PH Detector Seminar - Friday, February 6, 2009

Vertex Detectors at LHC

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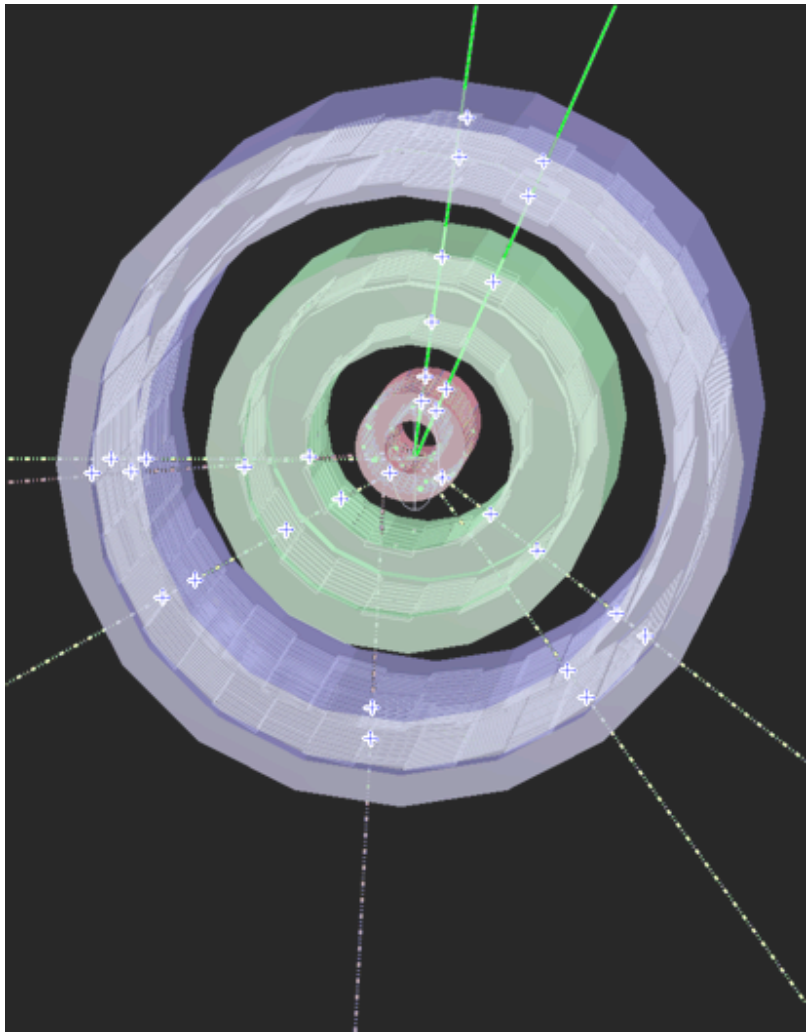
CERN/PH-AID-DT

ALICE Experiment

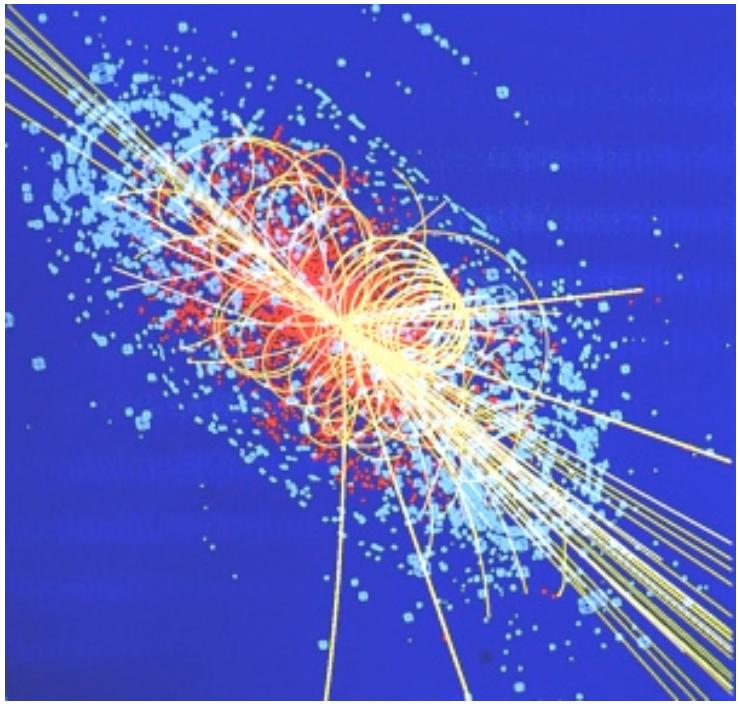


Outline

- LHC vertex detectors overview
- The innermost layers - hybrid pixel detectors
- Wish list for vertex detectors
  - Radiation issues
  - Material budget
- Summary and Thanks

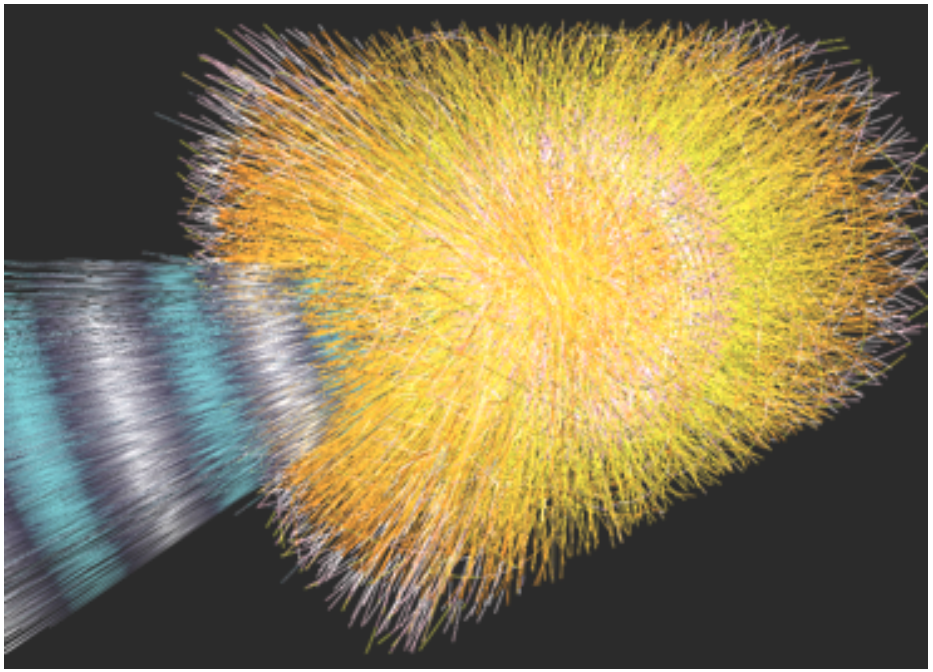
LHC Vertex Detectors Overview

Vertex Detectors at LHC have to comply with different environments and have to meet many technical challenges.



CMS: simulated Higgs decay

http://cms-project-cmsinfo.web.cern.ch/cms-project-cmsinfo/Media/Images/Gallery/Events/Simulations/Higgs/index.html

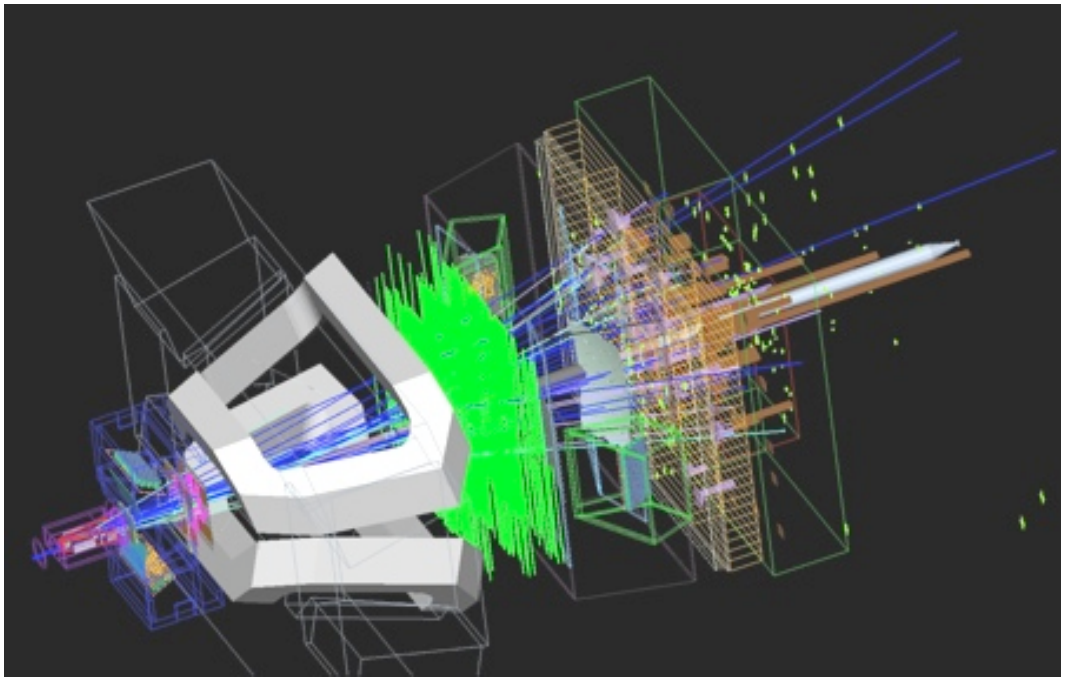


ALICE: simulated Pb-Pb event

http://mediaarchive.cern.ch/MediaArchive/Photo/Public2/photo-bul/bul-pho-2007-073.jpg

Some Physics Questions to be Answered at LHC

- Higgs mechanism
- Supersymmetry
- CP-Violation
- Chiral symmetry breaking
- Deconfinement
- .....

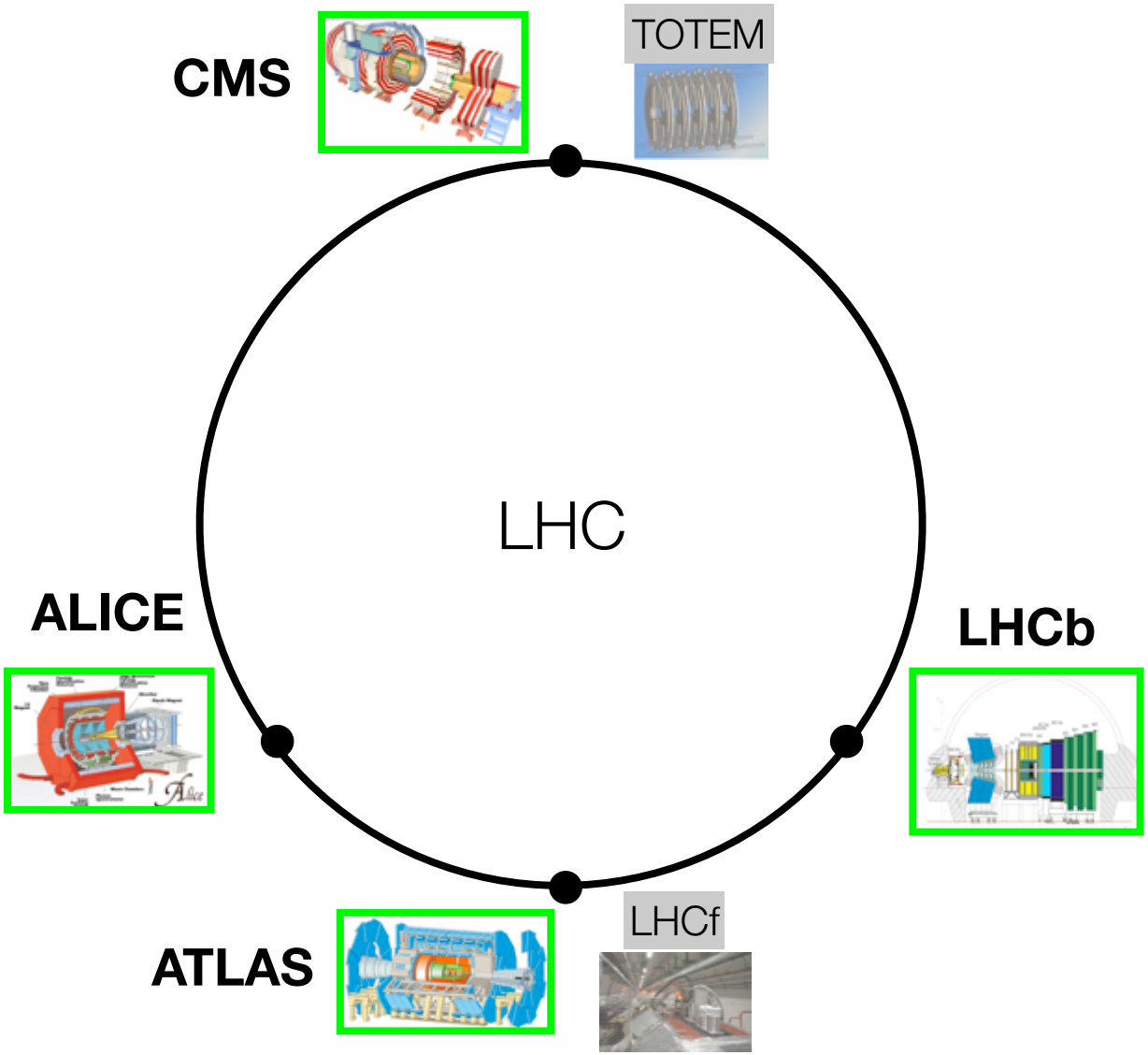


LHCb: simulated Bs to J/psi Phi event

http://cdsweb.cern.ch/record/1123158

…questions will almost all be addressed by all experiments, however specific ones are of central interest to each experiment

LHC Experiments



References

- The ATLAS Experiment at the CERN Large Hadron Collider (The ATLAS Collaboration), G. Aad et al 2008 JINST 3 S08003

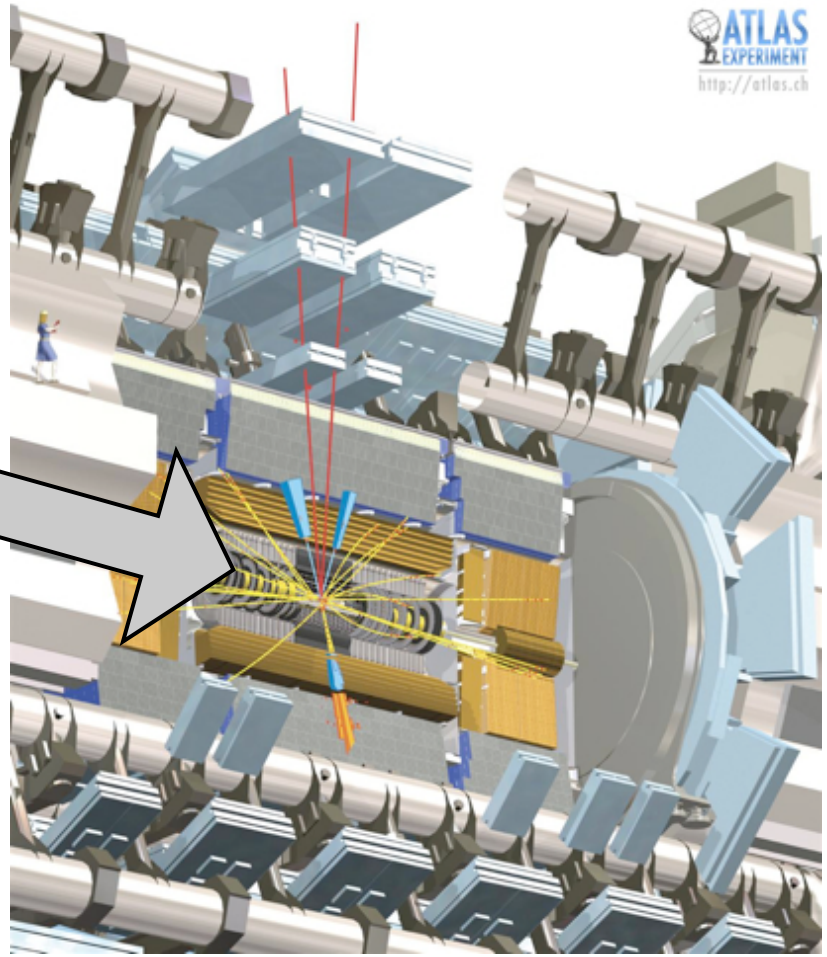
- The CMS experiment at the CERN LHC (The CMS Collaboration), S. Chatrchyan et al 2008 JINST 3 S08004

- The ALICE experiment at the CERN LHC (The ALICE Collaboration), K Aamodt et al 2008 JINST 3 S08002

- The LHCb Detector at the LHC (The LHCb Collaboration), (JINST), A. Augusto Alves et al. 2008 JINST 3 S08005

Vertex Detectors

Look only at innermost layers



http://cdsweb.cern.ch/record/1096079

Vertex Detectors at LHC

- All 4 large experiments use silicon detectors as vertex detectors.
- In ALICE, ATLAS and CMS the innermost layers are made of silicon pixel detectors and of silicon strip layers at larger radii.
- **High luminosity and high multiplicity environment. Pixel detectors keep occupancy at few % level.**

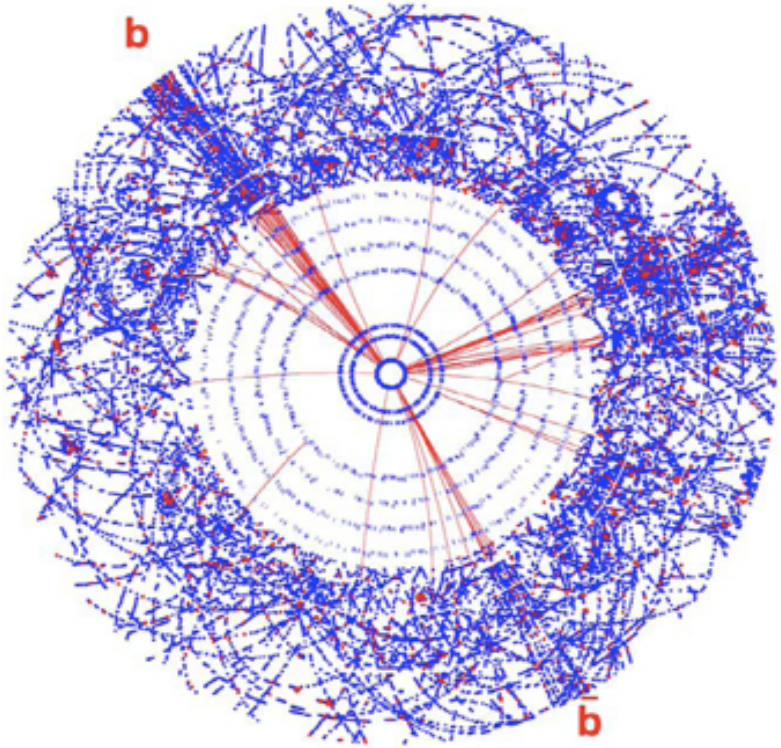
  Example:

  ALICE pixel inner layer: max. occupancy for central Pb-Pb 2.1% (max. 8000 tracks/|η| at mid-rapidity)
- **Cost limits the use of current pixel systems at larger radii.**

ATLAS Barrel Inner Detector

$H \rightarrow b\bar{b}$

at design luminosity 10^{34} cm^{-2} s^{-1}



http://instrumentationcolloquium.lbl.gov/The_ATLAS_pixel_detector.pdf

Choices on Silicon Vertex Detectors

Physics and experimental conditions determine choices, e.g.:

- **Granularity**
- **Radii of the layers**
- **Number of layers**
- **Readout electronics**
- **Radiation tolerance**
- **Material budget**
- **....**

Next slides:
Summary and comparison of some key parameters

https://lhcb-vd.web.cern.ch/lhcb-vd/images/pparcphotos/album/slides/LHCb_054.html

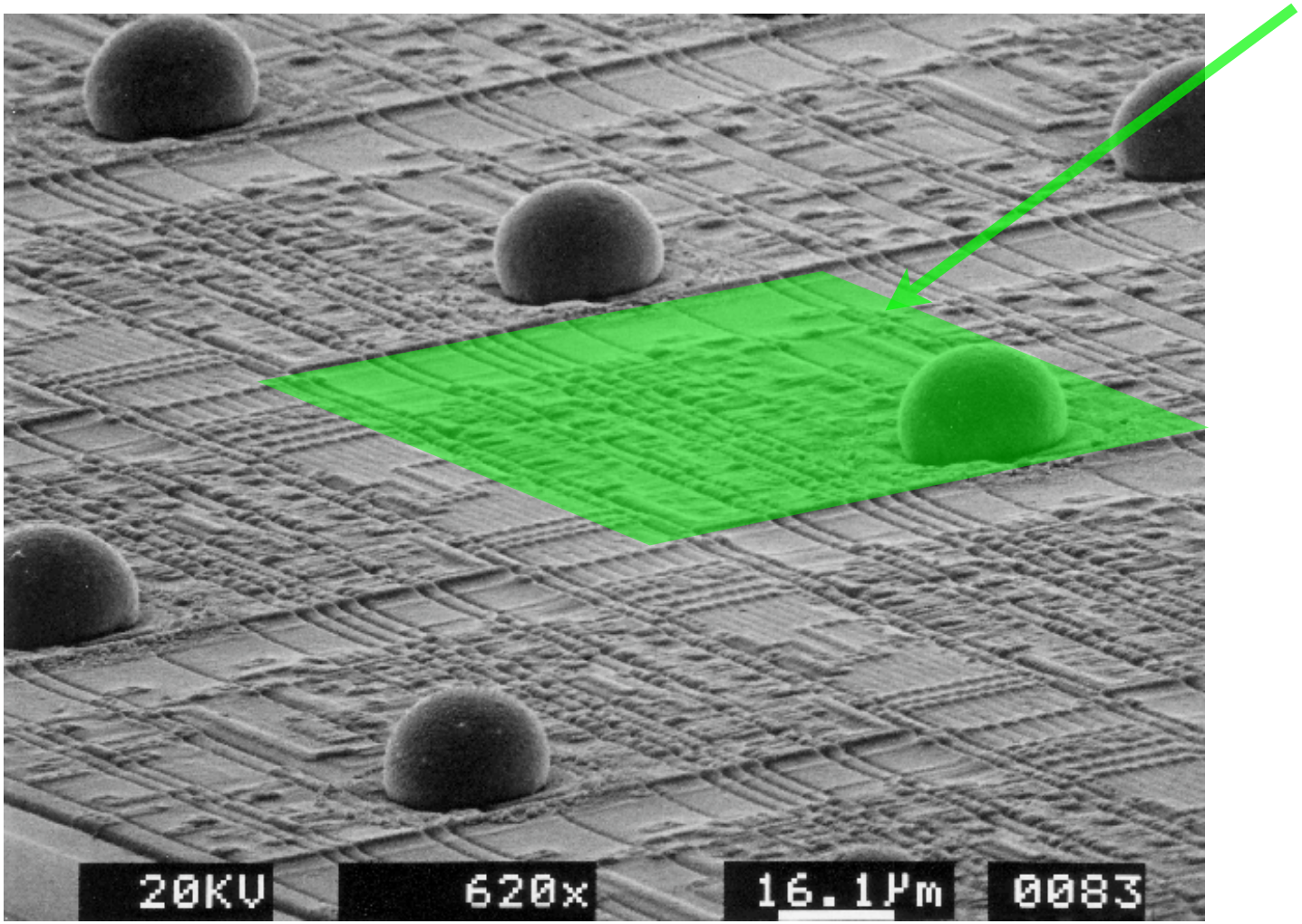
Granularity

Innermost Barrel Layers (Pixel):

Pixel Size	z [μm]	Rφ [μm]
ALICE	425	50
ATLAS	400	50
CMS	150	100

- Adequate spatial resolution
- Smaller in rφ to match with magnetic field direction
- Partially governed by space requirements for electronics

CMS Silicon Pixel Detector



One readout pixel cell (100 µm x 150 µm)

PSI_30 chip with In bumps

R. Horrisberger/PSI

Silicon Layers

Innermost Barrel Layers (Pixels):

	#	radius [mm]	beampipe inner radius (wall thickness) [mm]
ALICE	2	**39** - 76	29 (0.8)
ATLAS	3	**50.5** - 88.5 - 122.5	29 (0.8)
CMS	3	**44** - 73 - 102	29 (0.8)

- The LHCb VELO is a forward geometry strip detector which uses 42 stations along z with an inner radius of 7 mm.
- ATLAS and CMS also use forward pixel detector disks.
- ALICE uses 2 layers of silicon drift detectors between the pixel and strip layers at radii of 150 mm and 239 mm.

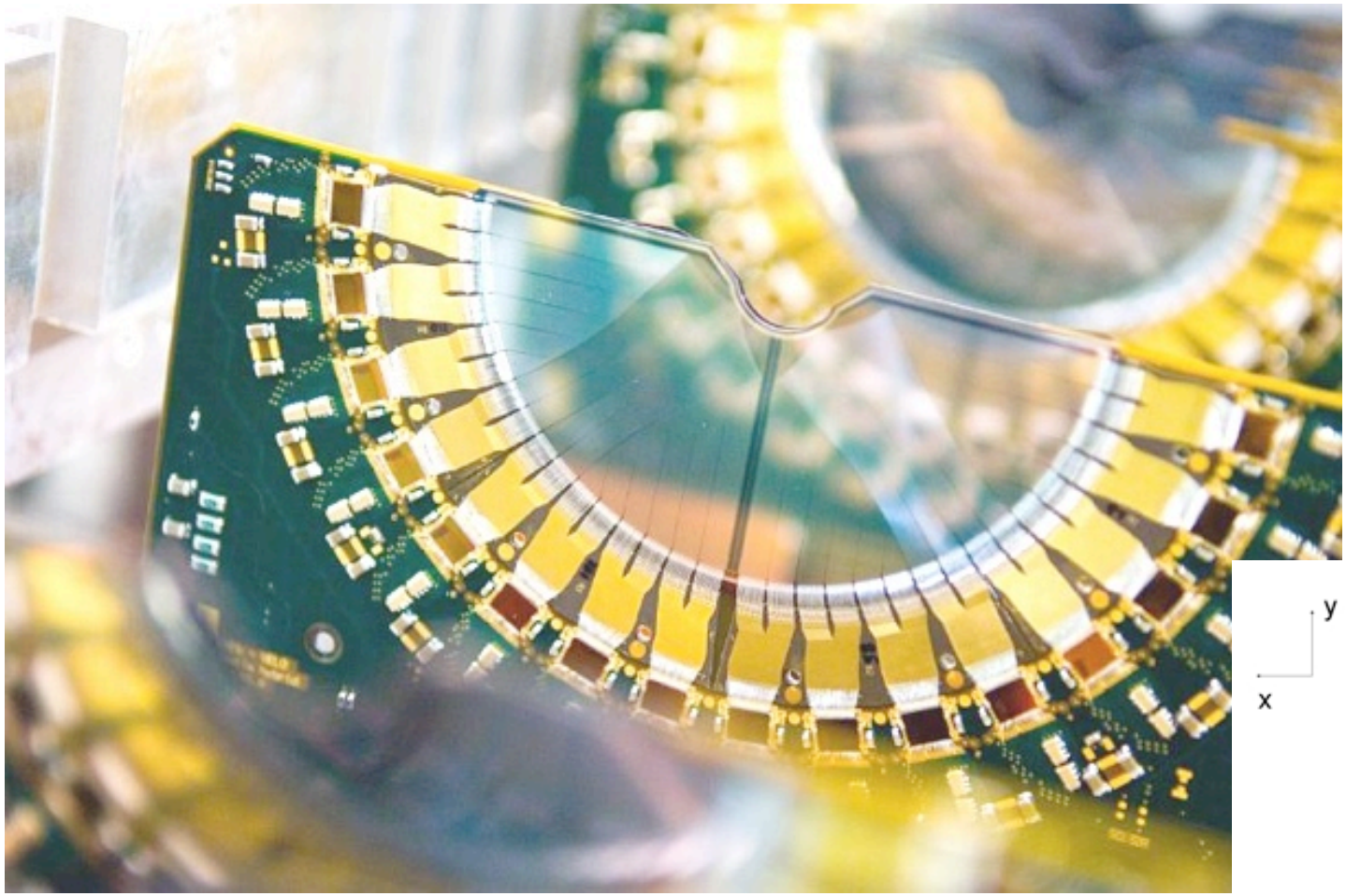
ALICE Silicon Pixel Detector

Inner Layer (average r=39 mm)

staggered mounting of modules around the beampipe

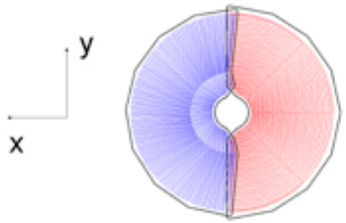
Minimum clearance of closest components to beampipe: ~5 mm

LHCb VELO



Silicon strip detectors
R and φ strips

2 detector halves
movable wrt to beam
position



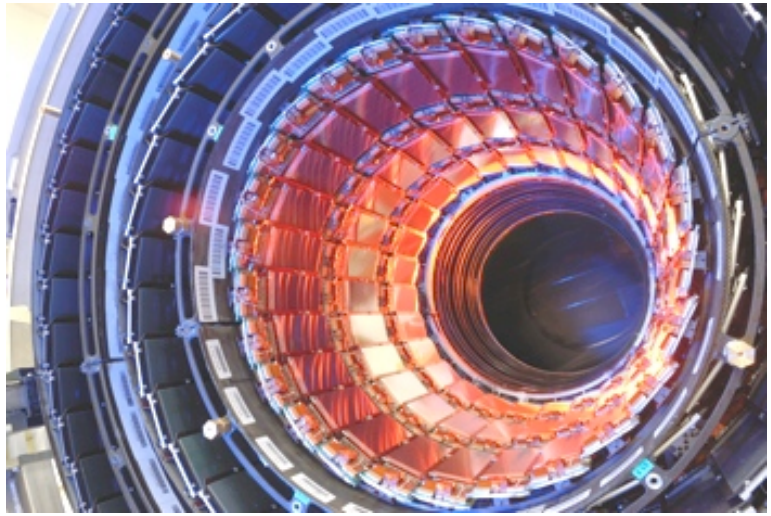
VELO fully closed
(stable beam)

https://lhcb-vd.web.cern.ch/lhcb-vd/images/pparcphotos/album/slides/LHCb_108.html

Silicon Layers

Strip Detector - Barrel Layers

	#	radii [mm]
ALICE	2	380 - 430
ATLAS	4	299 < R < 514
CMS	4+6	255 < R < 1080



CMS Tracker Inner Barrel

http://cms-project-cmsinfo.web.cern.ch/cms-project-cmsinfo/Media/Images/Gallery/Tracker/TIB/index.html

ATLAS and CMS also use forward pixel and strip detector disks.

Spatial Resolution σ(z), σ(Rφ)

Pixel Detectors - Barrels

	[μm]	pixel cell size z x Rφ [μm^2]
ALICE	100 (z); 12 (Rφ)	425 x 50
ATLAS	115 (z); 10 (Rφ)	400 x 50
CMS	~ 15-20	150 x 100

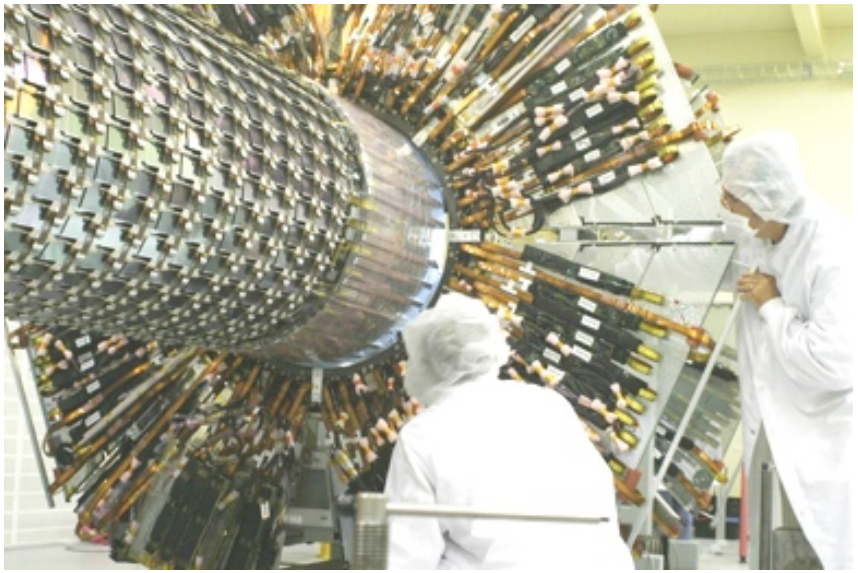
- Intrinsic resolution
- CMS and ATLAS have analog information
- ALICE uses binary readout
- Will be operated in magnetic field:
  ALICE: 0.5 T
  ATLAS: 2 T
  CMS: 4T
- Different sensor thicknesses (200-285 μm)

Spatial Resolution σ(Rφ), σ(z)

Strip Detectors - Barrels:

	[μm]	pitch [μm]
ALICE*	830 (z); 20 (Rφ)	95
ATLAS	580 (z); 17 (Rφ)	80
CMS	~23-52 (Rφ); (z)	80 to 183

* ALICE uses double sides strip detectors

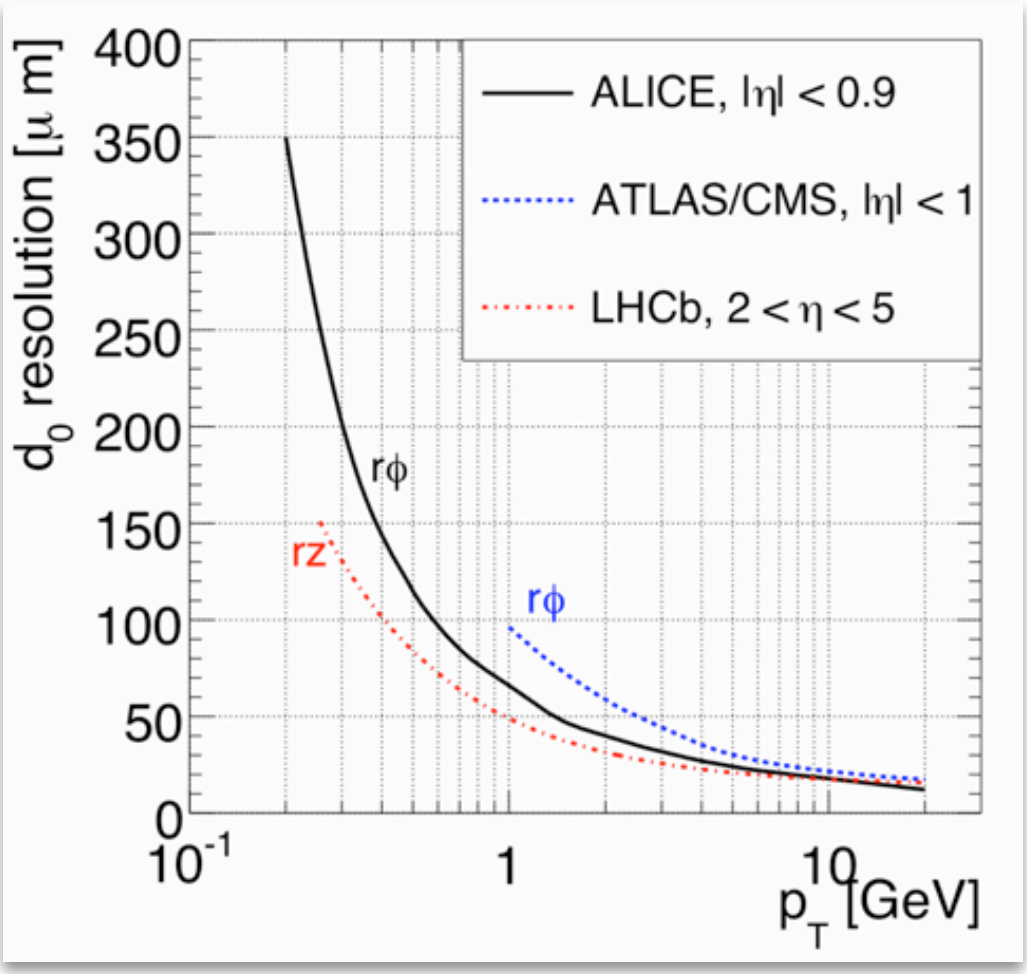


ATLAS SCT Barrel

http://atlas.ch/photos/inner-detector-sct.html

Impact Parameter Resolution

$\sigma_{d0} \cong \sigma_{\text{detector resolution}} \oplus \sigma_{\text{multiple scattering}}$



S.Alekhin et al.
HERA and the LHC - A workshop on the implications of HERA for LHC physics:Proceedings Part B, arXiv:hep-ph/0601013.

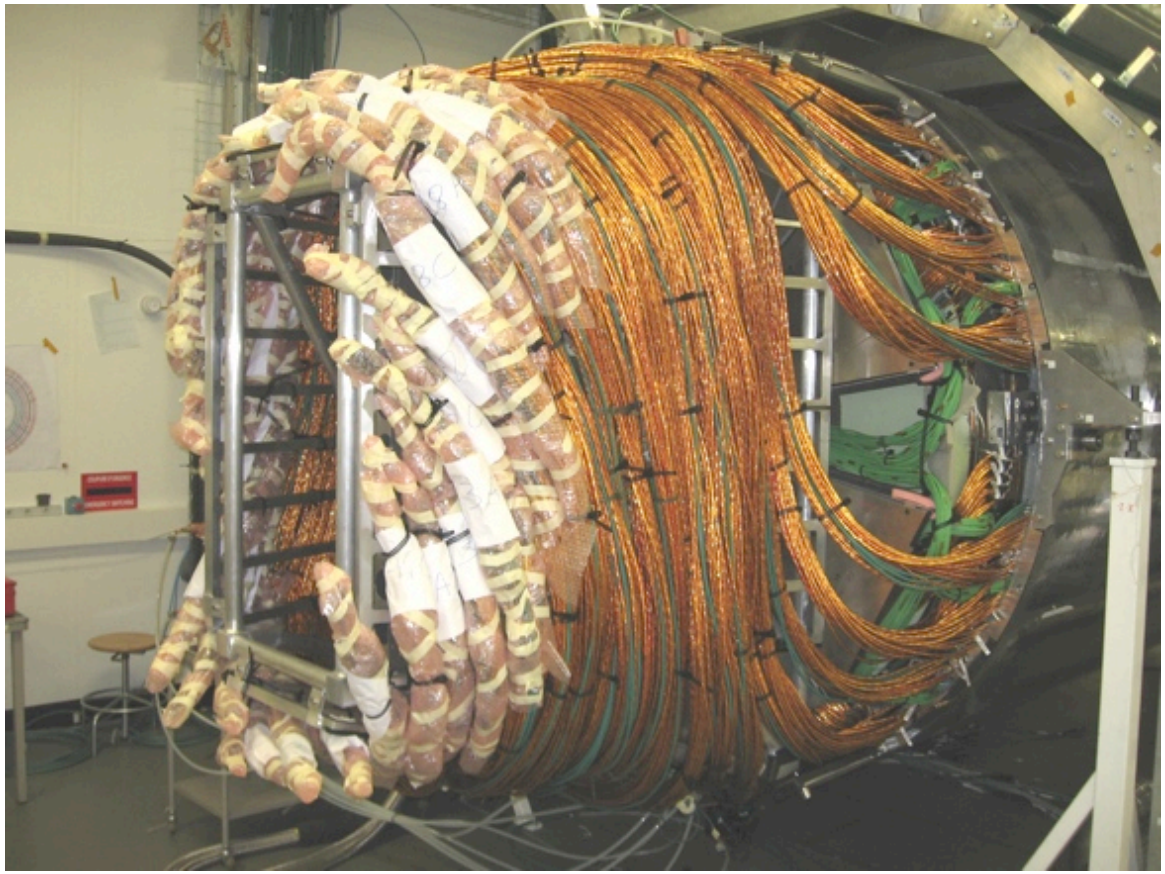
Inner Tracking Systems (Silicon) - Channels and Area

	ALICE	ATLAS	CMS	LHCb (VELO)
Total Area [m^2]				
Strips	5	61	198	0.2
Drift	1.3			
Pixels	0.2	1.8	1	
Number of Channels [x 10^6]				
Strips	2.6	6.3	9.3	0.17
Drift	0.13			
Pixels	9.8	80.4	66	

ALICE Pixels - CMS Tracker (Area)

CMS Tracker

ALICE Pixel



http://cms-project-cmsinfo.web.cern.ch/cms-project-cmsinfo/Media/Images/Gallery/Tracker/Full/index.html

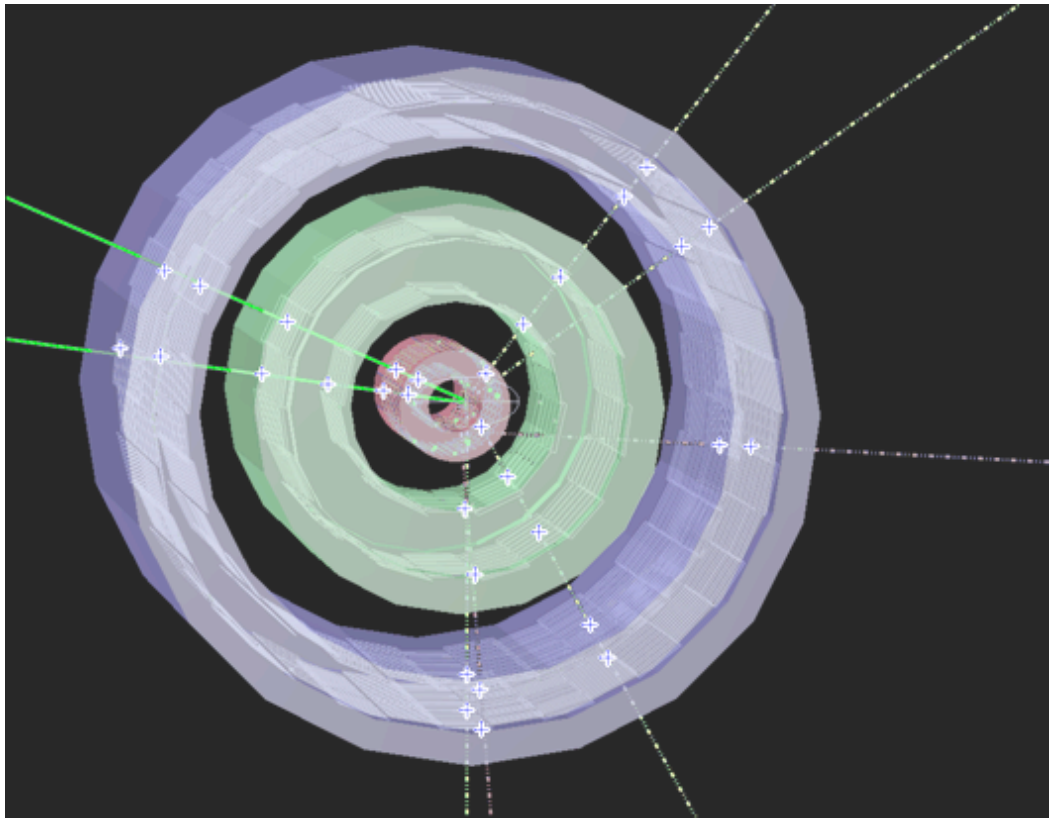
LHC Vertex Detectors

- Large, highly complex silicon systems
- High number of readout channels

- Needed to address different challenges:
  - Production and testing of “almost industrial quantities”
  - Technical aspects, such as cooling, radiation tolerance, etc.
  - System integration
  - ...

- Take into consideration that all aspects are also interlinked (granularity - power dissipation - cooling - ....)

...all with the same goal - find the Vertex



ALICE Inner Tracker - reconstructed event while
Beam 2 circulated in the night of September 11/12, 2008

Outline

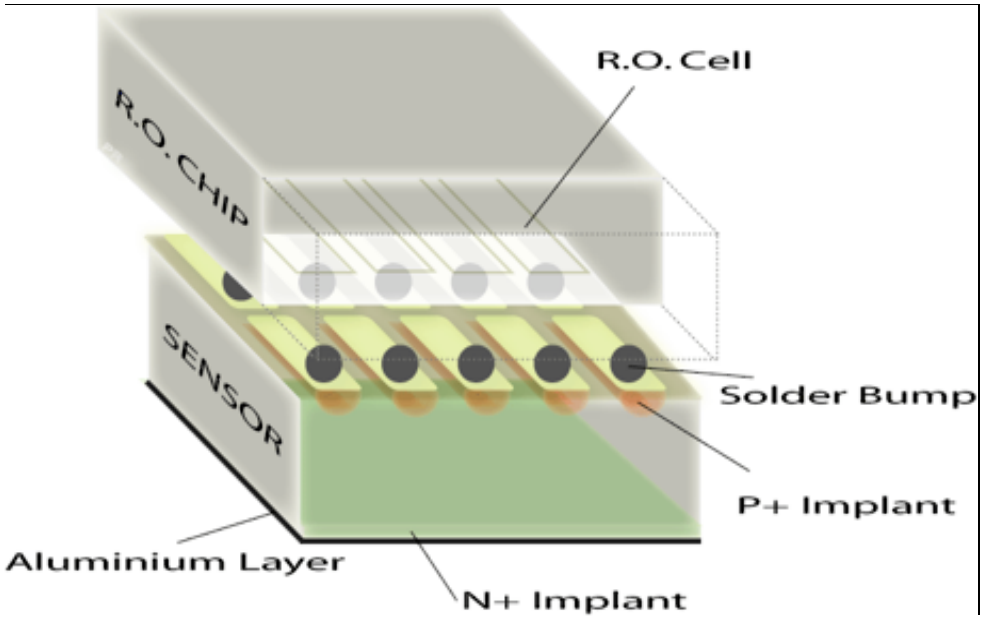
- LHC vertex detectors overview
- **The innermost layers - hybrid pixel detectors**
- Wish list for vertex detectors
  - Material budget
  - Radiation issues
- Summary and Thanks

Innermost Tracking Layers

ALICE, ATLAS, CMS use
Hybrid silicon pixel detectors

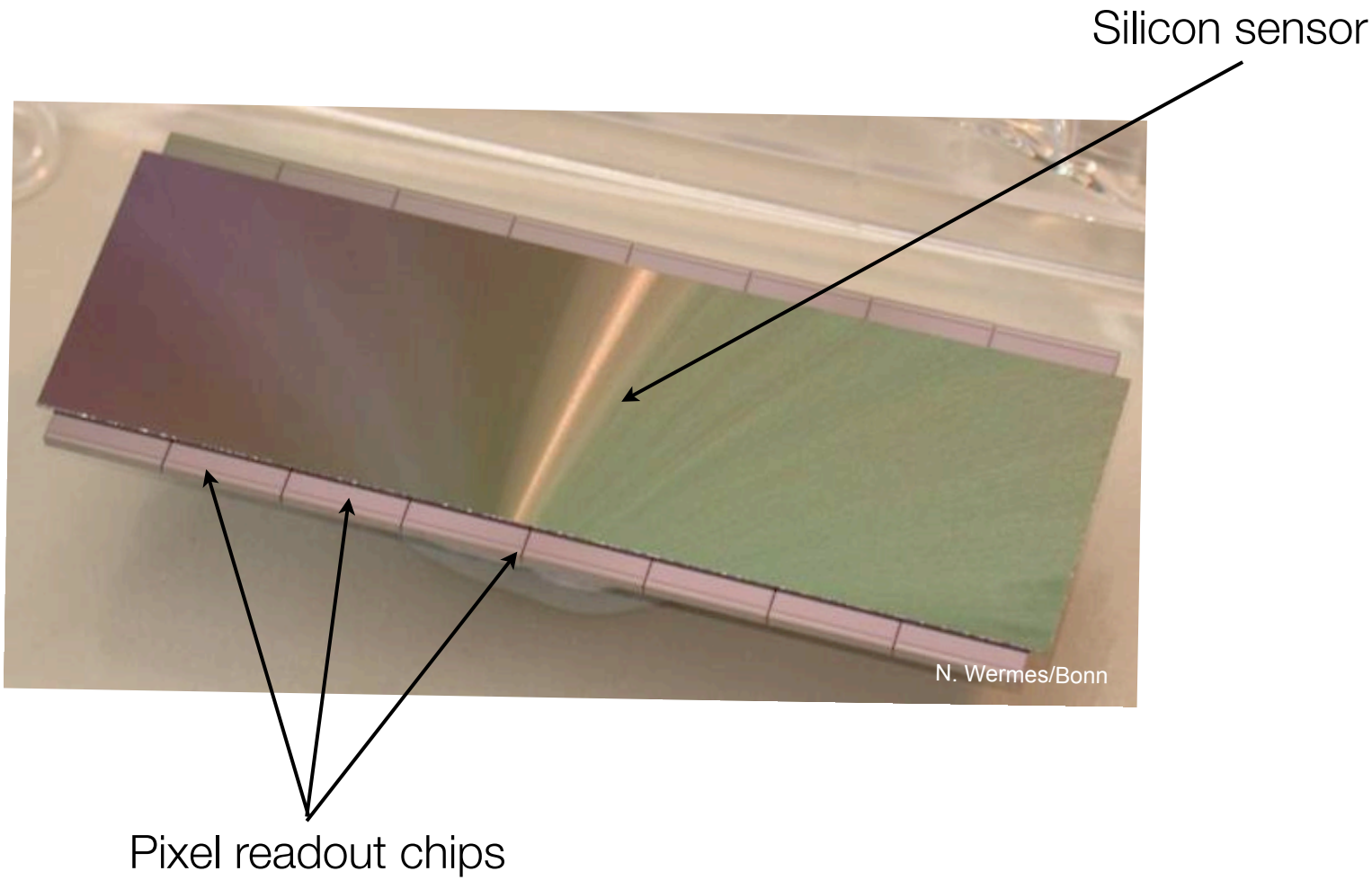
Consist of 3 parts:

- Sensor
- Readout chip
- Bump bonds



Detector and electronics readout can be optimized separately.

ATLAS Pixel Detector



Hybrid Pixel Detectors - Historic Bracket -1/4

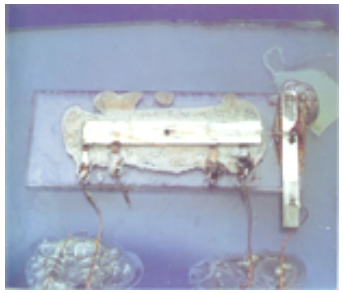
- Two main ingredients required for first silicon pixel detectors (after planar process allowed to produce pixel sensors):
- VLSI (Very Large Scale Integration) technology to produce complex ASICs (Application Specific Integrated Circuit)
- Interconnect technology based on flip-chip bonding (connections of ~20μm between each sensor pixel cell and the corresponding readout cell in an ASIC)
- “recent” development (from ~1990)

Hybrid Pixel Detectors - Historic Bracket -2/4

www.chiphistory.com

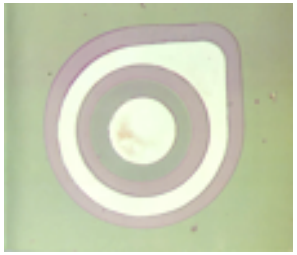
1947

www.chiphistory.com



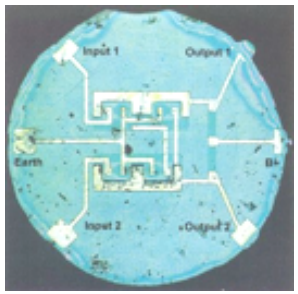
1958

http://smithsonianchips.si.edu/



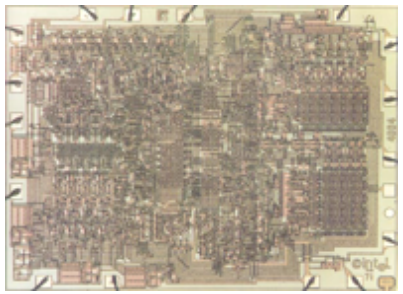
1959

www.chiphistory.com

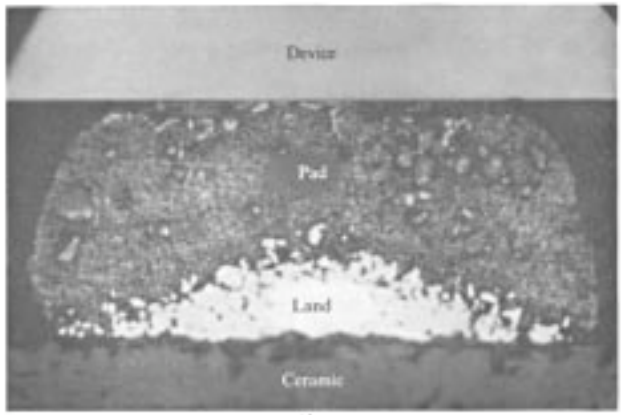


1961

http://smithsonianchips.si.edu/



1970



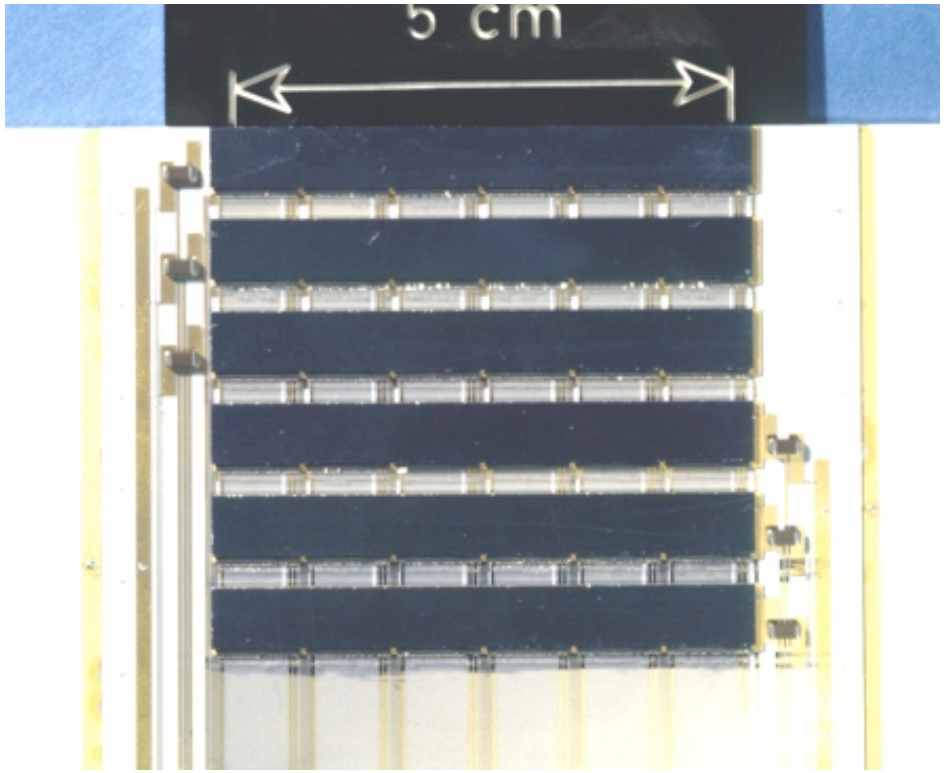
(b)

Miller, IBM, 1969

Flip chip bonding

- Controlled collapse chip connection – C4 by IBM ~1969 (e.g. mainframe computers)
- Studies in automotive for voltage regulators (GM Delco)

Hybrid Pixel Detectors - Historic Bracket - 3/4



OMEGA D

36 000 pixels

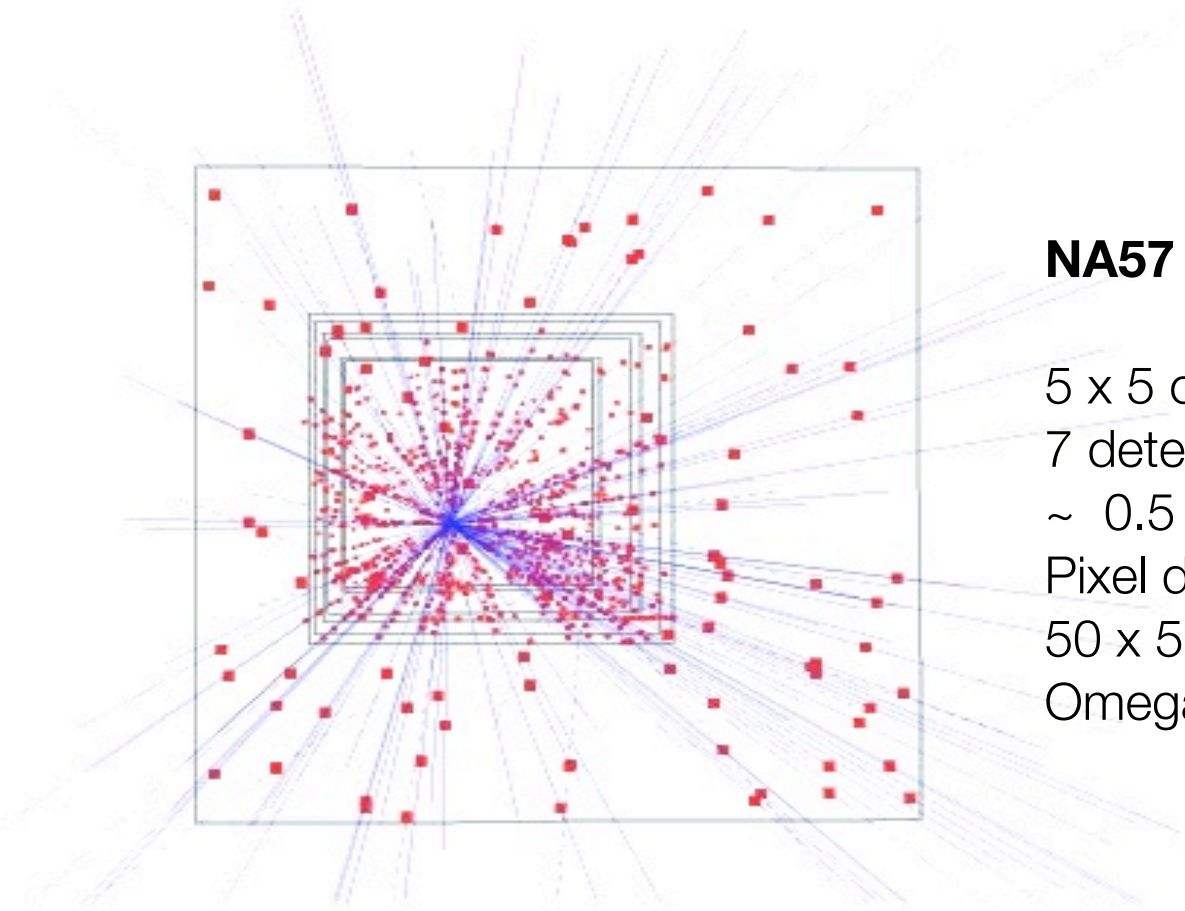
6 ladders of 6 chips

Each chip has 1000 pixels

[E. Heijne, E. Chesi]

Work carried out by RD19 for WA97/CERN

Hybrid Pixel Detectors - Historic Bracket - 4/4



NA57 (1997)

5 x 5 cm2 area
7 detector planes
~ 0.5 M pixels
Pixel dimensions: 75 x 500 μm^2 and 50 x 500 μm^2
Omega2 and Omega3 chips

Outline

- LHC vertex detectors overview
- The innermost layers - hybrid pixel detectors
- **Wish list for vertex detectors**
  - Material budget
  - Radiation issues
- Summary and Thanks

Wishlist for Vertex Detector

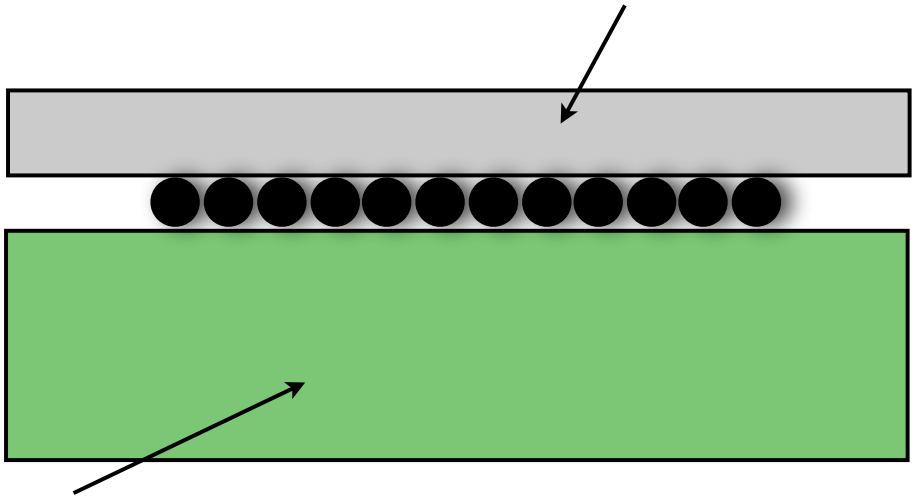
- High radiation tolerance
- Minimum material
- High granularity
- Minimum power consumption
- Efficient cooling
- Trigger capability
- Easy access
- ....

Radiation Effects in Hybrid Pixel Detectors

- Innermost detector - highest radiation levels

- Distinguish between effects in the readout electronics and the sensor.

Readout chip:
non ionizing energy loss; **total ionizing dose**



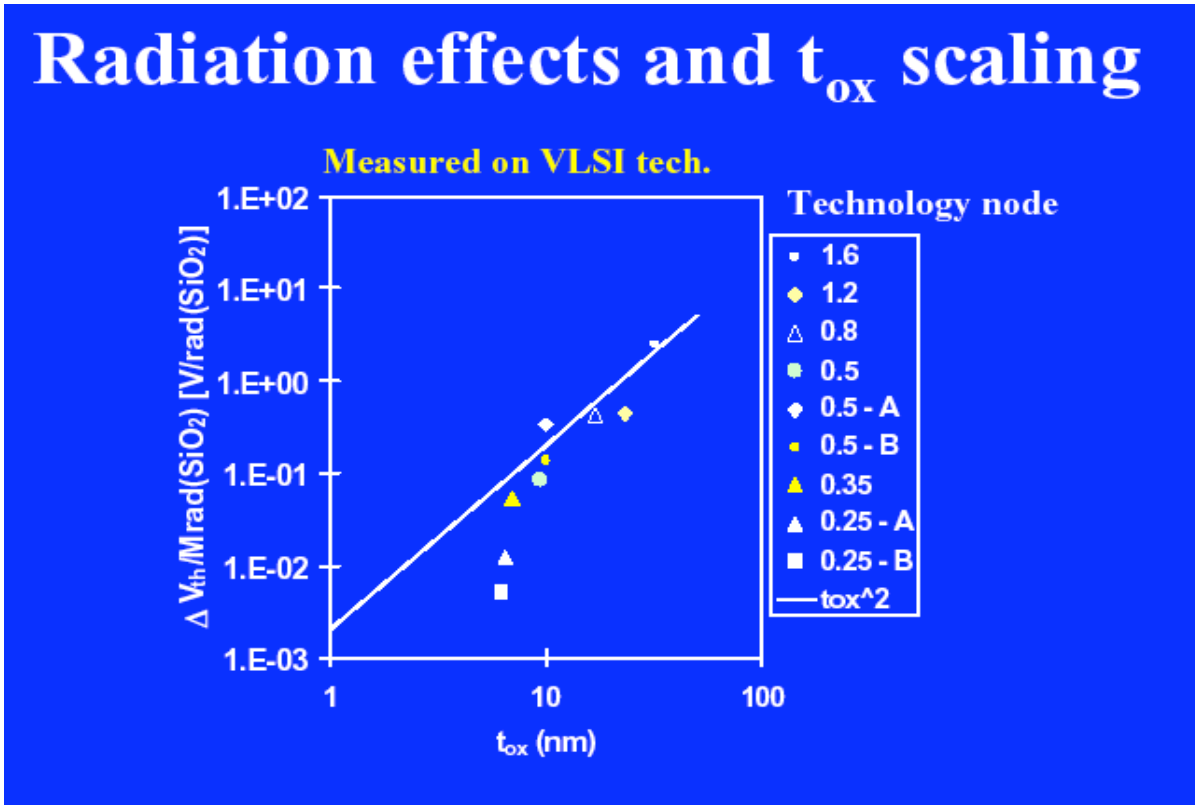
Silicon sensor:
non ionizing energy loss; total ionizing dose

Radiation Levels in the Vertex Detectors at LHC

	TID [kGy]	Fluence 1MeV n eq. [cm^{-2}]	Time
ATLAS Pixel*	500	1×10^{15}	10 years
ATLAS Strips	100	2.0×10^{14}	10 years
CMS Pixels	840	3×10^{15}	10 years
CMS Strips	70	1.6×10^{14}	10 years
ALICE Pixel	2.7	3.5×10^{12}	10 years
LHCb VELO	50	1.3×10^{14}**	1 year

ATLAS and CMS values cited for innermost layers for pixels and strips for 500 fb^{-1}
* averaged (B-layer to be replaced)
** inner part, inhomogeneous irradiation

Radiation Damage Effects - ASICs



Using a smaller technology node CMOS process reduces threshold-shift.
Use enclosed layout for transistors and guard rings to reduce leakage

F. Faccio/CERN;

N. S. Saks, M.G. Ancona, J.A. Modolo, "Radiation effects in MOS capacitors with very thin gate oxides at 80oK," IEEE Trans. Nucl. Sci. Vol. NS-31, No. 6, pp. 1249-1255, December 1984.

Radiation Induced Effects - Sensors

Radiation (hadrons) induces defects in the silicon crystal lattice (bulk defects) which can be electrically active >> **macroscopic effects**

- **Change of effective doping concentration (depletion voltage)**
  - -complex annealing behavior
  - -can result in very high operating voltages (and thus very high currents)
  - -using n-in-n detectors under-depleted operation is possible
  - -material dependence (e.g. oxygenated, different producers, ..)

- **Increase of leakage current**
  - -higher shot noise
  - -risk of thermal runaway
  - -need to ensure current stability
  - -current anneals after irradiation (speed depends on temperature)

- **Increased charge trapping**
  - -loss of signal
  - -different annealing for electrons and holes

Choice of Sensors and Operating Temperature

Selection to extend the lifetime of the detector of:

- sensor material (oxygenated, ...)
- device type (p-in-n, n-in-n, n-in-p)
- operating temperature

Example: Reduce operating temperature

- to reduce leakage current
- prevent thermal runaway (but slows down current annealing after irradiation)
- to slow down the voltage annealing
- presents also technical challenges for mechanical stability (TEC), humidity control or access and maintenance
- requires cooling system that is also in agreement with the material budget constraints

Silicon Pixel Detector Technology Choices

Sensor	ALICE	ATLAS	CMS	LHCb VELO
P-in-n	x			
N-in-n			x	
N-in-n ox		x		x*
Electronics				
0.25μm CMOS	x	x	x	x
Temperature [°C]				
T(°C)	+25	-7	-10	-5

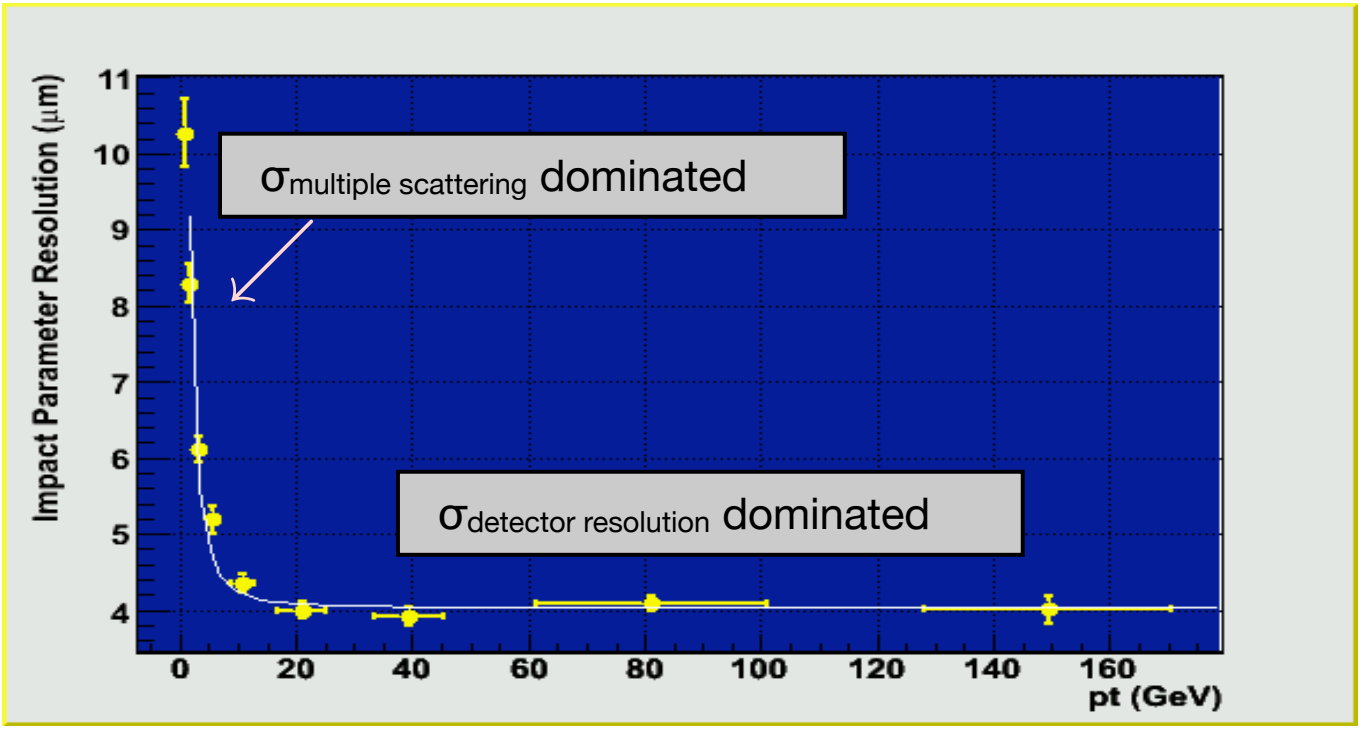
* one n-in-p module installed

Material Budget

- Strongly influences vertex finding
- Impact parameter resolution:

$$\sigma_b \cong \sigma_{\text{detector resolution}} \oplus \sigma_{\text{multiple scattering}}$$

where $\sigma_{\text{multiple scattering}}$ dominates at low p_t



Example: ALICE Experiment

several sub-systems optimized for ultra-relativistic heavy ion collisions:

- high multiplicity

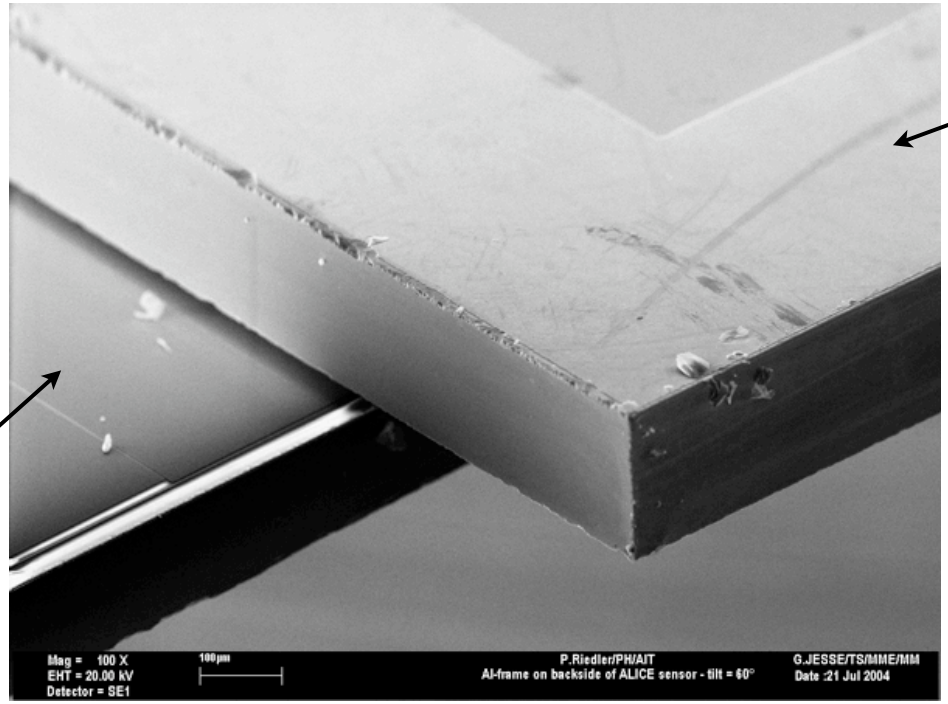
- provide large dynamic range for **momentum measurements from tens MeV/c** (collective effects, acceptance for resonance decays)to over 100 GeV/c

>> stringent material budget constraints (13% X_0 up to the end of the TPC)

Hybrid Pixel Detectors - Material Budget

- Small pixels represent small capacitance, thus high S/N > sensor thickness can be adjusted to smaller values

- **But....hybrid pixels have several contributors to the mass budget each needs to be optimized separately**



Silicon sensor

Readout chip (Si)

Sensor and Readout Chip Thickness

	Si sensor [μm]	X_0 [%]	ASIC [μm]	X_0 [%]
ALICE	200	0.21	150	0.16
ATLAS	250	0.27	180	0.19
CMS	285	0.30	180	0.19

X_0 (Si) = 9.36 cm

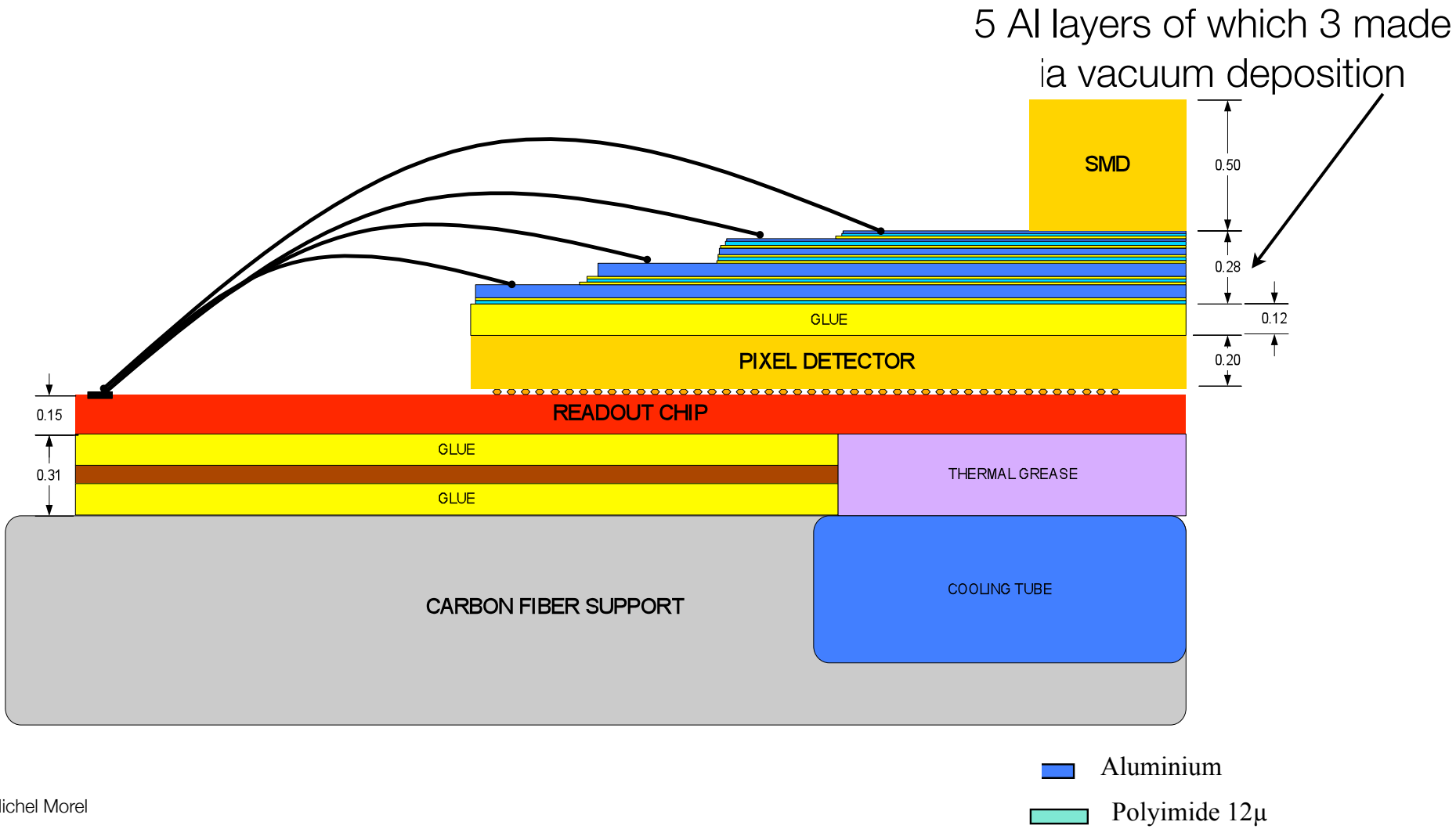
Example: ALICE Pixels

Material in one pixel layer:

- Carbon fibre support: 200 μm
- Cooling tube (Phynox): 40 μm wall thickness
- Grounding foil (Al-Kapton): 75 μm
- Pixel chip (Silicon): 150 μm
- Bump bonds (Pb-Sn): diameter ~15-20 μm
- Silicon sensor: 200 μm
- Pixel bus (Al+Kapton): 280 μm
- SMD components
- Glue (Eccobond 45) and thermal grease

Total material budget ~1.1%X_0 per layer (active region)

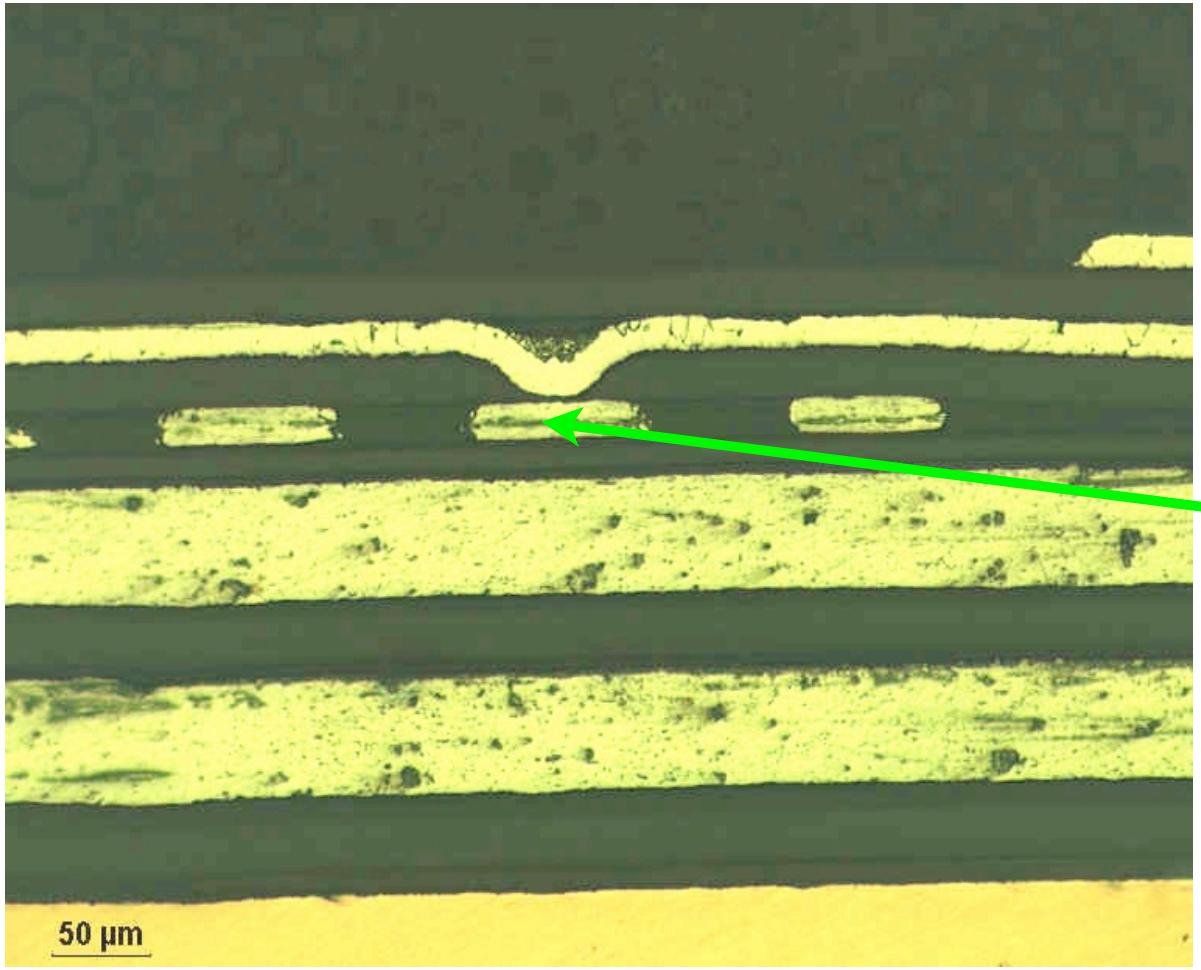
ALICE Pixel Layer - Schematic Cross Section



Michel Morel

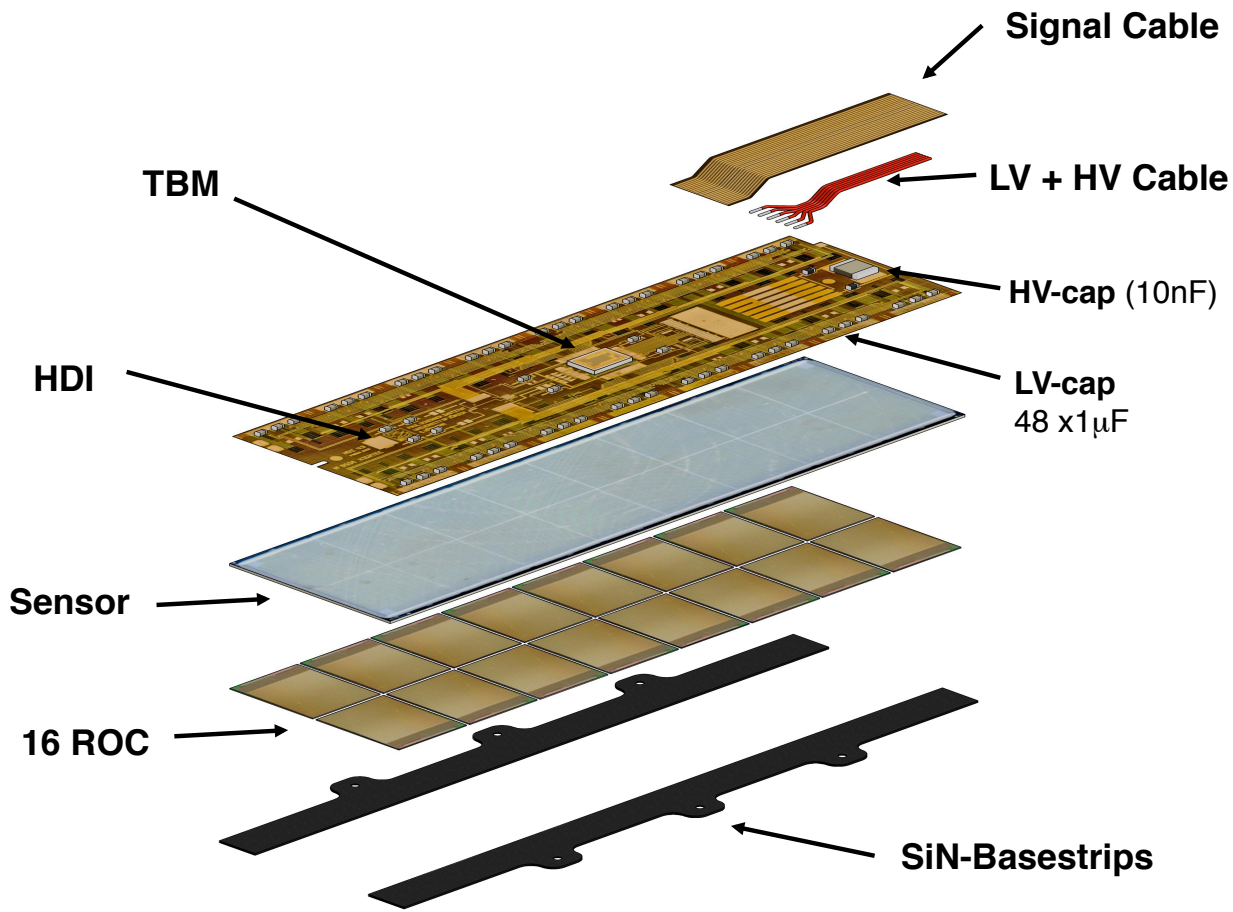
ALICE Pixel Bus

SEM picture of pixel bus cross-section



- Wire bonds to the readout chips+MCM
- Provides data -, control- and power-lines between readout chips and MCM
- Al vias between two Al layers
- Several years development phase with prototyping using Cu and Cu/Al buses
- Produced at CERN (EN/ICE)

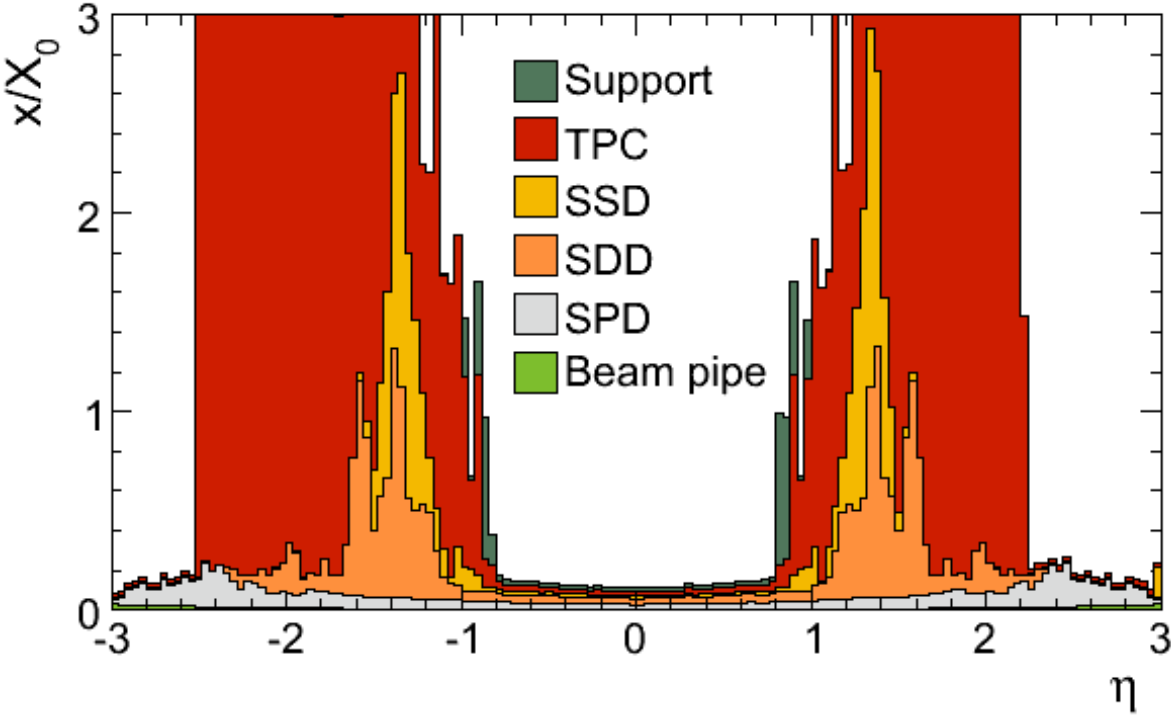
Example: CMS Pixel Module



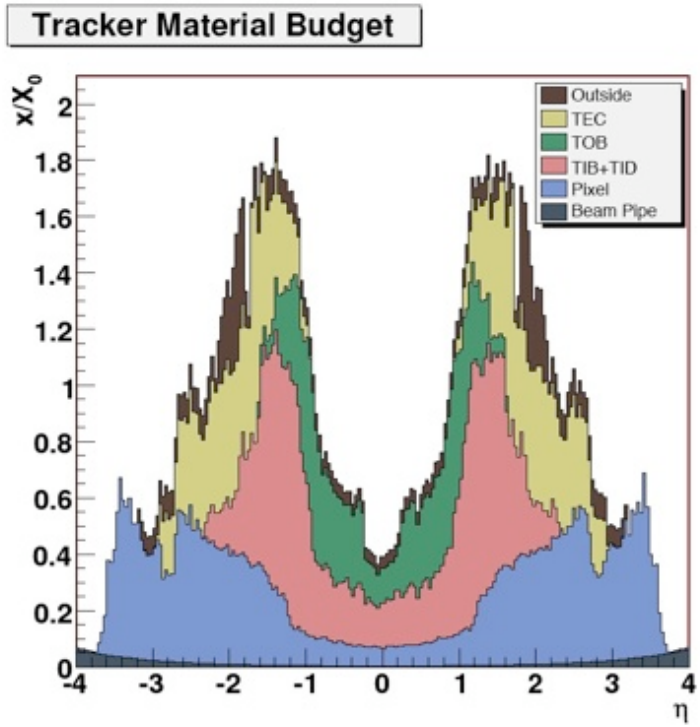
R. Horisberger/PSI

ALICE and CMS Material Budget

ALICE



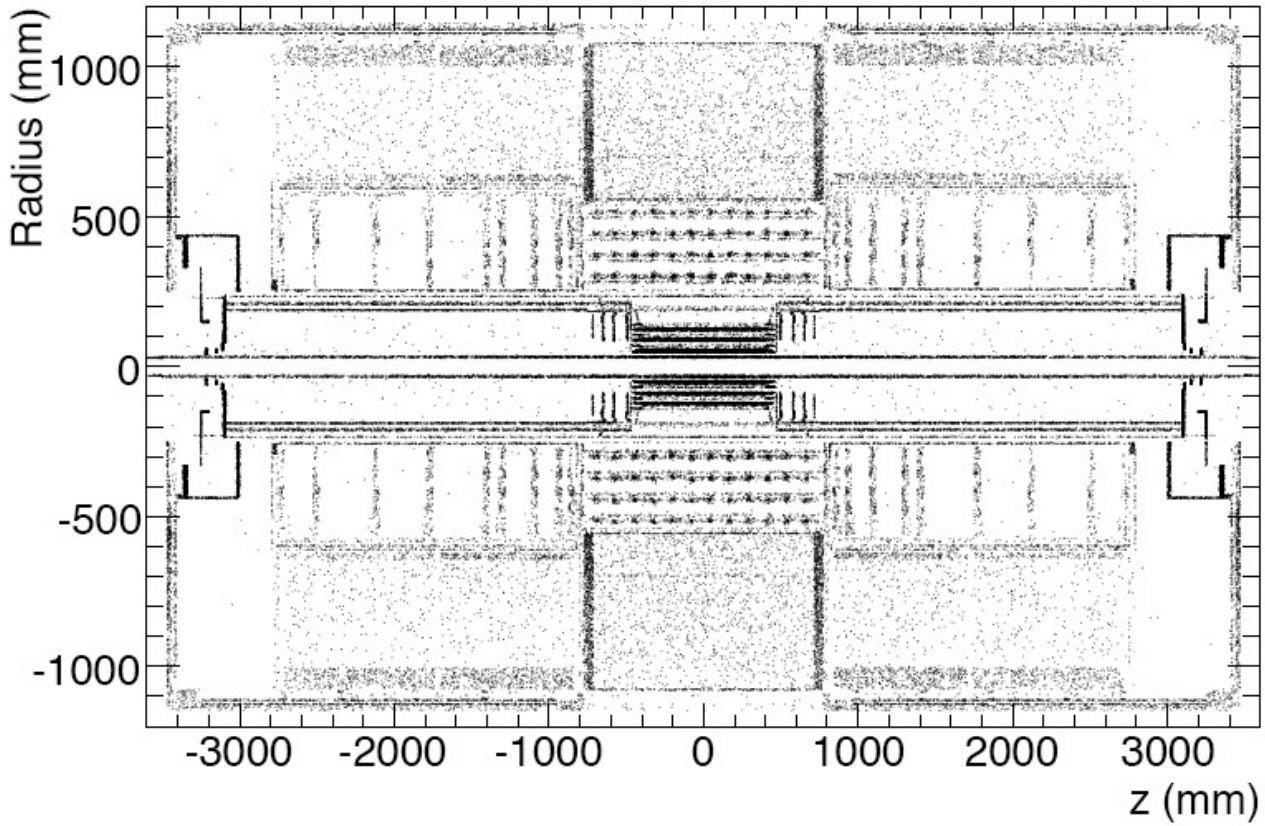
CMS



Boris Hyppolite

ATLAS - Mapping of Photo-Conversion

conversion electrons from photons from π^0/η decays



ATLAS X_0: exit last pixel plane: 0.108 at η=0

Summary

- Large and complex vertex detector systems have been installed in the four large LHC experiments.
- Silicon detectors will provide the necessary information for excellent vertexing in a challenging environment.
- Many technical challenges have been met during design, construction and installation.
- Looking forward to exciting new physics!

Thanks !

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