Online Muon Reconstruction in the ATLAS Muon Spectrometer at the Level-2 stage of the Event Selection

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Outline

- Introduction to the LHC and the ATLAS Trigger/DAQ
- MuFast: the Level-2 standalone muon reconstruction algorithm
- Online implementation
- Tuning with data
- Experience with 2011 data taking

The LHC challenge to ATLAS Trigger/DAQ

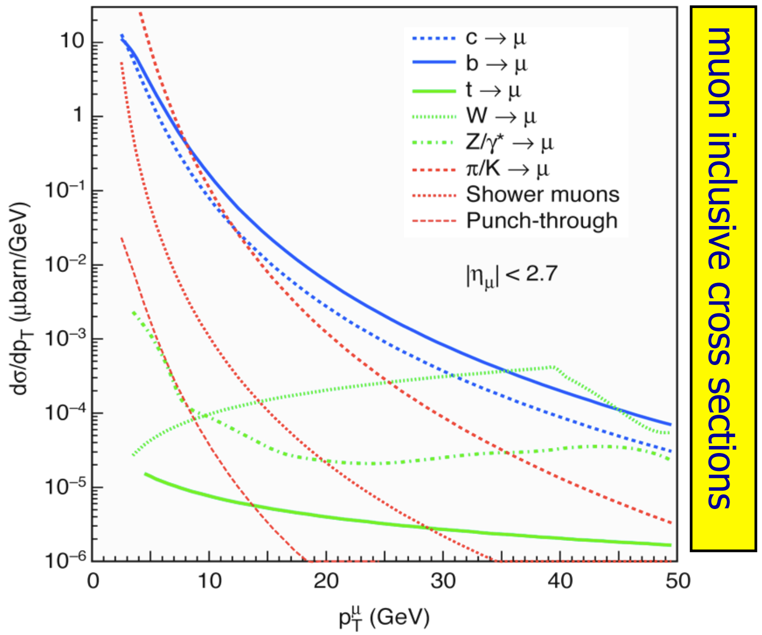
LHC: proton-proton collisions @ ECM = 14 TeV

L = ~10^{34} cm^{-2} s^{-1} ⇒ <24> interactions per bunch crossing @ 25 ns interval

1 year at L = 10^{34} cm^{-2} s^{-1} ⇒ ∫Ldt ≈ 100 fb^{-1}

Challenge to the ATLAS Trigger/DAQ

- *interaction rate 10^9 Hz, offline computing can handle $O(10^2$ Hz).*
- *cross section of physics processes vary over many order of magnitude:*
  - *Inelastic: 10^9 Hz*
  - *W → l ν: 10^2 Hz*
  - *tt production: 10 Hz*
  - *Higgs (100 GeV): 0.1 Hz*
  - *Higgs (600 GeV):10^{-2} Hz*
- *ATLAS has $O(10^8)$ read-out channels → average event size ~1.6 MByte*



Rapidly falling muon background cross section means a sharp efficiency turn on is essential!

ATLAS: the Trigger/DAQ system

(more details given by E. Pasqualucci in "*Performance and Operational Experience with the Heterogeneous Farm of the ATLAS Trigger and Data-Acquisition System*")

Level-1(hardware FPGA/ASIC)

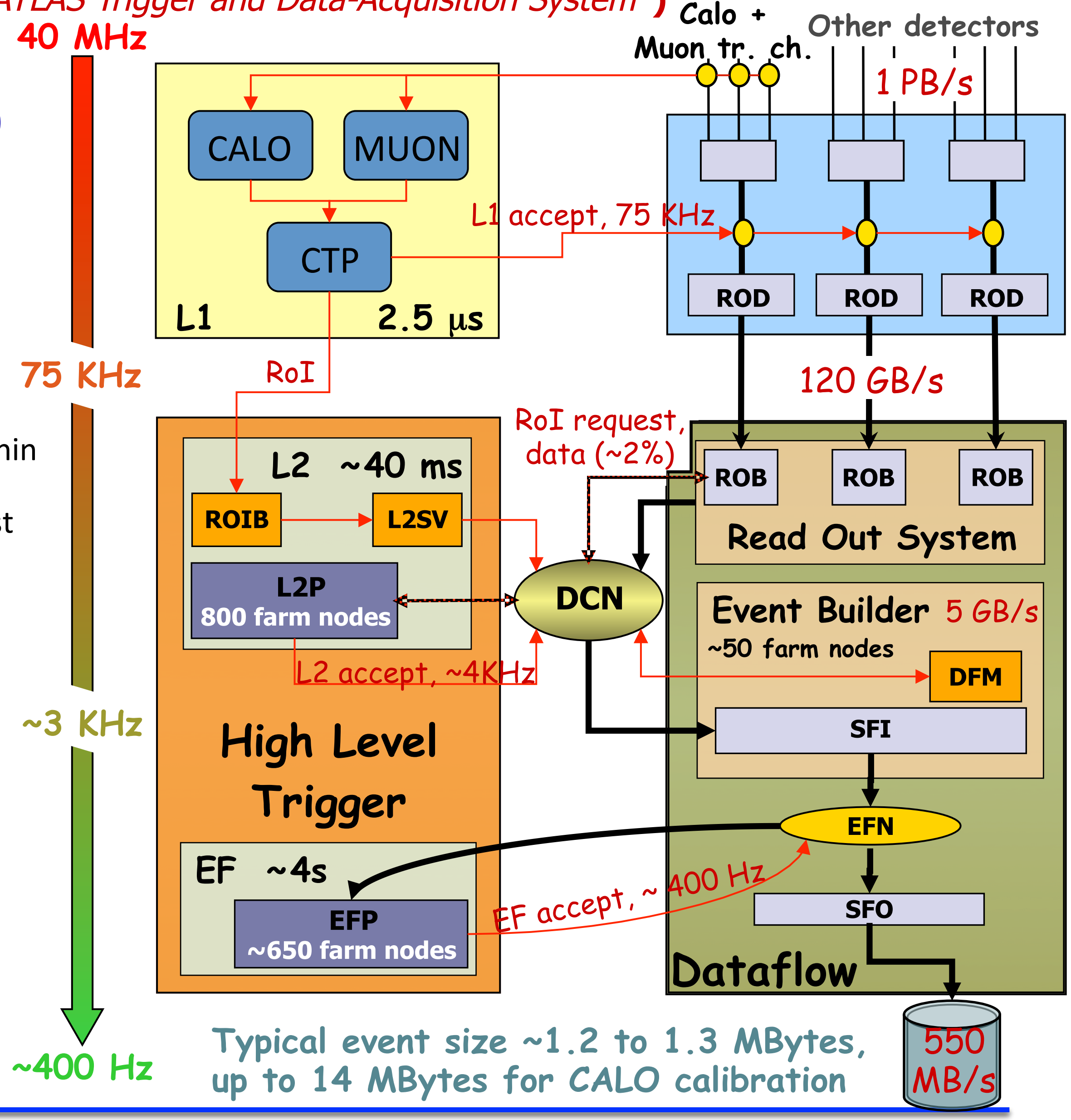
- analyzes coarse granularity data from CALO and MUON detector;
- identifies the Region of Interest (RoI), seeds Level-2.

Level-2 (software based)

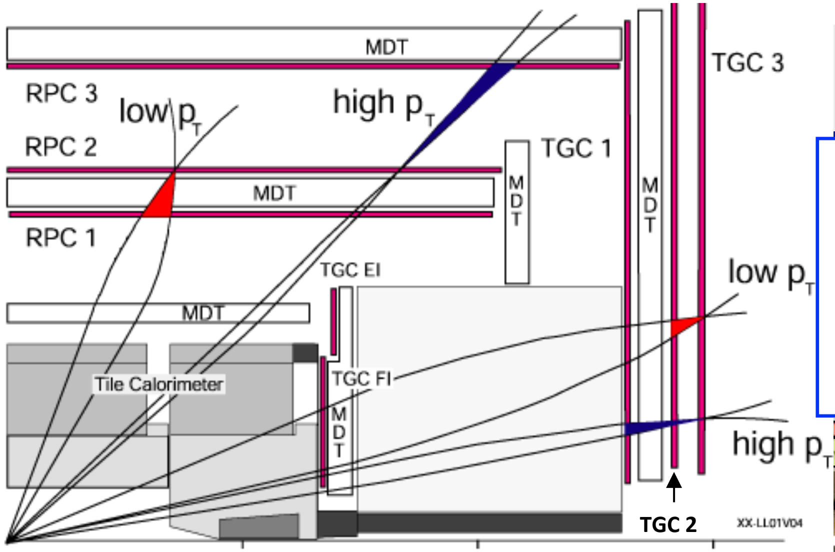
- accesses full granularity data within the RoI (2% total event size);
- uses algorithms optimized for fast rejection.

Event Filter (software based)

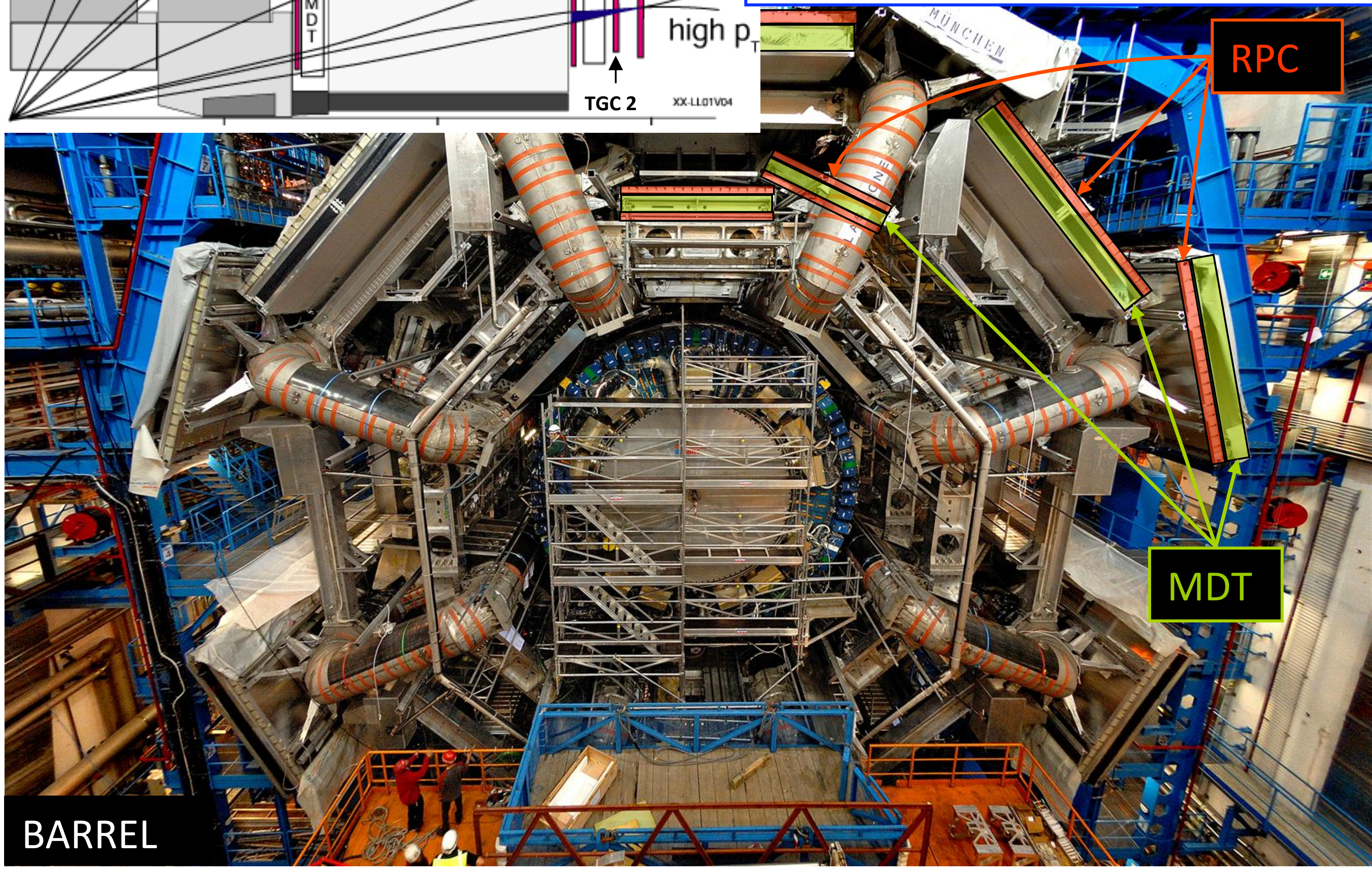
- uses offline algorithms;
- full event access;
- exploits the seed from Level-2.

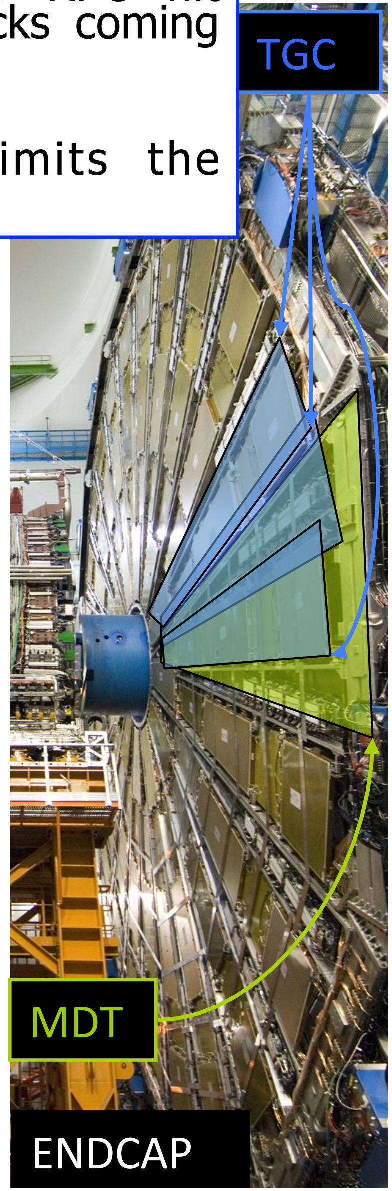


ATLAS: LVL1 Muon Trigger



- LVL1 Searches for TGC or RPC hit patterns compatible with tracks coming from I.P.;
- uses coincidence windows;
- the design resolutions limits the sharpness of the turn on.





MuFast, the Level-2 muon standalone trigger

standalone trigger: online muon reconstruction of the Muon Spectrometer data

First task of the Level-2 muon trigger:

- confirm the Level-1 trigger with a more precise p_t estimation within a "Region of interest (RoI)".

To perform the muon reconstruction, RoI data are gathered and processed in three steps:

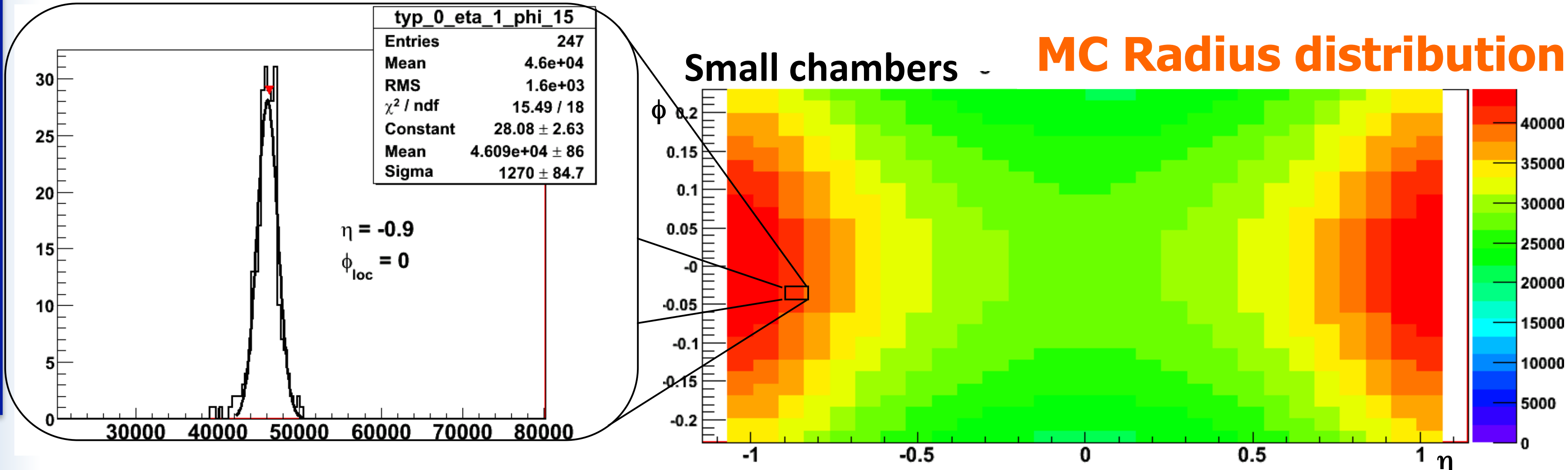
1) "Global Pattern Recognition" involving trigger chambers and positions of MDT tubes; trigger hits are used as a seed for the muon track. MDT hits are collected within narrow roads along the seed;
2) "Track fit" performed separately in each MDT chamber, without exploiting the magnetic field map but using only MDT drift time measurement with all calibrations. The track curvature is computed from three (or two out of three) precision points;
3) Fast "p_t estimate" with Look-up-table (LUT) method: no use of time consuming fit methods.

Result → η,ϕ,direction of flight in the spectrometer, and p_T at the interaction vertex.

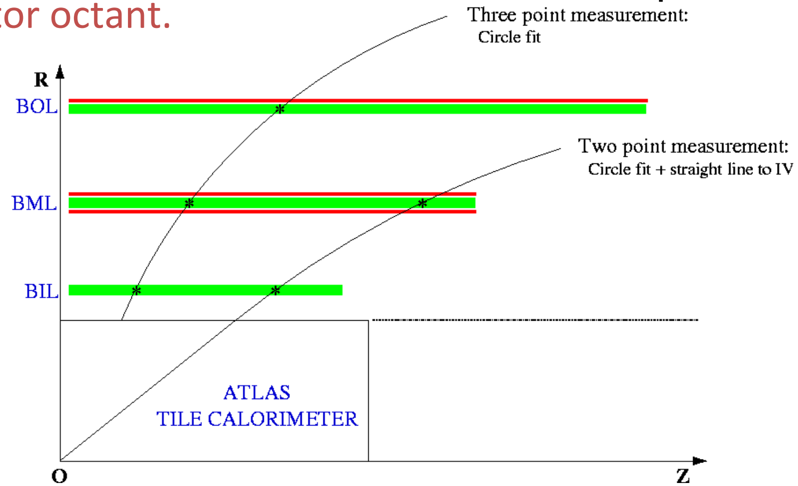
MuFast barrel: momentum reconstruction

LUT with curvature radius (r)

Prepare Look Up Tables (LUT) as a set of relations between values of r and p_T for different η, ϕ regions ($r = f(\eta, \phi, p_T)$).



→30 x 60 (η, ϕ) tables for each detector octant.



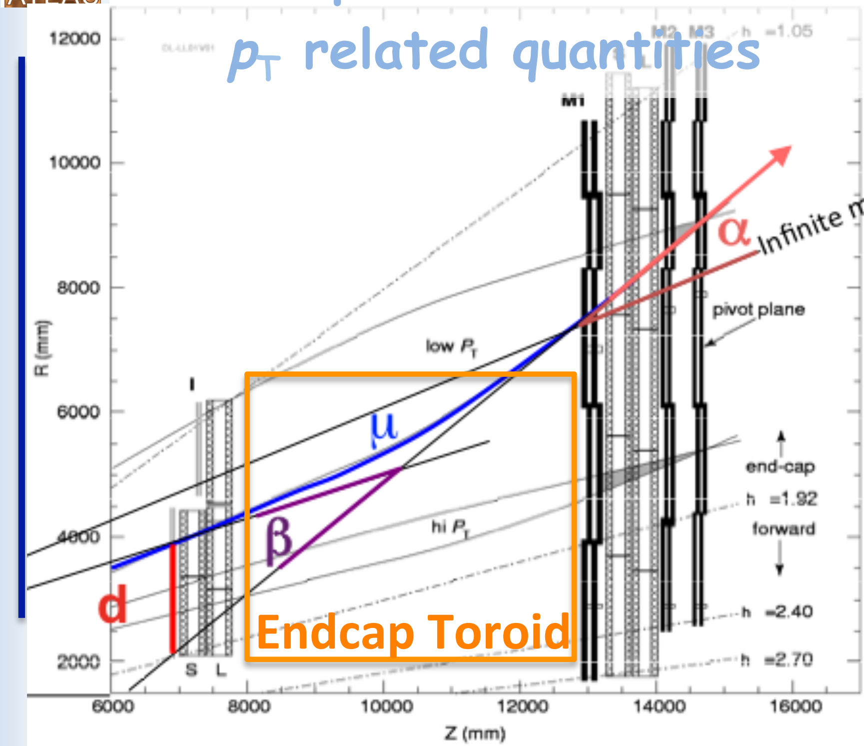
Use linear relation between r and p_T to estimate p_T.

$$r = A_1 \cdot p_T + A_0$$

Use of curvature radius: ~ 7 % of efficiency recovered by the two point measurement (we can miss a precision point in one station).

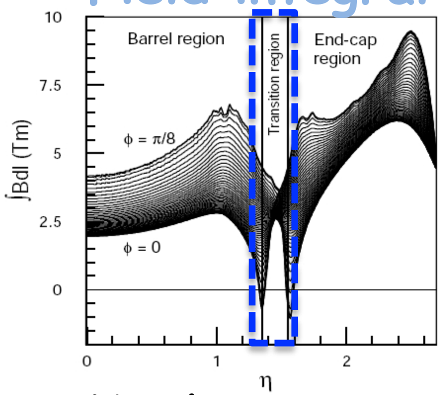
MuFast Endcap: a different track model

Endcap transverse view, p_T related quantities

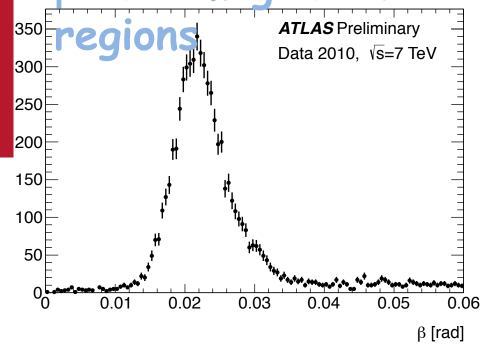


Field inhomogeneity doesn't allow for a global track description with radius or sagitta

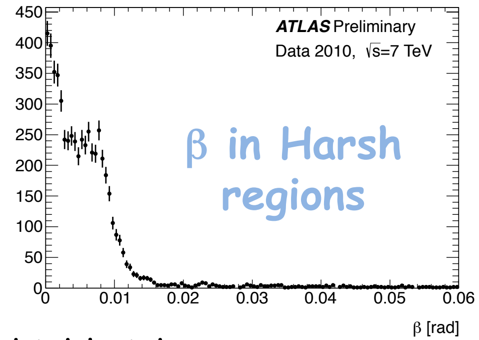
Field integral



β in homogeneous regions



β in Harsh regions



Harsh regions:
Where magnetic field is highly inhomogeneous the crossing of the two slopes is not well defined.

Pattern recognition:

- parametrize the track path using the muon p_T (from TGC) as a seed. to estimate the misplacemet d among the slope in Middle station and the innermost hits (allows for 10 cm roads)

p_T estimation:

- low-p_T use α measured in the MDT Middle station or improved with the use of the MDT Outer station;
- high-p_T use β angle because α is more sensitive to alignment and IP size.

→ Resolution worse than barrel

Operation in 2010

Level-2 muon inclusive trigger was part of the HLT selection since the first days of data taking

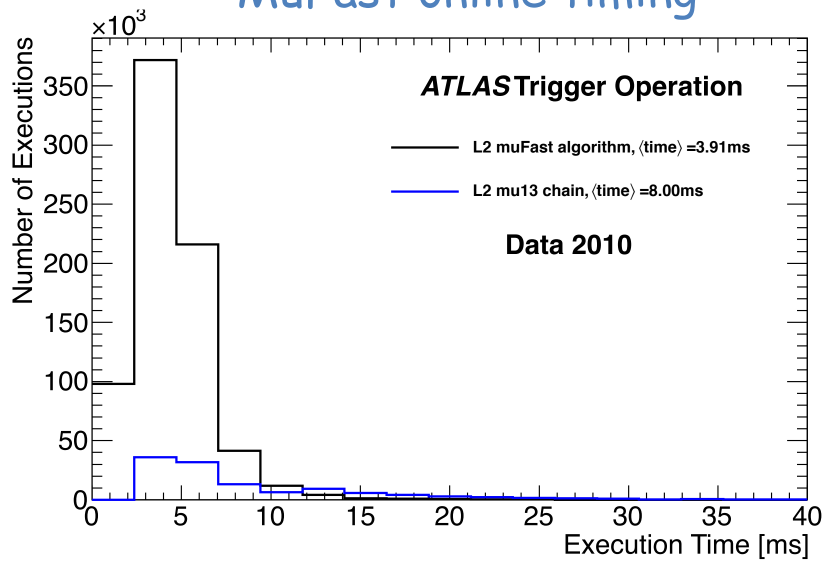
In 2010 algorithms were operated untuned because at the beginning:

- Muon statistic not enough in the high-p_T region;
- alignment of MS not available;
- RPC trigger timing not yet optimal;
- TGC LVL1 operated at lowest possible threshold;

Almost unbiased selection of muons performed for providing statistics to time RPC trigger:

- thresholds value modified to recover the performances (bad tuning).

MuFast online timing



New features developed to exploit the MuFast selection for special purposes

OutOfTime chains, selecting the muon triggers out of the bunch crossing time with an efficiency of 84% for muons coming from the IV:

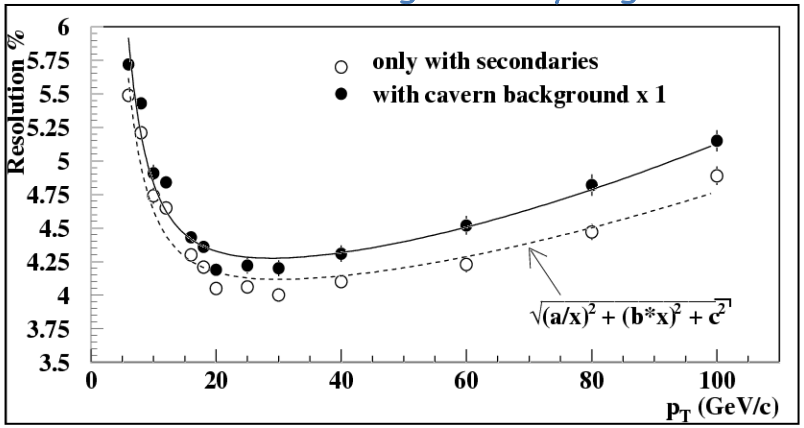
- Helps the RPC commissioning;
- Improves the hunt for the slow particles;

Special cuts for the endcap selection, to reject large LVL1 fake rate when the LVL1 endcap is operated at lowest threshold

Details about these special setup are in the backup slides

Tuning the physics performance in the barrel

IEEE Trans. Nucl. Sci., vol. 53 (2006) n. 3 , description of dead material missing and only regular sectors



Knowledge of alignment crucial for the tuning job

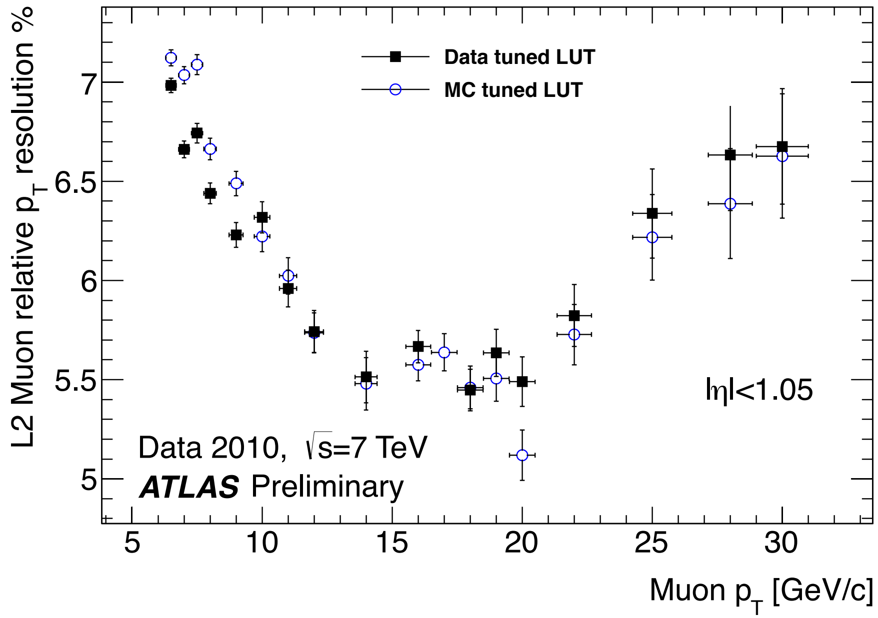
Offline reprocessing of

- ~300 nb^{-1} delivered by MU6 (low-p_T)
- ~10 pb^{-1} delivered by MU15 (high-p_T)

with the best alignment knowledge; high-p_T tuning suffers from lack of statistics

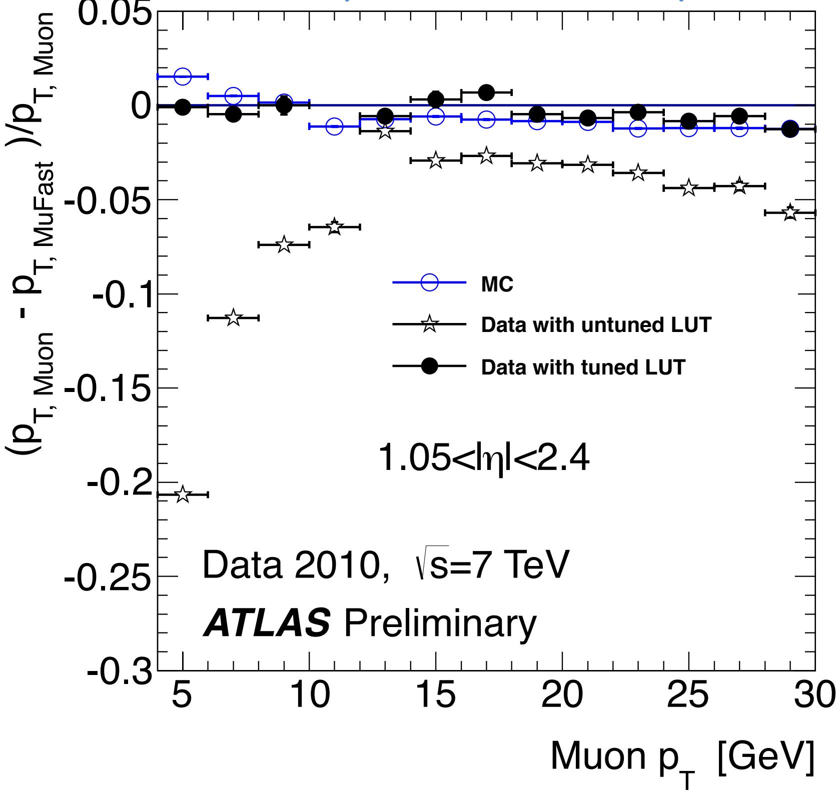
Resolution after tuning agrees with the ones achieved at the first design stage within ~15%. The MC simulation performed for the design studies did not included the description of the dead material in the Muon Spectrometer

MuFast resolution after tuning, all sectors

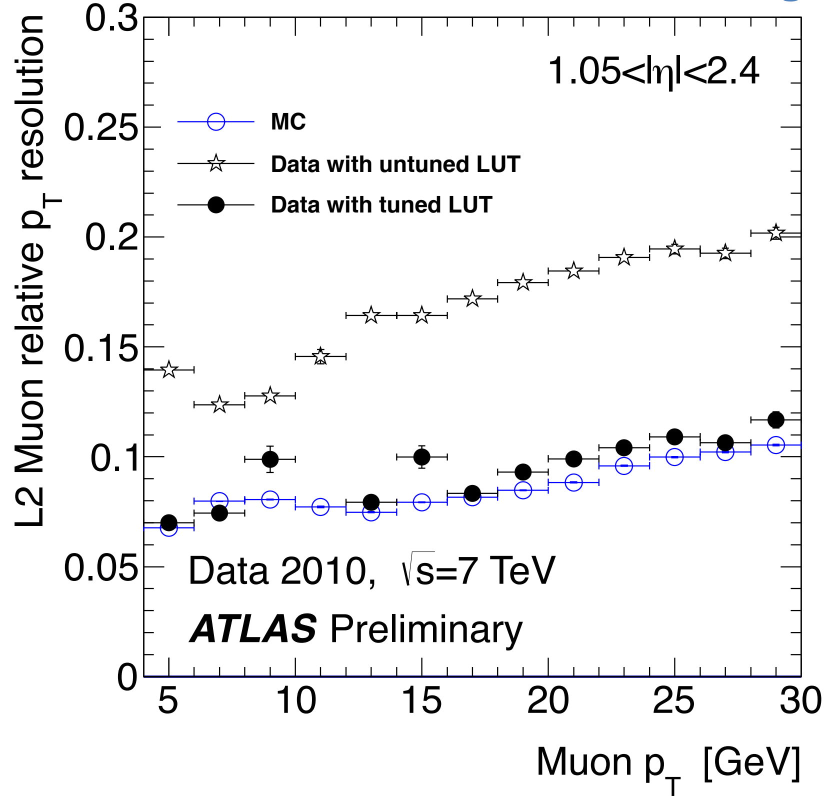


Tuning the physics performance in the endcap

Shift of the p_T estimated by MuFast



MuFast resolution after tuning



LUT computed for different p_T muon values (6GeV and 20 GeV)

p_T estimation from linear interpolation among LUT parameters suffers from shift from the expected value (left plot); additional tuning needed for correct this effect

Resolutions agrees with the past MC design study

2011 operation: resolutions

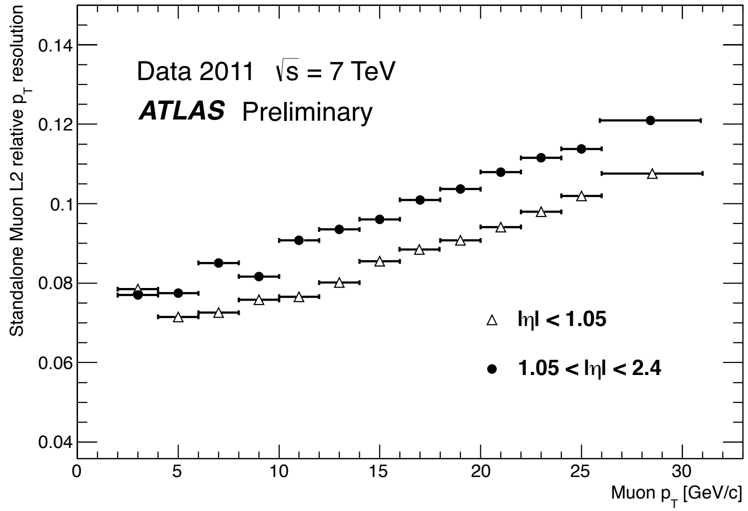
Resolution measured matching the offline reconstructed prompt muon with the MuFast output

Performance at high-p_T worse than what was achieved in the tuning studies:

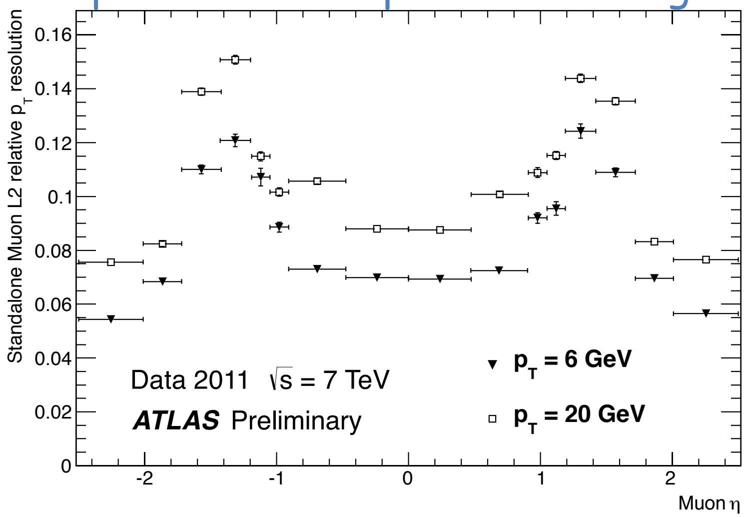
- likely due to alignment changes among 2010 and 2011.

The algorithm was not retuned because the performance are good enough to provide the needed rate reduction.

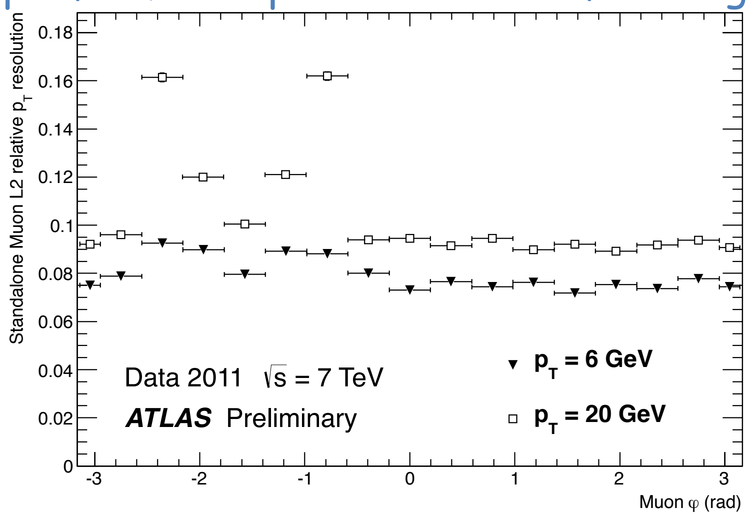
MuFast p_T resolution for prompt muon



MuFast p_T resolution vs η, performace spoiled in endcap transition region



MuFast p_T resolution vs ϕ, high-p_T muon performace spoiled in barrel feet region



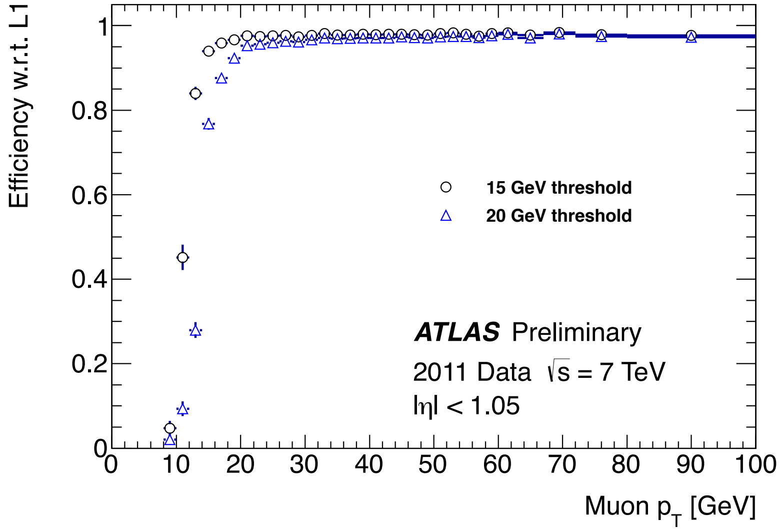
2011 operation: efficiencies

Efficiency computed w.r.t. LVL1 with tag and probe method

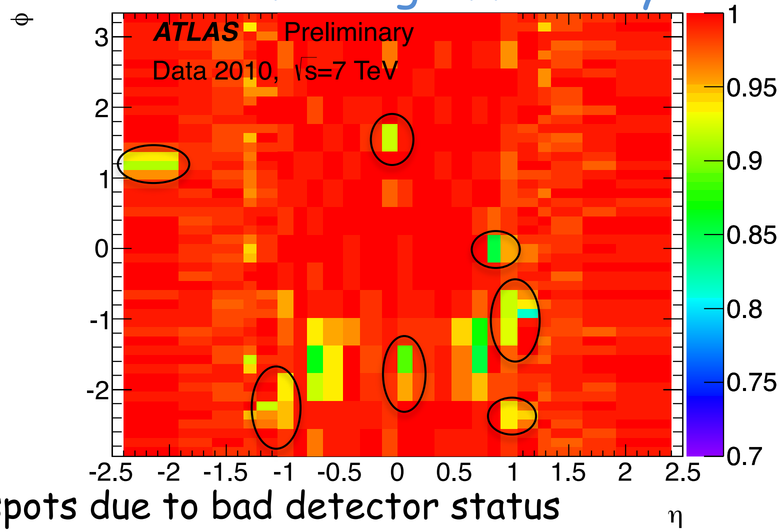
The observed rate reduction factors for a LVL1 input rate from a given p_T threshold are:

LVL1 input rate from 4 GeV th.:	~2.2
LVL1 input rate from 6 GeV th.:	~1.6
LVL1 input rate from 10 GeV th.:	~3.3
LVL1 input rate from 15 GeV th.:	~2.7
LVL1 inout rate from 20 GeV th.:	~2.4

Turn on curve for the barrel

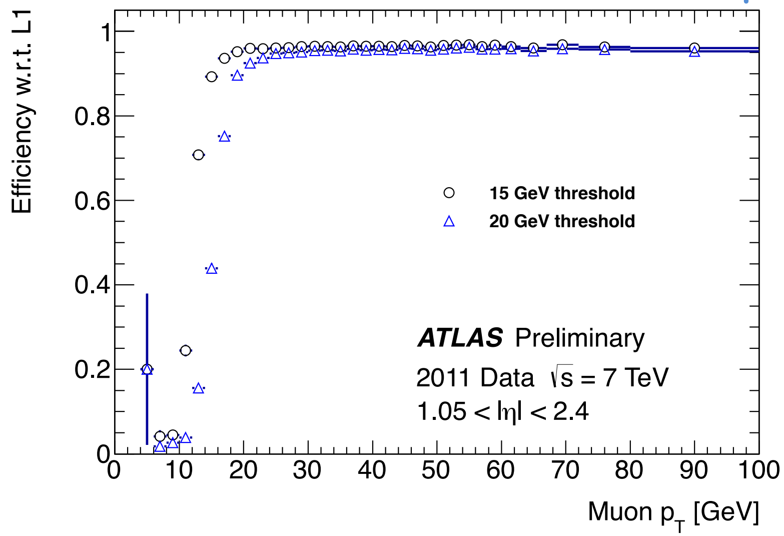


Track finding efficiency



Hot spots due to bad detector status and/or timing

Turn on curve for the endcap



Conclusions

L2 Muon standalone fully commissioned

The software infrastructure (interfaces to the HLT steering and menus, monitoring, data streaming) works under actual data taking conditions. The performance in data taking is understood. With the use of the best knowledge of the detector conditions the physics performance matches the Monte Carlo studies.

Level-2 muon standalone algorithm contributes to ATLAS event selection

L2 muon performs event selection since the beginning of the data taking in 2010 and serves data for online detector Data Quality and Monitoring (muon calibration stream). It allows for a reduction of a factor of about 2 of the LVL1 rate within 10% of the Level-2 latency time. It provides the seed for the combined reconstruction and the muon isolation trigger algorithms.

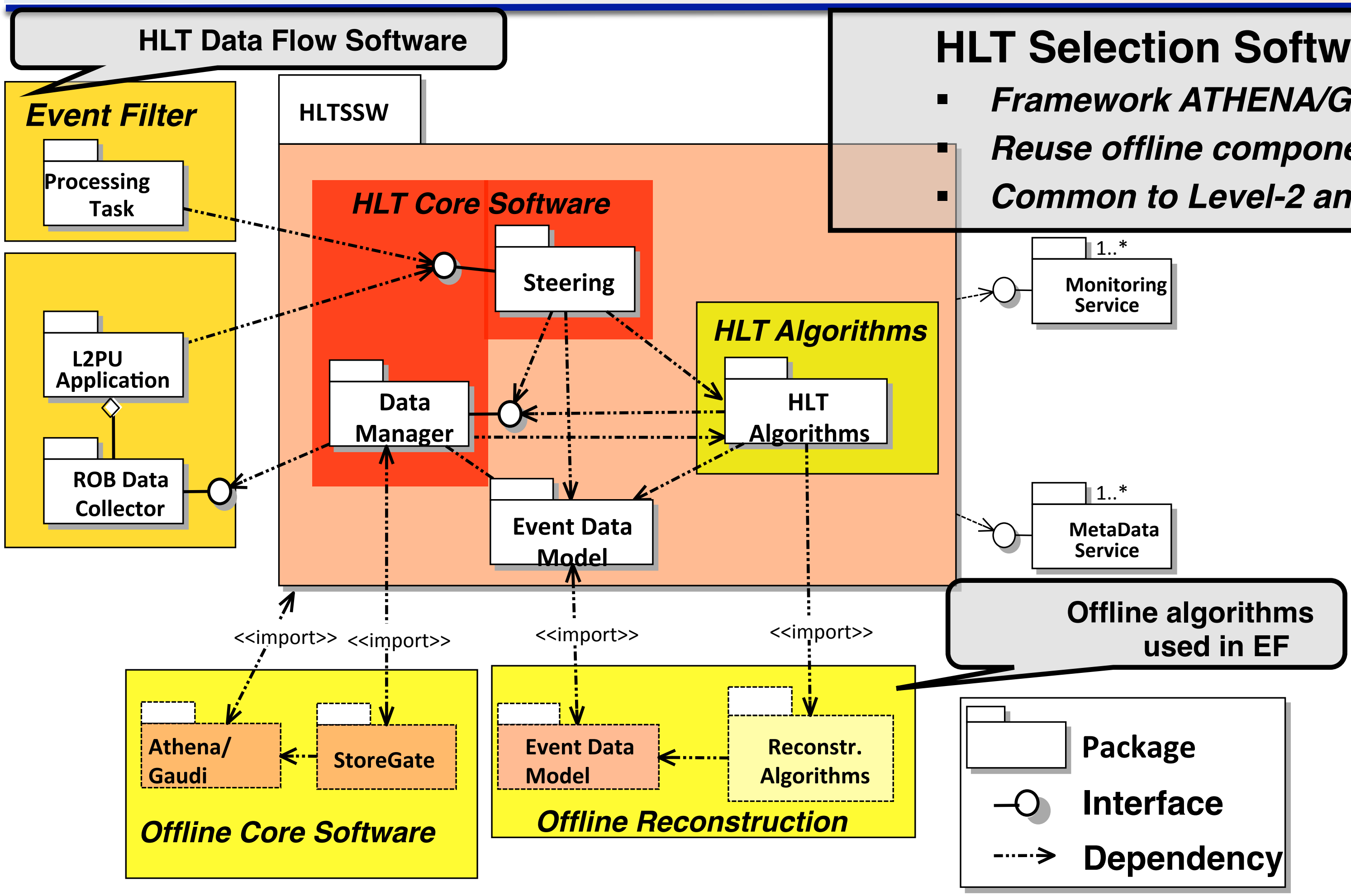
Operation were robust

L2 muon provided good stability and responsiveness while operated with non standard conditions of the LVL1 trigger

Lot of understanding driving further operation and upgrade work

BACKUP SLIDES

The HLT Selection Software



HLT Selection Software

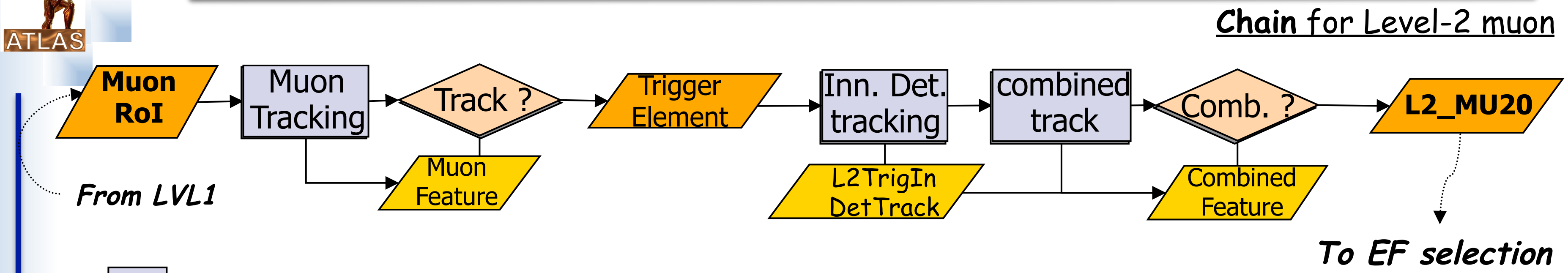
- *Framework ATHENA/GAUDI*
- *Reuse offline components*
- *Common to Level-2 and EF*

Integration into online proceeds through steps, cross checking performances with offline

- single-node setup with online emulator exercising the RoI-based data access;
- multi-node setups exercising the full online infrastructure;

Performance and functionalities tested in technical runs and combined detector runs

The HLT Steering



HLT steering manages the execution of the selection code

- algorithms configurable by parameters;
- applies early rejection: abort full chain as soon as a selection steps fails;
- applies prescales and passthrough factors;
- caches full history of TE and FEX and writes them into the HLT result:
  - allows navigation through the steps of the trigger decision;
  - avoids multiple execution of the same feature extraction;
  - allows offline re-run of trigger selection with different Hypo cuts;

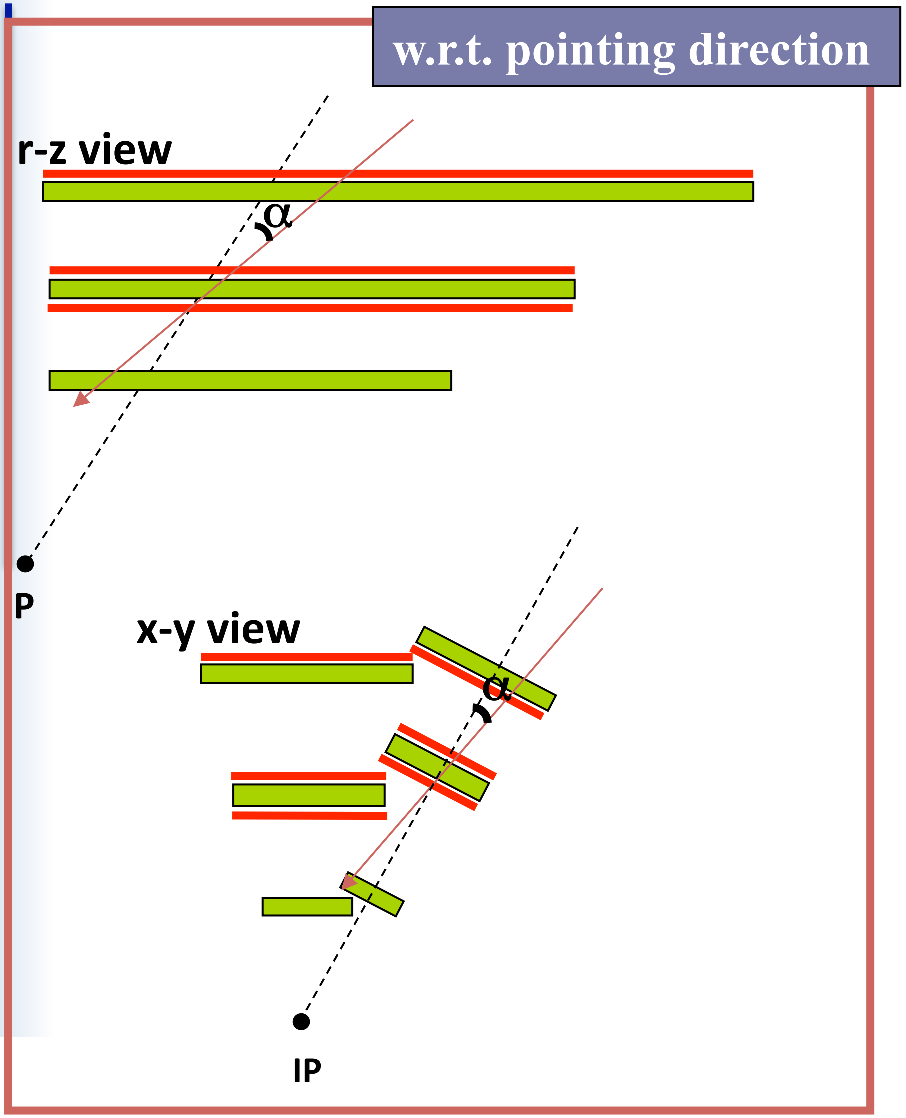
Collection of Chains implements the trigger menu

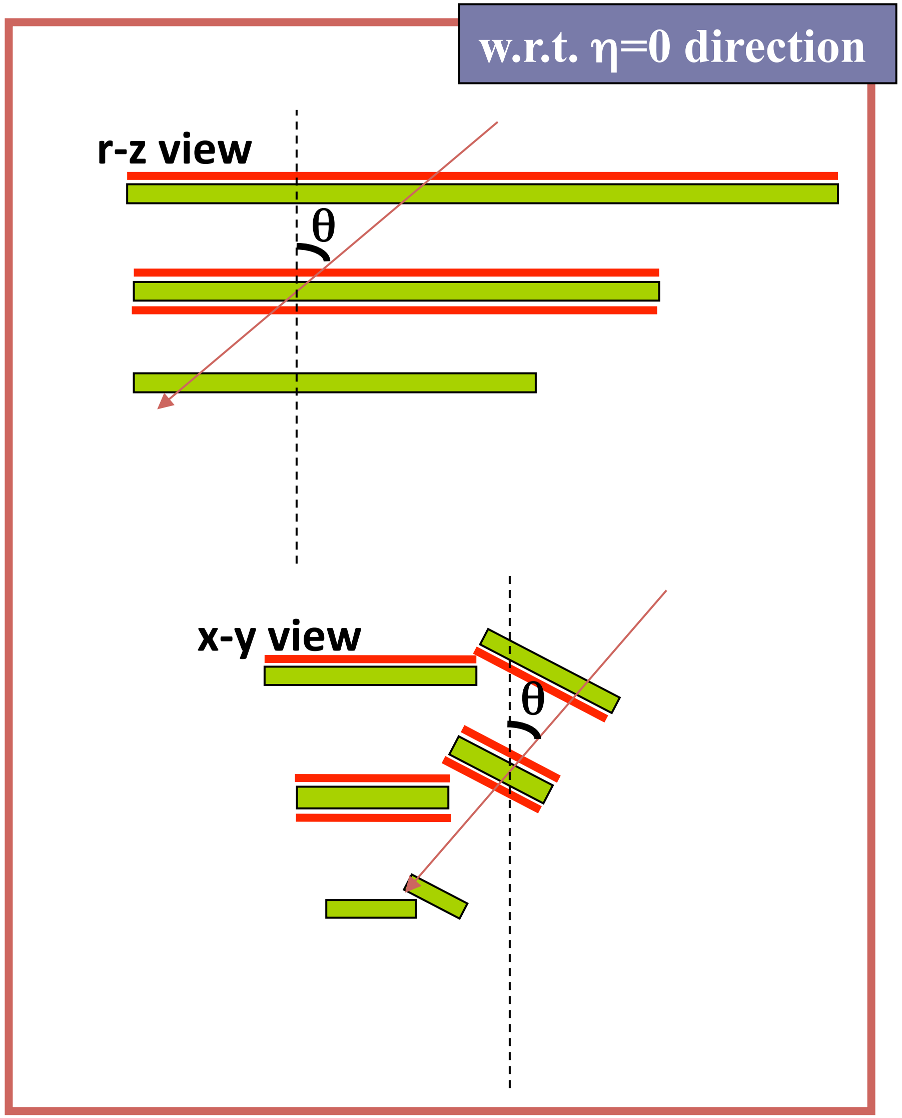
- in python or xml, recorded in the Trigger Configuration Database

Steering used to select events in the 2008 cosmic data taking.

Definitions

- Angle of muon track defined as follows





Moving towards operation: cosmic runs

The HLT was operated in parasitic mode in cosmic data taking, after having changed the working parameters of the LVL1 system.

Invaluable experience provided for the commissioning of the muon trigger and the full HLT as well:

- perform functional tests of all the HLT components;
- increase the robustness of the trigger code againts data corruption;
- implement procedure to handle/debug unexpected conditions;
- debug in the experimental system the data access mechanism and the pattern recognition;
- check that both online and offline monitoring are worth for trouble shooting;
- verify the work model for updating the condition data;

Issues on Level-2 muon software: access updated hardware maps

provide ad hoc maps (first from ASCII file, then move to access from data base)

- Muctpi cabling (i.e. RoI indexing) and ROS/ROB cabling;
- RPC/MDT/TGC detector cabling;

thus allowing transparent run among Monte Carlo and online

Commissioning: issues on cosmic events

Selected by LVL1 Muon trigger, exercise MS algos and ID tracking

No beam clock: timing provided by trigger Muon Trigger Chambers

- Phase issues in read-out/calibration of trigger and precision muon chambers (MDT), transition radition tracker (TRT), etc.

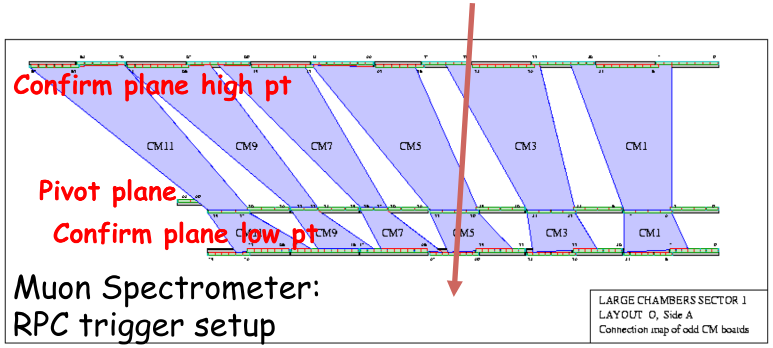
No IP pointing: selected tracks distributed over d0, z0

- track selection unbiased in the *r-z* view for most of the runs

MUON

The *r-z* view could not be fully reconstructed @ L2 because algorithms are designed for pointing tracks and data access happens in pointing trigger towers

Possible to relax pointing requirement to study efficiency / rejection.



ID Tracking

Significant modification to get tracks needed for Inner Detector alignment.

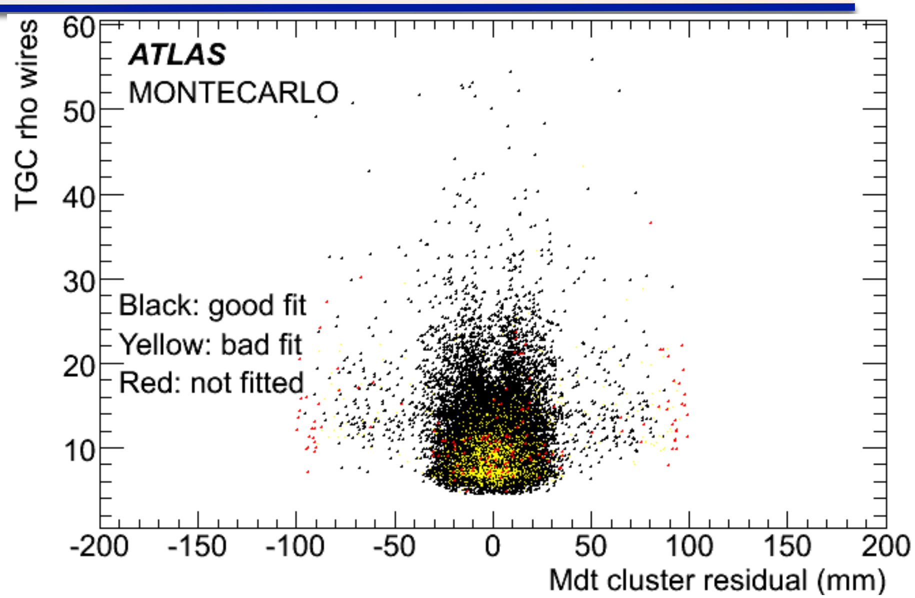
Commissioning: μFast MDT cluster finding

MDT cluster residual (w.r.t. TGC seed)

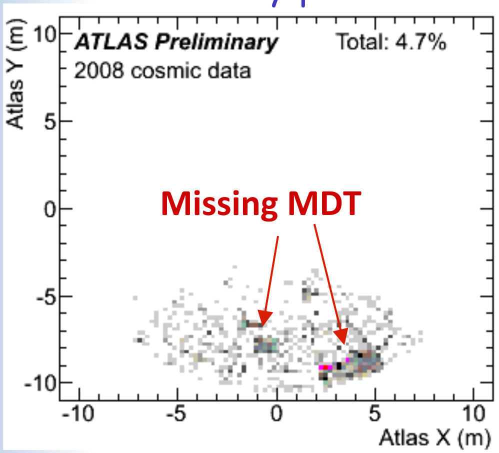
vs

nr. of TGC hits used as seed

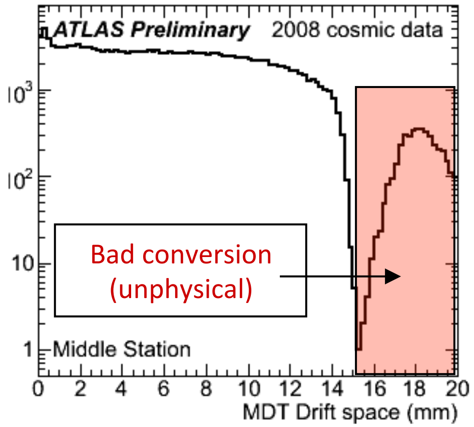
- **Cluster finding efficiency**: 93%
  - 4.7% inefficiency due to missing MDT data
  - 2% inefficiency due to bad MDT calibration

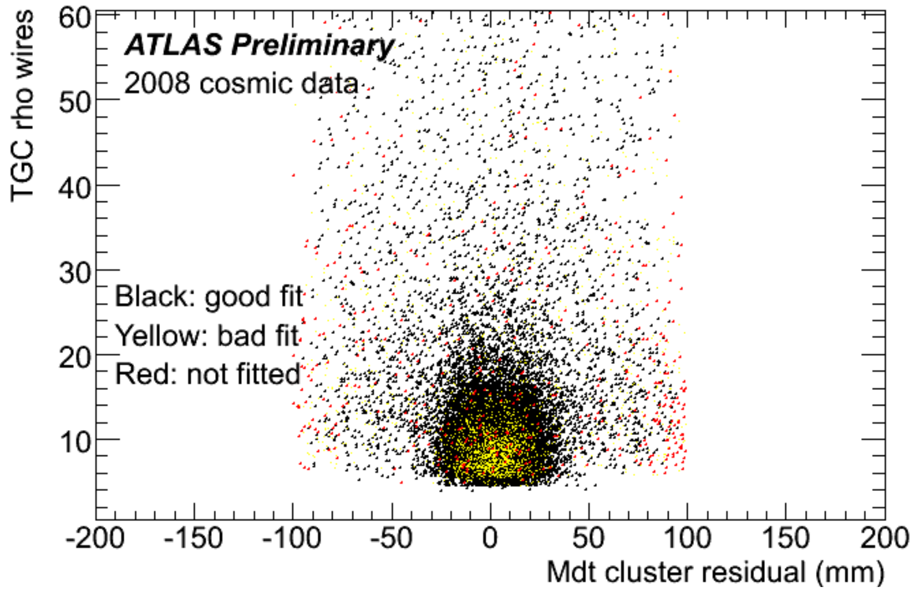


Inefficiency position



Drift space from time



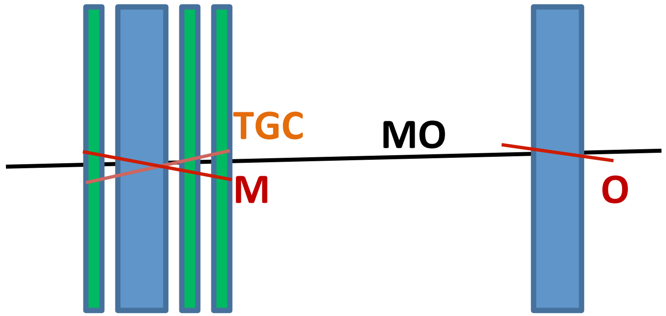


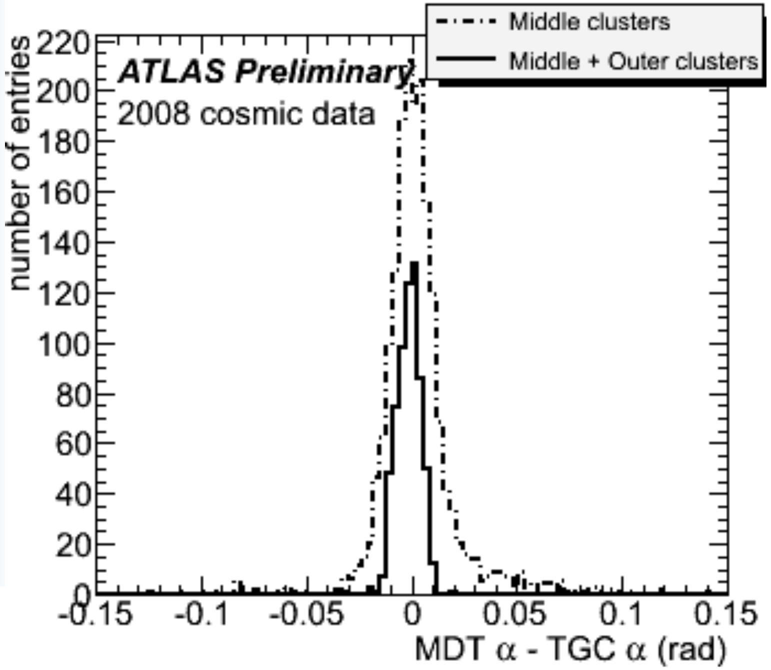
Commissioning: μFast cross check on alignment

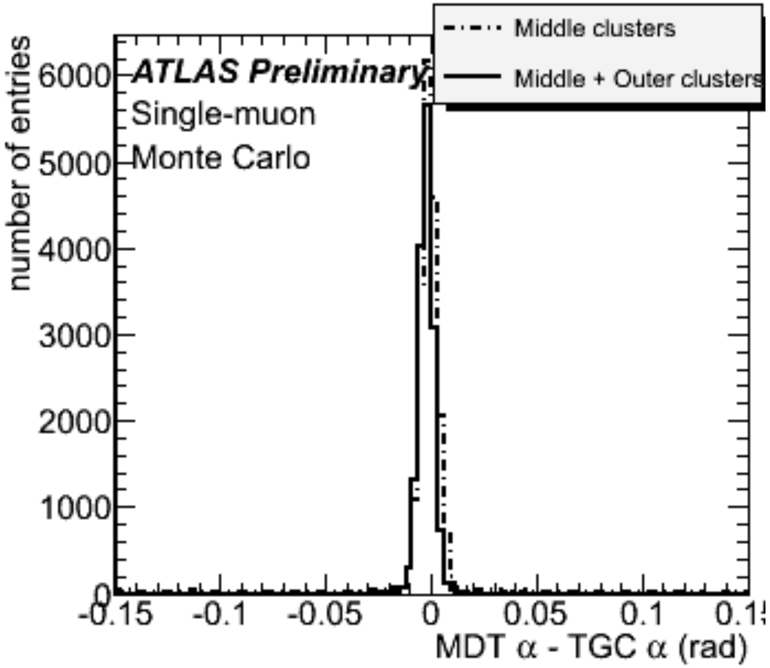
Cross check of alignment: match α angle measurement from TGC and MDT

with only Middle fit:
- poor match due to noise and bad MDT calibration;

with Middle+Outer fit:
- good match, performance limited by alignment



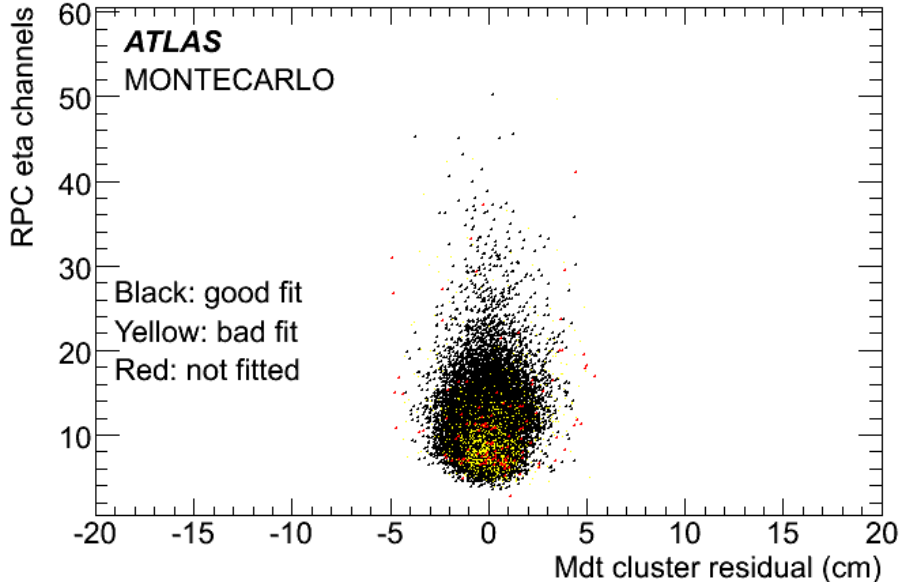




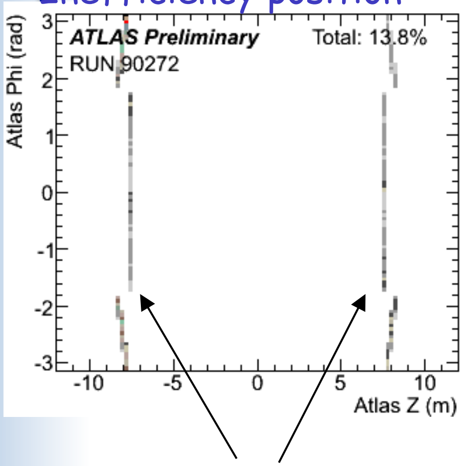
LVL2 muon: μFast MDT cluster finding

MDT cluster residual (w.r.t. RPC seed)
vs
nr. of TGC hits used as seed

- **Cluster finding efficiency:** 85%
  - 13.8% inefficiency due to missing MDT data
  - 1% inefficiency due to bad MDT calibration

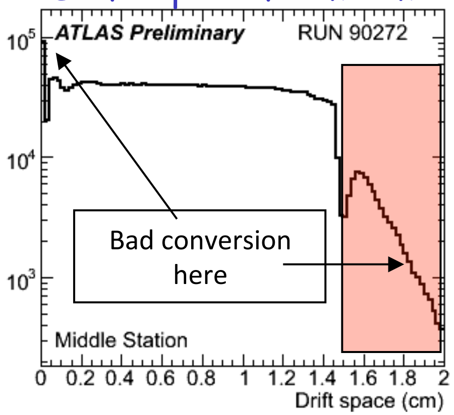


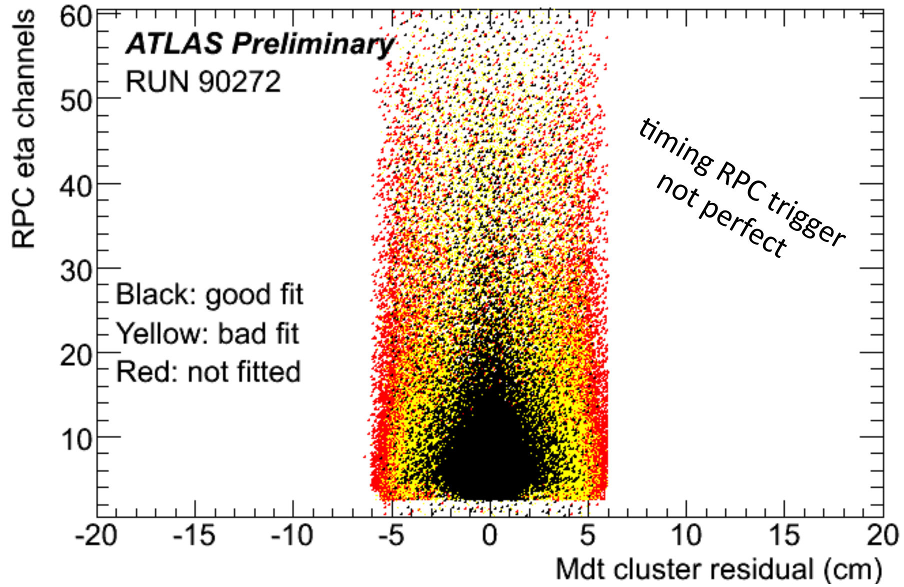
Inefficiency position



Expected border effect due to poor track pointing

Drift space from time





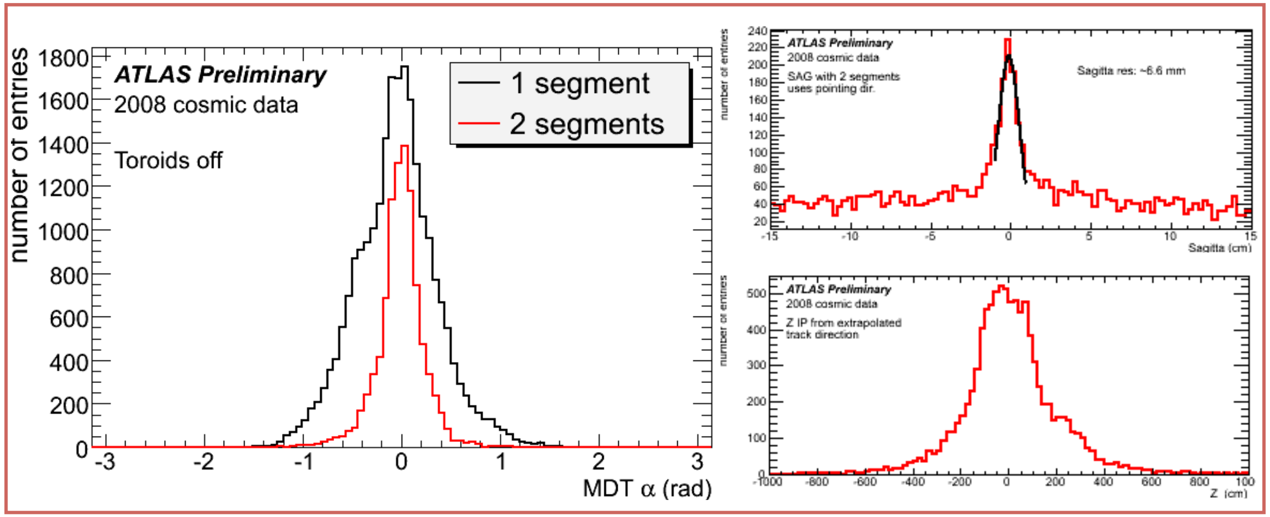
Commissioning: μFast track reconstruction

No magnetic field: straight tracks, cross check pattern recognition and reconstruction
MDT α angle: angle of MDT fit (in Middle Station) slope w.r.t. pointing direction

Algorithm assumes tracks are pointing to the IP

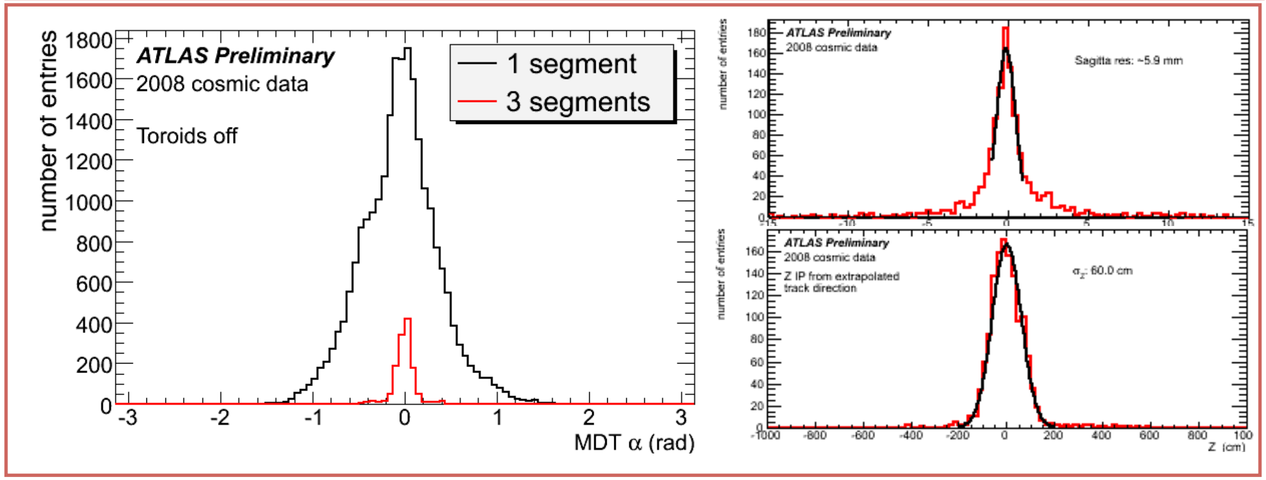
<u>2 out of 3 segments:</u>

- high efficiency on non pointing tracks;
- poor performance on the Sagitta reconstruction.



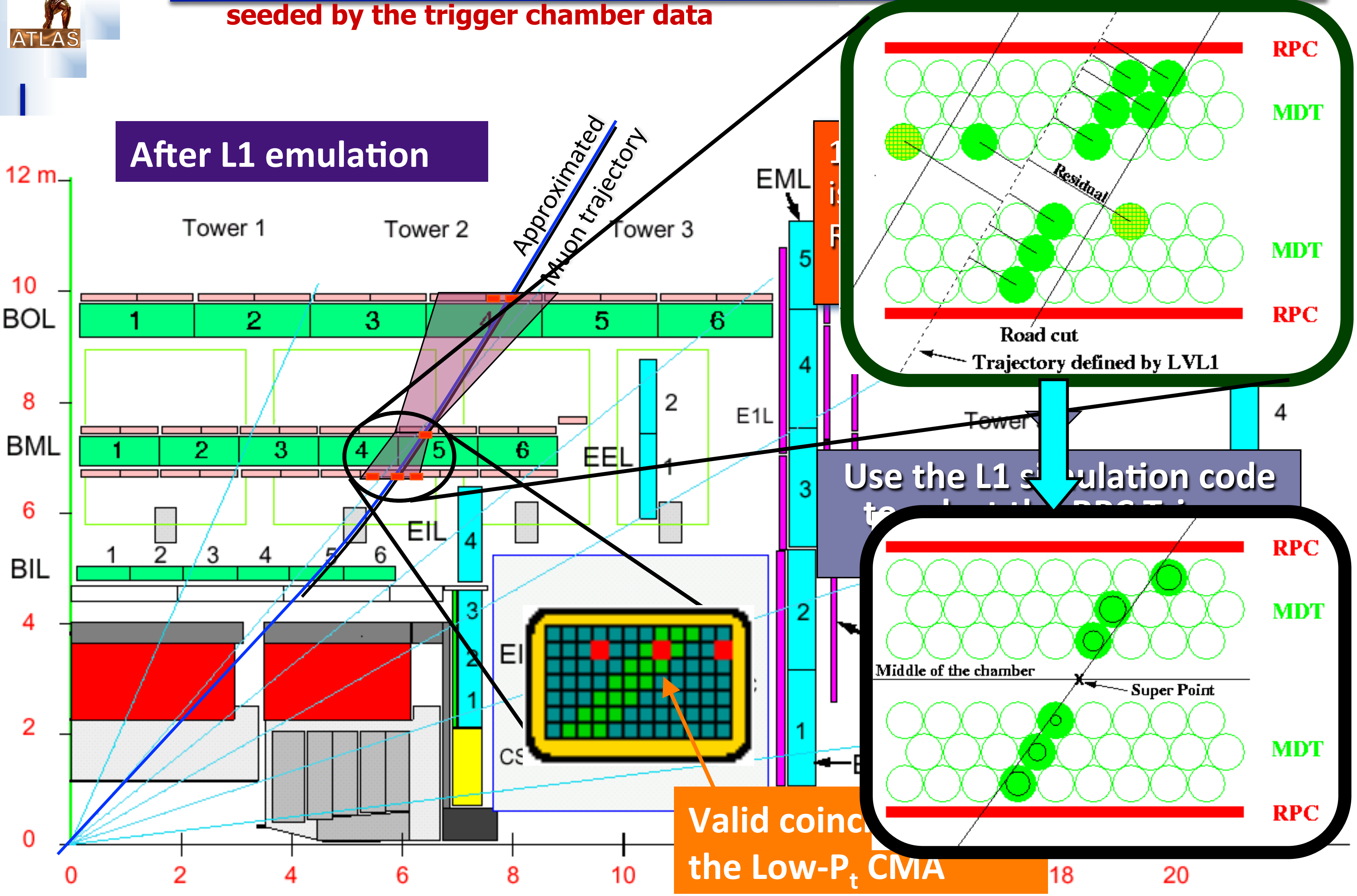
<u>3 out of 3 segments:</u>

- low efficiency on non pointing tracks;
- good Sagitta reconstruction, performance limited by the alignment.



μFast barrel: pattern recognition

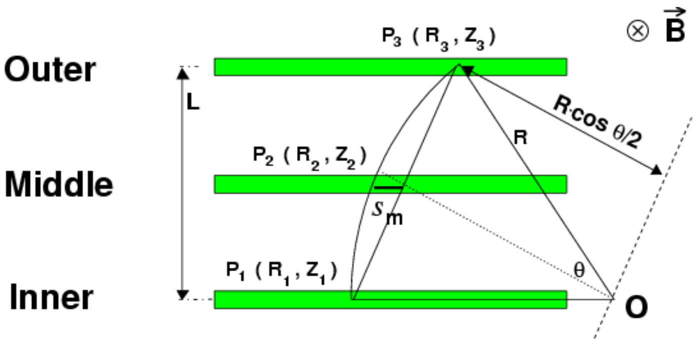
seeded by the trigger chamber data



μFast barrel: momentum reconstruction

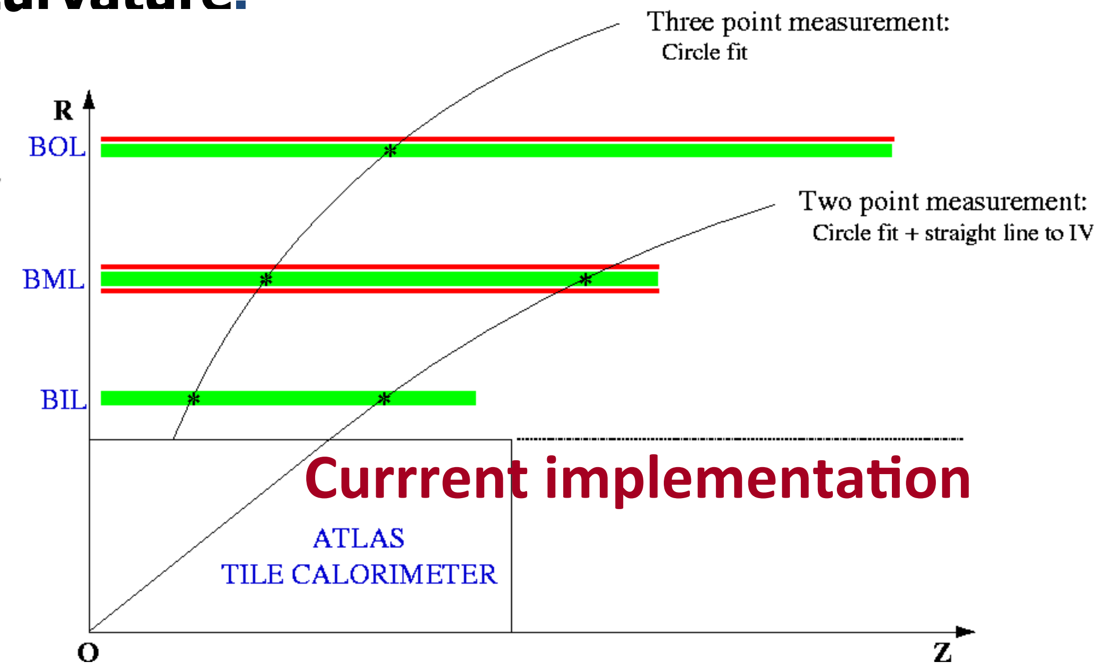
Radius vs. Projected Sagitta

The barrel field is rather homogeneous and allows a very naive estimation of the track curvature.



$$s_m = \left[\frac{Z_3 - Z_1}{R_3 - R_1} \cdot (R_2 - R_1) + Z_1 \right] - Z_2$$

OLD implementation

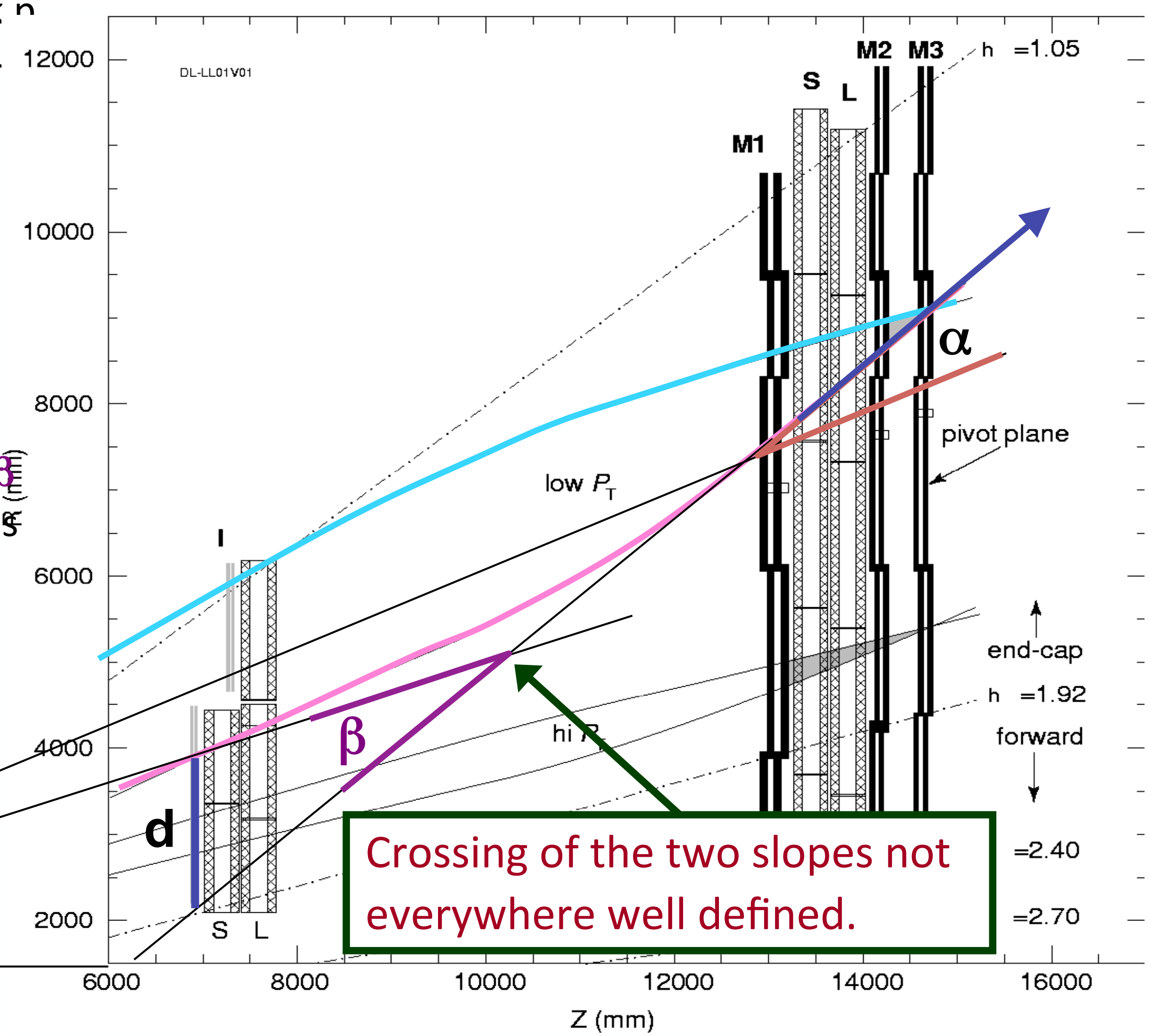


Projected sagitta depends on the direction of the incoming track, while radius doesn't.

Radius + IV allows to measure the curvature with two points only → recover the efficiency near detector holes, avoid the use of EEL.

Endcap: describing track path and measuring p_T

- One quantity related to the displacement of the Innermost hit with respect to the Middle slope segment:
  - Distance **d**, related to the track p
  - This will allow reducing the wir
- 2 angles related to p_T
  - α uses the middle station segment direction and the line from IP to triplet
  - β uses the middle station segment direction and the line from IP to inner station point. β is only available for ~1/2 muons

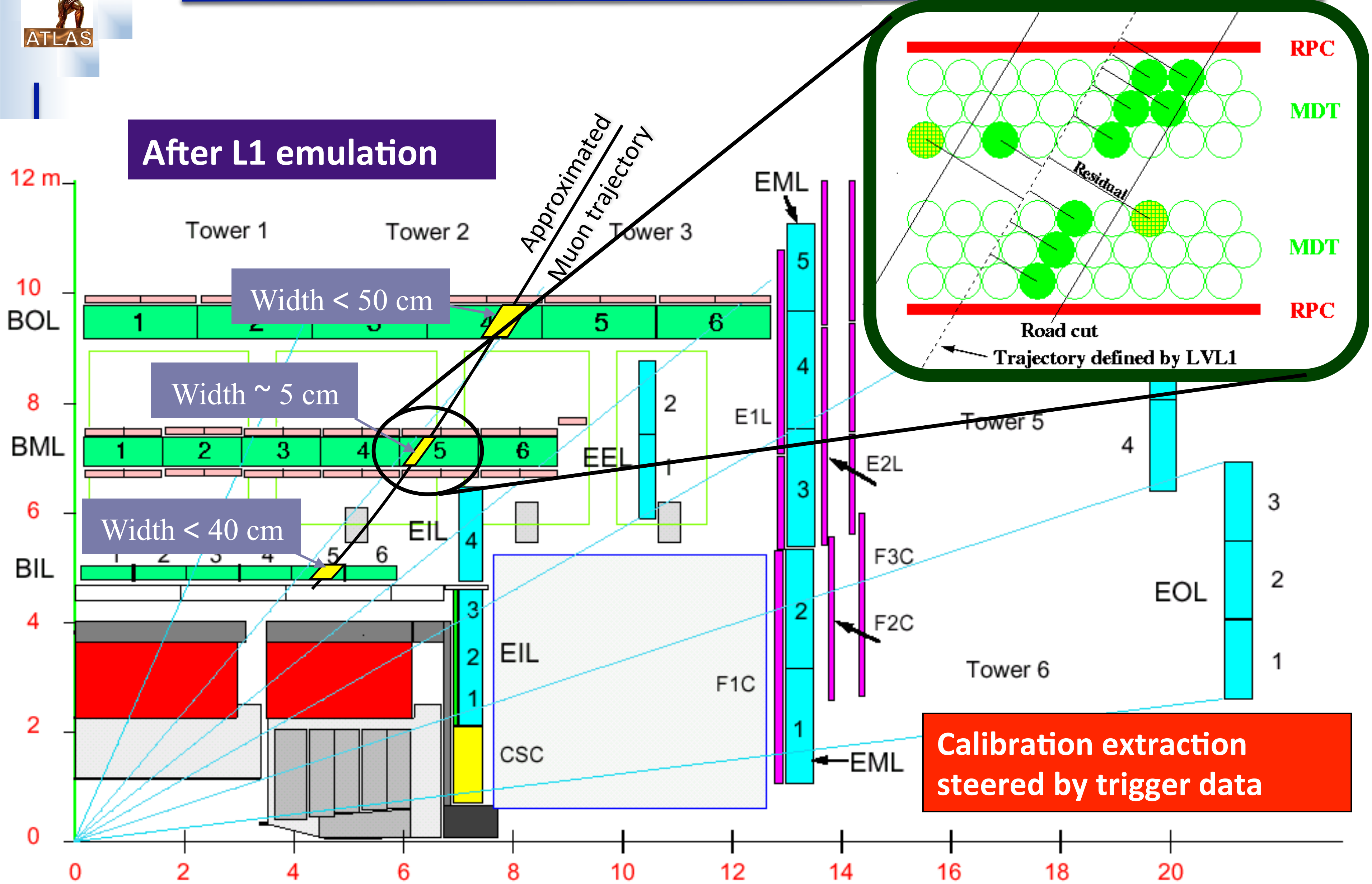


LUT granularity:

24 bin in phi/Octant

30 bin in eta, from 1 to 2.5

Calibration stream: data access



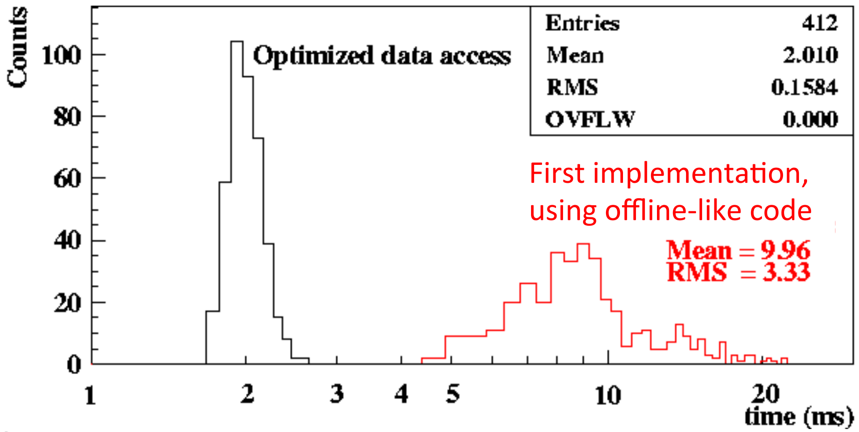
Calibration extraction steered by trigger data

Online integration

Main topics for the online operation:

- Comply with the general online requirement and latency time;
- Trigger monitoring for:
  - Data access;
  - Detector status;
  - Quality of the Level-1 seed;
  - Condition data;
  - Performance delivered;

MuFast timing on XEON CPU @ 2.40 GHz



- Allow transparent running in online and offline;
- Integration in the HLT steering, selection chain for the trigger menu;
- Event Data Model for the offline monitoring and the algorithm tuning;

Additional request for μFast:

- implementation of a dedicated selection and event streaming (**muon calibration stream**) to deliver good tracks for Muon Spectrometer calibration and MDT detector online monitoring.

details about monitoring and calibration stream are in the backup slides

Calibration stream: data format and data handle

Two basic requirements: modularity, reduction of data size.

- cope with:
  - event dependent data content;
  - possible corruption of data during the transmission;
  - short time (< 100 μs) for collecting data into the stream, and size to be keept less than 1 KBytes.

Data into the calibration stream are organized into a hierarchical structure:

- Header: contains physics on the reconstructed track, plus pointers to navigate through all the data components of the event; each components has its proper header, footer and byte counters allowing for checking the data integrity;
- MDT fragment: hold the MDT payload; only 4 data words per each hit tube to reduce the data size;
- RPC fragment: hold the complete RPC data from a PAD; uses a had hoc format to reduce the data size and decoding time inside μFast;
- TGC and CSC fragments: same payload as in the bytestream.

Access to calibration data is handled by special classes inside μFast:

- provide functionality for: encoding/decoding and navigating all the data fragments;
- used inside Athena for: building data converters to feed application that runs in the framework;
- used in standalone compilation for: build utilities (like a data dumper) and procedure to be used inside Root macros;

Calibration stream: dump of calibration data

HEADER

```
[ abba0011 ]  |--> CALIBRATION EVENT DATA, mdt rpc
[ 00000210 ]  |--> total size in bytes=528
[ 0fa24166  ]  |--> eta=0.4002,  phi=1.6742
[ f f f f ed3f  ]  |--> pt=-4.801
[ 00000024 ]  |--> mdt data at byte 36
[ 00000178 ]  |--> rpc data at byte 376
[ 00000000 ]  |--> tgc data at byte 0
[ 00000000 ]  |--> csc data at byte 0
[ 000001e4 ]  |--> data size in bytes=484 bytes
```

MDT

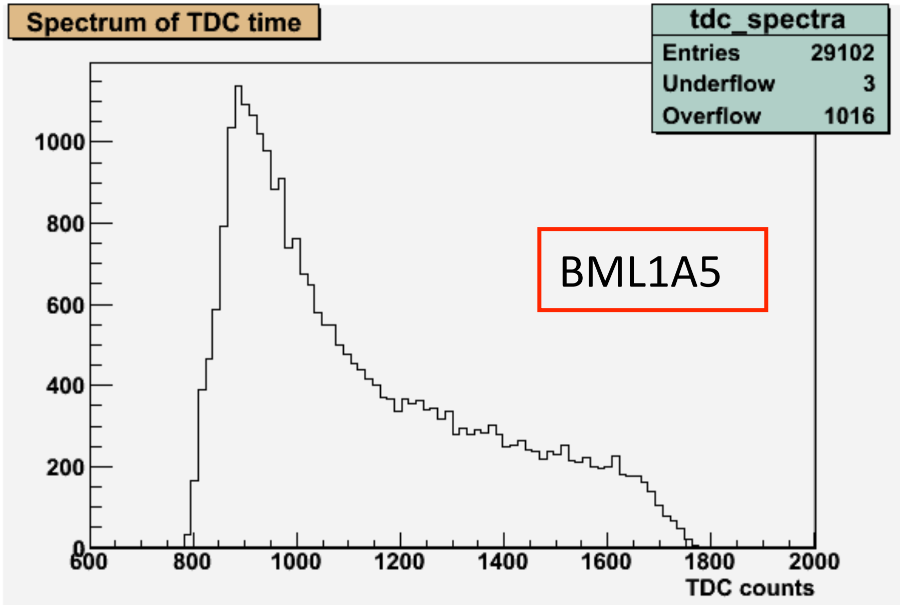
```
[ adda0014 ]  |-->   MDT FRAGMENT,  number of hits= 20
[ 00000154 ]  |-->   Total size in bytes=340
[ 00000140 ]  |-->   Mdt data size in bytes=320
                    ---------------------------------------
[ 0841801e ]  |-->   Name/Eta/Phi/Mul/Lay/Tube = /2/2/3/1/1/31
[ 00250016 ]  |-->     Leading edge: coarse time=37, fine time=22
[ 00000000 ]  |-->     Trailing edge: coarse time=0, fine time=0
[ 00944198 ]  |-->     Width =148,  Phi=1.6793
[ 0841901f  ]  |-->   Name/Eta/Phi/Mul/Lay/Tube = /2/2/3/1/2/32
[ 0032000e ]  |-->     Leading edge: coarse time=50, fine time=14
[ 00000000 ]  |-->     Trailing edge: coarse time=0, fine time=0
[ 00824198 ]  |-->     Width =130,  Phi=1.6793
[ 0841901e ]  |-->   Name/Eta/Phi/Mul/Lay/Tube = /2/2/3/1/2/31
[ 002b001d ]  |-->     Leading edge: coarse time=43, fine time=29
[ 00000000 ]  |-->     Trailing edge: coarse time=0, fine time=0
[ 00924198 ]  |-->     Width =146,  Phi=1.6793
                    ---------------------------------------
[ abb1fede ]  |-->   Trailer tag
[ 0014adda ]  |-->   END OF MDT FRAGMENT,  hits=20
```

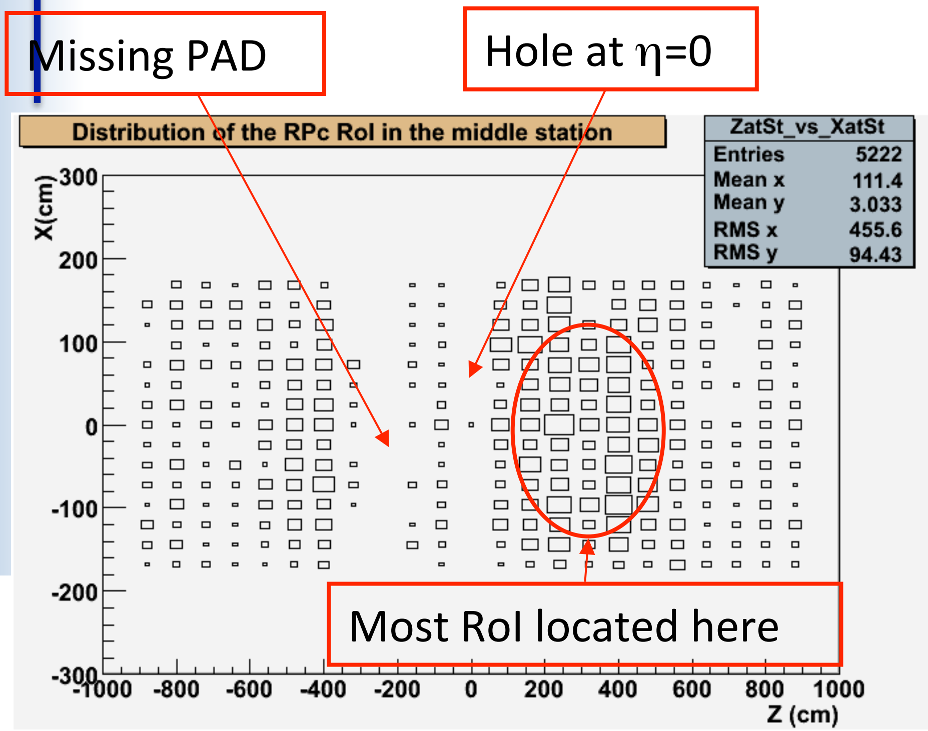
RPC

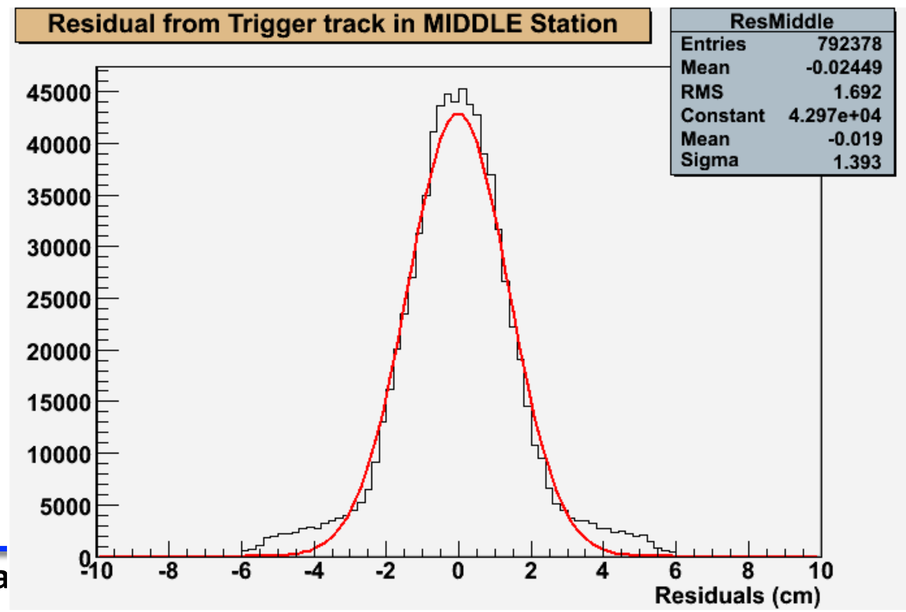
```
[ acca0008 ]  |-->   RPC FRAGMENT,  number of matrices= 8
[ 00650008 ]  |-->   SUBYSID = 101,  sector ID = 8
[ 10000000 ]  |-->   PAD ID = 1,  status word = 0,  error code = 0
[ 00000090 ]  |-->   Total size in bytes=144
[ 00000074 ]  |-->   RPC data size in bytes=116
[ 00070778 ]  |-->   CMAID = 0,  FEL1ID = 7,  FEBCID = 778
[ 00000007 ]  |-->   CRC = 0,  HitNum = 7
[ 26172368 ]  |-->     BC=4,TI=6,ijk=0,CH=23     | BC=4,TI=3,ijk=3,CH=08
[ 236a2469 ]  |-->     BC=4,TI=3,ijk=3,CH=10     | BC=4,TI=4,ijk=3,CH=09
[ 25a926d7 ]  |-->     BC=4,TI=5,ijk=5,CH=09     | BC=4,TI=6,ijk=6,CH=23
[ 26e30000 ]  |-->     BC=4,TI=6,ijk=7,OV=0,TH=3 |
[ 20070777 ]  |-->   CMAID = 1,  FEL1ID = 7,  FEBCID = 777
[ 00000004 ]  |-->   CRC = 0,  HitNum = 4
[ 23582359 ]  |-->     BC=4,TI=3,ijk=2,CH=24     | BC=4,TI=3,ijk=2,CH=25
[ 235a2499 ]  |-->     BC=4,TI=3,ijk=2,CH=26     | BC=4,TI=4,ijk=4,CH=25
[ 40070777 ]  |-->   CMAID = 2,  FEL1ID = 7,  FEBCID = 777
[ 00000007 ]  |-->   CRC = 0,  HitNum = 7
[ 230e1f5a  ]  |-->     BC=4,TI=3,ijk=0,CH=14     | BC=3,TI=7,ijk=2,CH=26
[ 215c225b ]  |-->     BC=4,TI=1,ijk=2,CH=28     | BC=4,TI=2,ijk=2,CH=27
[ 219b23ce ]  |-->     BC=4,TI=1,ijk=4,CH=27     | BC=4,TI=3,ijk=6,CH=14
[ 23e30000 ]  |-->     BC=4,TI=3,ijk=7,OV=0,TH=3 |
[ 60070777 ]  |-->   CMAID = 3,  FEL1ID = 7,  FEBCID = 777
[ 00000001 ]  |-->   CRC = 0,  HitNum = 1
[ 22400000 ]  |-->     BC=4,TI=2,ijk=2,CH=00     |
[ 80070777 ]  |-->   CMAID = 4,  FEL1ID = 7,  FEBCID = 777
[ 00000001 ]  |-->   CRC = 0,  HitNum = 1
[ 2f170000  ]  |-->     BC=5,TI=7,ijk=0,CH=23     |
[ a0070777 ]  |-->   CMAID = 5,  FEL1ID = 7,  FEBCID = 777
[ 00000000 ]  |-->   CRC = 0,  HitNum = 0
[ c0070777 ]  |-->   CMAID = 6,  FEL1ID = 7,  FEBCID = 777
[ 00000001 ]  |-->   CRC = 0,  HitNum = 1
[ 2c0e0000 ]  |-->     BC=5,TI=4,ijk=0,CH=14     |
[ e0070777 ]  |-->   CMAID = 7,  FEL1ID = 7,  FEBCID = 777
[ 00000000 ]  |-->   CRC = 0,  HitNum = 0
[ abb1fede  ]  |-->   Trailer tag
[ 0008acca ]  |-->   END OF RPC FRAGMENT,  number of matrices=8
```

Calibration stream: monitoring plots

- μFast reconstruct only pointing tracks: ~6k tracks reconstructed over 80K trigger;
- nice correlation RPC-MDT seen in the Middle chamber
- correlation in othe staion not so good, but the efficiency for finding the muon hits into the roads > 99%
- Size of the calibration event: ~ 500 Bytes





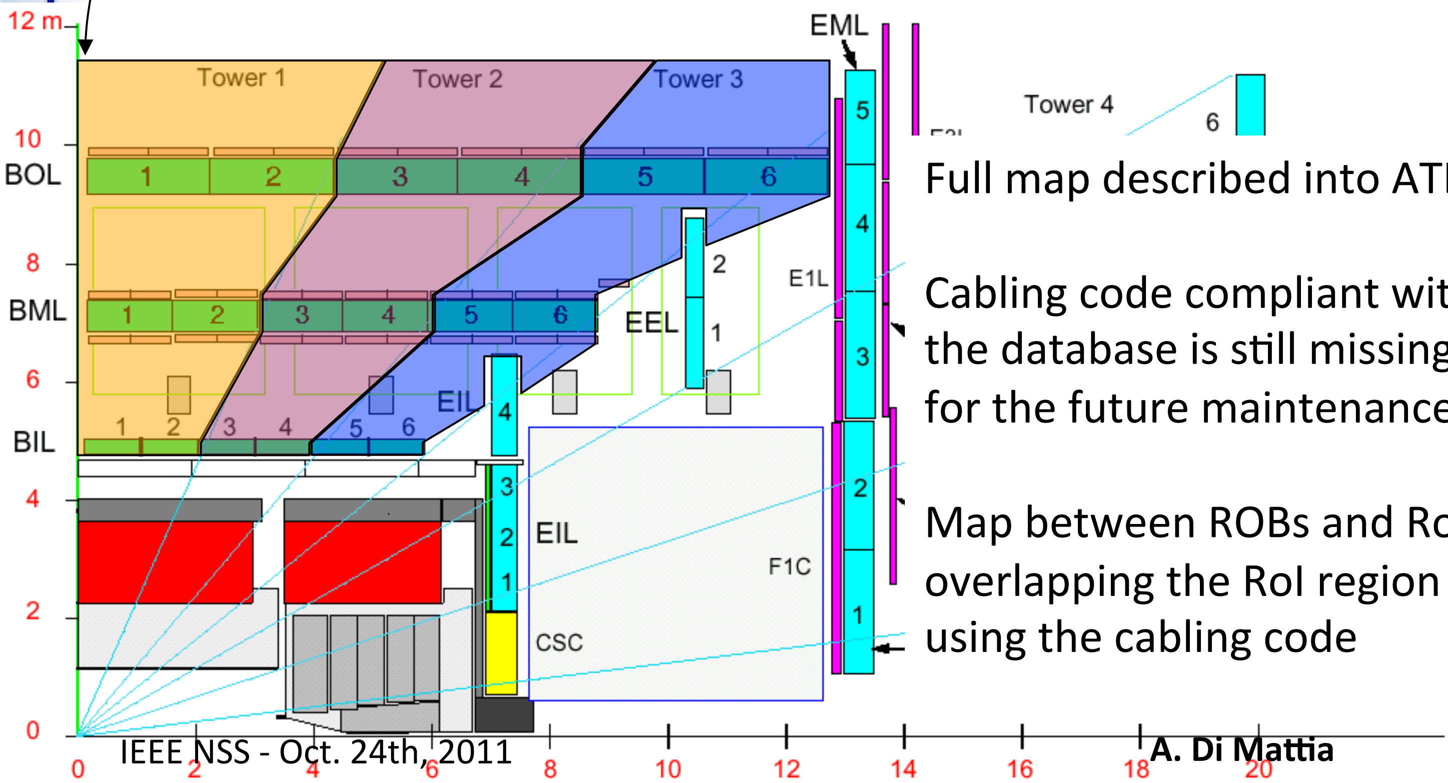


MDT readout, map between RoI and ROBs

MDT bytestream organization:

ROD -> Chamebr System Module (CSM) -> TDC ->TDC channel

- 1 CSM read 1 MDT chamber; one CSM can have up to 18 TDC;
- 1 AMT (Atlas Muon TDC) can have up to 24 channel (= “tubes”);



Full map described into ATL-DAQ-2003-023

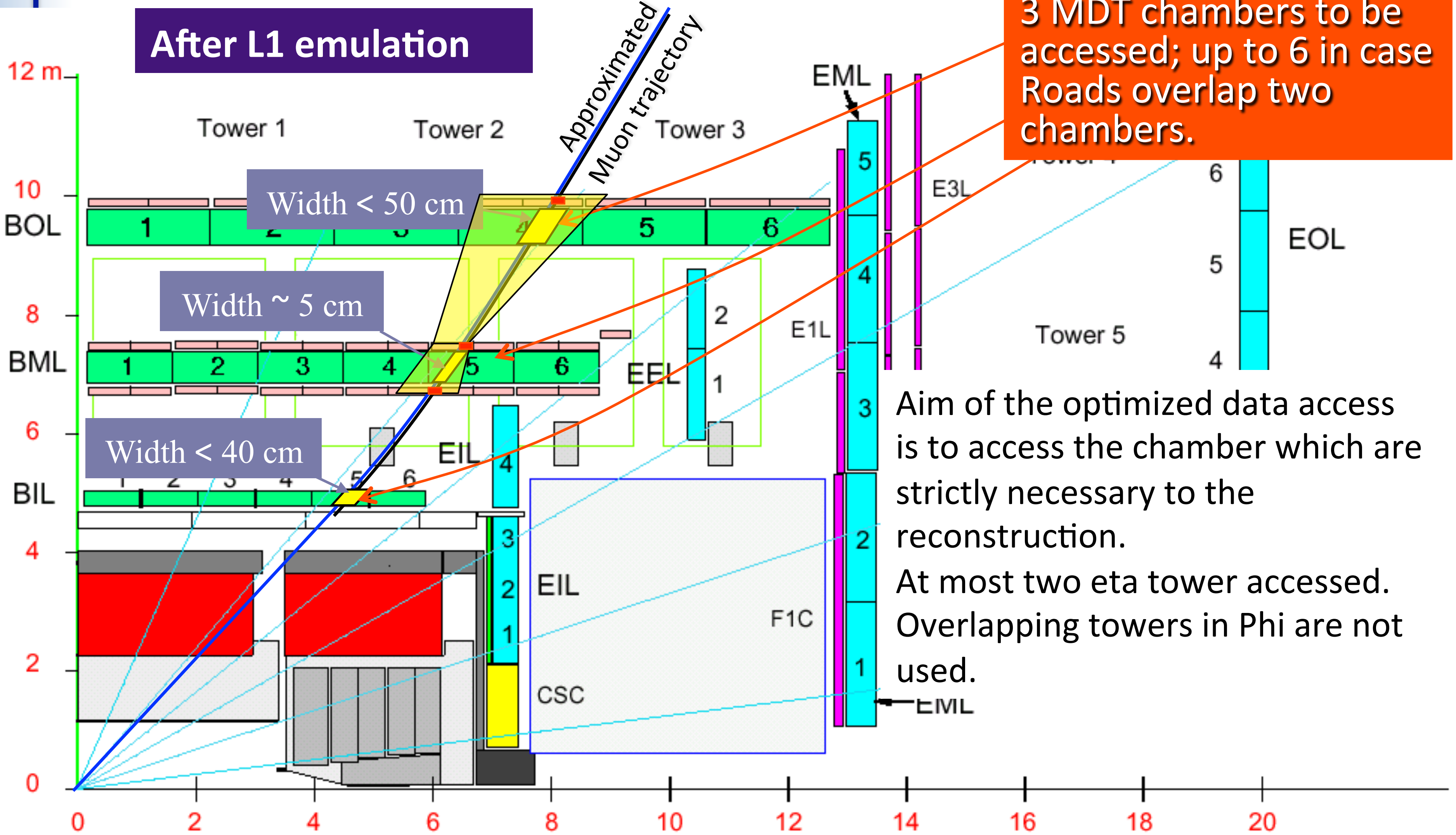
Cabling code compliant with it, but the access to the database is still missing. Very important for the future maintenance.

Map between ROBs and RoI produced by overlapping the RoI region with MRODS using the cabling code

MDT optimized data access

Use muon roads

After L1 emulation



3 MDT chambers to be accessed; up to 6 in case Roads overlap two chambers.

Aim of the optimized data access is to access the chamber which are strictly necessary to the reconstruction.

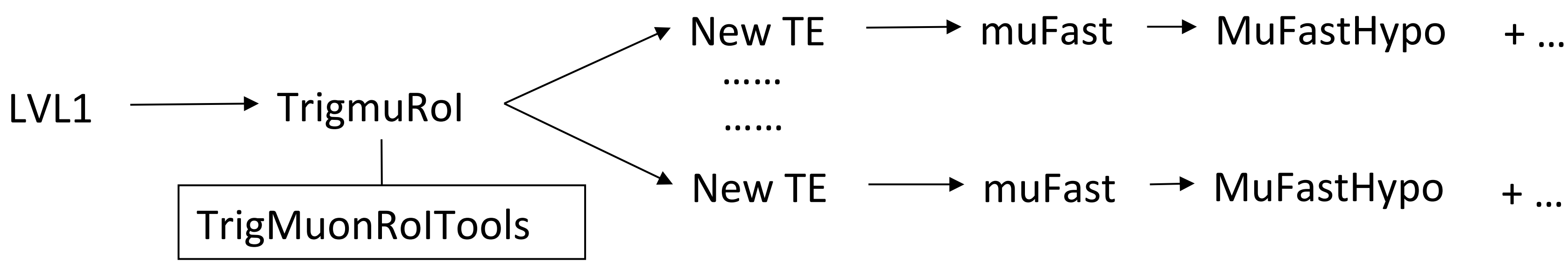
At most two eta tower accessed.

Overlapping towers in Phi are not used.

OutofTime selection: implementation

Key idea: retrieve the missing seed of the out of time RoIs

- **TrigMuonRoITools**: access the Muctpi DAQ ROB and looks for muon RoIs out of time;
- **TrigmuRoI**: runs unseeded and creates a new TE for each out of time muon RoI;
- **MuFast_OutBCID**: process out of time RoI data to search for track segments;
- **MufastHypo_OTR**: check number of segments reconstructed;



Selection chains optimized for acceptance:

- mu0_OutOfTime1 – 1 segment required;
- Mu0_OutOfTime2 – 2 segments required;