Design of the FCC-hh Muon Detector and Trigger System

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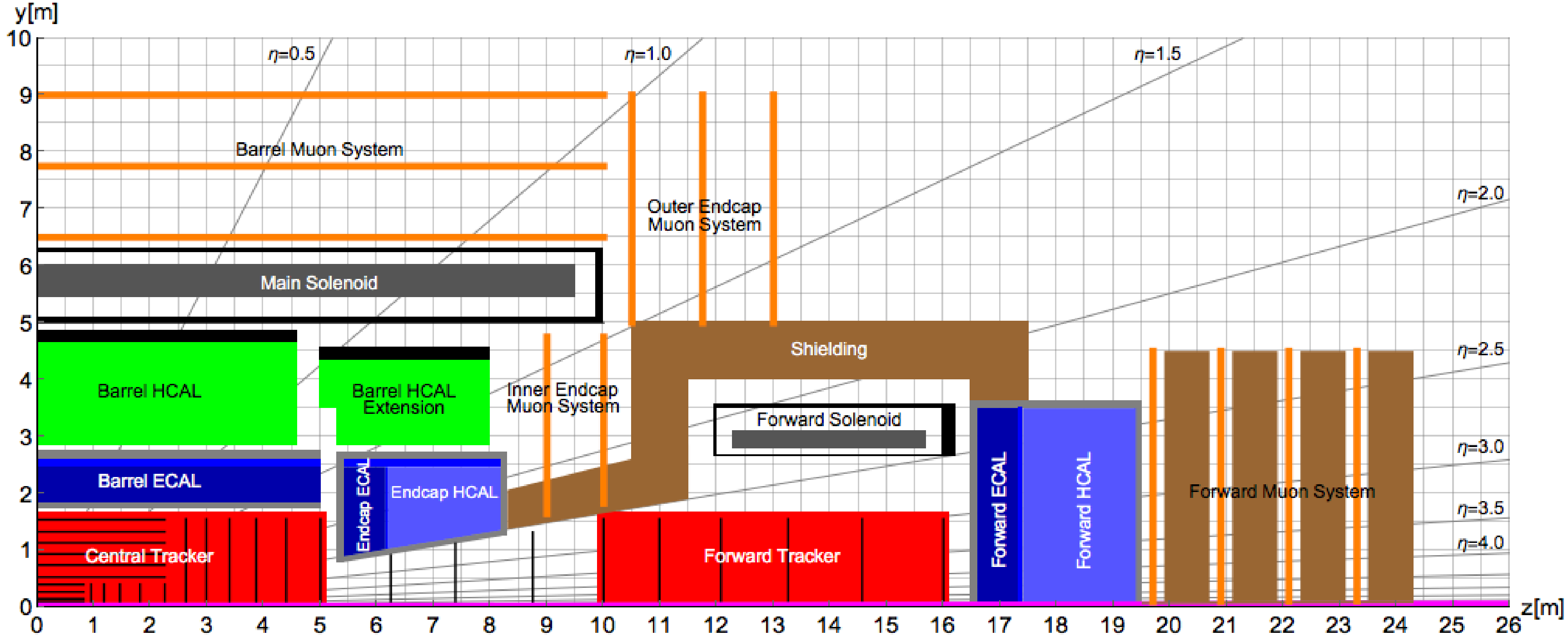
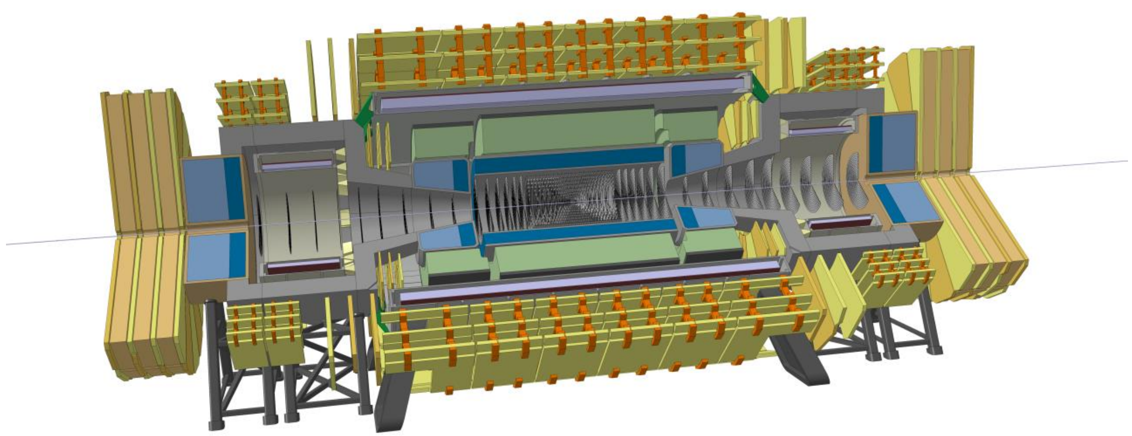
including studies by Yuji Enari and Koji Terashi, Univ. of Tokyo,

and by Zbynek Drasal and Werner Riegler, CERN

Reference Detector Layout





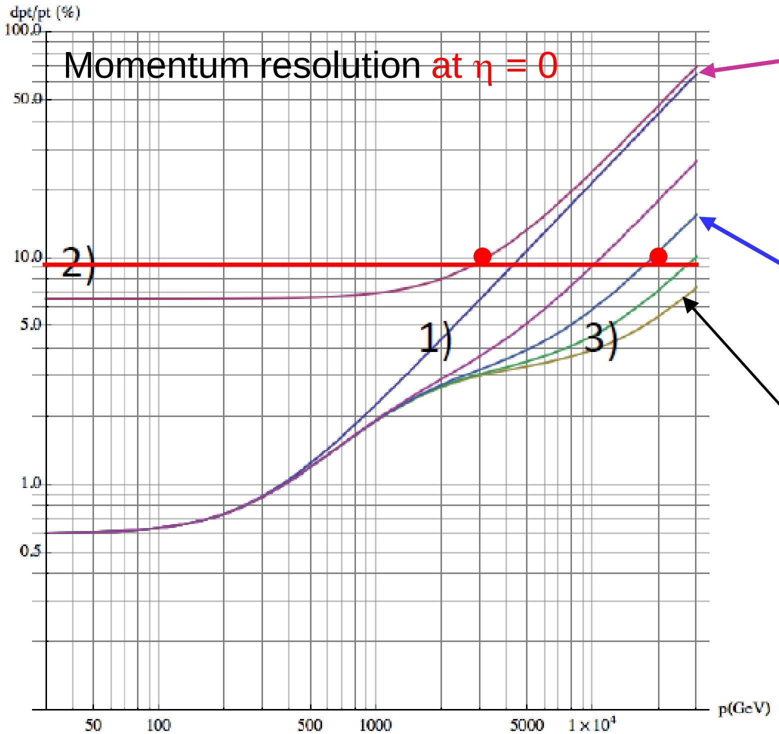
Performance Goals for a FCC-hh Muon Detector

Three methods for muon momentum measurement:

1) Inner tracker only with muon identification in muon system.

2) Standalone muon system track angle measurement at coil exit (redundancy for $p_T > 3$ TeV).

3) Combined tracker and muon system (point) measurement at coil exit (for $p_T > 2$ TeV).



p_T (GeV)

Analytical calculation,
Werner Riegler, FCC Week 2017

With 70 µrad muon detector angular resolution:

< 10% standalone momentum resolution up to 3 TeV, equal to tracker resolution

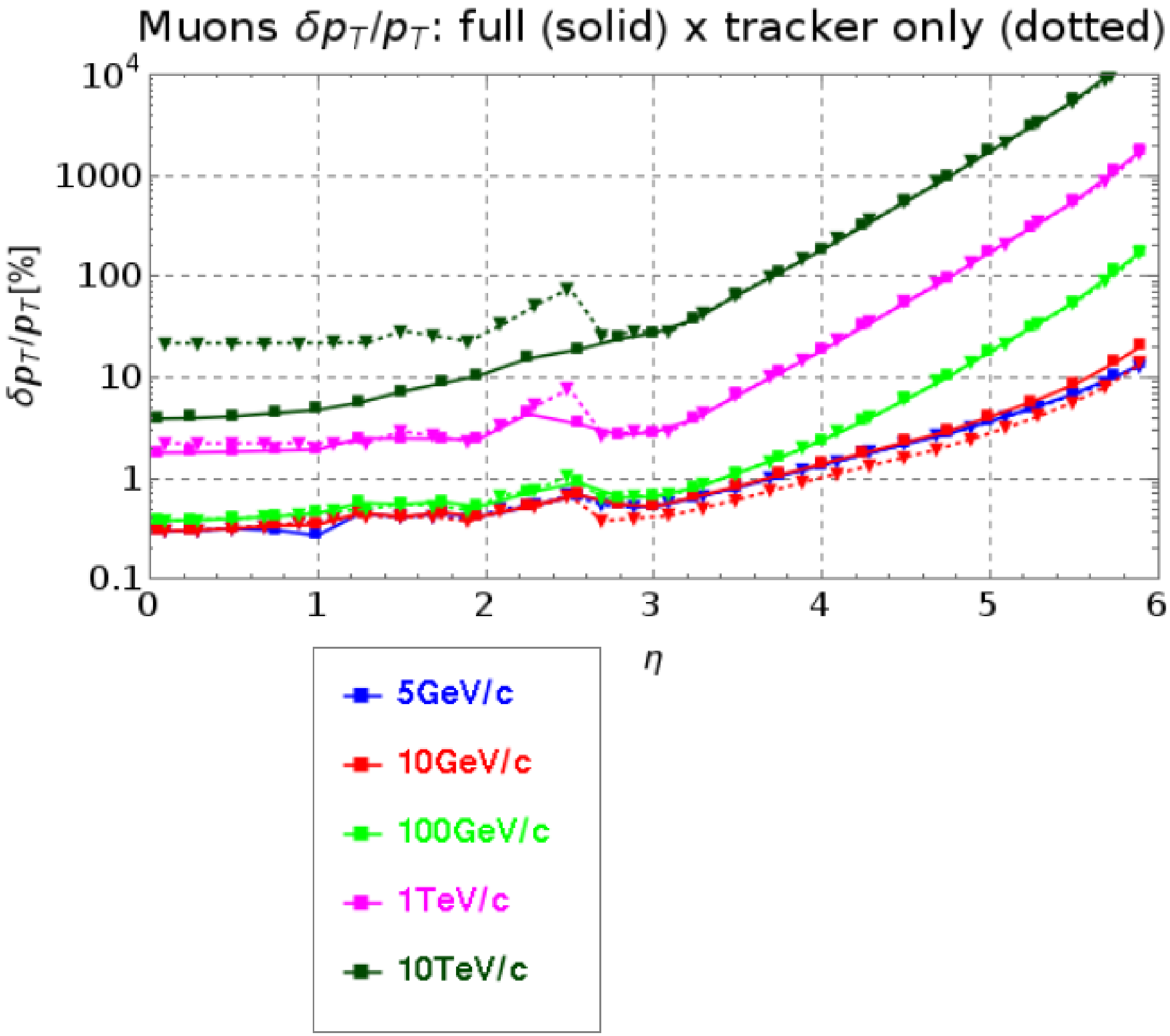
5% standalone MSC limit below 1 TeV

With 50 µm muon detector spatial resolution:

< 10% combined momentum resolution up to 20 TeV.

Multiple scattering limit for combination

Combined Momentum Resolution



Improvement by muon system for $p_T > 1$ TeV and $|\eta| < 2.5$.

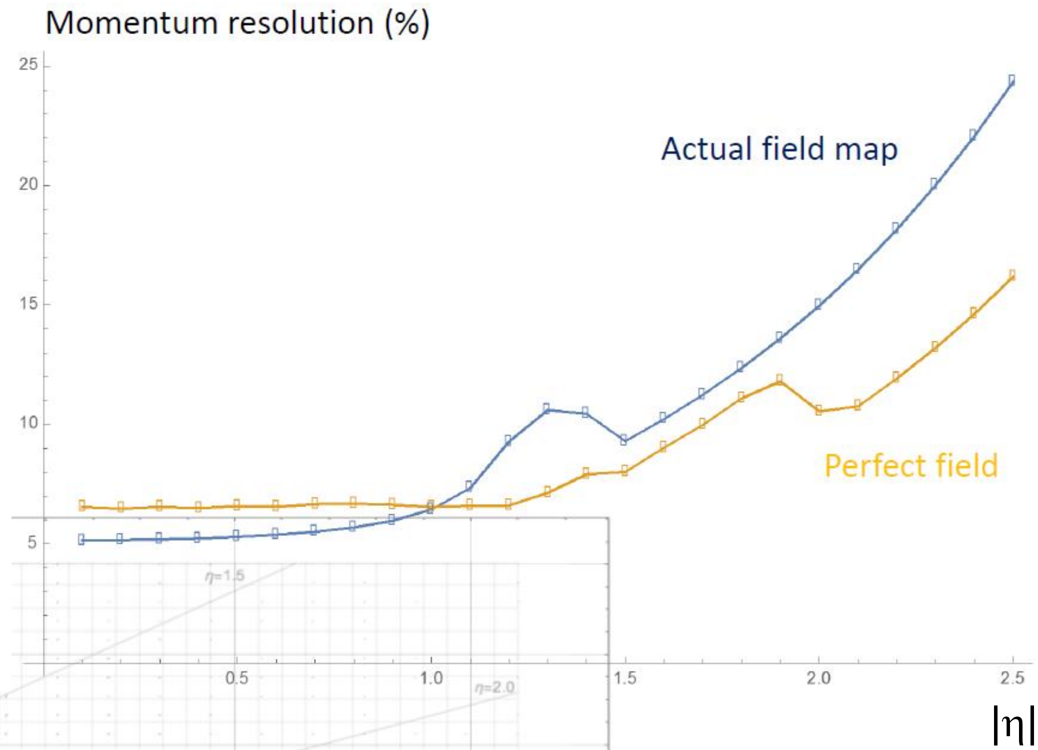
Analytical calculation, Zbynek Drasal.
Detailed scattering material distribution taken into account.

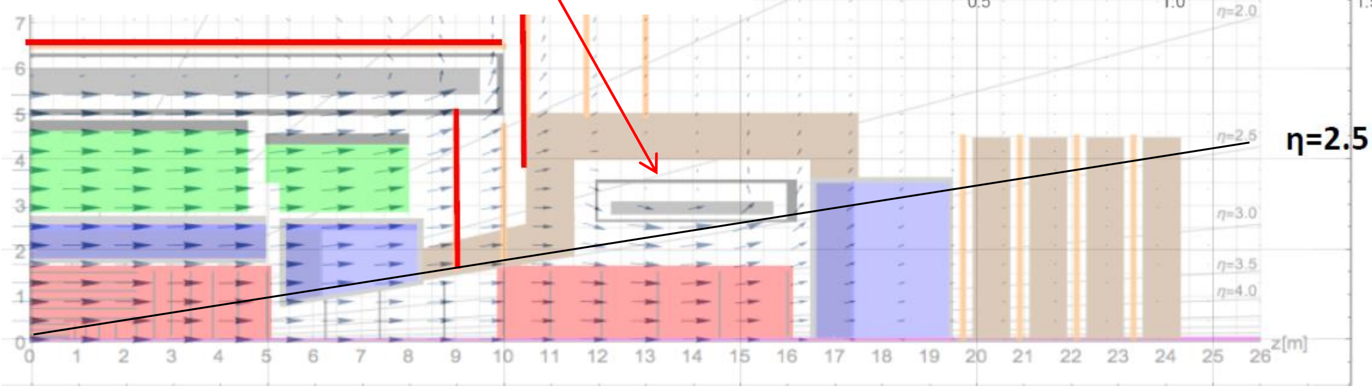
Standalone Momentum Resolution for Trigger

Momentum resolution at low $p_T < 100$ GeV dominated by multiple scattering, independent of detector resolution.

For 200 X_0 of scattering material in front of the muon system and perfect chamber resolution 5 - 25% standalone p_T resolution from $\eta = 0$ up to $|\eta| = 2.5$ for 1st level muon trigger.

Solenoidal B field in forward direction ($|\eta| > 2.5$) not suitable for precise standalone momentum measurement for trigger (p_T resolution > 80%).



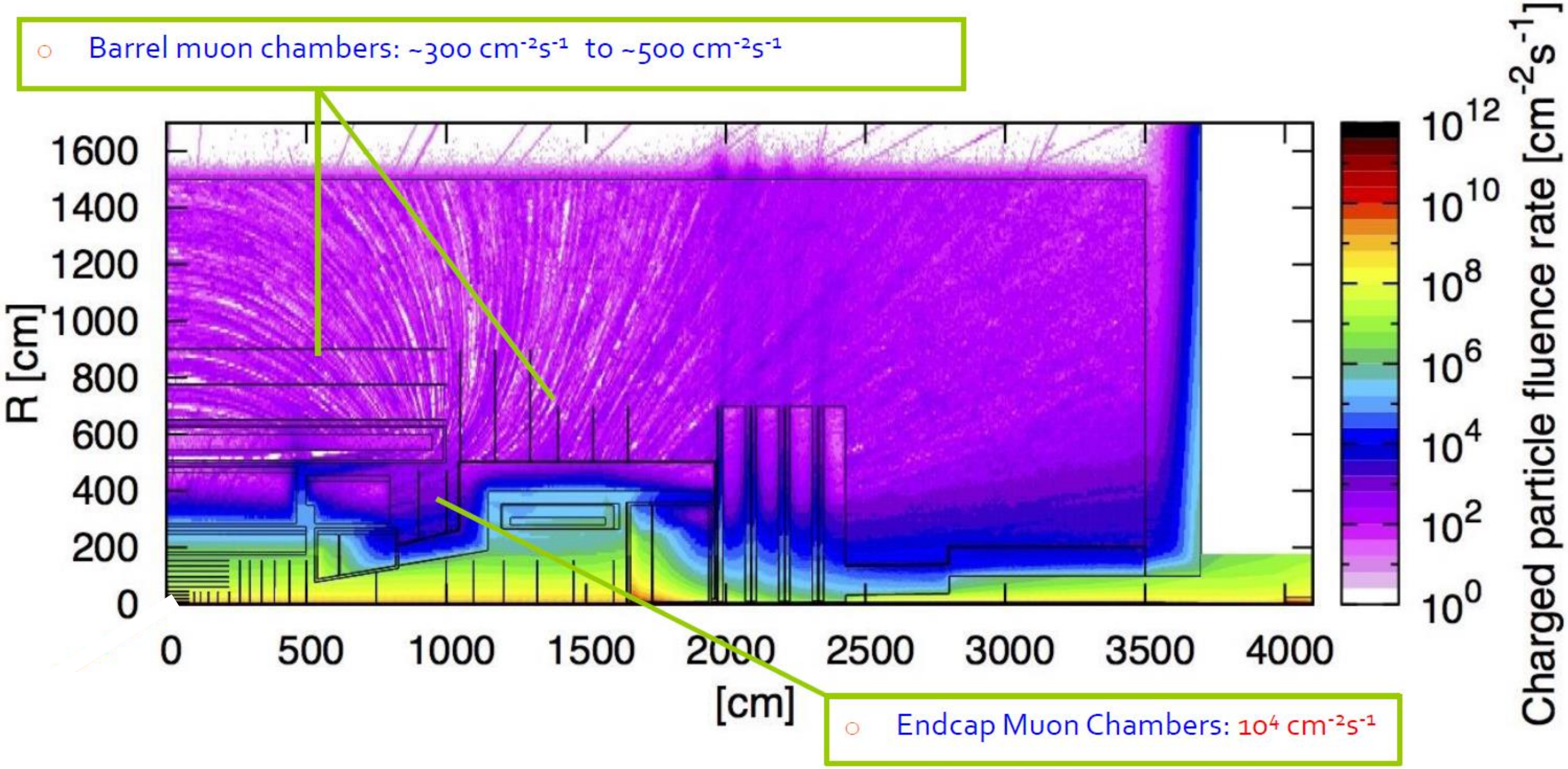


Analytical calculations by Werner Riegler

Radiation Environment: Background Hit Rates in Muon Chambers

For detector performance and layout studies additional safety factor of 2.5 is taken into account, i.e.
maximum rates in barrel and outer endcap ($|\eta| < 1.5$): 1.25 kHz/cm^2,
in inner endcap 1 ($1.5 < |\eta| < 1.9$): 2.5 kHz/cm^2,
in inner endcap 2 ($1.9 < |\eta| < 2.1$): 25 kHz/cm^2,
in forward region ($|\eta| > 2.1$): 25 – 250 kHz/cm^2.

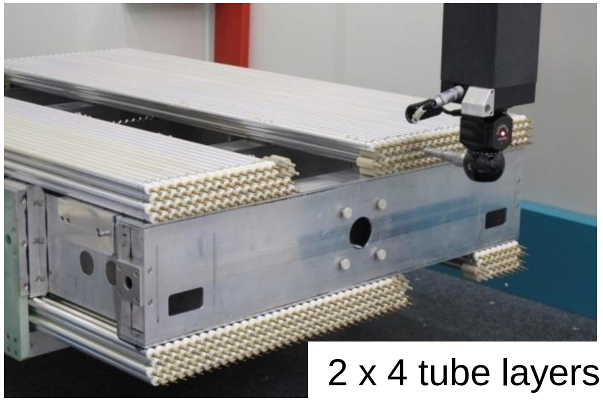
Charged Particle Fluence @ L=30x10^{34}cm^{-2}s^{-1}



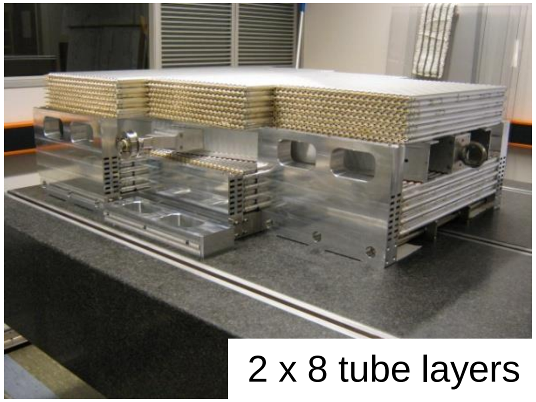
FLUKA simulation, I. Besana, FCC Week 2017

Suitable Detector Technology: sMDT Chambers

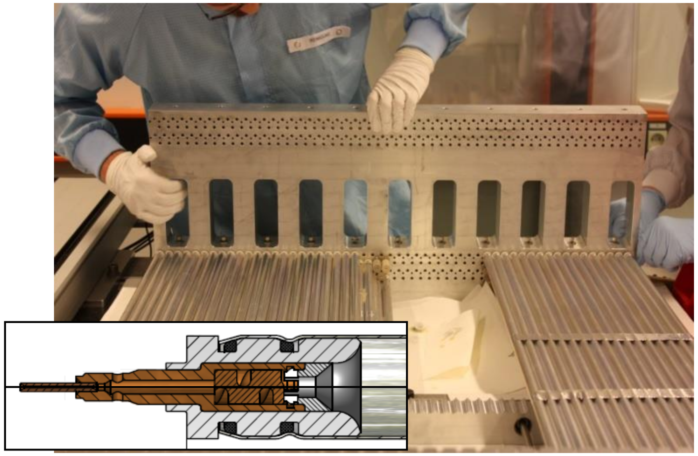
- Like the ATLAS MDT chambers, they combine high reliability and robustness with high mechanical accuracy (< 20 µm sense wire positioning accuracy) and spatial resolution (< 40 µm) over large areas. Cost effective technology.
- With 15 mm (sMDT) instead of 30 mm (MDT) drift tube diameter: 10 x higher rate capability. Verified by measurements in the CERN GIF++ gamma irradiation facility up to the highest expected background radiation rates (28 kHz/cm^2).
- sMDT chambers designed for this environment. Already in operation in ATLAS. Large scale construction for ATLAS muon spectrometer upgrade for HL-LHC.
- Use the same operating parameters as MDTs. No aging observed with Ar:CO_2 (93:7) drift gas at 3 bar up to 9 C/cm charge accumulation on wire (15 x ATLAS requirement).
- Design, materials and construction method optimised for large scale production. Allows for high-precision monolithic two-multilayer detectors for precise track angle measurement without need for an optical alignment system like in ATLAS.



2 x 4 tube layers

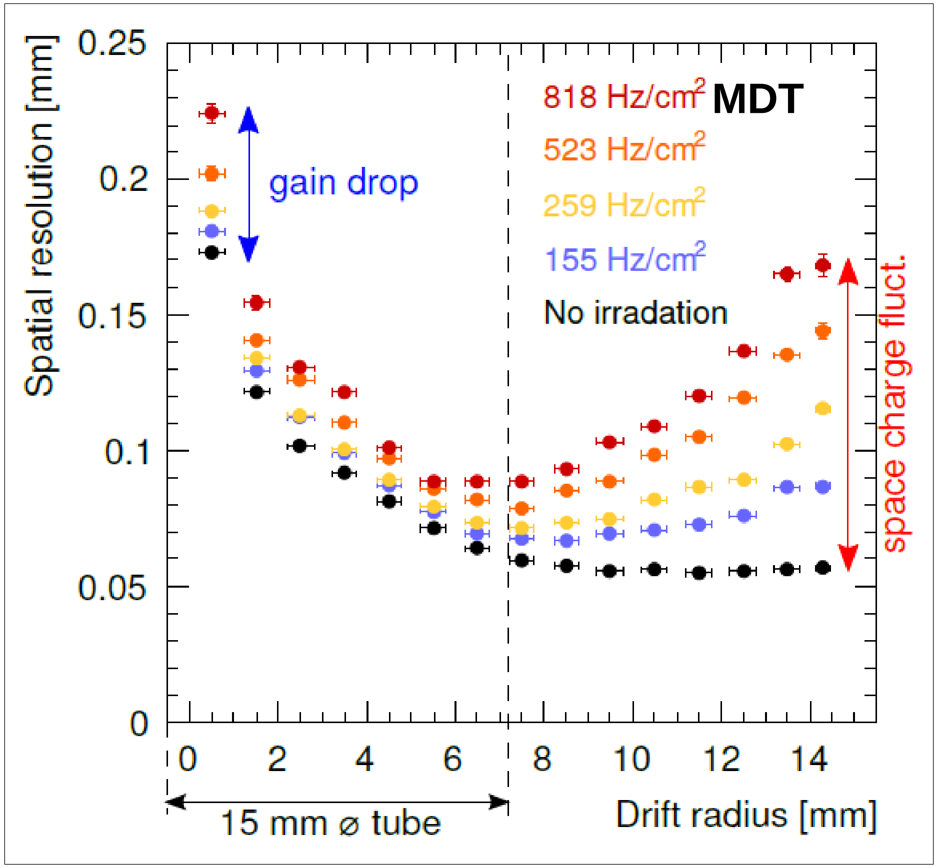


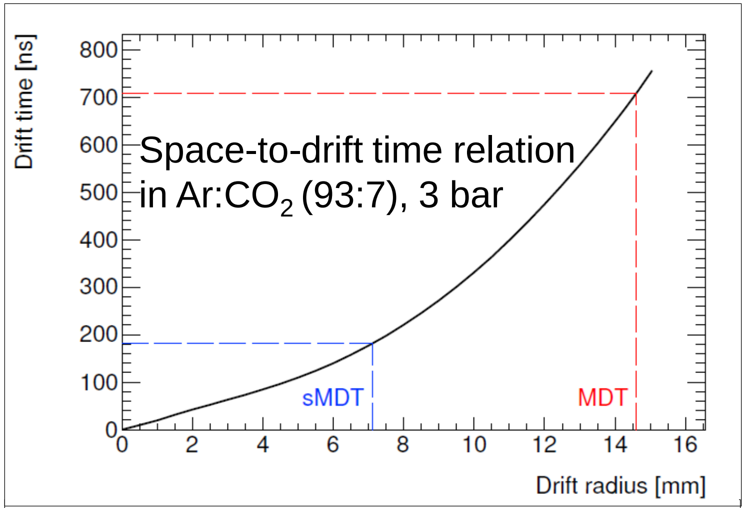
2 x 8 tube layers

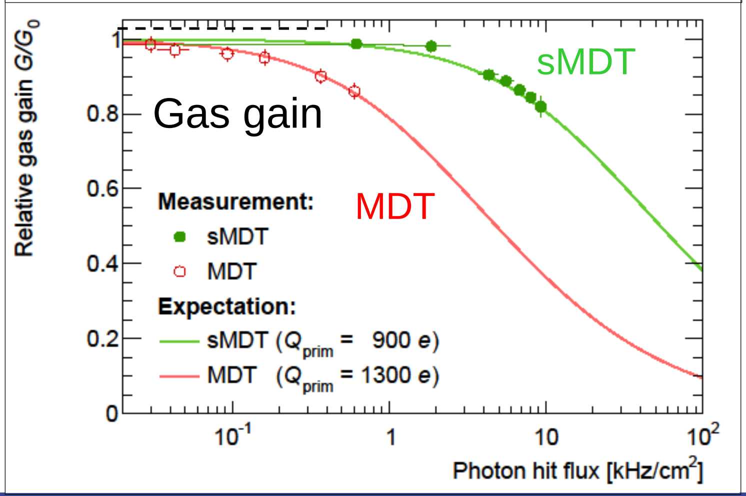


15 mm tube diameter, optimum for aluminum drift tube technology at high rates:

- Effect of space charge fluctuations eliminated for drift radii r < 7.1 mm (linear r-t relation).
- Gain loss suppressed proportional to r^3, i.e. by factor 8 compared to MDTs.
- 4 x shorter max. drift time, 2 x smaller tube cross section, i.e. 8 x lower occupancy.



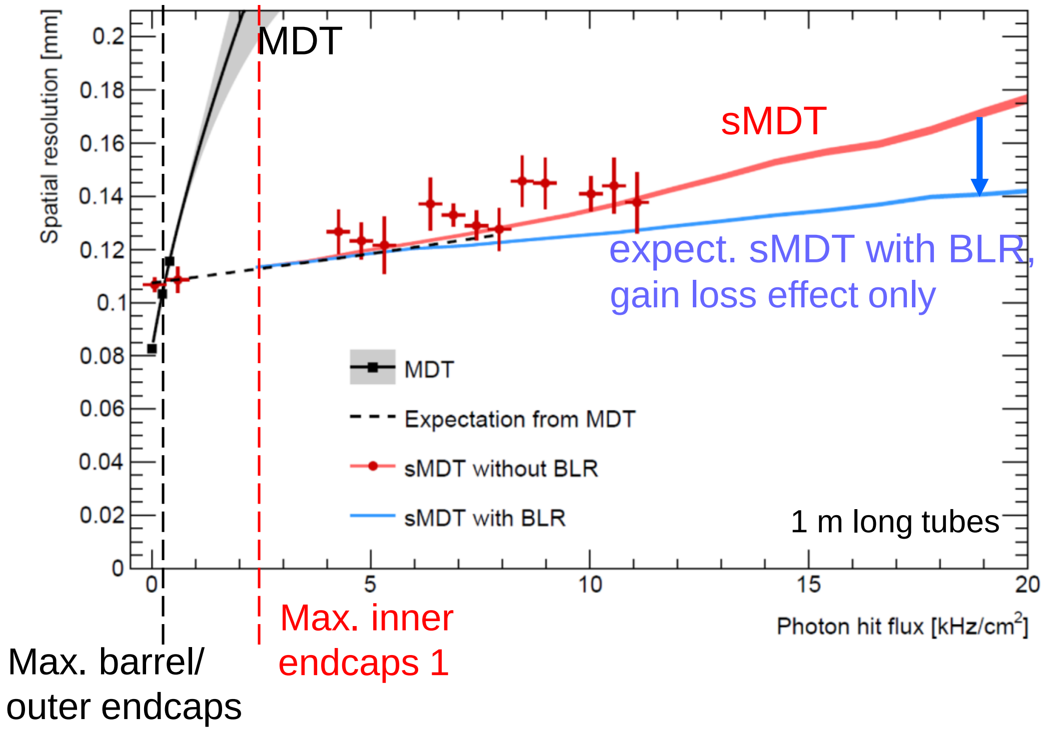


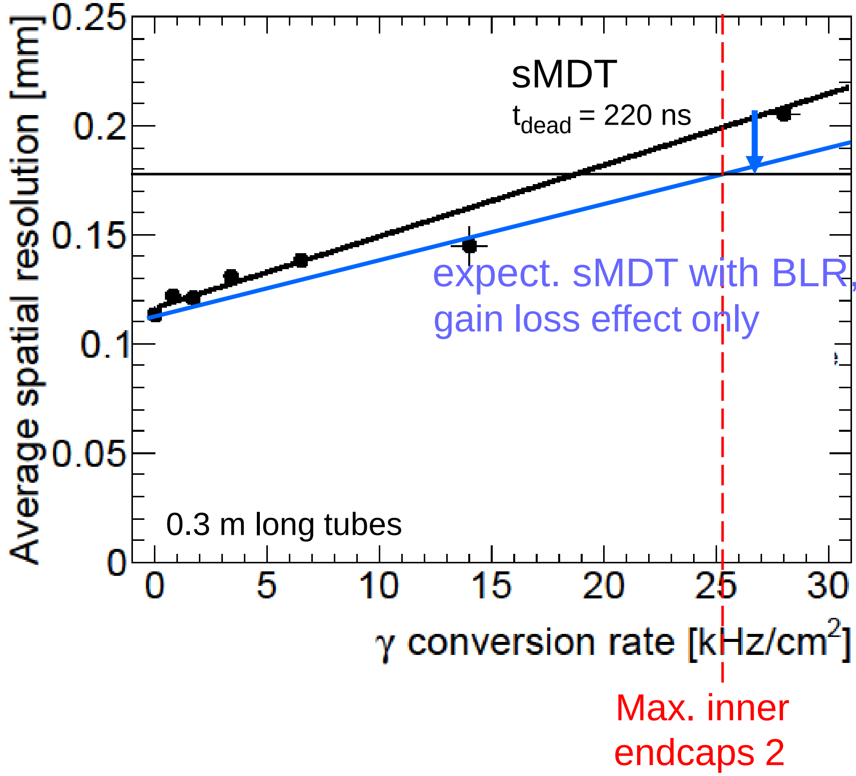


Measurements performed at the CERN Gamma Irradiation Facility.

sMDT Spatial Resolution

Measurements at the CERN Gamma Irradiation Facility (GIF++) using ATLAS MDT readout electronics (bipolar shaping, 220 ns minimum deadtime) and improvement with fast baseline restoration (BLR) elx.: input for detector performance studies and layout optimisation:



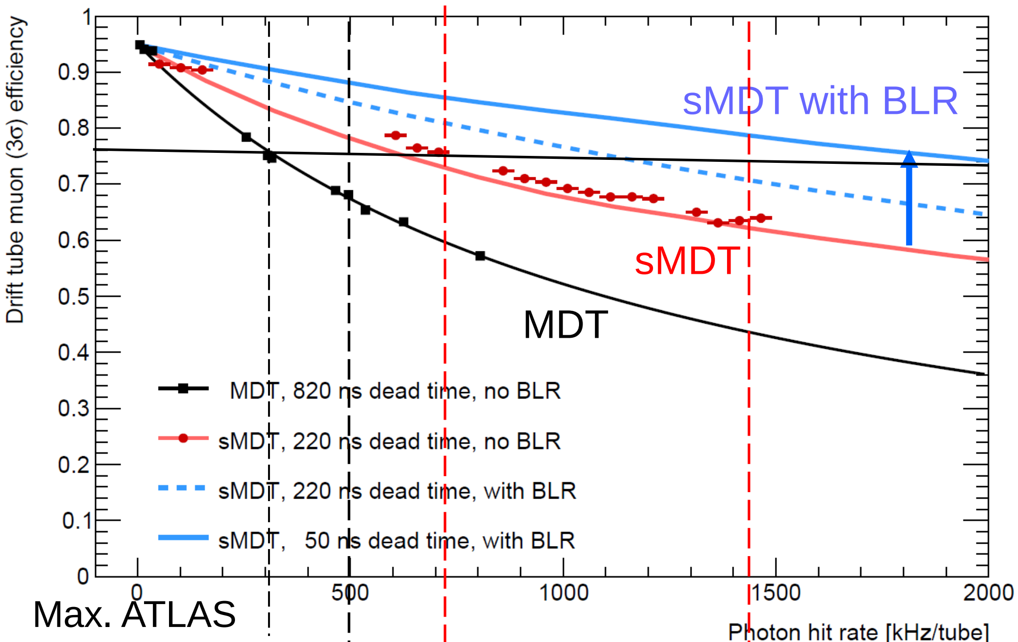


sMDT BLR electronics is under development, similar to ATLAS TRT FE electronics, to avoid muon signal distortion and resolution and efficiency degradation due to signal pile-up on background pulses for bipolar shaping.

Tracking Efficiency

Single-tube muon efficiency

drop due to masking of muon hits
by background pulses



Max. ATLAS MDT

Maximum barrel/ outer EC, 2.8 m tubes

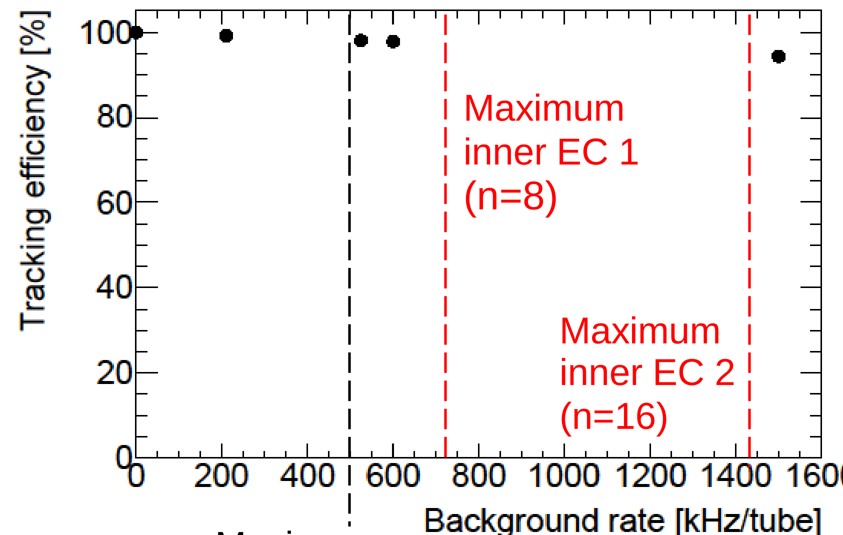
Maximum inner EC 1, 2.1 m tubes

Maximum inner EC 2, 0.4 m tubes

Measurements performed at the CERN Gamma Irradiation Facility as input for muon tracking simulation)

Track finding efficiency

(4 out of n tube layers)



Maximum barrel/ outer EC (n= 8)

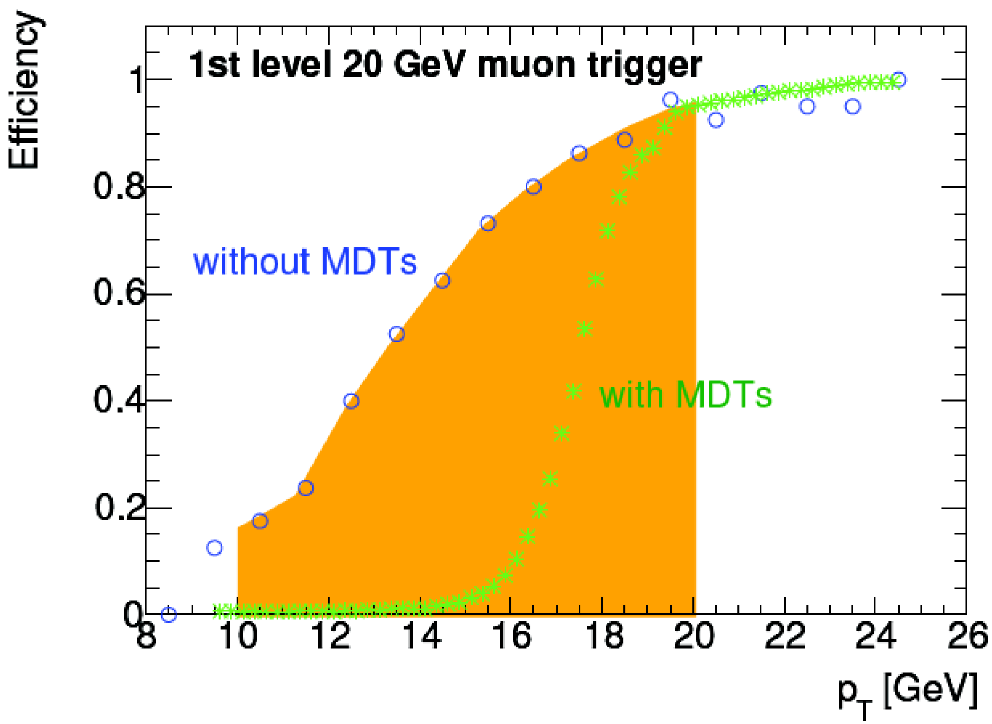
- GEANT4 simulation of muon detector

⇒ With 0.4 m long tubes maximum acceptable fluence 35 kHz/cm^2, i.e. 2000 kHz/tube.

sMDT-Based 1st Level Muon Trigger

- To suppress the high low-p_T muon rate at FCC-hh, a 1st level muon track trigger with high momentum resolution near the single-muon trigger threshold of 10-20 GeV is desirable.
  ⇒ Achieved by streamed, triggerless readout of the sMDT chambers and track angle-measurement in the two tube multilayers.

- Concept will be implemented in ATLAS at HL-LHC making use of the high spatial resolution of the MDT and sMDT chambers.
  Fast muon track reconstruction with high resolution feasible already with present FPGA and ARM processor technolgies within < 4 µs latency at the expected background rates.

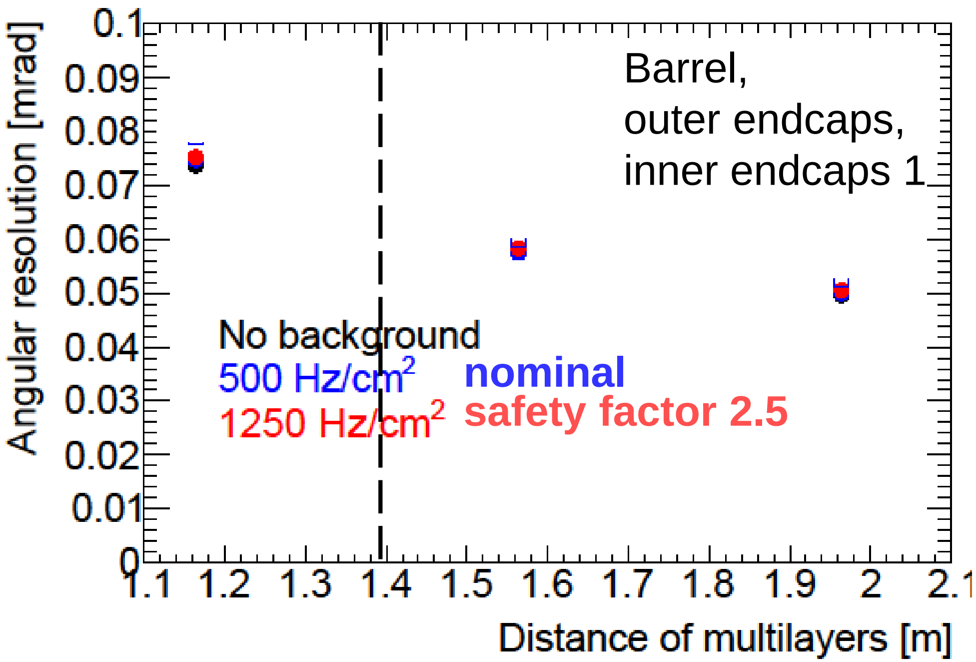


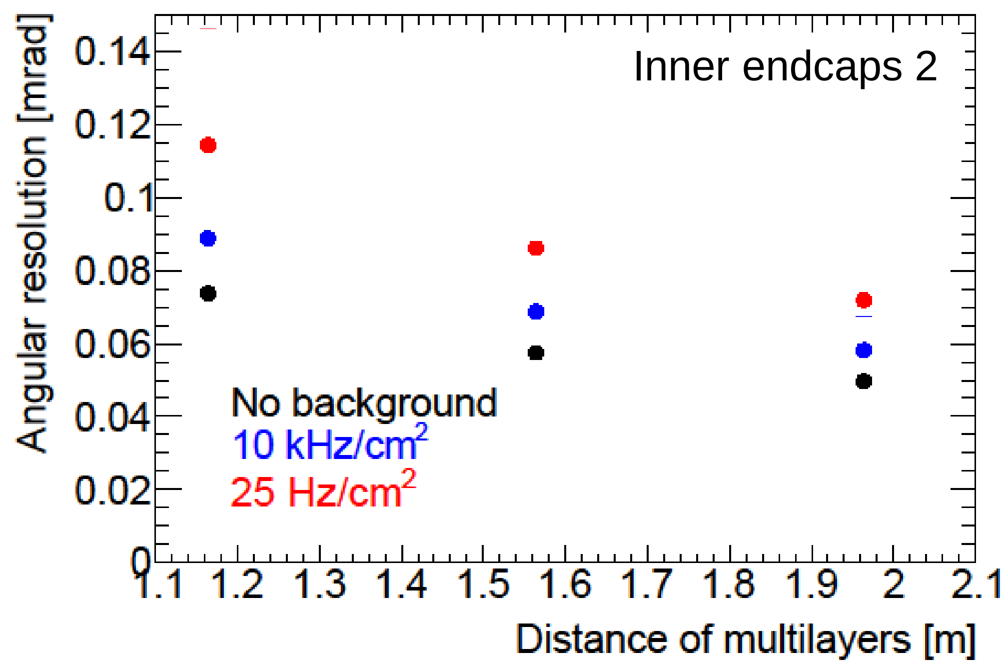
sMDT Muon Detector Simulation – Layout Optimisation

Detailed GEANT4 simulation of muon tracking in the sMDT detectors taking into account the reference detector material in front of the muon system and the detailed magnetic field map.

sMDT response, muon efficiency and spatial resolution as function of drift radius at the maximum irradiation rate tuned to the measurements,

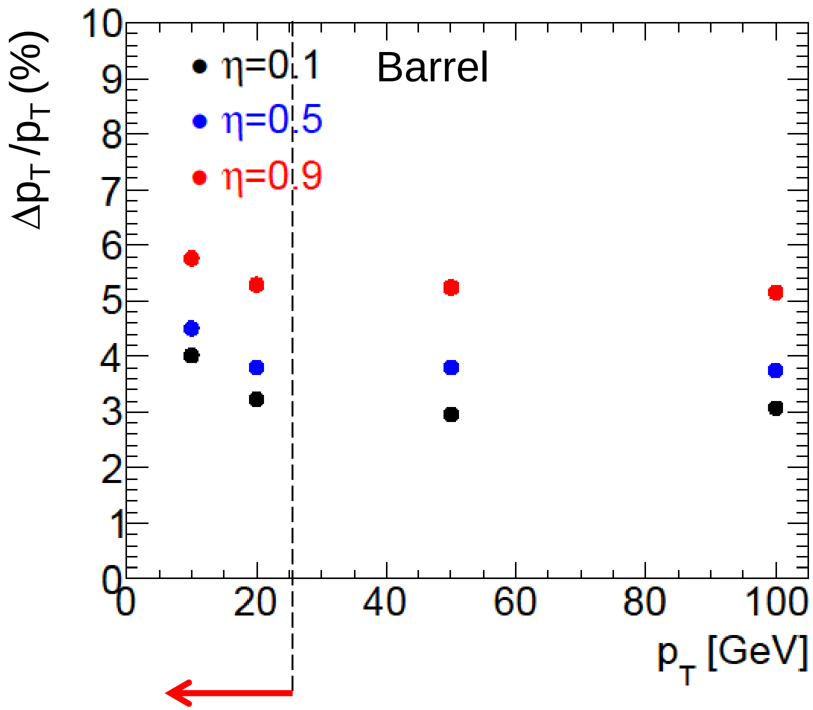
Standalone detector angular resolution (2 x 4 layers) for $p_T > 100$ GeV as function of multilayer distance:

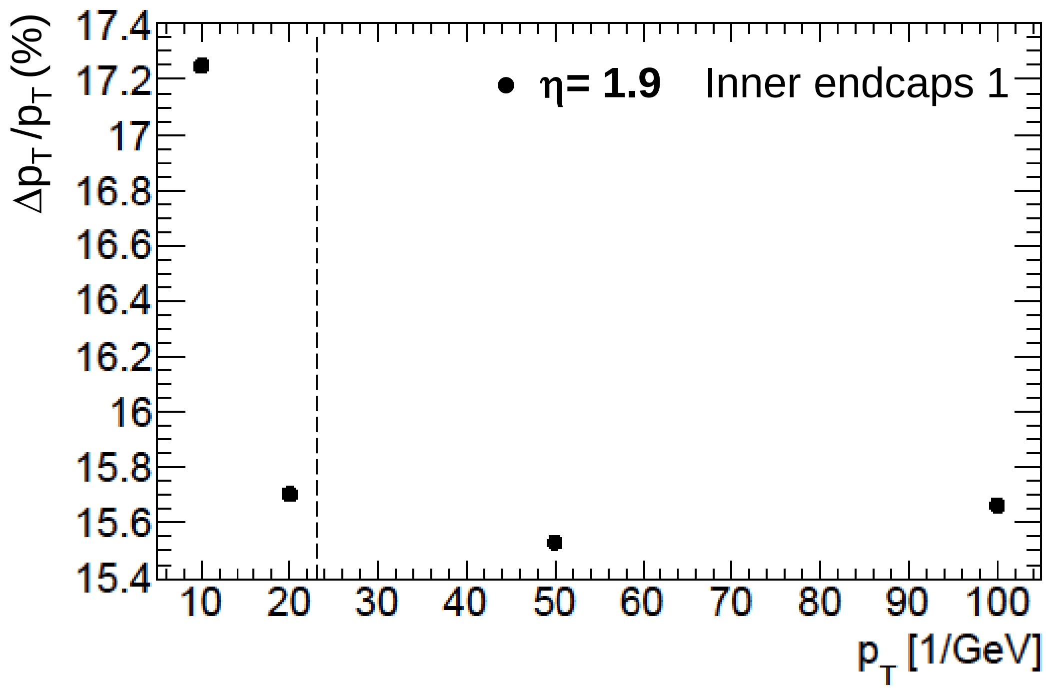




Track Angle Measurement – Standalone Momentum Resolution

Standalone momentum resolution for p_T < 100 GeV (MSC limit):





Relevant for sMDT-based trigger

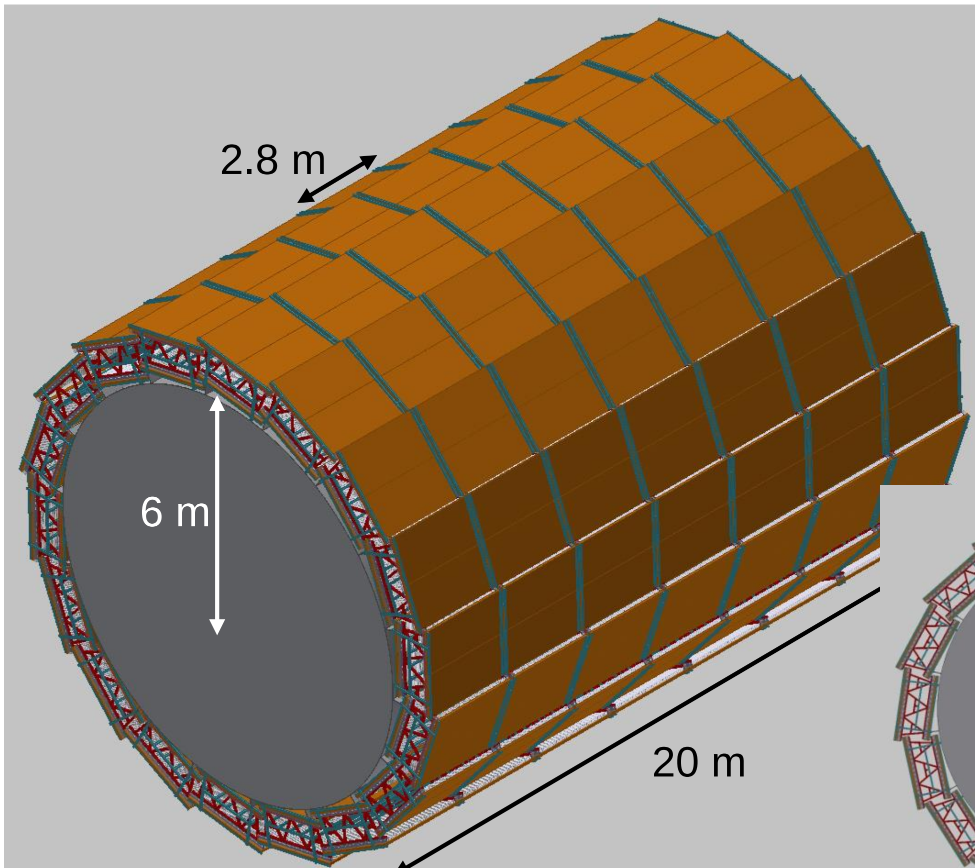
In agreement with analytical calculations by W. Riegler
and independent full simulation by Y. Enari and K.Terashi

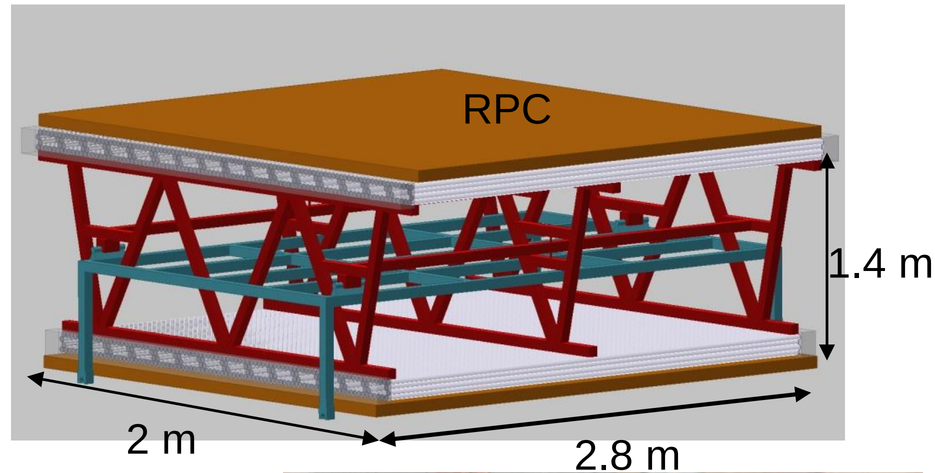
Muon Detector Layout – Optimised with the Simulation

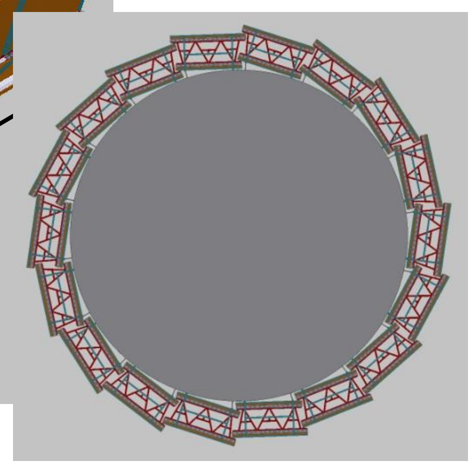
Barrel and outer endcaps:

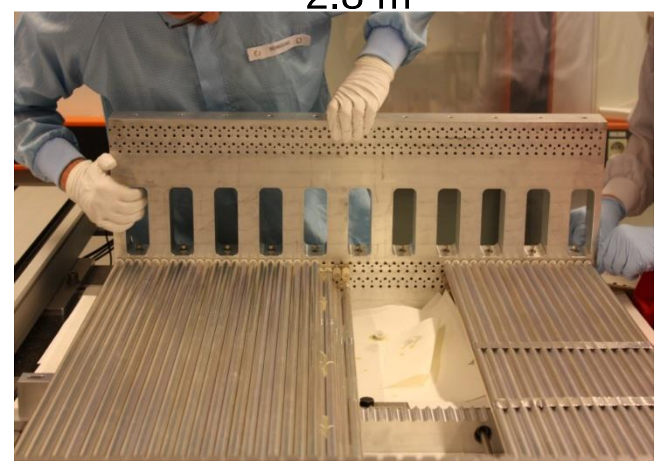
2 x 4 layers of 2.8 m long drift tubes (axial in barrel, radial in outer endcaps) with 1.4 m multilayer distance provide 40 µm spatial resolution, 60 µrad angular resolution, 100% tracking efficiency up to the maximum background rates.

Monolithic sMDT construction, no optical alignment of multilayers needed. Chambers well accessible.









Muon Timing

In case of 5 ns bunch crossing interval:

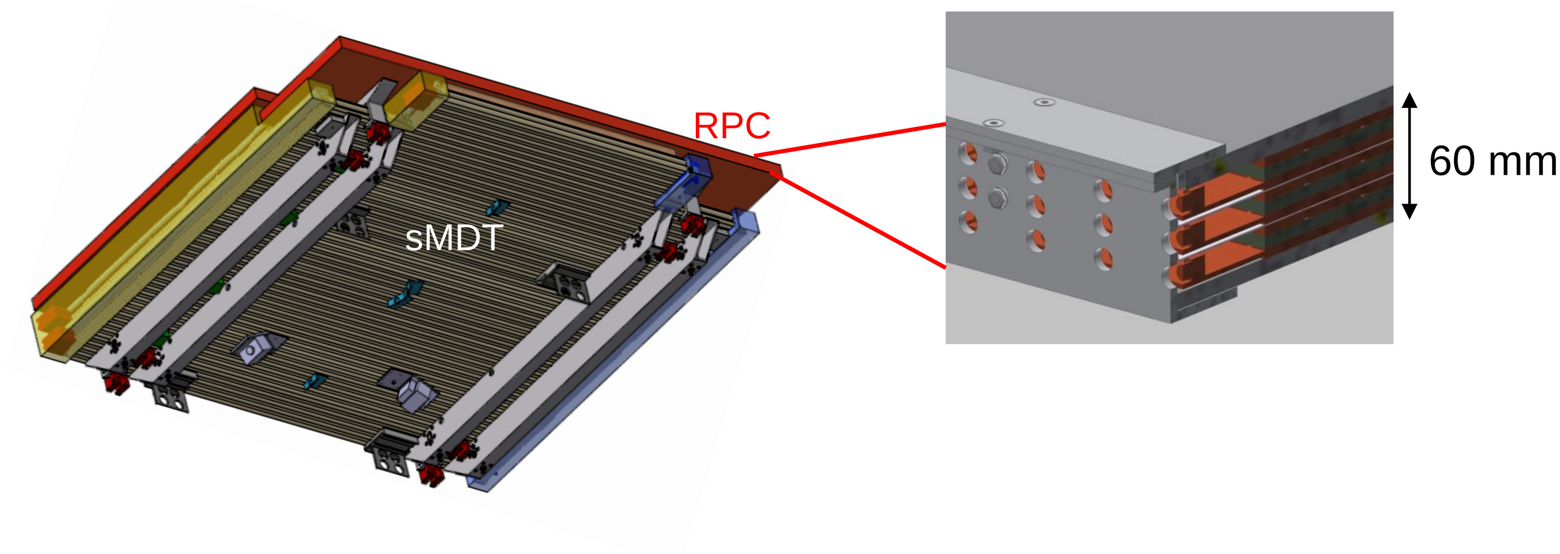
Additional thin-gap RPC chambers with 1 mm gas gap, 0.4 ns time resolution and a few millimeter 2D spatial resolution for muon BCID.

Can also provide seeds for the sMDT based muon trigger.

Operation at fulll efficiency at only 5.8 kV.

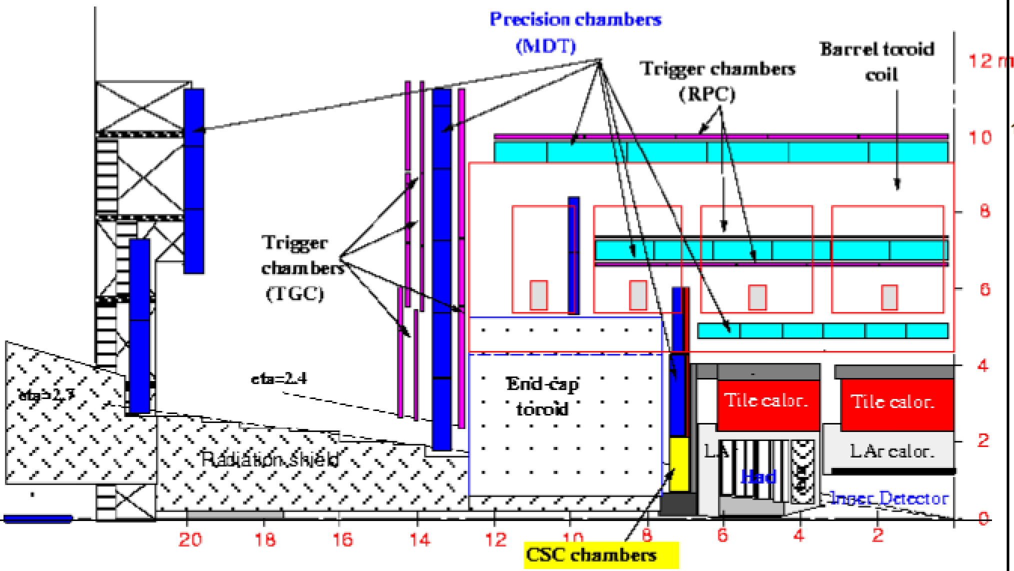
Due to vast improvements in the sensitivity of the amplifiers, 15 times lower signal charge and corresponding longer lifetime than present RPCs, sufficient at least for irradiation rates in barrel and outer endcaps.

Will be used in ATLAS for HL-LHC upgrade in conjunction with sMDT chambers: gas gap triplet with η and ϕ strip readout of only 6 cm thickness:



sMDT Muon Detector Layout

ATLAS detector



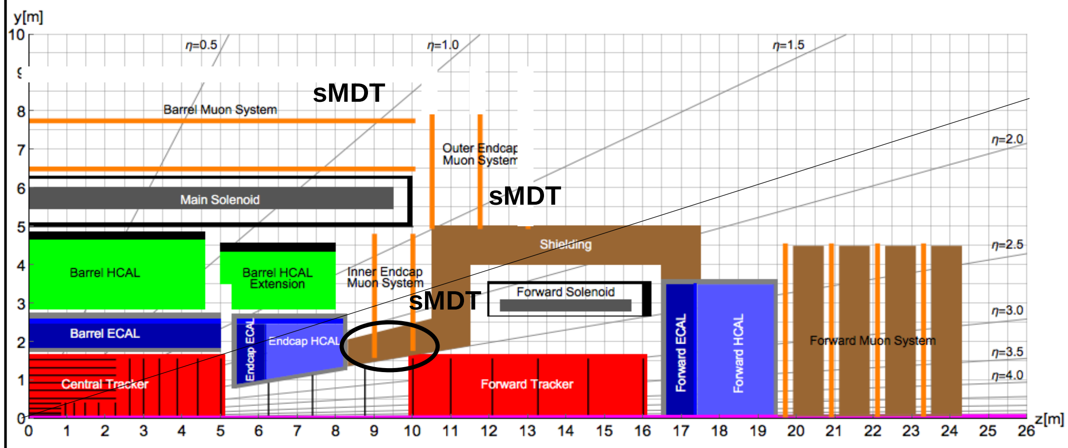
Precision muon track sagitta measurement with 3 layers of MDT chambers in barrel and endcaps in a toroidal magnetic field.

Standalone and combined momentum measurement.

5000 m² precision tracking area with 1150 MDT chambers and 360k tubes.

Precision optical alignment system required.

FCC-hh detector reference layout



Barrel and outer endcaps (|η| <1.5):

2 x 4 layers of 2.8 m long sMDT tubes (axial).

Inner endcaps:

1) 1.5 < |η| < 1.9: 2 x 4 layers of 2.1 m tubes (radial),
2) 1.9 < |η| < 2.1: 2 x 8 layers of 0.4 m tubes (radial) to achieve same resolution as in the barrel.

⇒ 1150 m² precision tracking area, with 234 sMDT chambers and 260k tubes.

No optical alignment system needed.

Region 2.1 < |η| < 2.5 (in shielding) to be investigated.

Conclusions

- Realistic muon detector design with existing sMDT precison tracking and trigger chamber technology for $|\eta| < 2.1$.
- Performance goals, including sMDT-based 1st level muon trigger resolution, verified with full muon detector simulation.
- Region $2.1 < |\eta| < 2.5$ with chambers inside present shielding needs more study.
- Solenoidal magnetic field for forward region $|\eta| > 2.5$ does not provide sufficient standalone momentum resolution for muon trigger.