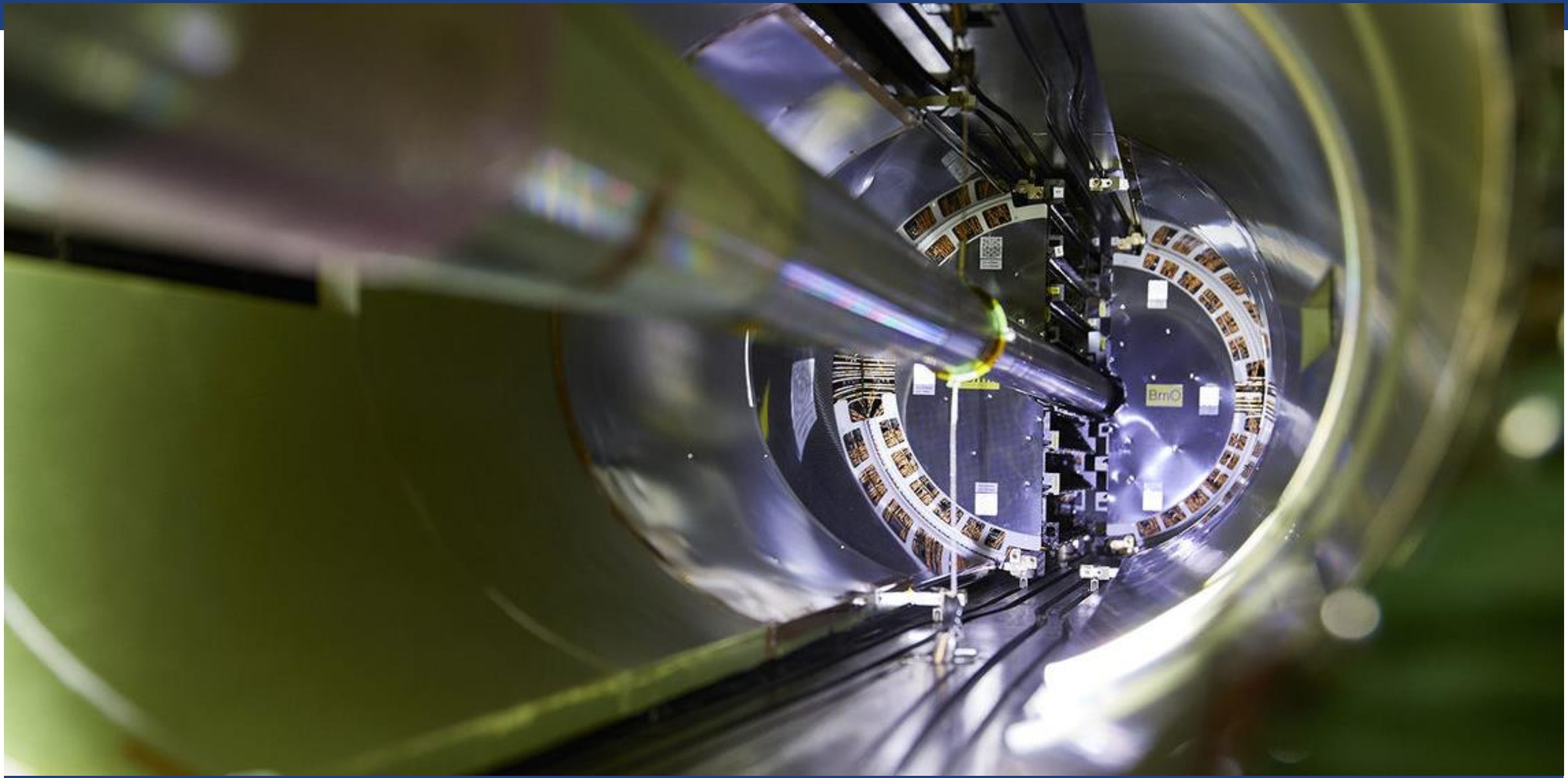
ETH zürich

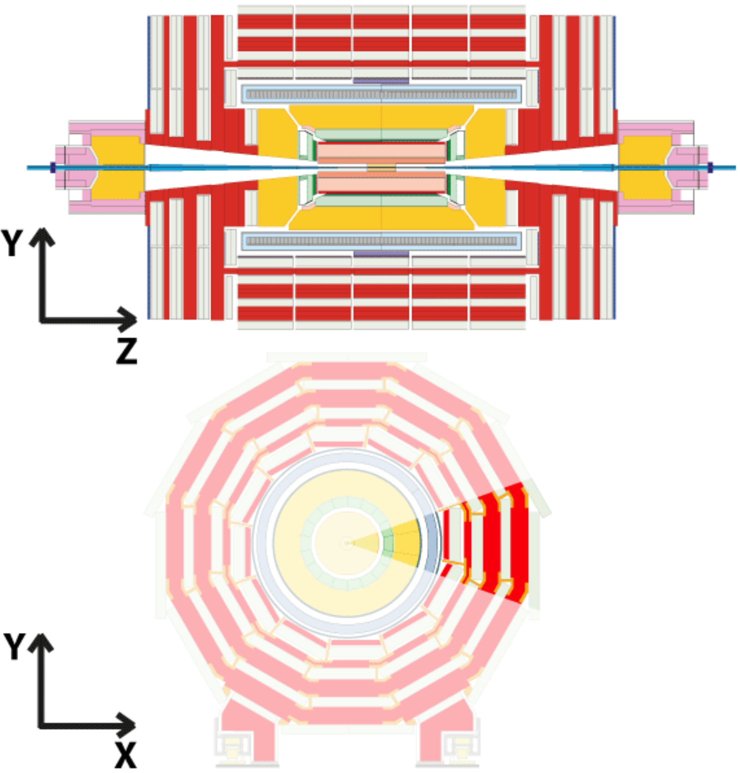


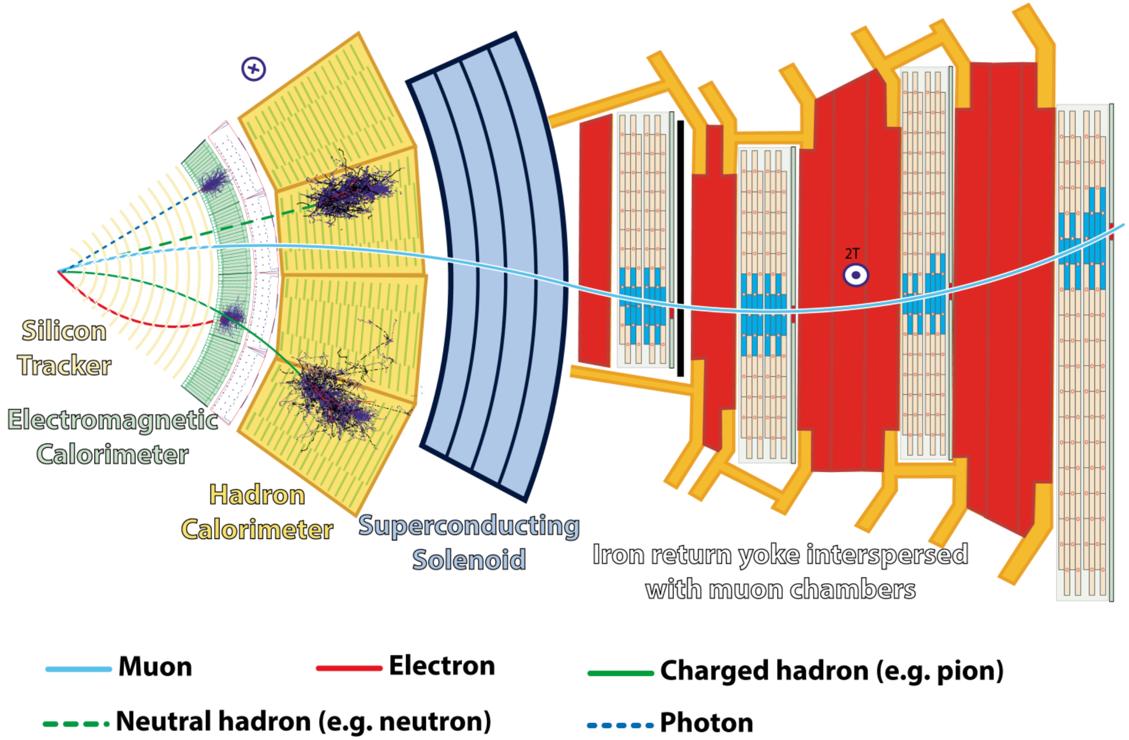
Design, construction, and performance of the new CMS pixel detector: conceptual differences to ATLAS pixels on micro- and macroscopic level

Malte Backhaus

IPA – Institute for Particle Physics and Astrophysics

CMS Experiment





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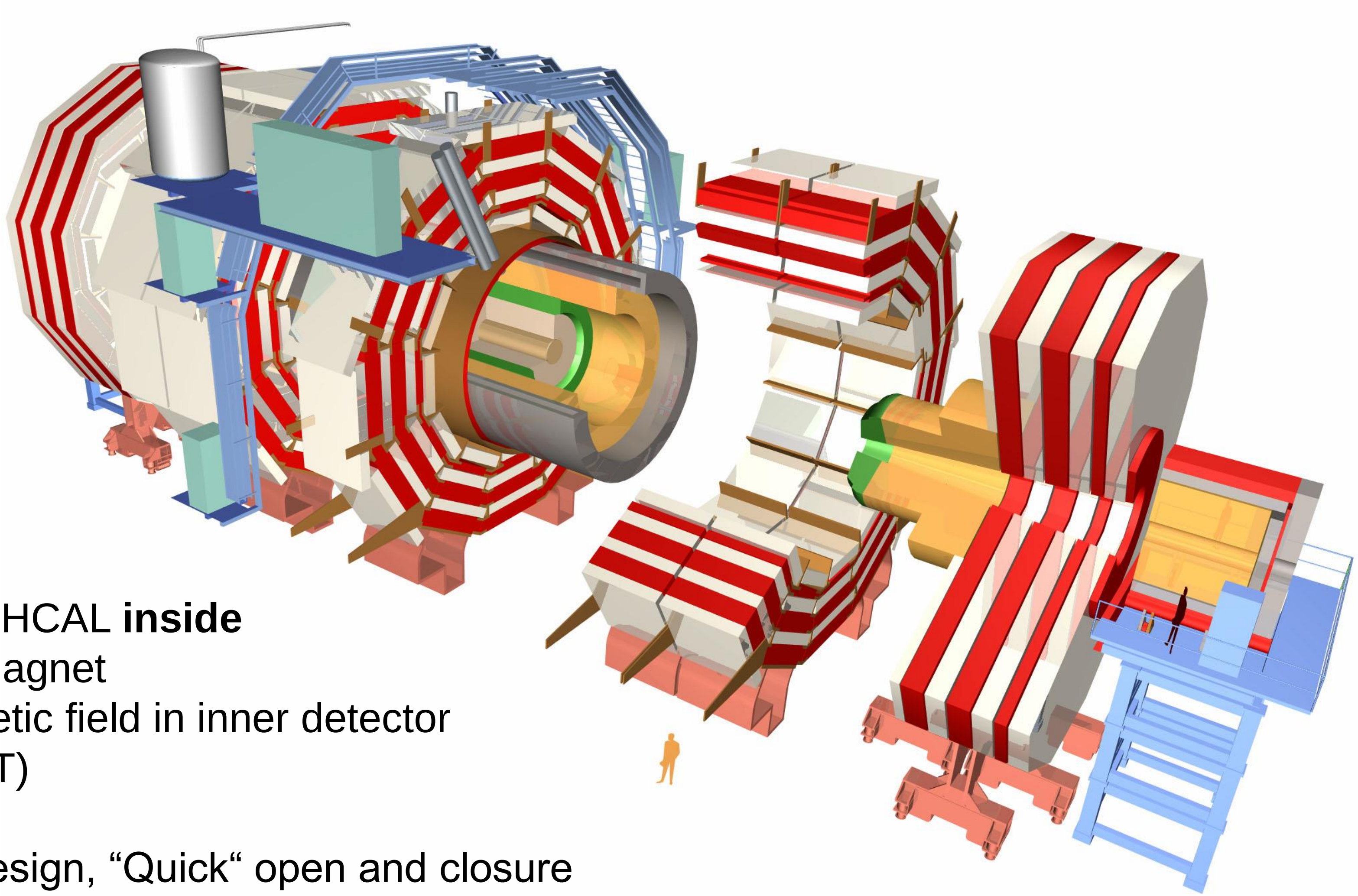
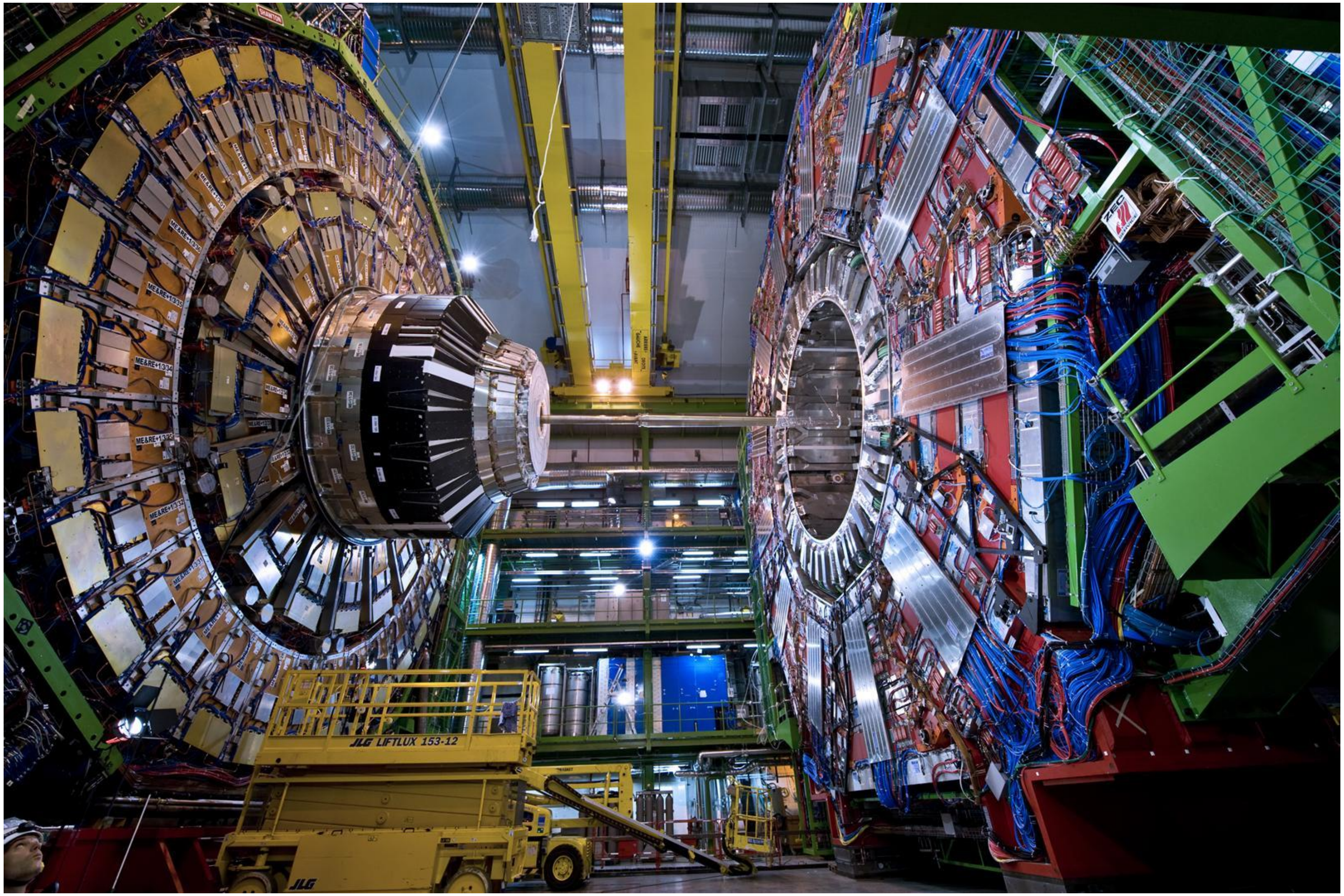


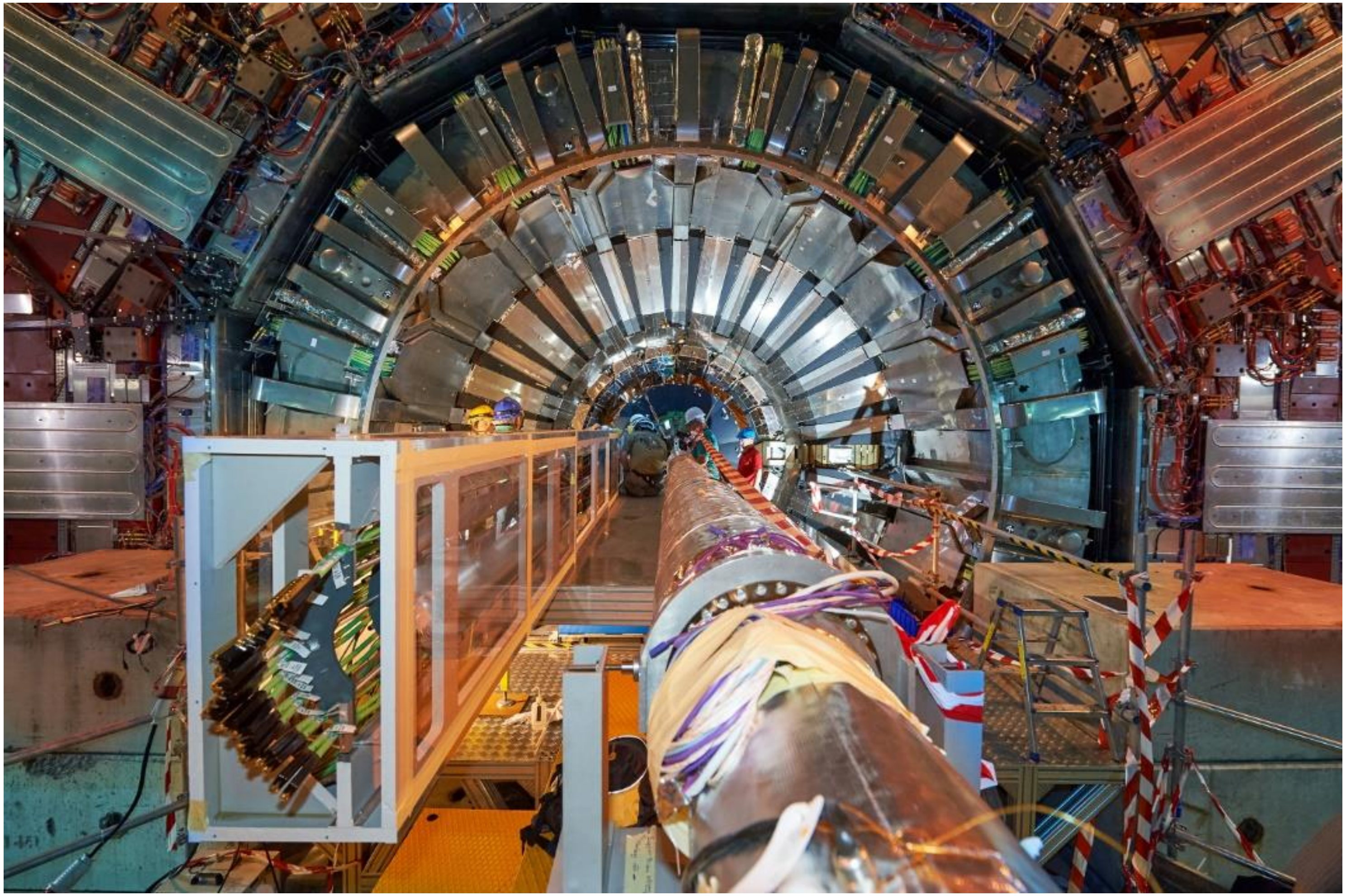
- ECAL and HCAL **inside** solenoid magnet
- ~4T magnetic field in inner detector (ATLAS: 2T)

- Modular design, "Quick" open and closure
- Access to components within ~14 days (ATLAS: ~6 months)

CMS Experiment



Insertion of CMS Pixel Detector: 2008



Insertion of new CMS Pixel Detector: 2017

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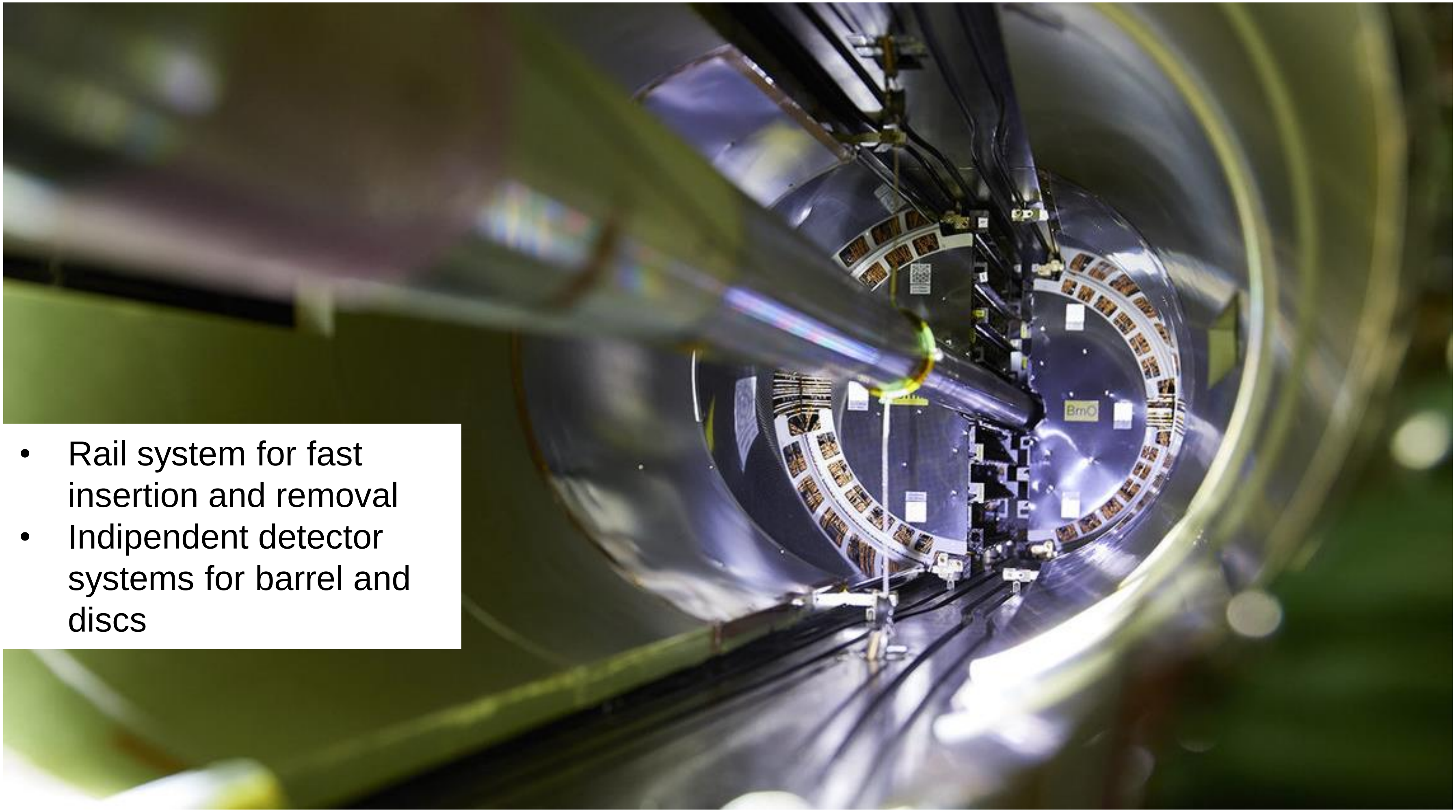
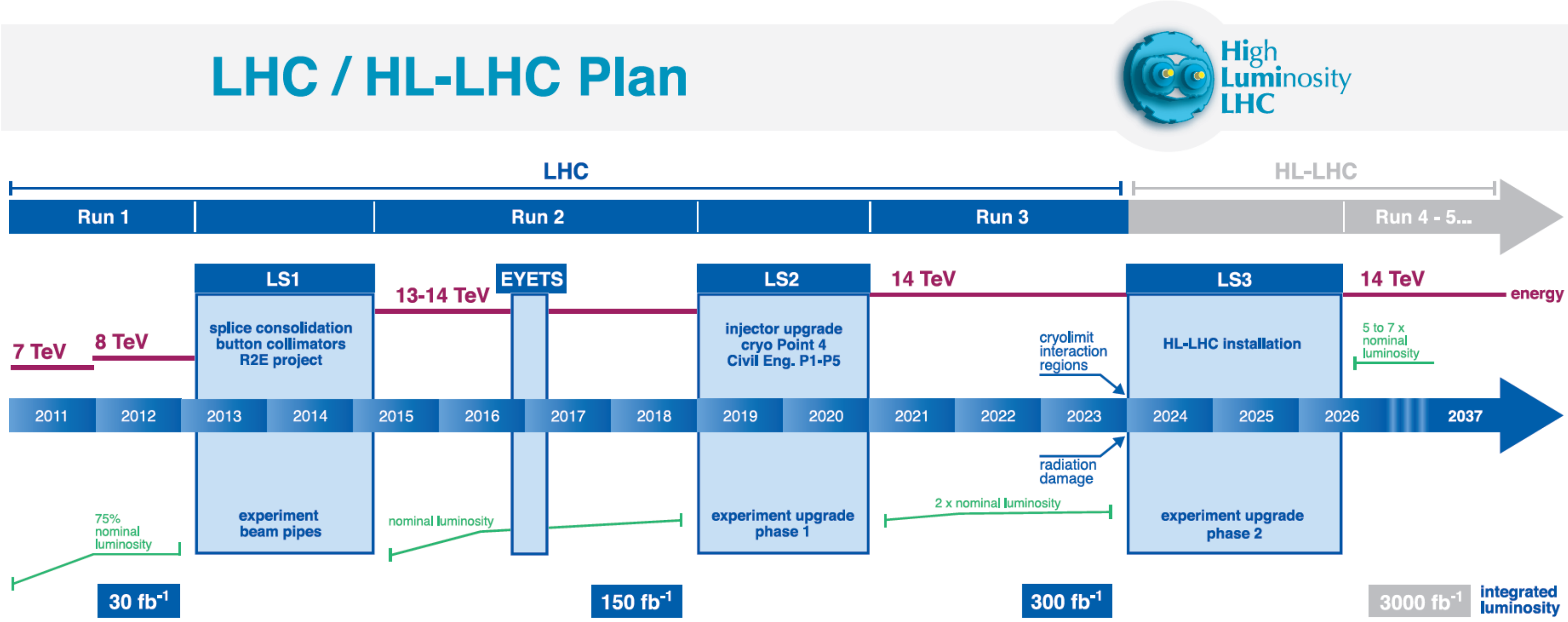


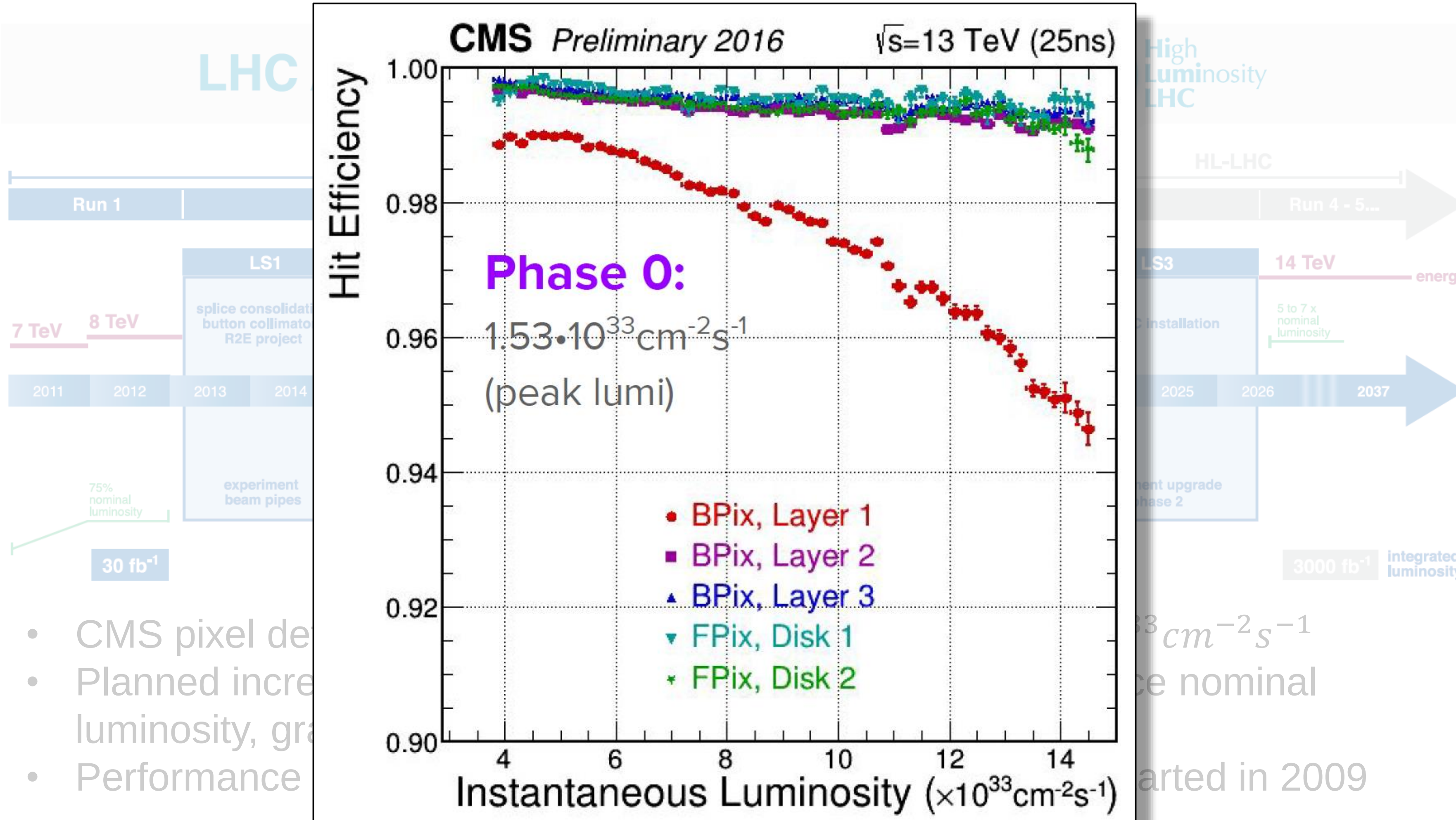
- Rail system for fast insertion and removal
- Indipendent detector systems for barrel and discs

Motivation for CMS Phase-I Pixels



- CMS pixel detector designed for peak luminosity of $10 \times 10^{33} cm^{-2} s^{-1}$
- Planned increase of luminosity after Long Shutdown 2 to twice nominal luminosity, gradual increase before LS2.
- Performance degradation anticipated, replacement project started in 2009

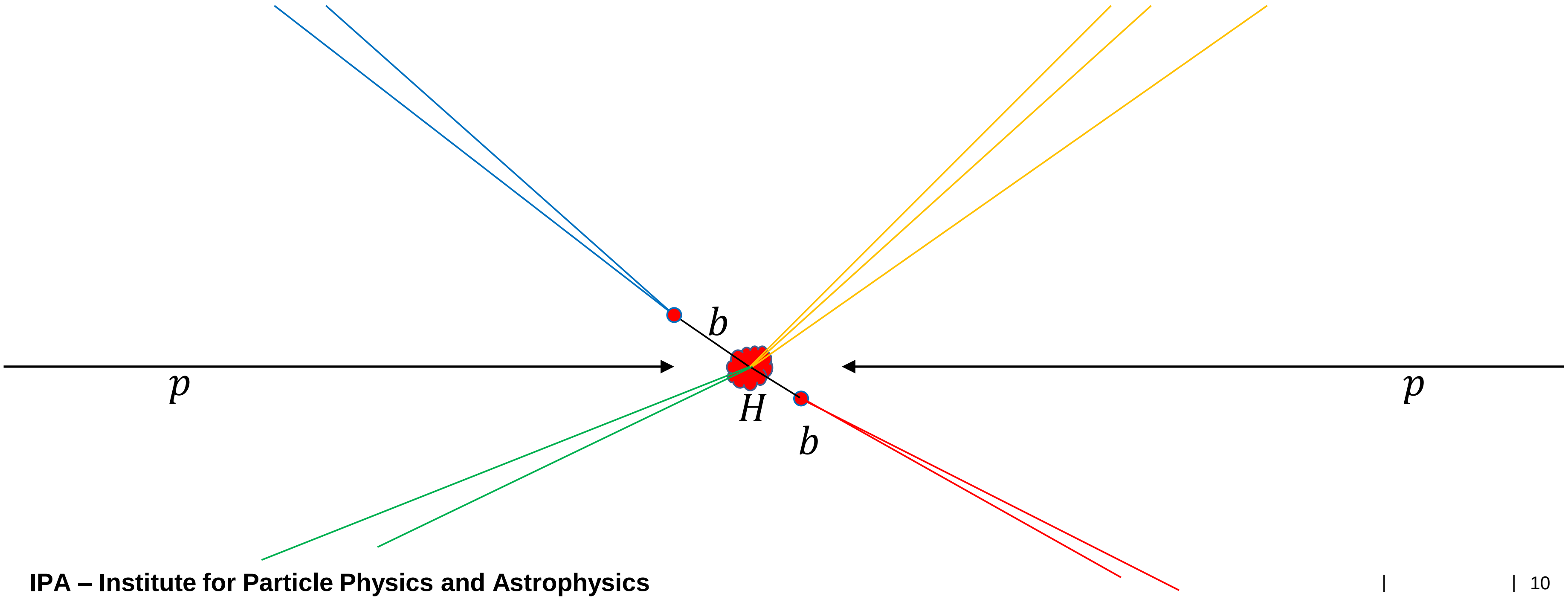
Motivation for CMS Phase-I Pixels



- CMS pixel de… …$^{3}\,cm^{-2}s^{-1}$
- Planned incre… …e nominal luminosity, gr…
- Performance … …arted in 2009

Secondary Vertex Identification

- Events with long lived hadrons (containing b-quarks and c-quarks) and τ-leptons are particularly interesting ($H \rightarrow b\bar{b},\ H \rightarrow \tau\tau,\ t\ \rightarrow bW^{\pm}$, ...)
- Decay in displaced *secondary vertices*



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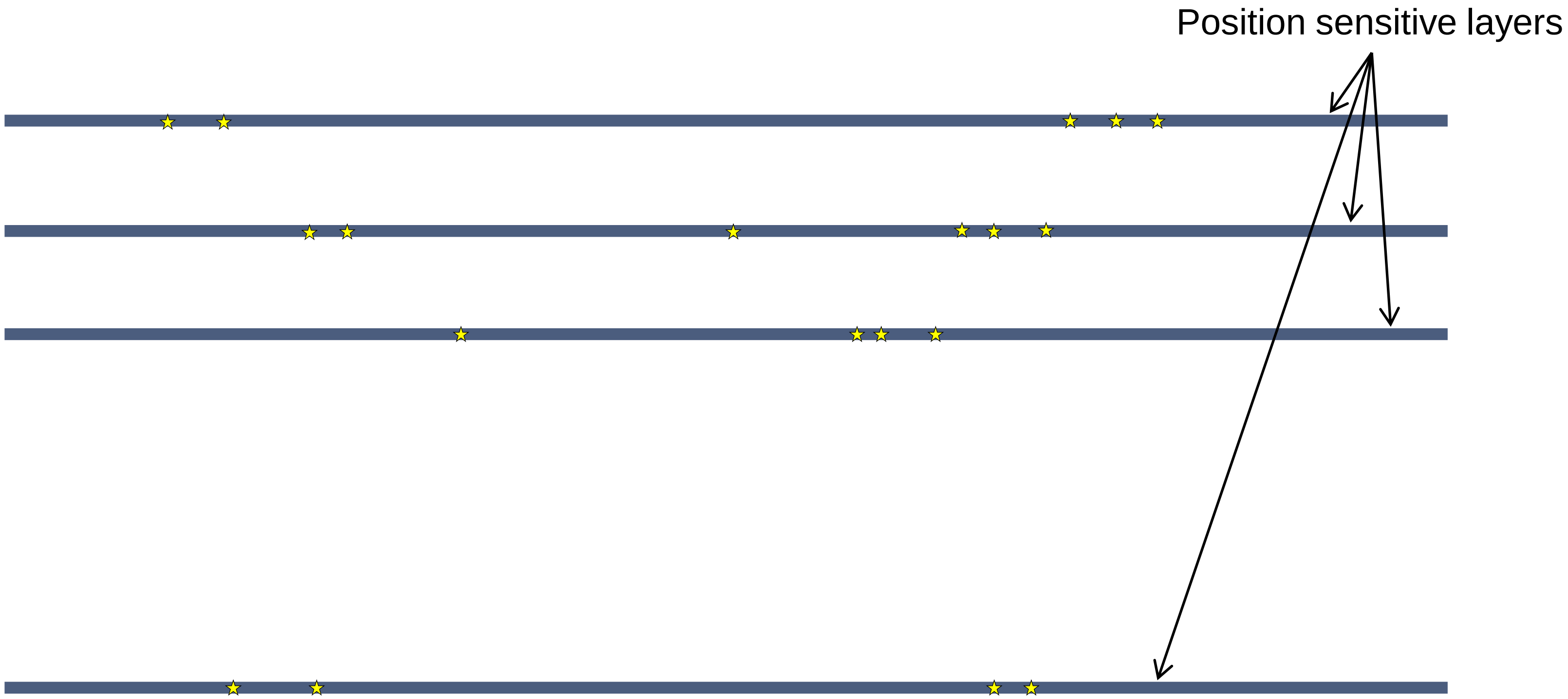

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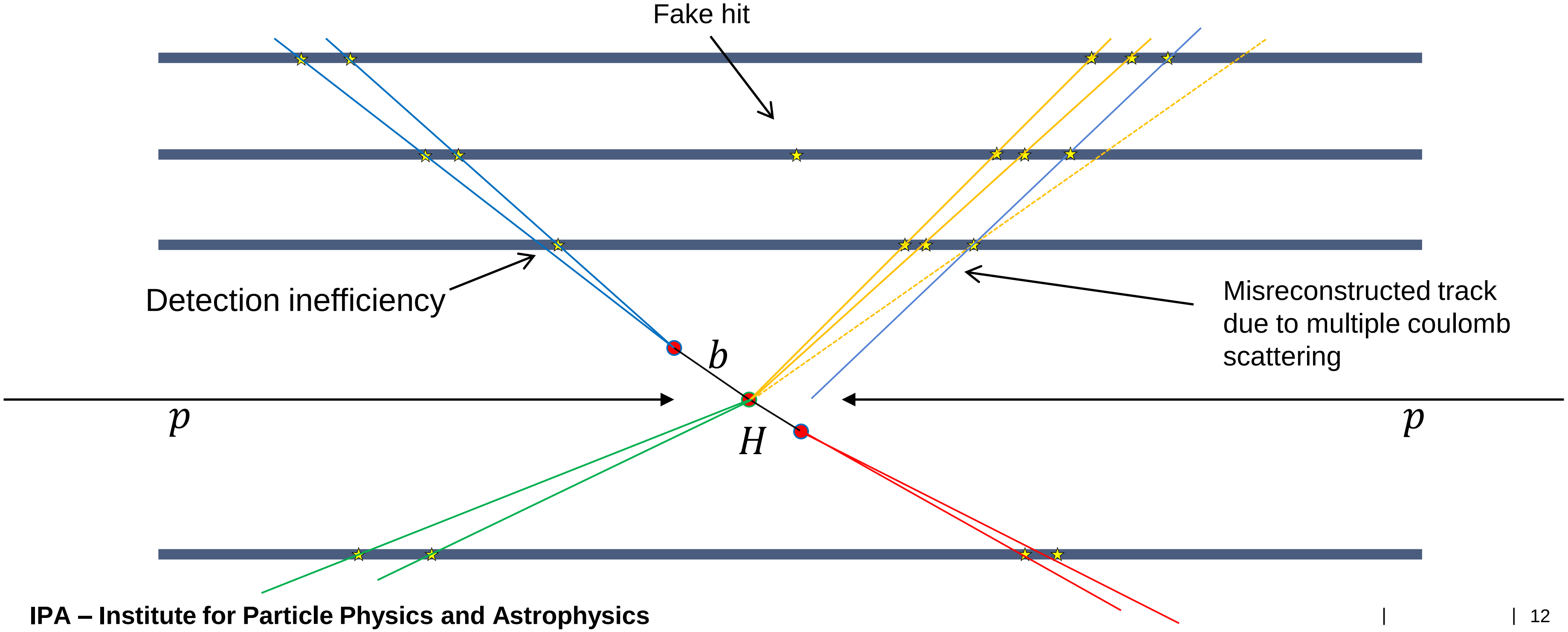


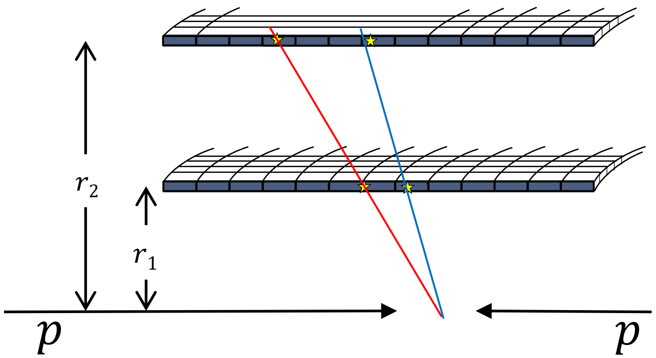
Requirements

- High detection efficiency
  + additional layer for tracking robustness
- Low fake-hit rate
- Low material
- High vertex resolution…

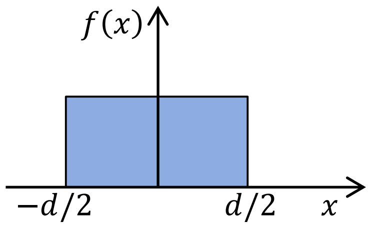
Simplified Vertex Resolution

Major vertex resolution dependencies → Simplified model:

- Two layers of 2D segmented detectors at r_1 and r_2
- Similar segmentation width d
- Full efficiency, no detection threshold



Spatial resolution:



$$\Rightarrow \quad \sigma = \frac{d}{\sqrt{12}}$$

Error propagation:

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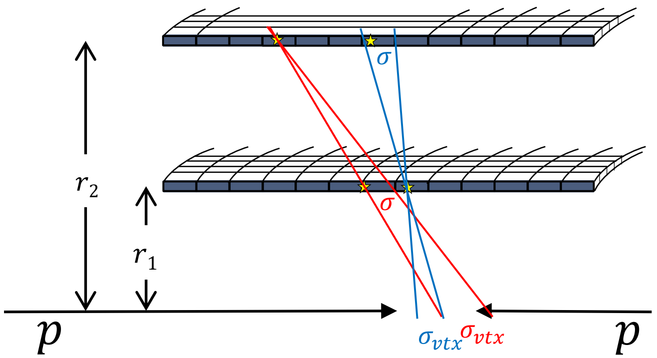

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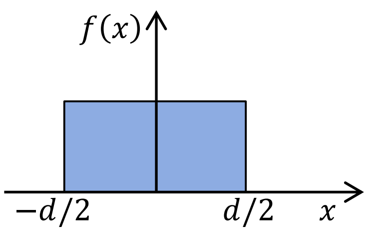

$$\Rightarrow \quad \sigma = \frac{d}{\sqrt{12}}$$

$$\sigma_{vtx} = \frac{r_2}{r_2 - r_1}\,\sigma \qquad \sigma_{vtx} = \frac{r_1}{r_2 - r_1}\,\sigma$$

Vertex Extrapolation:

$$\sigma_{vtx} = \sigma_{vtx} \oplus \sigma_{vtx} \cong \sqrt{\left(\frac{d}{\sqrt{12}}\right)^2 \cdot \left(1 + \frac{r_1^{\,2}}{(r_2 - r_1)^2}\right)}$$

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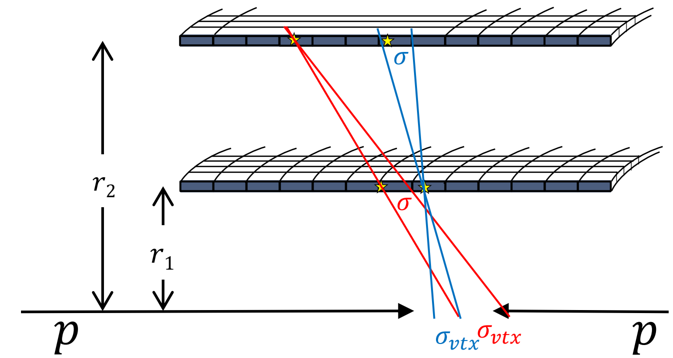
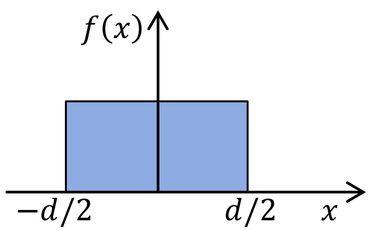


Spatial resolution:



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Vertex Extrapolation:

add MS

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Error propagation:

Requirements

- High detection efficiency
  + additional layer for tracking robustness
- Low fake-hit rate
- Low material
- High vertex resolution…
  - High spatial resolution
  - Small distance to interaction point
  - Large lever arm

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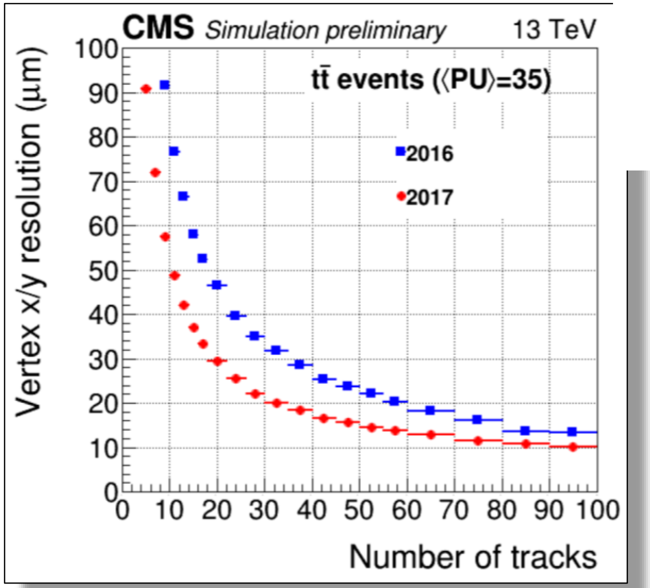

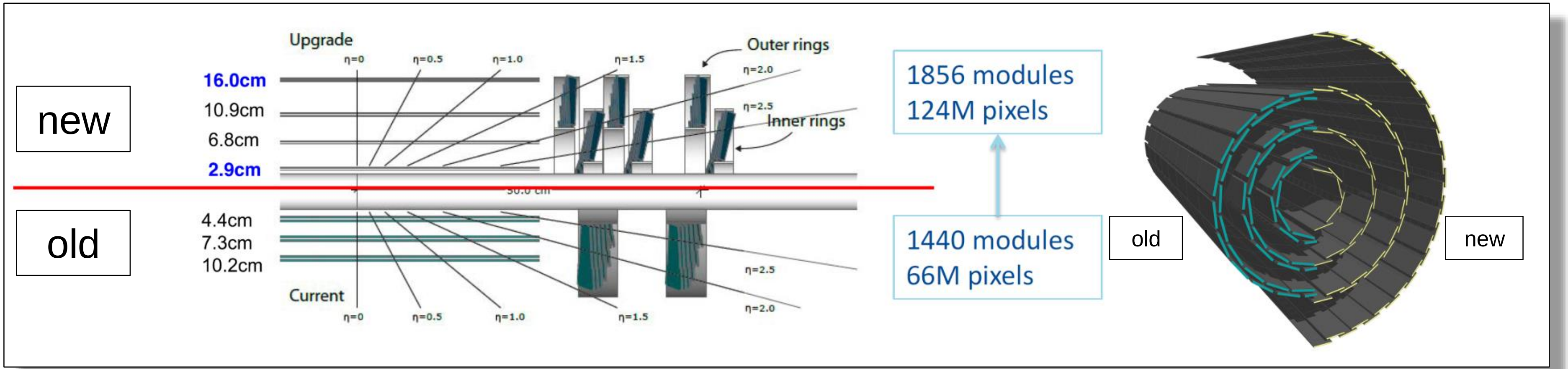

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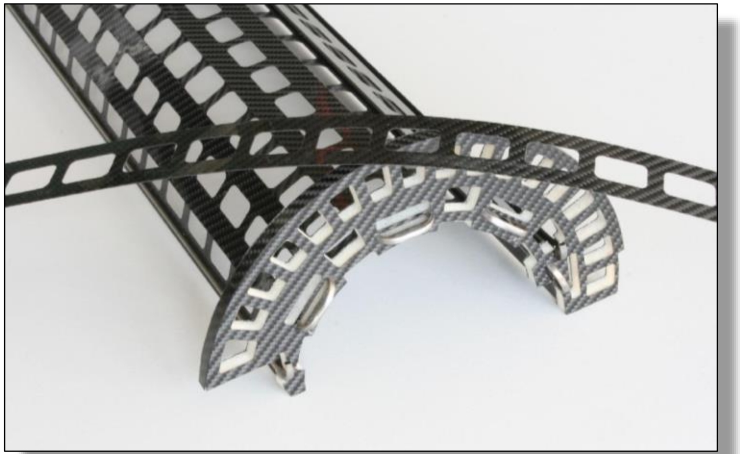
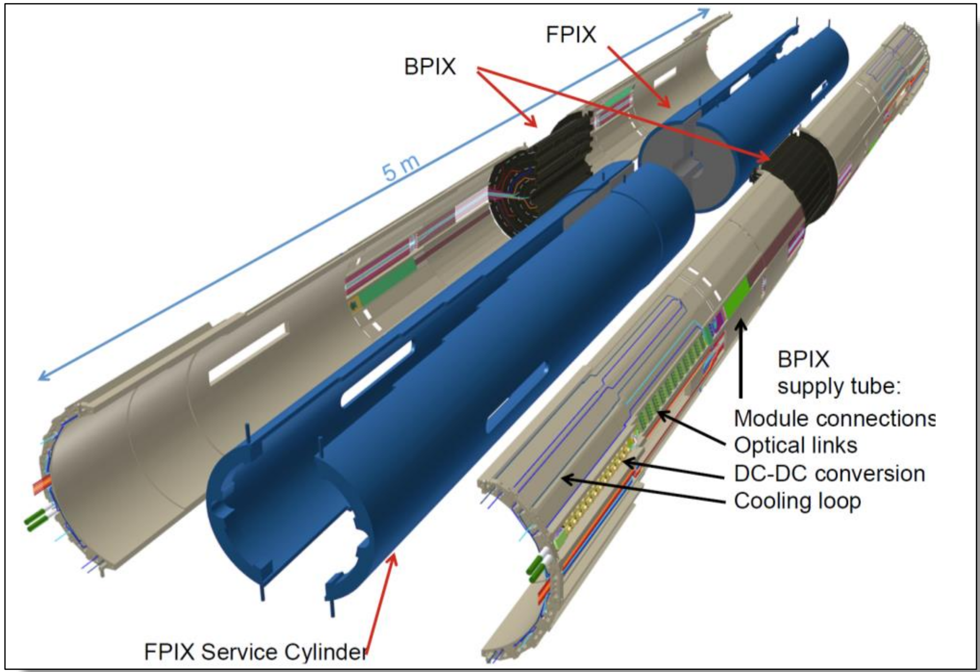
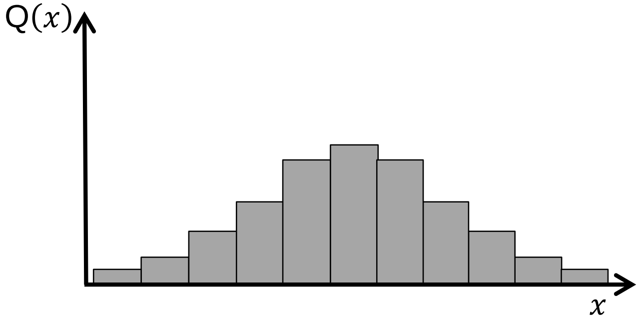
- DC-DC power system
  → four layers without service material increase
- CO_2 bi-phase cooling
- Leightweight carbon support ladders / rings
- Service components placement at larger z





Towards high spatial resolution – ATLAS IBL

- Small segmentation pitch improves resolution: $\sigma = \frac{d}{\sqrt{12}}$
- ATLAS IBL: $50\ \mu m\ \ r\phi$ resolution → $\sigma = 15\ \mu m$
- Analog charge information → charge weighting → improved resolution



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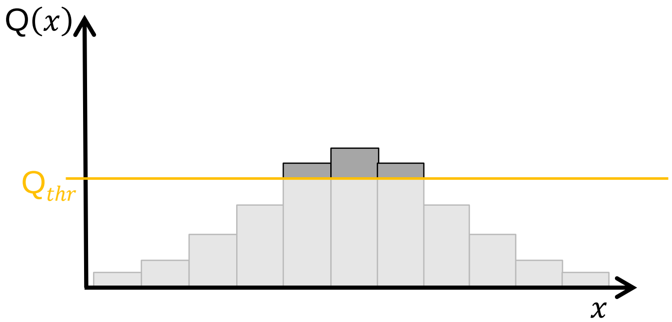

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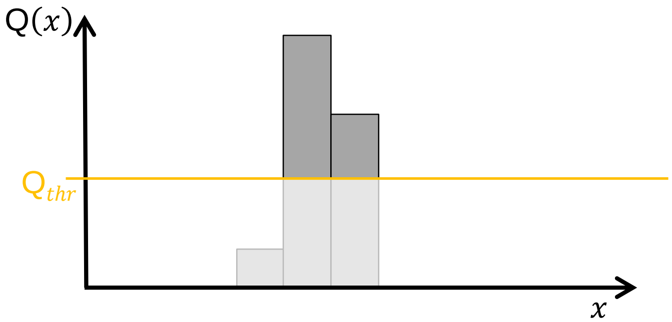
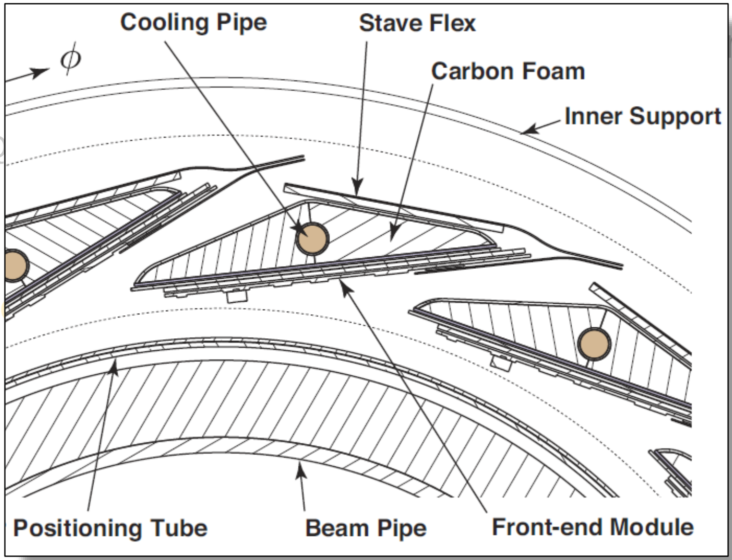
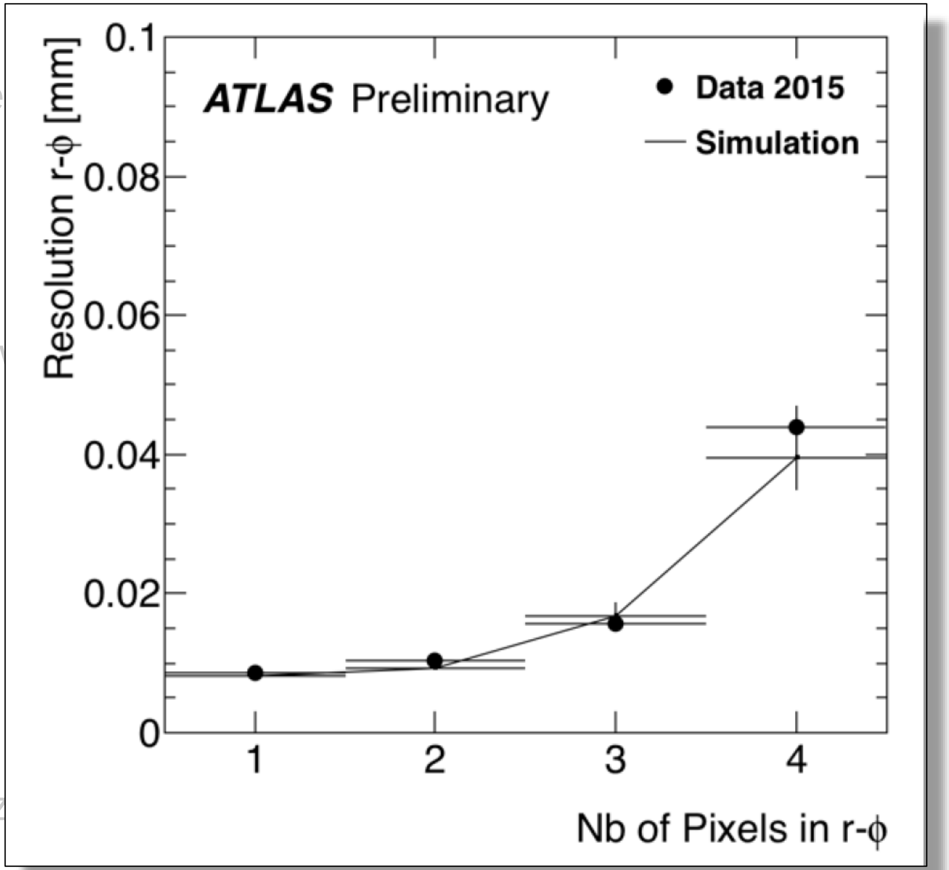


- Design system for 2-3 pixel cluster size

Towards high spatial resolution – ATLAS IBL

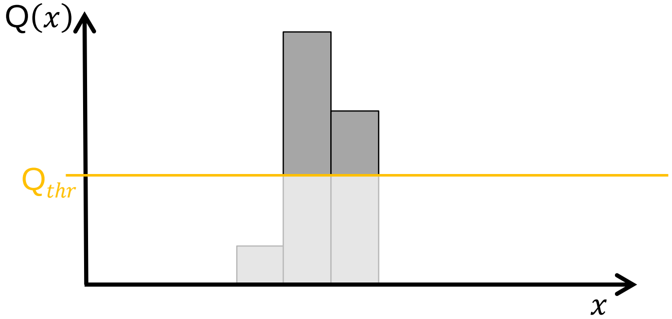
- Tilt of staves by 14°
  → 2-3 hit cluster size due to incident angle
- Resolution improvement:
  $15\ \mu m\ \rightarrow \sim 9\ \mu m$





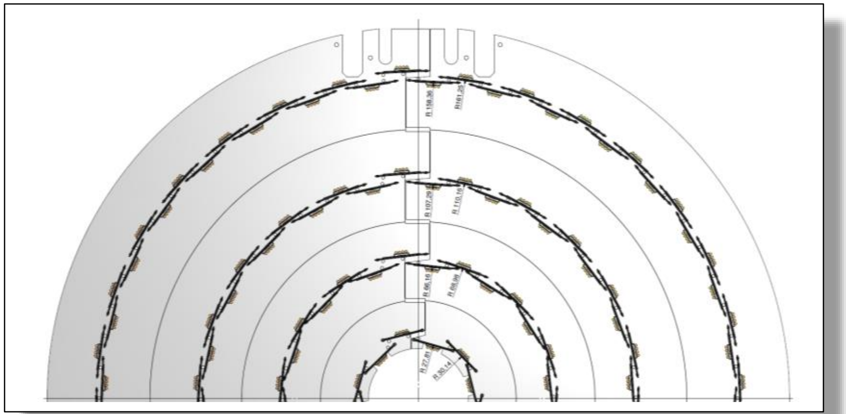
Towards high spatial resolution – CMS Pixel

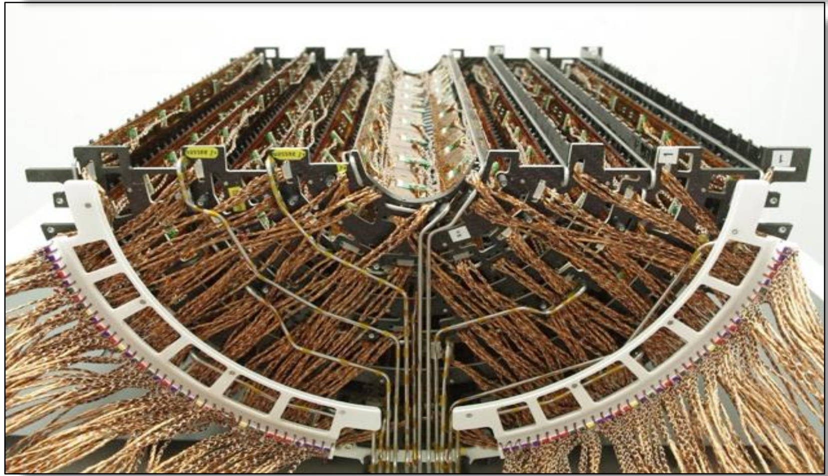
- Small segmentation pitch improves resolution: $\sigma = \frac{d}{\sqrt{12}}$
- CMS pixel: $\mathbf{100\ \mu m}\ r\phi$ resolution → $\boldsymbol{\sigma = 30\ \mu m}$
- Analog charge information → charge weighting → improved resolution



- Design system for 2-3 pixel cluster size

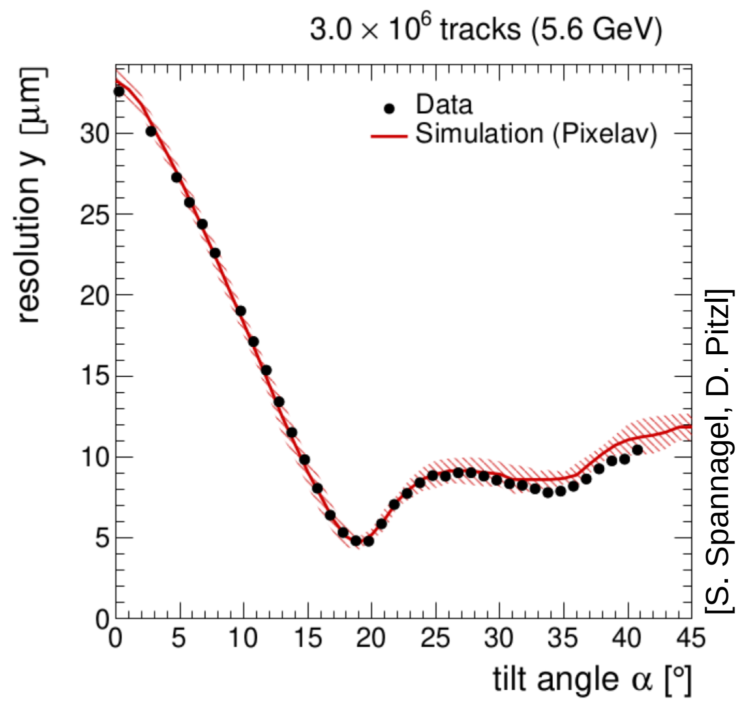
Towards high spatial resolution – CMS Pixel





- No tilt of ladders
  → orthogonal incident angle
- Use strong magnetic field in CMS
  → Charge drift in Lorentz angle ($21°$)
  → 2-3 hit cluster size
- Massive resolution improvement if charge resolution is good ($100\ \mu m$ pixel pitch)
  → Analog pixel cell readout
  → 8bit ADC
- Sensor thickness chosen for optimal cluster size
  → $285\ \mu m$ active thickness
  → Expected performance decrease after type inversion / partial depletion

Towards high spatial resolution – CMS Pixel



- $100\ \mu m$ direction, 1.5 ke threshold
- $4.8\ \mu m$ resolution at optimal angle $(19.5°)$ and at Landau-Peak

- No tilt of ladders
  → orthogonal incident angle
- Use strong magnetic field in CMS
  → Charge drift in Lorentz angle $(21°)$
  → 2-3 hit cluster size
- Massive resolution improvement if charge resolution is good $(100\ \mu m$ pixel pitch)
  → Analog pixel cell readout
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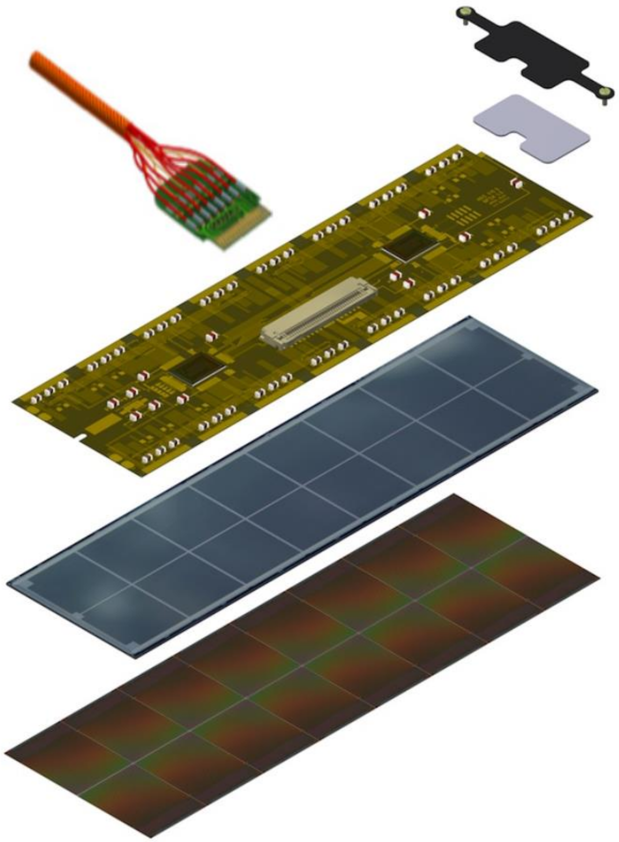
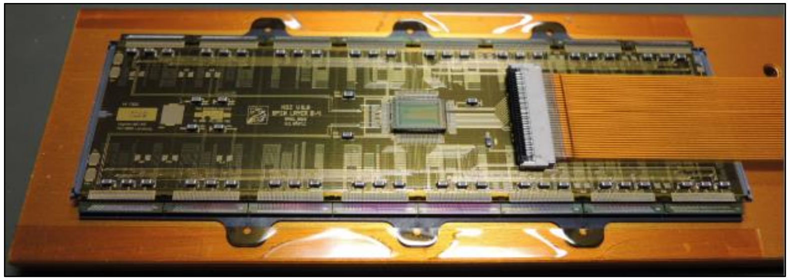
Modules for CMS phase 1 pixels

- Sensor:
  - Same as phase 0, 16 ROCs per sensor
  - n-in-n silicon design, 4160 pixels / ROC
  - pixel size: $100\ \mu m \times 150\ \mu m$
  - Edge pixel size increased, no ganged pixels
  - $285\ \mu m$ active thickness
- ROC (ReadOut Chip):
  - $250\ nm$ CMOS technology
  - $160\ Mbit/s$ readout
  - All transistors enclosed layout, manual layout and routing
  - Column-drain architecture with analog readout, single on-chip ADC for digital data transmission
- TBM (Token Bit Manager):
  - Interface to ROCs + readout control of ROCs, $400\ Mbit/s$ readout
  - Different number of TBM cores for variable bandwidth:
    L3 + L4: 1 core, L2: 2 cores, L1: 4 cores

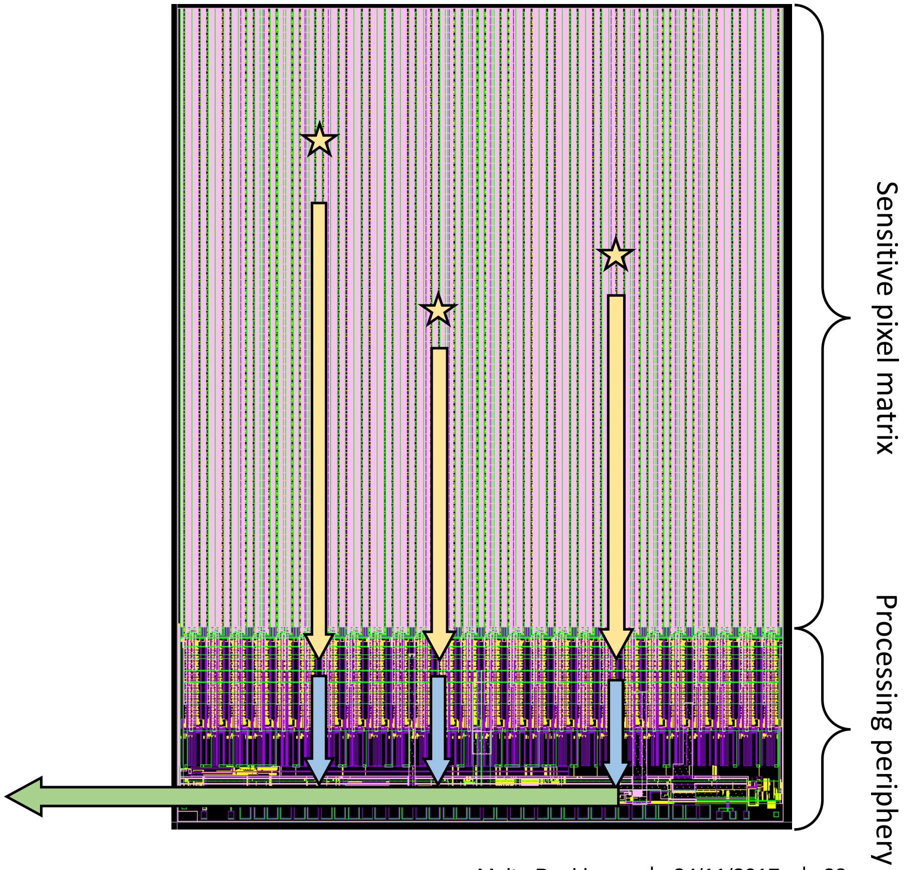




Readout chip overview

- Column drain architecture:
  1. Copy **all** hits from matrix into buffers
  2. Wait for trigger
  3. Digitize hit and send data (or delete hit)
  - Very similar architecture in ATLAS FE-I3, digitization using ToT mechanism
    → clock in matrix, increased current consumption
  - Fully analog matrix readout in CMS pixels
    → no clock in matrix, low current consumption

Designed by PSI



Readout

- Column dra
  1. Copy all hi

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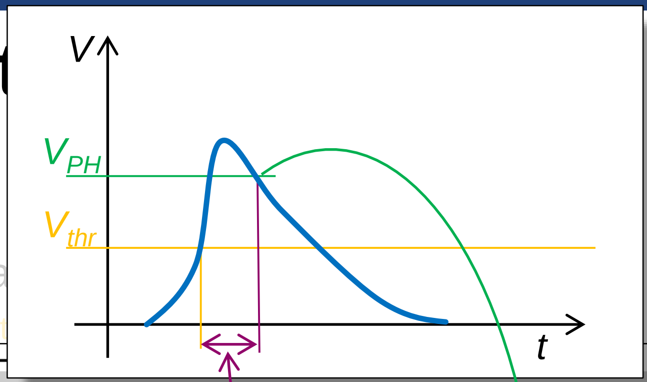

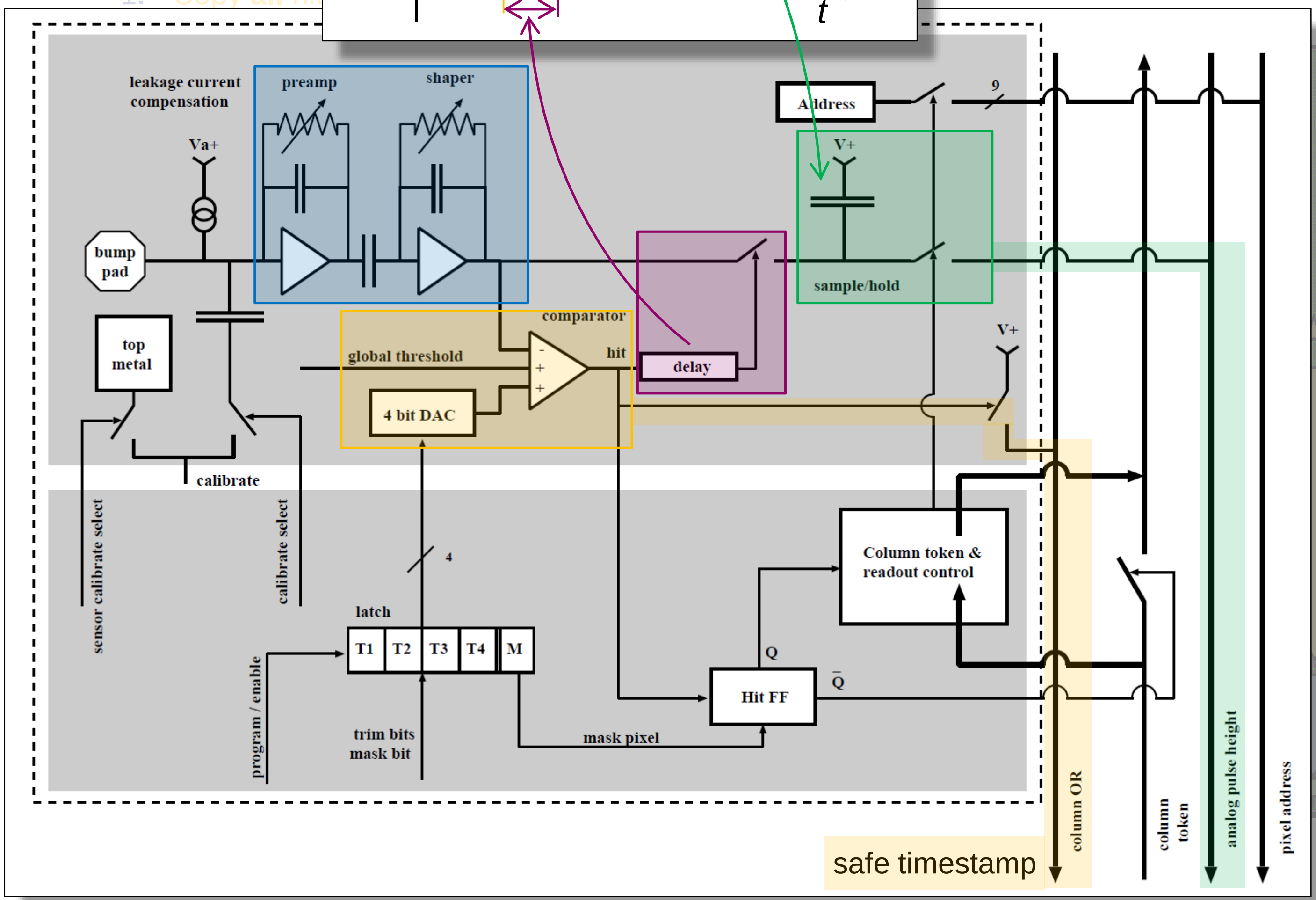

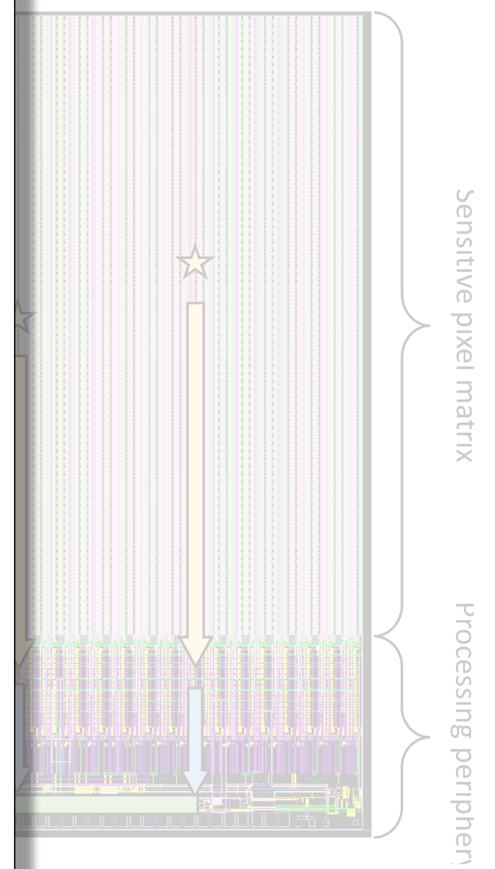

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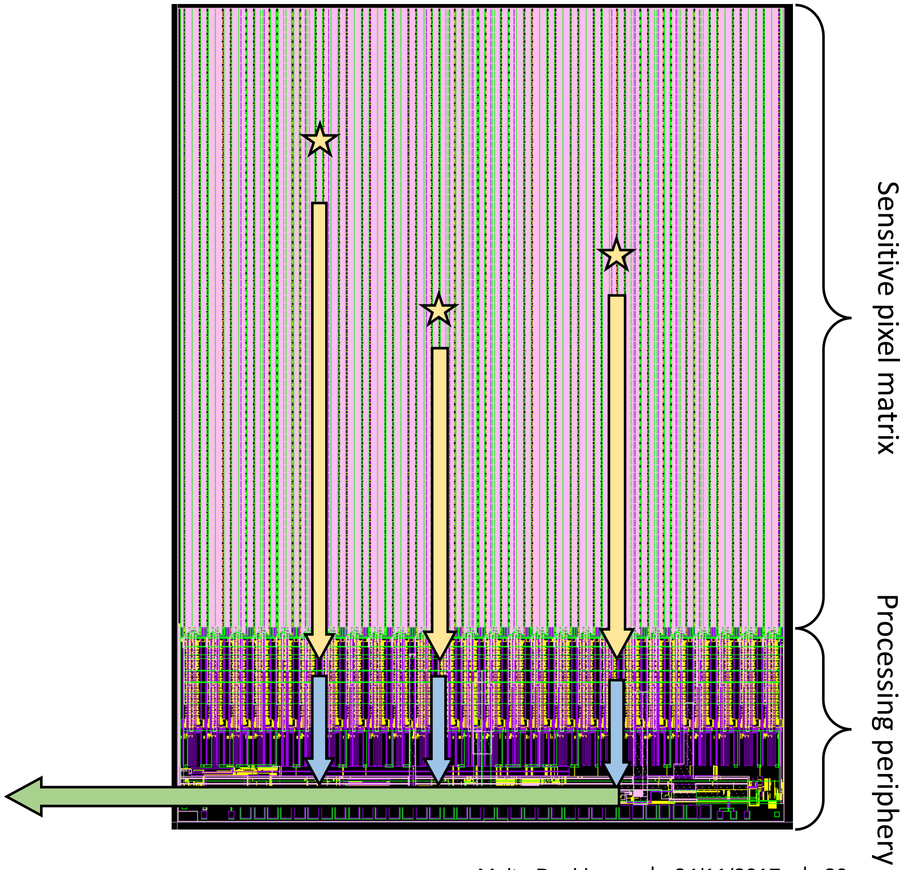
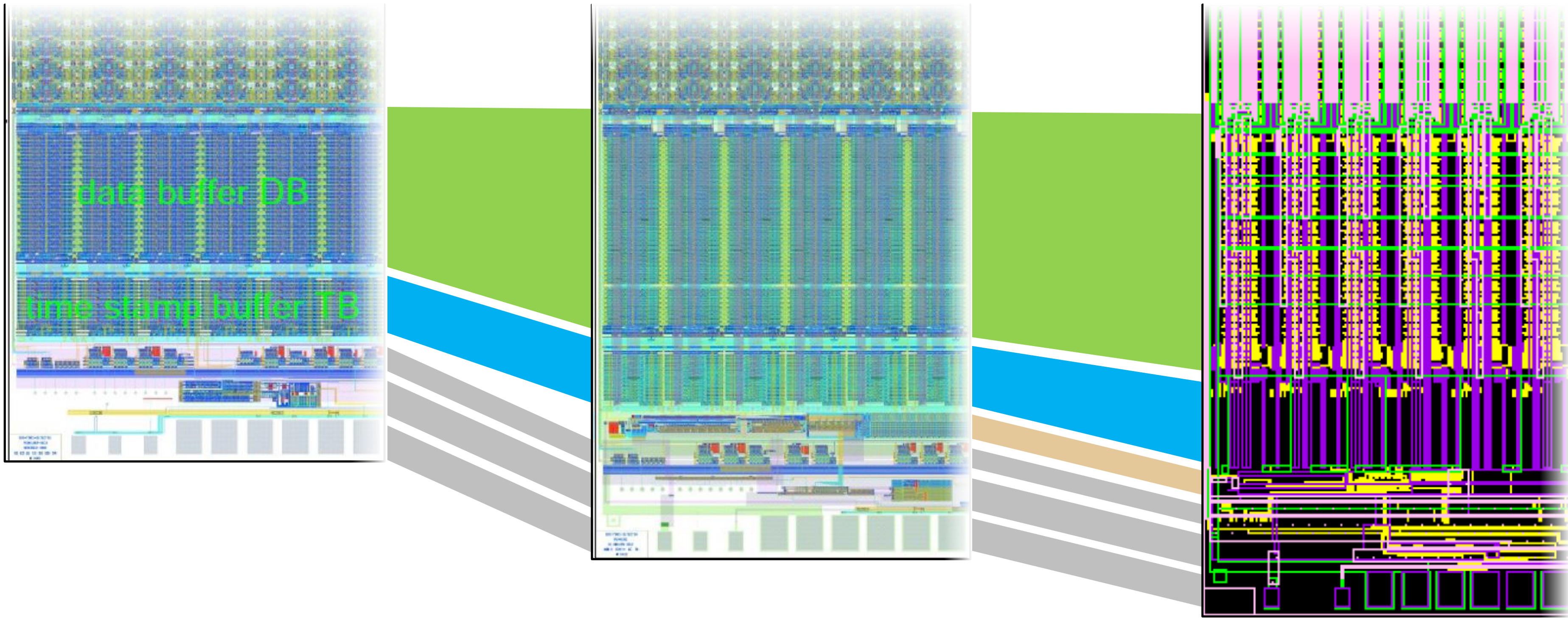
    → clock in matrix, increased current consumption
  - Fully analog matrix readout in CMS pixels
    → no clock in matrix, low current consumption
- $0.1\ W/cm^2$ power consumption (FE-I4: $0.2\ W/cm^2$)
- Size: $7.9\ mm \times 10.2\ mm$
- $160\ Mbit/s$ readout
- $< 2000\ e$ threshold
- $8\ bit$ pulse height charge information
- Data loss: 1.6% at 150 MHz/cm^2
  → Buffer depth increase wrt. phase 0
  → Inefficiency due to copy time

Designed by PSI



From CMS phase 0 to phase 1 ROCs

PSI46 – phase 0 all layers | psi46dig – phase 1 L2-L4 | PROC600 – phase 1 L1



PSI46 – phase 0 all layers

- DB: 32, TB: 12
- RO: 40 MHz analog
- Analog Column Drain architecture

psi46dig – phase 1 L2-L4

- DB: 80, TB: 24
- RO: 160 MHz (digitized)
- Analog Column Drain architecture
- ADC + 64 ReadOut Buffers

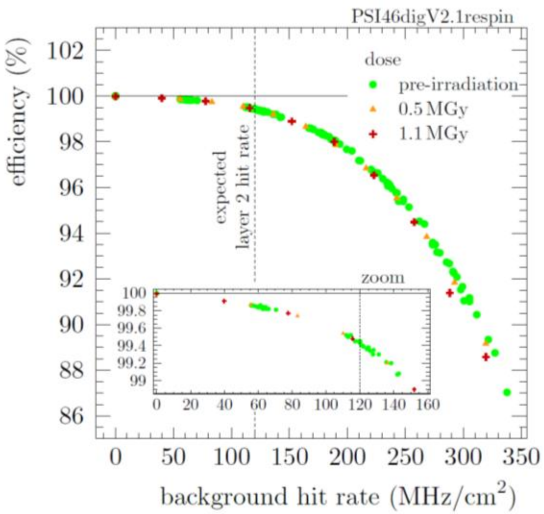
PROC600 – phase 1 L1

- DB: 4x56, TB: 40
- RO: 160 MHz (digitized)
- Analog *dynamic cluster* Column Drain architecture
- ADC + 64 ReadOut Buffers

Phase 1 ROCs efficiency

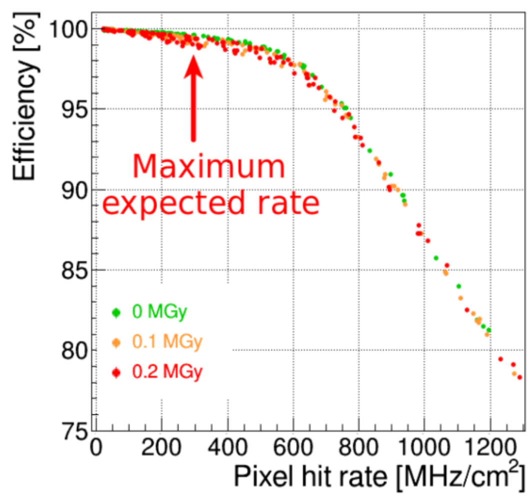
- Generate flux with xrays or protons → measure pixel hit rate
- Test charge injection in single pixel → measure detection efficiency
- Significant efficiency increase wrt. phase 0 ROCs
  → increase of buffer depth (+*cluster copying* in PROC600)
- Performed on all modules during QC tests for efficiency validation

psi46dig – xrays



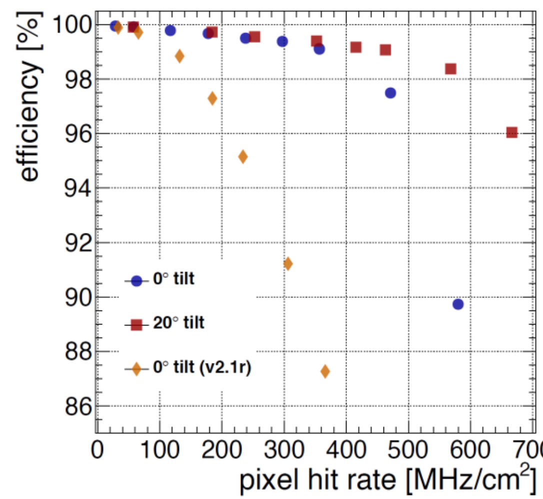
[J. Hoss]

PROC600 – xrays



[M. Meinhard]

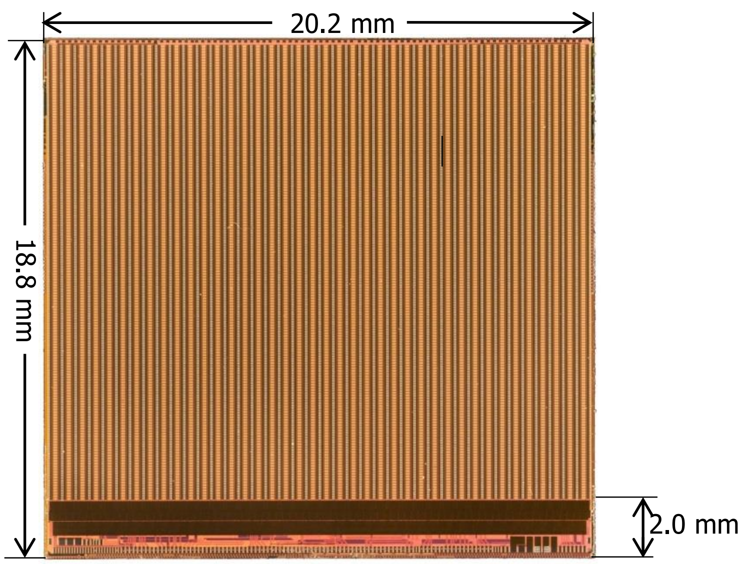
PROC600 – protons

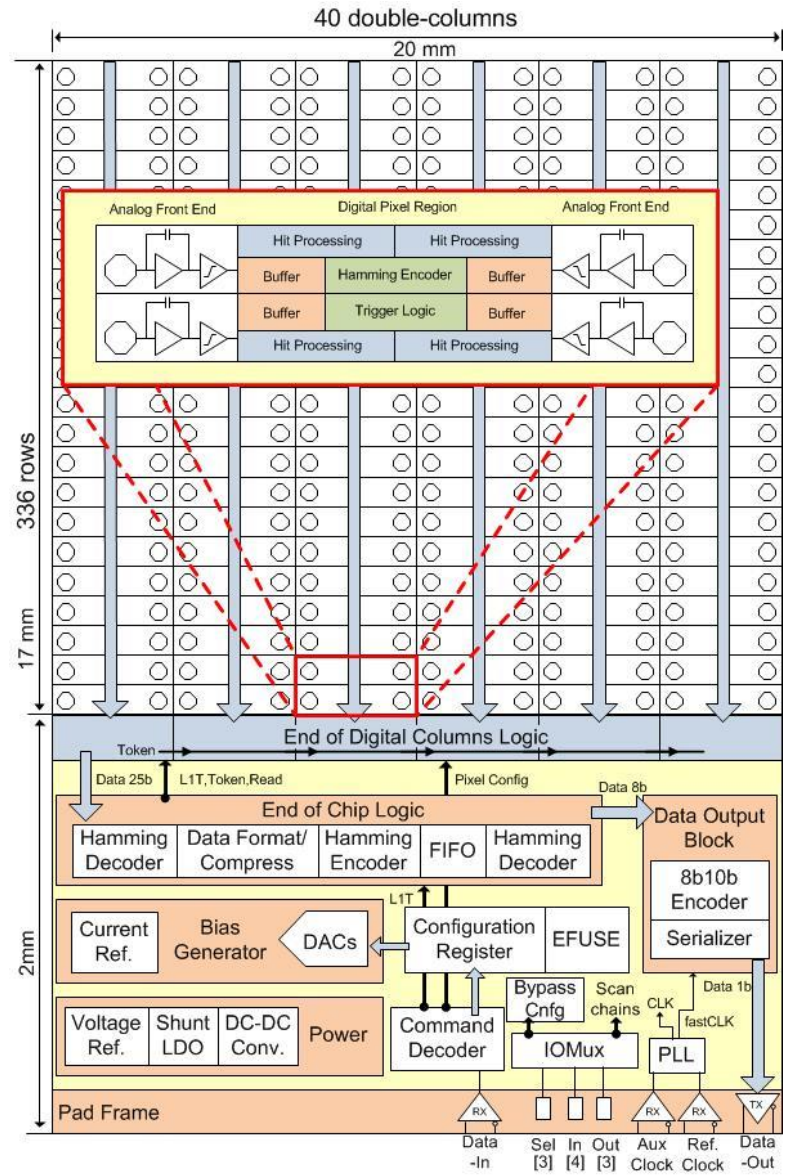


[P. Berger]

FE-I4 Overview

- Largest chip in high energy physics:
  19 x 20 mm² → ~6 times size of FE-I3 or CMS ROCs.
- No column-drain architecture:
  avoid copying of untriggered data
  → buffer and trigger logic in pixel cell
  → increase of digital logic
  → power consumption: $0.2\ W/cm^2$
- Readout structured in four pixel regions,
  → efficient cluster readout

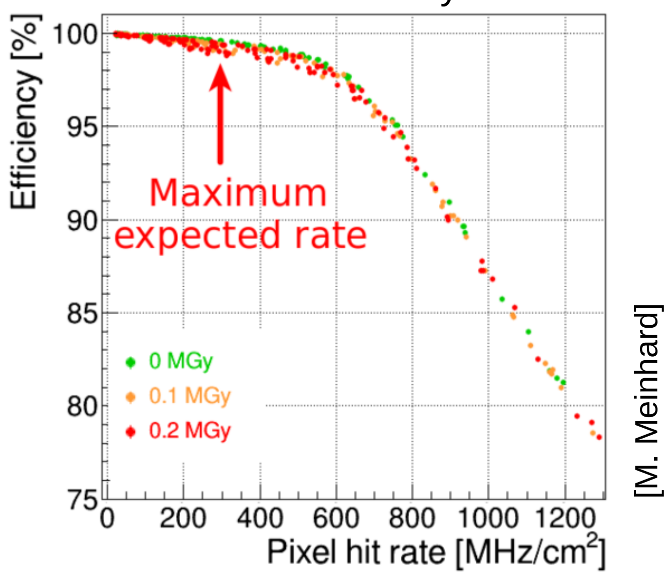




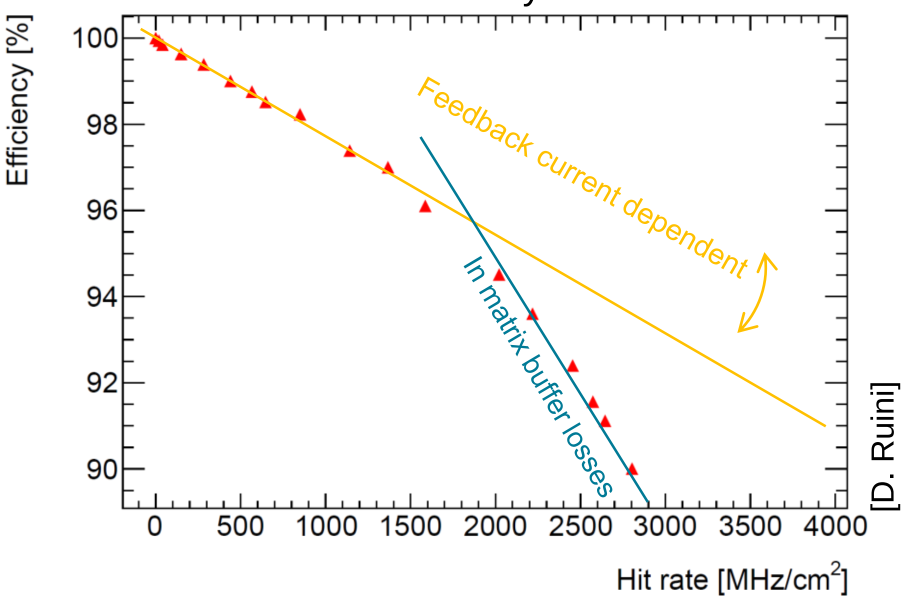
ATLAS FE-I4 effciency

- Efficiency validation in FE-I4 can be done with internal injection (done during QC tests)
- Performed comparison measurement using xrays and similar settings
- Pulse Height measurement allows faster amplifier return than ToT
  → higher efficiency
- Significanly less copy/buffer inefficiency in FE-I4

PROC600 – xrays



FE-I4 – xrays



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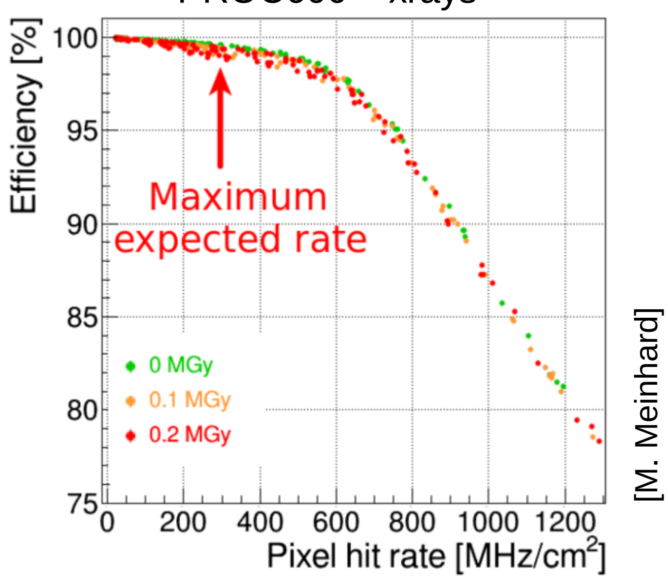
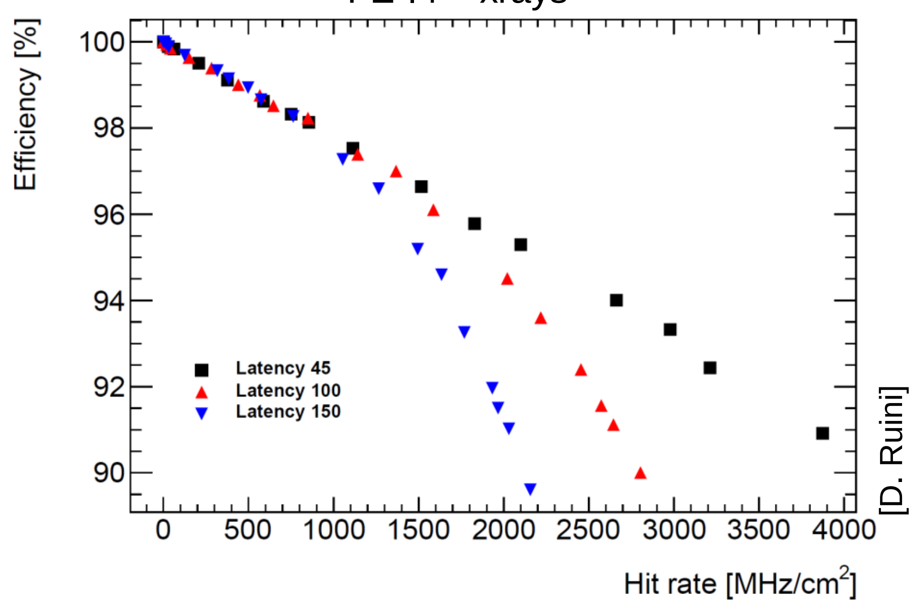
- Significanly less copy/buffer inefficiency in FE-I4

PROC600 – xrays

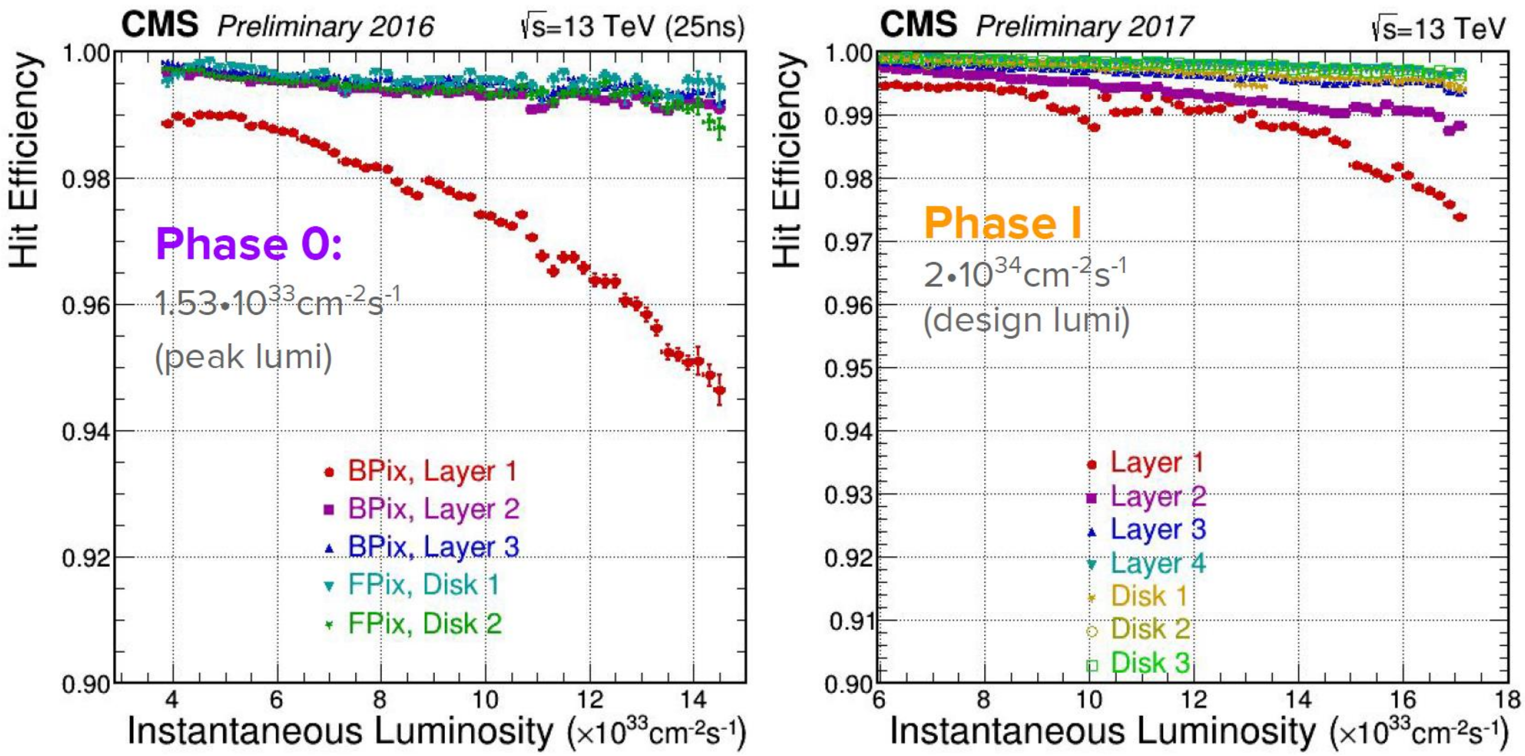


FE-I4 – xrays



ETH zürich

Efficiency improvement in detector

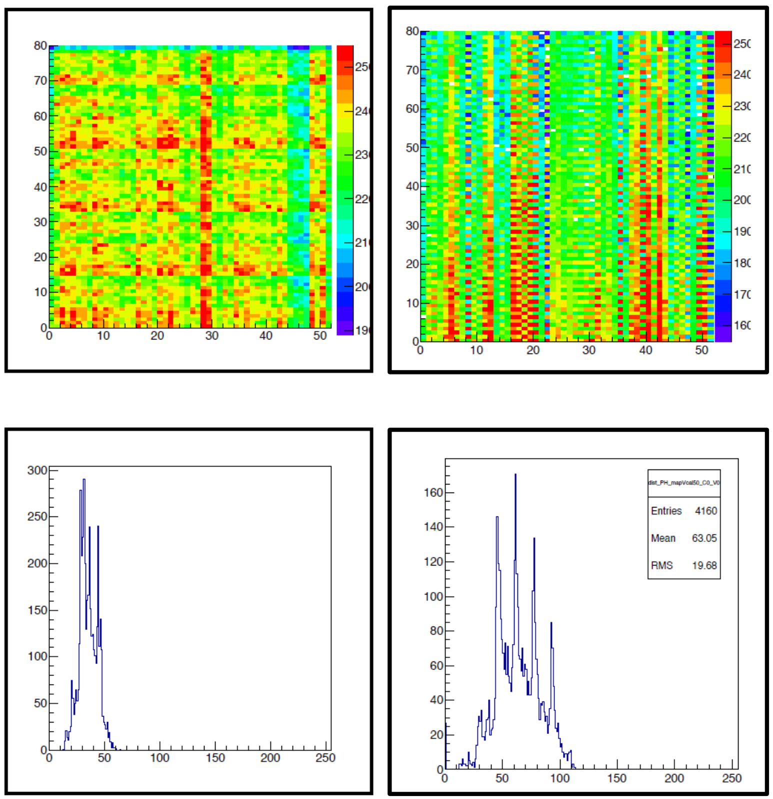


- CMS phase 1 pixel detector with very good hit finding efficiency
- Even the new Layer 1 at smaller radius exceeds phase 0 performance, at $12 \times 10^{33} cm^{-2} s^{-1}$: 96% → 99% (radius: $4.4\ cm \rightarrow 2.9\ cm$)

Phase 1 ROCs charge resolution

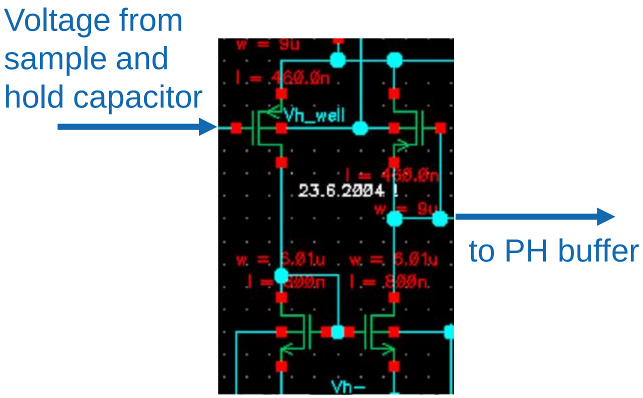
- No pixel by pixel PH adjustment

digv21respin | PROC600



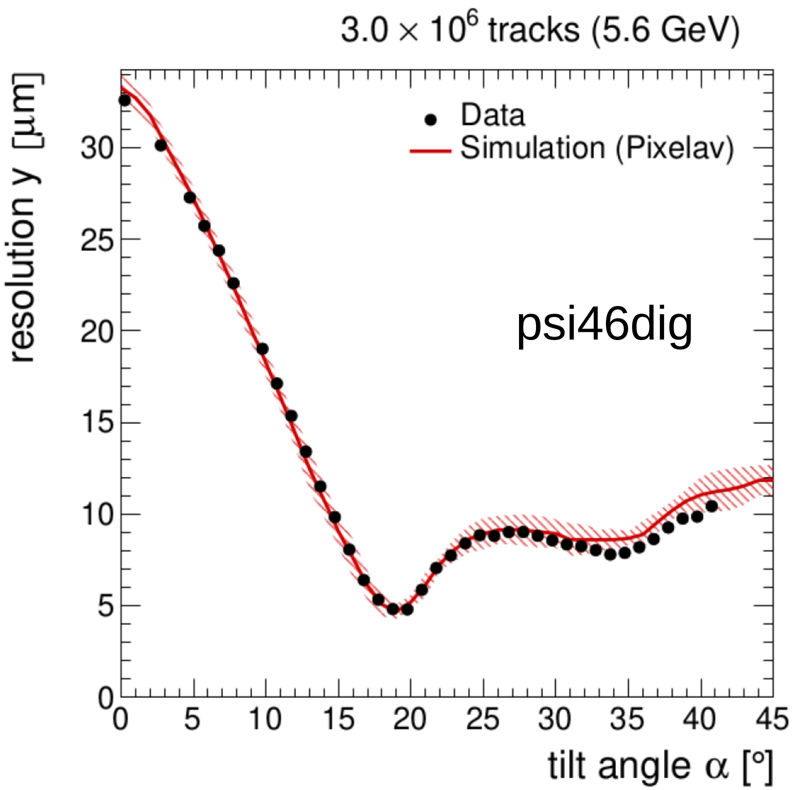
[D. Zhu]

- Good uniformity in psi46dig
- Parallel copying of four hits in PROC600
  → four current mirrors per double column in same area
  → reduction of transistor size required
  → relative production variation increased



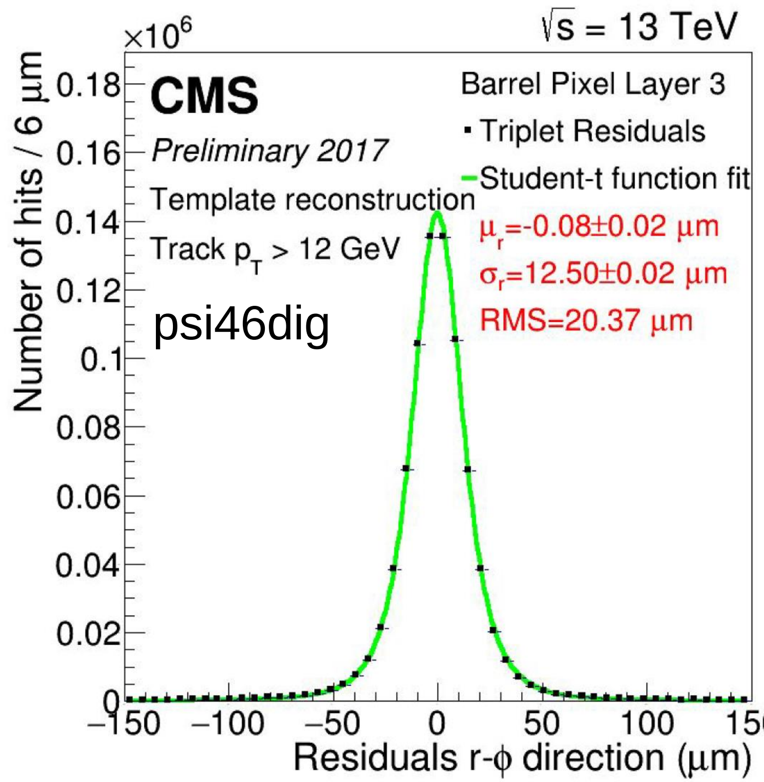
Phase 1 detector performance: spatial resolution

Testbeam



- $100\ \mu m$ direction, 1.5 ke threshold
- $4.8\ \mu m$ resolution at optimal angle ($19.5°$) and at Landau-Peak

Detector

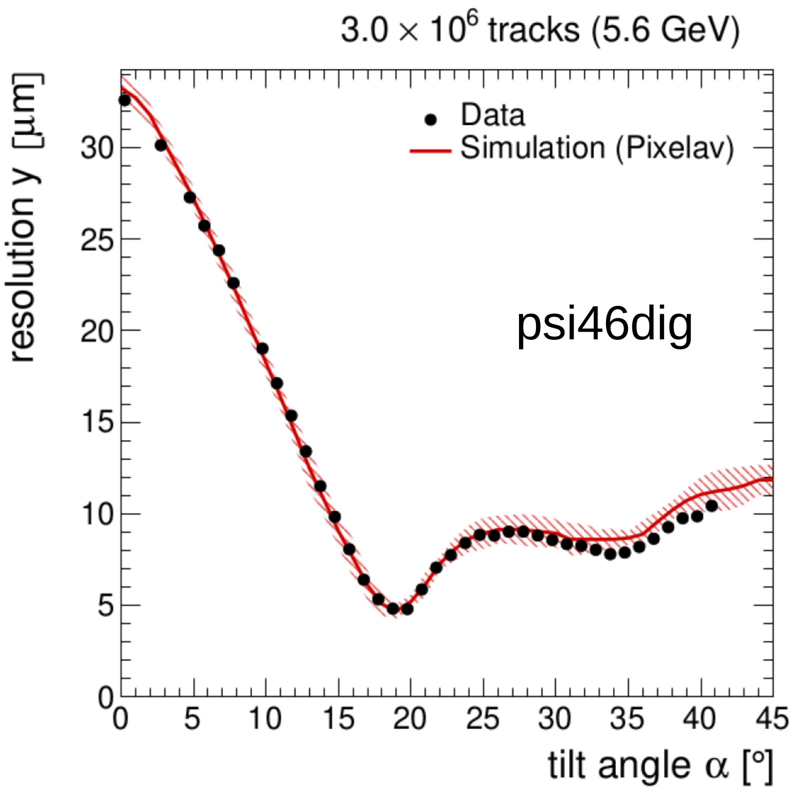


- $12.5\ \mu m$ resolution in CMS in Layer 3 (1.5 ke threshold, good Q resolution)

ETH zürich

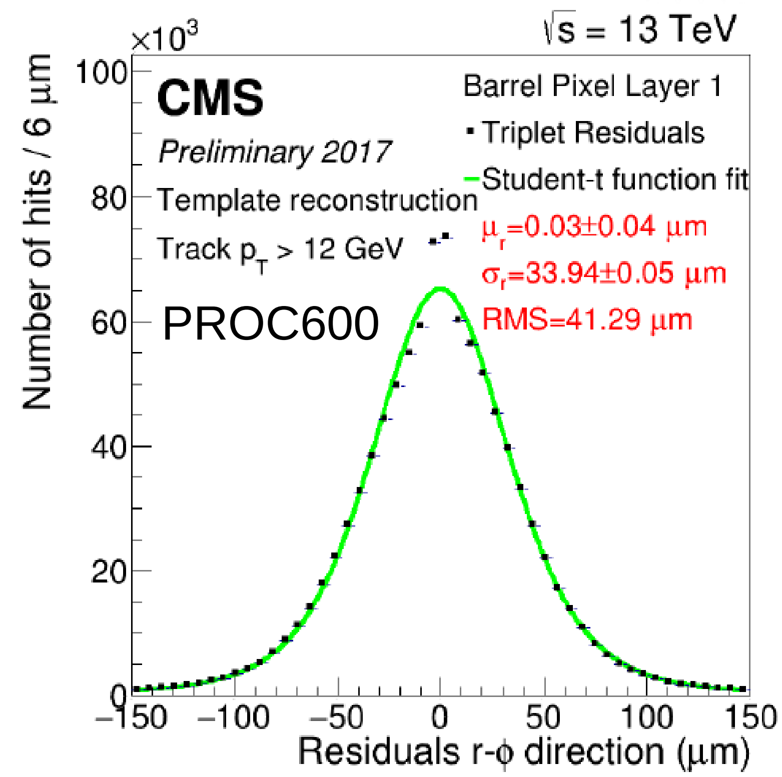
Phase 1 detector performance: spatial resolution

Testbeam



- $100\ \mu m$ direction, $1.5\ \mathrm{ke}$ threshold
- $4.8\ \mu m$ resolution at optimal angle ($19.5°$) and at Landau-Peak

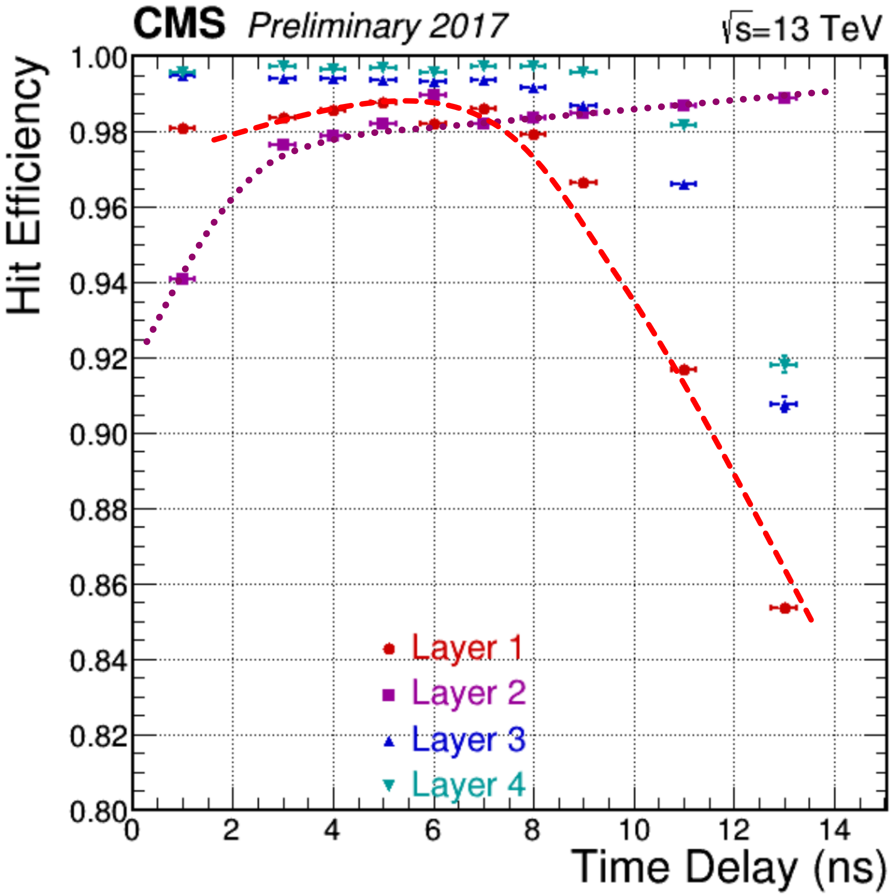
Detector



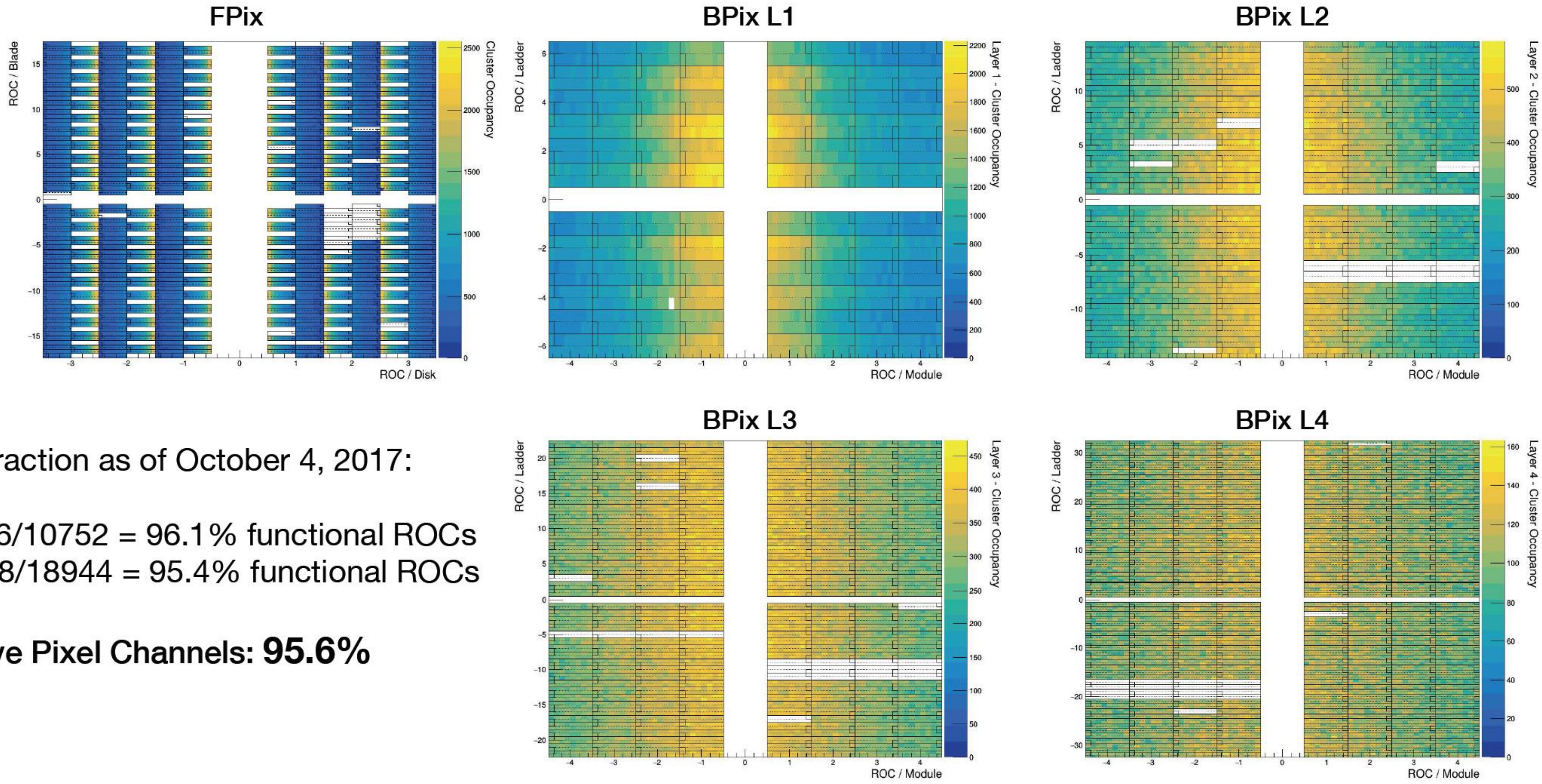
- $12.5\ \mu m$ resolution in CMS in Layer 3 ($1.5\ \mathrm{ke}$ threshold, good Q resolution)
- Layer 1: higher thr. and less Q res

Phase 1 detector performance: timing

- Fine time adjustment in pp collisions
  → PROC600 faster than psi46dig
- Layer 1 and layer 2 on same clock link
- Timing optimized for layer 1 efficiency
  → slightly early for layer 2
- Improved situation by adjusting on-chip bias settings



Phase 1 detector performance: occupancy

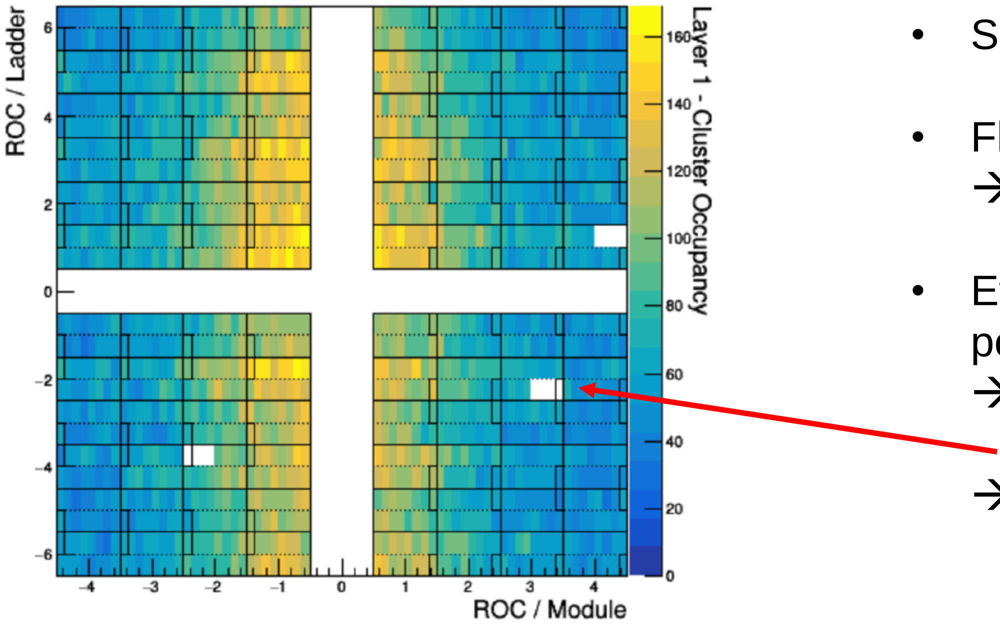


Detector fraction as of October 4, 2017:

FPix 10336/10752 = 96.1% functional ROCs
BPix 18068/18944 = 95.4% functional ROCs

Total Active Pixel Channels: 95.6%

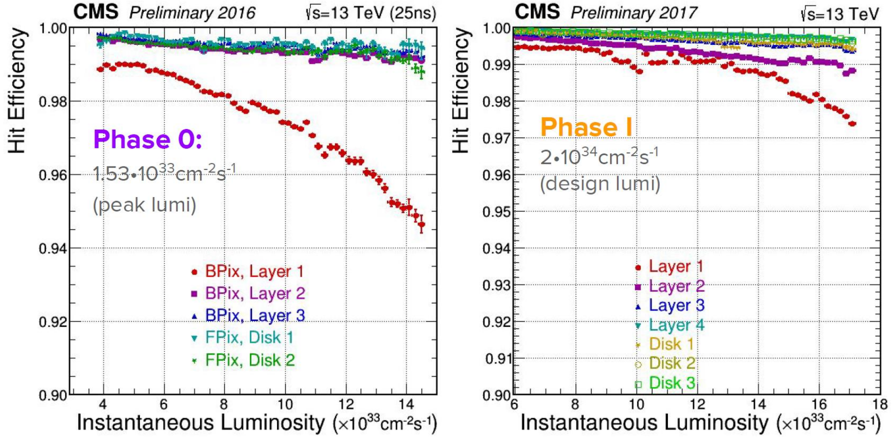
Phase 1 detector performance: TBM SEUs



- SEU problem in TBMs observed
- FlipFlop not connected to reset
  → recovery with power-cycle
- Effect depending on luminosity, position, module type (# TBM cores)
  → Layer 1 most effected,
  holes with granularity of 4 ROCs
  → dynamic inefficiency maps

Summary

- CMS installed a completely new pixel detector in February/March 2017
- Construction as well as commissioning very challenging
  → many difficult issues solved or optimizations found
  → detector shows good or better performance than previous detector in 2017!
      → Congratulations to the commissioning and operation team!
- Performance of detector "dynamic", commissioning still ongoing and new challenges appearing
  → action needed for 2018 run
- Hopefully efficient use of winter break
  → Rapid access to detector pays off!



backup

Readout chip overview

- Column d
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