Performance of the CMS Pixel detector for the Phase 1 upgrade at HL-LHC

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PSD9, Aberystwyth
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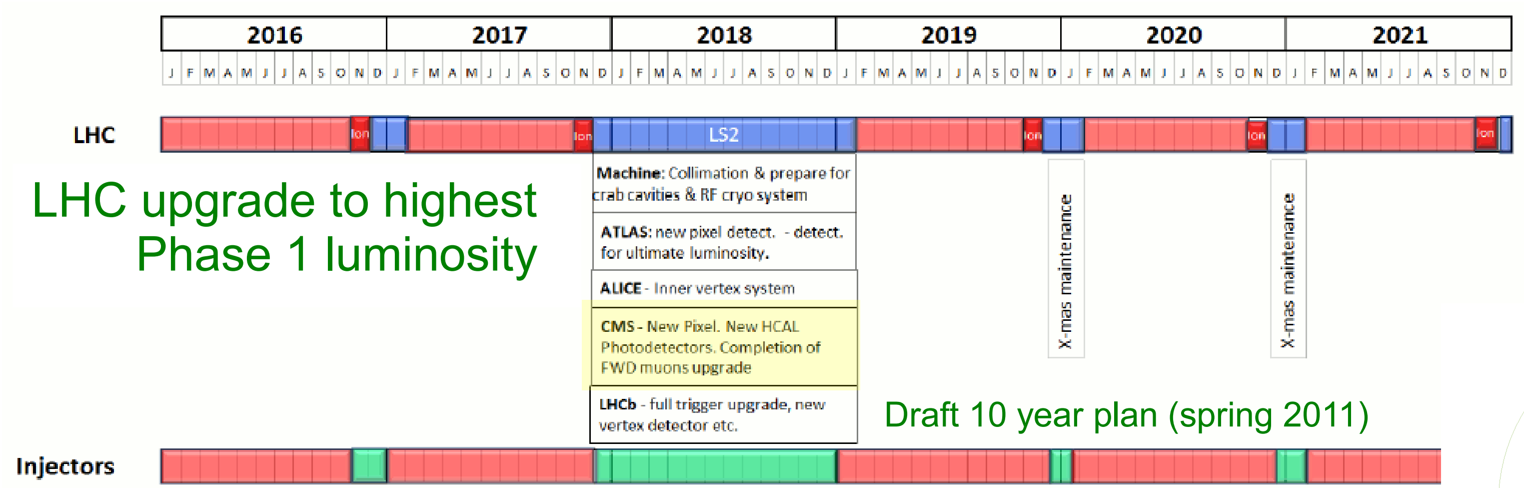
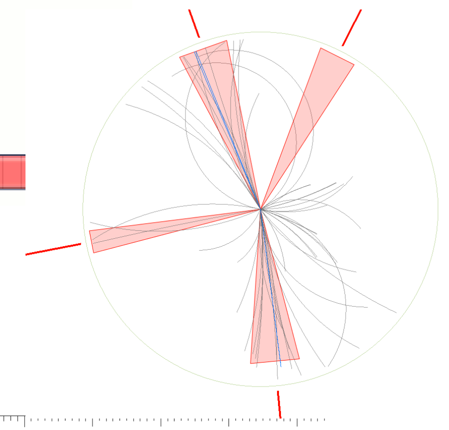
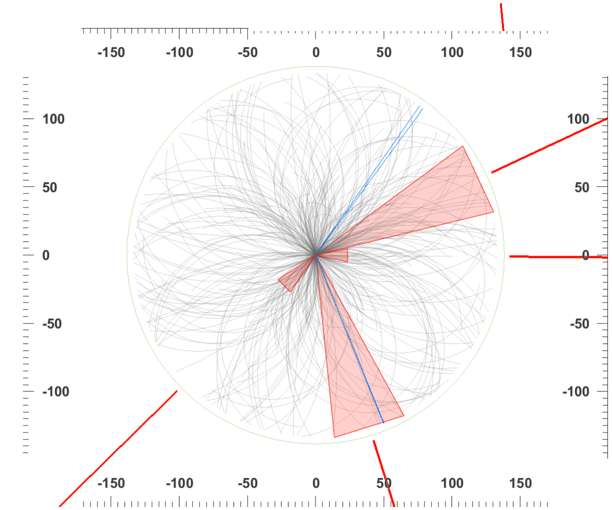
HL-LHC: implications for the CMS pixel system





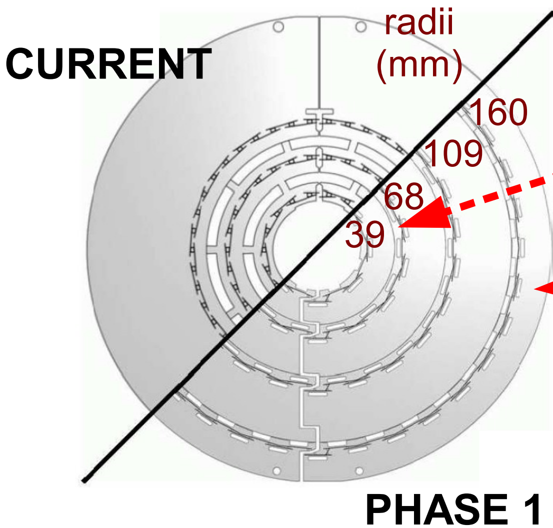
The current pixel detector was not designed to operate with luminosities of $\mathbf{2 \times 10^{34}\ cm^{-2}\ s^{-1}}$ and above –

- High occupancy in very dense tracking environment affects pattern recognition capabilities
- Severe limitations due to ROC dead time
- Radiation damage
- Geometric acceptance and amount of material can be improved



→ New detector design to keep high efficiency and good track seeding / b-tagging performance

The Phase 1 upgrade of the CMS pixel detector



Completely new and enhanced pixel system –

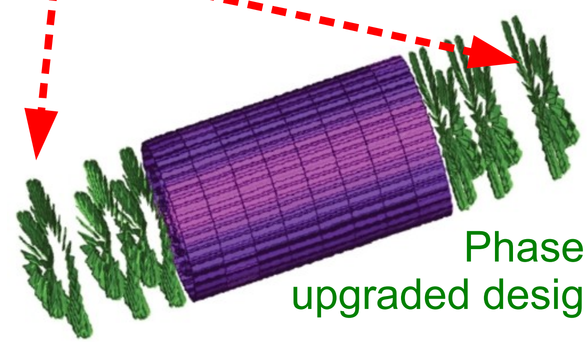
Radius of **innermost barrel layer** reduced from 44 to **39 mm** (34 mm being considered)

Additional **4th barrel layer** (r = 160 mm)

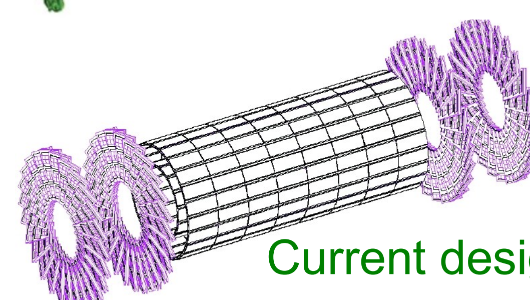
Additional **3rd end cap disk** on either side (z = ± 516 mm)

} good 4-hit coverage over the whole acceptance

→ Total of 1856 modules with ~125 M channels (~ **1.9 × current system**)



Phase1 upgraded design



Current design

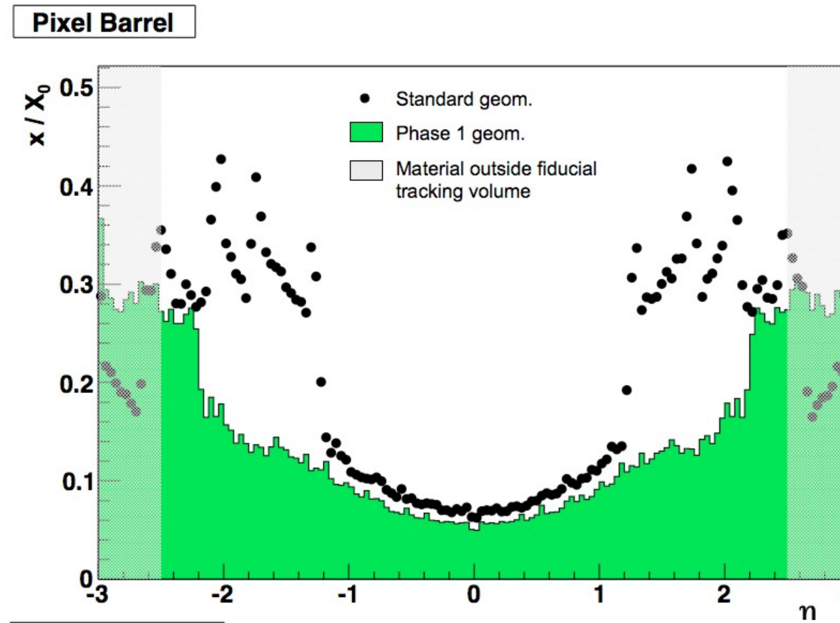
Constraints & requirements –

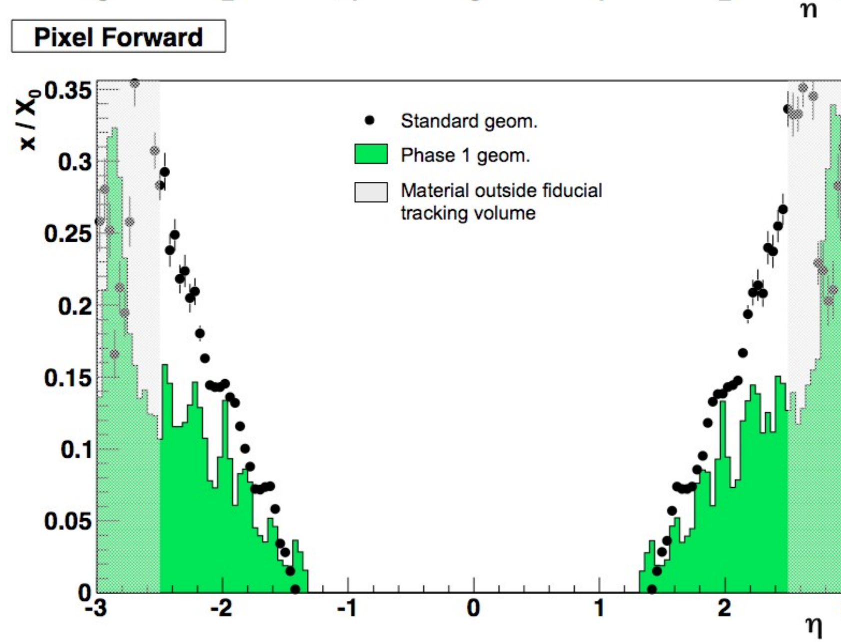
- Re-use current services, cabling and fibers due to space restrictions
- Amount of material in the detector must not increase

Phase 1 Pixel Detector: material budget

Strong reduction of material budget despite additional instrumentation –

- New ultra-light support structure (carbon fiber / Airex)
- Electronics services partially moved outside the tracking volume
- 2-phase CO_2 cooling system
- DC-DC conversion powering scheme
  → more components can use current cables
- New beam pipe: smaller radius (planned)





Phase 1 Pixel Detector: ROCs & sensors

New ROCs under design –

- Larger data buffers account for higher occupancy
- Digital readout with on-chip ADC (320 Mbps mplexed) – **3 x faster** on same fibers
- Buffered readout allows simultaneous read/write – reduced dead time:

Current detector

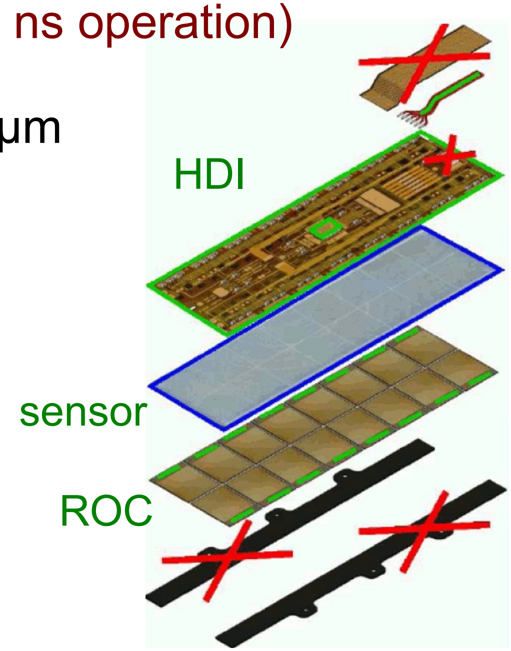
Subdet	% loss 25 ns	% loss 50 ns
BPIX1	16	50
BPIX2	5.8	18.2
BPIX3	3.0	9.3
-	-	-
FPIX	3.0	9.3

Upgraded detector

Subdet	% loss 25 ns	% loss 50 ns
BPIX1	4.7	9.4
BPIX2	1.5	3.1
BPIX3	0.6	1.2
BPIX4	0.28	0.59
FPIX	0.6	1.2

$\mathscr{L} = 2 \times 10^{34}\ cm^{-2}\ s^{-1}$: data loss / dead time on inner barrel layer reduced by 70% (25 ns operation)

- ROCs in barrel layers 1,2 thinned to 75 μm, all others 200 μm
- New micro-twisted pair cables (ROCs → optohybrids)



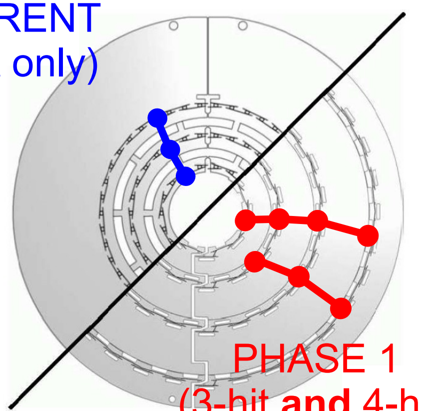
Sensor / module design similar to the current one –

- Same n^+-on-n technology and 100×150 μm pixel size
- Sensor material yet to be decided
- Only one single module type with 2×8 ROCs

Phase 1 pixel performance: studies & expectations

Simulation studies with highest Phase 1 luminosities –

- $\mathscr{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$: expect about **50 "soft" interactions** (pile-up) **superposed** on the signal events → very high hit & track density



Phase 1: upgrading to 4-hit seeds –

- **Lower fake seed rate** due to additional hit constraint
- Use 3-hit **and** 4-hit seeds in a multi-step iterative tracking: **higher efficiency** due to better redundancy
- Shorter extrapolation distance to strip detector: more precise track parameter estimates

Further improvements expected from lesser amount of material –

- Better track parameter estimates
- Improved electron track reconstruction

} Due to reduced secondary interactions

Taking into account reduced data loss in upgraded detector –

- Due to new ROC design (s. previous slide)

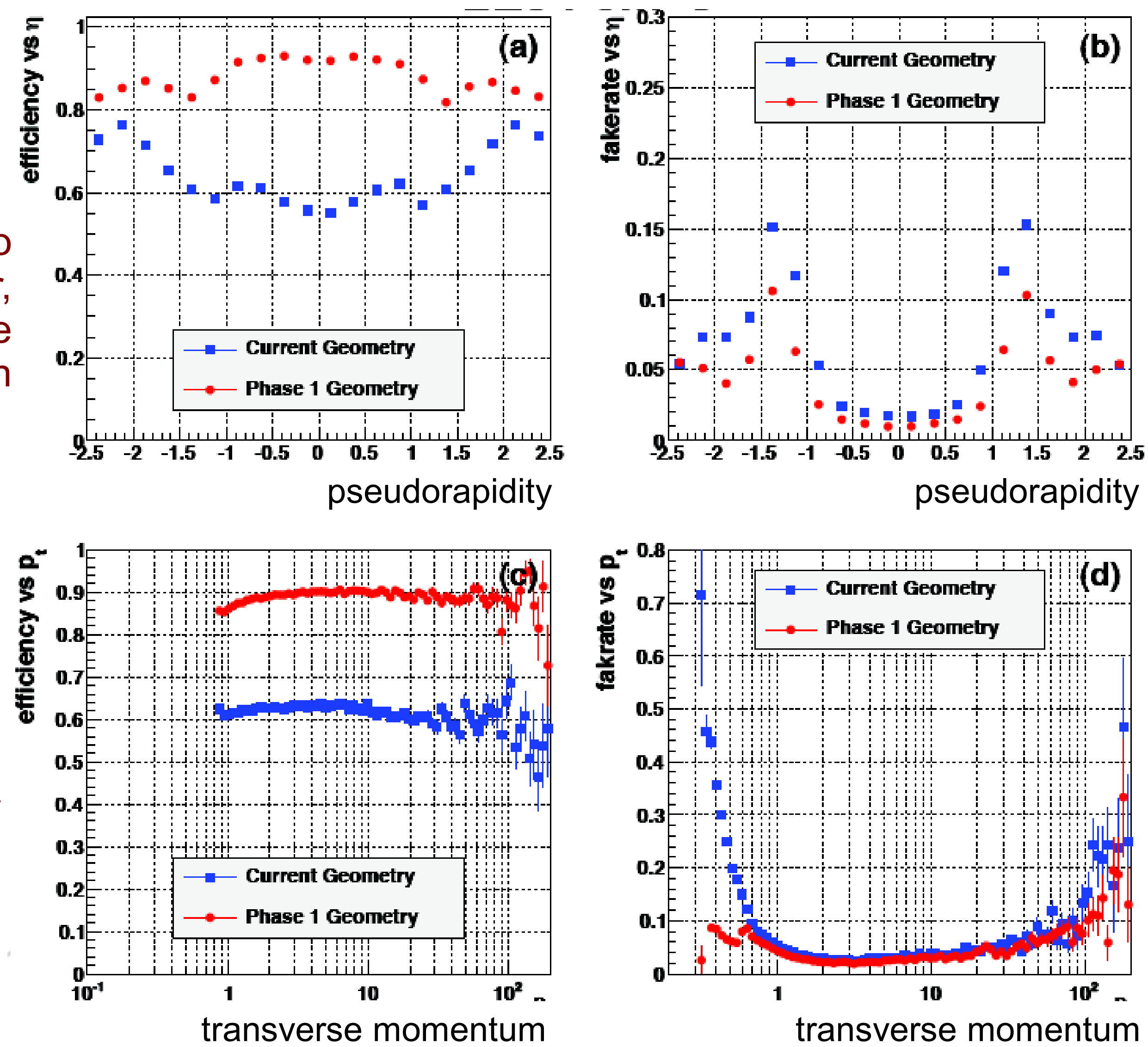
Tracking efficiency

- all-silicon iterative (multi-step) track reconstruction -

ttbar, high luminosity (2×10^{34} cm^{-2} s^{-1})

Efficiency up to 50% higher, particularly in the central region

Lower fake track rate, particularly in forward and transition region



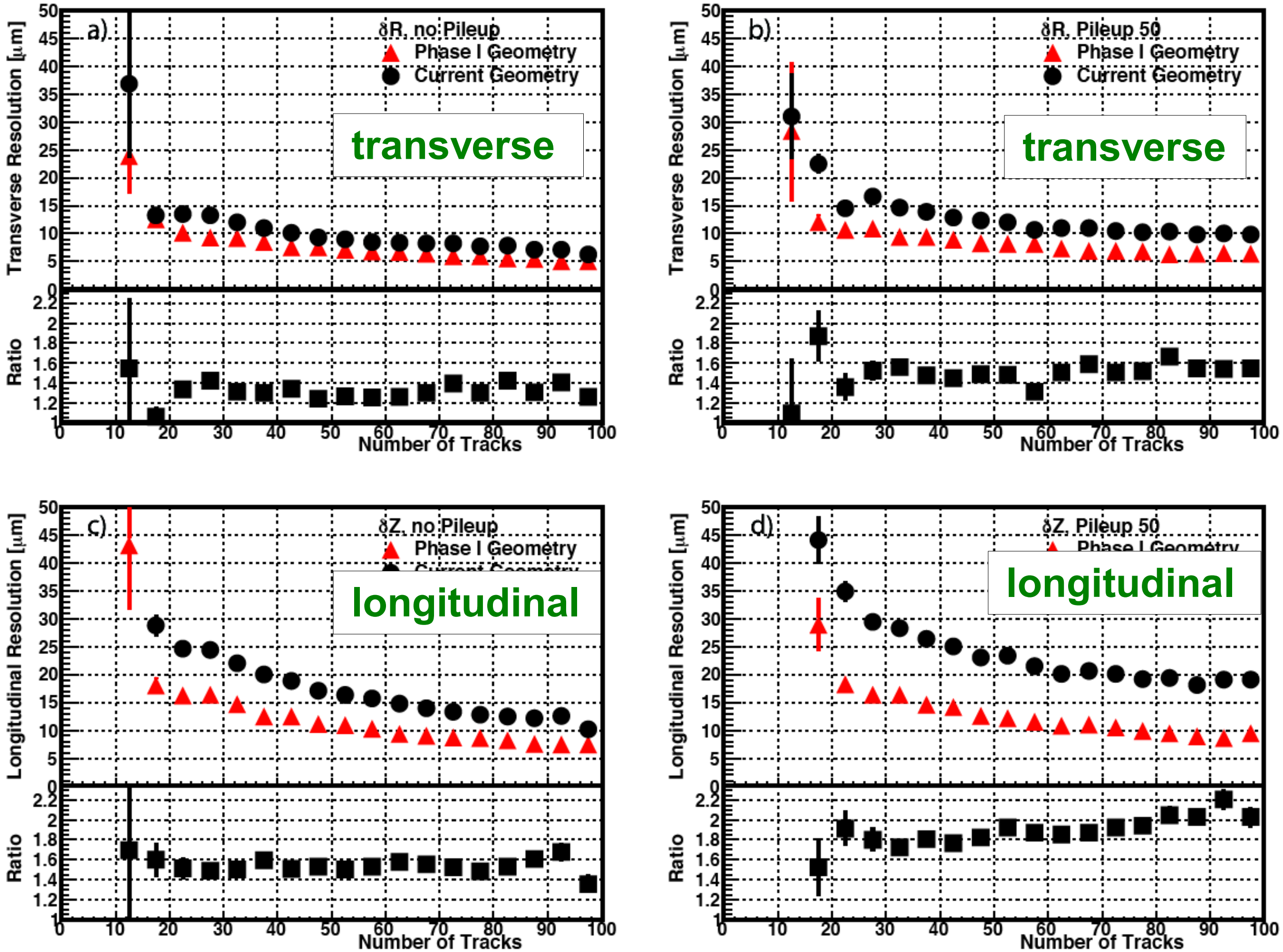
Higher efficiency over whole range of momentum

Strongest improvement in low momentum range

Primary vertex resolution

low luminosity

high luminosity ($2x10^{34}$ cm^{-2} s^{-1})



Important quantity for –

- Identification/resolution of multiple interactions
- Lifetime measurements (b-tagging)

~ 50% improvement

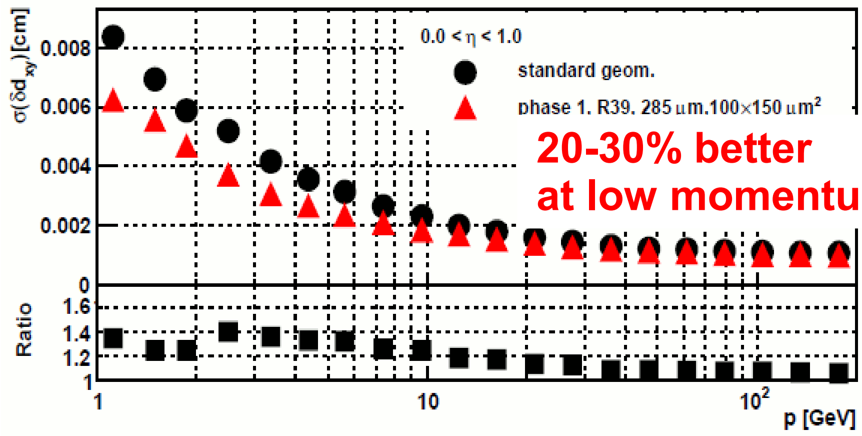
Strong improvement with upgraded detector –

- Similar results for secondary vertices

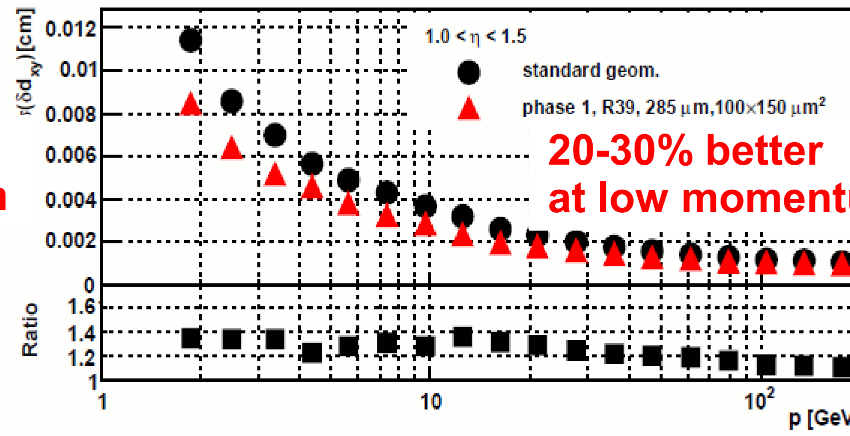
> 60% improvement

Track impact parameter resolution

Transverse impact parameter



20-30% better at low momentum

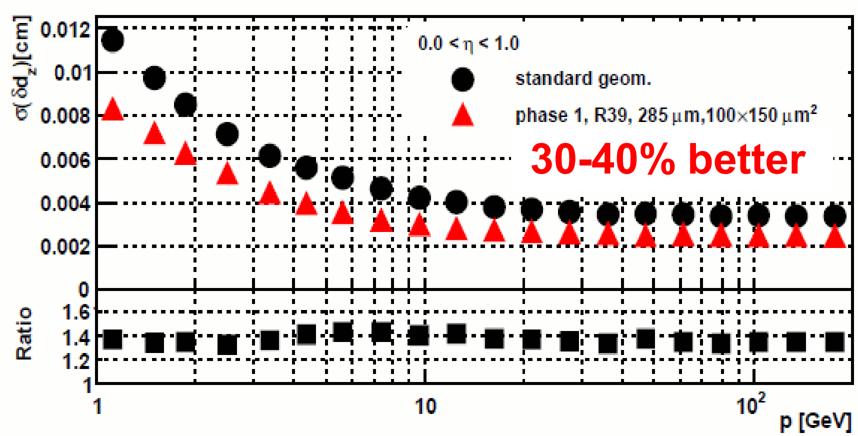


20-30% better at low momentum

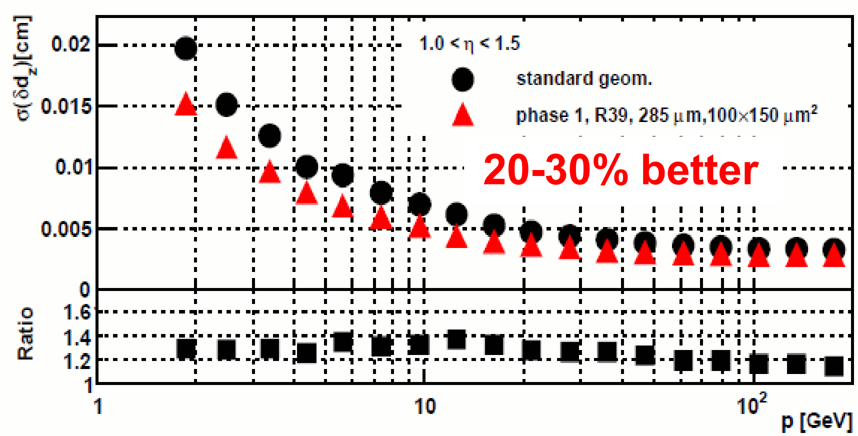
$0.0 < \eta < 1.0$ (central barrel)

$1.0 < \eta < 1.5$ (forward barrel)

Longitudinal impact parameter



30-40% better



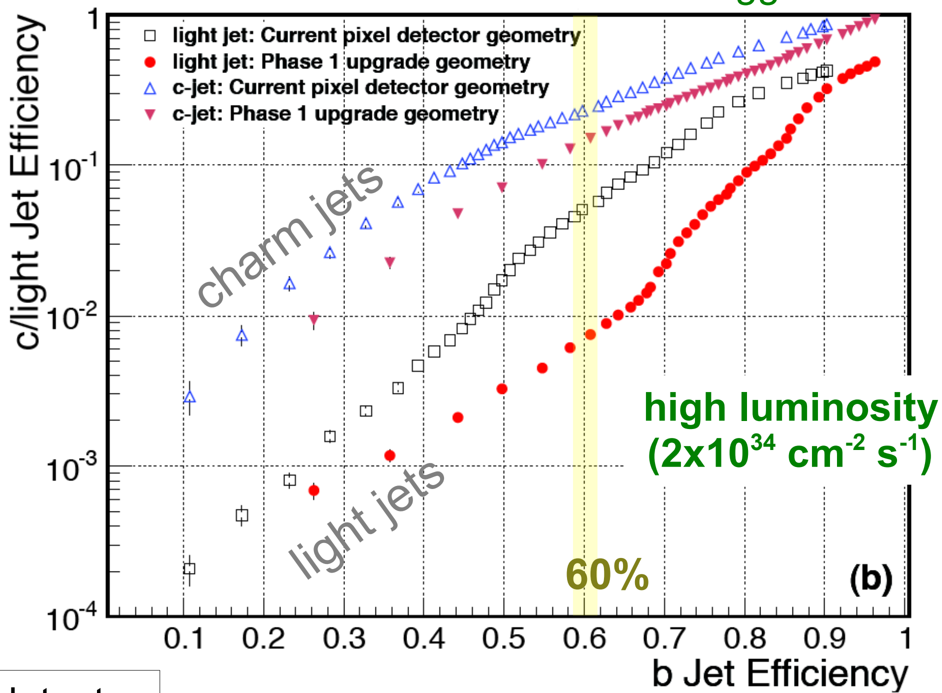
20-30% better

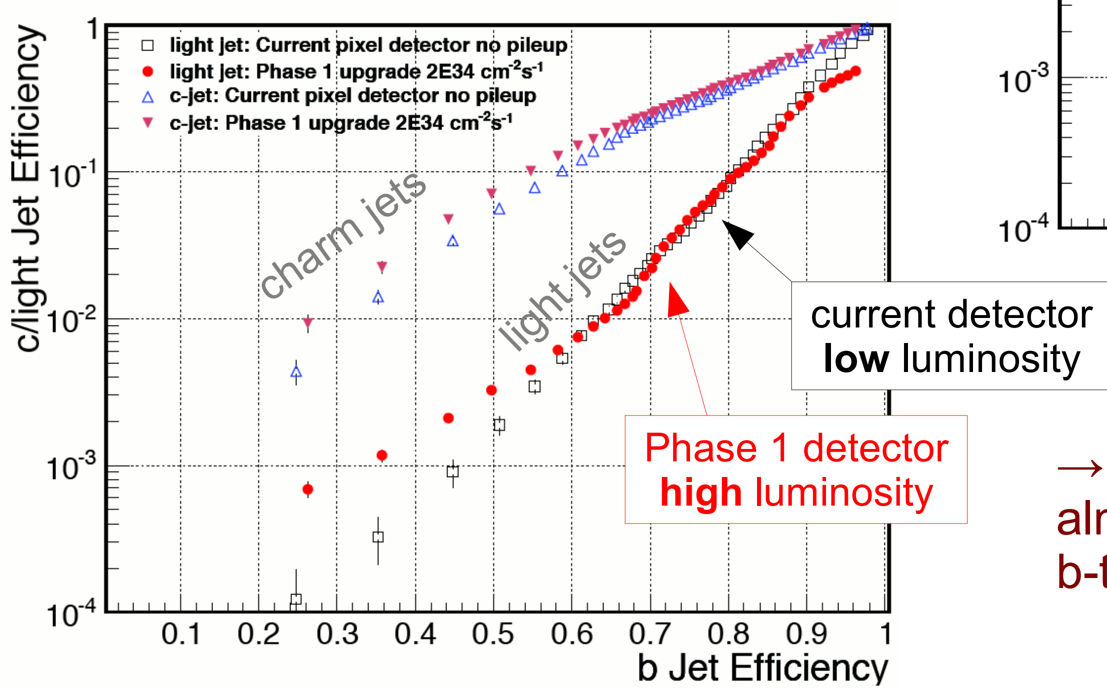
B-tagging performance

Expect degraded b-tagging performance with high luminosity –

- Essential for processes involving b / τ – key feature for new physics searches
- Phase 1 design performs much better than current detector
- e.g. mistag probability 6 times smaller for 60% tagging efficiency (light jets)

ttbar / combined sec. vertex tagger



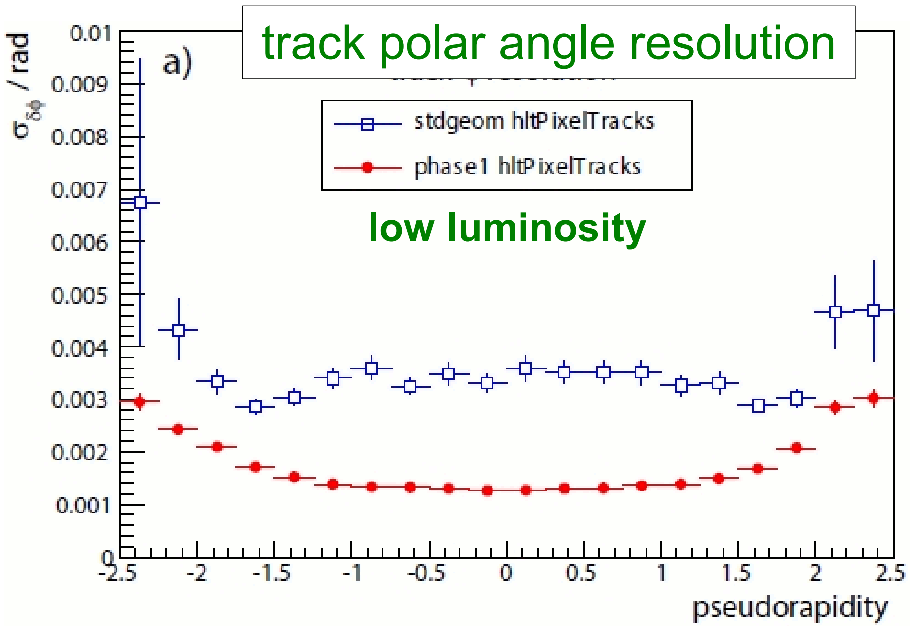


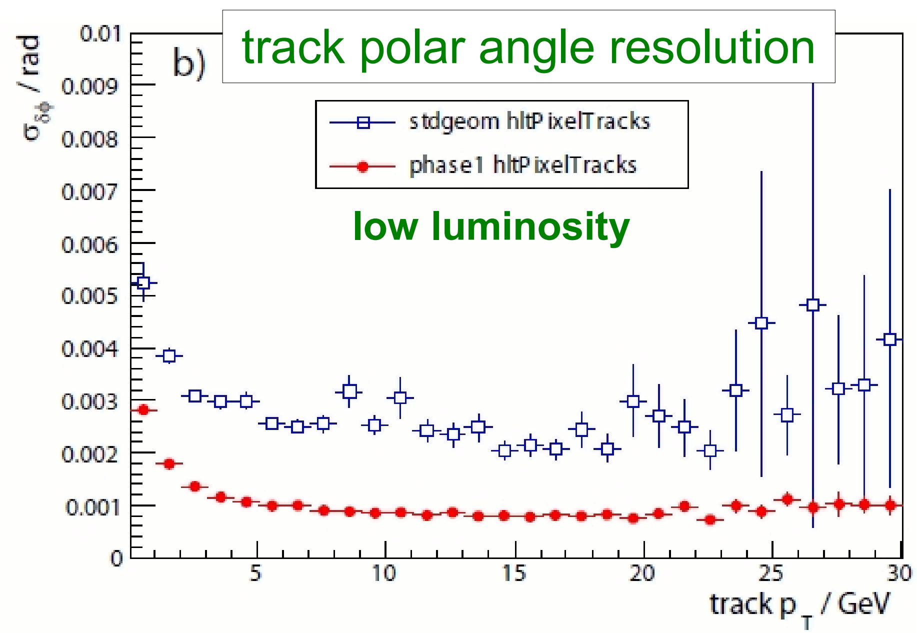
→ The upgraded detector can almost fully compensate for HL b-tagging performance degradation

Pixel-only tracking performance

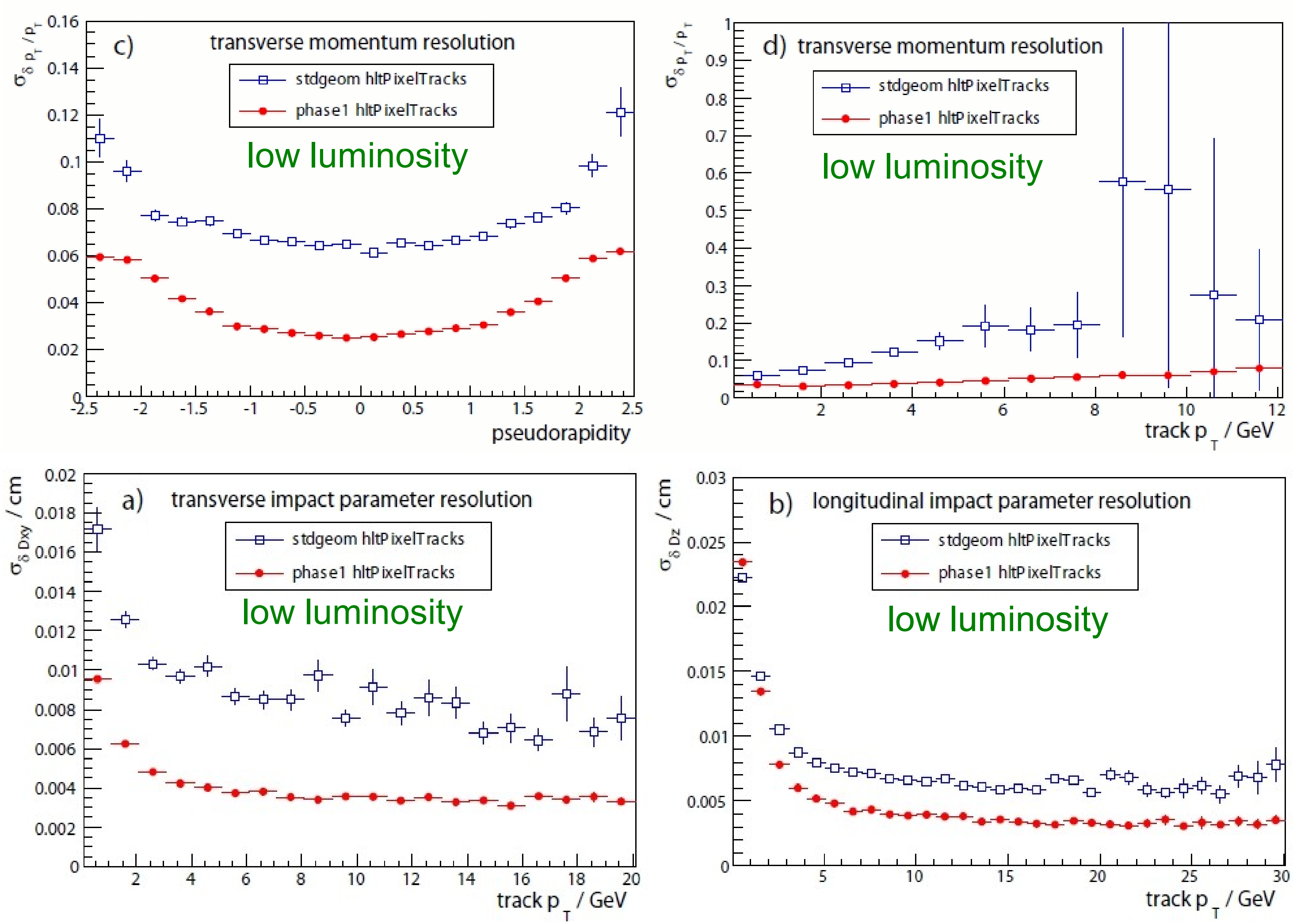
Pixel-only tracks play an important part in the event reconstruction –

- **Pixel-ony tracks**: reconstructed from hits in the pixel detector only
- Used for initial vertexing during track reconstruction / b-tagging in HLT
- **Drastic improvement** in track quality due to additional instrumentation
- Yet only studied in low luminosity environment (no multiple collisions)





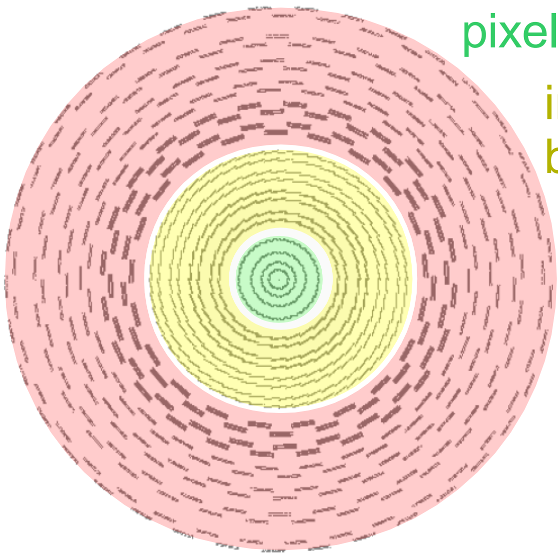
Pixel-only tracking performance



Transverse momentum: overall improvement in resolution by a factor of ~ 2

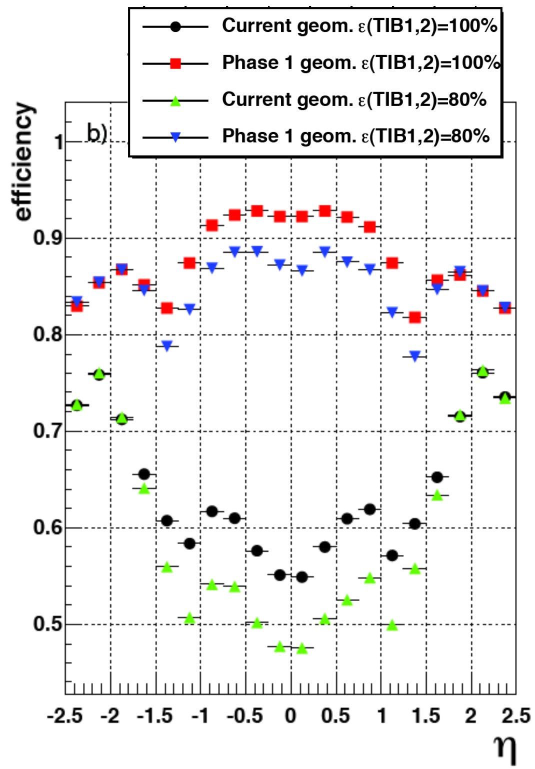
Impact parameters: important for initial vertex finding and future b-tag triggers

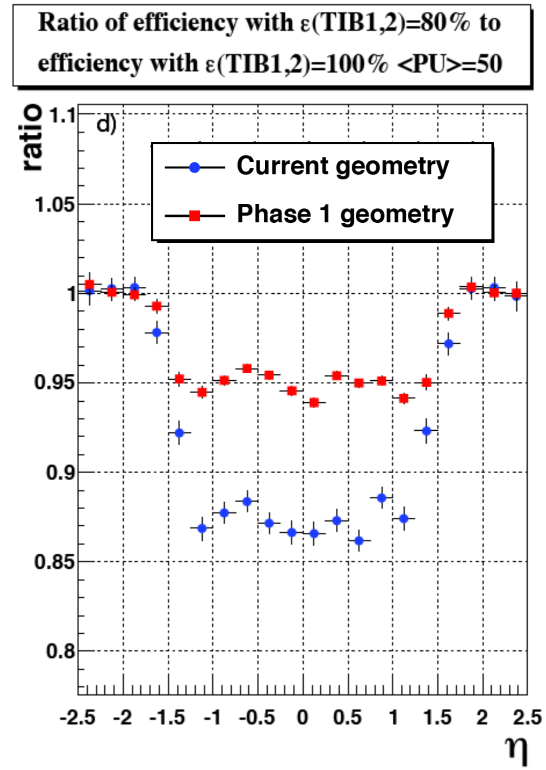
Recovery of strip tracker inefficiencies



Enhanced pixel detector could recover possible inefficiencies in the strip detector –

- Studies with degraded inner barrel performance: simulate 20% hit inefficiency in innermost 2 layers





Overall tracking efficiency degraded –

- **13%** with current pixel system
- Only **5%** with upgraded system

→ Additional pixel barrel layer can partially compensate for strip detector inefficiencies

Summary & Outlook

New CMS Pixel detector design for high luminosity operation –

- Additional barrel layer and end cap disks: 4-hit-seeding
- Significantly less material in tracking volume: improved track quality
- New ROC design with buffered digital readout: better efficiency with high luminosity

Improvements in tracking and vertexing –

- Higher track finding efficiency, better vertex (up to 50%) and track impact parameter (20-30%) resolutions

Better b-tagging performance –

- New detector can maintain efficient b-tagging with high luminosity

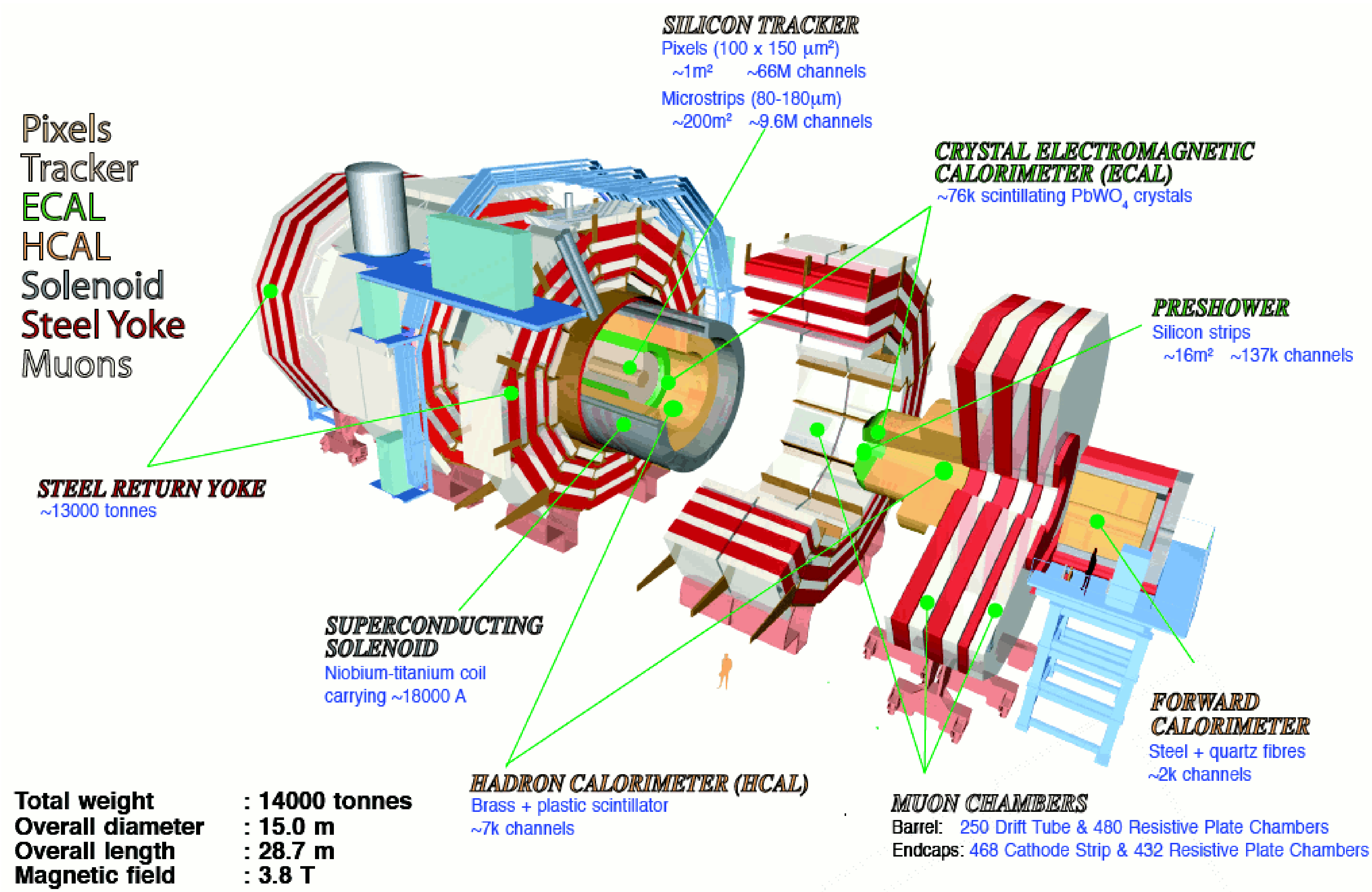
Pixel-only tracks –

- Drastically improved tracking capability shown for low luminosity
- Studies for high luminosity / impact on vertexing and b-tagging are ongoing

Physics studies for the upgraded CMS detector are beginning

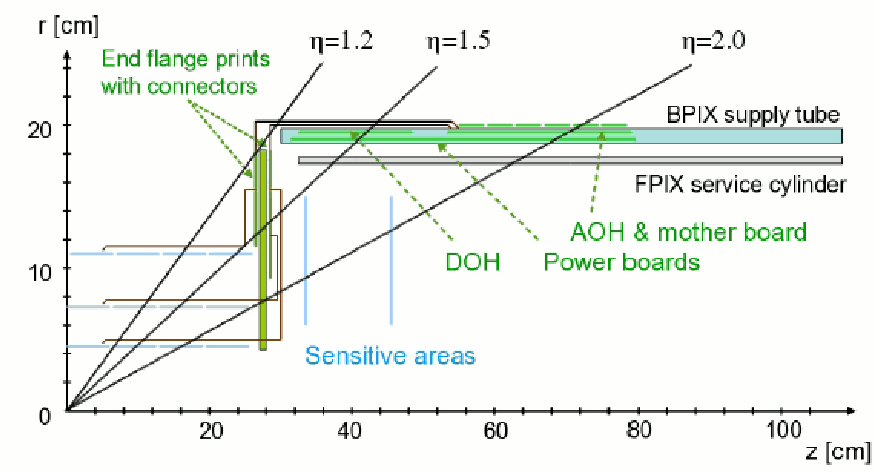
- Additional slides -

CMS Experiment

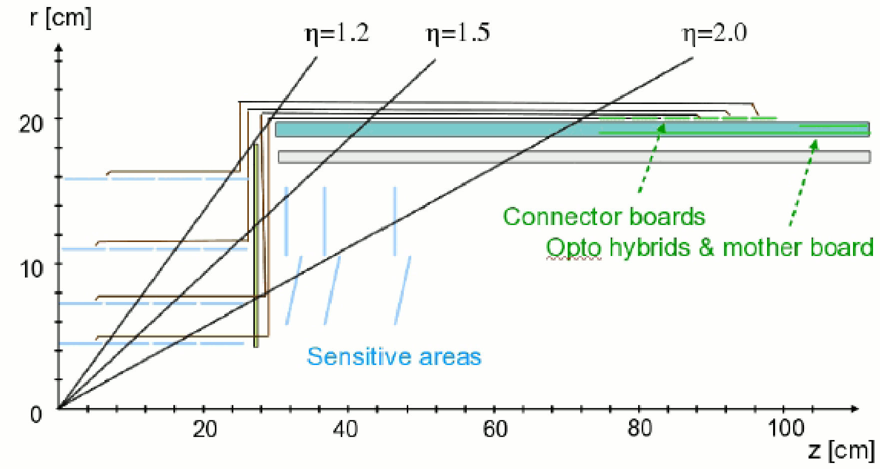


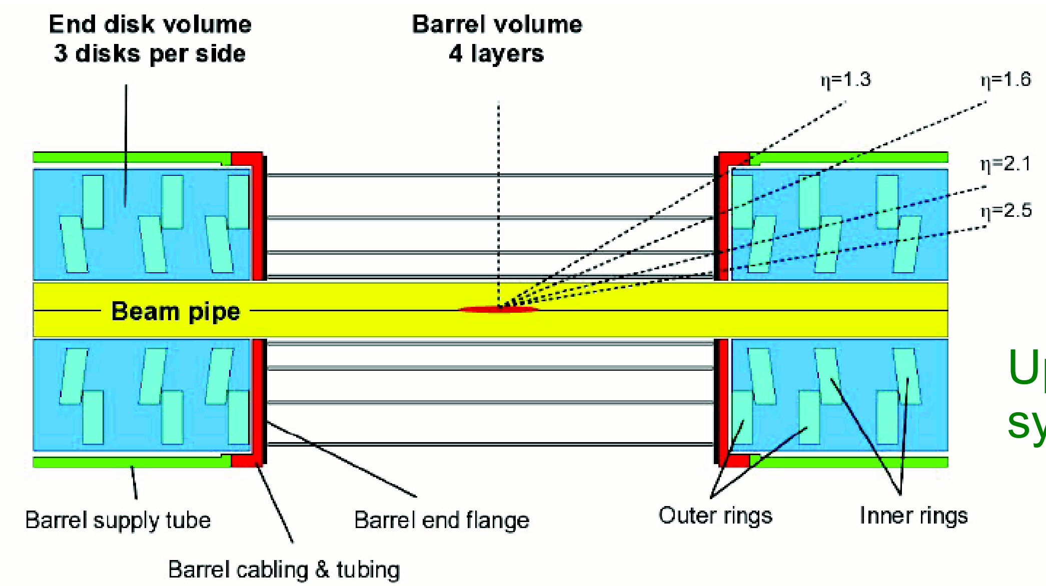
The Phase 1 upgrade of the CMS pixel detector

Current system



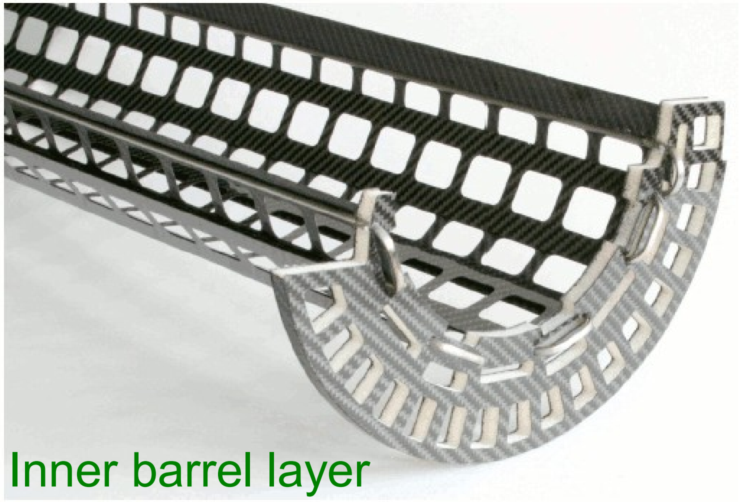
Upgraded system



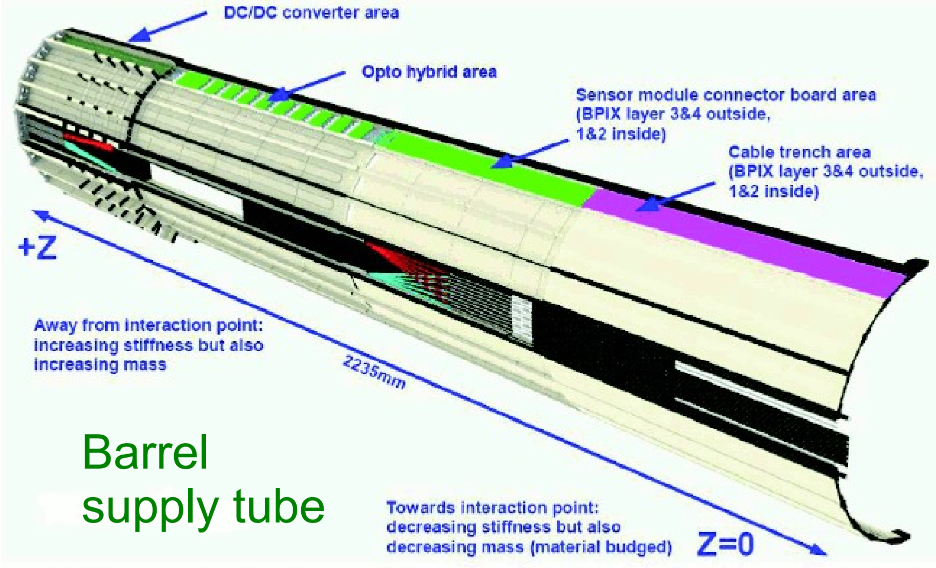


Upgraded system

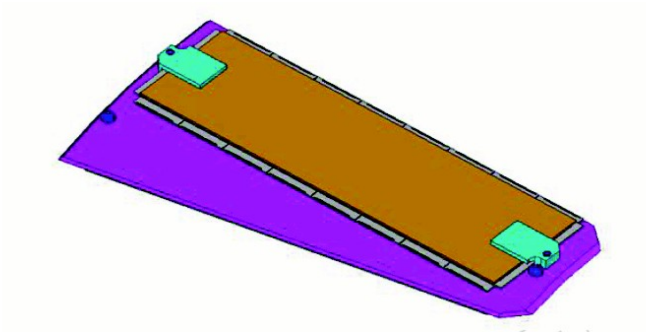
The Phase 1 upgrade of the CMS pixel detector



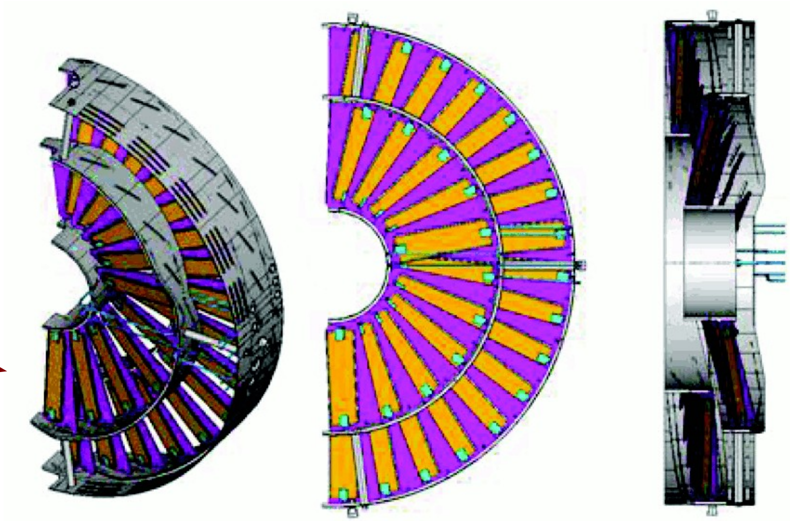
Inner barrel layer mechanics (prototype)



Barrel supply tube



Upgraded forward pixel blade



Upgraded forward pixel half disk design