ATLAS MDT AMT Simulations for LHC Run3 and HL-LHC

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On behalf of the ATLAS Collaboration

TIPP2023

6th Technology and Instrumentation in Particle Physics

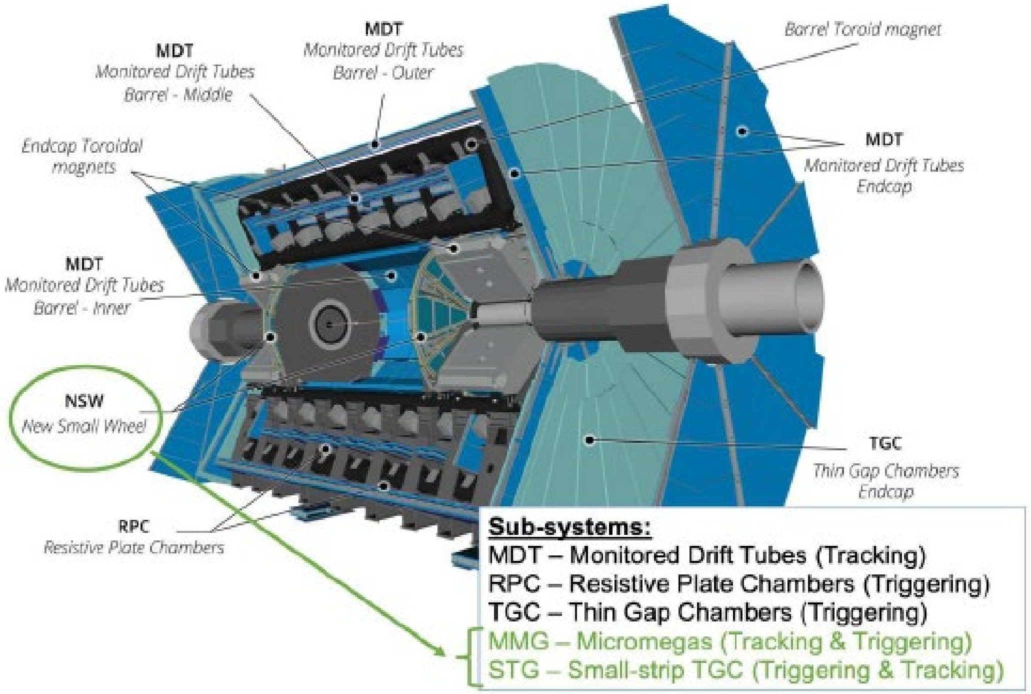
Cape Town, South Africa; Sept. 4-8 2023

Contents

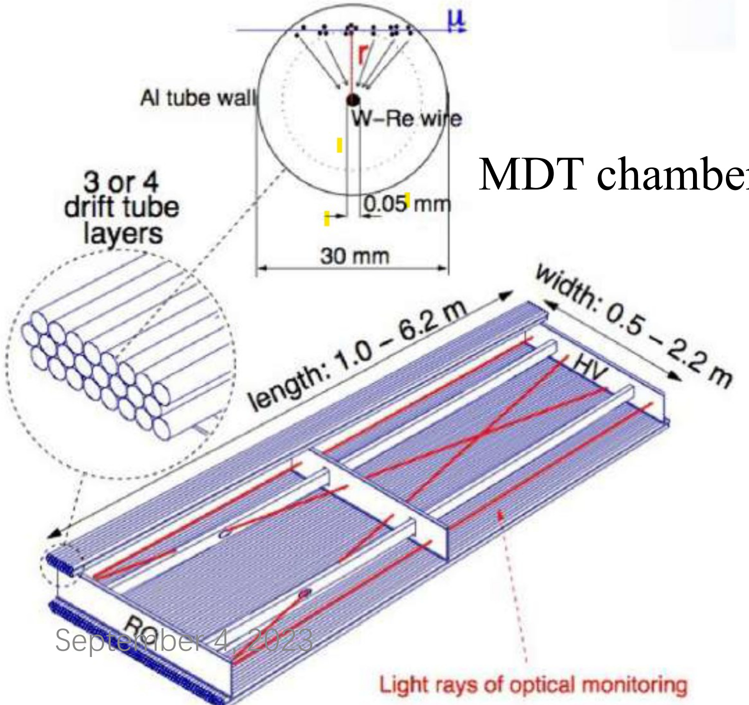
- Introduction
- ATLAS Muon TDC (AMT) Simulation
- Results
- Summary

Introduction

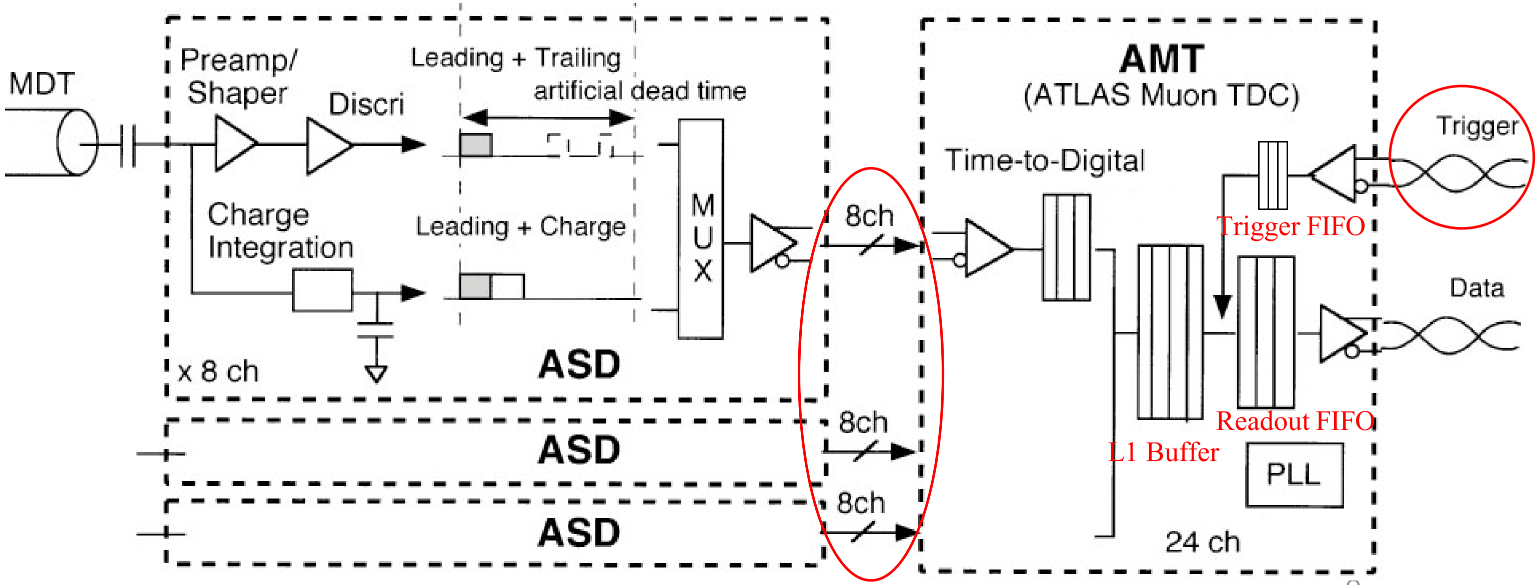
- MDT (Monitored Drift Tubes) chambers provide precise and reliable tracking and momentum measurement in the ATLAS muon spectrometer (average tube resolution 80 μm).
- An MDT chamber consists of 2 multi-layers of 3/4-layer precision aluminum drift tubes.
- Each MDT chamber has up to 18 Front-End Electronic boards ("mezzanine"), which contain three custom-designed 8-channel Amplifier/Shaper/Discriminator (ASD) chips and one 24-channel TDC.



The Atlas Muon Spectrometer



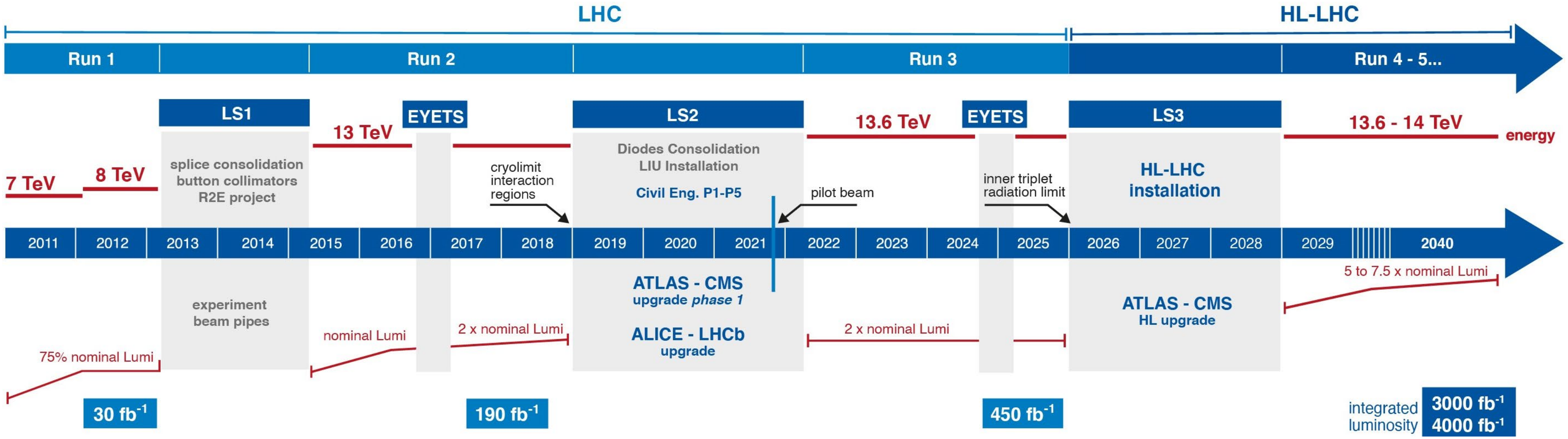
MDT chamber



MDT Front-End Electronics

Introduction

- In Run 3, ATLAS is expected to be run with L1 rate at ~100 kHz under luminosity up to 3x10^{34} $cm^{-2}s^{-1}$ –> Challenge to the present MDT mezzanines (designed to work at lumi. 1.0x10^{34} $cm^{-2}s^{-1}$ originally);
- During HL-LHC period, the instantaneous luminosity is expected to be pushed up to 7~7.5×10^{34} $cm^{-2}s^{-1}$ –> New MDT TDC is planned to be used in all MDT chambers and work in trigger-less mode;
- However, it's possible that some mezzanines on some chambers can not be replaced due to limited accessibility.



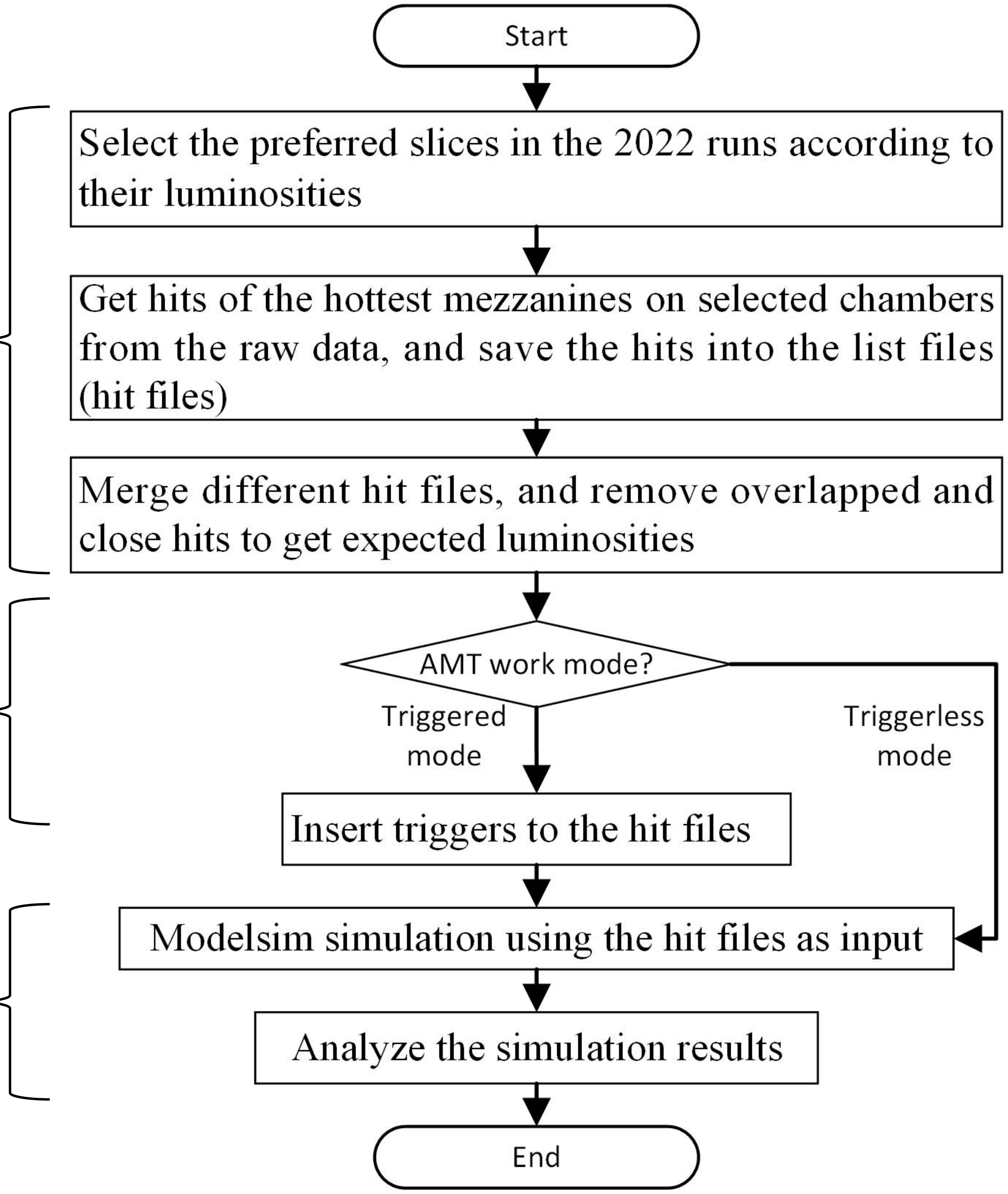
- We study the MDT front-ends (AMT) performance at high luminosity with L1 100 kHz by simulation to make sure no MDT FE operation issue in Run 3;
- We also simulate the AMT behavior in trigger-less mode with luminosity up to 7.5x10^{34} $cm^{-2}s^{-1}$

AMT simulation: Workflow for AMT simulation

Prepare input files with high luminosity hits for simulation

Generate and insert triggers

Simulation & Analysis

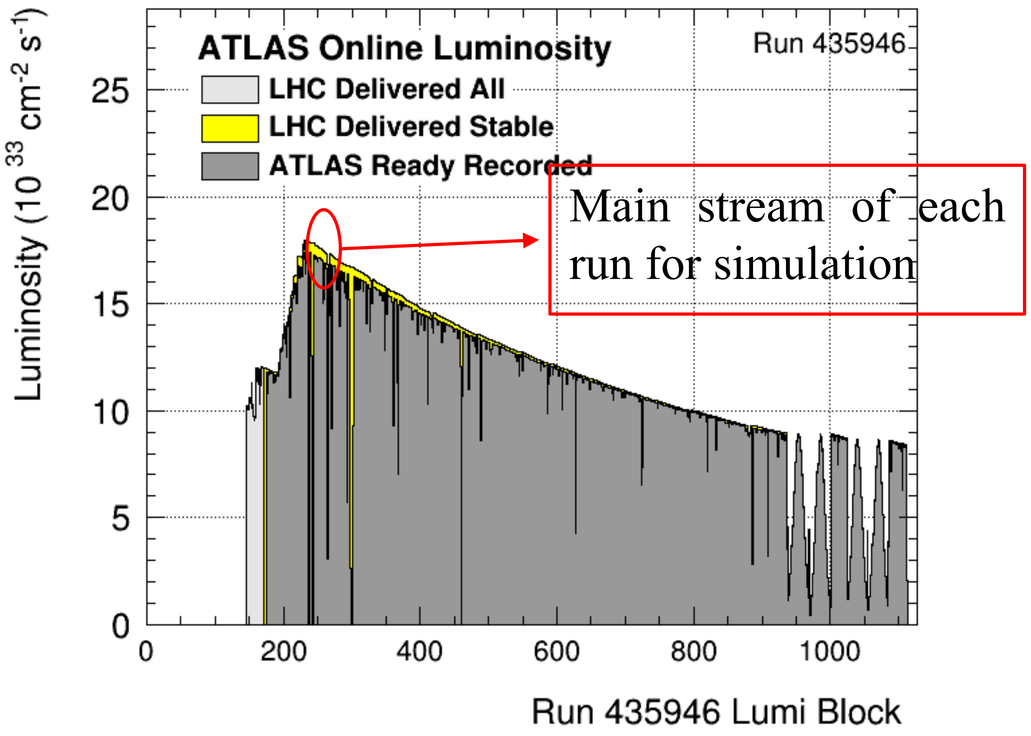


AMT simulation: Prepare High Luminosity Hit files

- Raw input from 2022 data, physics main stream.
- Hit files from multiple runs are merged to get expected luminosities:
  - For Run 3 Simulation: 1.08 ~ 5.01 ($\times 10^{34}$ cm^{-2}s^{-1})
  - For HL-LHC Simulation: 2.98 ~ 7.44 ($\times 10^{34}$ cm^{-2}s^{-1})

Step: ~ 0.5 $\times 10^{34}$ cm^{-2}s^{-1}

- Too close (interval < 500 ns) and overlapped hits (leading, leading, trailing, trailing …) are removed



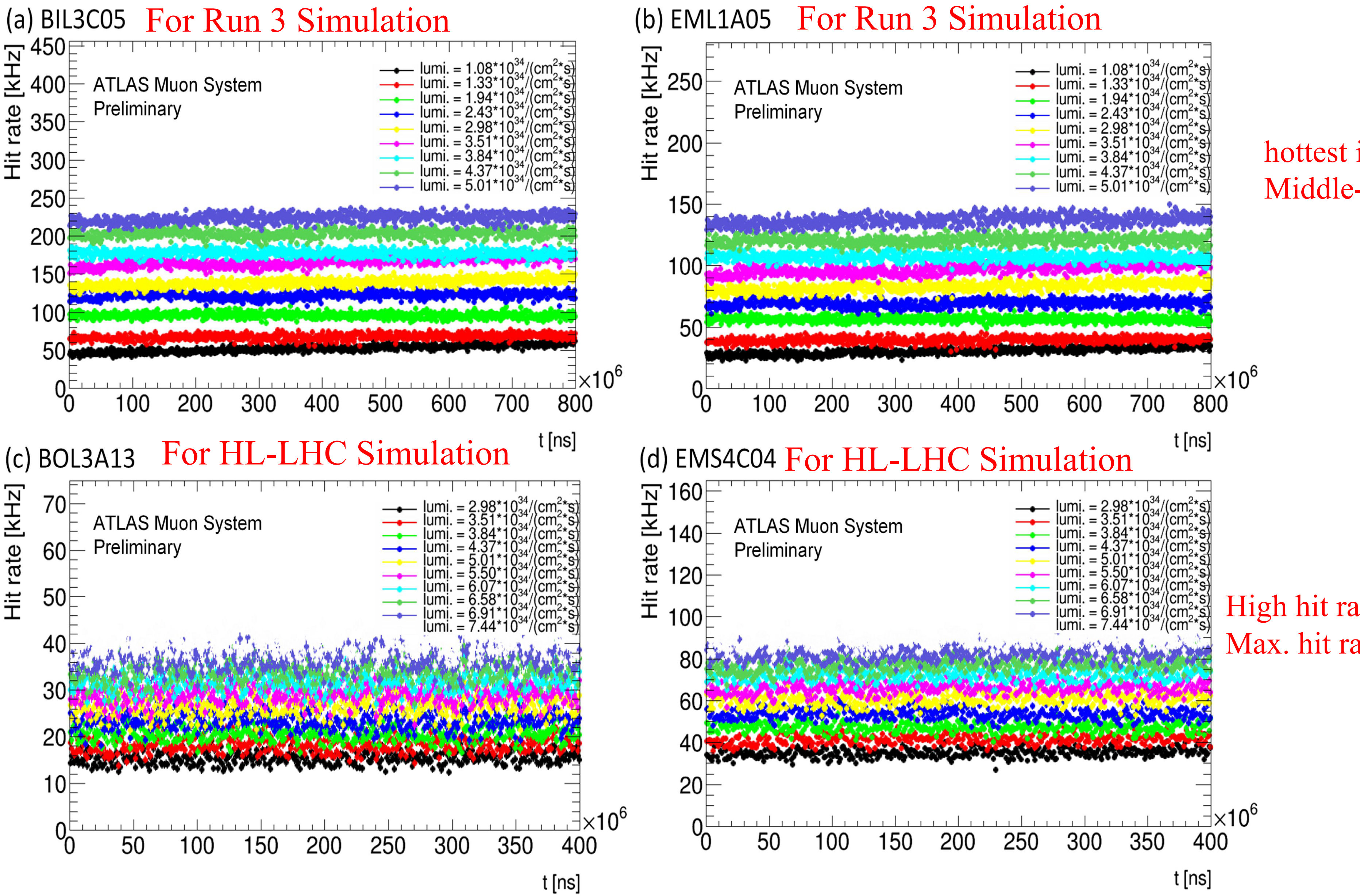
AMT simulation: Prepare High Luminosity Hit files

For Run 3 Simulation

For Run 3 Simulation

hottest chamber
Max. hit rate ~ 220 kHz/tube

hottest in End-cap
Middle-layer chambers



For HL-LHC Simulation

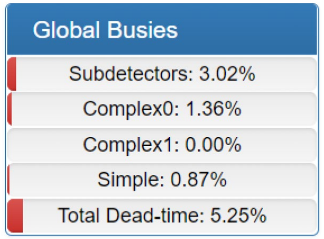
For HL-LHC Simulation

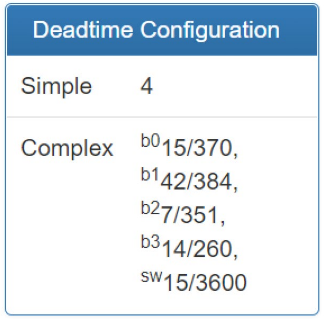
Low hit rate
Max. hit rate ~35 kHz/tube

High hit rate
Max. hit rate ~80 kHz/tube

MDT tube hit rates from the hottest mezzanine on selected chambers with different luminosities

AMT simulation: Generate and insert triggers



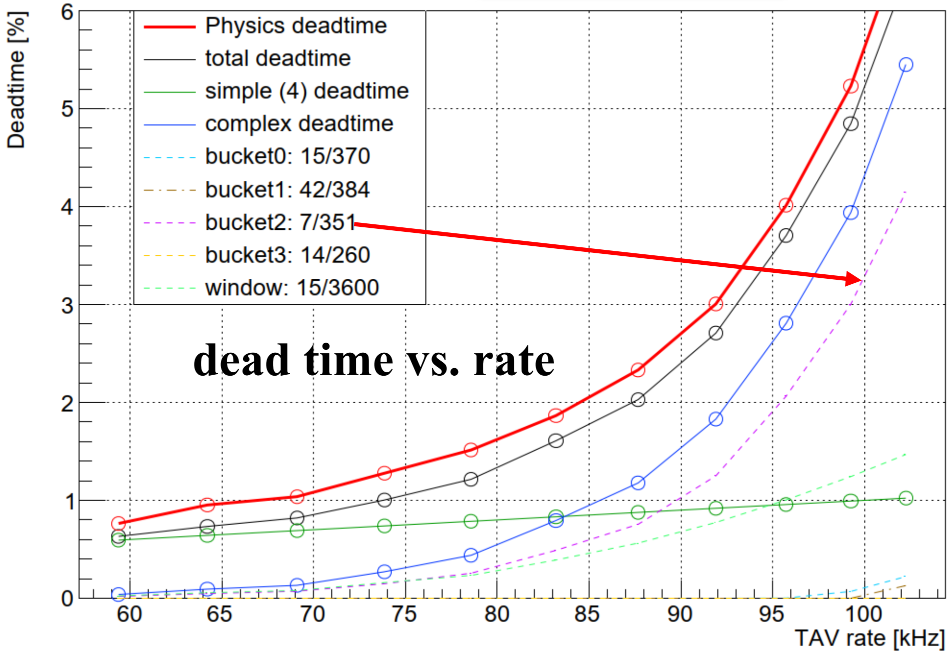


- **Simple dead time**
- 4-BC (Bunch-Crossing, 25 ns per. BC) dead time after each trigger
- **Complex dead time**
- Based on **leaky bucket algorithms** (with a size S and a rate R):

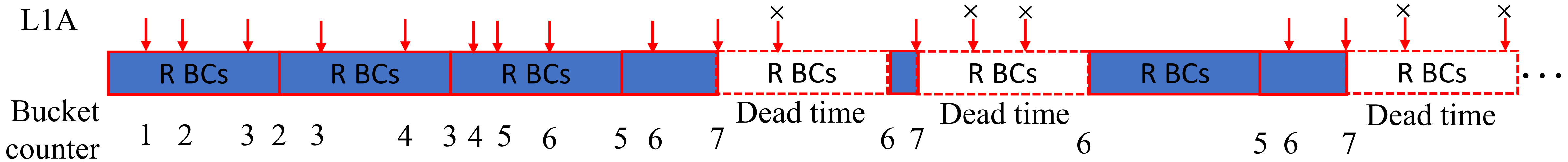
  -the bucket counter is increased by +1 at each L1A (L1 Accepted)

  -the bucket leaks at a rate R, i.e. the counter is decreased by -1 every R BCs

  -when the bucket full, i.e. counter = S, L1A are vetoed by R BCs.
- 5 different complex deadtime settings now, of which b2 (S / R = **7/351**) is the main contribution

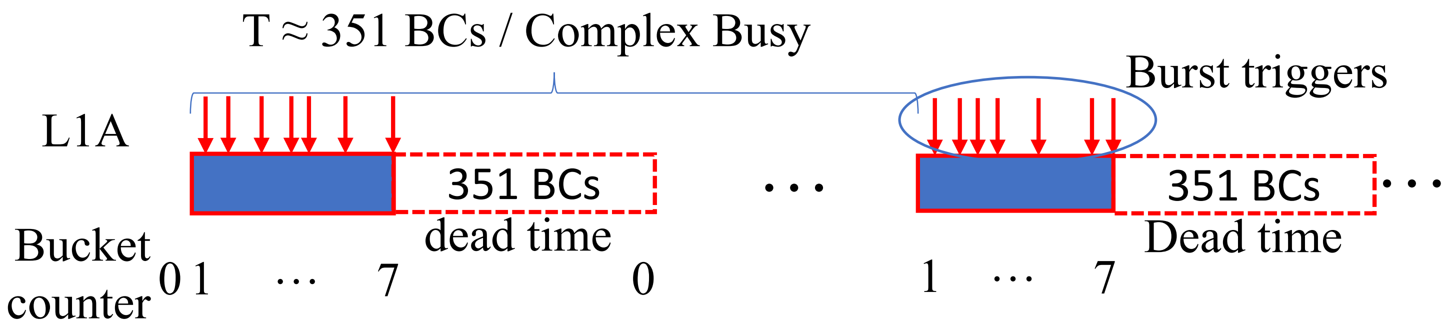


Complex dead time in real situation

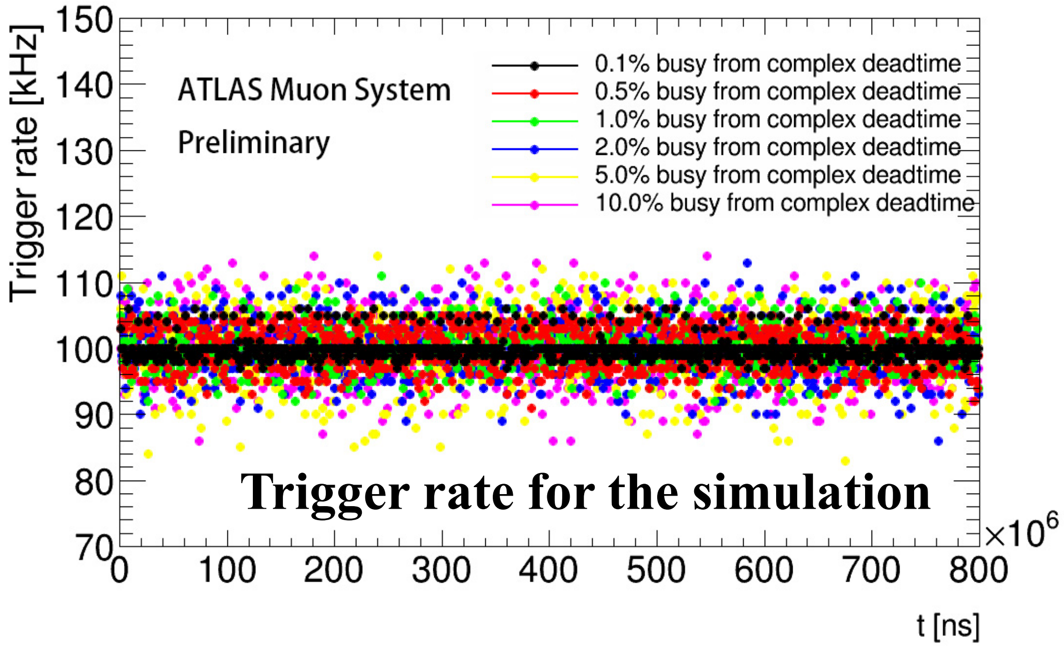


AMT simulation: Generate and insert triggers

- 1. Generate **100 kHz Poisson distributed triggers** with 100 ns simple dead time;
- 2. Generate **Burst triggers** in a simplified leaky bucket model
    - Generate burst triggers in extreme case: 7 Poisson distributed L1As in 351 BCs followed by 351-BC complex dead time for one block;
    - Insert the blocks into the 100 kHz triggers by Poisson distribution with the probabilities of **Complex busies (L1 busy fraction from complex dead time):** 0.1%, 0.5% (roughly average case), 1.0%, 2%, 5.0% (extreme case), 10% (may happen in an instant)
- 3. Randomly remove the simple triggers to **rescale total trigger rate to 100 kHz**



Burst triggers &complex dead time for the simulation

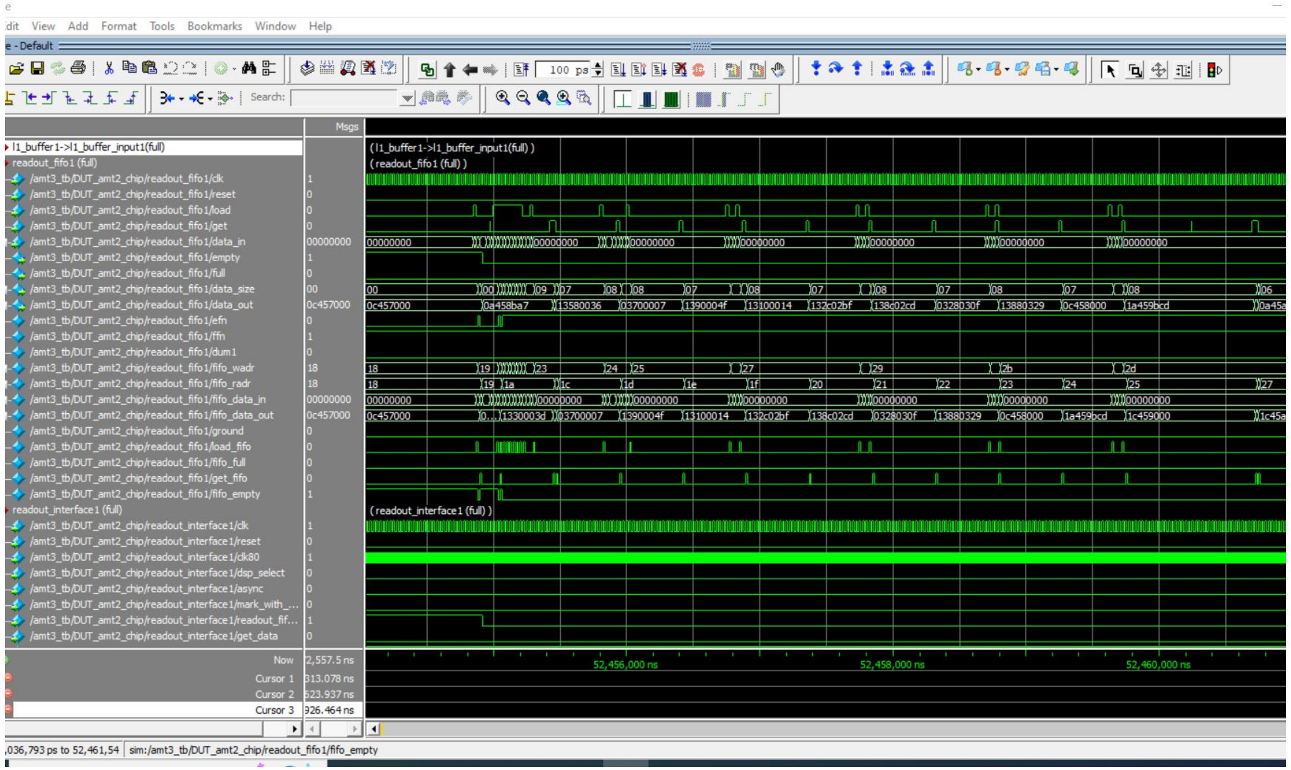


More burst triggers as the complex busy increases

AMT simulation

- **Modelsim simulation**
  - AMT is designed by Verilog language, use the source code for simulation;
  - Import exactly the same libraries of AMT chip to Modelsim for simulation

- **Based on 2022 Run 3 MDT AMT setup**
  - For Run 3 (triggered mode):
    - Edge mode (measure leading & trailing edge, hit charge can be calculated by pulse width)
    - Readout time window: 1300 ns
  - For HL-LHC (trigger-less mode):
    - Edge mode;
    - Leading-edge ONLY mode.
  - Serial readout at 80 Mbps

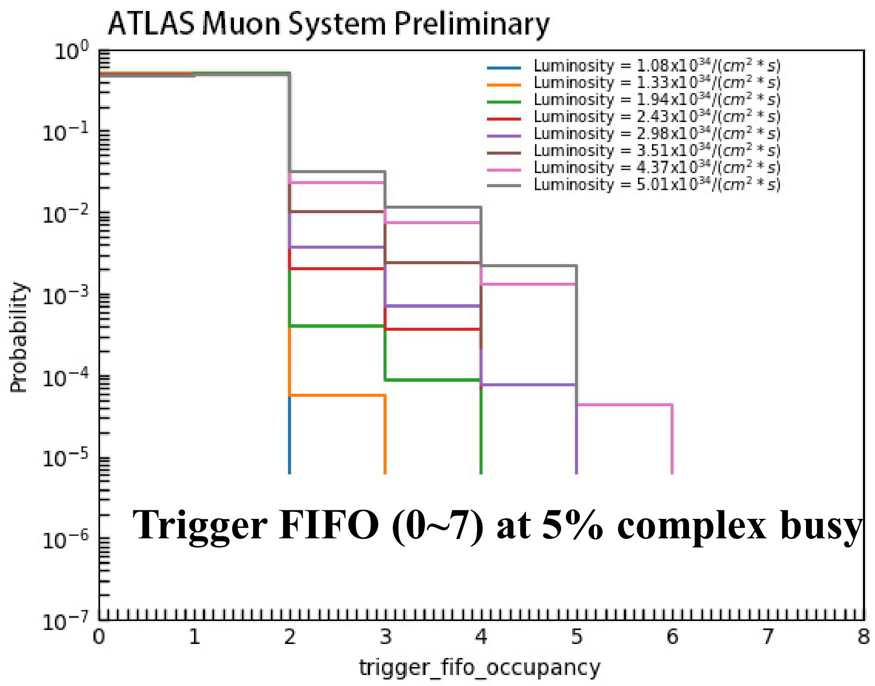


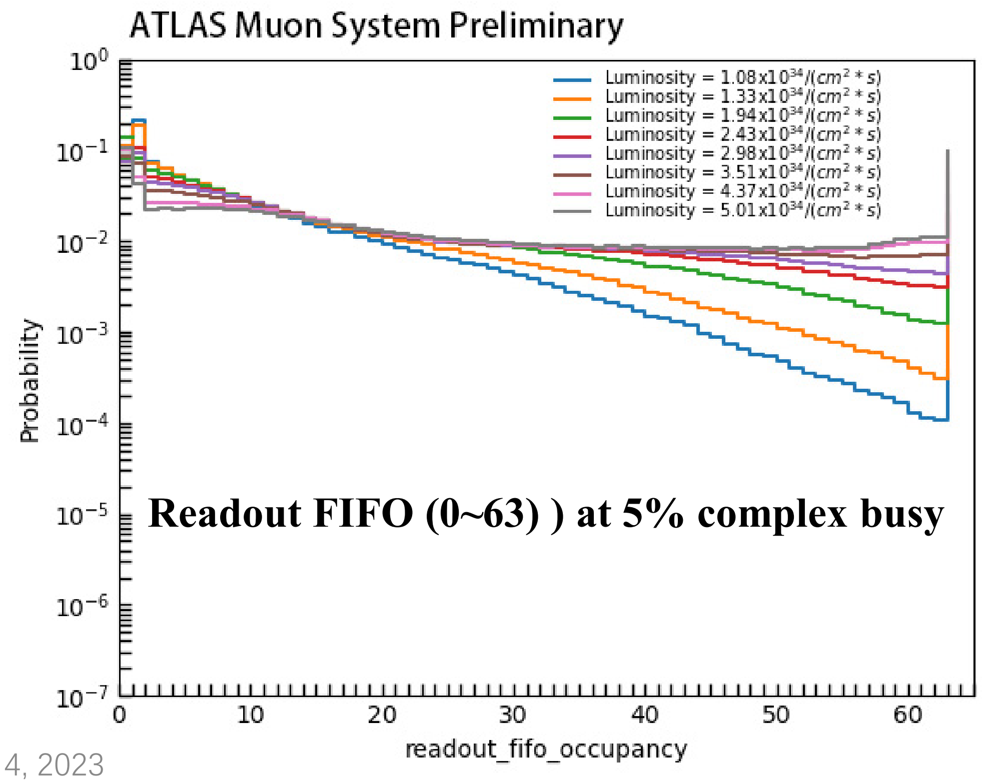
Modelsim Simulation for AMT (Modelsim: A commercial software for simulation of hardware description languages)

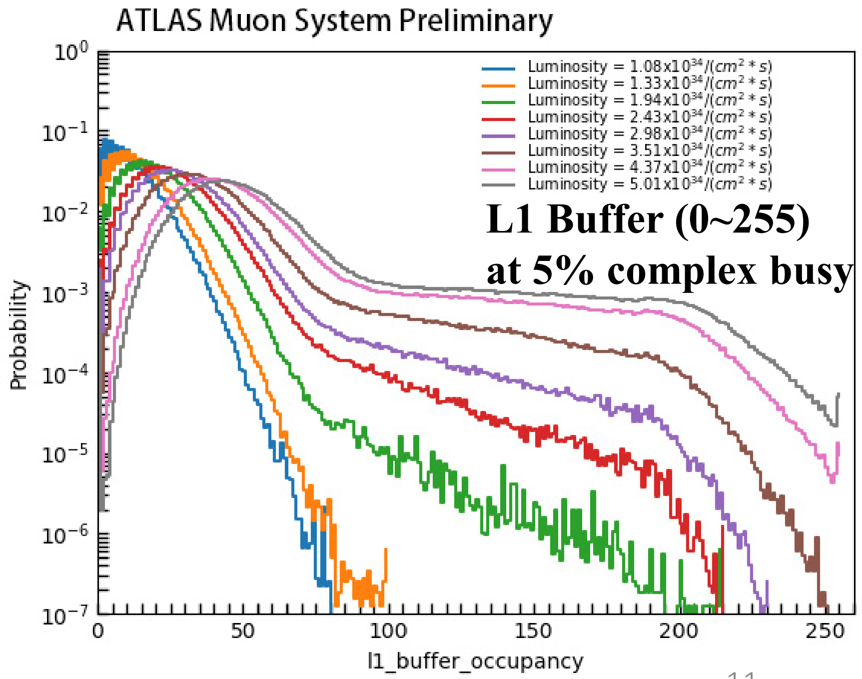
Results-Simulation for Run 3

- **BIL3C05** Triggered mode

- **More trigger bursts ➔ Higher complex busy.**
- Higher luminosity and trigger bursts results in higher buffer occupancies and more readout FIFO overflows.







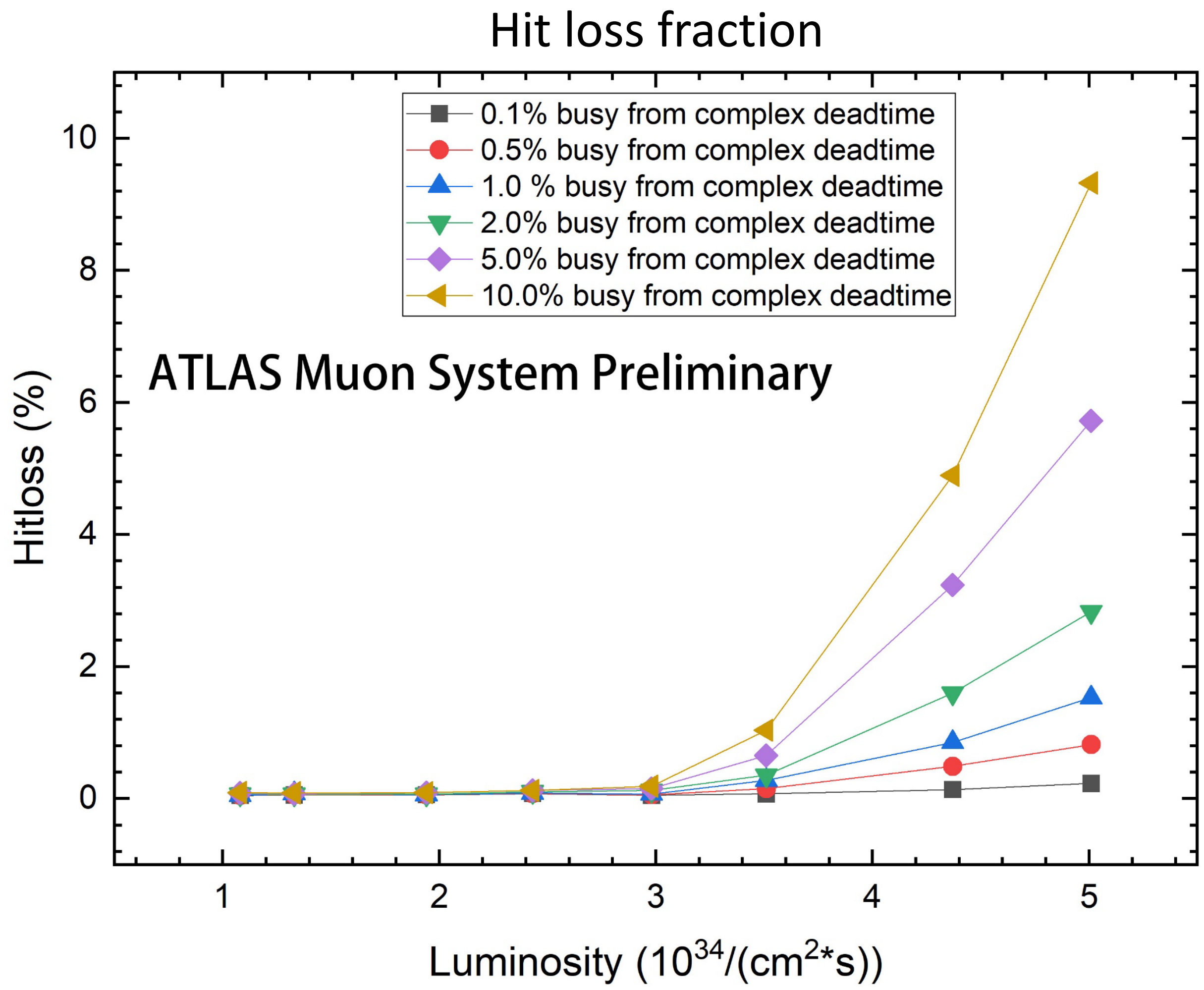
Results-Simulation for Run 3

- **BIL3C05** (hottest chamber)
- $Hit\ loss\ fraction = 1 - \frac{\#\ of\ measured\ hits}{\#\ of\ expected\ hits}$

- Lumi and trigger bursts↑ → Buffer occupancies ↑ → Overflow ↑ → Hit loss ↑

- The hit loss fraction is lower than 5% at luminosity of 5.01 x10^{34} cm^{-2}s^{-1} and 5% complex busy.

- The hit loss fractions of the EML1A05 chamber are lower than 0.1% and can be ignored overall.

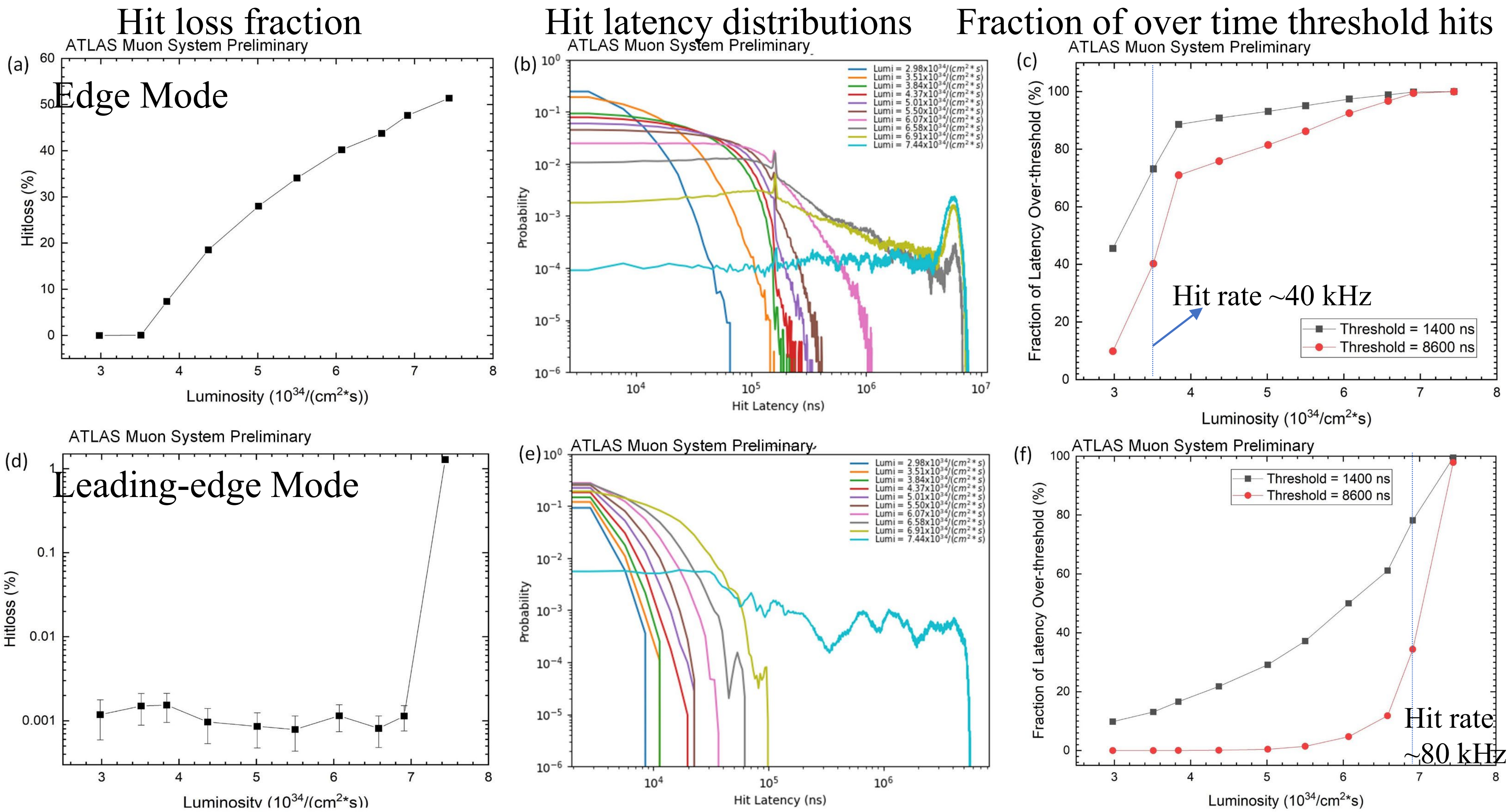


- The MDT front-ends can work without problem in Run 3 with L1 100 kHz and luminosity up to 5x10^{34} cm^{-2}s^{-1}.

Results-Simulation for HL-LHC

- **EMS4C04** (high hit rate)
- Trigger-less mode
- Hit rate ~80 kHz at Lumi 7.44×10^{34} cm^{-2}s^{-1}

- In HL-LHC period, the hits should be sent out by MDT TDC (hit latency) in 1.4 μs to be used as L0MDT trigger, and 8.6 μs to be readout.



- The fraction of over 8.6 μs hits is lower than 5% for hit rates below 80 (40) kHz of leading edge ONLY (both edge) mode, in line with theoretical value. It reaches almost 100% at max lumi even on leading-edge mode.
- The hits from EMS4C04 with the present mezzanines can not be used for both of trigger and readout.

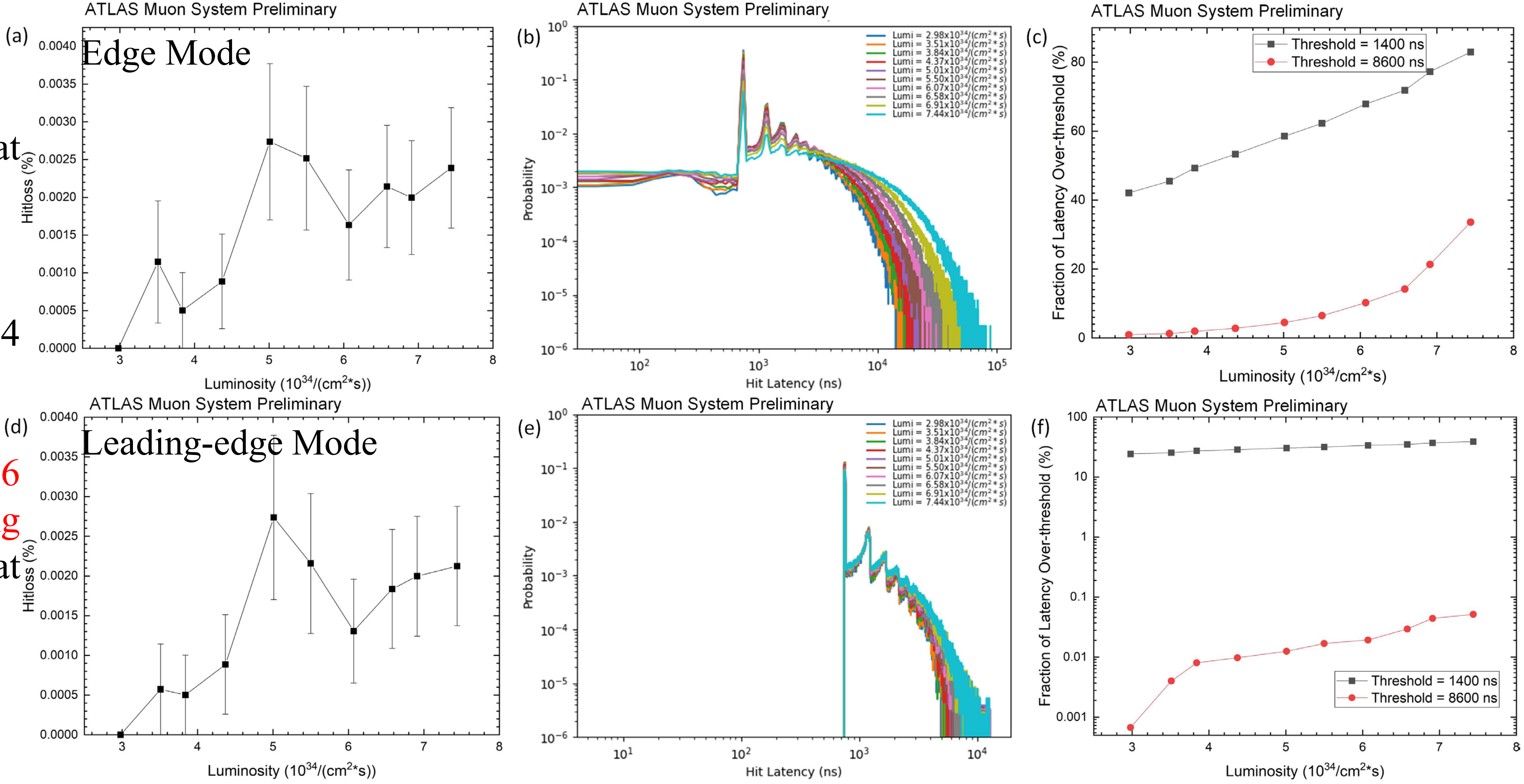
Results-Simulation for HL-LHC

Hit loss fraction | Hit latency distributions | Fraction of over time threshold hits

- **BOL3A13**(low hit rate)
- Trigger-less mode
- Hit rate < 40 kHz at Lumi. 7.44×10^{34} $cm^{-2}s^{-1}$

- The fractions of over 1.4 μs hits are 30% or more.

- The fractions of over 8.6 μs hits are tiny on leading edge ONLY mode even at max lumi.



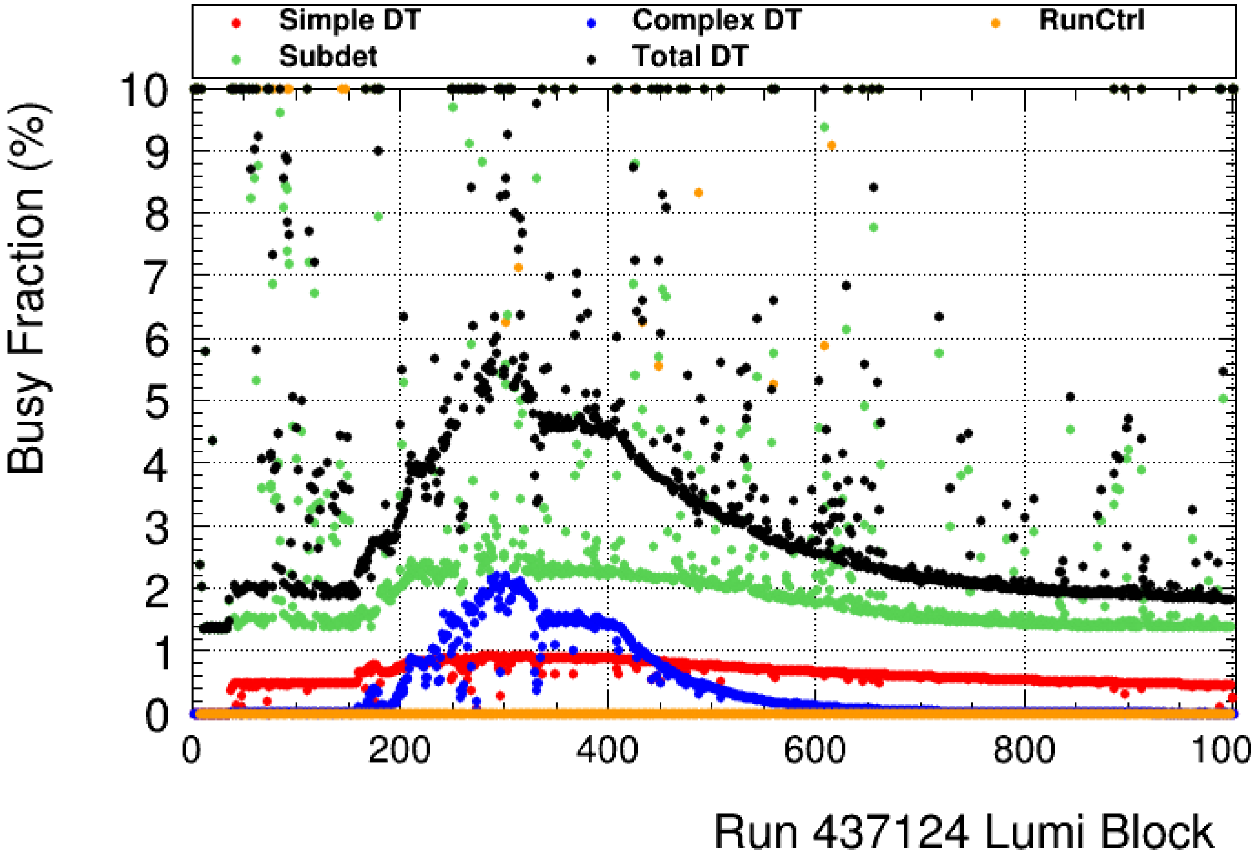
- The present mezzanines in low hit rate chambers (< ~80 kHz) could be used with leading edge ONLY mode for readout, but hits from those mezzanines could not be used for triggers in L0MDT.

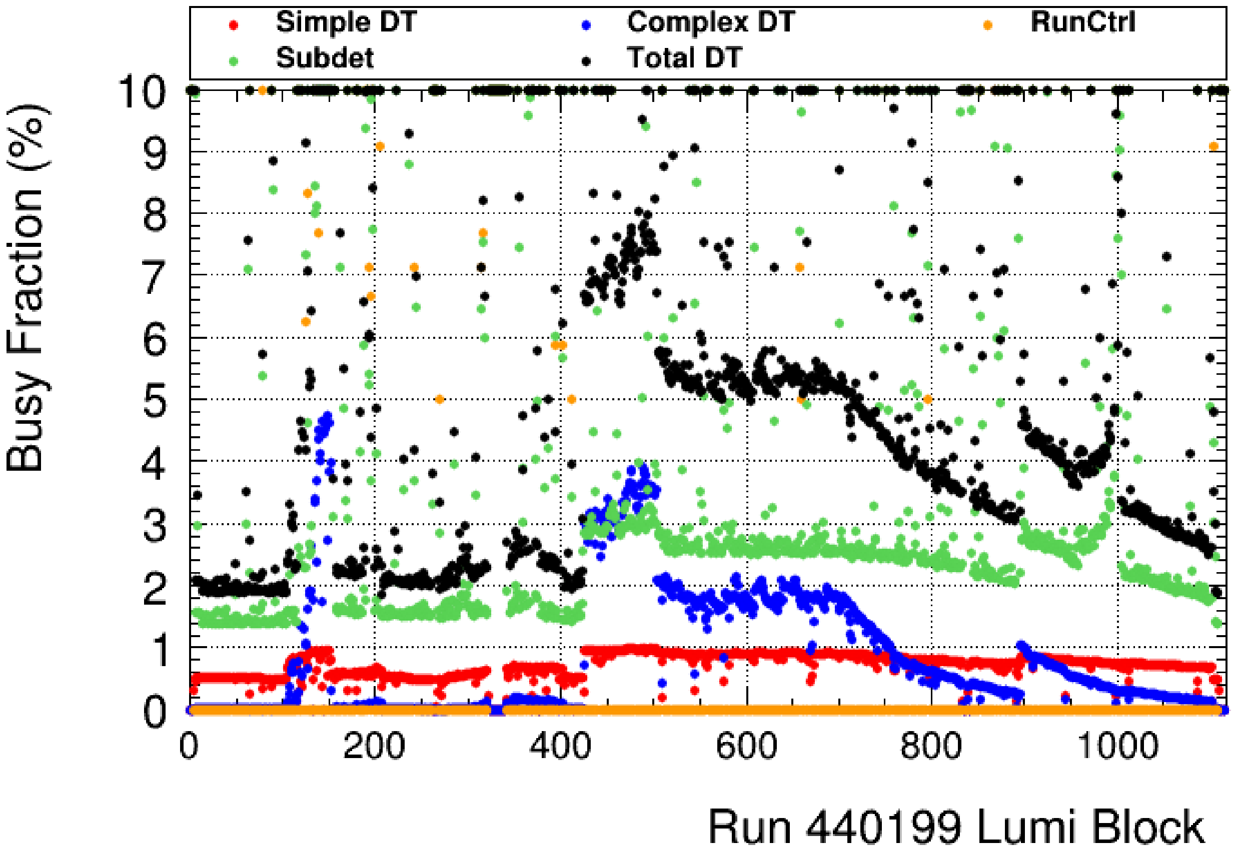
Summary

- Simulations have been performed of the ATLAS Muon TDC (AMT) for the MDT chambers;
- The hit loss fractions are strongly correlated with AMT buffer overflow;
- **For Run 3 (AMT on triggered mode):**
  - The hit loss fraction is lower than 5% even the luminosity reaches 5.01 $\times 10^{34}$ $cm^{-2}s^{-1}$ at L1 rate 100 kHz, which is perfectly acceptable;
  - The hit loss fractions in end-cap chambers are negligible;
  - AMT will work without problem under conditions of high luminosity and L1 100 kHz in Run 3.
- **For HL-LHC period (AMT on trigger-less mode):**
  - The hits from the chambers with the present mezzanines cannot be used as L0MDT triggers.
  - The current mezzanines on the low hit rate chambers (< ~80 kHz) could be used in readout at leading edge ONLY mode, i.e., without hit charge/ADC measurement.

Backup

L1 Busy Fraction in real situation





Hit Loss Fraction

- **Hit Loss Fraction Estimation**
- Hit loss fraction = 1 – (# of measured hits) / (# of expected hits)

- **Measured hits :** leading edges recorded by the AMT simulation from L1;
- **Expected hits:** leading edges in the trigger matching window

- Most of the hits from AMT simulation are same with expected hits.

Time measurement results

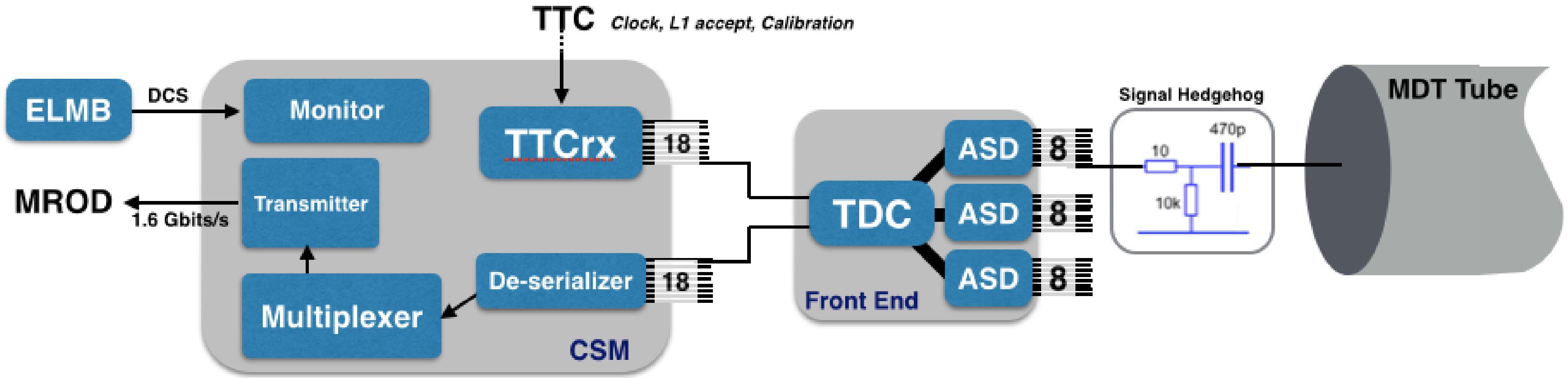
5	9382.81	12500.00	192.97
14	9450.78	12500.00	260.94
2	9564.84	12500.00	375.00
19	9571.88	12500.00	382.04
8	10086.72	12500.00	896.88
0	10317.19	12500.00	1127.35
6	29413.28	32550.00	173.44
18	29582.81	32550.00	342.97
6	29998.44	32550.00	758.60
12	30004.69	32550.00	764.85
2	30054.69	32550.00	814.85
8	30111.72	32550.00	871.88
22	30304.69	32550.00	1064.85
13	34842.97	37500.00	653.13
23	34962.50	37500.00	772.66
21	35012.50	37500.00	822.66
19	35083.59	37500.00	893.75
20	35198.44	37500.00	1008.60
2	35239.84	37500.00	1050.00
12	35317.97	37500.00	1128.13
20	35198.44	38450.00	58.60
2	35239.84	38450.00	100.00
12	35317.97	38450.00	178.13
14	35475.00	38450.00	335.16
8	35541.41	38450.00	401.57
11	36475.78	39450.00	335.94
10	36532.03	39450.00	392.19
7	36725.00	39450.00	585.16
5	36769.53	39450.00	629.69
13	36923.44	39450.00	783.60
6	37021.88	39450.00	882.04
0	37077.34	39450.00	937.50
16	37106.25	39450.00	966.41
14	37180.47	39450.00	1040.63
8	37210.16	39450.00	1070.32
12	37229.69	39450.00	1089.85
8	37210.16	40500.00	20.32
12	37229.69	40500.00	39.85
17	37352.34	40500.00	162.50

Expected hits

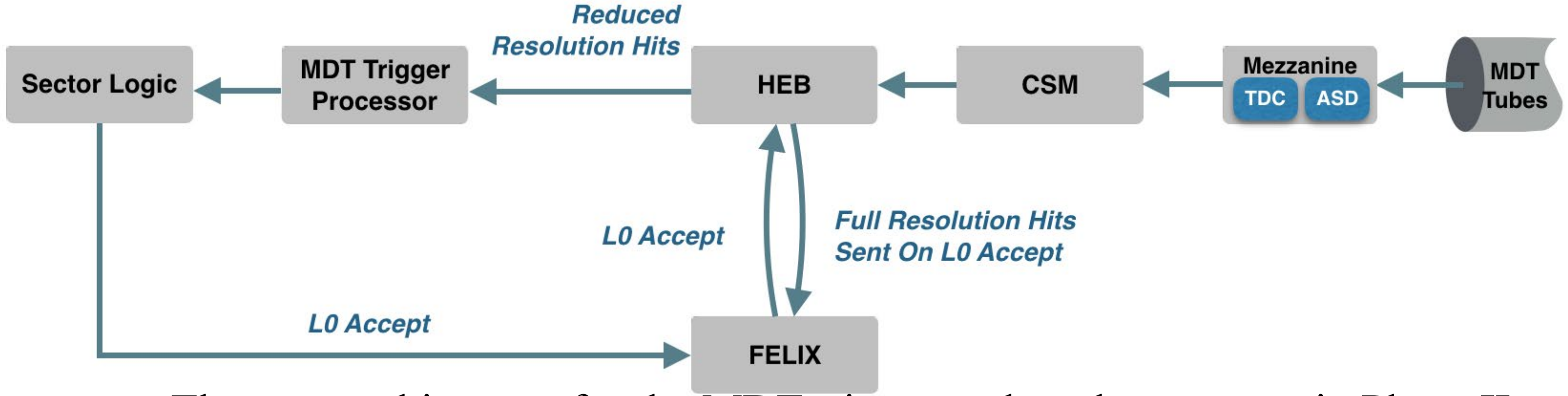
192.969
260.938
375
382.031
896.875
1127.34
173.438
342.969
758.594
764.844
814.844
871.875
1064.84
653.125
772.656
822.656
893.75
1050
1008.59
1128.12
100
58.5938
178.125
335.156
401.562
335.938
392.188
585.156
629.688
783.594
882.031
937.5
966.406
1070.31
1089.84
1040.62
20.3125
39.8438
188.281
162.5
290.625
273.438
353.125

Simulated hits

MDT trigger and readout system



Block diagram of the present MDT trigger and readout system



The new architecture for the MDT trigger and readout system in Phase II.

Latency considerations for trigger and readout in HL-LHC period

In HL-LHC period, L0MDT and L0 latency are 2.8 µs and 10 µs. The hits should be sent out by MDT TDC in 1.4 us and 8.6 µs to be used as L0MDT and to be read out considering time of flight (from collision point to the detector, max latency about 140 ns), the tube drift time (max ~700 ns), and fiber from CSM to L0MDT (max ~110 m, latency ~550 ns)