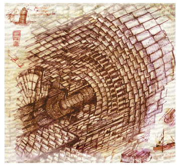
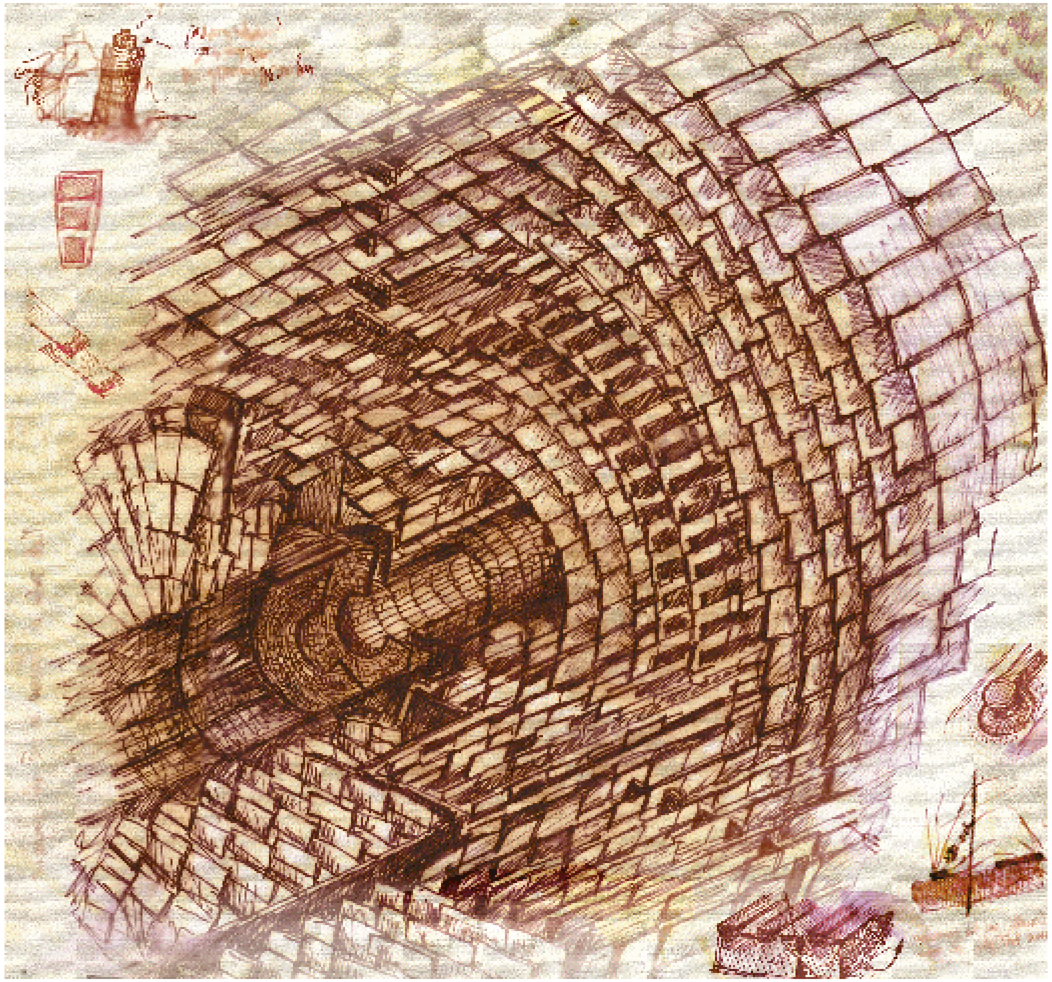
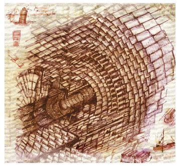


The CMS Silicon Tracker





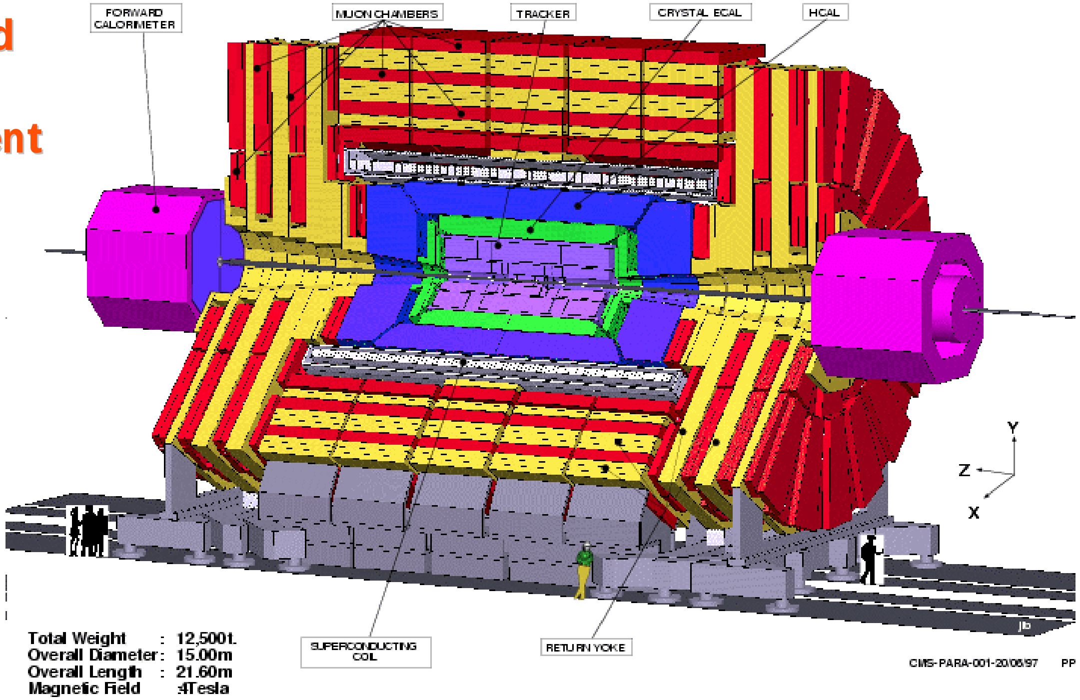
The CMS Detector

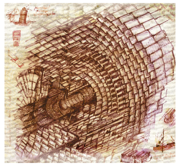
Long 4Tesla Solenoid for Tracking up to h ~ 2.4 (13*6m)

m system in return iron
First m chamber just after Solenoid
(max. sagitta)
Extends lever arm for Pt measurement

ECAL & HCAL inside Solenoid

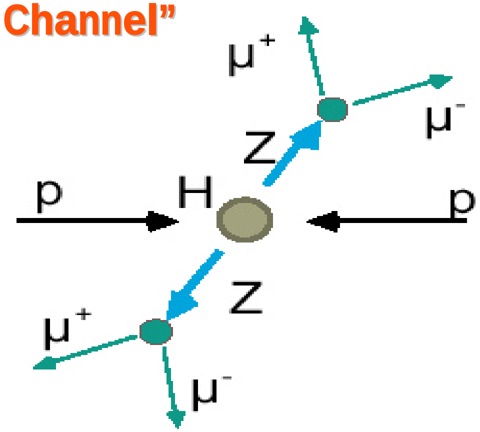
22m Long, 15m Diameter
14'000Tons





High Luminosity Physics at the LHC

“Golden Channel”



Tracker Requirements:

Efficient & robust Pattern Recognition algorithm

⇒Fine granularity to resolve nearby tracks
⇒Fast response time to resolve bunch crossings

Ability to reconstruct narrow heavy object

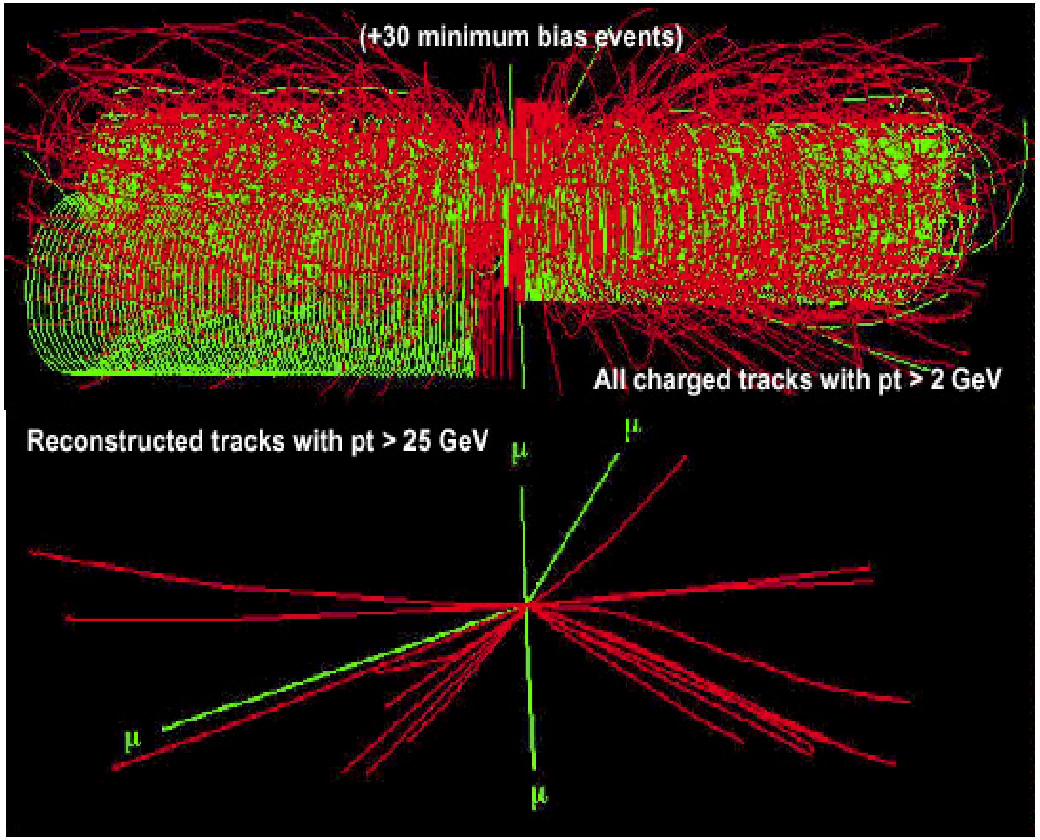
⇒1~2% Pt resolution at ~ 100GeV

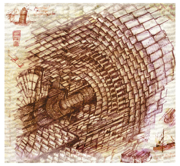
Ability to tag b/t through secondary vertex

⇒Good impact parameter resolution

This Workshop: Physics with b & t tags!

pp & High luminosity => “mess”





Basic design and performance considerations

To set the scale for the momentum measurement, recall that:

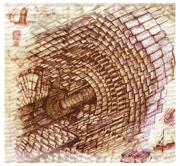
The CMS B Field = 4T and the TK Radius ~ 110 cm result in:

1.90mm sagitta for 100 GeV P_t track

To set the scale for speed and granularity, recall that:

At high luminosity there will be about 20 min. bias events every 25ns crossing
These will result in a very high charged particle flux (modified the B field)

R =	10cm	25cm	60cm
$N_{ch}/(cm^2*25ns)$ =	1.0	0.10	0.01



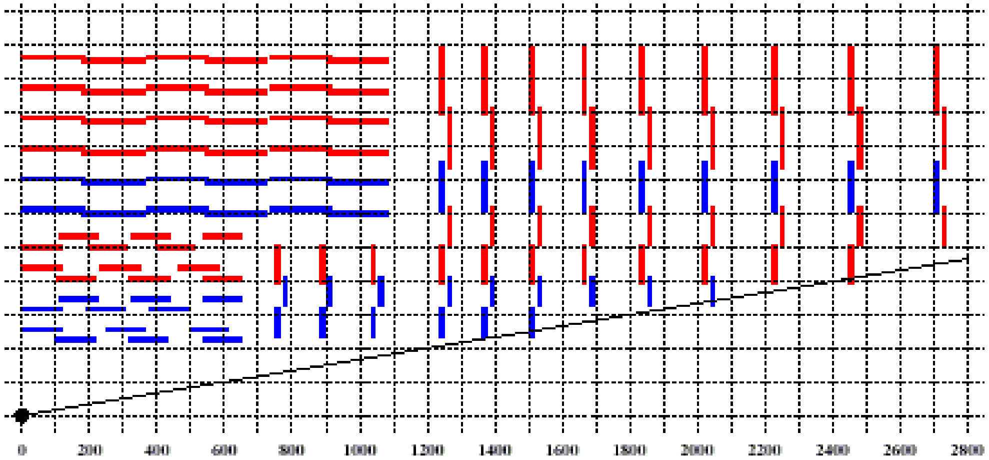
The CMS Tracking Strategy

Rely on “few” measurement layers,
each able to provide
robust (clean) and precise coordinate determination

Two to Three Silicon Pixel, and Ten to Fourteen Silicon Strip Measurement Layers

Radius ~ 110cm, Length ~ 270cm

h ~ 1.7



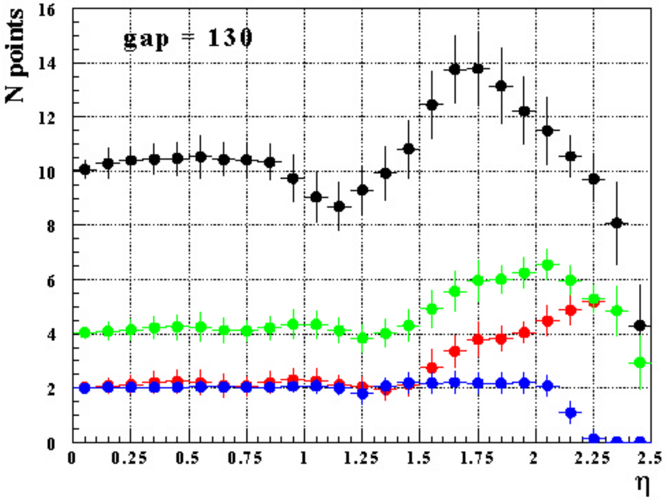
6 layers
TOB

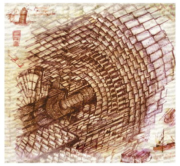
4 layers
TIB

3 disks TID

9 disks TEC

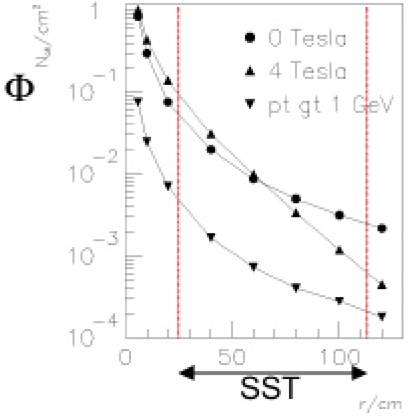
Single detector
Two detectors
back to back





Design considerations for CMS SST: Cell size & strip pitch

Efficient & clean track reconstruction is ensured provided occupancy below few %



At small radii need cell size < 1cm^2
and fast (~25ns) shaping time
This condition is relaxed at large radii

$\Delta P_t / P_t \sim 0.1 * P_t$ (P_t in TeV)
allows to reconstruct Z to $\mu^+\mu^-$ with
$\Delta m_Z < 2$GeV up to $P_t \sim 500$GeV

Twelve layers with (pitch/ $\sqrt{12}$) spatial resolution and 110cm radius give a momentum resolution of

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

A typical pitch of order 100μm
is required in the phi coordinate
To achieve the required resolution

Strip length ranges from 10 cm in the inner layers to 20 cm in the outer layers.

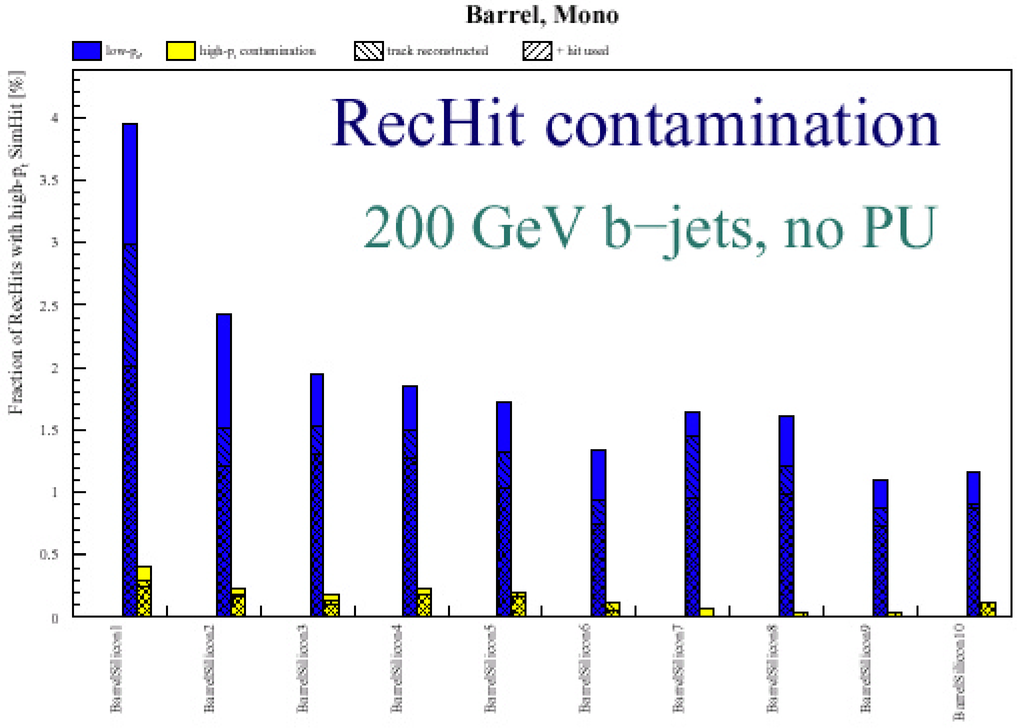
Pitch ranges from 80μm in the inner layers to near 200μm in the outer layers

Robust and clean hits

Hit contamination is ~ 4% in the first Silicon layer
Less than ~ 2% elsewhere

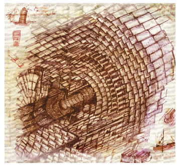
4%

2%



Hatching:

- SimTrack was reconstructed
- RecHit in that layer was used in the RecTrack



Robust Pattern Recognition

Combinatorial Trajectory Builder

Starting from the seed:

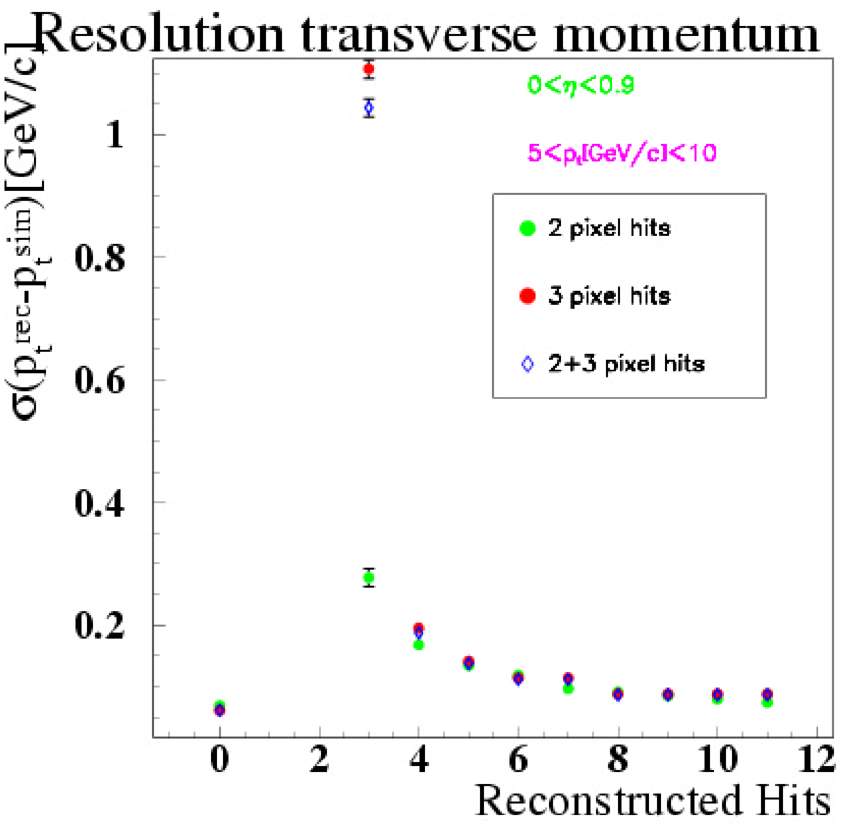
- The initial trajectory is propagated to the next layer, accounting for multiple scattering and energy loss
- On the new layer, new trajectories candidates are constructed, with updated parameters (and errors) for:
  - each compatible hit in the layer
  - An ‘invalid’ hit (or ‘empty’ hit), to account for the possibility that the track did not leave a hit in the layer
- Start again with these new trajectory candidates for the next layer.

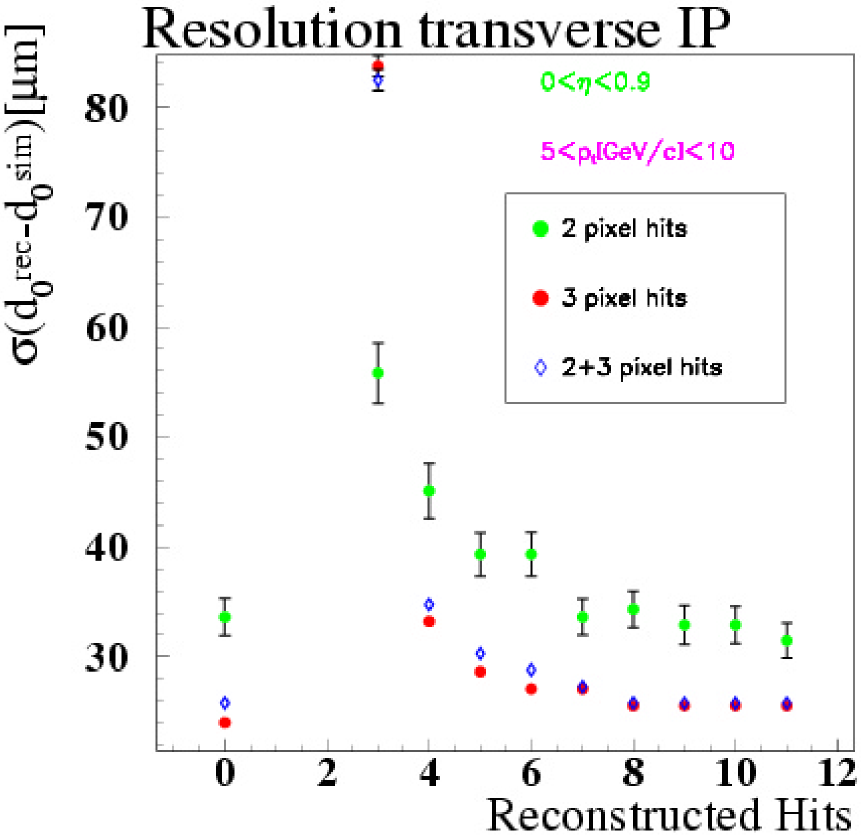
↣ All trajectories are grown to the next layer in parallel to avoid bias.

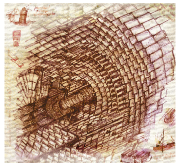
↣ The number of trajectories to grow is limited according to their χ^2 and the number of invalid hits.

Partial Track reconstruction

Good track parameter resolution
already with 4 or more hits







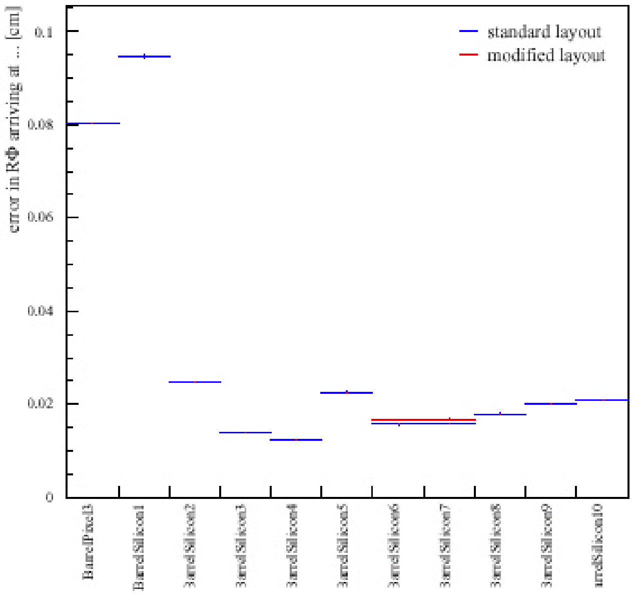
Robust Pattern Recognition

Good track parameter resolution with 4 or more hits

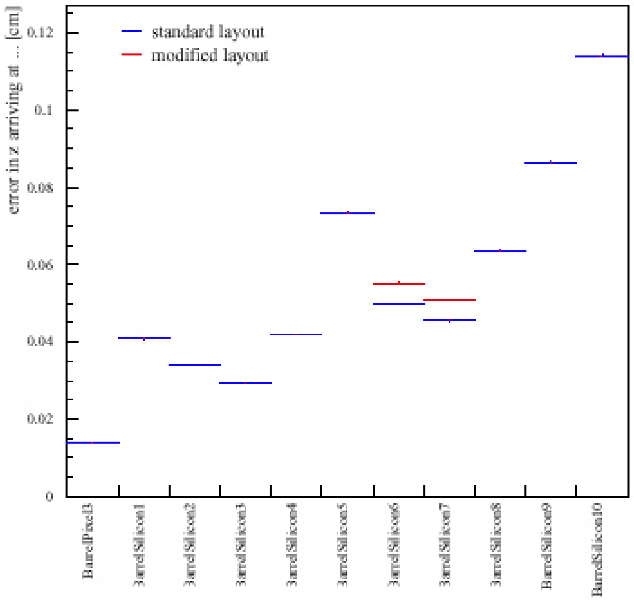
=> Small uncertainties on the predicted track state

Uncertainty in $r-\varphi$ and $r-z$ of the predicted state

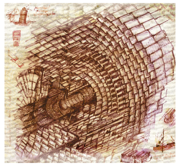
200 GeV *b* jet without PU



Uncertainty in $r-\varphi$



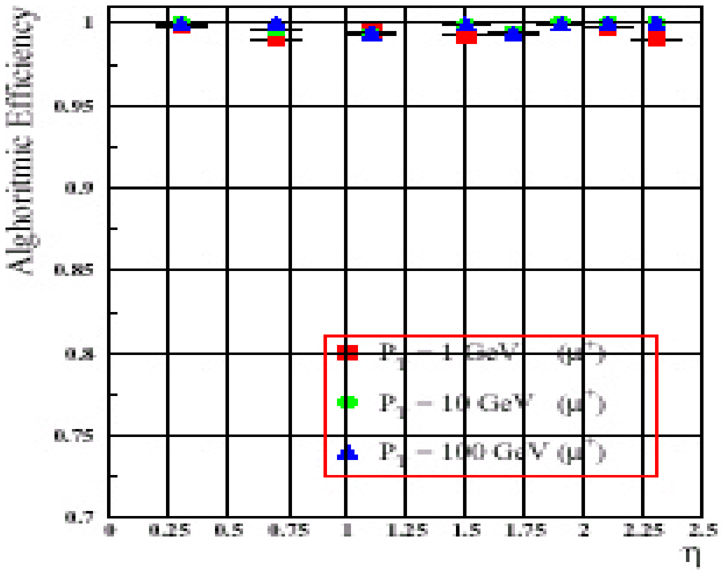
Uncertainty in $r-z$

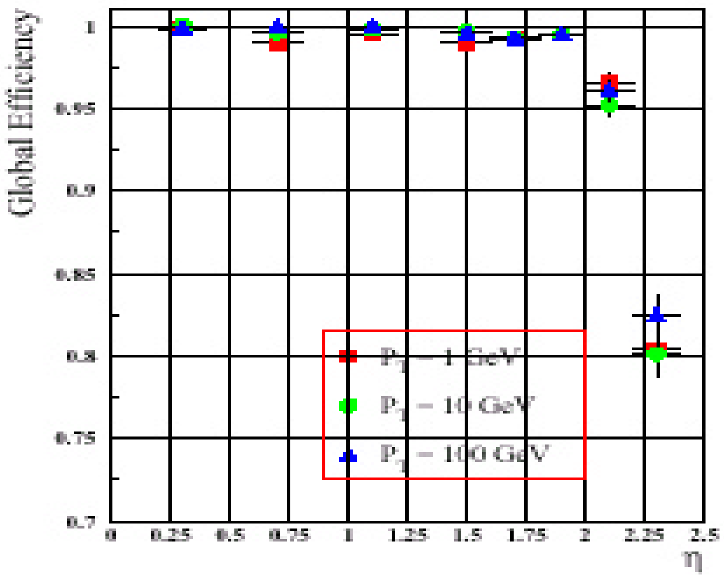


Track seed efficiency (Muons):

Starting from pixel seeds, combinatorial Kalman filter:

require 2 out of 3 Pixel hits compatible with vertex & minimum Pt threshold





Global efficiency: selected Rec.Tracks / all Sim.Tracks

Algorithmic efficiency: selected Rec.Tracks / selected Sim.Tracks

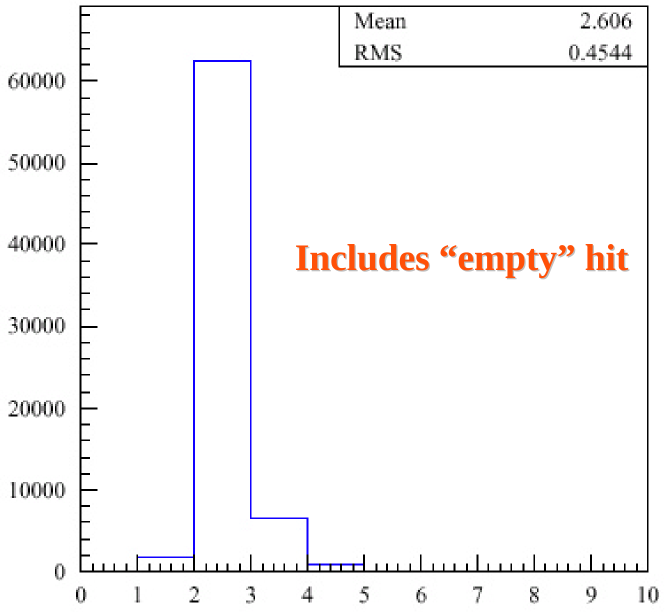
(Sim.Track selection: at least 8 hits, at least 2 in pixel)

Global efficiency limited by pixel geometrical acceptance

Robust Pattern Recognition

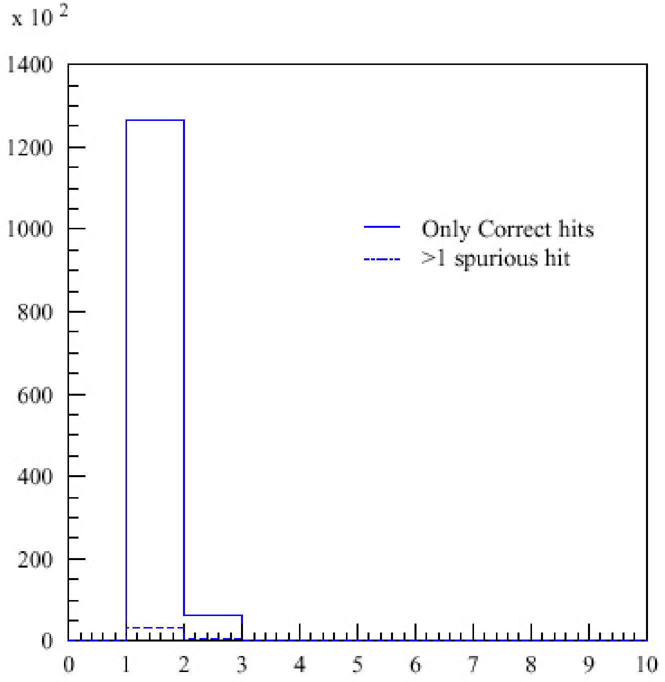
Propagation from Barrel Pixel 2

100 GeV *b* jet without PU



Includes “empty” hit

Number of candidates on BarrelPixel 3

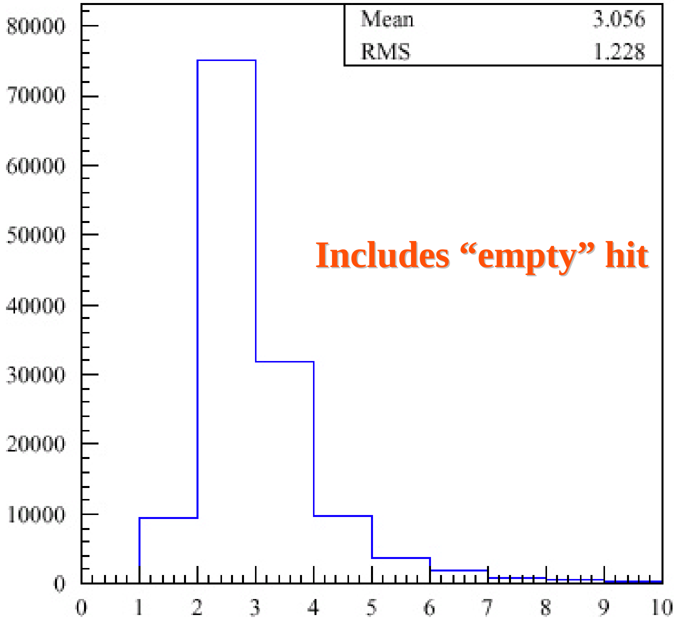


Number of Trajectory candidates formed (only valid hits)

Robust Pattern Recognition

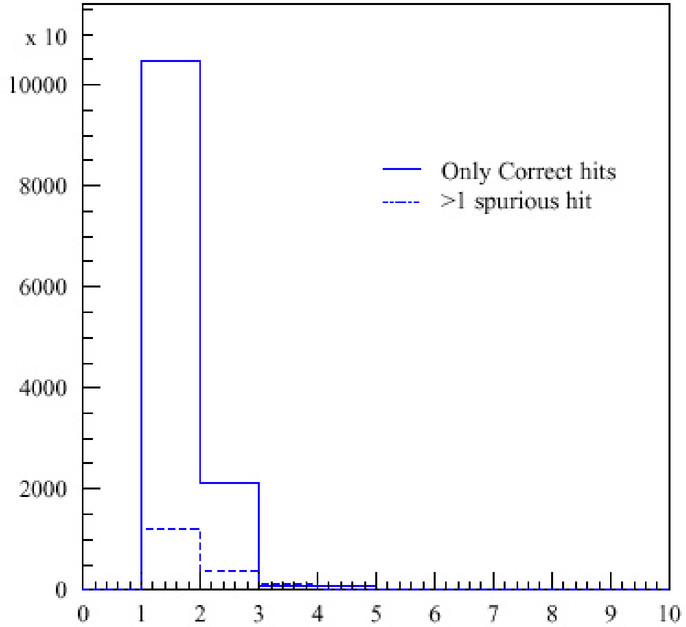
Propagation from Barrel Pixel 3

100 GeV *b* jet without PU



Includes “empty” hit

Number of candidates on BarrelSilicon 1

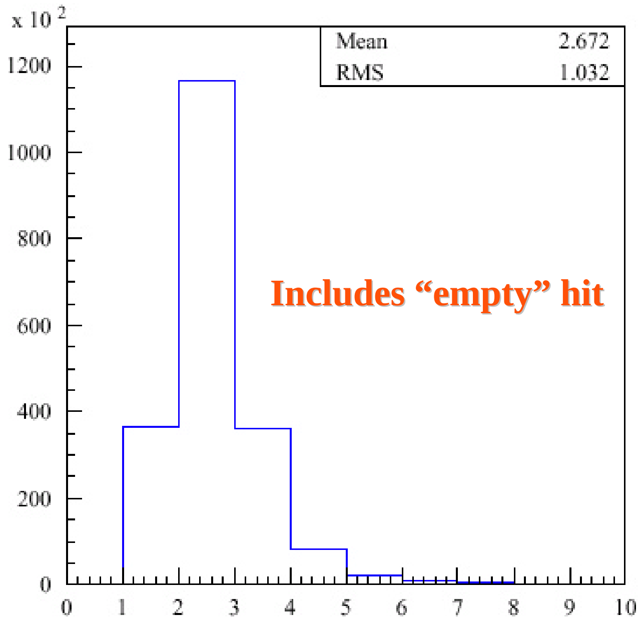


Number of Trajectory candidates formed (only valid hits)

Robust Pattern Recognition

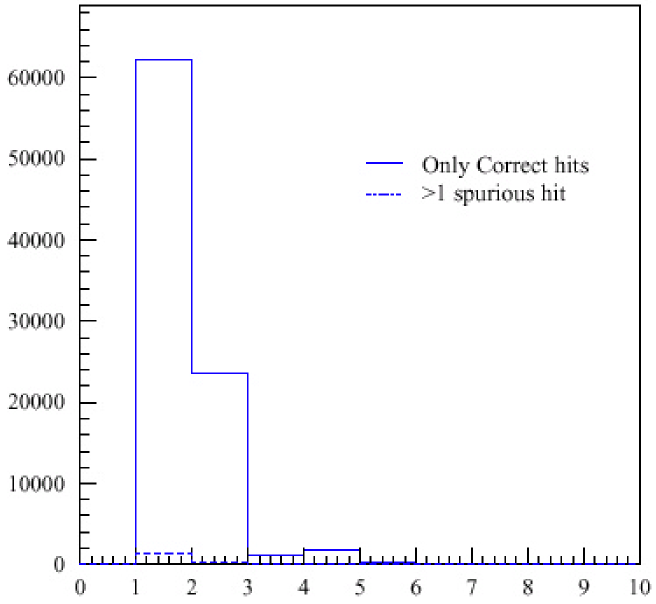
Propagation from Barrel Silicon 1

100 GeV *b* jet without PU



Includes “empty” hit

Number of candidates on BarrelSilicon 2

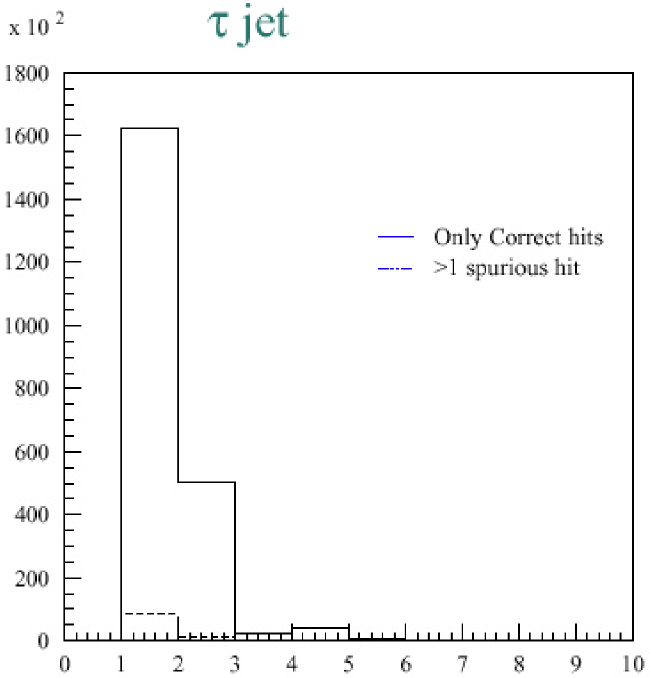


Number of Trajectory candidates formed (only valid hits)

Robust Pattern Recognition

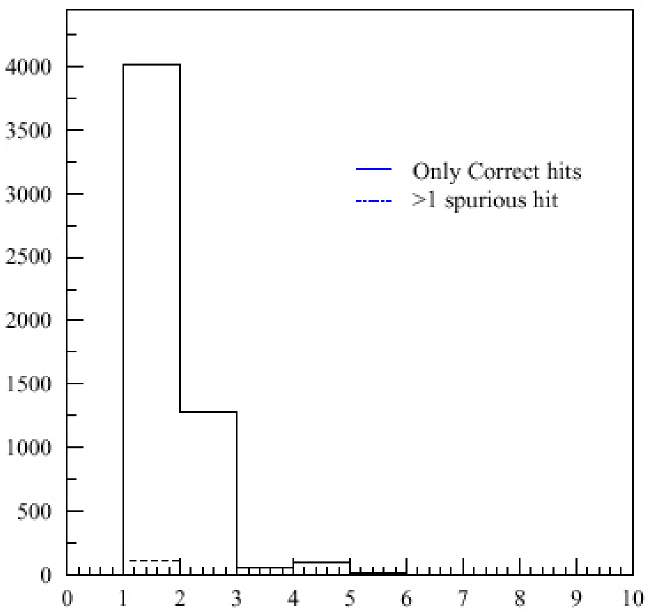
Propagation from Barrel Silicon 1

τ jet

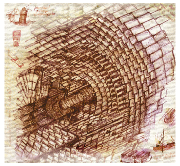


Number of Trajectory candidates formed (only valid hits)

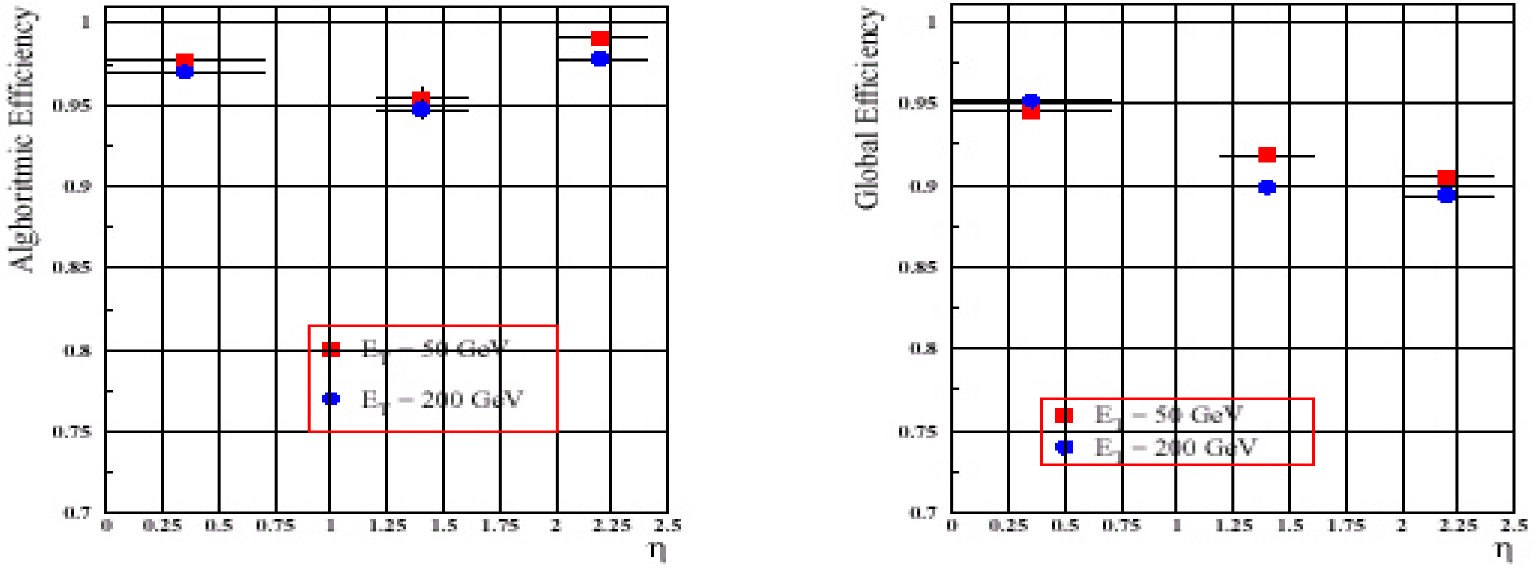
200 GeV *b* jet with PU



Number of Trajectory candidates formed (only valid hits)



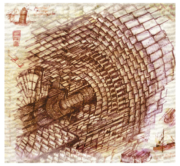
Track reconstruction efficiency in jets



Efficiency for particles in a 0.4 cone around jet axis

No significant degradation compared to single pions

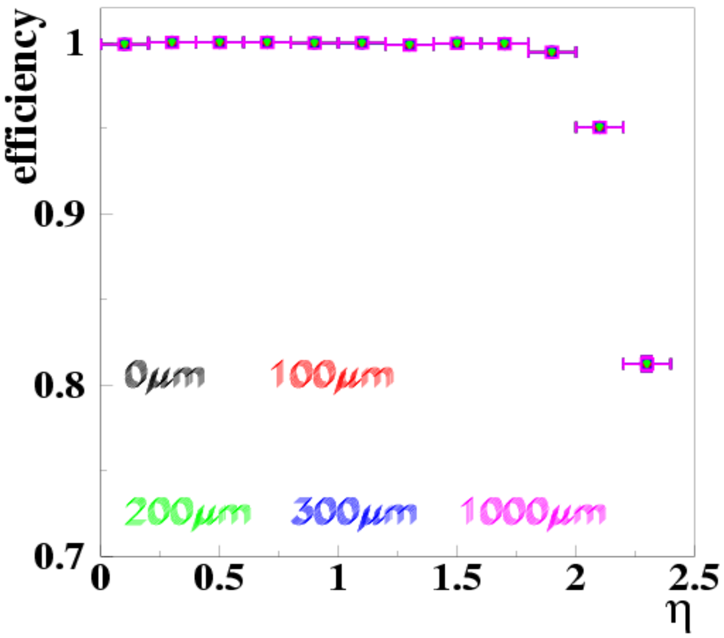
Loss of efficiency is dominated by hadronic interactions in Tracker material

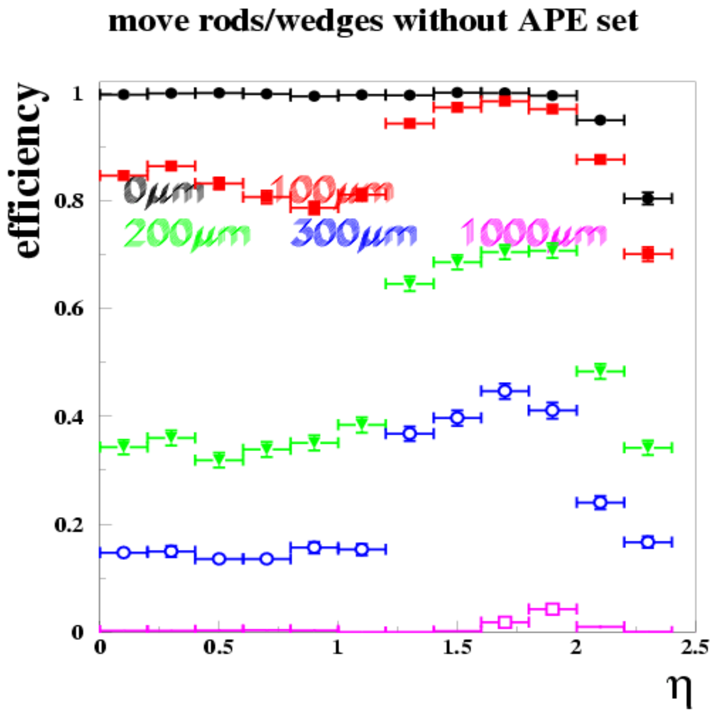


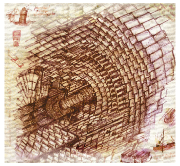
Misalignment Studies (single-m)

track reconstruction (single-m, P$_t$ =100GeV)

random movements of rods / wedges + setting the Ali.Pos.Err. accordingly

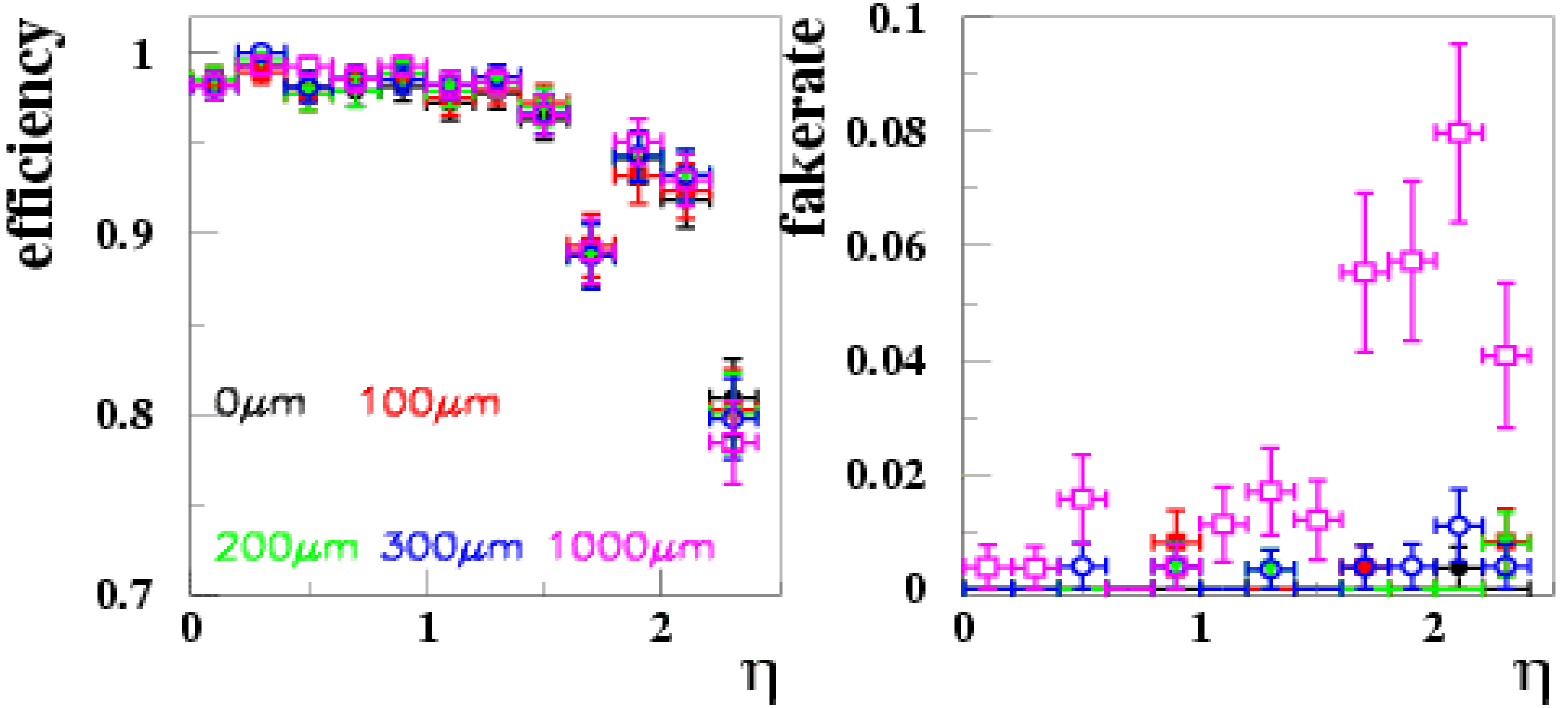



move rods/wedges without APE set



W ® mn events with pileup at $2*10^{32}$

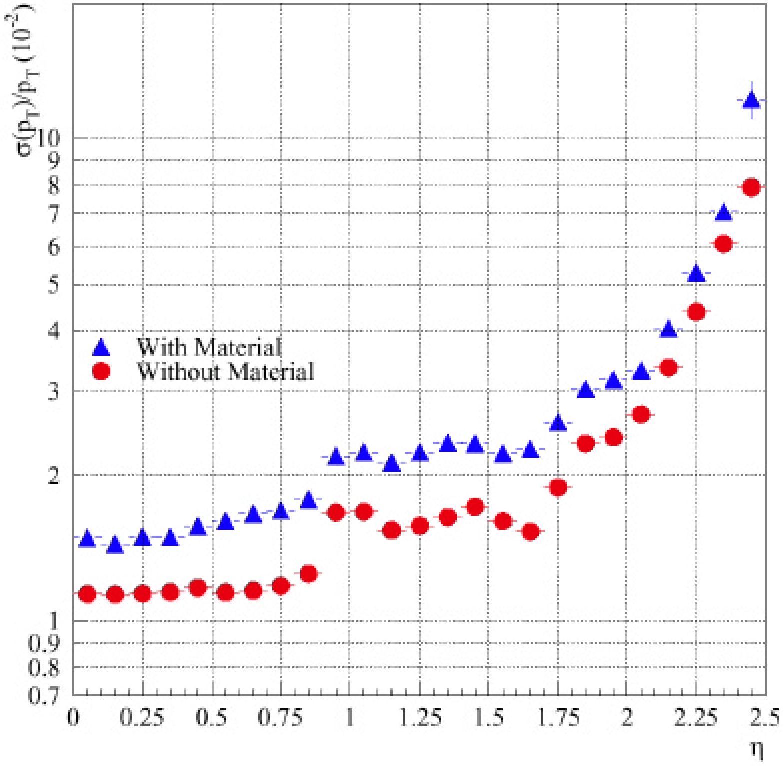
Pattern recognition works efficiently and cleanly
with misalignments of up to 1mm, at $2*10^{32}$

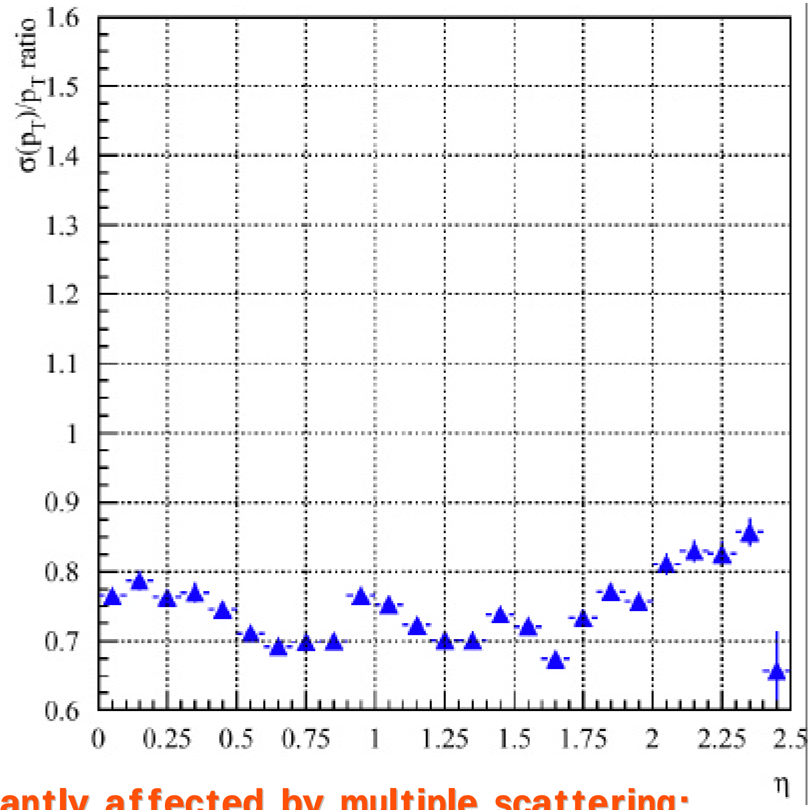


random movements of rods / wedges; reconstruct tracks with P_t > 20GeV

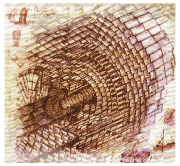
Pt Resolution For High Momentum Muons

The CMS Tracker provides ~ 1% Pt resolution over ~ 0.9 units of h,
and 2% Pt resolution up to h ~ 1.75, beyond which the lever arm is reduced





Even at 100 GeV muons are significantly affected by multiple scattering:
a finer pitch, and higher channel count
Would therefore yield only diminishing returns in improving the Pt resolution



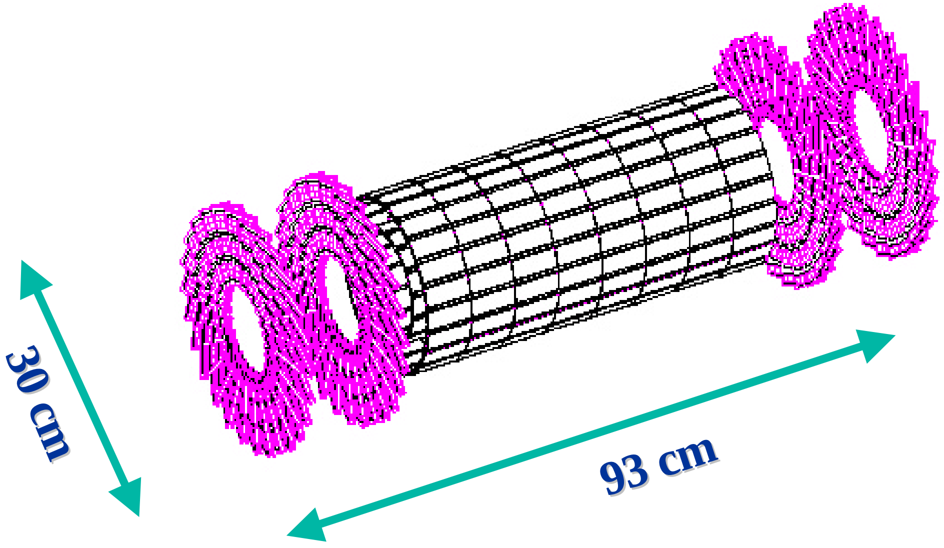
The CMS Pixel Vertex detector: Silicon strips have become pixels

The region below 20cm is instrumented with Silicon Pixel Vertex systems

The Pixel area is driven by FE chip
The shape is optimized for resolution

4 10^7 pixels

Shaping time ~ 25ns



CMS pixel ~ 150 * 150 mm^2

With this cell size, and exploiting the large Lorentz angle

We obtain $IP_{trans.}$ resolution ~ 20 mm for tracks with P_t ~ 10GeV

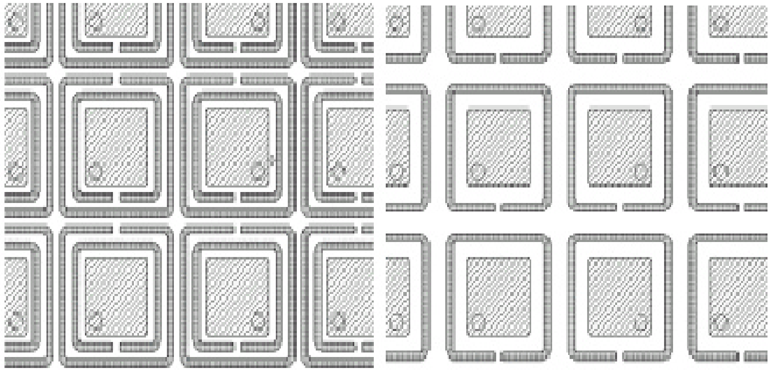
With this cell size occupancy is ~ 10^{-4}

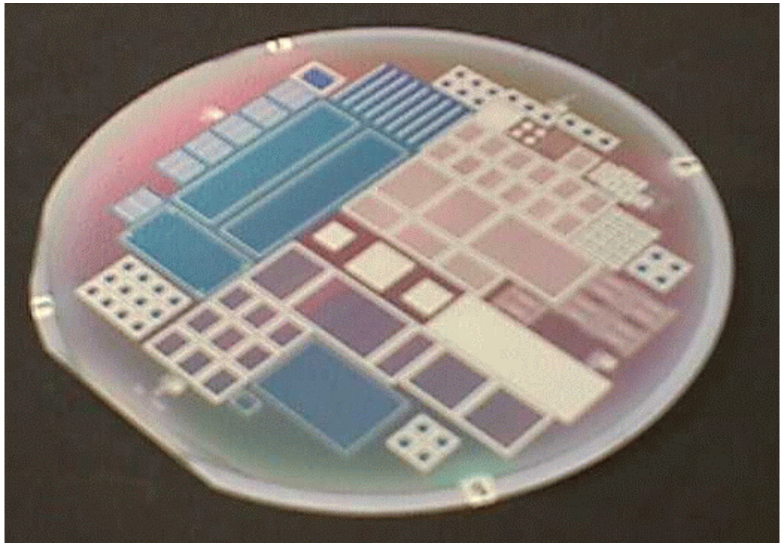
This makes Pixel seeding the fastest
Starting point for track reconstruction
Despite the extremely high track density

Pixel Vertex detectors for the LHC

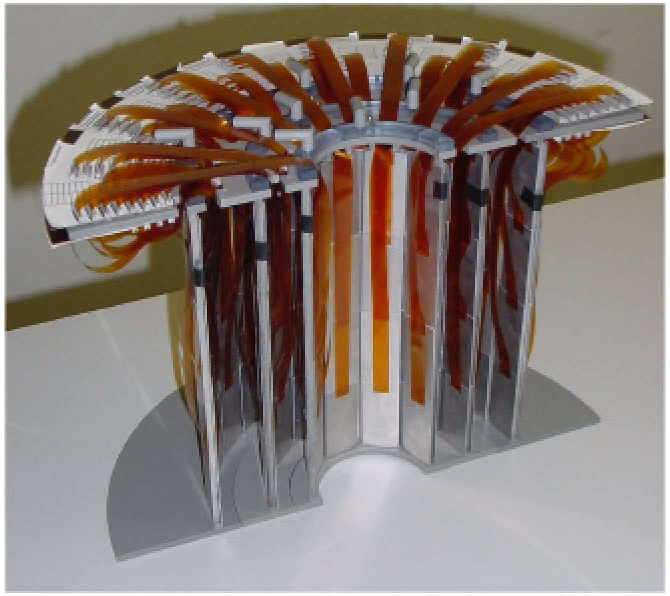
Highest radiation environment:

- Specific program of sensor R&D
- Partial depletion, despite High V_{bias}
- n-on-n technology (collect e^- not holes)
  - The "back-side" of a double-sided sensor
  - Uses much of that know-how
    (process in some ways simpler)
  - Specific issues:
    P-stop design to ensure
    pixel biasing & isolation
    Open p-stop, "p spray" …
- Oxygenated bulk may allow lower bias voltage operation, especially for charged hadron induced damage (dominant)





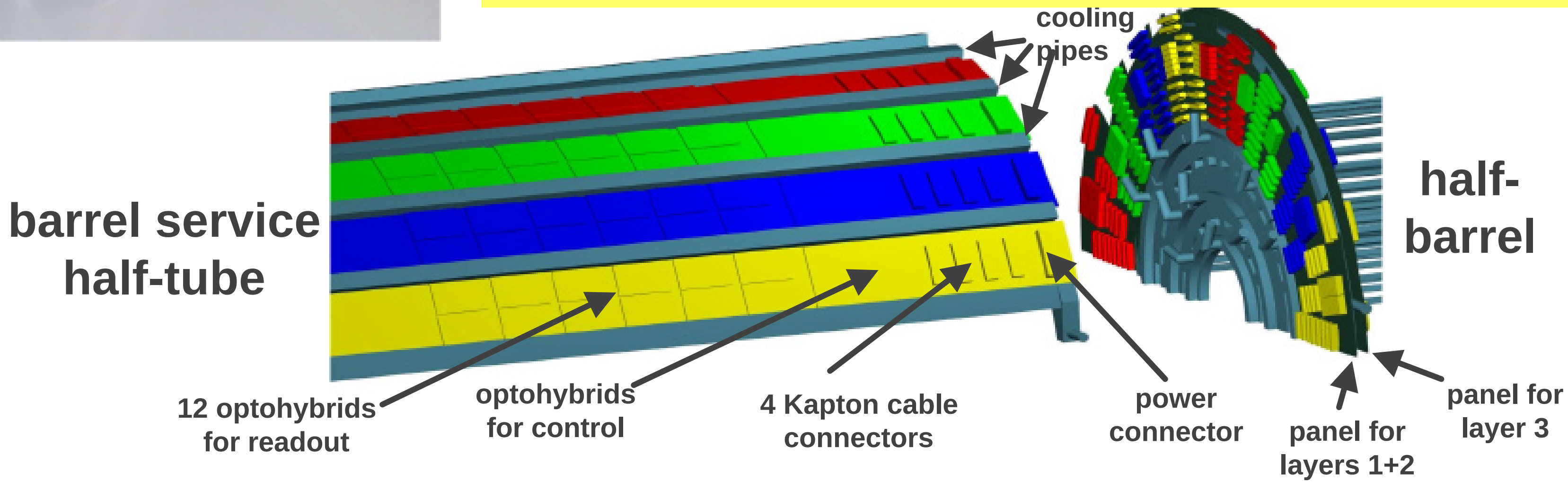
Pixel Barrel Organization

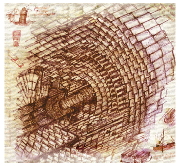


Pixel barrel is organized in sectors:

- Each module is connected by a 20 trace Kapton cable and an 8 circuit power cable to the barrel endflange panel. Front panel for layers 1+2, rear panel for layer 3.

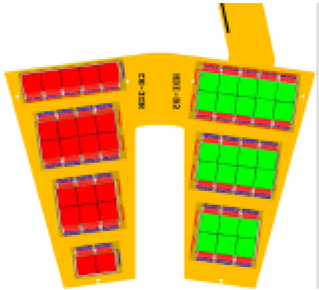
- On endflange panel, power and signals are combined sector-wise.
- Short flexible cables connect to one of eight sectors on the service half-tube.
- In each sector electro-optical conversion takes place on opto-hybrids.





Pixel Disks Organization

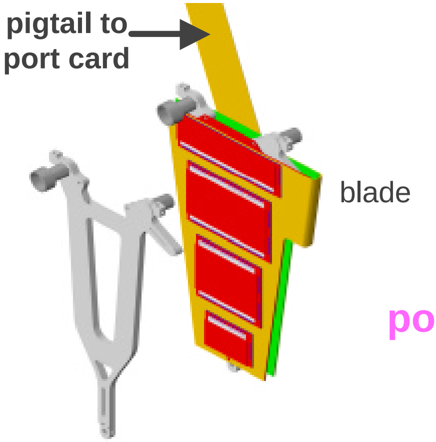
Organization of f/b pixel disk services

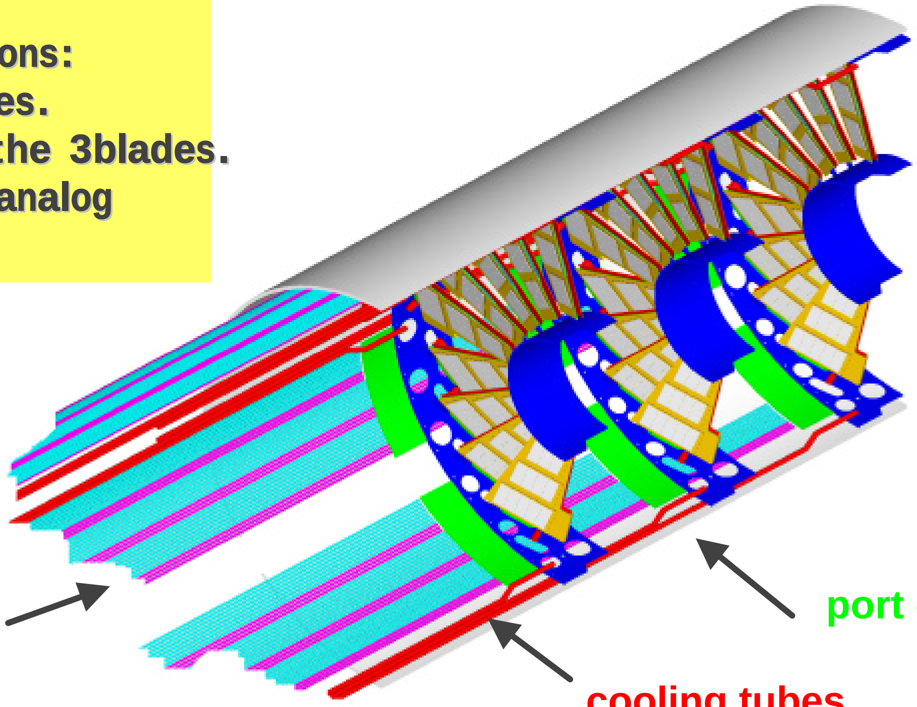


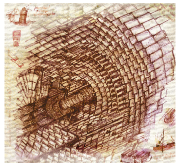
Half-disks composed from 12 blades are integrated into a 2.2 m long half-tube that carries all services to the end of the tracker.

There will be a single pigtail per blade that will carry both signals and power to a “port card”. There is one port card for 3 blades

The port card will have the following functions:
- It will distribute the power to the 3 blades.
- It will house one set of control links for the 3blades.
- It will house 12 laser drivers for the 12 analog links of the 3 blades (4 links per blade).

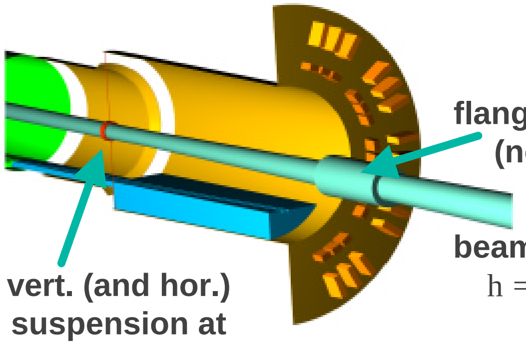






CMS Pixel Detector Integration

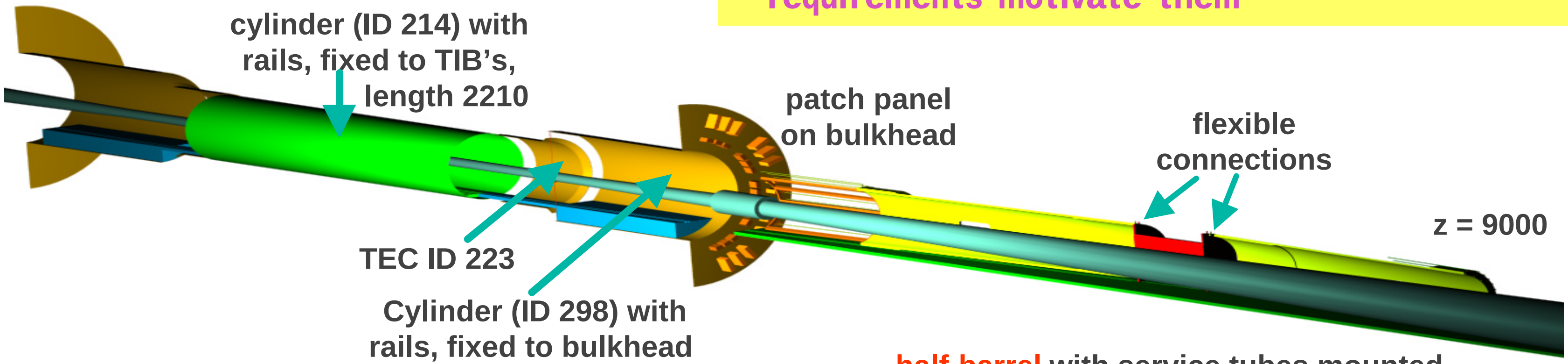
- Pixel is last detector to be inserted.
- First insert barrel halves, followed by end disks.
- Remove pixel for each beam pipe bake-out and for replacement of dead layers due to radiation. Lifetime of innermost layer ~2y at full luminosity.
- Making use of 10m opening of CMS end caps considerably shortens insertion time of barrel.
- Can look forward to upgrade programs, if physics requirements motivate them



flange, bellows (no valve)

beam pipe
h = 4.9

vert. (and hor.) suspension at z=1700 mm



cylinder (ID 214) with rails, fixed to TIB's, length 2210

patch panel on bulkhead

flexible connections

z = 9000

TEC ID 223

Cylinder (ID 298) with rails, fixed to bulkhead

half-barrel with service tubes mounted on rails for 10 m opening of end cap

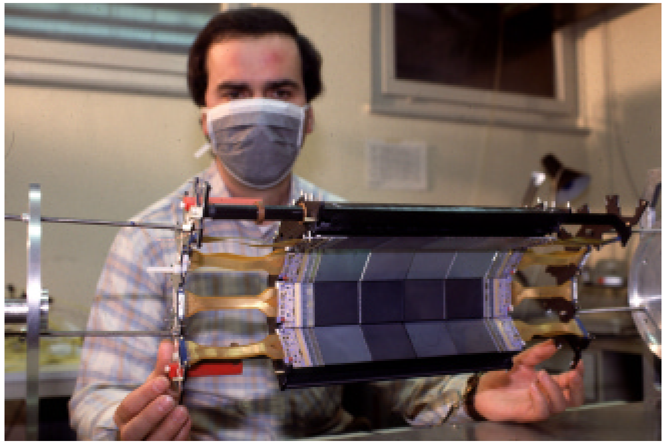
The LEP Silicon Strip Vertex Detectors

The 4 LEP experiments started with gas chambers, both for tracking and vertex reconstruction.

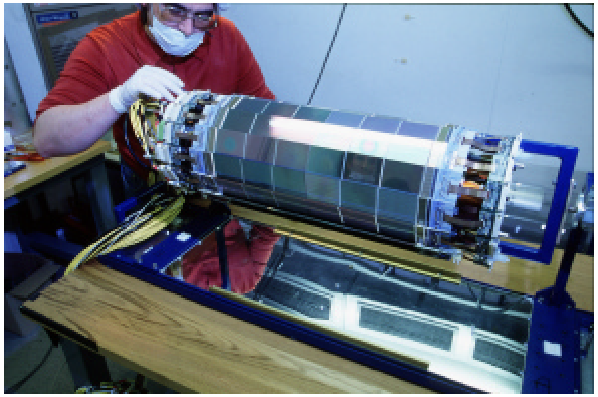
Upgraded to become better & better, Bigger & bigger

The 4 LEP installed Silicon Strip Vertex Detectors, either single or double-sided, within a couple of years of LEP startup

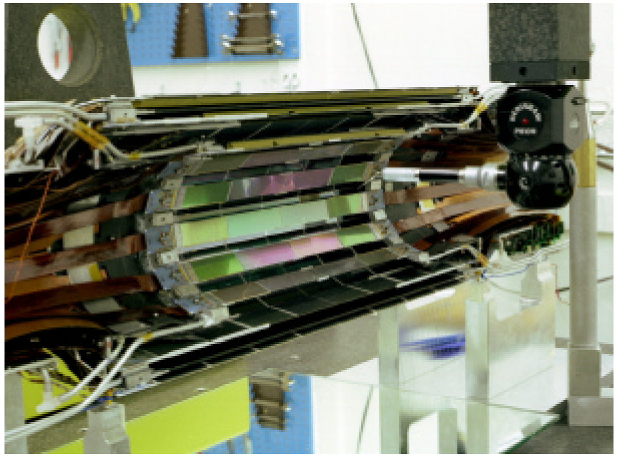
These opened the way for precision b-physics at LEP



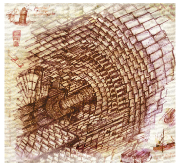
Aleph 1991



Aleph 1998



Delphi 1998



From silicon strip Vertex to strip Tracking

Single-sided, AC coupled, polysilicon biased sensors have become a mature technology

Costs have decreased, and large scale production is now possible

High level of expertise for FE IC design and system aspects of O(10$^{5)}$ channels

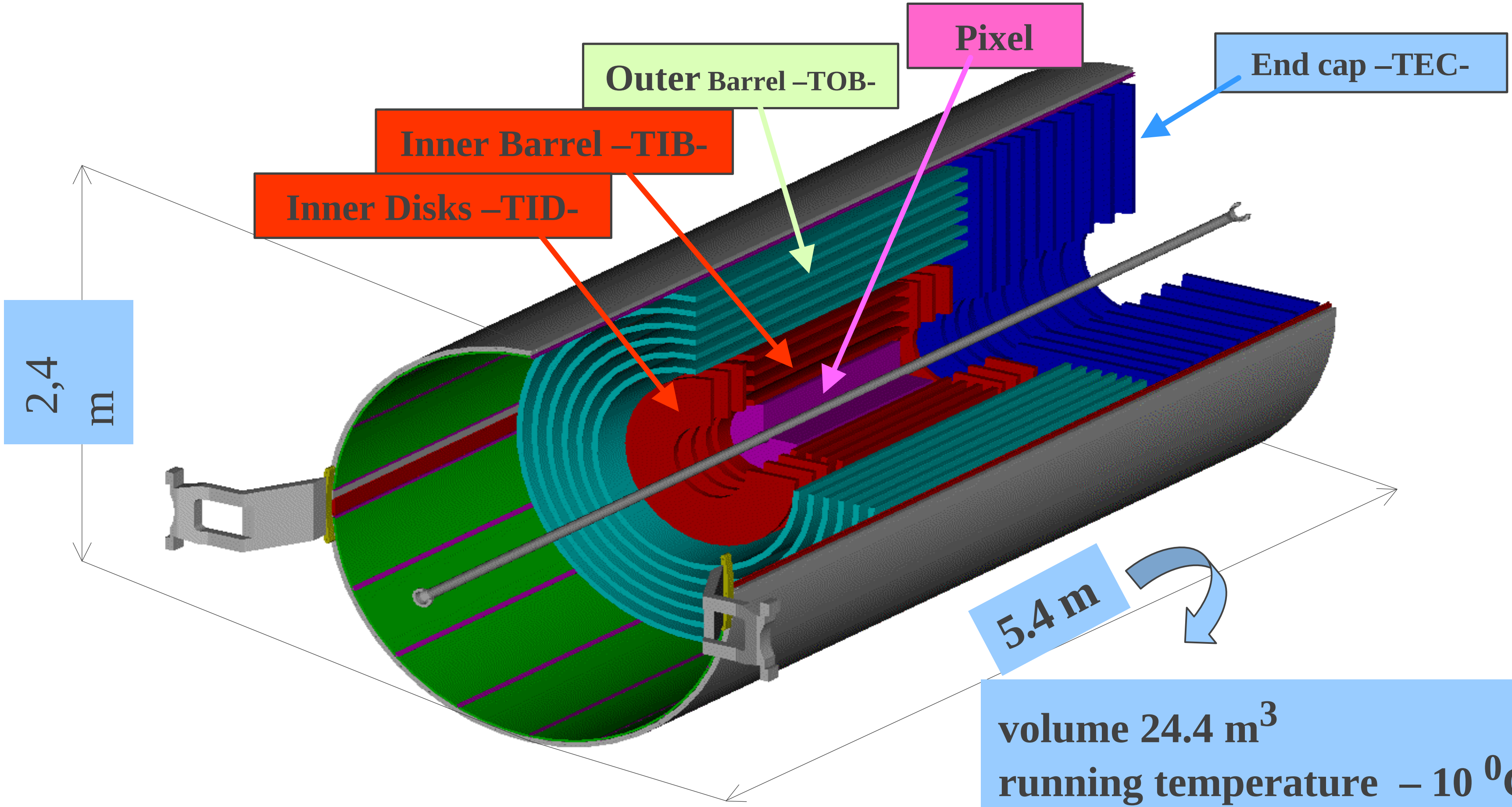
Move to detectors with a high level of independent tracking capability

⇒ A few m^2 : CDF – D0

⇒ Several * $10^1 m^2$: ATLAS

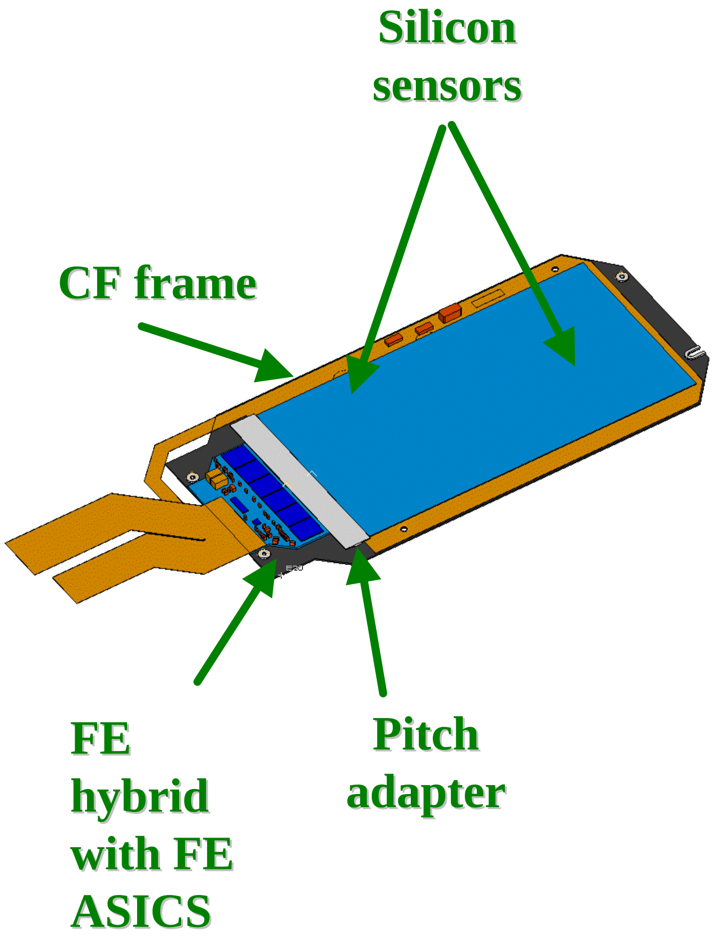
⇒ A couple * 10^2 m^2 : CMS

The CMS Tracker



volume 24.4 m^3
running temperature – 10 ^{0}C
dry atmosphere for YEARS!

SST Module level Components



9,648,128 strips ° channels
75,376 APV chips

Reliable, High Yield Industrial IC process

6,136 Thin sensors
18,192 Thick sensors

6,136 Thin detectors
(1 sensor / module)
9,096 Thick detectors
(2 sensors / module)

Large scale 6" industrial sensor production

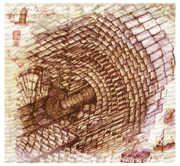
440 m^2 of silicon wafers
210 m^2 of silicon sensors

3112 + 1512 Thin modules (ss + ds)
5496 + 1800 Thick modules (ss + ds)

Automated module assembly

25,000,000 Bonds

State of the art Bonding machines

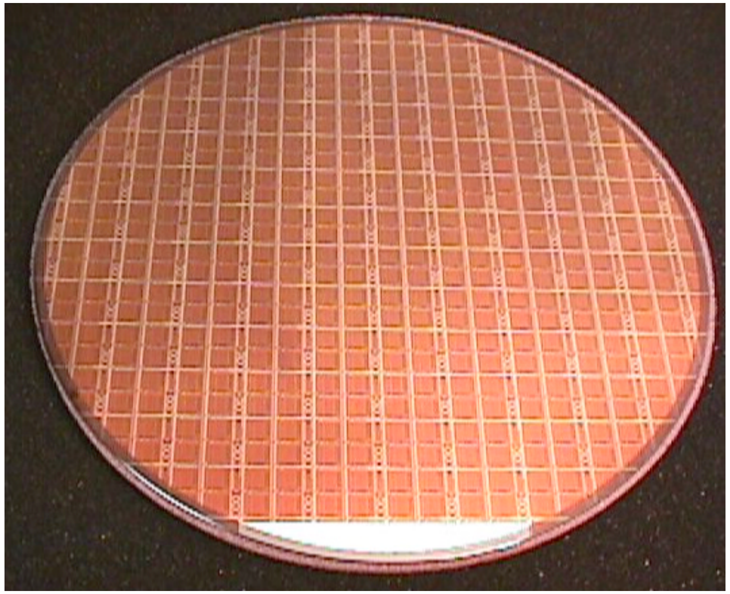


0.25m FE chip set: Production wafer layout

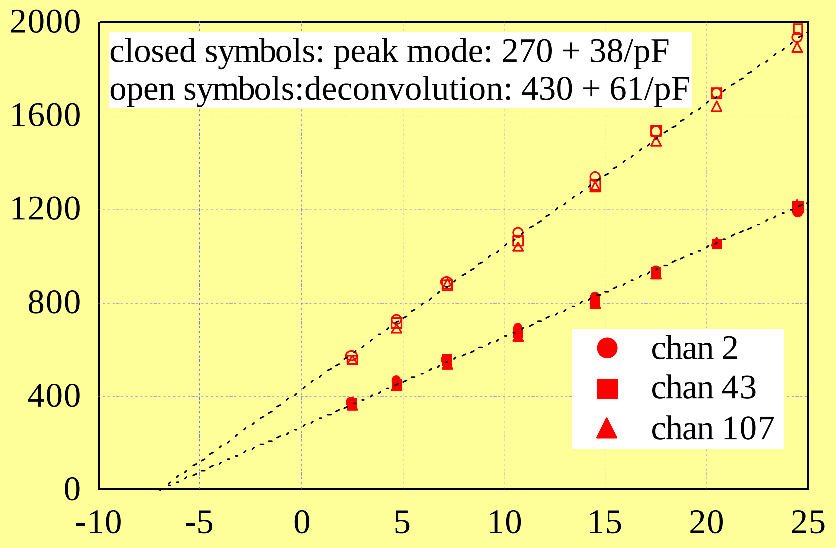
Full Chip set tested, mask are final

APV25 8” Wafer

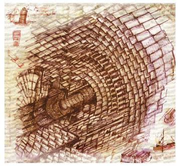
- Overall size 200mm
- APV25 die ~ 400
- APVMUX+PLL die ~ 100



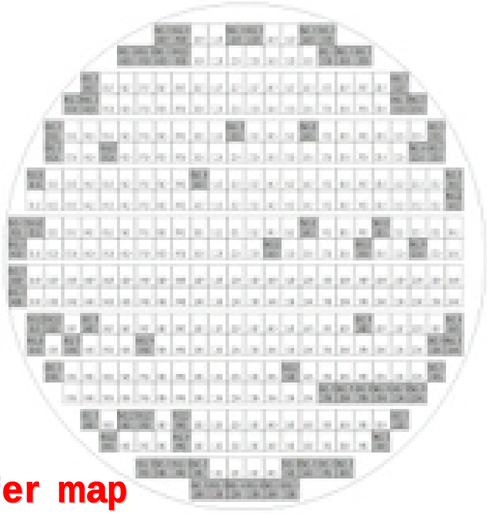
APV25 chip: 0.25m
ready for production



Radiation insensitive
Excellent noise performance



APV25 test results



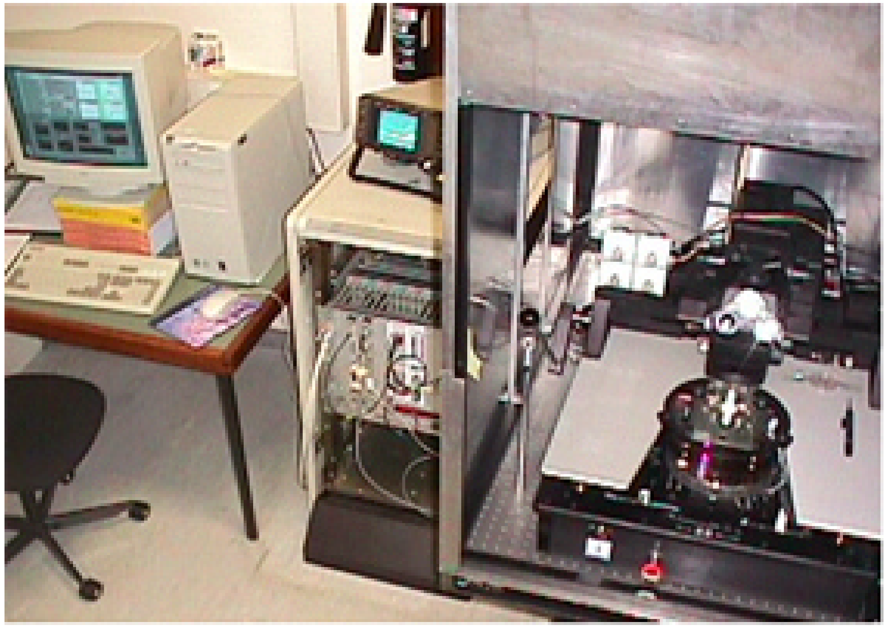
Typical tested wafer map

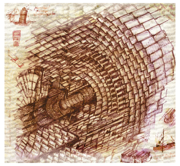
Automatic wafer probing
- 9 wafers probed - 75% yield of perfect chips
    - most failures at wafer periphery

Two cut wafers retested as individual die
- statistics limited: upper limit 1% good die failed
- but no bad chips accepted

Test time < 2mins/chip
- 1 8inch wafer per probe station per day
- can complete testing in ~1-2 years

Irradiation results
- x-ray, pion & neutron - all excellent
- tests with heavy ions and pions
    - 8 chips x 10 LHC years
    - low SEU rate, no permanent damage or latch up

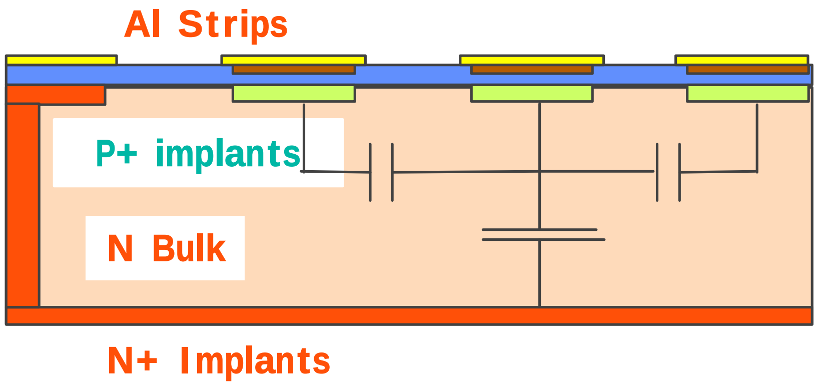


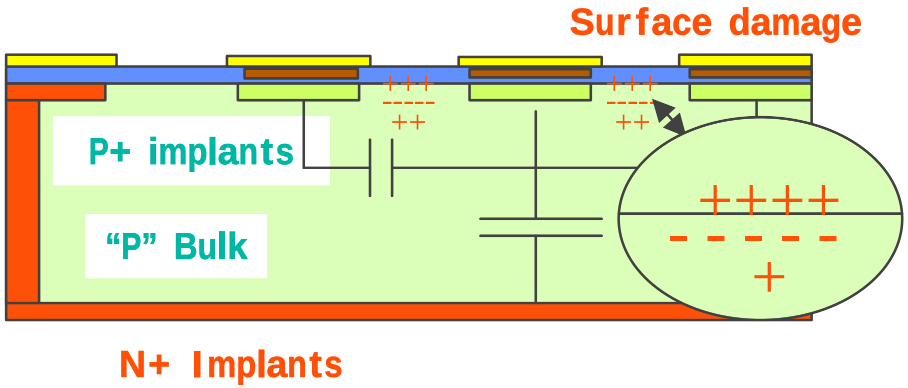


The radiation hard P-on-N strip detector

ATLAS, CMS, ROSE …

Single-Sided Lithographic Processing
(AC, Poly-Si biasing)





Radiation hardness "recipe"

P-on-N sensors work after bulk type inversion,
Provided they are **biased well above depletion**

Match sensor resistivity & thickness to fluence
To optimize S/N over the full life-time

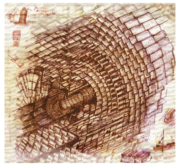
Follow simple design rules
for guard & strip geometries

Use Al layer as field plate to remove high field
Region from Si bulk to Oxide
(much higher V_{break})

Take care with process: especially implants…

Surface radiation damage can
increase strip capacitance & noise

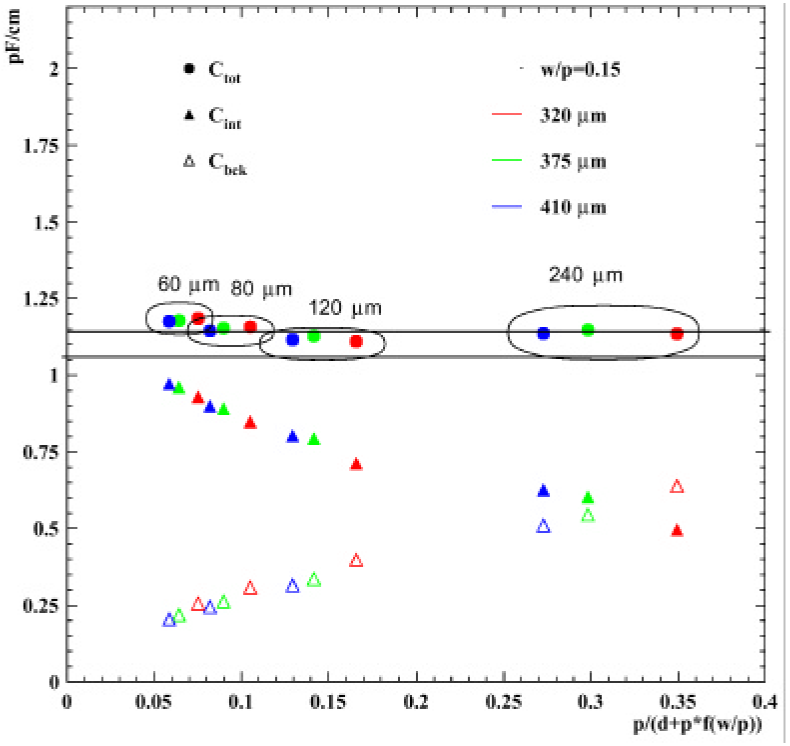
Use <100> crystal instead of <111>

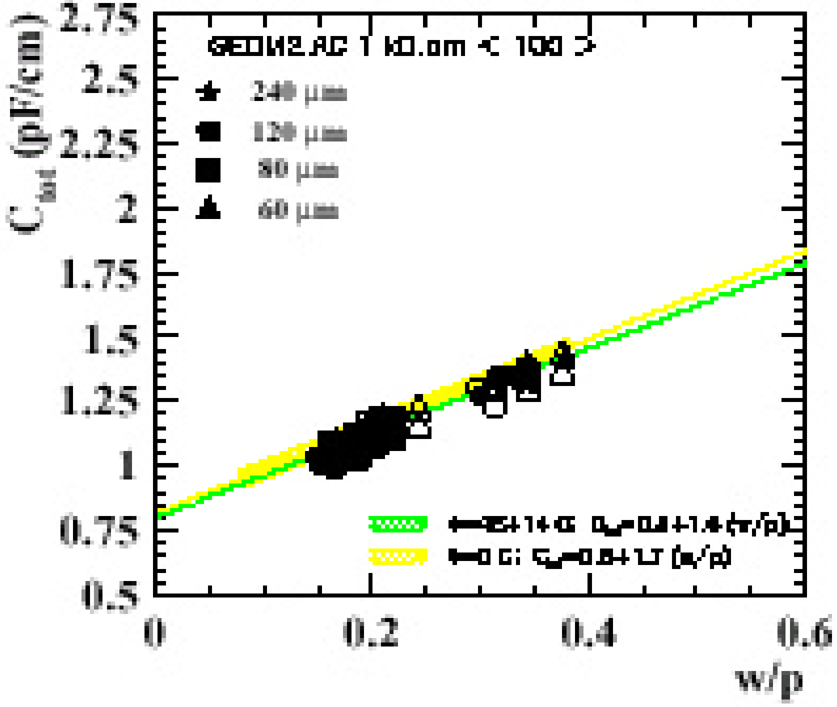


Silicon Sensor Geometry

Strip capacitance ~ 1.2pF/cm for w/p = 0.25
Independent of pitch and thickness

Insensitive to irradiation
for <100> crystal lattice



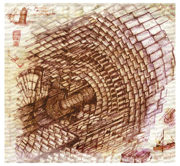


Expected S/N after irradiation

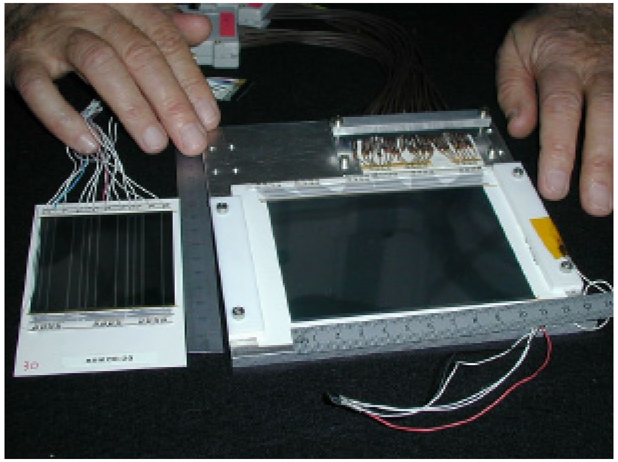
Use 320mm thick Si for R < 60cm, Strip ~ 10cm

Use 500mm thick Si for R > 60cm, Strip ~ 20cm

S/N ~ 13 for thin sensors, short strips
S/N ~ 15 for thick sensors, long strips



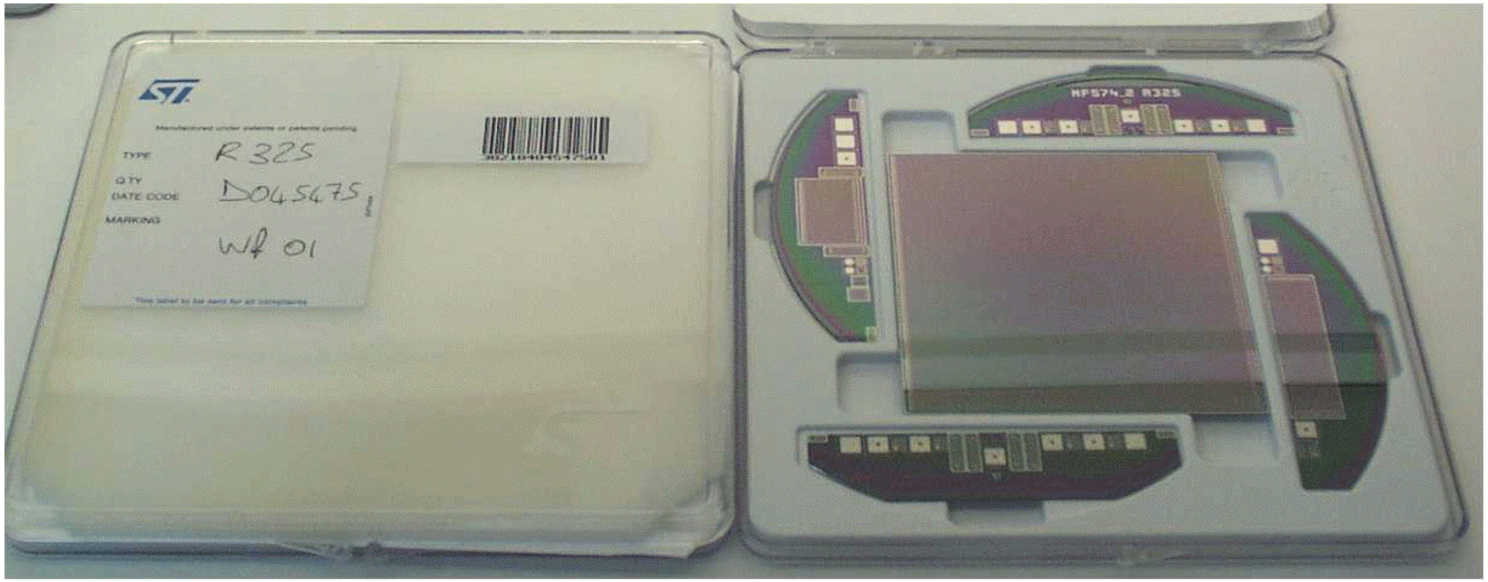
Status of CMS Silicon Strip Tracker (SST)



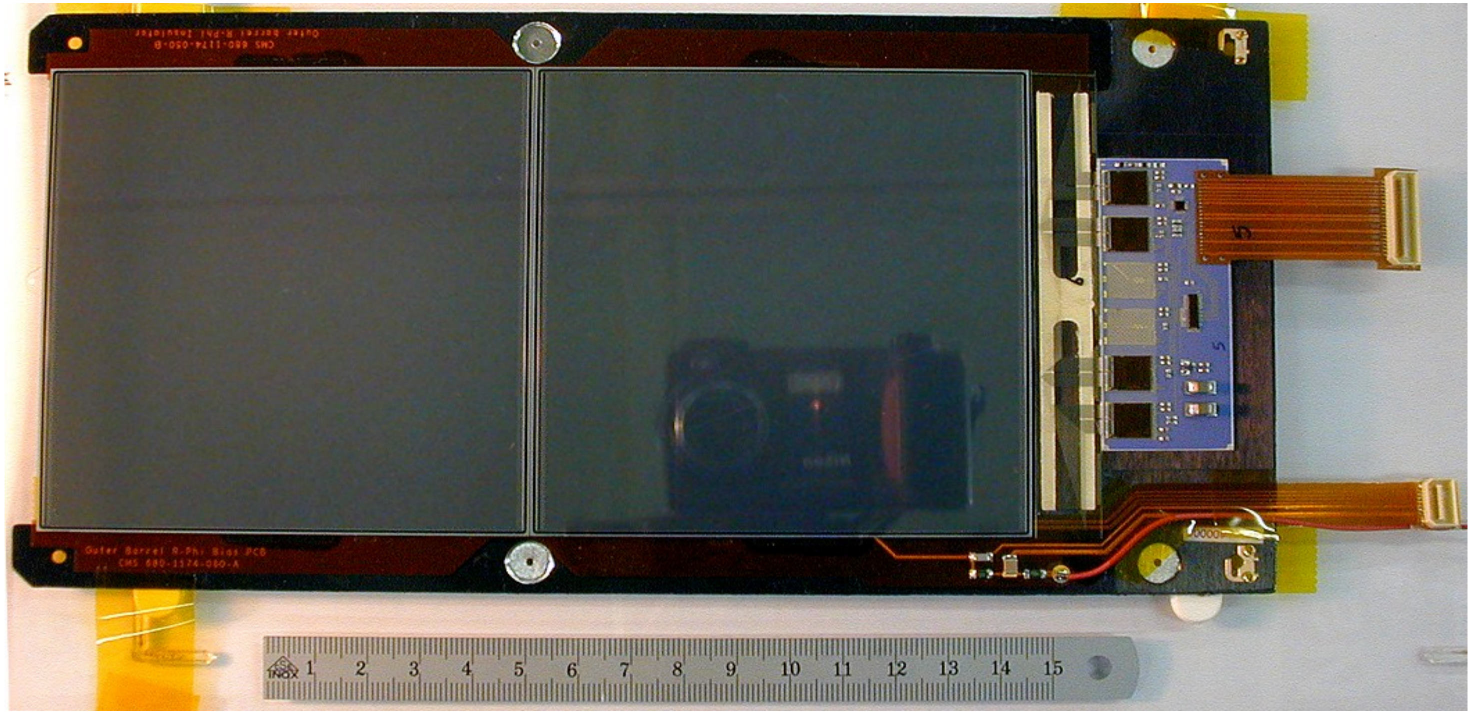
The CMS SST exploits 6” technology:

Useful surface/wafer ~ 2.5 * that of 4” wafers

Large scale high quality sensor production in modern Industrial lines available from more than one vendor



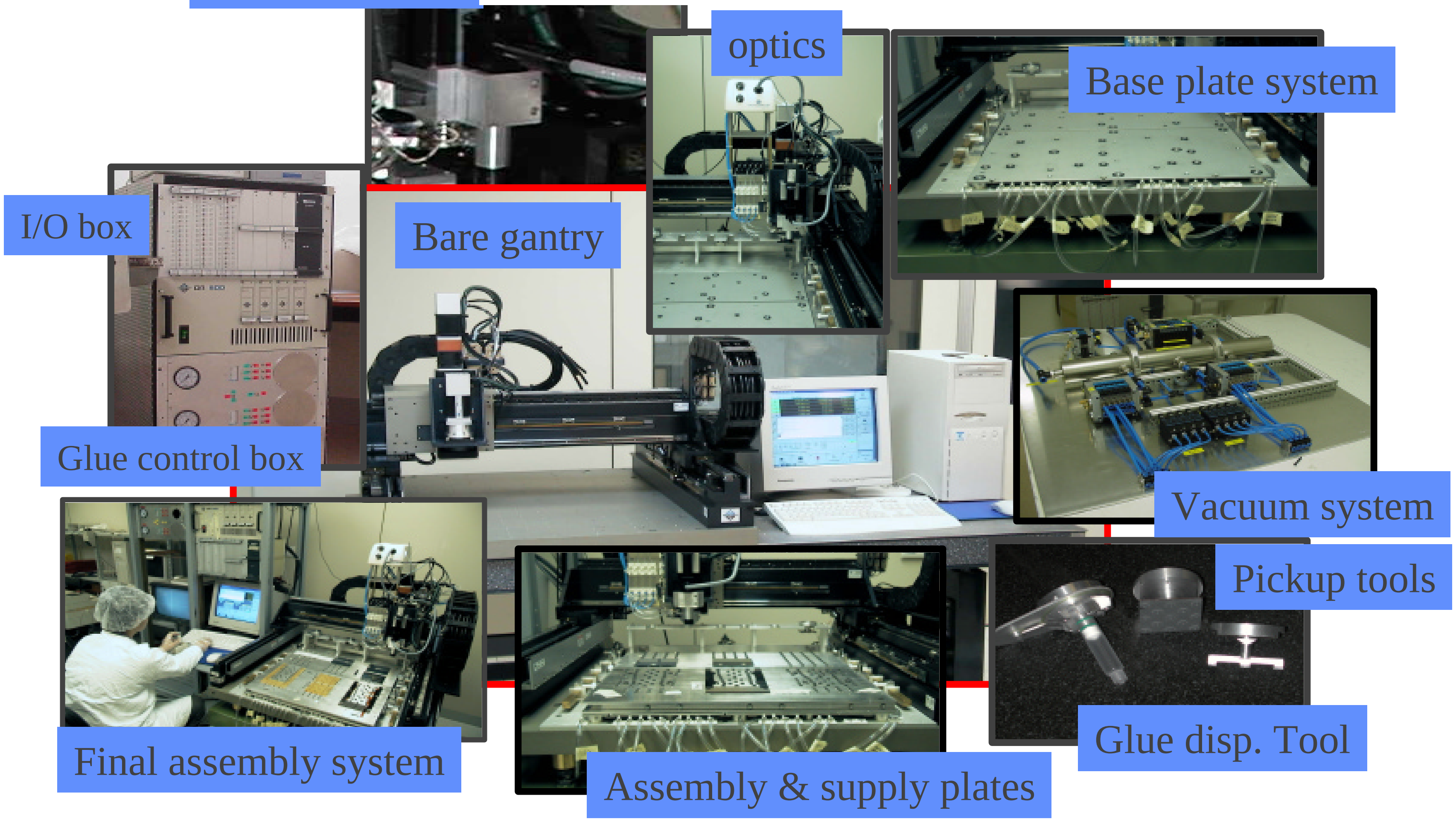
A fully assembled CMS SST Module (TOB)



Situation is rapidly evolving toward full module production

High precision glue dispensing and Pick & Place Robotic Device: The “Gantry”

all the Gantry tools



Camera support

optics

Base plate system

I/O box

Bare gantry

Glue control box

Vacuum system

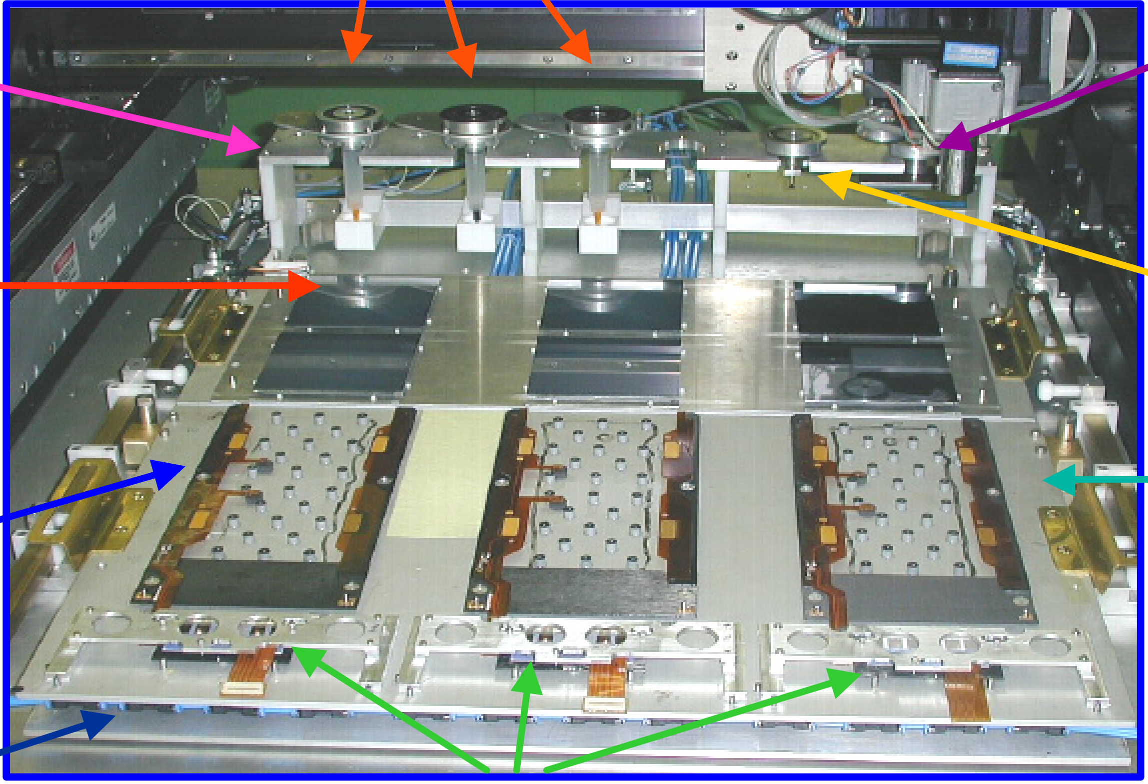
Pickup tools

Final assembly system

Glue disp. Tool

Assembly & supply plates

The Gantry in action
Assembly of 3 TOB Modules



Glue dispensing syringes

Tool rack

Sensor pick up tool

Silicon sensors

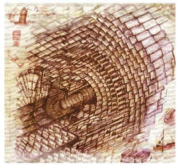
Hybrid pick up tool

Carbon fiber frames

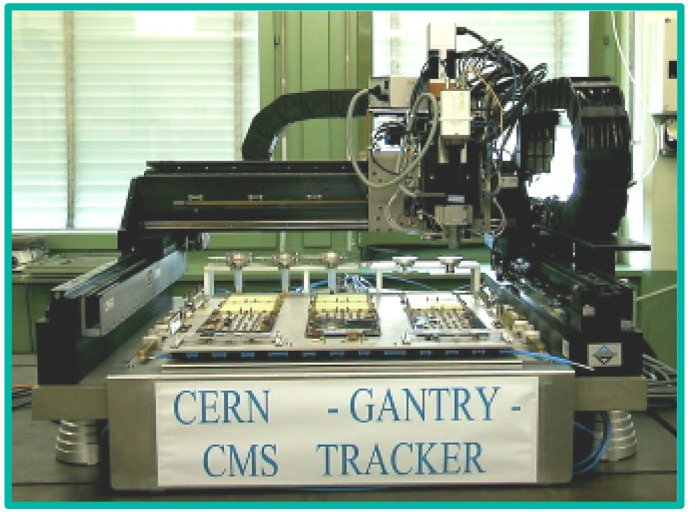
Assembly platform

Vacuum system

Hybrids



Placement accuracy and reproducibility with automatic pattern recognition



"Gantry see, Gantry do"

The gantry system localizes automatically the components to be assembled by searching for a Marker with a camera

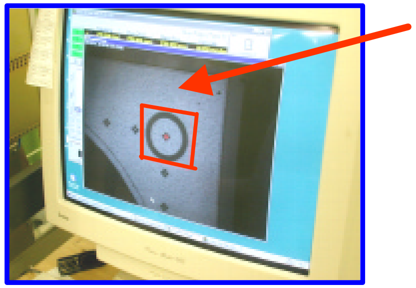
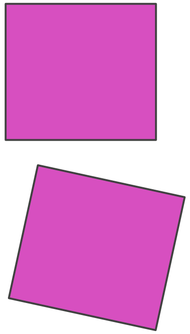
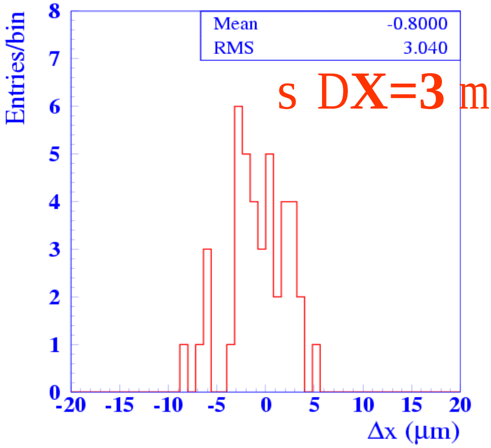
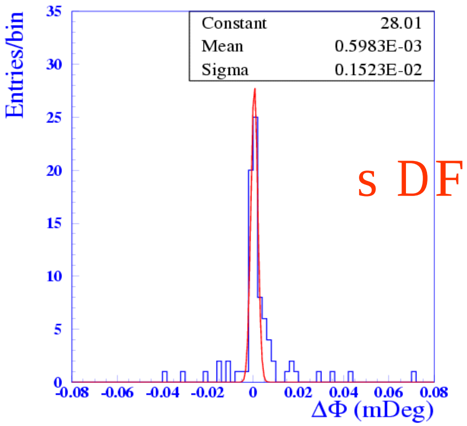


Image found





s D**X=3** m**m**

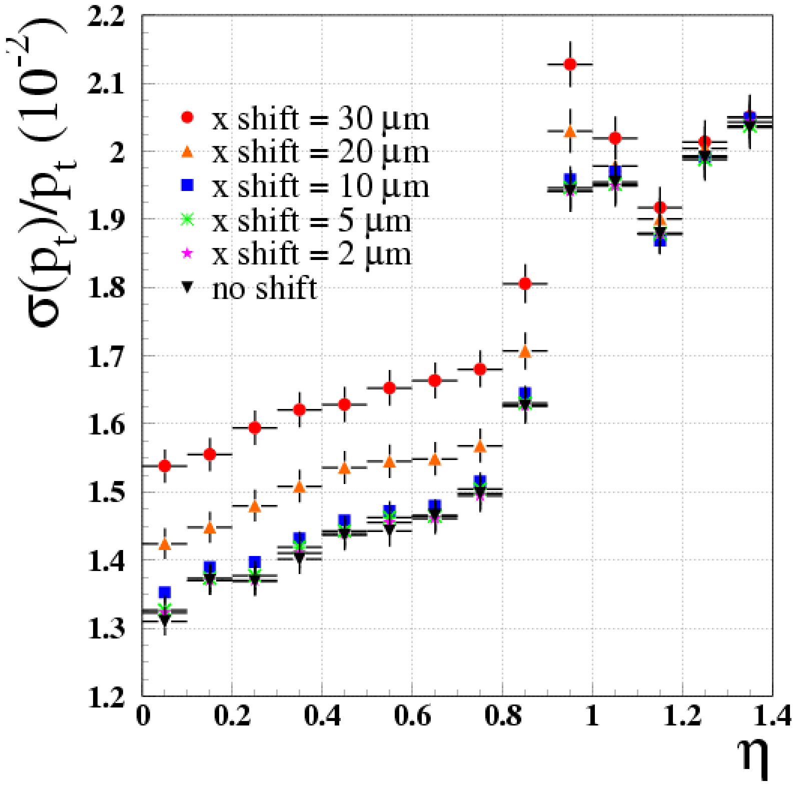


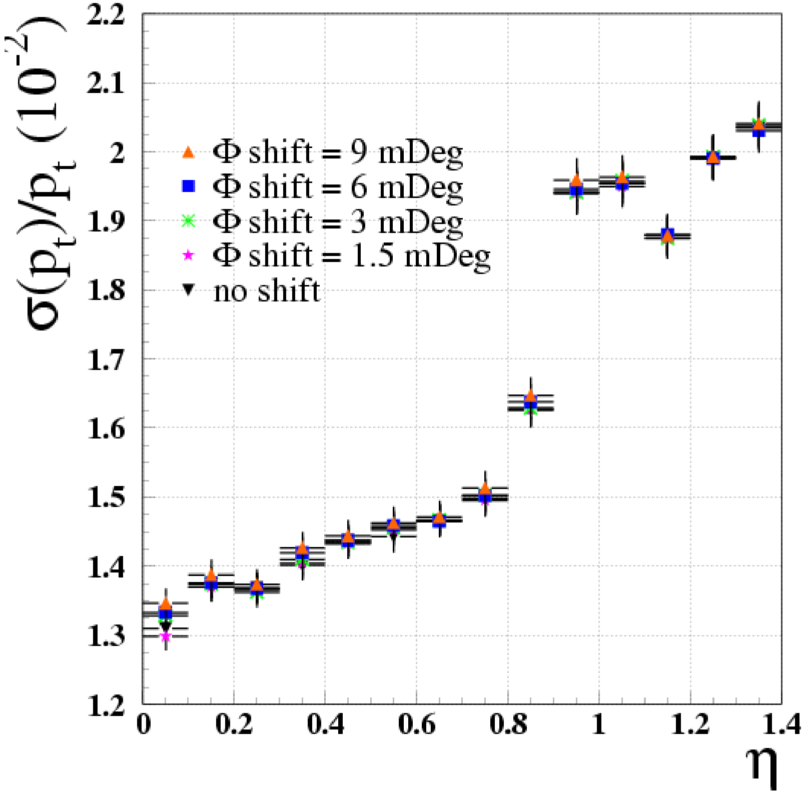
s DF**=1.5 mrad**

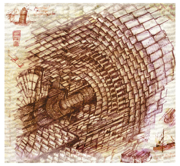
Influence of sensor misalignments on Track Pt resolution

Single μ sample, Pt=100 GeV; Decomposed X-movement and Φ rotation:

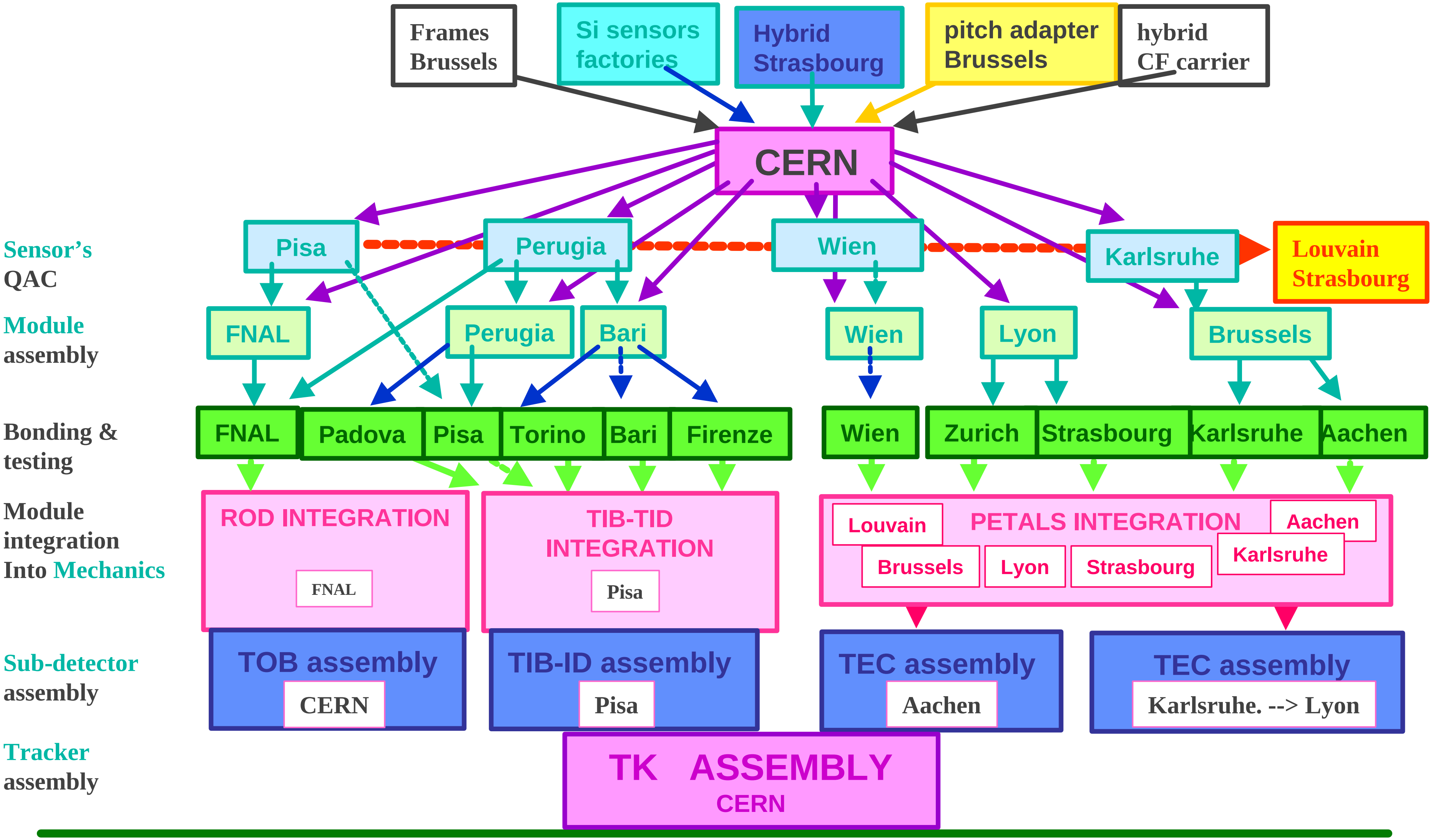
Precision achieved is well below intrinsic hit resolution







CMS SST Assembly Logistics: A lot of horse power & a great deal of organization



Frames Brussels

Si sensors factories

Hybrid Strasbourg

pitch adapter Brussels

hybrid CF carrier

CERN

Sensor's QAC: Pisa, Perugia, Wien, Karlsruhe, Louvain Strasbourg

Module assembly: FNAL, Perugia, Bari, Wien, Lyon, Brussels

Bonding & testing: FNAL, Padova, Pisa, Torino, Bari, Firenze, Wien, Zurich, Strasbourg, Karlsruhe, Aachen

Module integration Into Mechanics:

ROD INTEGRATION
FNAL

TIB-TID INTEGRATION
Pisa

PETALS INTEGRATION
Louvain, Brussels, Lyon, Strasbourg, Karlsruhe, Aachen

Sub-detector assembly:

TOB assembly
CERN

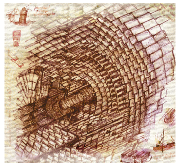
TIB-ID assembly
Pisa

TEC assembly
Aachen

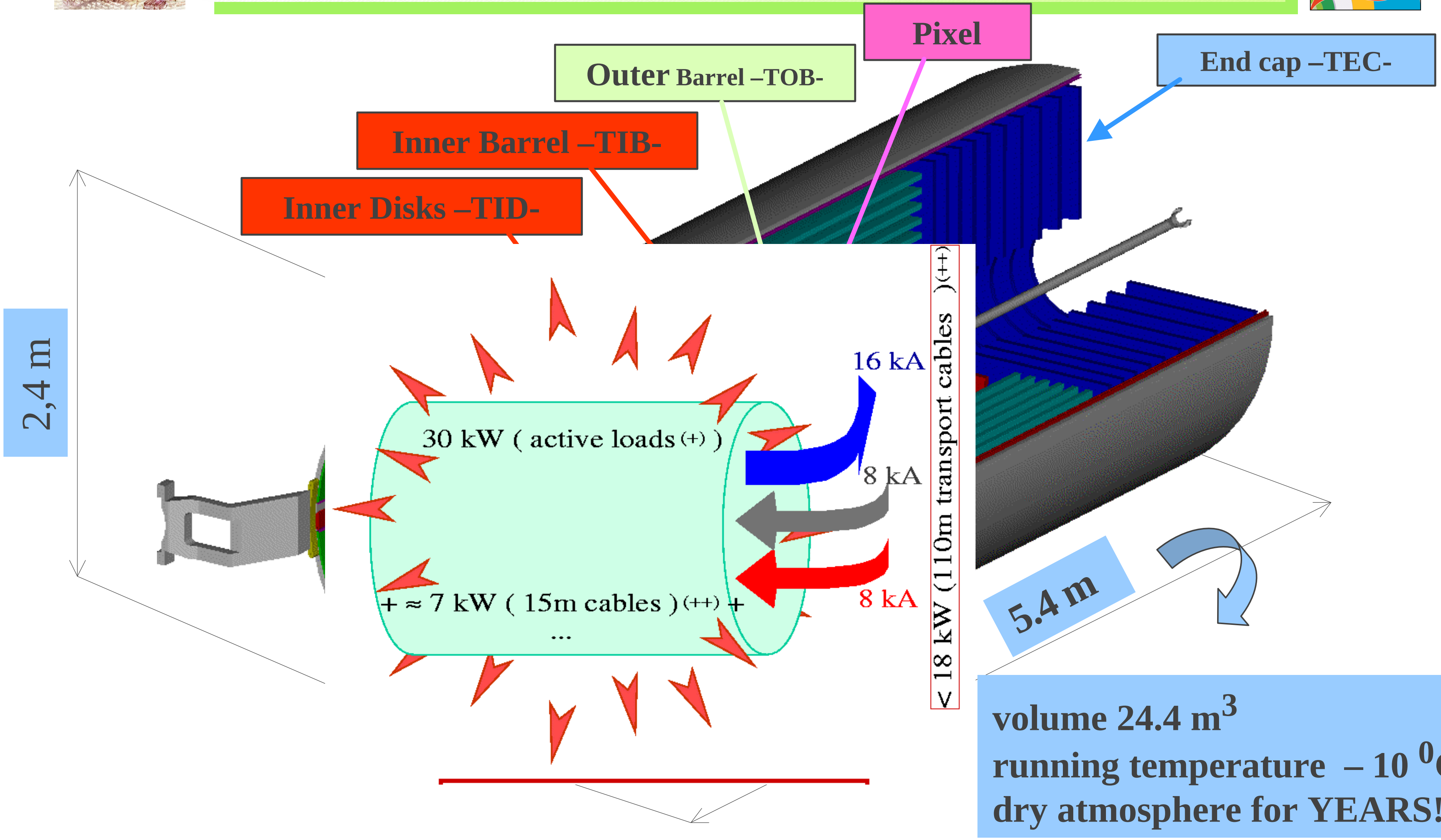
TEC assembly
Karlsruhe. --> Lyon

Tracker assembly:

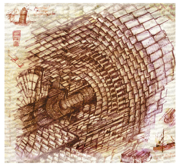
TK ASSEMBLY
CERN



The CMS Tracker services



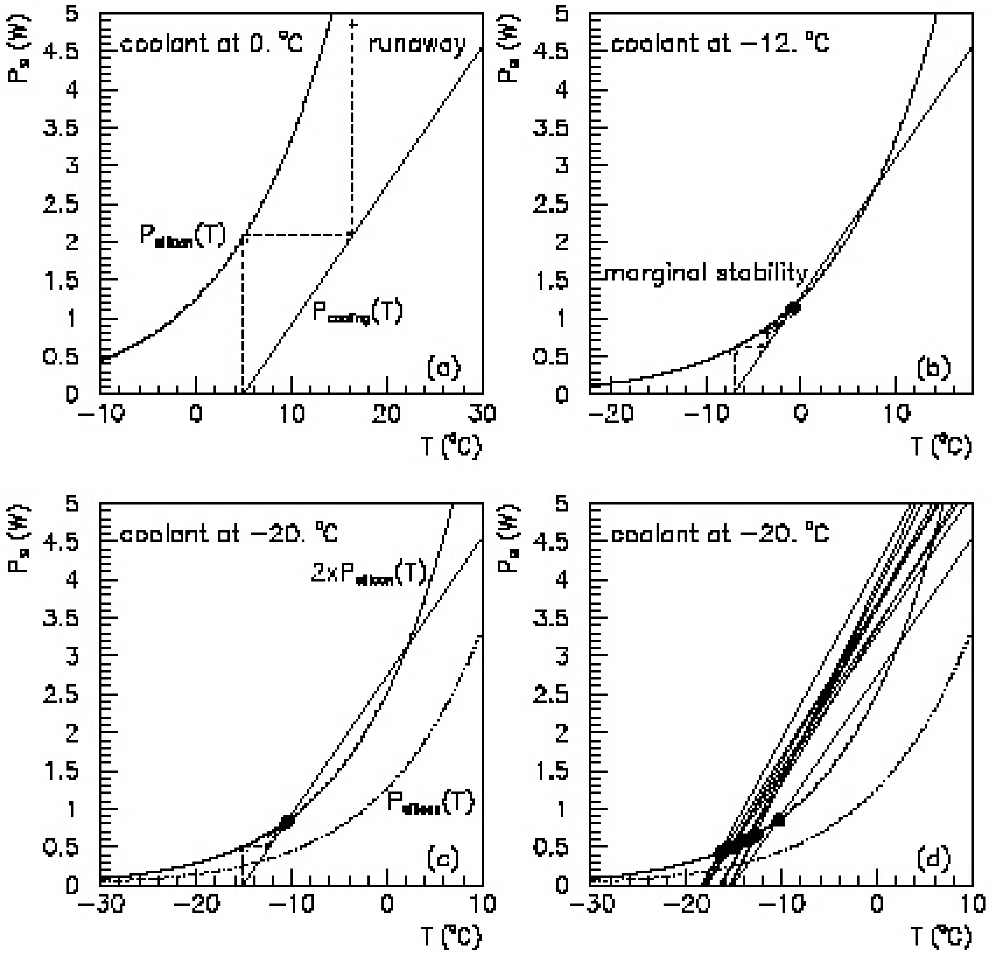
volume 24.4 m^3
running temperature – 10 ^{0}C
dry atmosphere for YEARS!



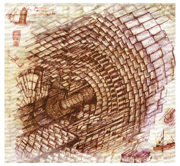
Why operate at –10C ?

“Reverse annealing” requires the sensors
to be kept below ~0C,
At least for most of the time

The exponential increase of leakage current
Drawn by a silicon sensor with Temperature
(about a factor of two for each 6 degree C)
Sets the more stringent requirement



As can be seen from the figures, given
The cooling efficiency achievable within
A reasonable material budget
The sensor temperature in operation must
Be maintained below –10C
This requires a cooling fluid temperature
Of below –20C within the Tracker volume

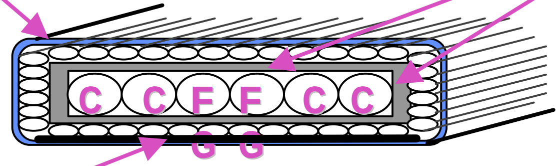


-10C operation => Active heat shields
Large W dissipation => Active cooling

This requirement applies not only to
the Tracker Volume itself,
but also to cable & cooling tube runs,
Which are integrated together

10 m long cable/cooling channel prototype

Experimental results in good
Agreement with FE calculation



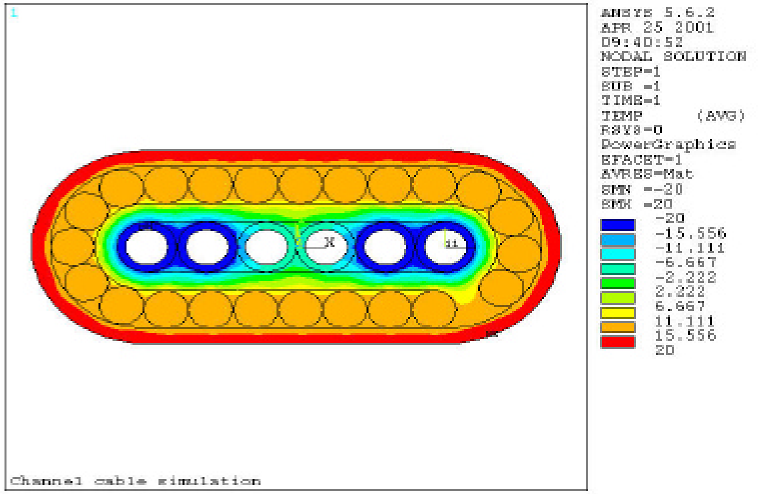
Aluminum enclosure

Inner Insulation foam 1 cm

Heating foils for power compensation

C : cooling pipes (C6F14)

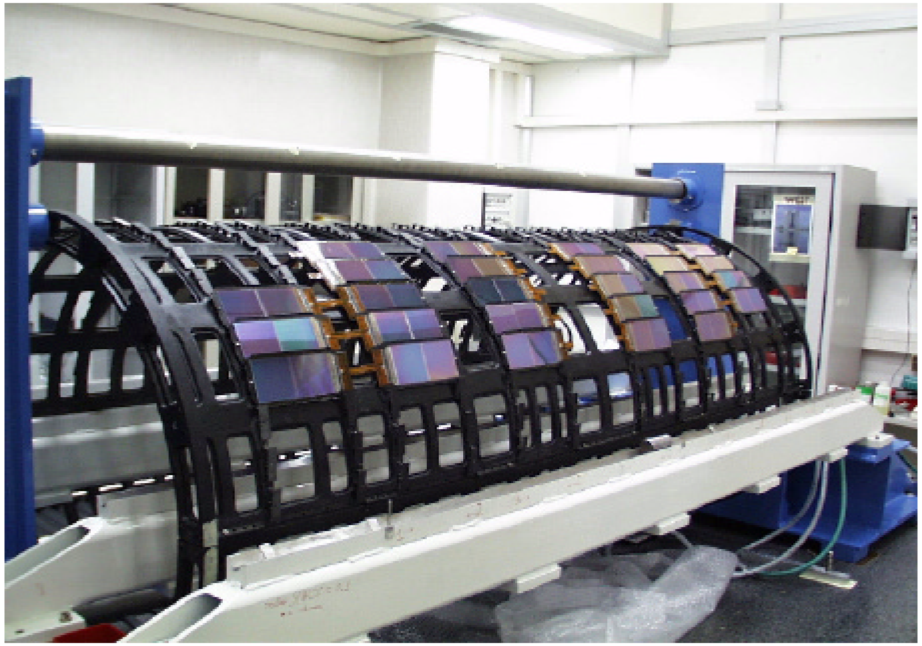
FG : flushing gas pipes (N2)

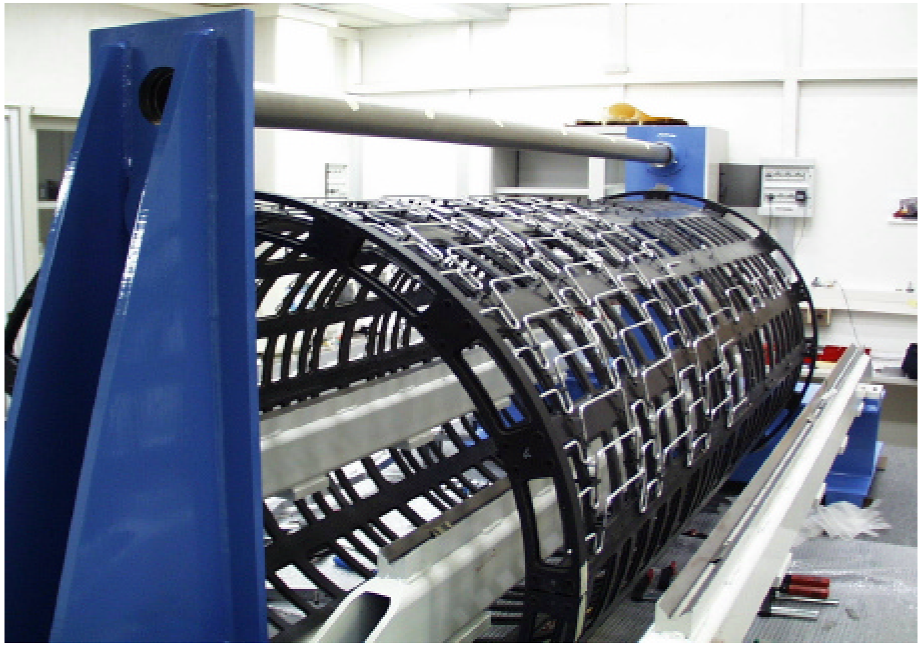


TIB Mechanics

In general, the Tracker support mechanics are mostly air:
CF space frames and/or Honeycomb structures

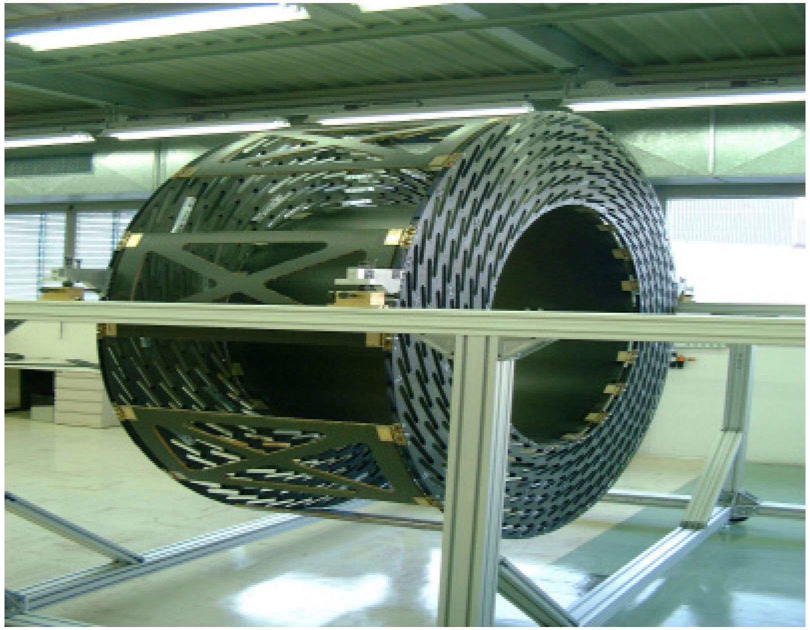
Local integration of cooling is a common feature of all the Support structures



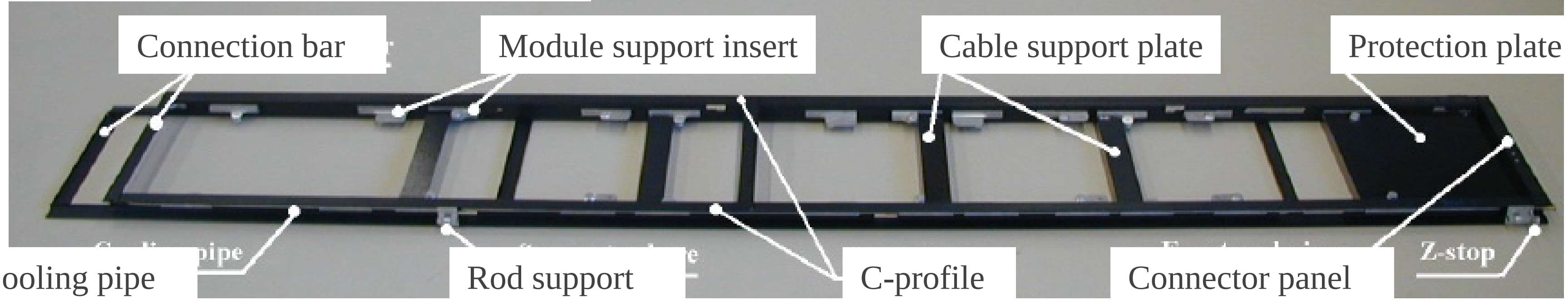


TOB Mechanics

- Validation of the final design
  - Big Wheel prototype, done 99-00
  - M200 prototype Rods, done 01
  - Module cooling tests, done 01
  - Rod integration and Cooling sector tests, autumn 2001

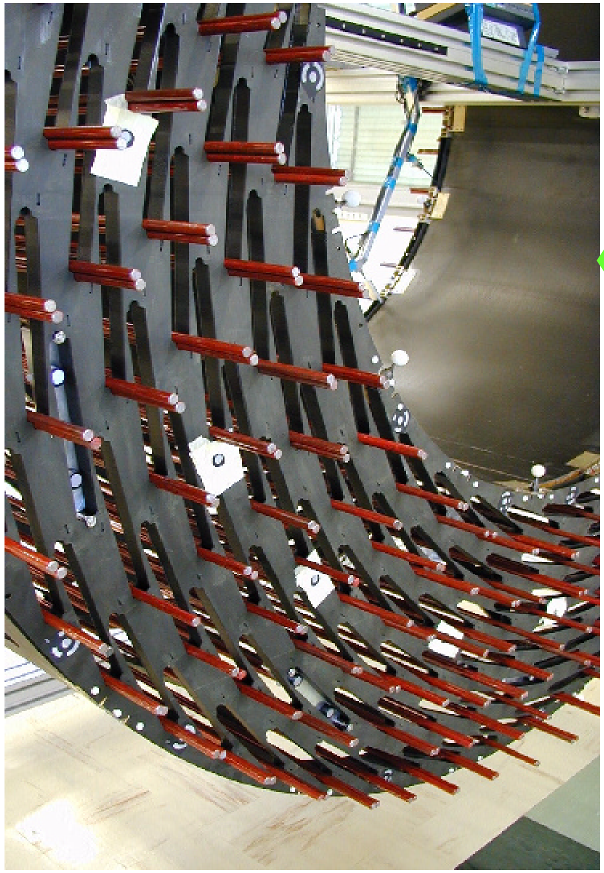


M200 Rod for 6 double-sided modules

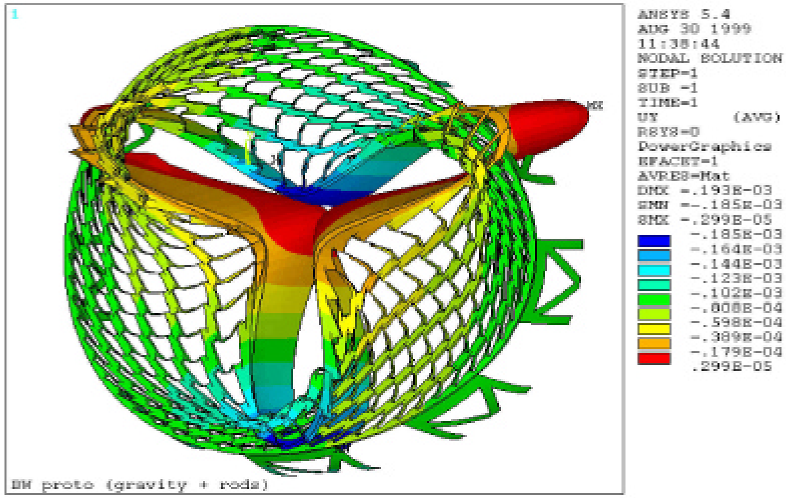


TOB deformations and stability

tests of deformation under full load
Survey: photogrammetry



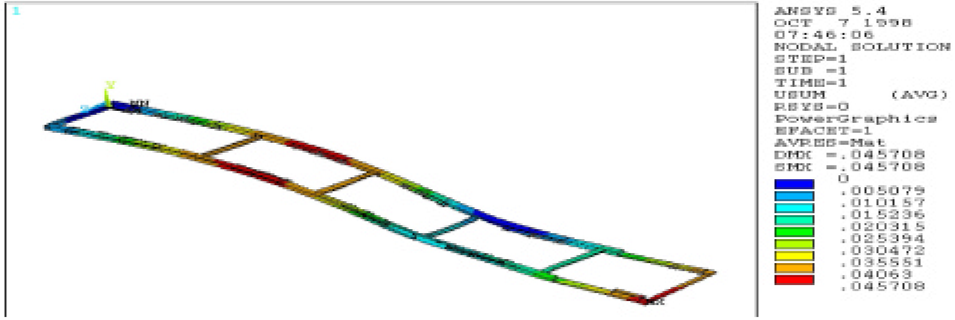
agree



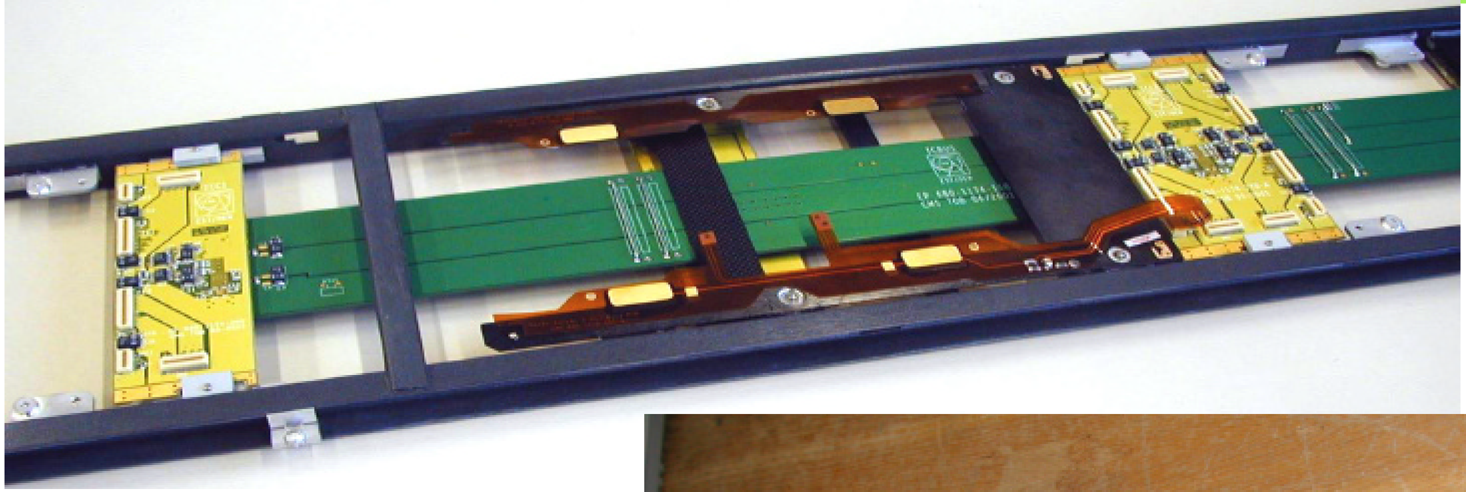
Prediction for CMS (K800/epoxy) Max displacement:

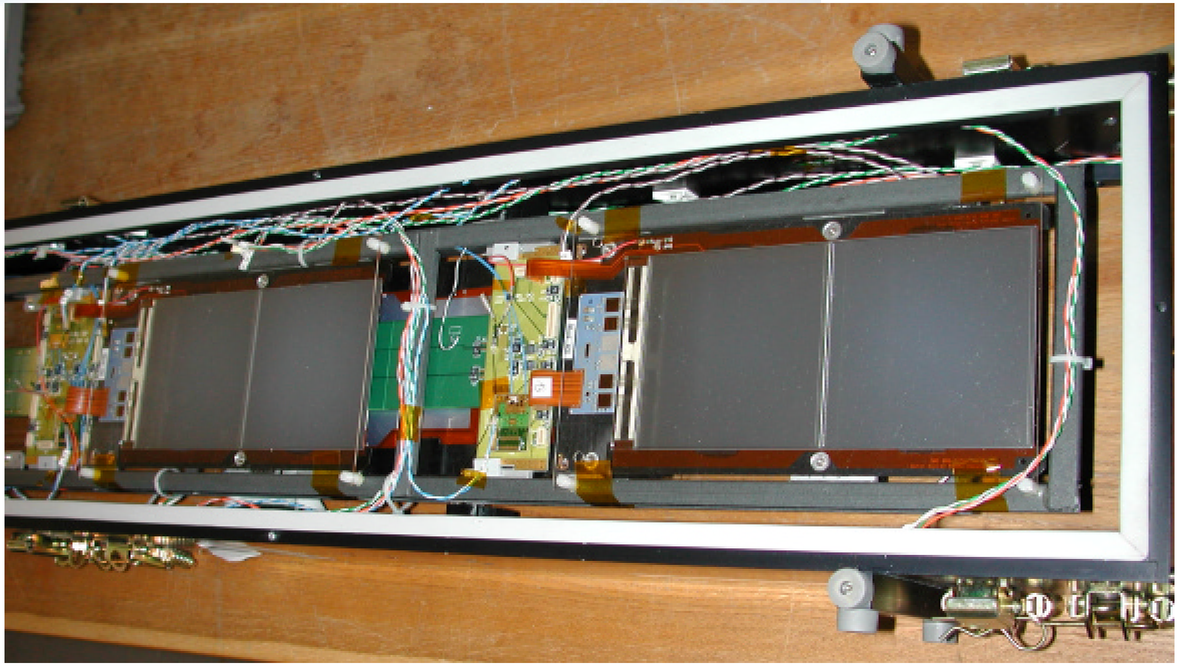
0.5 mm under full load (50mm for the Rod)

0.1 mm for DT; 0.3 – 0.03 mm humidity



ROD pictures as "from last Friday"

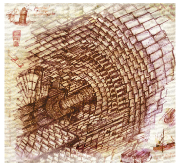




Extensive System tests

well under way, prior

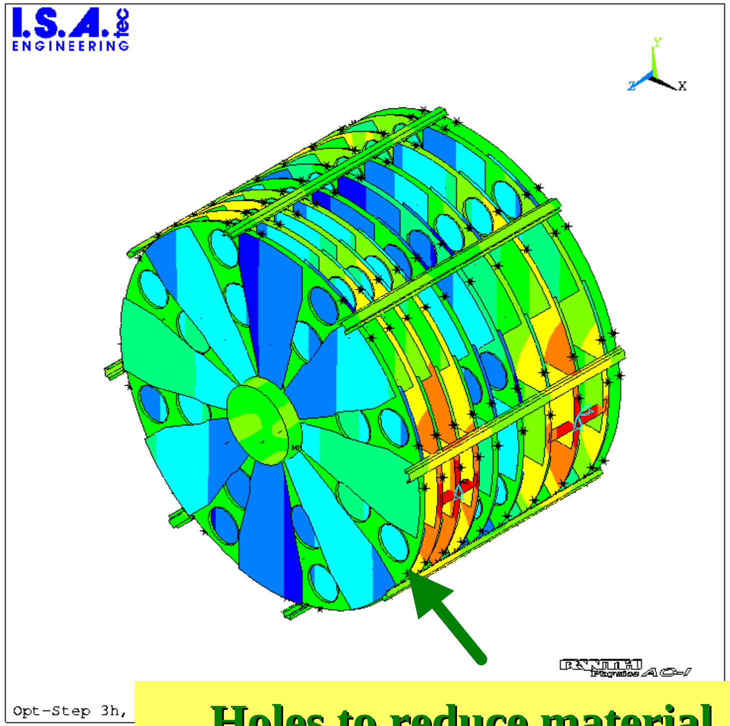
To going into full production



TEC Detector Wheel System (DWS) Finite Element Analysis, Results

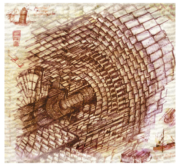
FE-Model:	Total Length = 1572 mm [corresp. cms1231], Total Mass = 495 kg Payload corresponding List (6.06.2001)
Support Plates:	3 x Ri = 229 mm; 6 x Ri= 309 mm [corresp. cms1231] s. Detailed Discription: CMS, Single Detector Wheel (Ri = 229 mm) Wheels with Ri=309 mm w/o Holes at R=340 mm Petal Fibre Orientation Reversed (0°/ 90°/ 45°/ -45°), i. e. 0° at Surface
End Plate:	Thickness = 83 mm (16,5 mm Support Plate + 66,5 mm Additional Plate) [corresp. cms1231]; Alignment System Simulated by Mass Points
Inner Tube:	Quasi-Isotropic 0,3 mm T300/EP; Thickness = 3 mm, Connected to Wheels by U-Brackets [corresp. cms01_1301_1]
Service Channels:	Quasi-Isotropic 0,3 mm T300/EP; Thickness = 2,5 mm [corresp. cms01_1301_1]
Load:	Acceleration of 1g with Inclination Angle 0,7 Deg. (to Plates)
Constraints:	Supports Connectiong Wheels 2, 3, 4 and 7, 8, 9 with Fixation at z = - 1573 mm and –2443 mm near 0° and 180°

FE-Model	Delta vertical Displacement [µm]	Delta axial Displacement [µm]	Delta horizontal Displacement [µm]
V3h	DWS: $\Delta uy = 123$ [C090] Petals+Legs: $\Delta uy = 105$ [C091]	DWS: $\Delta uz = 193$ [C092] Petals+Legs: $\Delta uz = 193$ [C093]	DWS: $\Delta ux = 78$ [C075]



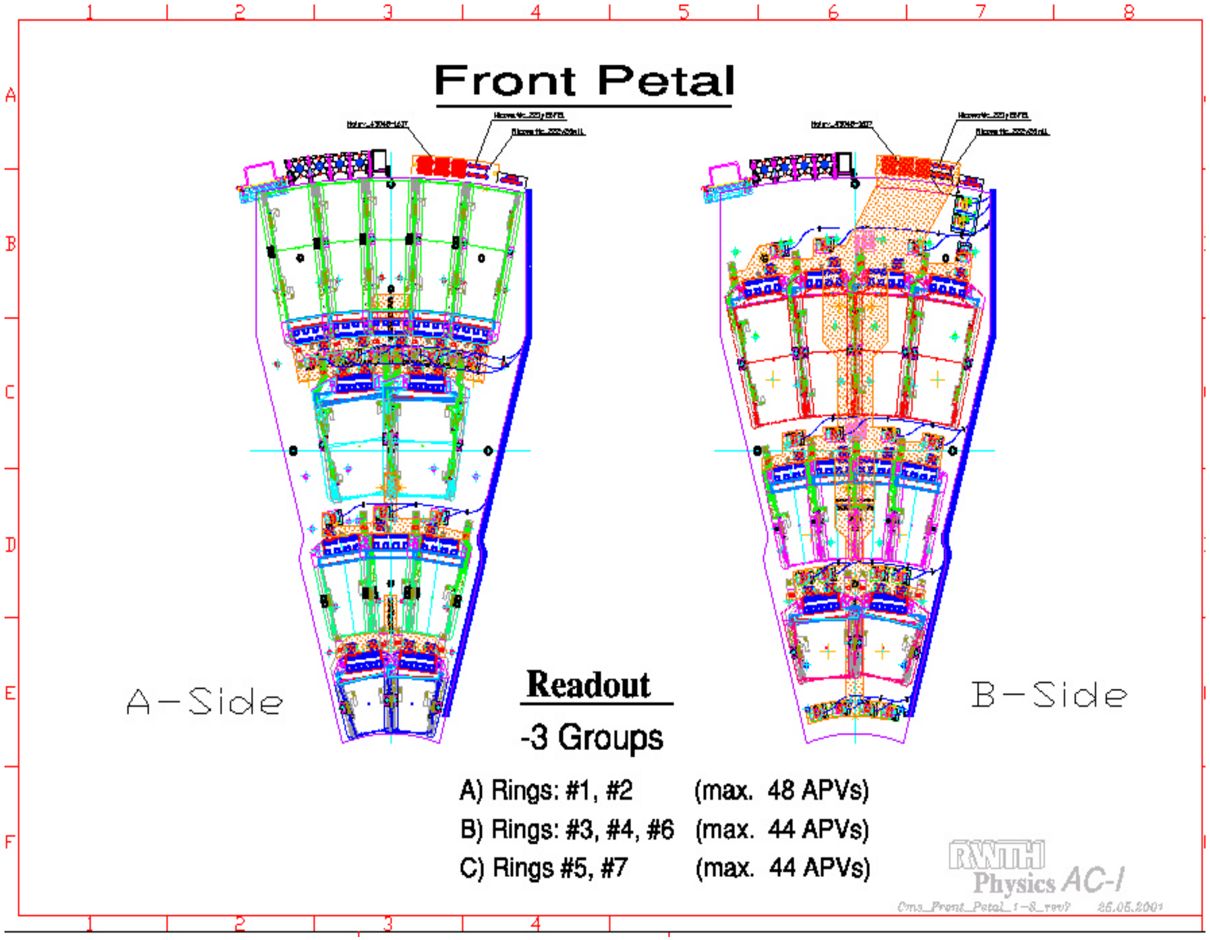
Holes to reduce material budget

This FEA is the last exercise that was needed in order to proceed with the order of the overall TEC structure



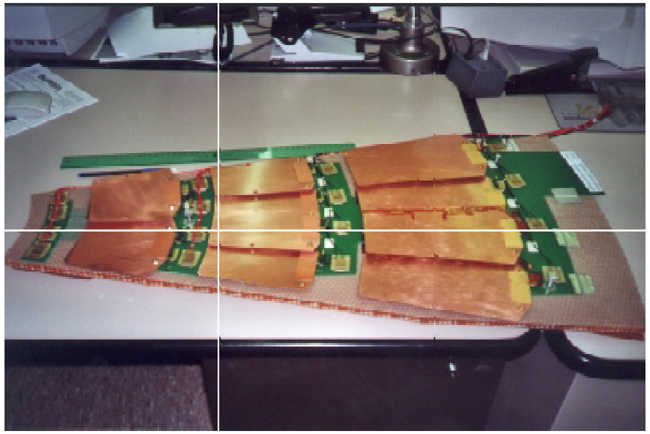
TEC COMPONENTS INTEGRATION

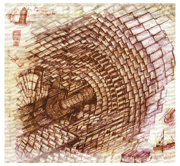
Detailed design completed



A) Rings: #1, #2 (max. 48 APVs)
B) Rings: #3, #4, #6 (max. 44 APVs)
C) Rings #5, #7 (max. 44 APVs)

Layout validated by mock-ups



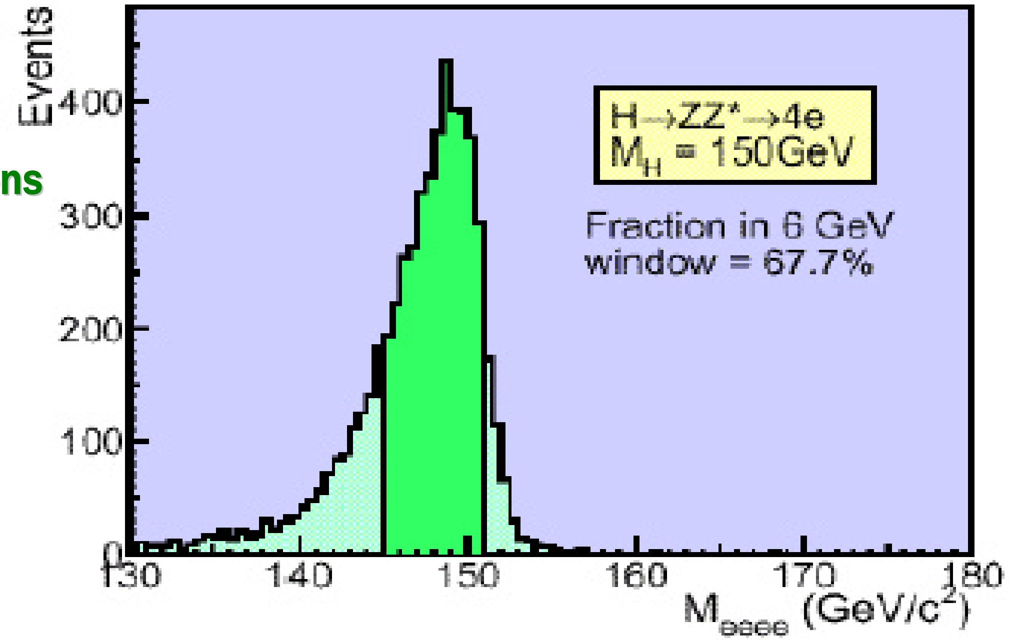


Material inside the Tracking volume

Degrades tracking performance, due to multiple scattering,
Bremsstrahlung and nuclear interactions
(see 100GeV μ Pt resolution)

Dominates energy resolution for electrons

Reduces (somewhat) efficiency for
usefully reconstructing H → γγ

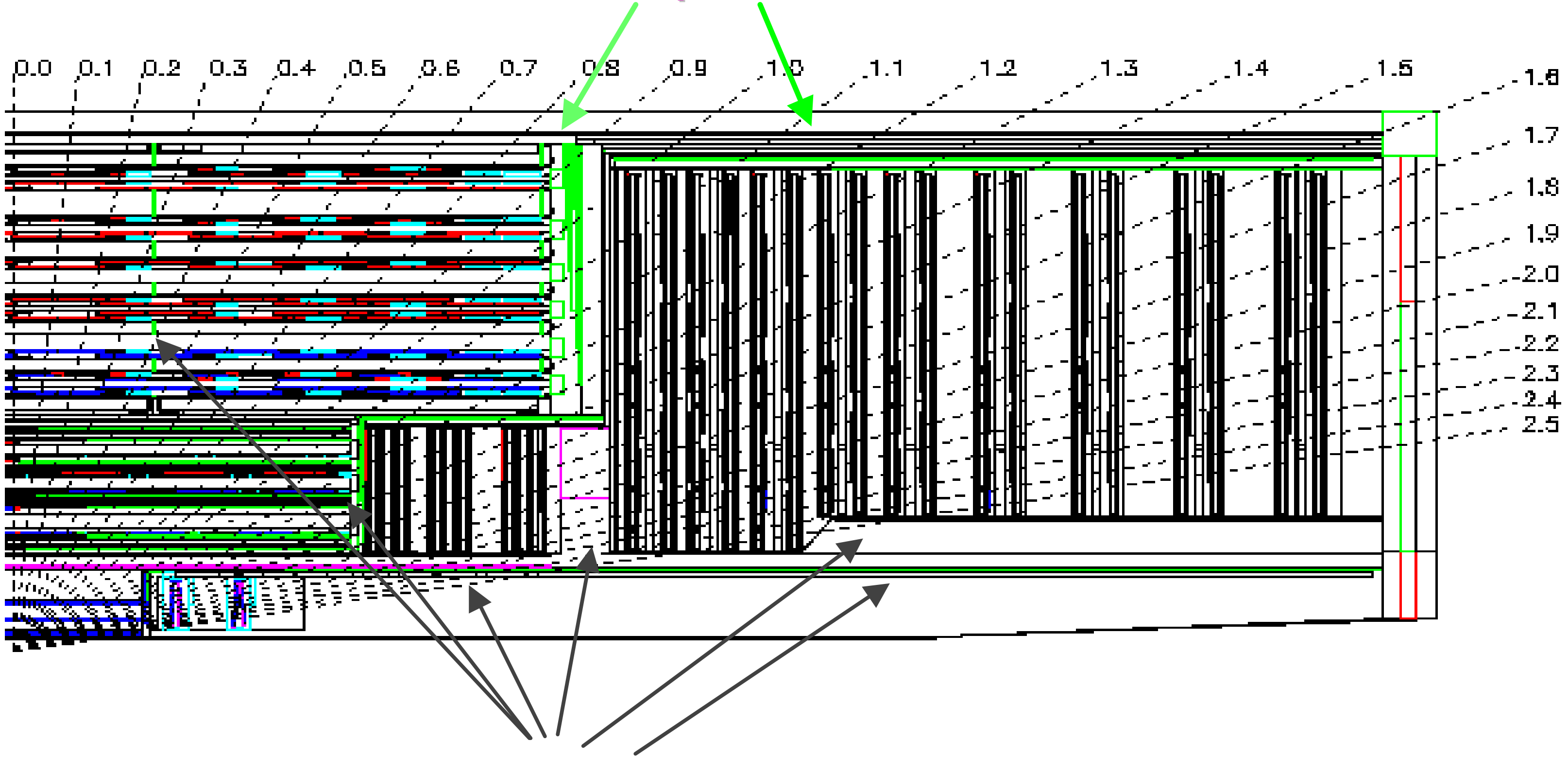


Material Budget minimization has been one of the
driving principles in the design of the CMS Tracker

Material Budget

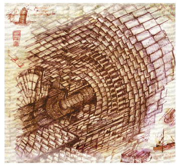
Determined from detailed GEANT simulation which includes latest engineering design

Analysis of material budget => important feed back for engineering design optimization



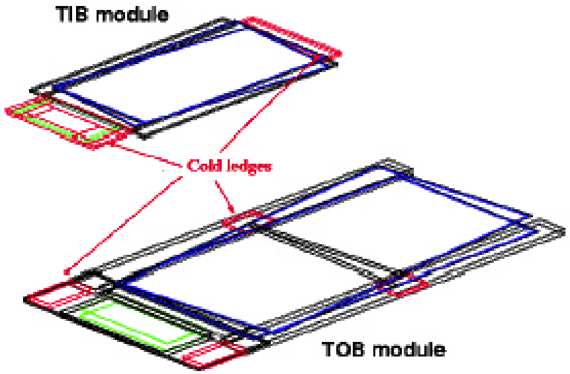
Cable paths

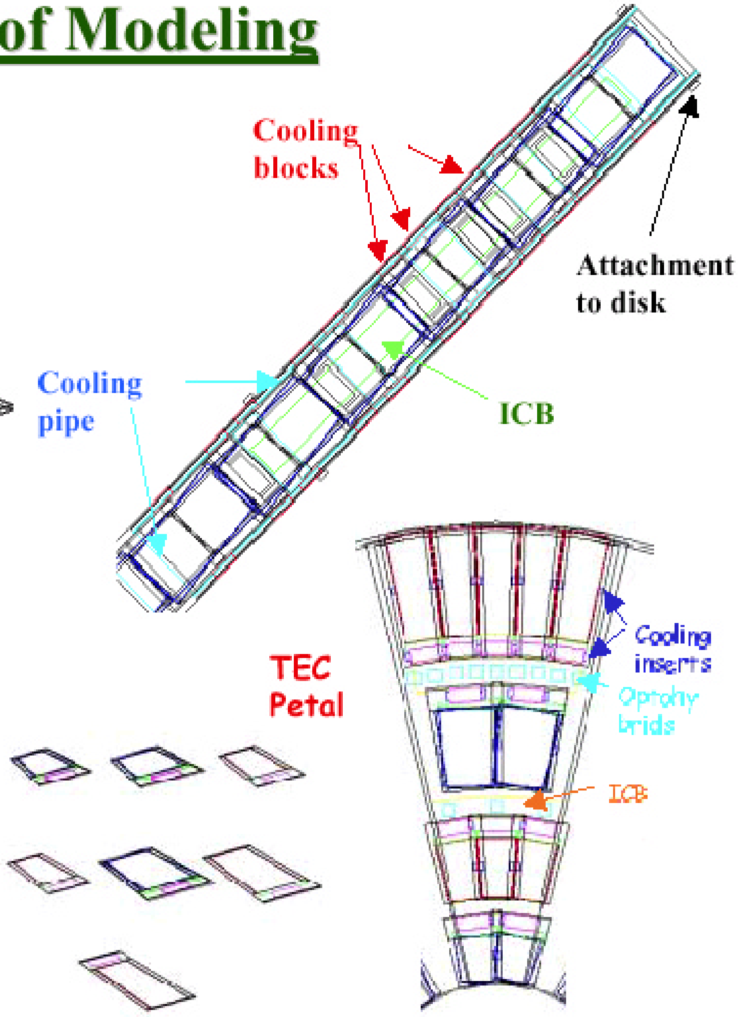
Support structures



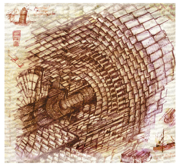
Material Budget: detail of modeling

Detail of Modeling





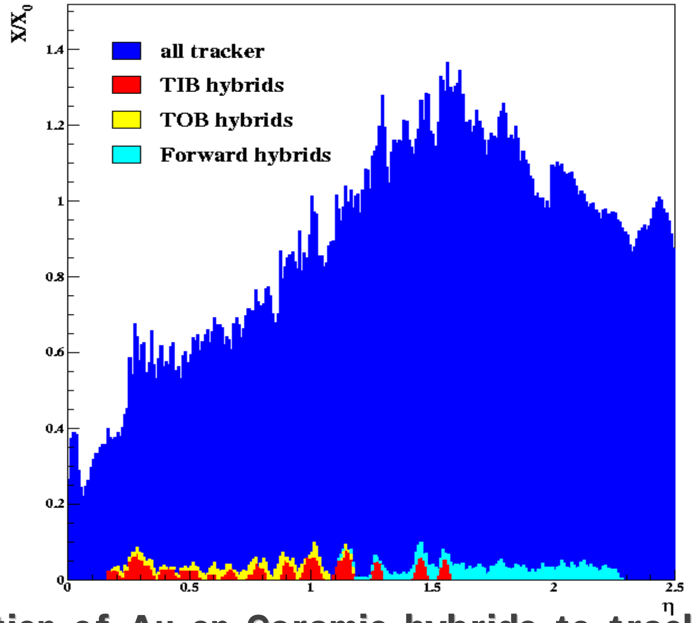
Care has been taken to model localized heavy material (e.g. Aluminium for cooling) separately



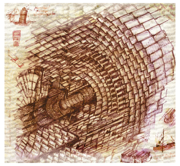
Efforts to reduce material budget (1)

- Light support structures: mainly CF space-frames and Honeycomb
- End cap wheels with holes ® 30 % reduction of material
- Cables inside the tracker have Aluminum as conductors
- Great care taken to minimize conductor and FR4 in local interconnect cards etc.
- For the smaller inner barrel, where the material hurts the most, the "mother cable" distributing power and signals will be Cu on Kapton

- Hybrids: For ease of production, we have abandoned the choice of Gold on Ceramic (was most dense module component) in favor of Copper on Kapton: This will reduce somewhat the Material Budget

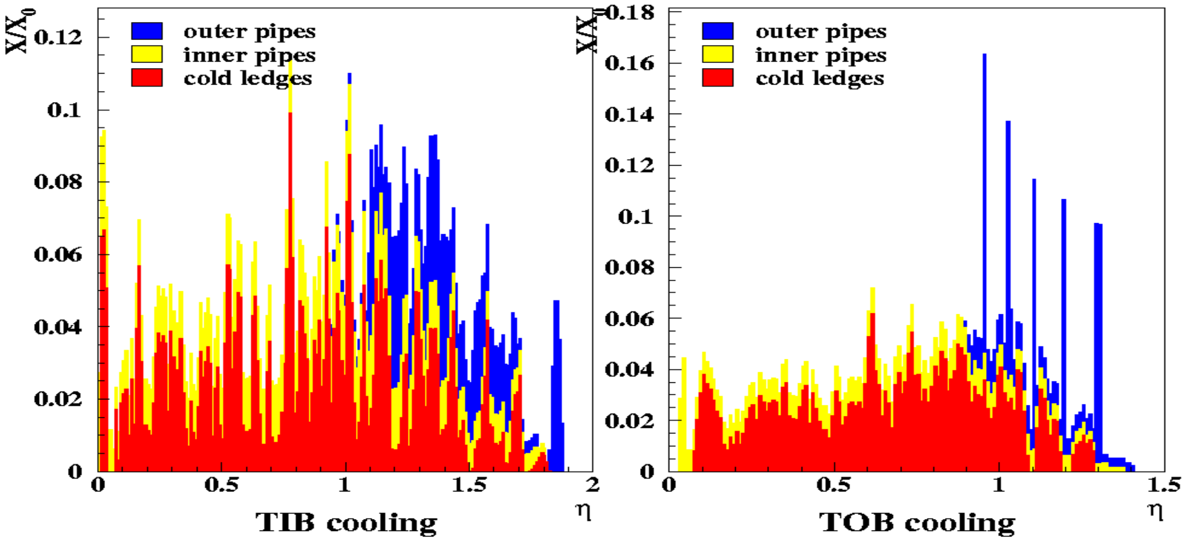


Contribution of Au on Ceramic hybrids to tracker X_0

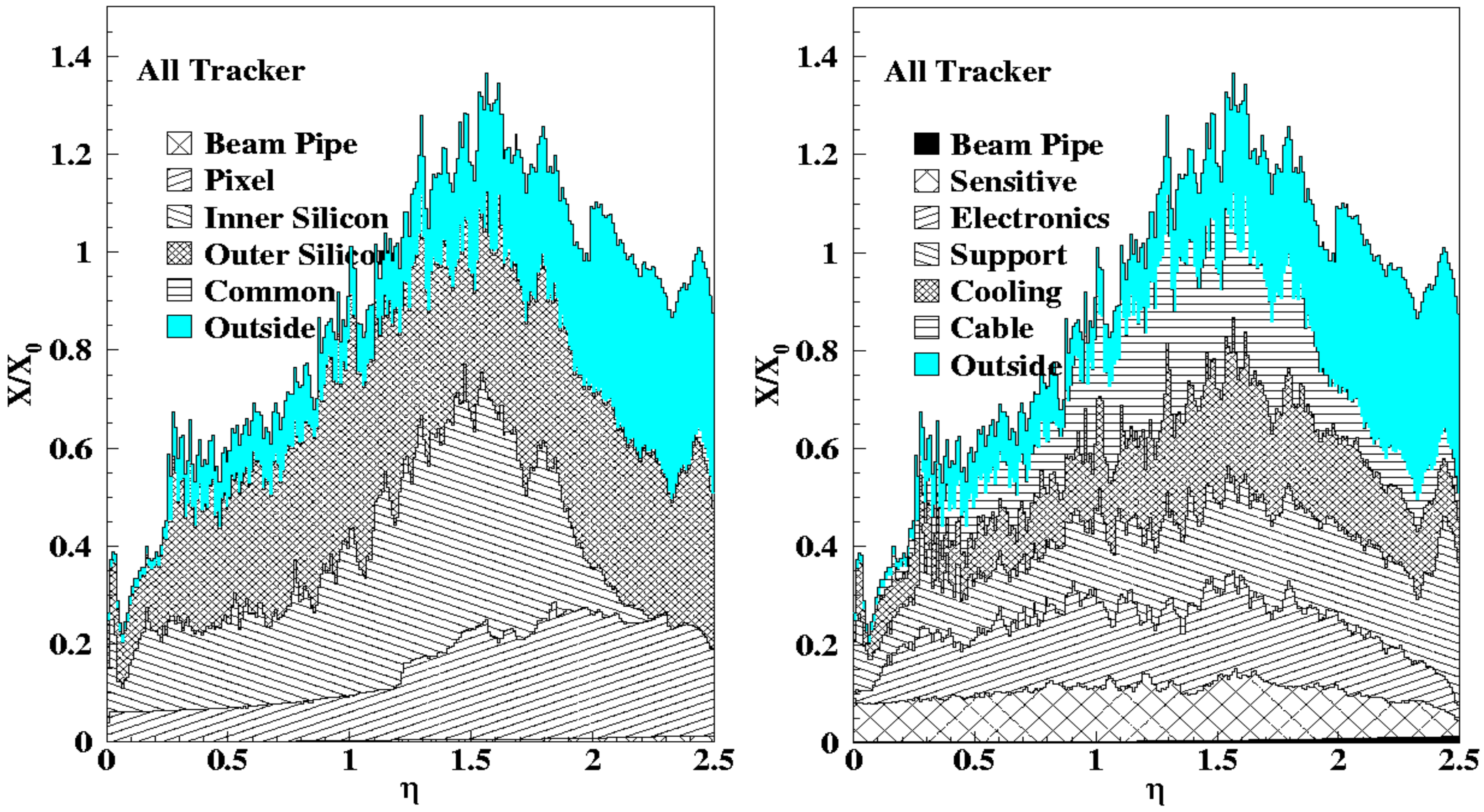


Efforts to reduce material budget (2)

- Cooling pipes of inner detector are Aluminum
- Radii and wall thickness have been minimized as much as possible,
- e.g. TOB arc pipes at end flanges: diameter 6 mm, skin 0.2 mm
  was 7.6 mm, 0.2 mm
- Cooling inserts (Al) are heavy, but cooling requirements are very stringent. Realistic cooling tests have been and are performed to see if further optimization is possible.

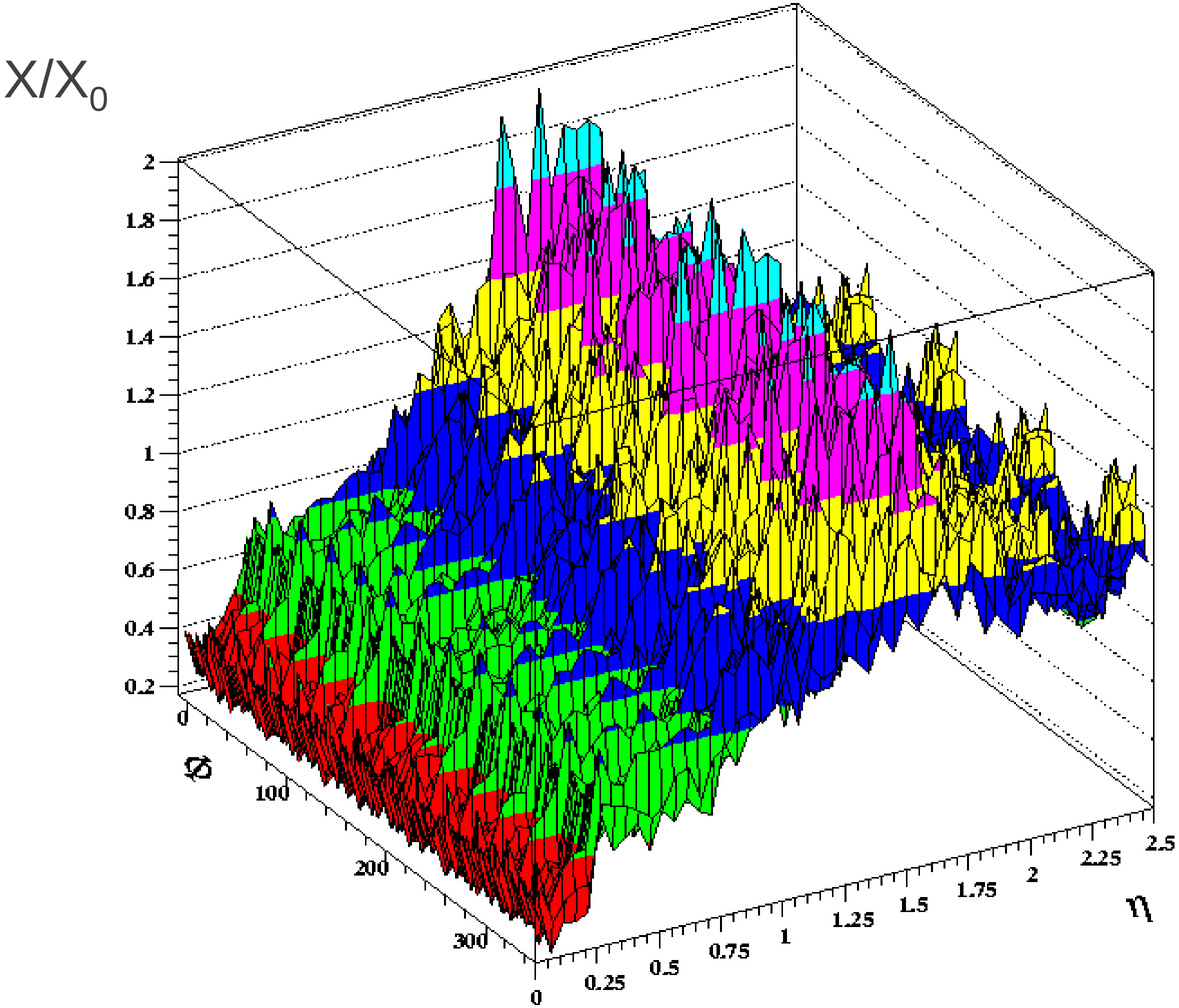


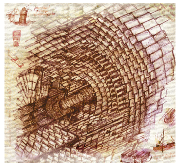
Radiation Length in the Tracker



As a result, nothing sticks out particularly, it just all adds up…

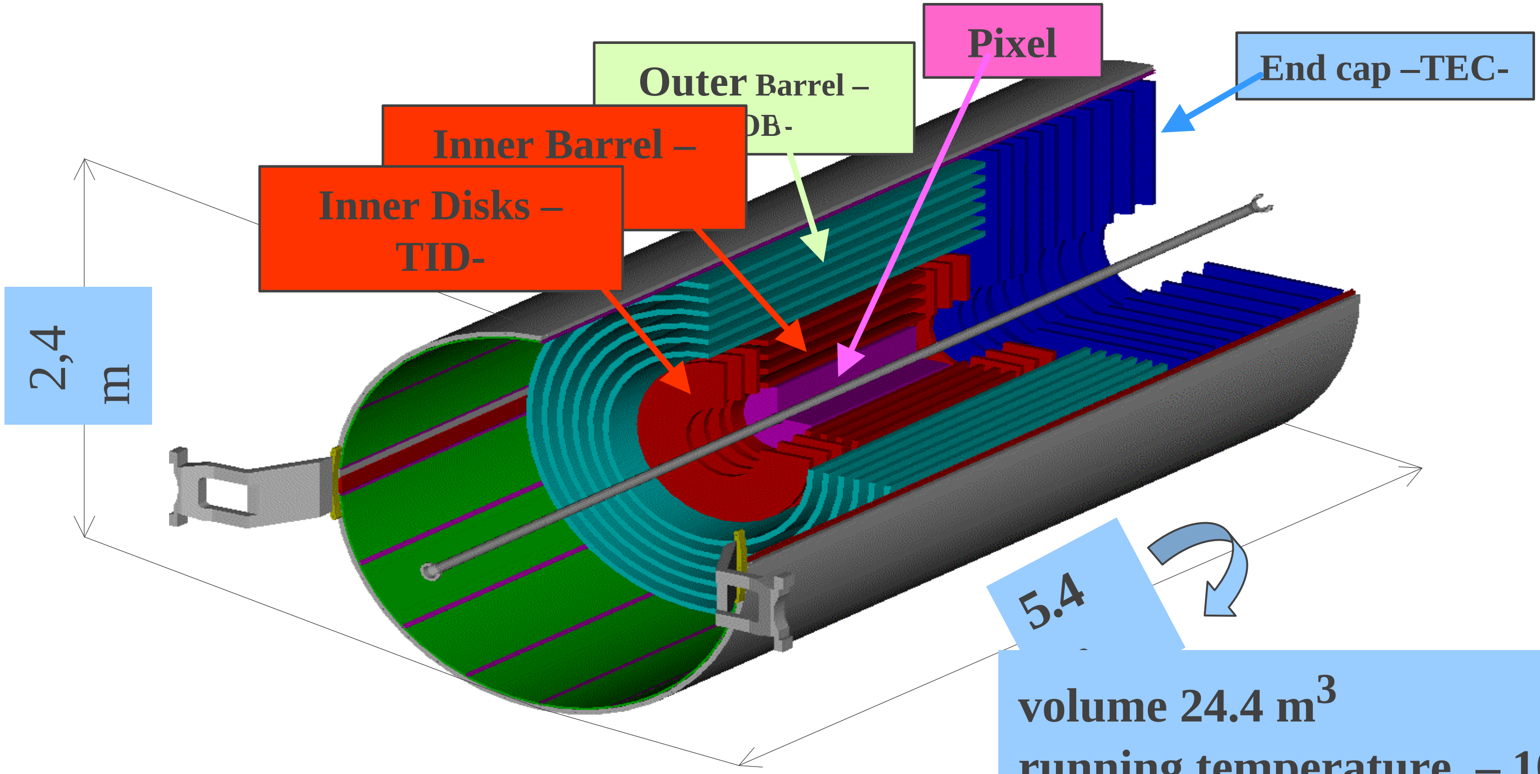
Radiation Length in the Tracker





The CMS Tracker

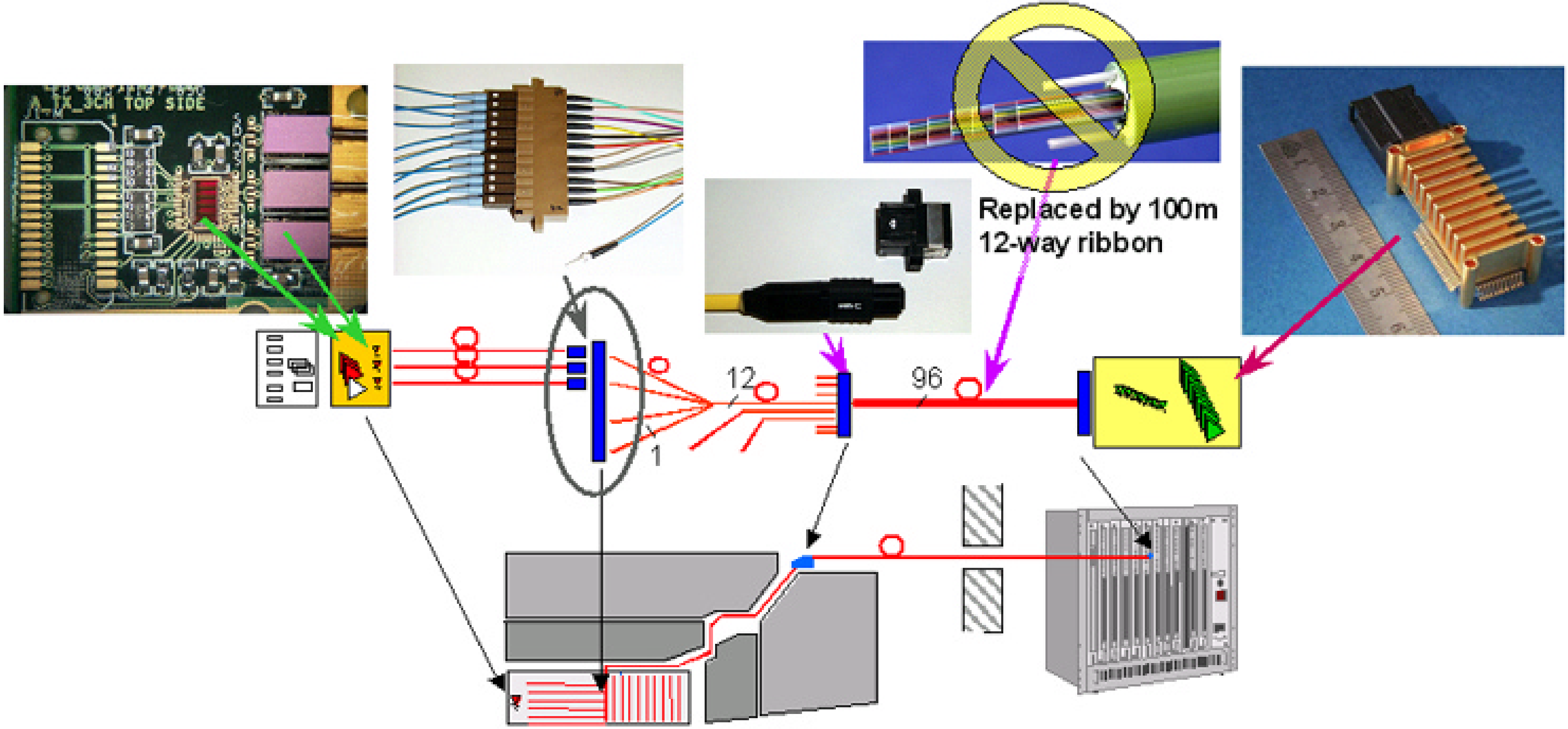
Large currents distributed to modules spread over a large volume
Conductor x-sections limited by material budget constraints
=> Potential for ground loops and common mode noise



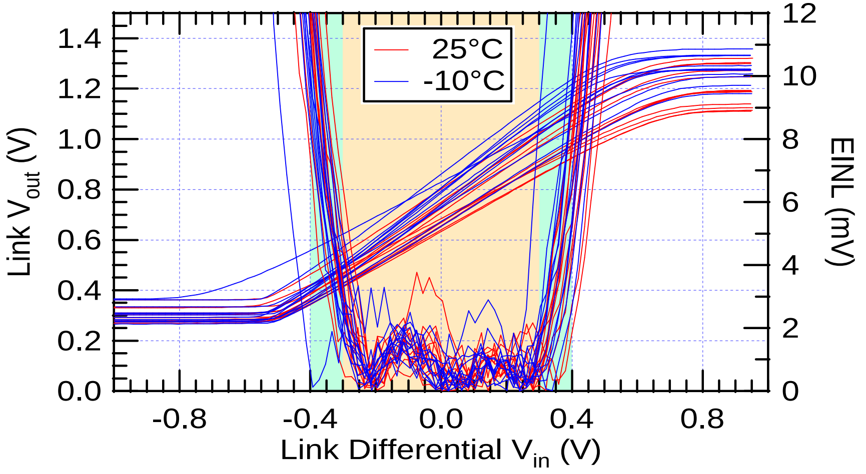
volume 24.4 m^3
running temperature – 10 ^{0}C
dry atmosphere for YEARS!

CMS Tracker Analogue Optical Link read-out

Full chain of all pre-final components in link, including 4 TEC-type Opto-hybrids Successfully demonstrated


Replaced by 100m 12-way ribbon

Full Link Test: Results



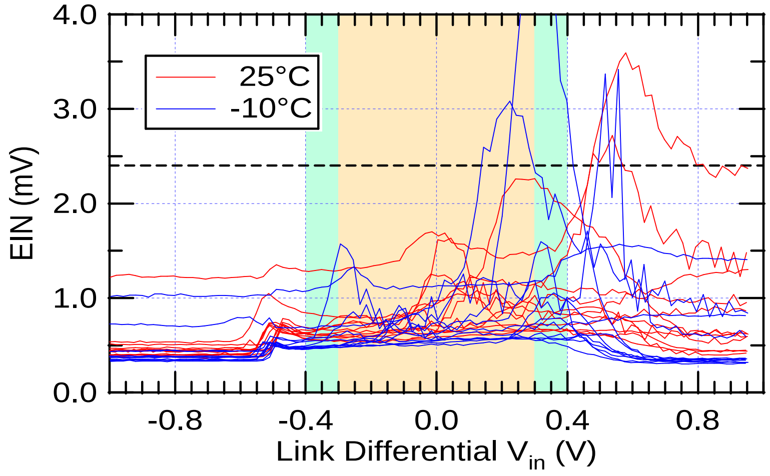
Very satisfactory results of pre-production components for both 25°C and -10°C at front-end.

Slight gain increase at lower temp.

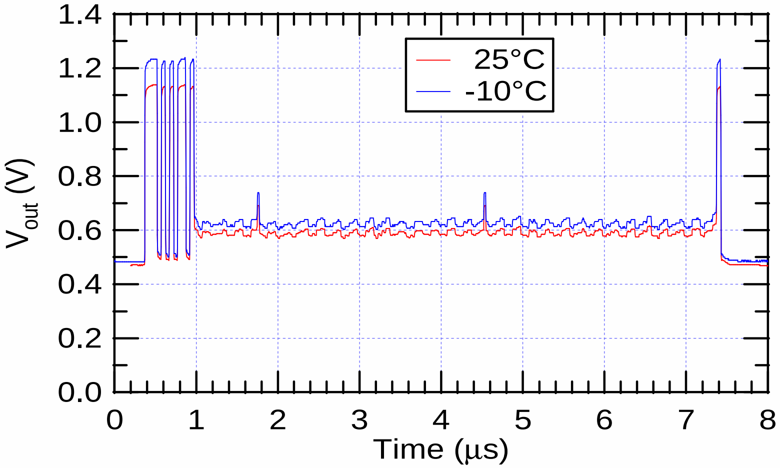
Noise and Linearity ok at low temp.

Ready for integration into Tracker system test.

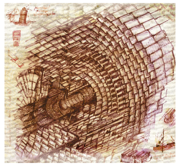
Now used for optical links throughout CMS



Note: 1MIP=100mV at input

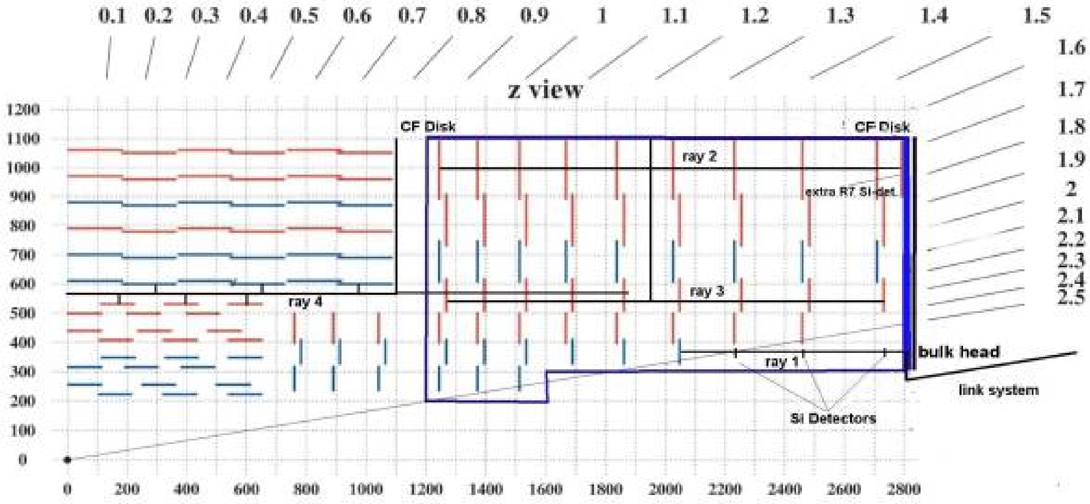


An APV25 analogue readout “frame”



Optical Alignment System

Goals of the optical alignment system



External alignment (rays 1):

£ **100 mm measurement** of TK **position w.r.t.** MS

£ **20 mrad measurement** of TK **orientation w.r.t.** gravity

(both for **joint** TK+MS **track fit**)

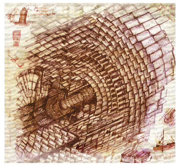
Internal alignment (rays 2,3,4):

£ **100 mm measurement** of Si-module **relative positions**

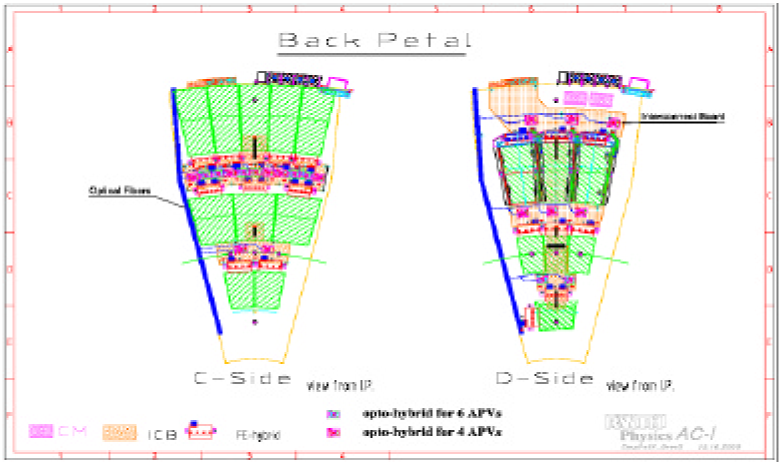
(for track **pattern recognition**)

£ **10 mm monitoring** of Si-module **positions stability**

(for track **parameter reconstruction**)



Internal Alignment System Implementation



Laser beams through End-Caps

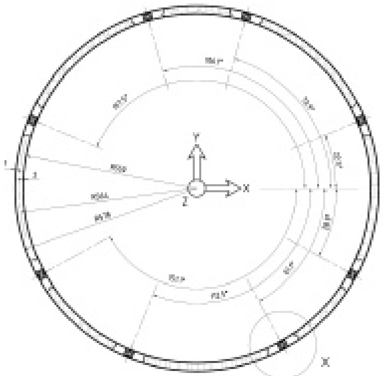
holes in **supports** (petals, wheels)

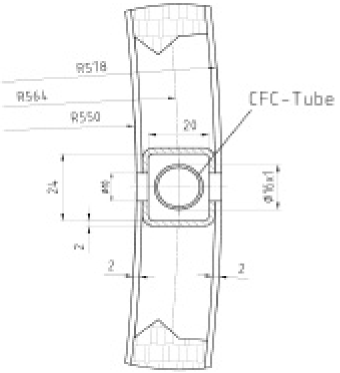
holes in **back-side metallisation** of Si-sensors (2500/24000)

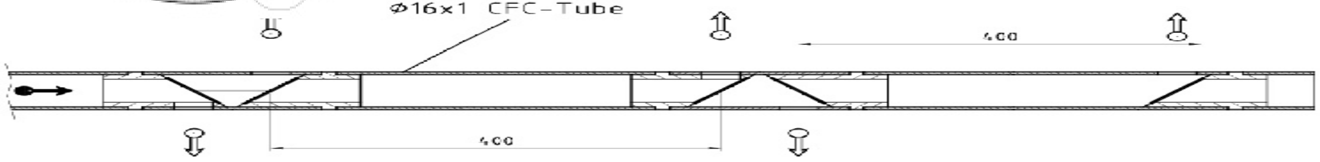
Laser beams through Barrels

structure gaps in **TOB inner shell**

alignment tubes inside these gaps fixed on **TOB support discs**

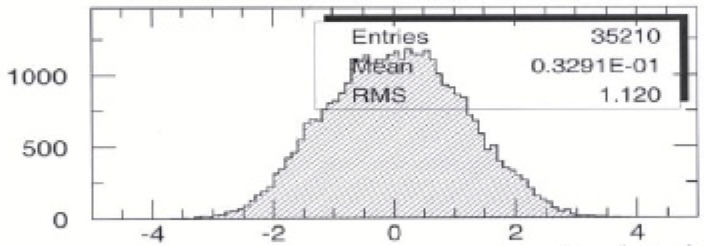




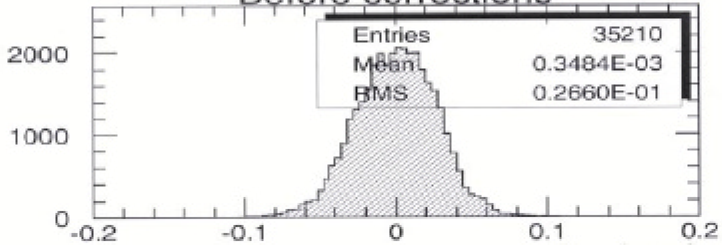


Internal Alignment System MC Simulation

8x2 axial monitors (rays 2 and 3)



Before corrections



After corrections

Track residuals in End-Caps

TEC: before applying alignment corrections

RMS = 1.1 mm

TEC: after applying alignment corrections

RMS = 27 μm

Track residuals in Barrels

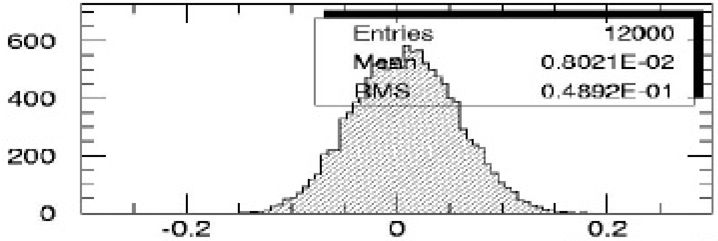
TOB: after applying alignment corrections

RMS = 49 μm

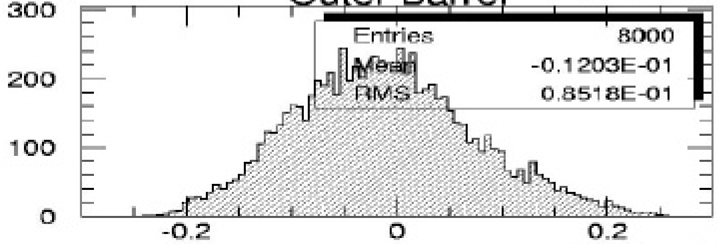
TIB: after applying alignment corrections

RMS = 85 μm

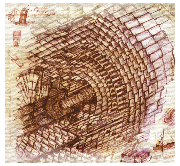
Track residuals after correction



Outer Barrel



Inner Barrel



Conclusions

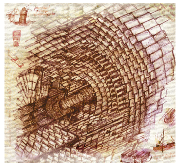
The technology used for Vertex detectors has evolved
from Strips (single or double-sided) with O(10^5) channels,
to Pixels, with O(10^7 - 10^8) channels

Strip technology, developed for use in Vertex detectors, has evolved
to be deployed in very large scale Tracking detectors

Currently, the CMS Silicon Tracker is the most extreme example of this trend

These steps forward have been made possible by combination of:

- Build up of expertise within the HEP community: LEP was a big part of this
- Extensive and successful R&D to understand sensor operation in high fluence environments
- Moving production of strip sensors to large volume 6” industrial lines
- The ability to substitute “standard” 0.25μm technology for custom Radiation Hard Front End read-out electronics



Conclusions

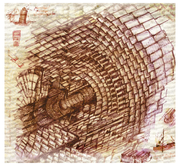
The LHC Pixel Vertex and Silicon Strip Trackers suffer from
significantly material within the fiducial acceptance region
Compared to previous Collider detector Trackers,
made unavoidable be
the high power dissipation and high current requirements of the present generation of FE Electronics and the related services,
as well as the need for large, rigid, mechanical supports, for
detector modules distributed within the tracking volume

The material within the tracking volume limits reconstruction efficiency and track parameter resolution

This is most evidently so for electrons, for which a specialized track reconstruction strategy is currently under development

The ECAL resolution for electrons, and converted g’s is also affected

Driven by these considerations, a great deal of engineering effort has gone into achieving the current level of material within the tracking volume



Conclusions

The CMS Silicon Tracker has robust performance in a difficult environment

The pixel vertex detector allows fast & efficient track seed generation,
As well as excellent 3-D secondary vertex identification

The fine granularity of the pixel and strip sensors, together with the analyzing power of the CMS 4T magnet allow for:

A good determination of track parameters with only a few hits (4~6)
Allows fast & clean pattern recognition, so that even with only 12~14
Measurement layers / track the design is sufficiently redundant
This capability will be used extensively at HLT level

A ~ 2% or better Pt resolution for 100GeV muons
Over about 1.7 units of rapidity