Operation and Performance of the sPHENIX MAPS Vertex Detector

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on behalf of the sPHENIX Collaboration

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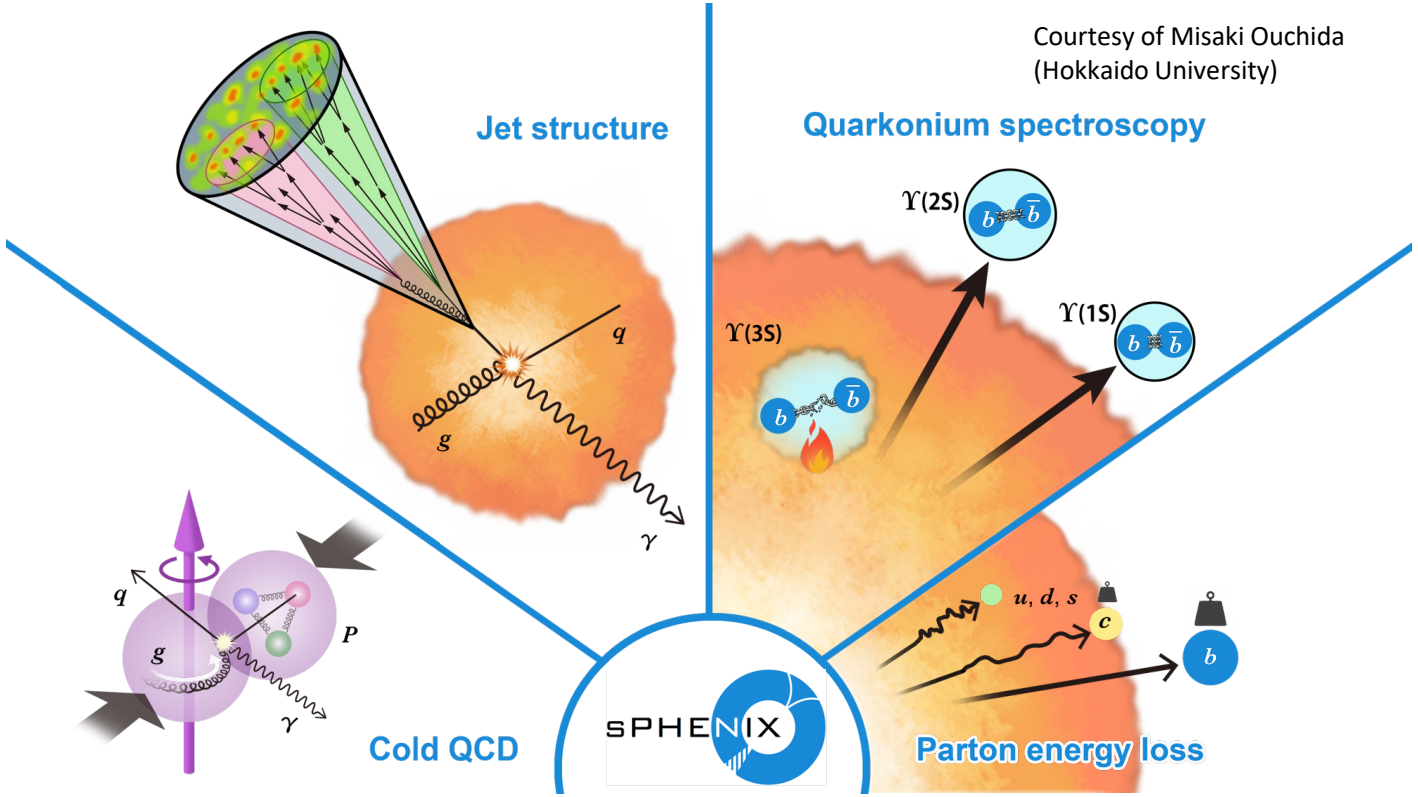
MITHIG work supported by

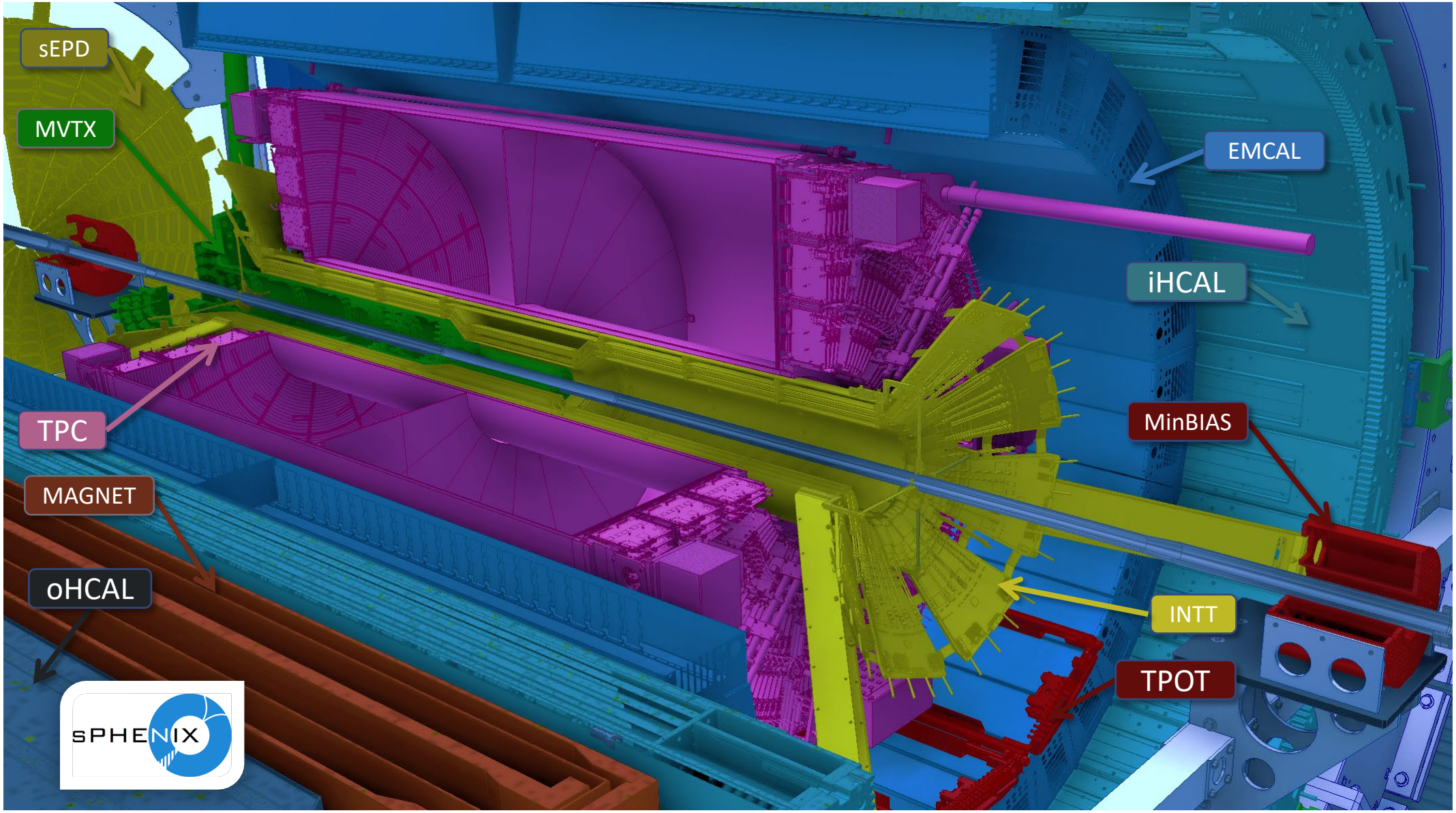
U.S. DEPARTMENT OF ENERGY

sPHENIX Overview

- General-purpose detector at RHIC, in operation since summer 2023
  - First new experiment at hadron collider since LHC
- Physics mission includes studies of:
  - Jet structure in heavy-ion and pp collisions at 200 GeV/A
  - Heavy-flavor spectroscopy
  - Studies of bulk dynamics in QGP
  - Spin observables from polarized proton beams

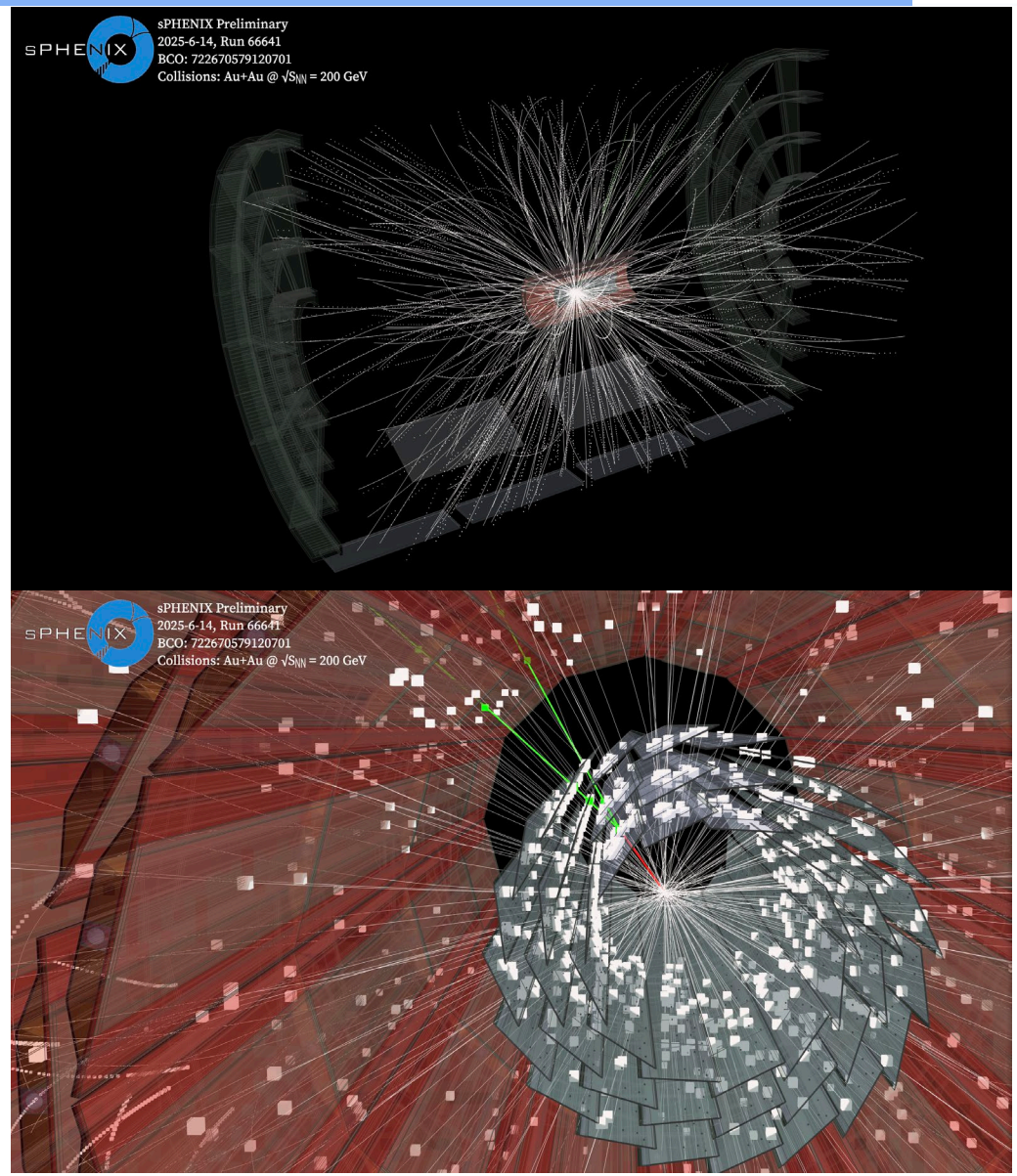


sPHENIX Detector



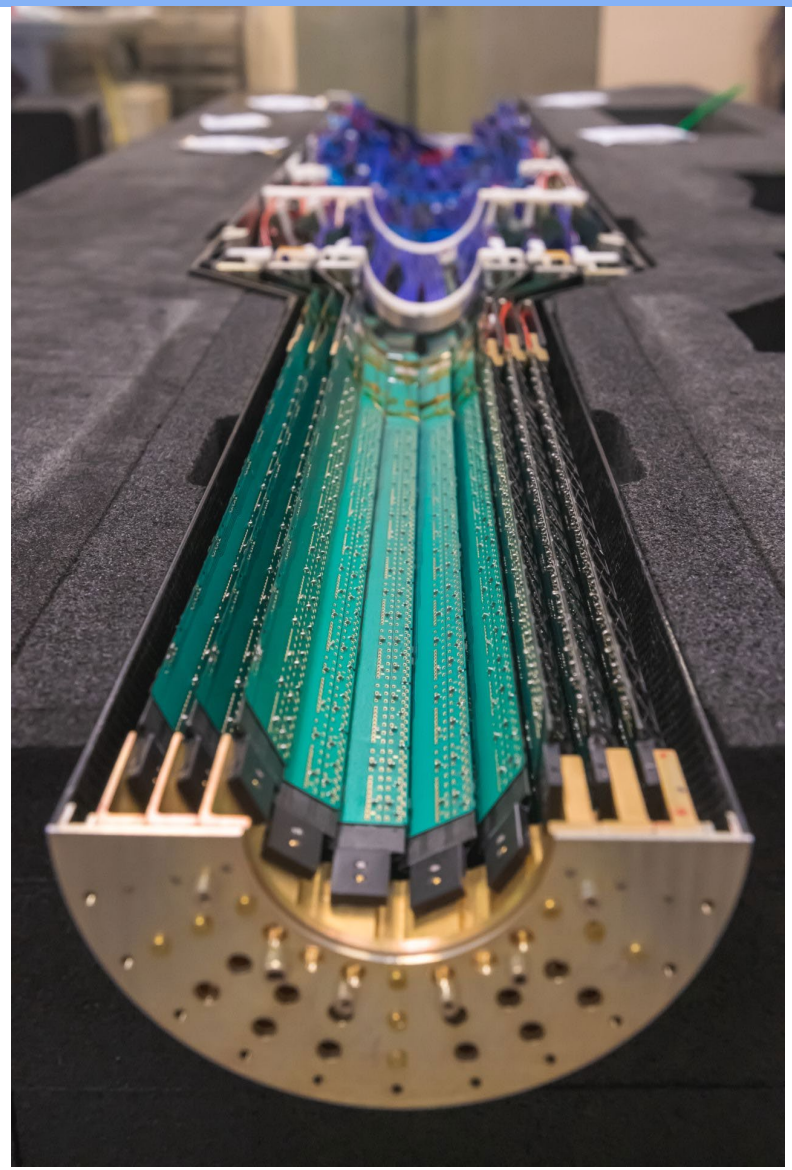
sPHENIX Tracking

- 55 layers of tracking sensors:
  - 3 layers of MAPS sensors for vertex determination (MVTX)
  - 2 layers of silicon strips for bunch-crossing determination (INTT)
  - 48 layers of TPC pads
  - 2 layers of MicroMegas for TPC calibration (TPOT)
- MVTX essential for vertex resolution, heavy-flavor program
- 100% streaming readout in MVTX allows for enriched track dataset

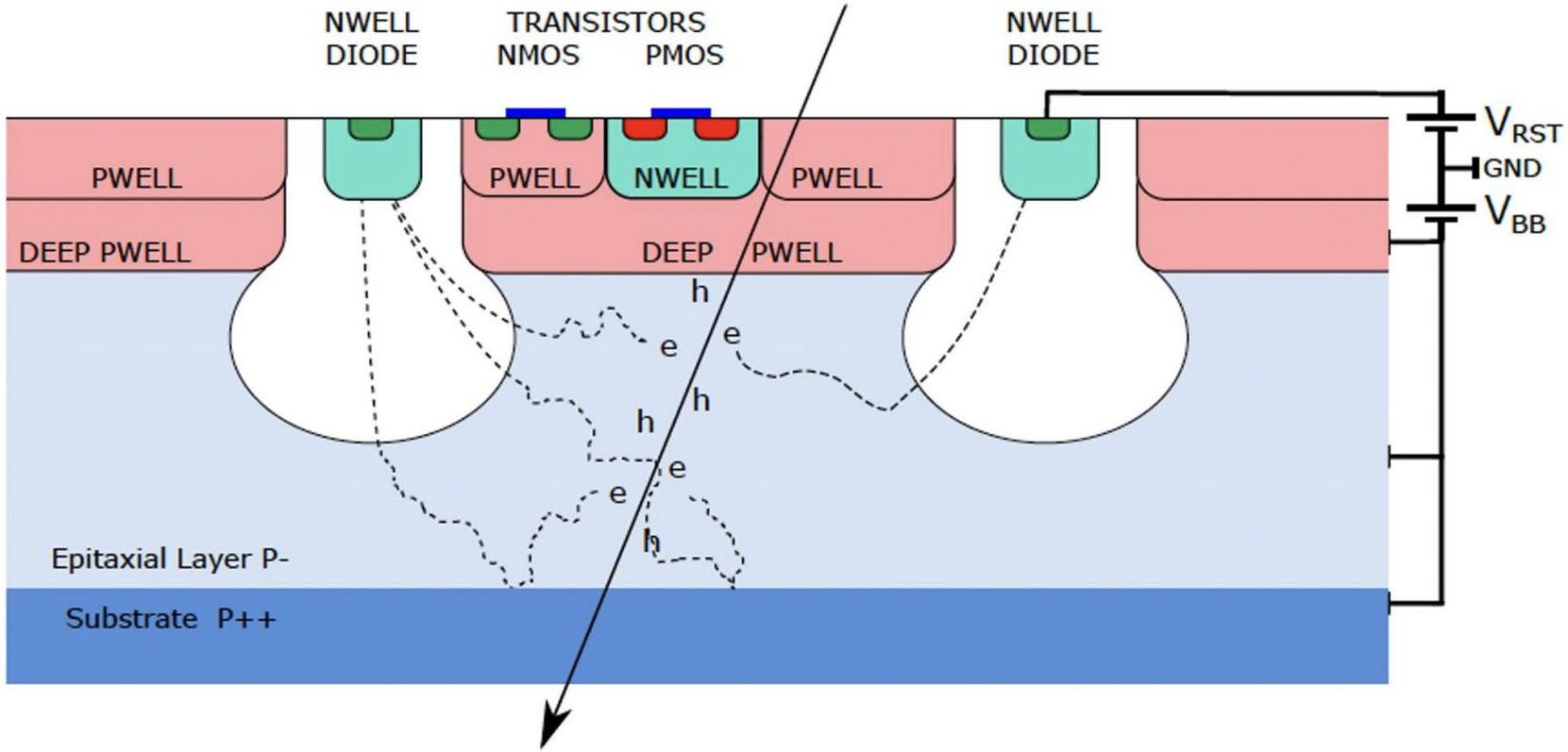


MVTX Overview

- sPHENIX MAPS-based VerTeX detector
- 3 layers of [12, 16, 20] staves, 48 in total
  - Situated [24, 32, 40] mm from beam axis
- Each stave contains 9 ALPIDE sensor chips (432 in total)
  - 512x1024 pixels per chip
  - Pixel pitch: 29.24 × 26.88 micron
- 226 million pixels in total

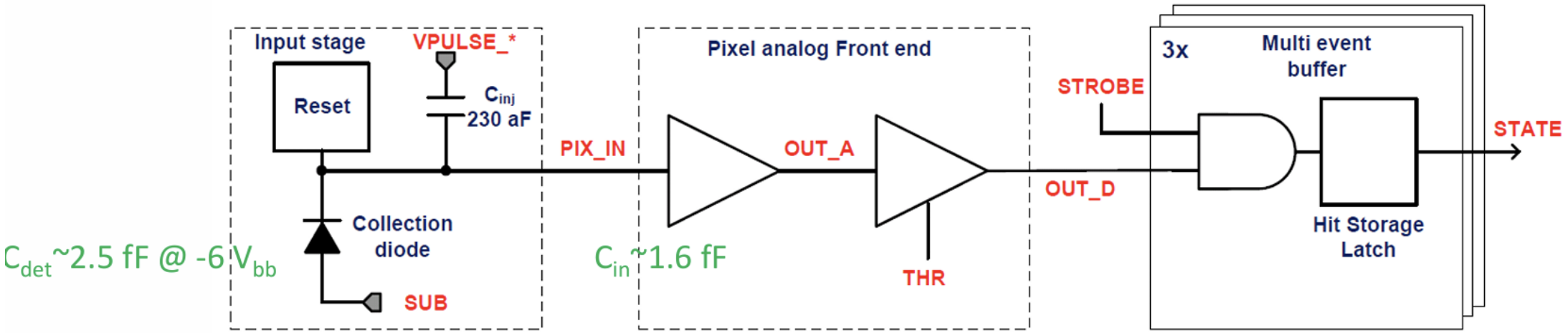


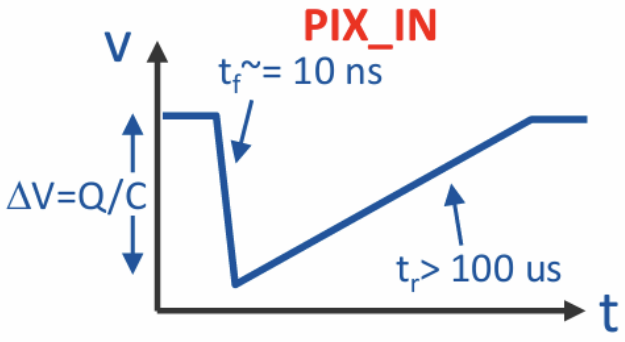
ALPIDE Sensors

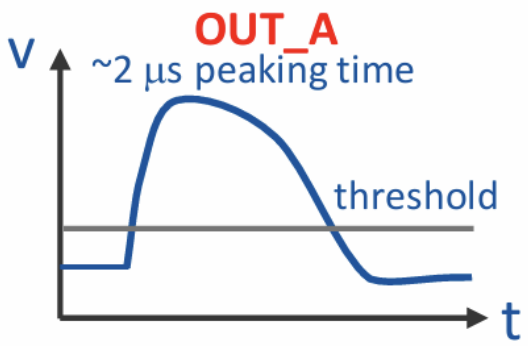


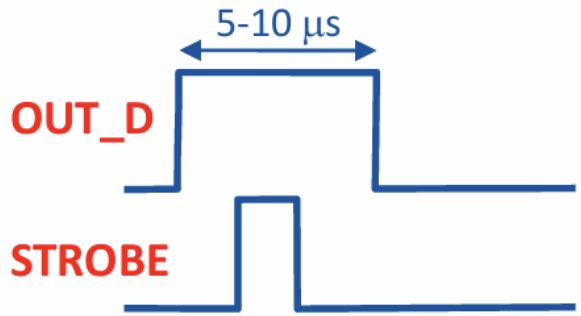
- CMOS MAPS sensor designed for ALICE ITS2
- Active area 15 x 30 mm, 50 micron thickness
- Charge collection via diffusion, O(50) ns
- Charges shared between adjacent diodes, no sharp pixel boundaries

Pixel Readout

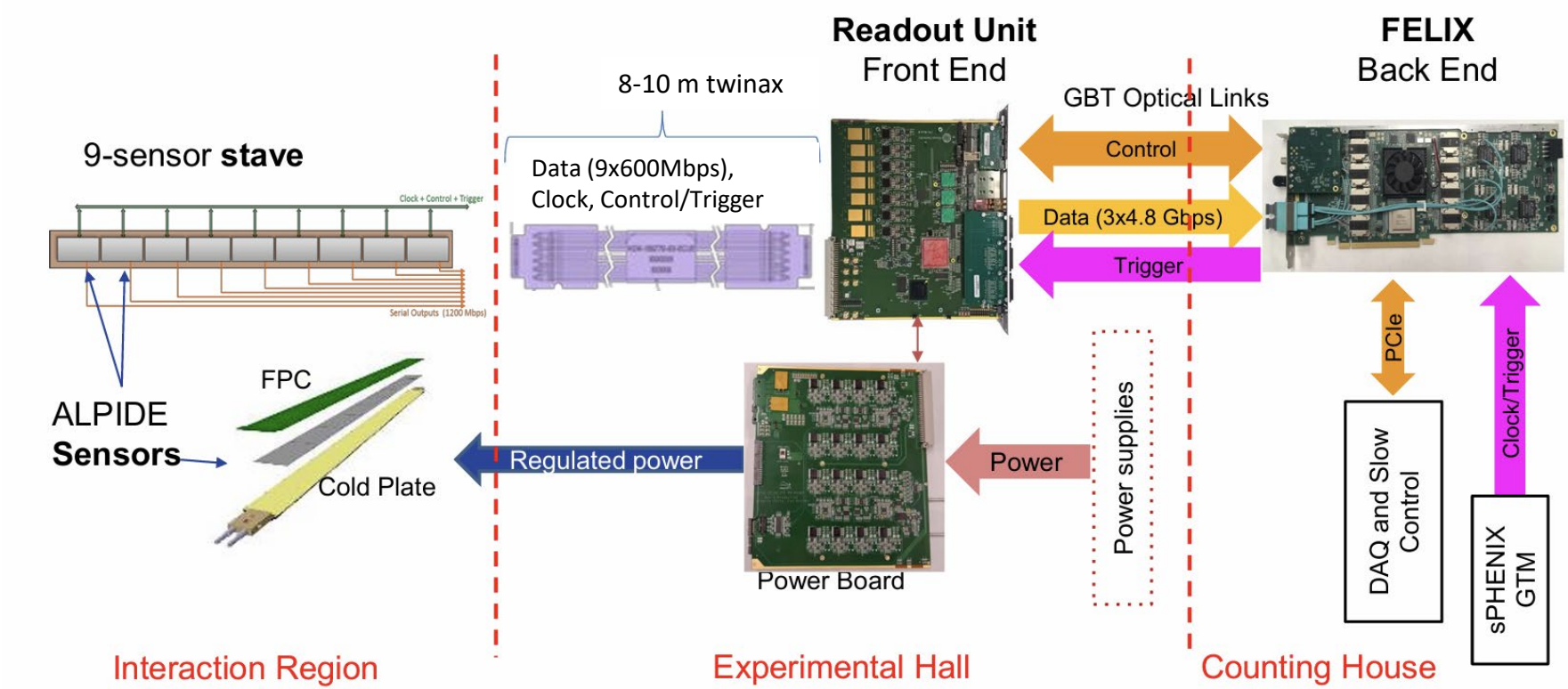








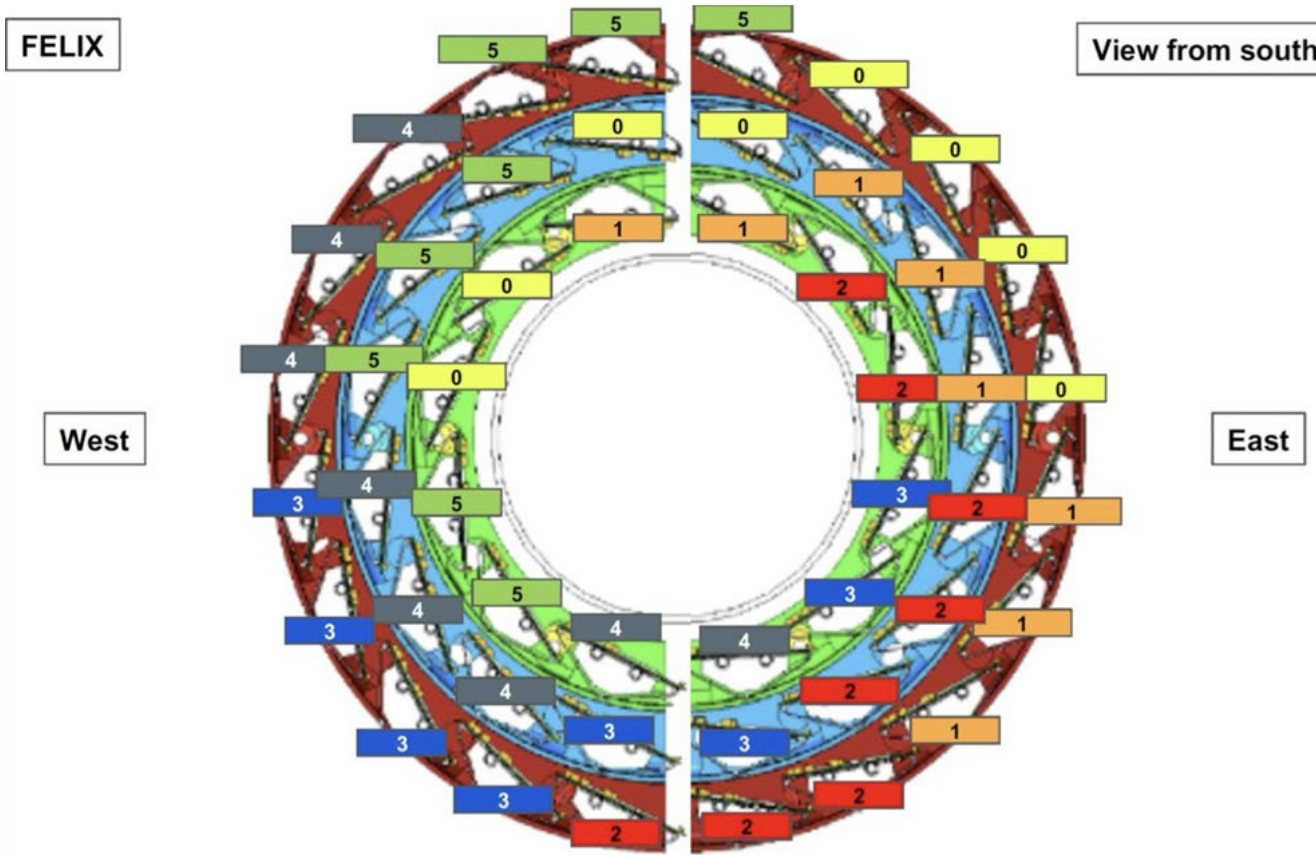
MVTX Readout Chain



- One Readout Unit (RU) per stave, one Power Board (PB) per 2 staves, and 8 RUs per FELIX
- Note: ALPIDE data lines in principle capable of 1.2Gb/s, but in practice signal degradation over twinax cable limits us to 600Mb/s data rate

FELIX Readout Interface

- PCIe card that receives optical communications from RUs and connects to downstream DAQ system
- Handles control, clock, trigger, and DAQ for RUs
  - Note on triggering: RU sends strobe triggers, FELIX sends heartbeat and “physics” triggers
- RUs allocated to FELIX modules such that one FELIX failing still leaves at least 2 hits on each track

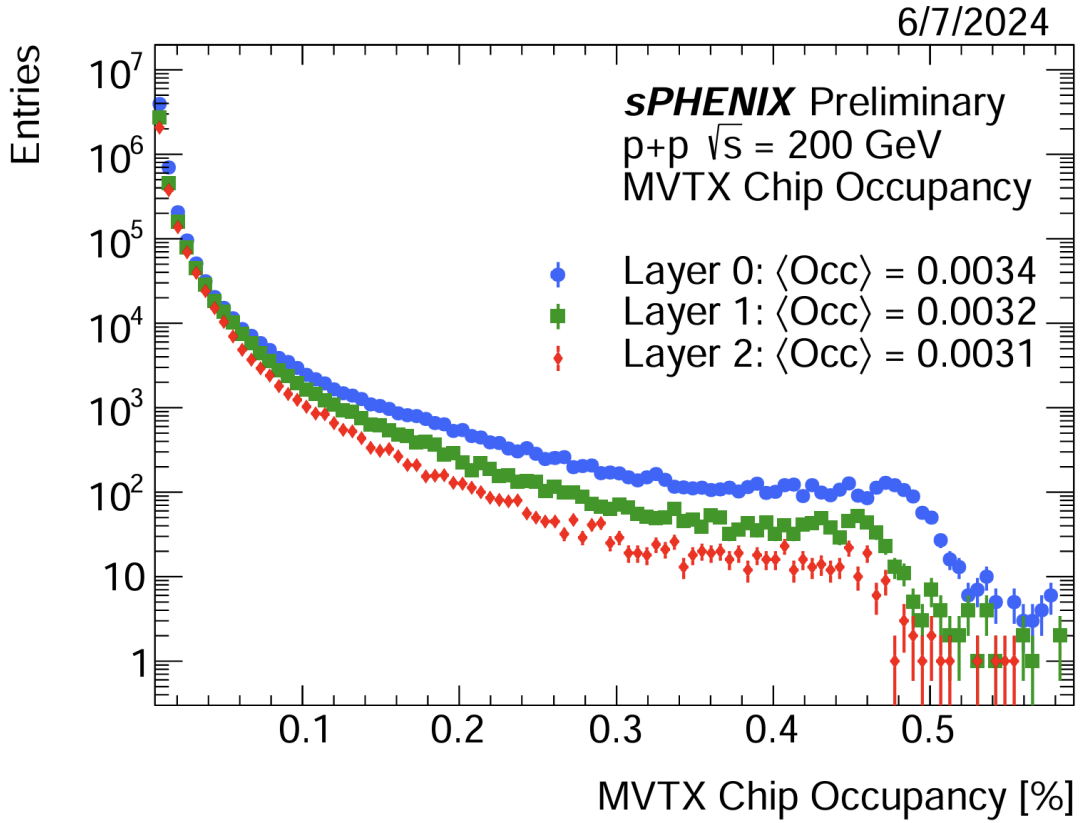


MVTX Control and DAQ Software

- Largely borrows from ALICE ITS2 software:
  - FELIX access and RU communication managed by ALICE-developed front-end software module
  - Command translation and automation managed by ITSCommLayer back-end software
  - Higher-level control functions and detector finite-state machine implemented in CERN-derived detector control system framework
- Major difference from ALICE: need to interface with FELIX
  - Wrapper library serves as interface between ALICE software and ATLAS-developed FELIX library

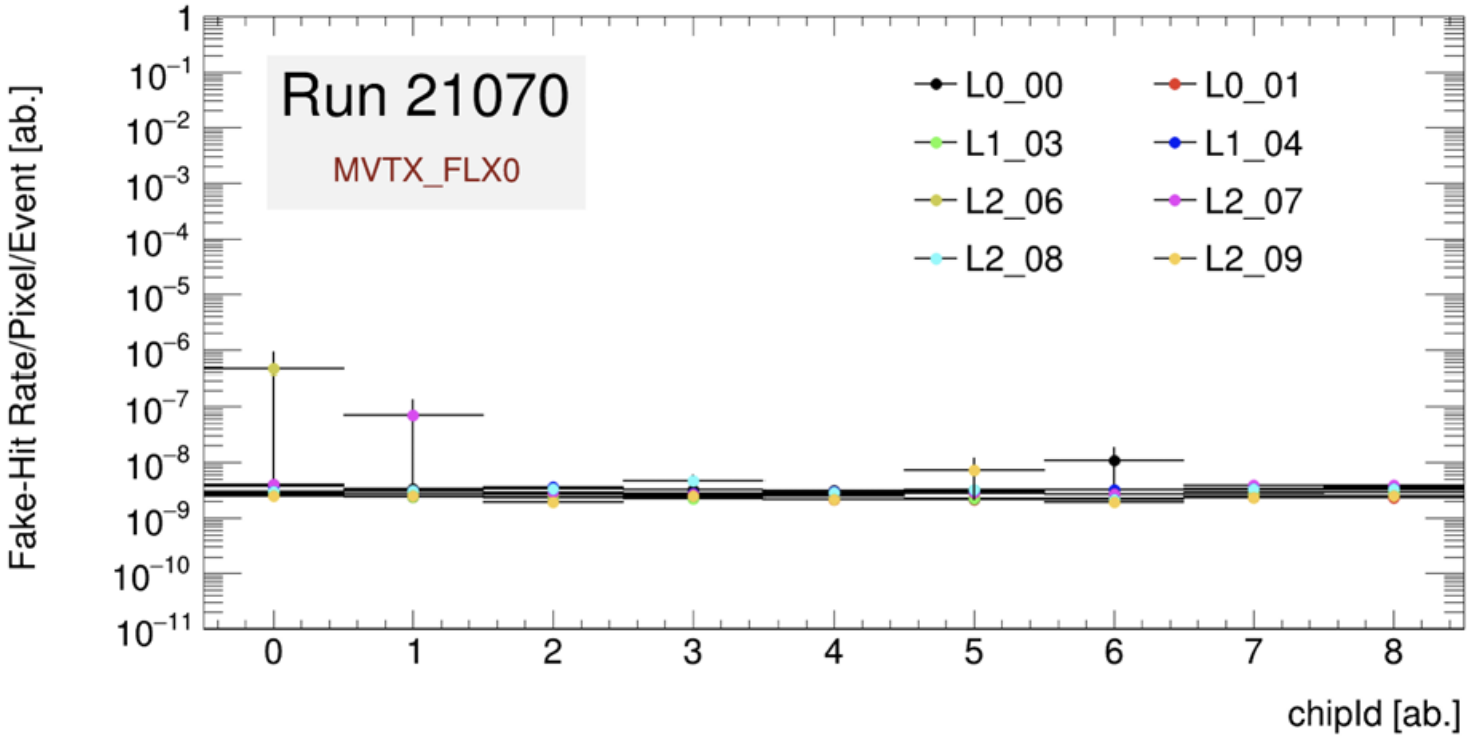
MVTX Performance: 200GeV pp Collisions, Summer 2024

Chip Occupancy Consistent with Expectations



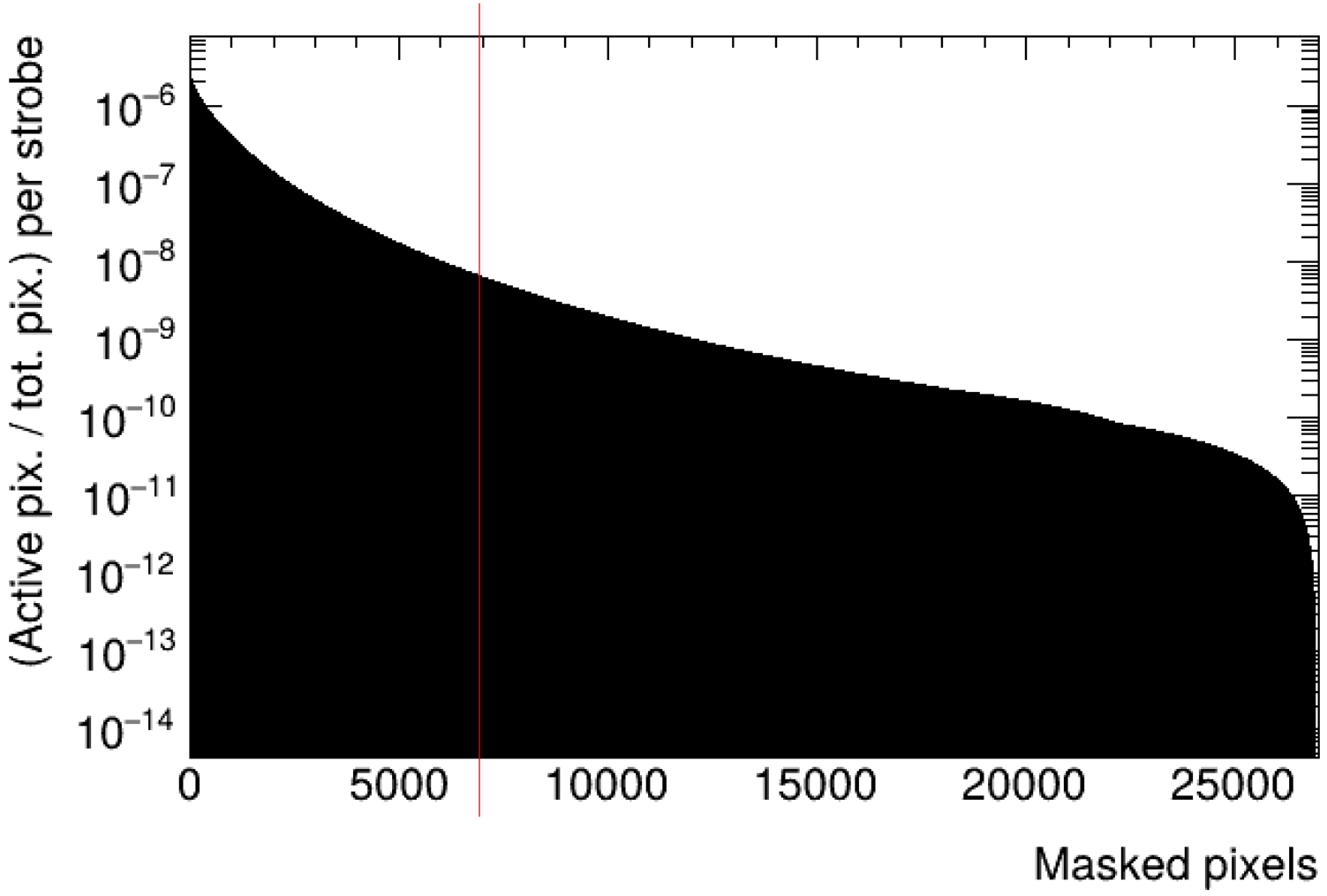
- Occupancy consistent with expectations for 100% streaming pp running

Low Fake Hit Rate



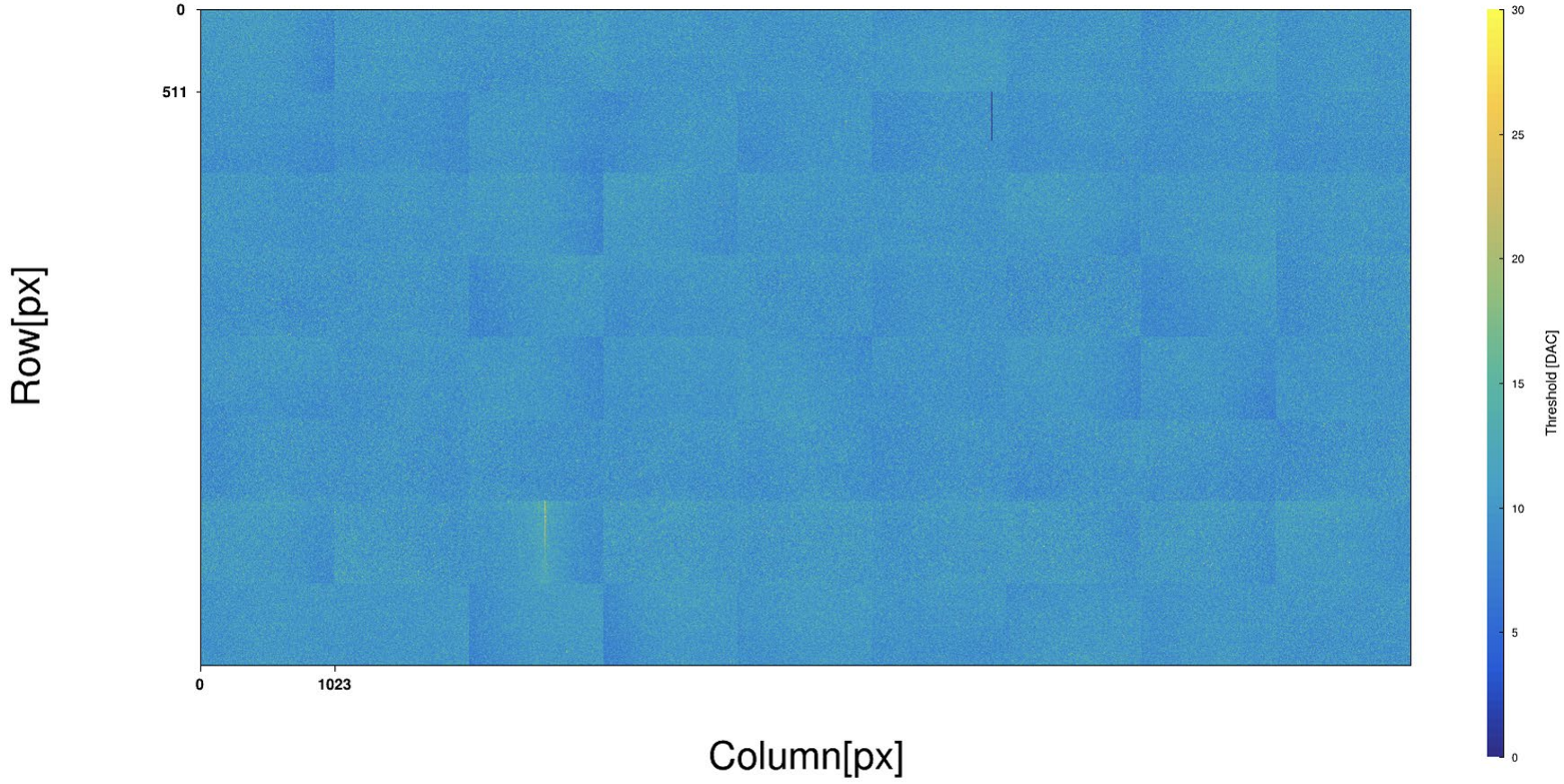
- Fake hit rate extremely low after masking hot pixels

Noisy Pixel Masking Effective and Minimally Invasive



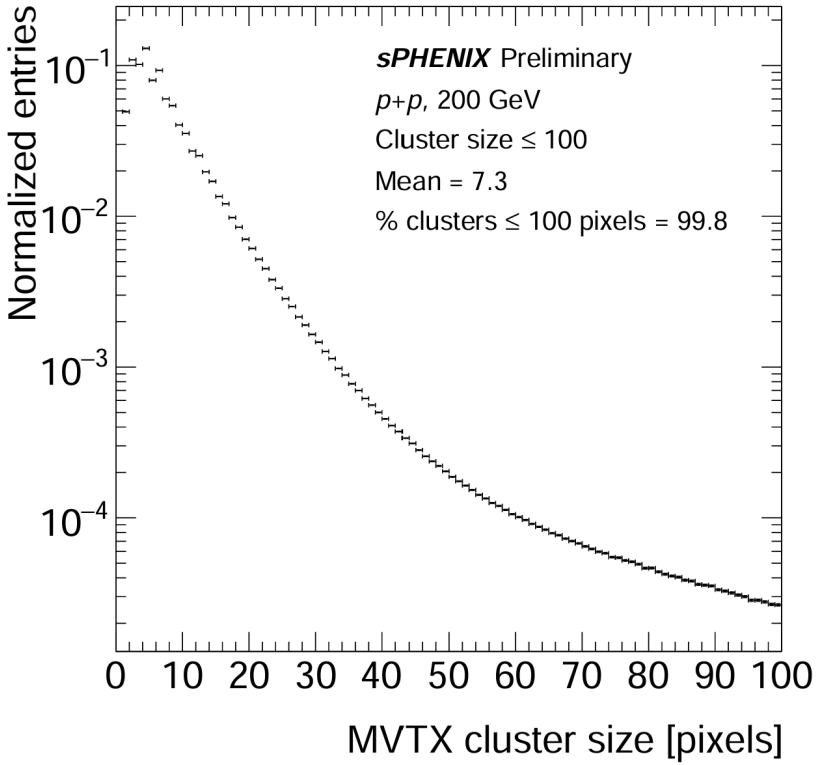
- Hot-channel masking reduces noise by orders of magnitude
- Very few noisy pixels (6958 masked out of 226 million = **0.003% of detector**)

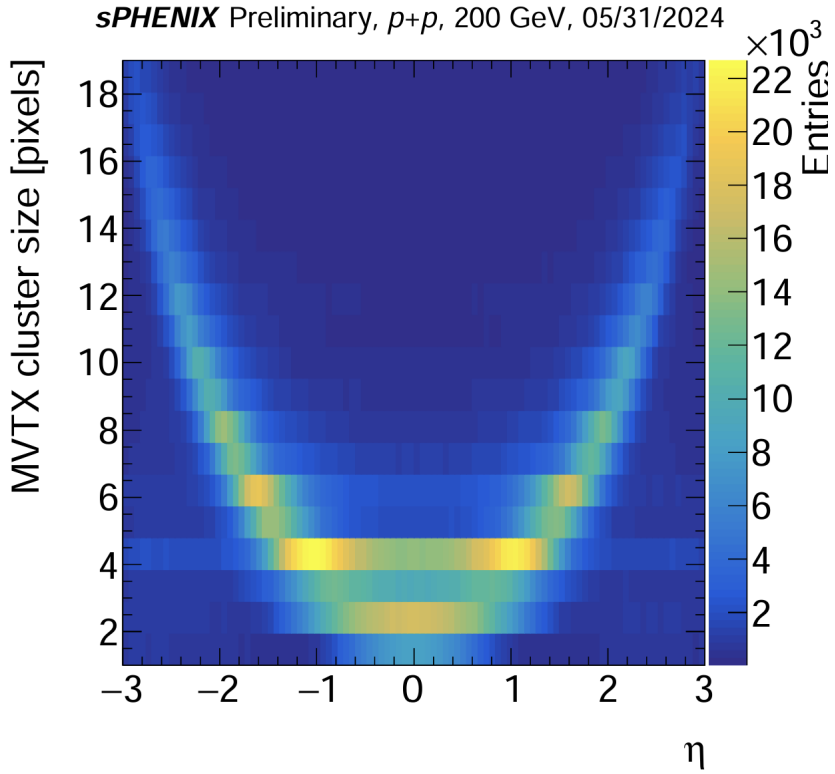
Comparator Threshold Map

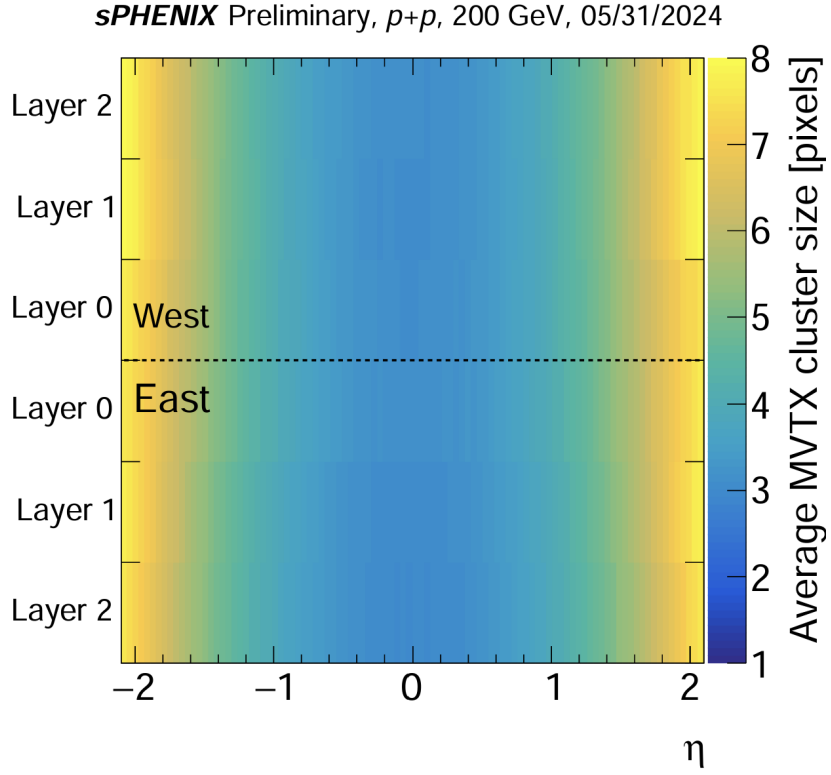


- After threshold tuning, **very uniform** comparator threshold, both within individual chips and across multiple chips

Clustering Studies

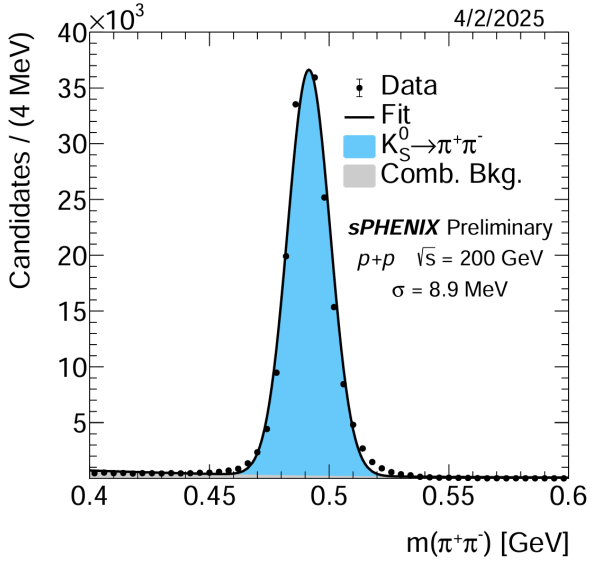


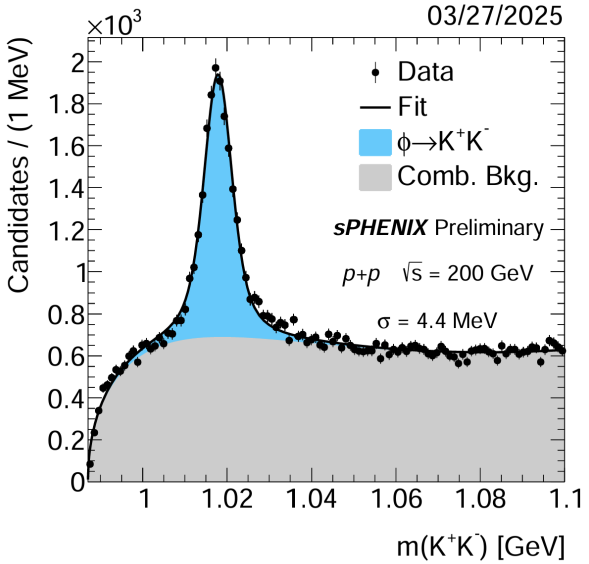


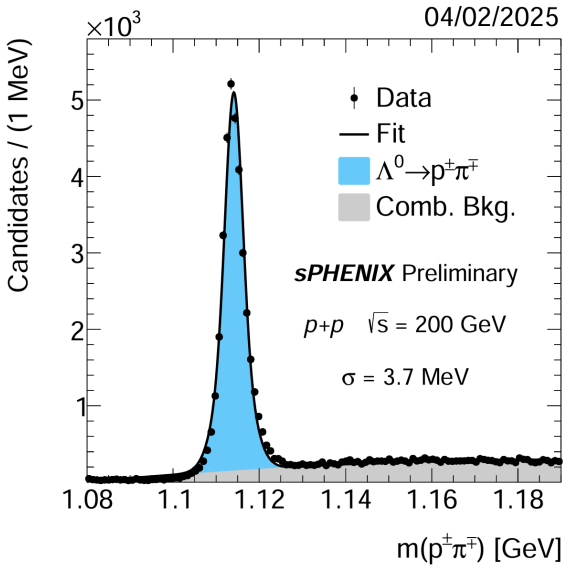


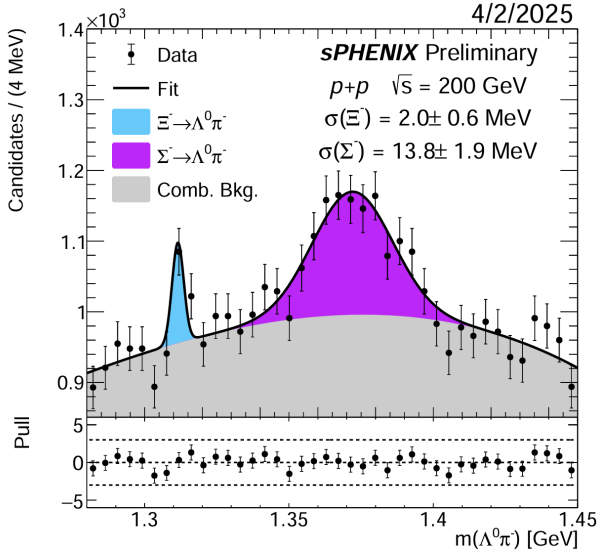
- Clustering algorithm based on connected components of adjacency graph

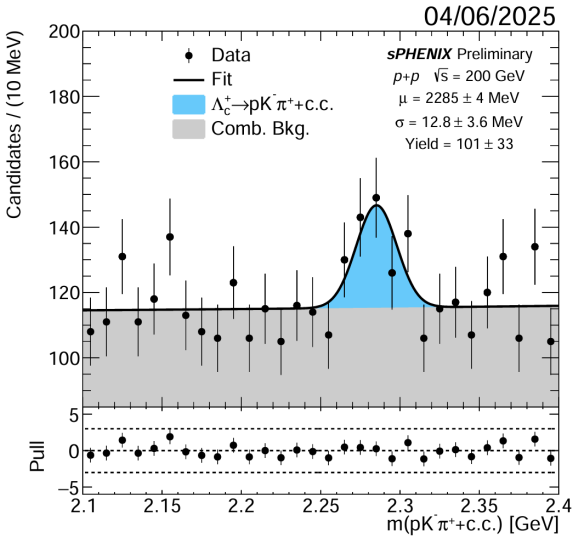
Decay Reconstruction in pp Collisions

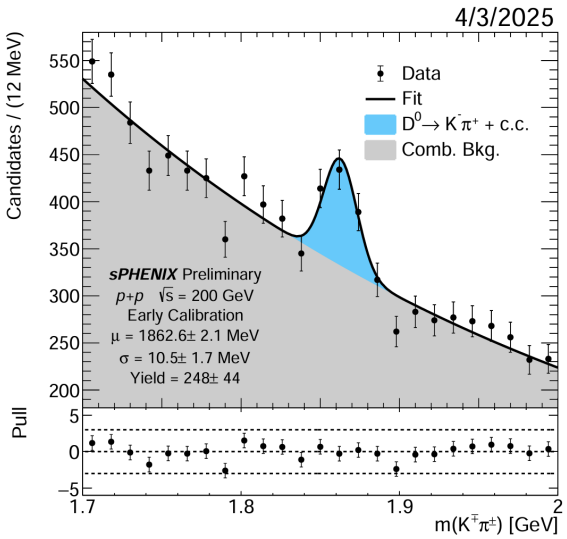




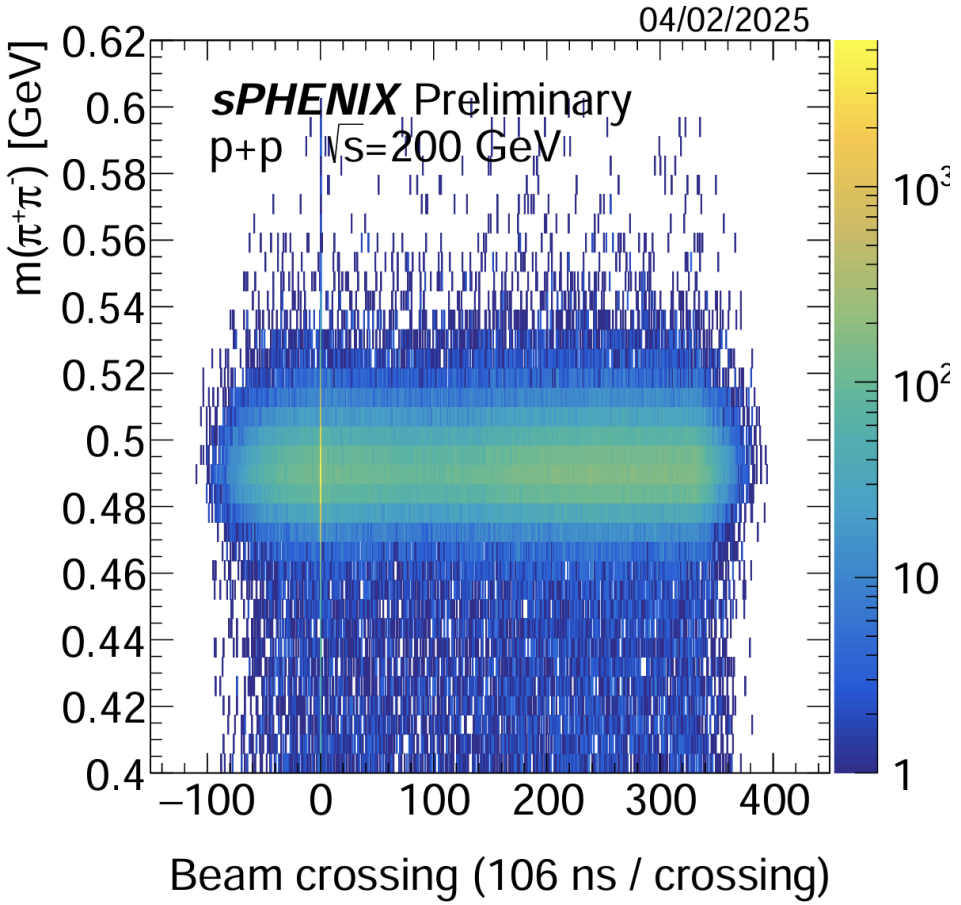








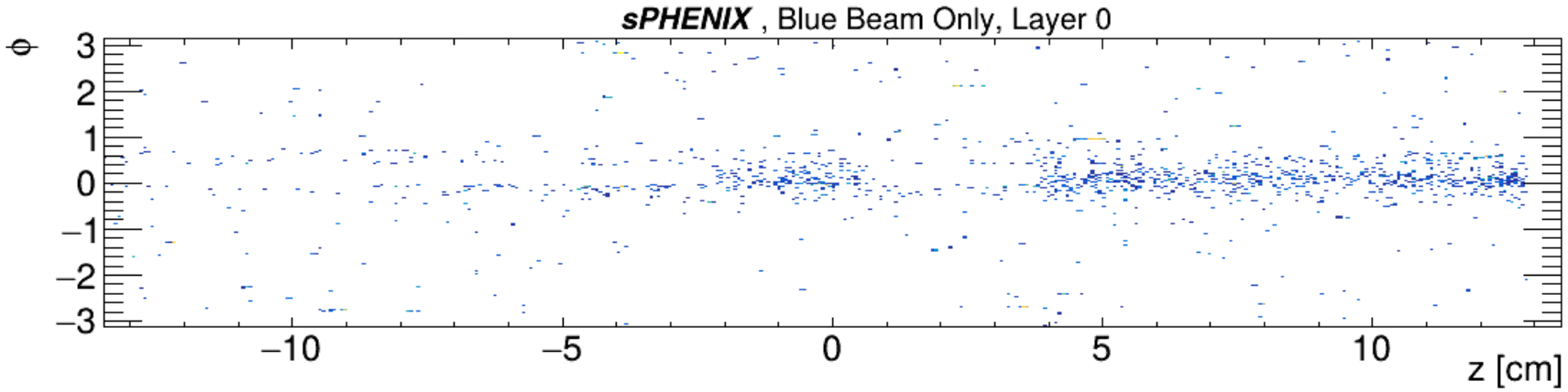
Successful Streaming-Readout Reconstruction

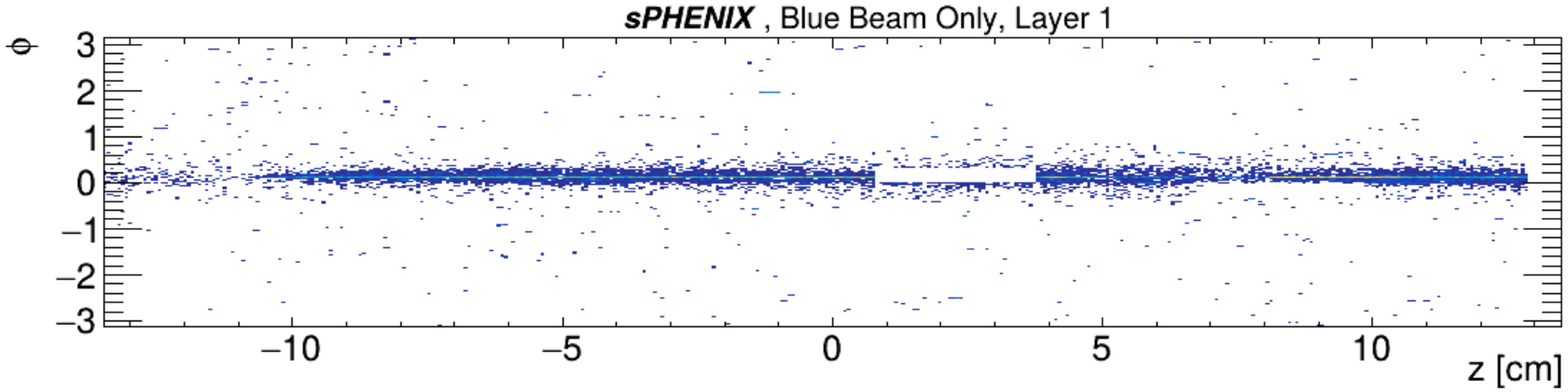


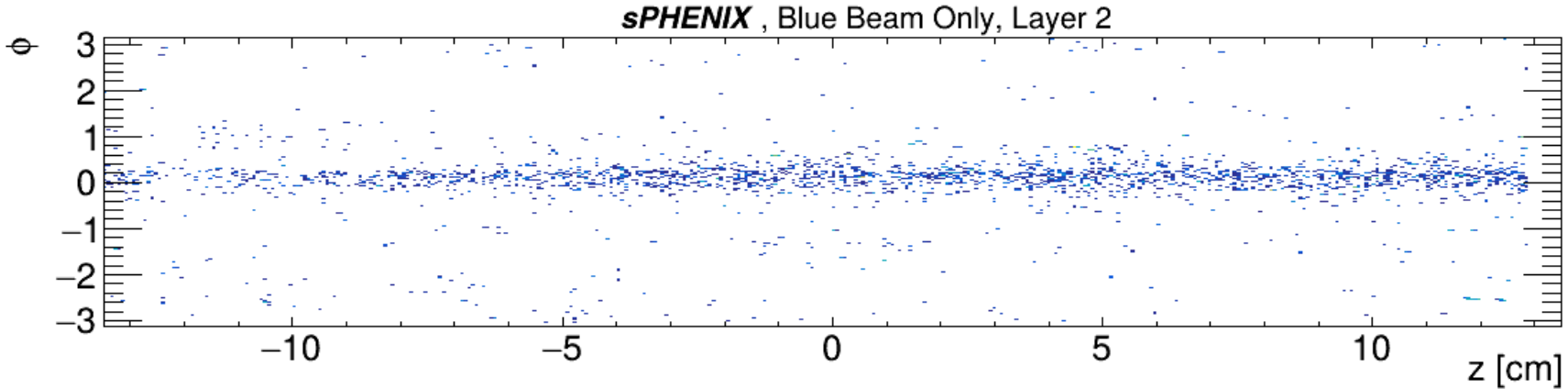
- K_S^0 mass peak consistent in height and placement across beam crossings – streaming readout works!

MVTX Performance: 200GeV/A AuAu Collisions, 2024 and 2025

Beam Background in AuAu







Consequences of Beam Background

- ALPIDE chips are zero-suppressed by construction; data volume is proportional to occupancy
- Large streaks cause huge occupancy, spiking data rate to RU
- RU gets overwhelmed, goes into timeout, no longer sends data
- ITSCommLayer restores operation by reconfiguring RU automatically (“autorecovery”)
  - One autorecovery takes about 12 seconds in total, from discovery of problem to restoration of operation
- Upshot: one of these incidents silences a stave for **multiple seconds at a time**
- Frequency of these incidents was initially found to be high enough to put some staves into constant autorecovery state (resulting in very little data from those staves)

Quantifying Impact of Beam Background

- Silencing a stave for several seconds -> no clusters from that stave -> certain tracks miss a layer of the MVTX
- Overall effect: a **phi-dependent, time-dependent loss in acceptance** for tracks requiring two or three MVTX clusters
- Acceptance loss can be quickly approximated:
  - Draw track-like lines/curves from center of MVTX outward in all directions
  - Find set of staves that intersect those “tracks”
  - Find fraction of those lines that don’t satisfy tracking cuts
- Acceptance plots automatically produced after each run

Mitigating Beam Background

- Three parallel strategies:
  - Accelerator configuration changes
  - Additional detector hardware to measure and mitigate background
  - MVTX configuration changes

Mitigating Beam Background

- Accelerator configuration changes:
  - Over 100 configurations tested, in later 2024 and early 2025 running
  - Scans over crossing angle, global orbit radius change, octupole magnet current, beamspot position, etc.
  - Eventually found collimator in incorrect location; repositioning this helped make background rates in 2025 lower than in 2024 AuAu

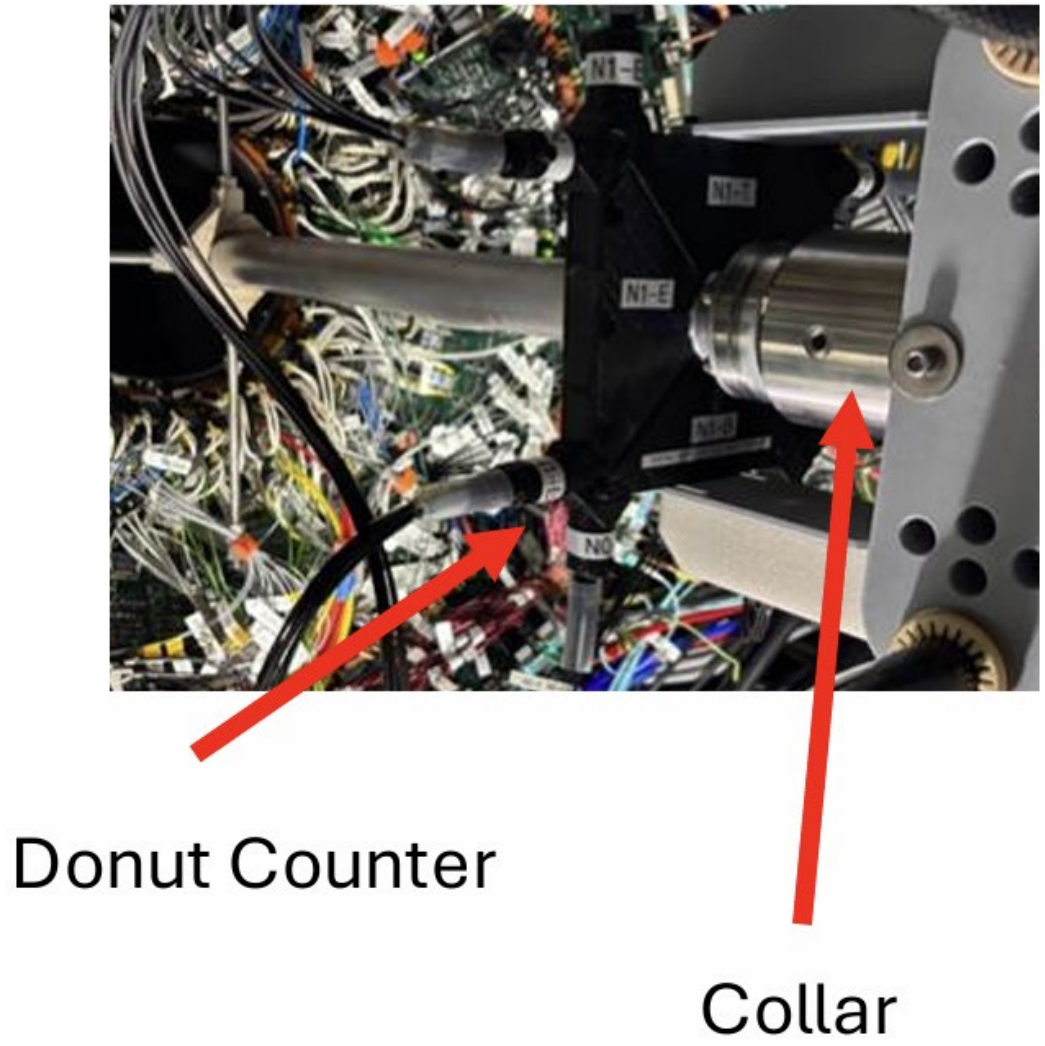
Task Force Findings and Actions

- Backgrounds result of a two part mechanism:
  - high amplitude particles strikes limiting aperture
  - secondary beam generated and strikes MVTX.
- Diagnostics added at each of the beampipe tapers (12.7→7.6 cm and 7.6→5.4 cm)
- The sector 8 yellow mask was determined as a potential source, ∼50 m upstream of IP8.
  - Tracking showed particles over a large energy range could strike the MVTX from this origin.
- The blue mask was moved into the yellow ring at IP4 to provide additional collimation.
- Gamma quads in sector 4 had added supplies to produce a dispersion bump at the new mask to remove high momentum particles.
- ”Collar” absorbers designed to be installed between last taper and MVTX to provide additional shielding.

Source: BNL C-AD 10

Mitigating Beam Background

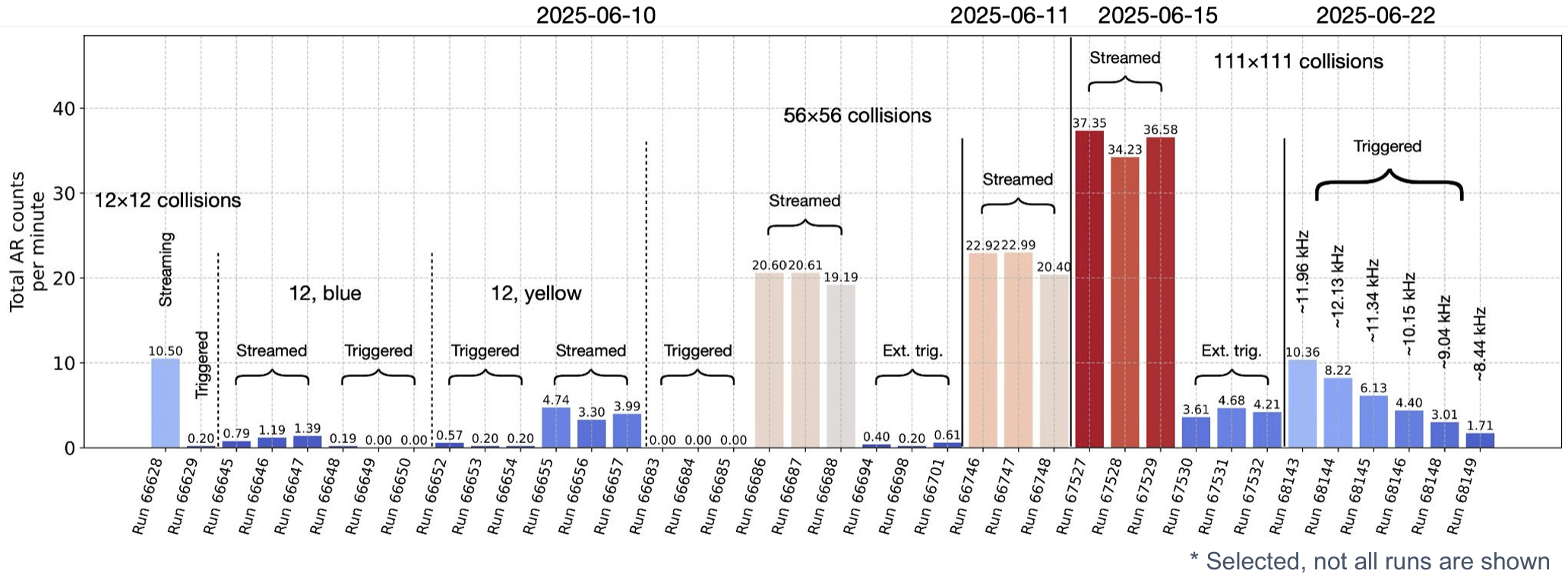
- Additional detector hardware to measure and mitigate background:
  - “Donut” scintillators around beampipe for fast beam background feedback to accelerator main control room
  - Steel collar surrounding beampipe was prepared in case additional absorption would have been helpful
    - So far, has not been installed



Mitigating Beam Background

- MVTX configuration changes tested:
  - Threshold changes: 100e -> 250e
  - RU firmware modifications
    - Allow larger maximum timeout length
    - Allow trigger throttling
  - Changes to run mode:
    - Streaming: 9.8μs strobe window with 100ns gap (which is covered by pixel signal duration of 6μs), sees 100% of firing pixels
    - Triggered: 100ns strobe window on trigger, only sees firing pixels whose 6μs signal duration overlaps with strobe
    - Extended: like triggered, but with longer strobe window (typically 10μs)

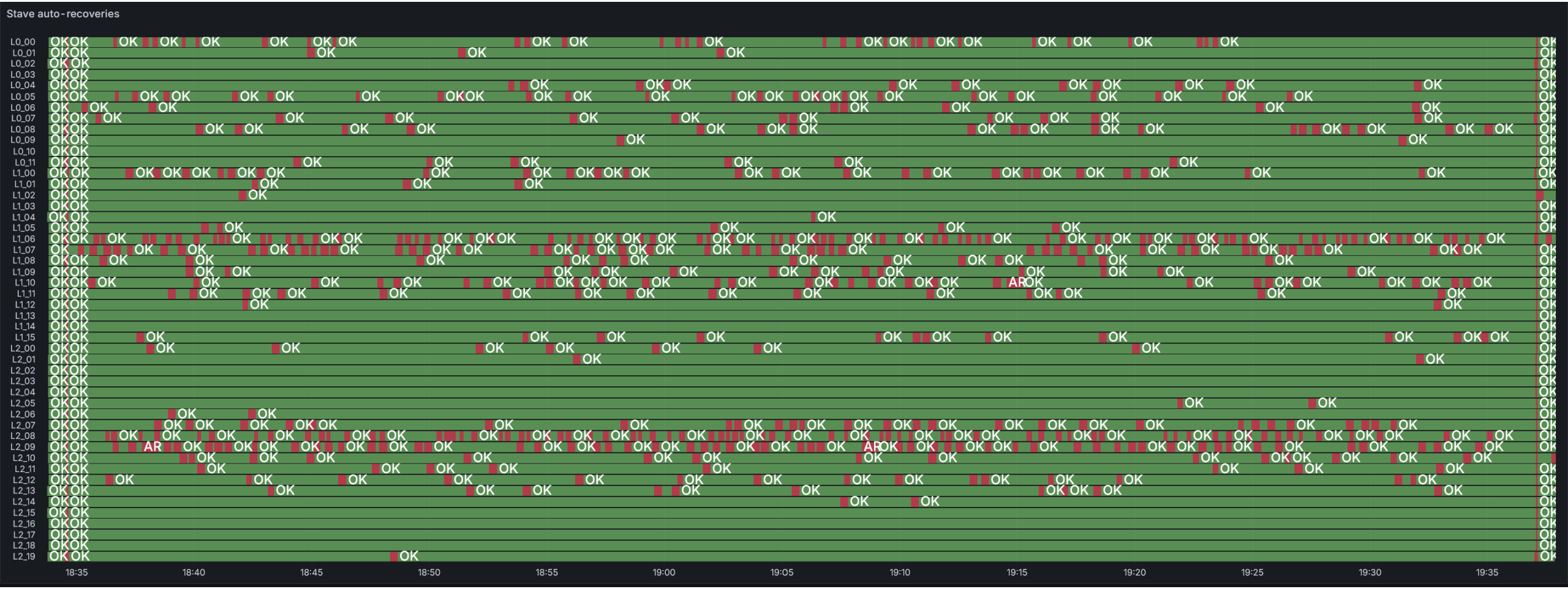
Beam Background Studies



* Selected, not all runs are shown

- Large difference in autorecovery frequency between streamed and triggered mode

Example Autorecovery Timeline



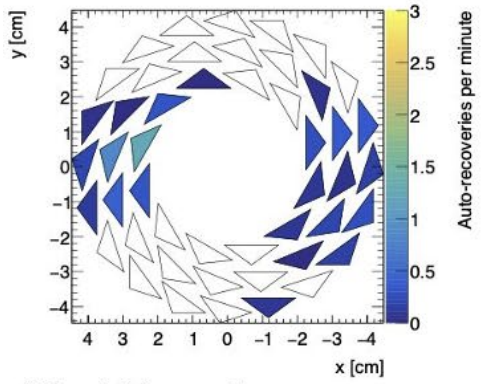
- Typical 1-hour run (from yesterday evening)

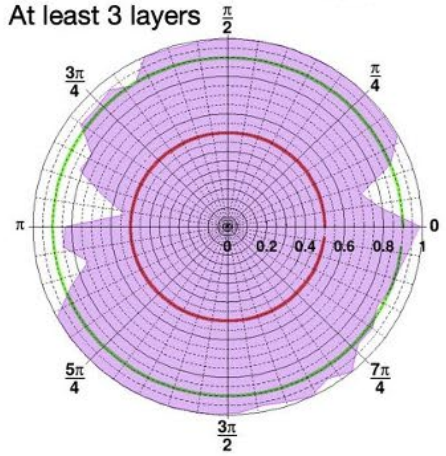
Example Acceptance Losses, 3 MVTX Layer Cut

111x111 collisions

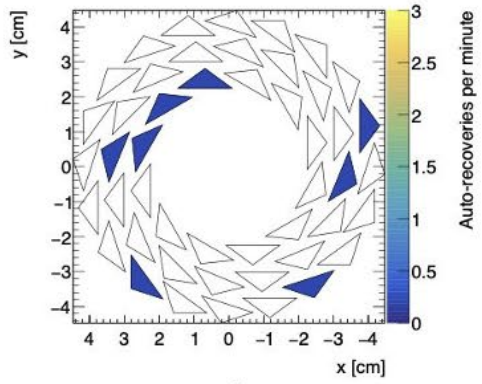
June 16th; **Triggered mode**

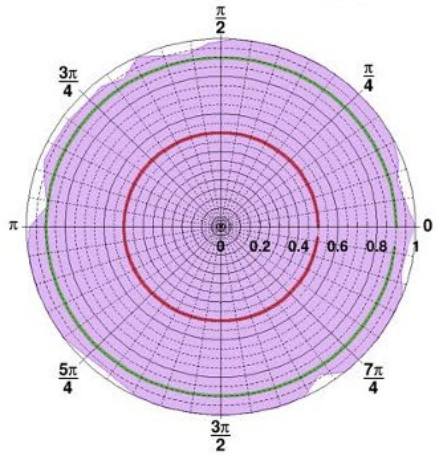
67568 (trig. rate 7.7~11.7kHz)



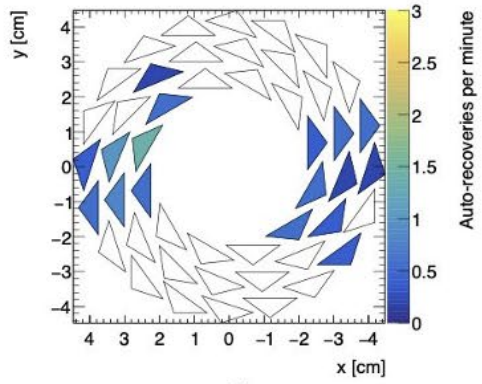


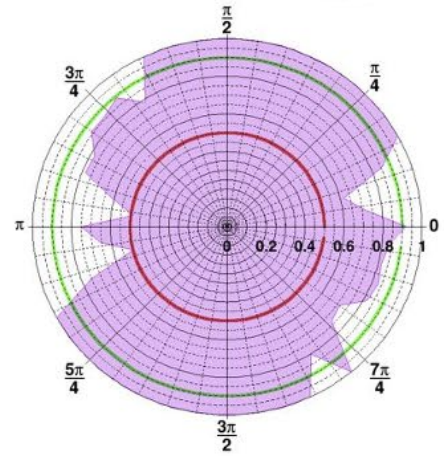
67581 (trig. rate 6.6~6.9kHz)



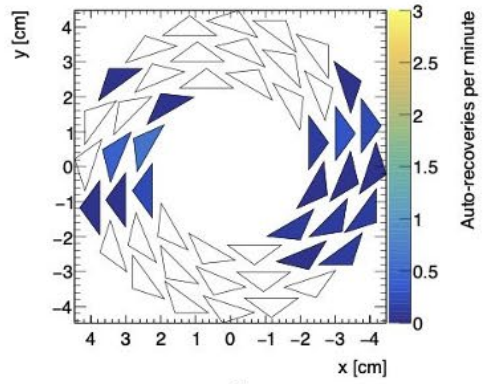


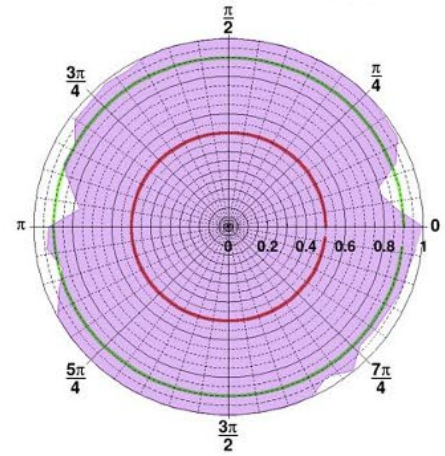
67583 (trig. rate 13.1~14.3kHz)





67587 (trig. rate 7.5~8.7kHz)



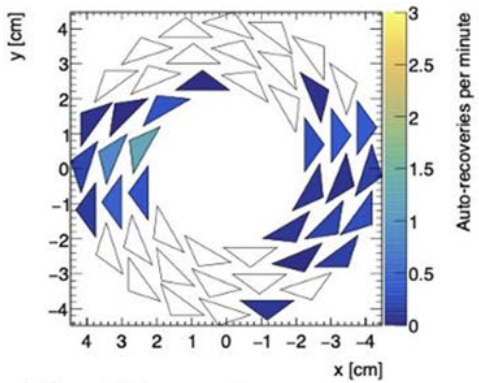


Example Acceptance Losses, 2 MVTX Layer Cut

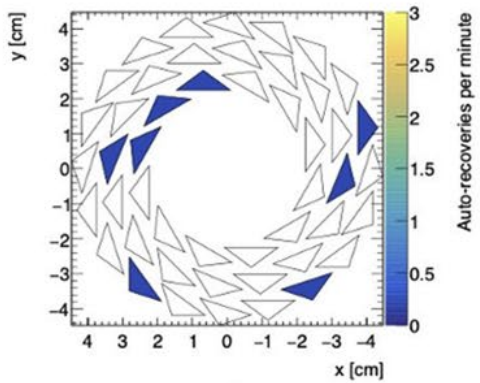
111x111 collisions

June 16th; **Triggered mode**

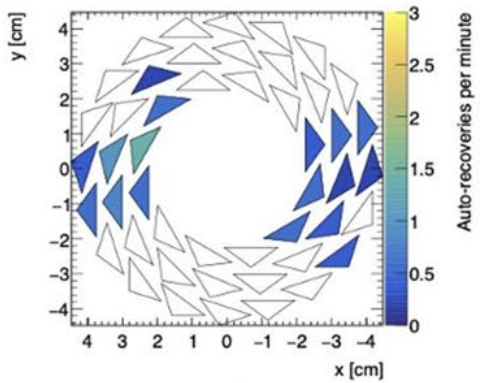
67568 (trig. rate 7.7~11.7kHz)



67581 (trig. rate 6.6~6.9kHz)



67583 (trig. rate 13.1~14.3kHz)



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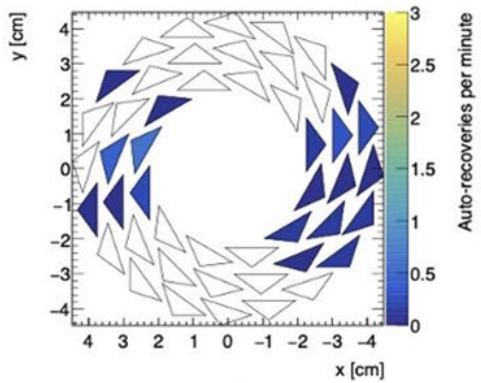
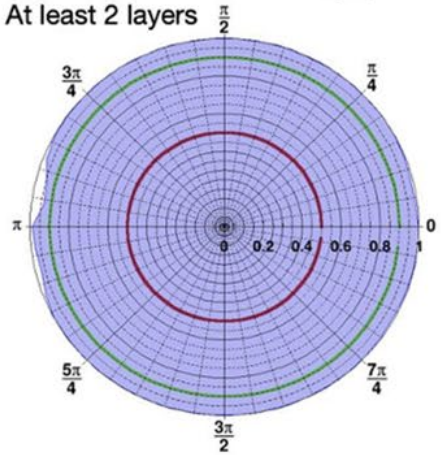
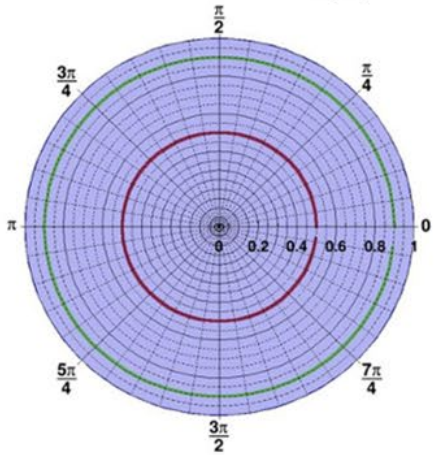
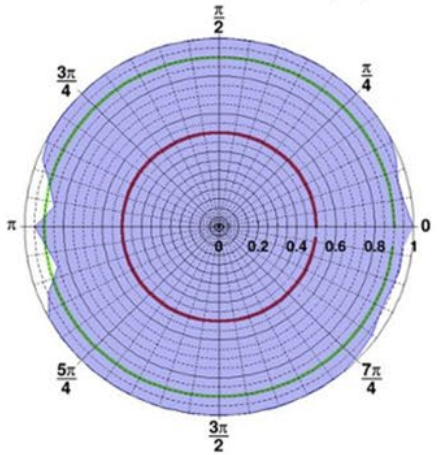
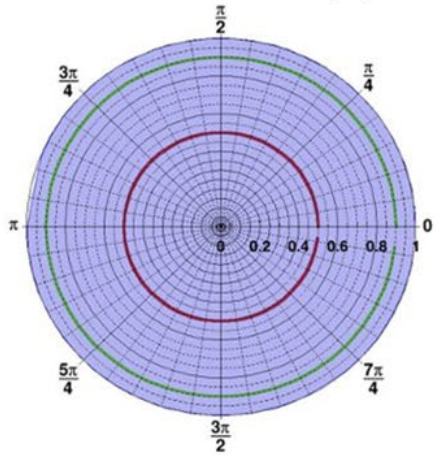


At least 2 layers

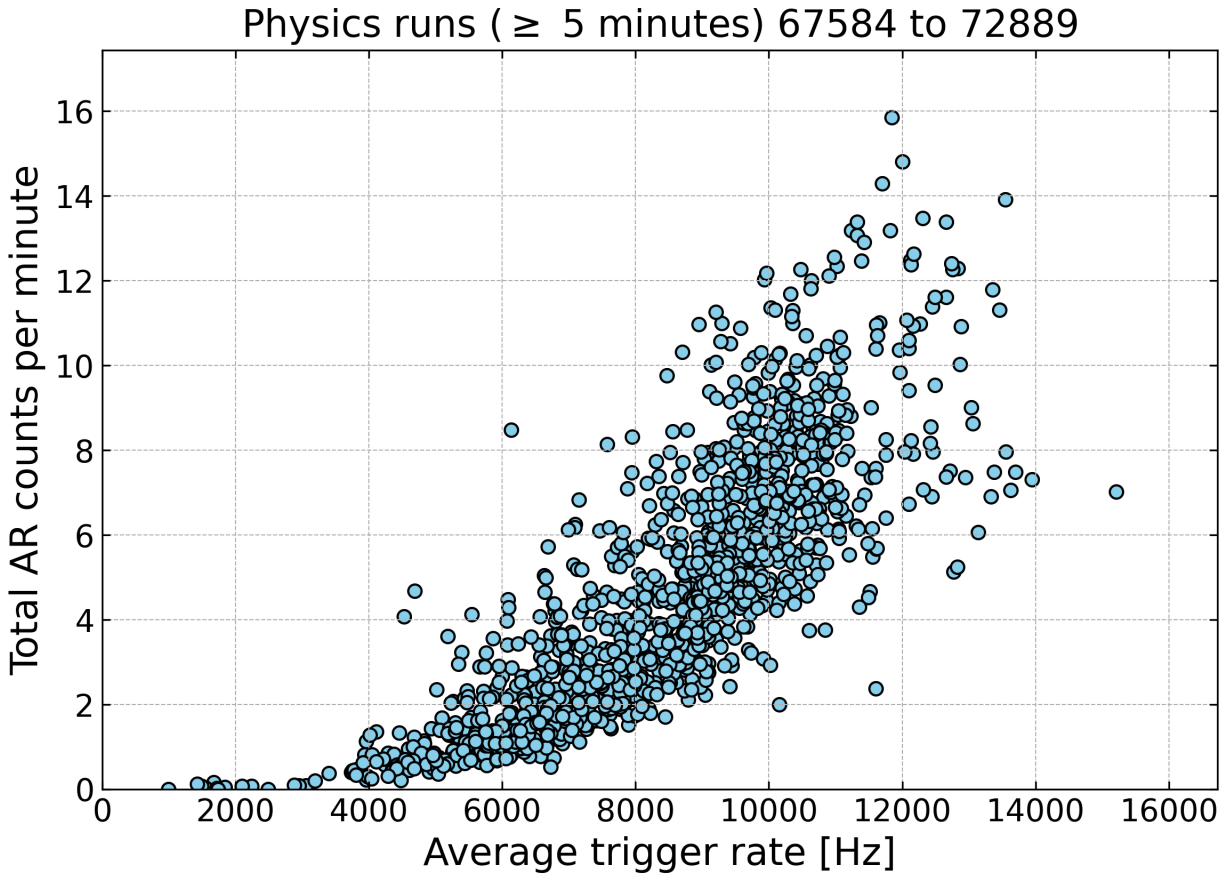


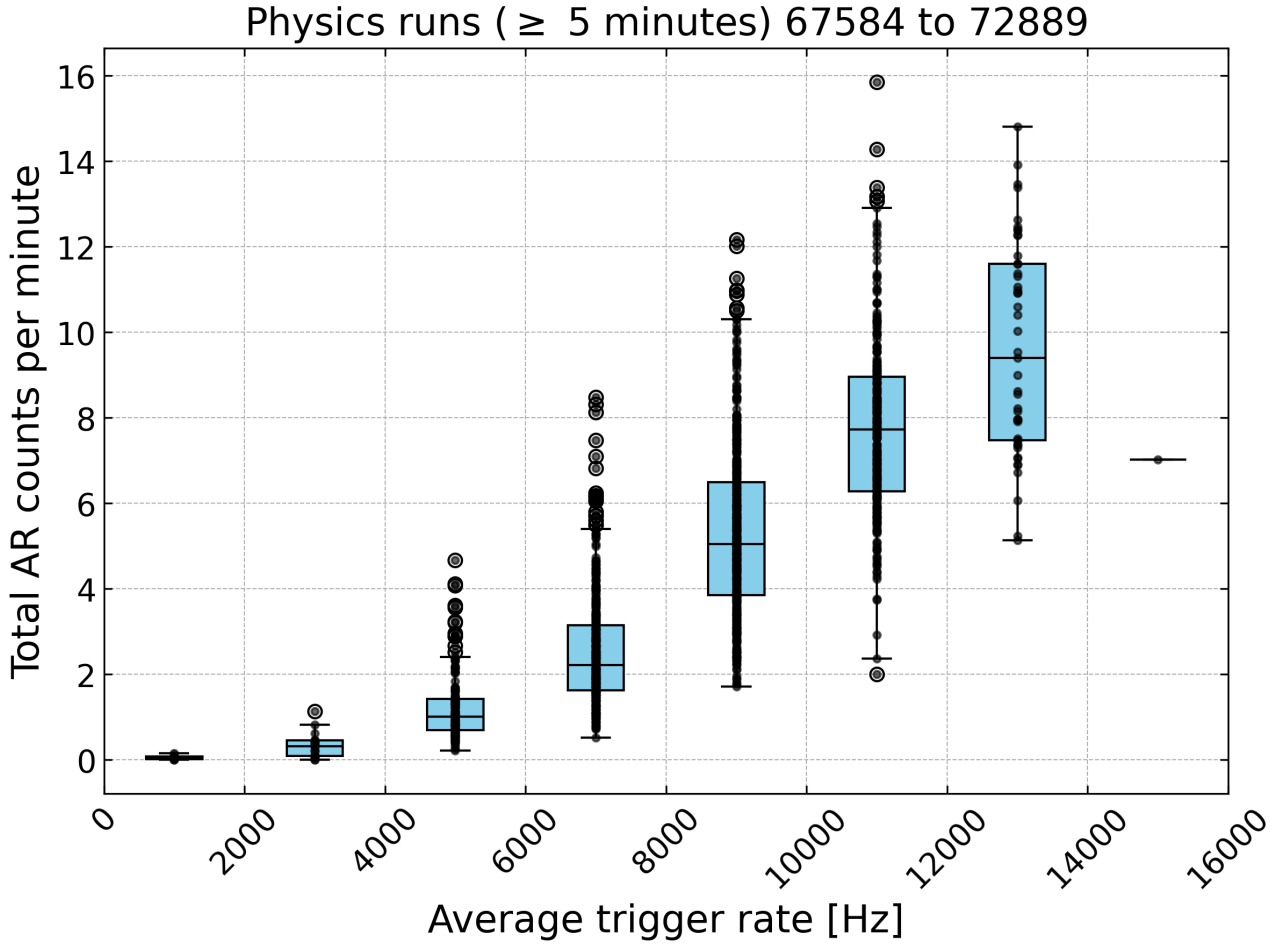






Autorecovery Rate vs. Trigger Rate

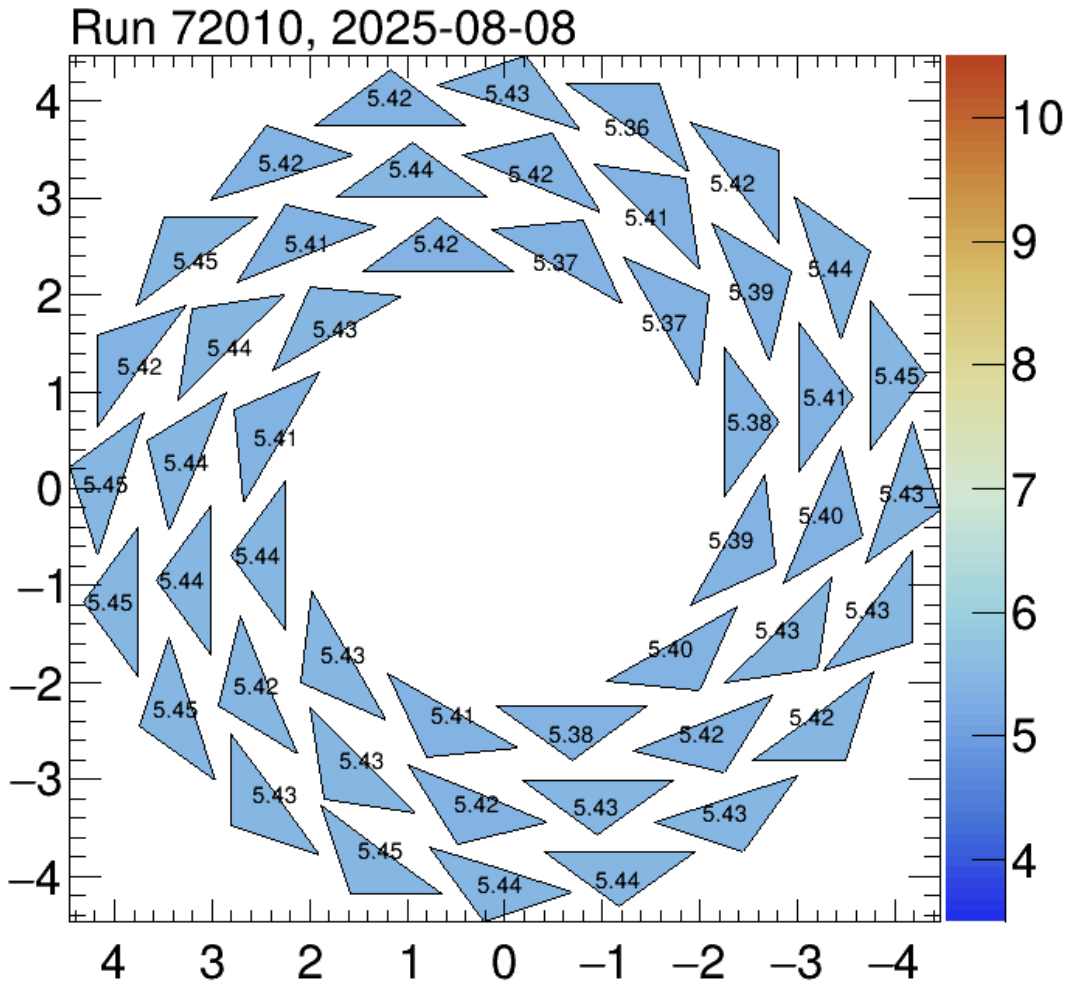


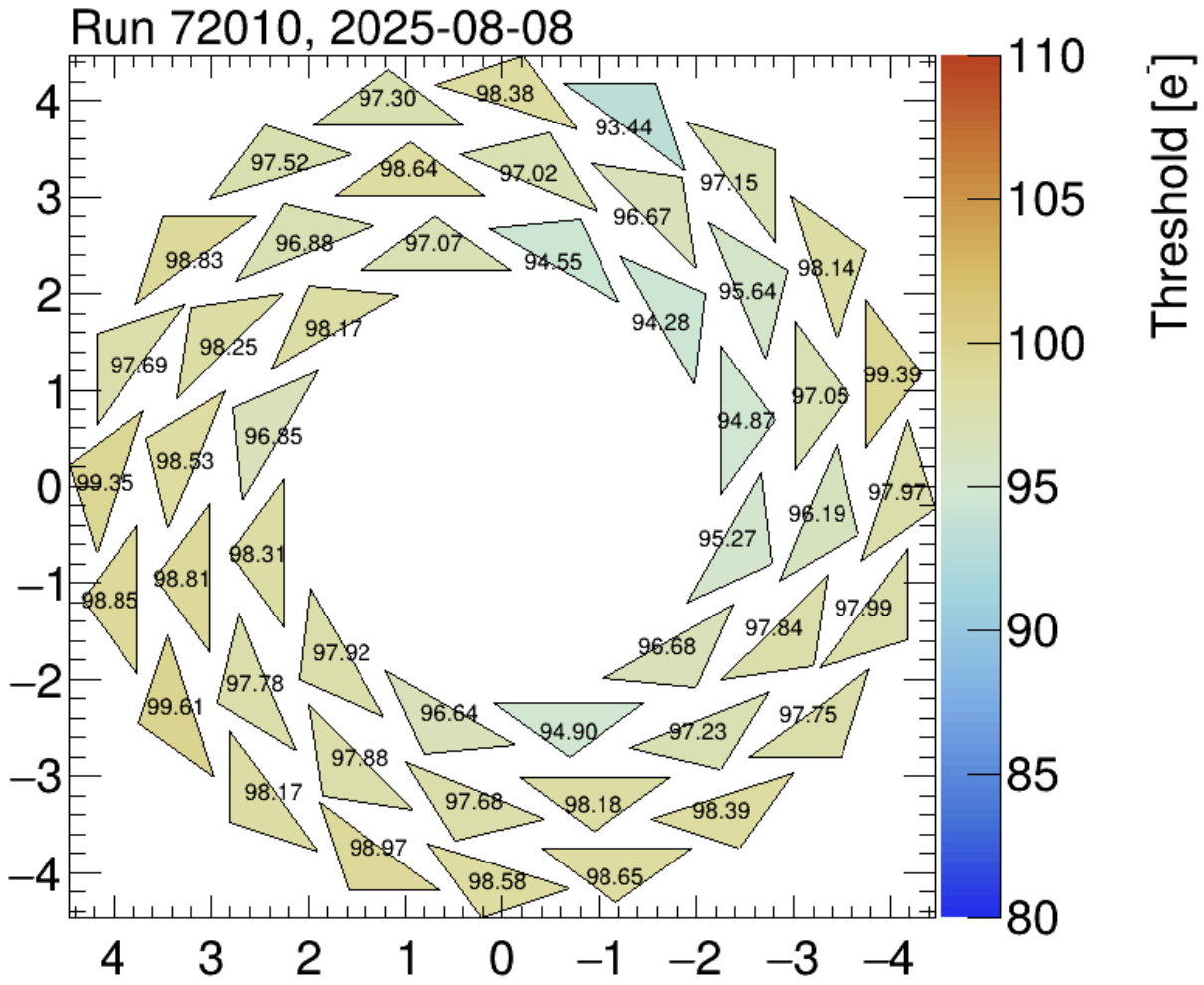


Background Studies Summary

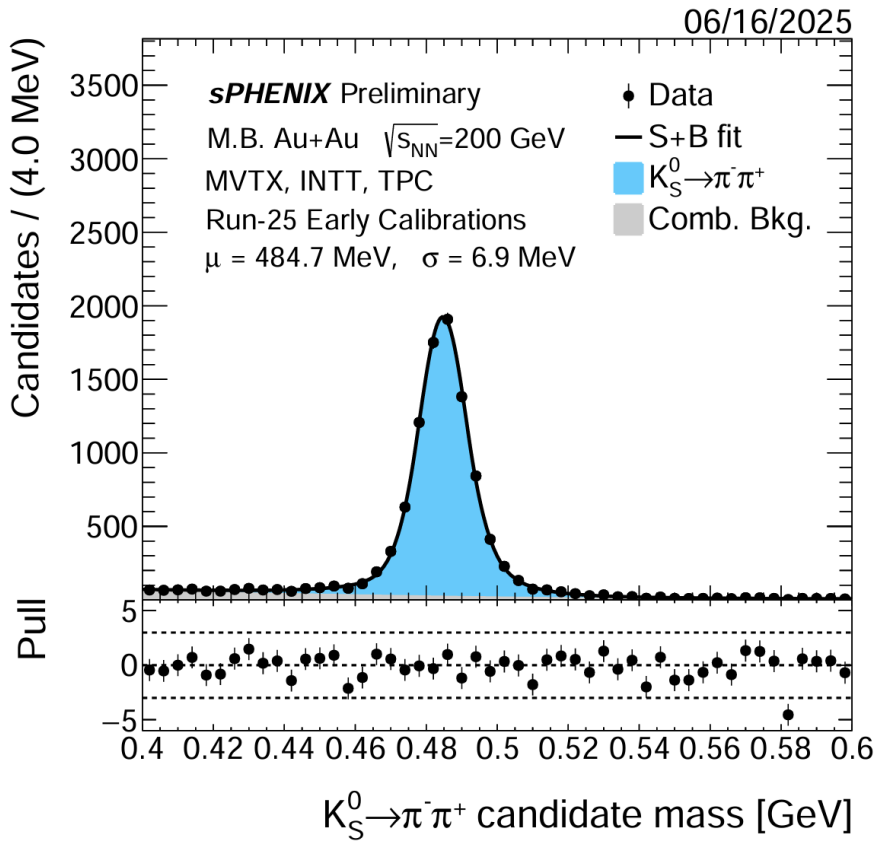
- Not possible to run in streaming mode in AuAu collisions at RHIC – even in optimal accelerator configuration, beam background rate still simply too high
- Triggered mode allows us to reach an acceptable rate of acceptance loss

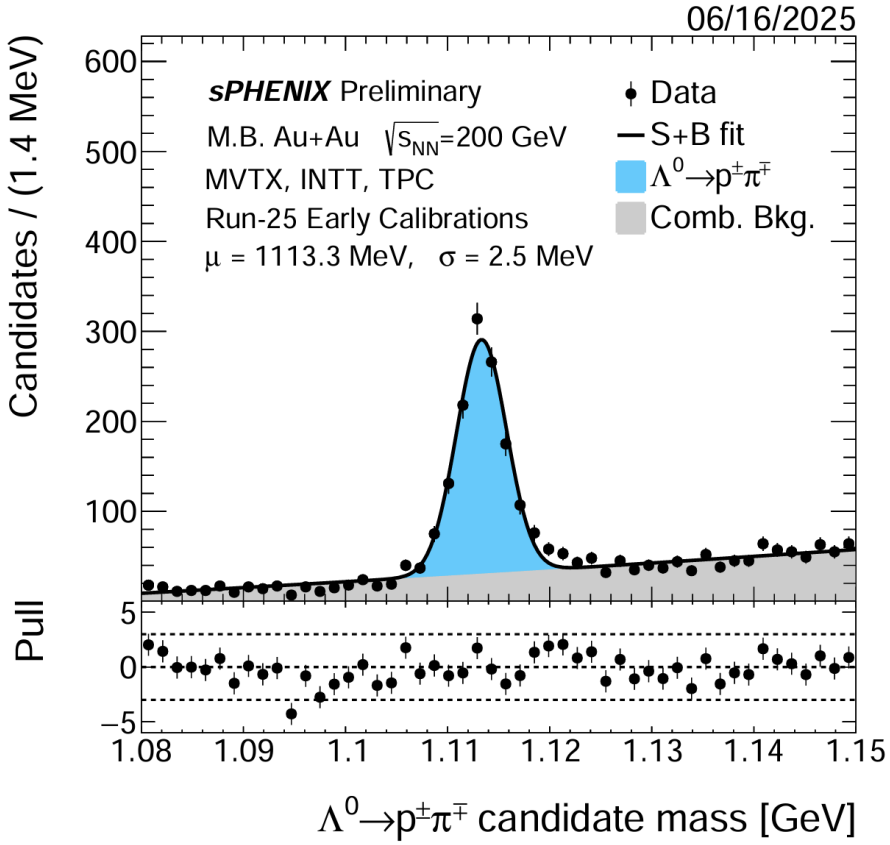
AuAu Temporal Noise and Threshold





AuAu Decay Reconstruction

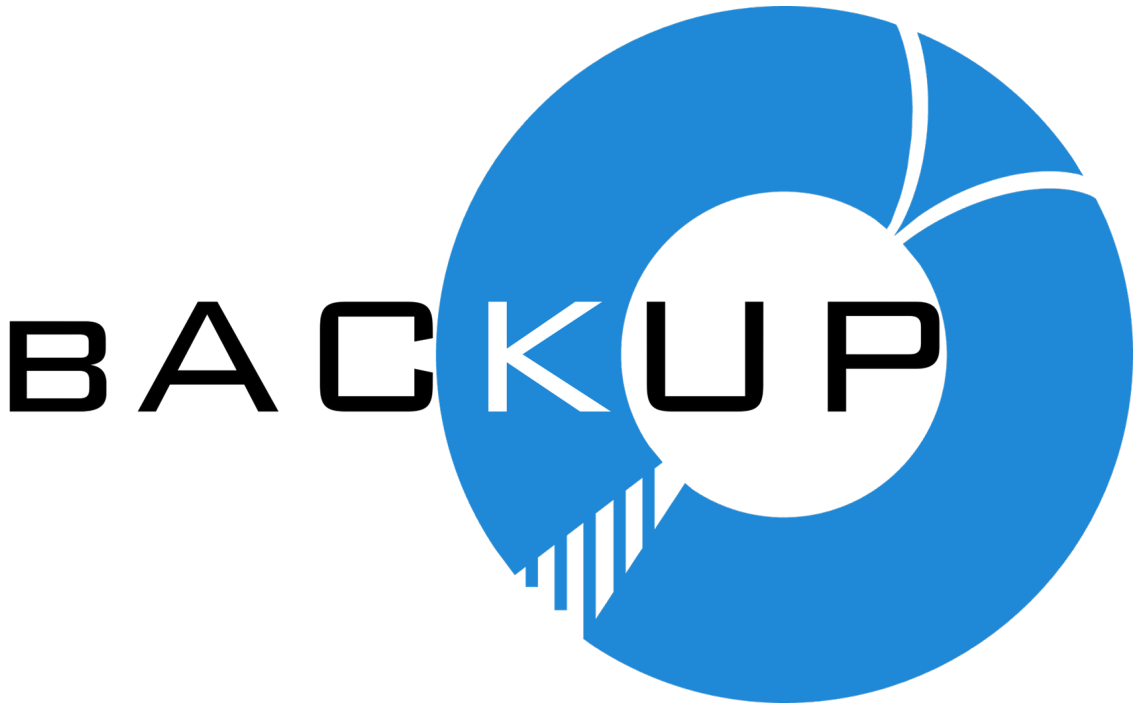




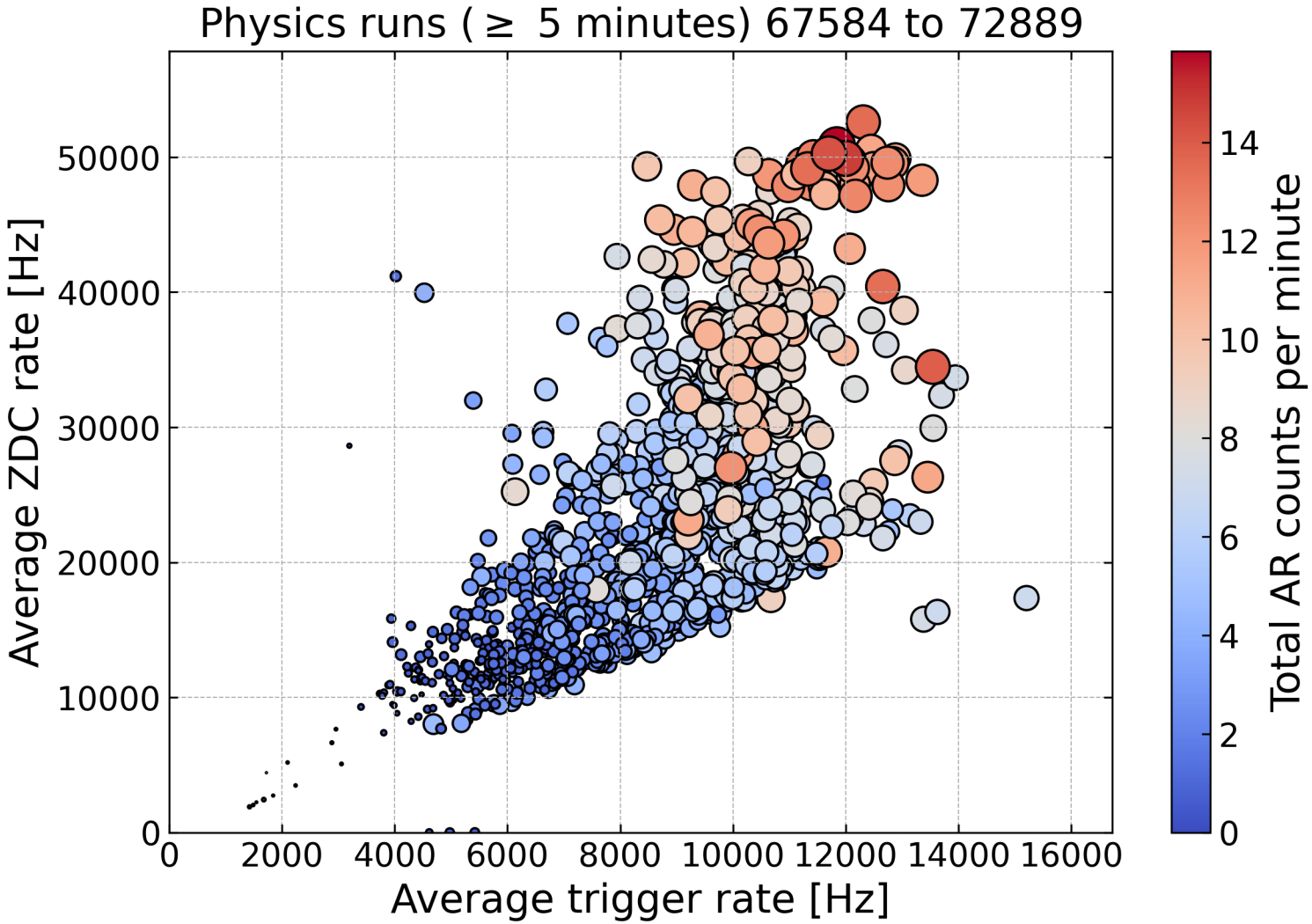
- Very preliminary results – more to come!

Summary

- sPHENIX MAPS vertex detector has operated for 2 years taking high-precision tracking data
- Pointing resolution from detector already instrumental in decay reconstruction and general tracking performance
- Challenges from beam background in AuAu running mitigated with a combination of accelerator configuration changes and a move to triggered mode
- Looking forward to smooth operation for the remainder of sPHENIX experimental program!

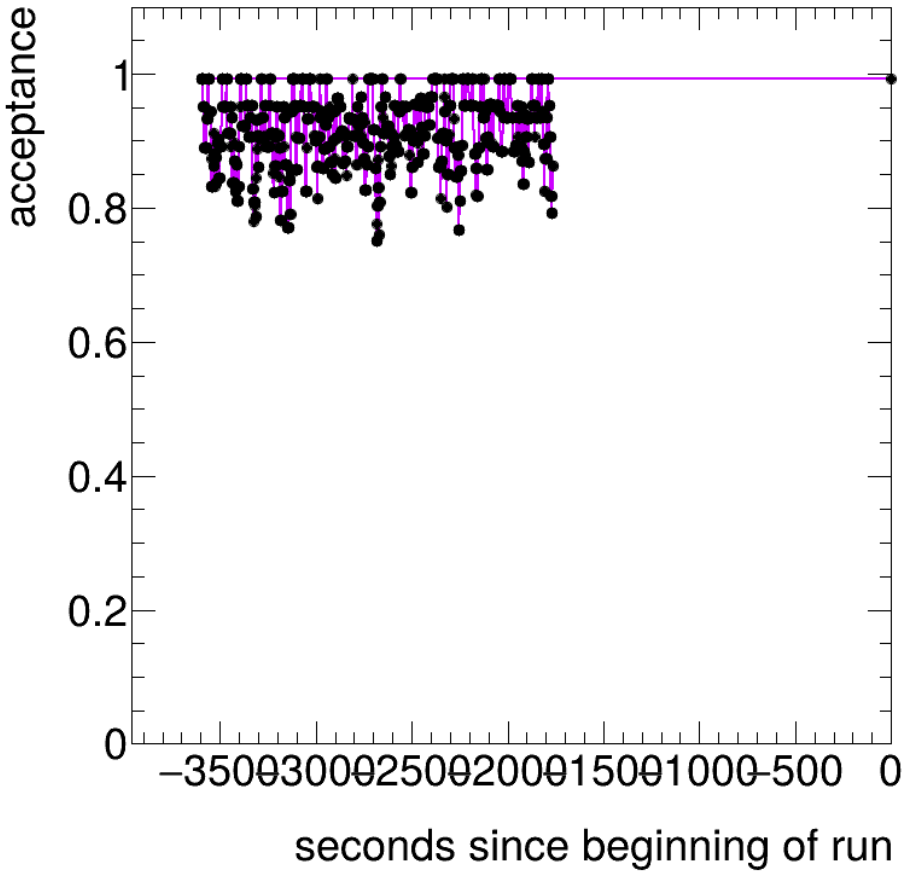

BACKUP

Autorecovery Rate vs. ZDC, Trigger

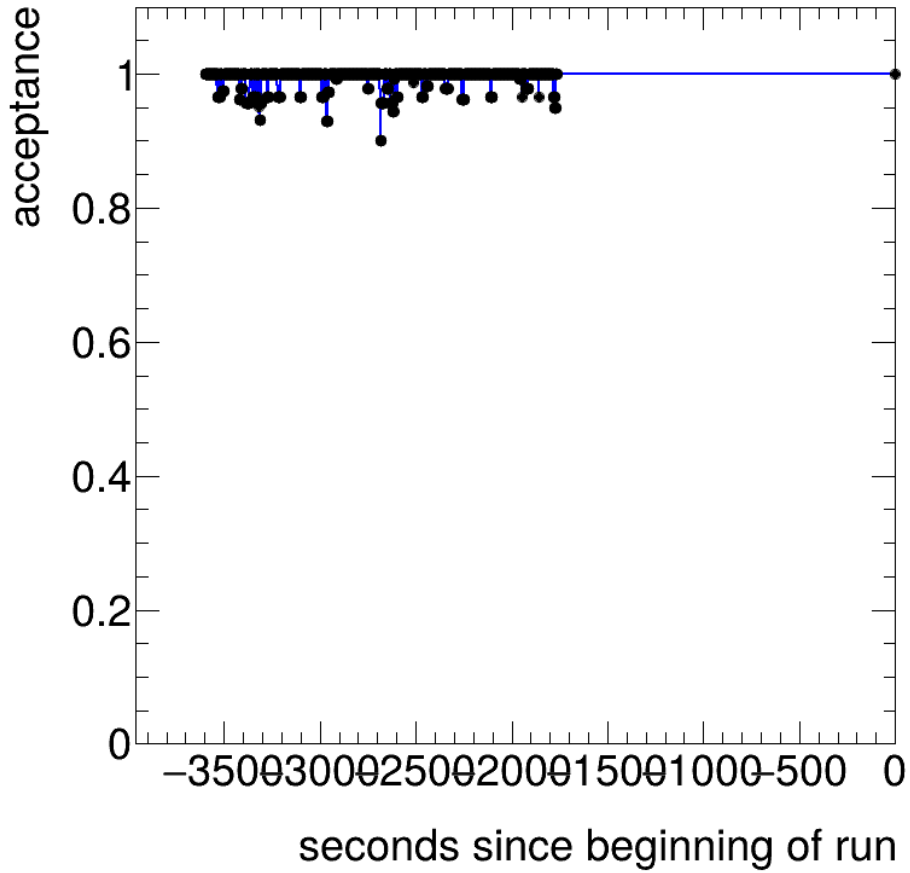


Autorecovery Rate vs. Time

Run 67568, 3 MVTX layer cut



Run 67568, 2 MVTX layer cut



MVTX Hit Efficiency vs. Trigger Latency