INSTRUMENTATION AT THE LHC

A CLOSER LOOK TO THE SILICON DETECTOR SYSTEMS

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The 8th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors at Academia Sinica, Taipei, December 5-8, 2011

25 Years ago

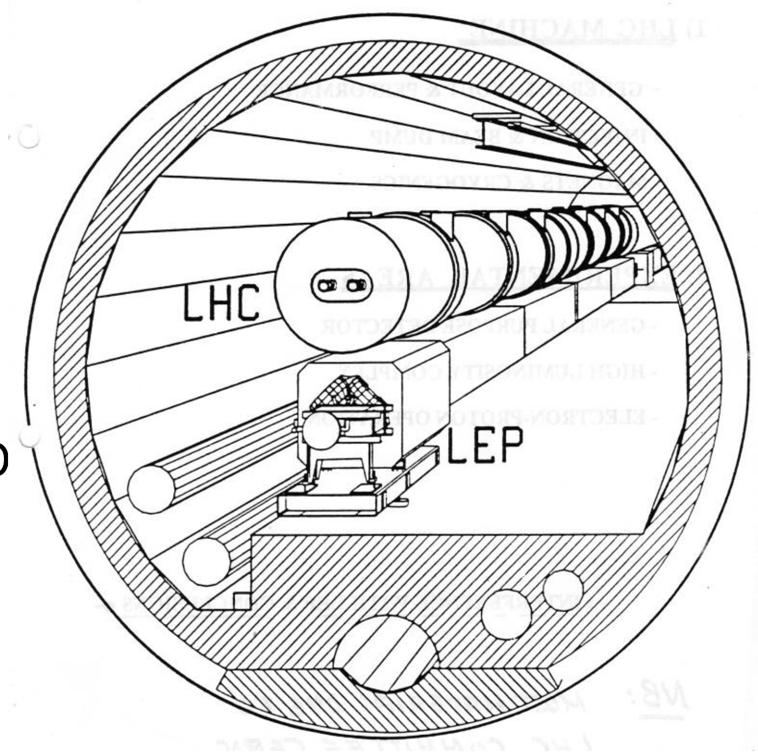
In mid/late 1980 the project of a high luminosity (>10^{34}cm^{-2}s^{-1}) hadron collider ($\sqrt{s}$=16 TeV) at CERN took shape.
LHC was planned as a competitor to the SSC (40 TeV and 10^{33}cm^{-2}s^{-1}) in the US (but earlier!!!).

Detector concepts for the high luminosity LHC:

- Focus on calorimetry and muon detection
- Widespread believe that vertexing and full tracking not possible at these luminosities.

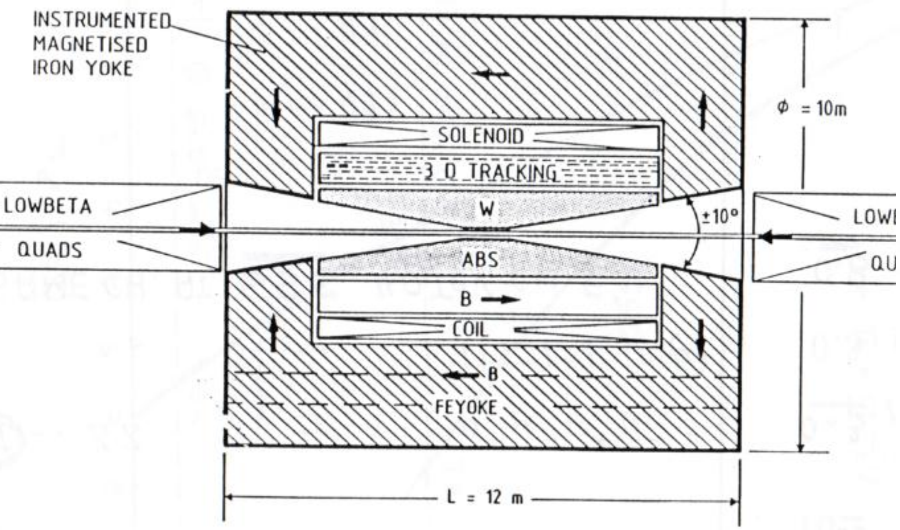
Typical detector proposals:

- Magnetic Iron „µball" + Calorimeters + TRD
- Beam dump type muon spectrometer

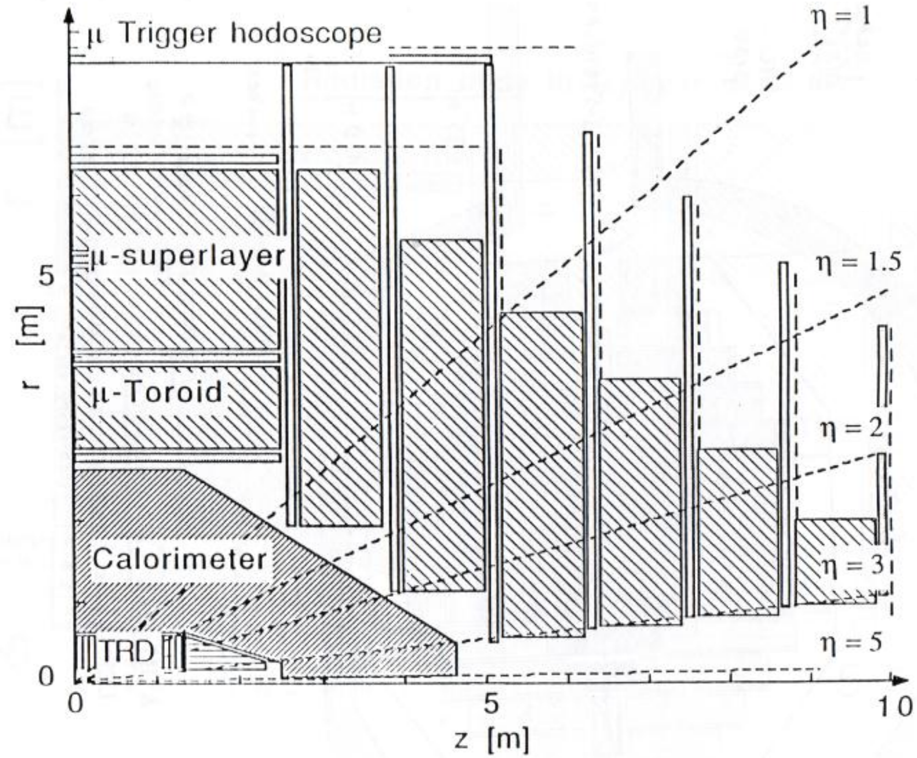


Detector Concepts* (1988)

Beam Dump type Experiment:



TRD+Calorimeter+Muon Hodoscope:



* for the LHC high luminosity option

Detector Concepts (1988)

However, in the same conference (Como 1988) some foresighted colleagues proposed already large tracker based on silicon microstrips for SSC and LHC experiments:

NIM A279 (1989) 223, H.F.-W. Sadrozinski, A. Seiden and A.J. Weinstein

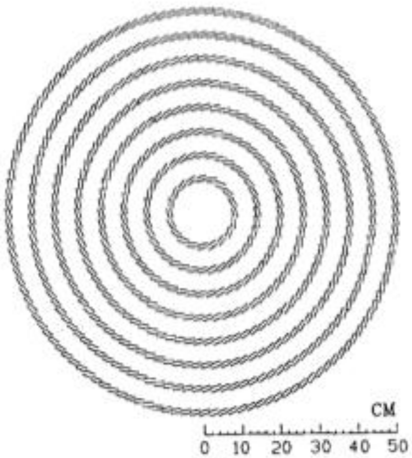


Fig. 3. Beam view of silicon tracking system. The out
is 50 cm.

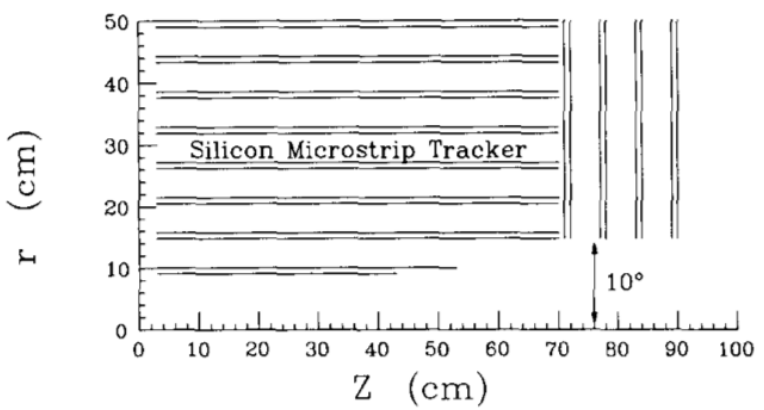


Fig. 14. Plan of silicon tracking system, with azimuthal symmetry.

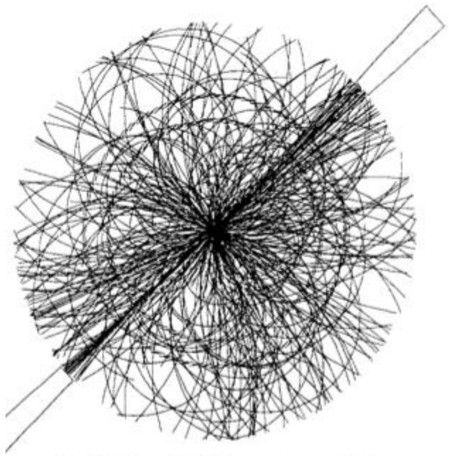


Fig. 8. High p_t ISAJET event in a 3 T field.

40 m² of silicon, σ_{pt}/p_t=8% at 1 TeV

Late 1980 till 2011

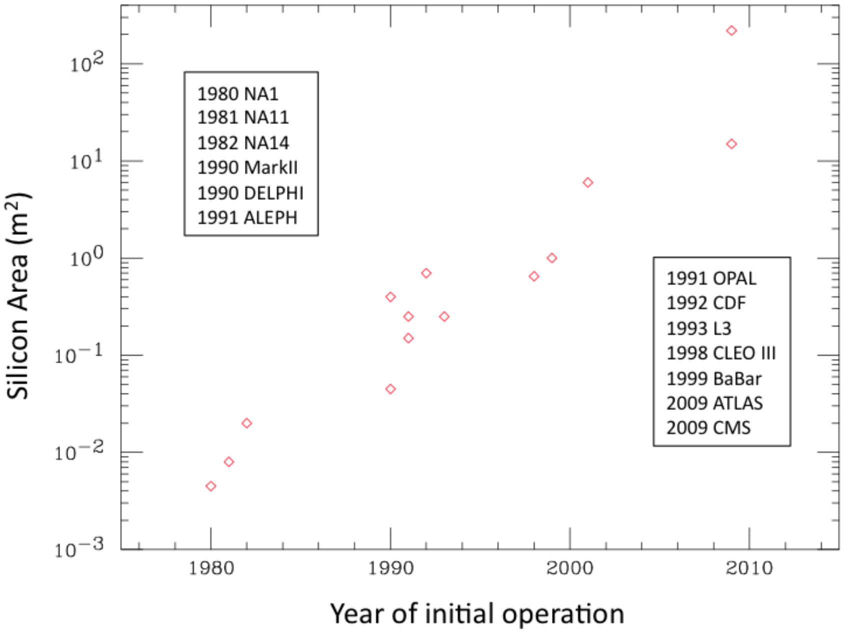
Huge development in the field of silicon detectors, electronics, connectivity, mechanics, cooling, etc.

- LEP Experiments first application in collider experiment 1989 - 2000
- CDF and DO first application at a hadron collider (1985*) – 1992 - 2011

  * no silicon detectors initially

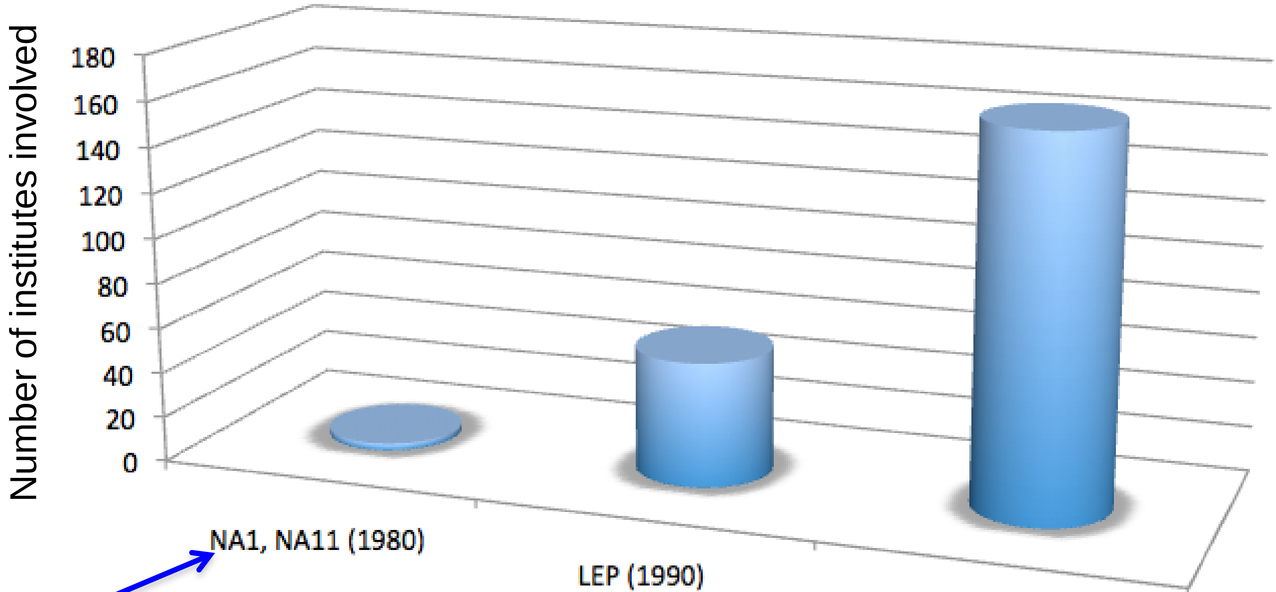
Silicon detectors became indispensable, they opened new fields of research (e.g. heavy flavour physics) and the size became larger and larger!

Plot stolen from presentation of D. Christian at TIPP 2011
(who has stolen from someone he can‘t remember whom)



1980 to 2011

But also number of physicists and institutes involved in silicon tracking systems grew:

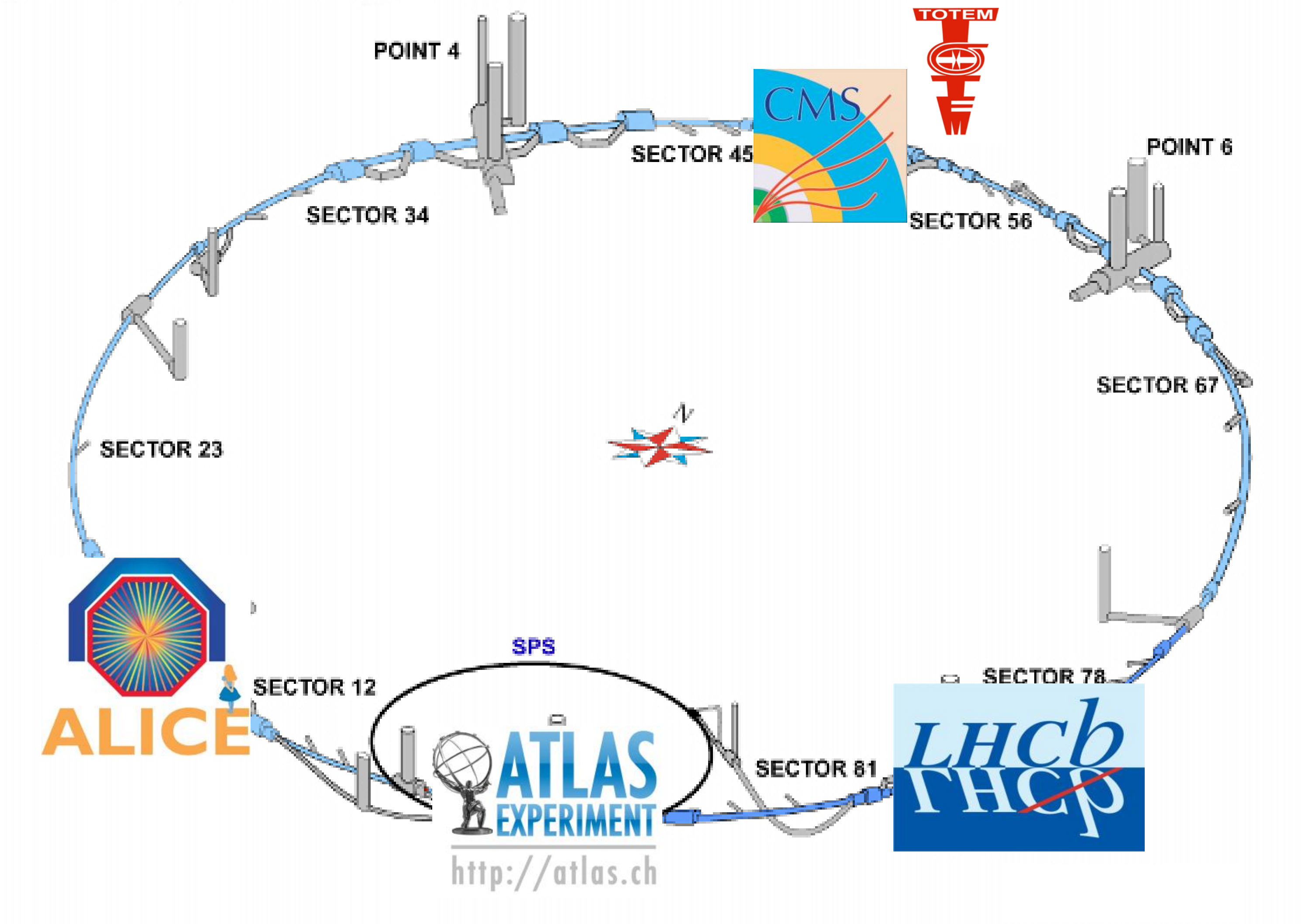


NA1 **one institute** (CERN), 8 physicists
NA11 **3 institutes** (CERN, TU Munich, MPI Munich)

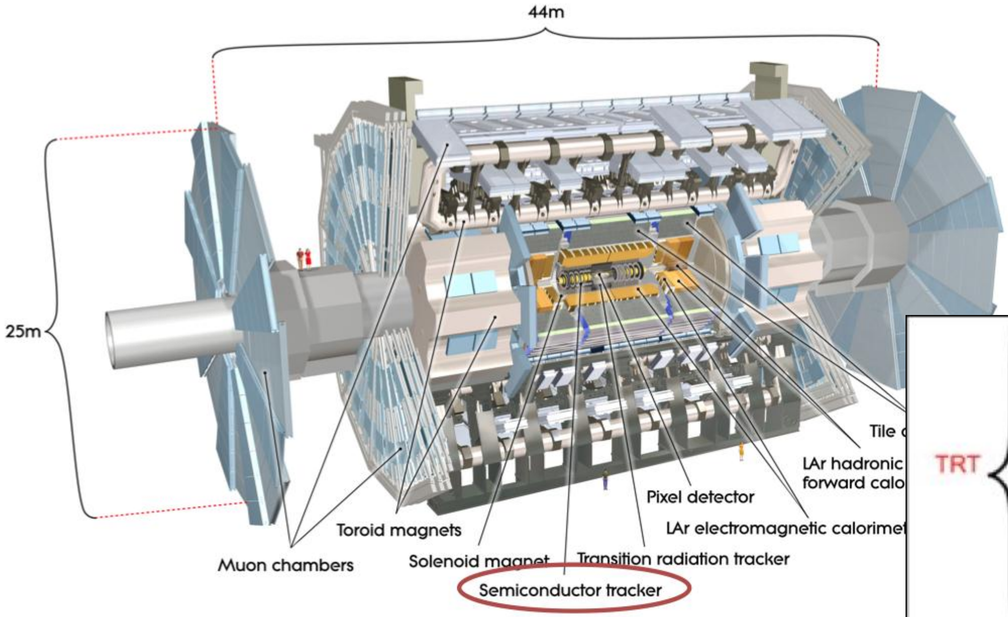
ALEPH, DELPHI, L3, OPAL
~ 55 institutes (1st Si detectors, number increased for upgrades)

ALICE, ATLAS, CMS. LHCb
~ 165 institutes involved

Experiments at the LHC

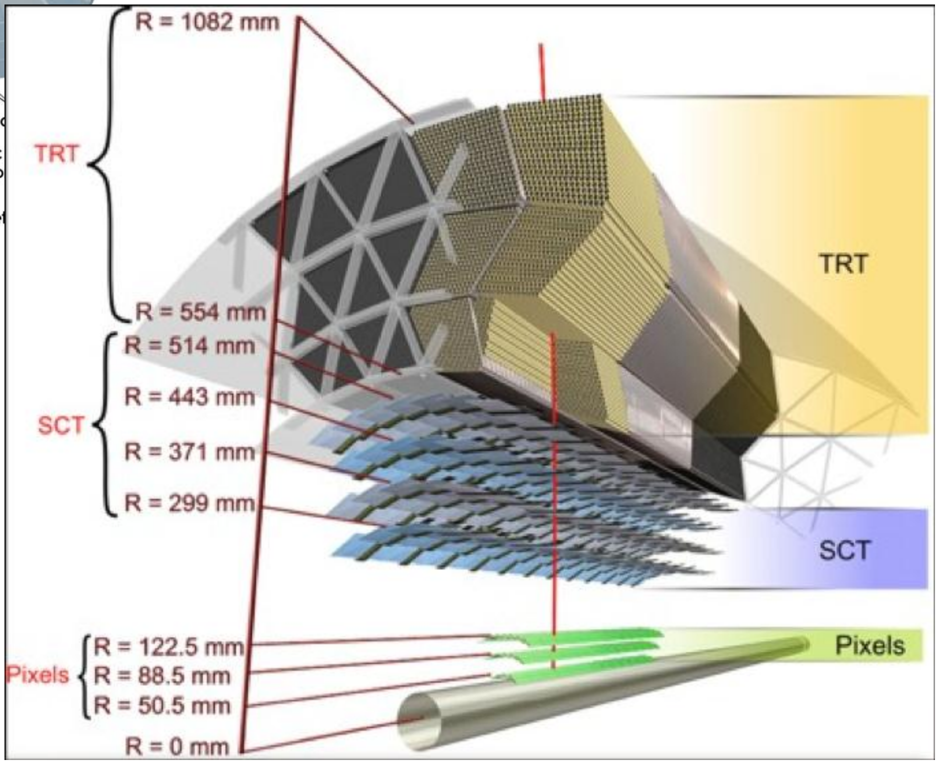


ATLAS

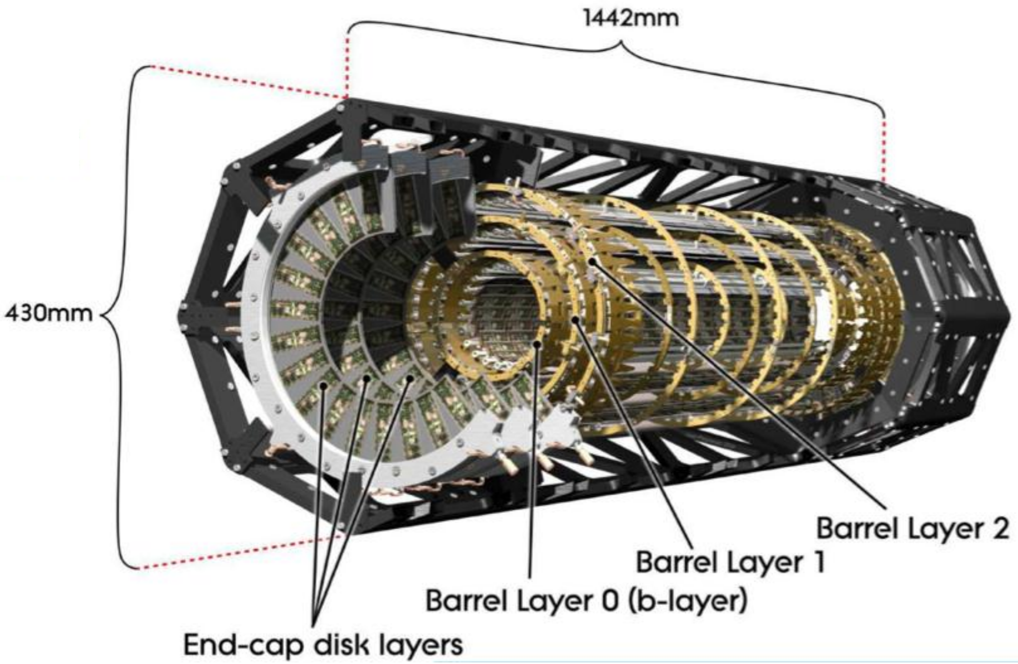


ATLAS Inner tracking system:

3 Si pixel layers, 3 discs - Pixel
4 Si strip layers, 9 discs - SCT
Transition Radiaton Tracker - TRT
(straw tubes emmbeded in fibre radiator)

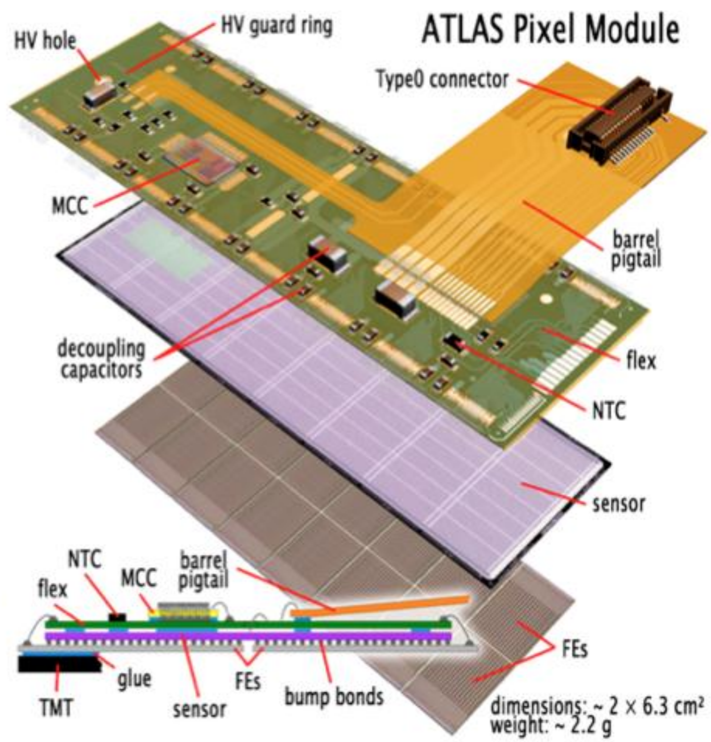


ATLAS PIXEL



Larges Pixel detector at LHC!

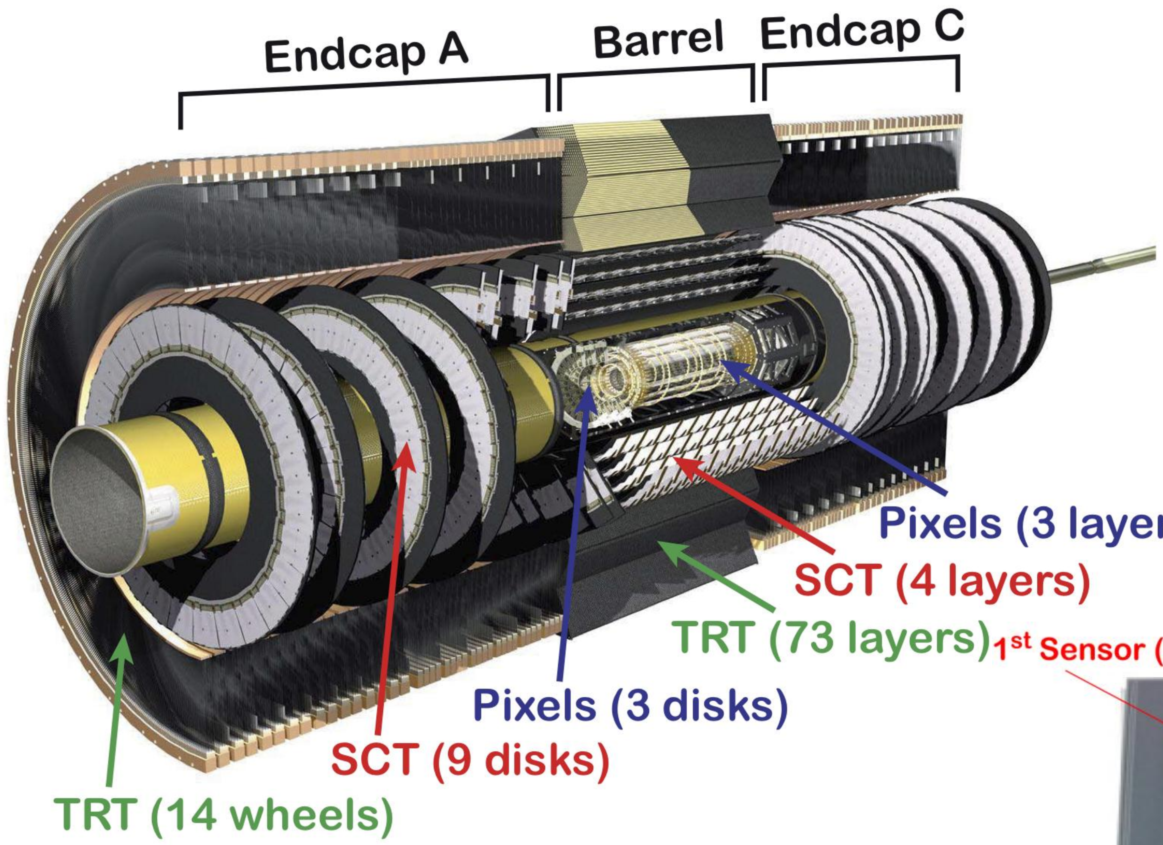
3 barrel layers: 1456 modules
3 disks per end-cap: 288 modules
80M readout channels
Innermost layer at radius 50,5 mm
Evaporative C_3F_8 cooling



96.8% of the detector active in data taking (The percentage of disabled modules only 2.1% up to 3.2% in 3 years of operations)

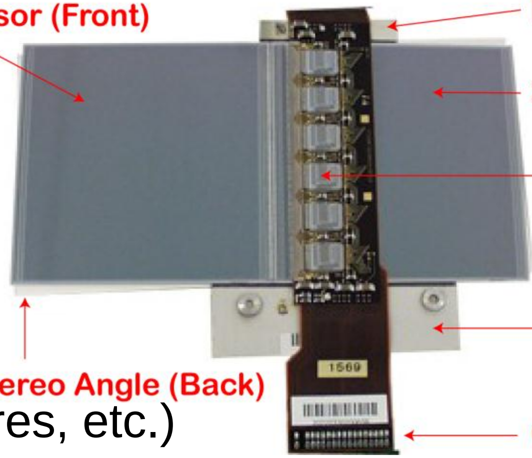
Readout chip measures pulse height by Time-over-Threshold
→ used for dE/dx measurement.

ATLAS SCT



4 Barrel layers: 2112 modules
2x9 endcap disks: 1976 modules
Coverage: 30 cm < r < 52 cm, |η|<2.5
Active material: 61 m^2 silicon
Readout: 6.3 million channels,
Binary readout
C_3F_8 cooling: -7° C ... +4.5° C

Modules: 2 single sided sensors glued back to back

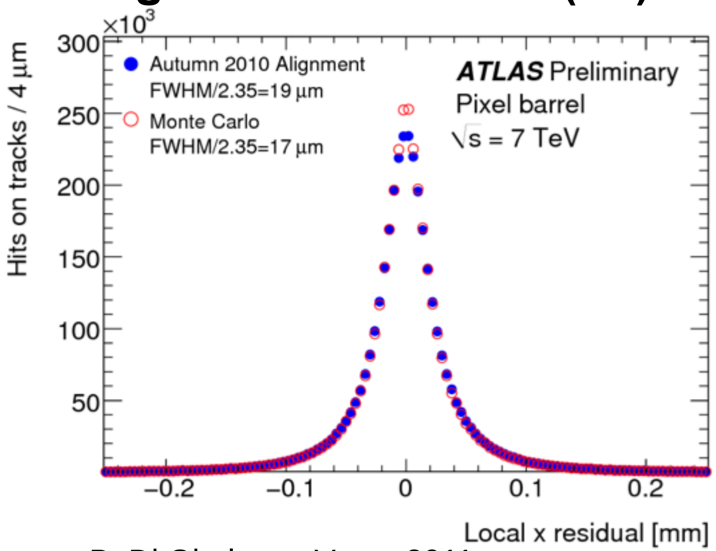


Less than 0.2% disabled noisy strips.
0,75% modules out of readout (cooling, TX failures, etc.)

ATLAS Performance

Excellent performance of ATLAS Pixel and Strip Detector

E.g. Pixel resolution (rΦ):

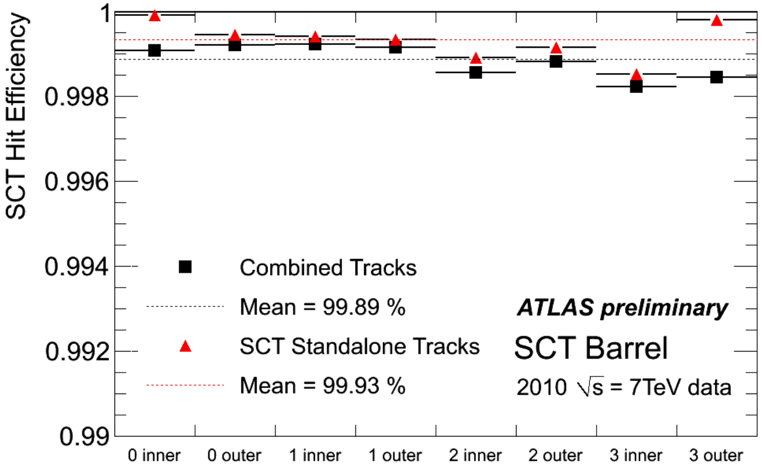


B. Di Girolamo, Vertex2011

Width close to MC of a perfectly aligned detector.

Pixel Hit to track association efficiency ~99%

E.g. SCT Hit efficiency barrel:



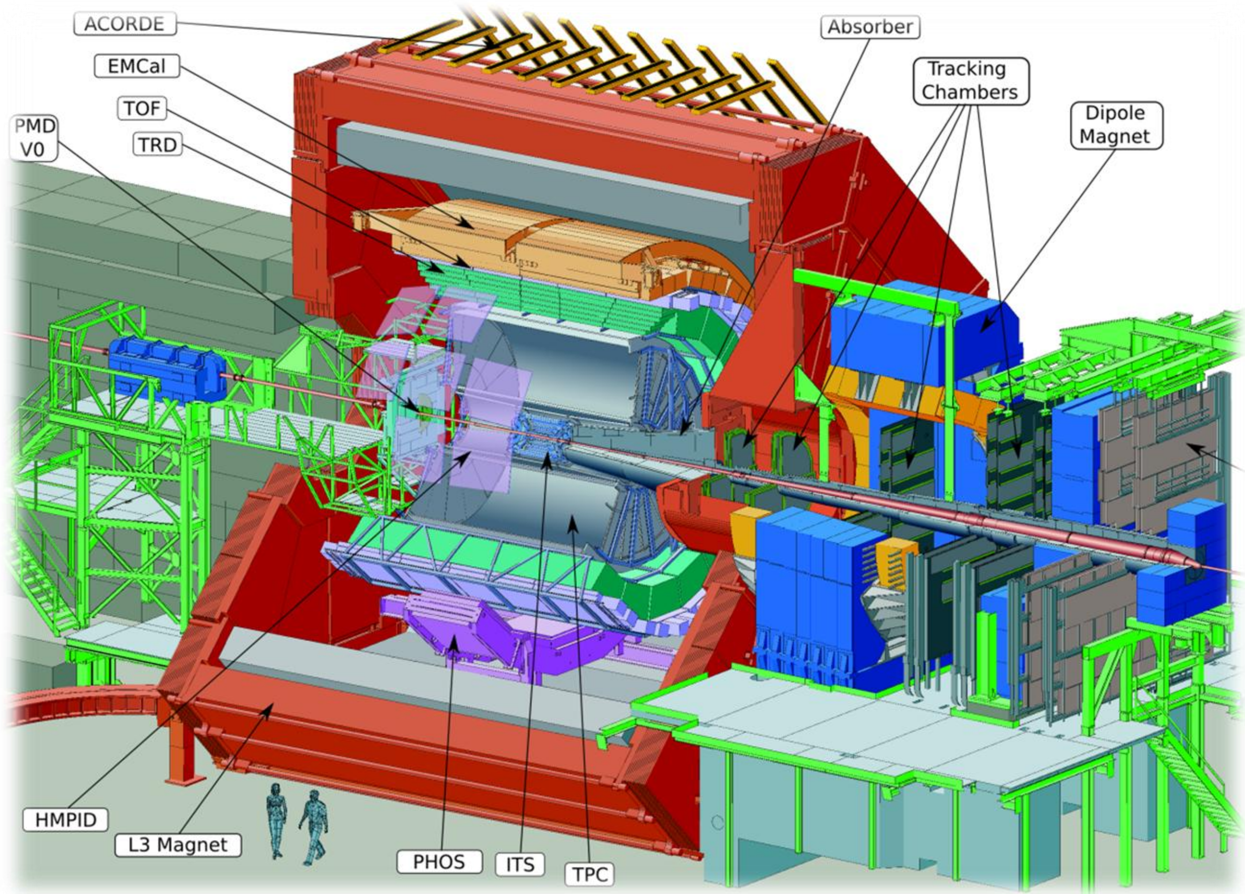
P. Haefner, Vertex2011

More details in talks by Cecile Lapoire (Pixel) and Dave Robinson (SCT).

ALICE

ALICE a dedicated heavy ion experiment

Lower luminosity $10^{27}cm^{-2}s^{-1}$ during Pb-Pb collisions,
but charged particle multiplicities of up to 8000 per unit of rapidity.



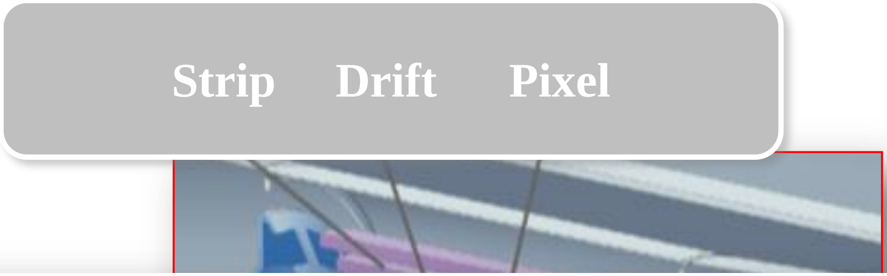
ALICE Inner Tracking System:

Largest TPC in the world: 5 m length, radius from 0.85 – 2.5 m, 88 m^3 gas volume

+ silicon system inside

ALICE Inner Tracking System

3 different silicon detector technologies:
- Hybrid Silicon Pixel Detector (SPD)
- Silicon Drift Detector (SDD)
- Double Sided Strip Detector (SSD)



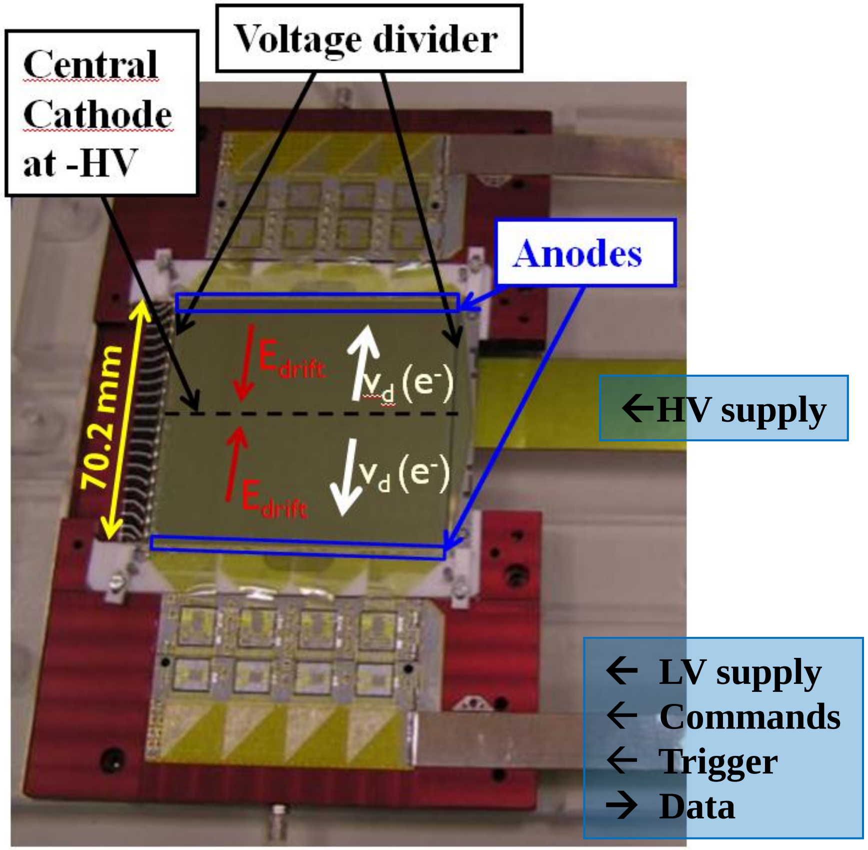
Layer	*Det.*	*Radius (cm)*	*Length (cm)*	*Surface (m2)*	*Chan.*	*Spatial precision (mm)*		*Cell (µm2)*	*Max occupancy central PbPb (%)*	*Material Budget (% X/X_0)*	*Power dissipation (W)*	
						rφ	*z*				*barrel*	*end-cap*
1	SPD	3.9	28.2	0.21	9.8M	12	100	50x425	2.1	1.14	1.35k	30
2		7.6	28.2						0.6	1.14		
3	SDD	15.0	44.4	1.31	133 K	35	25	202x294	2.5	1.13	1.06k	1.75k
4		23.9	59.4						1.0	1.26		
5	SSD	38.0	86.2	5.0	2.6M	20	830	95x40000	4.0	0.83	850	1.15k
6		43.0	97.8						3.3	0.86		

Operation 2010/11 not without problems:

SPD: 1,8% low eff. or dead channels, cooling problems effecting ~30% of modules
SDD: 1,5% dead + 0,7% noisy channels, 6% modules out of aquisition
SSD: 1,5% dead or noisy channels, 8% modules out of aquisition

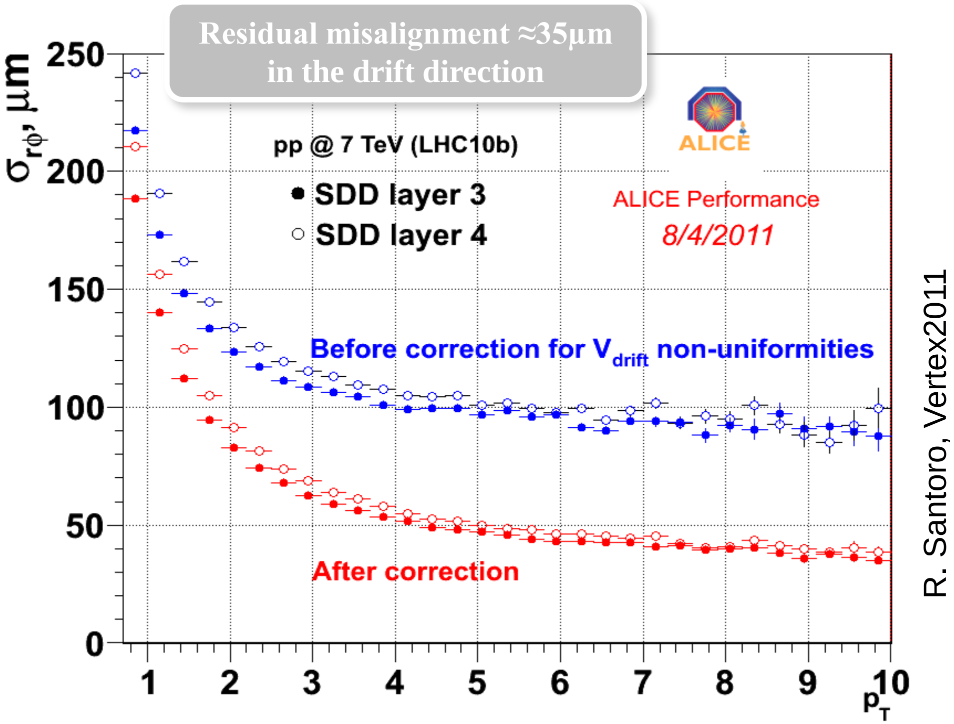
R. Santoro, Vertex2011

ALICE Silicon Drift Detector



Challenging calibration: interplay between alignment, drift velocity and time-zero calibration.

Alignment, before and after drift velocity correction:

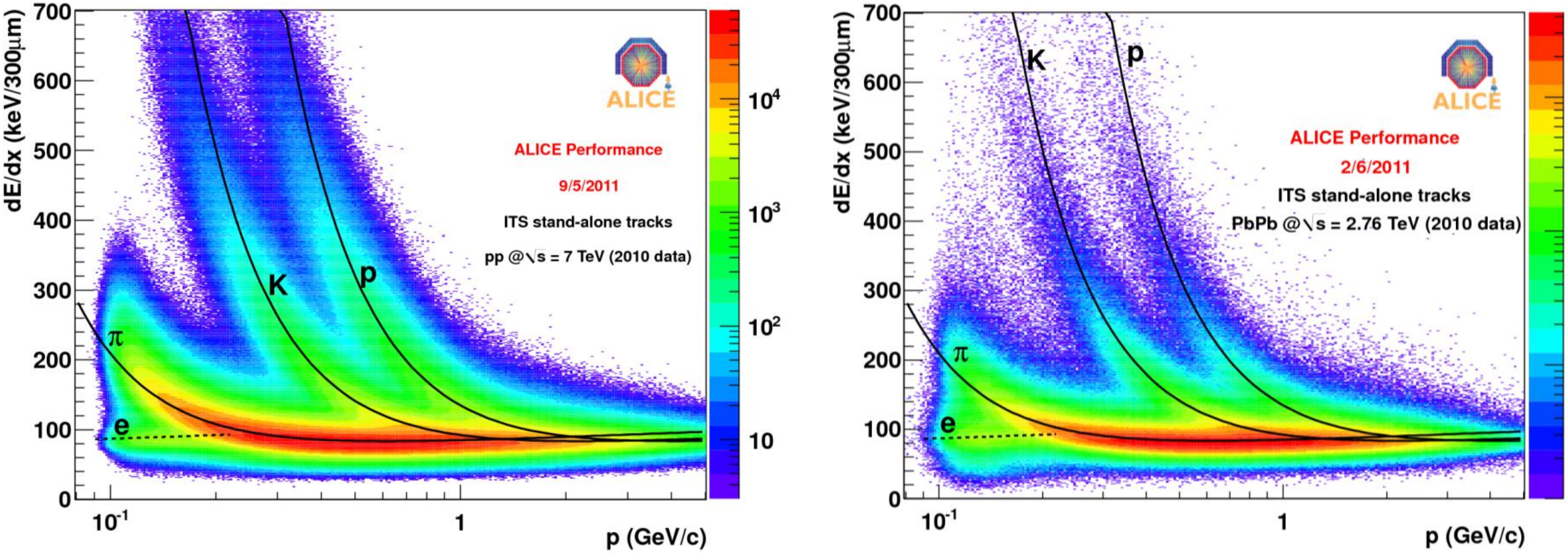


ALICE Particle ID

4 out of 6 silicon layers with analogue information (SDD and SSD)

Results for particle identification in p-p and Pb-Pb data

- ITS standalone tracks
- Hadron separation below 100 MeV/c ← **Low momentum cutoff of 100 MeV**
- Good pions / kaons separation up to 0.5 GeV/c
- Good pions and protons separation up to 1 GeV/c



R. Santoro, Vertex2011

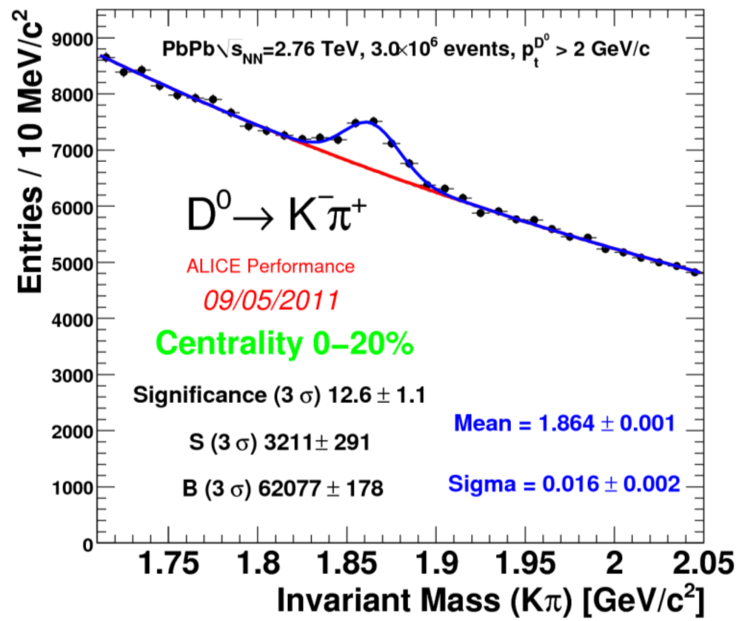
D meson reconstruction in PbPb

Pb – Pb collisions (2010)
2.76 TeV/nucleon (≈ 30 M events MB)

Prove of the ITS performance:

Find charm decays in Pb-Pb collisions (crucial is the ITS impact parameter resolution).

e.g. D0:

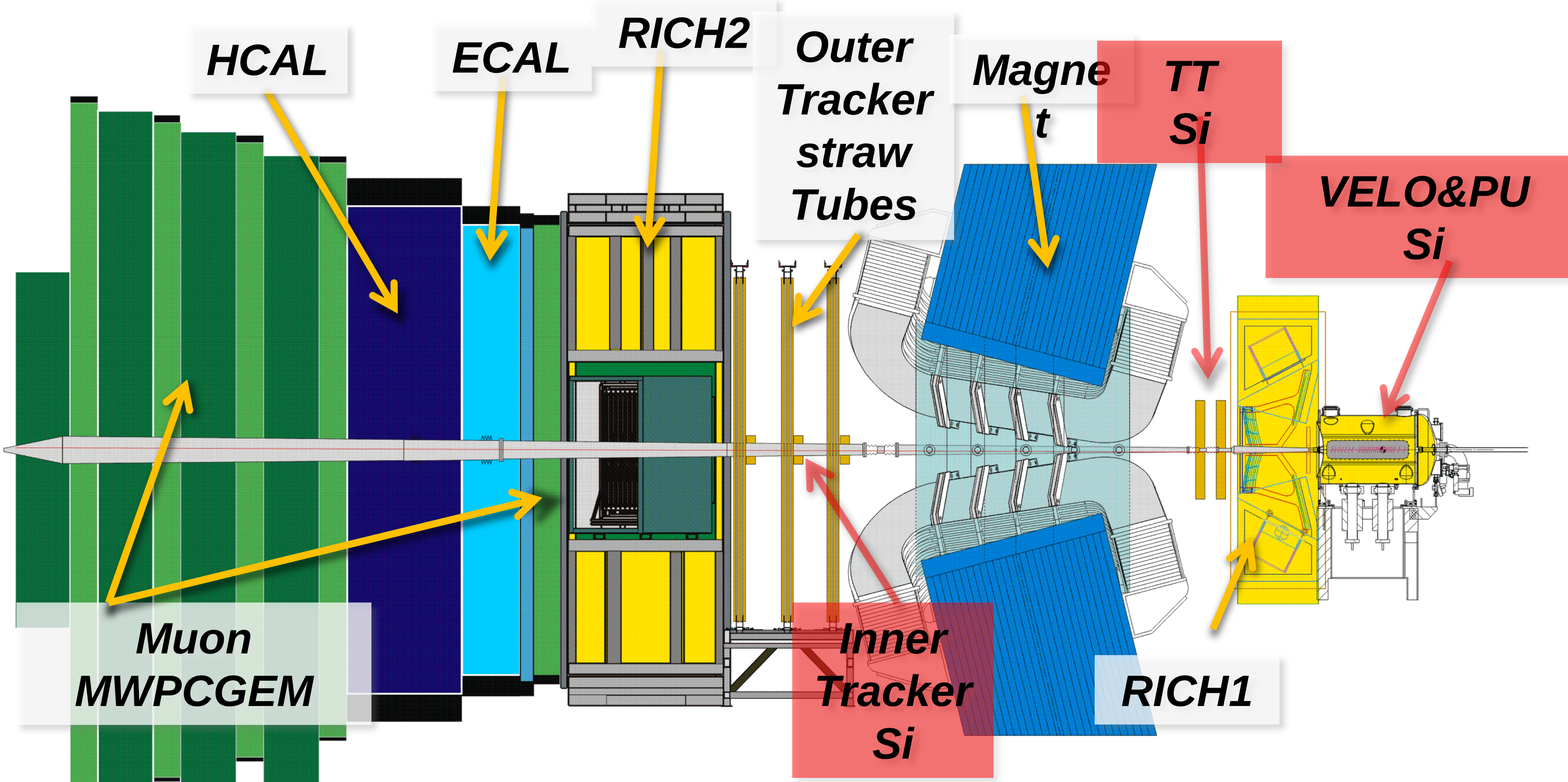


R. Santoro, Vertex2011

More details in talk by Vito Manzari.

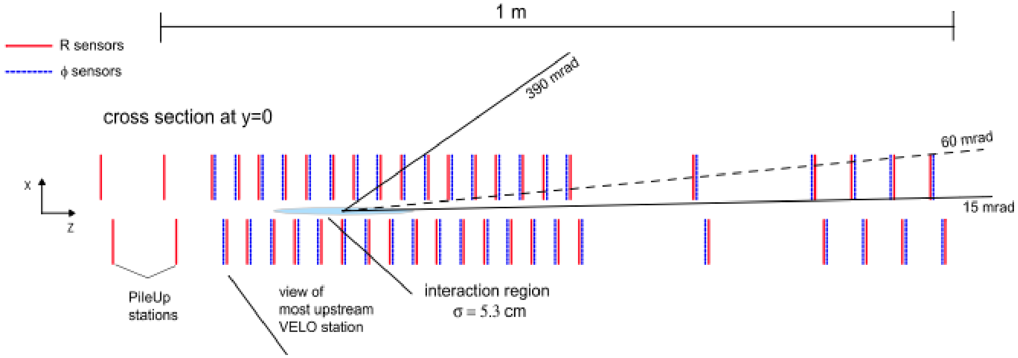
LHCb

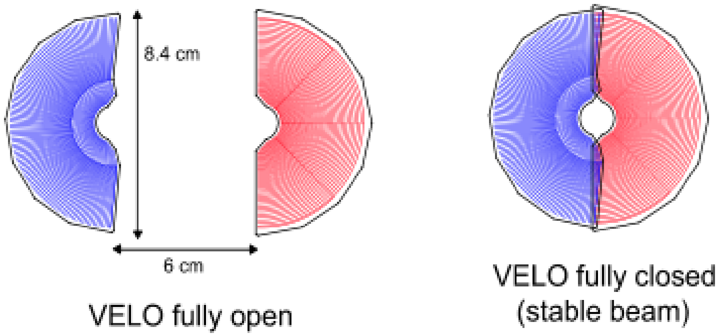
LHCb experiment dedicated to heavy flavour physics

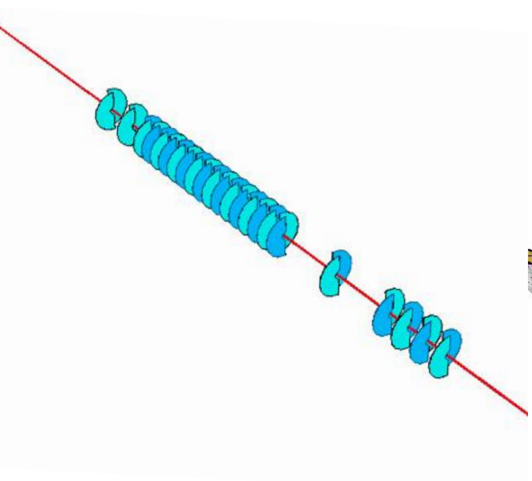


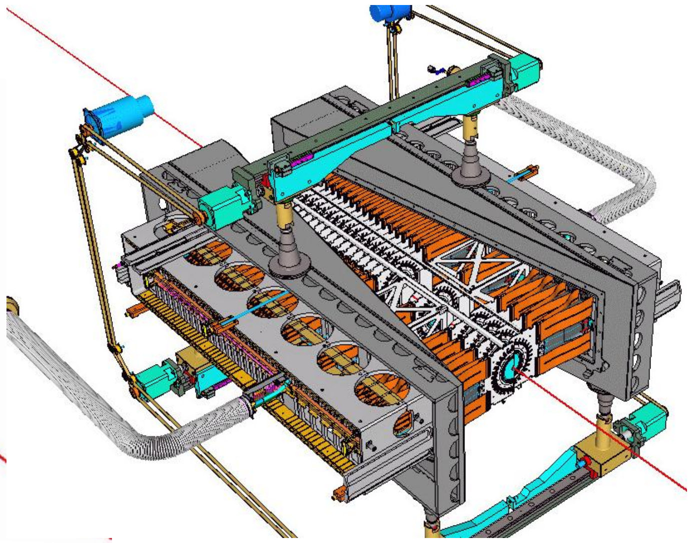
Inner Tracker see talk by Greig Cowan.

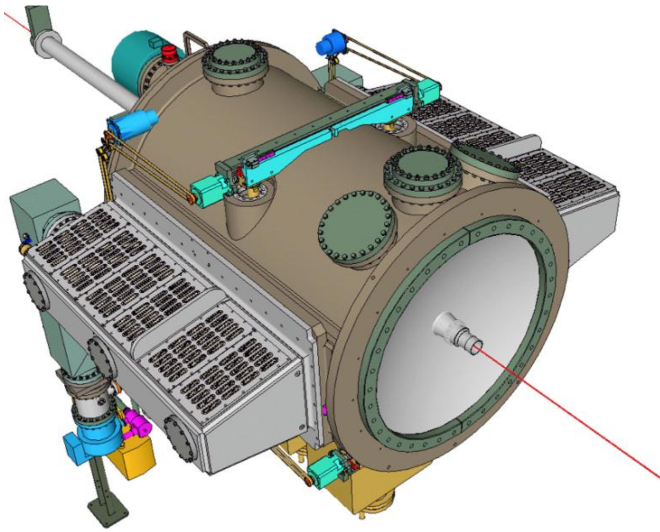
VELO: Vertex Locator





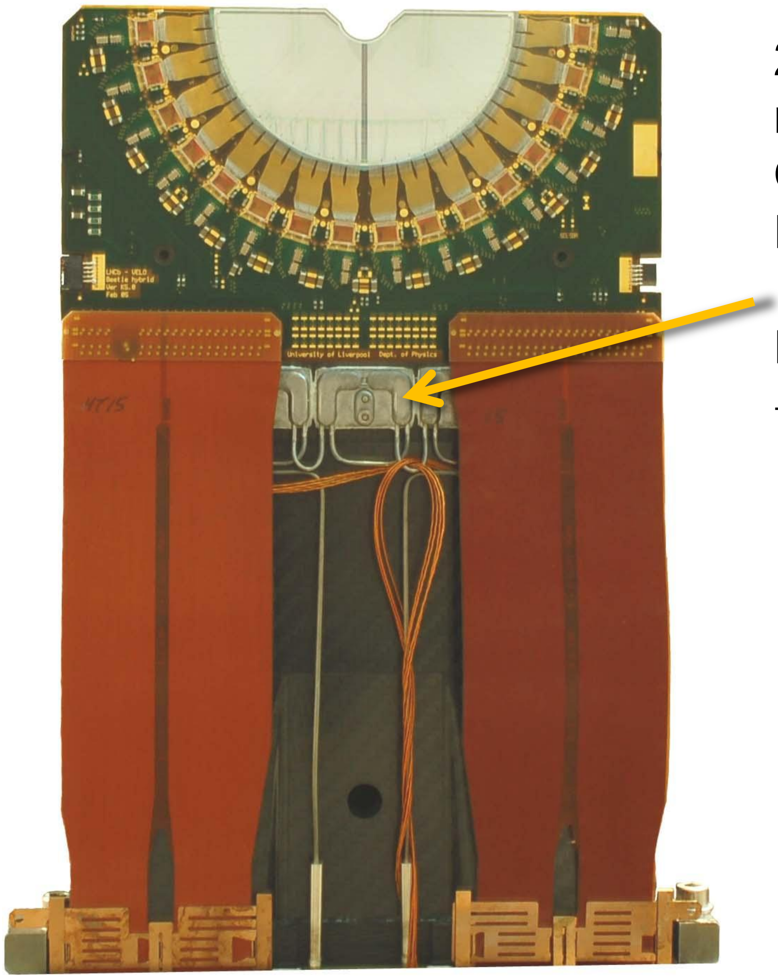






During stable beams closest silicon 7 mm from the beam.

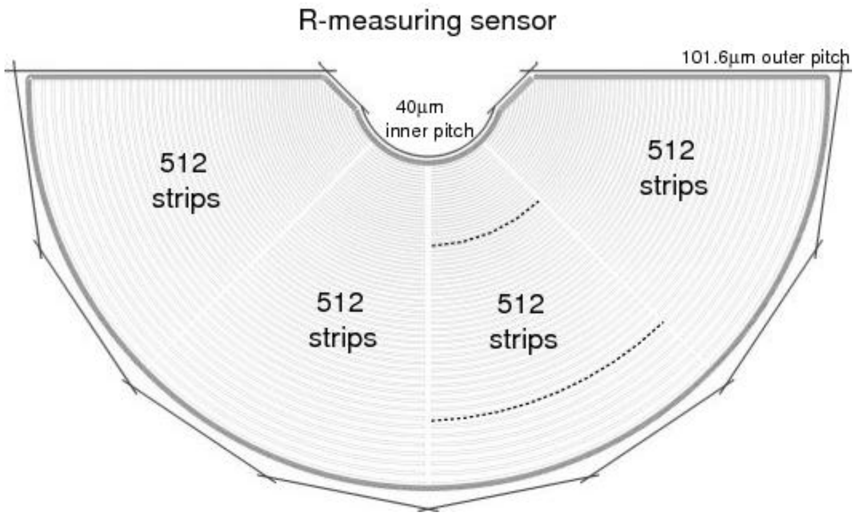
VELO Modules



21 modules per half (r and Φ sensor per module)
n-n sensors (300 µm, pitch 40 µm – 100 µm)
Operated in secondary vacuum (separated from LHC vacuum by 300 µm foil)

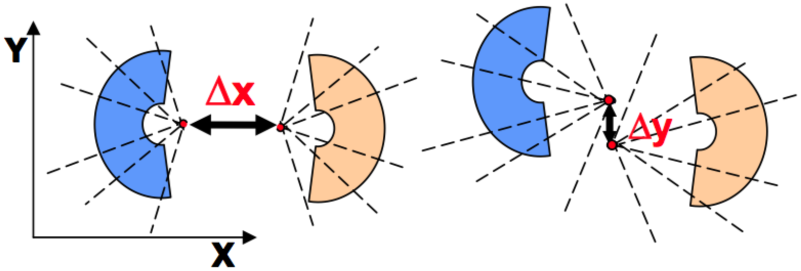
Evaporative CO_2 cooling at -30 C
→ no problems during operation.

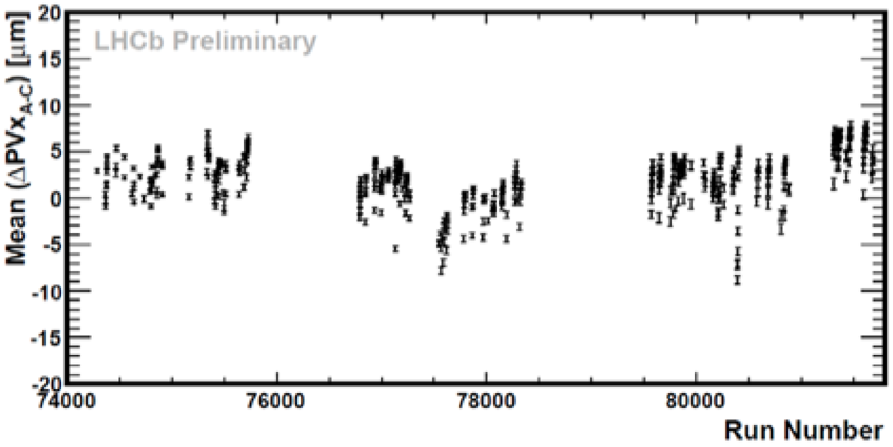
Quasi circular sensors with inner opening:



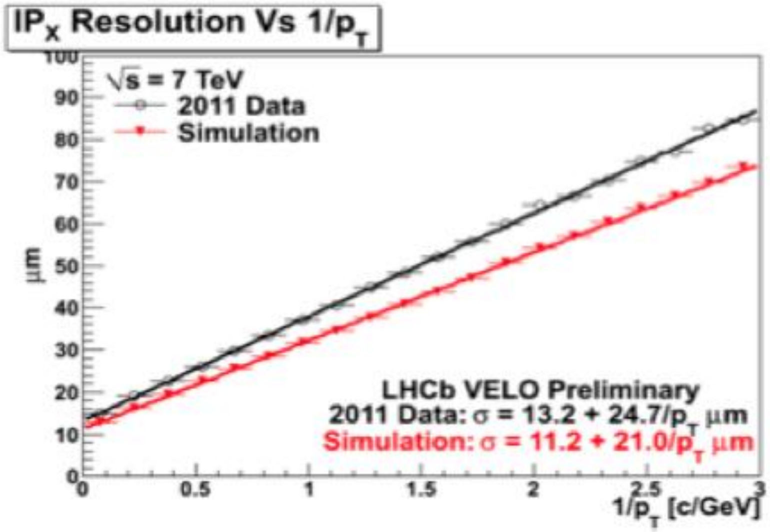
Alignment and impact parameter resolution

Stability of two half alignment ±5 μm/ ±2 μm in x/y
Method: reconstruct primary vertex with the two halfs





Impact parameter resolution for high p_t tracks 13 μm.



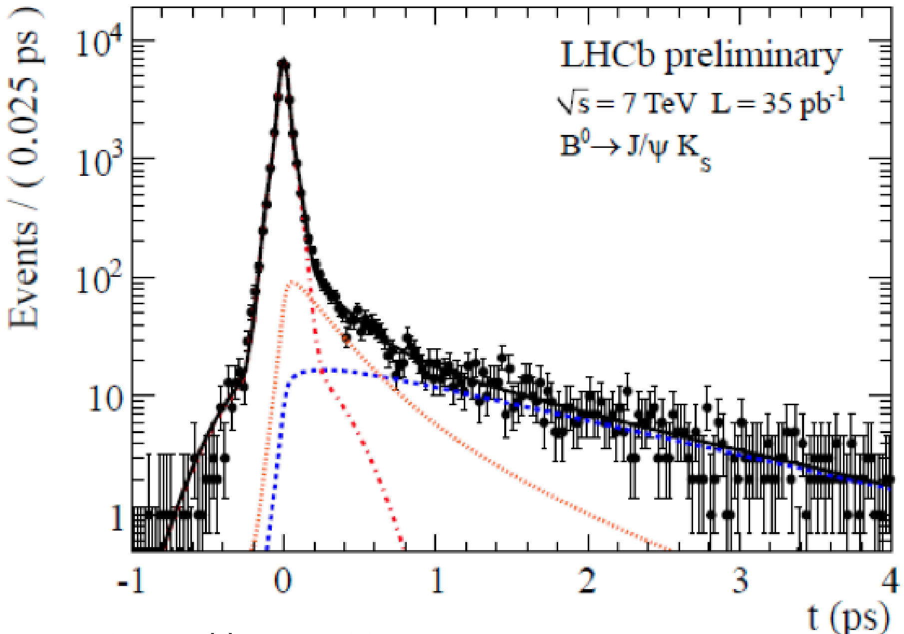
MC predicts 11μm

Discrepancy is under investigation (summer 2011)
Possible reasons are material description, alignment effects.

Time Resolution

Time resolution important, e.g. to measure $B_s^0 - \overline{B}_s^0$ mixing frequency.

Time resolution obtained from promt J/ψ = 50 fs !



S. Borghi, Vertex2011

More details in talk by Paula Collins.

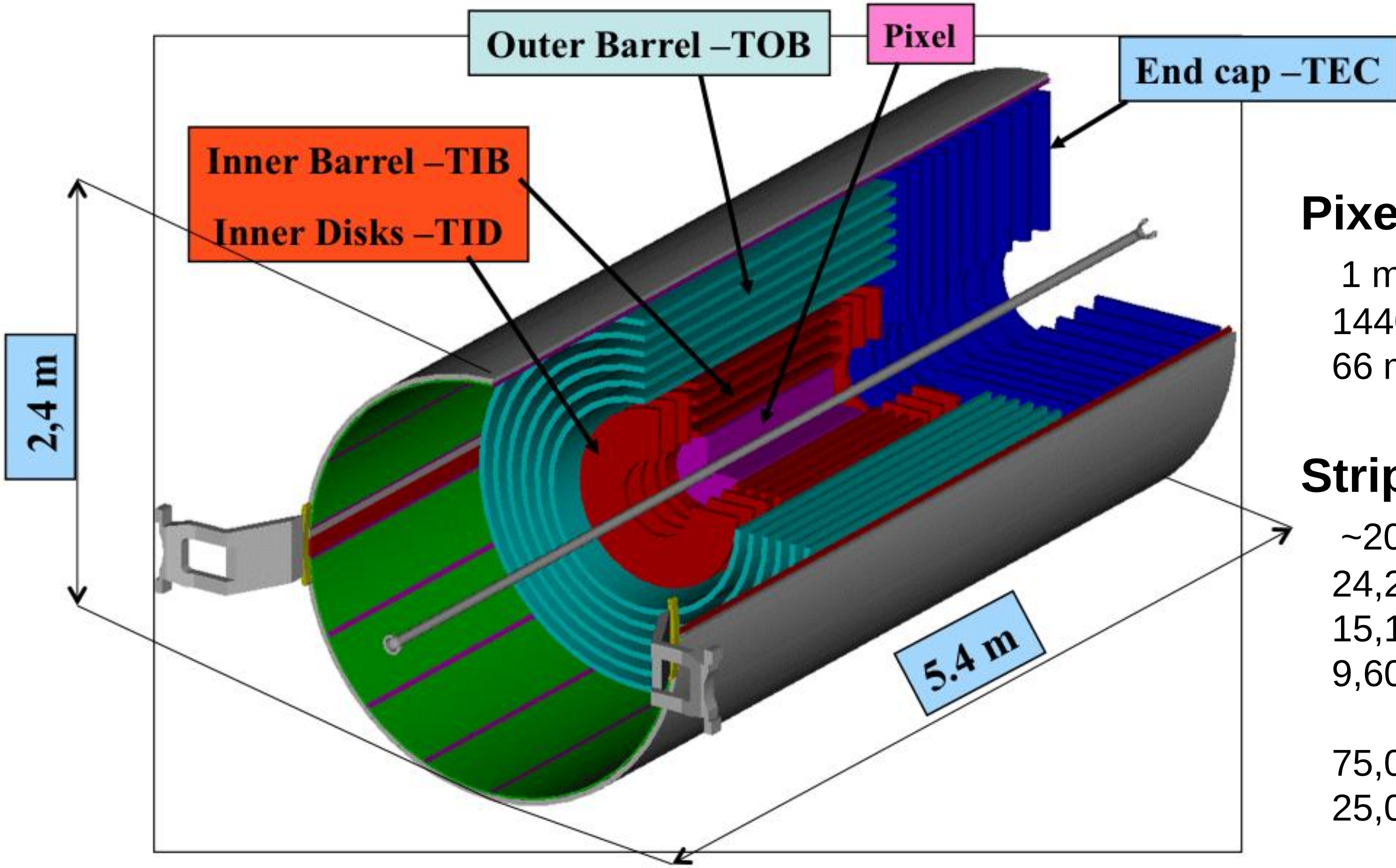
CMS

First experiment with full Silicon tracker system.

Largest Silicon Detector ever built.

+ Silicon strip sensors inside the preshower detector
Talk by Chia-Ming Kuo and poster by Kai-Yi Kao.

CMS Tracker



Pixel detector:

1 m^2 detector area
1440 pixel modules
66 million pixels

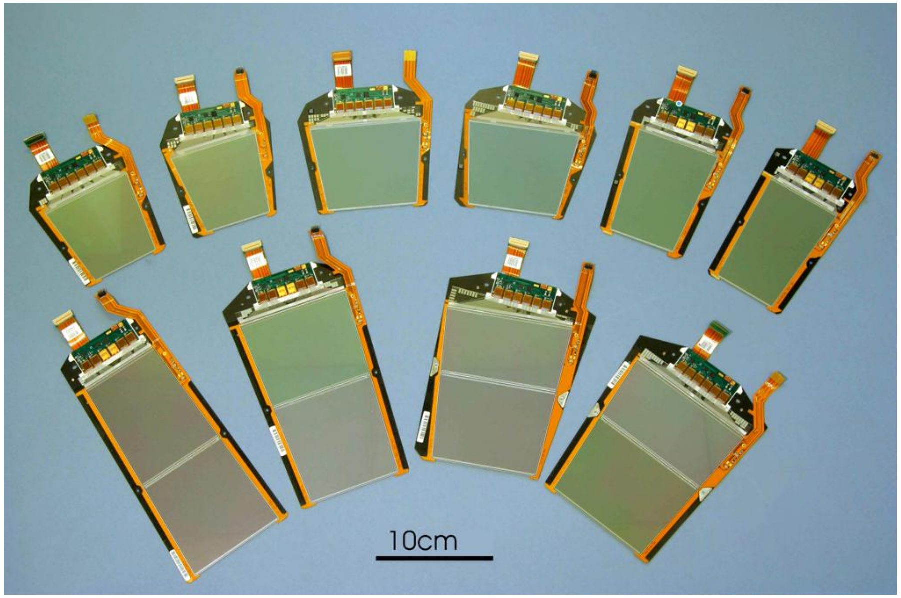
Strip detector:

~200 m^2 of silicon sensors
24,244 single silicon sensors
15,148 modules
9,600,000 strips
≡ electronics channels
75,000 read out chips (APV25)
25,000,000 Wire bonds

CMS Strip Detector

15148 modules in 27 mechanically different geometries – real mass production.

Examples for end cap geometries:



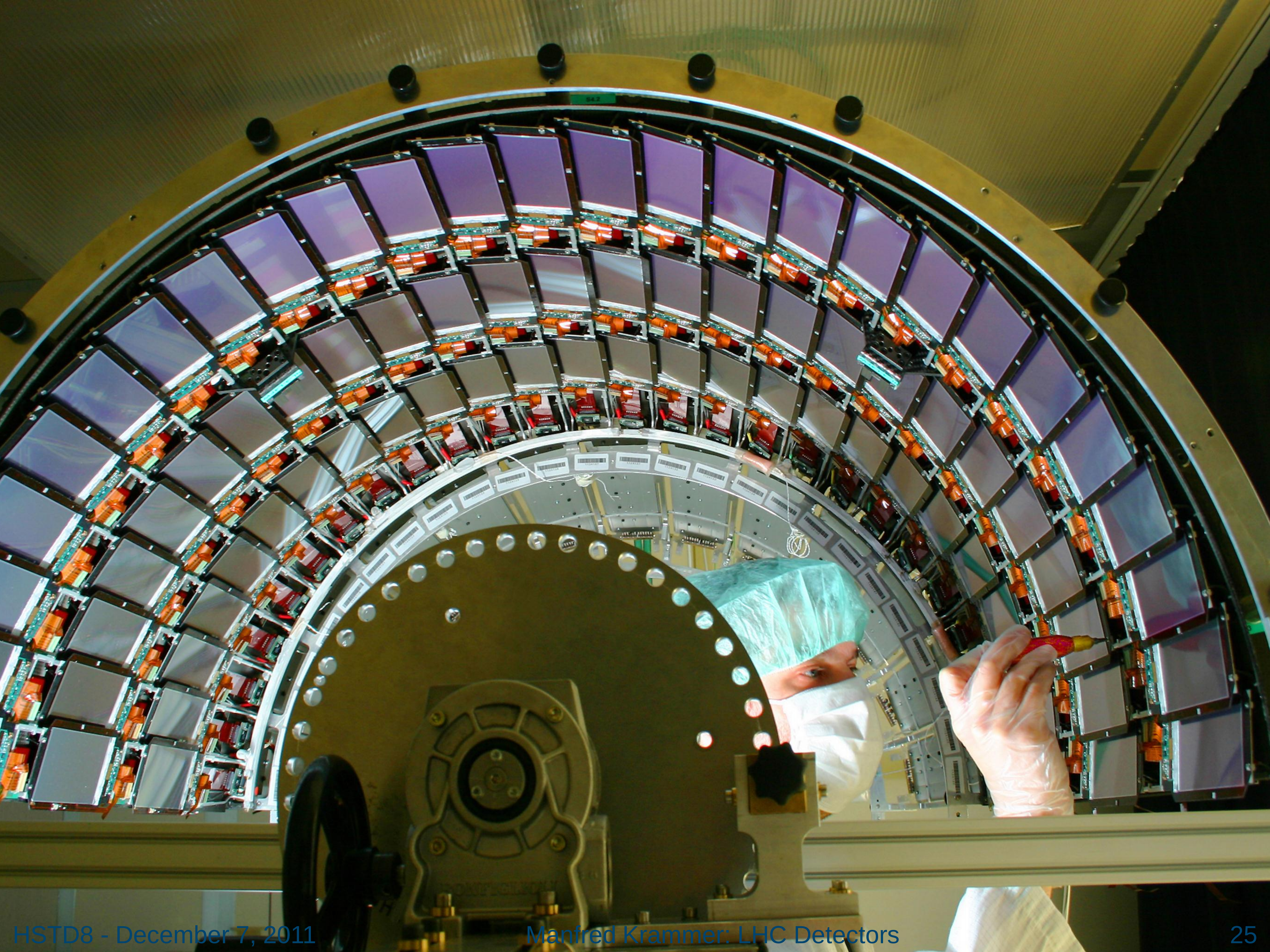
Single sided sensors:

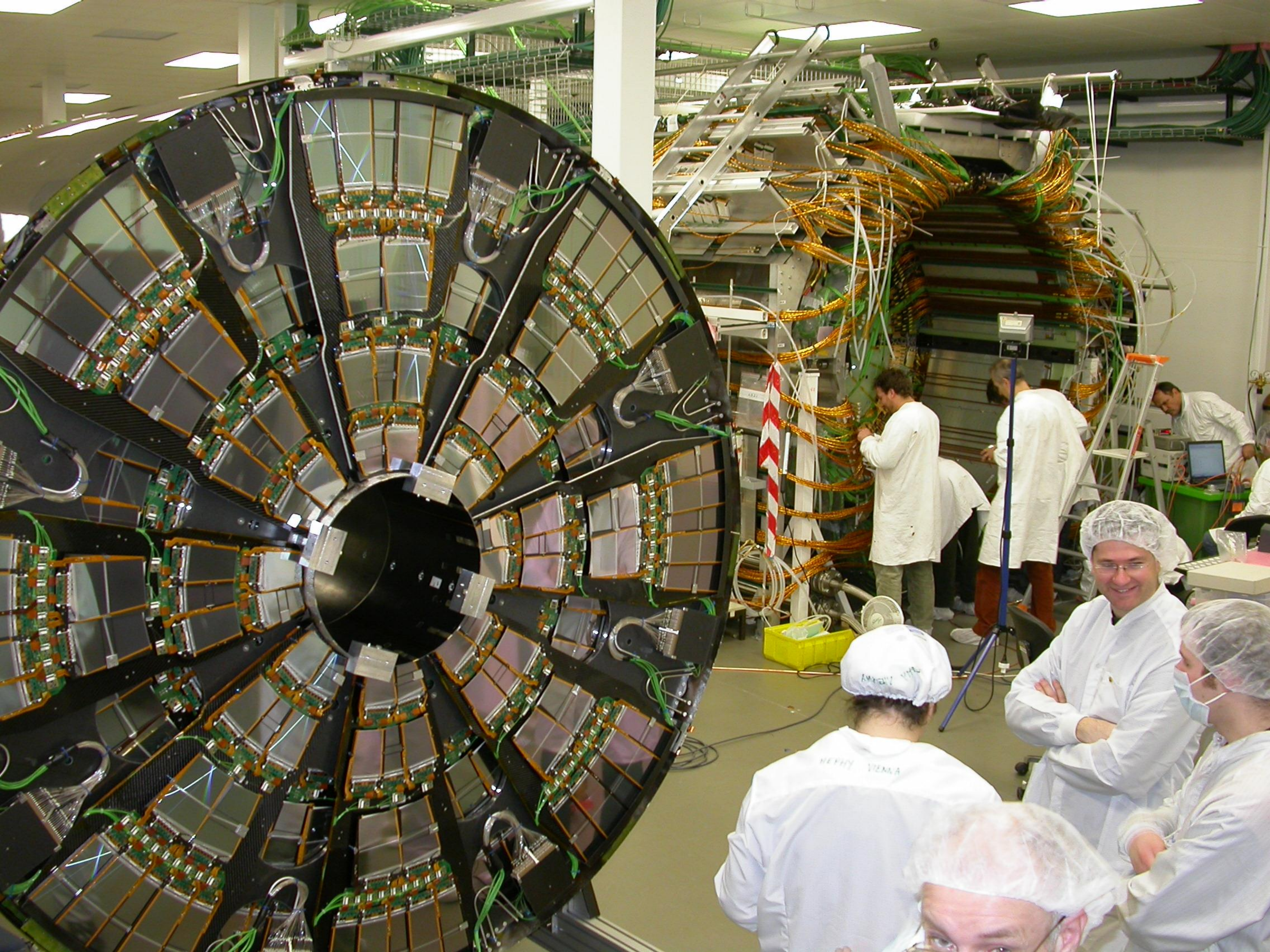
- p^+ on n
- thickness 320 µm and 500 µm
- two different wafer resistivities

Stereo modules with sensors back to back.

Cooling C_6F_{14} at present set to 4ºC. Some problems with leak rate (5 out of 90 cooling loops shut down)

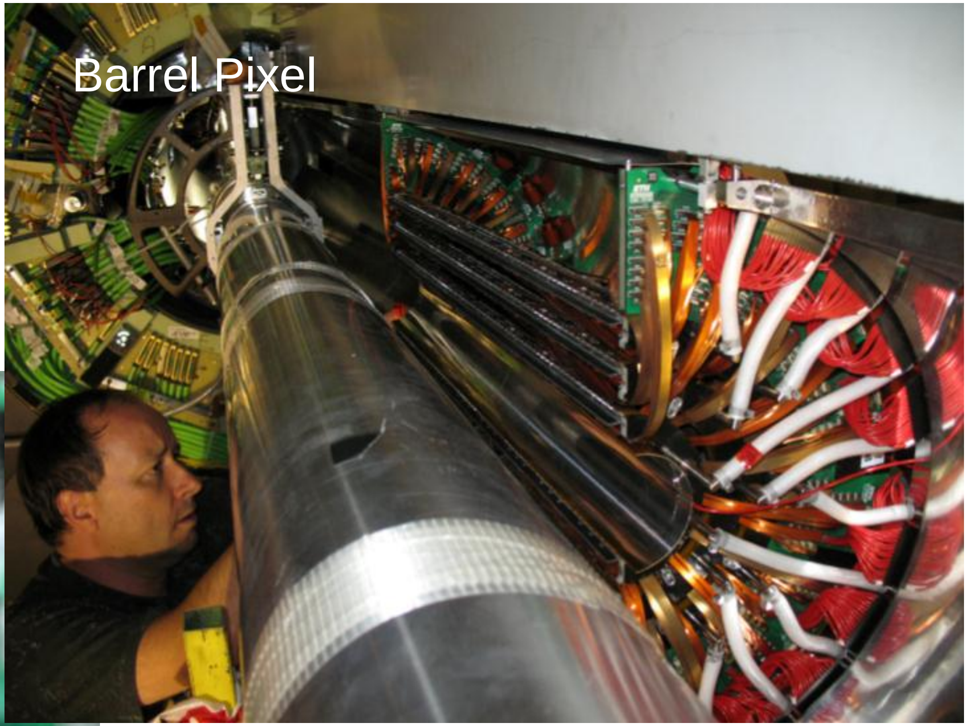
Status: 2.2% dead channels

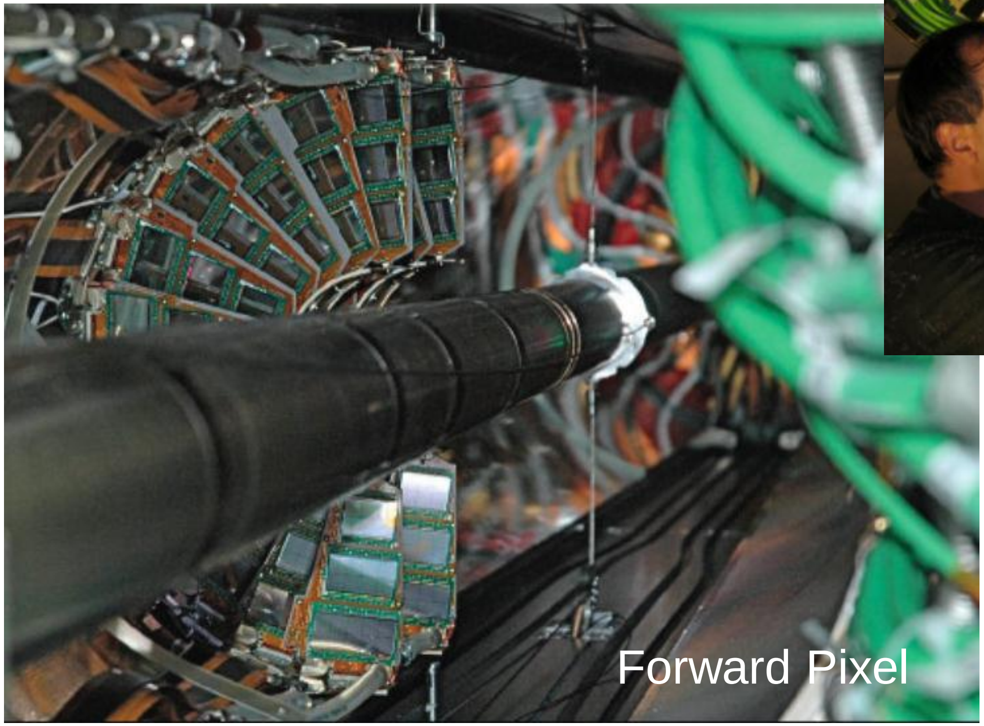



HEPHY VIENNA

CMS Pixel Detector

Pixel is inserted on rails.
→ can be extracted for maintenance
(done winter 2010)



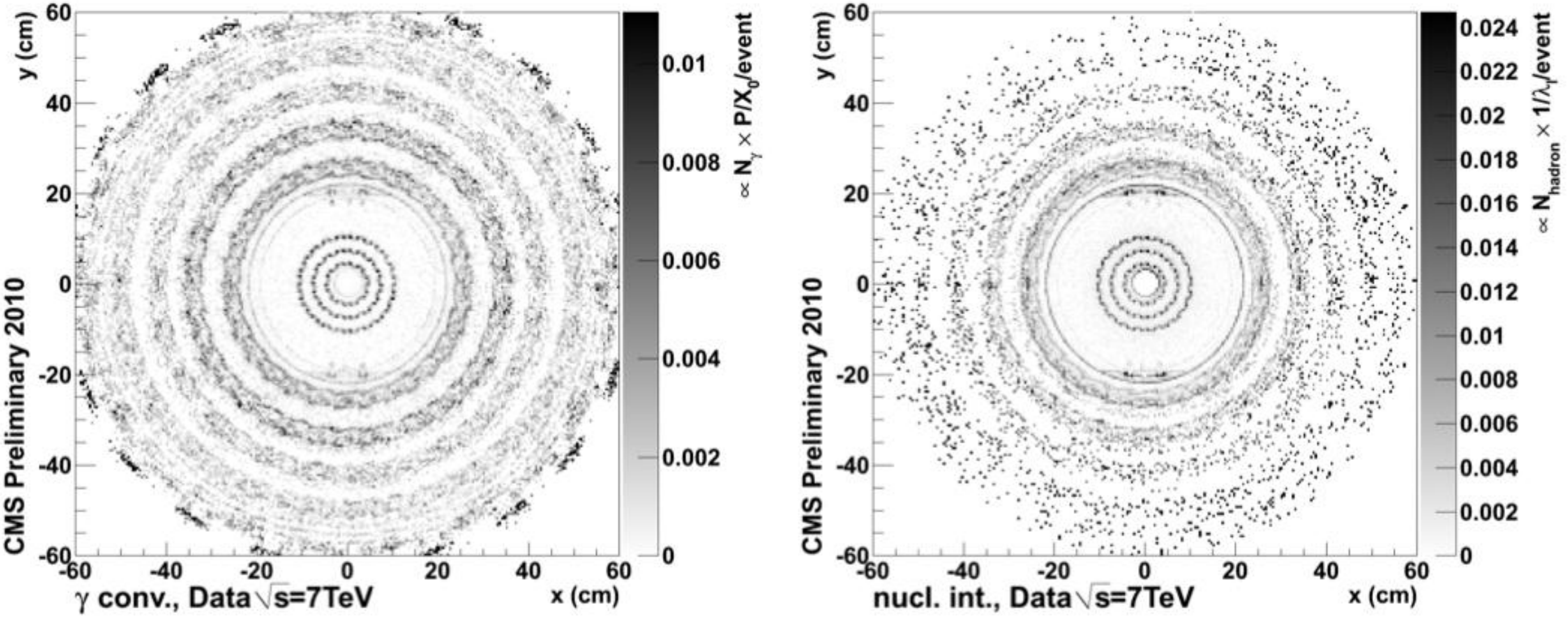


Pixel status: 96.9% functional ROCs (15324 from a total of 15840)

Frequent firmware updates necessary.

Probing Detector Description

Knowlege of material distribution of the tracker is crucial for physics analysis.
Use counting of photon conversions and nuclear interactions to probe material.



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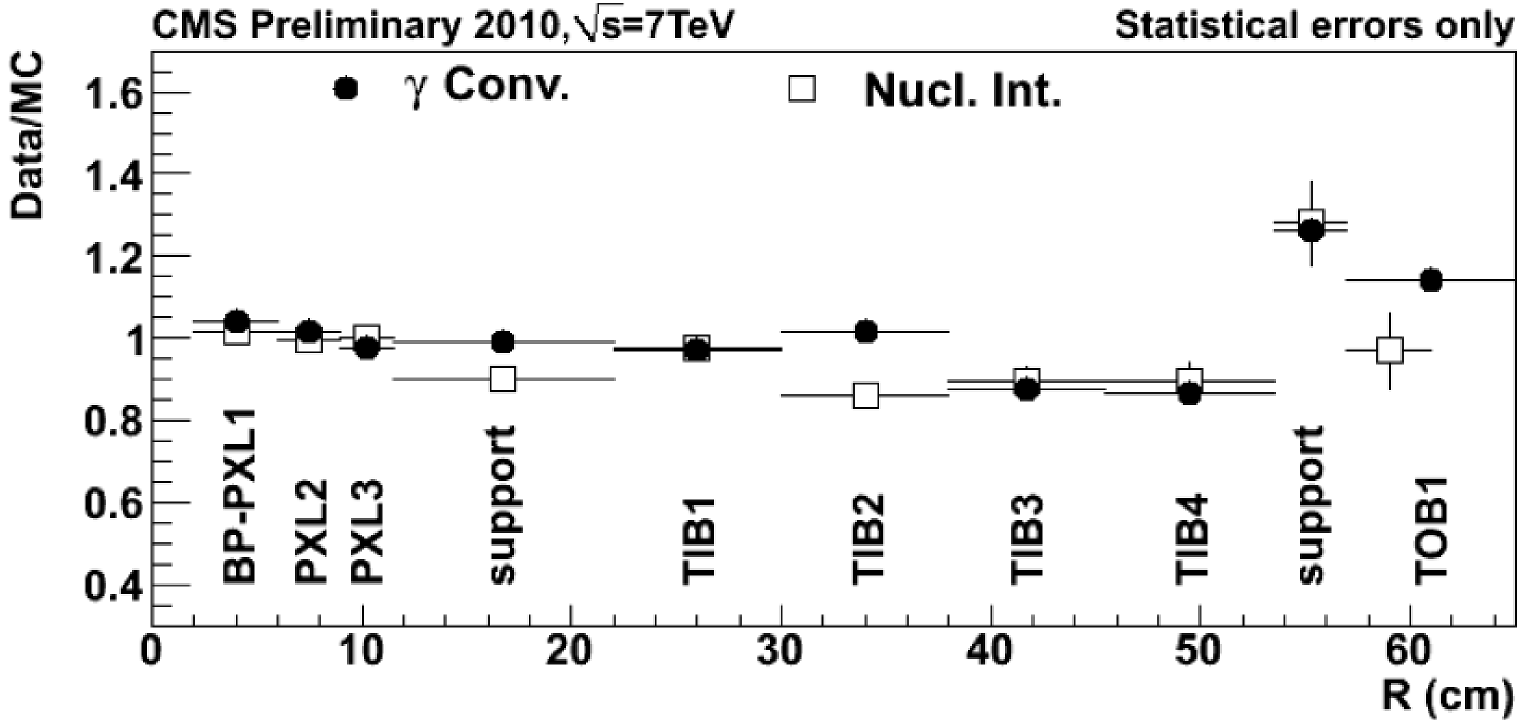


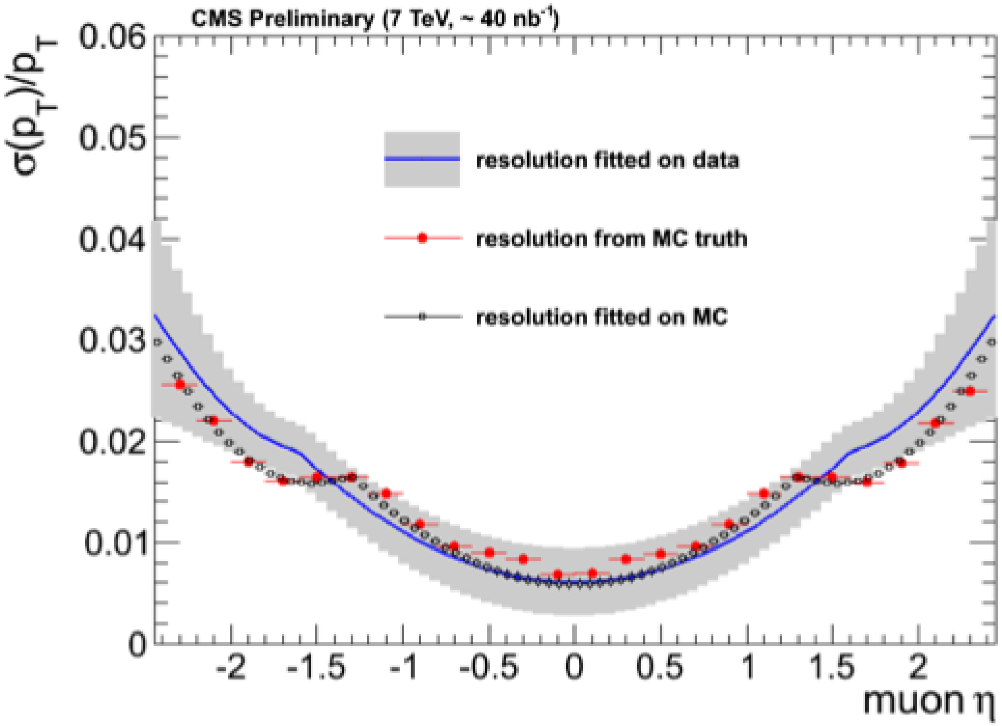
Good agreement within 10%!

CMS Tracker Performance

Resolution on transverse momentum measured using J/ψ mass line-shape. Tracks from J/ψ have on average a momentum of a few GeV. At this momenta the inner tracker dominates the momentum measurement.

Sensitive to:

- Knowledge of the tracker material
- Alignment
- B field
- Reconstruction algorithms



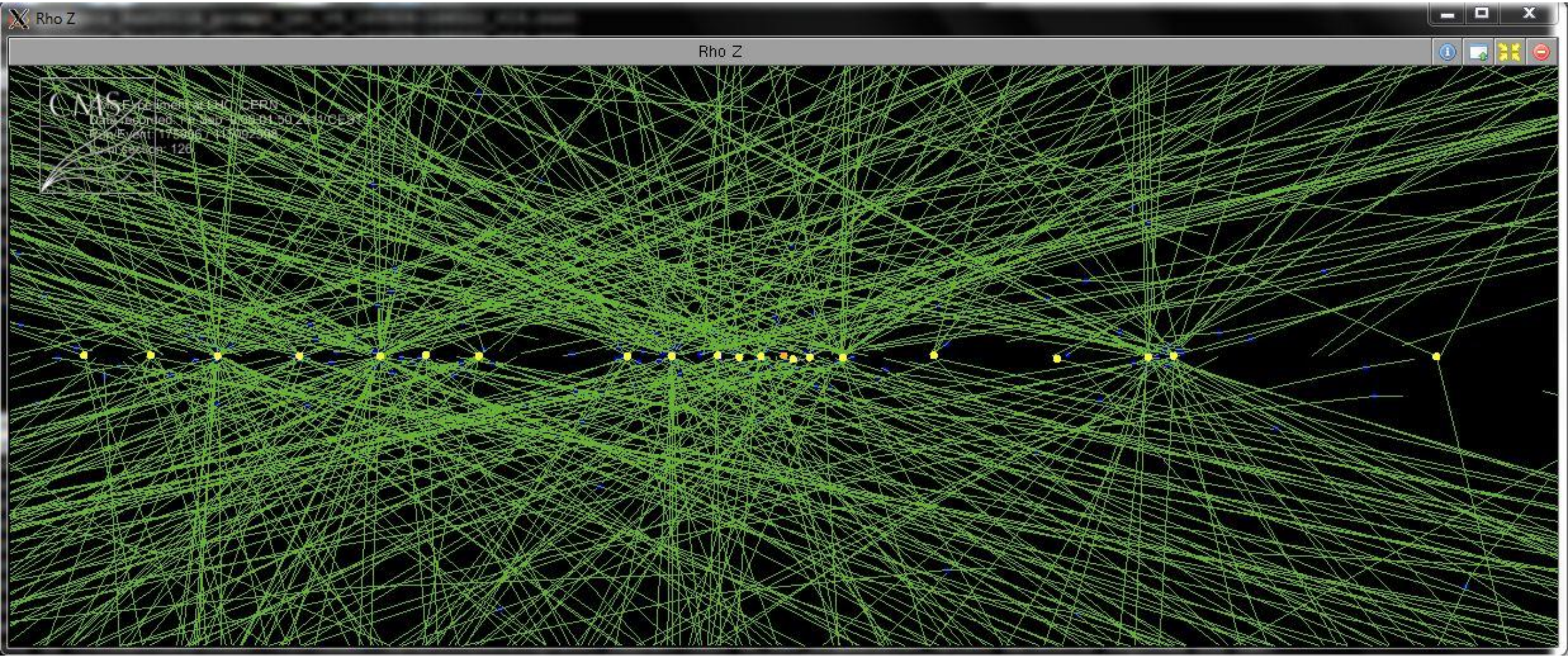
CMS PAS TRK-10-004

In general good agreement with MC (~5%, some deviation in the transition region of barrel to end cap).

More results in talk by Francesco Palmonari.

Tracking at High Pile Up

Event with 20 vertices:



~ 10 cm

And all vertices nicely reconstructed........

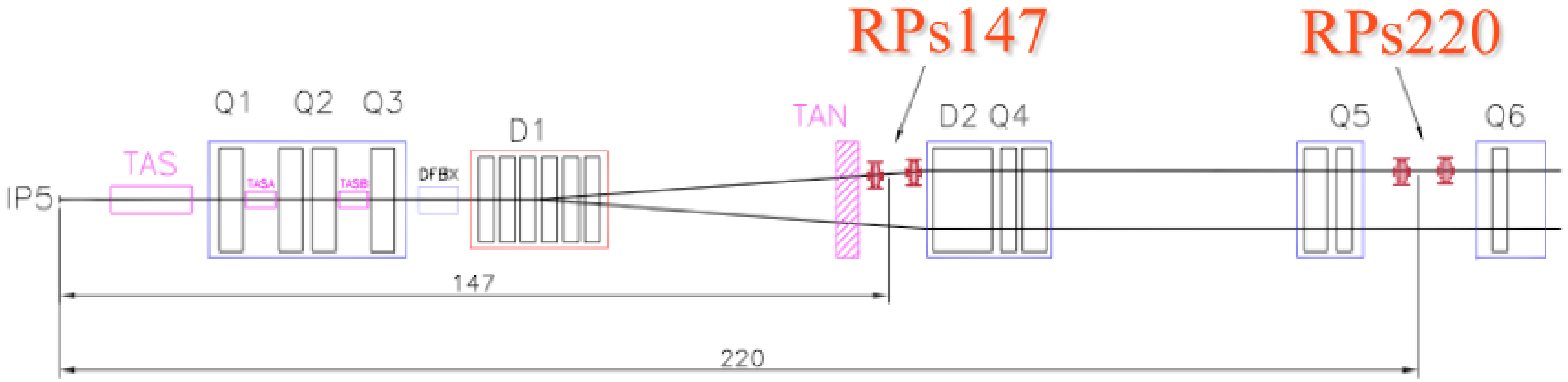
TOTEM

Last but not least..........TOTEM

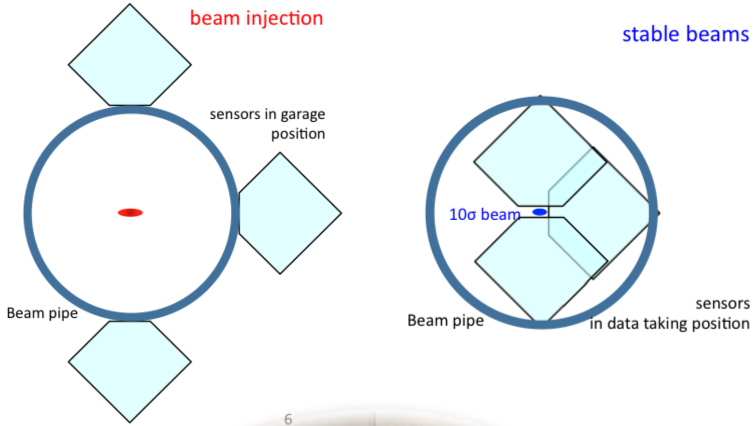
TOTEM is dedicated to the measurement of the total cross section, elastic scattering and diffraction dissociation at the LHC.

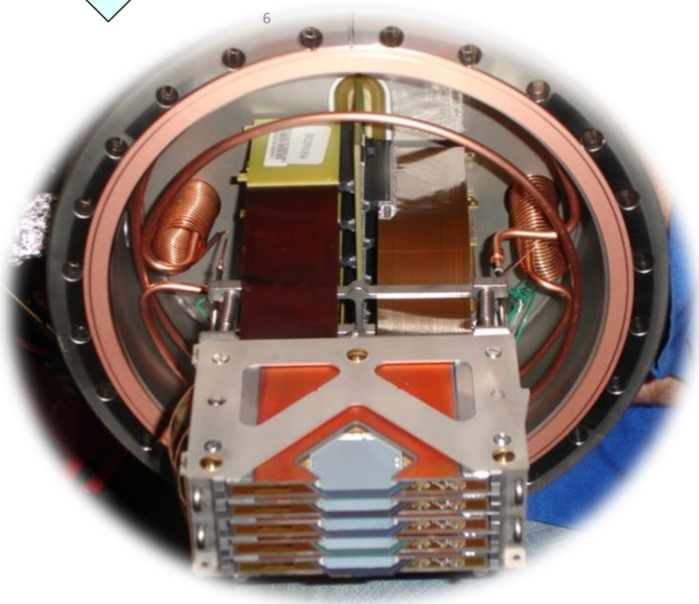
Cathode strip chambers at 10.5 m, Triple GEMs at 14 m

AND **silicon sensors in Roman Pots at 147 m and 220 m** from the interaction point (IP5 CMS).

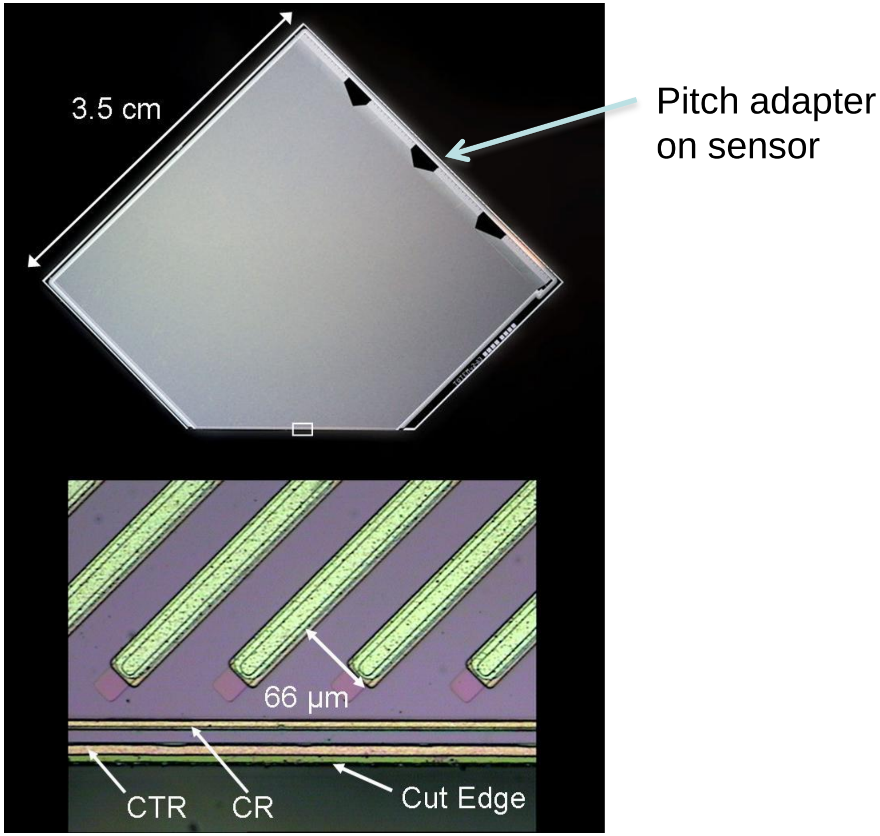


TOTEM Edgeless Sensors





240 edgeless sensors
122880 readout channels
Active strips only 50 µm from edge



Closest approach of the system foreseen: 10σ of the beam.

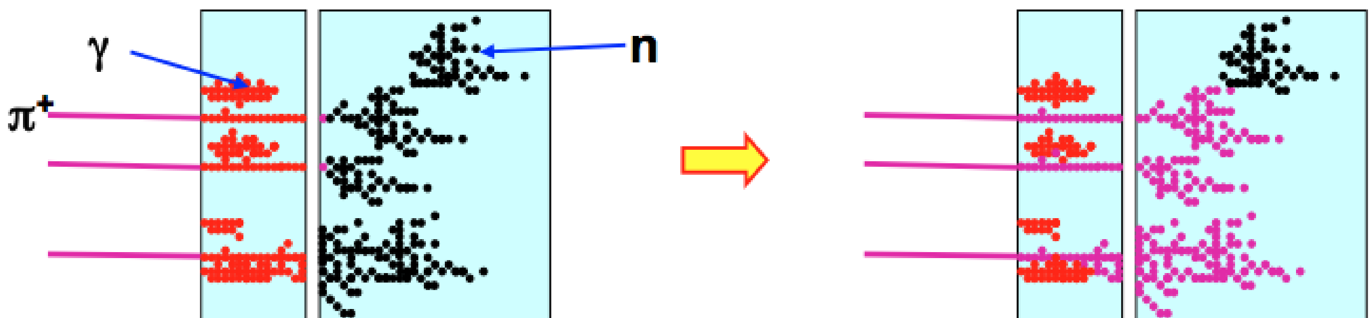
Summary

Experiment	Detector	Silicon Area m²	Nr. of channels Millions
ATLAS	SCT	61	6,27
	Pixel	2,2	80
ALICE	SPD	0,21	9,8
	SDD	1,31	0,133
	SSD	5	2,6
LHCb	VELO	0,0055	0,172
	TT	8,2	0,143
	IT	4,2	0,129
CMS	Pixel	1	66
	SST	200	9,6
	Preshower	16	0,137
TOTEM		0,294	0,123
LHC total		**300 m^2**	**175 Million**

Particle Flow

Reconstruct all particles and combine the information from tracking with the measurements in the electromagnetic and hadron calorimeter
→ improve measurement of Jet energy, MET, Tau identification.

Particles in jets	Fraction of energy in jets	Detectors	Single particle resolution (CMS)
Charged Hadrons	**65 %**	**Silicon Tracker**	**$\sigma_{pt}/p_t \sim 1\%$**
Photons	25 %	Elm. calorimeter	$\sigma_E/E \sim 2{,}8\%/\sqrt{E}$
Neutral Hadrons	10 %	Elm. and had. calorimeter	$\sigma_E/E \sim 100\%/\sqrt{E}$

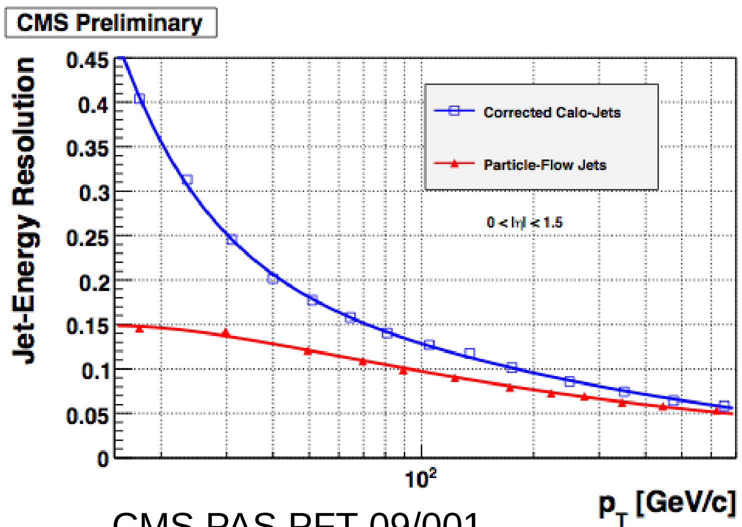


Calorimetry only: $E_{JET} = E_{ECAL} + E_{HCAL}$

Particle Flow: $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

Particle Flow vs. pure Calorimetry

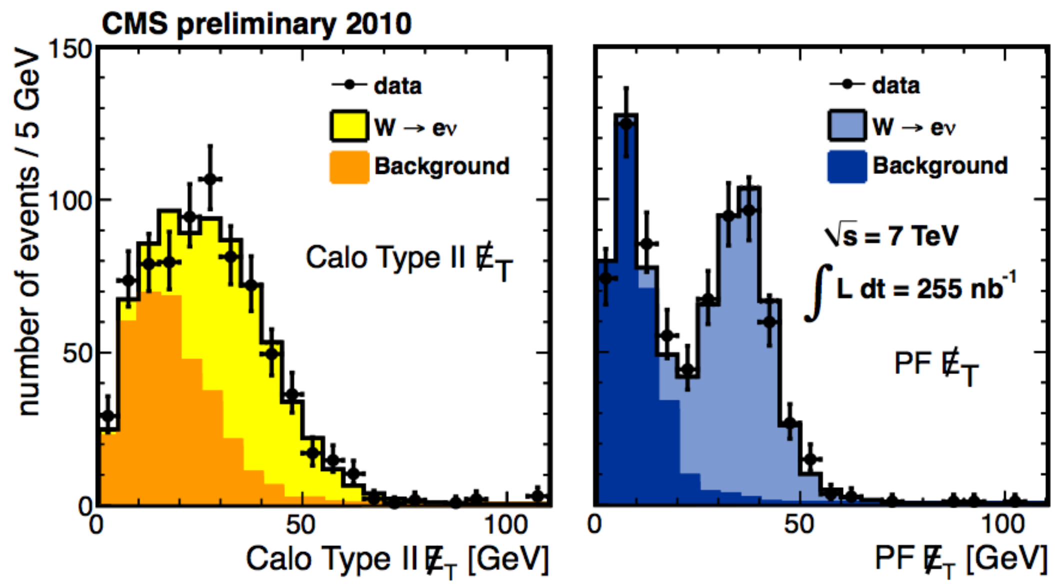
Jet energy resolution (MC):



CMS PAS PFT-09/001

MET distribution in W → eν candidate events (Data and MC):

Calorimeter MET: Particle Flow MET:



CMS PAS JME-10-005

Silicon trackers improve Jet, Tau and Missing E_t measurements as well !

Conclusion

• All LHC experiments have installed large to very large silicon tracking systems - probably larger and more sophisticated than most optimistic physicists have dreamed 25 years ago!

• Silicon systems operating very succesfull and stable with low number of dead channels – except various cooling problems – was this component underestimated?

• Physics performance reaching design figures and even better – see following talks.

THANK YOU FOR YOUR ATTENTION !