TWEPP19: Topical Workshop on Electronics for Particle Physics
Santiago de Compostela, sept. 2-6, 2019

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

R. Richter, MPI Munich

On behalf of the ATLAS Muon Collaboration

Concepts, Plans and Questions

- The HL-LHC challenge.
- How to find Muons?
- Good muons and bad muons.
- What do muons tell us?
- Scrutinizing the quality of the muon p_T.
- Fast trigger chambers helped by slow MDT?
- Detectors and instruments.
- The hard currency in triggering: latency.
- The construction program for the MDT Readout.
- The Muon Trigger in the ATLAS trigger community.
- Summary.

The HL-LHC Challenge

The total inelastic p-p cross section

	10^{34} cm^{-2}s^{-1}		$7.5 * 10^{34}$ cm^{-2}s^{-1}	
σ [barn]	evt. rate [kHz]	evts./crossing	evt. rate [kHz]	evts./crossing
0.088	880,000	22	6,600,000	165

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

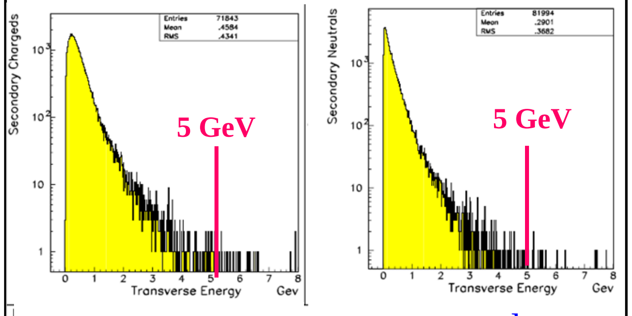
- At a luminosity of 7,5 * 10^{34} cm^{-2}s^{-1} we expect about 7 * 10^9 interactions/s = 170/BX
- Looking for muon related physics, we consider about 5 per million worth recording, i.e. ~ 35 kHz.
- How do we select them for the first level trigger?

A hopeless task?

HL-LHC Luminosities and Physics with Muons

Mother nature is helping!

p_T distrib. in minimum bias events



charged tracks

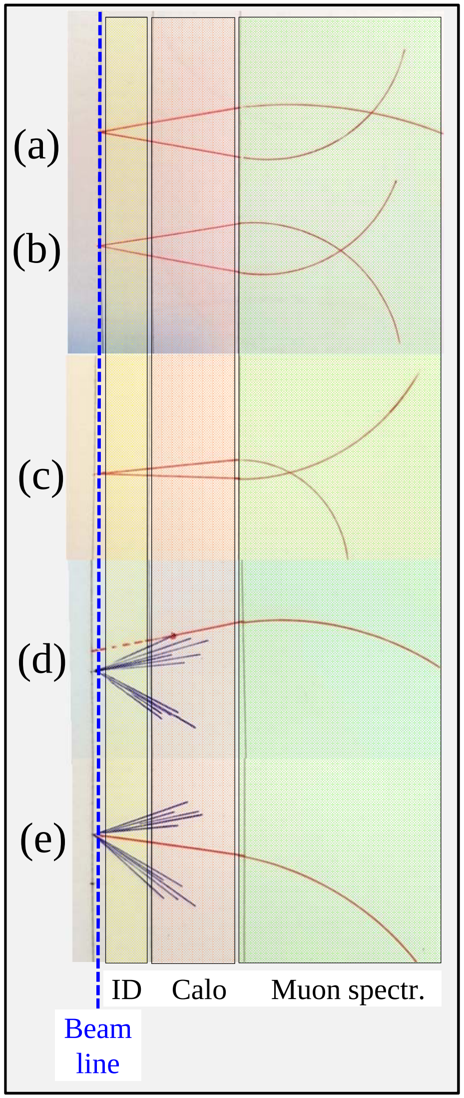
neutrals

The big majority is minimum bias, i.e. low p_T:

- Charged tracks curl inside the ID. → Do not reach the Muon Spectrometer.
- Most of the γ/e deposit little energy in the ECAL → do not reach trigger threshold of 20 GeV.
- Physicswise of no interest.
- This discards the majority of all interactions.

- „Interesting physics“ mainly comes from heavy objects (Z, W, t...), decaying into energetic leptons with high transverse momentum (p_T), typically > 20 GeV
- The μ‘s are particularly interesting:
  - authentic witnesses of the object‘s decaying habits, flying nearly unperturbed across heavy detector components
  - very rare objects: only ~ one muon in about 1000 beam crossings
- Lets give them a closer look!

Frequent μ-signatures at the LHC



Prompt μ-pairs (a) and (b), 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 by the MUCTPi if outside a predefined mass window.

(d) This μ does not extrapolate to the IP vertex and is close to a jet, most likely coming from an in-flight decay of a π or K in a jet → rejected by the Global Trigger.

(e) The angular separation of this high-p_T muon from the jets is

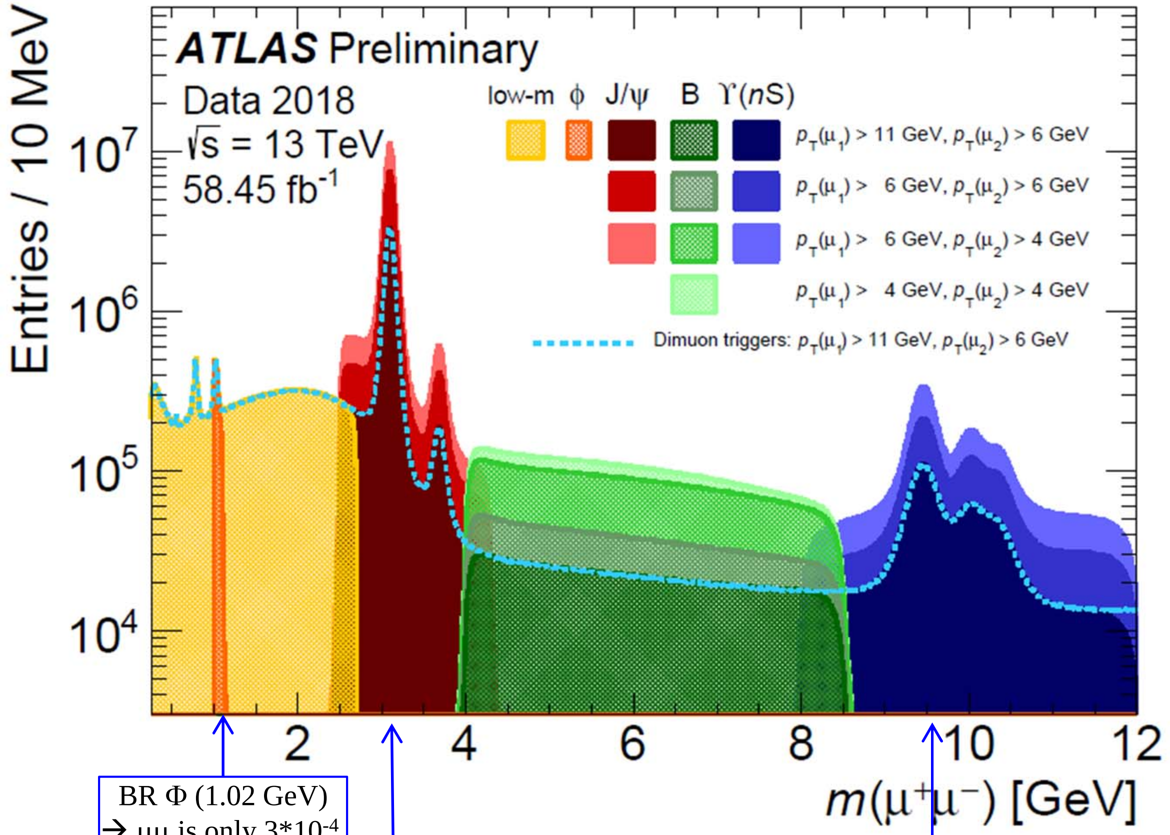
sufficiently large („isolation“) and it comes from the IP vertex.
→ retained in the Global Trigger

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

Results from the Dimuon Trigger in Run 2

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

(appying 4 sets of p_T thresholds)



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

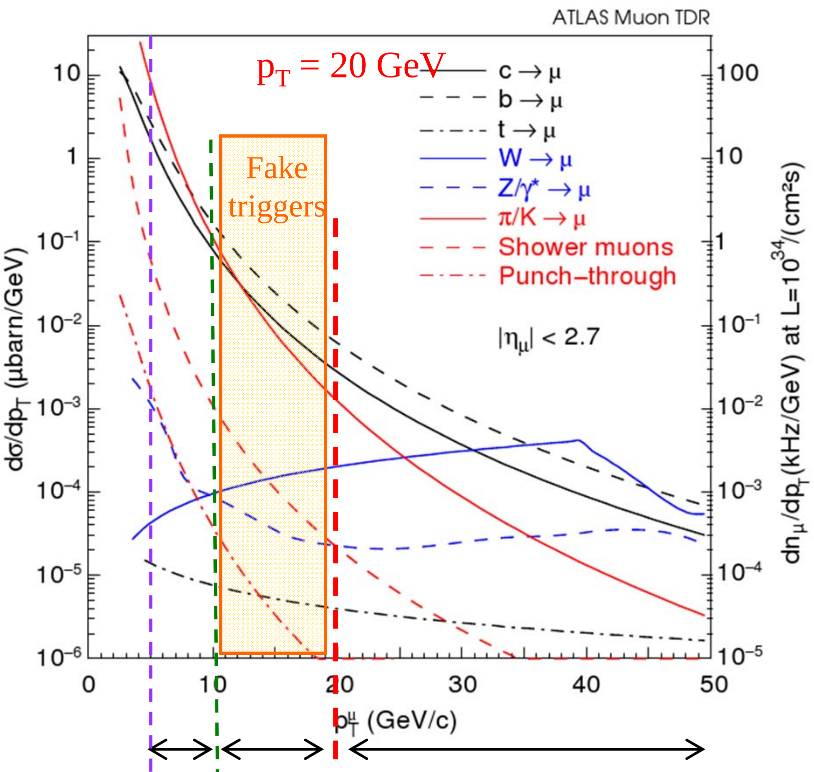
BR J/Ψ(3.1 GeV)
→ μμ is 6 %

BR Y (9.46 GeV)
→ μμ is 2.5 %

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

- → Lowering the threshold from 11 to 6 and finally to 4 leads to a signal increase of about 3.
- → In this analysis the muons from the ~10^7 J/Ψ and Z (not shown) are used for a fine-tuning of the p_T calibration in all η/ϕ regions of ATLAS.

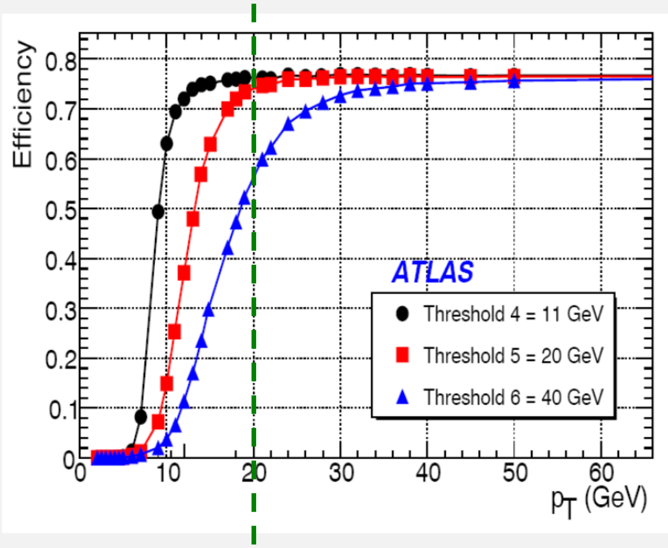
The inclusive μ spectrum and the trigger selectivity for single muon tracks



Most interesting for physics

σ	[nb]	16000	890	47
trg. rt. Ph-I	[kHz]	160	8.9	0.4
trg. rt. Ph-II	[kHz]	1200	67	3.0

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



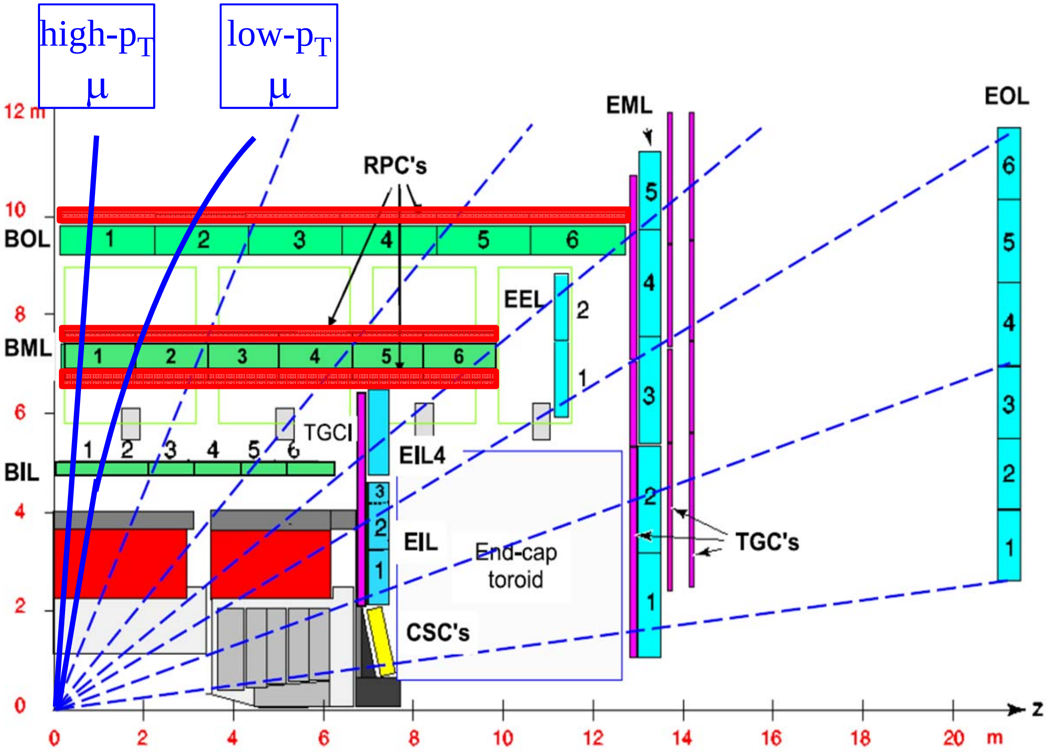
Rate of single muon triggers depends on the p_T resolution of the trigger system. → Need high spatial resol. along the track to keep rates down.

		10^{34} cm^{-2}s^{-1}		7.5 * 10^{34} cm^{-2}s^{-1}		sagitta [mm]
p_T [GeV]	σ [μb]	rate [kHz]	evts./BX	rate [kHz]	evts./BX	
6	8.8	88	0.0022	660	0.0165	100
10	0.93	9.3	0.0002	70	0.0017	60
20	0.04	0.4	1.00E-05	3.0	7.50E-05	30

From ATLAS Trigger performance 1998 (CERN/LHCC98-15)

A quick look at the structure of the Muon Spectrometer

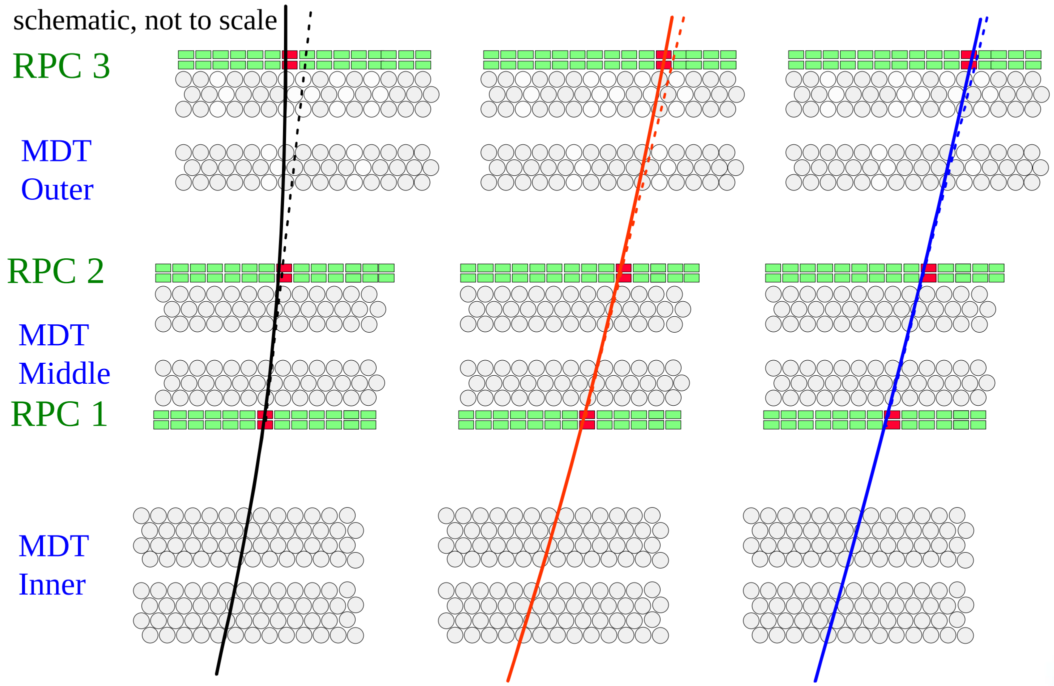
(Phase-I)



- Chambers in the MS are arranged in 6 projective sectors along η and 16 along Φ.
- In each sector , 3 layers of precision MDT are matched to 3 layers of „fast“ trigger chambers, forming a trigger tower.
- Trigger signals are processed per sector in the Sector Logic.
- Trigger info from the 192 trigger sectors is collected in 2 processors , one for barrel and EC, the MuCTPi. From there, the trigger candidate is forwarded to the CTP.
- The Readout of the MDT follows a separate path. MDT and trigger data only meet at the L2 trigger.

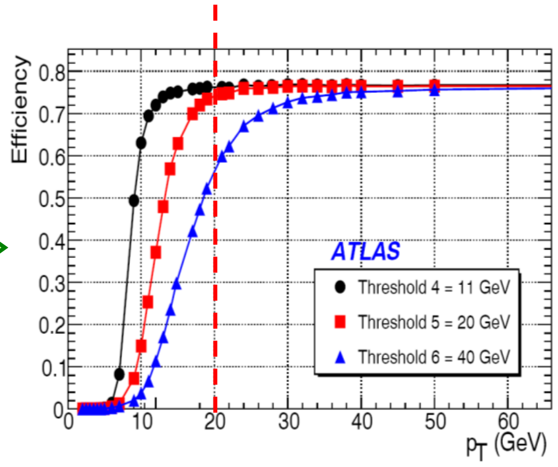
p_T resolution of in the single muon trigger in Run 1&2

(Example Muon Barrel)



p_T	10 GeV	20 GeV	40 GeV
sagitta	48 mm	24 mm	12 mm
$\sigma_\mu > p_T$:	890 nb	47 nb	3 nb
theoret. trig. rt. at HL-LHC	30 kHz	3.7 kHz	0.3 kHz

← RPC strip width ~30mm → σ ~ 10 mm



← MDT accuracy is σ ~ 0.1 mm

Using the MDT hits for L1:

(a) much better spatial resolution

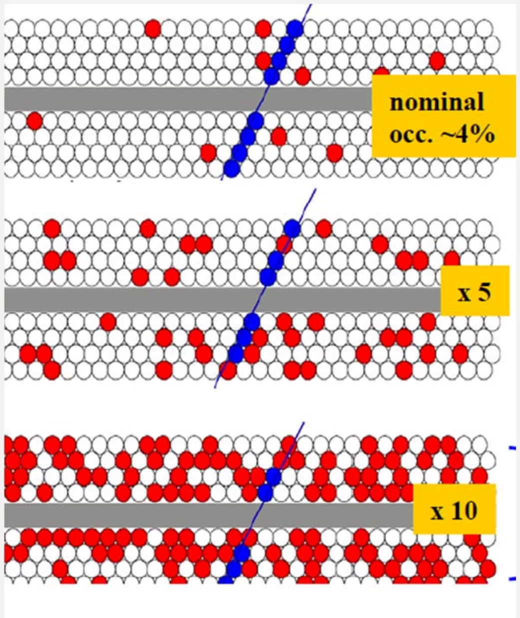
(b) increase of the track length due to the Inner MDT layer

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

(d) smarter electronics (!) needed

The RPC trigger is blind for small deviations from a straight track due to insufficient spatial resolution. → Accepts many muons below 20 GeV. Actual rate goes from 3.7 to ~ 20 kHz.

How to combine RPC/TDC and MDT info?



Hopeless:

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

Need to ask your friends from TDAQ:

a) to supply coordinates for trigger candidates from Sector Logic (RoIs)
b) to kindly wait until…
   - MDT drift is over
   - data have been read out
   - decision about track-to-RoI match is done
   - arrival of yes/no

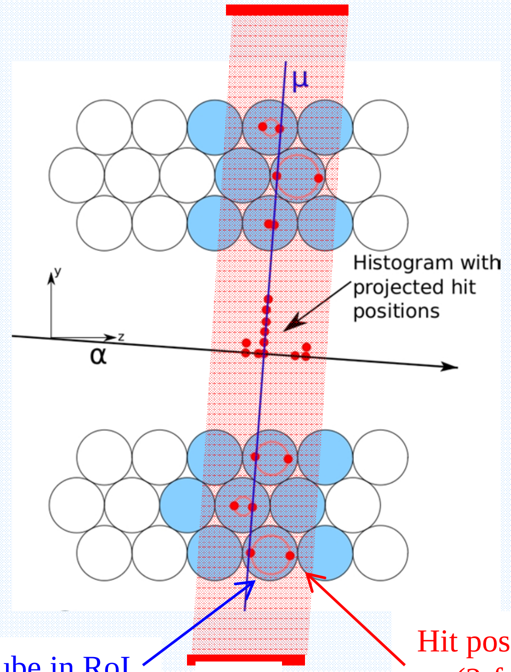
3 Methods proposed for MDT track finding:

a) the histogramming approach
b) use of the Legendre Transformation
c) use of the Associative Memory technic

The histogramming method and results from simulation

The histogramming method

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



Tube in RoI
w. drift
radius

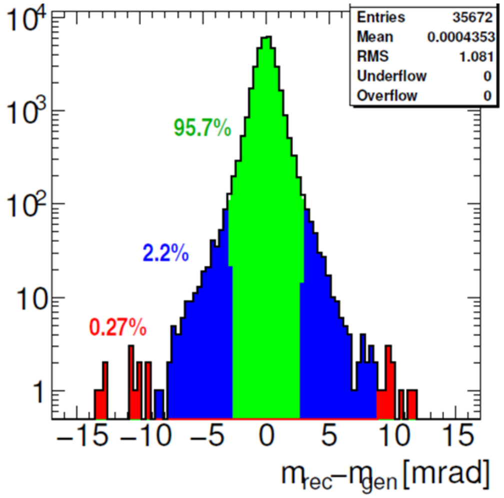
RoI

Hit positions
(2-fold
ambiguity)

Simulation

Taking into account inefficiencies due to

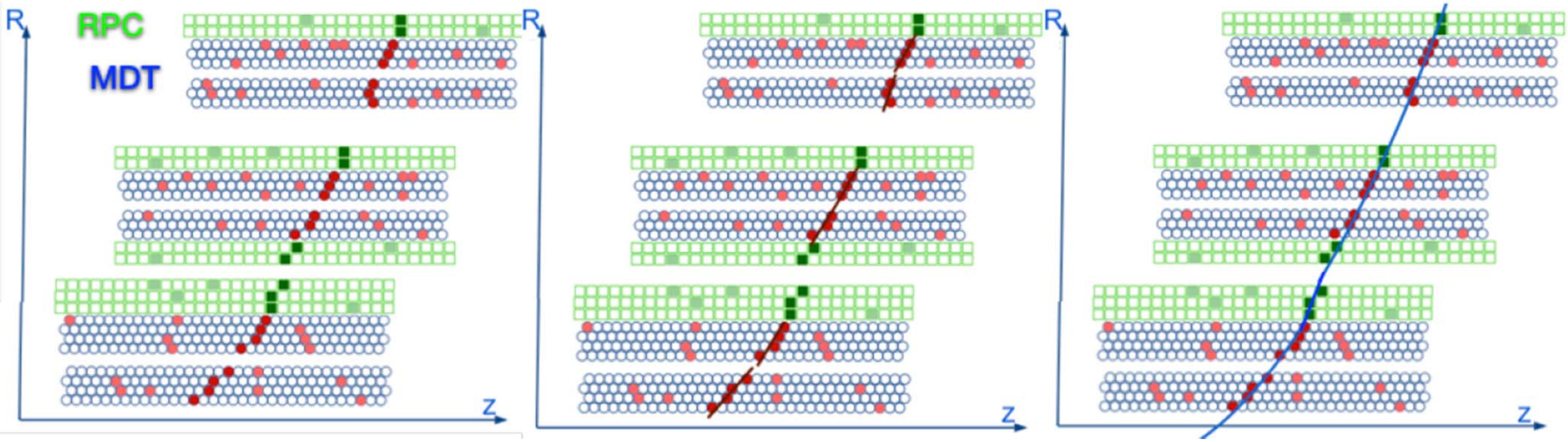
- inert material (MDT walls)
- corruption by δ-rays
- masking of „good“ hits by cavern background (10% occup. assumed)



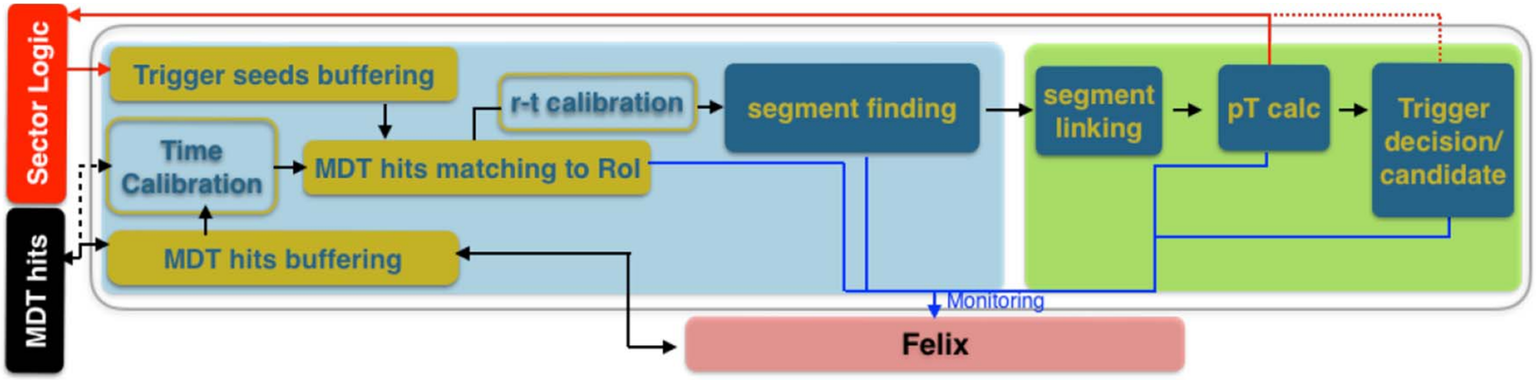
The diagram shows the difference between generated and reconstructed slopes for 35 k events. Categories are good, medium and poor for Δm < 3, < 9 and > 9 mrad.

For most tracks, the MDT coordinates provide a substantial improvement of the slope measurement.

Finding a track in a MDT

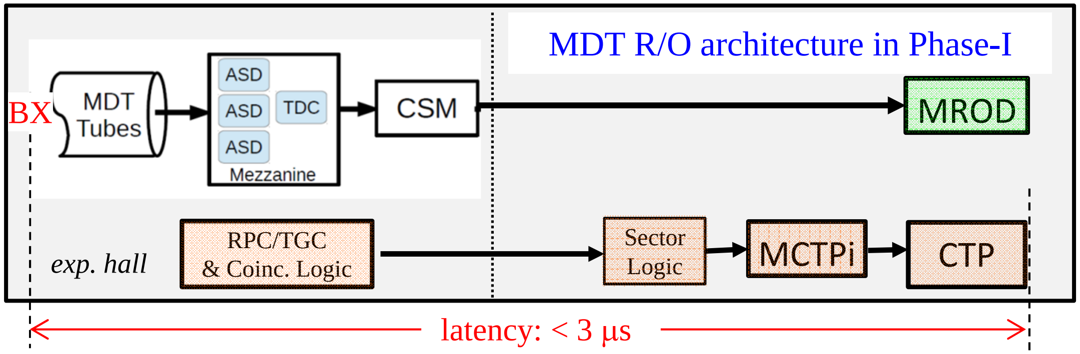


(a) get the raw hit pattern from the MDT (b) find track segments using RPC seeds (c) link segments and determine p_T



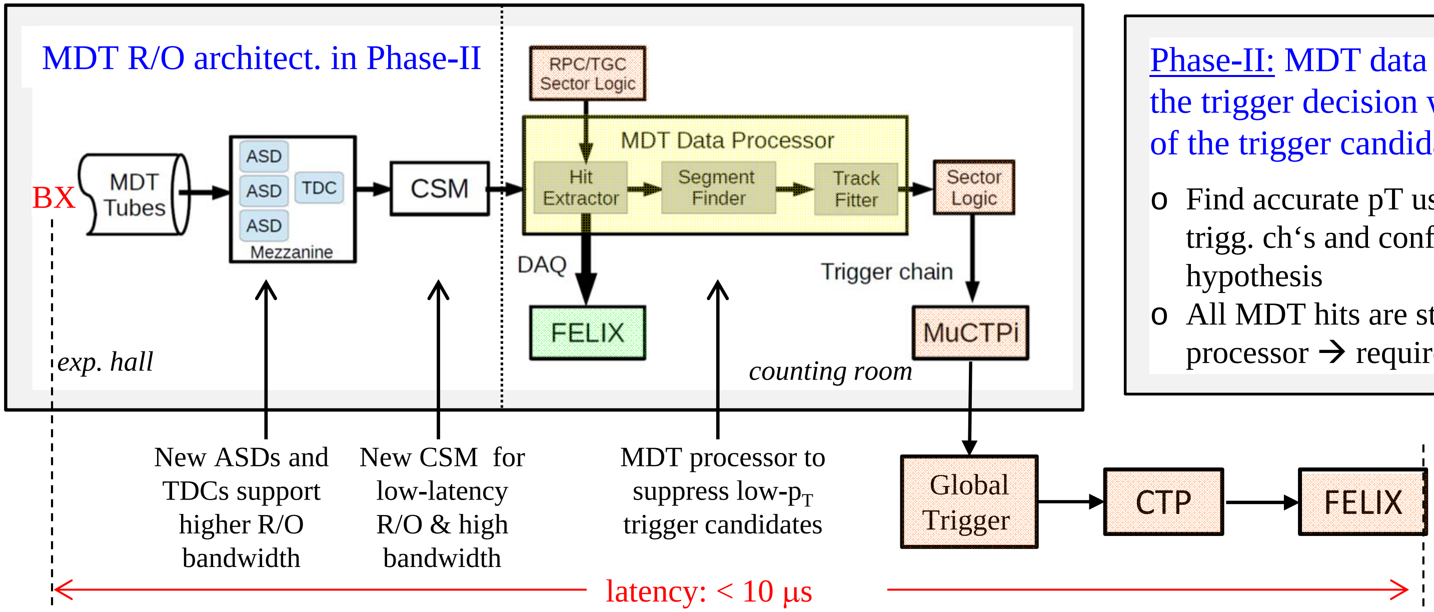
From K. Ntekas, march, 20, 2018

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



New ASDs and TDCs support higher R/O bandwidth

New CSM for low-latency R/O & high bandwidth

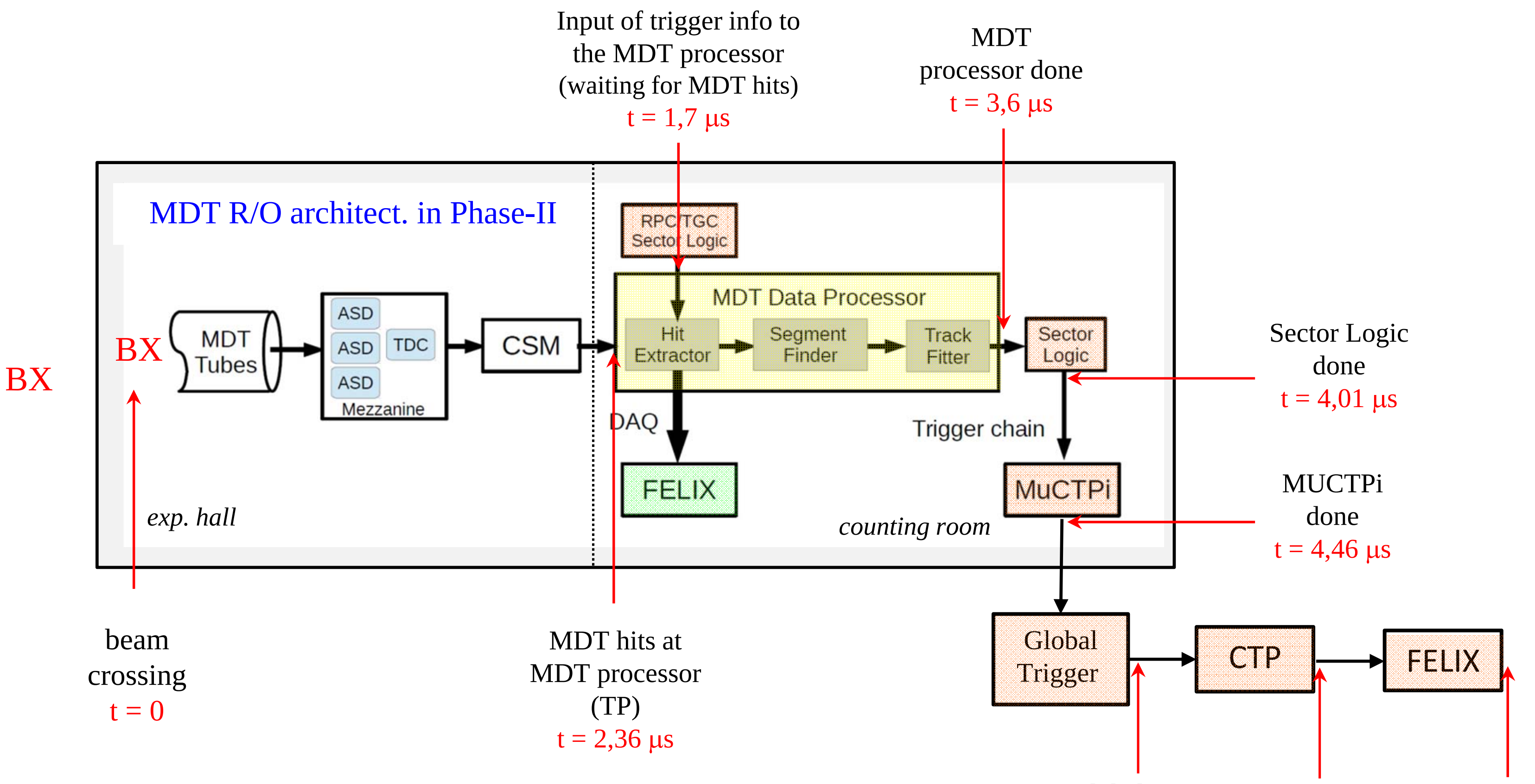
MDT processor to suppress low-p_T trigger candidates

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

- Find accurate pT 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) no problems with TID (c) easy to service – BUT … (d) needs more bandwidth, processing power …

Accumulation of Latency along the Muon Trigger Path



BX

Input of trigger info to
the MDT processor
(waiting for MDT hits)
t = 1,7 µs

MDT
processor done
t = 3,6 µs

Sector Logic
done
t = 4,01 µs

MUCTPi
done
t = 4,46 µs

beam
crossing
t = 0

MDT hits at
MDT processor
(TP)
t = 2,36 µs

Global trigg.
done
t = 5,86 µs

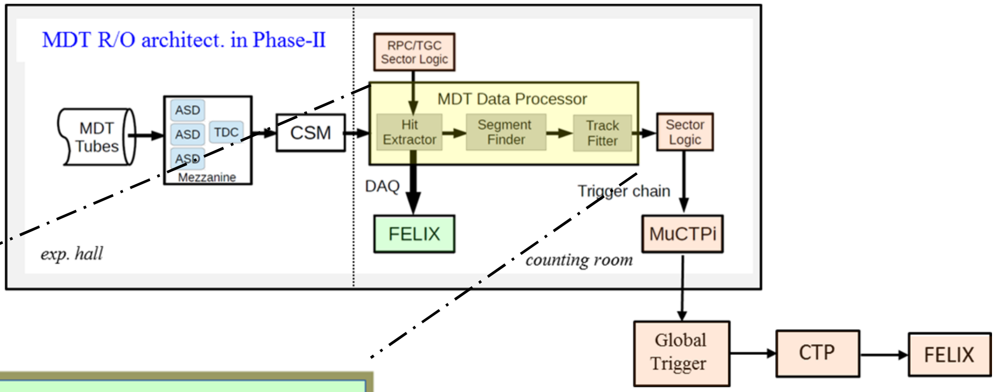
CTP done
t = 6,69 µs

FELIX done
→ broadcast
Trigger to the
frontends
t = 6,9 µs

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)

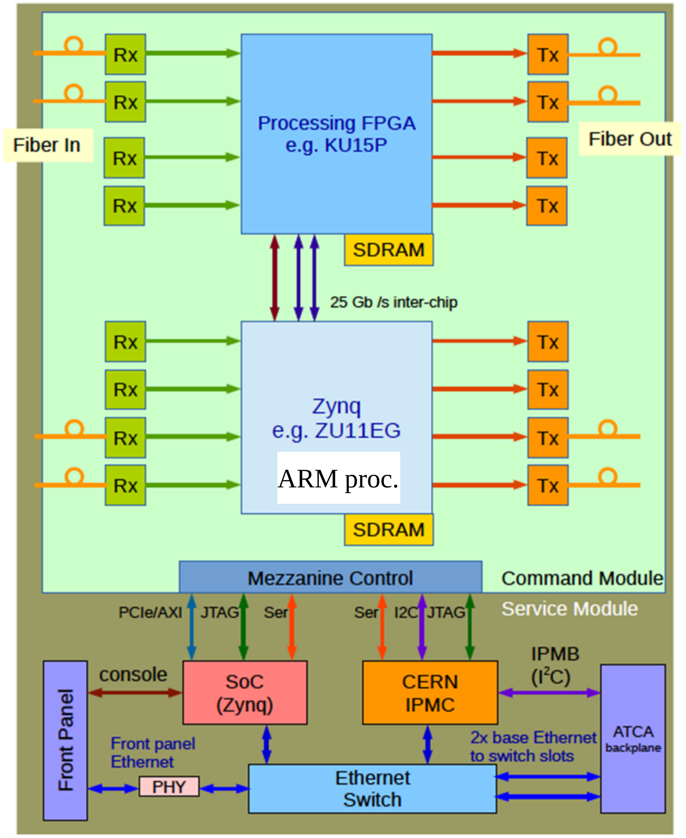
Zooming into the MDT Trigger Processor



MDT data from Barrel Middle and Inner

MDT data from Barrel Outer

SL of this Sector



back to SL

to FELIX

to CSM

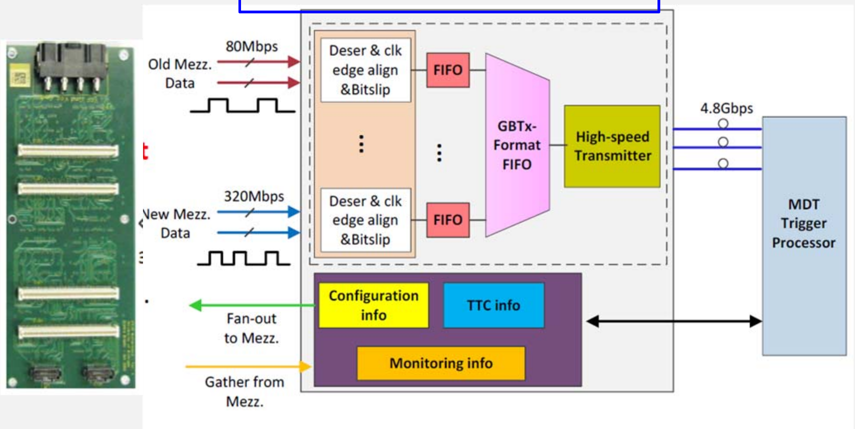
Service module for Configuration & external Communication

For more details, see poster by Davide Cieri at this workshop.

2 Options for the CSM under study

CSM = Chamber Service Module

The FPGA based CSM



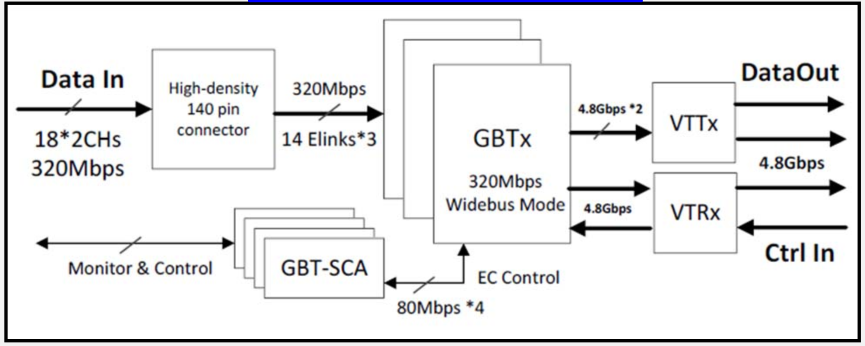
PROs

- Flexibility in FPGA firmware design
- Can easily handle migration from Ph-I to Ph-II

CONs

- Questions on FPGA SEU in Phase II
- Maintenance needed for firmware
- Difficult access

The GBTx-based CSM



PROs

- Radiation hard ASICs from CERN
- No firmware design/maintenance needed
- Low power consumption, low cost

CONs

- Functionality fixed by GBTx ASIC
- Small ASIC chip needed for JTAG distribution (Mezzanine Card control)

→ Prototypes exist for both concepts at Univ. of Michigan

From Xueye Hu, Univ. of Michigan, apr., 18th, 2018

Implementation of h/w for the MDT trigger

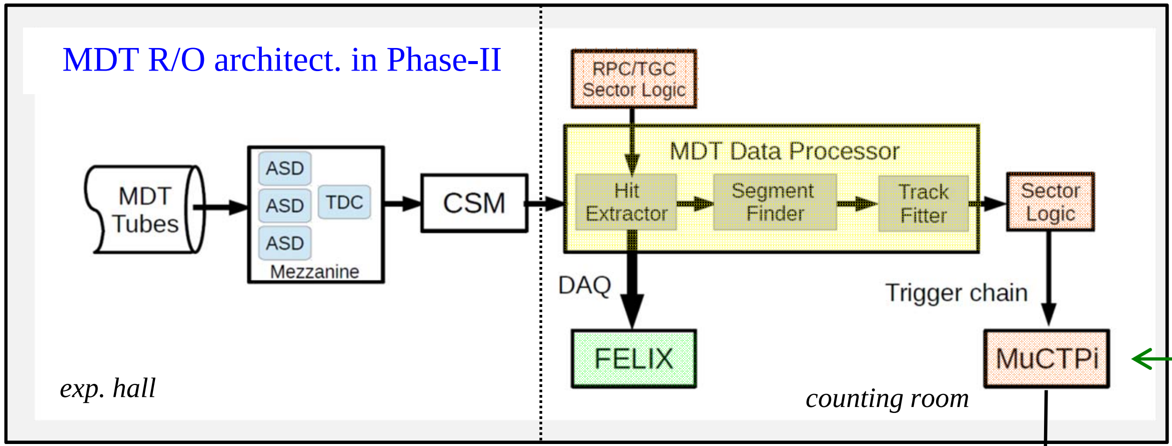
Compo-nent	Function	# of devices	technology	Location	Performance Criteria	Status (aug. 2019)
ASD	8-ch preamp	60 k	IBM/GF 130 nm	Frontend board	gain, thresh. matching, ENC, functionality	devices from engineering run under test
TDC	24-ch	20 k	TSMC 130 nm	Frontend board	bandwidth, latency, transmission rate	working protype ASIC
CSM	serving 18 TDC	1.5 k	GBTx, FPGA	On-chamber	transmission rate, latency, data integrity	prototypes for 2 versions
L0 Muon Trigger	serving 3 MDT	1.5 k	GBTx, FPGA, Zync, ARM proc.	USA15	p_T determ., latency, interface to SL, transm. speed	prototypes

Production, test, prototyping of Hardware well advanced for Phase-II

Step-by-step refinement of the L0Muon trigger

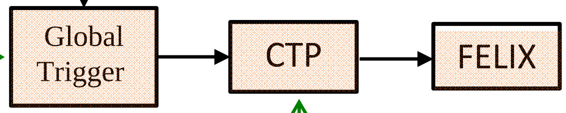
(a) The MDT Processor: Refinement of the p_T measurement

NB: Matching of tracks from the Muon Spectrometer to the ITK will not be done for L0.



(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 $\mu\mu$ inside limits
- isolation btw. muon and jets



(d) The CTP: controls
- trigger menu
- performs prescaling
- takes final L0 trigger decision

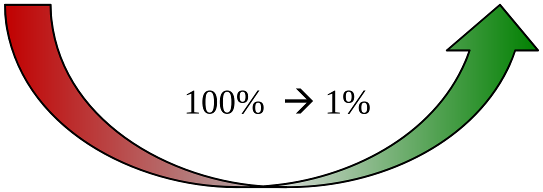
Data from TDAQ TDR, table 5.5 (Dec. 2017)

Trigger Menu foreseen for 1 MHz L0 Rate

Triggered at L0:
~ 1 MHz

Permanently stored
by EF:
~ 10 kHz

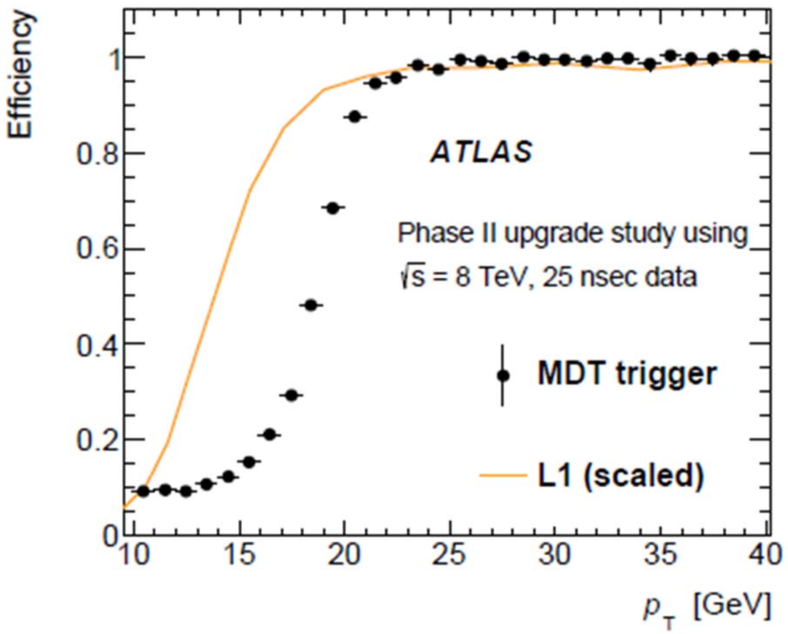
		Run 1	Run 2	Run 3	Run 4	Regional Tracking	Event Filter Rate
		kHz	*kHz*	*kHz*	*kHz*	*kHz*	*kHz*
Muon Spectrom.	**single μ**	9,3	15,5	15	**38**	38	**1,5**
	di - μ	1,9	5,2	4	**10**	5	**0,2**
Calori-meter	**single e**	19	27	14	**200**	40	**1,5**
	di - e	6,5	1,7	5	**40**	10	**0,2**
	others	38,3	25,6	62	771	334	7,0
	total	**75**	**75**	**100**	**1059**	**334**	**10,4**



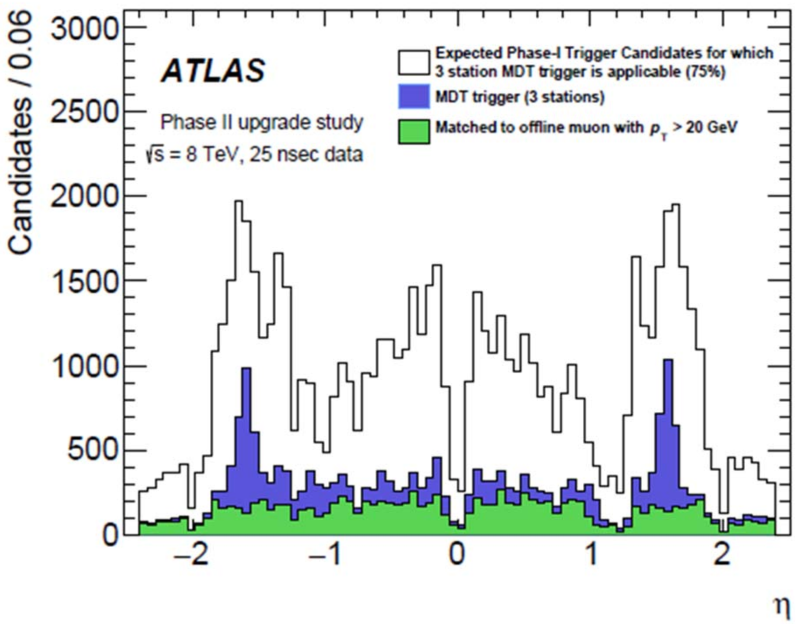
100% → 1%

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

Expected reduction of low-p_T fake triggers using the MDT



Relative efficiency of the MDT 3-station trigger with respect to the Phase-I first-level muon trigger vs. $p_{T,}$ measured in the offline reconstruction.



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

- White distribution: before Phase-II
- Blue: Using the MDT info at L1
- Green: Full off-line analysis

Oliver Kortner, MPI

Summary

Substantial reduction of the L1 Muon trigger rate due to use of high precision MDT track co-ordinates.

Complete replacement of existing Readout Electronics required.

Development of new modules well under way in accordance with time schedule.

Some technical options still open, presently studied with fully functionioning prototypes.

Not all power consumption / cooling issues completely defined/solved yet, but no show stopper in sight.

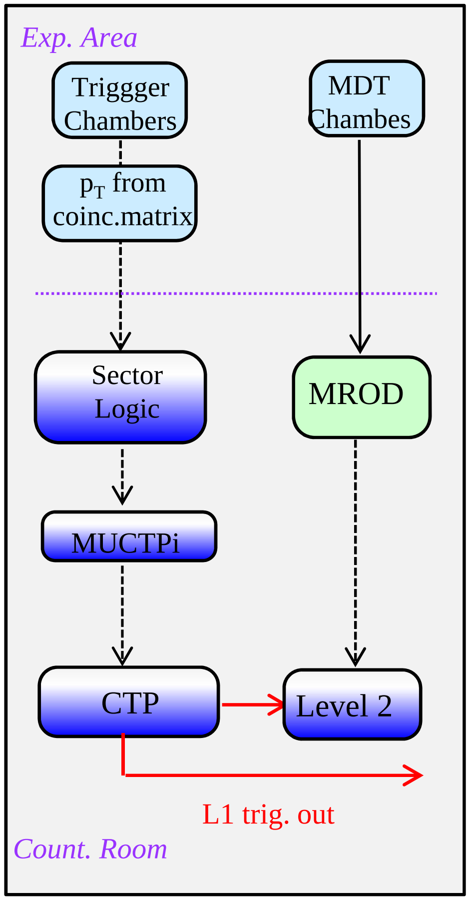
SPARES

Bibliography

- 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

The Muon Trigger path in Phase I and II

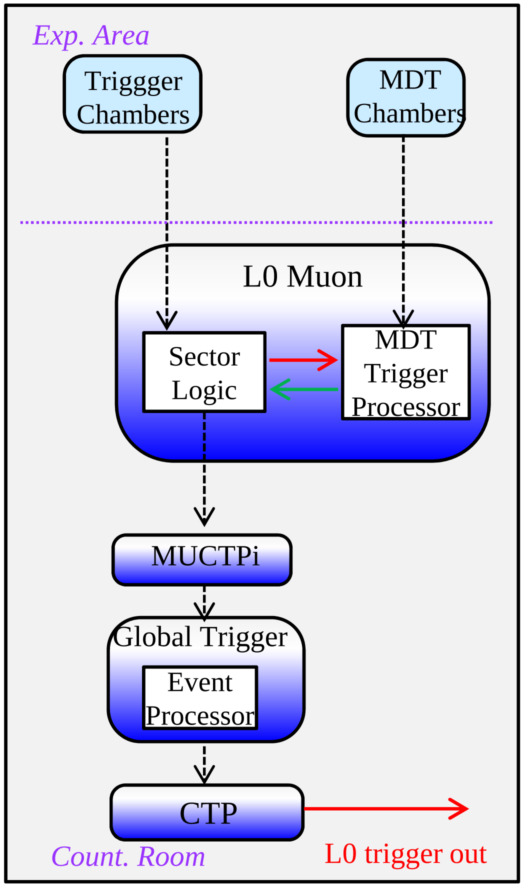
Phase-I Muon Trigger


Exp. Area
Triggger Chambers
p_T from coinc.matrix
MDT Chambes
Sector Logic
MROD
MUCTPi
CTP
Level 2
L1 trig. out
Count. Room

Trigg. chambers deliver trigger candidates with raw p_T from a local coincidence matrix.

MDT are only read out on a L1 trigger (saving R/O bandwidth.)

Phase-II Muon Trigger


Exp. Area
Triggger Chambers
MDT Chambers
L0 Muon
Sector Logic
MDT Trigger Processor
MUCTPi
Global Trigger
Event Processor
CTP
L0 trigger out
Count. Room

Trigg. chambers send raw to SL.

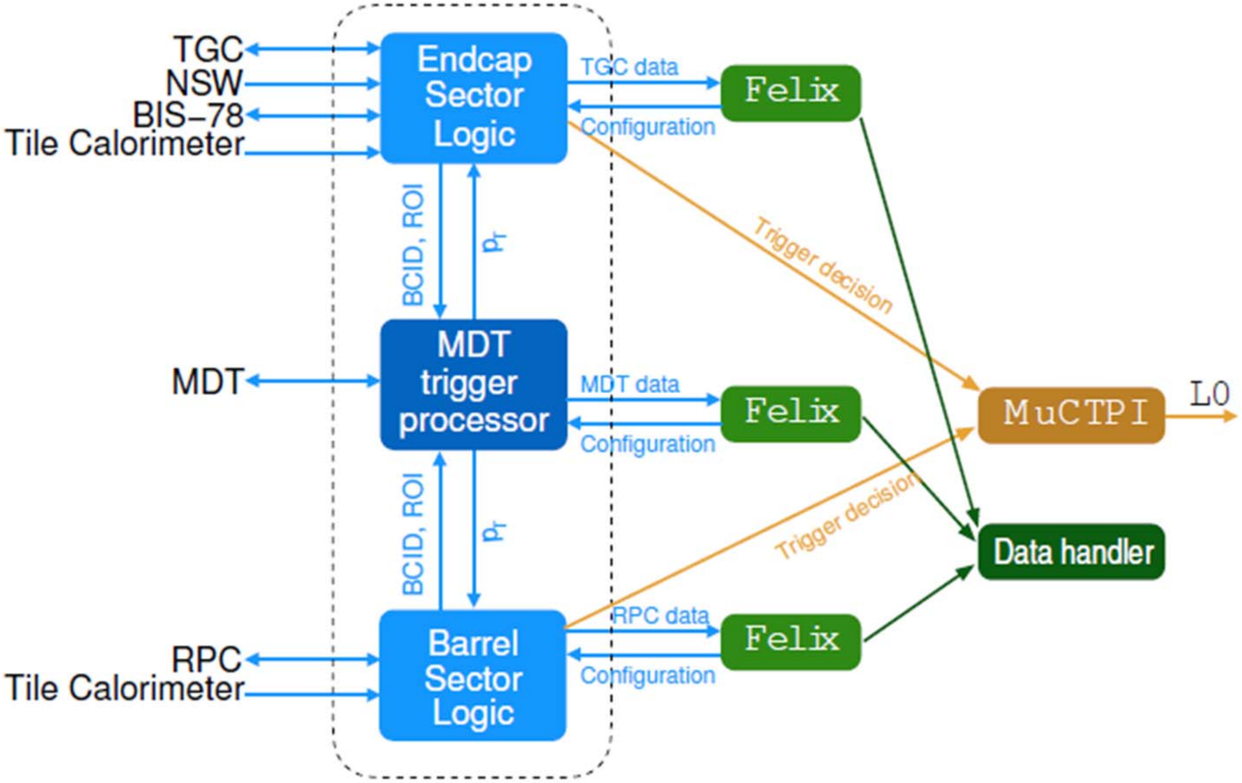
→ Trigger candidates selected by SL. position and slope of the muon candidates are sent to the MDT trigger processor.

All MDT data are streamed to the MDT trigger processor. Tracklet coordinates of muon candidates are seeds to find corresponding track segments in the MDT.

If MDT confirms p_T above threshold, SL forwards candidate to MuCTPi and Global Trigger.

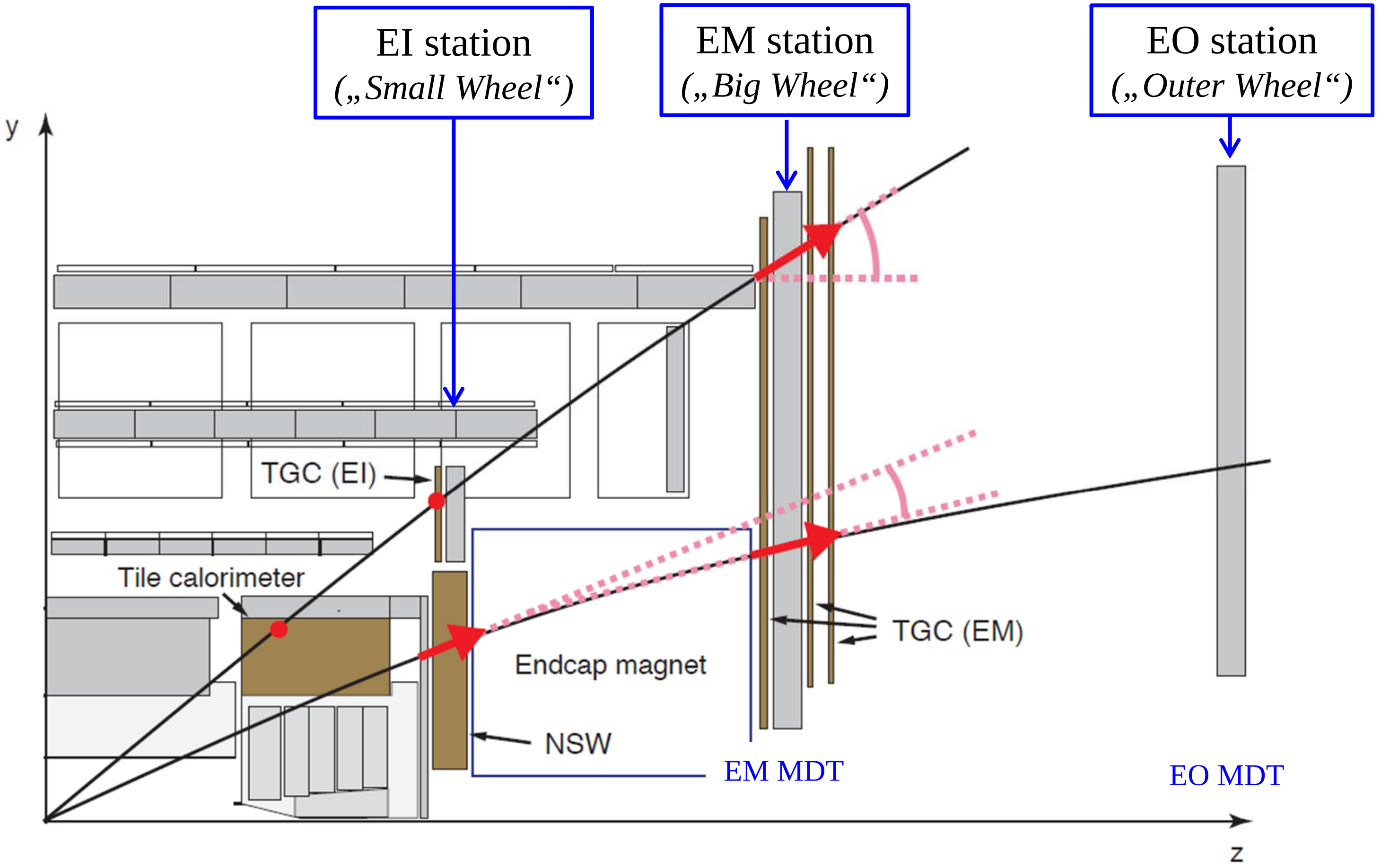
Global Trigger checks e.g. on isolation from jets, reports to CTP.

Overall Muon trigger and readout scheme in Phase-II



Muon trigger and readout scheme. The muon trigger decision is made in the endcap and barrel sector logic (SL) using data from the muon trigger chambers (TGCs and RPCs), from the Tile calorimeter, and from the MDT trigger processor. The trigger decisions of the SL's are collected by the MuCTPi. All muon hit data are read out through the Front-End Link Interface eXchange (FELIX) and passed to the HLT and the down-stream readout system.

The L1 selection in the endcap in Phase-II



- The NSW determines the track angle in the R/Z plane with ~1 mrad accuracy.
- To match this accuracy of the angular measurement with the one in the „Big Wheel“, the MDT precision info will be needed for L1