Streaming Readout for JLab 12 GeV Experiments

Introduction to Streaming Readout

Streaming Readout Realization at 12 GeV

- **Joint effort** Experimental Nuclear Physics, Fast Electronics, Scientific Computing
- **R&D for CLAS12, TDIS, SoLID; LDRD**

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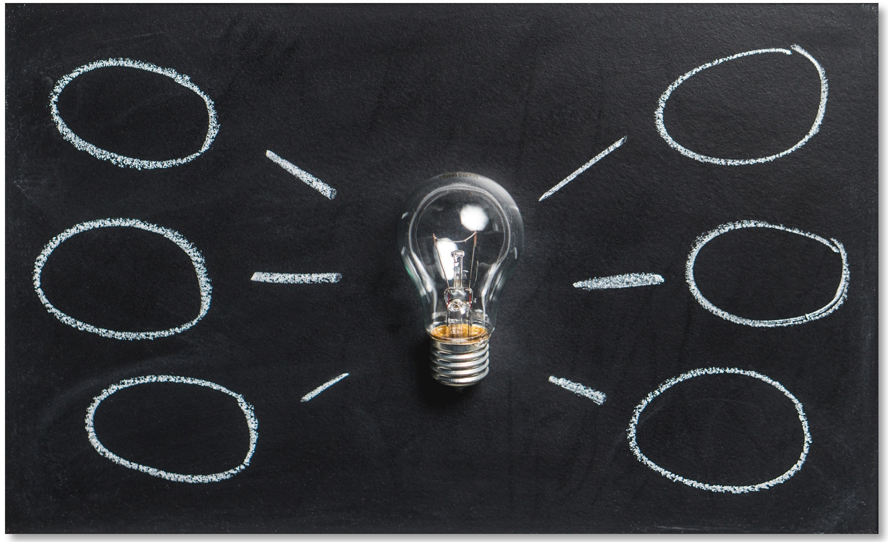
Towards the next-generation research model in Nuclear Physics

Science & Industry remarkable advances in electronics, computing, and software over last decade

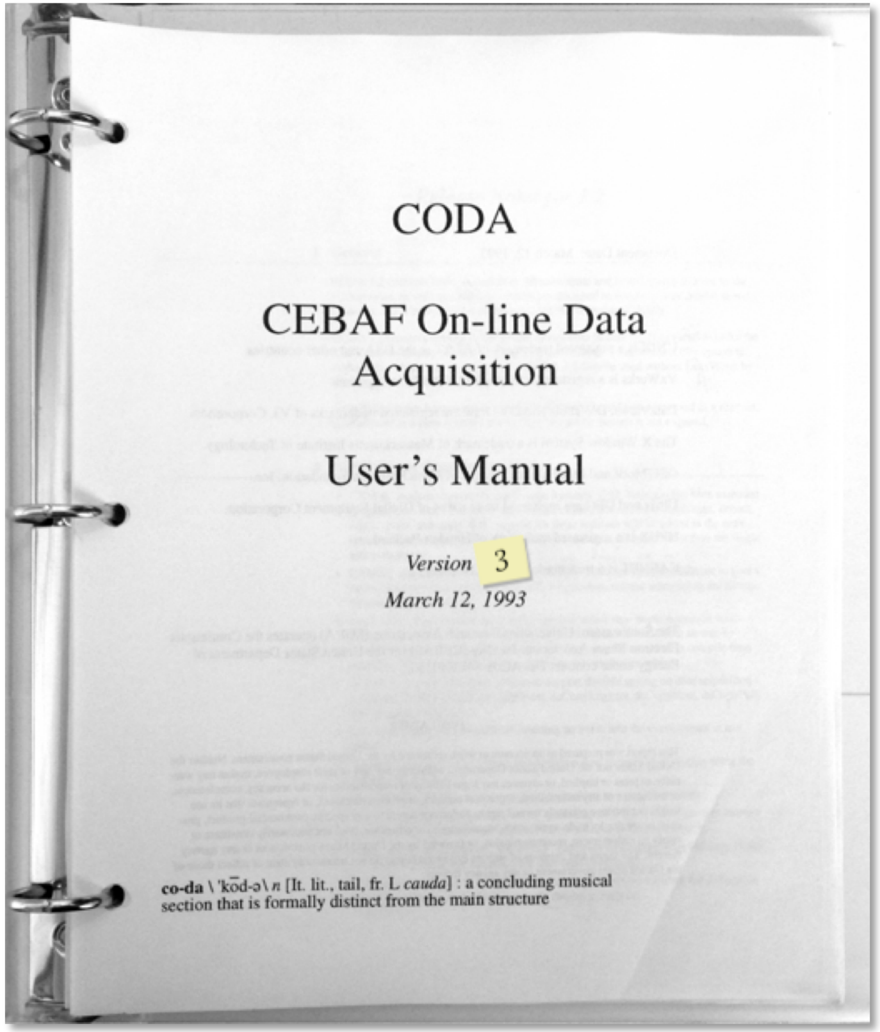
evolve & develop **Nuclear Physics research model** based on these advances



Roles of computing Data processing from data acquisition (DAQ) to analysis largely shaped by kinds of computing that has been available
Example Trigger-based readout systems

Advances in electronics, computing, and software Unique opportunity to think about new possibilities and paradigms
Example Streaming readout systems

CODA: Trigger-based readout system



Based upon assumptions in traditional DAQ design

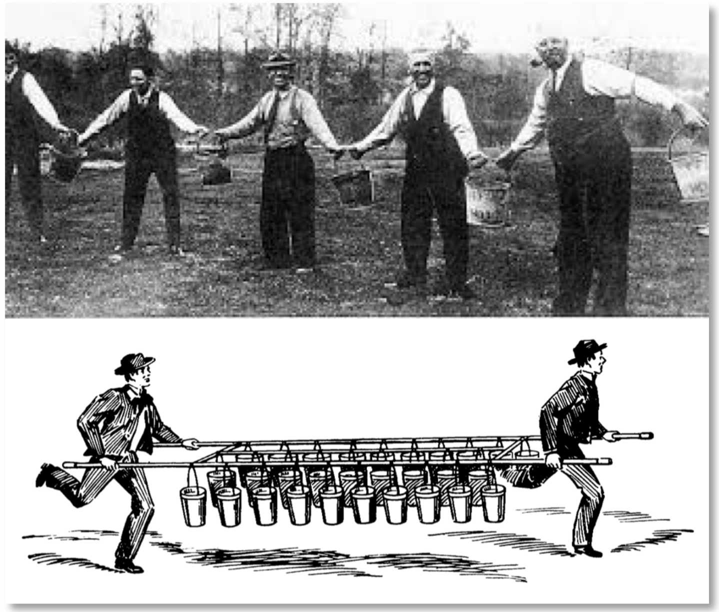
- The data rate from a detector is impossible to capture with an affordable data acquisition system without a trigger to reduce event rates.
- Even if the untriggered data rate could be captured, it would be impossible to store.
- Even if it could be stored the full dataset would represent a data volume that would require impractically large computing resources to process.

With computing advances Assumptions no longer valid

Limitation in trigger-based readout systems

- bias to low-energy particles
- do not deal well with event-pileup
- not an ideal for complex, general-purpose detectors

Alternative readout mode: Streaming



Traditional trigger-based readout

- data is digitized into buffers
- trigger starts readout
- parts of events are transported to an event builder where they are assembled into events
- at each stage the flow of data is controlled by *back pressure*
- data is organized sequentially by events

Streaming readout

- data is read continuously from all channels
- validation checks at source reject noise and suppress empty channels
- data then flows unimpeded in parallel channels to storage or a local compute resource
- data flow is controlled at source
- data is organized in multiple dimensions by channel and time

Jefferson Lab

Streaming Readout: Trigger-less data acquisition

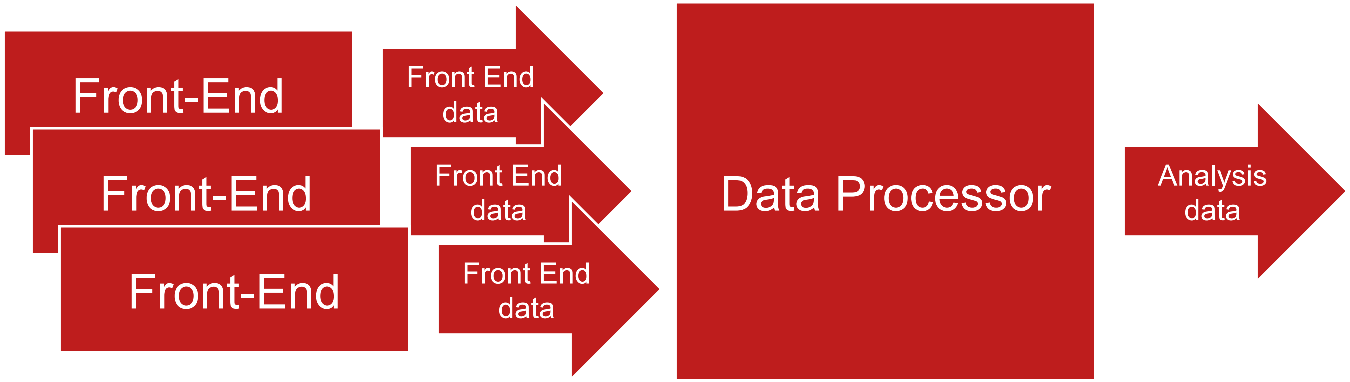
Definition of Streaming Readout

- Data is digitized at a fixed rate with thresholds and zero suppression applied locally.
- Data is read out in continuous parallel streams that are encoded with information about when and where the data was taken.
- Event building, filtering, monitoring, and other processing is deferred until the data is at rest in tiered storage.

Advantages of Streaming Readout

- simplification of readout (no custom trigger hardware and firmware)
- trigger-less readout:
    - beneficial for experiments that are limited by event-pileup or overlapping signals from different events
    - beam time is expensive so data mining or taking generic datasets shared between experiments is becoming popular: loosen triggers to store as much as possible
- opportunity to streamline workflows
- take advantage of other emerging technologies

Streaming Readout and (near) real-time processing



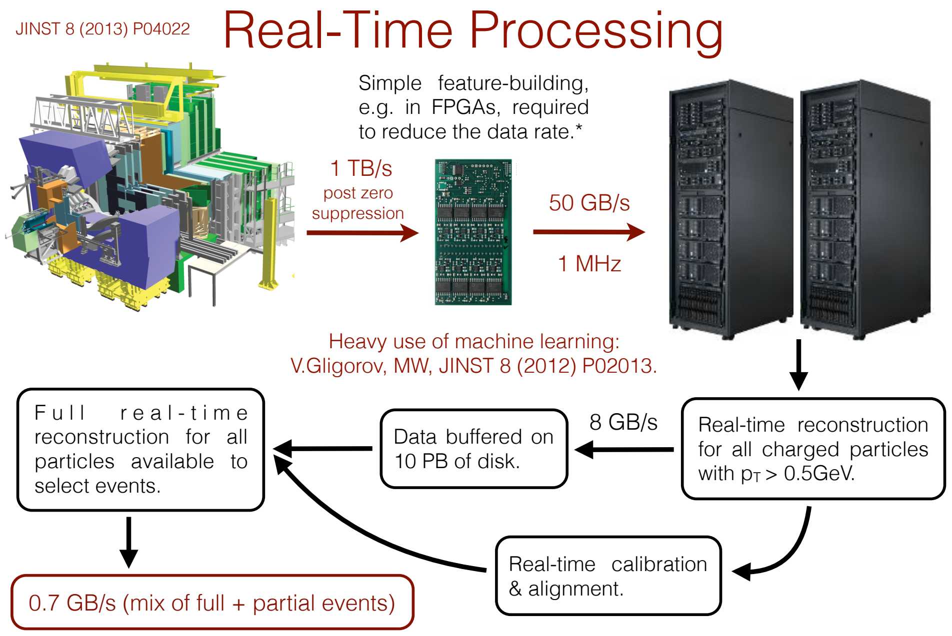
Data Processor

- assembles the data into events
- outputs data suitable for final analysis (**Analysis data**)

Features

- ideal for AI
- automated calibration in (near) real time
- automated alignment in (near) real time
- reconstruction in (near) real time
- event filtering into analysis streams based on full event information
- automated anomaly detection
- responsive detectors (conscious experiment)

LHCb Example



*LHCb will move to a triggerless-readout system for LHC Run 3 (2021-2023), and process 5 TB/s in real time on the CPU farm.

Integration of DAQ, analysis and theory to optimize physics reach

Research model with seamless data processing from DAQ to data analysis

- blurring of online and offline analysis evolves into near real-time analysis
- not about building the best detector but the best detector that fully supports:
  - streaming readout
  - fast algorithms for alignment, calibration, and reconstruction

Realization of Streaming Readout

Scientific Computing

EPSCI

Fast Electronics

Nuclear Physics

Halls A/C

Hall B

Hall D

Electron-Ion Collider

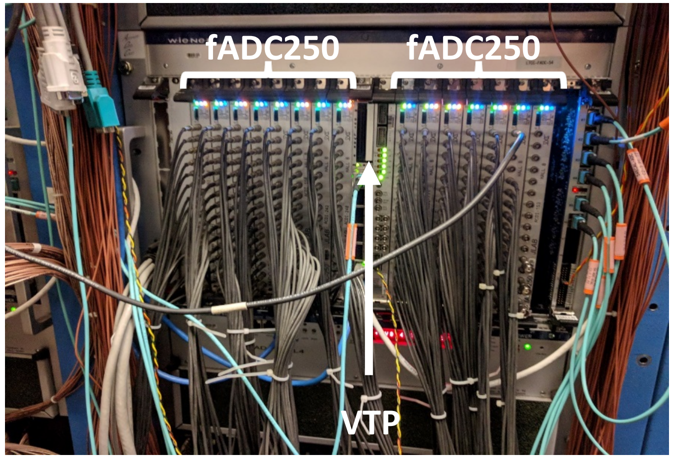
Fast electronics: fADC250 and VTP for trigger-based readout system

fADC250

- 16 channel, 250Msps, 12bit waveform sampling ADC
- VME readout using 200MB/s 2eSST (shared for all fADC250 in crate)
- VXS serial interface (up to 20Gbps) to VTP
- ~1,000 modules in use at JLab (mainly CLAS12 and GlueX)

VTP

- up to 20Gbps link to each fADC250
- all fADC hits (charge & time) reported to VTP over this link
- 4GB DDR3 (200Gbps bandwidth)
- 5 QSFP (to connect to other VTPs or
- ~50 modules in use at JLab
- Used in trigger applications (calorimeter cluster reconstruction, general purpose timing and geometry coincidence application, global trigger bit processing)



fADC250 DAQ Crate

Modifying fADC250 and VTP for streaming readout B. Raydo et al.

Collect fADC250 hits in the VTP

- **initial tests** used the fADC250 trigger hit data: pulse integral charge and 4ns timestamp
- **no longer needed** ADC250 firmware for event building
- **next several months** use resources to implement pulse processing features
  - high resolution timestamp and charge (i.e. improve 4ns timestamping to sub-ns)
  - add raw pulse waveform data mode
  - add pile-up detection

Interface VTP interface to computer network to bring fADC hit data into computers

- implemented up to 4x 10Gbps Ethernet streaming readout from each VTP
- TCP sockets are used to establish link directly with servers to stream data
  - allowed standard/commercial networking hardware/infrastructure to be used immediately. Standard O/S socket libraries are then used receive this data.

Tracking of data/efficiency losses

- VTP sends TCP data for 65us windows of FADC hits, specifying the window number, timestamp.
- Large buffers on the VTP smooth bursts of high fADC hit data rates to maximize efficiency
- When network back pressure is present and VTP buffers are full, a full 65us window of data will be dropped – easy to track by the receiving server. We will underutilize the server and network to avoid data loss.

Streaming Readout tests at CLAS12 Hall B

CLAS12 is considering streaming DAQ as a possible future upgrade (part of a luminosity design increase). They already have a significant investment in fADC250 and VTP hardware making the front-end equipment cost to upgrade very low if the streaming developments become viable options Jefferson Lab. In addition to front-end firmware, network infrastructure, and computing resources, significant work on the backend data processing software is still needed.

Task force

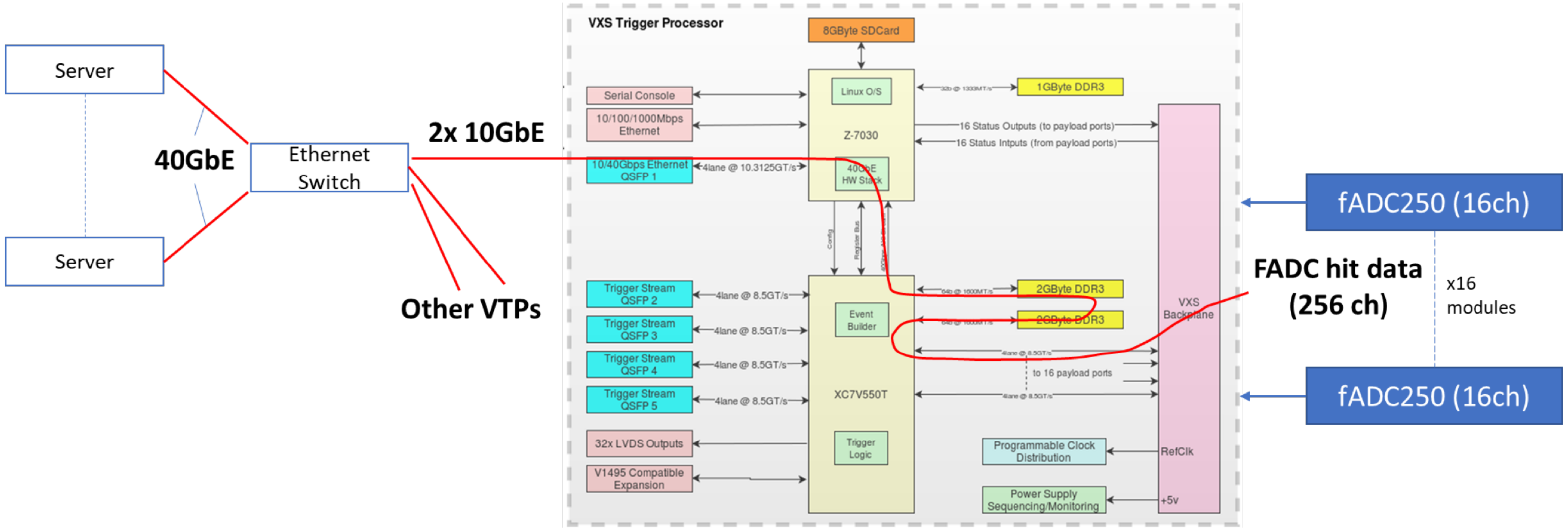
- assess the current CLAS12 DAQ/Trigger configuration and identify the limiting factors
- assess existing DAQ alternative technologies (e.g. streaming readout) and identifying the most suitable to upgrade CLAS12
- quantify the expected improvement (DAQ rate, on-line monitoring/reconstruction, trigger algorithms implementation)
- evaluate in details the effect of implementing a L3 trigger and implications to streaming path
- identify changes in the current scheme and resources needed to implement a CLAS12 online monitoring/reconstruction

Define a work plan, estimate costs and identify resources, evaluate synergies with other projects.

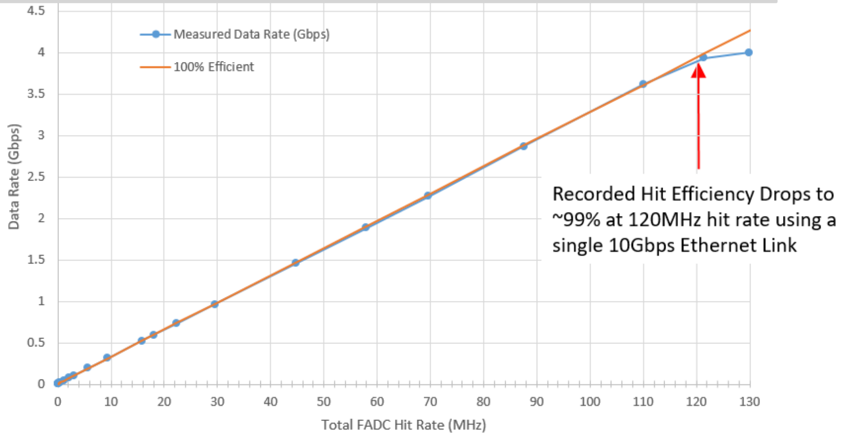
Streaming Readout test using the CLAS12 forward calorimeter Hall B

Front-end setup 2 VXS crates, each with VTP w/ 2x 10GbE optical links, 11 FADC250 modules, 336 PbWO crystals w/APD

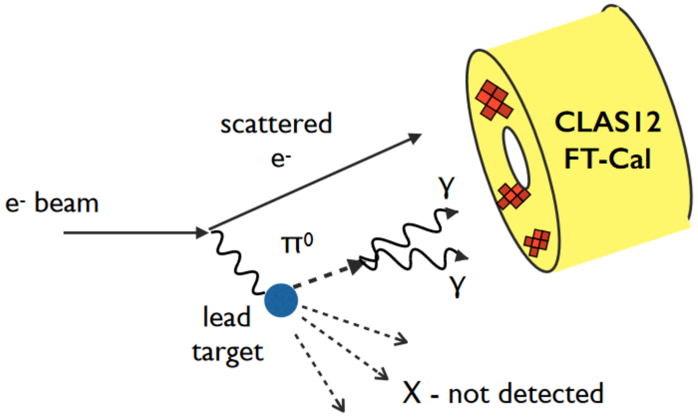
Backend setup servers connected to front-end ethernet switch by 40GbE. Combination of CODA, TRIDAS (by INFN), JANA2, ROOT for configuration, event selection, event reconstruction, and online monitoring



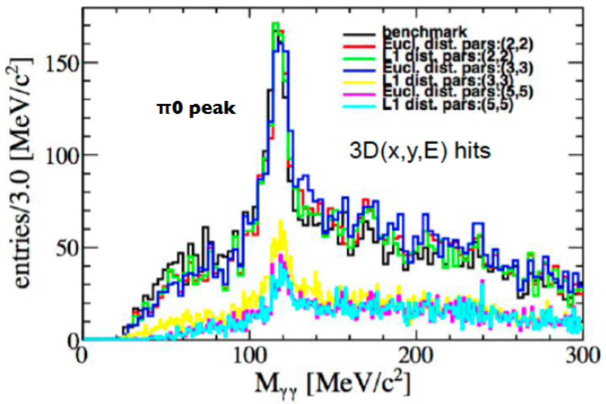
Rate capability Close to 1MHz rate per FADC channel before suffering efficiency loss (nearly 2x better after recent bandwidth improvements)



π^0 reconstructed signal from streaming readout rest



Double cluster π0 mass as obtained by an unsupervised hierarchical clustering algorithm implemented in JANA framework by C.Fanelli



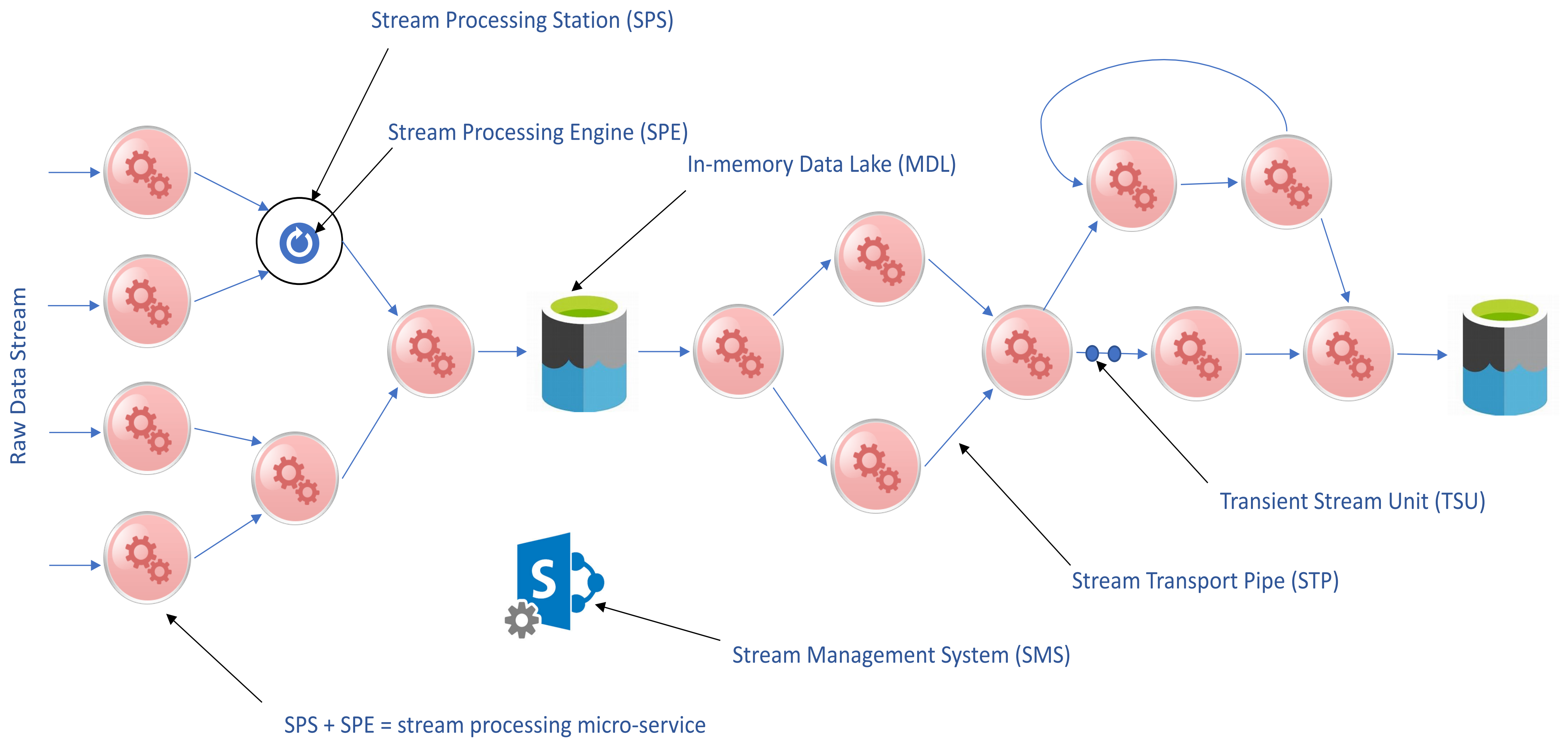
Environment for Real-time Streaming Acquisition and Processing EPSCI

- ERSAP is a hardware/software system that will process unbounded streams of continuous data at scale over distributed heterogeneous resources in (near) real-time.

- Designed using reactive micro-services architecture within a flow based programming paradigm.

- Based on CODA, CLARA and JANA2
  - experience and lessons learned during many years of operations
  - high speed Data Acquisition coupled with distributed, multi-threaded data processing
  - easy integration of offline software into streaming system

ERSAP: Data-stream processing pipe-line



ERSAP: Design Rationale

- Smaller and independent code bases. Reinforce a maximum independence and isolation of functional components.

- Fault tolerant

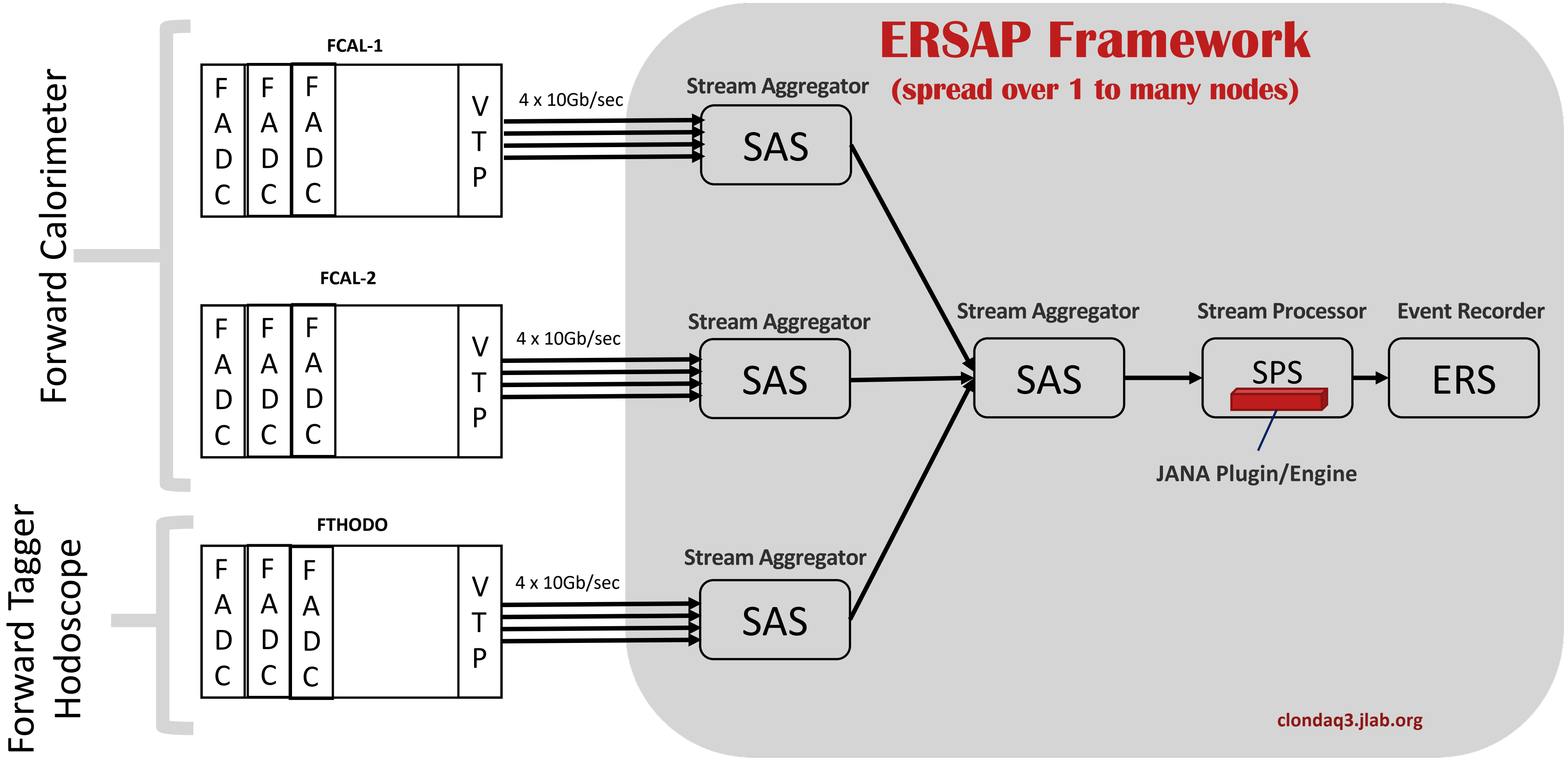
- No other dependencies other than data (loose coupling)
  - can run on heterogeneous hardware and software infrastructures

- Agile to evolve over time due to
  - Requirement changes
  - Environment changes
  - Errors or security breaches
  - New equipment added or removed
  - Improvements to the system

- Encourages contribution and inclusion of new technologies

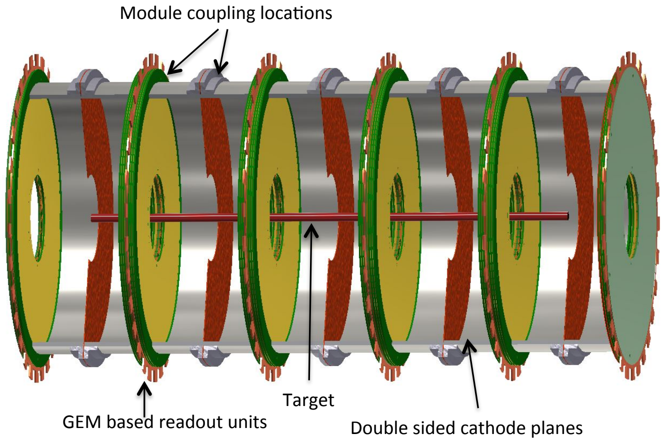
Hall-B VTP Test Setup 2

Currently active in Hall-B and used for SRO system development



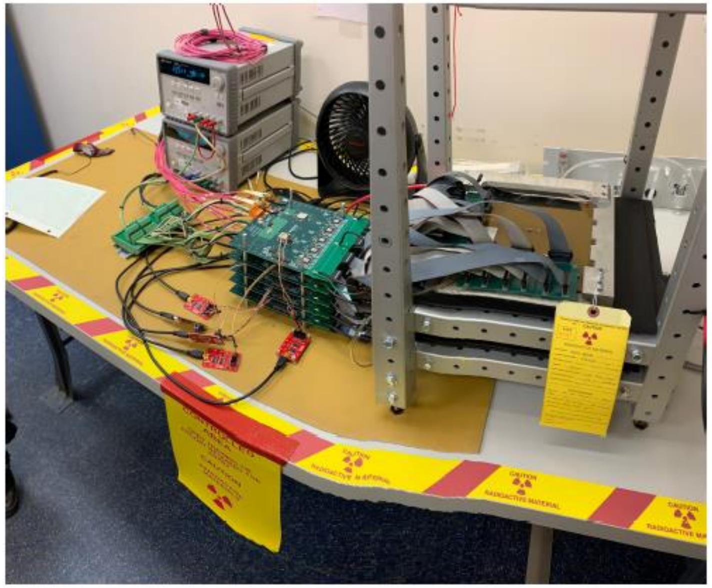
Tagged Deep Inelastic Scattering (TDIS)

- **Hall A** Super Big-Bite (SBS)
- **measurement** tagging for meson structure via the Sullivan process
- **science goals** meson structure functions and PDF
- **detection of low momentum spectators** GEM based multiple TPC (mTPC), reduced drift time in mTPC allows for triggered or streaming readout



TDIS Streaming Readout Prototype

- **SAMPA** novel front-end ASIC developed for streaming readout of GEM based ALICE TPC
- **ongoing tests** study GEM pulse data and stream continuously
- **preliminary results** stream trigger-less GEM data (768 channels) in DAS and DSP modes at 45 Gb/s via 5 ALICE front-end cards (FECs)
- **next steps**
  - using FELIX hardware and software for read out GEM data
  - integrate FELIX hardware and software into CODA

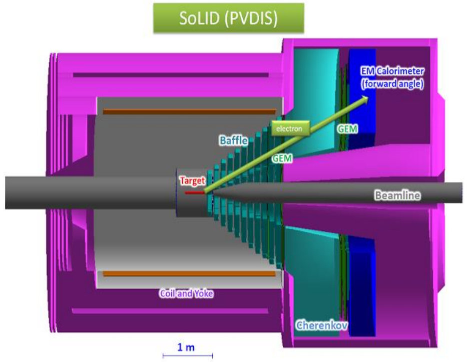


SoLID Streaming Readout considerations

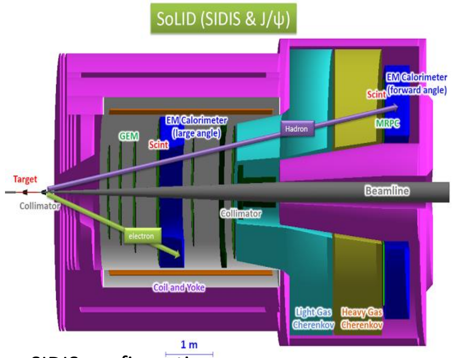
A. Camsonne et al.

high luminosity experiment: L = 10^{39} $cm^{-2}s^{-1}$
PVDIS Parity Violation In DIS
SIDIS TMD measurements
J/ψ origin of mass

- **Default** Trigger-based readout
- **Streaming Readout considerations**
  - straightforward for PVDIS
  - more difficult for SIDIS
  - need to evaluate required computing resources
- **Electronics considerations**
  - fADC250 and VMM3 for GEMs support streaming mode
  - SAMPA chip also good option provided sufficient radiation hardness



- PVDIS configuration
  - Inclusive DIS electrons
  - Trigger Calorimeter + Cerenkov
  - 30 individual sectors
  - 12 KHz/sector = less 500 KHz total



- SIDIS configuration
- Trigger :
  - Electron trigger : Calorimeter+Light Ga Cerenkov
  - Pion trigger
    - Scintillator + calorimeter
  - Main trigger : coincidence eπ
- 100 KHz of coincidence eπ
- J/ψ 30KHz triple coincidence ee^-e^+

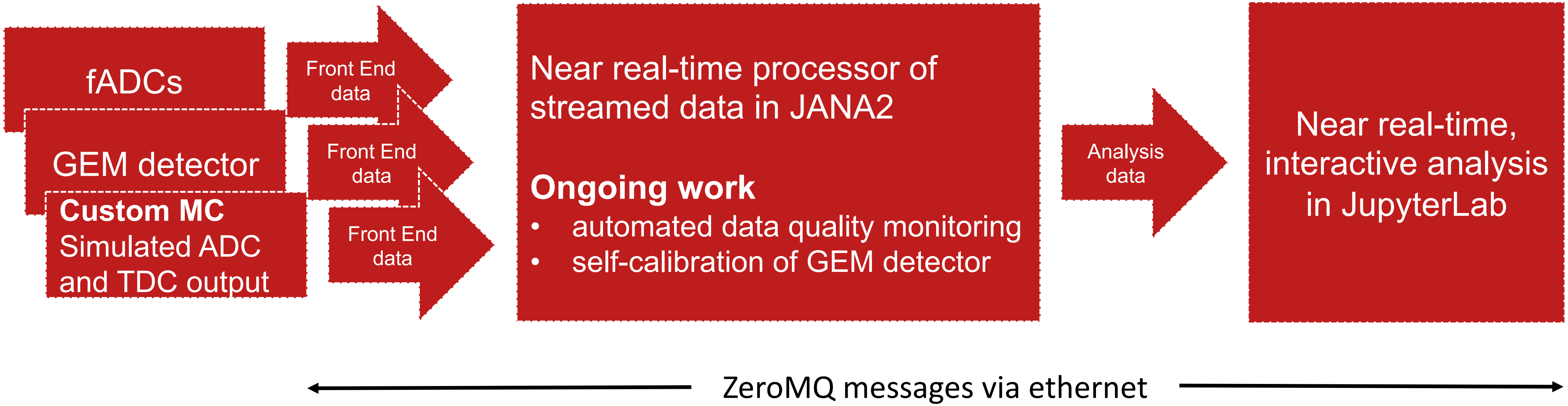
Seamless integration of DAQ and analysis using AI

M. Diefenthaler et al.

LDRD goal

prototype components of streaming readout at NP experiments
→ integrated start to end system from detector read out through analysis
→ comprehensive view: no problems pushed into the interfaces

prototype (near) real-time analysis of NP data
→ inform design of new NP experiments

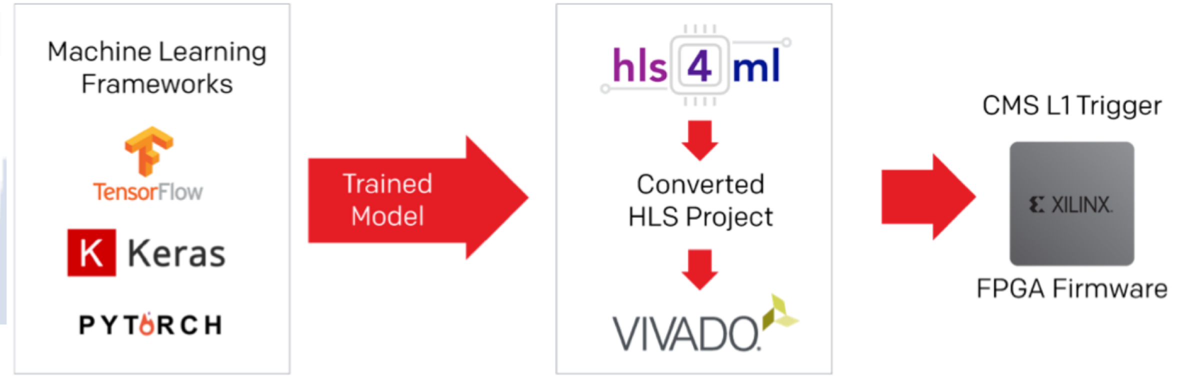


Goal build real-time event filter based on physics signatures

Status Started to work on test setup

- The setup will be used to identify and optimize artificial neural network algorithms and topologies, suitable for real-time FPGA applications.
- It will also be used to perform beam tests in Hall-D with GEM-TRD and calorimeter prototypes as PID detectors to estimate performance of ML on FPGA in a real-time environment.
- Test results could be used to calculate resource scaling for planned large scale experiments (SoLID, EIC, etc.).
- Results on performance and price could also serve as a feasibility study on building a full scale ML-FPGA filter for current experiments such as CLAS12 and/or GlueX.

Vivado High-Level Synthesis (HLS) transforms a C, C++, or SystemC design specification into Register Transfer Level (RTL) code for synthesis and implementation



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Over the last decade remarkable advances in electronics, computing, and software changed assumptions upon which data acquisition system designs for Nuclear Physics experiments are based

New possibilities and paradigms for JLab 12 GeV

- reevaluate the near- and long-term R&D of detector readout and analysis
- joint effort by Experimental Nuclear Physics, Fast Electronics, and Scientific Computing
- streaming mode considered for CLAS12, TDIS, and SoLID
- R&D on (near) real-time analysis

Streaming Readout effort at JLab coordinated with the EIC community

- EIC Streaming Readout Consortium (eRD23)
- Yellow Report Initiative by EIC User Group