Rate capability of small-diameter Muon Drift Tube precision tracking chambers with new fast readout electronics for HL-LHC and Future Hadron Colliders

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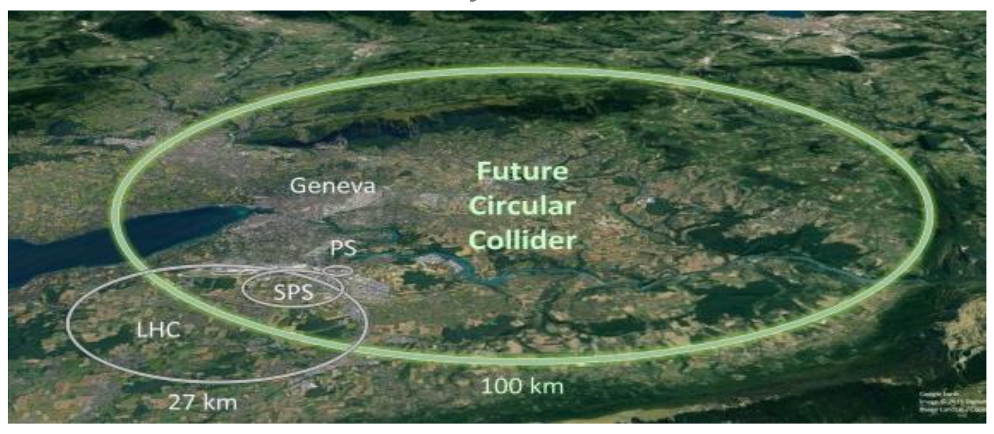
1. New Future Circular Hadron Collider (FCC-hh) Experiments

Possible location for the FCC-hh



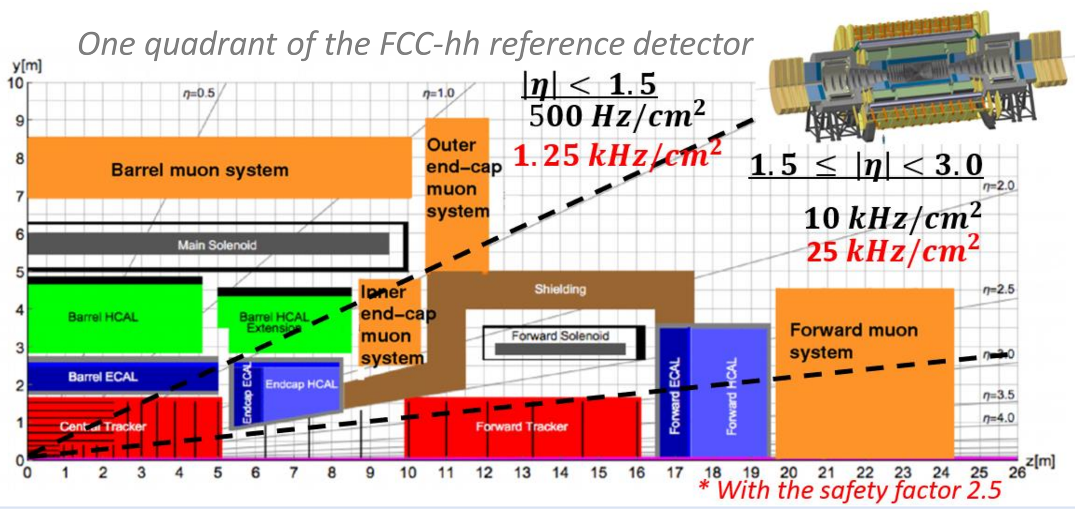
The Future Circular Collider (FCC) study is developing designs for a new research infrastructure to host the next generation of higher performance particle colliders to extend the research currently being conducted at the LHC, once the High-Luminosity phase (HL-LHC) reaches its conclusion in 2040 [1].

- **Probing of Higgs-Boson properties, searches for physics beyond the Standard Model**
- **$100\ km$ circumference with $16\ T$ dipole magnets**
- **Instantaneous luminosities: $30 \times 10^{34}\ cm^{-2}s^{-1}$**
- **Integrated luminosity: $20\ ab^{-1}$**
- **Center-of-mass energy: $\sqrt{s} = 100\ TeV$.**

A muon system will surround the solenoid. It will consist of four 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.

One quadrant of the FCC-hh reference detector

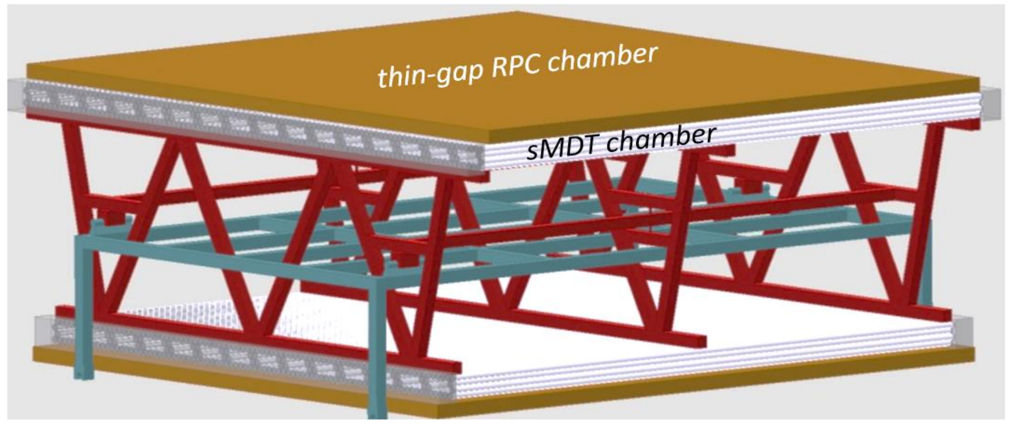


*With the safety factor 2.5

- **The Muon System will have to provide a muon trigger.**
- **Deflection angle α measurement of muon p_T.**
- **An angular resolution of $70\ \mu rad$ is required for a high momentum resolution up to $p_T = 1\ TeV$.**

2. Precision sMDT chambers for FCC-hh Muon System

An angular resolution of $70\ \mu rad$ can be achieved with small-diameter Monitored Drift-Tube chambers, so-called "sMDT chambers". The muon detectors will be exposed to a large background of neutrons and γ rays, which will lead to counting rates of up to $500\ Hz \times cm^{-2}$ in the barrel and the outer end-cap muon system and up to $10\ kHz \times cm^{-2}$ in the inner endcap and forward muon system. sMDT chambers can be operated at counting rates of up to $30\ kHz \times cm^{-2}$ and background occupancies of up to 30% [2].



2×4 layers of $15\ mm$ diameter drift tubes at $1.5\ m$ multilayer distance provide the required angular resolution.

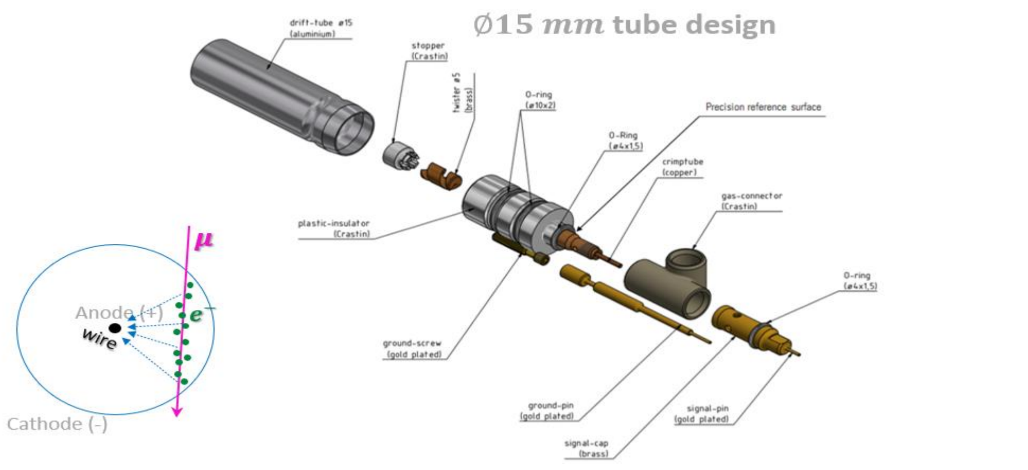
Advantages of the sMDT chambers:

- **The small–diameter MDT detector technology developed for the upgrade of the ATLAS detector can operate in an environment up to $\sim 30\ kHz/cm^2$.**
- **High reliability and robustness.**
- **Cost-effective way solution for precise track point.**
- **Angle measurement over large areas (about $\sim 1200\ m^2$).**
- **Can achieve resolution of better than $50\ \mu rad$ and $70\ \mu rad$.**

Main Goal is to achieve the required angular resolution of $70\ \mu rad$ with an sMDT chamber with two quadruple layers at $1.5\ m$ distance, the single tube resolution must not exceed 150 µm.

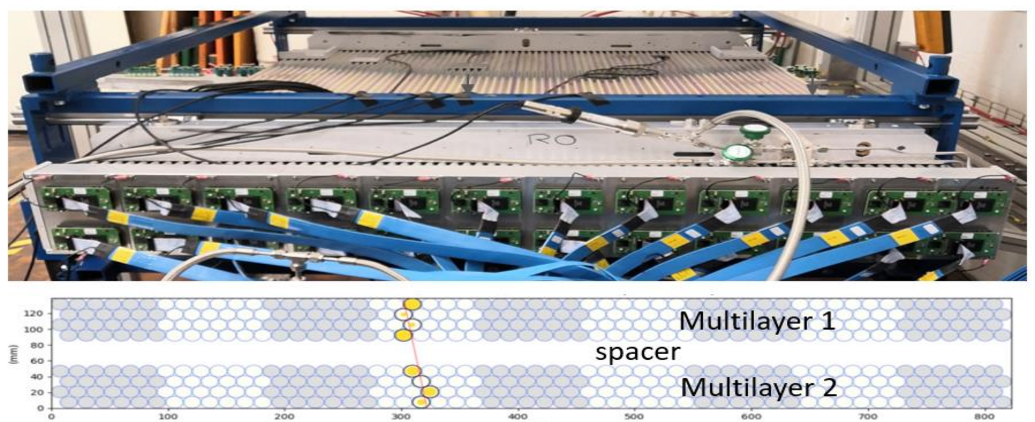
3. New small Drift Tube Detector Technology

$\varnothing 15\ mm$ tube design



New sMDT for the ATLAS Muon System upgrade

Properties	New sMDT
Tube diameter, Wall thickness	$15\ mm$, $400\ \mu m$
Anode wire diameter	$50\ \mu m$
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	$\sim 175\ ns$
Single tube Space resolution at 500 Hz/cm² background rate	$110 \pm 2\ \mu m$



- **Faster Max. Drift times $\sim 175\ ns$.**
- **High mechanical accuracy ($\sim 5\ \mu m$ sense wire positioning accuracy).**
- **Spatial resolution ($< 40\ \mu m$) over large areas.**
- **10 times high-rate capability.**
- **Aging effect measured and didn't observe with $Ar:CO_2$ (93:7) drift gas at 3 bar up to $9\ C/cm$ charge accumulation on wire.**

New sMDT stations already installed in the ATLAS Muon System during LS2 2019-2022

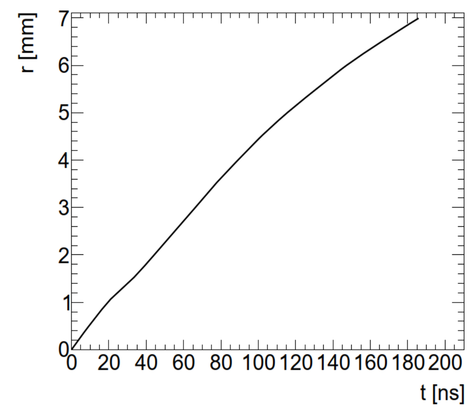
Design, materials and construction method optimised for large scale production. It allows for high-precision monolithic two-multilayer detectors for precise track angle measurement [3].

4. High-Rate Phenomena in sMDT Chambers

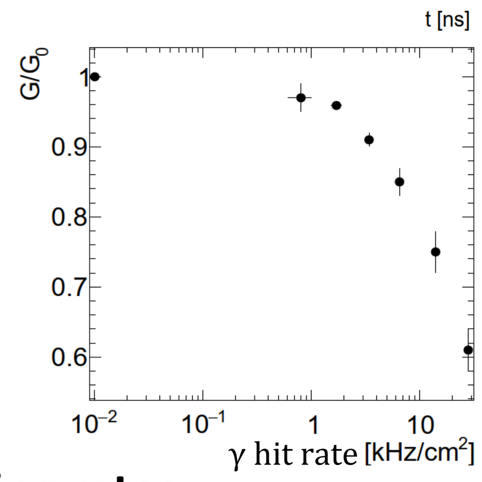
Spatial resolution and gas gain loss in drift tubes due to space charge effect

- Altered electric field inside the tube due to a constant positive space charge ρ_γ :

$$E(r) = \frac{U_0 - \frac{1 \rho_\gamma}{4 \epsilon_0} R^2}{ln \frac{R}{r_0}} \times \frac{1}{r} + \frac{1}{2} \frac{\rho_\gamma}{\epsilon_0} r$$



- Due to the linearity of the space drift-time (r-t) relationship the electron drift velocity is unaffected by the modification of the electric field.
- Only consequence of the altered $E(r)$: gas gain drop due reduced field at the anode wire.

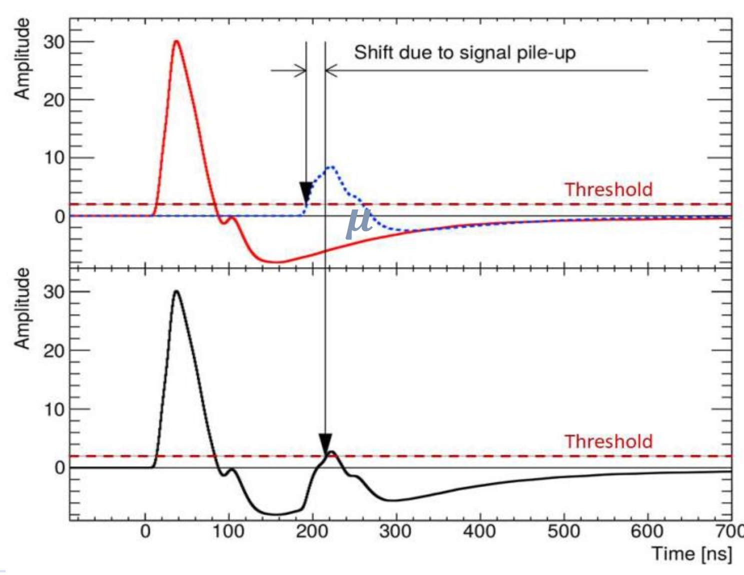


→ **Negative Results:** deterioration of the tube spatial resolution and muon detection efficiency.

→ **Solution:** need to adjust the operating voltage U_0 to compensate for the drop in the gas gain.

Standard *Diethorn formula* can be used to predict the necessary adjustment

Readout electronics signal pile-up at high counting rates



- A bipolar shaping technique is used by ATLAS sMDT in order to avoid baseline shift associated with unipolar shaping.

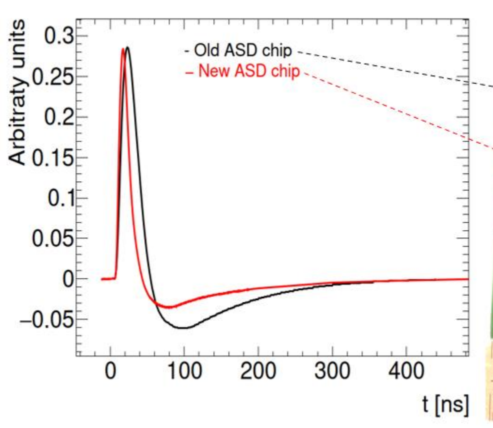
Disadvantage: the large and long undershoot of equal area after the positive signal pulse.

- Muon hits falling into the negative tail of a preceding γ hit get deteriorated leading to a degradation of the spatial resolution.

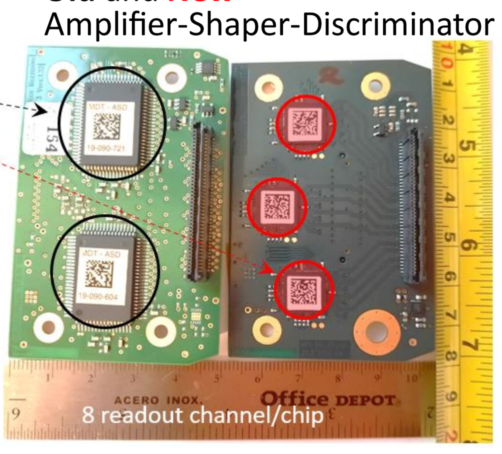
5. Improved pulse response of the new readout chip

To improve the performance of the new sMDT chambers, as well as the existing MDT detectors installed at the ATLAS muon spectrometer new readout ASD chip has been developed at the Max-Planck Institute in Munich, and used for the HL-LHC era, as well as can be used for FCC-hh experiments.

Delta pulse response



Old and **New** Amplifier-Shaper-Discriminator



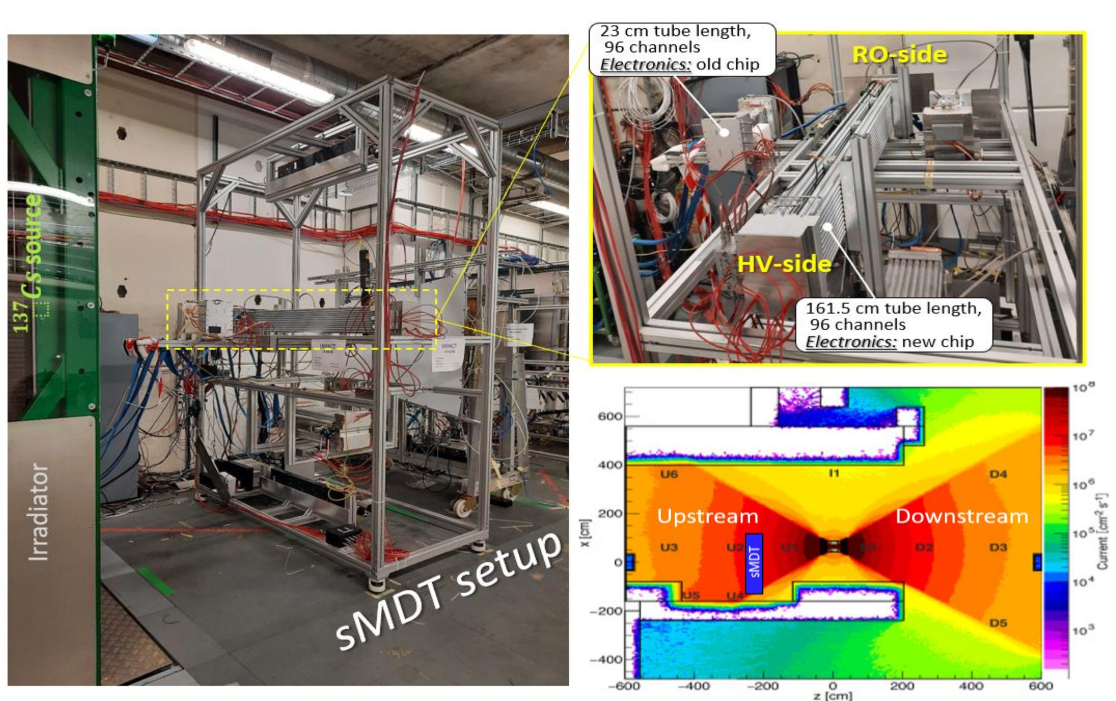
The **main advantage** is the shorter peaking time:

→ **Reducing discriminator threshold crossing time jitter.**

→ **Faster baseline recovery, reducing the signal pile-up effects at high counting rates.**

→ **Improved chip design leads to an overall noise reduction, which makes the discriminator threshold adjustment essentially unnecessary.**

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++).

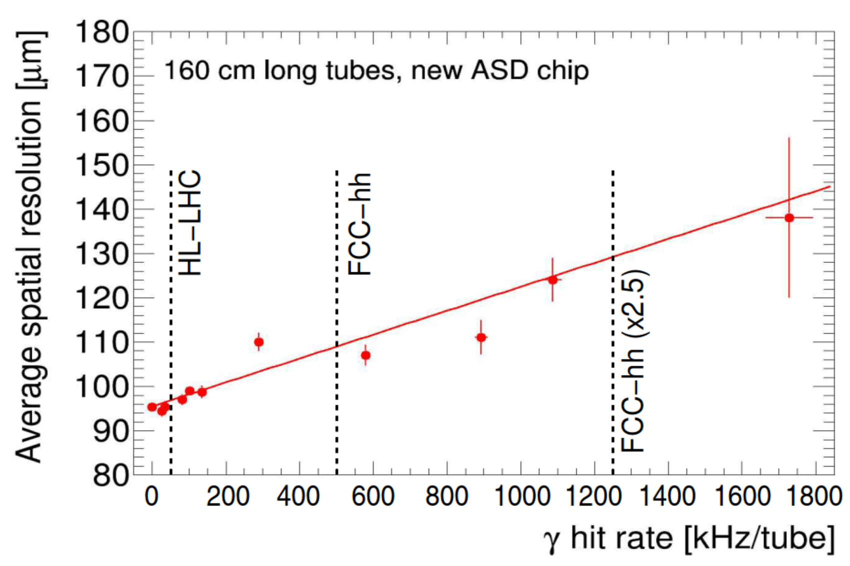
The sMDT detector under test is placed at $\sim 2.0\ m$ from the source in the upstream field:

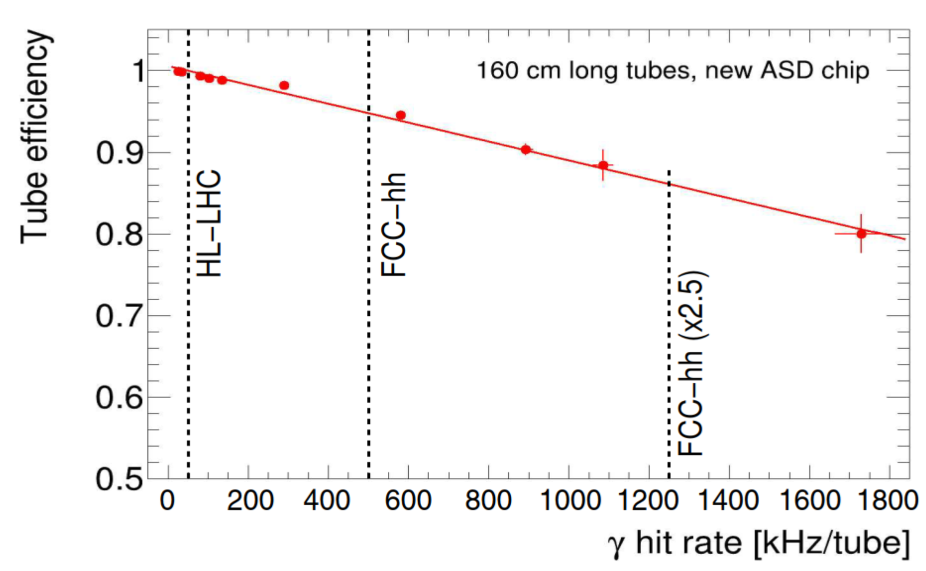
- a high-energy muon beam ($100\ GeV/c, \sim 10^4\ muon/spill$), from secondary SPS beam line H4 in EHN1.
- a gamma photons ($662\ keV$), from ^{137}Cs source with flux from 0 (source OFF) up to $\sim 10^7\ \gamma/cm^2 \cdot s$ by using different absorber (ABS) settings [4].

sMDT's operating condition:

- Gas mixture: $Ar:CO_2$ (93:7) @3 bar
- Operating working point: 2730 V ($G = 2 \times 10^4$)

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





- By using the operating voltage adjustment technique, the good spatial resolution result of $\sim 135\ \mu m$ at the highest rate of about $1.7\ MHz/tube$ has been achieved which correspond to the 30% occupancy of the sMDT detector.

→ **This result achieved thanks to the short shaping time implemented in the new ASD chip that also minimized the pile-up effect.**

- Tube muon detection efficiency of more than **80%** at the $1.7\ MHz/tube$ counting rate (30% occupancy) has been achieved.

→ **This result demonstrate that we can ensure that more 99% muon track reconstruction efficiency with 8-layer drift tube of sMDT detector.**

✓ **Small-diameter Drift Tube Detector (sMDT) technology is the ideal choice for the cost-effective instrumentation of large-area muon systems when high spatial resolution is required.**

✓ **sMDT chambers with new read-out electronics can be operated with the high spatial resolution and muon detection efficiency up to the highest background rates expected at future hadron collider experiments.**

✓ **It is still necessary to further optimize and improve the performance of the readout electronics to fully exploit the sMDT rate capability.**

[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] D. Pfeiffer et al., The radiation field in the Gamma Irradiation Facility GIF++ at CERN, https://doi.org/10.1016/j.nima.2017.05.045