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Radiation-Hard Smart-Pixel Detector ASIC ReadOut with Digital AI in 28nm

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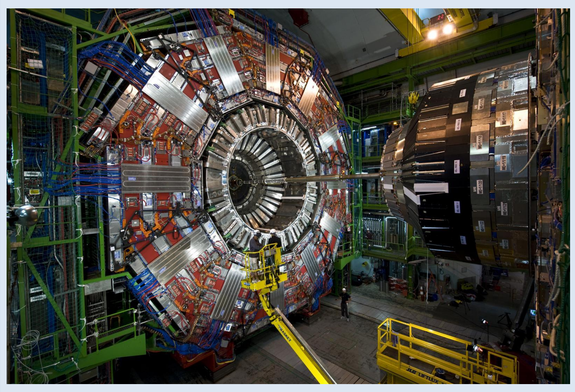
APPLICATION

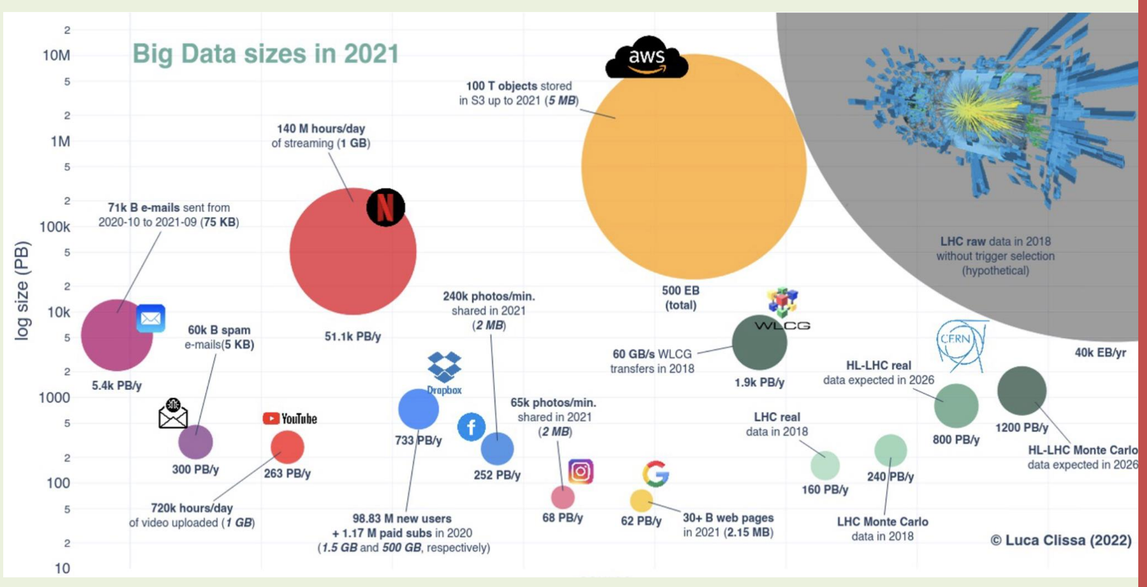
Phase II upgrade HL-LHC CMS



- 5 times improved luminosity
- 7 times higher interaction rate
- Raw data generation of 40ZB/year

CHALLENGE

Data Bottleneck

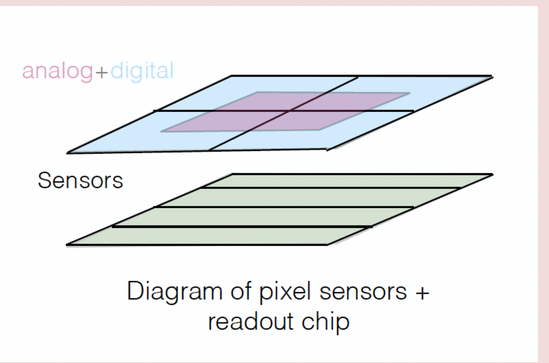


More than 90% of the raw data is generated by one detector sub system

→ silicon pixel detector ←

PROTOTYPE OVERVIEW

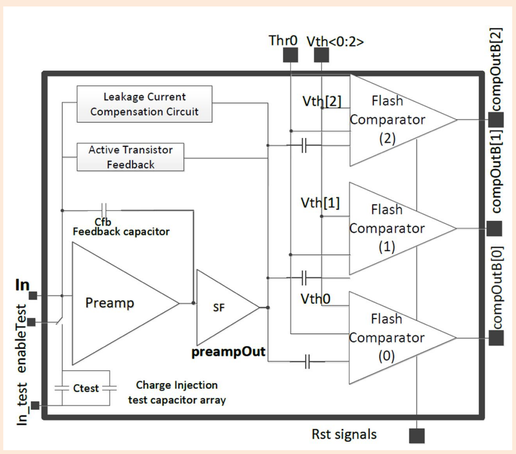
ROIC for hybrid Pixel Detector



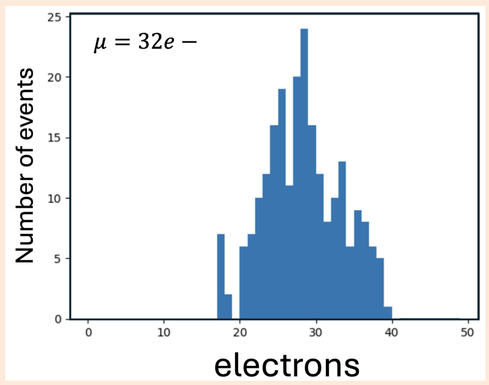
- Low power, low noise preamplifier with a leakage compensation technique is needed.
- A low power synchronous comparator architecture with auto-zero capability to create an in-pixel ADC with distinct reset and compare phases is required
- On chip data reduction capability using **AI/ML** techniques

ANALOG FRONT END PROTOTYPE

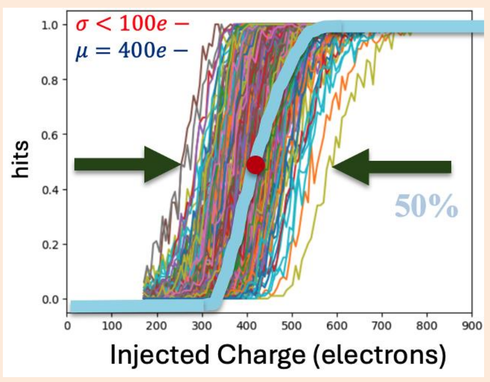
Pixel Measurement



- AFE Prototype designed in HPC+ 28nm
- ROIC pixel size is 25µm x 25µm
- Preamplifier dynamic range 64aC – 2.1fC
- **Radhard** by design: 50nA leakage compensation
- Sampling at bunch crossing rate: 40MSPS
- Offset cancellation with auto-zero
- Equivalent noise charge (ENC) 31e- with 400e- threshold (no sensor cap)
- Total charge dispersion <100e- across entire matrix with 400e- threshold (no sensor cap)
- Pixel Power ~5uW



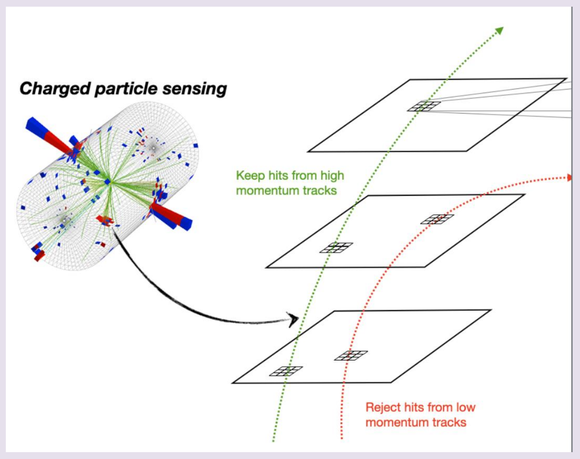
ENC extracted with 400e- equivalent threshold voltage and no sensor capacitance connected to the ROIC

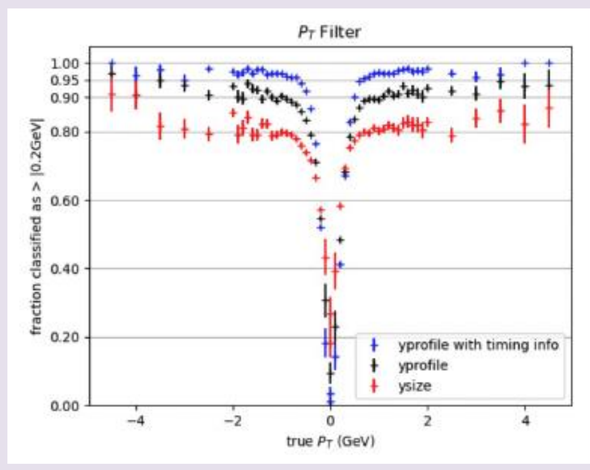


S-curves of total dispersion for all hit comparators in the array with 400e- equivalent threshold voltages and no sensor capacitance connected to the ROIC

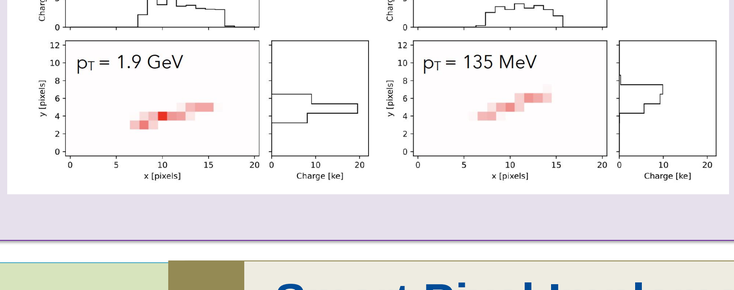
AI/ML FILTERING MODEL

Filtering Algorithm for momentum Classifier





Charge projection on the y-axis correlates with momentum

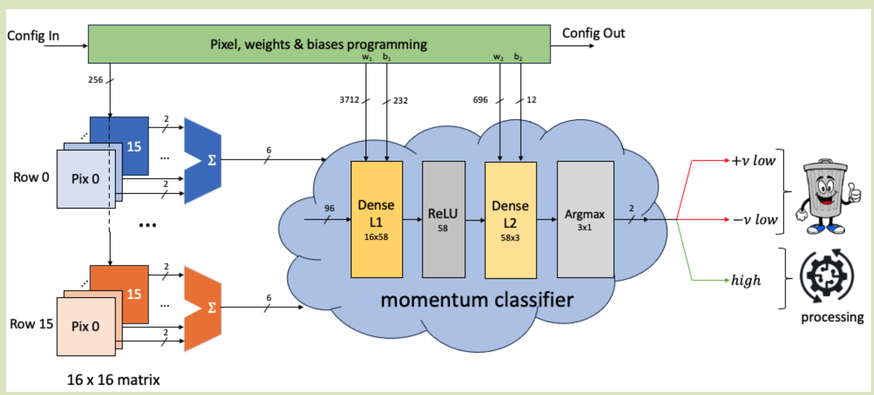


- Classifier models reject between 50% to 75% of the clusters
- More power savings due to reduced I/O transfer

Reference:
[1] Jieun Yoo1,*, Jennet Dickinson et al., "Smart pixel sensors: towards on-sensor filtering of pixel clusters with deep learning". Published 14 August 2024 "Machine Learning: Science and Technology", Volume 5, Number 3.

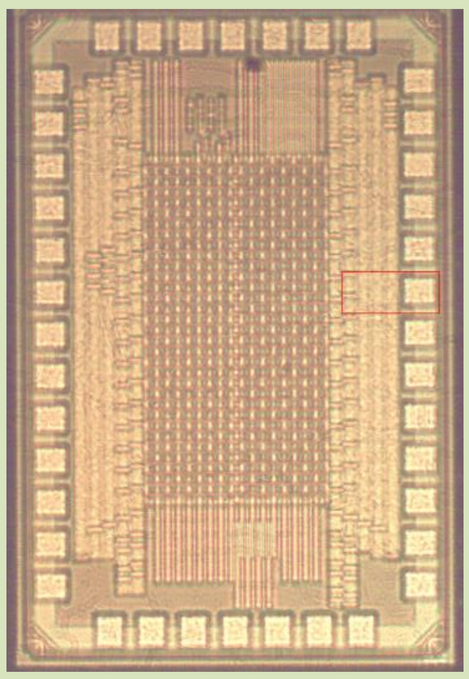
AI/ML IMPLEMENTED WITH HLS4ML

On-Chip Digital Momentum Classifier



- **Co-Design** development with analog frontend pixels connected to a fully combinatorial digital classifier
- **Combinatorial** design reduces dynamic power
- Digital power estimated to be 300uW for 256 pixels → ~1uW/pixel
- Total power density (AFE + digital) < 1W/cm2

1.5mm^2 ASIC



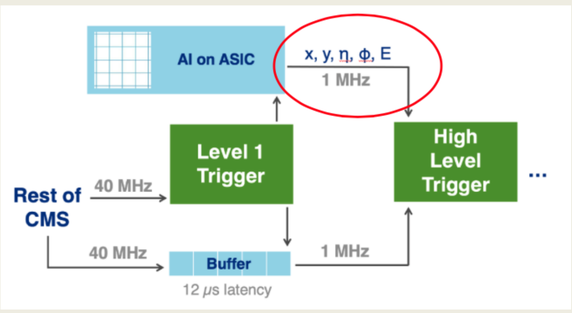
ASIC validation ongoing

FUTURE WORK

Smart Pixel Implementation

Study and implement analog/hybrid AI/ML algorithm that can be distributed throughout the detector:

- Explore **analog** algorithms to efficiently process sensor signals at the **source**.
- Compression (or featurization)
  1. Train algorithms to extract real time physics data for triggering on interesting collisions
  2. Readout only the critical physics data instead of the raw detector data and figure out the calibration loop



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