High rate capabilities and performance of muon chambers

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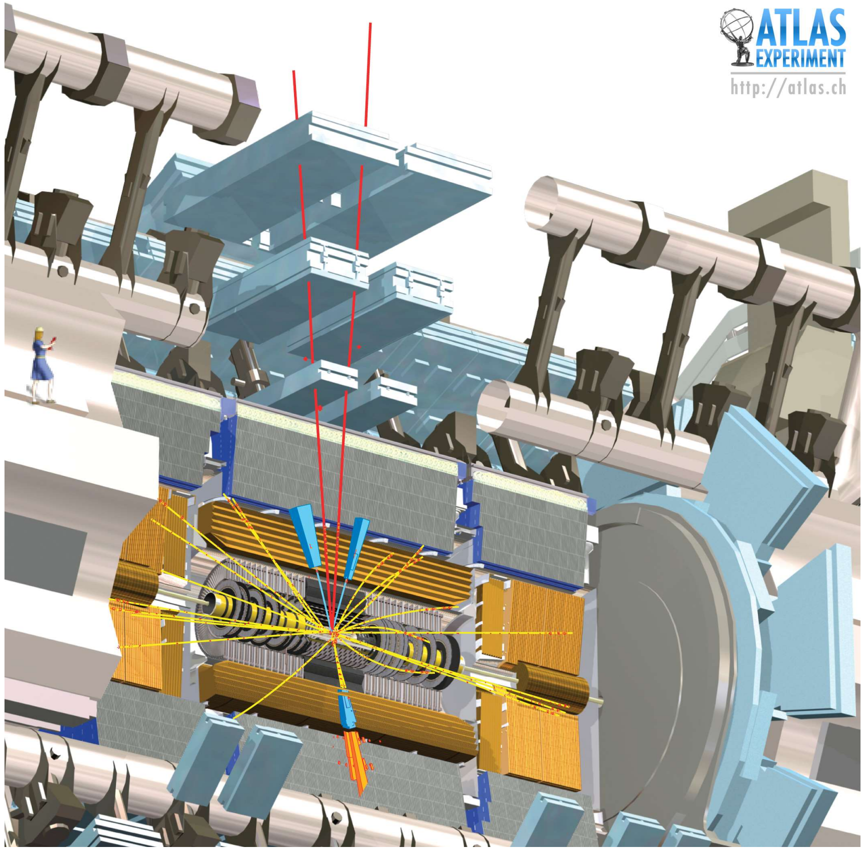
MAX-PLANCK-INSTITUT FÜR PHYSIK

Agenda

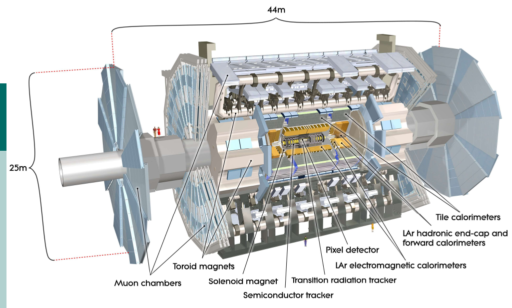
1. Detector overview and upgrade of the muon system
2. Muon chamber working principle and commissioning
3. Readout electronics signals concepts
4. Effects of background radiation on chamber performance

An overview of the ATLAS Experiment and its detector components



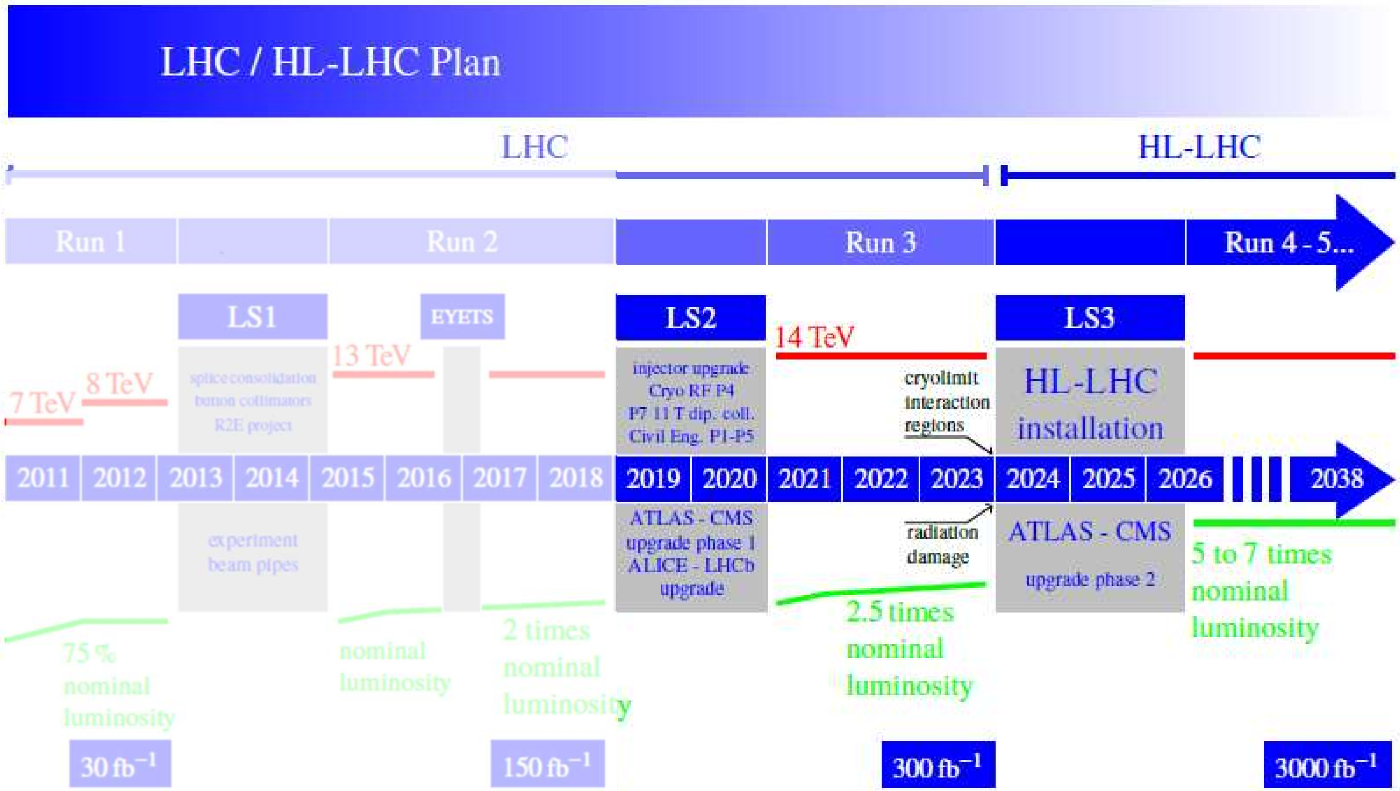
Detector components

- **Inner Detector:**
  - Pixel Detector
  - Transition radiation tracker
  - Semiconductor tracker
- **Calorimeter System:**
  - LAr electromagnetic / hadronic calorimeters
  - Tile calorimeters
- **Muon spectrometer:**
  - Cathode strip chambers
  - Monitored drift tubes
  - Resistive plate chambers
  - Thin gap chambers



Focus today:
Monitored drift tubes
(MDTs)

Upgrade Plan HL-LHC, BIS 78 upgrade project and future FCC capabilities



HL-LHC upgrade

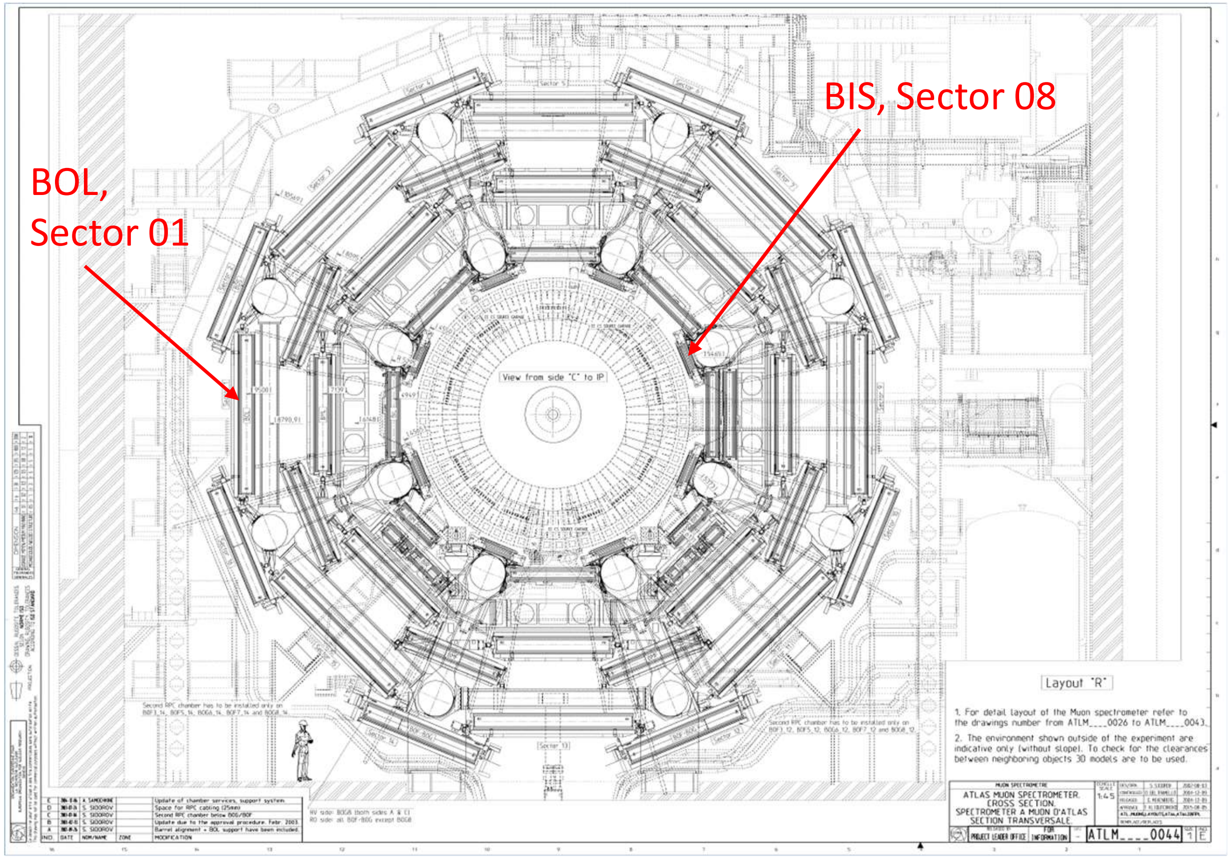
High data and radiation rates at the High Luminosity LHC call for **upgrades**

Background hit rate scales with the **instantaneous luminosity**

Ideal test for future hadron collider experiments like the **FCC** with up to **30 times LHC instantaneous luminosity**

BIS78 muon chamber pilot project currently **being installed**

Detailed cross section of the muon spectrometer and the corresponding nomenclature I



Nomenclature I

Region of the Detector:

- **B**arrel (**E**ndcap)

Layer:

- **I**nner, **M**iddle, **O**uter

Size:

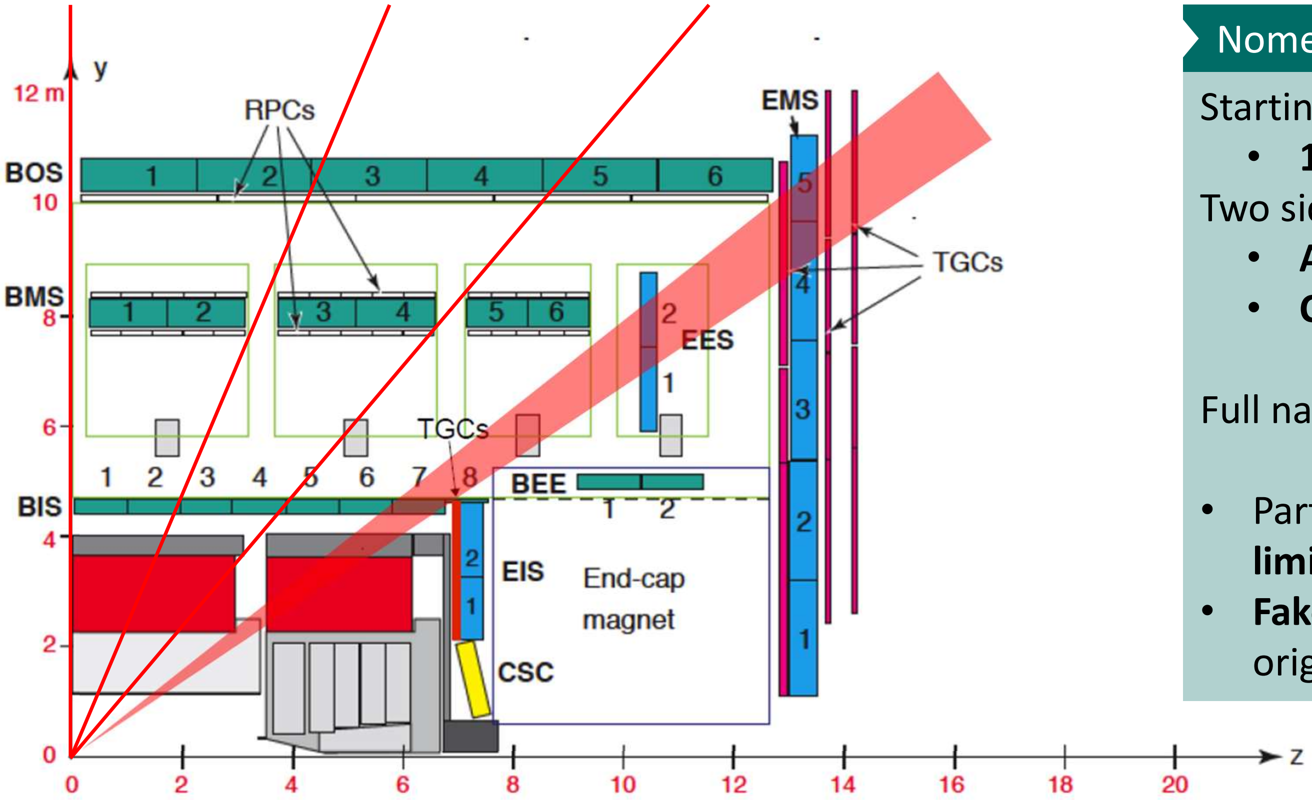
- **L**arge, **S**mall

Sectors:

- **1-16**, starting at 09:00 here

Additional names for chambers in special parts of the detector (e.g. Bottom Regions)

Detailed cross section of the muon spectrometer and the corresponding nomenclature II, muon triggers



Nomenclature II, limited muon trigger

Starting from the interaction point:

- **1-6** (8), outwards

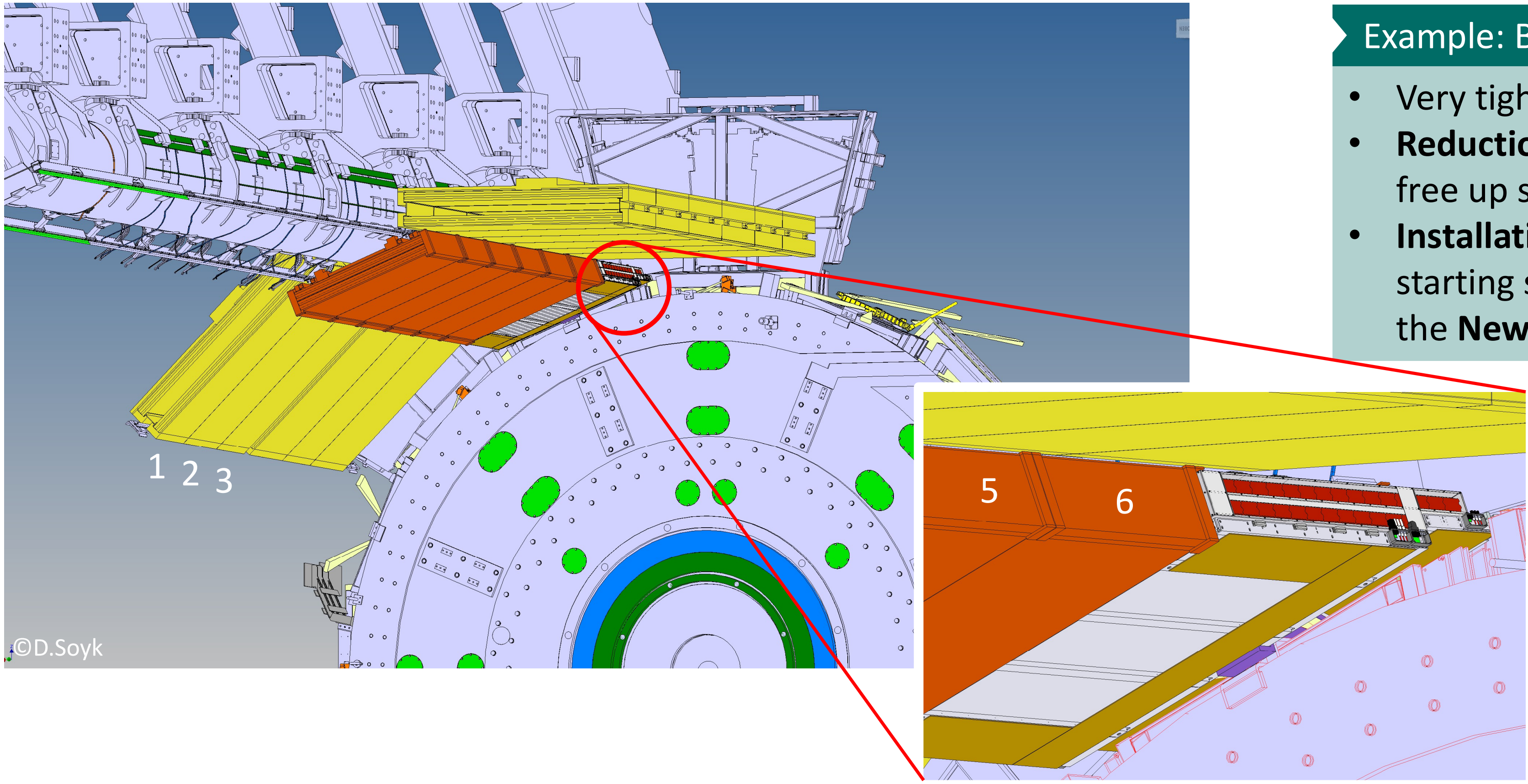
Two sides:

- **A** (Airport)
- **C** (Charlies Pub)

Full name example: **BIS6 A04, BIS78 A04**

- Partially instrumented regions lead to **limited muon trigger acceptance**
- **Fake triggers** from charged particles not originating from IP, reduction with BIS RPCs

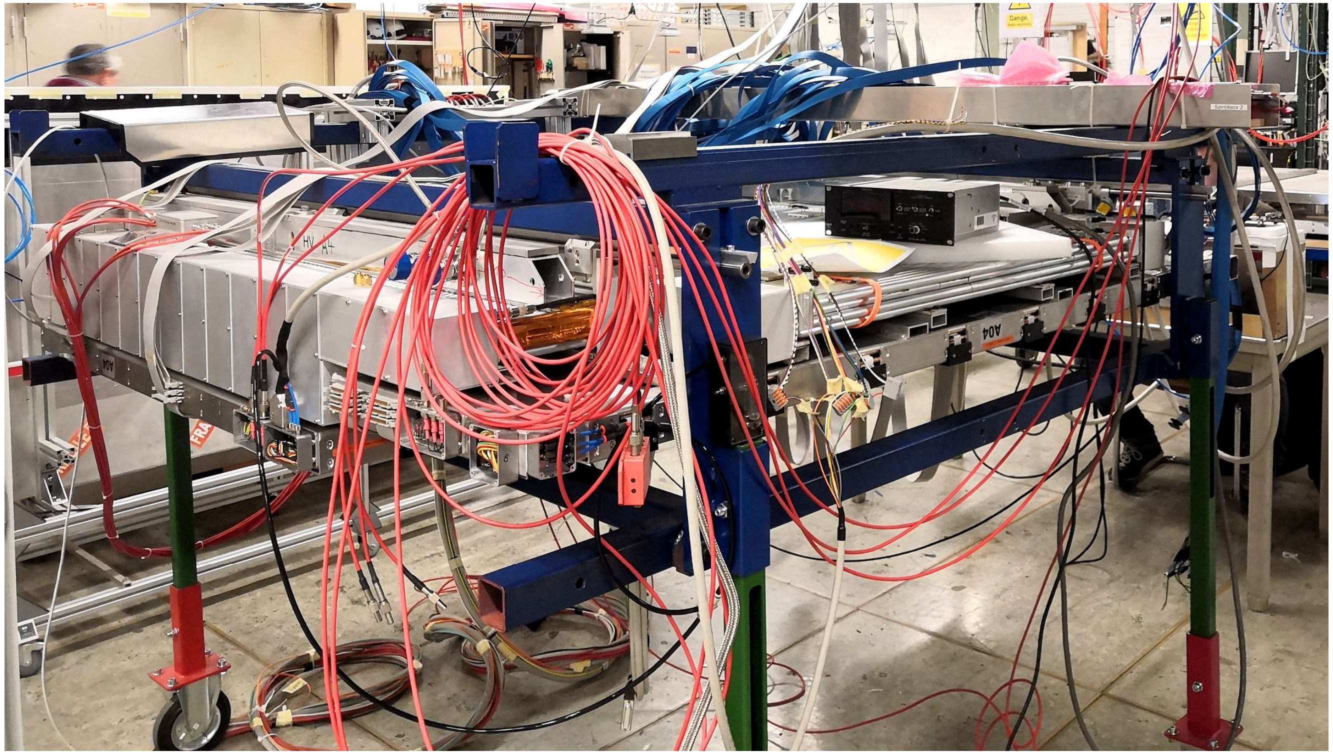
Positioning and drawing of a BIS78 chamber with integrated RPCs



Example: BIS78 A04

- Very tight **space constraints**
- **Reduction of tube diameter** to free up space
- **Installation of first chambers** starting soon, in parallel with the **New Small Wheel (NSW)**

The new BIS78 sMDT (small Monitored Drift Tube) chambers for the ATLAS Upgrade



Example: BIS78 A04

- Reduction of the drift tube diameter from **30mm to 15mm**
- BIS7 and BIS8 part produced as one chamber
- **8 Layers of tubes,** separated by a spacer, forming two Multilayers
- **Implementation of RPC detectors** without increasing the overall height
- Integrated **muon tracking** and **triggering capabilities**
- **HL-LHC capabilities**
- Chamber production at MPI and **integration with RPCs at CERN**

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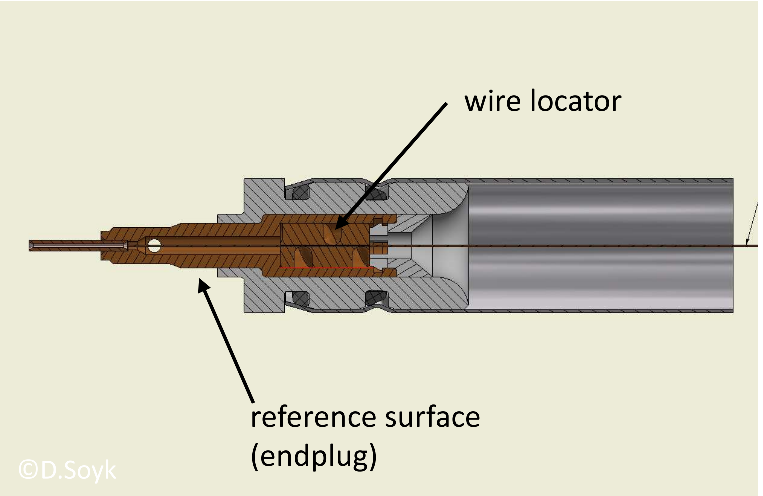
2. **Muon chamber working principle and commissioning**
3. Readout electronics signals concepts
4. Effects of background radiation on chamber performance

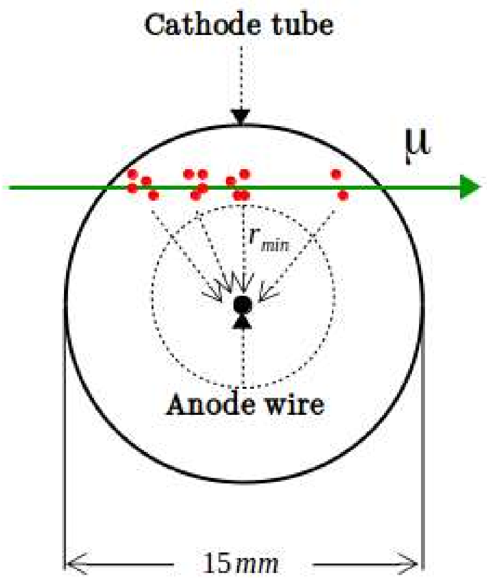
Design and production steps of the (s)MDT drift tubes and chambers

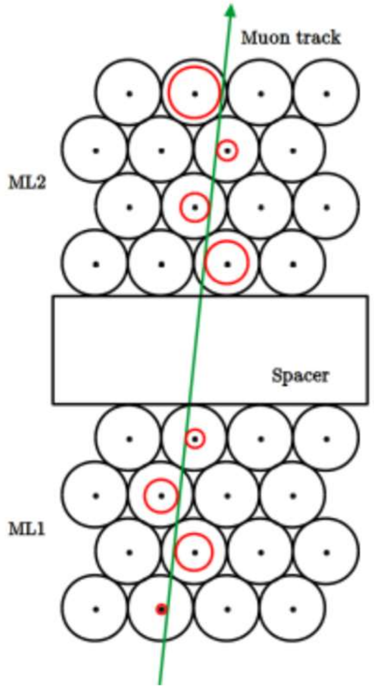


Chamber production steps

- **Single tubes** are produced **in clean room conditions**
- **Various tests** ensure the quality of the tube (wire tension, dark current, leakage)
- **Tubes are glued** to each other layer by layer - **precise positioning of endplugs** in positioning block – better than 10µm precision achieved
- Addition of **support structures**
- Installation of **faraday cages** and **gas distribution** system
- Installation of **HV system** on one side**, read-out electronics** on other side
- Installation of the **in-plane measurement** system

Working principle of the sMDT drift tubes and muon chambers I



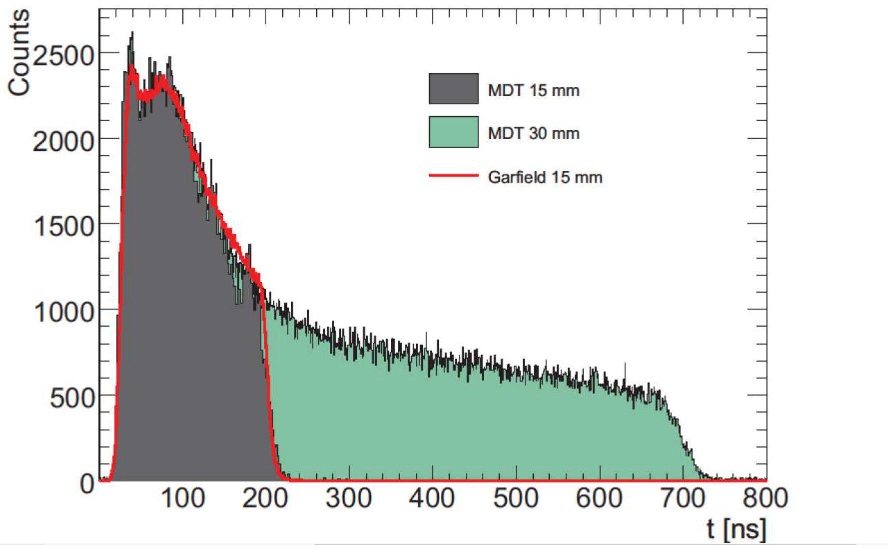


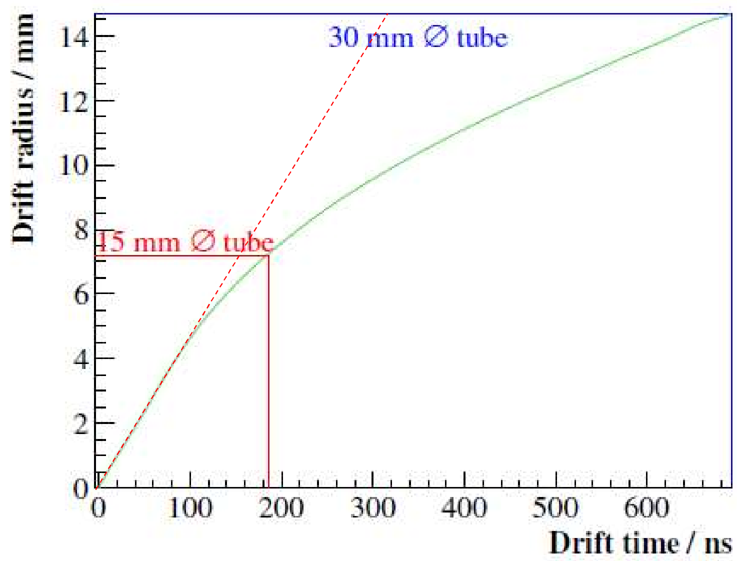
Signal generation

- Charged **particles ionize gas**, number of electron-ion pairs is **function of used gas** (Ar/CO2; 93:7; 3bar)
- 50µm diameter gold plated W/Re wire
- ***E(r)~V/r;*** sMDT wire potential: 2730V
- Drift velocity ***v=µE*** *;(µ…charge mobility)*
- **Gas Gain**(amplification): **20000** (Charge in Avalanche/Amount of primary ionization)

- Particle **momentum determination**:
  - Deflection of charged particle in magnetic field ***p[GeV/c]=0.3*B[T]R[m]*** *for q=e*

Working principle of the sMDT drift tubes and muon chambers II





Signal generation

- Measurement of electron **drift time** is converted to a **drift radius**, reduction of max drift time for sMDT nearly 4 times
- **Nonlinear r-t** relation for **Ar/CO_2**, chosen due to good ageing properties (no wire ageing, tested up to 9C/cm)

Commissioning and performance tests of sMDT chambers

Dark current

- Tubes checked prior to installation
- Limit of ***0.5nA/tube at 2730V***
- For a whole Multilayer ***~200nA***
- Broken wires detectable through current

Leakage

- Leakage rate below ***2n*10^{-8} bar l/s*** *for n* tubes in chamber
- Accounting for **temperature changes**
- Test prior and **first test after transport** to CERN

Noise

- Determination of accidental hit rates
- Random trigger is used noise rate determined for each tube in chamber
- A rate of ***1kHz*** results in negli-gible occupancy of ***0.02%*** for a sMDT readout time window

Resolution

- Scintillator setup and **cosmic muons** used for measurement
- **Difference** of measured **drift radius** and distance of **reconstructed track** from tube wire

Efficiency

- Scintillator setup and **cosmic muons** used for measurement
- **Single tube** and **chamber efficiency** determined via exclusion of tube/layer and checking of hits with recon-structed tracks

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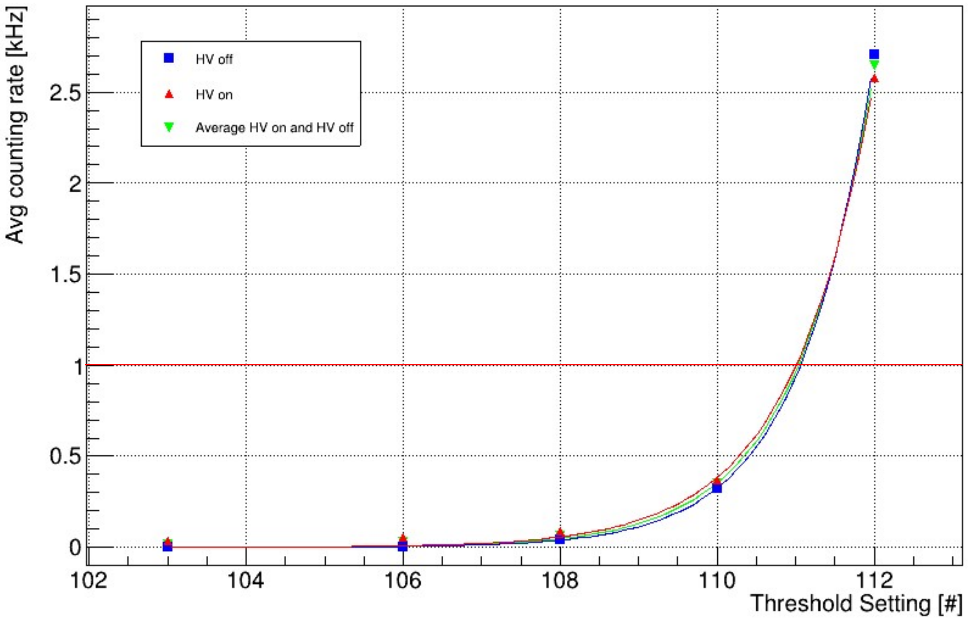
Noise determination – Example chamber data: BIS78 A6 at CERN



Code	Threshold value (mV)
103	-49
106	-43
108	-39
110	-35
112	-31

Noise rate due to stochastic voltage fluctuations

- Strongly dependent on **chosen threshold** value of readout chip
- Dependent on **chosen hysteresis** (avoiding multiple threshold crossings)
- A threshold of ***-39mV*** and hysteresis of ***2.5mV*** corresponds to signal of ***20 primary electrons***

- First tests of powered RPC on chamber A4 did not yield higher noise rates
- New readout chip currently being installed on chambers promises **much lower threshold settings** (down to *10-20mV* lower)

Commissioning and performance tests of sMDT chambers

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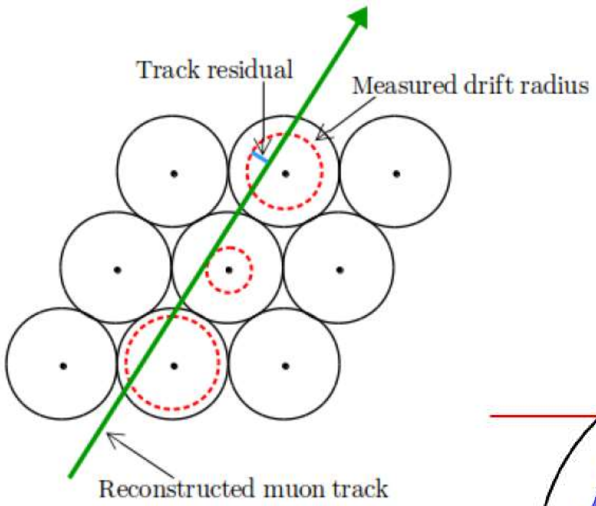
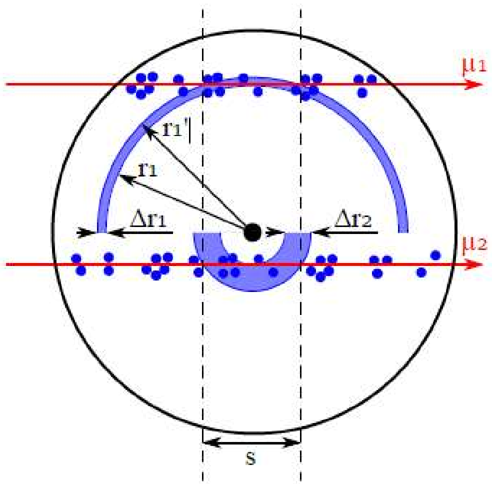
Resolution determination and dependency on the drift radius





Resolution

- Connection of **drift radii** from hit tubes with a **tangent straight line**
- Definition of **track**, as line which **minimizes the residuals** (*δ=drift radius (r) - track distance to wire (d) with* σ^2*=Var(δ)*)

- **Dependency** of resolution on the **drift radius**:
  - s being the distance with enough primary electrons to generate a signal
  - Worse resolution closer to the wire
  - Average corrected single tube resolution of ***83µm for MDT*** and ***106µm for sMDT*** tubes

Commissioning and performance tests of sMDT chambers

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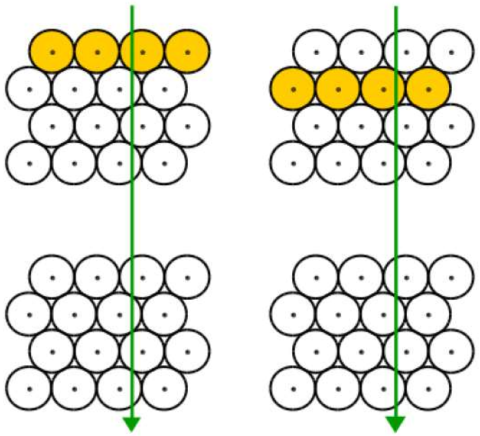
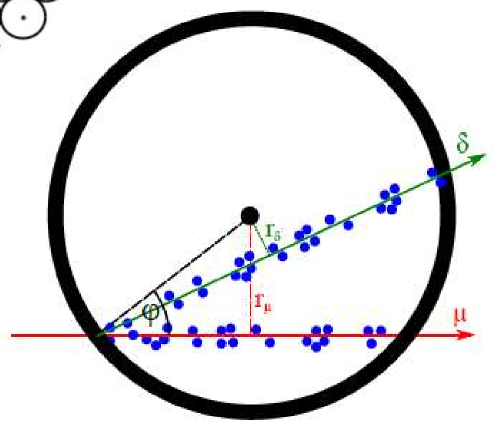
Efficiency determination, the 3σ-efficiency definition and δ-e⁻ masking





Efficiency

- **Probability**, that a drift tube **records a hit**, if a reconstructed **track passes through** the tube
  - Reconstruction of track with all tubes
  - Step wise exclusion of tubes and checking for hits
  - $\varepsilon_{tube} = \frac{\#\ hits\ matching\ tracks}{\#\ tracks\ crossing\ the\ tube}$

- With ~10-20% probability a **μ hit in the wall** produces a **δ-electron**
  - **3σ-efficiency requires** a hit to also match the **expected value** of the drift radius within **3 times** the spatial **resolution**
  - 3σ tube-efficiency of ~95%, decreasing with r

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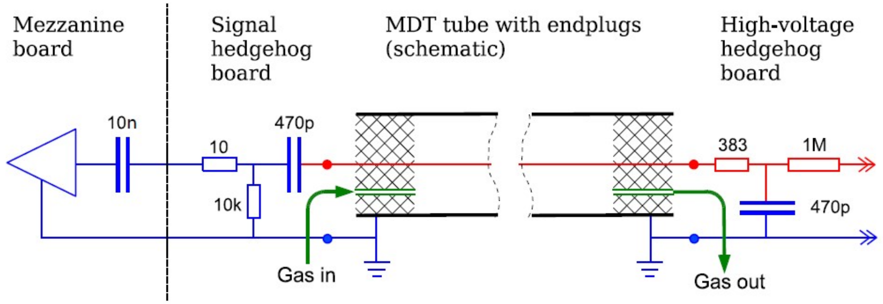
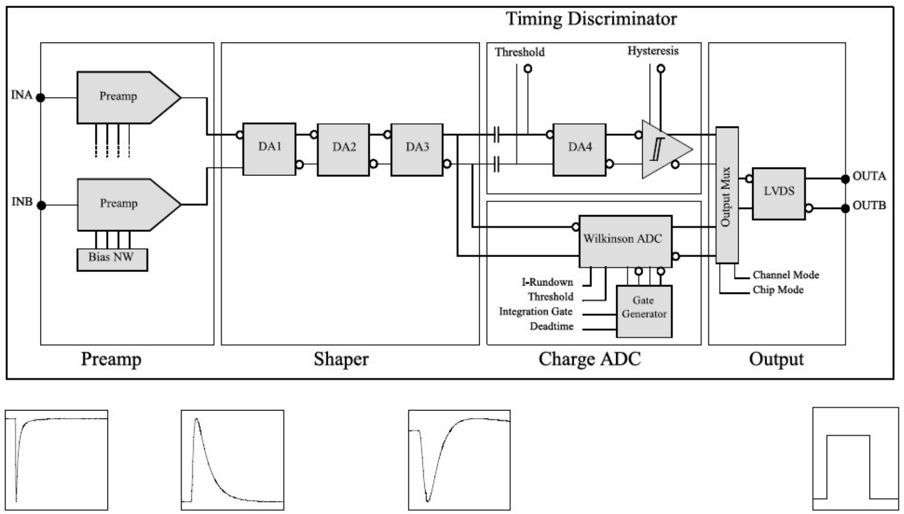
Front end readout electronics concept and signal forming

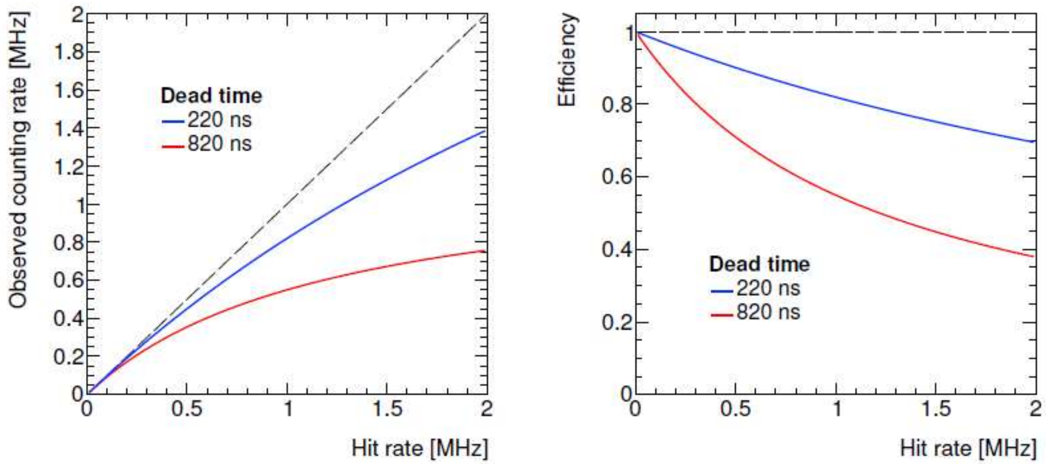




Readout Electronics

- ASD chip: **A**mplifier **S**haper **D**iscriminator
  - ADC Mode: Leading edge of pulse is integrated and output **pulse width** represents **charge**
  - **Dead time** can be adjusted to max. drift time to **avoid multiple threshold crossings**
- Dependency of **threshold crossing** time on **amplitude** causes so called **time slewing**
  - **Correction** via knowledge of **charge**
  - At an effectively shifted threshold at high background rates, this affects the crossing time
- 3x8 ASD signals are converted in a TDC and sent to a CSM module (up to 18 cards)

Effects of high background on electronics – Dead time effects



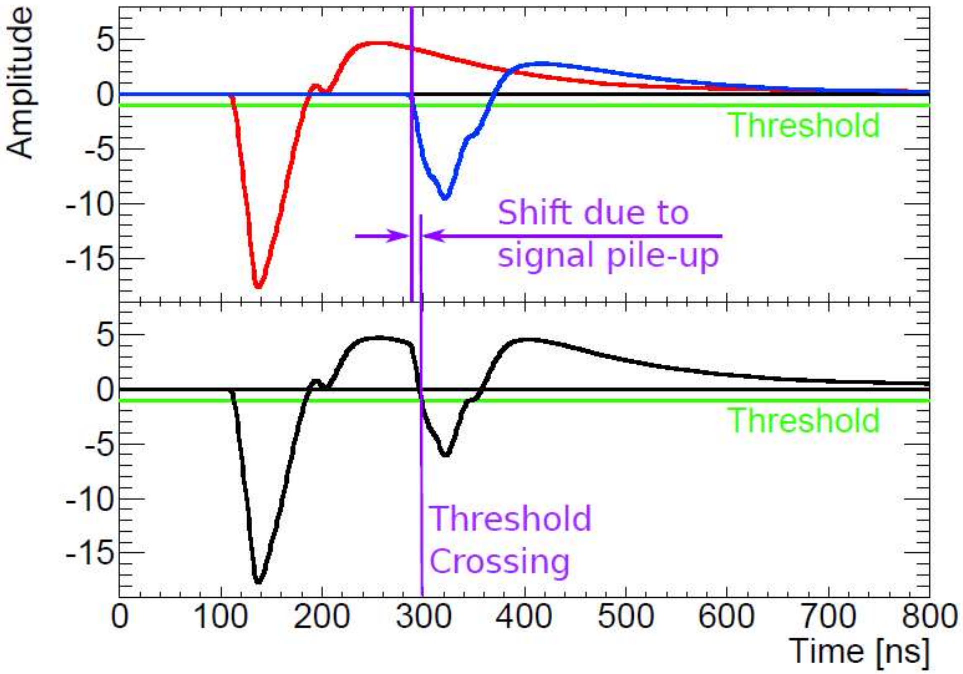
$$\varepsilon(N) = \frac{\varepsilon_0}{1 + N \cdot m_{\text{hit}} \cdot t_{\text{dead}}}$$

Dead time effects

- All **hits** arriving **after a threshold crossing** in defined dead time are **lost** (non-extendable)
- **Direct impact on efficiency** to detect a hit belonging to a muon track
- Degradation depends on dead time, as well as the counting rate of background hits arriving randomly in time

- *N…hit rate, m_{hit}=hit multiplicity* (avg threshold crossings per hit)
  - **Reduce dead time** and keep **multiplicity low**
  - Reduction of dead time from 820ns to 220ns without increase of multiplicity for sMDT's

Effects of high background on electronics – signal pile up for bipolar shaping (ASD chip)

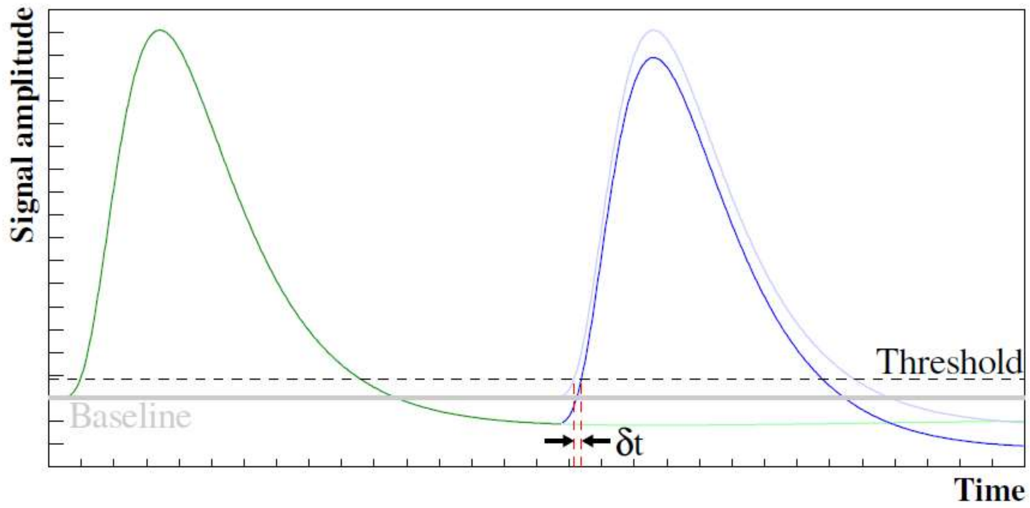


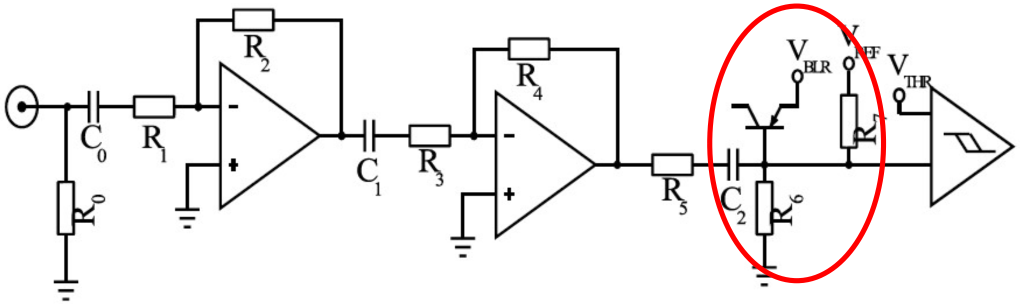
Signal pile up

- **Large** and long **undershoot of same area** as incoming pulse (bipolar)
- At high counting rates, **hits may arrive too early** until electronics are back to the base line
- This can cause a **superimposed signal,** which has a different amplitude, causing **time slewing** and wrong corrections
- Additional **efficiency loss** can be observed
- **Degradation** of the **resolution** of secondary hits

- Possible improvement at high rates: **active baseline restoration**

Unipolar shaping and discrete shaping methods with active baseline restoration





Active baseline restoration

- No pure **unipolar shaping**, as tubes are **decoupled via a capacitor**, which differentiates the signal
- **Long tail** leads to **baseline shift** with increasing hit rate and time slewing
  - **Restoring of baseline** before discriminator

- Active baseline restoration **cuts off undershoots** and ‘cancels’ tail
  - 2 stage amplification and shaping
  - Capacitor C_2 differentiates away undershoot from previous stages
  - Remaining **negative undershoot** is **short-circuited via diode**, depending on V_{BLR}

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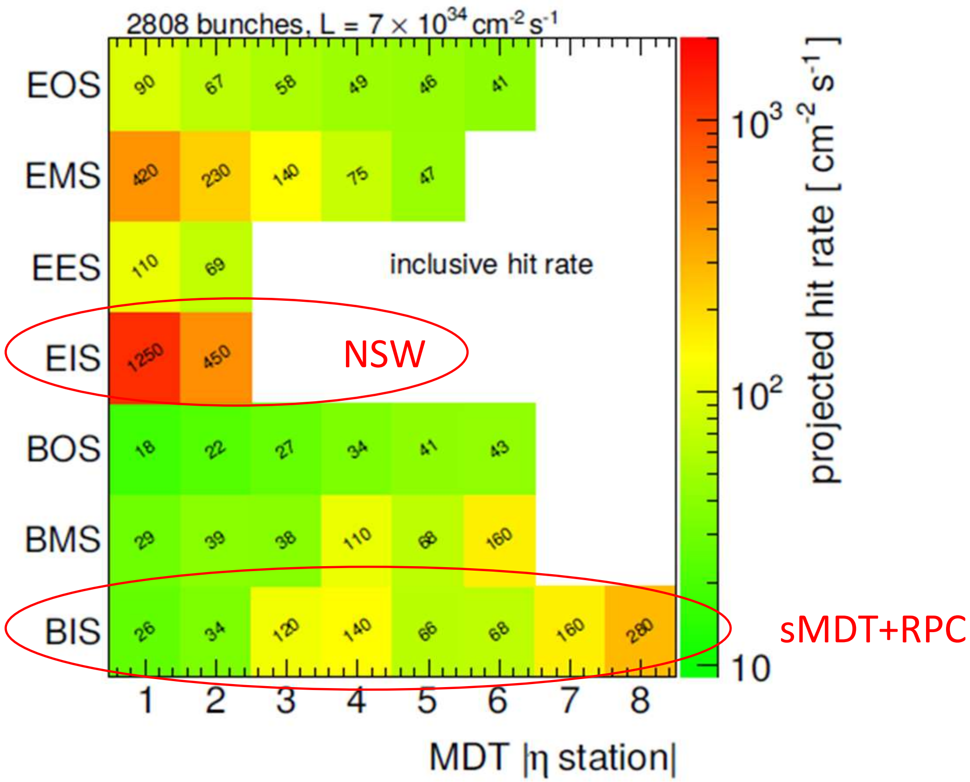
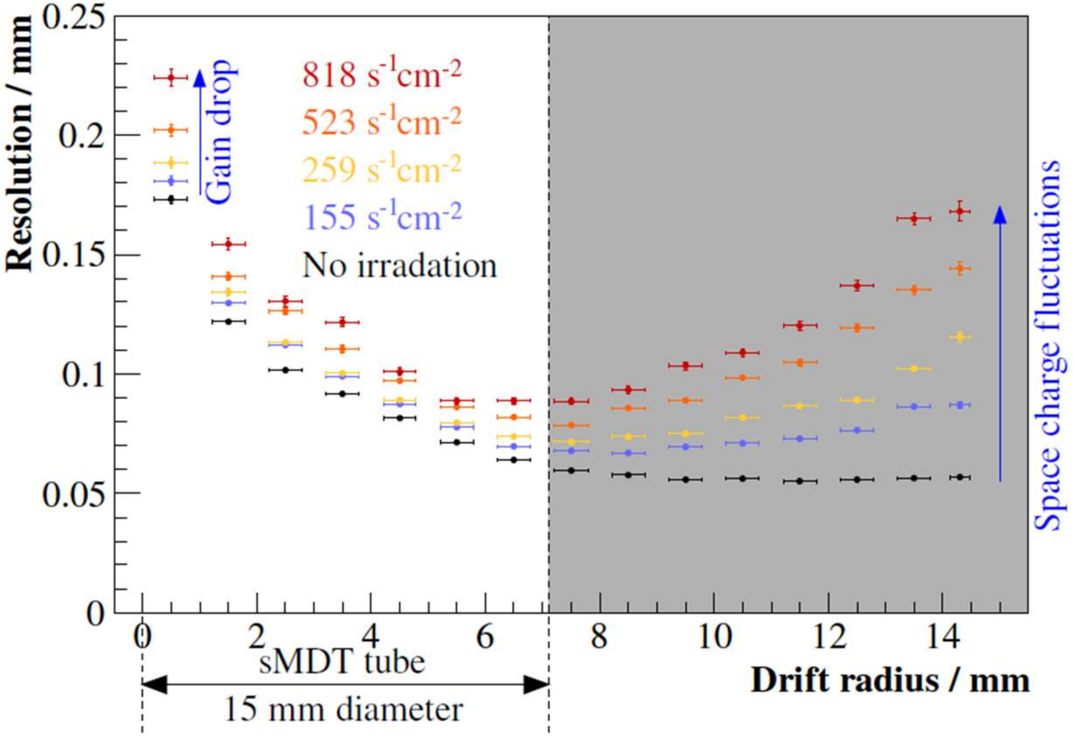
(s)MDT chamber requirements for predicted HL-LHC background rates and future hadron colliders



Background rates and requirements

- **Majority of hits** in the muon detectors not caused by muons but the **cavern background**
- Background **scales** with **instantaneous luminosity**
- **Safe operation** of MDT tubes up to **500Hz/cm² or 300kHz/tube** counting rate
  - Above, **resolution and efficiency suffer** from high **occupancy** and **space-charge** effects
  - **HL-LHC** operation does **not require replacement** of MDT chambers
  - **Electronics** however need to be **upgraded**
  - **BIS chamber** replacement to **free space for RPCs**
- **FCC** could reach **30x nominal** LHC Luminosity (with **~1500Hz/cm²** background rate for muon barrel)

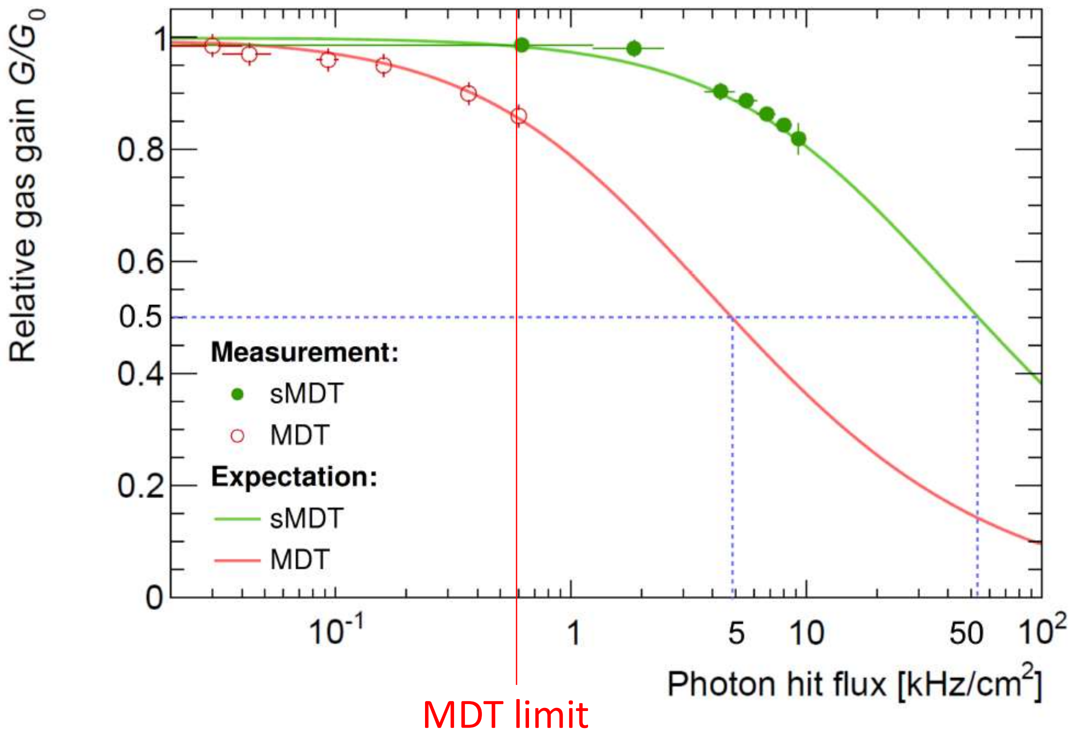
Resolution dependency on drift radius and background radiation effects



Resolution at background irradiation

- Secondary hits of collision products, around 1MeV energy, Compton electrons from tube walls
- Ion drift time *~1ms* for sMDT, *~3ms* for MDT tubes
- Two effects:
  - Dominant **gain drop** (reducing the electrical field and modifying the gas gain) for small drift radii – lower resolution due to time slewing
  - Dominant **space charge fluctuations** (and thus variations of drift velocities) for large drift radii – the more linear r-t relation for sMDT tubes reduces this effect

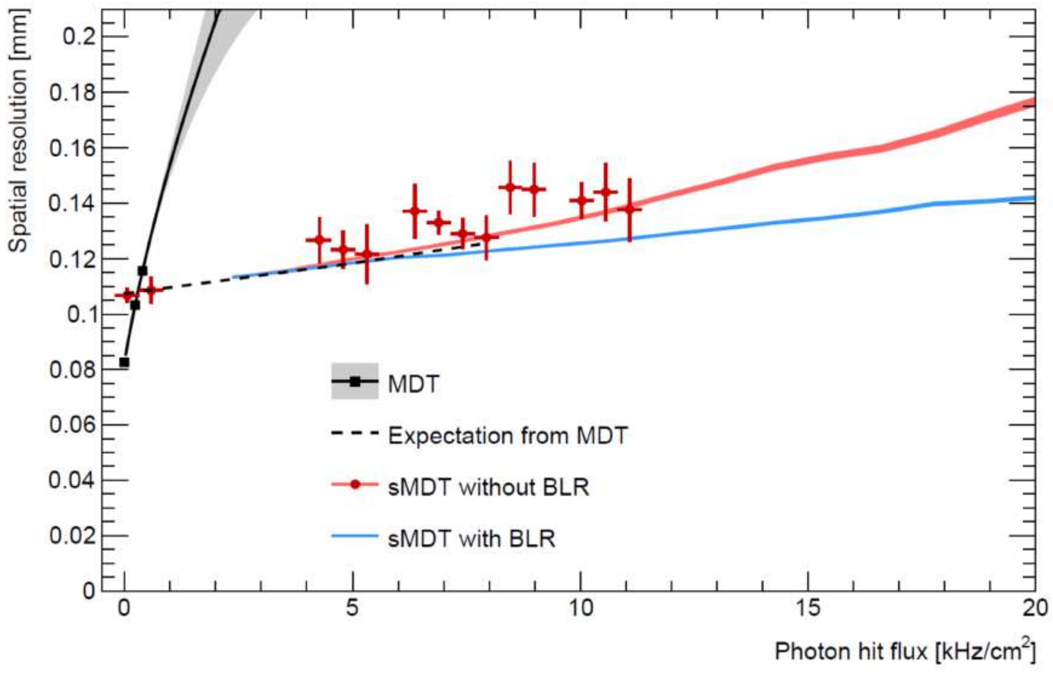
Gas gain modification in (s)MDT tubes at high background rates



Gas Gain at background rates

- Charge Q_{prim} deposited by background hit, multiplied by Gain G in vicinity of wire
- Reduction of Gas Gain due to **field modification** and effectively **changing the threshold**
  - Leads to **lower resolution** due to time slewing
- Dependence of Gas Gain on irradiation rate can be calculated iteratively using Diethorns formula (gas amplification affects amount of space charge)
- Effective **voltage drop** caused by gain drop:
  - $\boldsymbol{\delta V \propto r^3_{max}}$; r_{max}=*Tube Radius*, Q_{prim}=*const.* for photons converting in walls
  - **Reduction** of tube **radius** by **factor of 2** makes tube **8 times less sensitive** to gain drop!

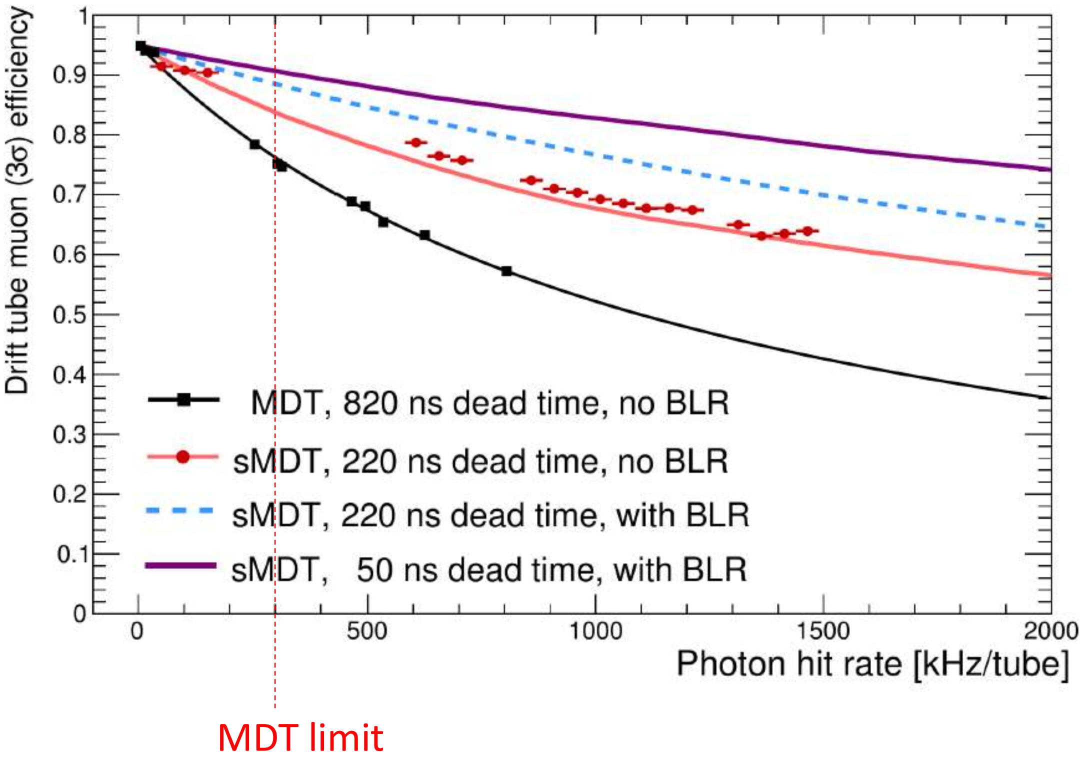
Effect of background radiation on resolution of (s)MDT chambers



Spatial resolution deterioration

- **Higher** single tube **resolution for MDT** tubes **without** background **radiation**
- Clear **superiority of sMDT** tubes at **high background** rates
- One order of magnitude higher background rates tolerable w.r.t. resolution
- **Good agreement** between GARFIELD **simulations** and **measurements** performed at GIF^{++}
- Further **improvements** with **new readout electronics** possible

Efficiency deterioration due to high background rates

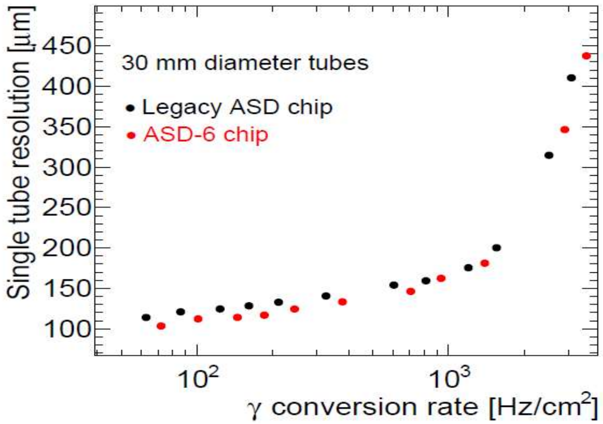


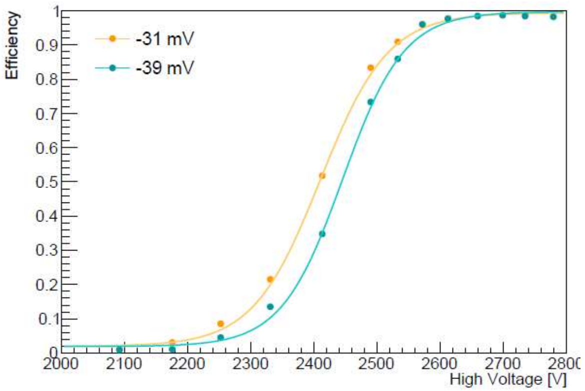
Efficiency deterioration

- Reduction of readout dead time ~4x to 220ns, just above max. drift time for sMDT
- Twice higher counting rates for MDT compared to sMDT (γ's mainly interact with tube walls – half the surface of the tube)
- Overall **8 times lower occupancy** for sMDT tubes
- Loss due to **masking of muon hits** by preceding **background pulses** strongly decreased

-> Increase of the 3σ-efficiency for sMDT tubes

New ASD chip capabilities for (s)MDT tubes





Electonics-new ASD

- **New ASD chips** for HL-LHC have been developed:
  - Reduced peaking time *15-> 12ns*
  - Doubled gain *10-> 21mV/fC*
  - Half r.m.s. noise *8-> 4 mV*
  - Reduced threshold spread: *12-> 4mV*
- Increase of efficiency and resolution at nominal ATLAS settings
  - Safe operation of **up to 1000Hz/cm^2**
  - Rates of 1500Hz/cm^2 would allow operation at the FCC (achievable with lower threshold due to reduced noise levels)
- Currently **first noise tests of final ASD chips** on prototype sMDT chambers **look promising**

Summary and Outlook – advantages of sMDT tubes and new read out electronics

Reduced tube diameter

- **Smaller form factor** allowing for combination and access of tight areas
- Strongly **reduced drift time** and thus **dead time** and 8x **reduced gain drop**
- Operation in nearly **linear r(t)** regime of Ar/CO_2 – elimination of **space charge fluctuations**
- **8x lower occupancy** due to half cross section exposed to radiation and 4x lower dead time
- Increased overall **high-rate capabilities** of around **one order of magnitude**

New electronics

- **Larger amplification** and **shorter peaking time** improve efficiency and resolution
- **Lower noise** promises **lower threshold** settings, increasing efficiency at high rates
- Development for **fast baseline restoration** to exploit full rate capabilities of sMDT tubes
- Improvement of the **whole readout chain** for HL-LHC

Ideal, flexible choice for high rate environments and future detectors