Performance of small-diameter Muon Drift Tube chambers with new fast readout ASIC at high background rates

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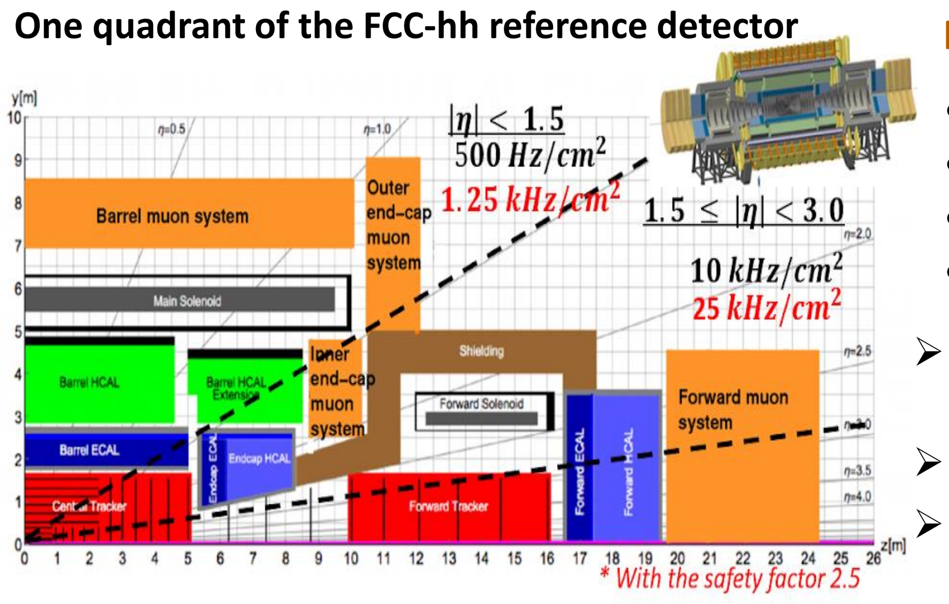
1. High background rates at Future Circular Hadron Collider (FCC-hh)

One quadrant of the FCC-hh reference detector



FCC-hh Muon system will consist of 4 parts:

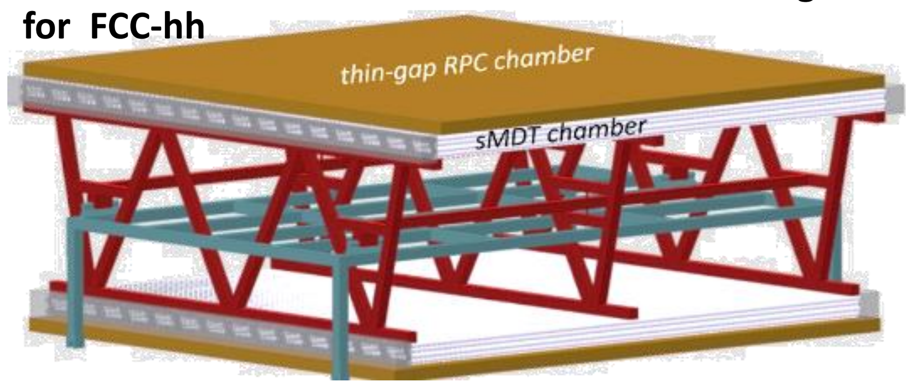
- $|\eta| < 1.0$: barrel;
- $1.0 \le |\eta| < 1.5$: outer endcap;
- $1.5 \le |\eta| < 2.2$: inner endcap;
- $2.2 \le |\eta| < 3.0$: forward

➢ Muon System will have to provide a muon trigger.

➢ Deflection angle α measurement of muon p_T.

➢ An angular resolution of 70 µrad is required for a high momentum resolution up to p_T = 1 TeV.

Small-diameter Muon Drift Tube chamber design for FCC-hh

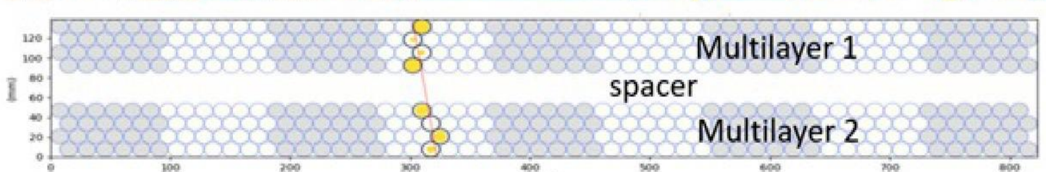


sMDT chambers with 2 x 4 layers of 15 mm diamater drift tubes at 1.5 m multilayer distance provide the required angular resolution.

The use of sMDT technology in the FCC-hh maintains high spatial resolution despite high background rates.

2. New small Drift Tube Detector (sMDT) Technology

96 sMDT chambers have already been constructed for the HL-LHC upgrade of the ATLAS Muon Spectrometer.



Properties	New sMDT
Tube diameter, Wall thickness	15 mm, 400 µm
Anode wire diameter	50 µm
Number of tube layers	8
Operating Gas Mixture	$Ar: CO_2$ (93:7)
Operating Pressure	3 bar
Operating HV working point	2730 V
Gas gain	2×10^4
Max. Drift time	~ 175 ns
Single tube Space resolution at 500 Hz/cm² background rate	110± 2 µm

Advantages of the sMDT chambers:

- ✓ High reliability and robustness.
- ✓ Cost-effective way solution for precise track point.
- ✓ Angle measurement over large areas (~1200 m²).

➢ High mechanical accuracy (~5 µm sense wire positioning accuracy).

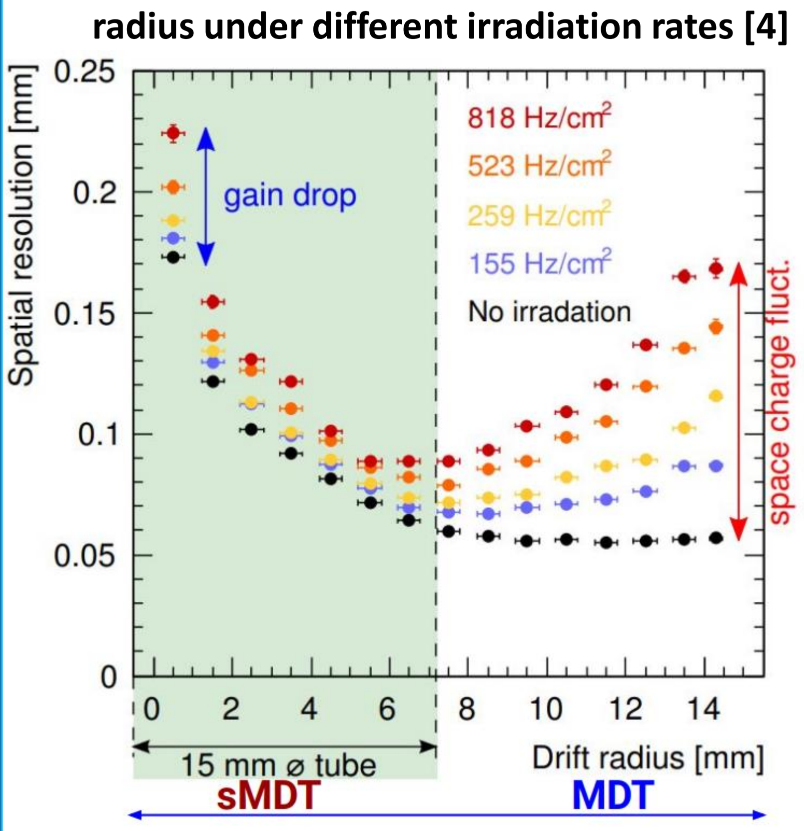
➢ Spatial resolution (< 40 µm) over large areas.

➢ 10 times high-rate capability.

➢ No aging effect observed with $Ar: CO_2$ (93:7) drift gas at 3 bar up to 9 C/cm charge accumulation on wire.

3. High Rate Performance of sMDT Chambers

Spatial resolution dependence on drift radius under different irradiation rates [4]



➢ Development of space charge under irradiation

➢ Gain drop ∝ r³

➢ Shielding of wire potential causes lower gas amplification at lower radii

➢ Space charge fluctuations cause deterioration of spatial resolution at large radii

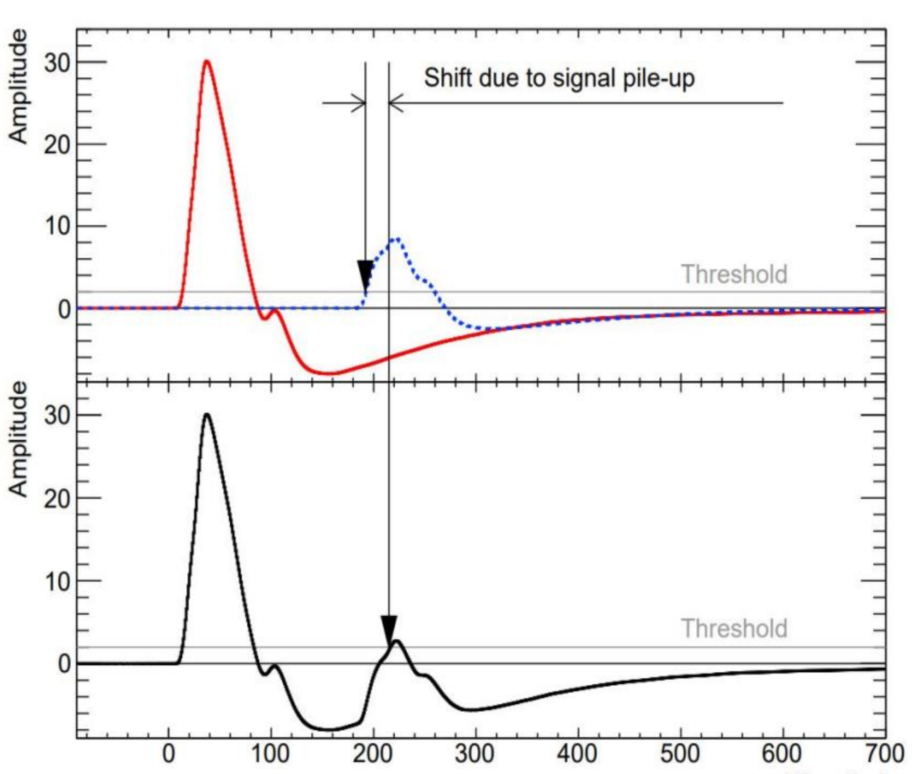
➢ sMDT chambers have demonstrated the capability to operate at rates up to 30 kHz / cm²

➢ Expected max. rates at HL-LHC in the BIS sector is 300 Hz / cm²

➢ Expected max. rates in barrel and outer region of FCC-hh is 1.25 kHz / cm²

4. Limitations of Readout Electronics

Effect of pile up under conditions of high rates due to bipolar shaping [4]



Current Readout Electronics

➢ Used in ATLAS

➢ *130 nm CMOS technology*

➢ Peak time of 15 ns with bipolar shaping

➢ Dead time of the electronics masks muon hits, reducing muon detection efficiency at high rates

➢ Signal pile up effect of muon hit following a background hit

Improvements

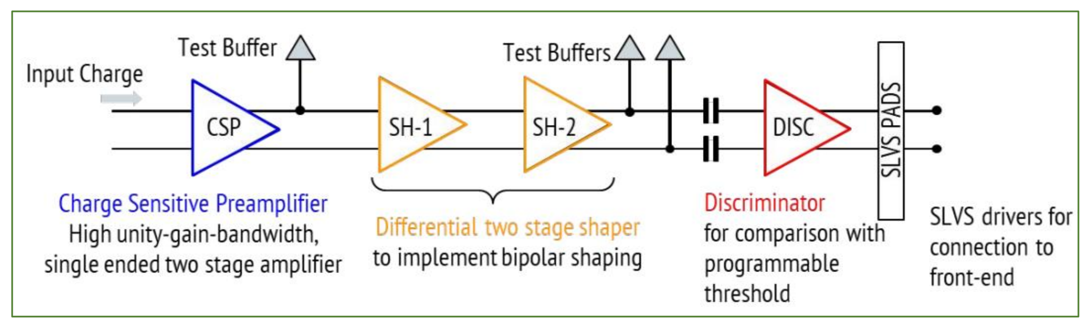
➢ *New 65 nm CMOS technology*

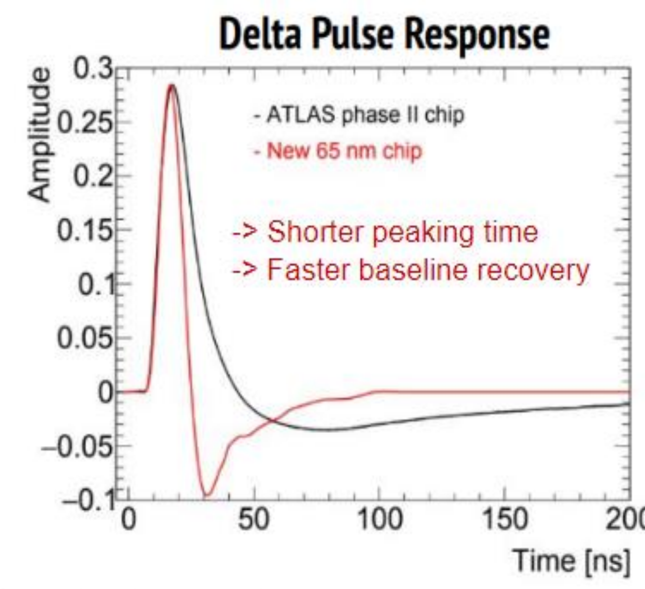
➢ Faster baseline recovery of the bipolar shaping scheme to reduce pile up

➢ Meant to handle FCC expected rates

5. New 65 nm ASD Chip

Four channels Amplifier/Shaper/Discriminator (ASD) fabricated in 65 nm TSMC CMOS technology developed by Max Planck Institute for Physics (Munich).





➢ Bipolar shaping selected to reduce effects of baseline shift at high signal rates.

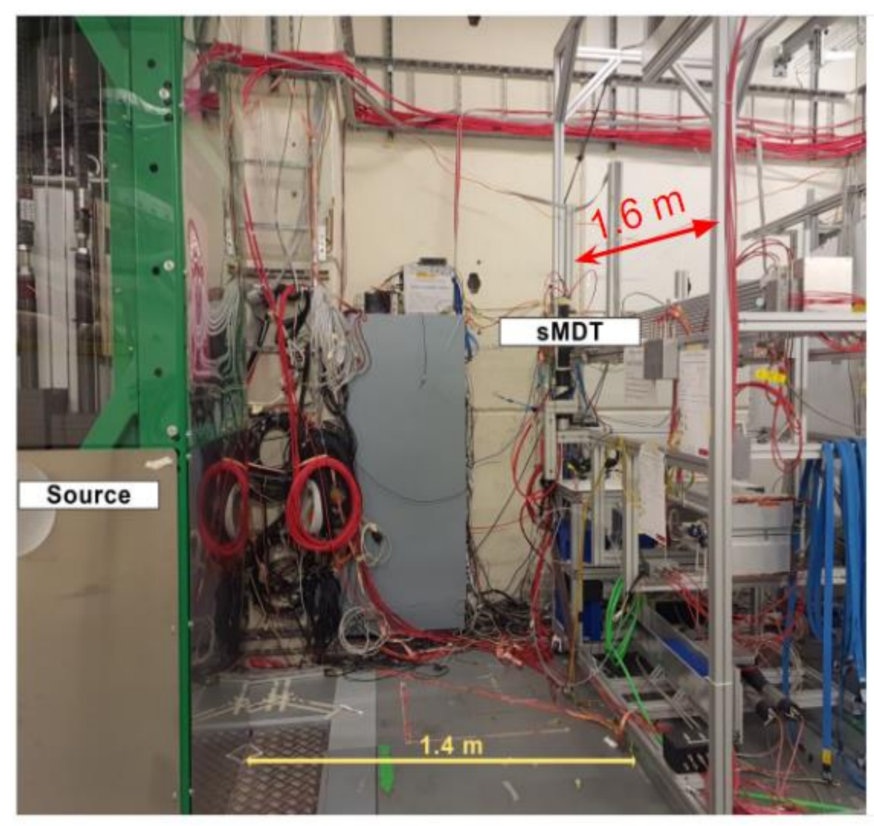
➢ Output available as low voltage differential signal and digital CMOS level signal.

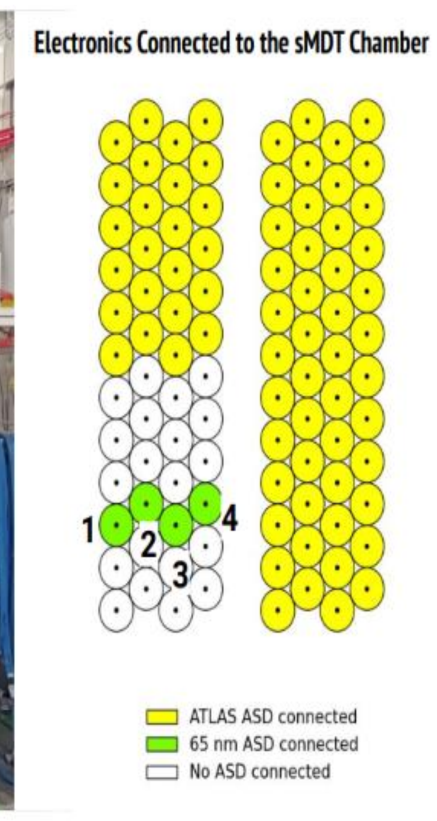
➢ Power consumption per channel 12.8 mW (61.2 % lower than for the current ATLAS ASD chip for HL-LHC phase II) and each channel occupies 0.235 mm² (43% of current ATLAS ASD chip area).

Note: *The current ATLAS ASD chip was developed at the Max Planck Institute (Munich) for the HL-LHC Phase-II Upgrade of the ATLAS Muon Spectrometer.*

6. sMDT Setup at CERN Gamma Irradiation Facility (GIF++)

The new ASD chips were tested on a sMDT chamber with 1.6 m long in CERN's Gamma Irradiation Facility (GIF++).





Setup description:

➢ One 65 nm ASD on prototype board connected to four tubes.

➢ Rest of the tubes equipped with ATLAS ASD for comparison.

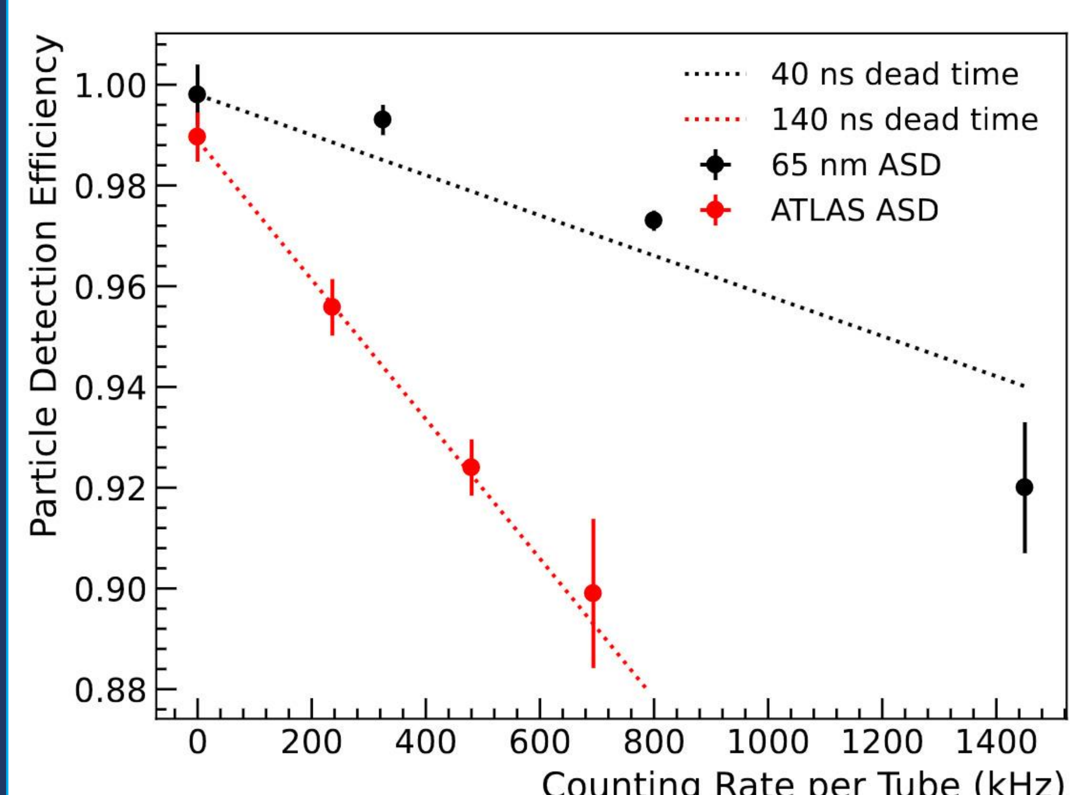
➢ Coincidence of GIF++ scintillators used as trigger.

sMDT operating condition:

➢ Gas mixture: $Ar: CO_2$ (93:7)

➢ Operating working point: **2730 V** (G = 2 x 10⁴)

7. Spatial resolution and muon detection efficiency as a function of the γ background rate



➢ Detection efficiency at zero background rates is 99%.

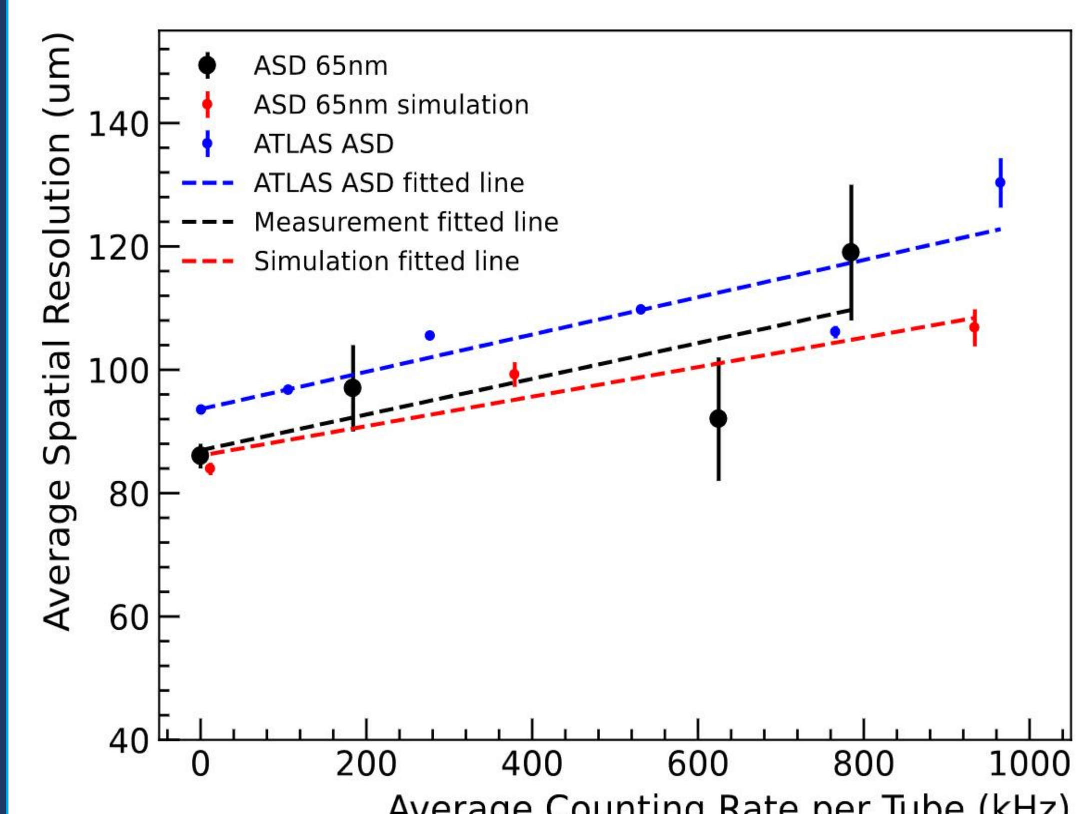
➢ Indicative of the dead time of the electronics

$$\epsilon = \epsilon_0(1 - n \cdot t_{dead})$$

where n = counting rate

➢ Translates to approximately 40 ns of electronic dead time.

➢ More than three times lower than for the current ATLAS ASD chip.



➢ No time walk correction applied.

➢ Resolution of 65 nm ASD chip better than the ATLAS ASD by about 10 µm.

➢ 1 MHz / tube of counting rate for this 1.6 m length of tubes corresponds to around 4 kHz/cm²

➢ Resolution of around 110 µm expected at 1 MHz / tube counting rate.

[1] M. Benedikt et al., FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3.
[2] O. Kortner et al., Design of the FCC-hh muon detector and trigger system, https://doi.org/10.1016/j.nima.2018.10.013
[3] H. Kroha et al., Design and construction of integrated small-diameter drift tube and thin-gap resistive plate chambers for the phase-1 upgrade of the ATLAS muon spectrometer, https://doi.org/10.1016/j.nima.2018.10.139
[4] B. Bittner et al., "Performance of Drift-Tube Detectors at High Counting Rates for High-Luminosity LHC Upgrades", Nucl. Instrum. Methods Phys. Res., A 732 (2013), 250–254
[5] N. Bangaru Design and Testing of Gaseous Detectors and Their Readout Electronics for Particle Detection at High Counting Rates, (2024), Masters thesis, CERN-THESIS-2024-048, https://cds.cern.ch/record/2896934?ln=en