universitätbonn

IFIC
INSTITUTO DE FÍSICA CORPUSCULAR

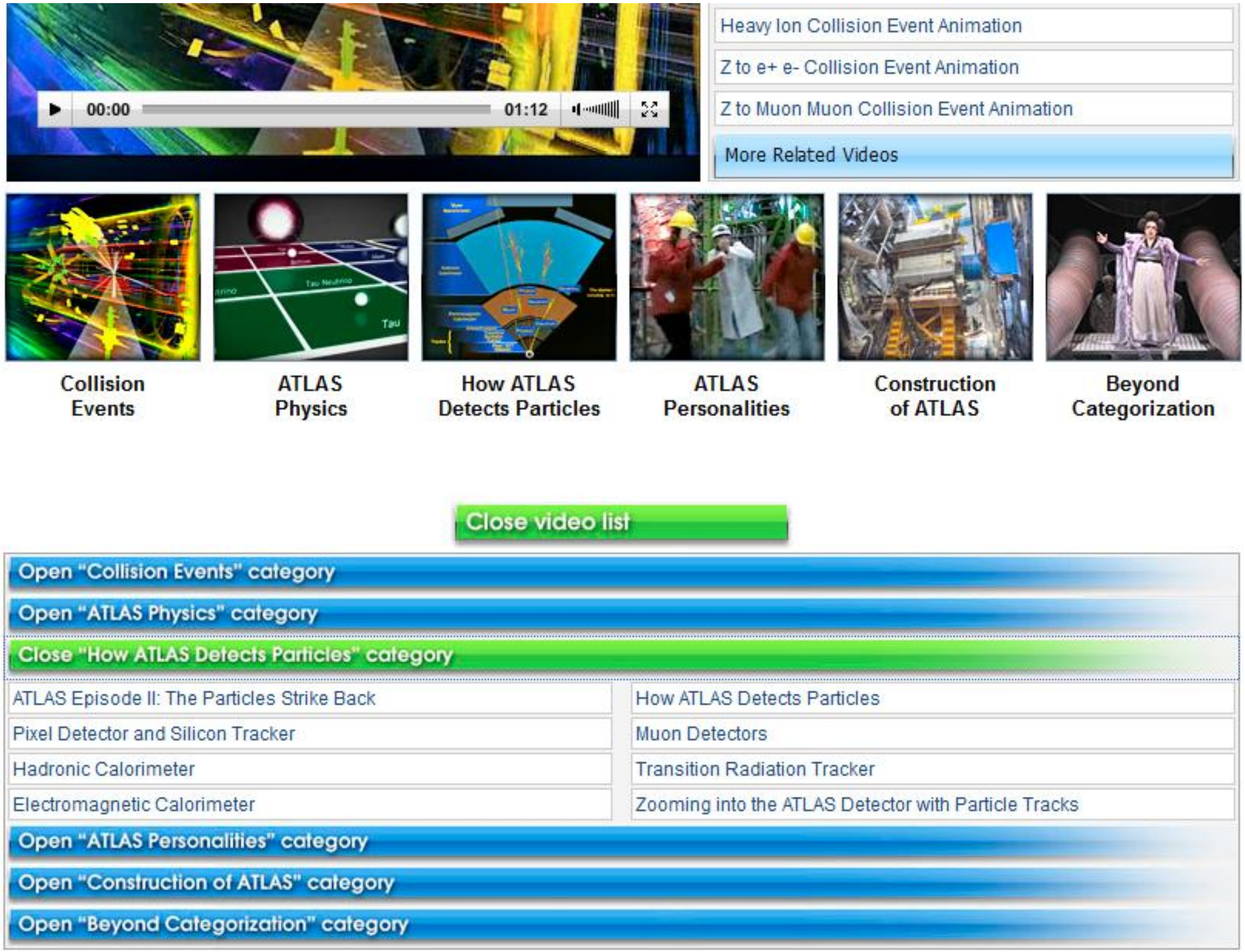
ATLAS

Dr. C. Lacasta, Dr. C. Marinas

cmarinas@uni-bonn.de

http://www.atlas.ch/multimedia/#

universitätbonn



Why?

In particle physics, the processes occur on a scale that is either too brief or too small to be observed directly.

We can not see or touch the particles... So, we need some tools through which, indirectly, study those processes.

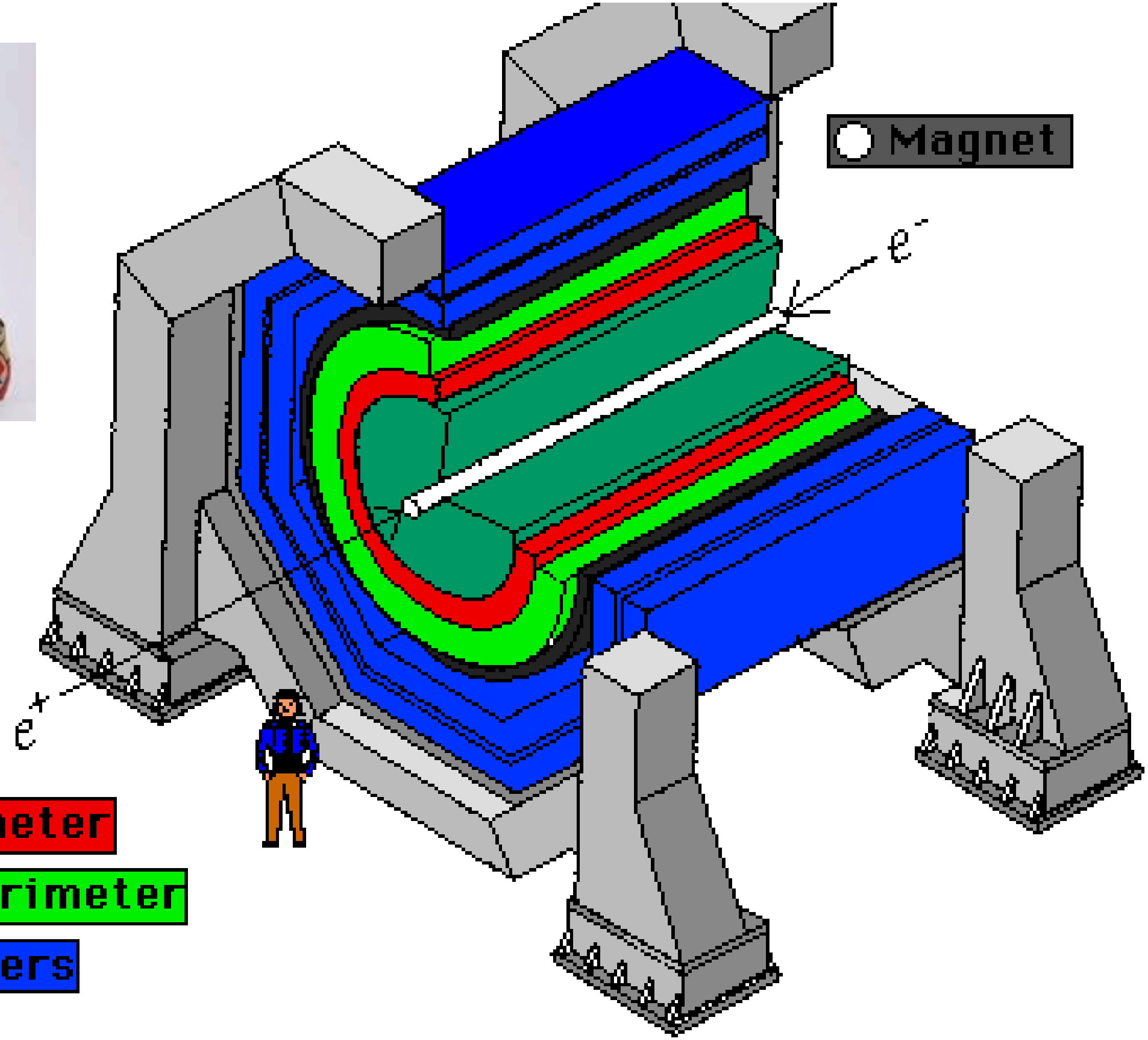
In particle physics, a **particle detector** is a device used to detect, track, and/or identify high-energy particles.

Generic Detector

Reconstruction of fundamental objects in a detector:

- Vertex and track reconstruction
- Photon/electron reco
- Jet reco
- Muon reco
- Missing energy

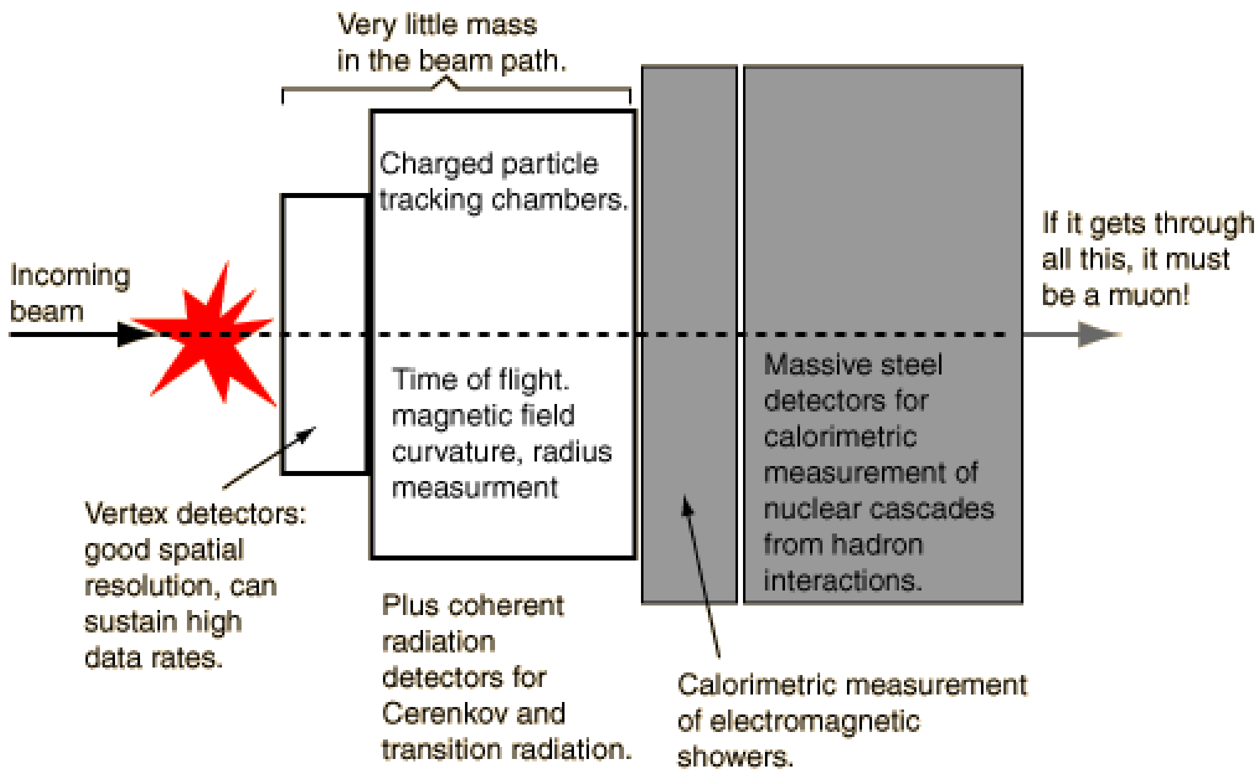
General Purpose Detector

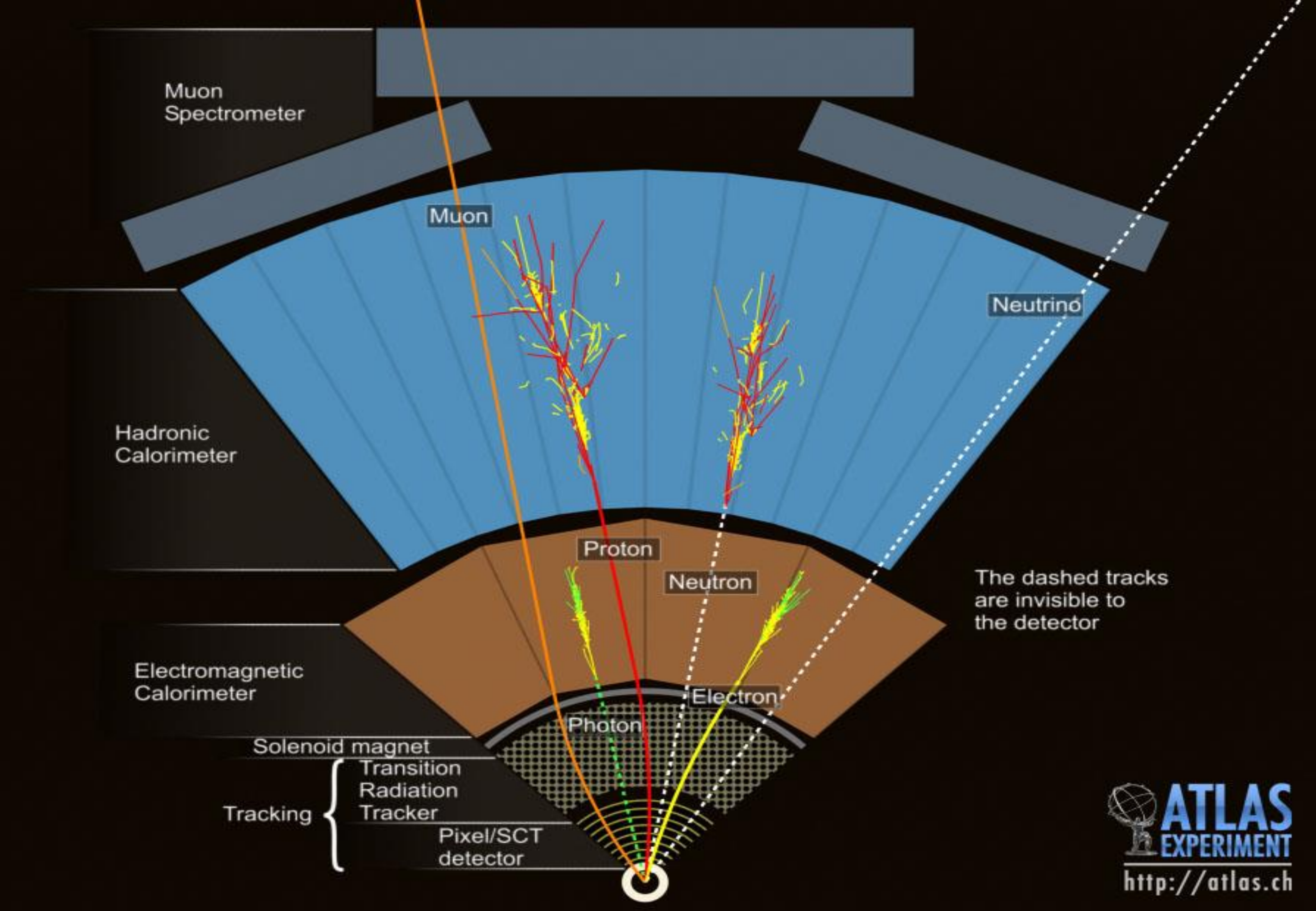


General Purpose Detector

Techniques for reconstructing the fundamental objects:

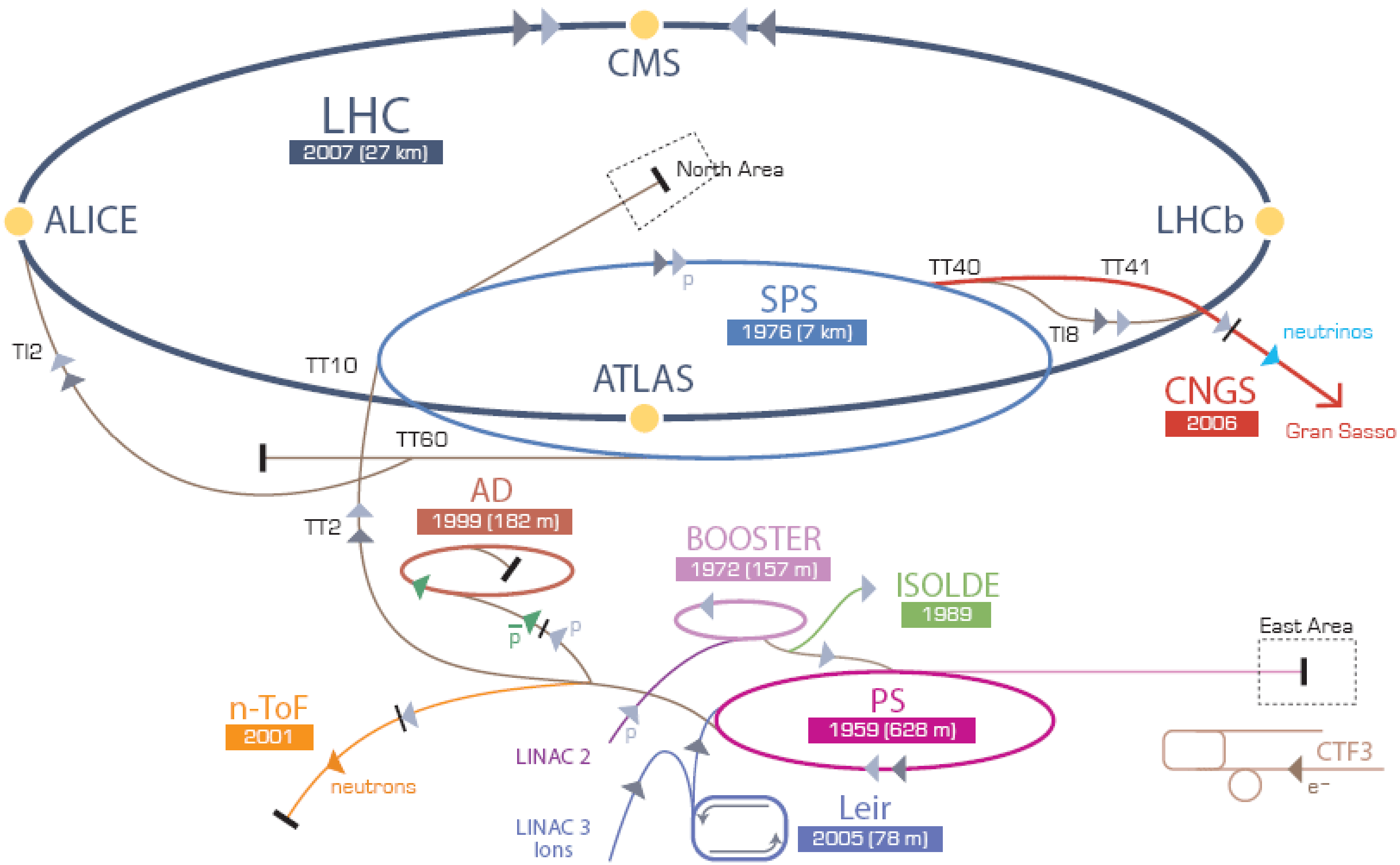
- Position and length of ionization trails.
- Time-of-flight
- Radius of curvature
- Cerenkov radiation
- Transition radiation
- Presence of neutrinos
- Electromagnetic showers
- Hadronic showers





Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

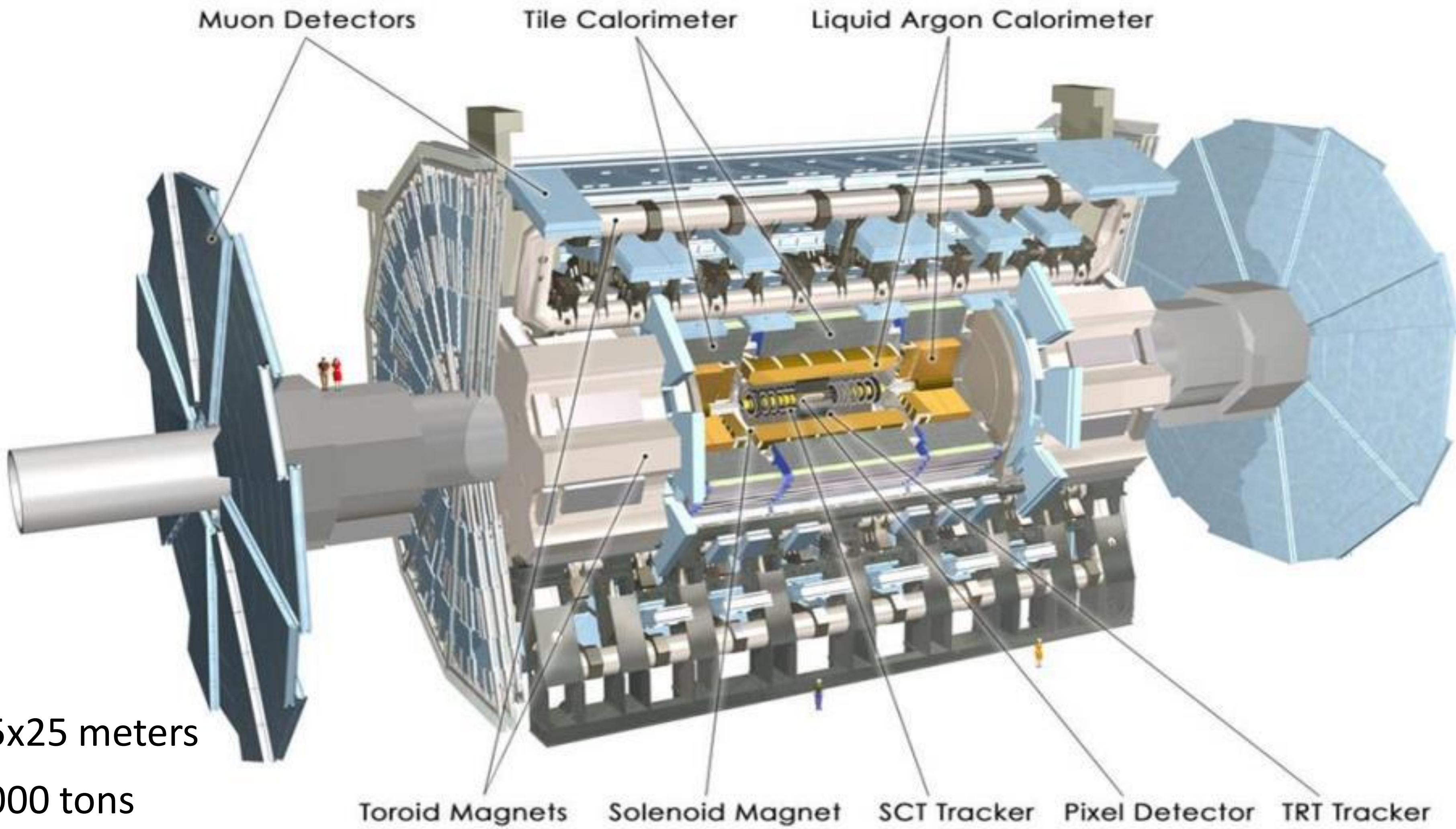
CERN Accelerator Complex



Requirements for the LHC Experiments

- ATLAS and CMS to be as “general purpose” as possible and as hermetic as possible
  - All possible physics channels from known to unknown
  - The dream of measuring everything with a surrounding sphere
- ALICE measuring on a MeV to GeV dynamic range
  - Heavy ions focus
  - Paying attention to material budget
- LHCb dedicated to b physics
  - A forward detector

ATLAS (A Toroidal LHC Apparatus)

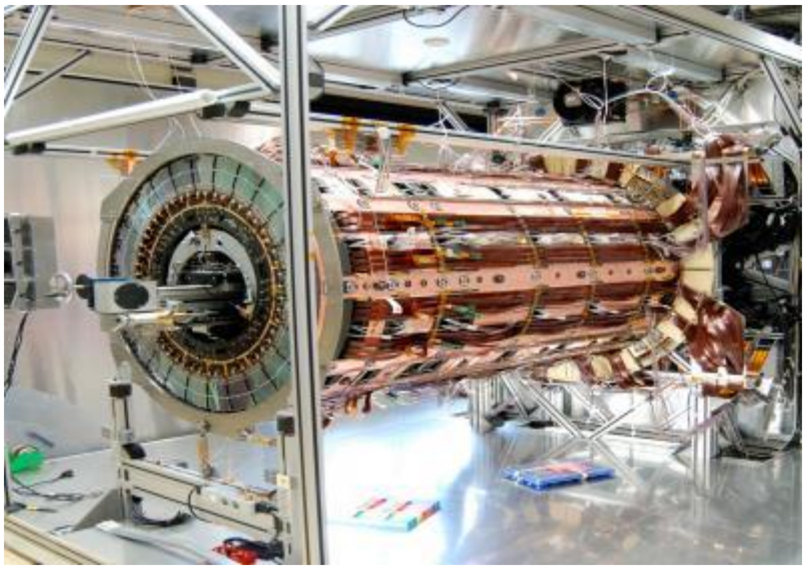


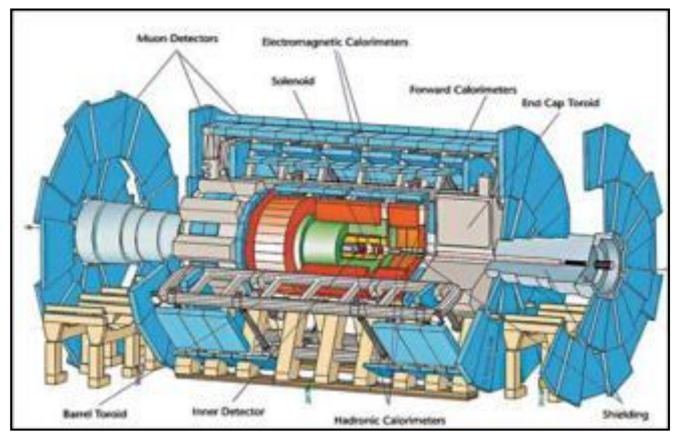
45x25 meters

7000 tons

Inner Detector

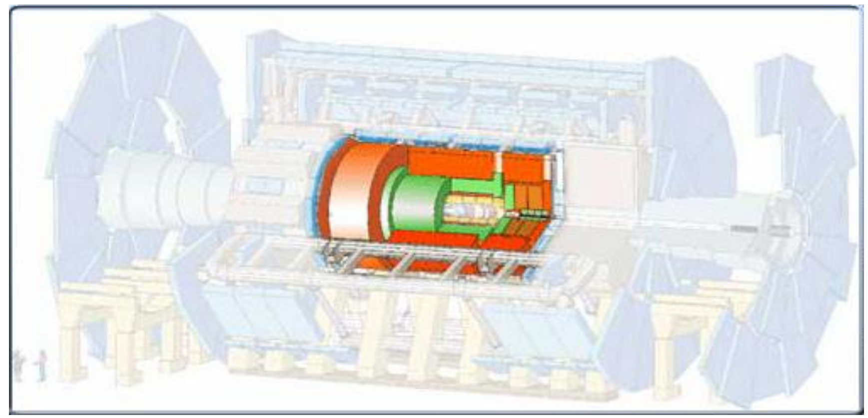
Measures the momentum of each charged particle

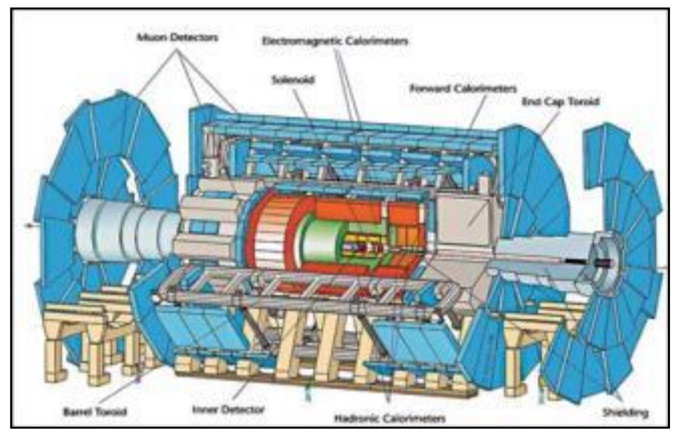




Calorimeters

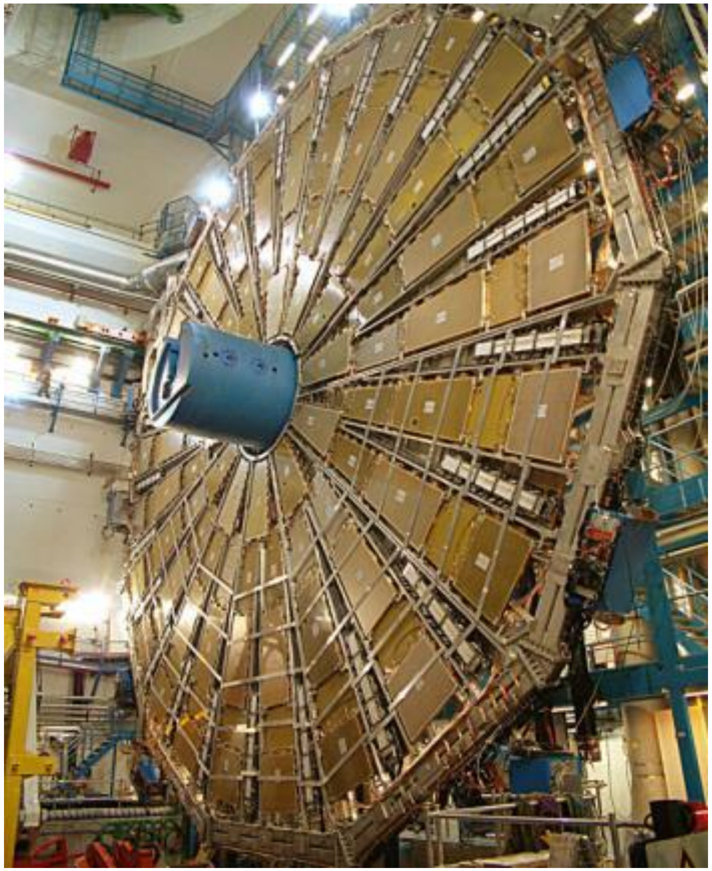
Measures the energies carried by particles

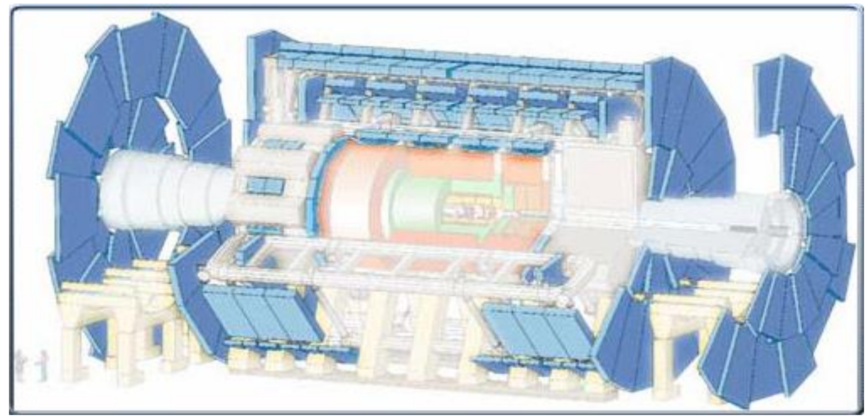


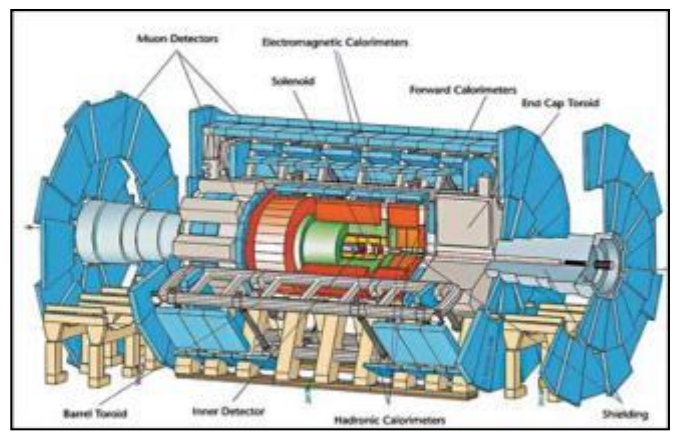


Muon Spectrometer

Identifies and measures muons



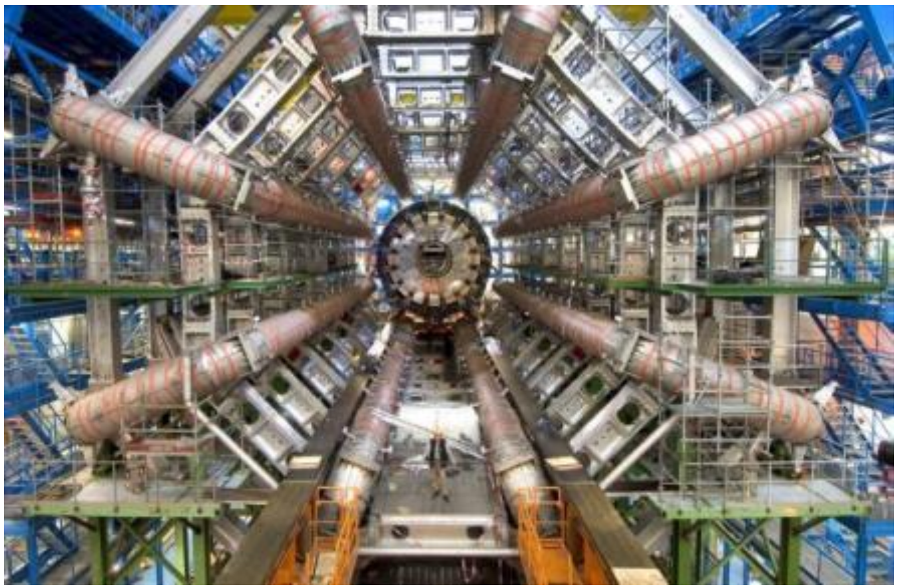


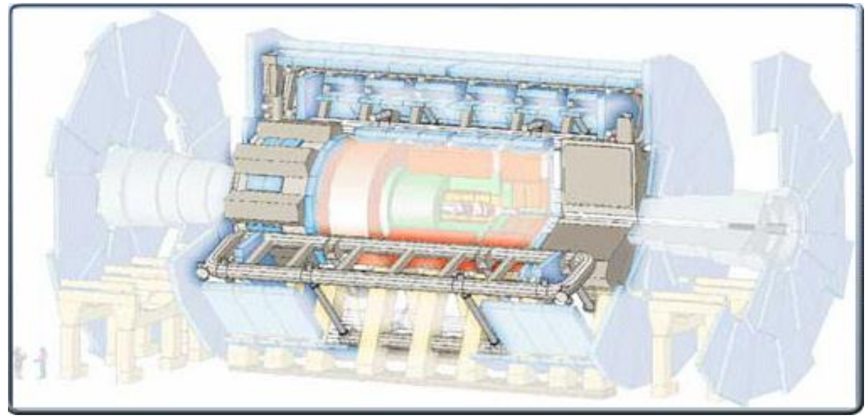


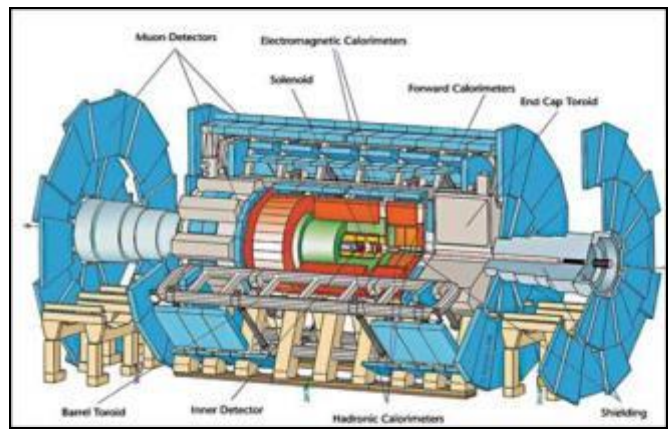
Magnet System

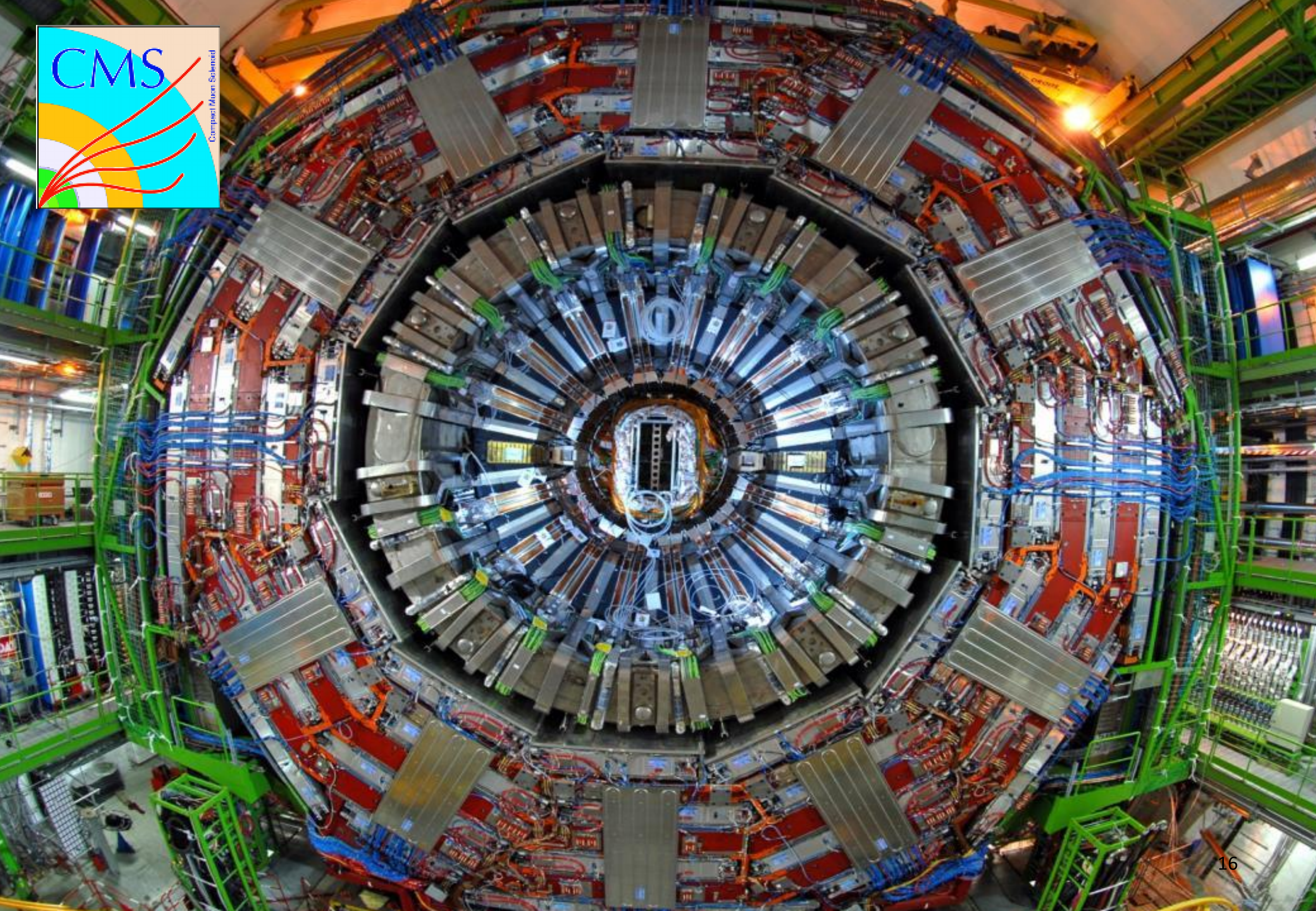
universitätbonn

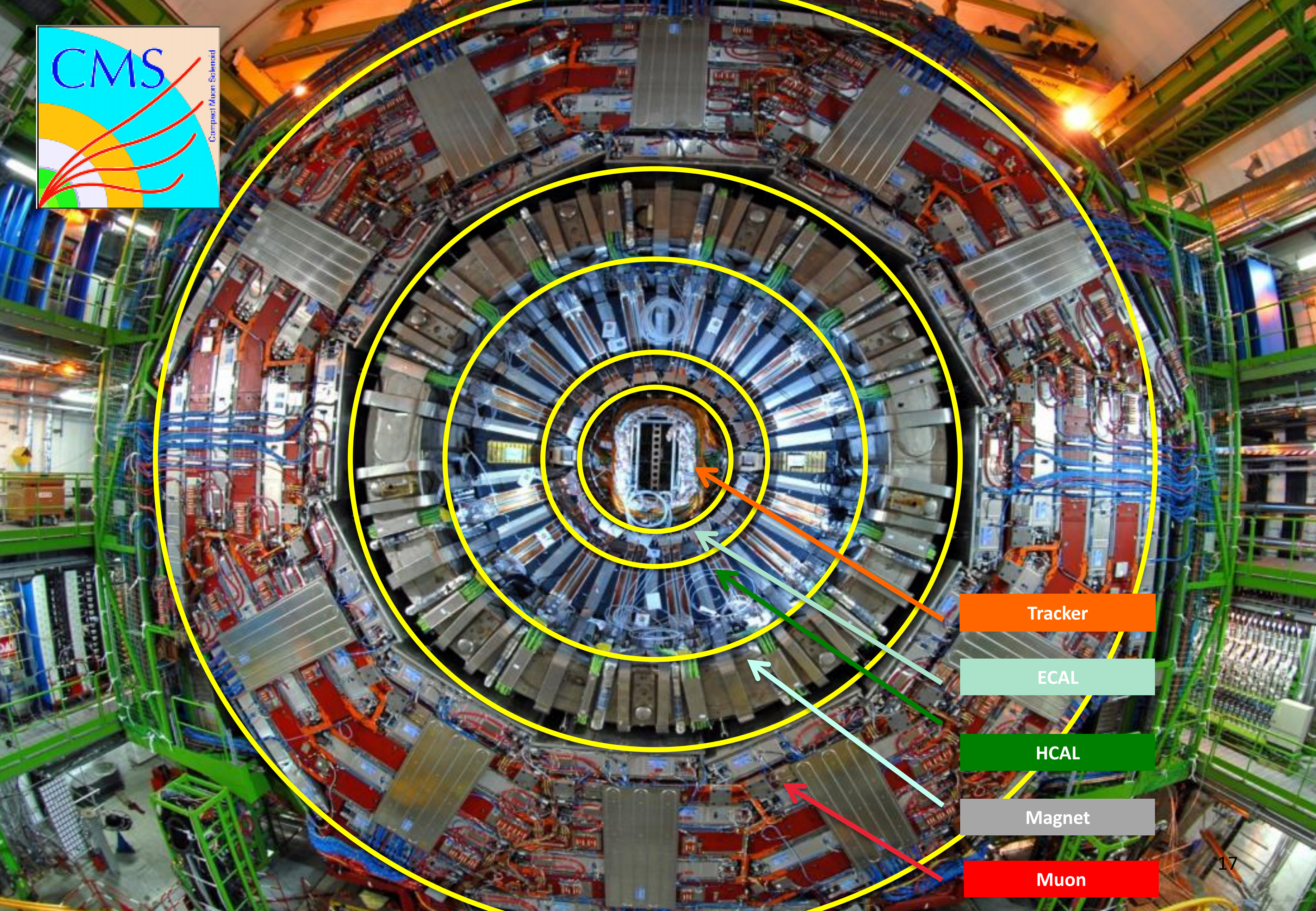
Bends charged particles for measuring momentum








CMS
Compact Muon Solenoid

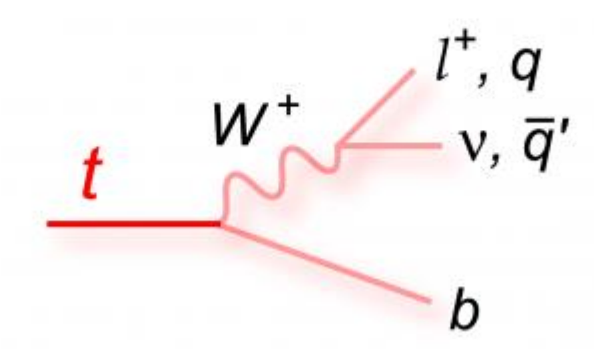

CMS
Tracker
ECAL
HCAL
Magnet
Muon

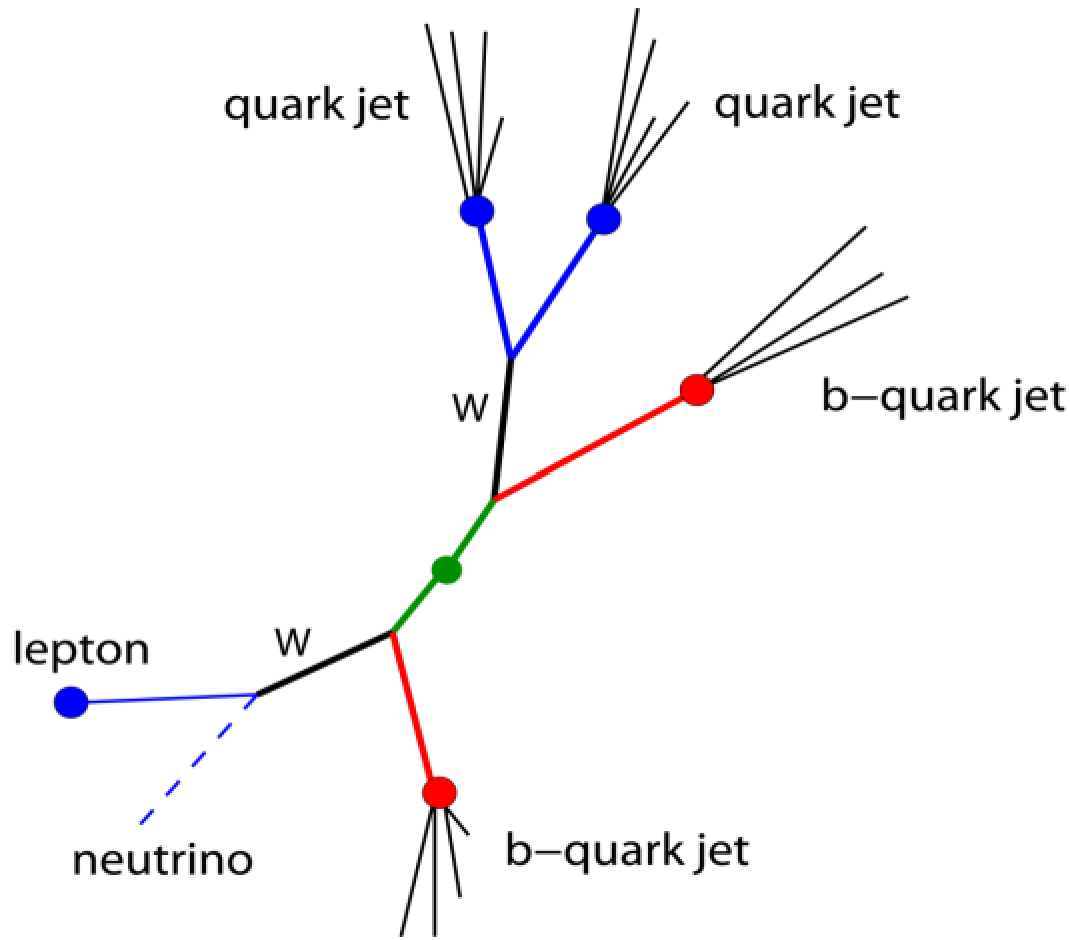
Complementary Approaches

	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region 2 Tesla	Solenoid Only 1 magnet Calorimeters inside field 4 Tesla
TRACKER	Si pixels+ strips TRT → particle identification $\sigma/p_T \sim 3.8\text{x}10^{-4}\ p_T \oplus 0.015$	Si pixels + strips No particle identification $\sigma/p_T \sim 1.5\text{x}10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim$ 10 % at 1 TeV standalone (~ 7% combined with tracker)	Fe → $\sigma/p_T \sim$ 15-30% at 1 TeV standalone (5% with tracker)

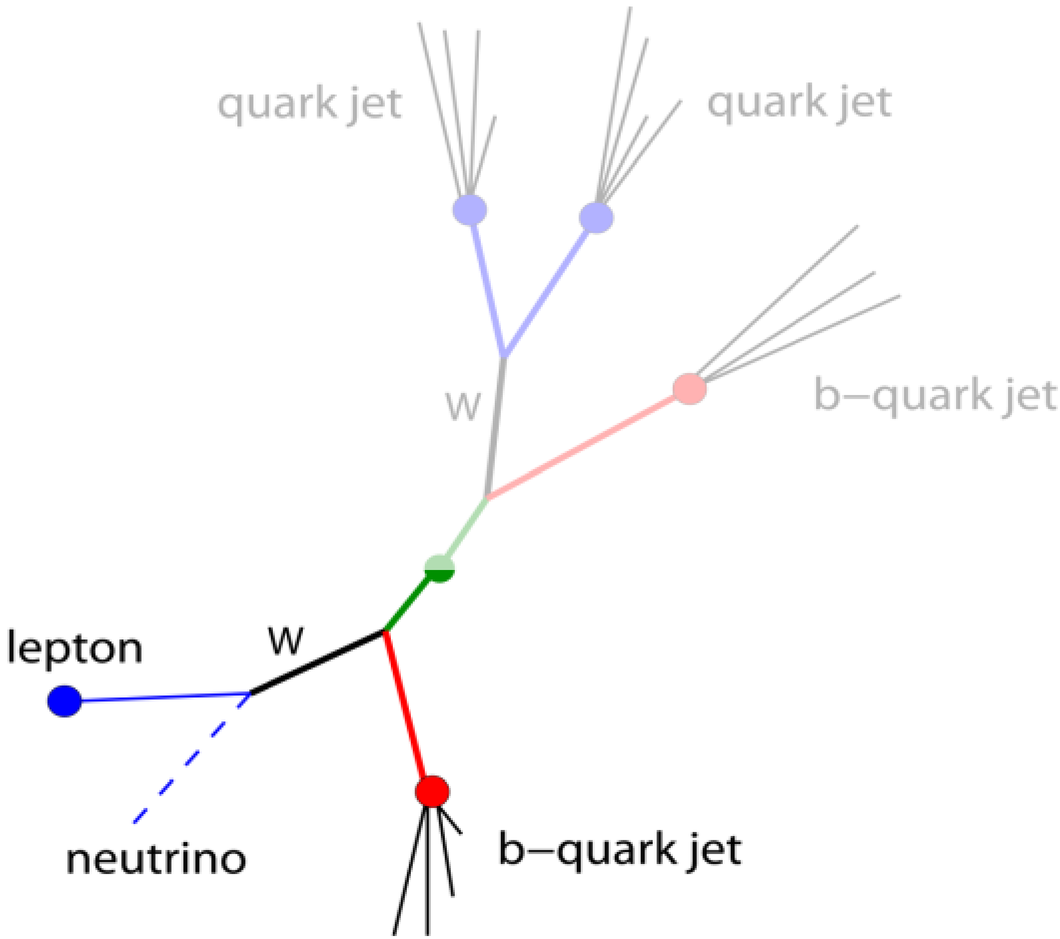
Generic Top Quark Event

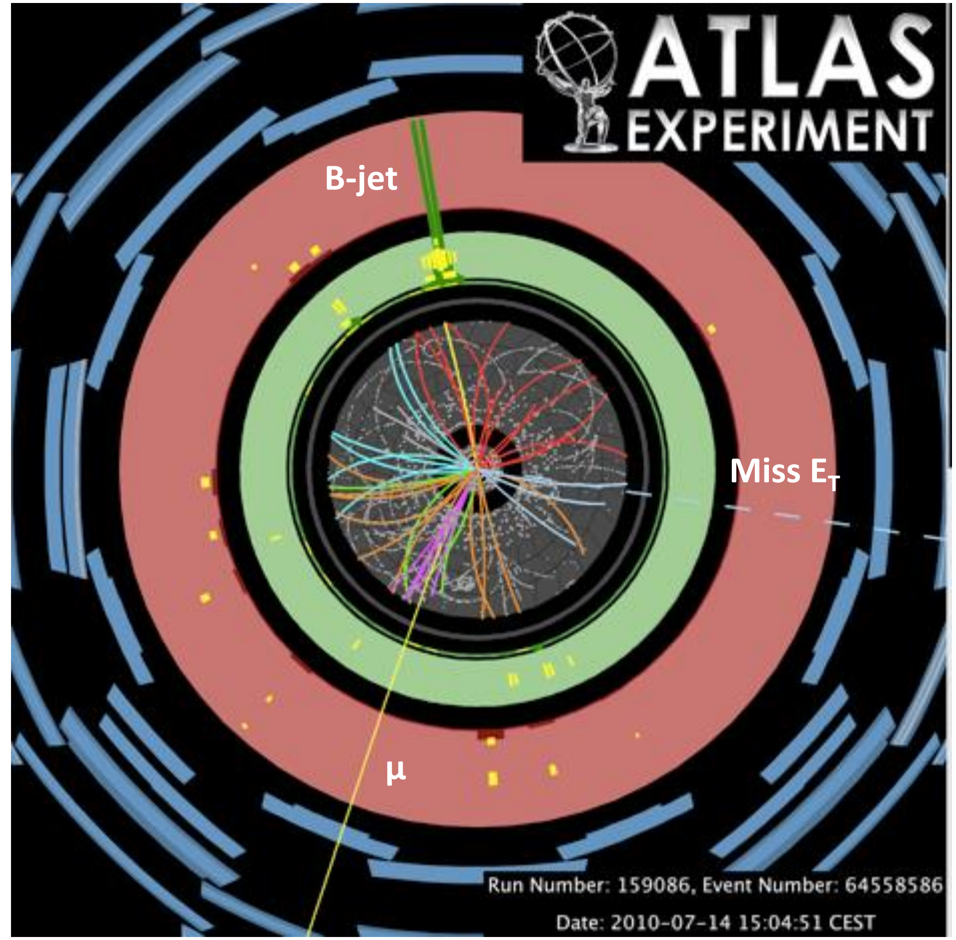
Let's try to understand how the detector is capable to reconstruct this picture





Detector Topology

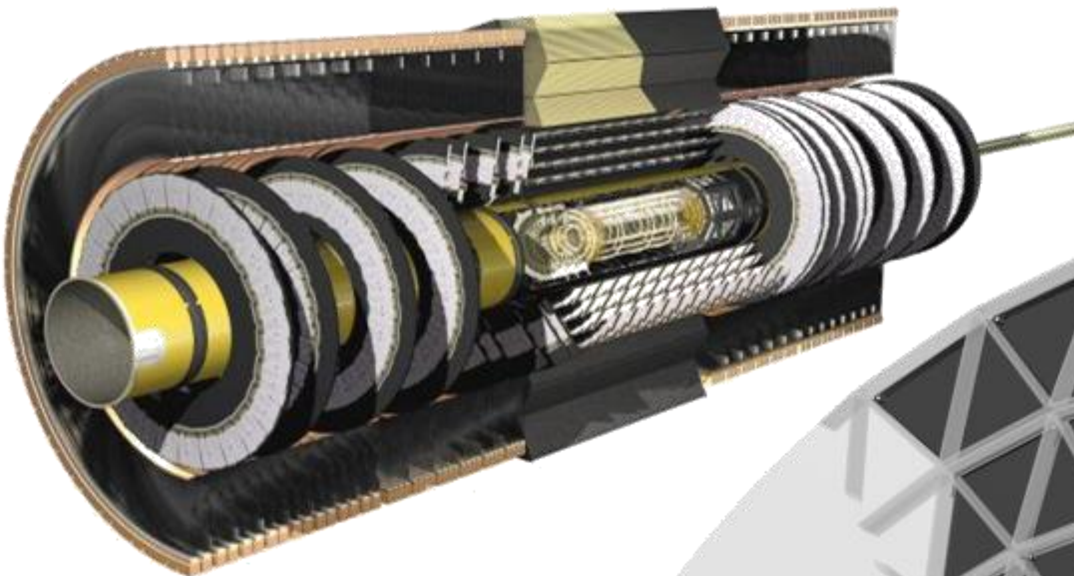




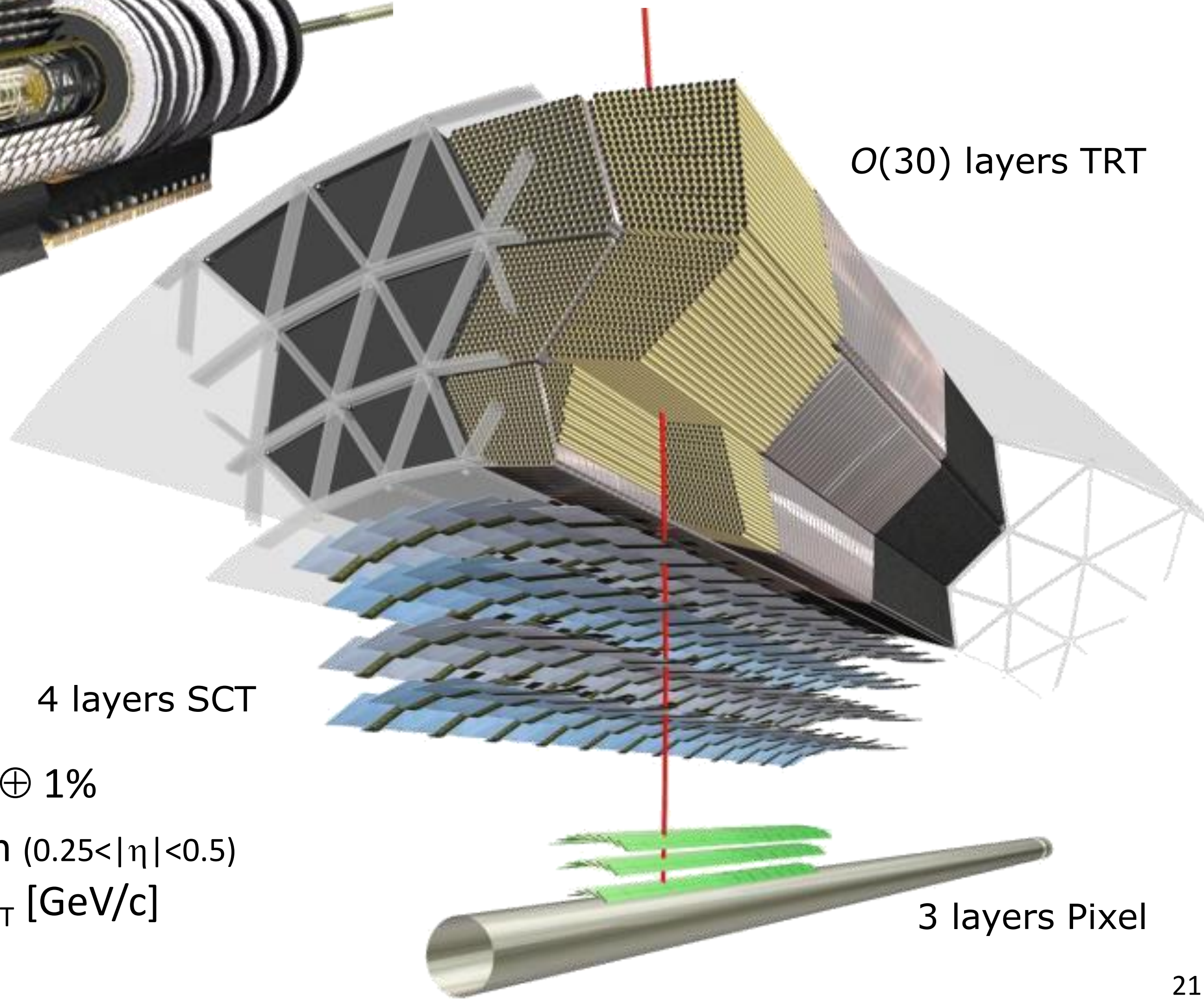
How do we get here?

ATLAS Inner Detector

universitätbonn



ATLAS inner detector

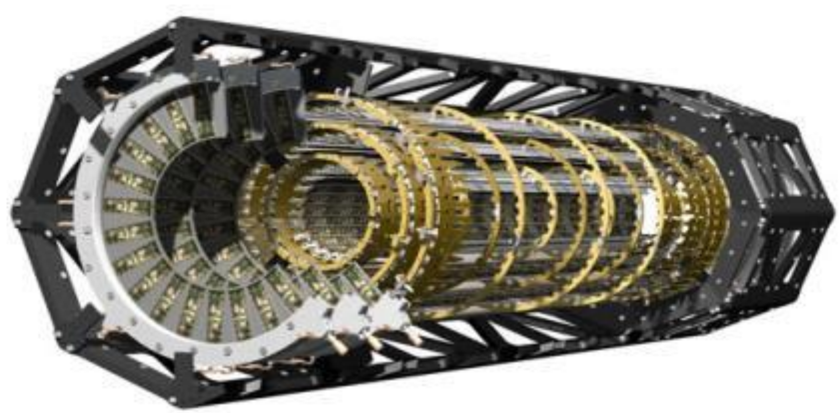


- Momentum resolution
  $\sigma(p_T)/p_T = 0.05\%\ p_T\ [GeV/c] \oplus 1\%$
- Impact parameter resolution (0.25<|η|<0.5)
  $\sigma(d_0) = 10\ \mu m \oplus 140\ \mu m\ /\ p_T\ [GeV/c]$

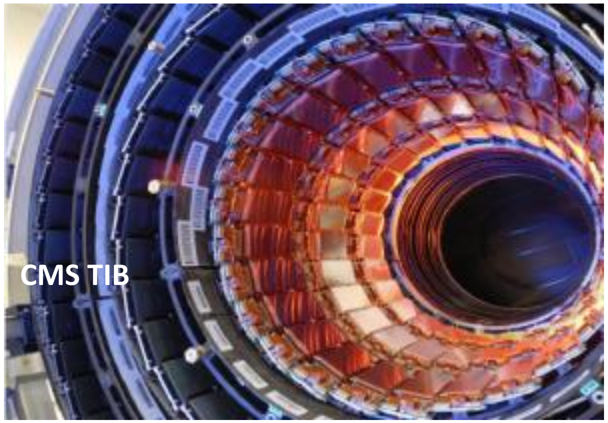
Pixel Detector

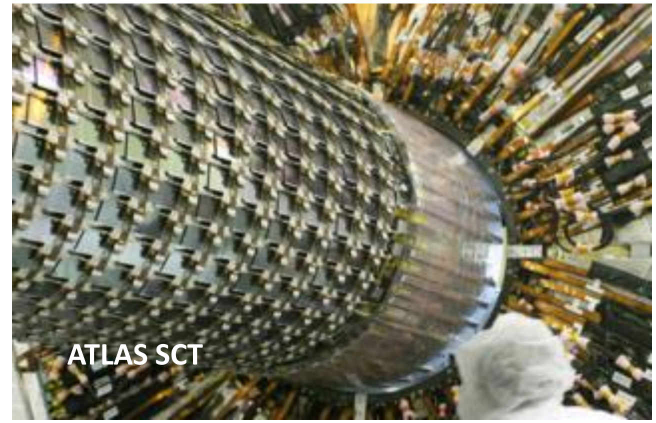
Determines:

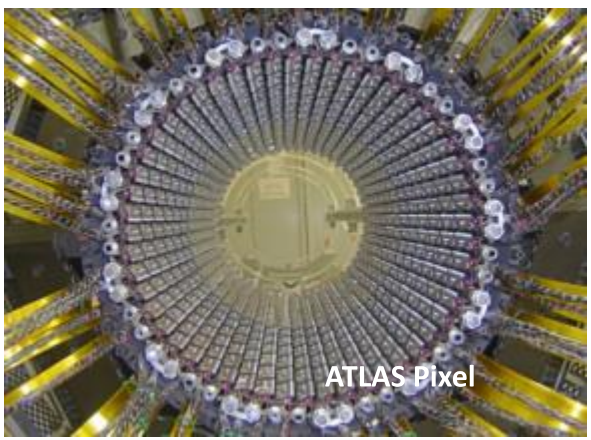
- Impact parameter resolution
- Ability of the Inner Detector to find short- lived particles such as B hadrons



Currently at LHC



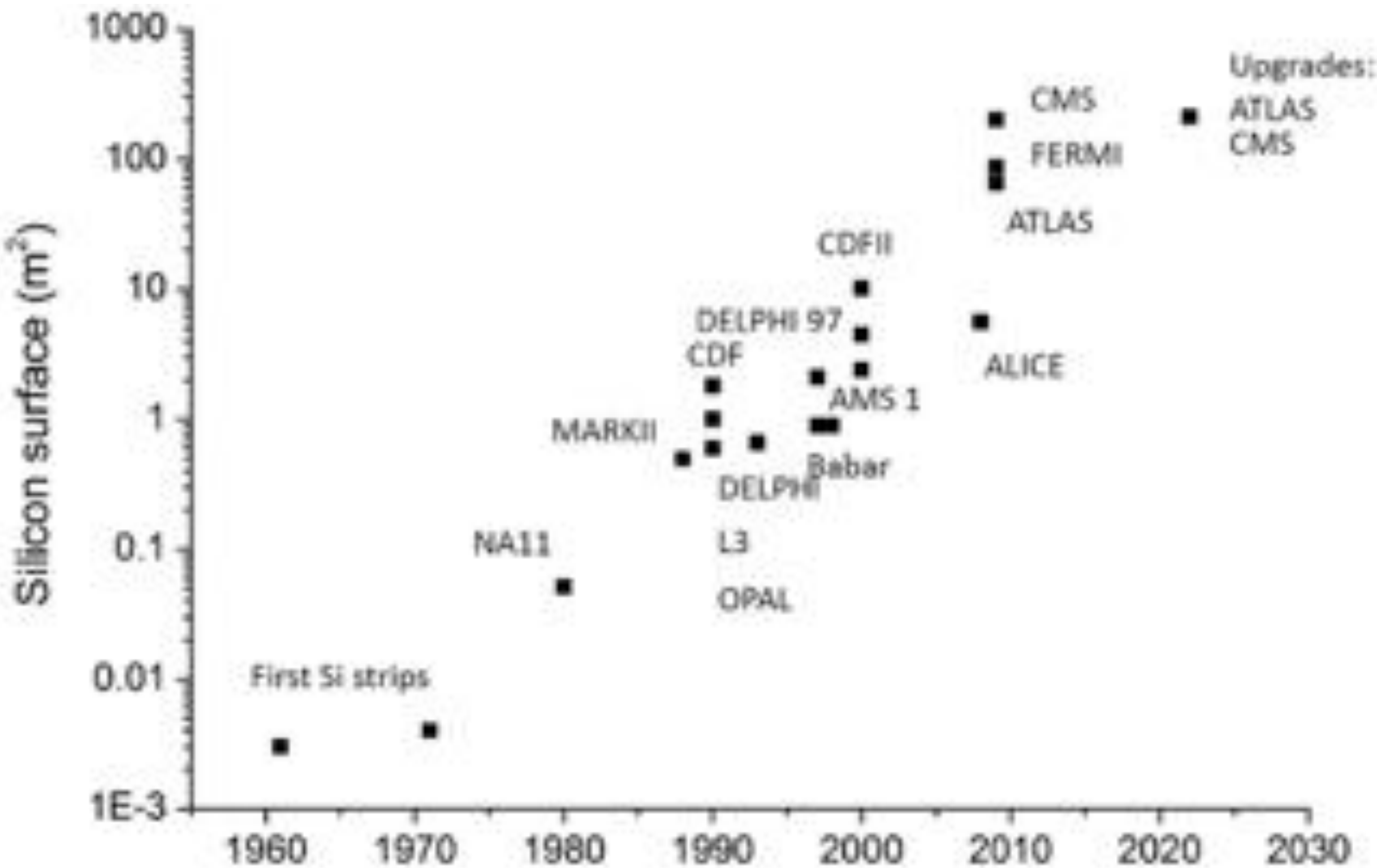




Lots of silicon everywhere

Size Does Matter

universitätbonn



The Pixel Master Table

universitätbonn

	Pixel size		Sensor Thickness (X_0)	ASIC Thickness (X_0)	Layers		beam-pipe inner radius	spatial resolution
	z [μm]	rϕ [μm]	[μm] (%)	[μm] (%)	[#]	radii [mm]	[mm]	[μm]
ALICE	425	50	200 (0.21)	150 (0.16)	2	39-76	29	100 (z) 12 (rϕ)
ATLAS	400	50	250 (0.27)	180 (0.19)	3	50.5-88.5-122.5	29	115 (z) 10 (rϕ)
IBL	250	50	200 (0.21)*	100 (0.11)	1	33.25	23.5	79 (z) 10 (rϕ)
CMS	150	100	285 (0.30)	180 (0.19)	3	44-73-102	29	~ 15

* IBL: decided to aim at using two technologies: planar sensors (200 μm) and 3D sensors (230 μm)

- The type of sensors differ, p-in-n for ALICE, n-in-n for ATLAS and CMS and LHCb VELO (with one n-in-p module installed)
- All using CMOS ASICs
- The operating temperatures (^{0}C) are +25 (ALICE), -20 (ATLAS), +18 (CMS), -5 (VELO)

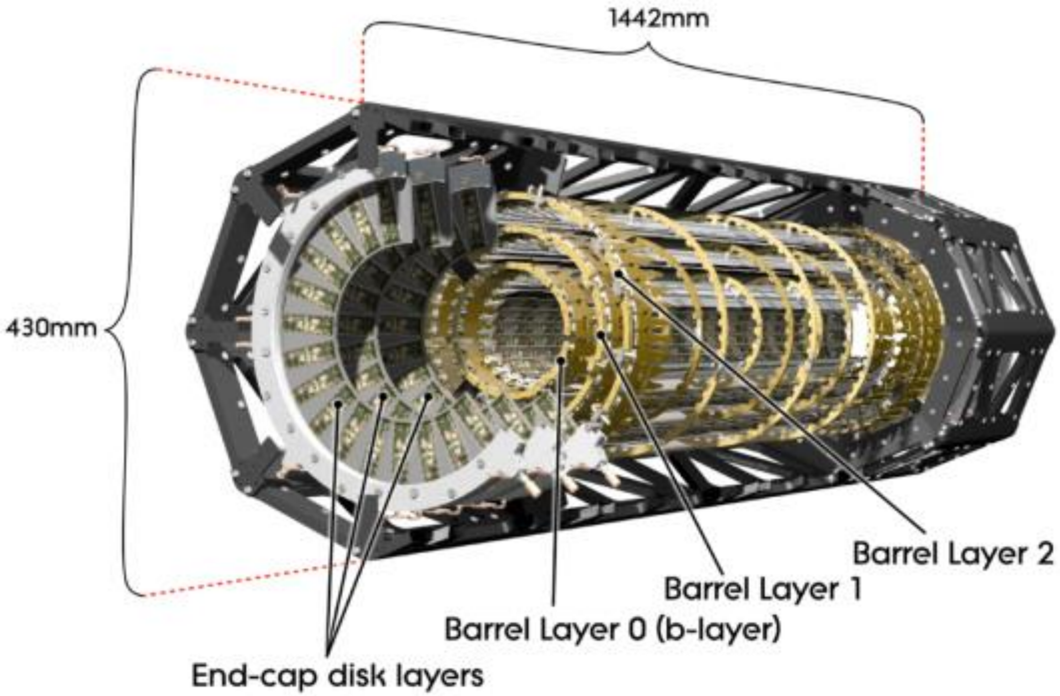
The Outer Layers

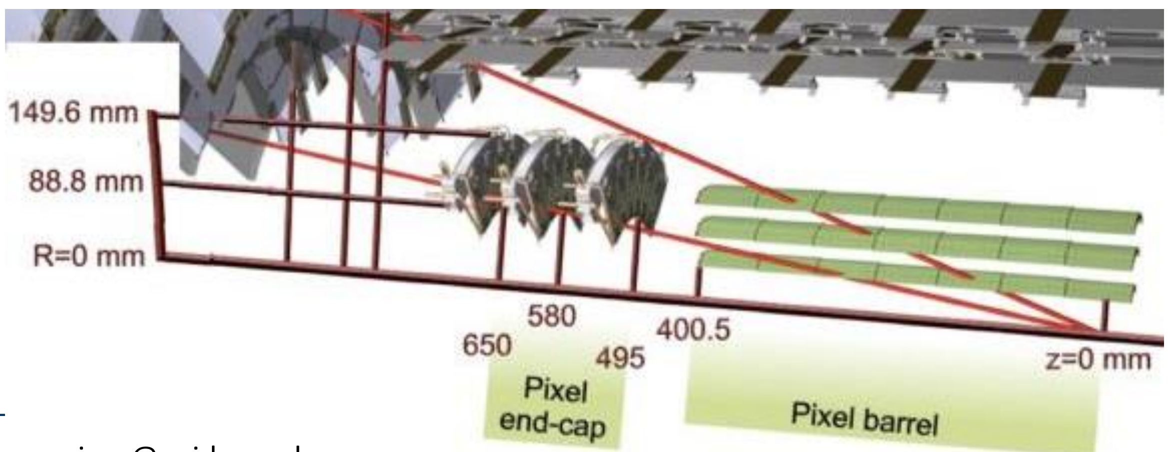
- CMS has a full silicon inner detector: 2 tons!
- ATLAS decided to invest in particle identification with straw tubes and radiators for transition radiation measurement
  - Advantage of inclusive isolated electron measurement, powerful tool for electron and photon studies in conjunction with e.m. calorimmetry
- Overall the **biggest** Inner Detectors ever built

	Strips	Layers		Spatial Resolution
	pitch [μm]	[#]	radii [μm]	[μm]
ALICE	95	2	380-430	830 (z) 20 (rϕ)
ATLAS	80	4	299 to 514	580 (z) 17 (rϕ)
CMS	80-183	3	255 to 1080	23-52 (rϕ)

The ATLAS Pixel Detector

universitätbonn



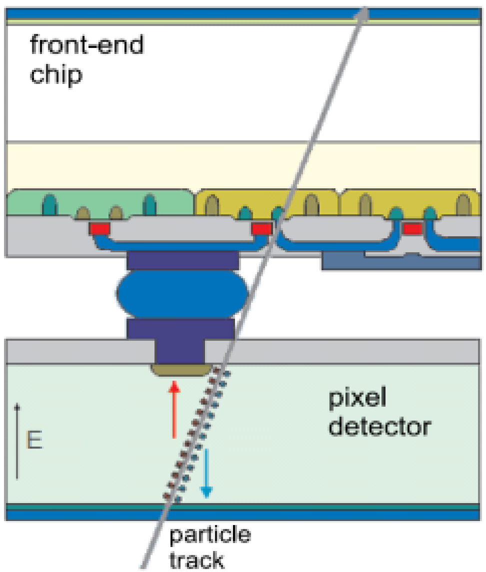


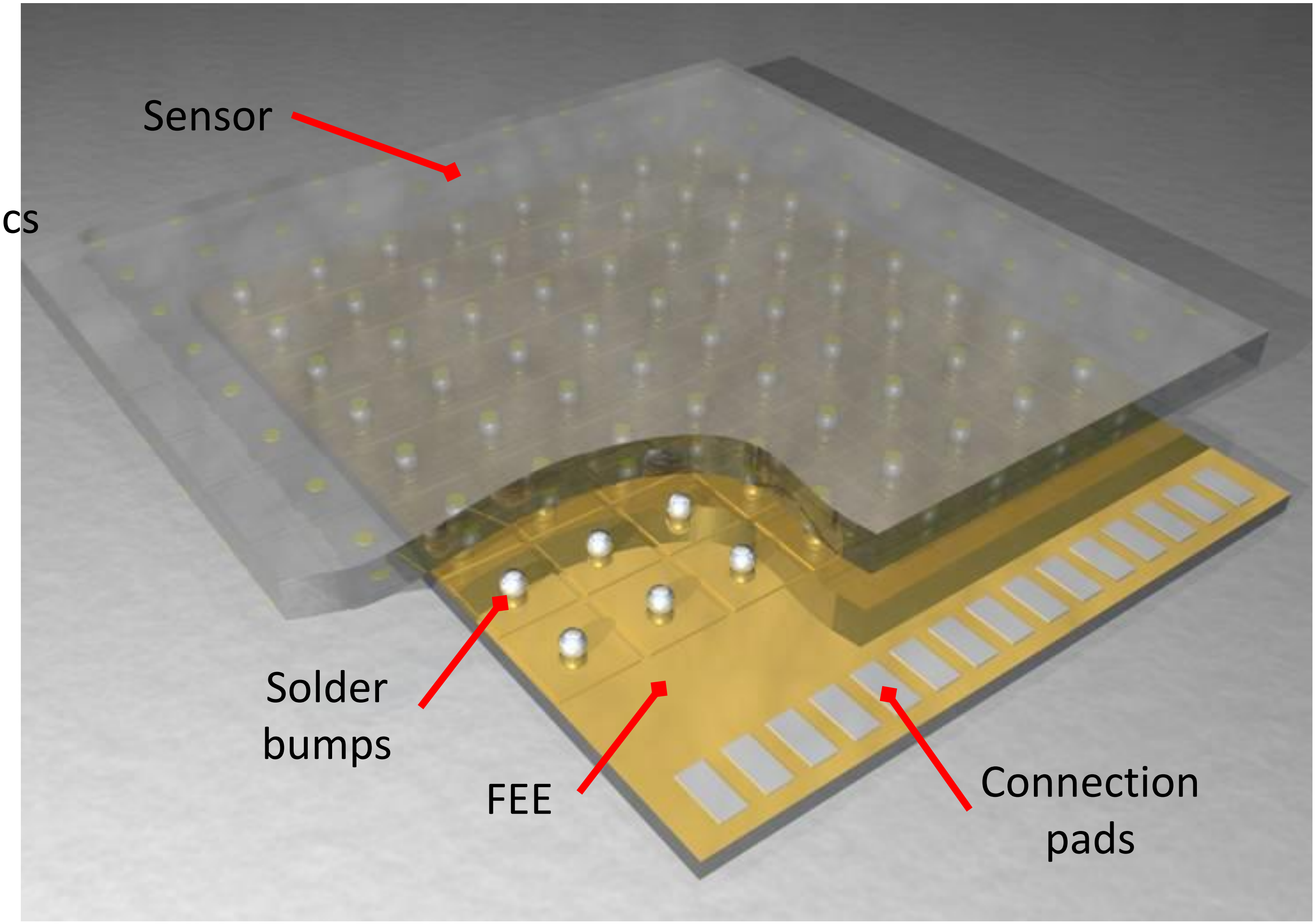
- **Three barrel layers:**
  - R= 5 cm (B-Layer),
    9 cm (Layer-1), 12 cm (Layer-2)
  - Modules tilted by 20º in the Rϕ plane to overcompensate the Lorentz angle.
- **Two endcaps:**
  - Three disks each
  - 48 modules/disk
- **Three precise measurement points:**
  - RΦ resolution:10 μm
  - η (R or z) resolution: 115 μm
- 1456 barrel modules and 288 forward modules, for a total of 80 million channels.
  - Environmental temperature about -13 ºC

Hybrid Pixel Detector

Fine pitch flip-chip of:
- Readout chips
- Si (planar or 3D)
- Or Diamond

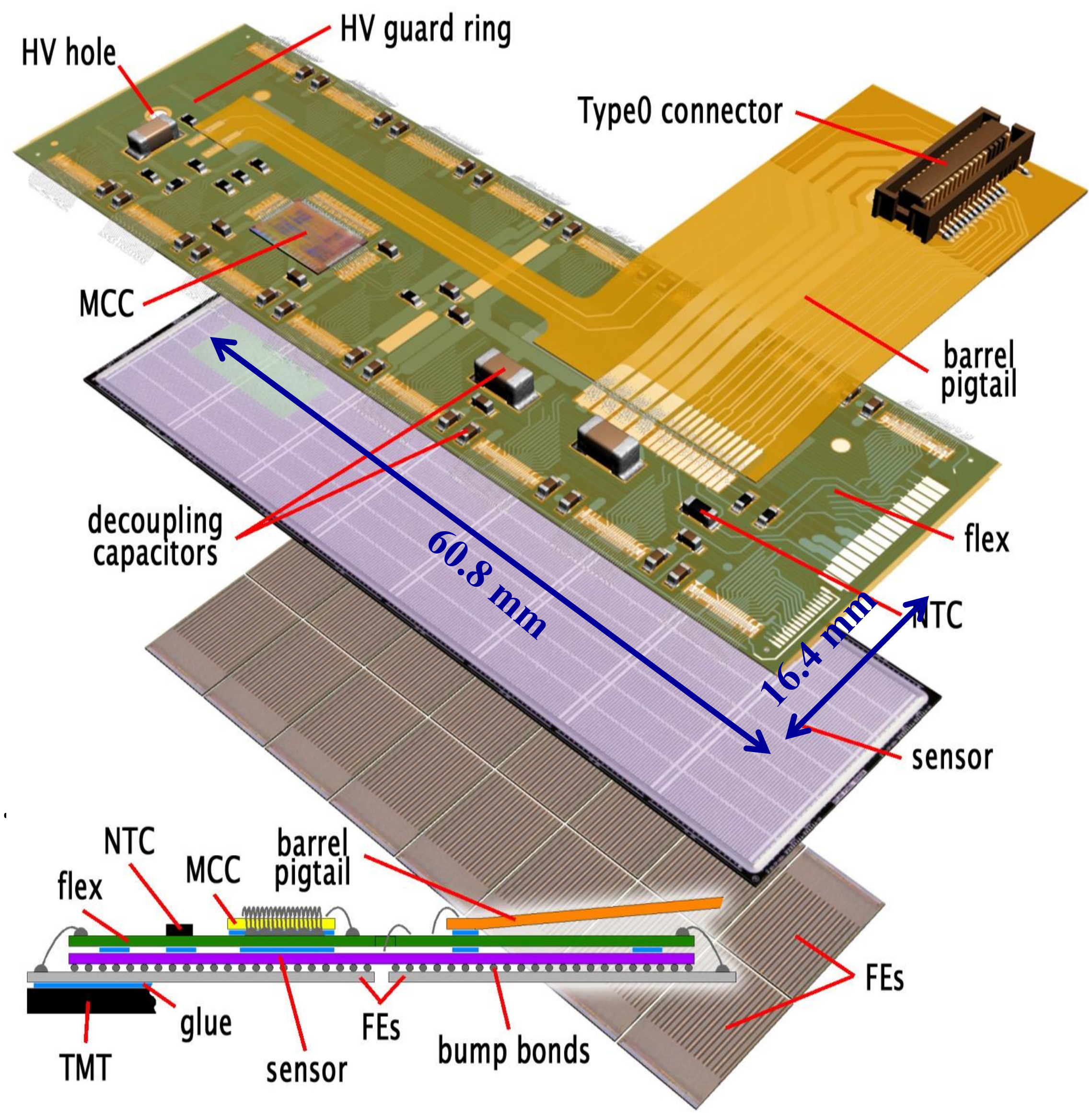
+ High density electronics
+ Moderate - good SNR
- High material budget
- Expensive assembly





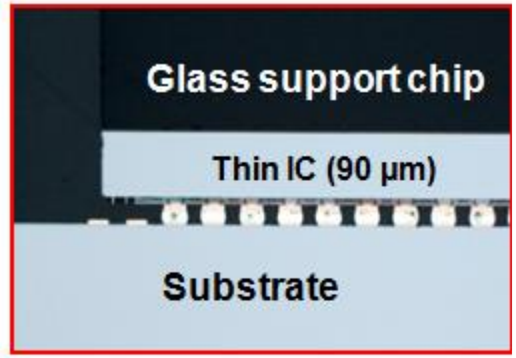
Module Overview

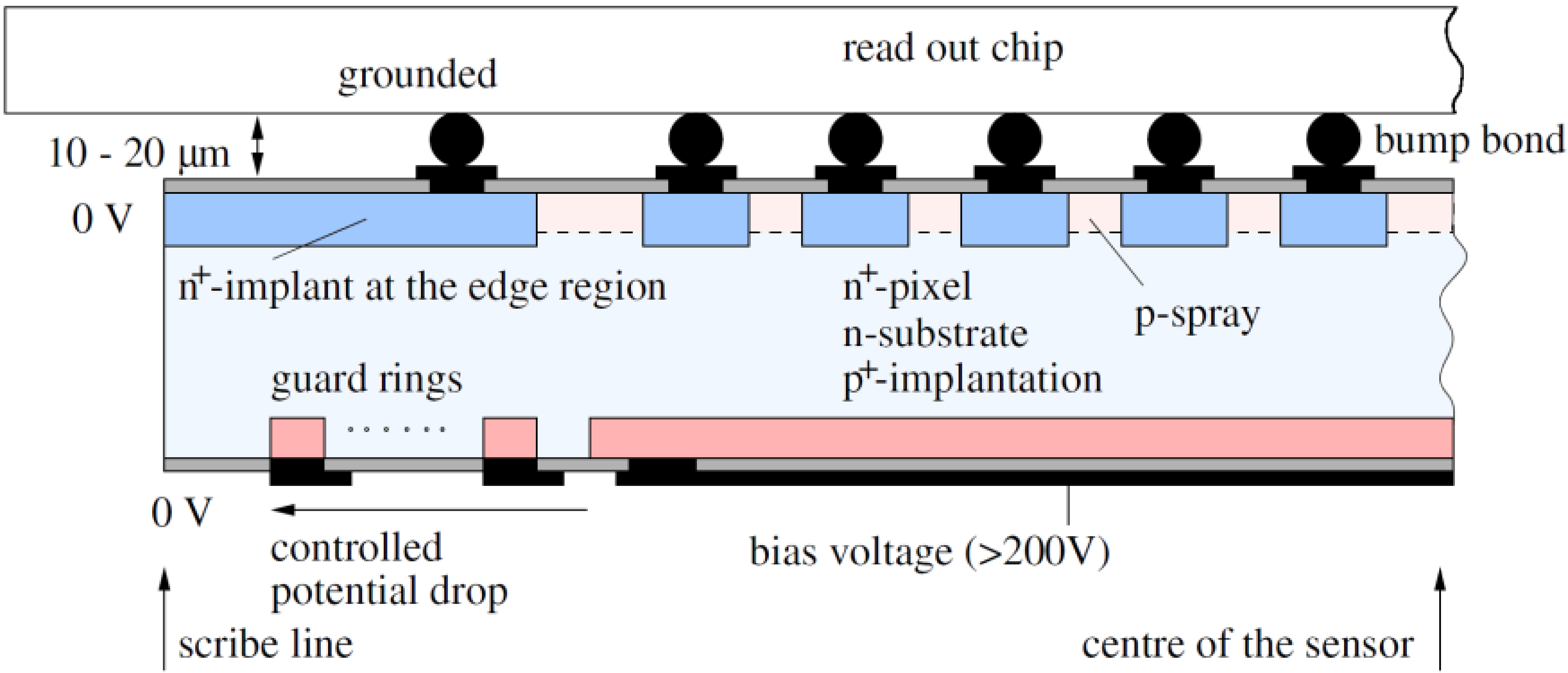
- **Sensor**
  - 47232 n-on-n pixels with moderated p-spray insulation
  - 250 μm thickness
  - 50 μm (RΦ) × 400 μm (η)
  - 328 rows × 144 columns
- **16 FE chips**
  - bump bonded to sensor
- **Flex Hybrid**
  - passive components
  - Module Controller Chip to perform distribution of commands and event building.
- **Radiation-hard design:**
  - Dose 500 kGy
  - NIEL 10^{15} n_{eq}/cm^2 fluence



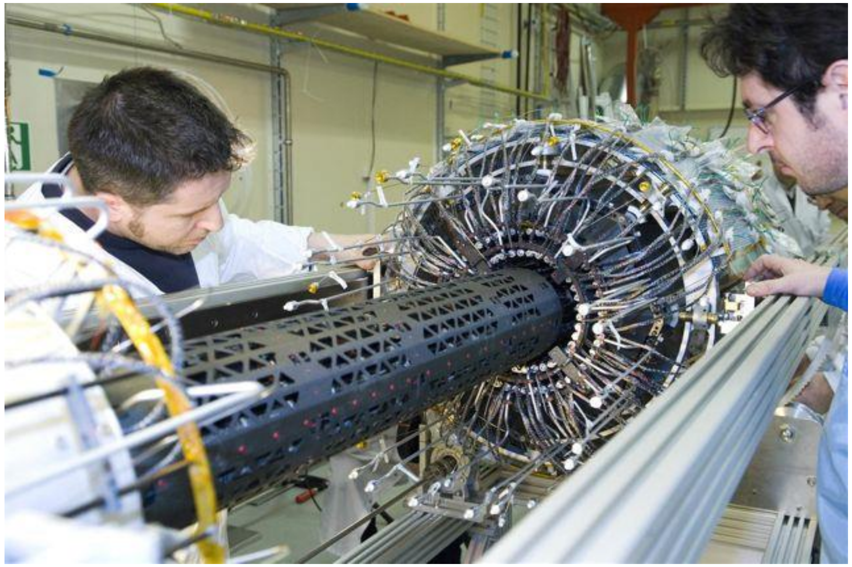
Present ATLAS Pixel Module

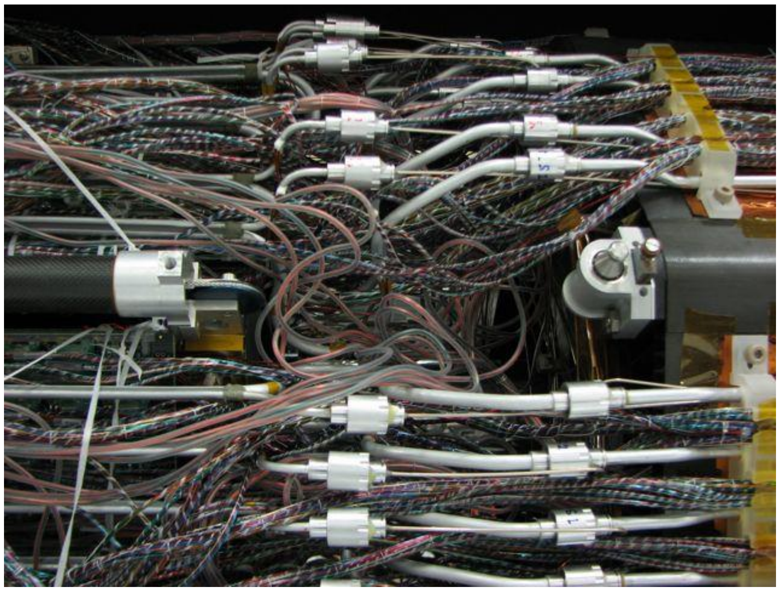
- Planar n-in-n silicon sensor
- n+ pixel
- n bulk, 250 µm thick
- p+ implantation
- Guard rings to reduce HV stepwise
- 46080 pixel cells, 400 µm x 50 µm

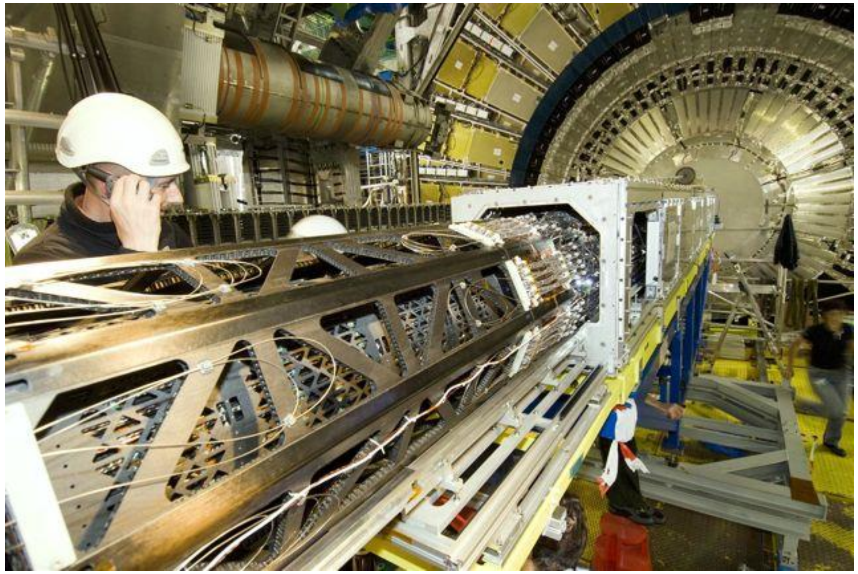




Pixel Installation

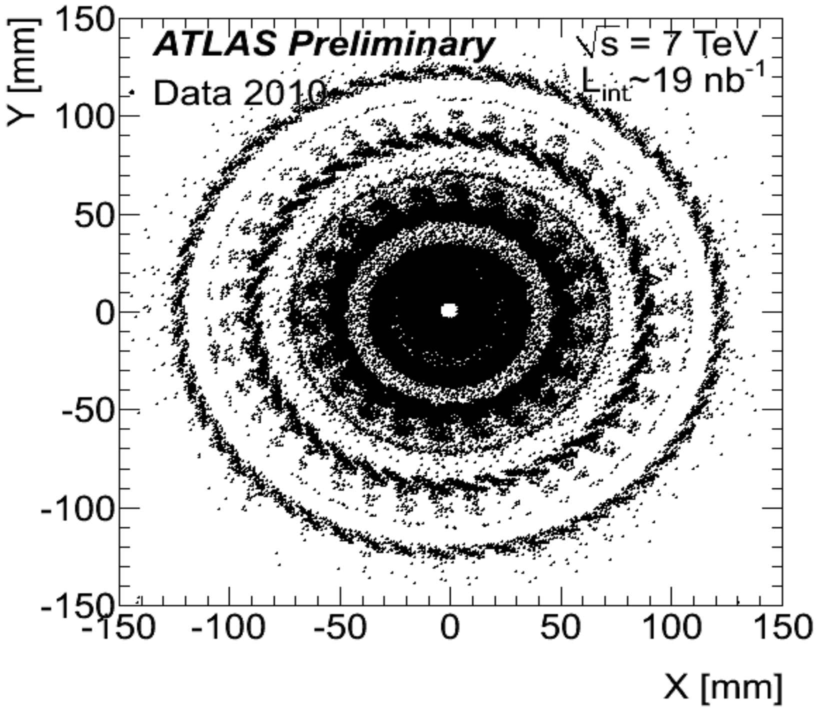


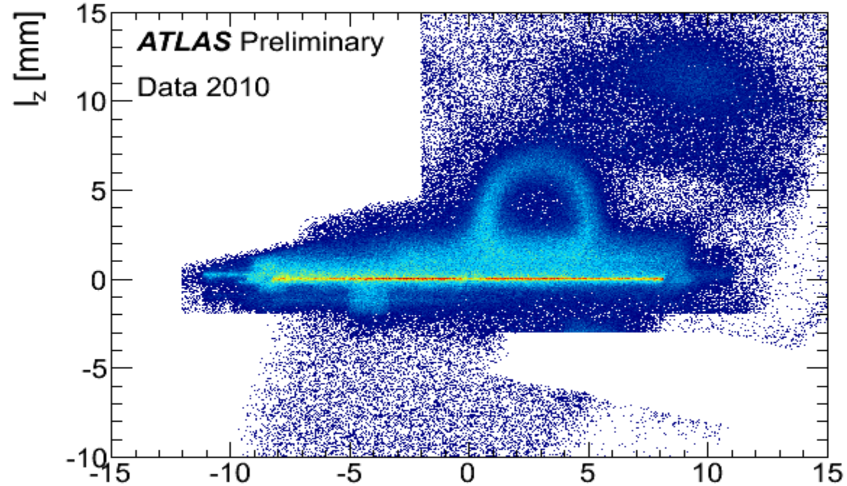


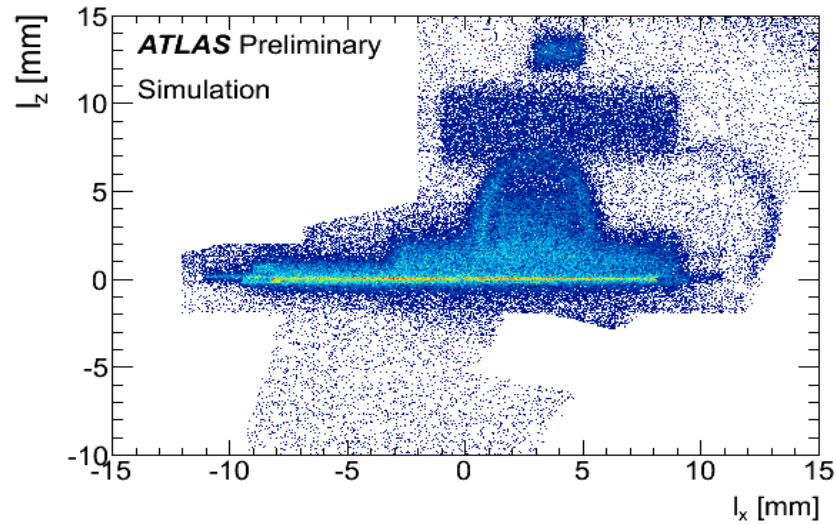


ATLAS Pixel Having Fun With Tracks

- Secondary vertices map for detector imaging







Role of Vertex and Tracker Detectors

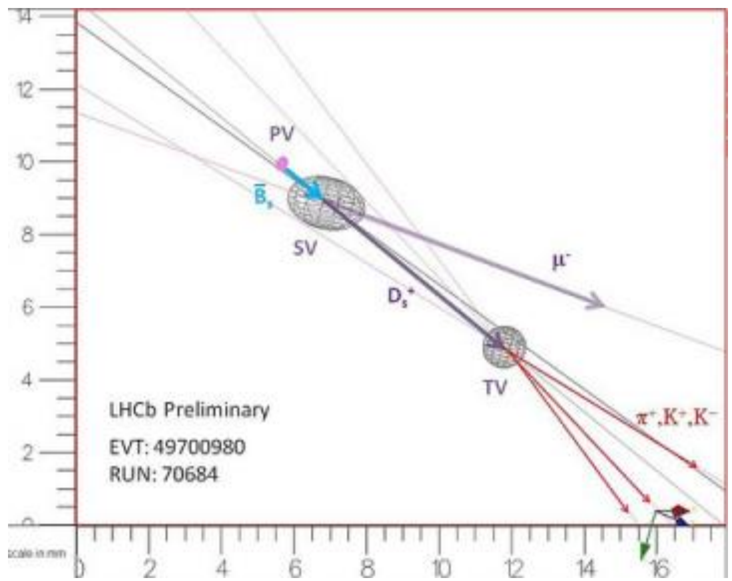
Measure the trajectory and the momentum of charged particles.
Extrapolate back to the point of origin. Reconstruct:

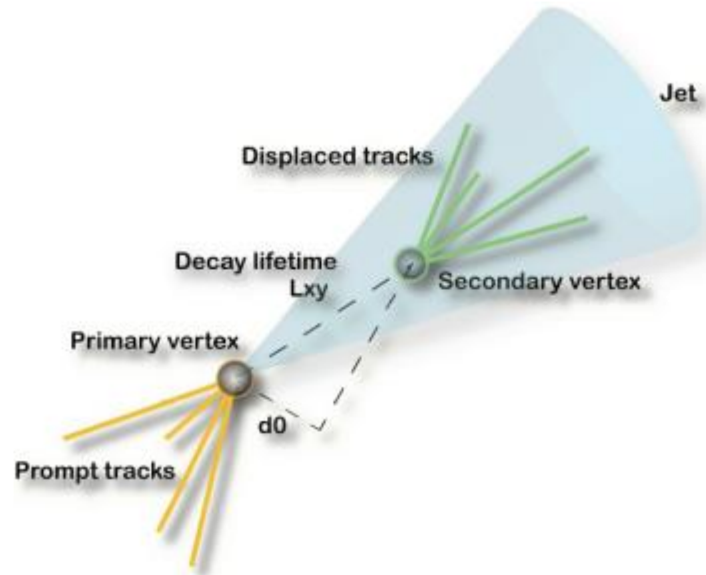
- Primary vertices

Distinguish primary vertices and identify the vertex associated with the interesting hard interaction

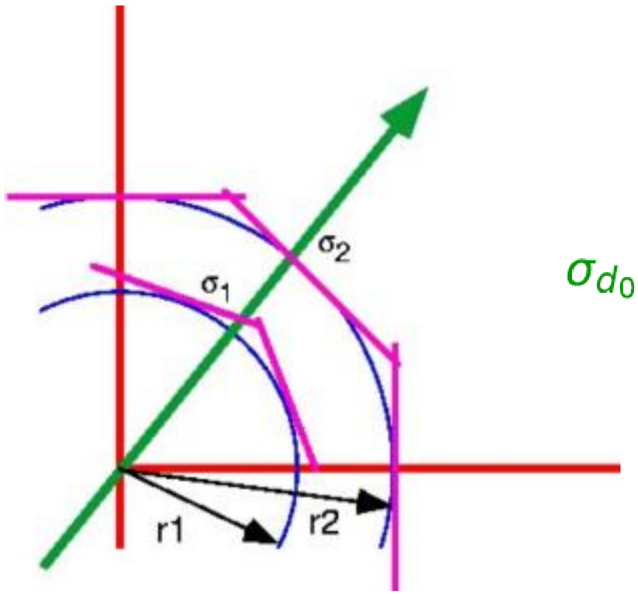
- Secondary vertices

Identify tracks from tauleptons, b and chadrons





Impact Parameter Resolution

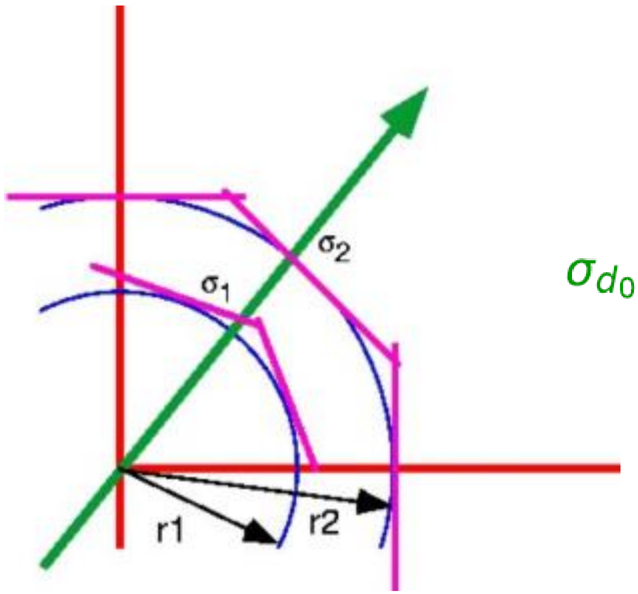


Small r_1, large r_2 and small σ_1 and σ_2

$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}}$$

Constant term (geometry)

Impact Parameter Resolution



Small r_1, large r_2 and small σ_1 and σ_2

Minimum thickness and light materials

$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{3/2}\theta} 13.6\text{MeV}\sqrt{\frac{x}{X_0}}$$

Constant term (geometry) — Multiple Coulomb scattering

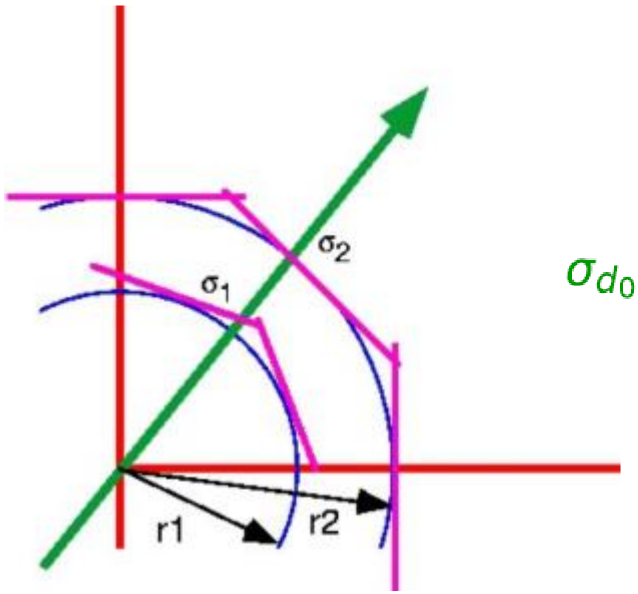
$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

	a (µm)	b (µm GeV)
LHC	12	70
STAR	12	19
Belle II	8.5	10
ILC	5	10

- Increase sensor granularity
  → More smaller pixels

Impact Parameter Resolution

universitätbonn



Small r_1, large r_2 and small σ_1 and σ_2

Minimum thickness and light materials

$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{3/2}\theta} 13.6\mathrm{MeV}\sqrt{\frac{x}{X_0}}$$

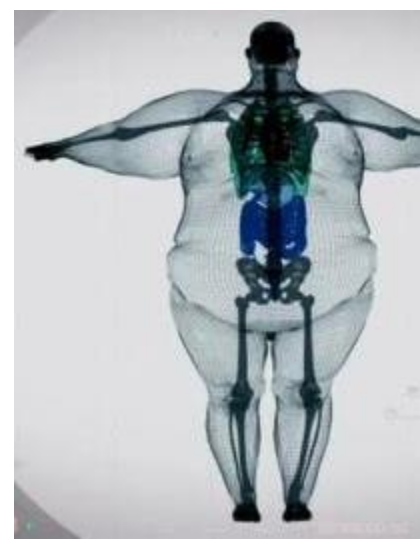
Constant term (geometry)

Multiple Coulomb scattering

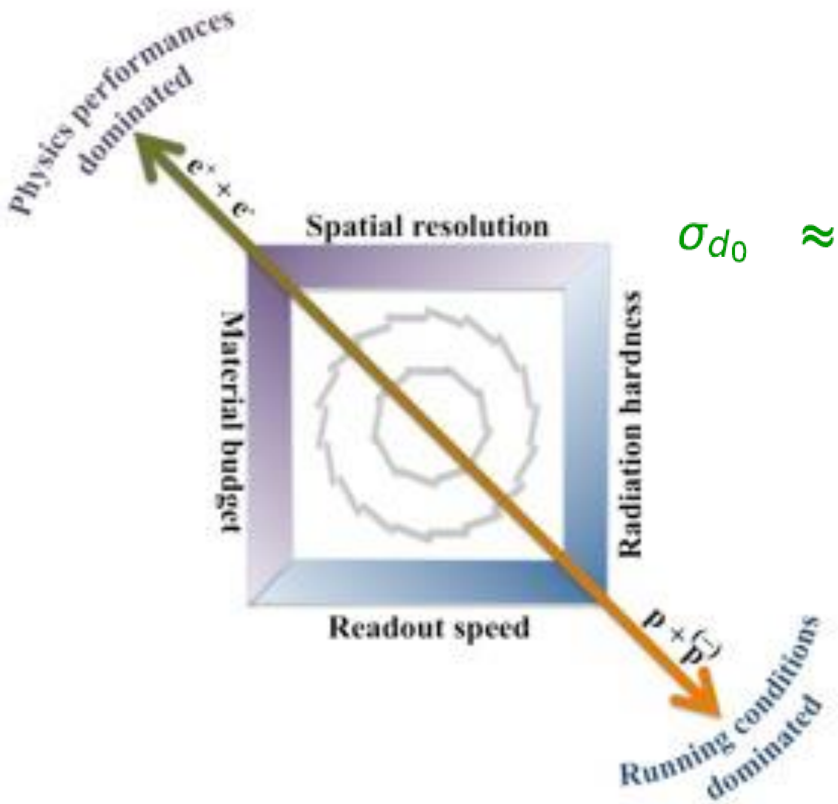
$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

	a (µm)	b (µm GeV)
LHC	12	70
STAR	12	19
Belle II	8.5	10
ILC	5	10

- Minimise material !!!



Impact Parameter Resolution



Squaring the circle
Make a compromise depending on your requirements!

Small r_1, large r_2 and small σ_1 and σ_2

Minimum thickness and light materials

$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{3/2}\theta} 13.6\text{MeV}\sqrt{\frac{x}{X_0}}$$

Constant term (geometry) — Multiple Coulomb scattering

$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

- First layer close to the IP
- Low material budget
    - Reduced services
    - Low power dissipation
- High granularity
    - Good spatial resolution
- Fast readout
- Radiation hardness

Spatial Resolution

universitätbonn

$$\sigma_{Position} = \frac{pitch}{\sqrt{12}}$$

Spatial resolution mainly determined by the pixel pitch

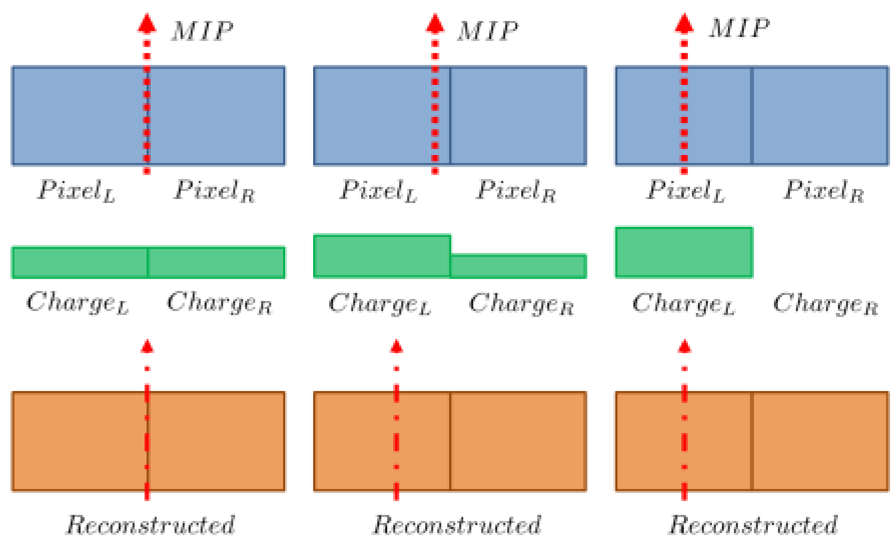
ATLAS Hybrid pixels: $p \sim 100\mu m \rightarrow \sigma_{Position} = 29\ \mu m$

DEPFET for Belle II: $p \sim 50\mu m \rightarrow \sigma_{Position} = 14\ \mu m$

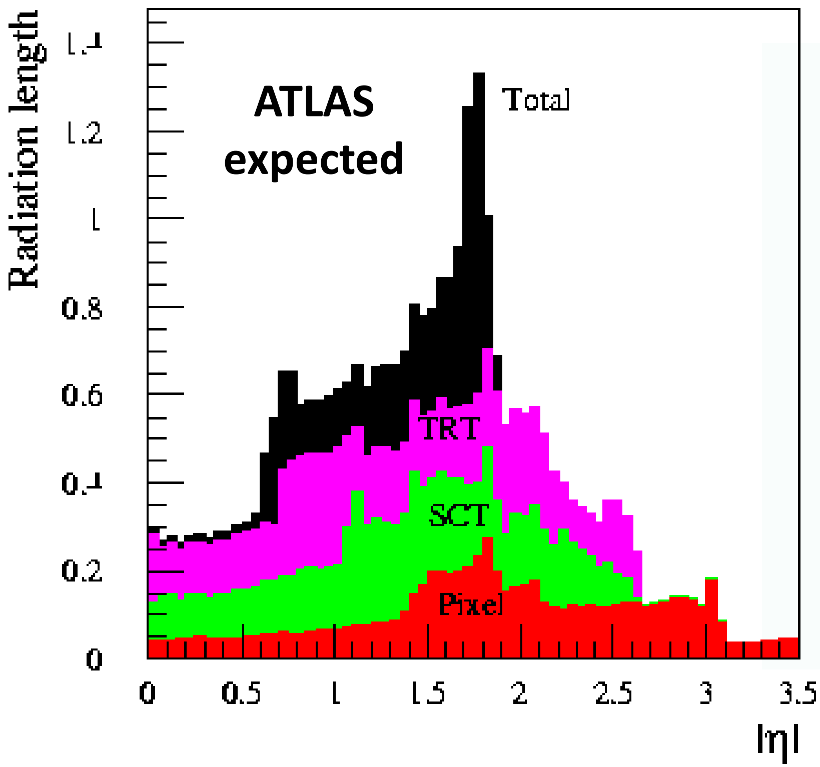
DEPFET for ILC: $p \sim 20\mu m \rightarrow \sigma_{Position} = 5.8\ \mu m$

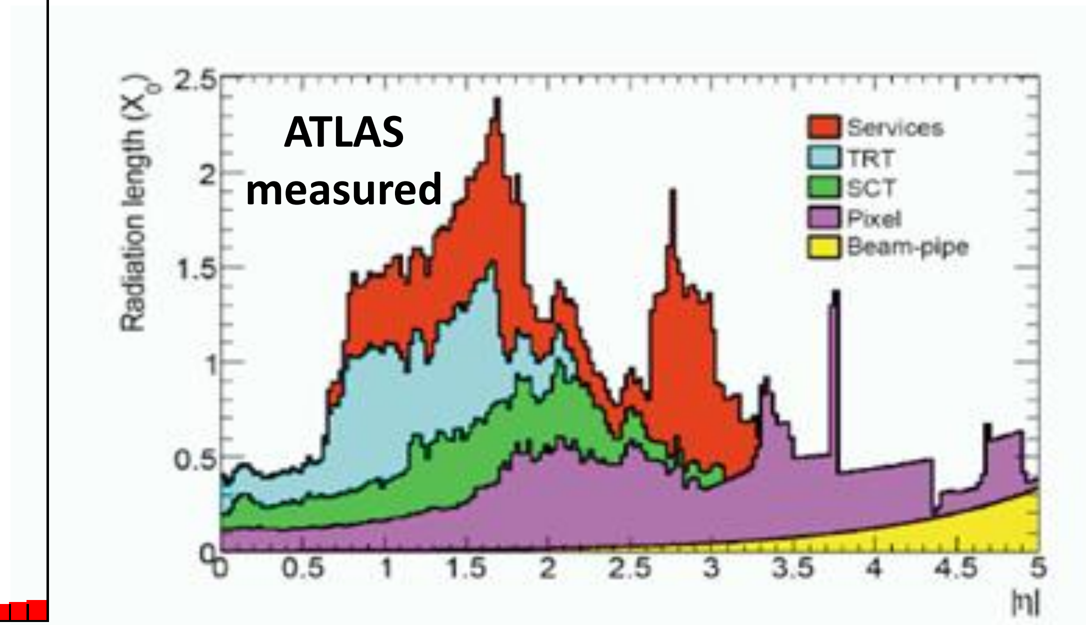
Other factors can have influence:

- Readout mode (analog or digital)
- Reconstruction algorithm
- Charge sharing



Material Budget





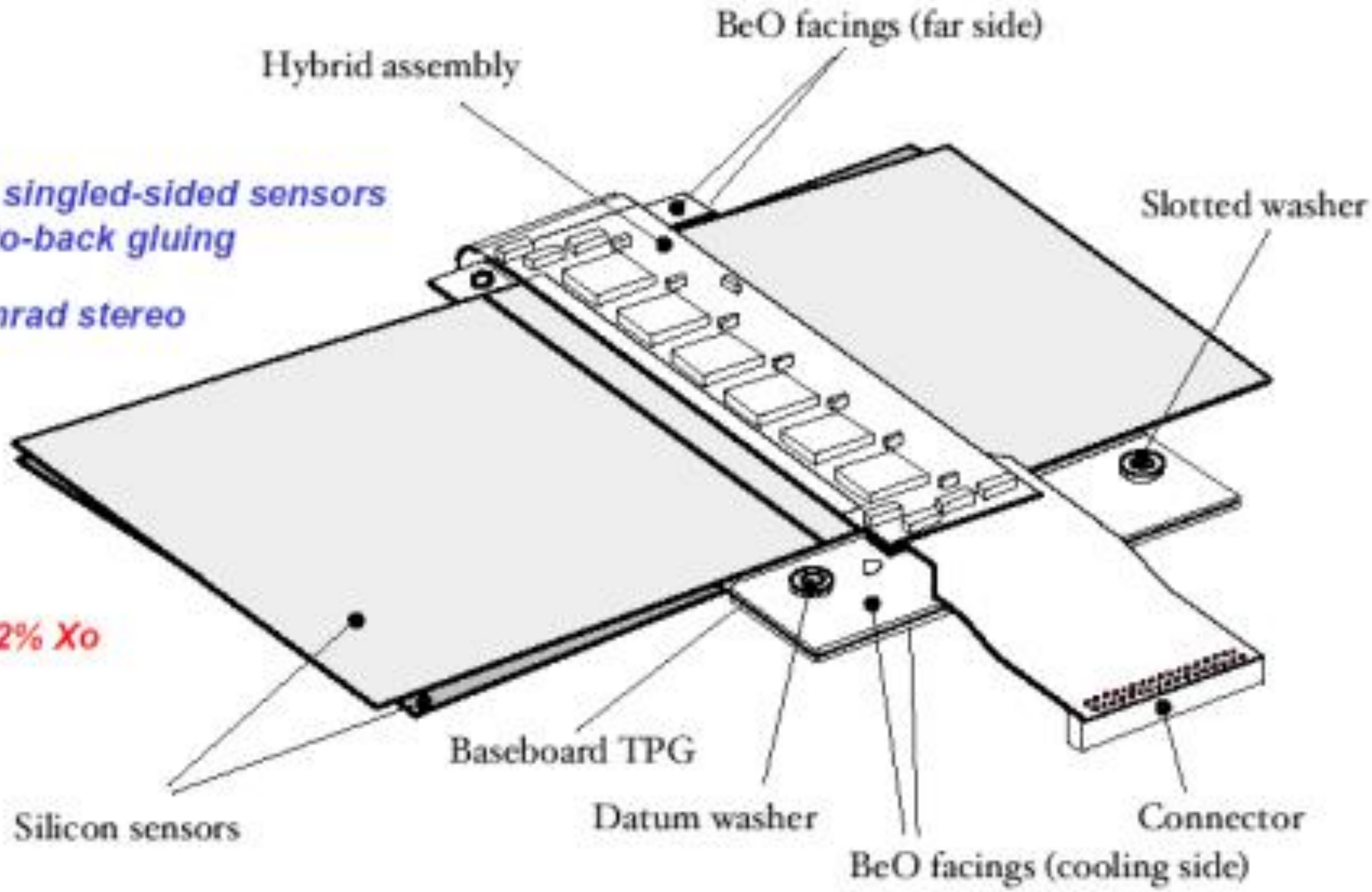
Both ATLAS and CMS slipped considerable in keeping x/X0 low!

From Clean Design…

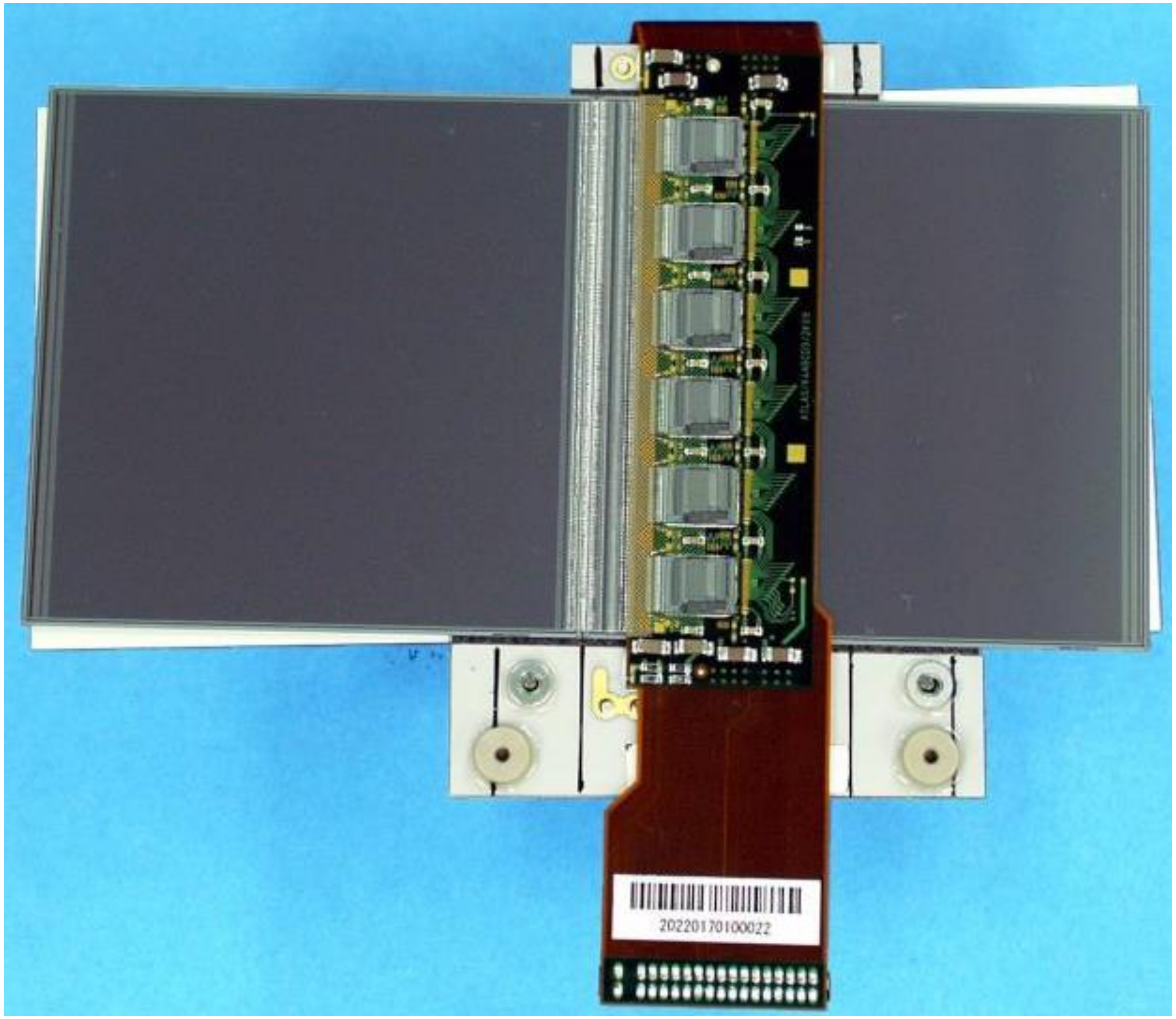
p-in-n singled-sided sensors
back-to-back gluing

40 mrad stereo

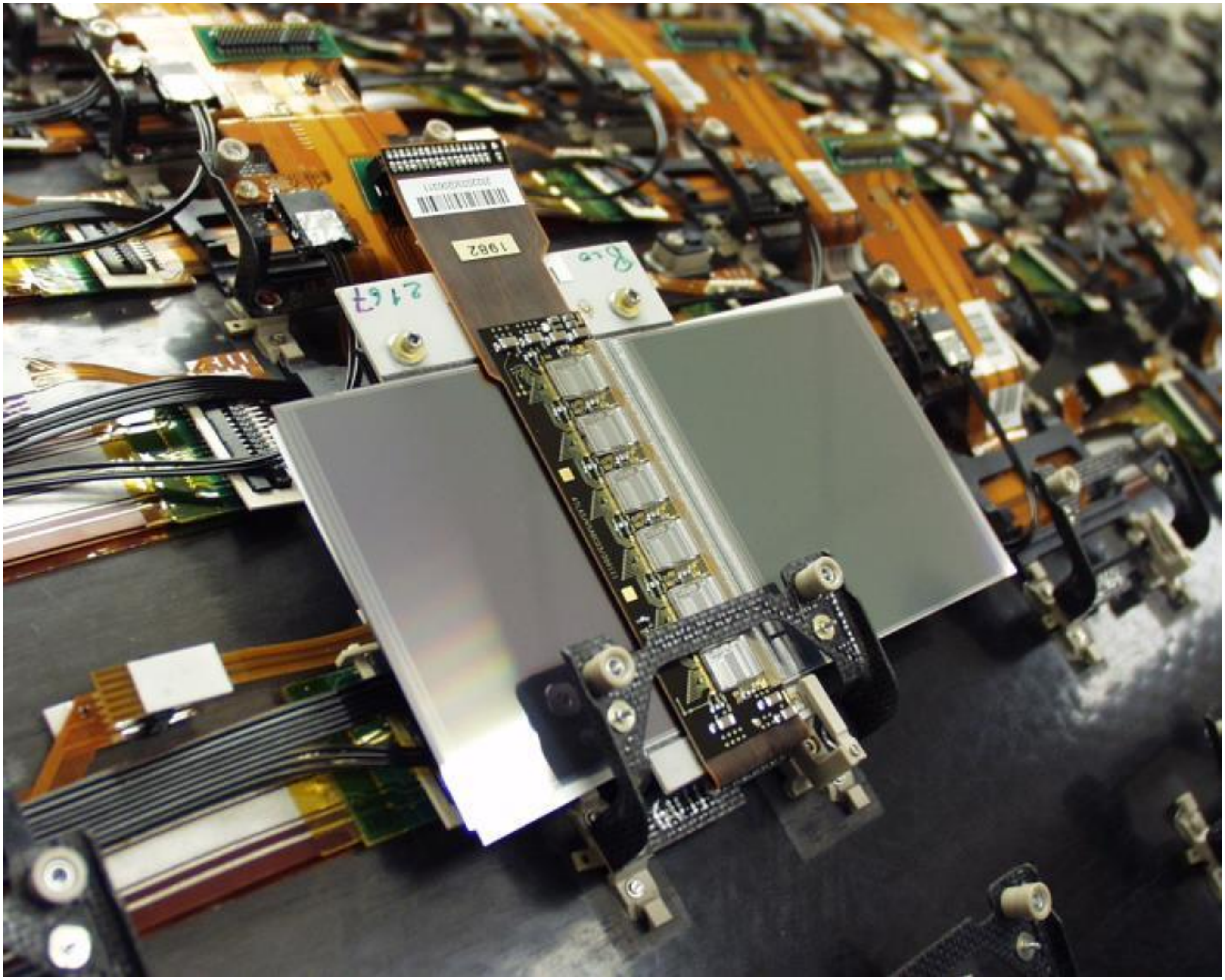
1.2% Xo



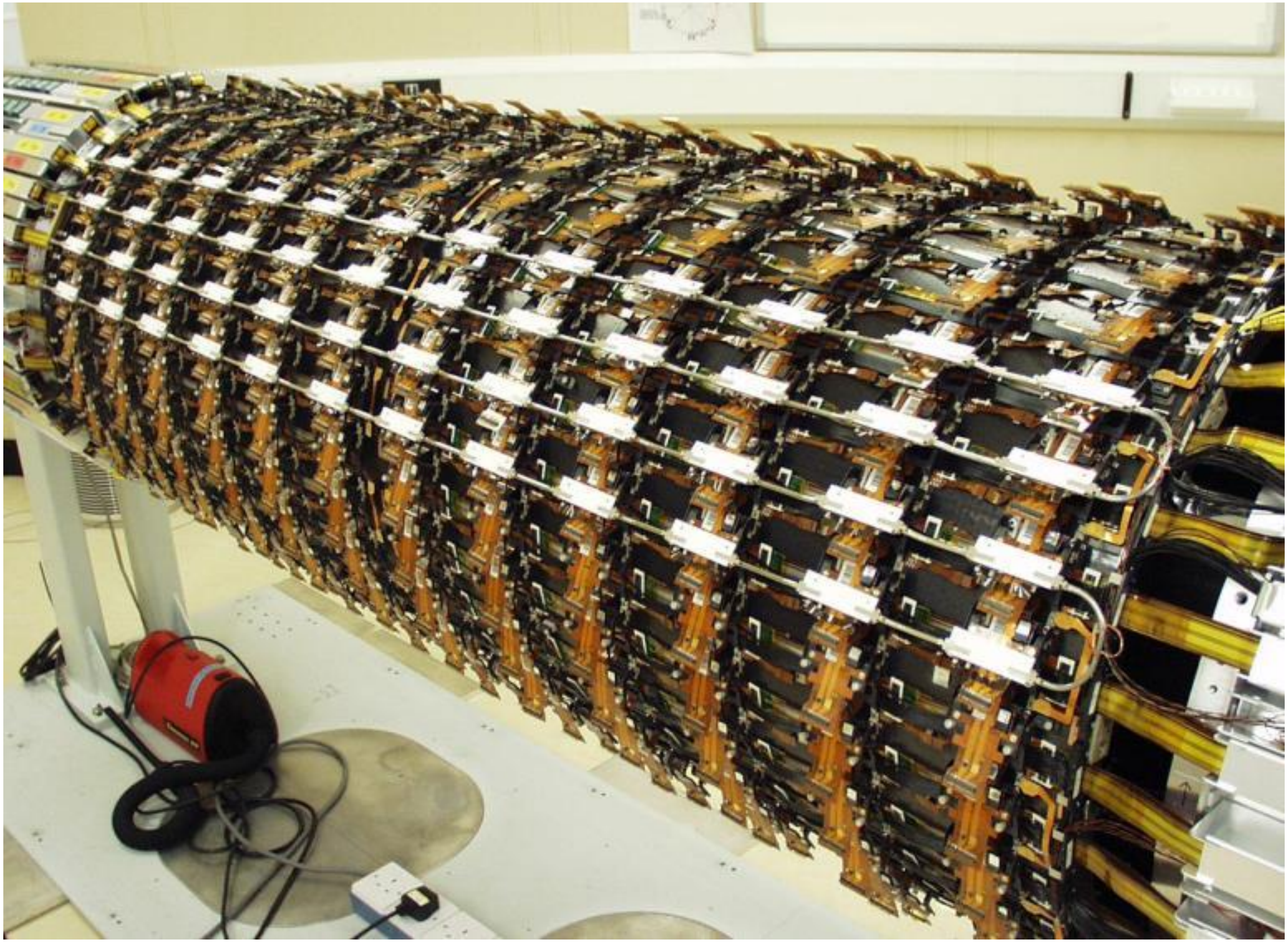
… Great Module Production…



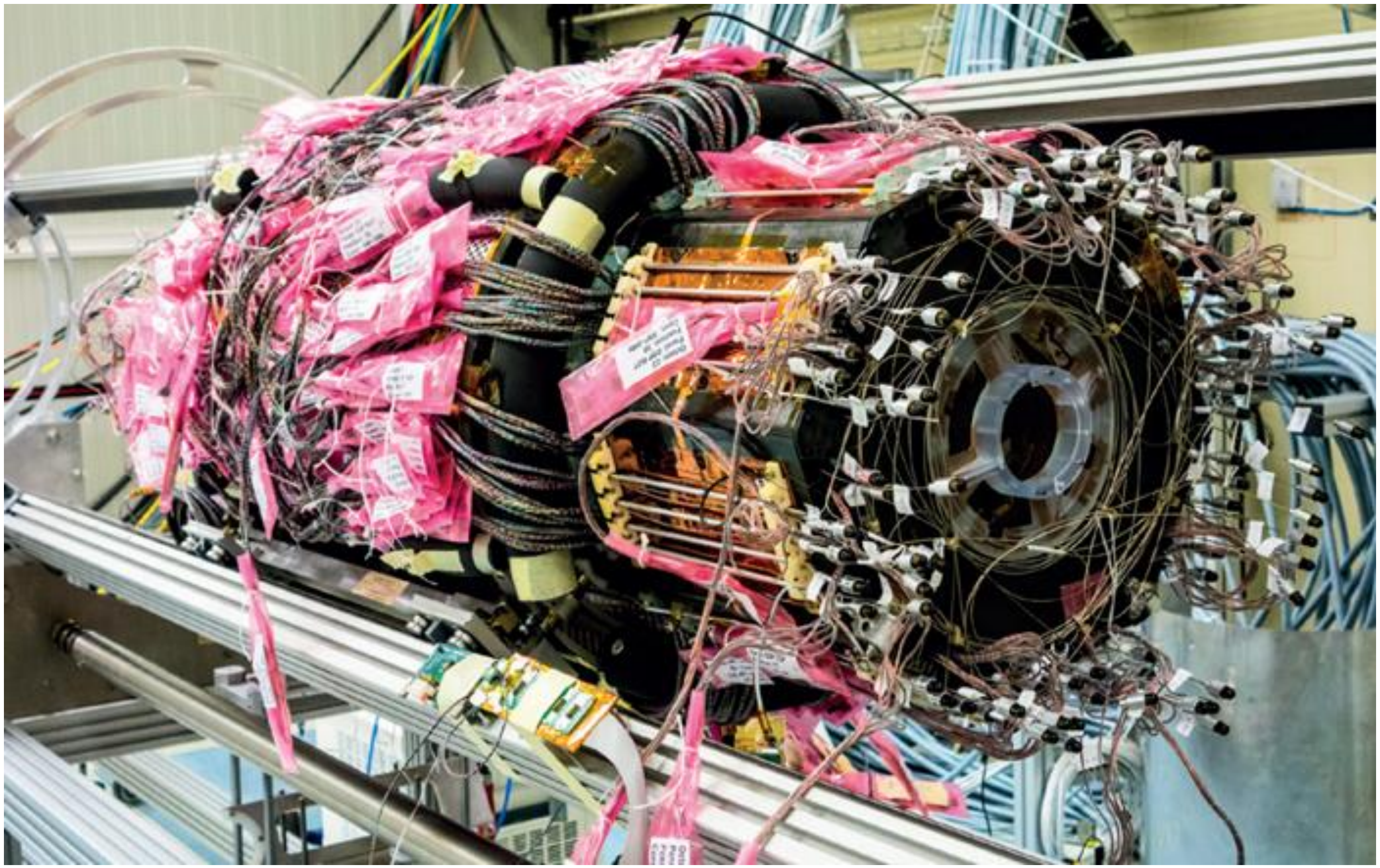
… Not So Light Mechanics…



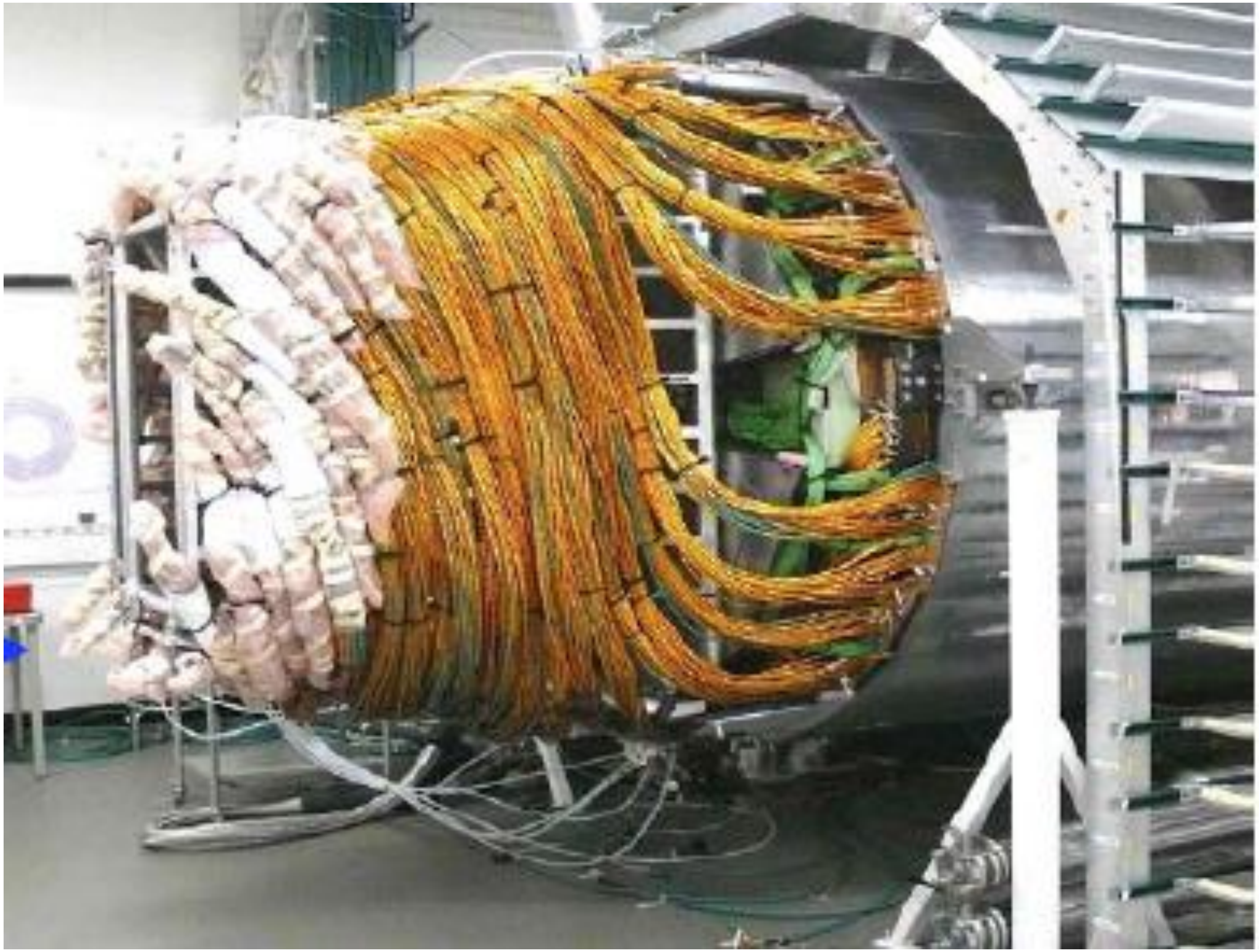
… Ah, Also Cooling…



… Some Additional Pipes …

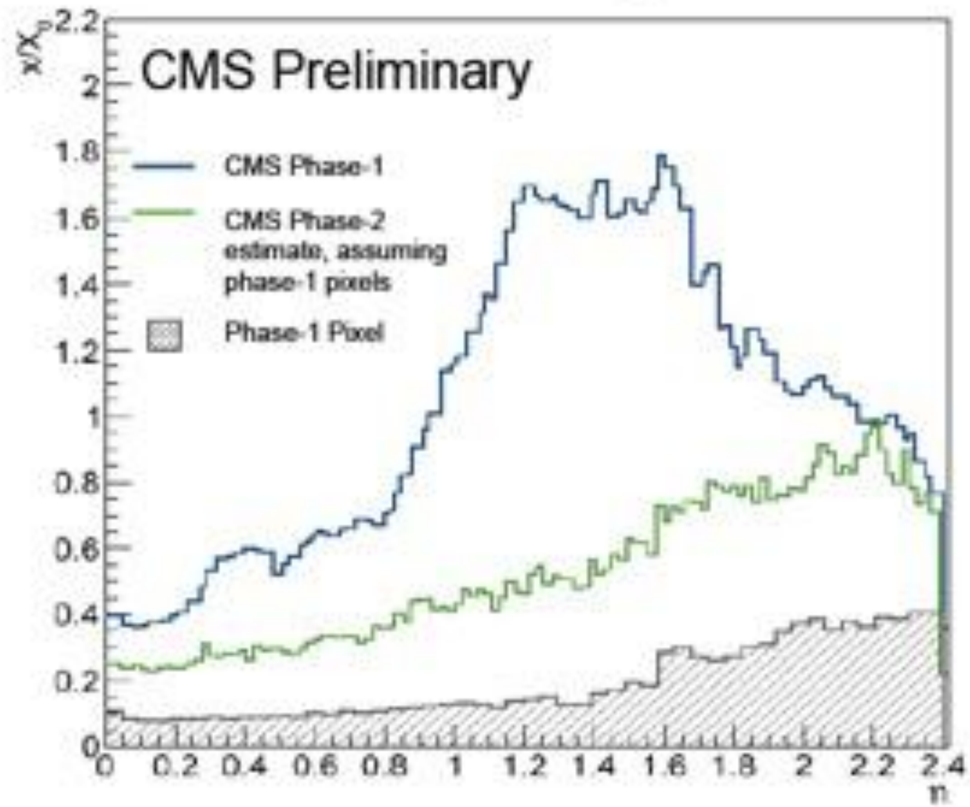


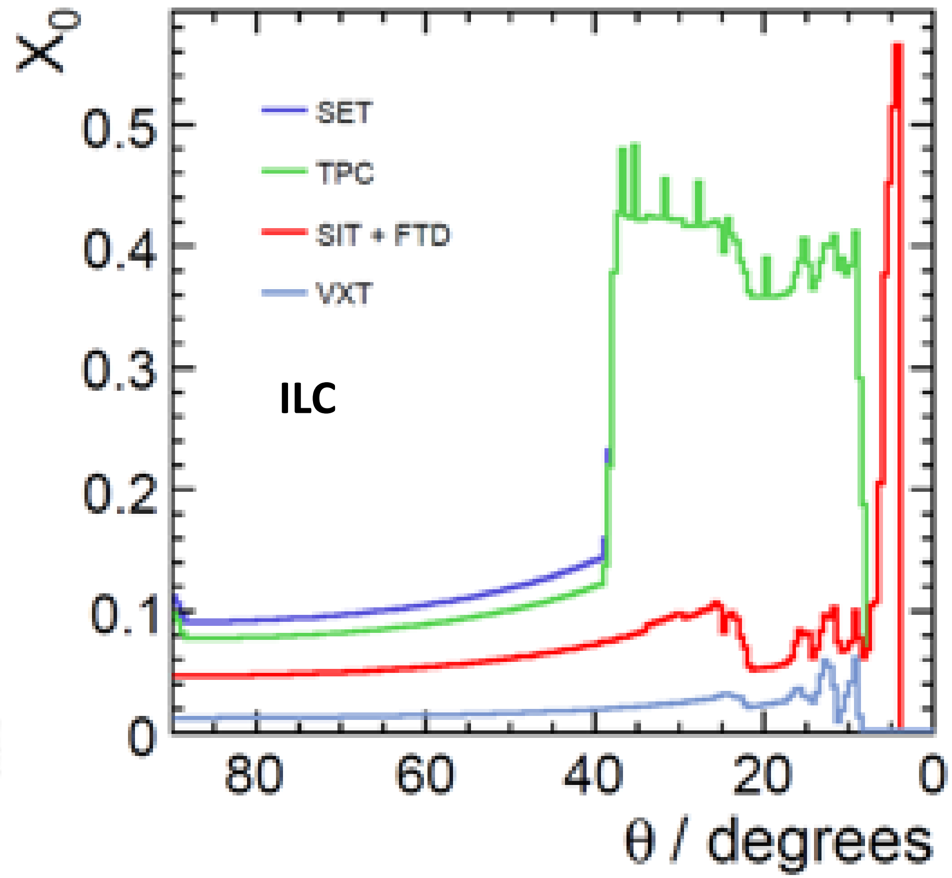
… Oh Wait, We Need More Cables…



Pay attention to all the design aspects from the very first moment!!

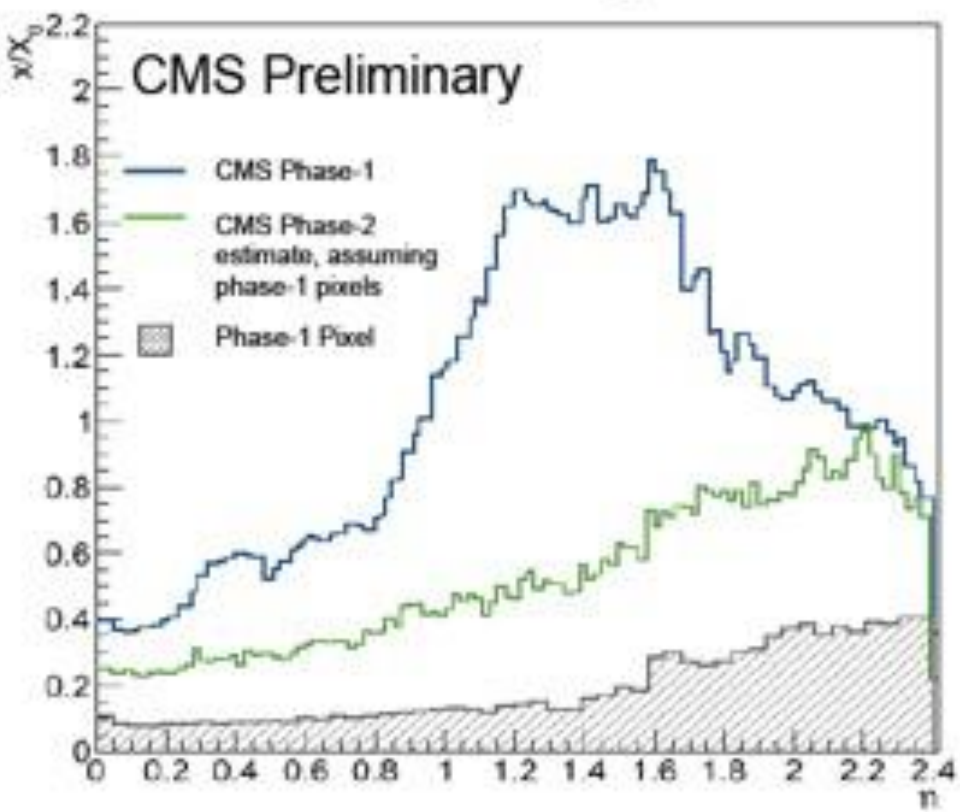
CMS Upgrade and ILC



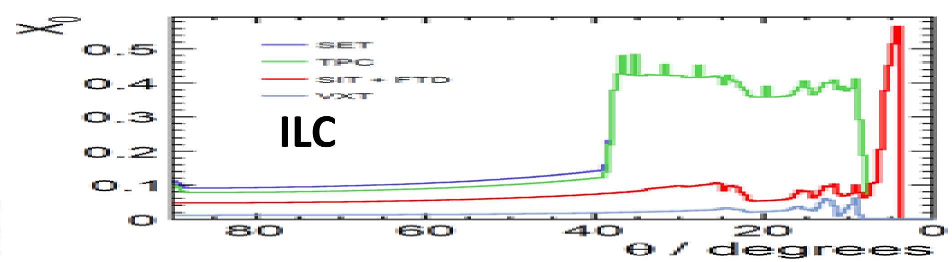


CMS aims to reduce the material budget a factor 2

CMS Upgrade and ILC

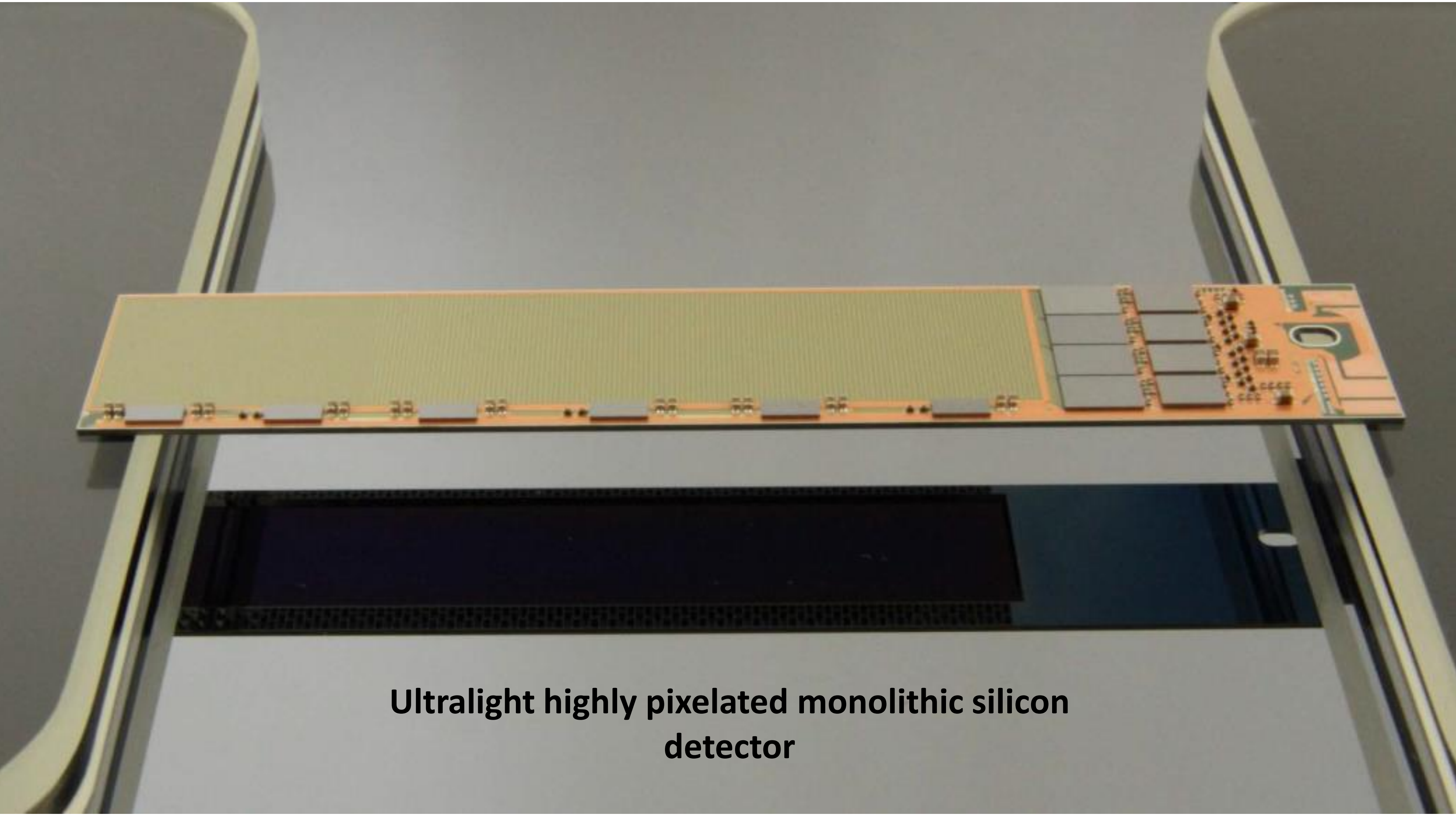


If we put things into the same scale…
ILC aims to be extremely lightweight



CMS aims to reduce the material budget a factor 2

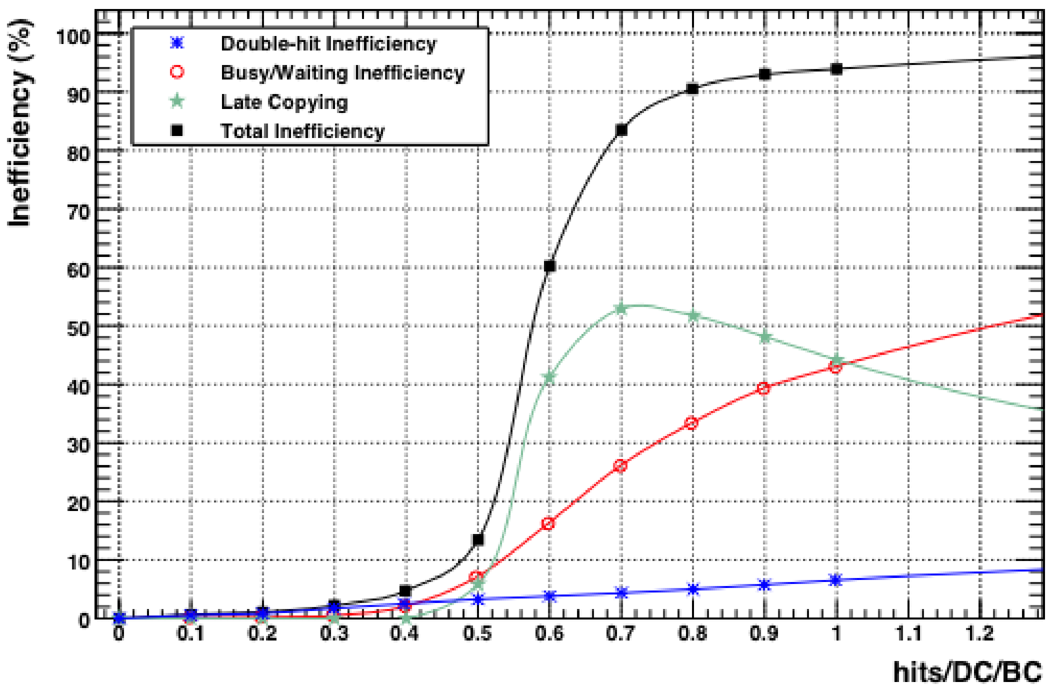
DEPFET Detectors

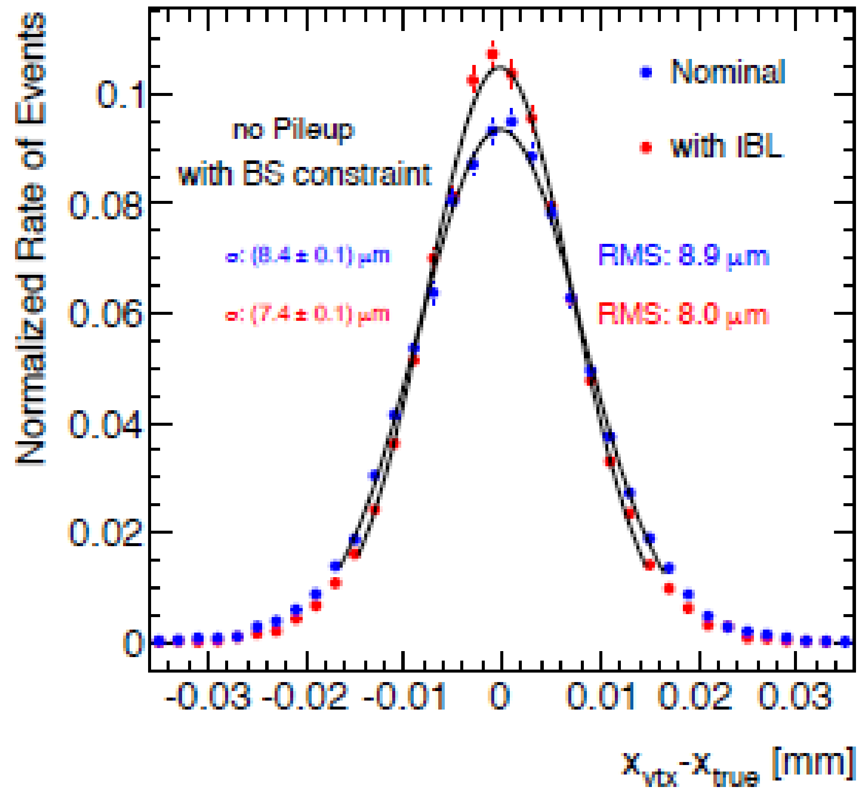


Ultralight highly pixelated monolithic silicon detector

IBL – The 4th Pixel Layer

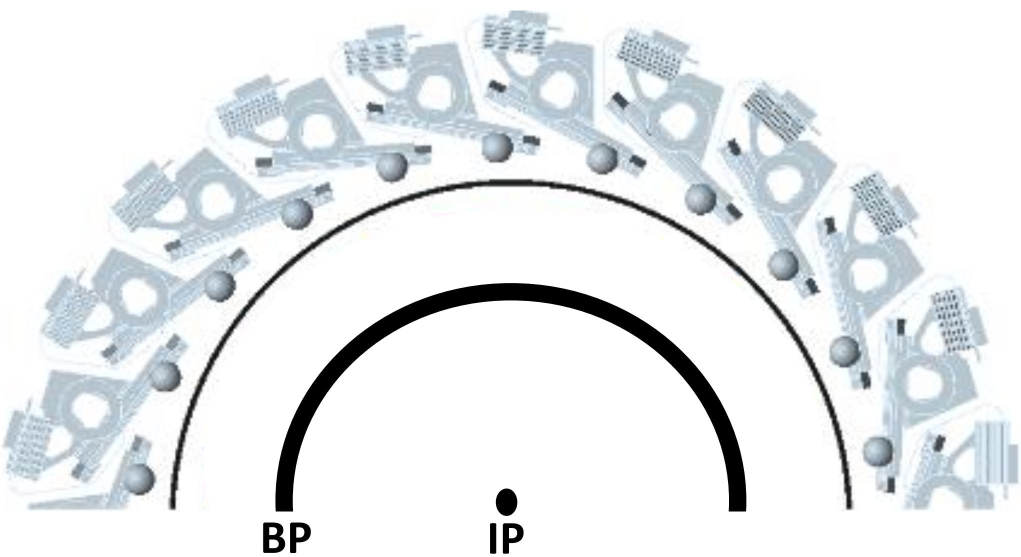
- Motivations for a 4th low radius layer in the Pixel Detector
  - Luminosity pileup, radiation damage and FE-I3 inefficiency
  - IBL improves tracking, vertexing and b-tagging for high pileup and recovers eventual failures in present Pixel detector.
  - Technology demonstrator towards HL-LHC

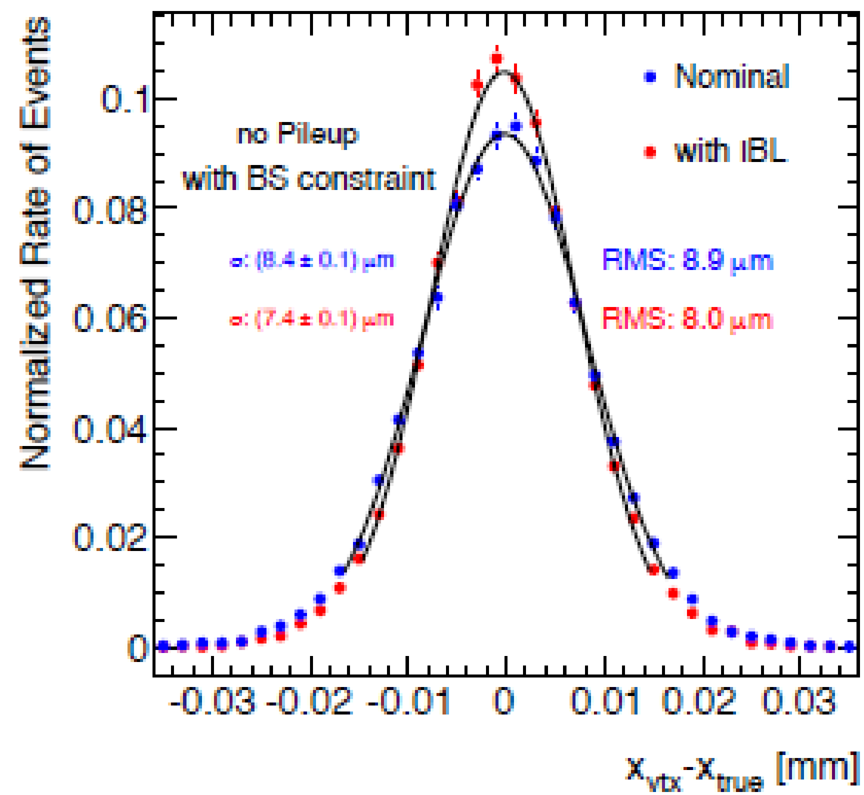




IBL – The 4th Pixel Layer

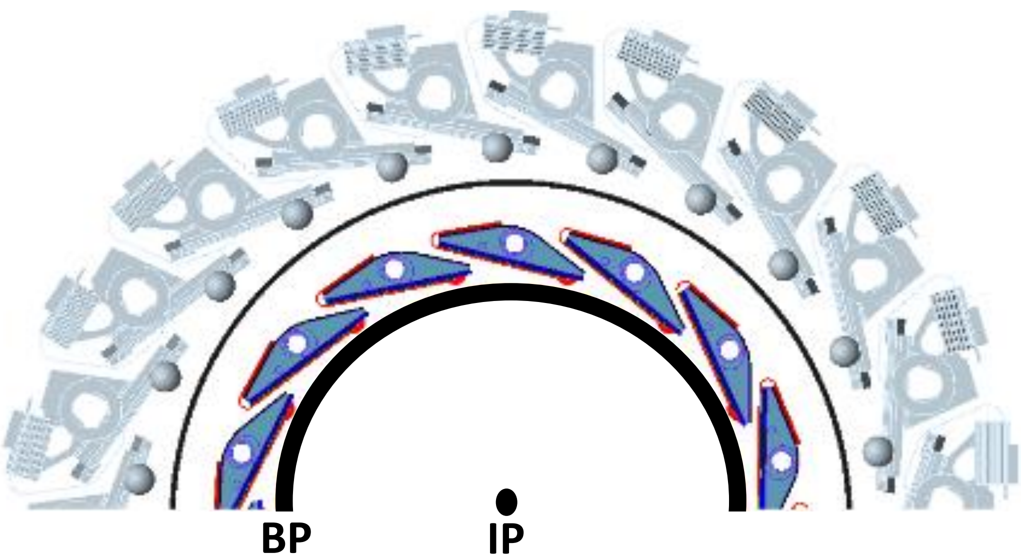
- Motivations for a 4th low radius layer in the Pixel Detector
  - Luminosity pileup, radiation damage and FE-I3 inefficiency
  - IBL improves tracking, vertexing and b-tagging for high pileup and recovers eventual failures in present Pixel detector.
  - Technology demonstrator towards HL-LHC

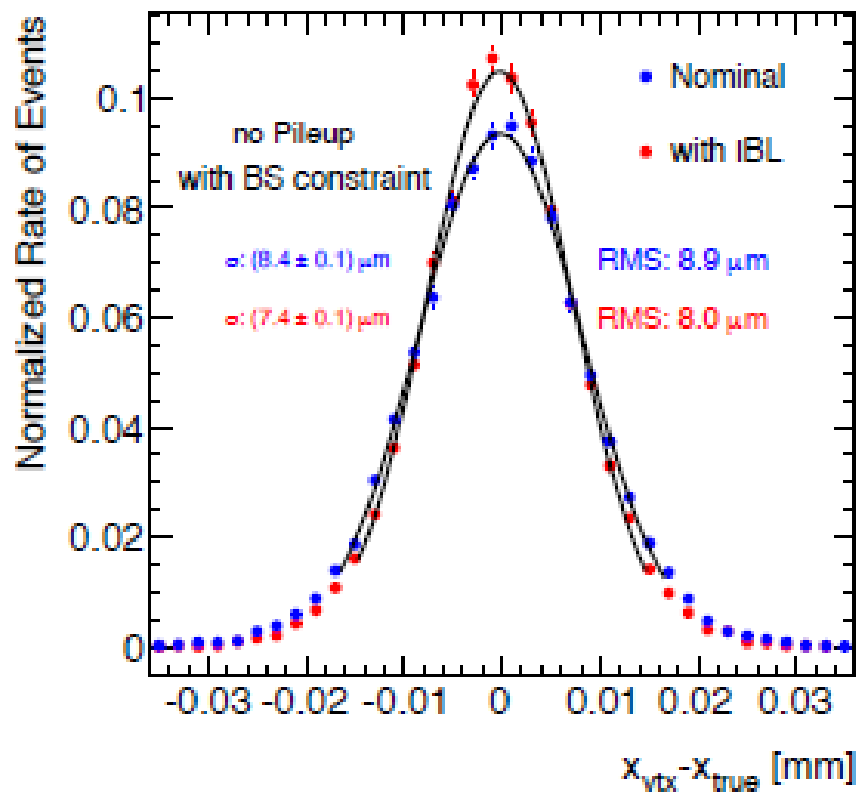




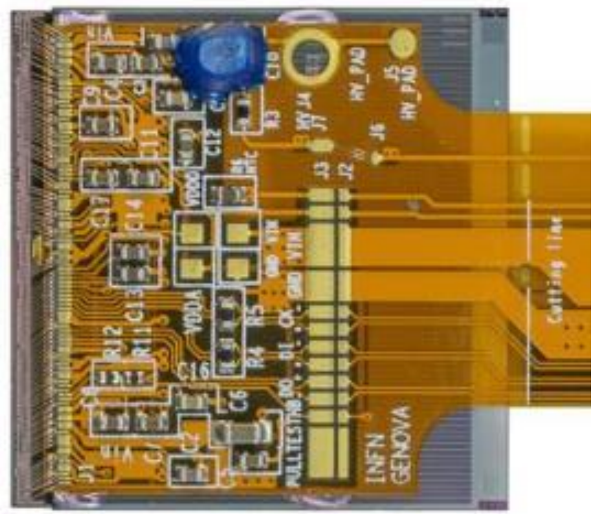
IBL – The 4th Pixel Layer

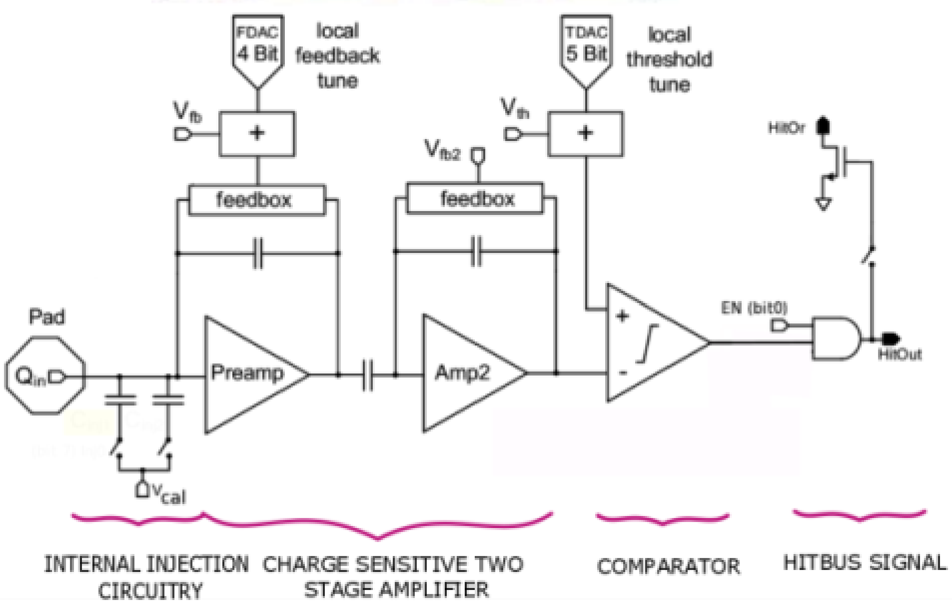
- Motivations for a 4th low radius layer in the Pixel Detector
  - Luminosity pileup, radiation damage and FE-I3 inefficiency
  - IBL improves tracking, vertexing and b-tagging for high pileup and recovers eventual failures in present Pixel detector.
  - Technology demonstrator towards HL-LHC





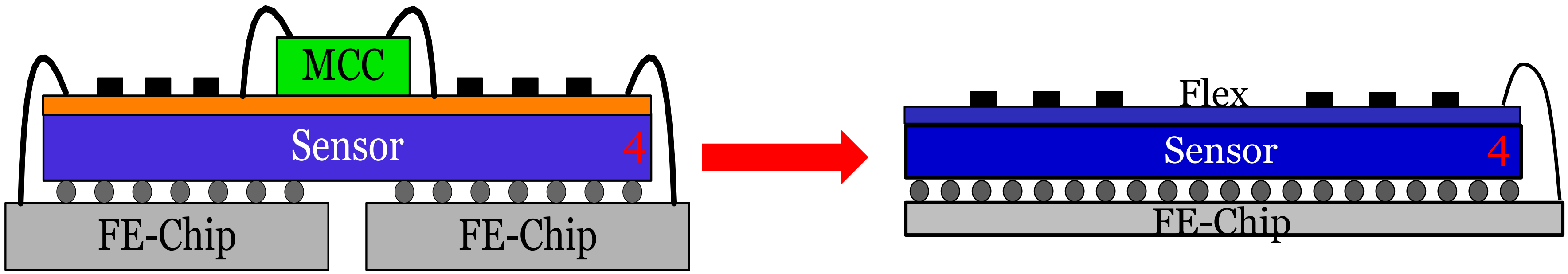
IBL Single Chip Modules



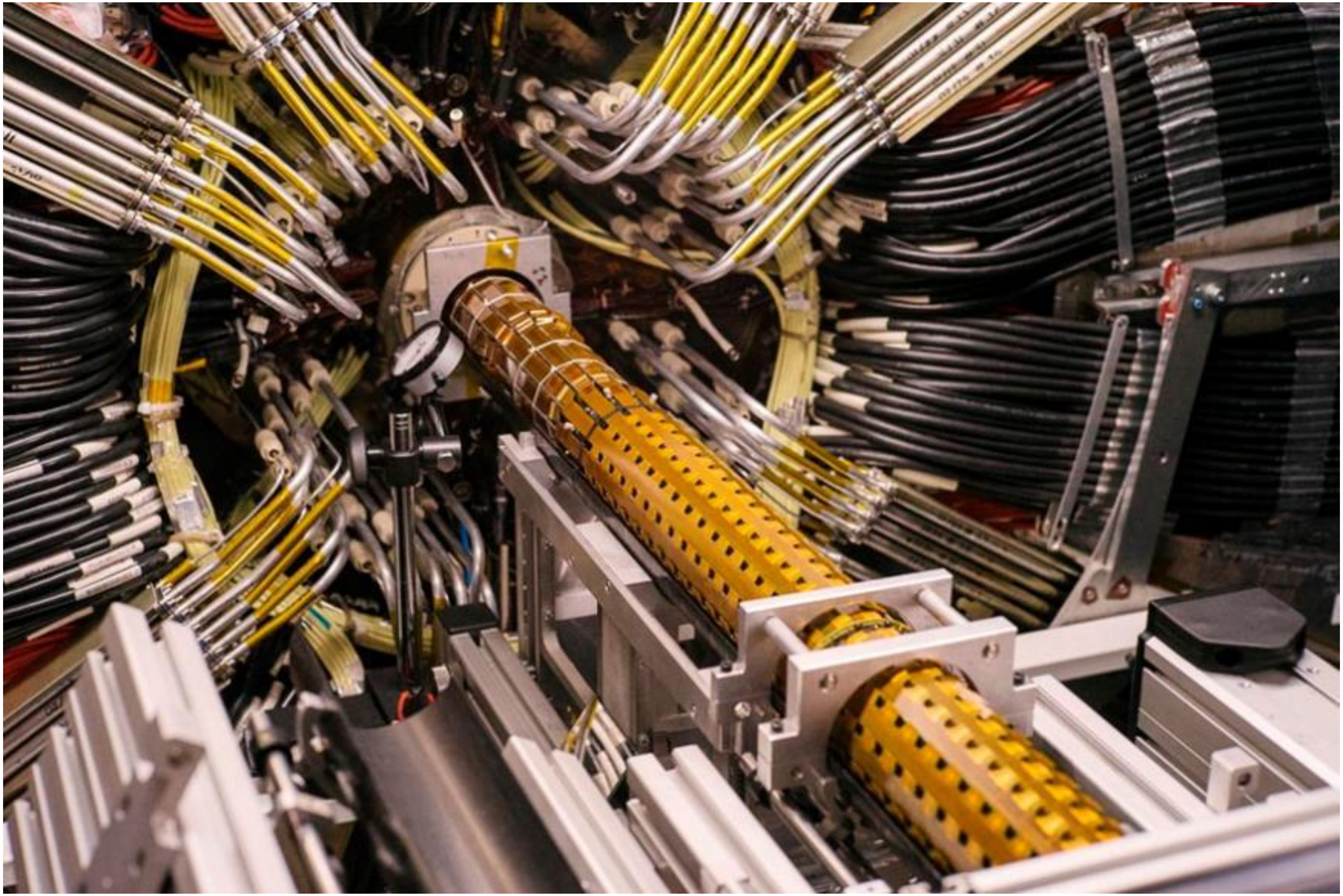


- FE-I4 read out chip
  High hit rates and radiation hard
  IBM 130 nm CMOS process
  Read out for 80x336 pixels
  Thickness=150 µm
  Physical size=**21x19 mm^2**
- Sensor:
  n-in-n planar
  Pitch=**50x250 µm^2**
  Thickness=200 µm
  Physical size=19x20 mm^2
  HV=60 V
  Power=1.2 W

Pixel Module and IBL



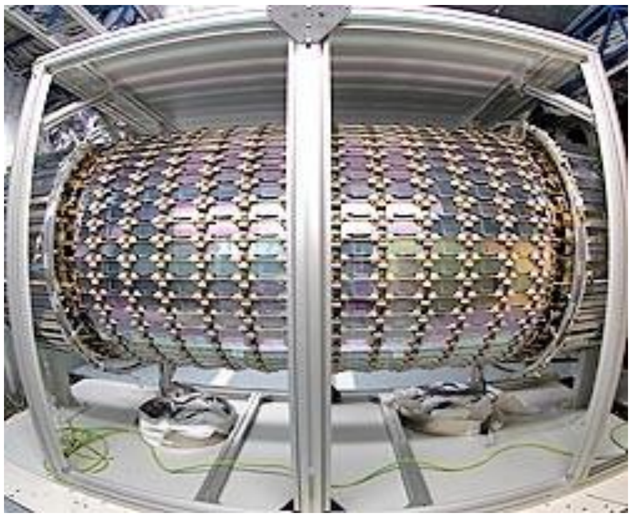
Insertable B-Layer

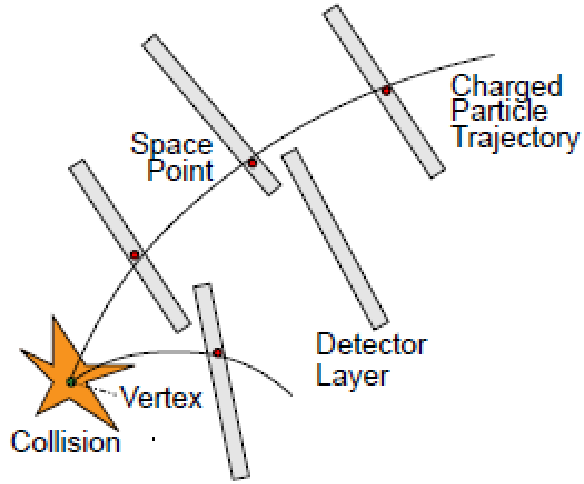


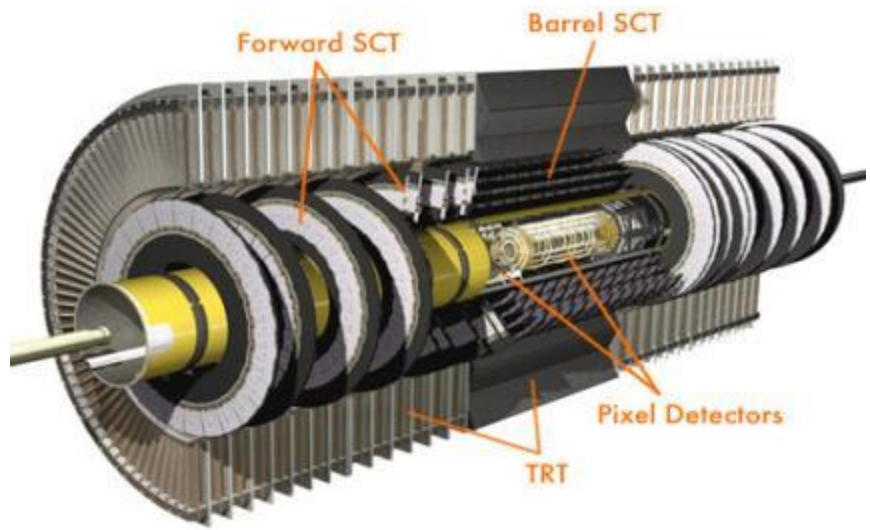
Strip Detector (SCT)

Measures:

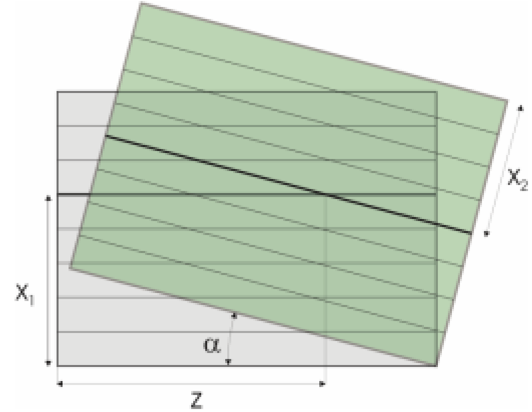
- Momentum
- Impact parameters
- Vertex position



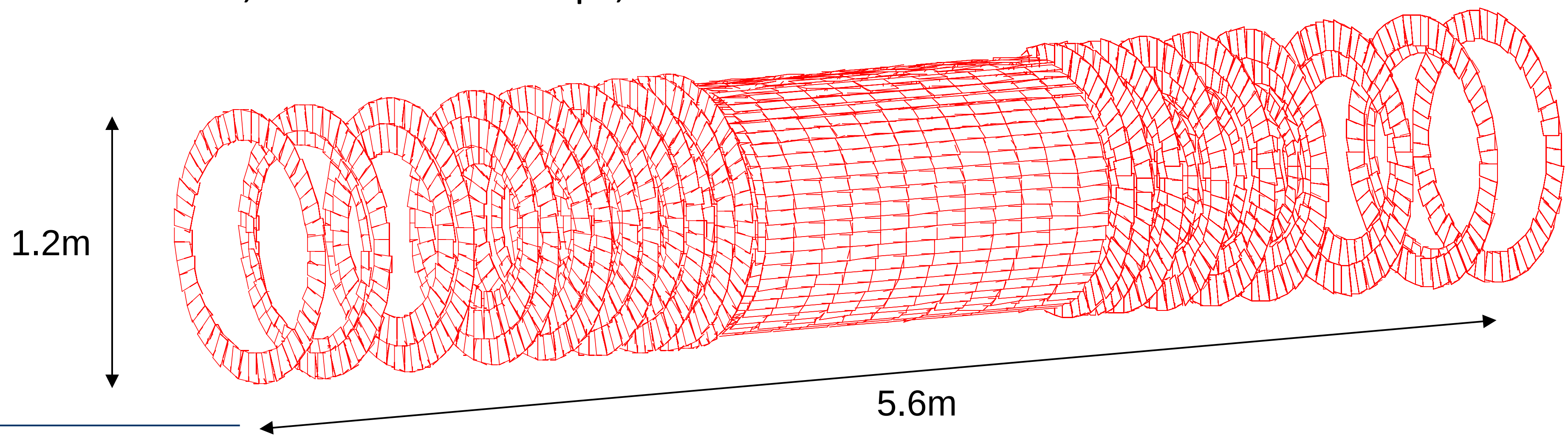




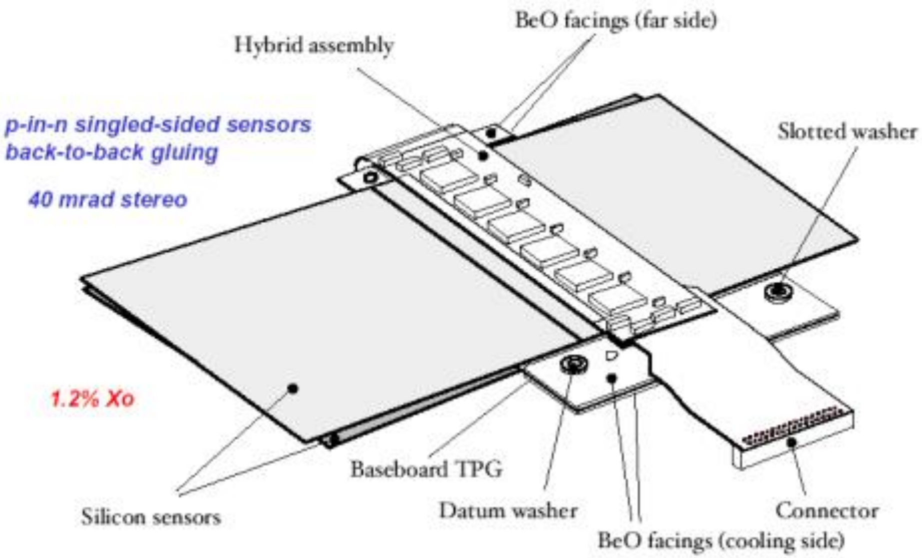
ATLAS Silicon Microstrip Tracker SCT

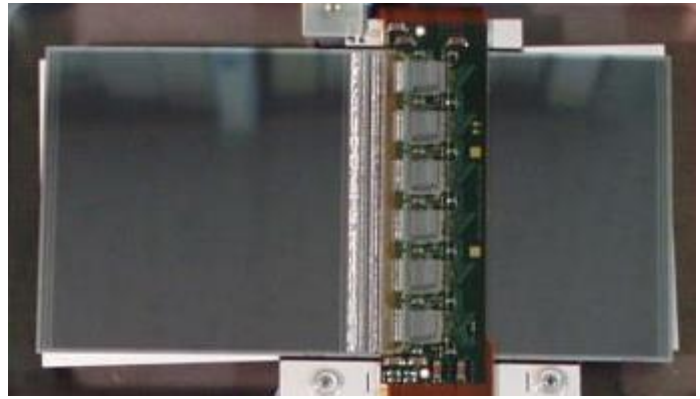


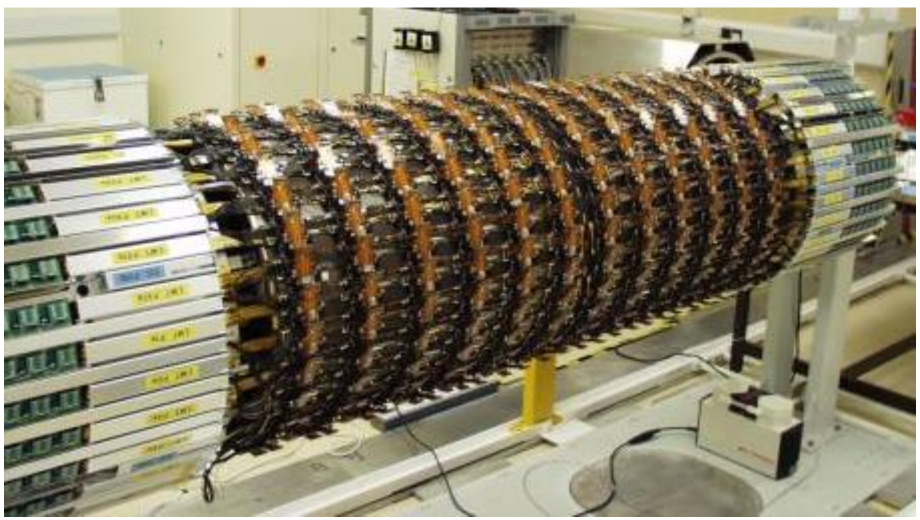
- 4 barrel layers
  - barrel radii: 300, 371, 443 and 514 mm; length 1600 mm
  - in total 2112 modules
- 2 x 9 forward disks
  - disk distance from z = 0: 835 - 2788 mm, radii: 259-560 mm
  - in total 1976 modules (3 rings: 40, 40, 52 modules each)
- all 4088 modules double sided (40 mrad single sided stereo)
- 15,392 sensors of total 61.1 m^2
- 49,056 front-end chips, total 6.3 M. channels



Barrel modules

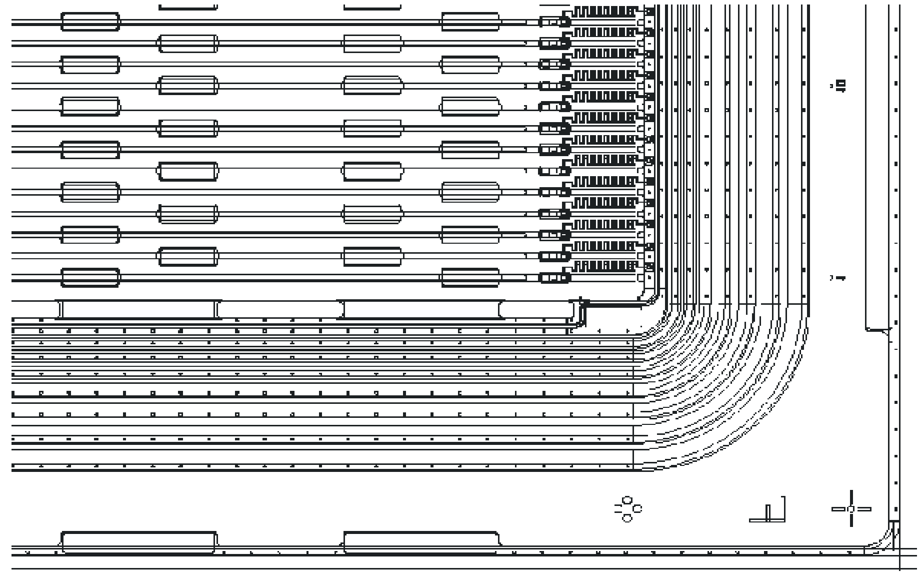


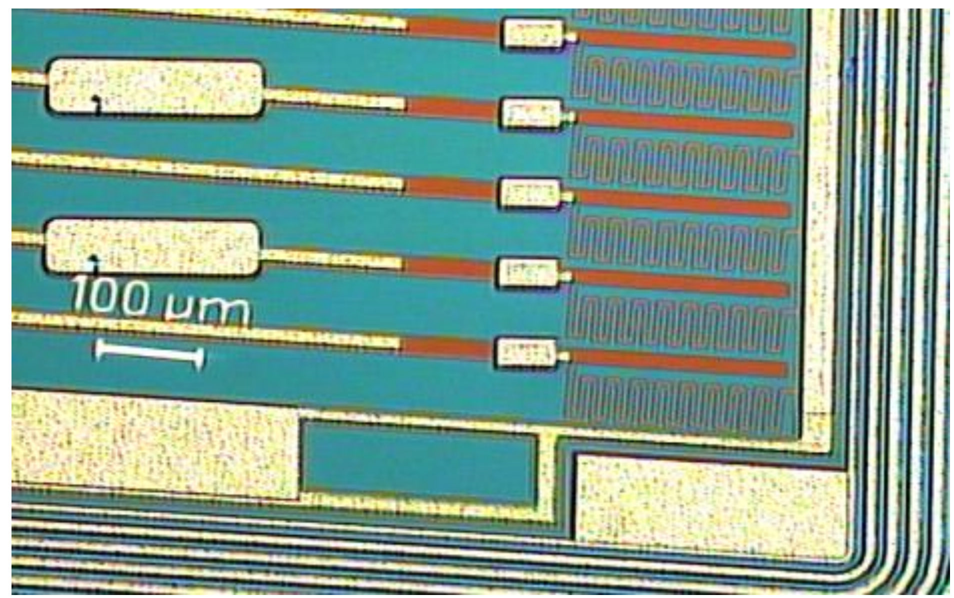




ATLAS SCT Sensors

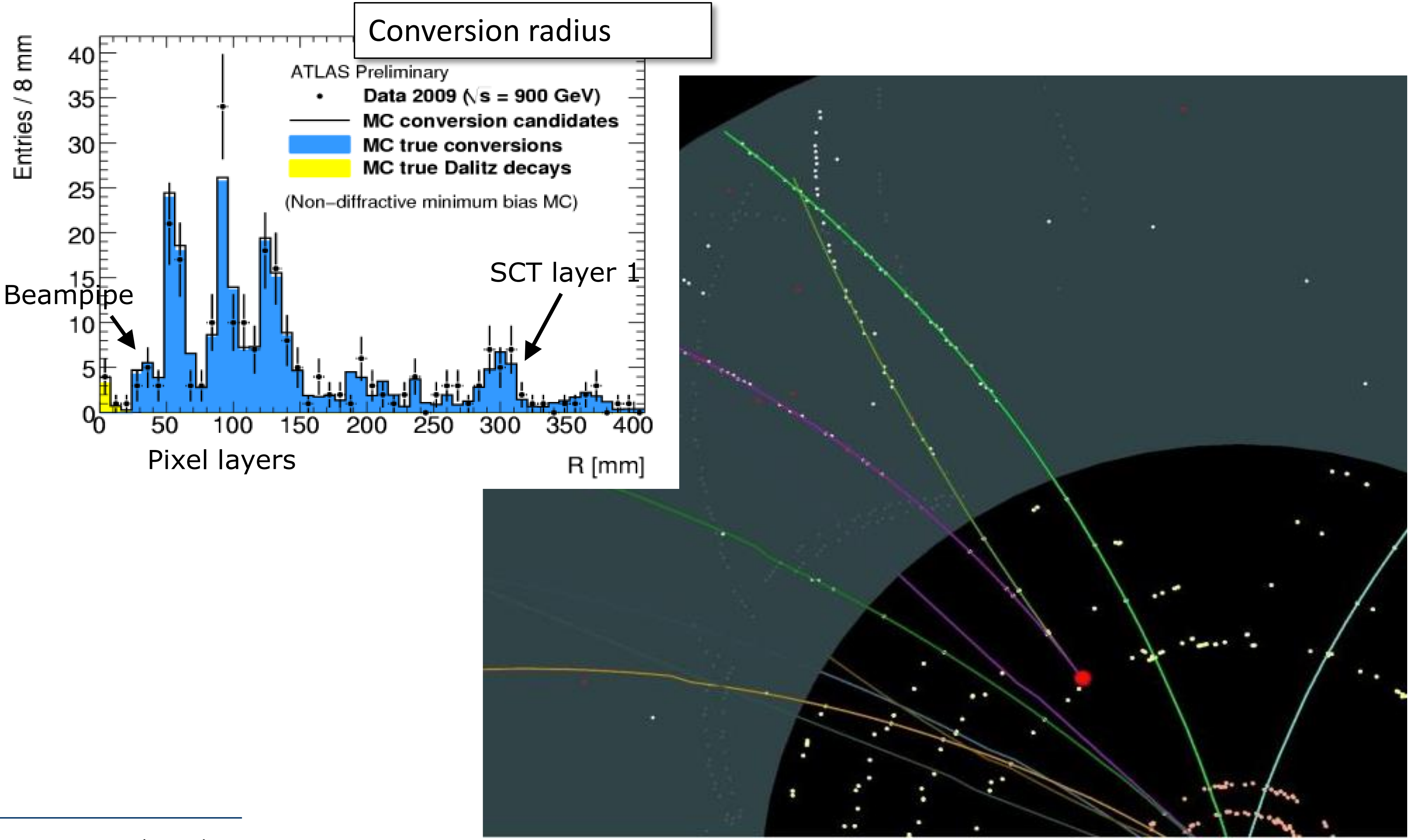
- p-on-n single sided detectors
- 285 µm thick
- 2-8 kΩ.cm
- Barrel
  - 64x64 mm²
  - 80 µm pitch
- Forward
  - 5 different wedge shaped sensors
  - radial strips
  - 50...90 µm pitch
- 768 read-out strips
- AC coupled to read-out
- Multiguard structure for HV stability

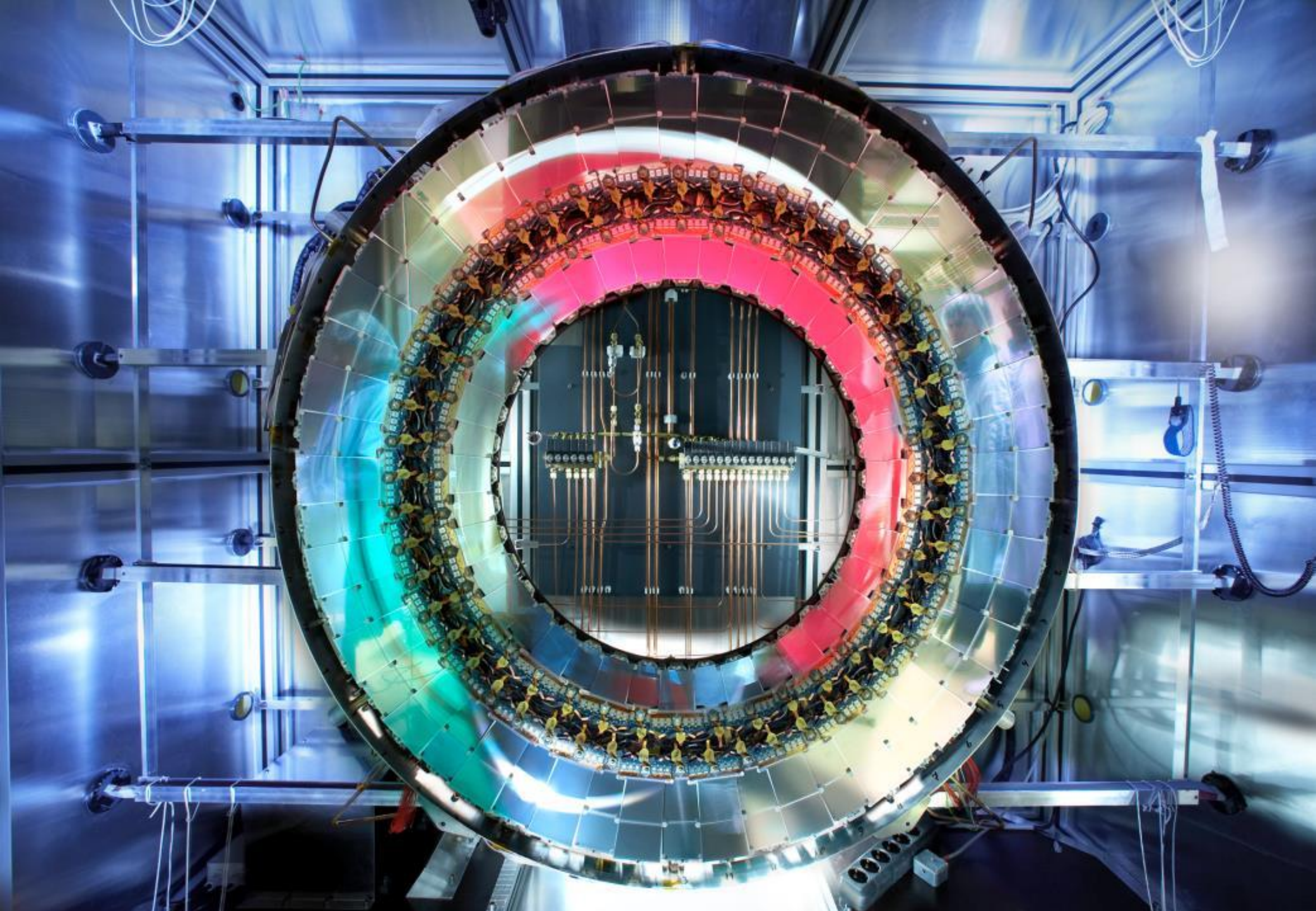




cmarinas@uni-bonn.de

Photon conversions

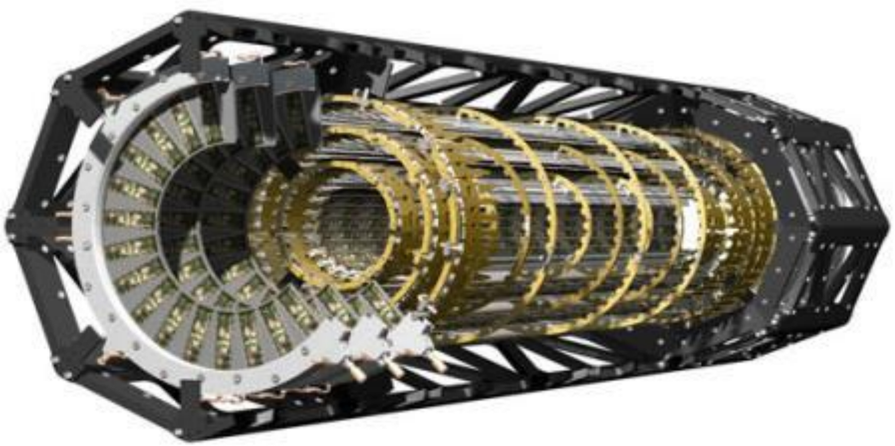




Transition Radiation Tracker (TRT)

universitätbonn

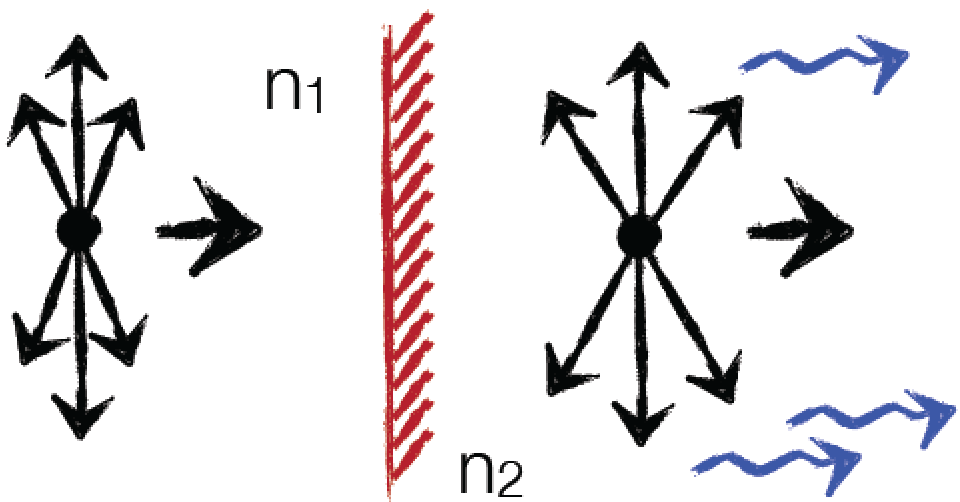
- Basic detector element: straw tube with 4 mm diameter, in the centre a 0.03 mm diameter gold-plated tungsten wire.
- The ends of a straw are read out separately
- Precision measurement of 0.17 mm (particle track to wire)
- Provides additional information on the **particle type** that flew through the detector, i.e. if it is an electron or pion



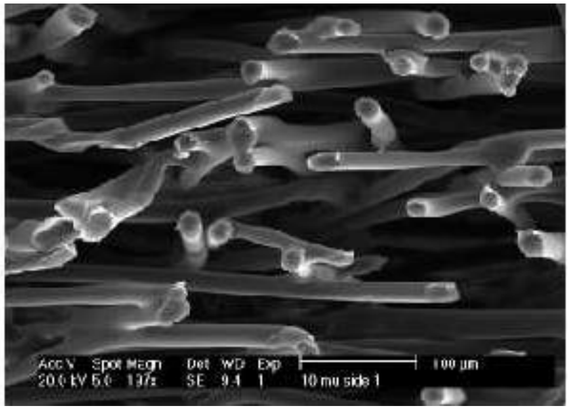
Transition Radiation phenomena

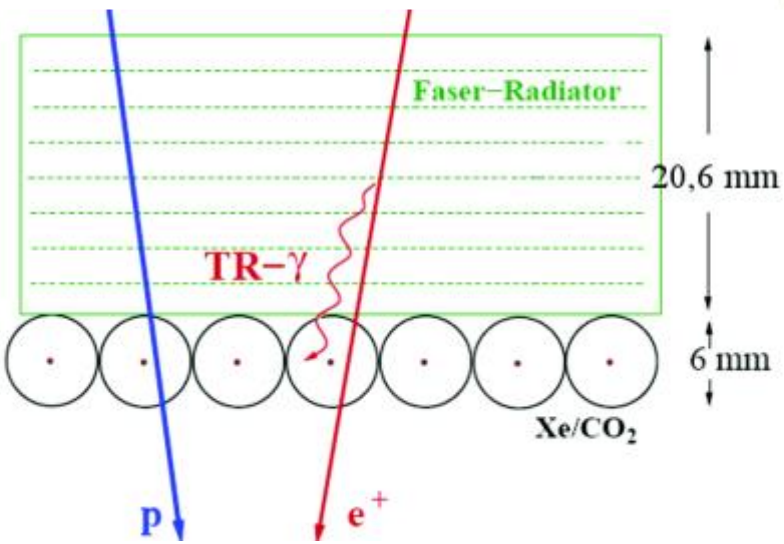
TR occurs if a relativistic charged particle (large Lorentz Factor) traverses a boundary between two media with different refraction indices ($n_i \neq n_j$).

The energetic charged particle polarizes the media around and rearrangement of the electric field yields to the emission of e.m. waves (T.R.) → Light!

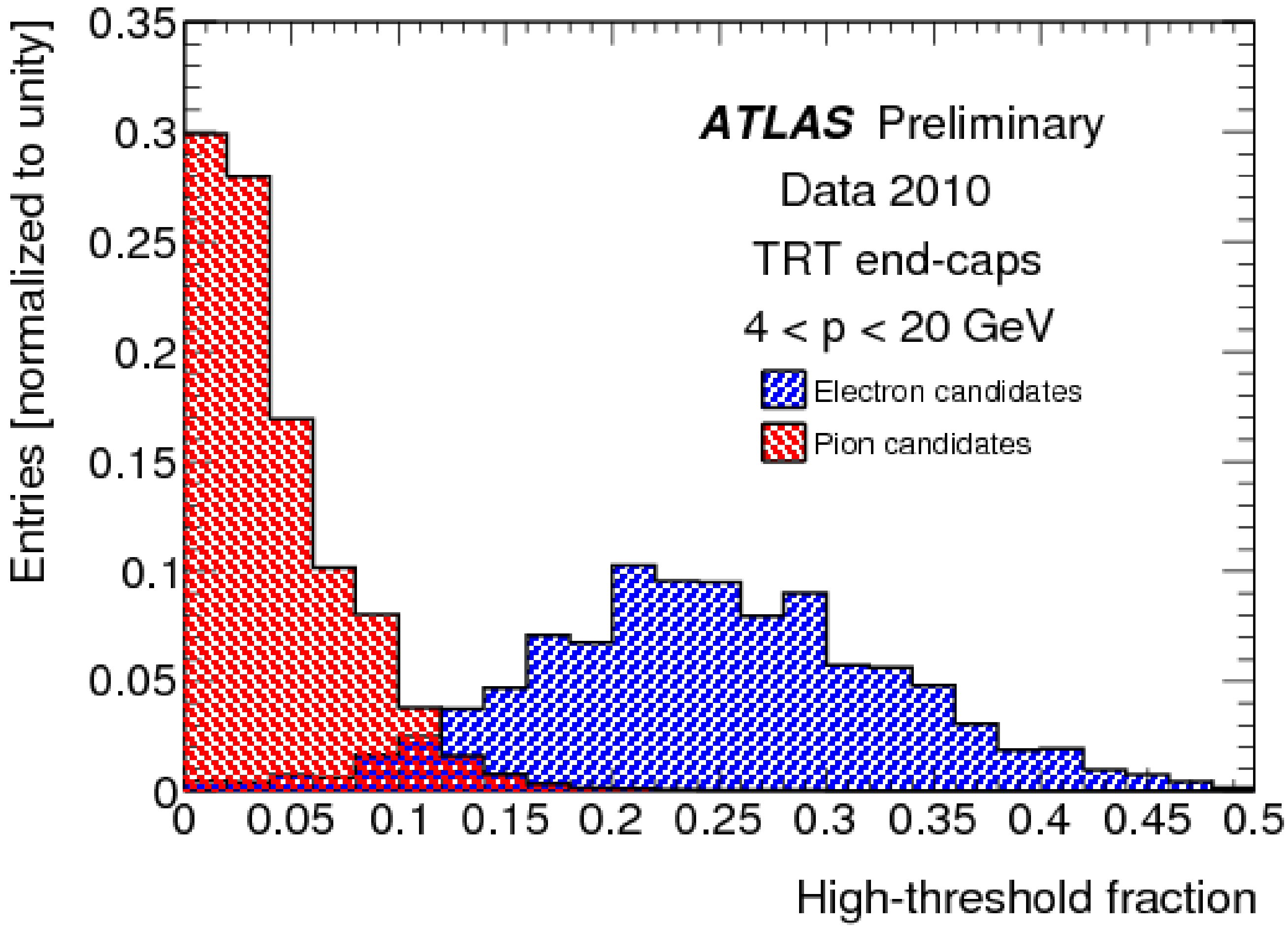


ATLAS TRT

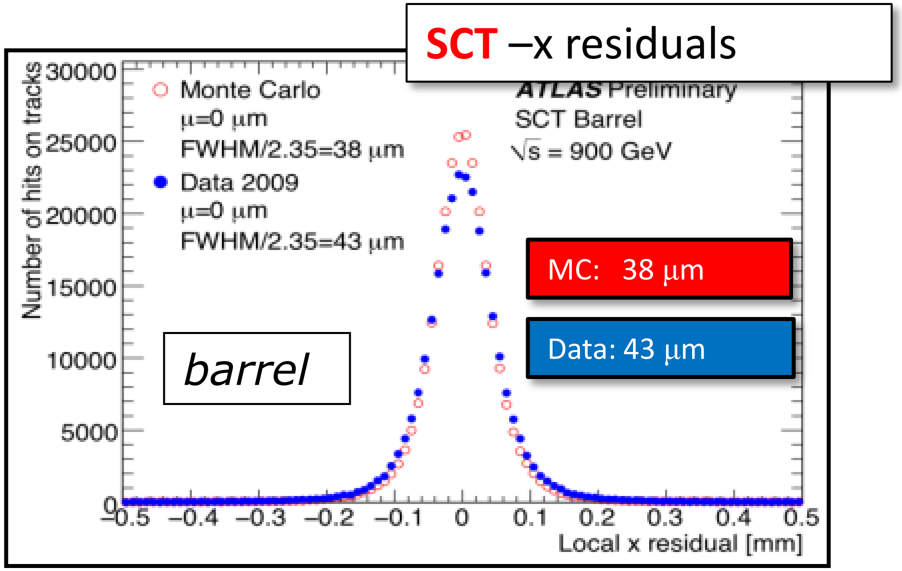

Acc.V Spot Magn Det WD Exp
20.0 kV 5.0 137x SE 9.4 1
100 µm
10 mu side 1

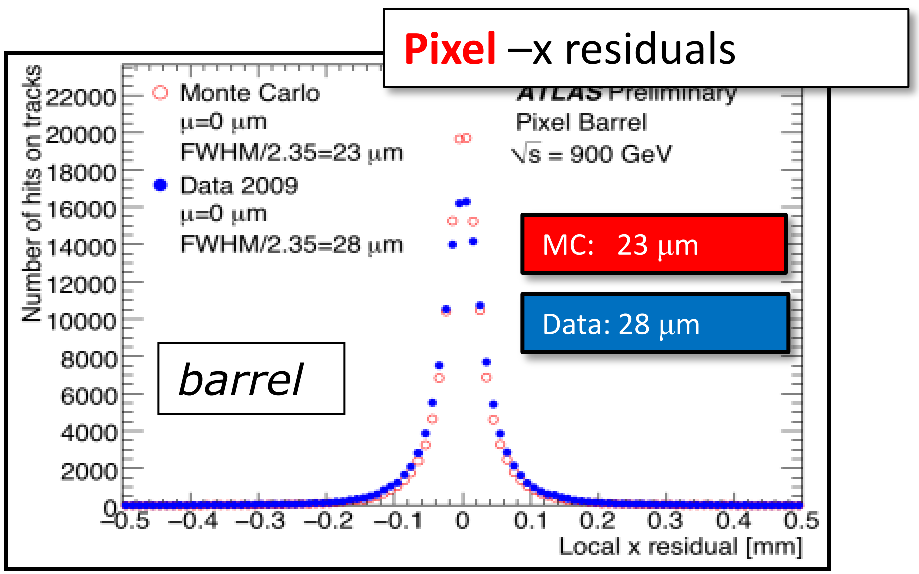

Faser−Radiator
20,6 mm
TR−γ
6 mm
Xe/CO2
p
e+

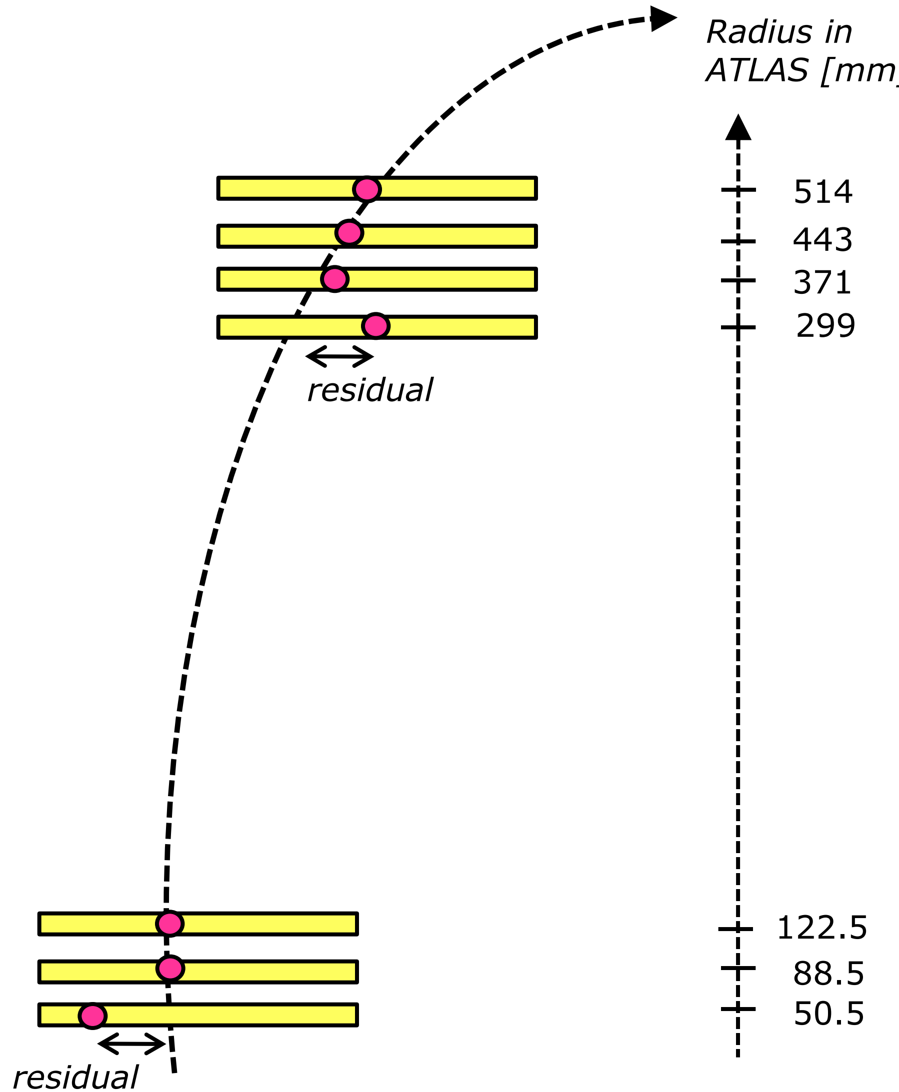
TRT Separation



Alignment tracking detectors

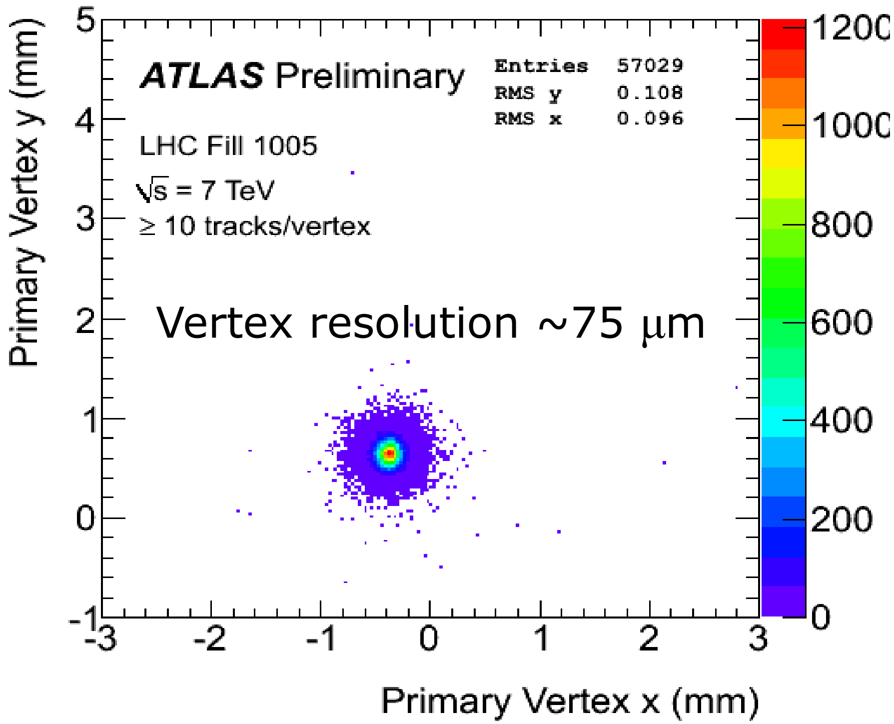




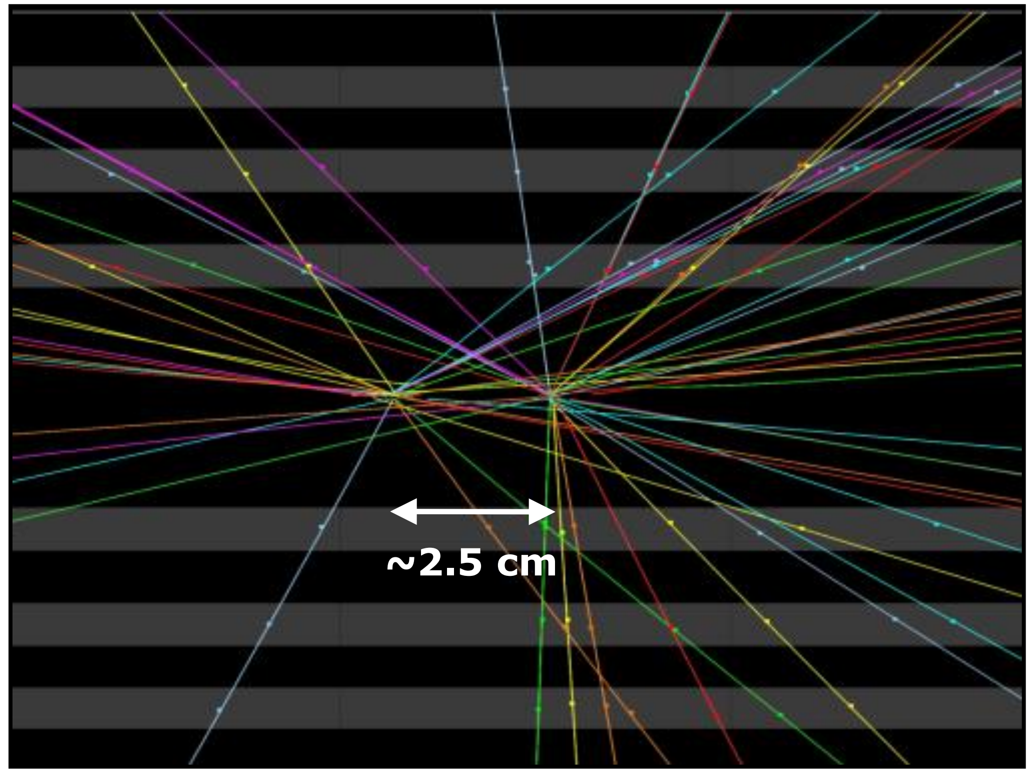


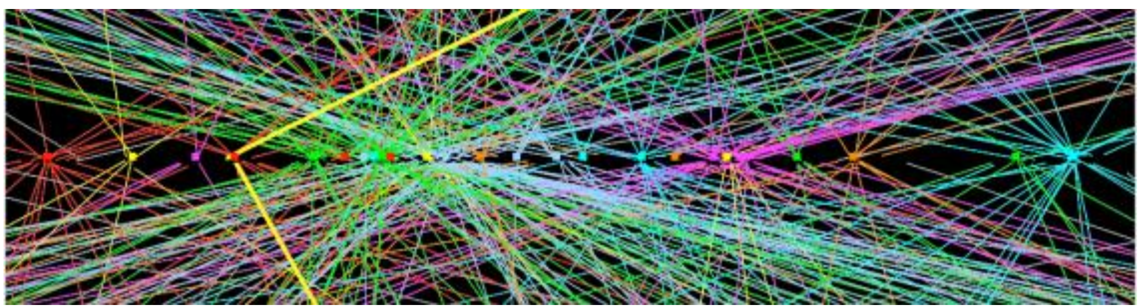
Vertexing

Primary vertices



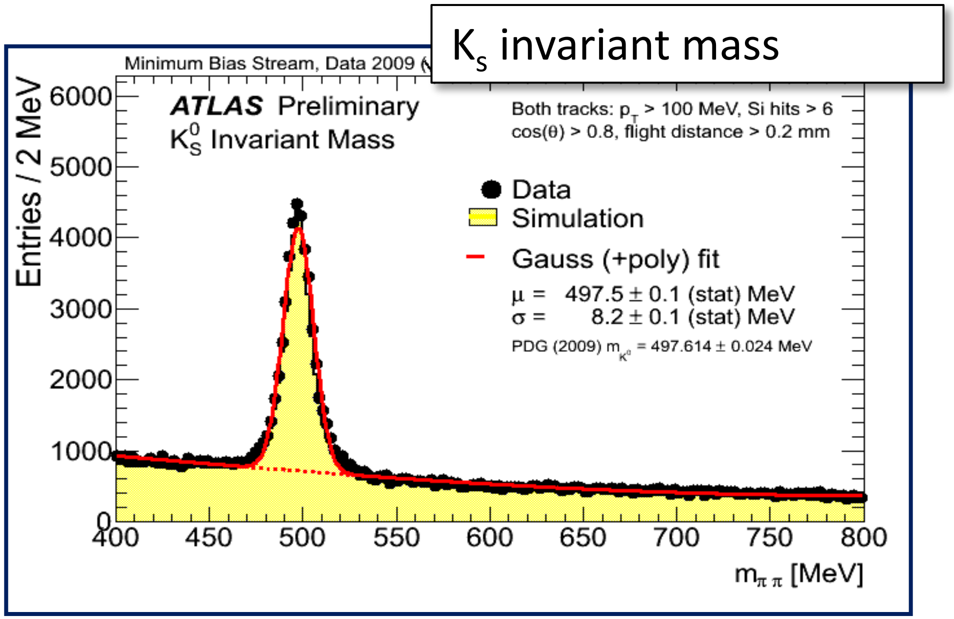
Pile-up events

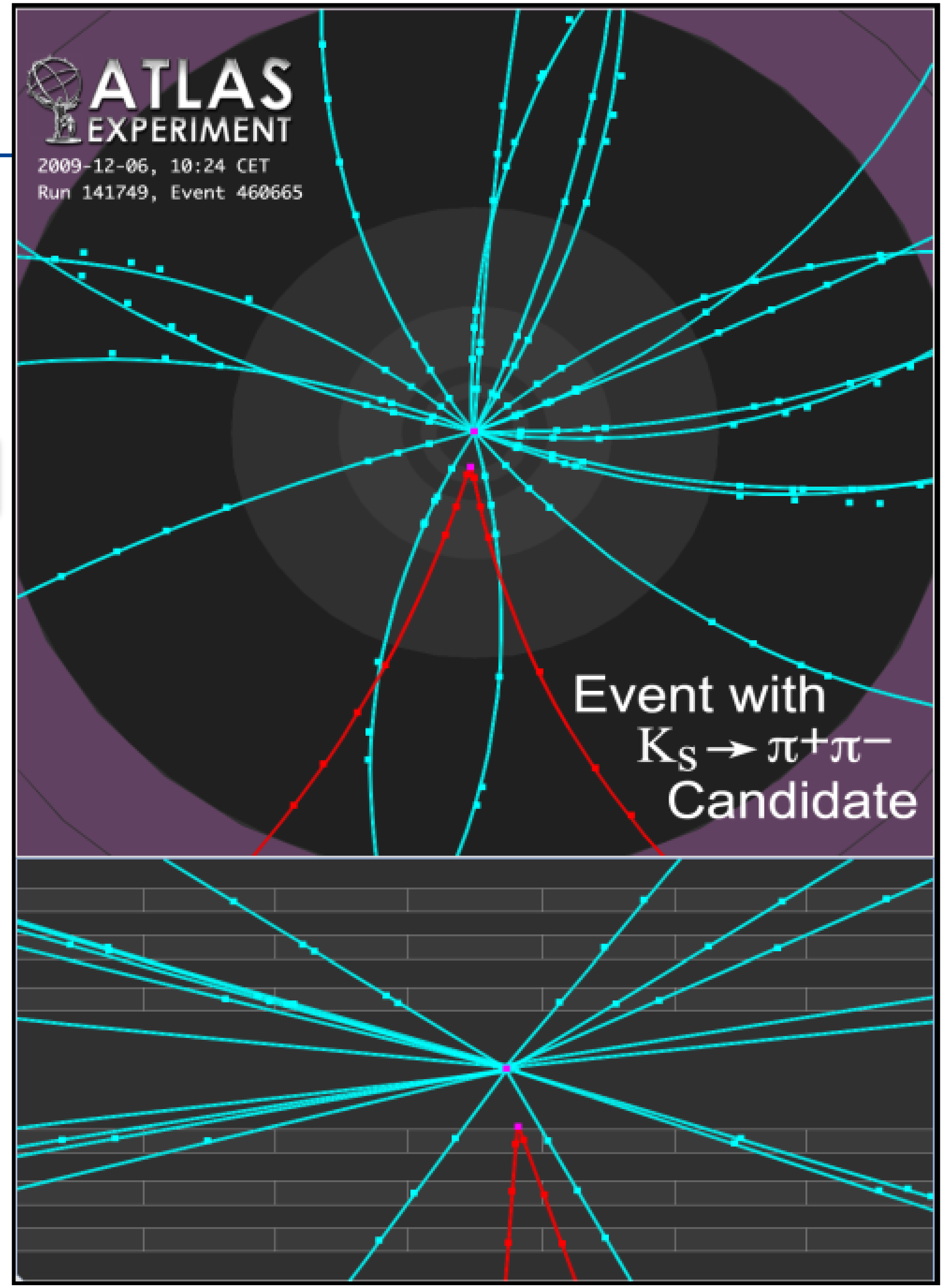




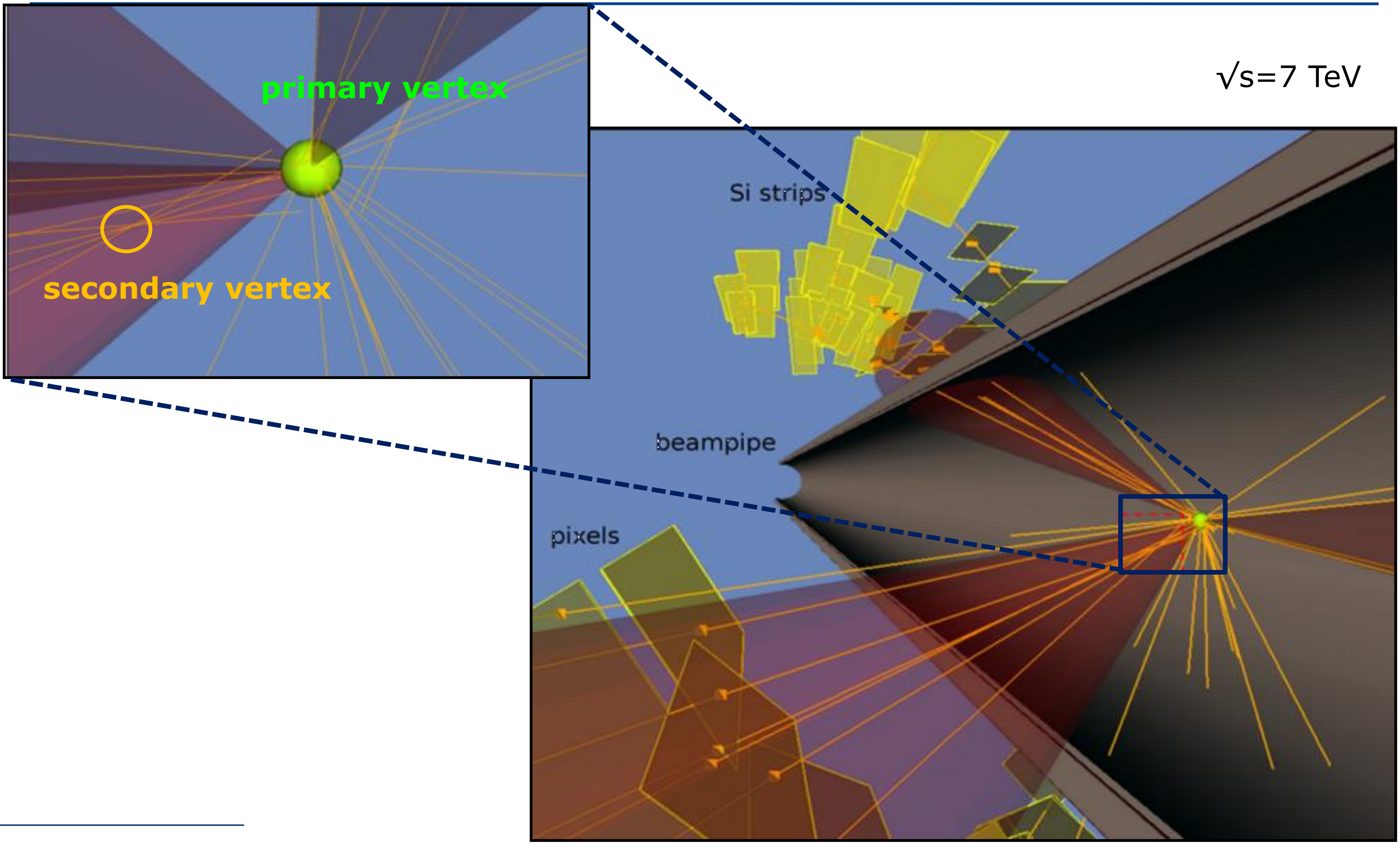
21 PV

Secondary vertices

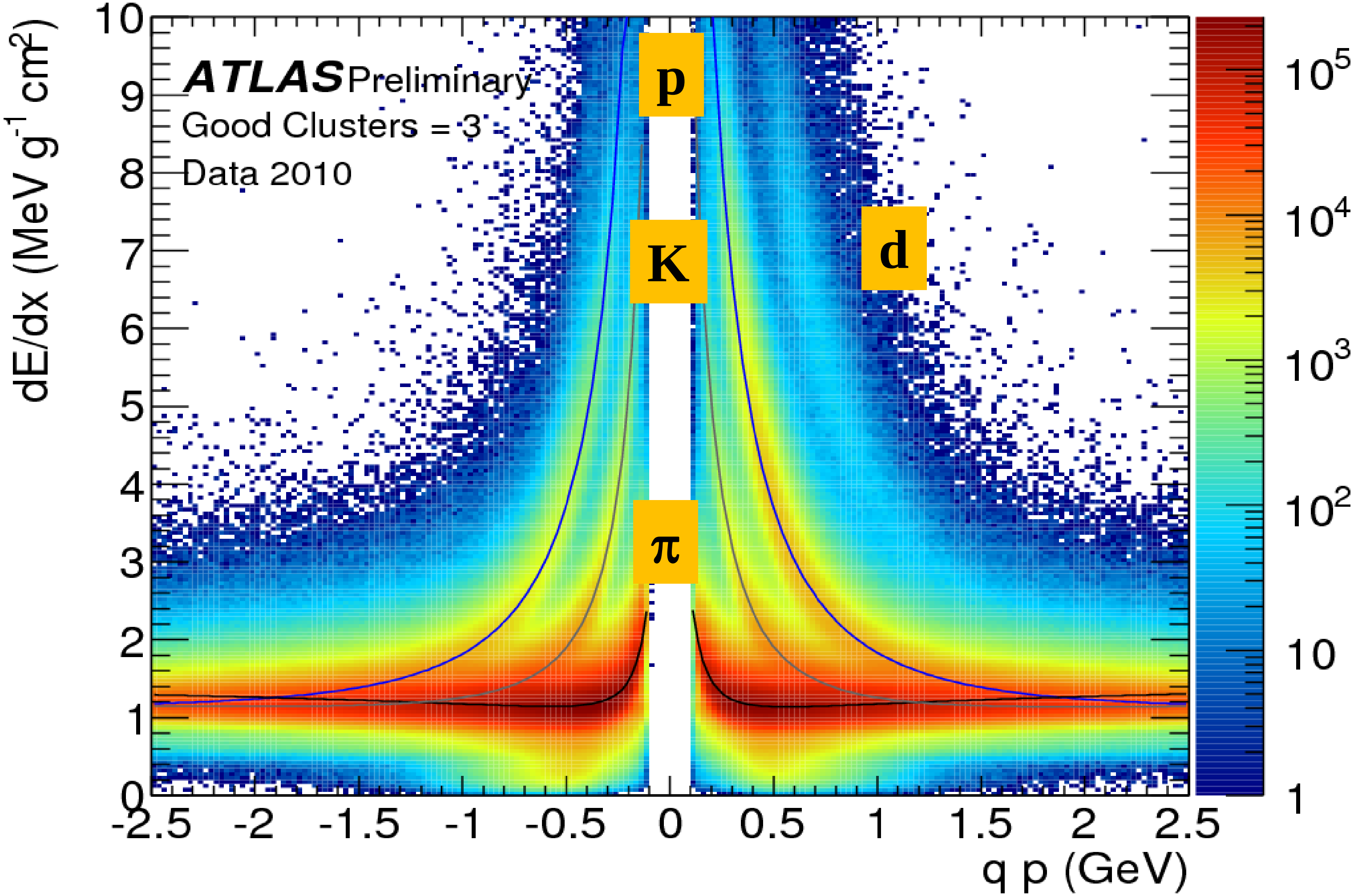




'Typical' b-jet candidate



dE/dx in Silicon: ATLAS Pixels

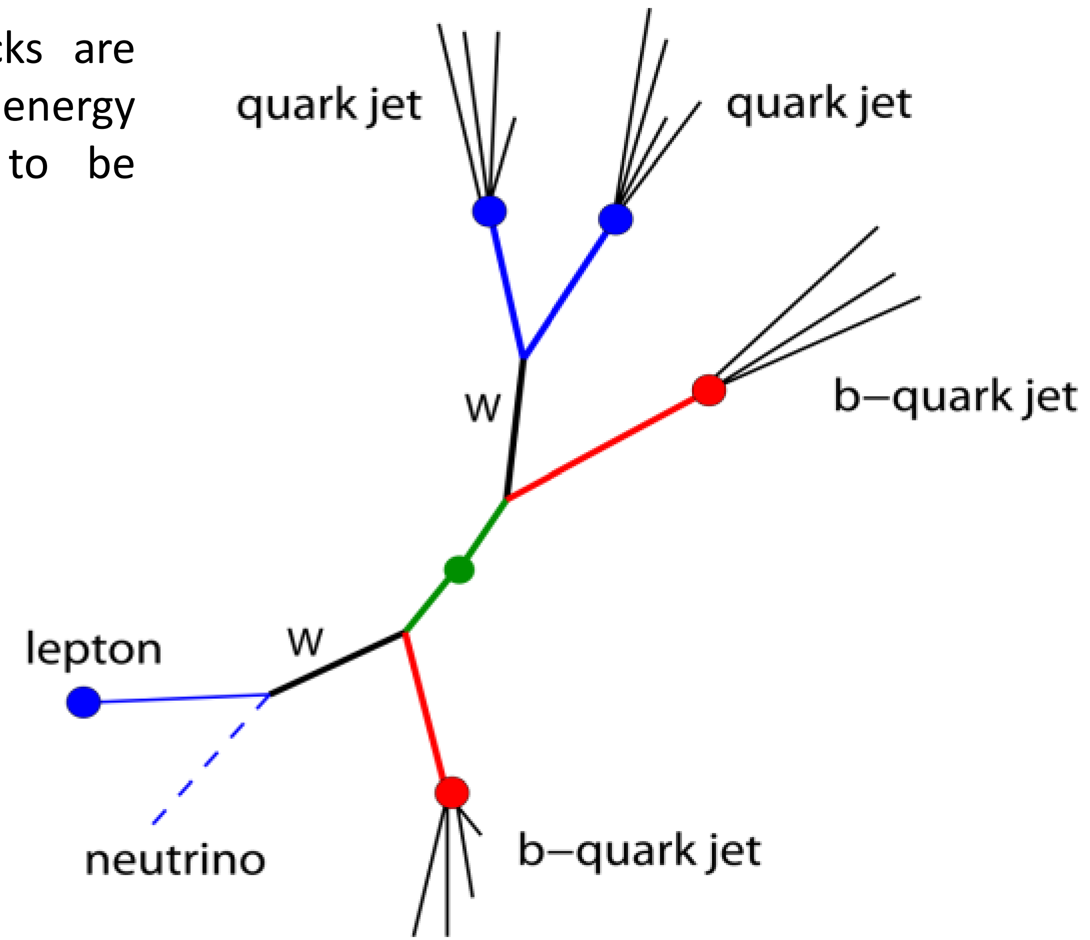


Energy measurement

universitätbonn

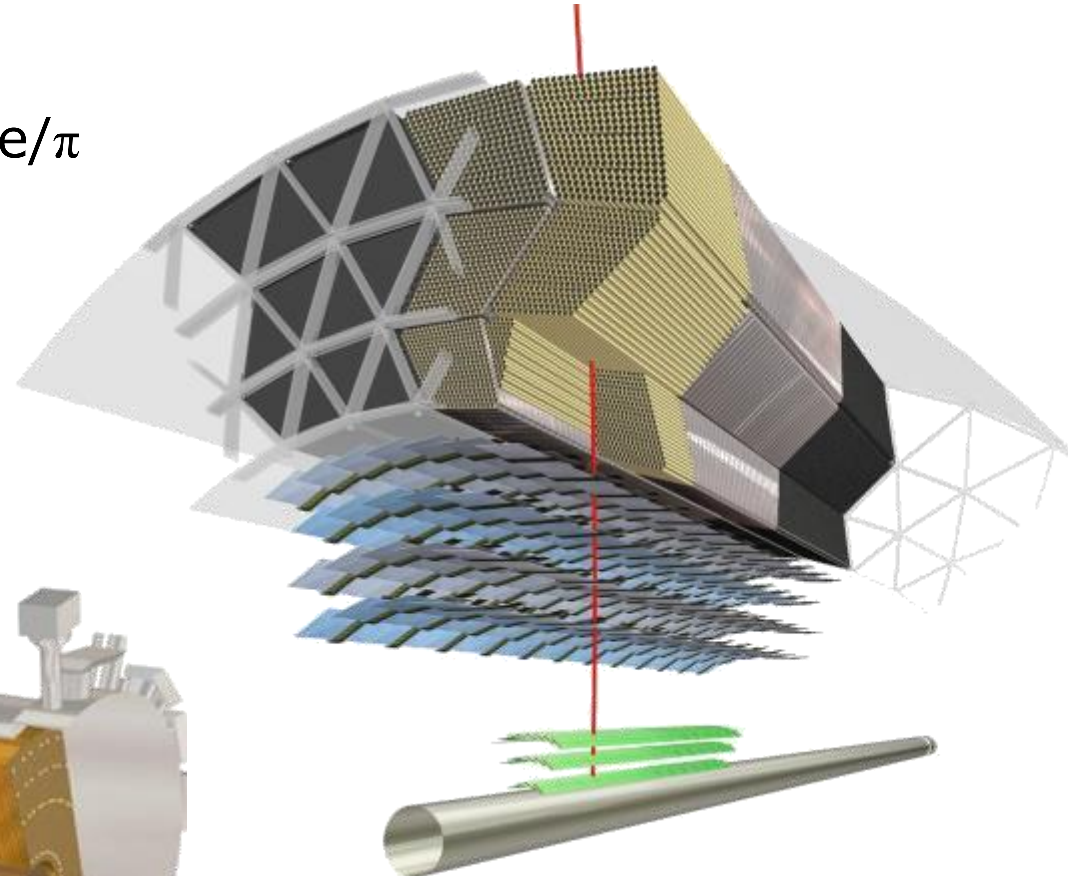
Once the vertex and tracks are reconstructed, the deposit energy in the calorimeters has to be measured:

Lepton → E.M. Calo.
Jet → Hadronic Calo.

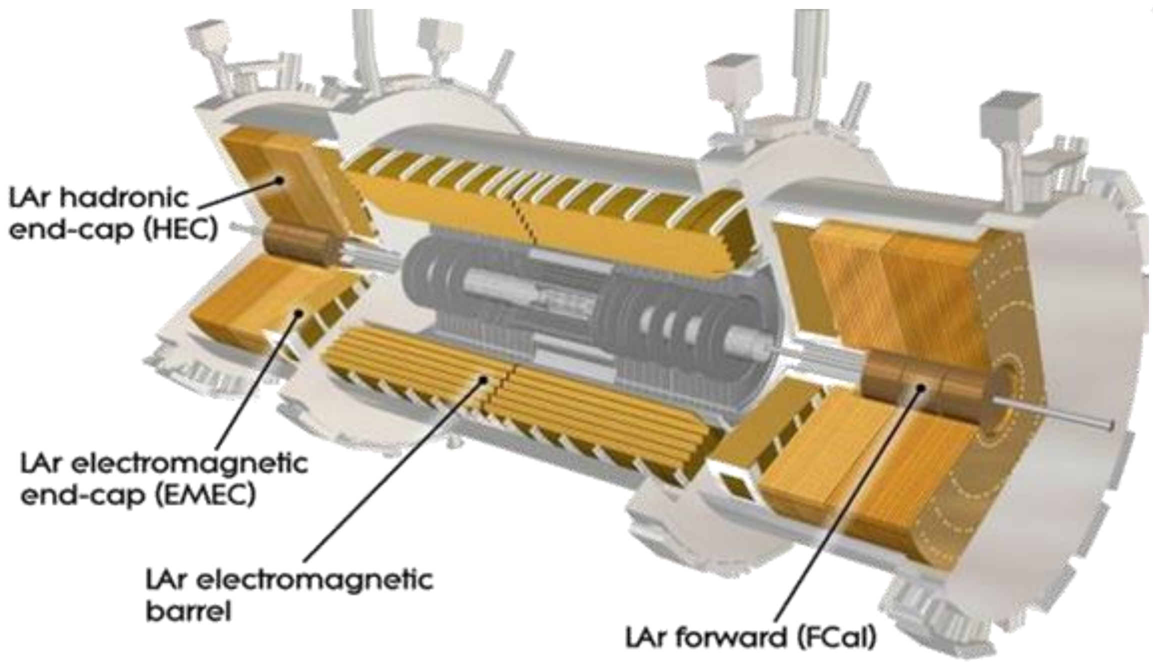


E.M. Calorimeter and PID

TRT helps in the e/π separation



Electromagnetic calorimeter

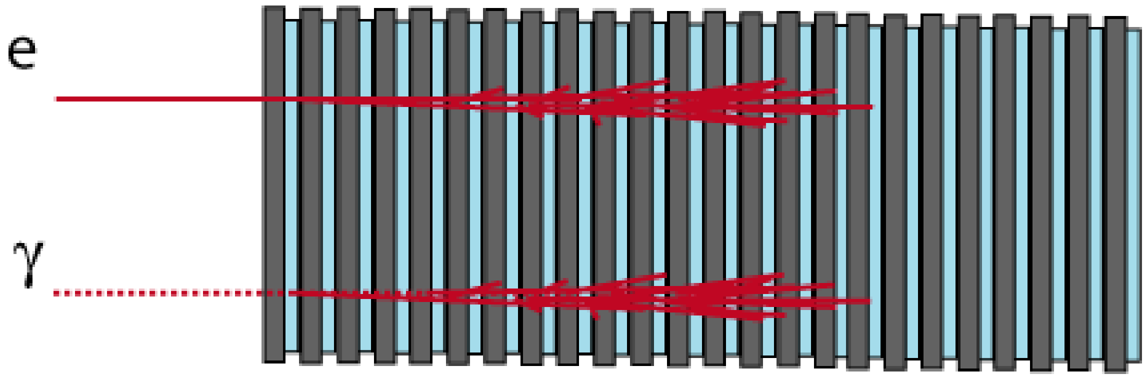


Liquid Argon / Lead

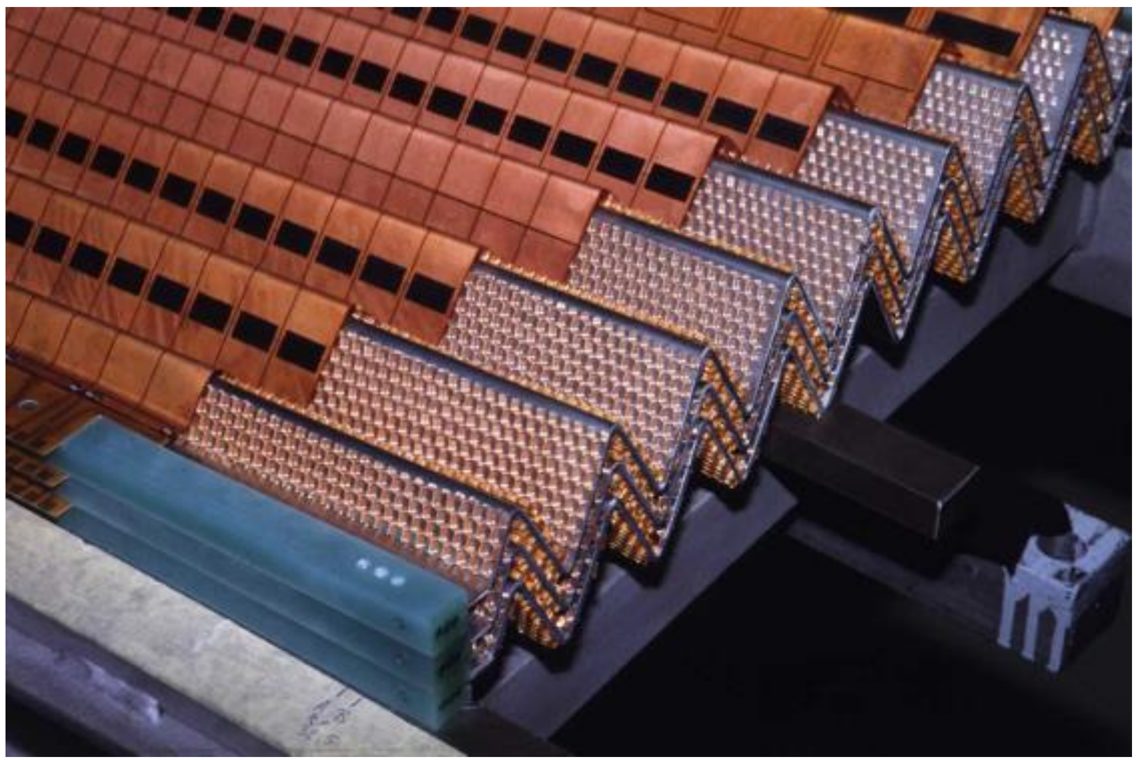
20-30 X_0

$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$

ATLAS Liquid Argon



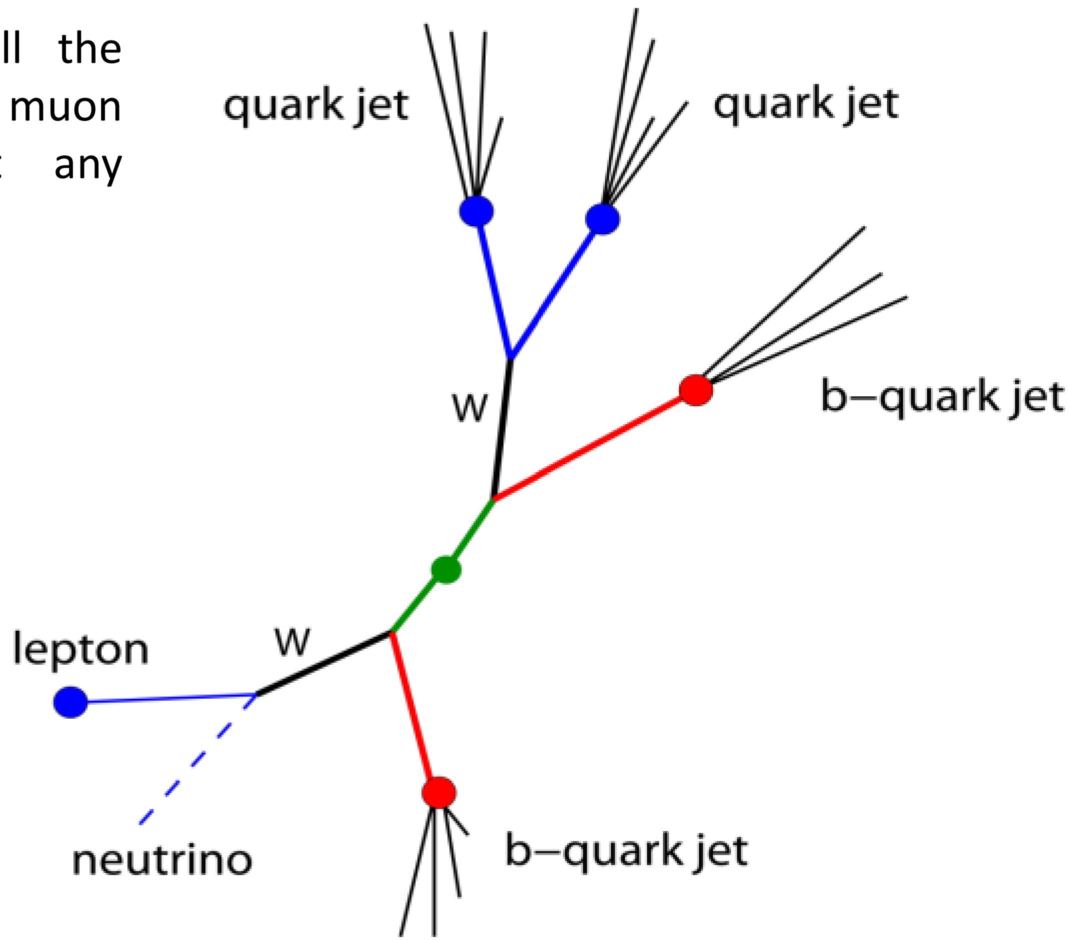
Sampling calorimeter
Alternating layers of absorber and active material



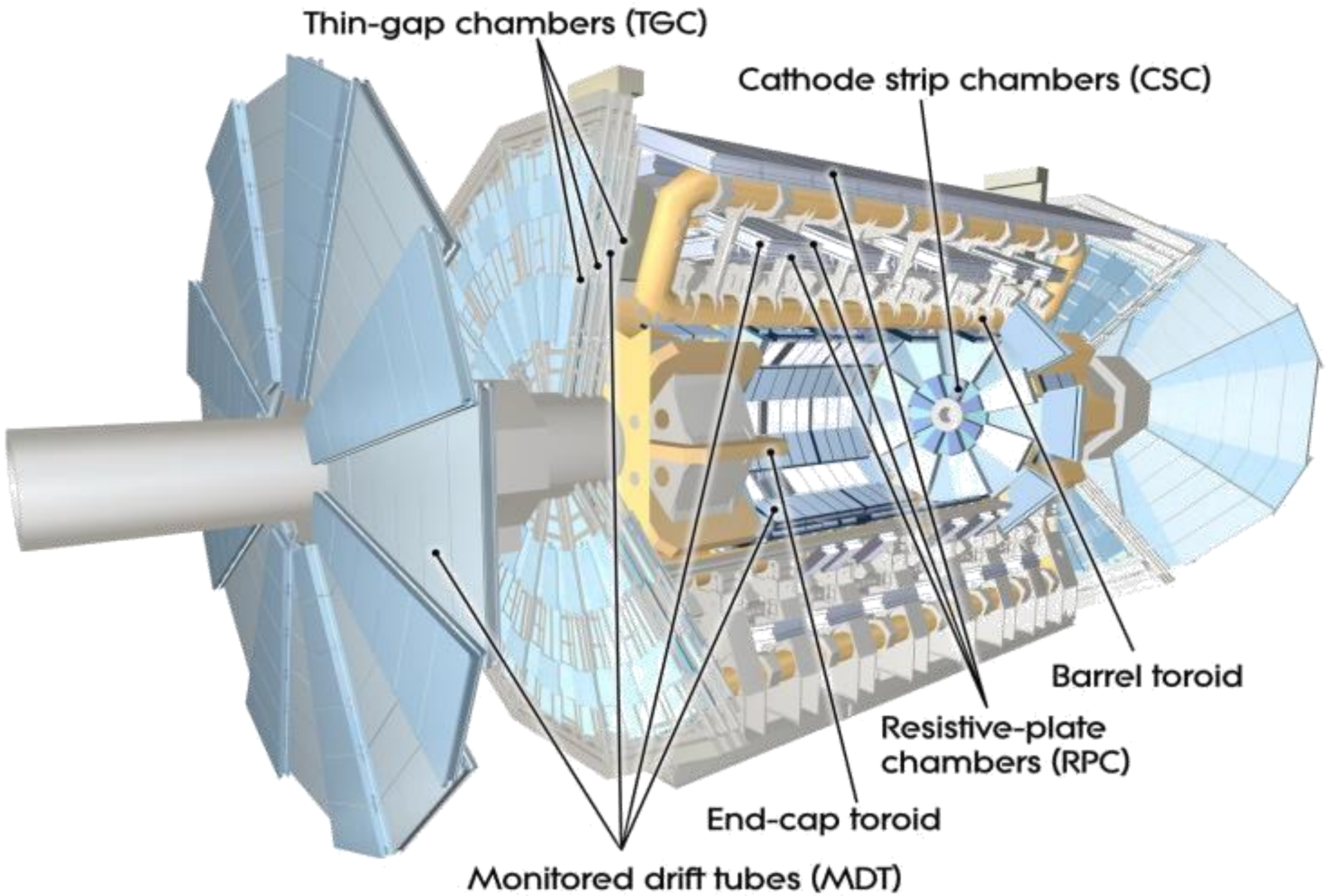
cmarinas@uni-bonn.de

Muon Chambers

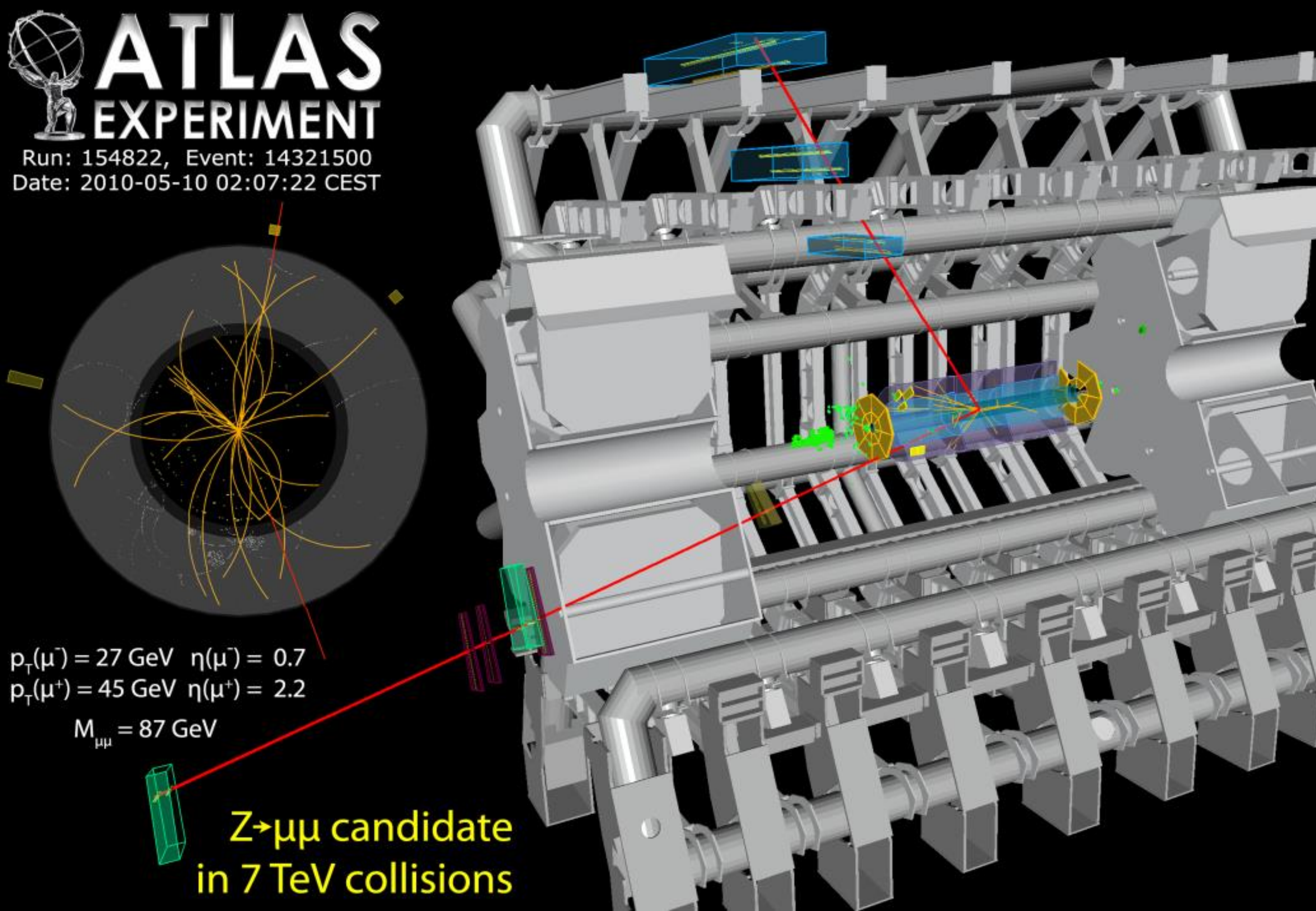
If a particle "survived" all the previous steps, must be a muon (neutrinos scape without any signature in the detector)



Muon Spectrometer



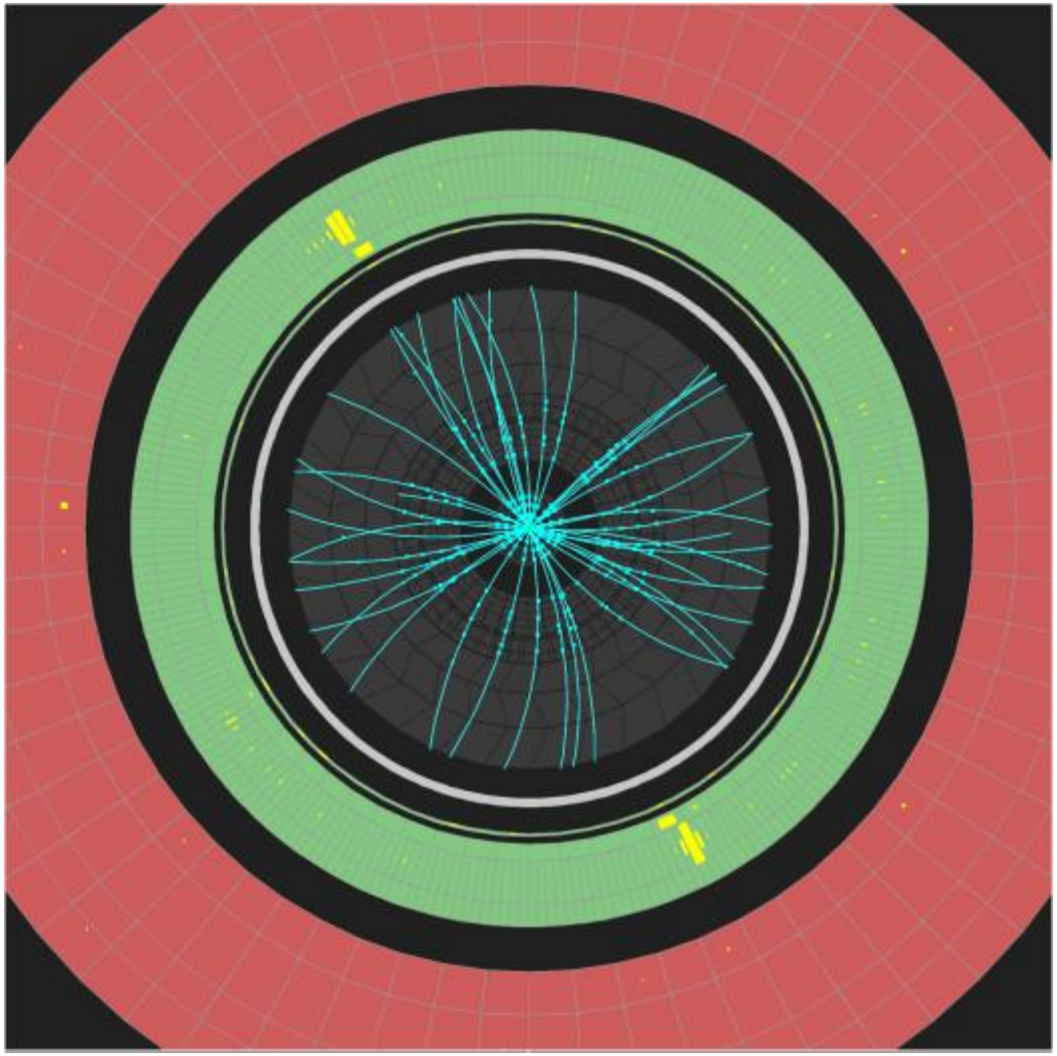
	Precision tracking	Trigger
Central	Monitored drift Tubes	Resistive Plate Chambers
Forward	Monitored drift Tubes	Thin Gap Chambers


ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions

Yes, already

THINKING ABOUT THE FUTURE

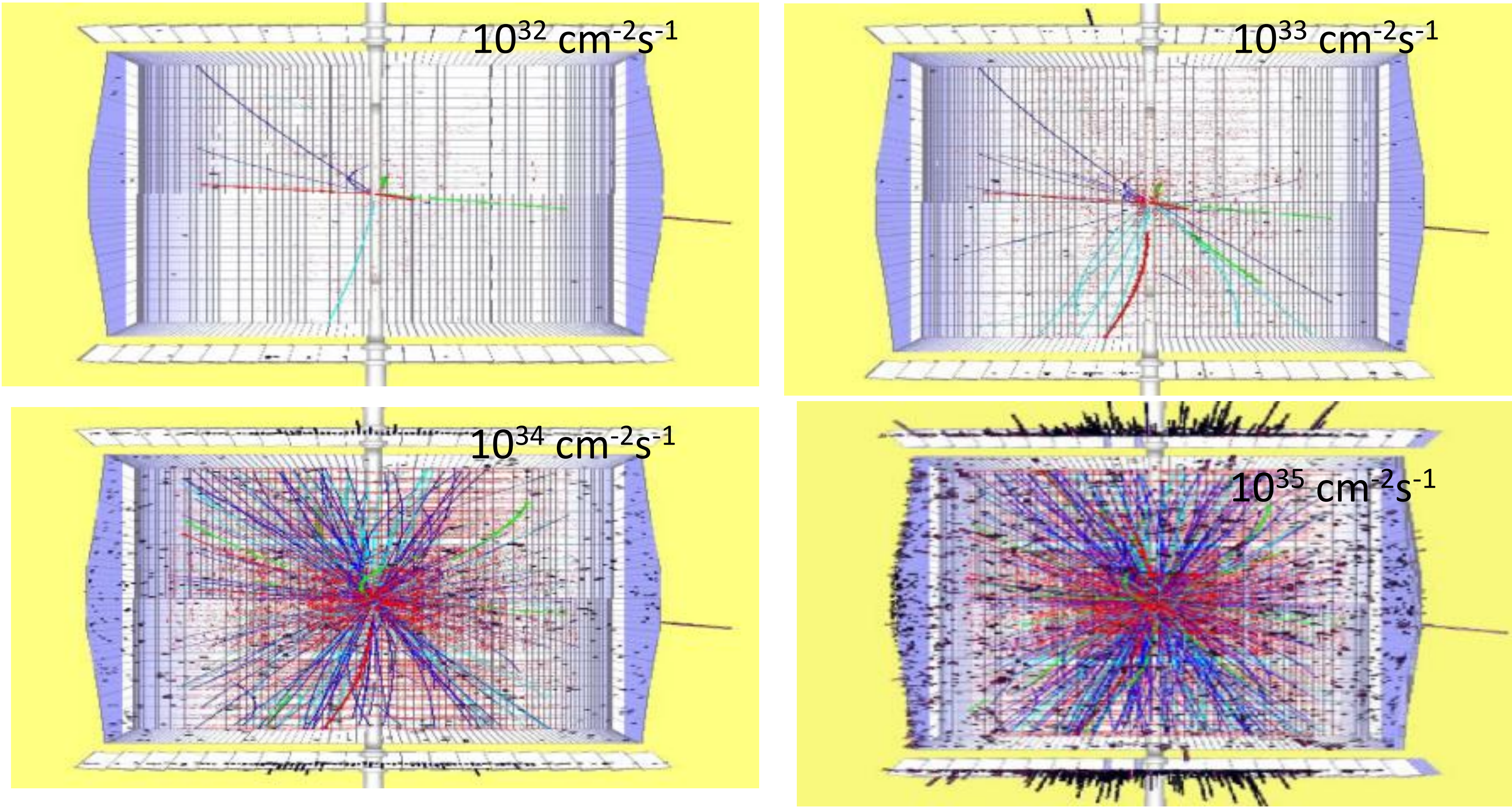
How to improve?



More data

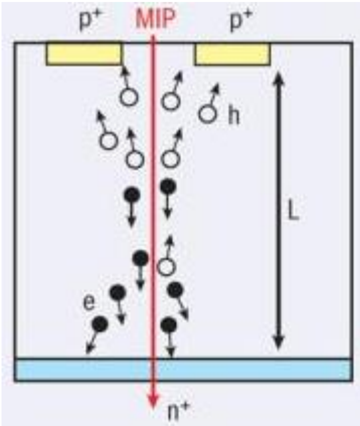
Better detectors

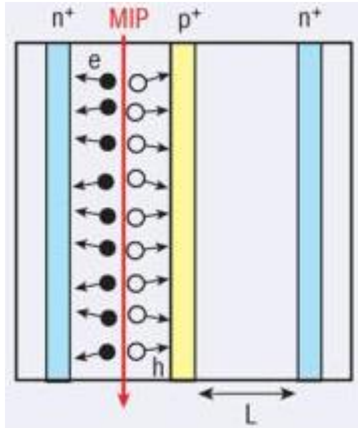
Increasing the luminosity

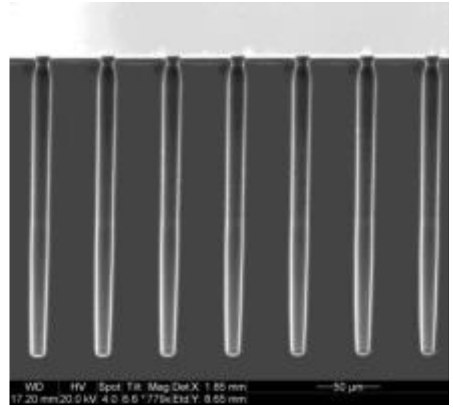


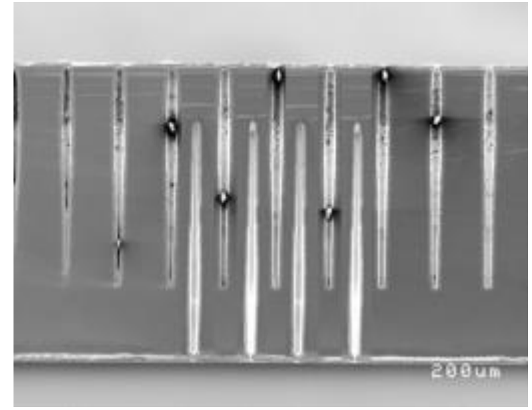
More events… but also higher backgrounds (highly pixelated, fast, rad hard)

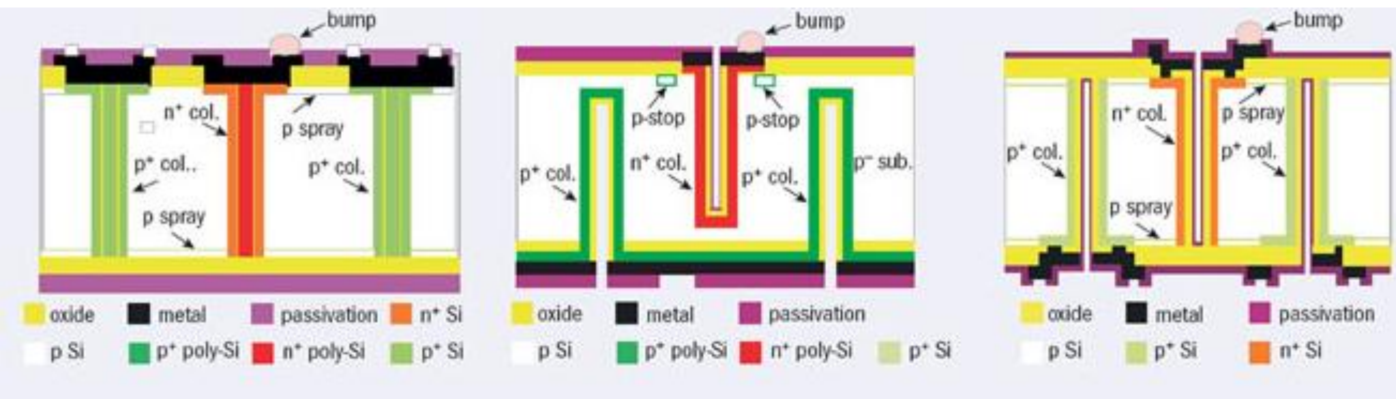
3D detectors for ATLAS Upgrade

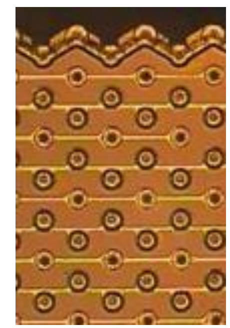




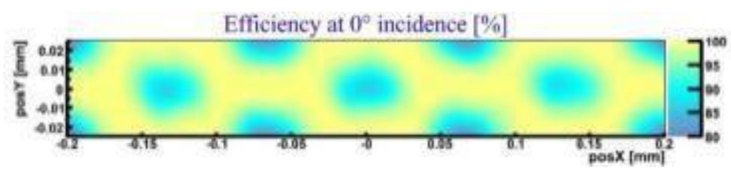






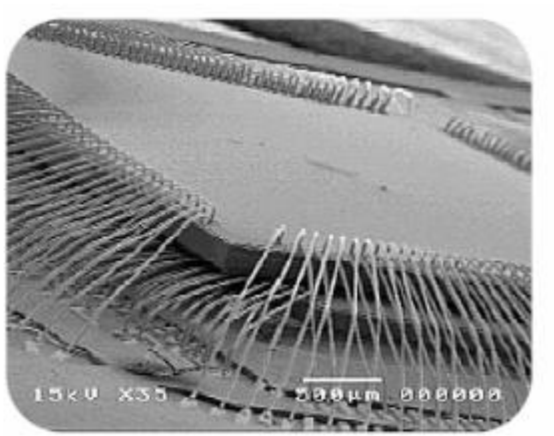


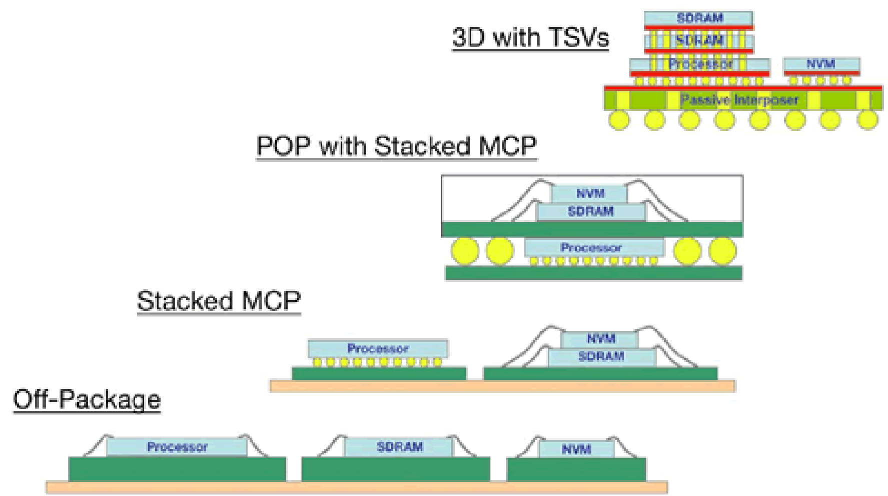
Low trapping
Low depletion voltage
Short drift time and no shift from Lorentz angle
Suited for extremely high irradiated environments



Packaging

Packaging is what makes your cell phone small



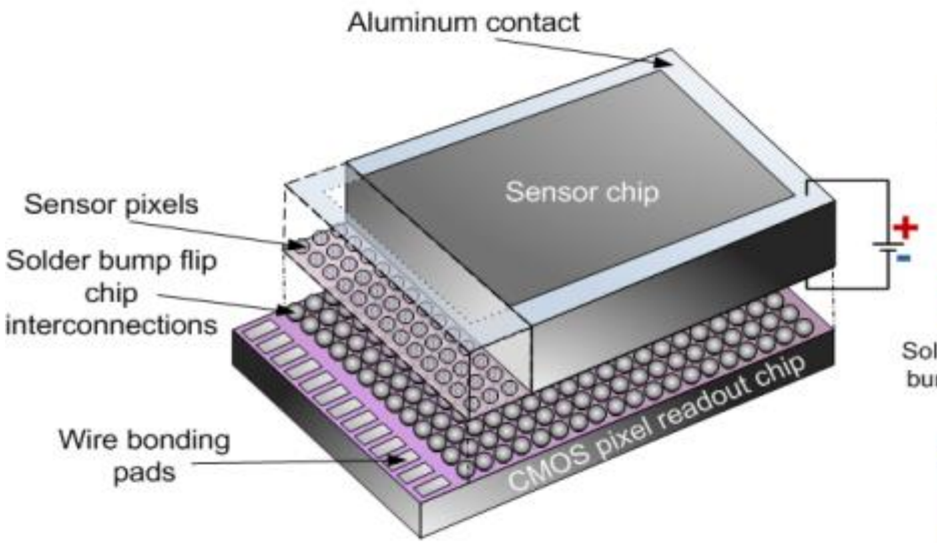


How to use this feature in HEP?

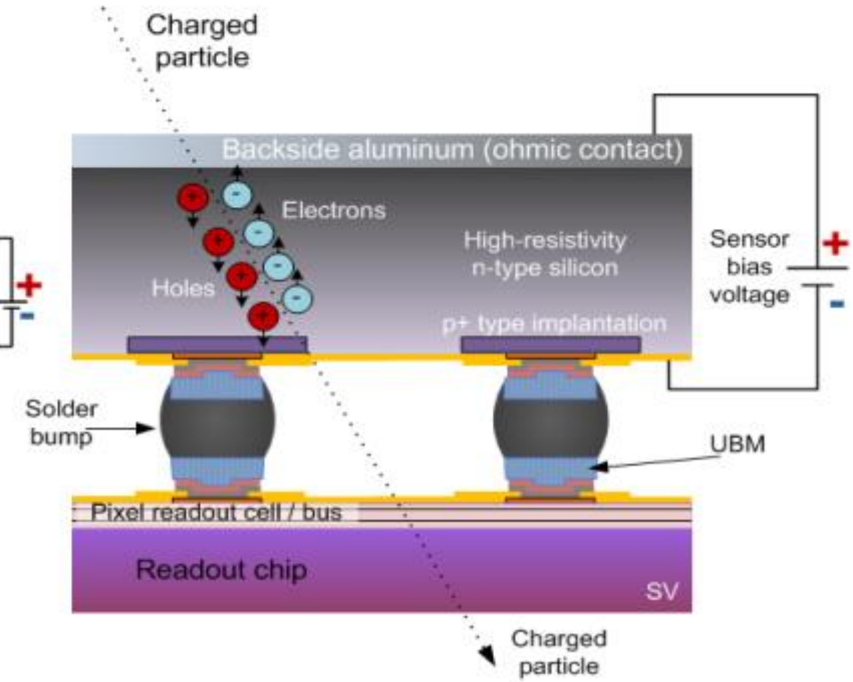
cmarinas@uni-bonn.de

Flip chip in pixel detectors

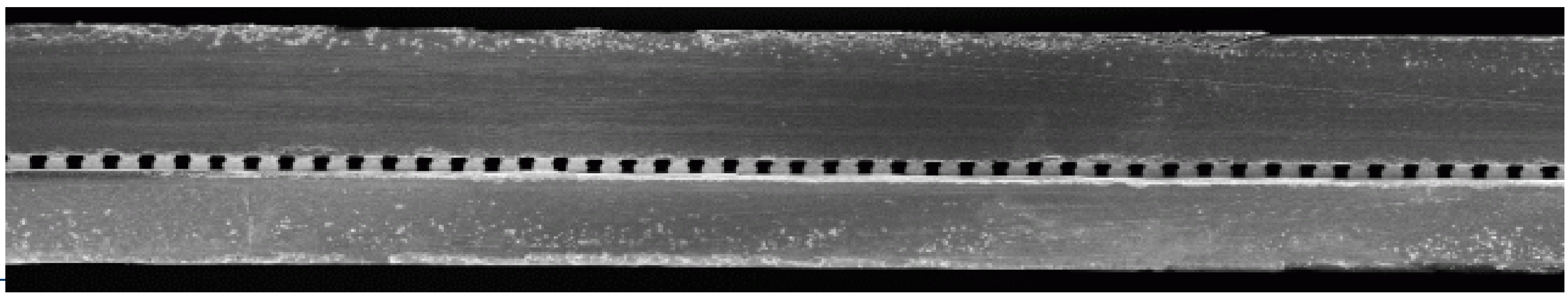
- Pixel detector consists of a sensor chip and readout chip which are connected with flip chip bumps



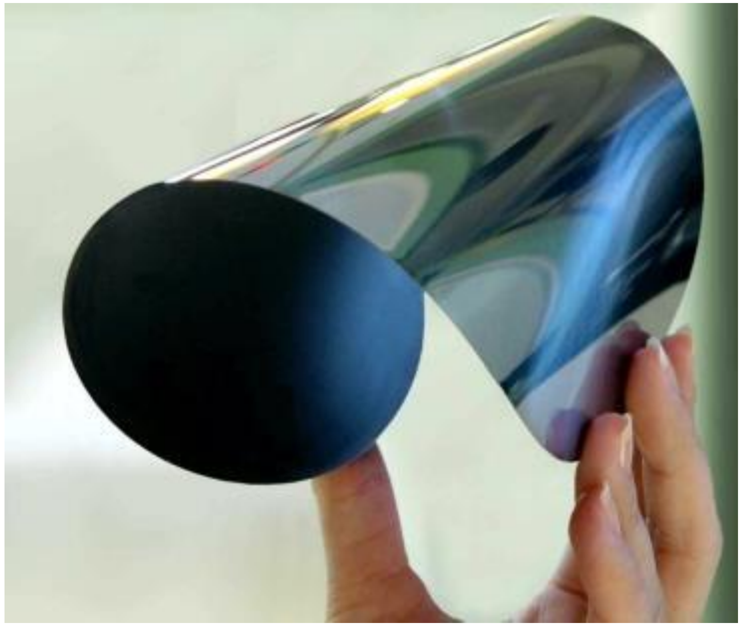
Generic pixel detector



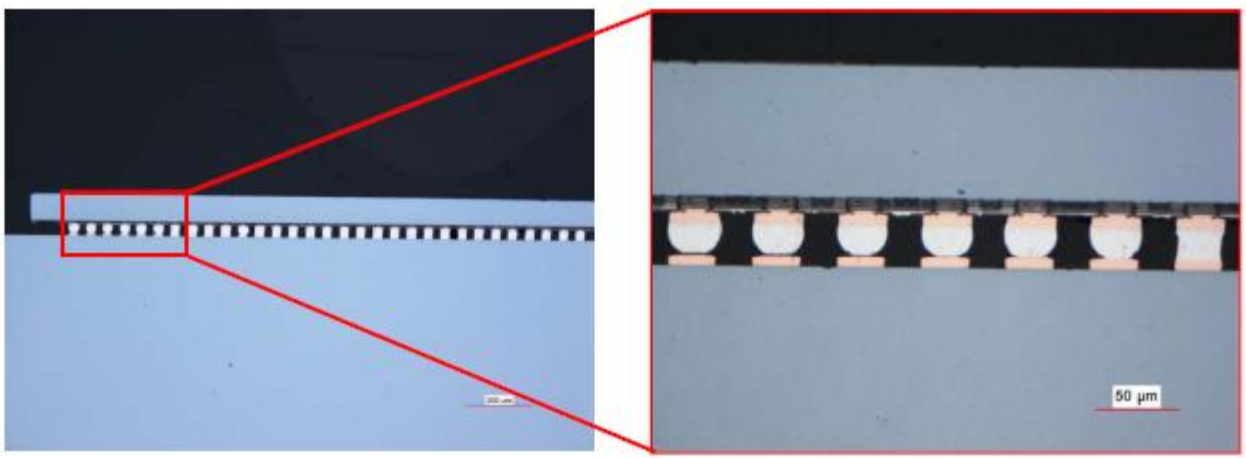
Cross-sectional cut



Thinned wafers



Signal-to-noise ratio suffers
Handling not trivial



Ting's speech at the Nobel Banquet, 1976

universitätbonn

Having grown up in the old China, I would like to take this opportunity to emphasize to young students from developing nations the importance of experimental work.

There is an ancient Chinese saying "He who labours with his mind rules over he who labours with his hand". This kind of backward idea is very harmful to youngsters from developing countries. Partly because of this type of concept, many students from these countries are inclined towards theoretical studies and avoid experimental work.

In reality, a theory in natural science cannot be without experimental foundations; physics, in particular, comes from experimental work.

国王，皇后陛下，皇族们，各位朋友：

得到诺贝尔奖，是一个科学家最大的荣誉。我是在旧中国长大的，因此想借这个机会向在发展国家的青年们强调实验工作的重要性。

中国有一句古话："劳心者治人，劳力者治于人。"这种落后的思想，对在发展国家的青年们有很大的害处。由于这种思想，很多在发展国家的学生们都倾向于理论的研究，而避免实验工作。

事实上，自然科学理论不能离开实验的基础，特别，物理学是从实验产生的。

我希望由于我这次得奖，能够唤起在发展国家的学生们的兴趣，而注意实验工作的重要性。

Thank you

cmarinas@uni-bonn.de