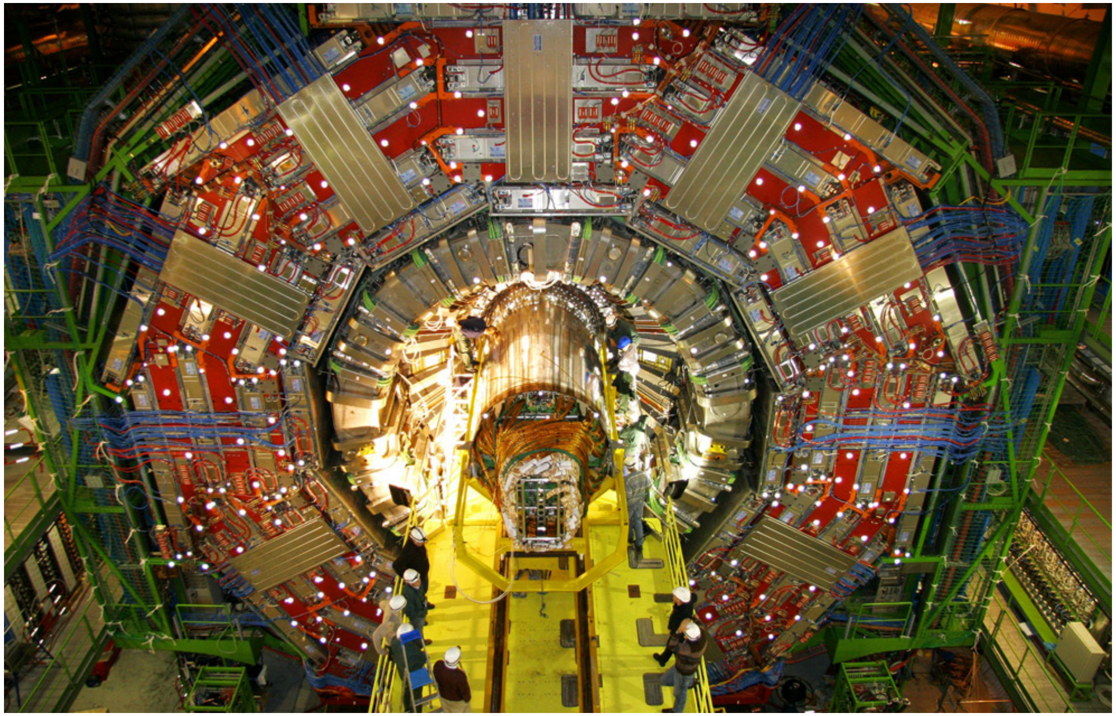


The CMS Tracker

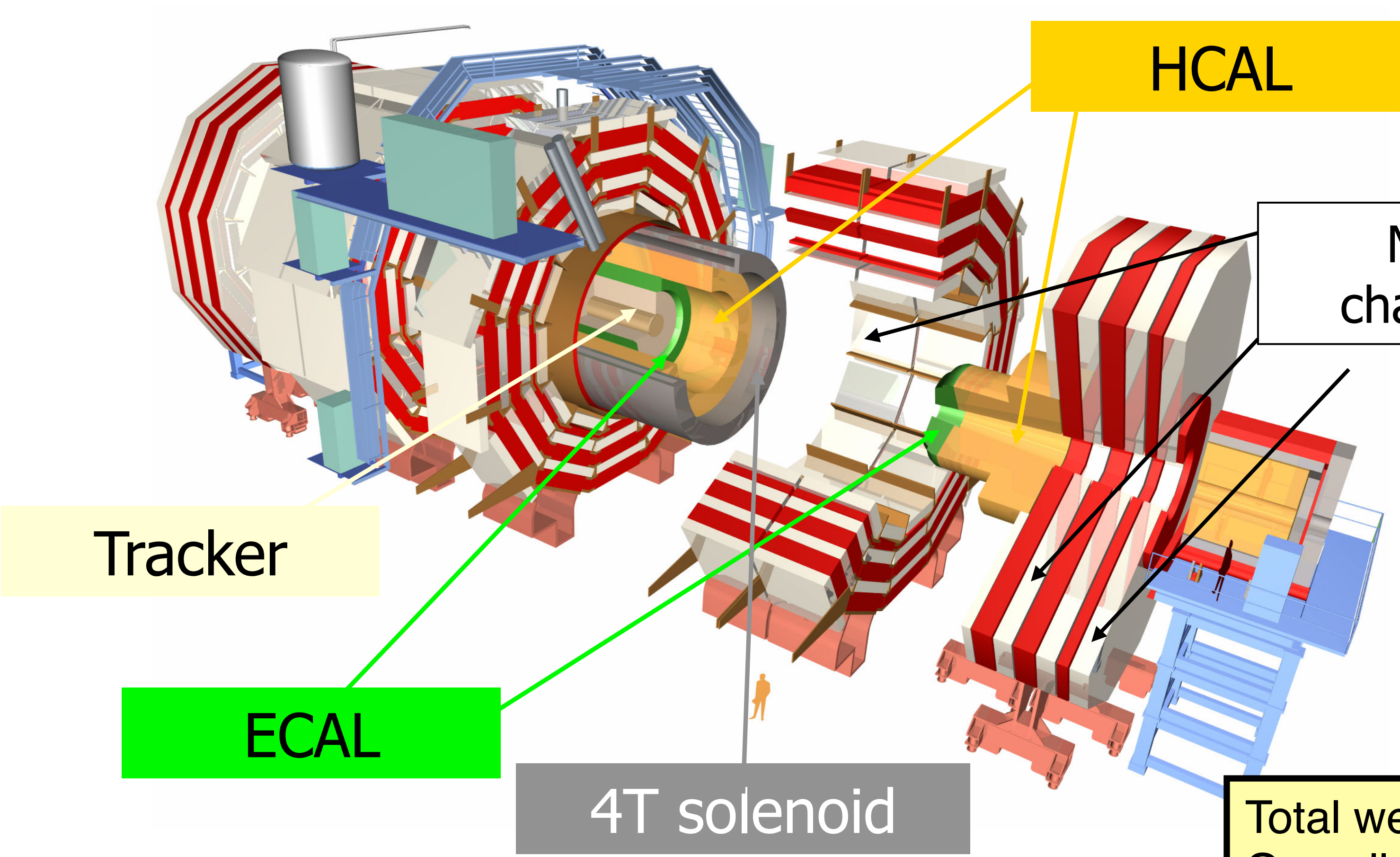
Silicon sensor and electronic system

A brief introduction to a part of CMS where Imperial played a major role

A practical example

Some material intended to complement the silicon sensor & electronics lectures with the practical implications of building such detectors

CMS Compact Muon Solenoid



Total weight: 12,500 t
Overall diameter: 15 m
Overall length 21.6 m
Magnetic field 4 T

The Compact Muon Solenoid experiment

- a general purpose detector for studying the full range of physics at the CERN Large Hadron Collider
  - expected to operate (nominally) for 10 years
  - ~500fb^{-1} with high radiation levels in tracking volume

R [cm]	Fast hadron fluence [cm^{-2}]	Dose [kGy]	Dose [Mrad]
4.3	246 10^{13}	830	83
22	16 10^{13}	67	6.7
115	2 10^{13}	2	0.2

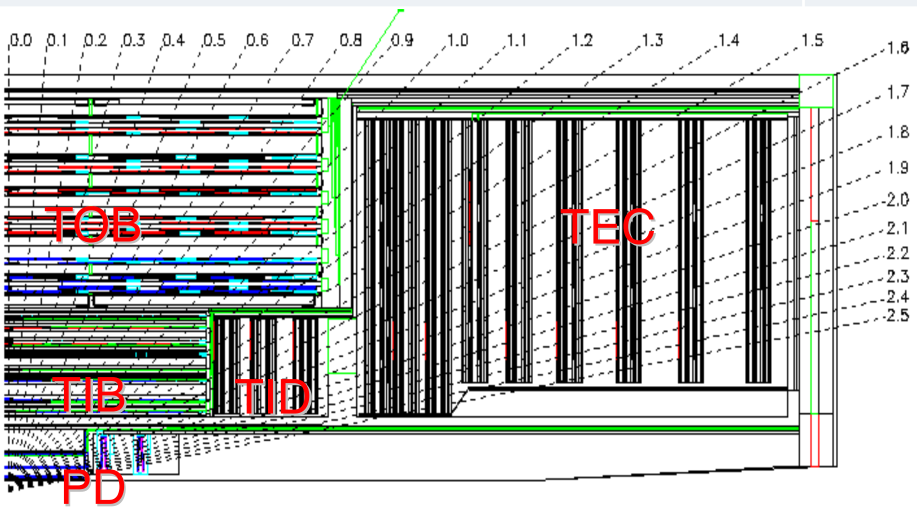
  - operation with heavy ions: ~ 1 month annually
- The All-Silicon Tracker
  - R ≈ 4 – 11 cm pixels
  - R ≈ 25 – 115 cm silicon microstrip detectors

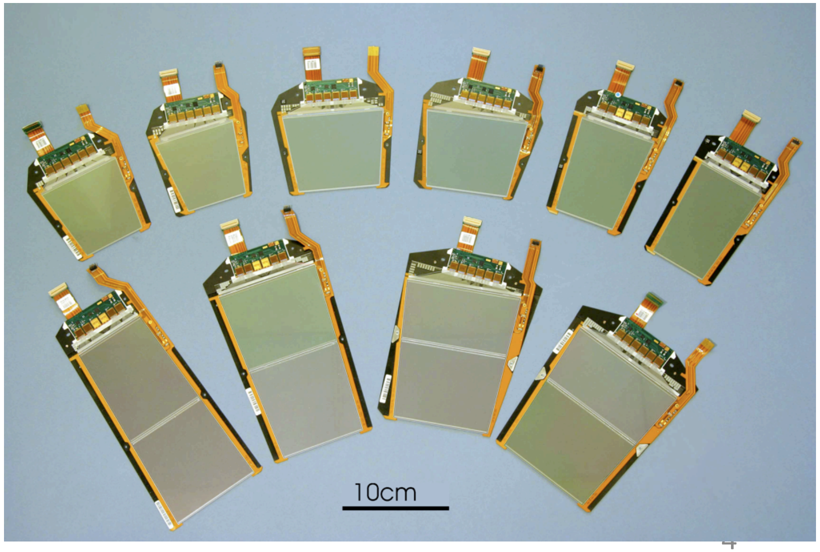
designed for general purpose tracking of charged particles in CMS

CMS Tracker and its sub-systems

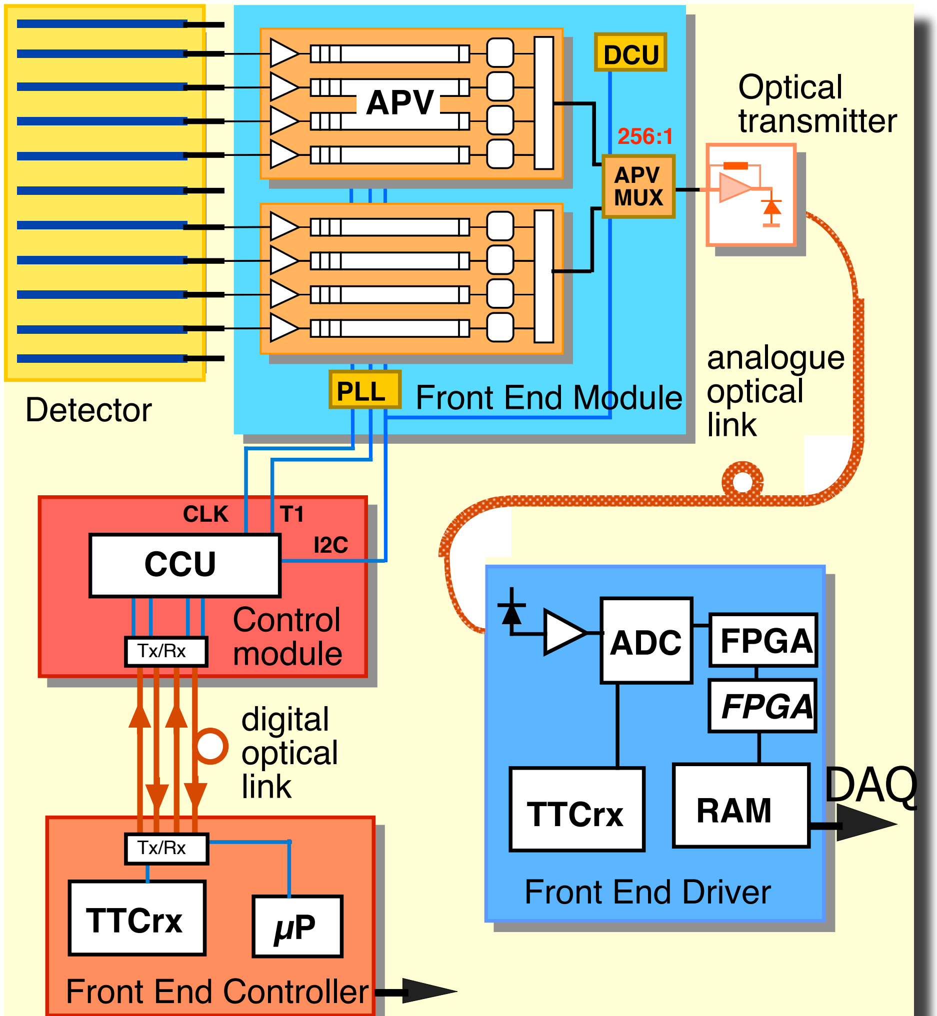
- Two main sub-systems: Silicon Strip Tracker and Pixels
  - pixels quickly removable for beam-pipe bake-out or replacement
  - SST not replaceable in reasonable time

Microstrip tracker	Pixels
~210 m^2 of silicon, 9.3M channels	~1 m^2 of silicon, 66M channels
73k APV25s, 38k optical links, 440 FEDs	16k ROCs, 2k olinks, 40 FEDs
27 module types	8 module types
~34kW	~3.6kW (post-rad)





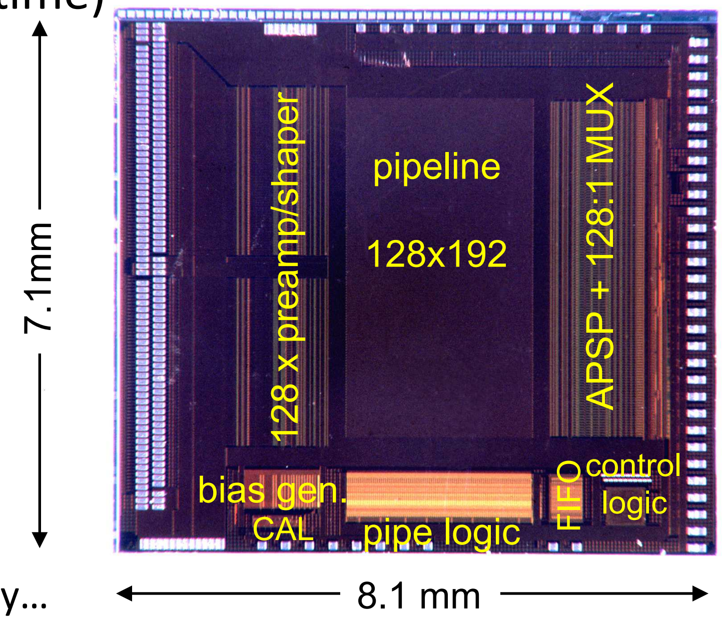
Tracker Electronic System

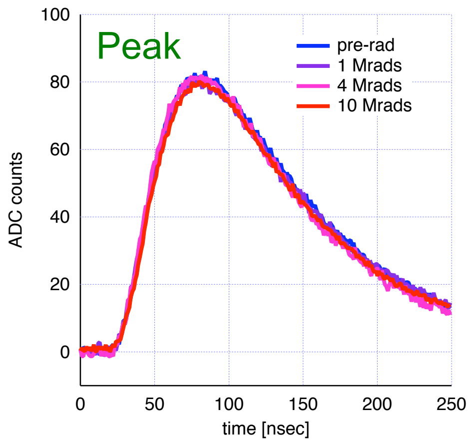


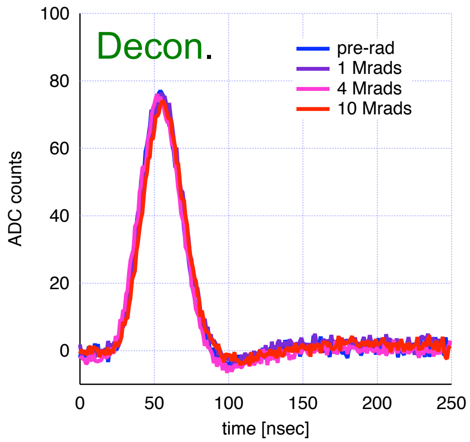
- Main features
  - Analogue readout
  - No on-detector zero suppression
  - Optical analogue data transfer
  - Control signals sent optically
  - Local electrical transfer
- Custom electronics on detector
  - radiation hard ASICs and optoelectronics
- Off-detector electronics
  - underground outside radiation zone
  - ADCs and zero suppression
  - ~500 FEDs, including spares
  - ~25 FECs

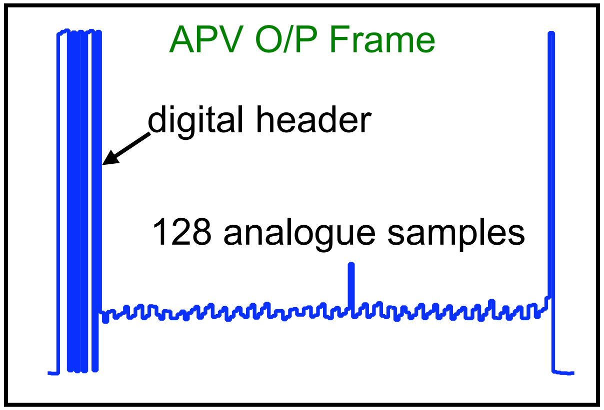
APV25

- Main features (many innovative, at the time)
  - Commercial 0.25µm CMOS ASIC
  - 128 readout channels
  - 50 ns CR-RC amplifier
  - 192 cell pipeline memory
  - alternate operating modes
    - peak & deconvolution
    - on-chip analogue signal processing
  - various ancillary functions
    - eg calibration, I^{2}C, programmable latency…



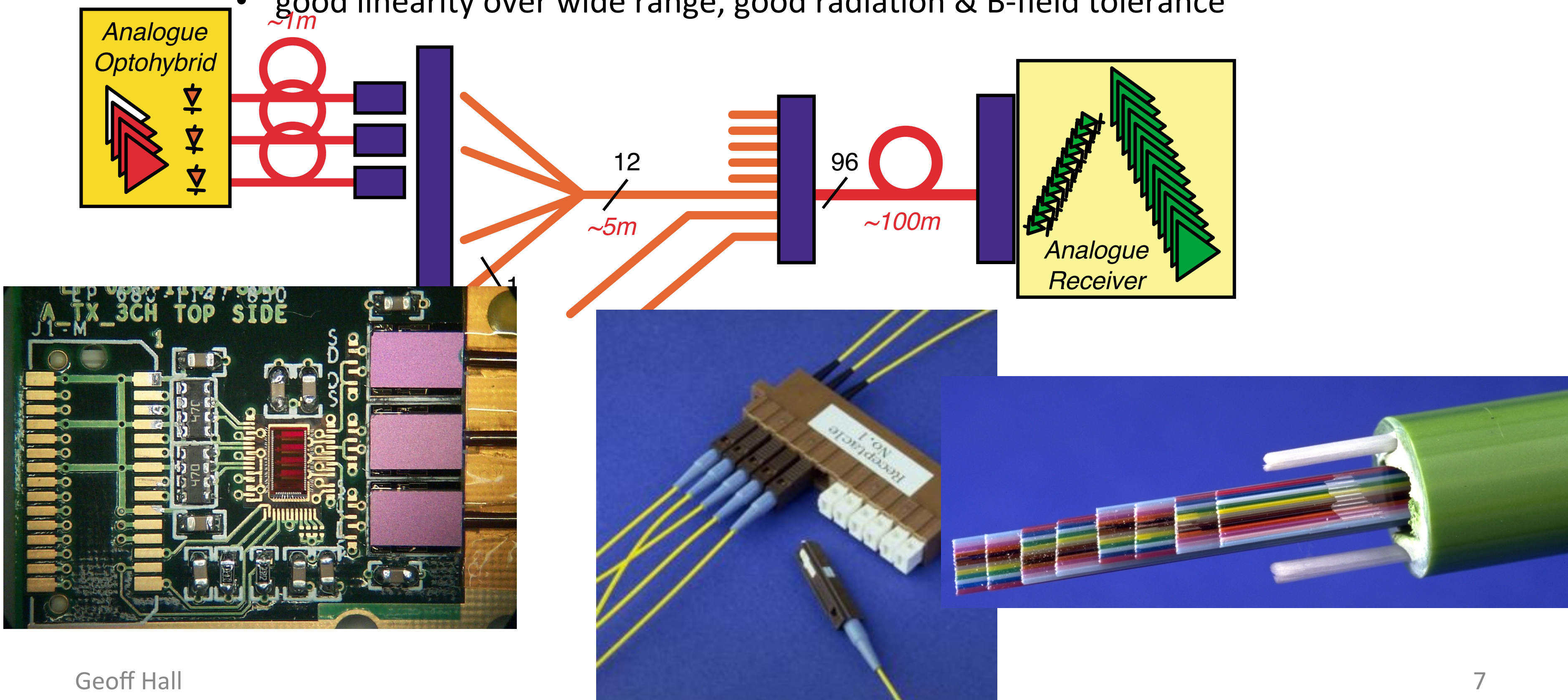






Optical links

- System developed for CMS Tracker mainly by CERN with industrial partners
  - vital technology, established for particle physics during LHC construction
    - "noise free", low power, high speed data transmission
  - 1.3µm single mode FP laser transmitters, III-V semiconductor Tx & Rx
    - good linearity over wide range, good radiation & B-field tolerance

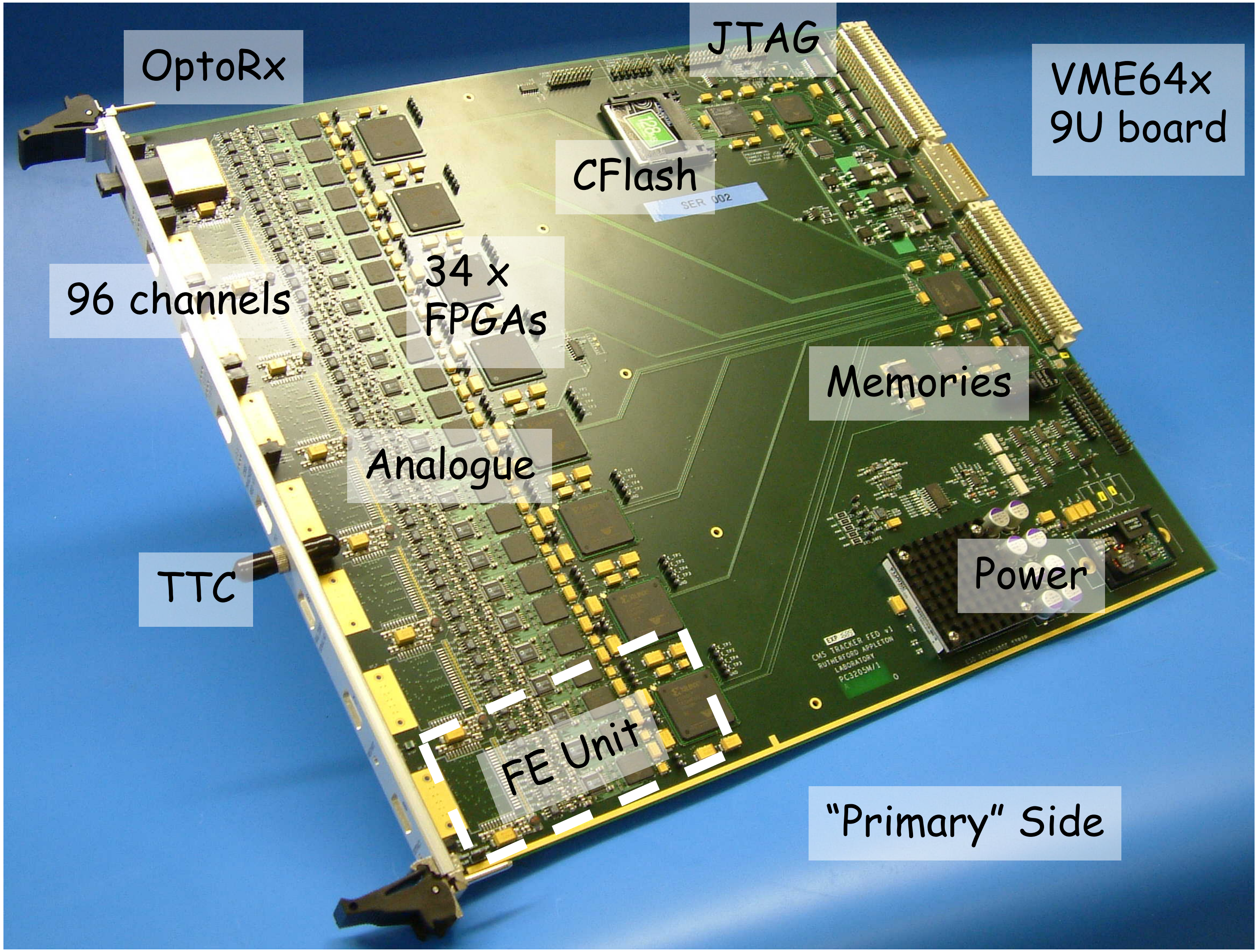


Now seems modest in comparison with latest technology

Front End Driver

Programmable digital logic board

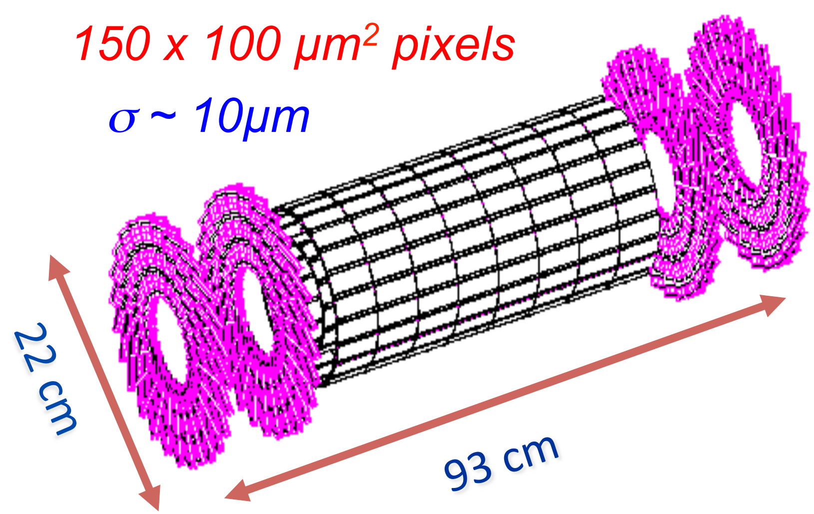
- opto-electric conversion
- digitisation
- data reordering
- baseline subtraction
- hit finding
- zero suppression
- data transfer via high speed S-link
- VME control and slow readout



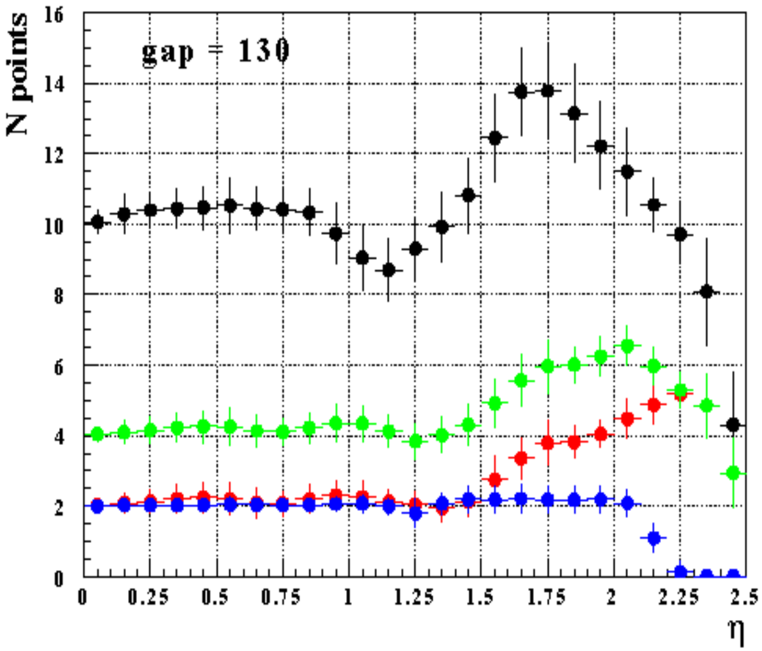
Tracking in CMS: strategy

- No detector of this type existed and LHC at 10^{34} $cm^{-2}s^{-1}$ is a very special challenge
  - ~35 events per crossing @ 40MHz: many 100s of tracks/event (radiation damage)
  - pileup of (partial) signals from previous beam crossings
- Rely on "few" measurement layers
  - each able to provide robust (clean) and precise coordinate
  - 2-3 pixel and 10-14 μstrip measurements
  - low material is an important objective

- Originally much uncertainty about performance vs number of layers
  - software for track reconstruction built at same time as simulations and detector
- Pixels provide precise 3D points in most congested region for seeding tracks in outer layers



Measured points



Total number of hits:

Double-side hits

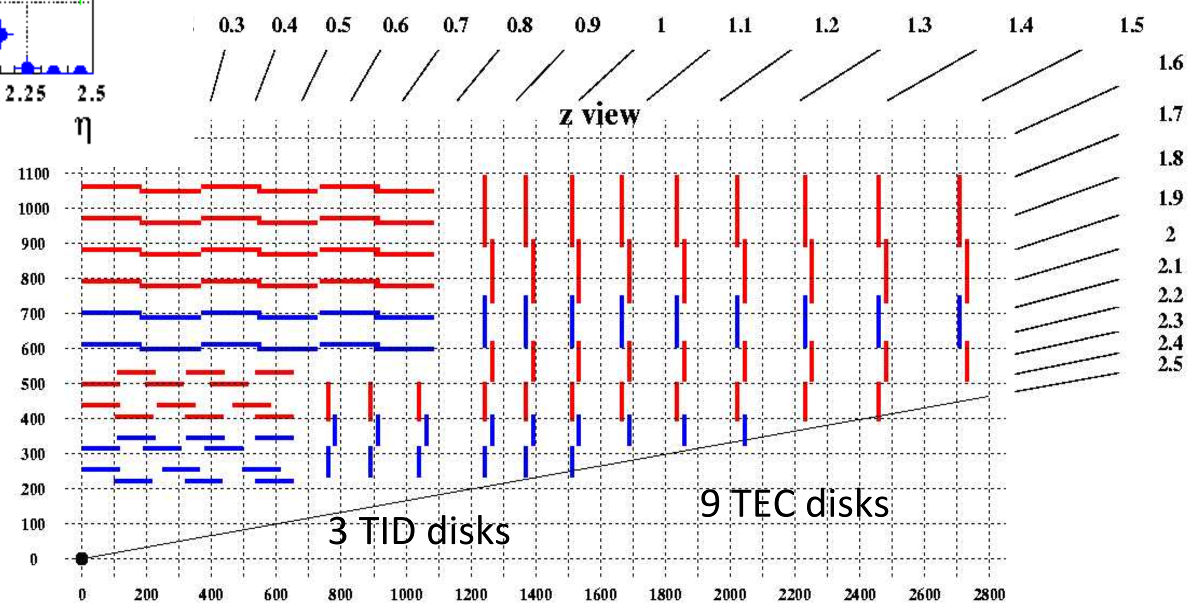
Double-side hits in thin detectors

Double-side hits in thick detectors

$$\eta = -\ln(\tan \theta/2)$$

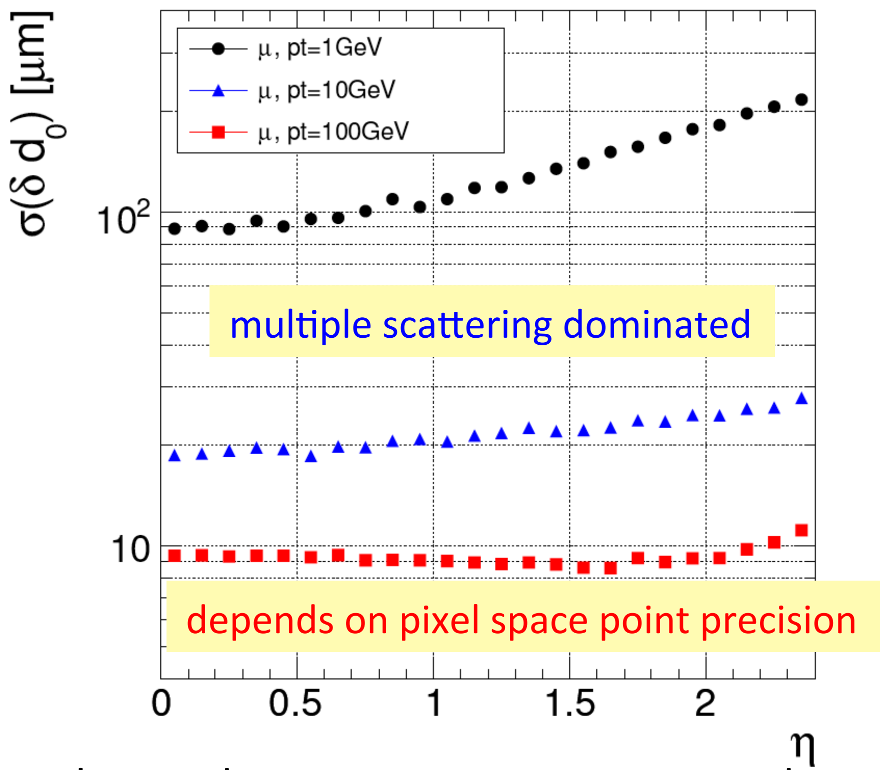
6 TOB layers

4 TIB layers

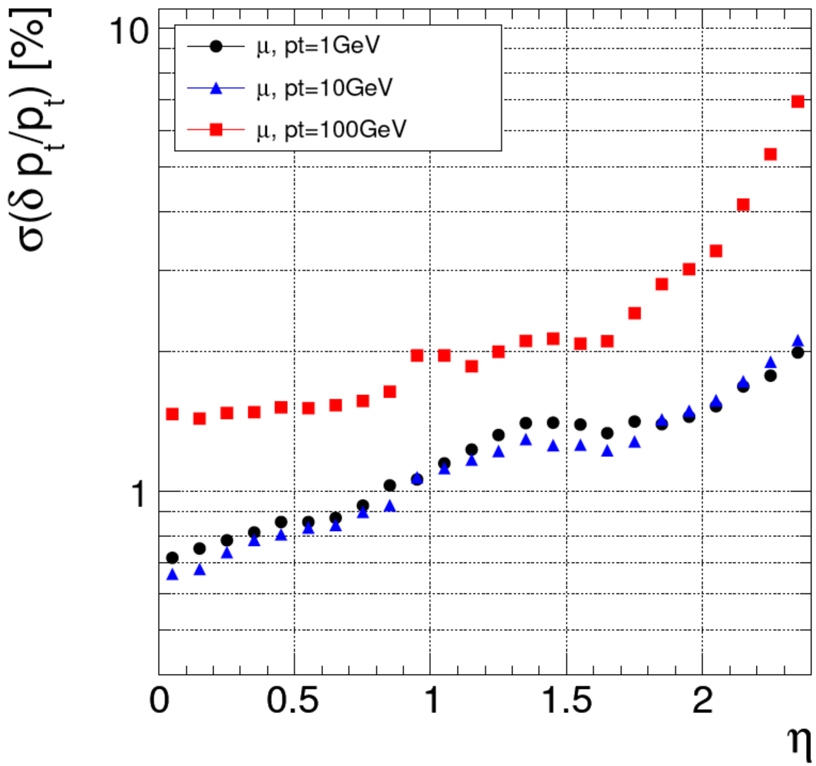


Performance from simulation

Transverse impact parameter



Transverse momentum



Both IP and momentum measurement depend on curvature measurement

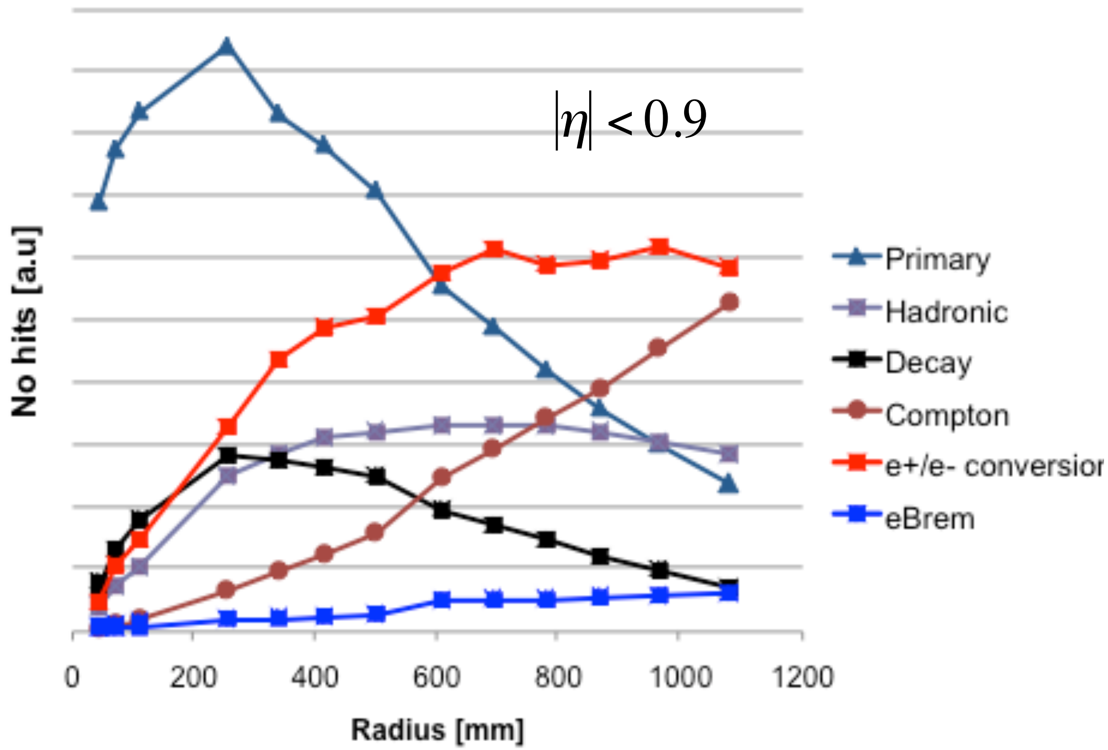
So performance limited by N_{points}, point precision, lever arm (& B) and multiple scattering

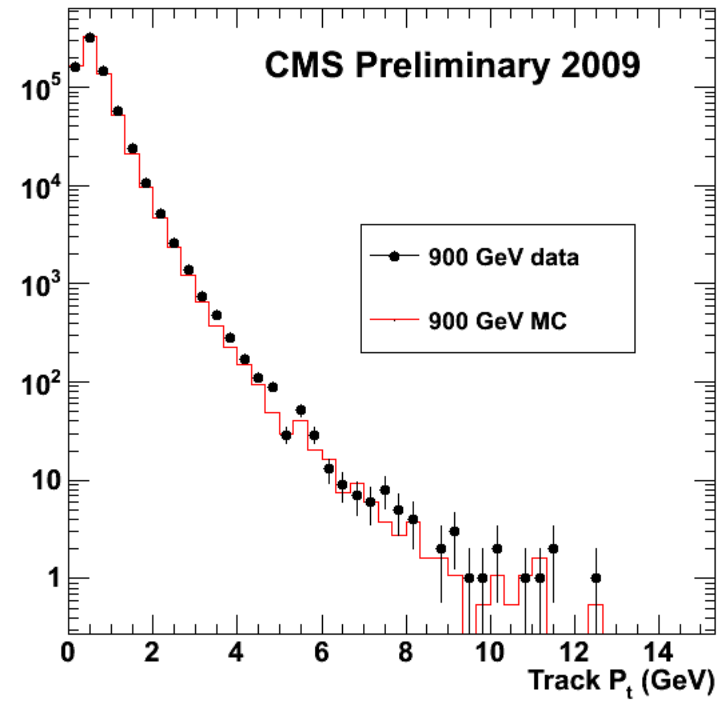
What is actually required? σ(p) -> σ (m): measure Z peak with natural width

spatial: to have good efficiency for b-decays

Effect of material on particles in the Tracker

- Nuclear interactions destroy and create particles

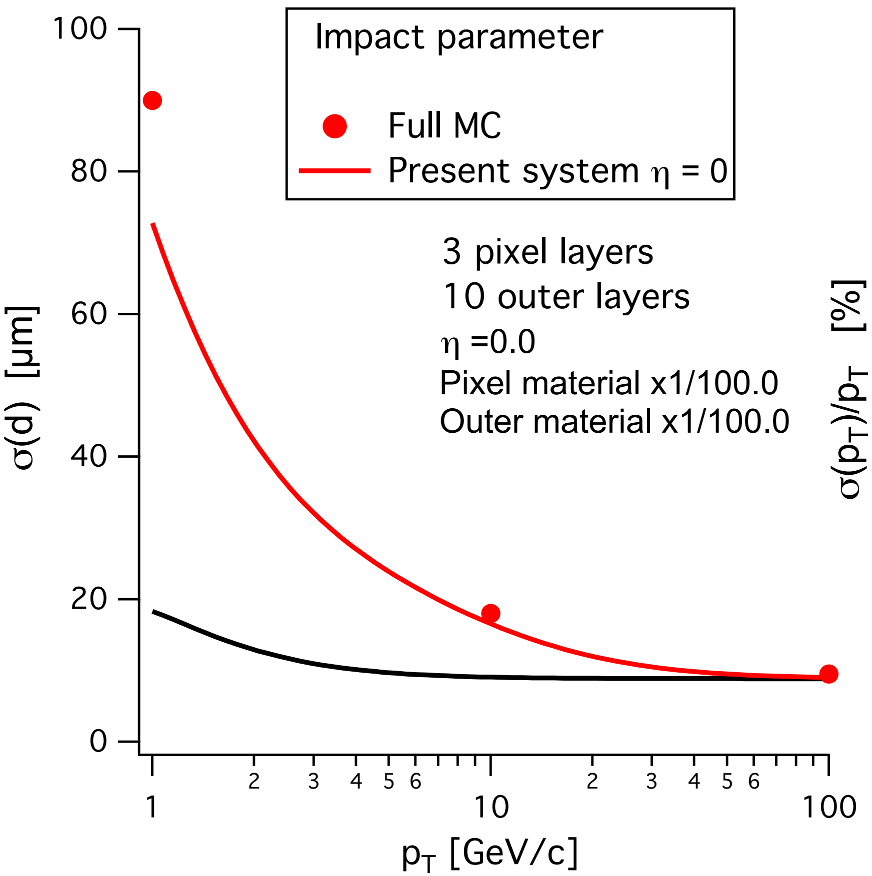


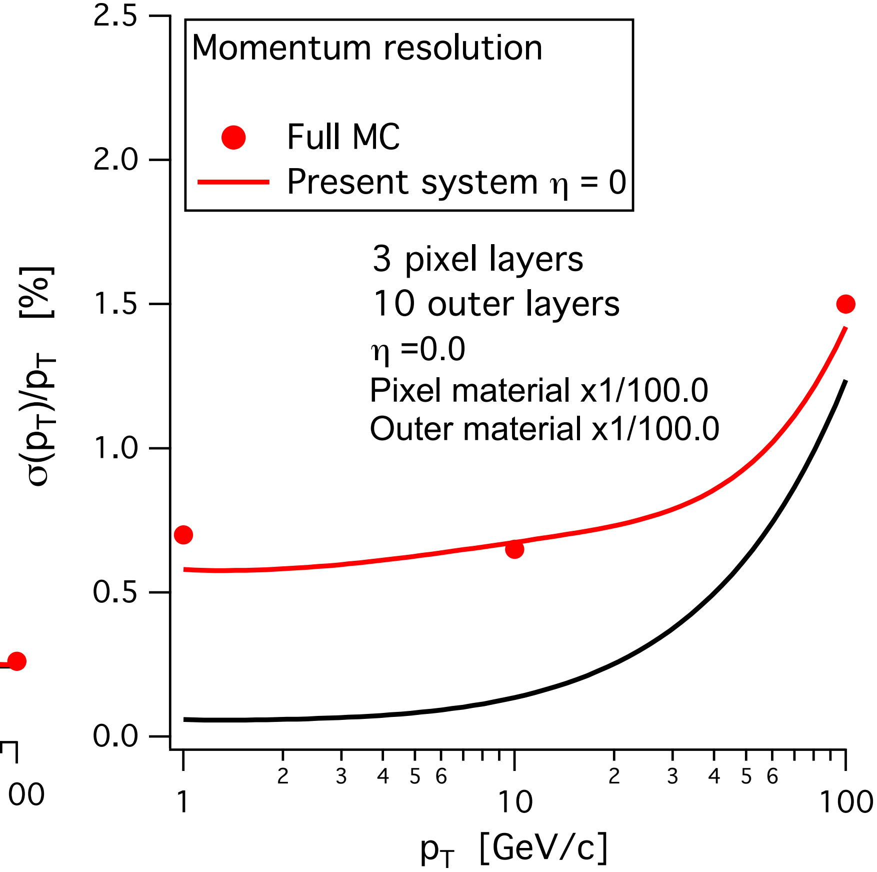


Vast majority of particles have low momentum

Effect of material on measurements

- compare real life with idealised detector: material reduced by factor 100
  - Simplified – but adequate – calculation





Summary of requirements for tracking detector

- **Minimum material** - but moderate number of layers
  - limit atomic (multiple scattering) and nuclear interactions
- **Low power** (to minimise material but cooling is not easy)
  - in practice 3.6 mW/channel for SST (~10M) and 55 µW/pixel (~66M)
- **Low electronic noise**
  - max 2000 e (~250 e pixels) but sufficiently low thresholds for low occupancy
  - occupancy 1-2% strips, 0.05% pixels, but tolerant to large fluctuations (eg HI)
- Operation in 4T **B-field and T ≈ -20°C**
- Ionising Dose & Single Event Effect **radiation tolerant**
- **Robust, stable, reliable** for long time with little or no access
  - simple (!) to operate, set up, control, calibrate and align
    - result of overall engineering, electronic design, and analogue information
  - very large software & significant firmware effort over long period
- Once all the above achieved, with sufficient granularity (& correct sensors etc) should guarantee good spatial precision!

SNAPSHOTS OF CONSTRUCTION
by worldwide effort

Austria, Belgium, Finland, France, Germany, Italy, CERN, Switzerland, UK, USA – *currently 62 institutes*

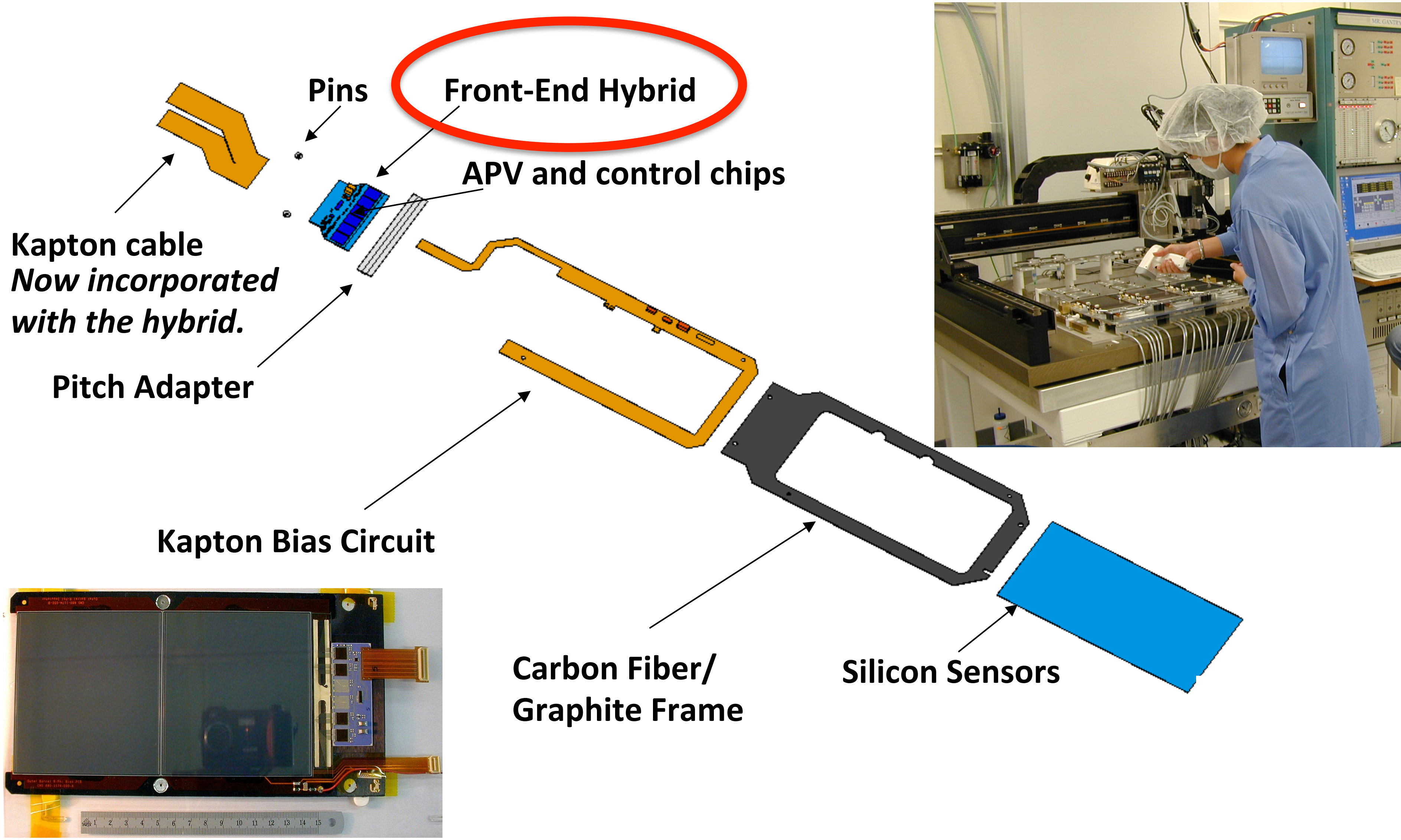
much movement of components and assemblies

Sensors, ASICs, hybrids procured and tested

some parts commercially: e.g. hybrids

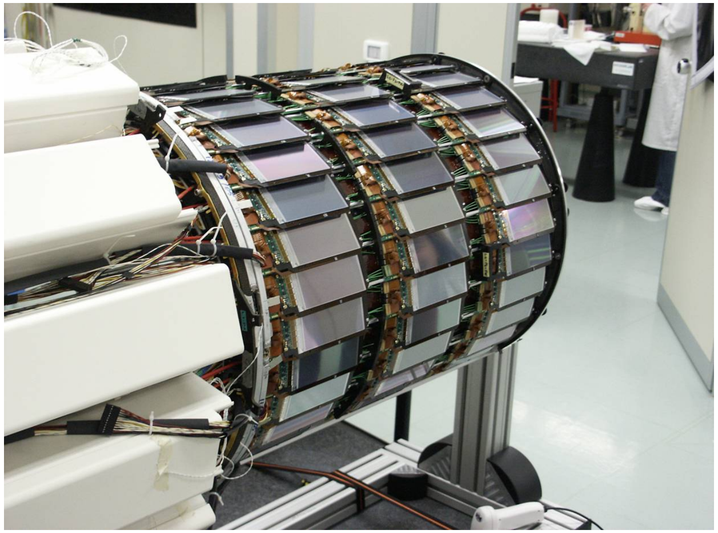
Modules constructed in our dedicated centres, using automated assembly methods…

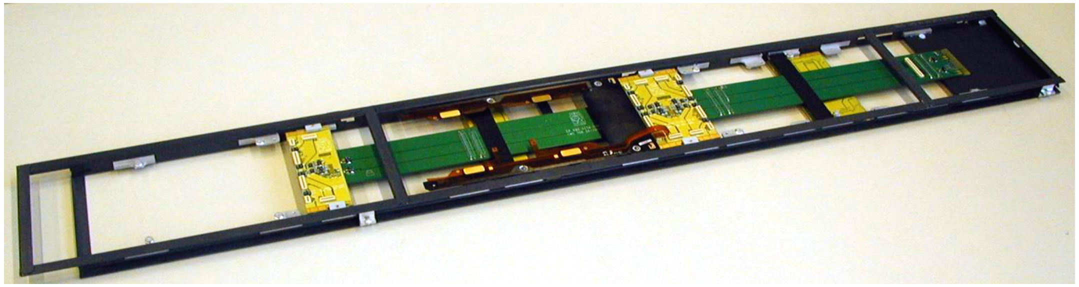
Module components



Modules and sub-system assembly

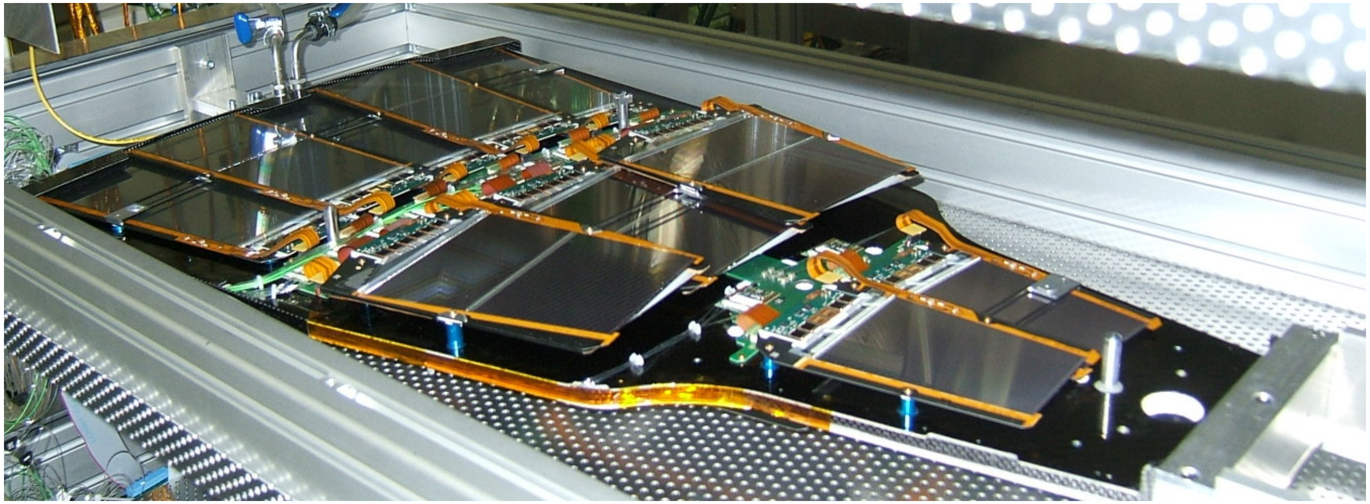
Inner barrel shells (Italy)



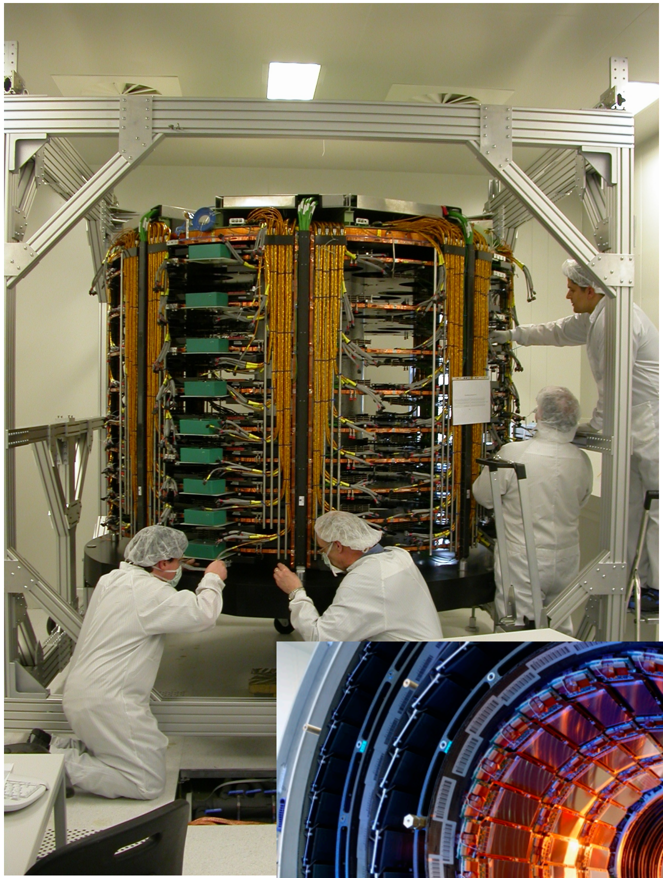


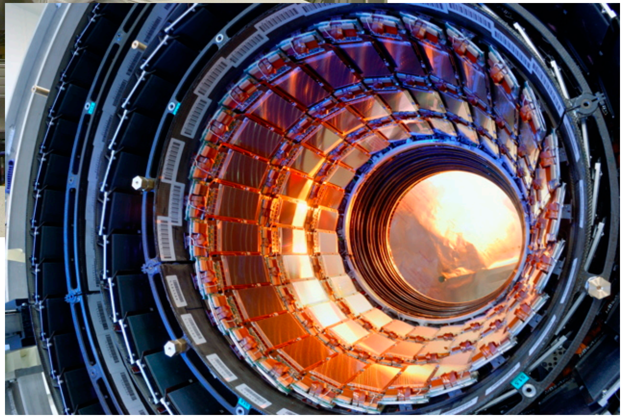
TOB modules and Rods (US, CERN)
Hybrids (industry)

Endcap petals
(Au, Ge, Be, Fr)



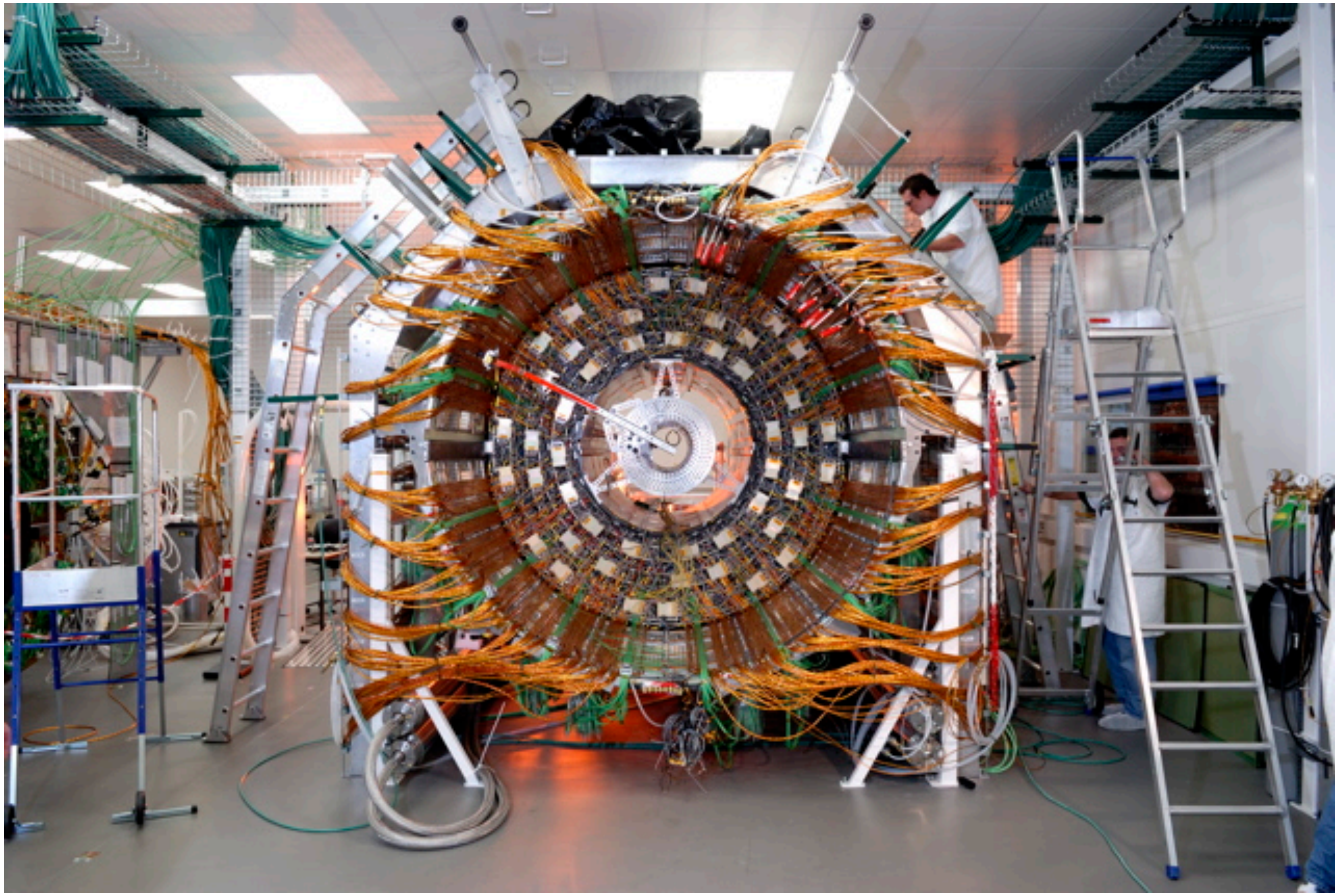
Sub-system integration



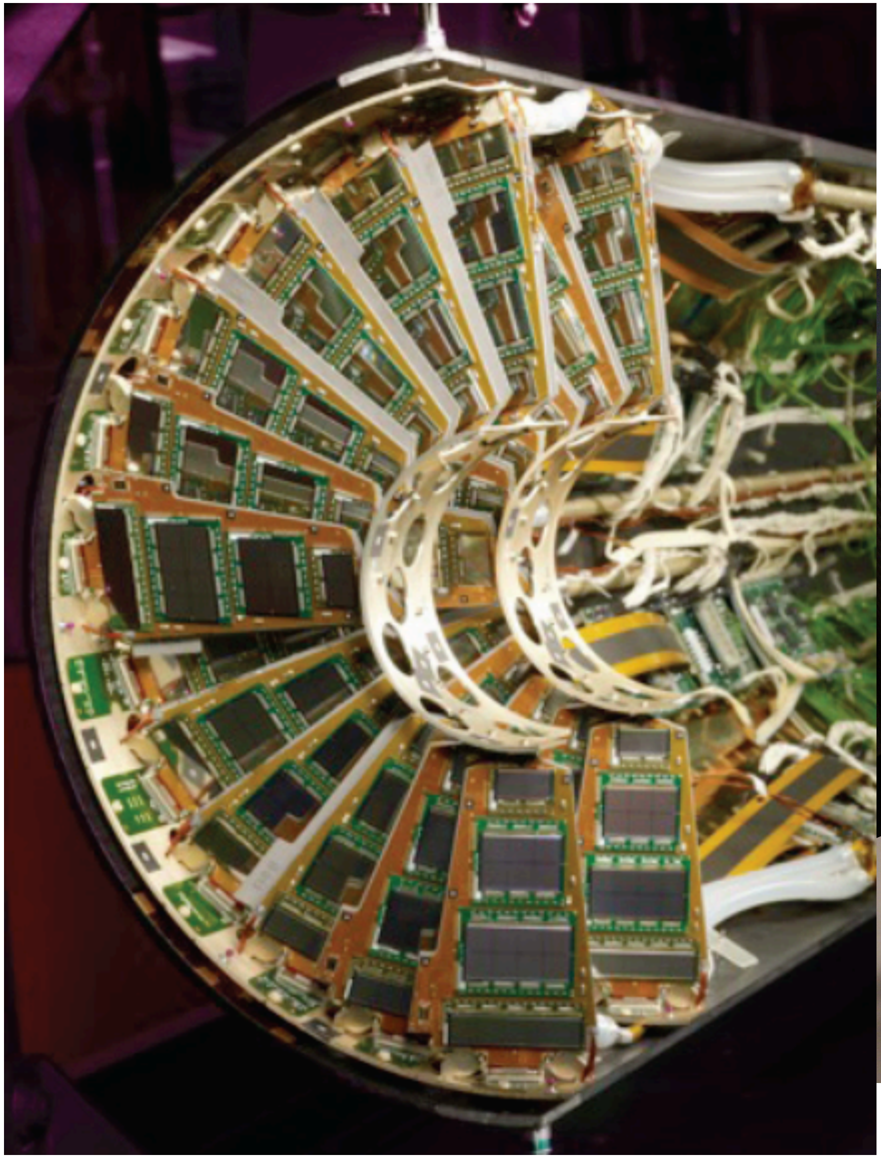


Integration at TIF

- Dedicated Tracker Integration Facility in CERN lab
  - assembled sub-systems, then added external cables, cooling, …



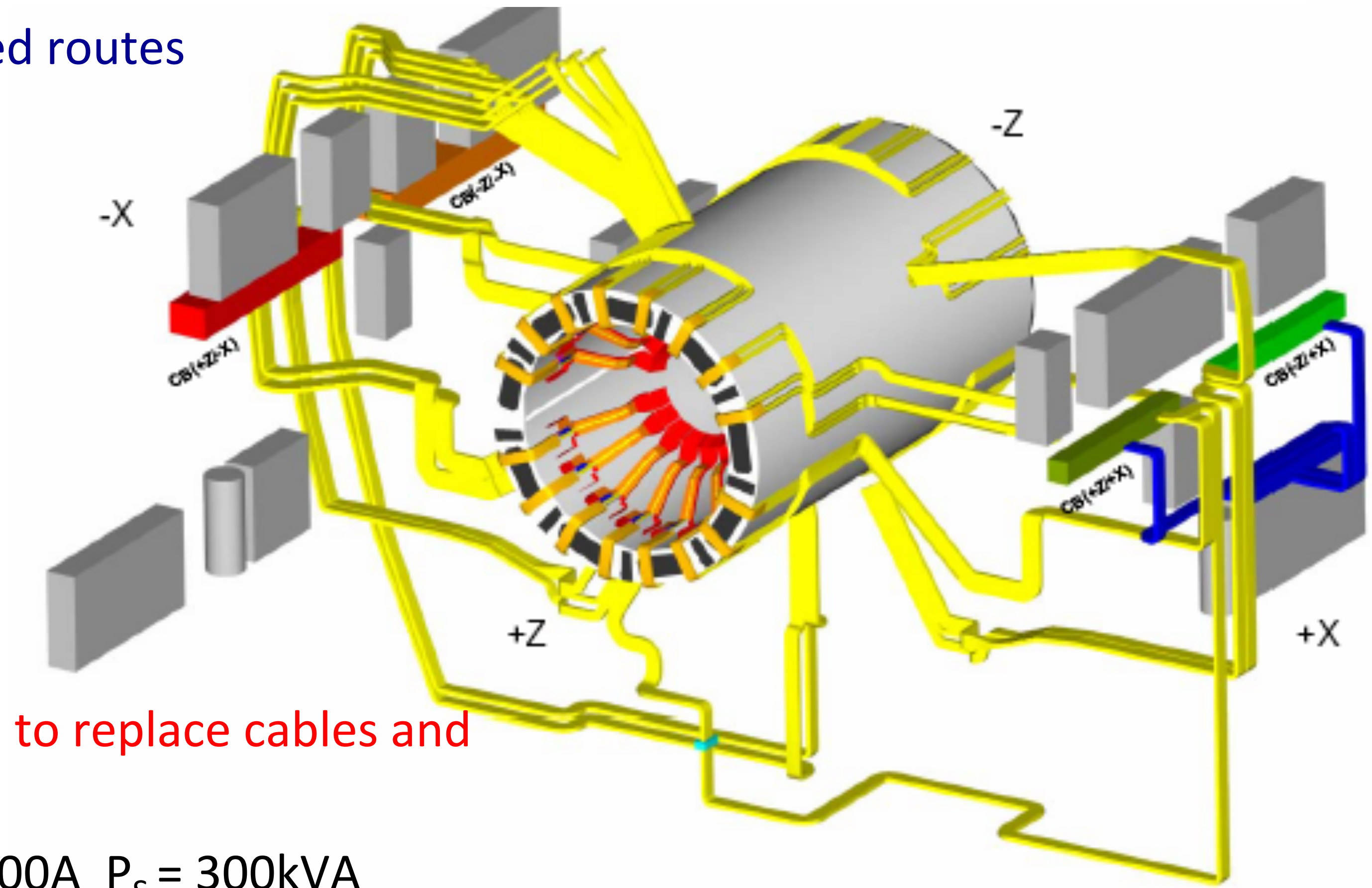
Pixel assembly



Tracker services

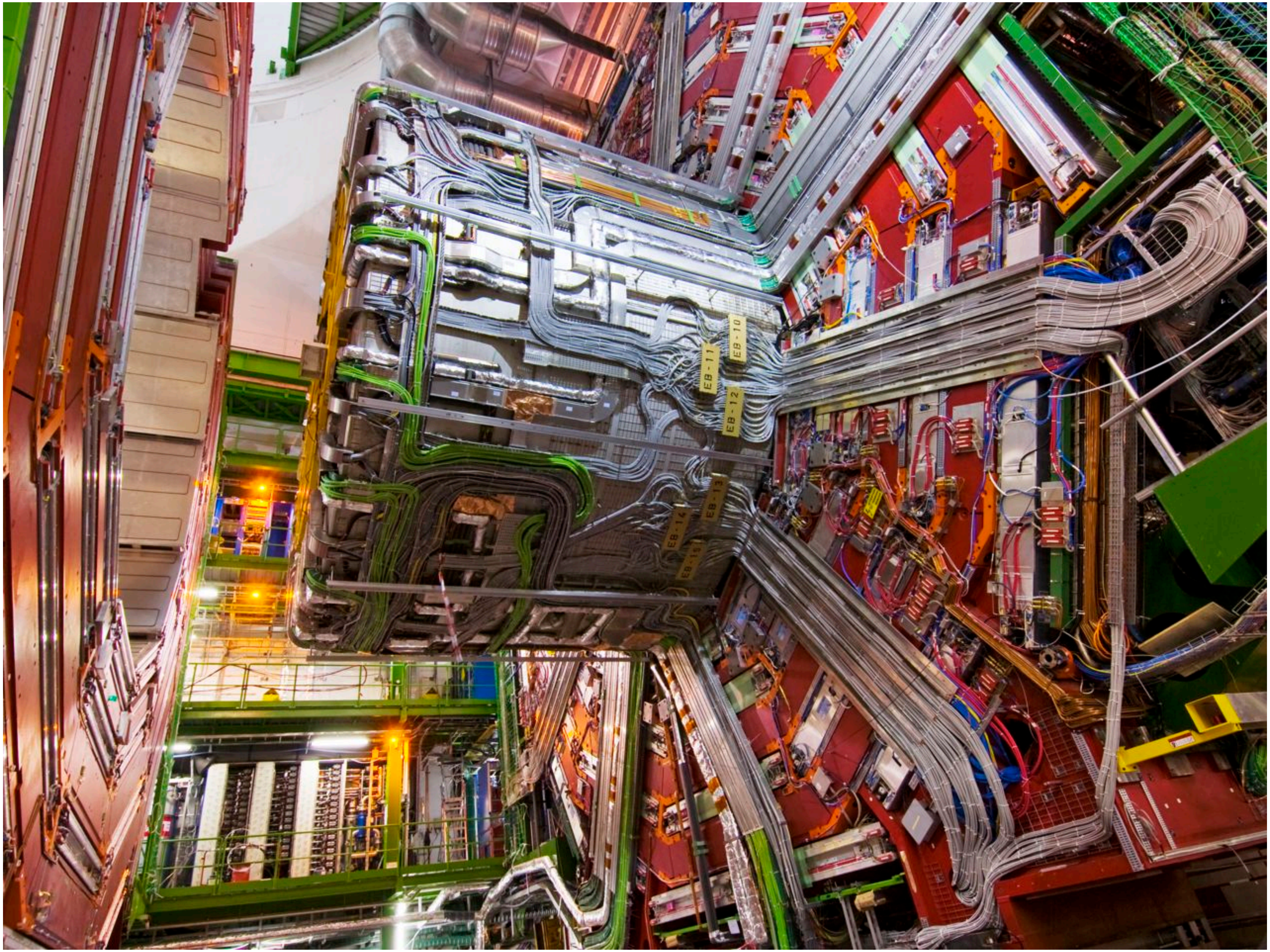
- *Installation of services was one of the most difficult jobs to complete CMS*

  – Complex, congested routes



It may be impossible to replace cables and cooling for upgrades

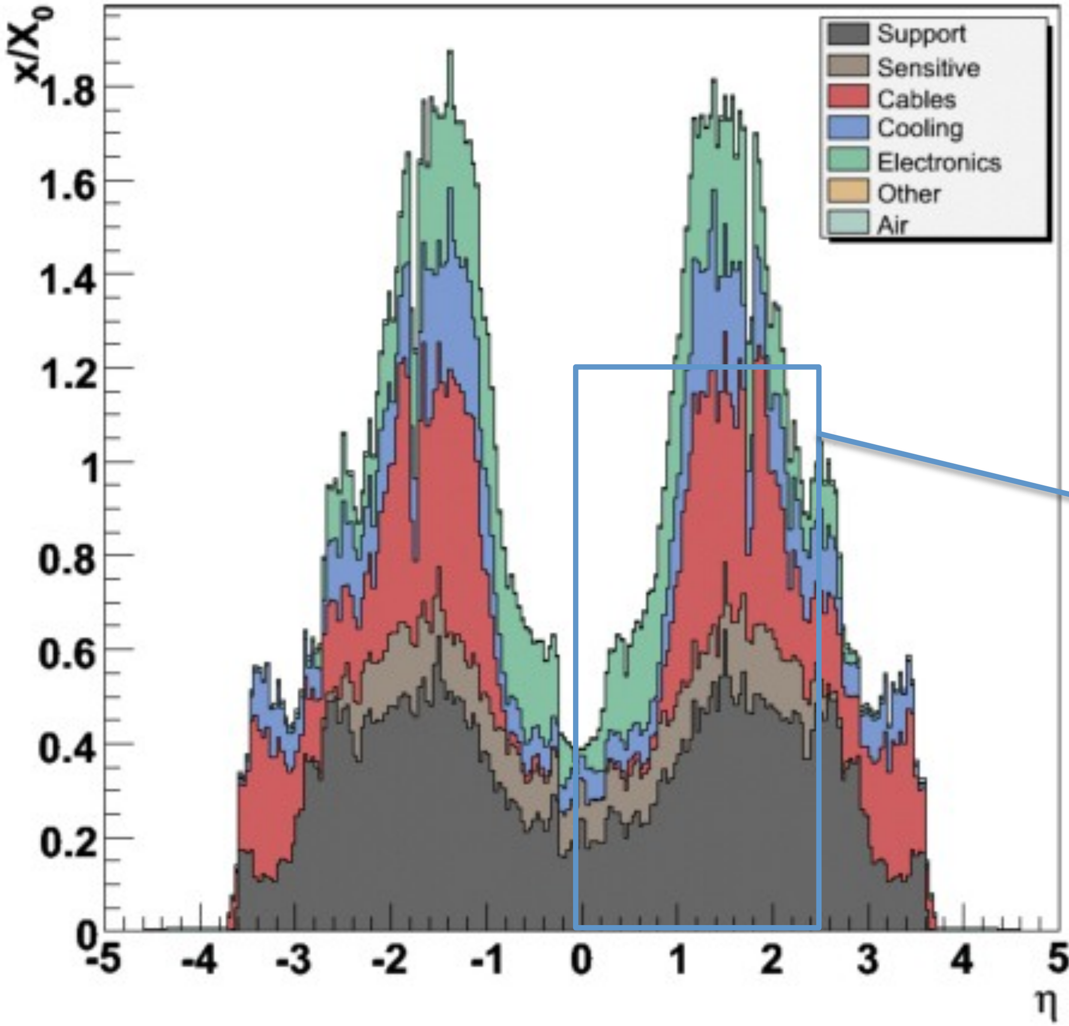
$P_{FE} \approx 33kW$ I=15,500A $P_S = 300kVA$


EB-11
EB-10
EB-12
EB-13
EB-14

RESULTS

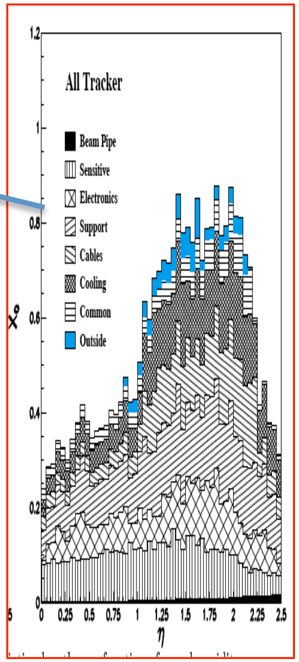
Material budget

- Final

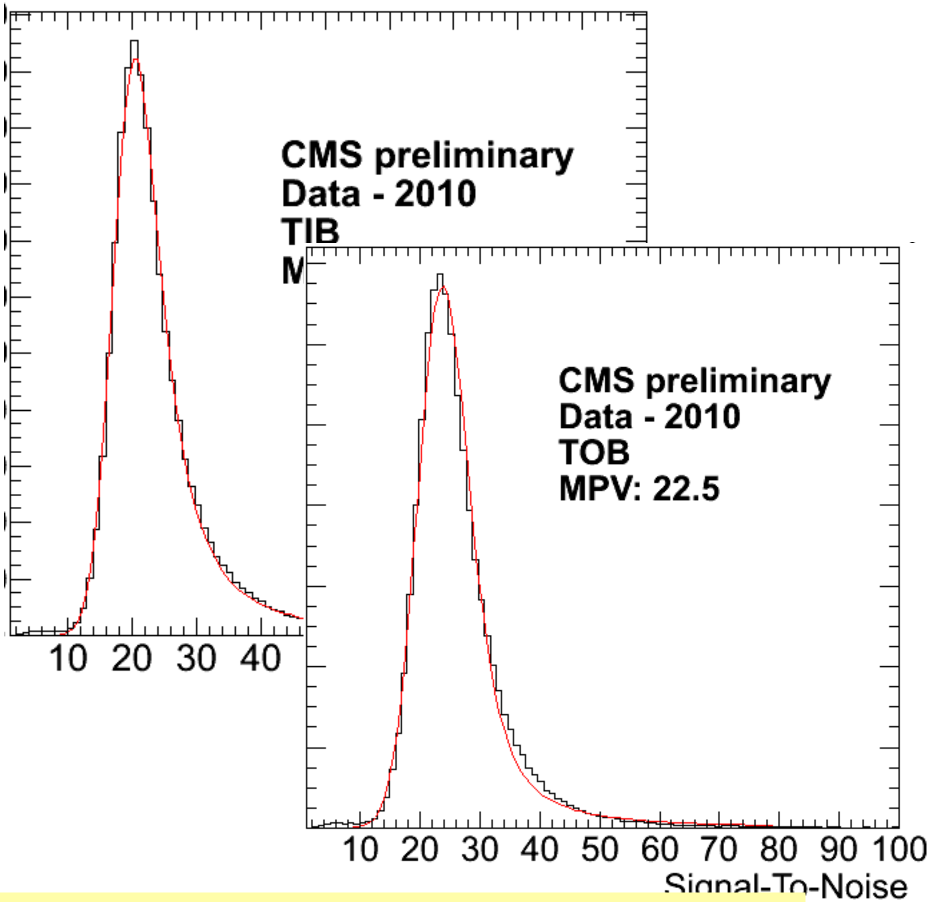


Significantly larger than hoped for in early design

TDR



Distorted plot to match scales



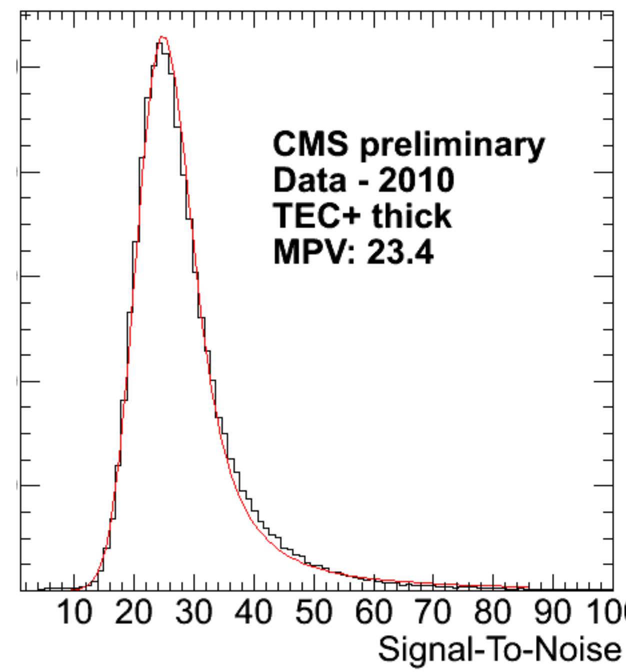
Signal to noise

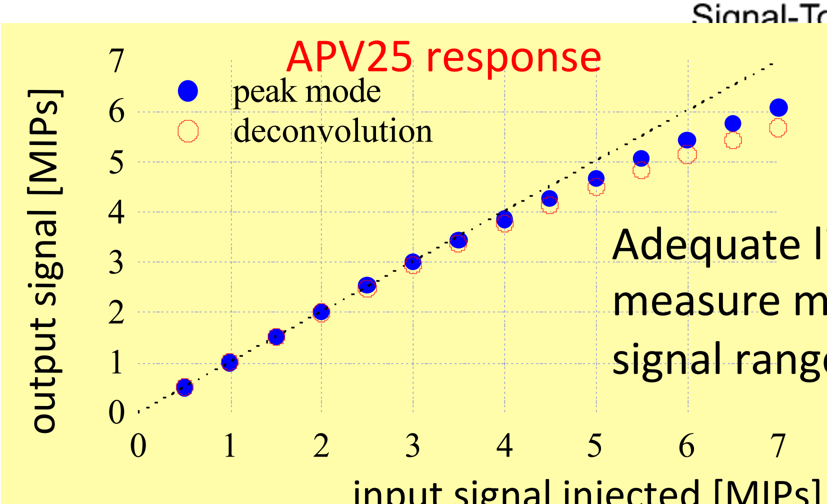
Measured in deconvolution mode

– 25 ns peaking time

Characteristic "Landau" shape results from statistical sampling of electromagnetic scatters (Coulomb) in thin layer

– occasional large fluctuations



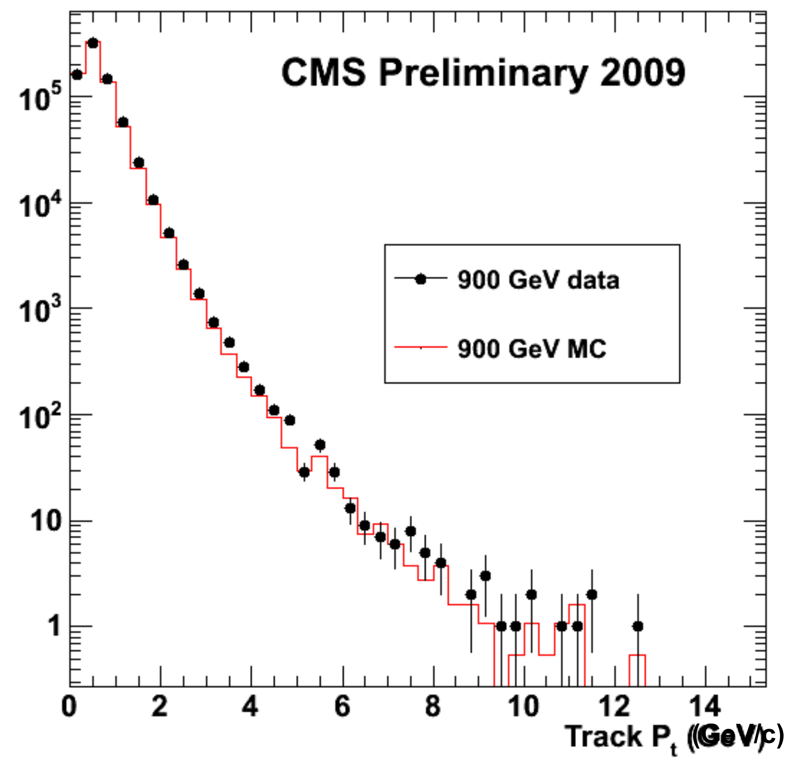


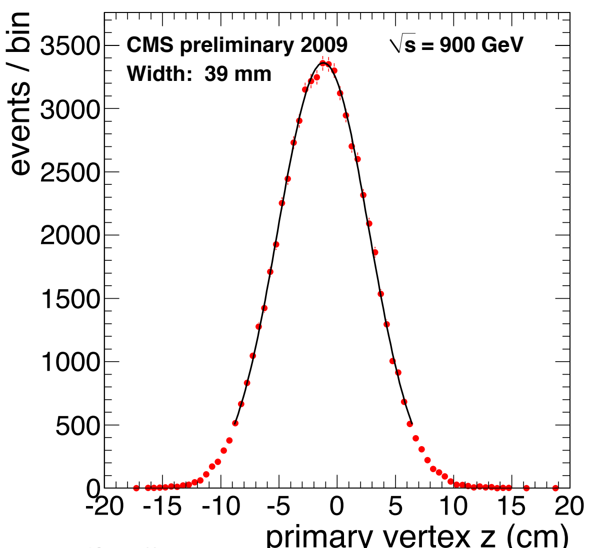
Adequate linearity to measure most of signal range

Very early results – many more published

Tracking performance

- Major software task
  - but strongly correlated to basic performance
  - alignment & calibration
  - mechanical and thermal stability
  - signals well separated from noise
  - point measurement precision
- Several track finding algorithms in use



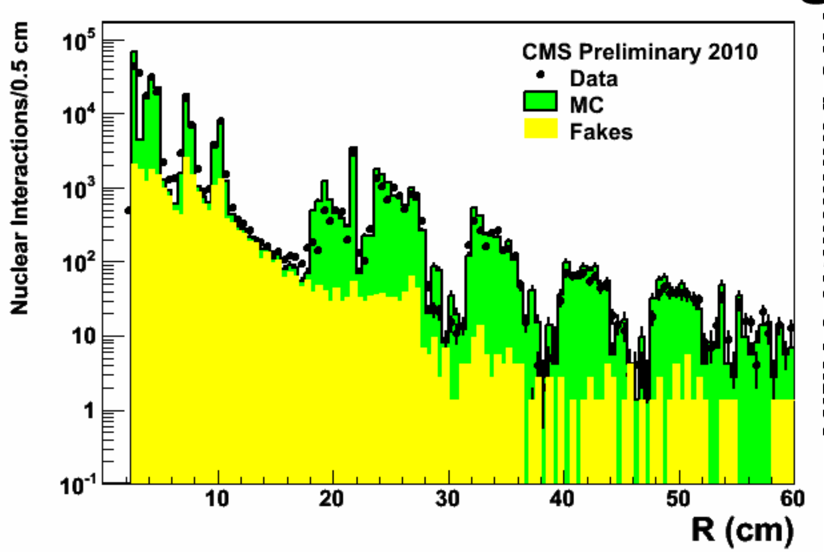


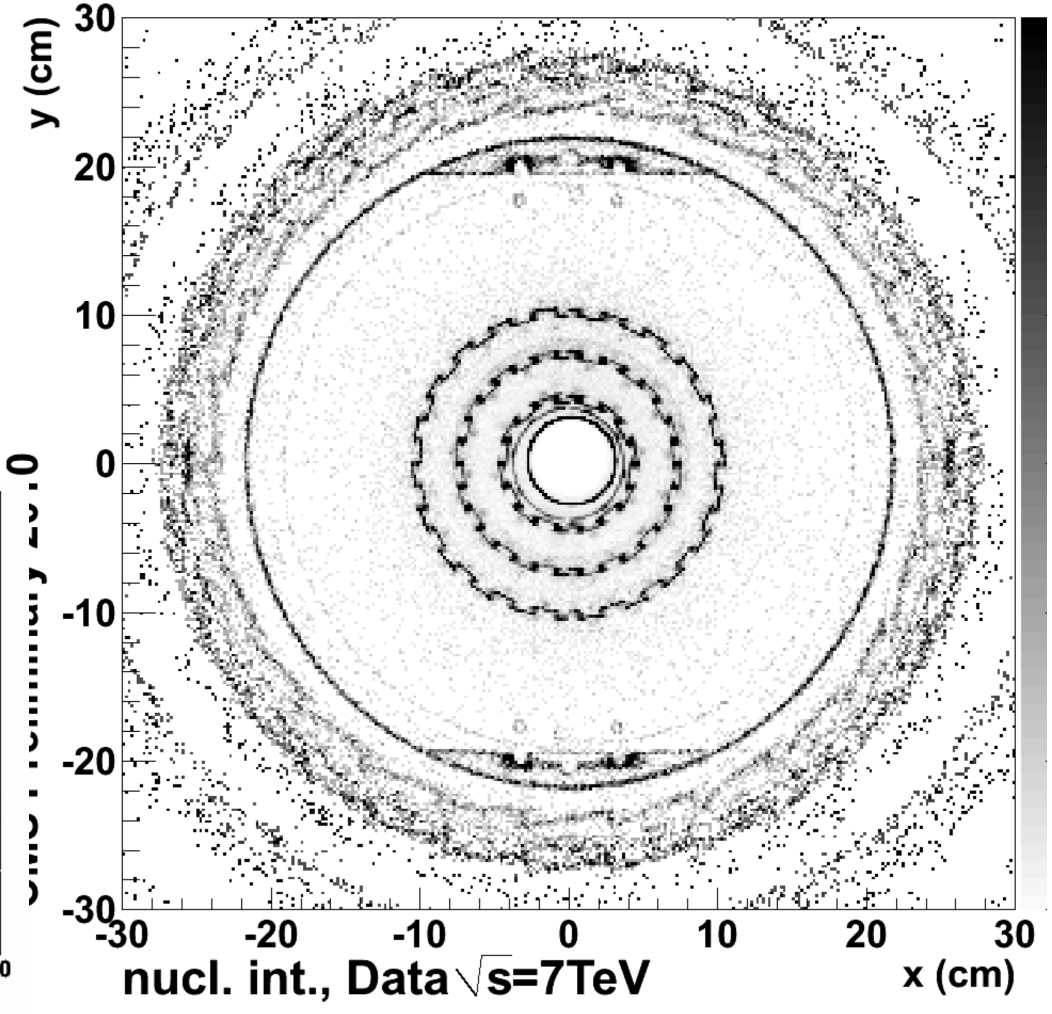
Considerable advance on original tracking objectives from TDR era

partially compensates for material in system

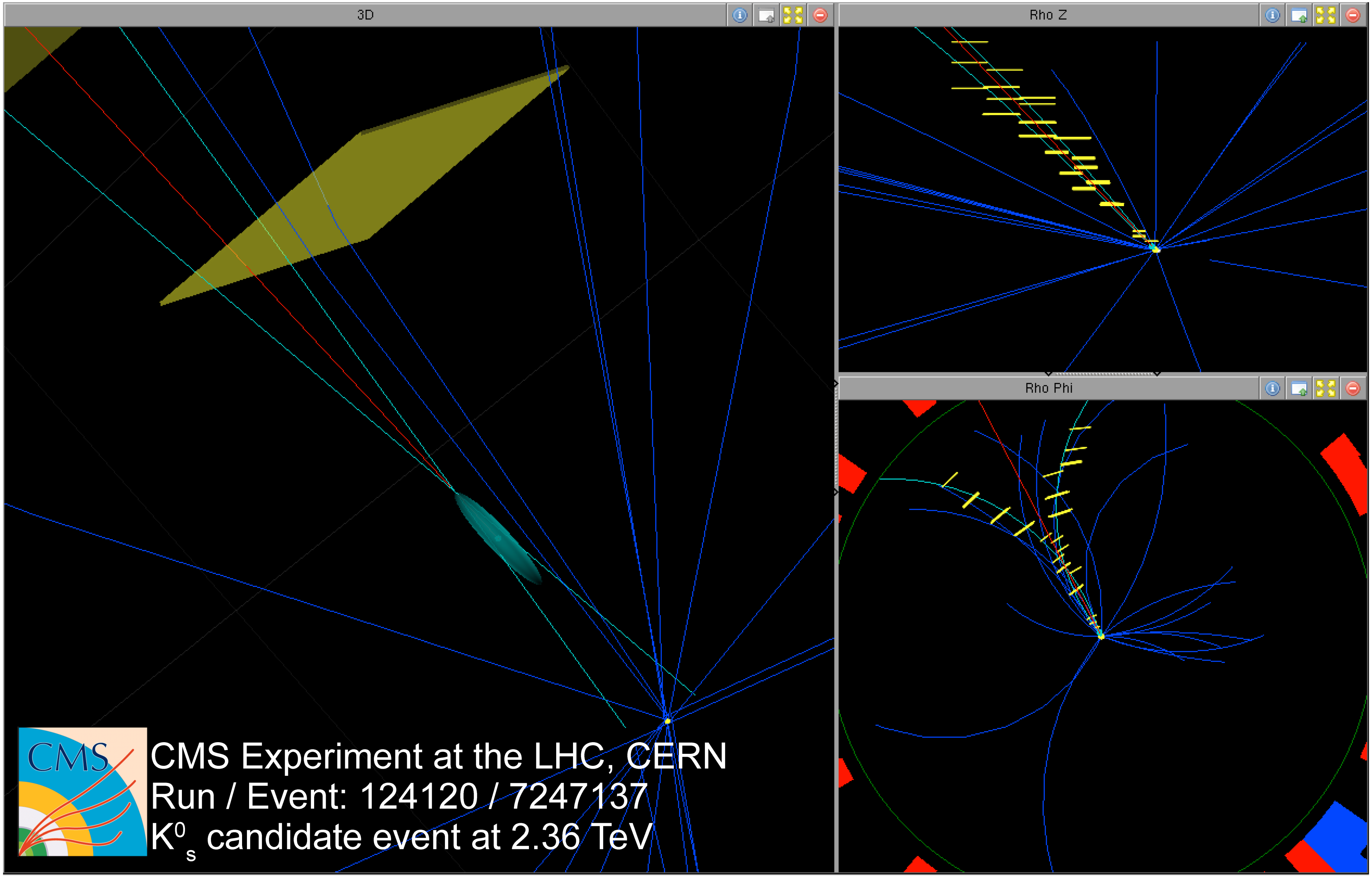
Material distribution

- Radiographs using particles
  - reconstruct nuclear interactions
    - similar plots also obtained using photon conversions
  - detailed understanding essential for physics backgrounds

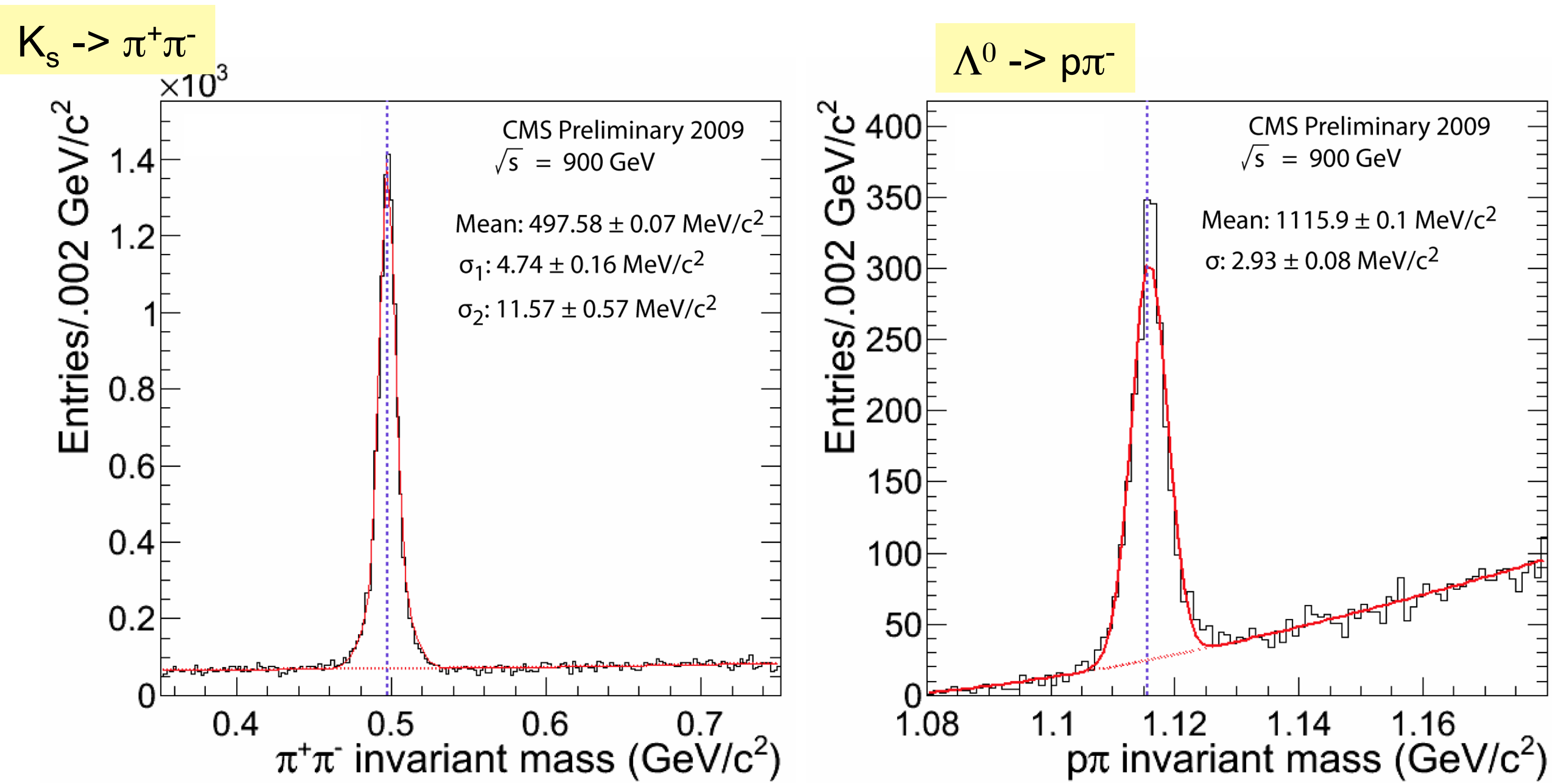




K^0_s candidate event at 2.36 TeV



Secondary – long-lived- decays



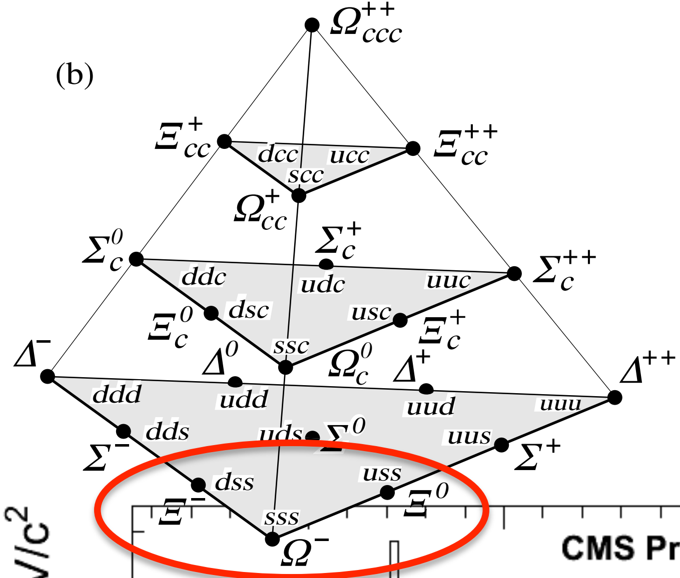
The relevance:

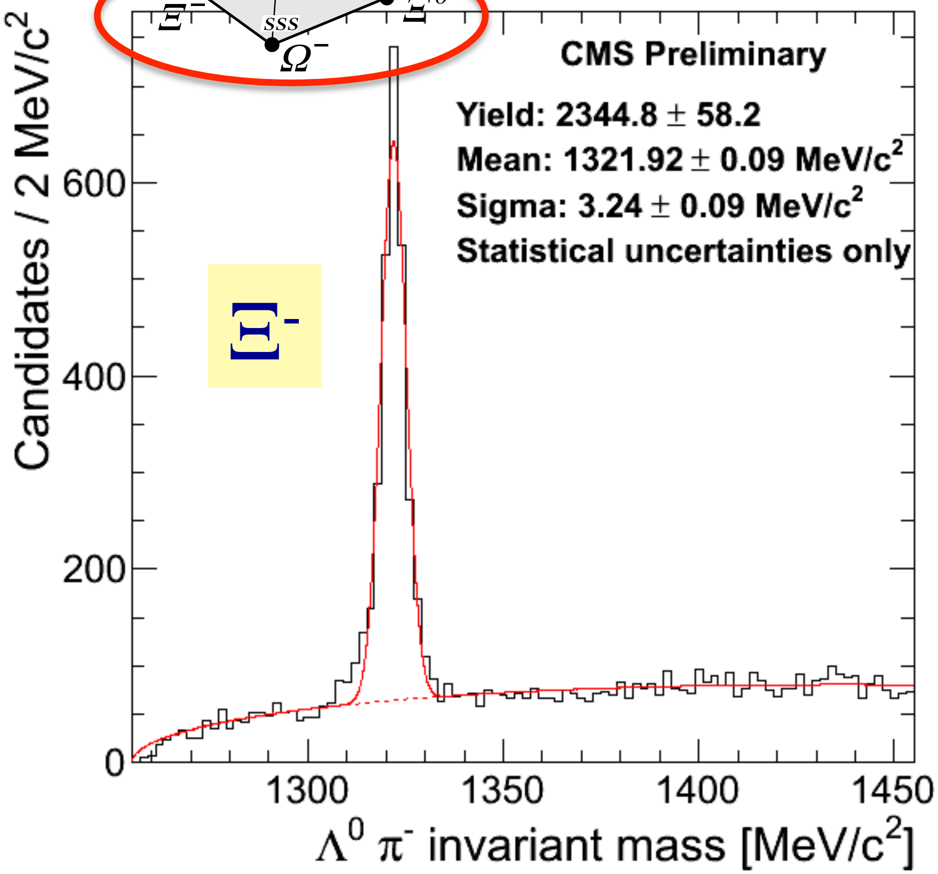
indicates quality of tracking & understanding of backgrounds, modelling of material (excellent agreement with Monte Carlos from early stage)

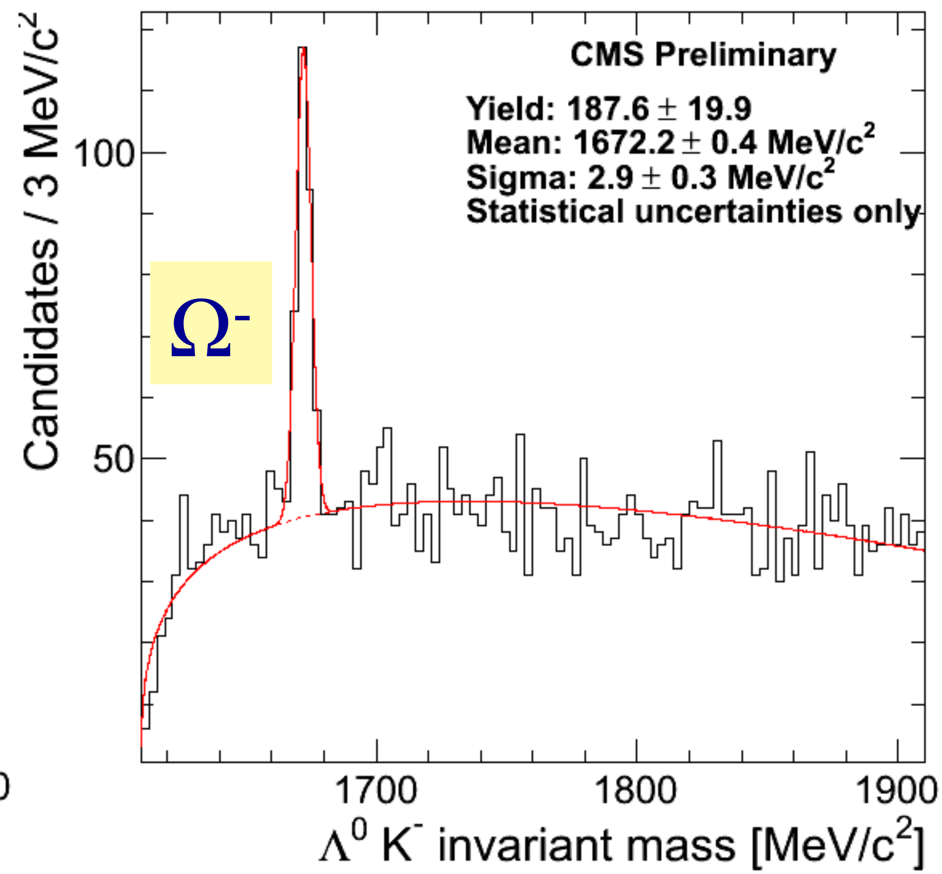
checks on magnetic field (most of K^0 mass appears as momentum)

Baryon resonances

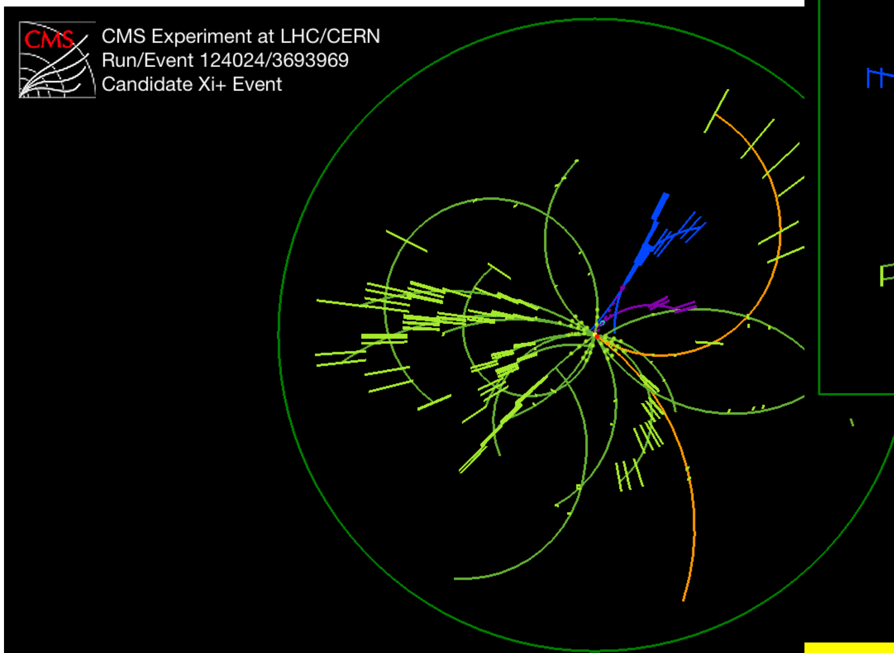
Excited, short lived states. The Ω^- [sss] was the prediction [Gell-Mann 1962] which began to make most people believe in quarks.

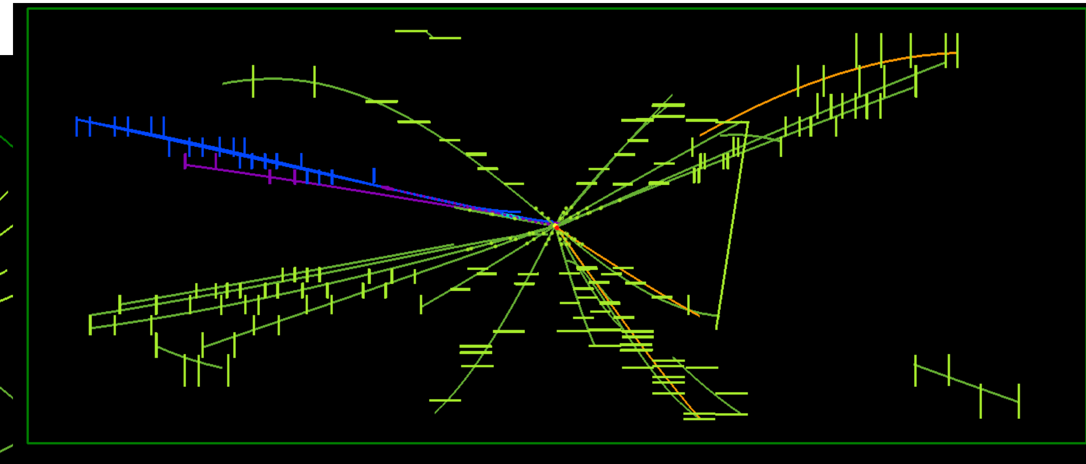


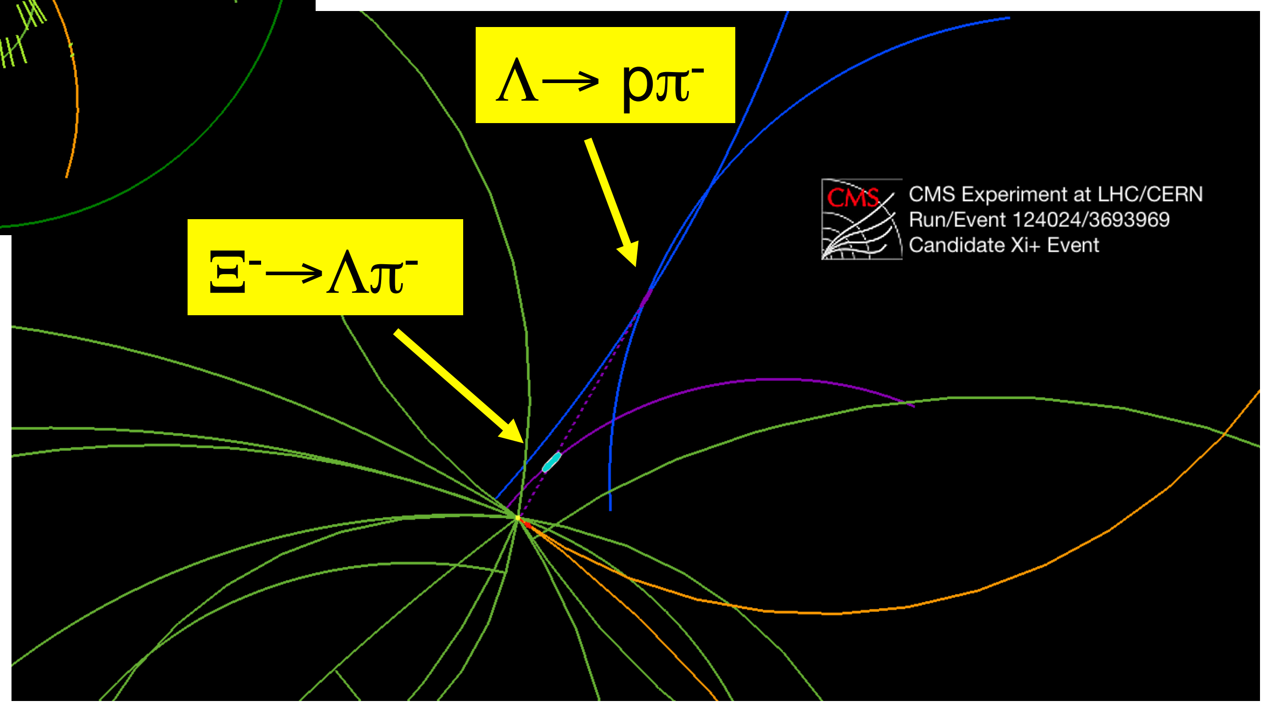




Ξ^- cascade reconstruction







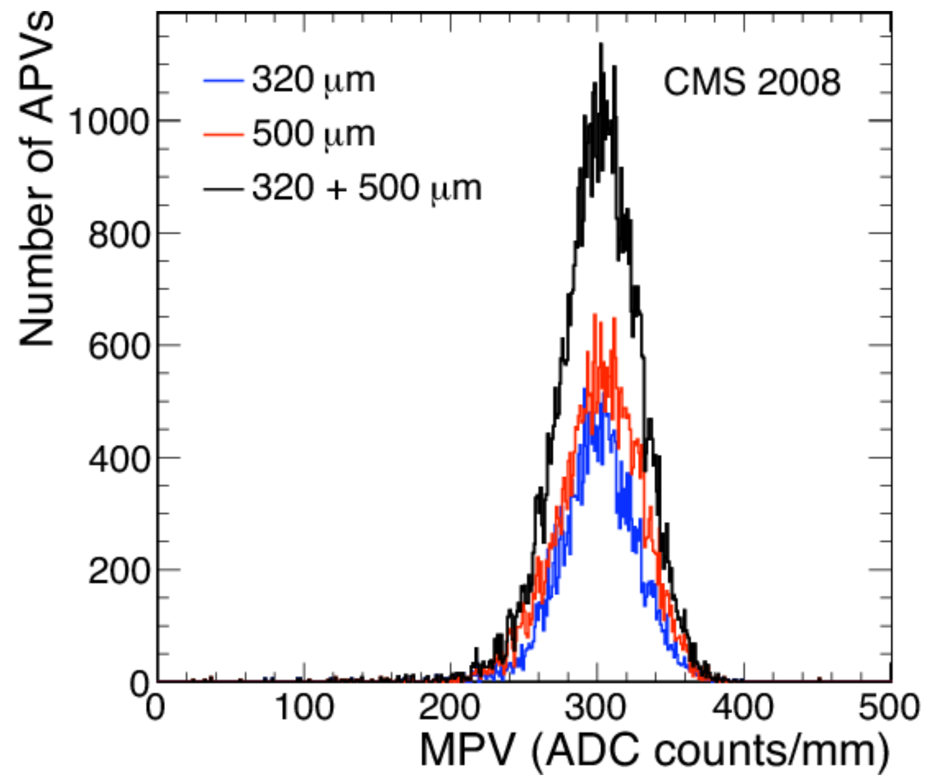
$\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^-\pi^-$

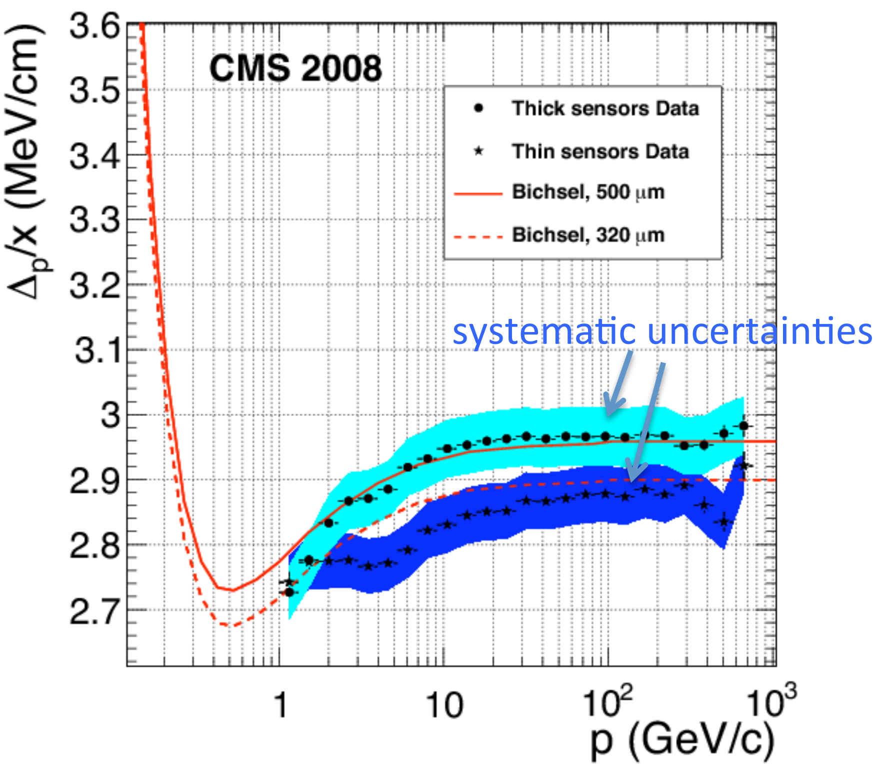
- Two detached vertices

Energy loss

Means of limited particle identification

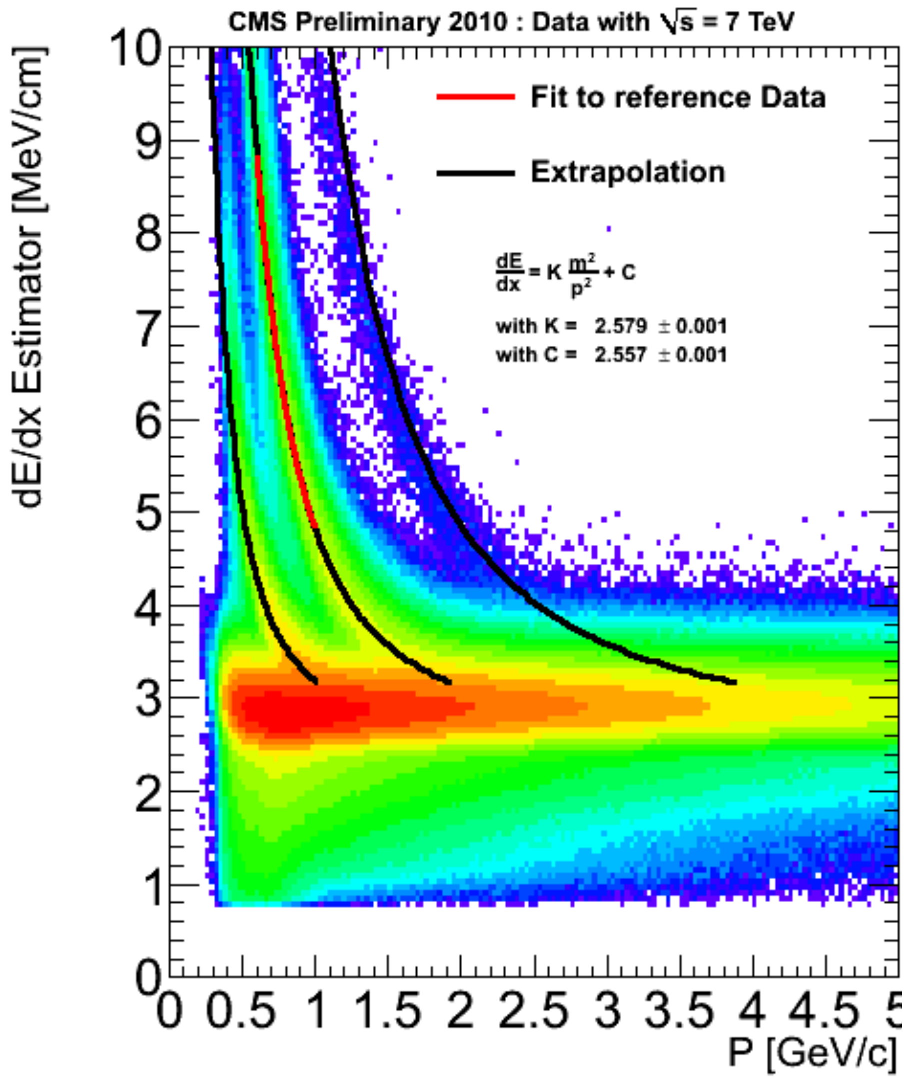
- For dE/dx, need to know conversion ratio electrons/ADC count
- Use cosmic muons (MIP) to calibrate all APVs → uniformity
- Path length corrected MPV of Signal

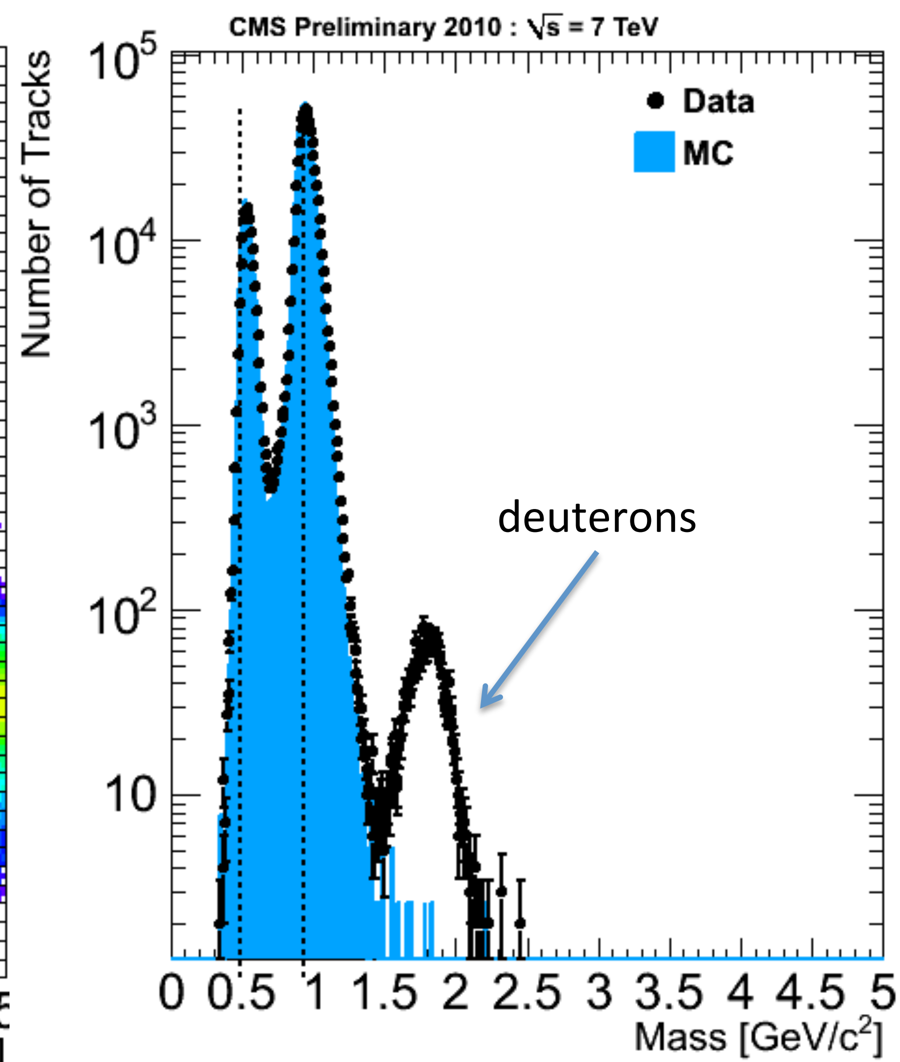




- Most probable energy loss/unit length
  - Use Landau-Vavilov-Bichsel theory
  - Fit as function of track momentum
  - Extract calibration constant for each sensor type

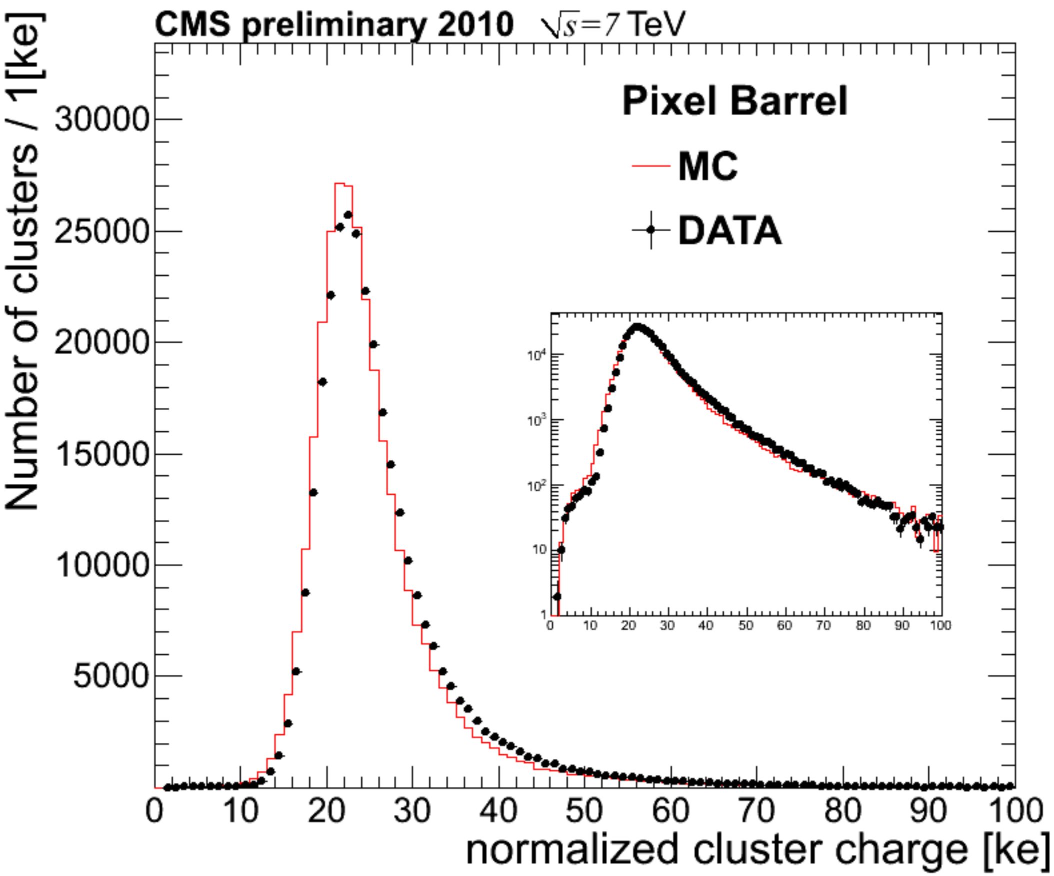
dE/dx in collisions

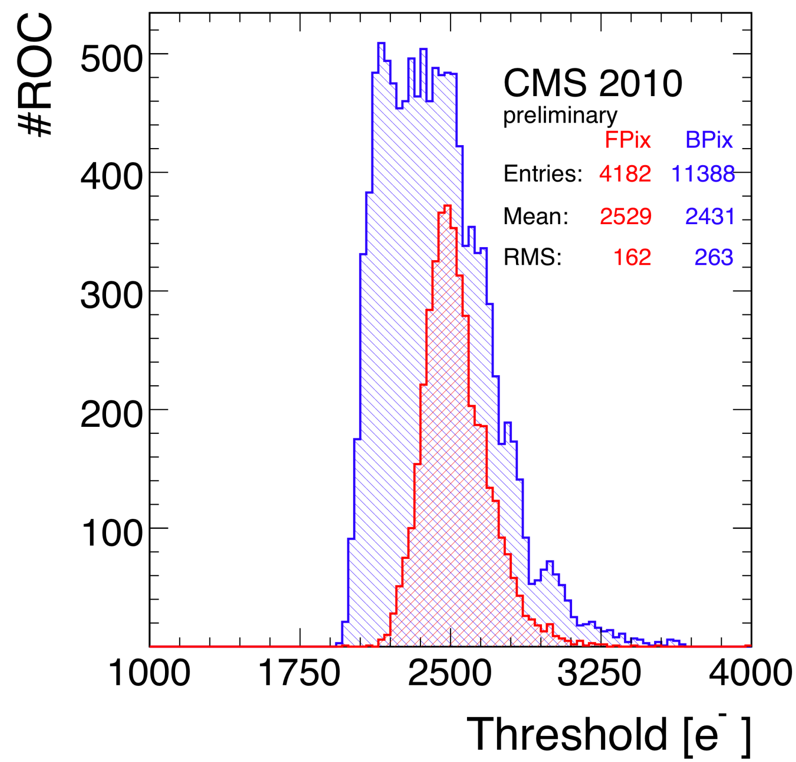




- Clear separation of kaons and protons, nice agreement with MC
    - Cut dE/dx > 4.15 MeV/cm

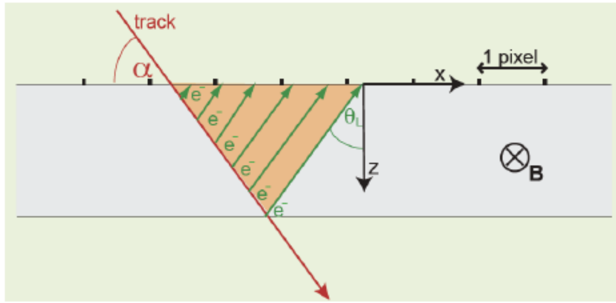
Pixels

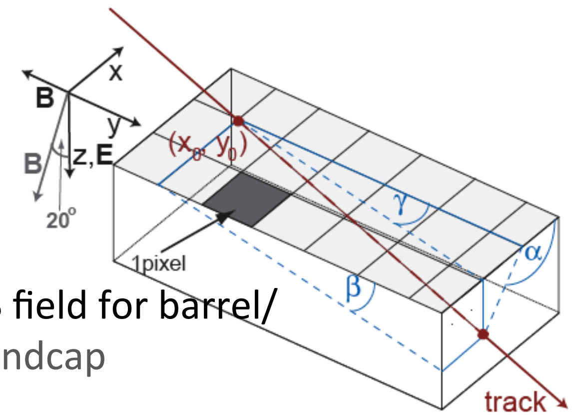

CMS preliminary 2010 $\sqrt{s}=7$ TeV
Pixel Barrel
MC
DATA
Number of clusters / 1[ke]
normalized cluster charge [ke]
0
10
20
30
40
50
60
70
80
90
100
5000
10000
15000
20000
25000
30000


CMS 2010
preliminary
FPix
BPix
Entries: 4182 11388
Mean: 2529 2431
RMS: 162 263
#ROC
Threshold [e⁻]
1000
1750
2500
3250
4000
100
200
300
400
500

Lorentz angle in pixels

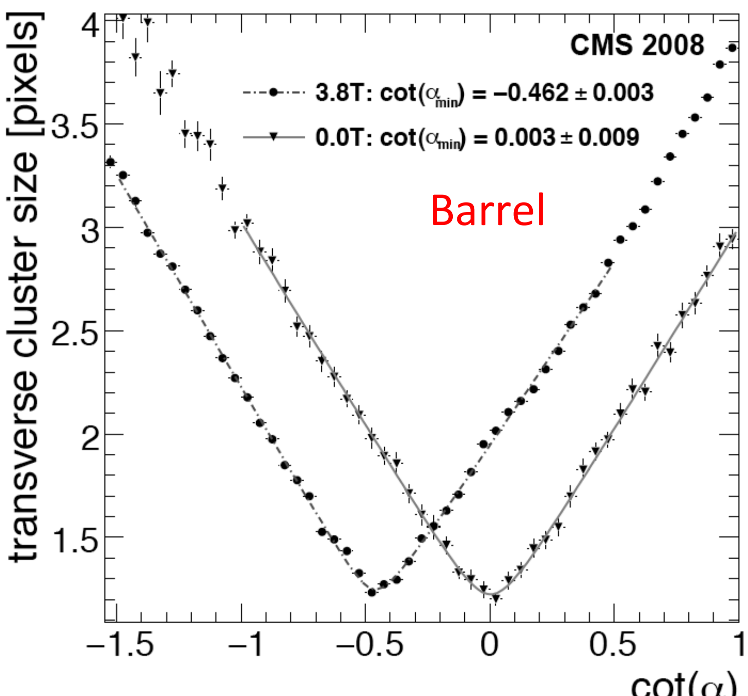
This is the trick which gives ~10µm resolution from 100µm pixels

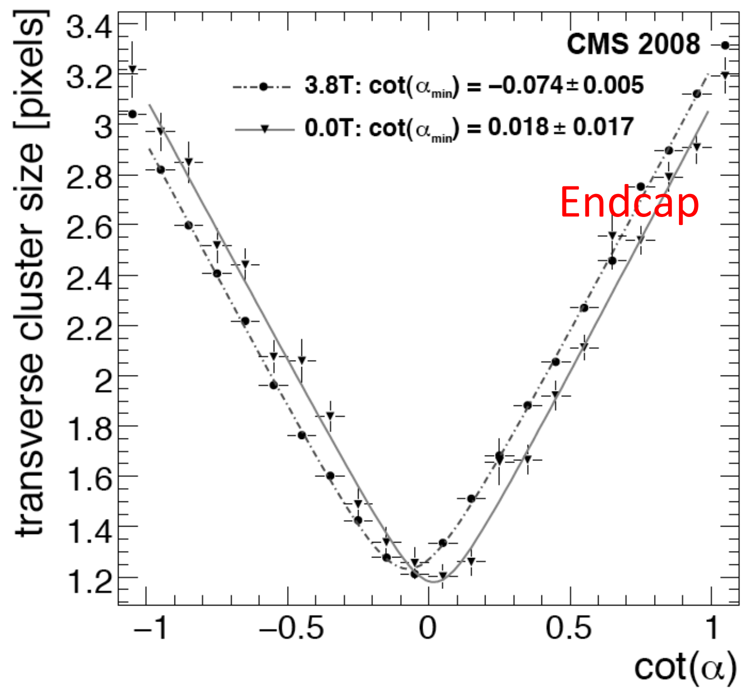




B field for barrel/ endcap

- ExB fields
  - enhances charge sharing between pixels
  - analogue interpolation improves precision





Summary

- The huge tracking system is perhaps the most remarkable CMS detector
  - a lot of advanced technology was mastered
- System has been very reliable and robust, with no significant problems
  - some radiation effects beginning to be visible (as expected)
- Software and analysis working exceptionally well

- The tracker contributes to almost all physics from CMS
  - primary and secondary particle reconstruction
  - particle flow
  - μ momentum
  - calorimeter shower identification and background removal

- The replacement in ~2023 will be even harder
  - and more demanding performance too