Performance of an MDT-based First-Level Muon Trigger for the ATLAS Detector at the HL-LHC

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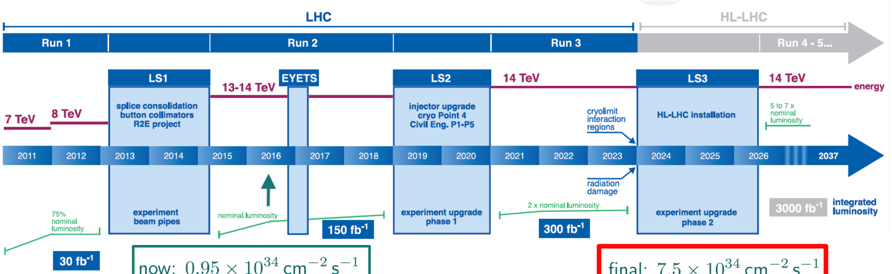
High Luminosity upgrade of the LHC



now: $0.95 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

final: $7.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

- Plan to increase the LHC luminosity by an order of magnitude.
  - Ultimate instantaneous luminosity: $7.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
  - $10\times$ increased background of n and γ rays in Muon Spectrometer.
- Reach of searches for new physics, and accuracy of measurements significantly increased.

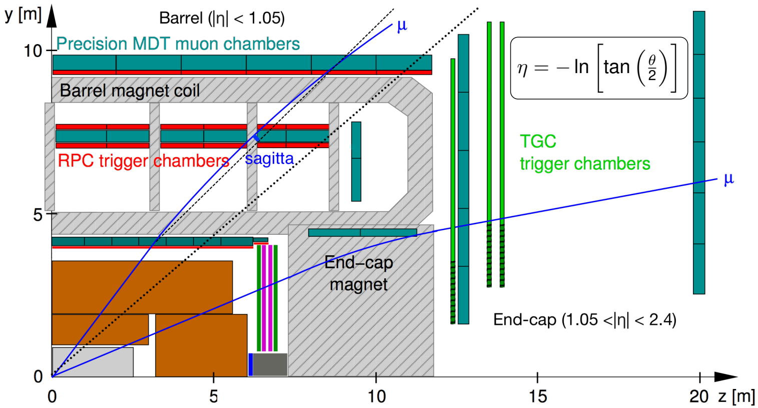
High Luminosity upgrade of the LHC

The intended physics programme for the HL-LHC requires

$\Rightarrow$ to maintain present trigger thresholds for physics at the electroweak scale ($\lesssim 20\,\mathrm{GeV}$).

$\Rightarrow$ new highly selective triggers, in particular also a new first-level muon trigger.

The ATLAS Muon Spectrometer at the HL-LHC



Momentum measurement from track sagitta (curvature) in three layers of muon chambers.

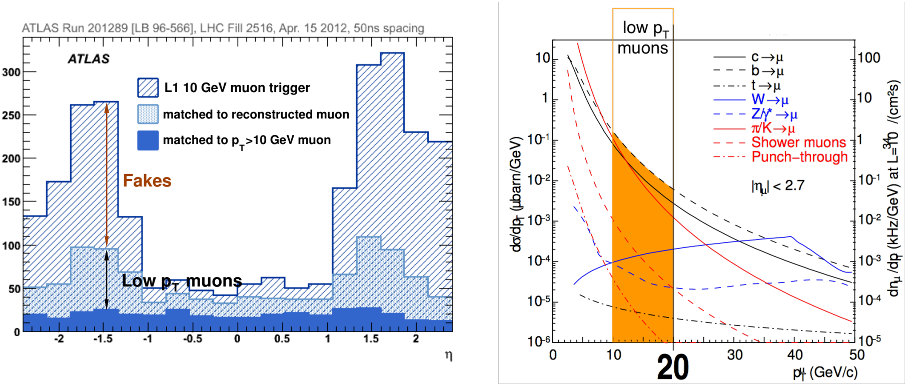
Fast trigger chambers, $\mathcal{O}$(1 ns) time precision:

- Resistive Plate Chambers (RPC),
- Thin Gap Chambers (TGC)

Precision tracking detectors, $\mathcal{O}$(35 μm) spatial resolution:

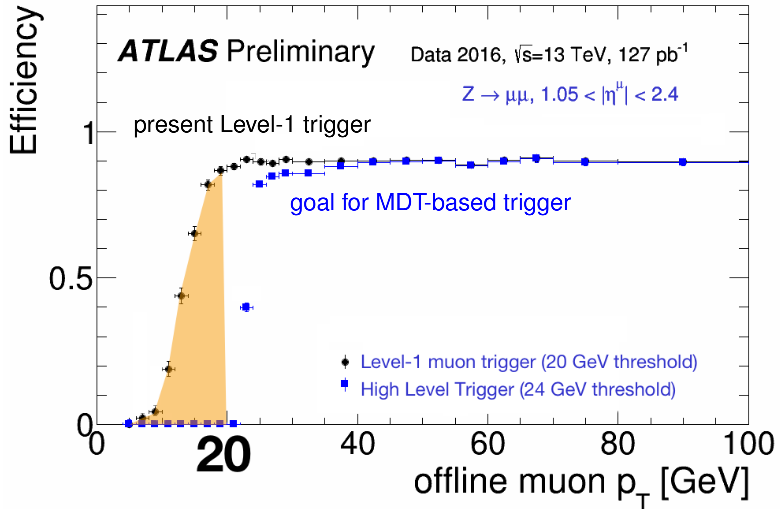
- Monitored Drift Tube Chambers (MDT), consist of 6-8 layers of 30 mm diameter drift tubes.

Contributions to the first-level muon trigger rate

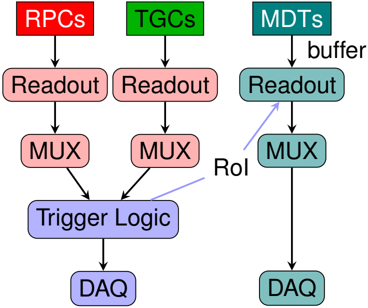


- Trigger rate is dominated by fake tracks in end-caps, and by high rate of low energy muons.
- Improved momentum resolution of the first-level trigger required for sufficient reduction of the trigger rate due to low energy muons.

Present single muon trigger threshold



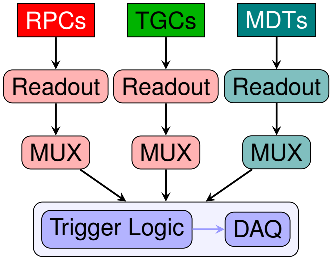
The ATLAS first-level muon trigger at the HL-LHC



Schematic diagram of present Level-1 muon trigger

- MDT chambers provide required momentum resolution for Level-1 trigger, comparable to present High Level Trigger, to reduce single muon trigger rate to $< 20\,\text{kHz}$ (with high efficiency and low fake rate).
- Due to the increased latency of $6\,\mu\text{s}$ after the Phase-II upgrade, it becomes possible to include MDT chambers in the first-level trigger decision.

The ATLAS first-level muon trigger at the HL-LHC



Schematic diagram of new MDT trigger

developed at MPP

- MDT chambers provide required momentum resolution for Level-1 trigger, comparable to present High Level Trigger, to reduce single muon trigger rate to < 20 kHz (with high efficiency and low fake rate).
- Due to the increased latency of 6 µs after the Phase-II upgrade, it becomes possible to include MDT chambers in the first-level trigger decision.

The ATLAS first-level muon trigger at the HL-LHC

Two topics are addressed in this talk:

1. Development and test of fast track segment reconstruction algorithms with custom Monte Carlo study, including background rates as expected for HL-LHC.
2. Investigation of trigger rate reduction with inclusion of MDT chambers using Run 1 data at $\sqrt{s} = 8\,\text{TeV}$, 25 ns.

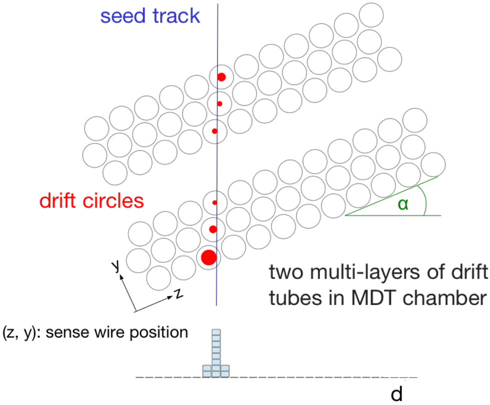
Track segment reconstruction:

- Pattern Reconstruction
- Track segments from straight line χ^2 fit ($y = mz + b$) to selected hits
- Choose candidate with:
  1. largest number of hits n_{hits},
  2. smallest χ^2

Three pattern recognition algorithms were studied:

- 1-D Hough transform
- 2-D Hough transform
- (new) Combinatorial Track Finder

1-D Hough transform

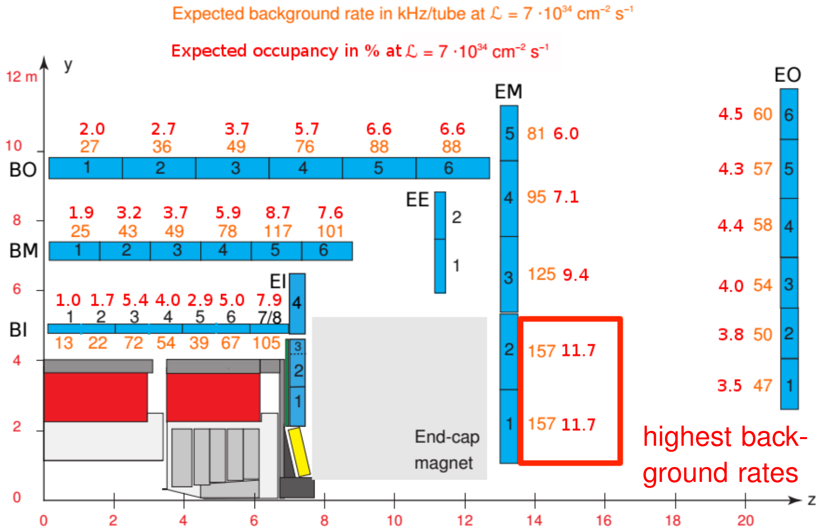


1. Use RPC/TGC track segment angle α as seed.
2. Fill projection

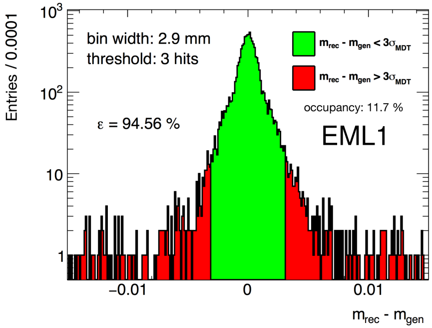
   $$d = z\cos\alpha + y\sin\alpha \pm r_{\text{drift}}$$

   of MDT hits onto seed track direction in histogram.
3. Use hits in maximum bin for straight line χ^2 fit.

Expected background rates at HL-LHC



Track segment reconstruction performance



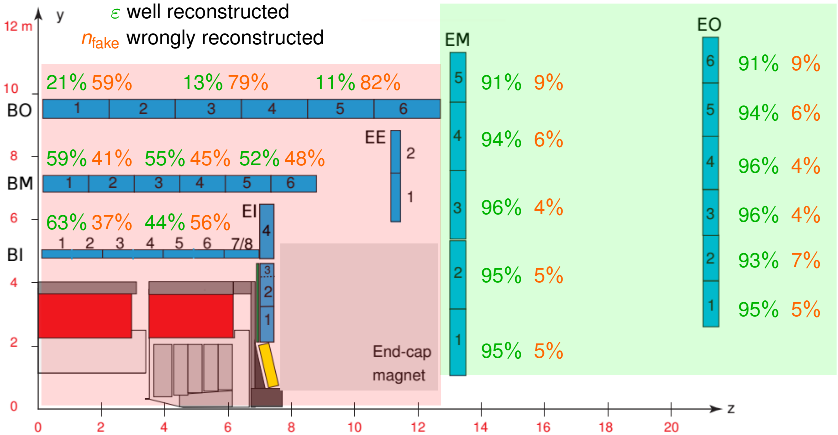
1-D Hough transform performance depends on seed track angular resolution:

- good in end-caps ($\sigma_\theta \approx 5$ mrad)
- lower in barrel ($\sigma_\theta \gtrsim 15$ mrad)

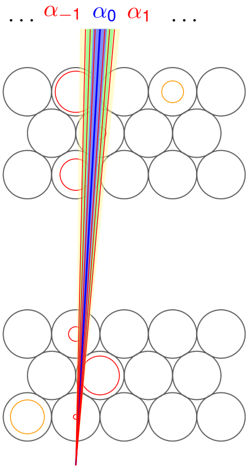
	$n_{hits} \geq n_{min}$	$n_{hits} < n_{min}$
$\lvert m_{rec} - m_{gen} \rvert < 3\sigma_{MDT,\theta}$	well reconstructed track segments (ε)	track segments rejected
$\lvert m_{rec} - m_{gen} \rvert > 3\sigma_{MDT,\theta}$	wrongly reconstructed track segments (n_{fake})	track segments rejected

Track segment reconstruction performance

1-D Hough transform



2-D Hough transform



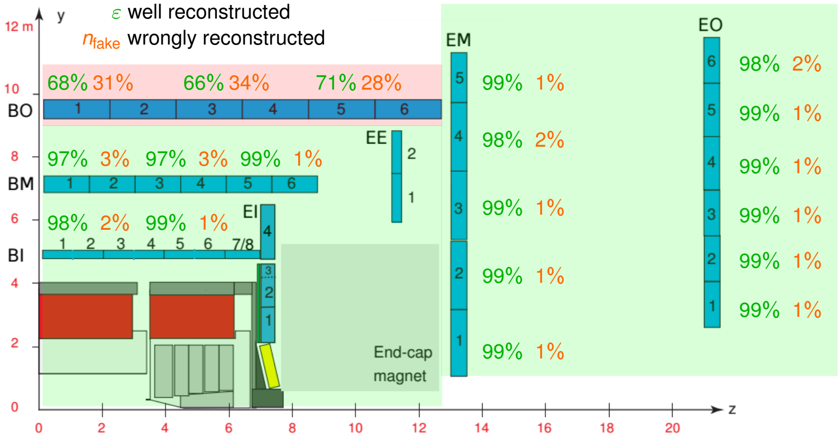
- Multiple 1-D Hough transforms for different bins α_i around seed track segment angle α_0
  $\Leftrightarrow$ scan 2-D parameter space in α and d.
- For each bin α_i
  - fill a histogram with

$$d_i = z \cos \alpha_i + y \sin \alpha_i \pm r_{\text{drift}},$$

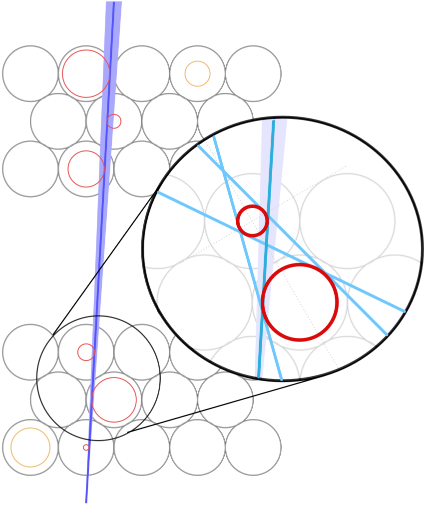
  - perform straight line χ^2 fits to hits in maximum bins (as before).

Track segment reconstruction performance

2-D Hough transform



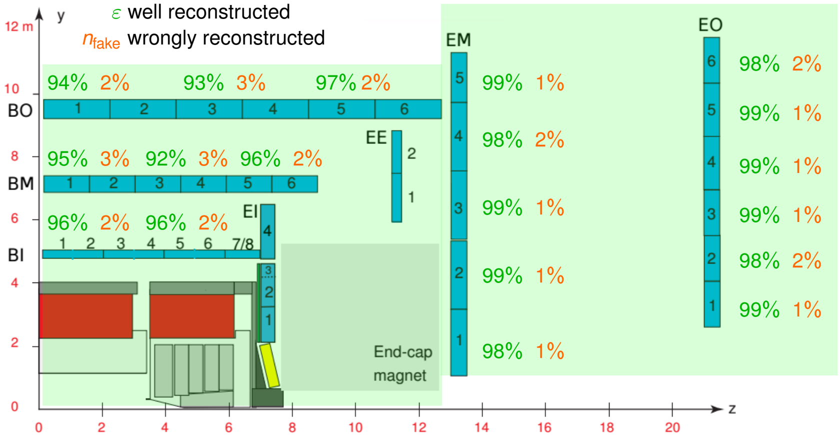
Combinatorial Track Finder new



1. For every combination of two drift circles in the same multi-layer: calculate the four possible common tangents.
2. Select tangents compatible with RPC/TGC seed track.
3. Calculate the average of the compatible tangents.
4. Find hits closest to the straight line.
5. Perform straight line χ^2 fit to these hits (as before).

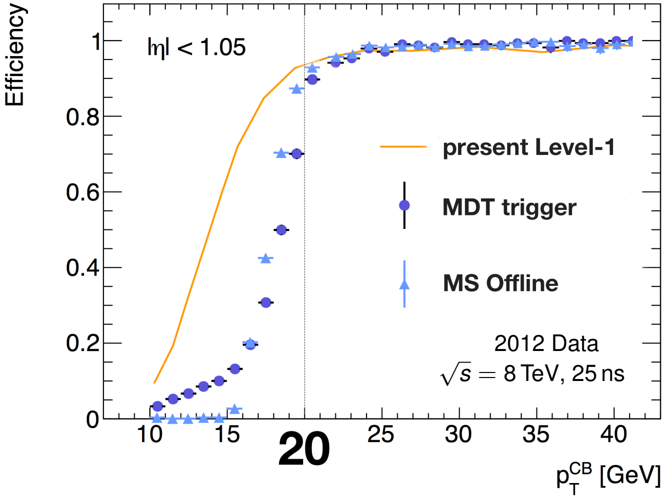
Track segment reconstruction performance

Combinatorial Track Finder

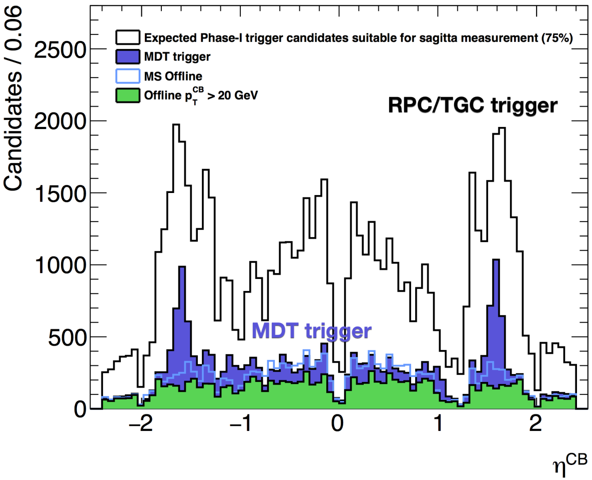


Rate reduction of the first-level single muon trigger

- Studied with ATLAS Run 1 data



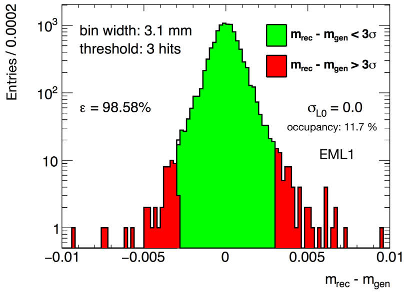
Rate reduction of the first-level single muon trigger

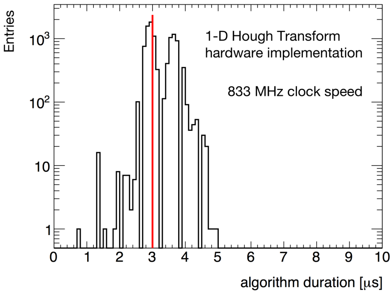


included in ATLAS Phase-II upgrade IDR

Rate reduction by 70%, therefore first-level muon trigger rate reduced to $< 20\,\text{kHz}$ for $p_T = 20\,\text{GeV}$ trigger threshold.

Hardware implementation





- Assembler code implemented at MPP on a 'System on a Chip' (XC7Z045 FFG900 -2 AP), FPGA + 833 MHz CPU.
- All events can be processed in $< 5\,\mu s$, close to intended processing time of $3\,\mu s$.
- Further optimisation possible with faster processors (1 GHz) and enhanced implementation.

Summary

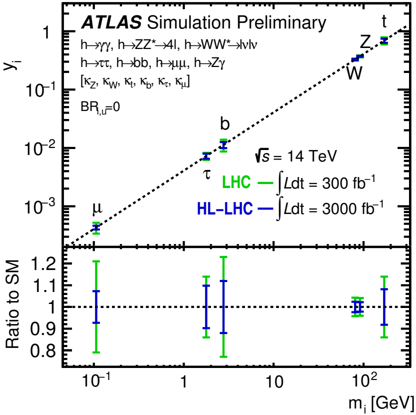
- Highly selective triggers are required to maintain trigger thresholds for physics at the electroweak scale at the HL-LHC.
- To reduce the single muon trigger rate to $< 20\,\text{kHz}$ it is required to include the MDT chambers in the first-level trigger decision.
- Fast muon track reconstruction algorithms have been developed, which can be performed within 6 µs latency.
- The new method developed, the Combinatorial Track Finder, based on all possible tangents to drift circles, gives high track segment efficiency $\varepsilon \approx 95\%$ in all regions of the ATLAS Muon Spectrometer and is insensitive to the seed precision.

Additional Slides

Physics Motivation

Significant improvements in the

- precision measurement of Higgs couplings and detection of possible deviations from SM values,
- searches for supersymmetric particles,
- searches for Dark Matter particles, e.g. in invisible Higgs boson decays.



⇒ Maintain present trigger thresholds for physics at the electroweak scale ($\lesssim 20\,\text{GeV}$).

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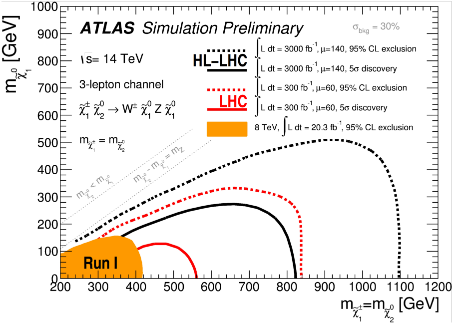

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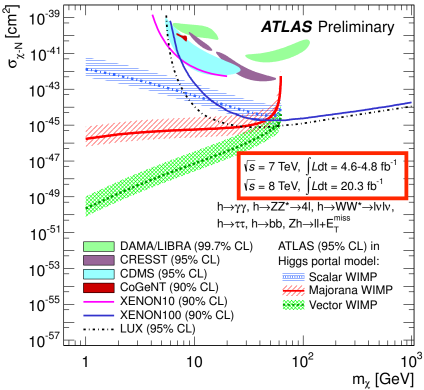

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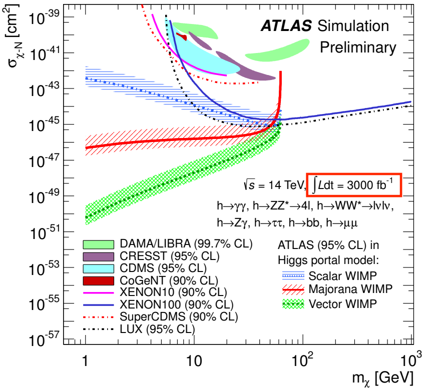
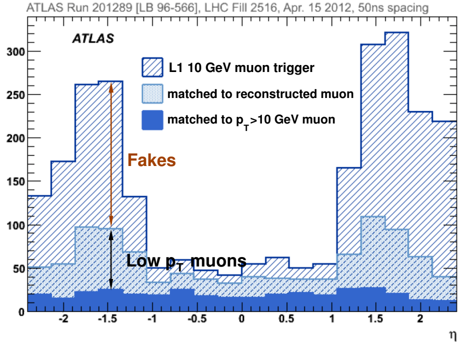
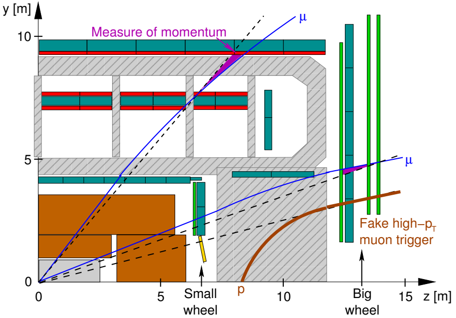


$\Rightarrow$ Maintain present trigger thresholds for physics at the electroweak scale ($\lesssim$ 20 GeV).

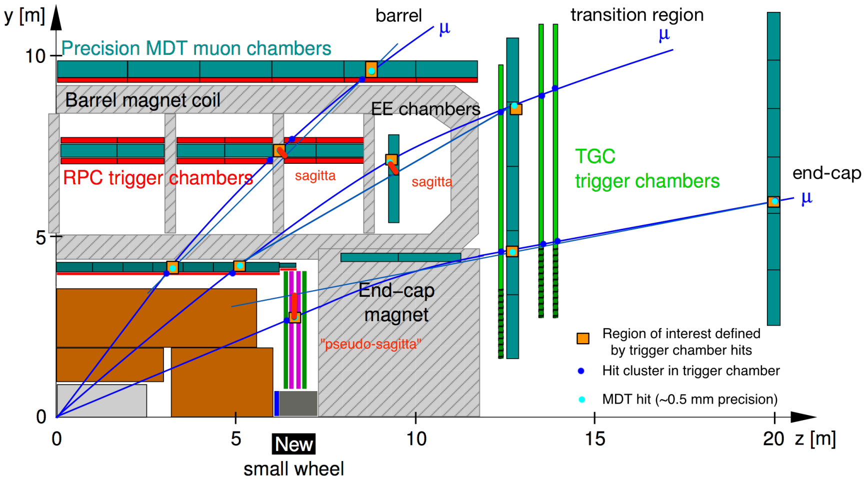
Avoidable background in end-caps





- Hadronic punch-through from the calorimeters gives rise to fake high-p_T muon triggers
- New Small Wheel (Phase-I upgrade) and Big Wheel coincidence will sort out fakes

Sagitta measurement



Parametrisation of $p_{\mathrm{T}}^{\mathrm{on}}$ in terms of s, ϕ, η

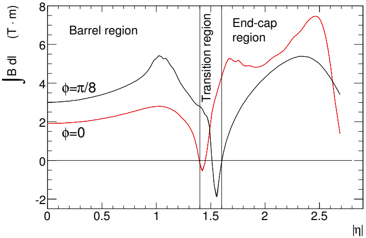
The inhomogeneous field integral in the spectrometer requires local corrections dependent on η and ϕ.

$$p_{\mathrm{T}} = \frac{eL^2 \cdot B(\phi, \eta)}{8s} \approx S_1(1/s) + P_2(\phi) + E_2(\eta),$$

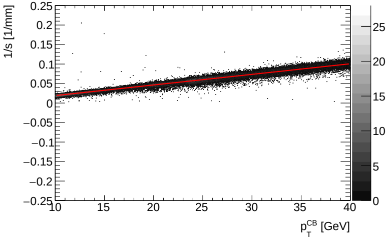
with

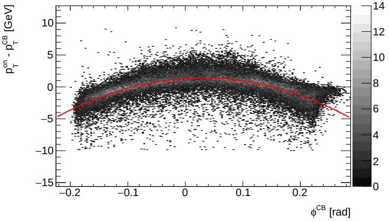
- $S_1 = (1/s - a_0)/a_1$
- $P_2(\phi) = \sum_{i=0}^{2} p_i \cdot \phi^i$
- $E_2(\eta) = \sum_{i=0}^{2} e_i \cdot \eta^i$

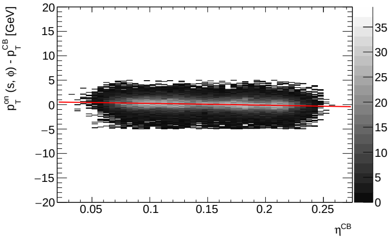
The parameters a_i, p_j, e_j are determined in an iterative fitting procedure.

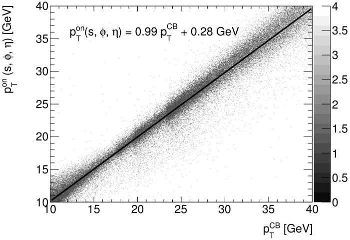


Iterative fitting procedure

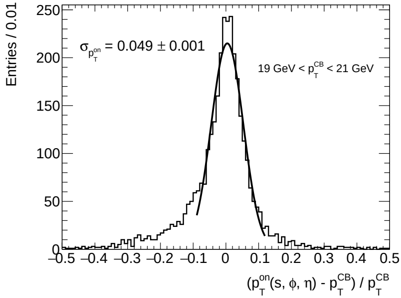


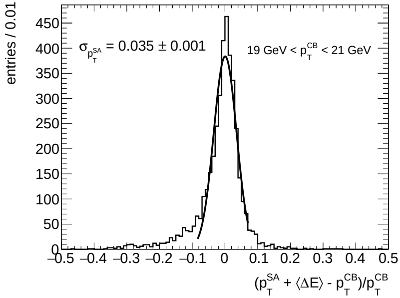






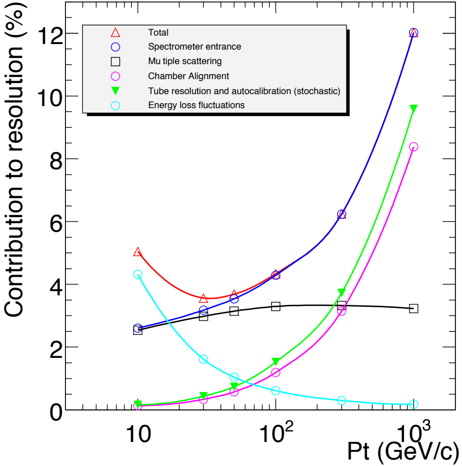
Momentum resolution of sagitta measurement



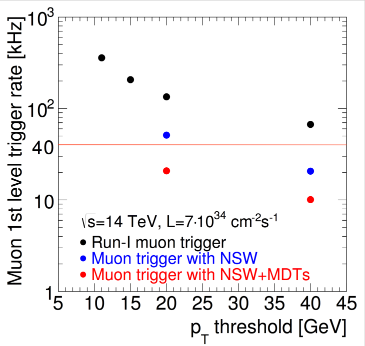


- p_T^{on} resolution at trigger threshold of 20 GeV: $\sigma_{p_T^{on}} = 4.9\%$, limited by energy loss fluctuations and multiple scattering
- MS Offline resolution at trigger threshold of 20 GeV: $\sigma_{p_T^{SA}} = 3.5\%$

Momentum resolution in ATLAS Muon Spectrometer



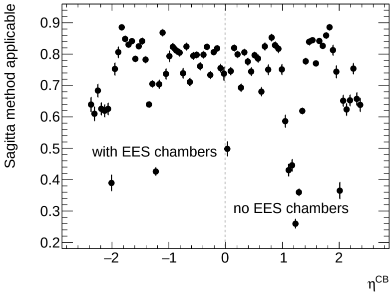
Expected Rate Reduction

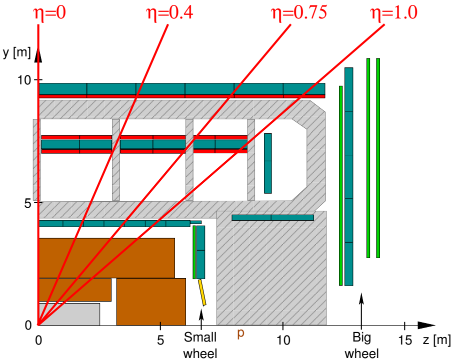


- 70% of all trigger candidates have 3 or more track segments and are suitable for sagitta measurement with rate reduction by 70%.
- Remaining 20% of all trigger candidates is suitable deflection angle measurement with rate reduction of 50%.
- Remainder (10%) is accepted by MDT trigger.

$\Rightarrow$ Combined rate reduction by 60% from 50 kHz (after Phase-I upgrade) to 20 kHz.

Sagitta measurement





- Sagitta measurement only possible for trigger candidates with ≥ 3 track segments.
- Detector upgrades will provide higher track segment efficiency for $|\eta| > 2.0$

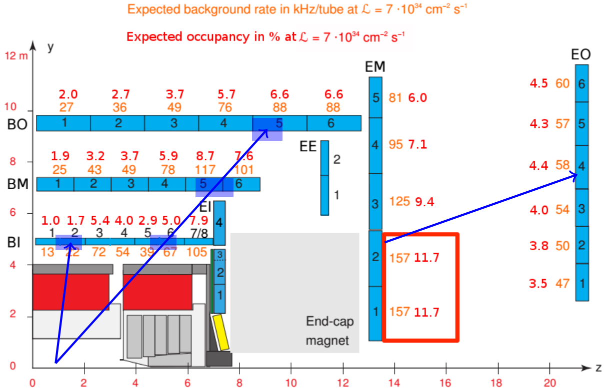
Event selection for rate study

Data sample: Run 1 ATLAS data at $\sqrt{s} = 8\,\text{TeV}$, 25 ns bunch spacing (Period M), consisting of runs 216399, 216416, and 216432

Step in event selection	Number of events
Expected Phase-I trigger events	122 701
Matched to off-line muon	109 950
$p_T^{CB} < 100$ and $p_T^{SA} < 100$	102 292
Sagitta method applicable	76 270

Assumptions for Monte-Carlo Performance Study

Predicted occupancy for HL-LHC [6]



RPC/TGC resolution

Chamber	σ_{seed} *m*
BI[1)]	0.020
BM	0.015
BO[1)]	0.080
EM[2)]	0.005
EO[3)]	0.005

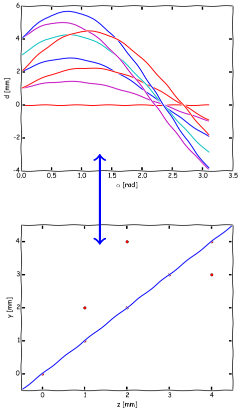
1) MDT segments with σ_{RPC}

2) TGC segments [7]

3) EM extrapolated

- Segment parameters for each chamber determined with Run-1 data
- No EO TGCs: slope extrapolation EM $\rightarrow$ EO with $\sigma_{\text{EO - EM}} = 0.0018$

Hough transform



Hough transform:

- Isomorphic map between points in coordinate space and sinusoidal curves in parameter space
- Maximum in parameter space defines straight line segment
- Implementation: fill histogram with

$$d_i = x \cos \alpha_i + y \sin \alpha_i \pm r_{\text{drift}}$$

- [1] ATLAS Phase-II Upgrade Scoping Document, CERN-LHCC-2015-020
- [2] Prospects for New Physics in Higgs Couplings Studies with the ATLAS Detector at the HL-LHC, ATL-PHYS-PUB-2014-017
- [3] New Small Wheel Technical Design Report, CERN-LHCC-2013-006
- [4] ATLAS muon spectrometer : Technical Design Report, CERN-LHCC-97-022
- [5] The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003
- [6] S. Sun, G. Conti, L. Jeanty, and M. Franklin, Predicting Hit Rates in the ATLAS Montior Drift Tube at $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ at $\sqrt{s} = 7$ and 8 TeV, ATL-COM-MUON-2013-011
- [7] Kouta Onogi, 修士論文 LHC アップグレードに向けた ATLAS 実験のミューオントリガー開発