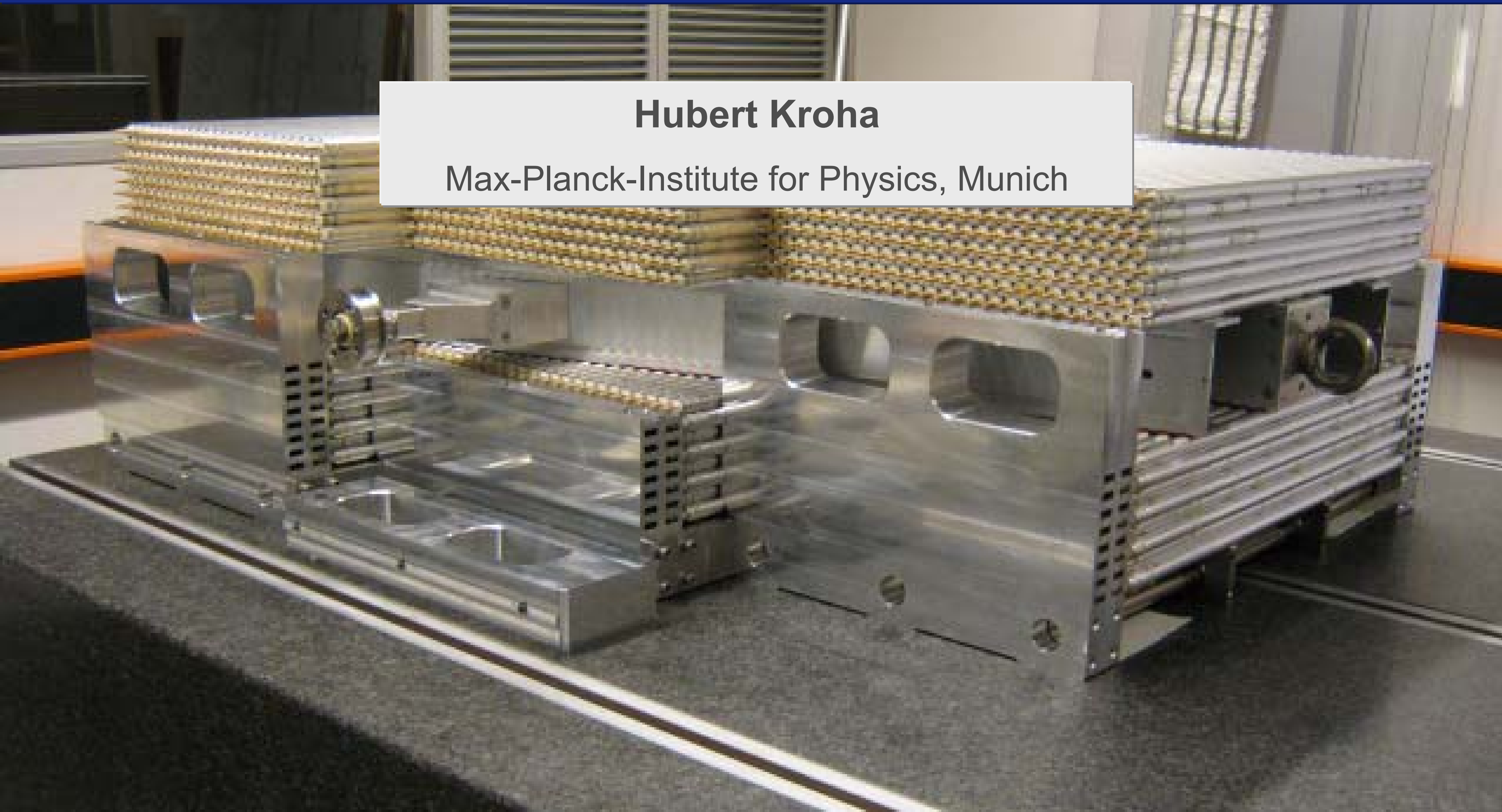
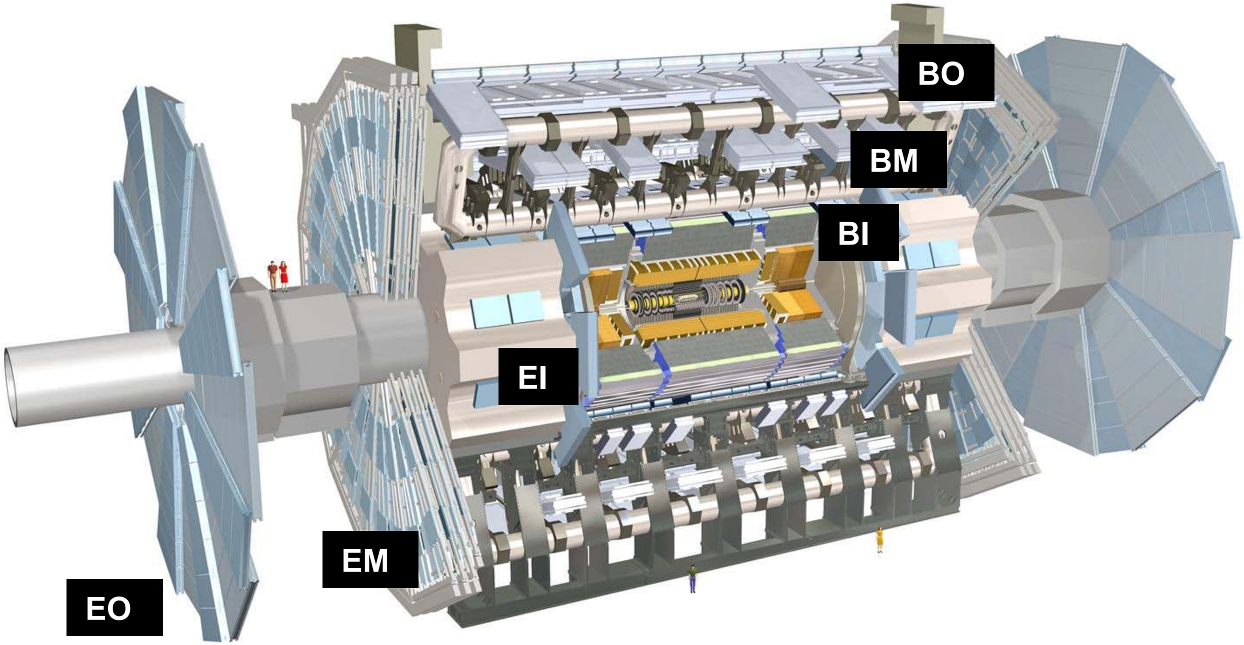
Small-Diameter Muon Drift Tube Detectors for Future Hadron Colliders

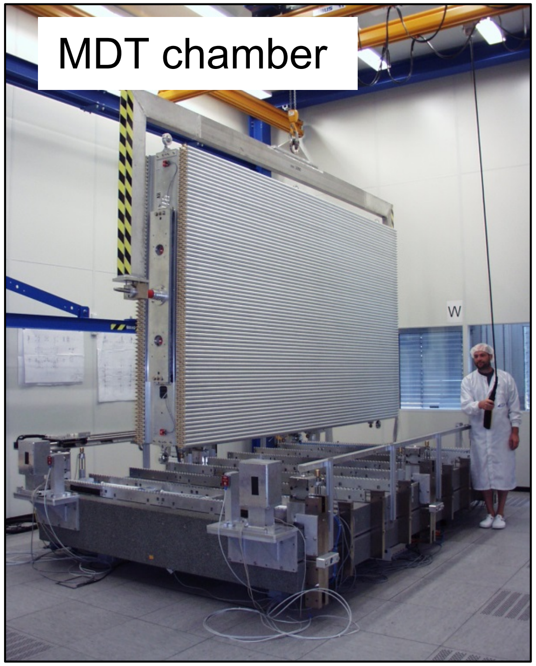


Hubert Kroha

Max-Planck-Institute for Physics, Munich

MDT Chambers of the ATLAS Muon Spectrometer





- About 1200 Monitored Drift Tube (MDT) precision tracking chambers with in total 350k drift tubes:
  sense wire positioning accuracy of 20 μm and chamber spatial resolution of 35 μm.
- Combined with 600 RPC (double gas gaps, barrel BM, BO) and 3600 TGC (endcaps) trigger chambers
  for L1 muon trigger, BCID and 2nd coord.measurement.
- Unprecedentedly high neutron and gamma background rates:
  up to 400 Hz/cm^2 in EI MDTs at LHC design luminosity.

MDT chambers prove to be very reliable and cost-effective high-precision detectors over large area without any signs of aging under the harsh operating conditions at LHC.

ATLAS Muon System Upgrades for HL-LHC

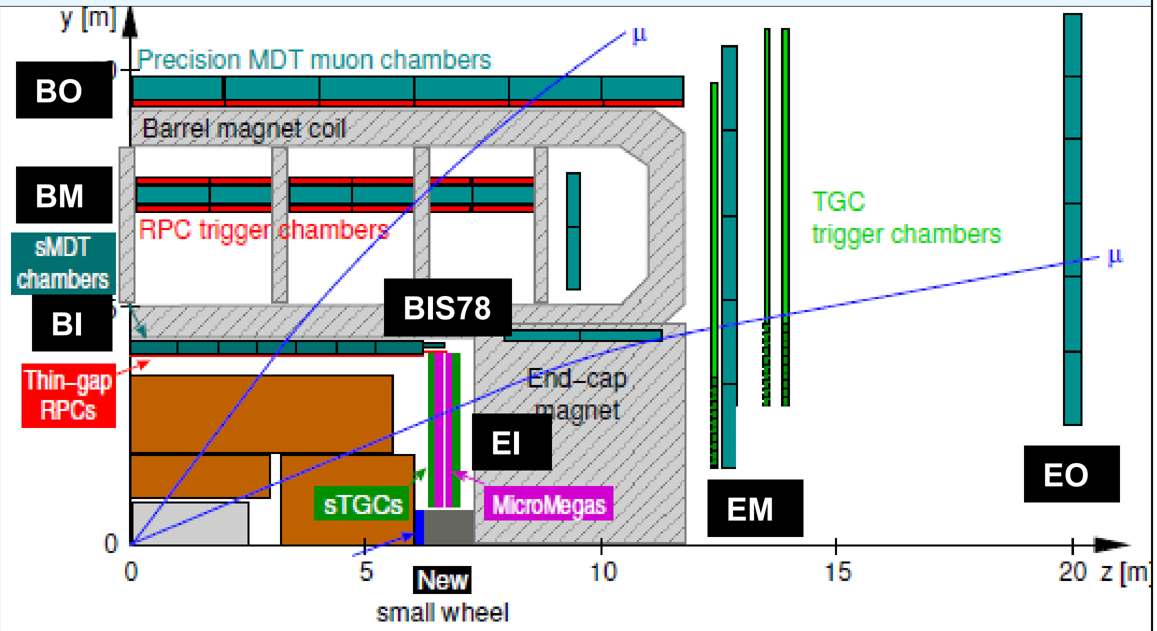
At HL-LHC: 7 times higher background rates require

1 Higher rate capability of the MDT detectors in the inner endcap layer (EI)

2 Lifetime of the RPC chambers in the barrel spectrometer

3 Higher p_T resolution of the 1st level muon trigger

4 Increased barrel trigger coverage



Phase 1 upgrades in 2019-2021 shutdown:

→ Replacement of EI layer with Micromega tracking and sTGC trigger chambers (New Small Wheels).

→ First replacement of inner barrel MDT chambers by integrated thin-gap RPC and sMDT chambers (BIS78).

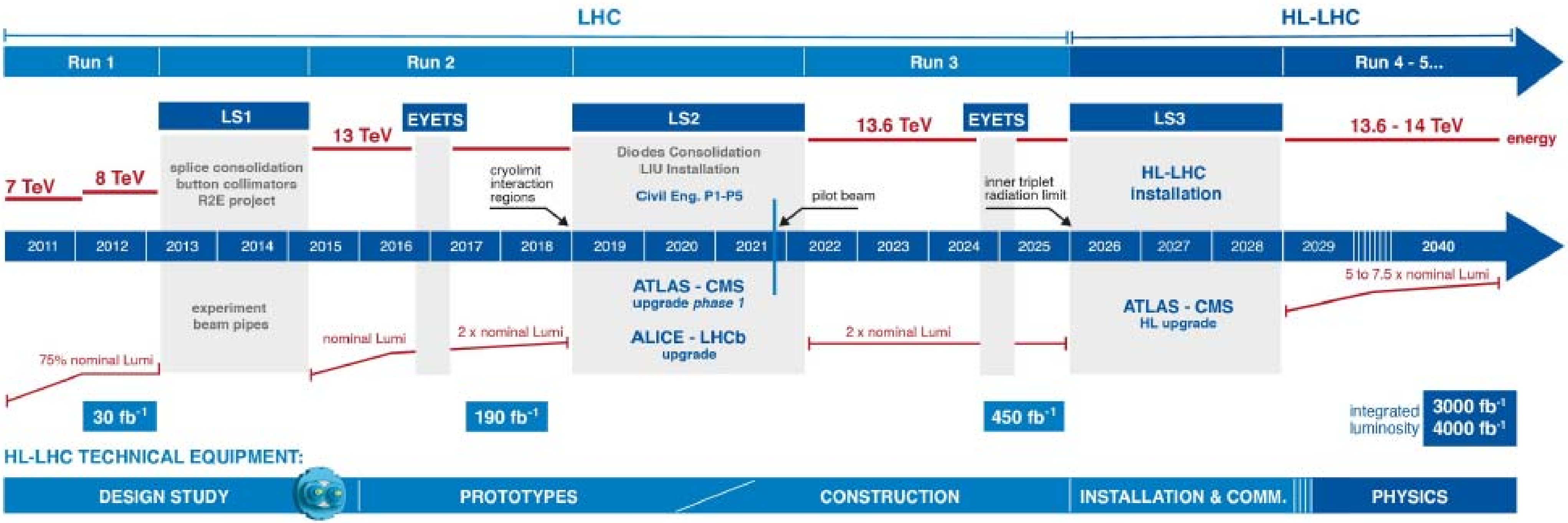
→ Closing of acceptance gaps with new sMDT chambers (BME, BMG).

Phase 2 upgrades in 2026-2028 shutdown:

→ Replacement of MDT chambers by new thin-gap RPC and sMDT chambers in the barrel inner layer (BIS/BIL 1-6).

→ Use of the (s)MDT chambers in the first-level trigger: hardware muon track trigger.

ATLAS Barrel Muon Chamber Upgrades



April 2014:
2 sMDT + RPC chambers
to improve acceptance and momentum resolution in the bottom barrel sector.
In operation since Run 2.

Jan. 2017:
12 sMDT chambers
to improve the momentum resolution (by factor of 2 at 1 TeV) in the detector feet.

2019-20: BI 7-8
16 sMDT + 32 RPC chambers
to improve the trigger selectivity and the rate capability in the barrel inner layer.
Pilot project for phase 2 upgrade.

New Small Wheels
to increase rate capability of tracking and trigger detectors and trigger p_T resolution together with MDT-based trigger.

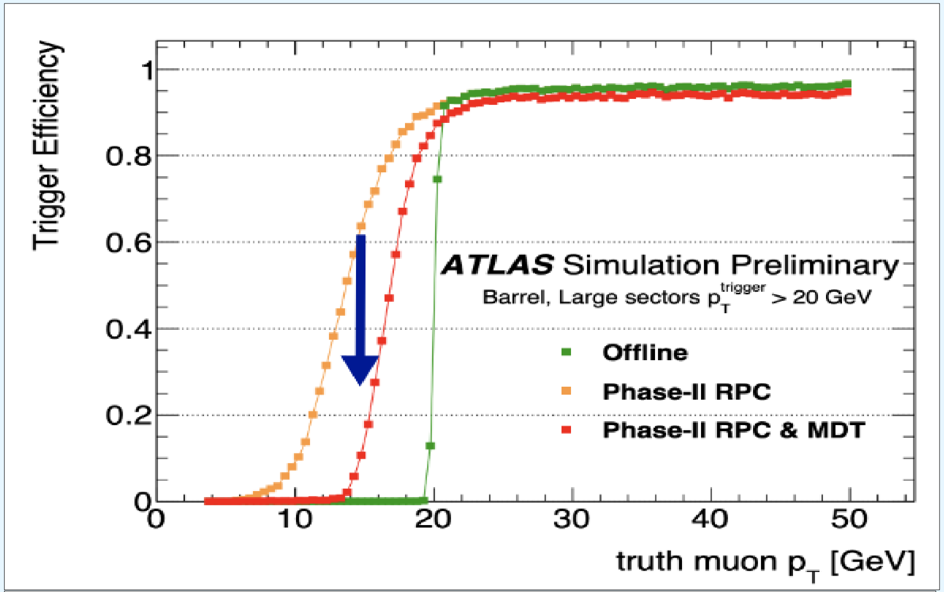
2024-26: BI 1-6
96 sMDT + 276 RPC chambers
for the barrel inner layer to increase the robustness of the barrel muon trigger system.

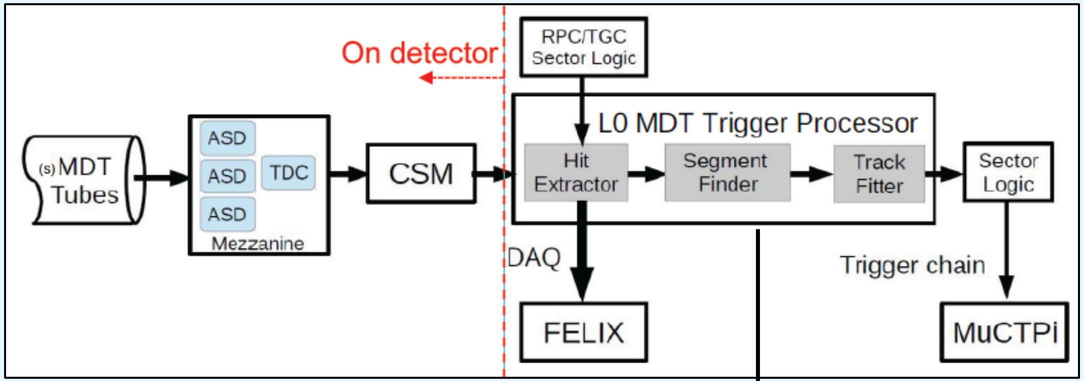
Use of (s)MDT chambers for the 1st level muon trigger
to increase p_T resol. and selectivity.

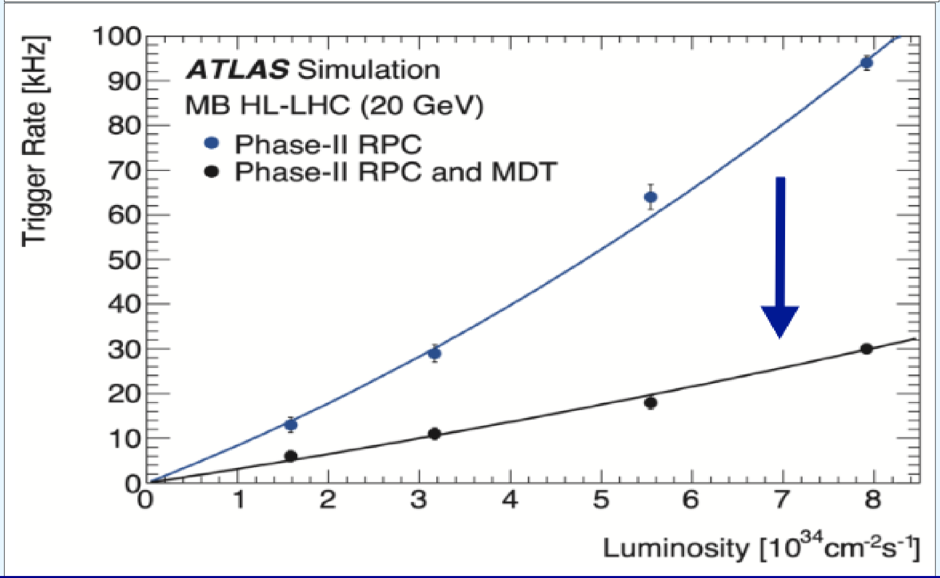
New MDT on-chamber electronics
because of 10 x higher trigger rate and MDT-based trigger.

ATLAS MDT First-Level Muon Track Trigger for HL-LHC

Nominal single-muon pT trigger threshold 20 GeV. Suppression of huge low pT muon background.

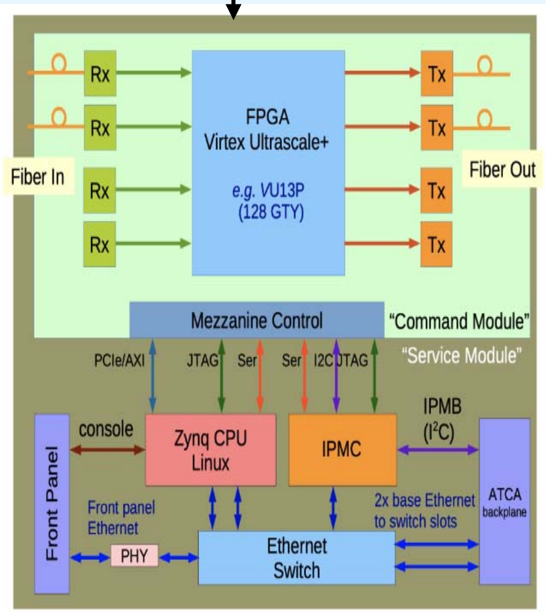




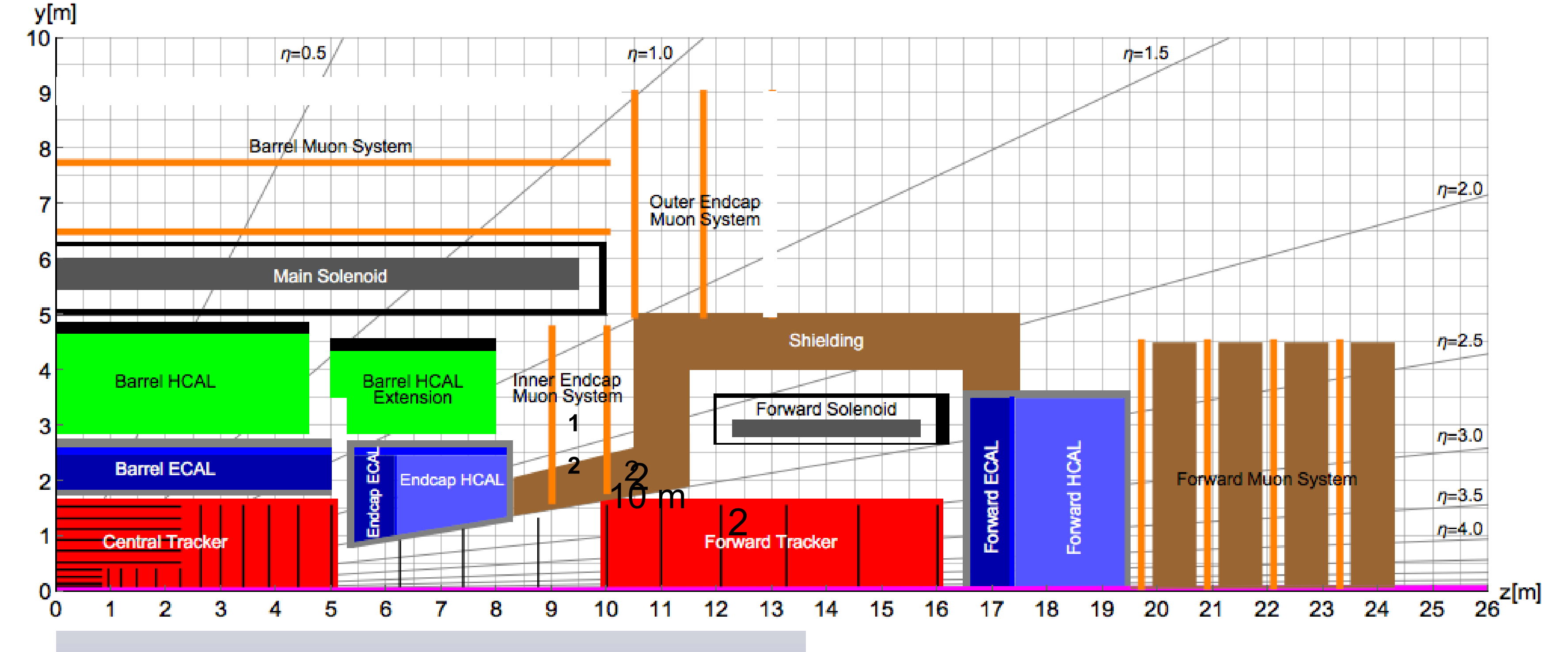


Pattern recognition, track fit, momentum reconstruction on FPGA within 1 μs.

Continuous trigger-less readout.



FCC-hh Reference Detector Layout



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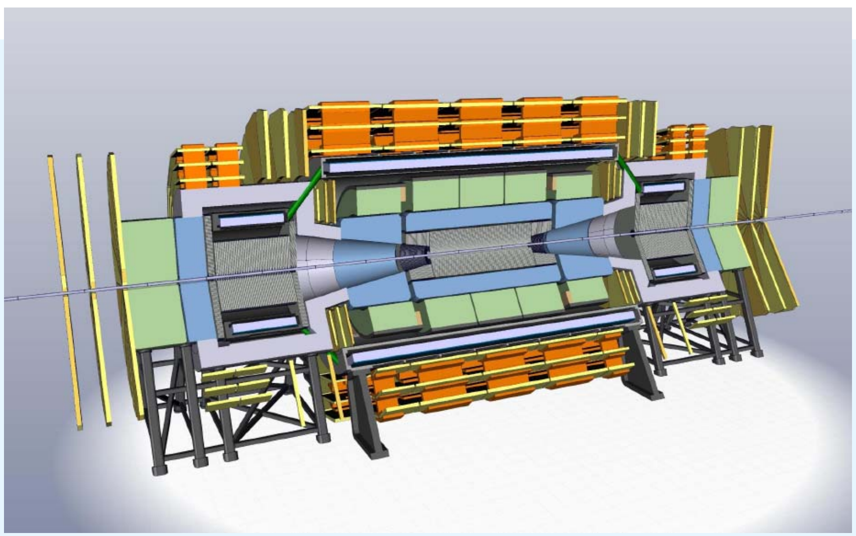


Conceptual Design Report 2018

Large solenoid surrounding central inner tracker and calorimeters.

Muon detectors outside.

Forward detectors with separate solenoids.

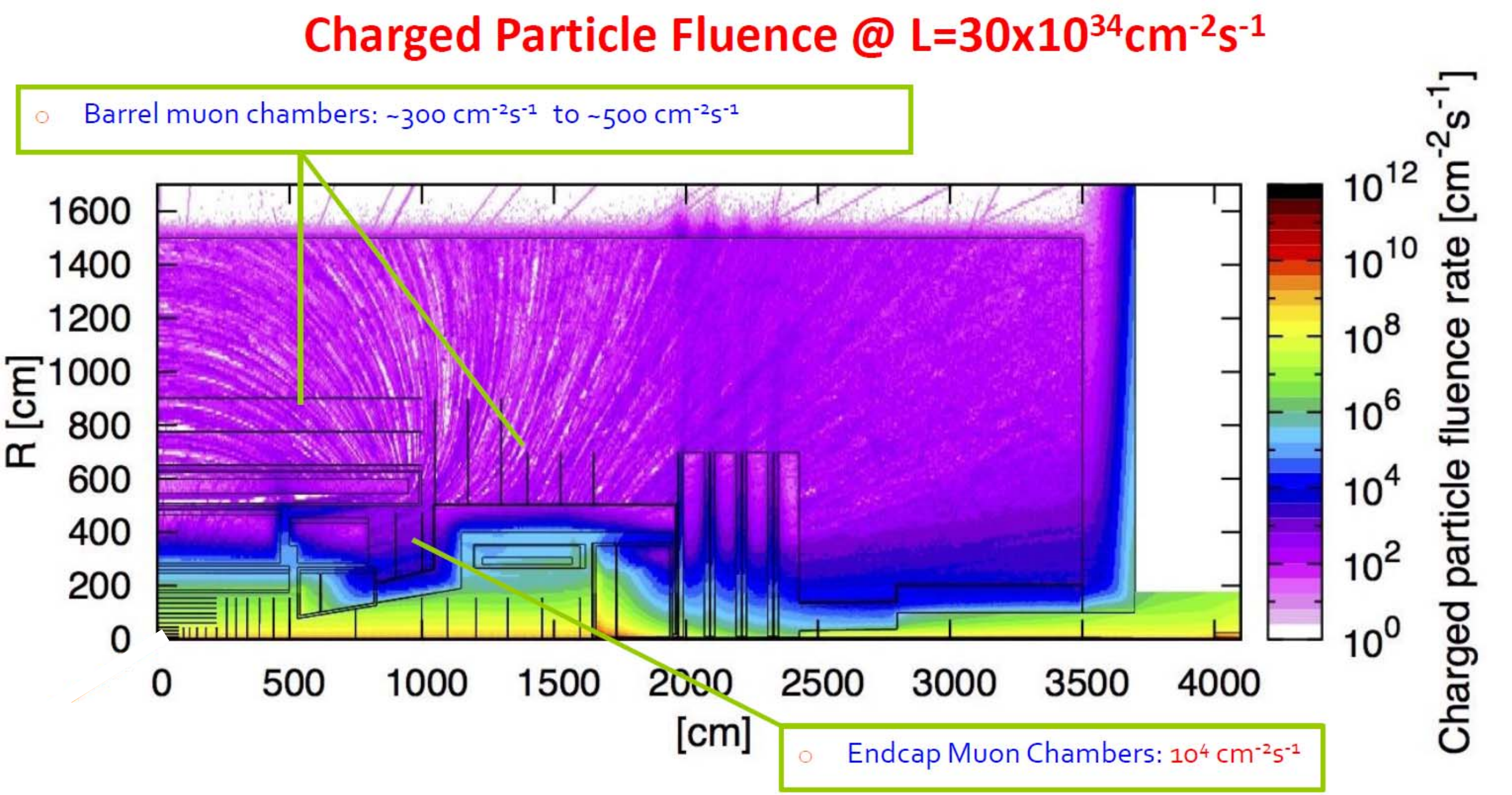
Radiation Environment: Background Hit Rates in Muon Chambers

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,

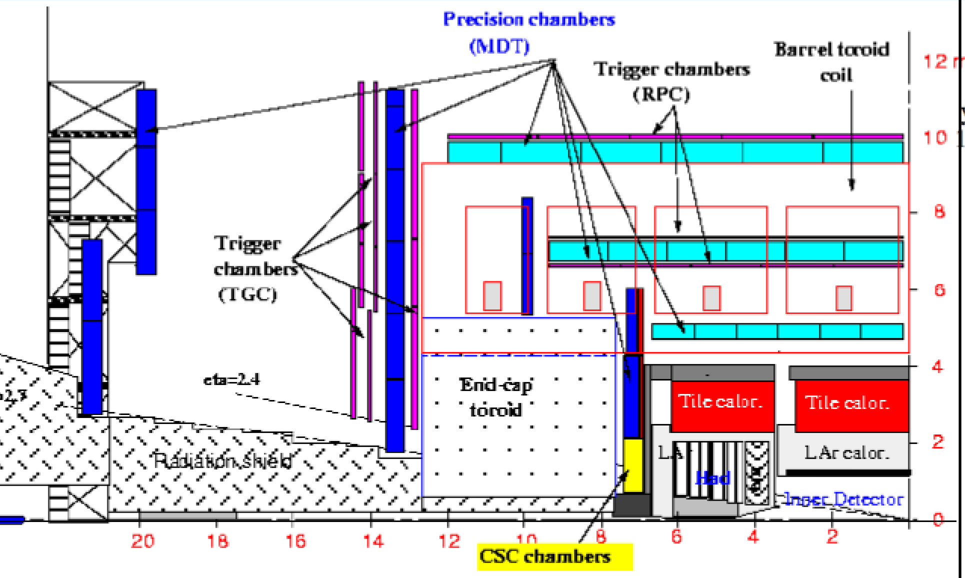
in forward region ($|\eta| > 2.1$): 25 – 250 kHz/cm^2.



FLUKA simulation, FCC Week 2017

Muon Detector Concepts

ATLAS



Muon track sagitta measurement with 3 layers of MDT chambers in a toroidal magnetic field.

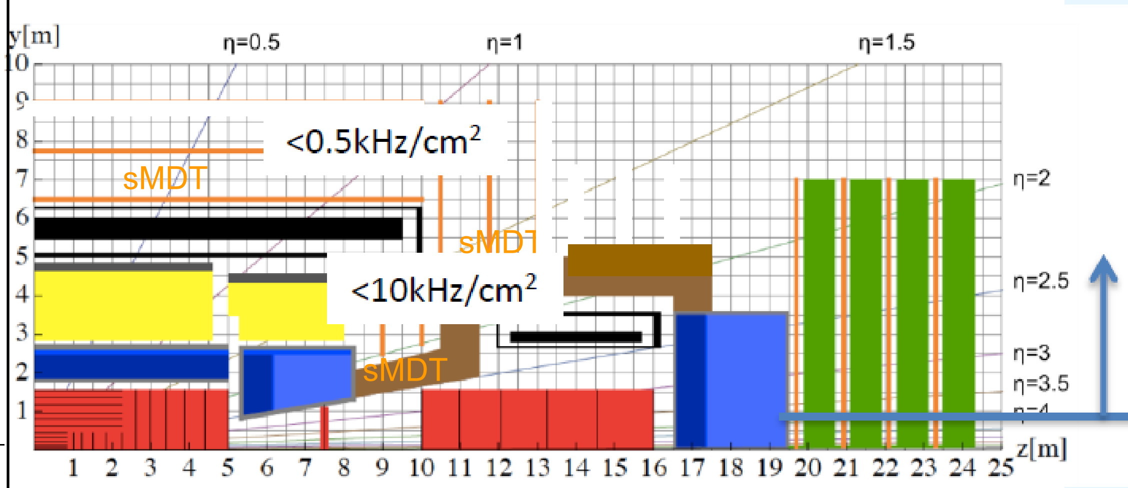
Standalone magnetic muon spectrometer.

5000 m^2 precision tracking area.

1200 MDT chambers with 350k channels.

Optical alignment monitoring system necessary.

FCC-hh baseline



Barrel and endcaps up to |η| = 1.8:
background rates at max. FCC-hh luminosity not higher than in ATLAS.

Precision muon tracking (together with ID) and standalone triggering with monolithic 2-layer sMDT chambers up to |η| = 2.5 without track curvature.

1000 m^2 precision tracking area.

200 chambers with 130k channels.

Optical alignment system not needed.

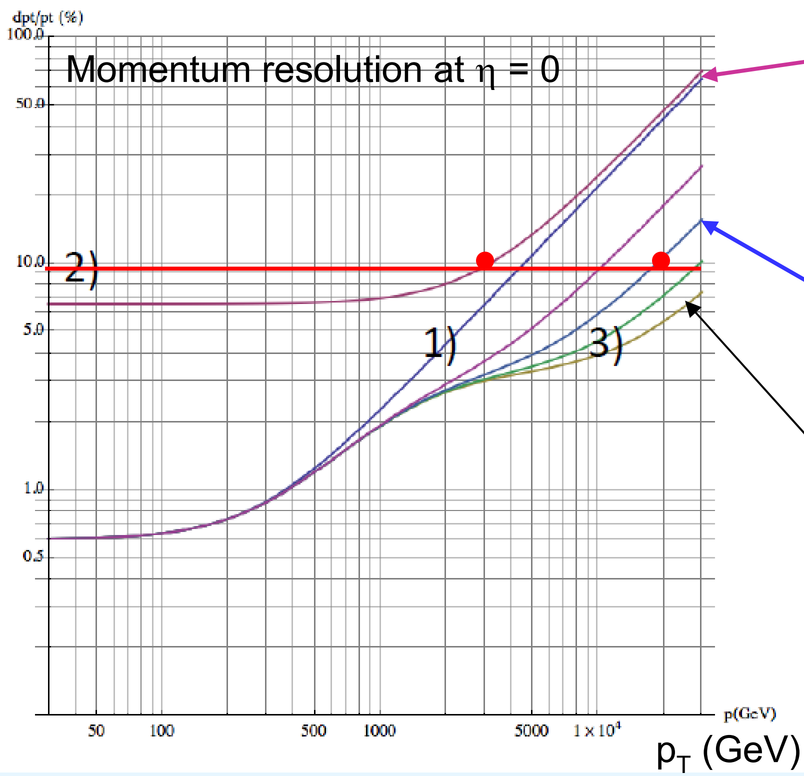
Performance Goals for a FCC-hh Muon Detector

Three methods for muon momentum measurement:

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

2) Standalone muon system track point/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).



With 70 μrad muon detector angular resolution:

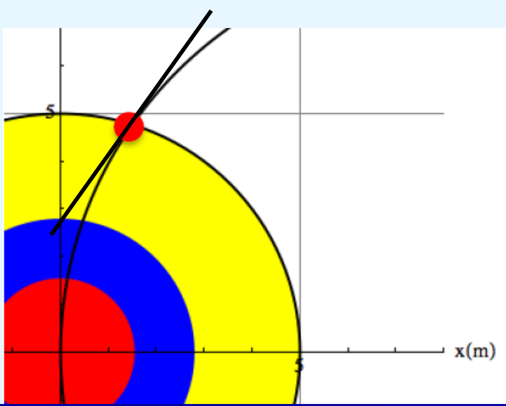
< 10% standalone momentum resolution up to 3 TeV, equal to tracker resolution, for first-level muon trigger

5% standalone multiple scattering limit below 1 TeV

With 50 μm muon detector spatial resolution:

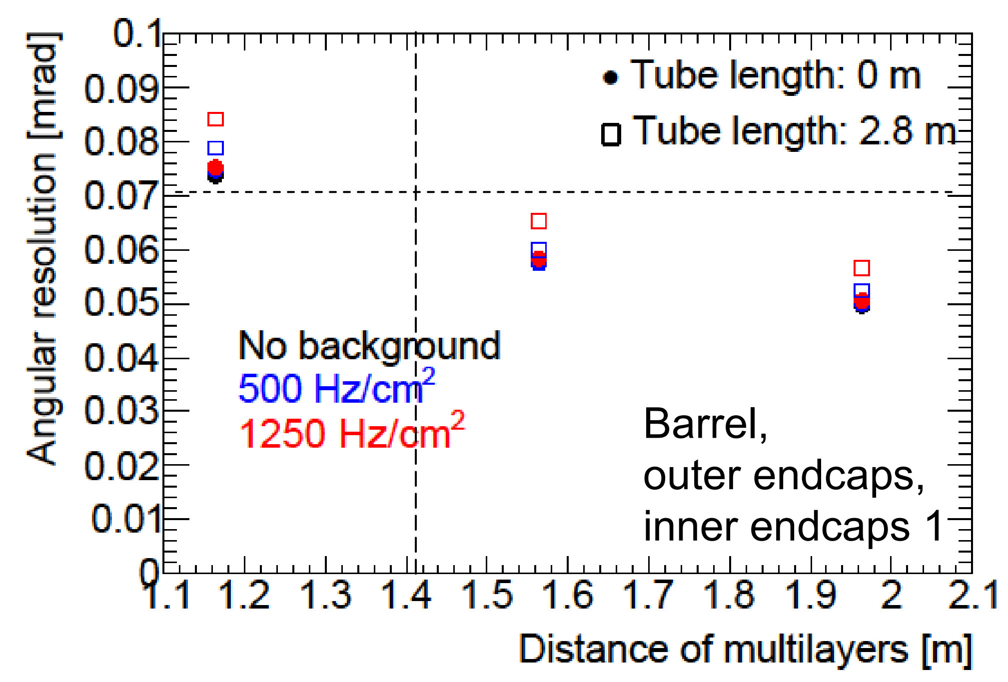
< 10% combined momentum resolution up to 20 TeV.

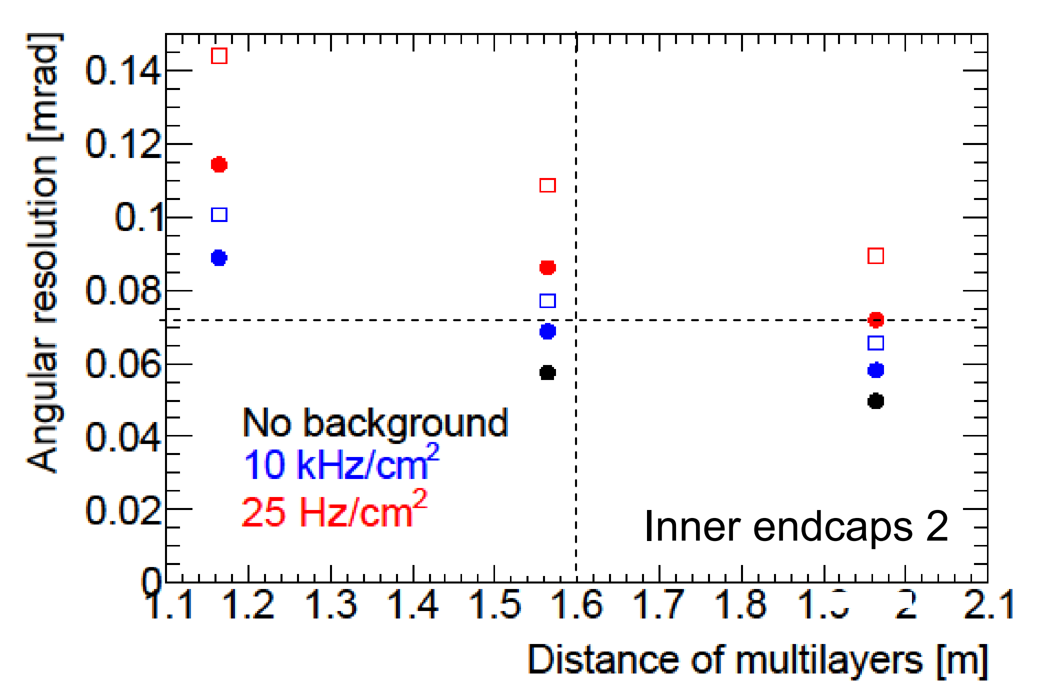
Multiple scattering limit for combination



CDR FCC-hh Detector, 2018

Standalone Angular Resolution for Trigger





GEANT4 simulation safety
with cavern background radiation rate nominal and with safety factor 2.5

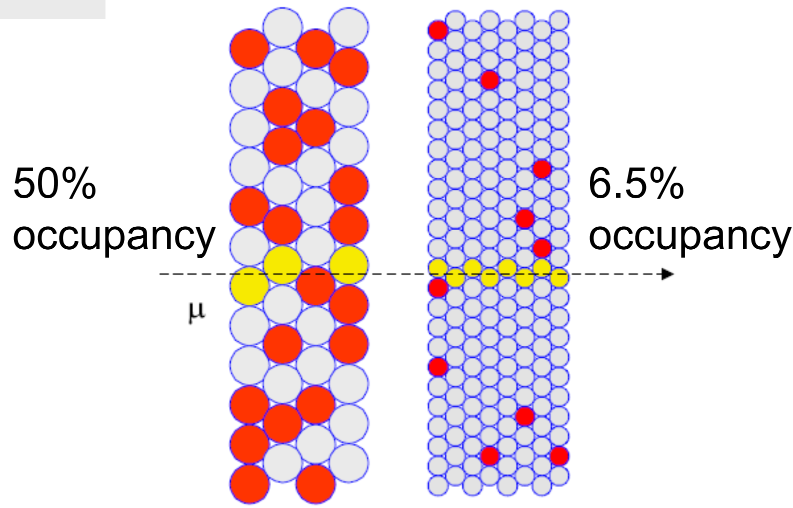
Small-Diameter Muon Drift Tube (sMDT) Chambers

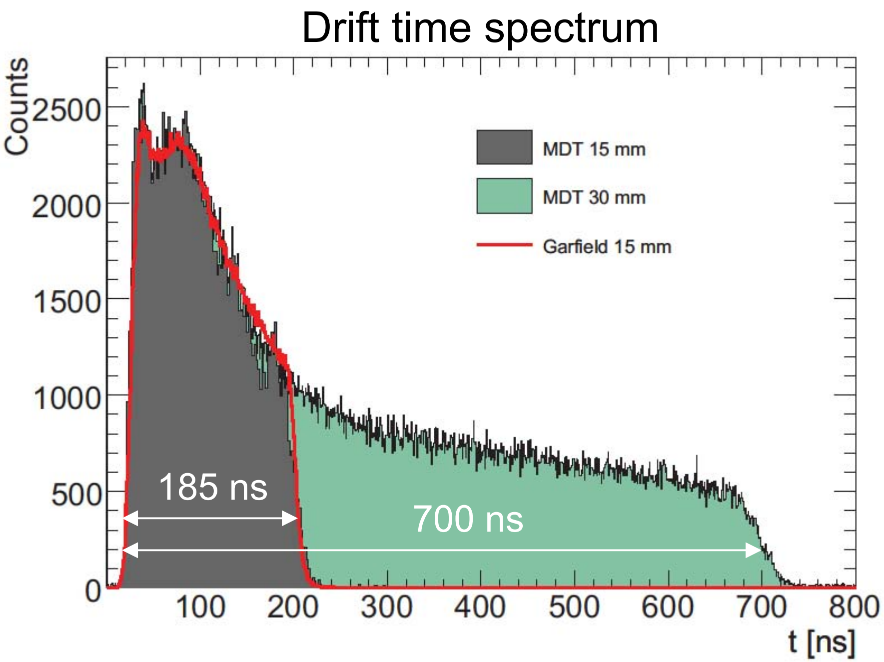
Drift tube diameter reduced from 30 mm (MDT) to 15 mm (sMDT)

at otherwise unchanged operating conditions:
$Ar:CO_2$ (93:7) at 3 bar, gas gain 20000.

- 8 x lower background occupancy:
  4 x shorter maximum drift time, 2 x smaller tube cross section).
- reduced electronics deadtime (≈ max. drift time) by factor of 4.

⇒ 10 x higher rate capability.





Also:

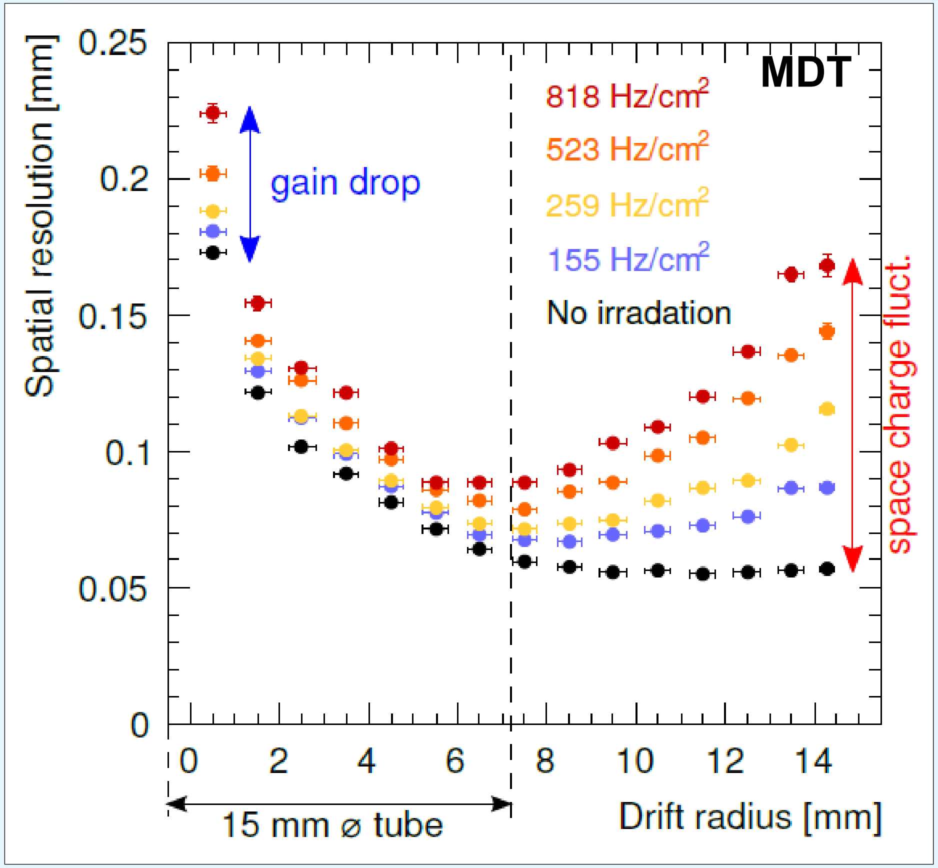
Twice as many tube layers fit into the same available detector volume.

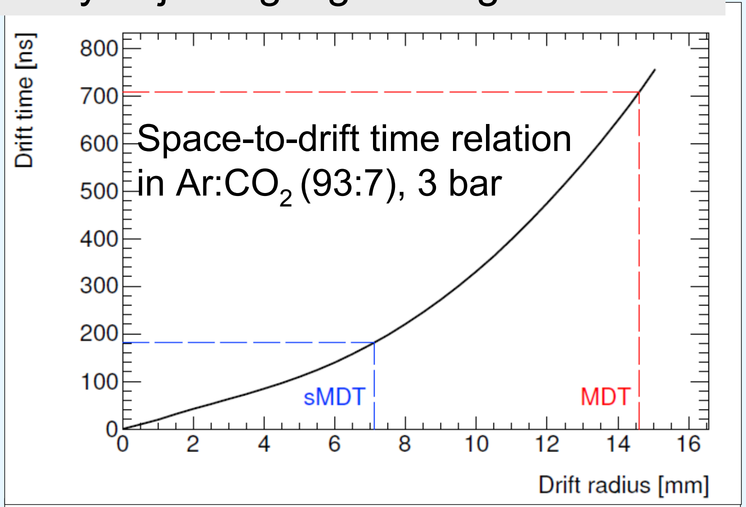
Space Charge Effects

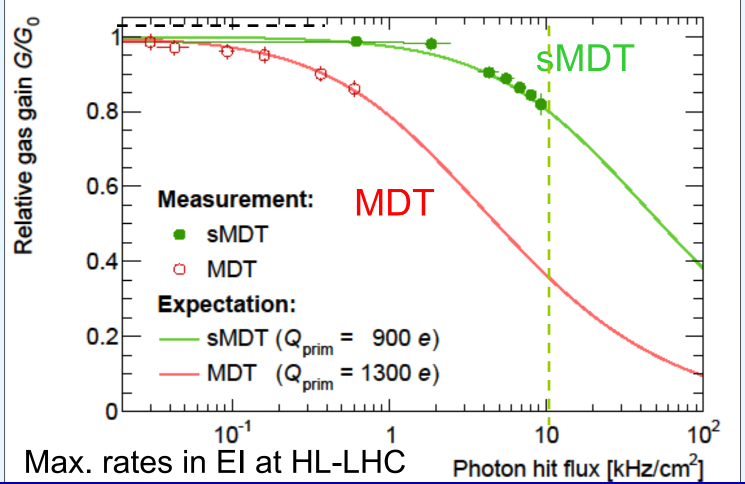
Why 15 mm tube diameter?

Space charge effects due to background radiation strongly suppressed in sMDT tubes:

- Effect of space charge fluctuations eliminated for r < 7.5 mm, linear r-t relation.
- Gain loss suppressed proportional to r^3, can be eliminated by adjusting high voltage.





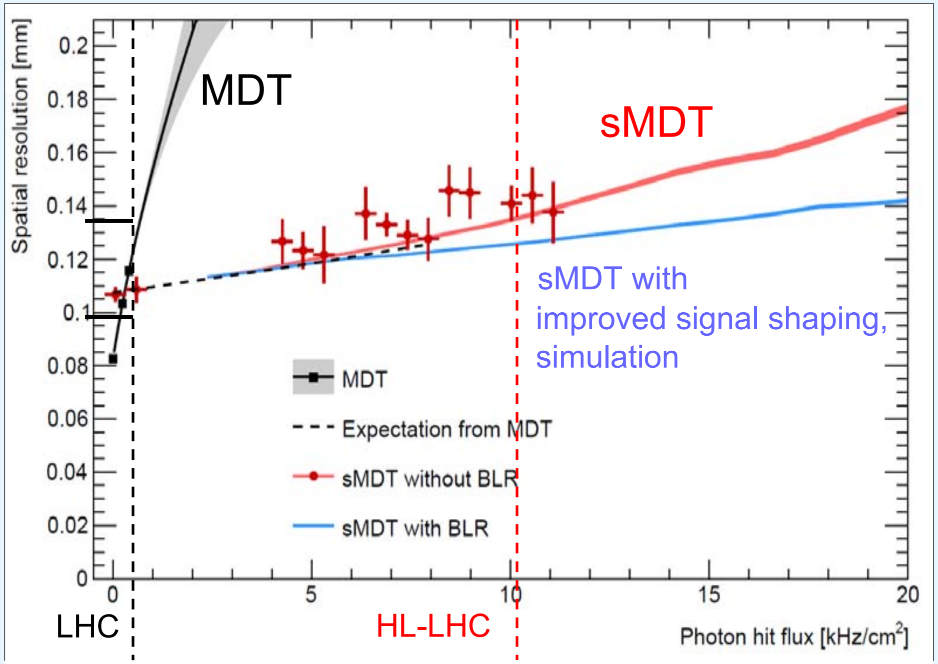


Measurements performed at the CERN Gamma Irradiation Facility

Rate Capability of sMDT Drift Tubes

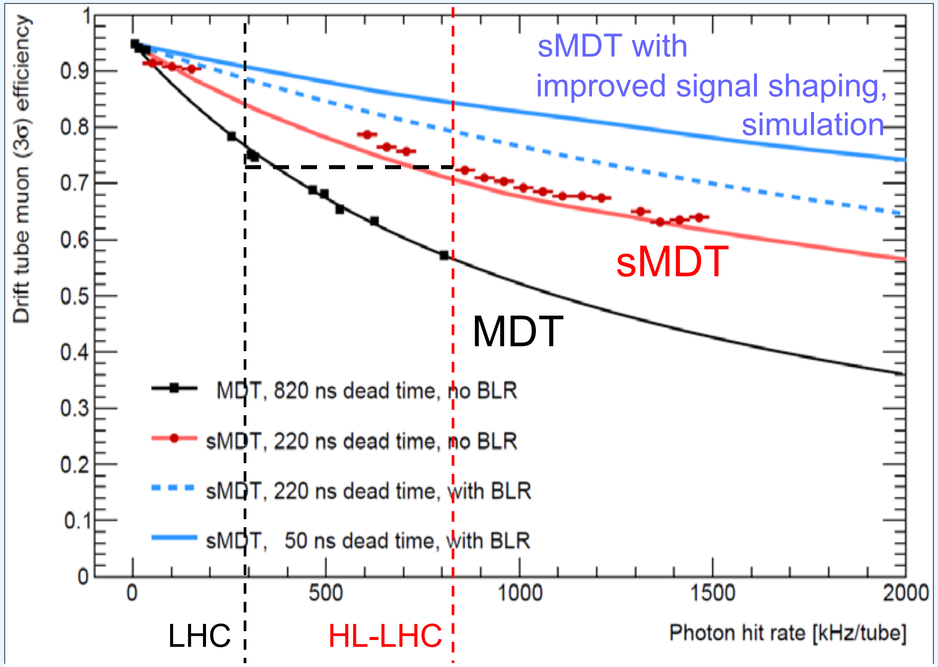
Test under γ irradiation in a muon beam at CERN with legacy ATLAS readout electronics

Average spatial resolution of drift tube



max. background flux: in EI layer

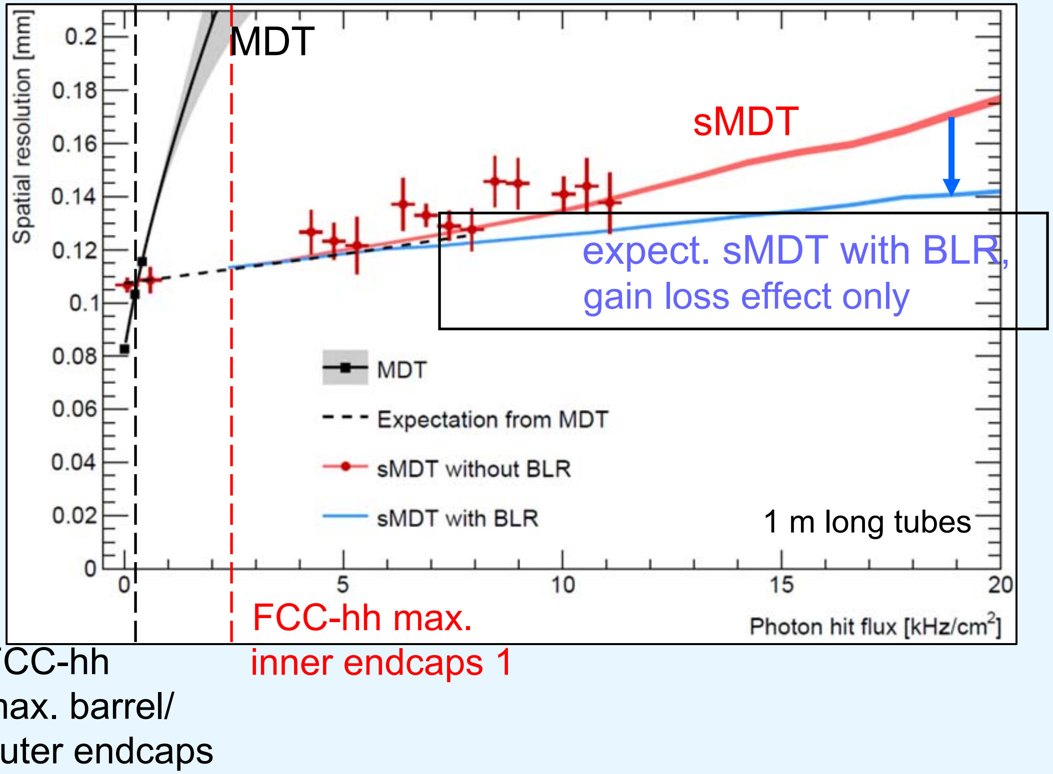
Muon efficiency of drift tube

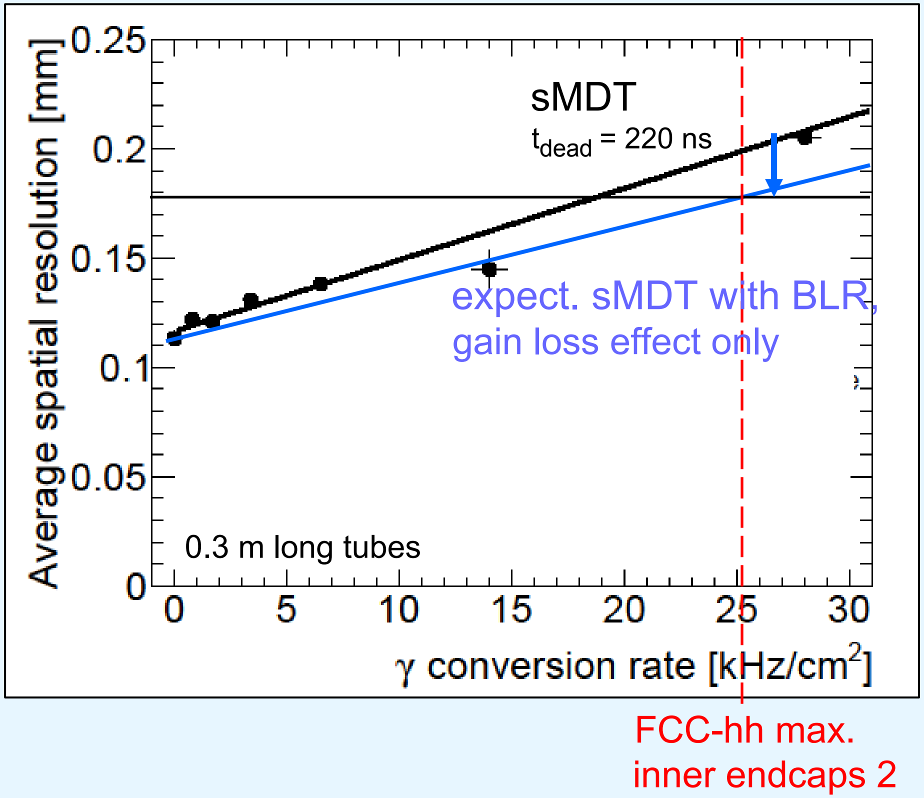


max. background hit rates: in EI layer

sMDT Spatial Resolution

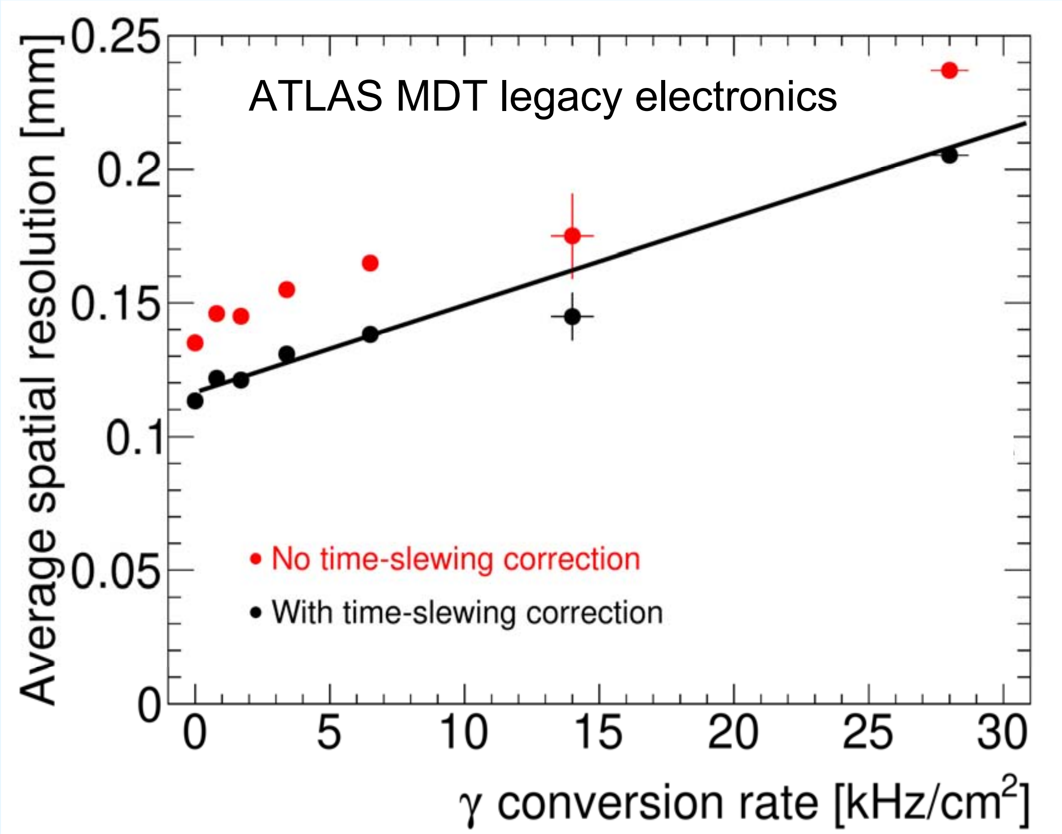
Measurements at the CERN Gamma Irradiation Facility (GIF++) using ATLAS MDT readout electronics (bipolar shaping, 220 ns minimum deadtime) and improvement with fast baseline restoration (BLR) elx.: input for detector performance studies and layout optimisation:

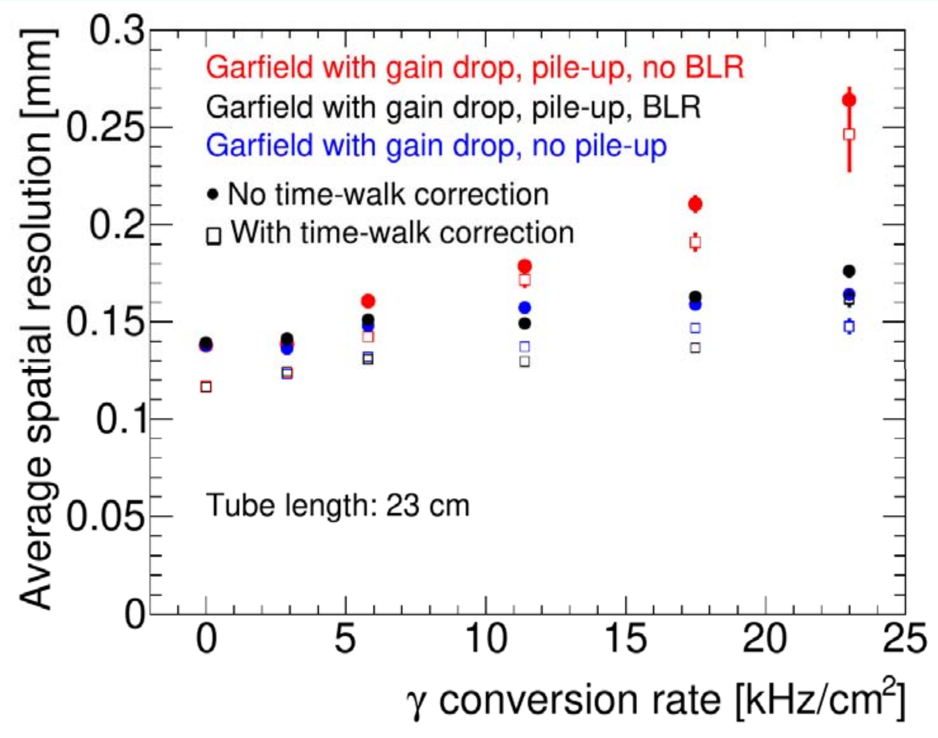




sMDT BLR electronics is under development, similar to ATLAS TRT FE electronics, to avoid muon signal distortion and resolution and efficiency degradation due to signal pile-up on background pulses for bipolar shaping.

Rate Capability of sMDT Drift Tubes





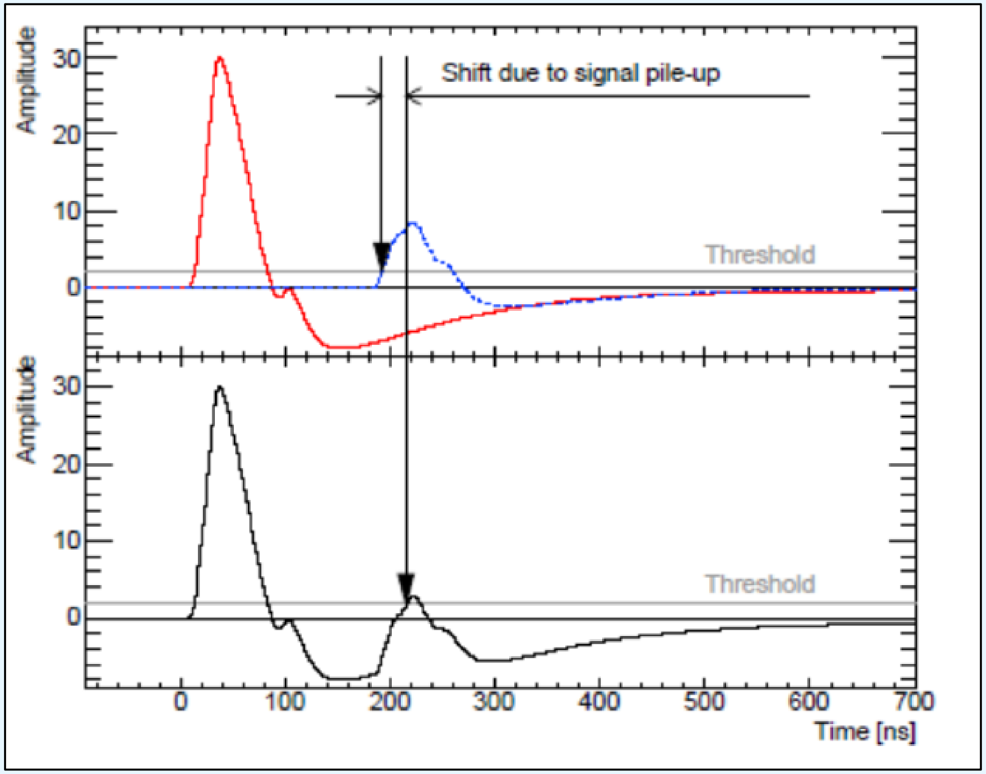
Contributions to resolution at high rates:
Gain drop and signal pile-up

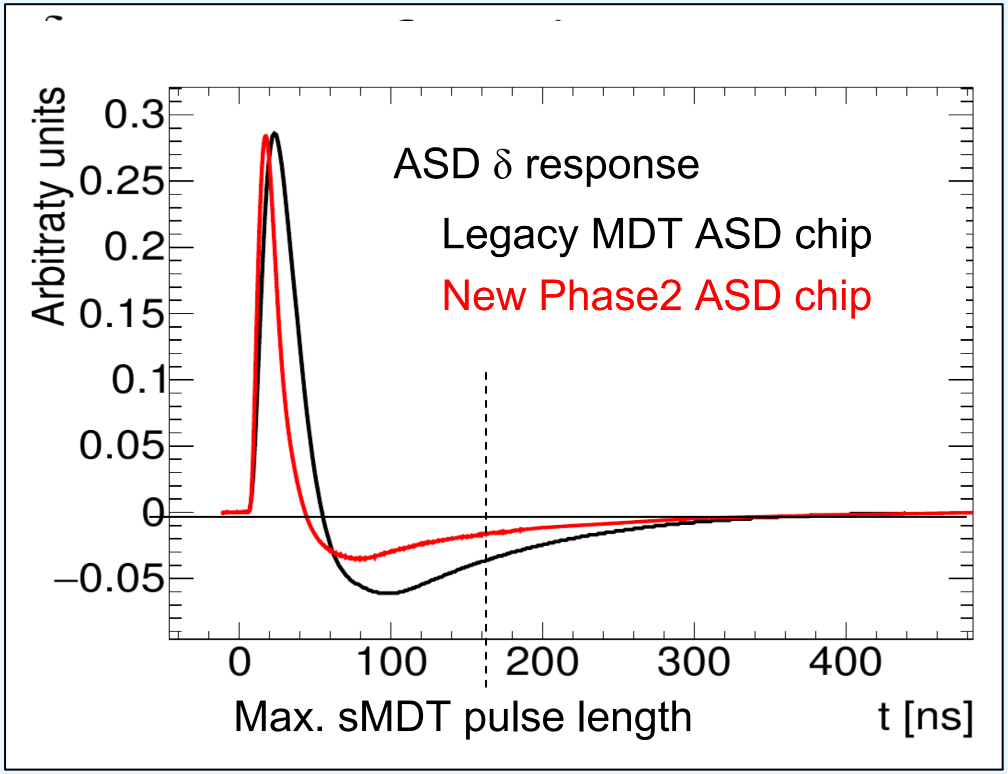
Readout Electronics for High Rates

Signal pile-up effects in readout electronics finally limit the sMDT rate capability.

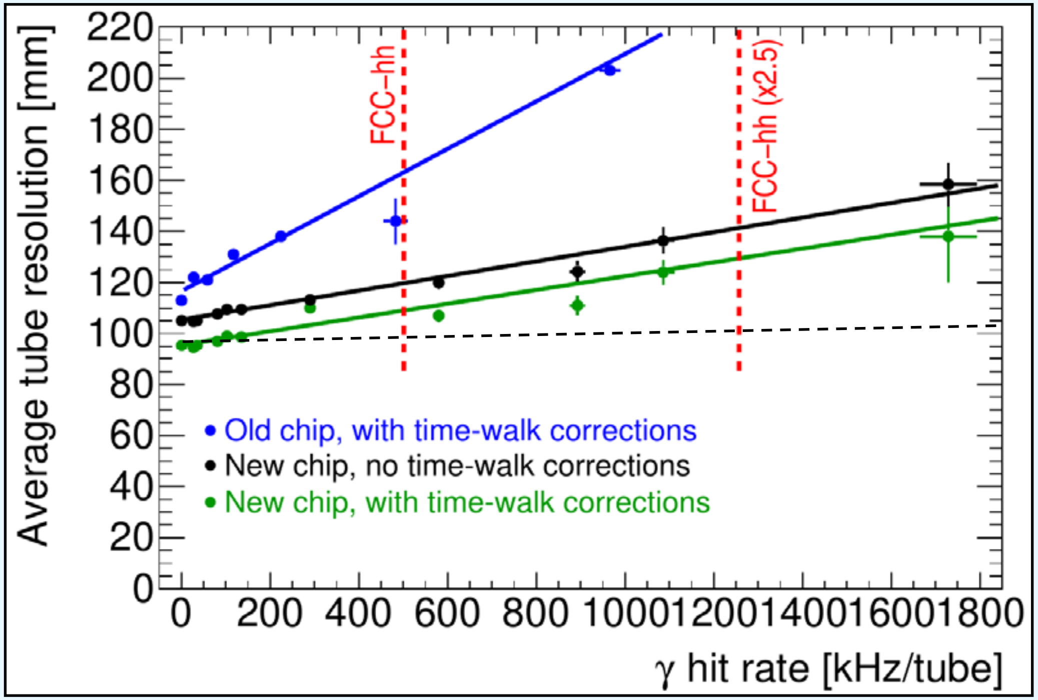
Compensation

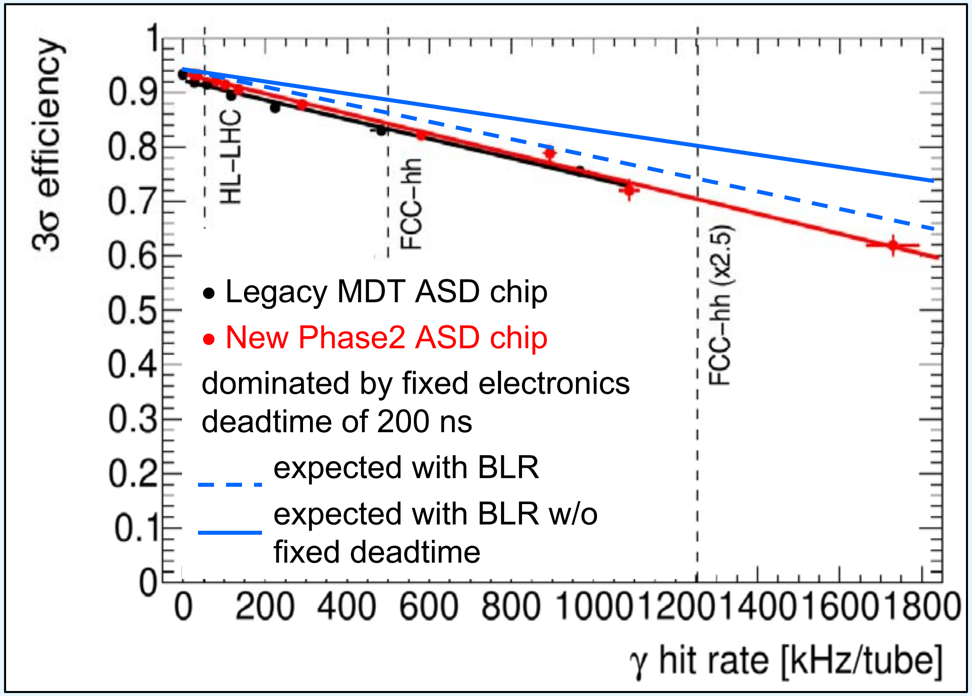
- by faster shaping with the same or better electronics noise: already for ATLAS Phase 2 and further improvements on the way
- ultimately by active baseline restoration: various techniques and implementation in 65 nm CMOS ASICs under development





Rate Capability of sMDT Drift Tubes



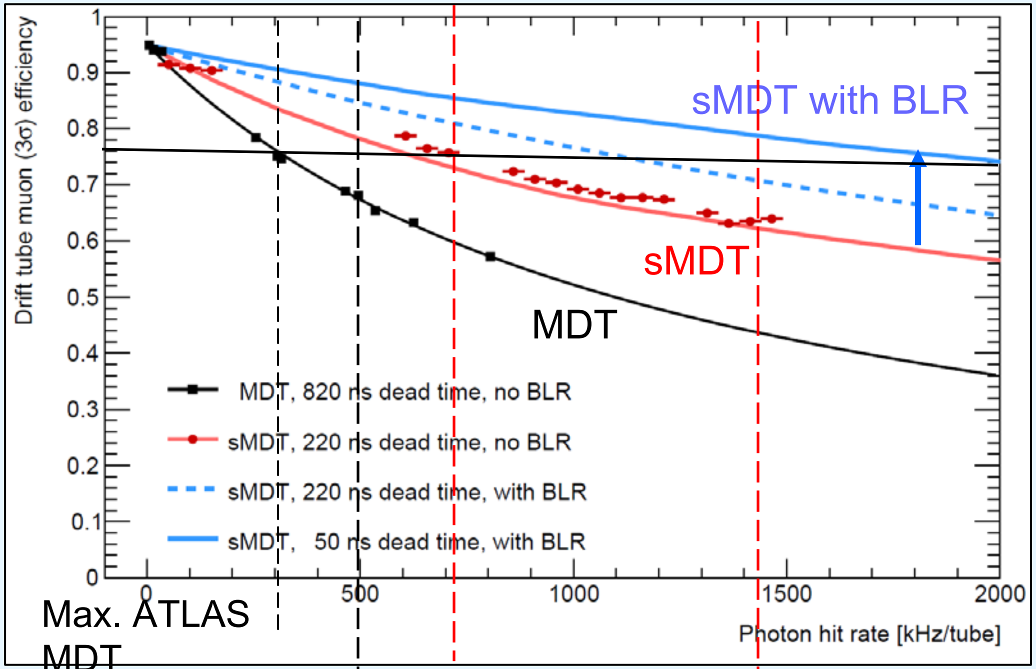


With gain loss compensation by HV adjustment as expected for measured counting rate.

Signal pile-up effects remaining with legacy ASD chip vs. new ASD chip for sMDTs at HL-LHC.

Muon Tracking Efficiency

Single-tube muon efficiency
drop due to masking of muon hits
by background pulses



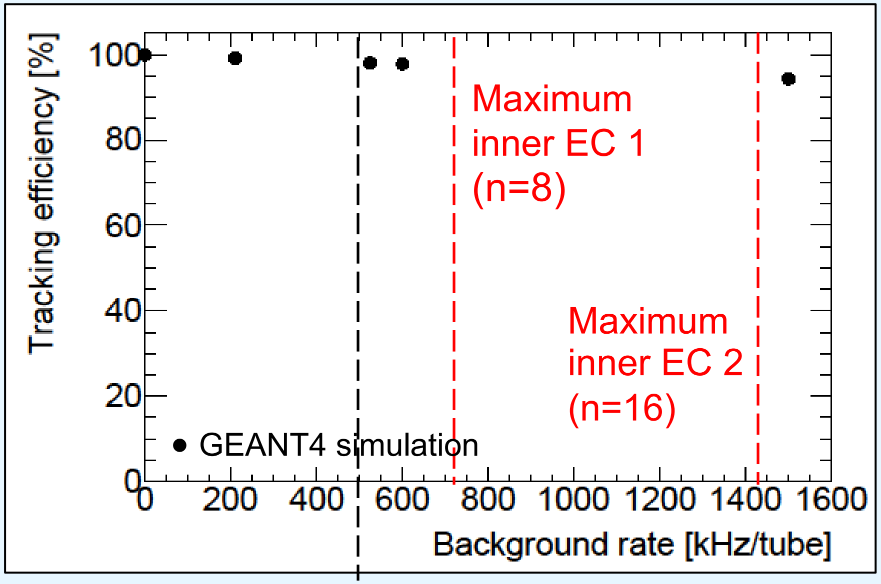
Maximum barrel/ outer EC, 2.8 m tubes

Maximum inner EC 1, 2.1 m tubes

Maximum inner EC 2, 0.4 m tubes

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

Track finding efficiency
(4 out of n tube layers)



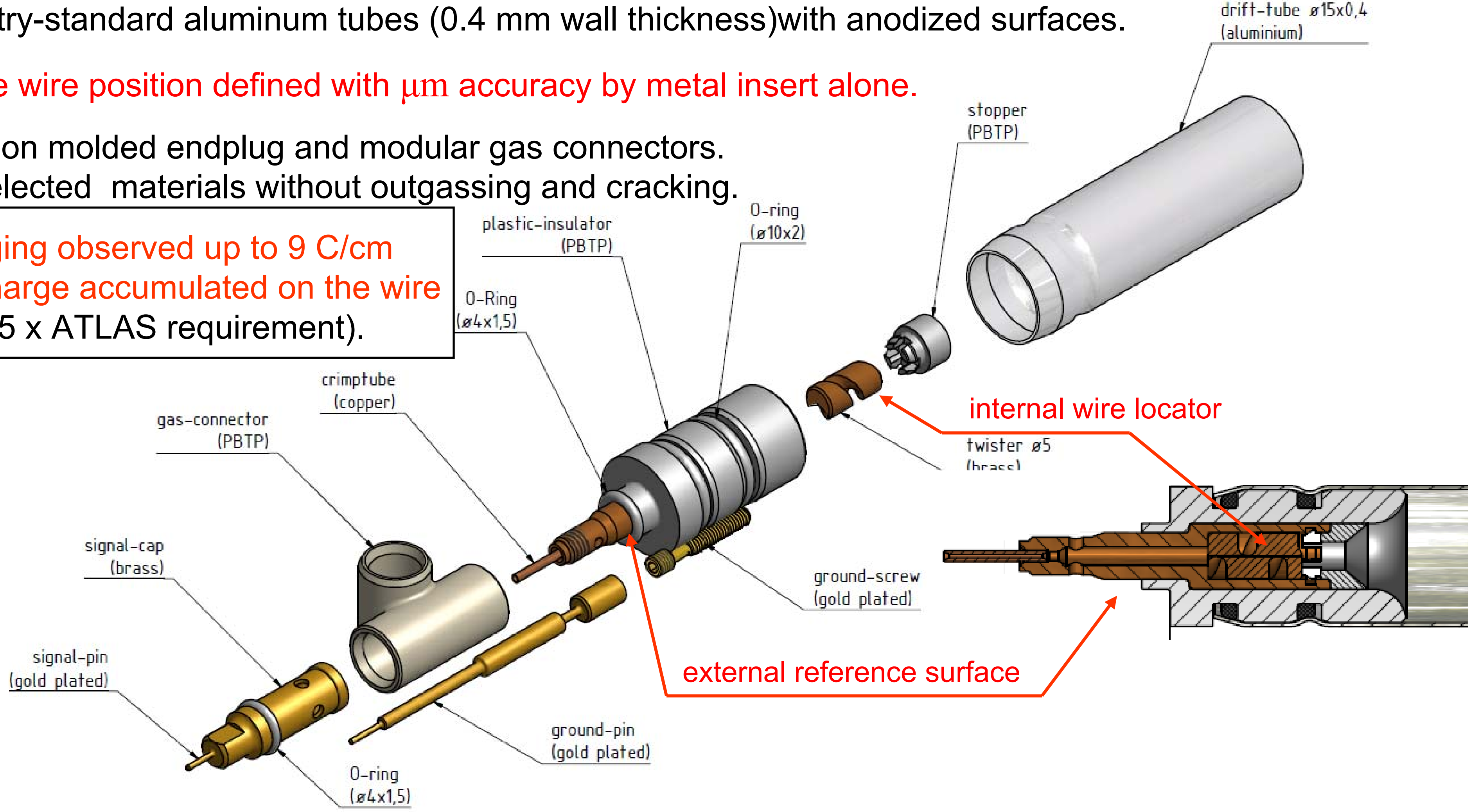
Maximum barrel/ outer EC (n= 8 = 2 x 4)

⇒ Acceptable fluences up to 35 kHz/cm^2 or 2 MHz/tube counting rates.

sMDT Chamber Design

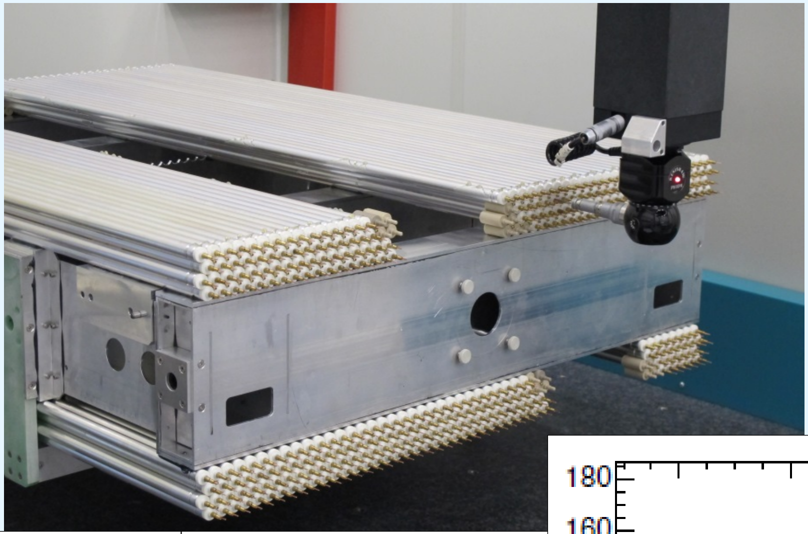
- Design optimized for mass production: automatized drift tube and chamber assembly. .
- Simplified low-cost drift tube design ensuring high reliability.
- Industry-standard aluminum tubes (0.4 mm wall thickness)with anodized surfaces.
- Sense wire position defined with μm accuracy by metal insert alone.
- Injection molded endplug and modular gas connectors.
  selected materials without outgassing and cracking.

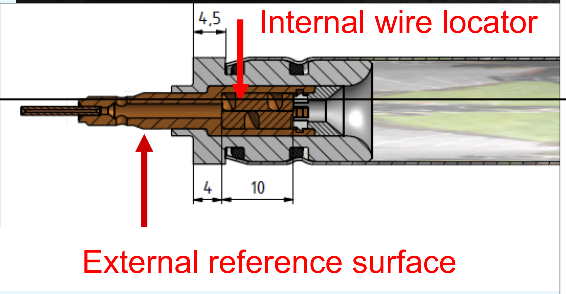
- No aging observed up to 9 C/cm
  charge accumulated on the wire
  (15 x ATLAS requirement).



Automated Drift Tube Assembly

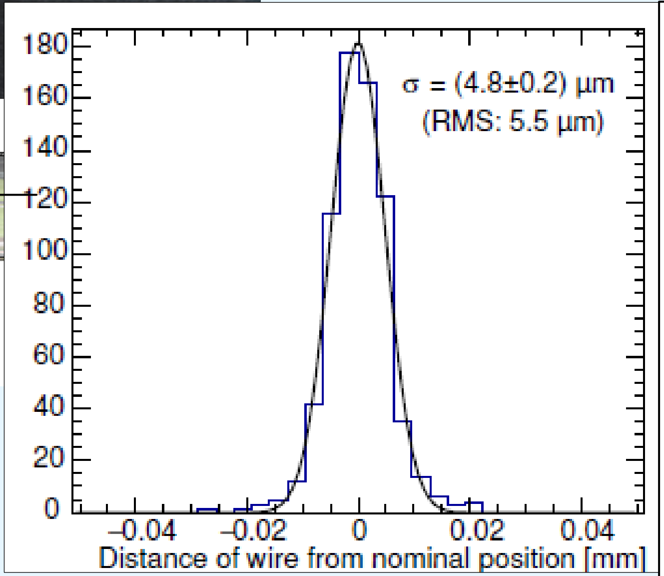
Quality Control: Mechanical Wire Position Measurement



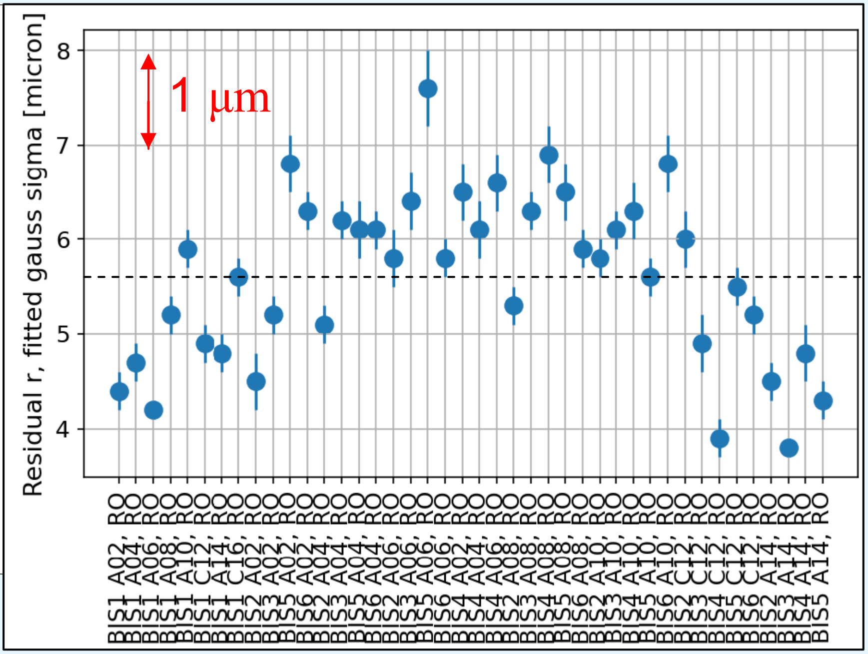


Measurement of individual sense wire positions with automated 3D coordinate measuring machine.

⇒ Wire positioning accuracy of 5 µm achieved.



sMDT mass production for ATLAS Phase 2 completed:

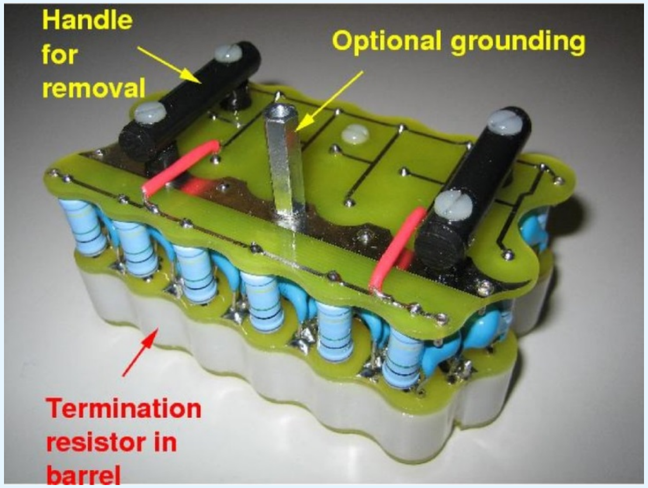


sMDT Chamber Construction

sMDT Mass Production

sMDT Readout Electronics

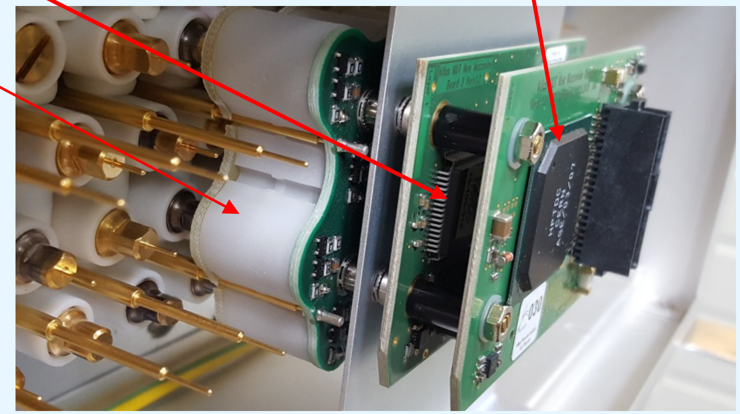
High-voltage
distribution boards (24 channels)

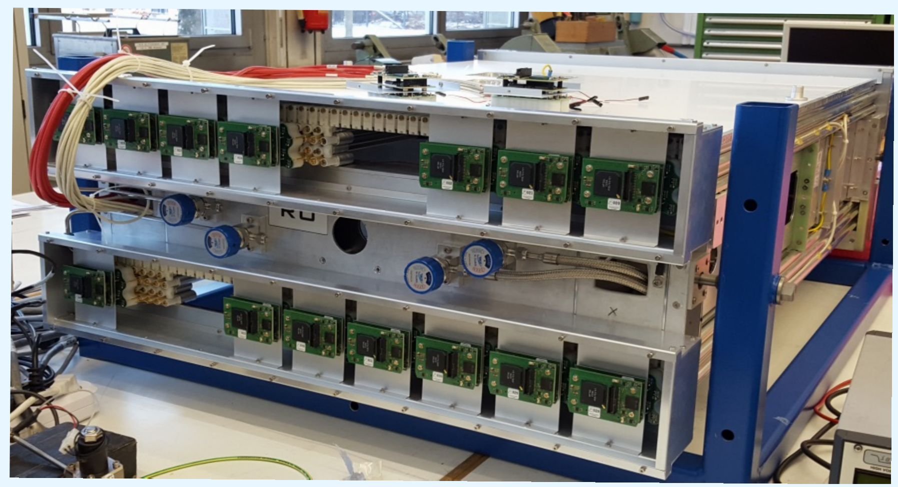


Signal distribution and readout boards (24 channels)

with three 8-channel amplifier-shaper-discriminator (ASD) chips in 130 nm GF CMOS and one TDC chip in 130 nm TSMC CMOS

Coupling capacitor in barrel





Challenge of 4 x denser tube grid:

Direct connection to endplug signal pins.

HV protection of termination resistors and coupling capacitors.

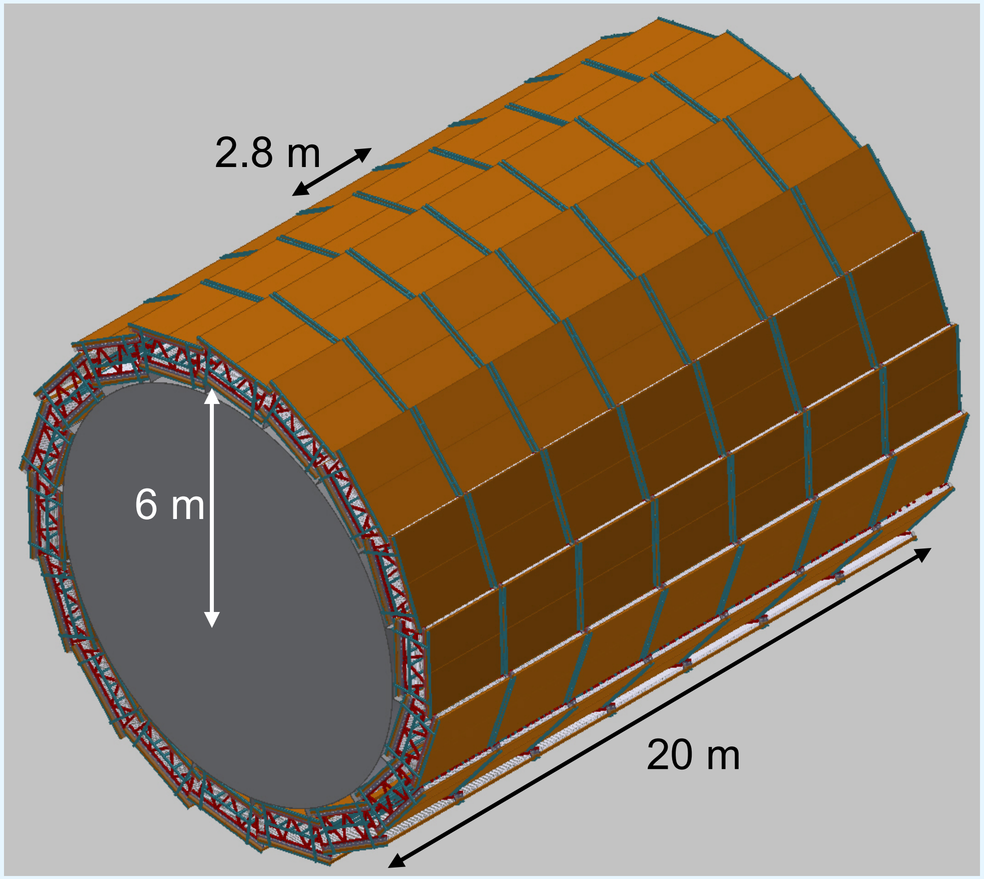
⇒ Stacked passive and active boards.

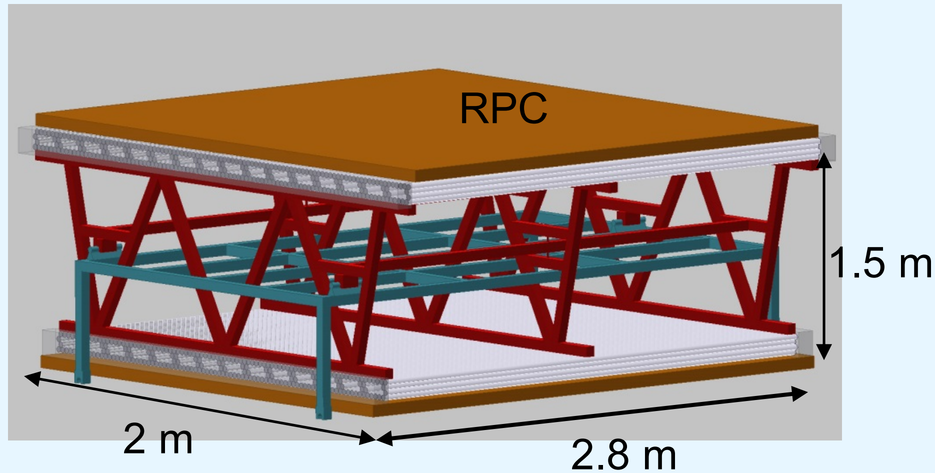
sMDT Chambers as FCC-hh Precision Muon Trigger Chambers

Drift tube chambers robust, cost-effective solution for high-precision tracking over large areas (cf. ATLAS).

High-precision monolithic two-multilayer detectors for precise track angle measurement without need for an optical alignment monitoring system.

2 x 4 layers of drift tubes at a distance of 1m with wire positioning accuracy of 20 μm provide < 50 μm spatial resolution, 70 μrad angular resolution, 100% efficiency.



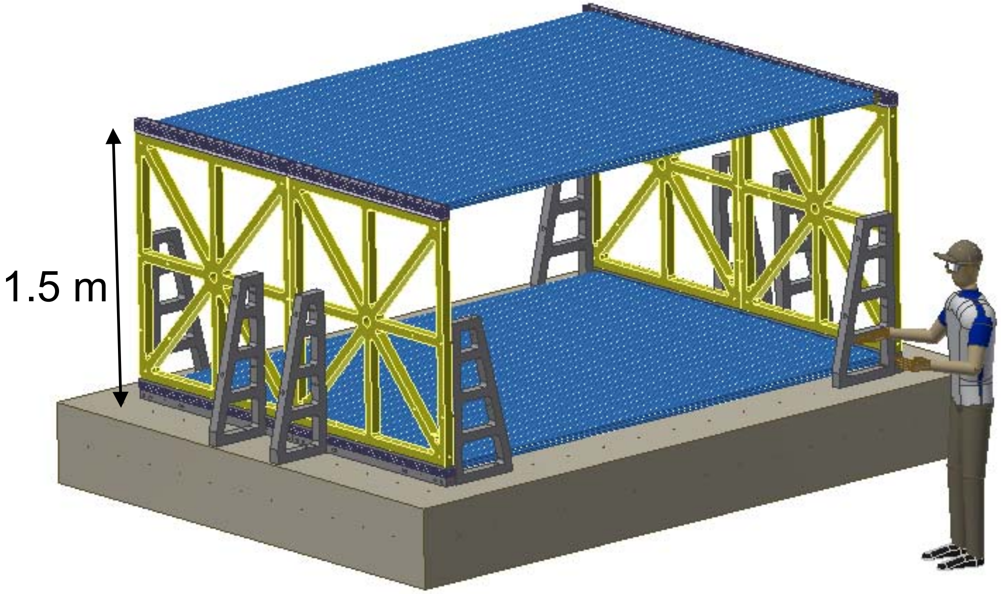


sMDT track angle trigger with continuous readout.

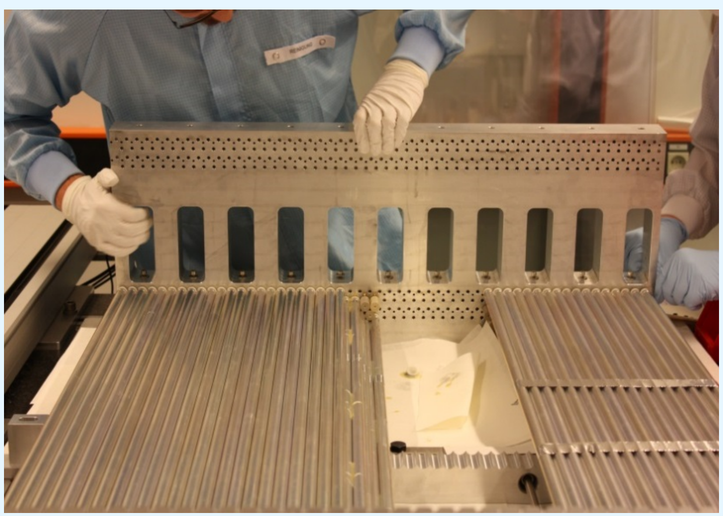
RPCs for BCID, coarse 2nd coordinate measurement, seeds for pattern recognition.

R&D on seedless sMDT trigger and BCID. 2nd coordinate measurement by double-ended readout of sMDTs and signal propagation time meas.

sMDT Development and Prototyping for Future Colliders



Precison assembly jigging

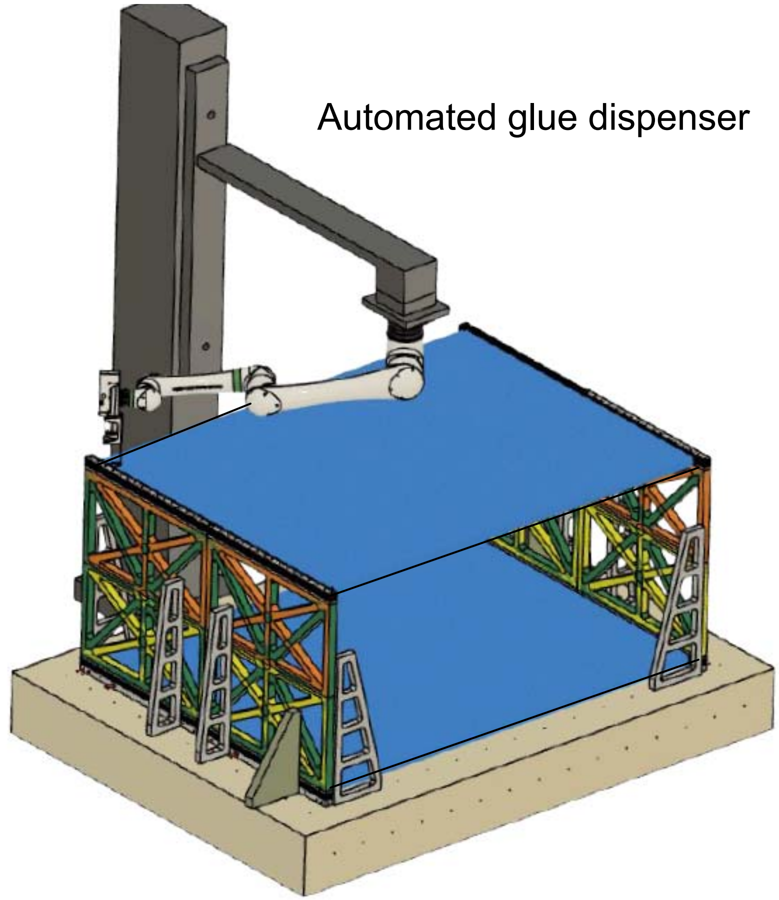


Automatisation of drift-tube production.

Automatisation of chamber assembly.

Transfer to industry.

In parallel with the same program for
RPC chamber mass production.



Summary

sMDT precison muon tracking deetctors also used for high spatial/angular resolution first-level muon trigger with continuous readout like already for ATLAS at HL-LHC.

Combined with RPCs for BCID, seeds for sMDT trigger, 2nd coordinate.

Seedless sMDT trigger and BCID under development.

→ Large area precision muon detector/trigger technologies for FCC-hh already available now up to $\eta = 2.5$.

→ Further improvement of rate capability with new FE ASICs with BLR; under development.