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Upgrade of the ATLAS MDT Readout and Trigger for the HL-LHC

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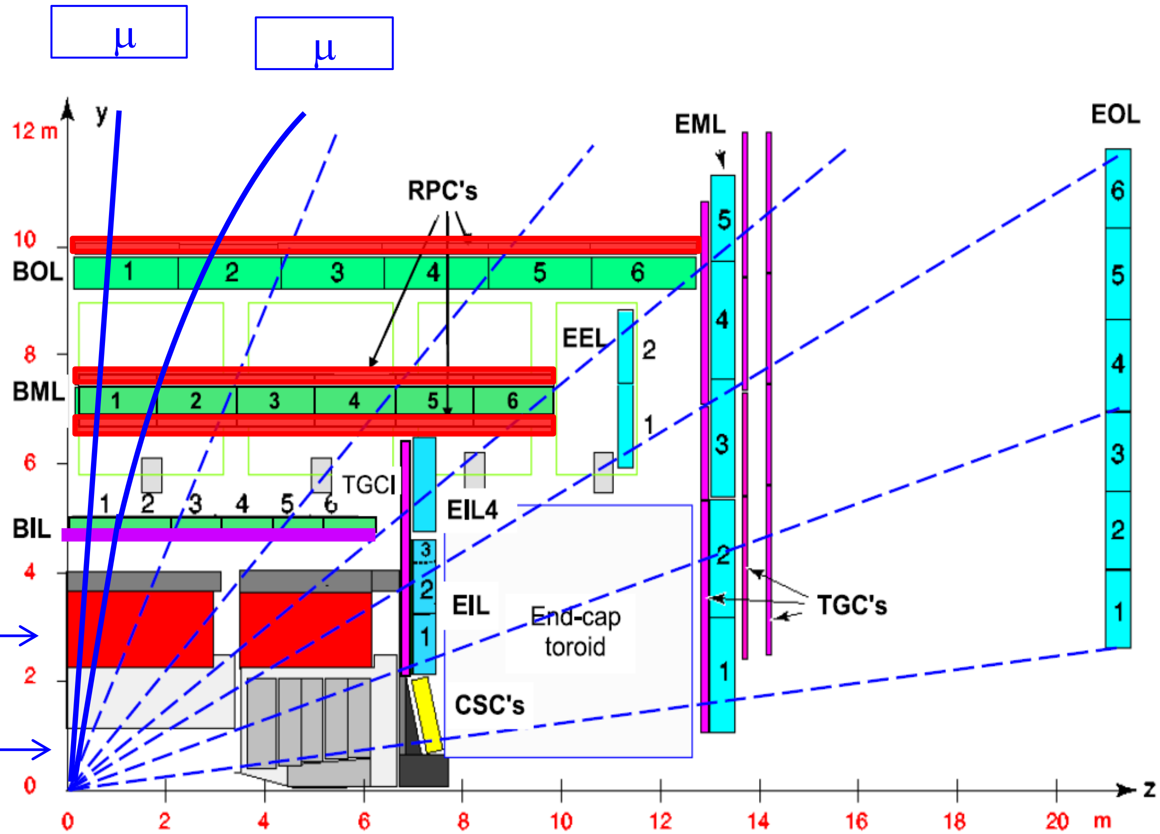
On behalf of the ATLAS Muon Collaboration

Structure of ATLAS

Muon detector

Calorimeters, absorbing γ's, electrons and jets

Inner Detector, recording charged tracks



→ At the HL-LHC, there will be 200 events per BX in the ID with ~ 1000 tracks per event and 40 MHz of beam crossings.

→ What does this mean for muon detection?

The HL-LHC Challenge

NB: $10^{34}/(cm^2*s) = 10^{10}/(barn*s)$

Rates from the inelastic p-p cross section

	Phase-I	Phase-II
σ (pp)	evt. rate [kHz]	evt. rate [kHz]
88 mb	880.000	6.600.000

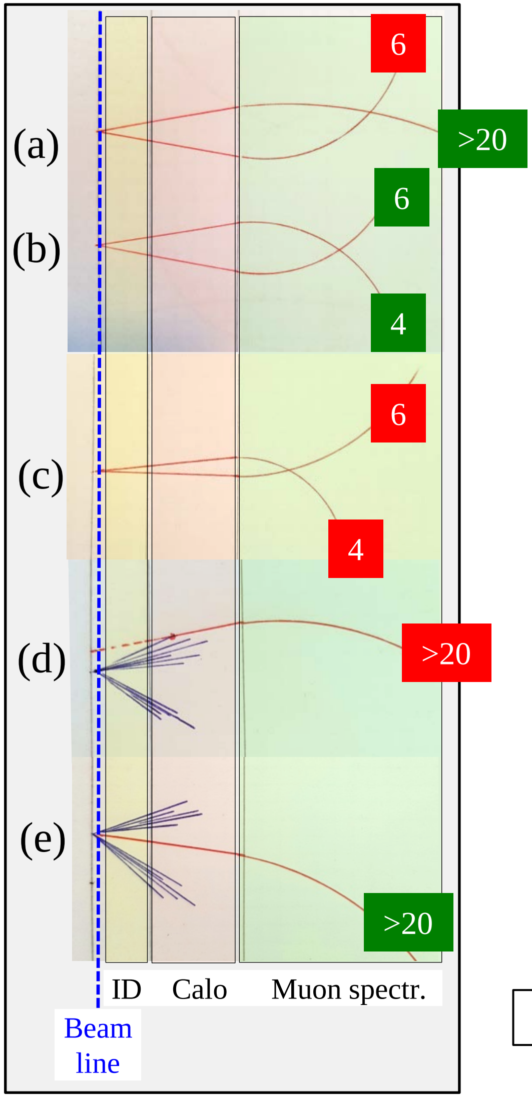
Rates seen in the Muon Spectrometer

		Phase-I	Phase-II
> p_T	σ (μμ)	evt. rate [kHz]	evt. rate [kHz]
6 GeV	8800 nb	88	660
10 GeV	930 nb	9,3	70
20 GeV	40 nb	0,4	3,0

Muons most interesting for physics →

- At the collision energy of 7+7 TeV we face a p-p cross section of 88 mb.
- At a luminosity of 7,5 * 10^{34} $cm^{-2}s^{-1}$ (Phase-II), this corresponds to ~200 evts/beam crossing (BX) with ~ 10^{12} tracks/s seen by the Inner Detector!
- Only a few of them are muons, able to penetrate the calorimeter.
- From those reaching the Muon Spectrometer, only a small fraction is interesting for physics. A p_T threshold of 20 GeV gives a σ of 40 nb and a rate of 3 kHz.
- The muon rate seen by a single chamber is even much lower. → A readout bandwidth of a few kbps would, theoretically, be sufficient.

A look at frequent μ-signatures at the LHC



Isolated μ-pairs (a) to (c), coming from the IP vertex.

a) At least one muon with p_T > 20 GeV („high-p_T") → Single Muon Trigger

b) Two muons, one of them with p_T > 6 GeV → Di-muon Trigger
The 2 muons may come from decays of, e.g.:
Z (92 GeV), J/Ψ (3.10 GeV), Y (9.46 GeV)

c) A muon pair with a very small opening angle → small invariant mass. May be rejected, if outside a given mass window.

Muons (d) and (e) in the presence of jets

(d) This μ is close to a jet and fails to extrapolate to the IP
→ most likely comes from an in-flight decay of π or K
→ to be rejected

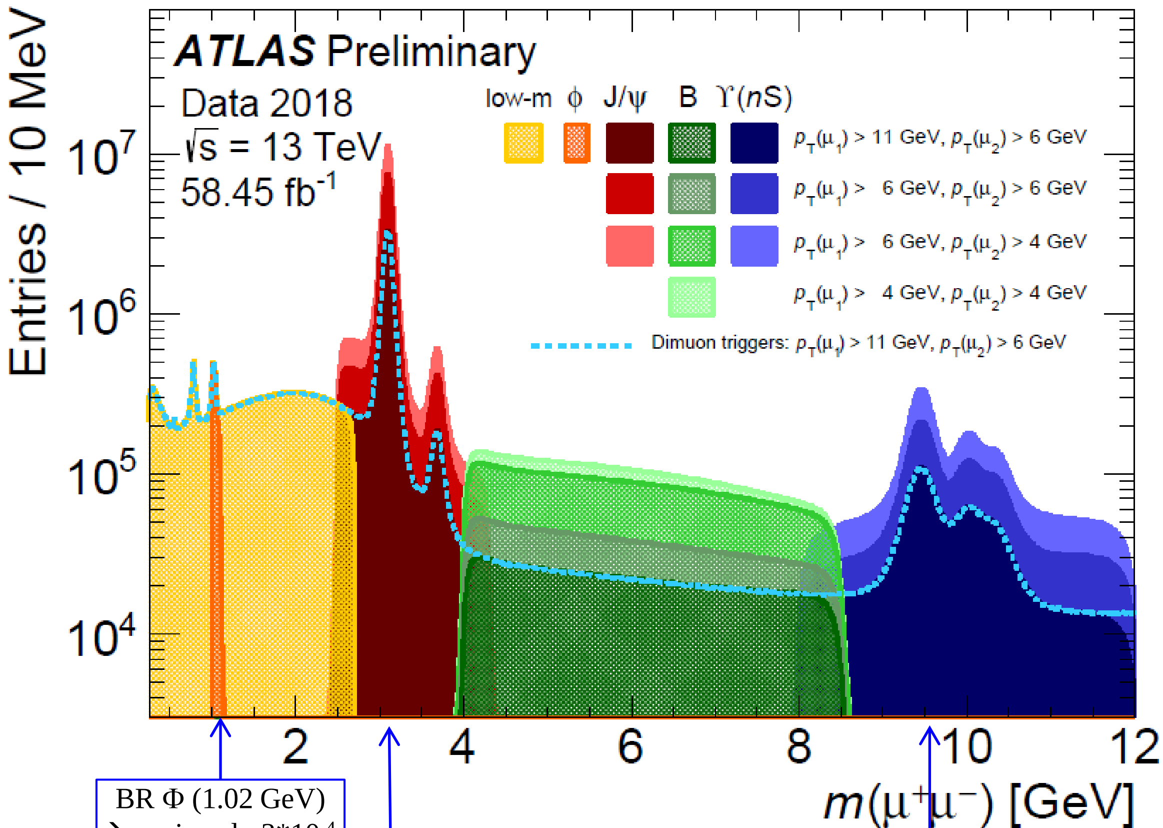
(e) High-p_T muon is well separated from jets („isolation")

→ retained for L0

NB: Diagrams are schematic. Track curvatures are strongly exaggerated.

Looking at the invariant μμ-mass in Phase-I

Invariant mass of μμ-pairs, tagged by the Di-muon trigger



BR Φ (1.02 GeV)
→ μμ is only $3*10^{-4}$

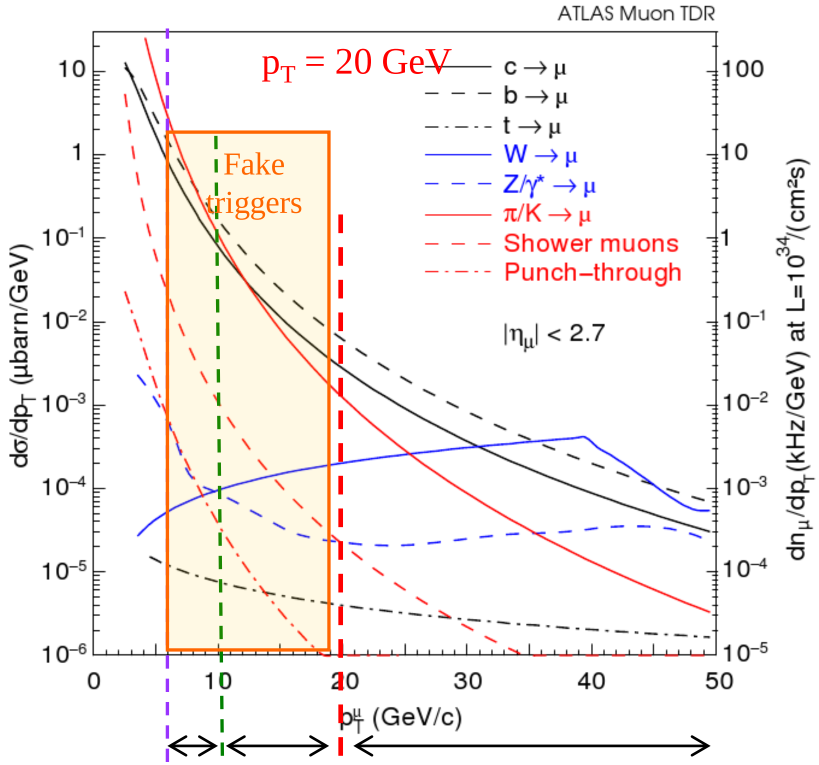
BR J/Ψ(3.1 GeV)
→ μμ is 6 %

BR Υ (9.46 GeV)
→ μμ is 2.5 %

The plot shows the recorded rates of Φ, J/Ψ and Υ as a function of the invariant $\mu^+\mu^-$ mass and of thresholds for the di-muon trigger.

→ Muon pairs with know mass are instrumental for the overall energy calibration of the Muon Spectrometer

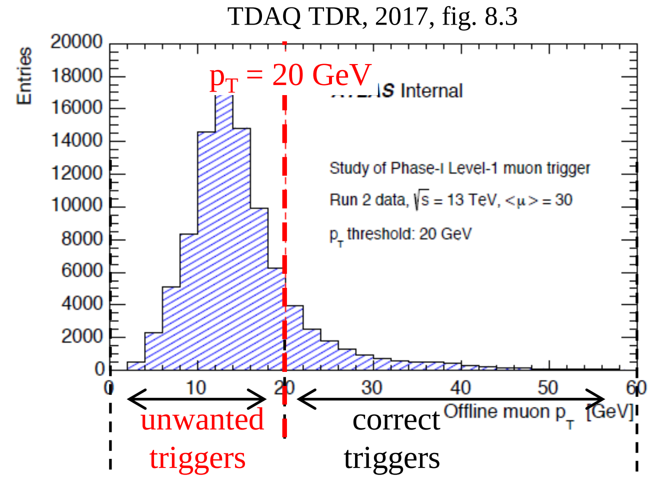
The inclusive μ Spectrum and Selectivity for Single Muon Tracks in Phase-I

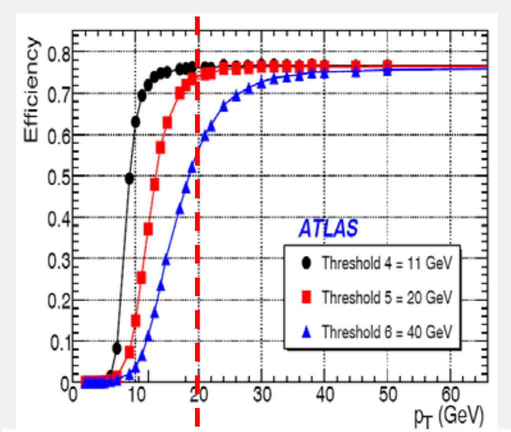


				Most interesting for physics
σ	[nb]	7900	890	40.0
trg. rt. Ph-I	[kHz]	160	8.9	0.4
trg. rt. Ph-II	[kHz]	1200	67	3.0

NB: Trigger rates are calculated from cross sections. Were not achieved in experiments!

TDAQ TDR, 2017, fig. 8.3



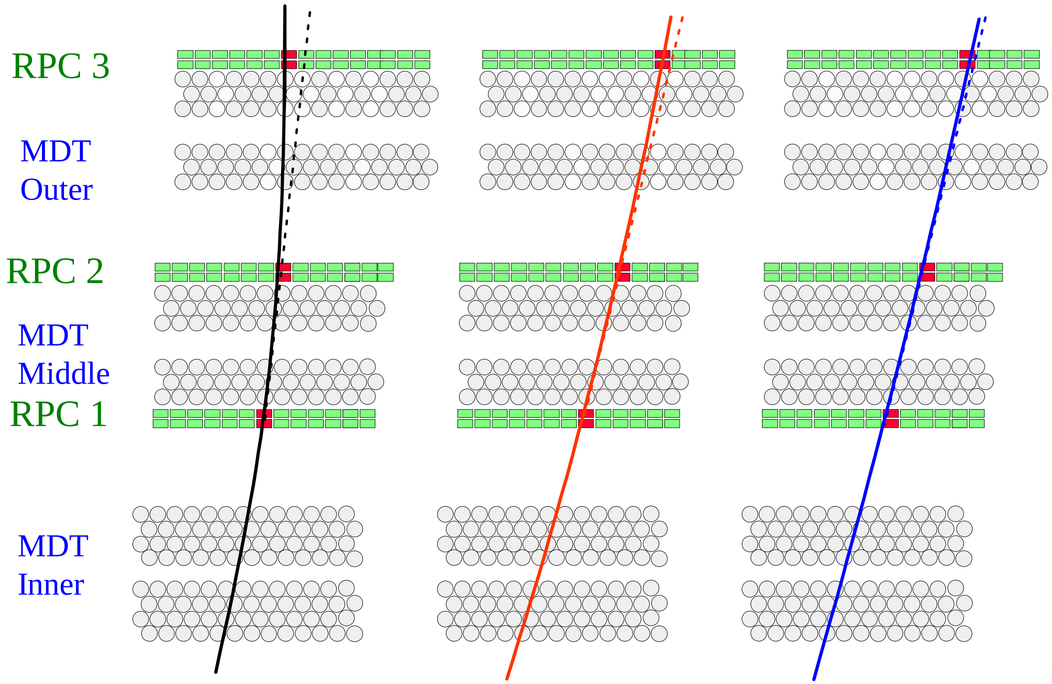


Rate of single muon triggers depends on the p_T resolution of the trigger system. → Need high spatial resol. along the track to keep rates down.

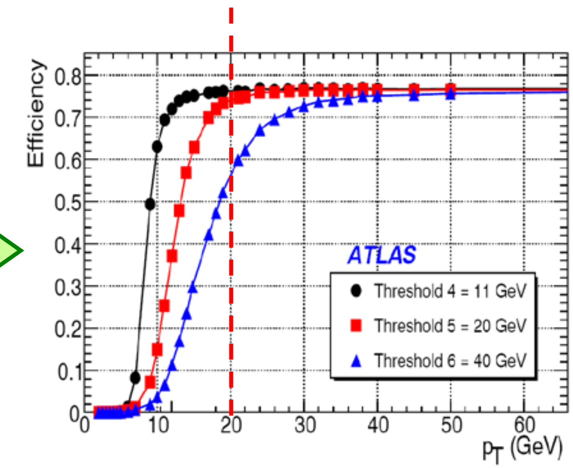
p_T Resolution of in the Single Muon Trigger in Phase-I

(Example Barrel)

schematic, not to scale



← RPC strip width ~30mm → σ ~ 10 mm



← MDT accuracy is σ ~ 0.1 mm

p_T	10 GeV	20 GeV	40 GeV
sagitta	48 mm	24 mm	12 mm
$\sigma_\mu > p_T$:	890 nb	40 nb	3 nb
theoret. trig. rt. at HL-LHC	30 kHz	3.0 kHz	0.3 kHz

The RPC trigger is blind for small deviations from a straight track due to insufficient spatial resolution. → Accepts many muons below 20 GeV.

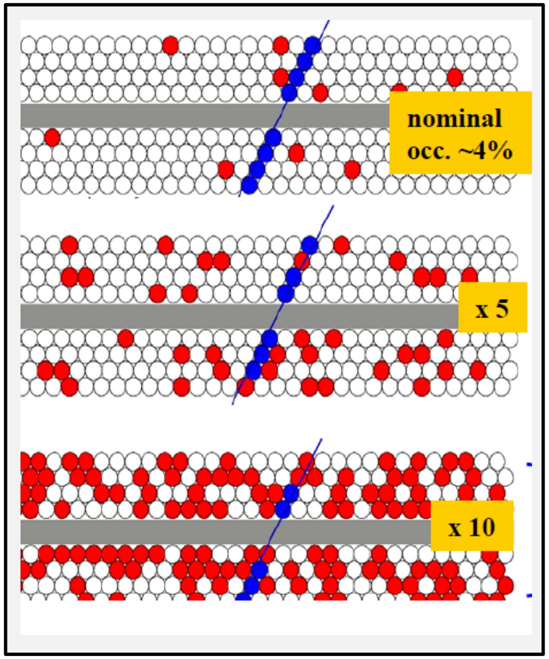
Using the MDT hits for L1:

(a) much better spatial resolution

(b) increase of track length due to the Inner MDT layer

(c) improved pointing accuracy to the IP due to the Inner MDT layer

The Cavern background of converted n/γ

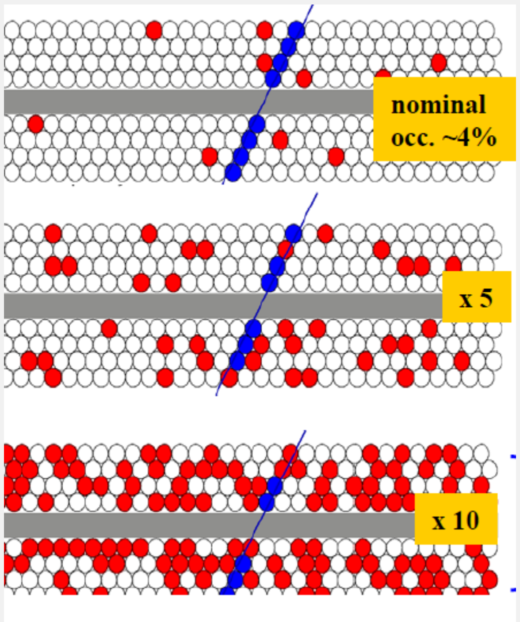


In ATLAS γ-rays create a large number of accidental hits in the MDT tubes. No way to distinguish them from „good“ muon hits!

Two problems:

- γ-hits can mask a muon hit → reduced efficiency and spatial resolution
- readout of the γ hits requires big readout bandwidth

Combining RPC/TGC and MDT info in the presence of γ-background



Hopeless:

Standalone identification of muon tracks in the MDT due to γ/n background.

Need a hint from the trigger chambers:

a) need coordinates for trigger candidates (RoIs) and BX to which they belong → know t0 of drift time → know co-ordinate in MDT

b) wait until…
- … MDT drift is over (< 750 ns)
- … MDT data have been read out
- … decision about track-to-RoI match is done

In Phase-I this method did not fit inside available latency!

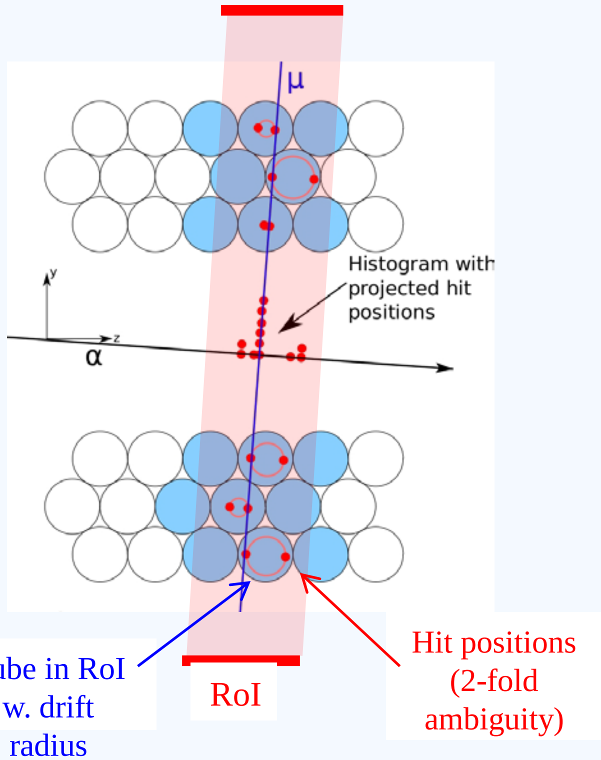
3 Methods proposed for MDT track finding:

As an example: the histogramming method

The Histogramming Method & Results from Simulation

The histogramming method

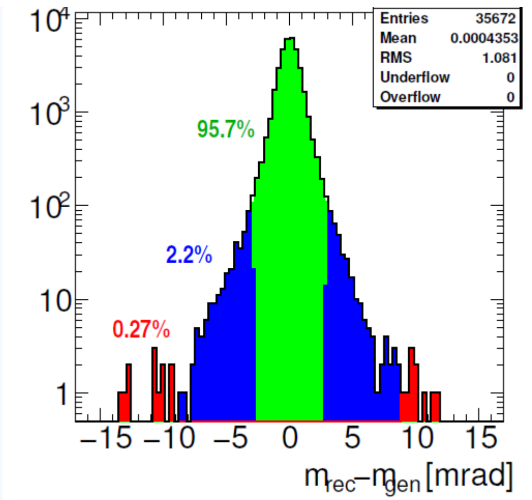
Projecting the hits along the direction, given by the RPCs. This yields the most likely trajectory.



Simulation

Taking into account inefficiencies due to

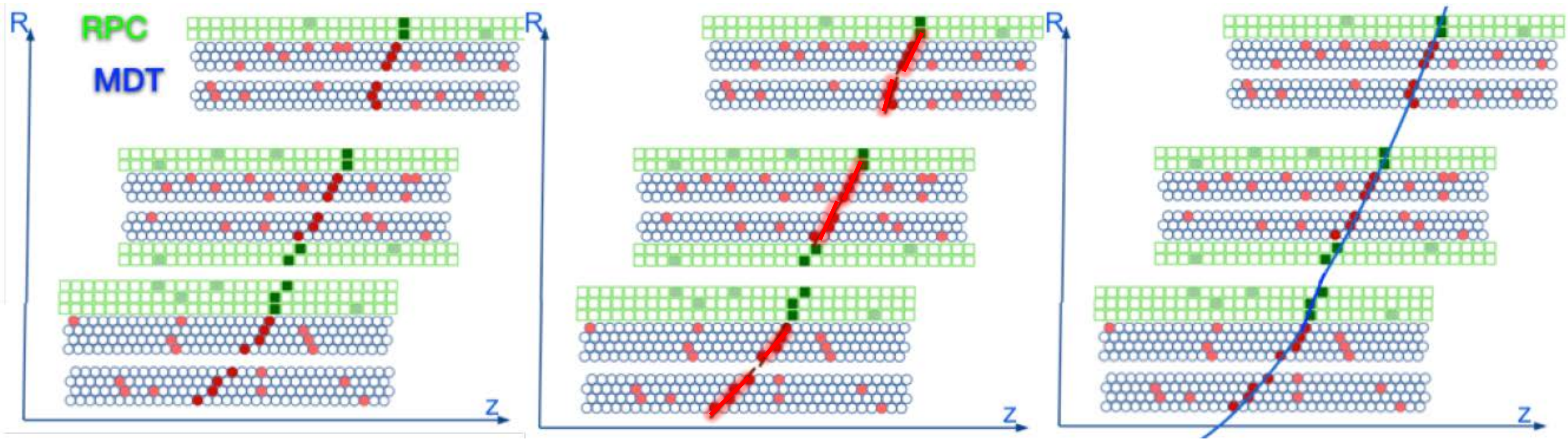
- inert material (MDT walls)
- corruption by δ-rays
- masking of „good" hits by cavern background (10% occup. assumed)



The diagram shows the difference between generated and reconstructed slopes for 35 k events. Categories are good, medium and poor for Δm < 3, < 9 and > 9 mrad.

For 96% of the tracks, the MDT coordinates provide a substantial improvement of slope and position measurement.

Finding MDT Track helped by the RPC



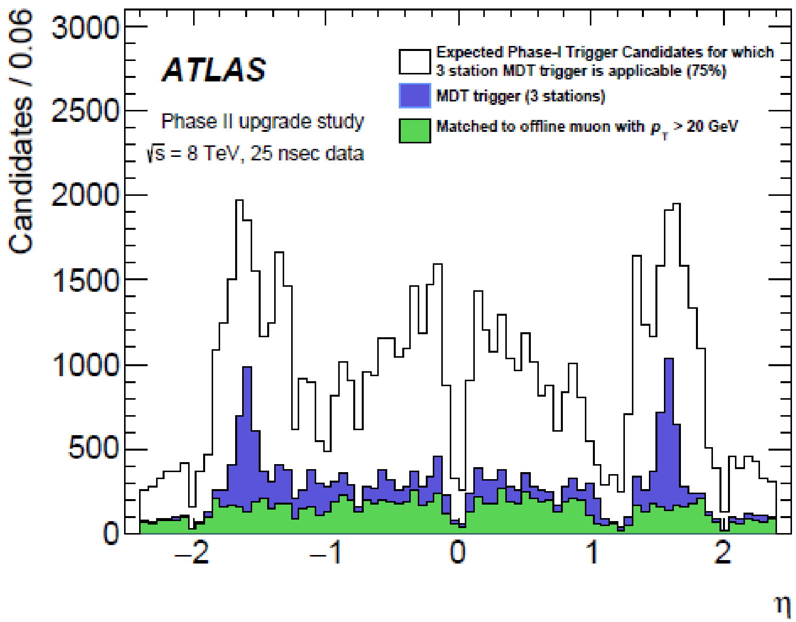
(a) get the raw hit pattern from the MDT

(b) find track segments using RoI from the RPC

(c) link the segments, determine sagitta and p_T

From K. Ntekas, march, 20, 2018

Expected reduction of low-p_T fake triggers using the MDT



ATLAS Muon TDR, 2017, fig. 3.17

The η distribution of muon candidates selected with a first-level p_T threshold of 20 GeV

- White: distribution before Phase-II
- Blue: Using MDT info at L1
- Green:
  → Full off-line analysis, fitting tracks in the Muon Spectrometer to corresponding tracks in the ID
  → Using a detailed magnetic field map in the transition region btw. Barrel and EC toroids

→ Factor ~ 4 rate reduction

Muon Trigger budget in Phase-II vs. Phase-I

Triggered at 75 kHz → Phase-I

Triggered at ~ 1 MHz → Phase-II

	Phase-I	Phase-II	Event Filter Rate
	kHz	*kHz*	*kHz*
single μ	15,5	**38**	**1,5**
di - μ	5,2	**10**	**0,2**
single e	27	**200**	**1,5**
di - e	1,7	**40**	**0,2**
others	25,6	771	7,0
total	**75**	**1059**	**10,4**

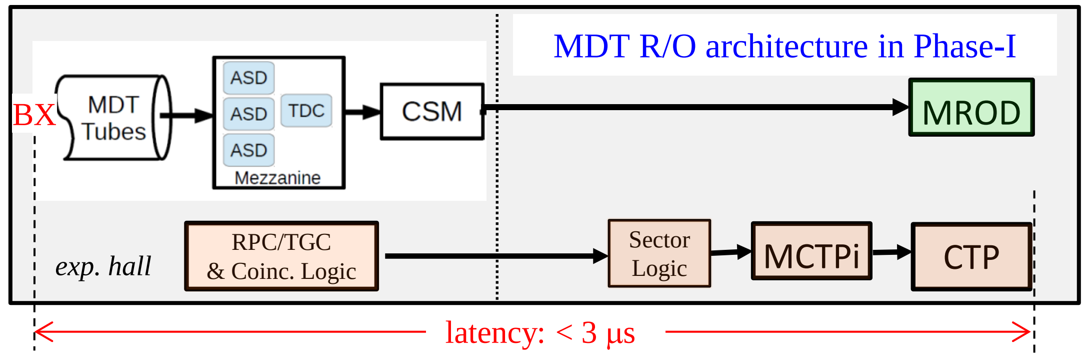
The EF performs offline-like analysis. Only ~1 % retained for permanent storage!

→ Due to the expected sharpening of the 20 GeV trigger threshold, the muon trigger budget requires only an increase of about a factor of 2, while the total trigger rate will increase by a factor of > 10.

Data from TDAQ TDR, table 6.4 (Dec. 2017)

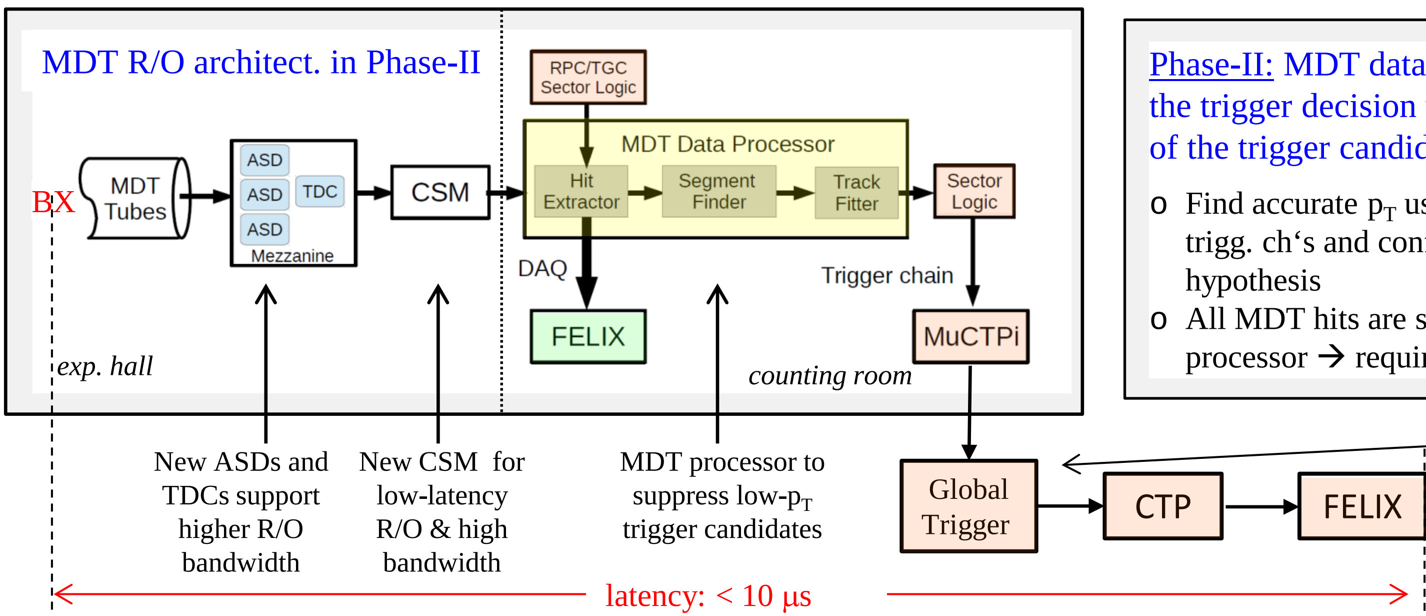
The L0MDT trigger: Technical Implementation

The MDT R/O architecture in Phase-II



Phase-I: MDT & Trigg. chambers are read out independently

- MDT R/O only on L1 trigger, saving bandwidth
- Trigg. ch's use hardware logic at the frontend to select trigger candidates

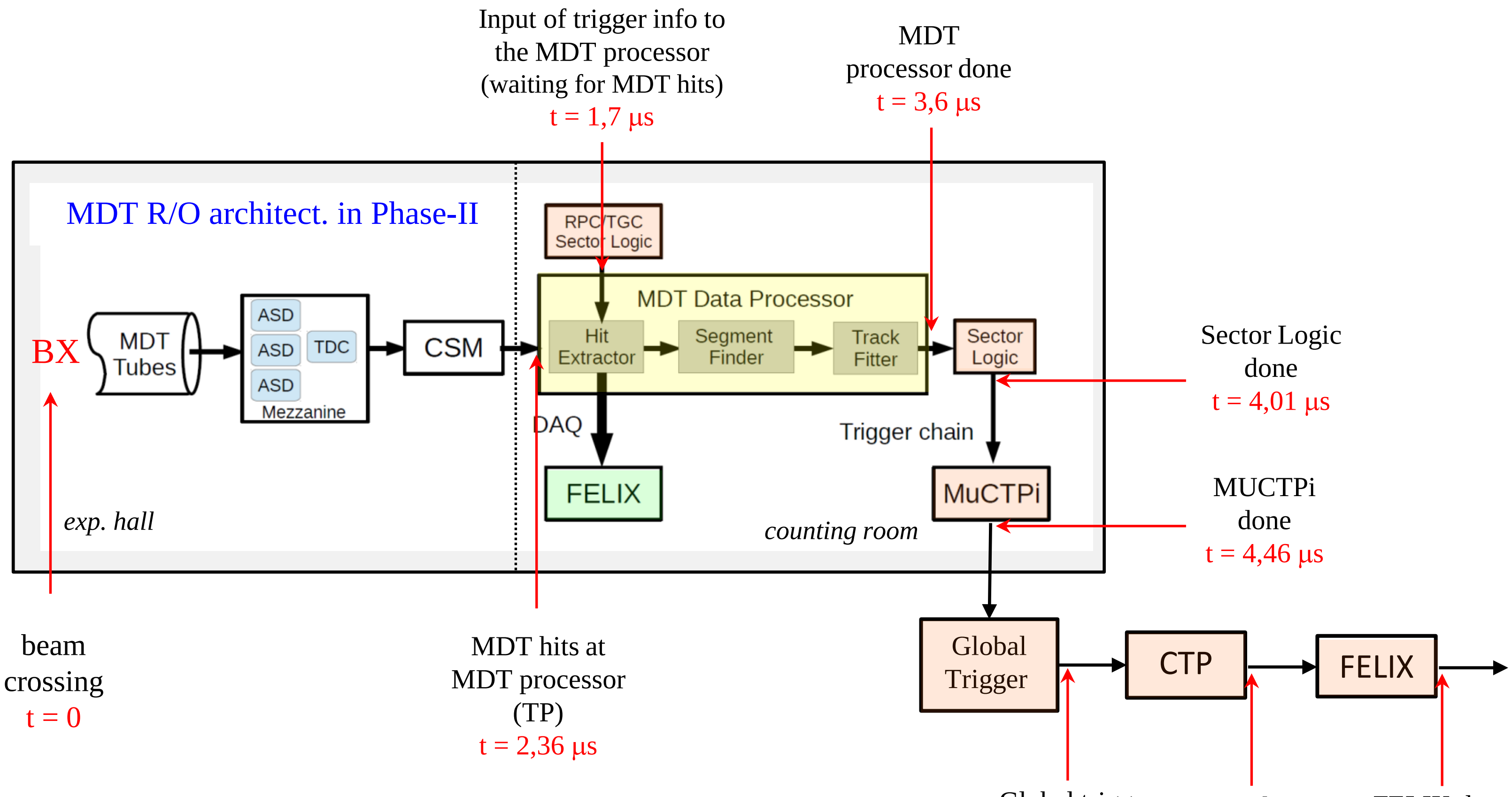


Phase-II: MDT data are used to sharpen the trigger decision w.r.t. the muon pT of the trigger candidate

- Find accurate p_T using ROI seed from trigg. ch's and confirm/reject trigger hypothesis
- All MDT hits are streamed to MDT processor → requires higher bandwidth

General concept of chamber readout: move decision making to the counting room:
(a) can combine info from various trigger sources (b) easy to service (c) no problems with rad-tol

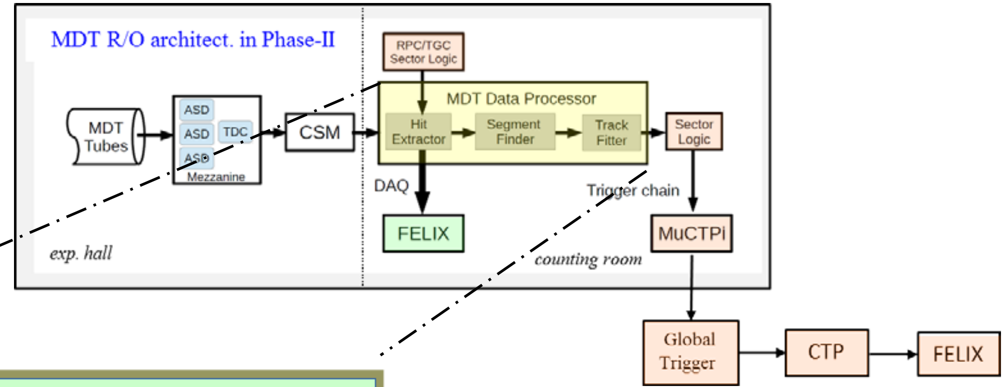
Accumulation of Latency along the Muon Trigger Path



Best estimate for L0 trigger latency:	6,9 µs
Maximum estimated latency value:	9,1 µs
Maximum allowed latency:	10,0 µs

Data from TDAQ TDR, table 5.5 (Dec. 2017)

Zooming into the MDT Trigger Processor

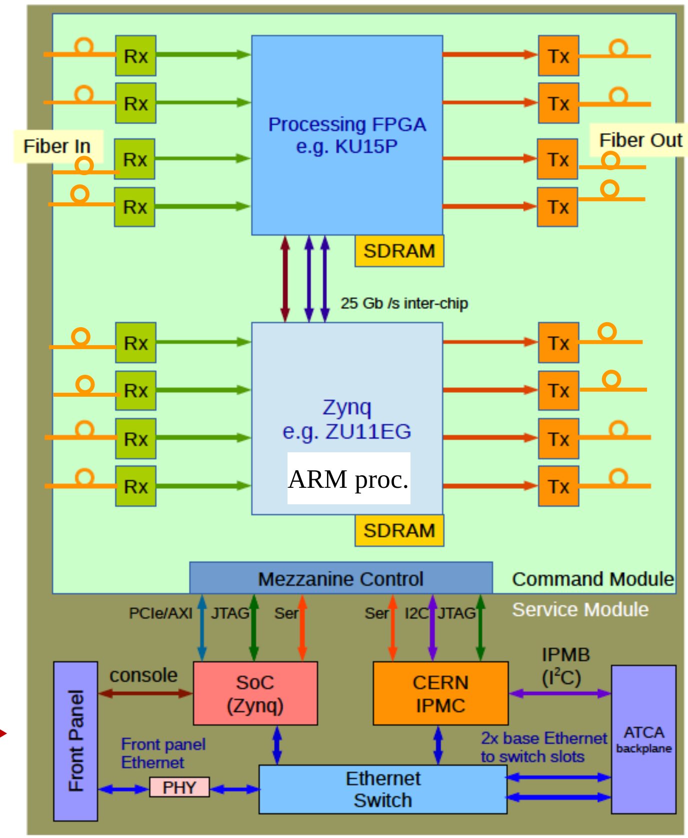


MDT data from Barrel Middle and Inner

SL of this Sector

MDT data from Barrel Outer

SL of this Sector



back to SL

to FELIX

to CSM

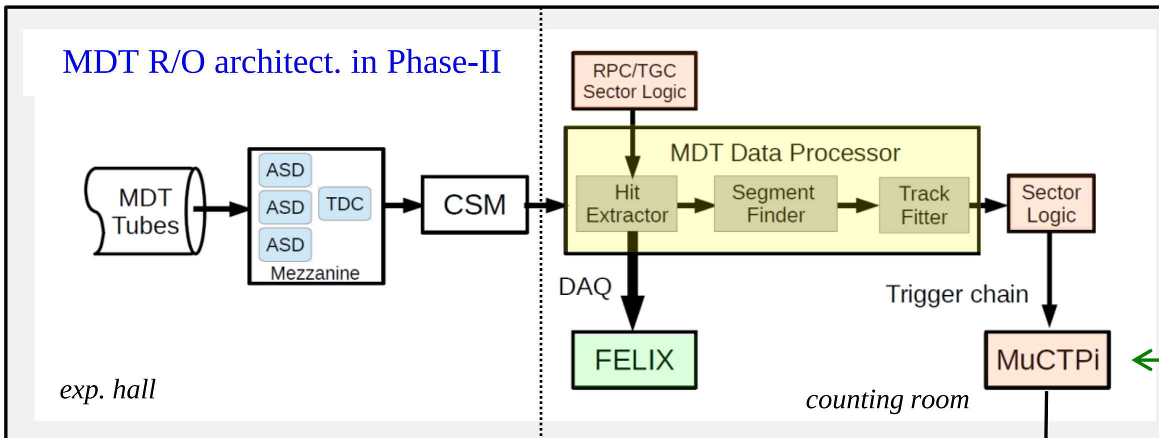
Service module for Configuration & external Communication

For more details, see paper by Eric Hazen and poster by Davide Cieri at this workshop.

The Step-by-Step Refinement of the L0Muon Trigger

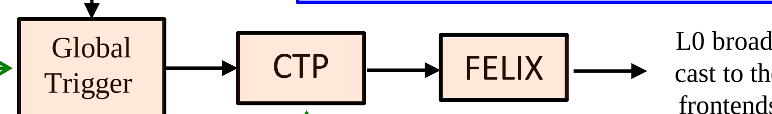
(a) The MDT Processor: Refinement of the p_T measurement

NB: due to limitations of latency and R/O bandw., tracking info from the ID is not available at L0 (cf. slide 12).



(b) The MUCTPI sees data from all sectors

- suppress double-counting of tracks (MDT sector overlap!)
- define trigger candidates



(c) The Global Trigger sees Muon and Calo trigger objects. Can run „offline-like“ algorithms. E.g.: require

- invariant mass of μμ inside limits
- isolation btw. muon and jets

(d) The CTP: controls

- trigger menu
- performs prescaling
- takes final L0 trigger decision

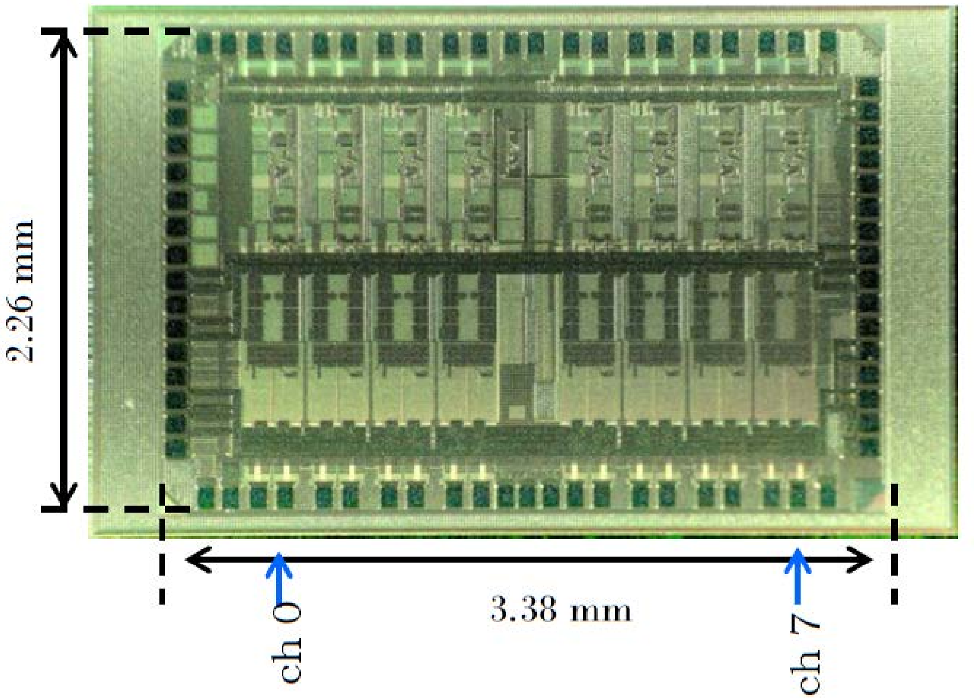
Data from TDAQ TDR, table 5.5 (Dec. 2017)

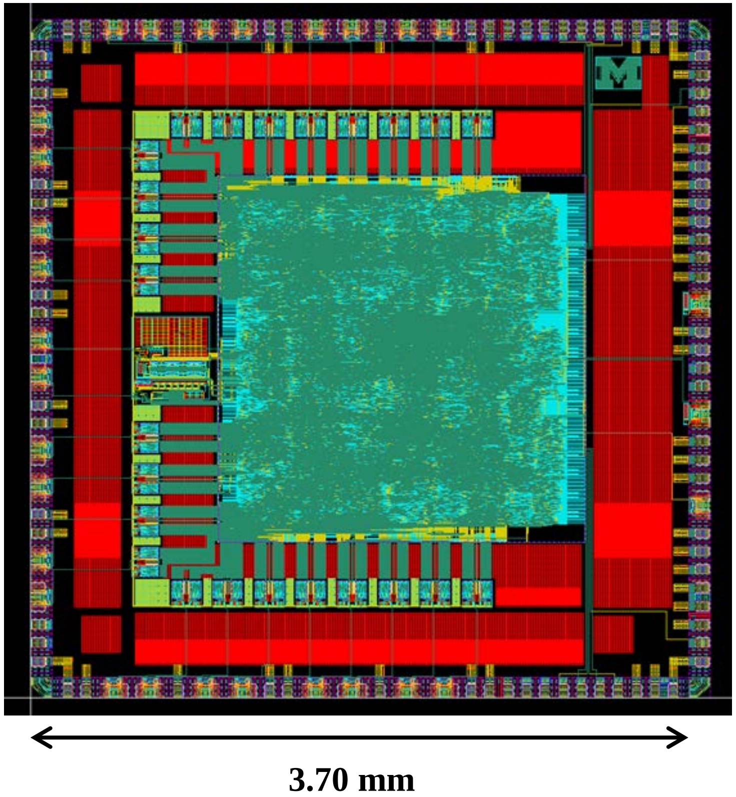
Implementation of h/w for the MDT trigger

Compo-nent	Function	# of devices	technology	Performance Criteria	Status (aug. 2019)
ASD ASIC	8-ch preamp	60 k	IBM/GF 130 nm	gain, thresh. matching, ENC, functionality	7k devices from engineering run are under test
TDC ASIC	24-ch	20 k	TSMC 130 nm	bandwidth, latency, transm. rate	working prototype
FE Boards	24-ch	20 k		3 different types needed	prototyping
CSM	serving 18 TDC	1.5 k	GBTx, FPGA	transmission rate, latency, data integrity	prototyping
L0 Muon Trigger	serving 3 MDT	1.5 k	GBTx, FPGA, Zync, ARM proc.	p_T determination, latency, interface to SL, transmission speed	prototypes

→ Prototyping, testing, production of Hardware is well under way

Newly developped ASICs for the MDT Readout





8-channel ASD in 130 nm IBM/GF technology. 7k chips from the enineering run are presently under test. Dimensions are 3.38 x 2.26 mm^2.

24-channel TDC in 130 nm TSMC technology. A fully functional prototype is presently prepared as production prototype for a MPW run.

Summary

Substantial reduction of the Muon trigger rate at L0 useing high precision MDT track co-ordinates.

Replacement of existing Readout Electronics for MDT and RPC/TGC due to bandwidth and L0 trigger requirements.

Development of new modules well under way. No show stoppers encountered.

Not all power consumption / cooling issues completely defined/solved yet. TC and Muon Group working on it.

SPARES

References

- TDR for the Phase-II *Upgrade of Trigger and DAQ*, ATL-COM-DAQ-2017-185, Dec. 2017
- TDR for the Phase-II *Upgrade of the ATLAS Muon Spectrometer* CERN-LHCC-2017-017 ATLAS-TDR-026. - 2017.
- Article: *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003
- Article: *The ATLAS Drift Tube Electronics*, JINST **3** (2008) P09001
- ATLAS Trigger Performance: *Status Report*, CERN/LHCC 98-15, 1998
- TDR of the ATLAS muon spectrometer: *Technical Design Report*, CERN-LHCC-97-022, CERN, 1997, URL: http://cds.cern.ch/record/331068