Muon Systems in LHC Experiments

SLAC Summer Institute
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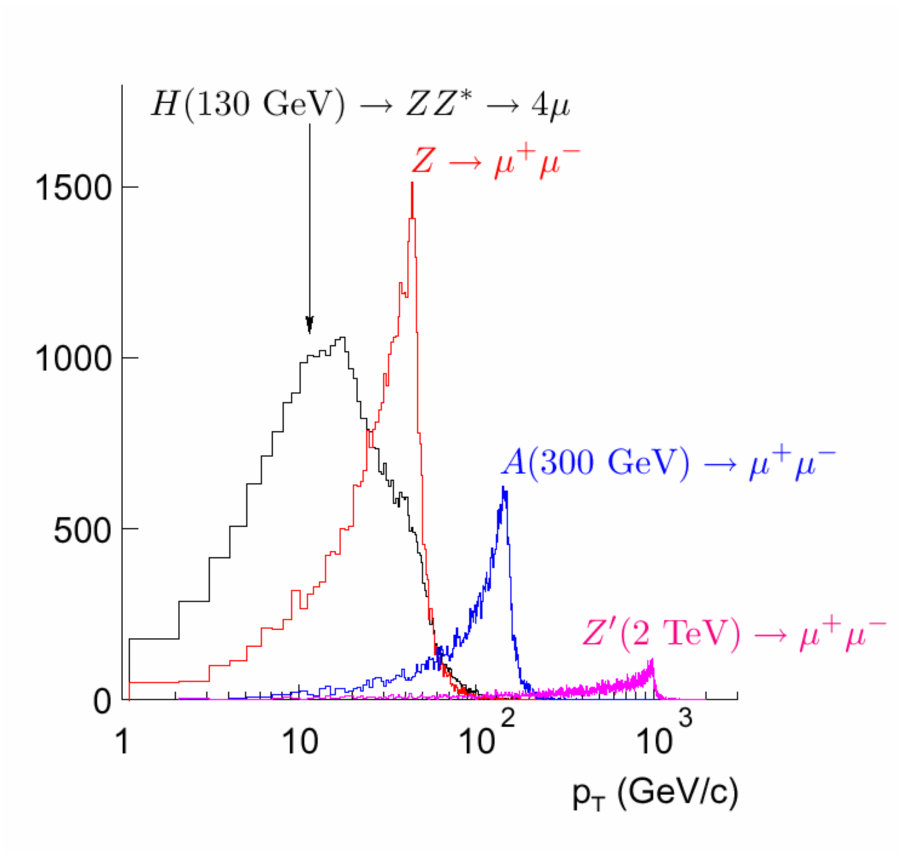
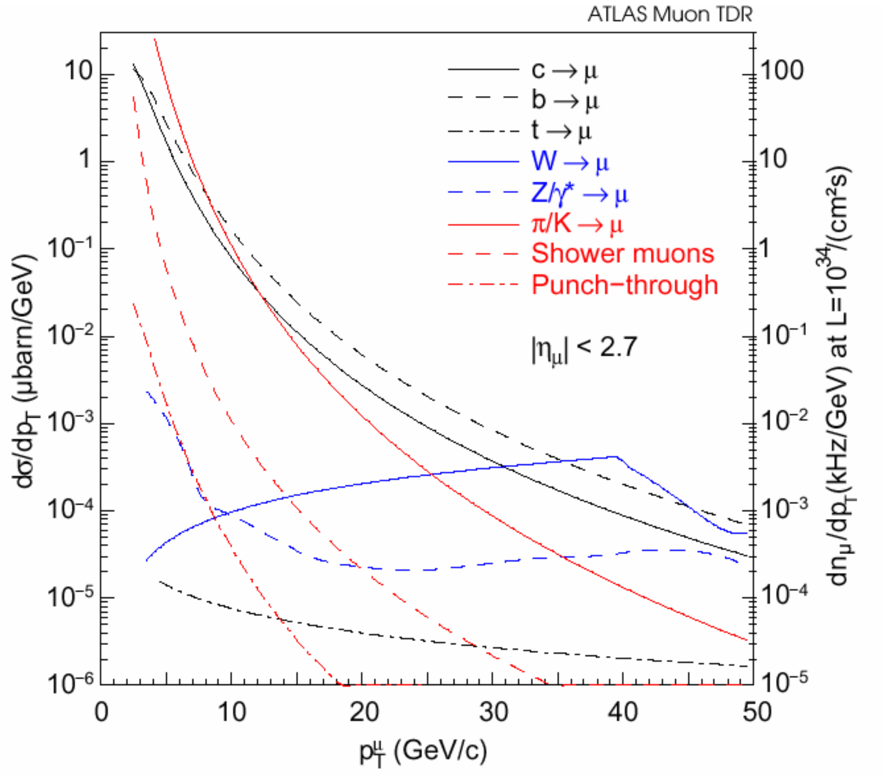
MIT

V 1.0

Signals and Irreducible Backgrounds

- Interesting processes have broad p_T spectra
- Most background are a low p_T
  - Trigger thresholds $p_T > 6$ GeV/c and $p_T > 20$ GeV/c





ATLAS – Kortner – Durham 06

LHC Muon System Design Goals

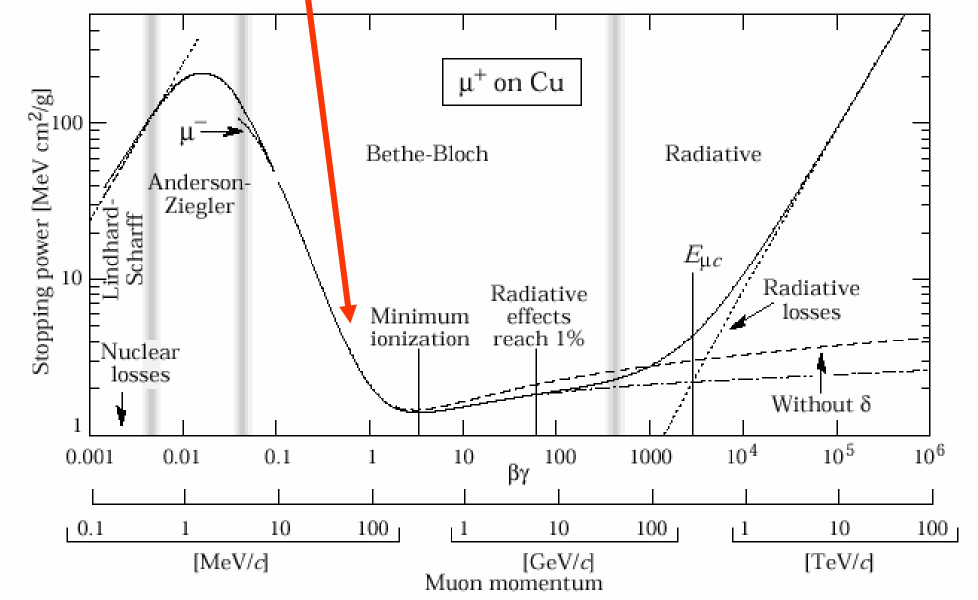
- Measure momenta p_T ~ 5 GeV/c to 1 TeV/c
  - Dictates strength & volume of B-field – both are ‘large’
  - Dictates tracking chamber resolution
- Clean muon identification
  - 15 to 20 λ filter required & is compatible with hadron shower containment of calorimetry
- Triggering & beam cross ID
  - Suppress ‘minimum bias’ events
  - Have to tag the beam cross of event – dictates good timing resolution
- Choice of chamber technologies
  - Triggering and tracking technology should not be sensitive to backgrounds – such as neutrons and photons
  - Chambers should be ‘thin’
  - Gaseous technologies practical for large areas required
    - Small size drift tubes (DT & MDT),Cathode Strip Chambers (CSC), Thin Gap Chambers (TGC), Resistive Plate Chambers (RPC)

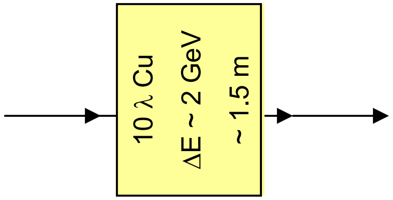
Basis for Muon Filtering

- dE/dx described by Bethe-Bloch and Radiative Effects

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

From PDG





- For energies $E_\mu > E_{\mu c} \sim 250$ GeV radiative energy loss becomes important – for example bremsstrahlung

$$\left.\frac{d\sigma}{dv}\right|_{\rm brem} = \alpha\left[2Zr_e\frac{m_e}{m_\mu}\right]^2\frac{1}{v}\left[1+(1-v)^2 - \tfrac{2}{3}(1-v)\right]\phi(q_{\min}) . \qquad (4)$$

Here, $\alpha = 1/137.036\ldots$, v is the fraction of the muon's energy transferred to the photon, and

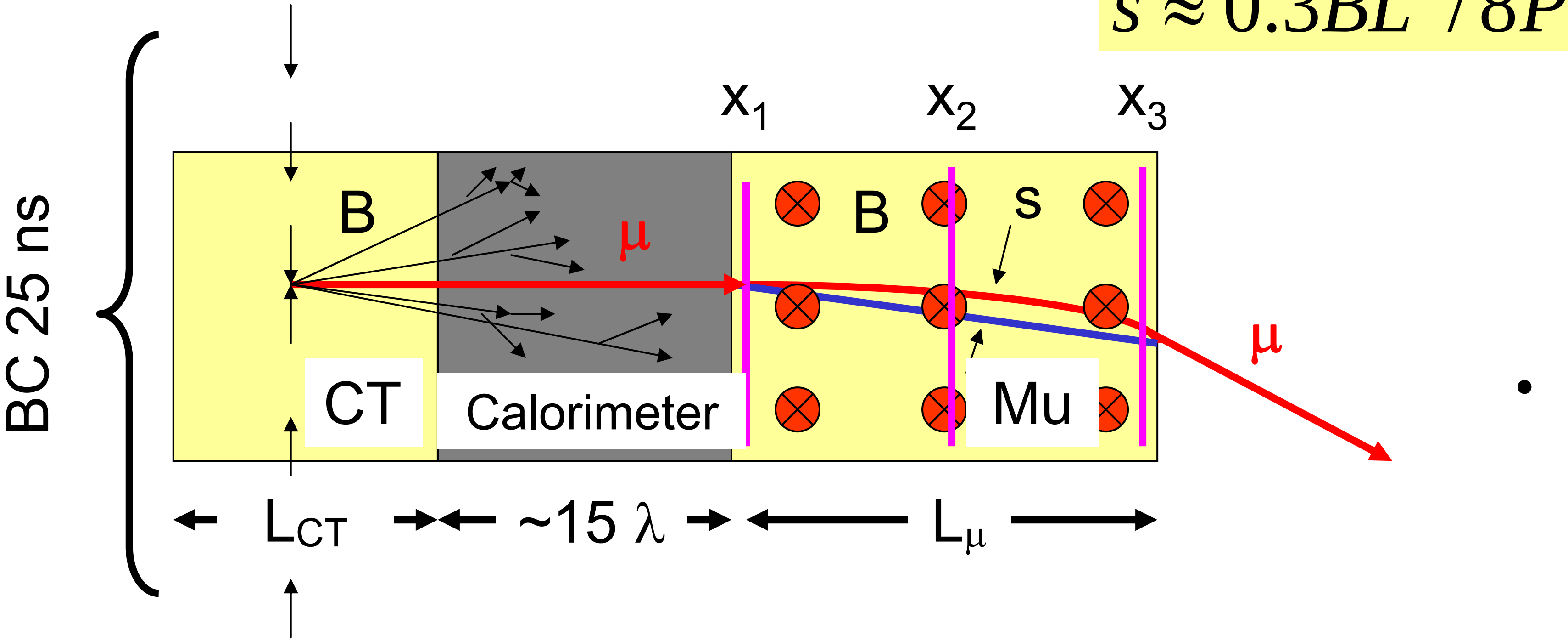
$$\phi(q_{\min}) = \ln\left[f_n\frac{m_\mu}{m_e}\frac{RZ^{-1/3}}{1+(q_{\min}/m_e)\sqrt{e}\,RZ^{-1/3}}\right] , \qquad (5)$$

From Sakumoto et al. PRD45, 3042 (1992)

Basics of a Muon System

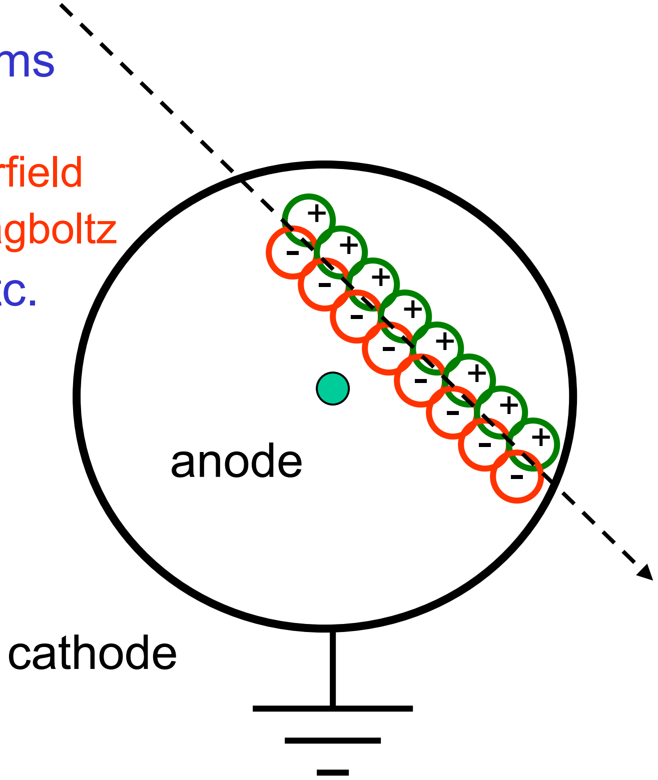
- Features
  - Muon filter – location & other functions
  - Momentum dispersion – shape of B-field & track sagitta
  - Tracking technology
  - Triggering technology & bunch cross tagging
  - Integration with central tracker

$$s \approx 0.3BL^2 / 8P$$



Basics of Gaseous Detectors

- Ionization ~ 100 e-ion/cm in Ar @ 1 bar
- Electrons accelerate to anode
  - Gas amplification 10^4 to 10^5 in strong field around anode
- Drift time of electrons to wire depends on details of gas & HV
  - Typical value v ~ few cm/μs
- Properties of drift chambers simulated by programs 'MAGBOLTZ' & 'GARFIELD'
  - http://ref.web.cern.ch/ref/CERN/CNL/2000/001/garfield
  - http://ref.web.cern.ch/ref/CERN/CNL/2000/001/magboltz
- Experimental data on drift velocities, L-angles, etc.
  - http://cyclo.mit.edu/drift/www/



Conceptually Simple – But there are Details

- There are ~ 1000 physicists working on muon systems at the LHC
- Estimate that ATLAS & CMS have ~ 400 each

ATLAS

2,000 collaborators

Muon TDR

Physics TDR

Trigger TDR

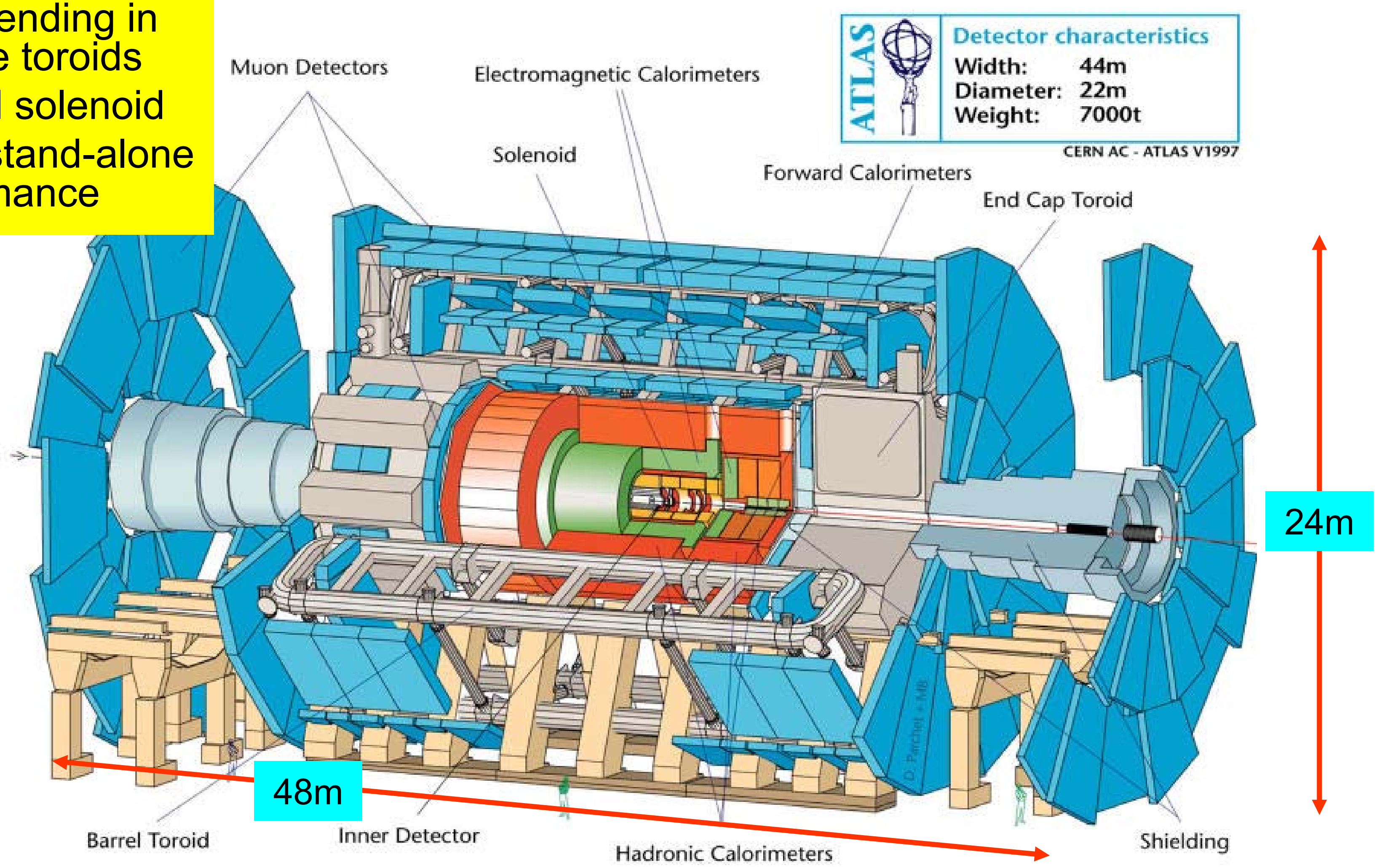
SLD

200 Collaborators

TDR entire exp.

ATLAS Muon System

- Main bending in air-core toroids
- Central solenoid
- Good stand-alone performance

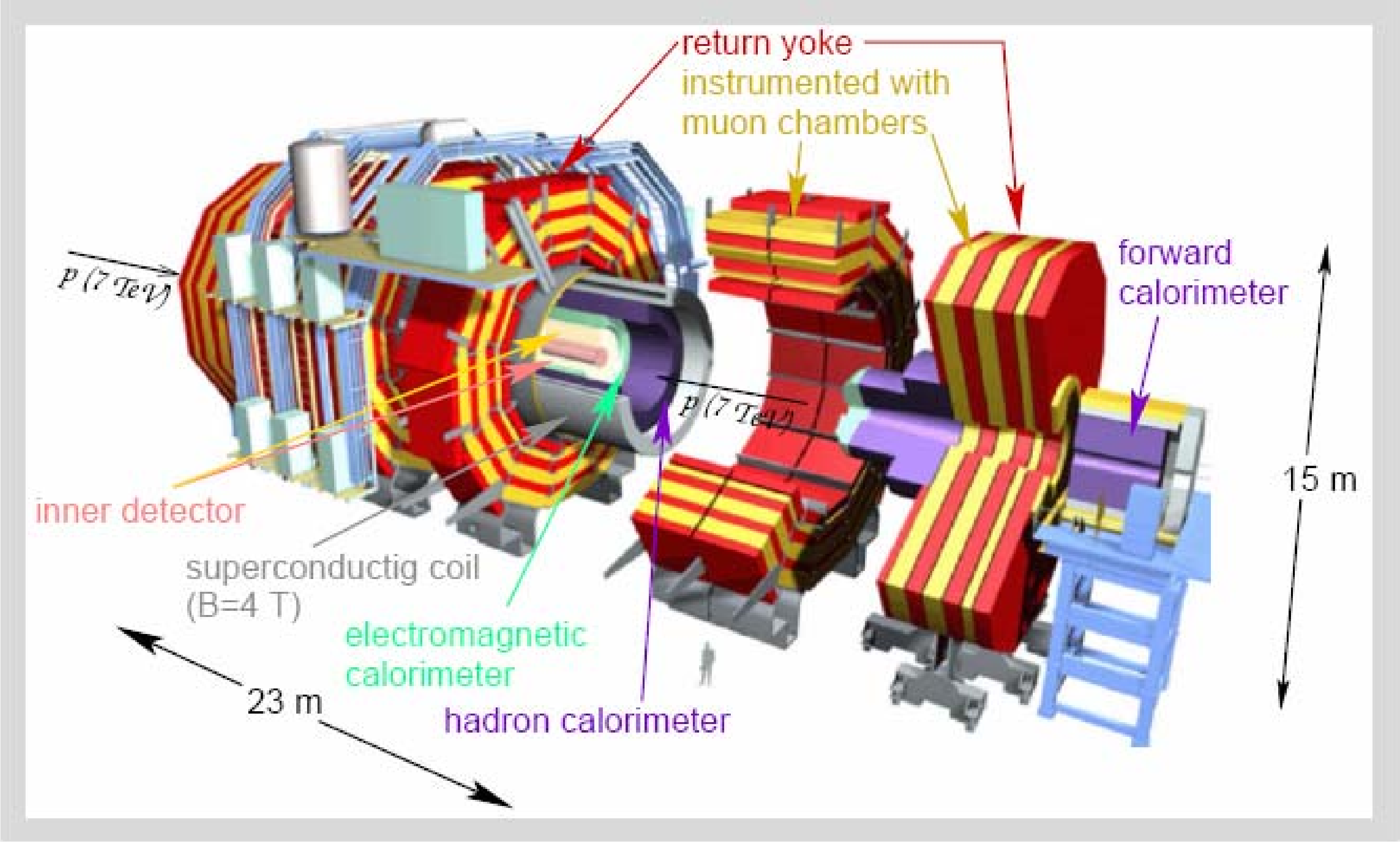


A Torodial LHC ApparatuS

The Muon System of CMS

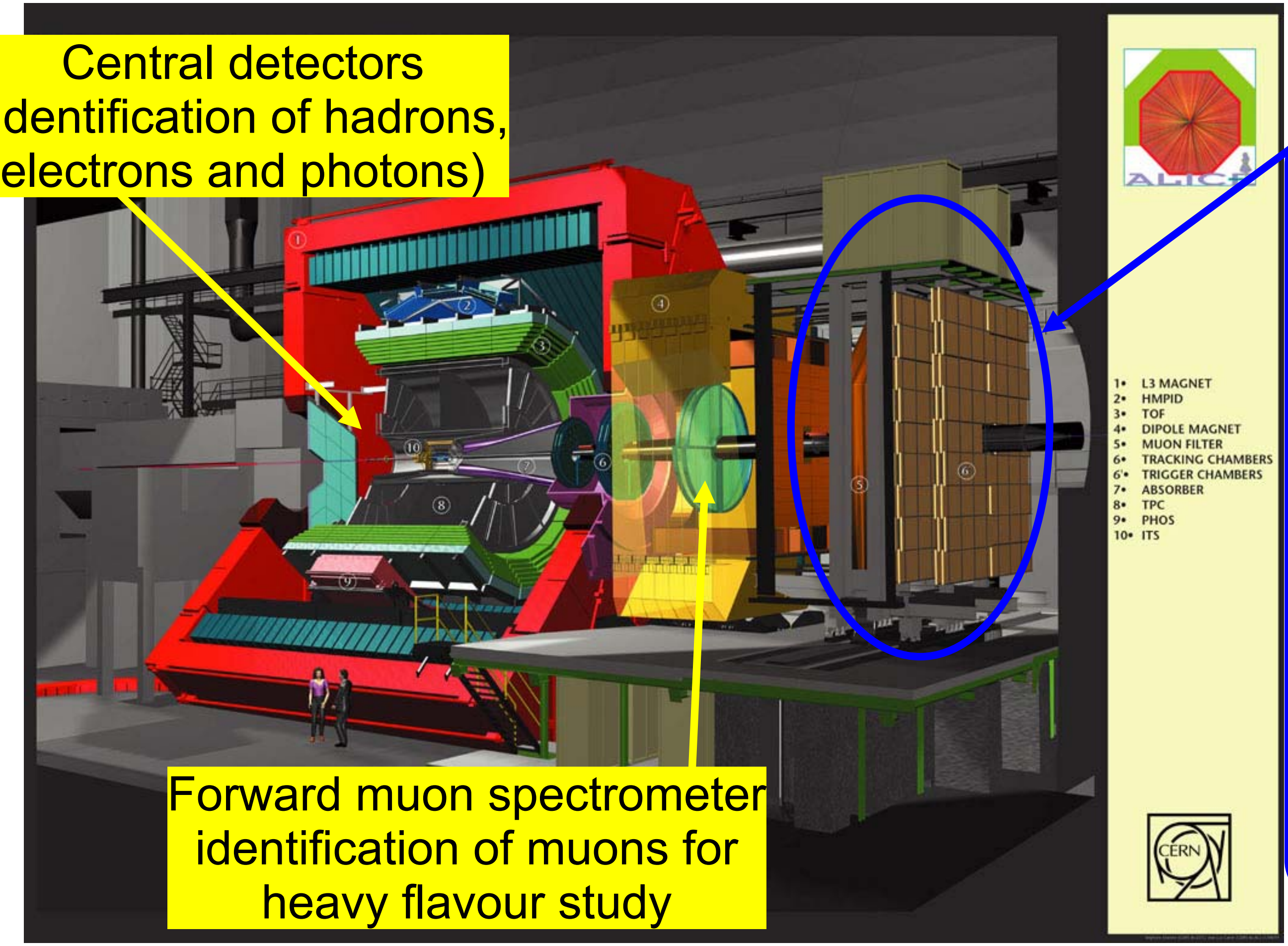
- Compact system
  - Strong Central Solenoid (4T)
  - Instrumented iron flux return

Compact Muon Solenoid



Muon System of ALICE

- Heavy Ion Experiment – uses RPCs for muon trigger



Central detectors (identification of hadrons, electrons and photons)

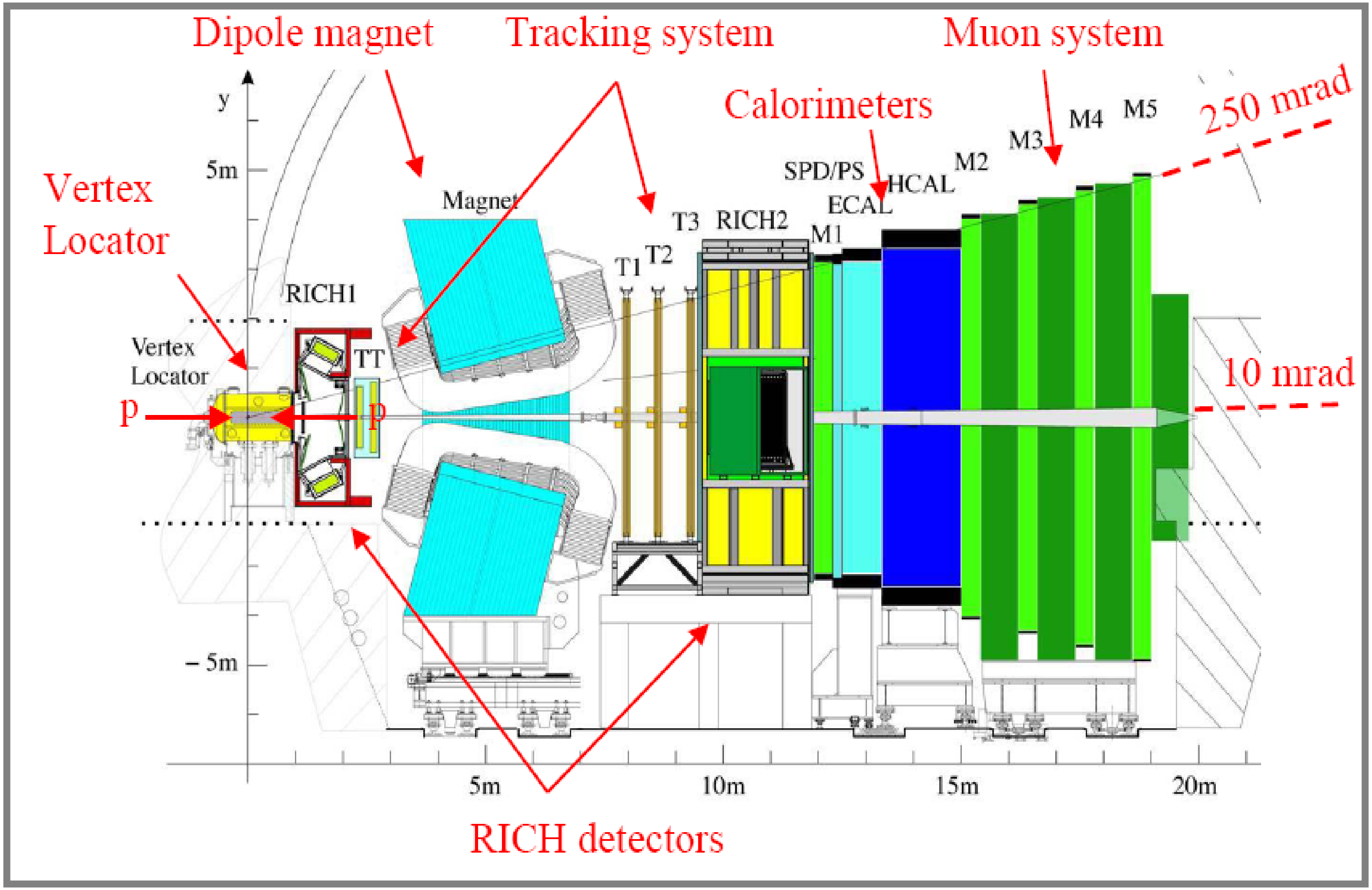
Forward muon spectrometer identification of muons for heavy flavour study

Muon trigger system :

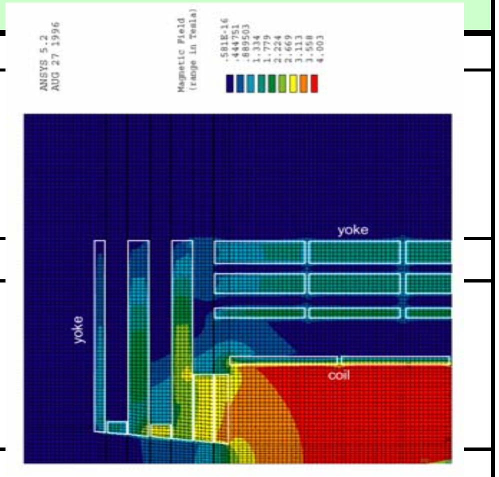
- 2 stations of 2 planes each
- 72 Resistive Plate Chambers (RPC) ~2.7 m x 0.7 m (~ 144 m^2)
- 20,992 electronics channels

Muon System of LHCb

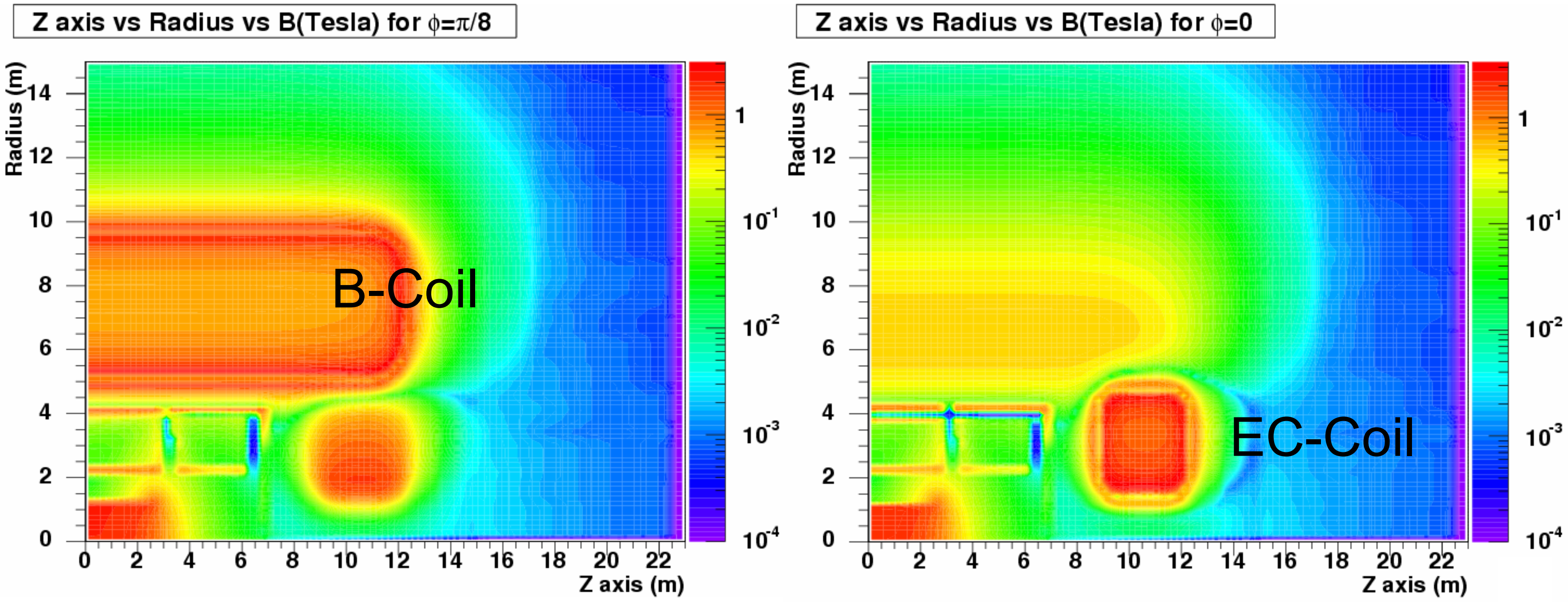
- Muons are detected as ‘tags’ for heavy quark flavor decays



B-Fields ATLAS & CMS

Magnetic Technology	ATLAS	CMS
Inner Tracker		
B-field	2.0 T	4.0 T
Outer Diameter	2.6 m	6.5 m
Length	5.3 m	12.9 m
B L of tracker itself	2 T m	4 T m
Stored Energy	38 MJ	2,700 MJ
Muon System		
<u>Barrel Region |η| < 1</u>		
Diameters	9.4 to 20.1 m	
B L	3 T m	
Stored Energy	1,080 MJ	
<u>Endcap Region 1 < |η| < 2.7 (2.5)</u>		
Diameters	1.7 to 10.7 m	
B L	6 T m	
Stored Energy	206 MJ	
<u>Solenoid Flux Return</u>	Fe Tile Cal	Fe ~ 2 T

ATLAS Toroidal B-Field



- Muon spectrometer
  - Physics requirements: Δ (∫Bldl)/∫Bldl < 4.10^{-3}
- Magnetic materials
  - Materials in cavern (catwalks, feet, etc.)

Validation:

Muon Air-core Toroids:

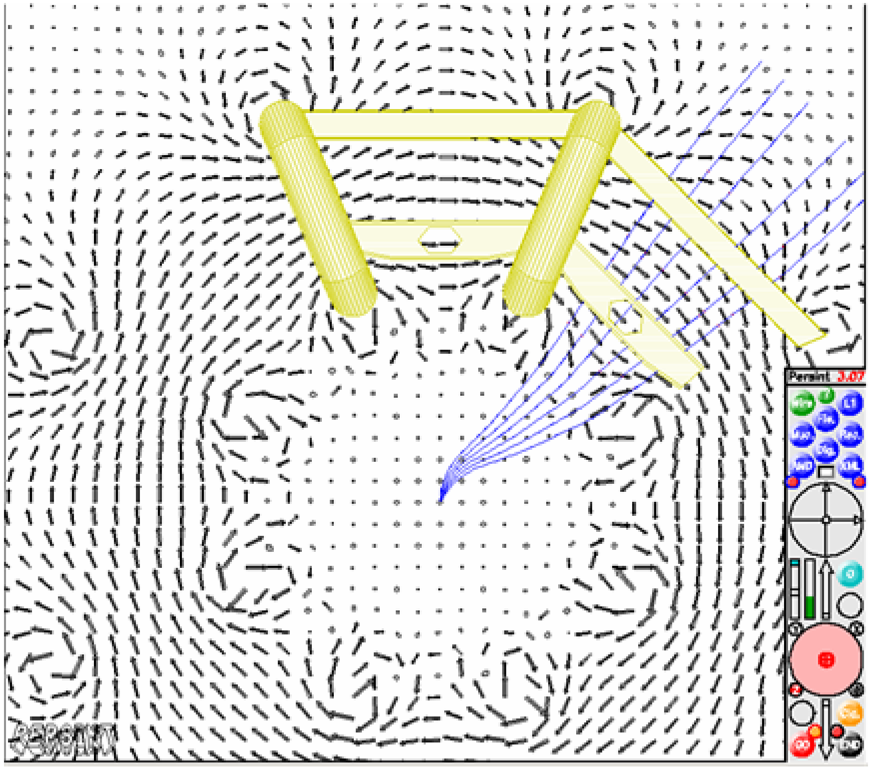
Sets of B-sensors mounted on chambers will be used to model location of conductors => B-field

Central Solenoid: Will be mapped

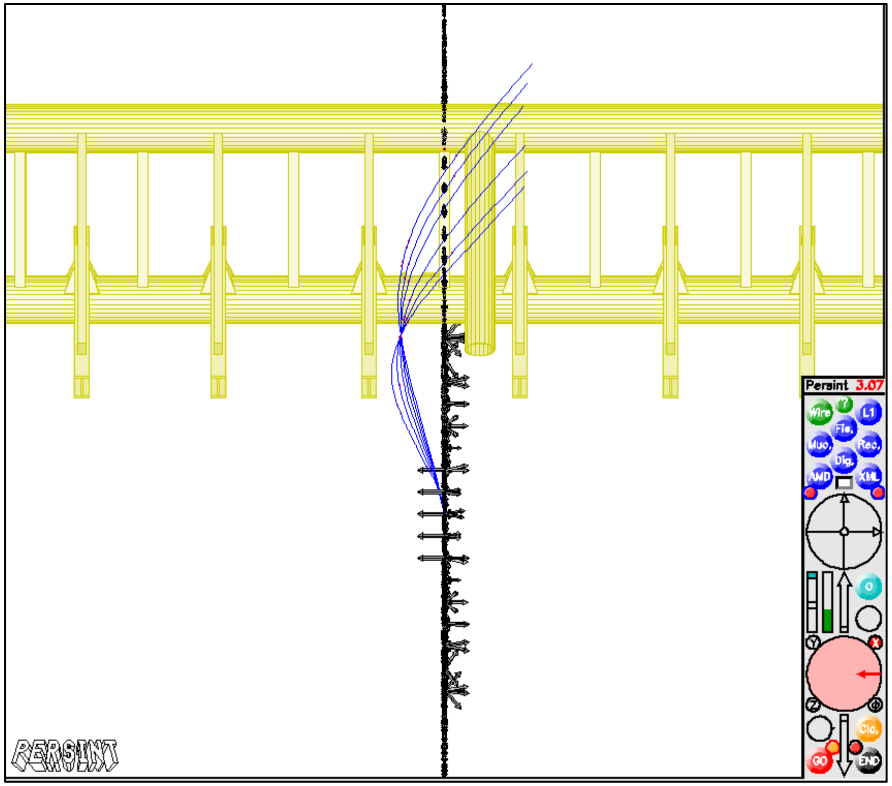
W. Kozanecki (CEA-Saclay)

Muon Trajectories in ATLAS

- Bending in every direction – non-uniform field
  - Central solenoid – bending in ϕ
  - Toroids – bending in η



(r,ϕ)



(r,η)

ATLAS Magnets

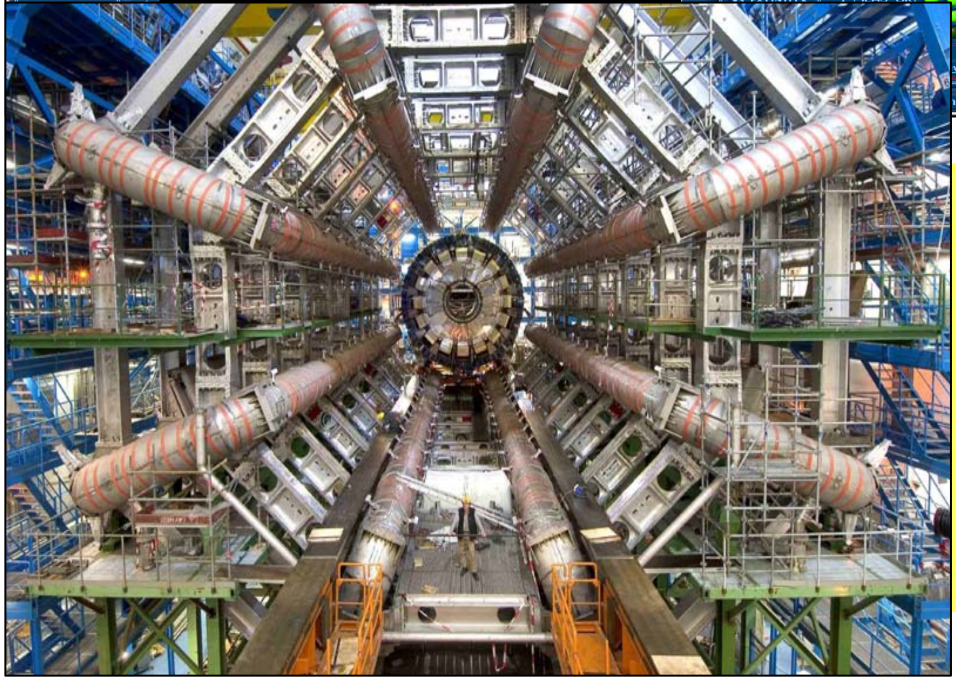
DATA VALID
STATE_PC: IDLE
STATE_VS: VS_READY
STATE_OP: NORMAL
STATE_PLL: PLL_NO_SYNCH
FB.MODE: IAB
LOAD.SELECT: MAGNET [0]
MODE.OP: NORMAL

IDiff [mA] -29.0000 IErr [mA] 12.0000 IRef: 1000.00 IMeas 999.988

I Graph Mode: Zoom

Reference [A] 1000

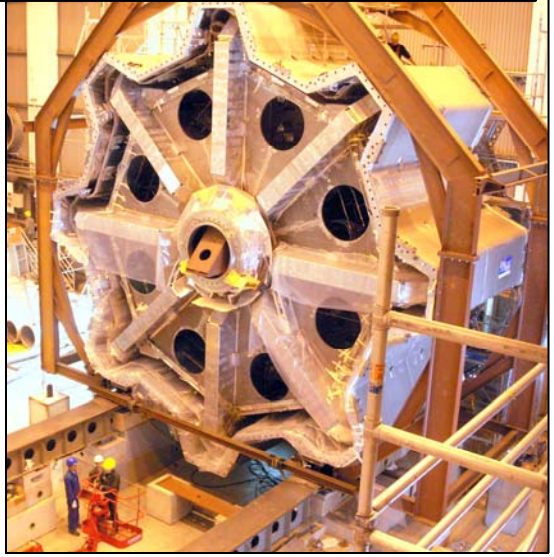

2 T @ 7.6 kA
Serves the inner detector tracking



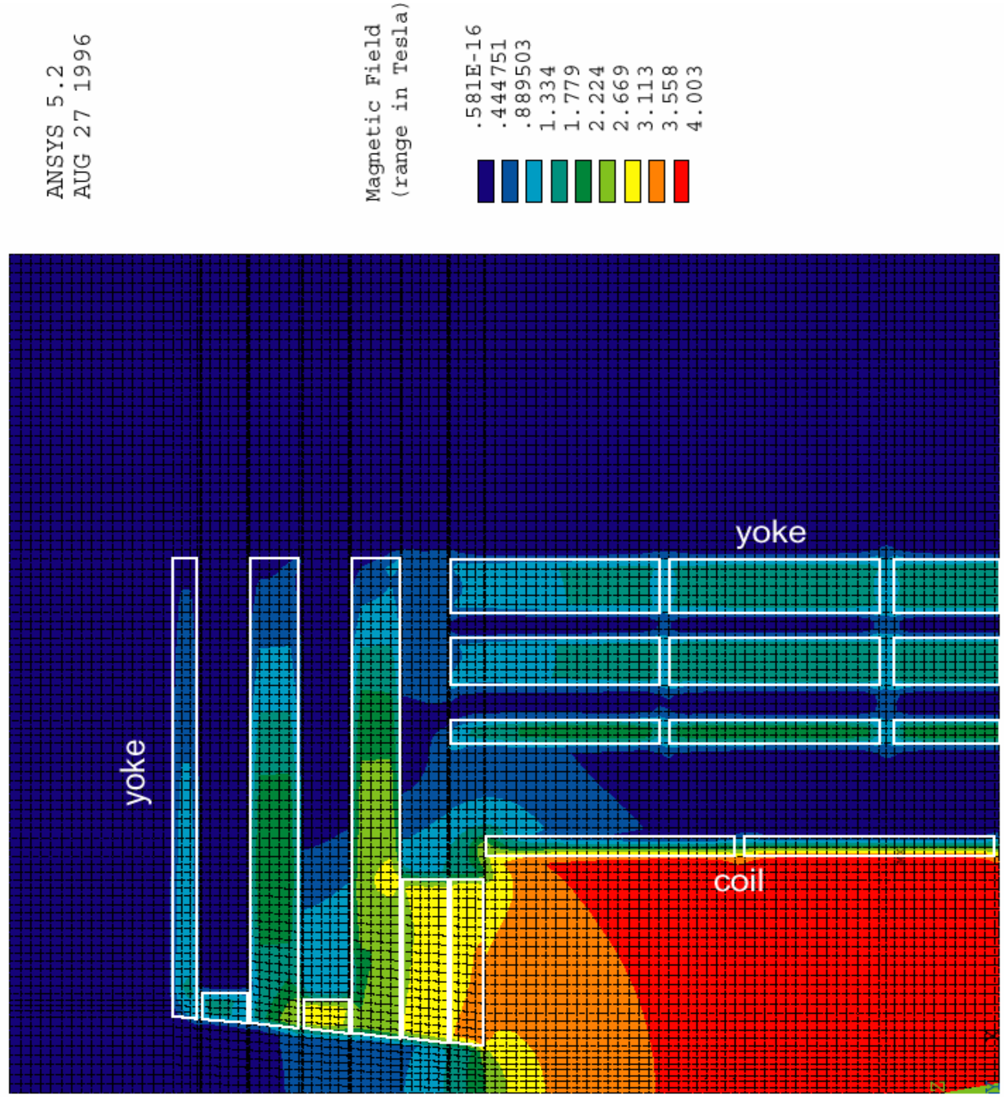
Solenoid installed, cooled and powered to 1 kA (op 7 kA)

Barrel toroid installed and cooling

Endcap toroids in assembly



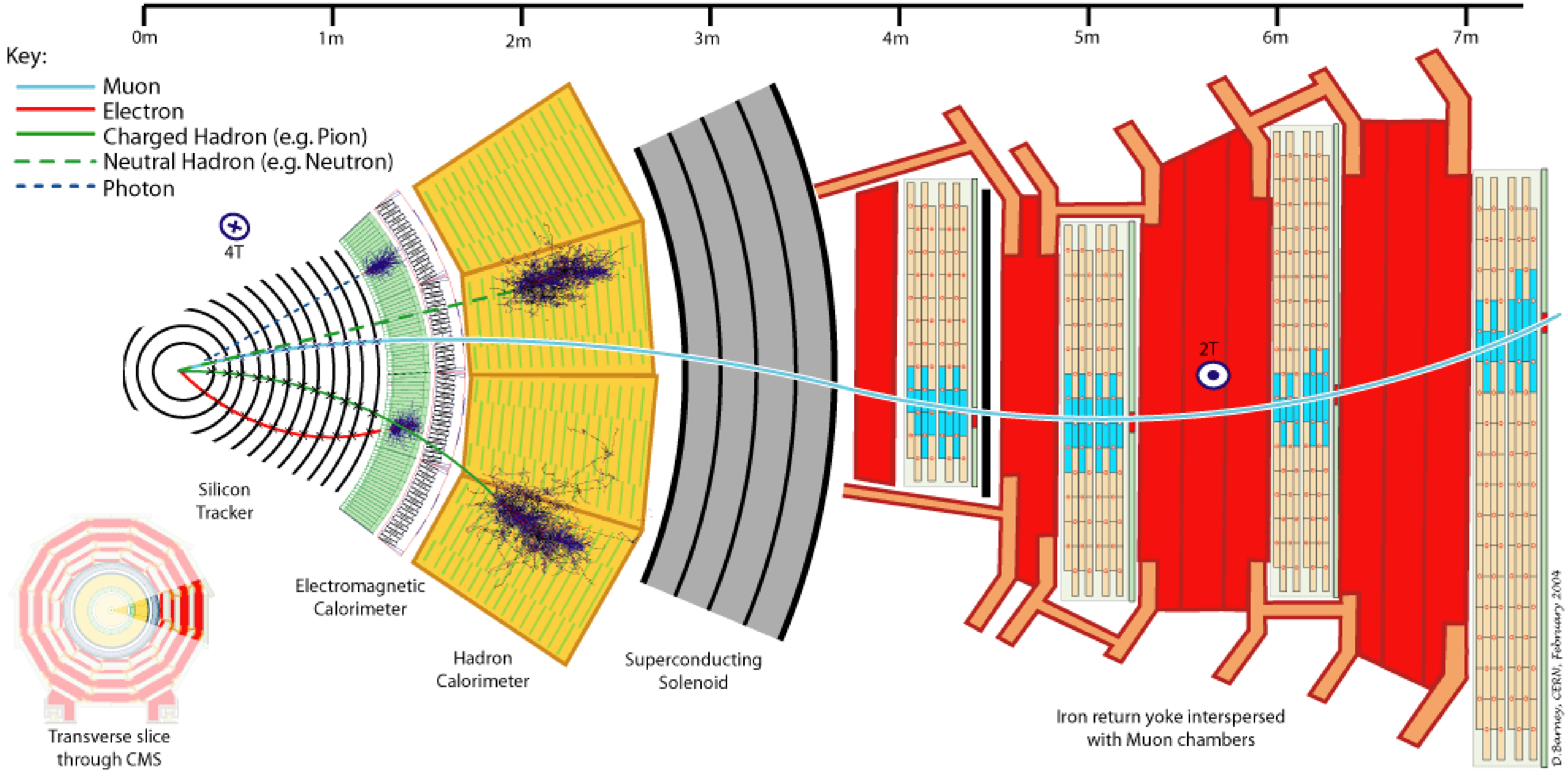
B-Field of CMS



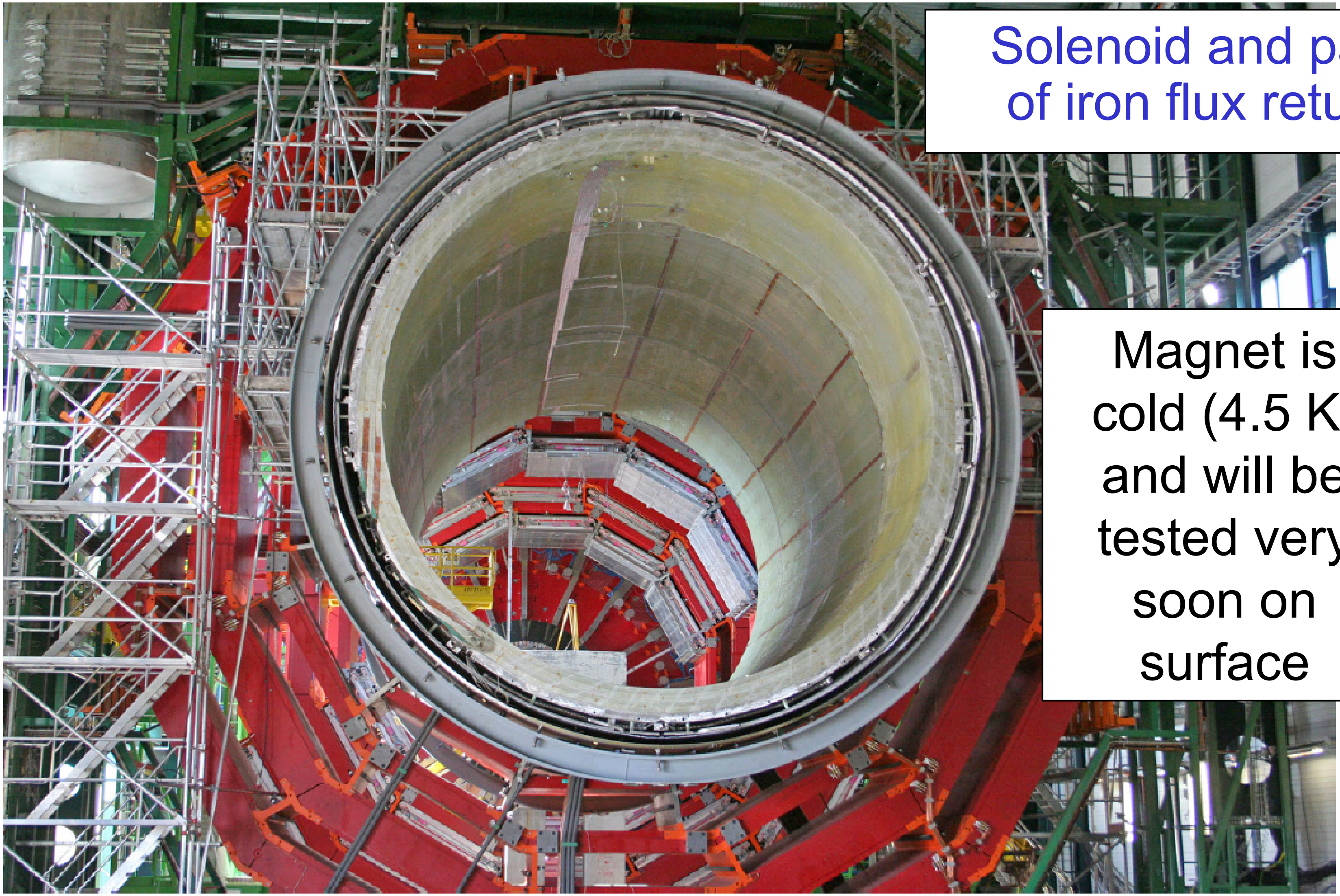
- Uniform Central Field @ 4 T
- Iron Flux return
  - Shields muon system
  - Provides opposite bending & allows stand-alone operation

Muon Trajectories in CMS

- Single magnetic system – central solenoid and iron flux return
- Precision central tracking & track linking – muon system to inner detector



CMS Solenoid & Flux Return



Solenoid and part of iron flux return

Magnet is cold (4.5 K) and will be tested very soon on surface

Designer’s Tool Kit - Resolution

- Resolution for momentum p
  - Momentum dispersion in B-field
    - Field Strength B
    - Length of measured track L

$$s \sim \frac{0.3\,B\,L^2}{8\,p}$$

  - Chamber spatial resolution
    - Constant a
    - Resolution of chamber $\sigma(X_{ch})$

$$\frac{\delta s_{ch}}{s} \sim \frac{a\,\sigma(x_{ch})\,p}{B\,L^2}$$

  - Multiple scattering in system
    - Constant α
    - Thickness of middle layer X_m

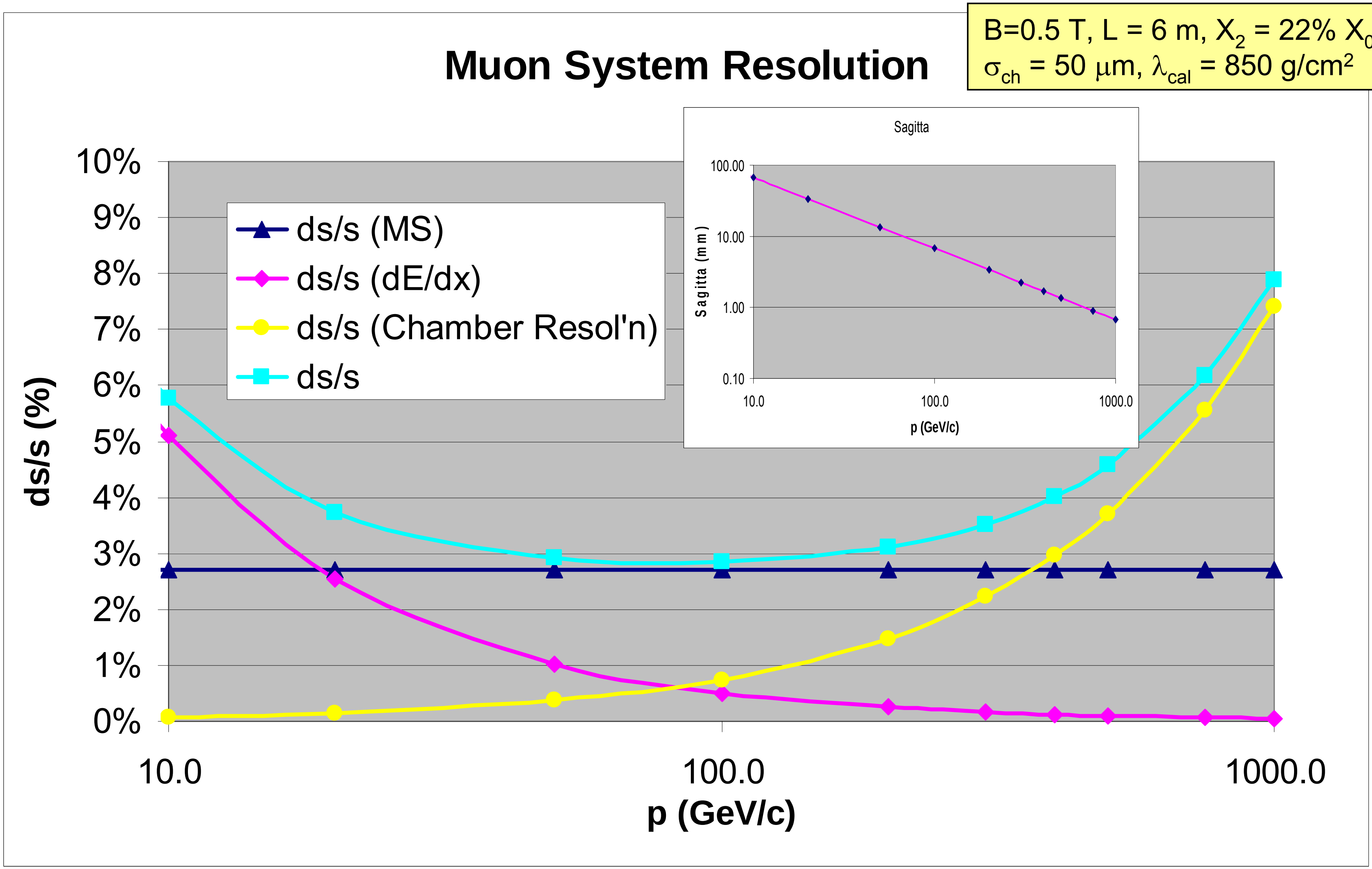
$$\frac{\delta s_{ms}}{s} \sim \frac{\alpha\sqrt{\frac{X_m}{X_0}}}{B\,L^2}$$

  - Energy loss fluctuations
    - Constant b
    - Thickness of dead mat’l X

$$\frac{\delta s_{dE/dx}}{s} \sim \frac{b\,\langle dE/dx\rangle X}{p}$$

‘Toy Model’ of a Muon System Resolution

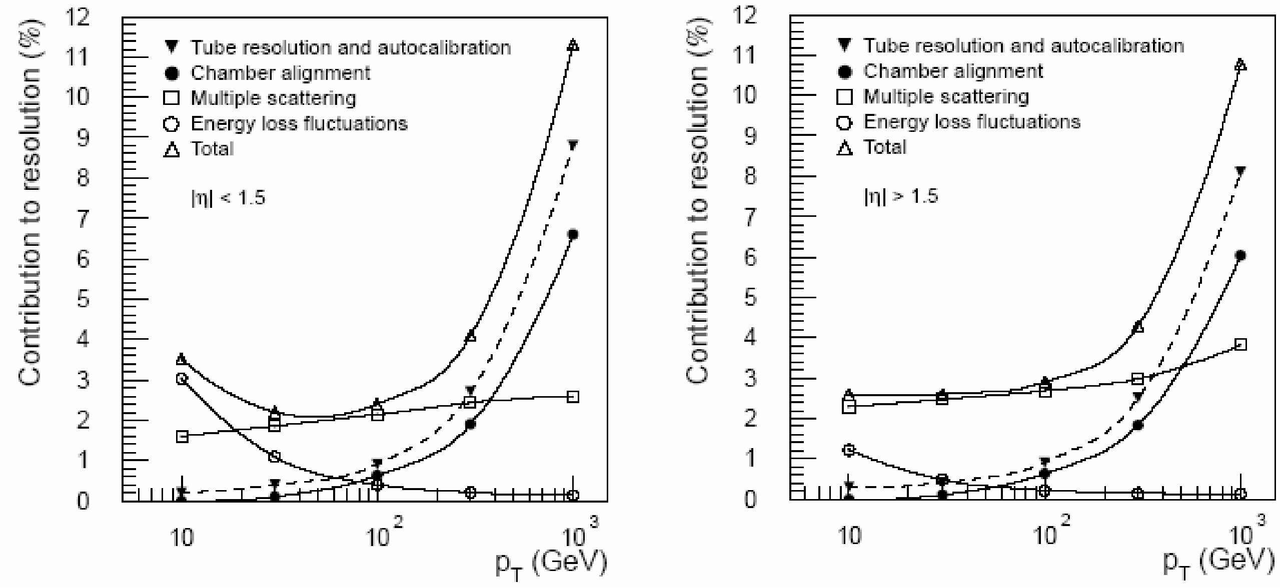
$B=0.5$ T, $L = 6$ m, $X_2 = 22\%\ X_0$
$\sigma_{ch} = 50\ \mu m$, $\lambda_{cal} = 850\ g/cm^2$



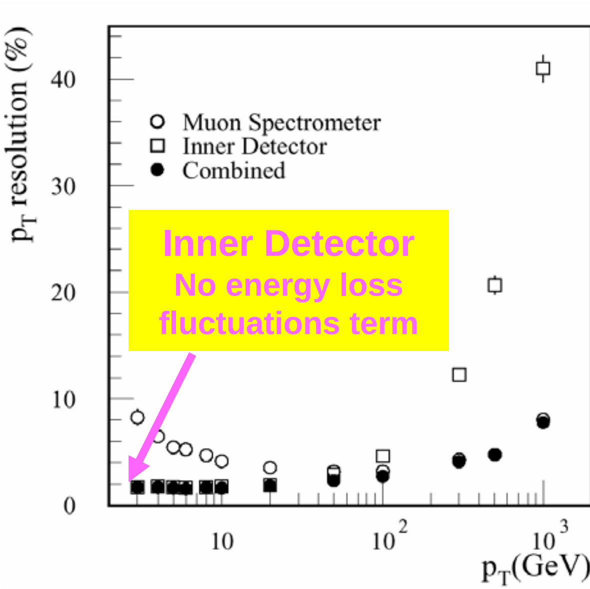
ATLAS Muon System Momentum Resolution

- Toroid system provides most of resolution at high p_T > 100 GeV/c
- But there is an azimuthal dependence – from non-uniform toroidal field

Stand-alone Performance



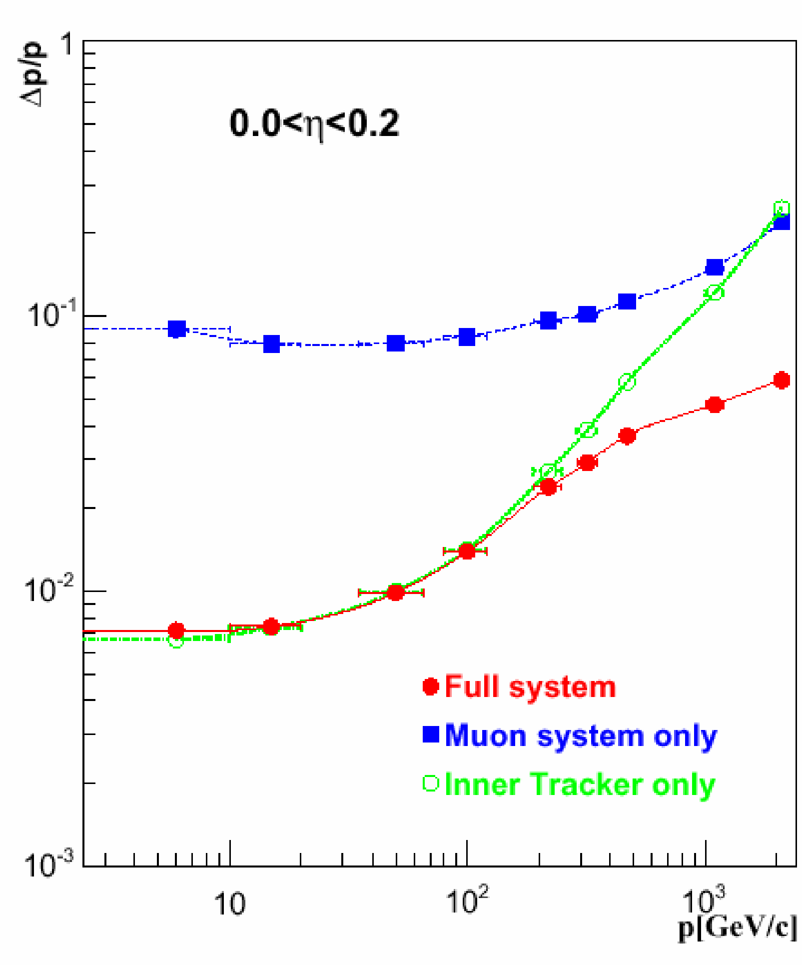
Combined Performance

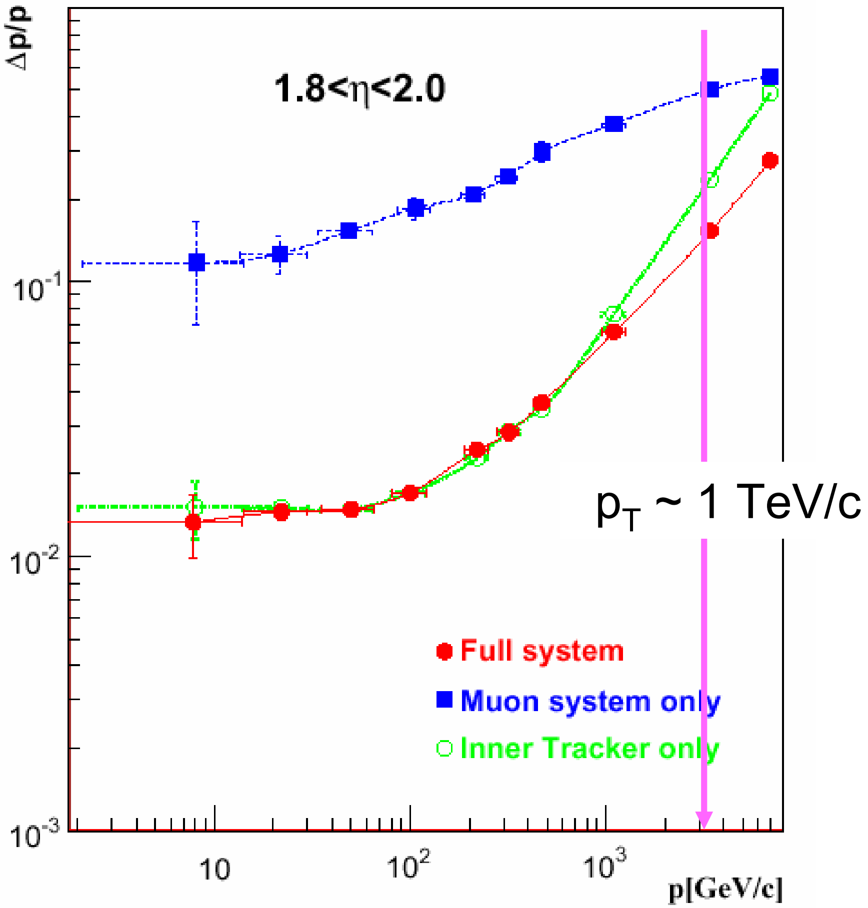


Inner Detector
No energy loss fluctuations term

CMS Muon System Momentum Resolution

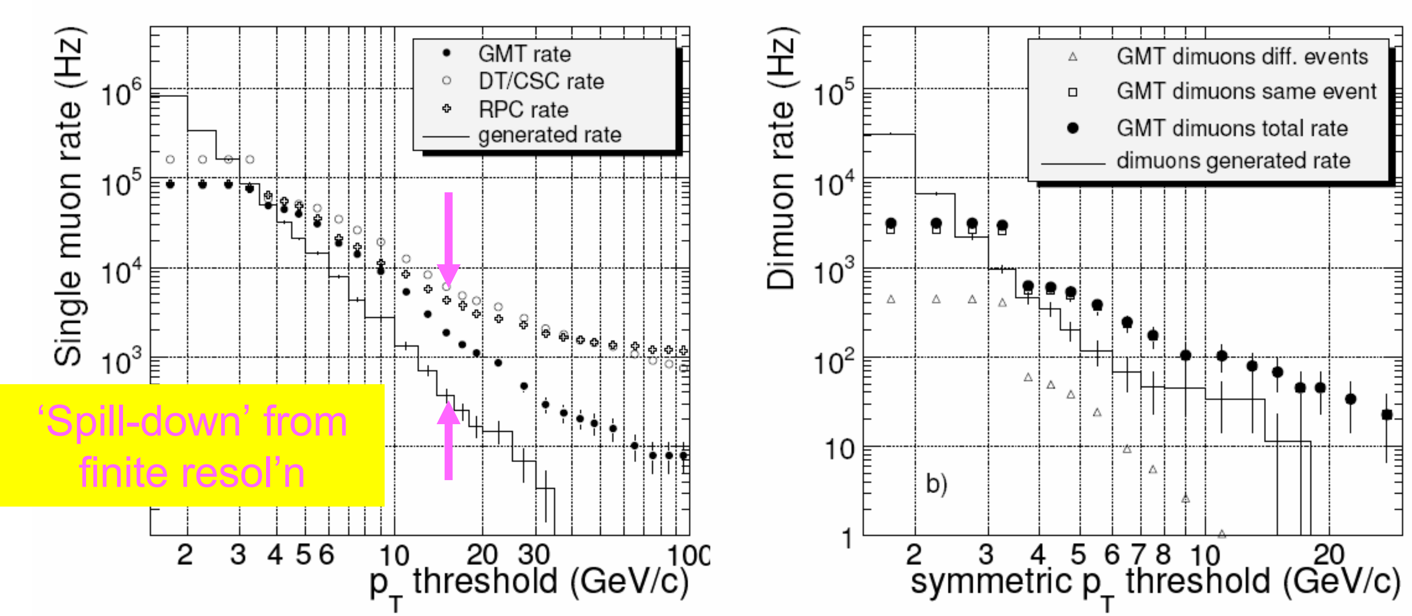
- Inner Tracker provides most of information – with uniform central field
  - CMS slightly better at $\eta \sim 0$
  - ATLAS slightly better at high $|\eta|$





Muon Trigger

- The most challenging component of a muon system at the LHC
  - Acquire interesting events w/o excessive demands on DAQ bandwidth



'Spill-down' from finite resol'n

LVL1 Trigger Rates @ 2 x 10^{33}

From CMS Physics TDR

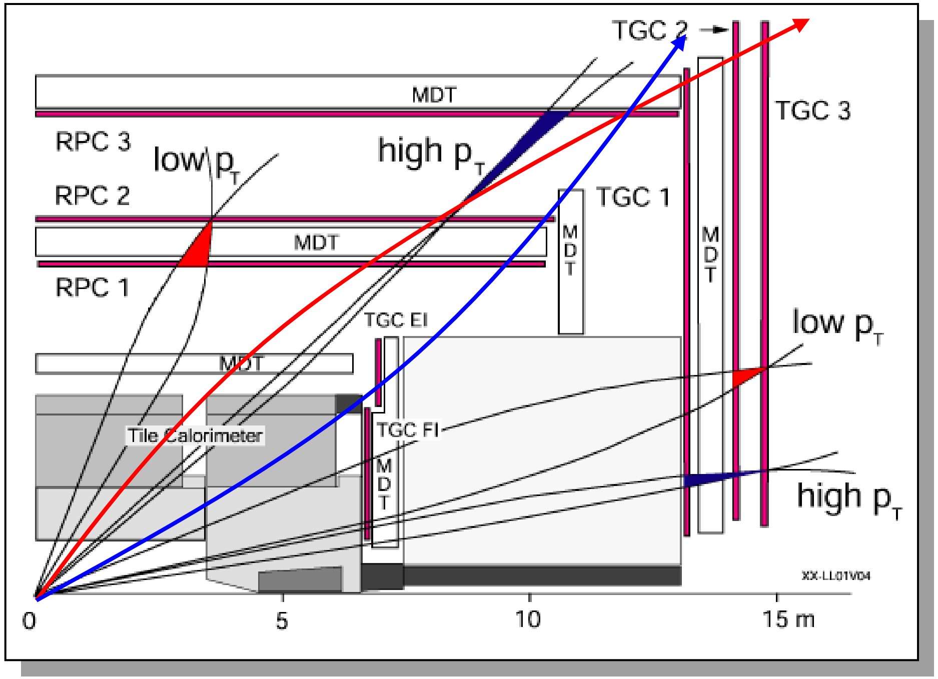
- LVL1 Trigger Menu
  - Example - ATLAS @ 10^{34}
    - **Single muon p_T > 20 GeV/c 4 kHz**
    - **Dimuons p_T > 6 GeV/c 1 kHz**

- pp inelastic σtotal ≈ 80 mb
  25 'soft' collisions every beam crossing
  @ 10^{34} cm^{-2}s^{-1}
- Higgs production σ(H) BR ~ 1 to 50 fb
- Higgs events / year ~ 50 to 2500 for ε ~ 50%

Muon Trigger - Basics

- Measurement made of ‘trigger primitive’ quickly, tag beam crossing, etc.
  - Define primitives around infinite momentum trajectory & allow deviations from that trajectory consistent with threshold
- Define trigger segments (ROI) in (η,ϕ) of width $(\delta\eta,\delta\phi)$
  - Develop Coincidence Matrix between chambers

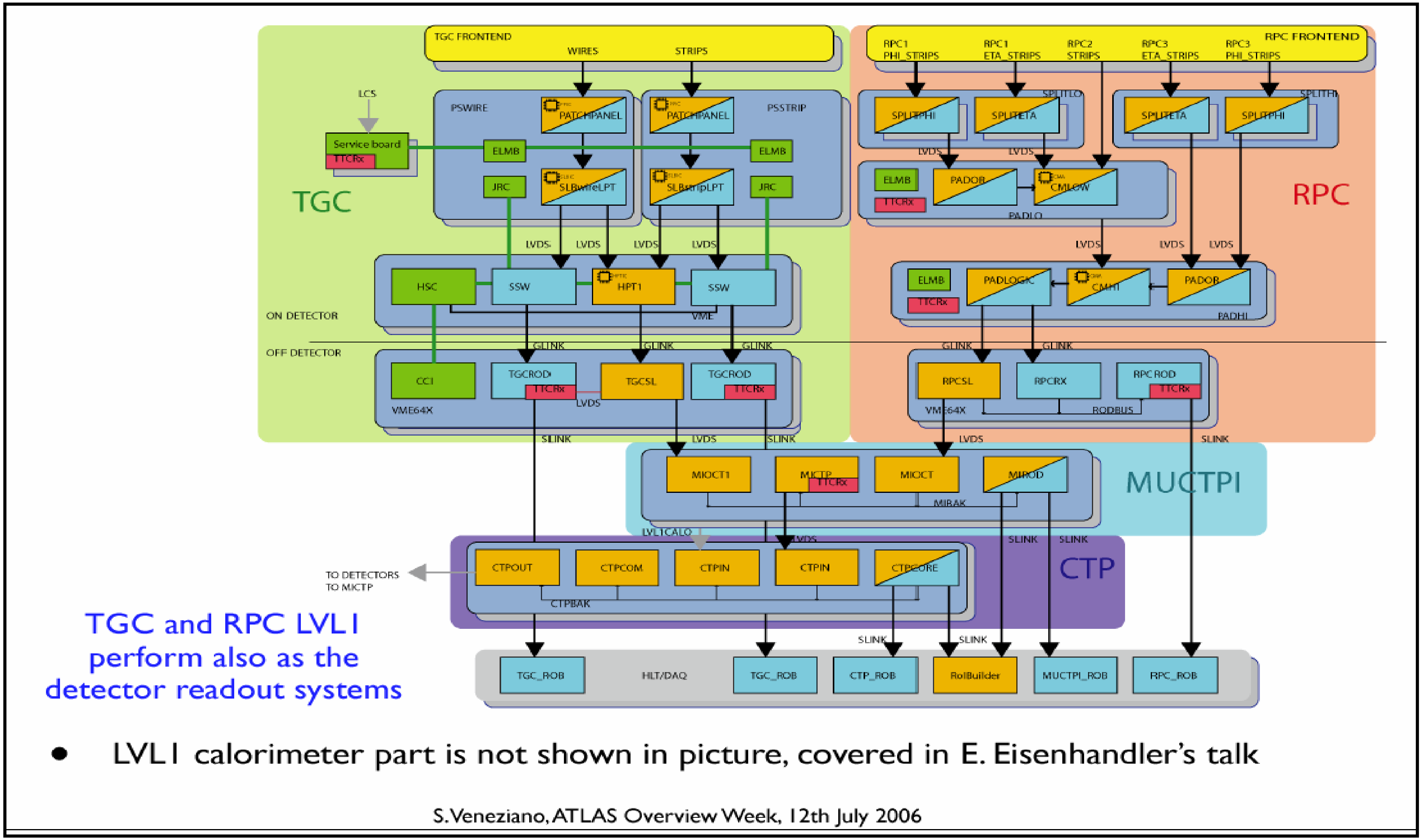
ATLAS



Trigger Latency-ATLAS

Time-of-flight		3 BC
Chamber response		1 BC
Propagation inside ROI		2 BC
Local processing		6 BC
(η,ϕ) – Logic		3 BC
Connection to Sector Logic		16 BC
Sector Logic		5 BC
Total	950 ns	36 BC

LVL1 Trigger System Layout - ATLAS



TGC and RPC LVL1 perform also as the detector readout systems

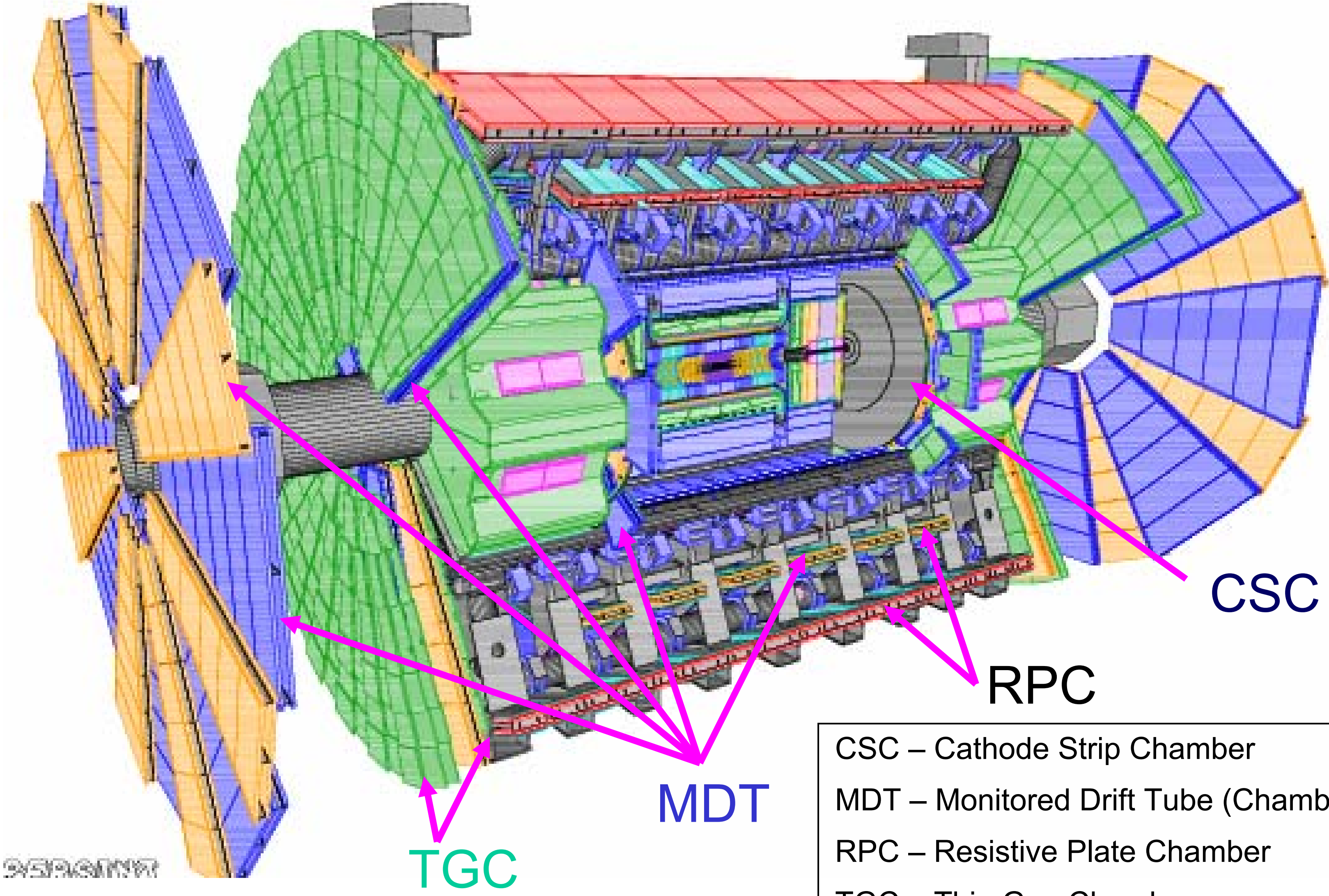
- LVL1 calorimeter part is not shown in picture, covered in E. Eisenhandler's talk

S.Veneziano, ATLAS Overview Week, 12th July 2006

Technology & Layouts – ATLAS & CMS

Chamber Technology	ATLAS	CMS
Inner Tracker		
Outer radius of Tracker	107 cm	110 cm
Technology	Silicon & Straw Tubes	Silicon
Min (X/X_0) $\eta \sim 0$	0.3	0.4
Max (X/X_0) $\eta \sim 1.7$	1.2	1.5
Drift Tubes	MDT	DT
Coverage	$\|\eta\| < 2.0$ inner, $\|\eta\| < 2.7$ middle & outer	$\|\eta\| < 1.2$
Number of chambers	1,170	250
Number of channels	354,000	172,000
Function	Precision Measurement	Precision Measurement, Trigger
Cathode Strip Chambers (CSC)		
Coverage	$2.0<\|\eta\| < 2.7$ inner layer	$1.2<\|\eta\| < 2.4$
Number of chambers	32	468
Number of channels	31,000	500,000
Function	Precision Measurement, 2nd Coordinate	Precision Measurement, Trigger
Resistive Plate Chambers (RPC)		
Coverage	$\|\eta\| <1.05$	$\|\eta\| < 2.1$
Number of chambers	1,112	912
Number of channels	374,000	160,000
Function	Triggering, 2nd Coordinate	Triggering
Thin Gap Chambers (TGC)		
Coverage	$1.05<\|\eta\| < 2.4$	
Number of chambers	1,578	
Number of channels	320,000	
Function	Triggering, 2nd Coordinate	

Technologies of ATLAS



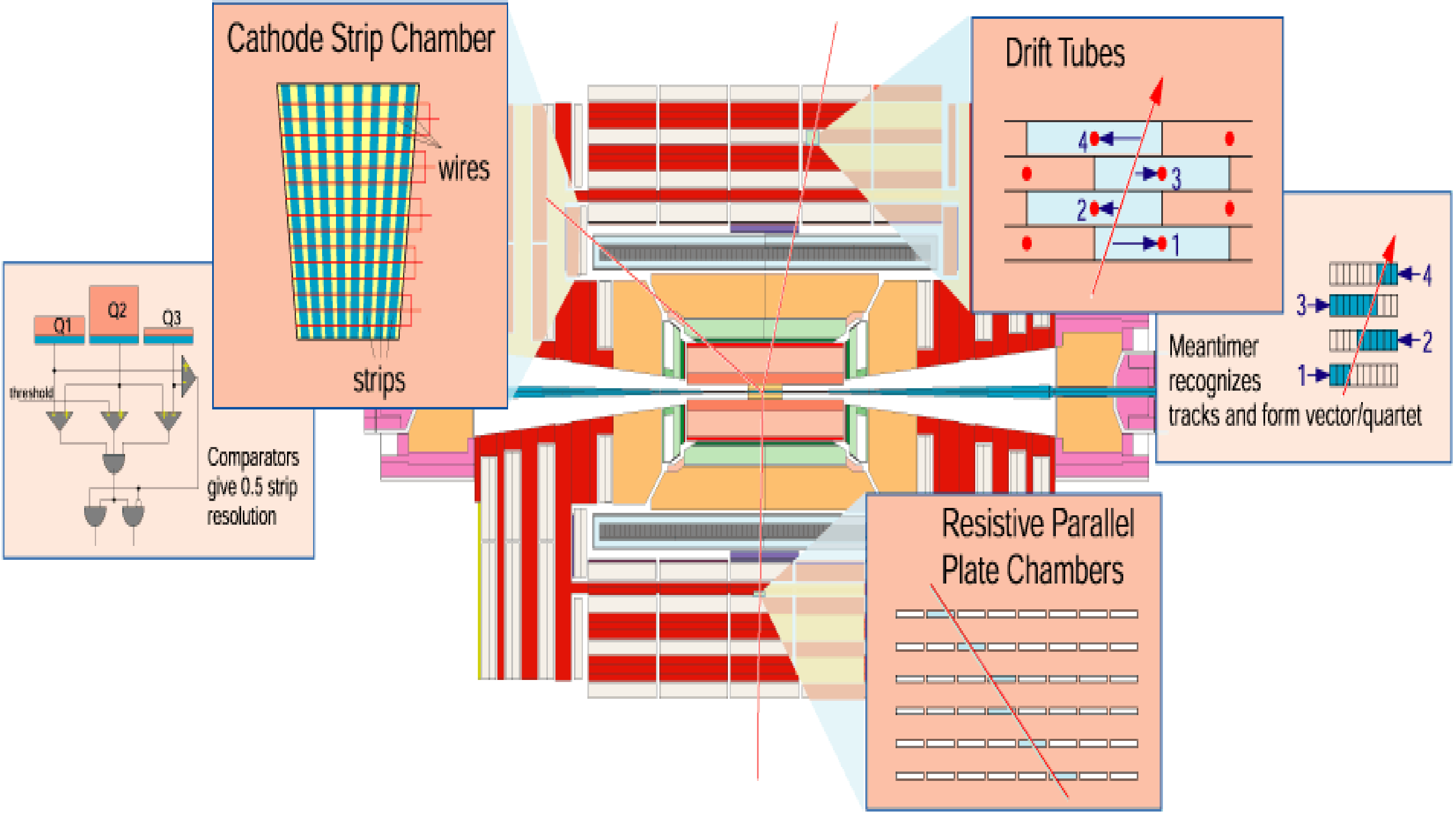
CSC – Cathode Strip Chamber

MDT – Monitored Drift Tube (Chamber)

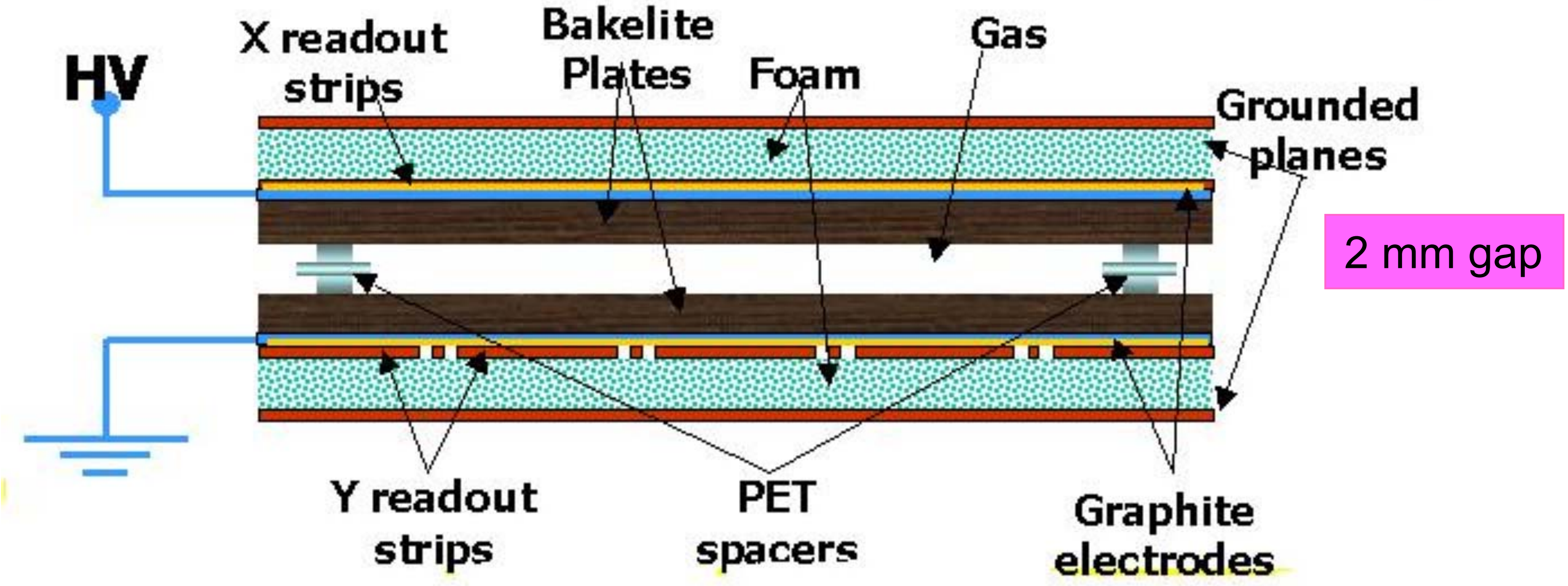
RPC – Resistive Plate Chamber

TGC – Thin Gap Chamber

Technologies of CMS



Resistive Plate Chambers

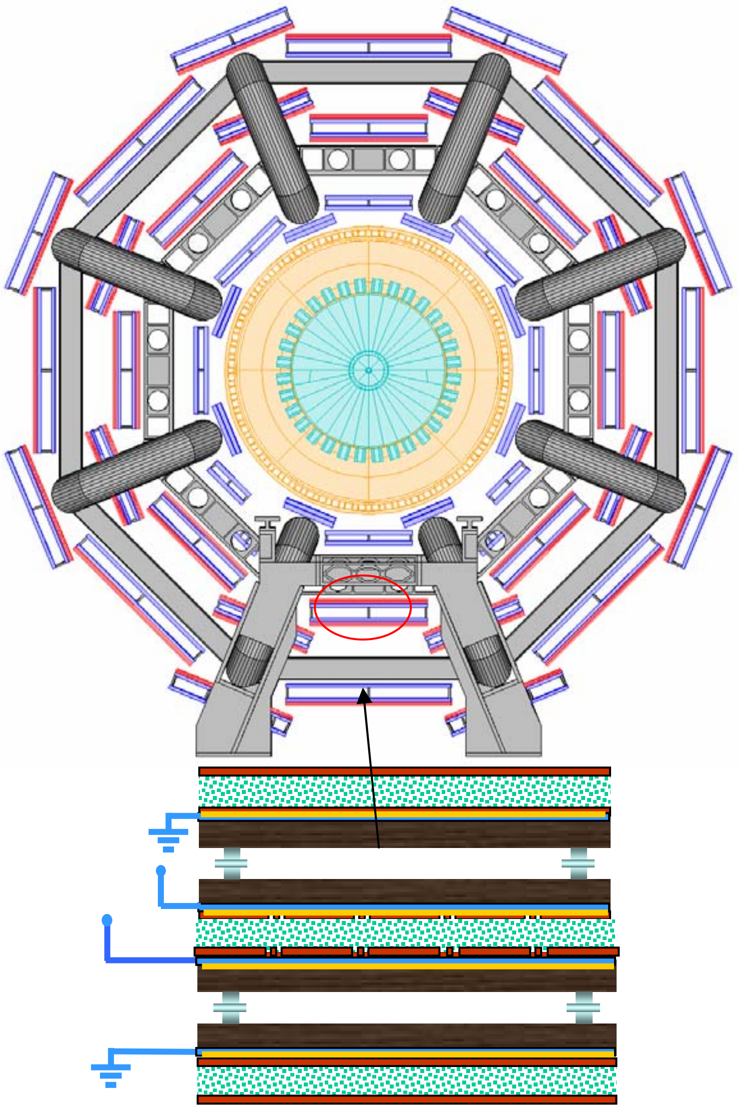


2 mm gap

- Intrinsically fast response ~ 1 to 2 ns for beam cross tag
- Provide both η and ϕ information
- Deployed in ALICE, ATLAS and CMS
- Although ~ 25 years old parameters still being studied

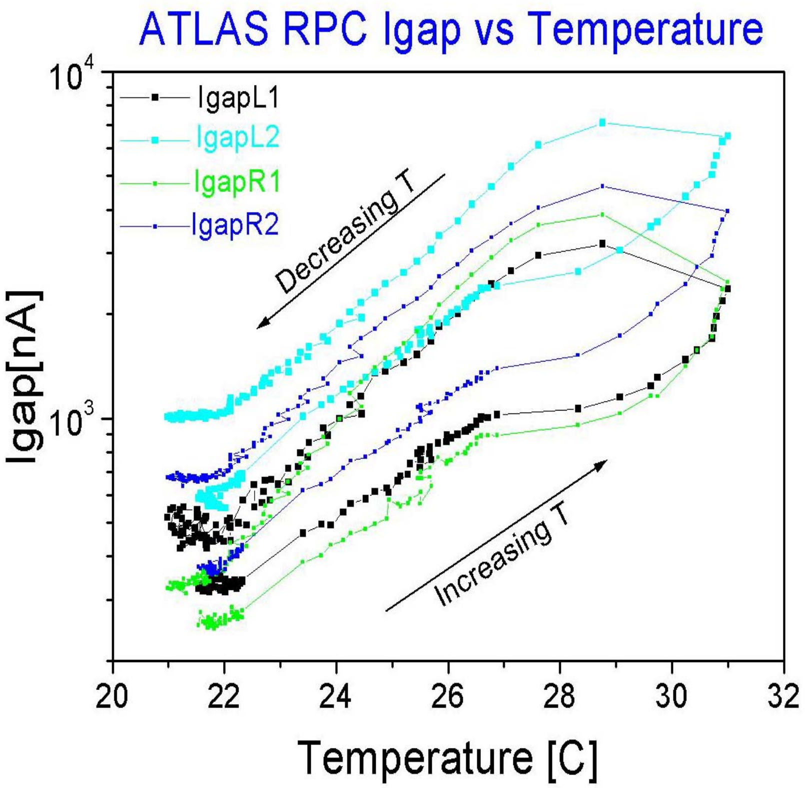
ATLAS RPC System

- Three RPC detector layers:
  - 2 in the middle station, 1 in the outer (380 MDT/RPC stations)
- Each layer:
  - 2 gas gaps and 4 readout planes for each detector element
  - Eta and Phi read-out copper strips panels, pitch ranging from 26.4 to 33.9 mm
- Each gap:
  - 2 mm gas gap with plastic laminate electrodes
  - plate resistivity : ~ 1- 4x10^{10} Ωcm
  - Gas mixture: $(C_2H_2F_4)$ 94.7% - (C_4H_{10}) 5% - (SF_6) 0.3%
- Performance:
  - RPCs working in avalanche mode
  - Efficiency: > 98%
  - Time resolution: ~ 1-2 ns
  - Spatial resolution: 5-10 mm
  - Rate capability: ~ 1000 Hz/cm^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

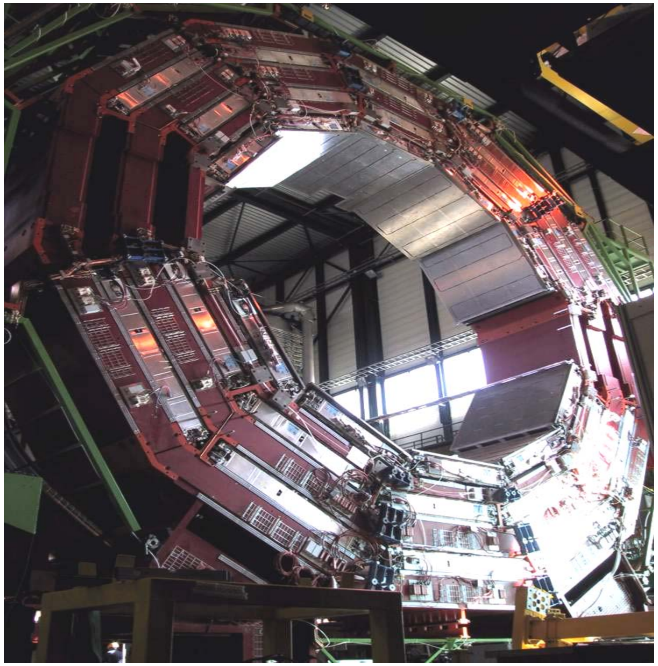


CMS DT-RPC Barrel Chambers

RPC-DT
Coupling

Insertion in
CMS Flux
Return

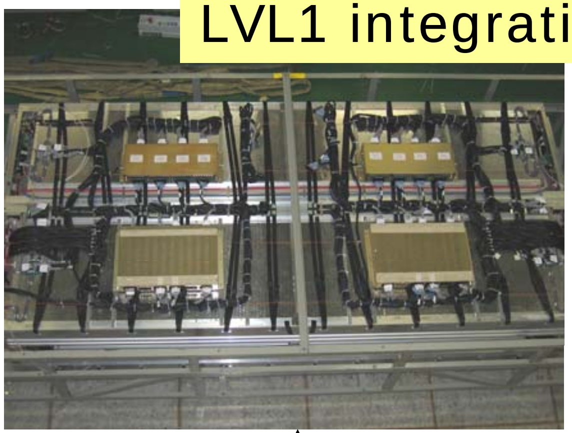
CMS Barrel
Wheel



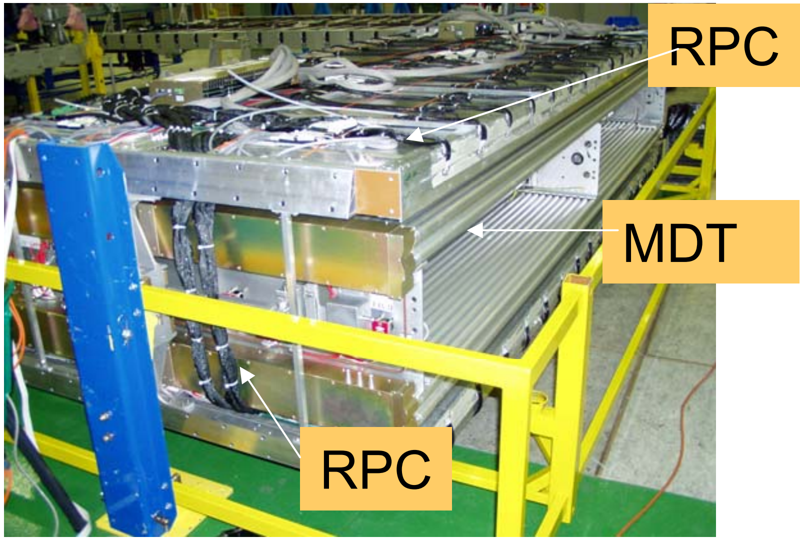
ATLAS Barrel Station Integration RPC/MDT/LVL1

RPC preassembly and cabling

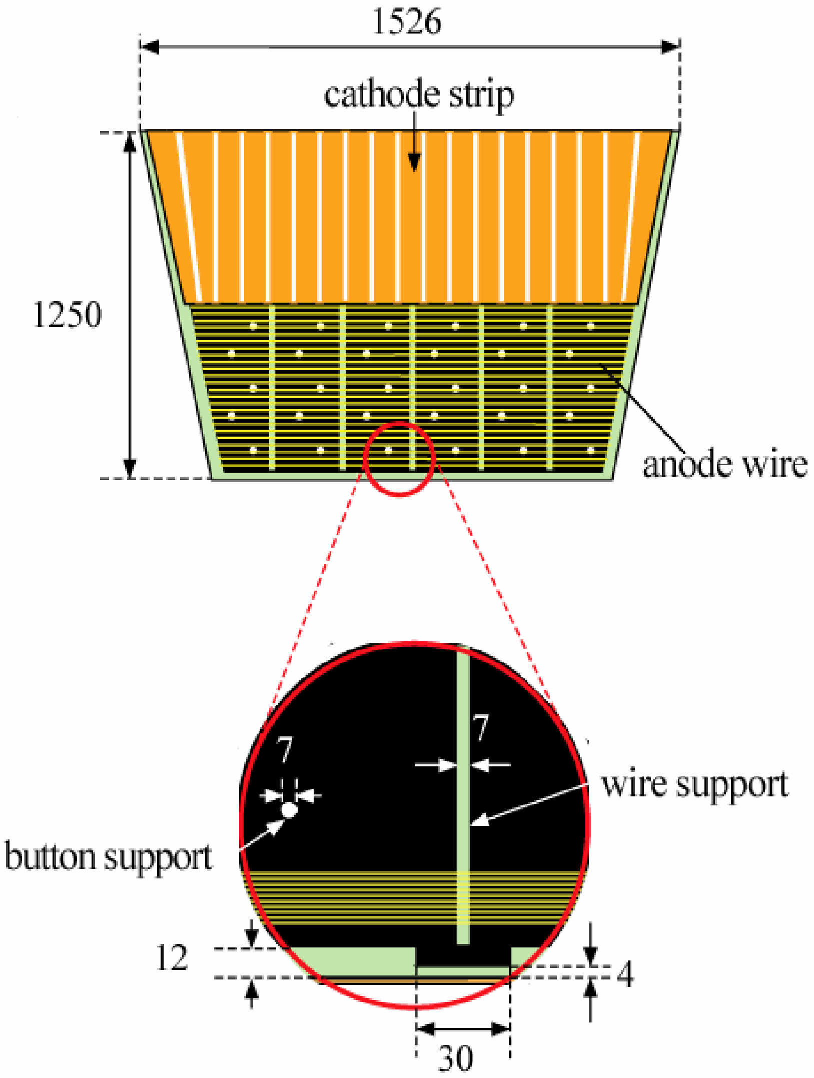
LVL1 integration



Integration with the MDT



Thin Gap Chamber (TGC) Trigger ATLAS EC



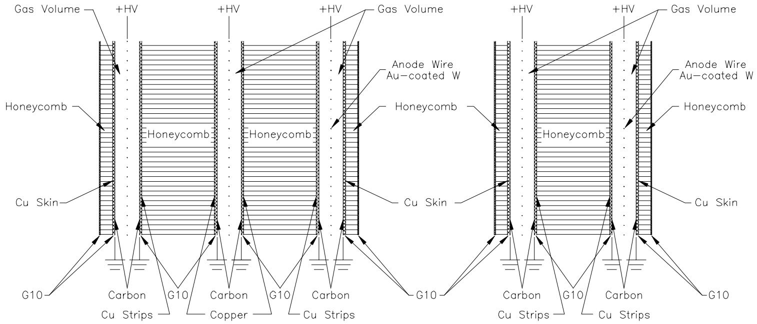
- Basic structure a MWPC with graphite cathode
- Signal is read from both anode wires and cathode strips
- Gap between ano-cath is 1.4 mm
- Wire spacing is 1.8 mm
- 50 μm tungsten wire
- Gas CO_2:n-Pentane (55 : 45)
- Efficient 25 ns tag

G. Mikenberg – Weizmann/CERN

ATLAS Thin Gap Chamber Wheels

- TGCs made in Israel, Japan, China for EC Trigger
- Installed on ‘Sectors’ of wheels in B180 @ CERN
  - A total of 6 wheels, 12 sectors each

Chambers, alignment & trigger electronics mounted & commissioned on sectors in B180



CSC - Principle of Operation

Gas: Ar:CO_2 80:20

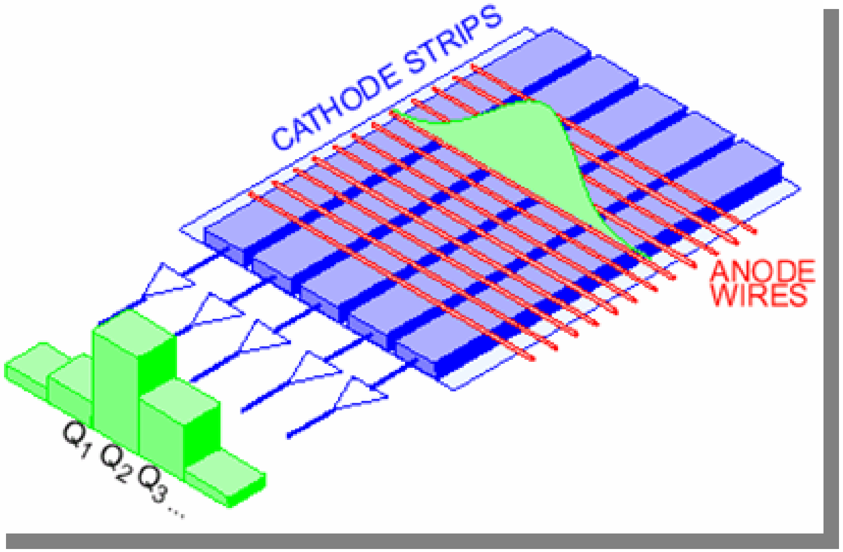
ATLAS

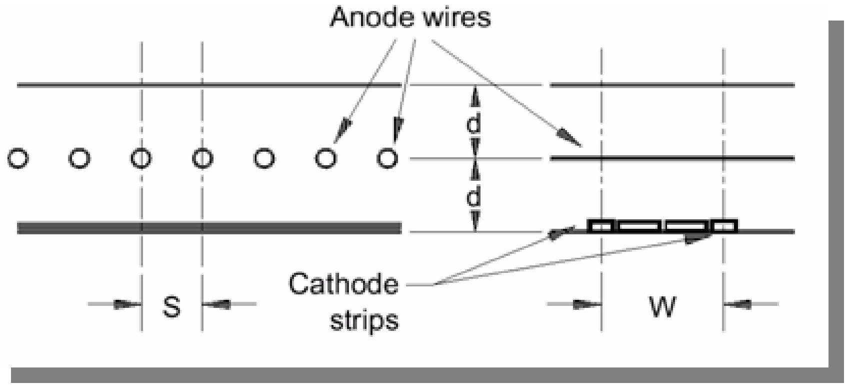
s = d = 2.54 mm

W = 5.6 mm

V. Polychronakos-BNL ATLAS

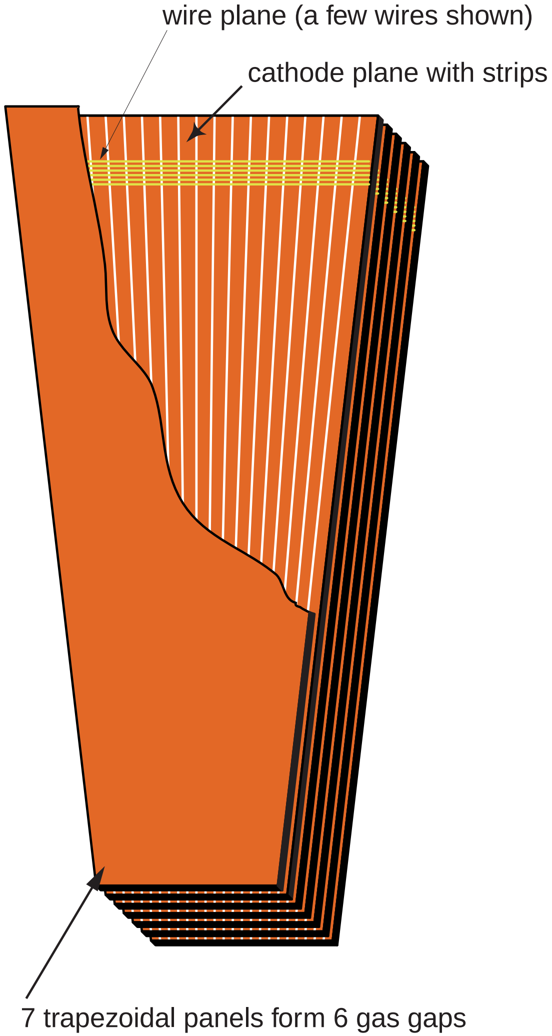
- Determine muon position by interpolating the charge on 3 to 5 adjacent strips
- ΣQi ~ Landau Distribution
- Measure Q1, Q2, Q3… with 150:1 SNR to get σ_x ~ 60 μm.
- Second set of y-strips measure transverse coordinate to ~ 1 cm.
- Position accuracy unaffected by *gas gain* or *drift time* variations.
- Accurate *intercalibration* of adjacent channels essential.





CSC Design Parameters - CMS

EMU Cathode Strip Chamber

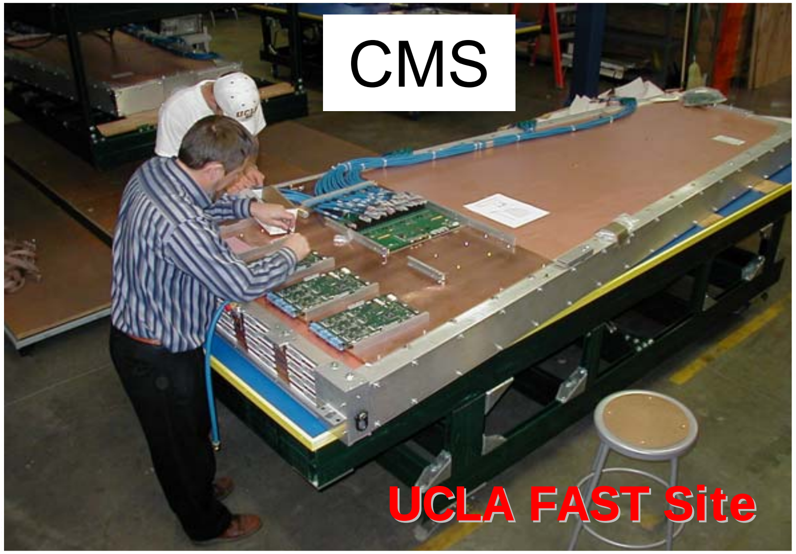


Overall size:	3.3 x 1.5/0.8 m^2 (trapoz)
7 panels form	6 gas gaps of 9.5 mm
Anode-Cathode:	h=4.75 mm
Anode wires:	d=50 μm, gold-plated W
Wire spacing:	s=3.2 mm pitch
Readout group:	5 to 16 wires (1.5-5 cm)
Cathode strips:	w=8-16 mm wide (1 side)
Gas:	$Ar+CO_2+CF_4=40+50+10$
Nominal HV:	3.6 kV
Gas Gain:	10^5
Trigg Resol'n	2 mm
Track Resol'n	100 μm

A. Korytov UoF - CMS

Final Assembly & Test – ATLAS & CMS

ATLAS

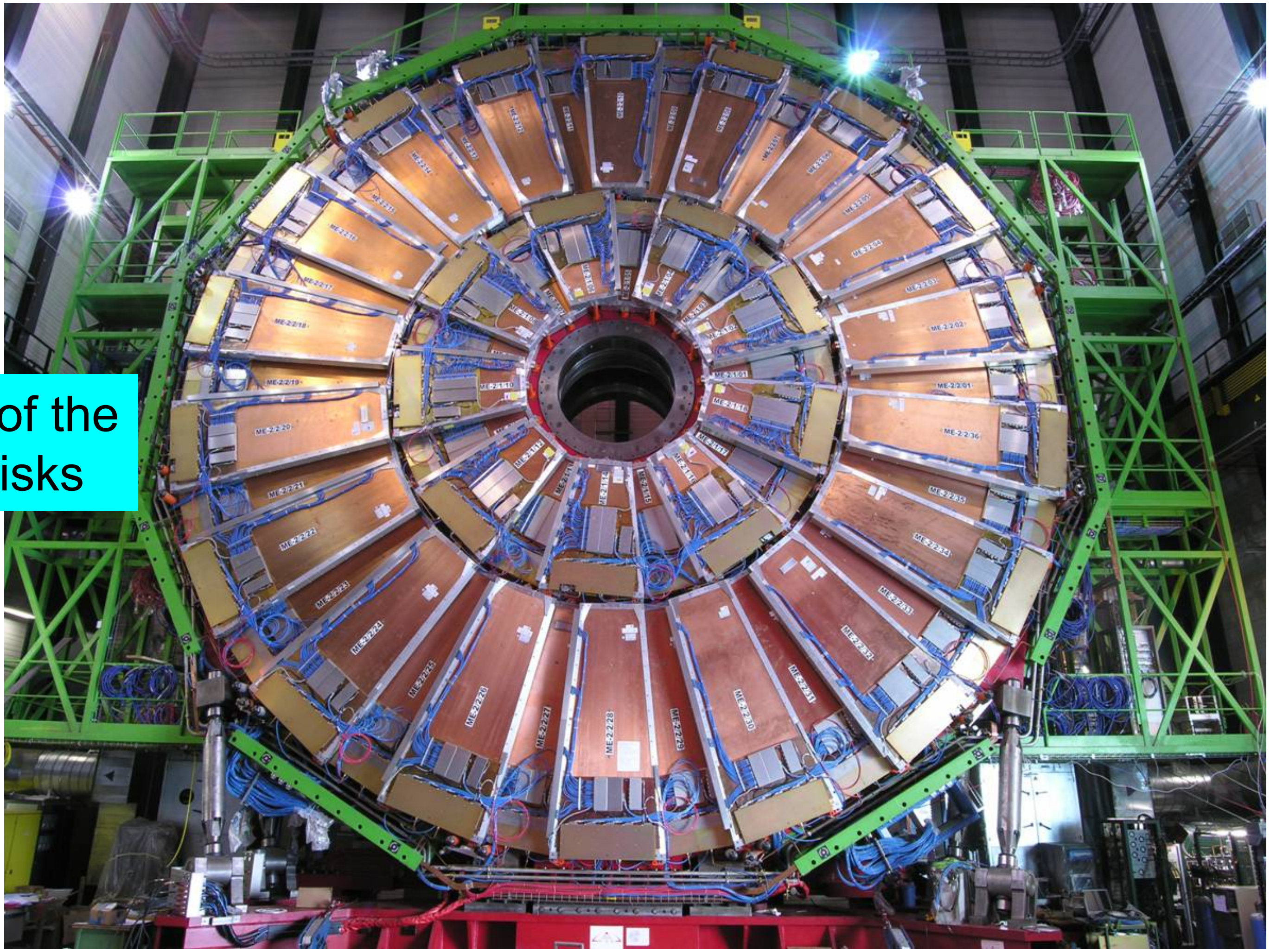

CMS

UCLA FAST Site


CMS

University of Florida FAST Site

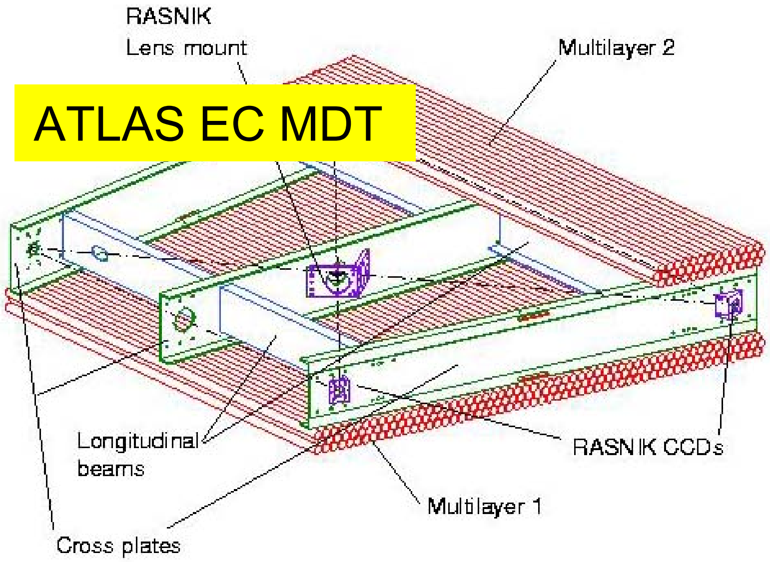
CSCs in CMS Endcap

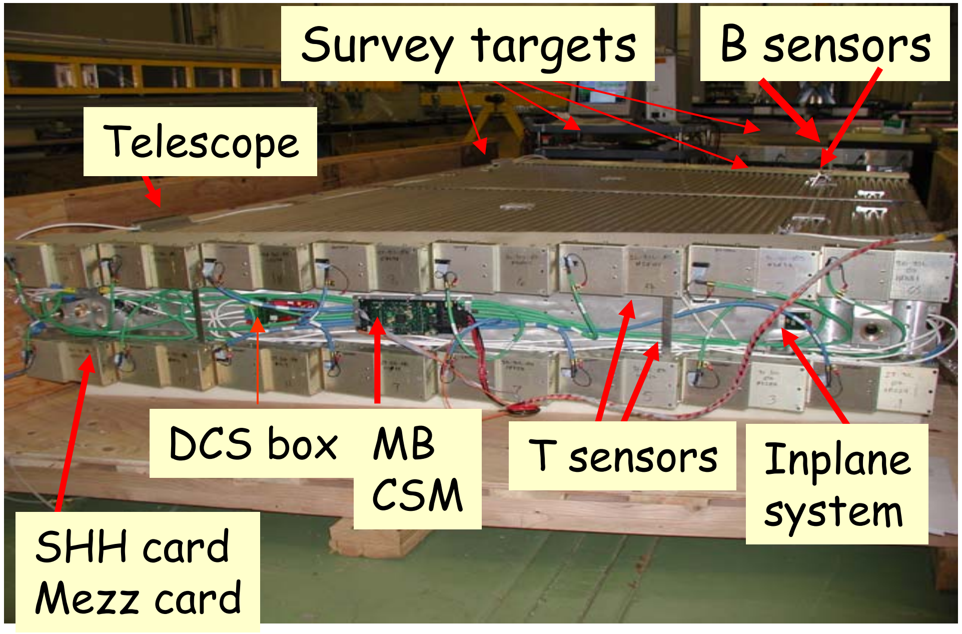


One of the EC disks

Drift Tubes - ATLAS

- MDT Deployed in Barrel & Endcap of ATLAS
  - Barrel middle and outer layers integrated with RPC
  - Inner barrel and all 3 layers of EC have MDTs

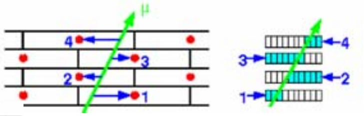


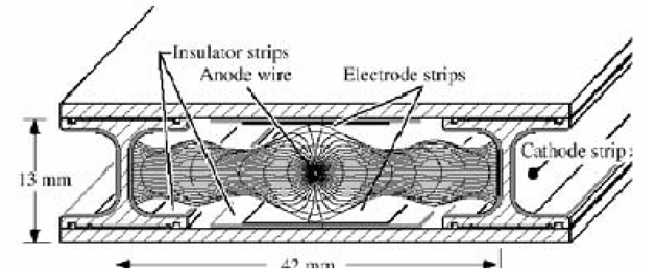


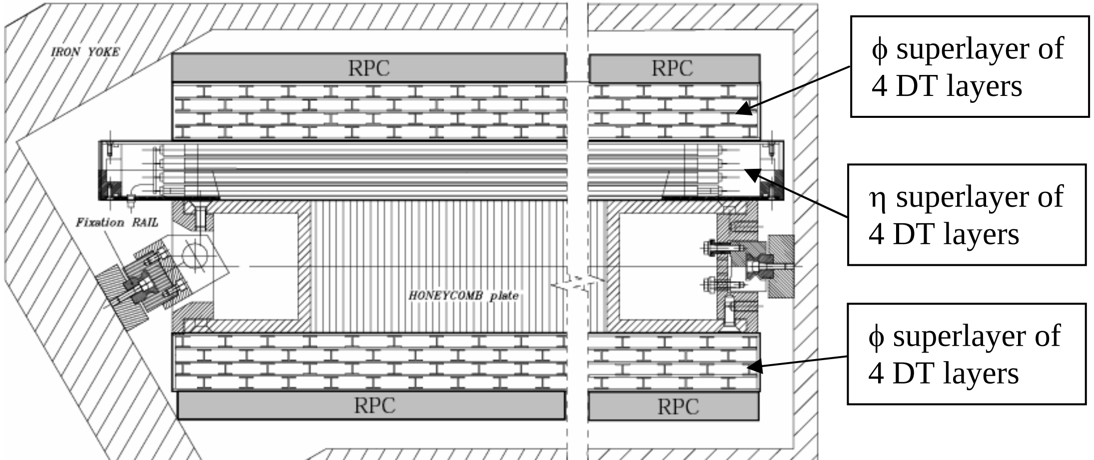
Gas: Ar:CO_2 93:7, Pressure: 3 bar
Tubes: 3 cm dia, Wire: 50 μm W-Re (Au)
Gain: 2×10^4, Max Drift: ~ 710 ns
Resol'n (tube): ~ 80 μm

Drift Tubes - CMS

- Drift Tubes deployed in CMS Barrel
  - Provides both ϕ (bend) and η (2nd coordinate)
  - Mean timer finds tracks and determines bunch crossing
  - Integrated with RPC stations that fast trigger







ϕ superlayer of 4 DT layers

η superlayer of 4 DT layers

ϕ superlayer of 4 DT layers

Gas Ar:CO_2 85:15, Pressure: 1+ε bar
'Tubes': 42 mm x 13 mm, Wire 50 μm Steel
Gain: ~10^5, Max Drift: ~ 380 ns
Resol'n: ~ 190 μm

Chamber Alignment

- A large enterprise for both ATLAS & CMS
  - Measure distortions of chambers themselves – ‘in-plane’ system
  - Measure location of chambers w.r.t. grid, barrel vs. endcap
  - Monitor location vs. time and correct for locations in track reconstruction

ATLAS

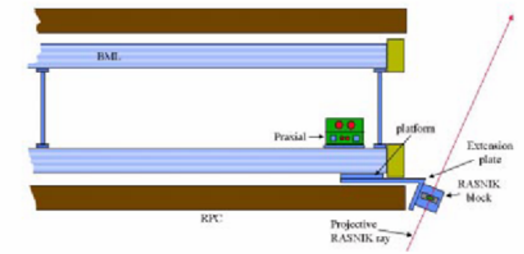
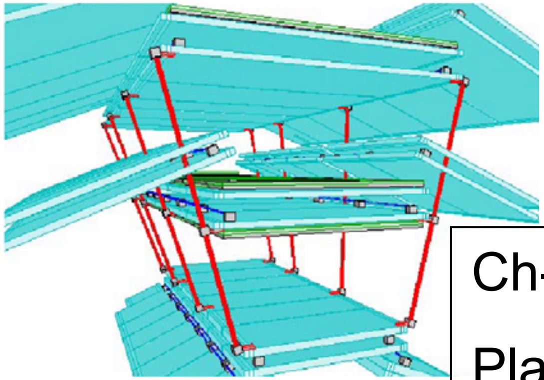


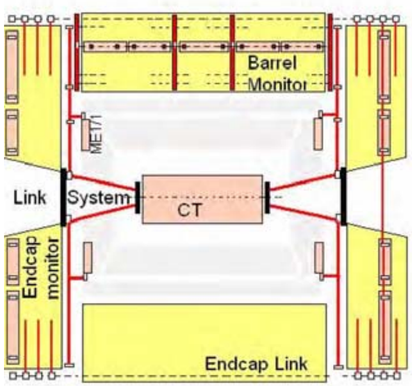
Figure 0-16 Sketch of the implementation of the optical sensor (BML lens) for the projective alignment.

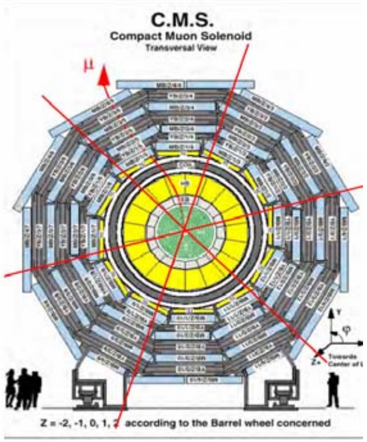


Ch-to-Ch ~ 40 μm

Placement ~ 5 mm

CMS





Ch-to-Ch ~ 100-500 μm

Placement ~ 5 mm

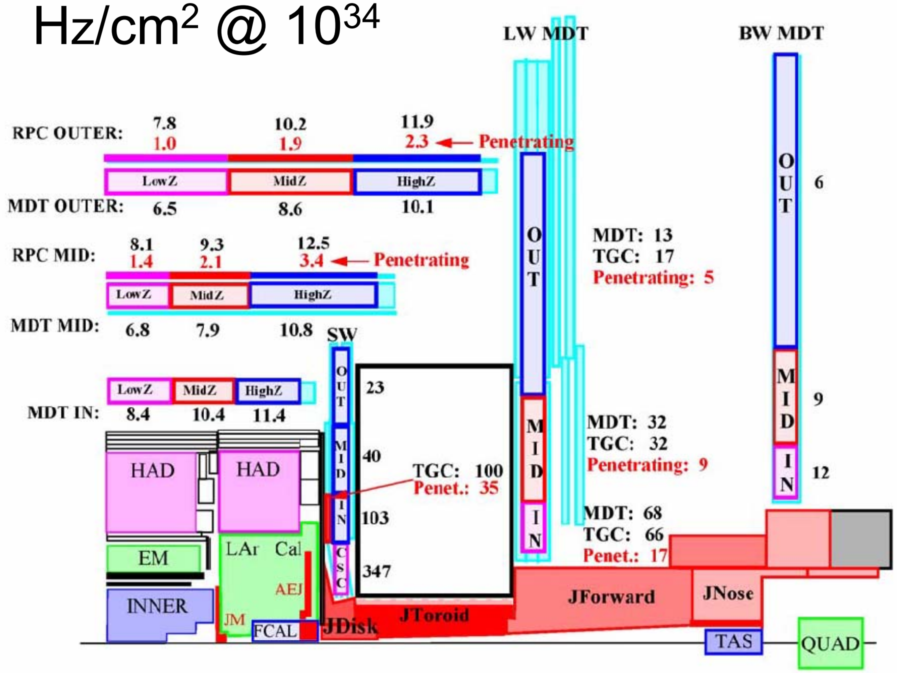
Radiation Environment

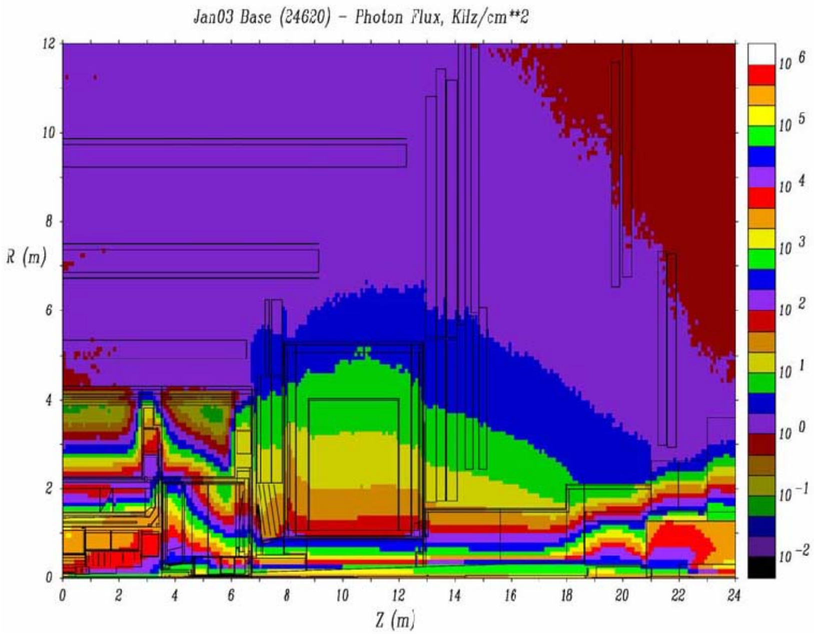
- LHC – neutrons & soft gammas
  - Inner tracker & muon endcaps
- Sensitivity to bkg.
  - Aging of chambers & electronics
  - Degradation of pattern recognition in presence of bkg.
  - Electronics sufficiently rad-hard
- The ‘trip through GIF’ @ CERN
  - ^{137}Cs gamma source
    - RPC, CSCs, DT, MDTs, TGCs
- Extensive simulations performed
  - FLUKA vs. GCALOR but put in 5X safety

Backgrounds in ATLAS Muons

- p-p collision produces many secondaries from interactions in collimators and calorimeters
  - Use FLUKA and GCALOR to estimate backgrounds photons, neutrons, charged particles (e+-, π, p)
  - Chambers have small efficiency for photons, neutrons ~ 10^{-3} to few 10^{-2}
  - Electronics should be sufficiently radiation hard

Hz/cm^2 @ 10^{34}





Installation & Commissioning

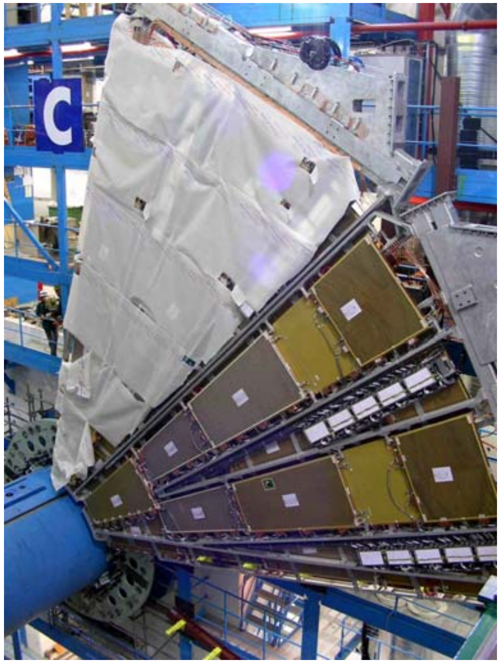
- ATLAS
  - Installation of barrel and endcaps underway
    - ~ 50% of barrel stations installed (to be complete by end '06)
    - TGC & MDT wheels under assembly (B180) and are being (complete in spring '07)
  - Chamber services are being installed & commissioned
  - Barrel toroid soon to be tested in situ
  - Endcap toroids installed & tested by Apr-07
  - Beam pipe closes Aug-07
  - First running by end of '07, 14 TeV in '08

- CMS
  - Barrel and endcap installation done on surface @Pt 5
    - >3/5 wheels DT-RPC stations installed
    - >90% EC disks CSCs installed
  - Testing of system done on surface
  - Solenoid cold & soon to be tested
  - Lowering of pieces in Oct -06 & assembly complete by Aug-07
  - Connection to services and final commissioning in pit
  - Beam pipe closes Aug-07
  - First running by end of '07, 14 TeV in '08

ATLAS Muons – Installation

Barrel Chamber installations in UX15

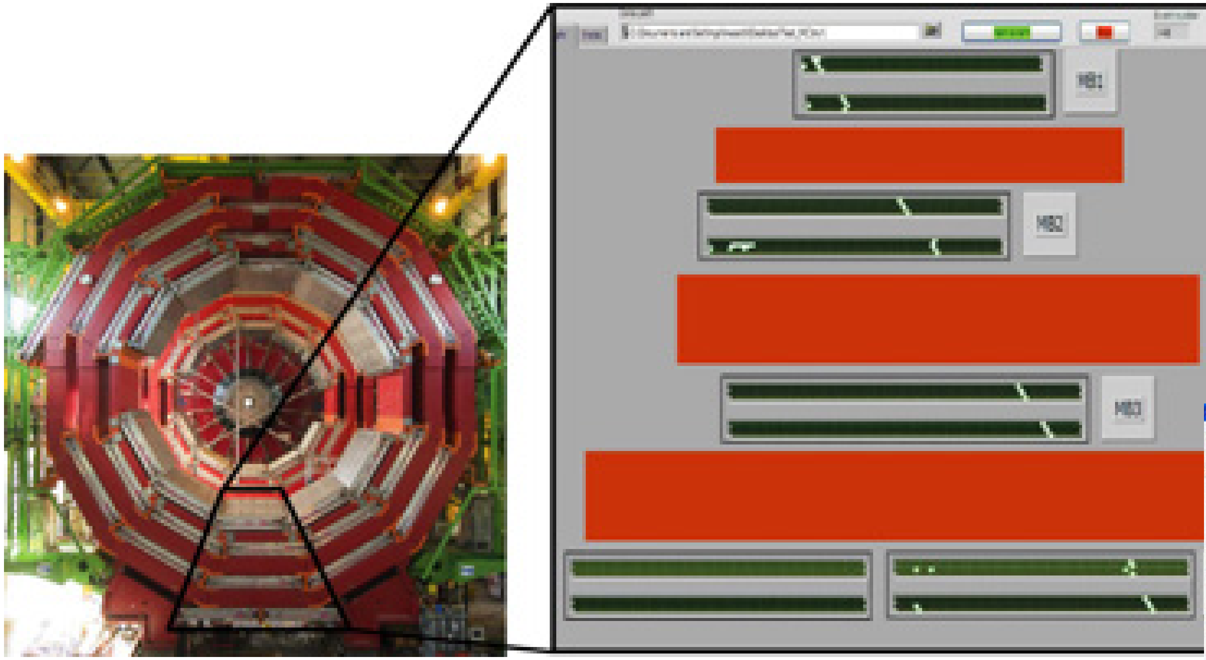
MDT ‘Big Wheel’ assembly in B180

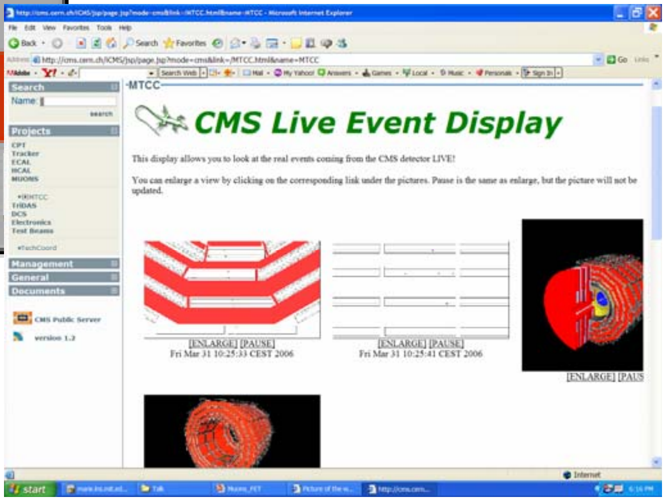


Thin Gap Ch 1 installation in UX15 – for EC trigger

Commissioning CMS Muon System

- Cosmic ray ‘Challenge’ with B-field
  - Test operation of essential systems prior to lowering in Pit
  - Cosmic tracks – data taken with trigger





CMS Live Event Display

This display allows you to look at the real events coming from the CMS detector LIVE!

You can enlarge a view by clicking on the corresponding link under the pictures. Pause is the same as enlarge, but the picture will not be updated.

[ENLARGE] [PAUSE]
Fri Mar 31 10:25:33 CEST 2006

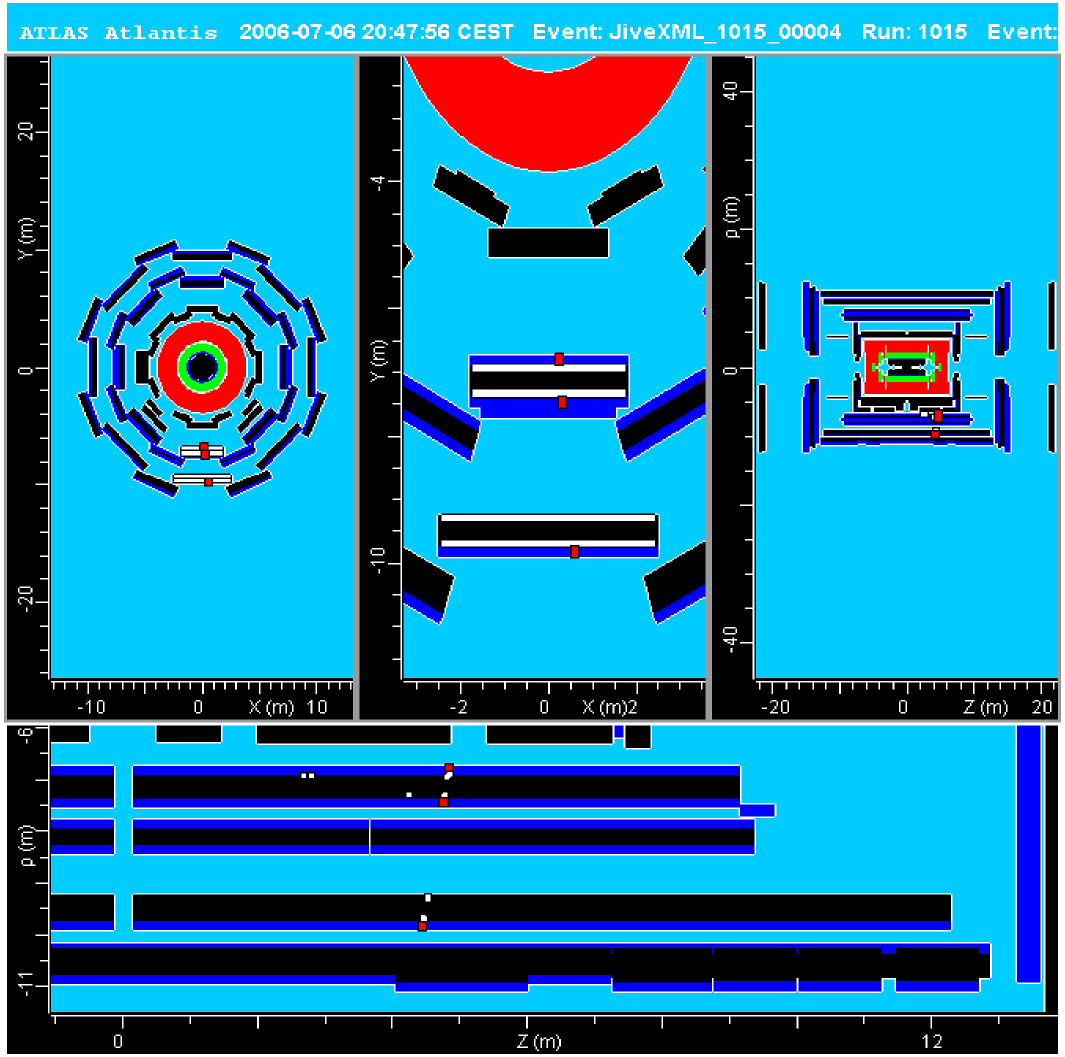
[ENLARGE] [PAUSE]
Fri Mar 31 10:25:41 CEST 2006

[ENLARGE] [PAUS

ATLAS Commissioning System in UX15

- RPC operated with the correct gas mixture at HV
  - Trigger signals from the LVL1 RPC trigger were delivered with a 50 Hz rate.
  - Data were taken reading-out all the RPCs of sector 13 and MDTs

E. Pasqualucci talk -Stockholm

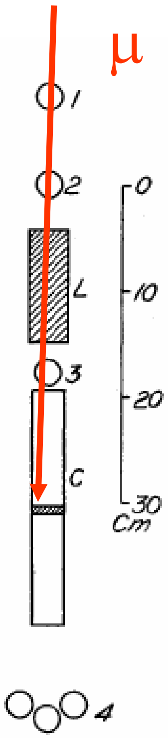


Conclusions

- Muon system may play a key role in Physics @ LHC
  - Many theorized channels have muon signatures
- All 4 experiments have made large investments
- ATLAS & CMS have complementary designs
  - Air-core toroid vs. Solenoid with instrumented flux return
  - Simulated performance roughly comparable for full systems
  - Major challenge is putting it all together & making it work
- Large effort continuing on Software Development
  - Goals are to tune the trigger and reconstruction algorithms
    - Use commissioning data to test algorithms
  - Prepare for first Beam
    - Tuning signals & ‘warm-up’ physics
  - In a few years the LHC program should be mostly data analysis

“Who ordered that” – I.I. Rabi

- Muons first detected in cosmic rays in a search for the mediator of strong interactions proposed by H. Yukawa, *Proc. Phys-Math. Soc. Japan17*, 48 (1935)
  - First observed by:
    - S. Neddermeyer and C.D. Anderson, *Phys. Rev*. 51, 884 (1937); J.C. Street and E. C. Stevenson, *Phys. Rev.* 51, 1005 (1937); Y. Nishina, M. Takeuti and T. Ichinomiya, *Phys. Rev.* 52, 1198 (1937)
  - The mass of detected particle was about right (200 x M_e) but far more penetrating by 12 orders-of-magnitude (Fermi, Teller, Weisskopf)
- Properties of Muon were that of a ‘heavy’ electron and remained a mystery for some time
  - What was observed was the first member of the Second Generation
- A mystery still – perhaps muon detection @ LHC will help answer I.I. Rabi



Early Muon Detector (circa 1937)

Street & Stevenson

Trigger + Absorber + dE/dx + Tracker in B-field

References

- ATLAS Muon TDR
- CMS Physics TDR
- General-Purpose Detectors for the Large Hadron Collider, Froidevaux & Sphicas
- Anna Di Ciaccio, Roma II
- Andrei Korytov – IEEE 2004 –CMS CSC EC
- ATLAS Radiation Backgrounds ATL-GEN-2005-001