Commissioning the CMS micro-strip tracker

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Overview

- Introduction
  - CMS and LHC
  - Requirements for tracker design
  - Micro-strip tracker readout system

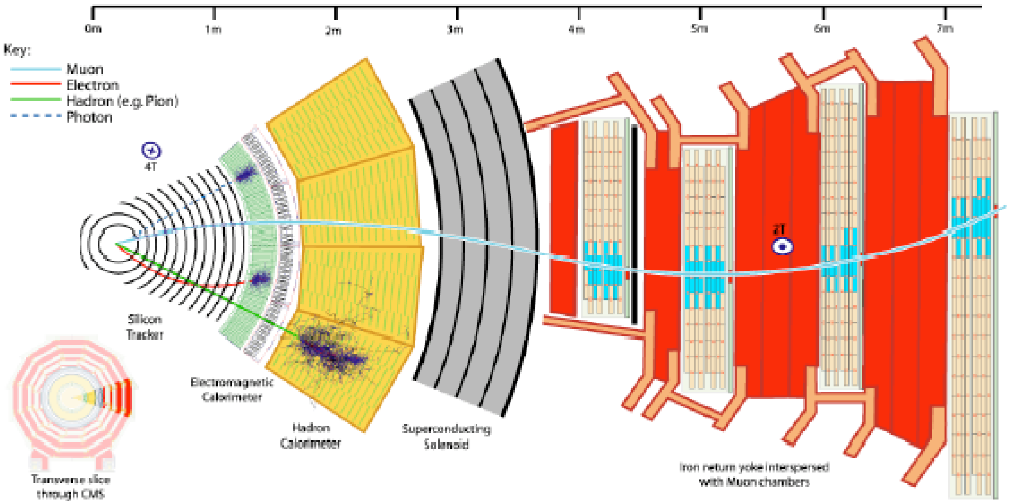
- Commissioning and operations
  - Magnet Test Cosmic Challenge
  - Tracker Integration Facility
  - Tracker commissioning at P5
  - Global runs and cosmic data-taking

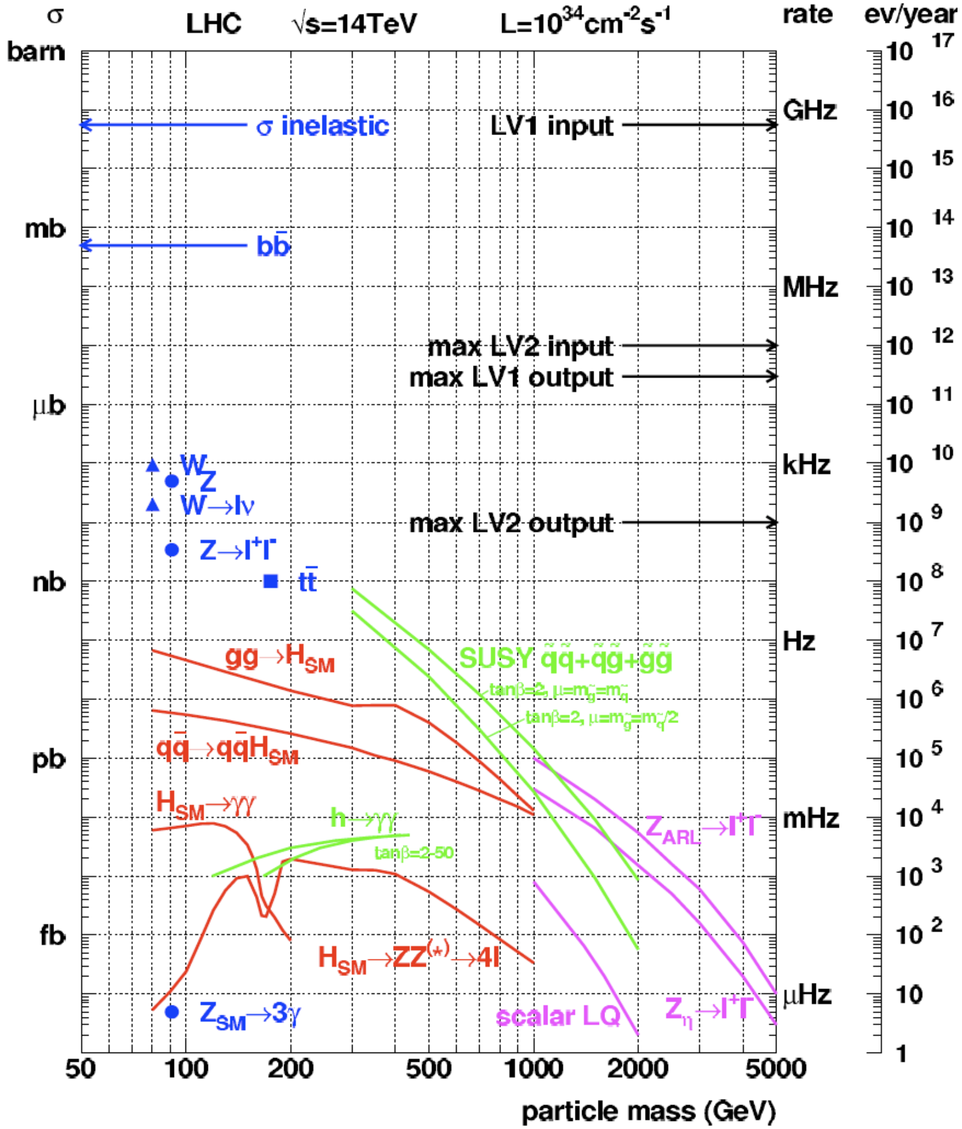
Design considerations for CMS

- LHC to probe physics at TeV scale
  - Requires high CoM energies
  - Requires large integrated luminosities

- QCD-dominated environment, so focus on:
  - Good muon id and momentum resolution
  - Good e/γ energy resolution, isolation, pi^0 rejection

  - Tracker: good charged particle momentum resolution and reconstruction efficiencies, vertexing, efficient tau id and b-tagging



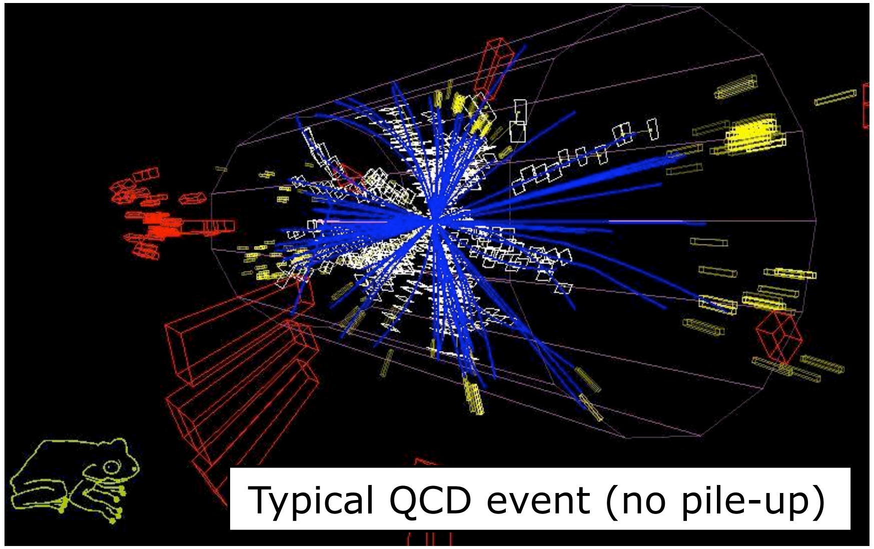


LHC environment

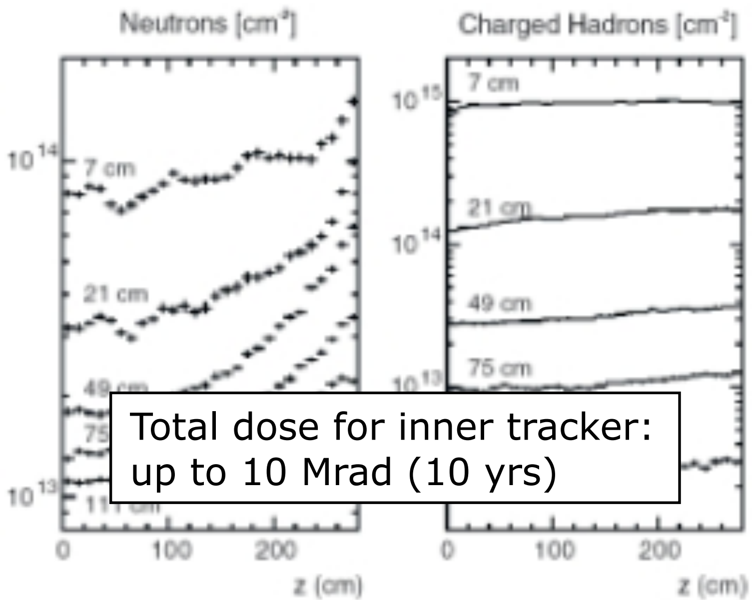
- Compared with Tevatron
  - ~7x increase in CoM energy
  - ~5x higher BX frequency
  - ~20x increase in luminosity

- High multiplicity environment
  - 20 super-imposed events per 25 ns
  - 1000 charged particles per 25 ns

- Consequences for (inner) detector design
  - Require rad-hard sensors and front-end ASICs
  - Need highly granular detectors for low occupancies
  - Need fast signal processing for BX id
  - Precision vertexing to identify signal event and decays


Typical QCD event (no pile-up)

beam parameter	p-p high	p-p low	Pb-Pb high	units
luminosity	10^{34}	2×10^{33}	10^{27}	$cm^{-2}s^{-1}$
energy per nucleon	7	7	2.76	TeV
bunch spacing	25	25	99.8	ns
particles per bunch	1.15×10^{11}	4×10^{10}	7.0×10^{7}	-
inelastic collisions per crossing	17.5	3.5	7	-

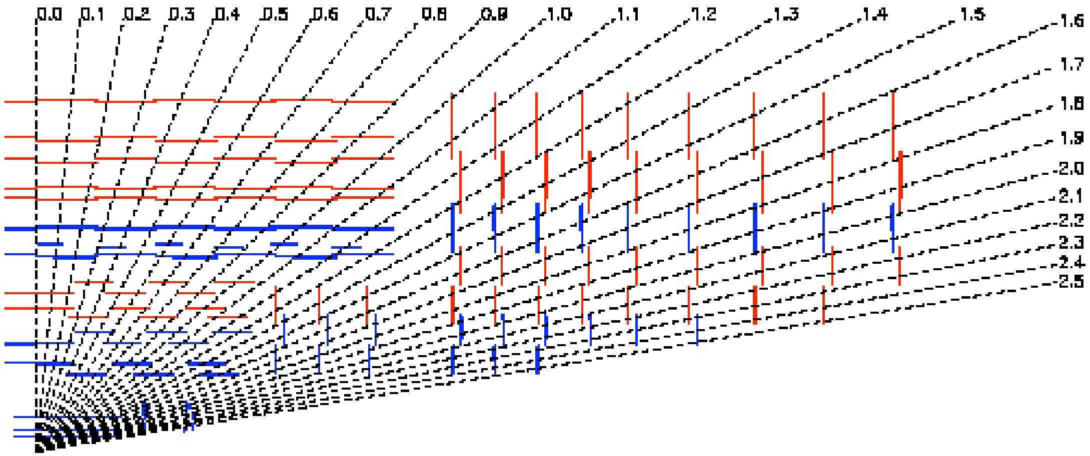


Total dose for inner tracker: up to 10 Mrad (10 yrs)

Design considerations for CMS tracker

- Full silicon design for micro-strip
  - MSGC not sufficiently rad-hard
  - More than 200 m2 active surface area
  - 10 (11) layers in Barrel (End-Cap)
  - Coverage up to |eta| < 2.4

- Requirements (constraints)
  - **Reliability** (inaccessible for 10 yrs)
  - **Radiation-hard** sensors and ASICs
  - **Many layers** (robust pattern recognition)
  - **Low noise** (small signals in Si)
  - **Low material budget** (Bremsstrahlung, photon conversions, multiple scattering)
  - **Low power** (less power cables, cooling)
  - **Fast signal processing** (BX id)
  - **High spatial precision** (vertexing)
  - **High granularity** (low occupancy)



region	layers	radius m	modules	thickness μm	mean pitch μm	resolution $r-\phi \times z$ $\mu m \times \mu m$
TIB	4	0.2-0.55	2724	320	81/118	23-34×230
TOB	6	0.55-1.16	5208	500	81/183	35-52×530
TID	3	0.55-1.20	816	320	97/128/143	23-34×230
TEC	9	1.20-2.80	6400	320/500	96-183	35-52×530

Pixel system

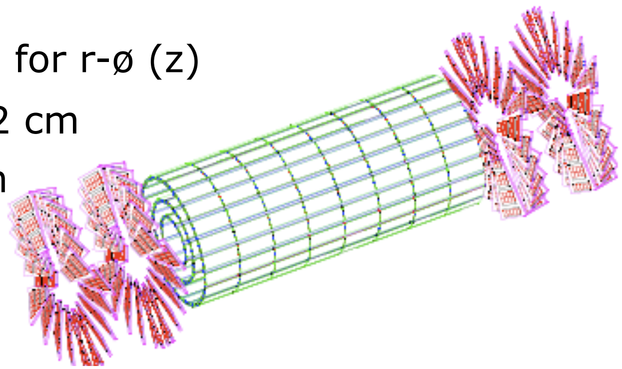
Resolution: 10 (20) μm for r-ø (z)

Barrel: r=4.4, 7.3, 10.2 cm

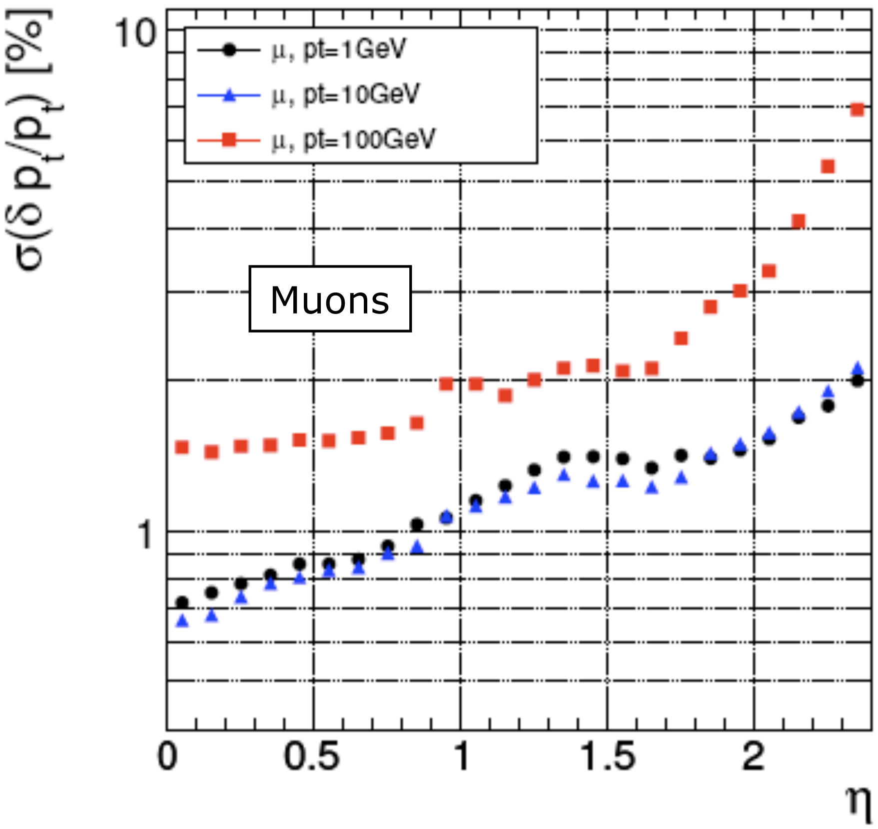
EndCap: r=34, 46.5 cm

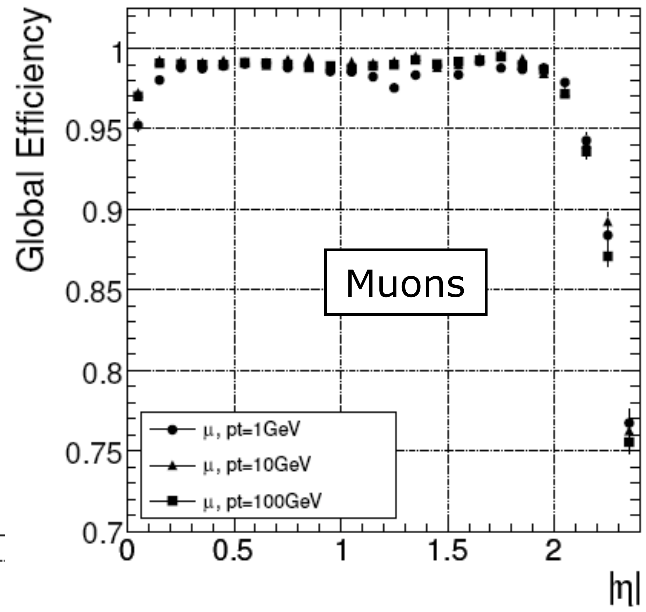
100 x 150 μm pixels

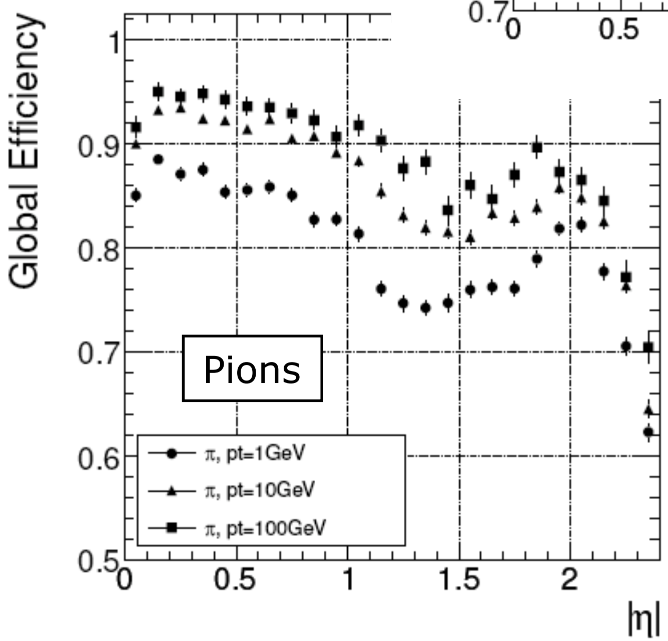
66M channels



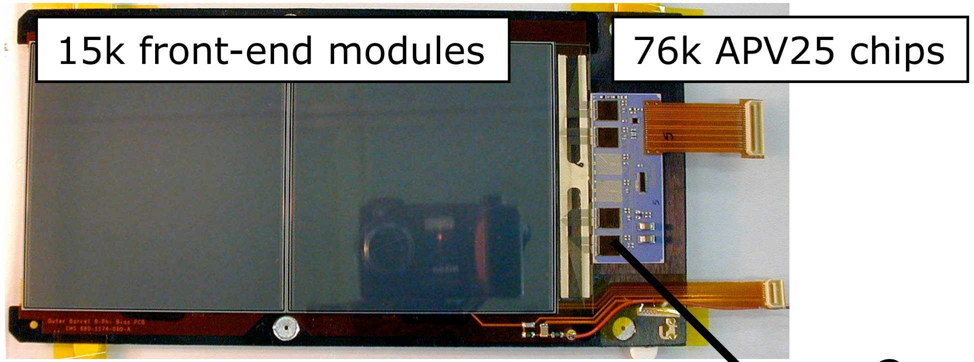
Tracking performance goals

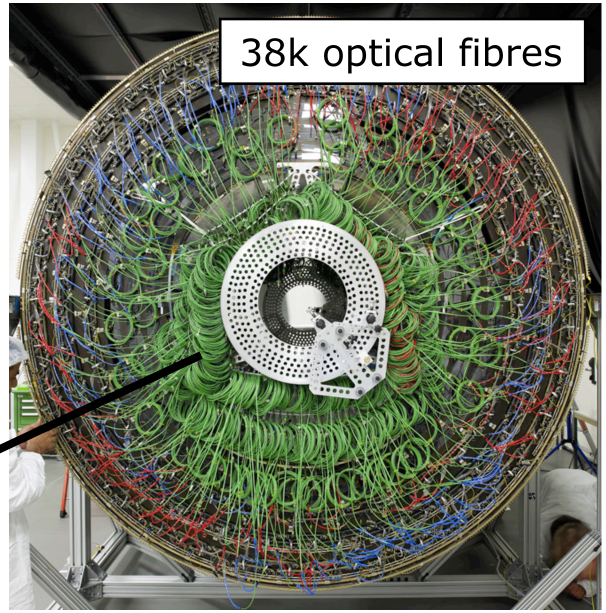


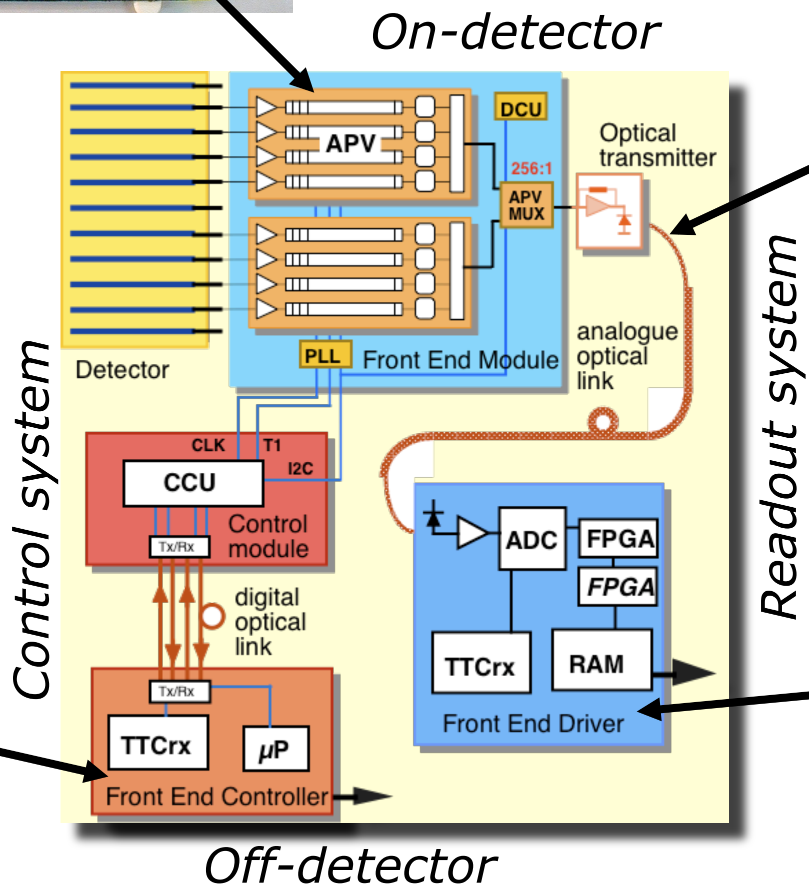


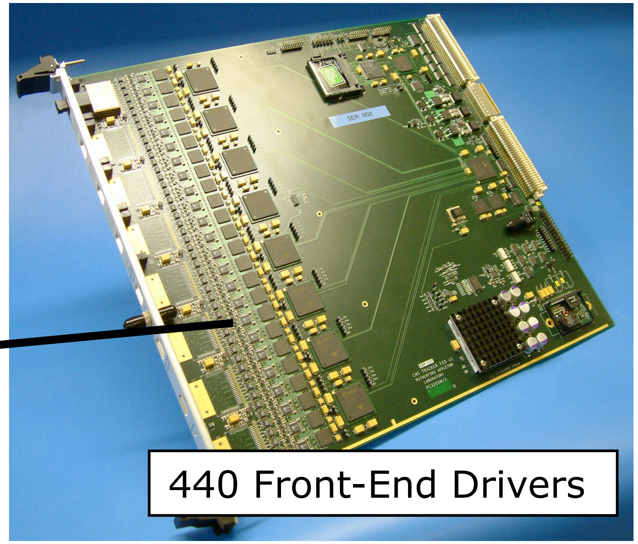


Control and readout (micro-strip tracker)





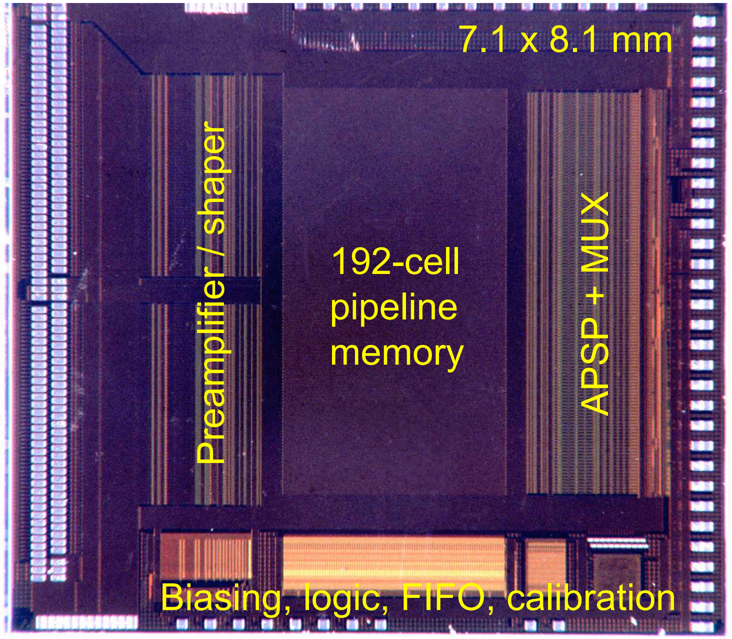


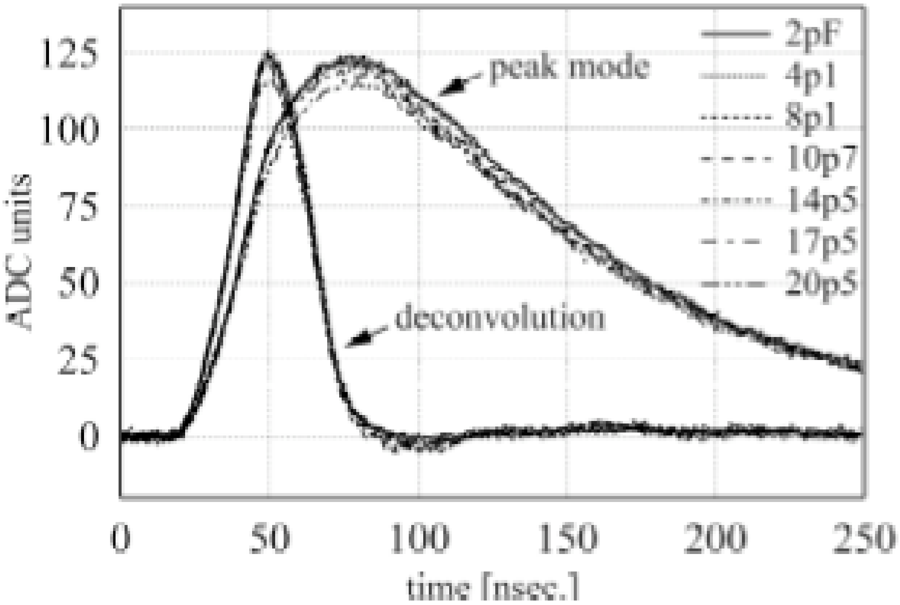


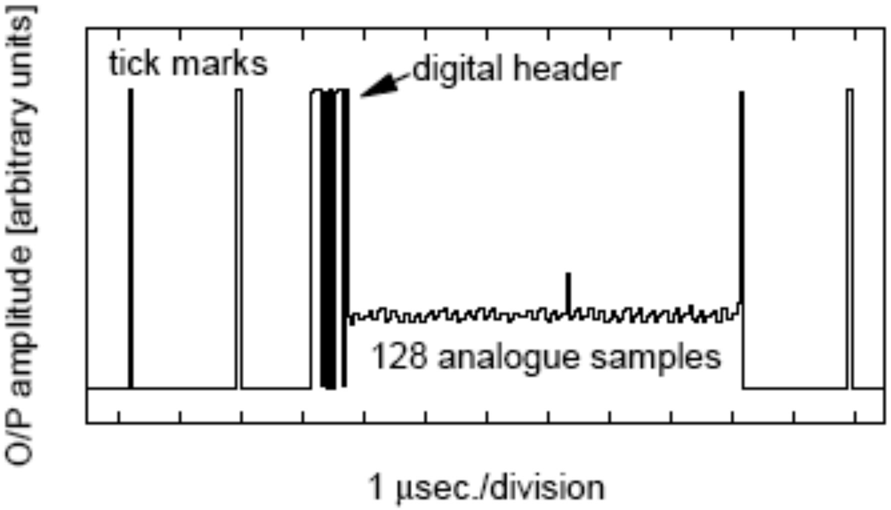
Front-end readout ASIC (APV25)

- 128-channel design
  - IC and RAL design using 0.25 μm CMOS commercial process
  - BX id as signal constrained to single 25 ns time window
  - Data frame contains BX info and 128 analogue samples

- Intrinsically radiation-hard
  - Thin transistor gate oxides, enclosed transistor geometries
  - 10 Mrad dose: no significant effect on performances

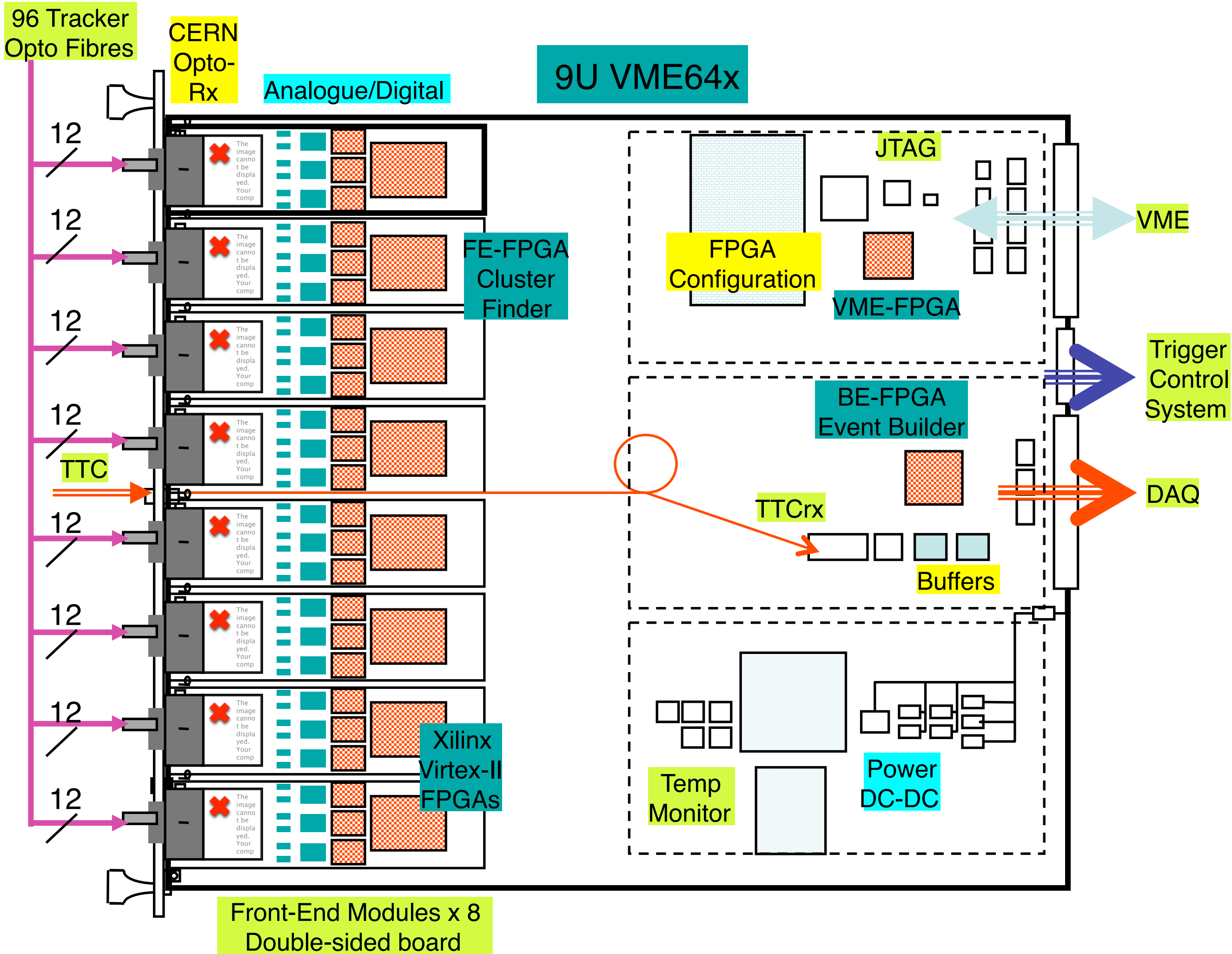






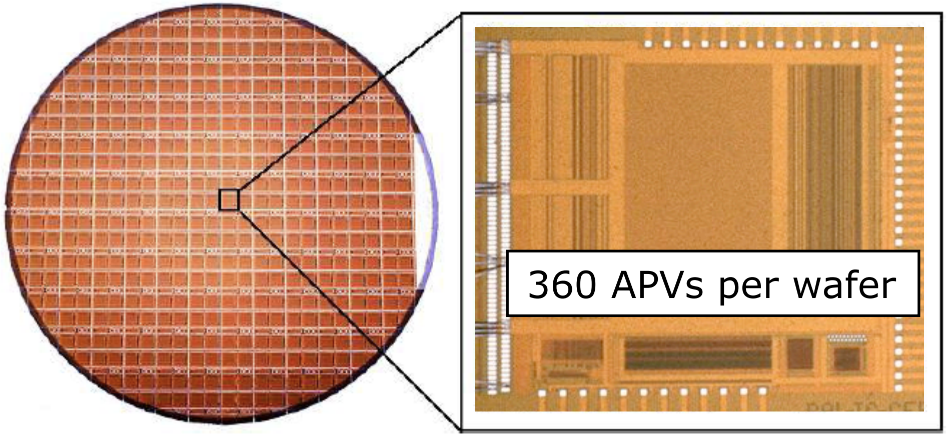
Off-detector receiver card (FED)

- Front-End Driver "receiver card"
  - VME64 form factor
  - RAL and Imperial
- Functions
  - Optical/electrical conversion
  - A/D conv. (10bit @ 40 MHz)
  - Zero-suppression
  - Data formatting
- Scale
  - Input from 192 APV25 chips
  - (25k detector strips)
  - 440 FEDs for μstrip tracker
  - (~700 for CMS)
- Data rates
  - Input: 3.4 GB/s
  - Output: ~200 MB/s



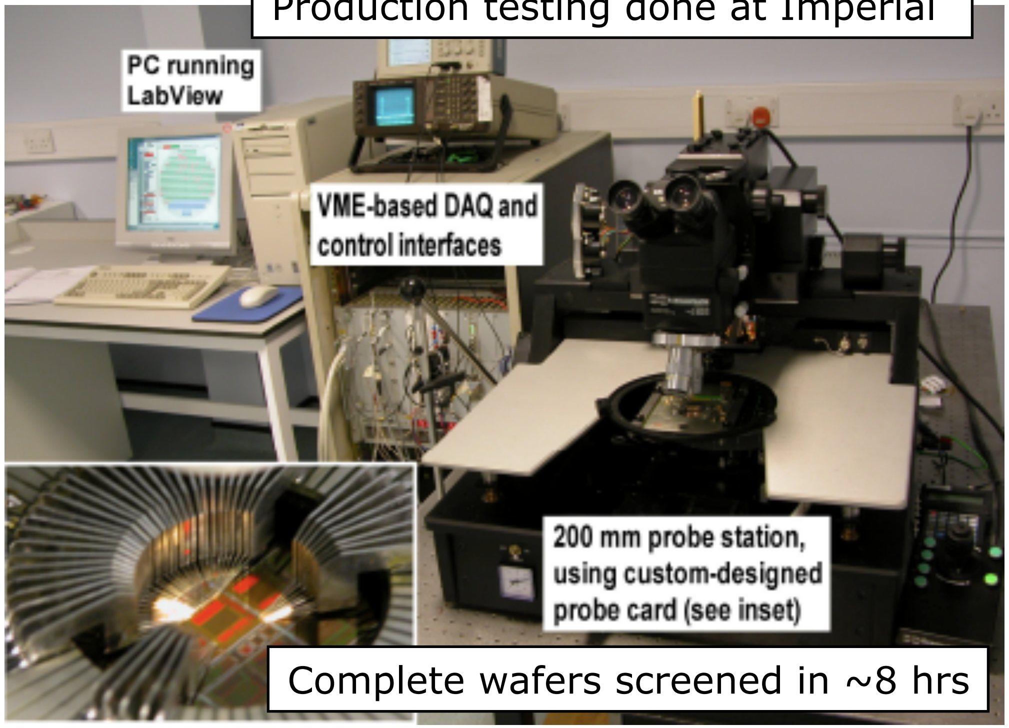
Production testing of the APV25

ASICs delivered in "lots" of 200 mm wafers

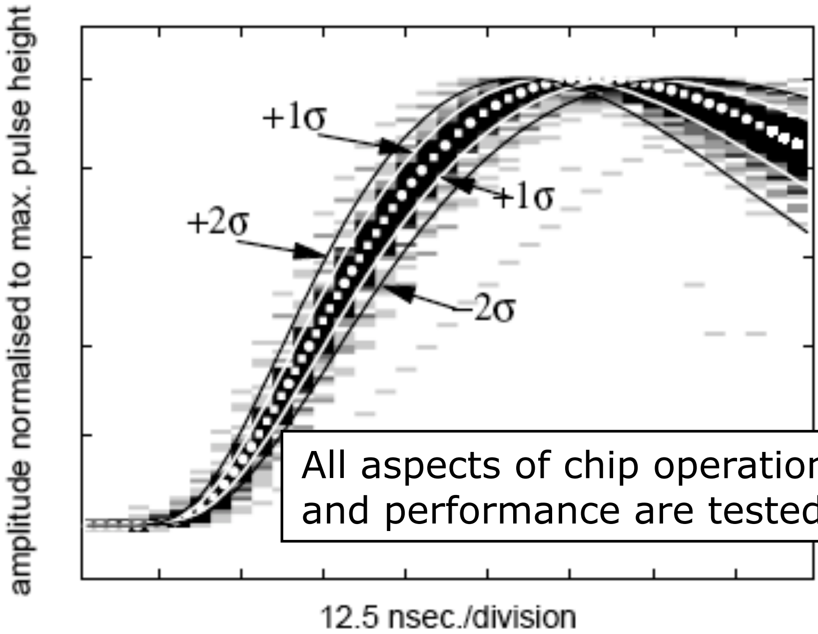


360 APVs per wafer

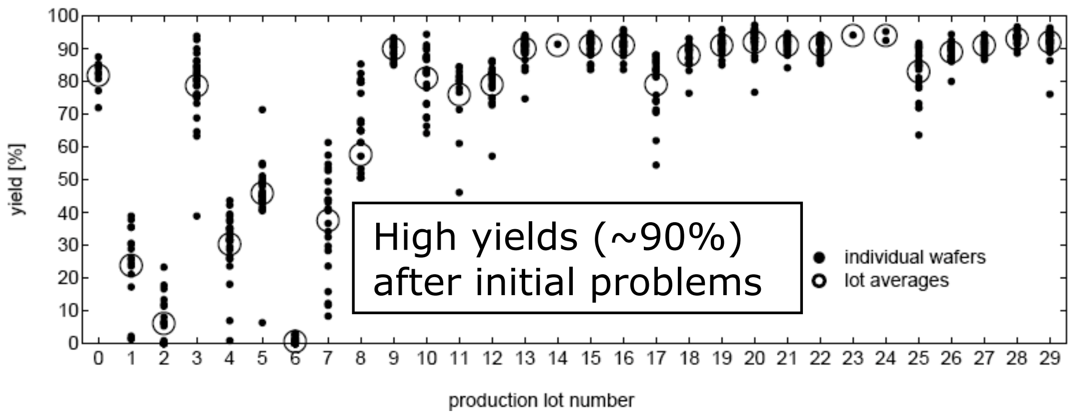
Production testing done at Imperial



Complete wafers screened in ~8 hrs



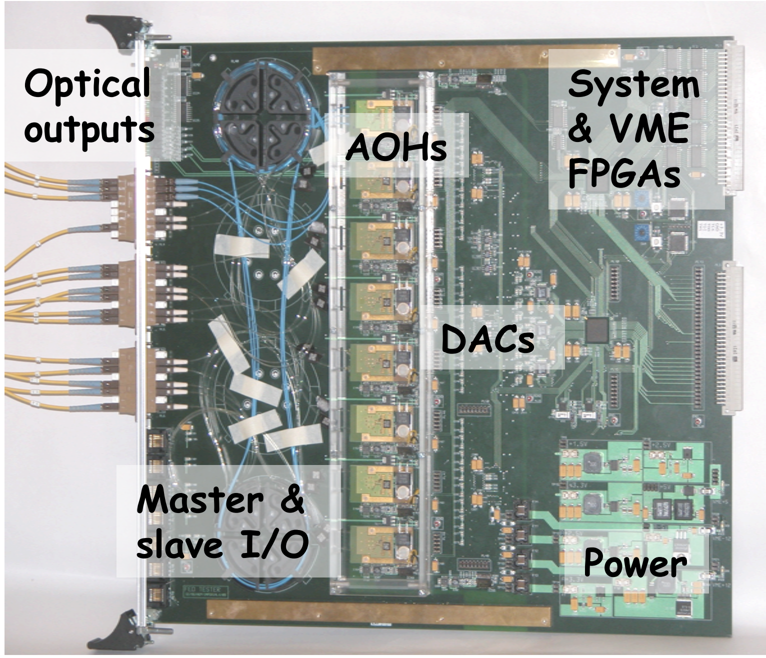
All aspects of chip operation and performance are tested

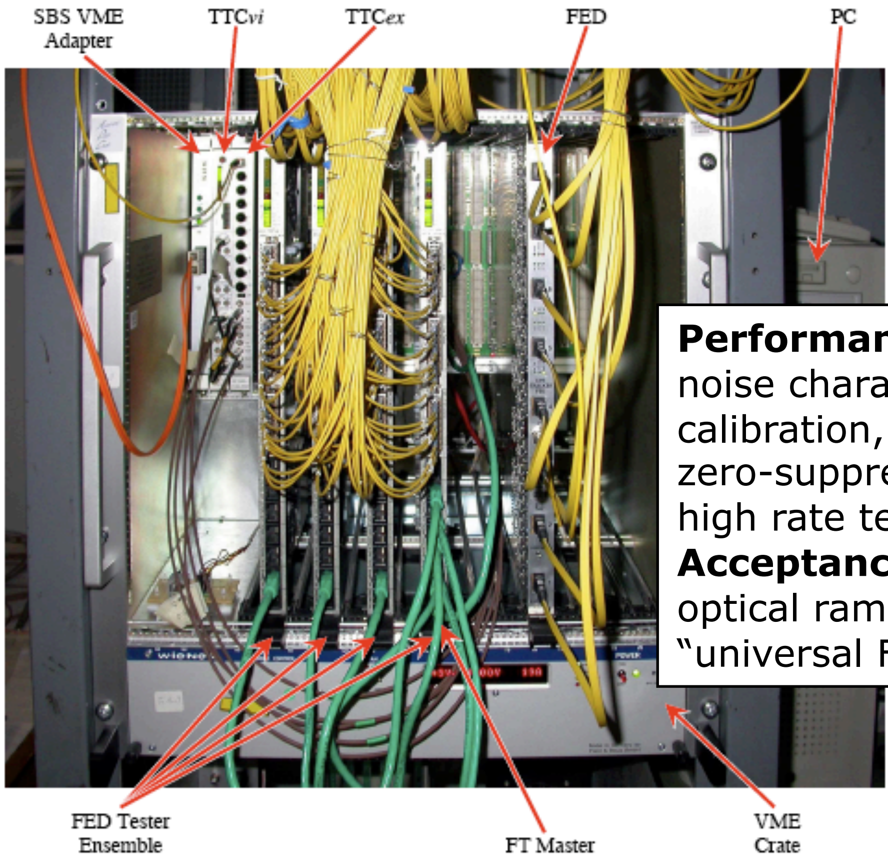


High yields (~90%) after initial problems

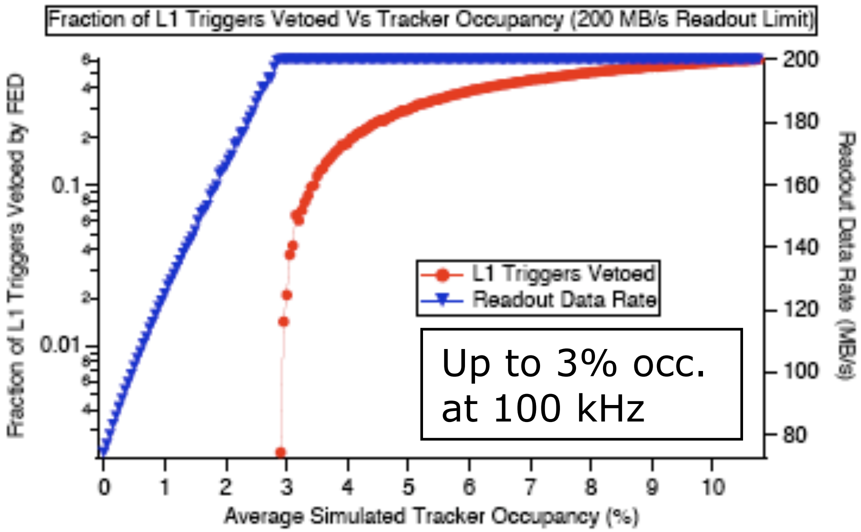
Production testing of FED

- “FED tester” used for performance and production tests
  - Provides D/A and E/O conversions for known input
  - FED output can be checked against known input signals





Performance tests: noise characterisation, calibration, crosstalk, zero-suppression, high rate tests
Acceptance tests: optical ramp tests, “universal FED” test



Up to 3% occ. at 100 kHz

Uncovered topics…

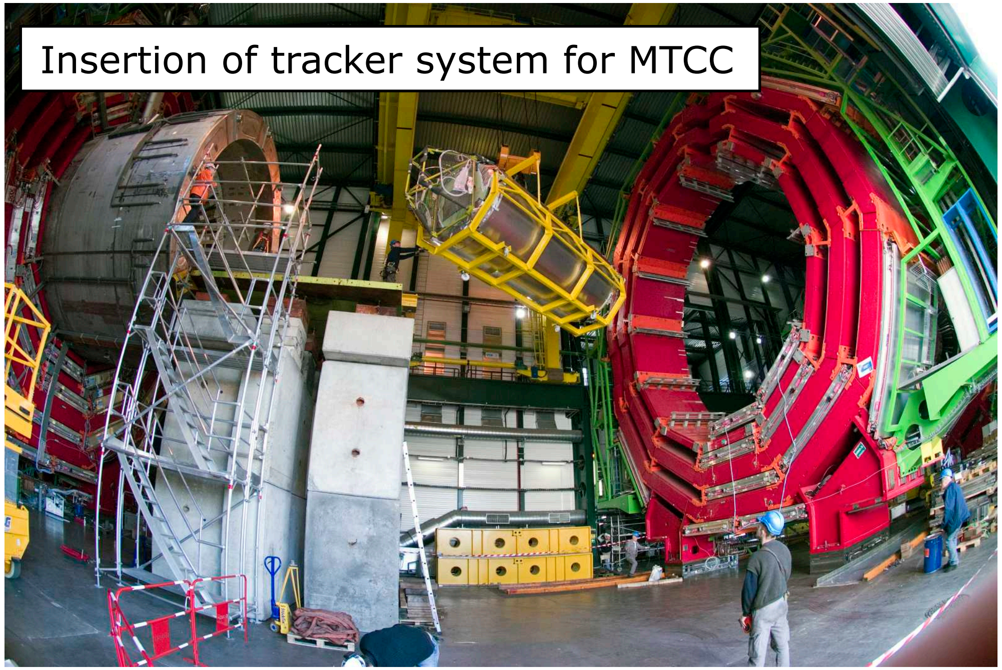
- Several areas of study on the tracker readout system are not covered in this talk
  - Radiation hardness qualification on the APV25
  - Single event upset studies on the APV25
  - Effect of highly ionising events on the tracker readout system
  - APV25 emulator (prevents pipeline overflows in APV25)
  - Performance studies on the APV25, optical link system and FED
  - And more…

- Worthy of a future seminar…

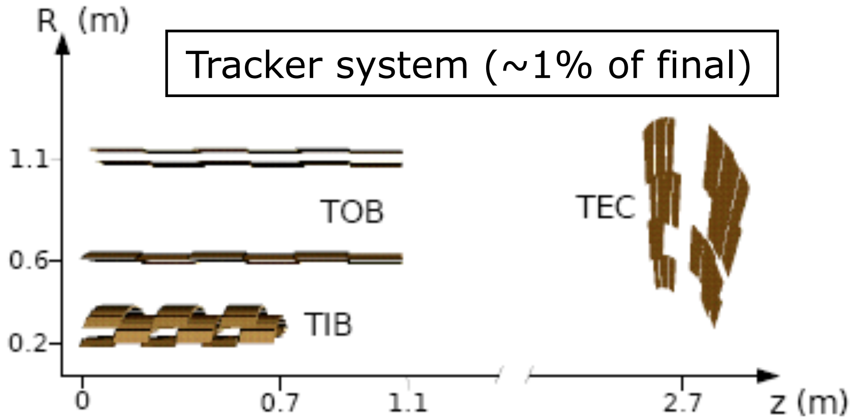
Magnet Test and Cosmic Challenge (MTCC)

- First CMS "slice test", during summer 2006
- Magnet test
  - Successful ramping of of magnet to 4 Tesla
  - Tests of service infrastructure and field mapping
- Cosmic challenge
  - Commission parts of all sub-dets (no pixels)
  - DAQ tests and global running

Insertion of tracker system for MTCC

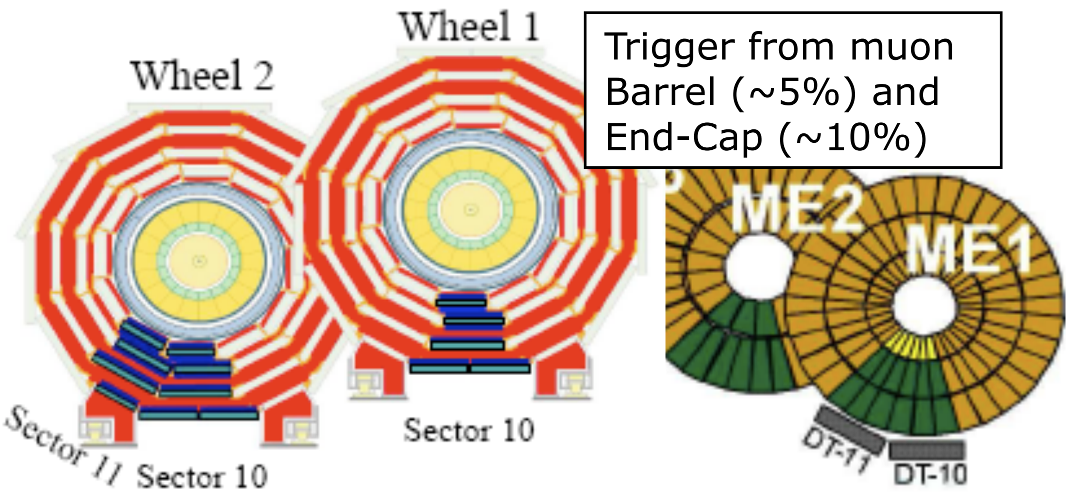


Tracker system (~1% of final)



Sub-det	Modules	Channels
TIB	75	46.1k
TOB	24	15.4k
TEC	34	20.0k

Trigger from muon Barrel (~5%) and End-Cap (~10%)

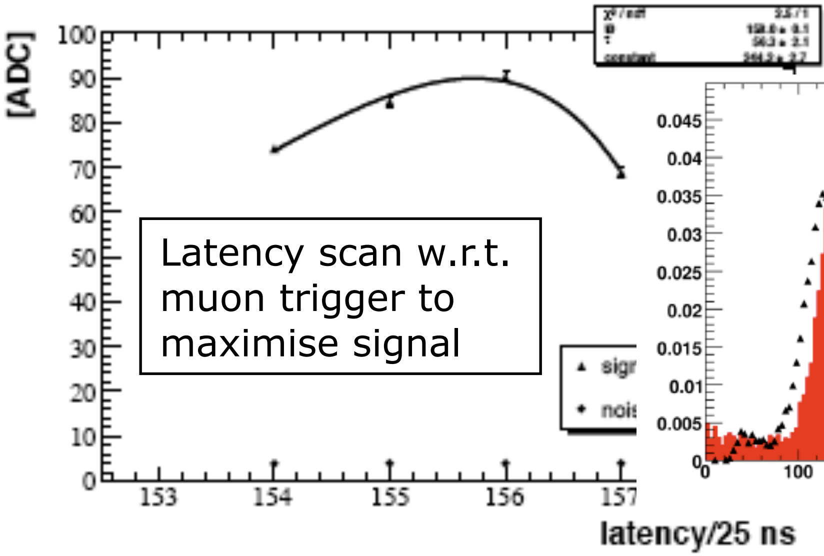


Magnet Test and Cosmic Challenge (MTCC)

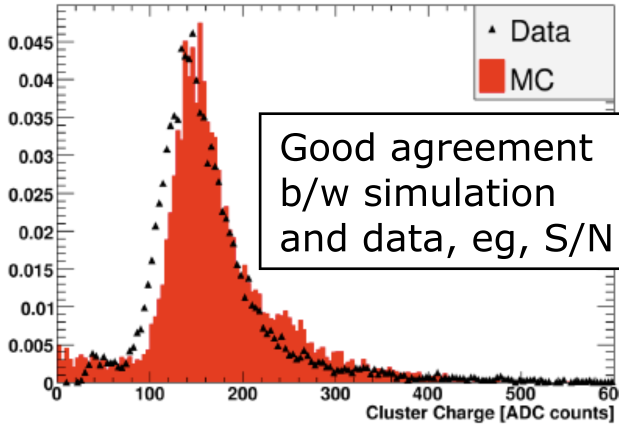
- Tracker achievements during MTCC:
  - Small system commissioned (configured, calibrated)
  - Synchronisation with muon trigger
  - Successful operation with central DAQ
  - Excellent and stable S/N performance
  - No operational issues with B-field

B-field [T]	Runs	Events	"Pointing"
0.0	43	11M	240k
3.8	38	14M	250k
4.0	4	2M	31k

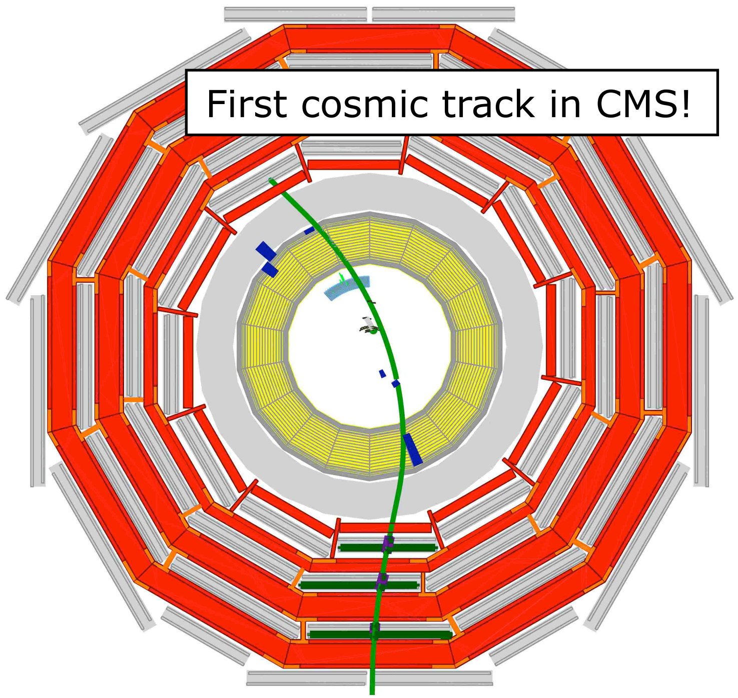
"3-week shift" for tracker DAQ experts!



Latency scan w.r.t. muon trigger to maximise signal



Good agreement b/w simulation and data, eg, S/N



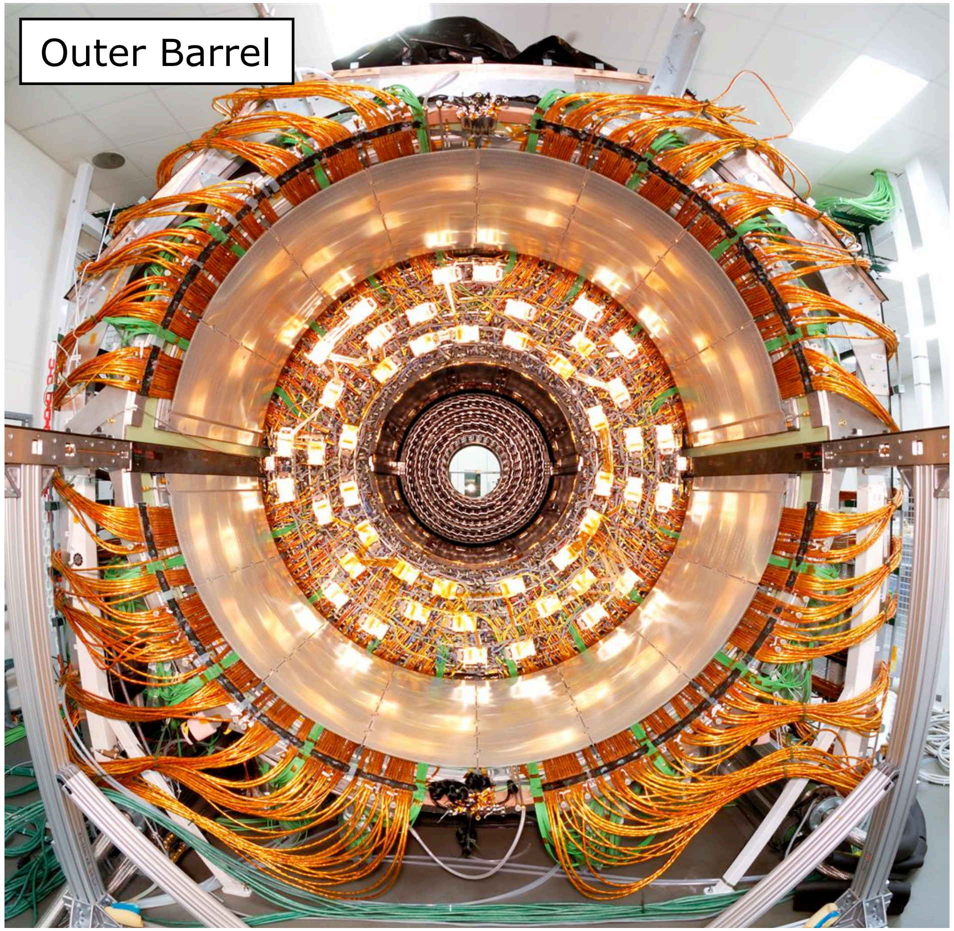
First cosmic track in CMS!

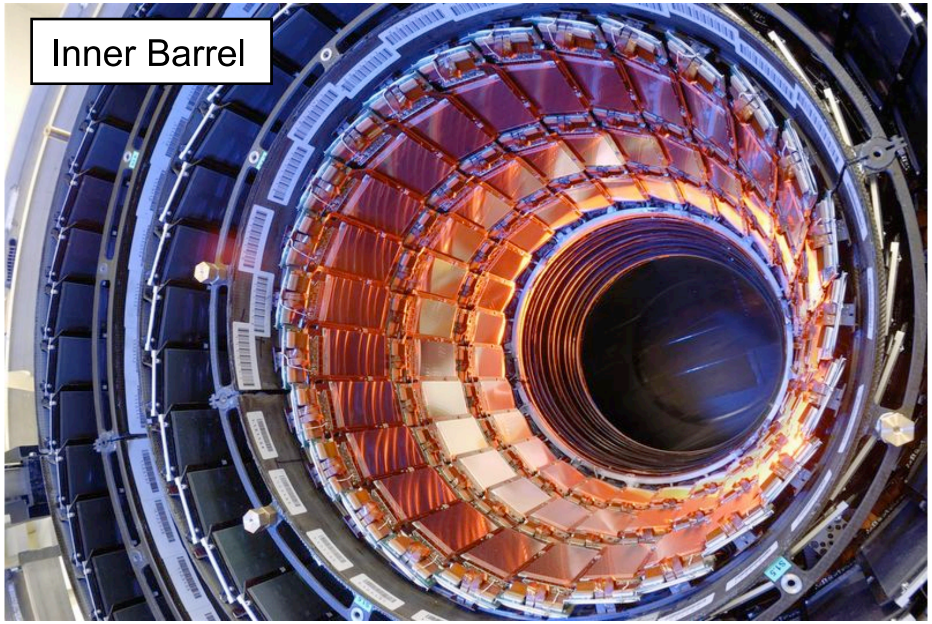
Tracker Integration Facility

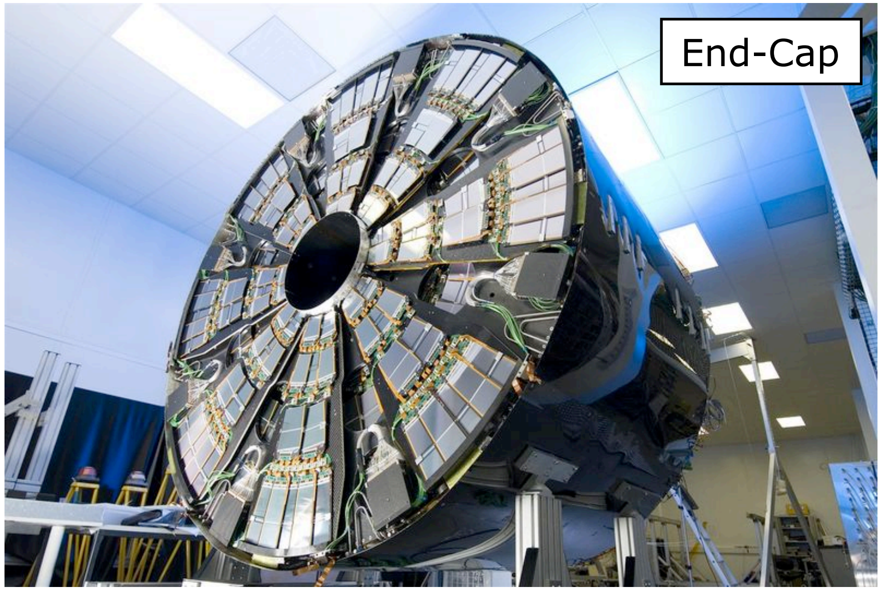
- Environmentally controlled clean-room
- Infrastructure to operate 1.6M channels
- Large cooling capacity (tests down to -15^{o}C)
- Tracker Analysis Centre in close proximity

- Tracker assembly completed at TIF in March 2007

Tracker sub-systems at the TIF



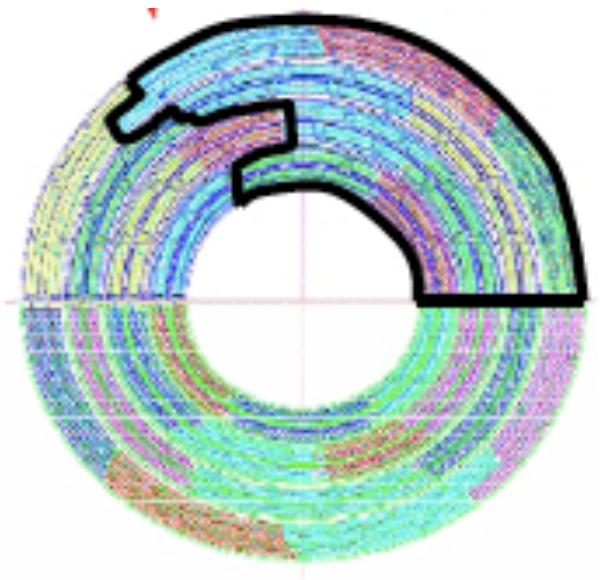


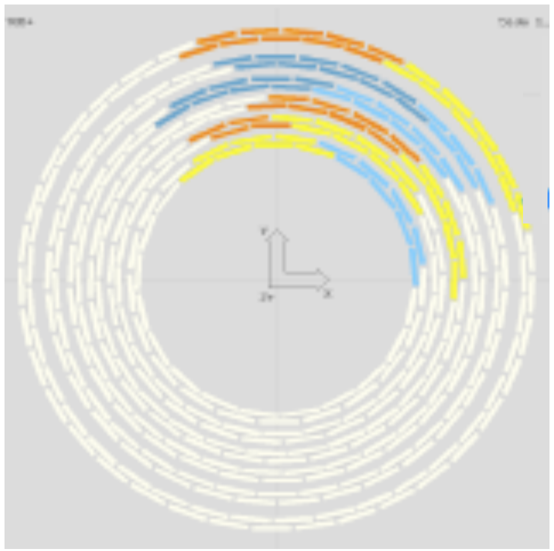


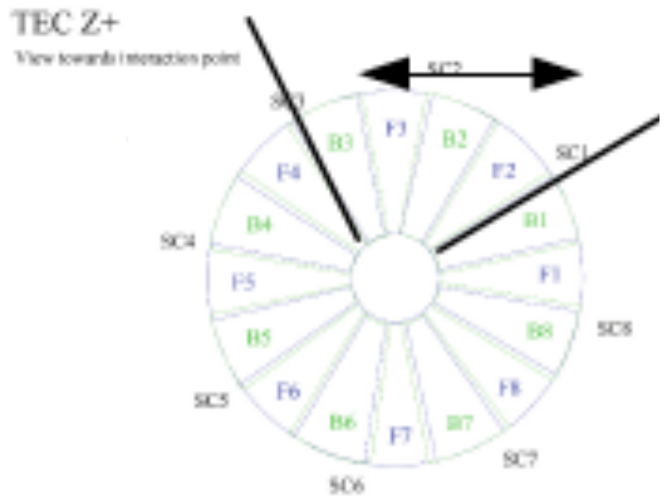
Commissioning “slice test”

- Extensive detector commissioning during spring
  - Commissioned ~15% of the tracker
  - Services and infrastructure (power, cooling, racks)
  - Development of software tools and procedures
- Data-taking with cosmic triggers up to July 2007

Sub-system	Modules	Fraction [%]
TIB+	640	36
TOB+	720	28
TEC+	800	25

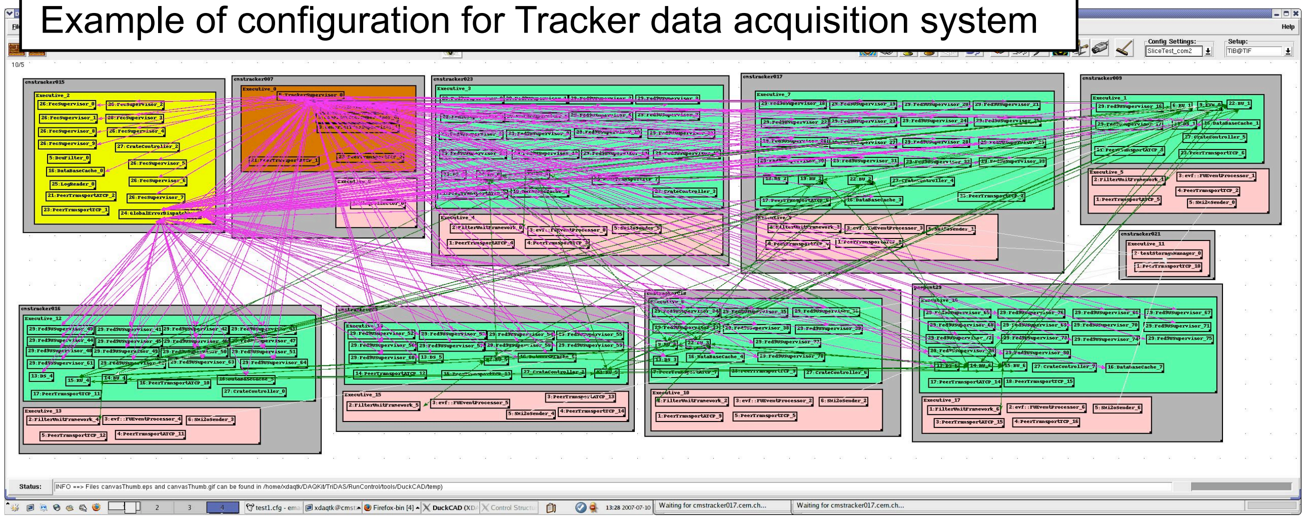




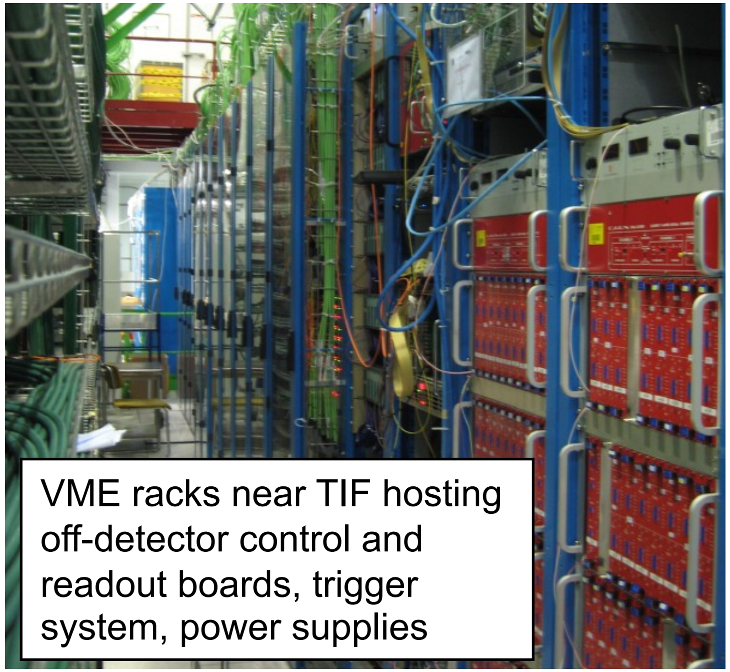


Large-scale tests using DAQ and DCS

Imperial College London

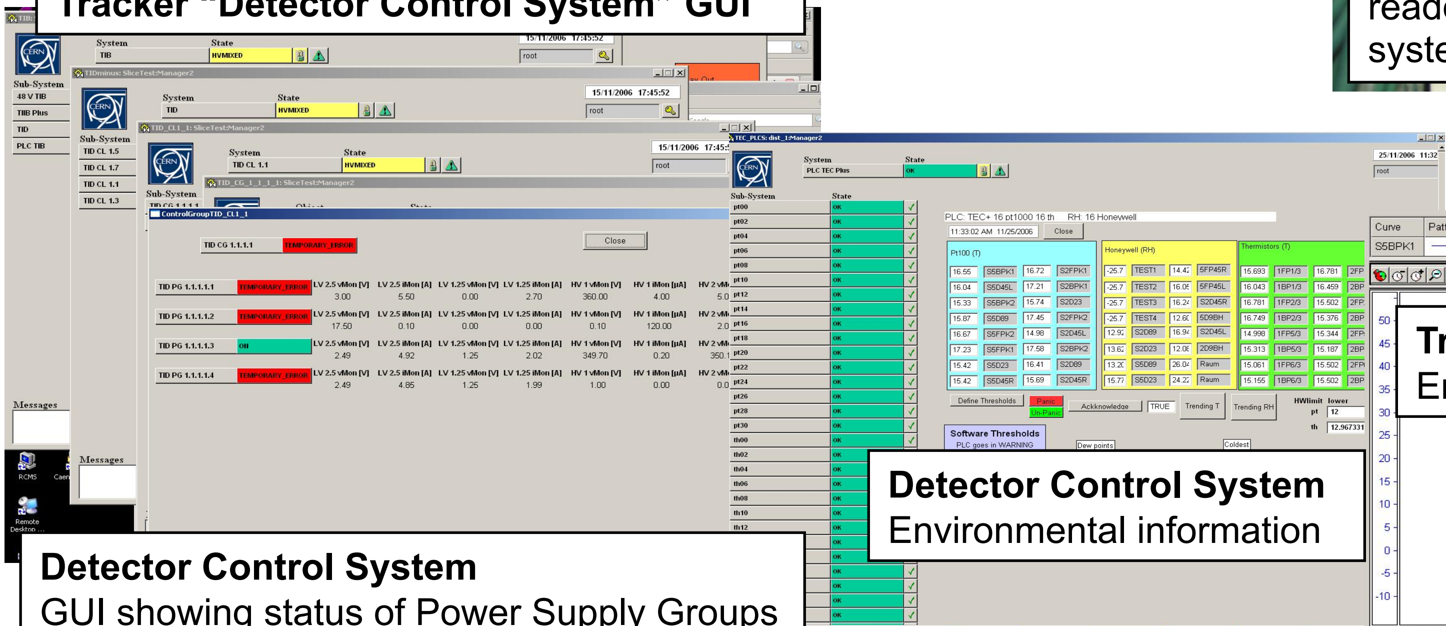


Example of configuration for Tracker data acquisition system



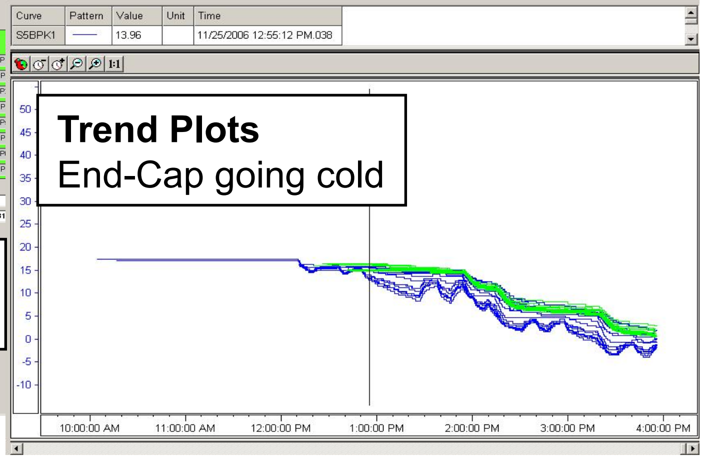
VME racks near TIF hosting off-detector control and readout boards, trigger system, power supplies

Tracker “Detector Control System” GUI



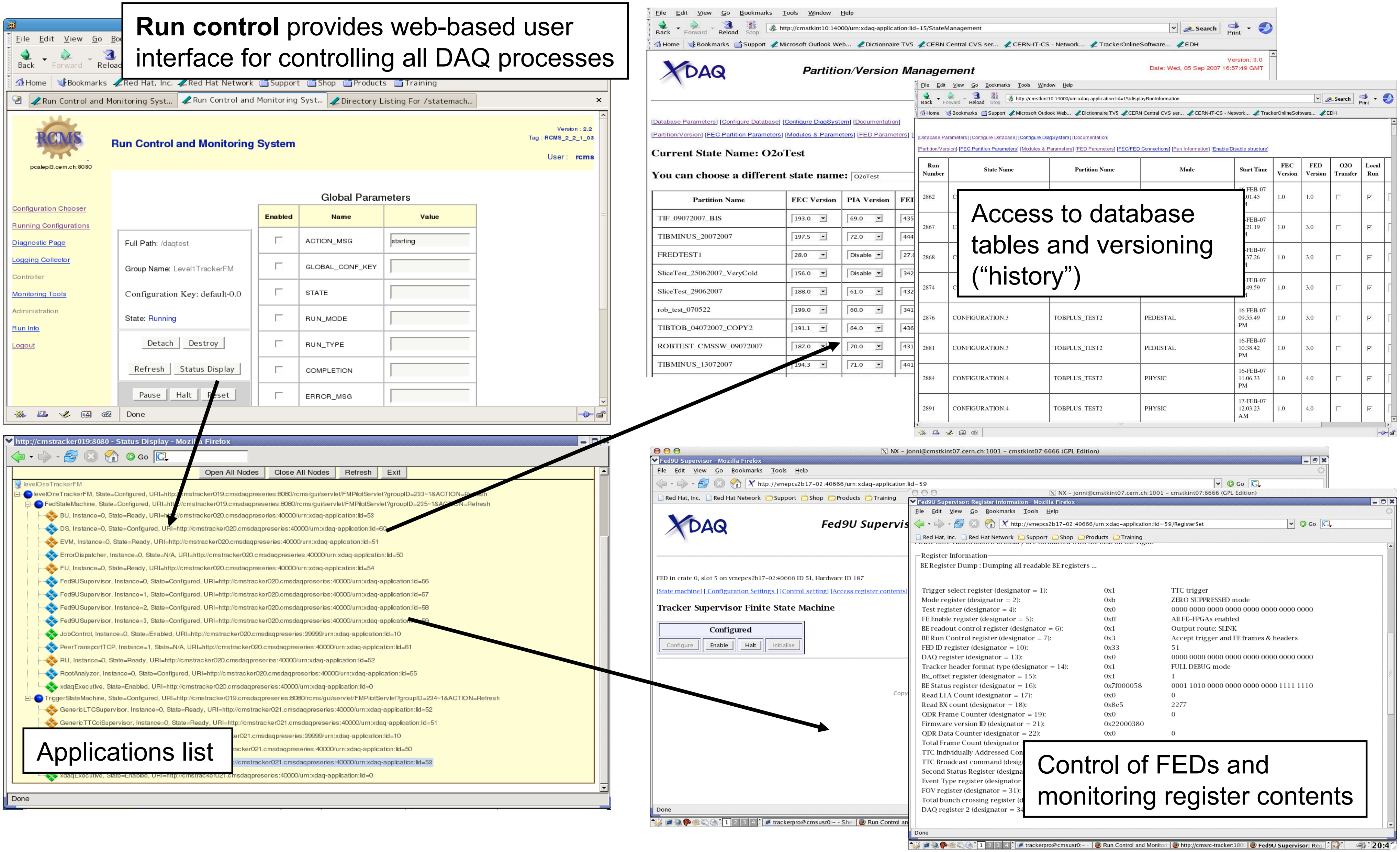
Detector Control System
GUI showing status of Power Supply Groups

Detector Control System
Environmental information



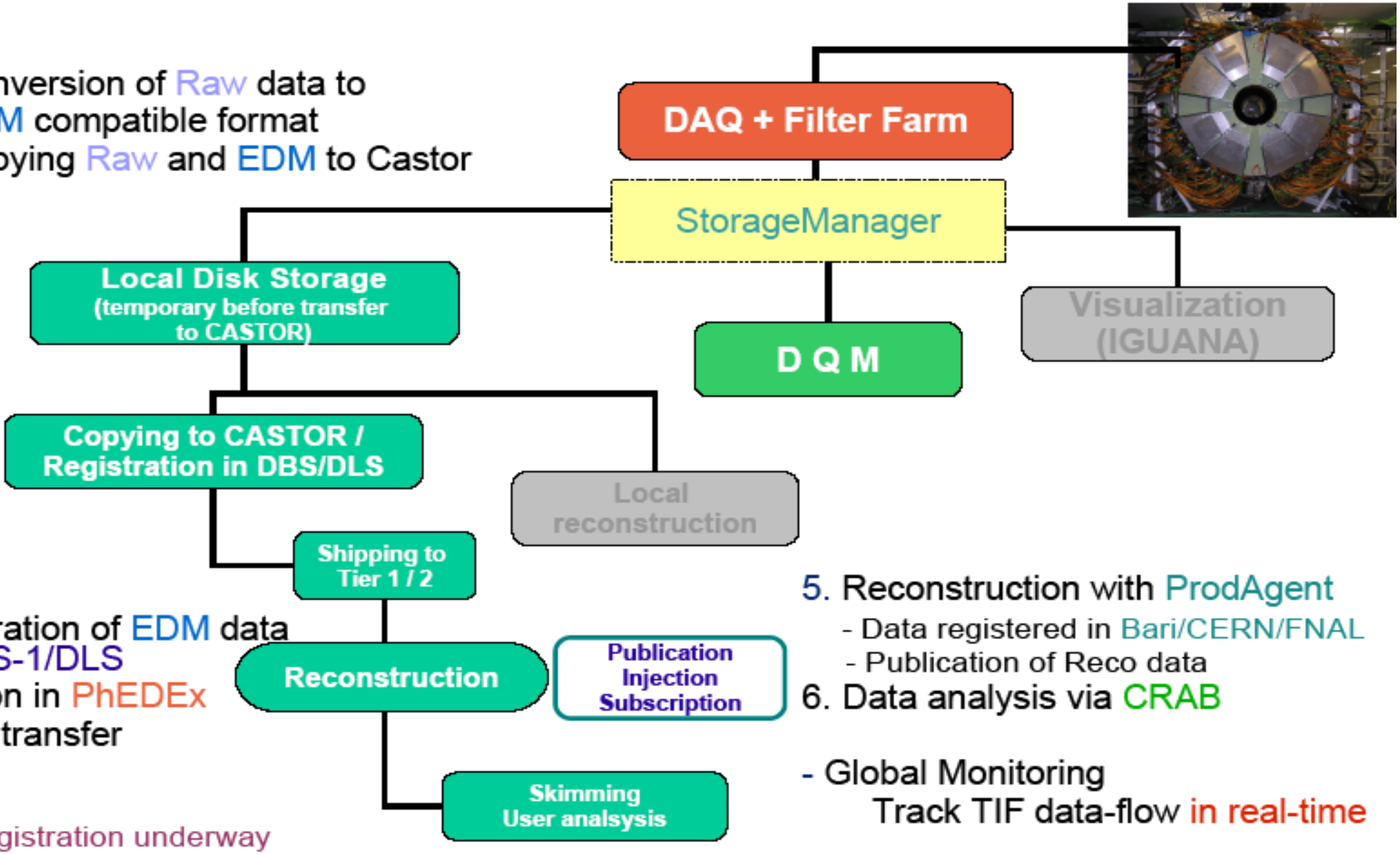
Trend Plots
End-Cap going cold

Run control


Run control provides web-based user interface for controlling all DAQ processes
Access to database tables and versioning (“history”)
Applications list
Control of FEDs and monitoring register contents

Dataflow and workflow

1. Conversion of Raw data to EDM compatible format
2. Copying Raw and EDM to Castor



3. Registration of EDM data in DBS-1/DLS
4. Injection in PhEDEx for the transfer

DBS-2 registration underway
(both Raw and EDM)

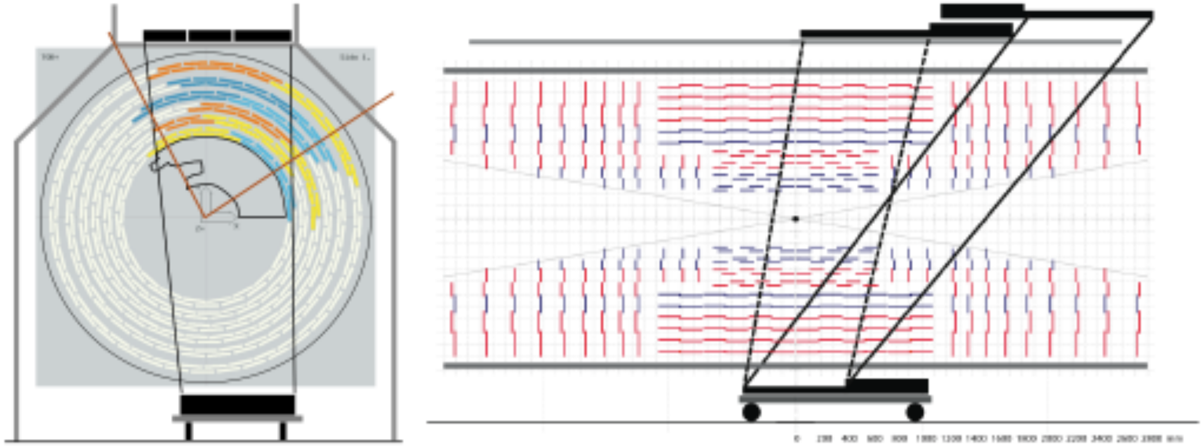
5. Reconstruction with ProdAgent
   - Data registered in Bari/CERN/FNAL
   - Publication of Reco data
6. Data analysis via CRAB

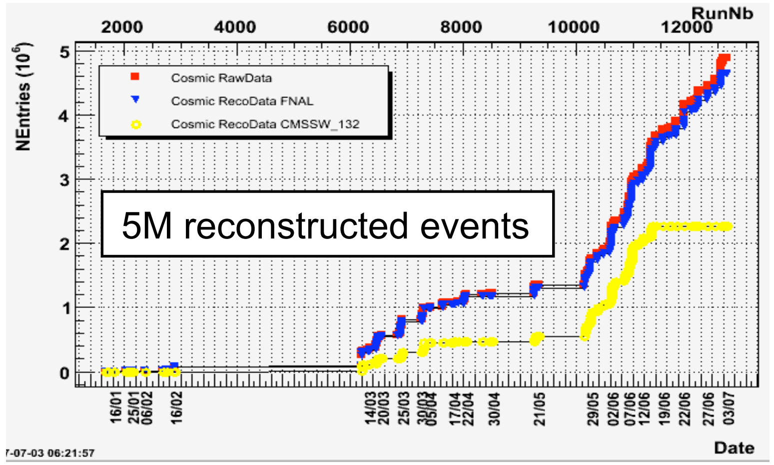
- Global Monitoring
  Track TIF data-flow in real-time

Migration of TIF data processing @ Tier-0 in progress

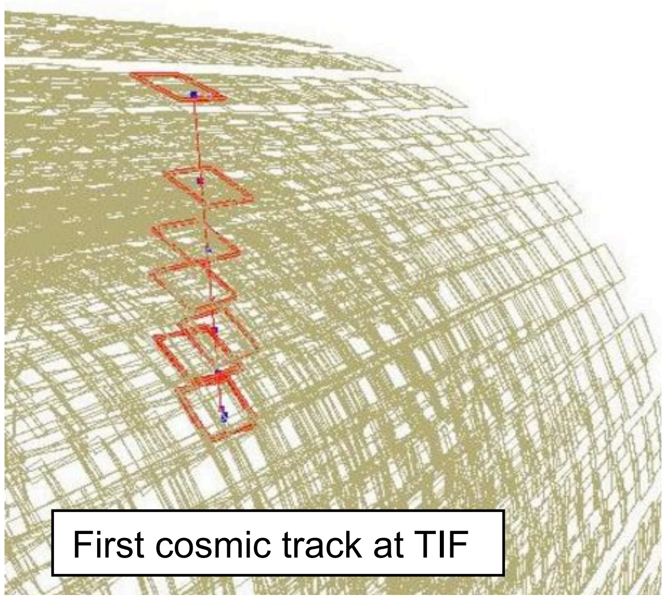
Cosmic triggers at the TIF

Trigger scintillator configuration (rate of few Hz)



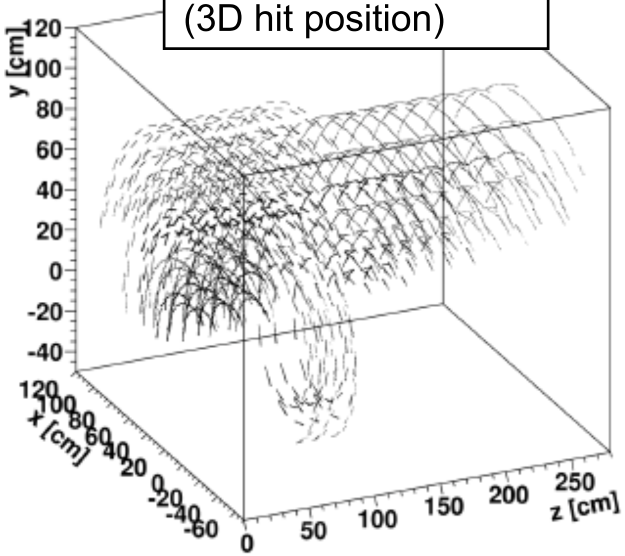


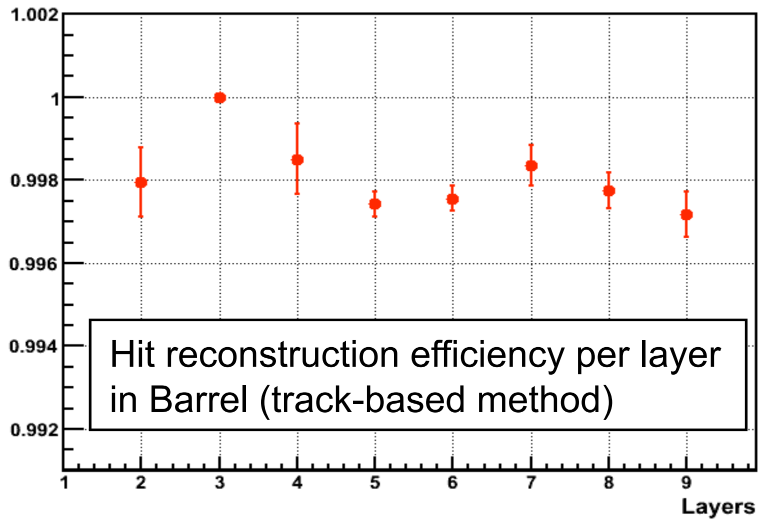
5M reconstructed events



First cosmic track at TIF

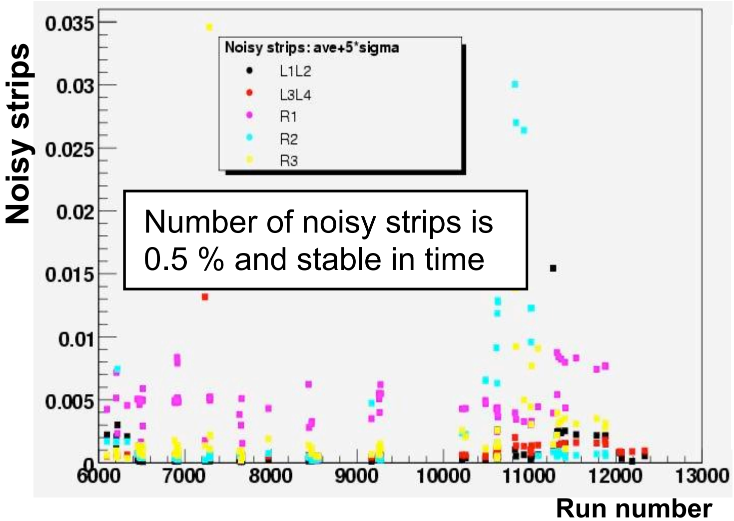
Illuminated detector (3D hit position)

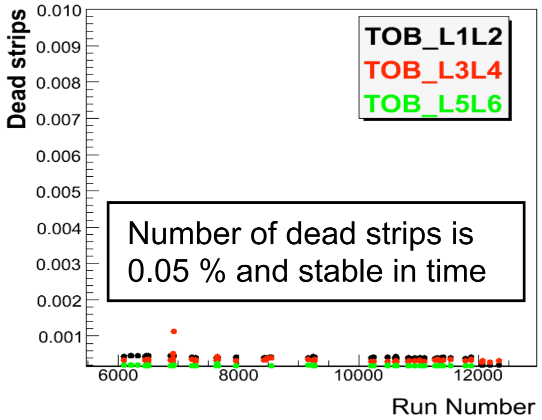


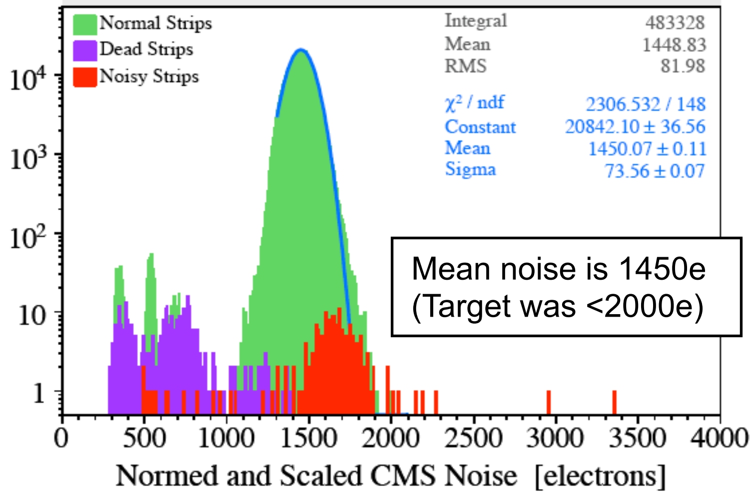


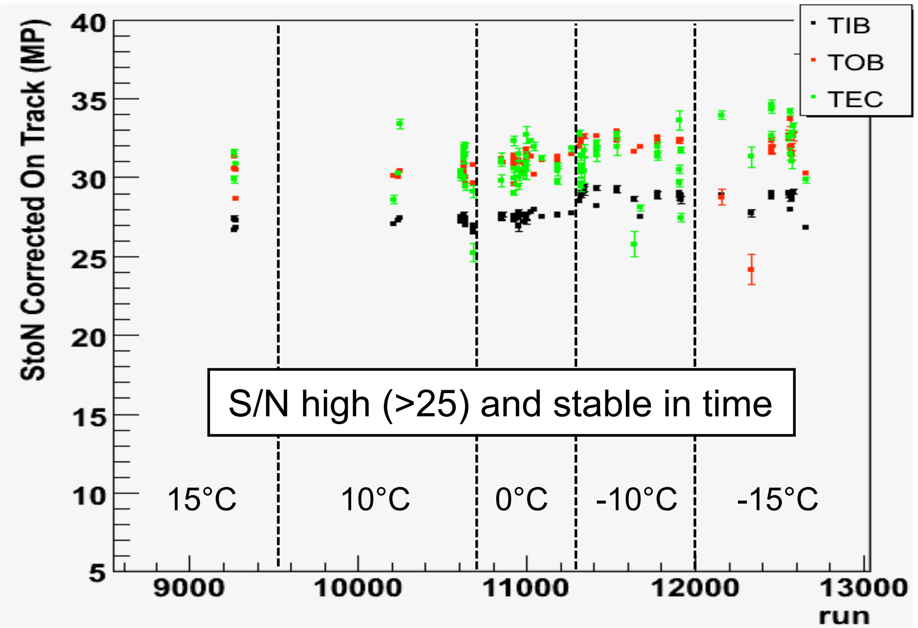
Hit reconstruction efficiency per layer in Barrel (track-based method)

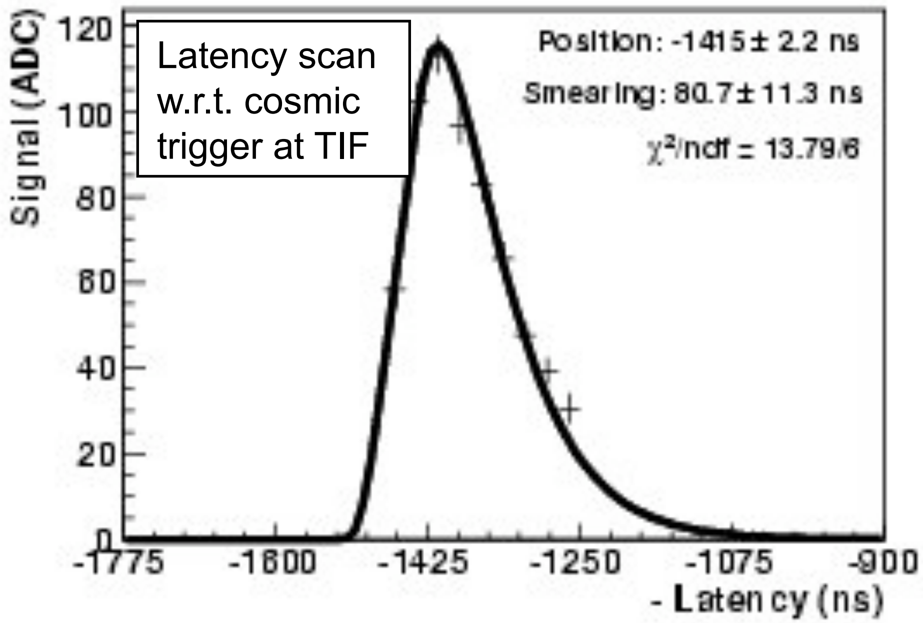
Signal and noise performance











Installation within CMS at P5

- Tracker installed on 15th December 2007

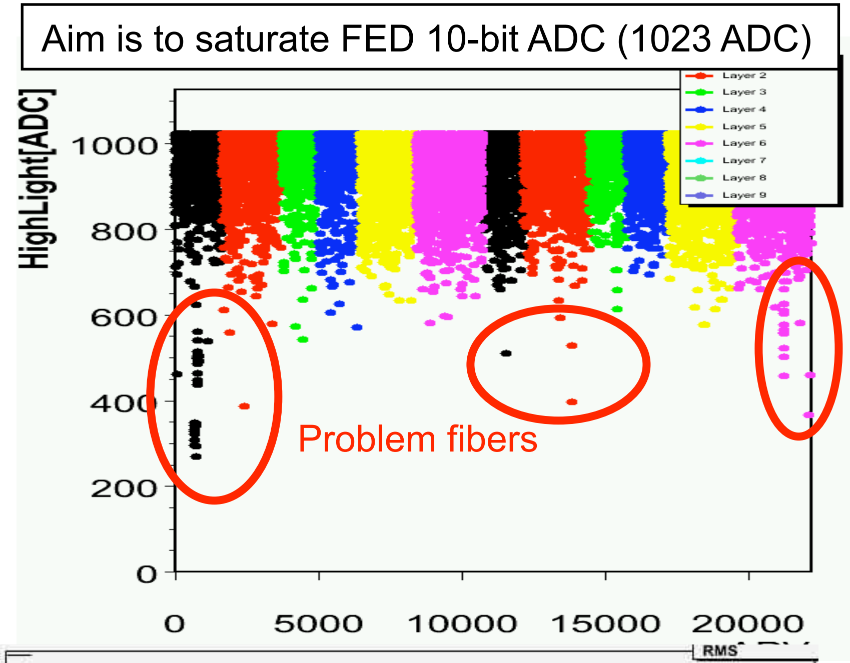
Commissioning procedures

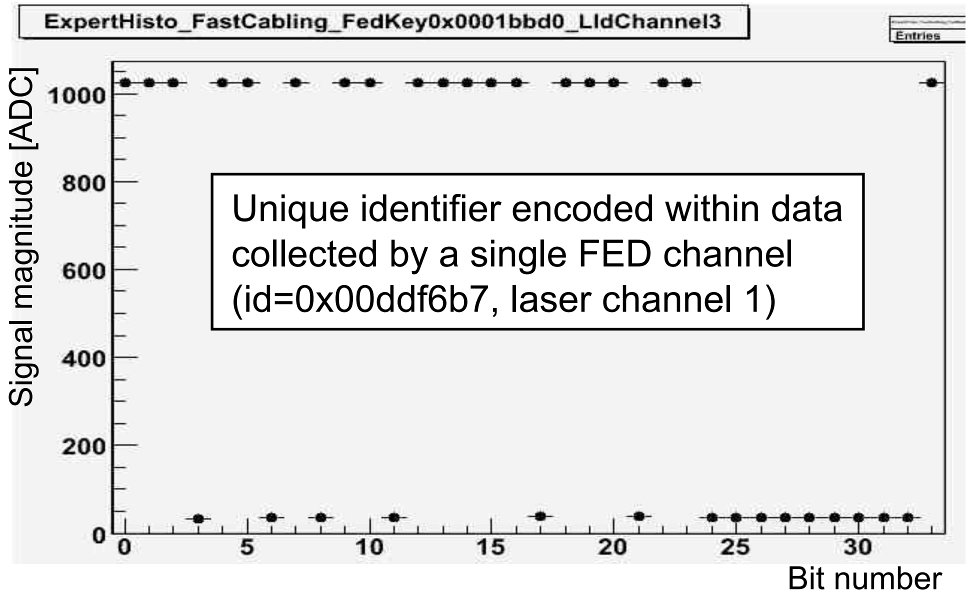
- Aim: synchronous operation with CMS, maximize S/N, minimize occupancies
  - Procedures are usually done in "stand-alone" mode using local DAQ prior to CMS global runs
- Connectivity
  - Test communication with front-end devices via control system
  - Determine readout fibre connections b/w front-end and off-detector FEDs (and flag any problems)
  - Establish HV/LV power supply connections to front-end devices and sensors
- Tracker calibration
  - Internal synchronization (guarantee synchronous sampling at the front-end)
  - Tune optical link system (optimise dynamic range and gain, calibrate)
  - Tune configuration of front-end ASICs (operational modes, biasing, gain settings…)
  - Tune and calibrate APV25 pulse shaping (maximise S/N, minimise "fakes" in adjacent BX)
  - Determine FED calibration constants (pedestals and noise constants, flag dead and noisy channels)
- Commission with CMS
  - Synchronize with global trigger (latency scans to "time in" tracker system)
- Other commissioning activities concerning services infrastructure and systems
  - Power Supplies, Detector Control and Safety System, VME electronics (trigger, control, readout)
  - DAQ software, databases, procedures

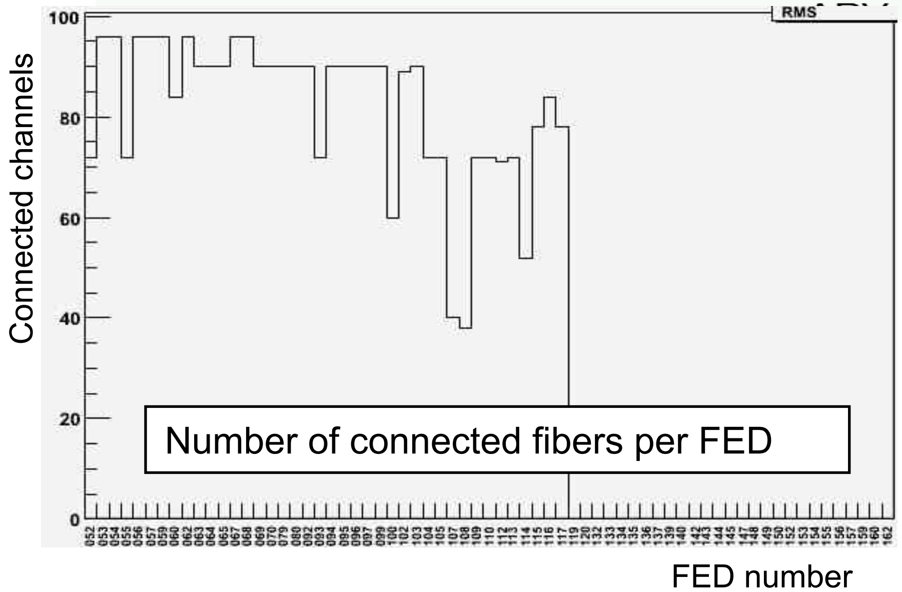
Readout fibre connections

- Readout system comprises 38k optical fibres
  - Require automated procedure to establish "cabling"

  - Aim: assign raw FED data to detector modules
  - (ie, fibre connections b/w FEDs and front-end APVs)
  - Global hit position inferred from geometry
  - Each front-end module has DCU chip with unique id
  - Data within each FED channel contains encoded id
  - Identifies faulty connections and abnormal FED settings

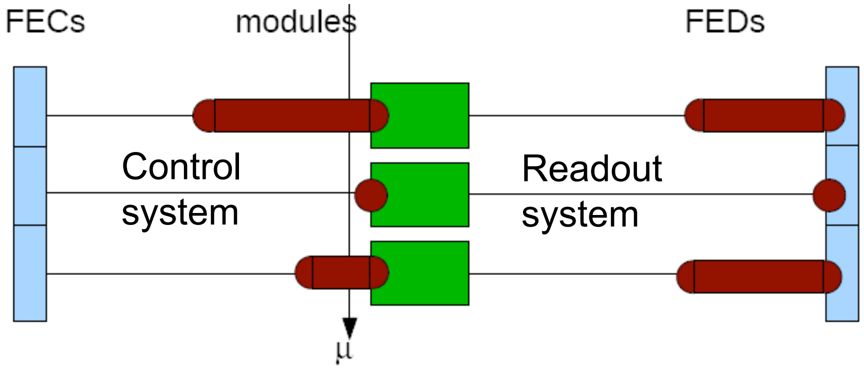


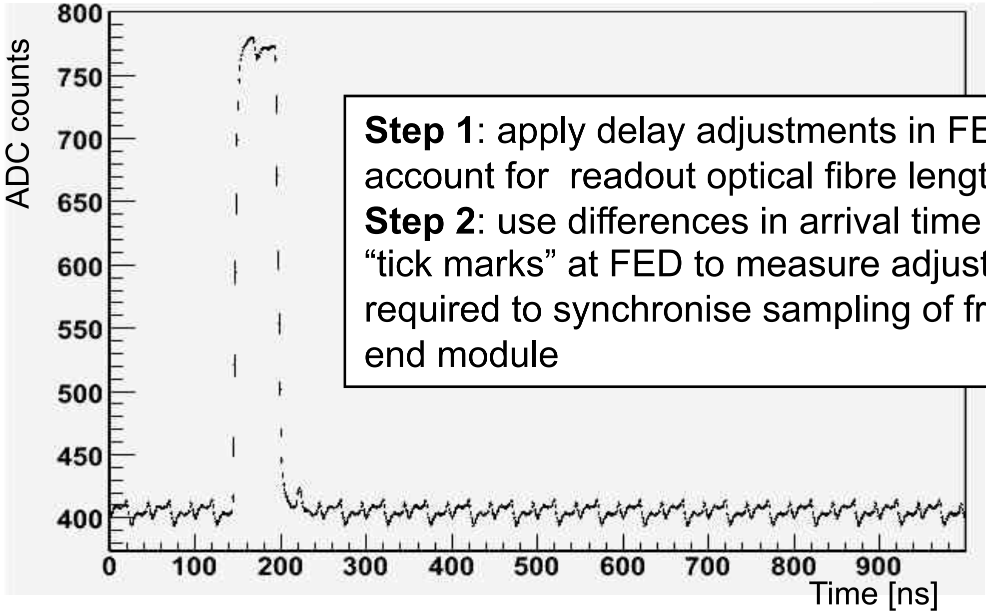




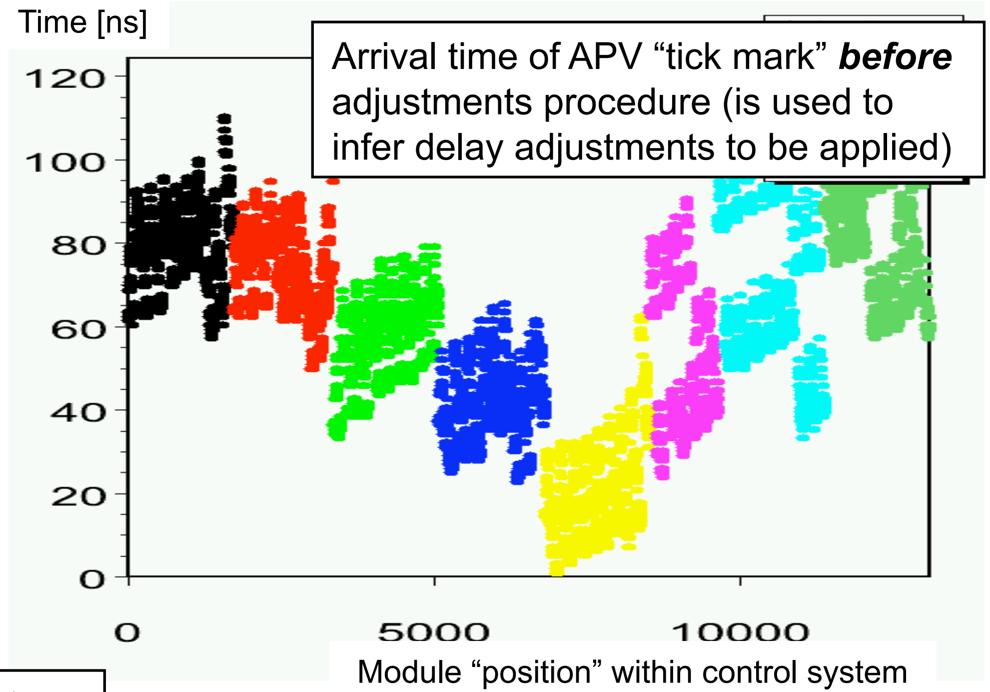
Synchronisation of APV25 chips

Delay adjustments must be applied to **front-end modules** and **FED FPGAs** to account for different signal propagation times in control and readout systems

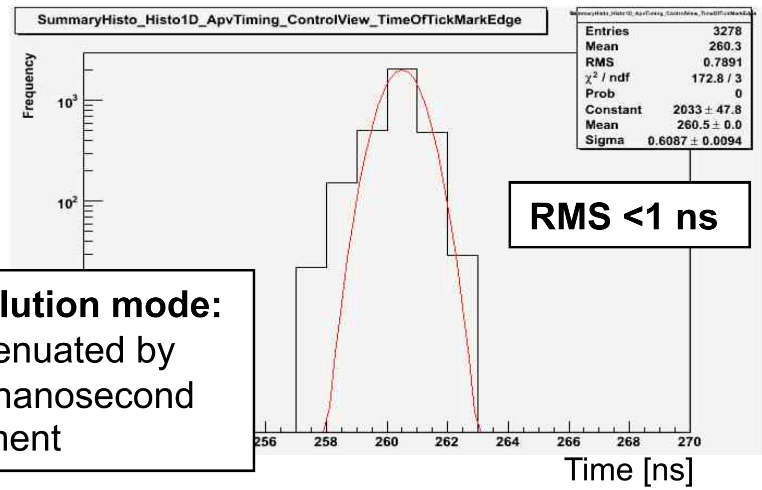




Step 1: apply delay adjustments in FED to account for readout optical fibre lengths
Step 2: use differences in arrival time of APV "tick marks" at FED to measure adjustments required to synchronise sampling of front-end module



Arrival time of APV "tick mark" ***before*** adjustments procedure (is used to infer delay adjustments to be applied)



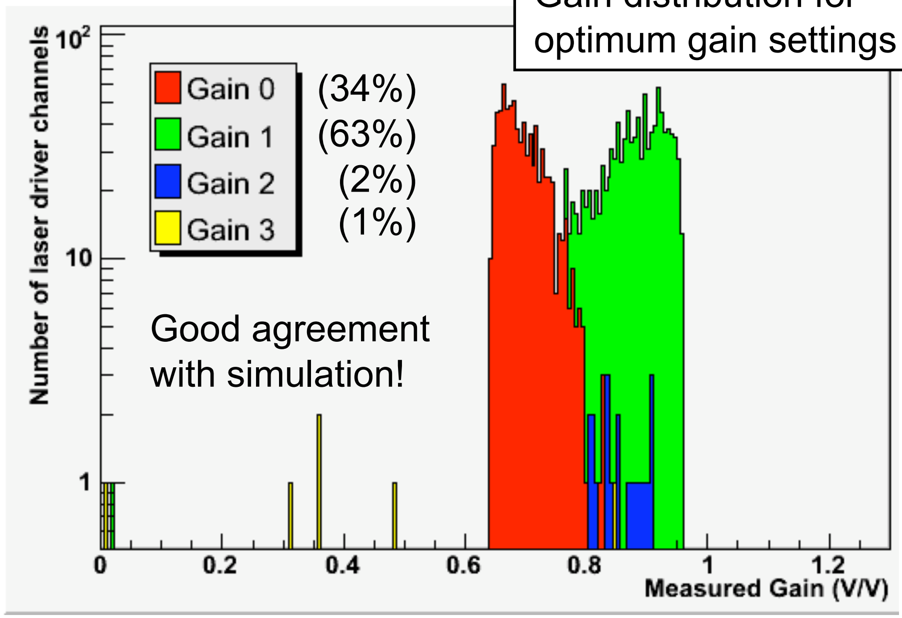
RMS <1 ns

Deconvolution mode: signal attenuated by ~4% per nanosecond misalignment

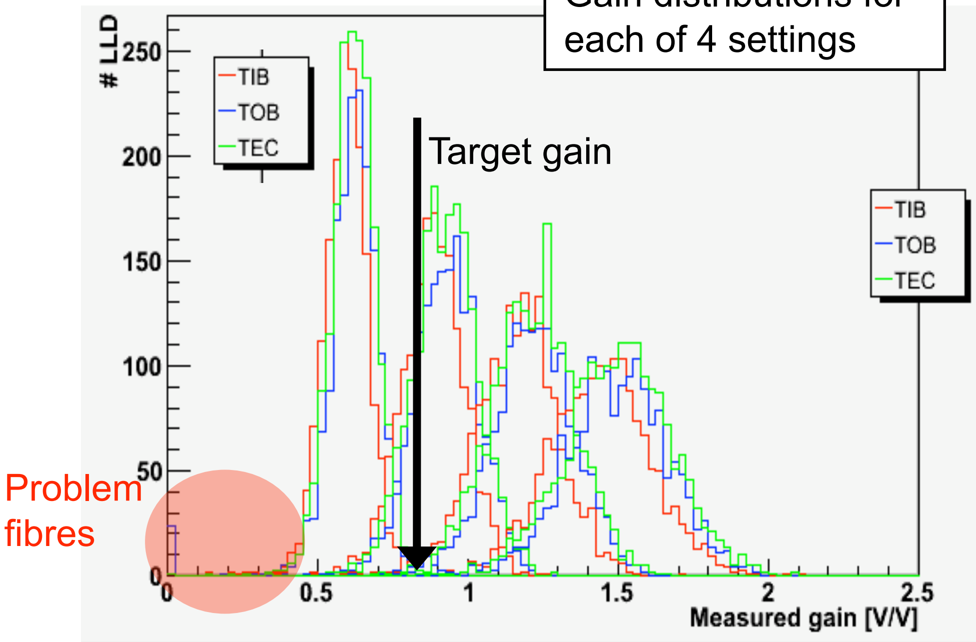
Tuning of readout optical link system

- Tune linear laser driver on front-end module
  - Four gain settings, target gain is 0.8 [V/V]
  - Tune bias setting to give max dynamic range
- Procedure allows to identify/measure:
  - Optimum gain, laser thresholds…
  - Best gain/bias settings

Gain distribution for optimum gain settings

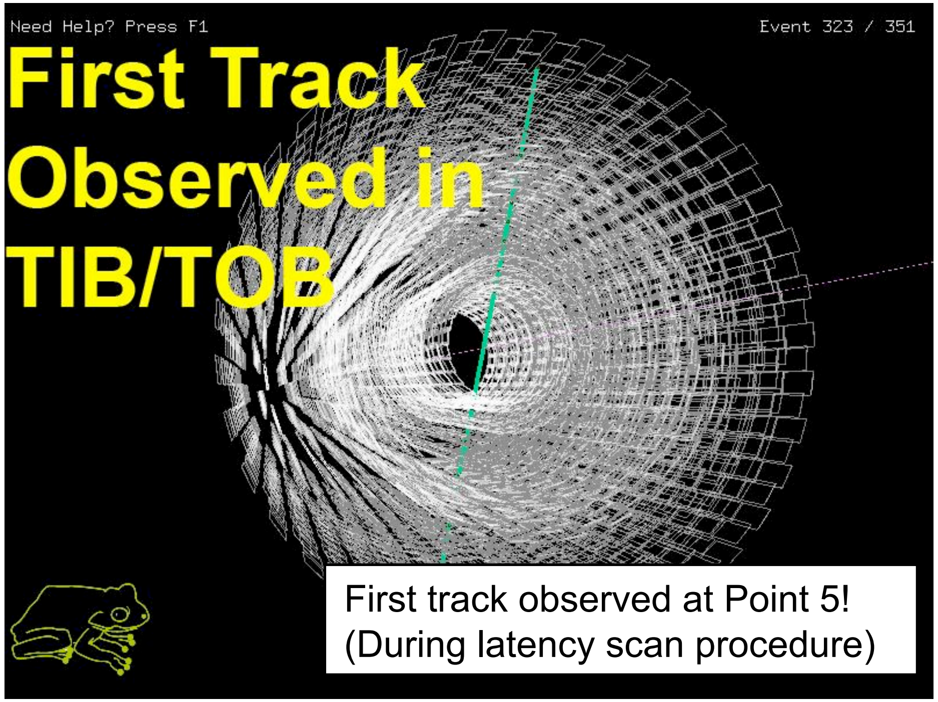


Gain distributions for each of 4 settings



Summary of commissioning results

- Modules or fibres are disabled if:
  - LV problems
  - Unable to configure device(s)
  - Unable to lock onto clock
  - Faulty fibre (“low light” or broken)
  - Some can be recovered
- Further ~1% modules exhibit noise problems
  - Largely due to power supply problems and tuning
  - Can be solved for most modules



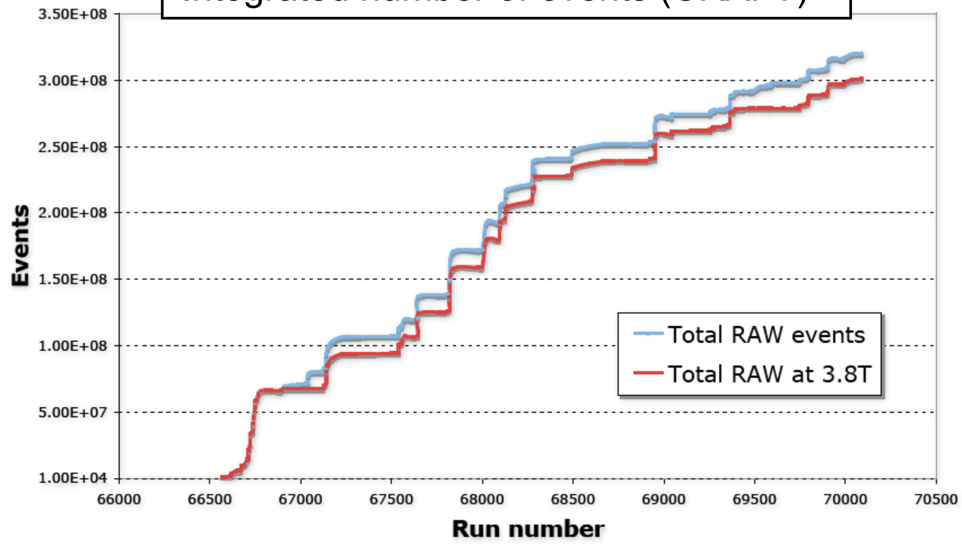
Working system for CMS global runs, as defined by commissioning procedures

Sub-system	Front-end modules			Fibre connections		Active [%] (max)
	Total	Responsive	Disabled	Total	Missing	
Outer Barrel	5208	5196	4	12043	19	99.5 (99.9)
Inner Barrel	3540	3481	0	9012	14	98.2 (99.3)
End-Cap +	3200	3183	6	7506	4	99.4 (99.9)
End-Cap -	3200	3192	2	7535	9	99.6 (99.8)

Global run operations

- Several flavours of global runs
  - CRUZET (Cosmic RUn at Zero Telsa),
  - CRAFT (Cosmic Run At Four Tesla)
  - MWGR (Mid-Week Global Run)
  - Private runs (eg, tracker/muon synchronisation)
- Tracker participation
  - CRUZET3 (mid-July, ~week)
  - CRUZET4 (late-August, ~week)
  - 95% "uptime" for CRAFT (Oct/Nov, 3 weeks)
  - Highest average L1 trigger rate: 550 Hz
  - Tracks: few Hz with DT top or bottom

Integrated number of events (CRAFT)



Global run type	B-field	
	off	on
CRUZET1 (no TK)	40M	-
CRUZET2 (no TK)	32M	-
CRUZET3	68M	-
CRUZET4	61M	-
MWGR	40M	-
Commissioning	76M	-
CRAFT	39M	290M

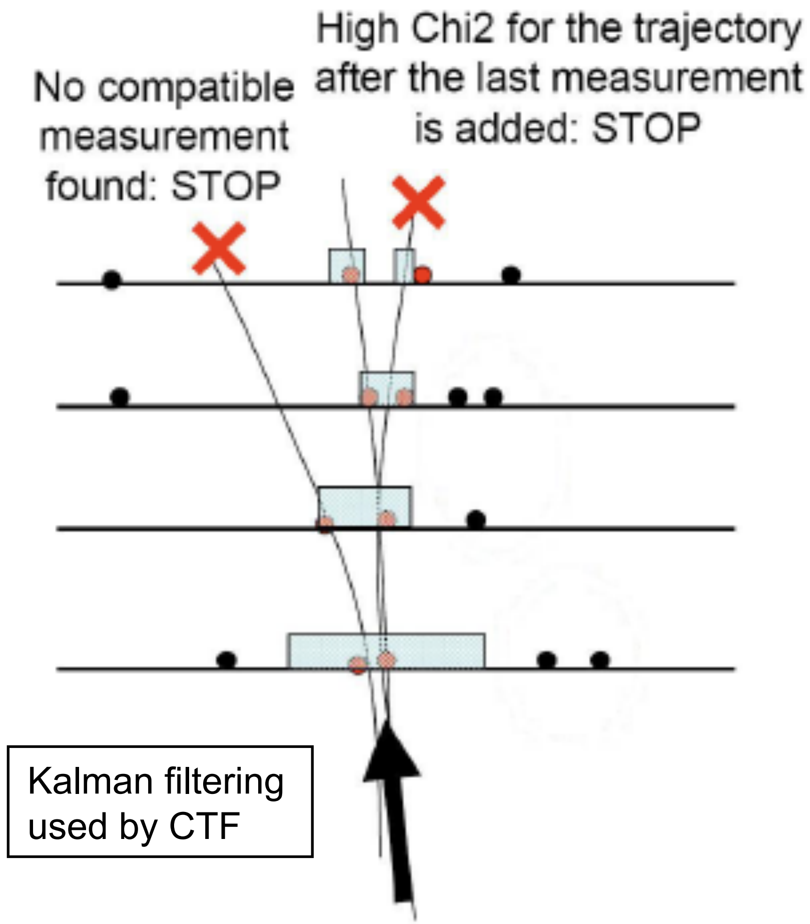
Datasets and statistics for CRAFT

Dataset	DBS Catalogue Name	Events
RAW	/Cosmics/Commissioning08-v1/RAW	451517246
RECO	/Cosmics/Commissioning08-PromptReco-v2/RECO	392004024
AlCaReco 1	/Cosmics/Commissioning08_CRAFT_V2P_StreamALCARECOTkAlCosmics0T_v7/ALCARECO	1319828
AlCaReco 2	/Cosmics/Commissioning08_CRAFT_V3P_StreamALCARECOTkAlCosmics0T_v11/ALCARECO	3607135
Pointing	/Cosmics/Commissioning08_CRAFT_V1P_TrackerPointing_v3/RECO	757992
SuperPointing	/Cosmics/Commissioning08_CRAFT_V3P_SuperPointing_v4/RECO	664326

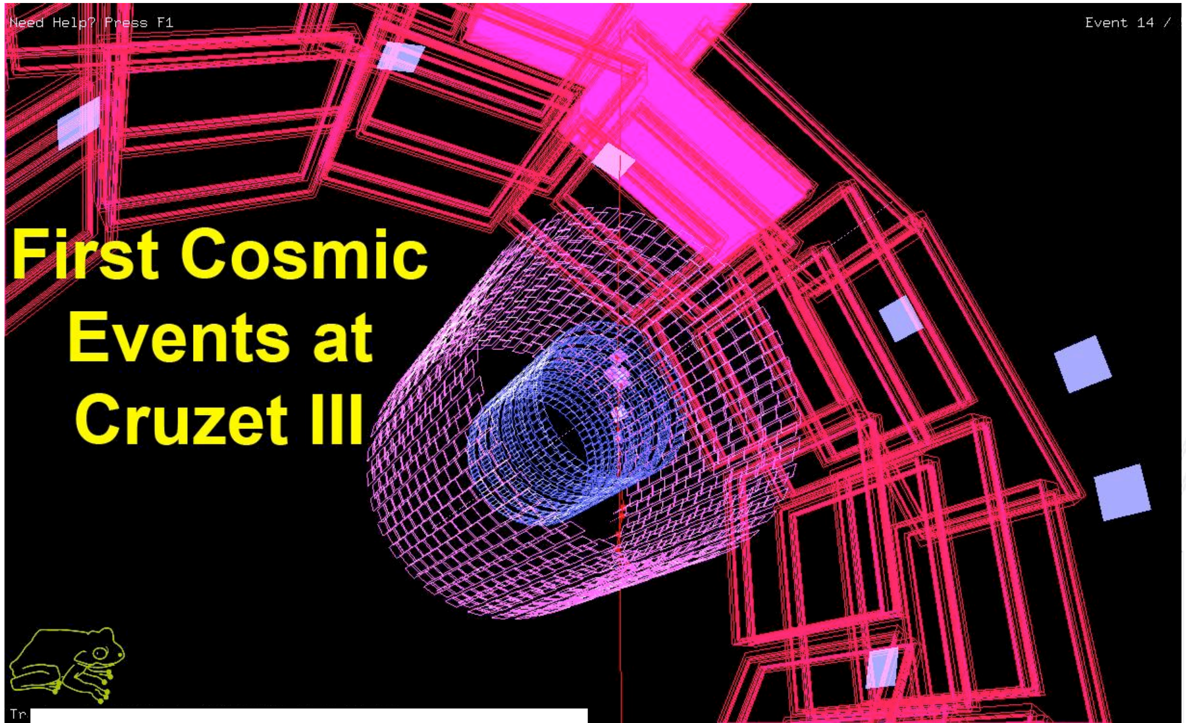
Track reconstruction

- Tracking algorithm: 3 steps
  - Seed creation: first estimate of parameters
  - Pattern recognition: associates hits to a track
  - Fitting procedure: best estimate of track parameters
  - (Only fitting procedure is common to all algorithms)

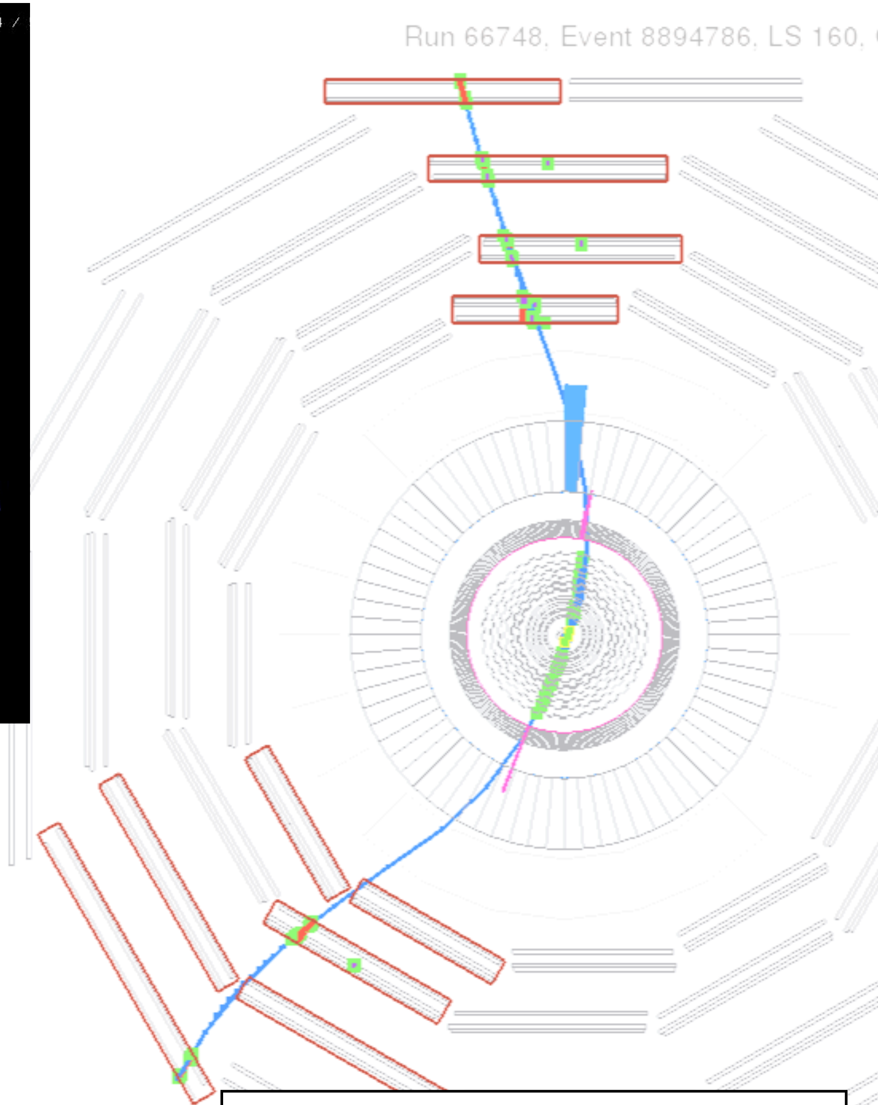
- Presently using three tracking algorithms
  - Combinatorial Track Finder (CTF, default)
  - Road Search (RS)
  - Cosmic Tracker Finder (CoTF)
  - (CTF/RS designed for pp collisions, CoTF for cosmics)



First tracks during CRUZET and CRAFT



First cosmic track through tracker barrel during CRUZET3



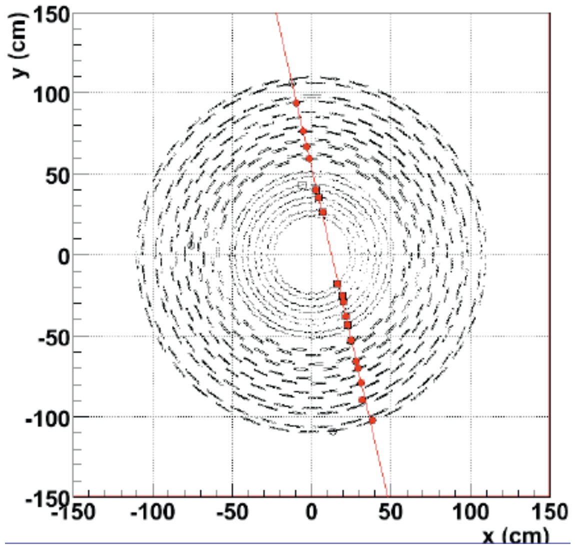
Track through micro-strip and pixel detectors with B-field of 3.8 T

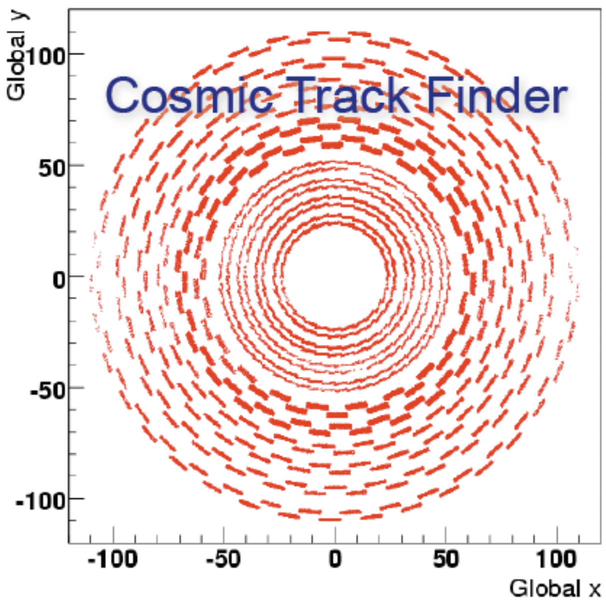
Detector coverage

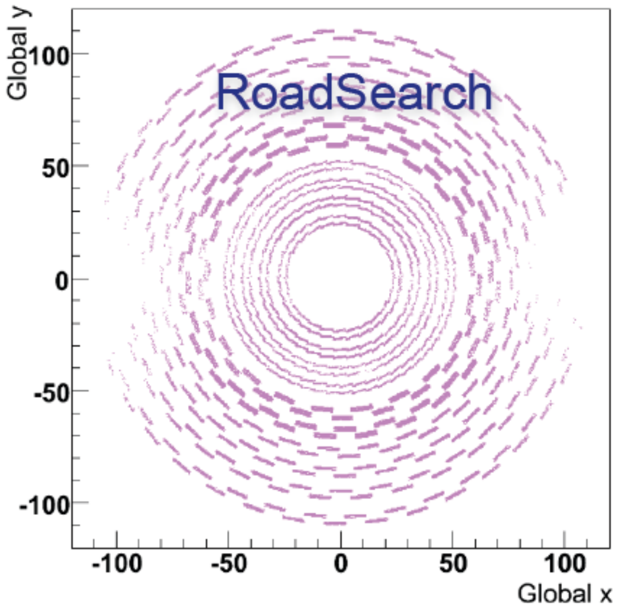
- Distribution of "on-track" clusters within barrel
  - Example track shown opposite
  - Hit density maps shown for three different tracking algorithms
  - Data from CRUZET3 runs (no B-field)

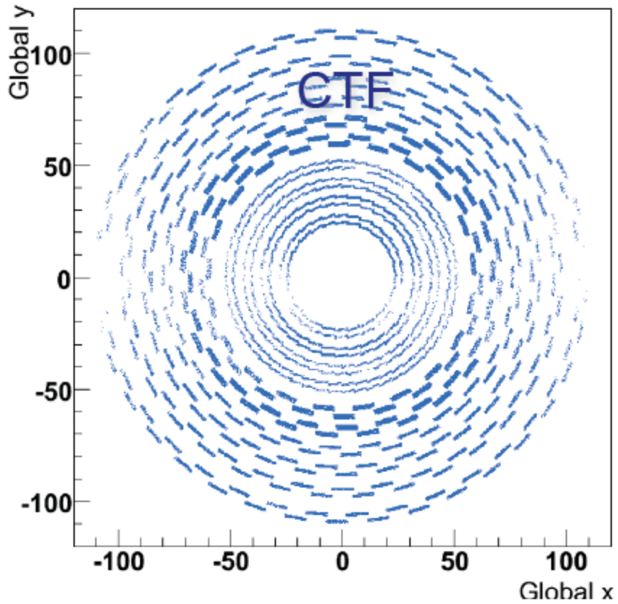
S/N for on-track clusters

	Expected S/N	Measured S/N
TIB	24	15
TIB	28	29



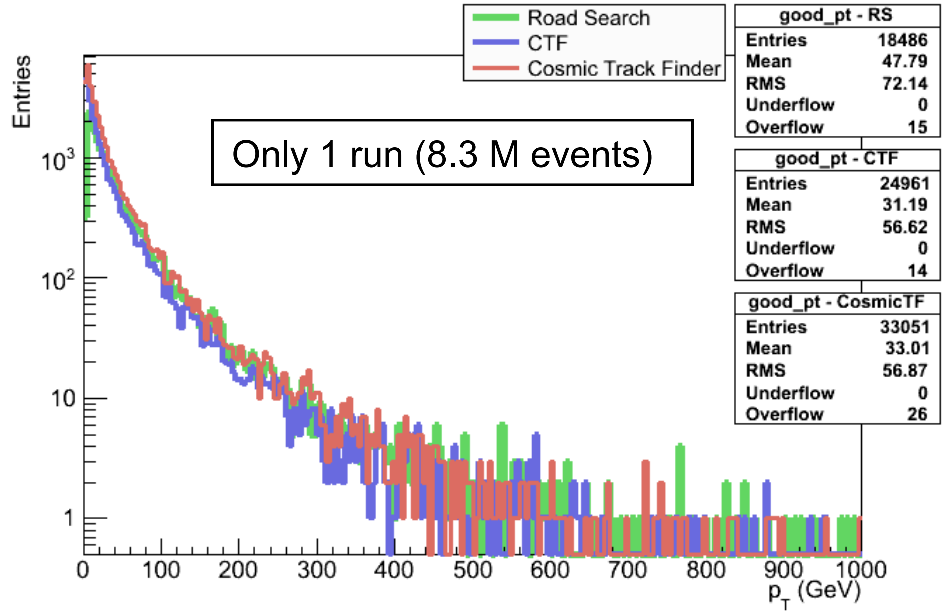


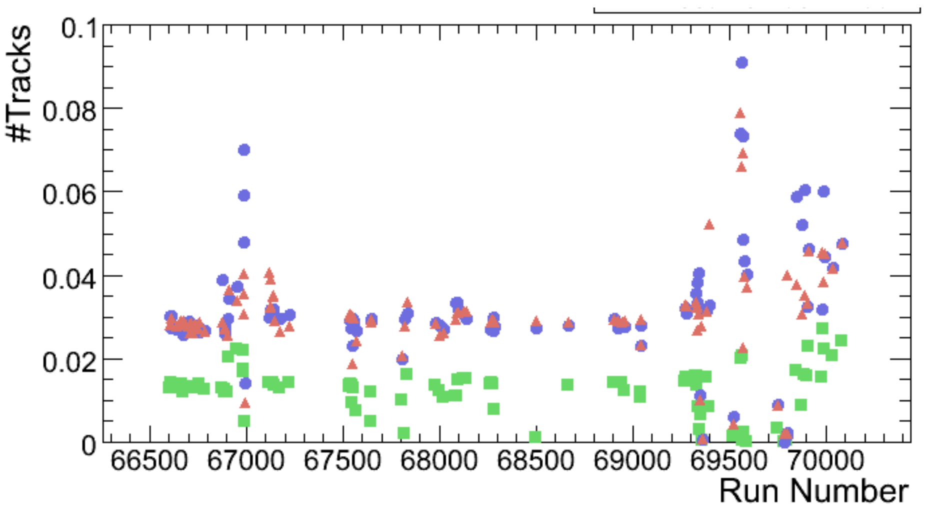


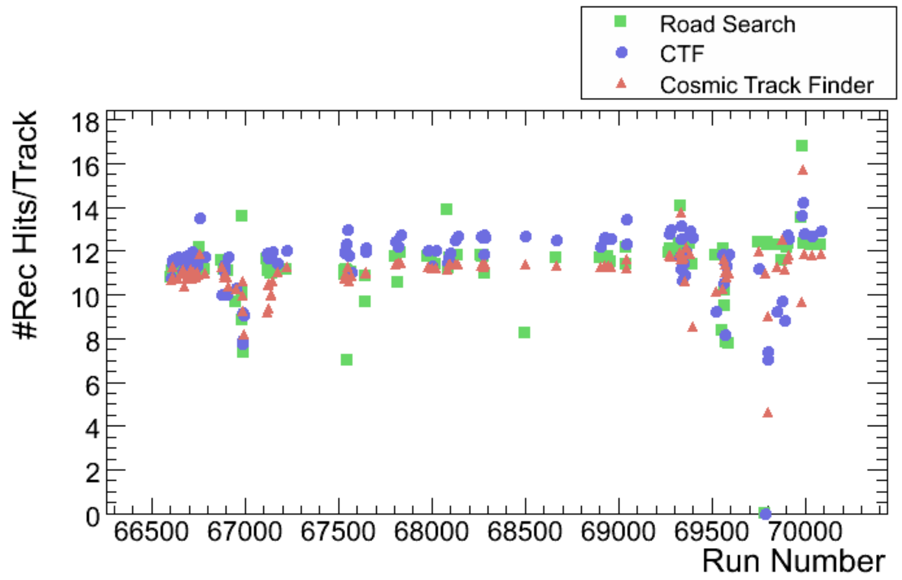


Track statistics and momentum spectrum

- CRAFT: 290M events processed
  - 6.3M events with 6.3M CoTF tracks (1/ev)
  - 4.8M events with 6.7M CTF tracks
  - 2.5M events with 2.6M RS tracks
- Track reco. efficiency given "pointing" muon
  - "Pointing" (@ tracker volume): 55-60%
  - "Super-pointing" (|x| < 40cm): 65-75%
- Based on spectrum, expect:
  - 2.4M tracks with > 20 GeV
  - 0.5M tracks with >100 GeV

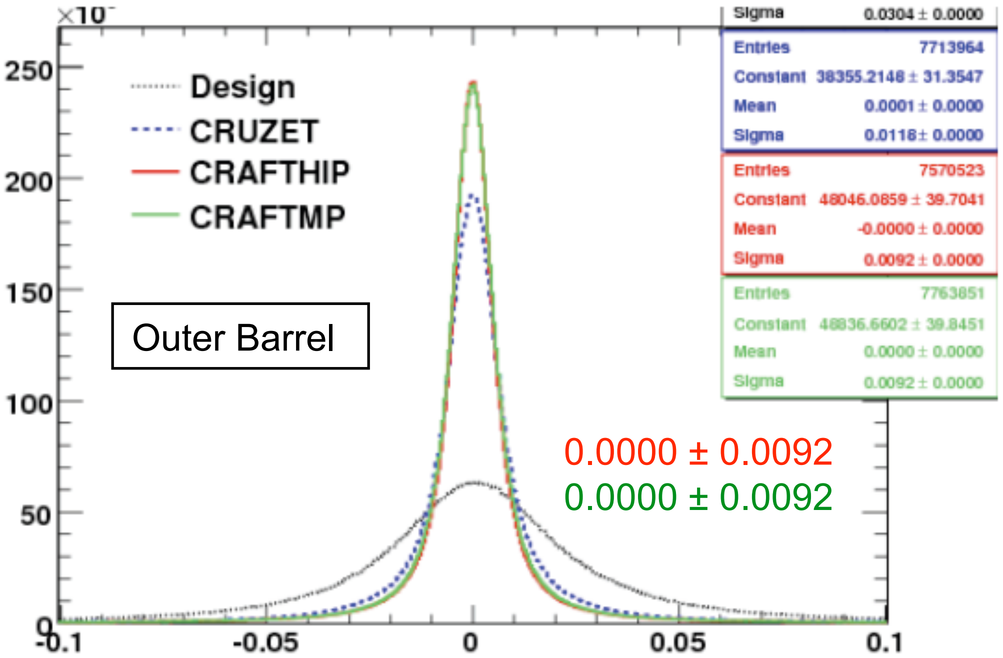


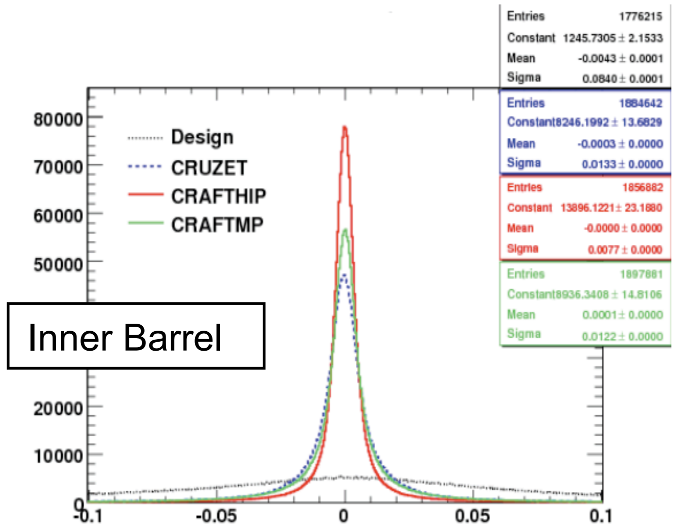


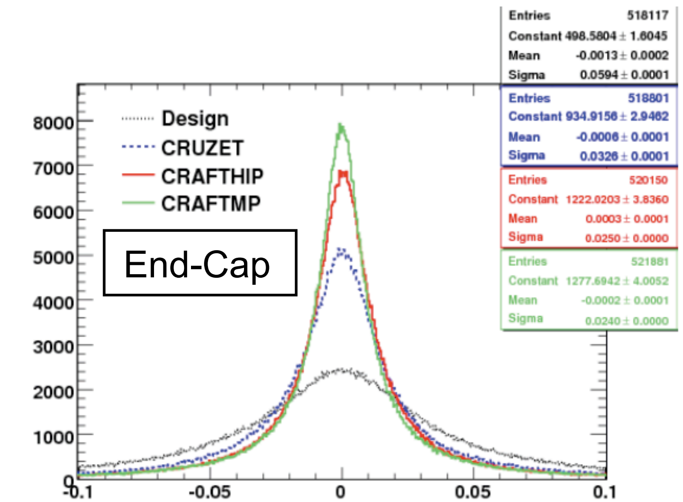


Residuals

- Two algorithms used
  - Millipede (layer-level alignment followed by module-level)
  - HIP (moduel-level alignment with survey constraint)
- Each plot (TIB,TOB,TEC) shows four curves
  - Residuals based on survey position
  - Based on alignment parameters from CRUZET data
  - Based on CRAFT data for both algos

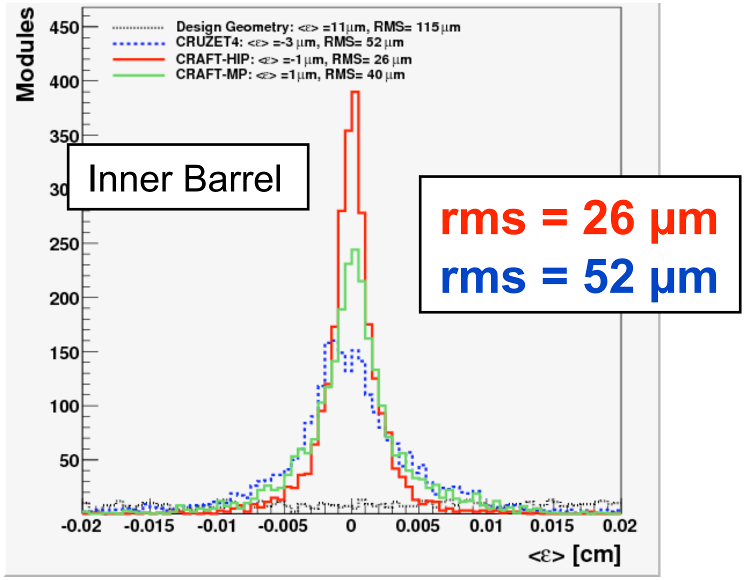


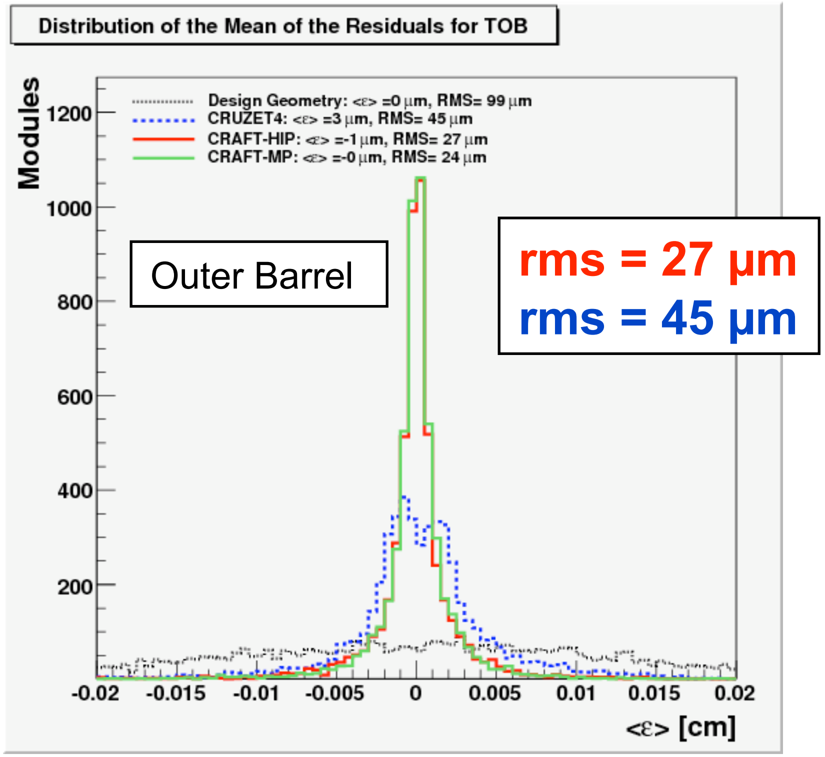


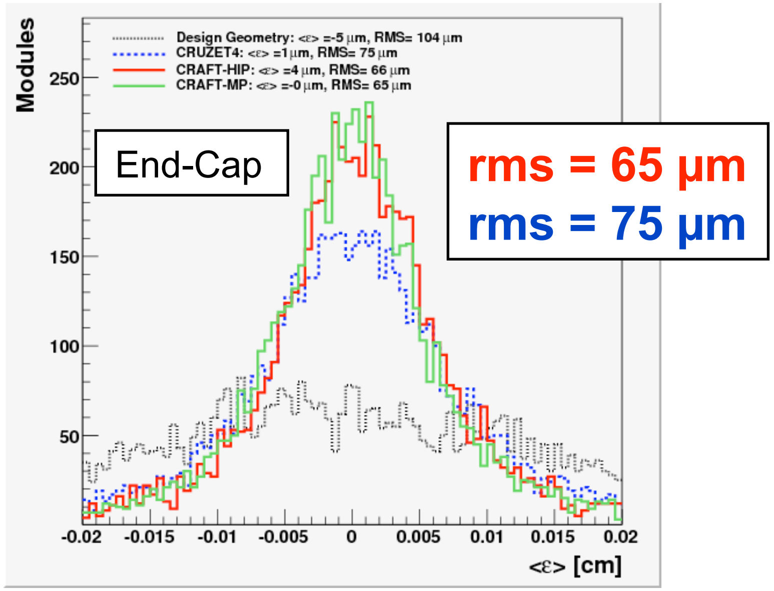


Mean residuals

- Plots contain one entry per module
  - Red is using HIP on CRAFT data
  - Blue is using HIP on CRUZET4 data
- Significant improvement using CRAFT data
  - Improvement for pixel barrel too: 112 μm to 47 μm

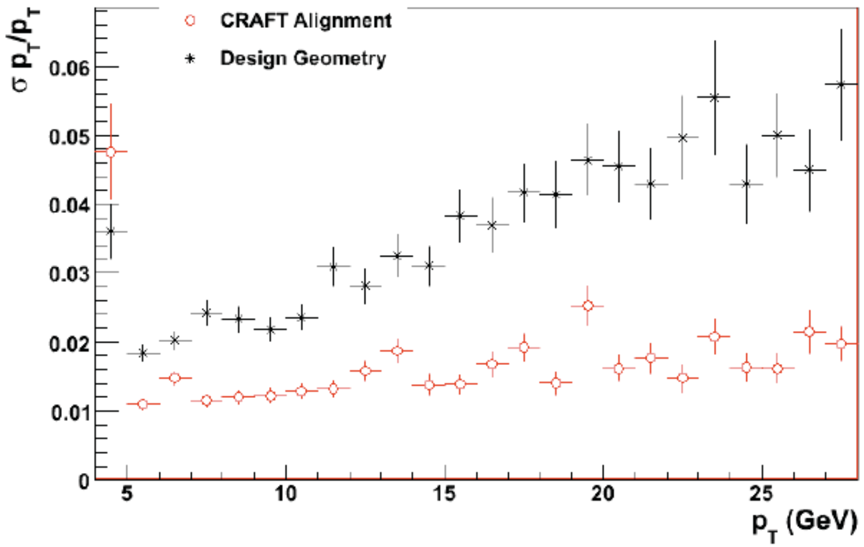


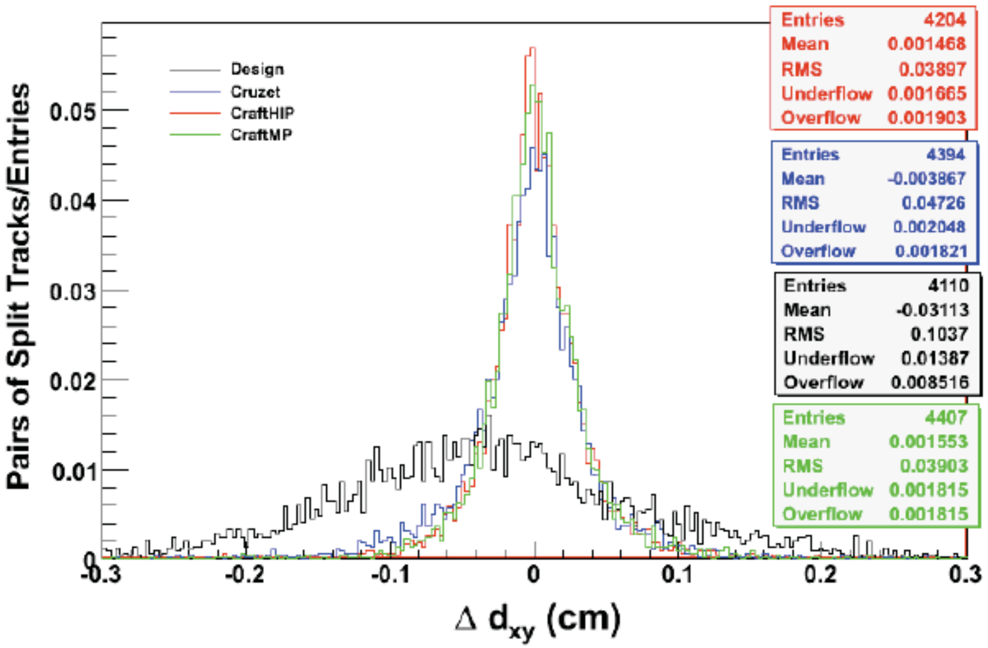


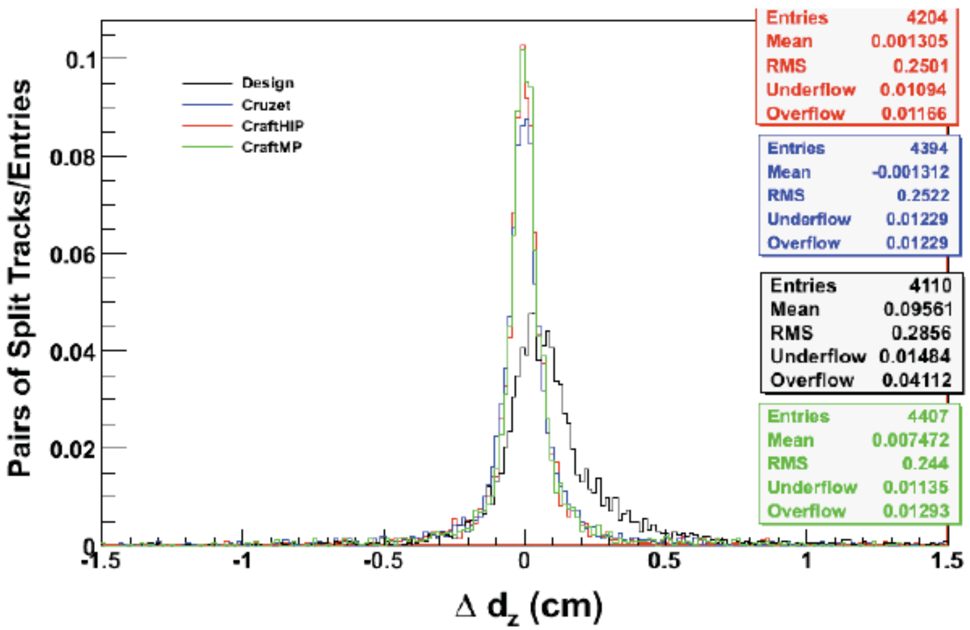


Track parameter resolutions

- Cosmic tracks split at centre
  - Two new tracks reconstructed
  - Comparison of parameters

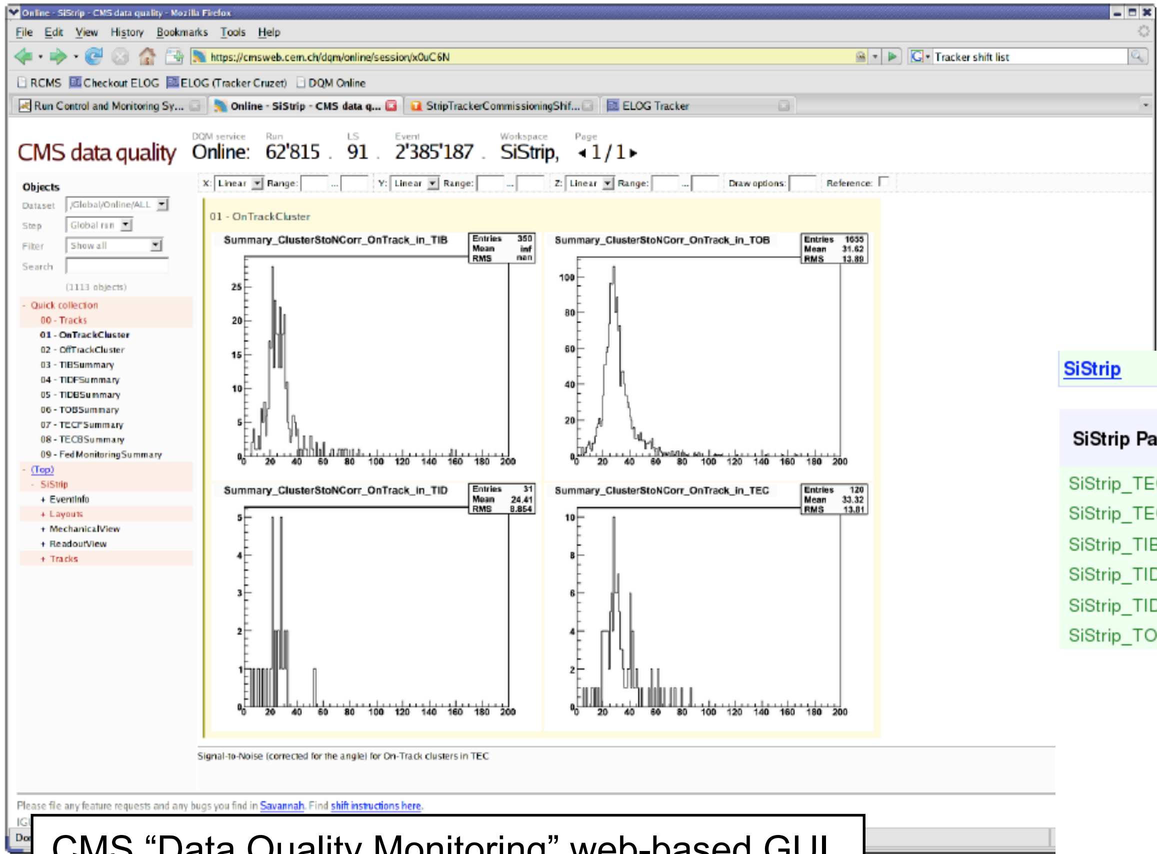






Detector monitoring

- Tracker has extensive monitoring tools for inspecting event data and reco objects
  - Provides immediate on detector performance issues and is used to classify runs quality
  - Feedback often very useful for shifters and experts
  - Has already revealed several, subtle effects in during global runs – some examples on next slides…

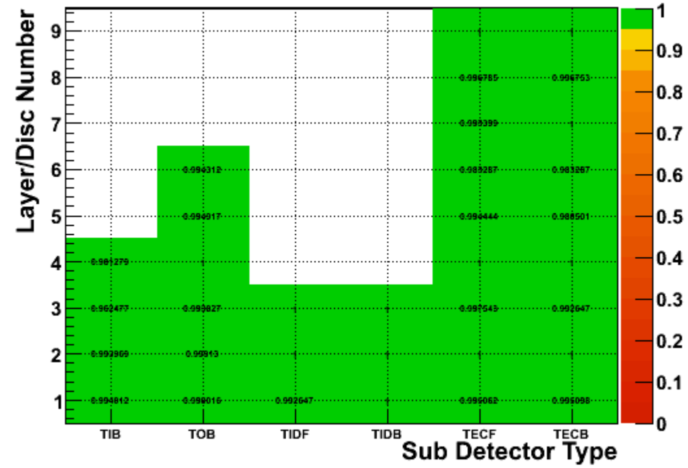


CMS “Data Quality Monitoring” web-based GUI, showing S/N for “on-track” clusters

Top-level summary of tracker status (fraction “good”), based on “logical OR” of Quality Tests applied to quantities extracted from module-level histograms

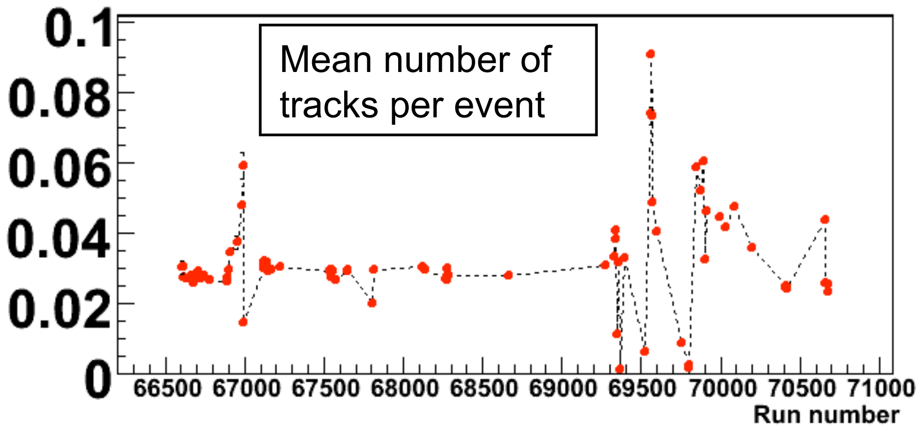
SiStrip	99.4%	66740	98 5340568	32" in future	1' 35" ago	14900	0.21	1273

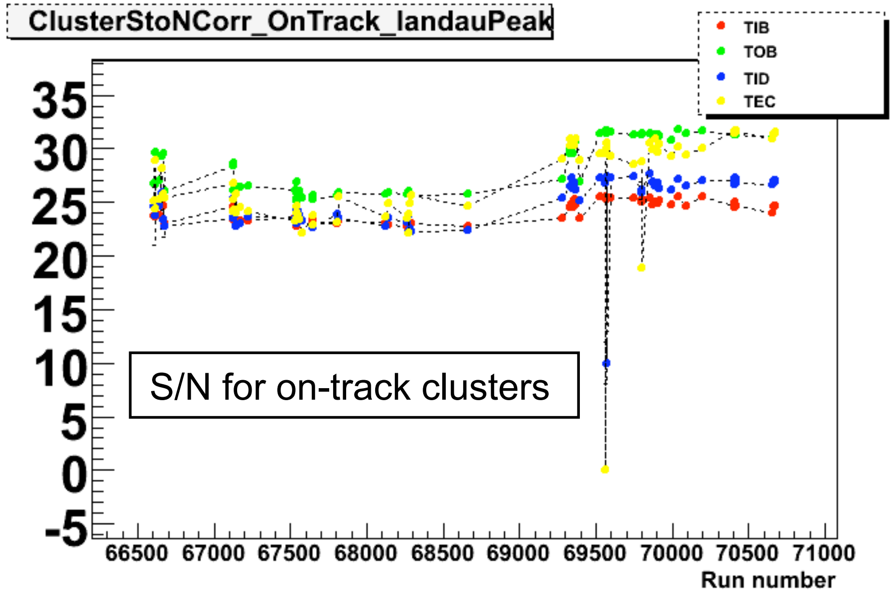
SiStrip Part	Status
SiStrip_TECB	99%
SiStrip_TECF	100%
SiStrip_TIB	98%
SiStrip_TIDB	100%
SiStrip_TIDF	100%
SiStrip_TOB	100%

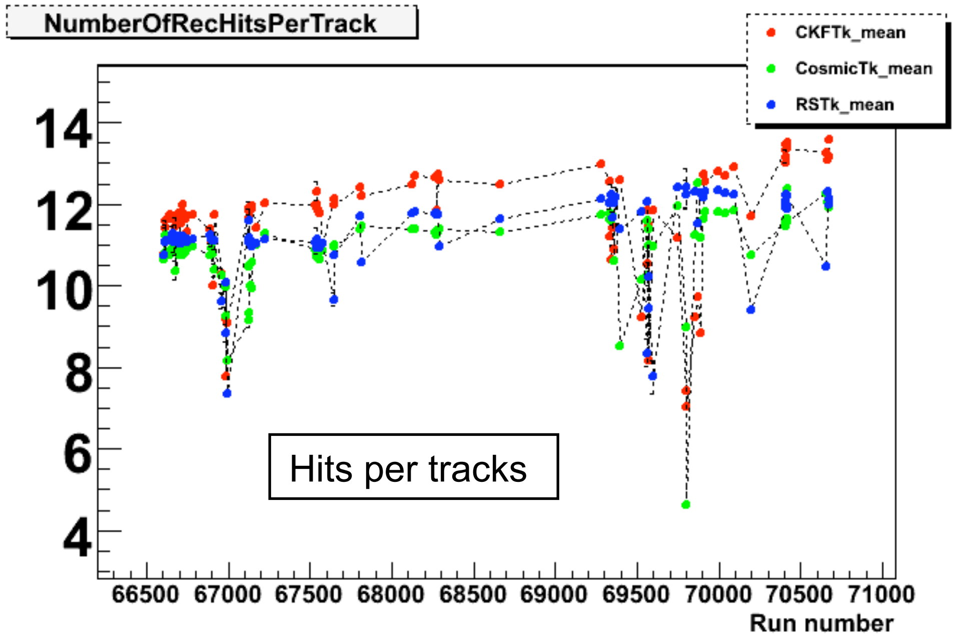


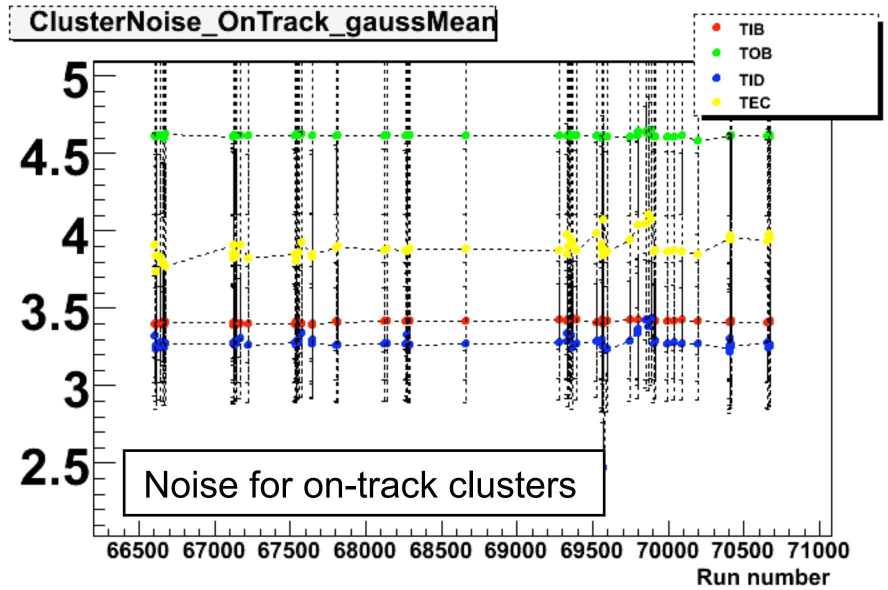
Some track-related trend plots

- Runs during the CRAFT data-taking period

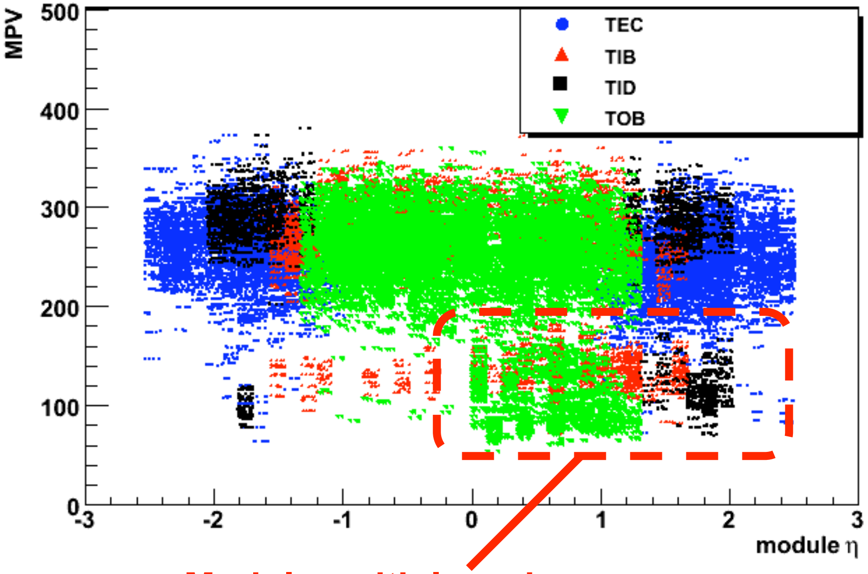




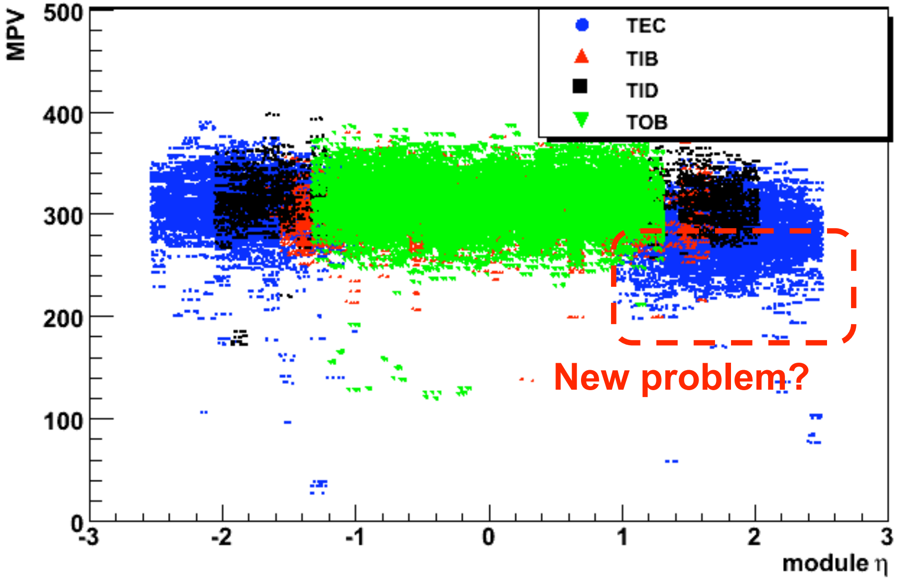




Front-end synchronization issues

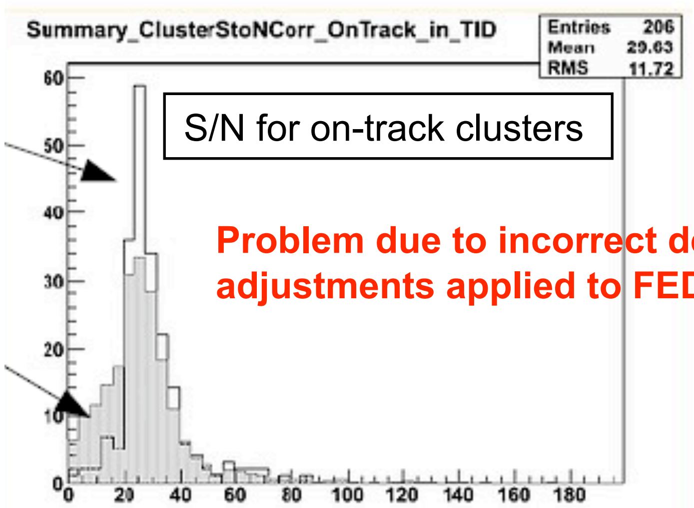


Modules with low charge

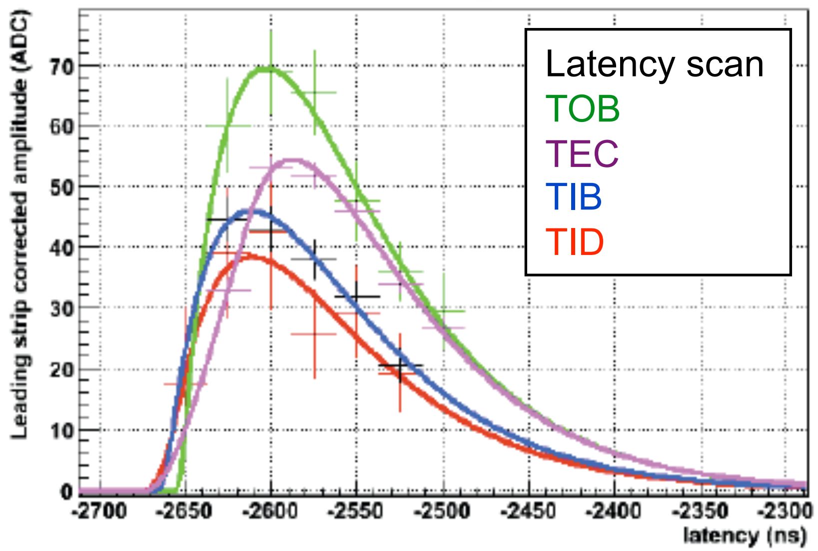


Before fix

After fix

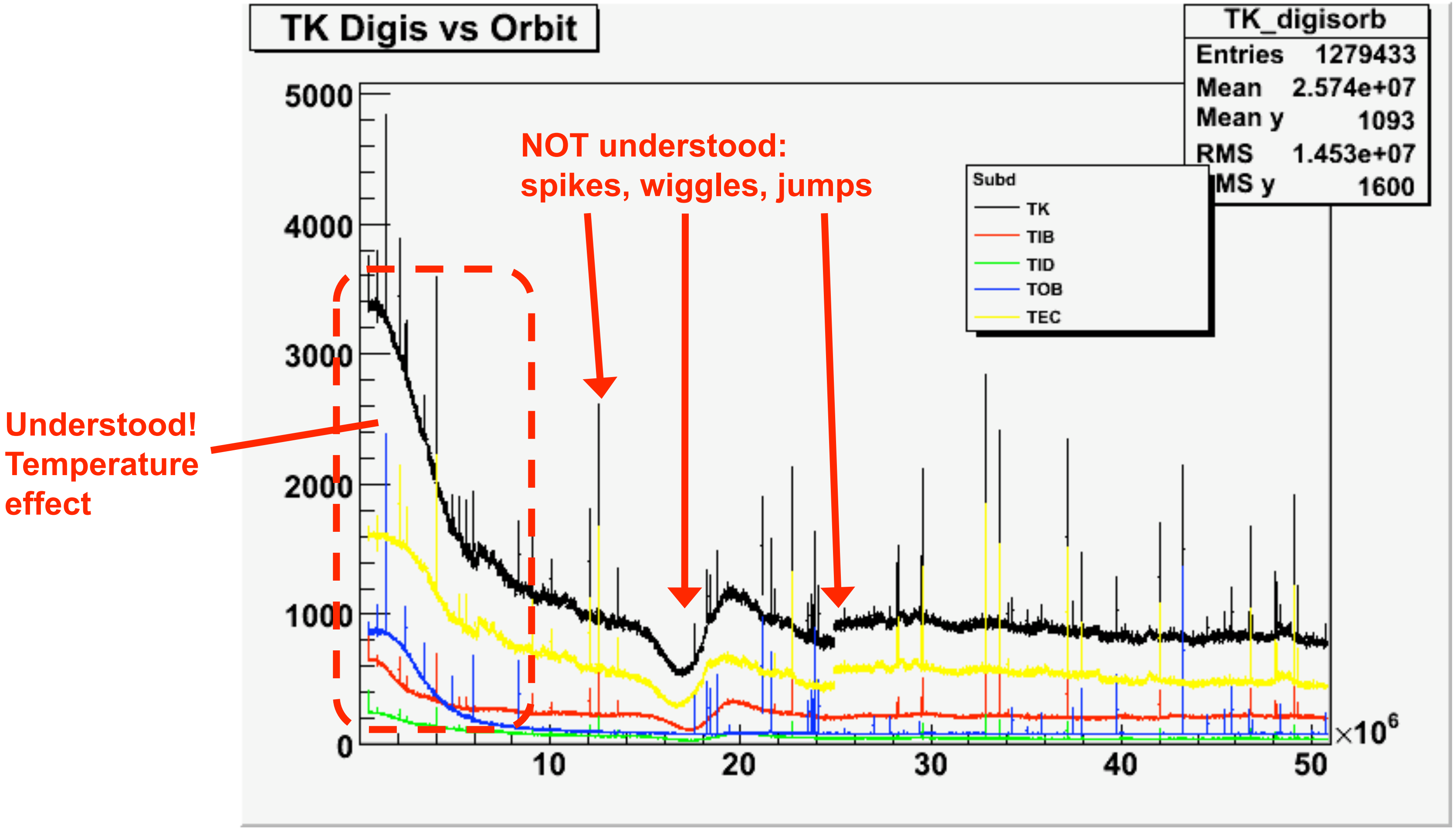


Problem due to incorrect delay adjustments applied to FEDs



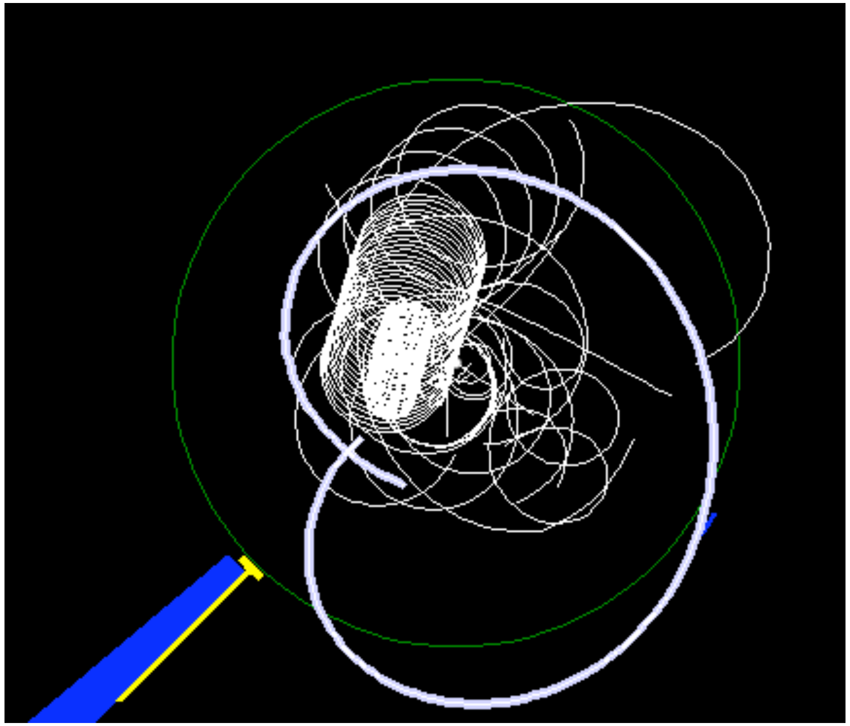
High-multiplicity events

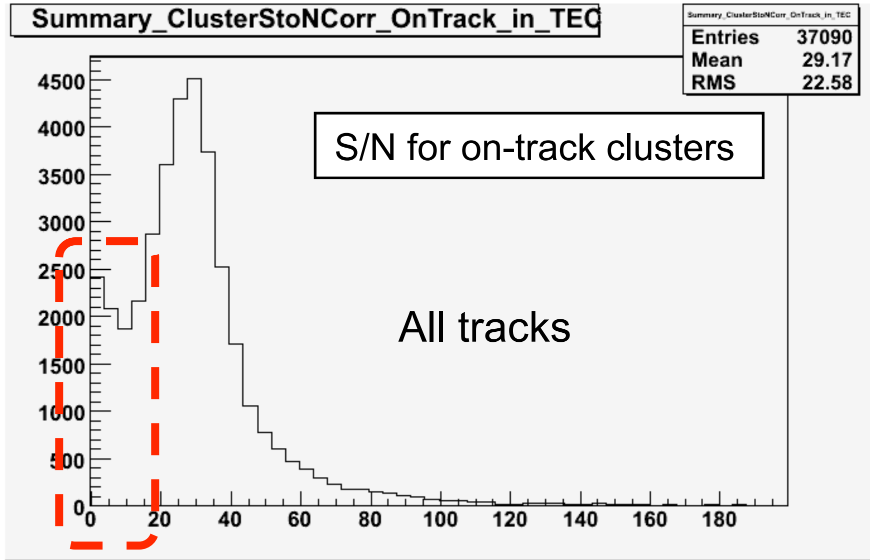
- Number of digis per event is not constant
  - Digis are equivalent to FED zero-suppressed data
  - Average number is 1000 c.f. 10M channels (so normally 10^{-4} effect)
  - (Can ignore contribution from cosmic muons – very small)

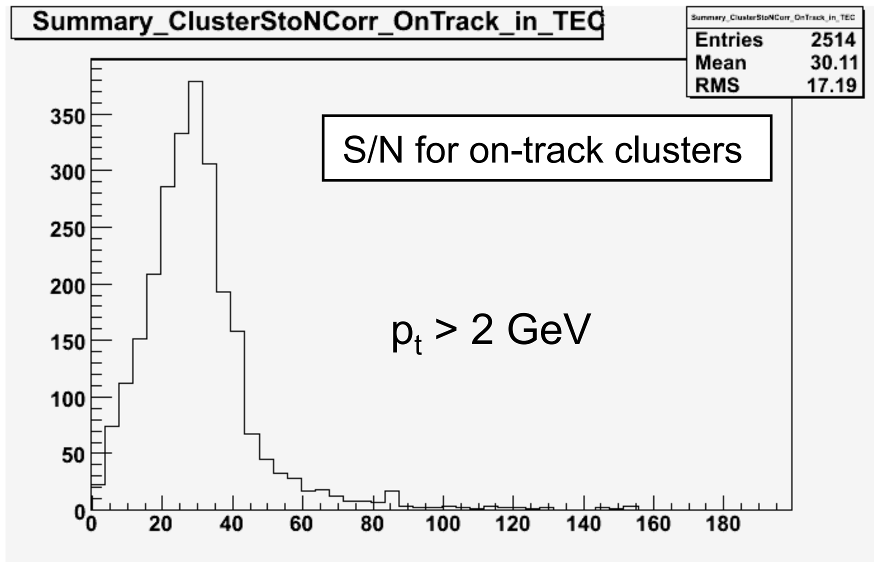


“High rate noise”

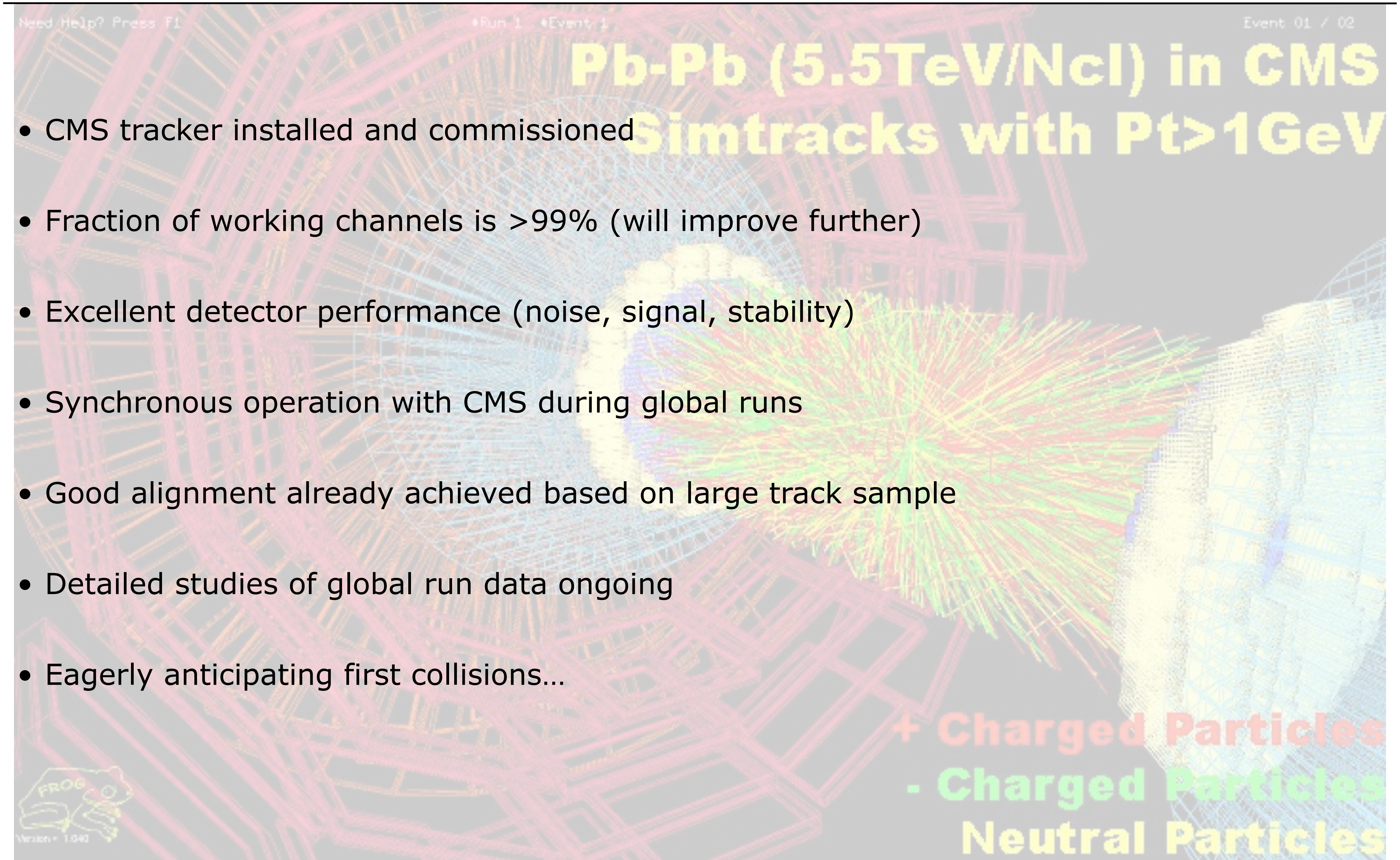
- Noise in few TEC modules at high trigger rates
  - Small fraction of modules (~10^{-3})
  - Low peak in S/N distribution for on-track clusters
  - Present only for low p_t tracks (“loopers”)
  - Appear to be susceptible to fake tracks in TEC
  - Source of the noise being investigated
  - Studies on-going, protection being prepared





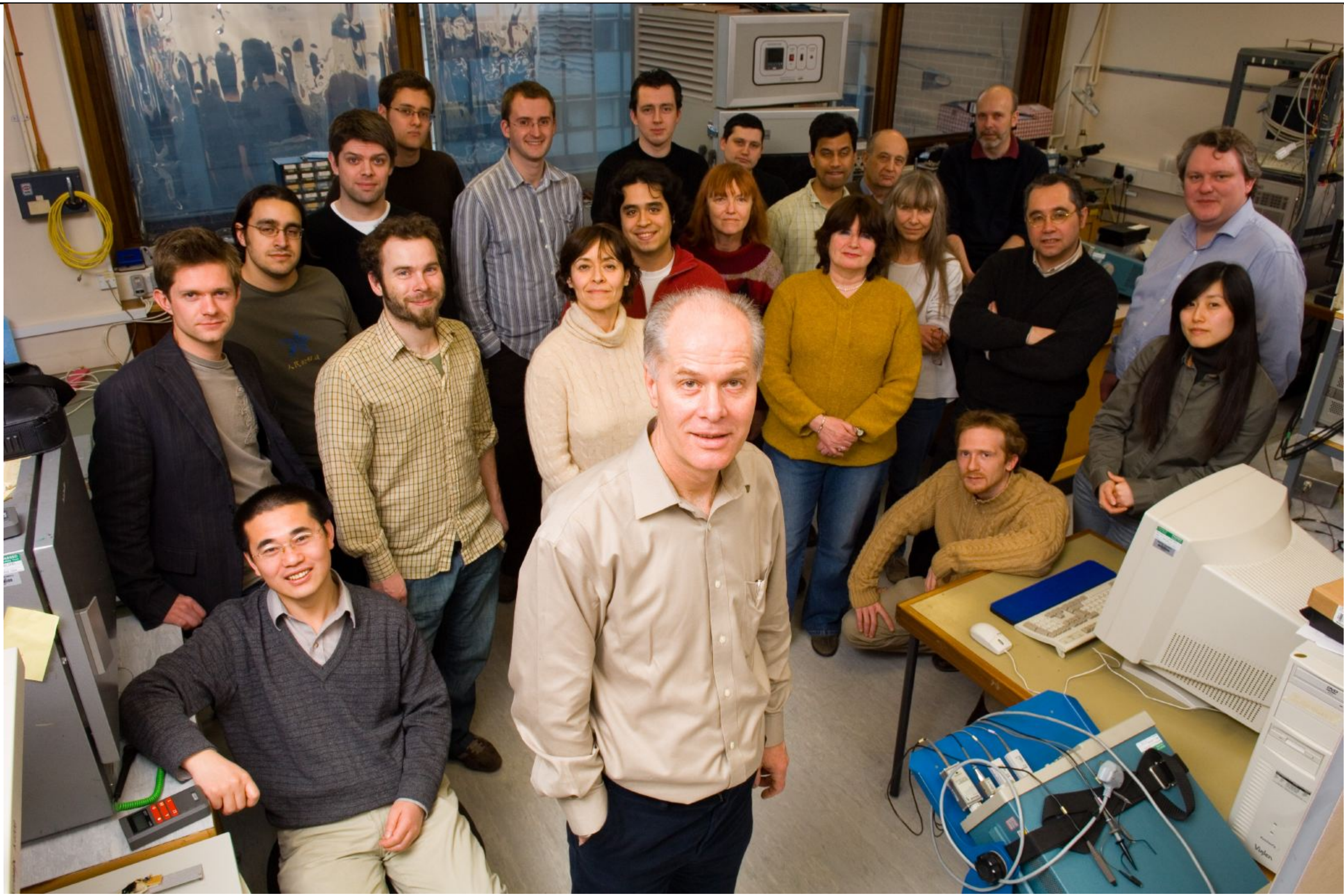


Conclusions

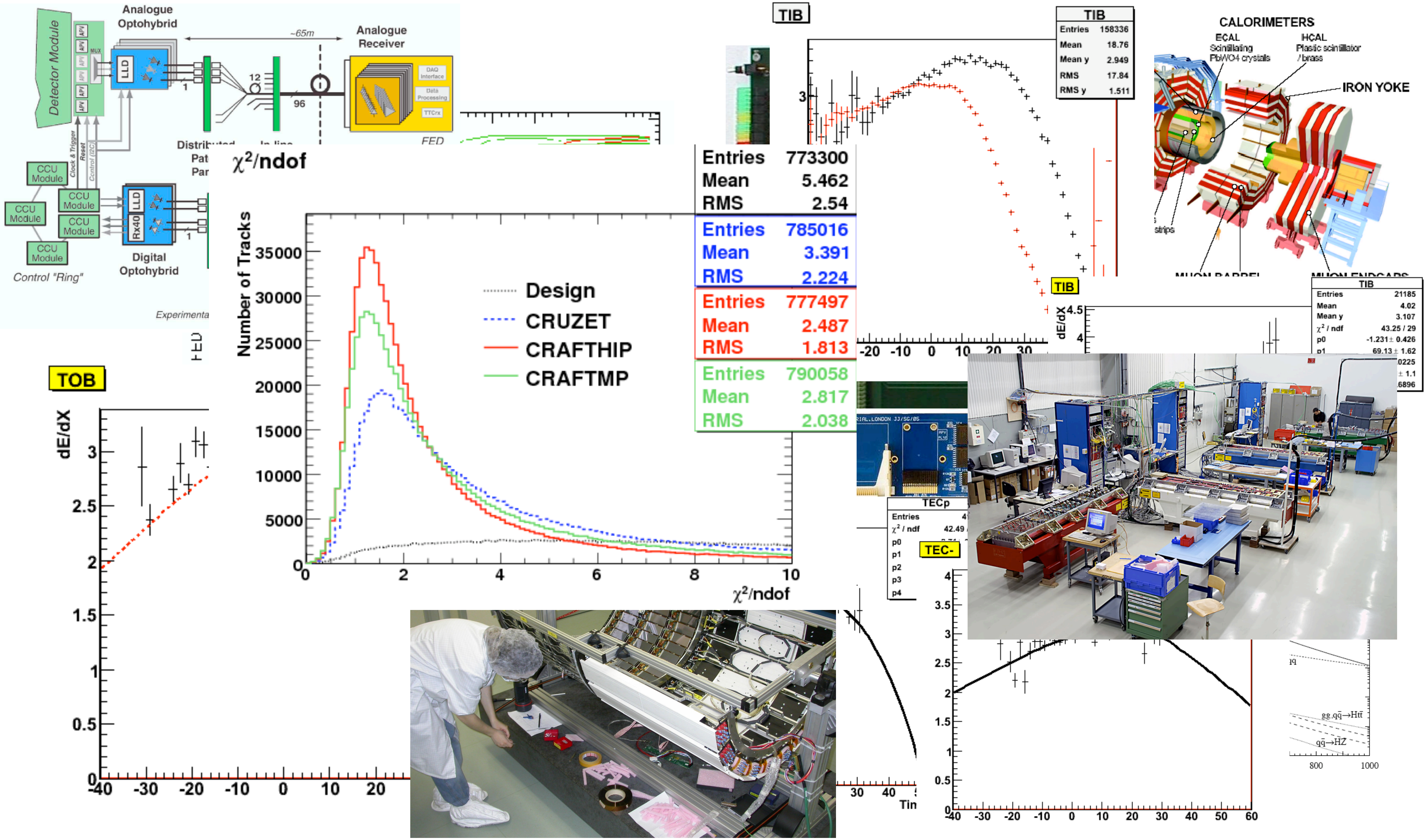


- CMS tracker installed and commissioned
- Fraction of working channels is >99% (will improve further)
- Excellent detector performance (noise, signal, stability)
- Synchronous operation with CMS during global runs
- Good alignment already achieved based on large track sample
- Detailed studies of global run data ongoing
- Eagerly anticipating first collisions…

(Some of) the Imperial CMS group



Misc



Analogue Optohybrid
Analogue Receiver
Detector Module
Digital Optohybrid
CCU Module
Control "Ring"
~65m
FED
χ^2/ndof
Number of Tracks
Design
CRUZET
CRAFTHIP
CRAFTMP
Entries 773300
Mean 5.462
RMS 2.54
Entries 785016
Mean 3.391
RMS 2.224
Entries 777497
Mean 2.487
RMS 1.813
Entries 790058
Mean 2.817
RMS 2.038
TIB
Entries 158336
Mean 18.76
Mean y 2.949
RMS 17.84
RMS y 1.511
CALORIMETERS
ECAL
Scintillating PbWO4 crystals
HCAL
Plastic scintillator /brass
IRON YOKE
TOB
dE/dX
TECp
TEC-