Smart Pixels: A Machine Learning Approach Towards Data Reduction in Next-Generation Particle Detectors

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Motivation

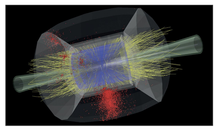
The ATLAS and CMS particle detectors at the Large Hadron Collider (LHC) collect data in the form of proton-proton collisions.

- The proton beam contains ~2808 bunches of protons
- Each "bunch crossing" produces ~ 60 interactions

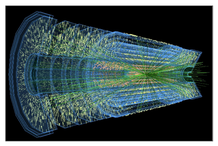
This is a **very large amount of data** to collect.

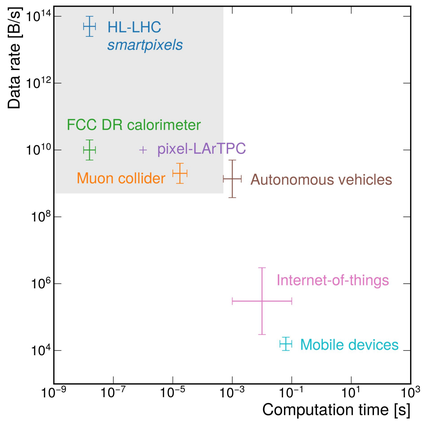
Next-generation particle detectors will contain even more interactions, resulting in even higher data rates!

Muon Collider
Large beam induced background



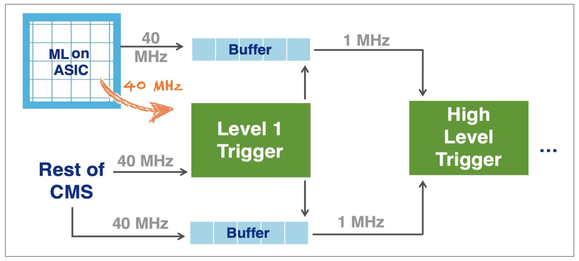
High Luminosity LHC
~200 interactions per bunch crossing





Strategy

How can we reduce the data rates in these detectors?
→ *Extract physics features with a regression model*, then implement the neural network on-ASIC
→ Detectors will be able to trigger/select interesting events using these particle properties (more compact) **instead of raw data**



What are the physics particle features we want to predict?

- Position (x, y) with uncertainties
- Incidence Angle (cotα, cotβ) with uncertainties

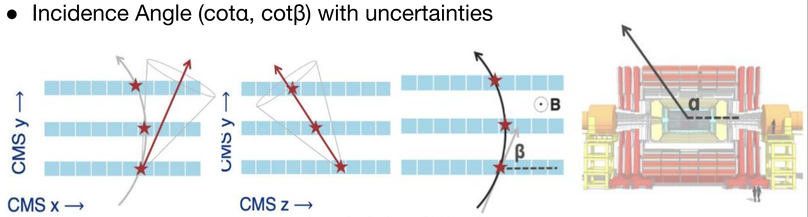
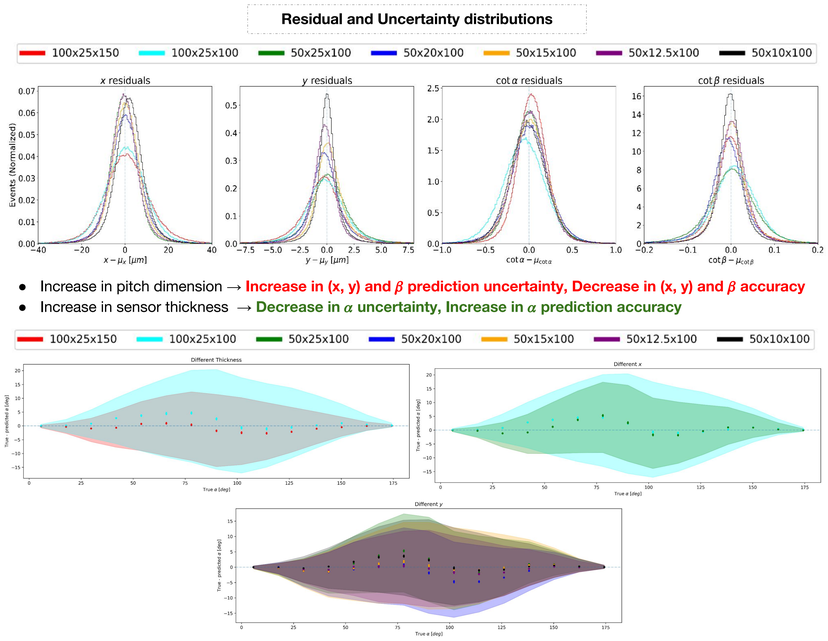
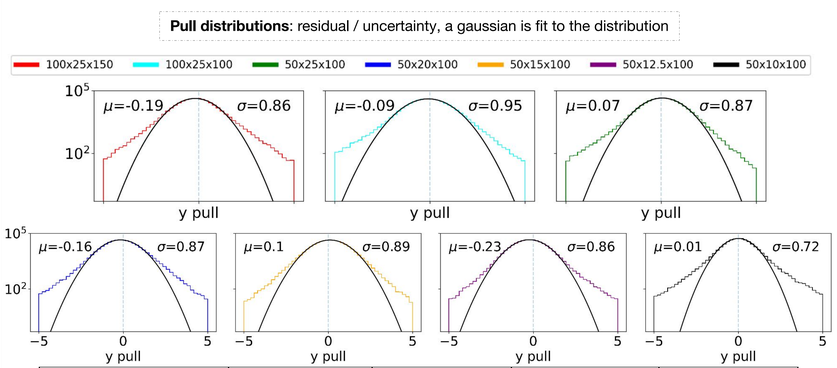


Image Credit: Jennet Dickinson

Performance



- Increase in pitch dimension → **Increase in (x, y) and β prediction uncertainty, Decrease in (x, y) and β accuracy**
- Increase in sensor thickness → **Decrease in α uncertainty, Increase in α prediction accuracy**



Pull distributions: residual / uncertainty, a gaussian is fit to the distribution

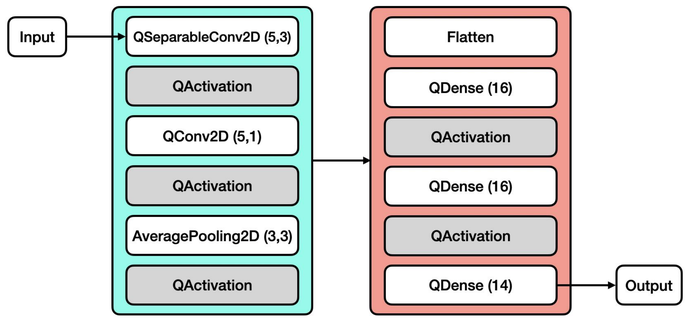
	x pull fit		*y* pull fit		cotα pull fit		cotβ pull fit	
Sensor Geometry [μm^3]	μ	σ	μ	σ	μ	σ	μ	σ
100x25x150	0.06	0.94	-0.19	0.86	0.16	0.72	-0.03	0.71
100x25x100	0.03	0.97	-0.09	0.95	-0.18	0.75	0.17	0.94
50x25x100	-0.08	0.85	0.07	0.87	0.02	0.80	0.04	0.93
50x20x100	0.03	0.90	-0.16	0.87	0.02	0.87	-0.17	0.84
50x15x100	0.04	0.88	0.10	0.89	0.02	0.82	0.05	0.75
50x12.5x100	0.07	0.98	-0.23	0.86	0.02	0.83	0.08	0.81
50x10x100	0.25	0.80	0.01	0.72	-0.05	0.84	-0.05	0.68

- Changing the sensor geometry does not have a significant effect on the variation of the pull distributions.
- This means that the accuracy of uncertainty predictions are independent of sensor geometry *within our studied range of pitch and thickness*.

Model Architecture

Batch size = 5000 | Number of Filters = 5 | Average Pooling Size = 3

Convolutional Layer Bits = 4 | Dense Layer Bits = 8 | Learning Rate = 0.001



Custom Loss:

→ Use predictions to construct 4-D multivariate normal distribution

→ Calculate likelihood for targets to fall in the predicted distribution

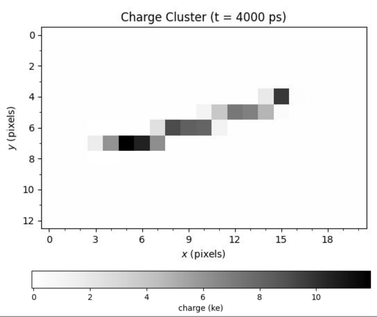
→ Loss = sum the negative log likelihoods (over the entire batch)

Dataset

The simulated dataset represents a charged pion passing through a 13x21 pixel array in the presence of a 3.8 Tesla external magnetic field. The data is structured into 20 discrete time slices, each separated by 200 picoseconds. Every slice records the charge deposited on the individual pixel sensors as the pion traverses the array.

Seven different datasets were used, characterized by the geometry of the pixel sensors:

x dim [um]	**y dim** [um]	**thickness** [um]
100	25	150
100	25	100
50	25	100
50	20	100
50	15	100
50	12.5	100
50	10	100



References

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2. Jennet Dickinson (December 6 2023). *Smart pixels with data reduction at source* [Seminar], High Energy Particle Seminar, Columbia University, New York, United States, https://www.physics.columbia.edu/events/high-energy-particle-seminar-smart-pixels-data-reduction-source-jennet-dickinson.