Evaluation of a streaming readout solution for Jefferson Lab experiments

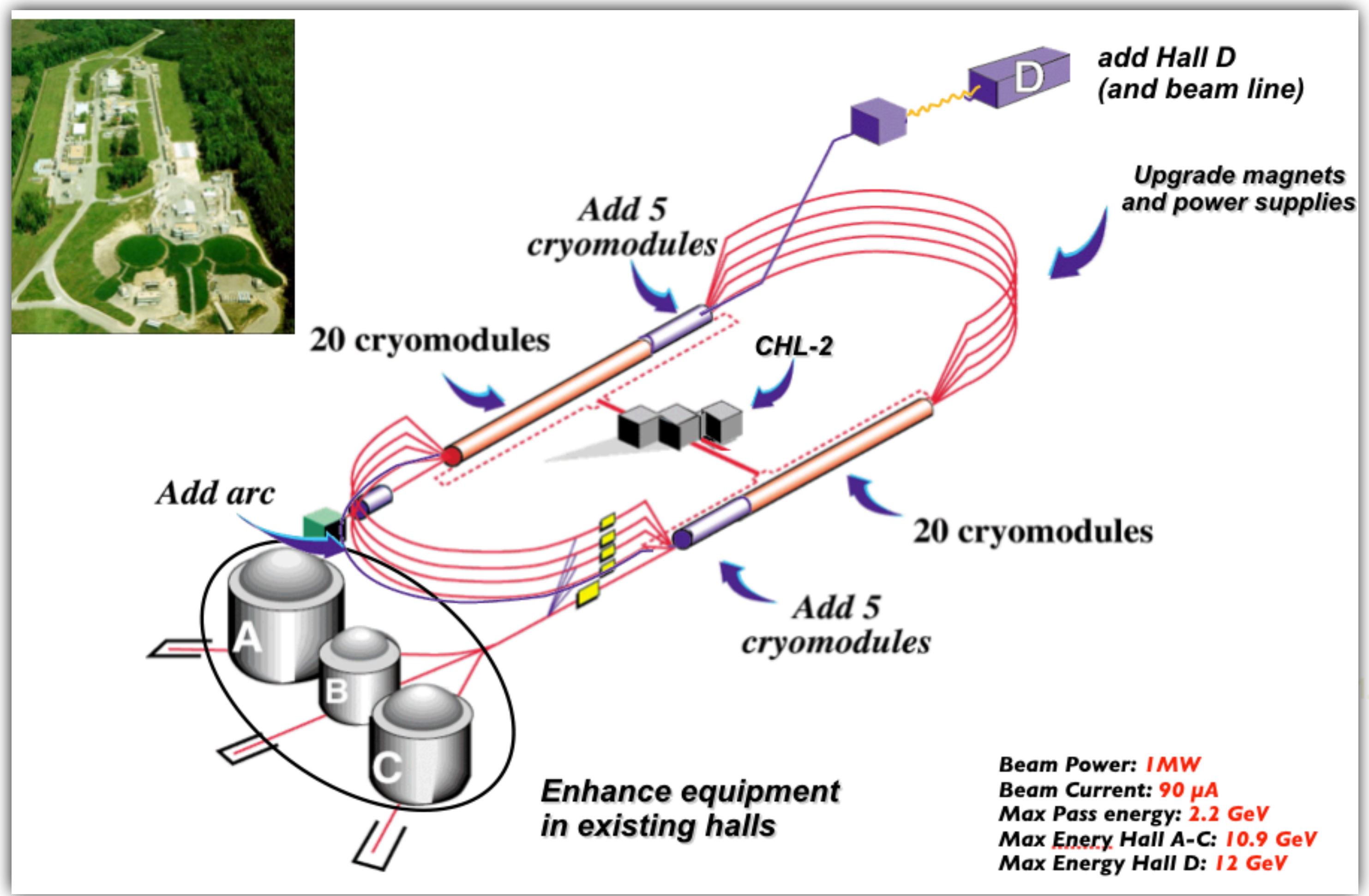
Marco Battaglieri
Jefferson Lab/INFN
(for JLab SRO Team)

Farnesina
Ministero degli Affari Esteri e della Cooperazione Internazionale

Supported by Italian Ministry of Foreign Affairs (MAECI) as Projects of great Relevance within Italy/US Scientific and Technological Cooperation under grant n. MAE0065689 - PGR00799

Jefferson Lab


Jefferson Lab's accelerator site

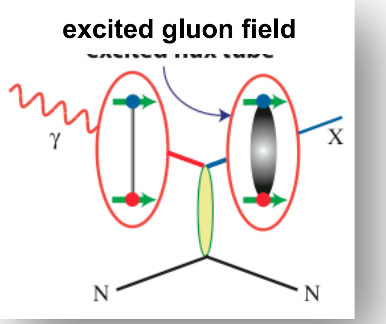


- ✳ Primary Beam: Electrons
- ✳ Beam Energy: 12 GeV
  - 10 > λ > 0.1 fm
  - nucleon → quark transition
  - baryon and meson excited states
- ✳ 100% Duty Factor (cw) Beam
  - coincidence experiments
  - Four simultaneous beams
  - Independent E and I
- ✳ Polarization
  - spin degrees of freedom
  - weak neutral currents

Luminosity > 10^7 -10^8 x SLAC
at the time of the original DIS experiments!

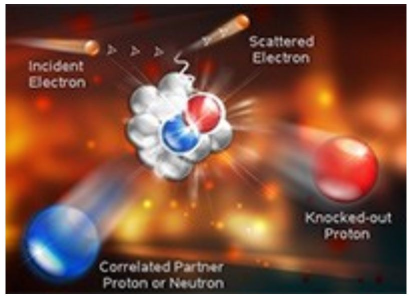
JLab Scientific mission

- What is the role of gluonic excitations in the spectroscopy of light mesons?

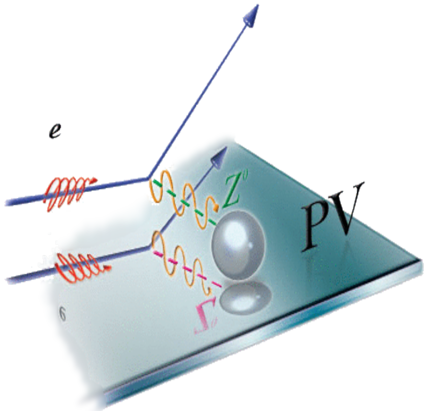


- Where is the missing spin in the nucleon? Role of orbital angular momentum?

- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?
- What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?

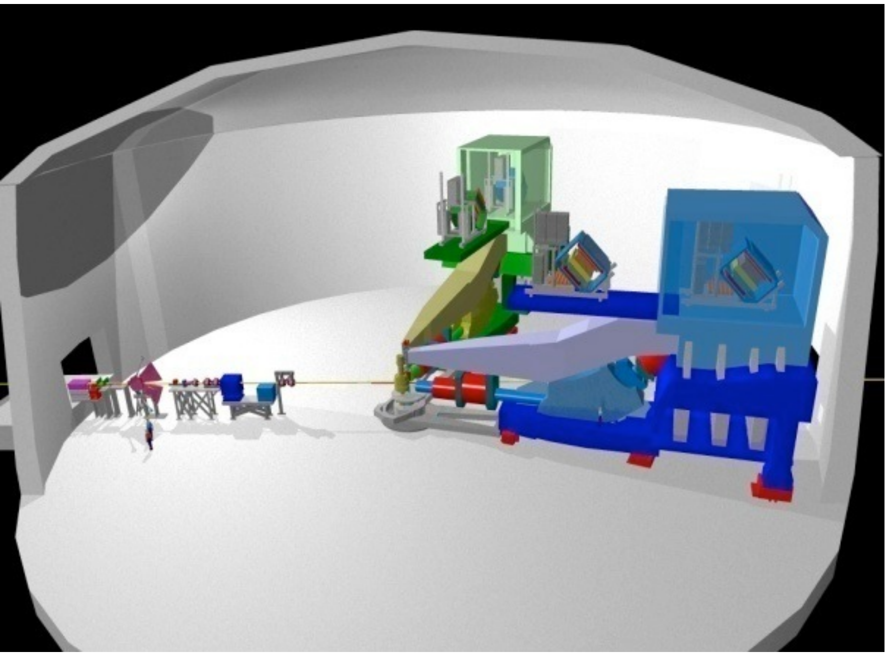


- Can we discover evidence for physics beyond the standard model of particle physics?

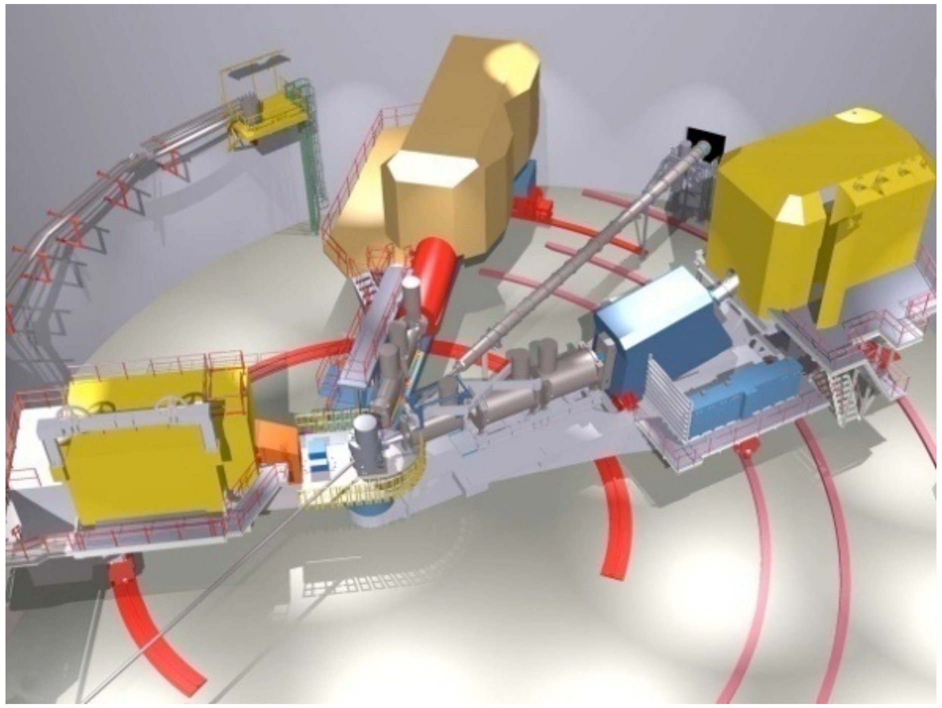


12 GGeV equipment

Hall A – High Resolution Spectrometers and new multipurpose large acceptance detectors

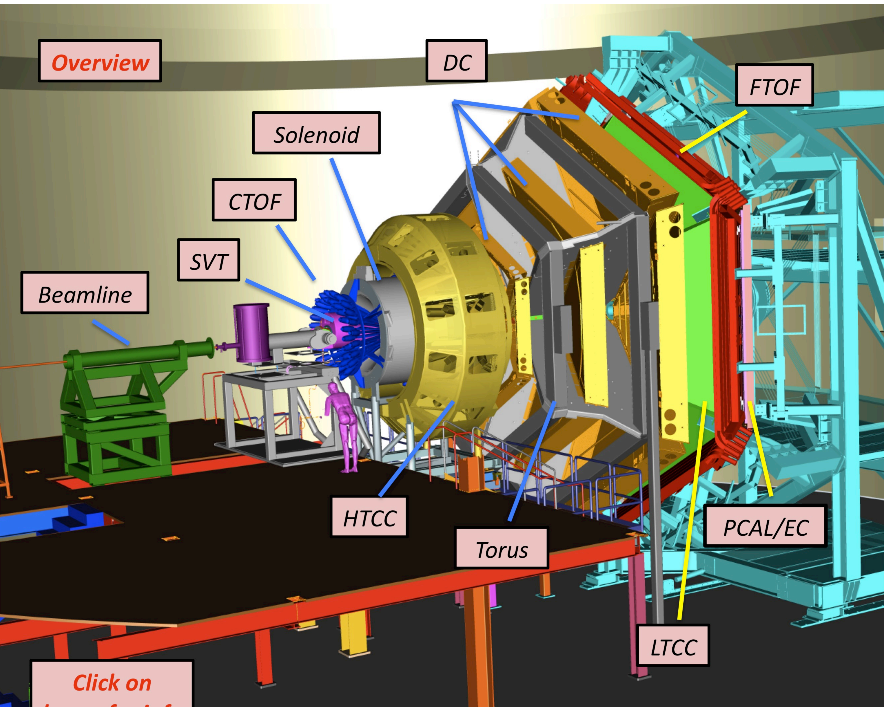


✳ short range correlations, form factors, and future new experiments: SOLID, MOELLER, SBS



Hall C – Super High Momentum Spectrometer (SHMS)

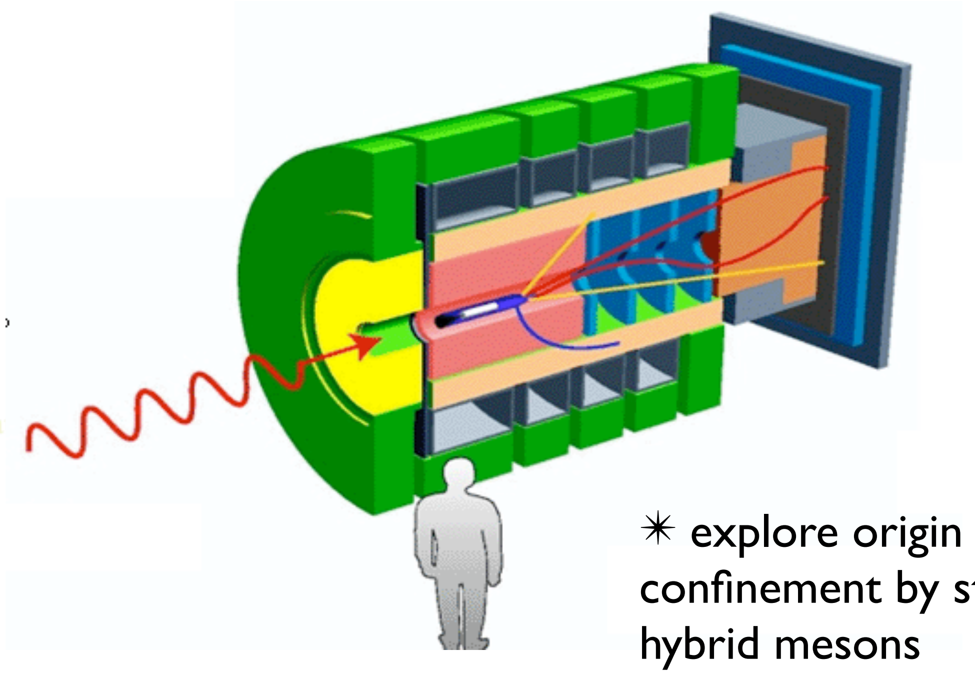
✳ precise determination of valence q properties in nucleons and nuclei



Hall B – Large acceptance detector CLAS12 for high luminosity measurements ($10^{35} cm^{-2} s^{-1}$)

✳ Understanding nucleon structure via GPDs and TMDs and hadron spectroscopy

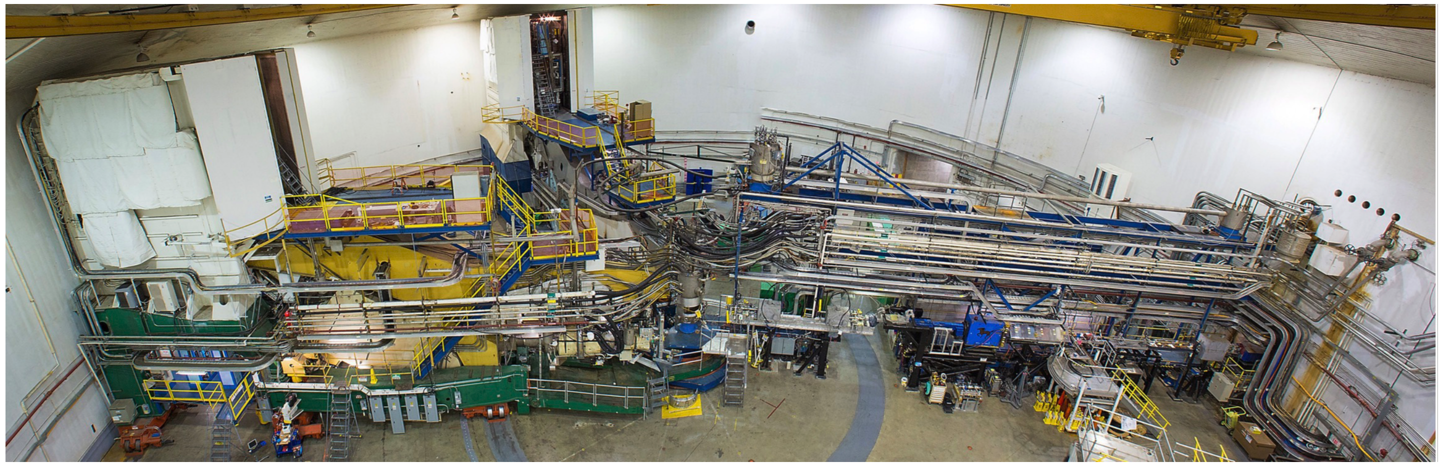
Hall D – GLUEx detector for photoproduction experiments



✳ explore origin of confinement by studying hybrid mesons

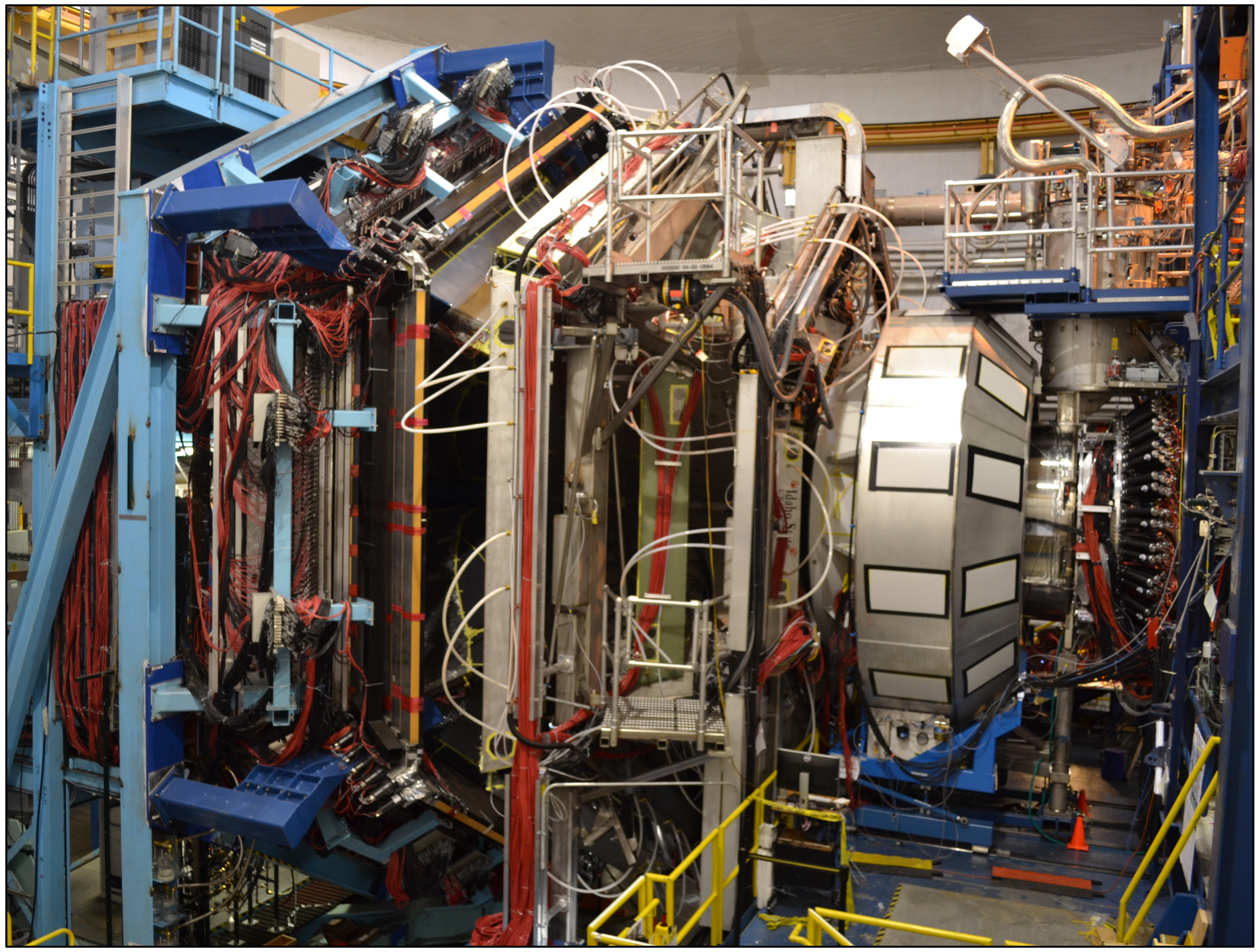
12 GeV equipment

Hall A

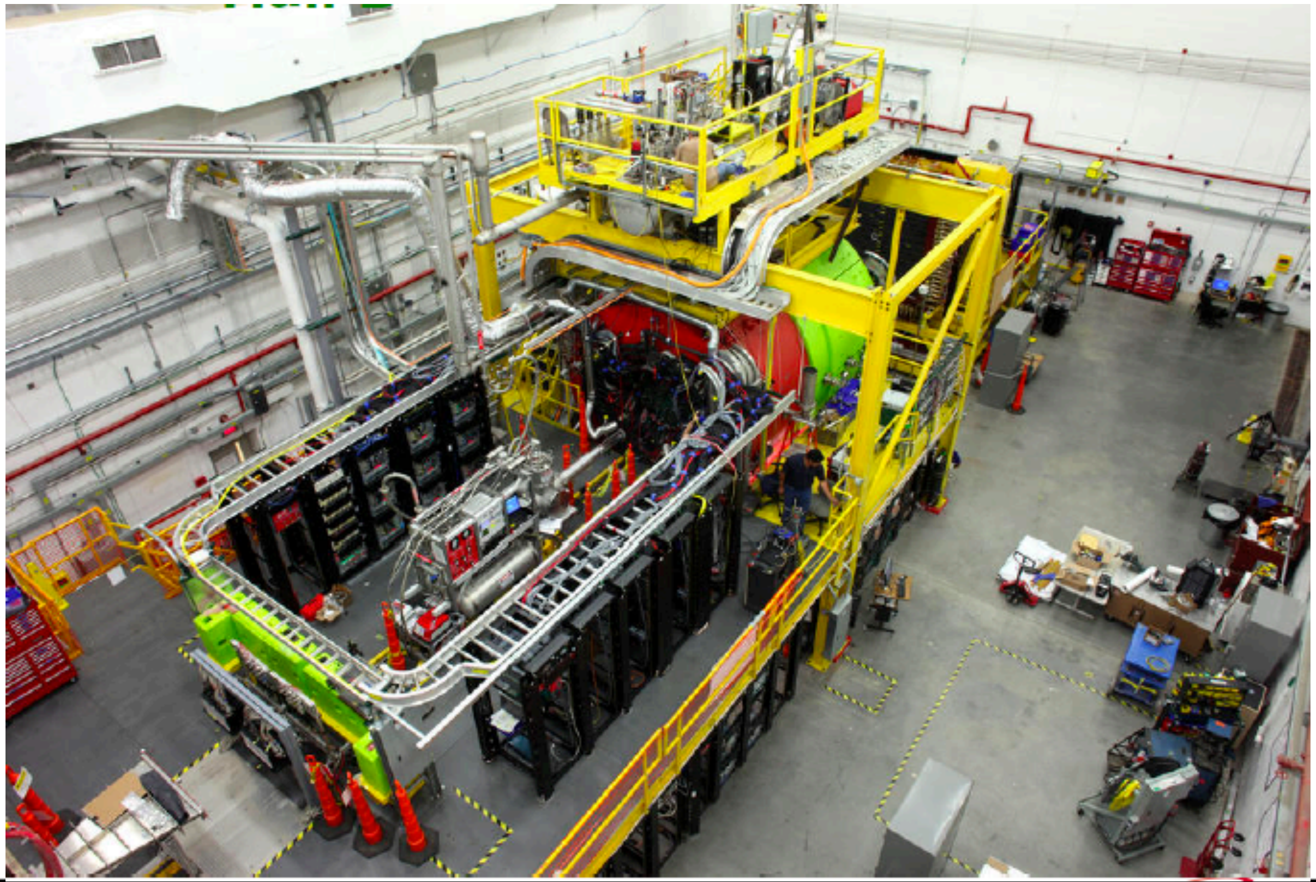


Hall C

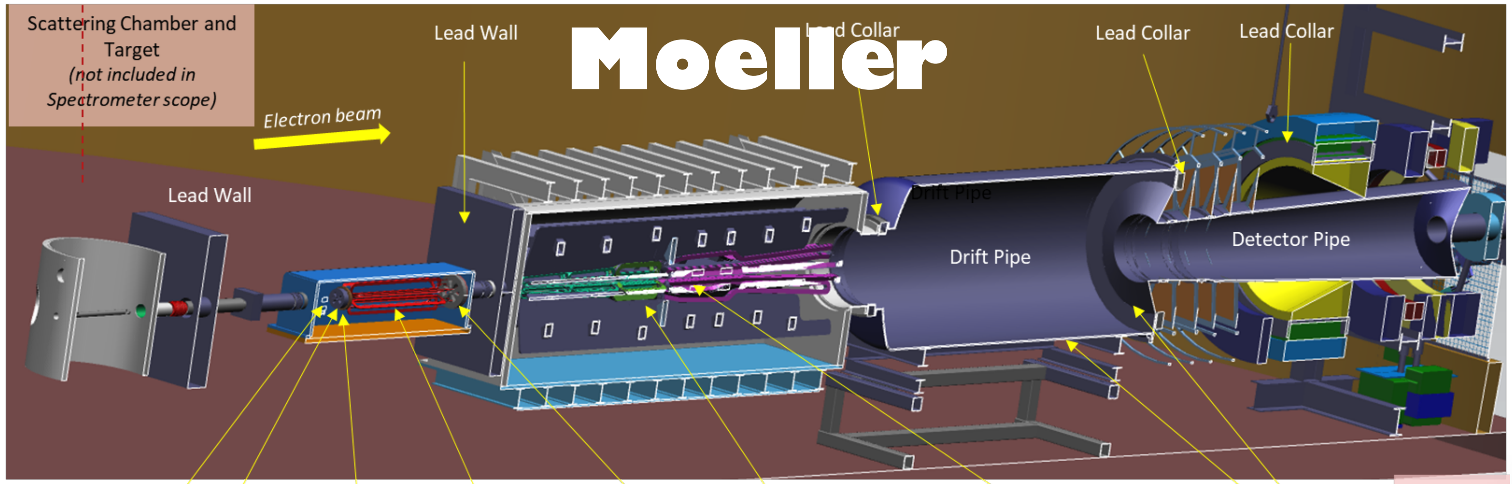
Hall B



Hall D

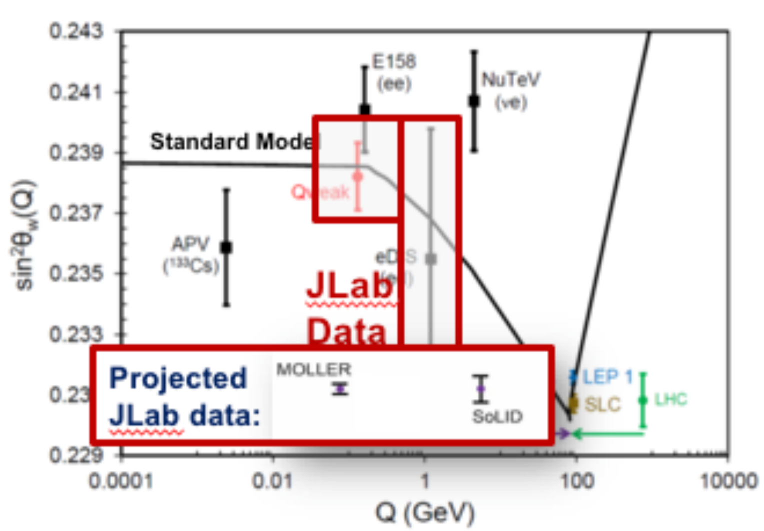


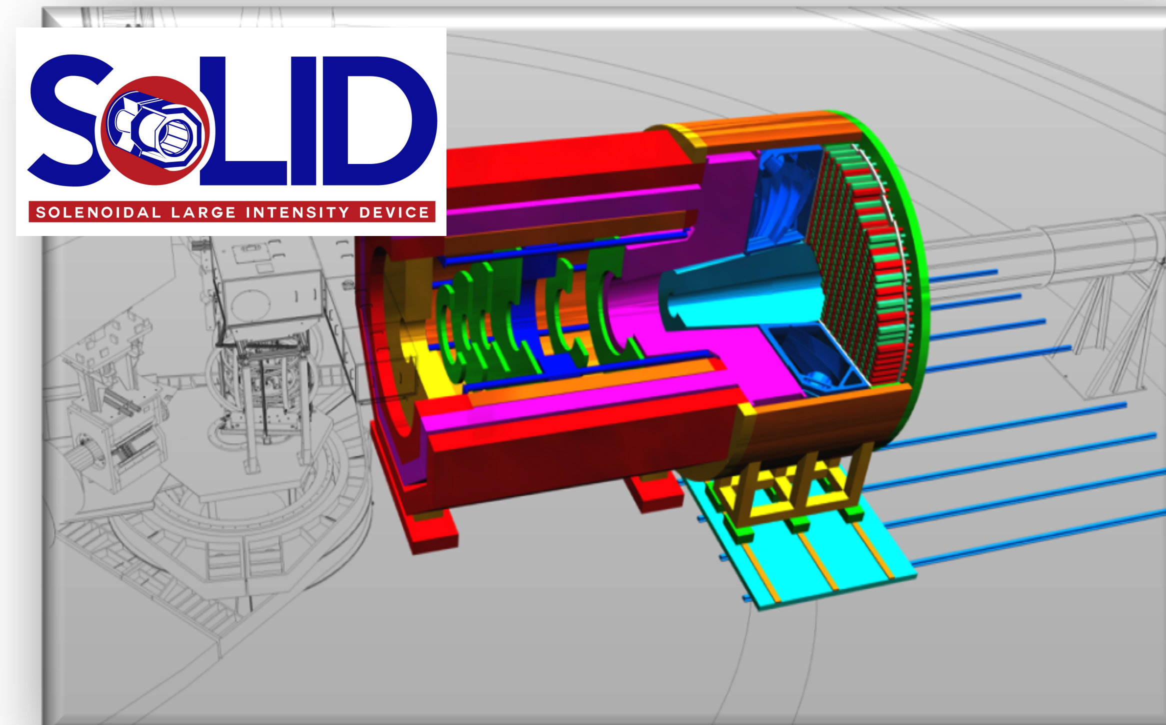
Future projects

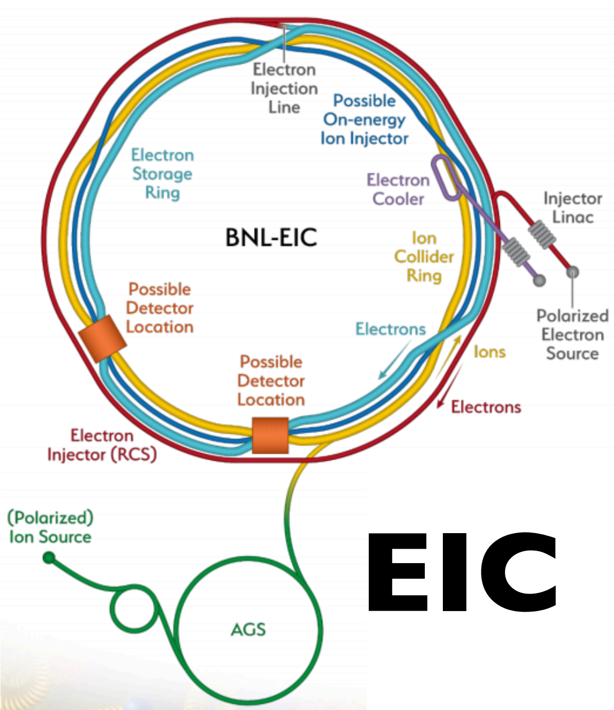


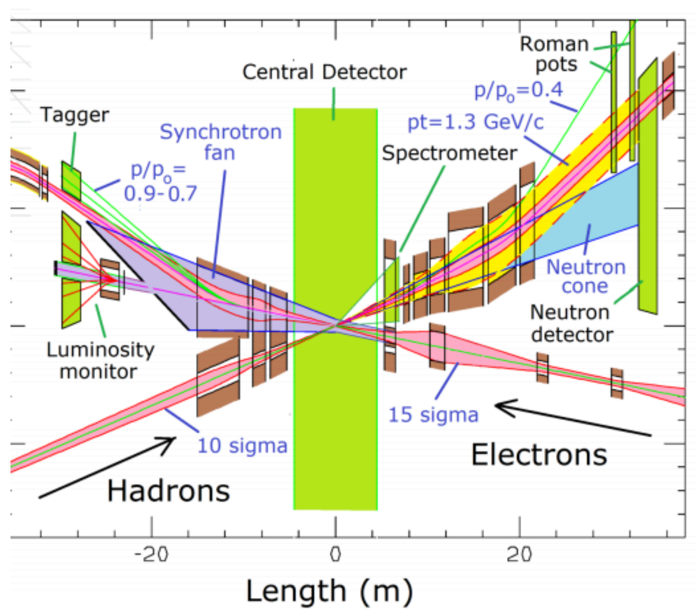
- Solenoidal Large Intensity Device – new multipurpose detector facility optimized for high luminosity and large acceptance, enabling very broad scientific program
- Unique capability combining high luminosity (10^{37-39} / cm^2/s) (more than 1000 times the EIC) and large acceptance, with full ϕ coverage to maximize the science return of the 12-GeV CEBAF upgrade

- Unique discovery space for new physics up to 38 TeV mass scale, with a purely leptonic probe
- CD-0 approved 2017, ready for CD-1









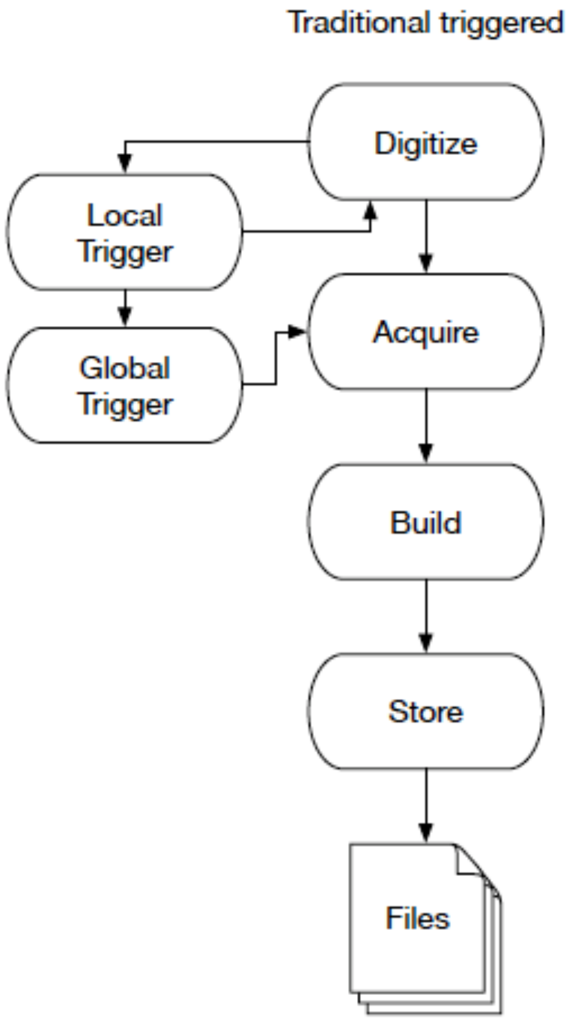
- Luminosity 100-1000 times that of HERA
- Polarized protons and light nuclear beams
- Nuclear beams of all A (p→U)
- Center mass variability with minimal loss of luminosity

- Large acceptance
- Frwrd/Bckw angles
- Precise vertexing
- HRes Tracking
- Excellent PID

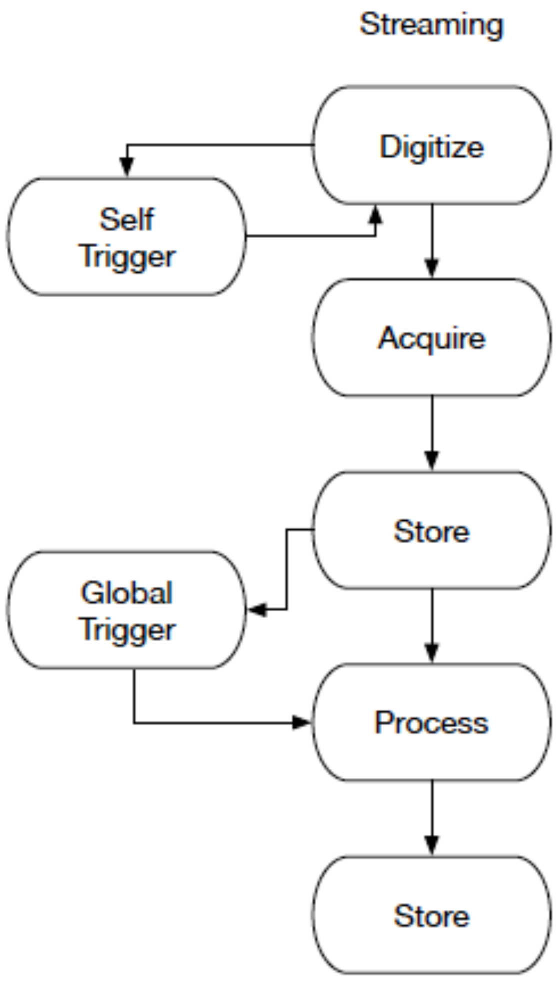
Streaming RO

Traditional (triggered) DAQ

- All channels continuously measured and hits stored in short term memory by the FEE
- Channels participating to the trigger send (partial) information to the trigger logic
- Trigger logic takes time to decide and if the trigger condition is satisfied:
  - a new 'event' is defined
  - trigger signal back to the FEE
  - data read from memory and stored on tape
- **Drawbacks:**
  - only few information form the trigger
  - Trigger logic (FPGA) difficult to implement and debug
  - not easy to change and adapt to different conditions



Streaming readout



- All channels continuously measured and hits streamed to a HIT manager (minimal local processing) with a time-stamp
- A HIT MANAGER receives hits from FEE, order them and ship to the software defined trigger
- Software defined trigger re-aligns in time the whole detector hits applying a selection algorithm to the time-slice
  - the concept of 'event' is lost
  - time-stamp is provided by a synchronous common clock distributed to each FEE
- **Advantages:**
  - Trigger decision based on high level reconstructed information
  - easy to implement and debug sophisticated algorithms
  - high-level programming languages
  - scalability

Streaming RO

Streming Read Out (RO) is one of the milestones of JLAB Agenda

- **Streaming RO is necessary for a long-term HI-LUMI upgrade of CLAS12**
  - Running CLAS12 at higher luminosity (wrt the designed $10^{35} cm^{-2} s^{-1}$) has been declared as a milestone for the FY20 JLab Agenda
  - The appointed PhysDiv Task Force (S.Stepanyan) identified a staged approach with an increase of 2x (keeping ε_{Rec}>85%)in 2-3 years (Phase I) timeframe and a 100x in 5-7 years (Phase II)
  - An update of the R1 CLAS12 DC with more dense detector (e.g. GEM) is expected in Phase I. A Streaming RO DAQ upgrade is necessary for the Phase II
  - With the current triggered technology the maximum possible event acquisition rate for CLAS12 is ~100 kHz (R~30 kHz now) replacing MM and CAEN TDCs
- **Streaming RO can be tested in Hall-D using the PS hodoscope**
  - Hall-D PS can be used as a beam test facility (fully parassitic) for a tagged electron/positron beam
- **Streaming RO is recognised as the leading DAQ technology for the EIC project**
  - CLAS12 can be used to test and validate detector/DAQ solutions for the EIC in a realistic on-beam condition
  - Using VTP readout CLAS12 can reuse 3/4 of existing triggered boards (fADC250) in streaming mode
  - Part of a lab-wide effort (involving Hall-C and Hall-D) to test EIC calorimetry

The CLAS12 detector

Forward Detector:

-TORUS magnet

- HT Cherenkov Counter

- Drift chamber system

- LT Cherenkov Counter

- Forward ToF System

- Preshower calorimeter

- E.M. calorimeter (EC)

Central Detector:

- SOLENOID magnet

- Barrel Silicon Tracker

- Central Time-of-Flight

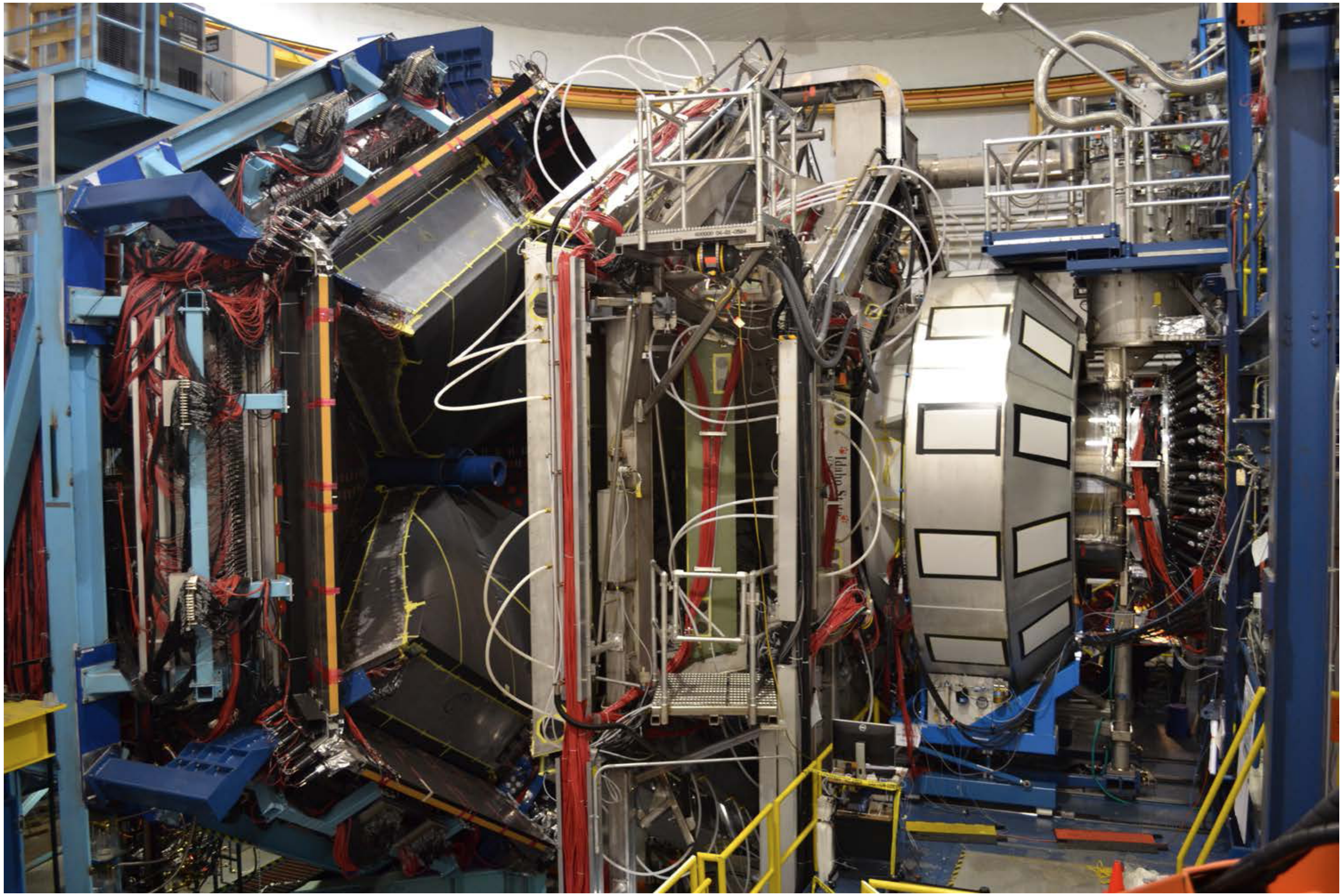
Upgrades:

- Micromegas (CD)

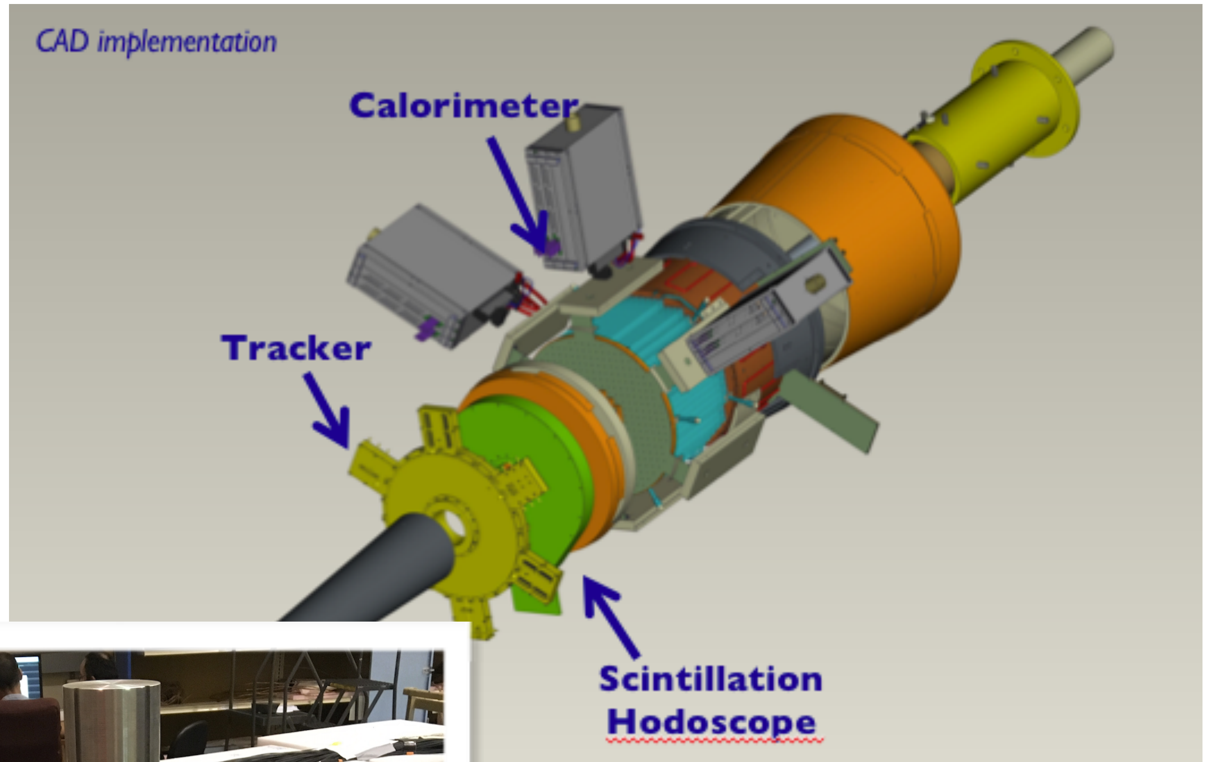
- Neutron detector (CD)

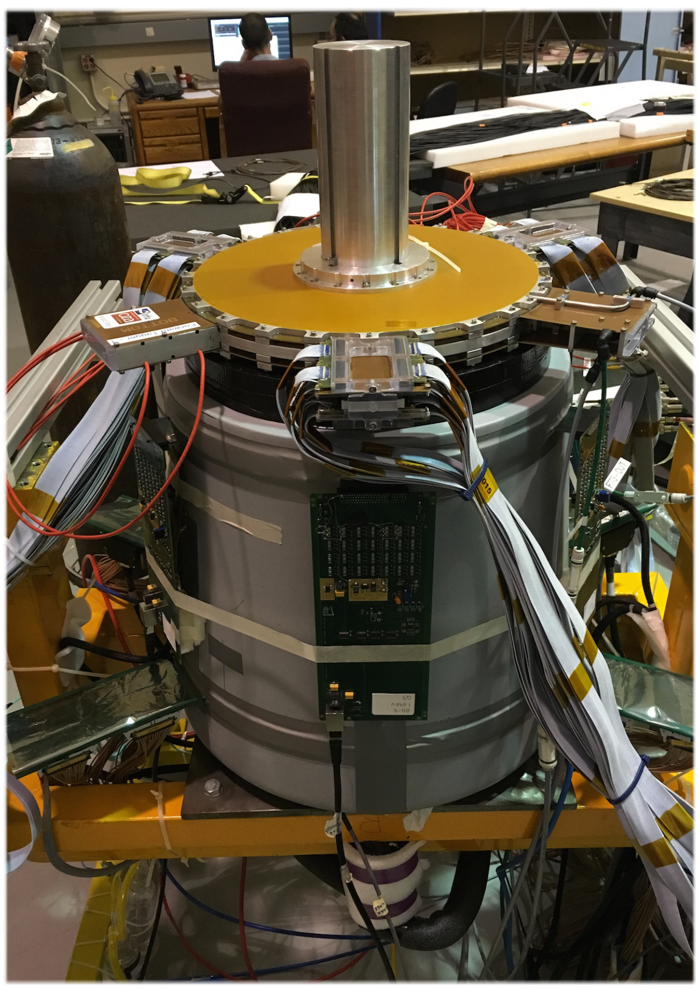
- RICH detector (FD)

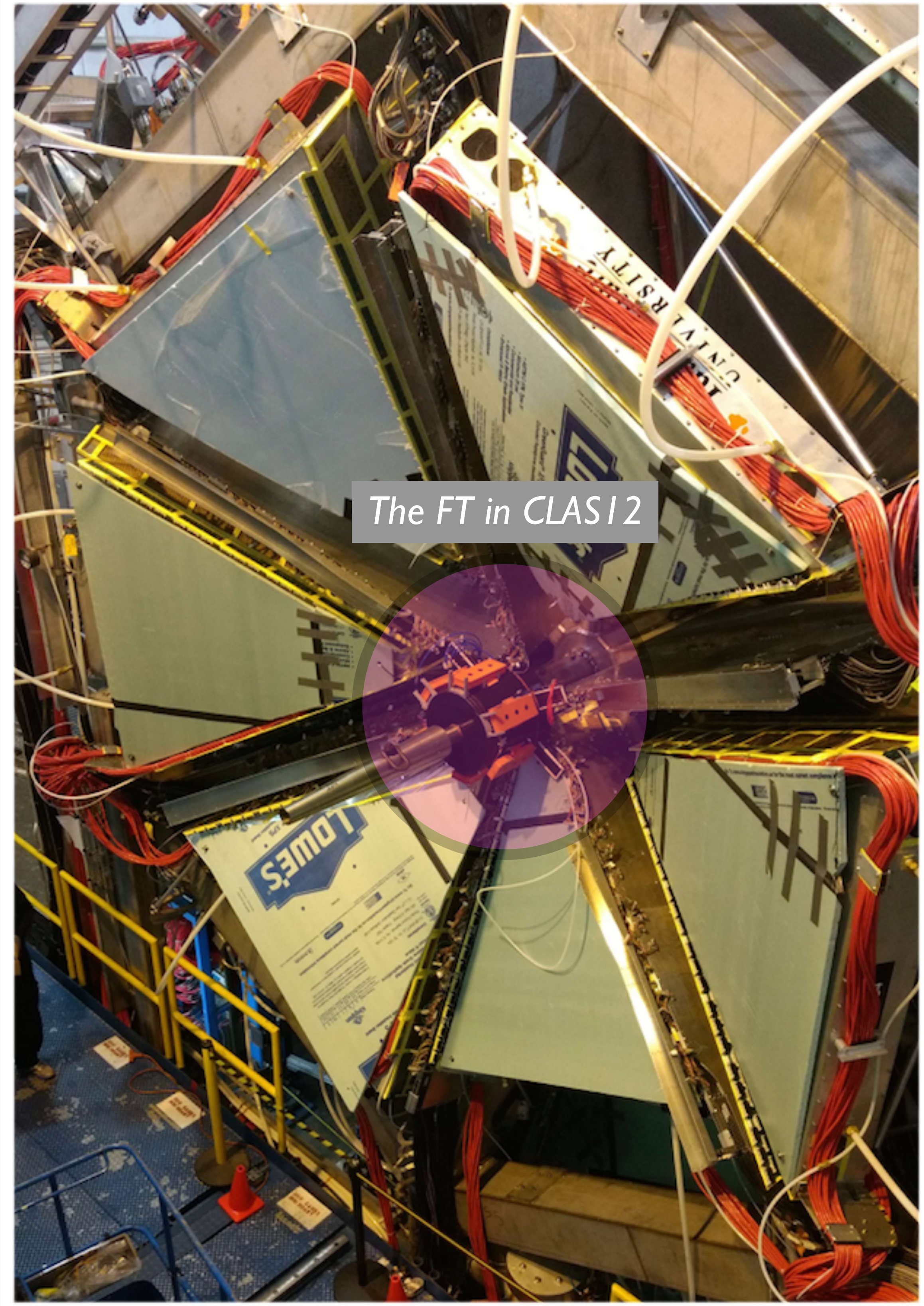
- Forward Tagger (FD)



CLAS12 and the Forward Tagger (FT)





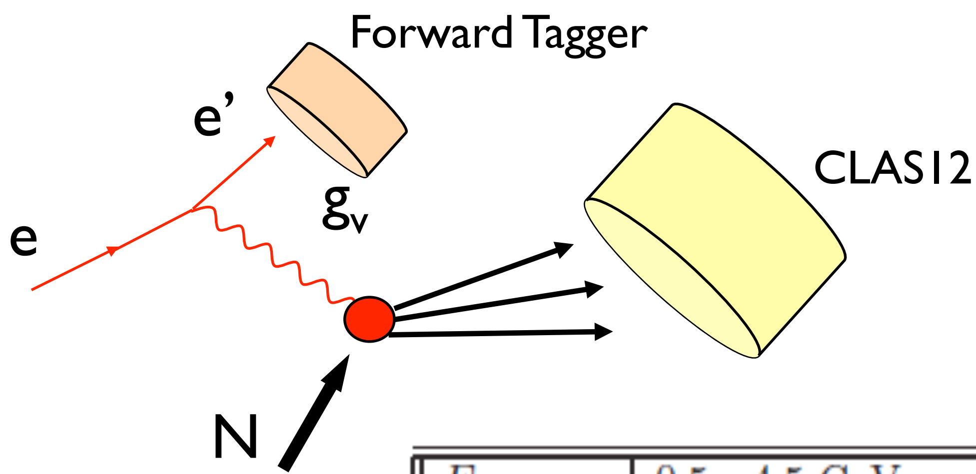


FT-Trck: MicroMegas
- electron angles and polarization plane

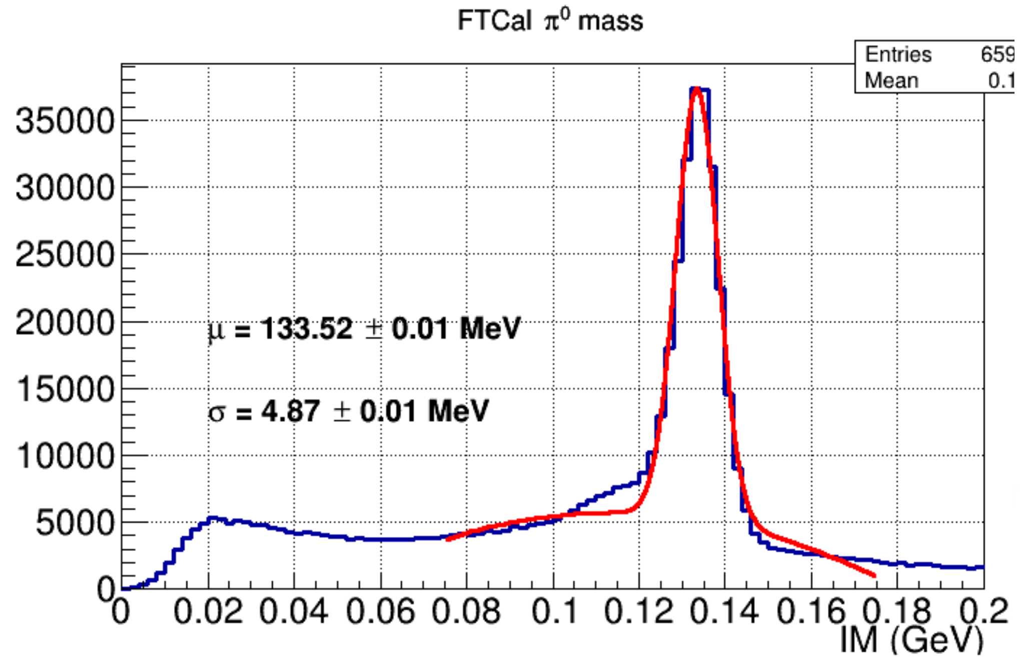
FT-Hodo: Scintillator tiles
- veto for photons

FT-Cal: $PbWO_4$ calorimeter
- electron energy/momentum
- Photon energy (ν=E-E')
- Polarization $\varepsilon^{-1} \approx 1 + \nu^2/2EE'$

FT performance

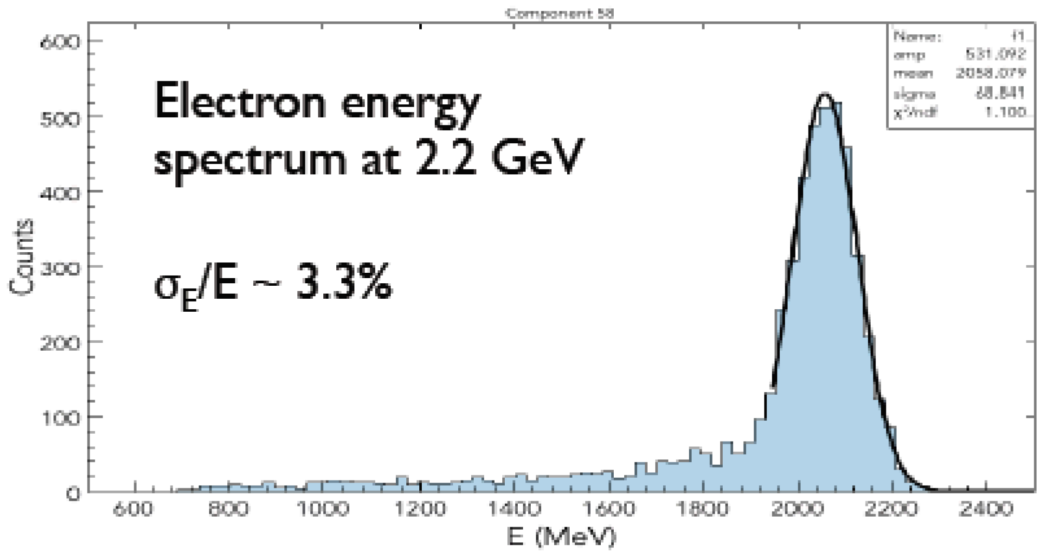


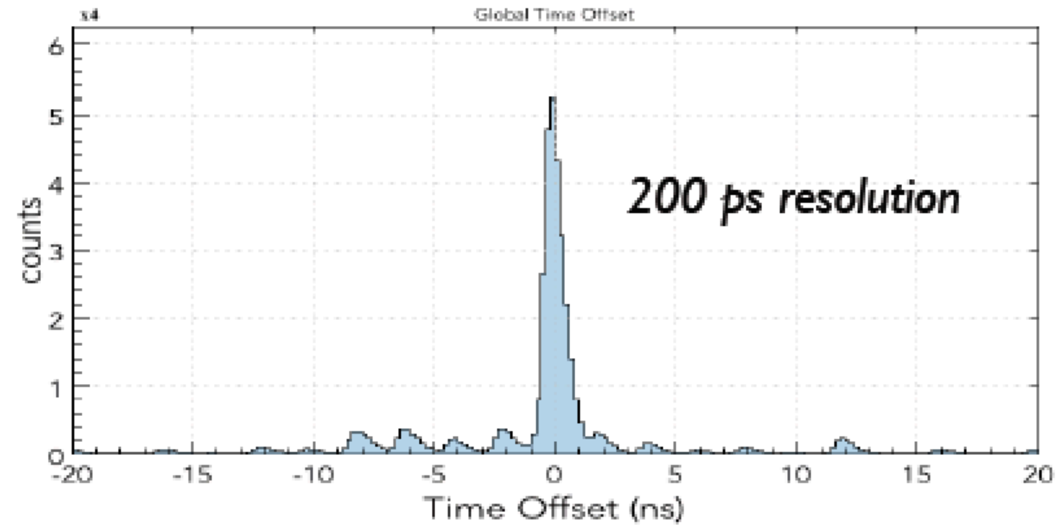
$E_{scattered}$	0.5 - 4.5 GeV
θ	2.5^o - 4.5^o
ϕ	0^o - 360^o
ν	6.5 - 10.5 GeV
Q^2	0.01 - 0.3 GeV^2 ($< Q^2 >$ 0.1 GeV^2)
W	3.6 - 4.5 GeV



Final calorimeter calibration based on real data:

- Energy calibration based on elastic data at 2.2 GeV and 6.4 GeV
- Timing calibration based on coincidence with forward CLAS12 detector





Streaming RO - CLAS12-FT tests

- SRO DAQ full chain test: FE + RunControl + Streaming ROsw + Rec
- On-beam tests
  - Run1: 10.4 GeV electron beam on Pb target in Jan/Feb 2020
  - Run2: 10.4 GeV electron beam on H2 and D2 targets in Aug/Sept 2020
- Hall-B CLAS12 Forward Tagger: Calorimeter + Hodoscope + (Tracker)

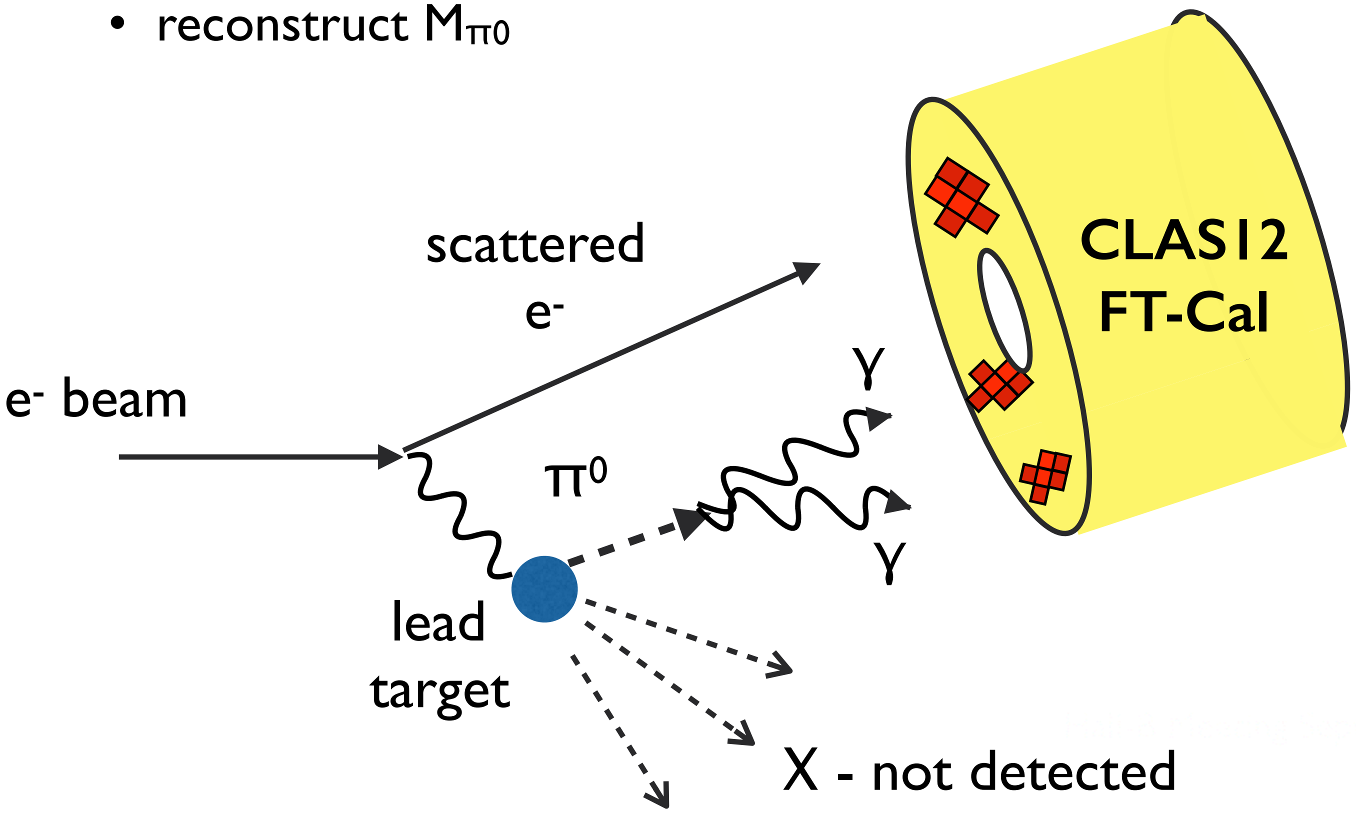
Goal:

- collect data with 1-2-3 clusters in FT-CAL
- Identify the reaction

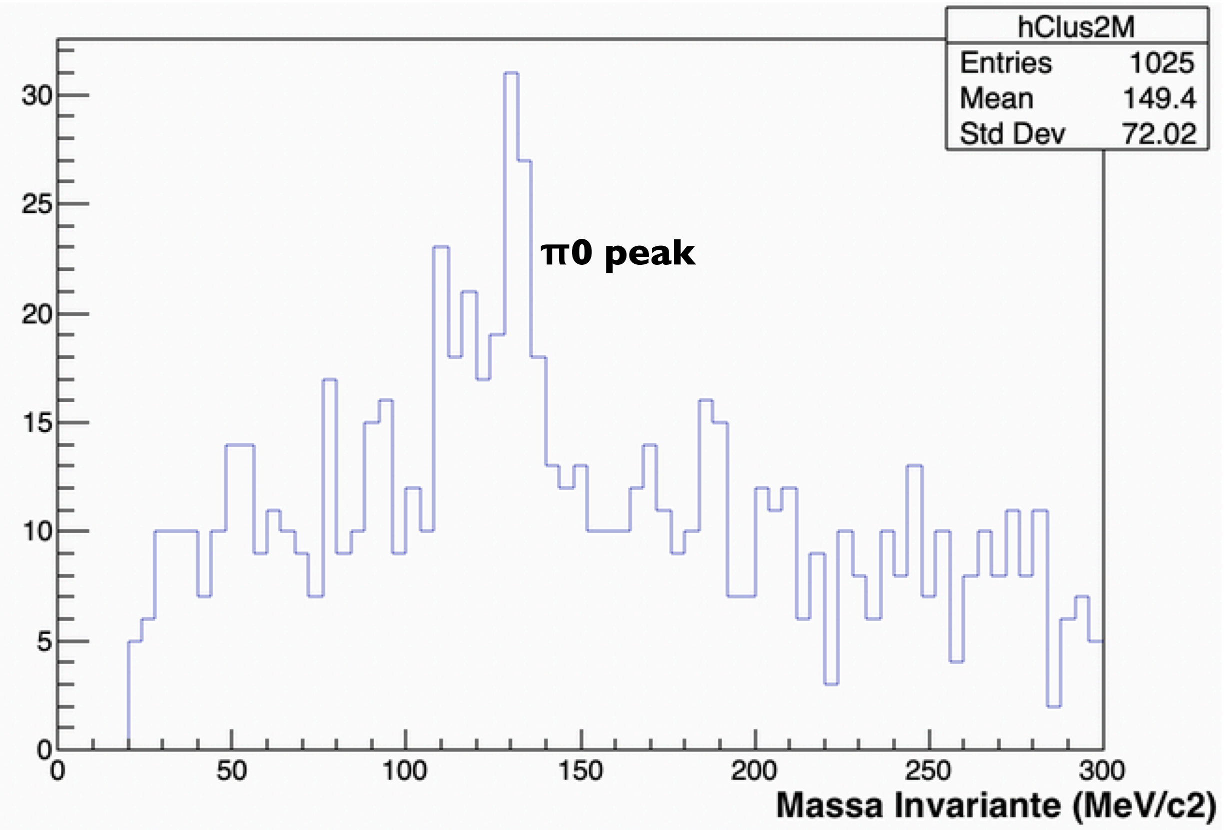
  $e\ H/D2/Al/Pb \rightarrow (X)\ e'\ \pi^0 \rightarrow (X)\ e'\ \gamma\ \gamma$
- reconstruct $M_{\pi 0}$

Test equipment

- FT-Cal: 332 PbWO crystals (APD)
- 10+12 fADC250 boards + 2 VTPs (in 2 crates/ROCs)
- FT-Hodo: 232 plastic scintillator tiles (SiPM)
- 15 fADC250 boards



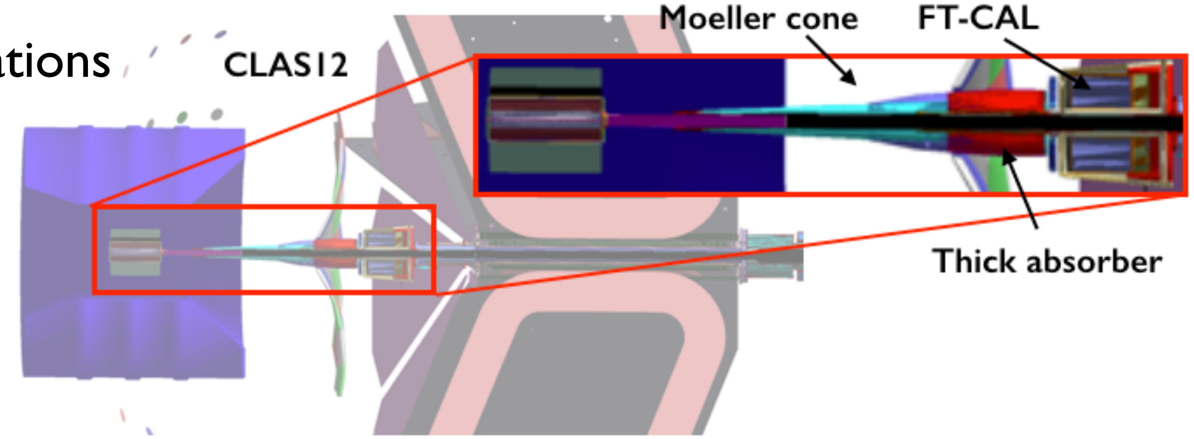
double-clusters (π0) mass obtained from FT-Cal RG-A data fed to TRIDAS

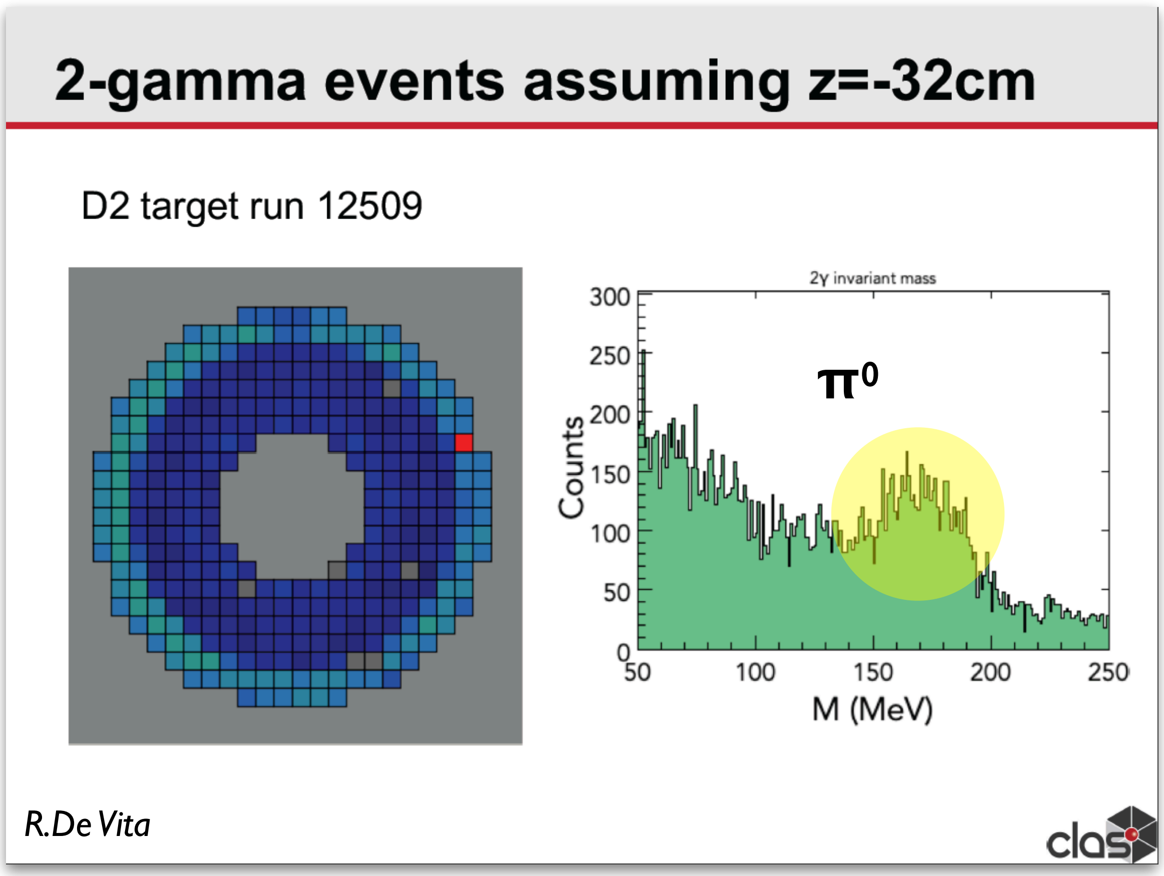


Hall-B Tests

M.Bondí, S.Vallarino

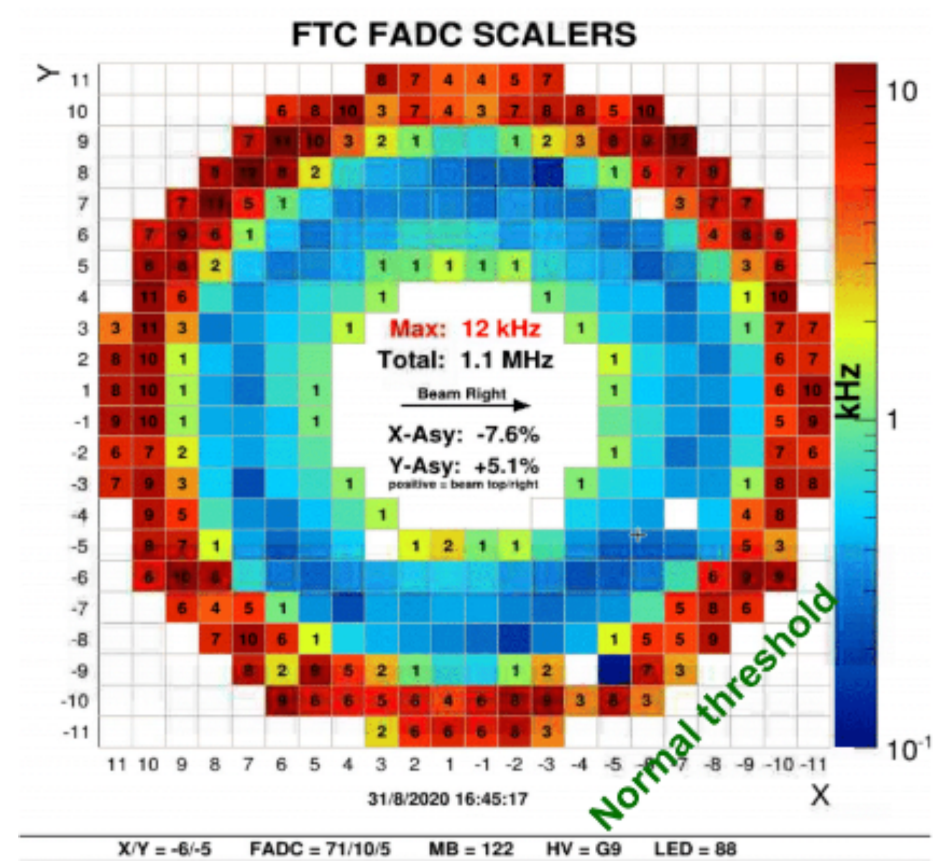
- Full GEANT4 simulations for the different experimental configurations
- Run1: no Moeller cone, nuclear (thin) target
- Run2: Moeller cone, longer target





- As a reference, data taken both in 'triggered' and SRO mode

- On-line scalers during Run2



SRO mode:
- L1 "minimum-bias": at least one crystal with energy > 2 GeV
- several L2 conditions in "tagging-mode" and "filtering-mode"
  - "standard" clustering algorithm: at least 2 clusters in FT-CAL
  - cosmic tracking
  - AI clustering algorithm: at least two cluster in the FT-CAL

Goal:
- study SRO performance: memory + cpu use, trigger eff., …
- Collect data for physics analysis: pi0 production on target
- Demonstrate t SRO s outperforms vs. a triggered DAQ

Streaming RO - CLAS12-FT tests

Front-End:
fADC250
VTP

SRO SW
TRIDAS

Online REC
JANA2

RunControl
CODA

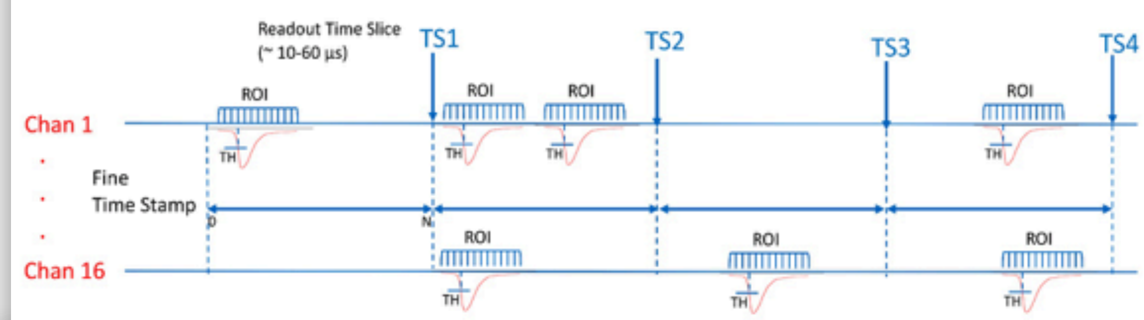
FrontEnd

D.Abbott, F.Ameli, C.Cuevas, P. Musico, B.Raydo

JLAB FADC in "Streaming Mode"

Streaming data can be thought of as Triggered mode where the trigger is a fixed pulser and you keep all the data for a single channel generated from the last pulse.

A 250 MHz FADC generates a 12 bit sample every 4ns. That's 3 Gb/s for one channel. A 16 channel module is 48 Gb/s. That is over twice the available VXS bandwidth. But we don't need ALL the data.



Within the FPGA we keep only the data around a Region of Interest (ROI) from each channel, along with a fine time stamp in each time slice window.

Depending on hit rates and available bandwidth , We can keep the individual samples or just compute a sum.

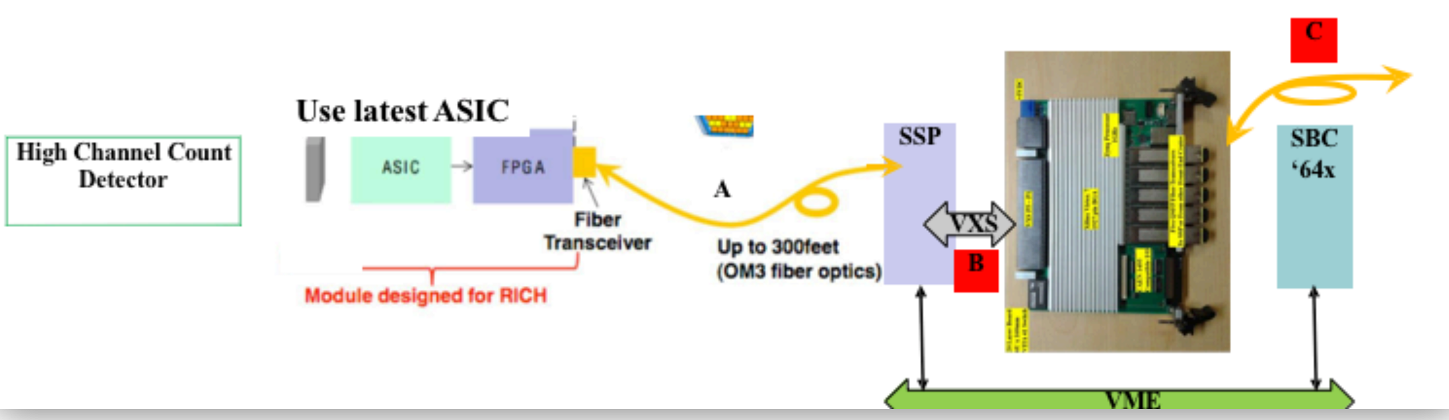
Jefferson Lab

Streaming DAQ Through the VXS Trigger Processor

Bypassing '64x Example

- A 1 SSP manages 32 LC fiber @2.5Gbps
- B 16 SSP/crate @20Gbps to VTP [4 lanes/@5Gbps]
- Streaming bandwidth 320Gpbs to VTP
- 40Gbe from VTP "CODA ROC"

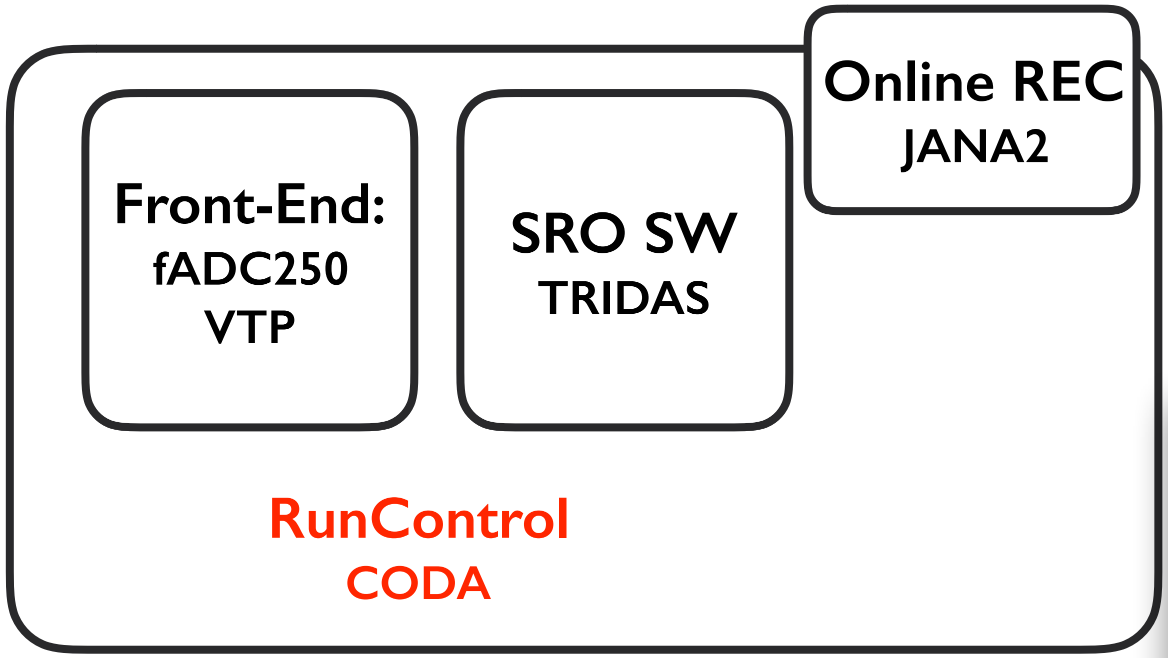
C VTP can perform significant data processing
192 channels for FPGA front end so,
Single VXS crate could stream
$192_{FPGA} * 32_{Links} * 16_{SSP} == 98304$ Chs



During tests:

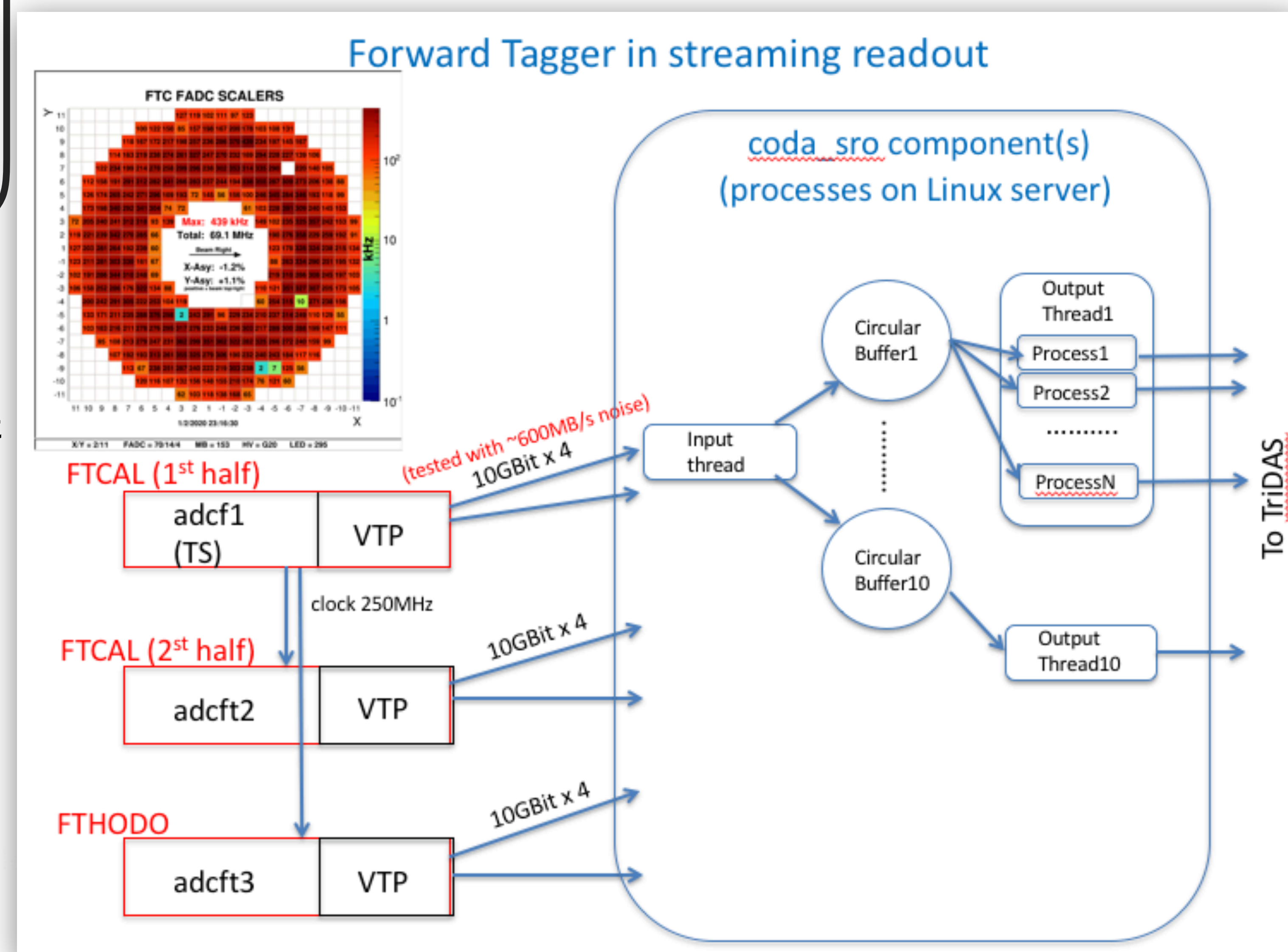
- Peak data rates ~150MBytes total
- Current VTP limit ~2GByte/sec
- Max: 10GBytes/sec

Streaming RO - CLAS12-FT tests



CODA

S.Boyarinov, B.Raydo, G.Heyes



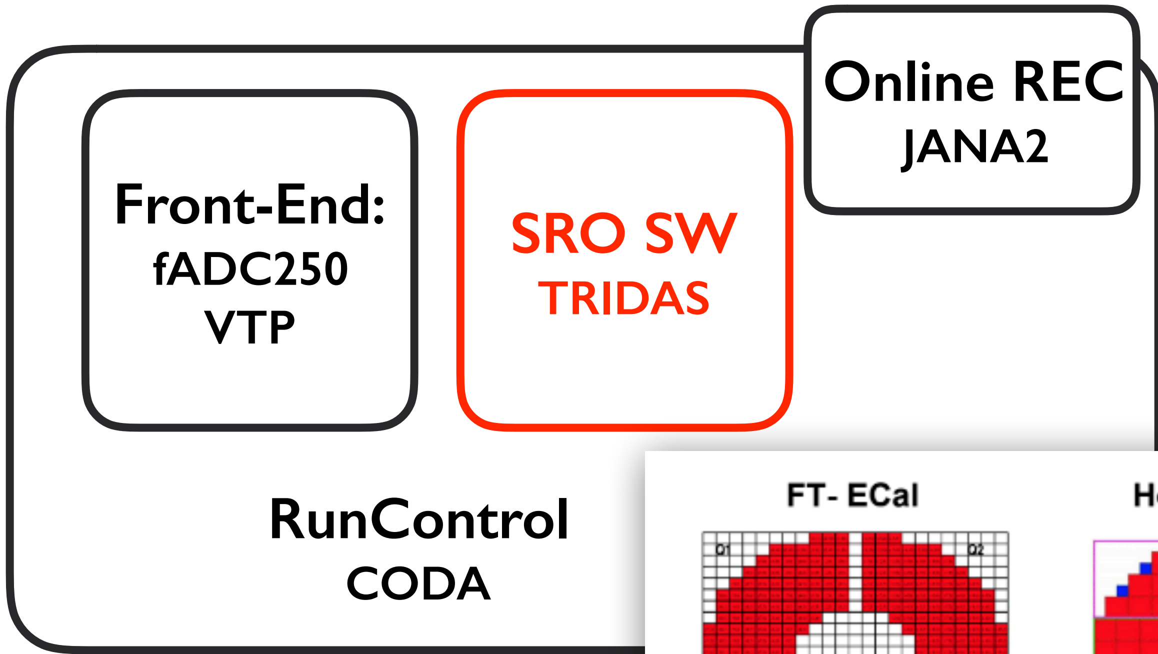
Cebaf Online Data Acquisition (CODA)

- Designed for trigger-based readout systems
- The Event Builder (EV) collects data from 100+ Readout Controllers (ROCs) and VXS Trigger Boards (VTPs)
- The Trigger Supervisor (TS) synchronizes components using clock, sync, trigger and busy signals.

CODA adapted to SRO mode:

- EB replaced with new SRO component and back-end software capable of gluing ROC information based on timestamp instead of event number.
- ROCs not send data on VME bus (only initial configuration)
- Readout performed by VTP boards over serial lines
- 20GBit/s per crate (up to 40GBit/s if needed.)

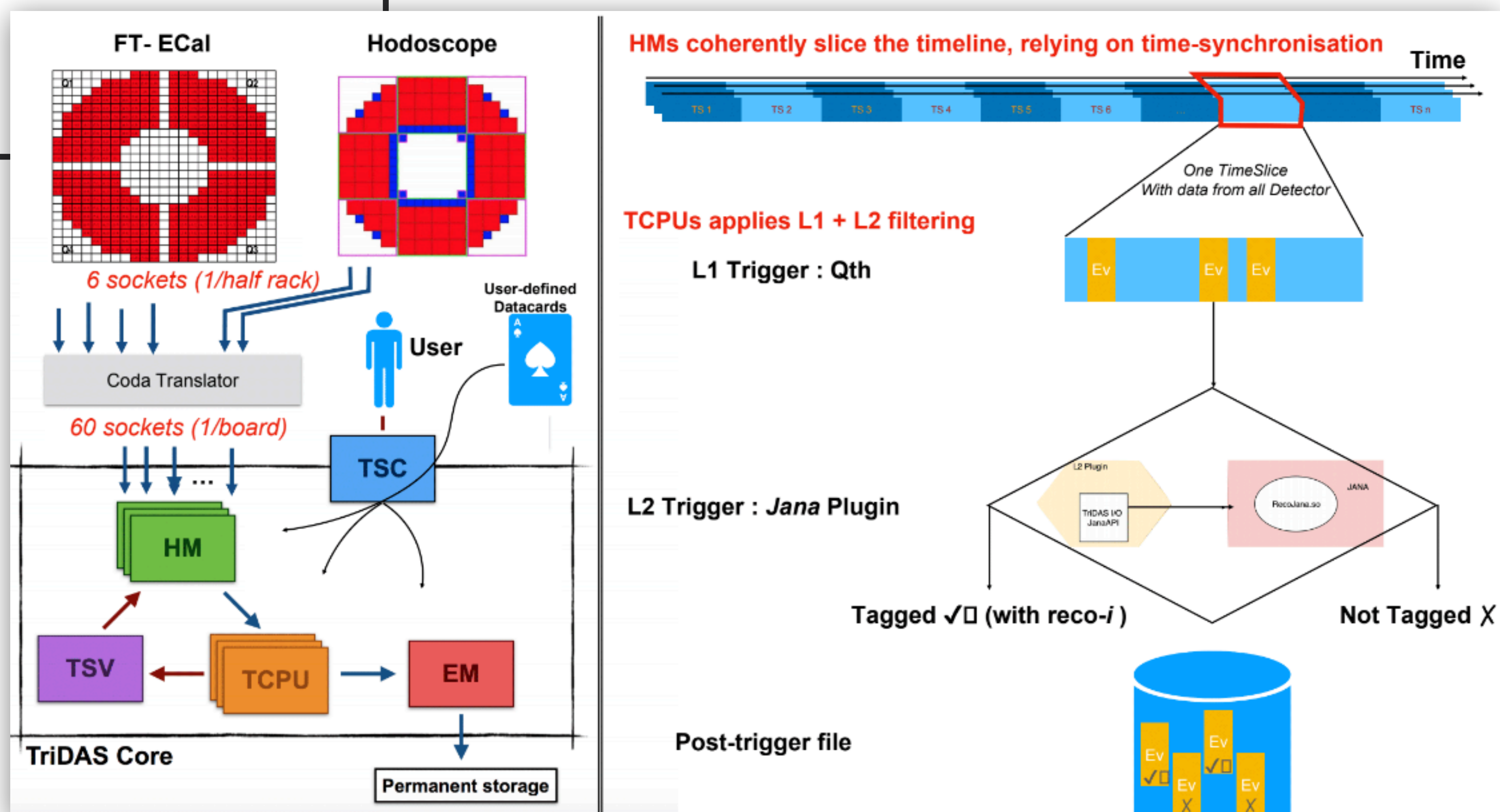
Streaming RO - CLAS12-FT tests



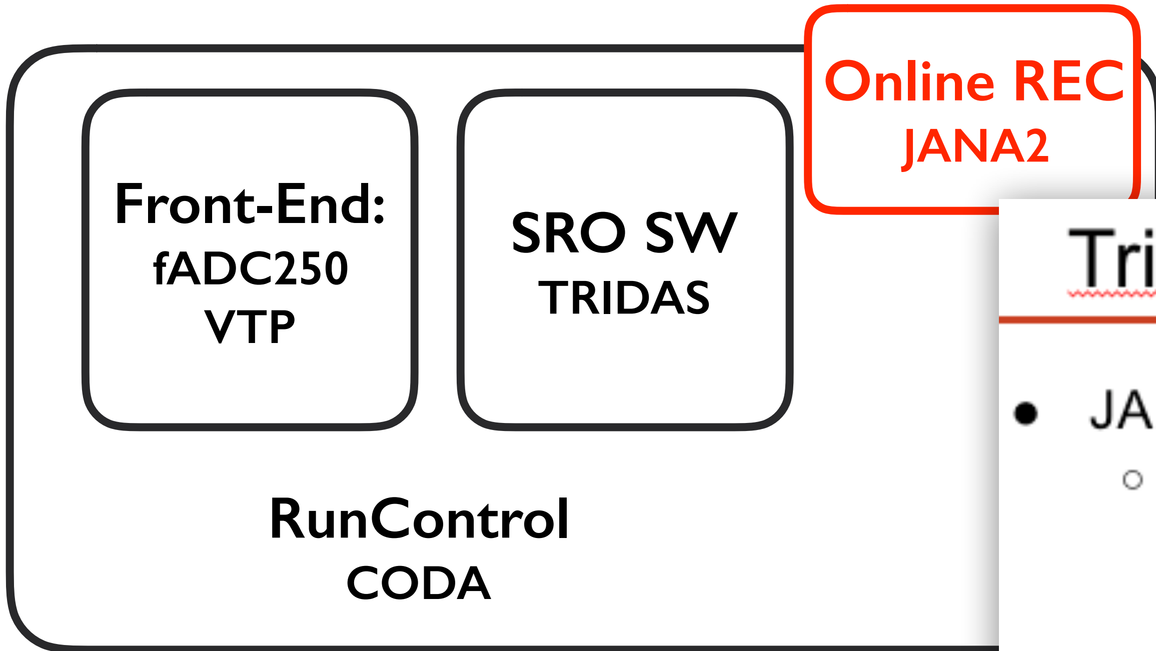
TRIDAS

T.Chiarusi, C.Pellegrino

- TriDAS: backend SRO sw framework
- developed for KM3_NET
- installed on Hall-B cluster
- Tested on multiple CPUs
- FT-Cal rate: 20-30 MHz
- Few hot-channels > 1 MHz
- Dta rate ~50MB/s
- Tests performed with different parameters (thresholds, HM, TCPUs)
- Profiling and performance

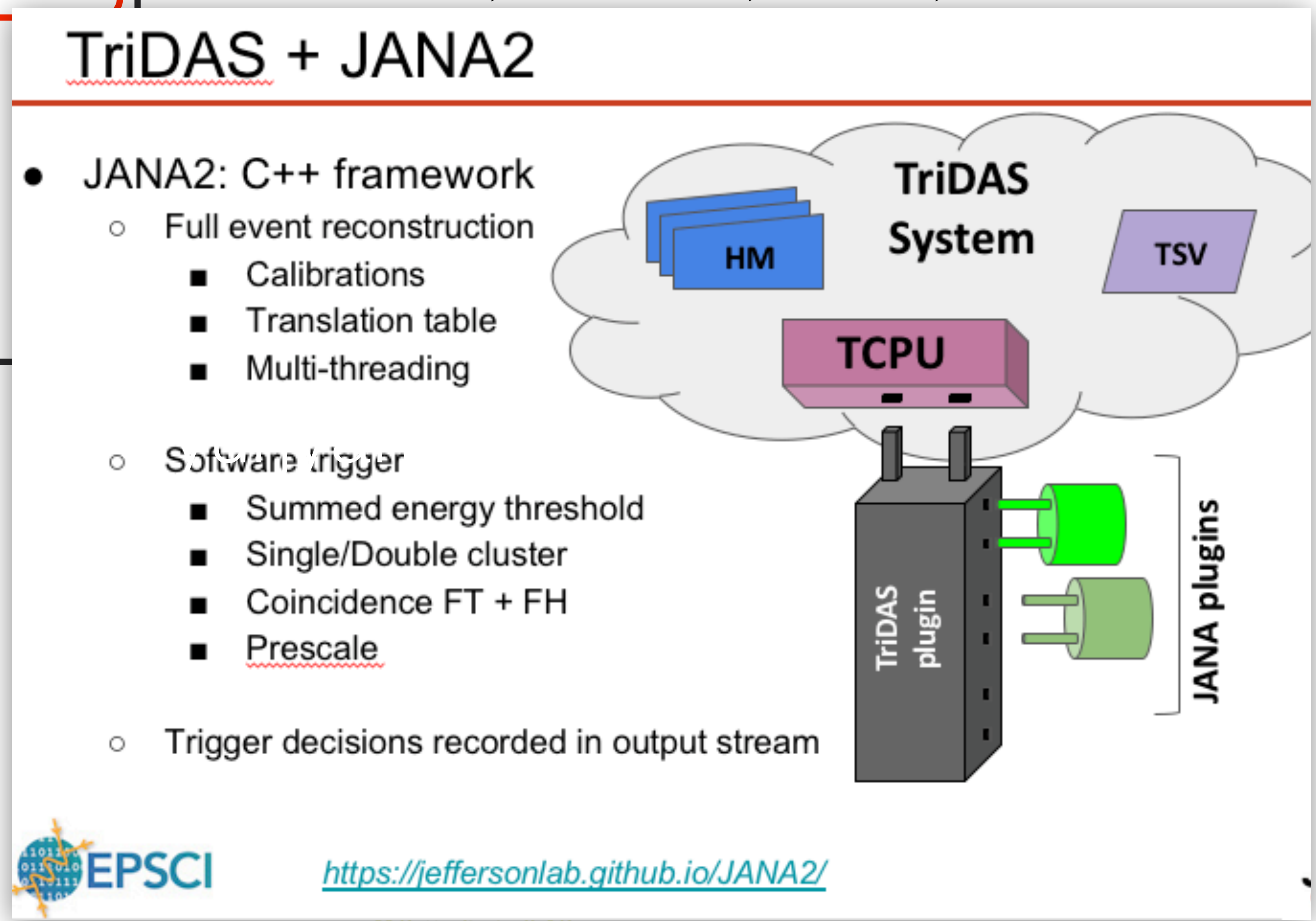


Streaming RO - CLAS12-FT tests



JANA2 + REC

N.Brei, D.Lawrence,
M.Bondi', A.Celentano, C.Fanelli, S.Vallarino



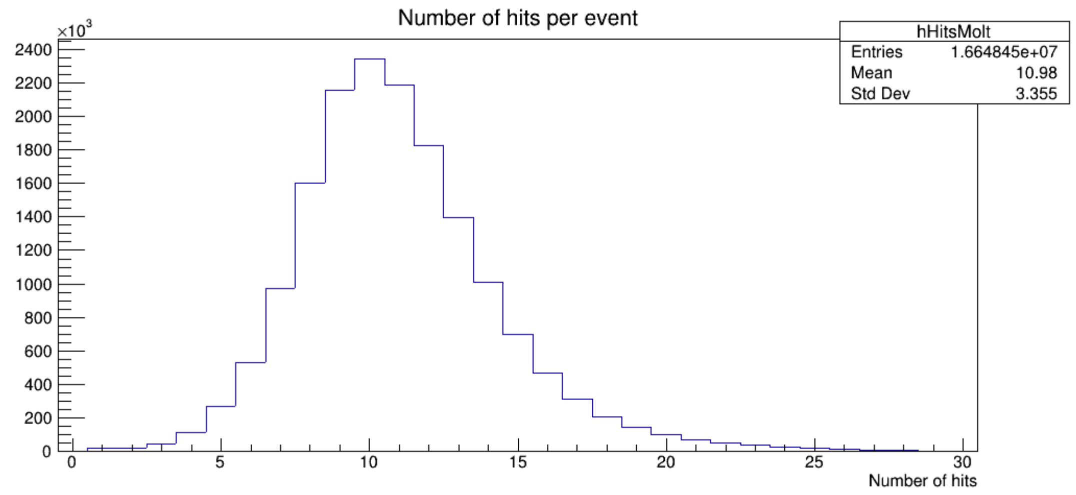
FE setup:
- FT-Cal only
- TET (on fADC250)=15/50,
- L1 threshold: 2000 (MeV)
- L1 time window: 400 ns

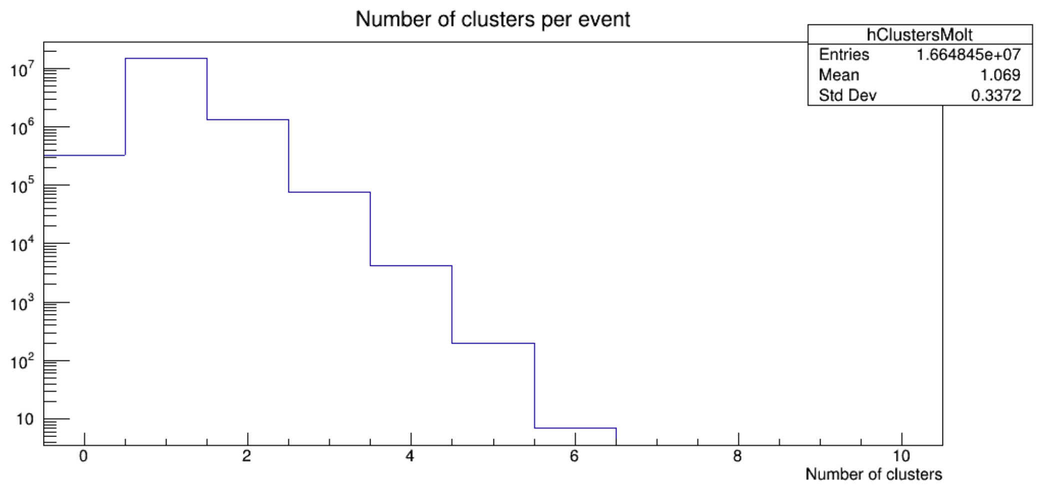
JANA2:
- L1 "minimum-bias": at least one crystal with energy > 2 GeV
- scaler (all L1 to diskS
- L2 plugins (*tagging* and *filetring*)
  - "standard" FT-CAL clustering ($N_{cluster} \geq 1, 2, 3$)
  - cosmic tracking
  - AI clustering algorithm: at least two cluster in the FT-CAL

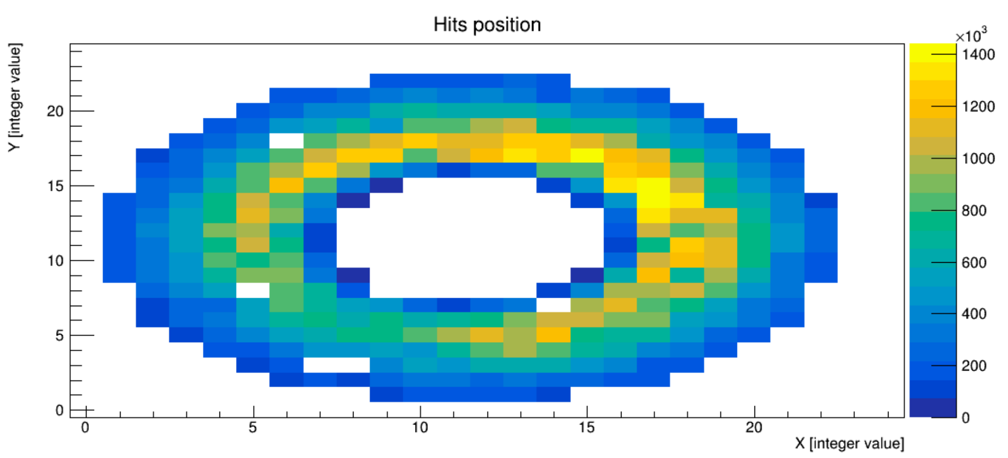
JANA Event Source plugin
- Read TriDAS file.pt files for offline analysis
- Offline algorithm development immediately available for use in Software Trigger
- Strong integration between online and offline

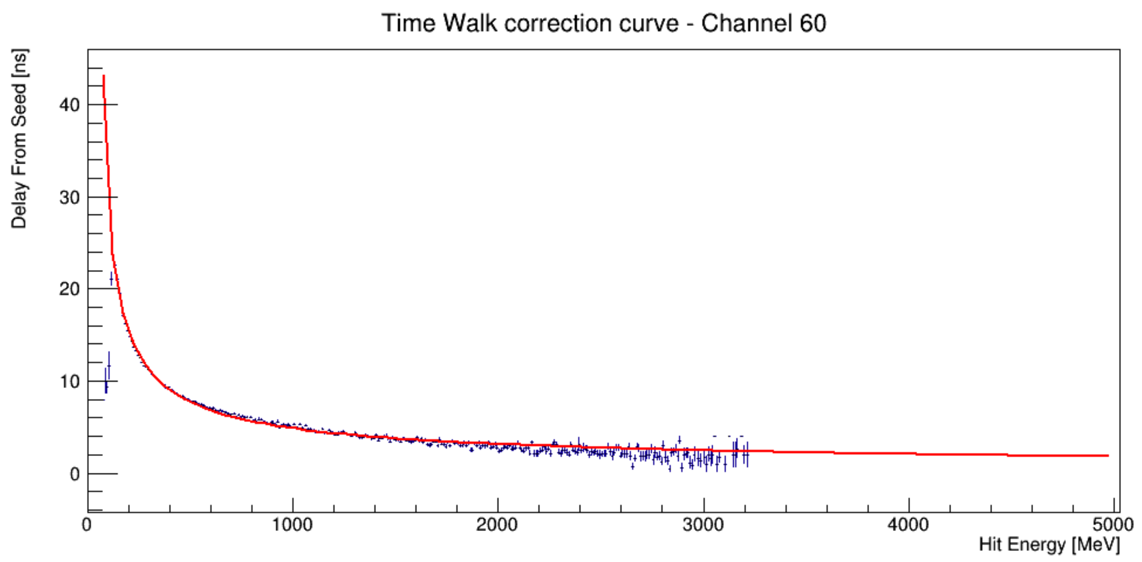
Run1 Data analysis

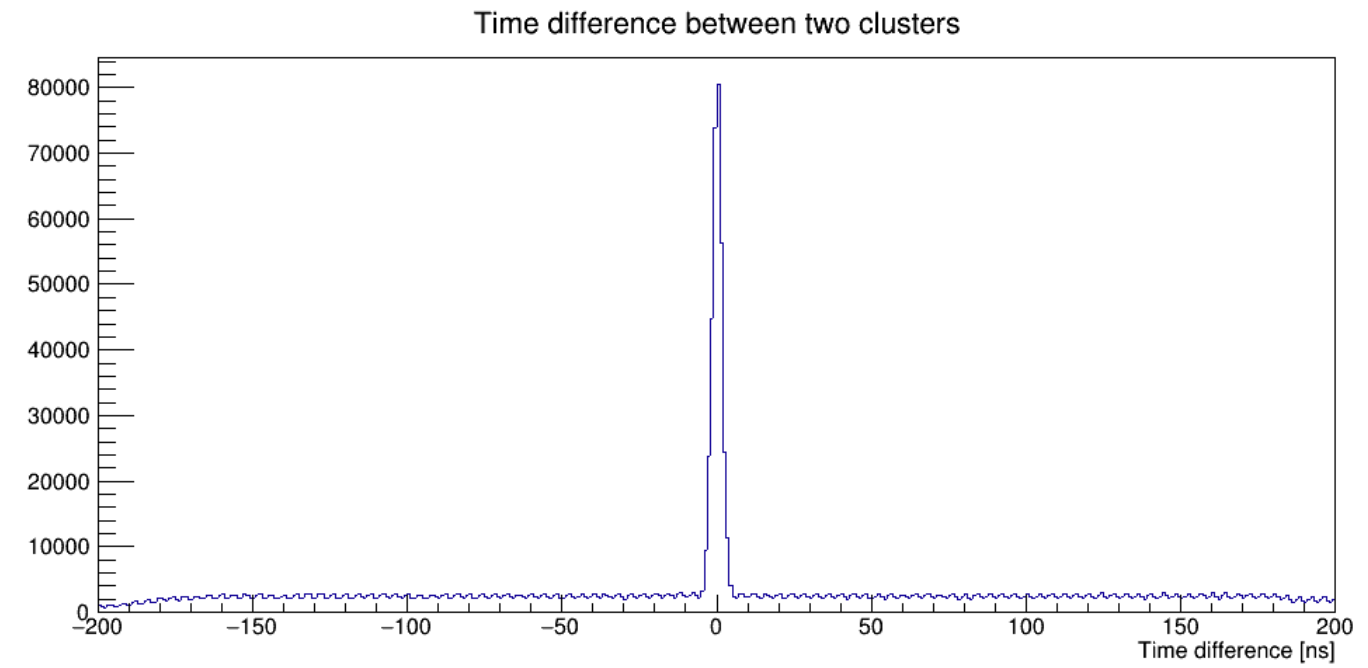
S.Vallarino, A.Celentano









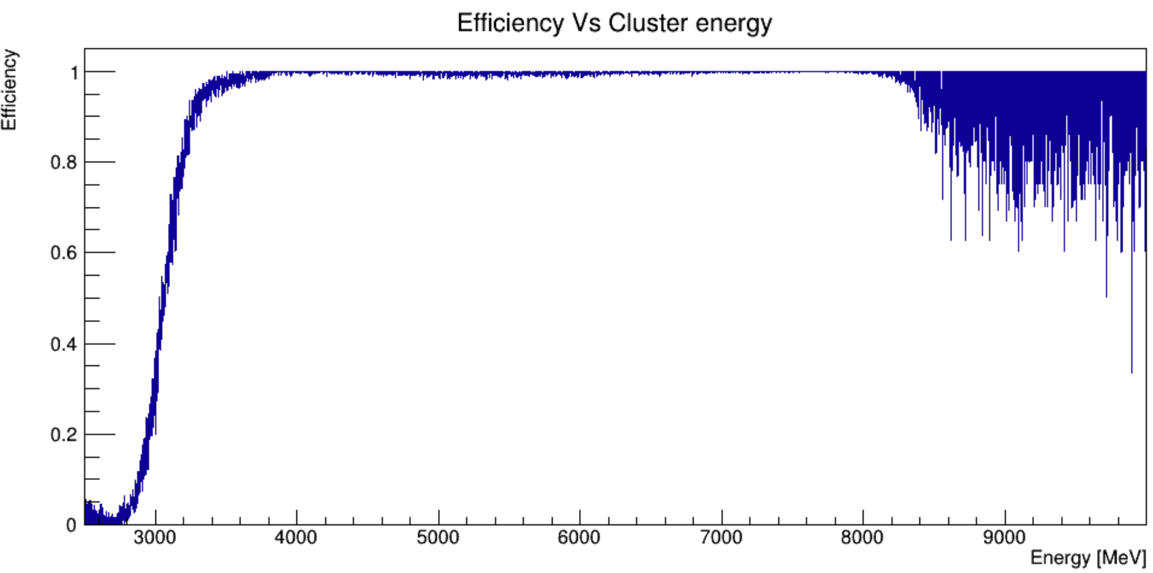


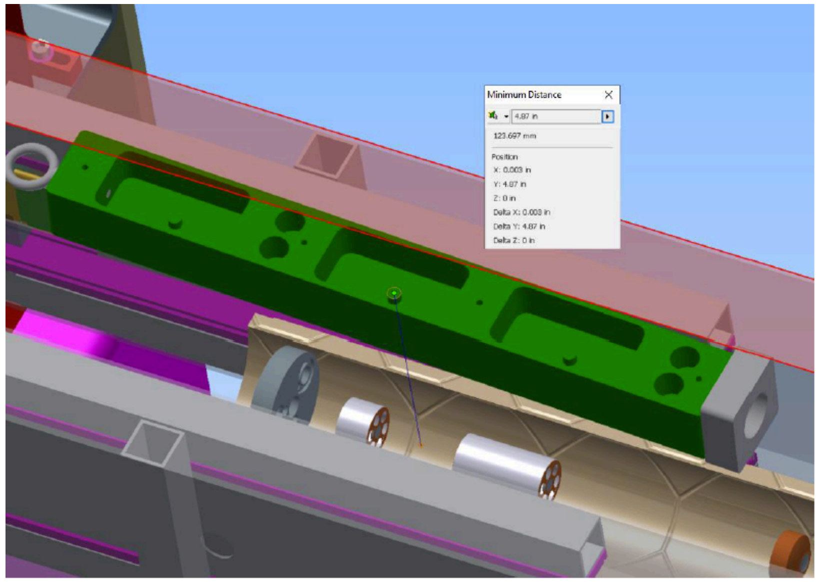
- Time-walk (time) and calibration (energy)
- SRO data behaves as expected (N_{hits}, $N_{clusters}$, $XY_{cluster}$, ΔT)

Run1 Data analysis

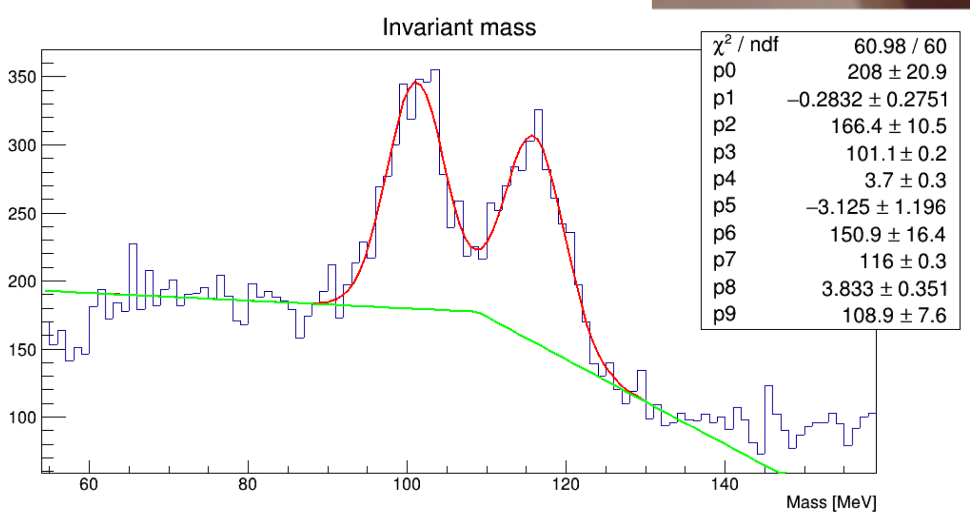
S.Vallarino, A.Celentano

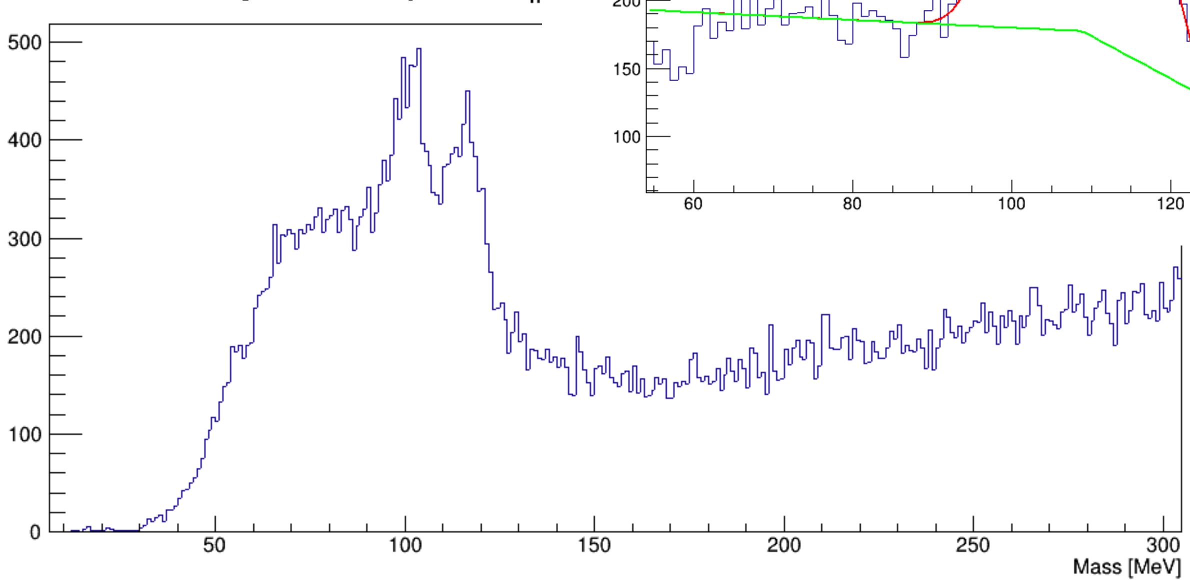
- Efficiency: comparison between online/offlin clustering

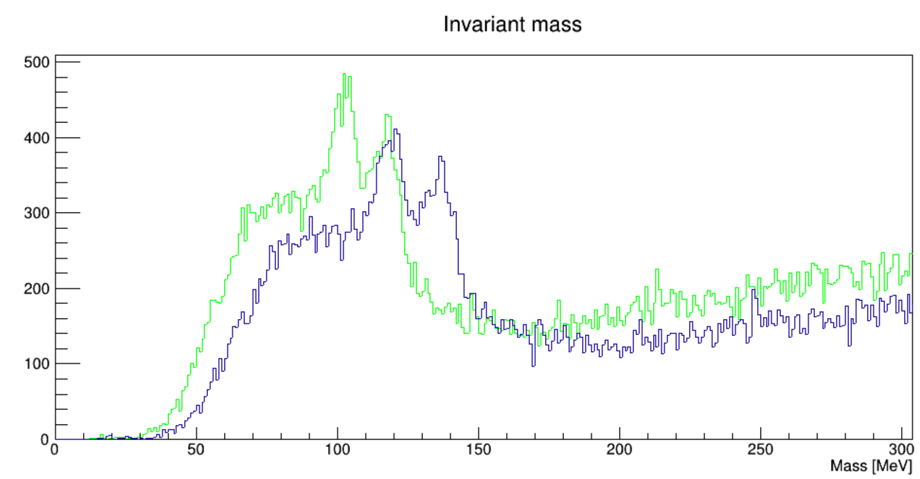




- Two pi0 peaks corresponding to two vertices (and a wrong assumption on the vortex position)







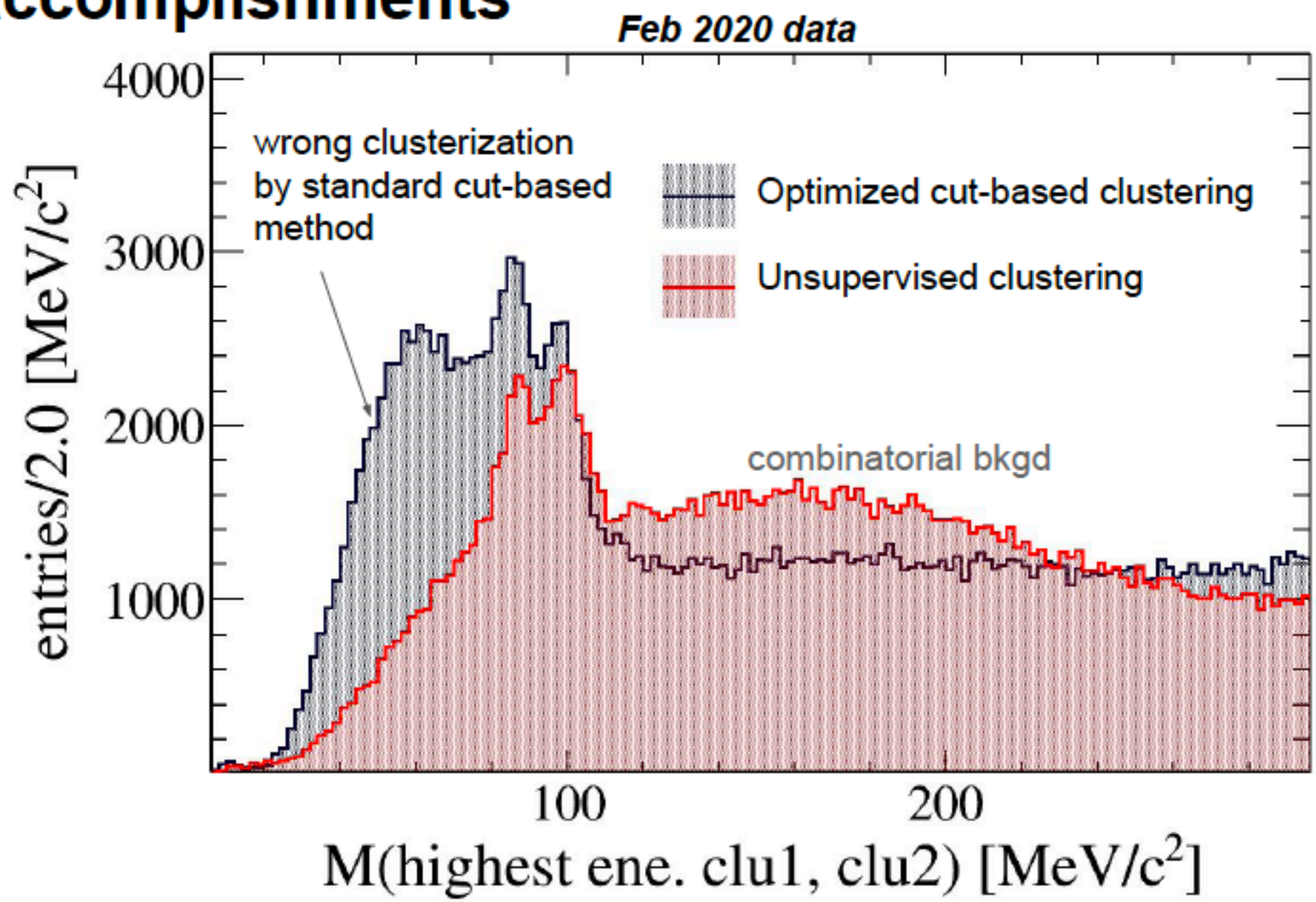
- Measured (expected) pi0 yield
  - Peak1 = 1600+-40 (2700+-500)
  - Peak 2 = 1500+-38 (2600 +-450)

Run2 data analysis in progress

Run1 Data analysis (AI-supported)

C.Fanelli

Accomplishments



*The cut-based clustering seems to assign more hits to the highest energy seed cluster.

- Implementation of AI supported L2 reconstruction algorithms for SRO: offline and online tests accomplished
- Unsupervised (no cuts required) hierarchical clustering generally robust against variations in experimental conditions
- AI tolerates larger hits multiplicities

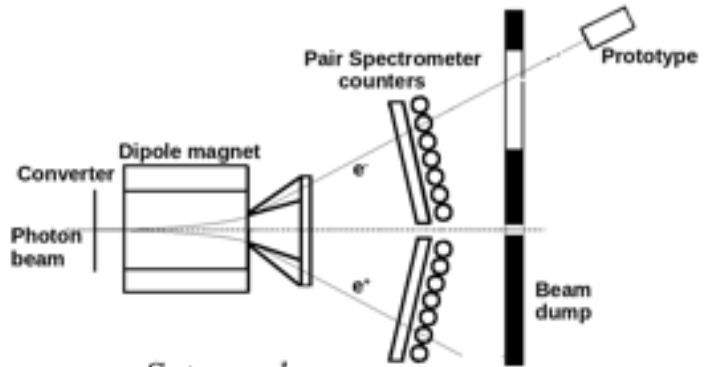
- Run1: off-line only
- Run2: real time!

Data analysis in progress

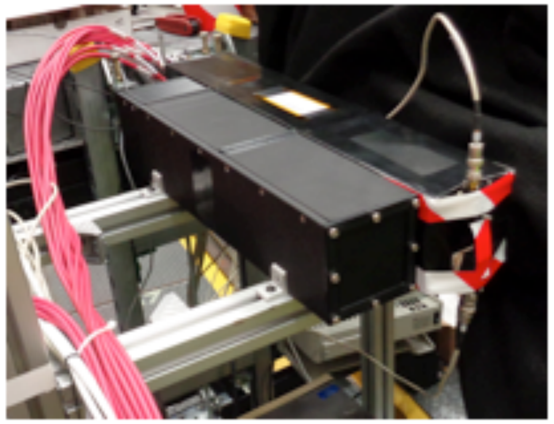
Streaming RO - Hall-D tests

V.Berdnikov, T.Horn

- HallD parasitic test beam area, secondary lepton beam with energy range (3-6) GeV
- *Triggered* DAQ with NPS and FCALII prototypes (baseline)
- New prototypes PbWO/SciGlass SiPM or PMT photosensors (3x3 matrix)
- SRO: preamps, fADC or WaveBoard digitizers



Setup scheme

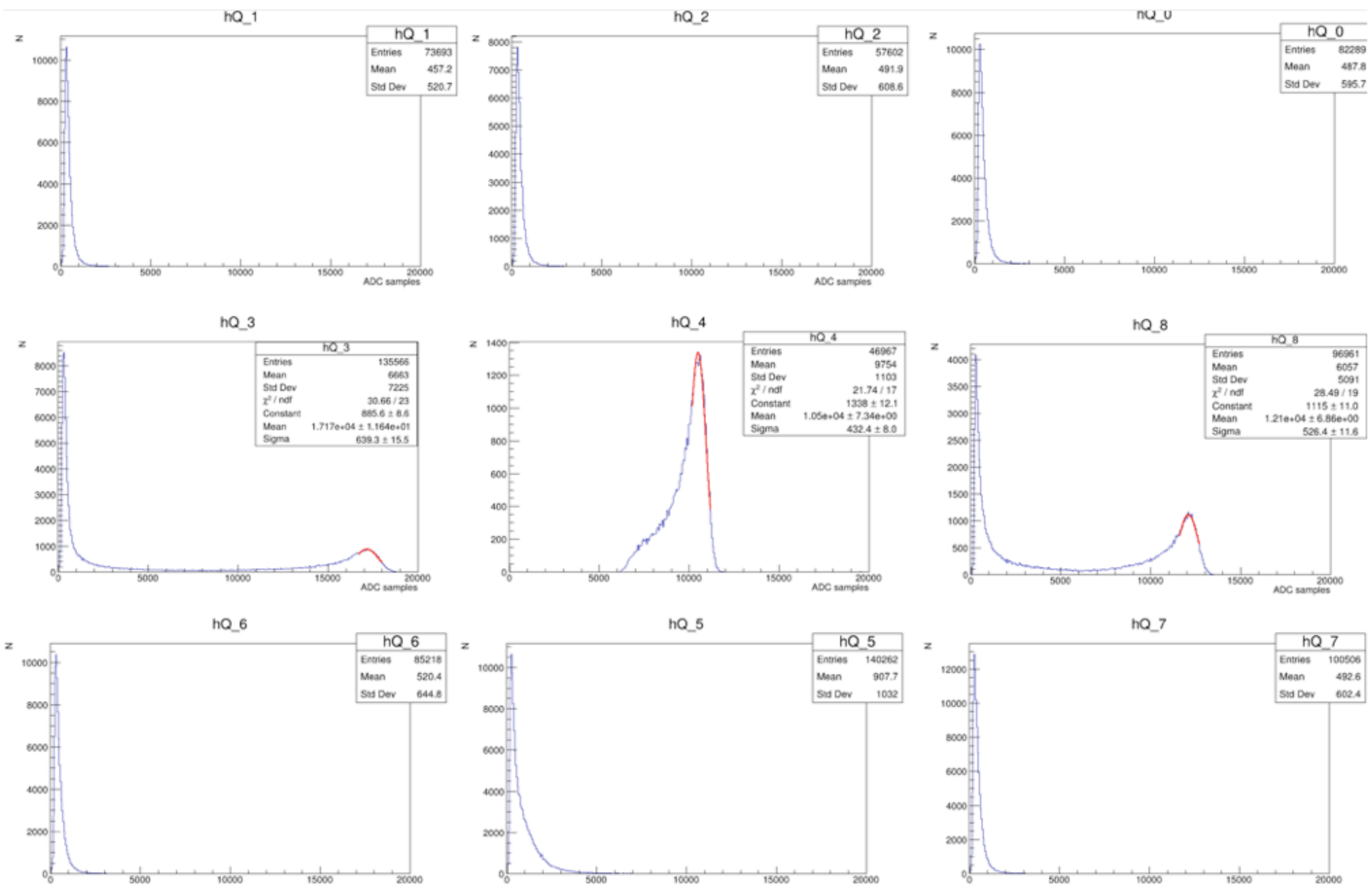


SiPM(left) & PMT(right) cal. prot.

Waveboard

Spring/summer run 2020 HallD tests:

- 3x3 PMT based PWO prototype installed
- Baseline performance established with GlueX triggered DAQ (parasitic mode)
- Central cell events hits (PS tile 59) correspond to ~ 4.5GeV lepton
- INFN WaveBoard fADC for SRO tests
- Scintillator pads in front of central cell installed for software L2 trigger
- SRO DAQ cabled/connected and tested



Calorimeter response, channel by channel

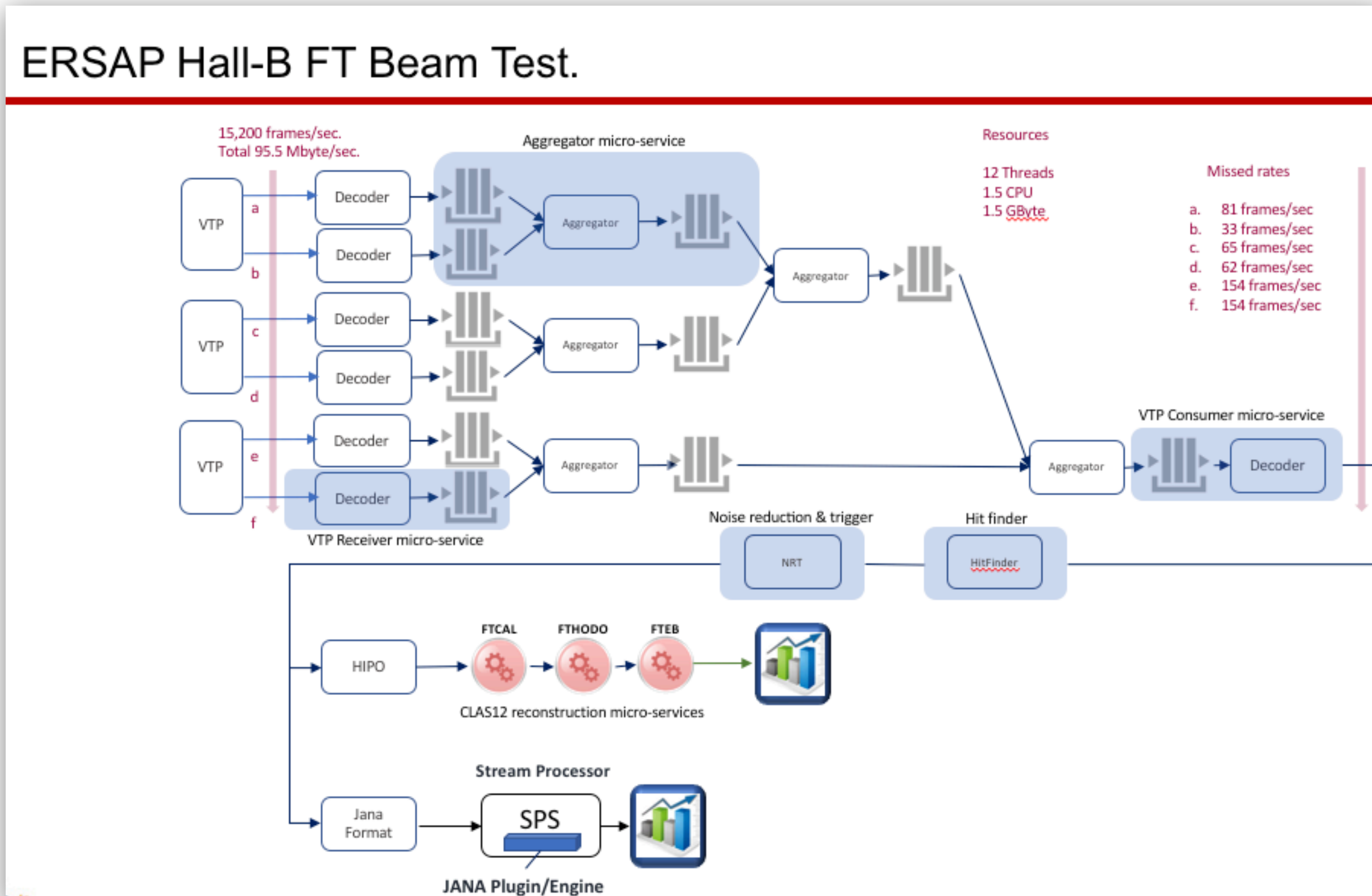
Data analysis in progress

Streaming RO - ERSAP

V.Gyurjyan

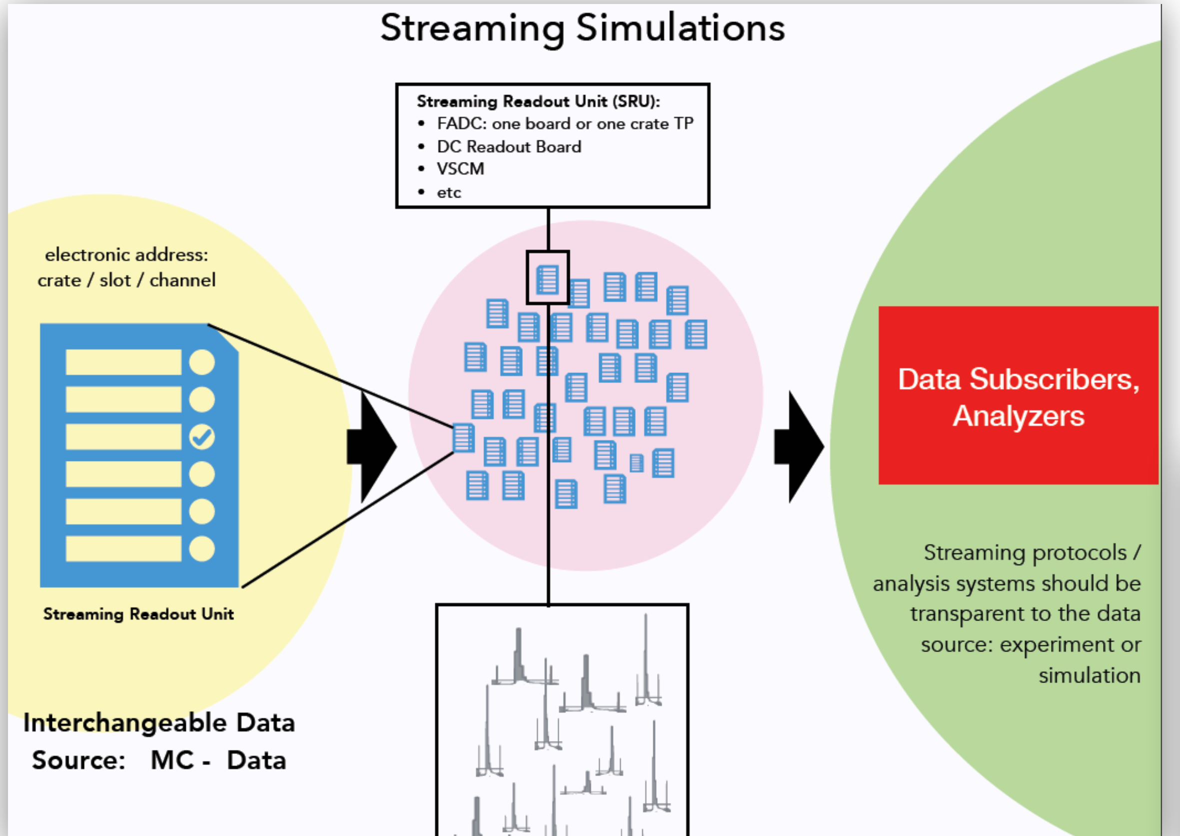
Reactive, event-driven data-stream processing framework that implements micro-services architecture

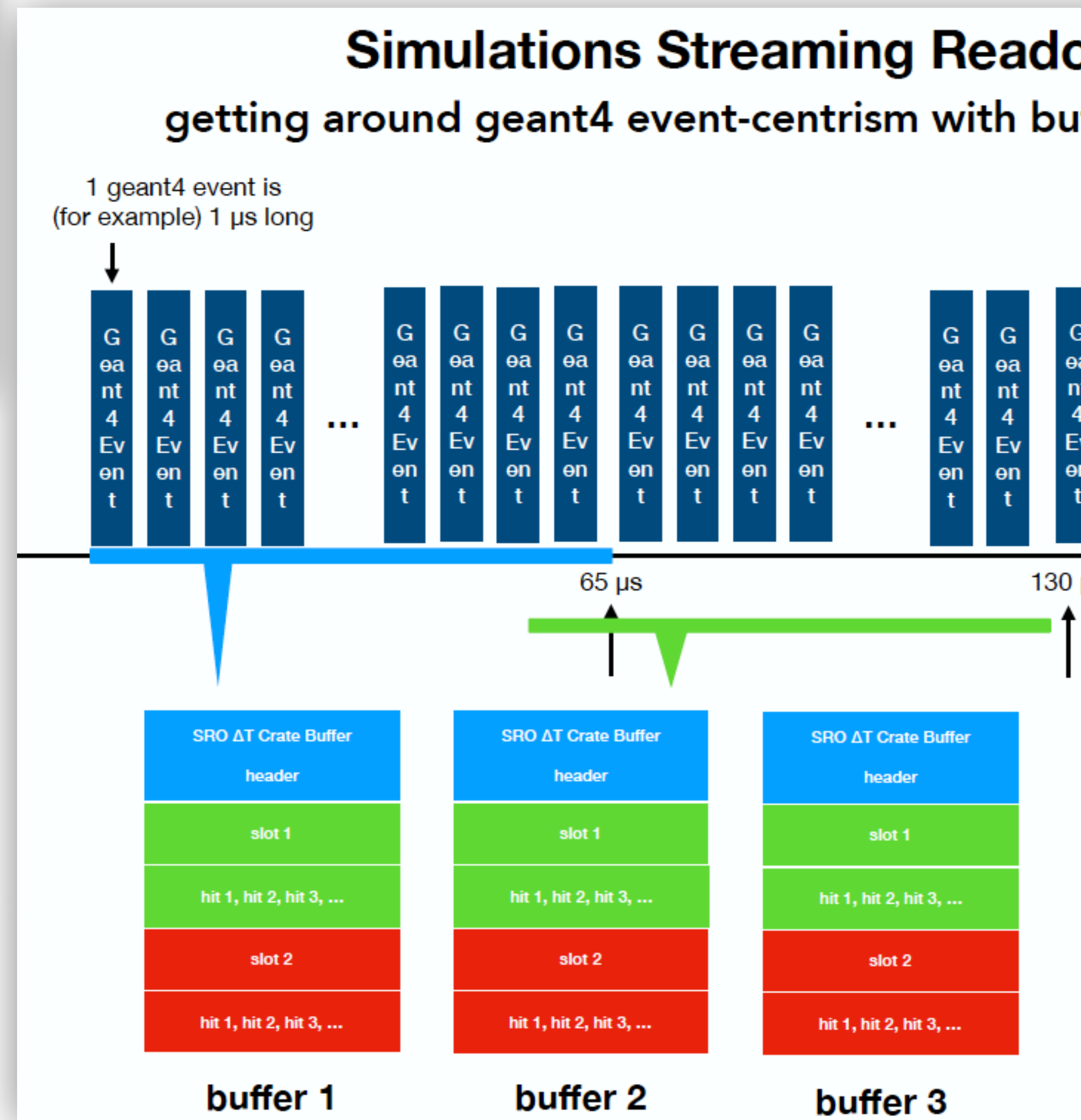
- Provides basic stream handling services (stream aggregators, stream splitters, etc.)
- Implements tiered memory architecture (stream cooling: hierarchical ring buffers, data lakes, etc.)
- Defines streaming transient-data structure
- Provides service abstraction to present user algorithm (engine) as an independent service.
- Defines service communication channel (data-stream pipe) outside of the user engine.
- Stream-unit level workflow management system and API
- Adopts design choices and lessons learned from JANA, CODA and CLARA



Streaming RO - GEANT4 MC

M.Ungaro





- Hits from a geant4 event can end on different buffers (propagation time, etc)
- Pile-ups are dealt naturally in this scenario

Summary

- Streaming Readout on-beam tests performed using the CLAS12-FT-Cal at JLab
- First step towards a full implementation for CLAS12 (Moeller, SOLID, EIC, …)
- The full chain (FE + SRO sw + ON-LINE REC) tested with existing hw
- Data taken in full streaming mode, analysis in progress (traditional and AI-supported)
- Parallel activity in a more controlled situation (Hall-D PS test e^-/e^+beam)
- Implementing the FT model in a SRO G4 MC to check the full chain
- Parallel effort for a JLab SRO framework based on micro-services architecture
- SRO prototype to be tested in view of a massive implementation of full CLAS12 SRO
- Built a real SRO prototype and a work team!

Many thanks to the whole JLab SRO team:
F.Ameli (INFN), MB (JLab/INFN), V.Berdnikov (CUA), S.Boyarinov (JLab) M.Bondí (INFN), N.Brei (JLab), A.Celentano (INFN), T.Chiarusi (INFN), C.Cuevas(JLab), R. De Vita (INFN), C.Fanelli (MIT), G.Heyes (JLab), T.Horn (CUA), V.Gyurjyan(JLab), D.Lawrence (JLab), L.Marsicano (INFN), P.Musico (INFN), C.Pellegrino (INFN), B.Raydo (JLab), M.Ungaro (JLab), S.Vallarino (INFN)