DOE Review of
Laboratory Detector R&D

Argonne National Laboratory

High – Performance Trigger & Data Acquisition Systems

Gary Drake
Argonne National Laboratory, USA

Rockville, MD

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Outline

- Trigger System R&D for Gamma-ray Telescope Arrays
- Trigger System R&D for Fast Track Trigger
- R&D on Next-Generation Pattern Recognition

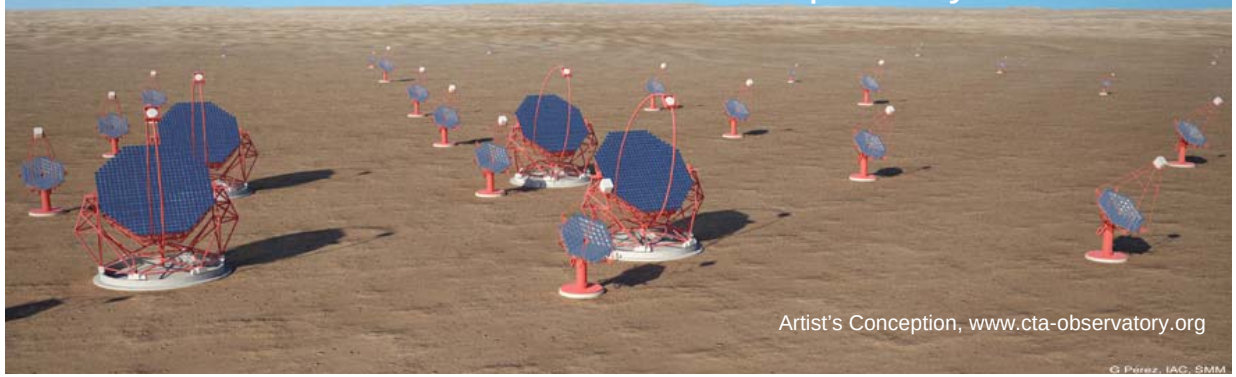
Trigger System R&D for Gamma-ray Telescope Arrays

Trigger System R&D for Gamma-ray Telescope Arrays

- **Current Generation**
  - 2 - 5 telescopes
  - VERITAS, HESS, MAGIC, CANGAROO…
- **Next Generation**
  - ~50 – 100 telescopes
  - CTA
  - Instrumentation Goals:
    - Increase Field of View
    - Increase sensitivity
    - Increase pointing accuracy
    - Observe more distant objects
  - **Science Goals (HEP)**
    - **Dark Matter**
    - **Quantum Gravity**
    - ⇨ ***Snowmass!***
- **Why HEP Instrumentation & Techniques are Relevant**
  - ~10 MHz/pixel → High rates
  - ~10K – 100K channels
  - Correlate events in multiple telescopes before read-out → High-speed trigger

Current: 4-Telescope VERITAS Array in Tucson, Arizona

Future: Cherenkov Telescope Array

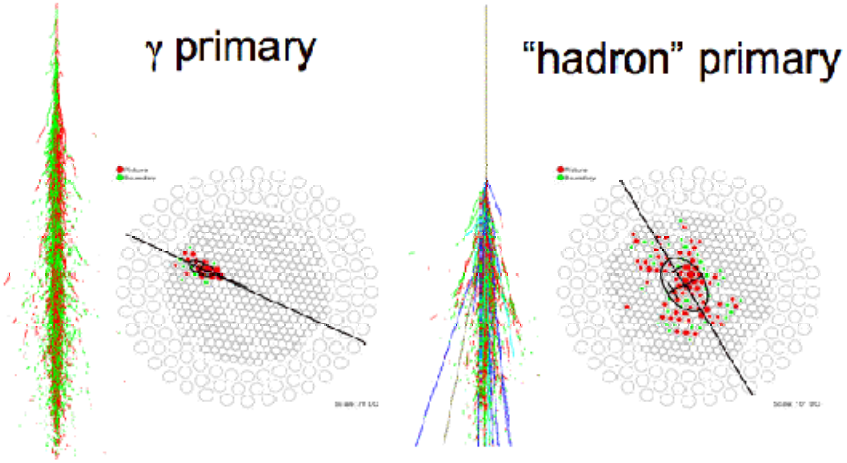


⇨ ***We have built a high-performance trigger for Veritas***
- ⇨ ***Performance has been excellent***
- ⇨ ***We at ANL have leading experience in telescope array triggers***

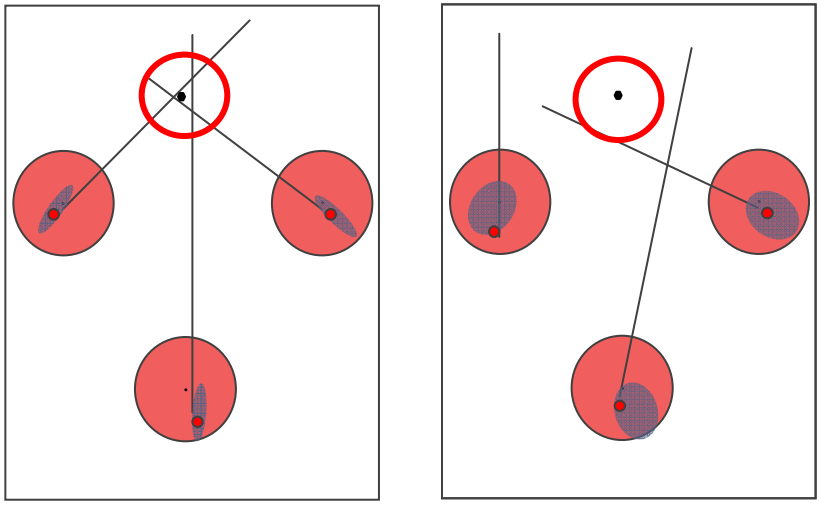
⇨ ***We are collaborators on CTA***
- ⇨ ***Seek to leverage Veritas & HEP experience***
- ⇨ ***Can make significant contribution***

Trigger System R&D for Gamma-ray Telescope Arrays (Cont.)

- **Primary Motivation:**
  - Trigger camera readout on gamma rays
  - Reject backgrounds from cosmic rays and muons
    - ⇨ ***Events have very different signatures***
      - Gamma rays are compact
      - Hadrons have a large spread in shower profile
      - Muons produce rings
    - ⇨ ***Can make use of event topology at the trigger level to improve trigger efficiency***
      - ⇨ ***Centroid moments***
      - ⇨ ***Parallax Width Displacement [1]***
  - Preliminary study: When implemented requiring correlation between a multiplicity of telescopes, can improve rejection of CR by X10, while keeping > 90% of gamma showers
    - Need large array to be truly effective



Showers from Interaction with Upper Atmosphere

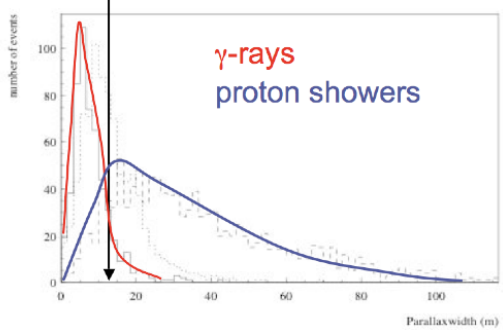


Images Seen in 3-Telescope Array
Method of Parallactic Displacement

(All Graphics Courtesy of Frank Krennrich)

⇨ *Rejects 90% of cosmic rays*

⇨ *Retains 90% of gamma-rays*



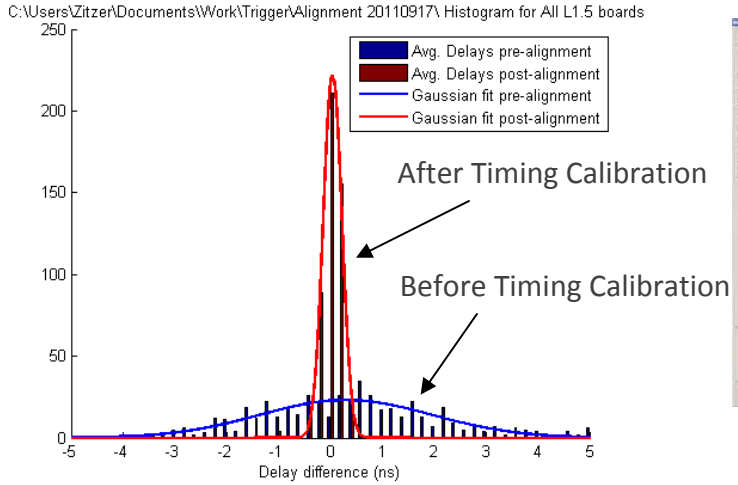
⇨ ***Differentiate these patterns <u>in real time</u>***

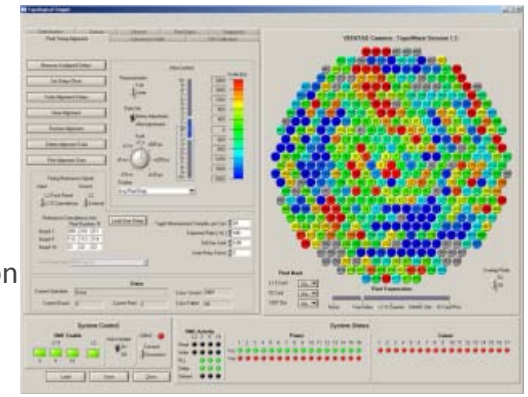
⇨ ***Goals: Increase DAQ efficiency;***
Lower the energy threshold at the trigger level

[1] Krennrich, F. and Lamb, R.C.Experimental Astronomy, 6, 285-292 (1995a)

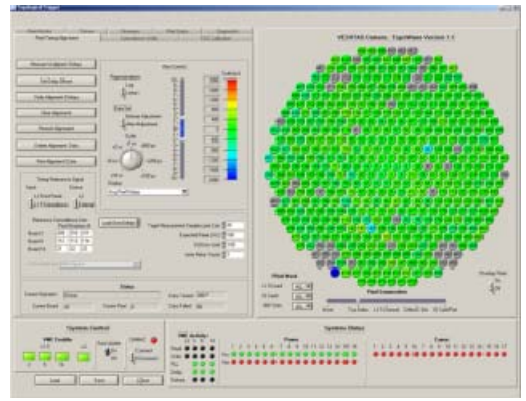
Trigger System R&D for Gamma-ray Telescope Arrays (Cont.)

- **Secondary Motivation:**
  - With good timing resolution across the telescope, can reduce energy threshold
  - Example: Veritas

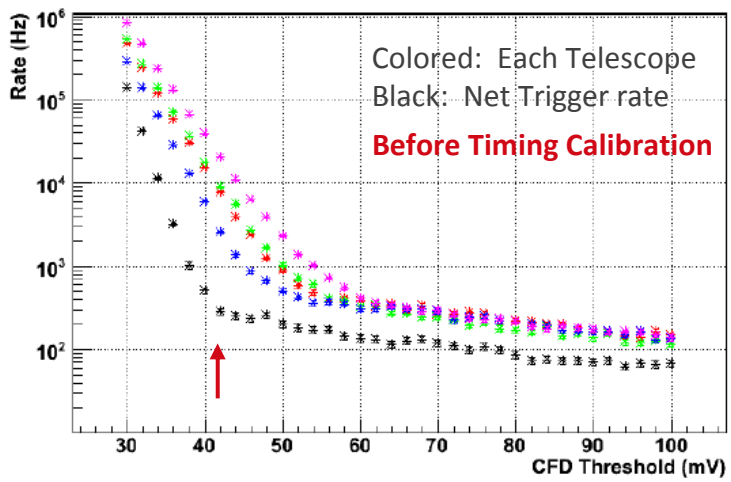


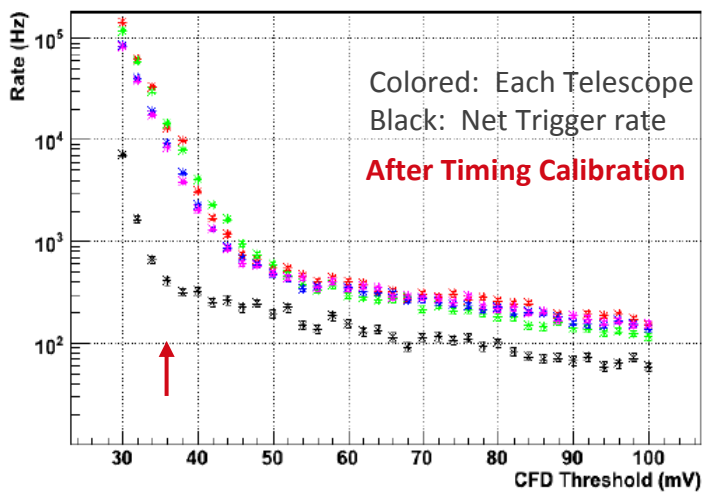


Before Timing Calibration



After Timing Calibration





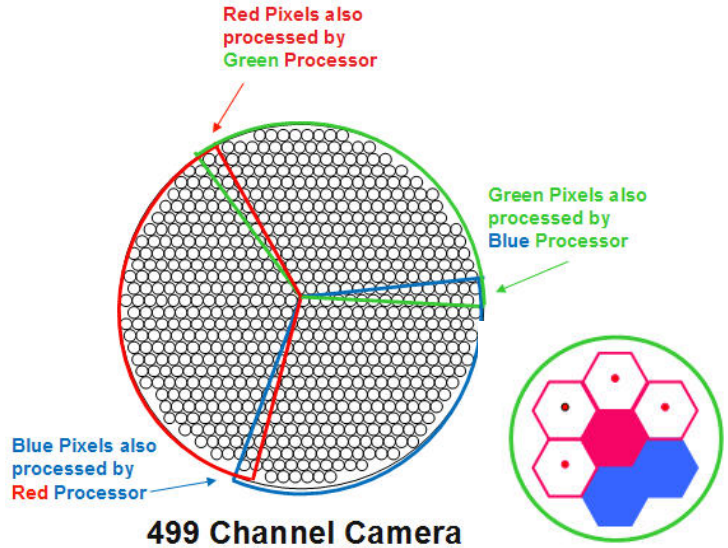
Plots & Display Courtesy of Veritas

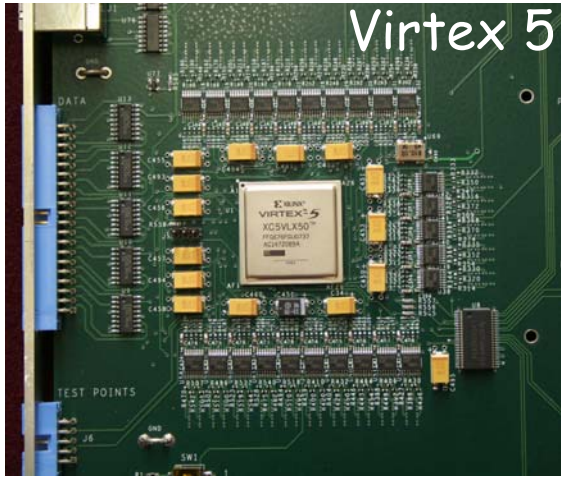
⇨ ***Good timing alignment can reduce the energy threshold of trigger – More- distant observations***

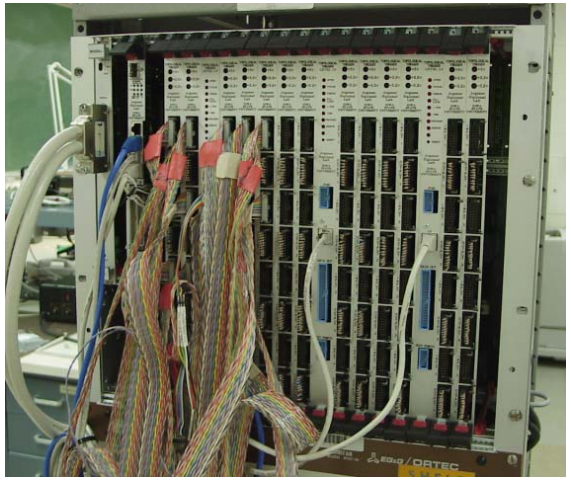
Trigger System R&D for Gamma-ray Telescope Arrays (Cont.)

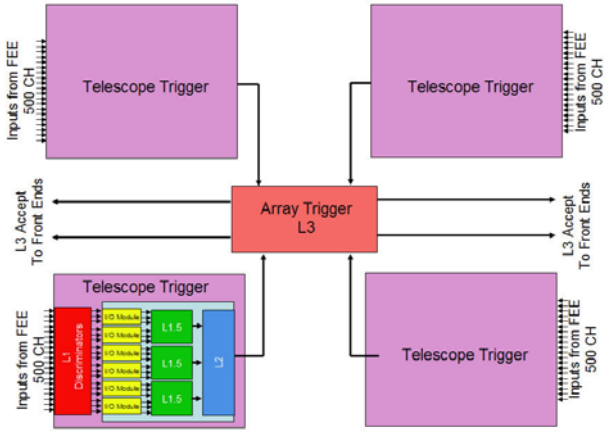
- Experience at Veritas
  - We have built and installed an upgraded trigger system
    - Full system design: L1, L1.5, L2, L3
    - 5-15 nS Time Window
    - 10 MHz Output Rate @ L2
  - Primary Technical Challenges
    - Process 500 channels at 10 MHz/CH - NSB
    - Process Neighbor Logic at 400 MHz
    - Custom, high-speed backplane

⇨ ***Fastest trigger of it's kind in existence – Unique ANL contribution***
⇨ ***Have achieved 2 nS timing accuracy across the focal plane***
⇨ ***<u>Upgrade completed</u> – Very successful – Excellent performance***
⇨ ***On time and on budget – Will support for the life of the experiment***







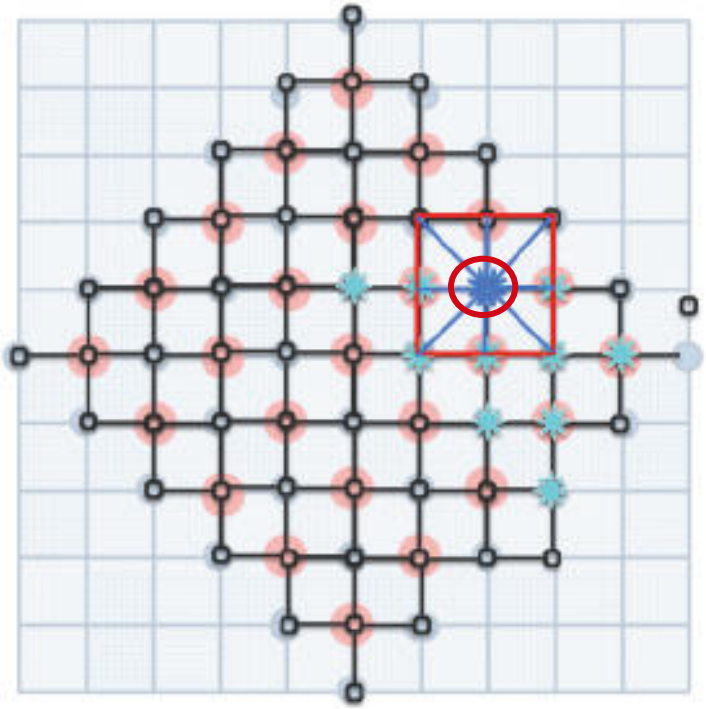


⇨ ***R&D funding: ANL Laboratory LDRD***
⇨ ***Built with Veritas project funds → Excellent leveraging of R&D to Project***
⇨ ***Now aiming at leveraging this experience for the next generation trigger***

Trigger System R&D for Gamma-ray Telescope Arrays (Cont.)

- **Trigger concept for a Large Array**
  - **Each telescope is the center of a Trigger Cell**
    - Trigger Cells have 9 telescopes except at edges
  - **Neighbors send centroid information to center telescope in a cell**
  - **Each central telescope uses information from it's own hits plus the centroid information from neighbors to trigger itself**

    ⇨ ***De-centralized trigger***
  - **Additional coordination with triggering the array is possible…**



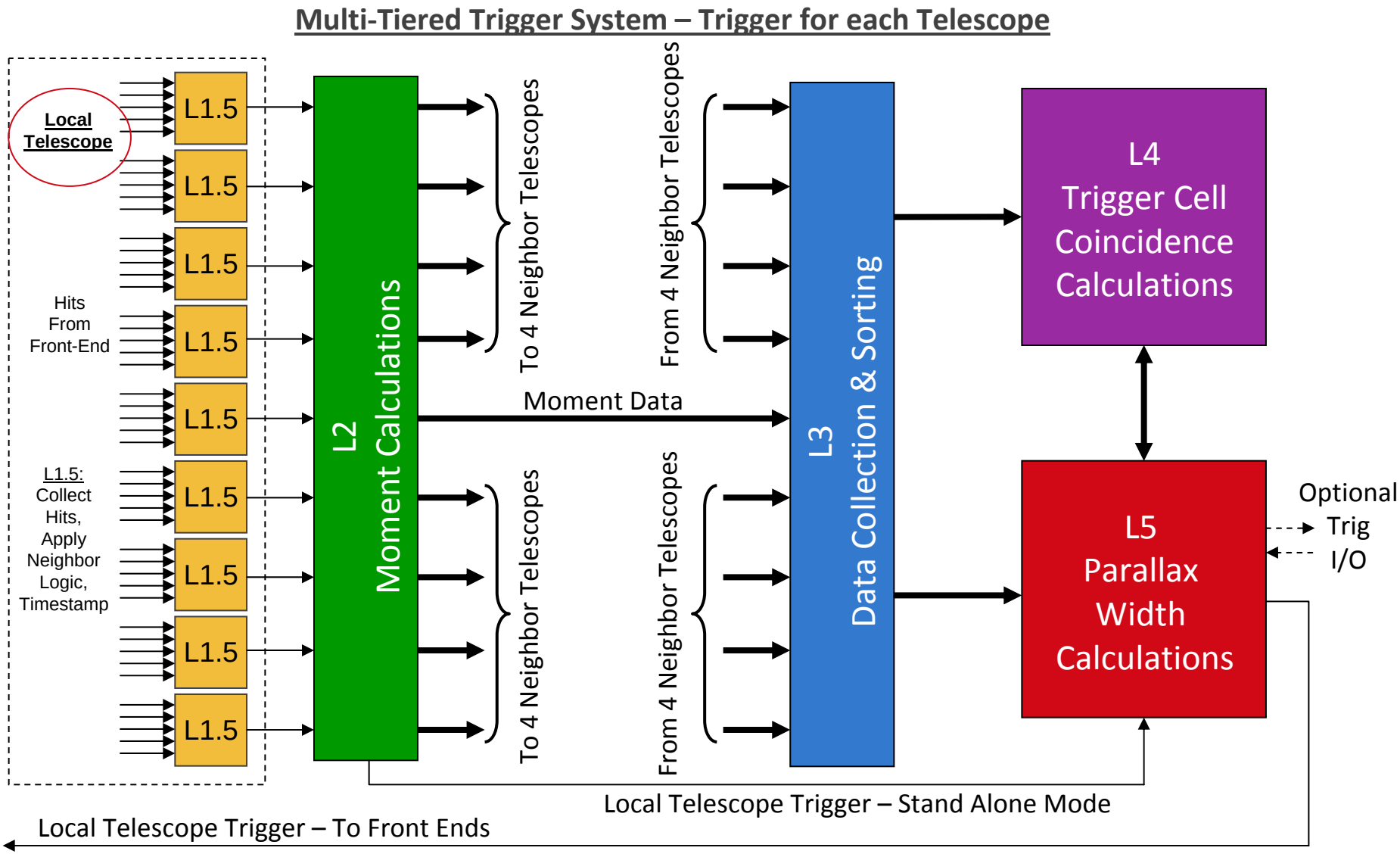
(Example Array Configuration)

Graphic by Frank Krennrich, ISU

⇨ ***Each telescope will have a local trigger processor using information from the neighbors***

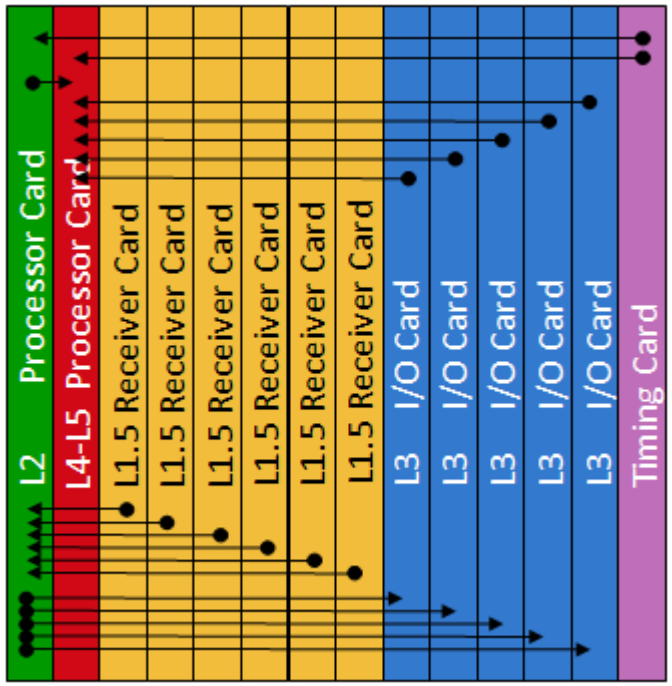
Trigger System R&D for Gamma-ray Telescope Arrays (Cont.)

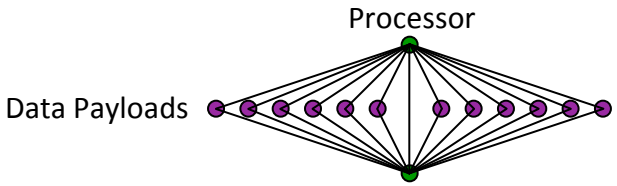
- **Block Diagram of a Distributed Topological Trigger for a Large Array**



Trigger System R&D for Gamma-ray Telescope Arrays (Cont.)

- **Conceptual design -**
  Uses Advanced Telecommunication Computing Architecture (ATCA) [2]
  - Dual Star Topology
  - A very flexible implementation:





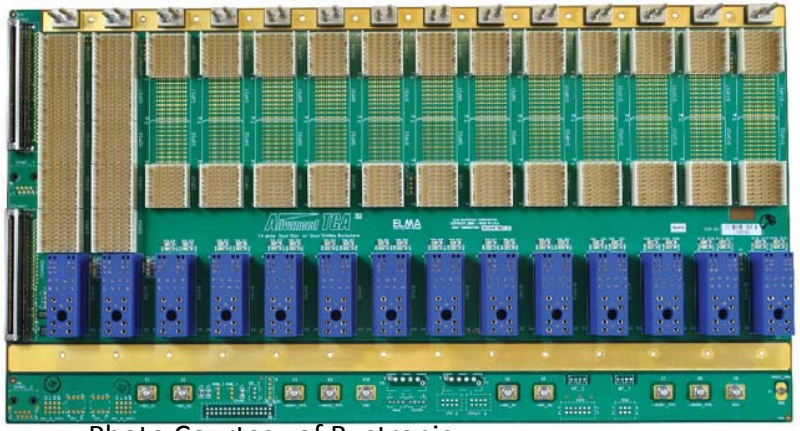


Photo Courtesy of Bustronic
http://www.bustronic.com/pdf/ATCA_DualStar.pdf

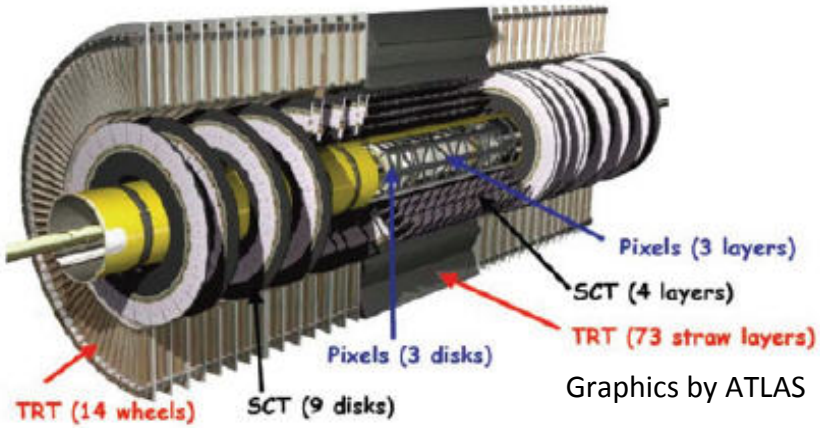
[2] http://www.a-tca.com/

⇨ ***<u>Not</u> requesting KA15 funding for this project at this time***
⇨ ***Will be seeking DOE funding for CTA (if approved)***
⇨ ***Very complementary with our other high-performance DAQ projects***
⇨ ***Leverages ANL experience with telescope triggers for next generation***

Trigger System R&D for Fast Track Triggers

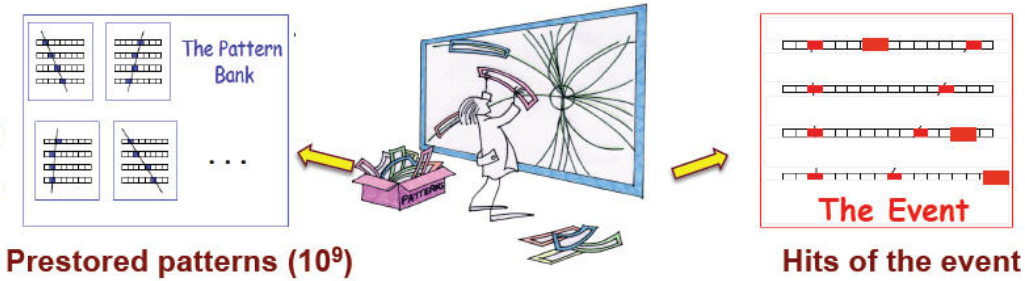
Trigger System R&D for Fast Tracking

- **Pattern recognition is highly desirable for HEP tracking detectors → But also very hard!**
- **Example: ATLAS**
  - Would like to identify tracks at L2
    - Heavy flavor, lepton isolation
  - Significant problem with pile-up

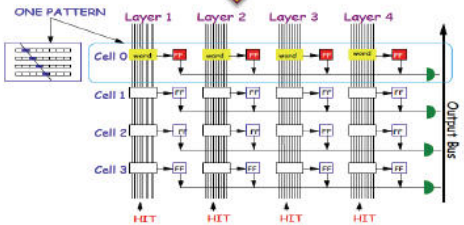


Graphics by ATLAS

Hardware Solution: Content-Addressable Memory



Content-addressable Memory (CAM)



Fast pattern recognition

- ⇨ *Hits are address to a memory*
- ⇨ *Contents contain permitted track*
- ⇨ *Then calculate Helix parameters*
- ⇨ *Used successfully in CDF*
- ⇨ *CAM is critical technology*

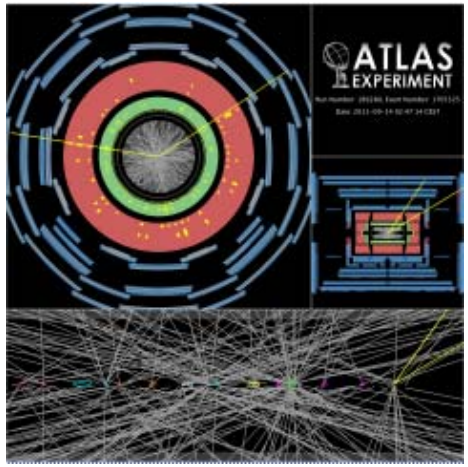
Plan:

- PIX 3 (&IBL)+SCT 4 axial, plus one more layer to be chosen
- SCT stereo layer extrapolation & 11-layer fit

Data Rates @ $\mathcal{L}$ = 3E34

- 100 KHz max. trigger rate
- 300 tracks/event
- 11 hits/track
- ~100 bytes/track + 40/event

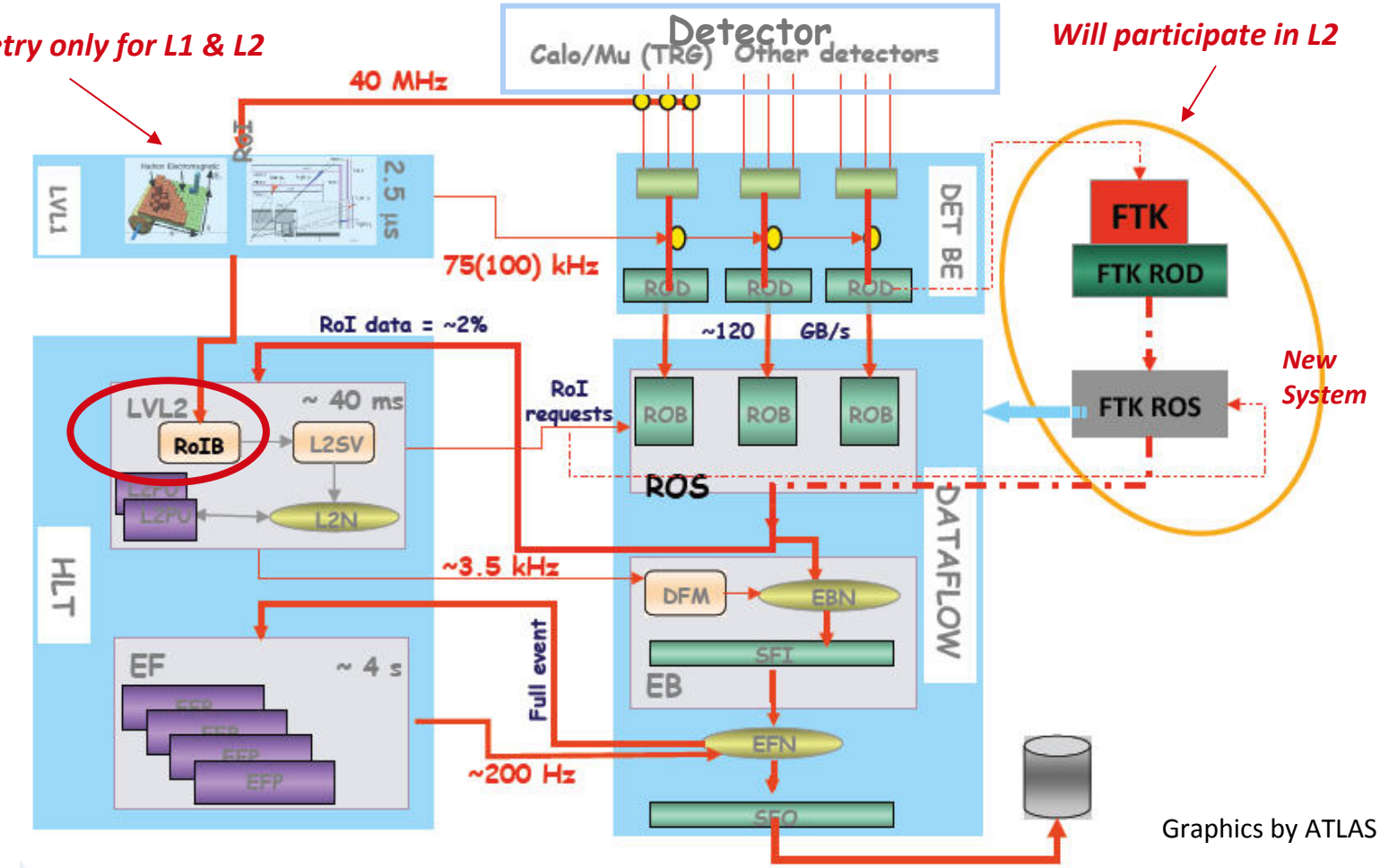
⇨ ~3 GByte/Sec input rate



- ⇨ *Event with 20 interactions*
- ⇨ *Want to identify each separately*

Trigger System R&D for Fast Tracking (Cont.)

- Block diagram of ATLAS TDAQ system with FTK

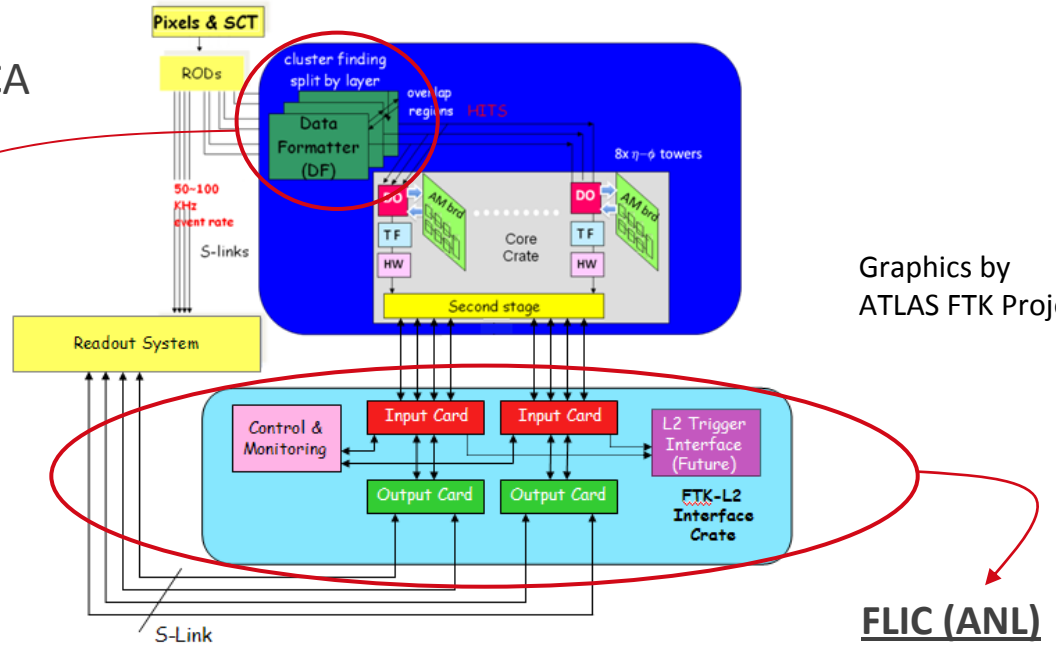


Graphics by ATLAS

- ⇨ *ANL has long experience in ATLAS TDAQ → L2 management; RoIB development*
- ⇨ *ANL has a leadership role in FTK*
- ⇨ *Experience positions us to make unique contributions to FTK*

Trigger System R&D for Fast Tracking (Cont.)

- **FTK System Block Diagram**
  - 2 components will use ATCA



Graphics by
ATLAS FTK Project

Data Formatter (FNAL)

- 222 (+56) SLINKs from PIX/SCT (+IBL) RODs
  - Clustering on Mezzanine cards
- 32 DF Boards
  - Two η−φ towers per board
  - ~8 input links per board for baseline design
- Data sharing between boards over ATCA full mesh backplane
  - 8 boards per shelf
- Data sharing between shelves via dedicated fibers
  - Two transceivers per slot for data sharing
- Sending downstream data via rear transition module (RTM) to AUX cards and 2nd Stage Boards
  - Two transceiver for AUX, two for 2nd stage per slot

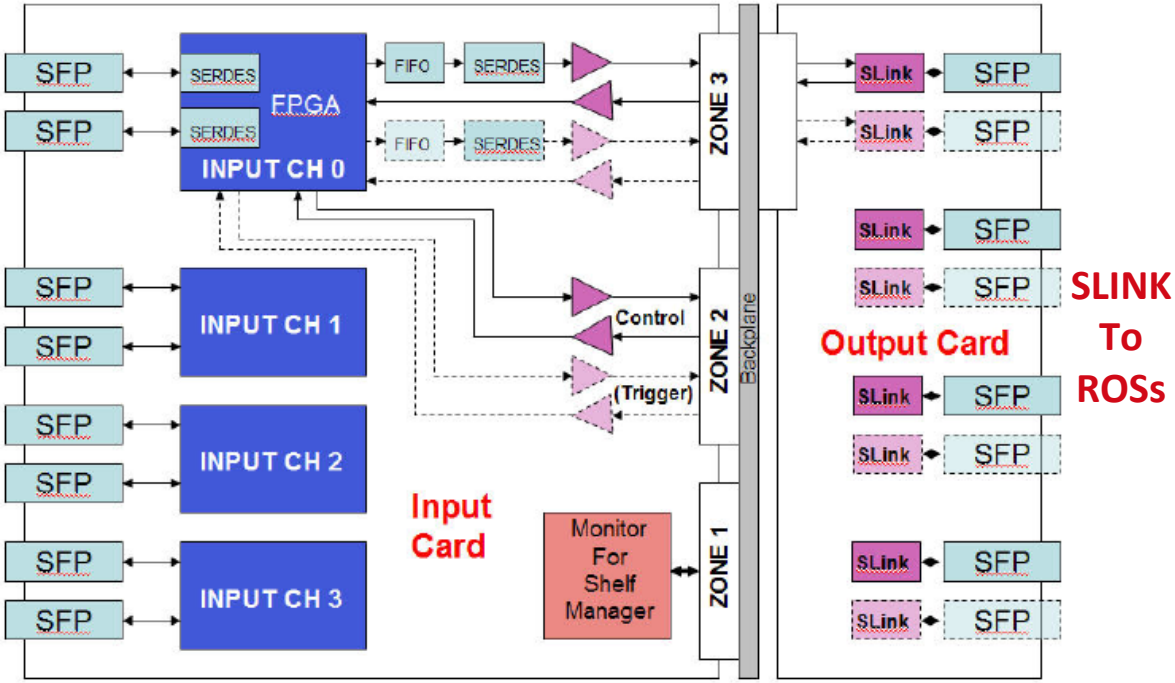
FLIC (ANL)

- 8 X 2 links from Core Crates
- 1 FLIC Crate needed
- 2 FLICs Total
- Full mesh backplane
- Zone 2 for:
  - Spy buffers
  - Future trigger capability

⇨ ***ATCA is an enabling technology → Powerful backplane communication fabric***

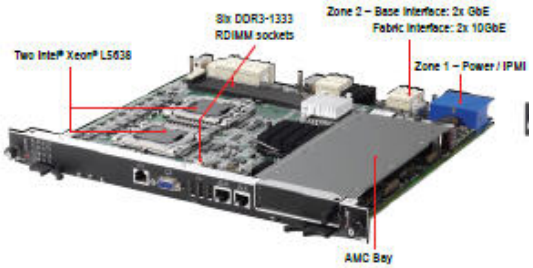
Trigger System R&D for Fast Tracking (Cont.)

- **FLIC Conceptual Design**



ASIS 6-slot ATCA Shelf

- 6-slot
- Full mesh



ADLink ATCA 6150 Blade

- Dual Intel Xenon L5638 Processor
- 10 Gbps Ethernet

- Project status:
  - Design in progress
  - 1st prototypes by fall, 2012

⇨ ***<u>Not</u> requesting KA15 funding to execute this design***
⇨ ***Have project funding for 2015 installation***
⇨ ***But – synergistic with other high-performance DAQ activities***

R&D for Next Generation Pattern Recognition

R&D for Next Generation Pattern Recognition

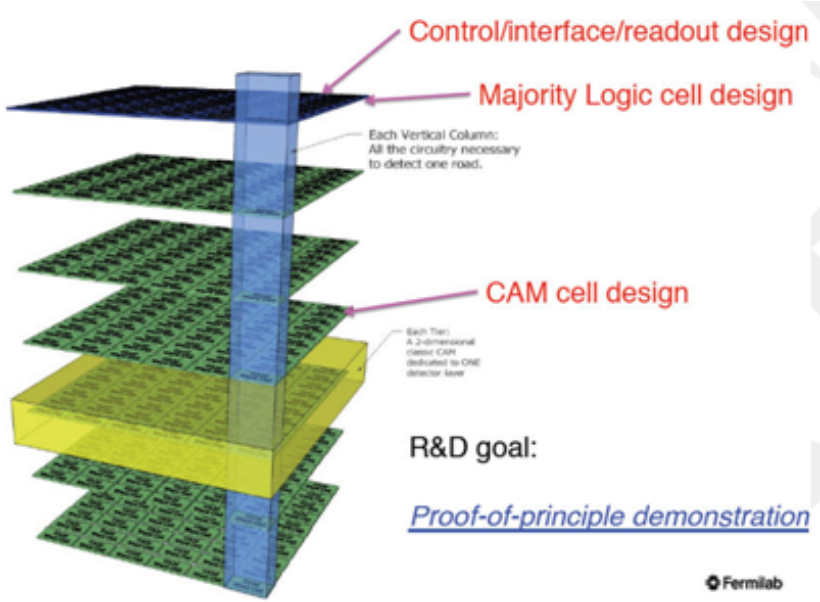
- **Driver: Tracking upgrades for the LHC Phase 2**
  - Will need to store ~1E9 patterns for the detector
  - Power, Speed, & density are critical parameters
  - Would like to use tracks in the L1 Trigger…
- **Enabling technology is the Associative Memory (AM) chip → Need dense feature size**
  - Current version of AM used in the Vertical Slice
    - ***180 nm, – 3.7K patterns/chip***
  - AM chip for 2015 (Italian contribution)
    - 65 nm, V1: 30K patterns/chip
    - ***V2: 60K patterns/chip***
  - 3-D AM chip → VIPRAM project
    - Collaboration: ANL, FNAL, UChicago
    - ***130 nM, but 3D gives ~6M patterns/chip***

    ⇨ ***Required to realize full FTK performance***
- **Potential for many applications within HEP**
  - Fine-grained calorimetry
    - Digital Hadron Calorimetry (see Repond talk)
    - Electromagnetic Calorimeters → CALICE
  - Mu2e – Significant confusion background
- **Potential for other applications outside of HEP:**
  - PET, Radiation scanners, Personal ID, Projectile tracking…

⇨ ***Ideal for any digital system requiring high-speed pattern recognition from hits or bits***

Traditional 2-D CAM

New 3-D PRAM → VIPRAM

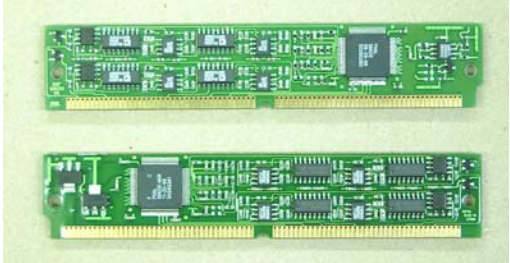


Graphics by Ted Liu, Fermilab

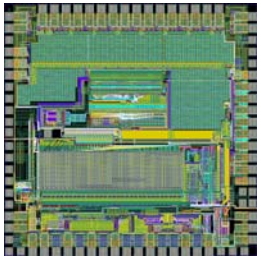
R&D for Next Generation Pattern Recognition

- **Responsibilities:**
  - FNAL: Specifications, chip design, chip test
  - ANL: Specifications, performance testing, system design, applications
- **Schedule**
  - ***Preliminary design work has begun***
  - ***~4 year plan***
  - ***Requires refinement of 3-D process with industry***
- **Strategic Strengths of Argonne**
  - Long involvement in ATLAS
  - Strong connection to ATLAS TDAQ & FTK
  - Long successful track record in:
    - Specifying ASICs
    - Testing ASICs at the bench
    - Building systems around chips
  - Long relationship with the Fermilab
    - Close relationship with FNAL ASIC Group
    - Close physical proximity
    - Strategic alliance through University of Chicago
  - Proven track record in delivering what we say…
    On time and on budget, meeting requirements…
    And, we provide support for the life of the experiment

SQUID
CDF Shower Max
20,000 CH



QIE5
MINOS Near Det.
10,000 CH



QIE10
ATLAS TileCal
(→10,000 CH)

DCAL3
CALICE DHCAL
10,000 CH

⇨ ***We are requesting KA15 funding to execute this design & development program***

R&D for Next Generation Pattern Recognition - Project

Summary Capability Gap

- Goal: Development of high-performance, high-speed, real-time pattern recognition
- Driver: LHC Upgrade → ATLAS
- Current: Computational; Off-line
- Future: Hardware; Real-time; Participate in L2 Trigger → L1 Trigger
- Science motivation: Improve event selection using tracking information

Approach

- 3-D chip design is the enabling technology
- Essential to achieve pattern density
- FNAL: ASIC design
- ANL: Performance testing; System design
- Leverages ANL connections to ATLAS TDAQ & FTK
- Leverages ANL expertise in building systems around chips

Benefit

- Critical technological development to implement a hardware track trigger
- Difficult (not possible?) without it
- This is a unique technological development that can have a major impact on event selection at the trigger level
- Other HEP applications: Fine-grained calorimetry
- Other applications: PET, Radiation scanners, Personal ID, Projectile tracking

Results and Deliverables

- If successful, will develop needed technology for next-generation pattern recognition
- Ultimate goal – L1 Track Trigger – Never done before
- A difficult aspect – working with industry toward maturing the 3-D fabrication technology
- 4-year R&D plan

Summary

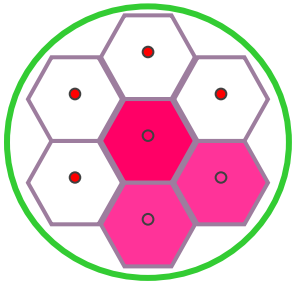
- **ATCA is the next (now) generation of Trigger/DAQ crate architectures**
  - High-speed backplane, fabric connectivity, processing power
  - Argonne has made significant progress up the (substantial) learning curve
- **R&D work ongoing & proposed at Argonne with ATCA**
  - One design in progress (FTK) – Not KA15 supported
  - Two applications may follow – Requesting KA15 support
    - R&D for telescope array trigger
      - Would allow strategic positioning for future array such as CTA
- **Seeking support for 3-D CAM chip development**
  - Driven by LHC Phase 2 Upgrade, but has several other applications
  - Important development for ATLAS → ANL has strategic position
  - Strategic collaboration with Fermilab → Synergistic strengths, close alliance

Backup Slides

Basics of a Topological Trigger

- **Receive *discriminated hits* (Level 1 Trigger) of each pixel in a camera from the FEE**
- **Form time window, & collect hits**
- **Process hits that have "3-fold neighbor coincidence" → Mostly rejects singles**
- **Calculate 1st & 2nd moments of images in each camera**
- **Use stereo view from multiple telescopes to project image back into the sky**
- **Identify γ-ray images by tight correlation of projection → Parallactic Displacement**
- **Do this with no dead time**

⇨ ***Goal is 1 nS timing resolution***



3-Fold Neighbor Coincidence, 7-pixel cell, Formed around primary pixel (Veritas)

→ List Of Hits + Time Stamp → X,Y Of Hits → 1st & 2nd Moments → Polar Coord. → Parallax Width

Basics of a Topological Trigger (Cont.)

- Method
  - **Calculate 1st moment of images in each telescope**

    $\Sigma x_i \qquad \Sigma y_i \qquad N_{HIT}$
  - **Convert to Polar Coordinates, & form vectors**

    $\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2}$

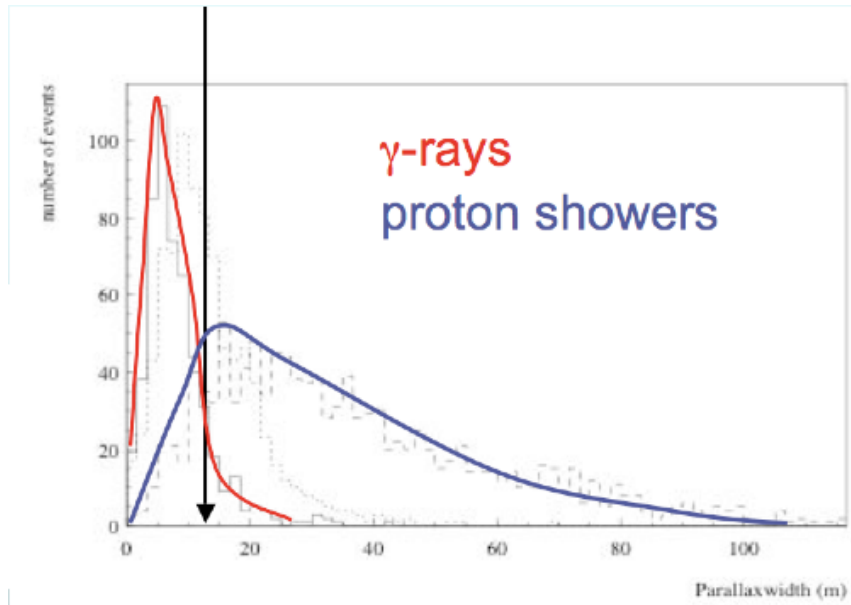
    $\phi = \arcsin(\bar{y} / \bar{r})$
  - **Calculate Parallaxwidth:**

$$Parallaxwidth \approx \sqrt{\frac{\sum_{i=1}^{n}(\vec{r}_i - <\vec{r}>)^2}{n}}$$

$$\vec{r}_i = location\ of\ intersection\ point\ i$$

$$<\vec{r}> = averaged\ core\ location$$

  - **Calculate 2nd Moments**
    - $\sigma_{xx}^2 \quad \sigma_{yy}^2 \quad \sigma_{xy}^2$
    - Evaluates "Goodness" of Fit



Monte Carlo simulation of γ / hadron separation capabilities using parallactic displacement. Simulation used array of (19) 10-meter telescopes spaced 60 meters apart.

⇨ ***Reject 90% of cosmic rays while retaining 90% of gamma-rays***