The CMS Tracker (and a Few Words about Tracking)

J-Term IV
August 3, 2009

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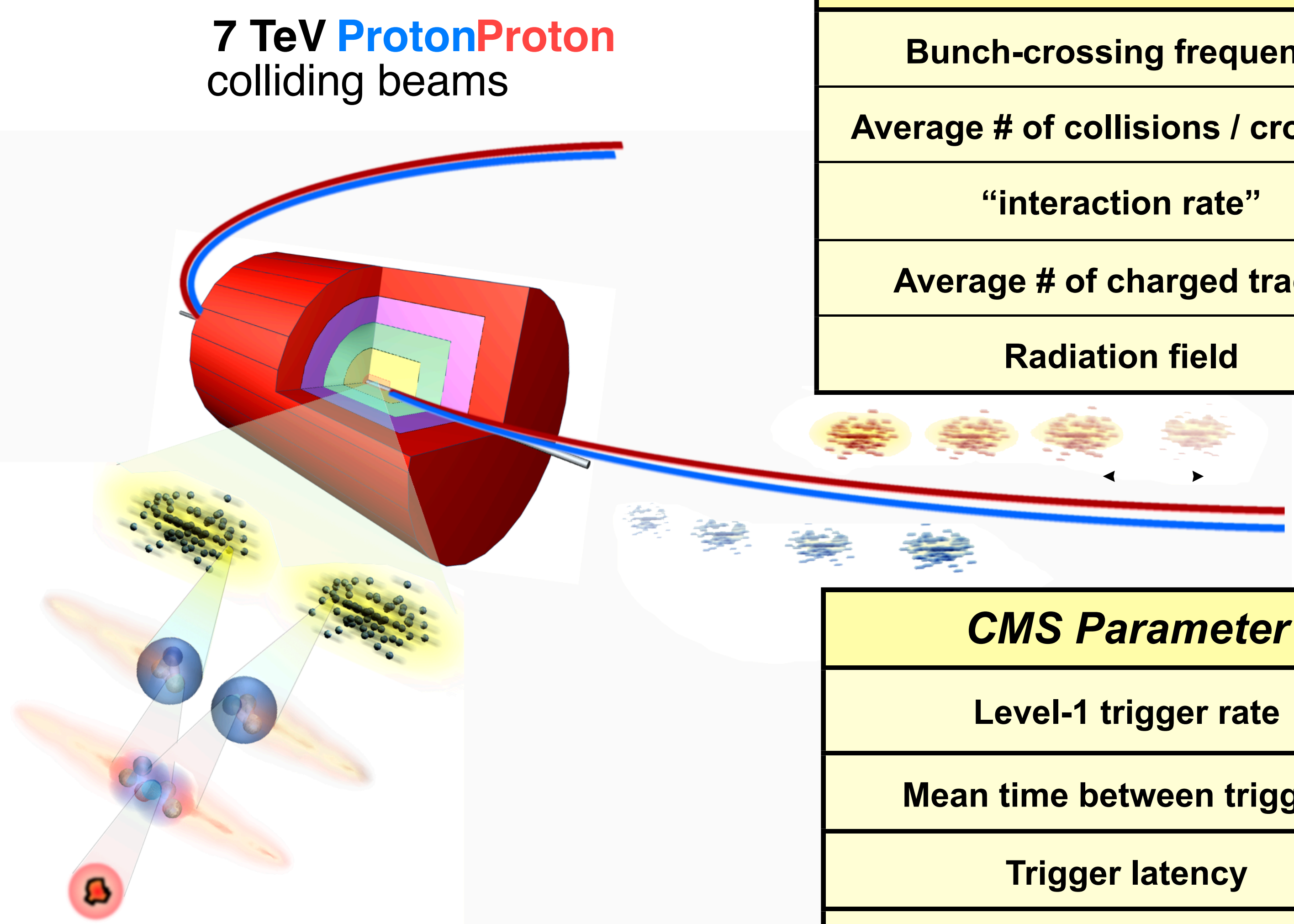
Outline

* *Tracker Design Philosophy and Goals*
* *Overview of CMS Tracker*
* *Description of Tracker Sub-Detectors*
* *Tracker Commissioning with Cosmic Rays*
* *Summary*

LHC Environment



Parameter	*Value*
Bunch-crossing frequency	40 MHz
Average # of collisions / crossing	20
“interaction rate”	~10^9
Average # of charged tracks	1000
Radiation field	severe

CMS Parameter	*Value*
Level-1 trigger rate	100 kHz
Mean time between triggers	10 μsec
Trigger latency	3.2 μsec
Solenoid field	4 T

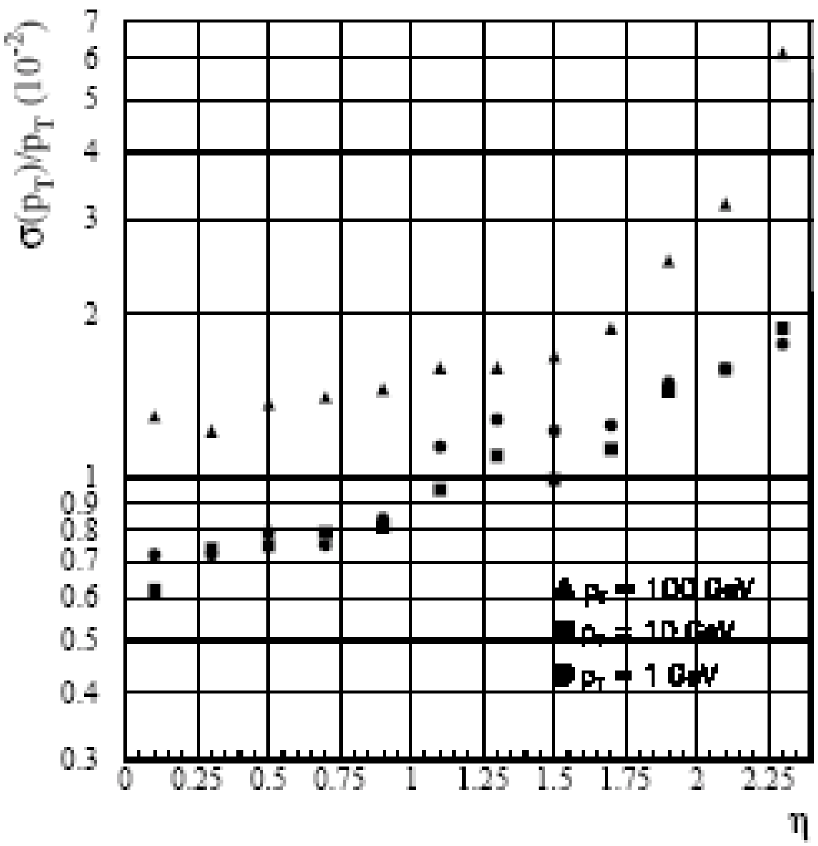
Tracker Design Philosophy

Higgs physics, SUSY, W´, Z´, etc. place constraints on the Tracker design

- Good momentum resolution for leptons from W, Z (W´, Z´) decays
- Minimizing material for electrons (bremsstrahlung, isolation cuts).
- Lepton isolation to suppress tt and Zbb bkgd for $H \rightarrow ZZ(^*) \rightarrow 4l^{\pm}$ modes
- Use isolation criteria to suppress γ-$\pi 0$(jet) from $H \rightarrow \gamma\gamma$ decays
  - Minimize material to limit γ conversions
- The ability to tag b-jets
  - Top quark decays
  - Signatures for new physics
- Identifying τ leptons through isolation and displaced vertices.
- Rare states will require very high luminosity
  - 10^{34} $cm^{-2}s^{-1}$ design L $\Rightarrow$ 20-30 superimposed minimum bias events.
  - 25 ns time resolution
  - Resistance to radiation damage

Design Goals

From Tracker TDR

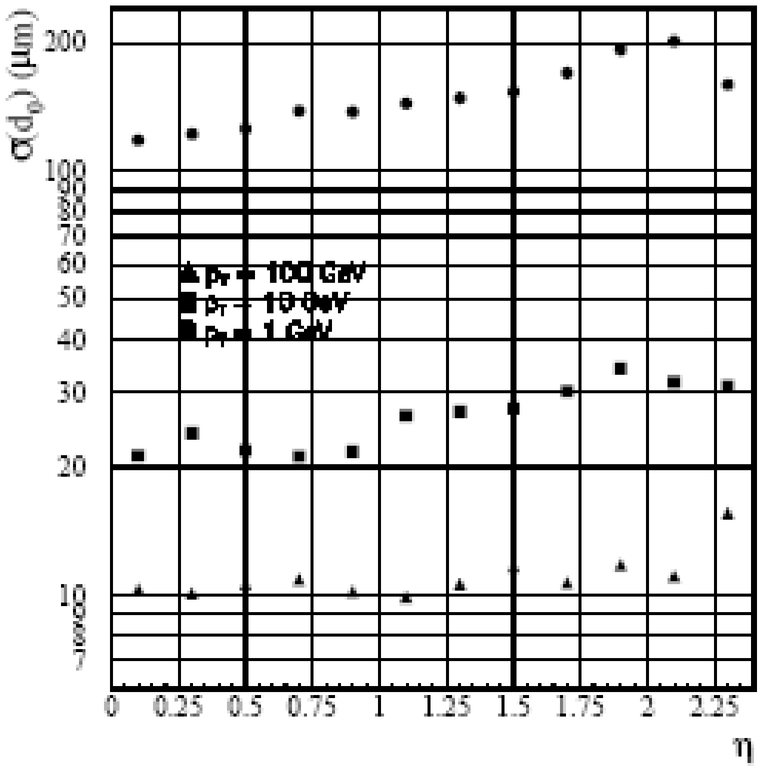


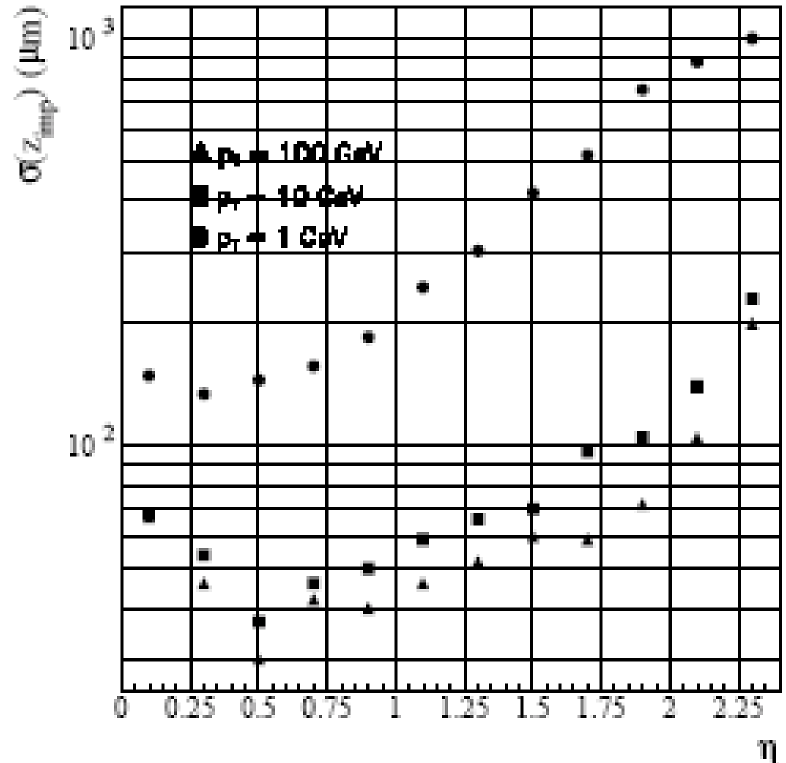
Tracker (only) transverse momentum resolution for muons.

- *High p_T isolated tracks*
  - $\delta p_T/p_T \approx (15pT \oplus 0.5)\%$ p_T in TeV for $|\eta|\leq 1.6$
  - Gradually degrading to $\delta p_T/p_T \approx (60p_T \oplus 0.5)\%$ for $\eta=2.5$
- *Well suited to reconstruction of narrow states decaying into charged particles.*
- *In combination with the outer muon system*
  - $\delta p_T/p_T \approx (4.5\sqrt{p_T})\%$ (p_T in TeV and for p_T>.1 TeV and η extending up to 2 units)
  - Combined system momentum resolution better than in stand alone Tracker.

Design Philosophy

From Tracker TDR - Assumes perfect alignment

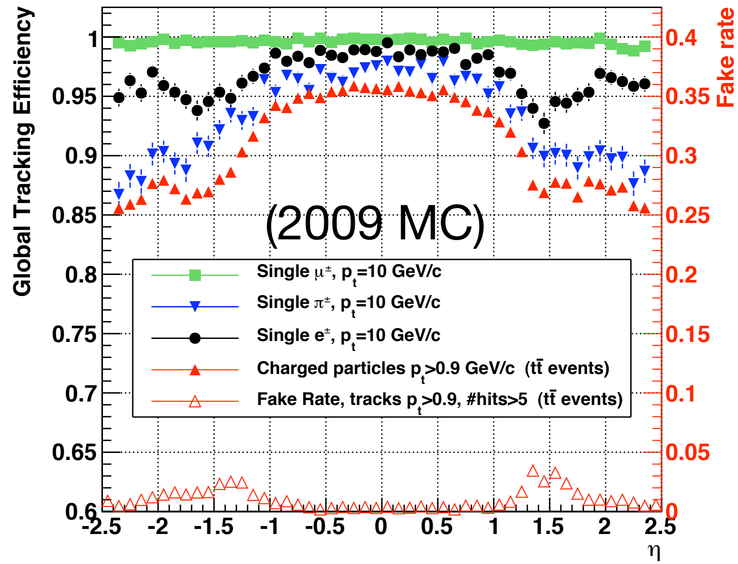




- *Transverse impact parameter resolution (left)*
  - Better than 35 μm over the full $|\eta| \leq 2.5$ range (for $p_T > 10$ GeV)
- *Longitudinal impact parameter resolution (right)*
  - Better than 75 μm up to $|\eta| = 1.6$

Other Design Goals

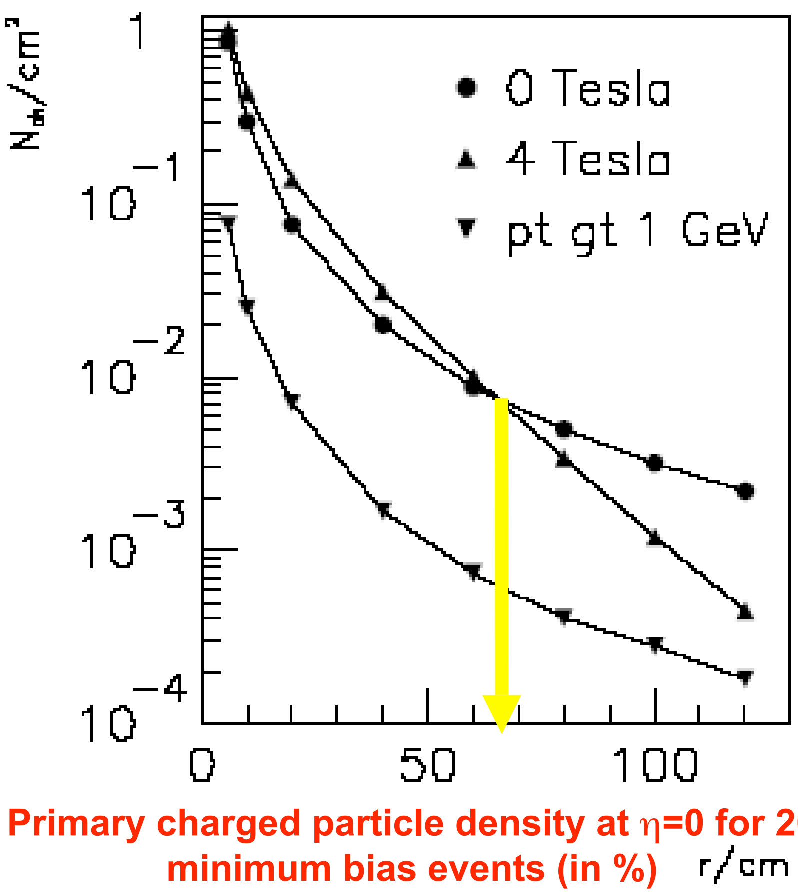
* *In jet environments charged hadrons with p_T > 10 GeV are reconstructed with efficiency~95%*
  - 85% for 1 GeV charged tracks
  - Better than 98% for muons over full η range (down to p_T ~1 GeV)
  - Above 90% for high energy electrons



* *Tagging efficiencies of 50% or better for central rapidity b jets between 50 GeV and 200 GeV E_T*
  - Mis-tagging probability 1-2%
  - 40% in forward rapidity region (for same mis-tagging rate)
* *Low rate of photon conversions in Tracker in H→γγ channel*
  - Somewhat degraded since original TDR

CMS Solenoid

Figure taken from TDR.



Primary charged particle density at η=0 for 20 minimum bias events (in %)

4 T magnetic field provided by super-conducting solenoidal magnet.

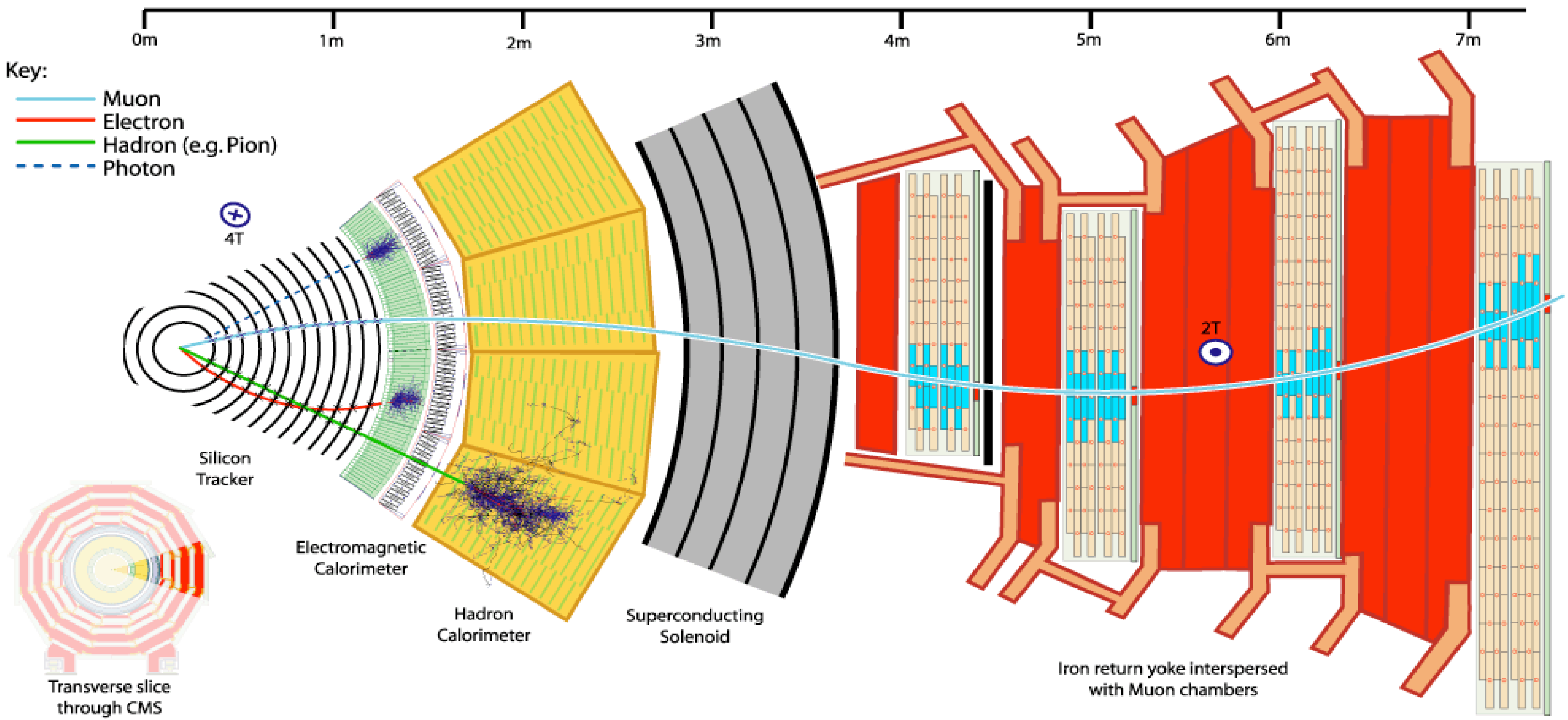
- Full analyzing power up to |η|≤1.6
- A charged particle with p_T = 1TeV will have a sagitta of 195 μm.

The high magnetic field affects event topologies (see plot)

- Low momentum tracks confined to small radius helical trajectories.
- Below r=65cm the charged track density falls more slowly with the field on; above 65cm the density falls more rapidly.

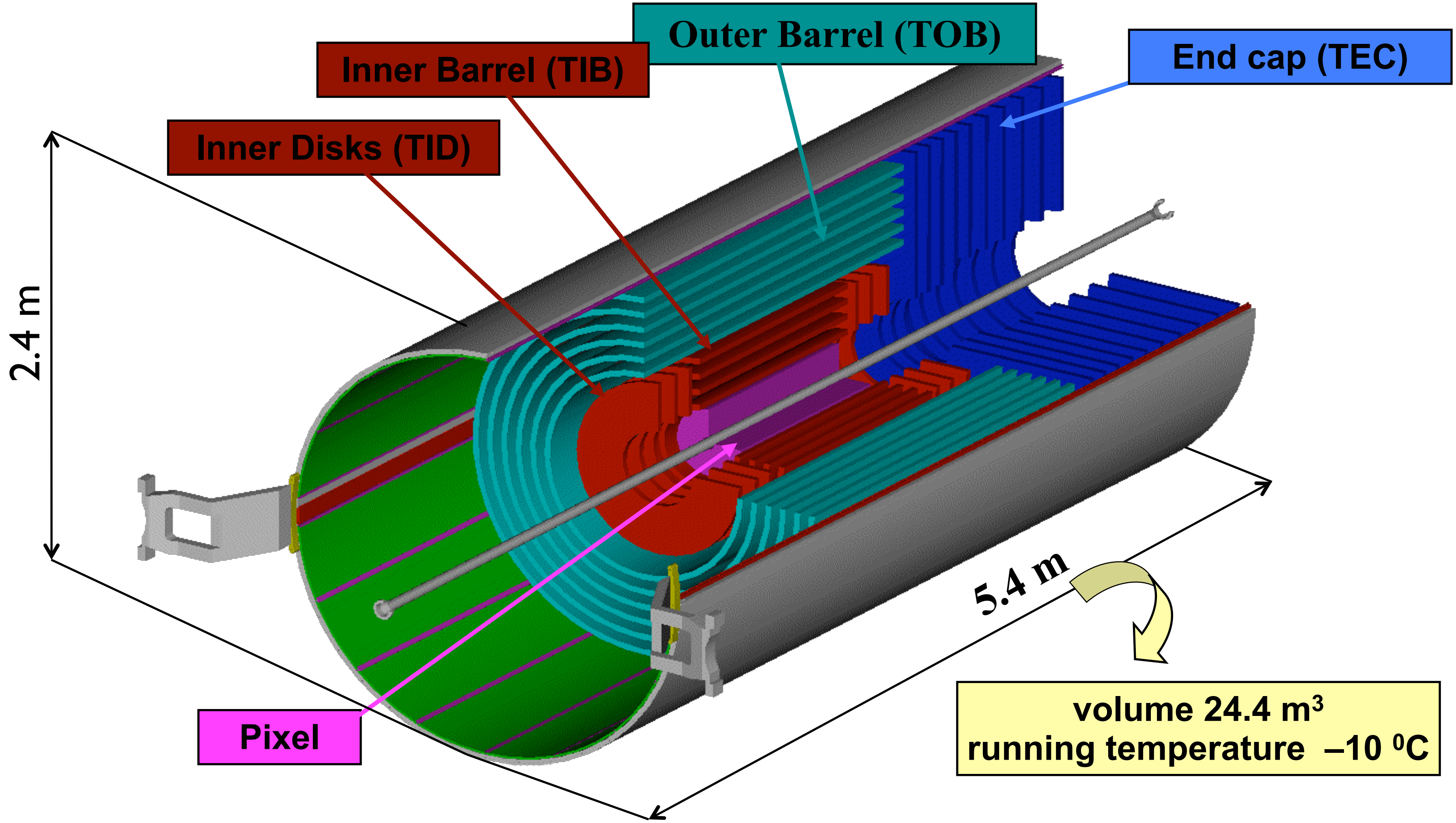
0 T ⇔ $1/r^2$

CMS Detector Slice



Muon chambers could be considered to be part of the Tracking System (for muons). For high p_T muons the combined system has a better momentum resolution. However, they are not the topic of this talk.

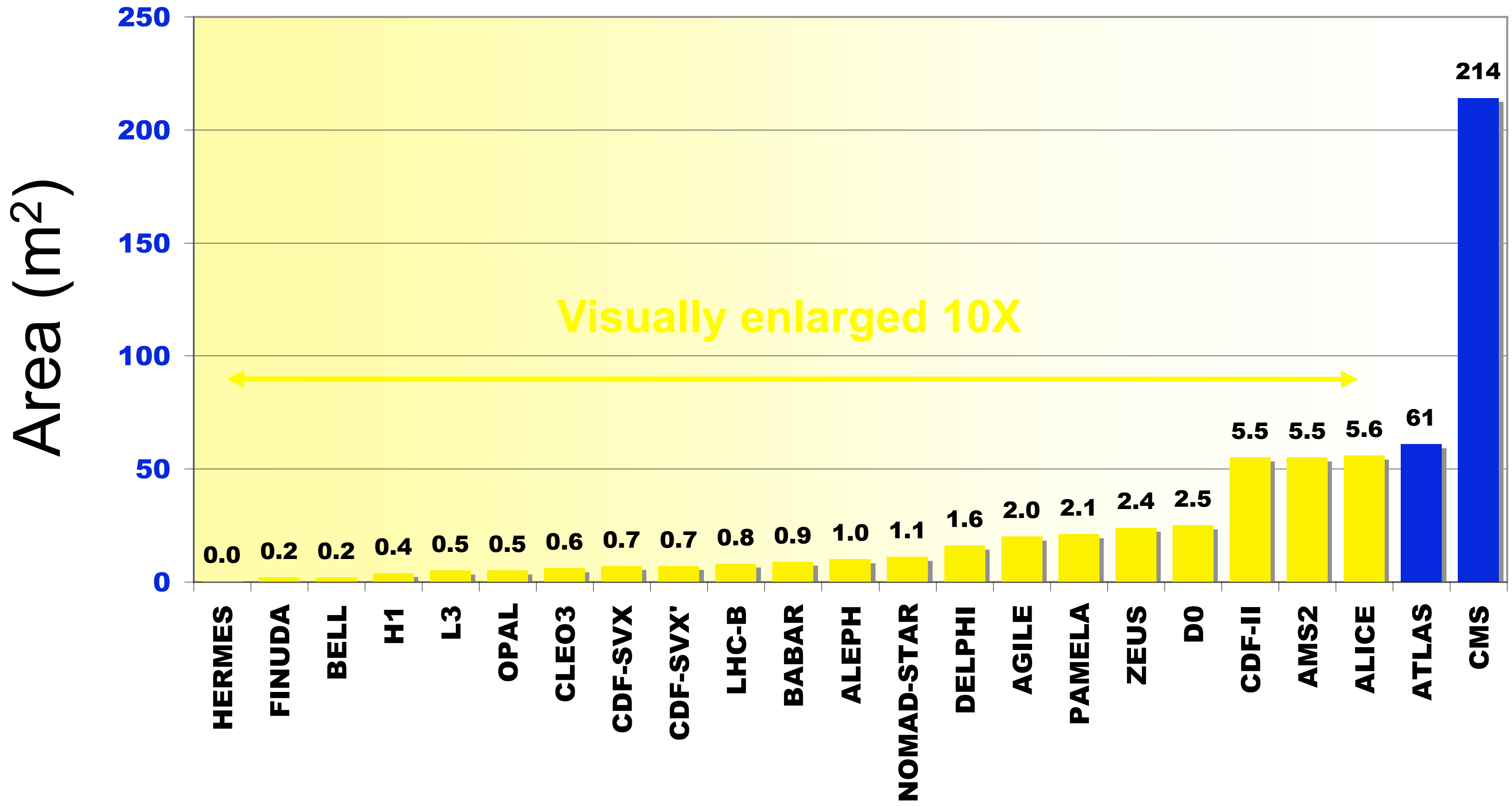
Tracking Volume



volume 24.4 m^3
running temperature –10 ^{0}C

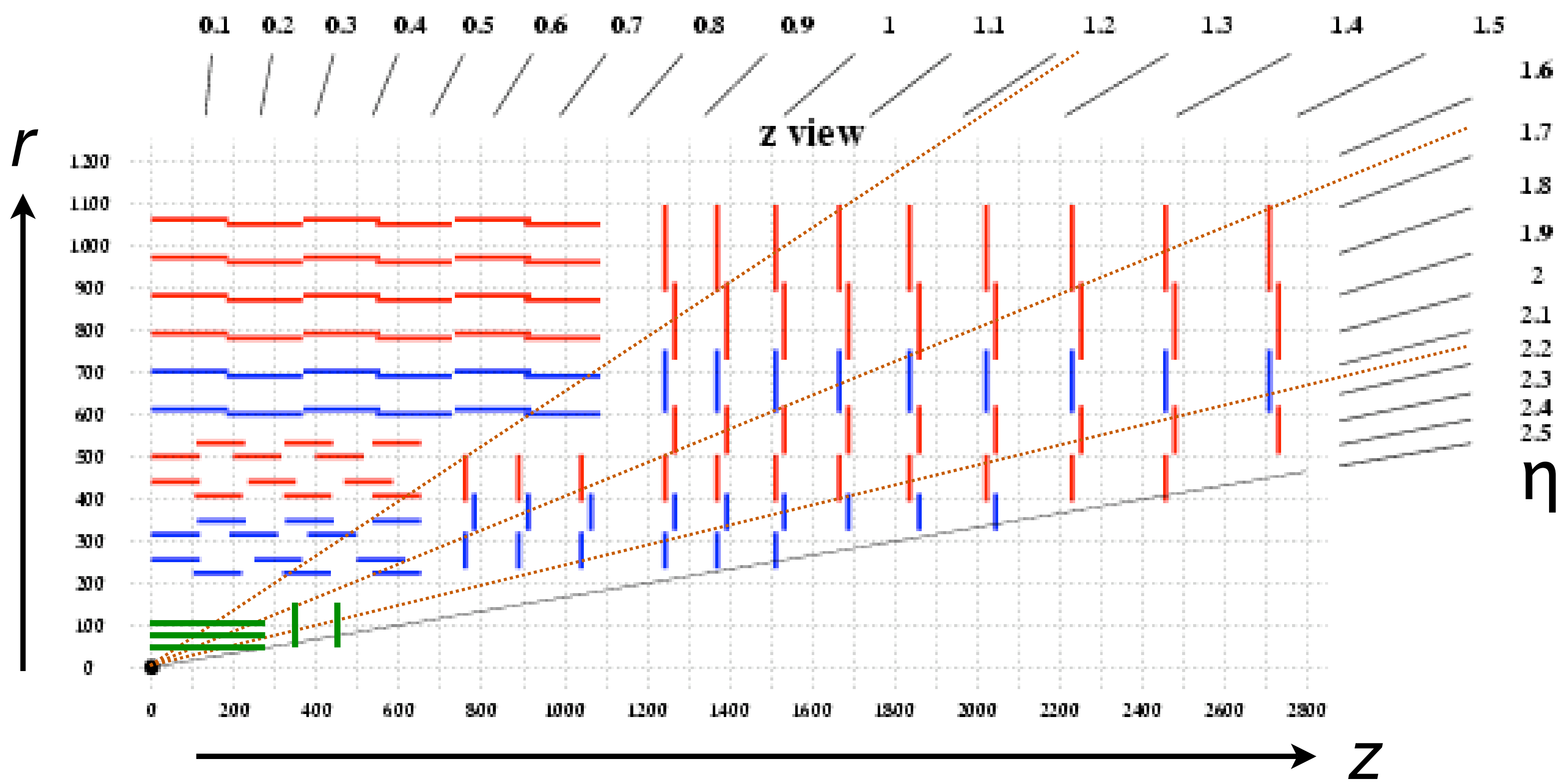
11.4 million silicon strips
65.9 million pixels in final configuration

Comparison with other Si Systems



Original slide and data provide by Marcel Demarteau (FNAL)

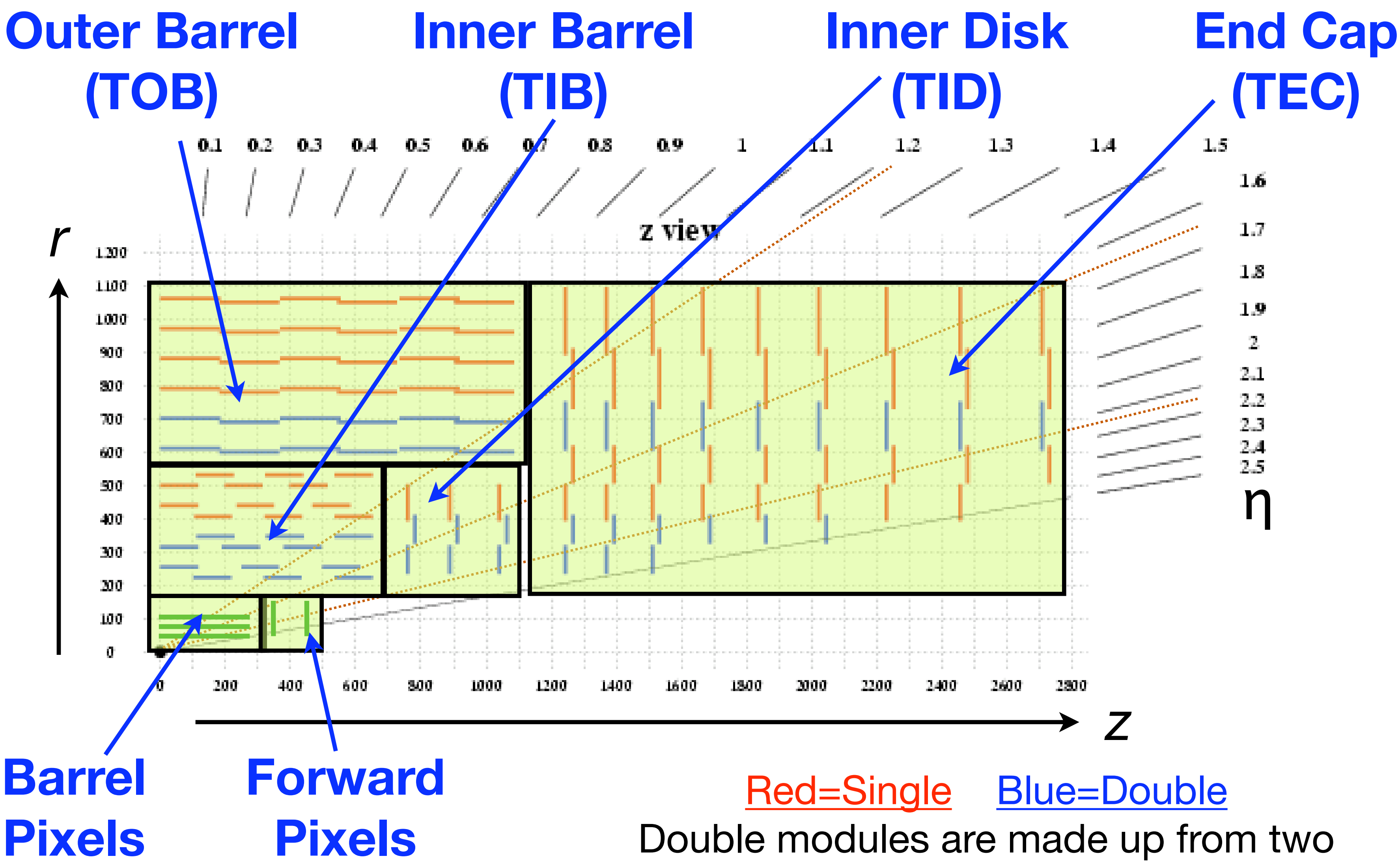
Summary of Tracking System



Red=Single   Blue=Double

Double modules are made up from two single sided modules glued back-to-back

Summary of Tracking System

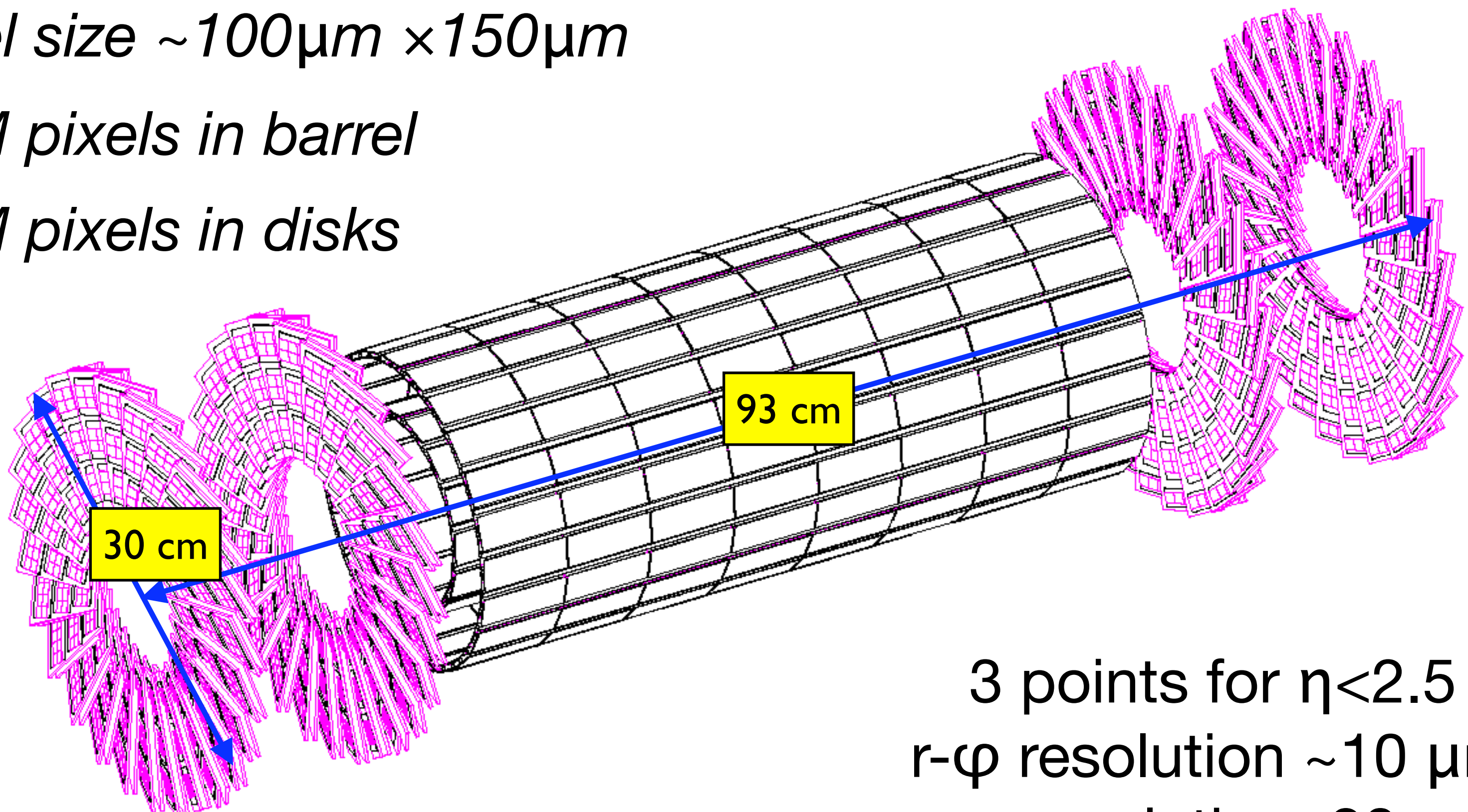


Red=Single Blue=Double

Double modules are made up from two single sided modules glued back-to-back

Pixel Tracker

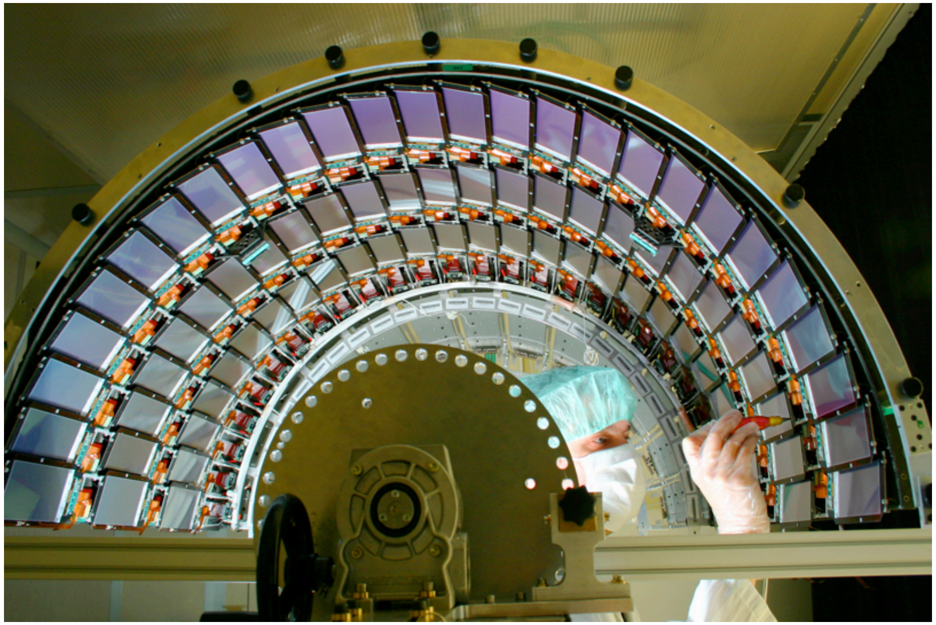
- *Barrel layers at r=4, 7, 11 cm*
- *Two disks at each end, z=34, 46 cm*
- *Pixel size ~100μm ×150μm*
- *48M pixels in barrel*
- *18M pixels in disks*



3 points for η<2.5
r-φ resolution ~10 μm
r-z resolution~20μm

TIB/TOB (Inner Barrel / Outer Barrel)

- *Tracker Inner Barrel (TIB) has four layers*
  - Spans roughly 25-52 cm in radius, |z|<65 cm
  - 80-120 μm pitch
  - Layers 1, 2 contain double modules for stereo measurements

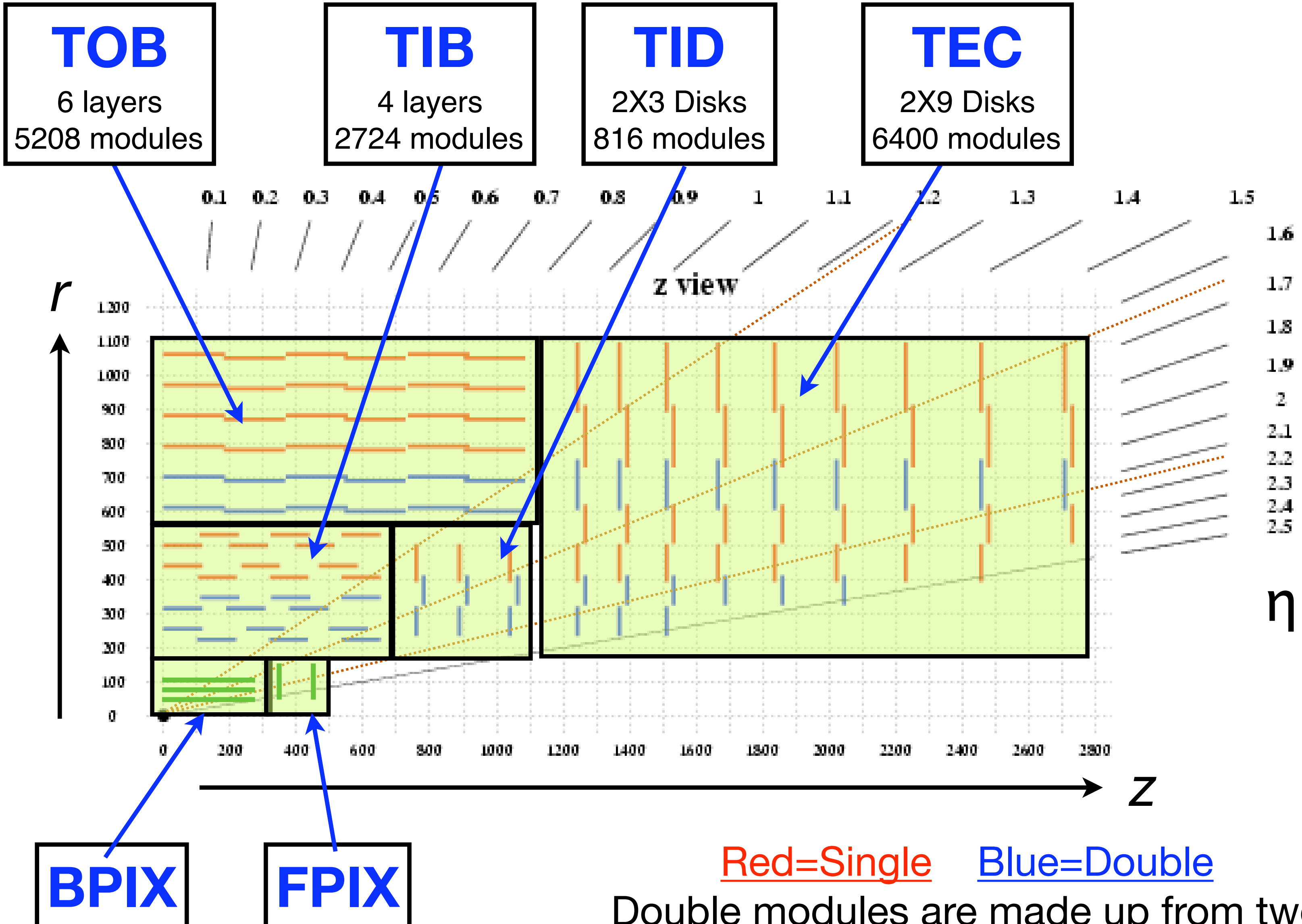


- *Tracker Outer barrel (TOB) has six layers*
  - Spans roughly 60-110 cm in radius, |z|<110 cm
  - 122-183 μm pitch
  - Layers 1, 2 contain double modules for stereo measurements
- *"Double" modules actually are made of two back-to-back axial +stereo modules (referred to as "Double" or "glued") with stereo modules rotated by 100 mrad*

TID/TEC (Inner Disk / End Cap)

- *Modules in TID, TEC have trapezoidal geometry*
- *TID has 3 disks at each end in z*
  - Each disk has 3 rings
  - Spans roughly 25-50 cm in radius, 75-110 cm in |z|
  - Rings 1, 2 contain double modules
- *TEC has 9 disks at each end in z, with 7 rings in each disk*
  - Rings 1-3 identical with TID rings
  - Rings 1, 2, and 5 double-sided
  - Number of rings per disk decreases with increasing |z|
  - Innermost disks span 25-110 cm in radius, 120-275 cm in |z|

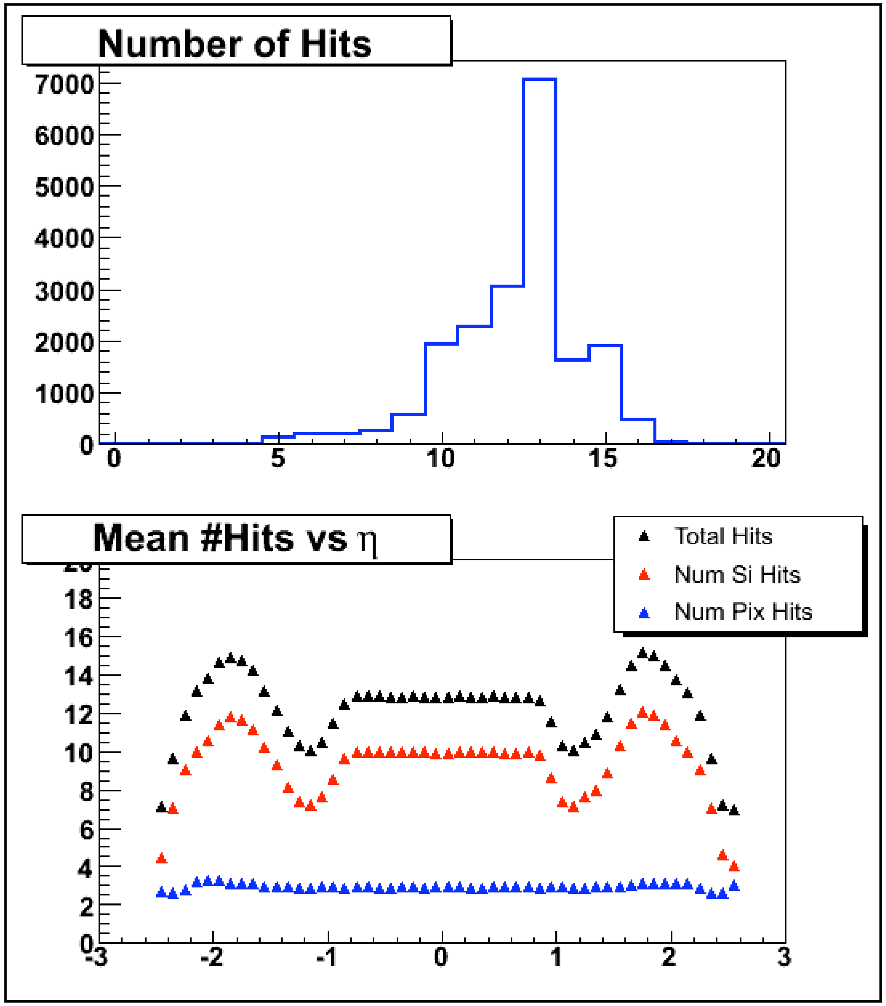
Summary of Tracking System



Red=Single   Blue=Double

Double modules are made up from two single sided modules glued back-to-back

Number of Points



Few hits on a track, but they are very precise

Sub-Detector	*Channels*
Pixels	66×10^6
Silicon microstrips	11.4×10^6
ECAL crystals	0.076×10^6
Preshower strips	0.137×10^6
HCAL	0.01×10^6
Muon chambers	0.576×10^6
TOTAL	78.2×10^6

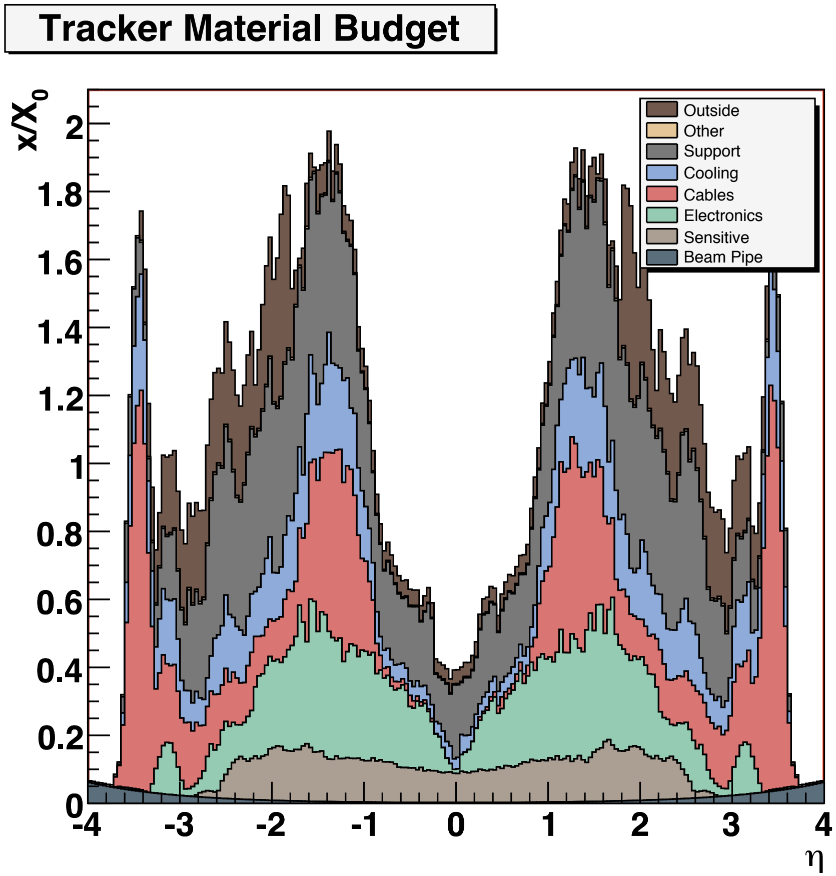
Tracker Occupancy: 1-3%

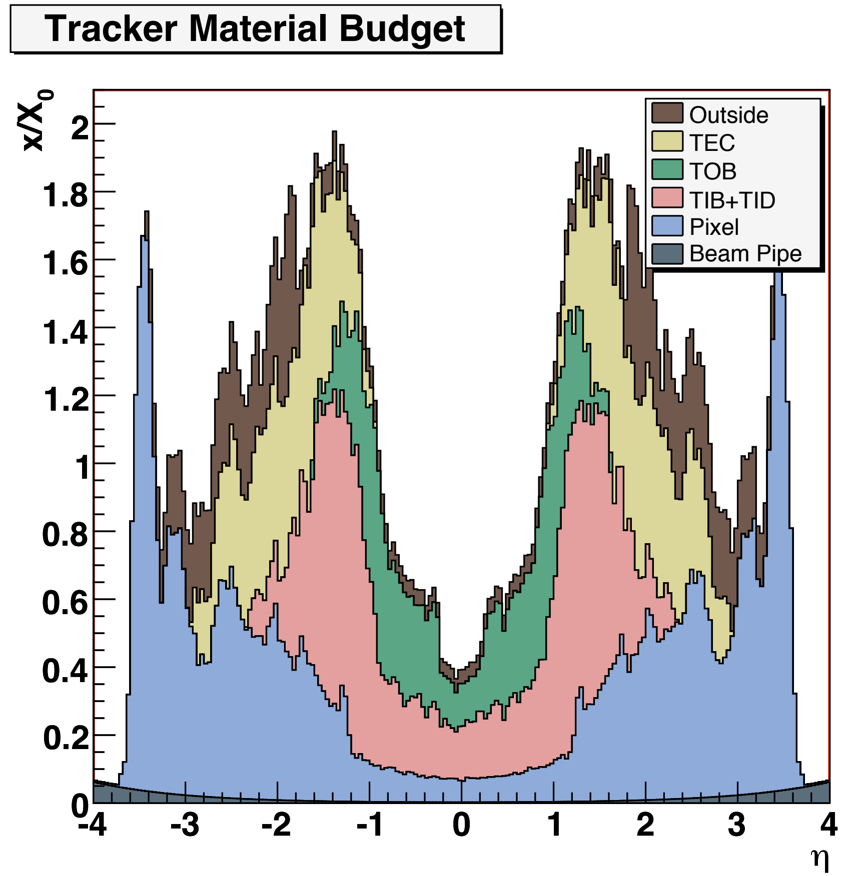
Comparison of ATLAS/CMS

	ATLAS	CMS
Tracker Radius	110 cm	115 cm
Tracker Length	7 m	5.4 m
Solenoid Field	2T	4T
Pixels		
# Barrel Layers	3	3
Barrel Radii	5.05, 9.85, 12.25	4.4, 7.5, 10.2
#Fwd Disks	3	2(3)
Disk Positions	49.5, 56.0, 65.0 cm	35.5, 48.5, 61.5 cm
Microstrips		
#Barrel Layers	4	10
# Disk Layers	9	9
Radial Span	25-50 cm	20-110 cm
Measurement points in central region	7 precision + 36 TRT	13 precision

ATLAS tracker includes straw layers

Material Budget



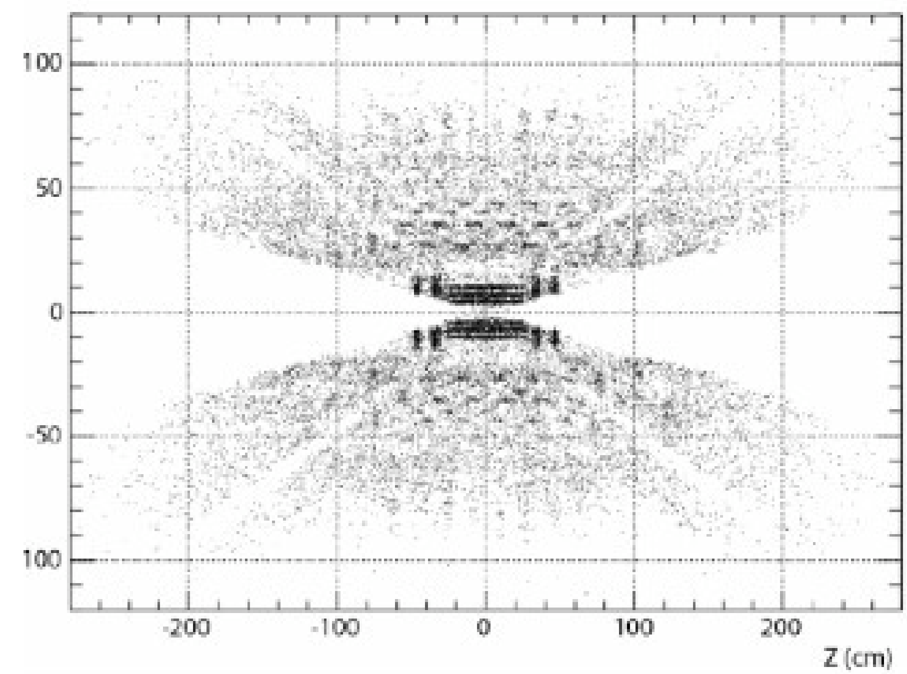


There is a significant amount of material in the Tracker

- More pronounced at higher η
- Major elements include the sensitive elements, electronics, support mechanics, cables, and cooling

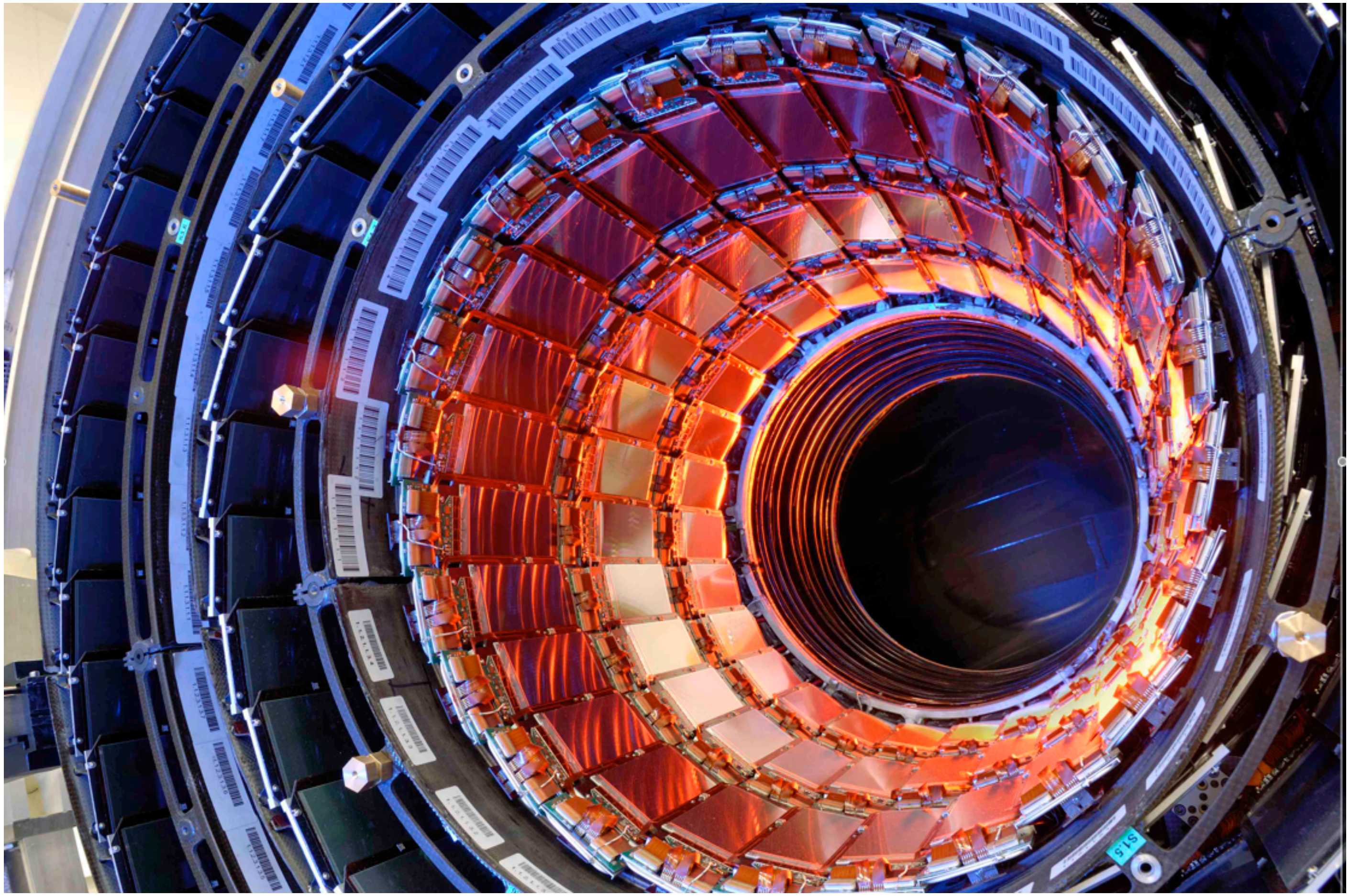
Photon Conversions

* *Simulation of conversions in Tracking System material*
  - Partly inspired by similar CDF study
  - Physics interest was H→γγ mode
  - Pixel elements are clearly visible and to some extent TIB
  - TOB blurred due to inefficiencies in reconstructing short tracks without any DS detectors (Improved some in recent work)
  - Can be used to study and verify material budget



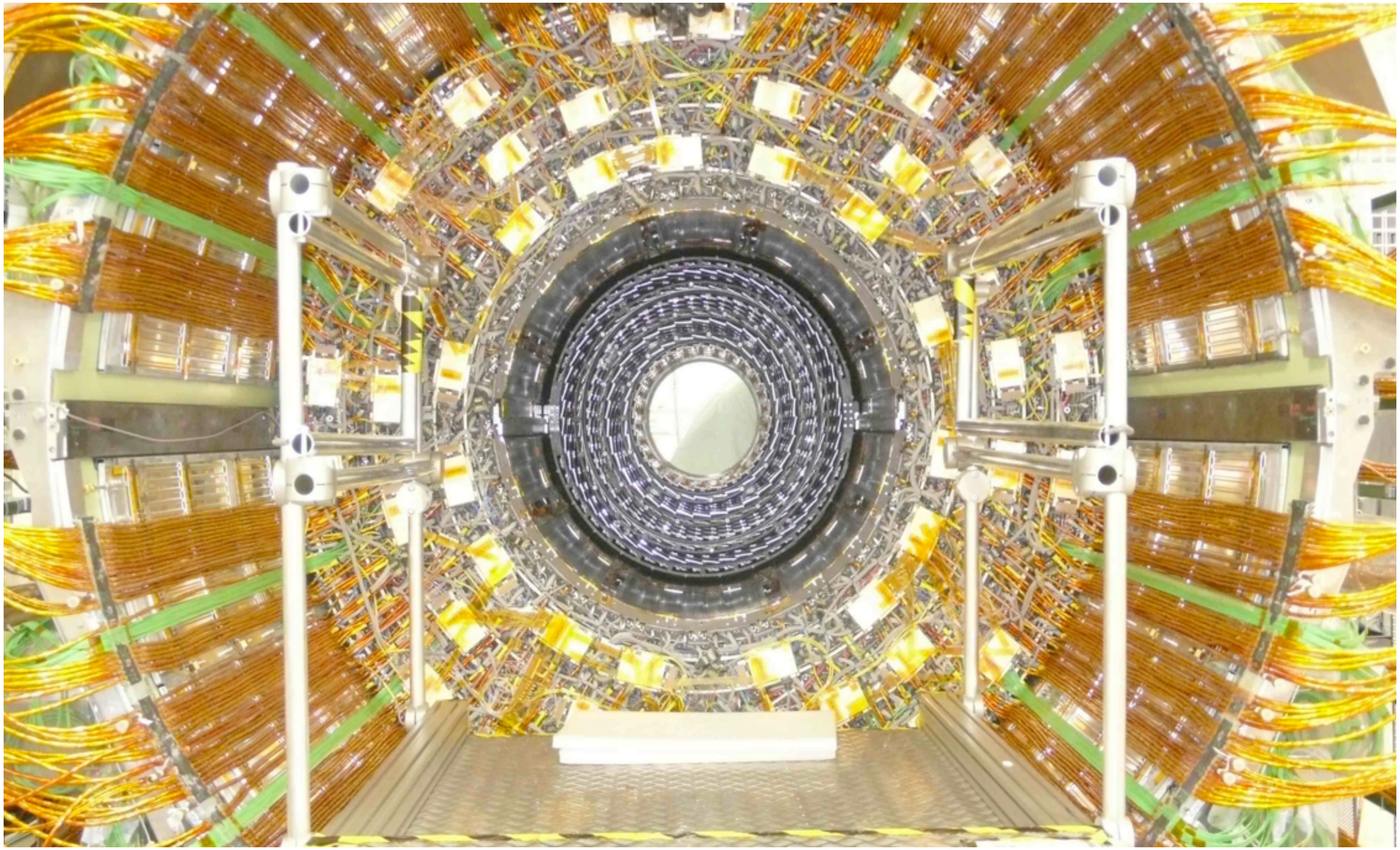
Reconstructed γ conversions
Study by Nancy Marinelli

Assembly of the Tracker at TIF



TIB / TID + at the TIF

Assembly of the Tracker at TIF

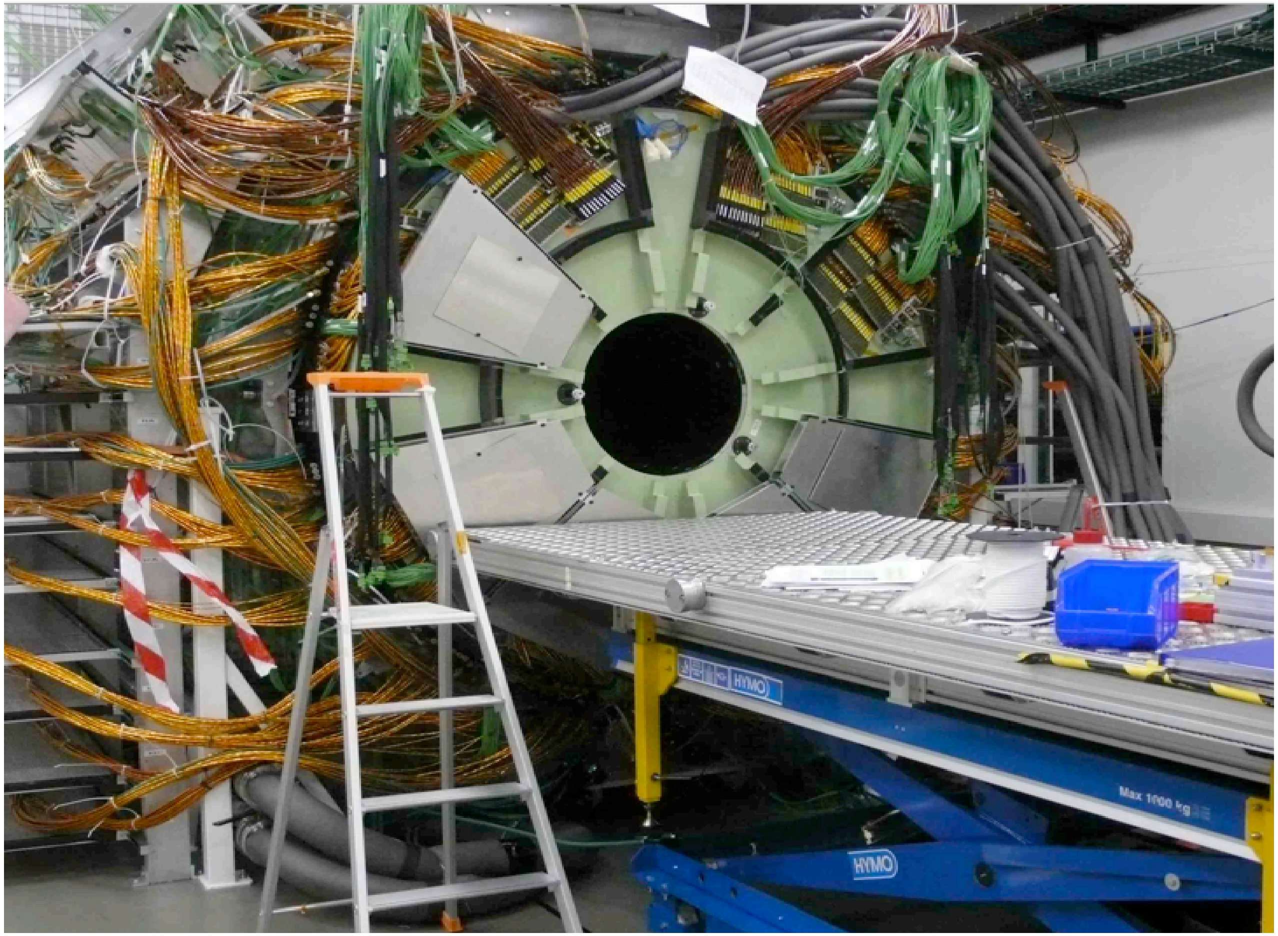


TIB + Integrated into TOB + late December 2006

Assembly of the Tracker at TIF

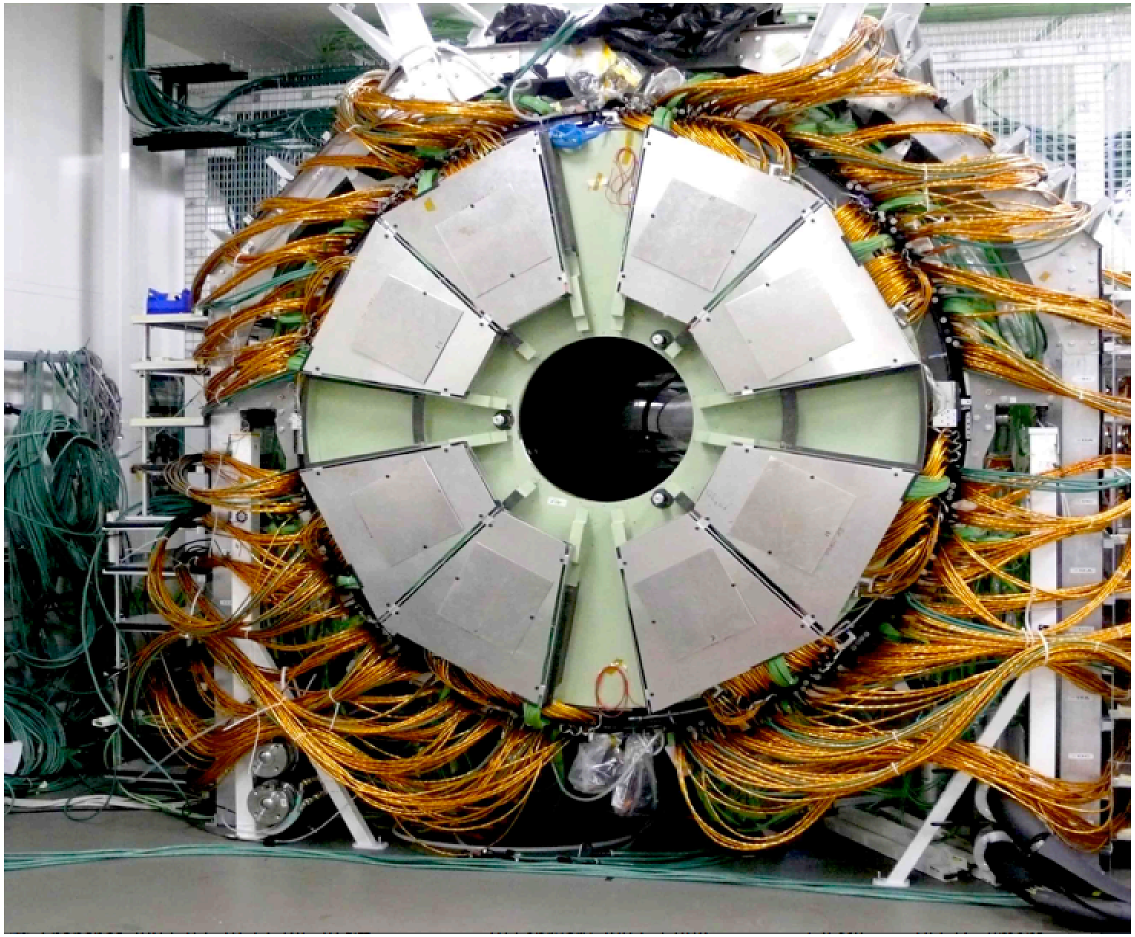
TEC + Arrives at TIF from Aachen

Assembly of the Tracker at TIF



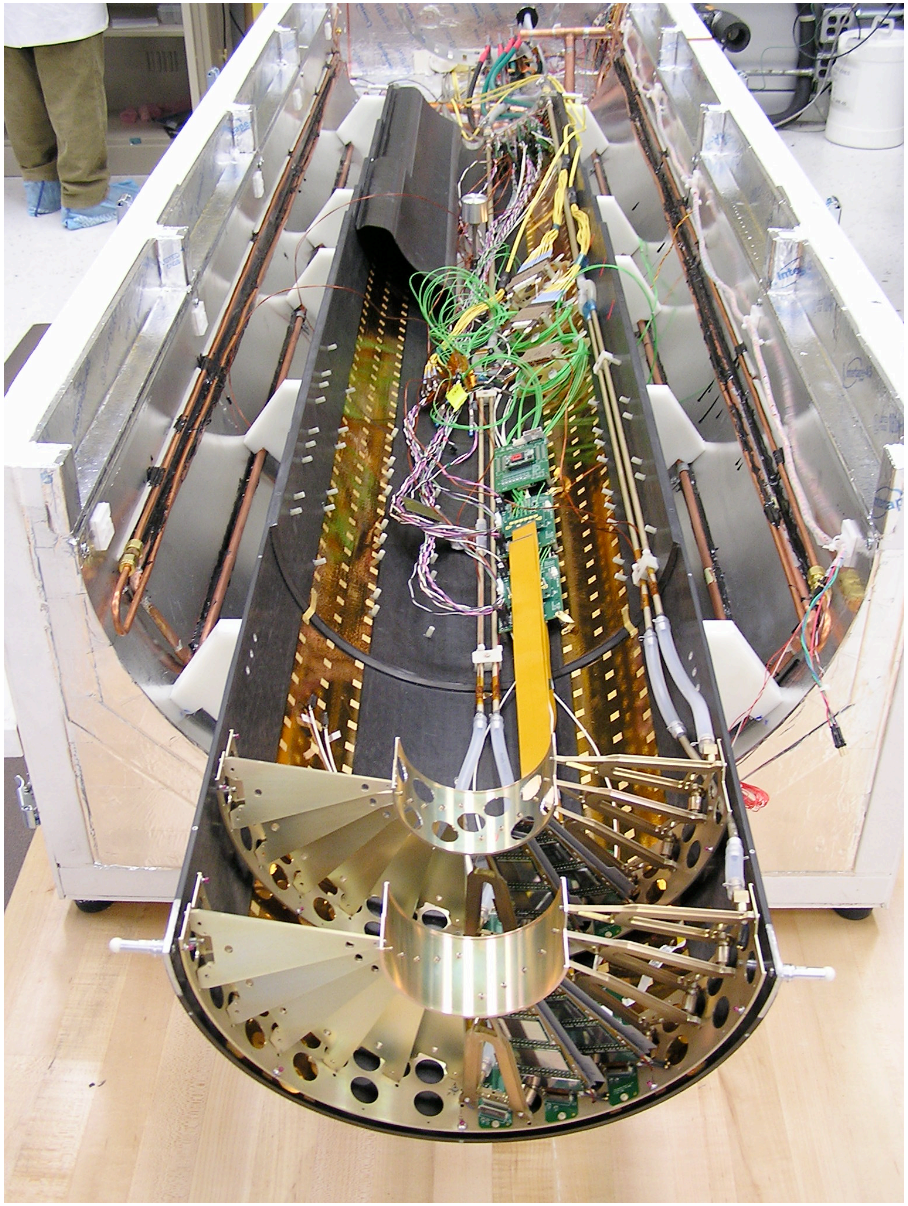
TEC+ Integrated into Tracker Support Tube

Assembly of the Tracker at TIF

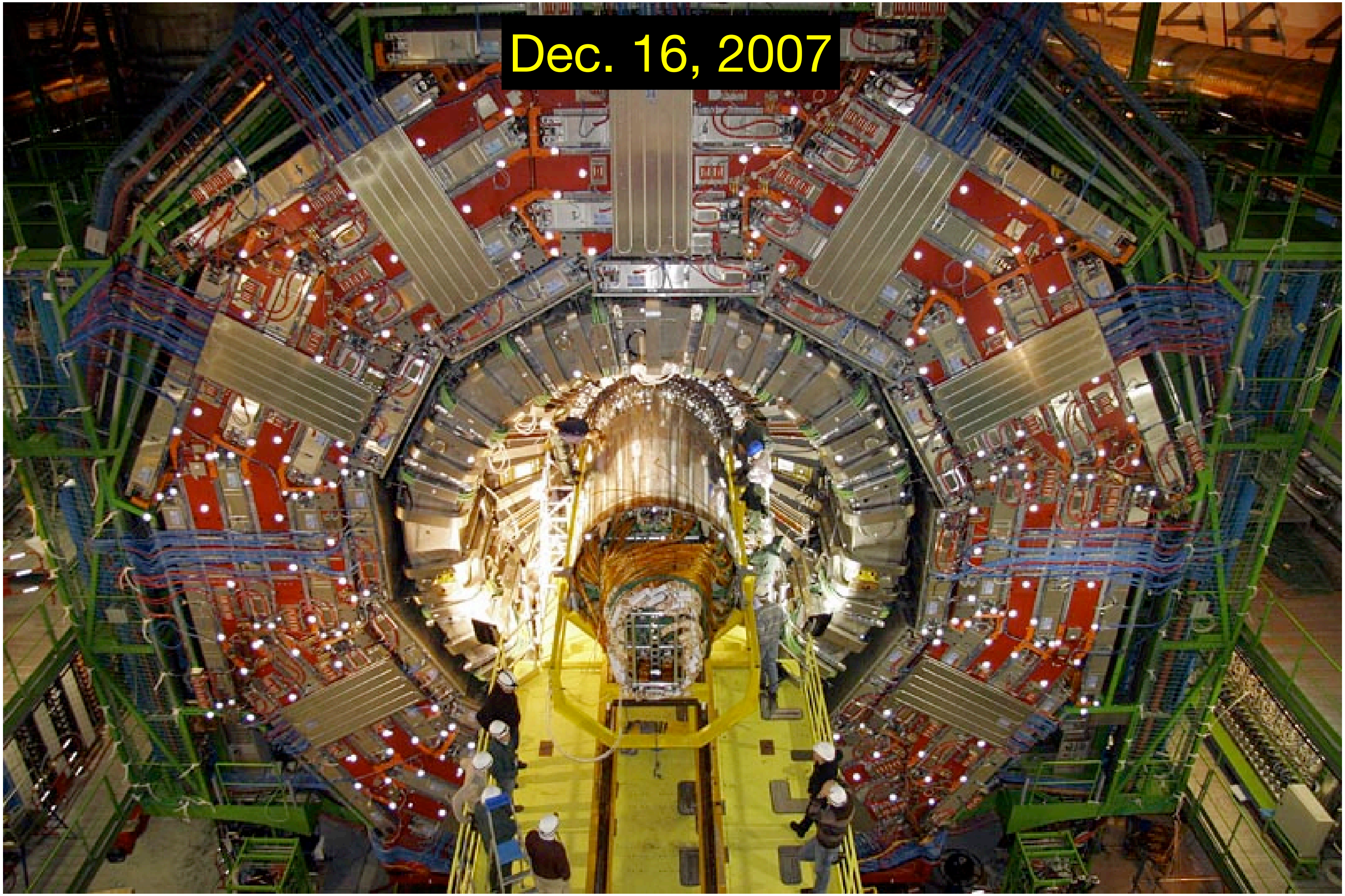


TEC+ Integrated into Tracker Support Tube

Forward Pixels

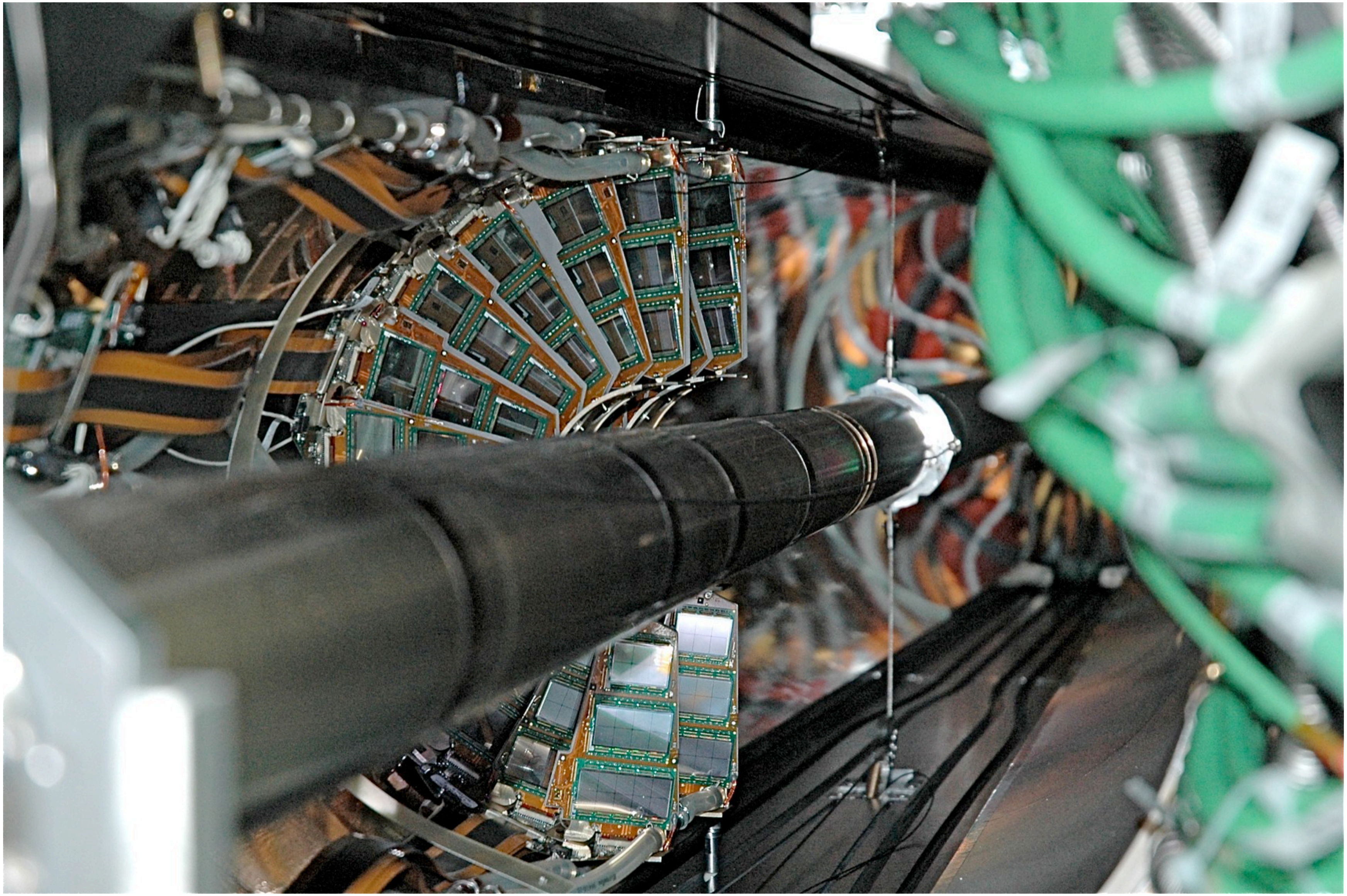


Tracker Installation at P5



Barrel Pixel Installation at P5

Forward Pixel Installation at P5



Final Assembly of Tracker at P5

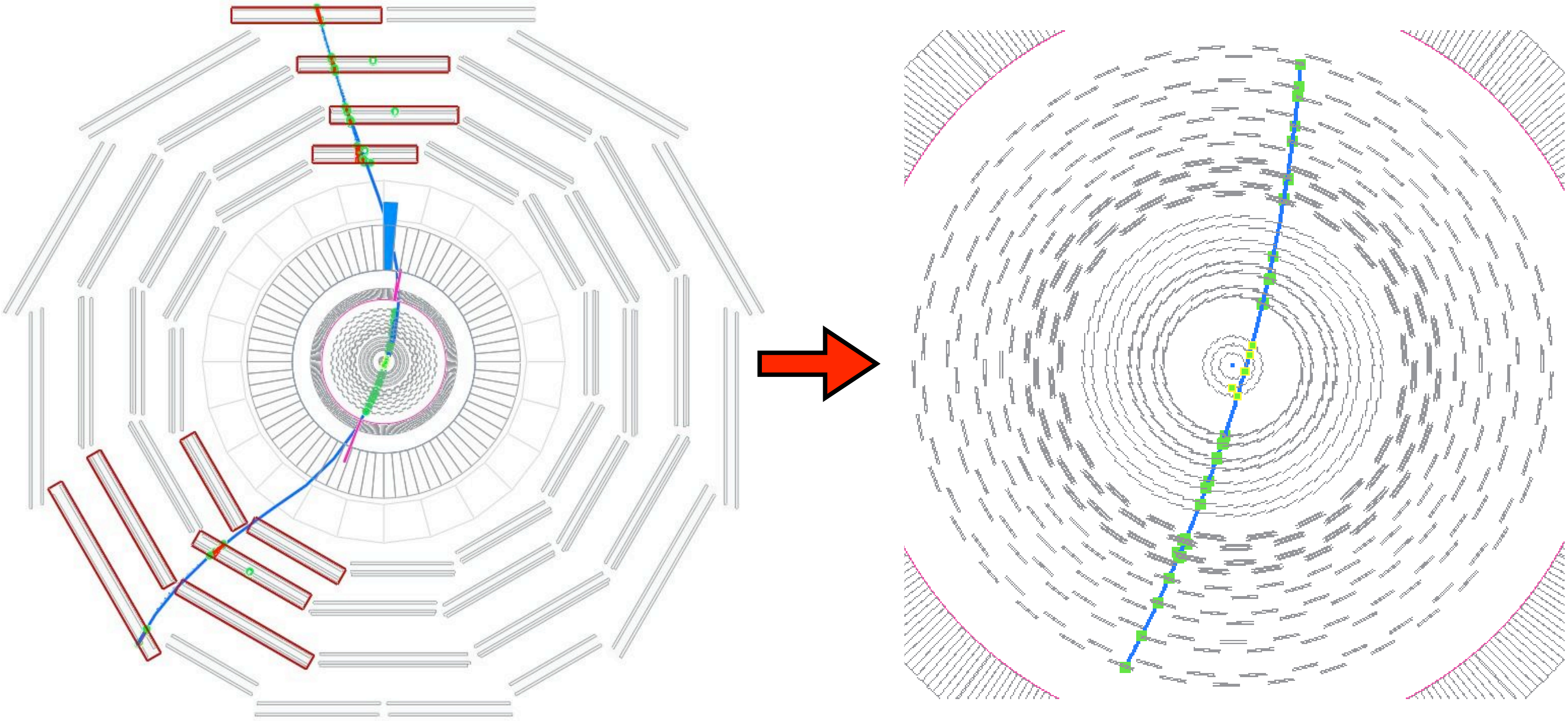
- *Strip tracker assembled at TIF then collected cosmics from January-July 2007*
  - January-July 2007 collected cosmic rays for initial commissioning and alignment
  - December 2007 strip tracker installed at P5
- *Pixel detectors installed just prior to closing of the detector prior in preparation for collisions in fall 2008*
  - Barrel pixel installation July 23-24, 2008
  - Forward pixel installation July 29-31, 2008

Tracker Commissioning with Cosmic Rays

- *Strip tracker first commissioned with cosmic rays at TIF from January-July 2007*
- *Summer, Fall 2008 recorded several million cosmic tracks at P5 with full tracker (strips and pixels) and with B-field*
  - Significant experience gained in operation of tracker
  - Careful studies made of detector performance
  - Performed detailed tests of track reconstruction to commission reconstruction as much as possible prior to collisions
  - Performed first alignment of full tracker

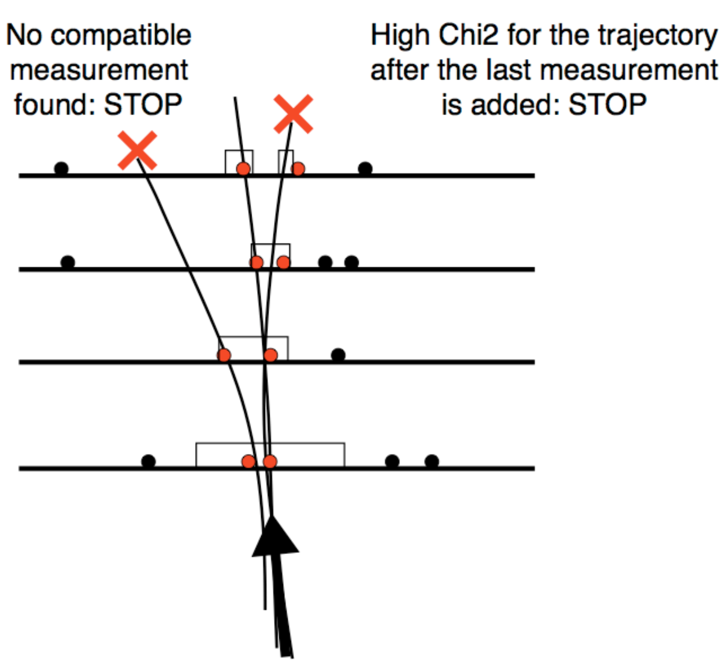
More on analyses in Zijin Guo's talk tomorrow

Tracker Commissioning with Cosmic Rays



Track Reconstruction at CMS

- *Default reconstruction of tracks is performed by the Combinatorial Track Finder (CTF)*
- *CTF uses a Kalman-filter approach to build the track by extrapolating the track layer-by-layer, adding compatible hits at each layer, and updating the track parameters*
- *Trajectory building stops when no more hits can be added or the trajectory has reached the end of the tracker*
  - For collisions, reconstruction goes inside-out, starting (usually) from hits in the pixel layers
  - For cosmics, the CTF was modified to go top-to-bottom, starting from hits in the outer strip layers
  - ***Other than the position of the seed, software used to reconstruct tracks in cosmics is the same that will be used for collisions***

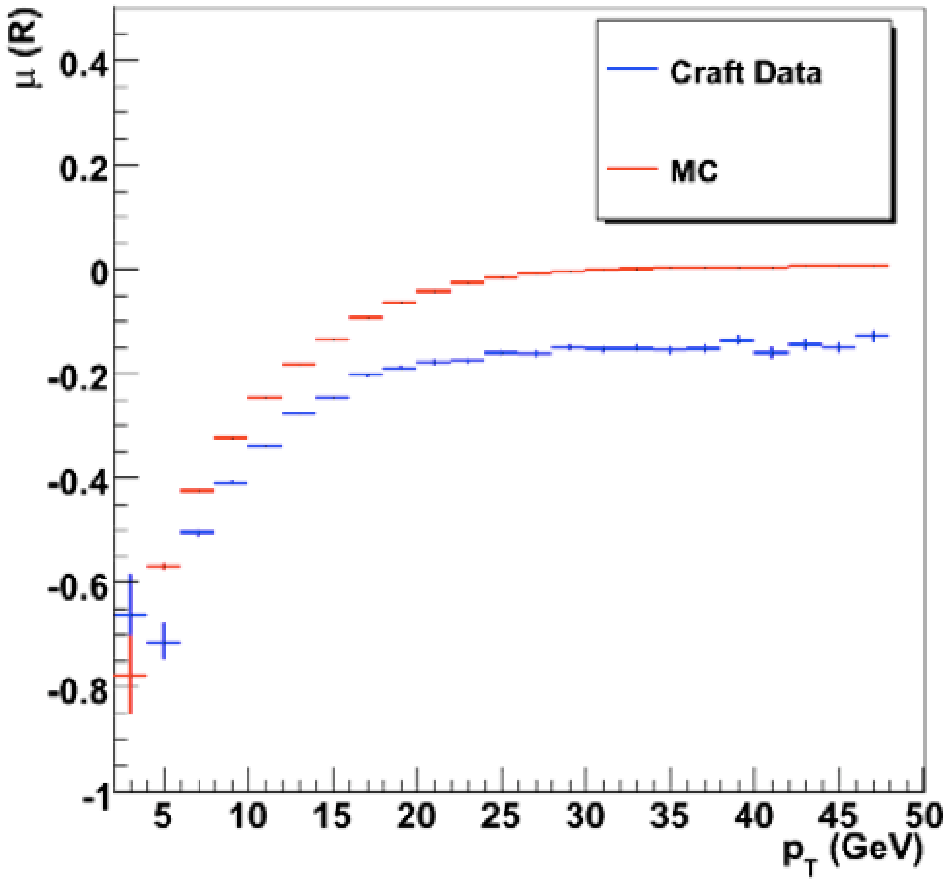


Tracker Commissioning with Cosmic Rays

* *One example of cosmic ray analysis: comparison of track P_T and Muon P_T*
  - Momentum measured independently in tracker and muon systems
  - Compare momenta from independent fits

    $R = (1/P_T^{mu} - 1/P_T^{trk}) / (1/P_T^{trk})$

  - Showed magnetic field in muon system was lower than expected



Current Status of Tracker

* *Full tracker was extensively tested in 2008 cosmic ray running*
* *During shutdown in early 2009, significant work on cooling for strip tracker, and extraction/repair of forward pixels*
  - Work on tracker completed in June
  - Tracker now operating again for several weeks
* *As of last week we are again reconstructing cosmic rays*
  - Cosmic run (CRAFT 09) will continue into September
* *Tracker goals for CRAFT 09*
  - re-align tracker following pixel work in shutdown
  - commission in mode that will be used for collisions
  - commission final version of reconstruction software

Summary

* *CMS strip and pixels trackers have been assembled, tested, installed at P5, and used to record cosmic rays*
  - Detector quality high, and performance excellent
  - Operational fraction close to 100%
* *Reconstructed tracks from cosmic rays have been used to demonstrate tracker performance and to align the tracker with better precision that what was originally expected at startup*
* *Tracker will continue to record cosmic rays for final commissioning prior to collisions this year*
* *For more information:*

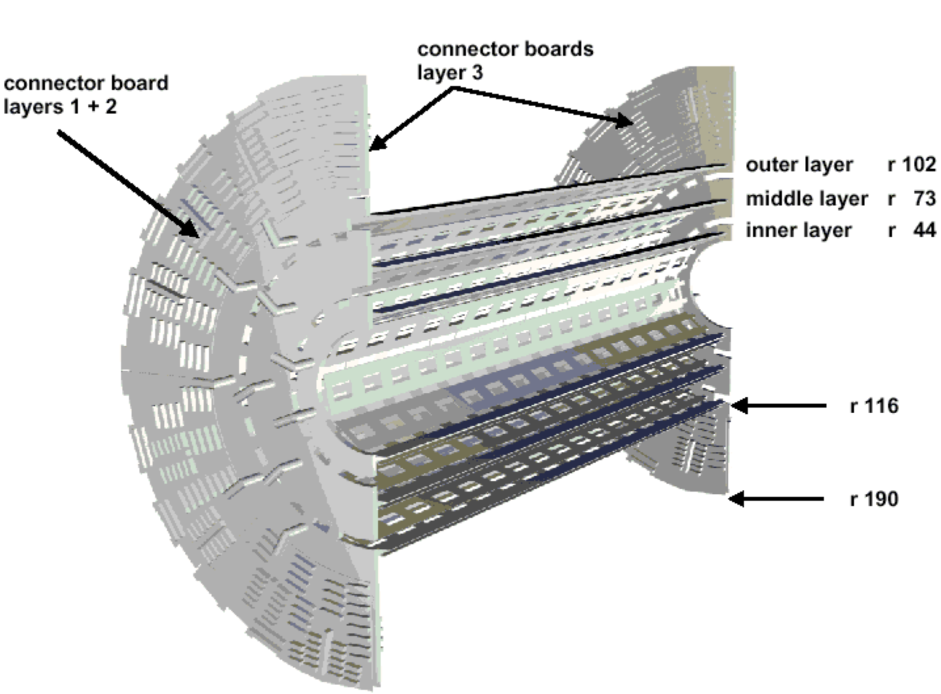
  http://cmsdoc.cern.ch/Tracker/Tracker2005/
* *Join the Tracking Group!*

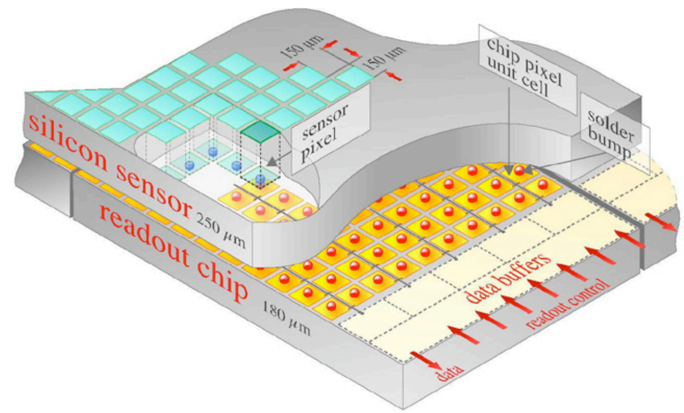
  https://twiki.cern.ch/twiki/bin/view/CMS/TrackingPOG

BACKUP

Barrel Pixel Geometry

	barrel 1	barrel 2	barrel 3
radius in mm	41.05 - 46.46	70.16-75.55	98.88-104.26
faces in phi	18	30	42
detector modules/half (1)	128/32	224/32	320/32
readout chips	2304	3840	5376
pixels (100*150)	9.6M	16M	22.4M
readout links	288	480	352





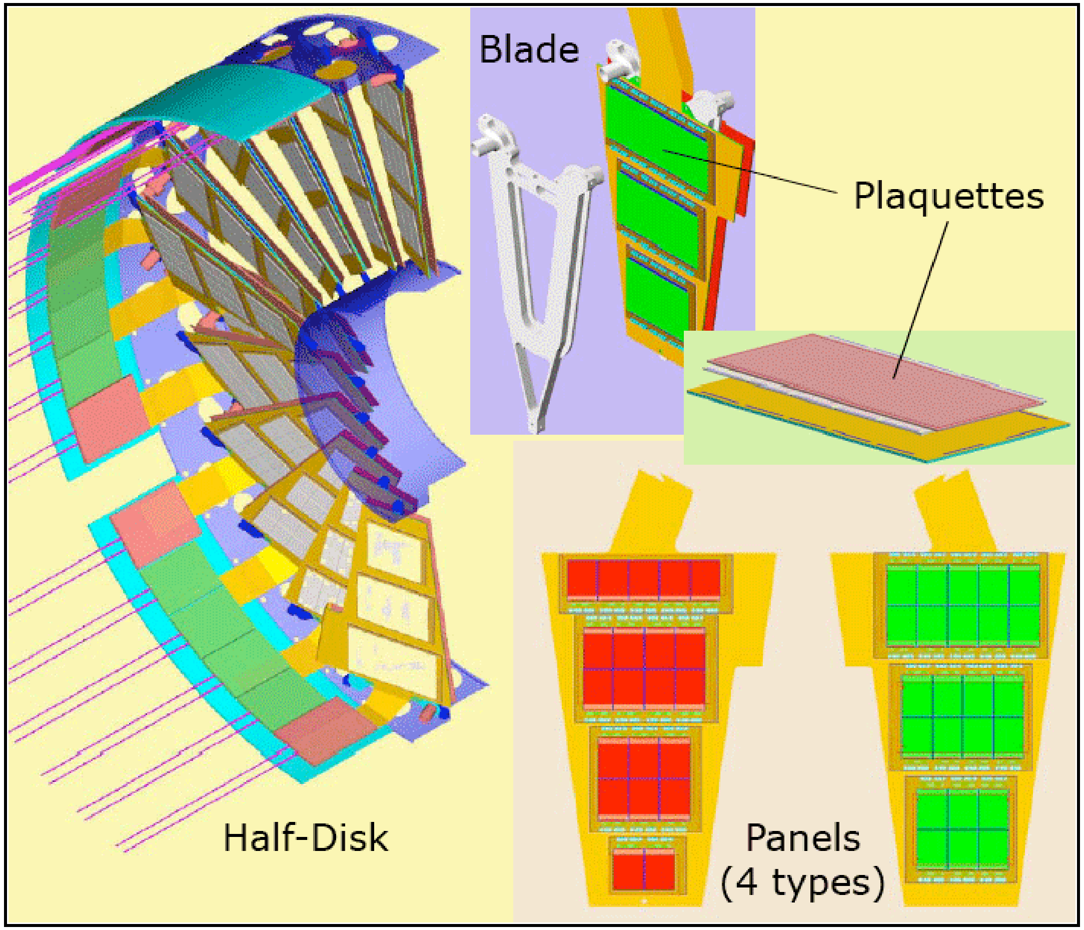
1 barrel ladder = 8 detector modules

2.2 mm gaps in Z

Left and right shells

Forward Pixels

- *24 blades in each disk*
- *Blades rotated by 20^o for charge sharing (Lorentz angle, track inclination)*
- *7 detector modules per blade (4 on front and 3 on back of the blade)*
- *45 read out chips/blade*
- *Room for another disk @ z=58.5 cm if needed*



Microstrip Detectors

* *Single-sided detectors cut from 6” wafers*
  - ‘Double-sided’ achieved by back-to-back stereo and axial modules.
  - Longest strip length: ~2x10 cm
  - Disk modules have trapezoidal shapes
* *Front-end electronics, optical hybrids, fiber optics, FEC, FED, etc common to all 3 sub-systems*
* *Shell, disk, barrel, and sector mechanics*
* *Beyond the front-end electronics many elements of the readout chain are similar or identical with those in the pixel systems.*

TIB/TID (Inner Barrel / Inner Disk)

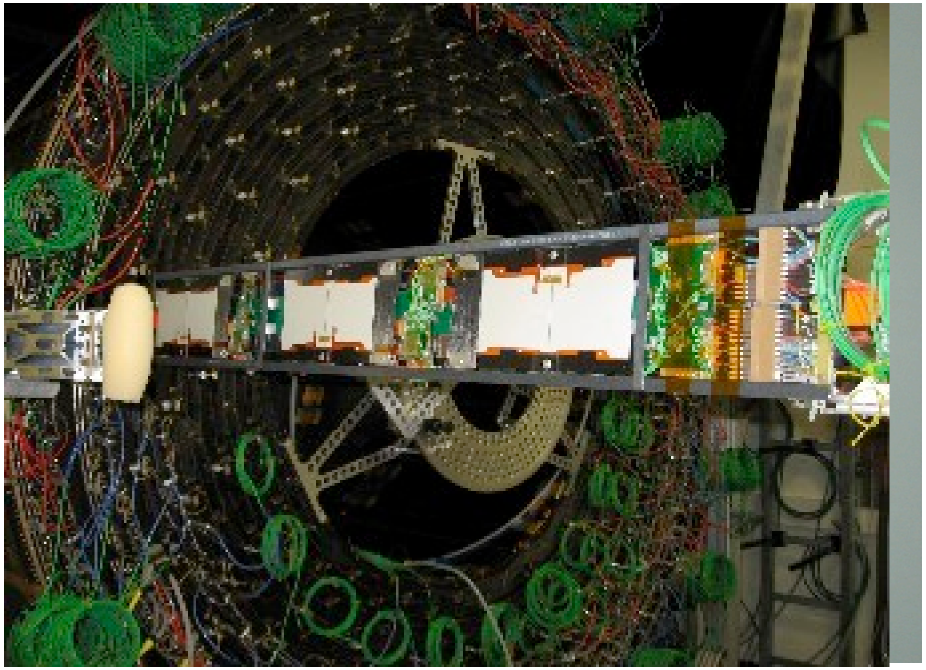
Layer #	Avg. radius	Modules in phi	Total # of modules	APV / det	Pitch phi	Pitch stereo	Total # of APVs
TIB1	255	26-30	336	6 + 6	80	80	4032
TIB2	340	34-38	432	6 + 6	80	80	5184
TIB3	430	44-46	540	4	120	-	2160
TIB4	520	52-56	648	4	120	-	2592

Ring #	Modules in phi	N of rings in z	Total # of modules	APV / det	P1/P2 phi	P1/P2 stereo	Total # of APVs
TID1	24	6	144	6 + 6	81/112	81/112	1728
TID2	24	6	144	6 + 6	113/143	113/143	1728
TID3	40	6	240	4	123/158	-	960

- *Inner barrel has four layers*
  - 9º tilt to compensate for Lorentz effect
- *TIB1 and TIB2 contain double-sided modules.*
- *Support structure in the form of shells with separation at z=0*
  - Each half contains 6 detectors in z.
- *TID disks have 3 rings that are identical to inner 3 rings of TEC disks*
  - 240 single modules and 288 double modules

TOB (Outer Barrel)

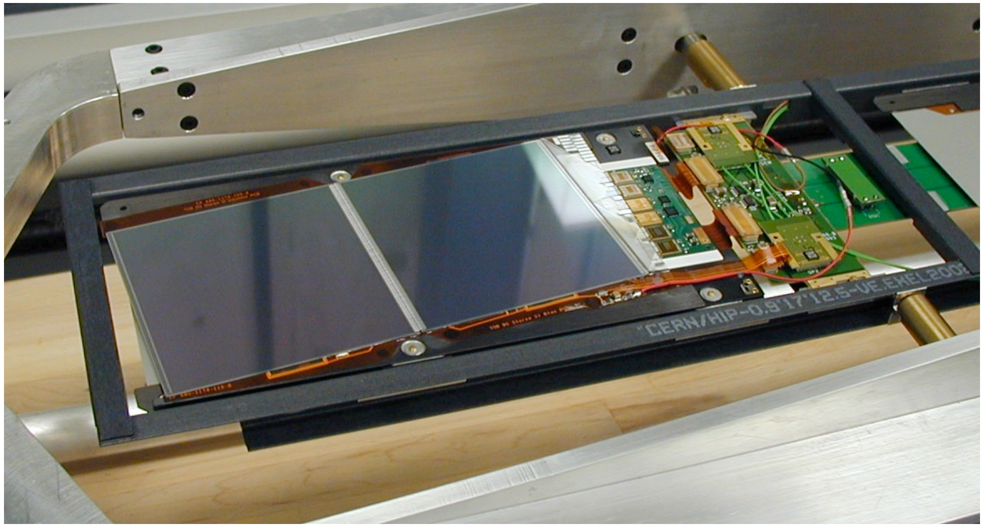
Layer #	Avg. radius	Modules in phi	Total # of modules	APV / det	Pitch phi	Pitch stereo	Total # of APVs
TOB1	608	42	504	4 + 4	183	183	4032
TOB2	692	48	576	4 + 4	183	183	4608
TOB3	780	54	648	4	183	-	2592
TOB4	868	60	720	4	183	-	2880
TOB5	965	66	792	6	122	-	4752
TOB6	1080	74	888	6	122	-	5328



5208 Modules, organized into 688 rods which go into 6 layers on the +/-Z sides of TOB "wheel"

- Layers 1, 2 Stereo
- Overlap in phi, Z
- No tilting for Lorentz effect
- Rods notched at ends to provide overlap at Z=0

TOB Modules



Tracker Outer Barrel consists of 5208 modules

Two sensors per module

- ~10 cm x 10 cm sensors, 500μ thick
- Stereo = 100 mrad tilt angle
- Small non-overlap region

Layers 1,2 are double-sided -- contain back-to-back axial+stereo modules

- “Double”, “twin”, “back-to-back”,“glued”
- 12 modules per DS rod; 6 for SS rods

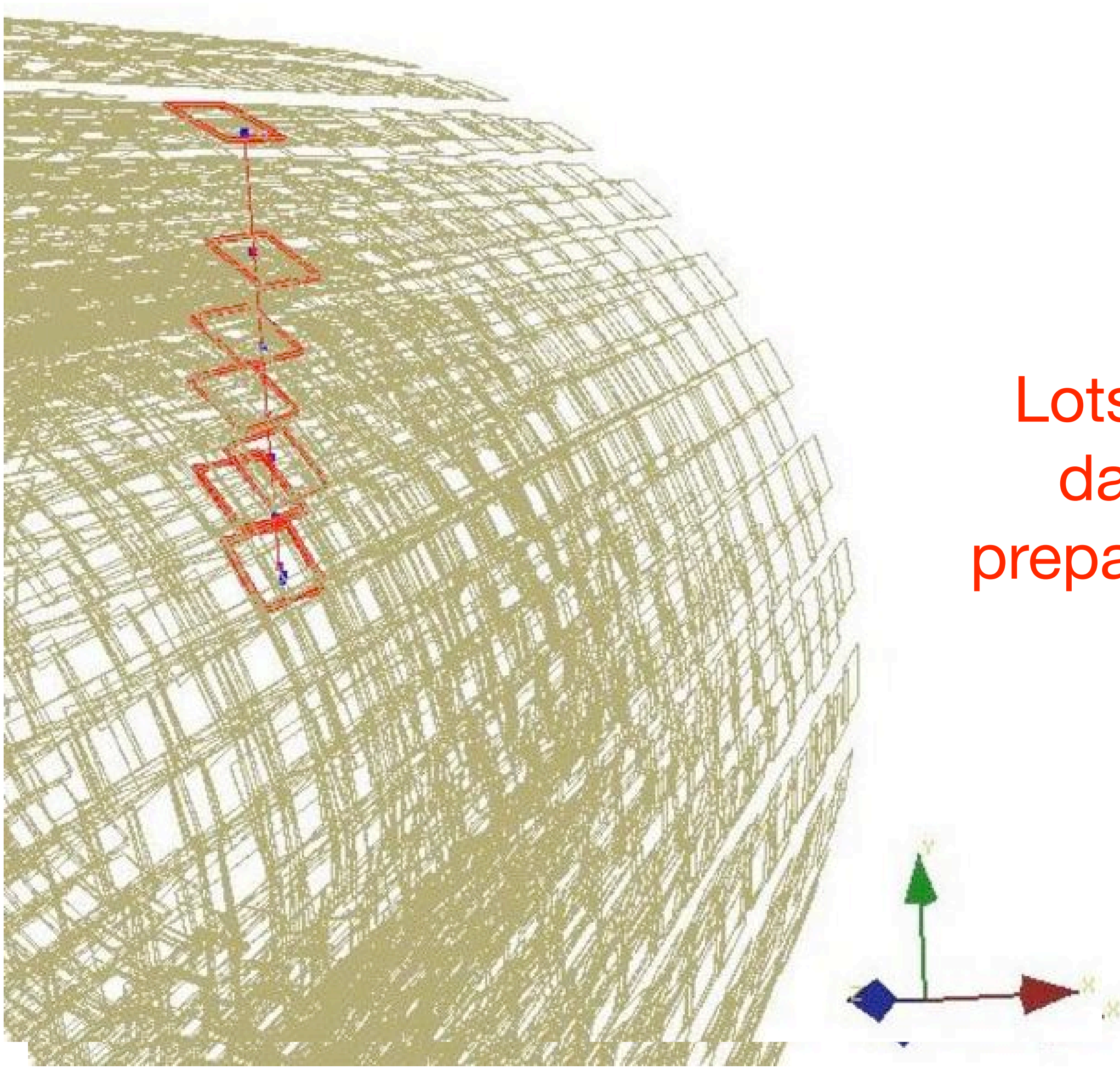
TEC (End Cap) System

Ring #	Modules in phi	N of rings in z	Total # of modules	APV / det	P1/P2 phi	P1/P2 stereo	Total # of APVs
TEC1	24	6	144	6 + 6	81/112	81/112	1728
TEC2	24	12	288	6 + 6	113/143	113/143	3456
TEC3	40	16	640	4	123/158	-	2560
TEC4	56	18	1008	4	113/139	-	4032
TEC5	40	18	720	6 + 6	126/156	126/156	8640
TEC6	56	18	1008	4	163/205	-	4032
TEC7	80	18	1440	4	140/172	-	5760

∗*Contains 7 rings*

- Rings 1-3 identical with TID rings
- Rings 1, 2, and 5 double-sided
- Number of rings per disk decreases with increasing |z|

Tracker Commissioning at TIF



Lots of interesting data studied in preparation for beam