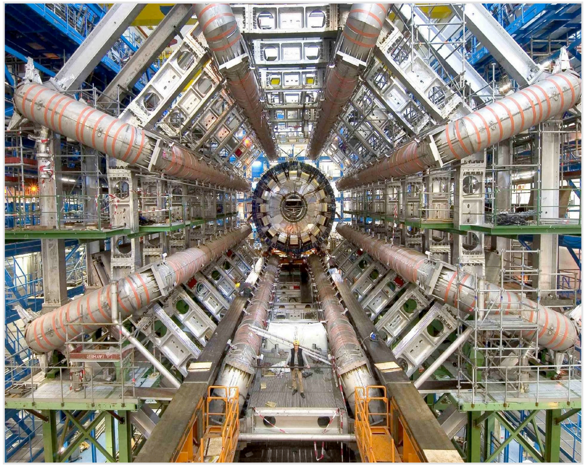
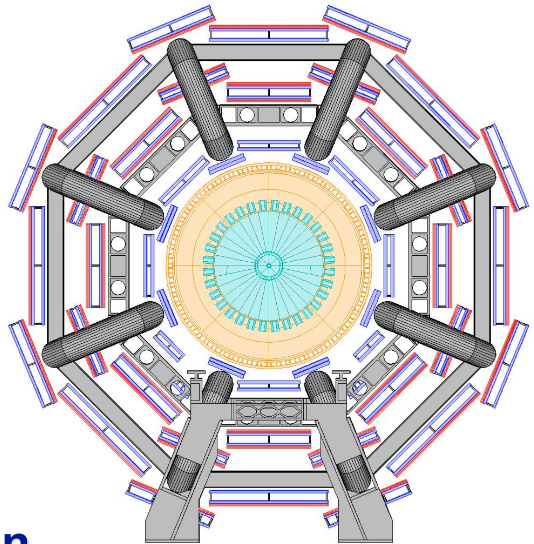
The ATLAS Muon Spectrometer

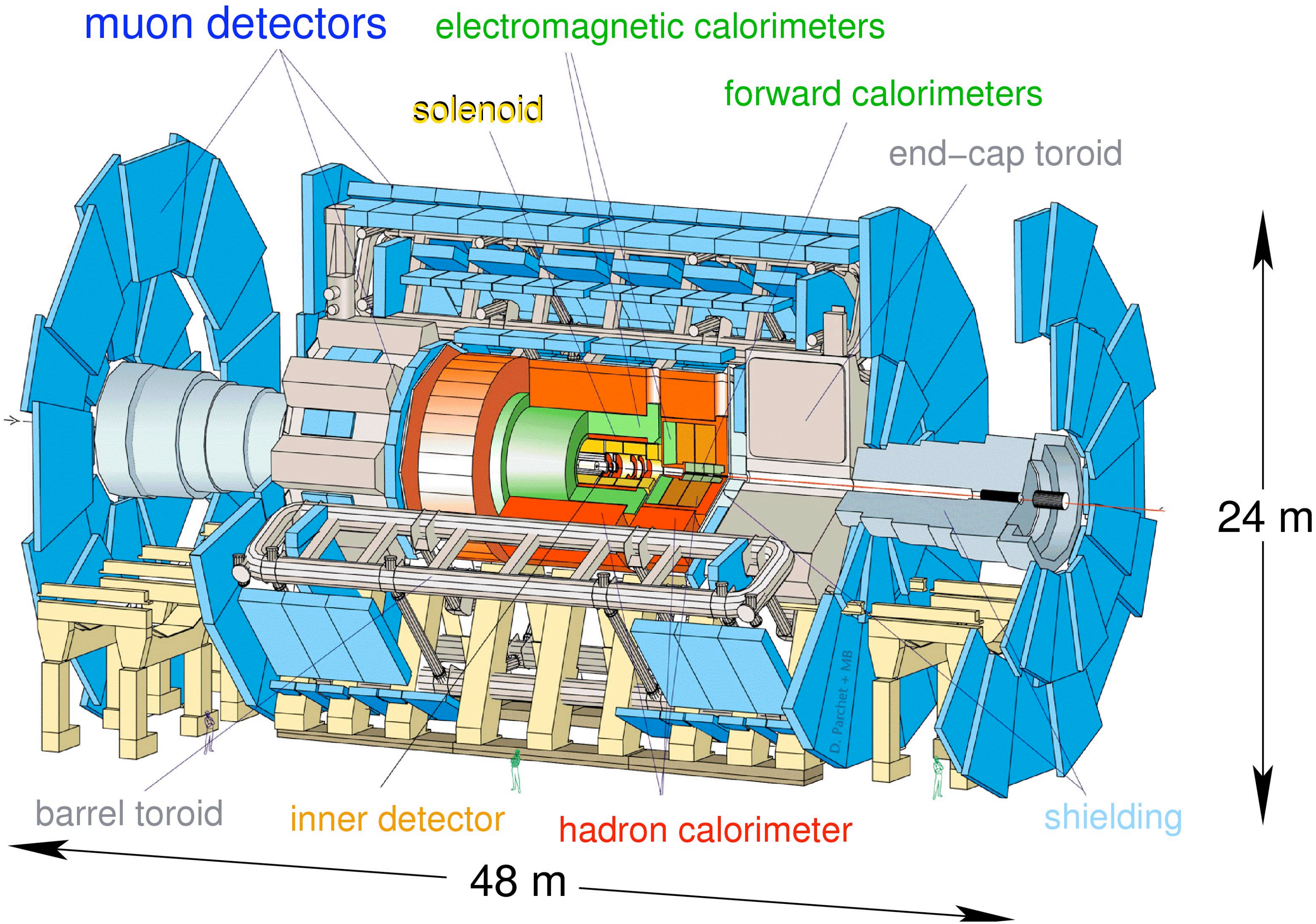
- Spectrometer Design
- Trigger Chambers
- Precision Chambers
- Alignment
- Installation & Commissioning
- Summary and Outlook



Silvia Schuh
CERN, PH Department
for the ATLAS Muon Collaboration

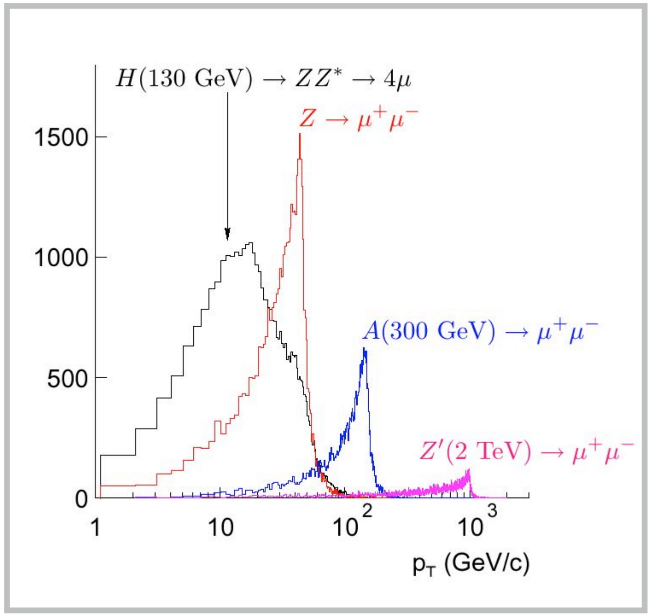


The ATLAS detector



ATLAS Muon Spectrometer Strategy

- **Physics @ LHC with Muons**
  - Muons: clear and robust signatures
  - Selected channels
    $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow ZZ \rightarrow 4l$
    $Z' \rightarrow \mu\mu$, $W' \rightarrow \nu\mu$ and more
  - Narrow resonances over high background
    - excellent momentum & mass resolution order few % up to highest single μ momenta
    - High efficiency single-μ trigger for wide p_T

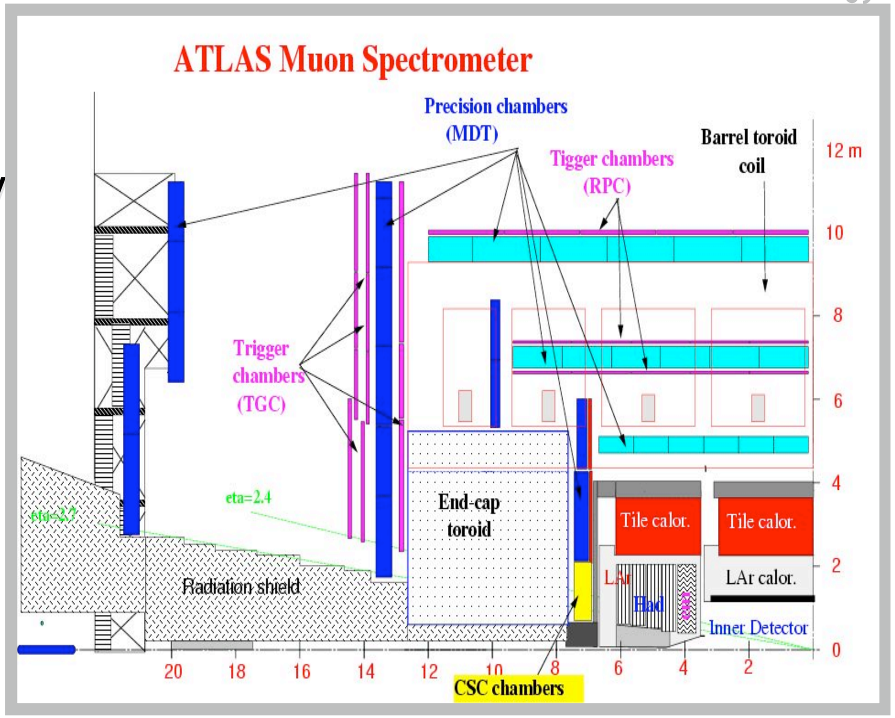


- **???**
- **New pp energy regime → Possibility of unexpected background rates**
- **➠conservative approach: clear & robust μ-signatures, Muon-Spectrometer with standalone momentum resolution**

ATLAS Muon Spectrometer Design

- **Goals**
  - standalone momentum measurement:
    ~10%@ pT ≥1 TeV/c, few % down to few 100 GeV/c
  - cover 5500m^2, $|\eta| < 2.7$
  - Background: ~10-100 Hz/cm^2, up to 1 kHz/cm^2, strongly η dependent
- **Achievable with:**
  - Open geometry: 3 air core toroids
  - Toroidal magnetic field: B = 0.3 - 2 T
  - Large lever-arm, projective geometry
- **Technologies**
  - Fast Trigger Chambers
    - **R**esistive **P**late **C**hambers
    - **T**hin **G**ap **C**hambers
  - High-precision tracking detectors
    - **M**onitored **D**rift **T**ube **C**hambers
    - **C**athode **S**trip **C**hambers
    - Alignment

Schuh,CERN



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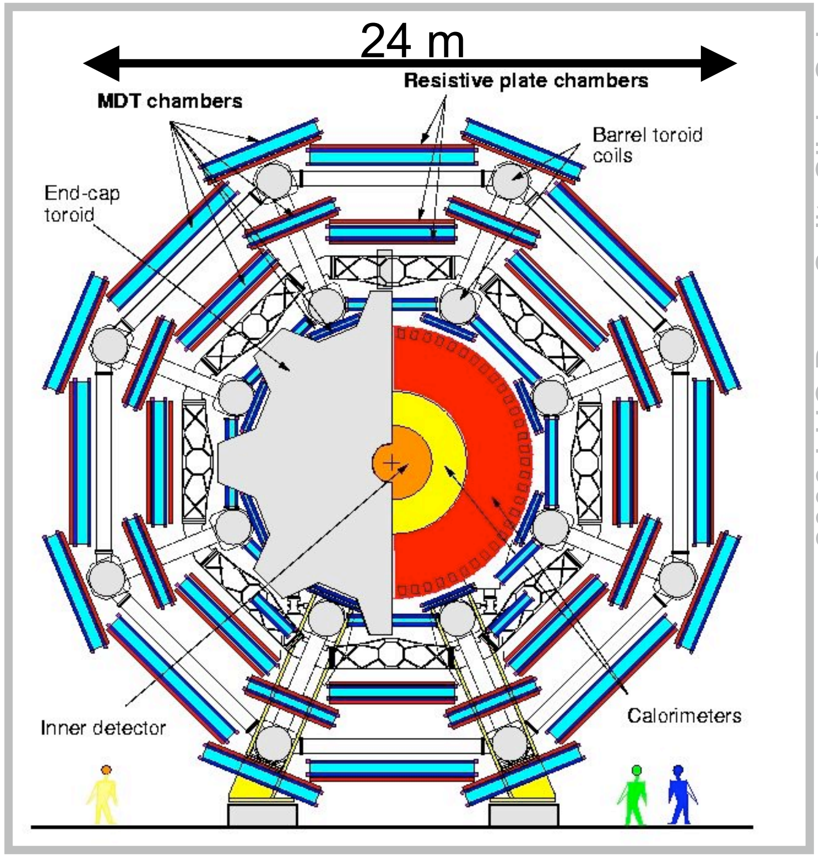
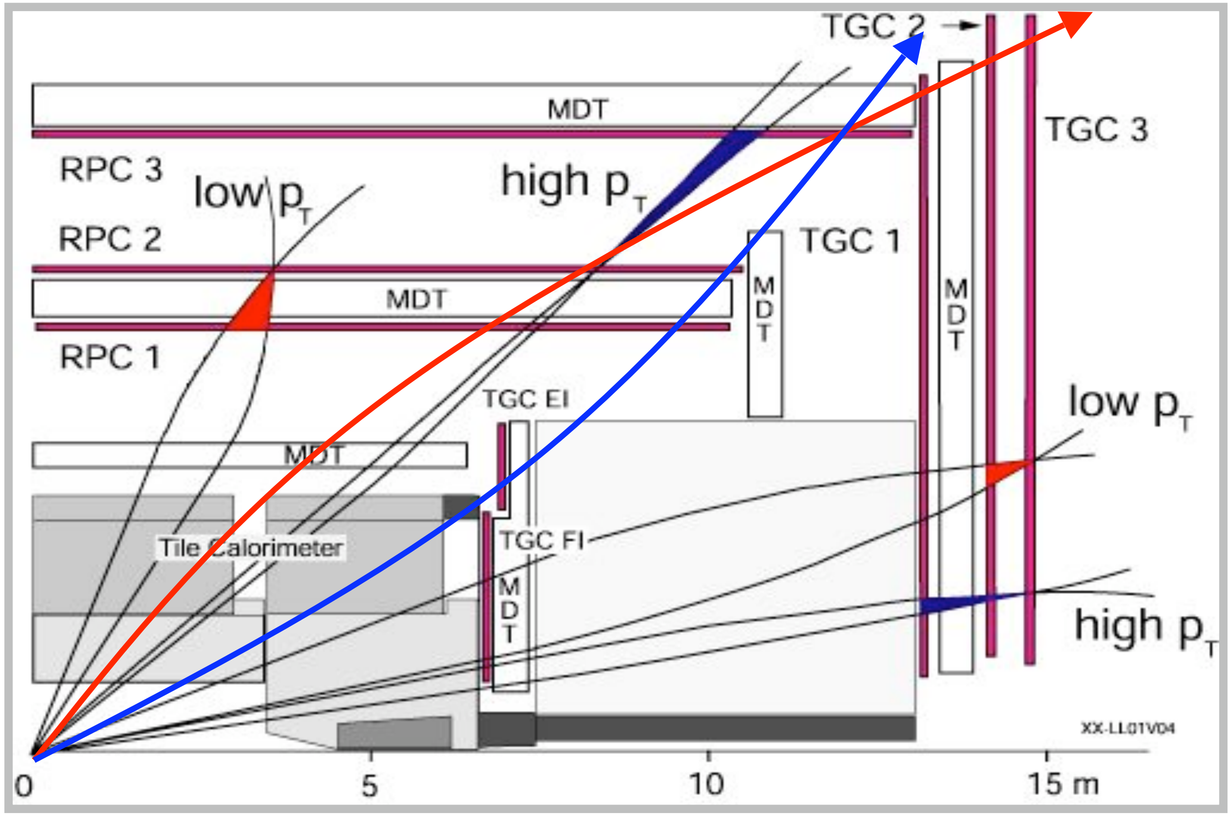


Muon Trigger Chambers

Trigger Chamber Requirements

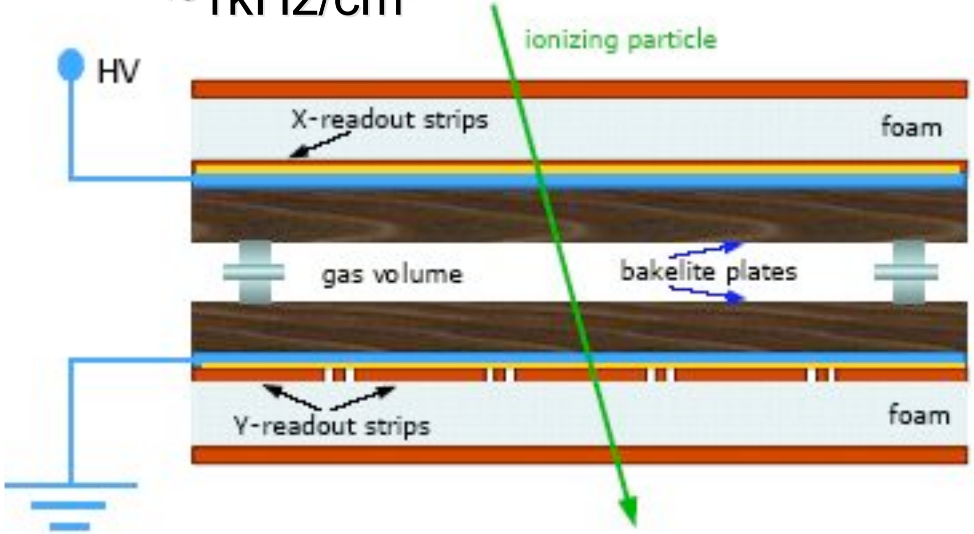
- **Fast: 1-2 ns, bunch-crossing ID**
- **Rough tracking: 1cm**
  - Region of Interest
  - Low and high-p_T trigger (6 & 20 GeV/c)



Trigger Chamber Design

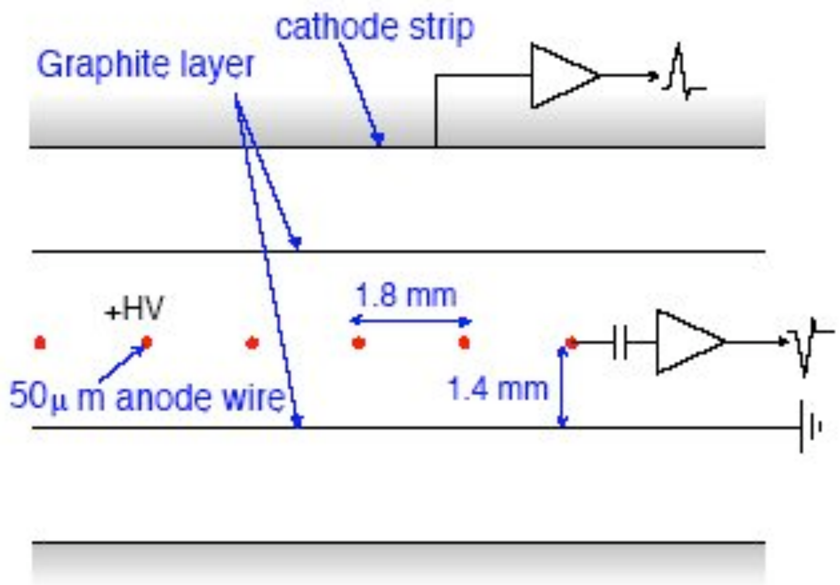
Resistive Plate Chambers

- 1116 chambers in barrel, rectangular, 3600m^2
- Gas gap between 2 resistive plates, resistivity: ~1-4x10^{10} Ωcm, pitch: 26.4-33.9 mm
- $C_2H_2F_4/C_4H_{10}/SF_6$ (94.7/5/0.3)
- σ_t~1ns, σ_x ~ 5-10mm, rates: ~1kHz/cm^2



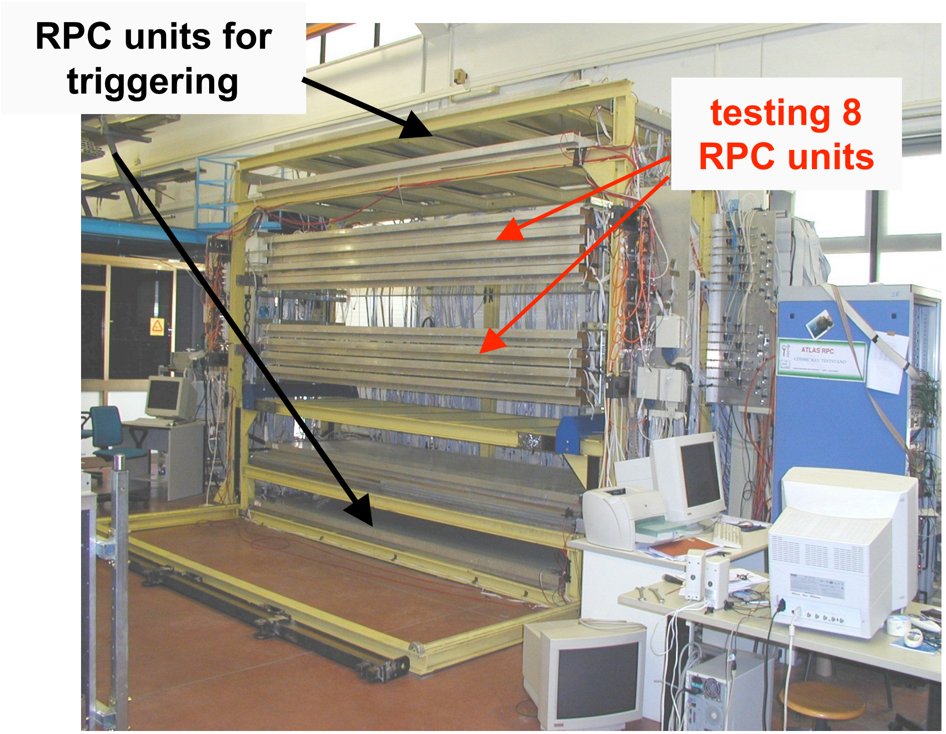
Thin Gap Chambers

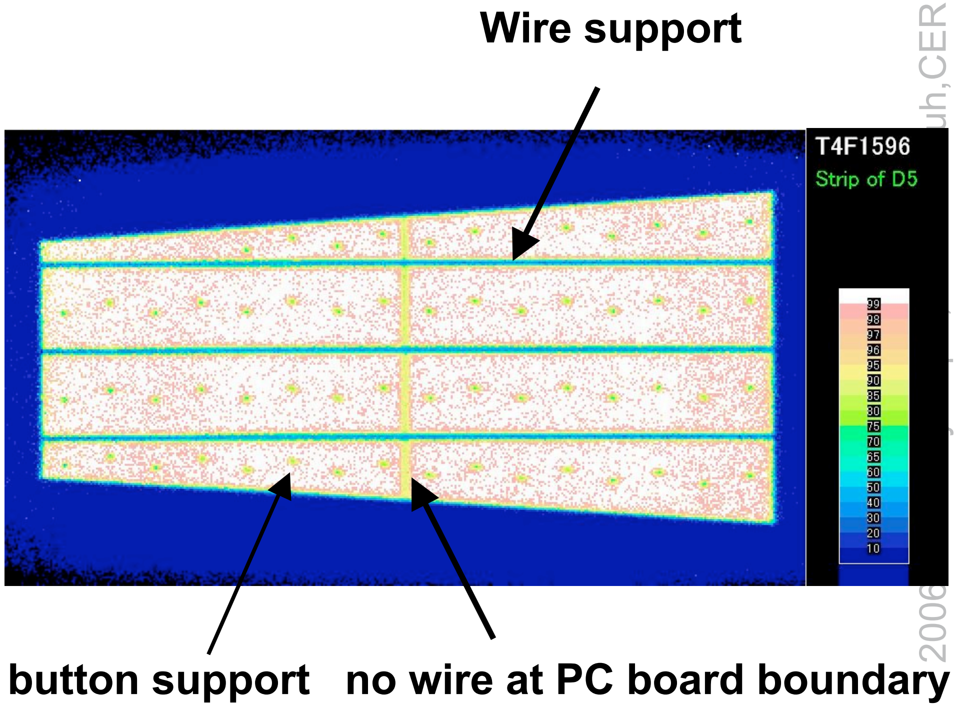
- 1578 chambers in endcap, trapezoidal
- MWPC with graphite cathode
- Readout 50μm wires & strips
- CO_2/n-Pentane (55:45)



Trigger Chamber Certification

Each chamber tested for efficiency and noise in cosmic ray stand





- **Average efficiency: 97% for RPCs, 95% for TGCs**
- **Additional tests on long-term stability and operation under high irradiation rates show reliable performance**

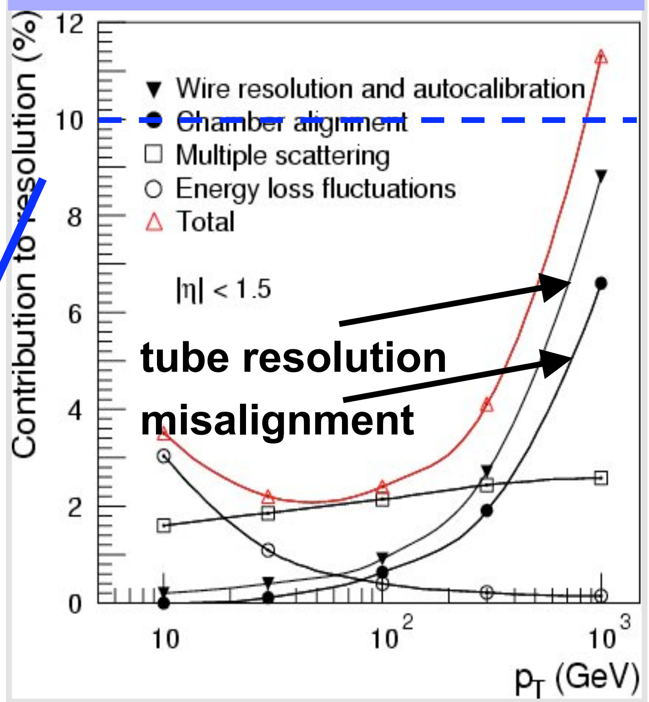
Muon Precision Chambers

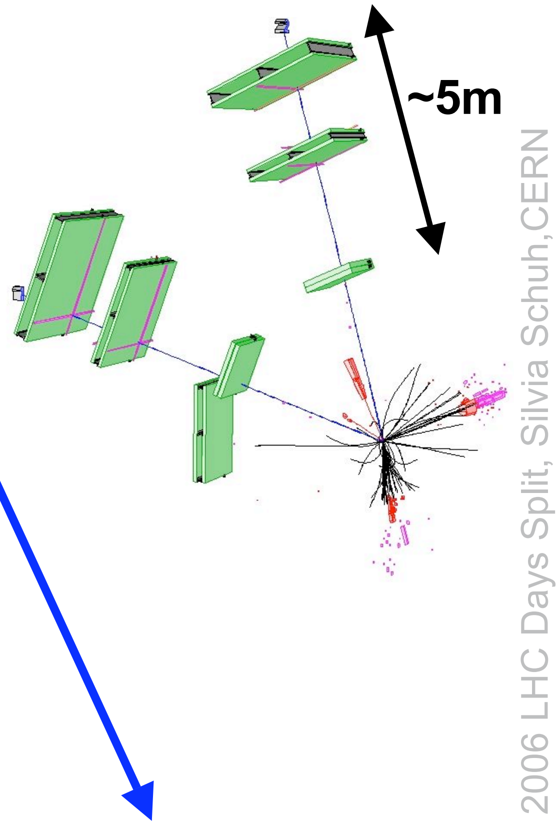
Precision Chamber Requirements

1TeV μ

Sagitta: 500-700μm

10%: 50μm





Precision Chambers

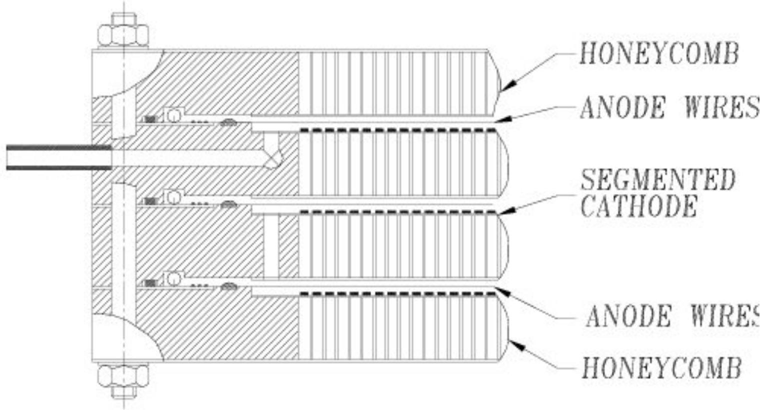
- **High Single Cell Resolution: 50μm**
- **High Mechanical Accuracy: 20μm**

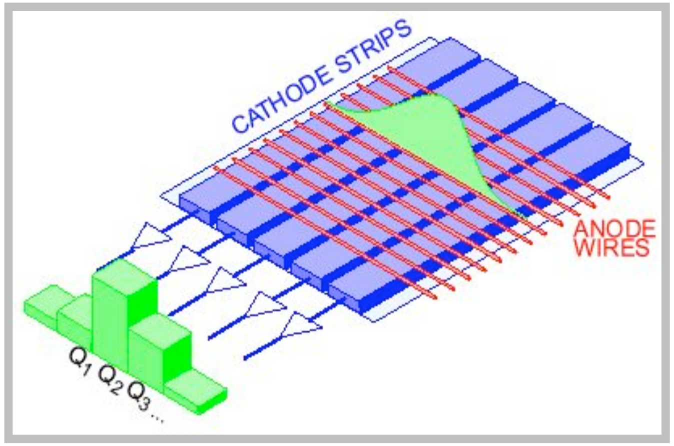
Complex Optical Alignment

- **Movements order mm:**
- **B field, temperature gradient Gravity**
- **Track bending correction**

Cathode Strip Chambers

- **Multiwire proportional chambers**
  - 2.0 < |η| < 2.7
  - 32 4-layer chambers, 31000 ch
  - Position measurement
    center-of-gravity of induced
    charge on cathode strips
  - $Ar:CO_2:CF_4$ at 3 kV
  - High granularity (strip pitch 5mm)
  - In region of high muon and background rates

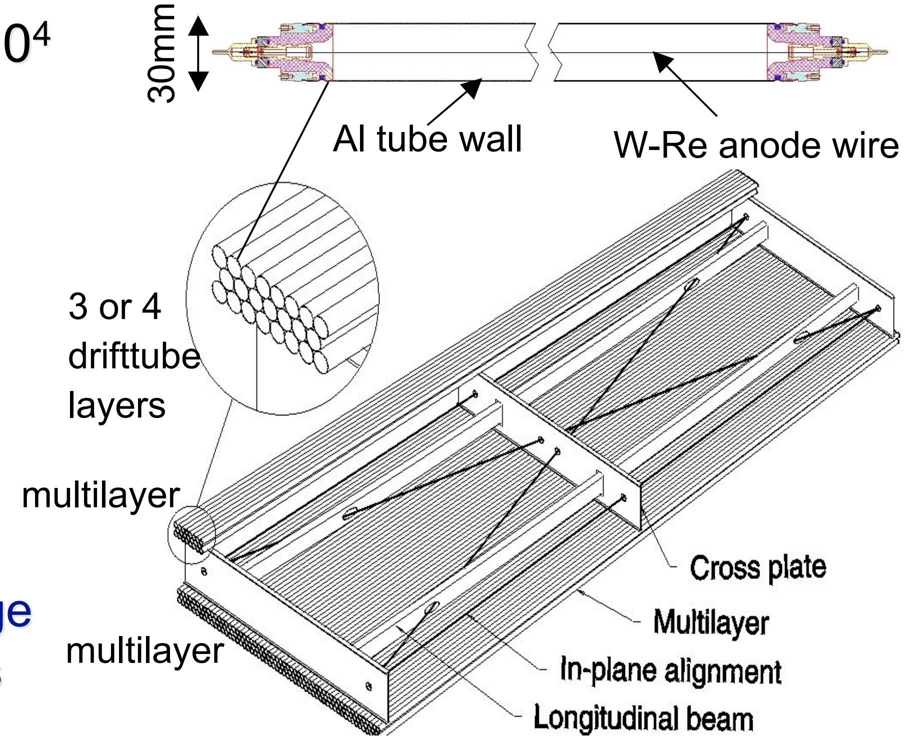




2006 LHC Days Split, Silvia Schuh, CERN

Monitored Drift Tube Chambers - Design

- **Single tubes**
  - 3cm∅, 400 μm Al wall, 50 μm W-Re wire
  - Ar/CO_2 (93/7) @ 3 bar, Gain~2×10^4
  - Single tube resolution: ~80μm
- **Chambers**
  - 2 multilayers with 3 or 4 mono-layers glued on either side of support structure, σ ~50μm
  - Monitored Drift Tube Chambers:
    - T-gradients, B fields, gravity: chamber movements in mm-range
      ⇒ Optical Straightness Monitors
- **Challenges**
  - **Wire positioning < 20μm r.m.s.**
  - **Required alignment < 40 μm**



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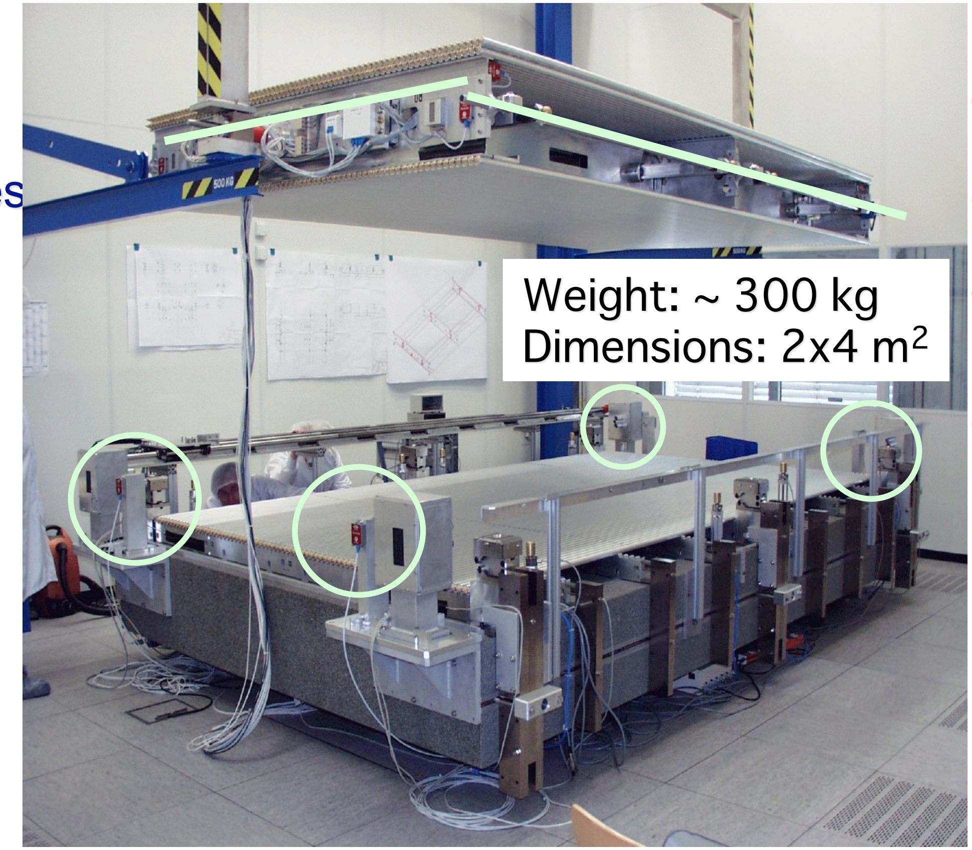
MDT Chamber Construction

- **Chamber wire placement < 20μm R.M.S. within full chamber**
  - High precision gluing: monitoring & certification!
  - Distributed production:
    - ~1200 chambers in 4 years
    - 13 institutes worldwide
    - various construction techniques & procedures
    - 1-10m²/rectangular (barrel) trapezoidal (endcap)

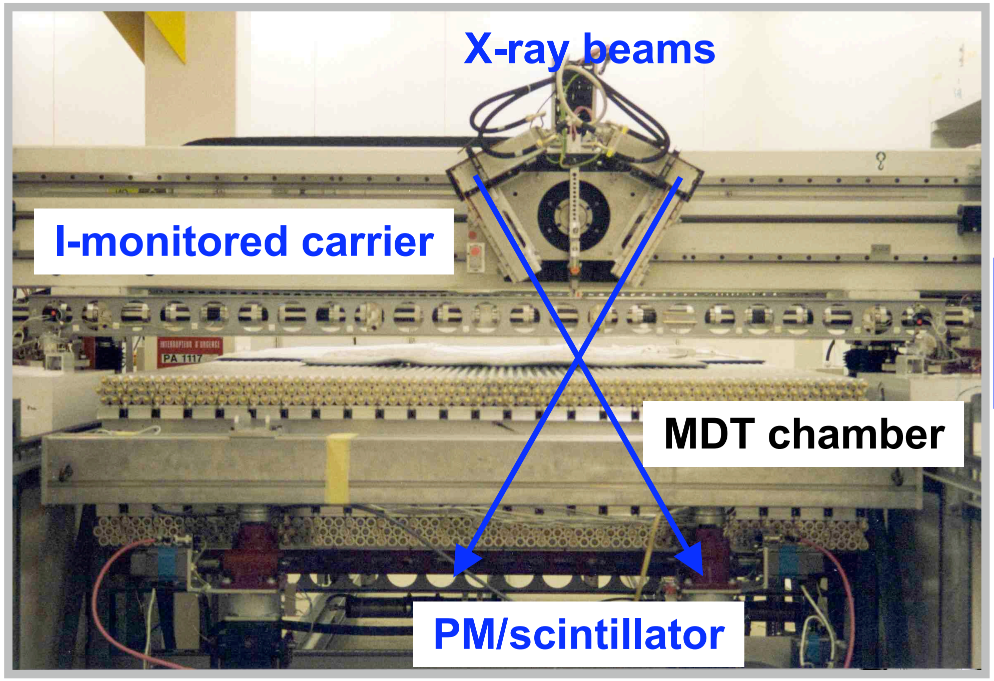
Endplug precision surface



MDT Mechanical Construction Certification

X-ray tomograph device @ CERN

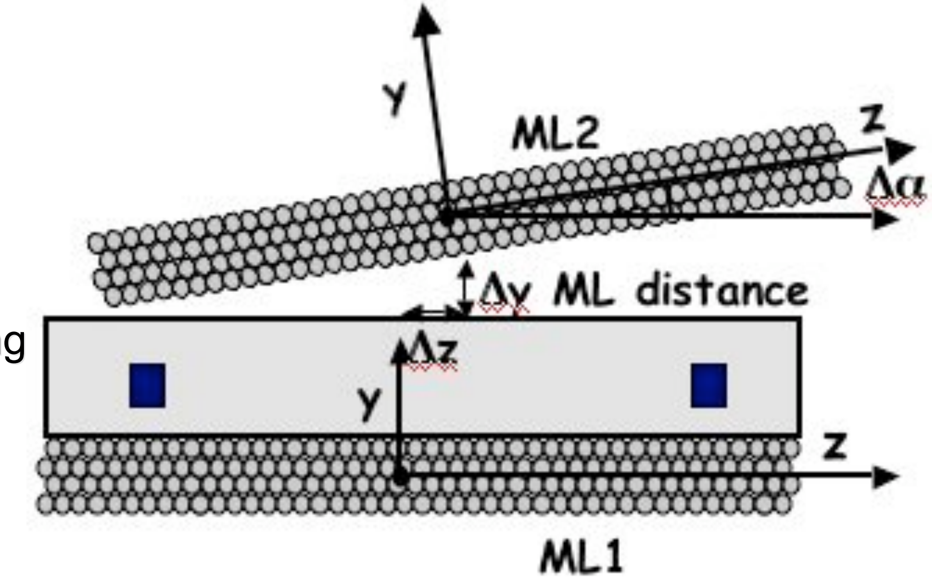
- Central mechanical quality control
- sampled ~15% of full production over 5 years
- Otherwise unobtainable information, longterm measurements

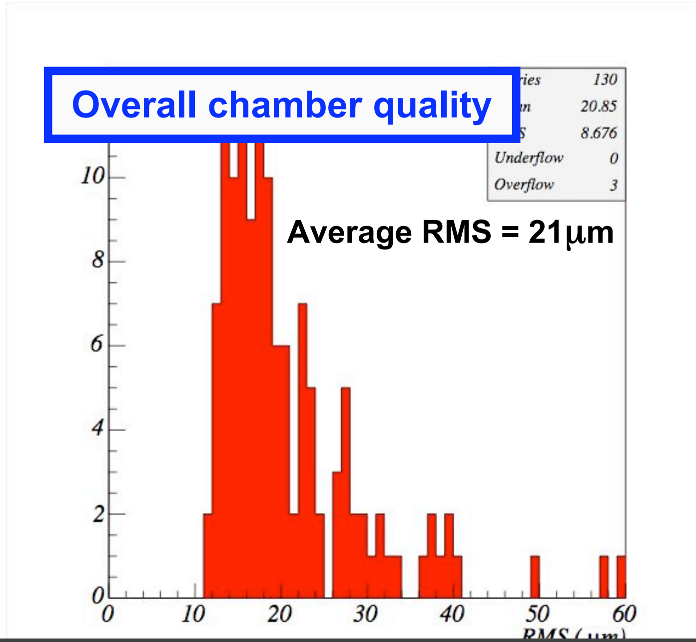


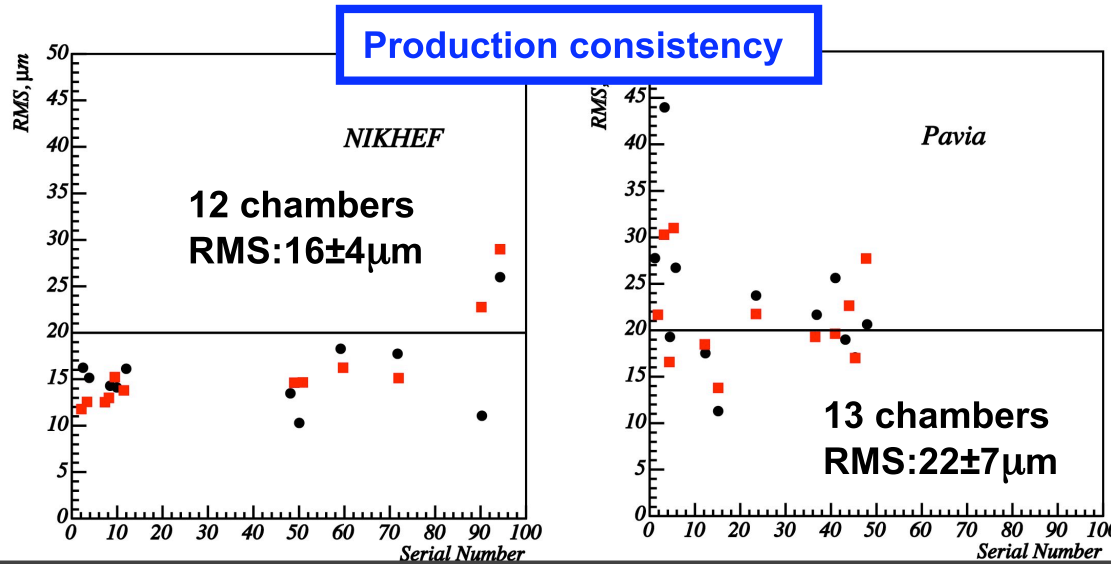
Wire measurement precision $2(\text{stat}) \oplus 2(\text{syst})$

MDT Mechanical Quality Control Results

- **8/2000-2005: ~180 of 1200 MDTs produced at 13 sites**
  - ✓ even largest MDTs with 20μm RMS precision
  - ✓ Several sites have average RMS: ~15±3μm
  - ✓ Cross-calibration of construction monitoring
  - ✓ Verification of procedure modifications or repairs
  - ✓ Production consistency
  - ✓ USE INFO in RECONSTRUCTION GEOMETRY



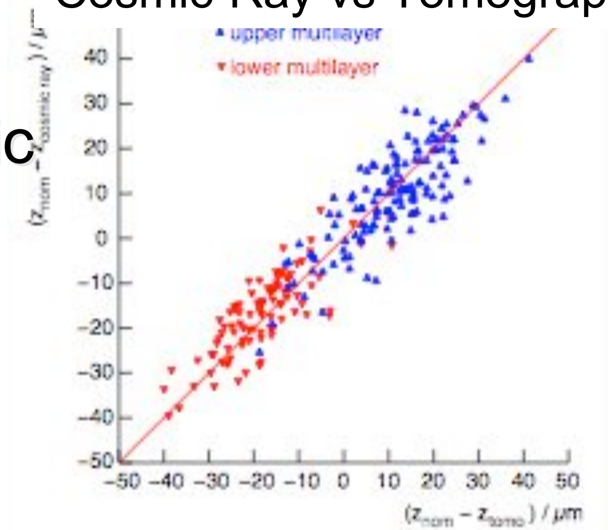


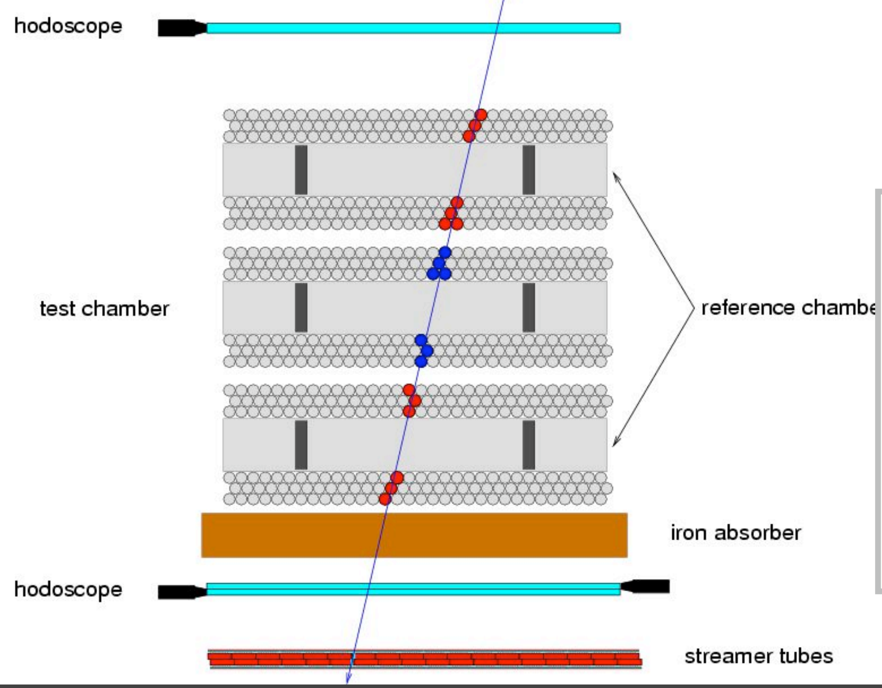


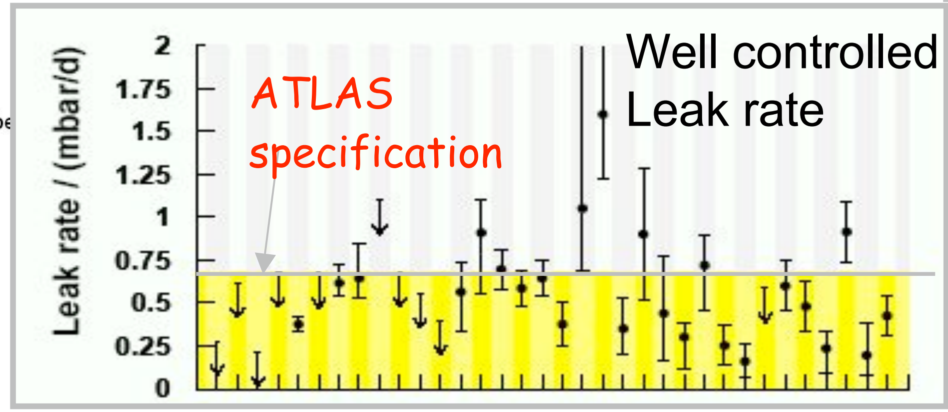
MDT Cosmic Ray Certification Test

- **All MDT chambers tested in Cosmic ray stands**
  - Noise test, leak rate + full checkout
  - Extract chamber geometry from cosmic stands (not all labs) - compares well
    $rms_y = 25\ \mu m$, $rms_z = 9\ \mu m$

Geometric consistency
Cosmic-Ray vs Tomograph



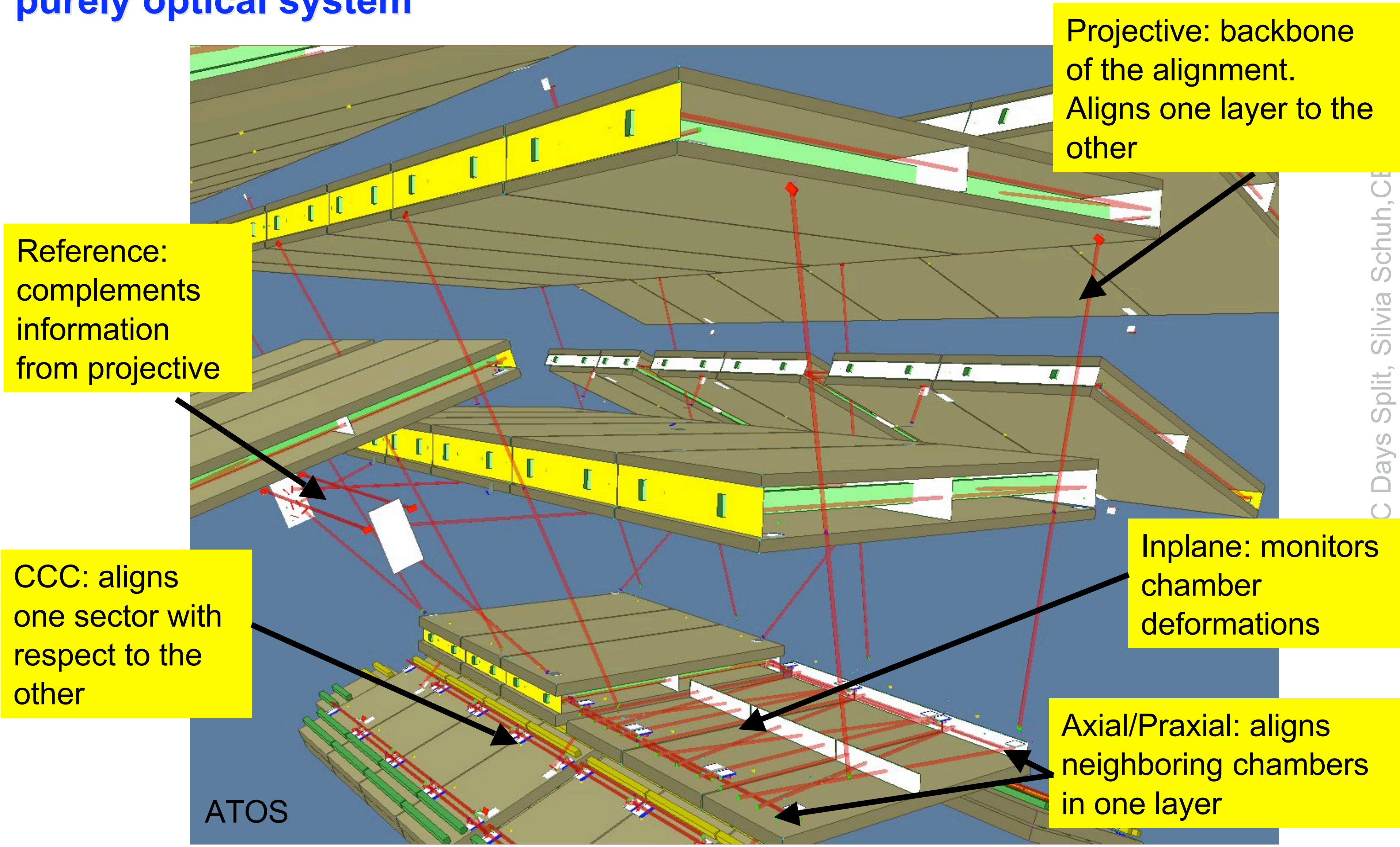




Muon Alignment

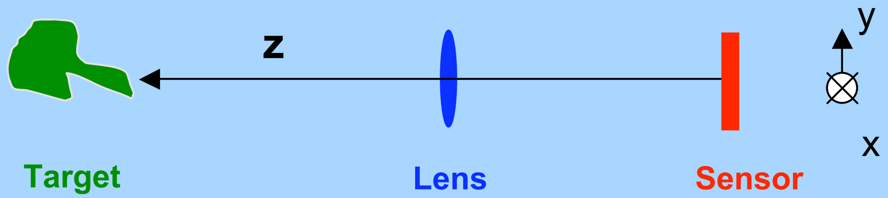
Layout of the optical sensors: barrel

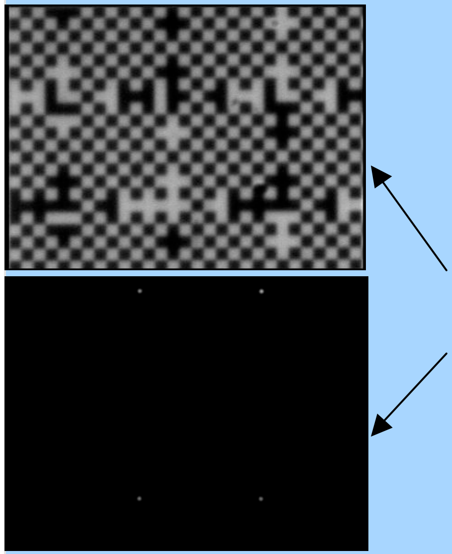
purely optical system



The optical alignment

3 point system: target, lens and a CCD

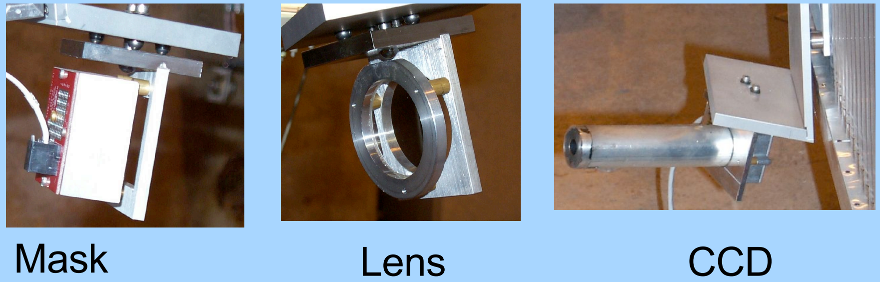


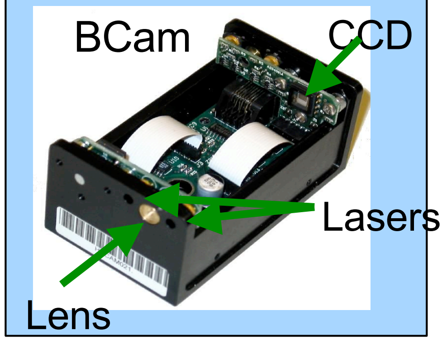


2 target types
- **Checker board**
- **Spot targets**

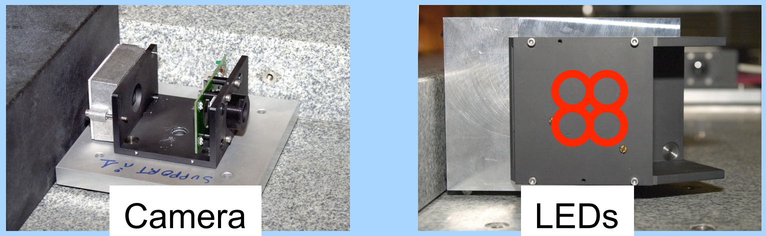
Image parameters
- Translation in x
- Translation in y
- Rotation around optical axis
- Magnification

RasNik





SaCam



Barrel: ~6000 optical lines

End Cap: ~7000 lines

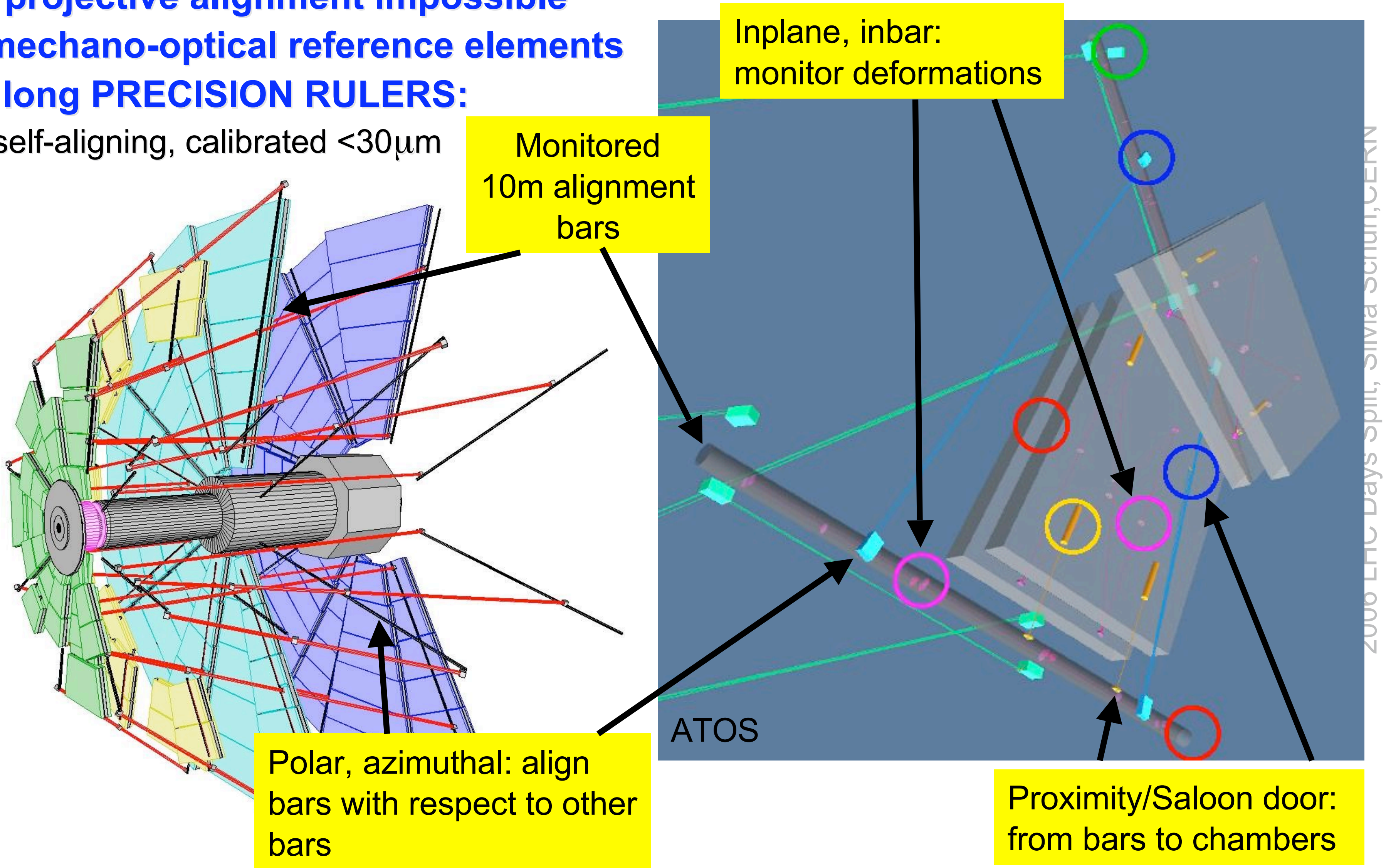
Layout of the optical sensors: end cap

fully projective alignment impossible

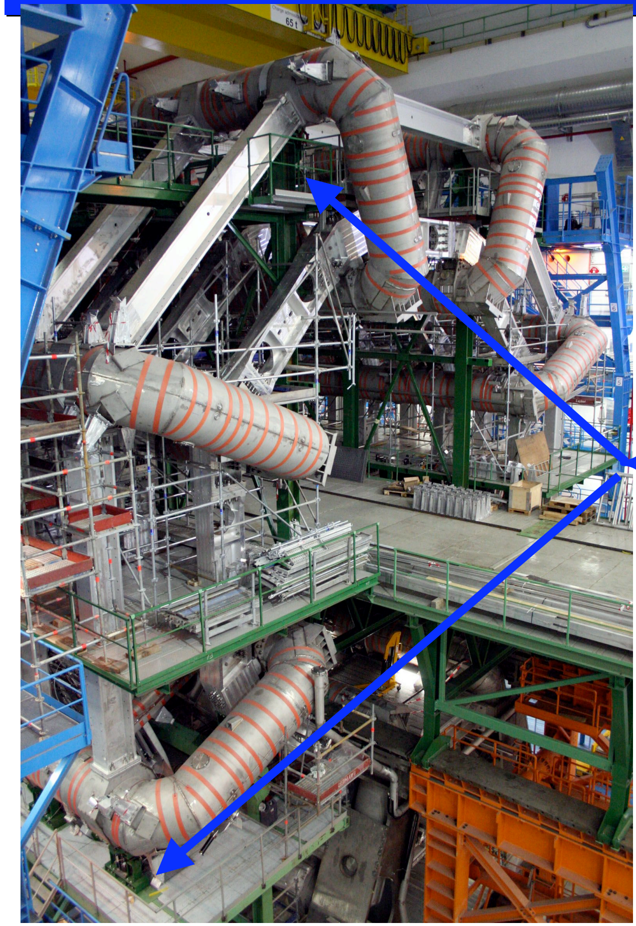
big mechano-optical reference elements

10m long PRECISION RULERS:

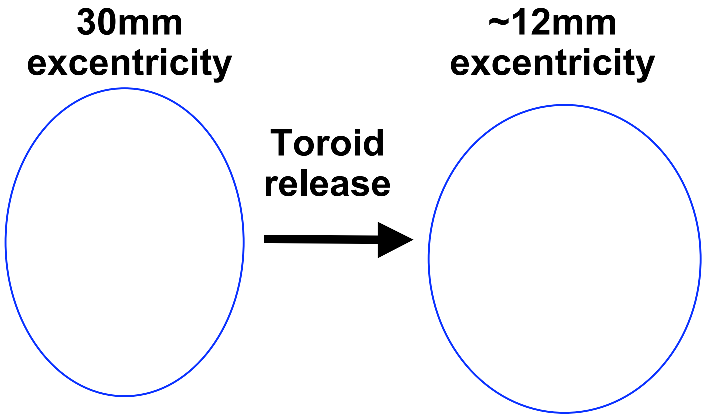
self-aligning, calibrated <30μm

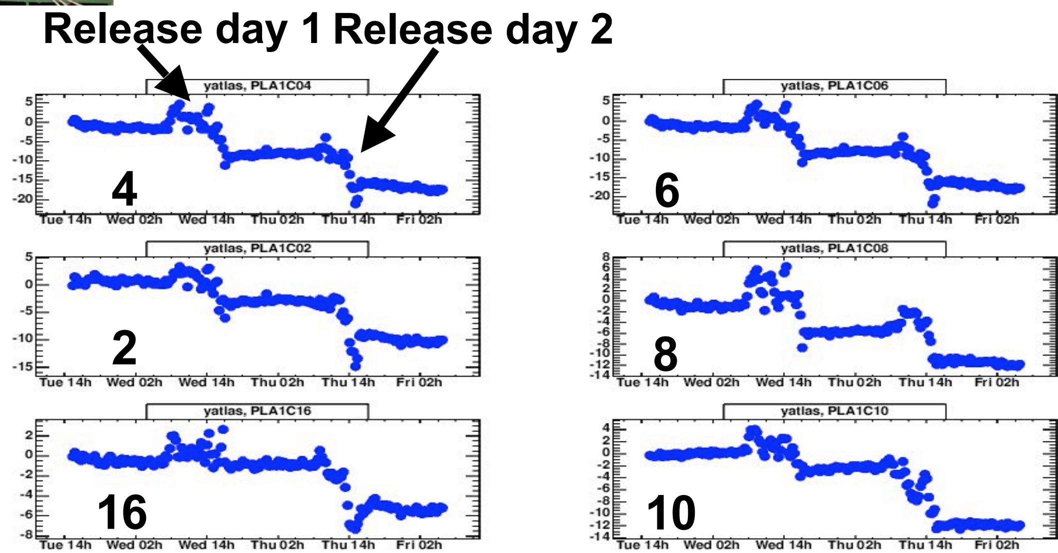


Alignment:Toroid release



- **Toroid supported by jacks during assembly**
- **Alignment monitored toroid deformation (reference system)**





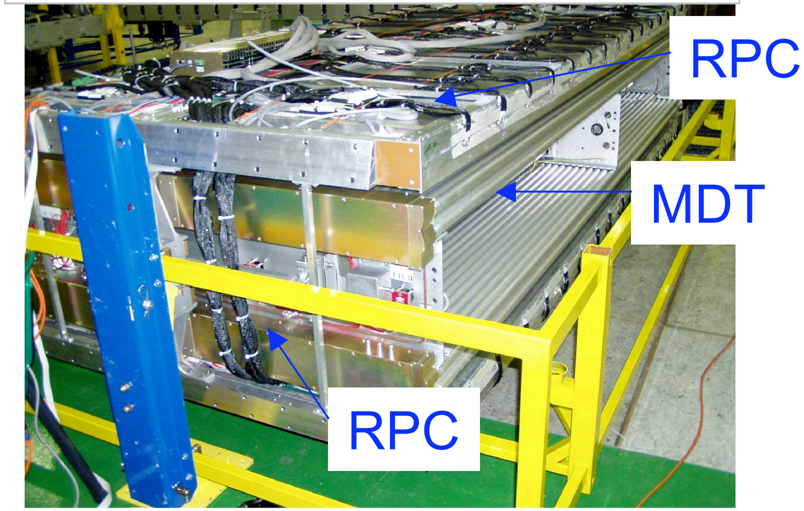
- **Deformation found consistent with calculation and survey**
  - Barrel Alignment: 17.6 mm
  - geometers: 17 mm
  - prediction (finite element): 18 mm

Installation & Commissioning

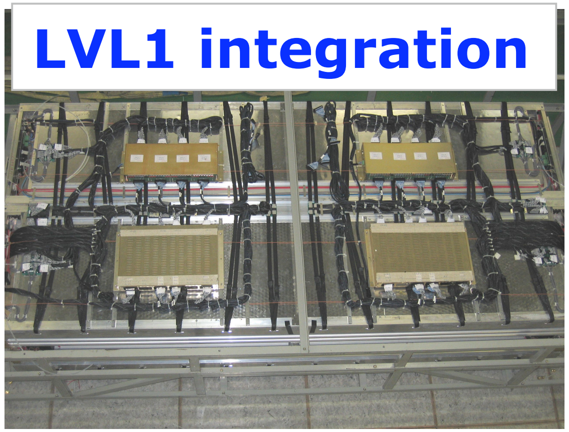
ATLAS Barrel Station Integration & Certification: RPC/MDT/LVL1

RPC preassembly & cabling

Integration with MDT



LVL1 integration

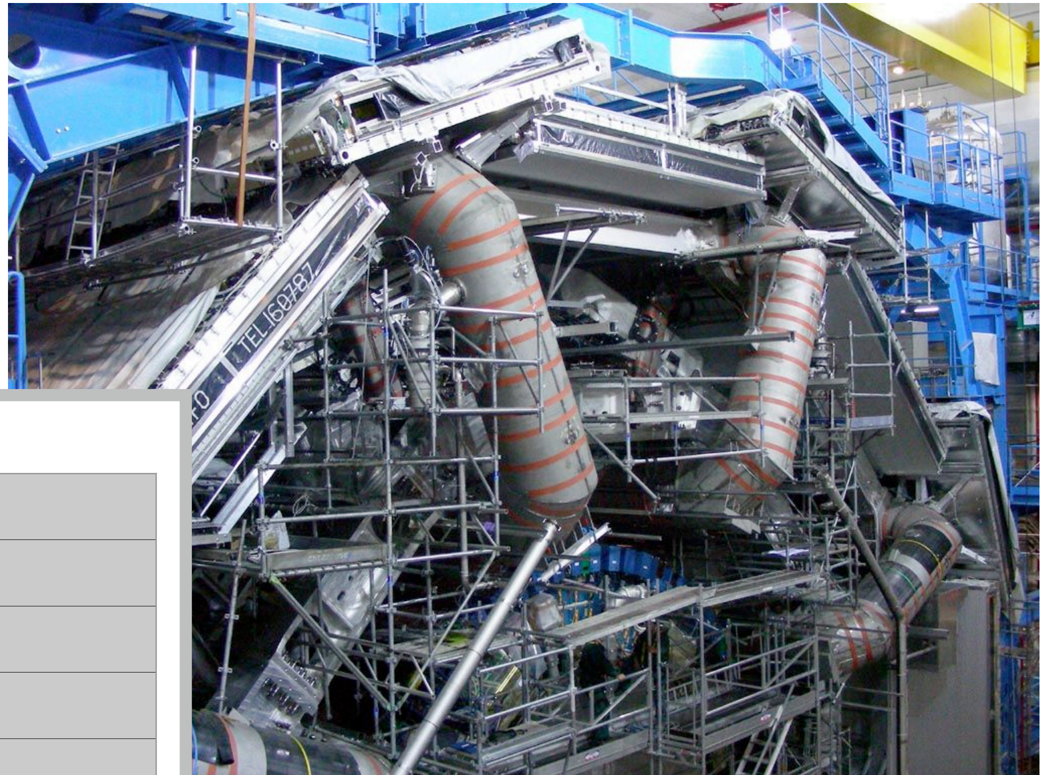


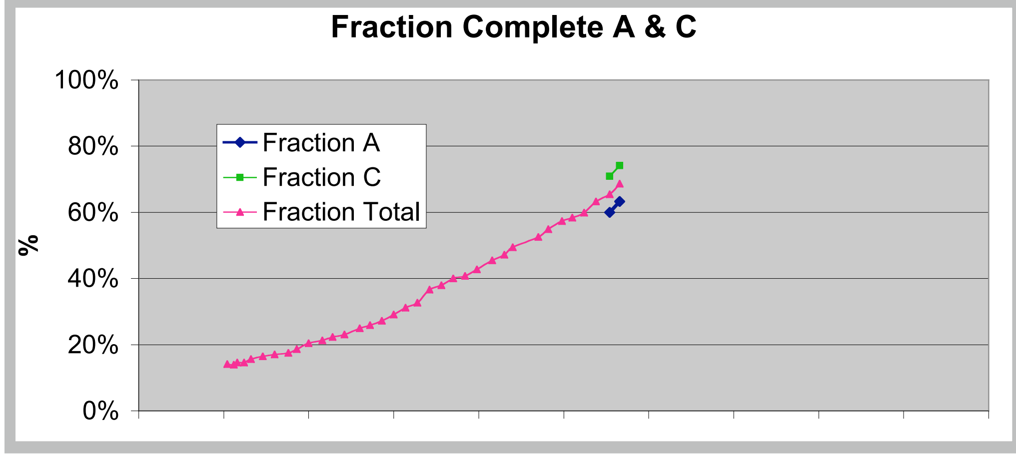
Full Muon Station: Cosmic Ray Test

Muon Chamber Installation: Barrel

Installation of a Barrel Muon Station

- **470 barrel muon stations installed (~70%)**
- **190 to go (20/week)**
- **Extrapolated finish: December ‘06**
- **… but: access sequence → spring ‘07**





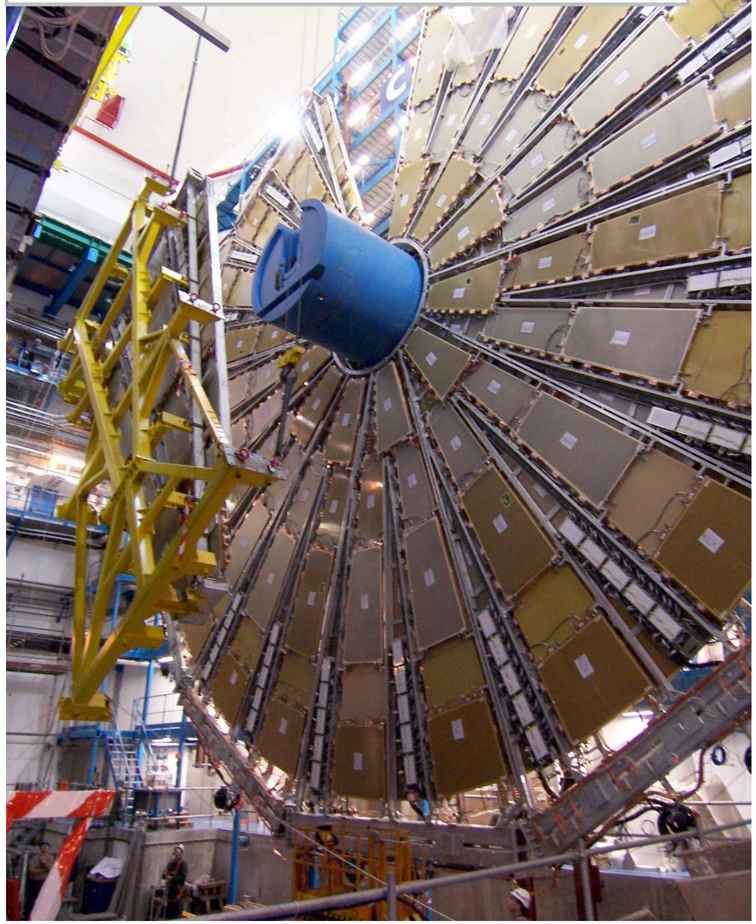
Muon Chamber Installation: Endcap

- EC installed on 'Sectors' of wheels, 6 wheels, 12 sectors each
- MDT & TGC sectors > 50% integrated

Expected finish: June '07

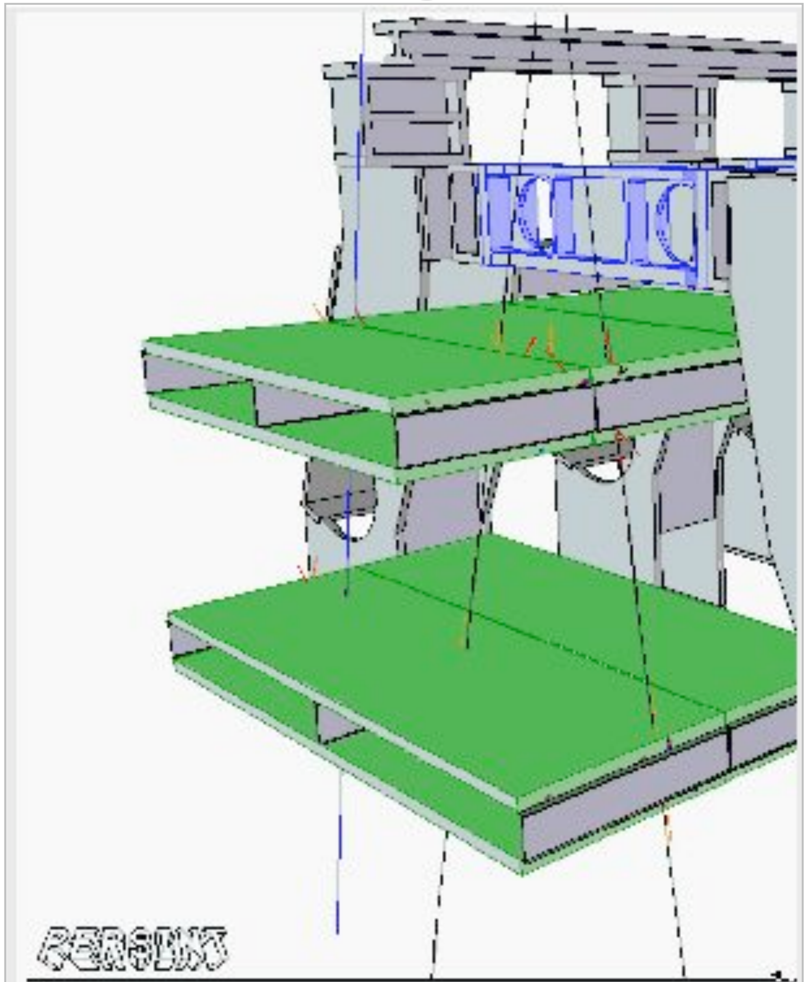
Endcap segments ready for installation

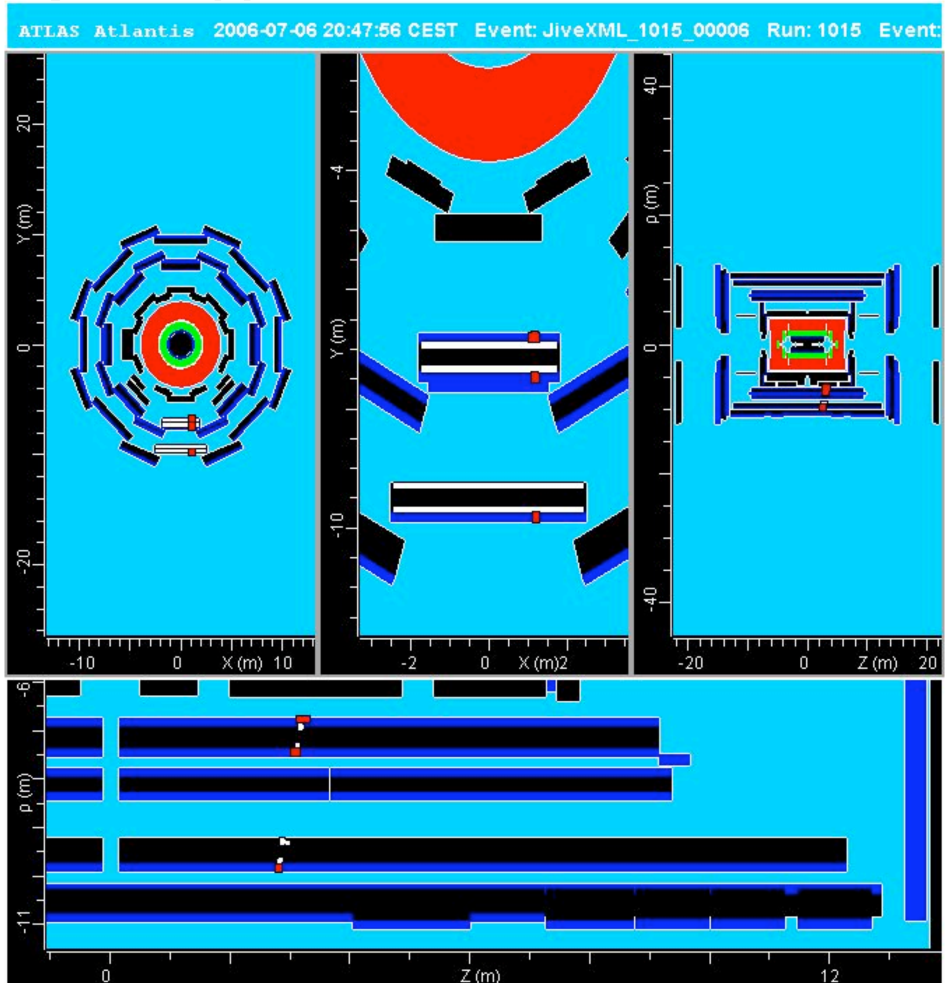
1st TGC C-side completed, 9/'06



Spectrometer Commissioning

- Full sector test: tracking, trigger, alignment (projective)
- Cosmic Ray data: MDT + RPC + Trigger (LV1), 6 stations from middle & outer layers in lowest sector
- Next: cosmics together with Inner layer & uppermost sector

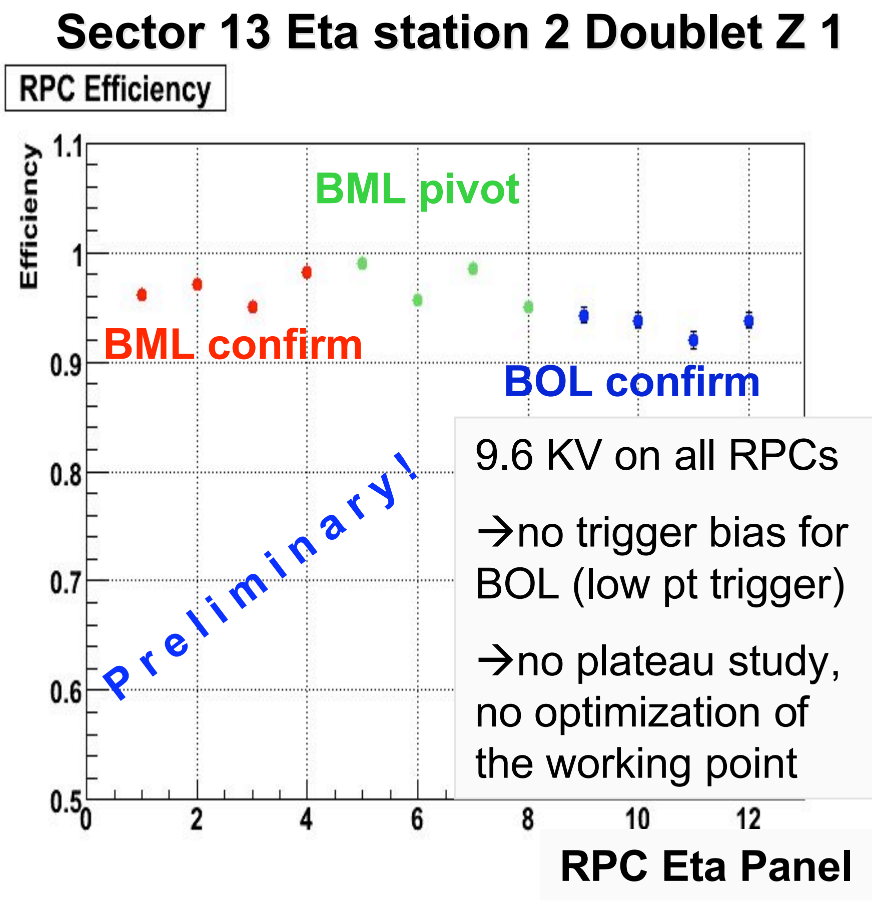




Spectrometer Commissioning

◆ RPC & MDT correlations

- Tool within ATHENA
- Segment reconstructed by MDTs projected to RPC gas gaps
- Preliminary MDT calibration and reconstruction tuning
- Each MDT chamber corresponds to two RPC gaps in the phi view → assign strip to the right panel (doublet phi=1 or 2):
  - Check if hit on eta view of other gap of same doublet
  - Check if hit on phi view in one of the two gaps



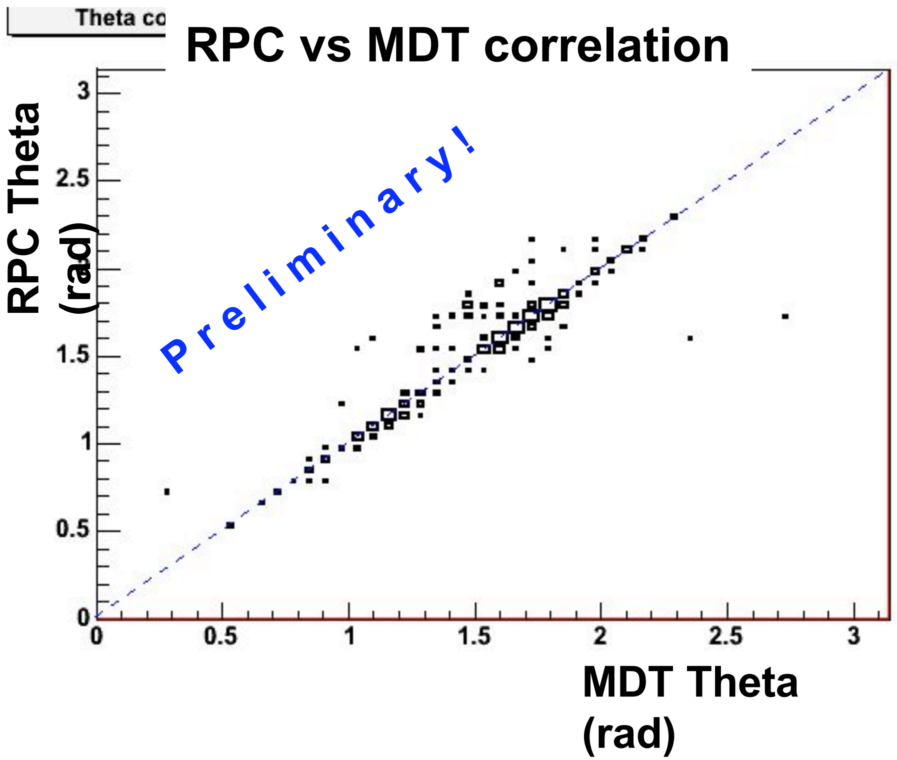
9.6 KV on all RPCs

→no trigger bias for BOL (low pt trigger)

→no plateau study, no optimization of the working point

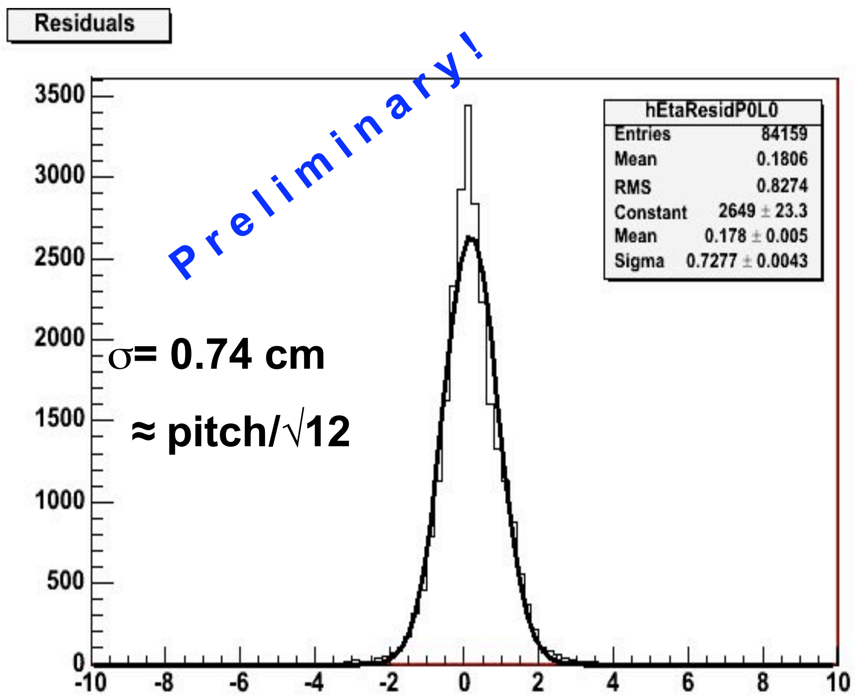
RPC commissioning: tracking

- **Perform fast RPC tracking for online before EF steps (no ATHENA)**



Good correlation between angle in r-z view reconstructed by Athena with MDT and by online code for RPC

Good tracking resolution on all planes



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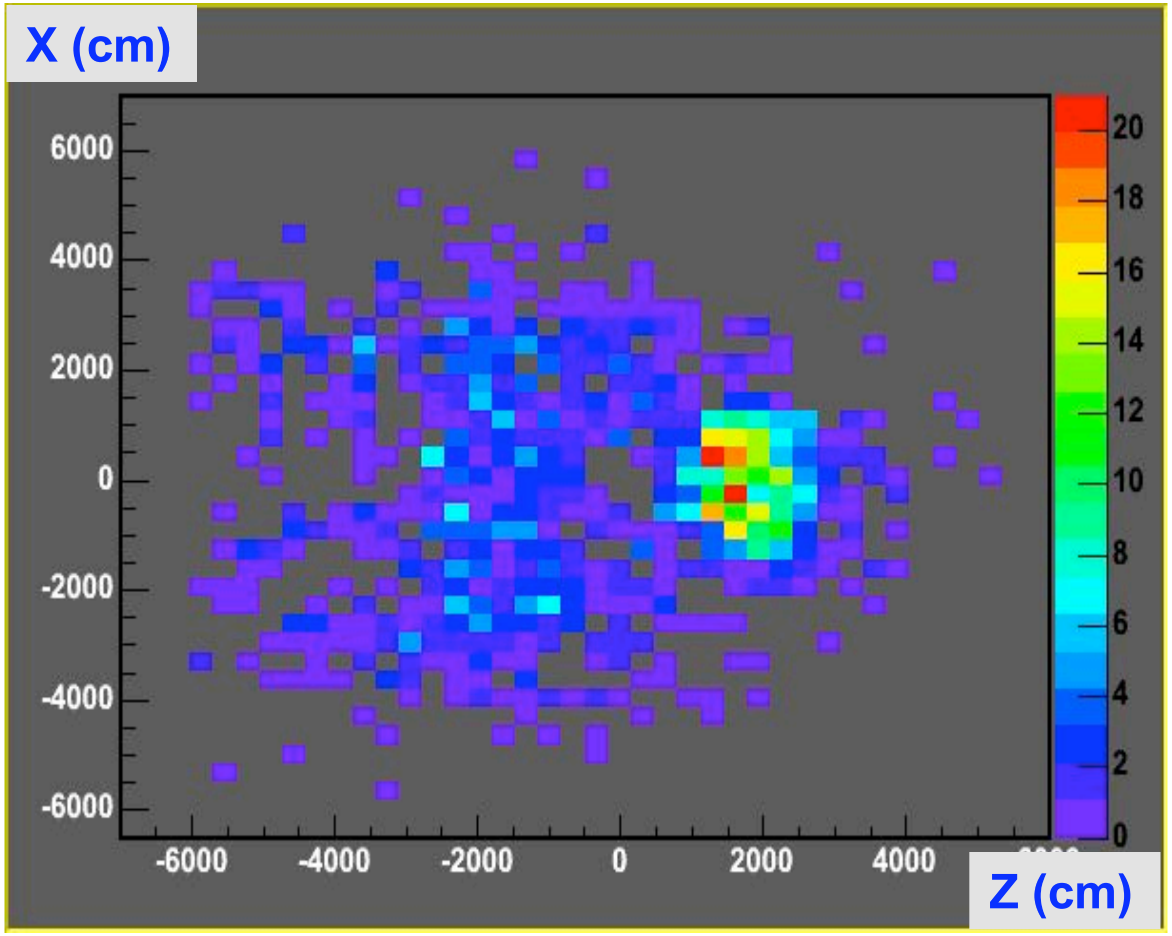
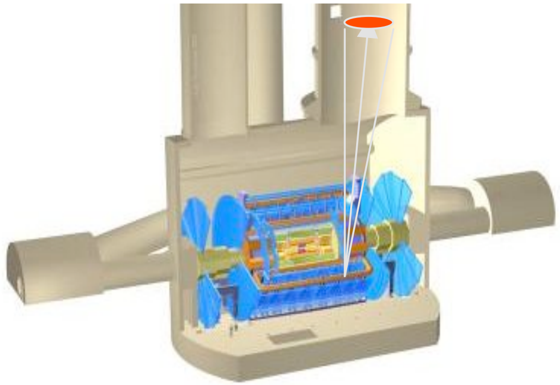
Commissioning with Cosmic data

For cosmic muons going through Sector 13 (4 rpc hits): simulate their impact point (X vs Z) at surface level





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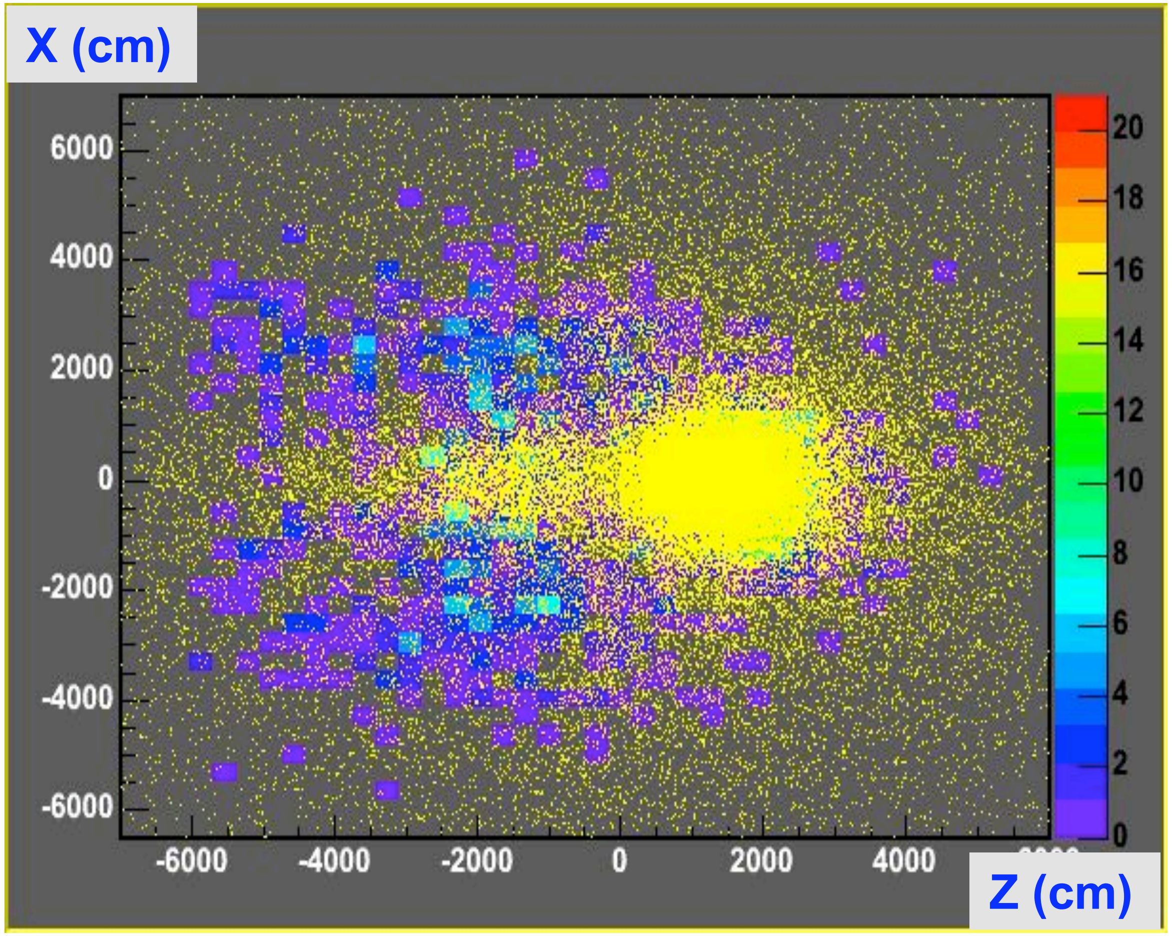
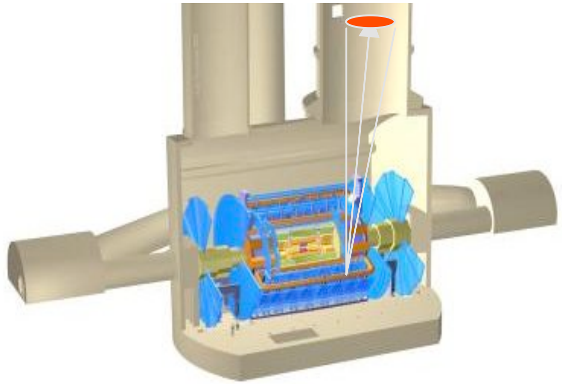
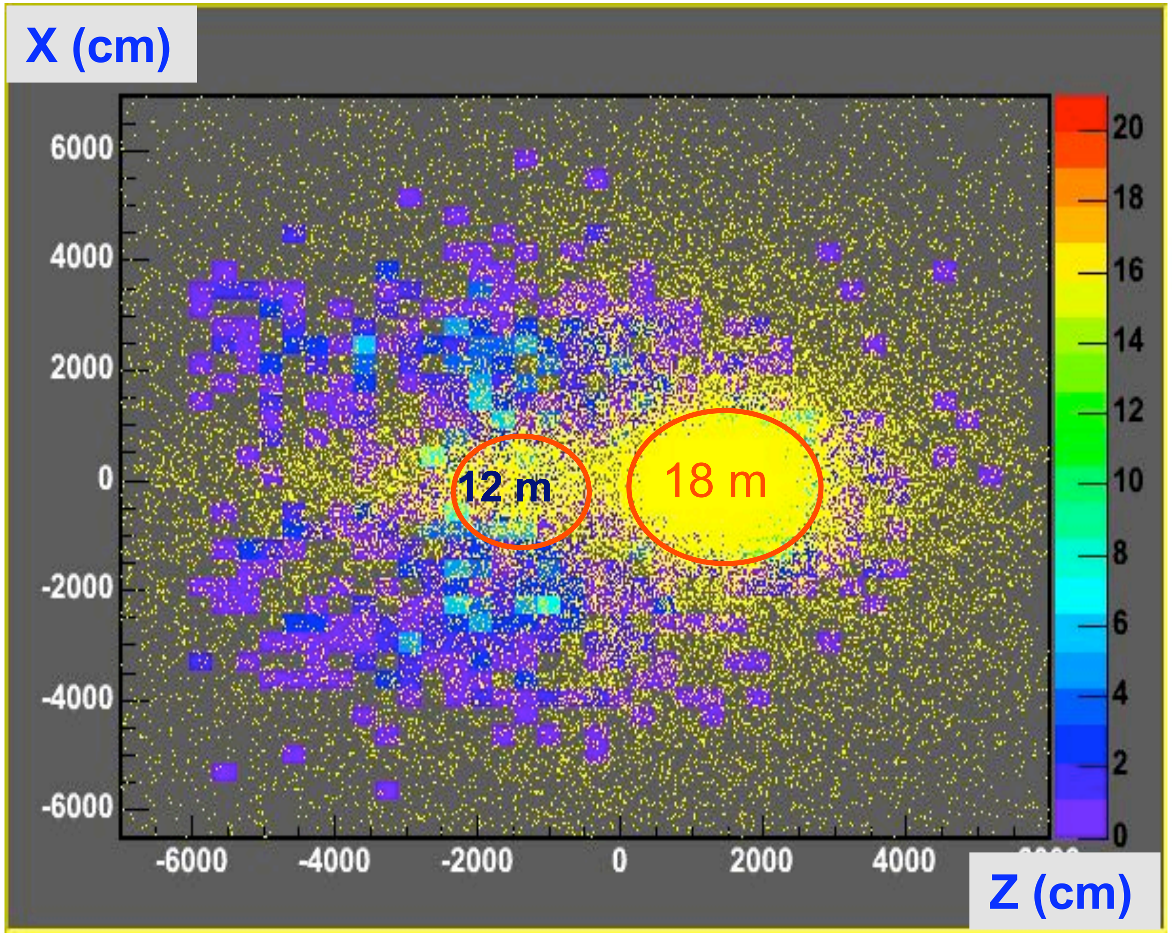


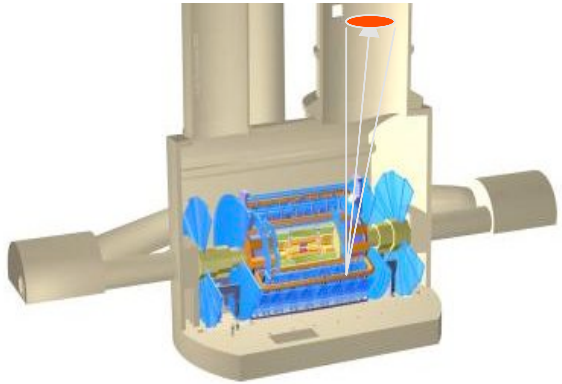


Tracks fitted through RPCs, extrapolated to surface

Commissioning with Cosmic data

For cosmic muons going through Sector 13 (4 rpc hits): simulate their impact point (X vs Z) at surface level

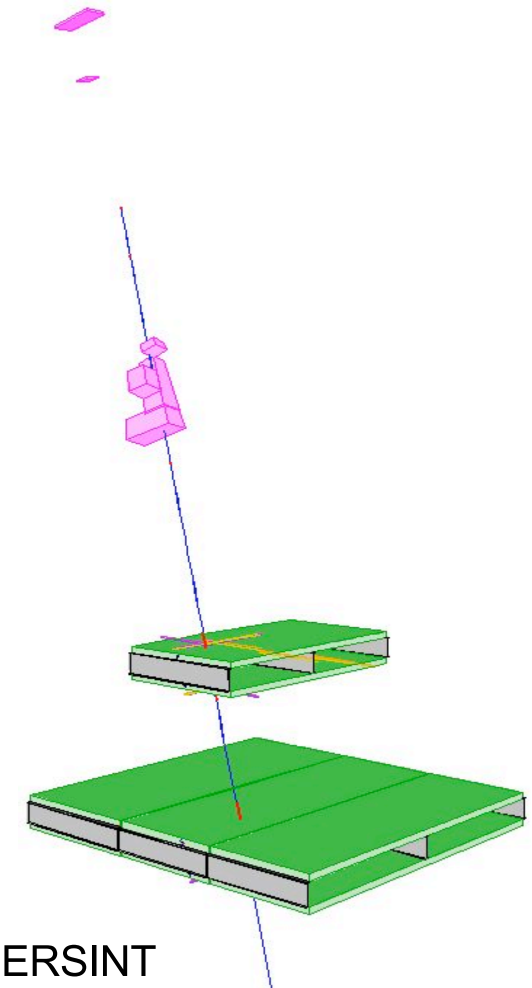




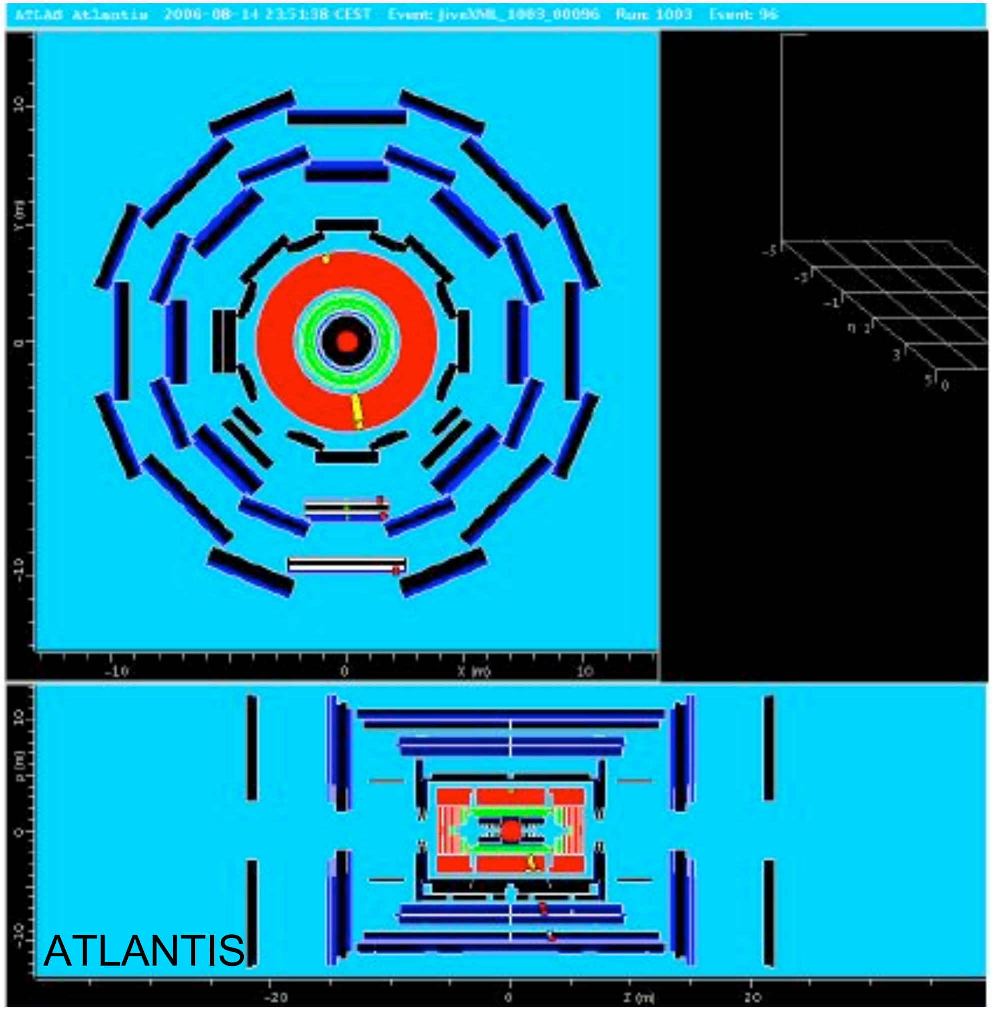
Tracks fitted through RPCs, extrapolated to surface

Combined Commissioning

- Cosmic ray data: MDT + RPC + Tile Calorimeter, middle August
- Trigger on RPCs
- Reconstruction in general ATHENA framework



PERSINT



Summary and Outlook

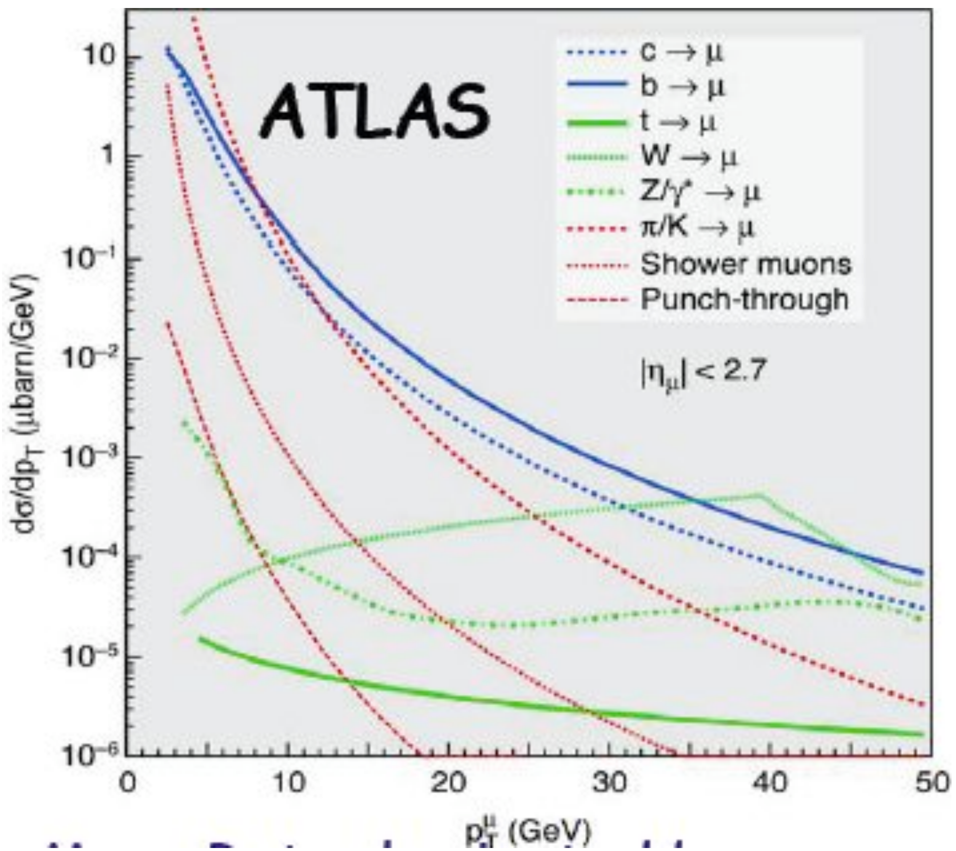
- **Production of muon system has finished**
- **Monitoring showed stringent construction criterions mostly achieved**
- **Installation in full swing, coming to end for some parts**
- **Commissioning of the installed barrel detector has begun**
  - Parts of 1 full sector: MDT + RPC + tiles
  - Toroid full current test starting "now"
  - Include more sectors into readout
- **Everything is on track for beam pipe closing end of summer next year**

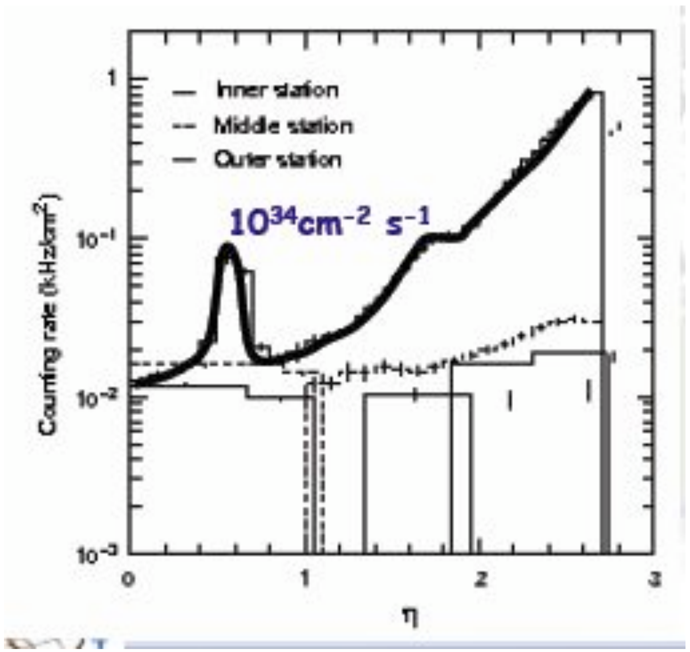
Exciting times ahead!

Backup Slides

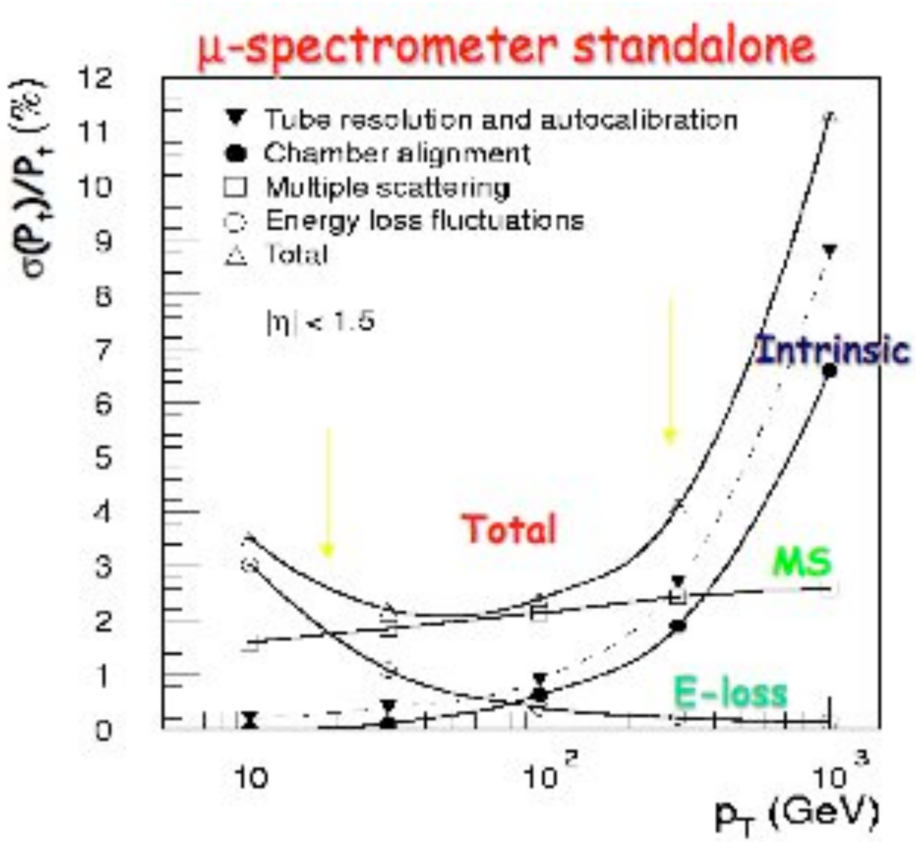
Counting rates in Muon Spectrometer

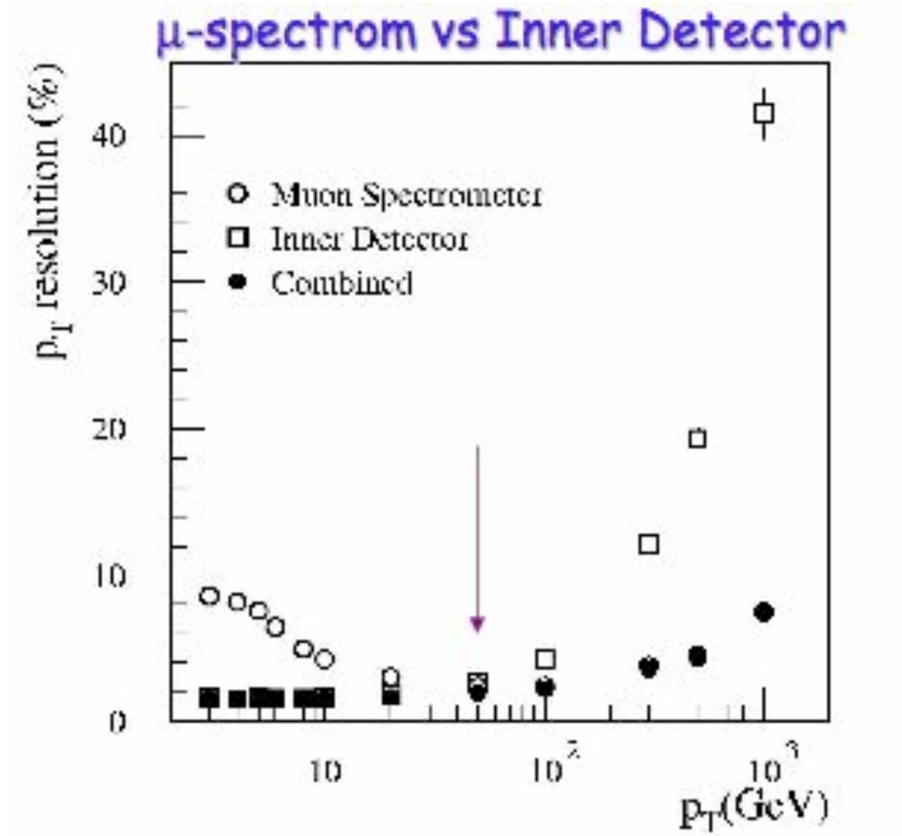
At nominal Luminosity





MDT momentum measurement performance

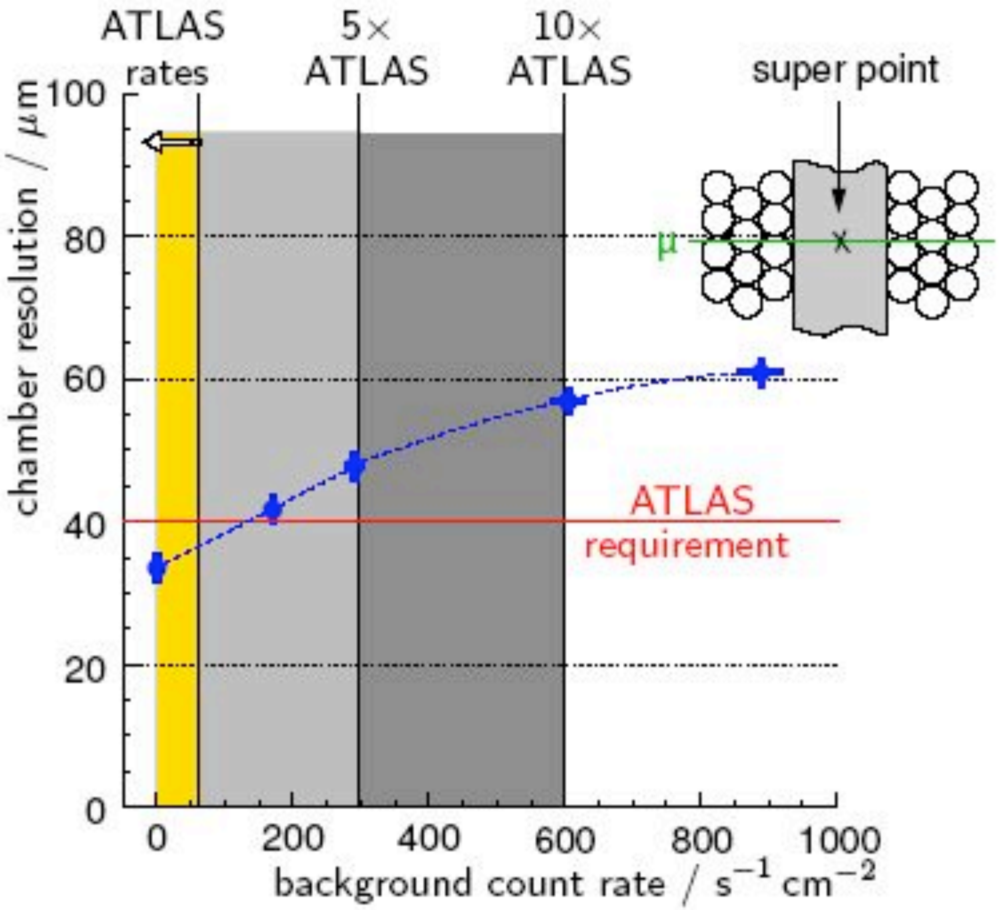


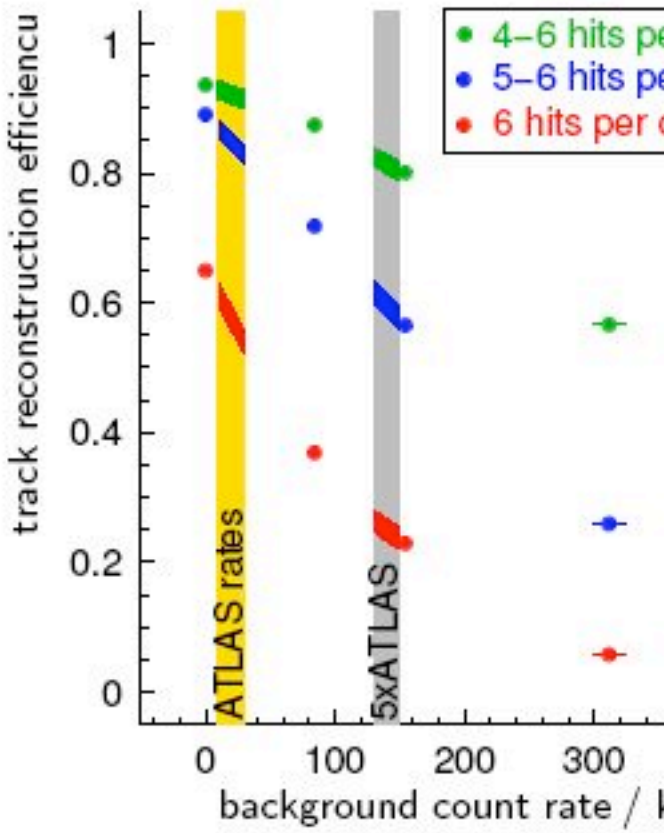


- μ-spectrometer resolution dominated by MS for 20 < p_T < 300 GeV
  - $\sigma(p_T)/p_T \sim p_T \times 10^{-4}$ (intrinsic) ⊕ ~2% (MS) ⊕ 0.3GeV/p_T (E-loss)
- μ-spectrometer dominant over ID for p_T > 50 GeV

Performance under High γ-Irradiat

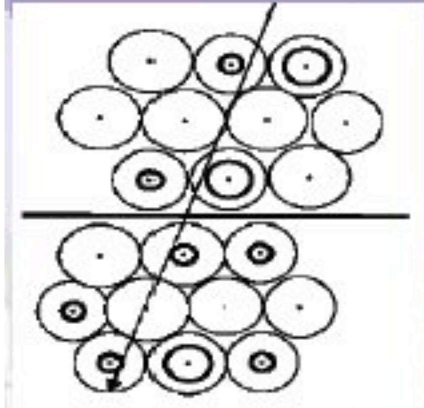
Test of the MDT-chamber response to muons
under influence of high background rates:





- performance within the requirements even

Muon Reconstruction principles

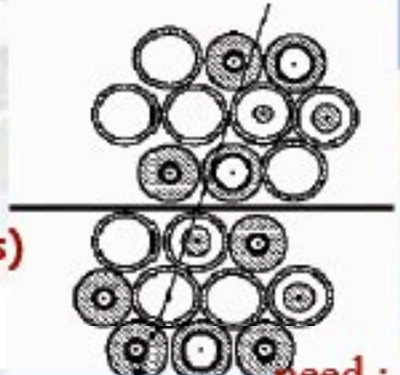


- precise, but very distant local measurements
- field very inhomogeneous
- material, to be taken into account
- "noise"
- RPC: strips in η and φ (cm)
  - areas of activity in which one will seek the segments

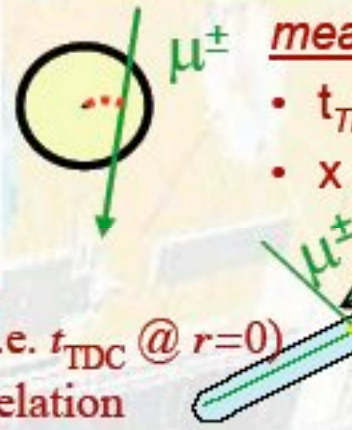
Drift time + RT = ring (80μm)
Segment = tangent with all these rings

BUT

- zone ineffective (center, edge)
- "noise" , "Dead time" (~700ns ~ Rayon tubes)

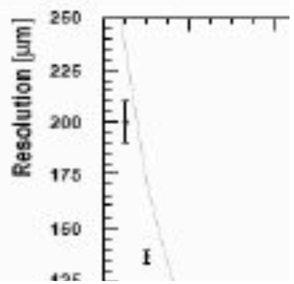


t_0 and



mea
- t_T
- x

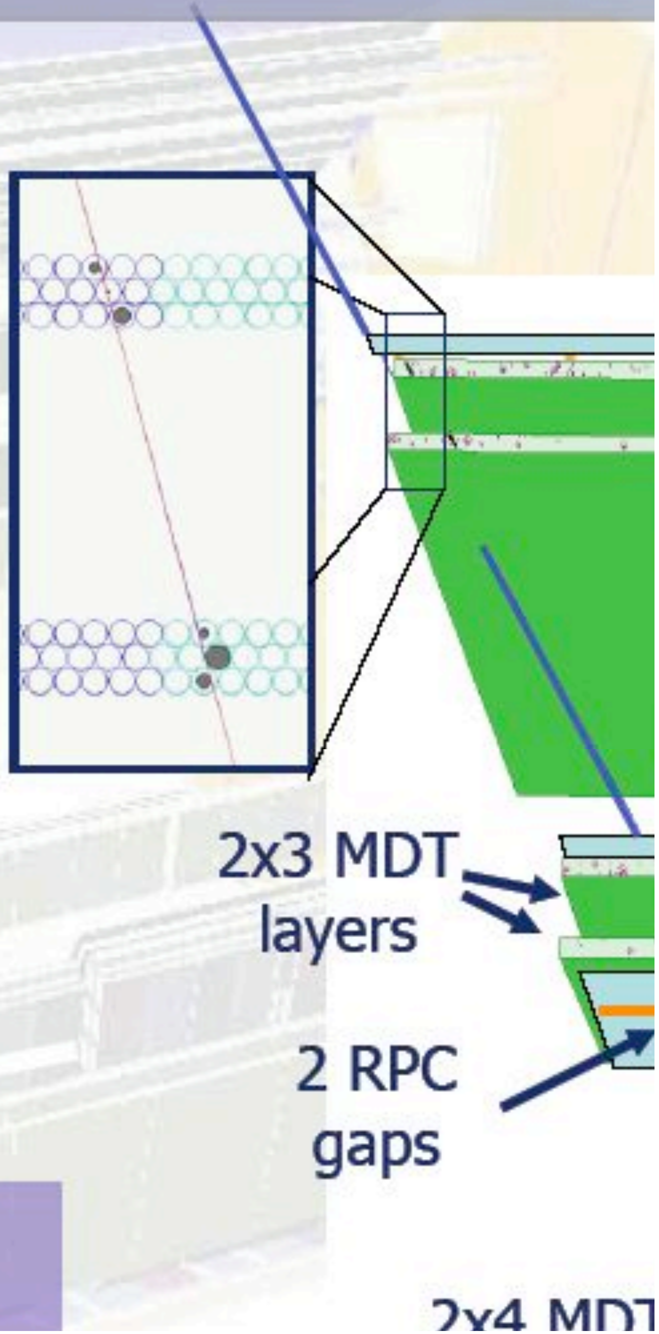
need :
- t_0 (i.e. t_{TDC} @ r=0)
- r/t relation
  (i.e. math function $t \rightarrow$



From a Precision Digit to a Precision Hit
The creation of an MDT hit starts by subtracting from the digits drift time, the time it takes to the signal for propagating along the tube-wire to the front-end electronics.
The MDT chambers do not measure the azimuthal coordinate along the wire, so to determine this propagation time, the overlap region of the wire with the trigger chambers φ measurements is used together with a signal-speed. The time is then corrected for the tof from the interaction point to the MDT tube. *The resulting drift time is subsequently*

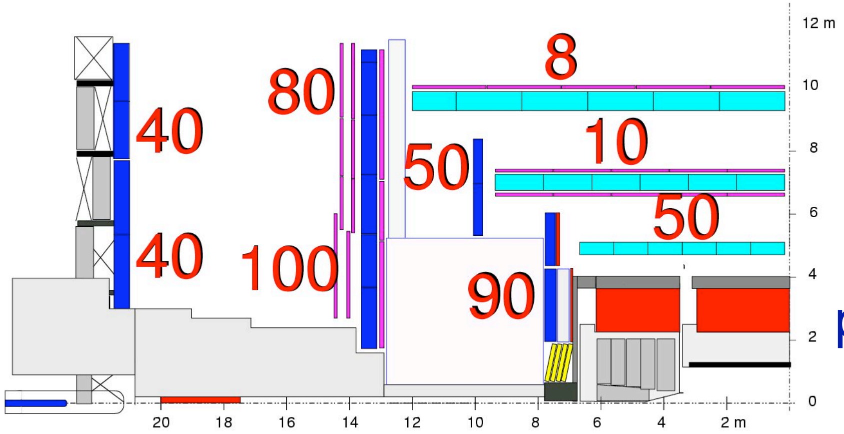
Measuring muons in MS Barrel sector

- Precision measurements of z in the bending direction of the MF ($\sigma z = 80\mu m$) with 3 MDT stations
- MDT station: 2 multilayers of 3 (4 in the inner station) layers of monitored drift tubes
- Trigger and measurements of z-ϕ coord. ($\sigma z\phi \sim 1cm$) with 2 RPC layers in the middle station + 1 RPC layer in the outer station
- RPC layer: 2 gas gaps read independently



Total: ~ 20 precision z measurements +
~ 6 z-ϕ measurements

Performance under LHC Conditions

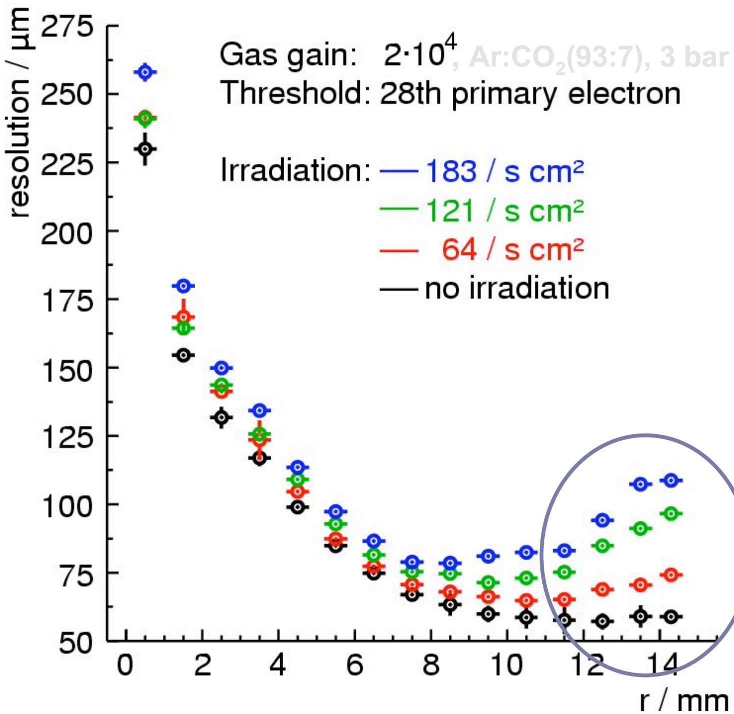


operation at unprecedentedly high n and γ background rates:

8 – 100 $s^{-1}cm^{-2}$

performance test of a large 6-layer chamber:

- high energy μ beam **(100 GeV)**
- γ-ray irradiation **(Cs-137 source with 740 GBq)**
- external reference **(silicon beam telescope)**



single tube resolution vs. drift radius

Single Tube Resolution

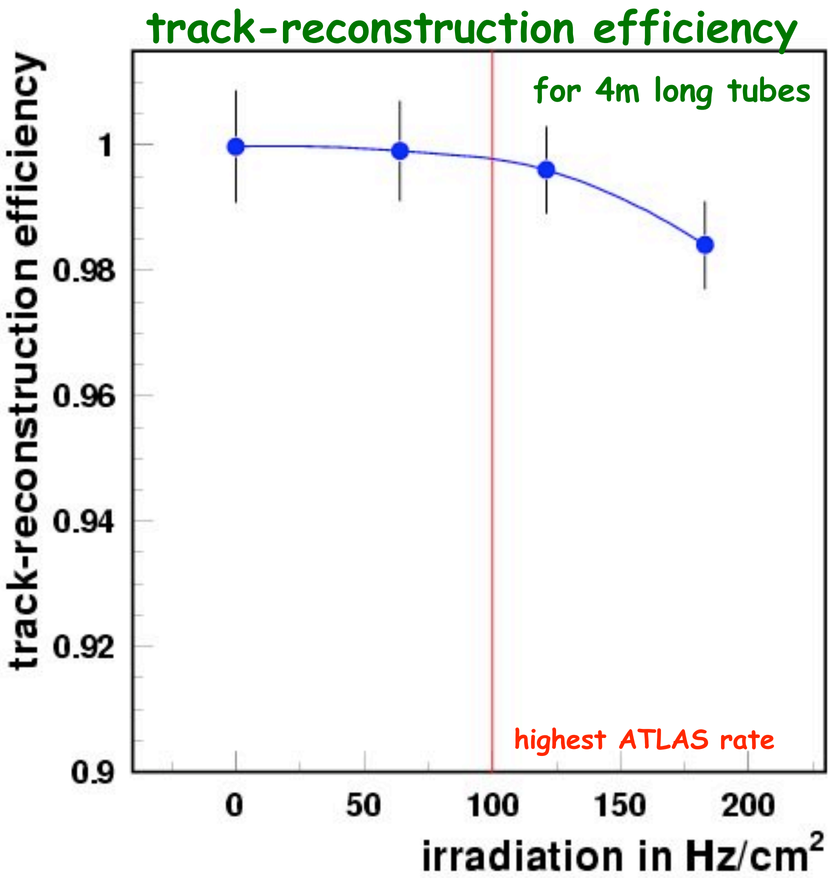
required resolution maintained even at high irradiation:

- 104 µm without irradiation
- degradation by 10 µm at highest ATLAS rates of 100 $s^{-1}cm^{-2}$

degradation due to space charge fluctuations

Efficiencies

extraction of tracking efficiency using the reference track in the Si telescope



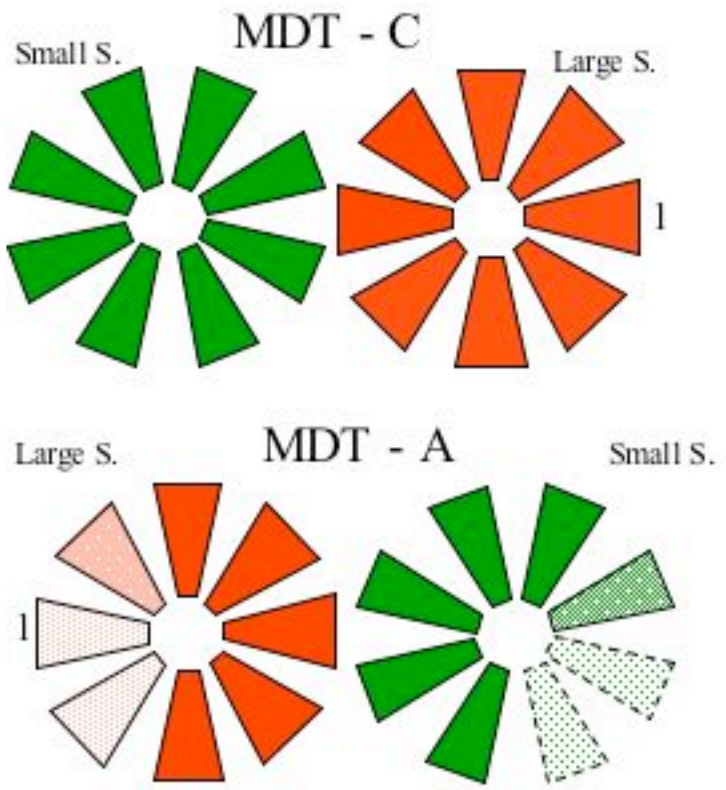
total track-reconstruction efficiency:

- ($99.97^{+0.03}_{-0.9}$)% without irradiation
- ($99.77^{+0.23}_{-0.8}$)% at highest ATLAS rate (for 4m long tubes)

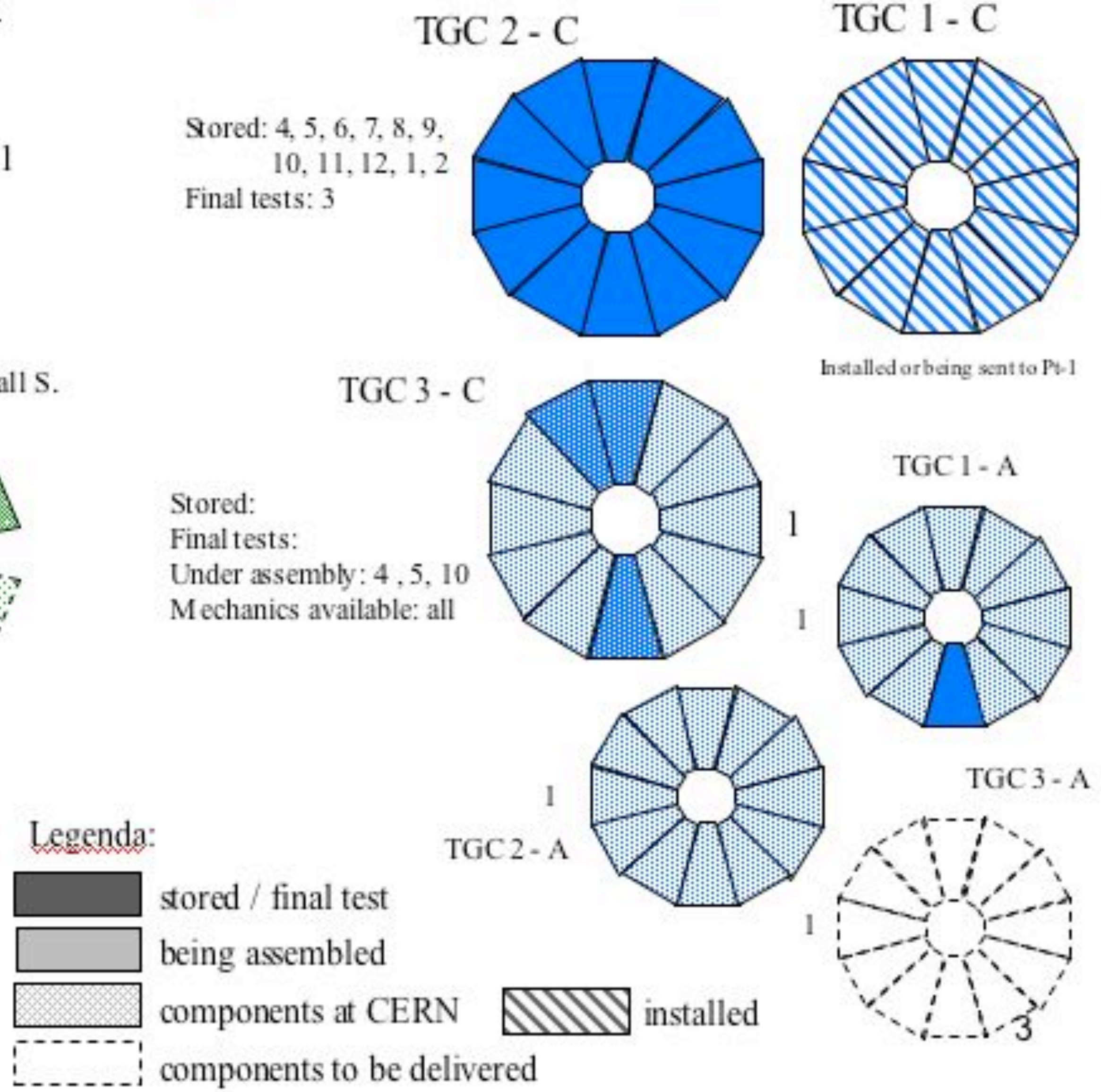
∅ even at highest expected irradiation
no deterioration of track-reconstruction efficiency

Pattern of assembled Endcap sectors

The number of sectors (being) assembled has passed the threshold of 50% of the total

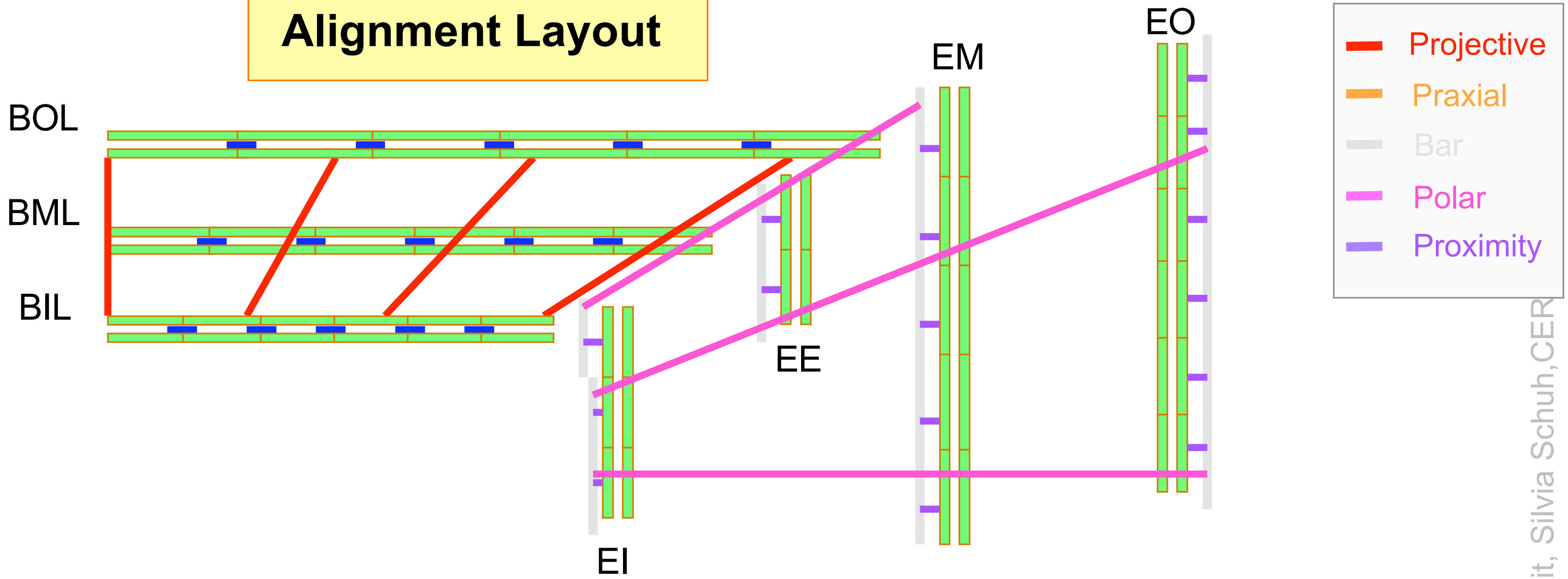


L-stored: 7, 9, 11, 13
L-final test: 5
L-under assembly: 3
L-mechanics available: all
S-stored: 4, 2, 16, 14
S-final test: 6
S-under assembly: 8
S-mechanics available: all

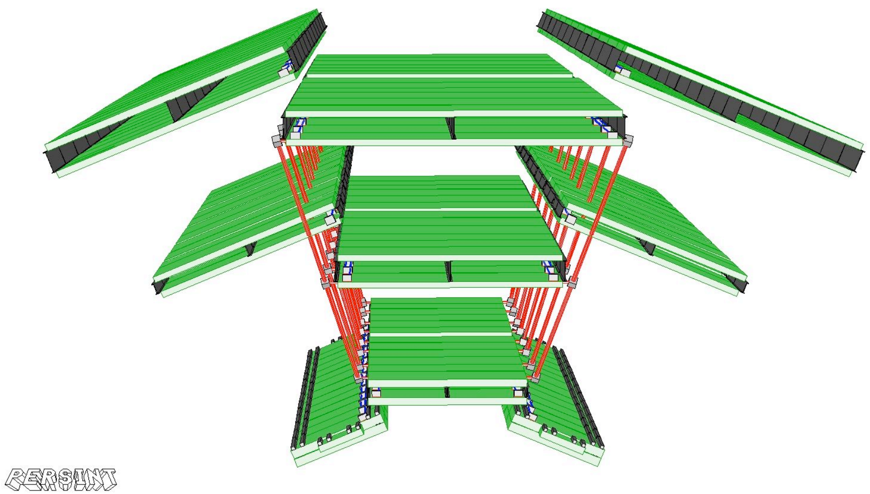


Sep. 6, 2006

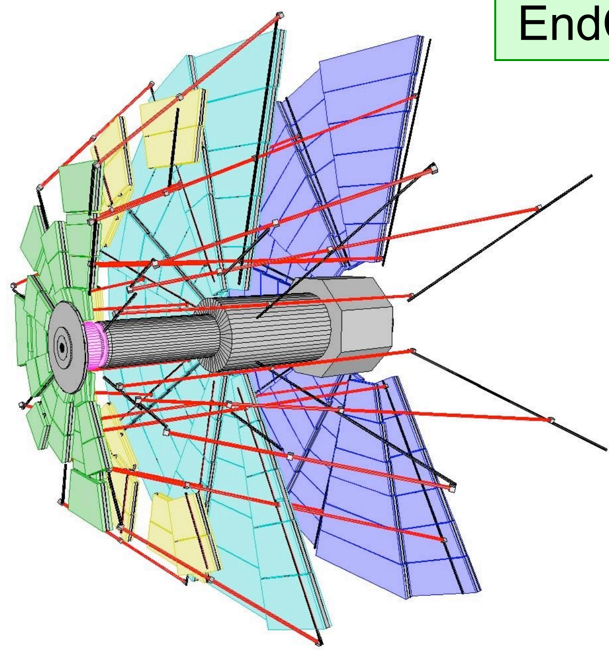
Alignment Layout



Barrel

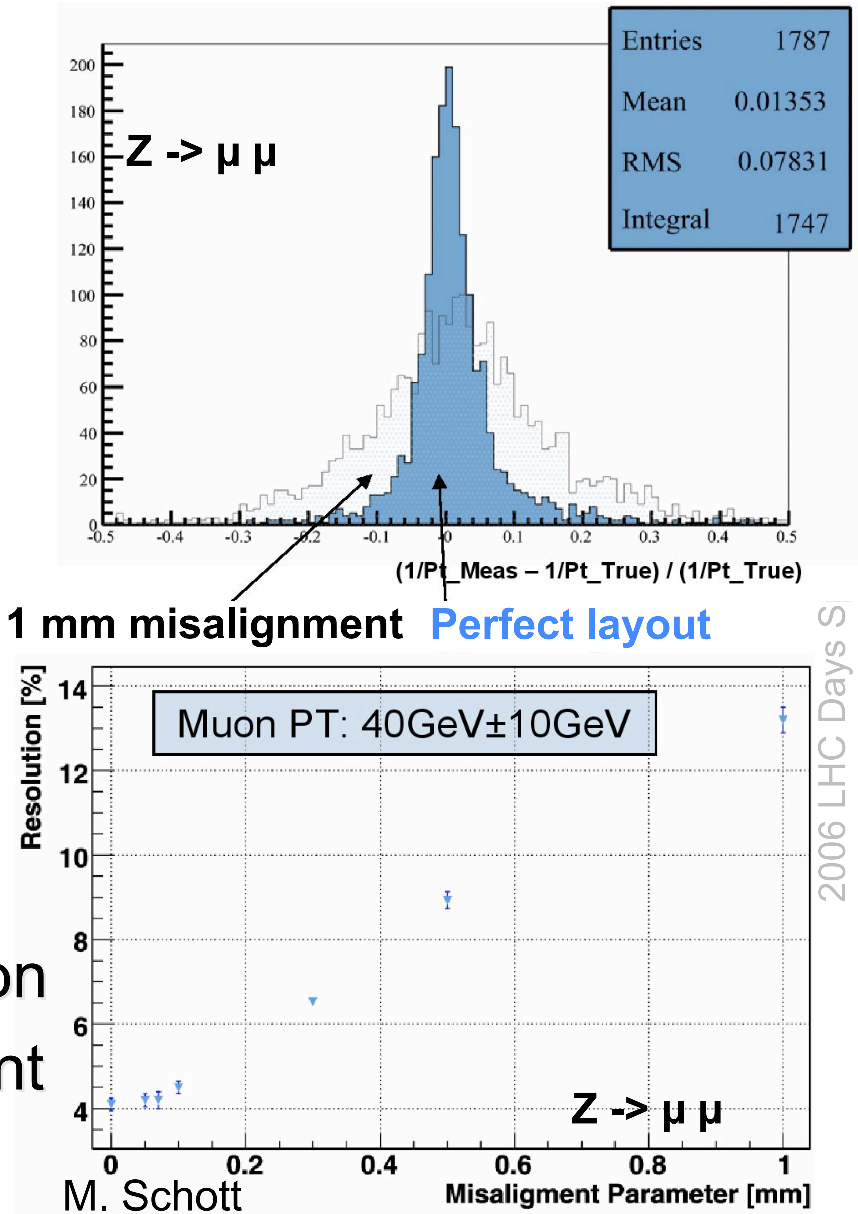


EndCap



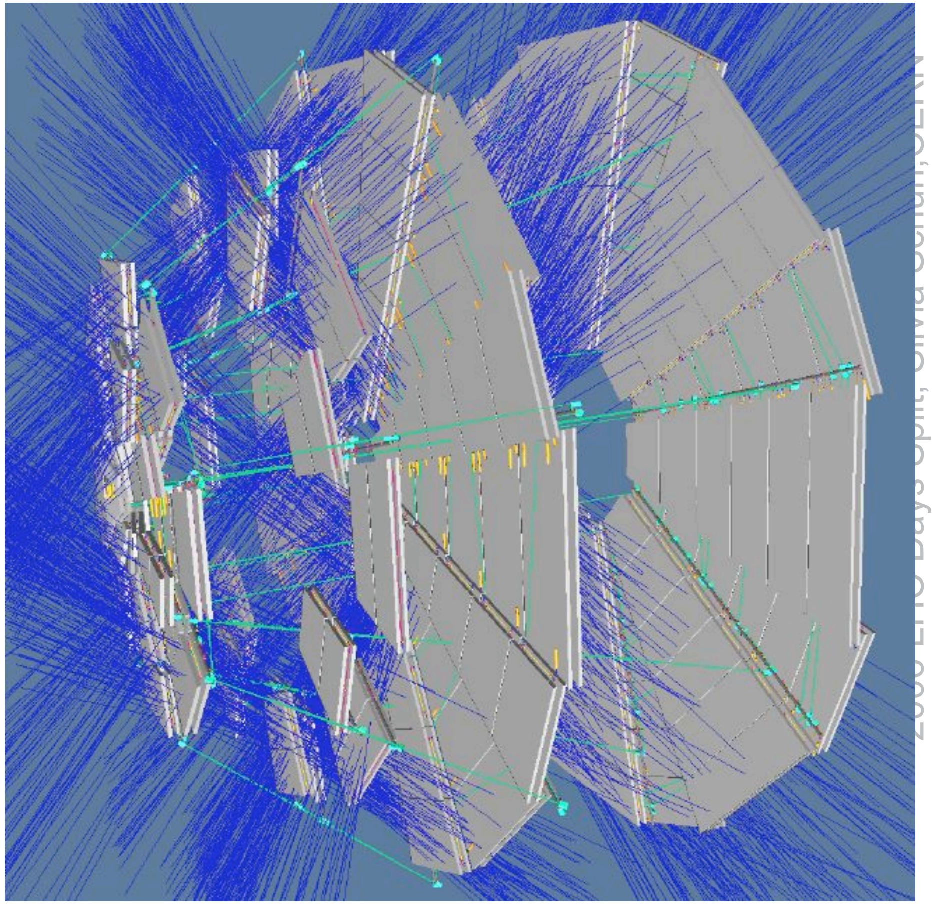
Misalignment impact

- **Sources of misalignment:**
  - Initial positioning of the chambers: 2 to 10 mm
  - Deformation of toroid due to weight (mm level)
  - Switch on B field (mm level)
  - Thermal expansion (< 1mm)
    - could evolve significantly in time
    - online monitoring needed
- **Impact of misalignment:**
  - big loss on momentum resolution
  - foreseen with 1mm misalignment even for low momentum tracks



Alignment with straight tracks

- **Several runs with straight tracks are foreseen:**
  - cosmic ray runs: some chambers poorly illuminated
  - beam halo: end-cap mainly
  - run with:
    - toroid off
    - solenoid on
    - high momentum tracks selected using inner tracker
- **Purpose:**
  - debugging the optical alignment
  - reference geometry of the relative alignment



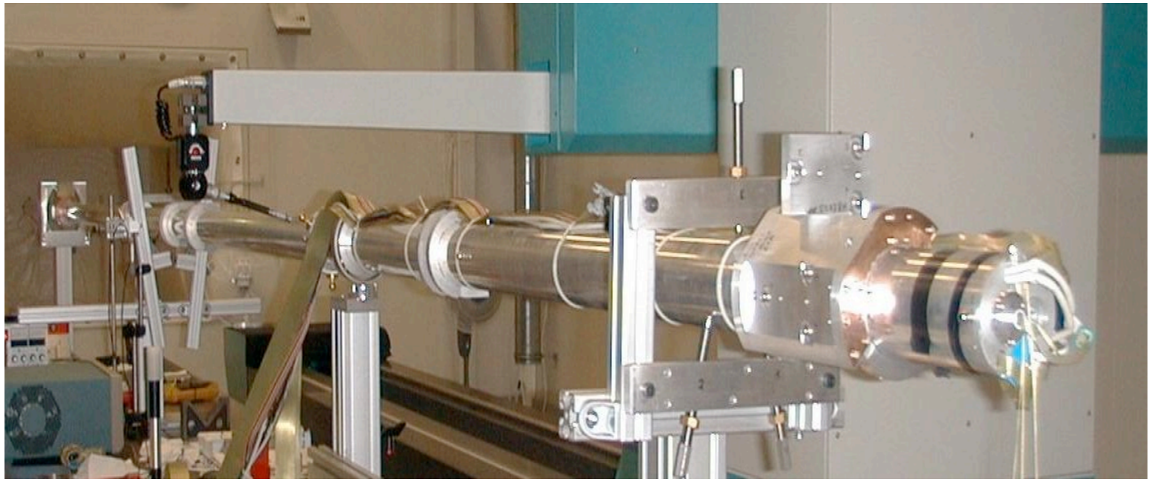
Endcap illuminated with cosmic rays

Alignment Device Positions

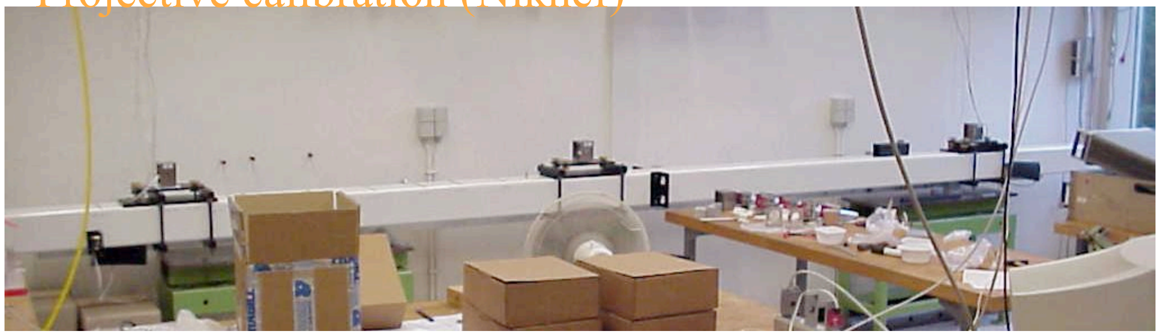
Calibration: knowledge of x,y,z,θx, θy, θz for all platforms, extension plates, alignment bars sensors, leds, targets with respect to the tubes/wire.

Many sites involved: Alignment sites + 13 chamber construction institutes.

Alignment bar under XMM (Freiburg)

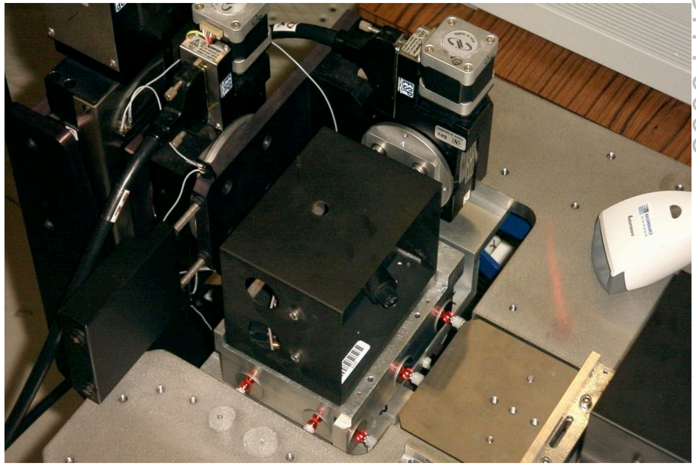


Projective calibration (Nikhef)

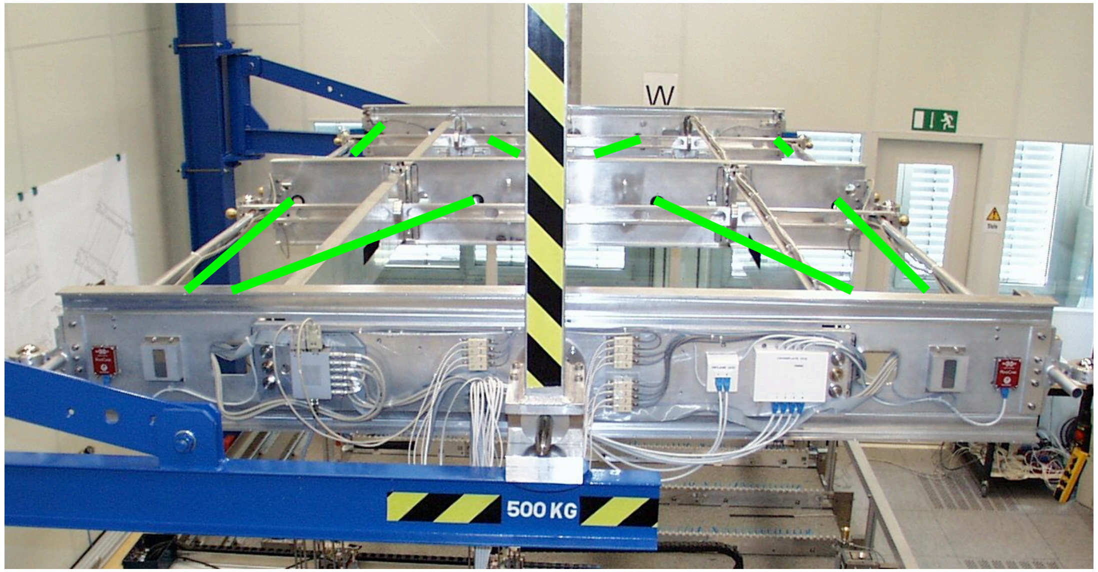


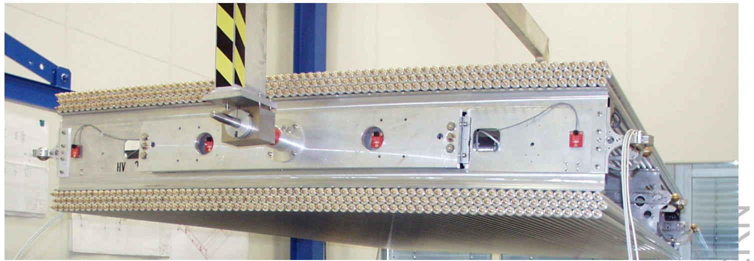
Positionning tools (BML chamber)

Praxial calibration (Saclay)

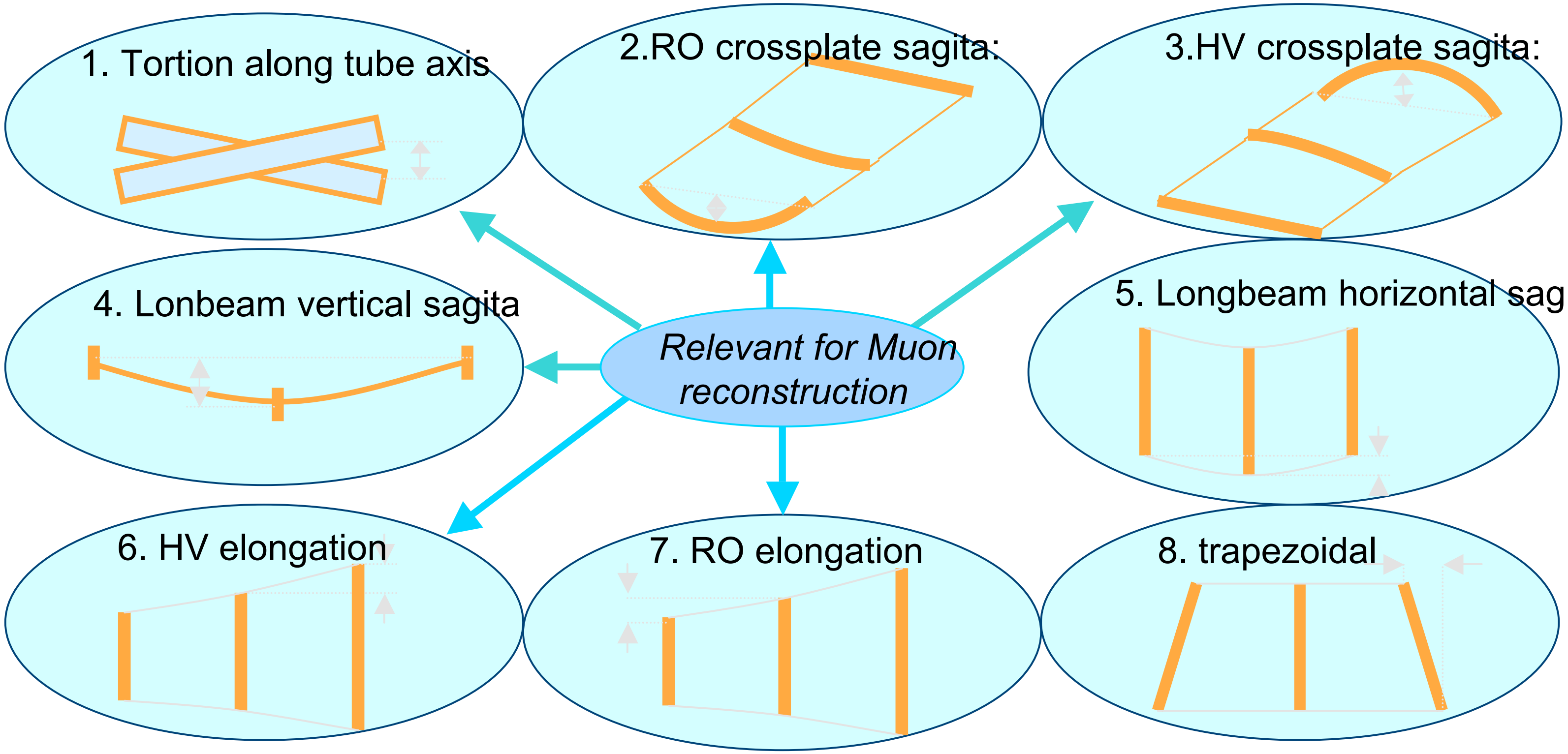


Chamber deformation





All MDTs monitored

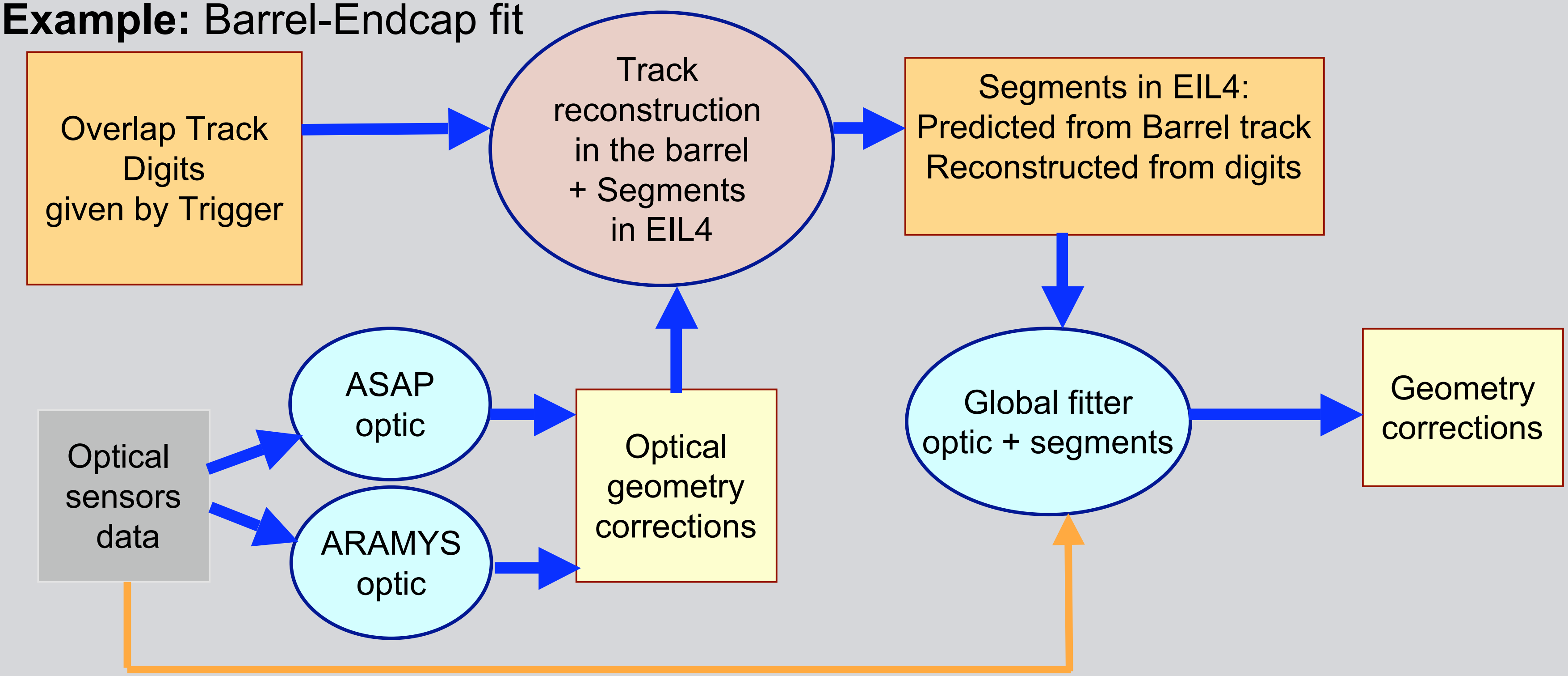


Straight and High Pt tracks

Straight and High pt tracks are used to align:
(1) Online for optically unconnected chambers
(2) Muon Barrel to Endcup (3) Inner tracker to Muon spectrometer
(4) Cosmics (5) Beam halo (6) Toroid field B=0 straight tracks

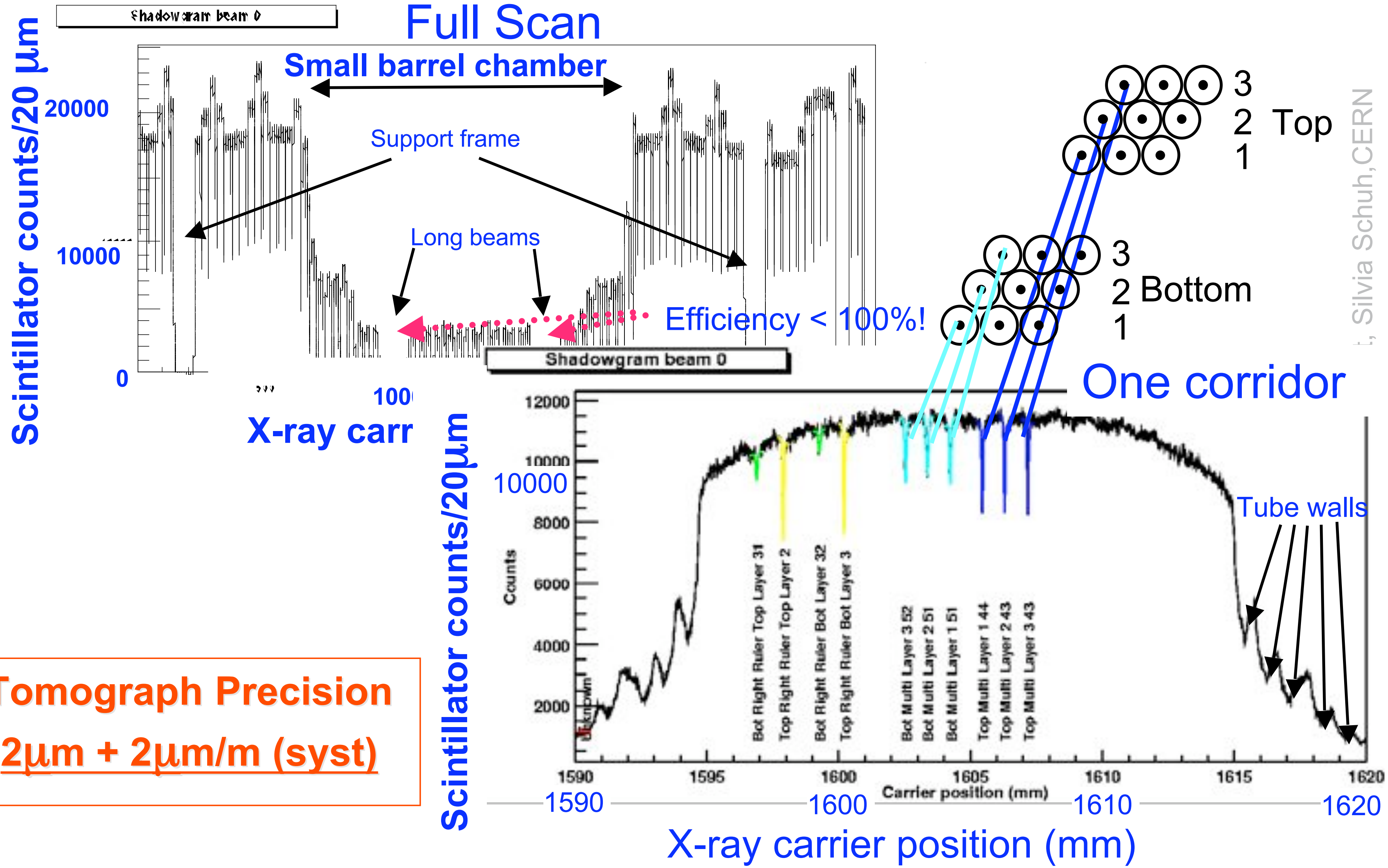
For cases (1)-(3) complex and automated dataflows to be managed, use of Tier2 center in Munich, ~50 Pcs running online

Example: Barrel-Endcap fit



On this topic: A lot of work has still to be done…..

X-ray tomograph measurement principle

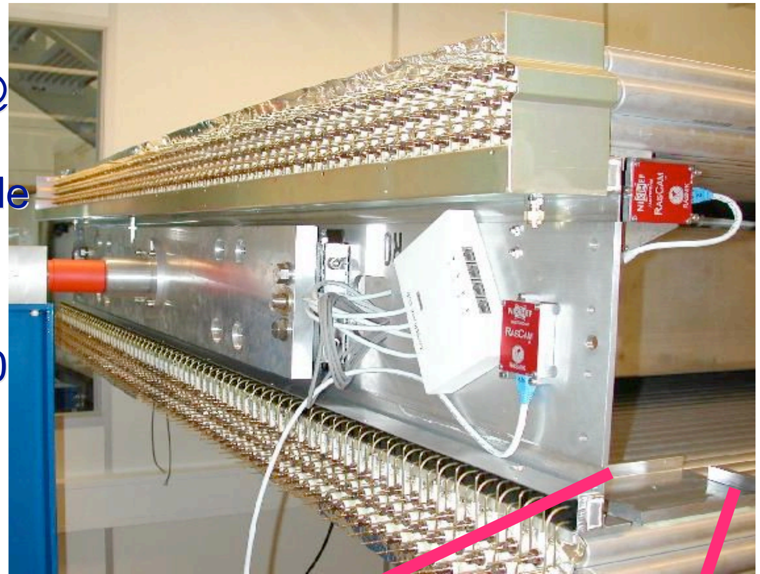


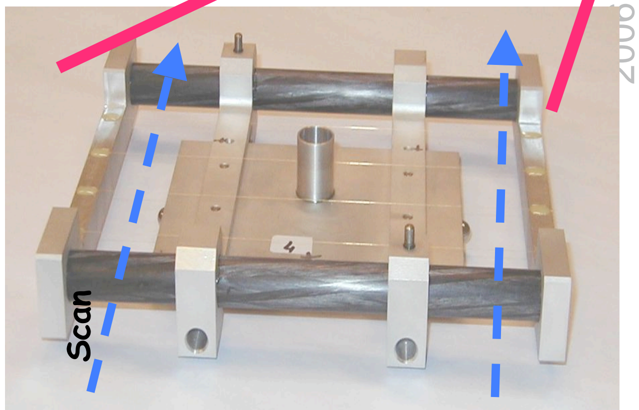
Tomograph Precision

2µm + 2µm/m (syst)

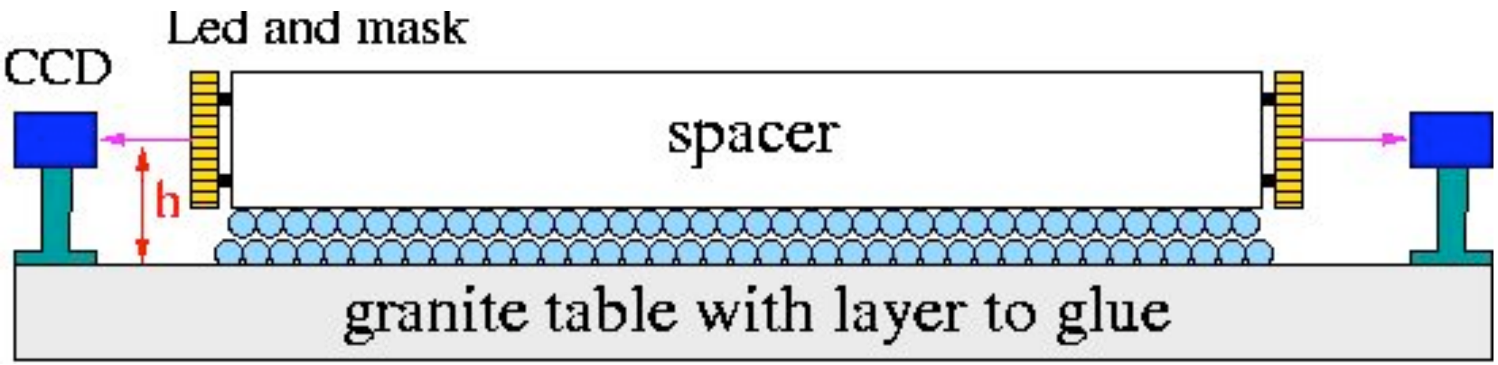
What is measured ?

- **Chamber wires**
  - measure 2-d wire positions for chamber cross-section near endplugs
    - precision combs control tube glueing precision @ endplugs (no wire locators!)
    - 3 measurements per chamber (1 per end + middle section)
  - each cross-section
    - 2900 mm long, X-ray carrier speed 0.5mm/s, 100 minutes/measurement
    - originally minimally motorized: 14 hours per measurement!! (now 90 min)
- **Precision objects glued to chamber**
  - alignment platforms can be measured
    - special tools with calibrated wires
      - mounted onto part glued to chamber
      - measure tool wires w.r.t. chamber wires





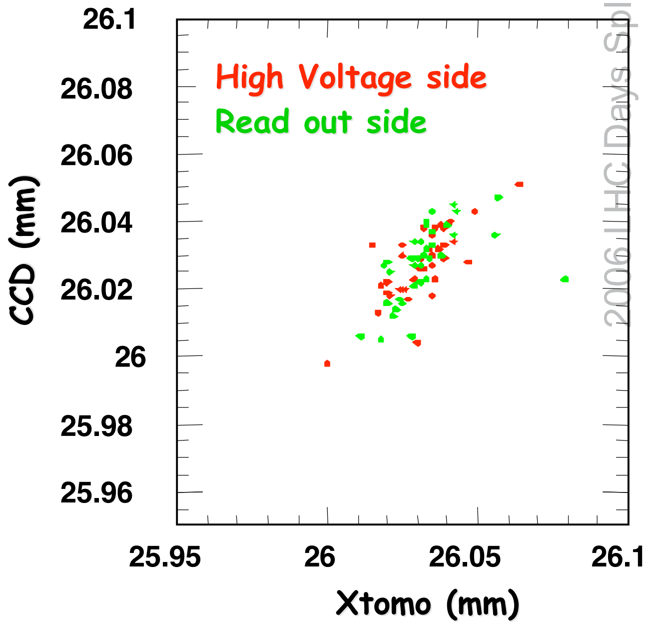
Cross check on inter-layer distance



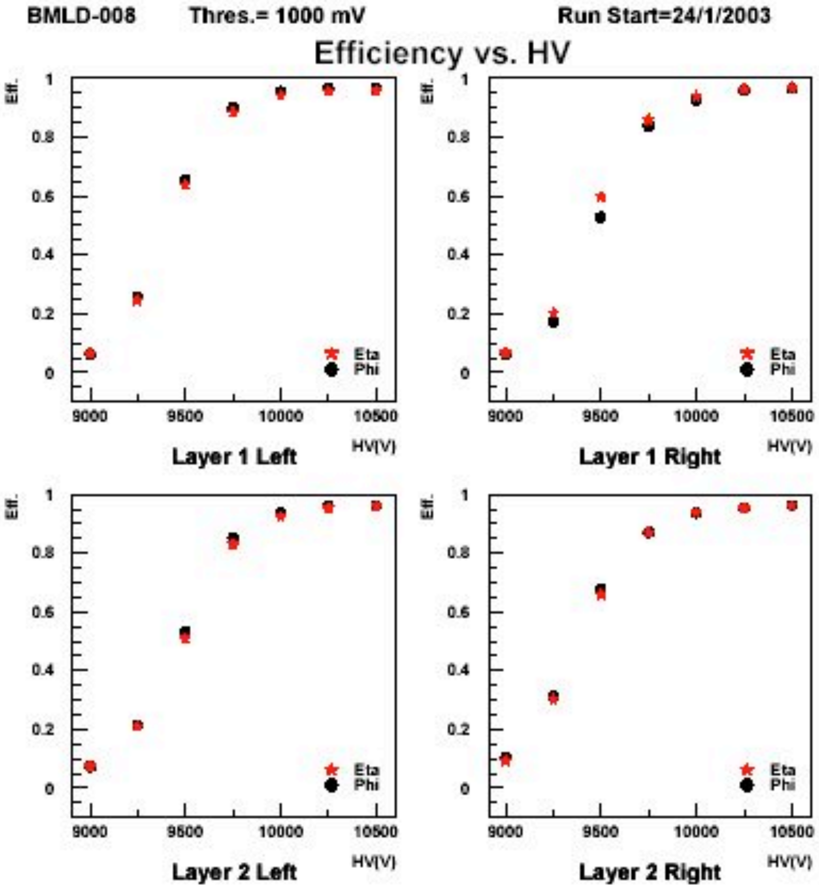
- **Layer distance measurement during construction**
  - measure h with CCD for each layer while glueing
  - h(L1) – h(L2) = distance Layer1 – Layer2
  - Good agreement with Tomograph results

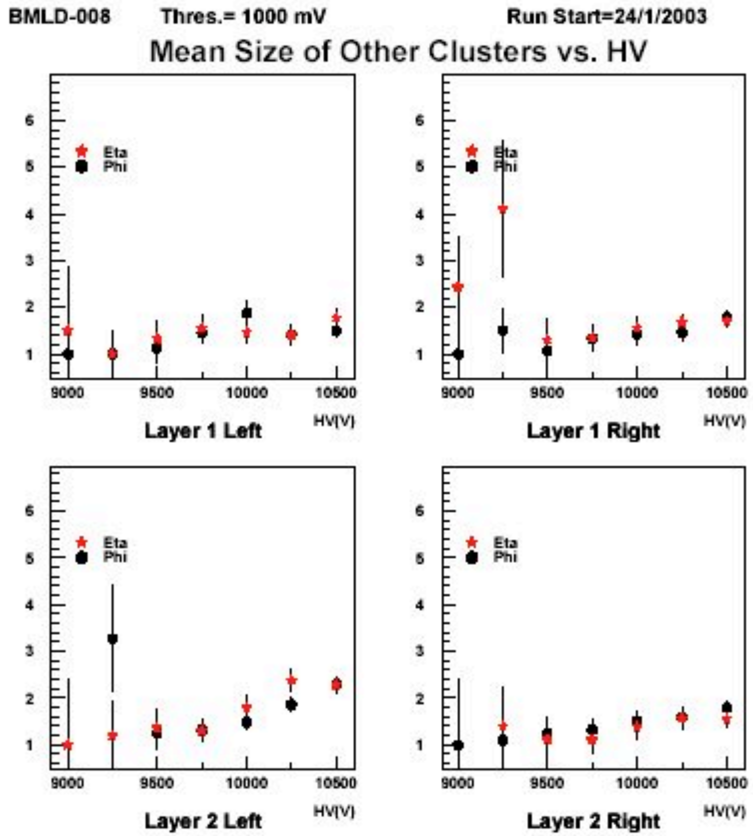
  Rasnik systems (LED-mask-CCD) used to monitor inter-layer distance during production phase!

- **Possibility to measure Multi-Layer distance**
  - use Tomograh data to extract CCD calibration

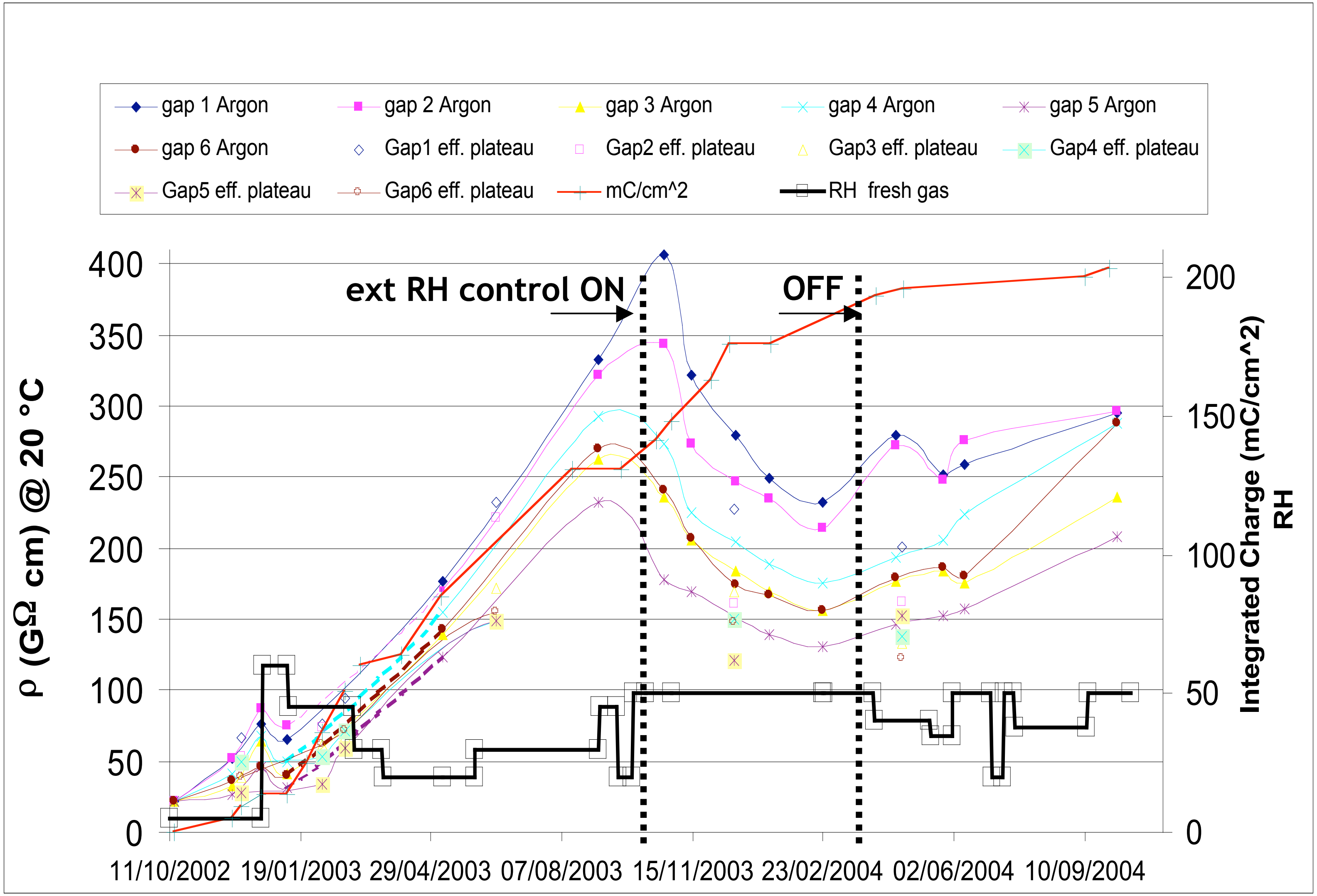


Trigger Chamber Certification

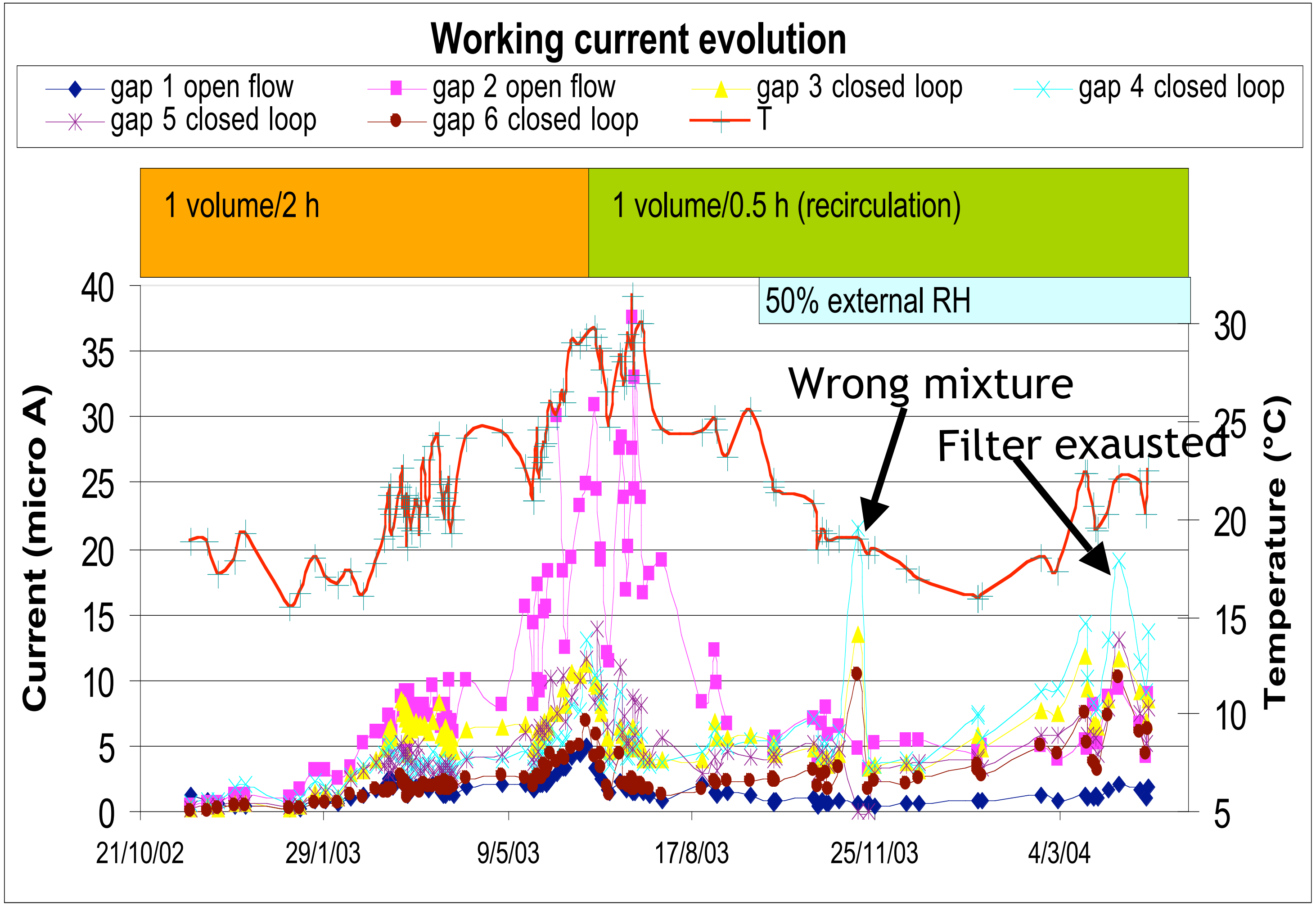




RPC aging: plate resistivity evolution

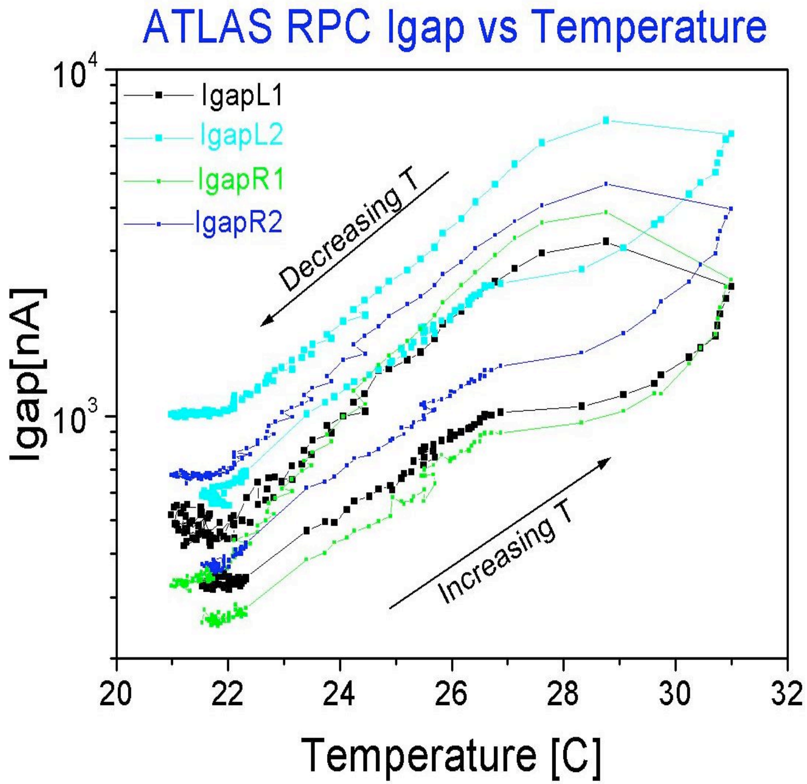


RPC aging: Current monitoring (2)



For Stable Operation of RPC

- **Control temperature**
  - Noise and current increase with T
    - Both an ohmic and gas multiplicative component (gas density)
- **Control gas**
  - Including small amount of water inside vs. outside
- **Bubble gas through water to capture HF from radiation decomposition of gas**
  - Gas system will be closed-loop
- **Tested in GIF (CERN) to last 10 years @ 10^{34} – but have to be very careful**



2006 LHC Days Split, Silvia Schuh,CERN

Installation Schedule