# The ATLAS Muon Spectrometer

**DPG Frühjahrstagung 2007**

**Heidelberg**

**6th March, 2007**

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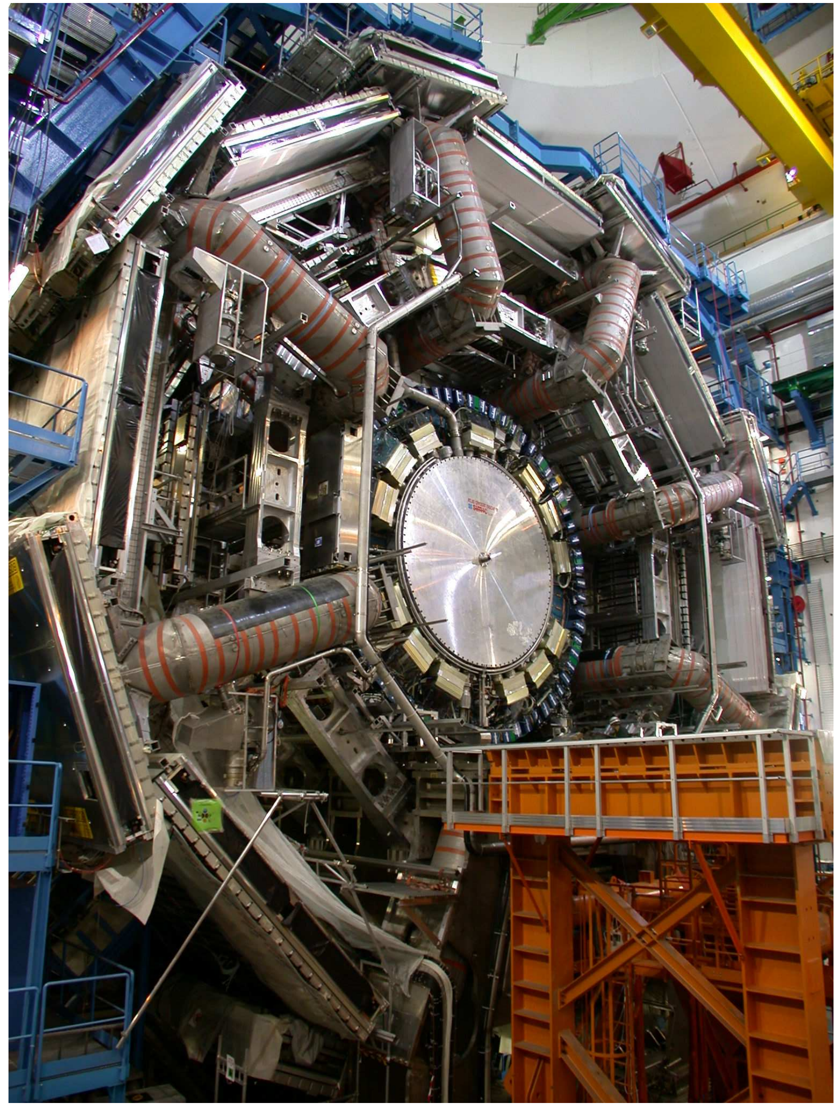
# Outline

- Concept of ATLAS Muon Spectrometer
- Large-Scale Production of ATLAS Precision Chambers
- Installation and Commissioning
- First Results from Cosmic-Ray Data Taking with Magnetic Field

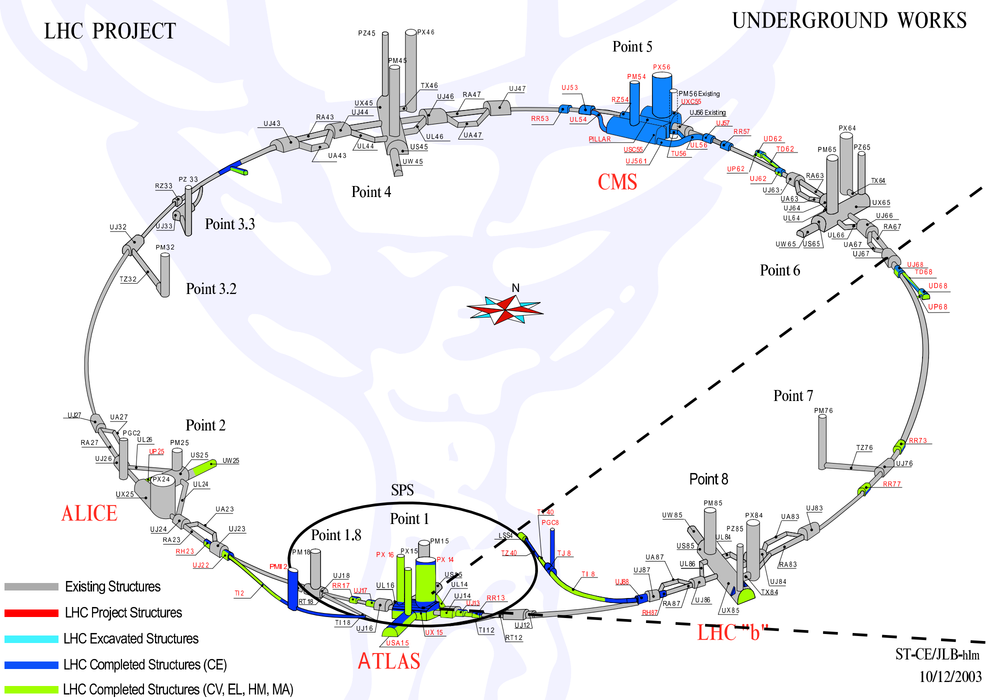
# Introduction

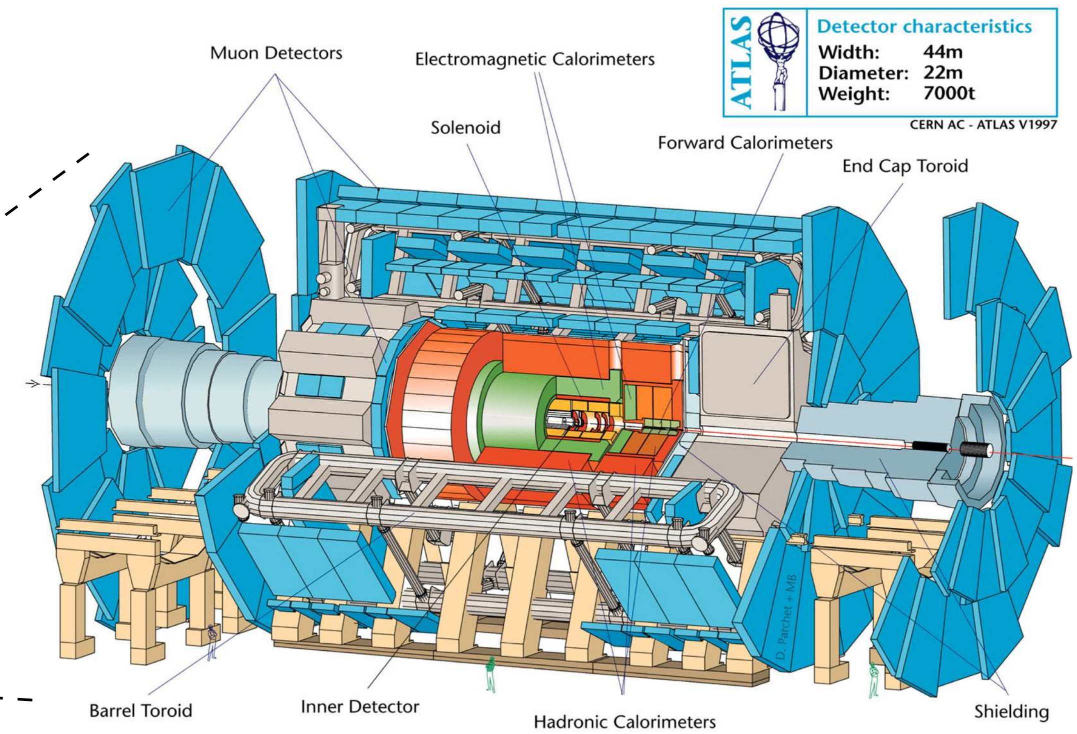


# LHC & ATLAS

- pp collisions at $\sqrt{s}$ = 14 TeV
- Luminosity: $10^{34}$ $cm^{-2}$ $s^{-1}$
- 40 MHz bunch crossing frequency

- 27 km circumference (LEP tunnel)
- 4 main experiments:
  ALICE, ATLAS, CMS, LHCb



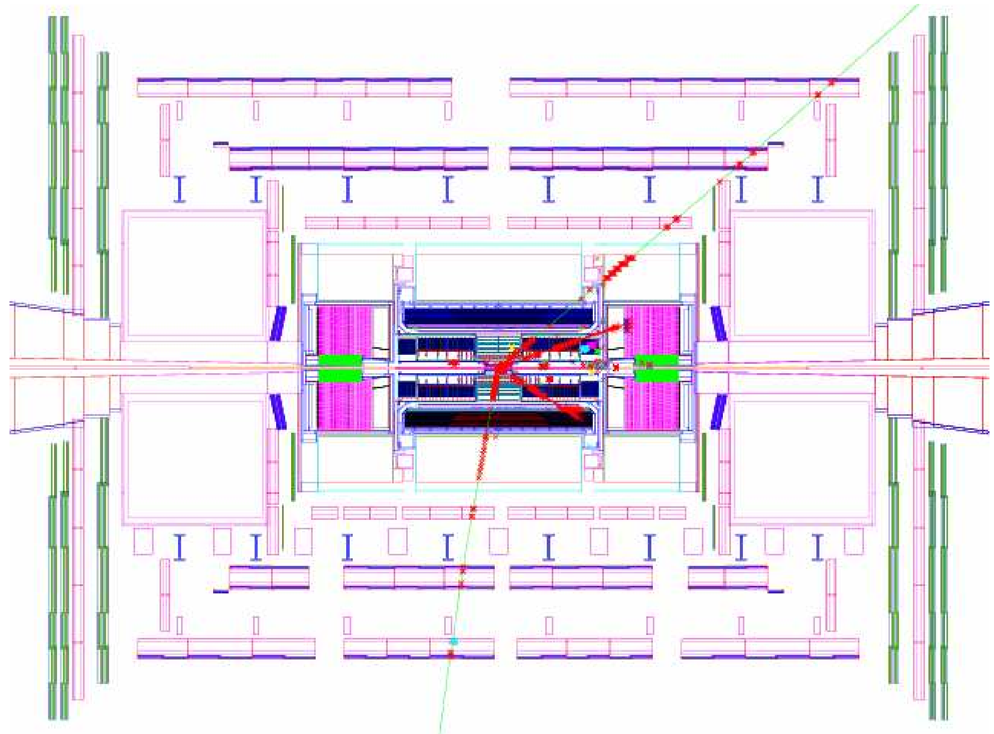




**Physics at TeV scale can be probed for the first time**

# Why do we need a Muon Spectrometer?

- Example processes of “new physics”
  - $H \rightarrow ZZ^* \rightarrow \mu\mu\ell\ell$
  - $A \rightarrow \mu\mu$
  - $Z' \rightarrow \mu\mu$
- Clean signature of final states with muons
- Good trigger capability/selectivity, identification and momentum reconstruction of muons over largest possible solid angle crucial for physics at LHC

$H \rightarrow ZZ^* \rightarrow \mu\mu ee$ Event



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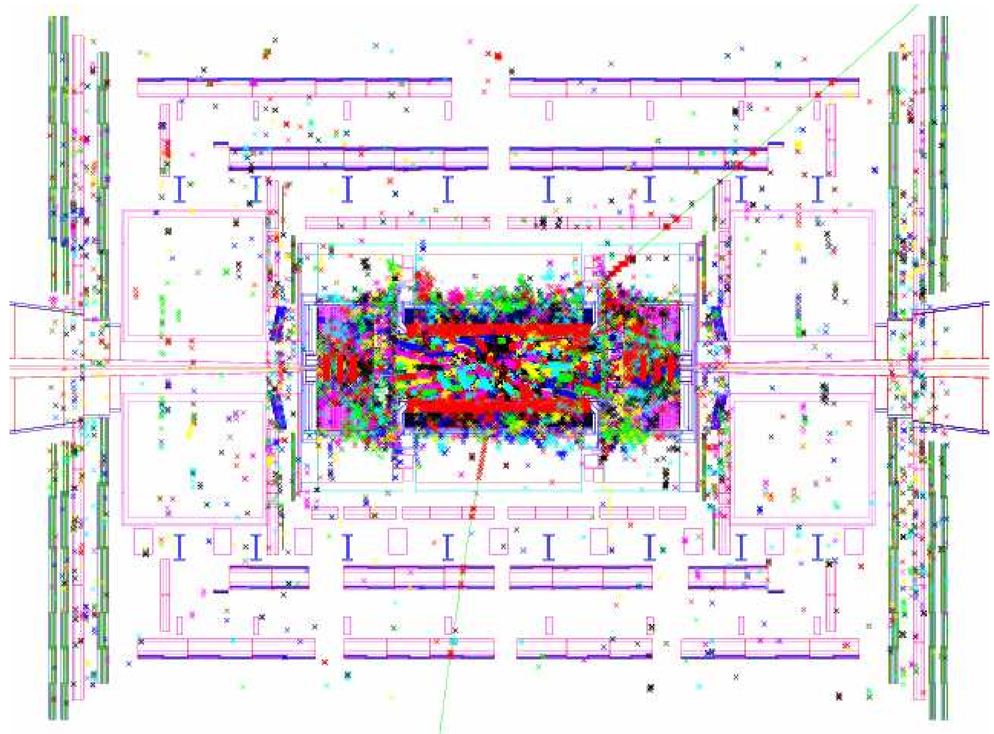


+ 23 min. bias events / bunch crossing
$\to$ 1750 additional particles

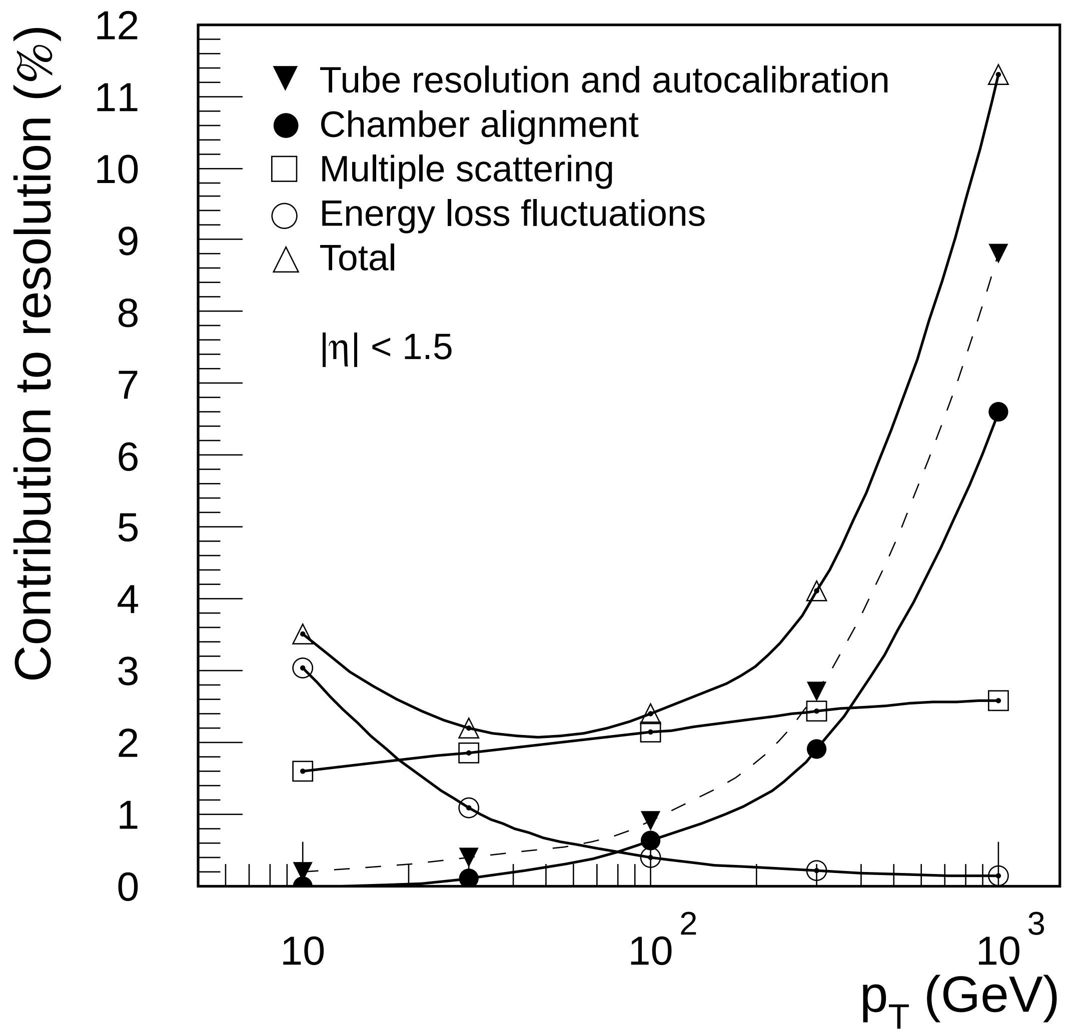
# The ATLAS Muon Spectrometer

## Design Philosophy

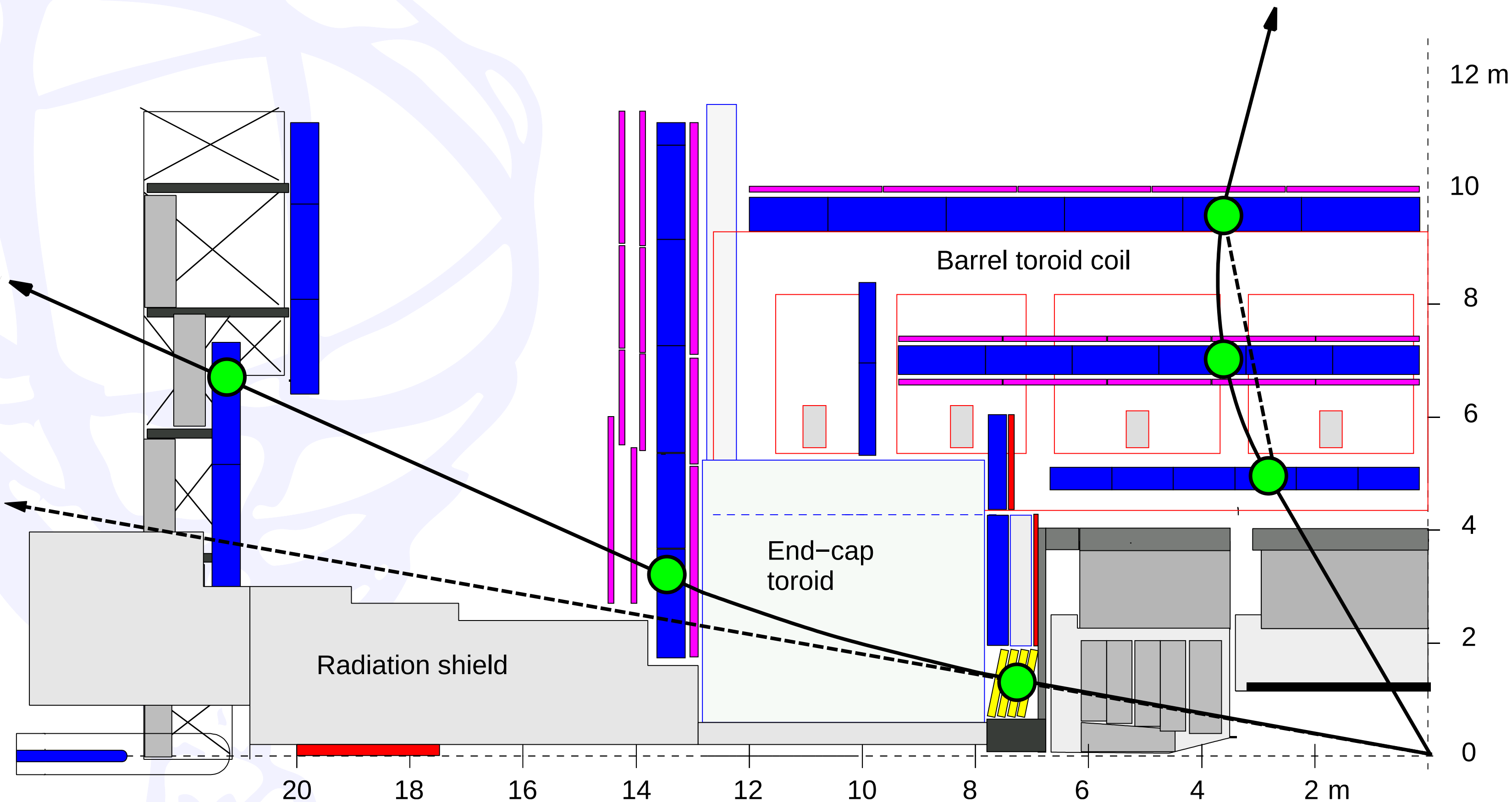
- $\Delta p_T / p_T < 10\%$ up to 1 TeV
- Coverage $|\eta| < 2.7$ ($|\theta| < 86^\circ$)
- Resolution independent of $\eta$
- Precise measurement of B-field

## Realization

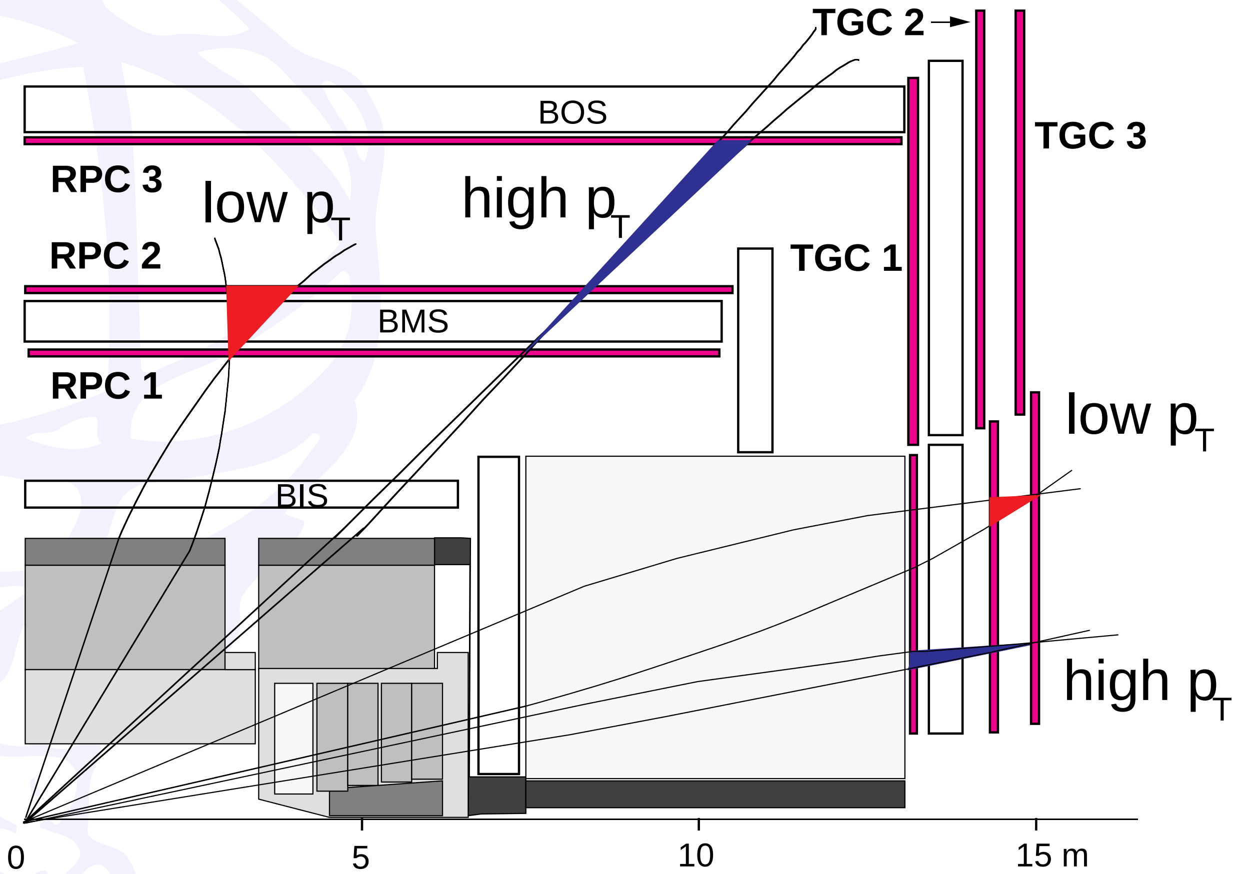
- Air core toroid magnet system
- Precision chambers
- Alignment system



# Principle of Momentum Measurement

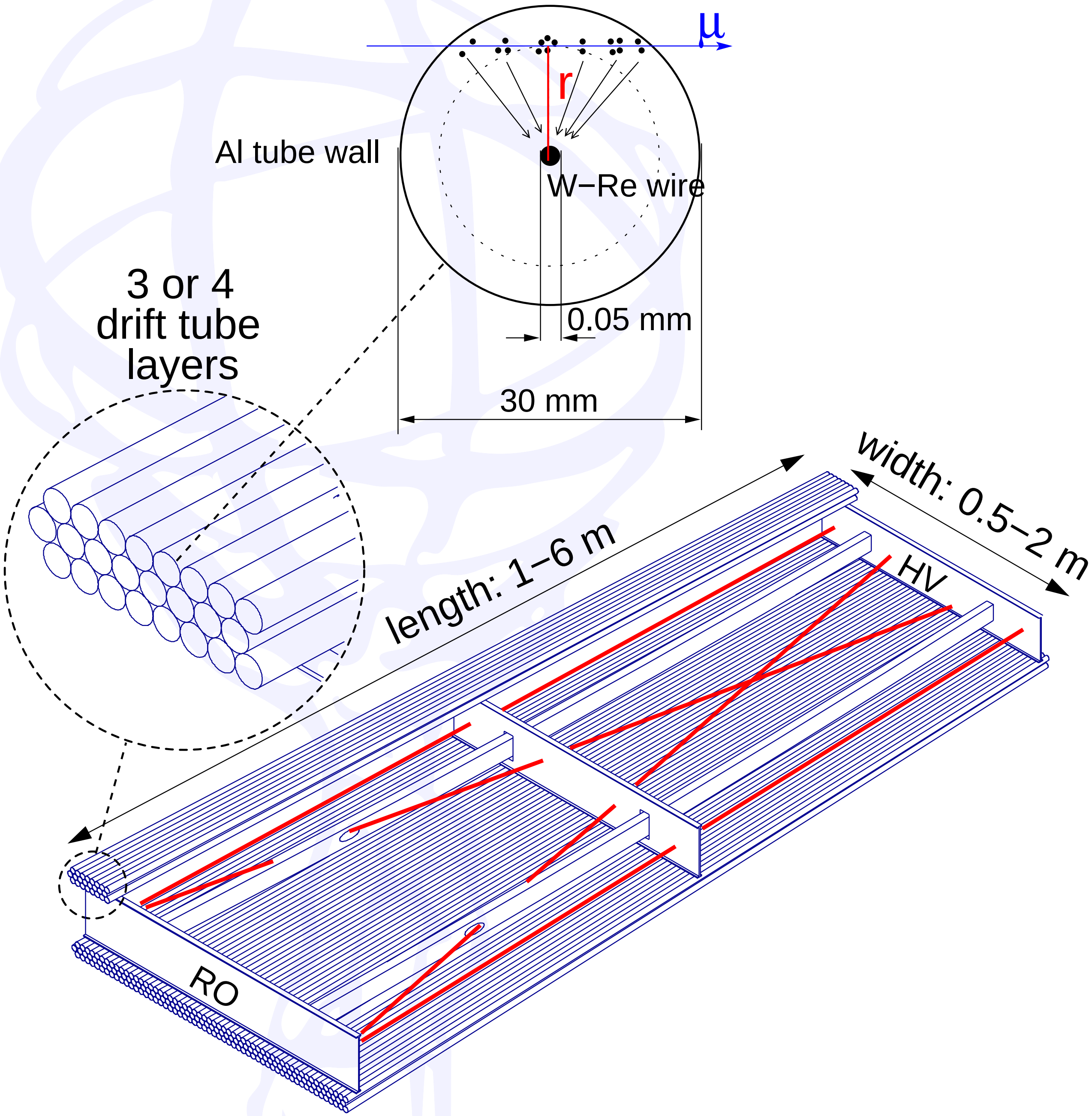



- 3 planes of precision chambers
- Barrel: 3 point sagitta measurement
- Endcap: point-angle measurement
- $p_T = 1$ TeV $\Rightarrow$ 500 $\mu$m sagitta
- 50 $\mu$m point resolution needed (including alignment across 5–10 m)



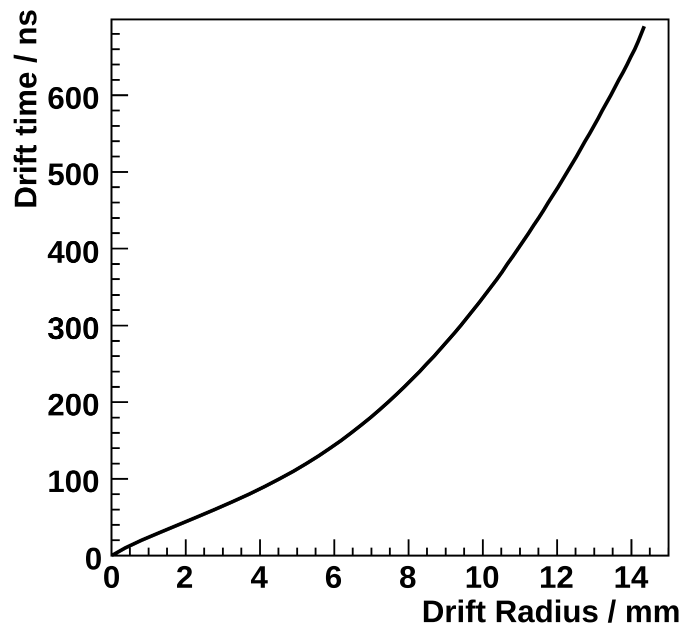

- Low $p_T$ trigger: 2 neighboring planes
- High $p_T$ trigger: 1 additional plane
- Bunch crossing period: 25 ns @ LHC
- Trigger chamber time resolution $< 10$ ns

# Monitored Drift Tube Chambers

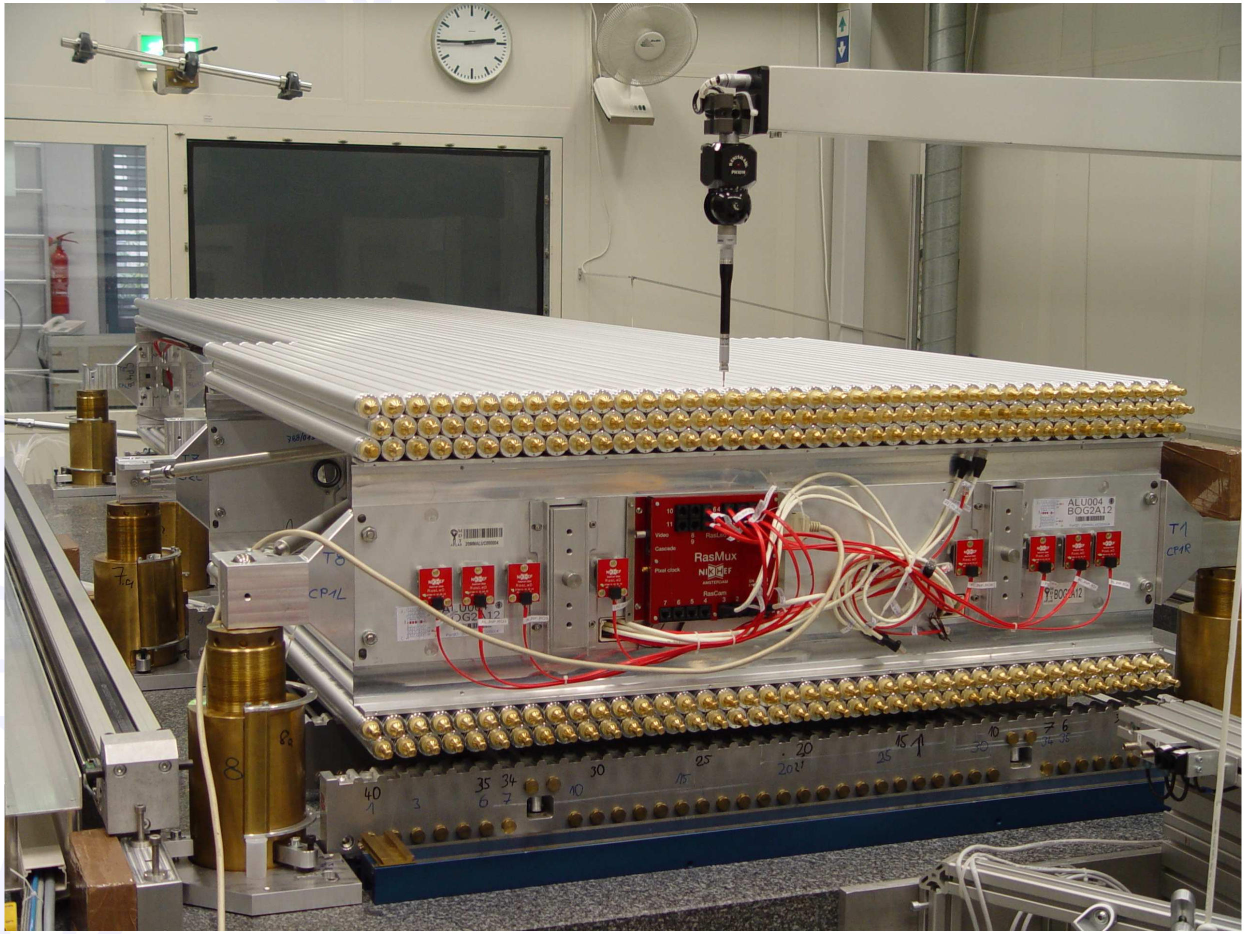



- Gas mixture: Ar/$CO_2$ = 93/7
- Pressure: 3 bar
- Gas gain: $2 \times 10^4$
- Max. drift time: $\approx$ 700 ns
- Drift Tube Resolution: 80 $\mu$m

**Space–Drift-Time Relation**



# Large-Scale Production of
# Monitored Drift Tube Chambers




**1200 Chambers with 380000 Drift Tubes—22 Institutes**

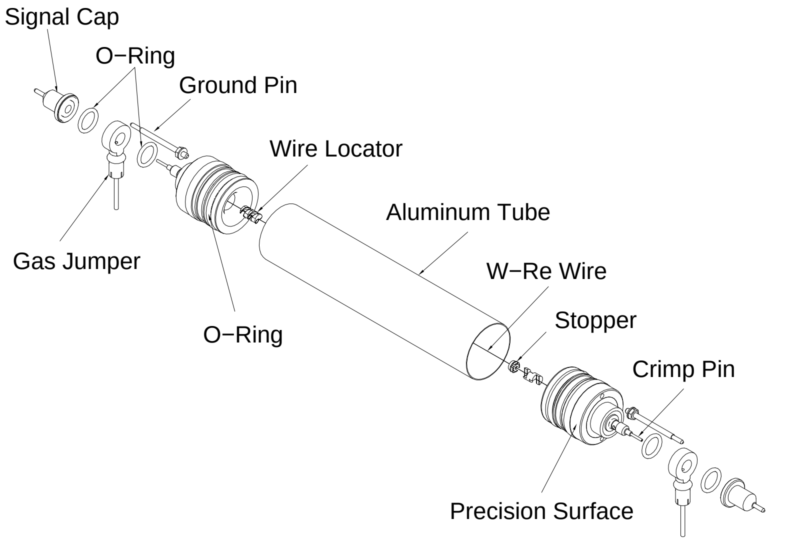
# German Contribution

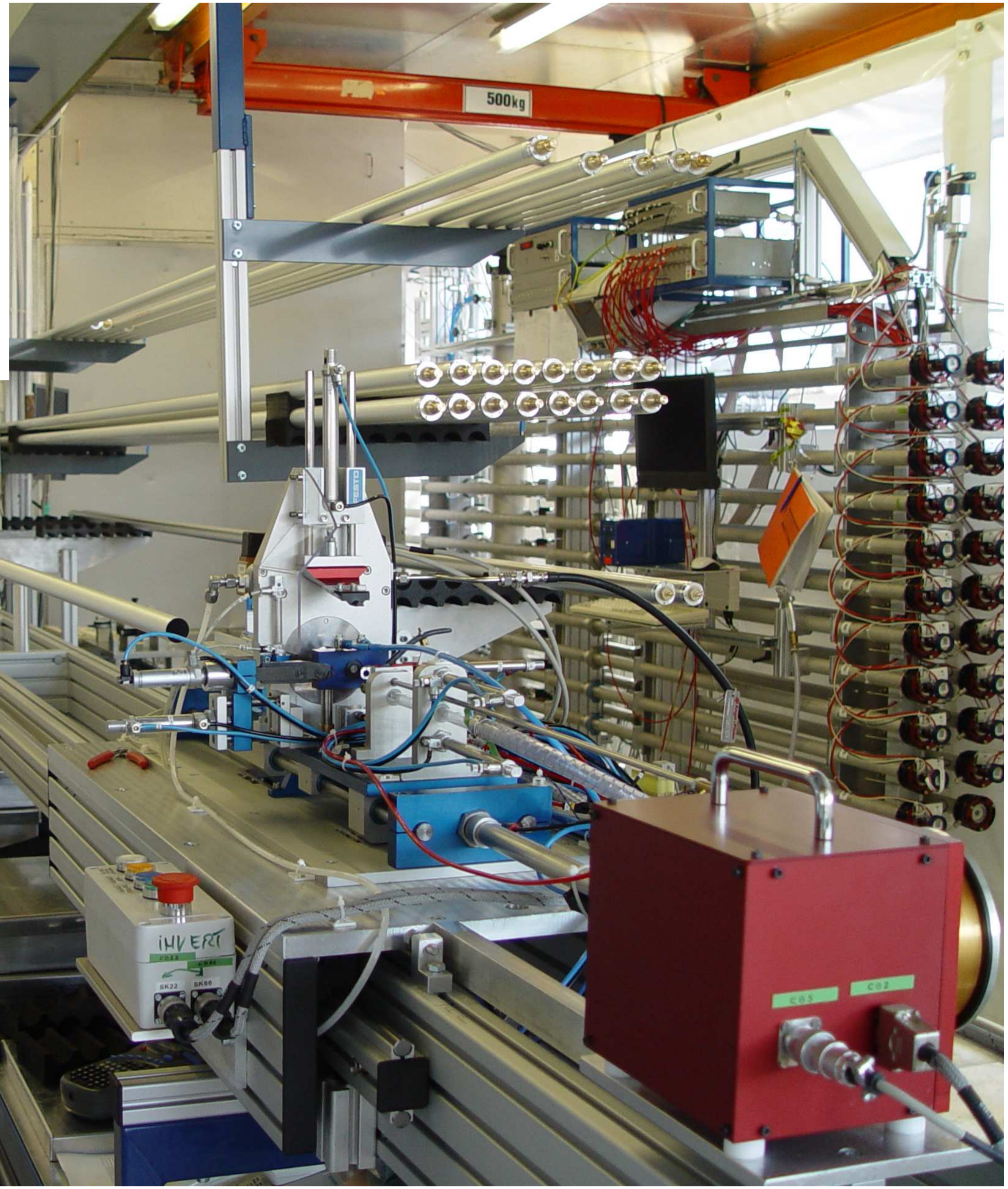
## 3 German Institutes

- **Albert-Ludwig-Universität Freiburg**
  - 18 MDT chambers for the outermost barrel layer in the detector feet region
- **Max-Planck-Institut für Physik and Ludwig-Maximilians-Universität München**
  - 88 MDT chambers for the outermost barrel layer

**German institutes built 1/6 of ATLAS barrel precision chambers**

# Drift Tube Production



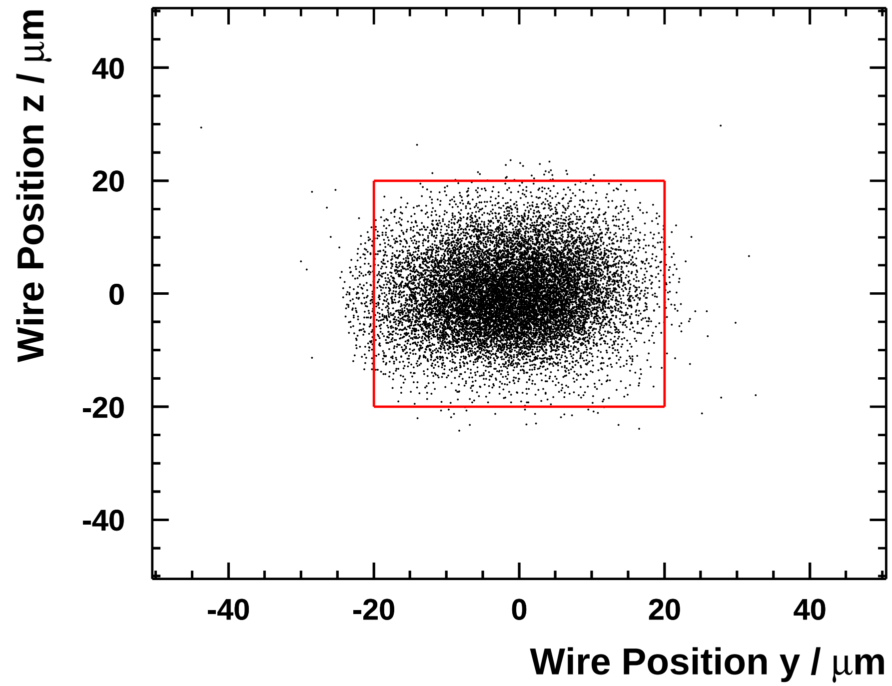



## Requirements

- Anode wire position known to 20 $\mu$m
- Wire tension: 350 $\pm$ 7 g
- Max. leak rate: 2 $\times$ $10^{-8}$ bar L/s
- Current @ 3400 V: $<$ 2 nA $\times$ $l_{Tube}$ / m

**Production Efficiency: $\approx$ 95%**

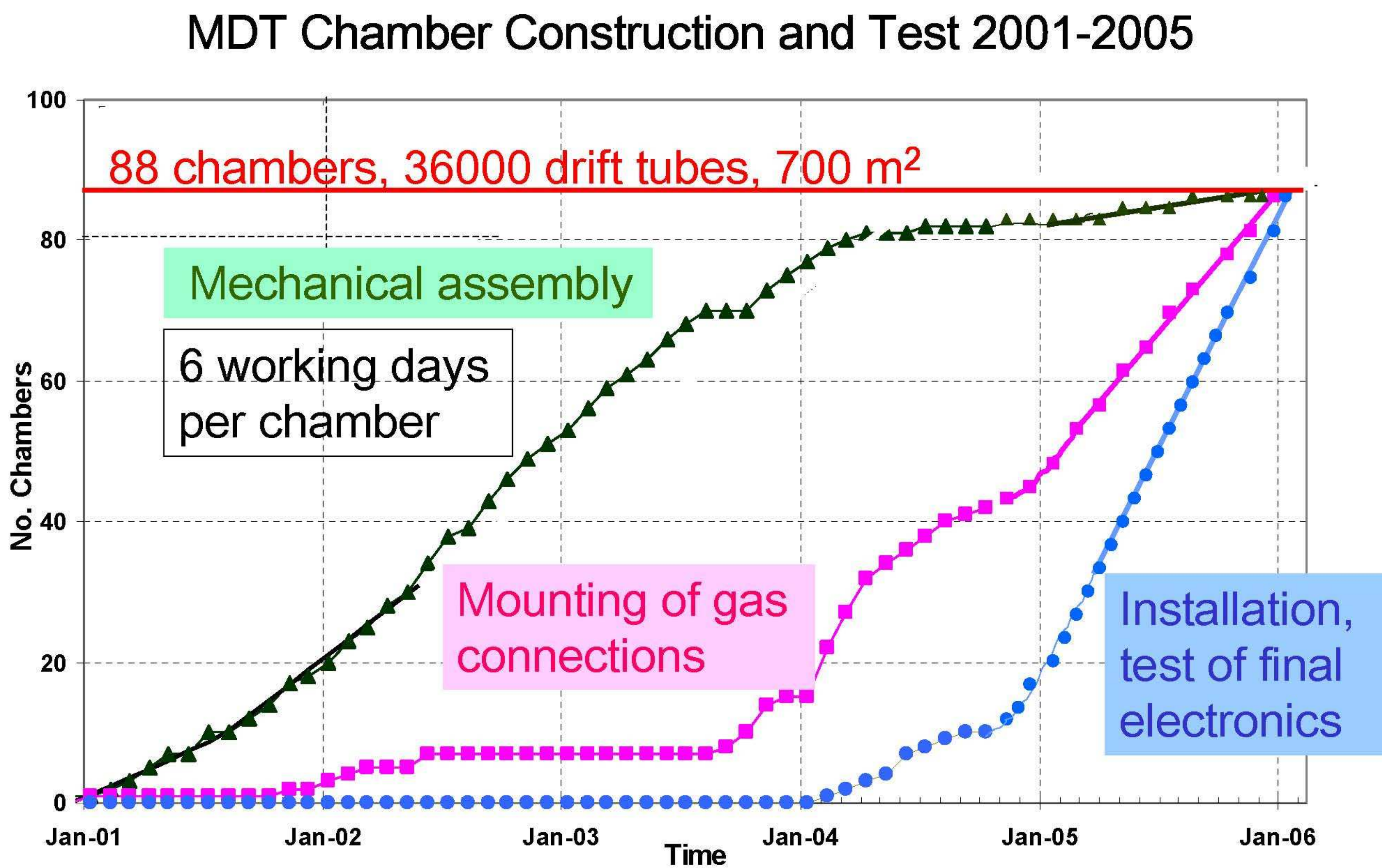
## Example: Anode Wire Positions



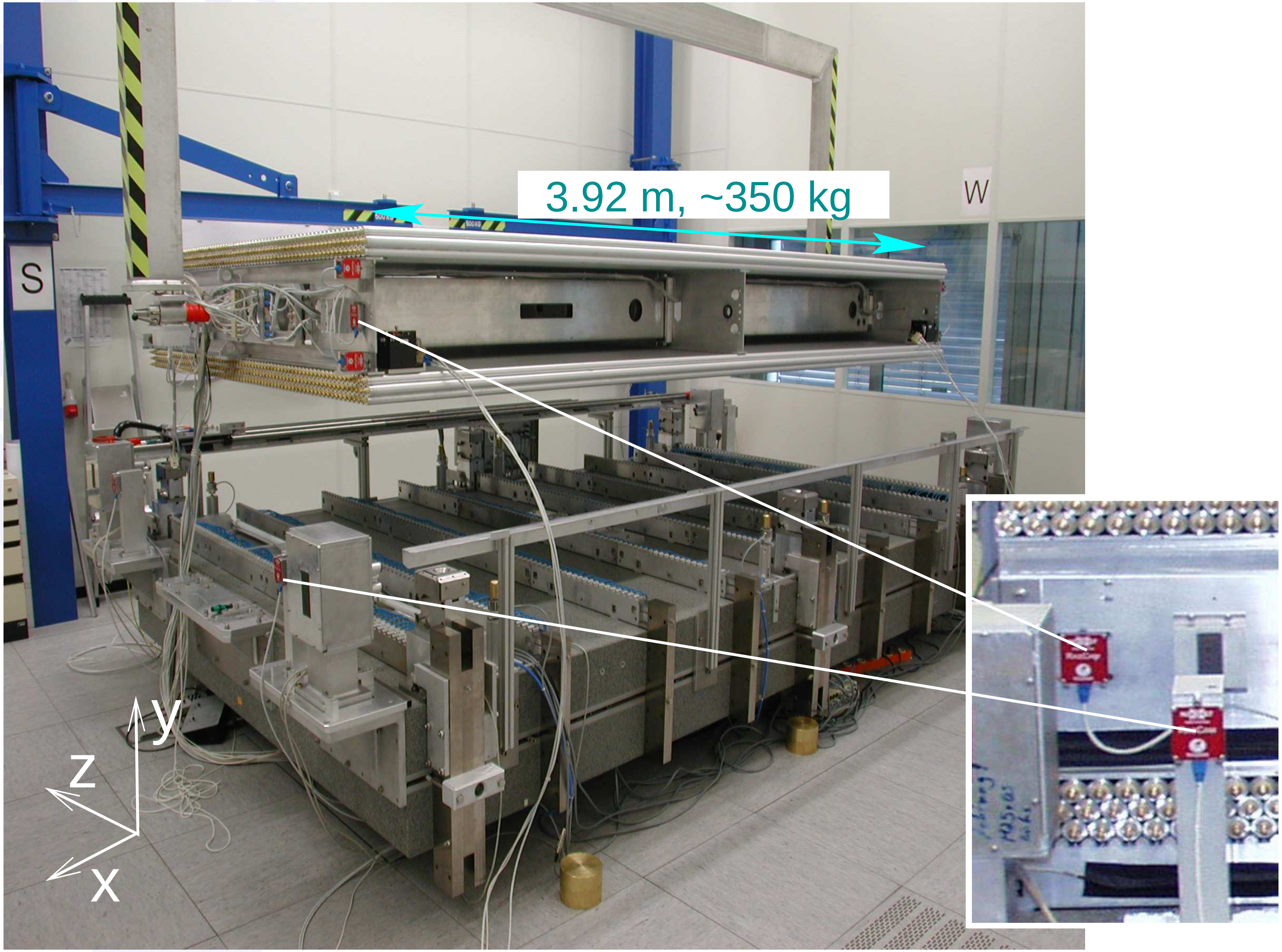

$\sigma_y = 8\mu$m, $\sigma_z = 6\mu$m

# Large-Scale MDT Chamber Production

## Example: At Max-Planck-Institut für Physik



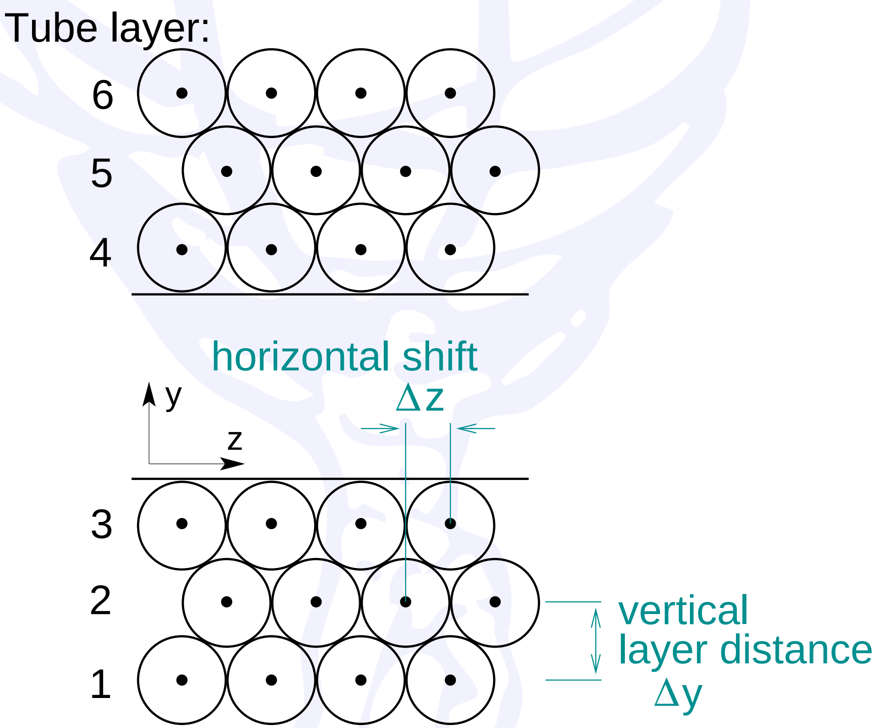
# MDT Chamber Assembly

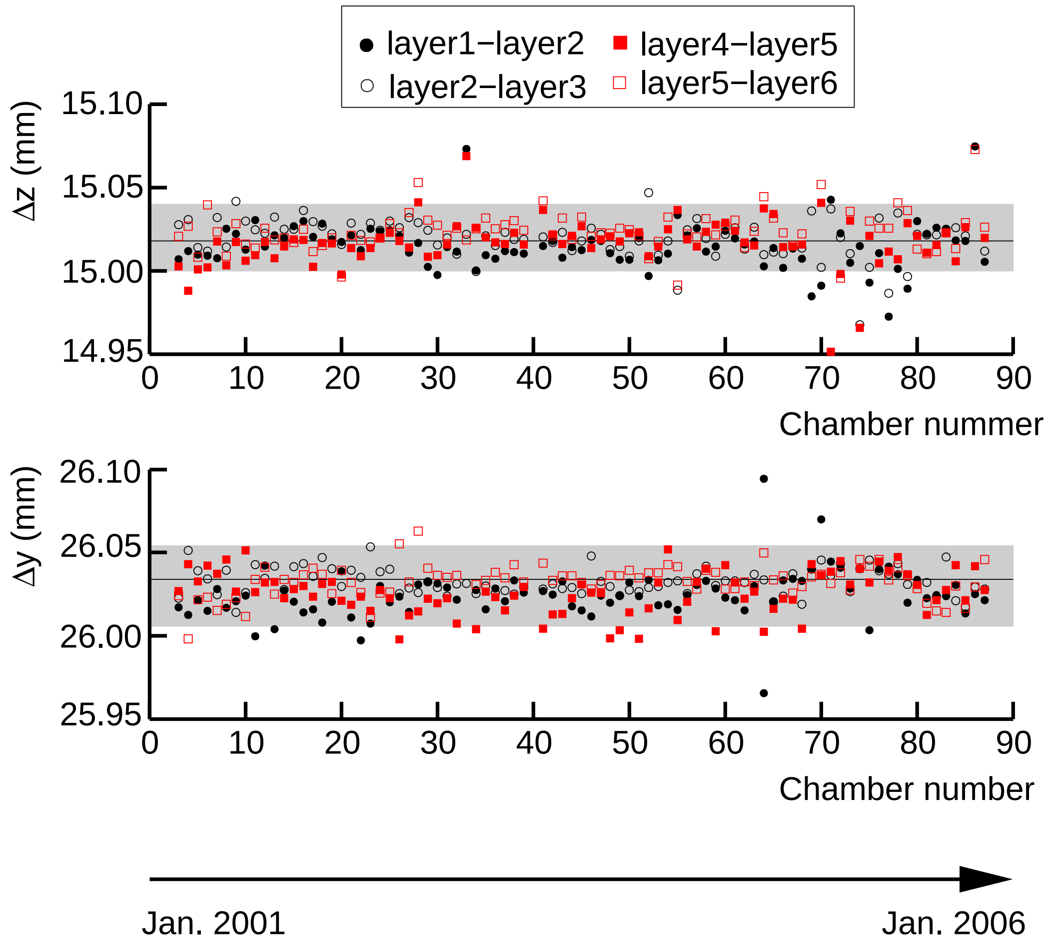



**Positioning precision: 5 $\mu$m, mechanical and optical monitoring**

# Geometry Monitoring: Neighboring Tube Layers

Nominal parameters:
$\Delta z$=15.018 mm
$\Delta y$=26.034 mm
$\Delta\alpha$=0



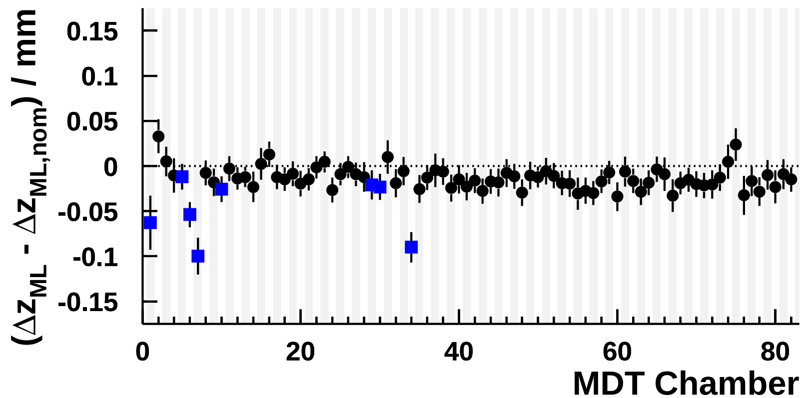




$$\sigma(\Delta z) = 9\ \mu m,\ \sigma(\Delta y) = 12\ \mu m$$

# Cosmic Ray Commissioning

## Example: Cosmic Ray Facility at LMU München

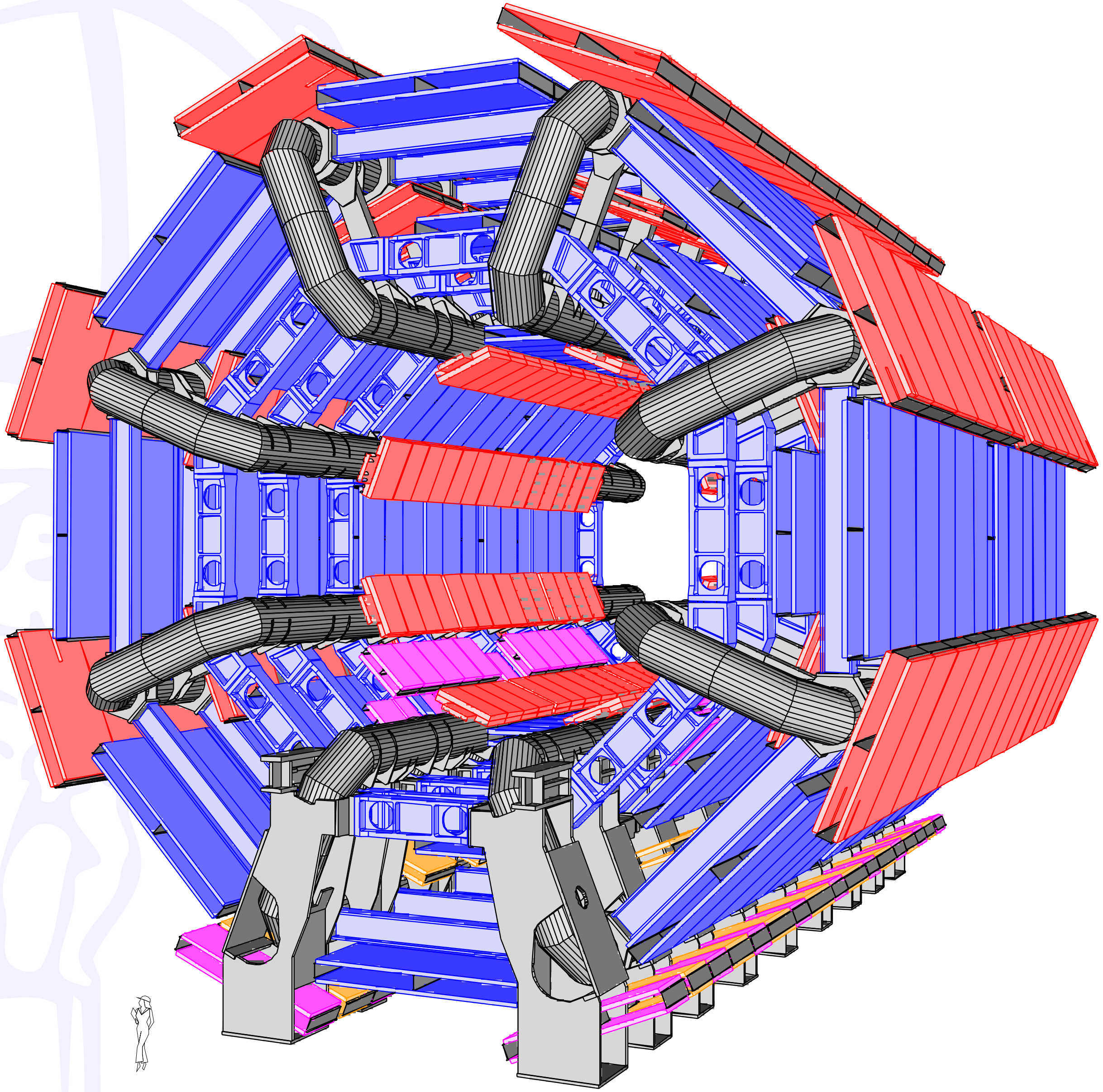
- Drift tube response & homogeneity
- Measurement of wire positions: accuracy $\mathcal{O}(10\mu\text{m})$ and chamber geometry parameters: accuracy $\mathcal{O}(2\text{–}5\mu\text{m})$



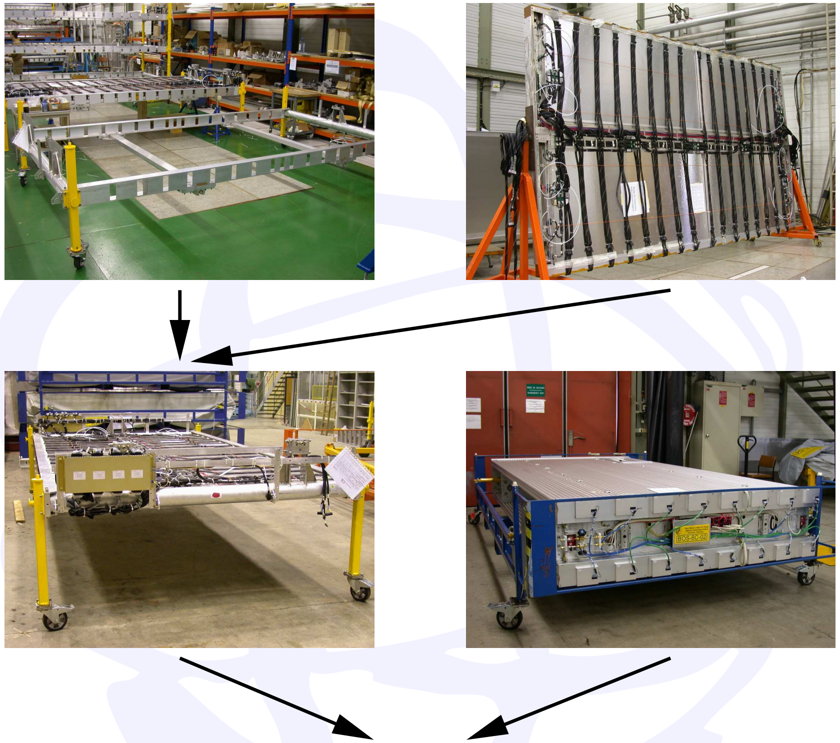

- Calibration rate: 2 MDT / week

**All 88 MPI MDT Chambers tested Sep. 2003–Jan. 2006**

# The ATLAS Barrel Muon Spectrometer



# Commissioning & Integration



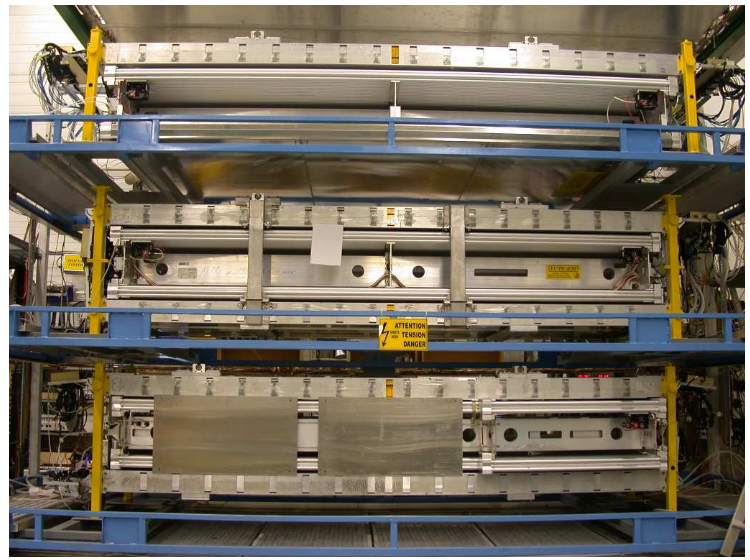
- Commission Monitored Drift Tube Chambers

**For middle and outer layers:**

- Test Resistive Plate Chambers
- Combine to muon station (weight: 1 t)
- Precise mechanical adjustment

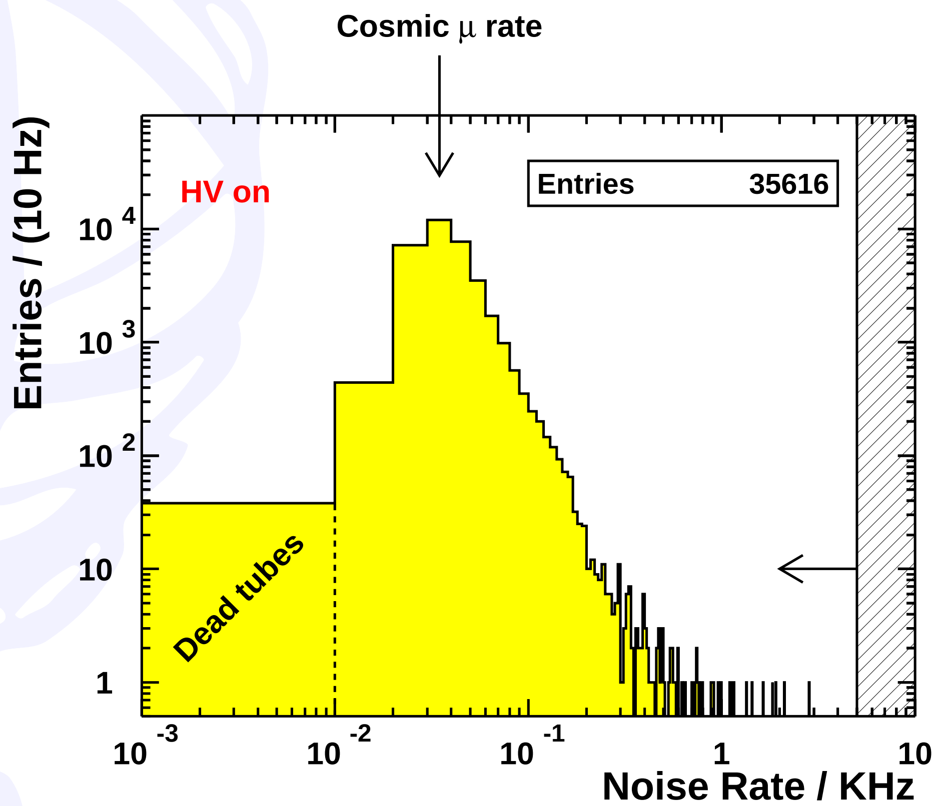
**All stations:**

- Cosmic Ray certification



## All 640 barrel muon stations successfully certified

## Example: MDT Noise Test



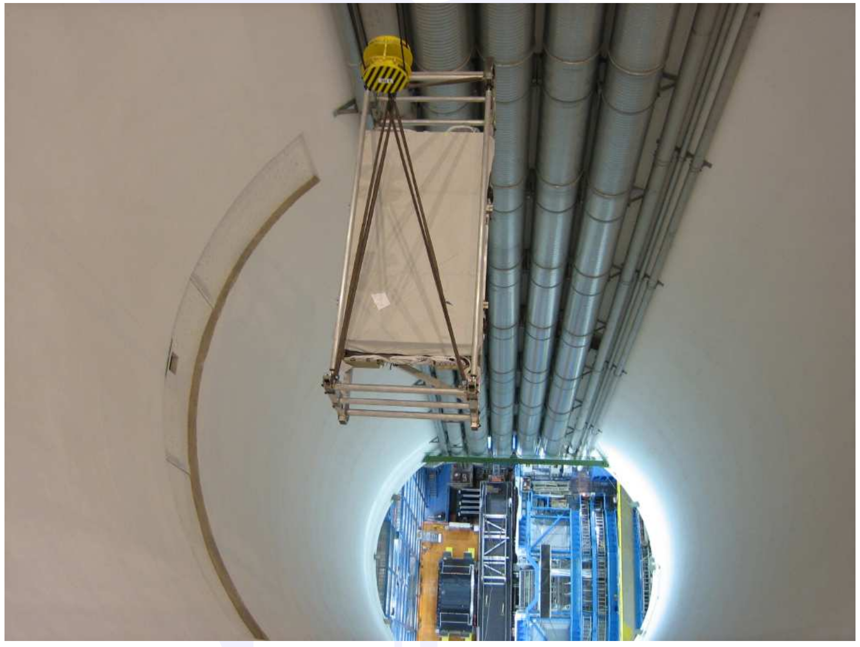

## Very low failure rate of all components:

- Electronics, alignment, HV etc. at 1% level
- Dead channels below 0.1%

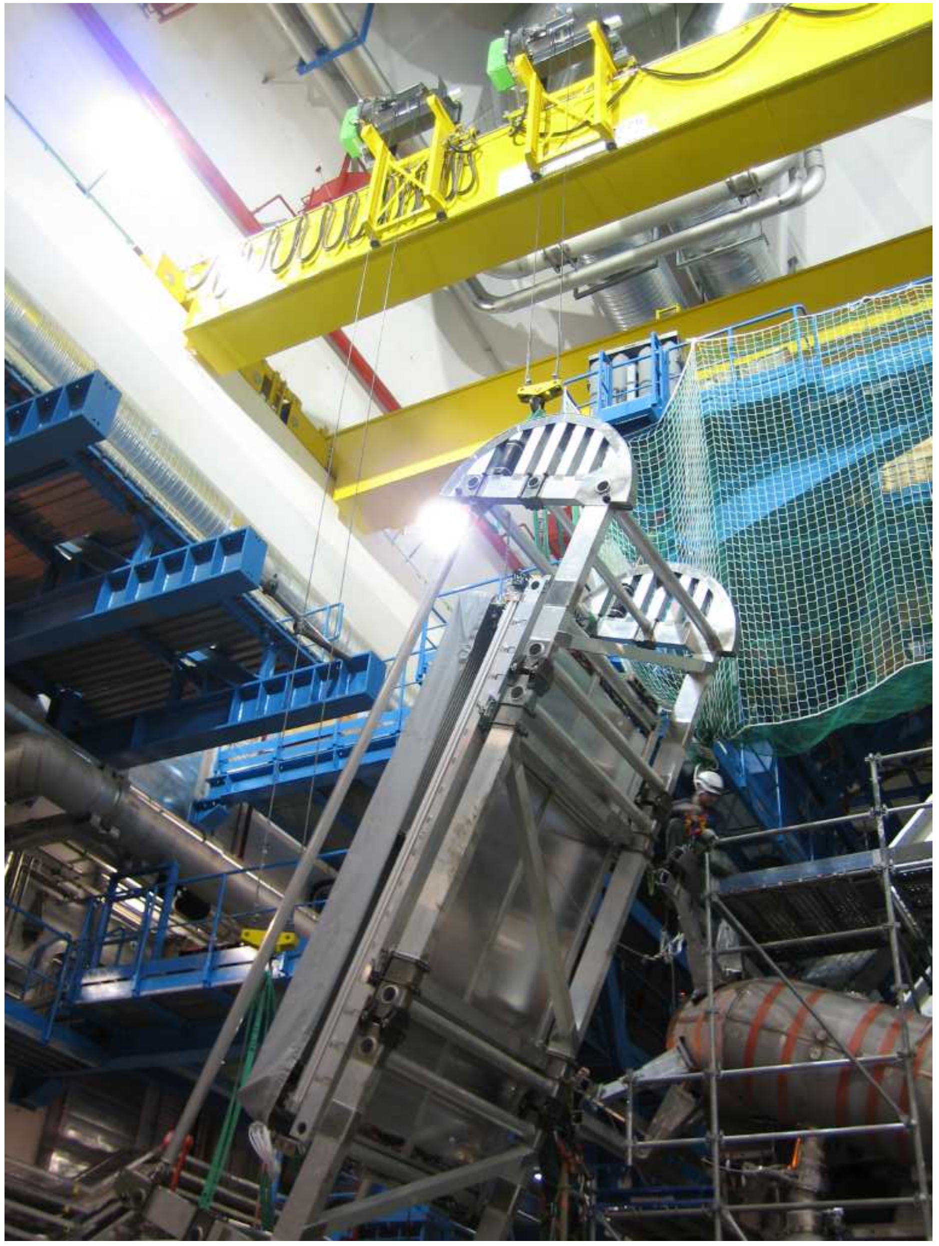
# Barrel Installation

## At the Surface

## On the way down to the Cavern. . .



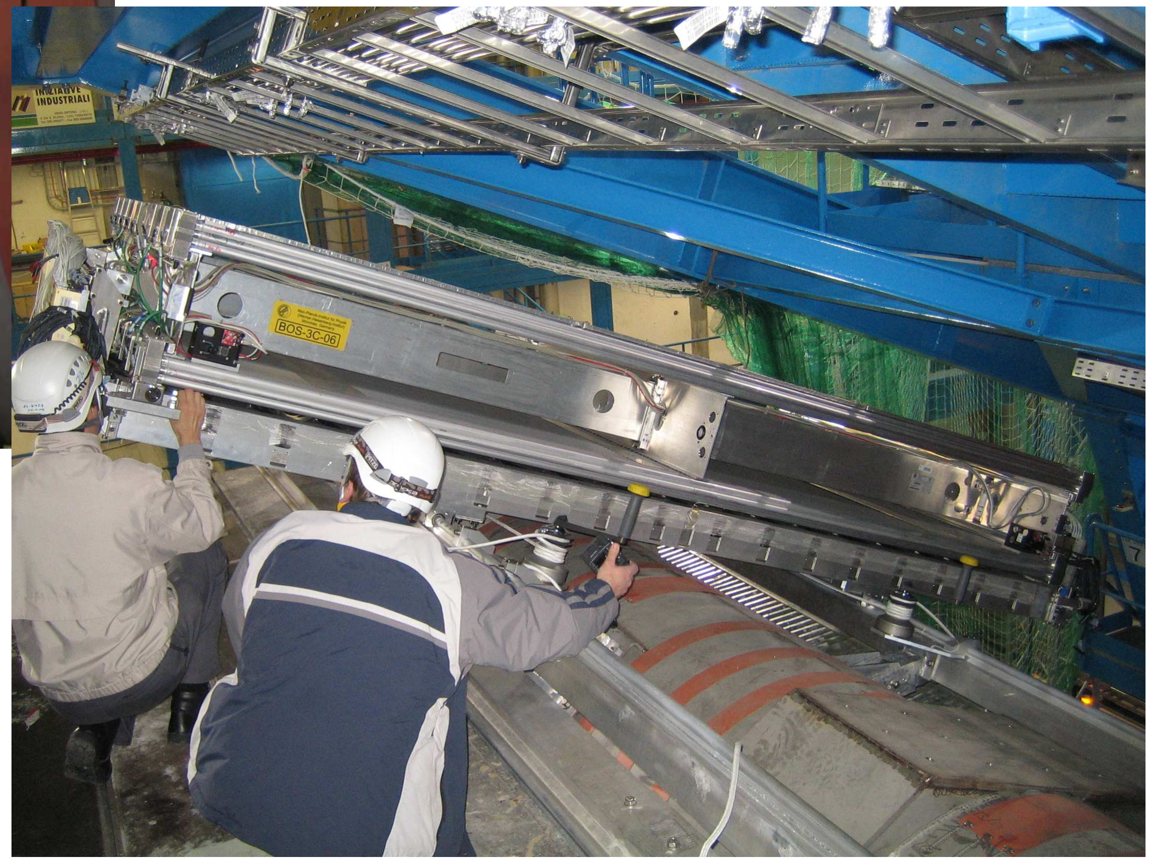
## Installation



# Barrel Installation

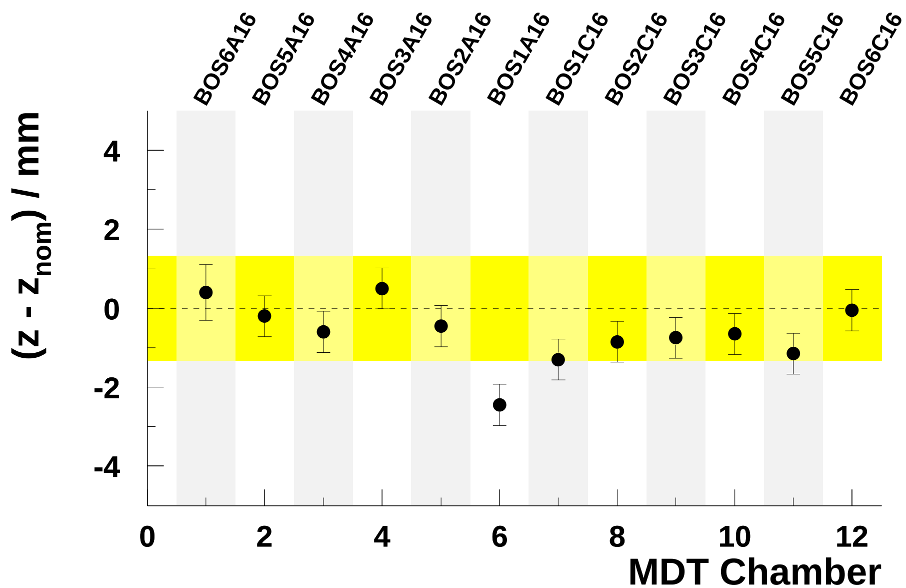
Docking to ATLAS rail system...


Installed Muon Station




**Installation rate: Up to 4 stations / day**

# Station Adjustment and Positioning



# Installation 92% complete

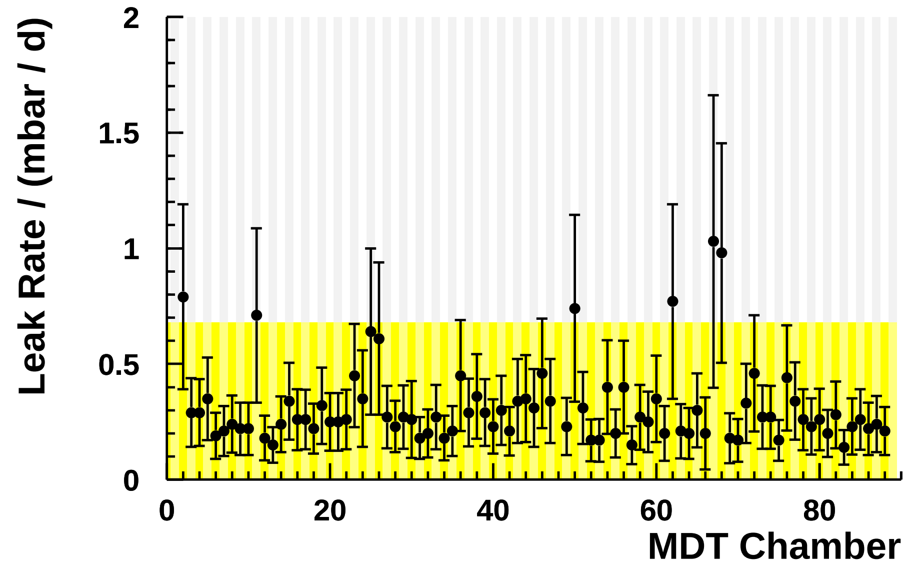
## Chamber Commissioning

- Testing of individual chambers starts immediately after installation

## Full Sector Commissioning

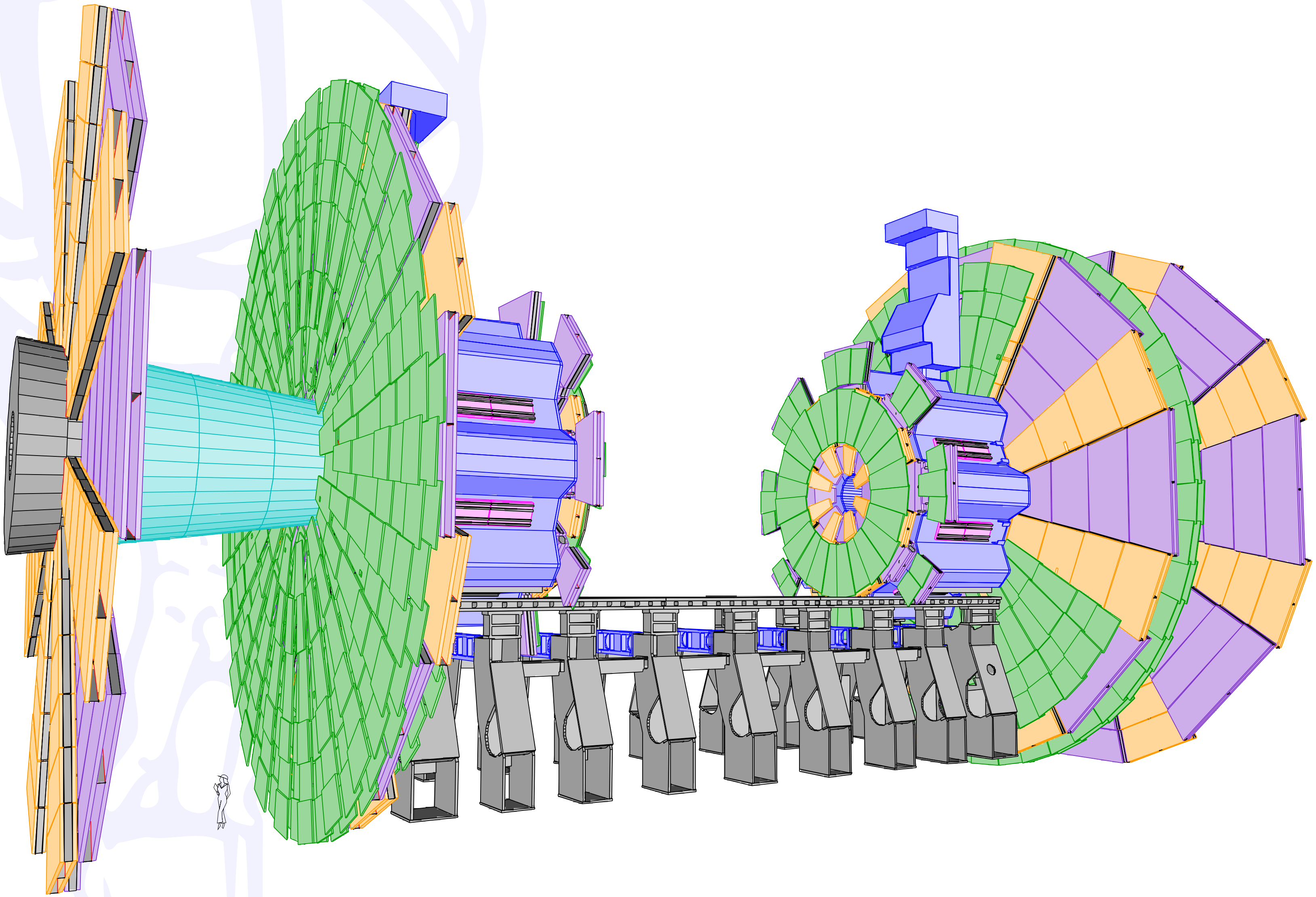
- March – November 2007
- 2 sectors / month (72 muon stations)
- Cosmic ray data taking

## Gas Leak Rates



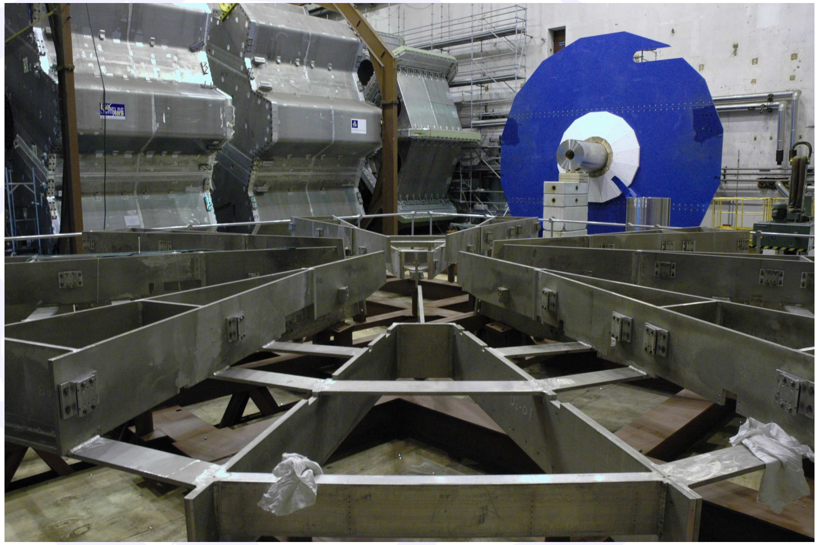

**285000 O-ring seals**

# The ATLAS Endcap Muon Spectrometer



# Commissioning & Sector Assembly

## MDT Small Wheel Support



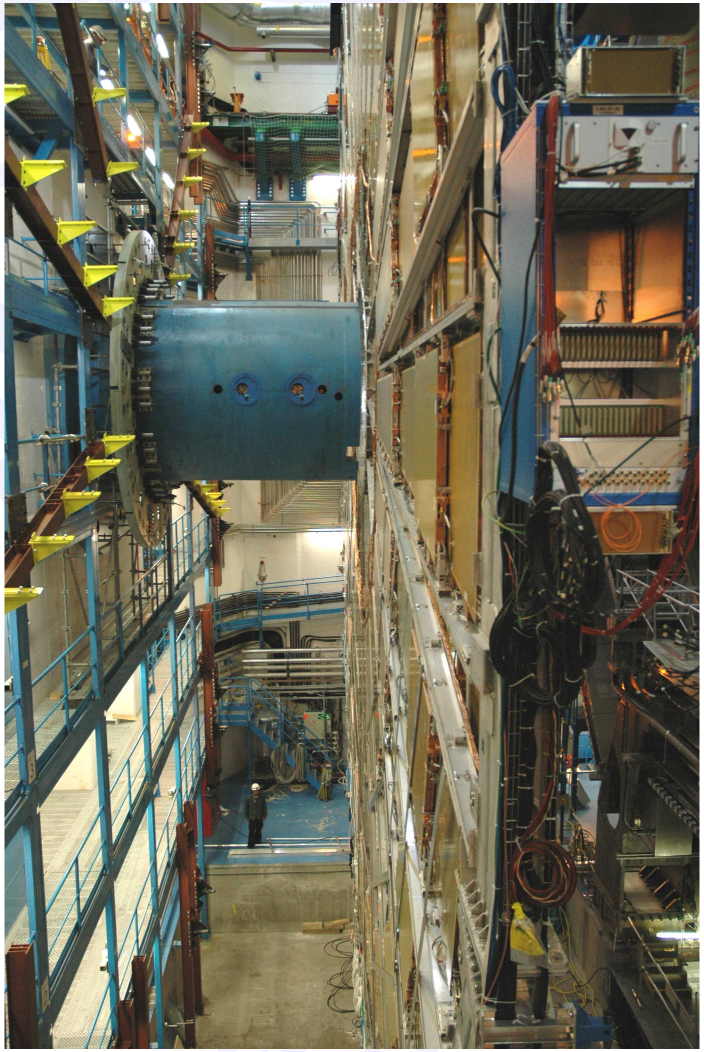
## TGC Commissioning

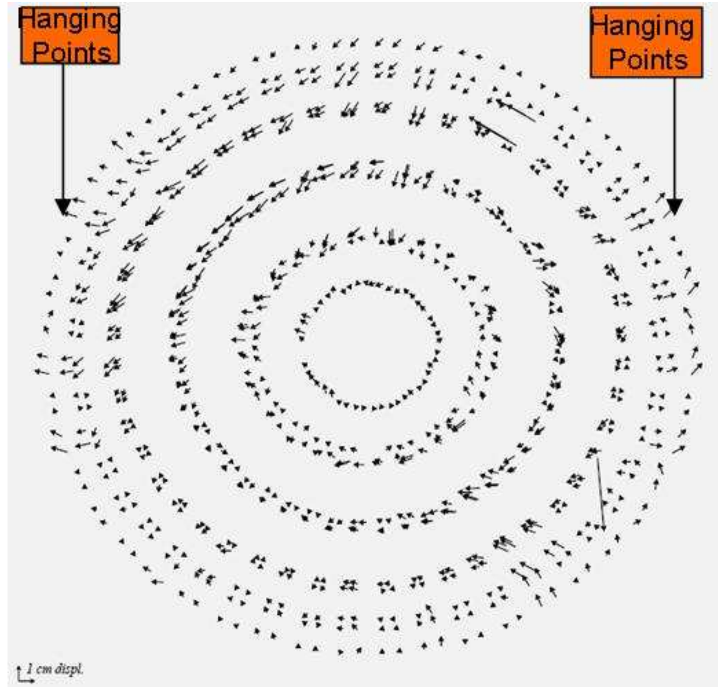
## MDT Sector

## TGC Sector Assembly

# Endcap Installation

## Release of First TGC Big Wheel, Nov. 2006

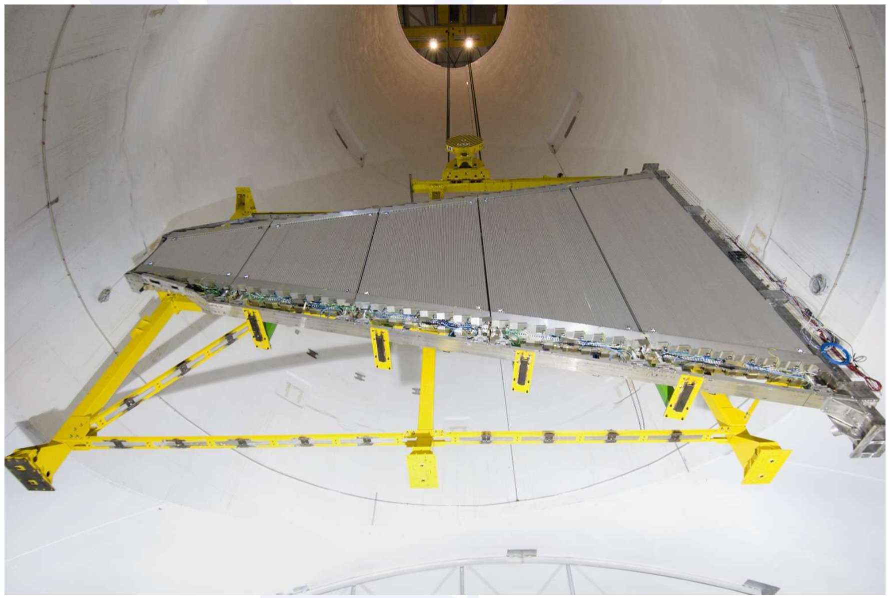





- Chamber positions measured with internal sensors during load transfer
- Optical Chamber survey after movement
  - Movement in wheel plane: few mm
  - Movement out of wheel plane: +/- 7 mm

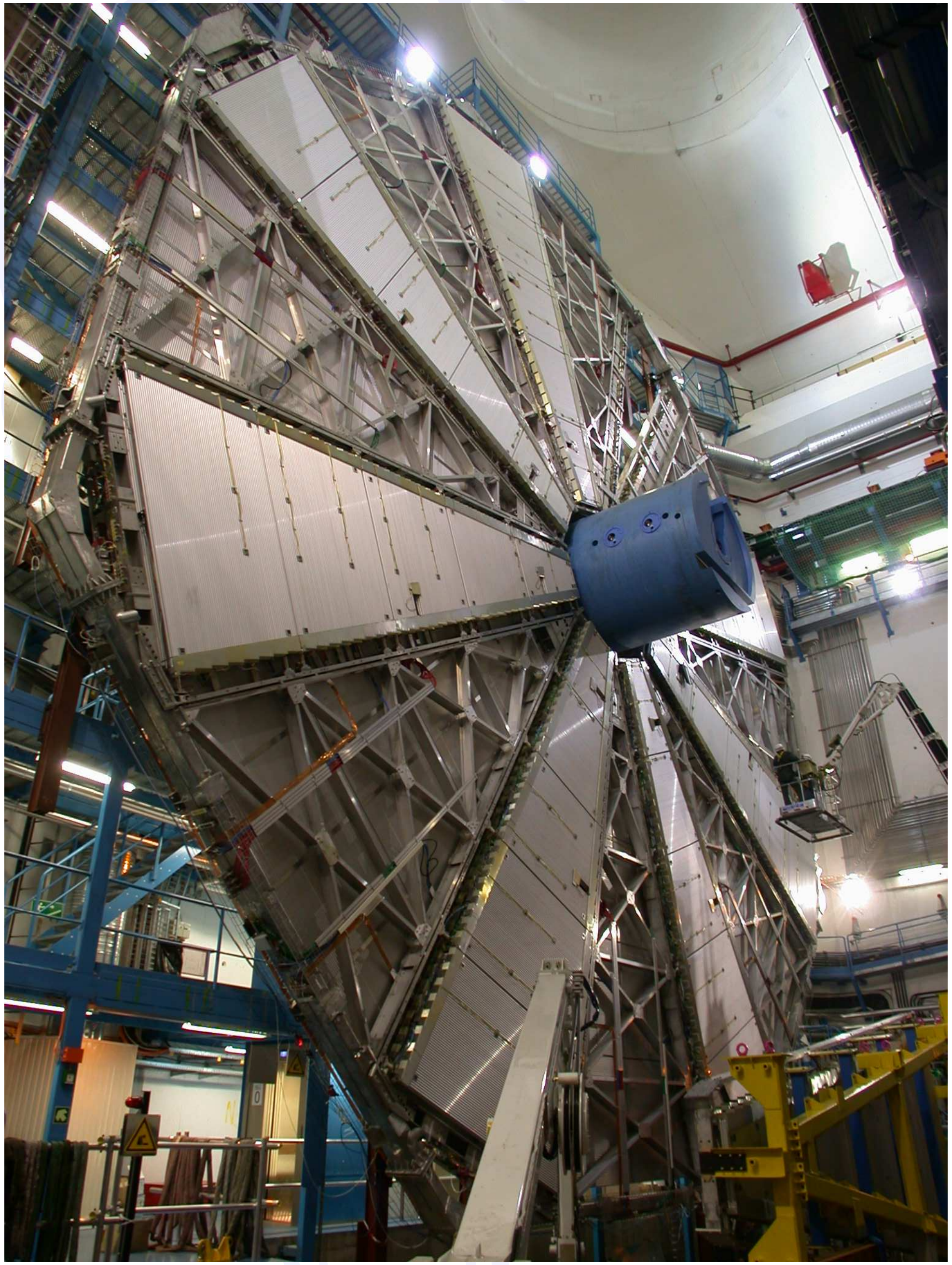
**No negative effect on detector integrity**
**Geometrical accuracy satisfactory**

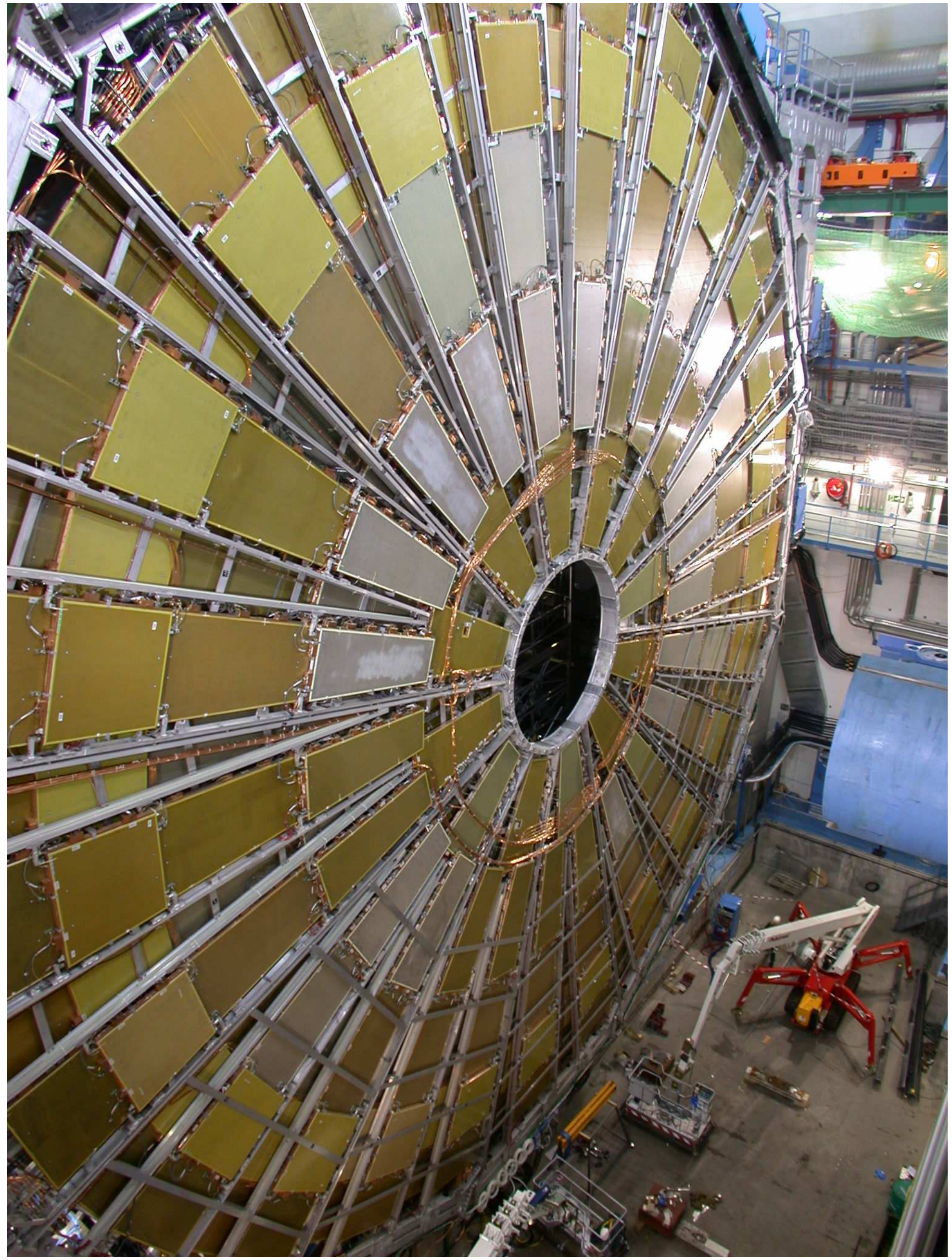
# Endcap Installation



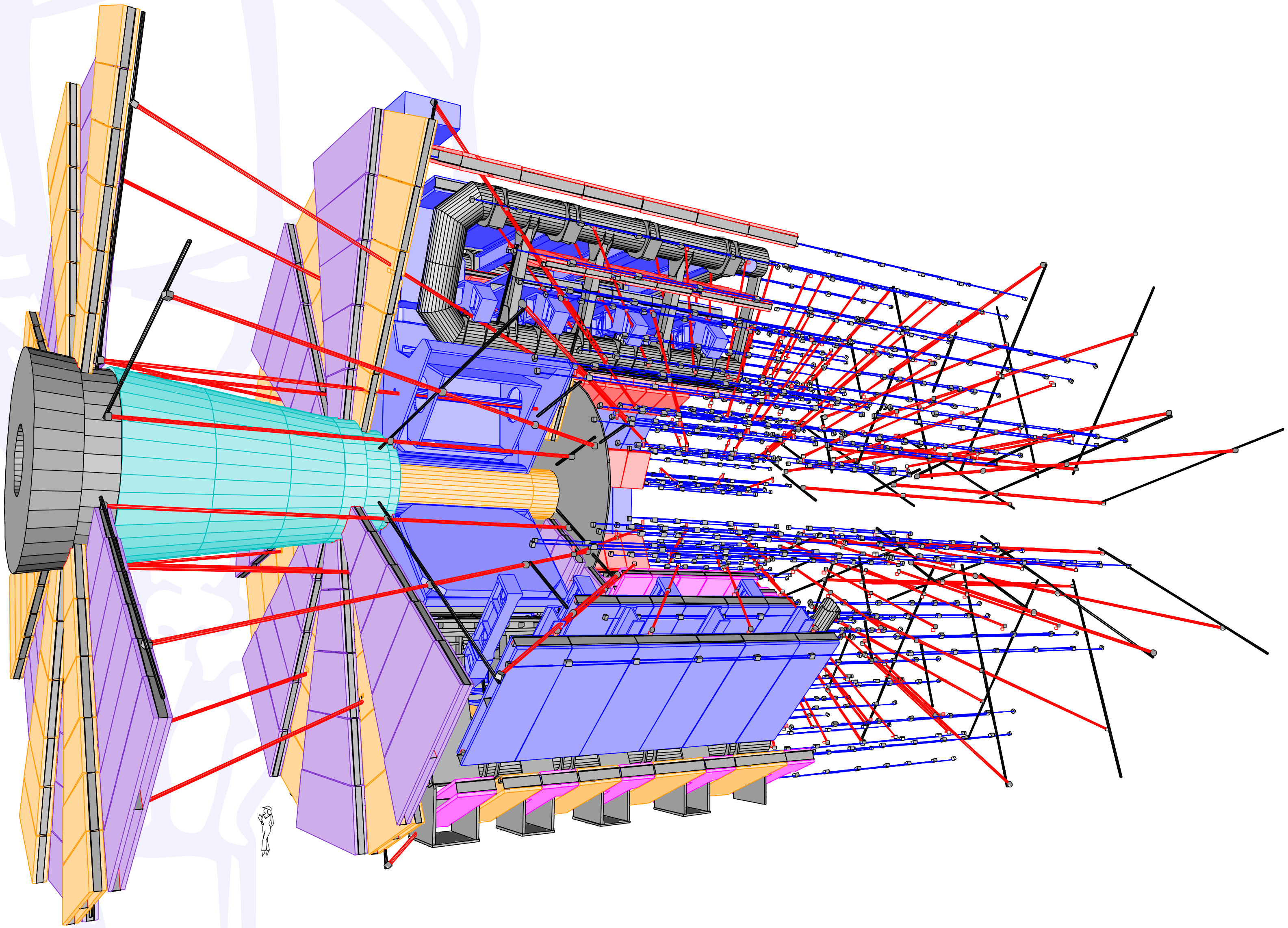
First MDT Big Wheel completed

# Endcap Installation

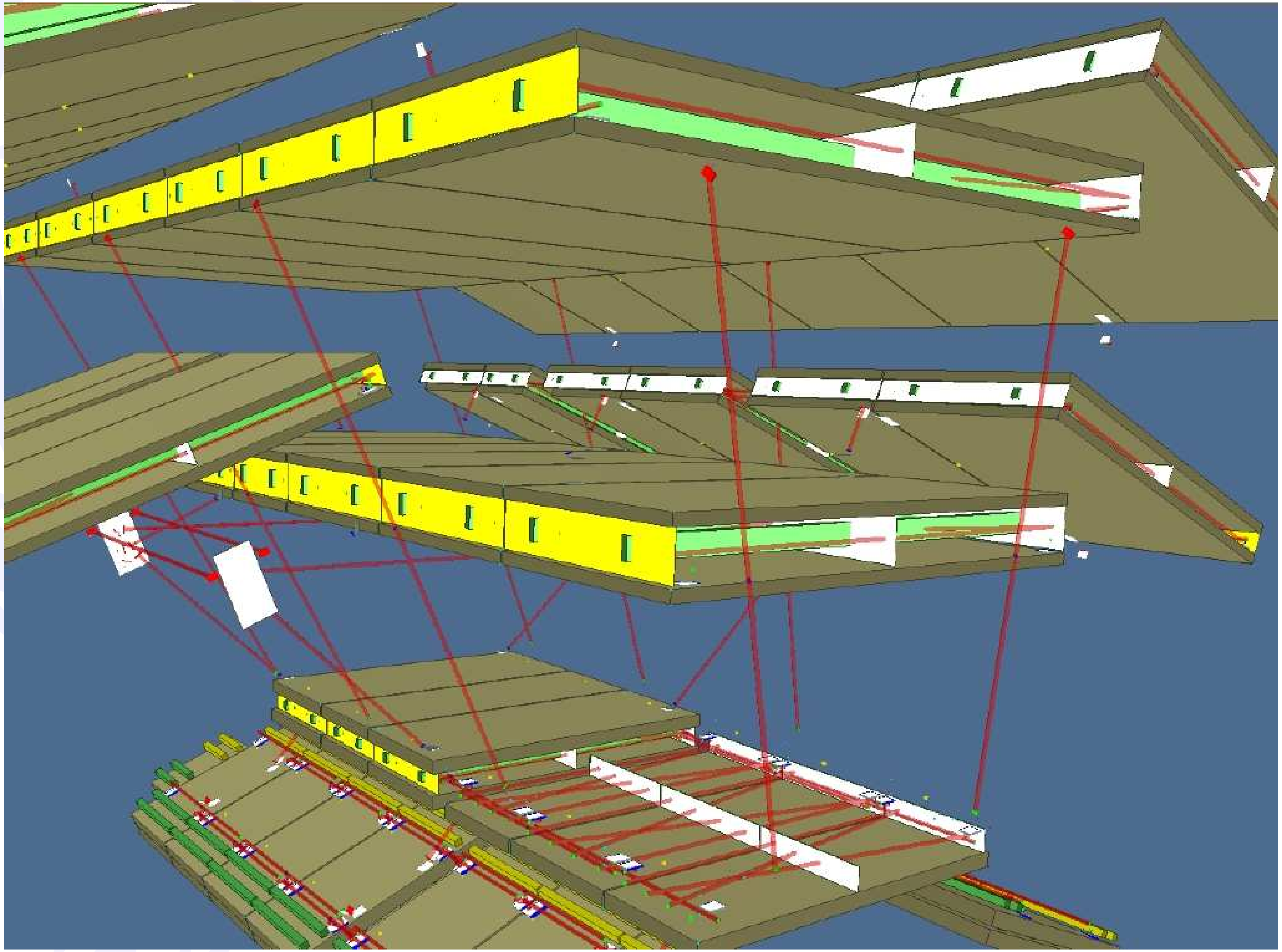




# The Alignment System



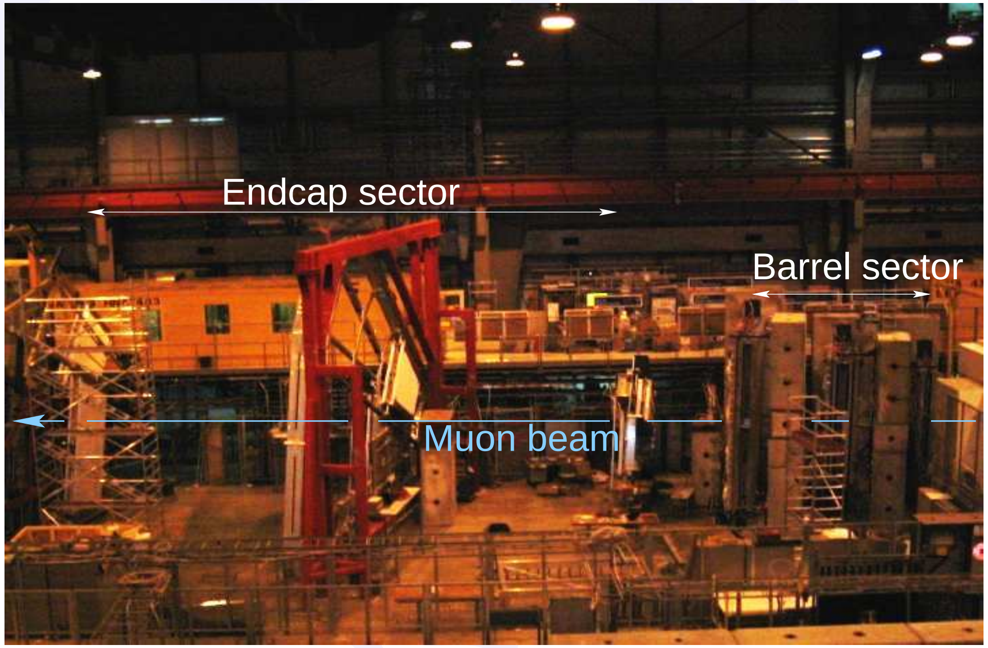
# Barrel Alignment System



**$\approx$ 6000 sensors in total**

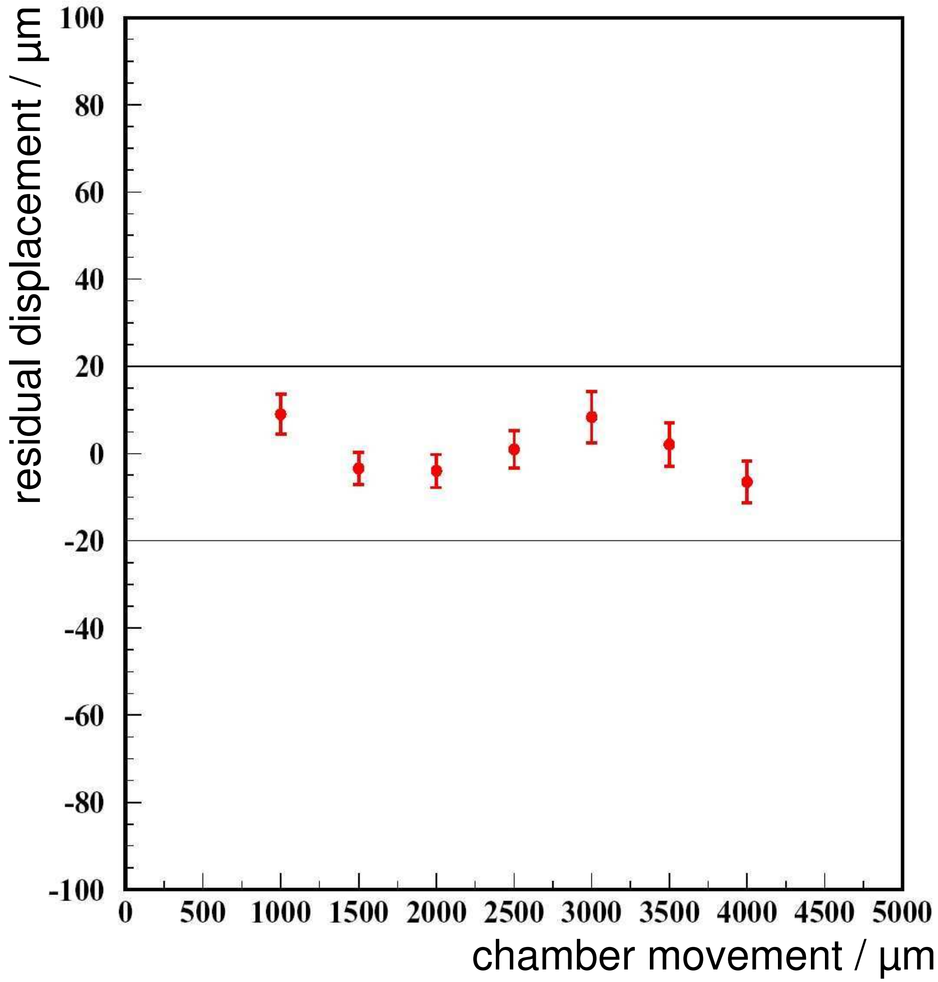
# Alignment System Test

## Setup H8 Test Beam 2003



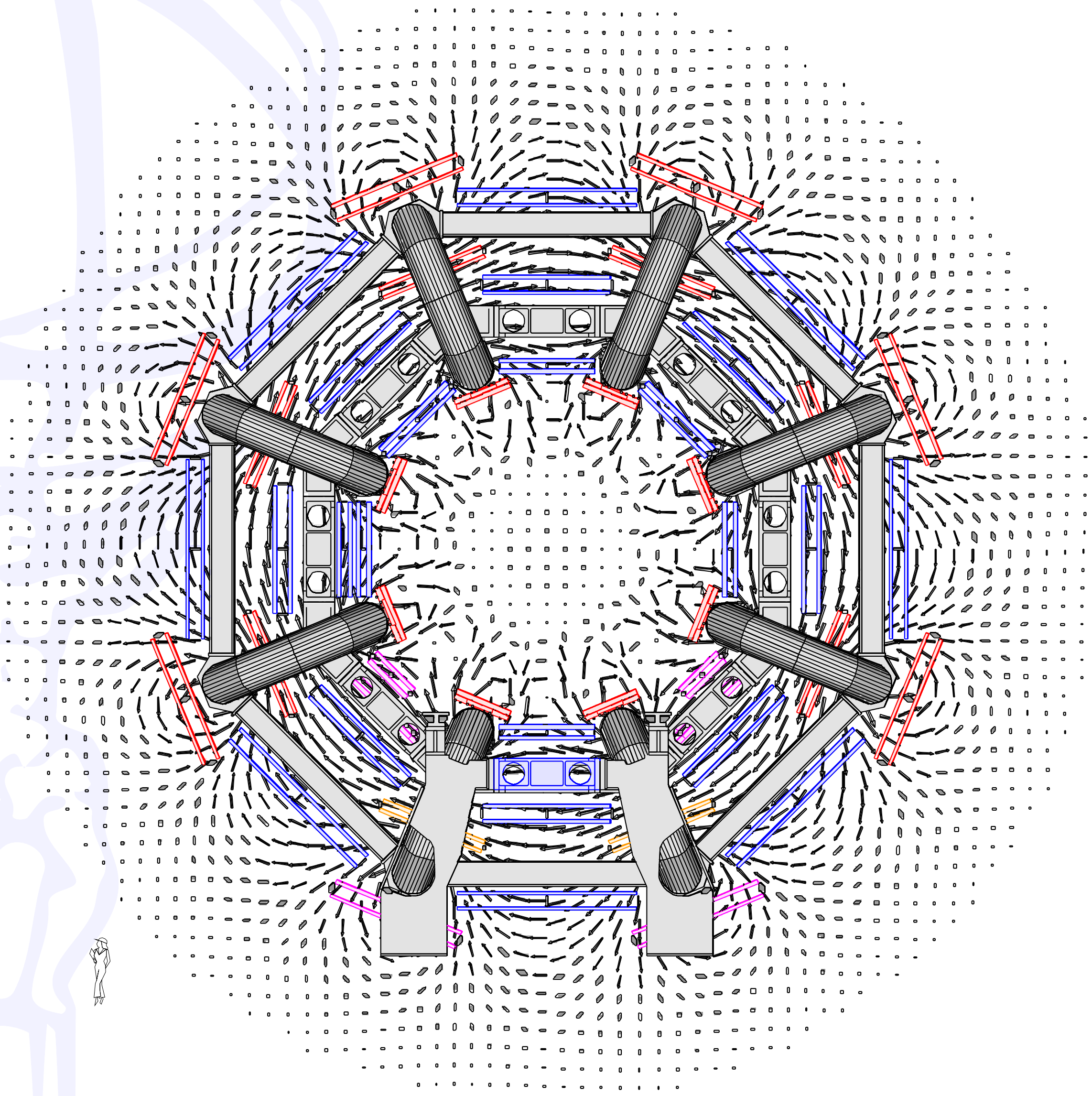

- Mockup endcap and barrel sectors: inner, middle, outer muon chambers
- Chambers movable

## Results



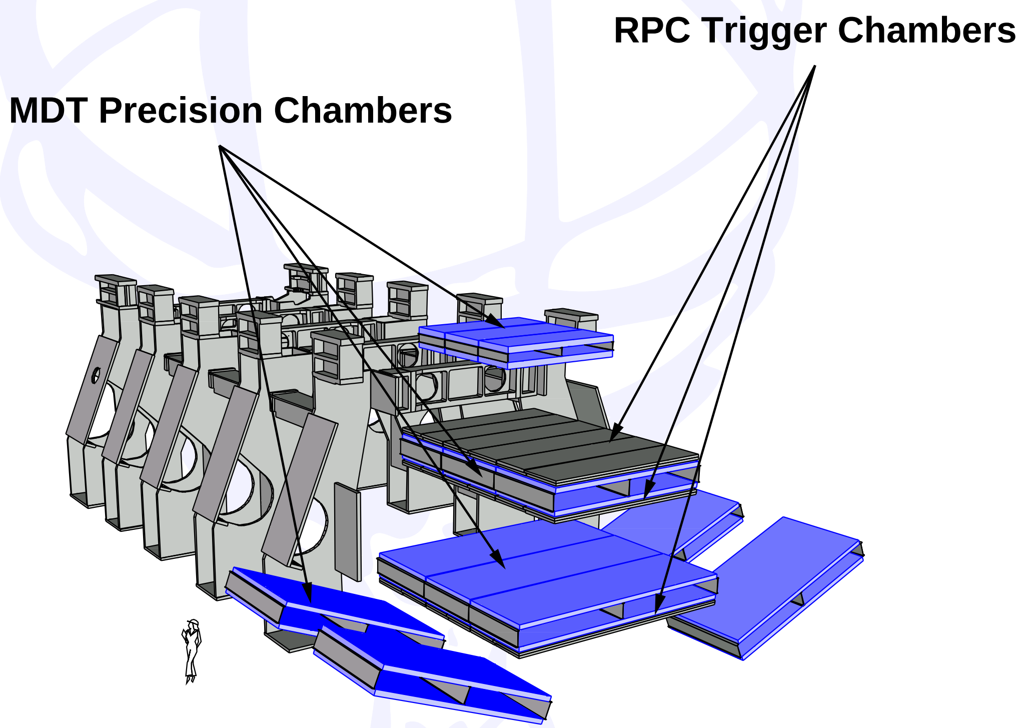

**Alignment system has required accuracy**

# First Results from the November 2006 Barrel Cosmic Run with Magnetic Field



# Nov. 2006 Cosmic Barrel Run

## Setup




- 18–19th November 2006
- Barrel Toroid at full field
  Current: 20.5 kA

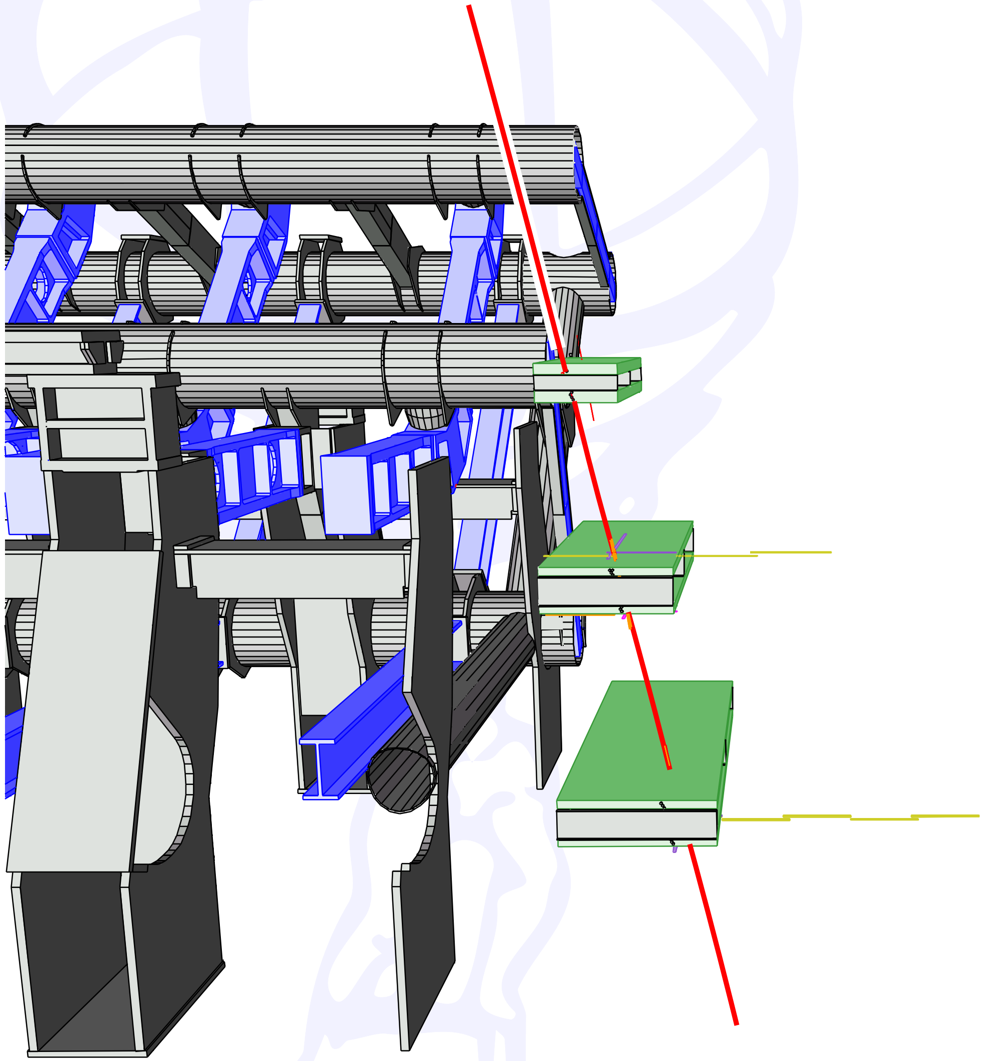
## Muon Instrumentation

- 13 Muon Stations (2% of barrel)
  - 1/4 sector
  - 2 stations in each neighboring sector
- Low- and high-$p_T$ trigger
- Muon barrel alignment (15% of barrel)
- Use of Central Trigger Processor
- DAQ & Online Monitoring

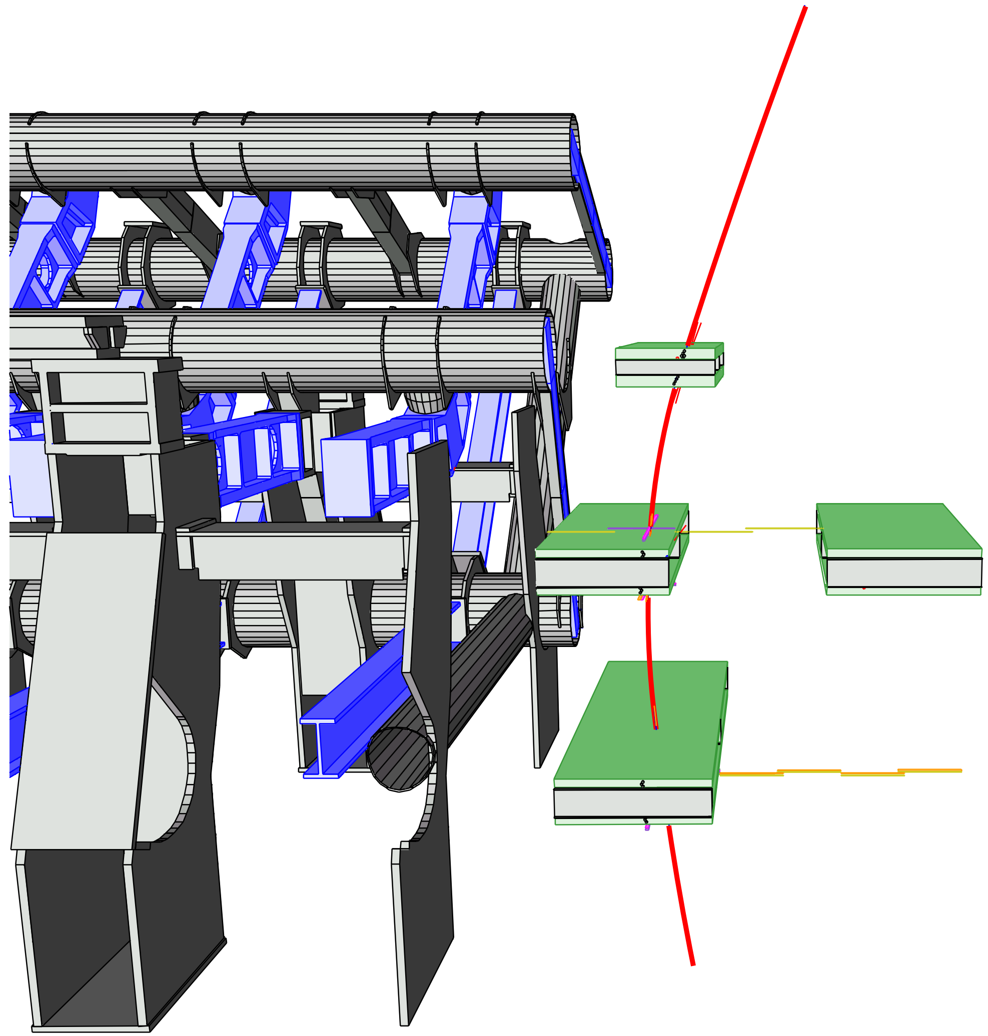
**First complete system test for barrel spectrometer**
**Up to now only components in magnetic field**

# Some Events

## High momentum Track

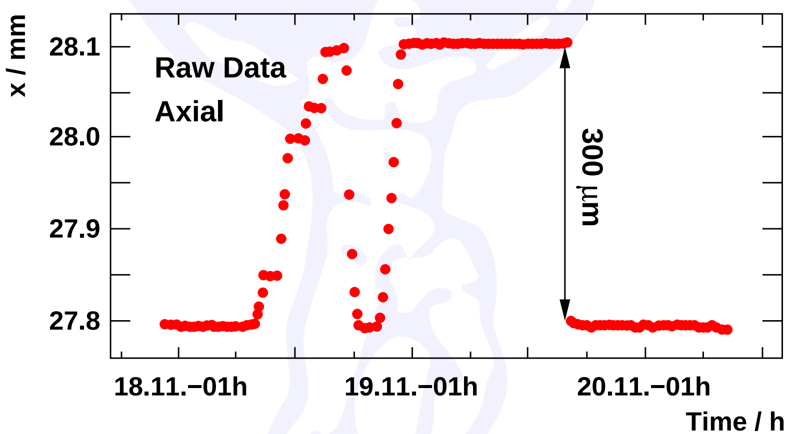


## Low momentum Track

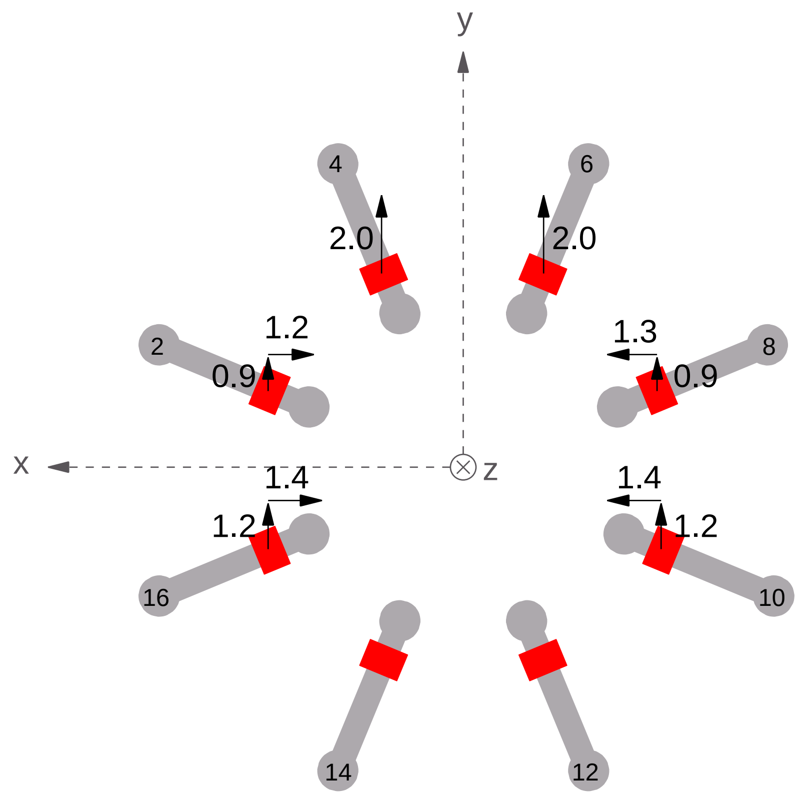


# Alignment System Results

- 15% of alignment system tested
  (875 lines, all subsystems)
- Deformation of barrel toroid as expected
  (no field $\longrightarrow$ full field)
- Chamber deformations: 100 $\mu$m
- Axial movements: 300 $\mu$m
- Projective tower movements: 500 $\mu$m



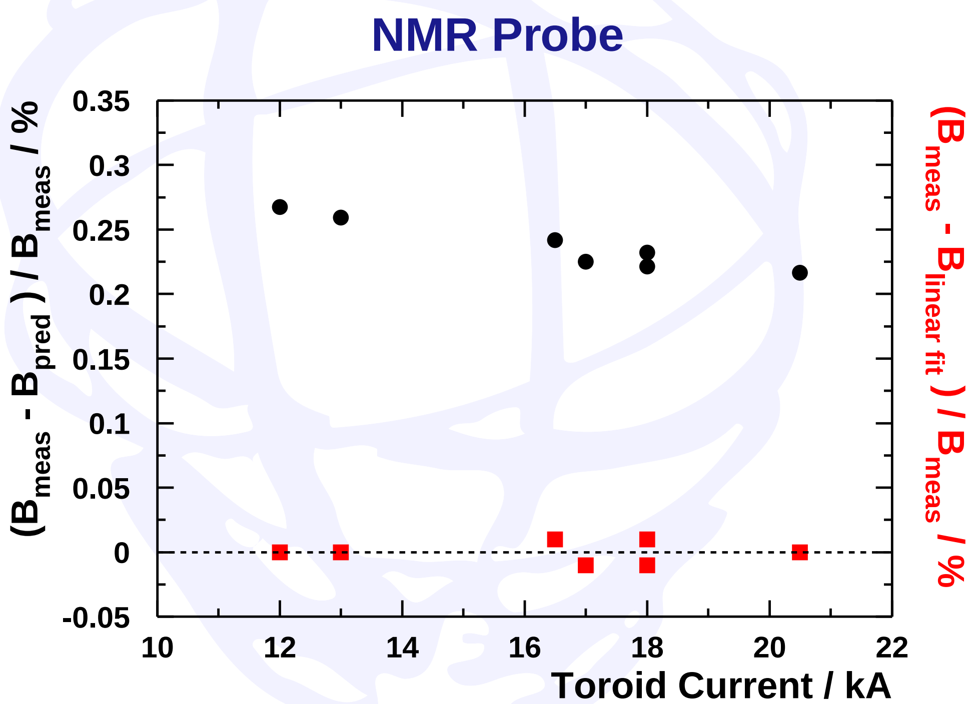

**Barrel Toroid Deformation at Full Field**




## Alignment system working and indispensable

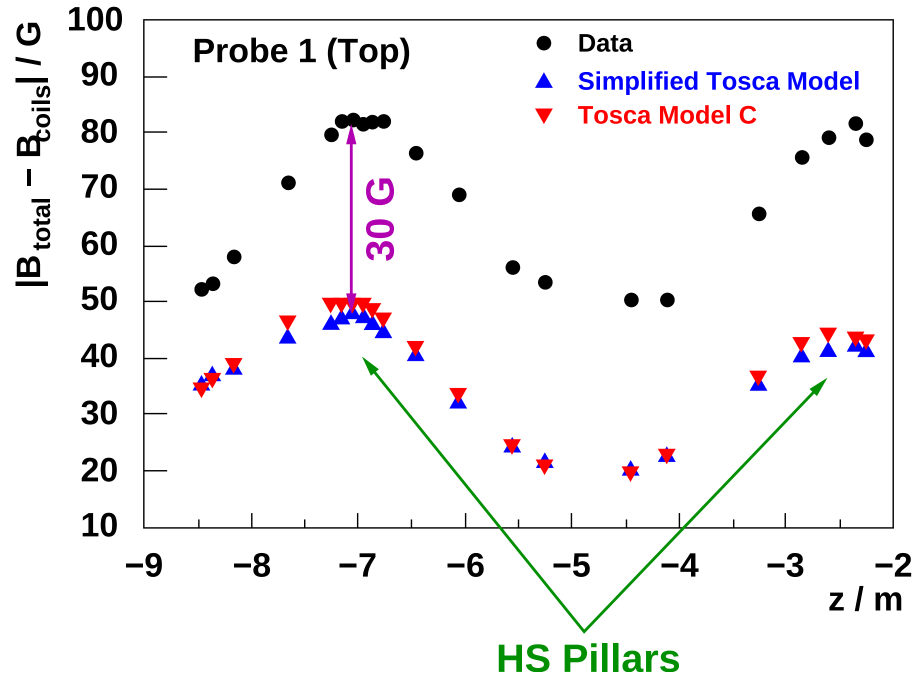
# Magnetic Field Measurements

## Predicted Field vs. Measurement




- Predicted field scaled from calculation at 10 kA
- Measurement at point with no gradient and very little magnetic pollution (middle MDT layer)
- Very good agreement

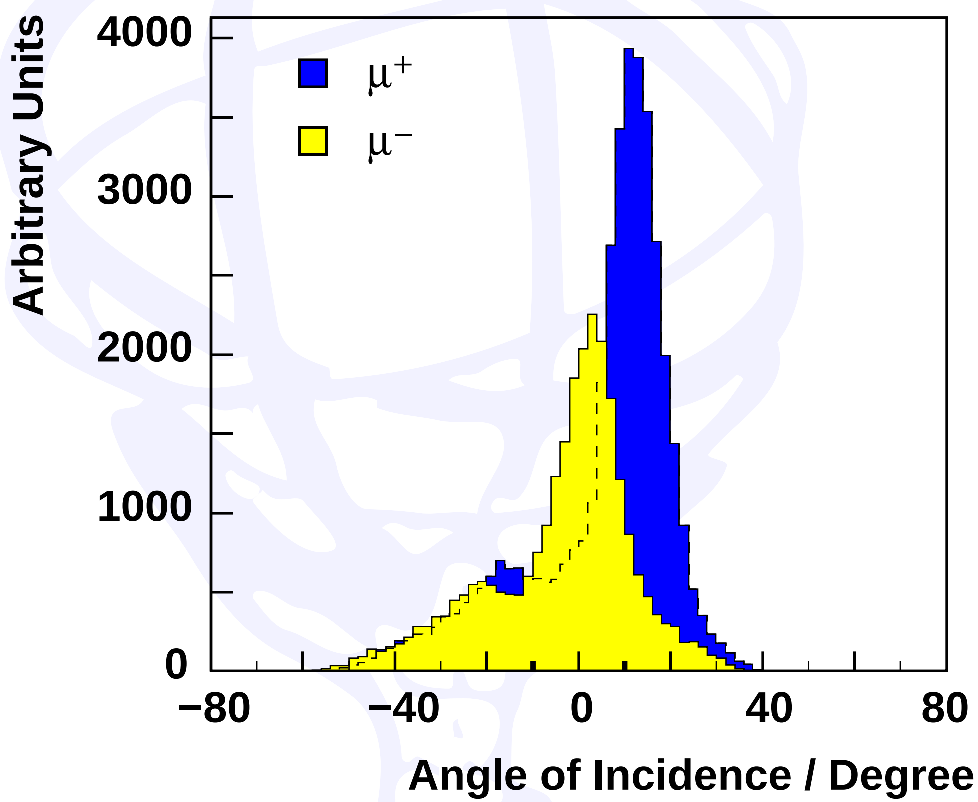
## Influence of the Surrounding Service Structure




- Service structure of steel
- Perturbations well simulated, can reach 500 G in some areas
- Model parameters will be further refined

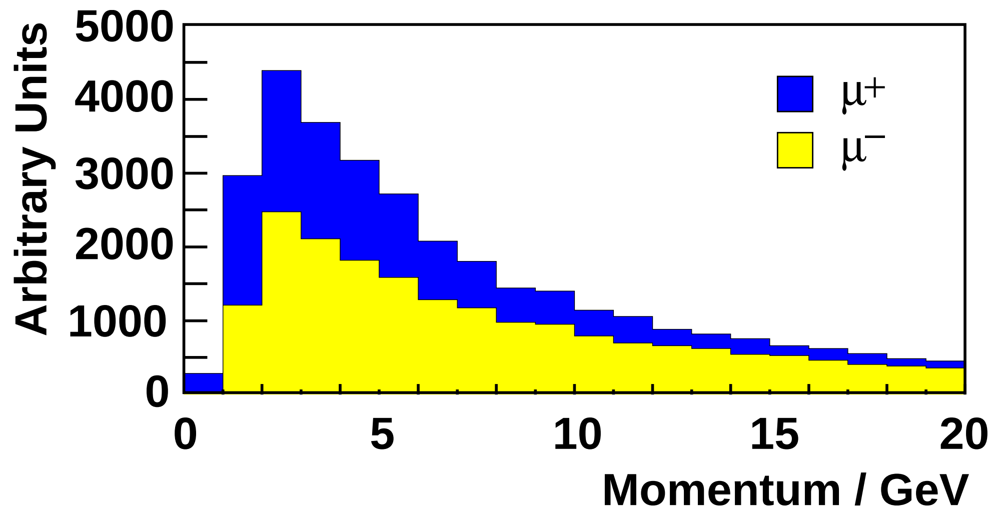
# Muon Spectra

## Angular Distribution




- Clear separation of $\mu^+$ and $\mu^-$
- Angular distribution consistent with geometry (two peaks correspond to near and far access shafts)

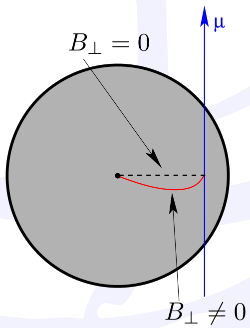
## Muon Momenta



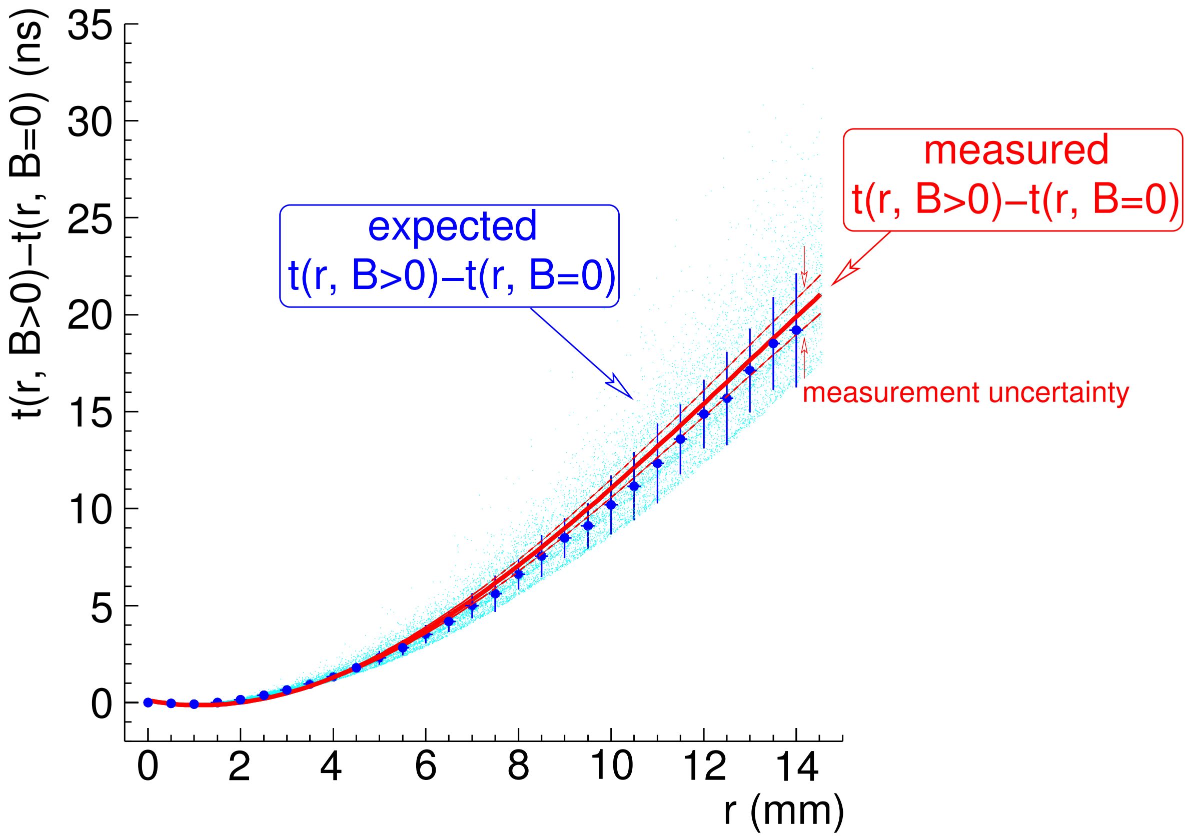

- Momentum spectra fall-off consistent with expectations
- Ratio $\mu^+ / \mu^- = 1.48 \pm 0.27$ in agreement with PDG value (1.25–1.30)
- Further Monte-Carlo studies in progress

## Influence of the Magnetic Field

- Magnetic field changes space–drift-time relation (Lorentz force)

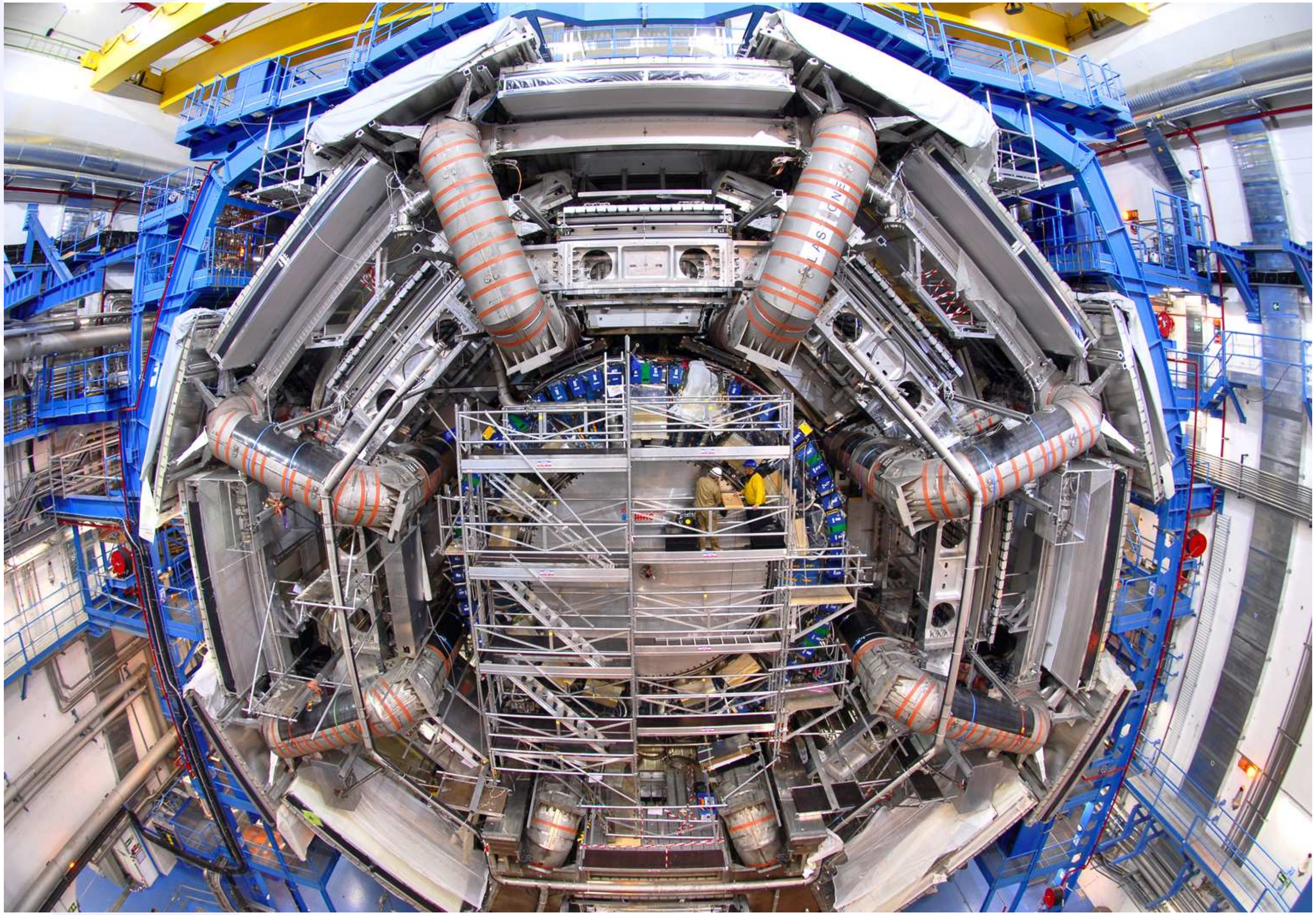



- Change of maximum drift time from testbeam measurements: 70 ns$/\mathbf{B}_\perp^2 \rightarrow$ 500 $\mu$m position error
- Model: $t(r, \mathbf{B}) \approx t(r, 0) + \mathbf{B}_\perp^2 \cdot f(v_{\mathbf{B}=0}, \mathbf{E})$ (fit to testbeam data $\rightarrow$ accuracy of 1 ns)




**Excellent agreement between measurement and expectation**

# Summary



# Summary

- Chamber production meets stringent requirements on accuracy
- Barrel muon spectrometer installation almost finished
- Endcap muon spectrometer well advanced
- System test of barrel muon spectrometer successful
  - Toroid at full field
  - Toroid Fast-Quench test
  - 1/4 sector of muon station tested
  - Trigger test (muon LVL1 with CPT, LVL2)
  - Very useful to study calibration of precision chambers
- Combined system test (with calorimeter) planned for March/April
- Beamline to be closed in August

**ATLAS Muon spectrometer will be ready to take data in November 2007**

# Thank you...

Giulio Aielli (INFN Roma II)

Christoph Amelung (CERN)

Gerjan Bobbink, Egge van der Poel, Jochem Snuverink (Nikhef)

Gabriella Gaudio (INFN Pavia)

Claudio Ferretti (University of Michigan)

Mauro Iodice, Fabrizio Petrucci (INFN Roma III)

Masaya Ishino (University of Tokyo)

Sandra Horvat, Oliver Kortner, Jörg v. Loeben (MPI Munich)

Witold Kozanecki, Rosy Nikolaidou (DAPNIA - CEN Saclay)

Michaal Maaßen, Stephanie Zimmermann (ALU Freiburg)

Giora Mikenberg (Weizmann Institute of Science)

Sotirios Vlachos (National Technical University of Athens)

## Please Note the Following ATLAS Muon Talks

Doris Merkl (LMU München), *Installation und Inbetriebnahme der ATLAS Myon-Driftrohrkammern*, **T 413.1**

Oliver Kortner (MPI München), *Kalibrierung und Alignierung des ATLAS Myon-Spektrometers*, **T 413.2**

Jörg v. Loeben (MPI München), *Test einer effizienten Methode zur Autokalibration der Orts-Driftzeit-Beziehung der ATLAS-Myon-Driftrohrkammern*, **T 413.3**

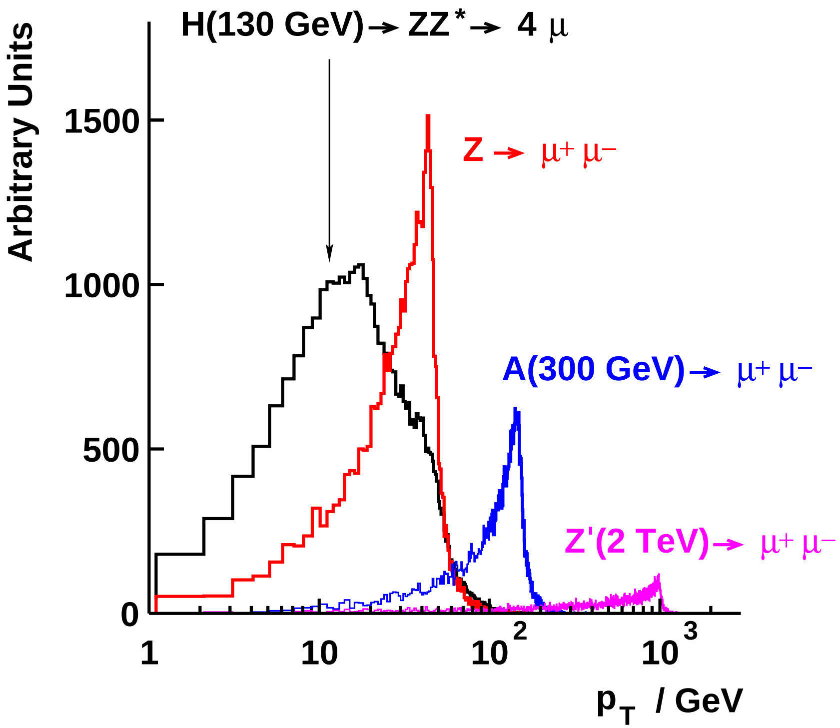
Jens Schmaler (MPI München), *Entwicklung eines Verfahrens zur Alignierung des ATLAS-Myonspektrometers mit Spuren*, **T 413.4**

Matthias Schott (LMU München), *Simulation und Software Validierung des ATLAS Myon-Spektrometers*, **T 413.5**

Thomas Müller (LMU München), *ATLAS MDT-Kammern im Neutronenuntergrund*, **T 413.6**

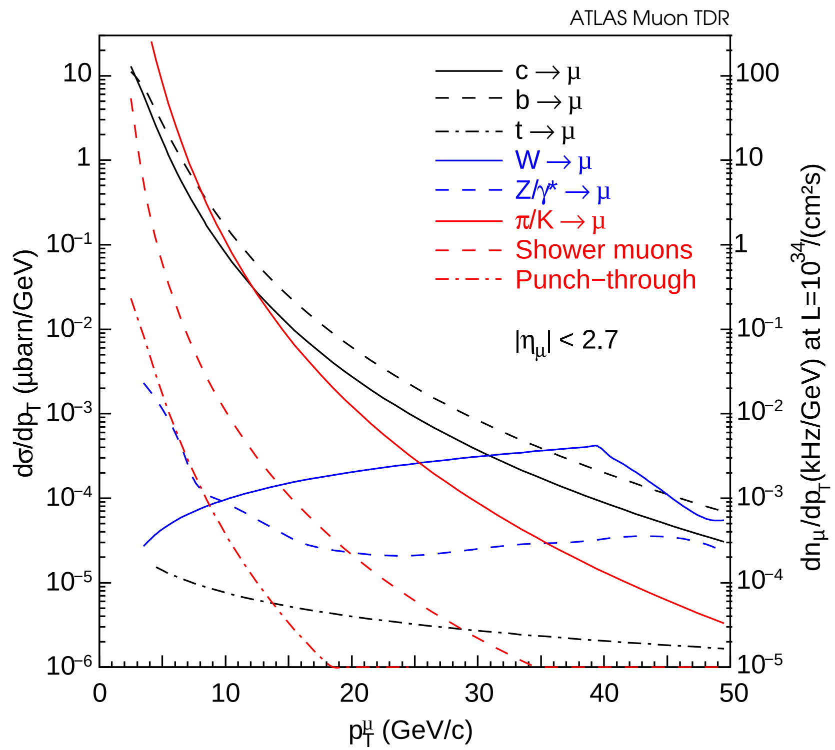
# Additional Slides

## Momentum Distribution




- Efficient muon ID and tracking over wide momentum range (1–$10^3$ GeV) needed

## Inclusive Muon Cross Sections




- Rejection of muons from $\pi$/K decays, shower muons, and hadronic punch through needed

Back ⟷

# Concept of Muon Identification

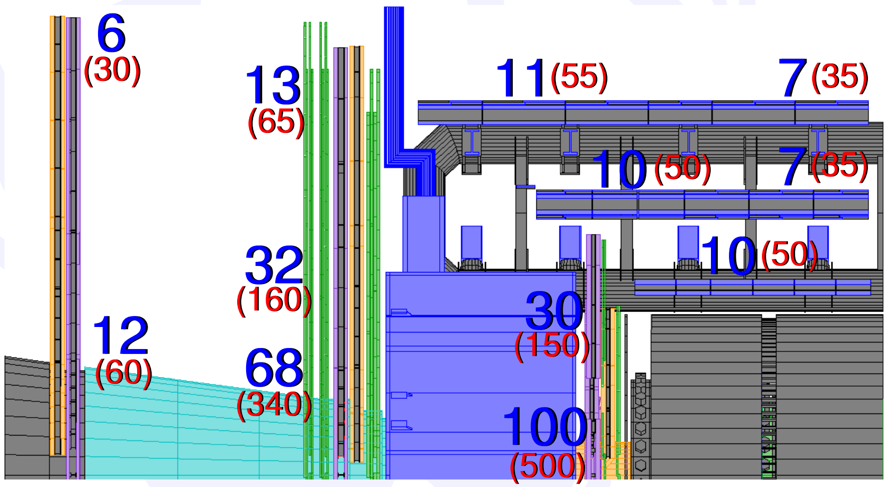
| Goal | Solution |
|---|---|
| • Minimization of hadronic punch-through | Muon system surrounding the calorimeters |
| • Suppression of muons from $\pi$/K decays | $p_T$ measurement with $\Delta p_T / p_T < 10\%$ + well matching inner-detector track |
| • Suppression of shower muons | As $\pi$/K muon suppression + small energy deposit in calorimeter |
| • Primary muons | Best possible momentum measurement and trigger coverage |

Back $\hookleftarrow$

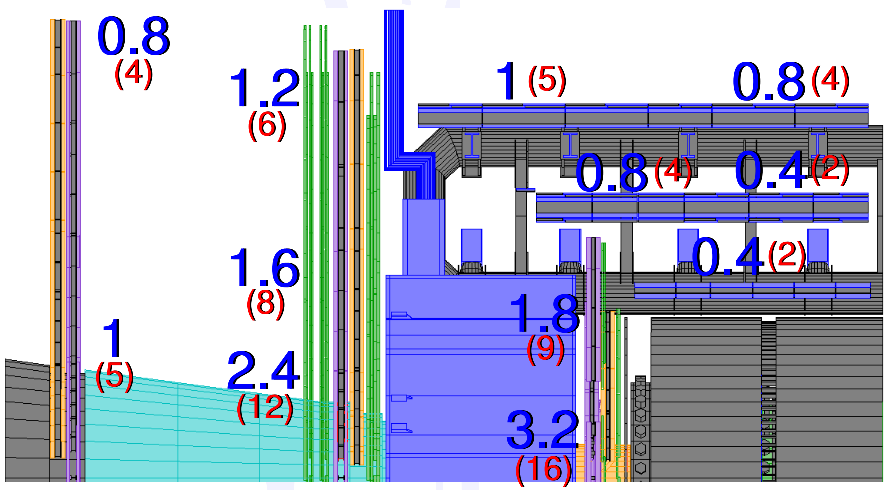
# Particle Rates

## Radiation Levels at $10^{34}/(cm^2\ s)$

### Rate (Hz/cm²)




### Occupancy (%)



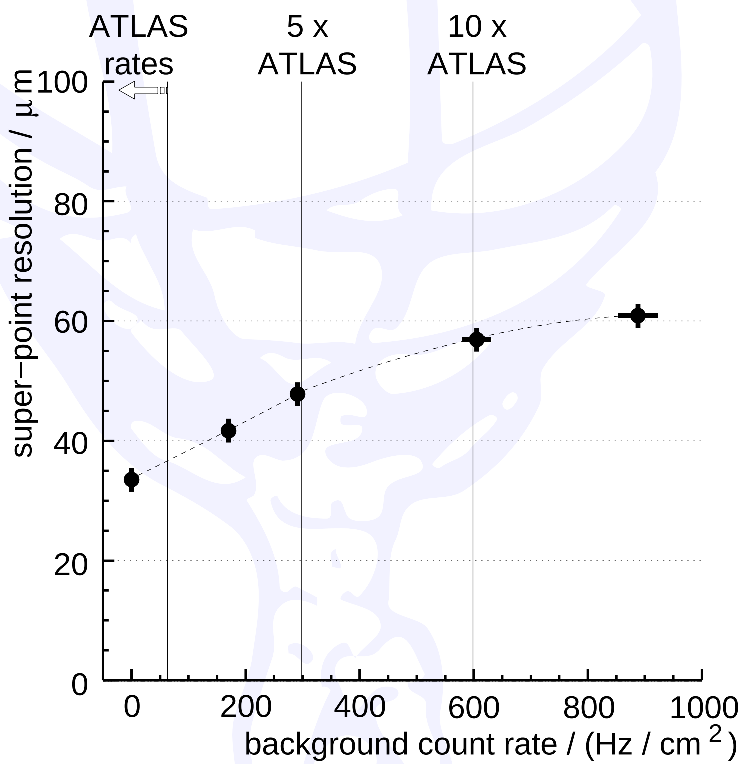

### Consequences

- High occupancy
  - Lower efficiency
  - Large read-out bandwidth required
- Degradation of resolution due to space charge fluctuations
- Aging
- Radiation damage to electronics

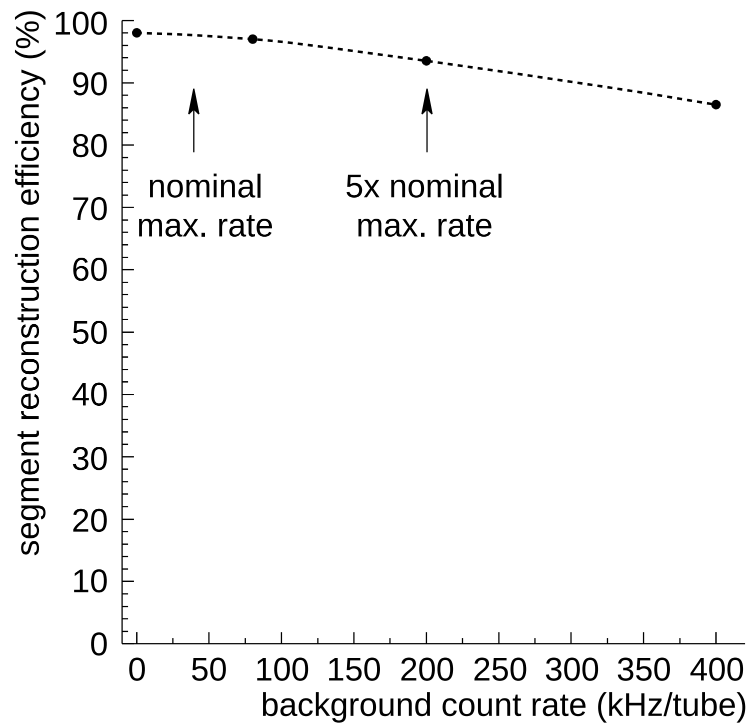
**All systems designed to work at expected bgd $\times$ 5**

# Test Beams Results from the GIF at CERN

## MDT Chamber Resolution




## Reconstruction Efficiency

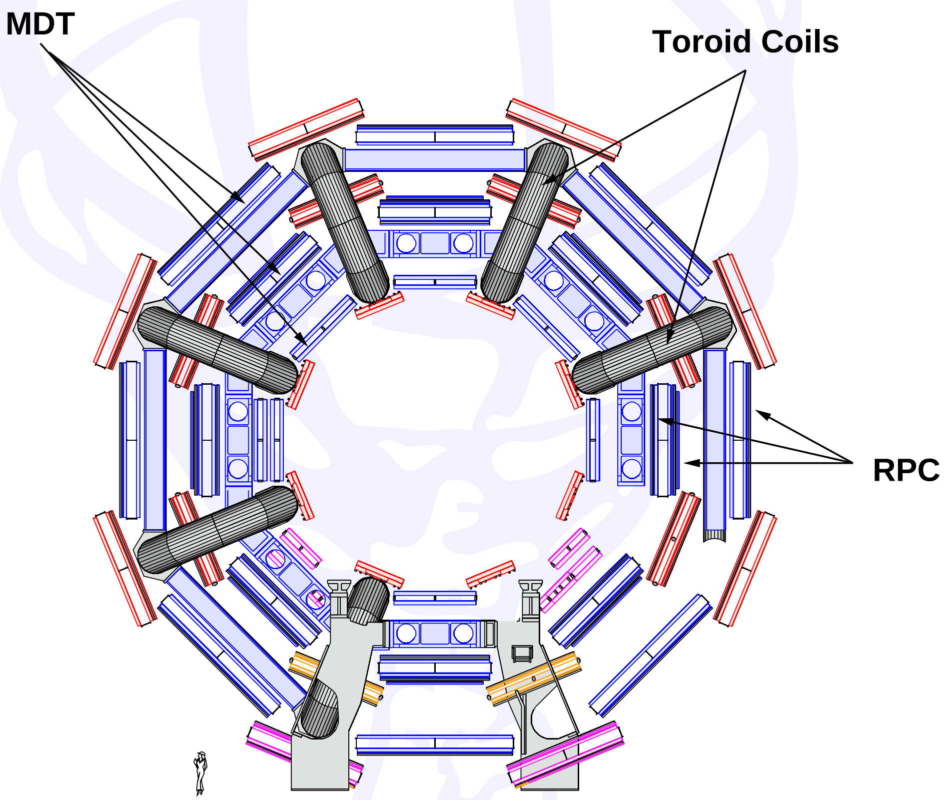



**MDT chambers can tolerate LHC rates without major loss of performance**

# Barrel Muon Spectrometer

## 640 muon stations

3 layers, 16 sectors




**Coverage:** $\eta < 1$

## Instrumentation

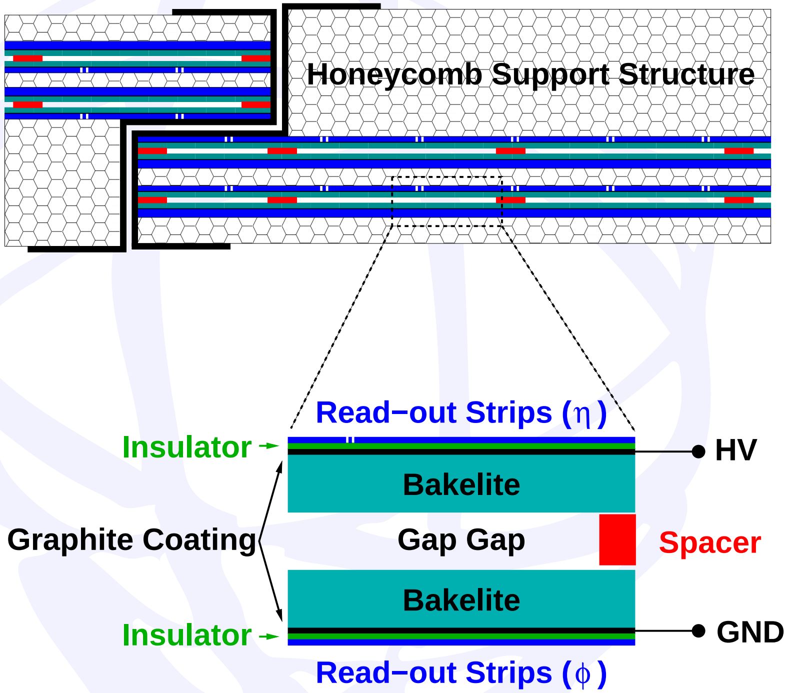
- 640 precision chambers
  Monitored Drift Tube (MDT) Chambers
- 686 trigger chambers
  Resistive Plate Chambers (RPCs)
  - 2 planes on middle MDT layer (low-$p_T$)
  - 1 plane on outer MDT layer (high-$p_T$)
- Precision and trigger chambers combined to muon stations to simplify installation

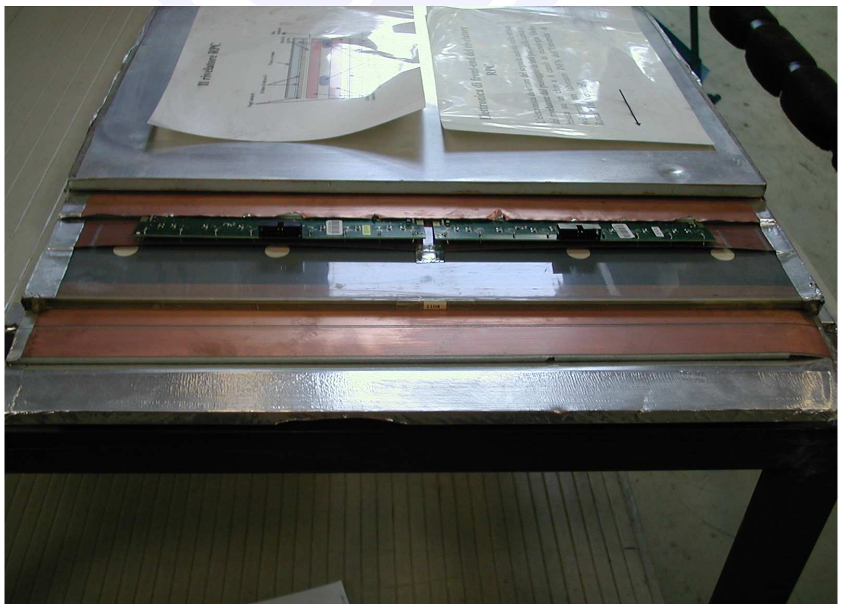
## Toroid Magnet

- Inner diameter: 9.4 m
- Outer diameter: 20.1 m
- Length: 25.3 m
- Field integral: 2–6 Tm
- Stored Energy: 1080 MJ

**Status: Surface station commissioning 100% complete**
**Installation 92% complete**

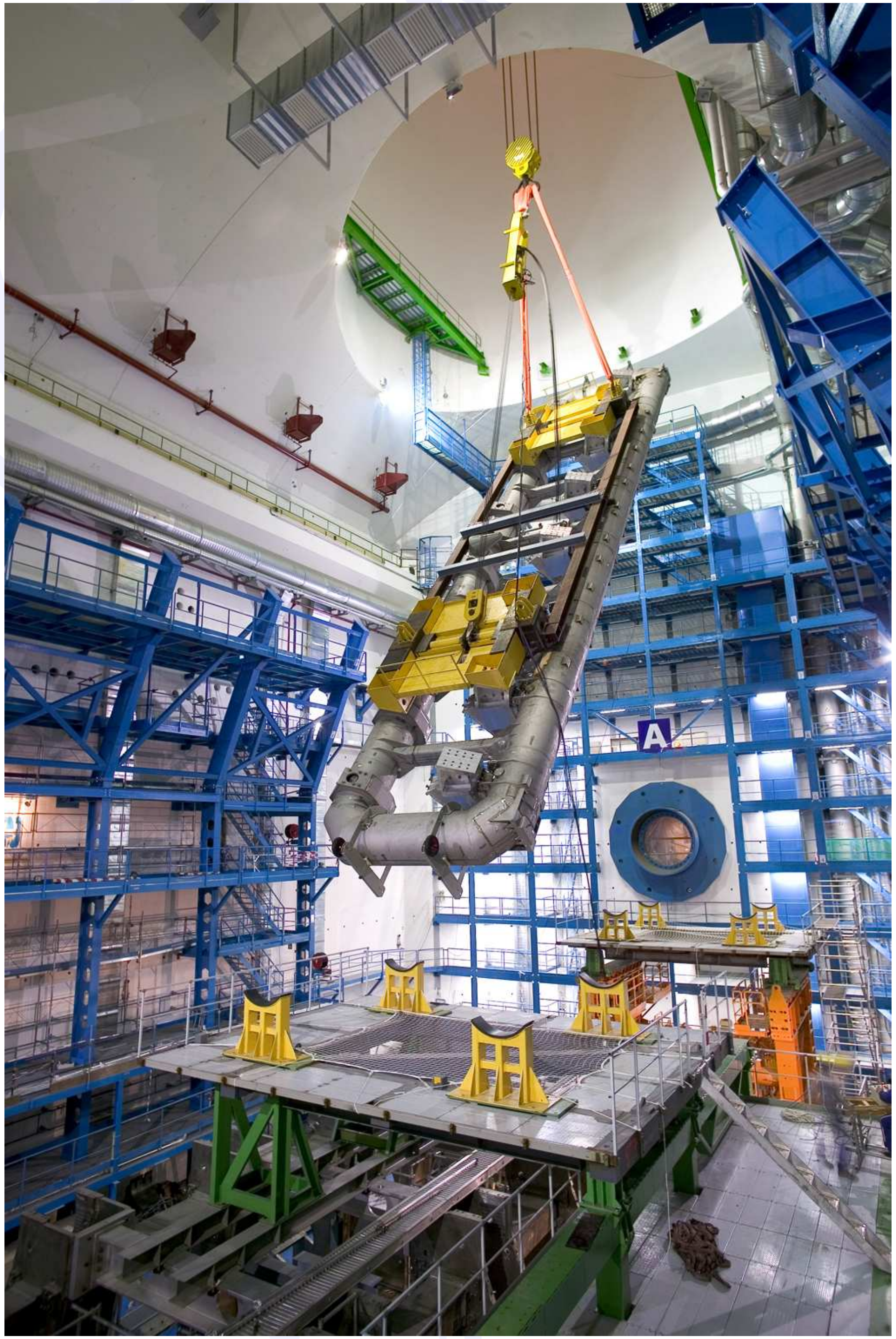
# Resistive Plate Trigger Chambers



- Chamber size: as MDT chamber
- 2 gas gaps per RPC
- Aluminum/honeycomb support
- RPC Parameters
  - 2 mm Bakelite plates
  - 2 mm gas gap
  - 2-dimensional read-out ($\eta$ and $\phi$)
  - Gas mixture: $C_2H_2F_4$/i-$C_4H_{10}$/$SF_6$ = 94.7/5/0.3
  - Pressure: atmospheric
  - High voltage: 9600 V (adj. to pressure/humid.)
  - Avalanche mode
  - Time resolution: few ns
  - Space resolution: 1 cm

# Barrel Toroid Installation

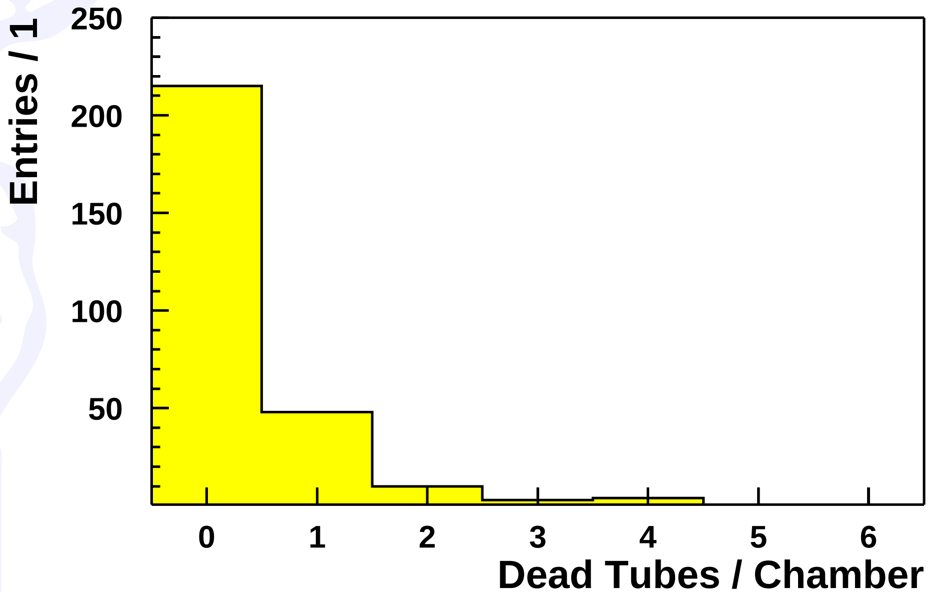



# Results from Commissioning

## Number of Dead Channels

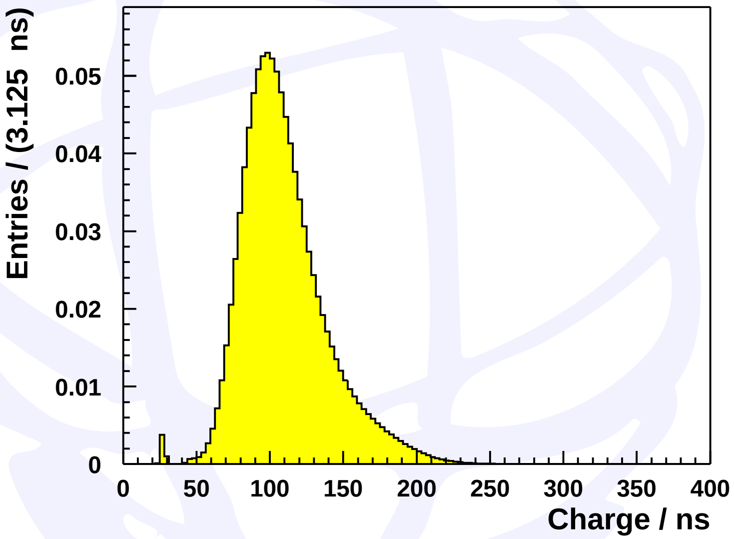
| Type | Channels | Dead Channels | Percentage / % |
|---|---|---|---|
| Barrel MDT | 184944 | 123 | 0.07 |
| Barrel RPC $\eta$-strips | 119904 | 884 | 0.74 |
| Barrel RPC $\phi$-strips | 253440 | 842 | 0.33 |
| Endcap MDT Big Wheel 1 A+C | 147072 | 61 | 0.04 |
| Endcap TGC Big Wheel 1 C | 30000 | 5 | 0.06 |

## Distribution of Dead Tubes in Middle and Outer Layer Barrel MDT Chambers

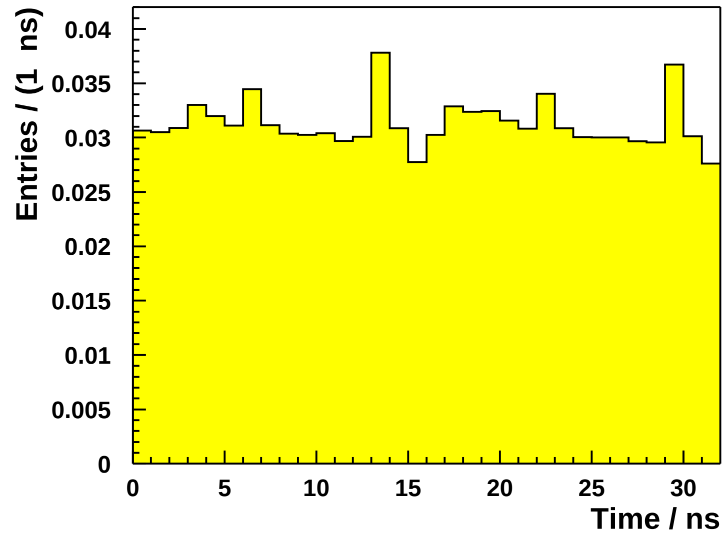


# Cosmic Ray Certification

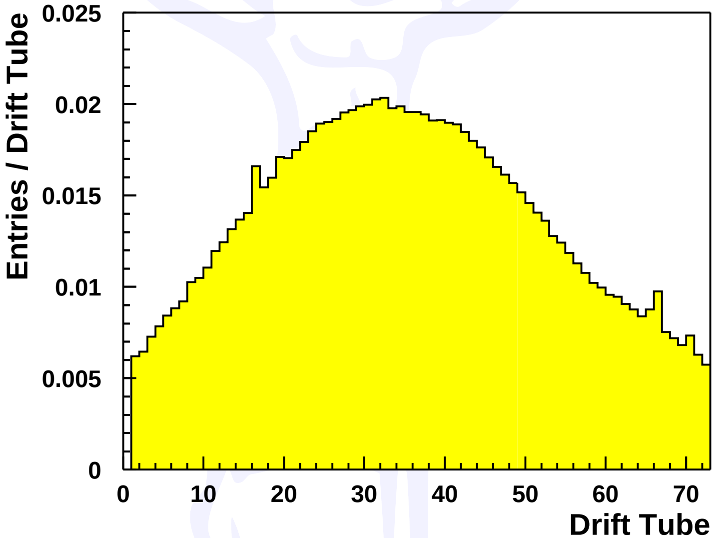
## MDT ADC Spectra



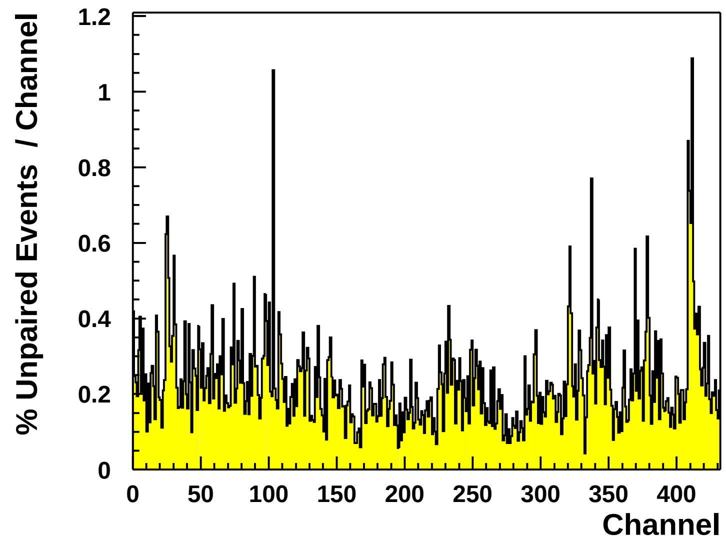

## MDT TDC Fine Time Spectra




## MDT Hit maps



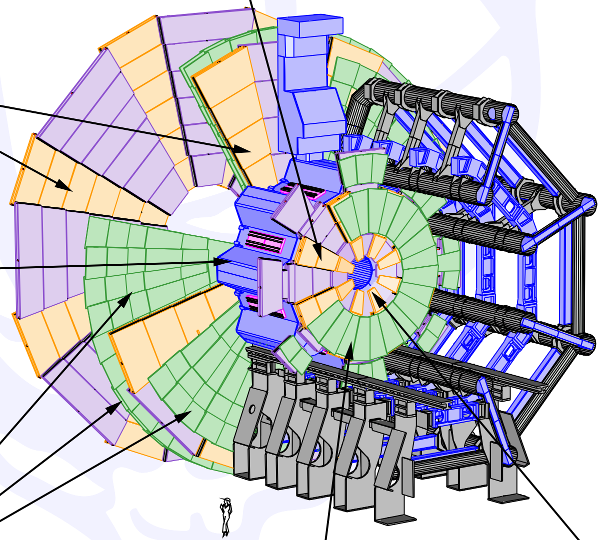

## MDT Unpaired Events



# Endcap Muon Spectrometer

**2112 muon chambers**

2 Small Wheels, 10 Big Wheels




**Coverage: 1 < $\eta < 2.7$**

## Instrumentation

- 534 precision chambers
  470 Monitored Drift Tube (MDT) Chambers
  64 Cathode Strip Chambers (CSCs)
- 1578 trigger chambers
  Thin Gap Chambers (TGCs)
  - 2 layer outside 1st MDT BW (low-$p_T$)
  - 1 layer inside 1st MDT BW (high-$p_T$)
  - 2nd coord.: 1 layer on MDT Small Wheel

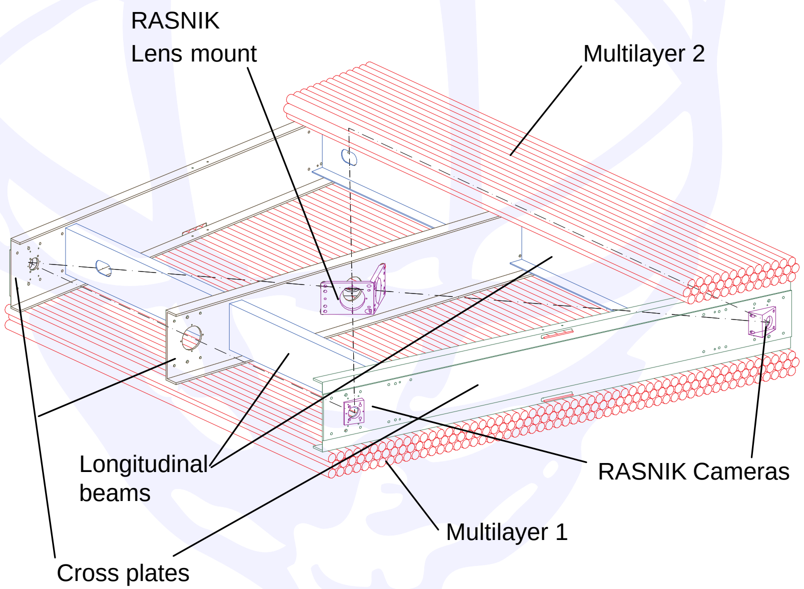
## Toroid Magnets

- Inner diameter: 1.7 m
- Outer diameter: 10.7 m
- Length: 5 m
- Field integral: 4–8 Tm
- Stored Energy: 2 $\times$ 250 MJ

**Status: MDT/TGC sectors 75% assembled**
**Installation of 1 MDT & 1 TGC Big Wheel completed**

# Precision Detectors

## Monitored Drift Tube Chambers

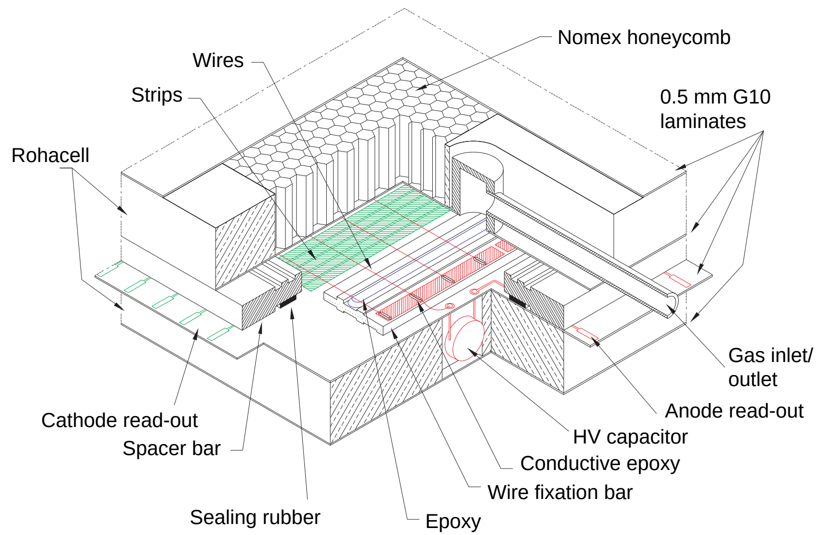



Same as barrel MDT chambers, but. . .

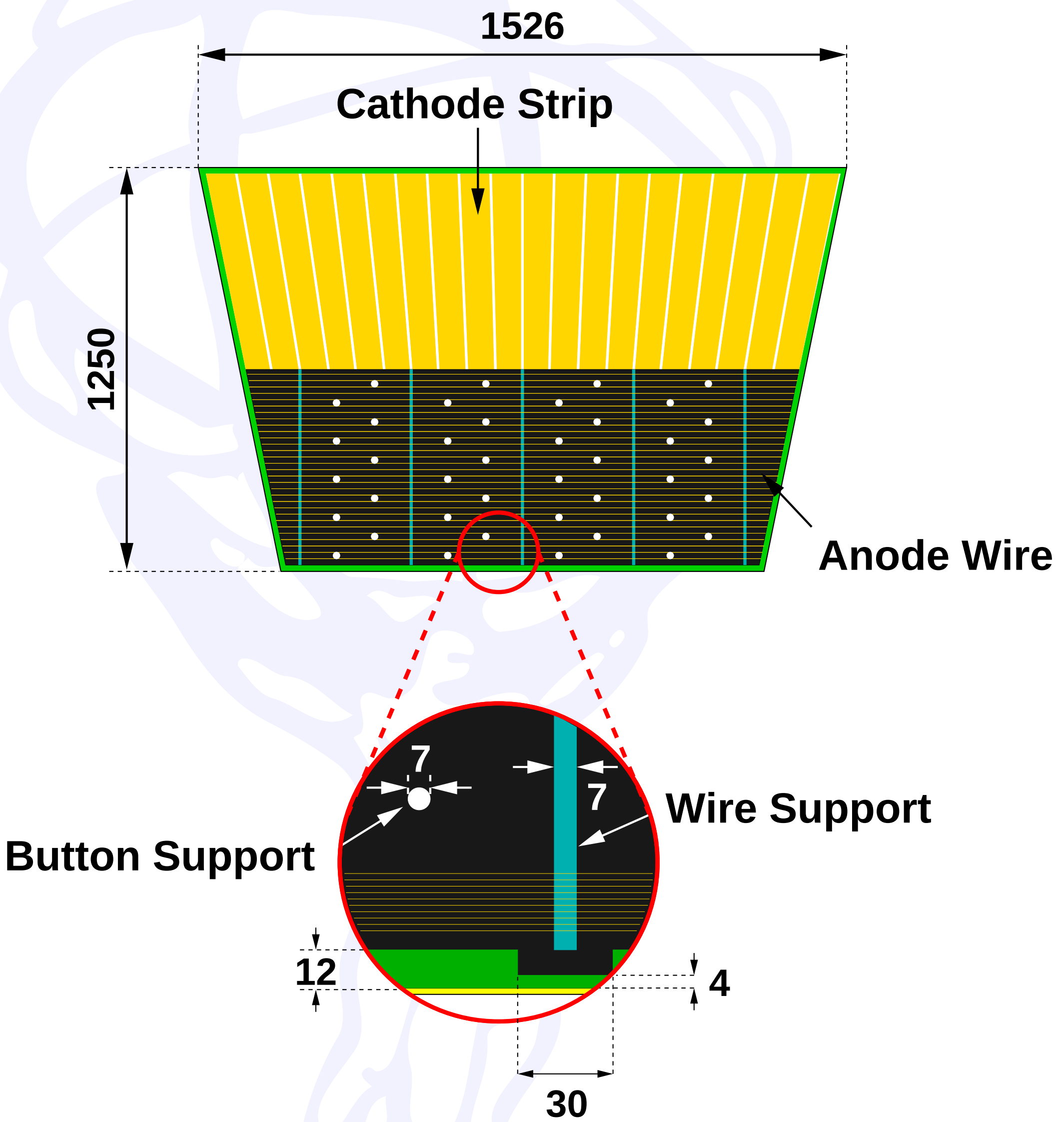
- Trapezoidal shape
- Chamber size: 2–10 $m^2$

## Cathode Strip Chambers

- Trapezoidal shape
- Chamber size: 1 $m^2$
- $2 \times 4$ layer units
- Low mass honeycomb support panels
- Wire spacing, anode-cathode gap: 2.54 mm
- 30 $\mu$m WRe anode wires
- 2-D cathode strip read-out with charge interpolation
- Resolution: 60 $\mu$m



# Thin Gap Trigger Chambers

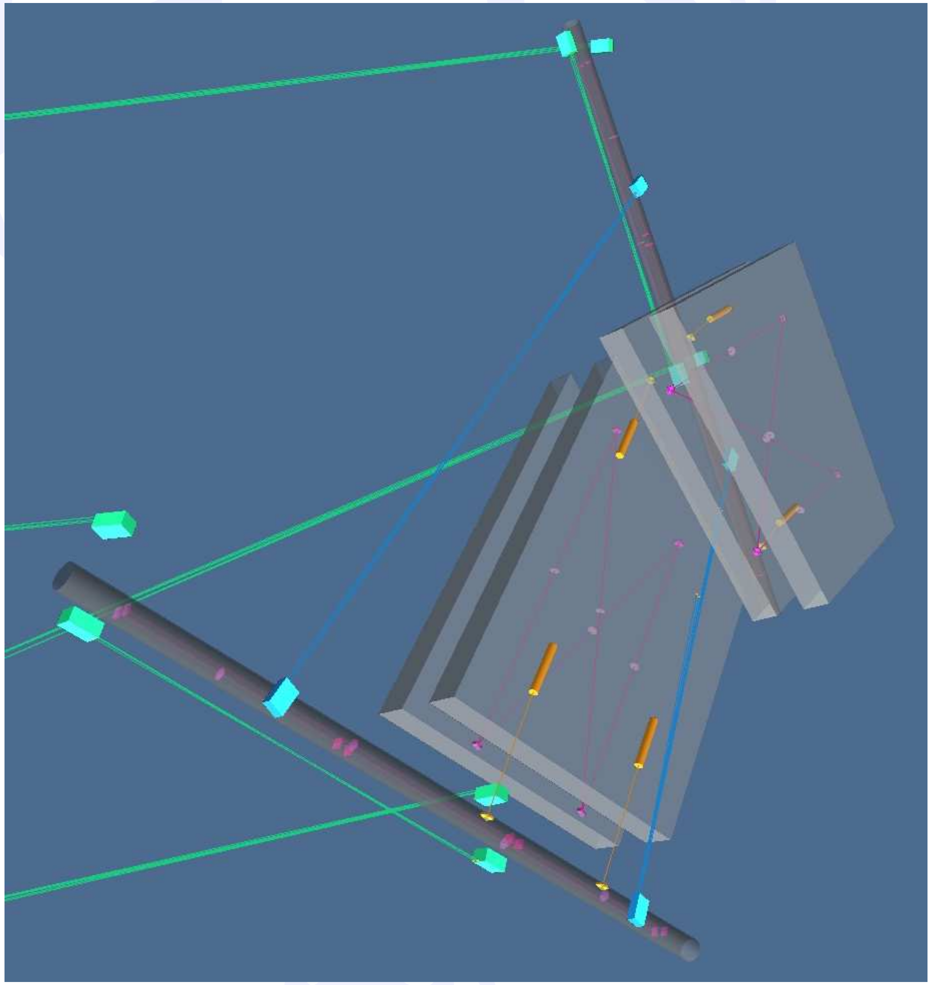



- Multiwire Proportional Chamber
- Chamber size: 1–3 $m^2$
- Combined to doublets or triplets
- Low mass honeycomb support panels

- Wire spacing: 1.8 mm
- Anode-cathode gap: 1.4 mm
- 50 $\mu$m W anode wires
- Gas mixture: $CO_2$/n-Pentane = 55/45
- Operated in saturated mode
- 2-D read-out (wires and cathode strips)
- Wires (4–20) grouped in dep. of $\eta$

# Endcap Alignment System

- $2 \times 4$ wheels of precision chambers
- Direct projective system not possible



- Reference grid of monitored alignment bars
  - Internal optical straightness sensors
  - Temperature sensors
- Polar sensors
  align bar to other wheel
- Azimuthal sensors
  align bars within wheel
- Planarity sensors
  align chamber to chamber
- Proximity sensors
  align chamber to bar
  align chamber to chamber
- Inplane sensors
  MDT chamber deformations

**6416 sensors in total — Alignment bars built at ALU Freiburg**

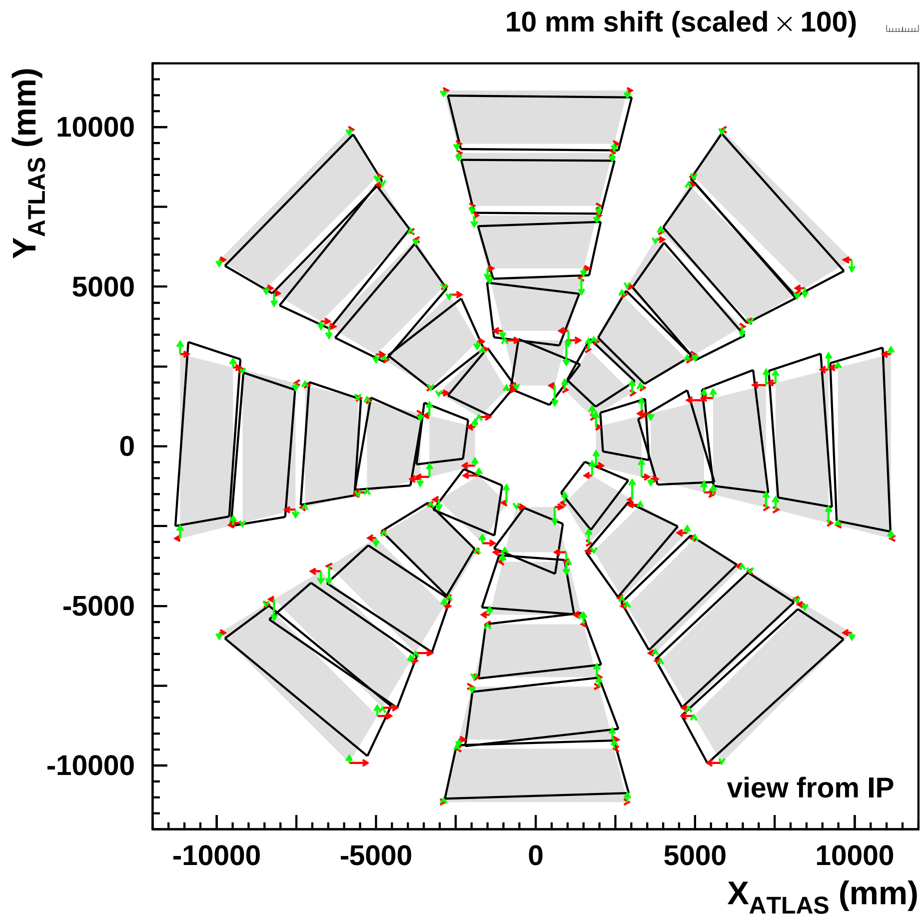
# First Results — MDT Big Wheel C during Construction

- Gray Area: nominal position
- Black Lines: actual position (scaled × 100)
- Red Arrows: shift in X-direction
- Green Arrows: Shift in Y-direction

### Results for lower 5 sectors

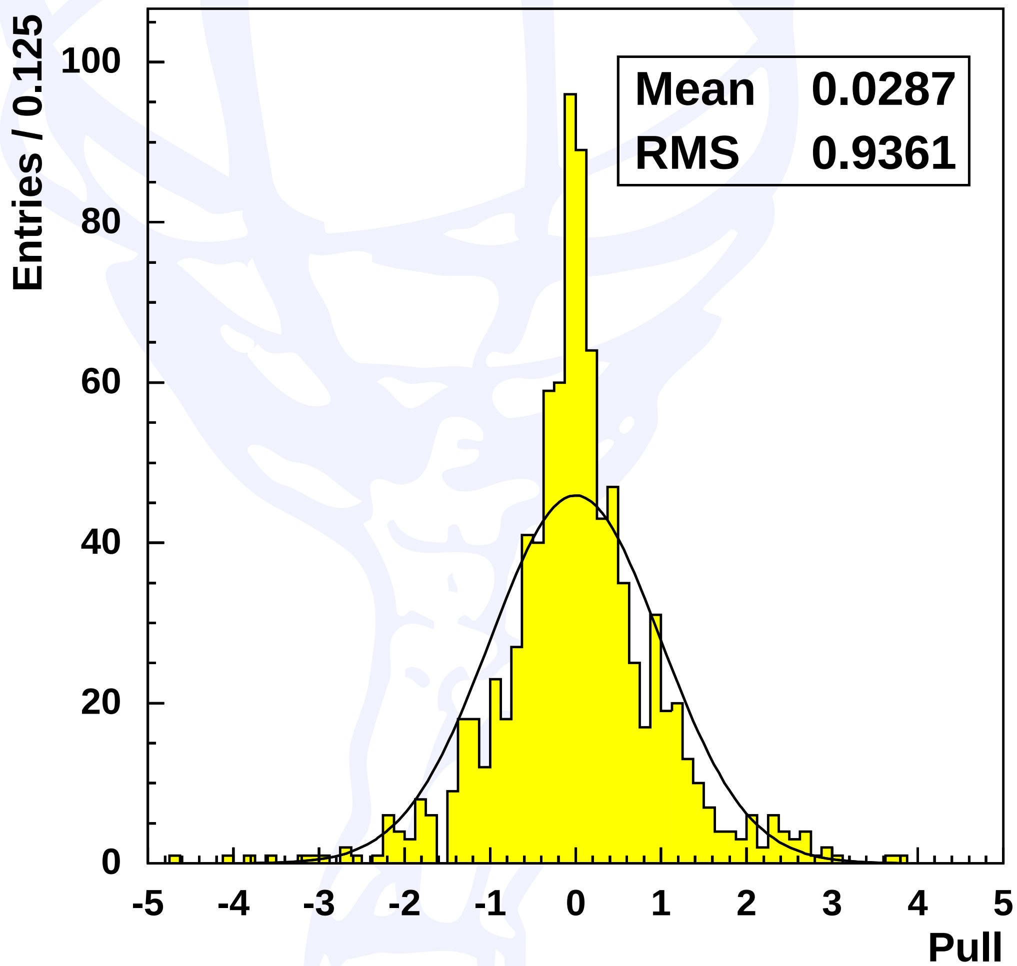
- $\Delta X$: 2 mm RMS (max. 6 mm)
- $\Delta Y$: 3 mm RMS (max. 8 mm)

## Displacement in Big Wheel plane

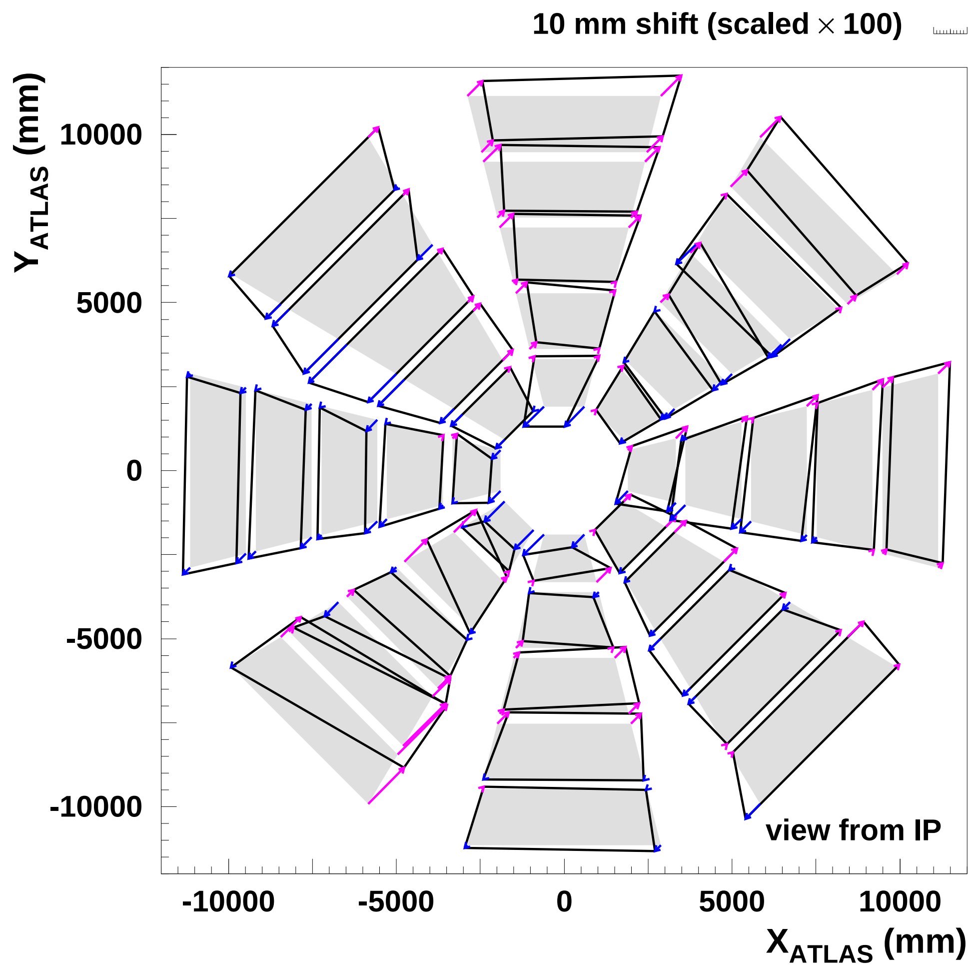



## Sector / chamber positioning better than expectation

## Pull Distribution (lower 5 sectors)




## Displacement perpendicular to Big Wheel plane



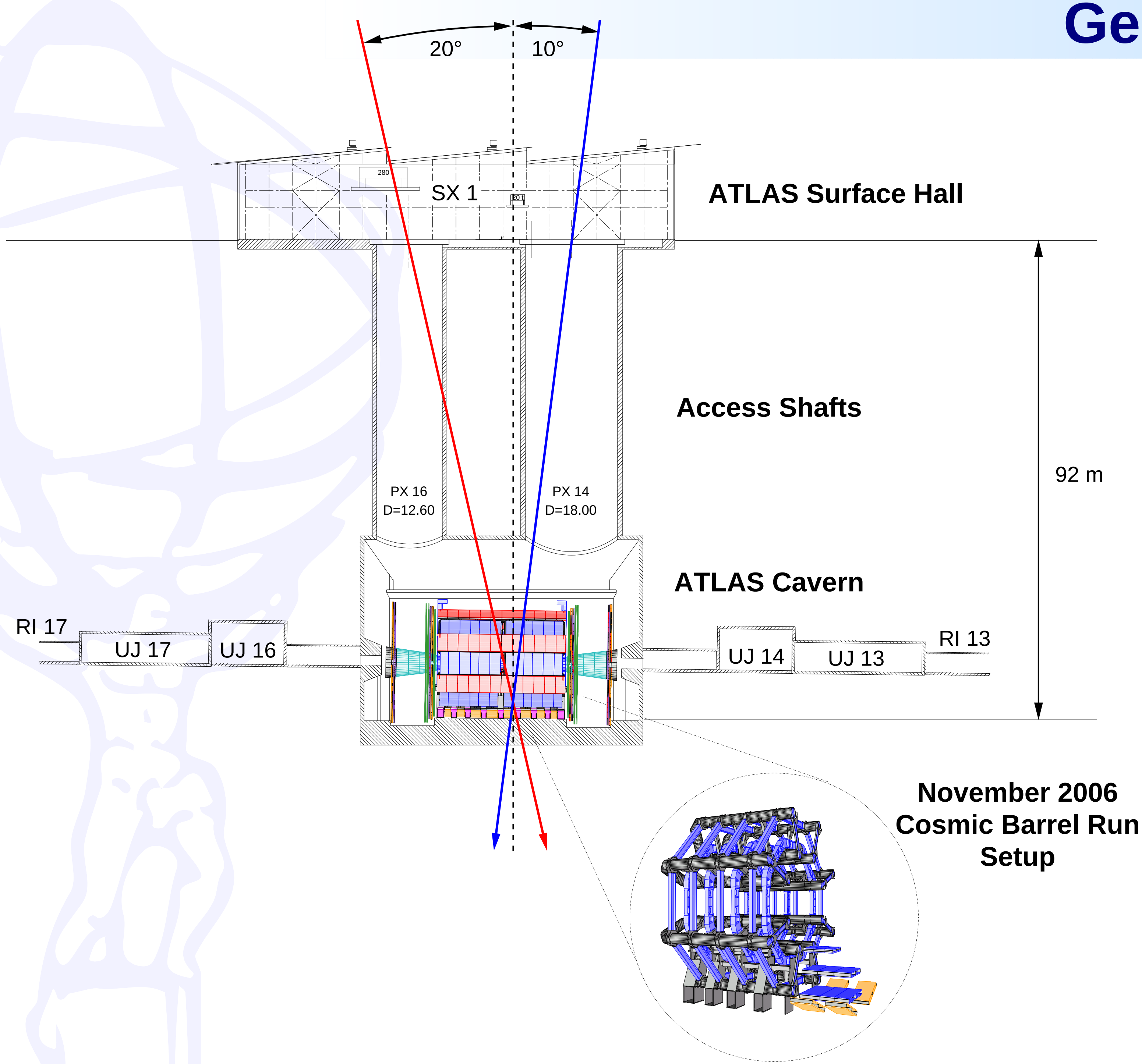
# Barrel Toroid Fast Quench Test

- Initiated if local loss of superconductivity in coils
- Energy dump / field breakdown in 60 s (normal ramp down: 3 h)
- Expected rate: 1 / year

## Results

- Toroid OK
- Detector Safety System successfully used to cut low voltage power supplies, ramp down high voltage power supplies
- No dangerous chamber deformations measured
- Induced currents in cable loops negligible (due to routing)

**Fast quench test successful**
**No damage to magnet or detector**


20°
10°
SX 1
ATLAS Surface Hall
Access Shafts
PX 16
D=12.60
PX 14
D=18.00
92 m
ATLAS Cavern
RI 17
UJ 17
UJ 16
UJ 14
UJ 13
RI 13
November 2006
Cosmic Barrel Run
Setup