Accelerating scientific discovery with Intelligent Detectors

Detectors probe ever-shorter distances+timescales, producing data at PB/sec rates.

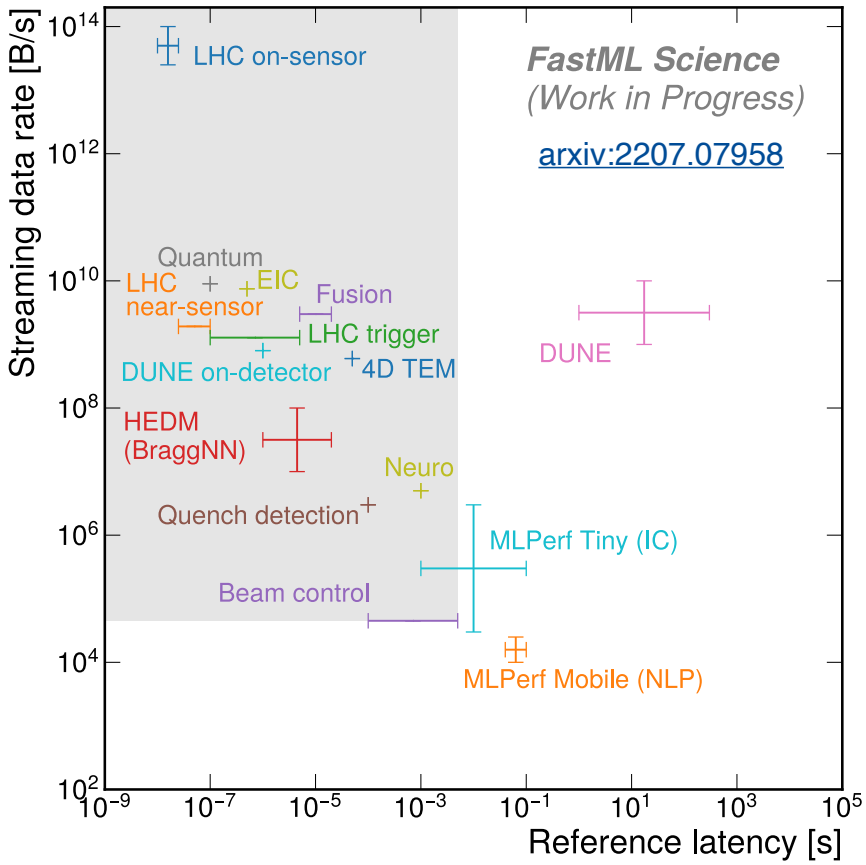
- Common challenges *across scientific domains!* → Driven by technology & science goals.

Intelligent, real-time analysis is key.

- Data distillation without information loss.
- Modern tools: FPGA, HLS, optical links,…
- AI/ML plays an increasing role.

Ongoing efforts are building new capabilities

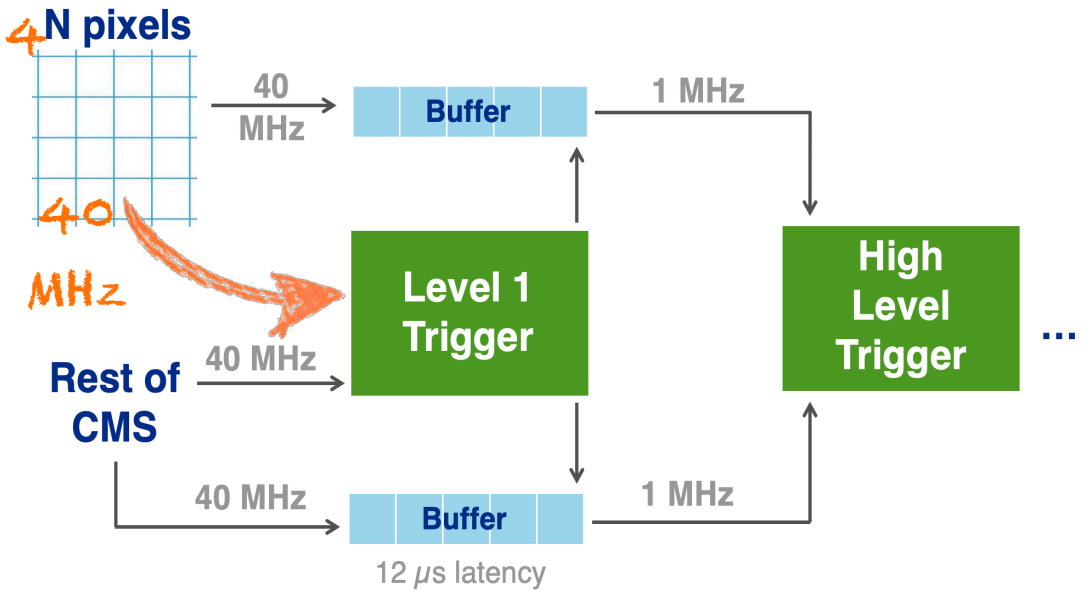
- Open tools for **hardware co-design**
  - Automate translation of models → circuits.
  - Find minimal resources, latency for the task.
- **Ecosystem of open data sets** and **benchmark tasks** to study deep questions.
  - Spur on new algorithms, tools, and hardware.
  - Robustness? Generalizability? Interpretability?



Case study: Smart Pixel sensors for collider detectors

Pixel detectors have the **largest data rates in HEP**!

- Measure charged particle tracks and vertices
- At the LHC, can only read out for triggered events



Next-gen detectors will provide

- Better resolution (position, angle)
- Precise timing information

What would we gain if we could analyze it all? Some aspirational targets:

- ***Higgs self-coupling****:* 5x increase in the low-m_{hh} spectrum from b-jet triggers.
- ***WIMP dark matter***: 50x rate for low-p_T / disappearing tracks / long-lived particles.
- ***New capabilities for high-rate, soft objects:*** e.g. dark sector BSM, B-physics, and more!

Smart Pixel sensors for data reduction at source

More details:
CPAD 2022

AI analysis of charge cluster shape on-ASIC, within the pixelated area

Filtering: read out only clusters that come from interesting tracks, e.g. high p_T

- Reject tracks with $p_T < 2$ GeV (corresponds to 95% of tracks)
- On-chip algorithm achieves ~ 3x reduction with 90% efficiency
- Investigating spiking neural network for energy-efficient implementation

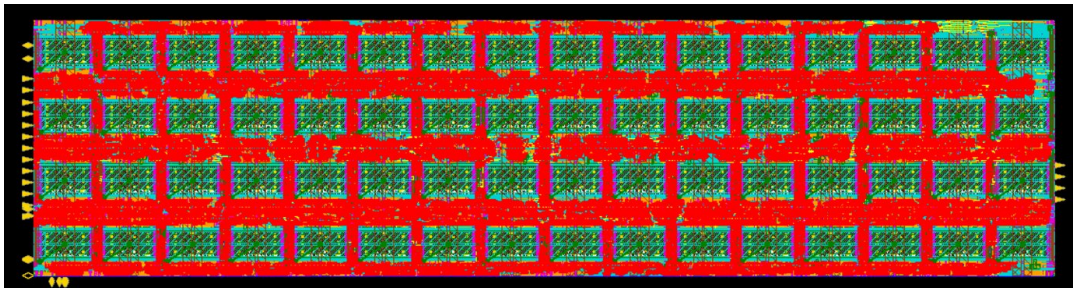


Fig. Prototype with 256 pixels. Classifier algorithm is highlighted in red.

Featurization: extract and read out particle properties instead of raw data

- Position, incident angle
- Mixture Density Network provides **prediction** and **meaningful error**
- Initial estimates show 1σ angular uncertainties ~10° with full precision. Potential for large reduction in track seeds!

Achieving this within power constraints requires leveraging new techniques in sensors, circuits, algorithms

Our simulated dataset is public!

Final messages to the community and P5

These activities stretch from **front of detector** to **cutting-edge CompSci & ML.**

- E.g. Smart Pixels bridge solid-state detectors (IF3) + readout (IF6) + trigger/DAQ (IF4) + ML (CompF03) + community engagement (Applications/Industry, CommF1).
- **Coherent efforts** are essential. Difficult when components are split across funding structures.

Open pathways to **enhance near-term experiments** with intelligent detectors.

- E.g. a "first wave" at the High-Lumi LHC will:
  - Add unique physics reach to the experiments.
  - Commission new technologies in a complete system.
  - Train the next generation with exciting, impactful upgrades.

Invest in Grand Challenges with the promise of great scientific leaps.

- Futuristic collider detectors, a 'self-driving' accelerator complex, …
- Galvanize cross-cutting efforts "under one roof" to render the impossible possible!