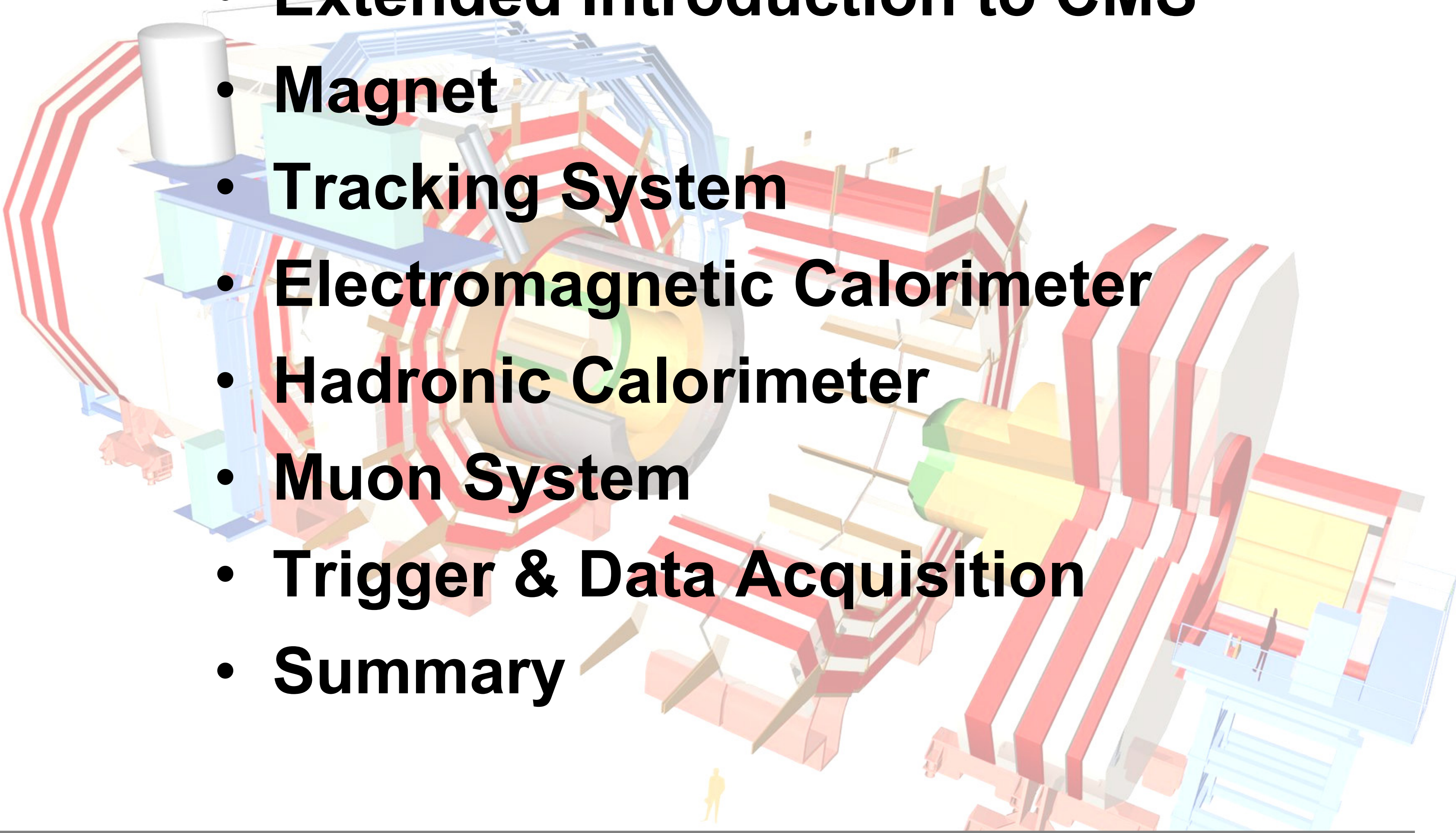
STFC RAL

Compact Muon Solenoid



- Extended Introduction to CMS
- Magnet
- Tracking System
- Electromagnetic Calorimeter
- Hadronic Calorimeter
- Muon System
- Trigger & Data Acquisition
- Summary

Ken Bell – Rutherford Appleton Laboratory

Physics Goals (as of 1994)

- General Purpose Detector at LHC: 14TeV pp, 40MHz
- Standard Model Higgs Boson
  - 85 – 160 GeV: Two photon channel
  - 130 – 700 GeV: Four lepton channel
  - 700 GeV – 1 TeV: $\ell\nu jj$ and $\ell\ell jj$ channels
  - 5σ discovery possible from LEP2 limit to 1 TeV ($10^5 pb^{-1}$)
- SUSY
  - MSSM Higgs: Two photon and four lepton channels
  - Tau and *b* tagging also important
  - Model-independent searches: high E_t Jets and missing E_t
- Heavy Ion Physics

- SM Higgs Boson used as performance benchmark

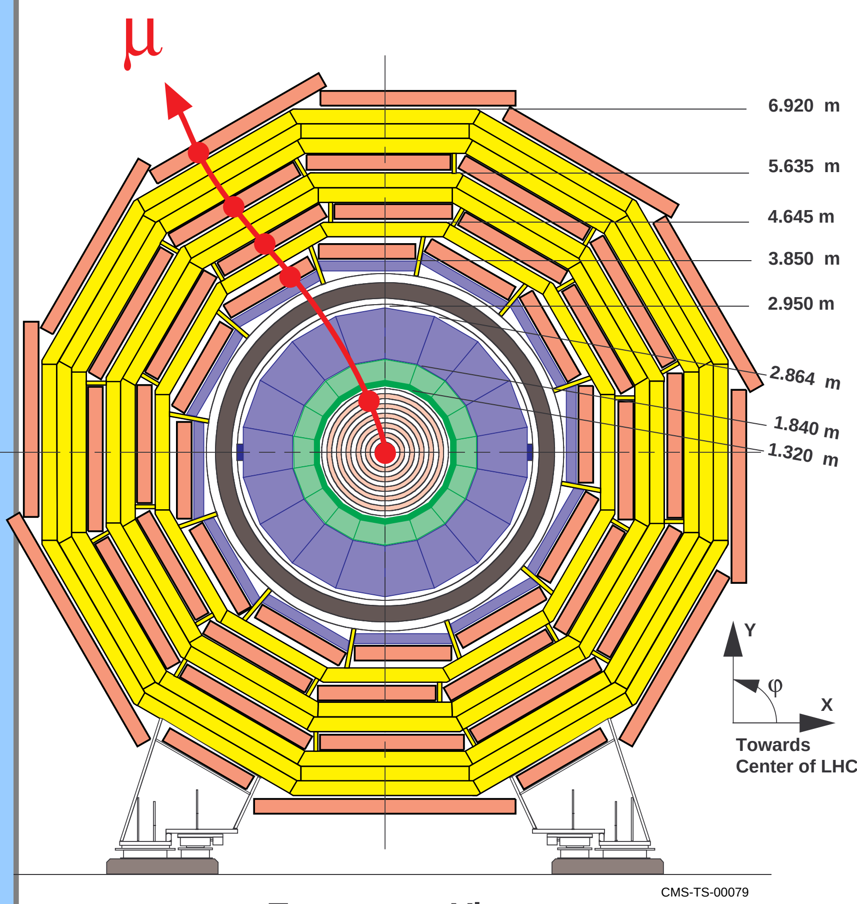
Design Drivers

1) Efficient, hermetic muon triggering and identification
   - Low contamination & good momentum resolution over $|\eta| < 2.5$
   - Di-muon mass resolution <1% at 100 GeV/c^2
   - Charge determination for muons with momentum ~1 TeV/c
   - $\Delta p_T/p_T$ ~5%
2) High-granularity, hermetic electromagnetic calorimetry
   - Coverage over $|\eta| < 3.0$
   - Good energy resolution, ~0.5% at E_T ~50 GeV
   - Di-photon mass resolution <1% at 100 GeV/c^2
3) Powerful central tracking system
   - Good charged particle momentum resolution and reconstruction efficiency
   - Good reconstruction of secondary vertices (for τ and *b*-jets)
4) Hermetic combined calorimetry system
   - Coverage over $|\eta| < 5.0$
   - Good resolution for detecting and measuring "missing" E_T and for reconstructing the mass of jet-pairs

Criterion 1 drives overall physical design of the detector through magnet design
Criteria 2&3 need special technologies to cope with challenging LHC environment

Engineering Solutions

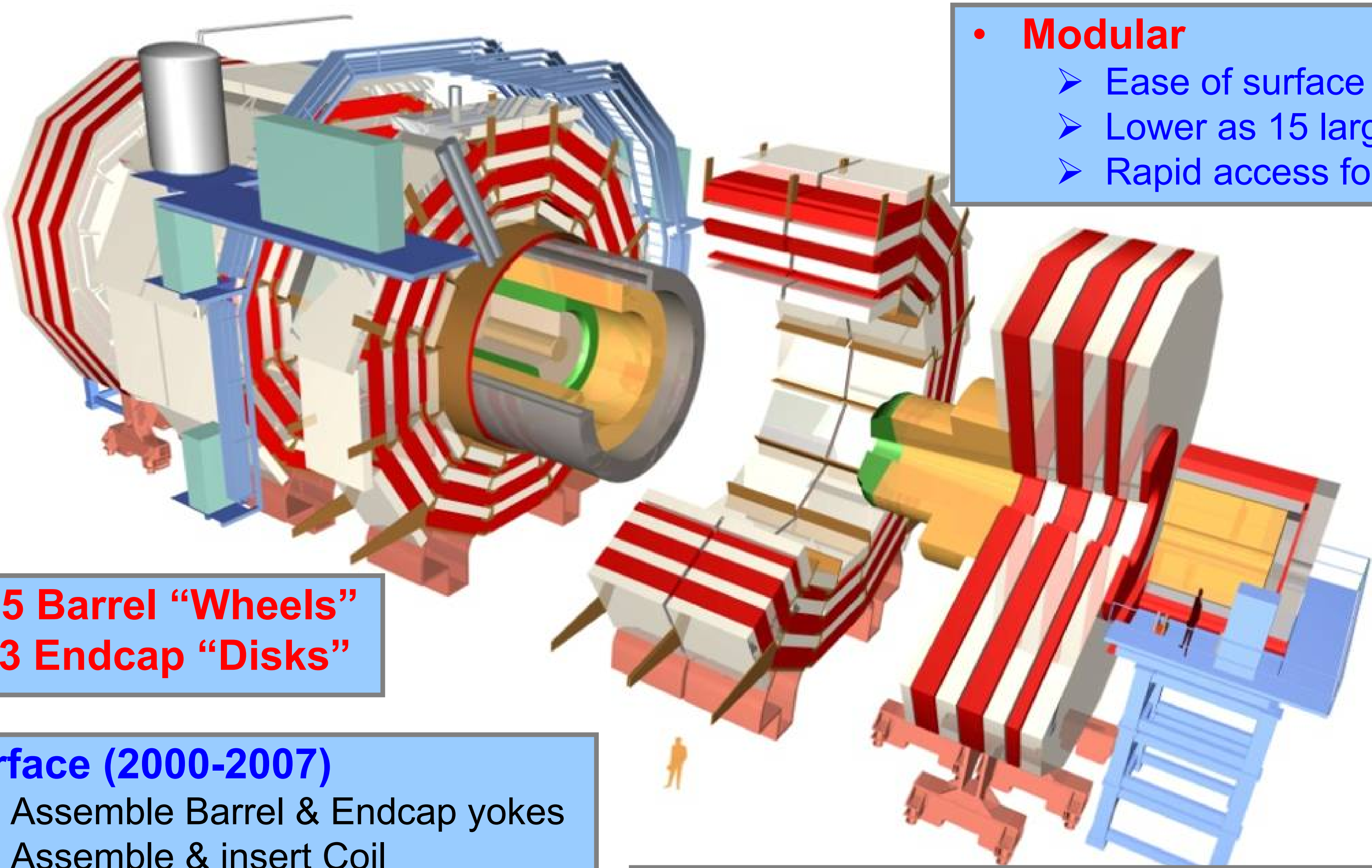
- Single high field (4T) solenoid
  - Largest practicably constructible
  - Compact design, but large enough BL^2
  - Contains all barrel tracking and calorimetry
  - Therefore solenoid can be thick
- Flux return yoke accurately constructed and instrumented for muon detection with redundant measuring systems
  - 4 stations 32 r-ϕ measurements (barrel DT) & 24 r-z measurements (endcap CSC)
  - Additional trigger from RPC layers
  - Sophisticated alignment system
- High-granularity electromagnetic calorimeter containing ~75k $PbWO_4$ crystals
  - $>22X_0$ in depth
- Tracking using 3-layer Si-pixel (66M channel) surrounded by 10-layer Si-strip (10M chans.) (210m² silicon: ~tennis court)
- Hermetic hadron calorimeter
  - Sampling type, brass/scintillator layers



Transverse View

Assembly Concept

- **Modular**
  - ➢ Ease of surface pre-assembly
  - ➢ Lower as 15 large pieces
  - ➢ Rapid access for maintenance



5 Barrel "Wheels"
3+3 Endcap "Disks"

- **Surface (2000-2007)**
  - ➢ Assemble Barrel & Endcap yokes
  - ➢ Assemble & insert Coil
  - ➢ Assemble & install HCAL
  - ➢ Install Muon chambers
  - ➢ (Pre-)cable detectors
  - ➢ Start commissioning
  - ➢ Test of coil & "ϕ-slice" of CMS

- **Underground (2006-2008)**
  - ➢ Install ECAL Barrel & Endcaps (preshower 2009)
  - ➢ Install Tracker and Beam-Pipe
  - ➢ Complete cabling
  - ➢ Close detector and finish commissioning

Performance Overview

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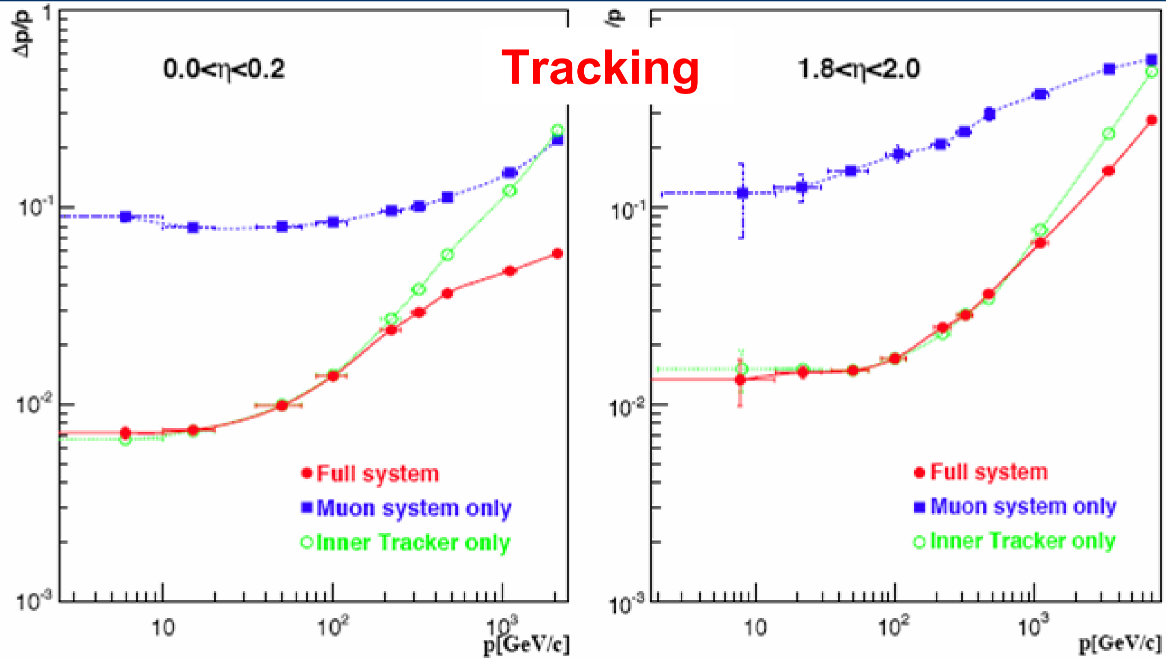

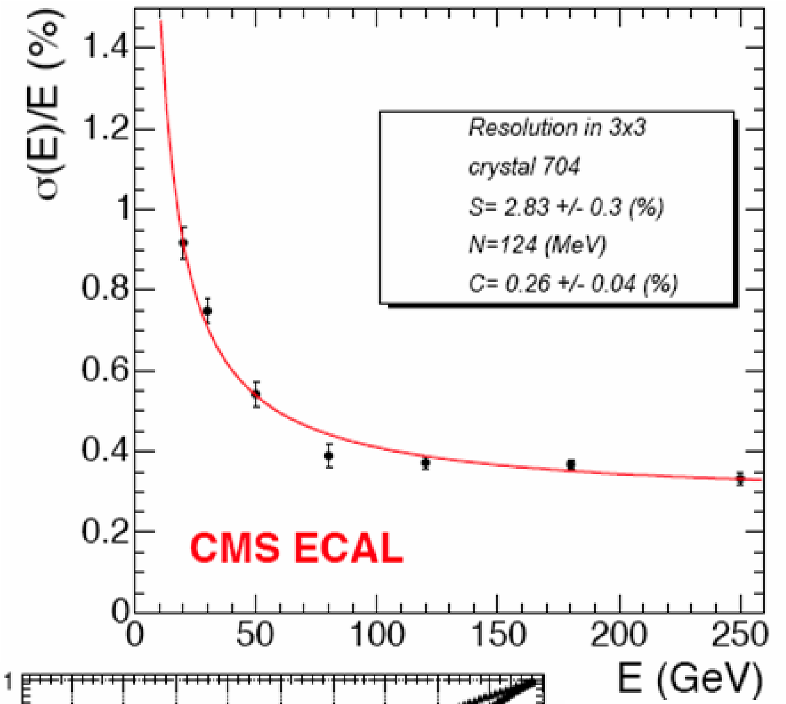

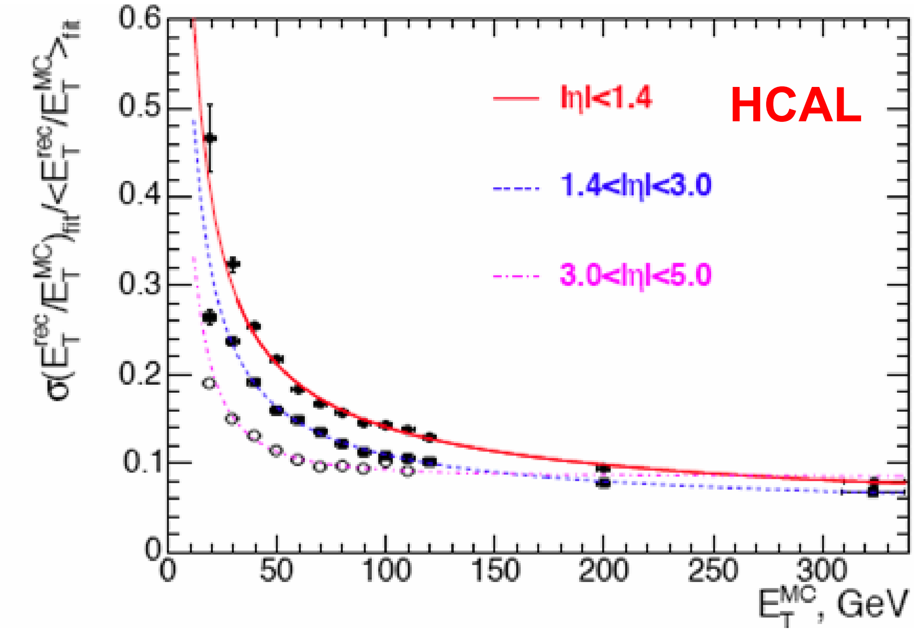

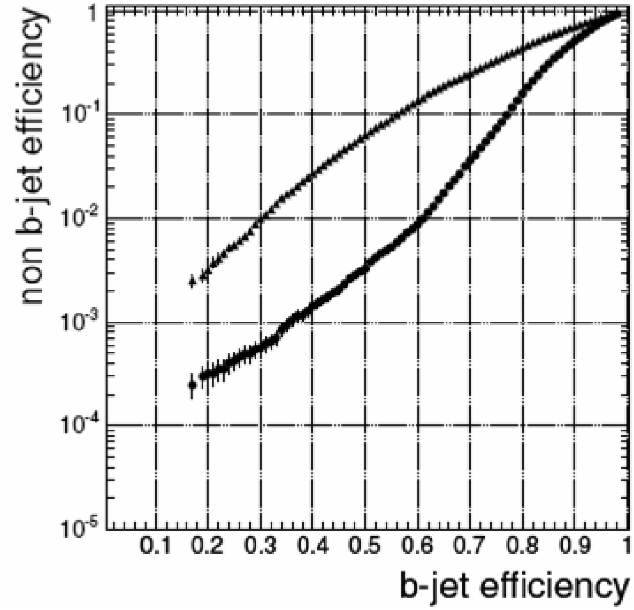

CMS Timeline

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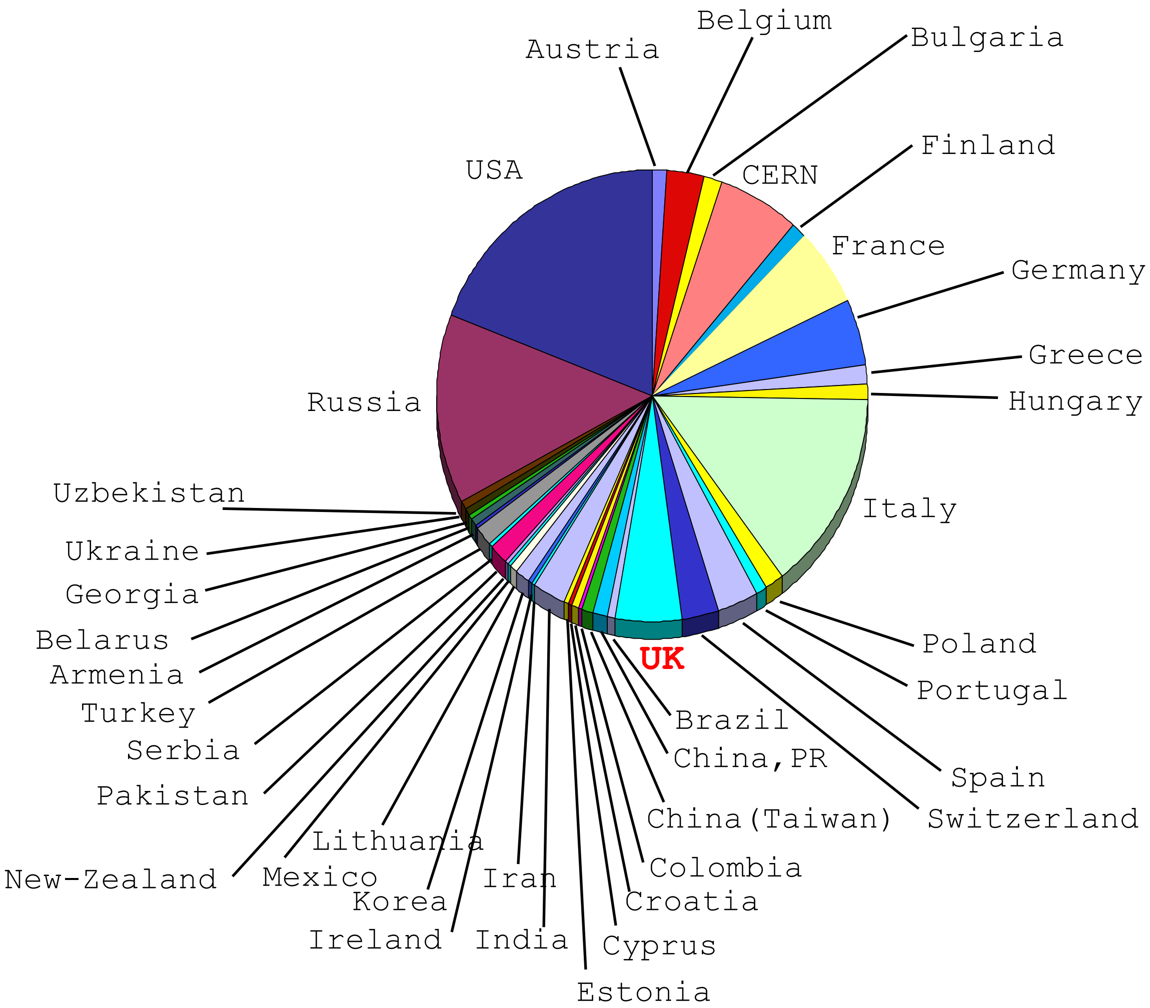
1984. Lausanne: Workshop on installing Large Hadron Collider in LEP tunnel
1987. CERN's long-range planning committee recommends Large Hadron Collider as right choice for CERN's future
1989. LEP Collider starts operation
1990. Aachen: ECFA LHC Workshop
1992. Evian les Bains: General Meeting on LHC Physics and Detectors
1993. Letters of Intent for LHC detectors submitted
1994. LHC approved
1995. CMS Technical Proposal **approved**
1998. LHC Construction begins
2000. **CMS assembly begins on the surface**; LEP Collider closes
2004. CMS experimental cavern completed
2008. **10-Sep: First circulating beams**
Oct/Nov: CMS: 4-week, 300M cosmic-ray, data-taking at 3.8T:"CRAFT"
2009. First proton-proton Collisions
2012. Reach design luminosity
2013. ?? Upgrade LHC Phase 1: increase design luminosity by factor 2-4
2017. ?? Upgrade LHC Phase 2: increase design luminosity by factor ~10

CMS Collaboration

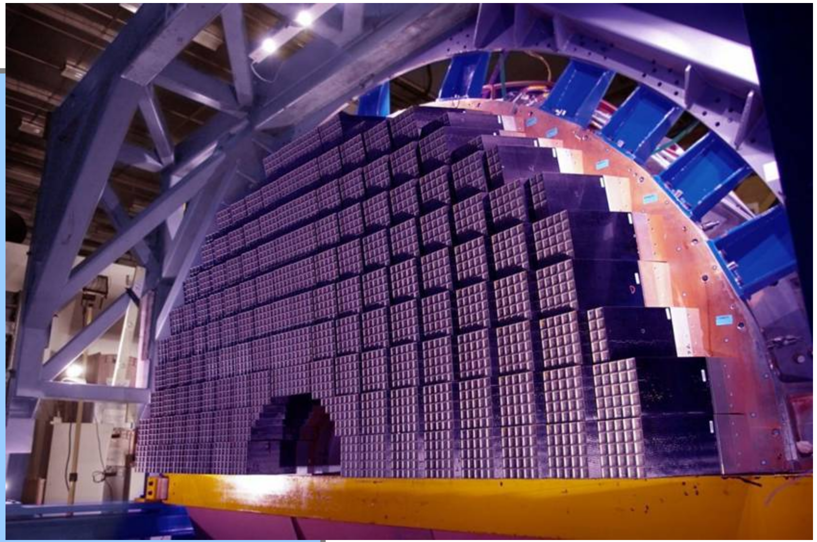
	Number of Laboratories
Member States	59
Non-Member States	67
USA	49
Total	**175**

	Nr Scientists & Engineers
Member States	1084
Non-Member States	503
USA	723
Total	**2310**

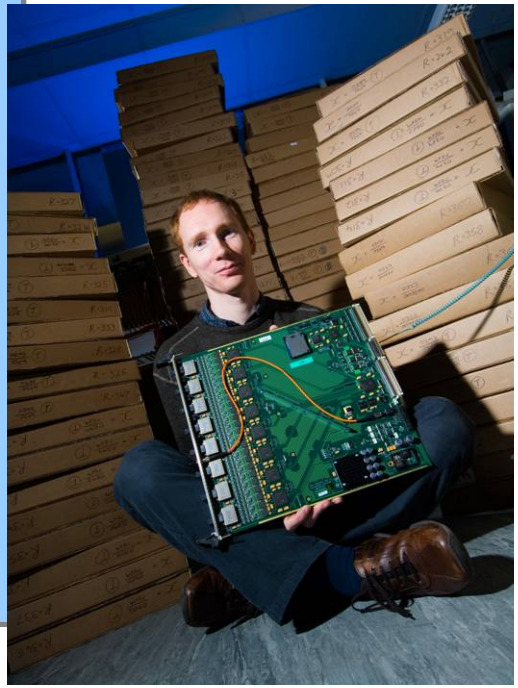


38 Countries
175 Institutions
2310 Scientists and Engineers

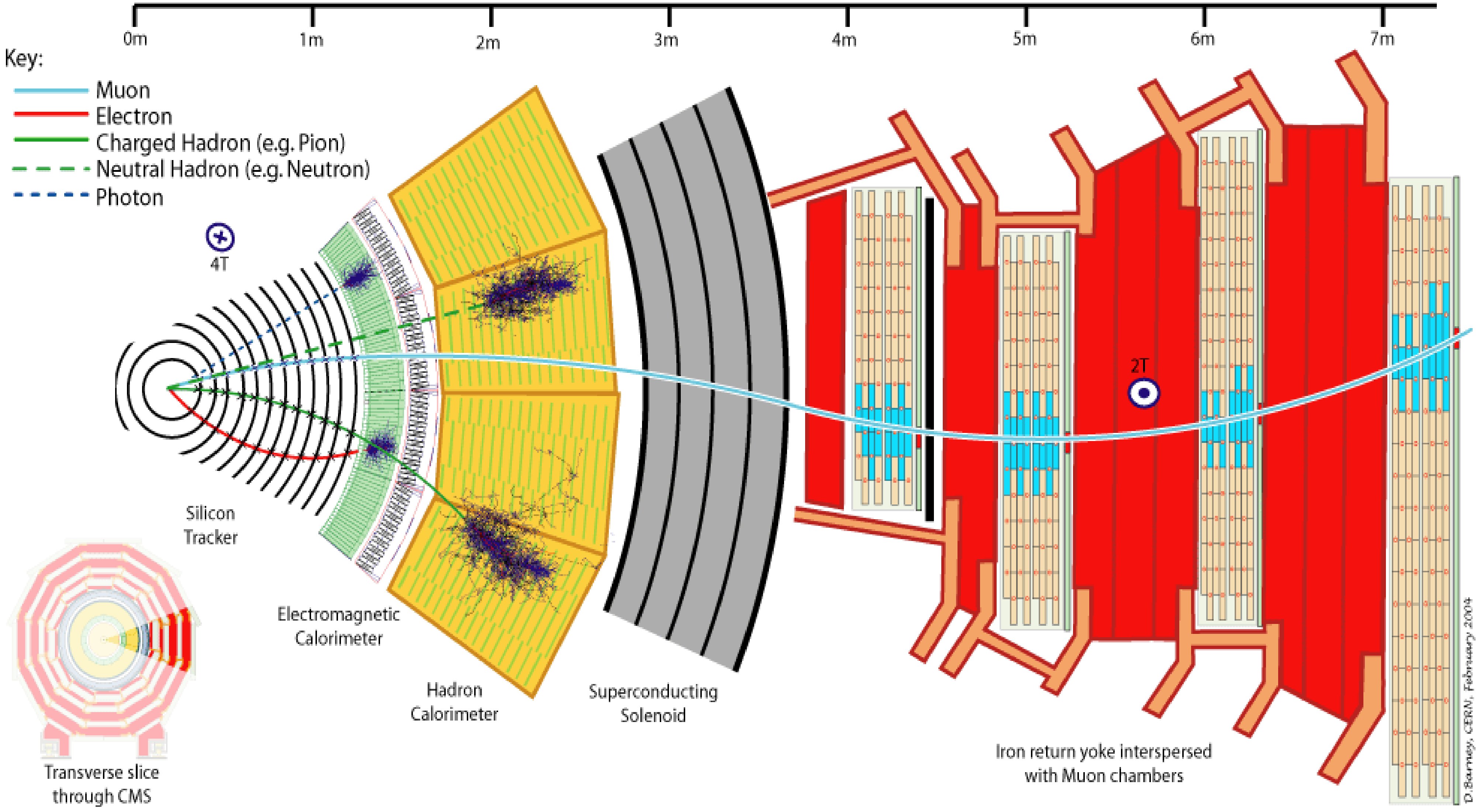
UK groups in CMS Detector



- UK is ~5% of CMS Collaboration
- Bristol University
  - ECAL & Global Calorimeter Trigger (GCT)
- Brunel University
  - Strip Tracker & ECAL
- Imperial College
  - Strip Tracker, ECAL & GCT
  - CMS Spokesperson (T.S.Virdee)
- Rutherford Appleton Laboratory
  - Strip Tracker & ECAL
  - Electronic & Mechanical Engineering Support
- Principal UK Strip Tracker involvement: Electronics & DAQ
- Principal UK ECAL involvement: Endcaps

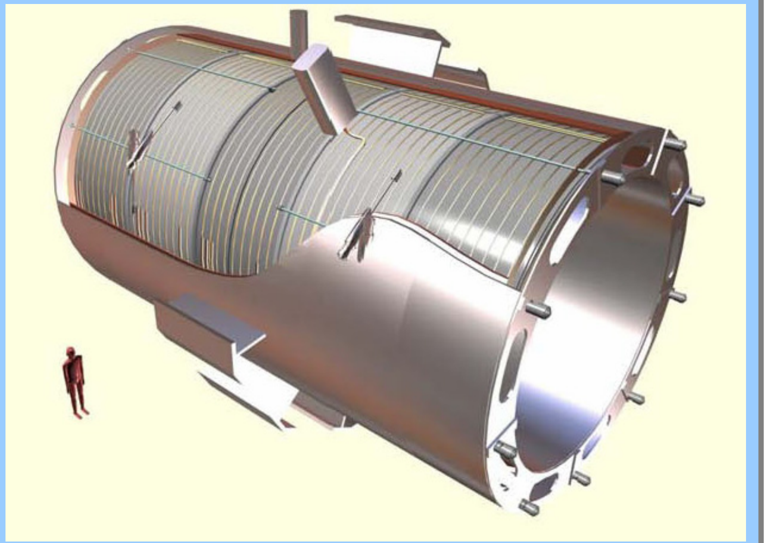


Detector Components



Magnet

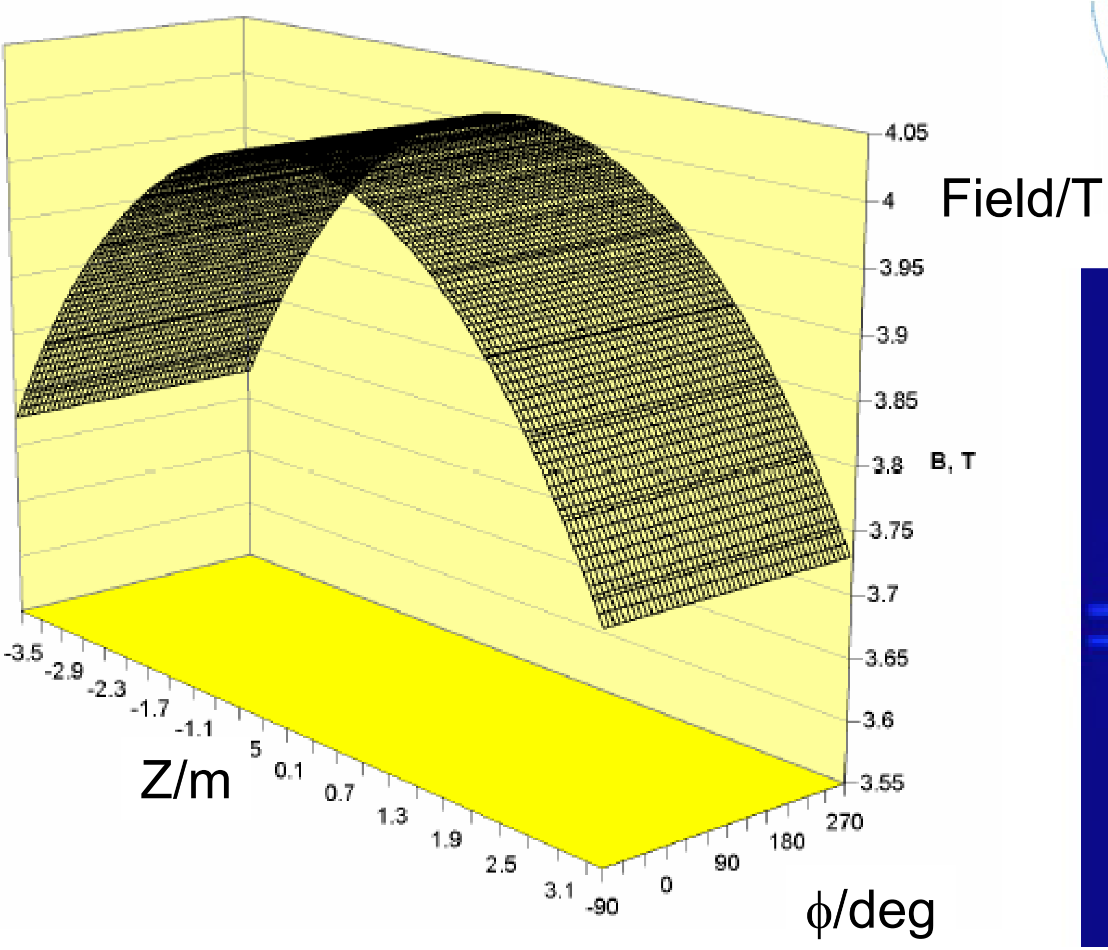
- Strong field (4T) with very large BL^2
- Central tracking and calorimetry inside solenoid
- World's largest SC solenoid
  - 12.5m long, 6.3m diameter
  - Many novel engineering aspects
  - NbTi conductor embedded in pure Al
  - Cold mass: 220 t
  - Nominal current: 19.5 kA
  - Stored energy at full field: 2.6 GJ

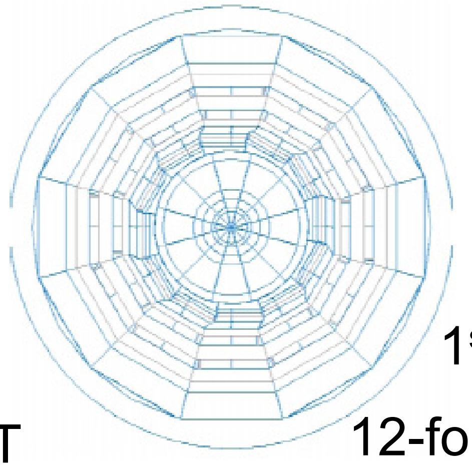


- Yoke
  - 22m long, 15m diameter, 10000 t of iron
  - 5 Barrel "wheels", 3+3 Endcap "disks"
- Operate at B=3.8T

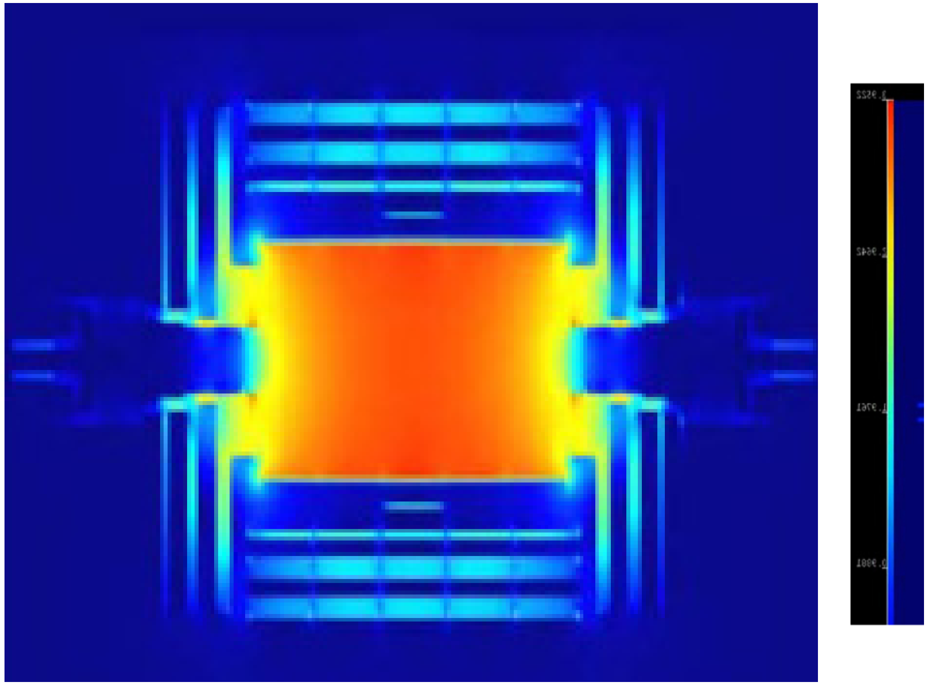
Field Mapping inside solenoid

Map on Surface, before TK & ECAL installed
Rotary arm field-mapper: **precision ~7 x 10^{-4}**
Raw magnetic flux density measurements:



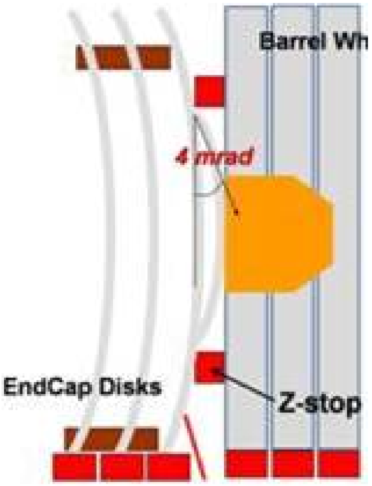


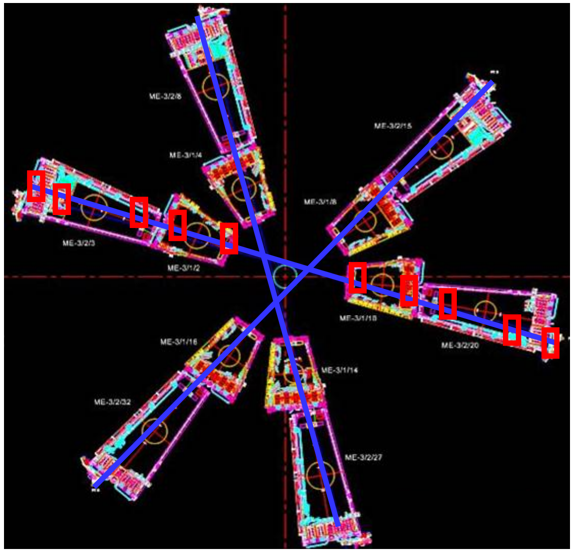
1st parameterisation:
12-fold symmetric model



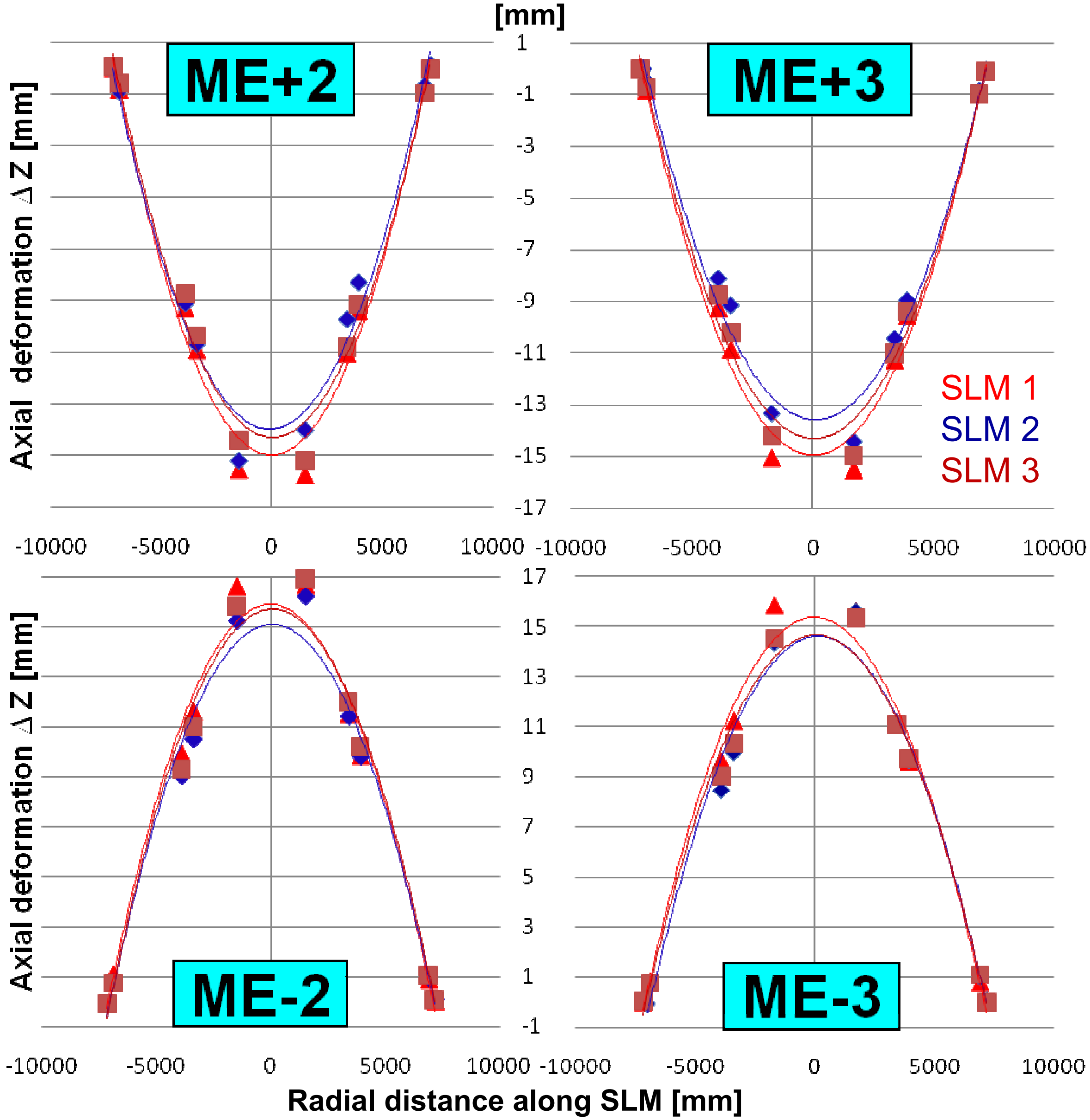
Map good to 20G inside Tracking volume

Measured Endcap Deformation at 3.8T





3 Straight Line Monitor (SLM) Laser Lines per Muon Endcap Station
10 optical CCD sensors per SLM

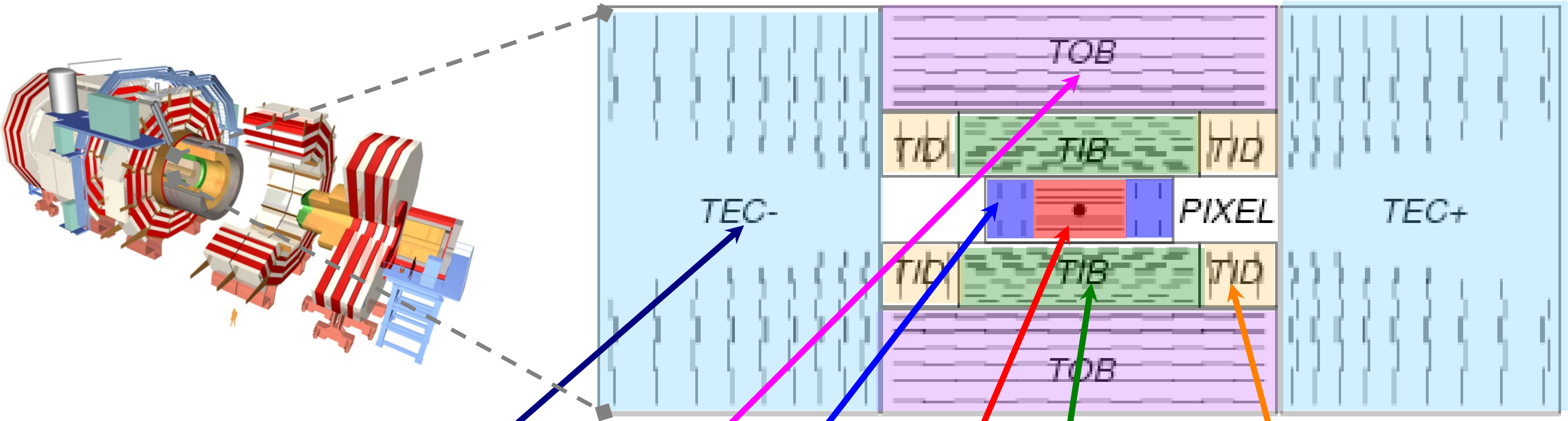


Measured ~15mm deformation agrees well with FEA prediction

STFC RAL

All-Silicon Tracker: Pixels & Strips

CMS



TEC - Tracker EndCaps
2x9 disks, 6400 modules

TID - Tracker Inner Disks
2x3 disks, 816 modules

TOB - Tracker Outer Barrel
6 layers, 5208 modules

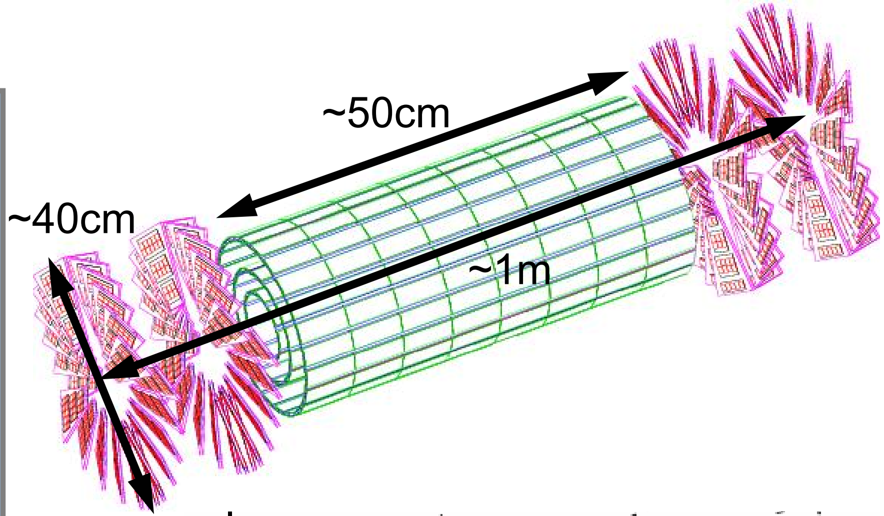
TIB - Tracker Inner Barrel
4 layers, 2724 modules

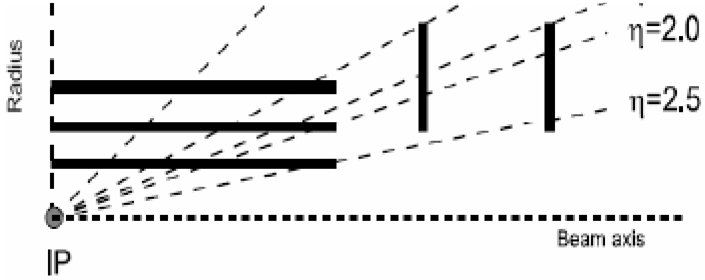
FPix - Forward Pixels
2x2 disks, 192 panels, 18Mpix

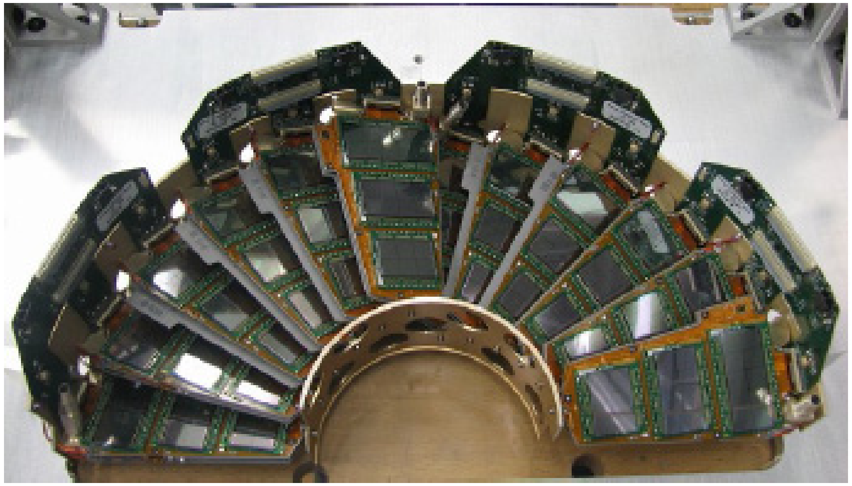
BPix - Barrel Pixels
3 layers, 768 modules, 48 Mpix

Pixel Tracker

- **Barrel Pixels**
  - 3 barrel layers at *r* of 4.3, 7.3, 10.4cm
  - 672 modules & 96 half modules
  - 11520 ROCs (48 million pixels)
- **Forward Pixels**
  - 2x2 disks at *z* = ±34.5 & ±46.5cm
  - Extend from 6-15 cm in radius
  - 20° turbine geometry
  - 672 modules in 96 blades
  - 4320 ROCs (18 million pixels)
- **Design allows for three high precision tracking points up to |η| of ~2.5**
- Active area: 0.78m² (BPIX), 0.28m² (FPIX)
- **Pixels 150μm x 100μm.**
  Hit resolution of 10μm (*r*-ϕ) & 20μm (z)
  expected due to charge sharing & B=4T
- **66M readout channels**

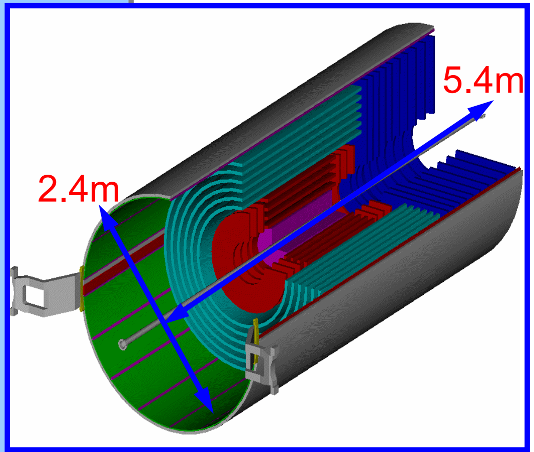


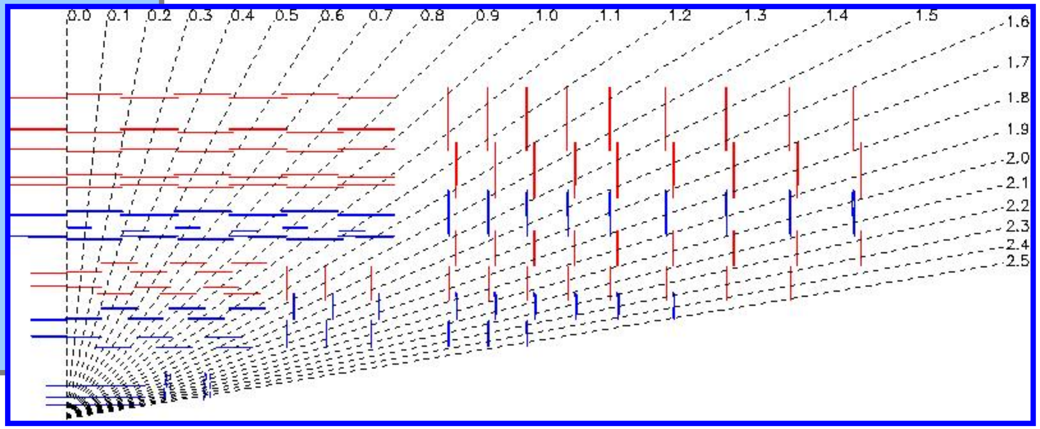




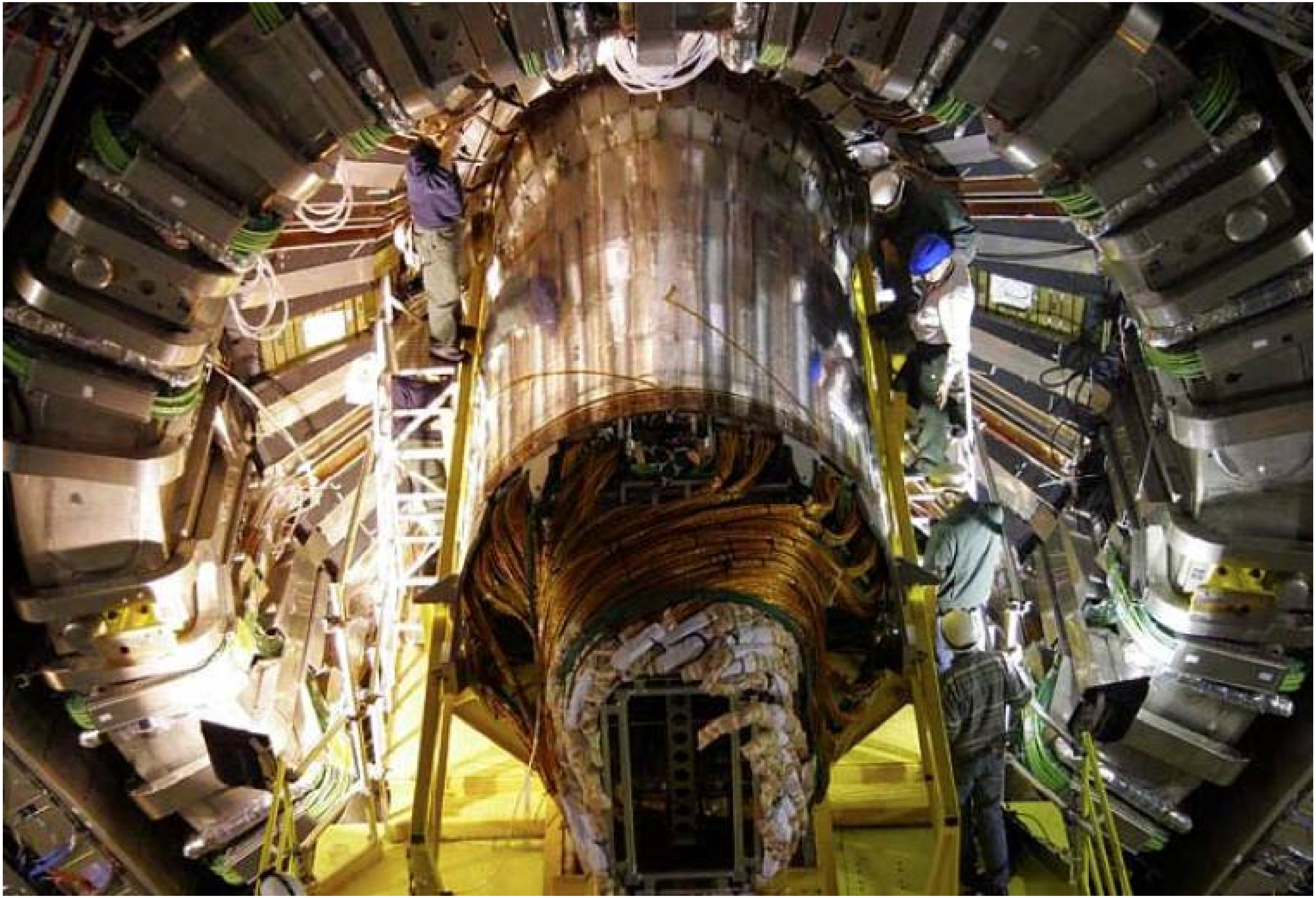
Silicon Strip Tracker

- **TIB**
  - 4 layers at *r* of 25-50cm. Pitch 81/118μm
  - Hit resolution 23-34μm in *r-ϕ*
- **TOB**
  - 6 layers at *r* of 50-110cm. Pitch 118/183μm
  - Hit resolution 35-52μm in *r-ϕ*
- **1st 2 layers of TIB/TOB: 100mrad stereo angle**
- **TID**
  - 2x3 disks at |*z*| of 70-115cm
  - Pitch 97/128/143μm
- **TEC**
  - 2x9 disks at |*z*| of 120-280cm
  - Pitch 96/126/128/143/158/183μm
- **1st 2 rings of TID, Rings 1,2,5 of TEC: stereo**
- **10 layer coverage in |η| to ~2.4**
- **Active area: ~210 m² Silicon**
- 75k APV front-end chips
- **9.6M readout channels**

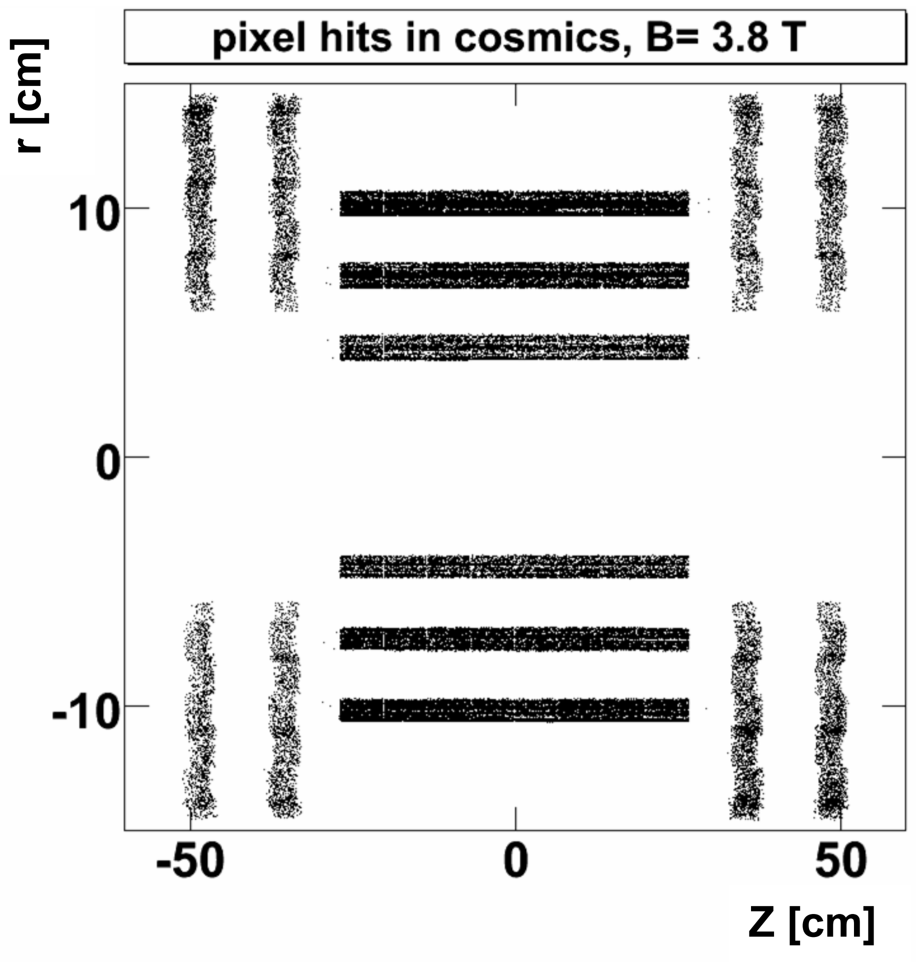




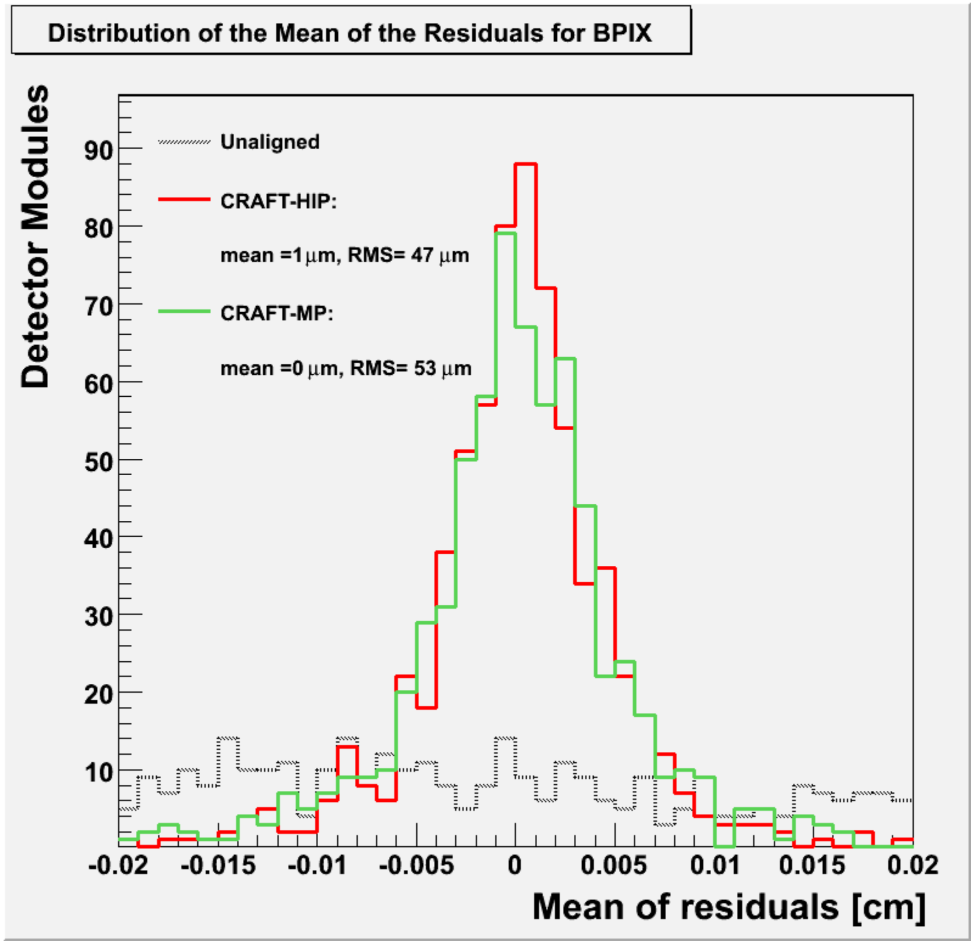
Strip Tracker insertion



Pixel commissioning in CRAFT

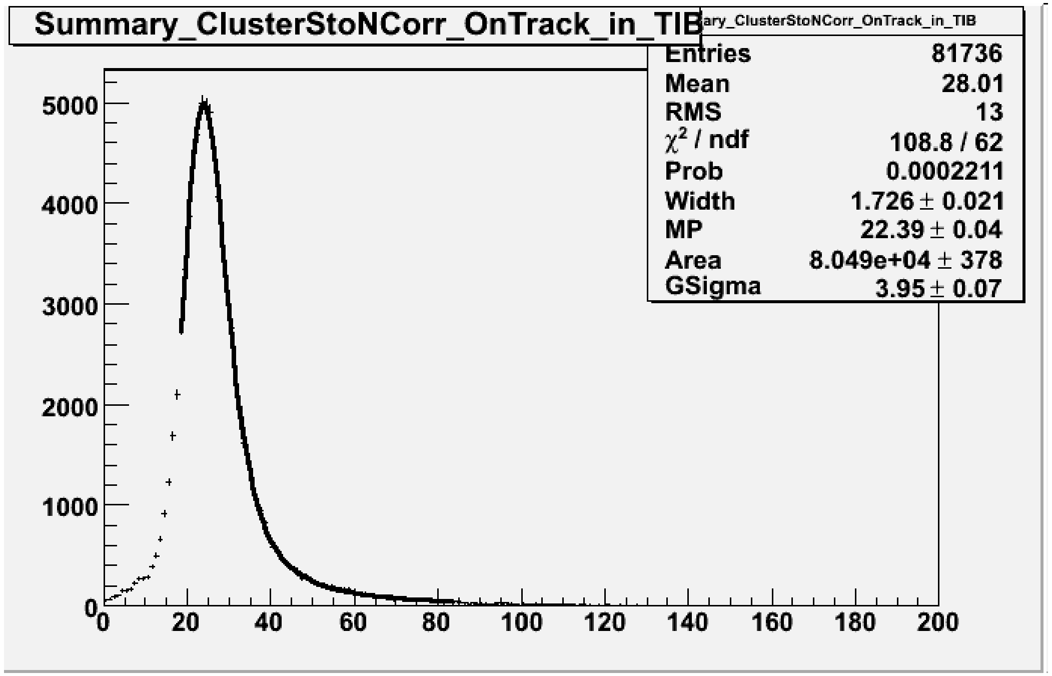


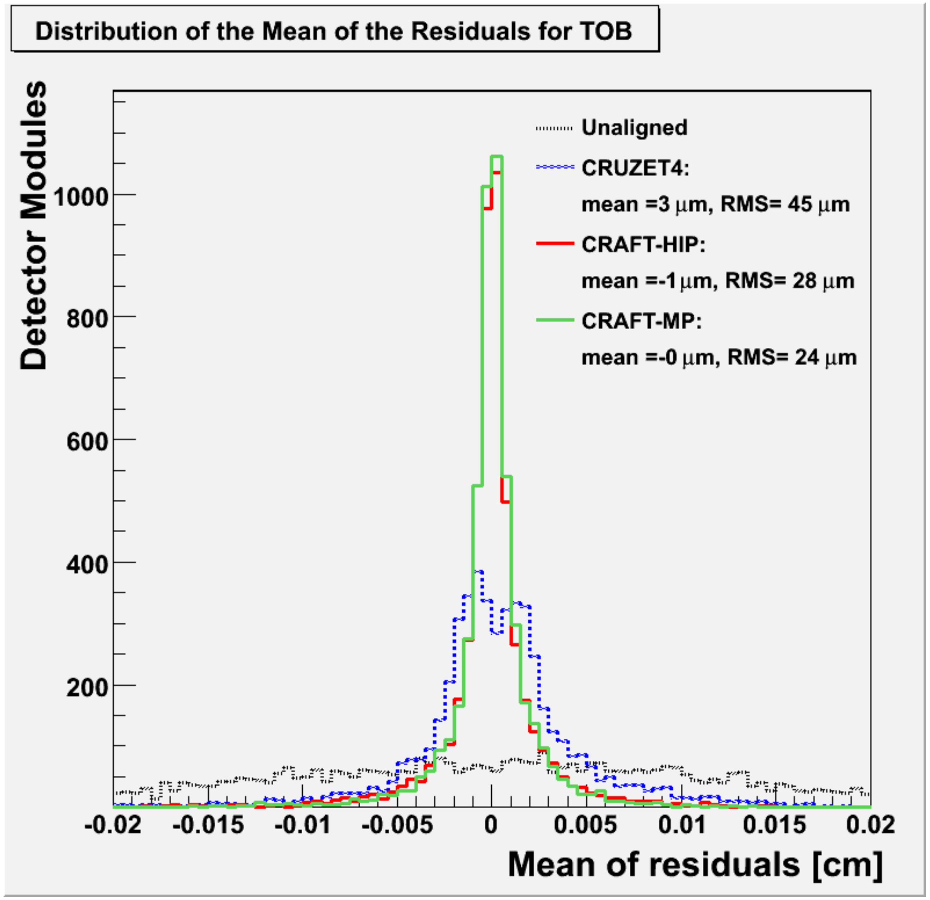
Pixel occupancy map



Barrel aligned at module level
(200-300 hits, 89% aligned)

SST commissioning in CRAFT





TOB thick sensors : S/N = 32

TIB/TID thin sensors : S/N = 27/25

TEC (mixed thickness) : S/N = 30

Conclude: Signal/Noise as expected

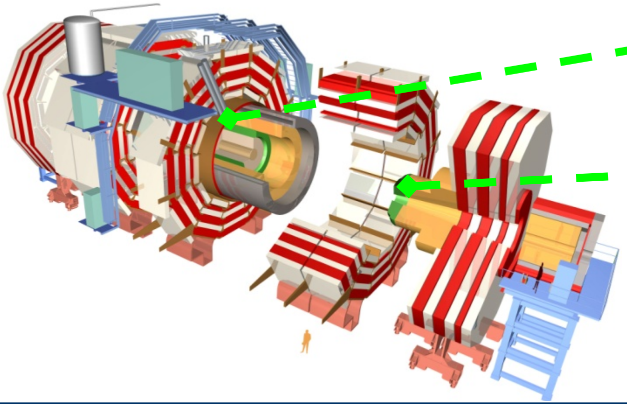
TIB aligned: rms= 26-40μm

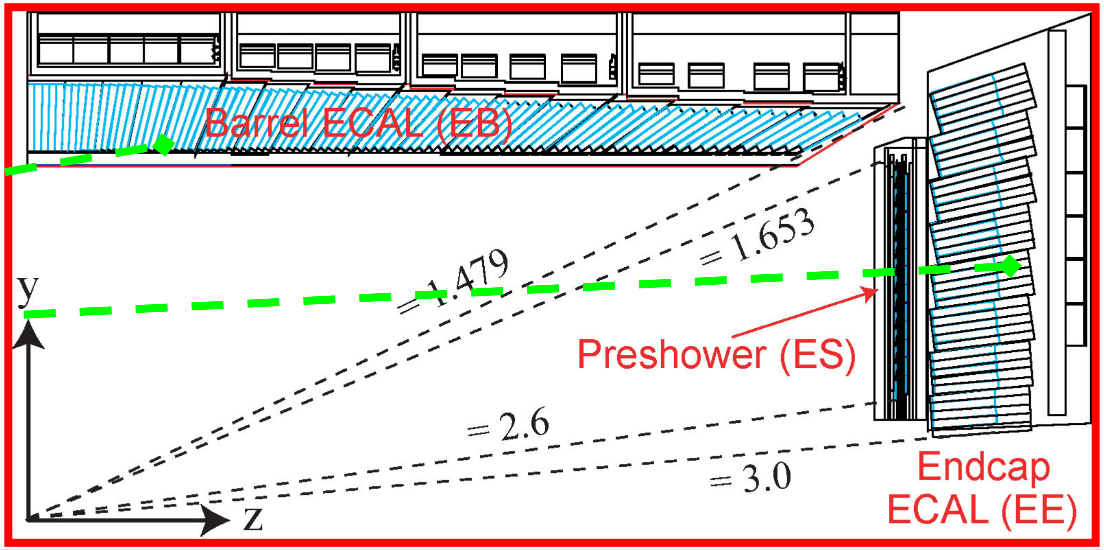
TOB aligned: rms= 24-28μm

ECAL

- Hermetic, homogeneous $PbWO_4$ calorimeter
  - ➢ Good energy resolution
- Why use $PbWO_4$ scintillating crystals?
  - ❖ Short radiation (X_0 = 0.89cm) & Moliere (2.2cm) length
  - ➢ Compact, fine granularity
  - ❖ Fast and radiation hard
  - ❖ Low light yield: compensate with high gain photodetectors which work in magnetic field
    - ➢ Avalanche Photodiodes (APDs) in barrel
    - ➢ Vacuum Phototriodes (VPTs) in endcaps

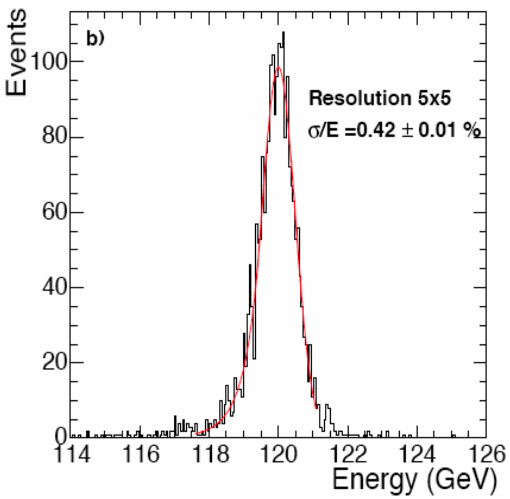
Extensive R&D needed:
~84 t of $PbWO_4$ (& APDs, VPTs)
[cf ~tens of g of $PbWO_4$ before CMS]



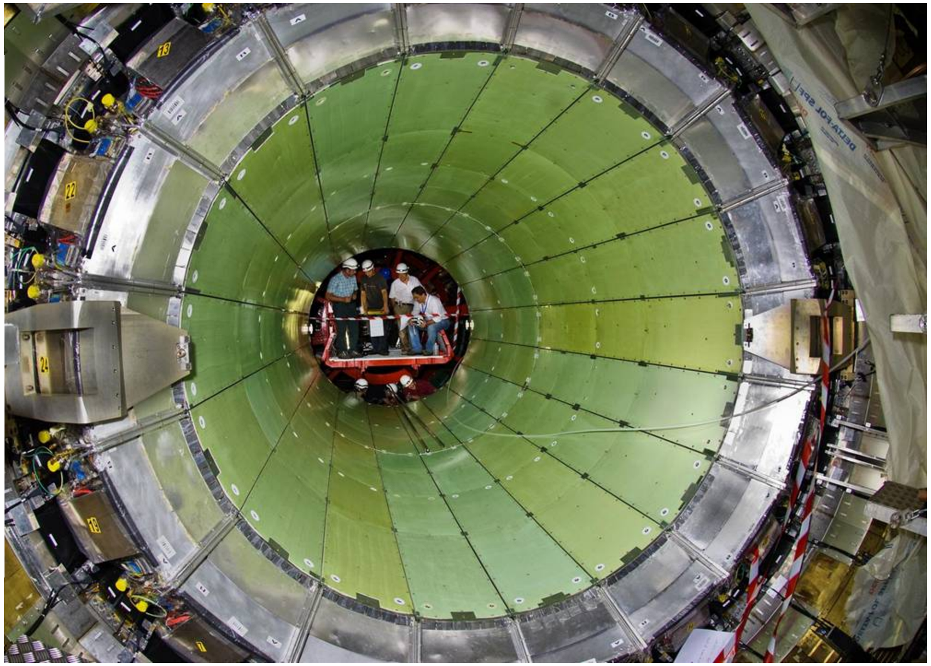


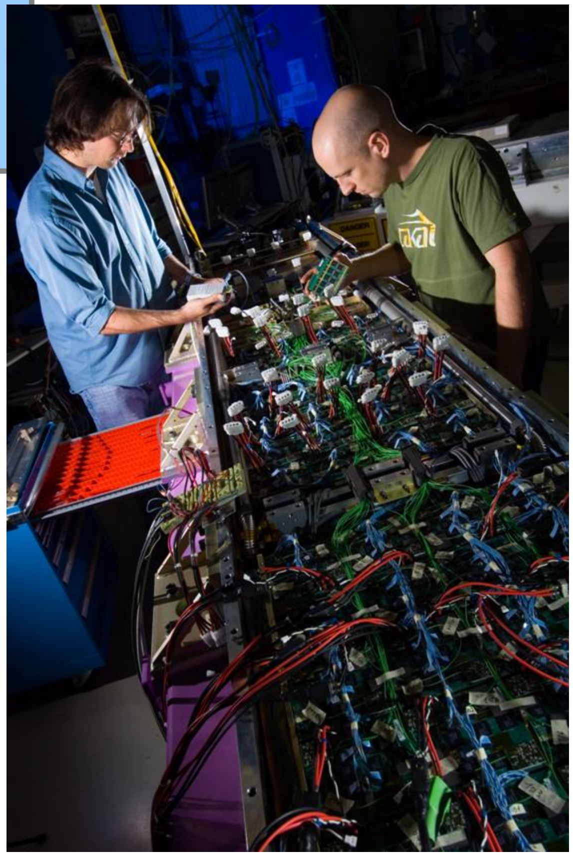
ECAL Barrel

- Barrel: 61200 crystals
  - 0 < |η| < 1.479, inner radius 129cm
  - 36 identical "supermodules"
  - Crystal covers 1º in η & ϕ
    - Front face 22x22mm^2, length = 230mm → 25.8 X_0
    - Quasi-projective geometry
    - All channels pre-calibrated to 1.5% (cosmic rays)



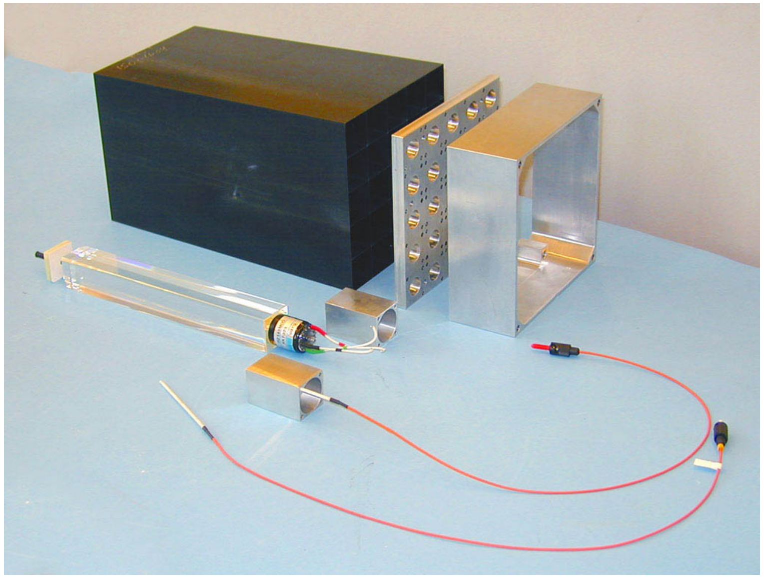
σ(E)/E = 0.42±0.01%



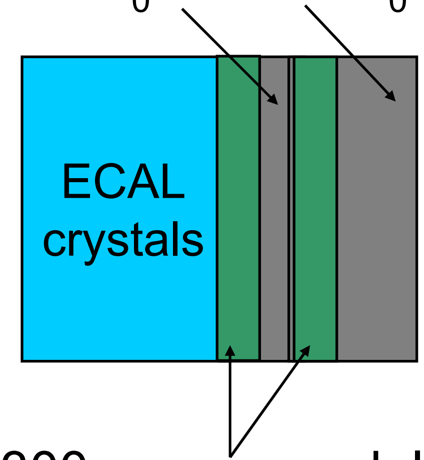


ECAL Endcaps

- Endcaps: 2 x 7324 crystals
  - 1.479 < $|\eta|$ < 3.0, $|z|$ ~314cm
  - 2 "Dees" per endcap
  - Crystals arranged in *xy* grid
    - Front face 28.6x28.6mm^2
    - Length = 220mm $\rightarrow$ 24.7 X_0
    - Quasi-projective geometry



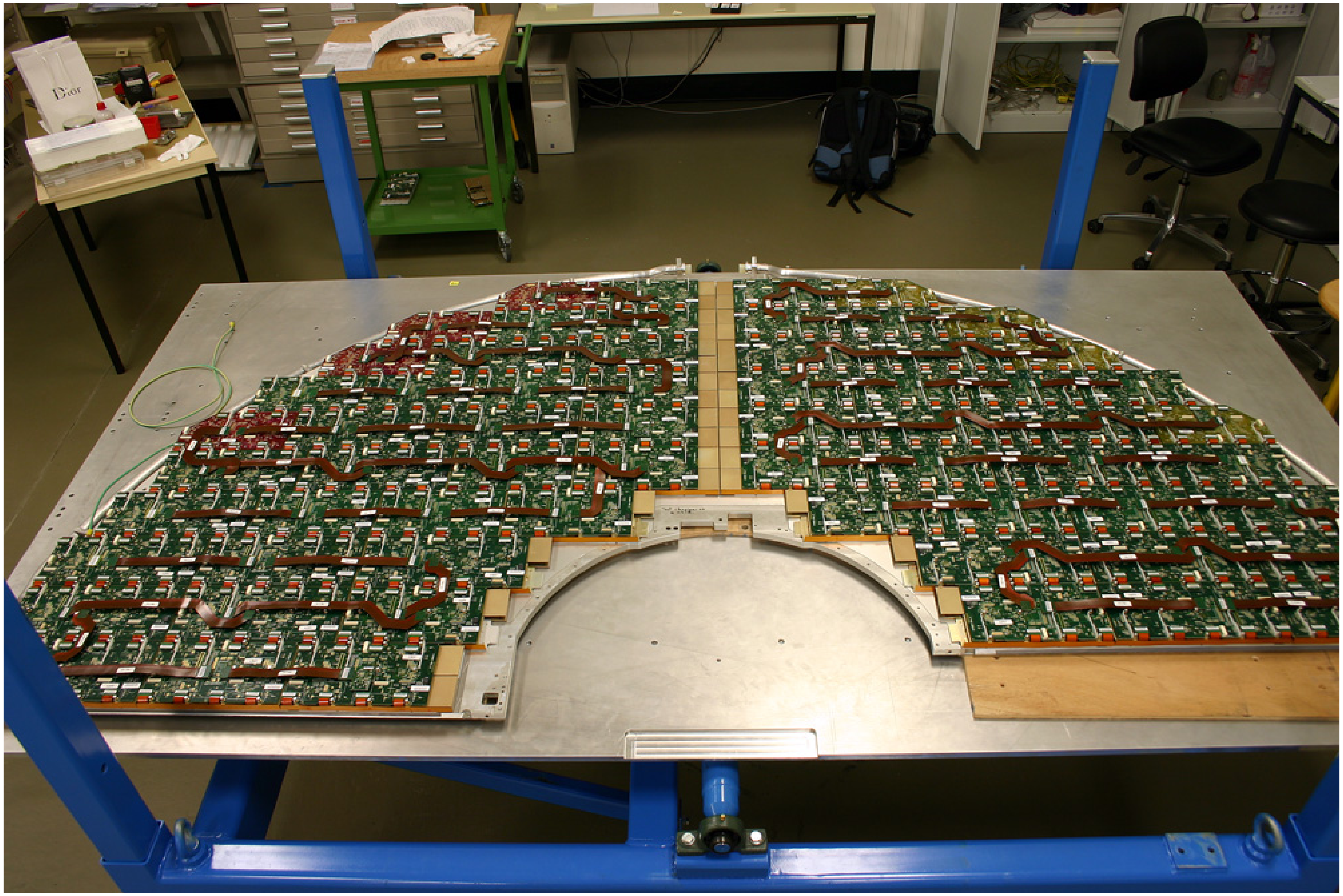
ECAL Endcap Preshower



4300 sensor modules
$20 m^2$ Silicon
138k channels

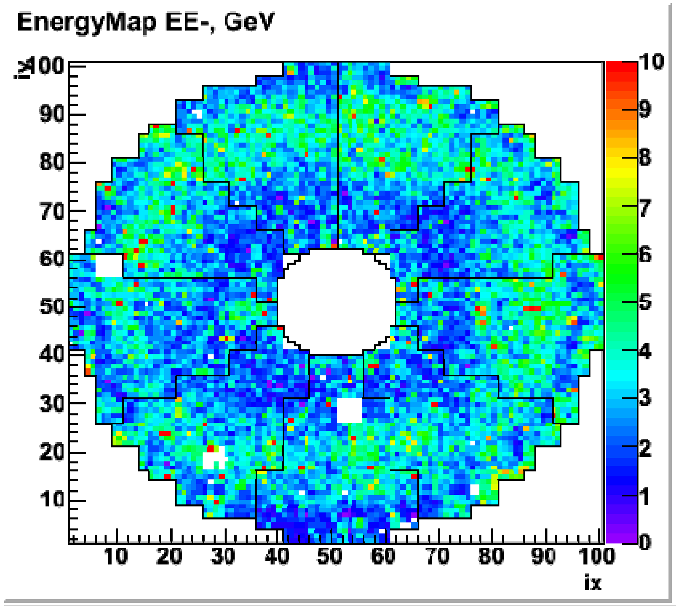
Final plane complete this month

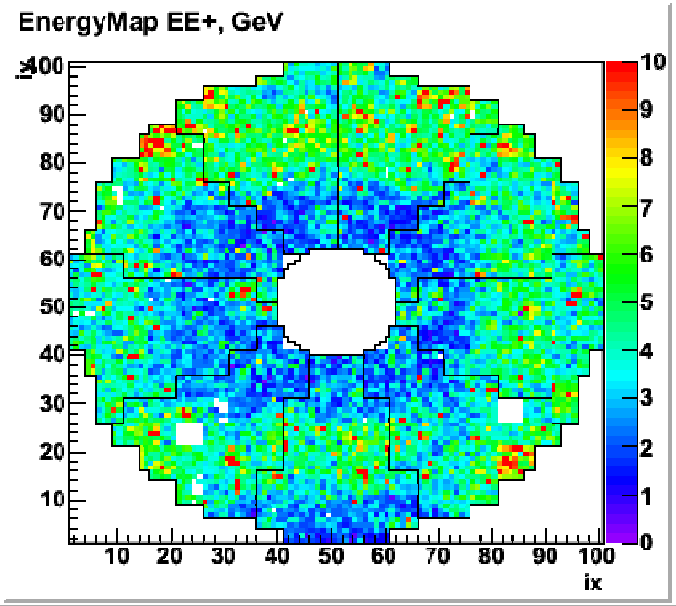
Both endcaps installed & checked-out by Easter 2009

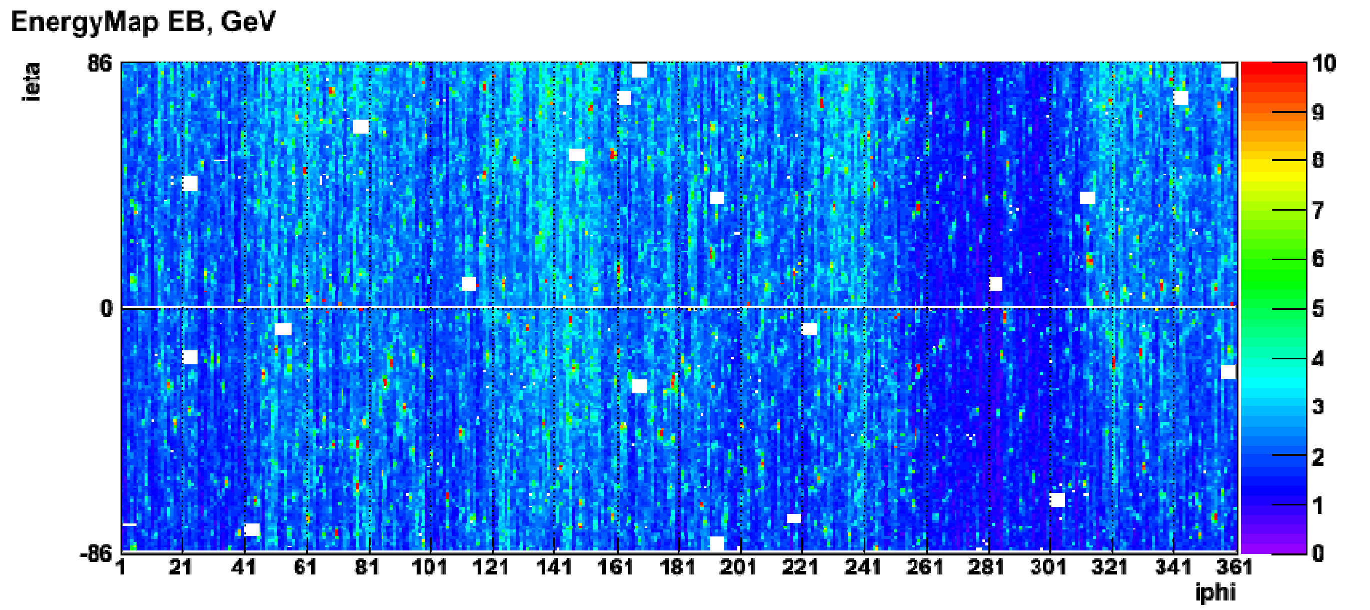


- **Identifies π^0 over $1.653 < |\eta| < 2.6$**
- **Improves purity of electron ID**
- **High granularity $\rightarrow$ improved electron & γ position determination**

ECAL Energy in Beam Splash Events







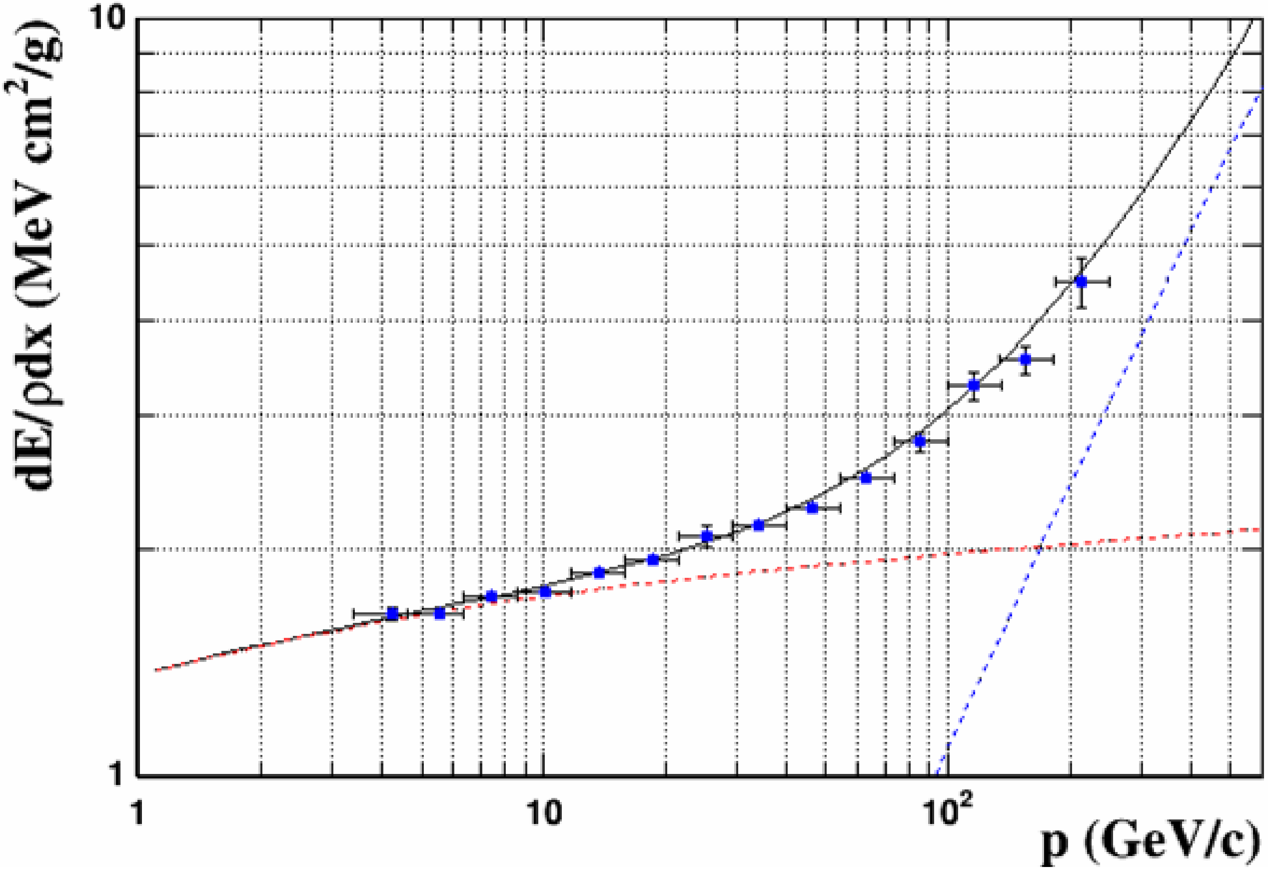
Energy Maps shown.

Beam splash events also used to determine channel timings

White areas to be recovered in 2008/09 shutdown

Calibrations not yet applied in Endcaps (lower response VPTs nearer beam pipe)

ECAL Stopping Power (CRAFT cosmics)



Stopping power of cosmic rays traversing ECAL, as function of measured momentum (Tracker)

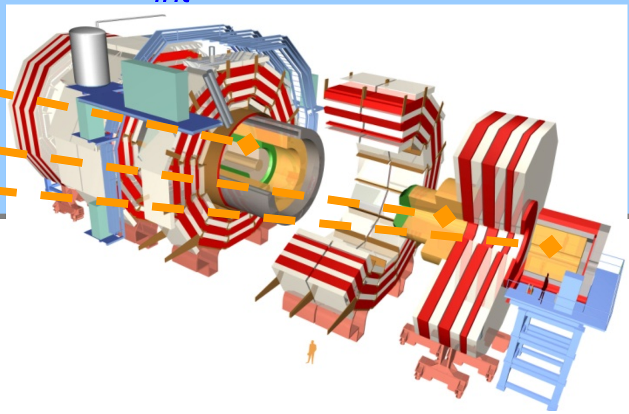
Dashed lines: contributions from collision loss (red) and bremsstrahlung (blue)

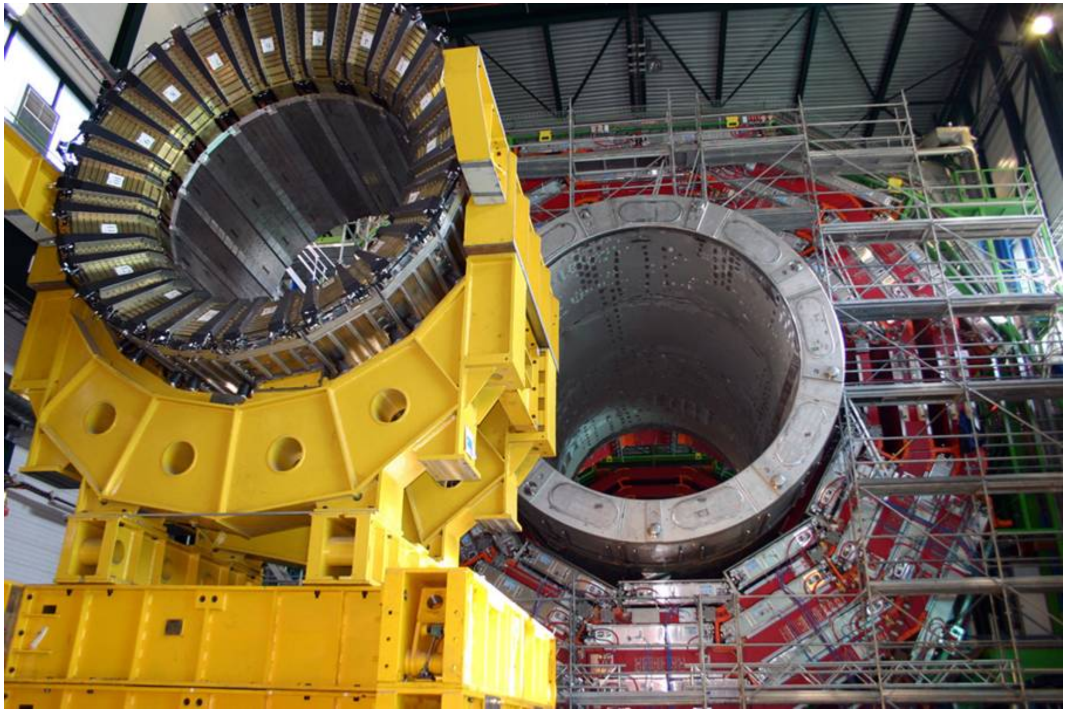
Errors: bin-width (x) & statistical (y)

Shows correctness of Tracker momentum scale & ECAL calibration from test beams

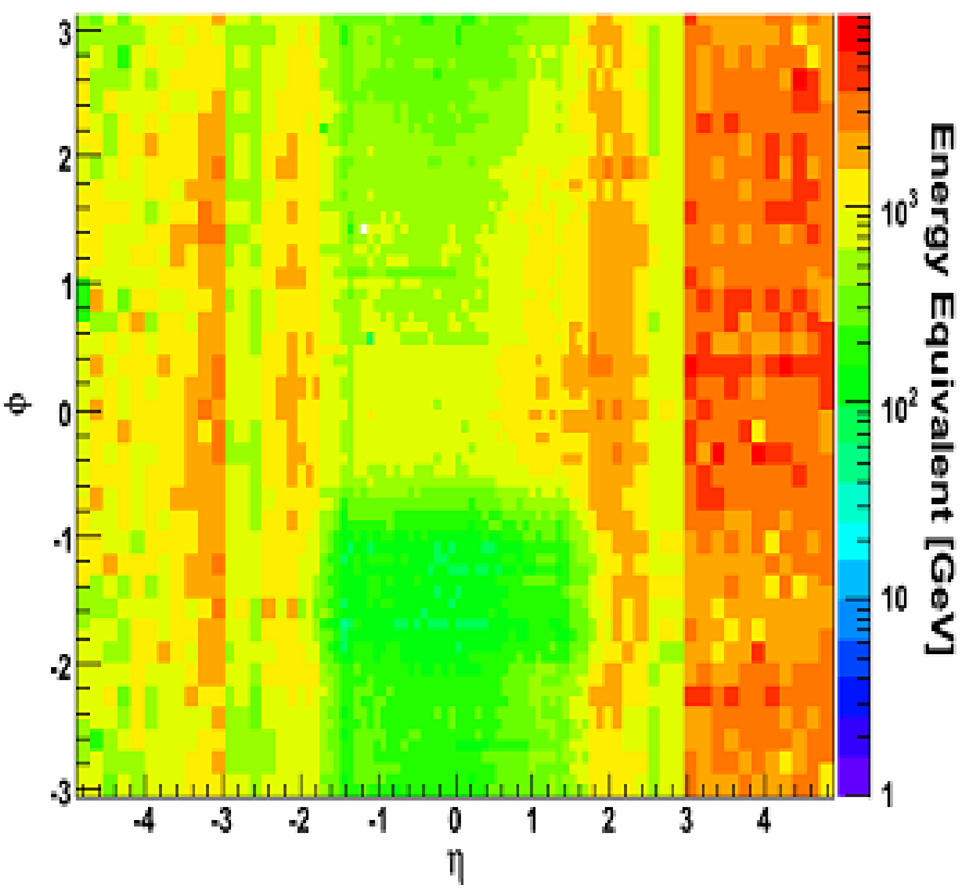
HCAL

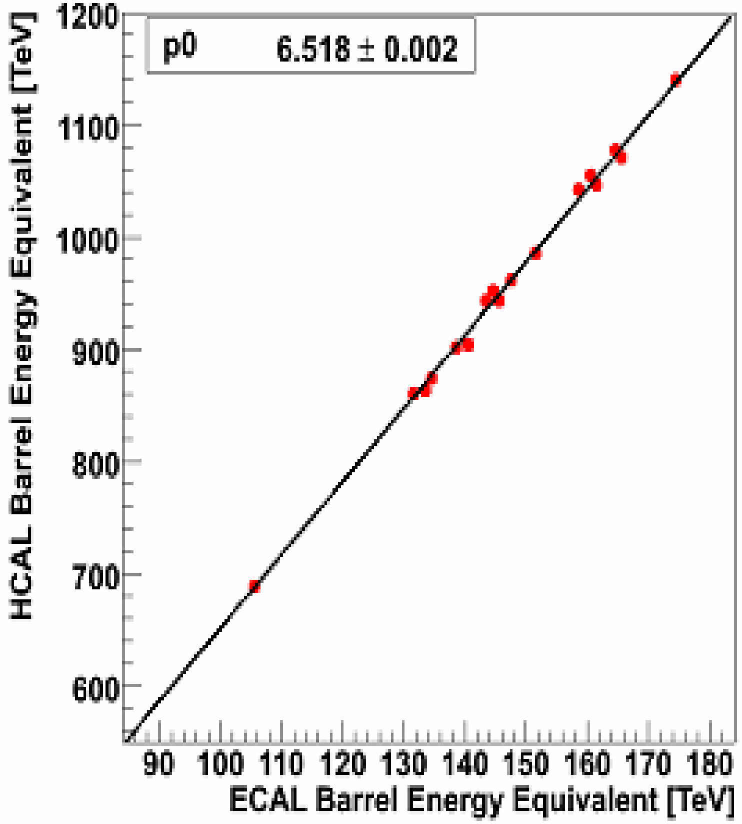
- Hermetic hadron calorimeter
  - Sampling type, brass/scintillator layers (HB, HO, HE). Hybrid Photo-Diodes
  - Barrel: $|\eta| < 1.4$, inside solenoid, single longitudinal sampling
  - Outer: barrel tail-catcher for $|\eta| < 1.26$ → $>11\lambda_{int}$ in depth
  - Endcap: $1.3 \leq |\eta| < 3.0$
  - Forward: $3.0 \leq |\eta| < 5.0$: Iron/quartz-fibre
  - σ/E (test beam): $\sim 97\%/\sqrt{E} \oplus 8\%$





HCAL & ECAL in Beam Splash Events



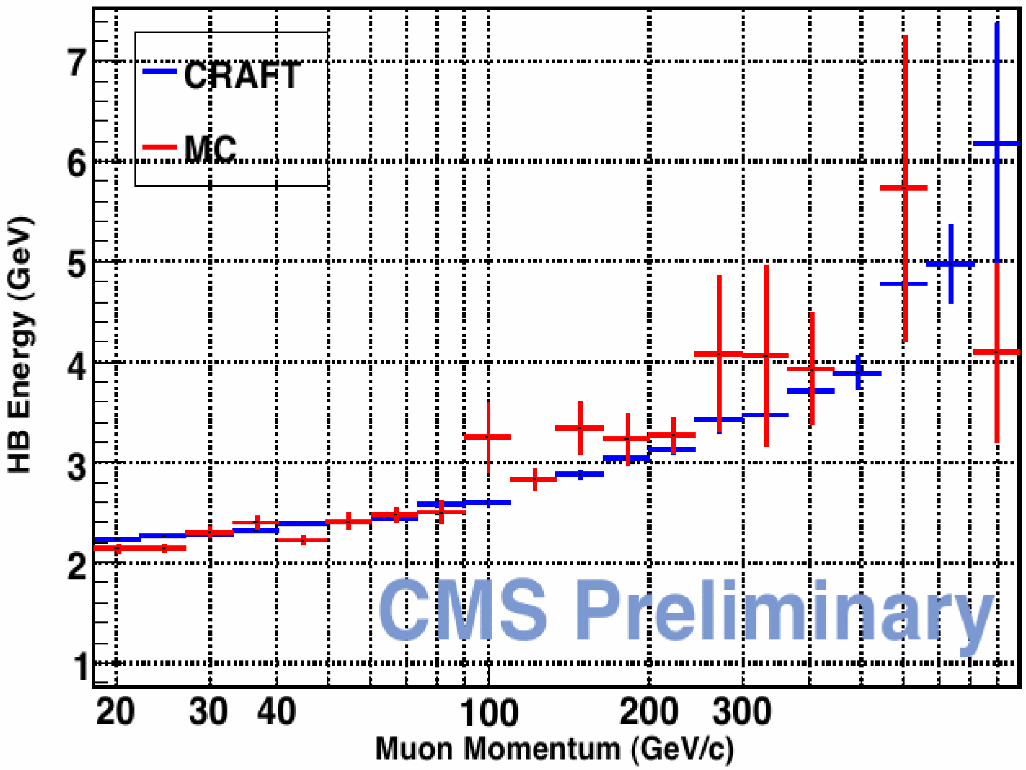


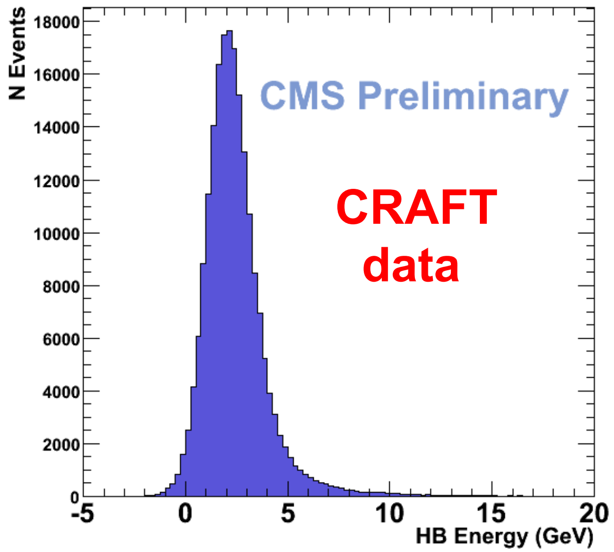
ECAL & HCAL energy deposits highly correlated

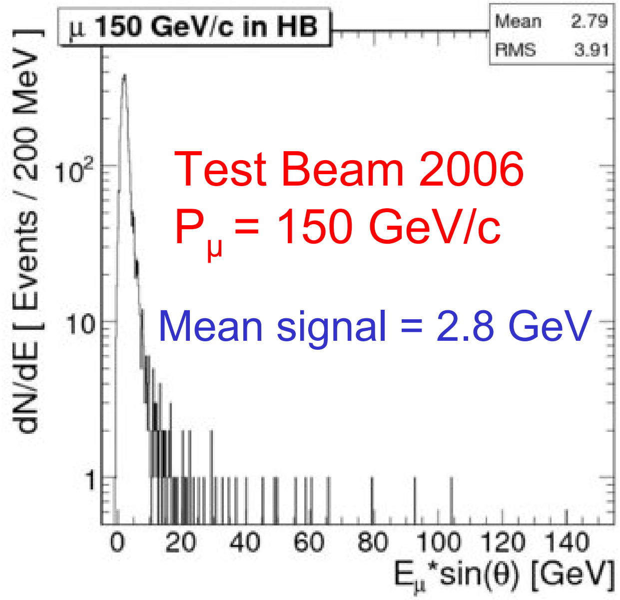
HCAL commissioning in CRAFT

Event selection:
Muon track matching in DT and Tracker
20 GeV/c < P_μ < 1000 GeV/c
CRAFT: 200 k events
MC: 15 k events

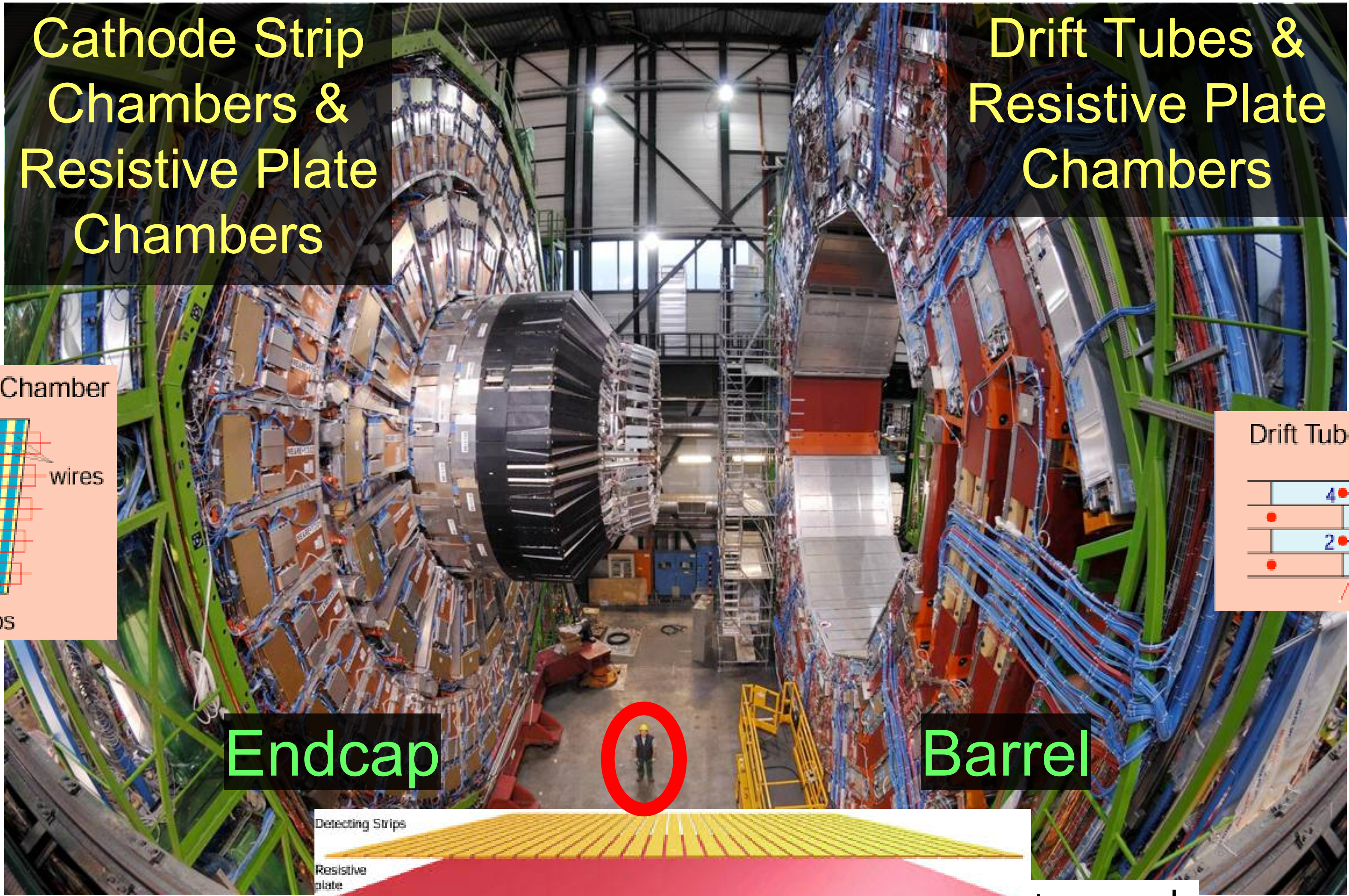
HB energy: signal from HB towers corrected for muon path length in HB



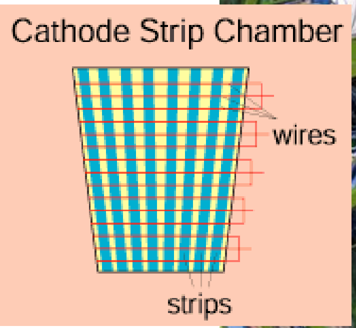




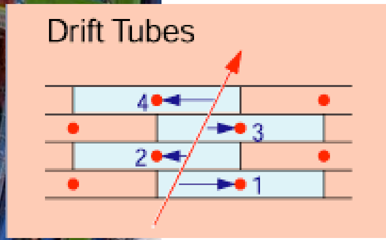
Muon System

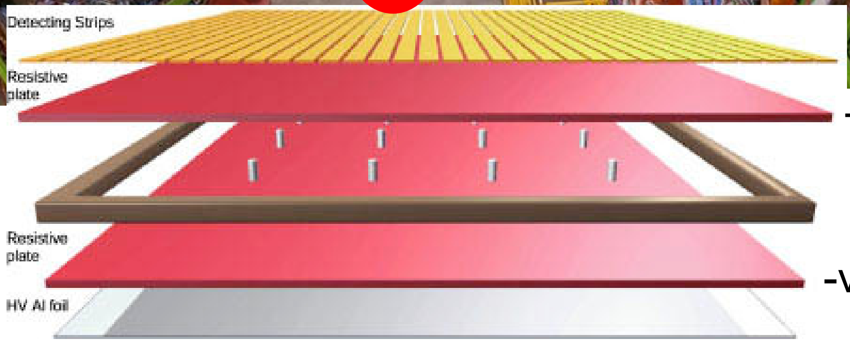


Wires = anodes



Strips = cathodes





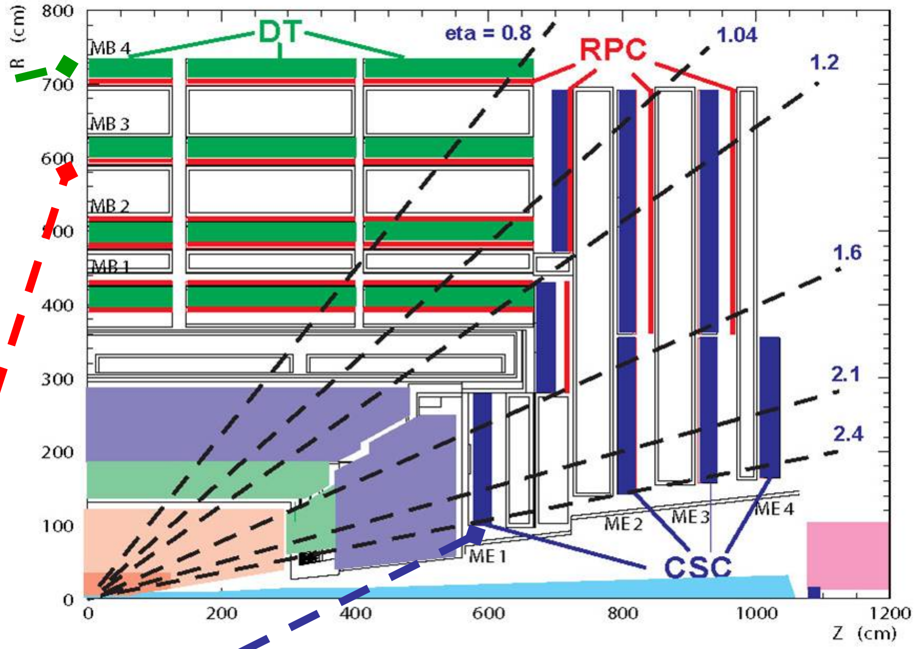
+ve anode

-ve cathode

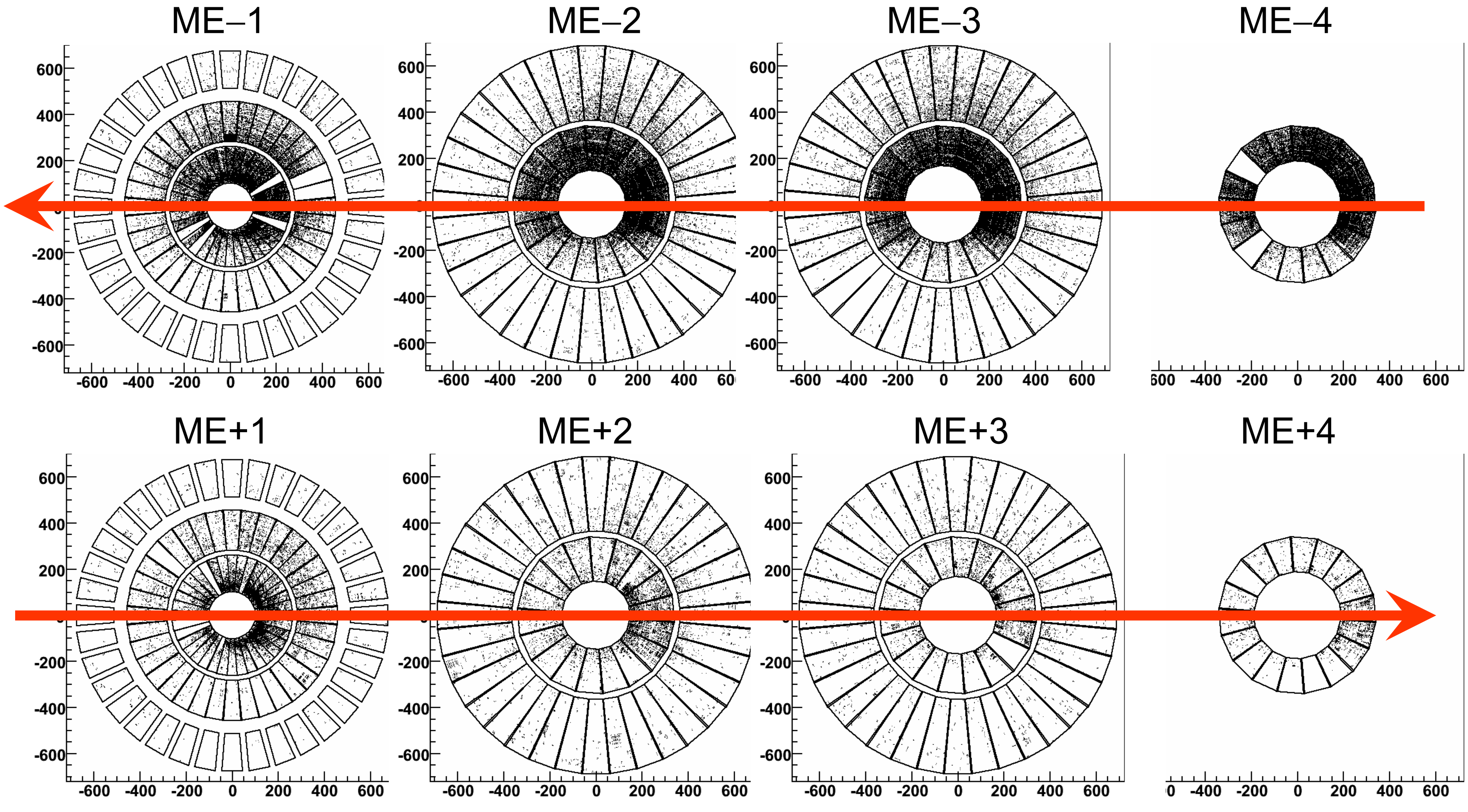
Resistive Plate Chambers

Muon System

- Two independent & complementary systems
- At least 4 layers
- Drift Tube Chambers (Barrel)
  - ❖ 250 chambers, 180k channels
  - ❖ Good muon resolution: $r\text{-}\phi$ ~100μm, Z~150μm, angle ~1mrad
  - ❖ Slower response (up to 400 ns)
  - ❖ Economical for use in low rate region
- Resistive Plate Chambers (Barrel & Endcap)
  - ❖ 1020 chambers
  - ❖ Muon spatial resolution: $r\text{-}\phi$ ~1.5 cm
  - ❖ Fast response, <3ns timing resolution
  - ❖ Relatively inexpensive
  - ➢ Dedicated to first level trigger
- Cathode Strip Chambers (Endcaps)
  - ❖ 468 chambers, 450k channels
  - ❖ Good muon spatial resolution: $r\text{-}\phi$ ~75–150μm, <2mm at trigger level
  - ❖ Close wire spacing → fast response 4ns timing resolution
  - ➢ Good for high rates

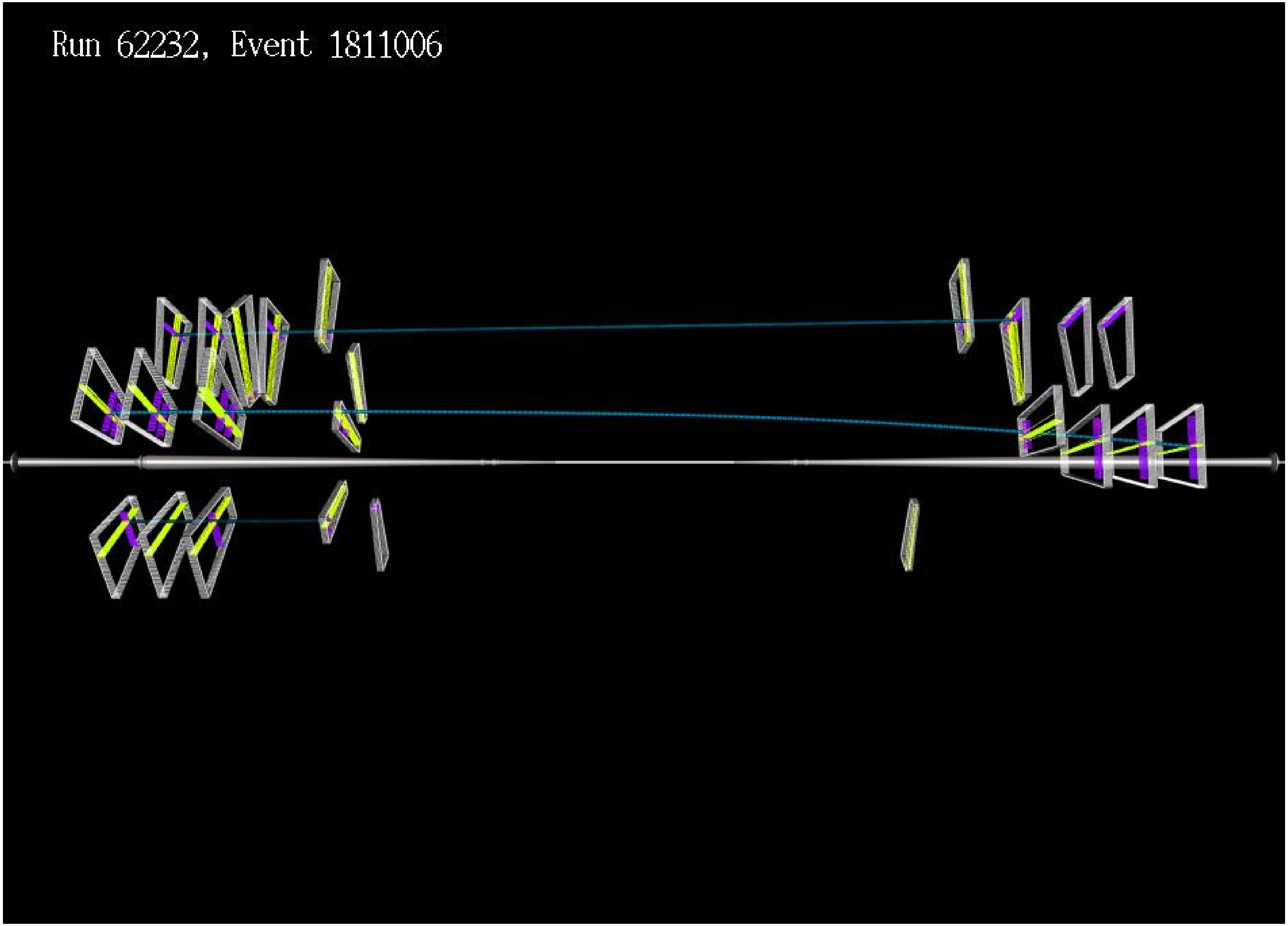


Beam Halo Hit Distribution in CSCs



Arrow indicates sequence beam traversed endcap disks:
Iron progressively absorbs halo muons…

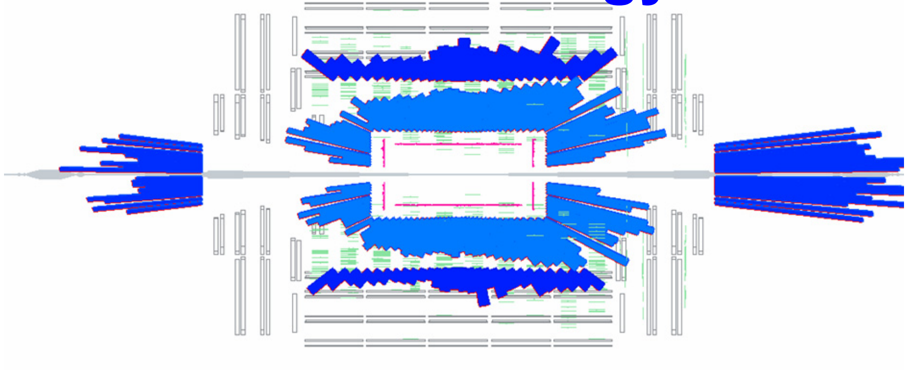
Beam Halo Muons Reconstructed in CSCs



DTs, HCAL & ECAL in Beam Splash Events

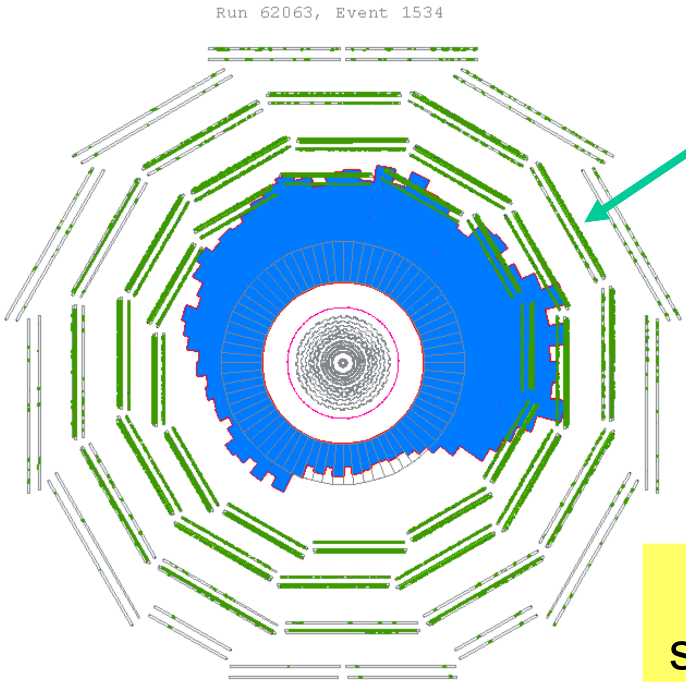
~2x10^9 protons on collimator ~150m upstream of CMS

HCAL energy

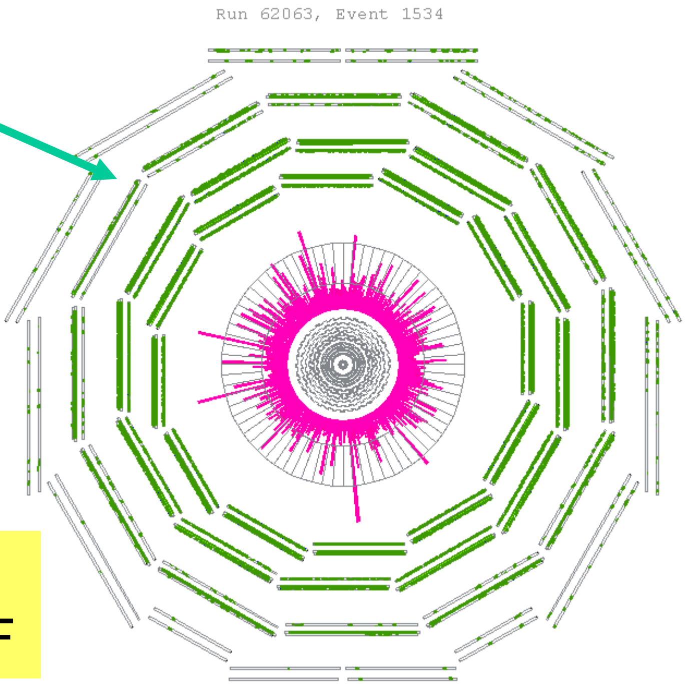


ECAL energy

Debris

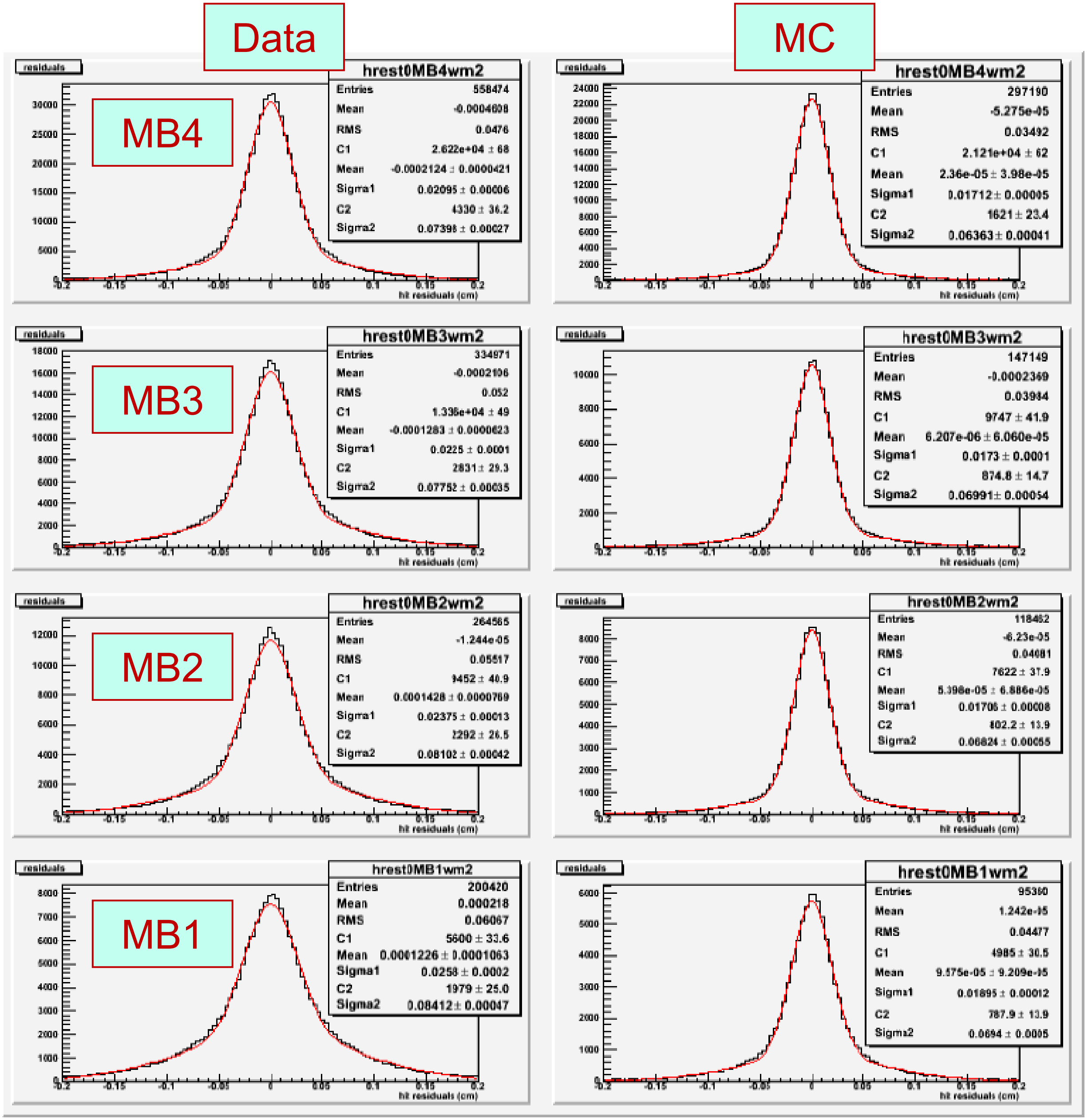


DT muon chamber hits



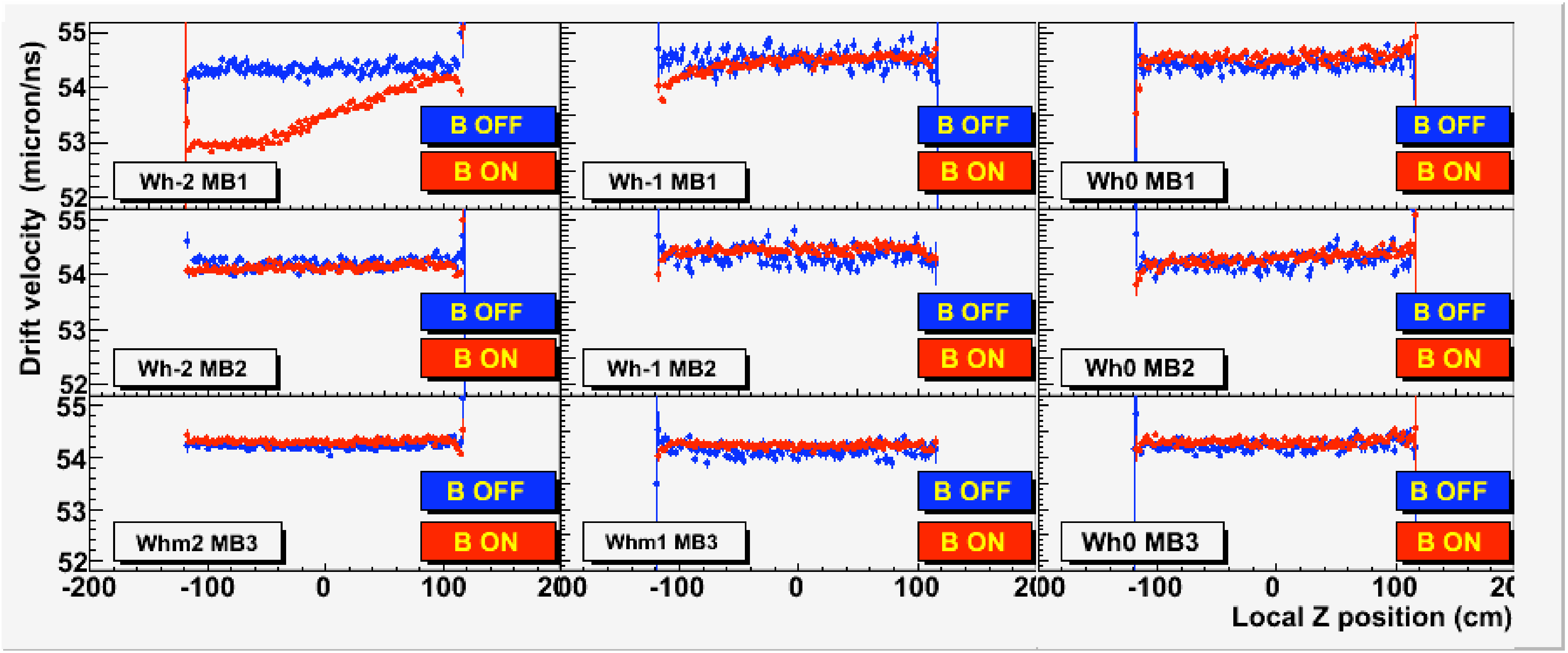
Inner tracking systems kept OFF

Muon DTs at CRAFT



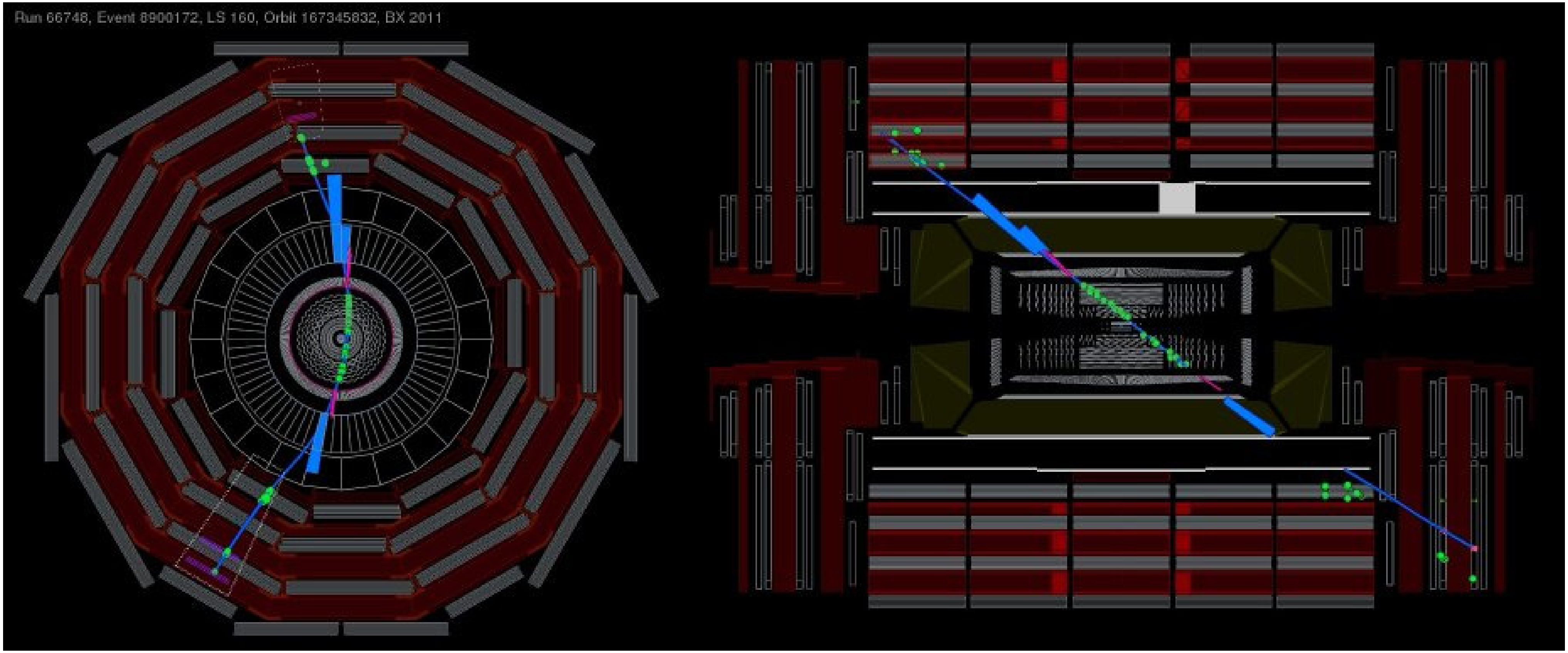
- **Chamber residuals:**
  - Reasonable agreement between data & MC after fitting arrival time of cosmic muon
  - Sigma ~200-260μm
  - Sector 4 of wheel -2 shown here
  - B-field degrades MB1 resolution in wheels +/-2

DT Drift Velocity Along Z, Field On/Off



- **Already have Drift Velocity determination from CRAFT data**
  - ❖ Innermost stations on outer wheels have largest radial field (eg Wh-2 MB1)
  - ❖ Highly suppressed zero on Y-axis: maximum difference in Drift Velocity is 3%

CRAFT: TK, ECAL, HCAL, Muon



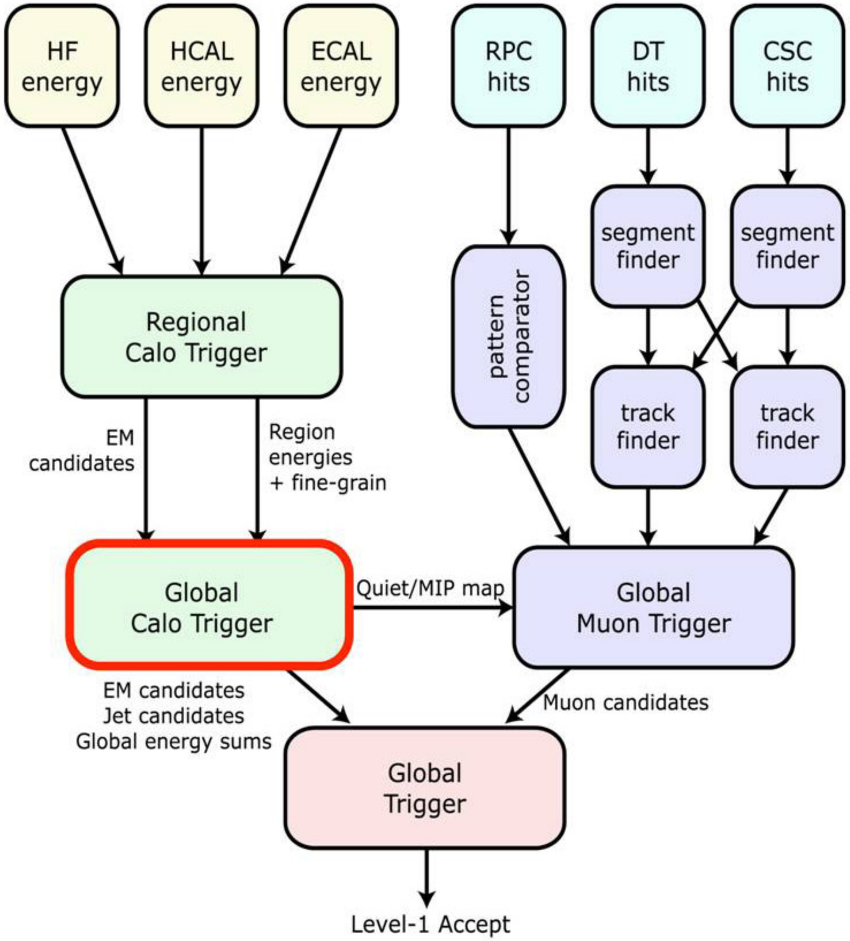
- Green: Tracker and Muon hits
- Magenta: ECAL
- Blue: HCAL

Trigger challenges at LHC

- Enormous data rate: 10^9 Hz of collisions
  - More than 1TByte/s
- Minimum bias in-time pile-up
  - 22 events per bunch crossing
- Out-of-time pile-up
  - Events from different bunch crossings overlaid
- Tiny cross sections for Higgs and new physics
  - Selection $1:10^{11}$
- All online
  - Can't go back and fix it. Events are lost forever!
- Level-1 (hardware): 40MHz → 100kHz
- Level-2 (software): 100kHz → ~100Hz

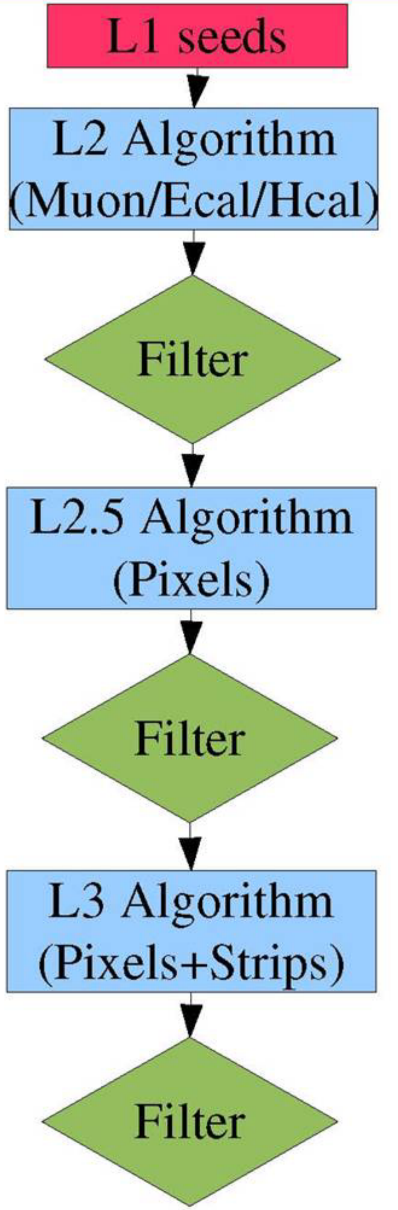
CMS Level-1 Trigger

- Muons
  - Three complementary detector systems
  - Share hits when available in overlap regions
  - Find best combination of information in Global Muon Trigger
- Electrons, jets, energy sums etc.
  - Combine ECAL and HCAL energies in Regional Calo Trigger and do local electron finding
  - Global energy sums and jets in the Global Calo Trigger →
- All objects contribute to L1 accept

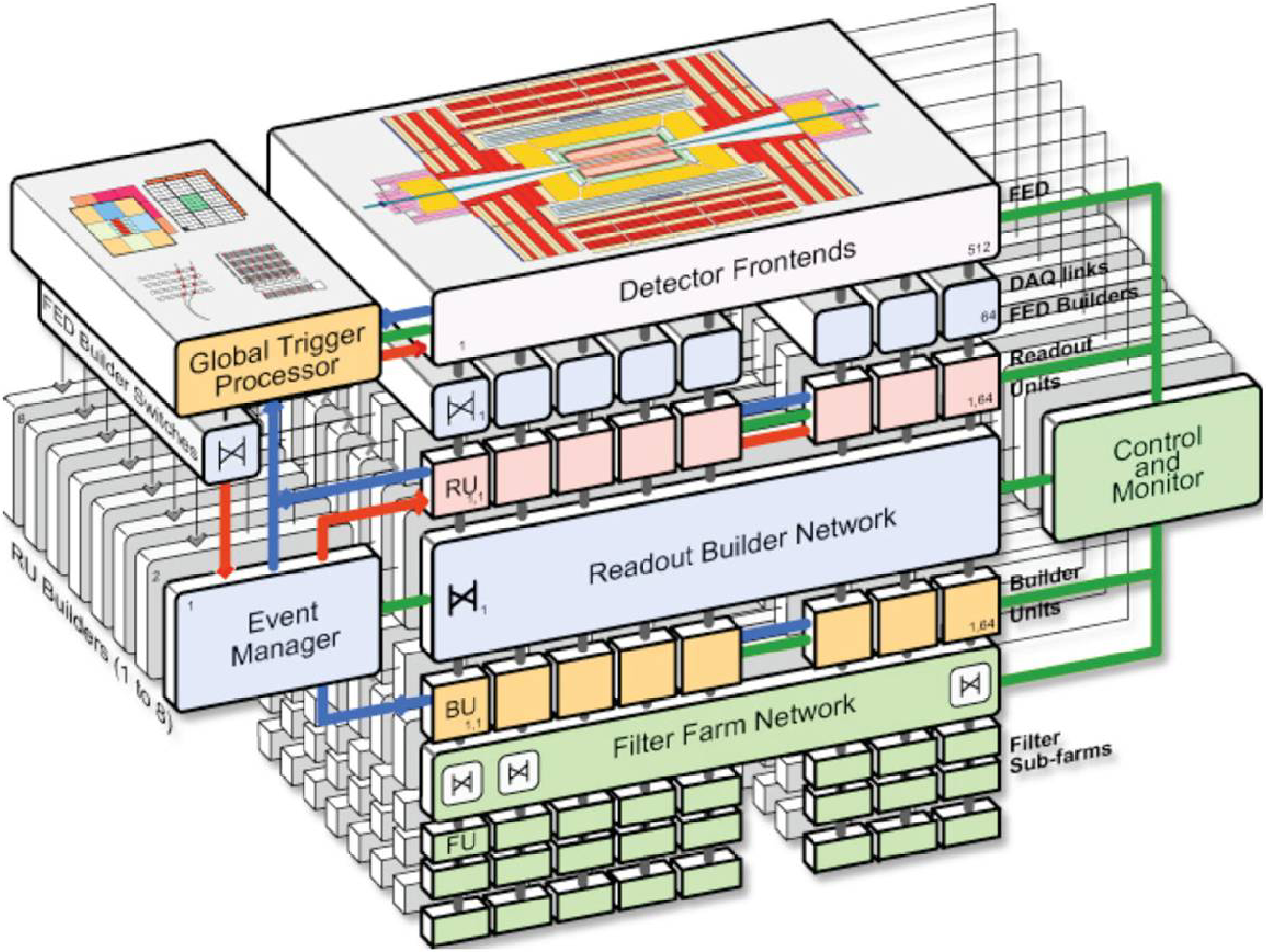


CMS Level-2 Trigger

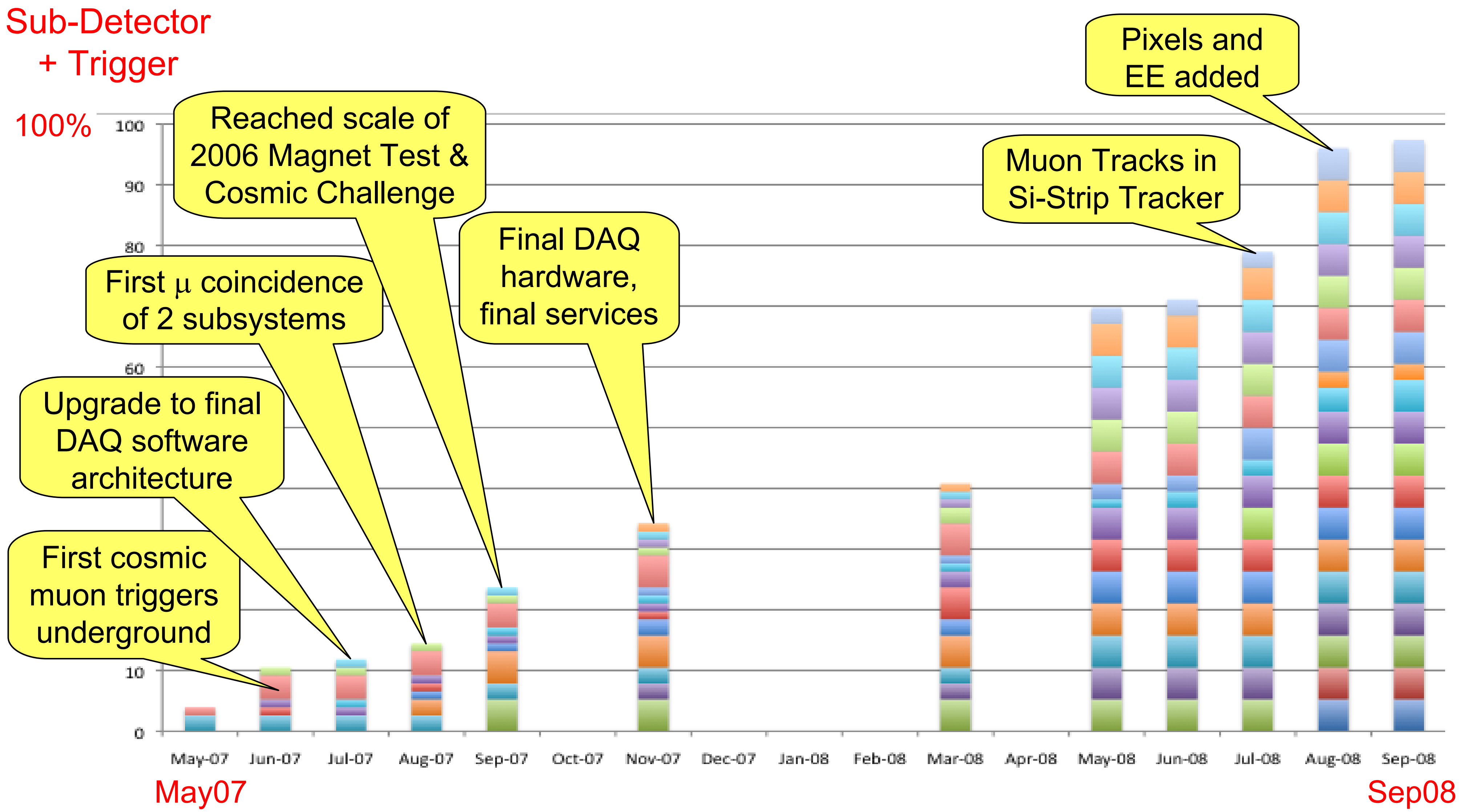
- High Level Trigger (HLT)
- Bandwidth/Timing constraints:
  - Each HLT trigger path is a sequence of filters
  - Progress from low- (Calo, Muon) to high- (Pixel, Strip) time-consuming algorithms
  - All algorithms regional (except jets)
    - Seeded by previous levels
  - Reco time is significantly improved by applying:
    - Regional data-unpacking
    - Local reconstruction (using one subdetector only)
- Runs on ~1000 Dual QuadCore CPUs at 2.6 GHz
- Major exercise in 2007 showed time/event OK



Data Acquisition Architecture



Underground Commissioning Progress



Winter 2008/2009 Shutdown

- Install and commission preshower detector
- Tackle infant mortality in detectors installed prior to 2008
- Finalise commissioning of detectors installed in 2008
- Address issues arising from CRAFT running
- Schedule for restart in 2009:
  - ❖Resume cosmic-ray data-taking at B=0T in April
  - ❖Close detector by end of May
  - ❖Extended CRAFT Run before 2009 LHC beams

Summary

- Construction of the CMS experiment is almost completed
- Commissioning work already carried out gives confidence that CMS detectors will operate with expected performance
- Integrated operation of subdetectors & central systems using cosmic-ray triggers is now routine, with near-final complexity and functionality
- Challenges conducted around the clock at 100% of 2008 load show that Computing, Software & Analysis tools are ready for early data
- Have already taken and analysed first beam-related data
- Preparations for rapid extraction of physics are well advanced
- Eagerly awaiting first LHC Physics during 2009

Back-Up

Back-Up

Cosmic Run at Four Tesla (CRAFT)

- **Aims:**
  - ➢ Run CMS for 4 weeks continuously to gain further operational experience this year
  - ➢ Study effects of B field on detector components (since MTCC)
  - ➢ Collect 300M cosmic events with tracking detectors and field
  - ➢ Aim for 70% efficiency
- **Facts:**
  - ➢ Ran 4 weeks continuously from 13-Oct to 11-Nov
    - ❖ 19 days with B=3.8T
  - ➢ 370M cosmic events collected in total
  - ➢ 290M with B=3.8T and with strip tracker and DT in readout
    - ❖ 194M with all components in