Collider Detectors III

How to build a new experiment

Physics as a guide

“Commissioning a large experiment”

We will talk about:

Going from the existing to the future

☞ From the Tevatron to the LHC

How do you design and build a new (actually two) detector?

☞ What is driving your choices?

☞ What kind of compromises between performances, human and budgetary resources you have to tackle?

LHC

The Large Hadron Collider is not yet operational

- ☞ Detectors are already built
  - ⇨ TDR written in mid-nineties of the last century
- ☞ Let's try to understand the intellectual path followed
- ☞ Physics case:
  - ⇨ Higgs
  - ⇨ New particles

- ☞ Simple ideas, difficult implementation

LHC parameters

$$L = \frac{\gamma f k_b N_p^2}{4\pi\varepsilon_n \beta^*} F$$

f	revolution frequency
k_b	no. of bunches
N_p	no. of protons/bunch
ε_n	norm transverse emittance
β^*	betatron function
F	reduction factor xing angle

Magnetic Field

p (TeV) = 0.3 B(T) R(km)

For p= 7 TeV, R= 4.3 km

⇨ **B = 8.4 T**

Beam-beam tune shift $\xi = \frac{N r_p}{4\pi\varepsilon_n}$

Energy at collision	E	7	TeV
Dipole field at 7 TeV	B	8.33	T
Luminosity	L	10^{34}	$cm^{-2}s^{-1}$
Beam beam parameter	ξ	3.6	10^{-3}
DC beam current	I_{beam}	0.56	A
Bunch separation		24.95	ns
No. of bunches	k_b	2835	
No. particles per bunch	N_p	1.1	10^{11}
Normalized transverse emittance (r.m.s.)	ε_n	3.75	µm
Collisions			
β-value at IP	β^*	0.5	m
r.m.s. beam radius at IP	σ^*	16	µm
Total crossing angle	ϕ	300	µrad
Luminosity lifetime	τ_L	10	h
Number of evts/crossing	n_c	17	
Energy loss per turn		7	keV
Total radiated power/beam		3.8	kW
Stored energy per beam		350	MJ

Physics

Which L ?

$qq \rightarrow qqH \rightarrow qqWW \rightarrow qql\nu jj$ with M_H= 800GeV.

$\sigma_{det}= \sigma(VBF) \times BR(l\nu jj) \times \varepsilon = 0.2\ 10^{-36} \times 0.2 \times 0.1= 4\ 10^{-39}\ cm^2$ (4 fb)

$Nev = L \times t \times \sigma$ for $t=10^7$ (1y) $Nev = 100 \rightarrow \langle L \rangle = 2.5\ 10^{33}\ cm^{-2}\ s^{-1}$

Lmax design $10^{34}\ cm^{-2}\ s^{-1}$

A L of 10^{34} can be reached with 2835 bunches of $1.1\ 10^{11}$ protons colliding every 25 ns.

At 14 TeV one expects : σ(total)=105 mb; σ(el)=28 mb;

One sees only σ(inel) ~ 80 mb

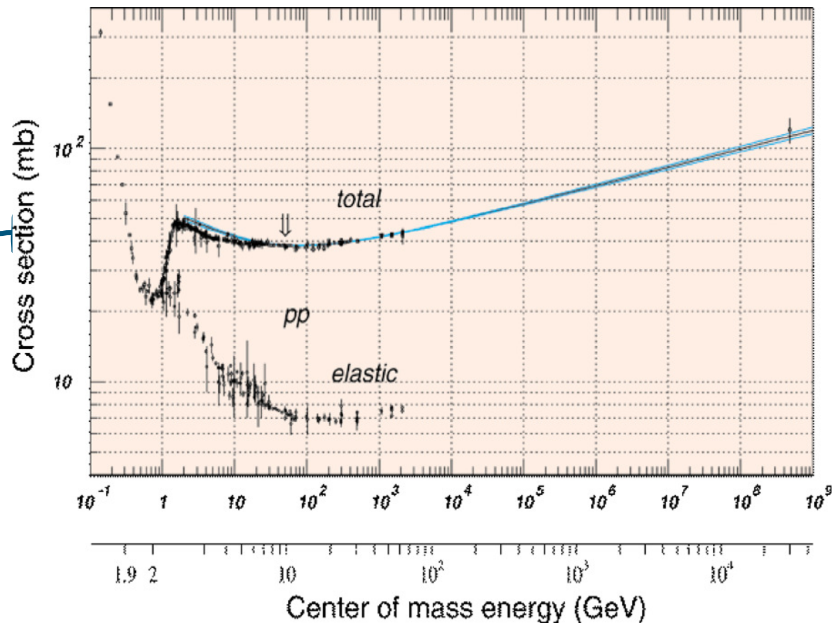
$\langle Nev/crossing \rangle = 10^{34} \times 80\ 10^{-27} \times 25\ 10^{-9}$ = .65 GHz ~ 20 int/ Bunch

pp cross-sections and minimum bias

of interactions/crossing:

- Interactions/s:
  - Lum = 10^{34} $cm^{-2}s^{-1}$=$10^{7}mb^{-1}Hz$
  - $\sigma(pp)$ = 80 mb
  - Interaction Rate, R = $8x10^{8}$ H
- Events/beam crossing:
  - Δt = 25 ns = $2.5x10^{-8}$ s
  - Interactions/crossing=20
- Not all p bunches are full
  - 2835 out of 3564 only
  - Interactions/"active" crossing = 20 x 3564/2835 = 25

$\sigma_{inel}(pp)\approx80$ mb@14TeV



Operating conditions (summary):
(1) A "good" event containing a Higgs decay +
(2) ~ 25 extra "bad" (minimum bias) interactions

Impact on detector design

LHC detectors must have fast response

- Otherwise will integrate over many bunch crossings → large "pile-up"
- Typical response time : 20-50 ns
  - → integrate over 1-2 bunch crossings → pile-up of 25-50 min-bias
  - → very challenging readout electronics

LHC detectors must be highly granular

- Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \rightarrow \gamma\gamma$ decays)
  - → large number of electronic channels
  - → high cost

LHC detectors must be radiation resistant:

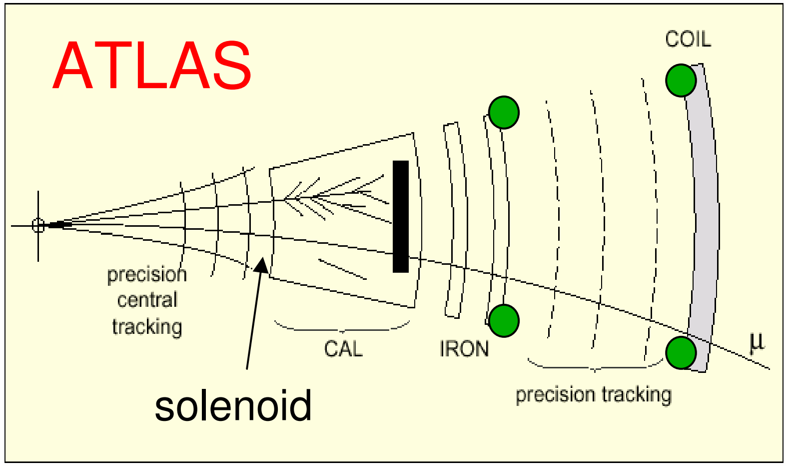
- high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters:
  - up to 10^{17} n/cm^2 in 10 years of LHC operation
  - up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)

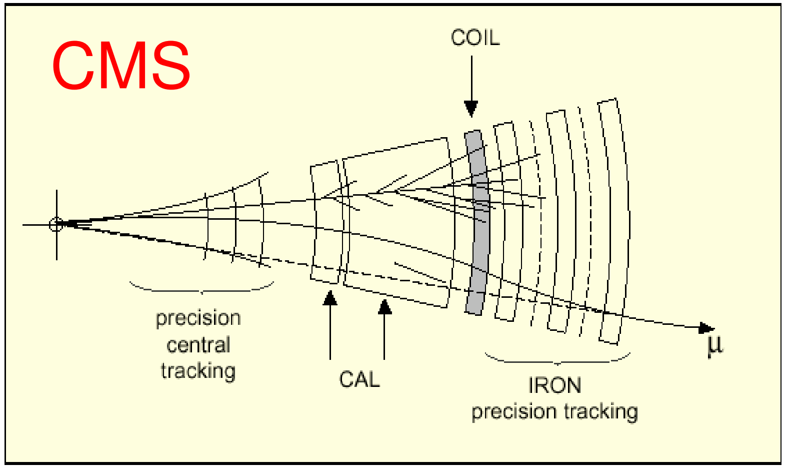
Basic principles

- Need "general-purpose" experiments covering as much of the solid angle as possible ("4π") since we don't know how New Physics will manifest itself
  - detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks,
  - Momentum/charge of tracks and secondary vertices (e.g. from b-quark decays) are measured in central tracker (Silicon layers).
  - Energy and positions of electrons and photons measured in electromagnetic calorimeters
  - Energy and position of hadrons and jets measured mainly in hadronic calorimeters.
  - Muons identified and momentum measured in external muon spectrometer (+central tracker).
  - Neutrinos "detected and measured" through measurement of missing transverse energy (E_T^{miss}) in calorimeters.

Detector Design

Atlas and CMS did opposite but complementary choices :





Atlas put the calo's behind the solenoid (B= 2T):

limited em energy resolution

Uses an Air toroid μ spectrometer

optimal μ momentum resolution

Four magnets in total.

CMS use an high field (B= 4T) solenoid placed after the calorimetry :

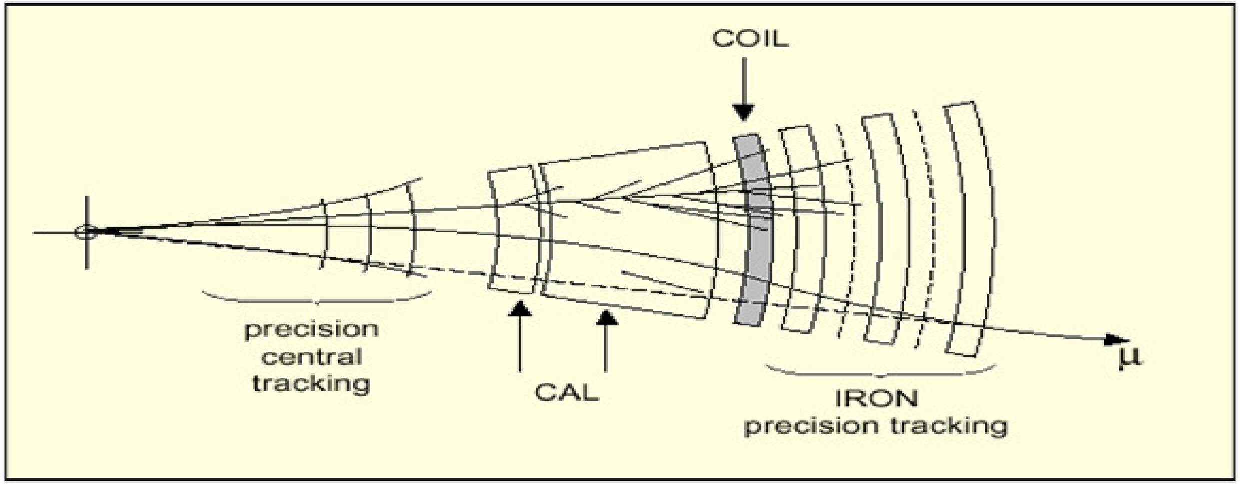
Optimal em energy resolution

The μ spectrometer uses the solenoid return flux. Only 1 (but big) magnet:

Designing an LHC experiment on a paper towel (cern cafeteria*)

- 4 T solenoidal field+ return yoke instrumented with a redundant
- muon system (main trigger component)
- Excellent e.m. calorimeter (high resolution On e,γ)
- Powerful silicon tracker (p is measured in the tracker and in the muon spectrometer; exploit the 20μm beam spot)
- All calorimetry inside the coil.

CMS



Private comm. Guido Tonelli

EM calorimetry

Need excellent energy resolution of EM calorimeters for e/g;

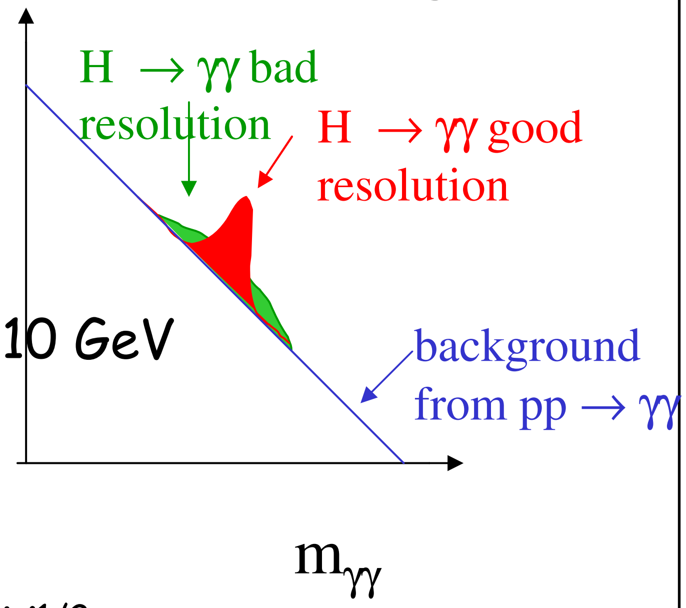
Example: H → γγ for low mass Higgs

Higgs width is very narrow, so

S/N directly ∝ to signal resolution

$S=N_S/\sqrt{N_B}\ \alpha\ \sqrt{L}/\sqrt{s(M)}$

For S~5 $L=20\,fb^{-1}$ $s(M)/M\sim1\%$ per $M_H=110$ GeV



$$\frac{\sigma_M}{M}=\frac{1}{2}\left(\frac{\sigma(E_1)}{E_1}\oplus\frac{\sigma(E_2)}{E_2}\oplus\frac{\sigma_\theta}{tg(\theta/2)}\right)$$

$$\frac{\sigma(E)}{E}=\frac{a}{\sqrt{E}}\oplus\frac{b}{E}\oplus c$$

$a < 5\text{-}10\%\ GeV^{1/2}$

b< 200-300 MeV

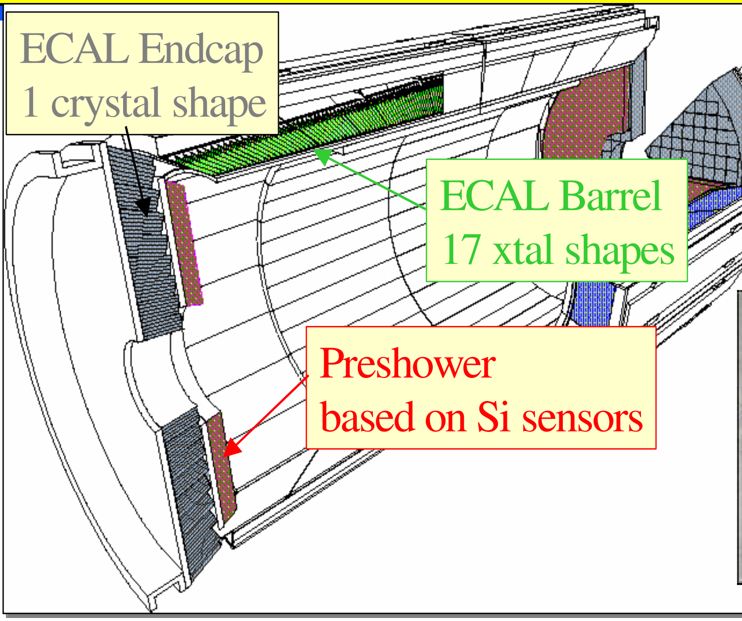
c< 0.5-0.7%

π^0 rejection: crystal size (isolation)

Shower direction

$\sigma(\theta)\approx 50\ mrad/\sqrt{(E/GeV)}$

CMS Electromagnetic Calorimeter

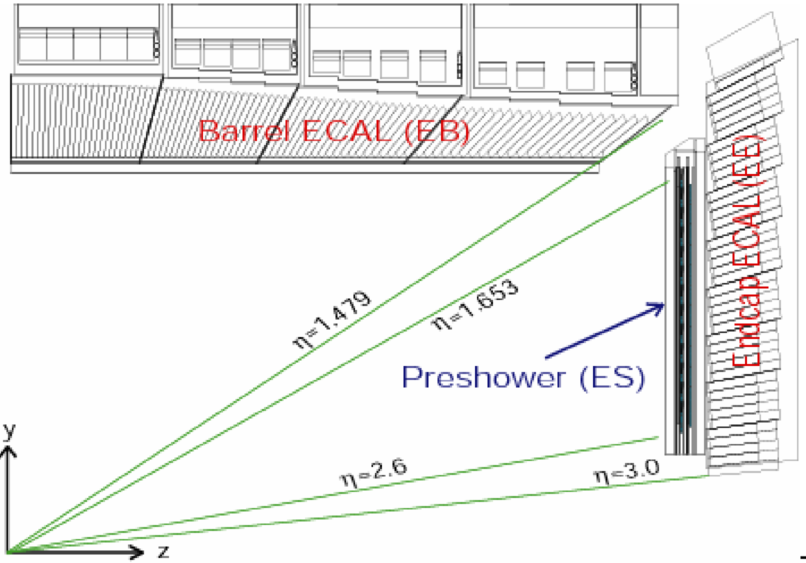


ECAL Endcap
1 crystal shape

ECAL Barrel
17 xtal shapes

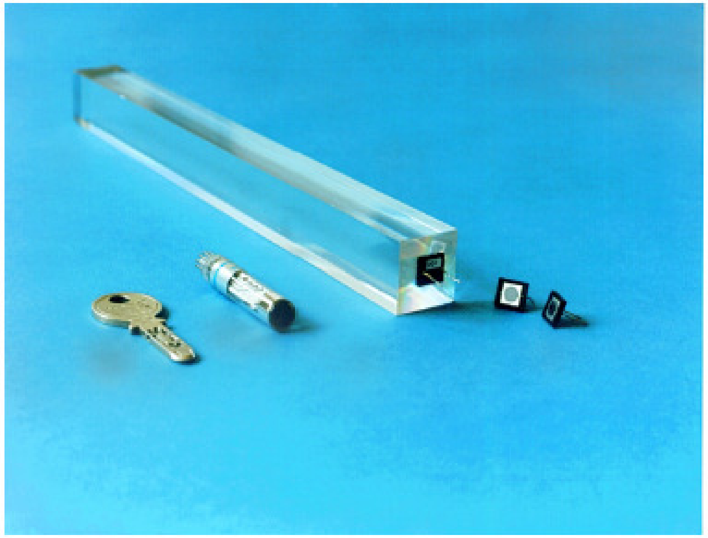
Preshower
based on Si sensors

Characteristics of $PbWO_4$
$X_0 = 0.89$cm
$\rho = 8.28$g/cm^3
R_M (Molière radius) = 2.2cm



Parameter	Barrel	Endcaps
Coverage	$\lvert\eta\rvert < 1.48$	$1.48 < \lvert\eta\rvert < 3.0$
$\Delta\phi \times \Delta\eta$	0.0175 × 0.0175	0.0175 × 0.0175 to 0.05 × 0.05
Depth X_0	25.8	24.7
# of crystals	61200	14648
Volume	8.14m^3	2.7m^3
Xtal mass	67.4 (T)	22.0 (T)

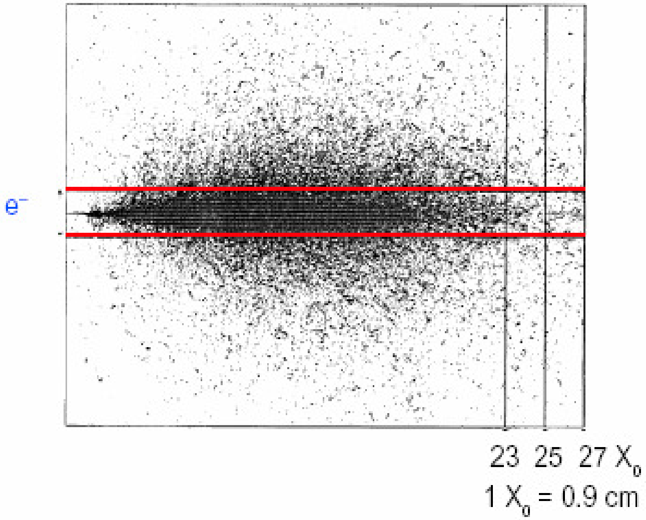
ECAL



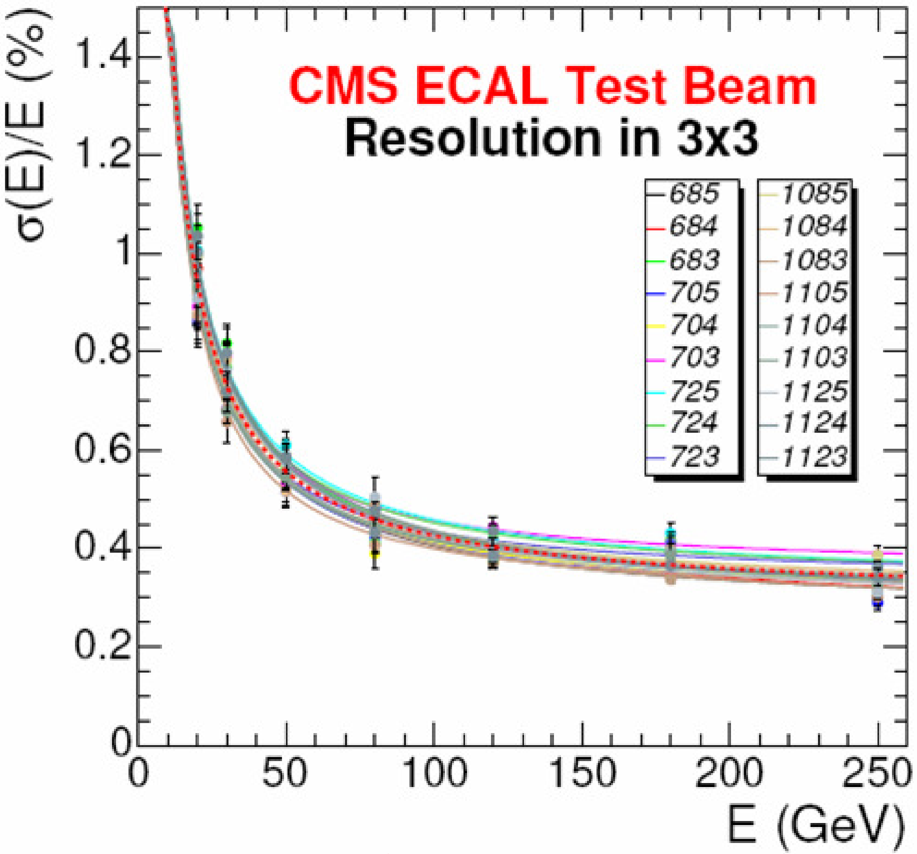
75.000 lead tungstate crystals (very compact); fast (95% light emitted in 25ns; highly granular (2.19cm Moliere radius)

Excellent energy resolution
Stochastic term (Photostatistics APD 4p.e./MeV)
Noise (electronics and pile-up)
Constant term (uniformity and calibration)

$$\frac{\sigma(E)}{E} = \frac{3\%}{\sqrt{E}} \oplus \frac{150\,MeV}{E} \oplus 0.40\%$$



Ecal intrinsic resolution : central impact



Mean resolution at each energy point:

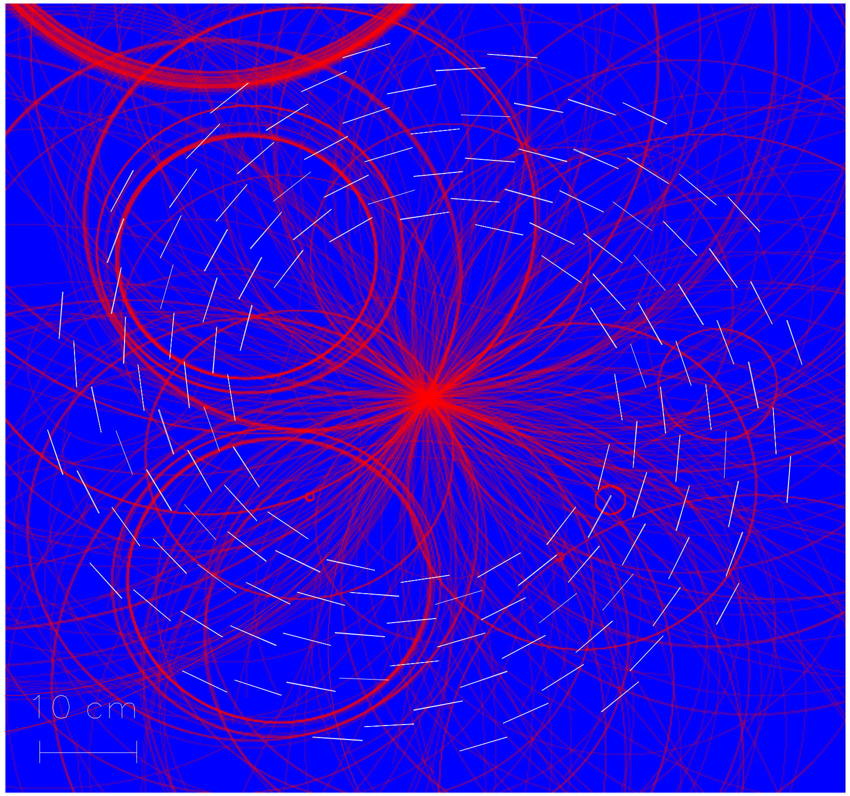
Energy (GeV)	Resolution (%)
20	0.94 ± 0.05
30	0.74 ± 0.04
50	0.56 ± 0.03
80	0.45 ± 0.02
120	0.40 ± 0.01
180	0.38 ± 0.01
250	0.34 ± 0.01

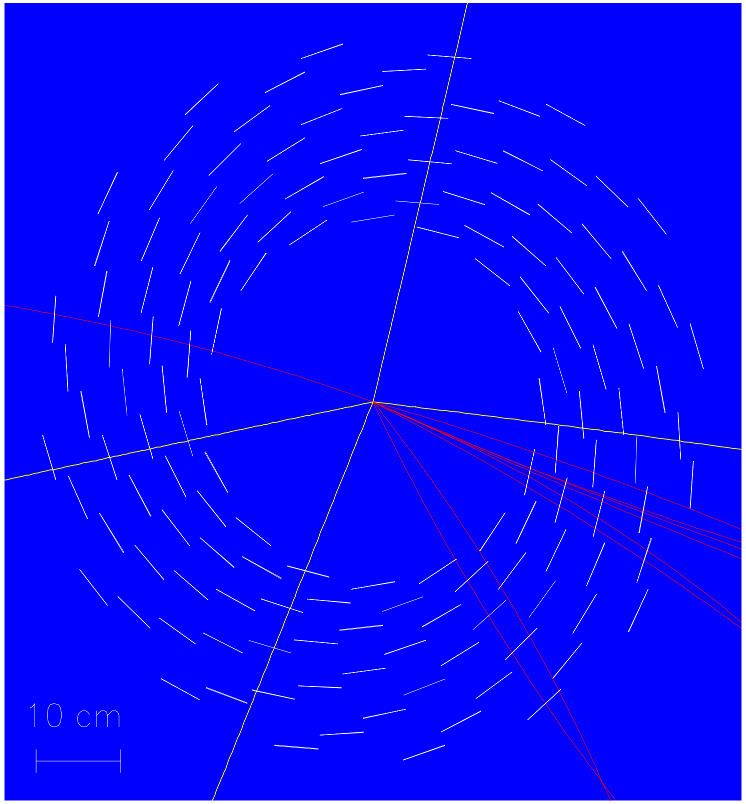
Mean resolution:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.9\%}{\sqrt{E}}\right)^2 + \left(\frac{125(MeV)}{E}\right)^2 + (0.30\%)^2$$

Tricks for tracking at LHC

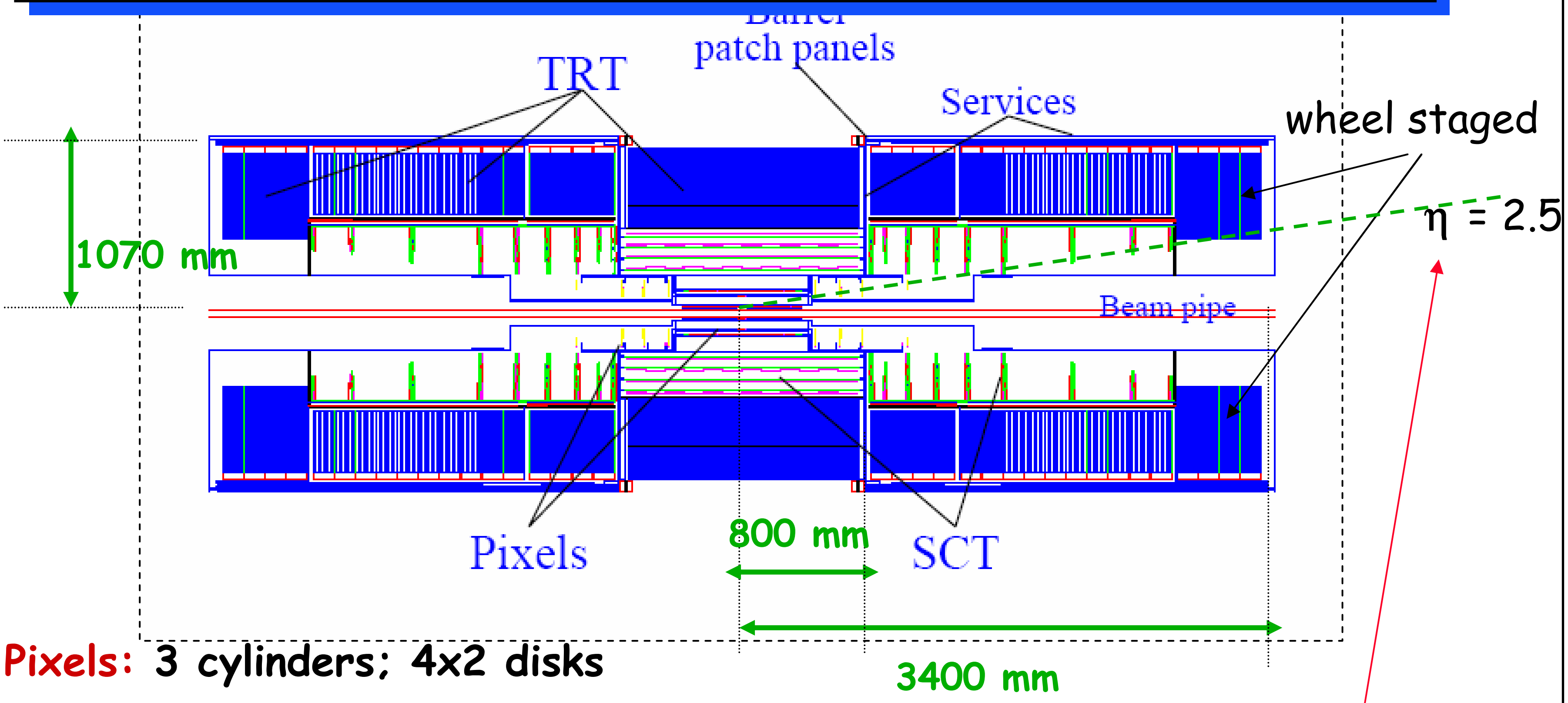
More than 1000 tracks per event. What to do for PR?





Make a “cut” on the transverse momentum of the tracks: p_T>2 GeV (the only interesting to reconstruct)

ATLAS Inner Detector Layout



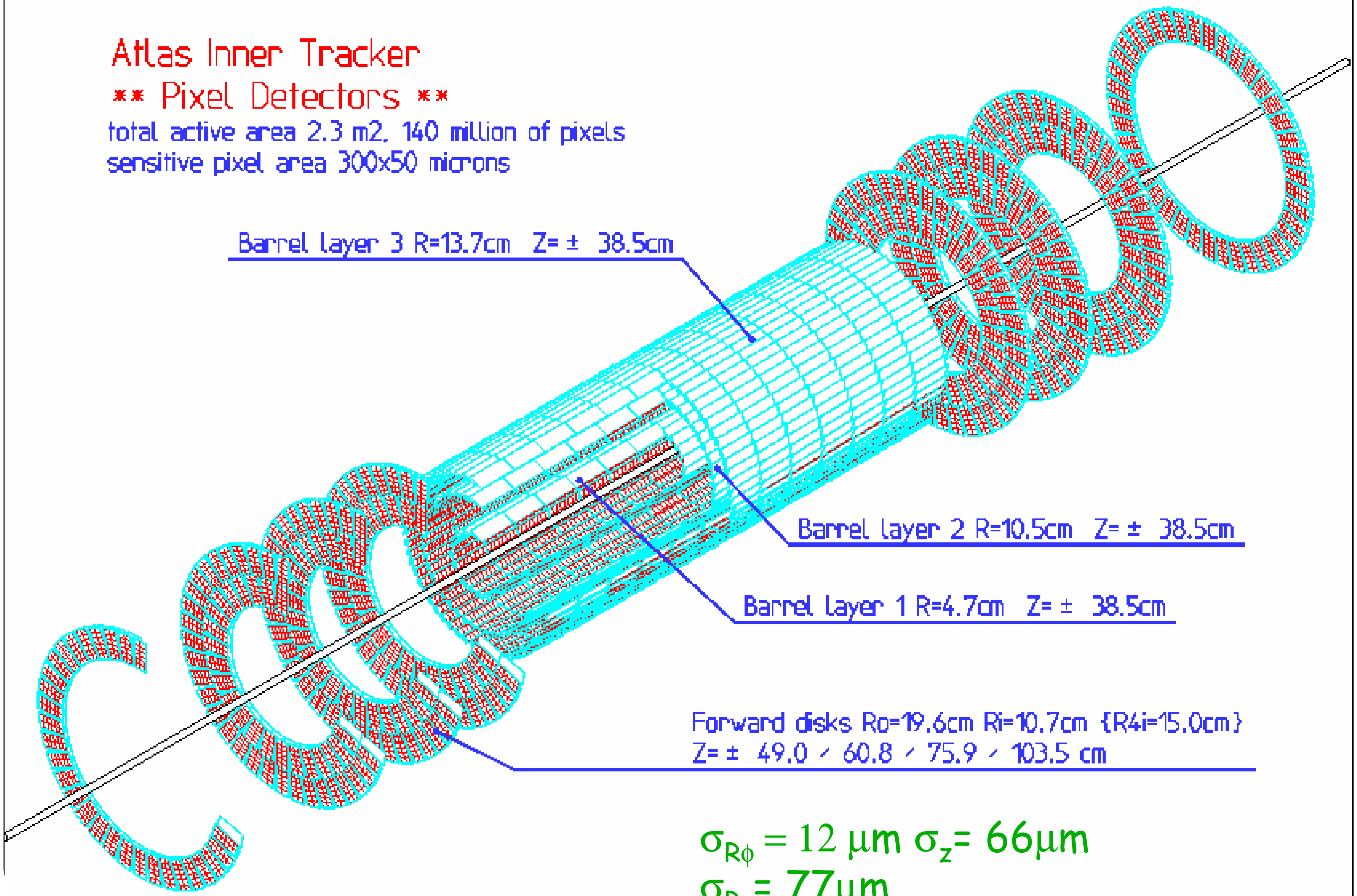
Pixels: 3 cylinders; 4x2 disks

SCT : 4 cylinders; 9x2 disks

TRT: Barrel and EC

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

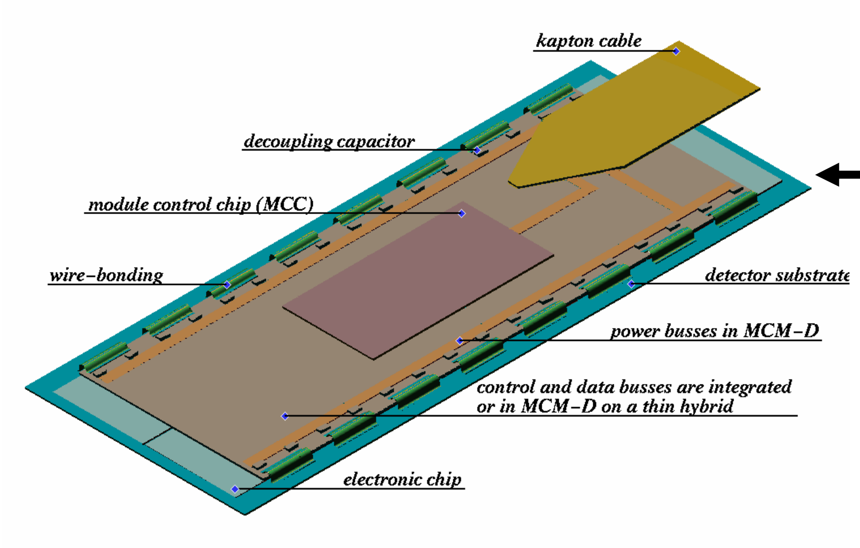
Pixel



$\sigma_{R\phi} = 12\ \mu m$ $\sigma_z = 66\mu m$

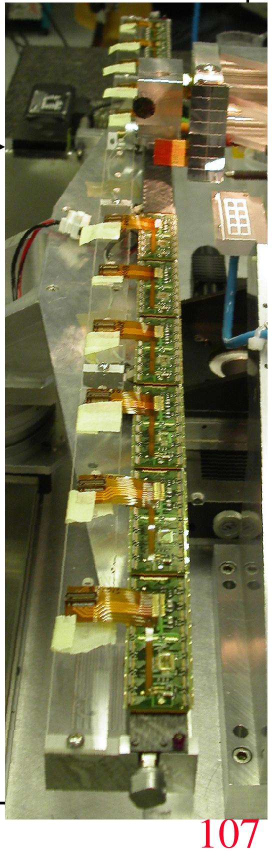
$\sigma_R = 77\mu m$

Pixel II



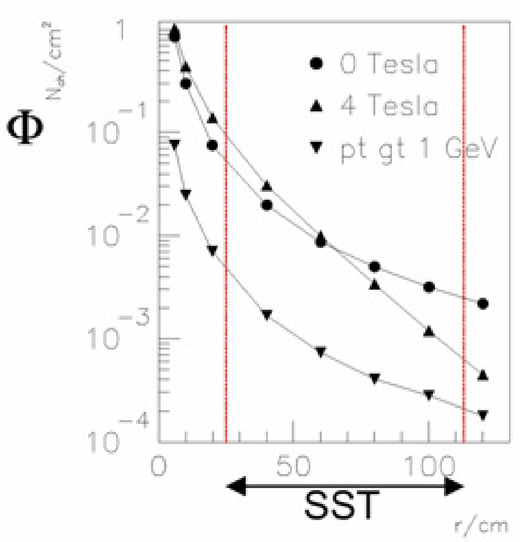
Each barrel module is 62.4 x 22.4 mm^2 and has 61440 pixels
One module is read out by 16 FE chips bump bonded on the detector

Modules are mounted on carbon fiber support in staves and after the staves on cylinders



Tracking Requirements-CMS

Efficiency: need low, ~few % occupancy; Resolution



Twelve hits; 4T field
spatial resolution: (pitch/ √12)
Radius: 110 cm
→momentum resolution:

$$\frac{\Delta p}{p} \approx 0.12\left(\frac{pitch}{100\mu m}\right)^{1}\left(\frac{1.1m}{L}\right)^{2}\left(\frac{4T}{B}\right)^{1}\left(\frac{p}{1Tev}\right)$$

→Need pitch ~100µm.

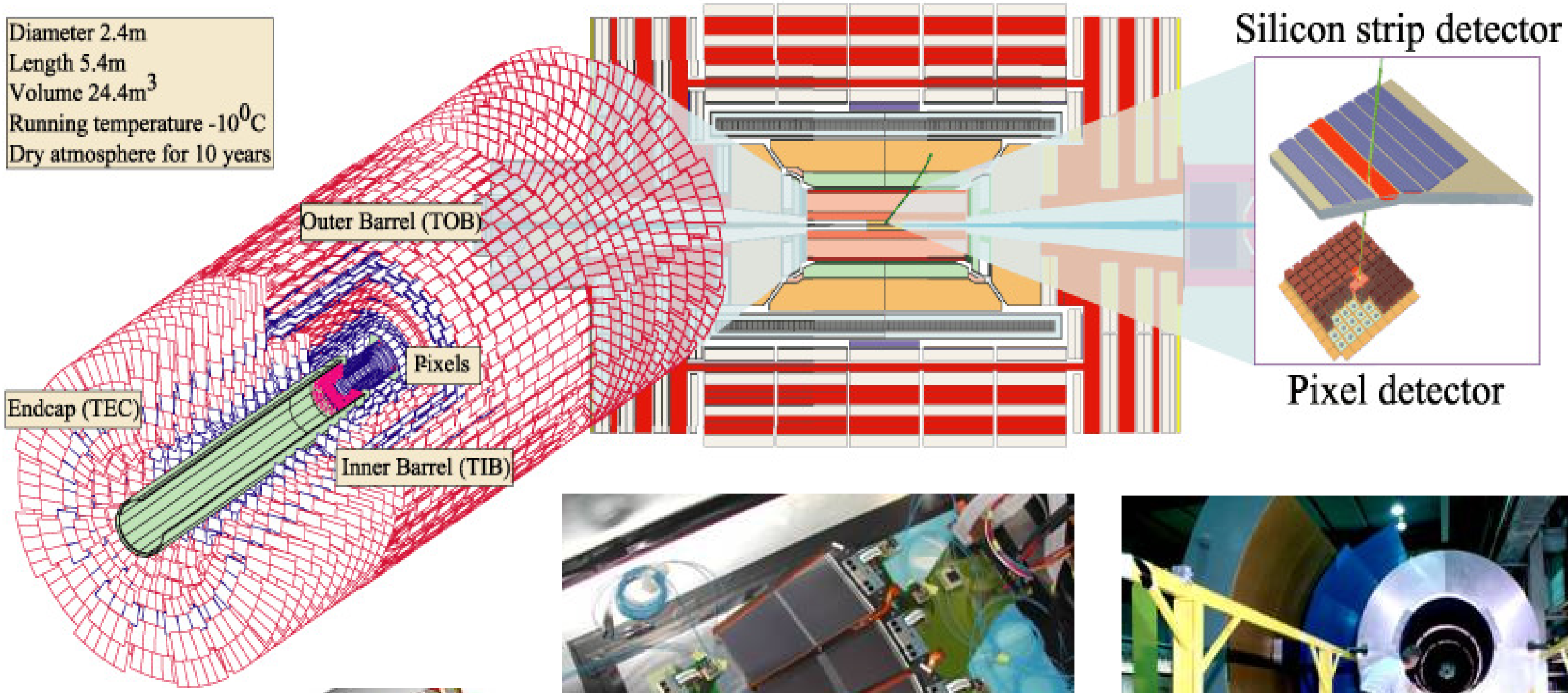
Strip size

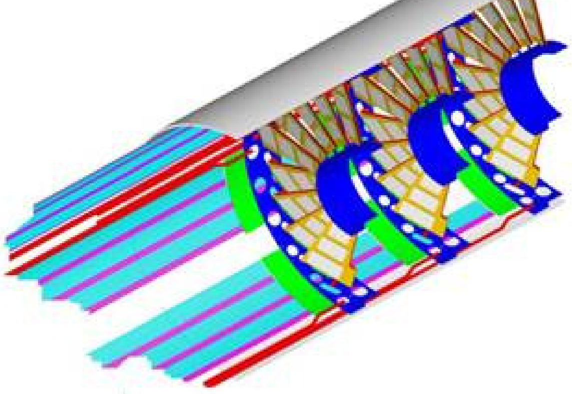
Strip length: 10cm (inner layers) to 20cm (outer layers).

Pitch: 80µm (inner layers) to 200µm (outer layers)

small radii: need cell size < 1cm^2 + fast (~25ns) shaping time

The CMS Tracker



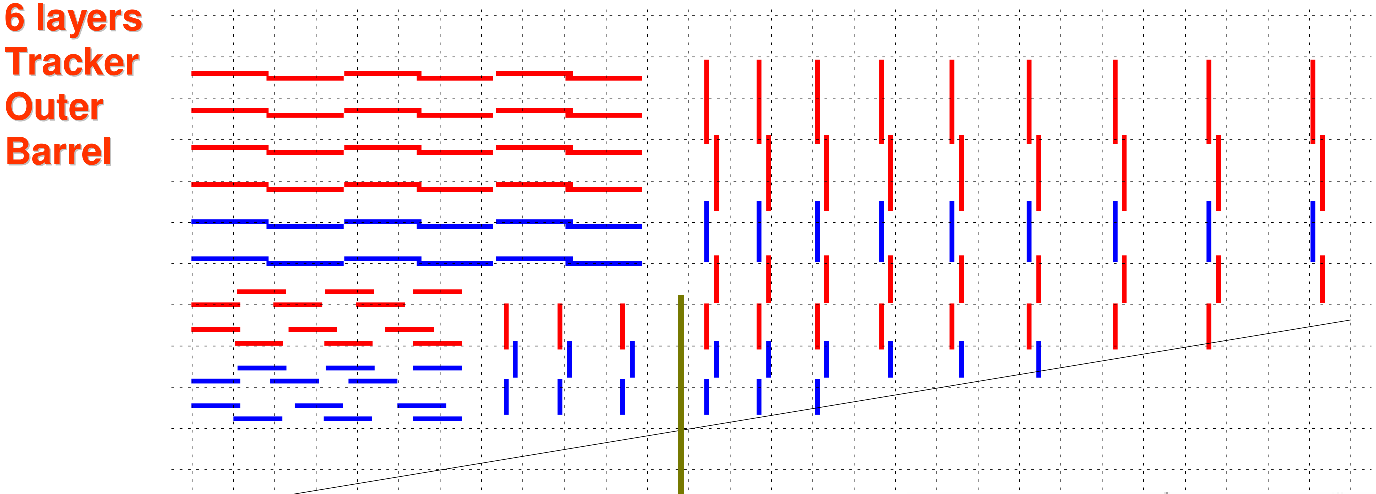


Pixel endcap disks

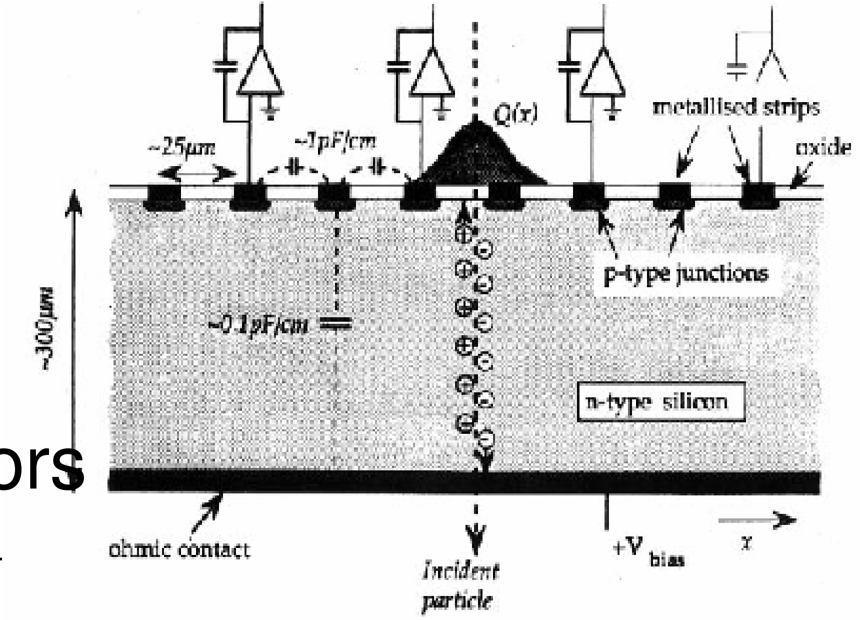
207m^2 of silicon sensors
10.6 million silicon strips
65.9 million pixels in final configuration!

CMS: Extreme longitudinal segmentation

Radius ~ 110cm, Length ~ 270cm



High granularity Silicon
Microstrip and Pixel detectors



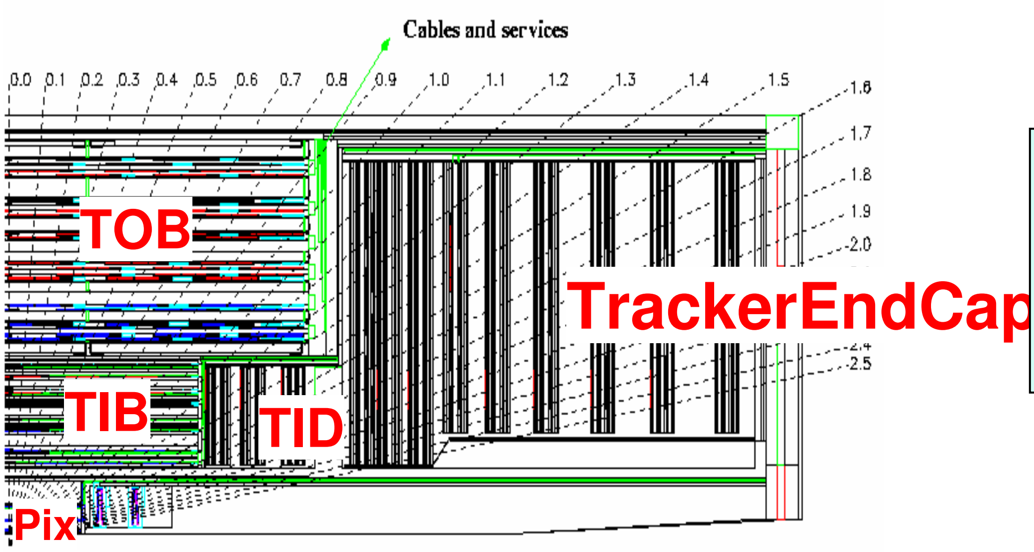
Detector commissioning

One of the most challenging tasks for a collider detector is the commissioning phase

- ☞Integrating a large number of subsystems
- ☞Define operating parameters
  - ⇨Difficult to change afterwards
- ☞Collect systematic information on electronics/detector behaviour
    - →Time consuming operation
  - ⇨Can be useful later on to fix problems

- ☞Test of DAQ/timing etc.

Tracker Integration

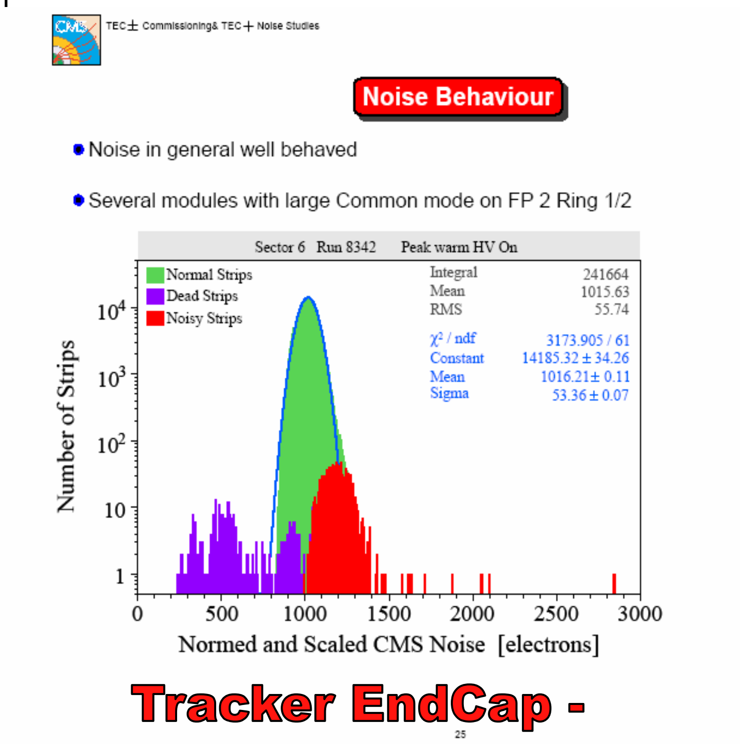


Inner tracker:
~ 220 m^2 of Si sensors
10.6 million Si strips
65.9 million Pixels

Status of CMS Tracker Integration

- All geographical parts (except pixels) integrated into Tracker Support Tube.
- 2/3rd of pixels modules assembled. Pixels system end-2007.

Commissioning the CMS tracker…



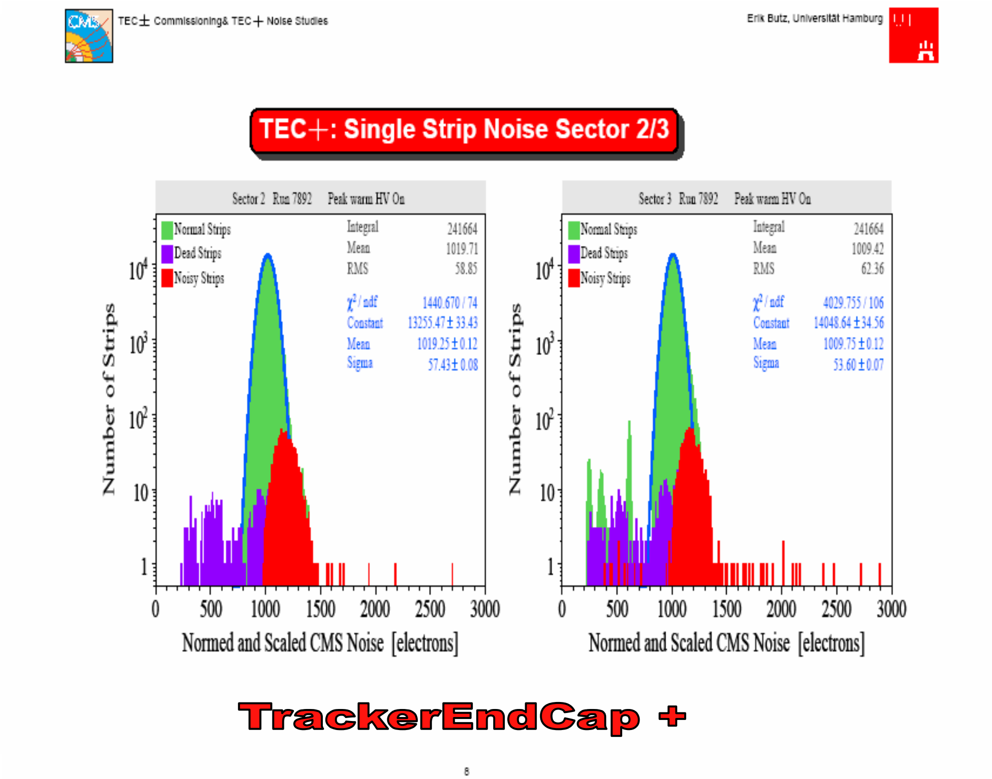
TEC± Commissioning& TEC+ Noise Studies

Noise Behaviour

- Noise in general well behaved
- Several modules with large Common mode on FP 2 Ring 1/2

Tracker EndCap -

25



TEC± Commissioning& TEC+ Noise Studies

Erik Butz, Universität Hamburg

TEC+: Single Strip Noise Sector 2/3

TrackerEndCap +

8

noise very good and stable.
Very few 'new' defects w.r.t pre-installation (3 lasers / 2832).
Under investigation.

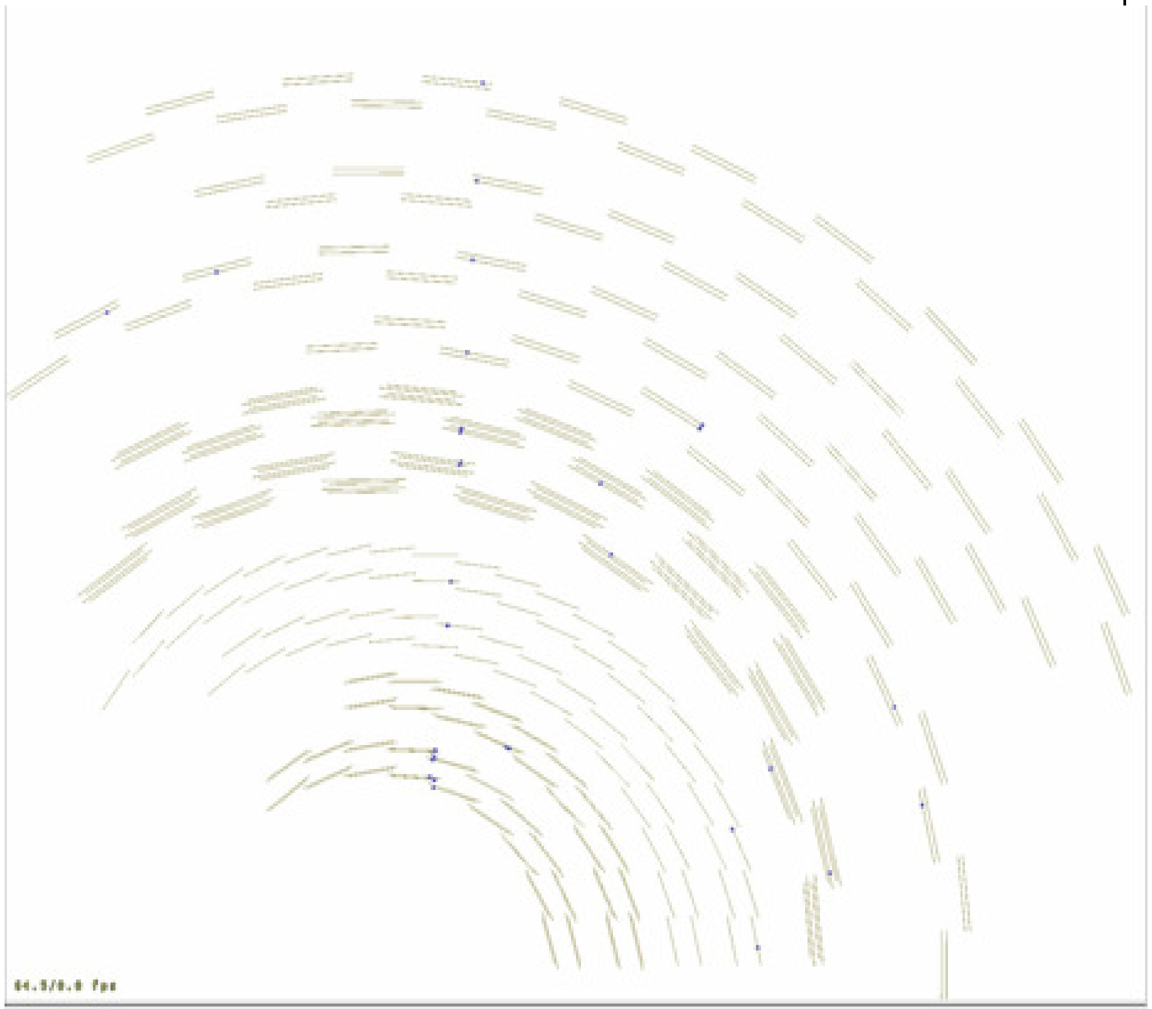
Status and Plans for the CMS Tracking Systems

A Cosmic Track

in TrackerOuterBarrel +

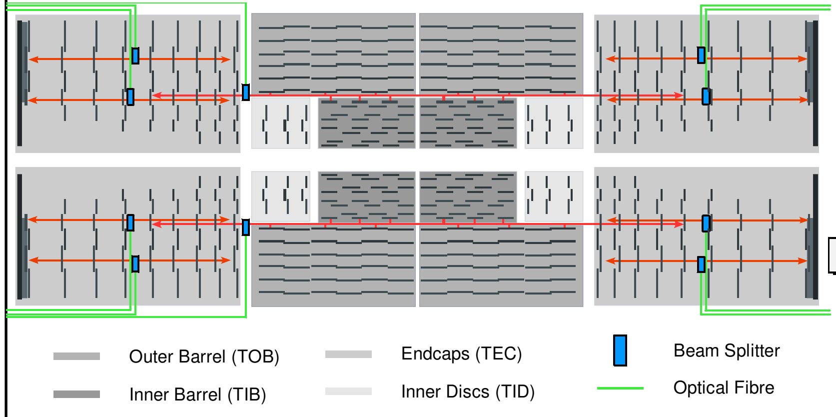
and

TrackerInnerBarrel +

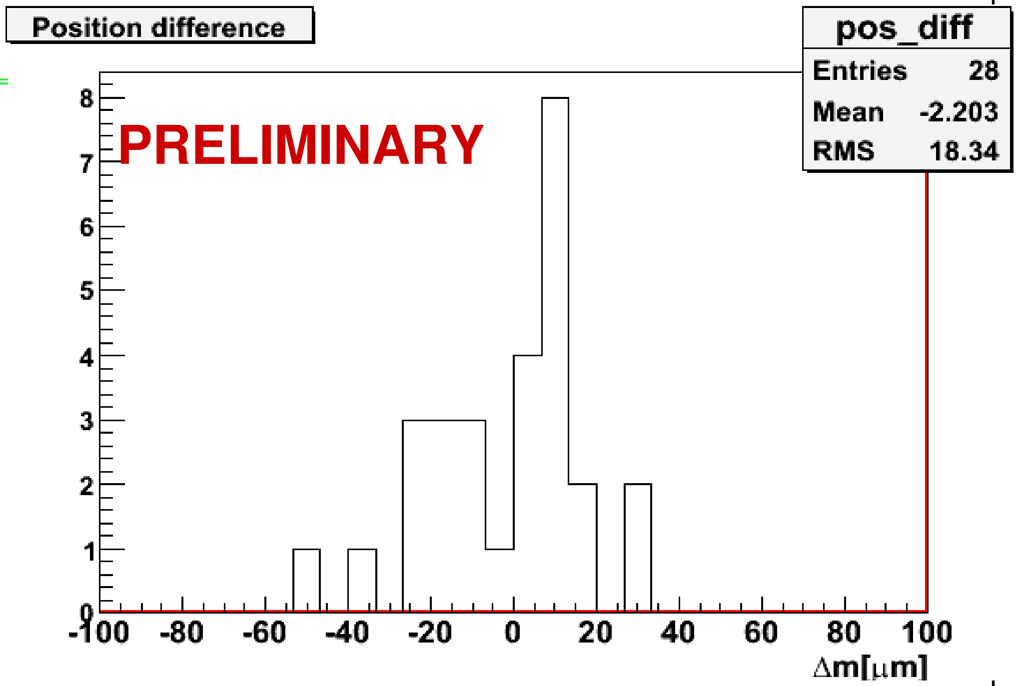


TK: moving with T

TK laser system n place to detect movements and deformations of the Tracker Sub-Detector with a precision better than 100 μm



Δalignment at RoomTemperature and 10°C



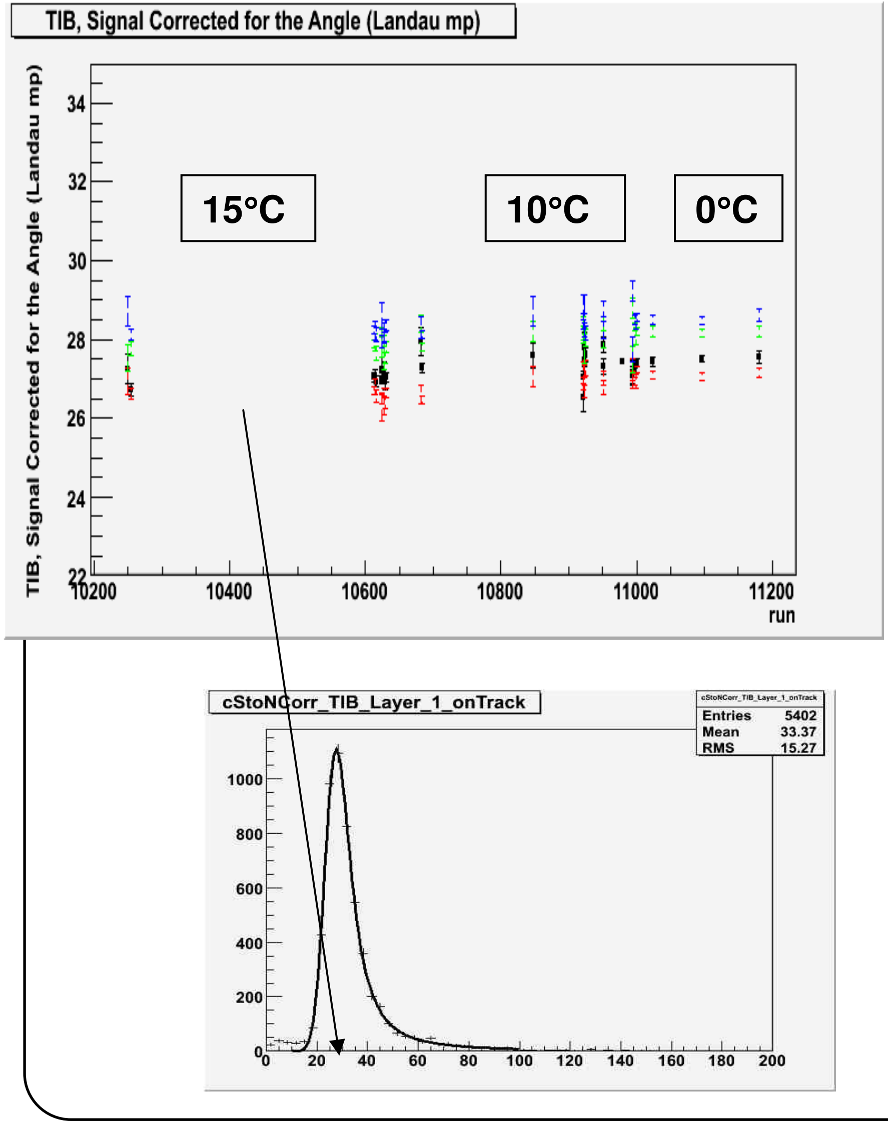
Observed differences

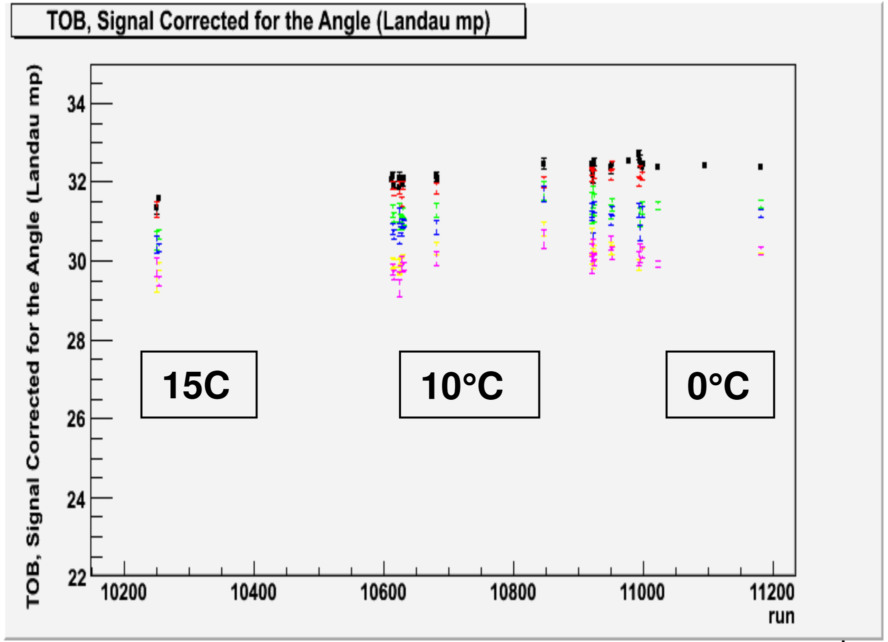
☞ RMS: 18 μm

☞ Max: 50 μm

No movement observed within measurement accuracy

TK: S/N .vs. T & t



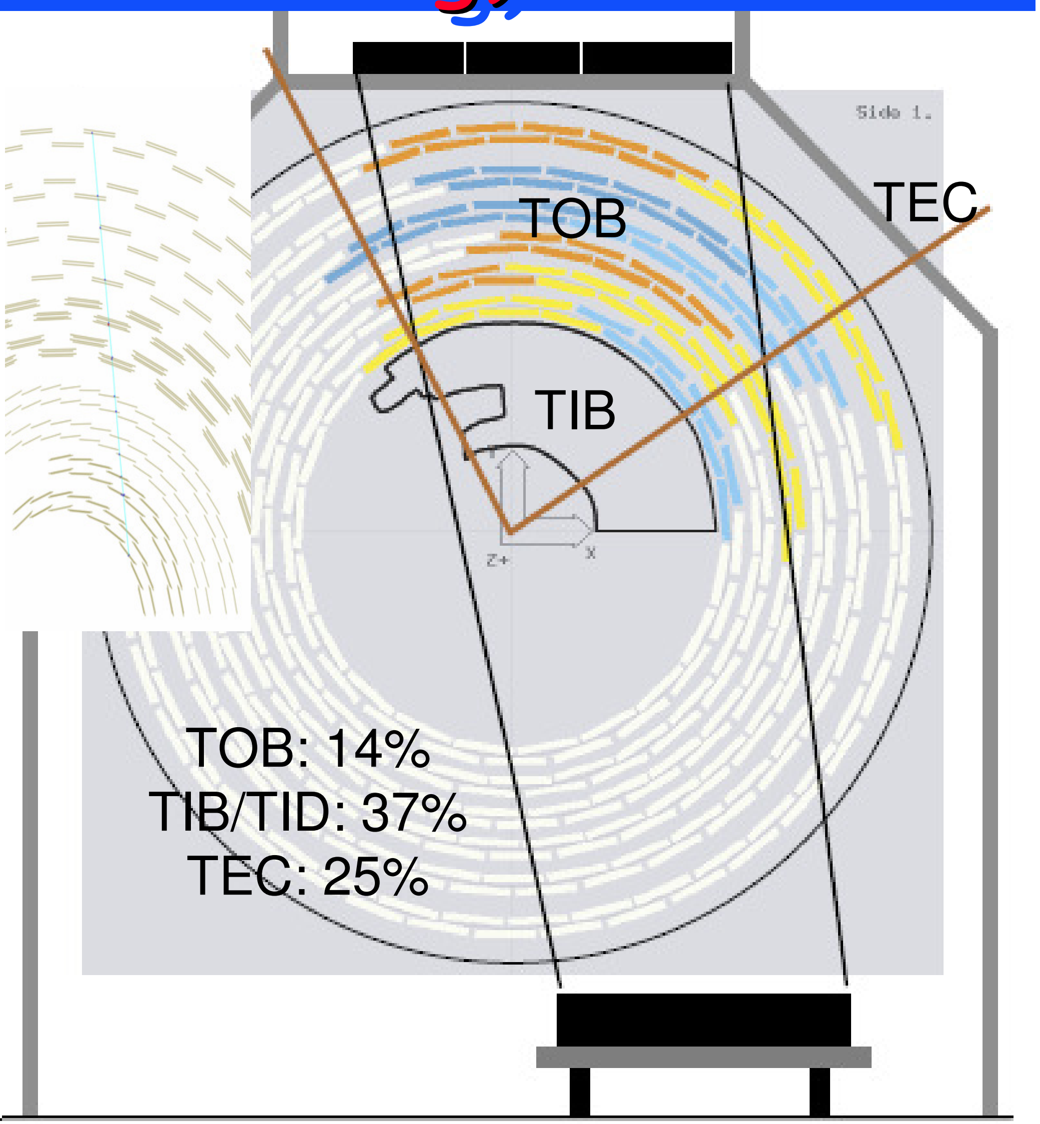


S/N performance stable in time and temperature (15°C,10°C, 0°C)

Fit to Landau convoluted with a gaussian. Plotted the most probable value

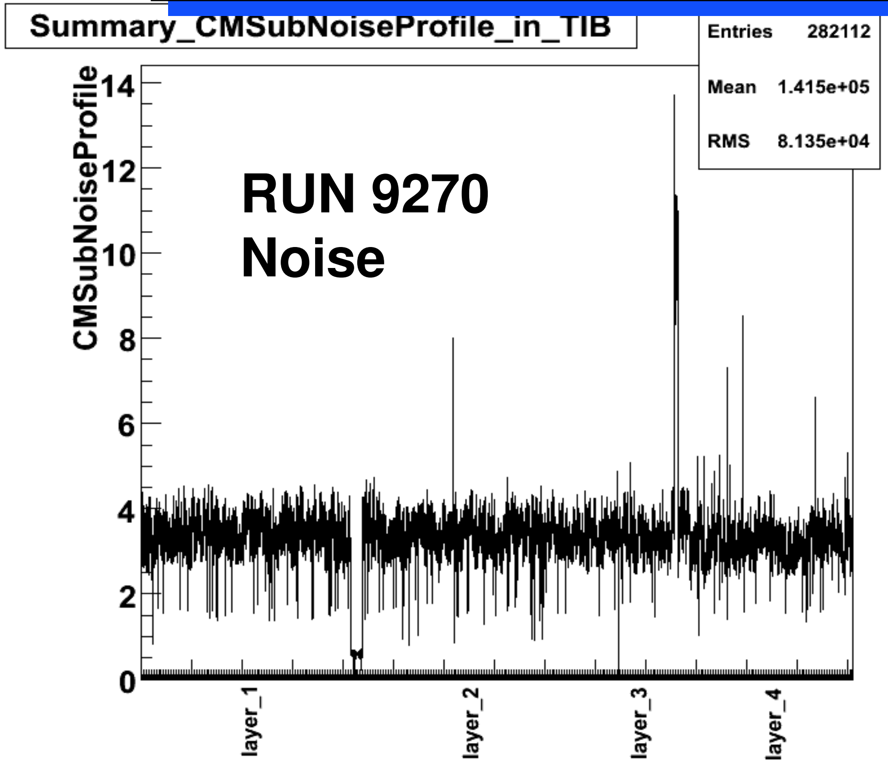
Tracker slice test (25%) (pre-commissioning)

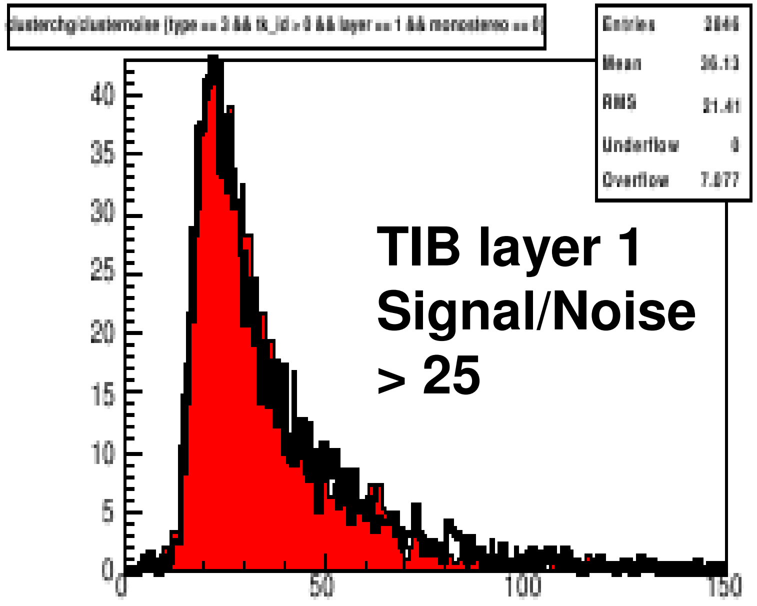
- A sector fully connected to the whole chain
- 3M events a +20^{0}C, a 0^{0}C e a -10^{0}C
- more tests (with pixels) in the future
- final installation in July (now)



TOB: 14%
TIB/TID: 37%
TEC: 25%

Noise and S/N





Data taking in Tracker Integration Facility

Physics run praticamente solo nei week-end

Today more than 3M data taken

Data quality controlled online

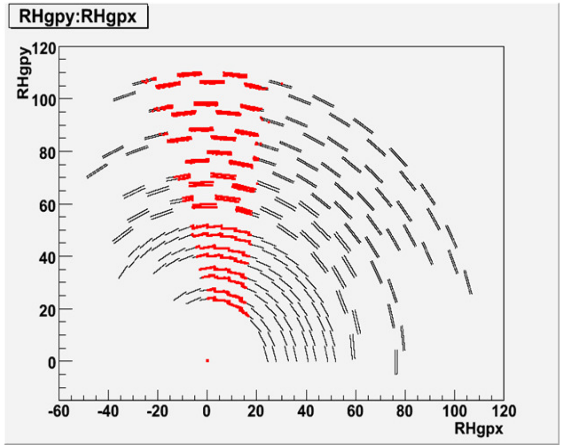
Check in real time noise in modules, occupancy, number of reconstructed tracks etc

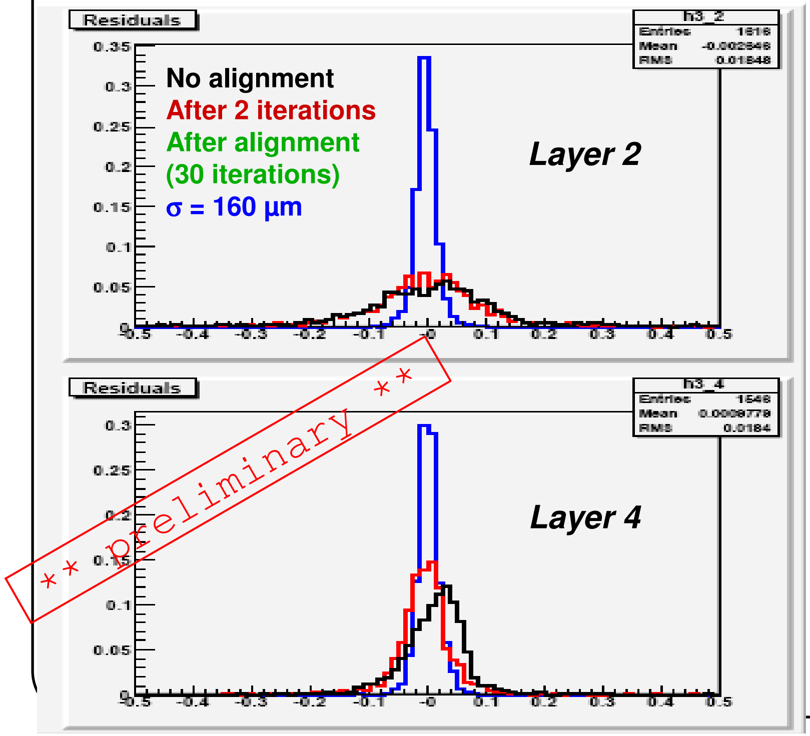
Alignment and efficiency

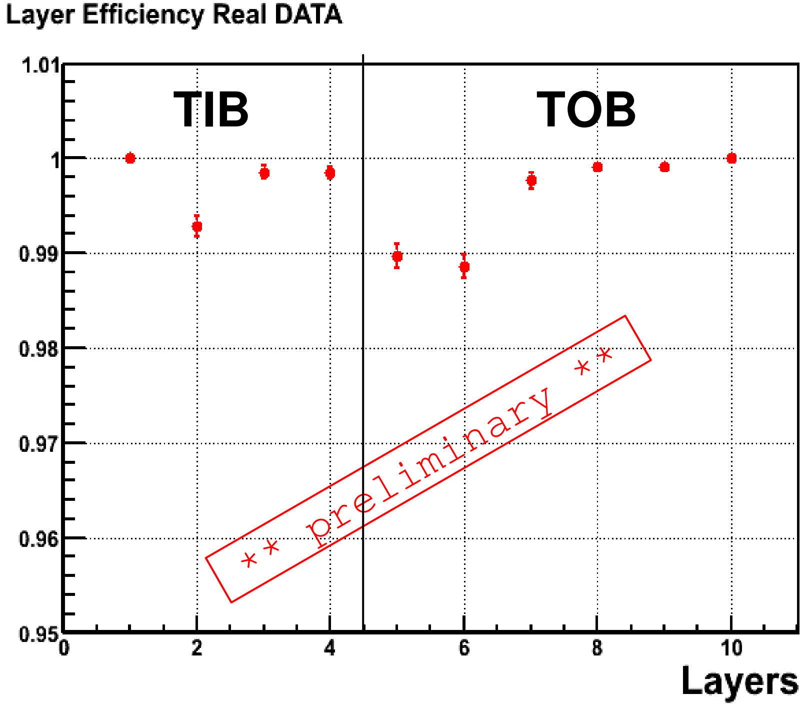
Aligning strings is the first step

- Local x and y for a 3 modules string floated
- Starting with an estimated error of 900 µm

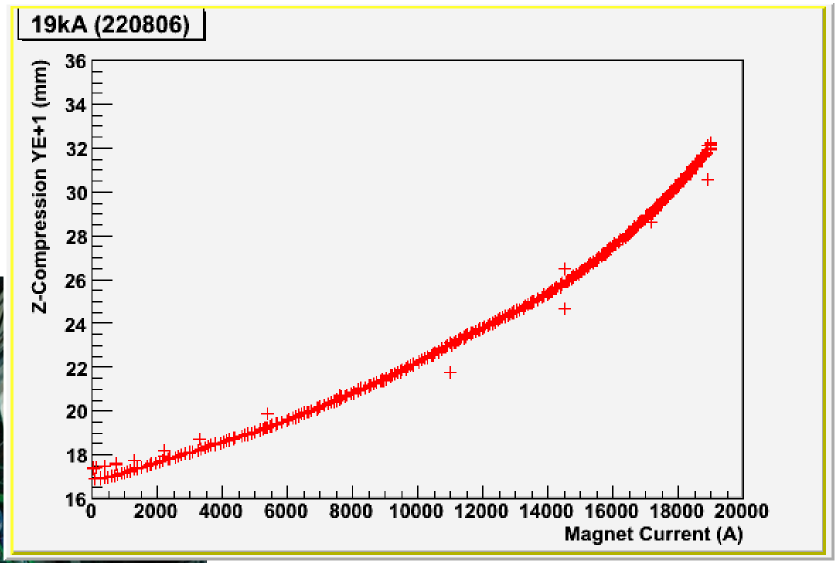
Nearly all strings converged after 30 iterations

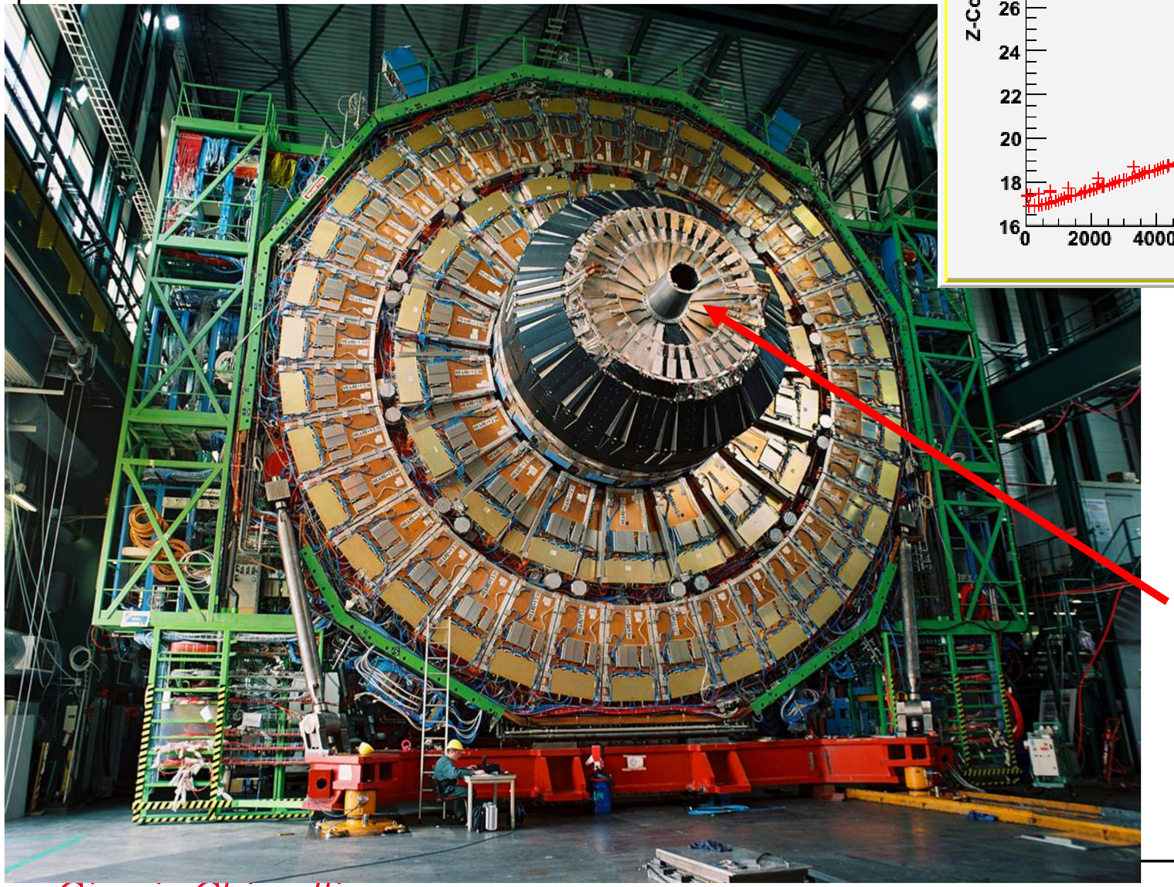






Large Magnetic Forces



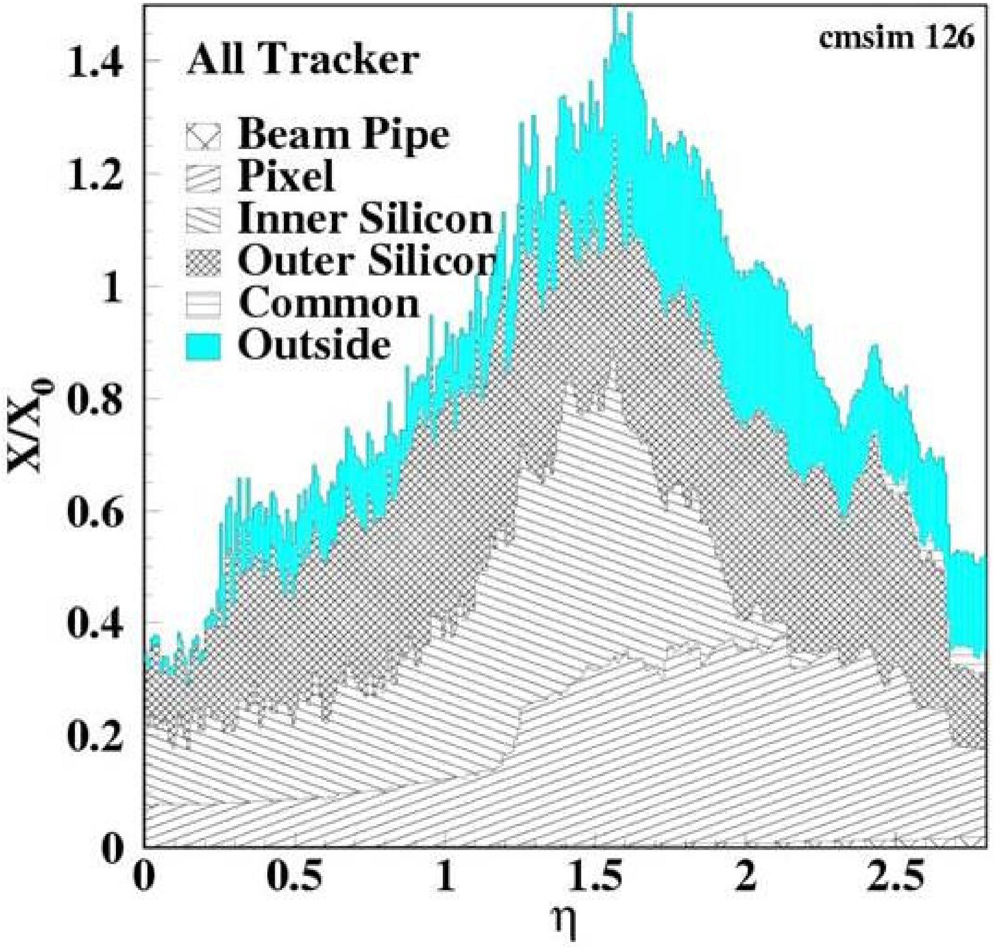


Because of magnetic forrse the “nose” of YE1 moves towards IP by 1.6 cm !

Challenge: Tracker material

CMSIM

(CMSIM)



A lot of material

- ☞ Challenge for pattern recognition
- ☞ possible impact on EM calorimeter resolution

Conclusion

Collider detectors are (essentially) systems of a number of specialized subdetectors

- ☞ In general it is difficult to have the "optimal" detector able to cover all the physics we are interested
  - ⇨ Compromises are in order
- ☞ Hope for the best, prepare for the worst
- ☞ They both will come
- ☞ Keep things simple and add redundancy whenever you can

Physics first

- ☞ must always be the driving force and the compass when you have to take a path