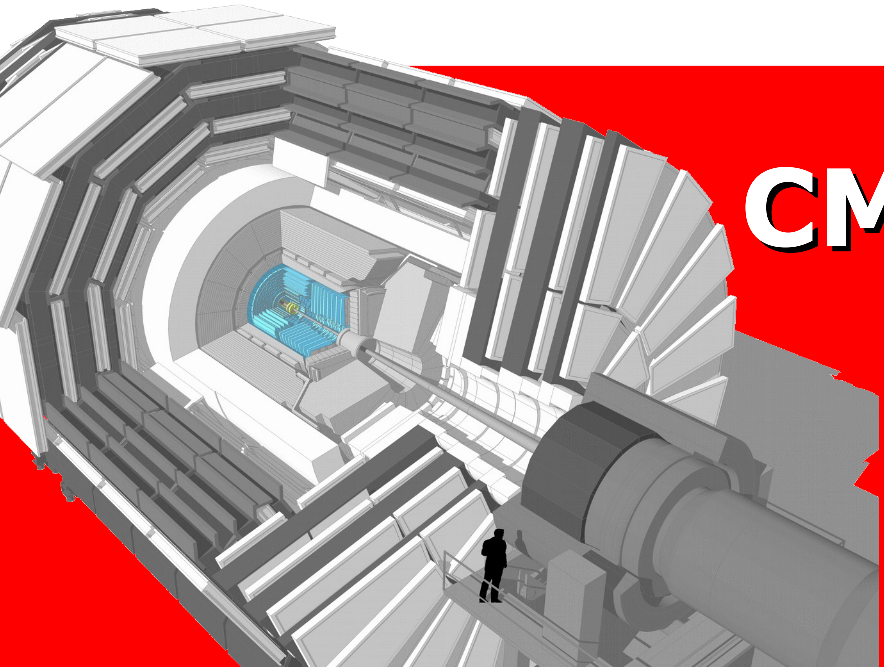


CMS Tracker Upgrades

R&D Plans, Present Status and Perspectives

Benedikt Vormwald
Hamburg University
on behalf of the CMS collaboration

EPS-HEP 2015
Vienna, 22.-29.07.2015

CMS Tracker Upgrade Program

	LHC						HL-LHC
	Run-I	LS1	Run-II	LS2	Run-III	LS3	
E_{CM}[TeV]	7-8		13-14		14		14?
L [$cm^{-2}s^{-1}$]	$7 \cdot 10^{33}$		$\geq 1 \cdot 10^{34}$		$\geq 2 \cdot 10^{34}$		$\sim 5 \cdot 10^{34}$
$\langle PU \rangle$	~21		≥25		≥50		≥140
$\int L \cdot dt$ [fb^{-1}]	~30		≥150		≥300		~3000

year	…	12	13	14	15	16	17	18	19	20	21	22	23	24	25	+10 years

CMS tracker	current	Phase-I upgrade	Phase-II

replacement of current pixel detector in order to deal with higher hit rates

production/assembly phase

replacement of entire tracker in order to deal with even higher hit rates, radiation doses, and pile-up conditions (trigger)

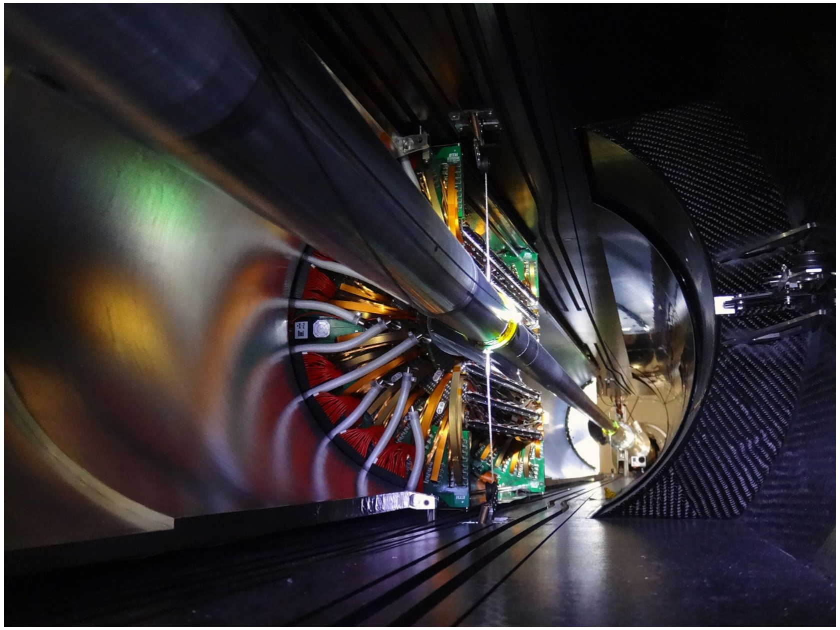
R&D/prototyping phase

Current CMS Pixel Detector

Status of present pixel detector

- present pixel detector has performed extremely well during LHC Run-I:
  - resolution: r-φ: 10µm, z: 20µm-40µm
  - efficiency: ε > 99%
- designed for
  - integrated luminosity: $\boldsymbol{\int L \cdot dt = 500\ \mathrm{fb}^{-1}}$
  - instantaneous luminosity:
    - $L = 1 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ @25ns
    - pile-up events: **<PU> = 25**
    - in 2012: <PU> = 35 @ 50ns

becomes relevant before LS3



Performance limitations

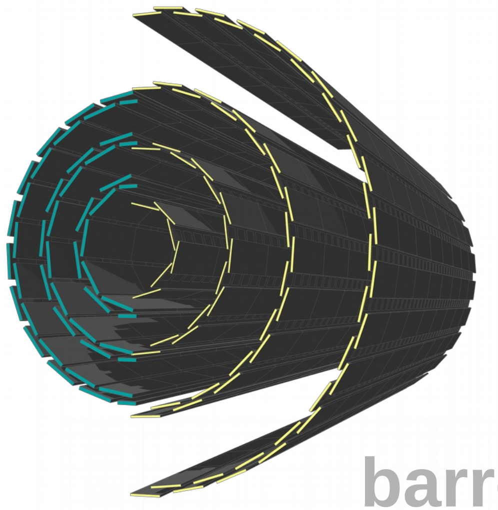
data loss at high occupancy and trigger rate	**higher fake rates** at high pileup	**radiation damage**	**material budget**

CMS Pixel Phase-I detector

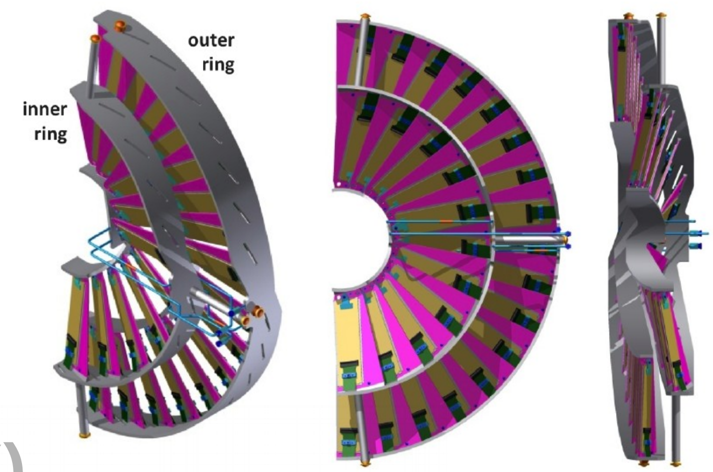
key features:

additional tracking layer	**optimized material budget**	**improved ROC**	**increased bandwidth**

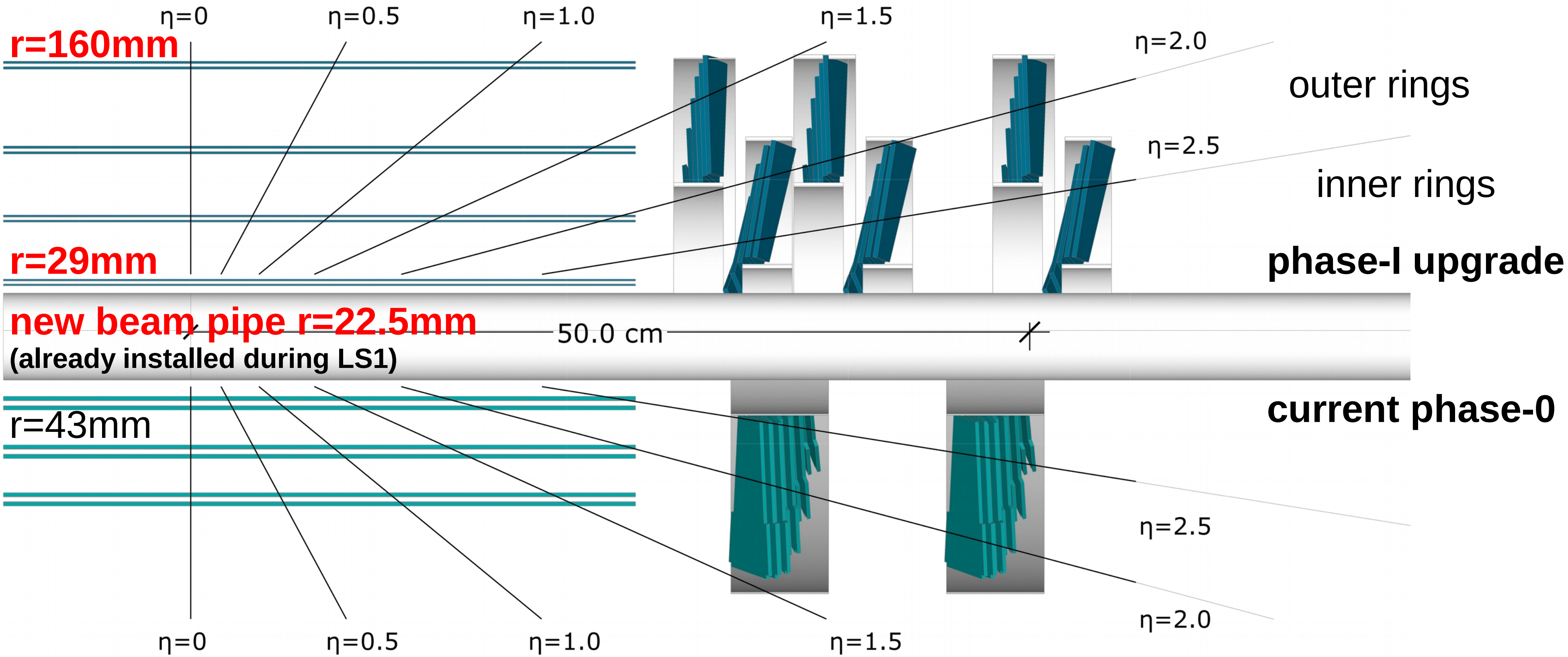
CMS Phase-I Pixel Detector – Geometry



- 4-hit coverage up to |η|<2.5
- closer first pixel layer (new beam pipe)
- turbine-like module arrangement in foward disks
- inner rings tilted for optimal radial and azimuthal resolution



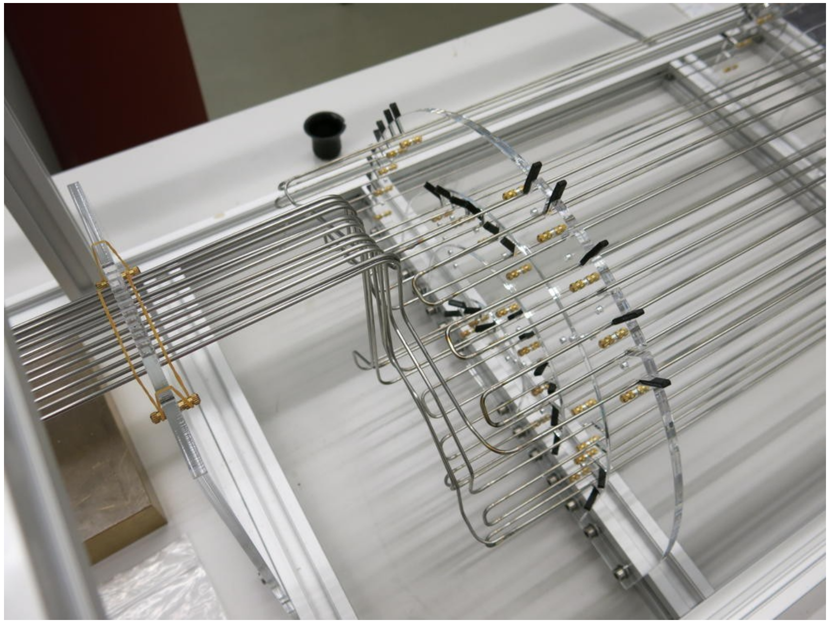
barrel (BPIX) **forward (FPIX)**

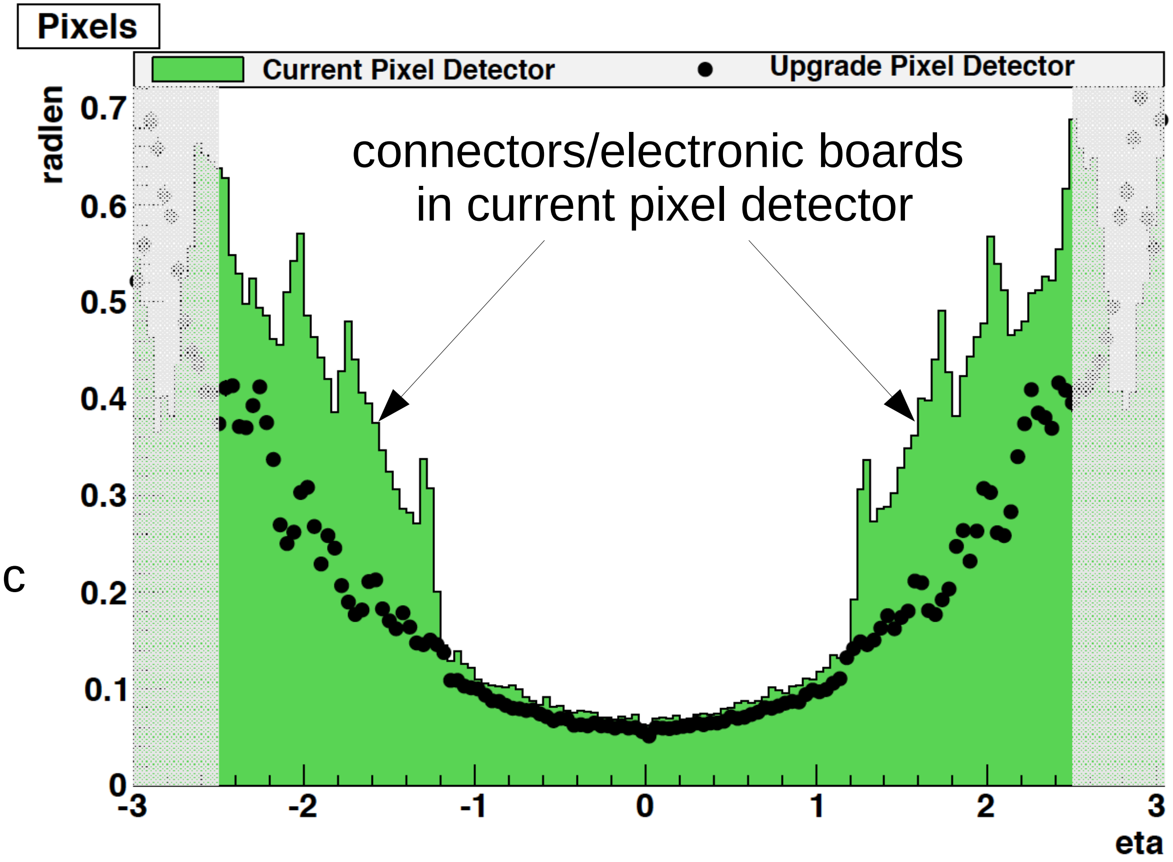


CMS Phase-I Pixel Detector – Material Budget

despite additional tracking layer:
material further reduced

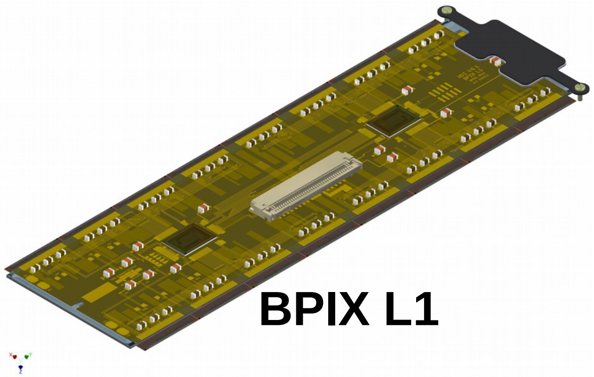
- **electronic boards/connectors moved to higher η**
- **lightweight support structures**
  - BPIX: CFRP/Airex foam compound with cooling loops as backbone
  - FPIX: graphite ring Thermo Pyrolytic Graphite (TPG) for blades

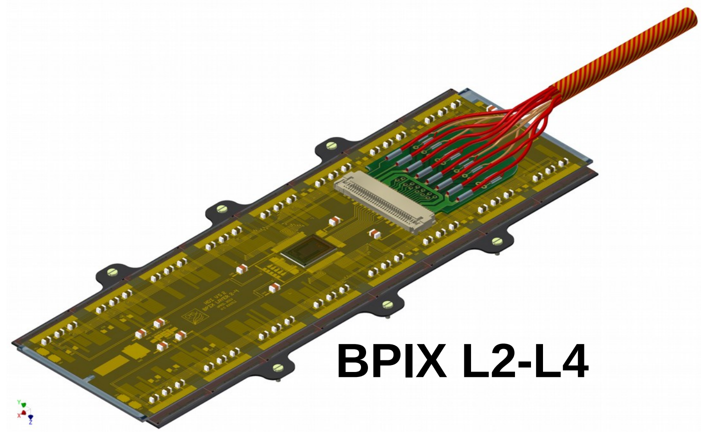


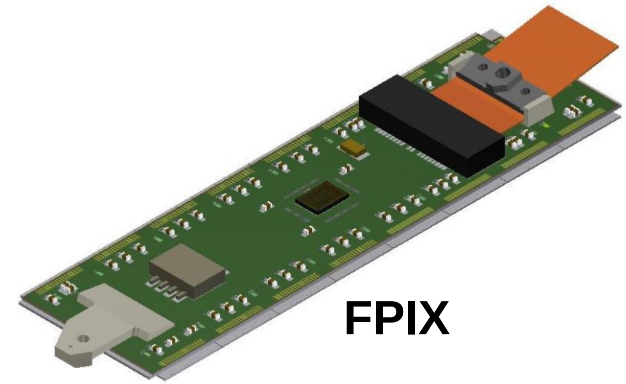


- **2-phase CO_2 cooling**
  - -20°C, option to go deeper
  - very lightweight
  - stainless steel cooling loops: diameter 1.6mm, wall thickness 50µm
  - cooling plant installed and commissioned during LS1

CMS Phase-I Pixel Detector – Modules







sensor

$(150\times100)\mu m^2$
280μm n-in-n

bump-bonded

readout chip

80x52 pixel
250nm CMOS ASIC
pulse-hight readout

token-bit manager

controls readout of 8/16 ROCs

high-density interconnect

flex print

unchanged compared to Phase-0

new ROC with digital RO based on PSI46

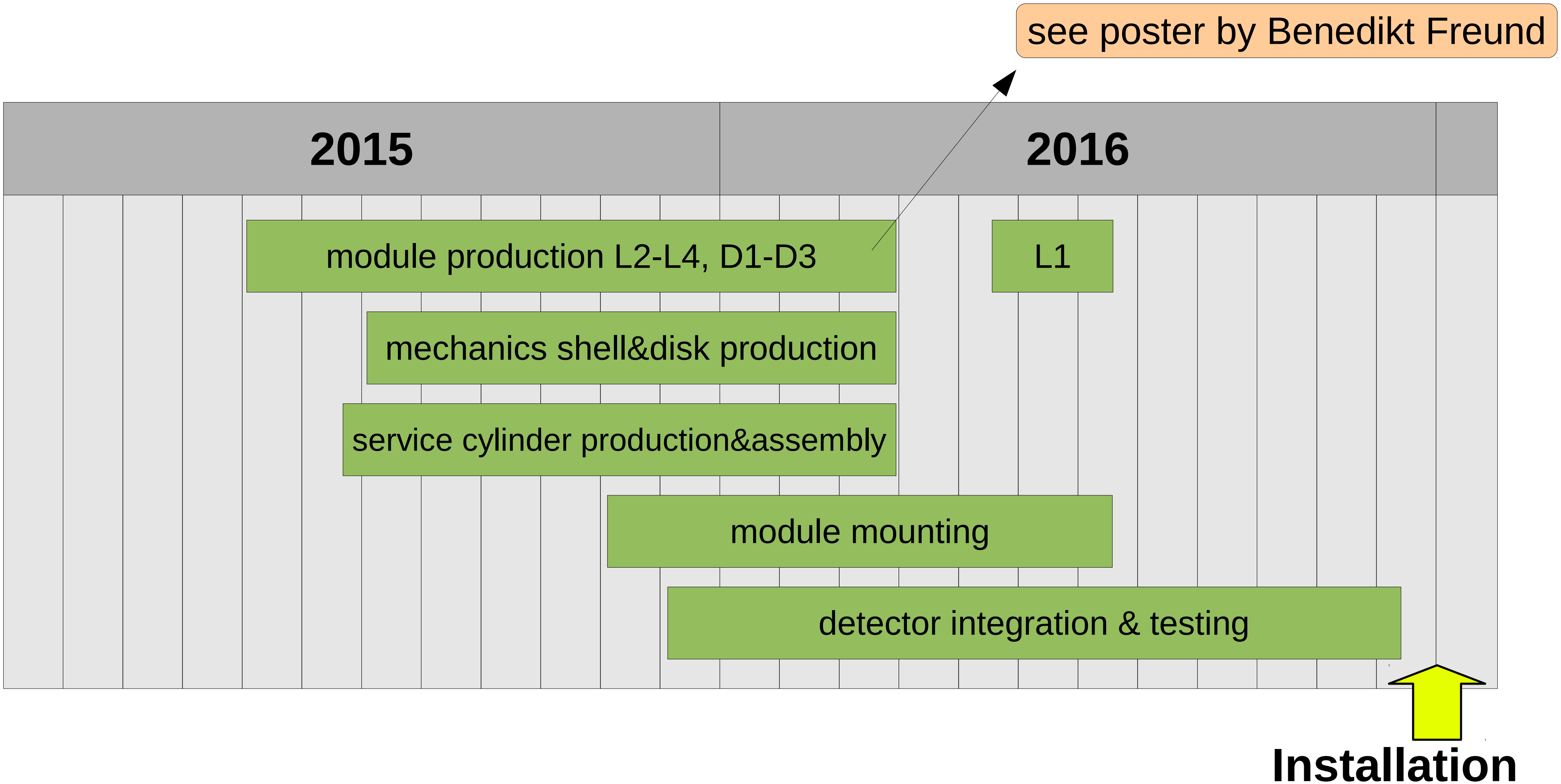
- on-chip digitization (8bit ADCs)
- increased buffers (hit, timestamp)
- reduced charge threshold (old: 3200e, new: 1900e)
- ***dedicated version for L1 under development***

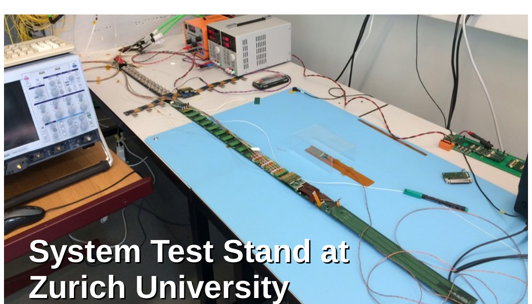
new digital TBM

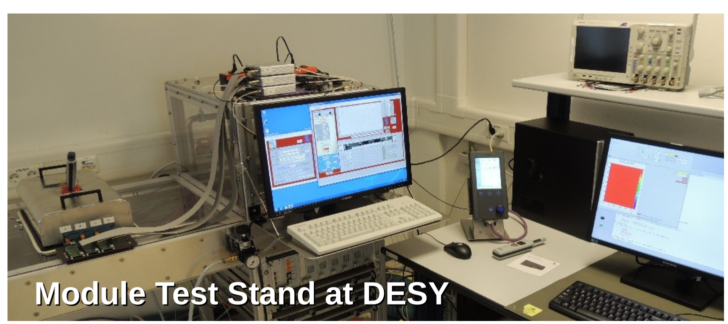
- old: 40MHz analog coding
  new: 160Mbit/s digital
- module out-bound datastream: 400Mbit/s

all components prepared for high integrated & instantaneous luminosities

CMS Phase-I Pixel Detector – Towards Installation



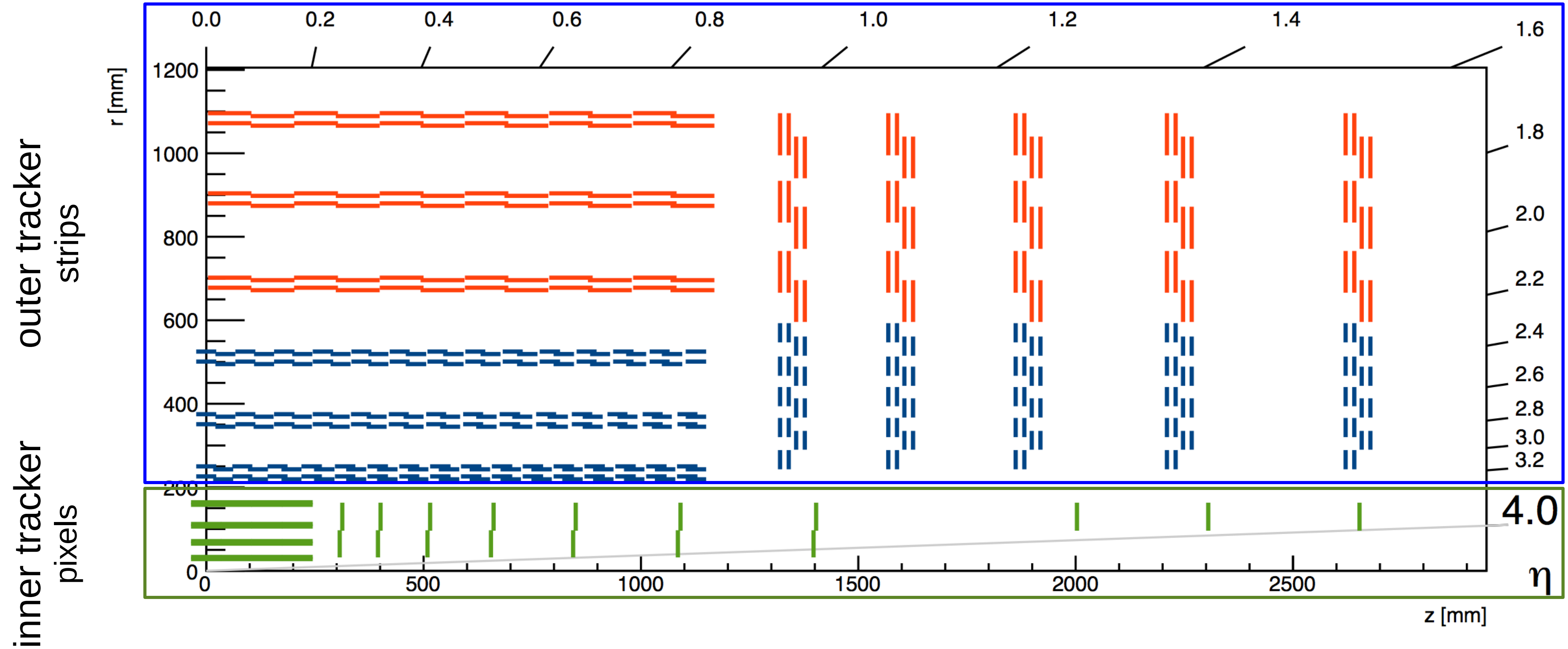

System Test Stand at Zurich University


Module Test Stand at DESY

X-ray Test Stand at Hamburg University

CMS Phase-II Tracker

2025-2035: CMS gets a completely new inner and outer tracker for HL-LHC



key features:

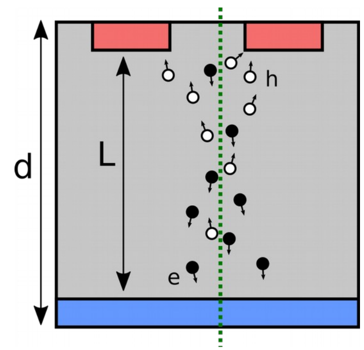
- **η coverage** — $|\eta|<4.0$
- **finer granularity** — factor 4-6
- **L1 track trigger**
- **radiation hardness**

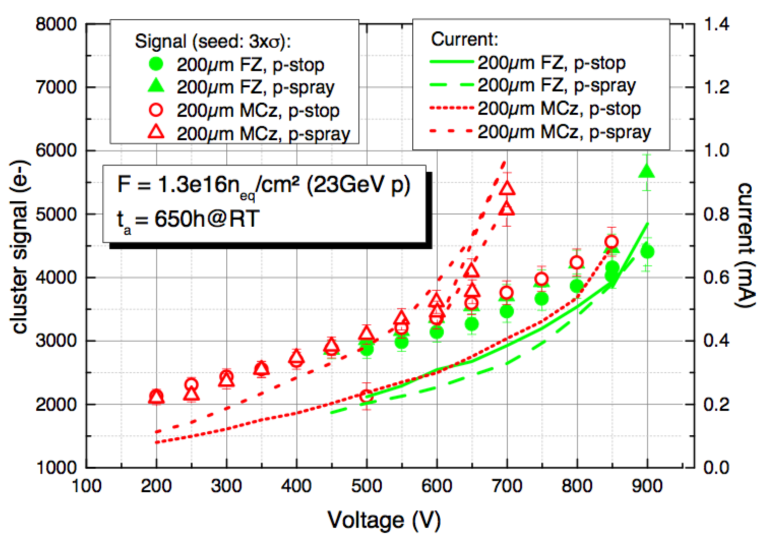
CMS Phase-II Tracker – Pixel Sensor Options

- expected fluence: ~$2\mathrm{x}10^{16}$ n_{eq}/cm^2 in first layer
- charge trapping reduces signal cluster charge and thus single hit efficiency
- solution: reduce drift distance

thin-planar sensor

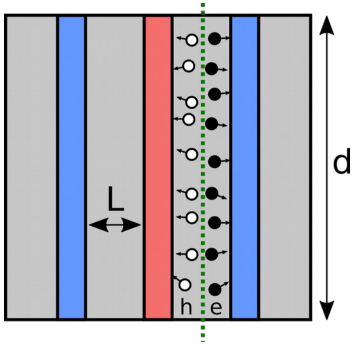
- drift length L<200µm (now: 300µm)
- ~4000e@800V after $1.3\mathrm{x}10^{16}$ n_{eq}/cm^2
- **outer and maybe inner layers**

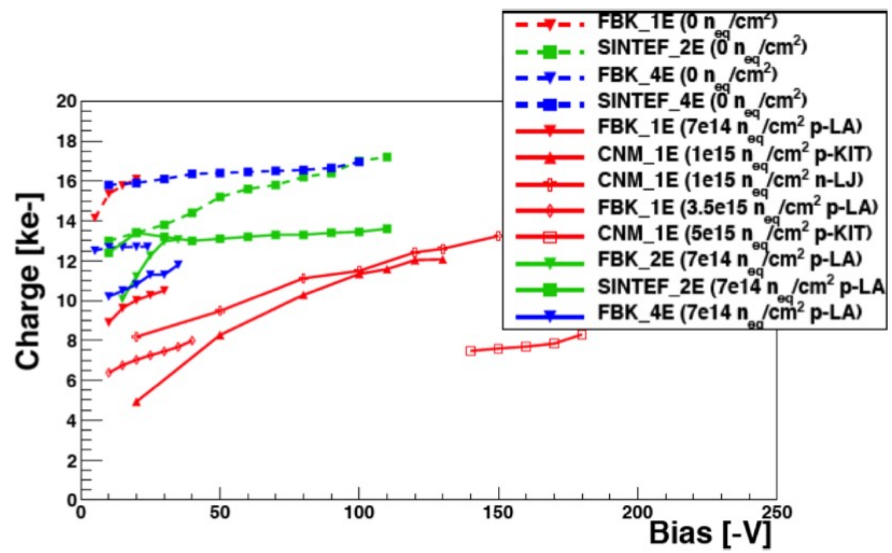




3D sensor

- shorter drift length L
- lower depletion voltage
- ~7000e@150V after $5\mathrm{x}10^{15}$ n_{eq}/cm^2
- technically more challenging
- **inner layers**



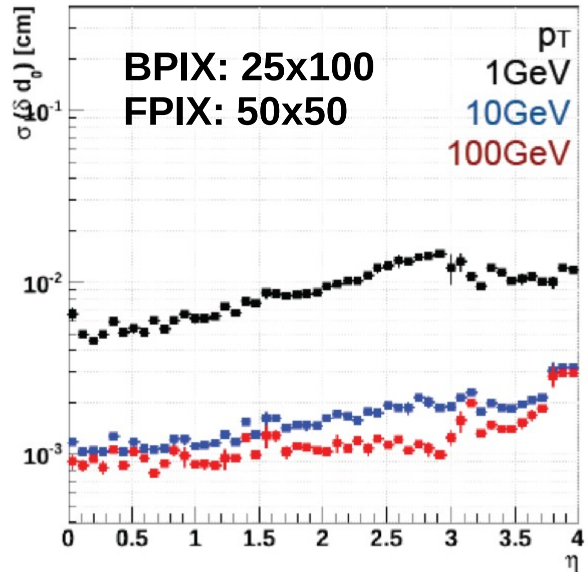


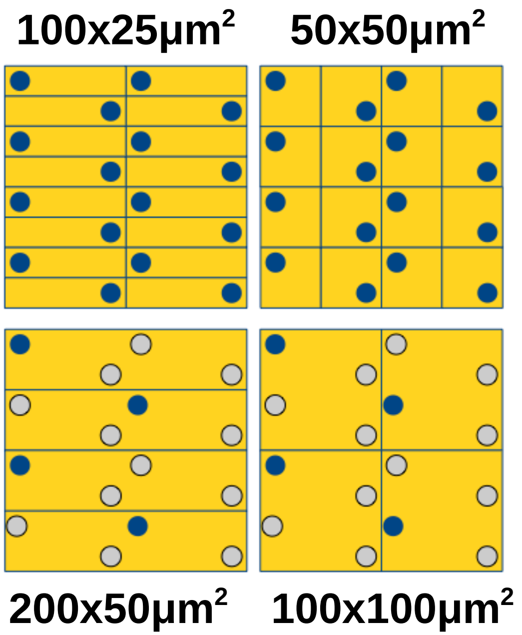
final decision based on **performance**, **radiation tolerance**, **cost/yield**

CMS Phase-II Tracker – Pixel Size and Readout

Pixel size

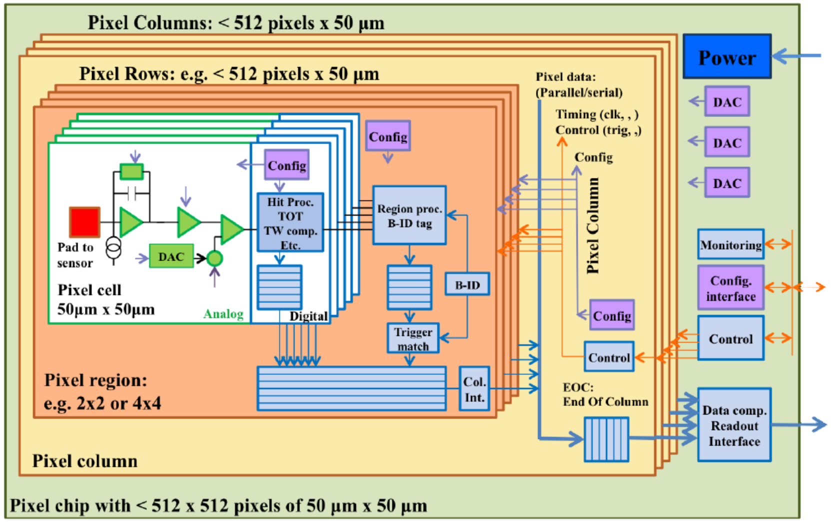
- affects
  - ➔ two-track separation
  - ➔ detector occupancy
  - ➔ high-p_T-track resolution
- factor 6 smaller pixels:
  (50x50)µm² or **(25x100)µm²**
  current pixel detector: (150x100)µm²
- option: **different pixel aspect ratio, larger pixels** in different parts of detector using the *same* ROC





Readout chip

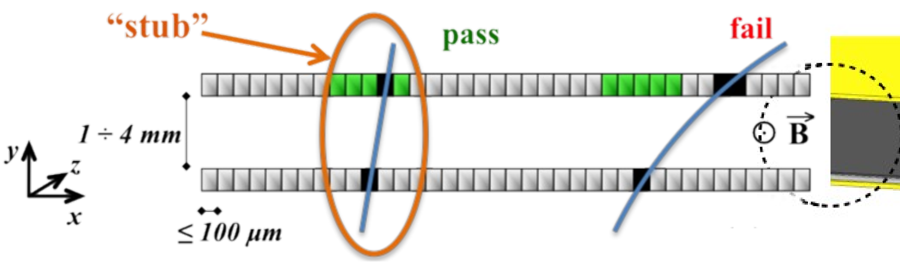
- **RD53 Collaboration** (20 institutes, CMS+ATLAS) develops demonstrator chip for 2016
- **65nm CMOS** technology
  - ➔ low power
  - ➔ radiation tolerant (up to 1Grad)
- larger **hit rate** (2GHz/cm²)
- increased **trigger rate/latency** (1MHz/12.5µs)
- low effective **threshold** (~1000e)

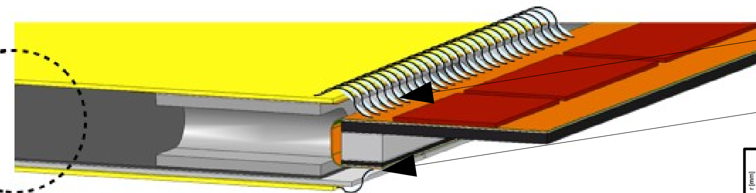


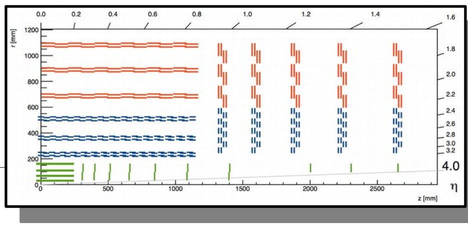
CMS Phase-II Tracker – Outer Tracker Modules

Concept of p_T modules

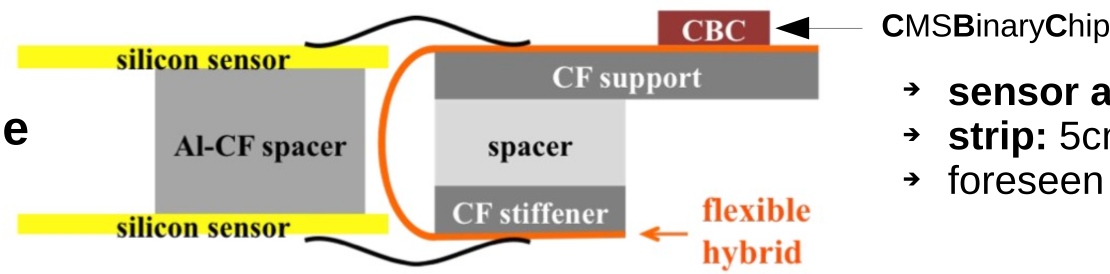
- calorimeter and muon-based triggers alone will no longer be sufficient to reduce rates due to PU and limited spatial resolution
- track information needed on L1 trigger level
- use hits in two close sensor-layers in magnetic field to filter high-p_T-hits





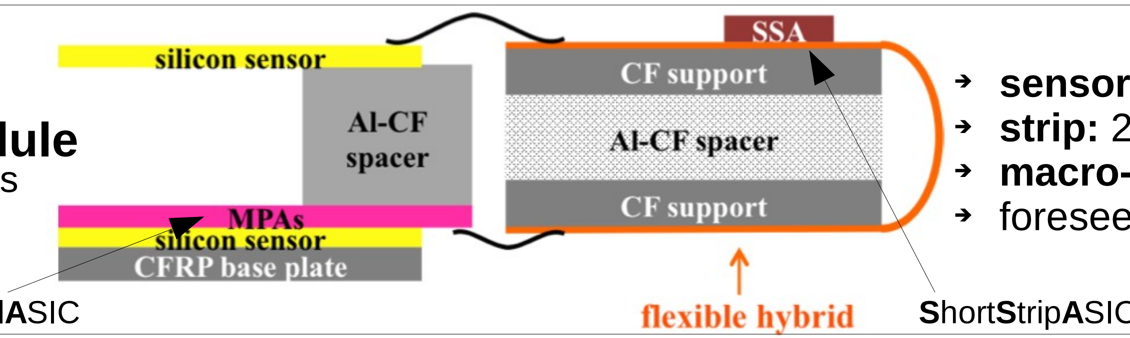


2S module
strips-strips



- → **sensor area:** 10x10cm^2
- → **strip:** 5cmx90µm (2·1016 channels)
- → foreseen for the outer layers

PS module
pixel-strips

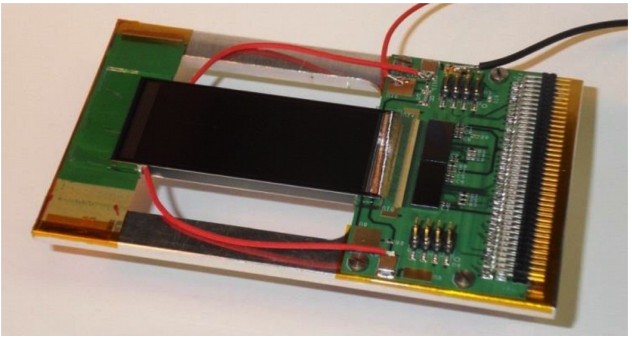


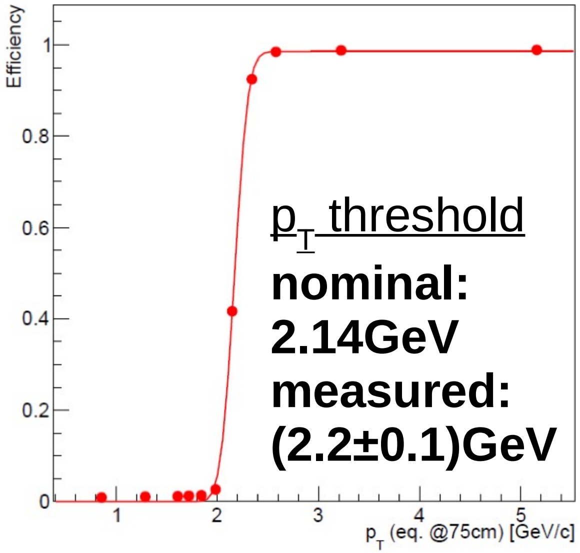
- → **sensor area:** 5x10cm^2
- → **strip:** 2.4cmx100µm (2·960 channels)
- → **macro-pixel:** 1.5mmx100µm (32·960 pixels)
- → foreseen for the inner layers

CMS Phase-II Tracker – Outer Tracker Prototyping

Early 2S prototype

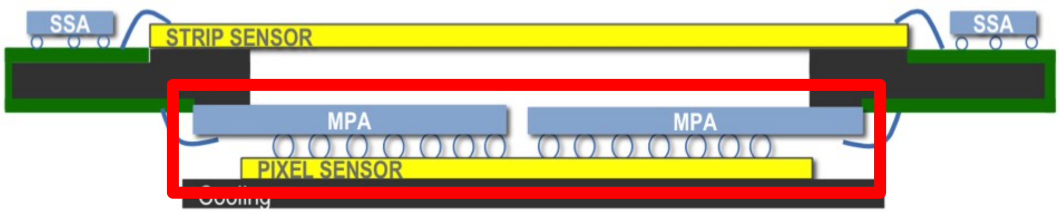
- mini 2S prototype built in 2013
- 2xCBC chip
- **stub-finding logic**
- nominal noise/threshold
- beam test at DESY in Dec 2013 and at CERN in Jun 2015





Small size PS-p prototype – MAPSA light

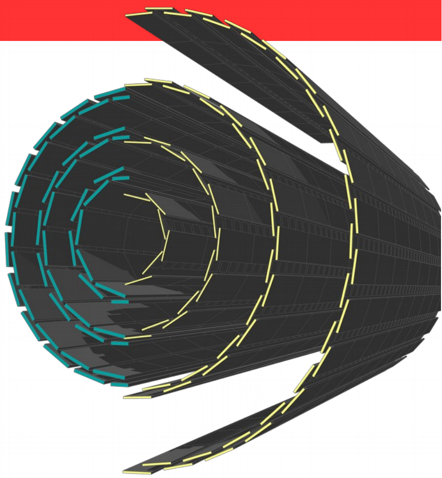
- scaled down version of the macro-pixel part of the PS module
- **M**acro**P**ixel**S**ub**A**ssembly
- MPA light chip
  - 16x3 (full: 120x16) pixel
- PS-p light sensor
  - material: FZ p-type (200µm)
  - 48x6 pixel
  - size: 7.8x12mm^2



prototyping phase for sensor and modules started
schedule: finished by end of 2017

Conclusions

Phase-I Pixel Upgrade

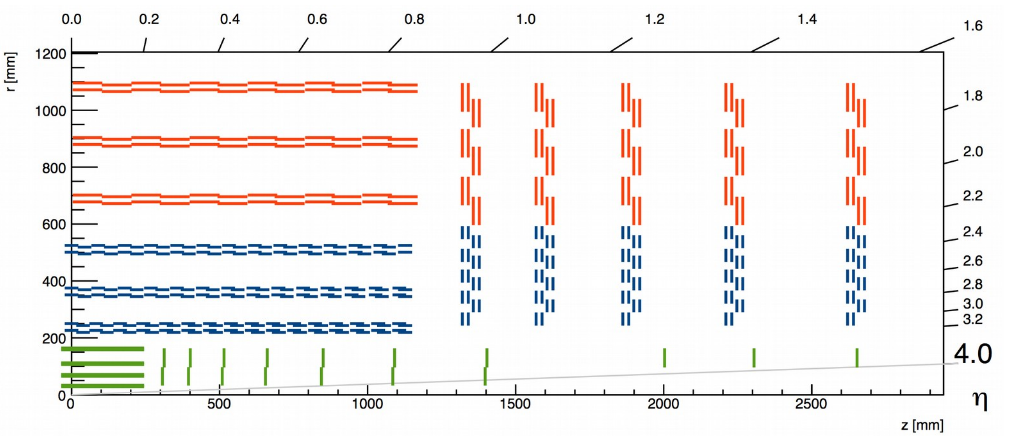


- new 4-layer pixel detector based on new digital readout chips
- production ongoing, no obstacles in sight
- installation during LHC EYETS 2016/2017

Phase-II Tracker Upgrade

- Technical Proposal just published

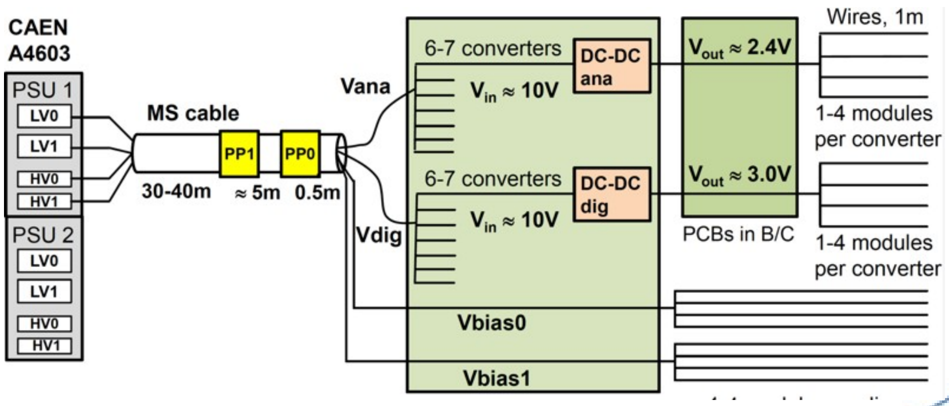
  CERN-LHCC-2015-10
- final Pixel concept under development
- Outer Tracker concept well advanced, first prototype modules available

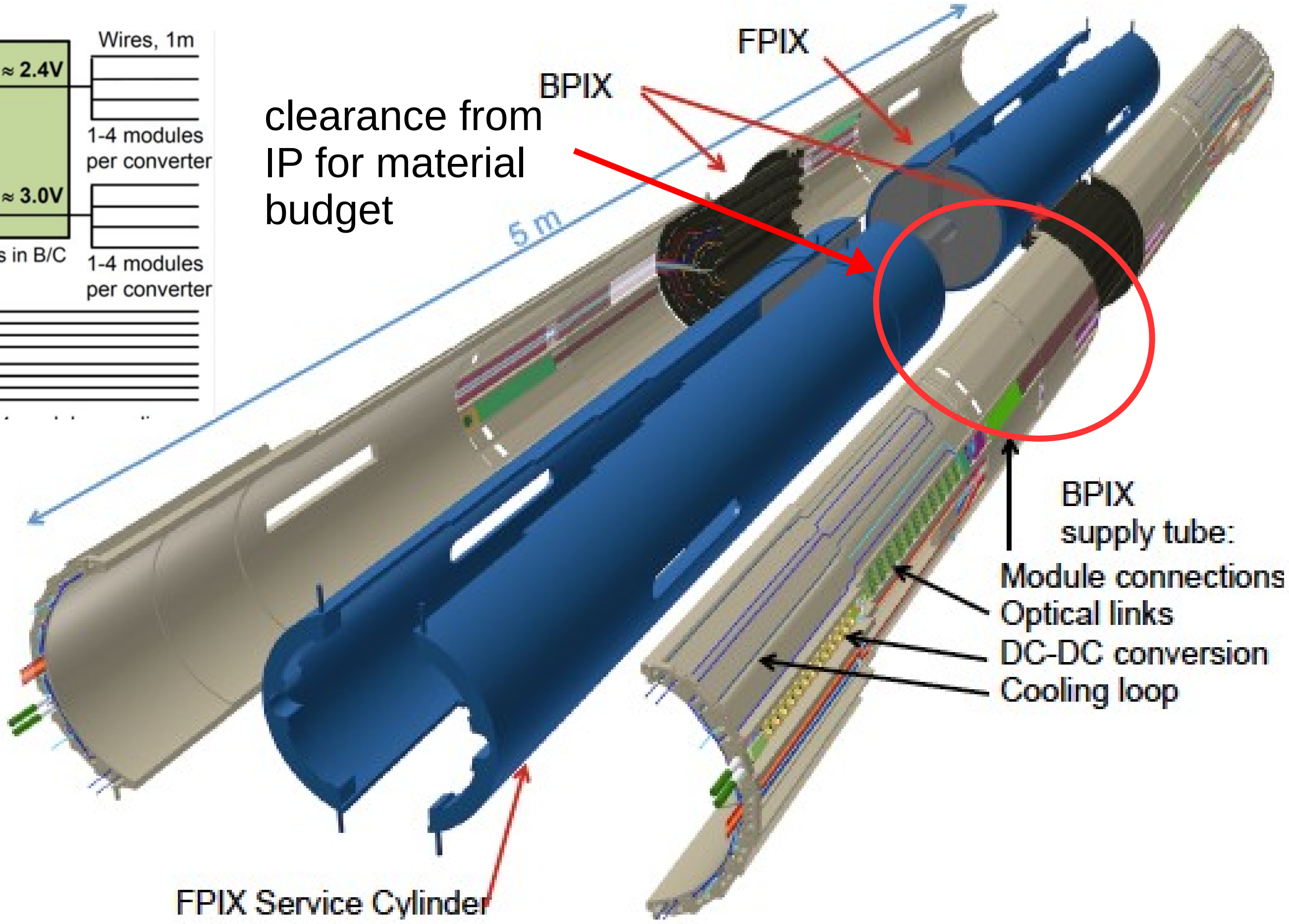


Rich R&D and physics program
of the CMS tracker for the next 20 years!

Backup Material

CMS Phase-I Pixel Detector – Powering&Service





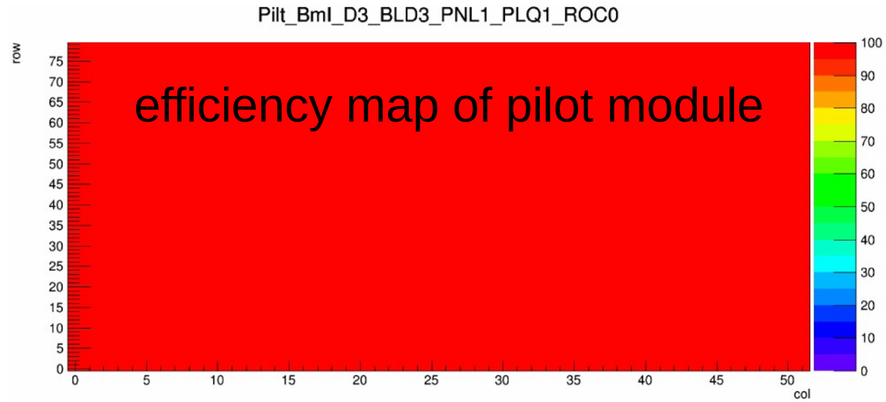
Powering
- 1.9 times more channels
- same power cables
- DC-DC conversion near the detector 10V to 2.4V/3.0V
- 1184 converters needed

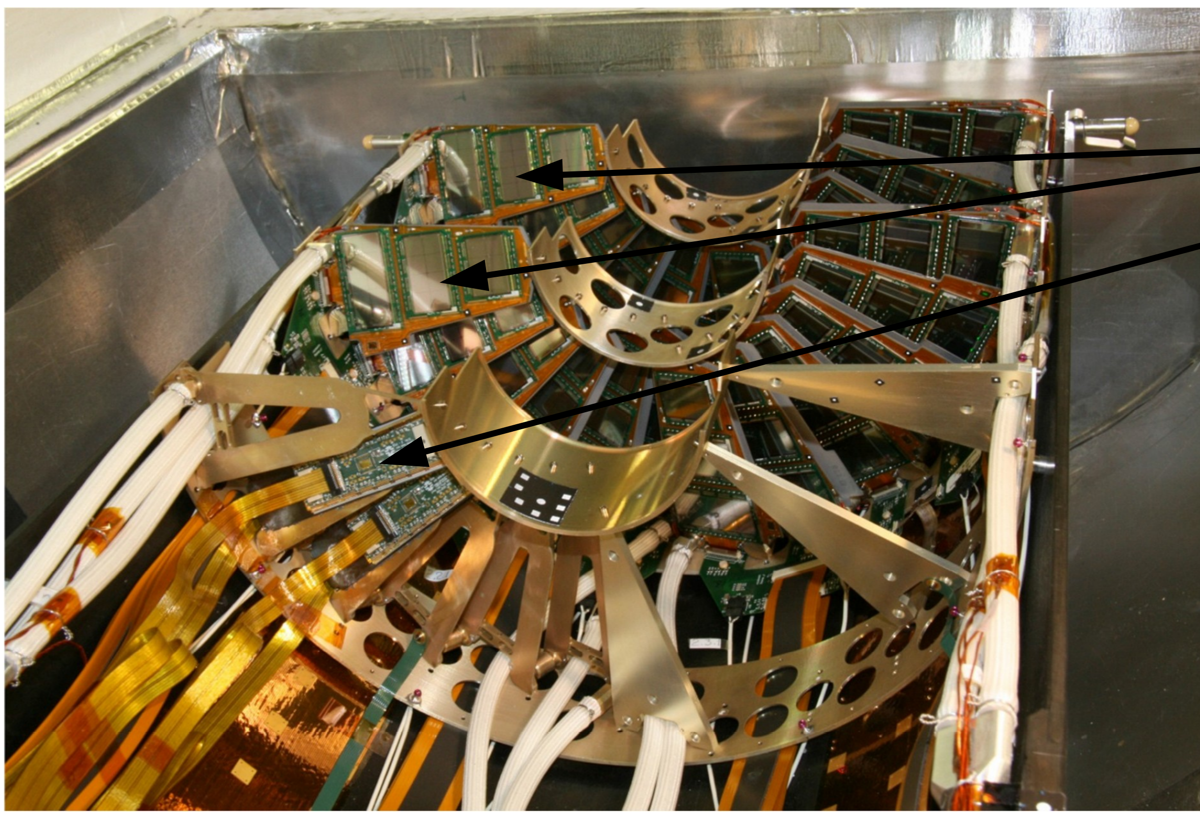
Connection to the outside world
- design idea: modular, easy-to-access
- Supply Tube (BPIX)/Service Cylinders (FPIX) house powering, cooling lines, readout electronics
- same mechanical envelope as Phase-0

CMS Phase-I Pixel Detector – Pilot System

8 phase-I modules installed on new third FPIX disk as **pilot system** during LS1

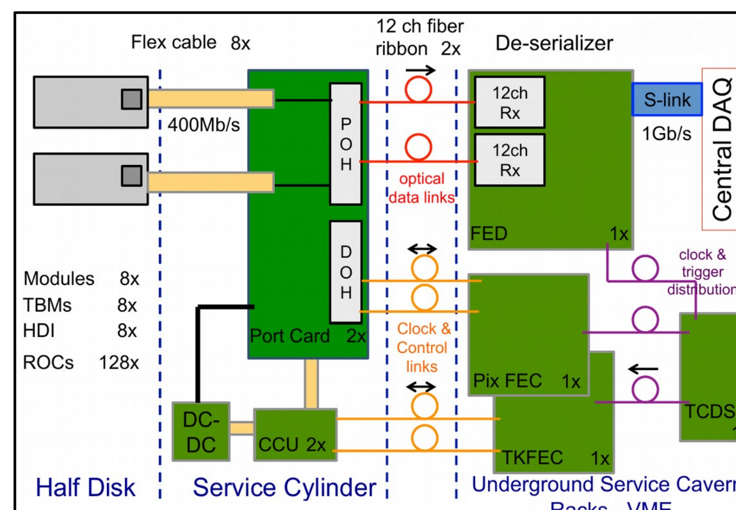
- develop and exercise full readout chain in CMS DAQ environment
- gain operation experience with new ROC/TBM



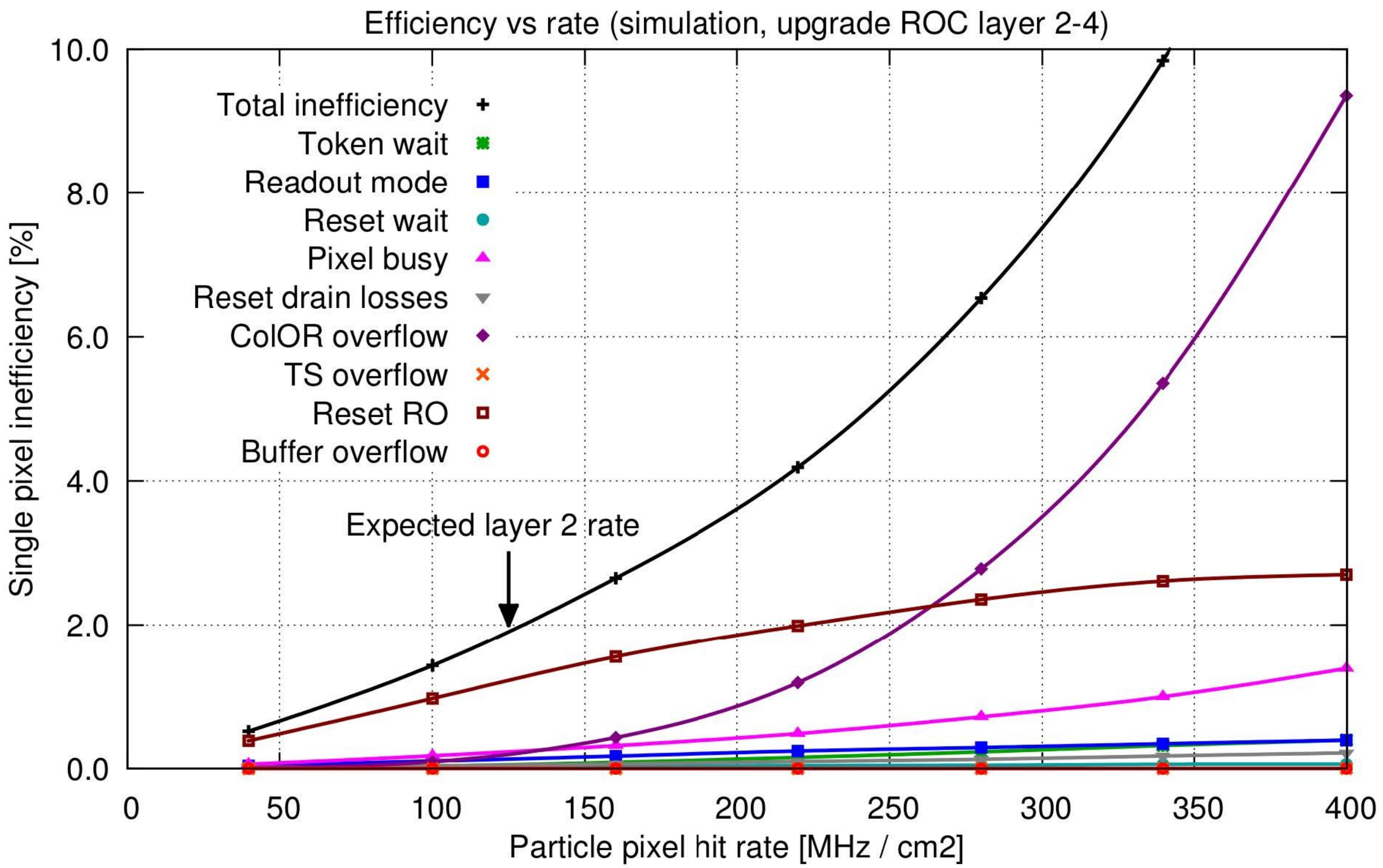


Phase-0 FPIX plaquettes

Phase-I FPIX module



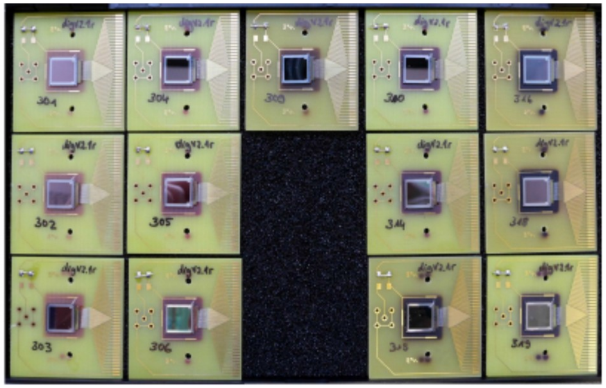
CMS Phase-I Pixel Detector – ROC Rate Capability

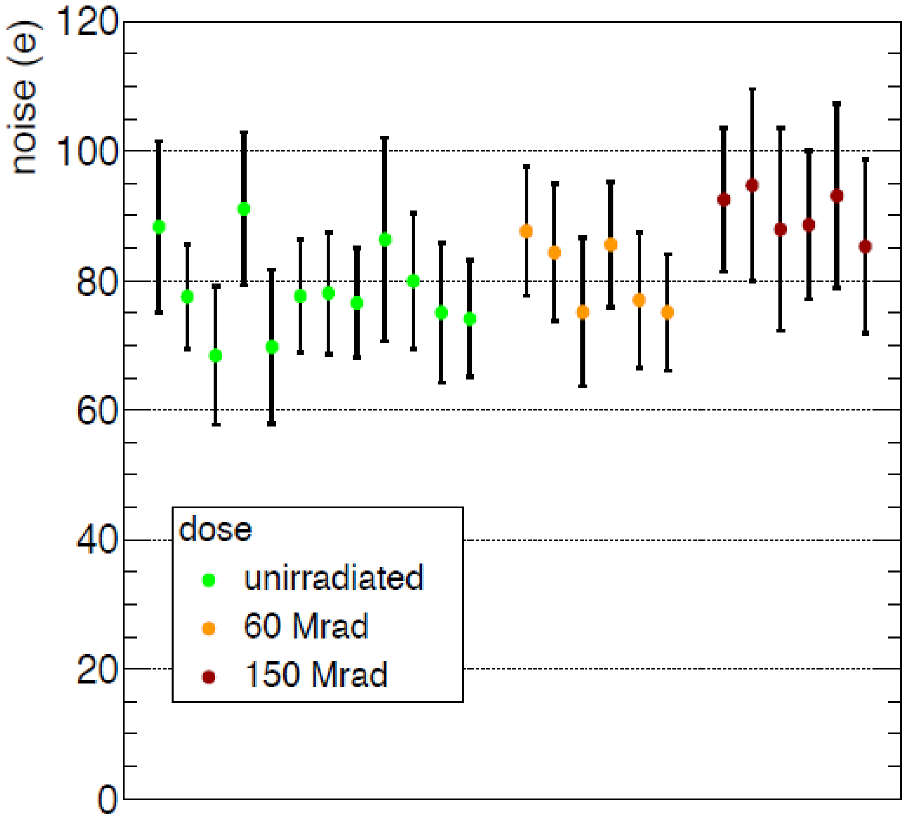


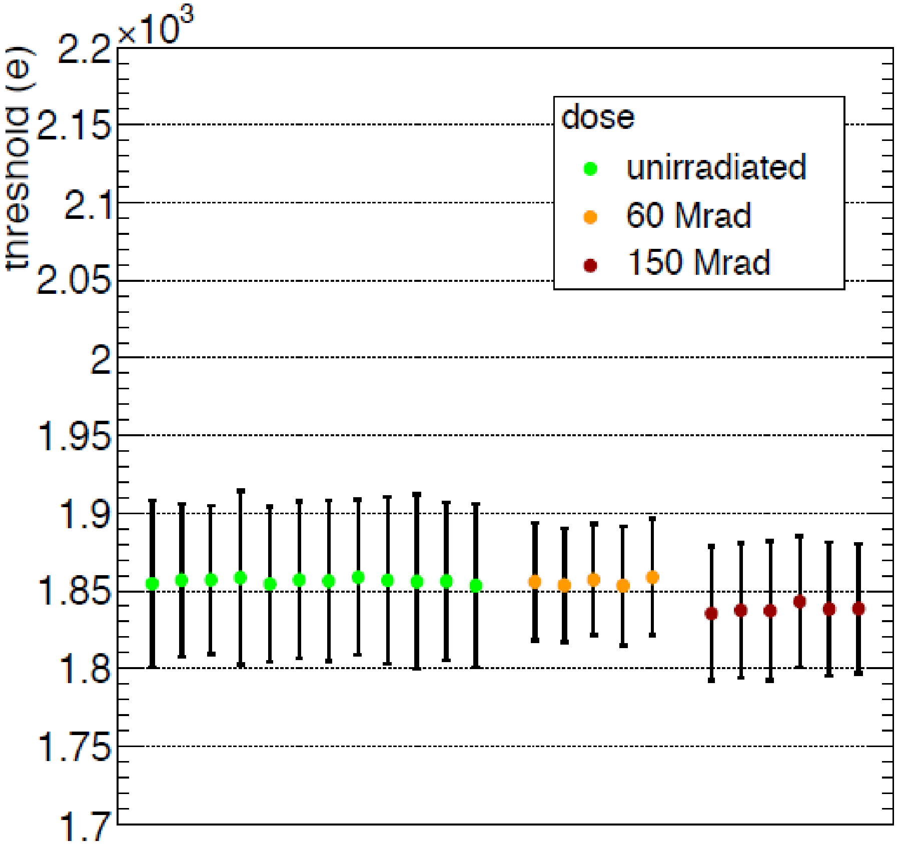
- tolerable inefficiency of <2% in BPIX L2-L4 and FPIX (<120 Mhz/cm^2)
- extrapolation to BPIX L1 (up to 580 Mhz/cm^2): inefficiency of >30%
- dedicated chip design in preparation

CMS Phase-I Pixel Detector – ROC Radiation Hardness

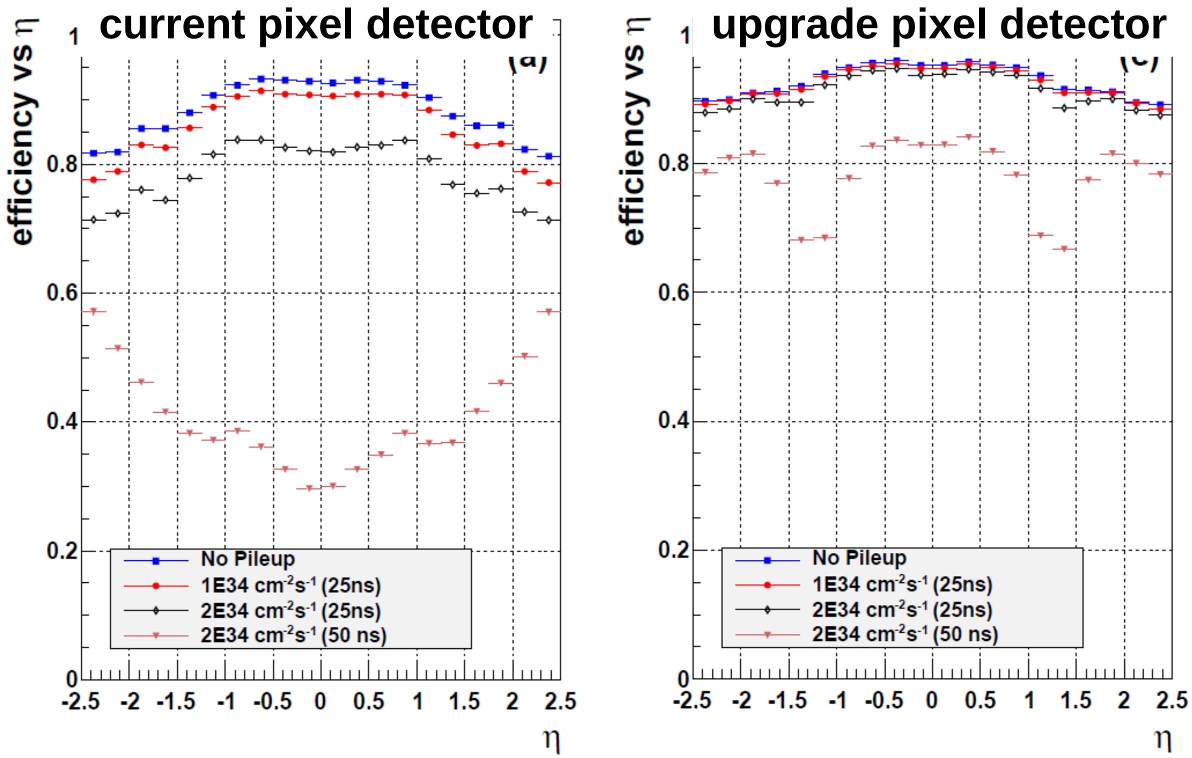
- expect 120Mrad in L1 after 500fb^{-1}
- irradiation of single chip modules (PSI46digv2.1respin) with 23MeV protons at Karlsruhe
- excelent performance after irradiation with even higher dose than expected



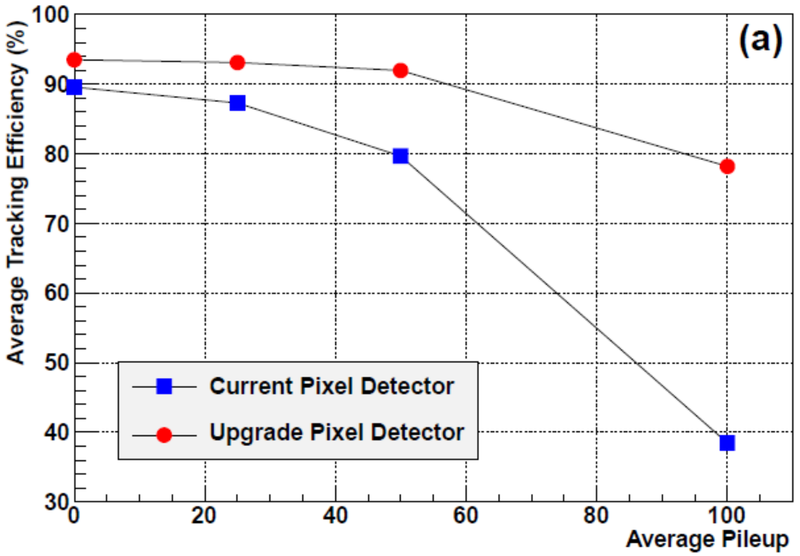




CMS Phase-I Pixel Detector – Tracking Performance

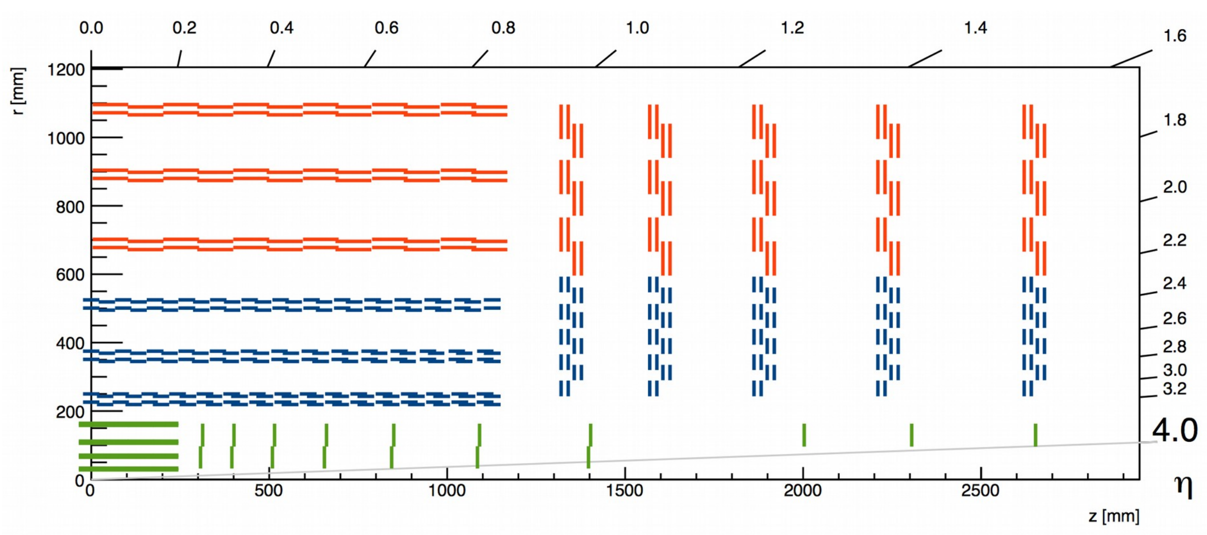


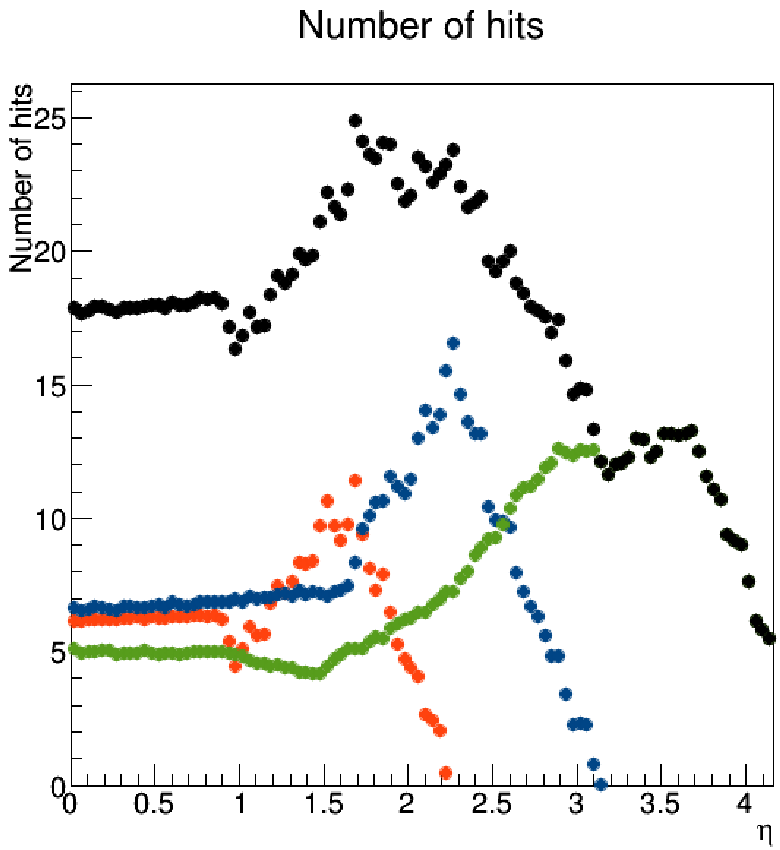
tracking efficiency
in $t\bar{t}$ sample



Phase-I upgade detector
much better suited for
high pile-up conditions

CMS Phase-II Tracker – Coverage

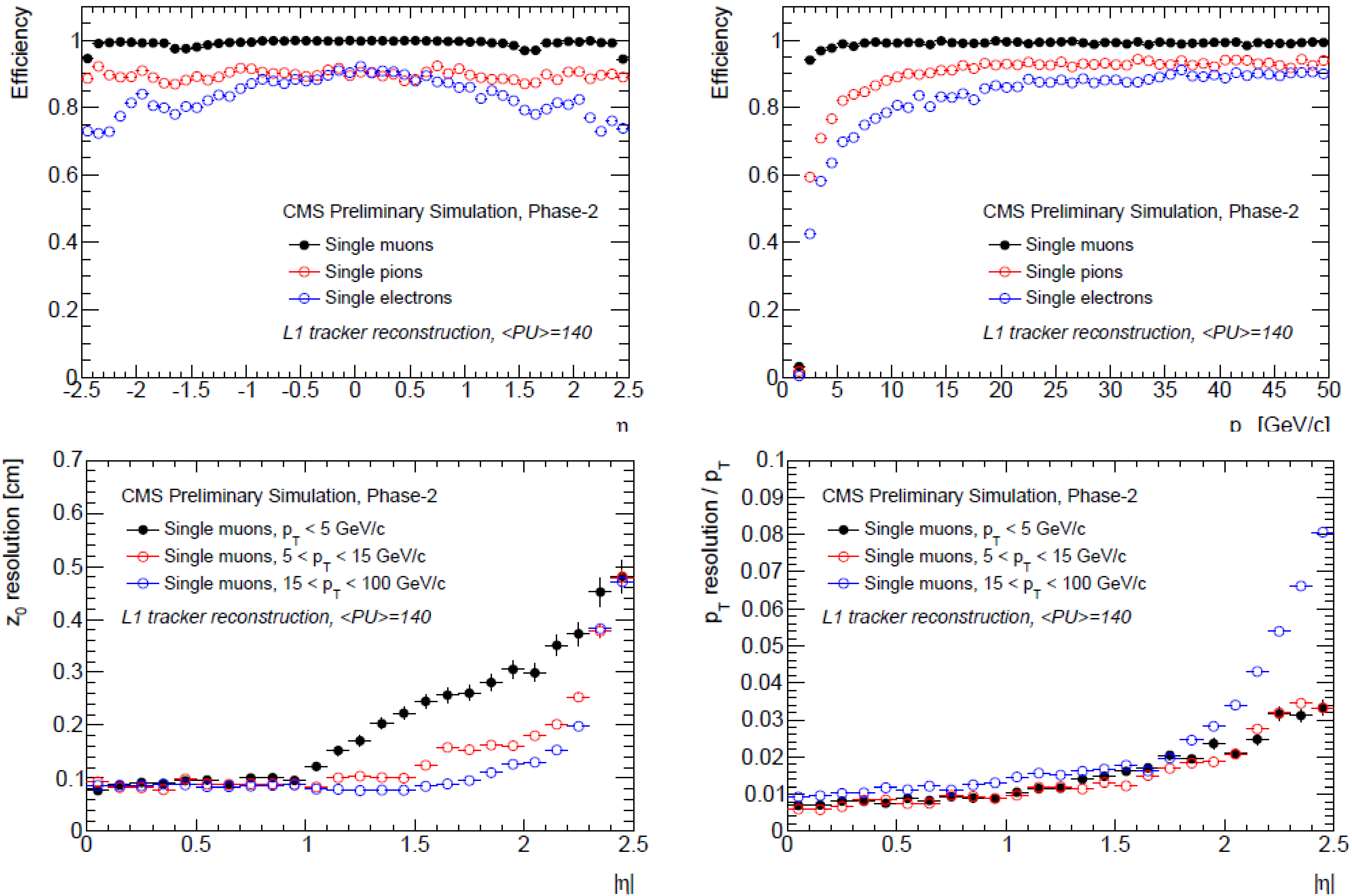




- ~10 points available for track trigger up to |η|<2.5 (40MHz!)
- coverage up to |η|<4 in full read-out

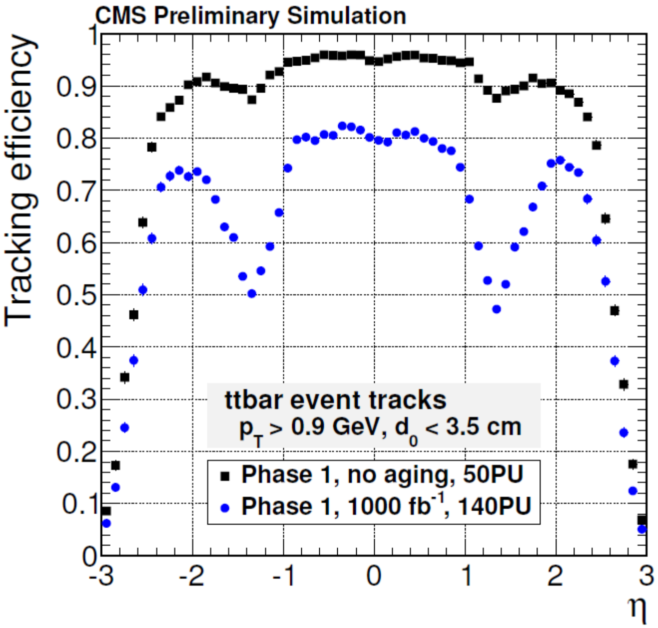
- all hits
- outer tracker hits (2S)
- outer tracker hits (PS)
- inner tracker hits (pixel)

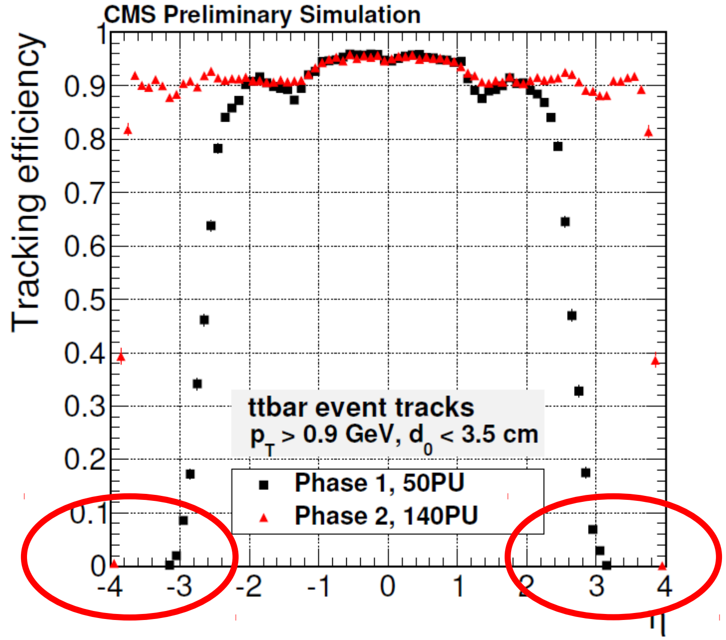
CMS Phase-II Tracker – Lvl1-Trigger Performance



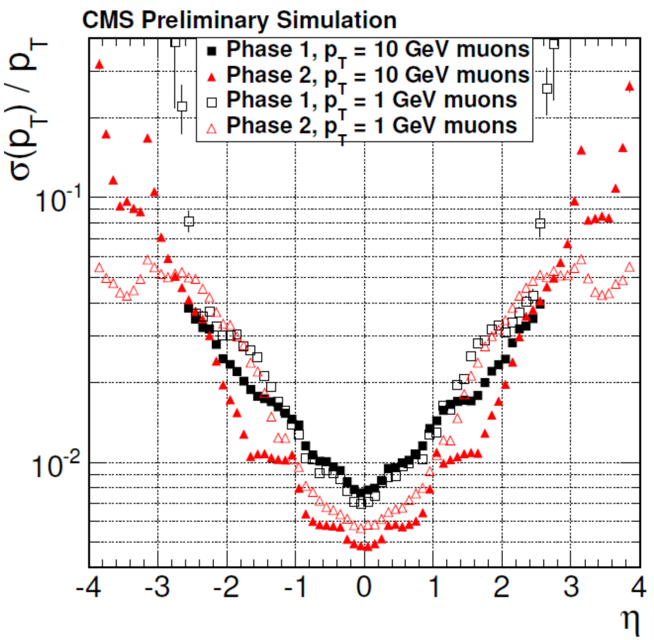
CMS Phase-II Tracker – Tracking Performance

tracking efficiency
in $t\bar{t}$ sample





tracking resolution
in single muon sample



Phase1 no aging, 50PU