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Minimally Destructive, Fast Silicon Instrumentation for a Beam Velocity Monitor of Low-Intensity Semi-Relativistic Muon Bunches

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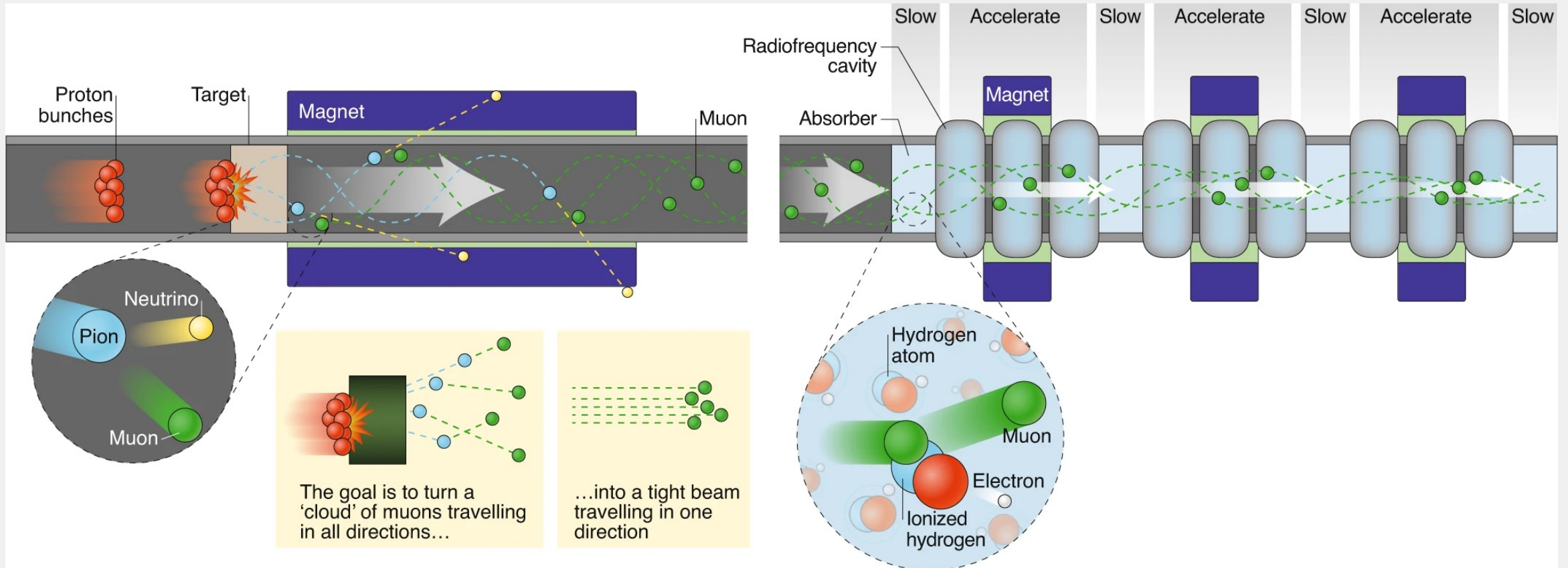
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- Beams are tertiary ($p^+ \rightarrow \pi^\pm \rightarrow \mu^\pm$), bunches initially enormous in phase space; typical beam cooling techniques take too long
- Muon ionization cooling demonstrated in a single-particle experiment; goal is to demonstrate feasibility of ionization cooling of muon bunches

The Muon Ionization Cooling Demonstrator



[Nature]

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- Bunches in the demonstrator $\sim 200\text{MeV}$, 10^6 muons/bunch (bunch size limited by proton source), 704 MHz rep. rate

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- Derive momentum from difference in mean timing on planes, use mean path length traveled by particles between planes in G4Beamline
- ~1m gap introduced for force handling/alignment girders every 2 cells



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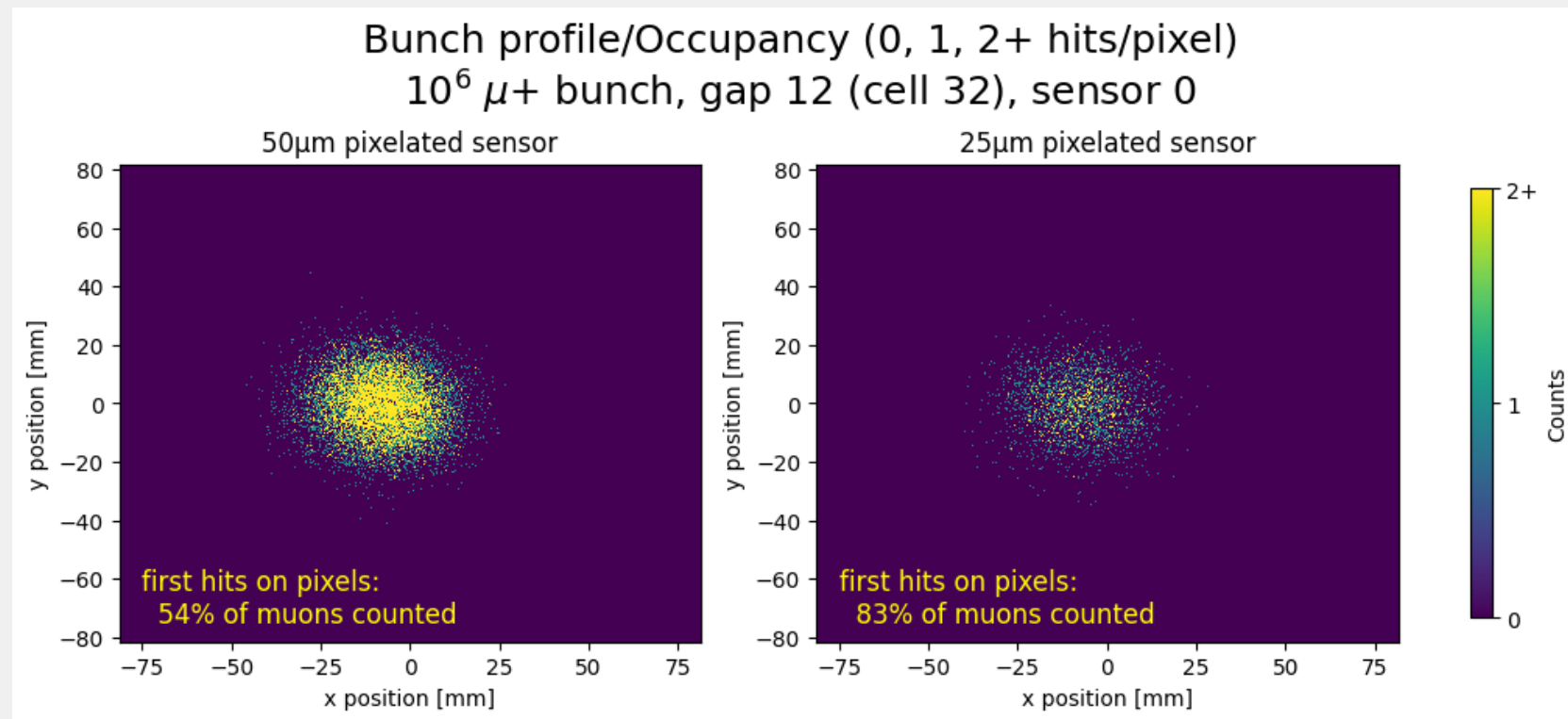
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- Don't require high fill factor, charge sharing

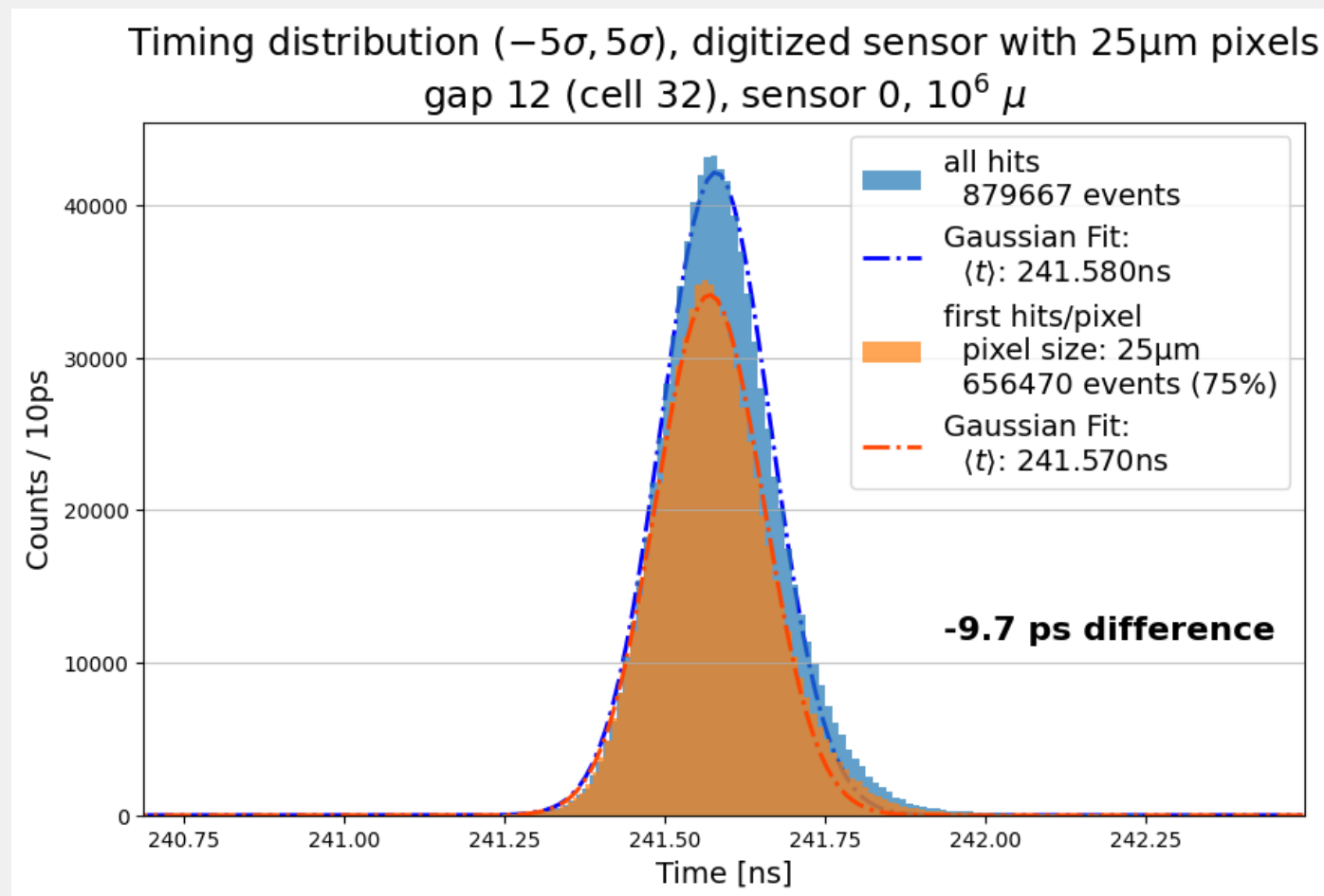
Occupancy

- Will only record first hit on each pixel; skews timing distribution early



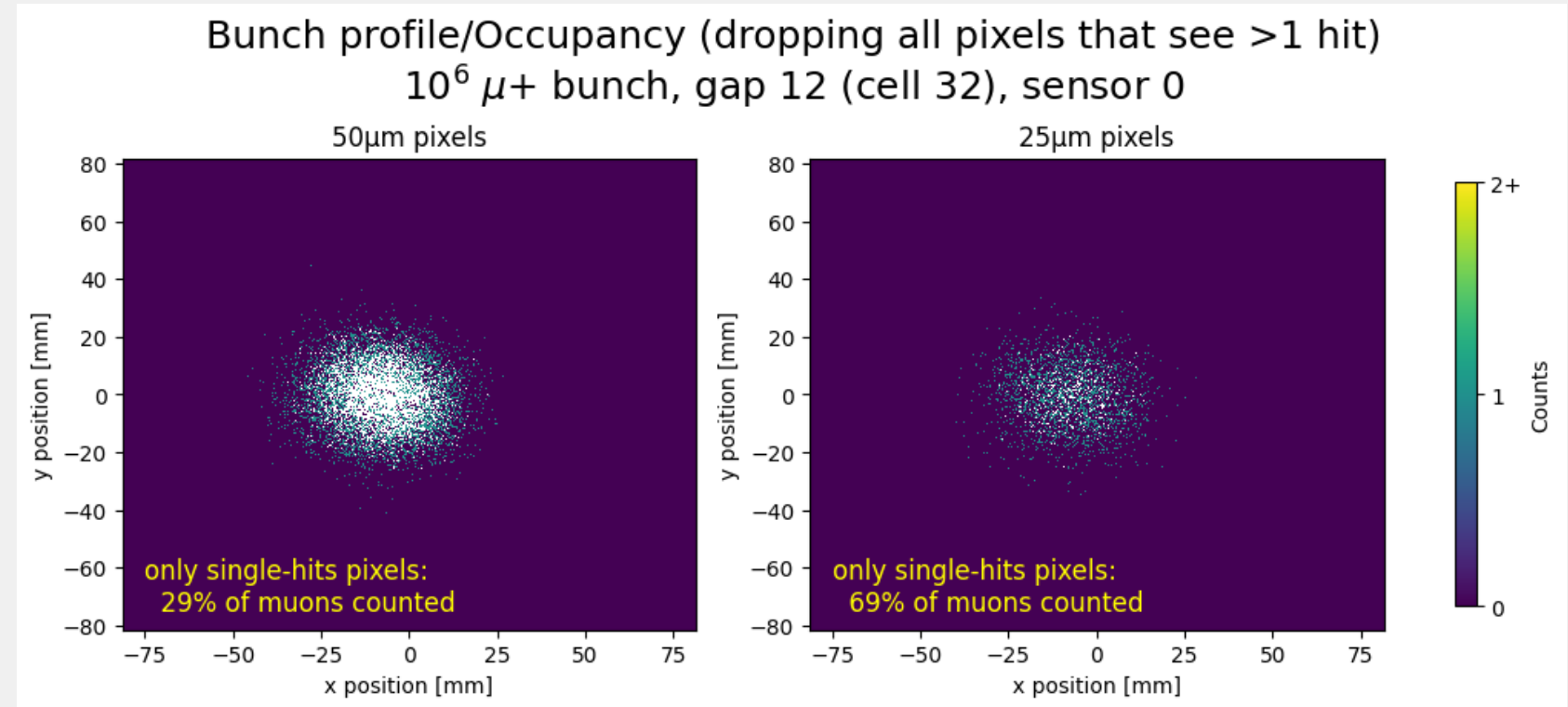
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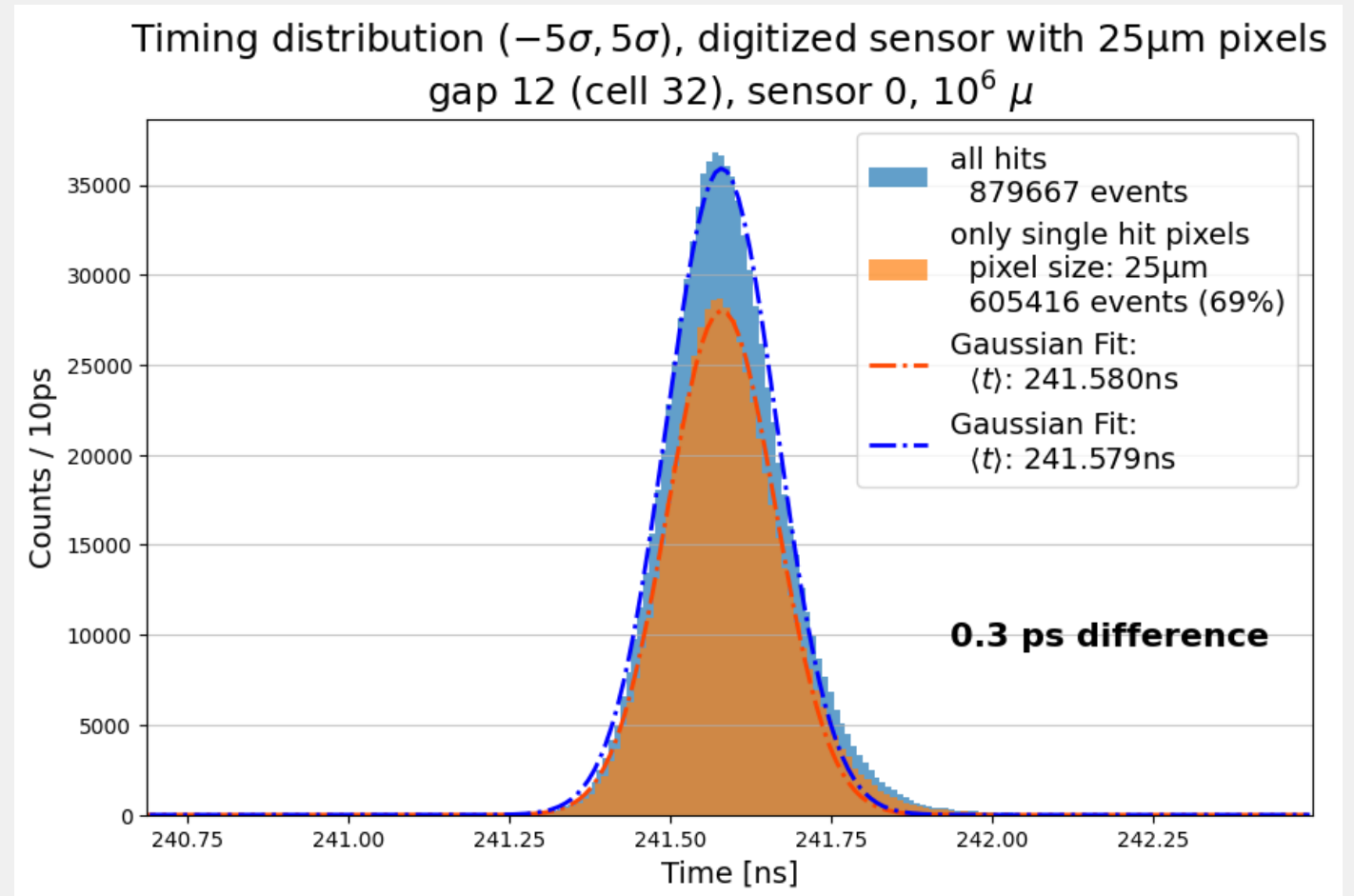
Time-over-threshold cuts

- Can use time over threshold information to see whether each pixel sees 0, 1, or ≥ 2 hits, and drop pixels that see >1 hit



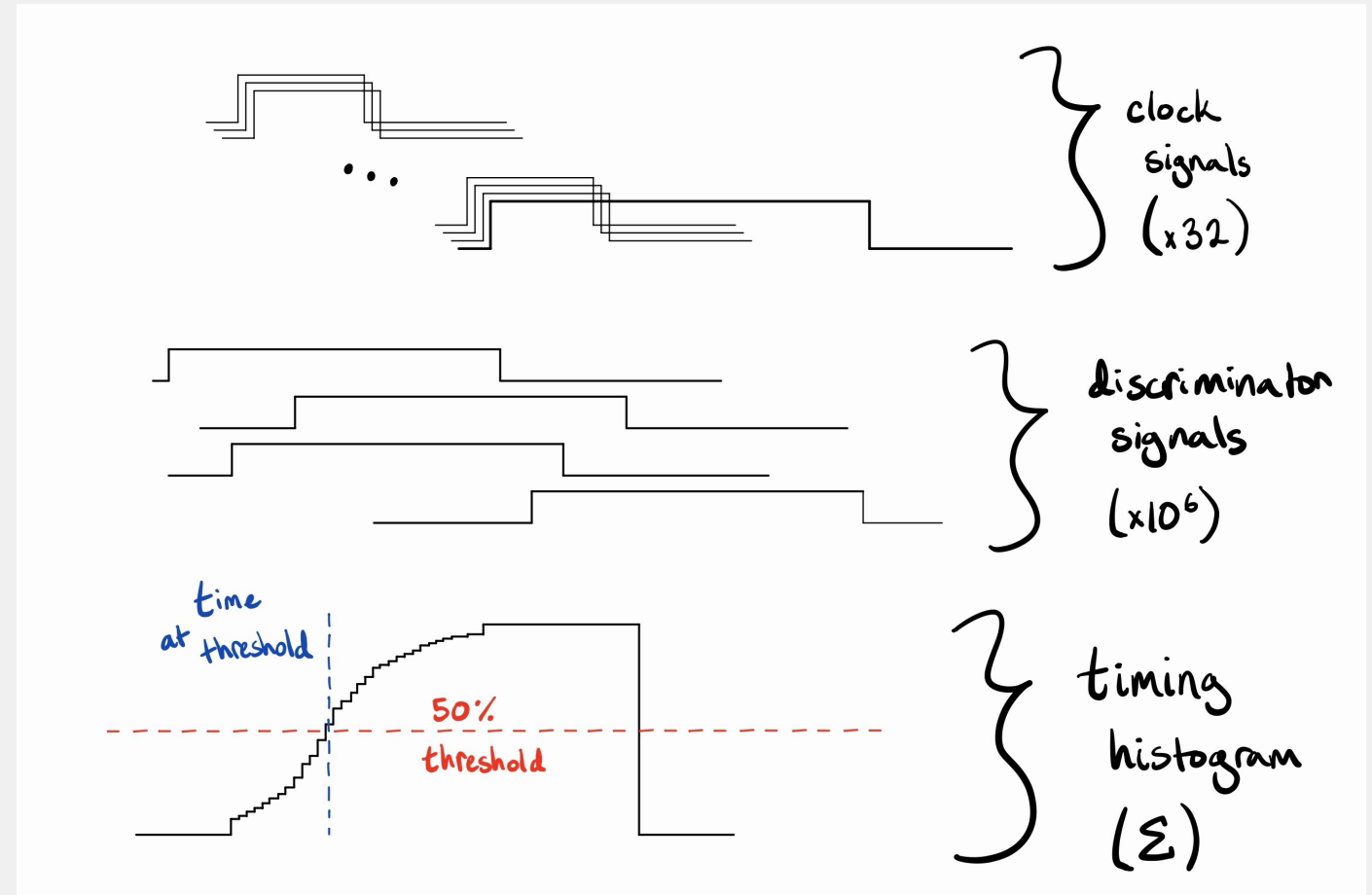
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Signal discrimination

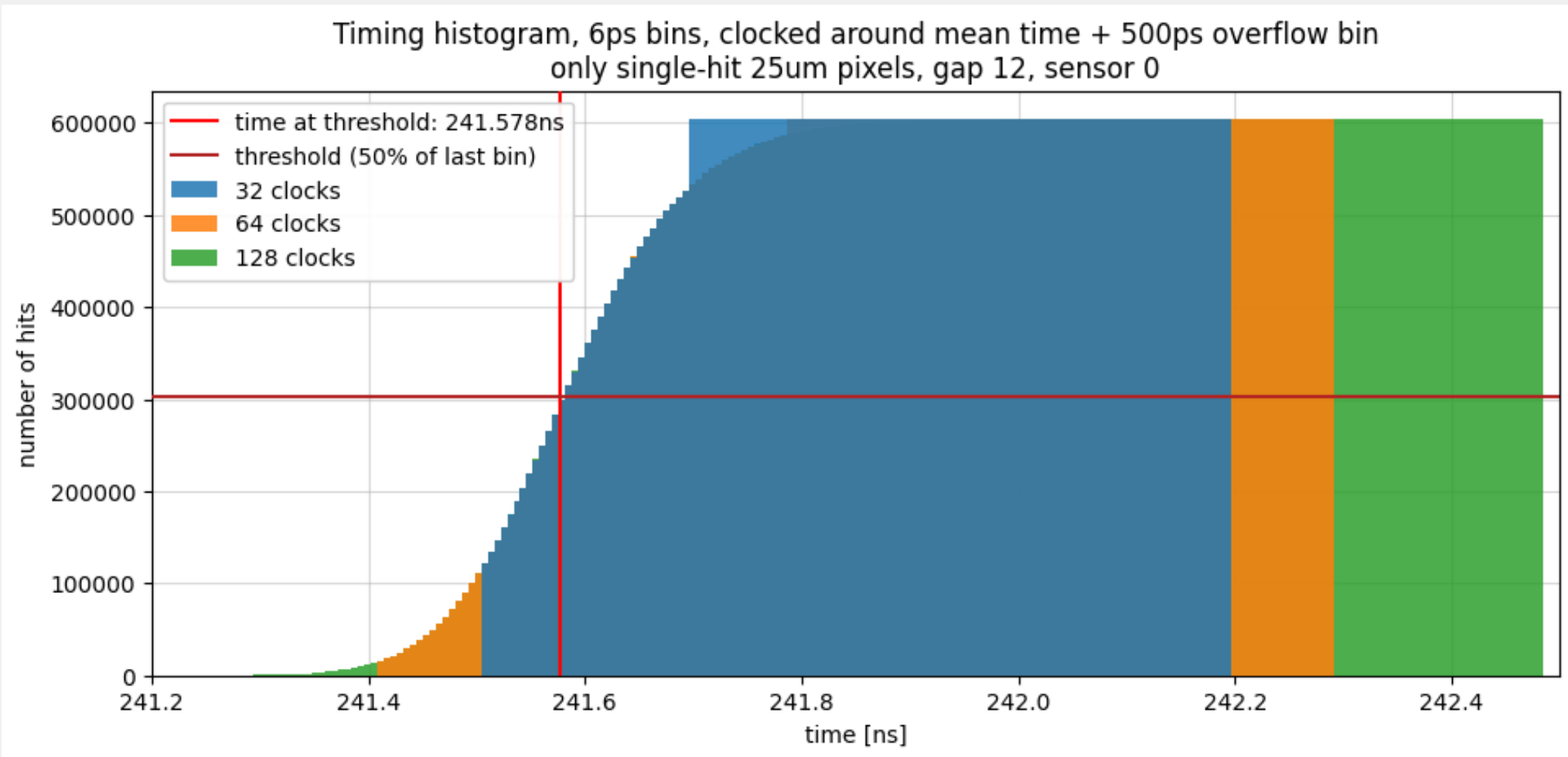
- Don't need full waveform digitization
- Use ~ 32 precision clock phases, 6ps staggering, get timing from discriminator rising-edge relative to the clock phases



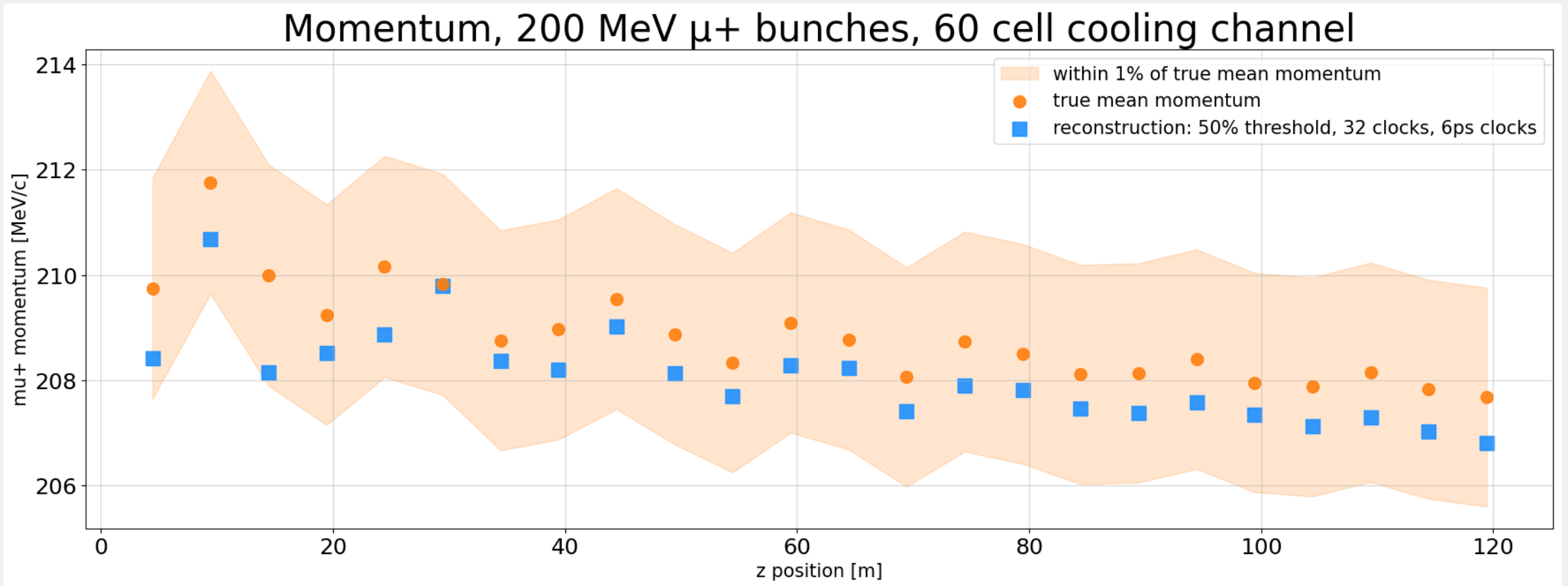
Signal discrimination

- Single bit digitization, one fast discriminator per pixel, and an FPGA—less expensive (\$) and computationally) than reconstructing full waveforms
- Can distribute clock to each sensor pair on same service card, ~ 1 ps precision

Timing reconstruction from simulation



Momentum reconstruction

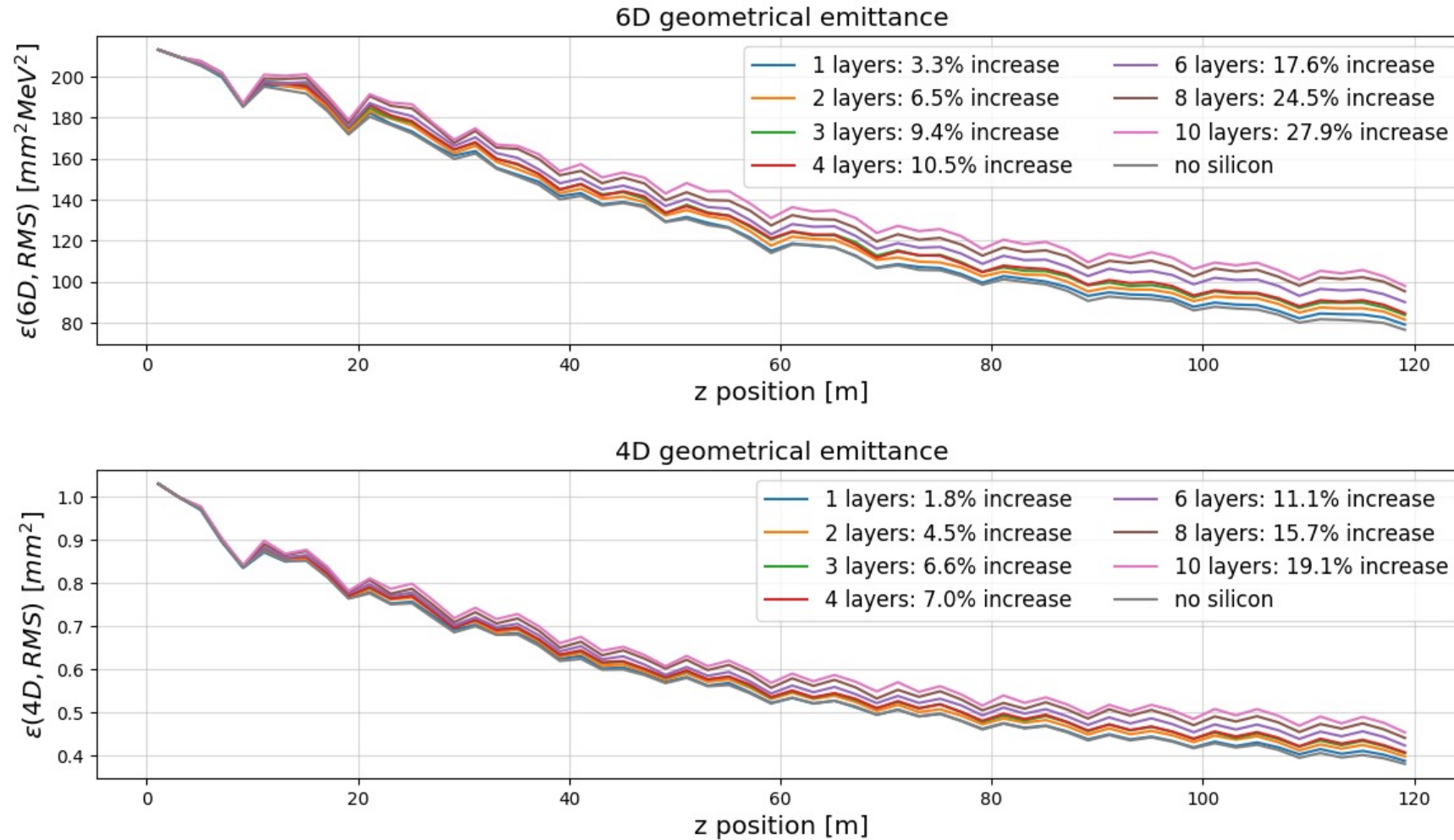


Increasing statistics

- Considered replacing the single plane on each side with multiple planes, to increase statistics
- Ultimately unnecessary; enough data on a single plane that 30-50ps resolution of each pixel was easily averaged out



Emittance (outliers 3σ from beam core dropped)
 2 groups of n 50 μm silicon layers per gap (every 5/2 cells), 60 cells



Development plan

- Have a Kria KR260 FPGA + readout board, setting up to run staggered clocks



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- Plan is to validate the concept on small array of pixels before scaling up



Conclusion

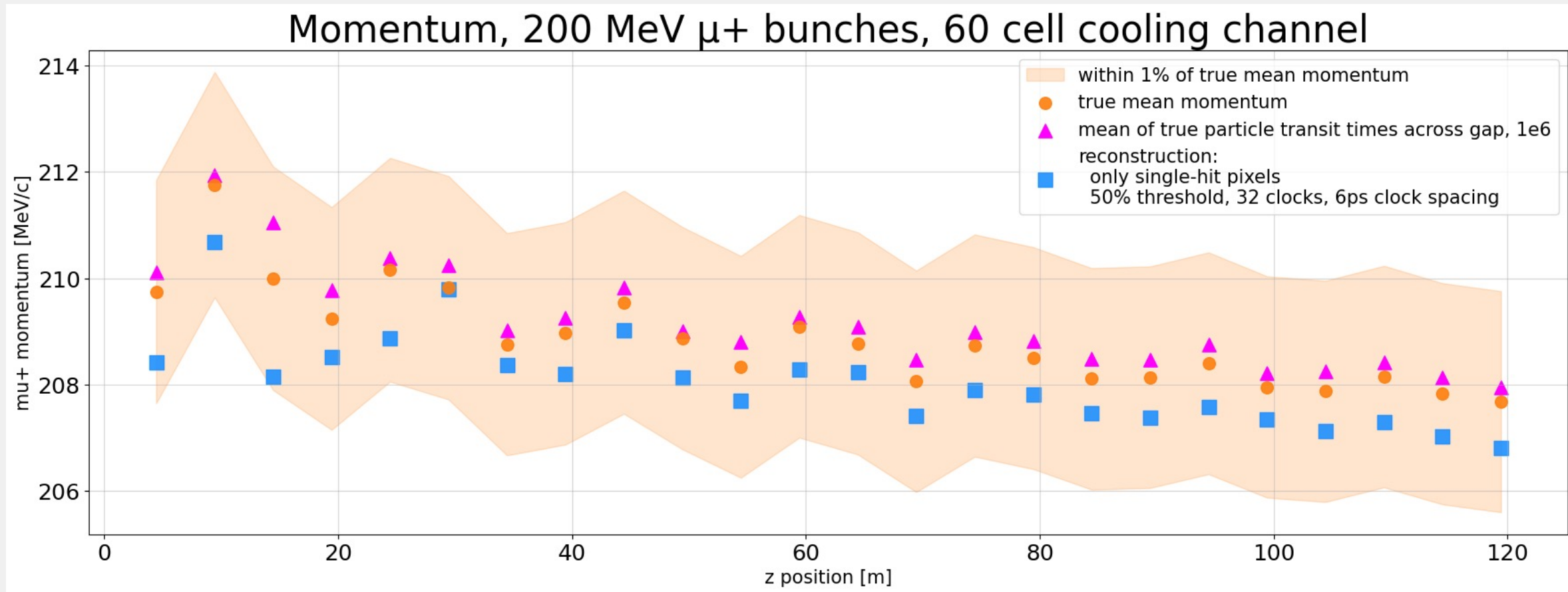
- Muon beams have increasing relevance for high-energy physics
- Beam instrumentation in the low-intensity regime requires a novel approach—this is the first beam monitoring system to use in-beam silicon sensors for high-precision snapshots
- Using silicon pixels for mean measurements of bunches allows new approaches to timing & readout systems



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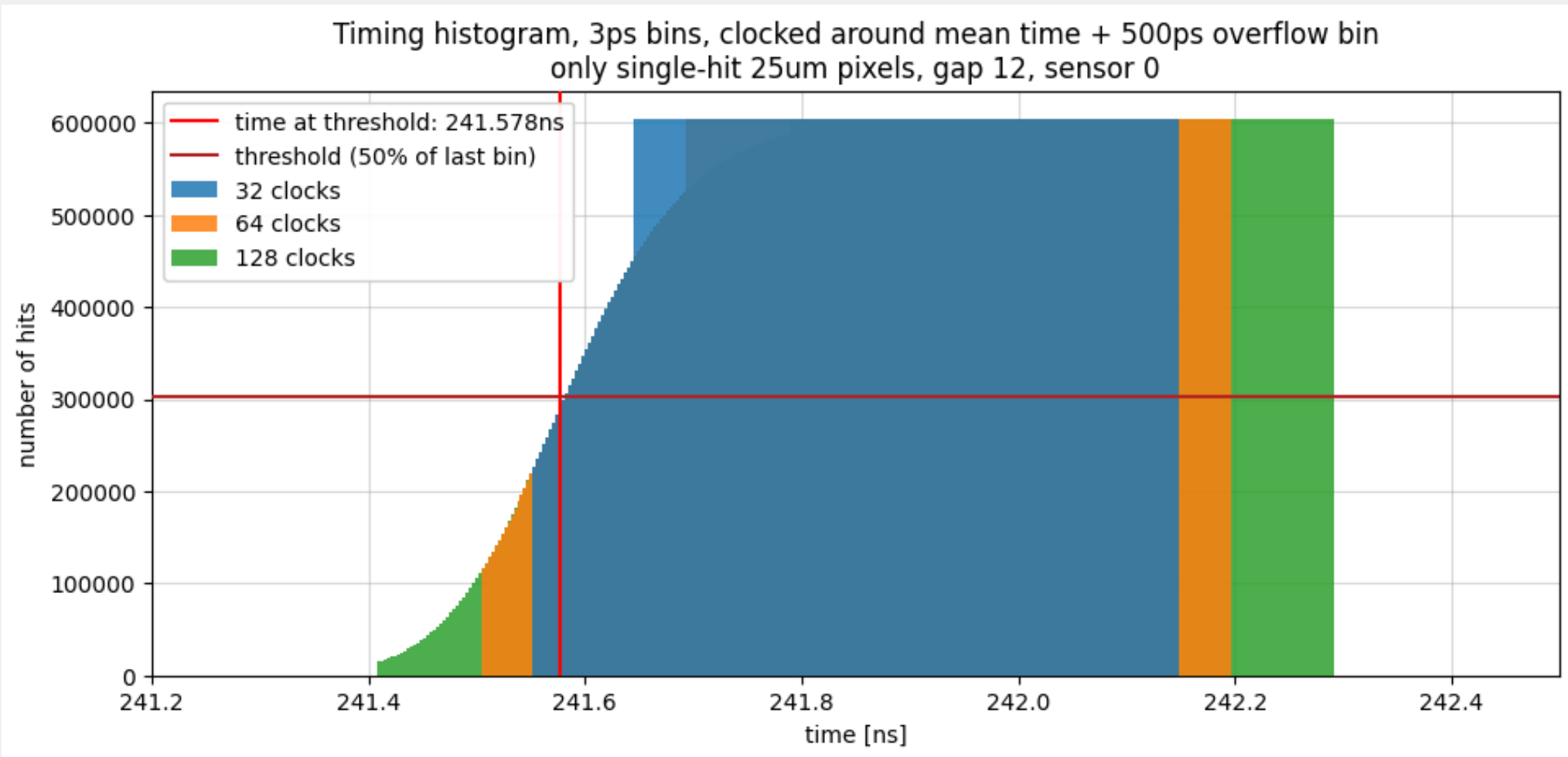
Backup:



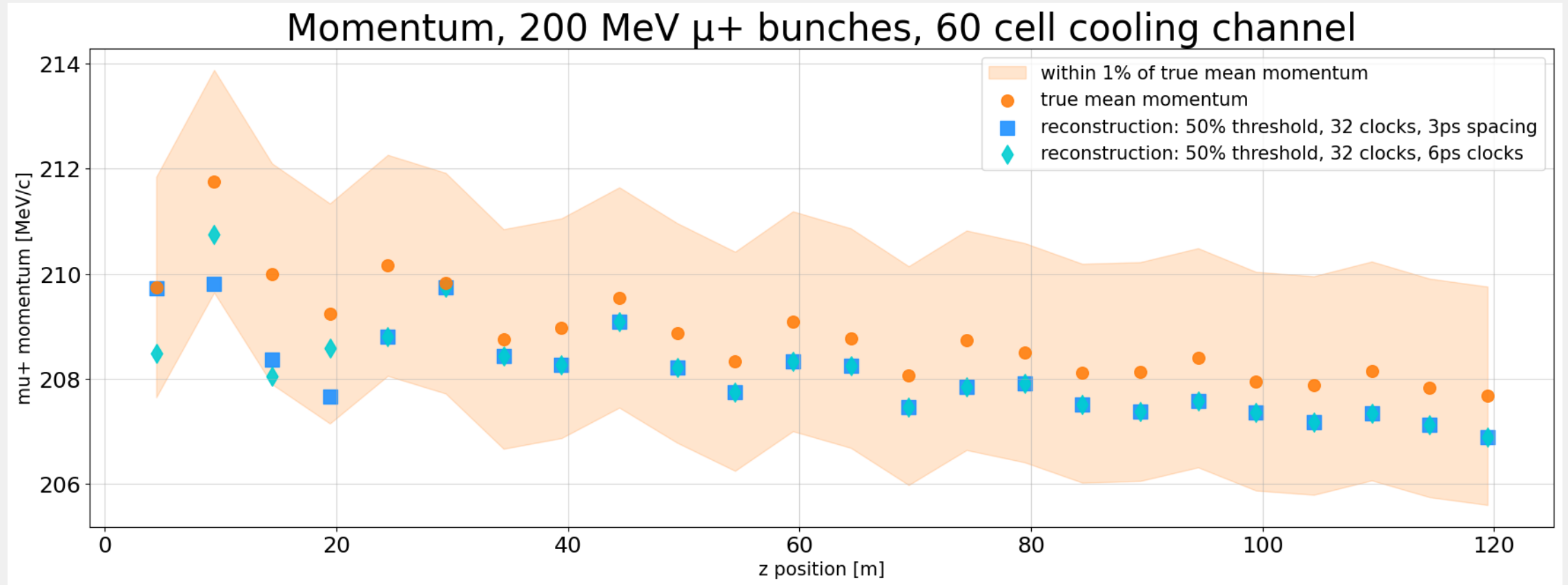
Emittance characterization

- Same pixel array scheme would be used for upstream emittance characterization
- Concept is to reconstruct 6D emittance with a series of closely spaced planar sensors
 - x , y from beam profile
 - px , py inferred from the changing beam spot size
 - E estimated from spaced planes, spread of mean timing t on planes
- Work of Leonardo Palombini, Donatella Lucchesi at the Università degli Studi di Padova

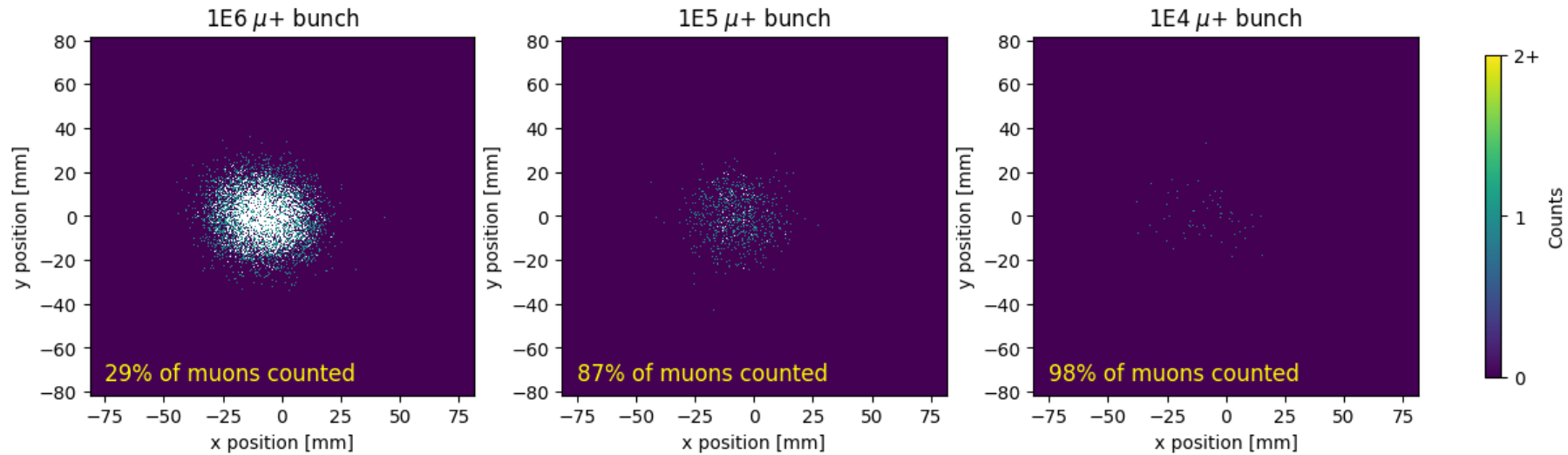
Timing reconstruction: 3ps



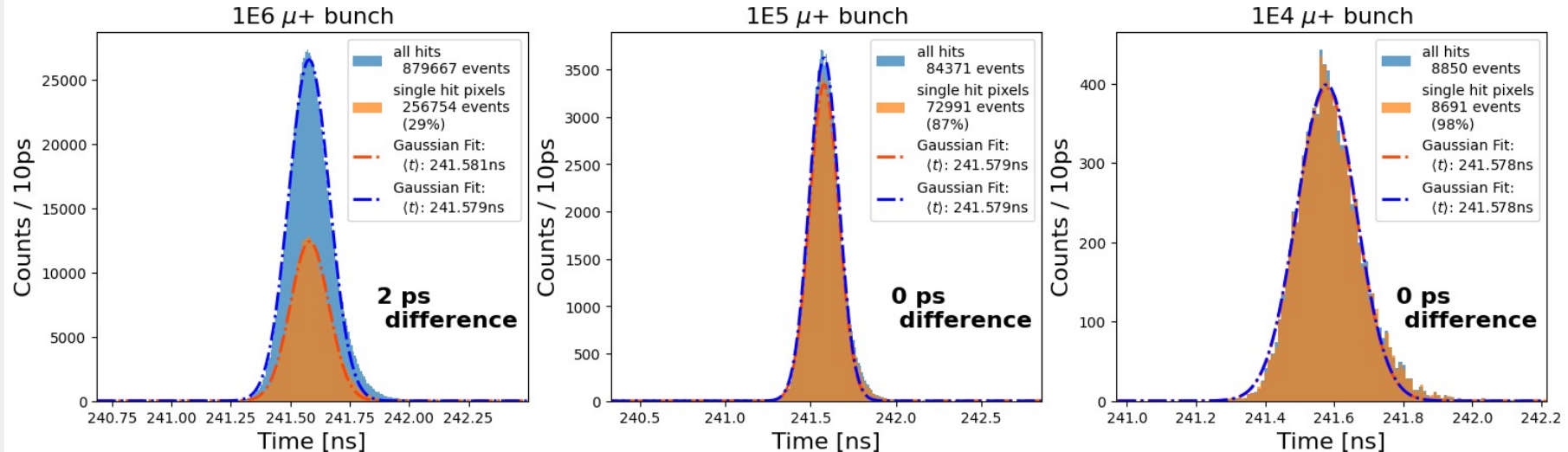
Reconstructed momentum: 3ps



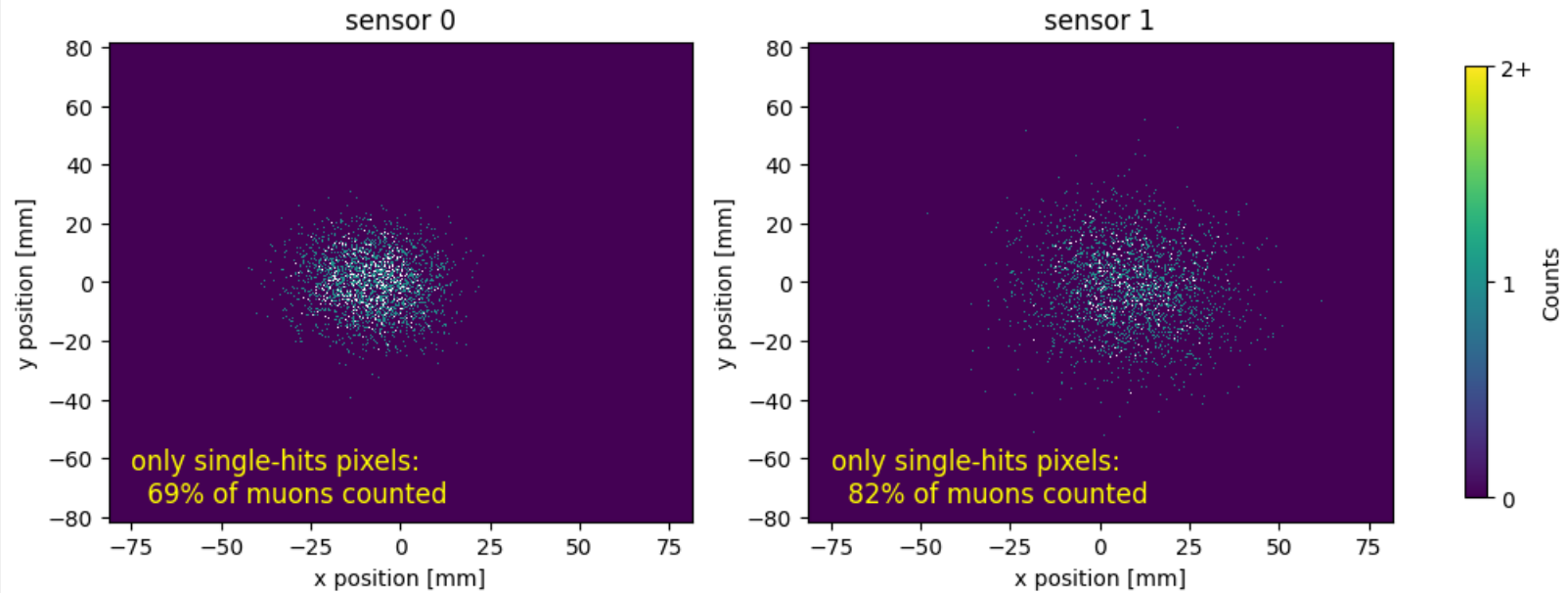
Bunch profile, 50 μ m pixelated sensor, gap 12 (cell 32), sensor 0
dropping all pixels with occupancy >1



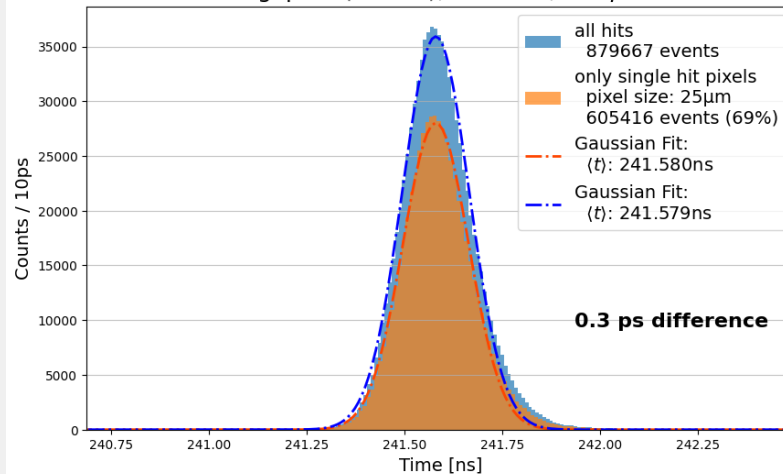
Timing distribution, 50 μ m pixelated sensor
gap 12 (cell 32), sensor 0



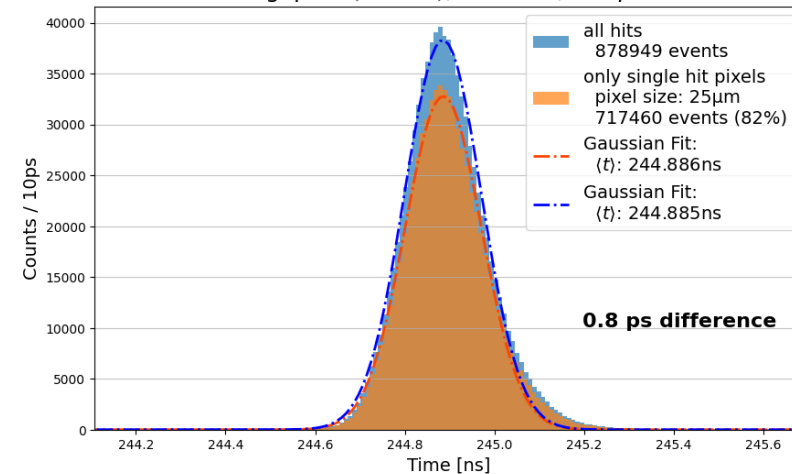
Bunch profile/Occupancy (dropping all pixels that see >1 hit) $10^6 \mu$ + bunch, gap 12 (cell 32), 25 μ m pixels

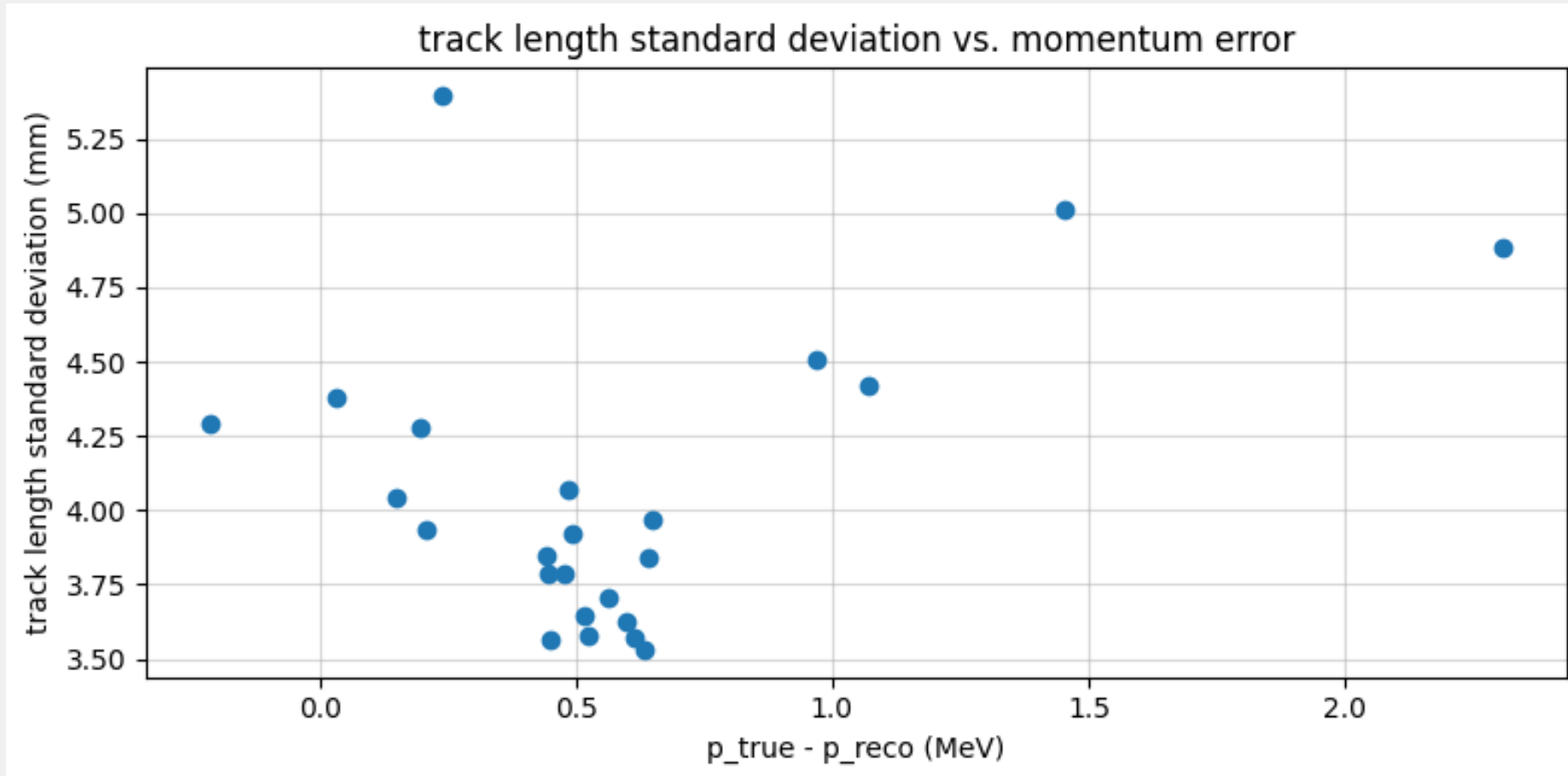


Timing distribution ($-5\sigma, 5\sigma$), digitized sensor with 25 μ m pixels
 gap 12 (cell 32), sensor 0, $10^6 \mu$

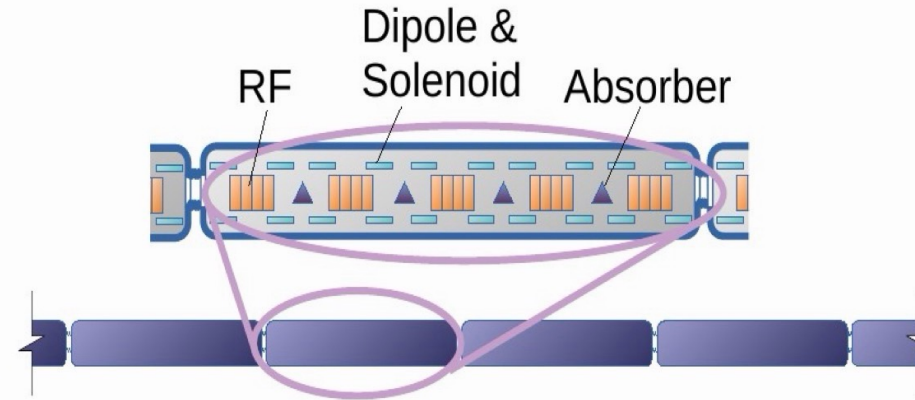


Timing distribution ($-5\sigma, 5\sigma$), digitized sensor with 25 μ m pixels
 gap 12 (cell 32), sensor 1, $10^6 \mu$





Demonstrator Challenges



- Engineering integration is principal challenge
 - Solenoid field can induce RF breakdown
 - “Bucking” solenoids require careful thermal & force management
 - Integration of ancillary equipment may be challenging
 - Beam instrumentation, vacuum, RF power
- Need to demonstrate luminosity performance
 - Transmission between cooling stages is crucial
 - 1 % transmission deviation in each stage → 40 % luminosity deviation