The ATLAS & CMS Tracking Detectors

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Outline

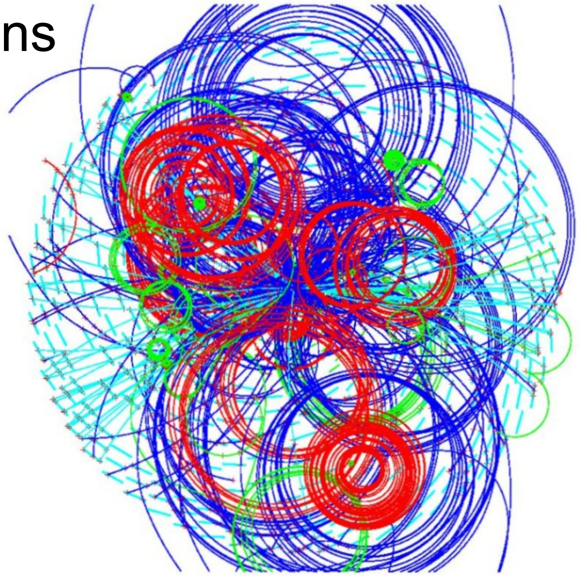
- Requirements
- Atlas & CMS tracker layouts
  - Micro-strip trackers
  - Pixel detectors
  - Transition radiation tracker
- Expected and observed performance
- Detector status
- Summary

Each topic is discussed for CMS and ATLAS

LHC Tracker Requirements

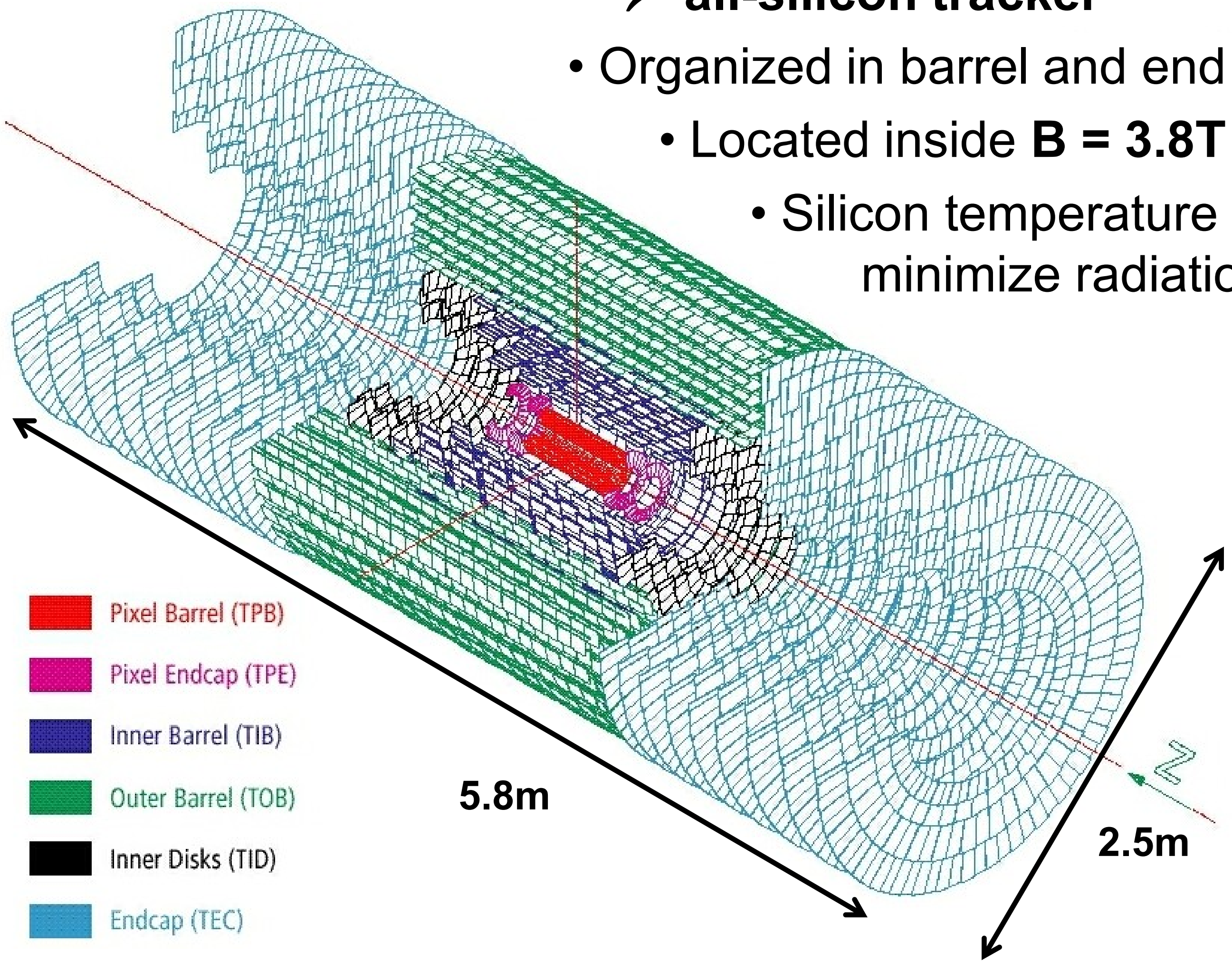
- Up to 1000 particles from 20 minimum bias events per bunch crossing $\rightarrow$ **fine granularity** to keep occupancy at few %
- Bunch spacing of 25ns $\rightarrow$ **fast electronics** to resolve bunch crossings
- **Efficient and precise tracking** $\rightarrow$ robust pattern recognition & precise alignment of the sensitive elements
- Excellent **momentum resolution** for low and high p_T tracks
- Precise reconstruction of primary & secondary vertices
- Low mass to minimize undesired particle interactions
- **Radiation hardness**
- Reasonable cost
- Low risk of failure

Solutions found by ATLAS & CMS are similar, but not identical.

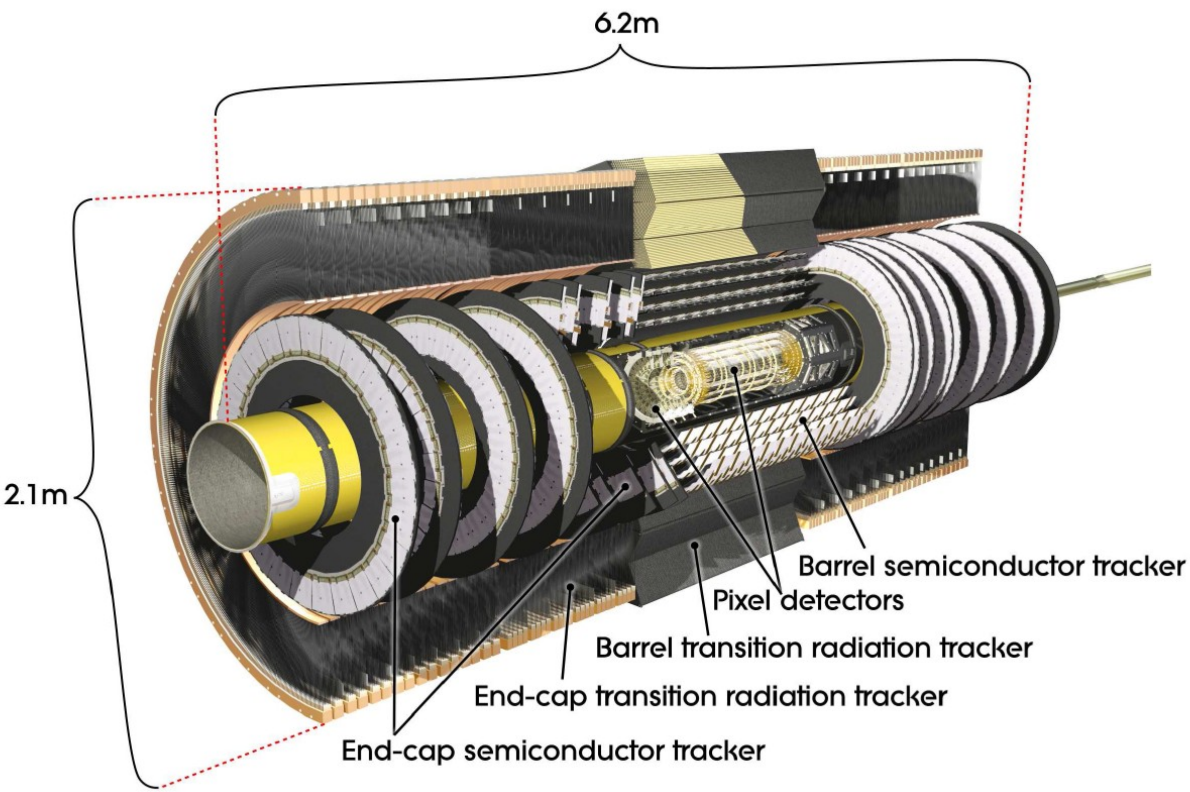


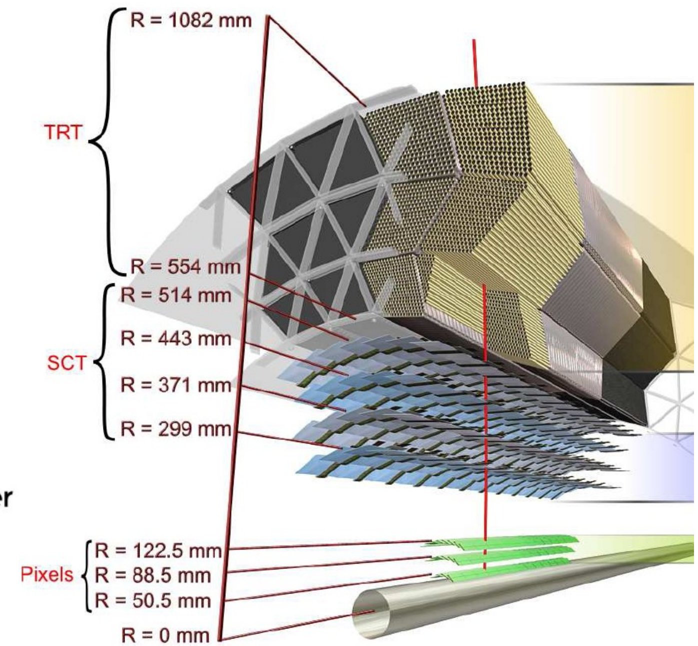
The CMS Tracker

- Silicon pixel detector and silicon micro-strip tracker
  → **“all-silicon tracker“**
- Organized in barrel and end caps (saves area)
  - Located inside **B = 3.8T solenoidal field**
    - Silicon temperature below -10°C to minimize radiation damage



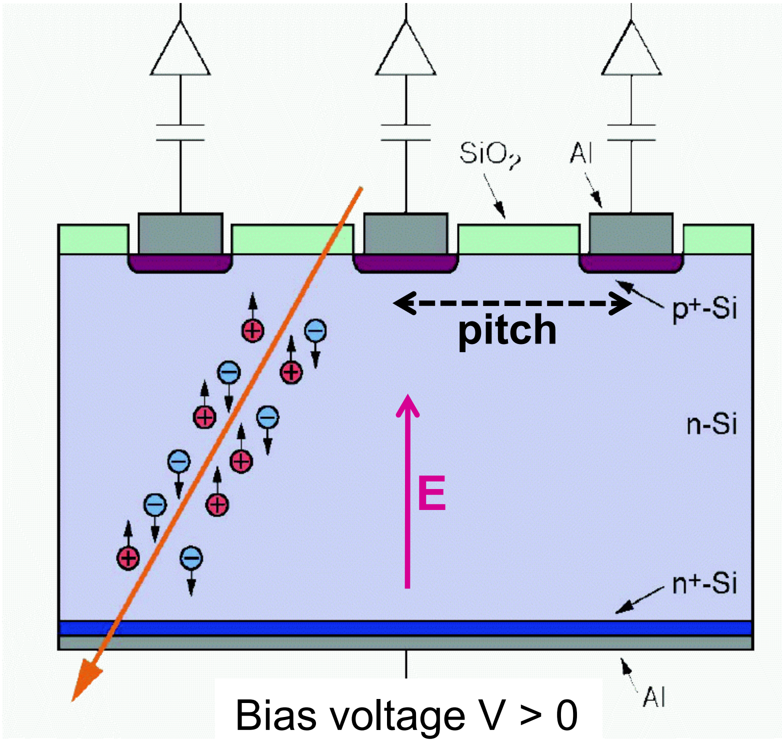
The ATLAS Tracker (= Inner Detector, ID)



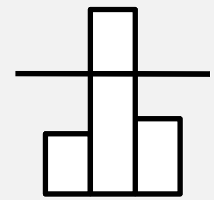
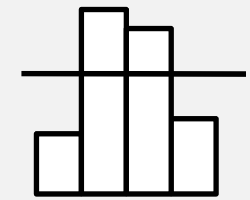


- Silicon pixel detector and micro-strip tracker (Semiconductor Tracker, SCT)
- **Transition Radiation Tracker** (TRT) with straw tubes for r > 0.5m
- Located inside **B = 2T solenoidal field**

Micro-Strip Detectors - Basics



Spatial resolution and read-out:

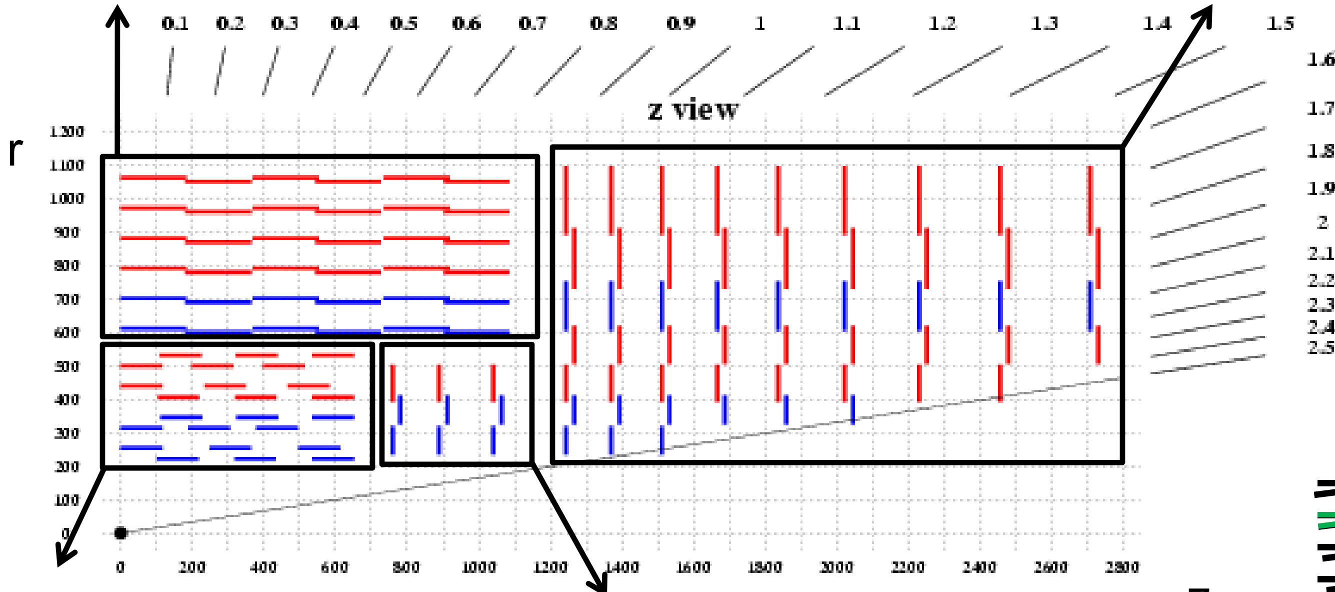
single-strip clusters	clusters with > 1 strips
	
analogue: Q_1 binary: 010	analogue: Q_1, Q_2; $\rightarrow x = (Q_1 x_1 + Q_2 x_2)/Q_{cluster}$ binary: 0110
Resolution = $p/\sqrt{12}$ (uniform distribution)	**Resolution better for analogue read-out**

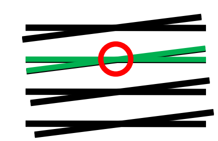
- Reverse biased diode; bias voltage 100-500V
- MIP ionizes detector material $\rightarrow$ 23 000 electrons in 300μm of silicon
- Electric field $\rightarrow$ electrons and holes drift to electrodes
- Segmentation of implants (strips, pixels) $\rightarrow$ spatial information (1D, 2D)
- Amplification, shaping, digitization

The CMS Silicon Strip Tracker

Tracker Outer Barrel (TOB)
p = 183μm (L1-4), 122μm (L5,6)

Tracker End Caps (TEC)
<p> = 97μm - 184μm



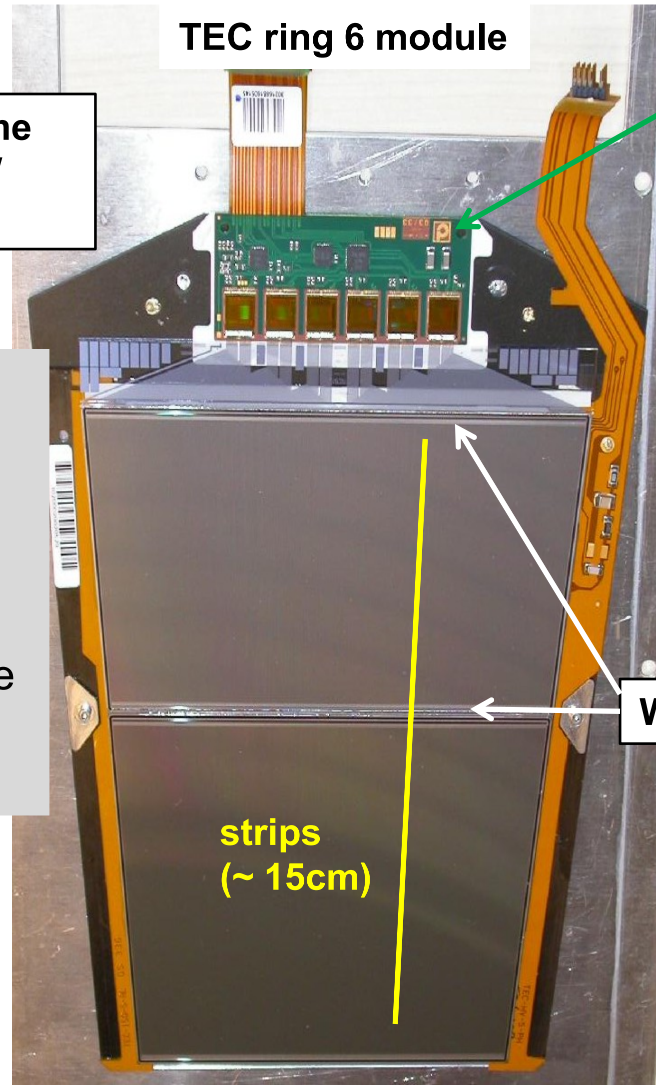


Tracker Inner Barrel (TIB)
p = 80μm (L1, L2), 120μm (L3, L4)

Tracker Inner Disks (TID)
<p> = 100μm - 141μm

- **Double-sided modules**: two **single-sided modules** mounted back-to-back with a stereo angle of 5.7° → position information along strips
- Resolution in barrel: 23-53μm in rφ (p/√12) and 230-530μm in z (p/√12/sin(5.7°))
- 9.3 million strips, 15 148 modules, 200m^2 of silicon
- Designed to stand fluences up to 1.6 x 10^{14}n$_{eq}$/cm^2 and a dose of 70 kGy, corr. to 500fb^{-1}

The CMS Silicon Strip Modules



Support frame
Carbon fibre / graphite

Front-end (FE)-hybrid:
4 or 6 APV25 read-out chips
0.25μm IBM CMOS process
Analogue readout
25ns effective shaping time

Kapton circuit for bias voltage/ isolation

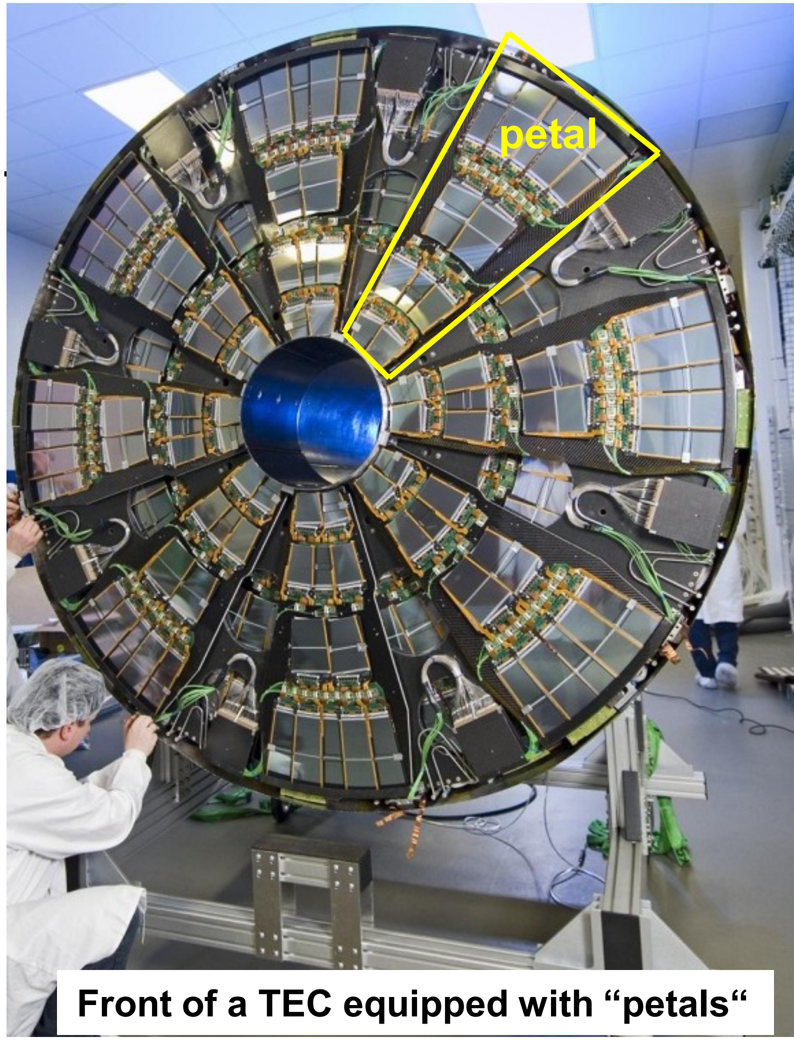
Wire bonds

- p-in-n sensors from 6 inch wafers ($\varnothing \approx$ 15 cm)
- r < 60cm : 1 sensor, 320μm thick (rad-hardness)
- r > 60cm: 2 sensors, 500μm thick $\rightarrow$ more charge (to compensate for higher noise of longer strips)

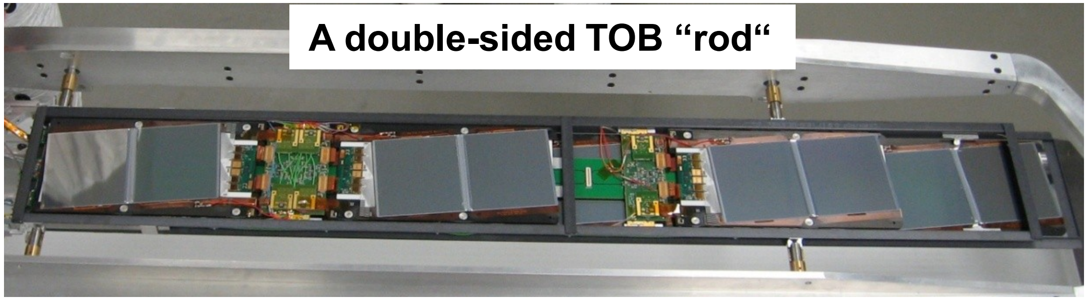
Simple module design, but 29 different types!

The CMS Silicon Strip Tracker

- High modularity: modules mounted onto separate carbon fibre support structures (rods, petals)
- Substructures mounted onto end caps disks and barrel wheels
- Optical read-out & communication
- “Simple“ C_6F_{14} monophase cooling system
- FE-power consumption 33kW

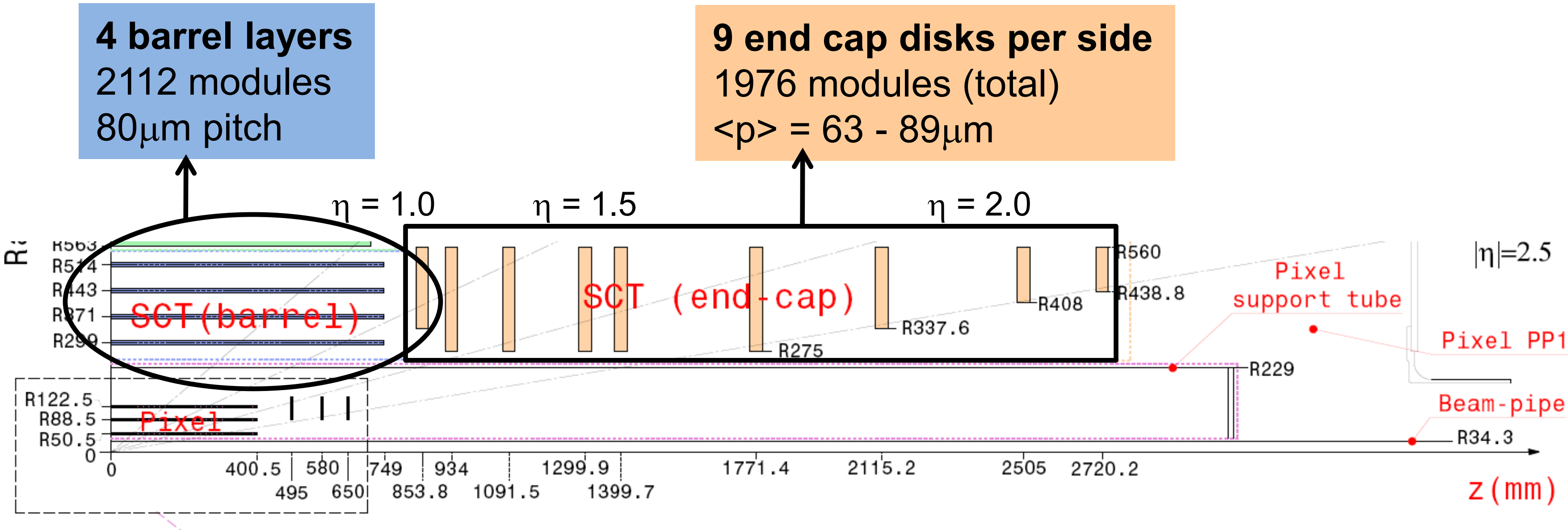


Front of a TEC equipped with “petals“



A double-sided TOB “rod“

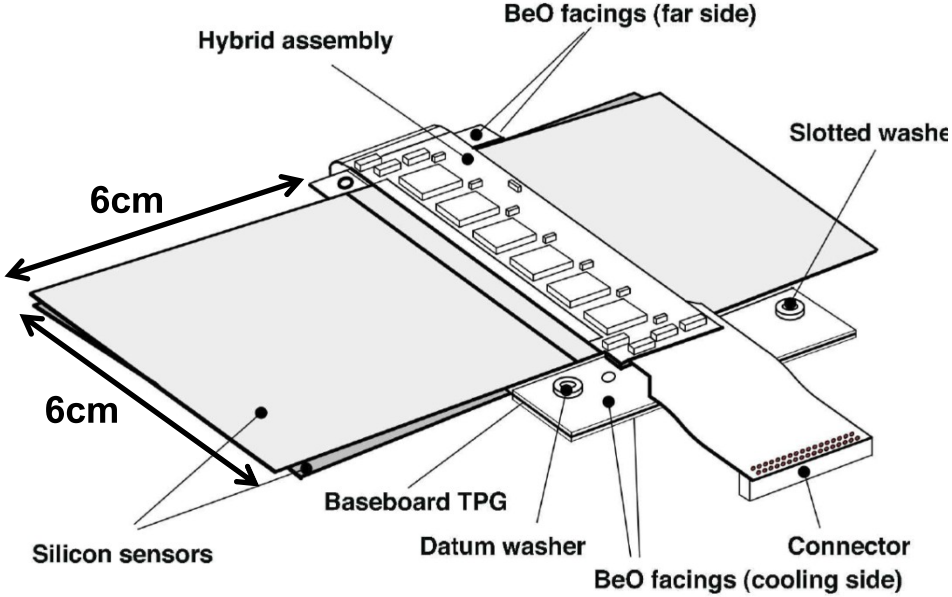
The ATLAS Silicon Strip Tracker



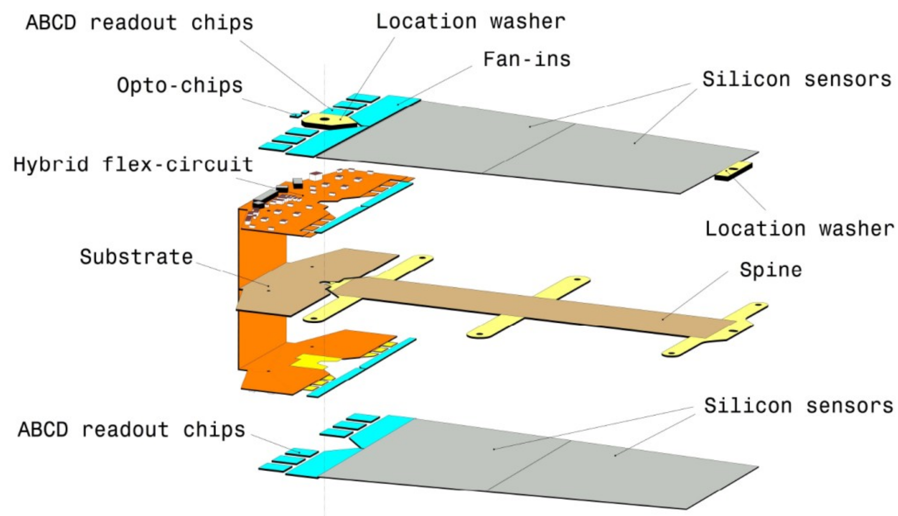
- **All modules are truly double-sided** with 40mrad (2.3°) stereo angle
- Expected spatial resolution: 17μm in rϕ (p/√12/√2) and 580μm in z/r (p/√12/sin(2.3°))
- 6.3 million strips, 4 088 modules, 63m^2 of silicon
- Evaporative C_3F_8 cooling system provides sensor temperature of ≈ –7°C

The ATLAS Silicon Strip Modules

Barrel module (all identical)

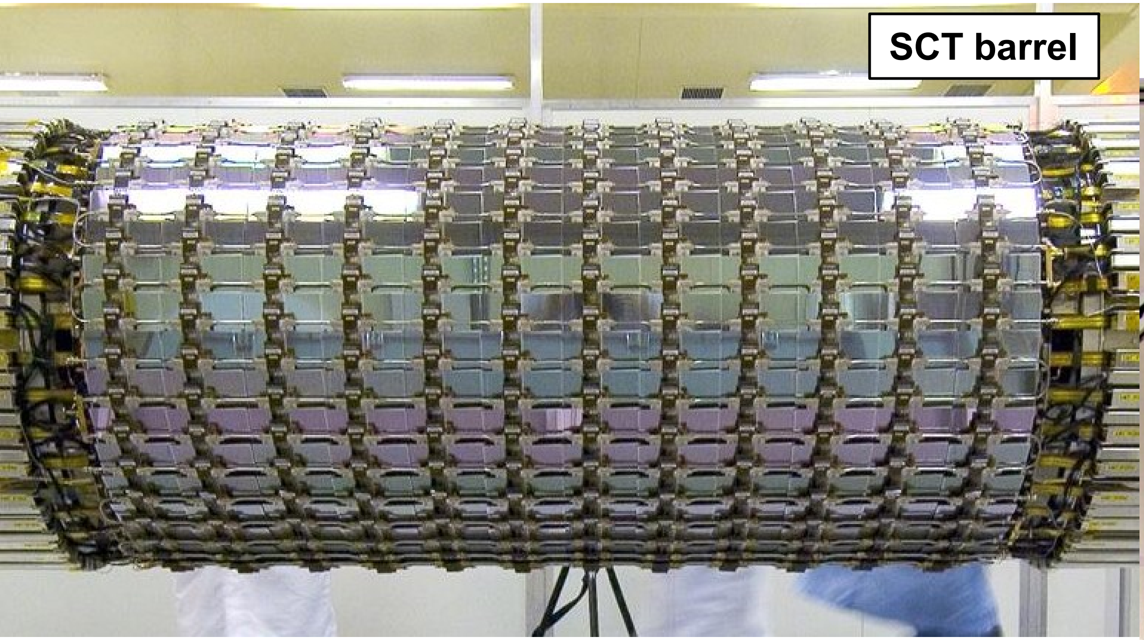


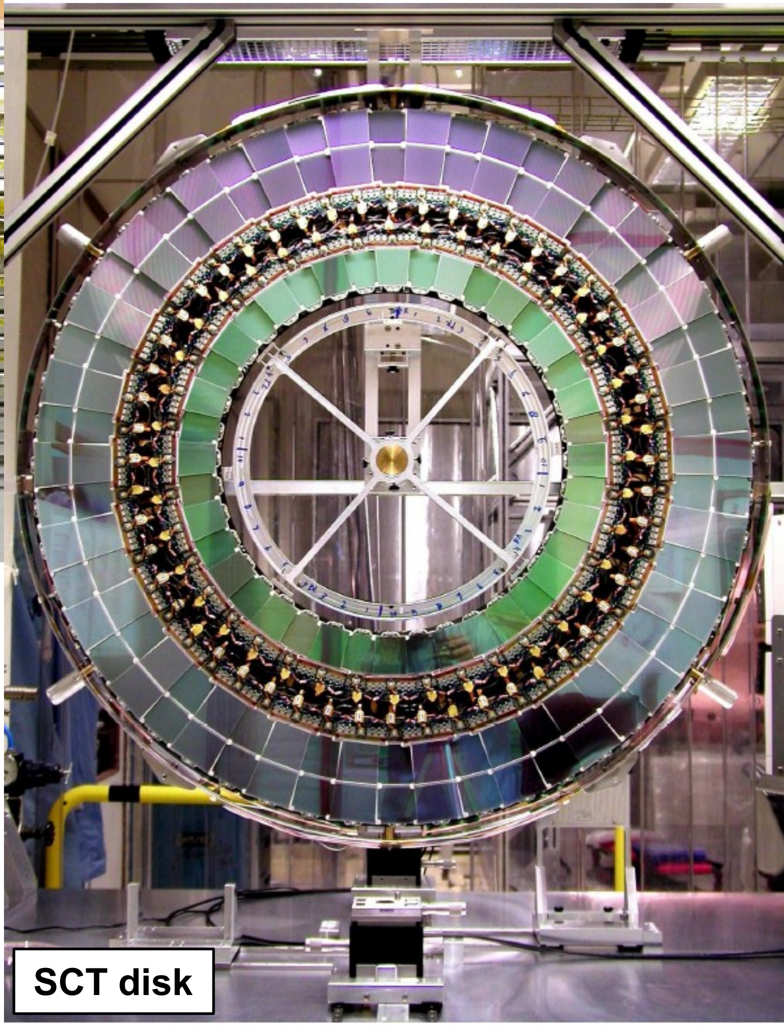
End cap module: 3 types



- 285μm thick p-in-n sensors from 4 inch wafers
- Tight requirements on cooling and mounting precision (e.g. barrel: 8μm build tolerance ⊥ to strips; achieved RMS: ± 2.1μm)
- Read-out ASIC in radiation-tolerant bi-CMOS DMILL technology
- Non-sparsified binary readout

The ATLAS Silicon Strip Tracker

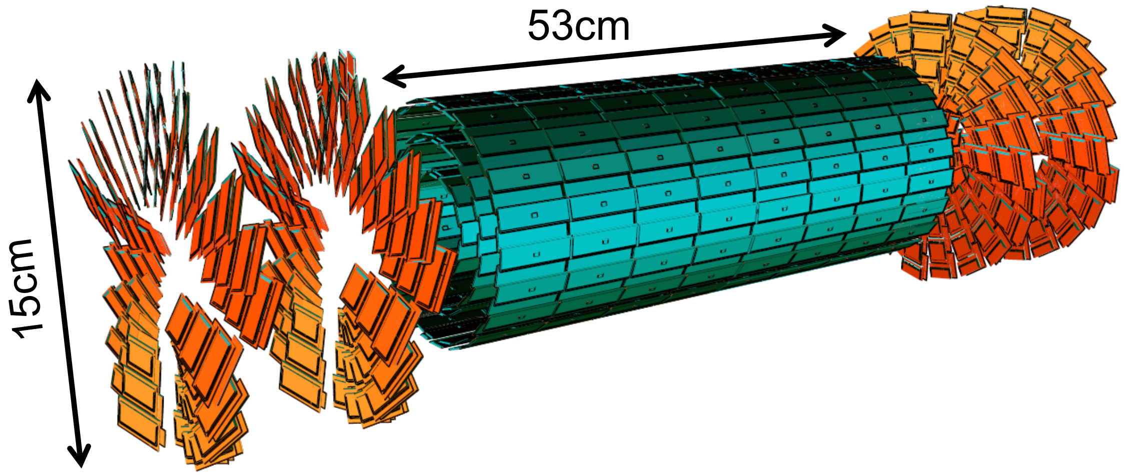




- Modules are directly integrated onto barrels/disks
- Optical read-out & communication
- 22kW initial FE-power

The CMS Pixel Detector

Barrel Pixels (BPIX):
3 barrel layers at 4.4, 7.3, 10.2cm
768 modules of 2 types

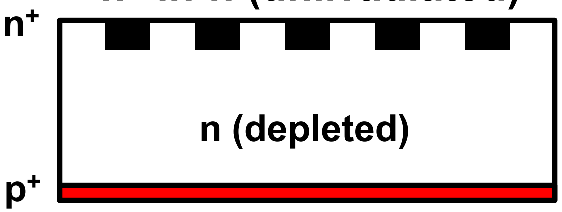


Forward Pixels (FPIX):
2 x 2 disks at z = ±34.5, ±46.5cm
192 panels of 4 types
Tilted by 20° for charge sharing

- Pixel cell size: 100μm (rϕ) x 150μm (z)
- Zero-suppressed readout of analogue pulse height $\rightarrow$ charge sharing due to Lorentz-angle & tilt leads to a spatial resolution of 15-20μm
- In total 66 million pixels and 1m^2 of silicon
- Designed to stand 6 x $10^{14} n_{eq}/cm^2$ = 2 years at design luminosity

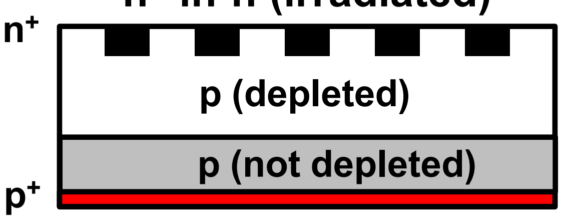
The CMS Pixel Detector Modules

n^+-in-n (unirradiated)

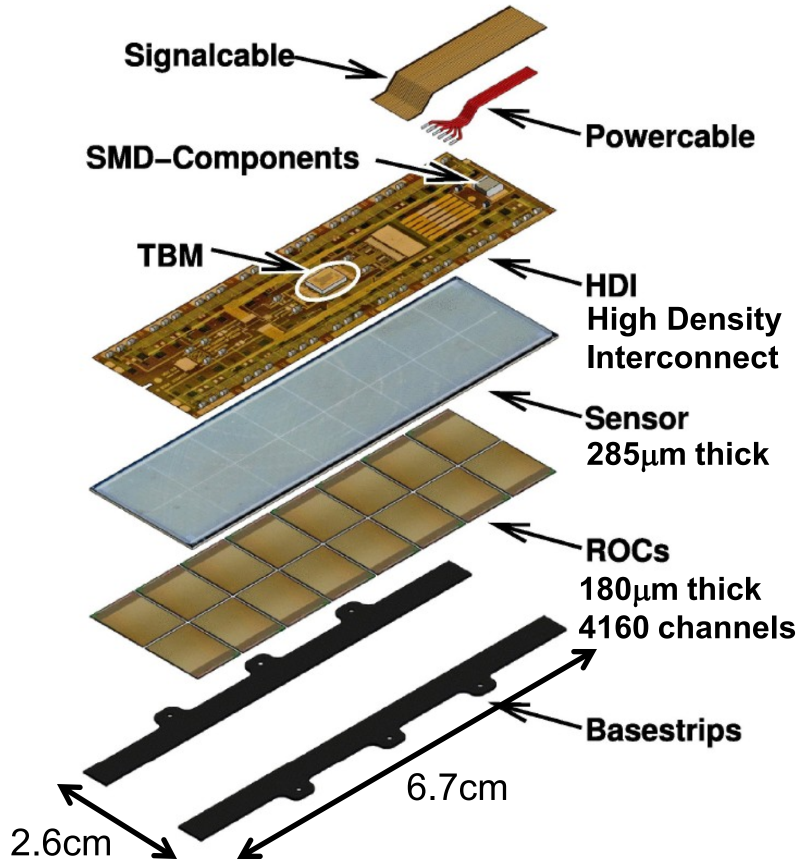


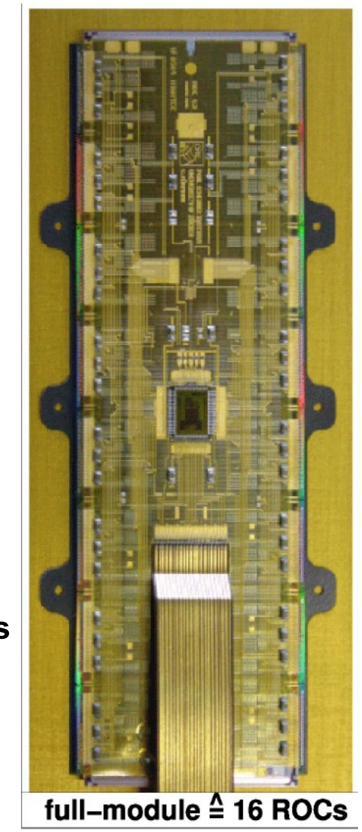
Depletion voltage ≈ 100V

n^+-in-n (irradiated)



Depletion voltage > 500V

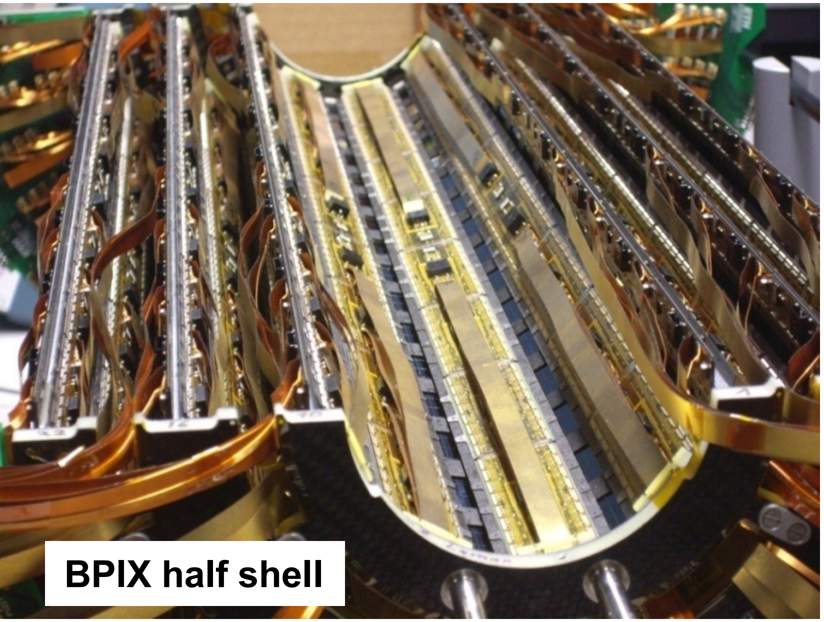


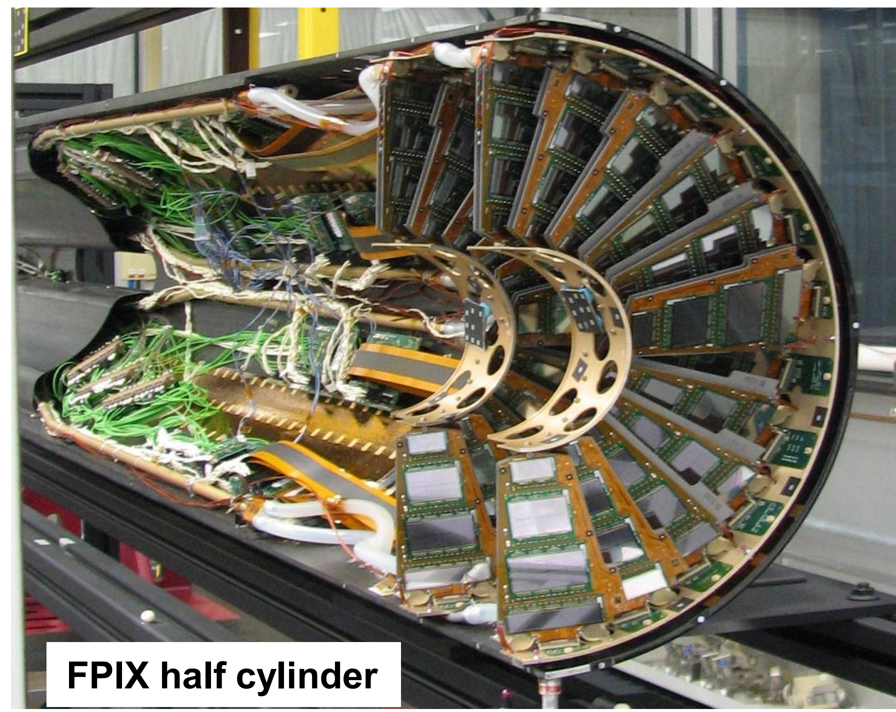


BPIX module, 2.2g

- n+ pixels on n substrate for radiation hardness, DC-coupled
- Hybrid technology: sensor bump-bonded to read-out chips (0.25μm CMOS)
- FPIX and BPIX sensors and modules differ (p-stop vs. p-spray isolation etc.)

The CMS Pixel Detector



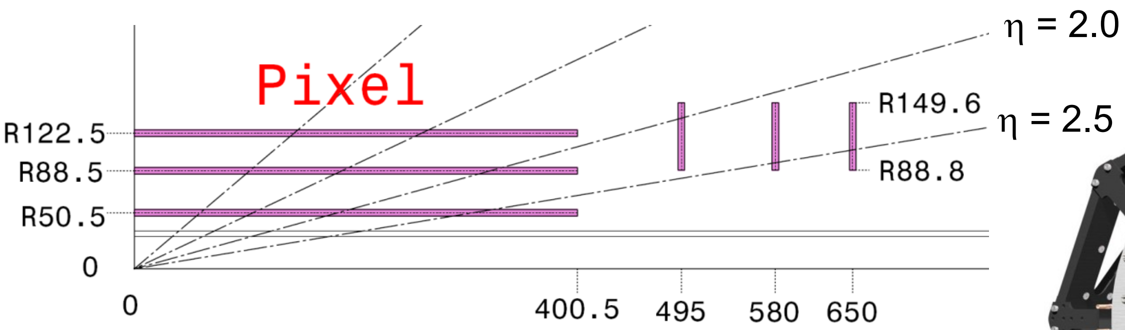


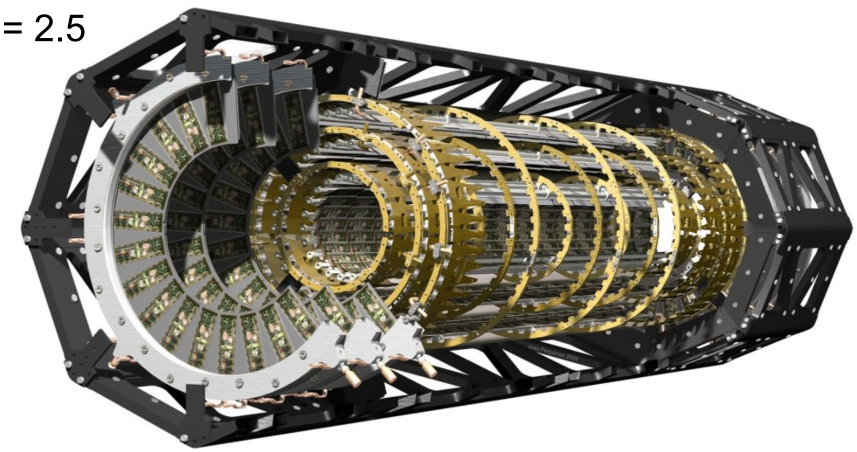
- Constructed in half-shells $\rightarrow$ extraction during yearly shut-downs possible
- Must be extracted for beam pipe bakeout
- Optical readout & communication
- C_6F_{14} monophase cooling system
- FE-power consumption: 3.6kW

The ATLAS Pixel Detector

Barrel:
3 layers at 5.1, 8.9, 12.3cm
1456 modules

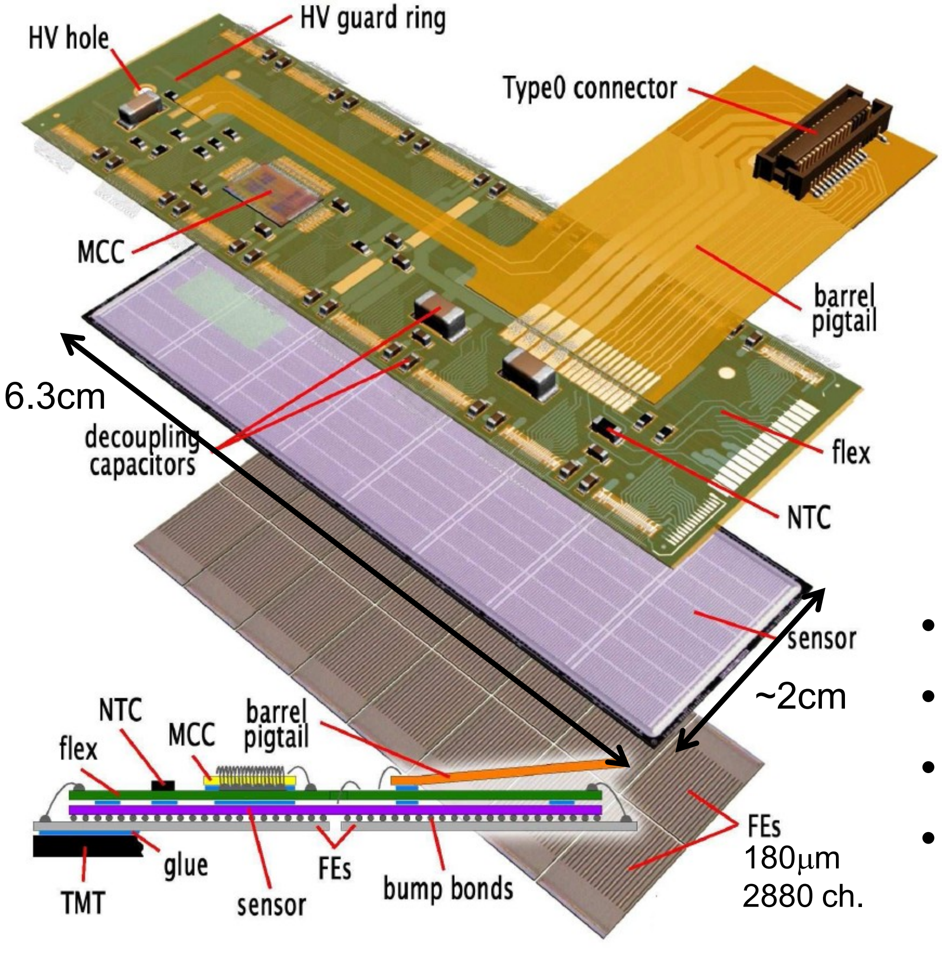
End caps:
2 x 3 disks at z = ±49.5, ±58.5, ±65.0 cm
144 modules

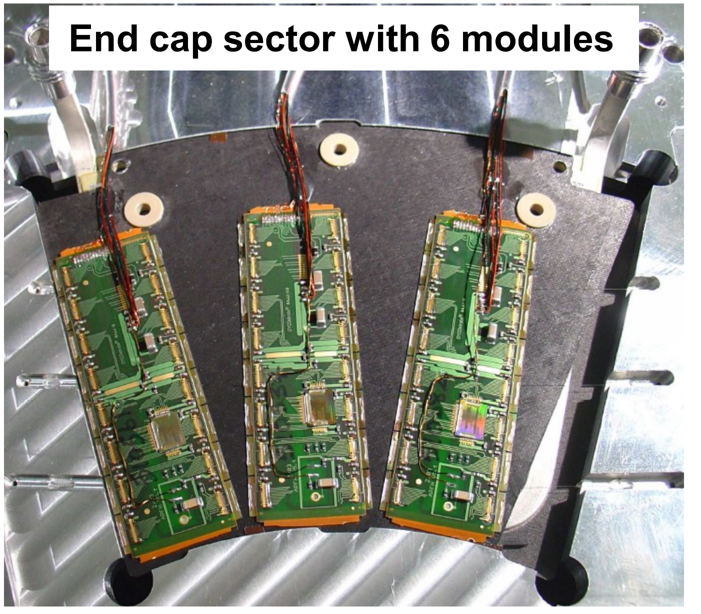




- Minimal pixel cell size: 50μm (rφ) x 400μm (z, r) → res.: 10μm in rφ / 115μm in z, r
- In total 80 million pixels and 1.7m^2 of silicon
- Inner layer must be replaced after 3 years at design luminosity
- Central part of beam pipe is part of the pixel system
- Evaporative cooling system with C_3F_8 ; sensor temperature ≈ –7°C

The ATLAS Pixel Detector Modules

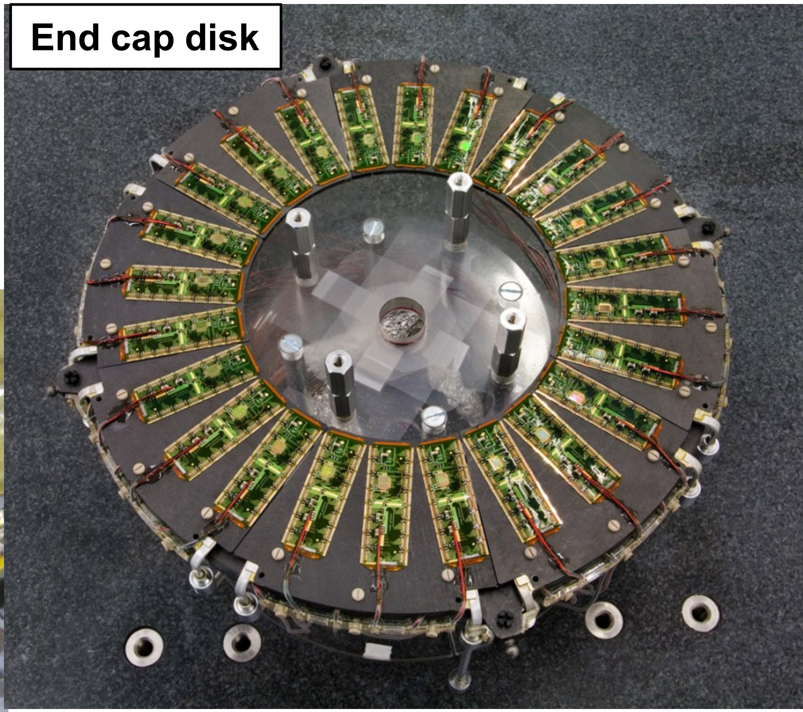




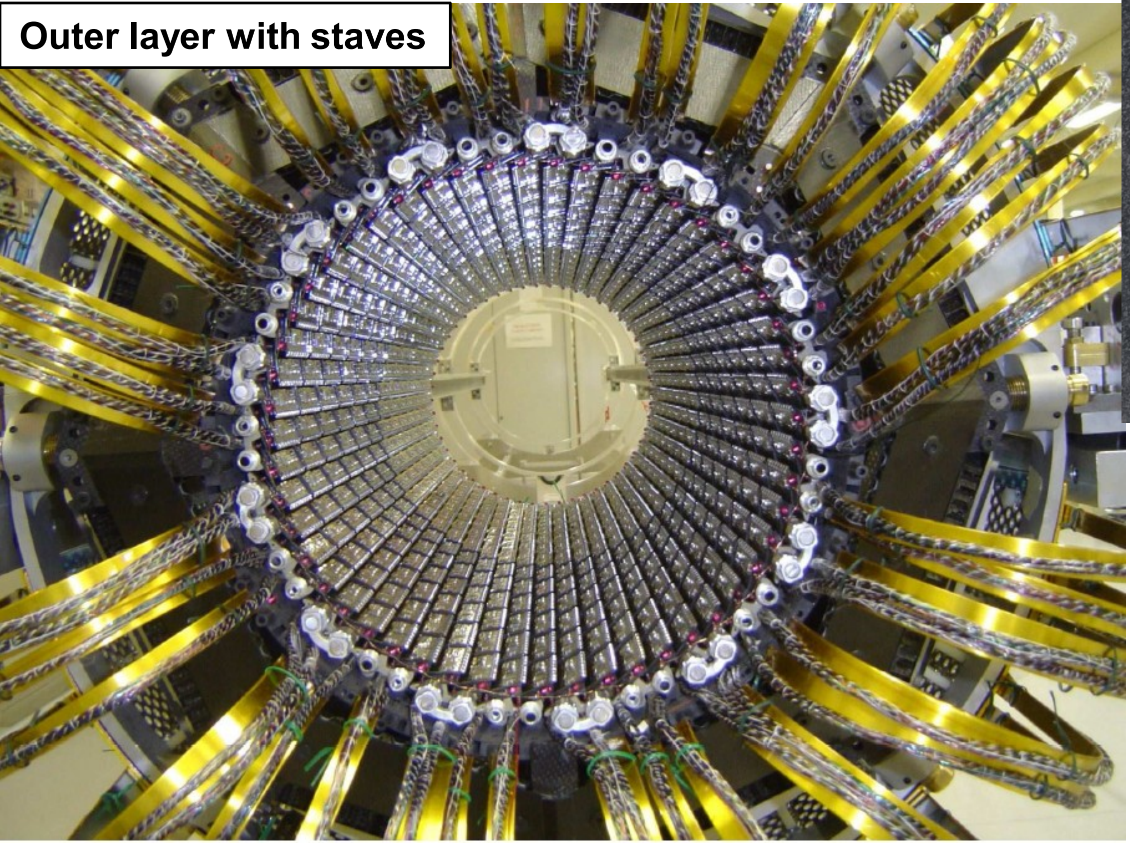
- n+-on-n, AC-coupled, 250μm thick
- Hybrid technology
- 0.25μm CMOS
- Digital read-out: charge is digitized as “time-over-threshold“
- All modules are basically identical

- Barrel modules mounted onto staves
- Optical read-out & communication
- Initial FE-power 6kW

End cap disk



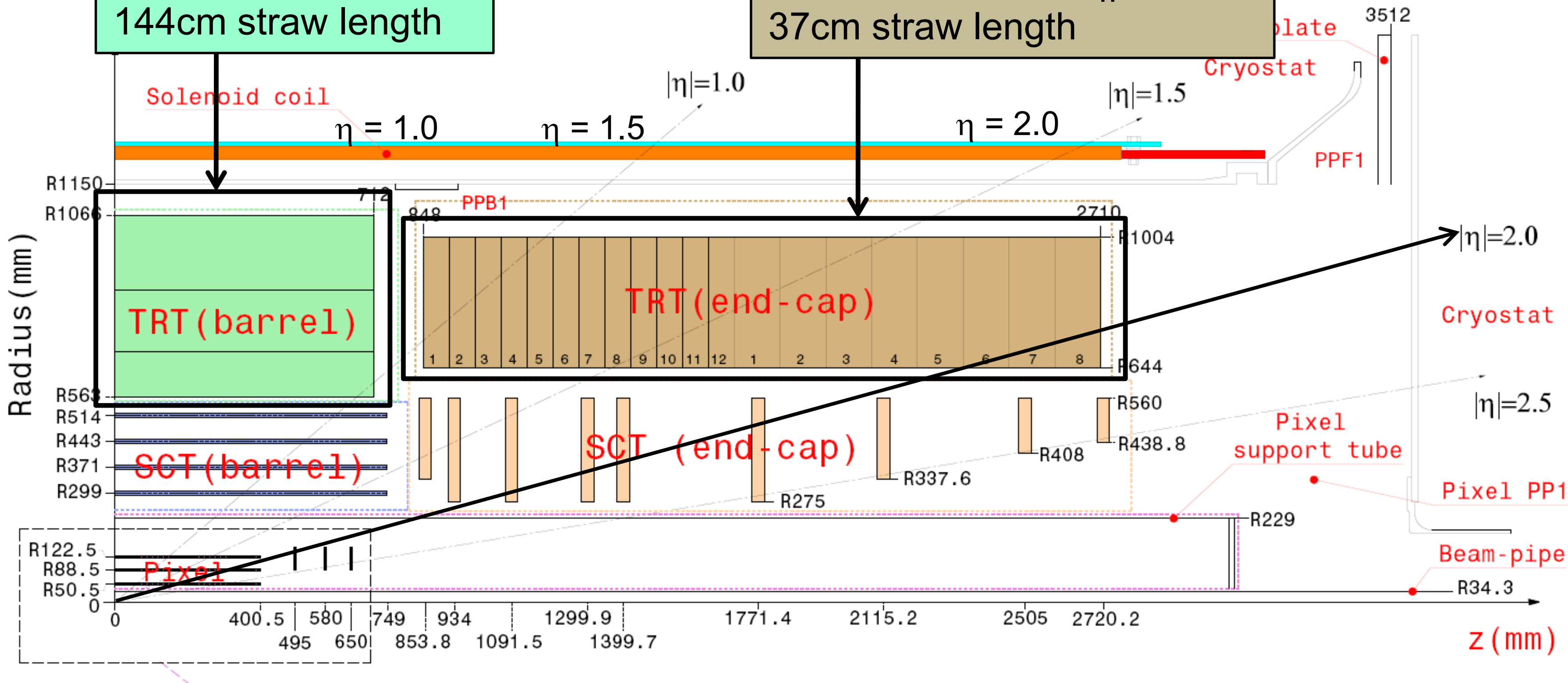
Outer layer with staves



The ATLAS Transition Radiation Tracker

TRT Barrel: 3 layers
52 544 straws || z
144cm straw length

TRT end caps: 2 x 20 disks
2 x 122 880 straws || r
37cm straw length



- Two functionalities: **continuous tracking + e/π separation** with transition radiation
- Acceptance: 35-40 hits up to |η| = 2 for p_T > 0.5GeV
- Operated at room temperature

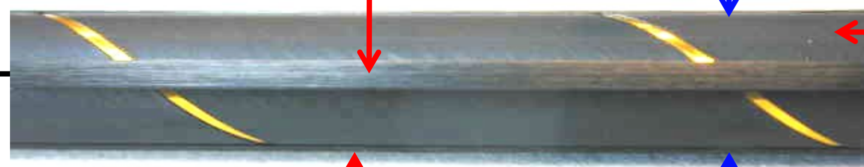
The ATLAS TRT Straw Tubes

Straw tube = proportional drift tube

Inside:
70% Xe, 27% CO_2, 3% O_2
gas gain 2.5×10^4

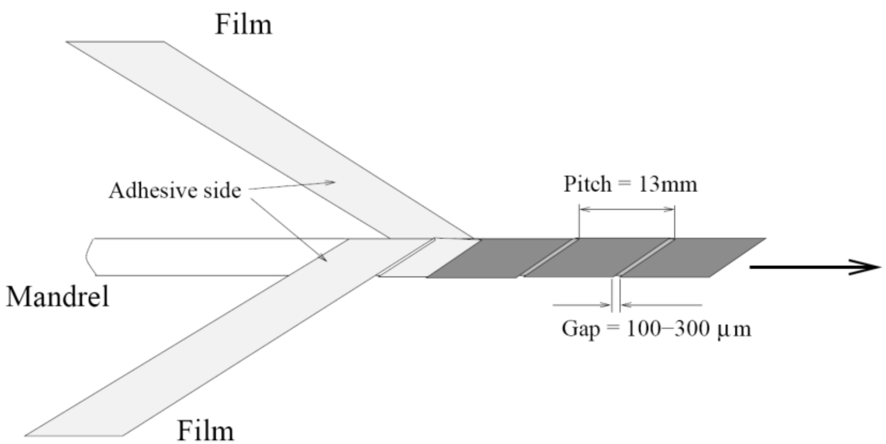
4 carbon fibre stiffeners

Anode wire:
$\varnothing$ = 31 μm
gold-plated tungsten
Offset < 300 μm

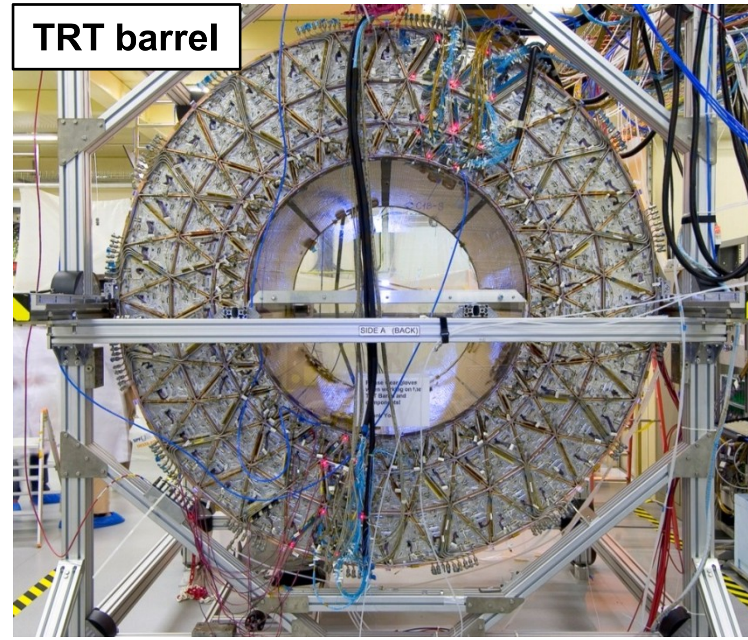


$\varnothing$ **4mm**

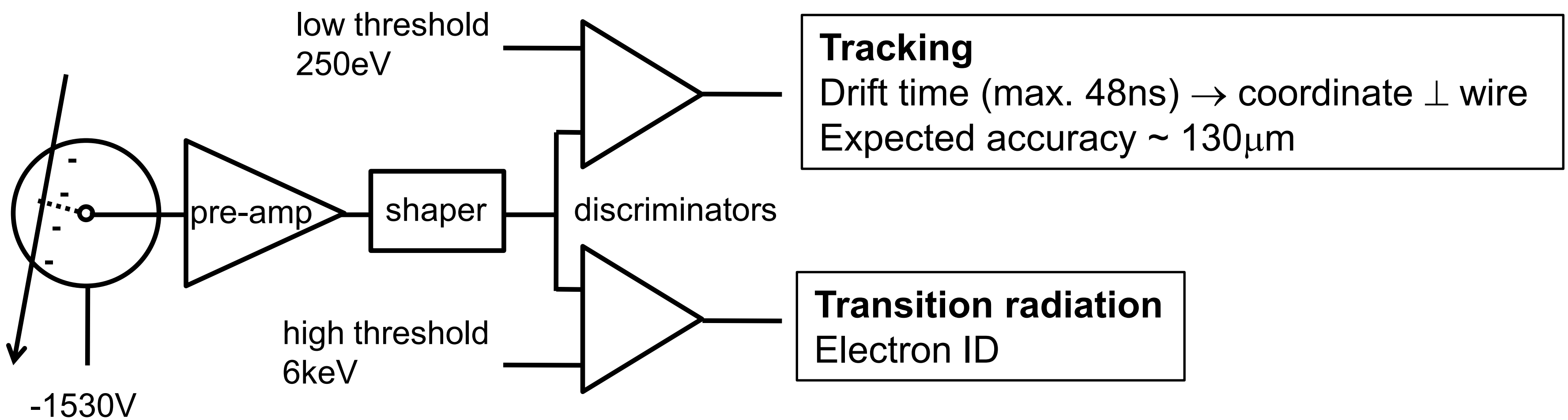
Two layers of Kapton film with
0.2 μm thick Aluminium cathode



The ATLAS TRT



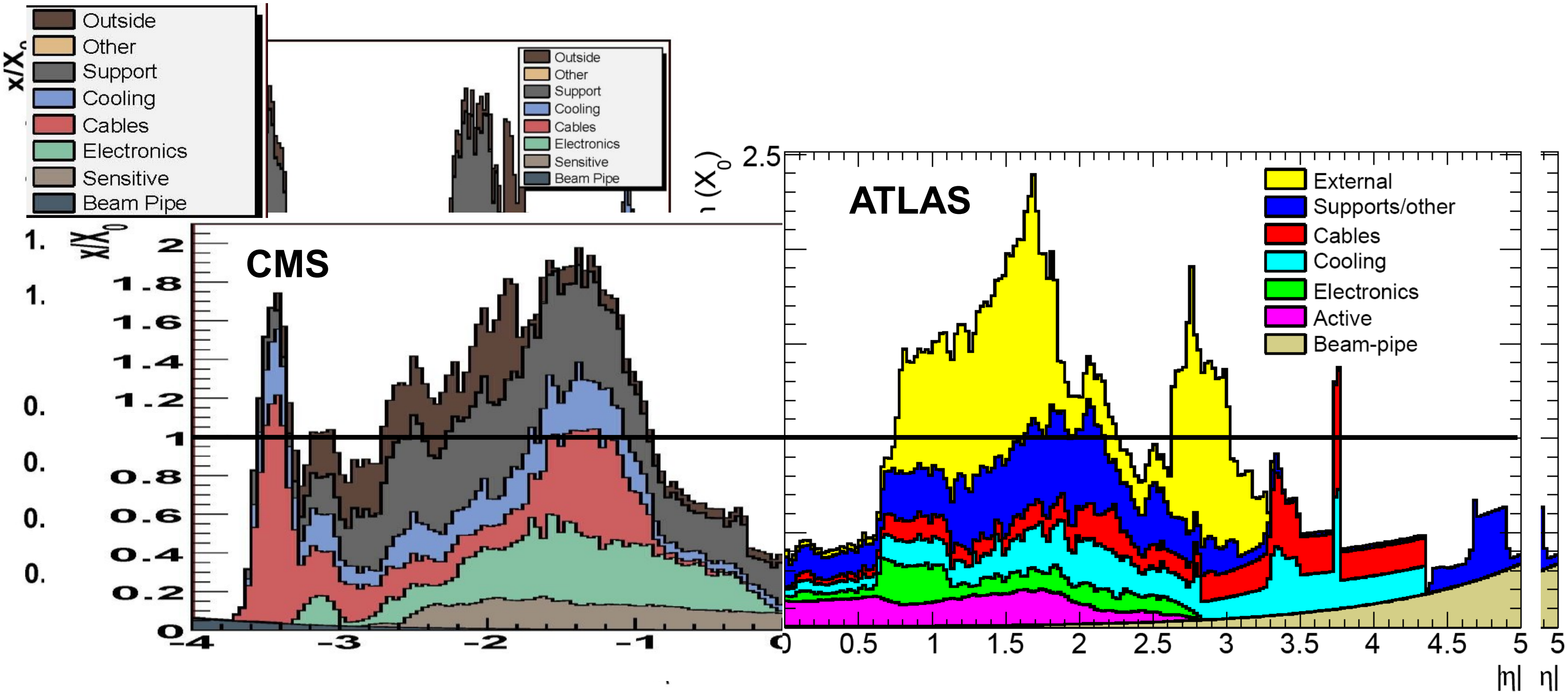
- If charged particle with $\gamma = E/m > 1000$ crosses boundary with diff. dielectric constants $\rightarrow$ **transition radiation**
- Radiator: polypropylene fibres (barrel) or foils (end cap)
- Photons are absorbed in Xenon gas
- 7 – 10 high threshold hits for e^- with $p_T > 2\text{GeV}$



Tracker Parameters for Reference

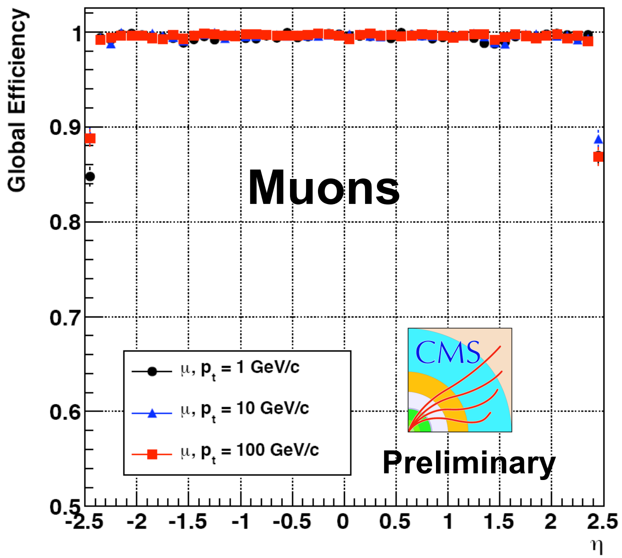
Component	Parameter	CMS	ATLAS
Magnetic field		4T	2T
Pixel	Technology	n^+-in-n	n^+-in-n
	Pixel size	100 x 150μm^2	50 x 400μm^2
	# of pixels	66M	80M
	Active area	1m^2	1.7m^2
	Read-out	Analogue	Time-over-threshold
	Res. rϕ x z	15-20μm both	10μm x 115μm
Silicon strips	Technology	p-in-n	p-in-n
	Pitch in barrel	80-183μm	80μm
	# of channels	9.3M	6.3M
	Active area	200m^2	63m^2
	Stereo angle	100mrad Some modules	40mrad All modules
	Read-out	Analogue	Binary
	Res. rϕ x z (binary)	23-35μm x 230/530μm	17μm x 580μm
TRT	Resolution rϕ		130μm

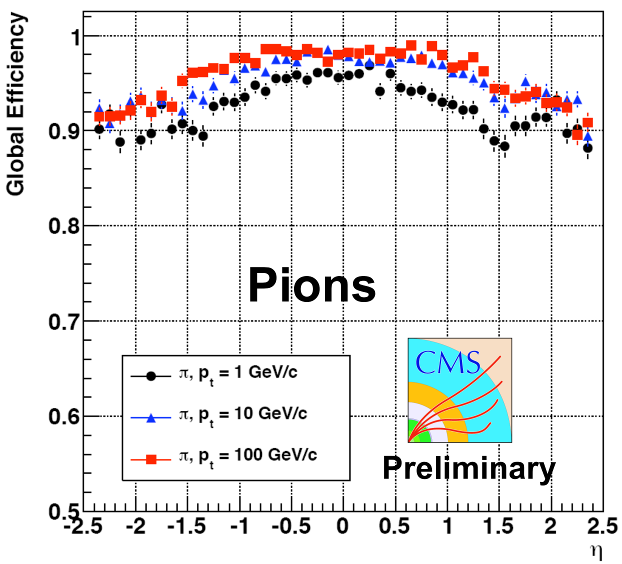
CMS & ATLAS Tracker Material Budget (X_0)



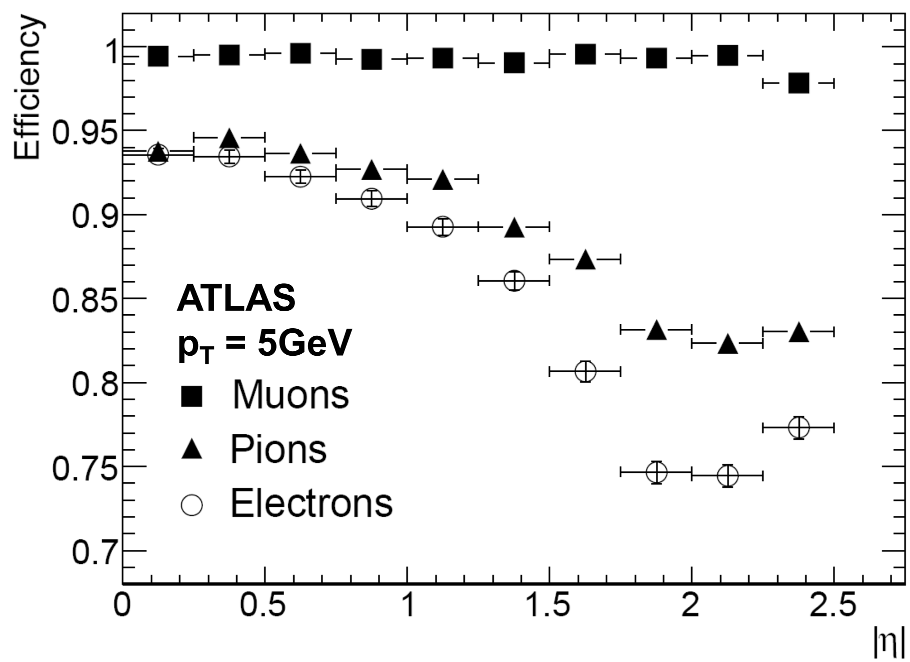
- Bremsstrahlung, photon conversion, multiple scattering, hadronic interactions
- Recall: after traversing **one** radiation length x_0 ...
  - ... the energy E_0 of an electron drops to E_0/e = 37% !
  - ... the conversion probability for a photon is 54% !
  - ... the RMS of the deflection for electrons with 1 GeV is ~ 50μm !

CMS & ATLAS Exp. Global Tracking Efficiency



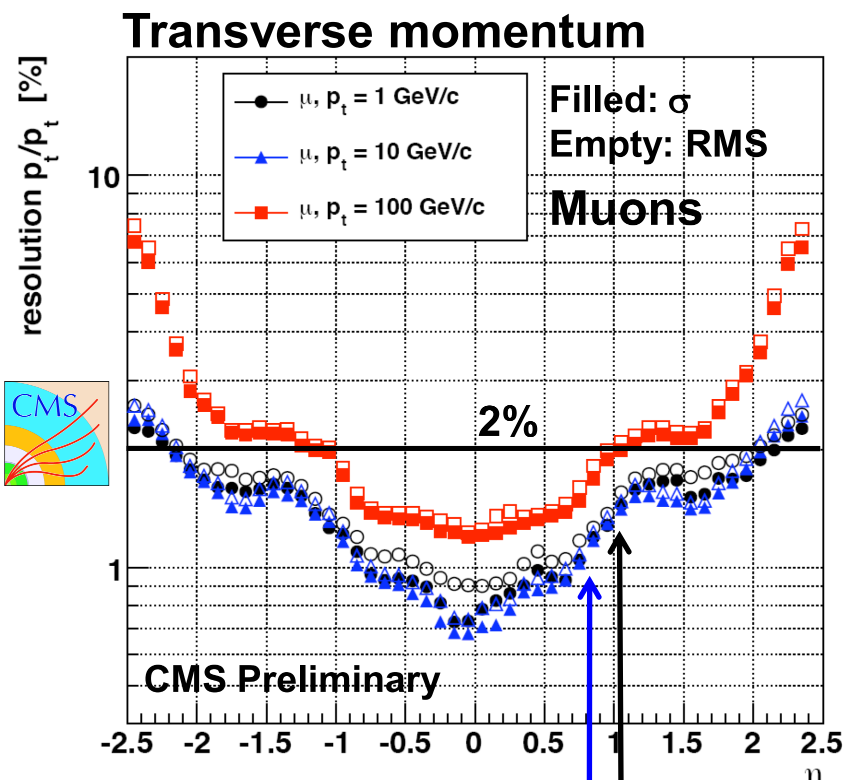


- CMS: preliminary simulation study with most recent material budget
- ATLAS: 2008 JINST 3 S08003

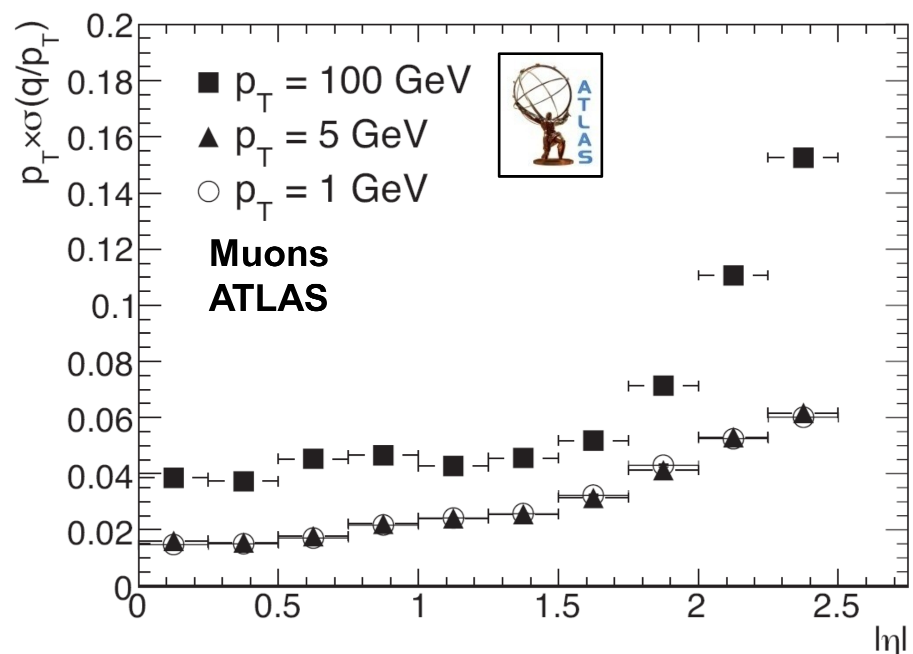


CMS & ATLAS Expected p_T Resolution

Reduction of lever arm for $|\eta| > 1.6$
Contribution from mult. scattering: 20-30%

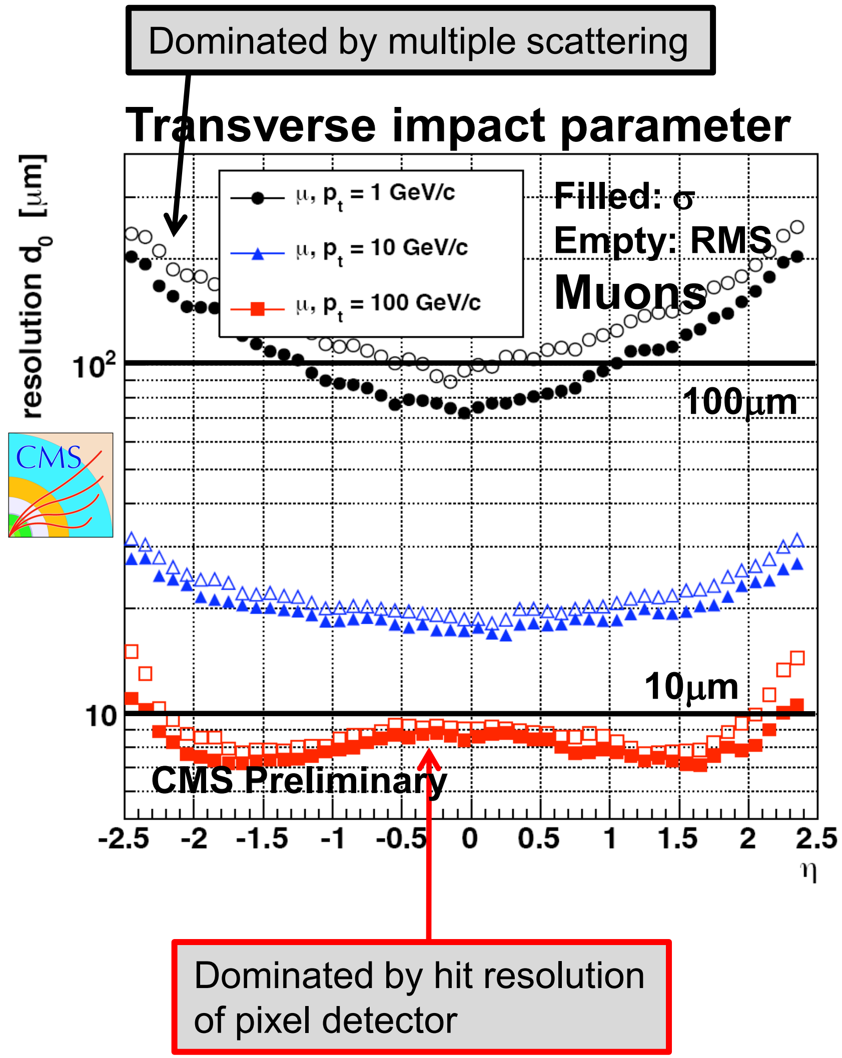


- CMS: preliminary simulation study with most recent material budget
- ATLAS: 2008 JINST 3 S08003
- Recall: B(ATLAS) = ½ B(CMS)



Dominated by multiple scattering,
resolution follows amount of traversed material

CMS & ATLAS Expected d_0 Resolution



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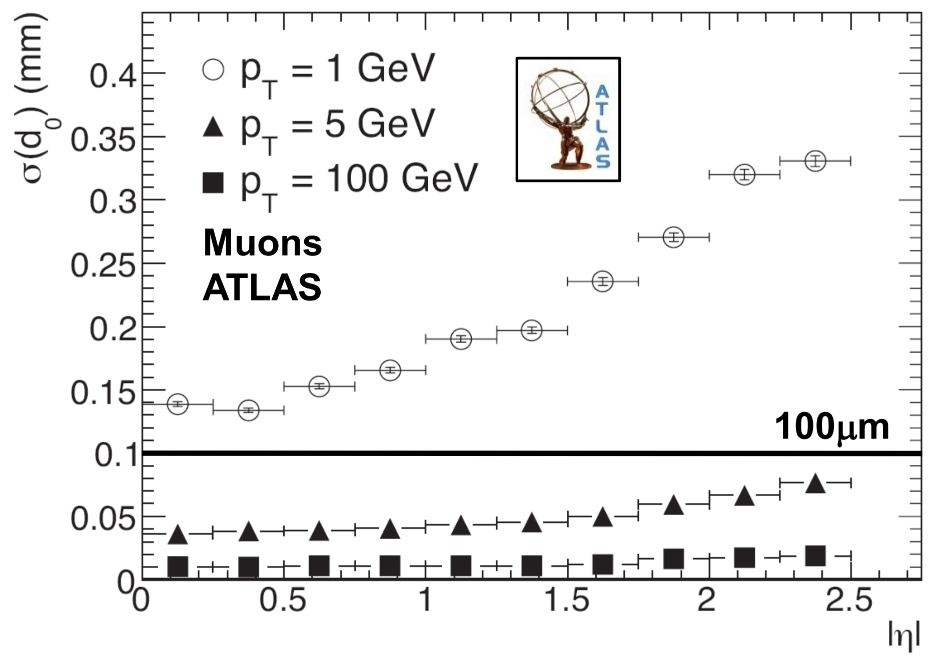


Cosmic Muon Data Taking 2008

- **Global data taking periods with magnetic field in autumn 2008**
- **CMS**: “**C**osmic **R**un **A**t **F**our **T**esla“ aka CRAFT 2008
  ~ 85k / 2.2M tracks in the pixels /strip tracker with magnet on
- **ATLAS**: ~ 190k / 880k tracks with pixel / SCT hits and magnet on
- Can only show approved results here!

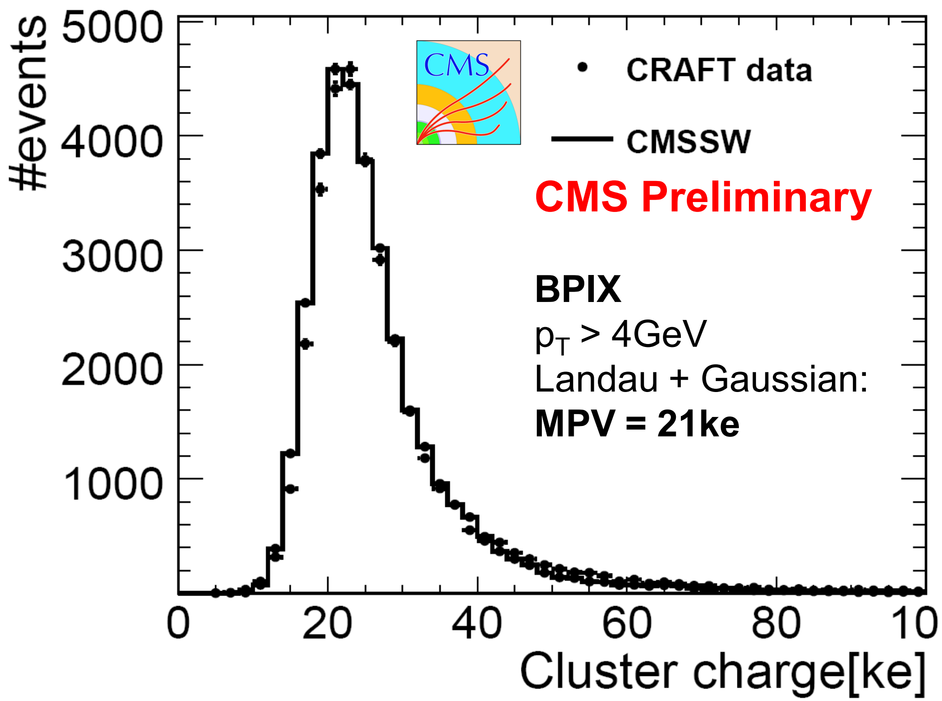
CMS	
Subdetector	Active channels
Pixel barrel	99.1%
Pixel forward	94.0%
Inner Barrel/disks	96.6%
Outer Barrel	98%
End Cap +	99.2%
End Cap -	97.8%

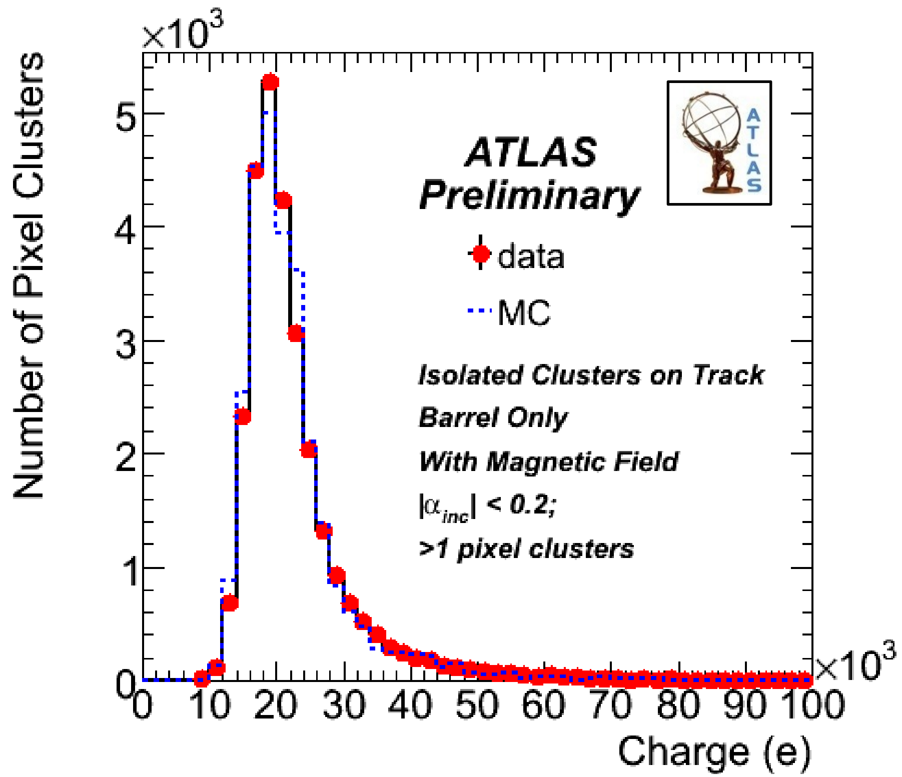
ATLAS	
Subdetector	Active channels
Pixel *	98.5%
SCT barrel	99%
SCT end caps	97%
TRT	98%

* In data taking: barrel 98%, end caps 85%

Pixel Detectors: Cluster Charge

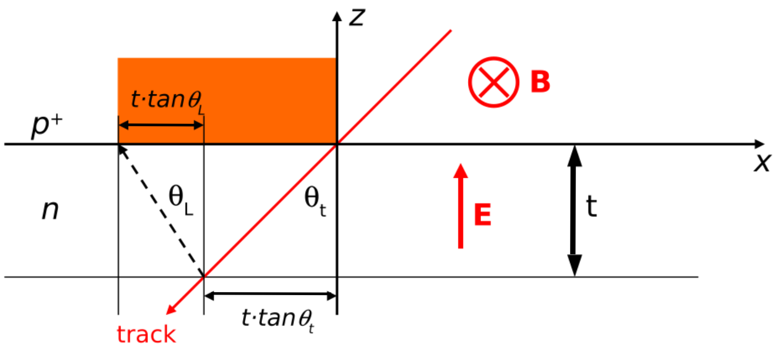
- Charge of on-track clusters
- Correction for track impact angle applied
- Clusters with > 1 pixels

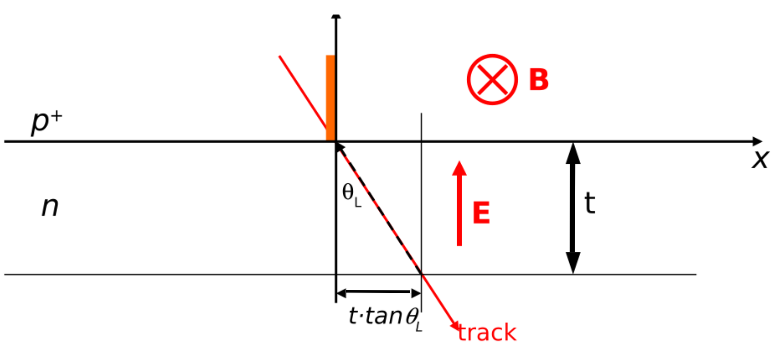


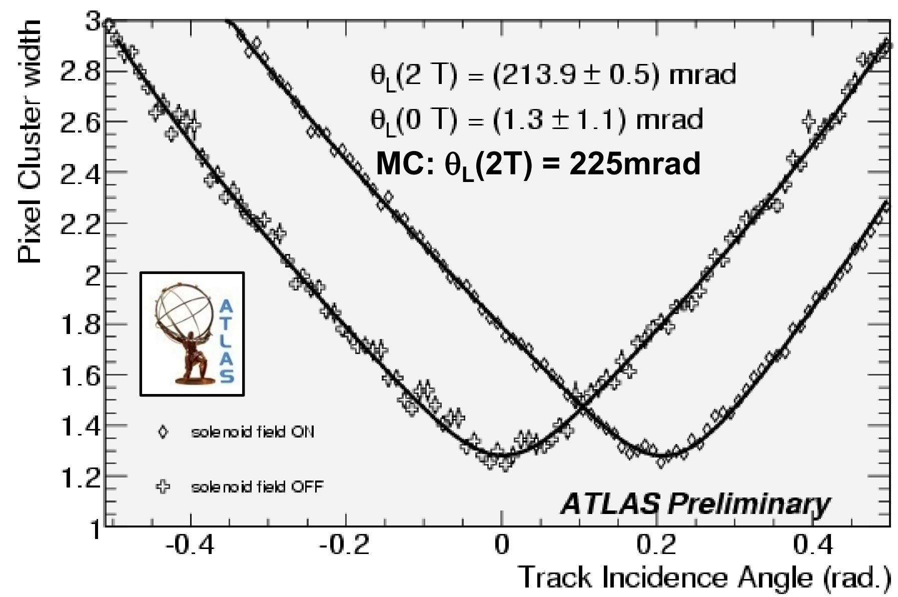


Pixel Detectors: Lorentz Angle

- B = 0 or B || E: charge carriers drift along E direction
- B $\perp$ E (barrel or tilt) $\rightarrow$ charge carriers drift with Lorentz angle θ_L
- Cluster position is shifted ($\rightarrow$ calibration) & broadend ($\rightarrow$ charge sharing)
- Cluster width is minimal for tracks with incident angle = θ_L
- $\tan(\theta_L) = B \cdot \mu_H$; Hall-mobility μ_H(T, V, t, fluence)

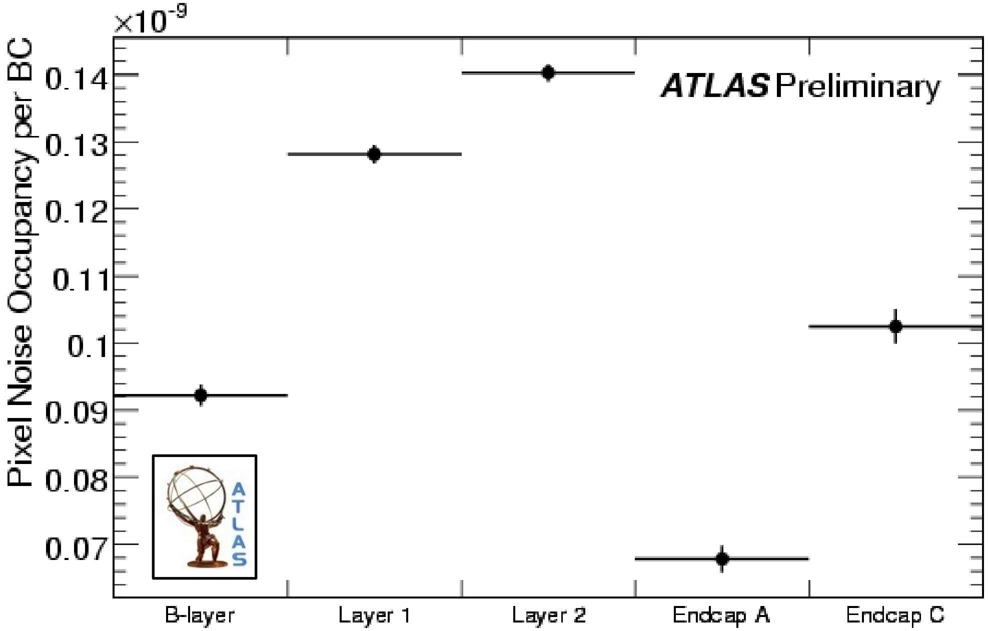






CMS: 24.8° $\pm$ 0.2°$_{stat}$ $\pm$ 0.7°$_{syst}$ observed,
24.3° expected

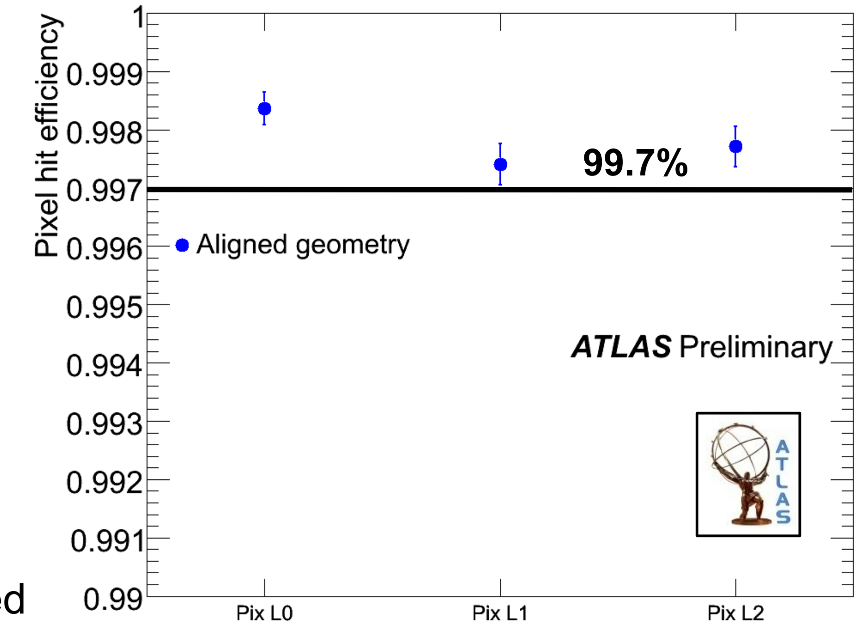
Performance of the ATLAS Pixel Detector



Noise occupancy

After masking of noisy channels ($< 10^{-4}$):

Noise occupancy $\approx 10^{-10}$

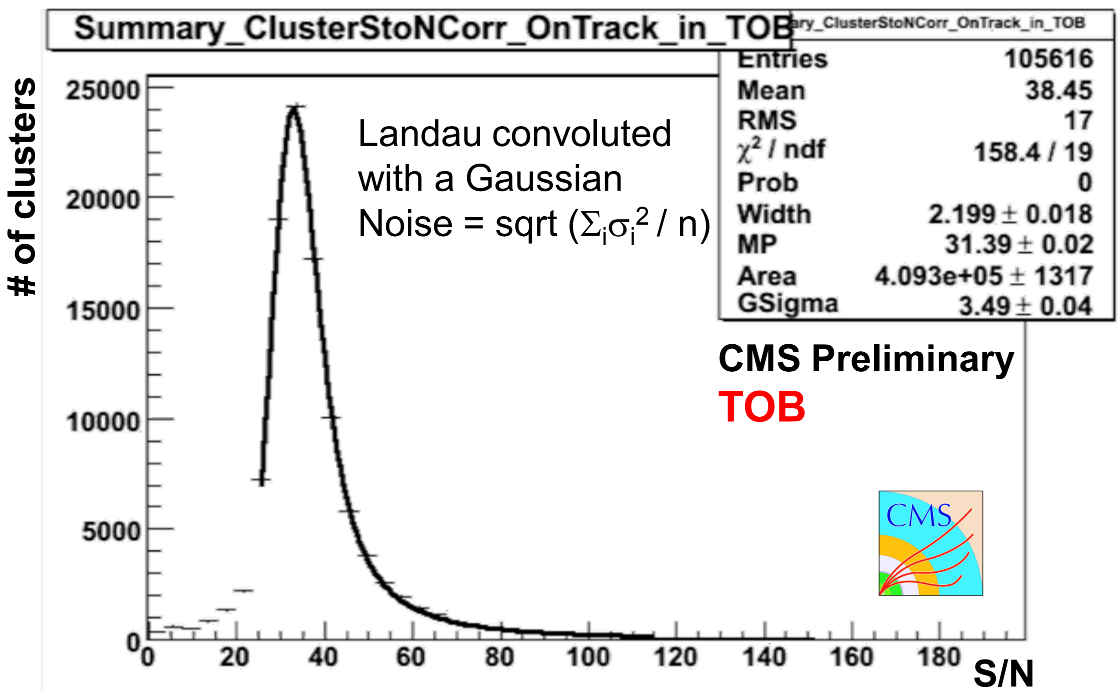


Intrinsic hit efficiency

Faulty modules have been masked

CMS Strip Tracker: Signal-to-Noise Ratio

- Distinguish real clusters from noise (N) by their signal (S) → high S/N desirable
- **Signal charge** depends on traversed length, i.e. sensor thickness and track angle → correction for track incident angle applied
- **Cluster noise N** depends on capacitance, i.e. strip length
- Values guarantee high hit efficiency even after irradiation (30-40% loss expected)

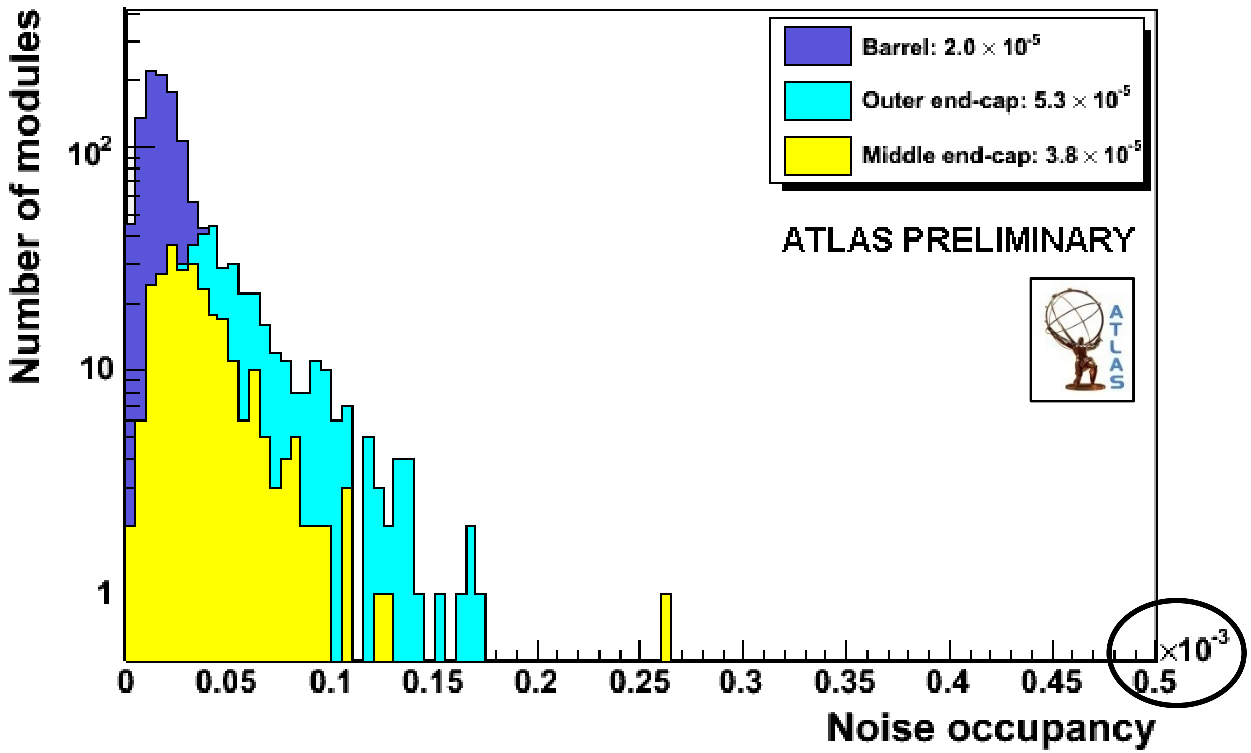


Subdetector	S/N MPV *
TOB (500μm)	32
TEC (500μm)	32
TIB (320μm)	25
TID (320μm)	28
TEC (320μm)	27

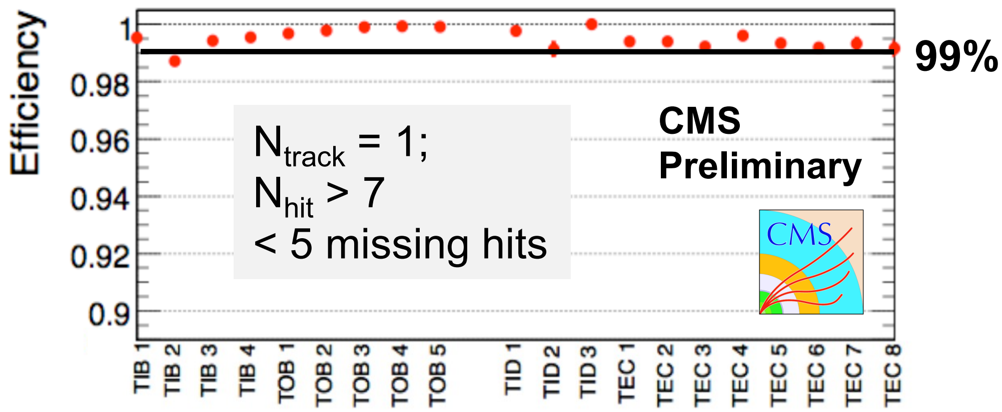
* in peak read-out mode

ATLAS SCT: Noise Occupancy

- Signal charge not measured with binary readout → noise occupancy should be small
- Specification **after** irradiation: 0.5 x 10^{-3}
- Note: noise in DMILL chips increases with irradiation

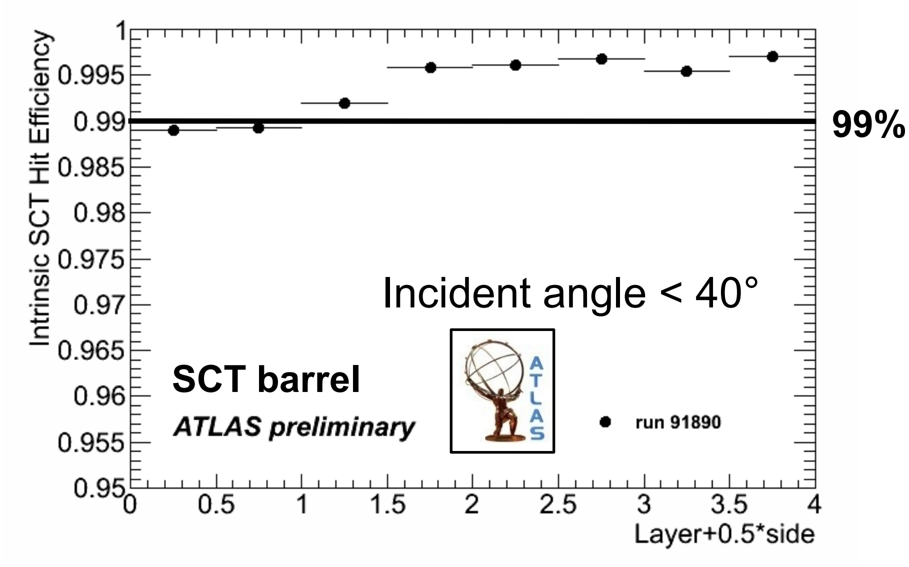


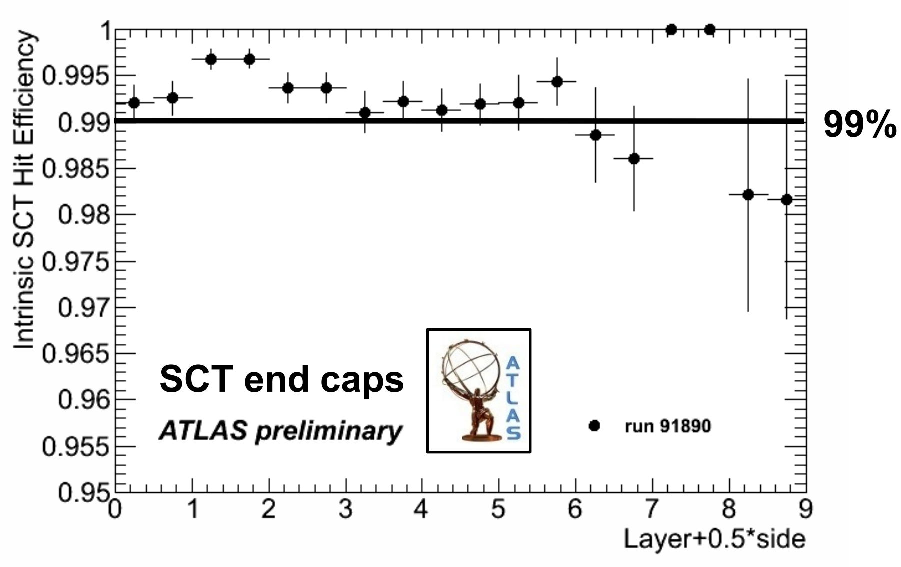
Hit Efficiency in Strip Trackers



Hit efficiency per layer

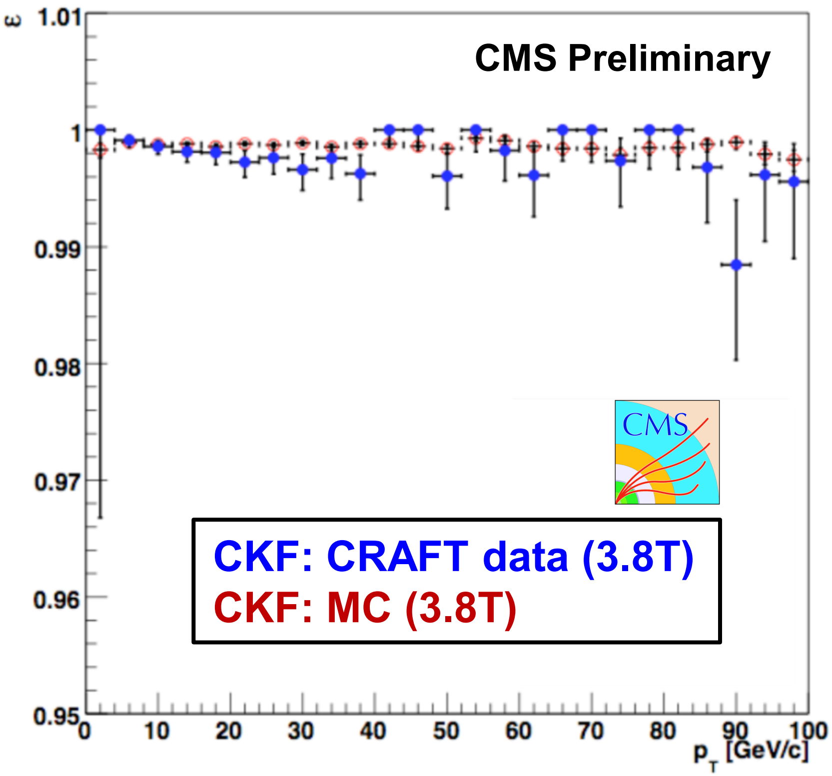
- Layer under study excl. from tracking
- Faulty modules are masked





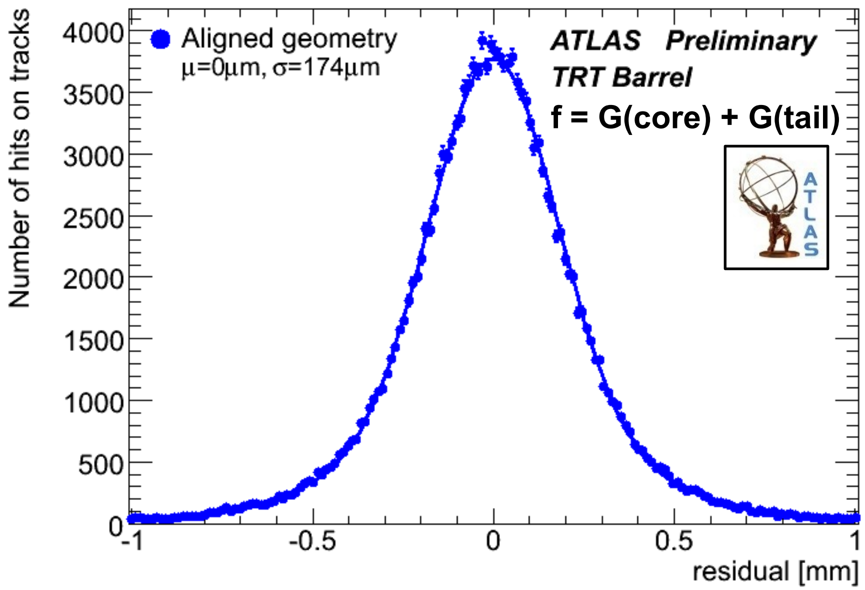
Track Finding Efficiency in CMS Strip Tracker

- Tracks reconstructed in muon drift tube chambers (“tag & probe“)
- pp-like topology: $|d_{xy}| < 30$cm, $|d_z| < 30$cm, $|\eta| < 1.0$, $0.5 < |\phi| < 2.5$



Efficiency [%]	Data	MC
Combinatorial Kalman Filter (CKF) default for pp	**99.5±0.1**	99.9±0.1
Cosmic Track Finder (CosmicTF)	**99.3±0.1**	99.7±0.1

Performance of the ATLAS TRT



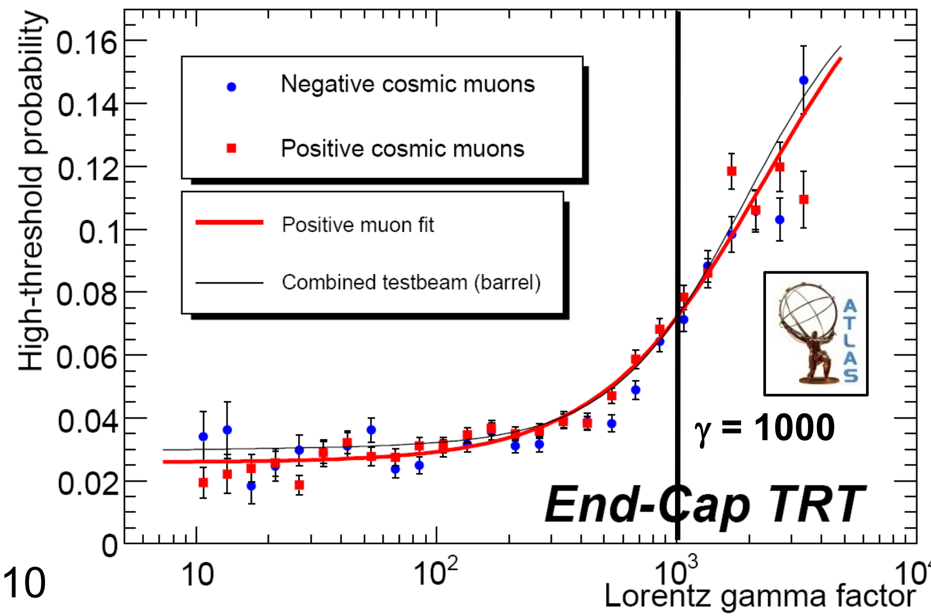
Spatial resolution in barrel

- Single track events with # TRT hits ≥ 45
- d_0 < 10cm

⇒ **σ = 174μm after alignment**

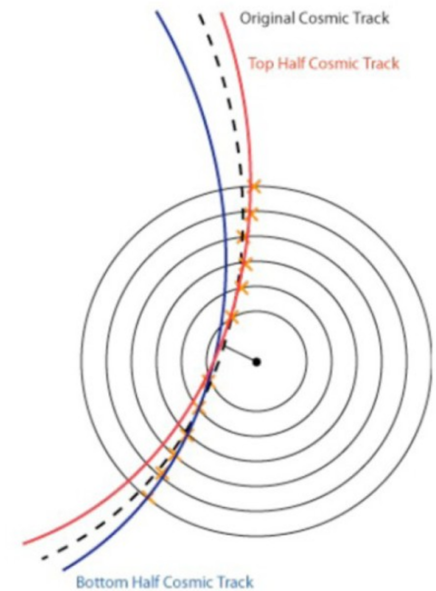
Transition radiation in end cap

- Rise of high-threshold probability signals onset of TR
- Similar result for barrel
- #TRT hits ≥ 20, #SCT hits ≥ 4, χ^2/ndf < 10

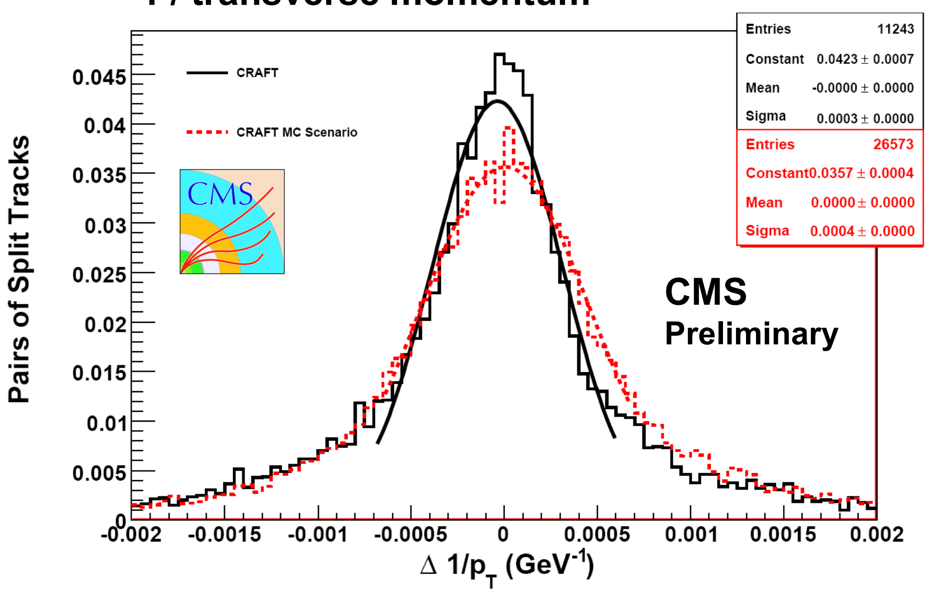


CMS Track Parameter Resolution

- Tracks split at point of closest approach
- Legs are fit separately and track parameters are compared
- Resolution from residuals, defined as $\delta x = x_1 - x_2 / \sqrt{2}$
- CKF, p_T > 4GeV, χ^2/ndf < 10, N_{BPIX} > 5, $N_{double\text{-}sided}$ > 1
- Aligned tracks are used, with Alignment Position Errors tuned to give Gaussian residual distributions



1 / transverse momentum



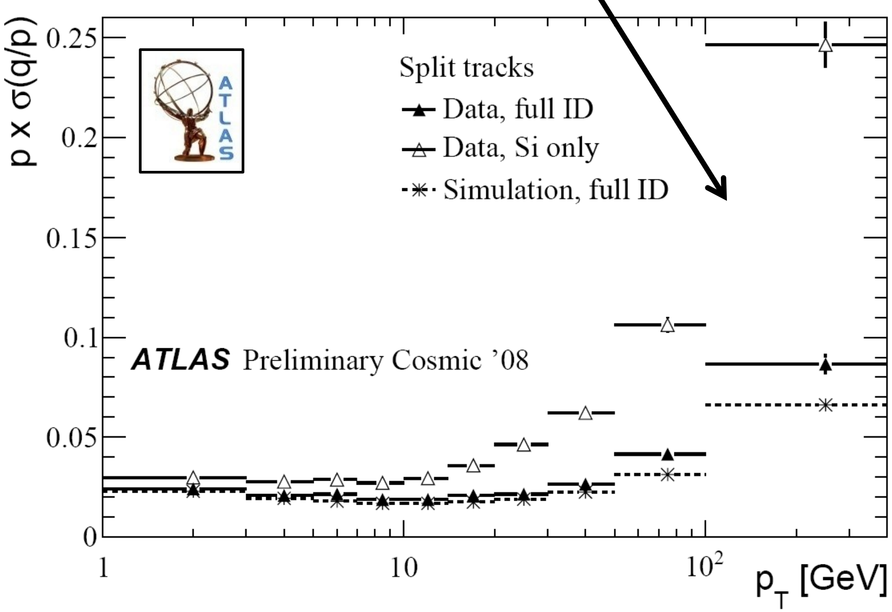
Track par.	σ
p_T	96MeV
d_{xy}	29μm
d_z	53μm
ϕ	0.21mrad
θ	0.63mrad

ATLAS Track Parameter Resolution

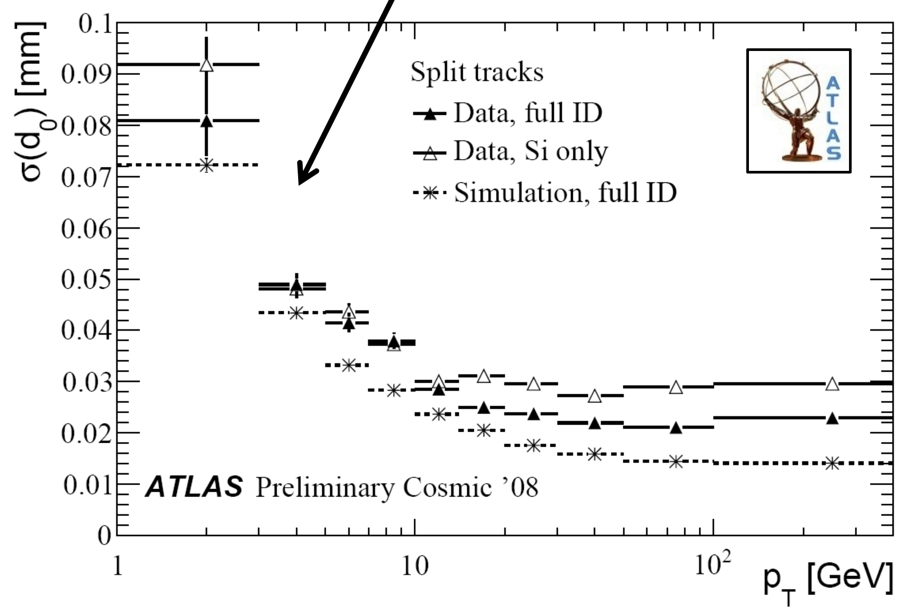
- Same method: split tracks
- Aligned tracks are used
- Difference to MC: remaining misalignment

pixel barrel hits ≥ 2
SCT barrel hits ≥ 6
TRT hits ≥ 25
$|d_0| < 4$cm
$p_T \geq$ 1GeV
In-time events

TRT extends lever arm



Multiple scattering



Status of the CMS Tracker

- **Main problems in 2008:**
  - C_6F_{14} cooling system was (very) leaky → major refurbishment: leak search, replacement of poor quality pipes, valves & manifolds etc.
  - FPIX: 1 high voltage short (cracked insulation) & 1 low voltage short (bad contact) FPIX has been extracted and repaired; 94% → 99% working channels
- **Commissioning has started several weeks ago**
- Cooling temperature of +4°C for 2009/2010 running established
- **Number of working channels:**
  - Pixel detector: BPIX 99%, FPIX > 97.5%
  - Strips: similar to or better than 2008, except TIB: one TIB cooling loop disconnected due to leak → 45 modules lost
- **CRAFT 09 starts mid July**

Status of the ATLAS Tracker

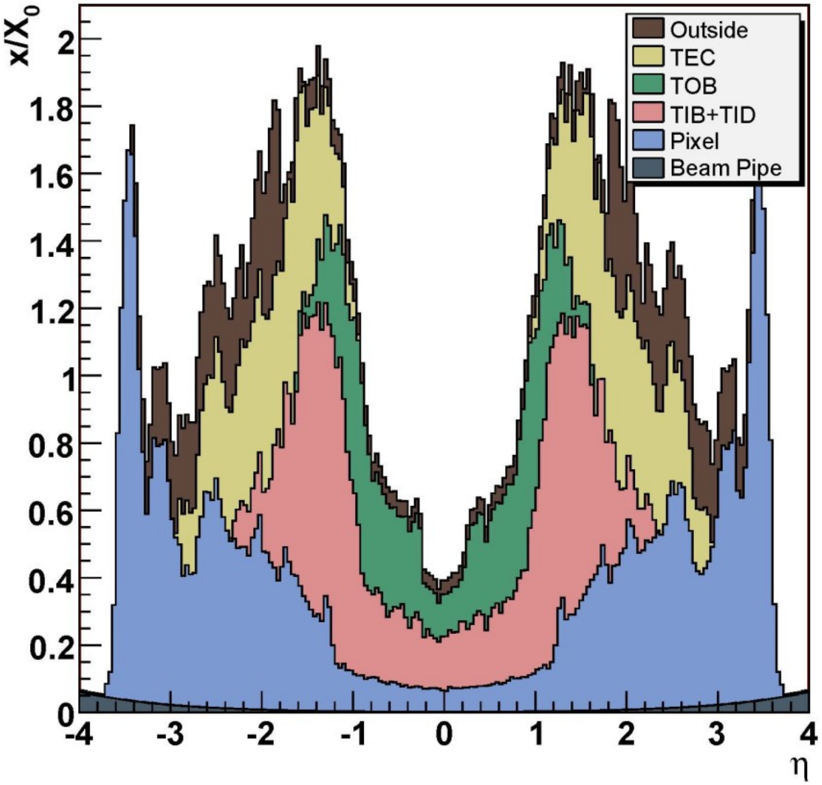
- **Main problems in 2008:**
  - Cooling system: 3 out of 6 compressors failed, 100kg C_3F_8 lost
    $\rightarrow$ repeared and operational since August 2008
  - Optical link: off-detector transeiver modules (TX) suffered from ESD during production, high failure rate $\rightarrow$ replacement from new production batch possible
- **Number of working channels:**
  - SCT: “The expectation for 2009 is that 99% of all 4088 modules will be working.“
  - TRT: “as 2008“ = 98%
  - Pixel detector: “expect 98.5% operational“
- **Commissioning and cosmic data taking is ongoing**

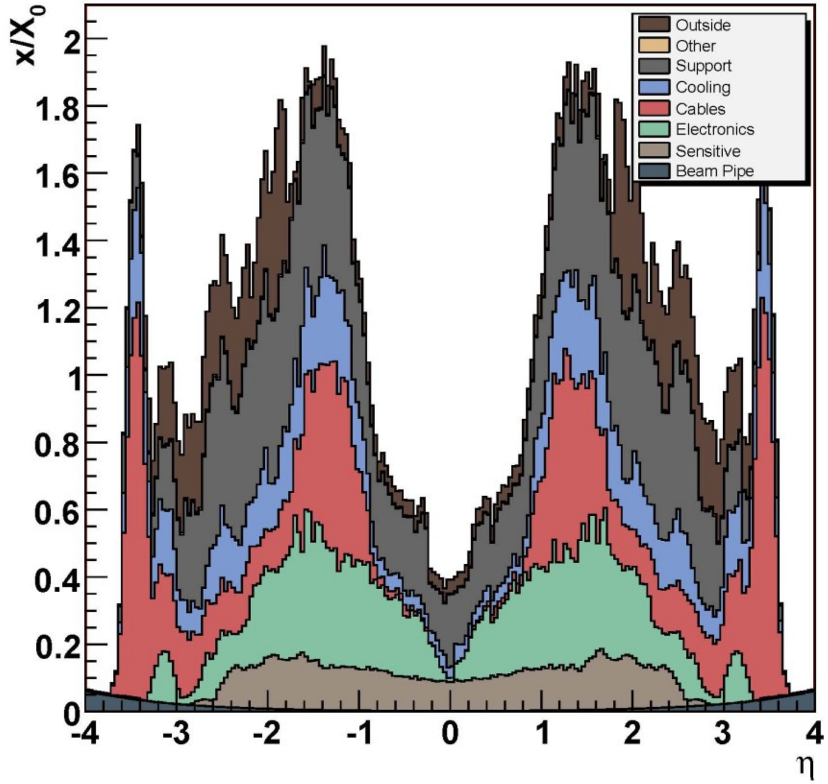
Summary

- The ATLAS & CMS trackers are complex instruments, designed to measure the particle trajectories with high precision in a challenging environment
- The performance with cosmics is being studied and preliminary results are promising
- Both trackers are on-track for running with beam in autumn 2009

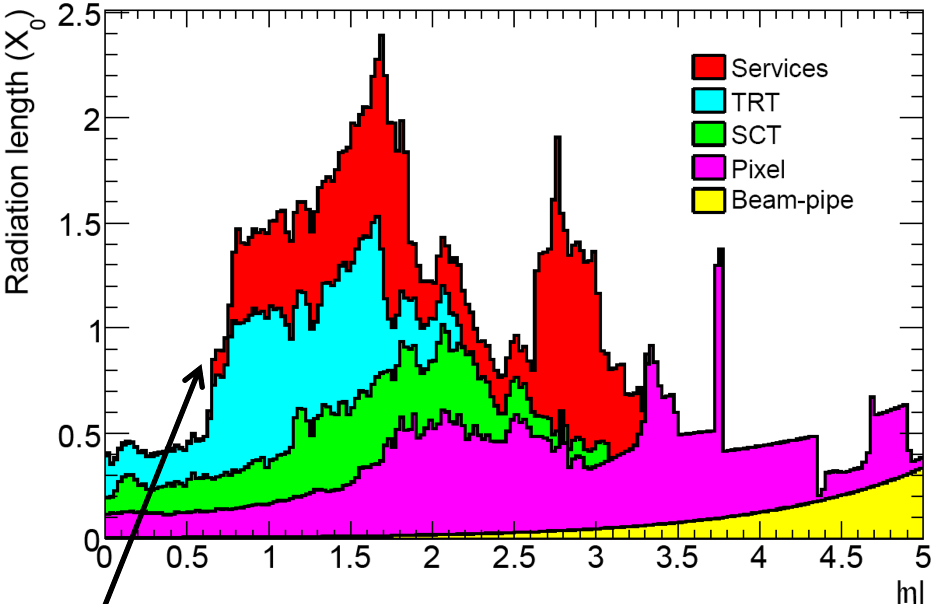
Back-up

CMS Tracker Material Budget (X_0)



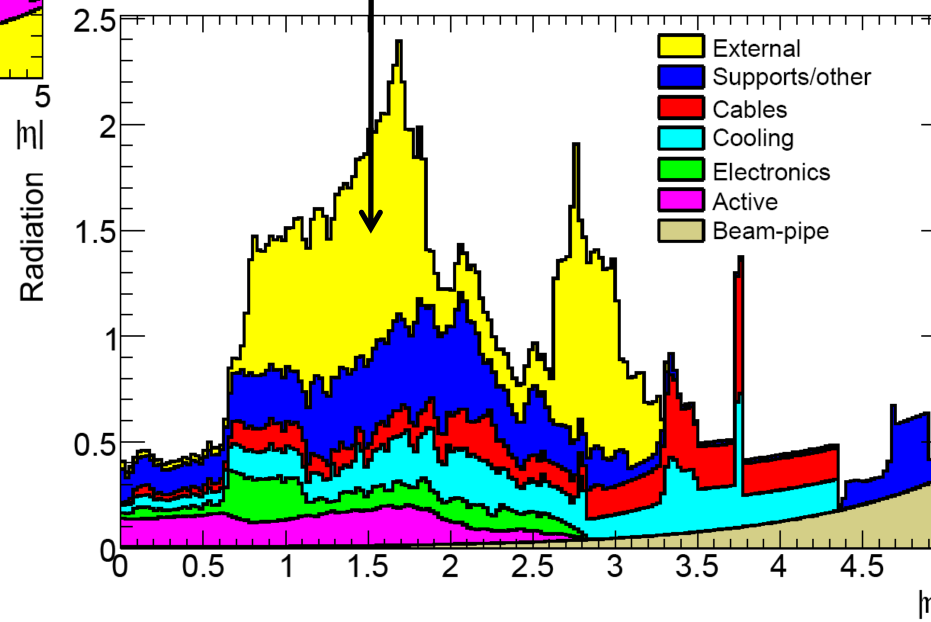


Atlas Tracker Material Budget (X_0)



Step at interface between barrel & end caps

"External": outside of inner detector envelope → degrades "only" ECAL



CMS Cosmic Run at Four Tesla (CRAFT)