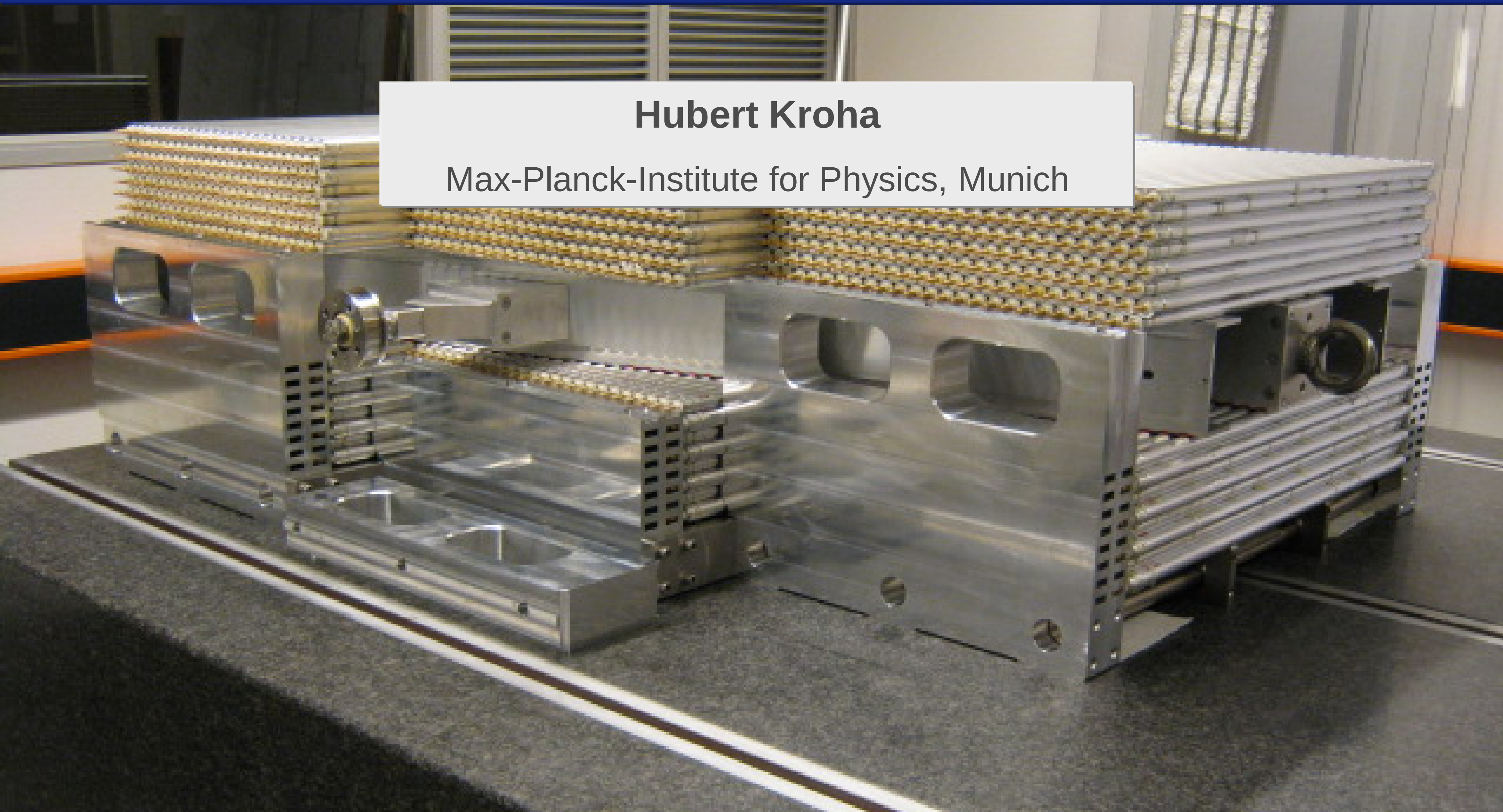
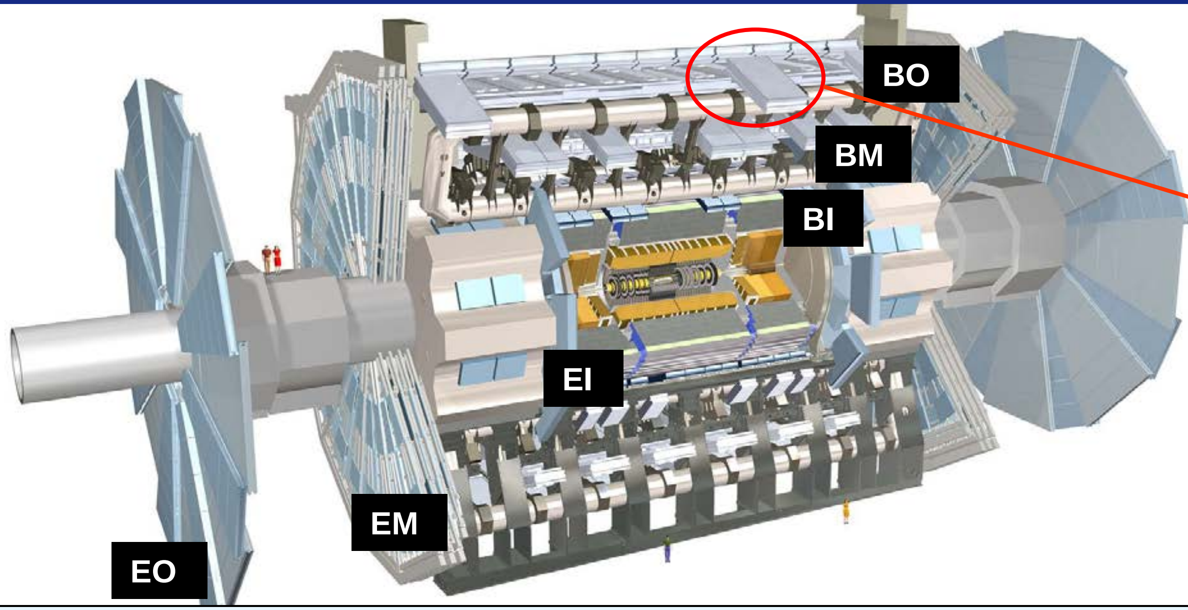
Small-Diameter Muon Drift Tube Detectors for Future Hadron Colliders

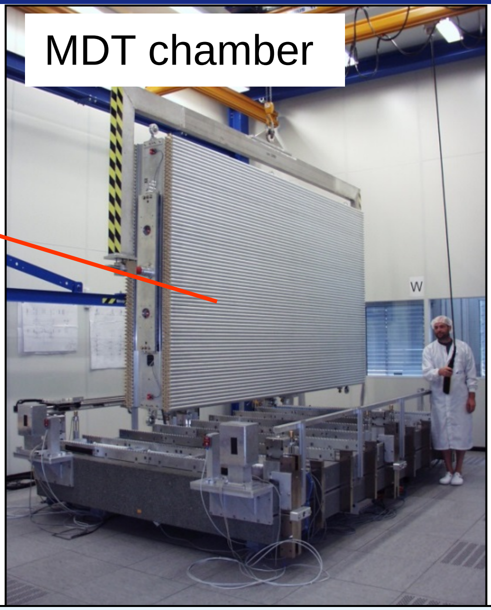


Hubert Kroha

Max-Planck-Institute for Physics, Munich

MDT Chambers of the ATLAS Muon Spectrometer





1200 Monitored Drift Tube (MDT) precision tracking chambers with 350k drift tubes:
sense wire positioning accuracy of 20 μm and chamber spatial resolution of 35 μm.
100 BO MDT chambers constructed at MPI, LMU and Freiburg.

Unprecedentedly high neutron and gamma background rates:
up to 400 Hz/cm^2 in the endcap inner layer (EI) at LHC design luminosity.

MDT chambers proved to be very robust and reliable detectors with high precision over large area (5000 m^2).
No signs of aging under the harsh operating conditions at LHC.

7.5 x higher luminosity and cavern background rates at HL-LHC than LHC design.

$\Rightarrow$ Development of small-diameter Muon Drift Tube (sMDT) detectors with 10 x increased rate capability.

Sufficient also for further 4 x luminosity increase at FCC-hh.

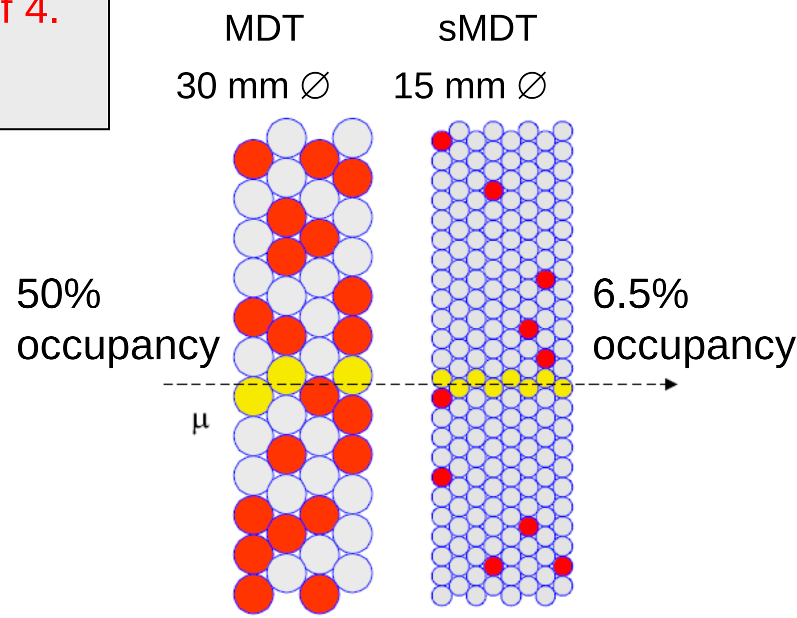
Small-Diameter Muon Drift Tube (sMDT) Chambers

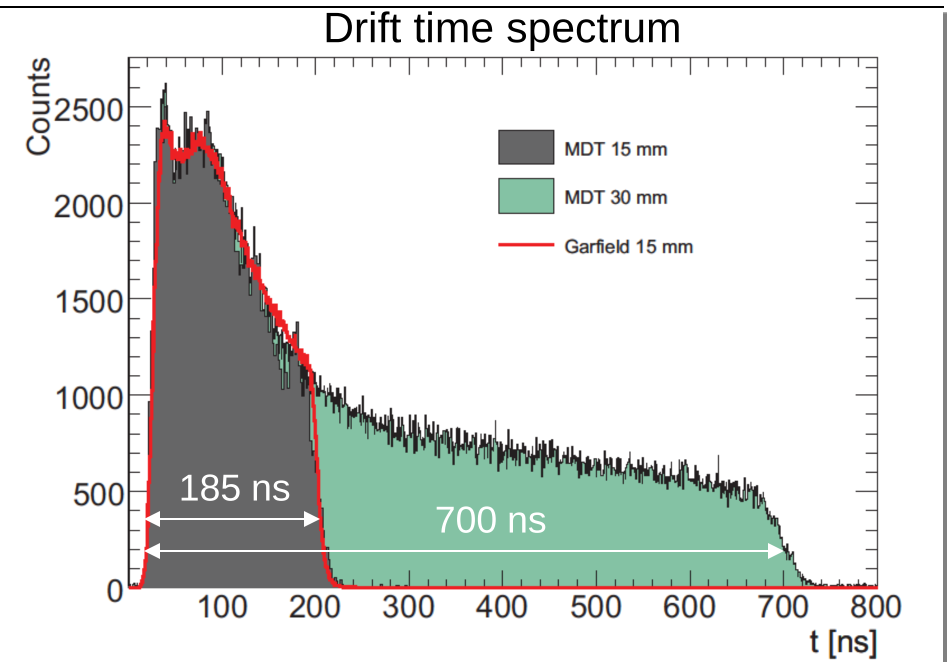
Drift tube diameter reduced from 30 mm (MDT) to 15 mm (sMDT)

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:

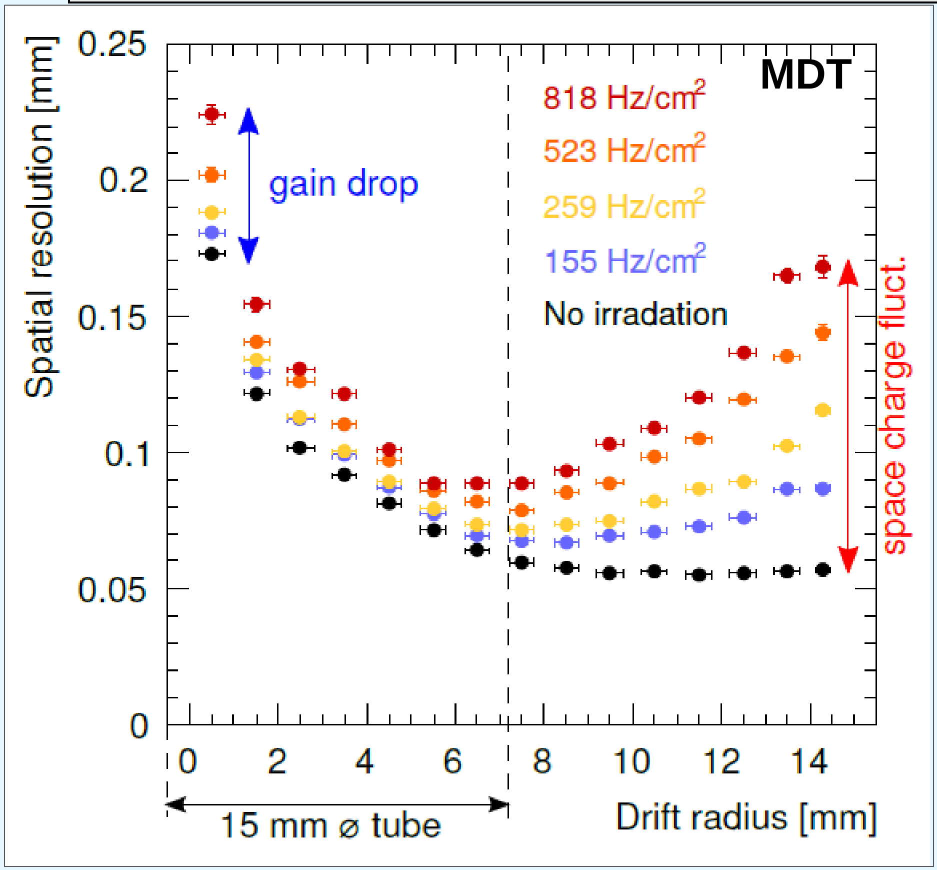
Twice as many tube layers fit into the same available detector volume.

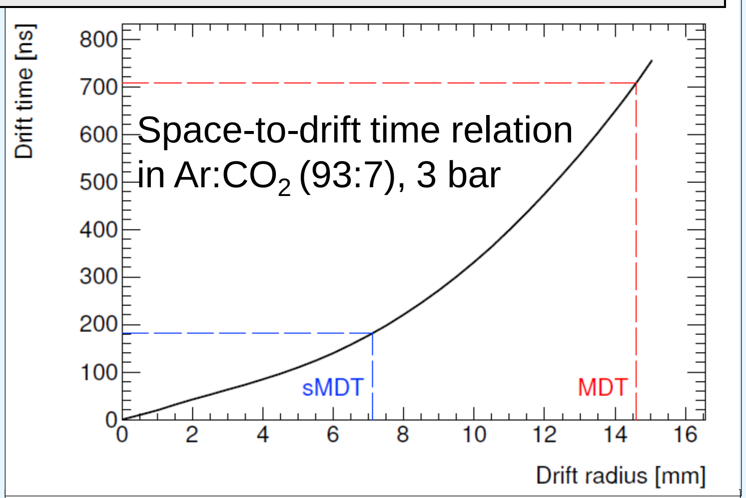
Space Charge Effects

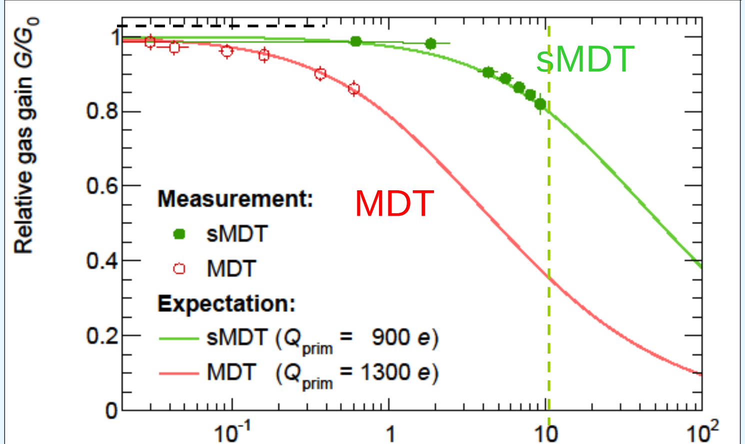
Why 15 mm tube diameter?

Space charge effects due to background irradiation 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 liminated by adjusting high voltage.







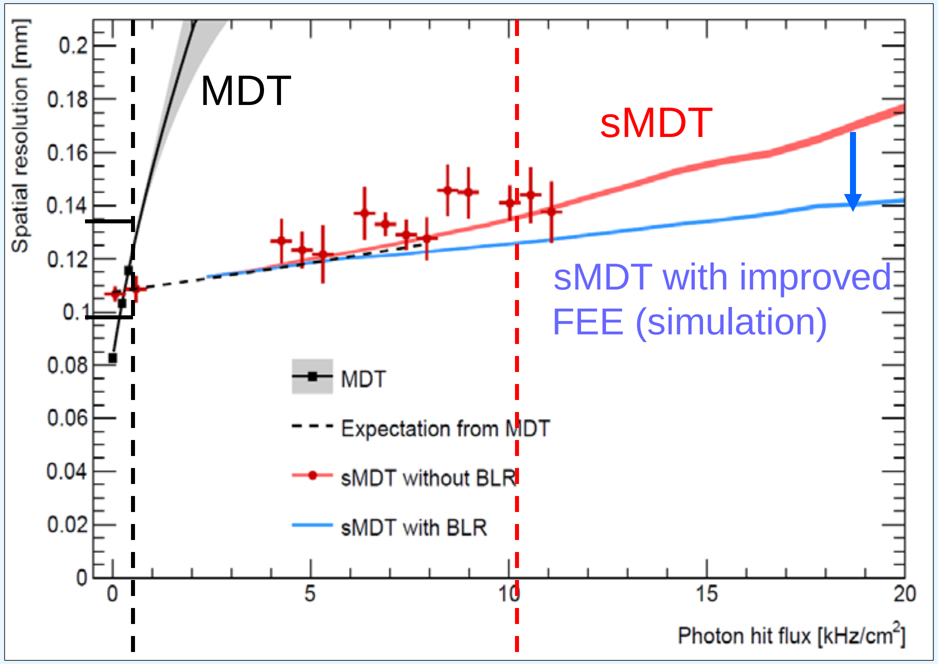
Measurements performed at the CERN Gamma Irradiation Facility

Max. rates in EI at HL-LHC

Rate Capability of sMDT Drift Tubes

Measurements in CERN Gamma Irradiation Facility with legacy ATLAS readout electronics.

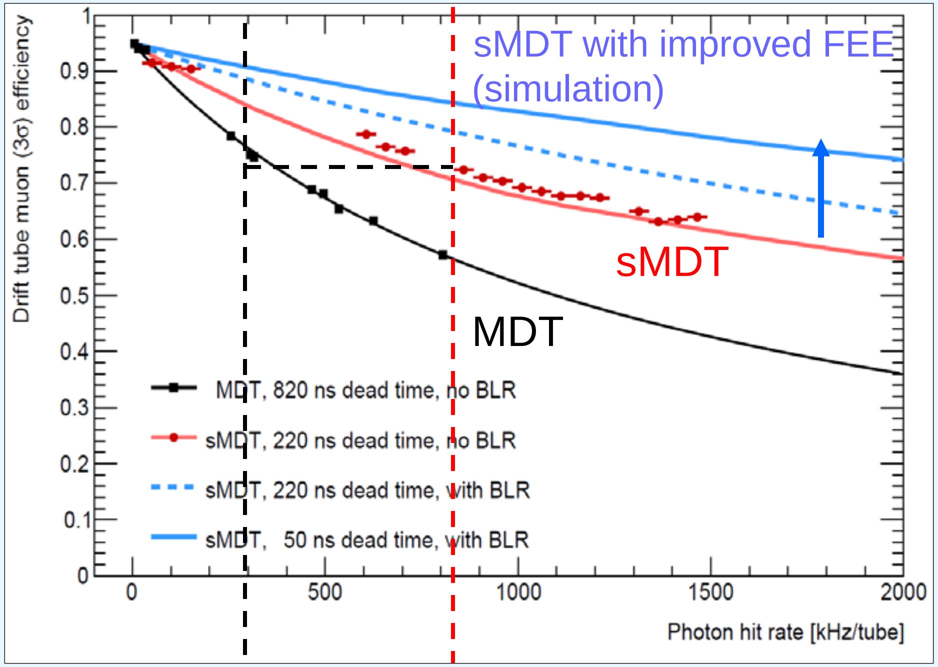
Average spatial resolution of drift tube



EI @ LHC

EI @ HL-LHC

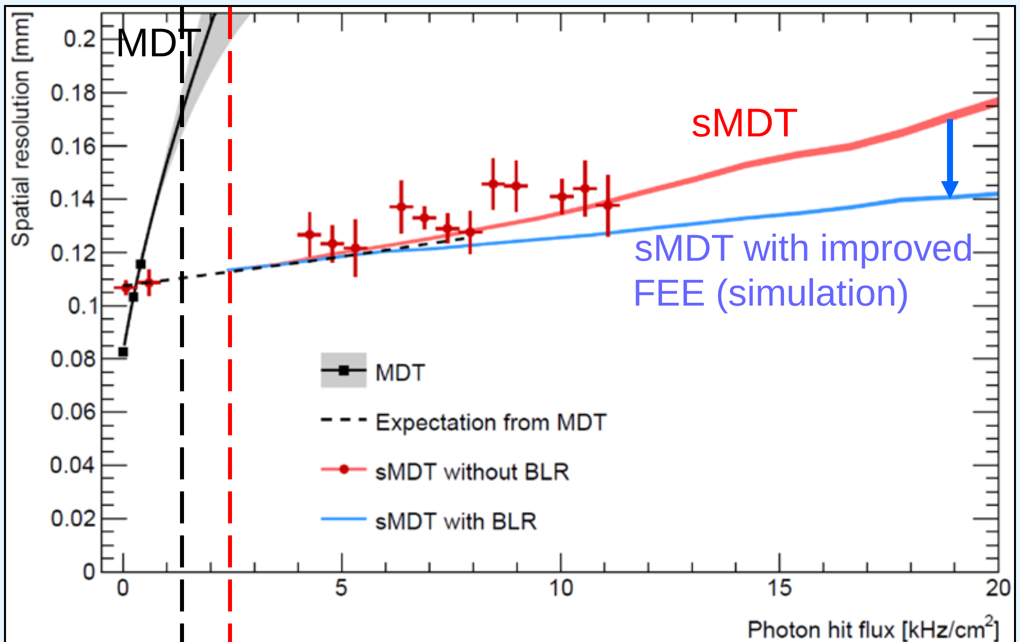
Muon efficiency of drift tube



EI @ LHC

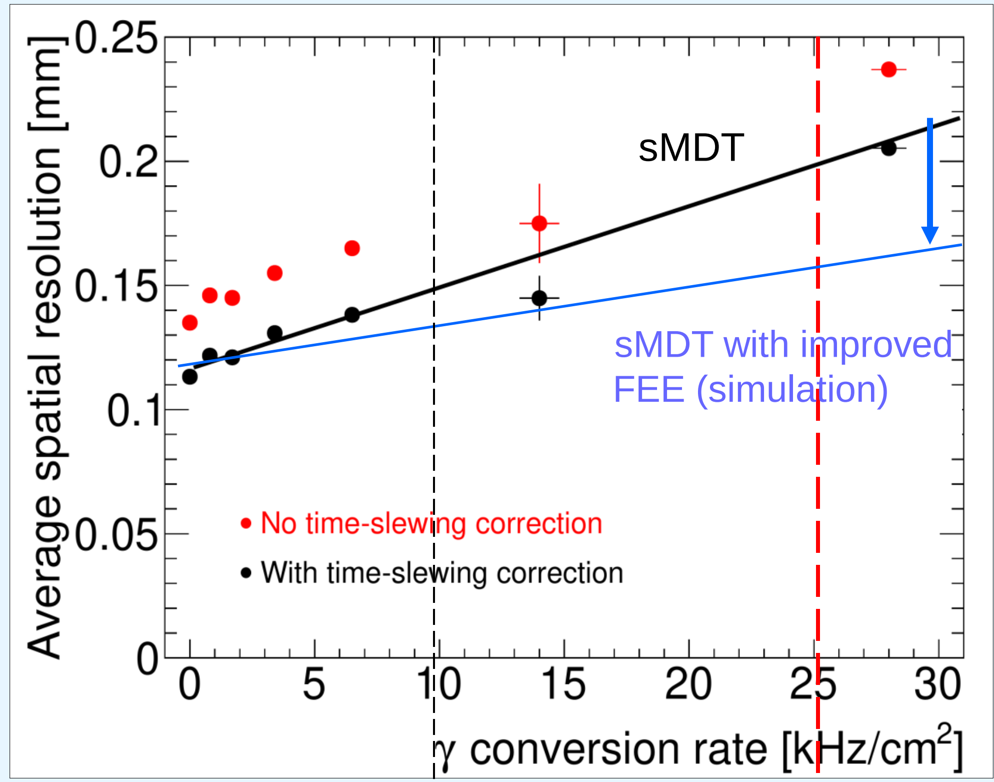
EI @ HL-LHC

sMDT Spatial Resolution



FCC-hh max. barrel/ outer endcaps (|η| <1.5)

FCC-hh max. inner endcaps 1 (|η| <1.9)



EI @ HL-LHC

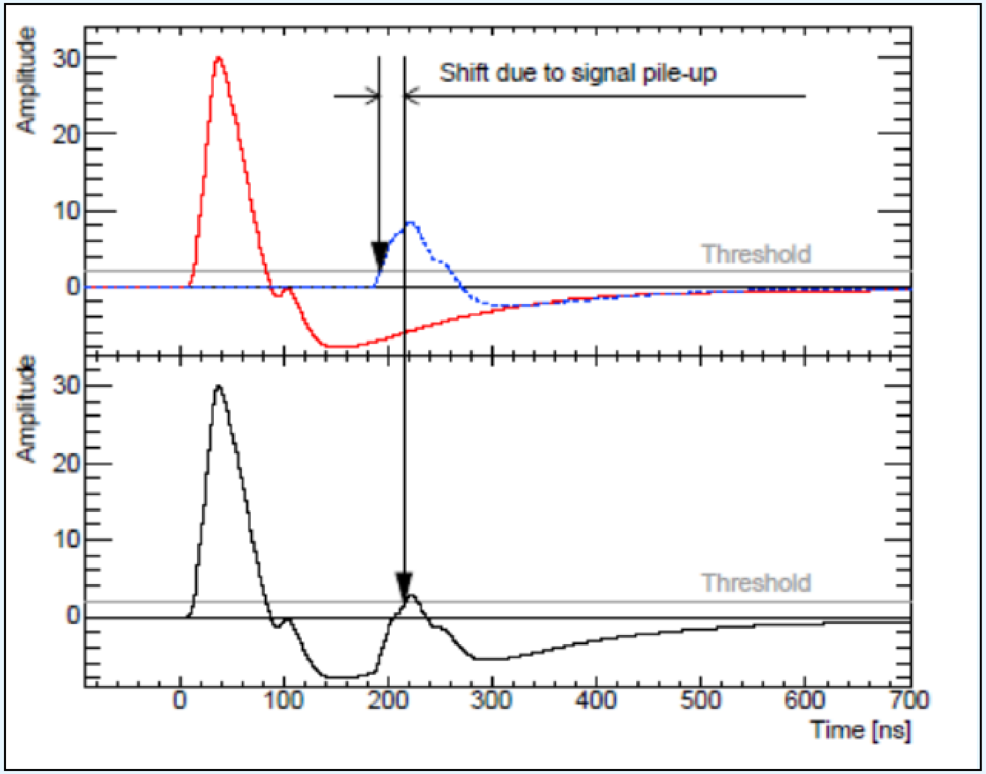
FCC-hh max. inner endcaps 2 (|η| < 2.5)

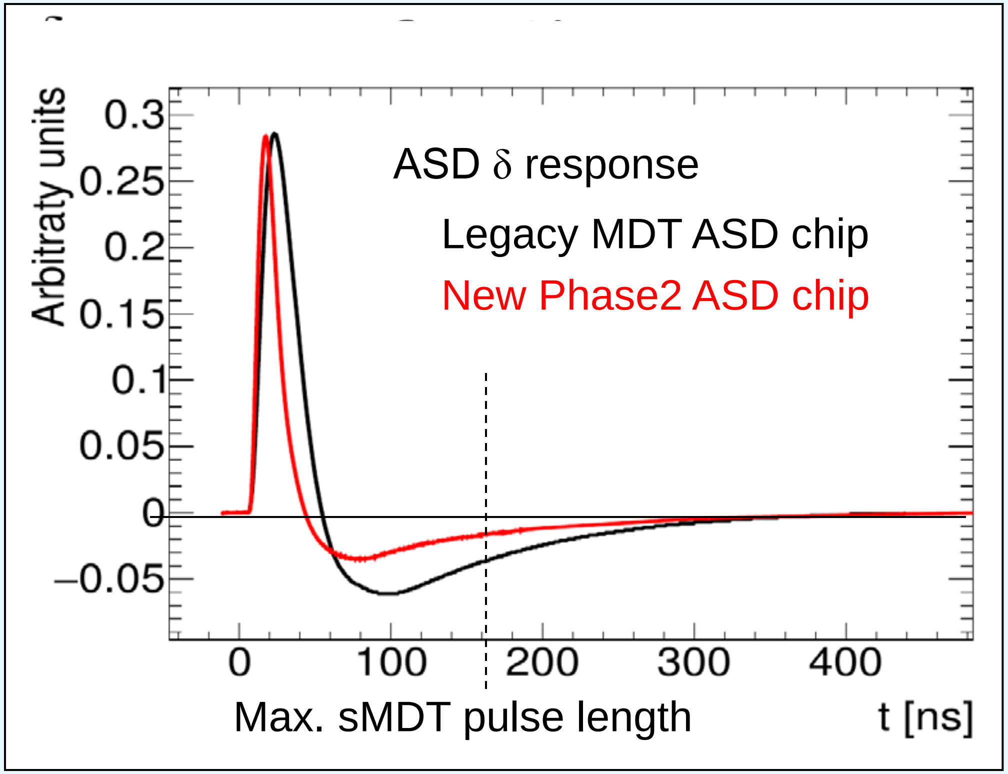
Readout Electronics for High Counting Rates

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

Compensation

- by faster (bipolar) shaping: already for ATLAS Phase 2 ASD ASIC and further improvements.
- ultimately by active baseline restoration: various techniques and implementation in 65 nm CMOS ASICs under development.

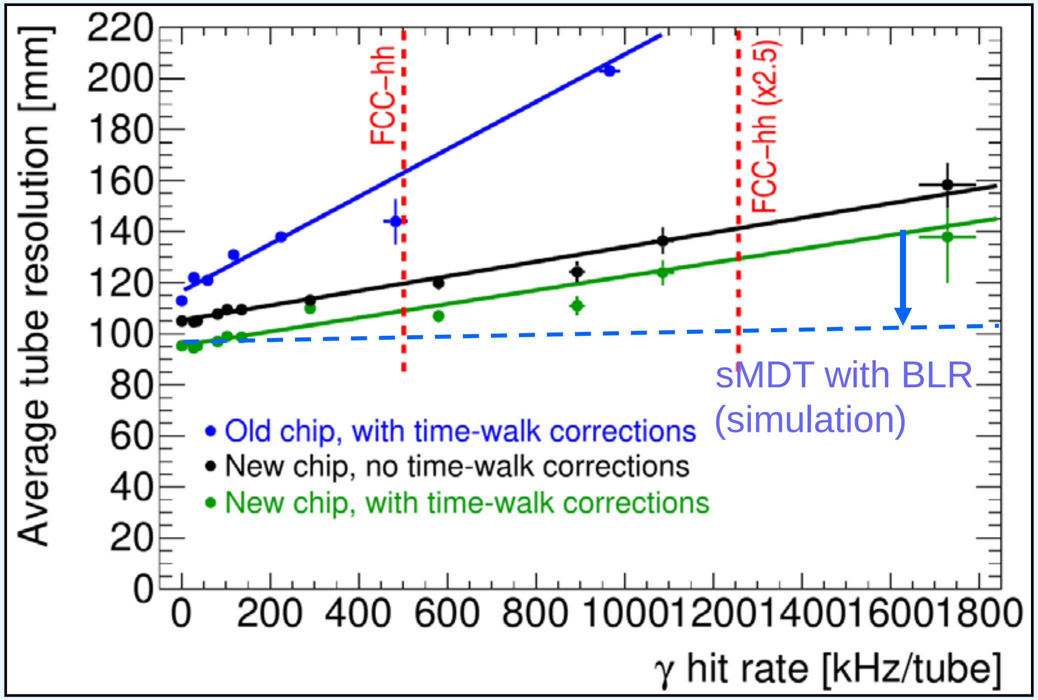


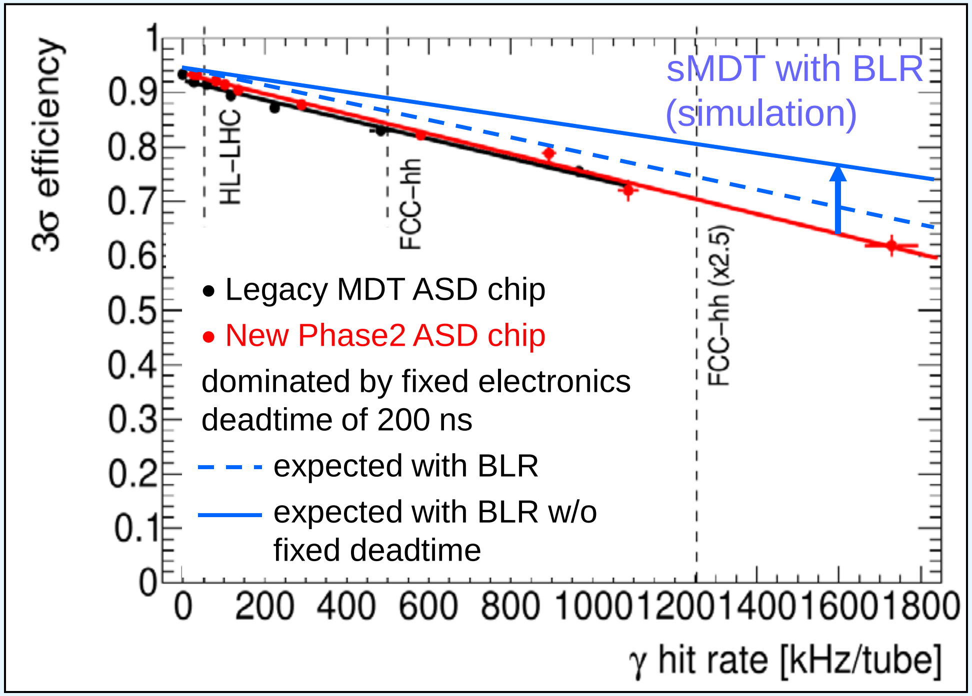


Rate Capability of sMDT Drift Tubes

With gain loss compensation by HV adjustment.

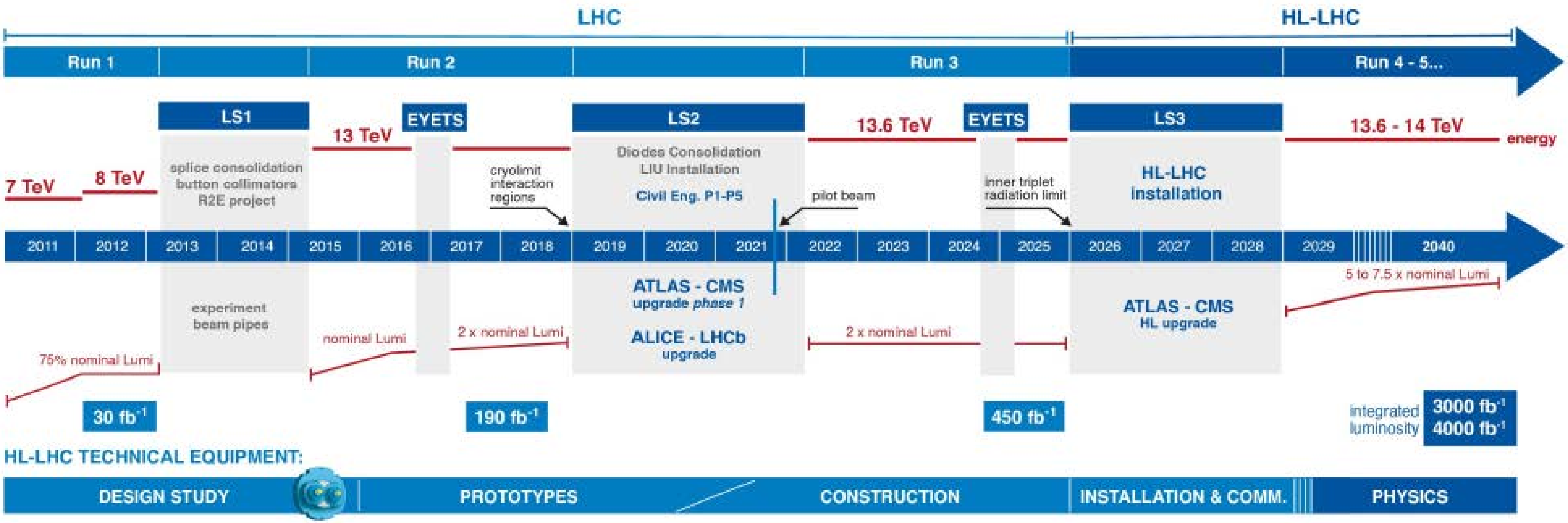
Signal pile-up effects remaining: - New FE ASD chip for sMDTs at HL-LHC vs.chip.
- Expectation with active baseline restoration (BLR).





$\Rightarrow$ sMDT operation up to background rates of 2 MHz/tube and 35 kHz/cm^2

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: BIS 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.

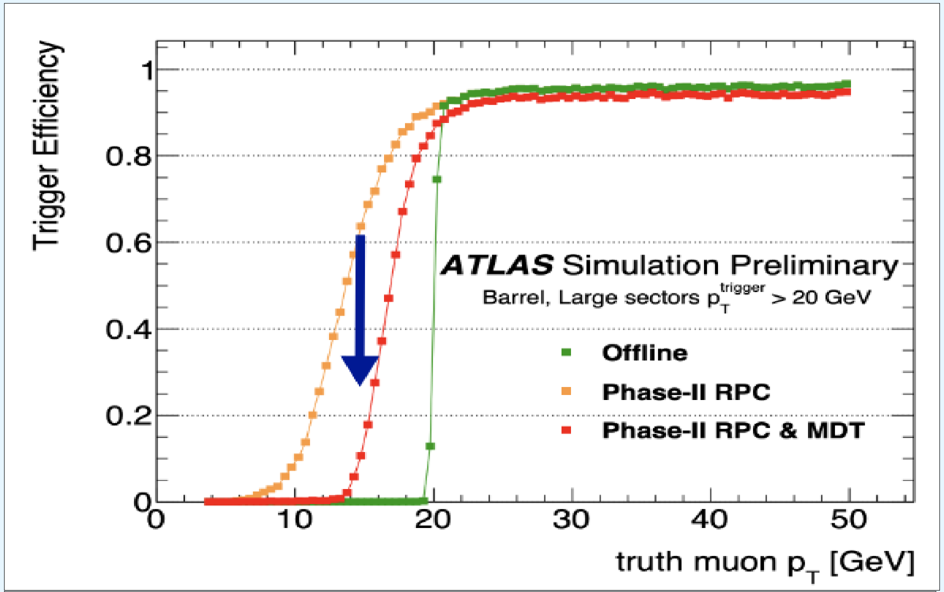
2024-26: BIS 1-6
96 sMDT + 276 RPC chambers
for the barrel inner layer
to increase the robustness
of the barrel muon trigger system.

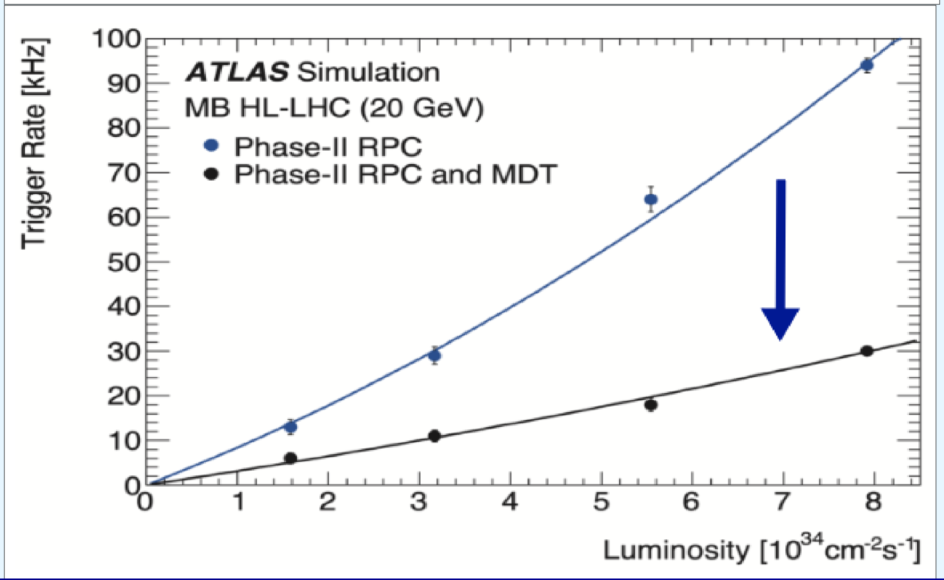
Use of (s)MDT chambers
for the 1st level muon trigger
to increase p_T resol. and selectivity.

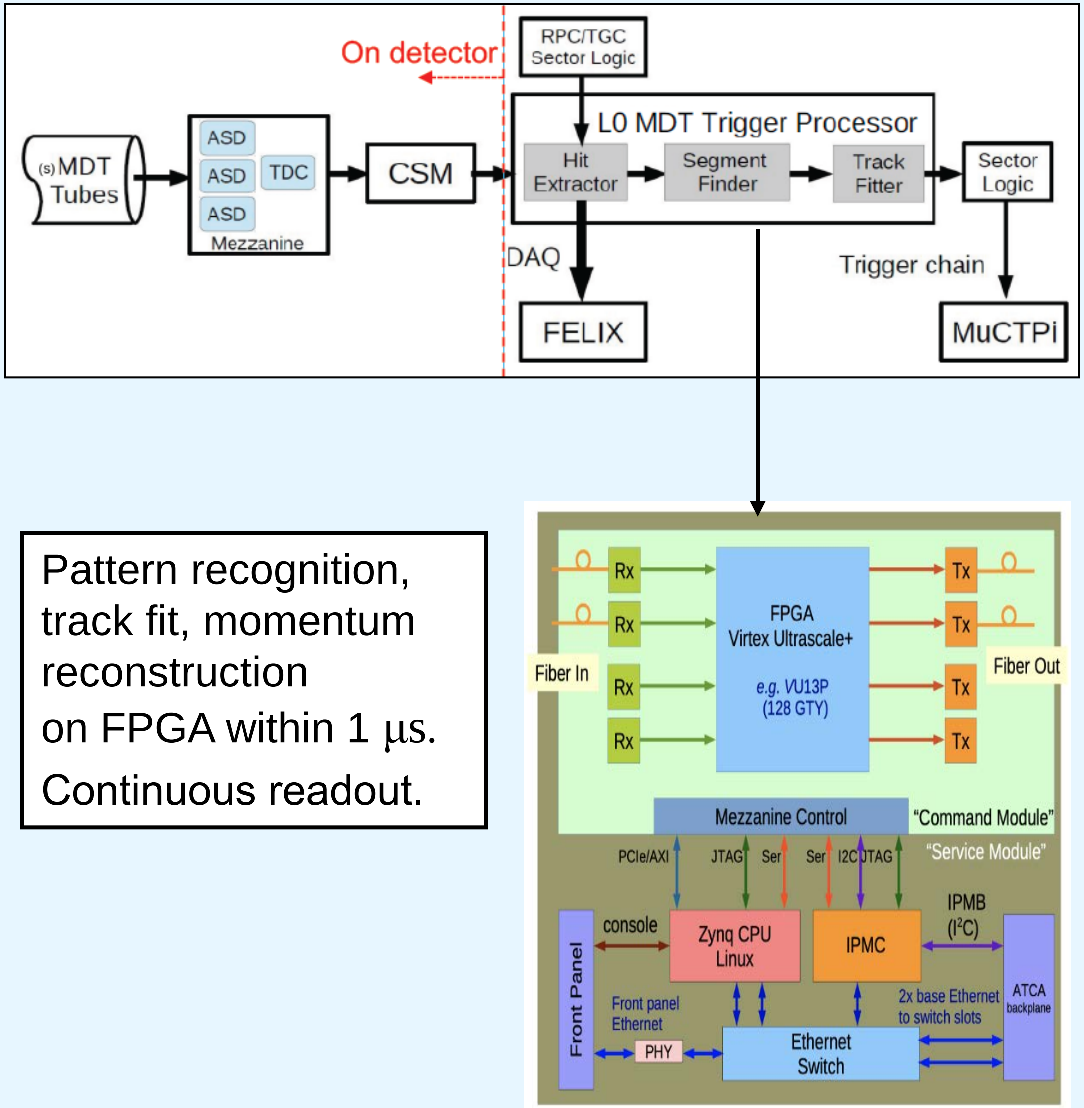
New MDT on-chamber electronics
because of 10 x higher trigger rate
and MDT-based trigger.

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.



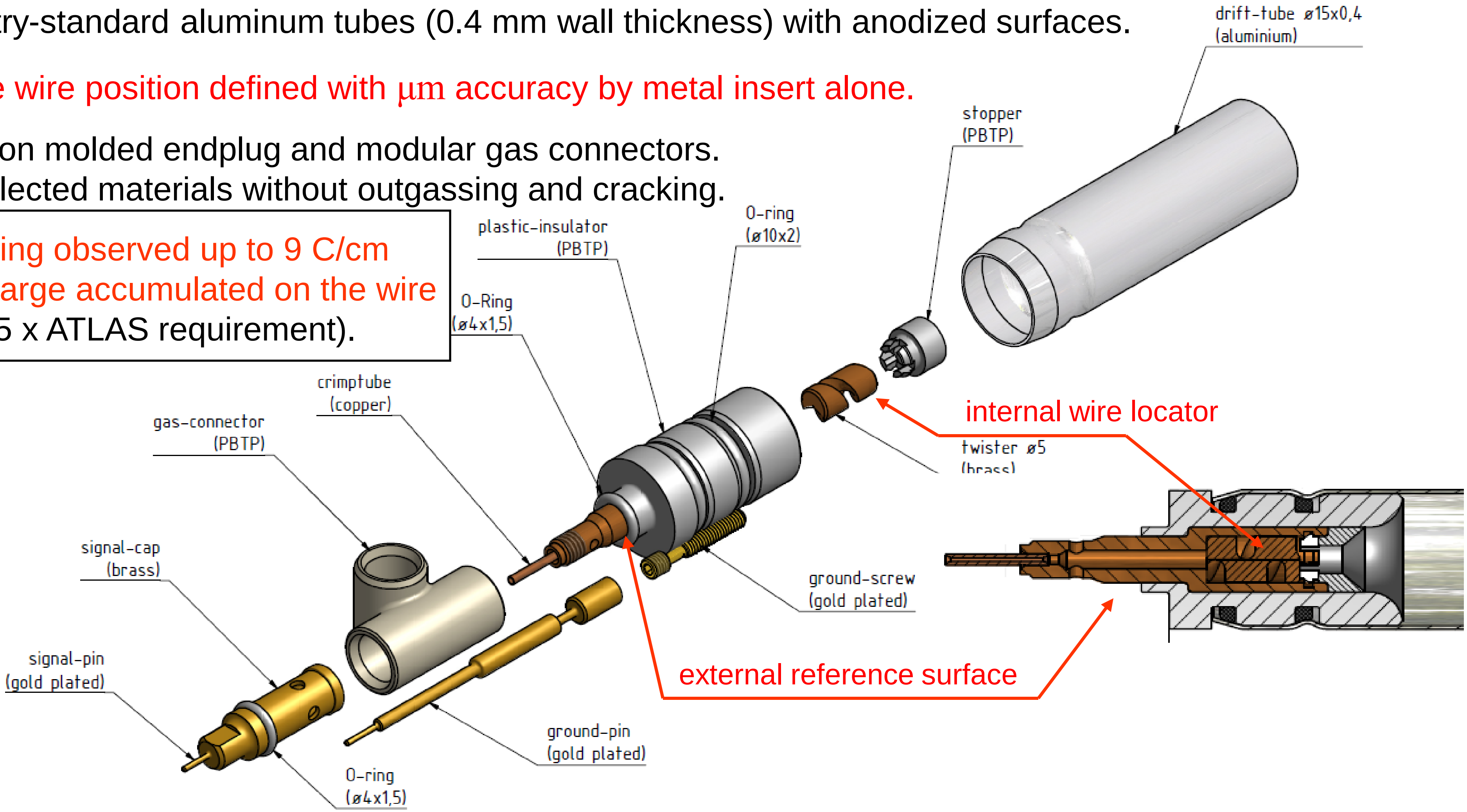




Pattern recognition, track fit, momentum reconstruction on FPGA within 1 μs.
Continuous readout.

sMDT Drift Tube 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 Facility

sMDT Chamber Construction


Precision assembly setup


Assembly hall at MPI


Drift tube positioning jig

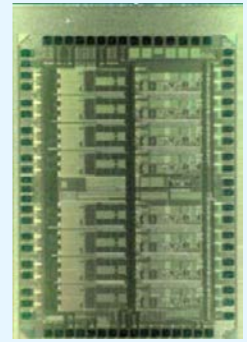

Automated glue dispenser

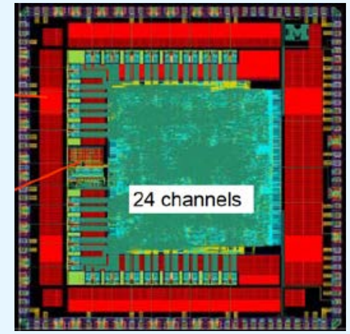

Storage and integration area at CERN

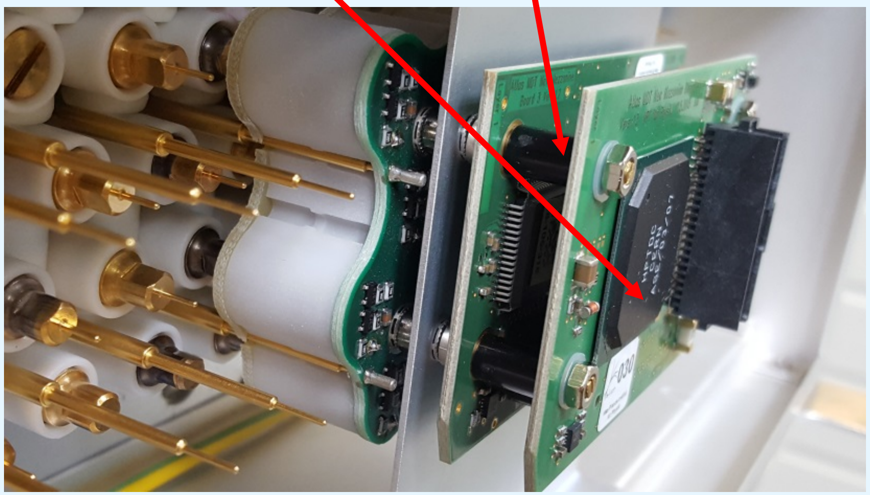
sMDT Readout Electronics

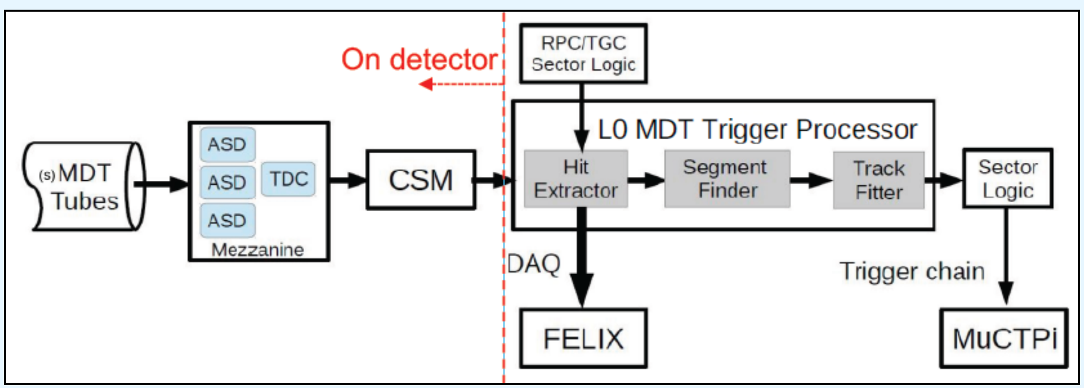
Signal distribution and readout boards (24 channels)

with three 8-channel ASD chips in 130 nm GF CMOS
and a TDC chip in 130 nm TSMC CMOS.

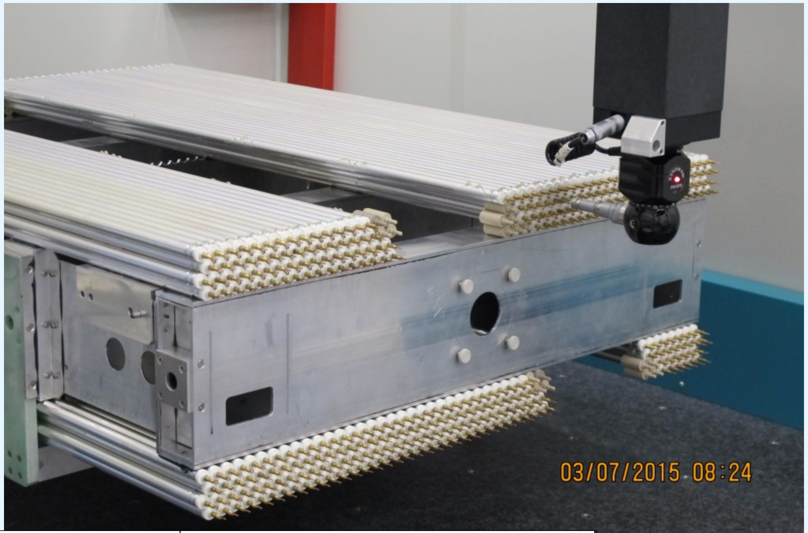


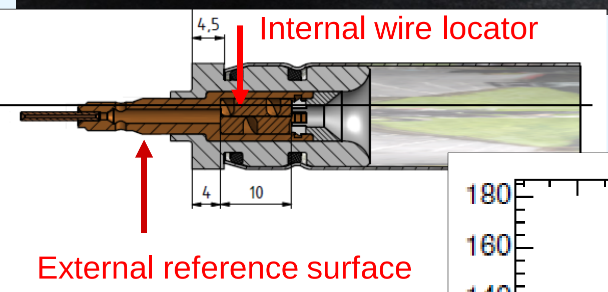


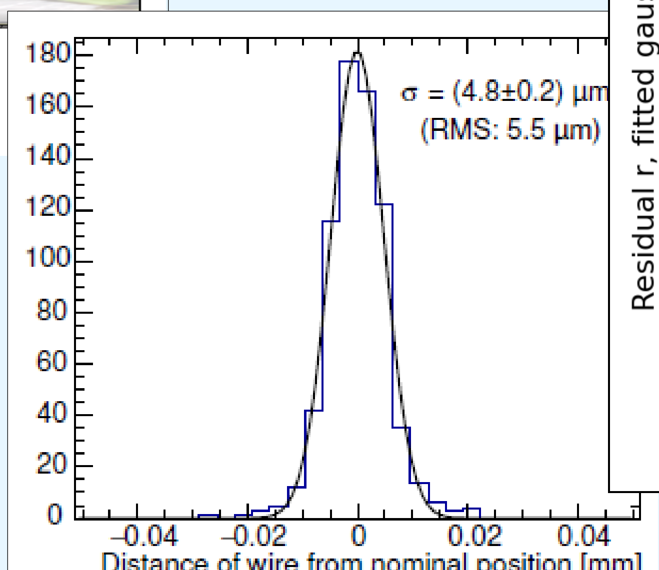




Mechanical Wire Position Measurement



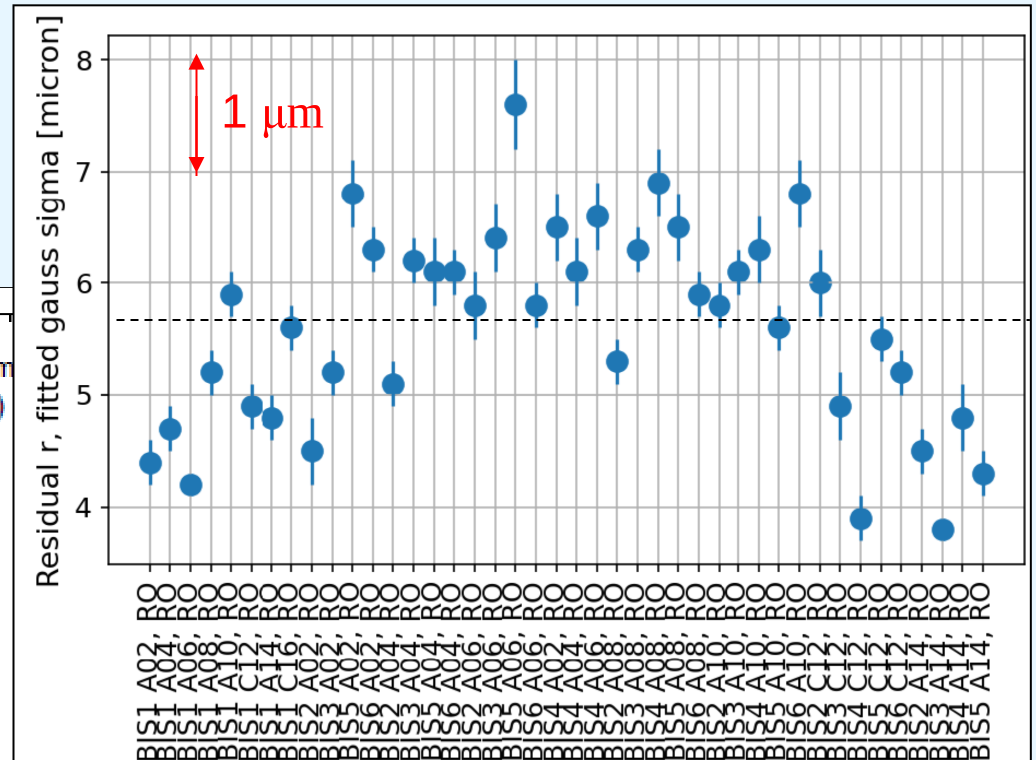




Measurement of individual sense wire positions with automated 3D coordinate measuring machine.

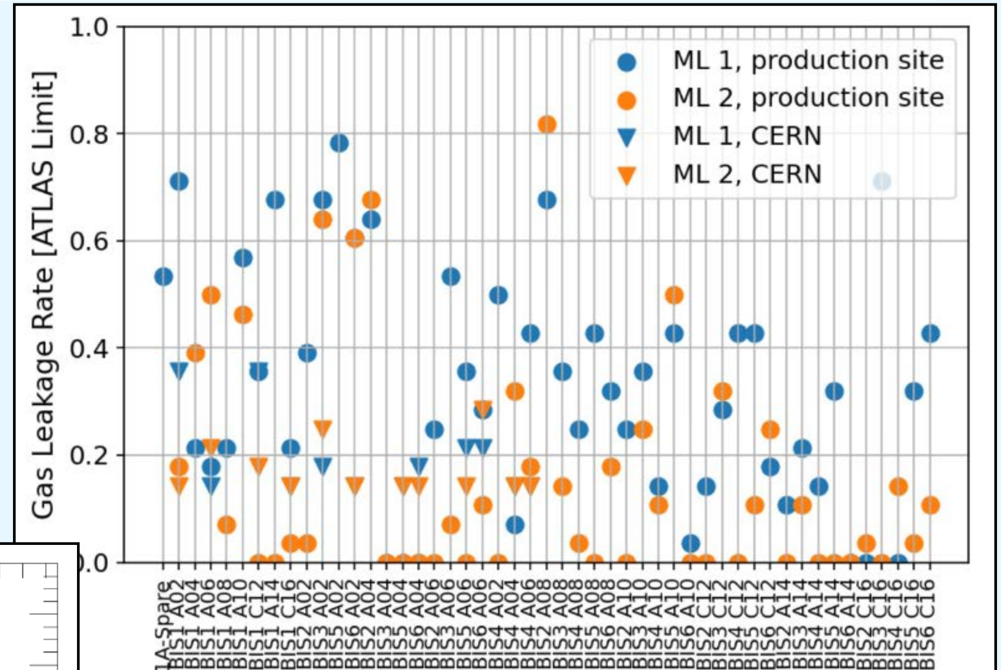
⇒ Wire positioning accuracy of 5 µm achieved.

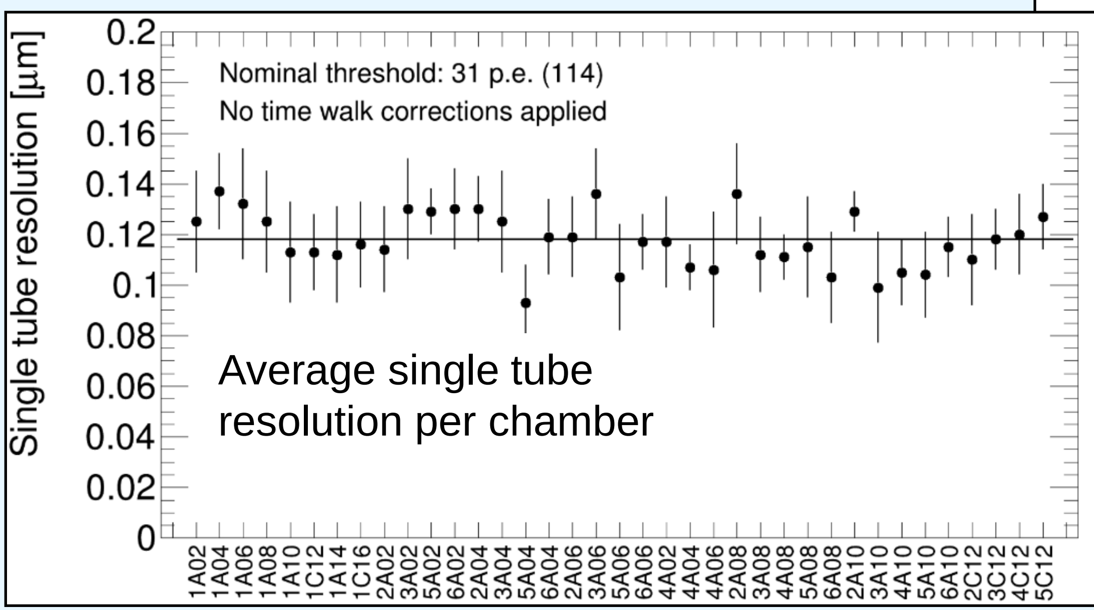
sMDT chamber production for ATLAS Phase 2 completed (48 chambers)



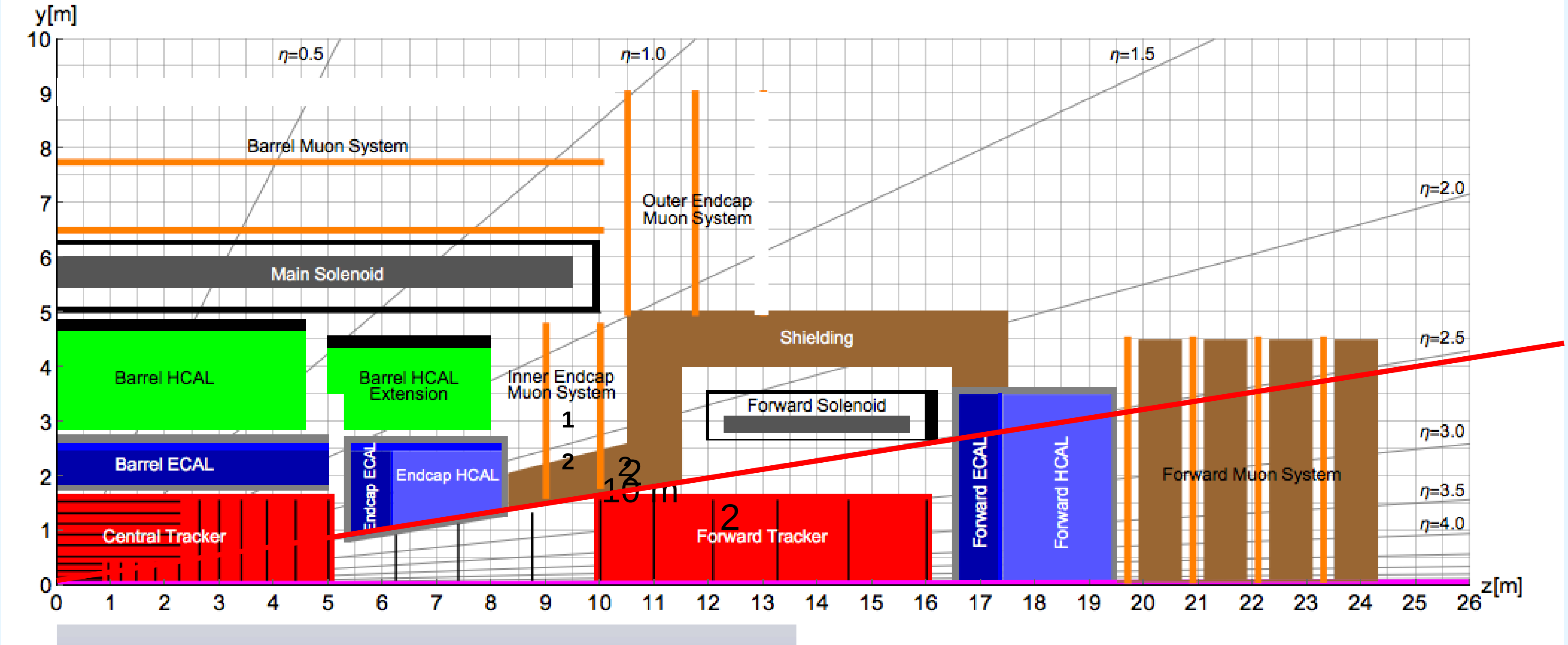
Chamber Performance in Mass Production

48 chambers constructed in the last two years, 2 working weeks per chamber





FCC-hh Reference Detector Layout



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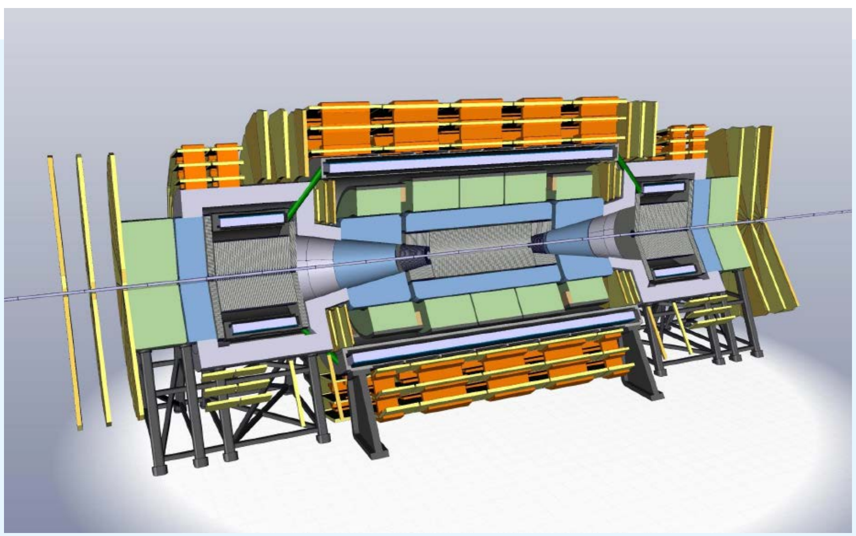


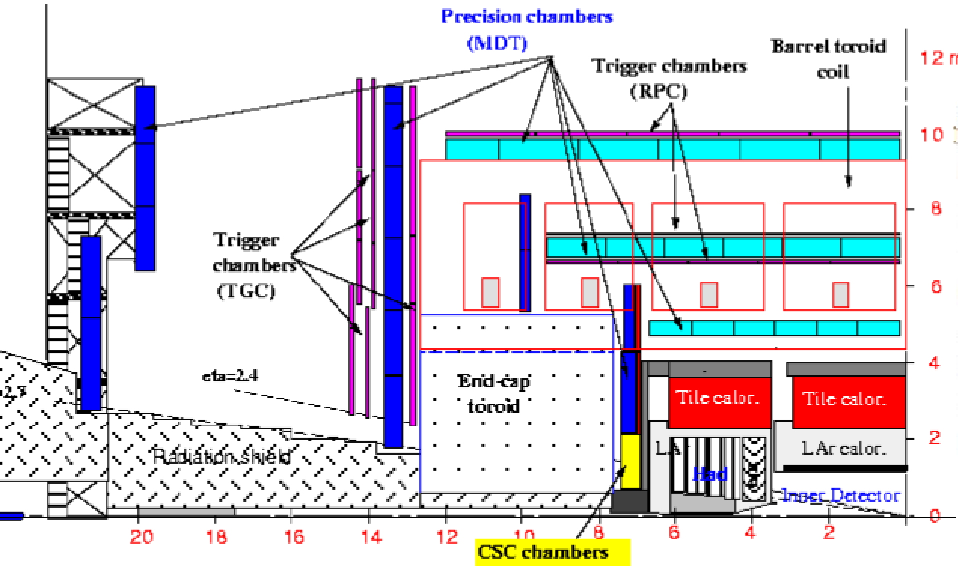
Conceptual Design Report 2018

Large solenoid surrounding central inner tracker and calorimeters.

Muon detectors outside.

Muon Detector Concepts

ATLAS



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

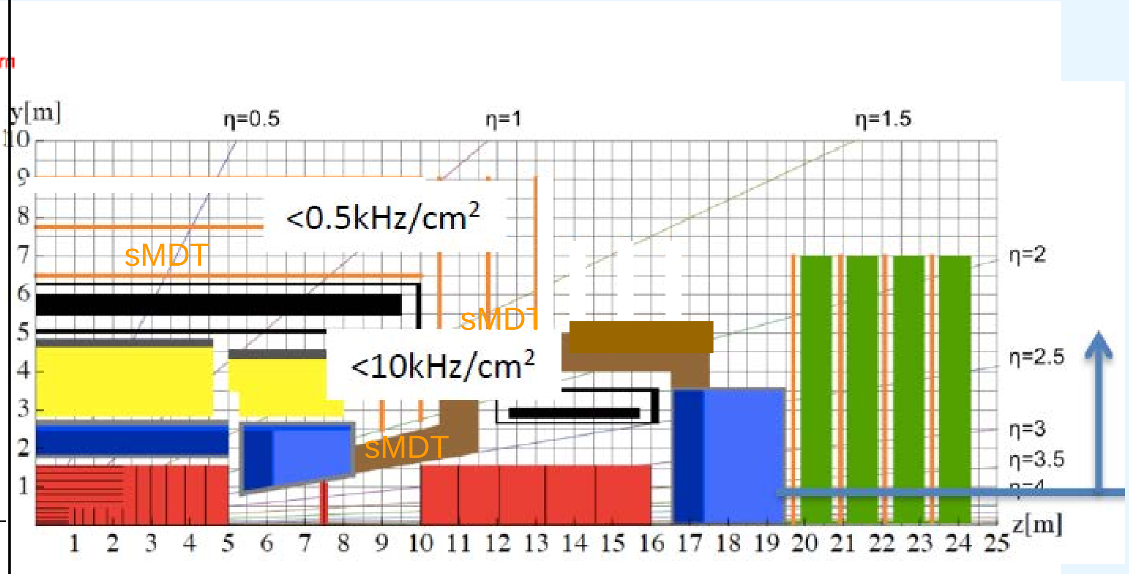
Standalone magnetic muon spectrometer.

5000 m² precision tracking area.

1200 MDT chambers with 350k channels.

Optical alignment monitoring system necessary.

FCC-hh reference detector layout



Barrel and endcaps up to |η| = 1.9:
background rates at max. FCC-hh luminosity not much higher than in ATLAS EI at HI-LHC.

Precision muon tracking (together with ID) and standalone triggering with monolithic 2-multilayer sMDT chambers up to |η| = 2.5 without point/angle measurement.

1000 m² precision tracking area.

200 chambers with 130k channels.

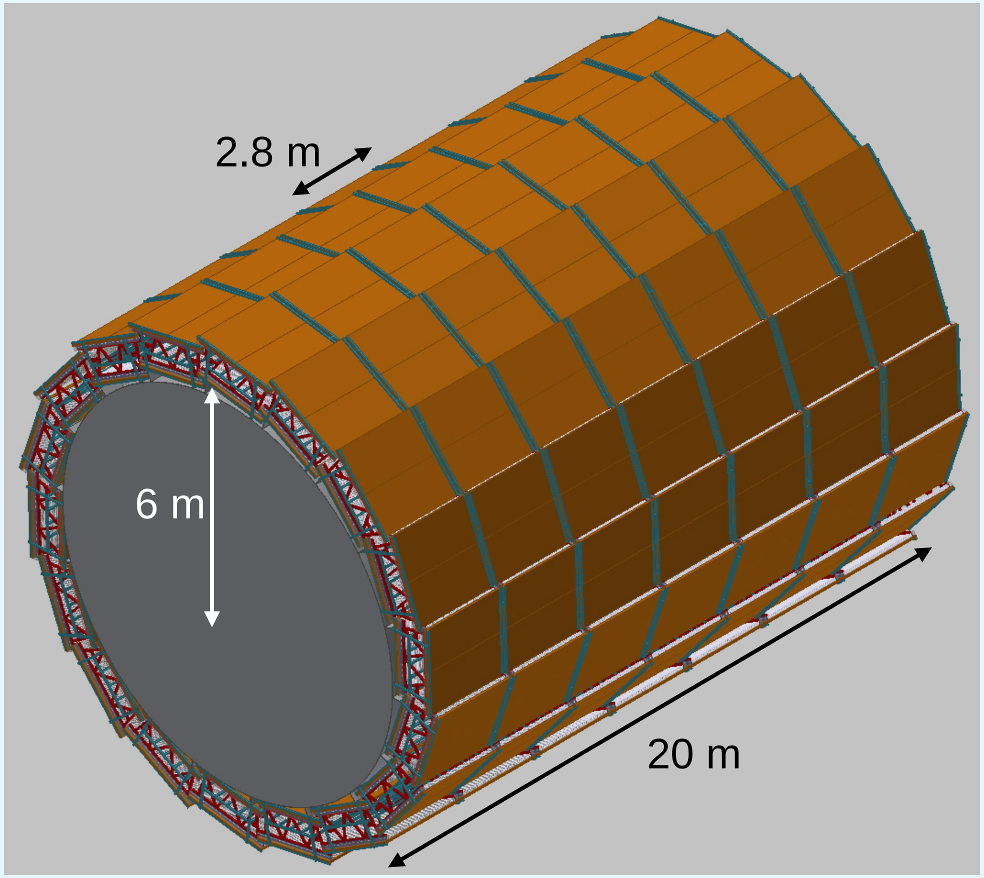
Optical alignment system not needed.

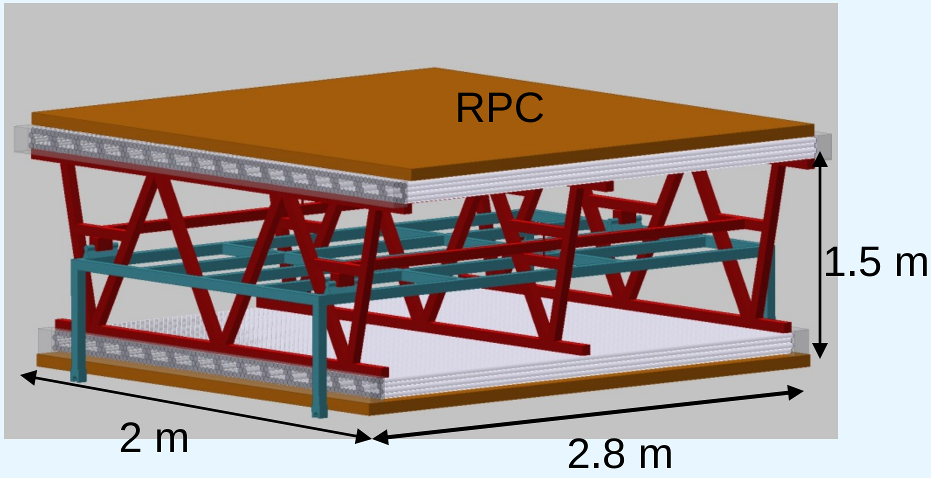
sMDT Chambers as FCC-hh Precision Muon Trigger Chambers

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, close to 100% efficiency.





sMDT track angle trigger with continuous readout.

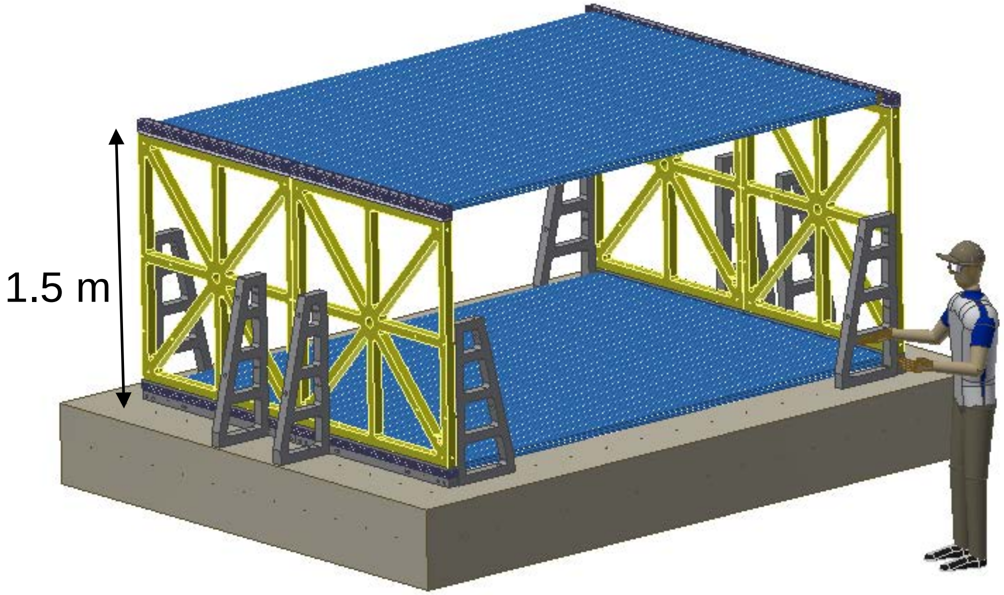
RPCs for BCID, coarse 2nd coordinate measurement, seeds for pattern recognition.

R&D on seedless sMDT trigger and BCID. 2nd coordinate measurement by double-sided sMDT readout with signal propagation time measurement.

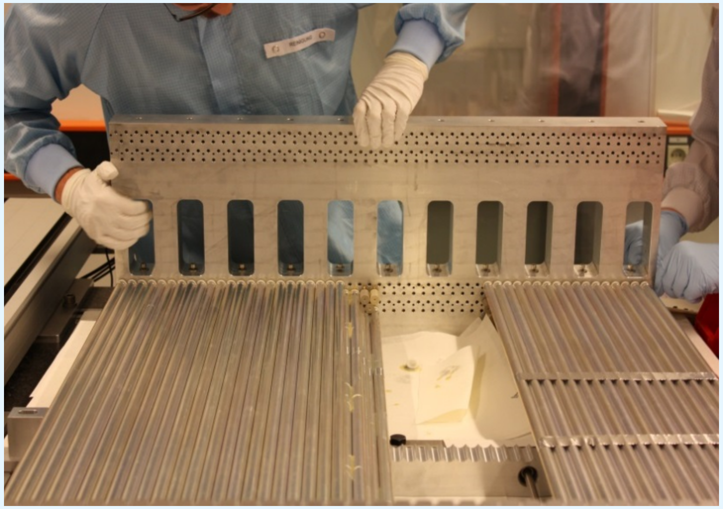
sMDT Development and Prototyping for Future Colliders

Automatisation of drift-tube production.

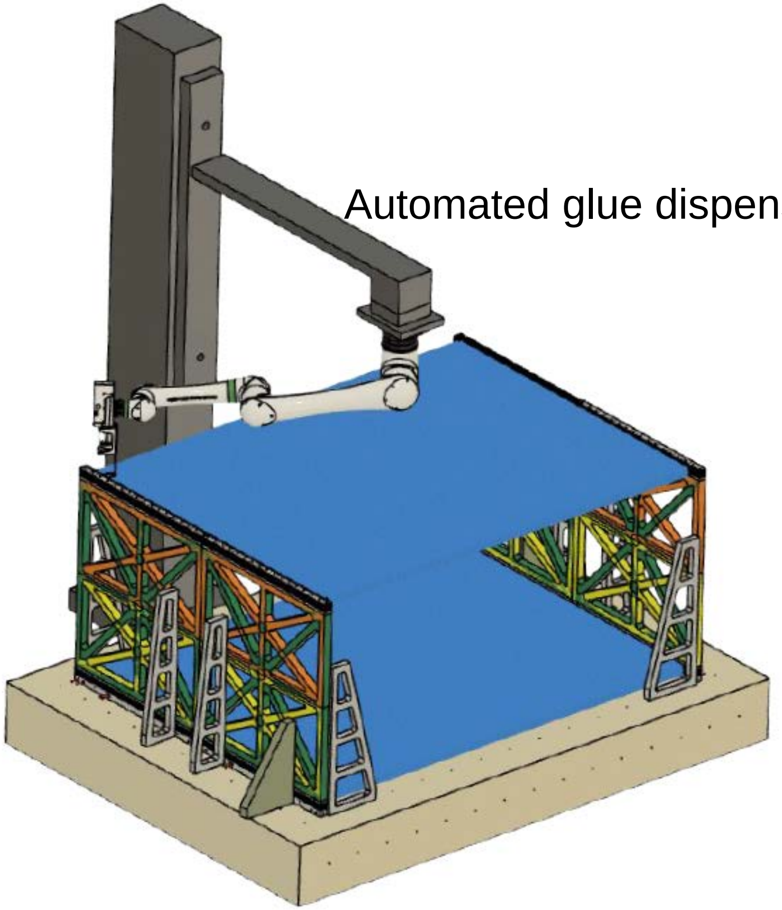
Transfer to industry; like for RPC production.



Precison assembly jigging



Automated glue dispenser



Summary

sMDT precison muon tracking detectors also used for high momentum-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 measurement.

Seedless sMDT trigger and BCID under development.

→ Large area precision muon detector and 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.