# High-Precision Luminosity Instrumentation for the CMS Experiment at the HL-LHC

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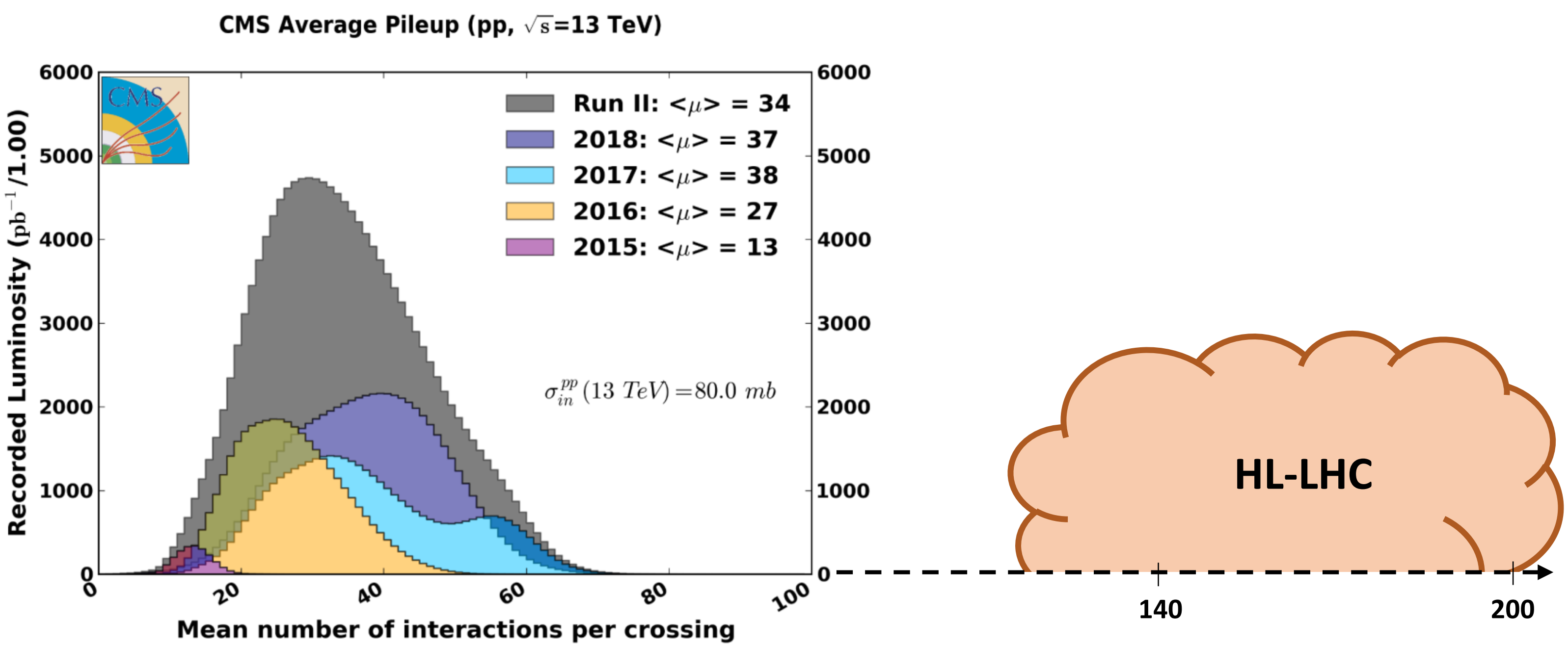
# High-Luminosity LHC

- *HL-LHC operation:* Pile-up of 140 (baseline) → Pile-up of 200 (ultimately)
- *Expected integrated luminosity in CMS:* $> 3000\ fb^{-1}$

→ New highly granular and radiation hard detector technology required



# Luminosity Instrumentation

- **Precision luminosity**
  - A deliverable of the *Beam Radiation Instrumentation and Luminosity* project (BRIL)
  - For CMS Physics (offline) + LHC and CMS operation (online)
  - Luminosity is single largest uncertainty in most precision measurements

  → Overall target precision for HL-LHC luminosity measurement: **1%**

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  - Stability over the full data taking period + monitoring of inefficiencies
  - High availability, irrespective of the "global" CMS data taking

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- ***Strategy***
  - Further exploiting other subsystems

  → Benefiting from other subsystems engineering and operations experience

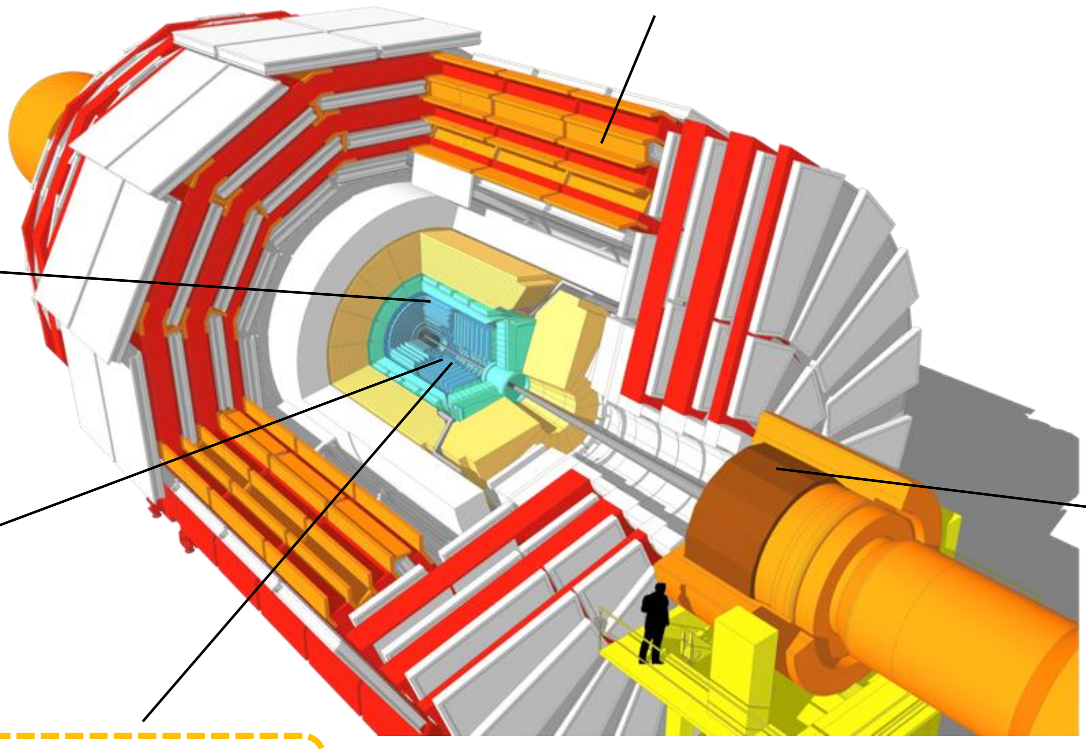
  → Several measurements to beat down systematic detector effects

# Luminosity Detectors

*HL-LHC prospects:*

Drift Tubes tracklets via backend or scouting

Outer Tracker Layer 3 stub counting



TEPX hit/cluster counting

Hadron Forward Calorimeter rings 31&32

TEPX Disk 4 Ring1 hit/cluster counting

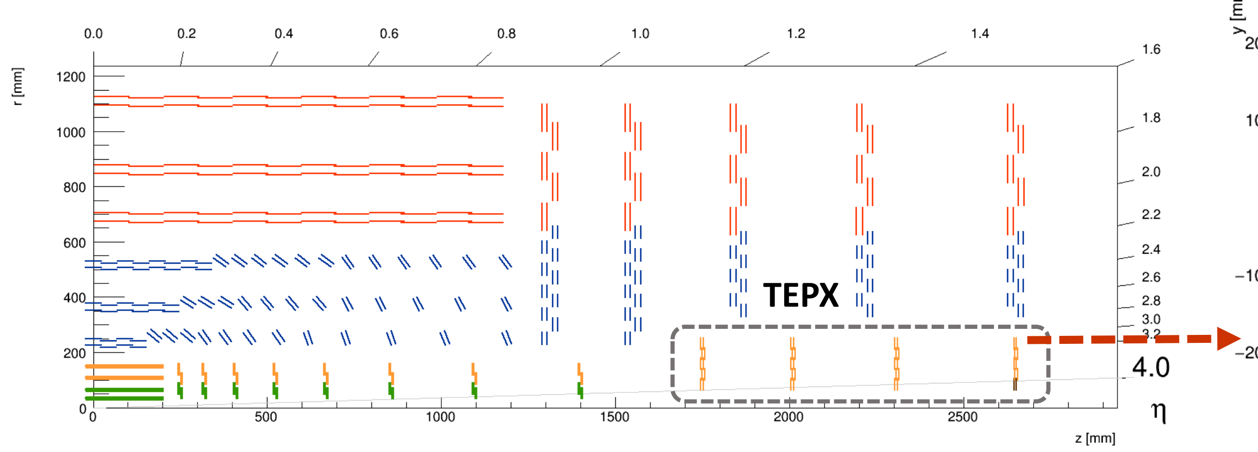
Standalone luminometer (location tbd)

# The Inner Tracker Endcap

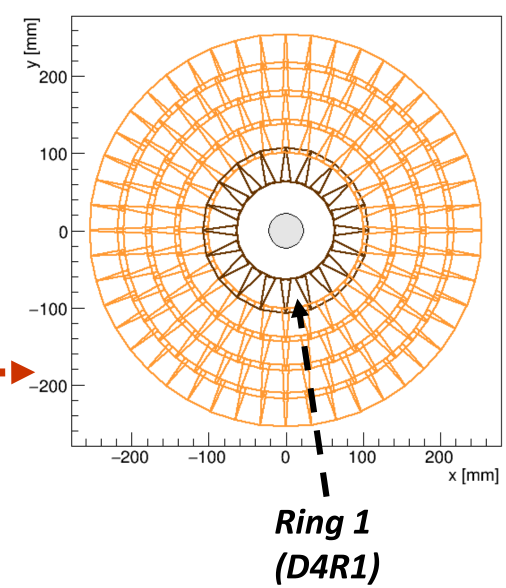
Advantageous characteristics of the **Tracker Endcap Pixel Detector (TEPX) [1]:**

- ***Geometry***: ~2 $m^2$ of active area with large fraction of overlapping area
- ***Location***: Higher z-positions allow for good separation between collision and incoming background products, low occupancy region
- ***Technology****:* Radiation hardness (~10 MGy), high granularity (25 x 100 µm pixels)
- ***Disk 4 Ring 1:*** Dedicated for luminosity and beam-induced-background only

*Proposed layout of the CMS Phase-II Tracker [2]*

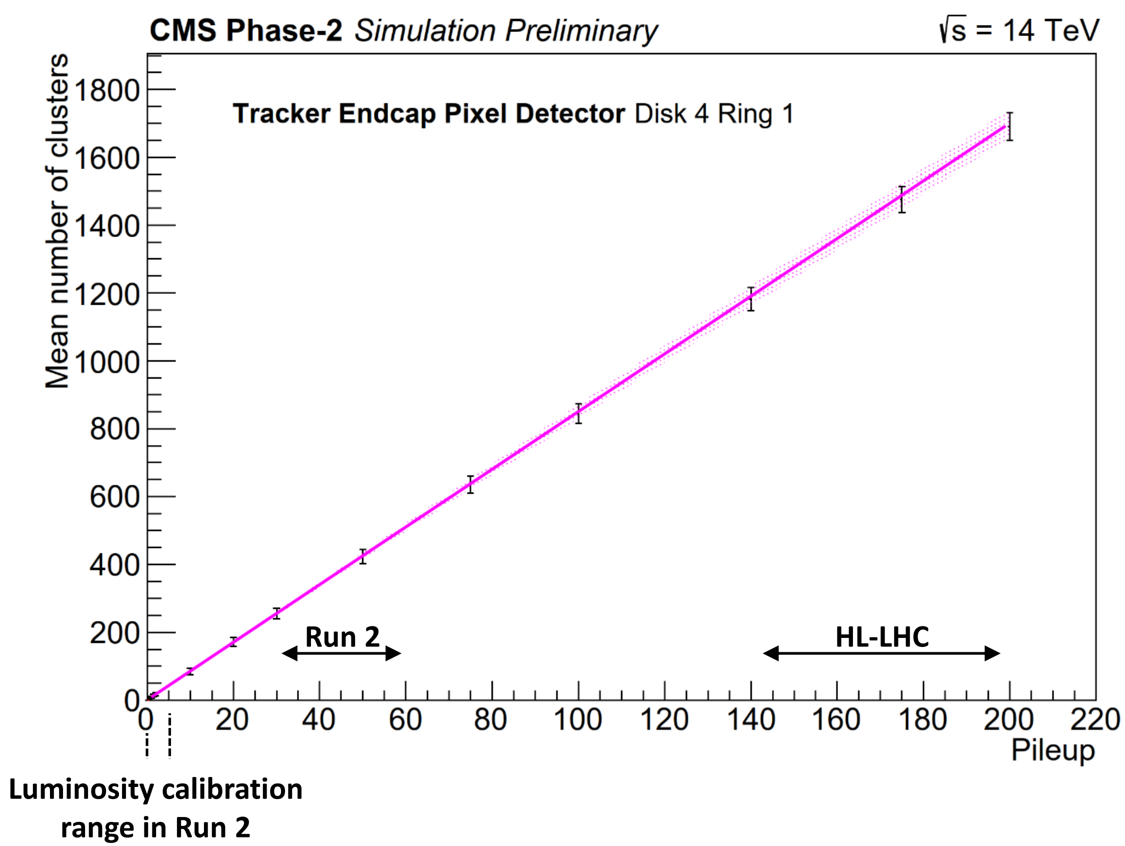



*TEPX Disk 4*



# Linearity Simulations

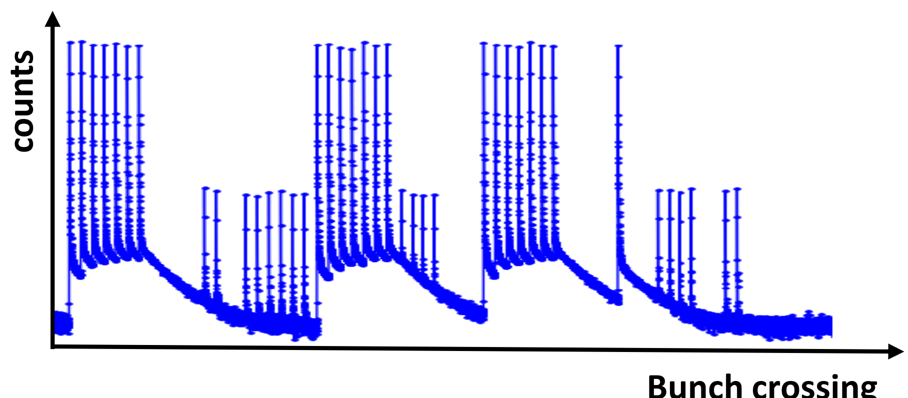
- Linearity studies in release *CMSSW_10_4_0_pre2* and *Inner Tracker geometry v. 6.1.3*
- Potentially interesting observables: ***hits, clusters and coincidences***
- Observation: Excellent linearity of number of cluster over whole pileup range



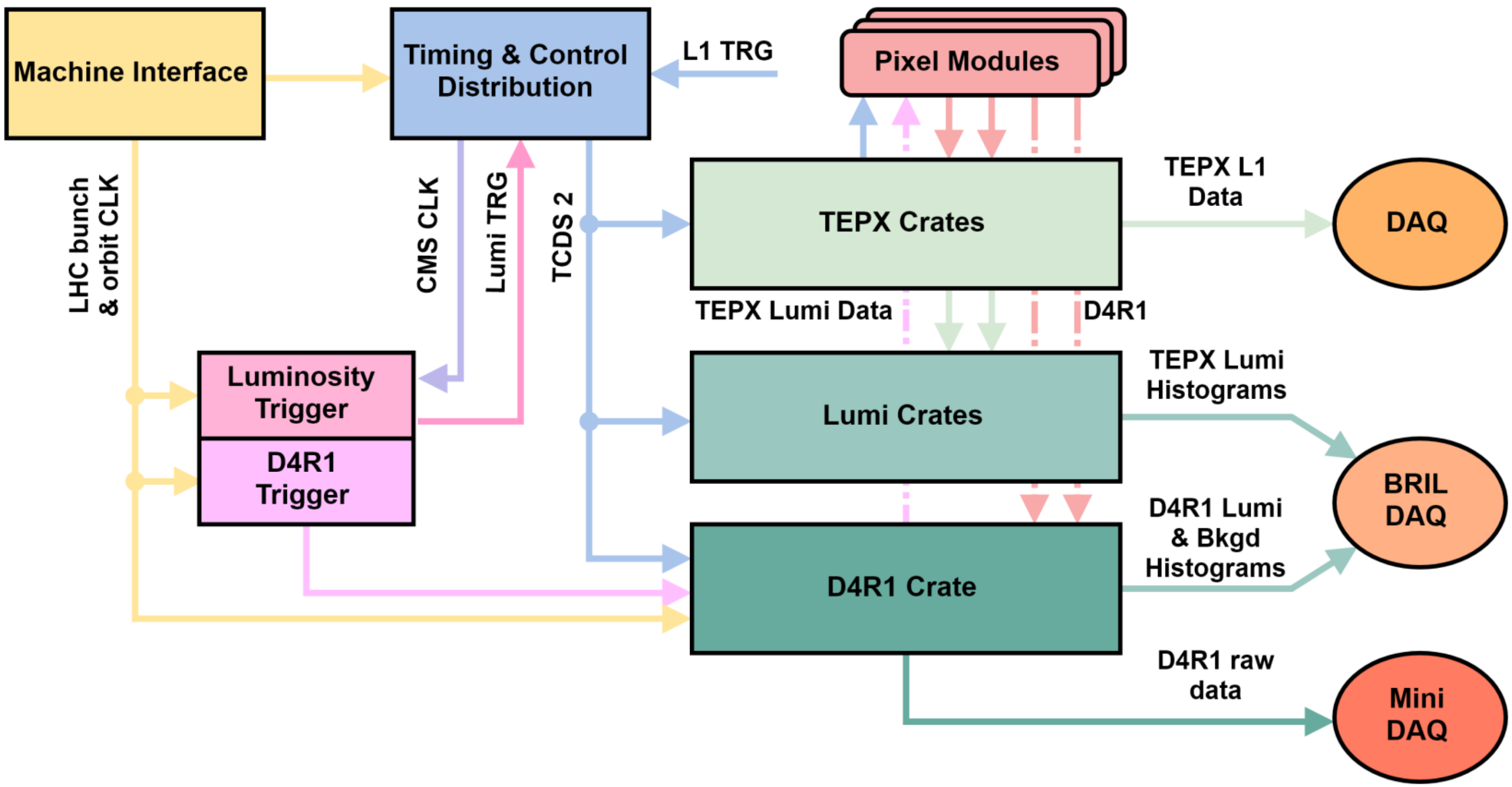
# Service Requirements

- *TEPX as principal luminometer:* High availability of services – even outside of "global" CMS data taking
- Independence of Disk 4 Ring 1:
  - Operation as luminosity detector <u>only</u>
  - Standalone, dedicated triggers (~750+75 kHz)
- Implementation of <u>two</u> different triggers required for rest of TEPX: Physics triggers (750 kHz) & Lumi trigger (~75 kHz)
- Triggers will be a mix of: Random, zero-bias, filling-scheme-based
- Adjustable trigger rates to achieve high precision in special runs
- No throttling of luminosity triggers without a hard requirement to do so

*Exemplary histogram of a generic algorithm*



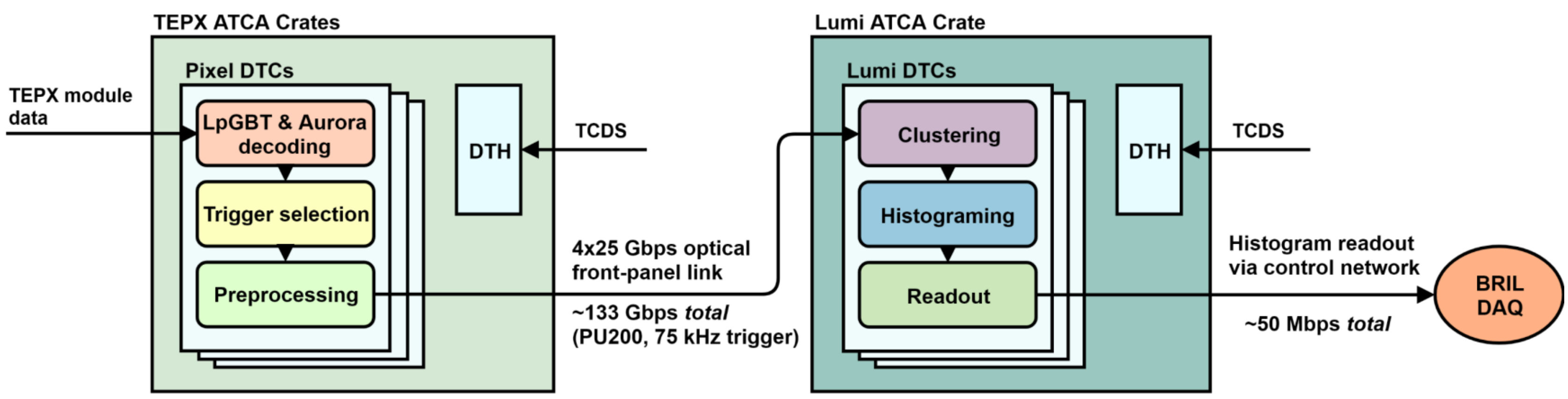
# System Architecture



# Data Readout

- Based on Monte Carlo simulations a standalone framework has been developed to simulate data rates towards the luminosity back-end system
- Framework features:
  - *Encoding:* Raw data hits are encoded in RD53B-specific binary trees
  - *Simple stream building:* One event per stream per module
  - *Not included:* Aurora or advanced stream building

*Data flow and back end system*



# Pixel Cluster Counting

**Pixel cluster counting (PCC) algorithm:**

- Counting number of clusters per event with specified granularity (e.g. per ring)
- Monitoring detector performance (cluster size etc.)
- Online corrections (afterglow, overlaps, dead modules, etc.)
- Established algorithm for **offline** luminosity determination in previous runs [3]
- Possibilities for **online** cluster counting:
    - *Software-based:* ~ 5 servers with 32 CPU cores each
        - \+ Common programming languages and paradigms
        - \+ Reuse of current clustering algorithm
        - − High latency, especially for high workloads
    - *Hardware-based:* ~ 8 ATCA blades with large scale FPGAs
        - \+ High amount of parallel computing power → low latency
        - \+ Use of common CMS back end technology
        - − "Expensive" firmware development in terms of time and expertise

# Pixel Cluster Counting

- Image processing algorithms
  - Established, well studied, high-speed FPGA implementations
  - E.g. Connected Component Labeling algorithm [6]
- In total 822 M pixels → 3.3 Gbit of 4-bit digitized pixel data
  - Inefficient use of memory, because data is zero-suppressed
  - Feasible when data stored in DRAM
  - Factor of 100 too big when stored in SRAM (assuming 8 UltraScale+ FPGAs)
- Moving window approach
  - Implemented in ATLAS Fast Tracker [5,6]
  - Saving FPGA resources, multiple parallel instances
  - Not adapted to new pixel chip and increased data rates
- To be investigated
  - Exploiting the quad core binary tree encoding
  - Heterogeneous approach using SoCs

# Summary

- HL-LHC conditions require new high precision, rad-hard luminosity instrumentation
- The properties and position of the Tracker Endcap Pixel Detector (TEPX) allow for high statistics measurement
- TEPX Disk 4 Ring 1 will be operated independently from rest of TEPX
- The number of clusters per TEPX ring is linear over a pileup range from 0 to 200
- An extra 10% (75 kHz) of dedicated lumi triggers are allocated for TEPX
- The system architecture is designed to avoid backpressure and to implement independent trigger types
- A data rate simulation framework has been implemented, estimating the maximum data rate for TEPX to ~133 Gbps at PU 200 and a trigger rate of 75 kHz
- Online pixel cluster counting in FPGA has been proven to be feasible in ATLAS for Run 2 and has to be investigated for CMS Run 4

# References


**[1]** CMS Collaboration, *The Phase-2 Upgrade of the CMS Tracker***,** CERN-LHCC-2017-009, CMS-TDR-014, 2017

**[2]** OT614_200_IT613 by G. Hugo

**[3]** CMS Collaboration, *CMS luminosity measurement for the 2018 data-taking period at* $s = \sqrt{13}\ TeV$, CMS-PAS-LUM-18-002 , 2019

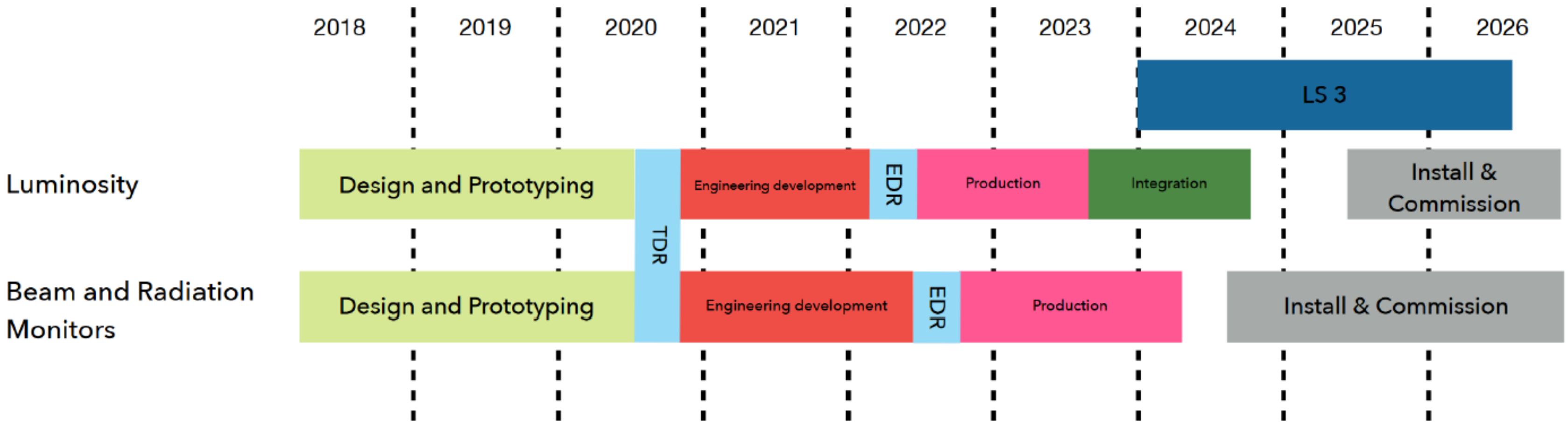
**[4]** S. Gkaitatzis, *Performance of a real-time multipurpose 2-dimensional clustering algorithm developed for the ATLAS experiment*, Proceedings, 5th International Conference on Modern Circuits and Systems Technologies (MOCAST), 2016

**[5]** M. J. Klaiber et al., *A Resource-Efficient Hardware Architecture for Connected Component Analysis*, IEEE Transactions on Circuits and Systems for Video Technology, Vol. 26, No. 7, 2016

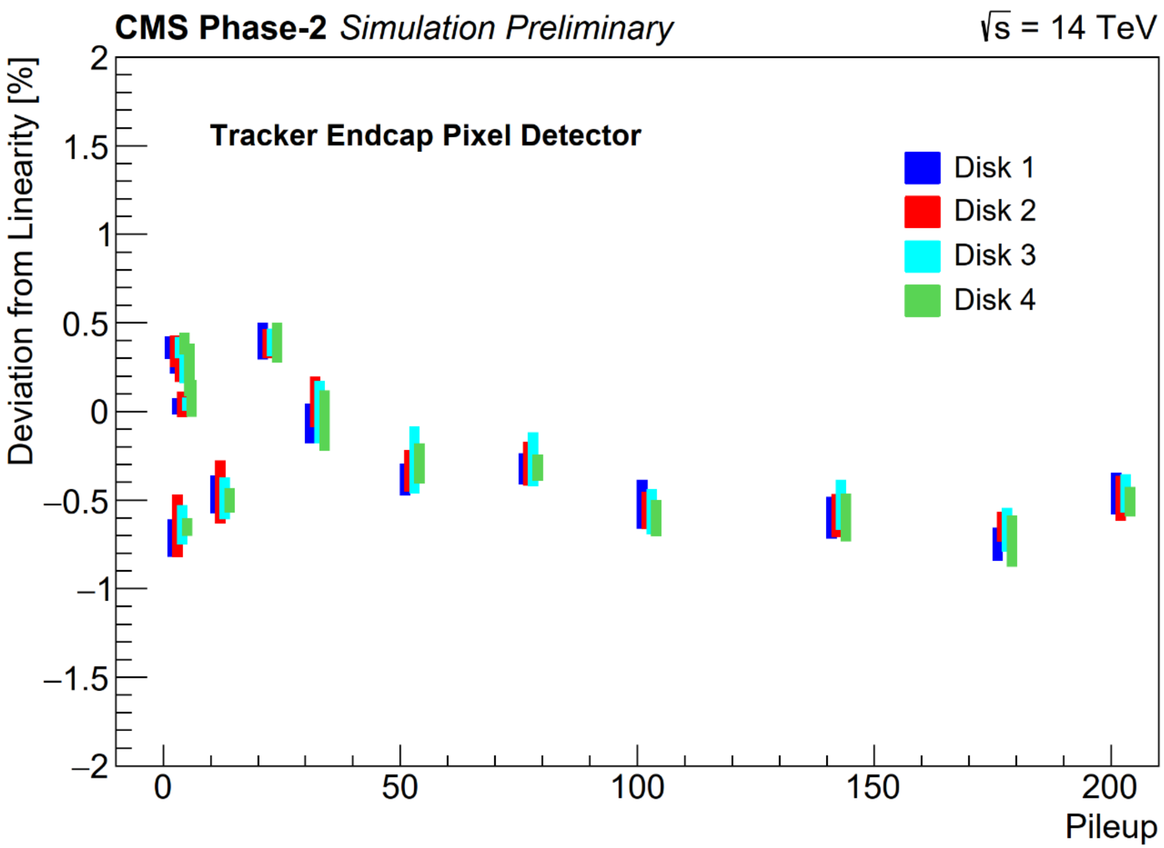
**[6]** C.-L. Sotiropoulou et al., *A Multi-Core FPGA-Based 2d-Clustering Implementation for Real-Time Image Processing*, IEEE Transactions on Nuclear Science, Vol. 61, No. 6, 2014

# Backup

# BRIL Schedule

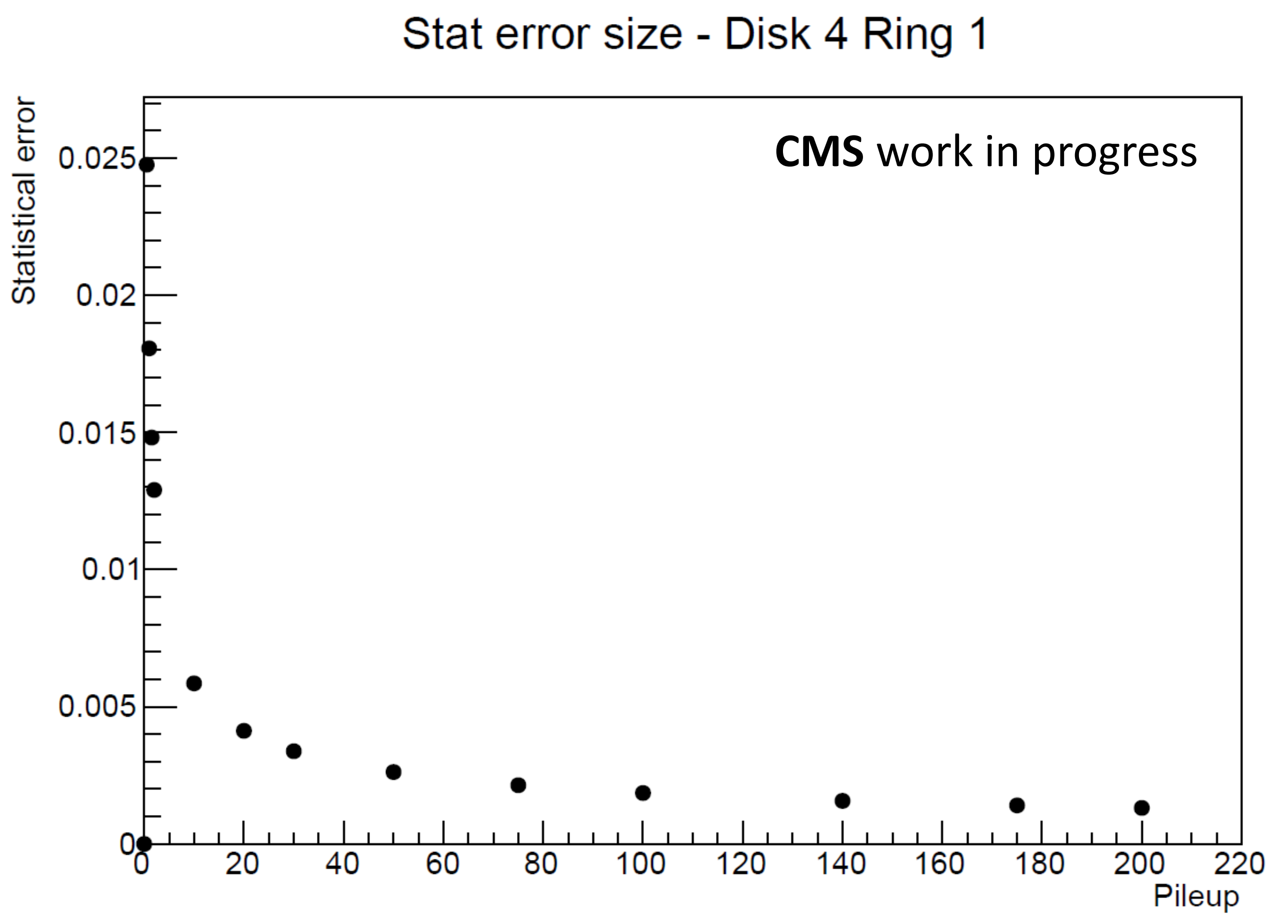


# Non-Linearity




Relative non-linearity for each disk of the Tracker Endcap Pixel Detector (TEPX). The deviation is calculated as the relative difference between the data point and the value of the fit function at the respective pileup value. For each disk, the size of the box is determined by taking the minimum and maximum deviations across all rings. For clusters, this deviation is smaller than 1% over a pileup range from 0 to 200.

# Statistical Error




*Size of statistical error per NB4 and 800 kHz zero-bias trigger for Disk 4 Ring 1*

# Data Rates

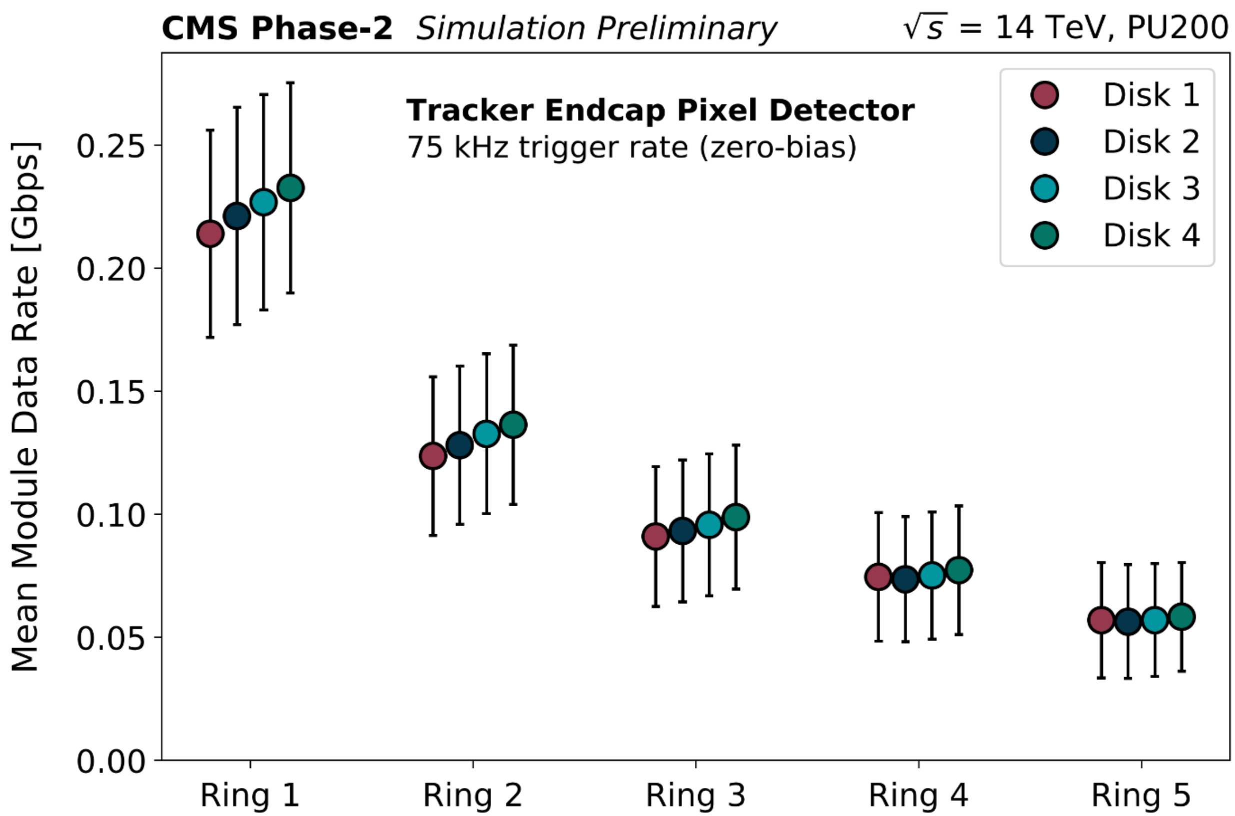
- Based on Monte Carlo simulations a standalone framework has been developed to simulate data rates towards the Lumi back-end system
- Features:
  - *Encoding:* Raw data hits are encoded in RD53B-specific binary trees
  - *Simple stream building:* One event per stream per module
  - *Not included:* Aurora or advanced stream building
- **Expected data rates (at PU 200, 75 kHz zero-bias triggers):**

| Ring 1 | Ring 2 | Ring 3 | Ring 4 | Ring 5 |
|---|---|---|---|---|
| 4.335 Gbps | 3.486 Gbps | 3.213 Gbps | 3.086 Gbps | 2.524 Gbps |

***Table 1:*** Expected mean data rates per ring of TEPX disk

- *Total rate per disk:* 16.643 Gbps
- ***Total rate TEPX:* 133.145 Gbps**

# Data Rates




*Simulated mean data rates per module for each ring of all TEPX disks at pileup 200 and a rate of 75 kHz of zero-bias triggers. The mean rates are shown with their standard deviation, accounting only for the RD53B-specific encoding and do not include overhead of any link layer protocol.*