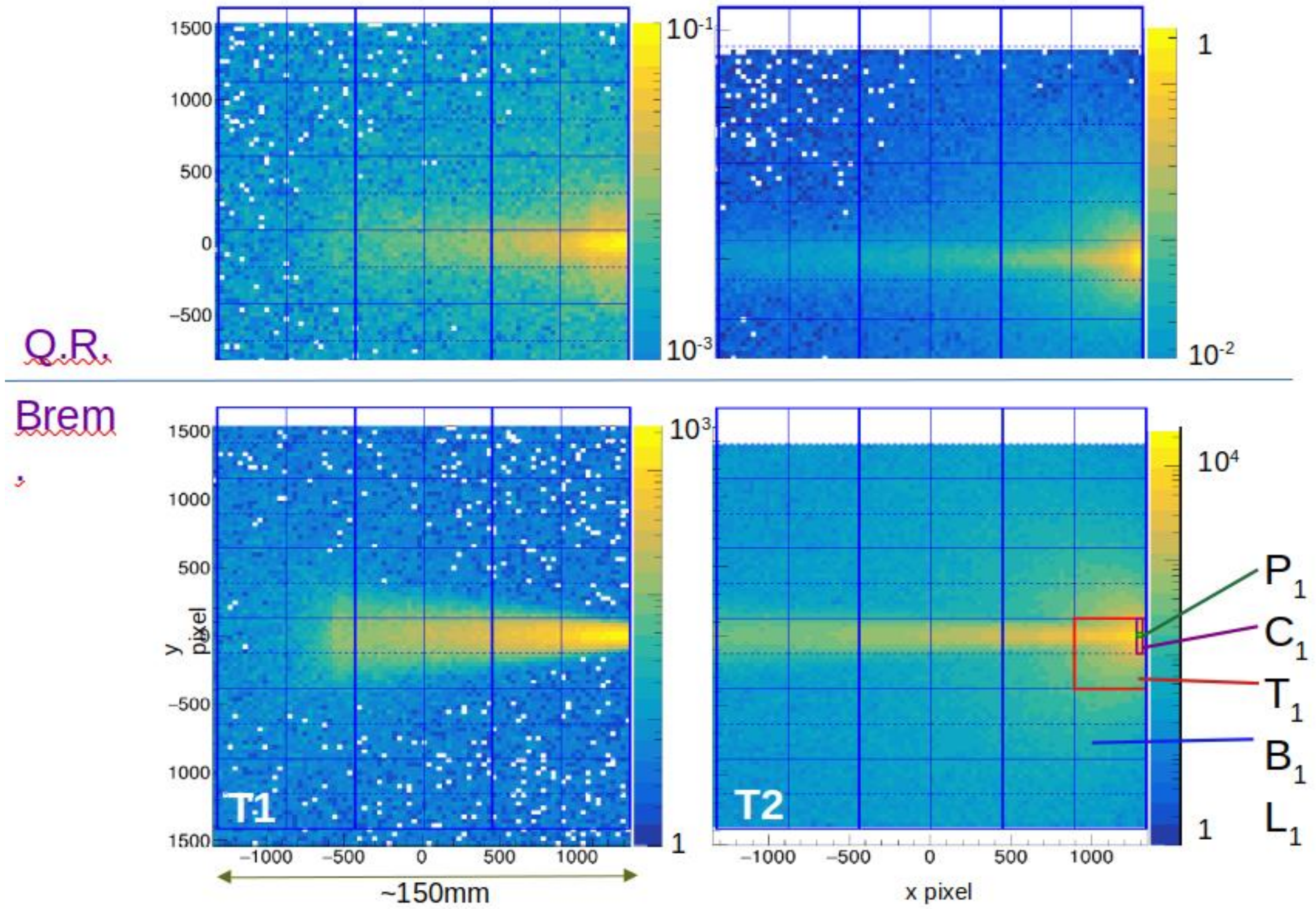


Figure 9: Low-Q^2 tagger rates kHz / pixel. (18x275 GeV @ 10^{34} $cm^{-2}s^{-1}$).

Technology: Timepix4

Challenges

Extremely challenging area of measurement which needs the best technology!

- **Data Rate**
- EIC Integration
- Background Rejection
- Momentum Reconstruction

Why is timepix4 the best choice? First and foremost, the only technology that will allow us to handle these rates!

			Timepix3 (2013)	Timepix4 (2019)
Technology			130nm – 8 metal	65nm – 10 metal
Pixel Size			55 x 55 µm	55 x 55 µm
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448 **3.5x**
Sensitive area			1.98 cm²	6.94 cm²
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA	TOT and TOA
		Event Packet	48-bit	64-bit **33%**
		Max rate	0.43x10⁶ hits/mm²/s	**3.58x10⁶ hits/mm²/s**
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel** **8x**
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-b **10x**
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr) **5x**
		Max count rate	~0.82 x 10⁹ hits/mm²/s	~5 x 10⁹ hits/mm²/s **8x**
TOT energy resolution			< 2KeV	**< 1Kev**
Time resolution			1.56ns	**~200ps**
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps (16x @10.24 Gbps)**

Figure 10: Comparison of specifications of Timepix3 vs Timepix4.

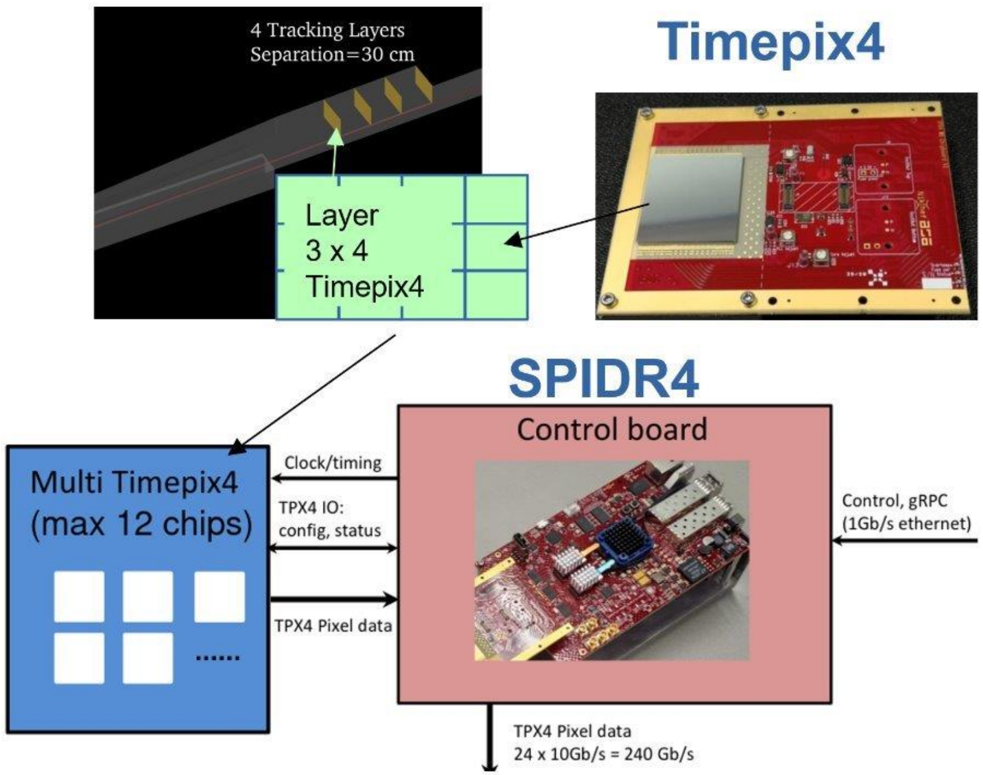


Figure 11: Example illustration of DAQ pipeline

Tagger Design

- Two tagger stations covering different energy ranges.
- Tracker consisting of 4 layers of Timepix4 detectors.
- Detector layer consisting of tiled Timepix4 ASICs using TSV.
- SPIDR4 readout
- Calorimeter based on the luminosity systems design for high rates.

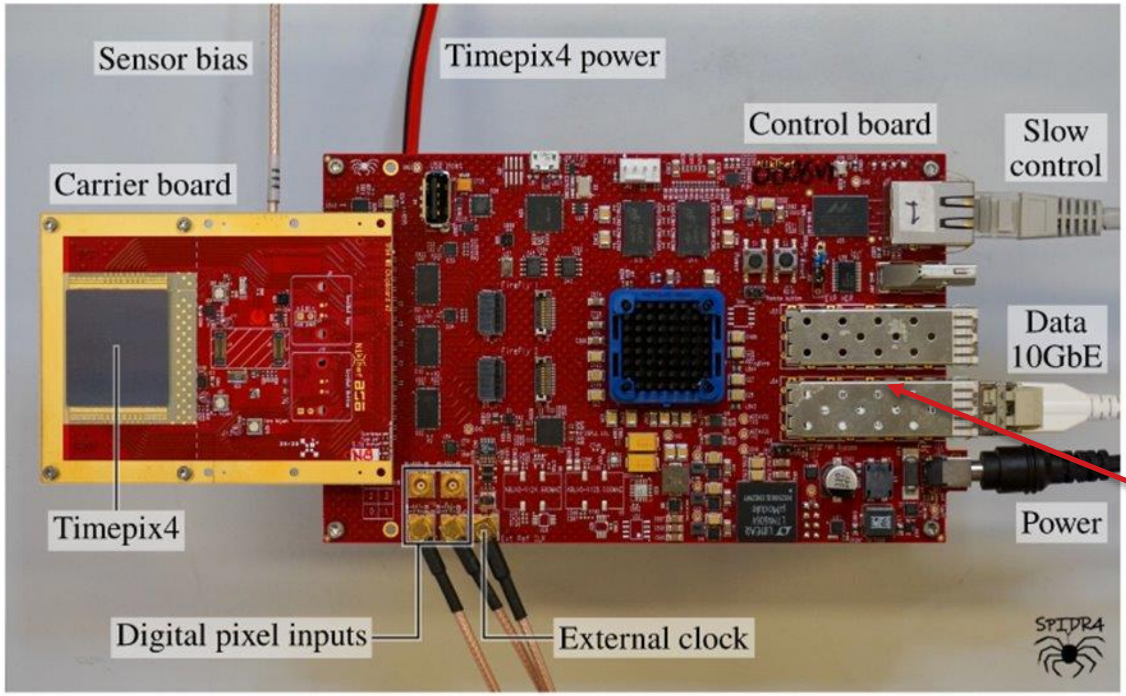


Figure 12: SPIDR4 readout - K. Heijhoff et al 2022 JINST 17 P07006

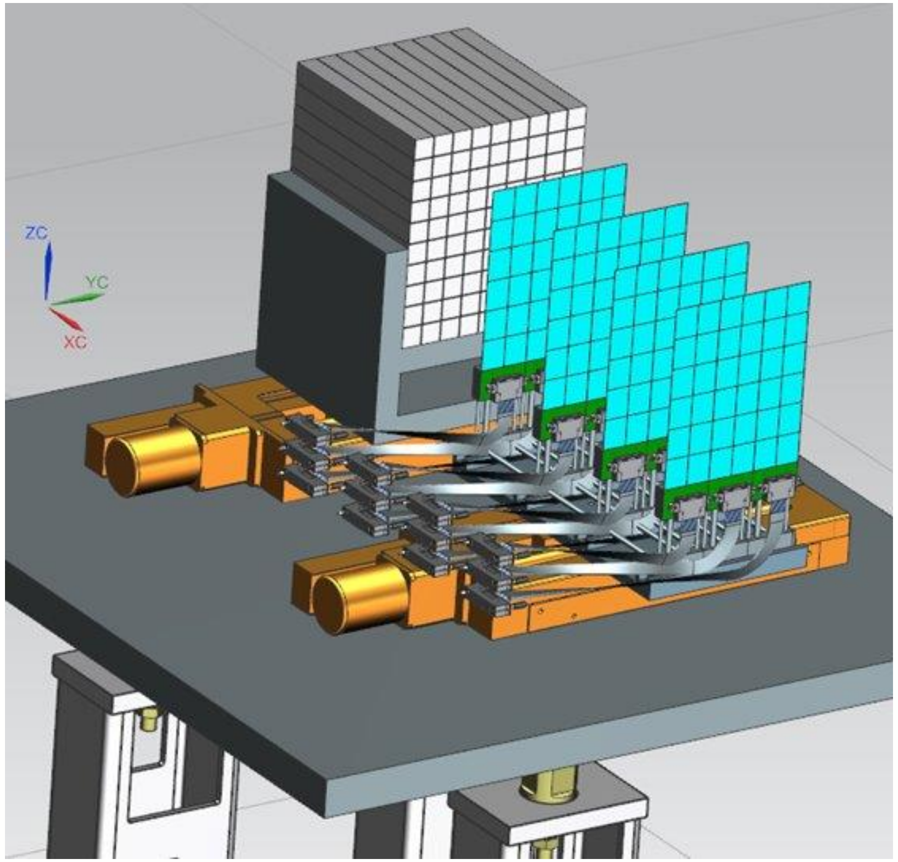


Figure 13: CAD model of a tagger station.

Prototyping Setup!

ePIC Low-Q2 Tagger - Acceptance

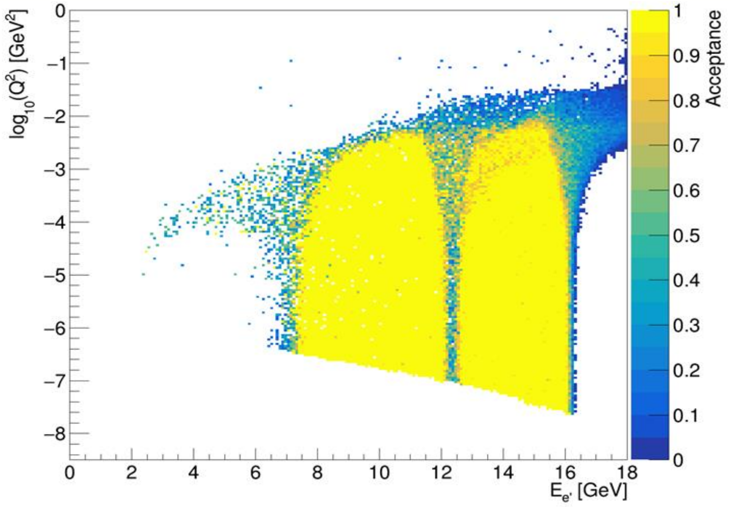


Figure 14: Acceptance of reconstructed low-Q^2 tagger electrons as a function of energy and Q^2

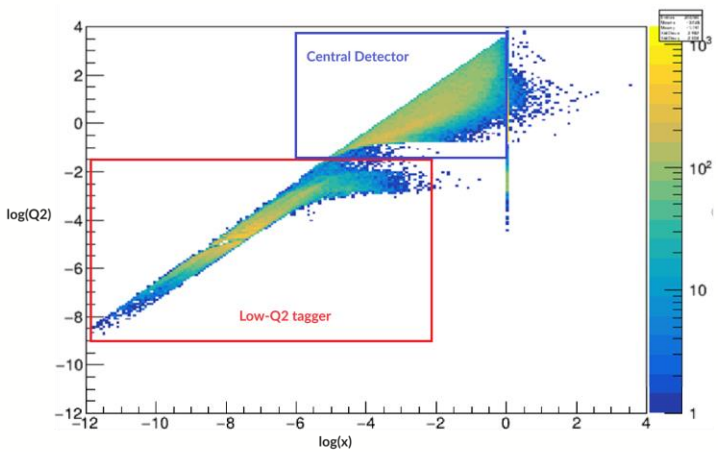


Figure 15: x-Q^2 acceptance showing central and low-Q^2 tagger.

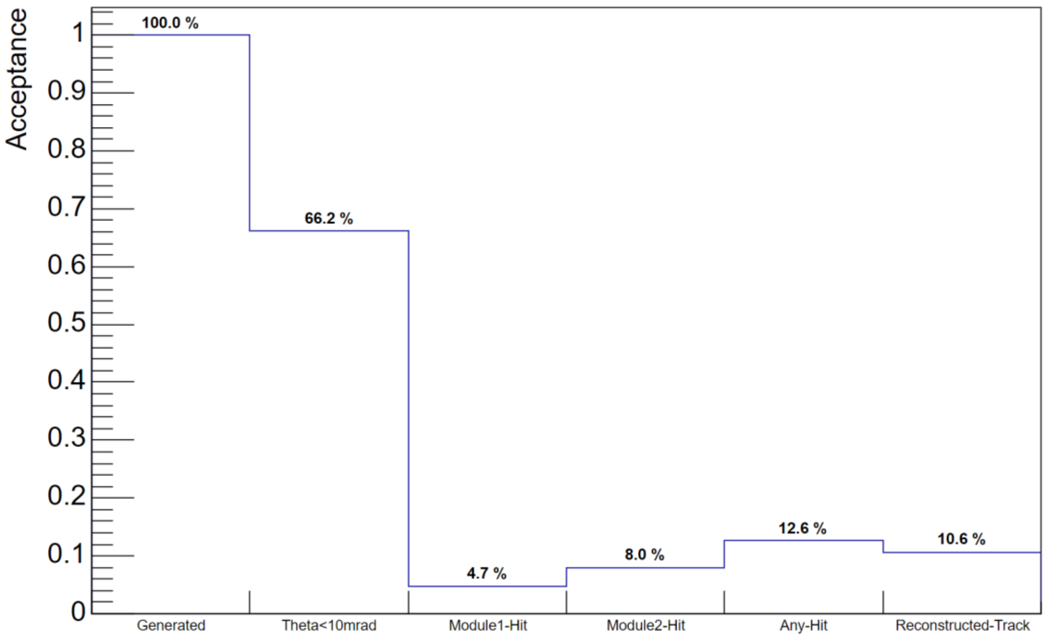


Figure 16: Integrated acceptance at various stages of track reconstruction.

Limitations

- Integrated acceptance of Quasi-real photoproduction events.
- Most events are produced at the highest energy, too close to the electron beam.
- Low energy lost in beamline magnets
- Q^2 gap between central detector due to beamline magnet configuration

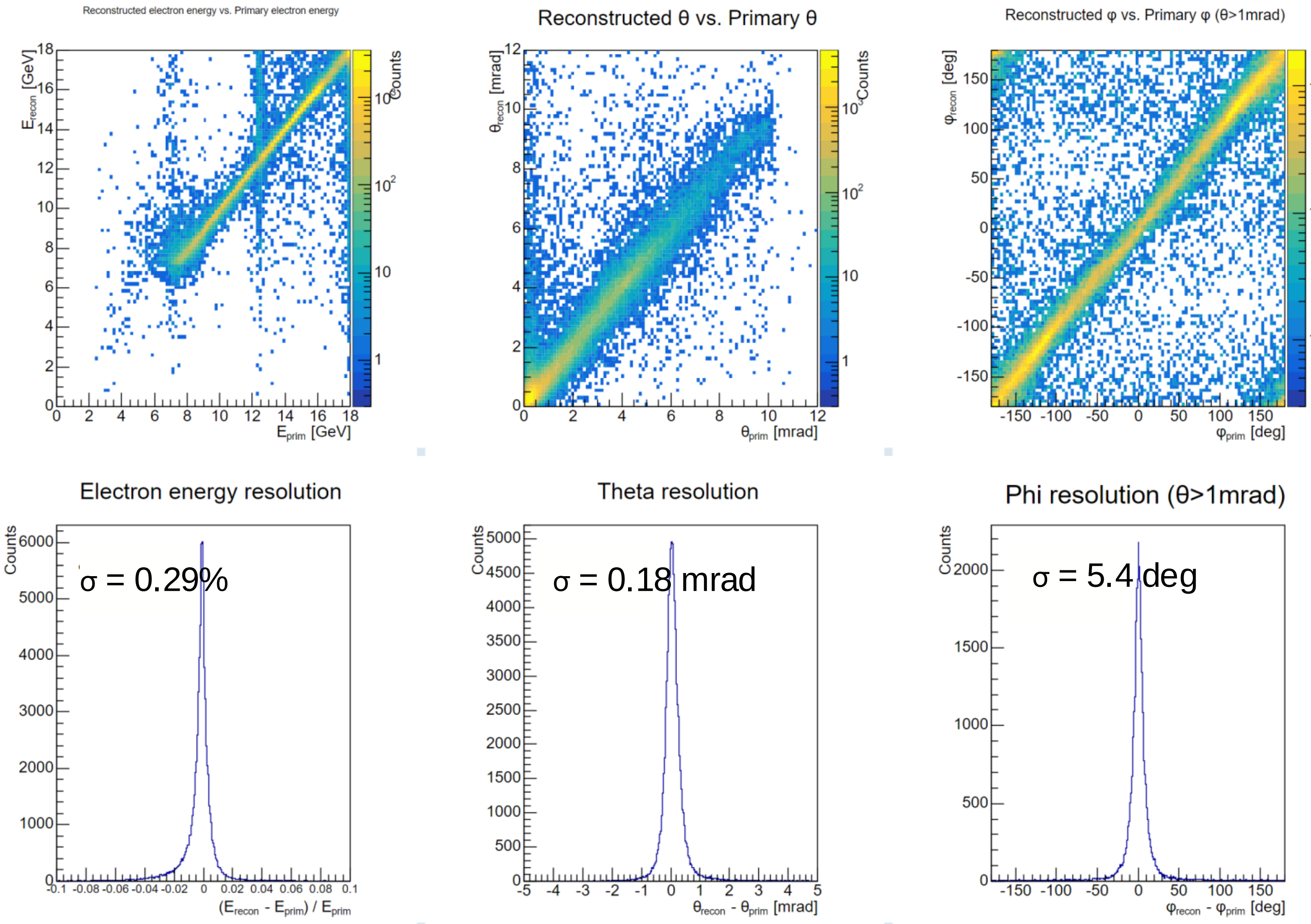


Figure 17: Reconstructed kinematics and resolution of Quasi-real photoproduction electrons. ϕ has been limited to where θ>1 mrad.

Limitations

- Fundamentally limited by the beam divergence
- ϕ can never be extracted below the beam divergence limit
- Limited acceptance where polarization will be possible

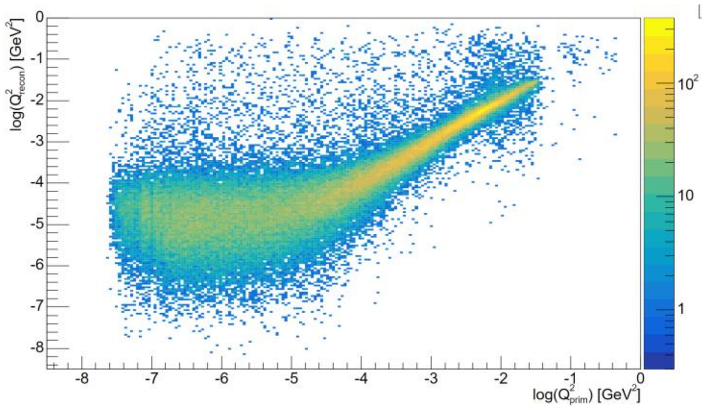


Figure 18: Reconstruction of Q^2 vs truth (generated) Q^2

Low-Q2 Physics

In addition to spectroscopy applications, detecting low-Q2 electrons allows measurements of other interesting channels!

Time-like Compton Scattering (TCS)

- TCS is the hard exclusive photoproduction of a lepton pair. Analogous to DVCS electroproduction.
- Provides access to nucleon Generalized Parton Distributions (PDFs) - crucial ingredient in nucleon tomography

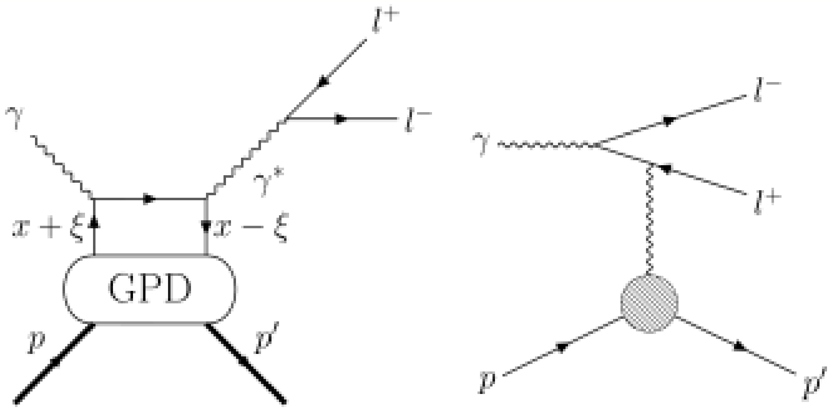


Figure 19: (Left) leading order TCS diagram and (right) BH term

Vector Meson Production

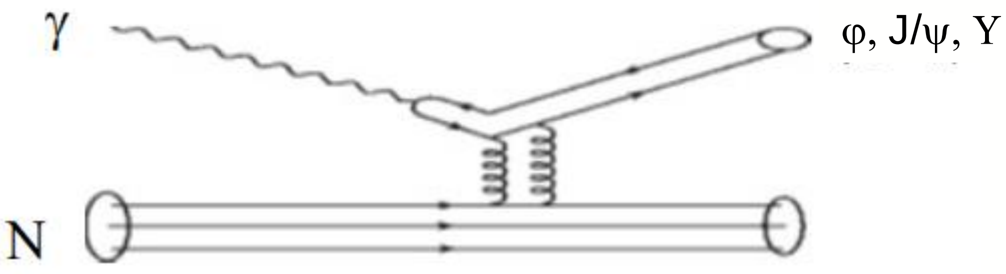


Figure 20: Leading order VM production via pomeron exchange.

- Exclusive VM production might shed light on bound meson-nucleon systems
- Provides access to gluonic GPDs and quarkonium distribution amplitudes

- Tagging these Q.R. photons allows us to reconstruct Q^2, W2, |t| etc
- Tracking and backward optics will allow for precision momentum and angular reconstruction
- Ultimately will provide access to the linear polarisation of Q.R photons -> more physics!

Y(4260) Spectroscopy Simulation Studies

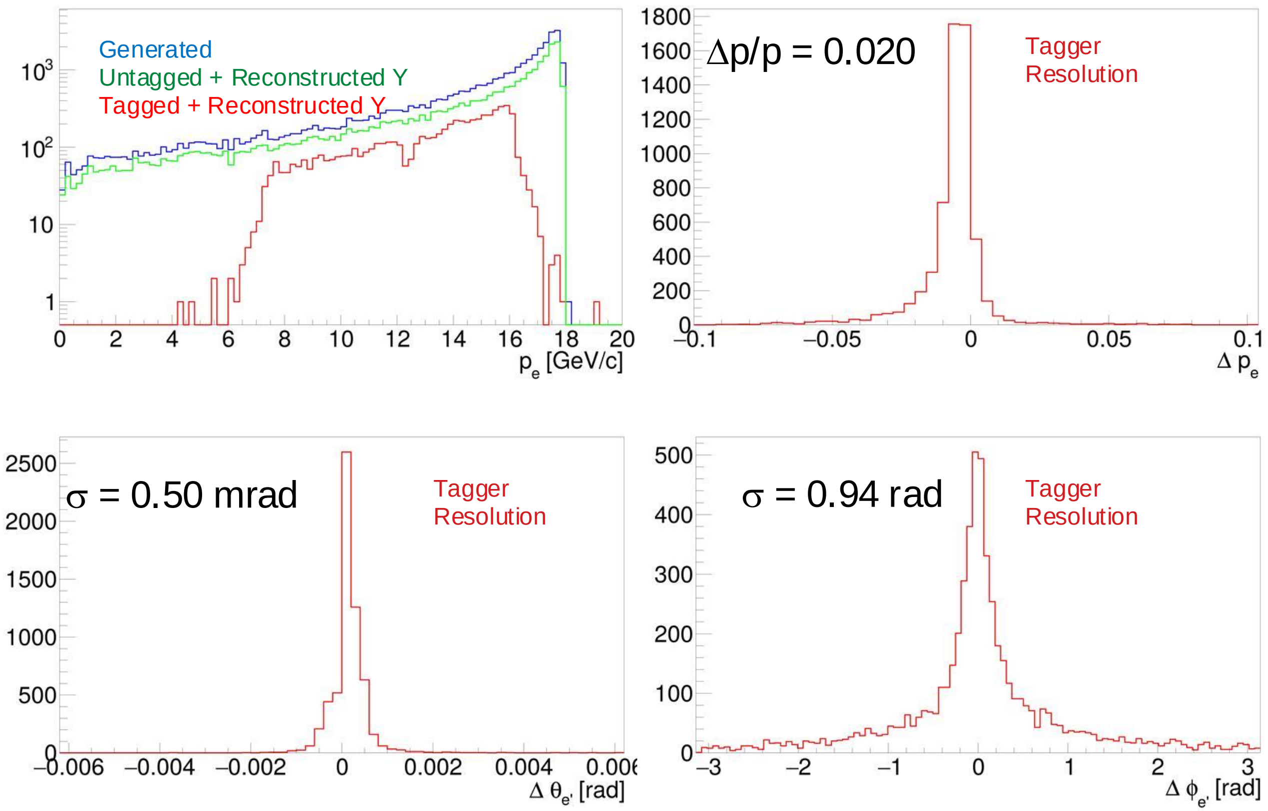
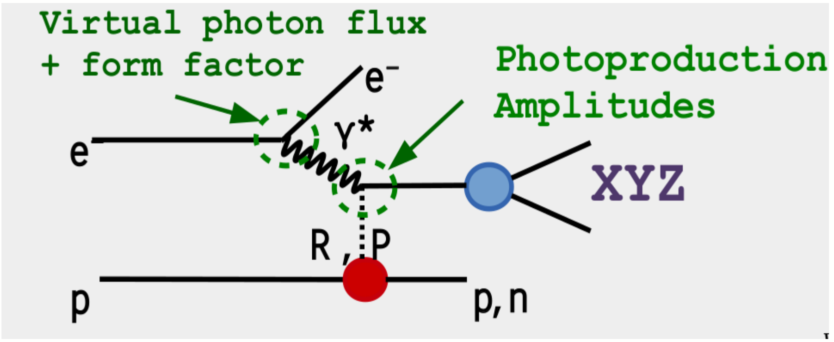


Figure 21: Simulation results for full physics channel of Y4260 photoproduction. (Top left) Acceptance and (rest) tagger resolutions.

~40k Events generated in elspectro:



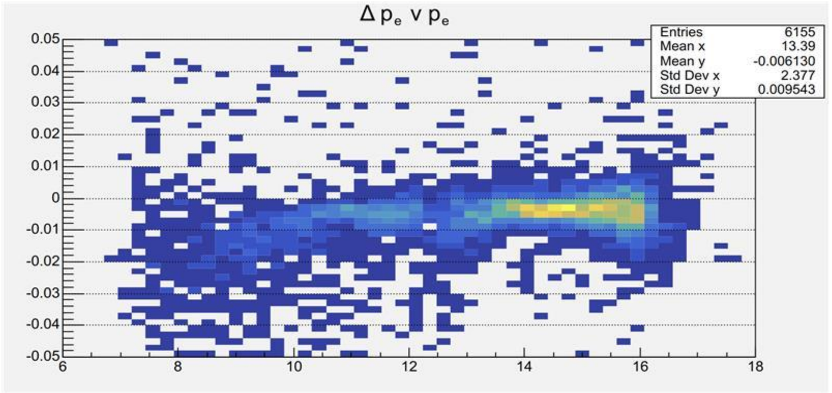


Figure 22: Correlation between reconstructed-generated and generated momentum of scattered electron.

Exclusive EIC spectroscopy studies have been very promising j.nima.2023.168238, J. Stevens, NSTAR24. Complementarity of far backward and far forward regions really allows these difficult precise exclusive measurements!

Plot Credit : Derek Glazier

Mainz Beam Test Feb 2025

Mainz Beam Test

Test Setup

- A2 Hall at MAMI
- Continuous (max) 1.6 GeV electron beam
- Timepix4 placed at high electron energy to maximize flux.
- Signal from plastic scintillators on focal plane fed directly into Timepix4

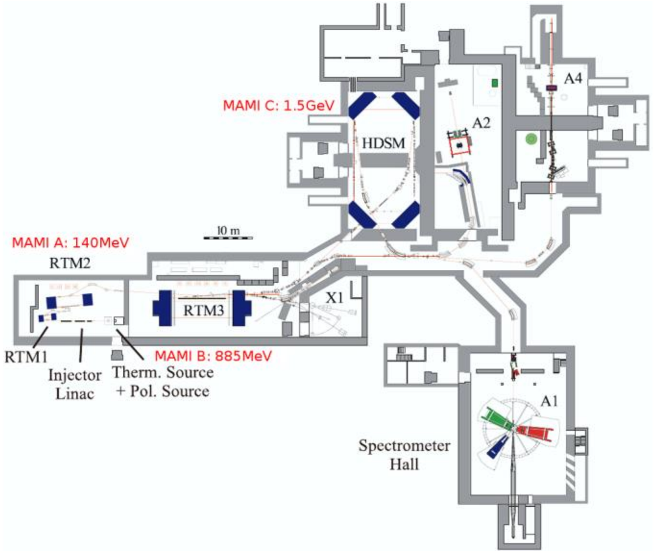


Figure 23: [The Mainz Microtron MAMI]

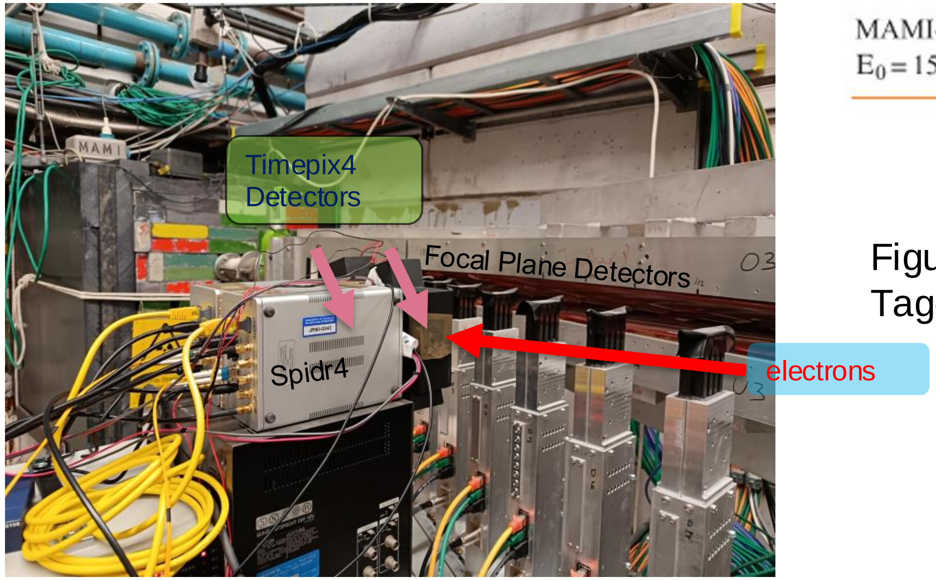


Figure 24: Timepix4 detector setup in A2 Hall, and Glasgow Photon Tagging Spectrometer.

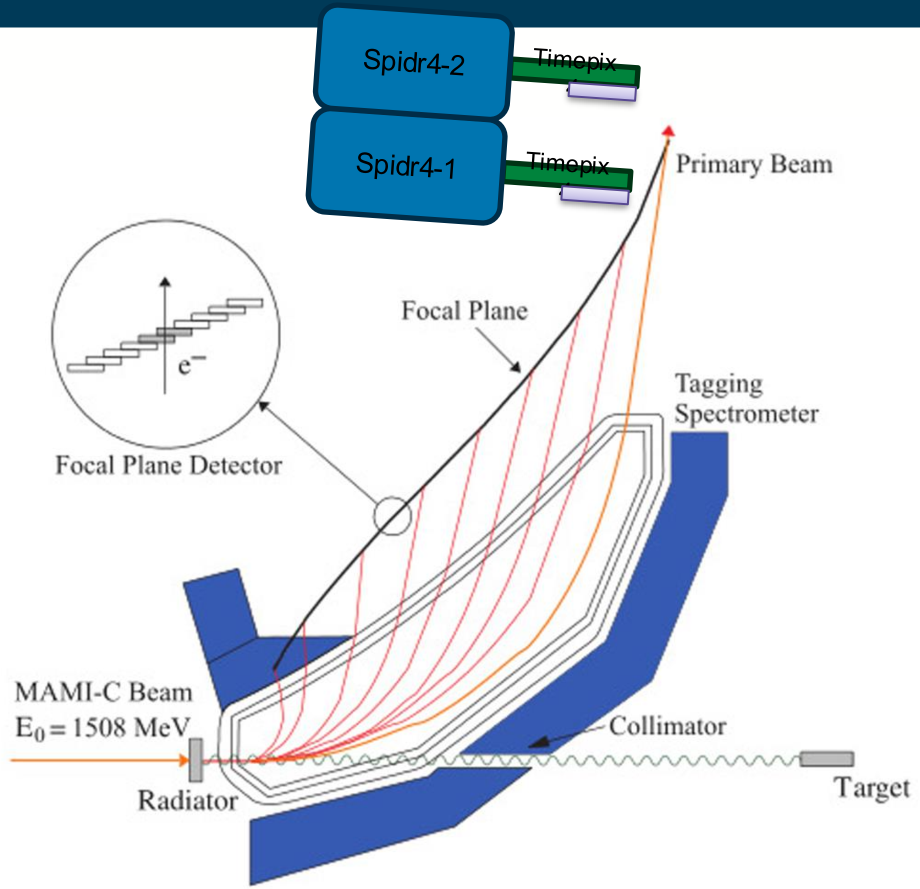


Figure 25: Timepix4 detectors and Glasgow Photon Tagging Spectrometer diagram (not to scale).

Timing Resolution

- Each chip's rootfile undergoes offline clustering.
- Then, search for coincidences between the two independent files within a configurable window.

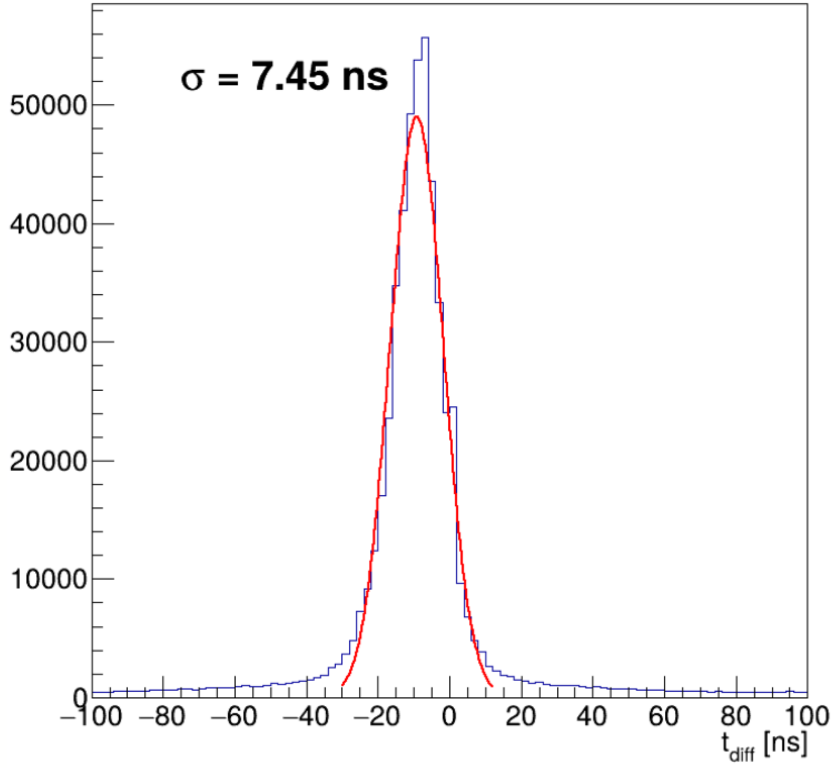


Figure 26: Time difference between raw clusters in each chip, within a 10000ns window.

Expect a ~ 10.2 ns bunch crossing time at EIC IP6.

7.45 ns coincidence resolution -> 5.26 ns single layer in beam resolution (120 ps intrinsic pixel timing resolution)

This data has NOT undergone timewalk corrections -> ongoing study. Ultimately combination of four time measurements per tagger station

Nevertheless, still meets the required performance for EIC beam bunch expectations.

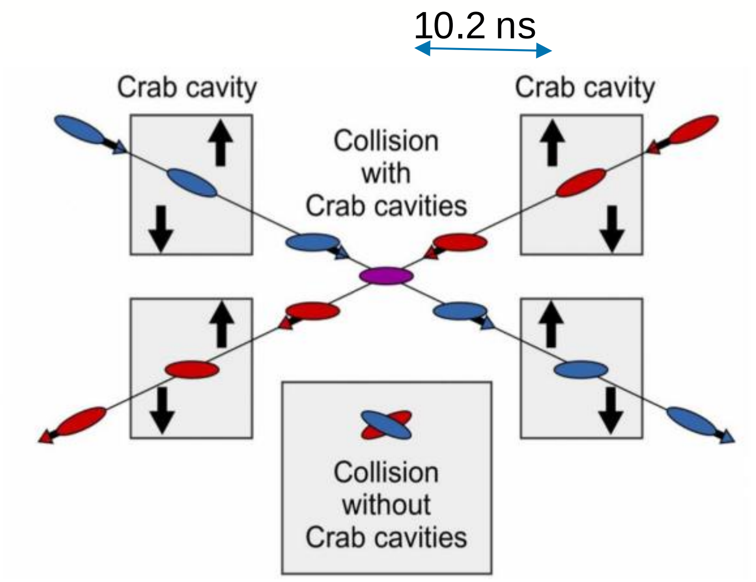


Figure 27: Beam bunch crossing diagram, bunches will cross every 10.2 ns

Mainz Beam Test

Position Coincidences / Differences

- Can inspect the 2D hit map of raw clusters, and when we cut on the timing coincidence peak
- X and Y position delta after +-100ns coincidence cut

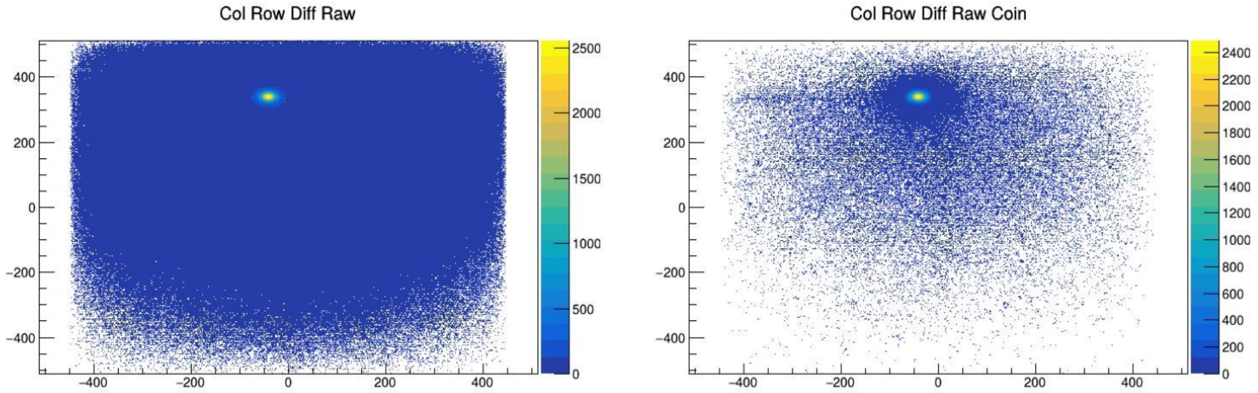


Figure 29: 2D hit map of pixel rows and columns for (left) raw clusters and (right) +-100ns timing coincidence cut.

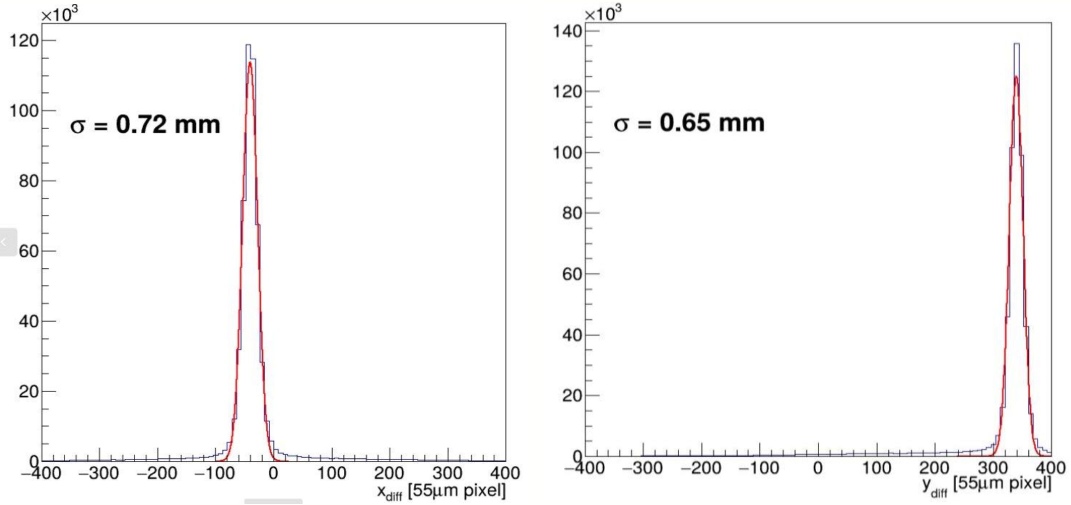
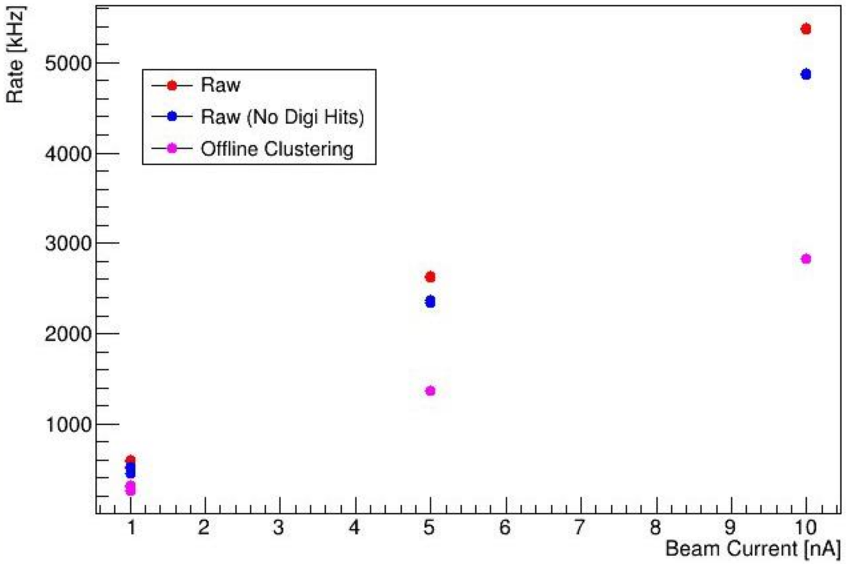


Figure 28: (Left) x , (right) y between chip 1 and chip 2 within +-100 ns coincidence time cut. Resolves the beam spot well.

- Cleanly resolve the beam spot (after some divergence)
- Single pixel position resolution is in practice 55 um
- Absolute position resolution is improved with cluster size

Early Efficiency / Rate Capability Studies

- Measured a linear response in raw rate with beam current increase to limit tested, for raw data and offline clusters
- No saturation detected, however many orders of magnitude away from EIC luminosities for now
- We have the capability of testing the rate limits in a test lab setting, ongoing efforts and analysis.



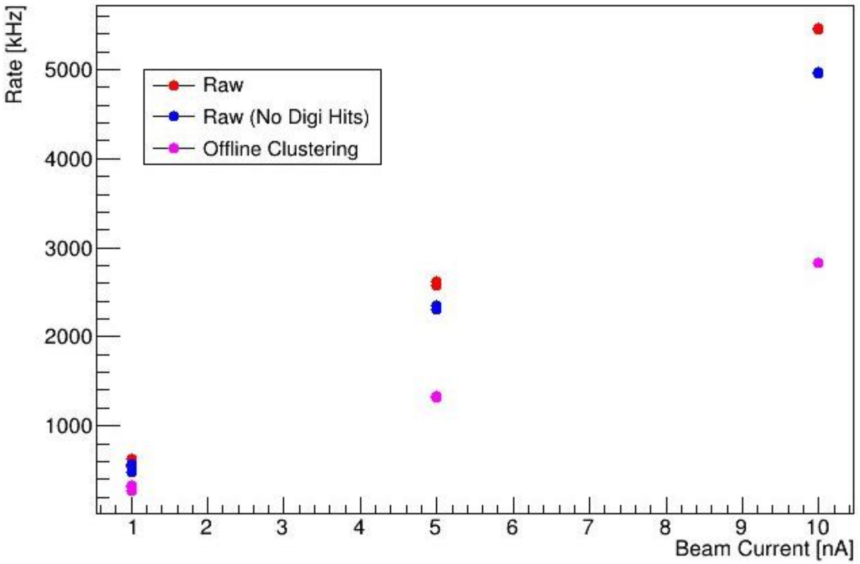


Figure 30: Rates for various data described in legend as a function of beam current, for (left) Chip 1 and (right) Chip 2.

Status and Plans

Status and Plans

Tracker

Date	
Jan 2024	2 x SPIDR4 kits in Glasgow
Summer 2024	Tests in Glasgow
Feb 2025	Beam test in Mainz
2025/2026	Engineering + Design + DAQ Integration
Dec 2025	Preliminary Design Review
Oct 2026	Start of construction
Oct 2030	Ready for installation

Calorimeter

Date	
May 2025	Final design complete, review, start of construction
Oct 2030	Ready for installation

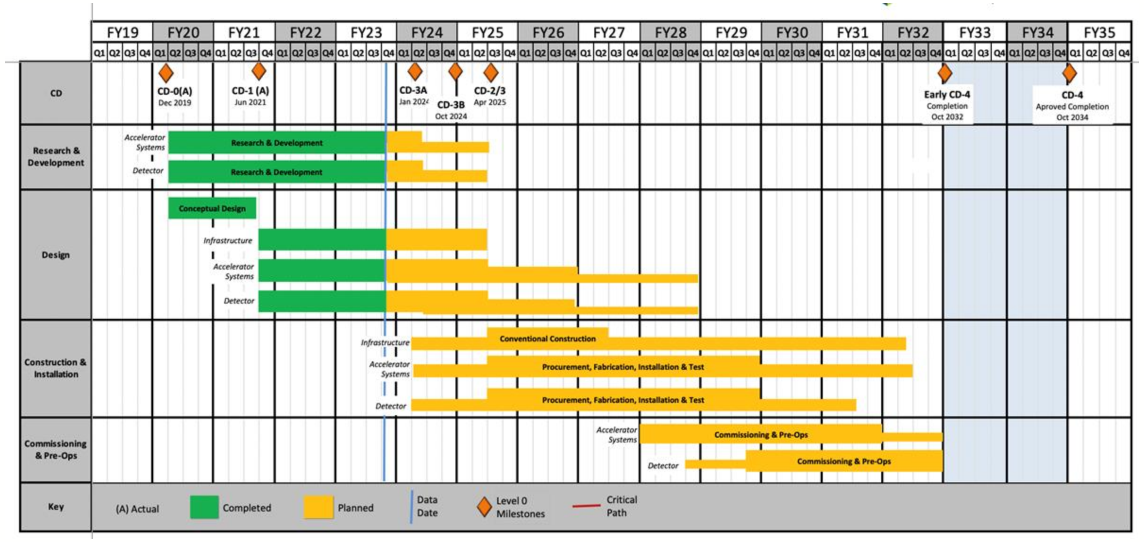


Figure 31: EIC Timeline. Dynamic and subject to possible change.

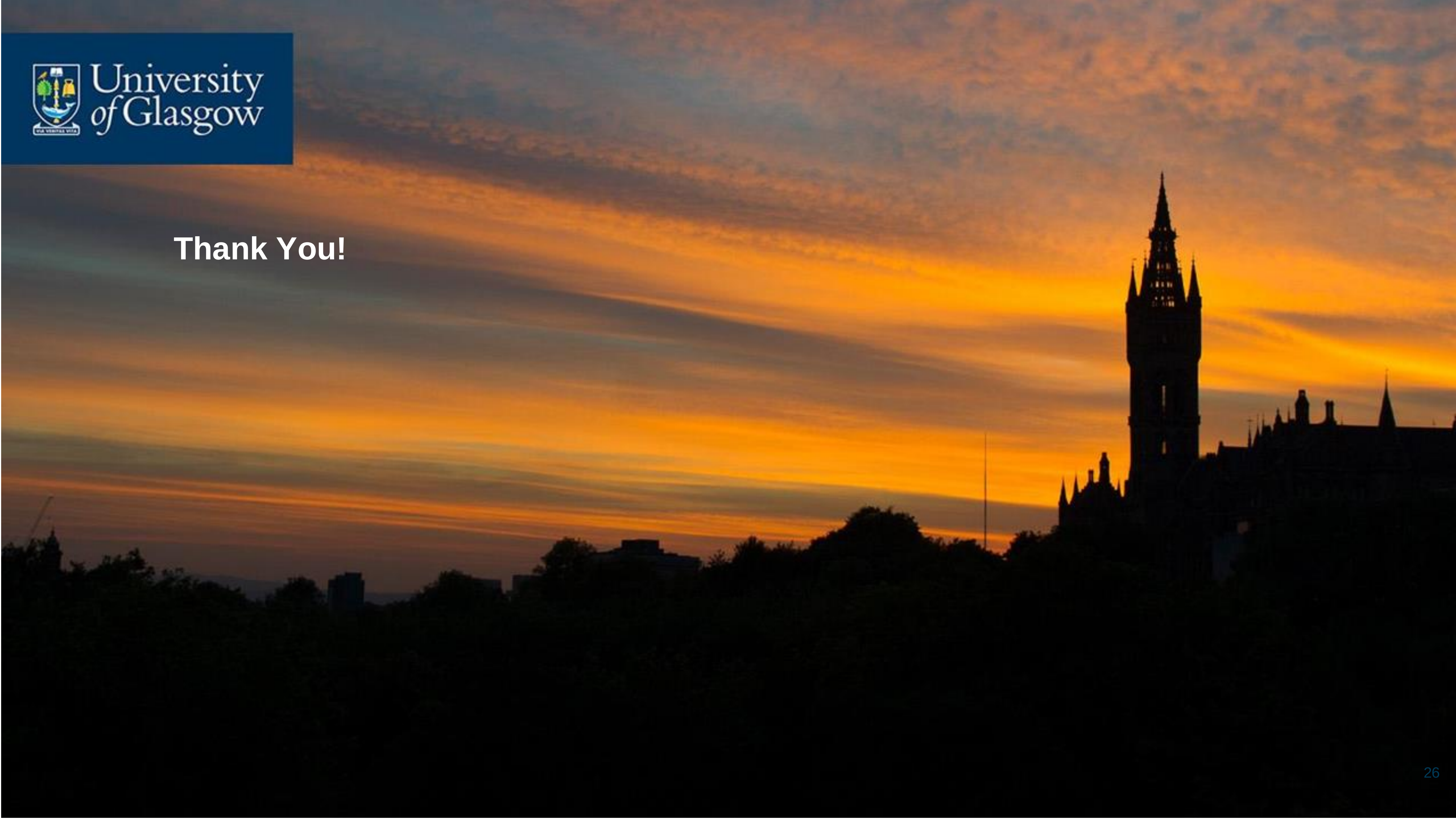
Status and Plans

Looking Forward

- Continue beamtime analysis.
  - Gain fuller understanding of detector and readout.
  - Explore clustering in reconstruction software.
  - Incorporate full digitization chain into simulation to benchmark limits.
- Further Tests in Glasgow
  - Use test pixel and pulse generator to test pixel readout limits.
  - Optimization of ToT and threshold to maximize readout rate.
- For next tests
  - Make 4-layer telescope.
  - Develop interface to edm4hep to allow benchmarking with EICrecon

Conclusions / Summary

- Development of Low-Q^2 tagger for ePIC detector experiment at future EIC Is well underway at Glasgow
- The tagger will extend our reach in Q2 down to effectively zero
- This will enable a rich number of additons to an already exciting potential physics program
    - Timelike compton scattering
    - Vector Meson photoproduction
    - Low Q^2 DIS
    - XYZ Spectroscopy
- Timepix4 technology will be used in order to achieve the best rate handling and kinematic reconstruction, which will be critical in the face of the extreme requirements placed on this system.
- Early photoproduction spectroscopy studies are producing promising results in the semi-inclusive and fully exclusive reconstruction regimes, exploting the far-backward and far-forward regions
- We have recently had a successful first beamtime test of a 2 chip/layer Timepix4 system, with a plan to build a 4 layer telescope this year
- Ongoing analysis of beamtime data, as well as planning and prototyping towards a full design and DAQ integration throughout this next year.



Thank You!

Backup

International Team

WBS 6.10 EIC Detector														
WBS-Item:	WBS 6.10.01 Detector Management	WBS 6.10.02 Detect. R&D & Physics Design	WBS 6.10.03 Tracking	WBS 6.10.04 Particle Identification	WBS 6.10.05 Electromagnetic Calorimetry	WBS 6.10.06 Hadronic Calorimetry	WBS 6.10.07 Magnets	WBS 6.10.08 Electronics	WBS 6.10.09 DAQ/Computing	WBS 6.10.10 Detector Infrastructure	WBS 6.10.11 Integration & Auxiliary Detectors	WBS 6.10.12 Detector Pre-Ops & Commissioning	WBS 6.10.13 Detector #2 Development	WBS 6.10.14 Polarimetry and Luminosity
CAMs:	Rolf Ent (JLab) & Elke-Caroline Aschenauer (BNL)	Thomas Ullrich (BNL) & Rolf Ent (JLab)	Rolf Ent (JLab) Interim	Beni Zihlmann (JLab)	Alexander Bazilevsky (BNL)	Oleg Eyser (BNL)	Renuka Rajput-Ghoshal (JLab)	Fernando Barbosa (JLab)	David Abbott (JLab) & Jeff Landgraf (BNL)	Rahul Sharma (BNL)	Yulia Furletova (JLab)	E.C. Aschenauer (BNL)	E.C. Aschenauer (BNL) & Rolf Ent (JLab)	Frank Rathmann (BNL)

Figure 32: Organisation of the EIC project CAMs

Yulia Furletova – FF/FB CAM

Andrii Natocii – Geant4 Synchrotron simulation

First Hardware Setup and Tests

Glasgow Tests

- Cosmic-ray / source tests by a summer student, Gregory, during summer 2024.
- Single chip, ironing out technical issues and readout code.

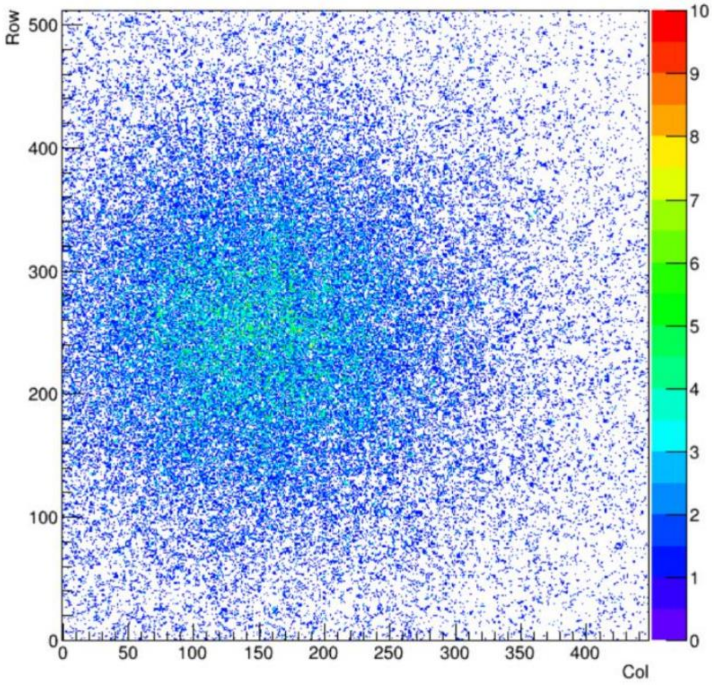


Figure 33: 2D Row/Column position distribution for 90Sr acquisition, for 30 seconds.

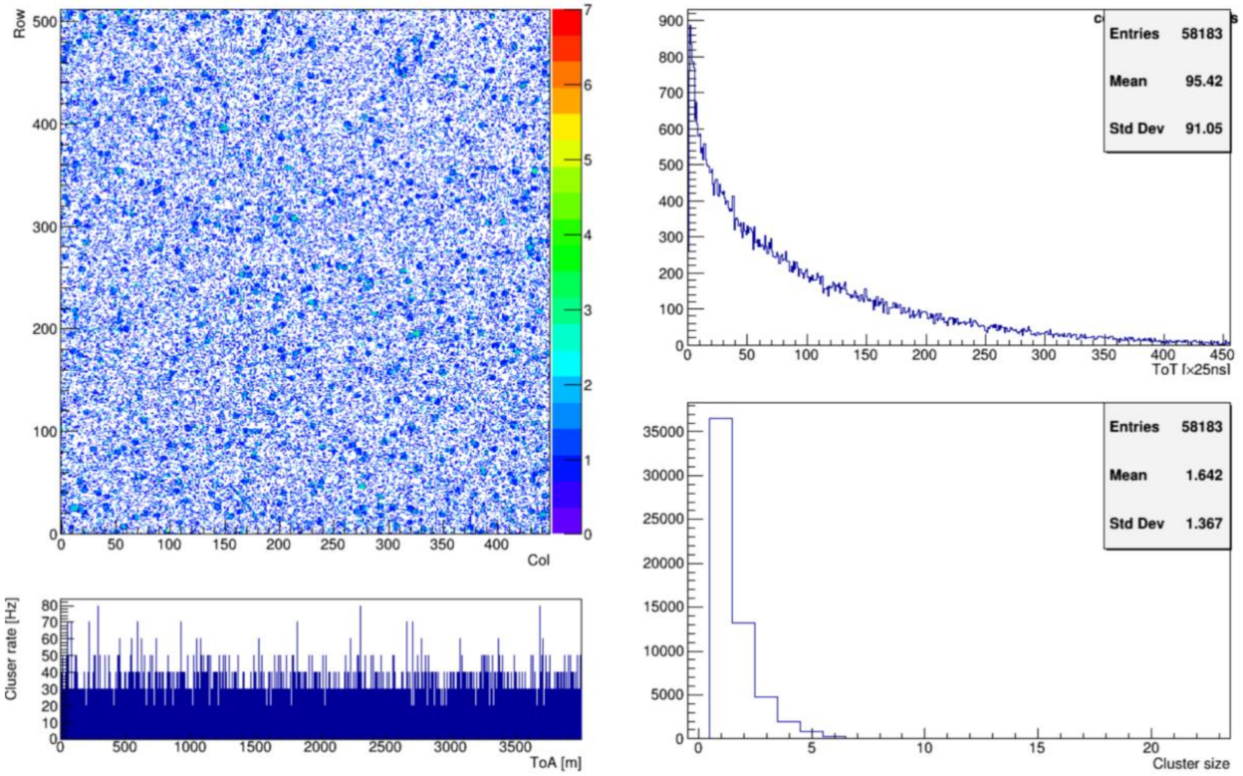


Figure 34: Cosmic-ray data over a weekend.

Timepix4 Development: Cooling

Cooling

- Each chip 2V up to 4.5A
- Air cooled with 4 fans
- 30°C environment in A2 Hall
- 40°C chips steady running

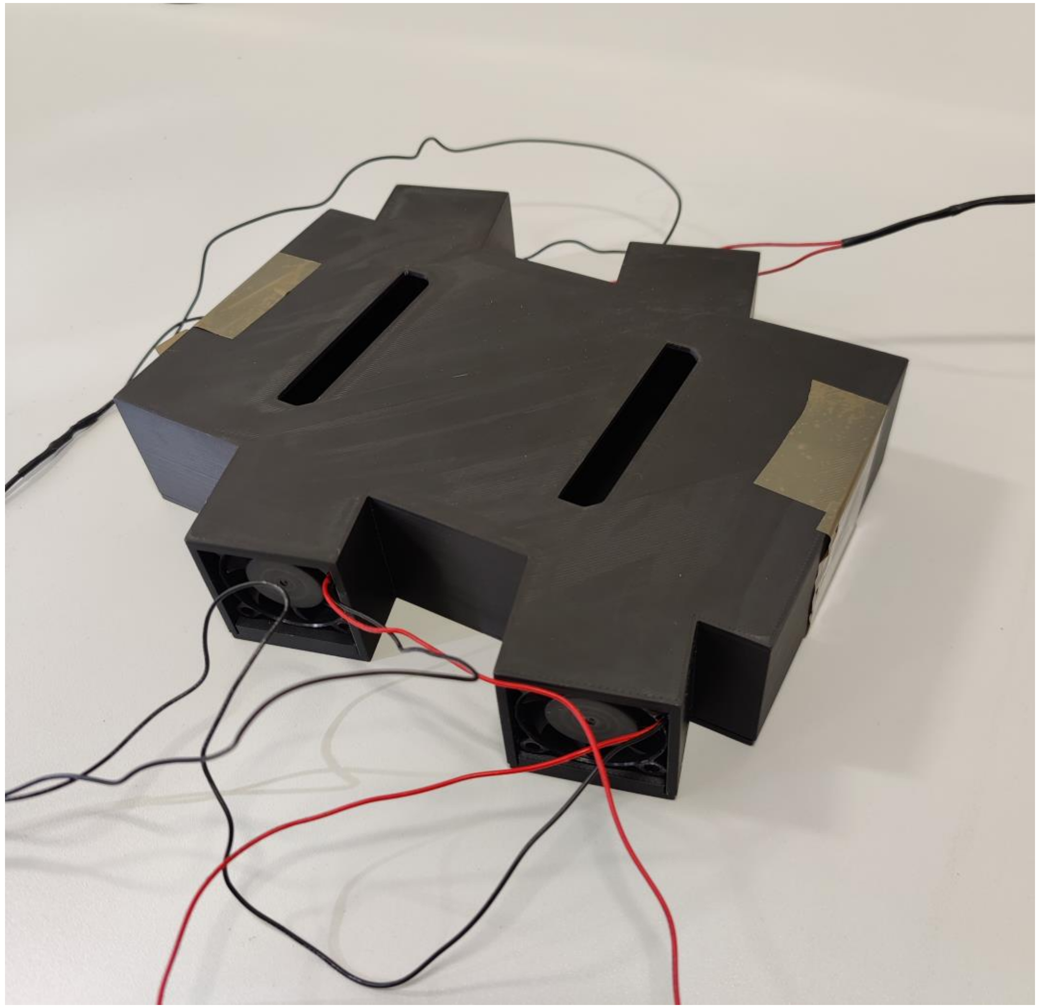
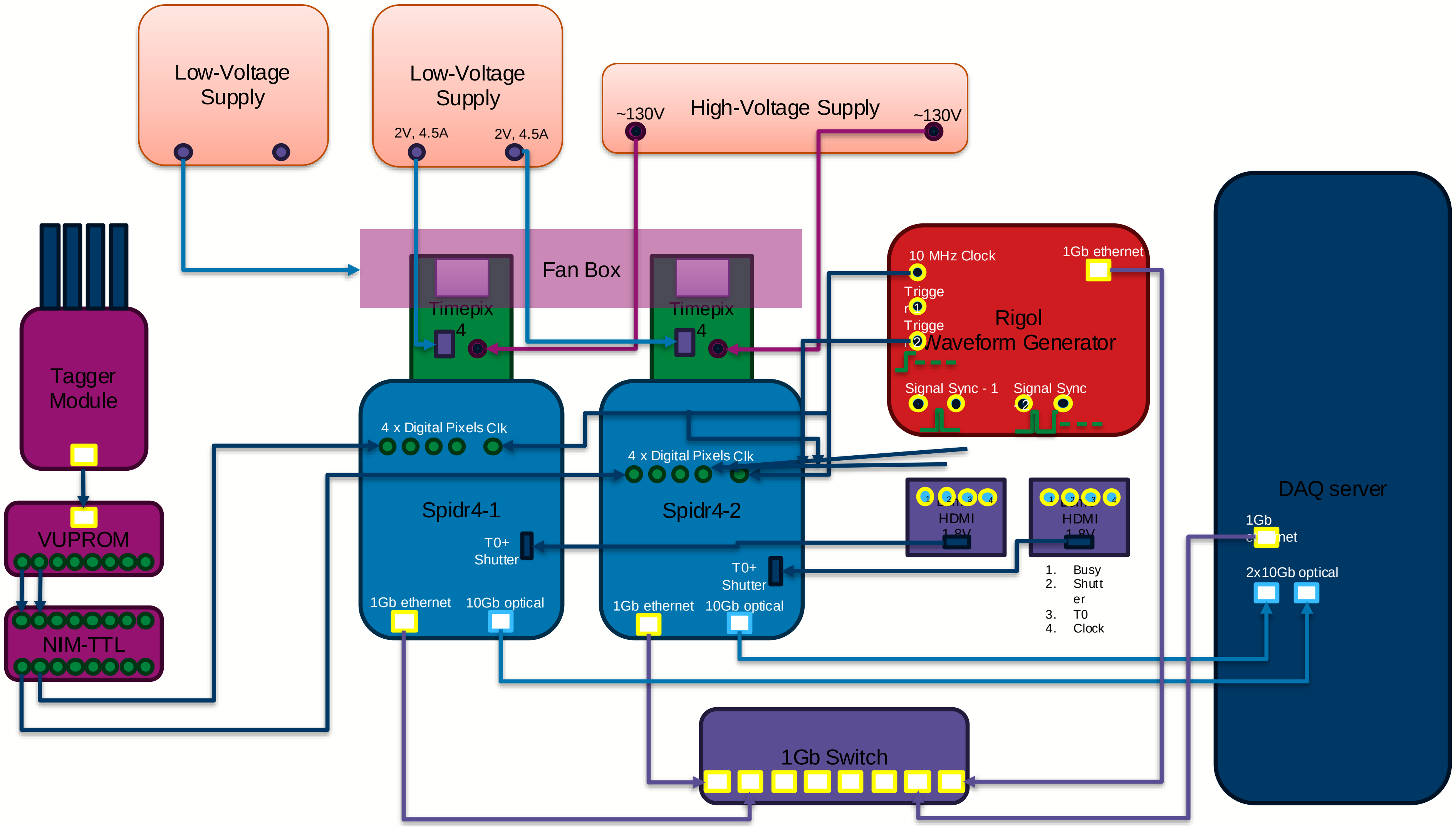
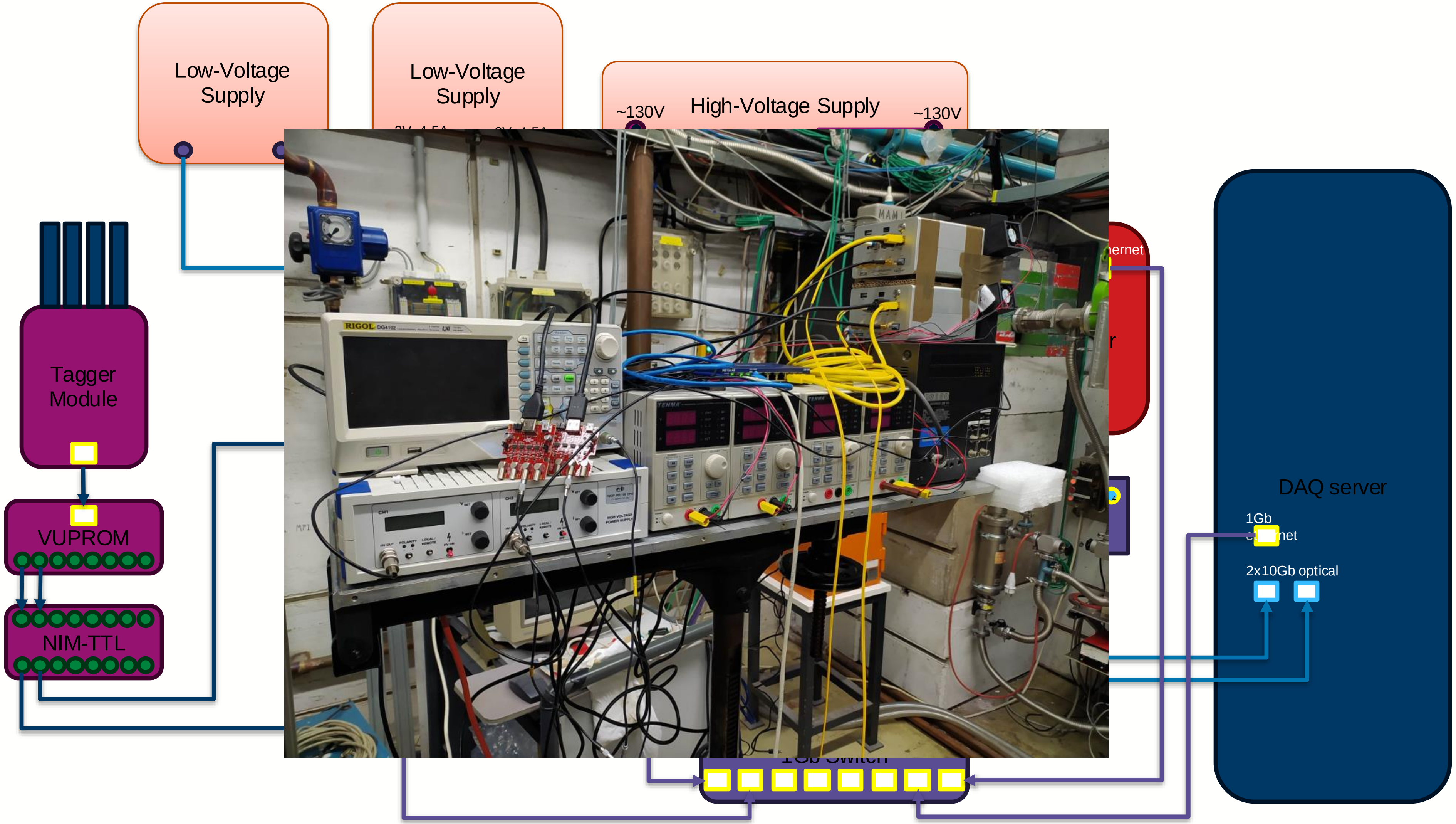


Figure 35: Current Timepix4 double layer (2 chip) cooling box by Ross McGarrie, Glasgow

Mainz Beam Test: Setup



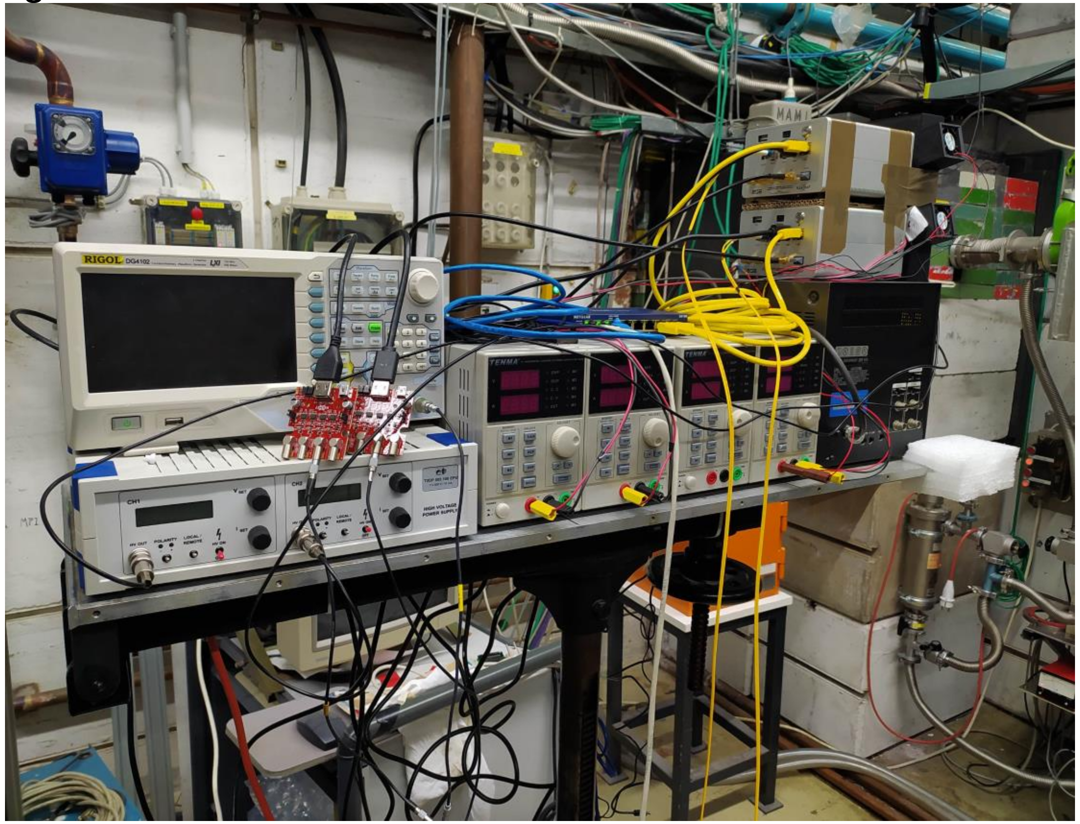
Mainz Beam Test: Setup



Mainz Beam Test

Running Conditions

- +130V bias, 300um silicon – unchanged.
- Primary electron beam current increased from 100pA to 10nA
  - Investigate rate dependence of the readout, mis-ordering of events.
- Detectors angled vertically @ 6 and 12 degrees.
  - Explore cluster shape
- Different tagger channels used in coincidence.
- Pixel threshold varied
  - Explore detected cluster size and optimize efficiency.



Mainz Beam Test

Timepix4 Raw Data (Single Chip)

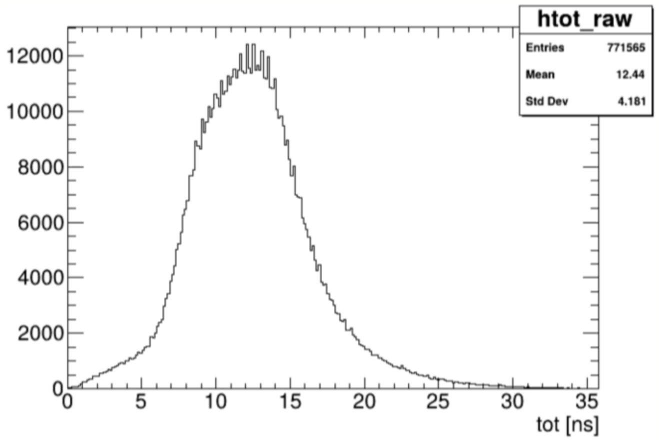


Figure XX: Time Over Threshold for raw hits in single chip data.

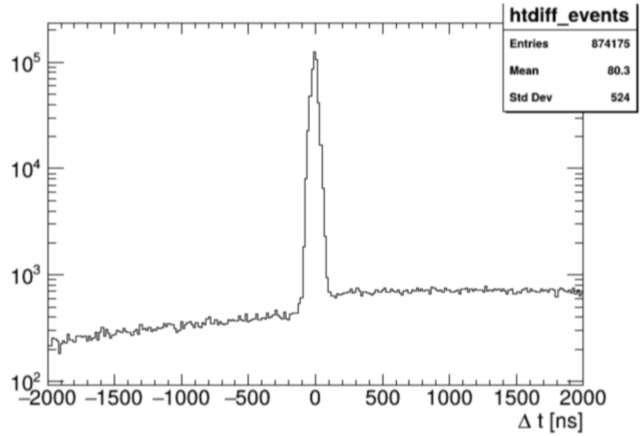


Figure 36: Time difference between hits in readout of single chip.

Clustered Data (Single Chip)

Shadow of tagger modules

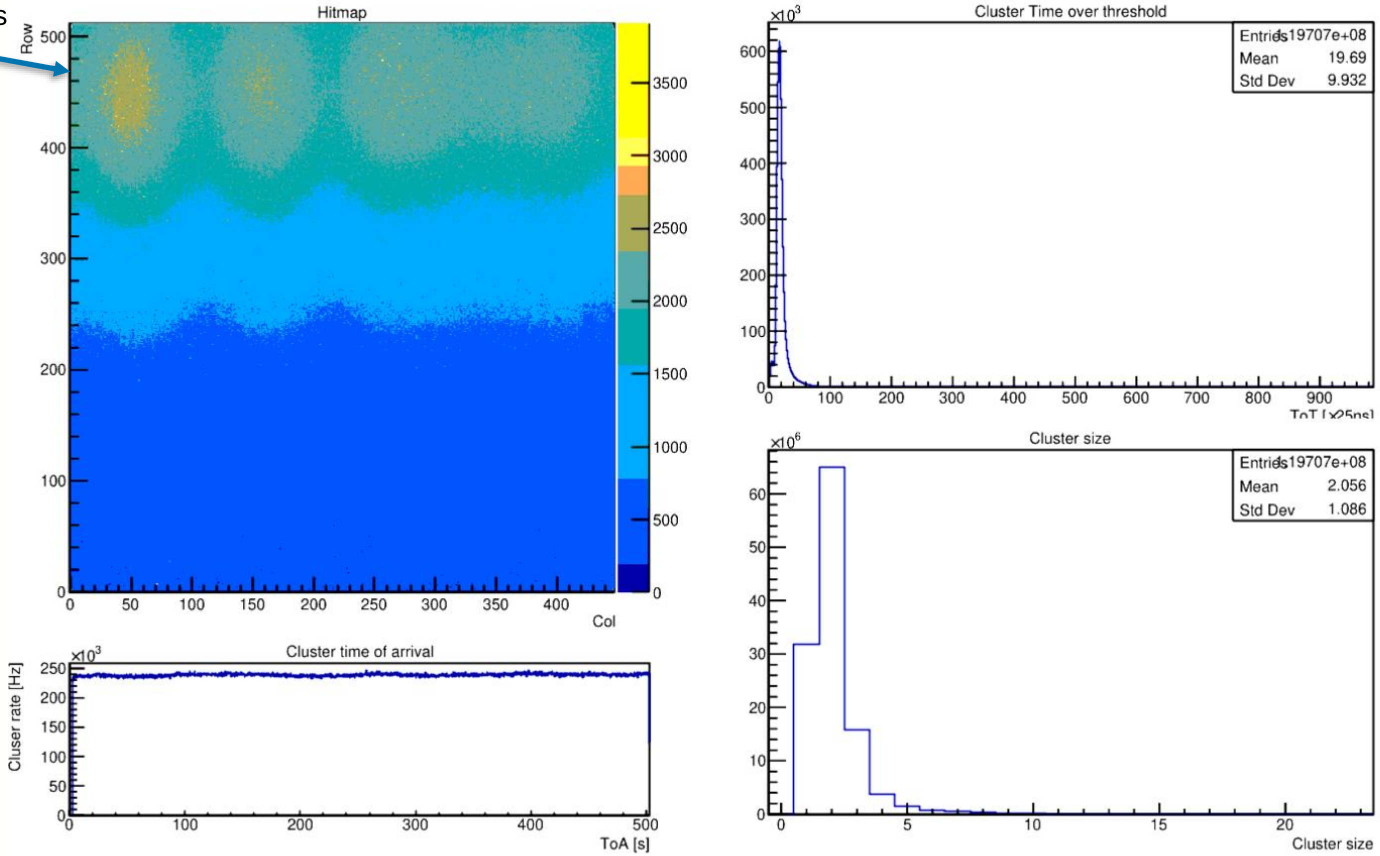


Figure 37: Clustered data for 500 seconds of beam.

Timing Coincidences

- Each chip's rootfile undergoes offline clustering.
- Then, search for coincidences between the two independent files within a configurable window.

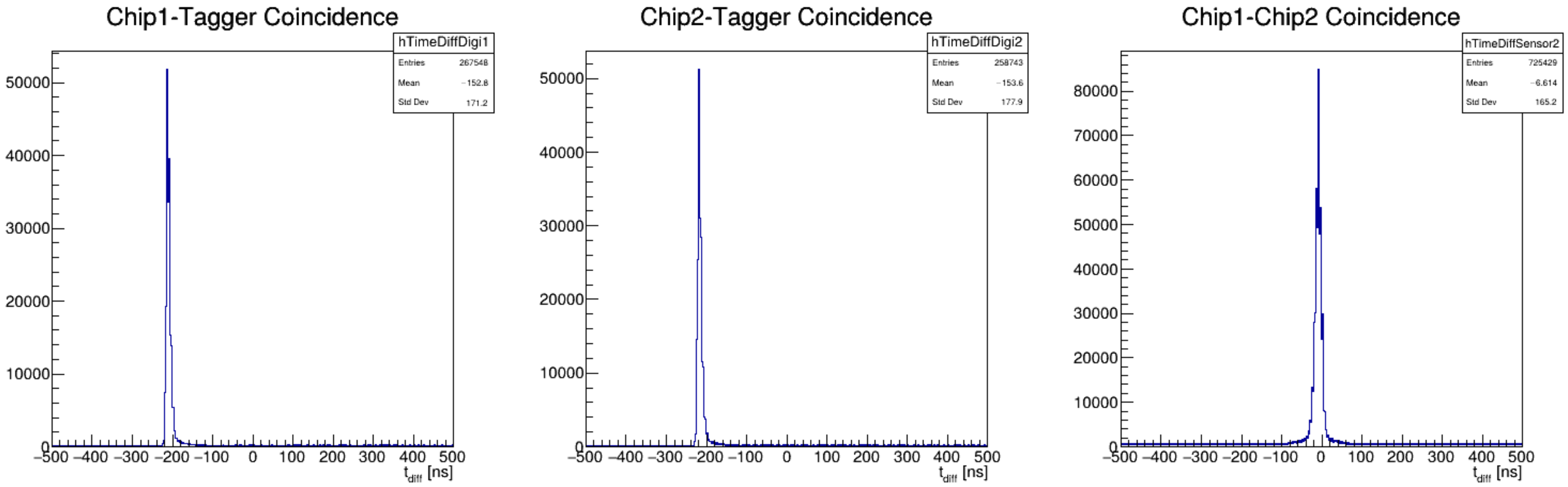


Figure 38: Timing coincidences between (left) Chip 1 and tagger, (middle) chip 2 and tagger, (right) chip 1 and chip 2.

Position Coincidences with Tagger

- We can inspect the x-y position of hits in each chip.
- Look at how this changes as we cut on the timing coincidence peak with the tagger
- Tagger modules shadows are *just* visible in the raw 2D position distribution.
- The tagger module being read into the Timepix4 becomes more enhanced

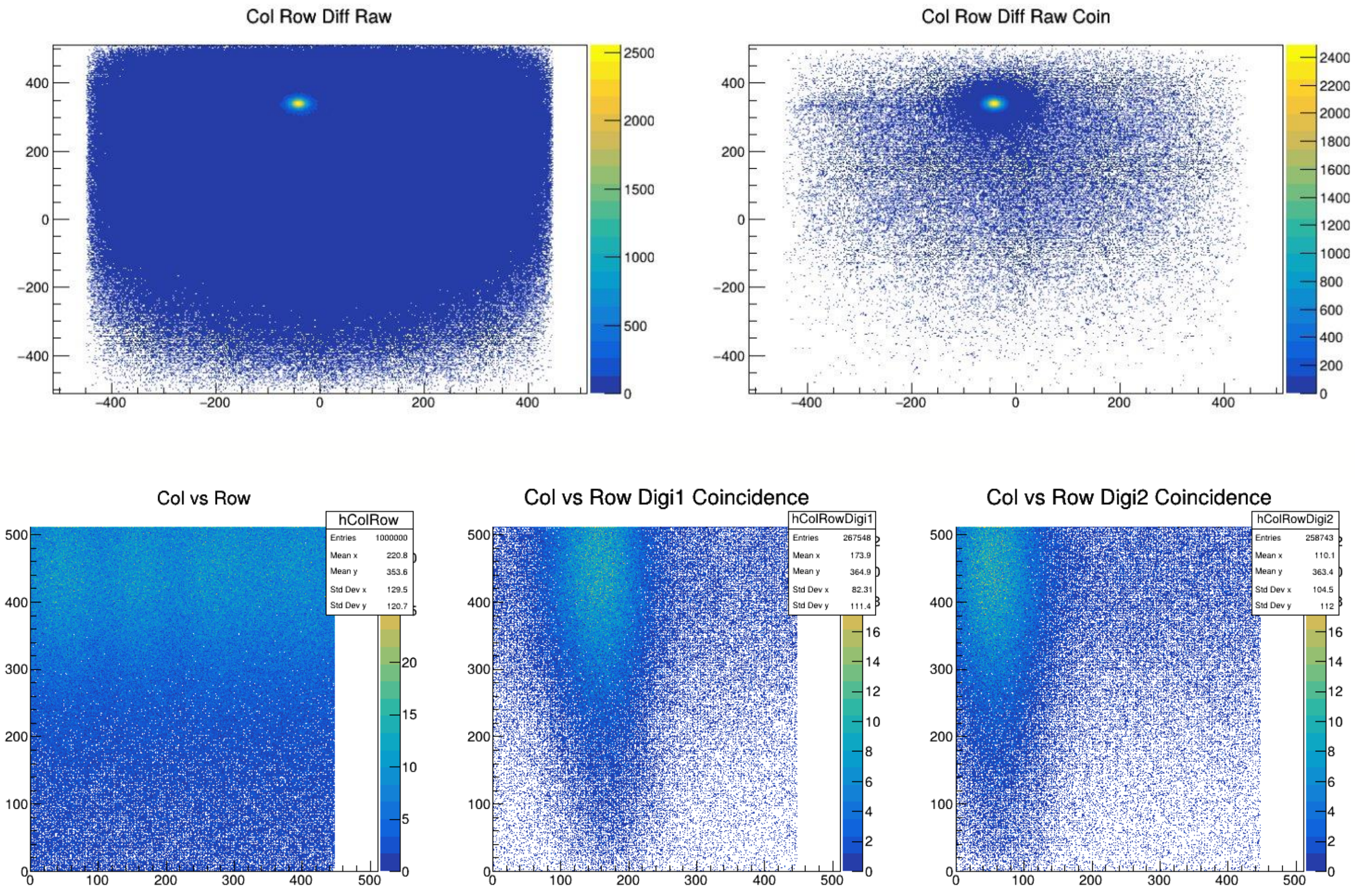
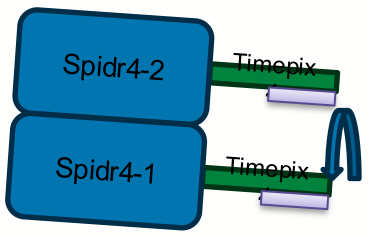


Figure 39: 2D Position coincidences for (top left) raw data, (top right) chip1-chip2 timing coincidence cut, (bottom left) raw single chip, (bottom middle) chip1-tagger timing coincidence cut and (bottom right) chip2-tagger timing coincidence cut.

Mainz Beam Test

Cluster Shape Studies (Tilt)

- Tilted the detectors slightly towards the beam. Expect an increase in average cluster size.
- Alignment in perpendicular axis not controlled causing overall decrease in average size for 6 degrees.
- 6 Degrees may have been too small a change combined with the change in relative height, to see a full effect.
- Here thresholds and beam current are fixed.



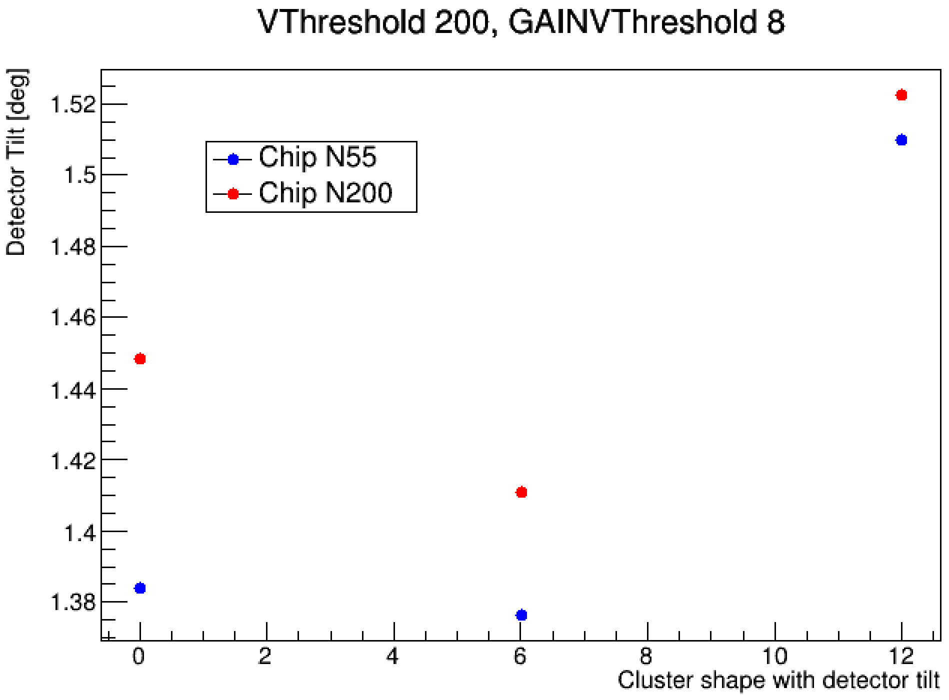
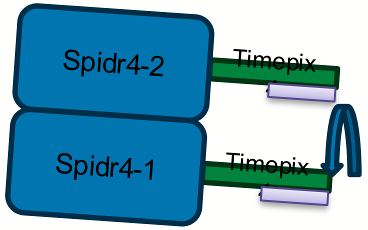


Figure 40: Cluster Multiplicity as a function of Detector Tilt.

Mainz Beam Test

Cluster Shape Studies (Tilt)

- Tilted the detectors slightly towards the beam. Expect an increase in average cluster size.
- Alignment in perpendicular axis not controlled causing overall decrease in average size for 6 degrees.
- 6 Degrees may have been too small a change combined with the change in relative height, to see a full effect.
- Here thresholds and beam current are fixed.



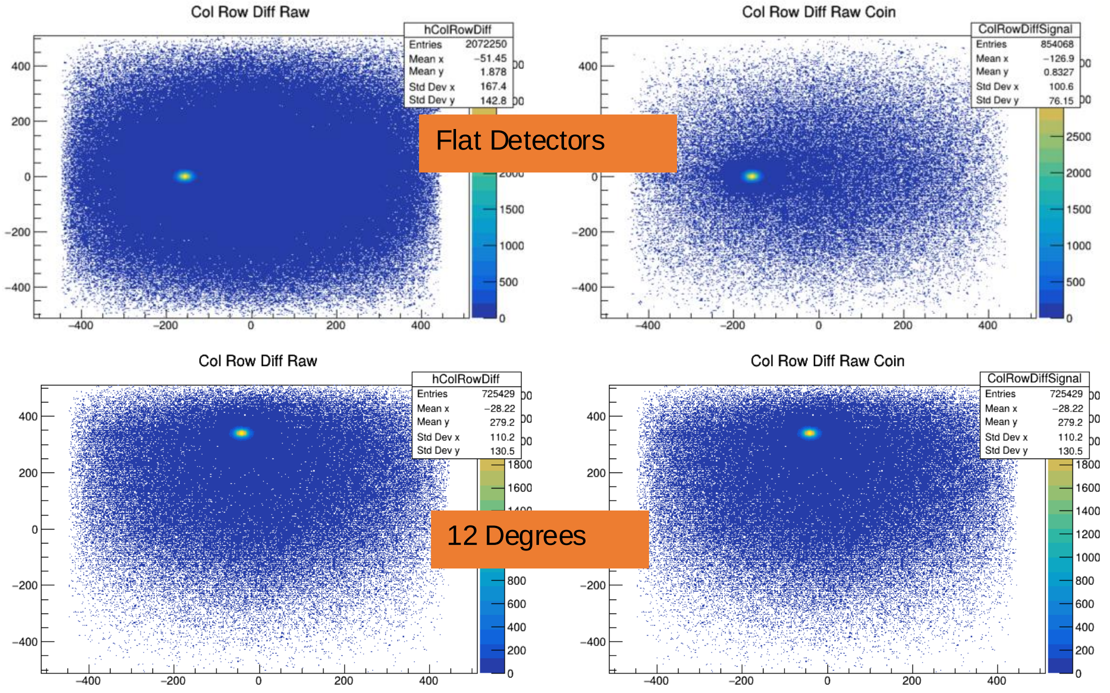


Figure 41: Position coincidences for (left) raw data and (right) coincidences between chip 1 and 2 for (top) no tilt and (bottom) 12 degree tilt.

Cluster Shape Studies (Thresholds)

- At a fixed beam current (1 nA), detector tilt (12 degrees) and Gain (8 arb), changed the VThreshold [arb] to measure effect on cluster size.
- Around 5 pixels became noisy when reducing the threshold.
- Need to investigate the VThreshold and Gain parameters.

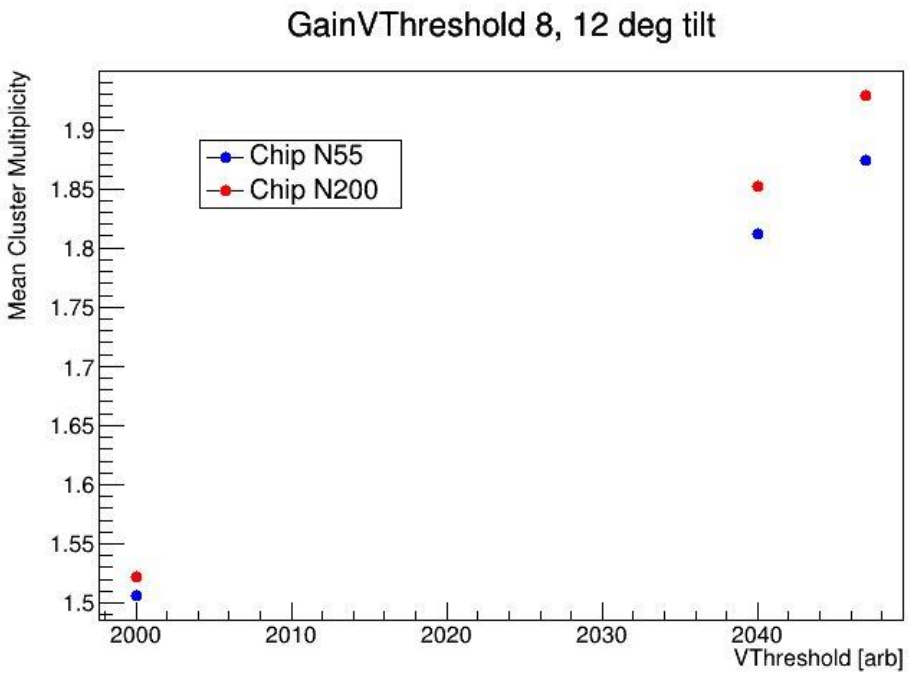


Figure 42: Mean cluster multiplicity as a function of the threshold applied to each chip, at 1nA with a 12 degree tilt.

Time Ordering With Clustering

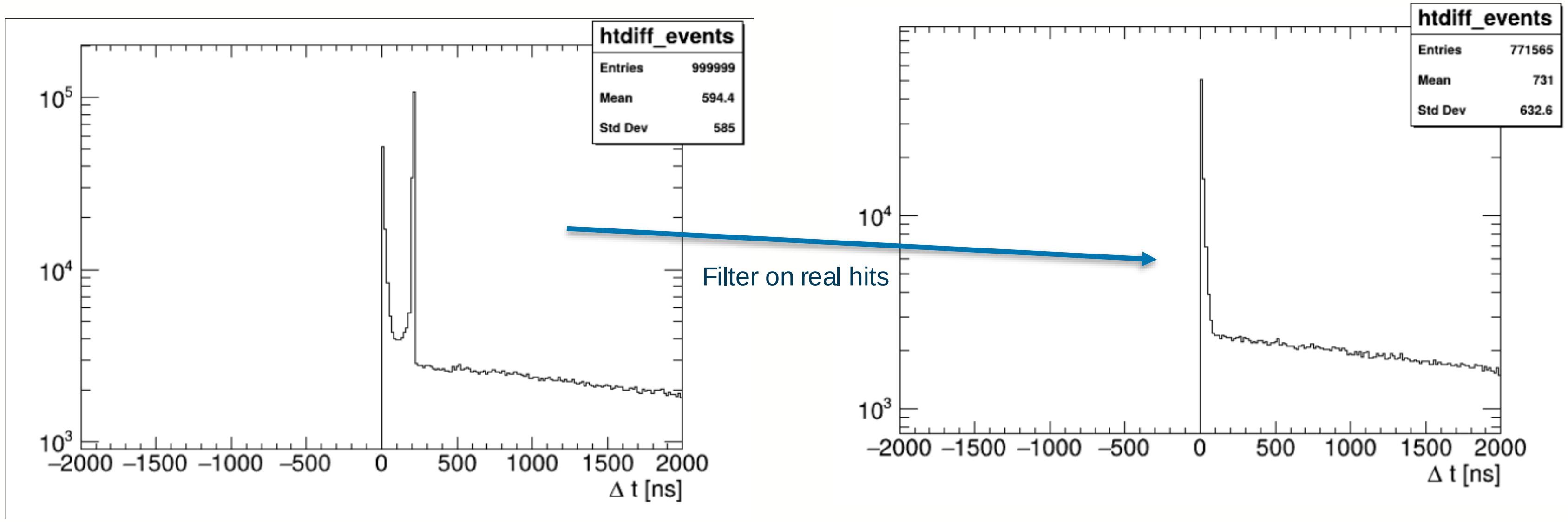


Figure 43: Time difference between *consecutive events* after offline clustering. Removing digital pixel input events coming from tagger. Sharp apparent coincidence indicating offline clustering perhaps not fully encapsulating all hits together.