Triggering In Particle Physics Experiments

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Outline

- Why Trigger?
  - Early Experiments
- Experimental Constraints
  - Cross Sections and Luminosity
  - Electron+positron, hadron machines
  - Multiple Interactions
- Efficiency and Deadtime
  - Minimizing deadtime
  - Queuing Theory

Material drawn heavily from IEEE NSS 2002 Workshop by Peter J. Wilson

- Signatures in Detectors
- Multilevel Trigger Systems
- Pipelined Trigger Systems
- Components of Modern Trigger Systems
  - Hardware Implementation
- The PHENIX Trigger System
- The (Near) Future
  - Trigger/DAQ at LHC
- "Non-Traditional" Expts.

Why Trigger?

- The purpose of a trigger system for an experiment is to select rare events and suppress background as efficiently as possible.
  - NOTE: This doesn't mean a trigger <u>only</u> selects the physics we want!

- A trigger system must match the **physics event rate** to the **data acquisition rate**.

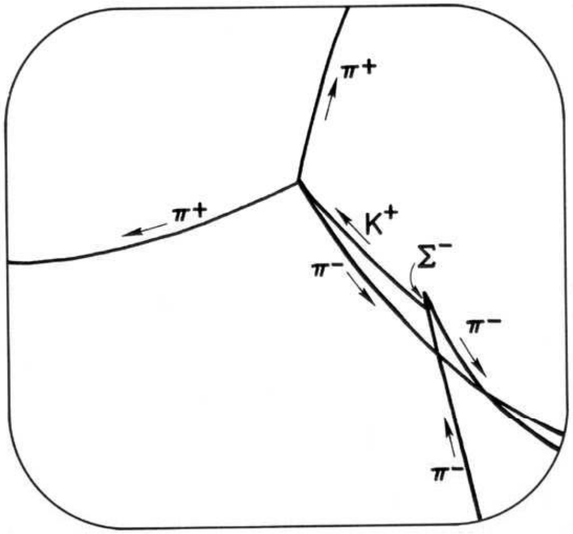
<u>Example</u>: CDF/D0 Trigger In Run-II

- Beam crossing rate of 7.6MHz
- About 750k channels at ~4 bytes each
  - Total of ~3MB per event
- "Event" data rate ~20 TeraBytes/s
- Zero suppression of unoccupied channels approx a factor of 10
  - "Event" data rate still ~2 TeraBytes/s
- Trigger rejects 99.999% of crossings
  - Data rate to tape now ~20 MegaBytes/s

Early Particle Physics Experiments

- Bubble Chambers, Cloud Chambers, etc. (4π)
  - DAQ was a stereo photograph!
  - Effectively no Trigger:
    - Each expansion was photographed based on accelerator cycle
    - High level trigger was ***human*** (scanners).
  - Slow repetition rate.
    - Only most common processes were observed.
  - Some of the high repetition experiments (>40 Hz) had some attempt at triggering.

- Emulsions still used in some ν experiments (e.g. CHORUS, DONUT).
  - Events selected with electronically readout detectors via scanning of emulsion seeded by external tracks



Early Fixed Target Triggers

1964 Cronin & Fitch CP Violation Experiment:

- K^0 mesons produced from 30 BeV protons bombarding a Be target
- Two arm spectrometer with spark chambers, Cerenkov counters and trigger scintillators
- Spark chambers require fast (~20ns) HV pulse to develop spark, followed by camera to photograph tracks (readout)
- Trigger on coincidence of scintillators and water Cerenkov counters
- Only one trigger level
- Deadtime incurred while film advances

Detector Layout of $K^0 \rightarrow \pi\pi$ Experiment of Cronin and Fitch (1964)

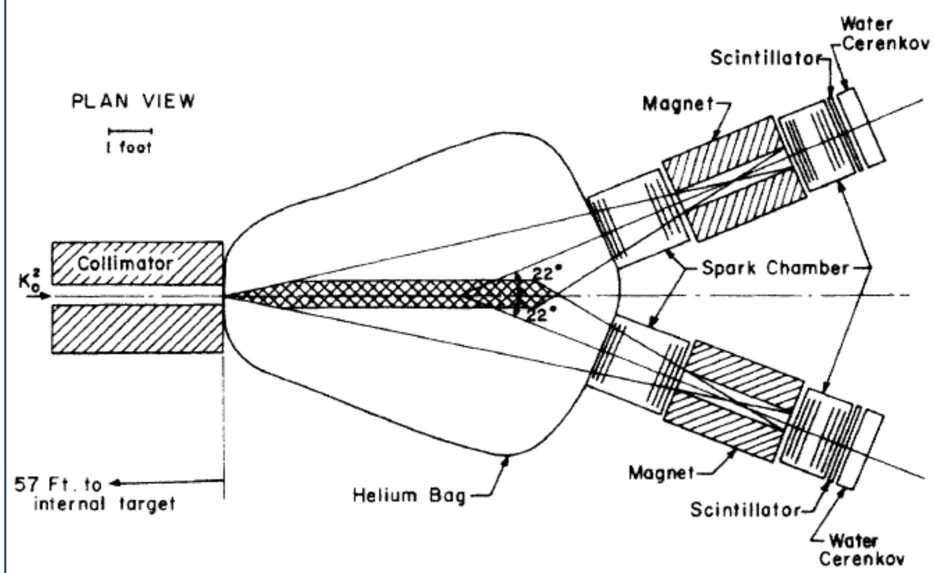


FIG. 1. Plan view of the detector arrangement.

Christenson, Cronin, Fitch and Turlay PRL 13, 138 (1964)

Experimental Constraints

Experimental Constraints

Different experiments have very different trigger requirements due to different operating environments

- Timing structure of beam
- Rate of producing physics signals of interest
- Rate of producing backgrounds

- **Cosmic Ray Expts** – no periodic timing structure, background/calibration source for many other experiments.
- **Fixed Target Expts** – close spacing between bunches in train which comes at low rep rate (~Hz)
  - Backgrounds from undesirable spray from target
  - Cosmics are particularly a background for neutrino beams
- **e^+e^- collider** – very close bunch spacing (few nsec), beam gas and beam wall collisions
- **ep collider** – short bunch spacing (96ns), beam gas backgrounds
- **pp/ppbar collider** – modest bunch spacing (25-400ns), soft QCD

Cross Sections and Luminosity

- Standard method of characterizing rates is:

Rate = σ L

σ = cross section (units of barn=$10^{-24}cm^2$)
The probability that an interaction will occur. If this were a game of darts, the larger the area of the dart board the more likely you will get the dart on the board.

L = luminosity (units of $cm^{-2}s^{-1}$ or $barn^{-1}\,sec^{-1}$)
Cross sectional density of the beams. The more particles per beam or the more compact (transverse) the higher the luminosity. For colliding beam, goes as the product of the two beam currents.

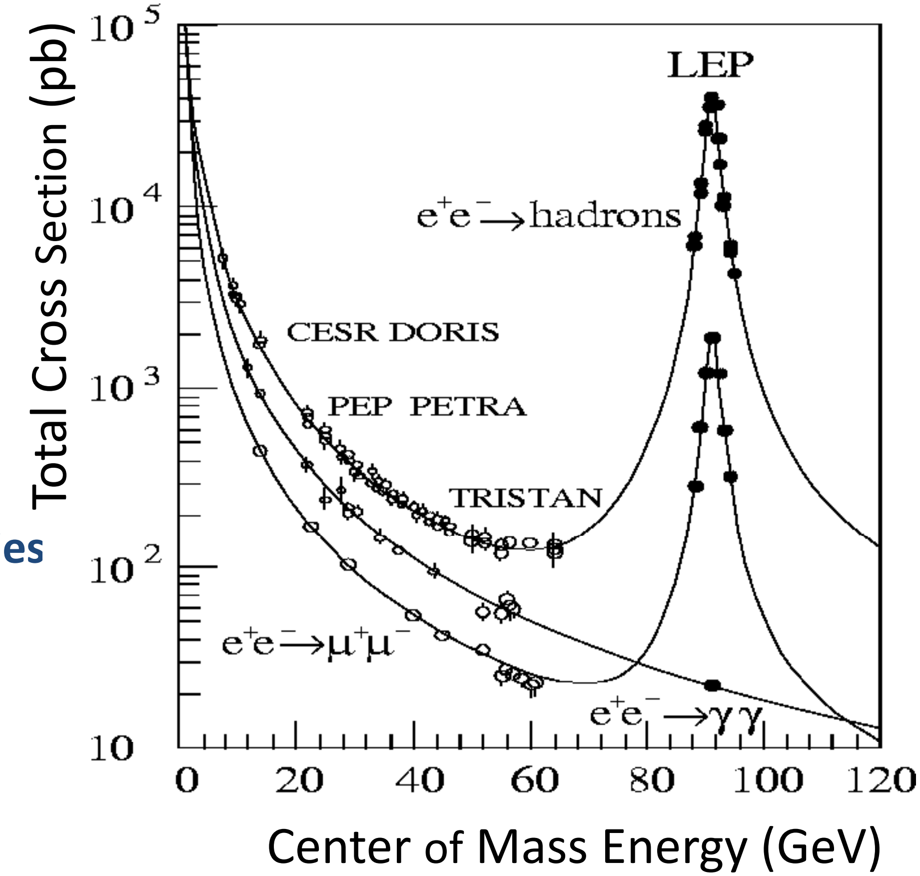
Convenient conversion: $L = 10^{30}cm^{-2}s^{-1} = 1\mu b^{-1}s^{-1}$

Cross Sections for e^+e^-

- At E_{cm}= 10.6 GeV (CESR/CLEO III)

	σ(Tot) (nb)	σ(Barrel) (nb)	σ(Endcap) (nb)
$e+e- \to e+e-$	72	19	53
$e+e- \to \gamma\gamma$	6.2	3.7	2.5
$e+e- \to \mu+\mu-$	0.72	0.60	0.12
$e+e- \to \tau+\tau-$	0.72	0.60	0.12
$e+e- \to$ hadrons	4		
Total	84		

Total rates of few hundred Hz at CESR luminosities (10^{33} cm^{-2} s^{-1} = 1 nb^{-1}s^{-1})

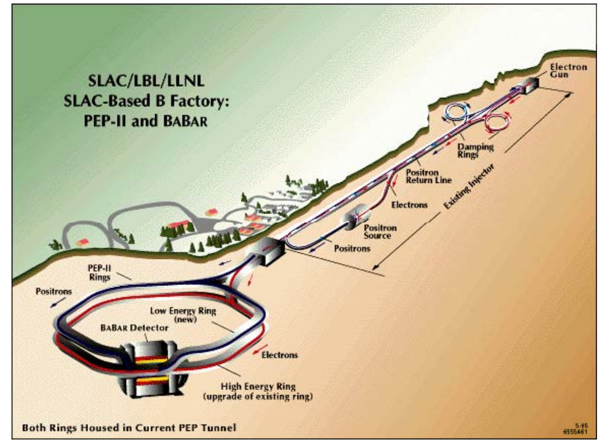


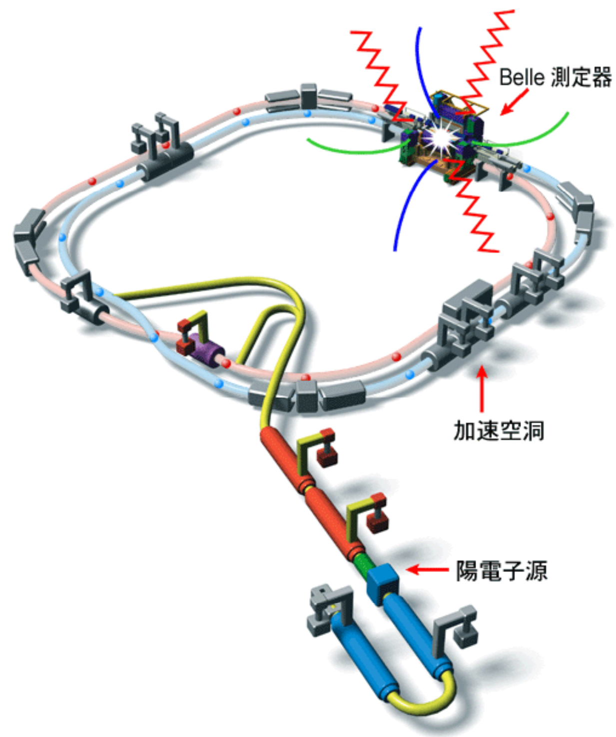
- At E_{cm} = 90 GeV (LEP, SLC on Z-boson)
  - 30nb to hadrons
  - 2nb to $\tau+\tau-$ or $\mu+\mu-$

Total rates of 5-10 Hz at LEP and LEPII luminosities ($2x10^{31}$ cm^{-2} s^{-1} = .01 nb^{-1}s^{-1})

B Factories (PEP II and KEKB)

- Designed from the start as high luminosity production machines
  - 10.58 GeV CM energy (Upsilon 4S)
- KEKB holds current world luminosity record:
  - 2.11×10^{34} cm^{-2} s^{-1} (peak)
  - crab crossing design
- PEP II achieved design goal
  - 3.0×10^{33} cm^{-2} s^{-1}
- Interaction rates as high as a few kHz



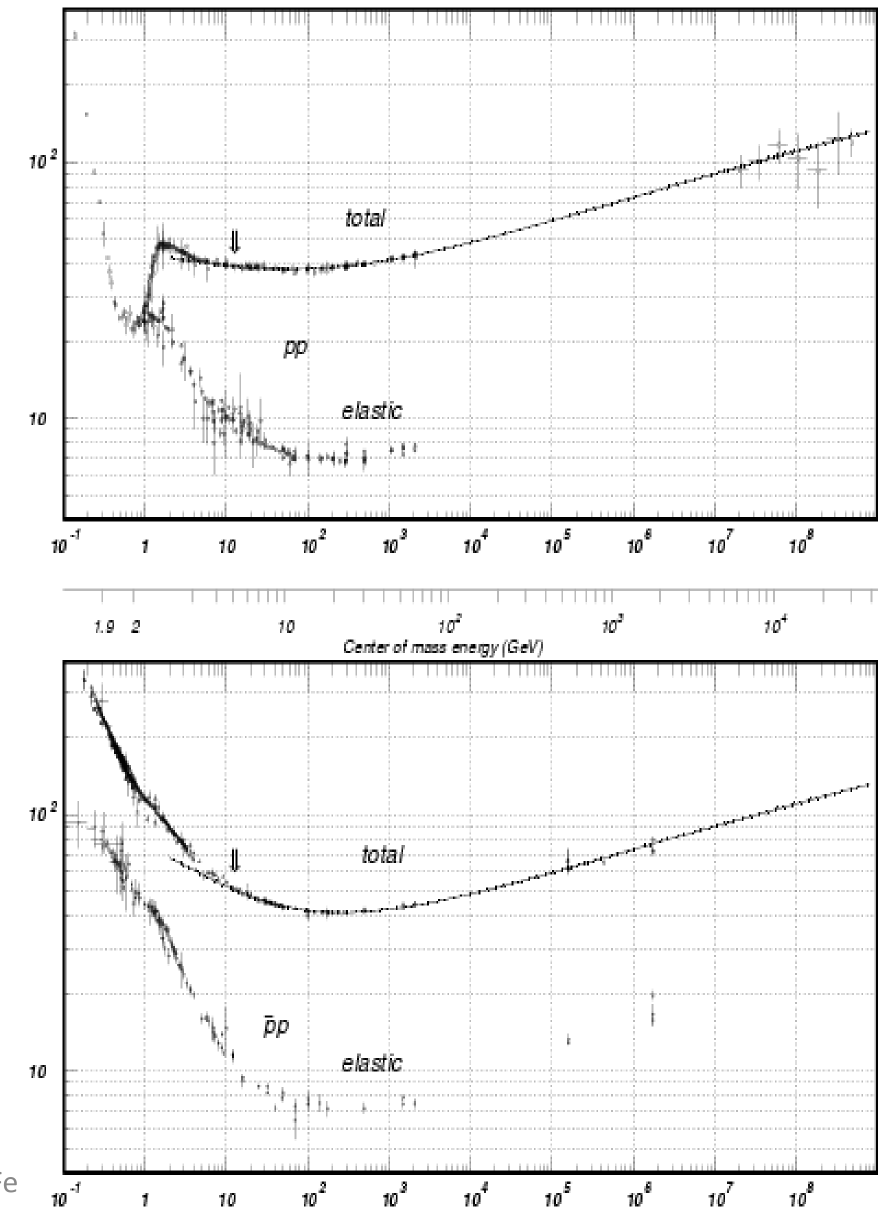


Cross Sections for pp/p$\bar{p}$

- ppbar at ~2 TeV (Tevatron)
  - Total cross section about 60mb
  - Dominated by inelastic scattering
  - At current Run II peak luminosity ~ $3x10^{32}$ cm^{-2} s^{-1} , interaction rate is ~20MHz

- pp at RHIC (200-500GeV)
  - Total cross section about 40-50mb
  - Dominate by inelastic scattering
  - Maximum luminosity at 500GeV ~$2x10^{32}$ cm^{-2} s^{-1} , interaction rate is ~8MHz

- pp at 14TeV (LHC)
  - Total cross section about 70mb
  - Dominated by inelastic scattering
  - LHC design luminosity: 10^{34} cm^{-2} s^{-1}
  - Interactions rates approach 1GHz (!)



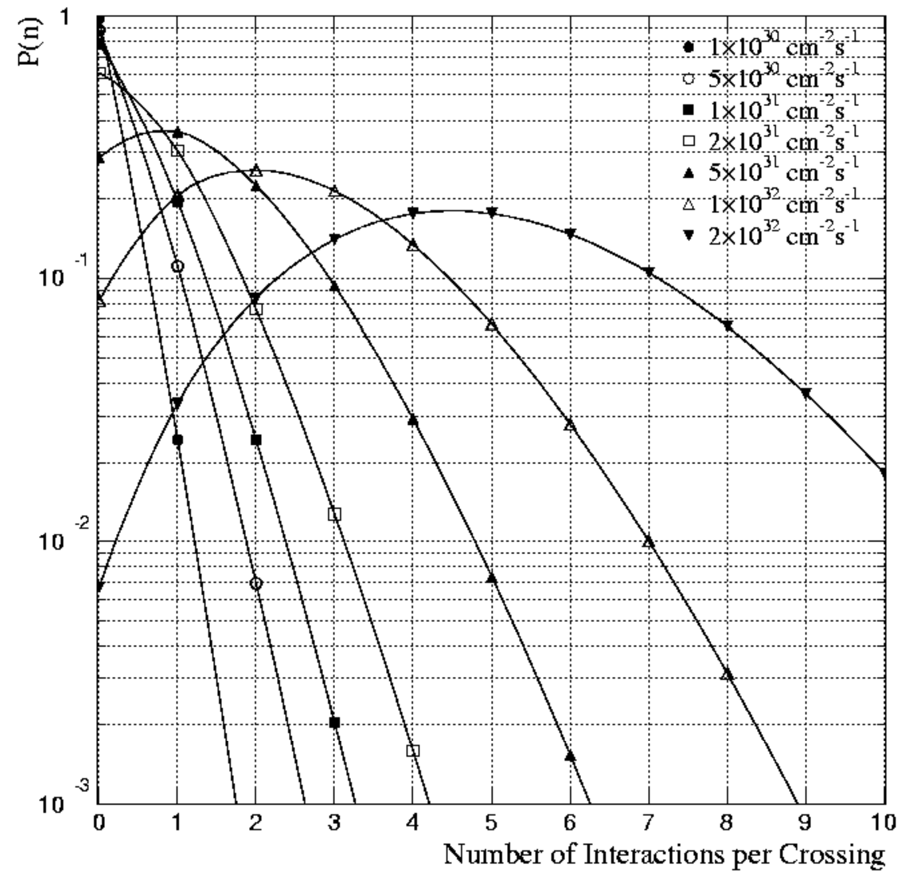
Multiple Interactions

- For hadron colliders (and some fixed target experiments) the interaction rate exceeds the machine bunch spacing causing multiple interactions per crossing:

  $\mu = \langle \text{Interactions/Crossing} \rangle$
  $= \sigma * L$ / Crossing Rate

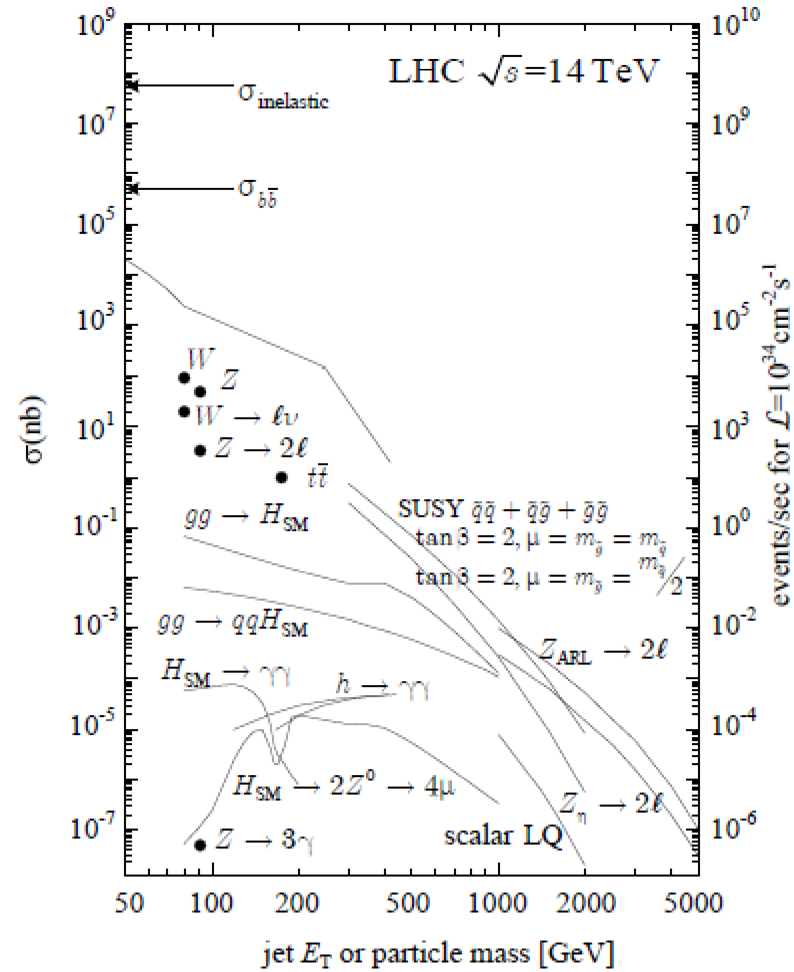
  - RHIC pp@500 GeV : $\mu \sim 1$
  - LHC : $\mu \sim 25$

- The number of interactions for each crossing is a Poisson distribution about the mean μ



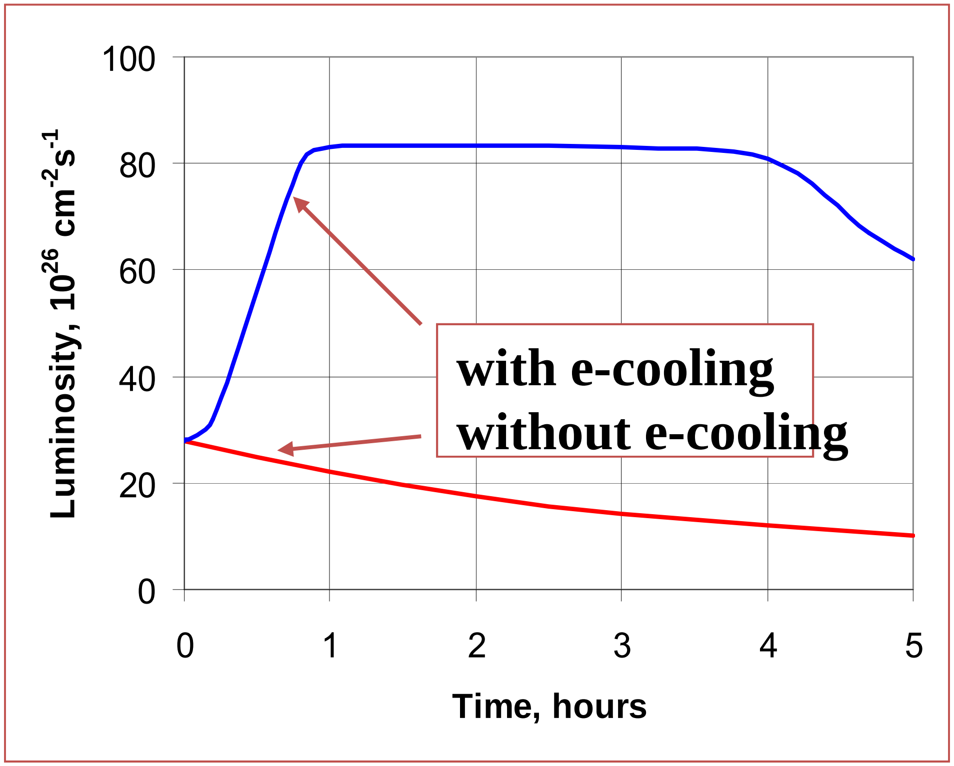
Particle Spectrum in pp (LHC)

- Cross sections for particle production vary by a factor of ~ 10^{10} (diffraction to Higgs)
- Spectrum is similar for higher energy machine (e.g. LHC) except higher mass particles are more accessible
- Triggering challenge is to reject low p_T/mass objects while keeping high p_T/mass
- Of course CDF, D0, LHCb want to keep a large fraction of b events as well…



Heavy Ions (RHIC-II)

- HI cross sections can be very large
  - AuAu inelastic cross section ~8b
- RHIC-II will provide ~$7x10^{27}$ cm^{-2} s^{-1}
  - Electron cooling will keep luminosity ~ constant vs. time.
  - Interaction rate ~50kHz
- Large variation in particle flux depending on collision centrality
  - Triggers will almost always have some centrality bias



Colliding Beam Machines Summary

Accelerator	Type	Energy (GeV)	Bunch Spacing (ns)	Luminosity ($ub^{-1}s^{-1}$)	Int. per Crossing
CESR (CLEO)	e+e-	10.6 (3-4)	14	1280	$\sim10^{-5}$
KEKB (Belle)	e+e-	10.6(3.5x8)	8 (2)	8256	$\sim10^{-5}$
PEP-II (Babar)	e+e-	10.6(3.1x9)	4.2	4600	$\sim10^{-5}$
LEP (Aleph, Opal, Delphi, L3)	e+e-	90-210	22,000	24-100	$\sim10^{-3}$
HERA (H1, Zeus)	ep	27x920	96	75	<<1
Tevatron (CDF, D0)	pp	1960	396(132)	36(200-500)	1(3-10)
RHIC-II (STAR, PHENIX)	pp/HI	200-500/200	106	200/0.01	1/<<1
LHC (Atlas, CMS, LHCb, Alice)	pp	14,000	25	10,000	25

Source: http://pdg.lbl.gov and experiment web sites

For e+e- and ep machines, cross sections are small and multiple interactions are negligible at all current machines

For e+e- even pileup in slow detectors (~1ms) not a large problem

At HERA beam-gas background (50-100kHz) can be problem

For hadron colliders: multiple interactions are a major issue for detector design, particularly tracking chambers, DAQ and Trigger

Efficiency and Deadtime

Efficiency and Deadtime I

The goal of trigger and DAQ is to maximize the amount data sent to storage (for later analysis) for a desired process with minimal cost:

$$\varepsilon = \varepsilon_{operations} * \varepsilon_{trigger} * (1\text{-deadtime})$$

- Relevant efficiency is for events that will be useful for later analysis:

$$\varepsilon_{trigger} = N_{good}(\text{accepted})/N_{good}(\text{produced})$$

- For low rate process (e.g. e+e- to hadrons, Higgs production at Tevatron or LHC) try to accept all signal in trigger ⇦ **Maximize efficiency**

- Deadtime is due to fluctuations when the rate into a stage of the trigger (or readout) approaches the rate it can handle (busy). Simple case of no buffering:

$$\text{deadtime} = (\text{Input Rate}) * (\text{Execution Time})$$

- Buffering incoming data reduces dead time, more buffering less dead time
  - If <Incoming Rate> > 1/<Execution Time>, dead no matter what!
- **Minimizing dead-time helps all processes (and all budgets!)**
  - 1% of machine time * 1 year = $$$$$

Efficiency and Deadtime II

- Need to ensure full efficiency when detector channels are broken, masking registers are used at the input from front-ends
  - For tracking mask **on** dead channels
  - For calorimeter mask **off** hot channels

- Need precise measurements of $\varepsilon_{trigger}$ and deadtime for cross-section measurements
  - Other cases (e.g. particle lifetime) need to evaluate other biases that trigger may introduce (e.g. removing long lived decays)

- Measure deadtime by scaling rates of operational states of Trigger/DAQ system
  - Constant attention required during running to limit deadtime

- Need Mechanisms to evaluate the efficiency and biases
  - Redundant, independent paths
  - Lower bias triggers with accepted with a prescale
  - Zero bias - trigger on accelerator clock structure
  - Minimum bias – trigger on very low energy scattering

Triggers and Deadtime

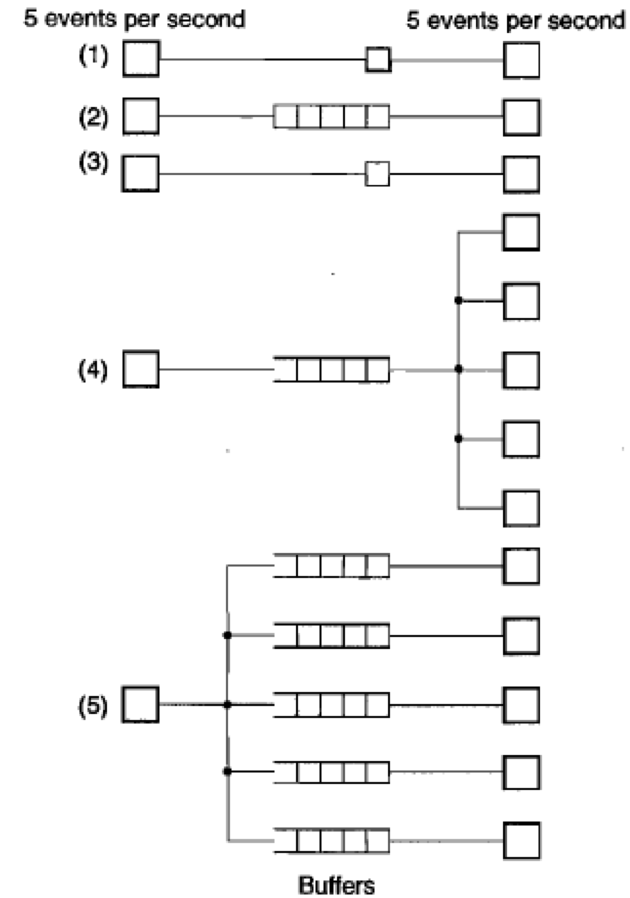
- Assume you get n_e events per second ($t_e=1/n_e$), and the time to record an event is t_R
  - The rate of recorded events is: $n_R= 1/(t_R+t_e)$
  - The fraction of all events recorded is: $f=n_R/n_e = (1+t_R/t_e)^{-1}$
- You can't change t_R. What if you can select only the events you want to record:
  - Trigger processor decision time t_p, triggered event rate n_t
  - Kn_t is rejected event rate (K is the rejection factor)
  - The rate of recorded (triggered) events is now $n_t = 1/((t_R+t_e) + K(t_p+t_e))$
- The fraction of events processed is now given by

$$f_P = \frac{n_t}{n_e} = \left(1+t_R/t_e\right)^{-1} \frac{K+1}{1+K\left(1+t_p/t_e\right)/\left(1+t_R/t_e\right)} = fG$$

If $t_p \ll t_e$, $t_R \gg t_e$ then $G \sim K+1$

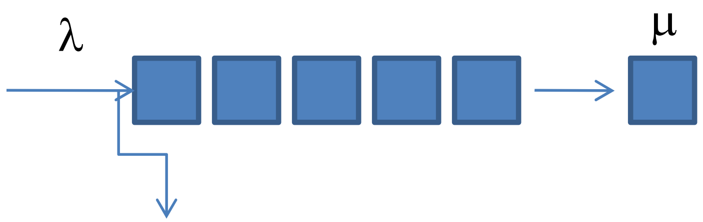
Minimizing Deadtime

- Introducing a trigger with decision time t_p increases your ability to select the physics you want
  - Increasingly important for rare events!
- How do we minimize deadtime even further?
  - Need to minimize the effect of the trigger decision time t_p
  - This can be accomplished by "buffering" events in front of a set of trigger processors
    - Works well for fixed target or asynchronous beam
  - Alternatively, trigger deadtime can be eliminated by "pipelining" the trigger
    - Works well for collider expts.



See *Data Analysis Techniques for High Energy Physics* by Fruhwirth, Regler, Bock, Grote and Notz.

Queuing Theory



- Consider a system with:
  - exponential arrival times with average rate λ
    - Equal probability of event arrival per unit time
  - exponential distribution of trigger service times with time constant μ (ratio $\rho = \lambda/\mu$)
    - Usually isn't exponential, but makes the math nice…
  - A buffer depth N, where the system will produce dead time if the buffer becomes full
  - The probability that the buffer will have N events in time interval [t, t+dt] is given by:

$$dP_n = \left[\lambda P_{n-1} + \mu P_{n+1} - (\lambda + \mu) P_n\right] dt$$

Queuing Theory (cont.)

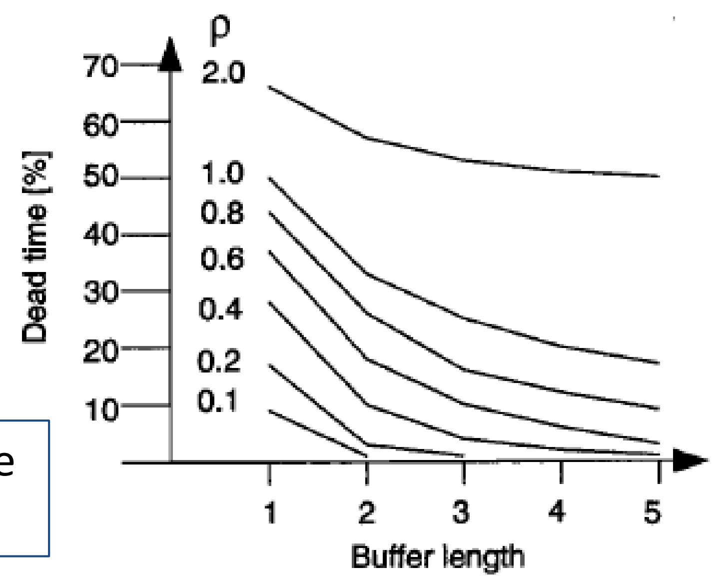
$$dP_n = \left[\lambda P_{n-1} + \mu P_{n+1} - (\lambda + \mu) P_n\right] dt$$

- Set the above equal to zero for a steady-state solution
  - Solve P_0 , P_N as a special case!
- Solve for the dead time as the probability (fraction of the time) that the buffer has N events

$$\tau = P_N = \frac{(1-\rho)\rho^N}{(1-\rho^{N+1})} \qquad \rho = \left(\frac{\lambda}{\mu}\right) \neq 1$$

$$\tau = \frac{1}{N+1} \qquad \rho = 1$$

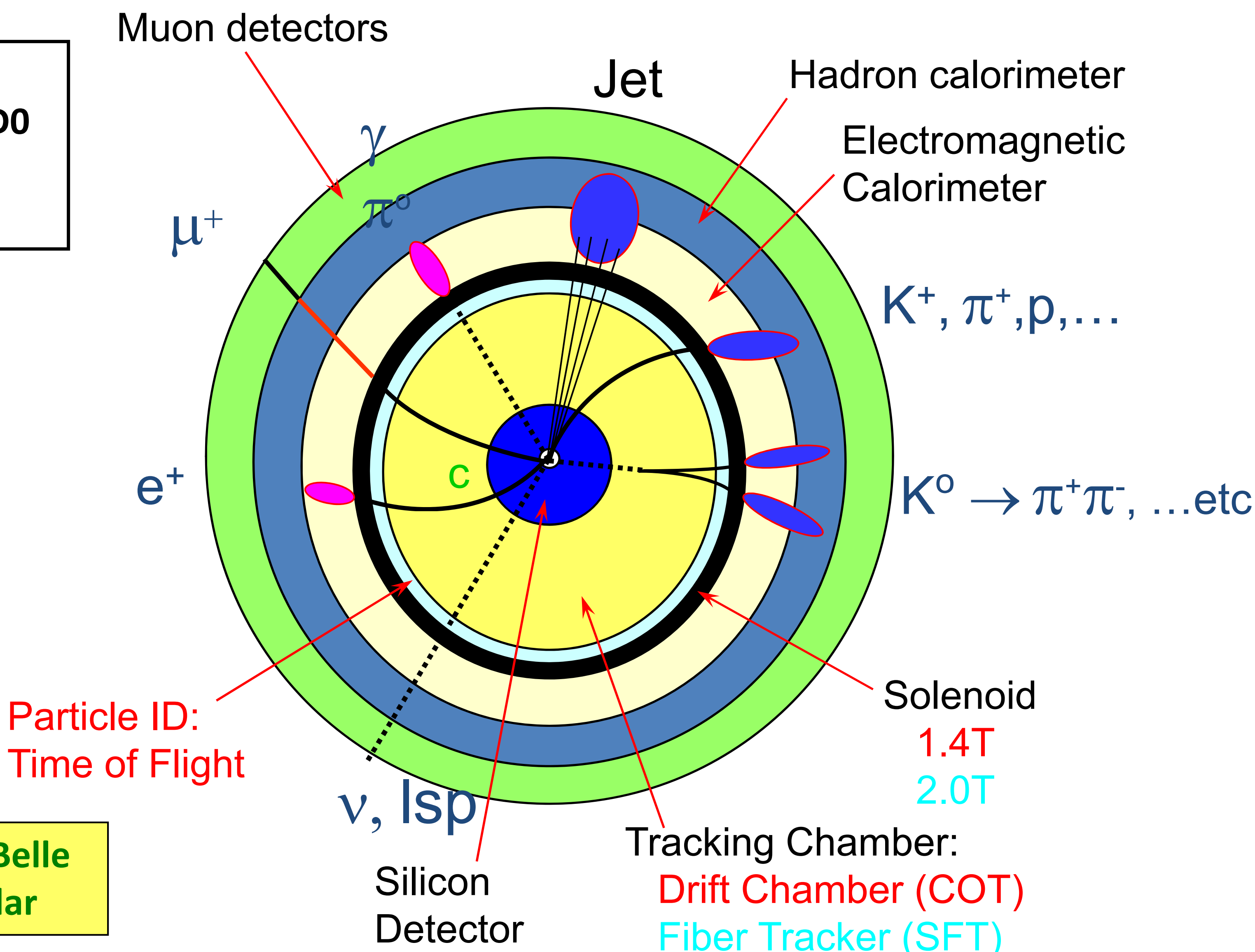
For ρ=1, if N=1 then deadtime = 50%. If N=5, the deadtime is reduced to 16%.



Signatures in Detectors

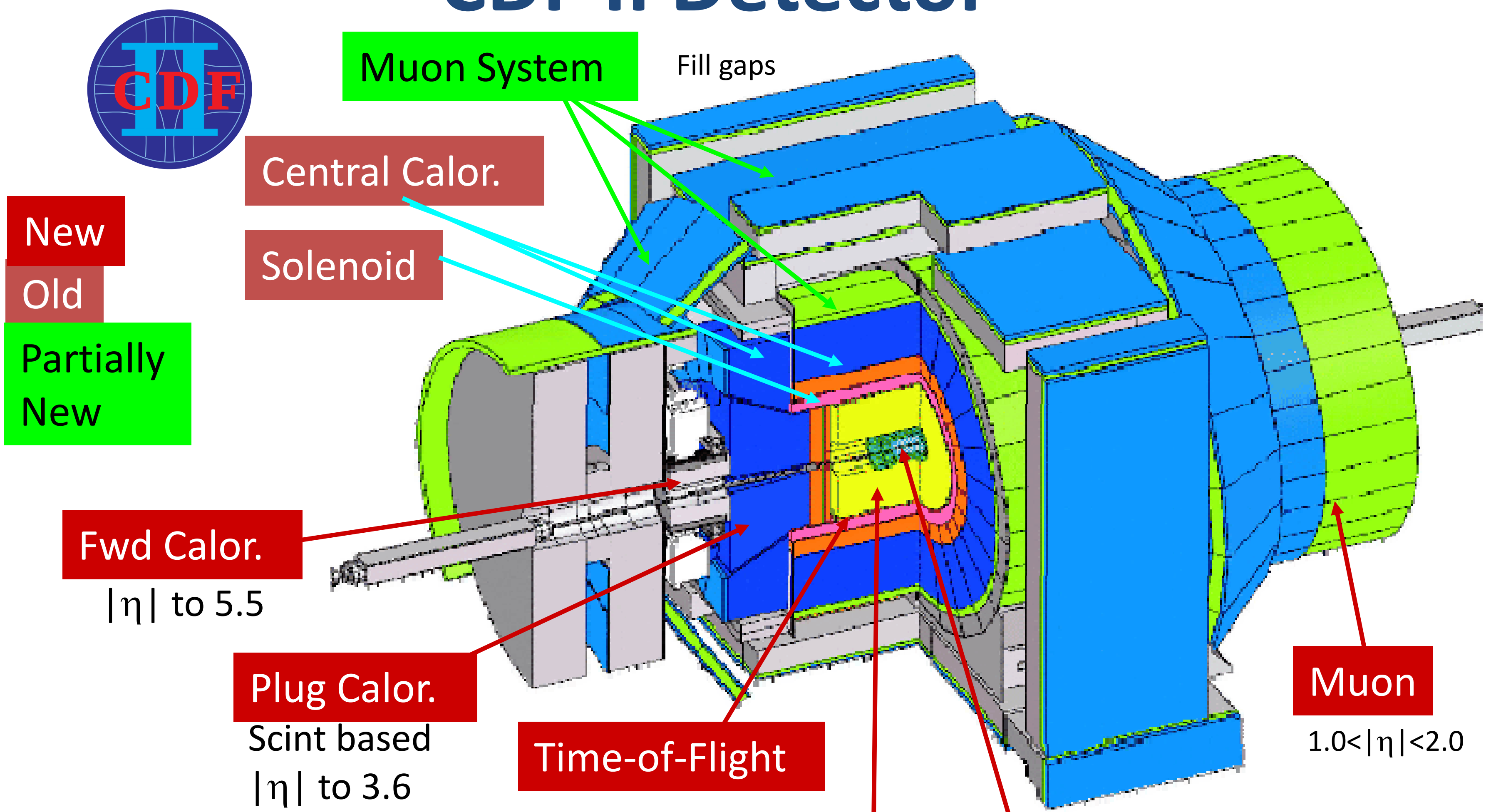
Collider Detector Schematic

Key
CDF and D0
CDF
D0



Babar & Belle very similar

CDF II Detector



Front End Electronics
Triggers / DAQ (pipeline)
Online & Offline Software

D0 Detector (Run-2)

New

Old

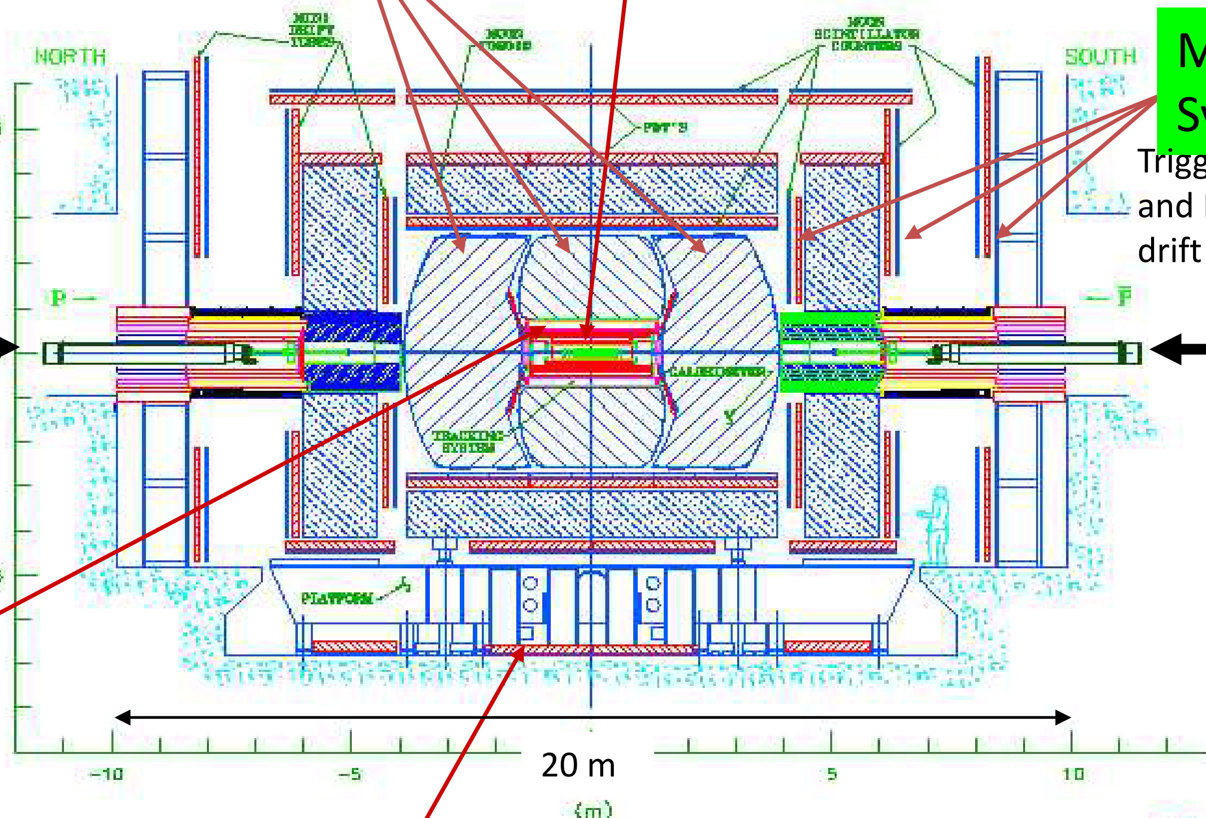
Partially New

Calorimeters

Tracker (Si, Fiber, Solenoid 2T)

Muon System

Trigger Scint and Forward drift tubes



p

p-bar

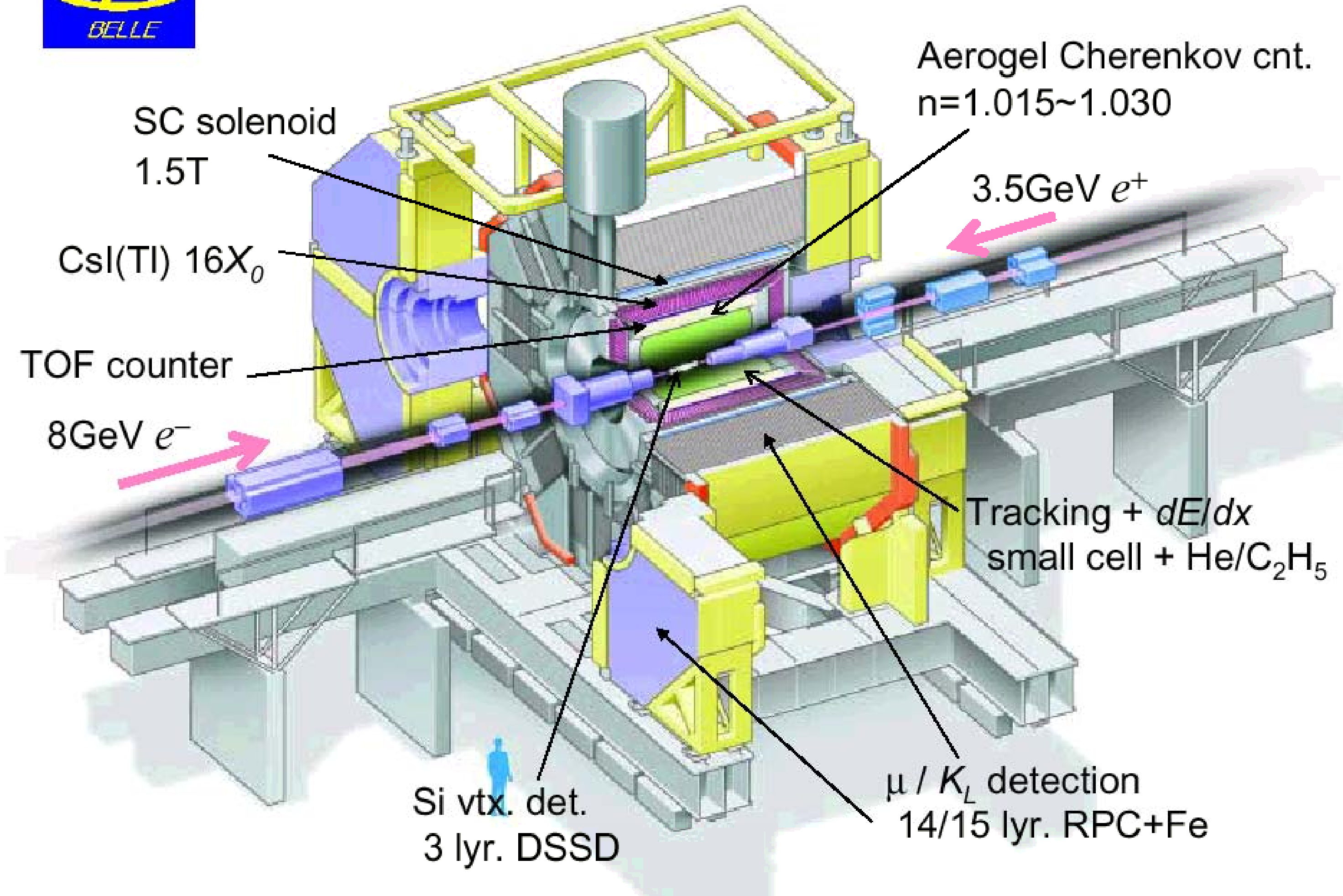
PreShower

Scint. Fiber Central and Forward

Electronics

Front End Electronics
Triggers / DAQ (pipeline)
Online & Offline Software

The BELLE Detector



Requirements for e^+e^- Triggering

Accept: (almost) all real collisions

Reject:

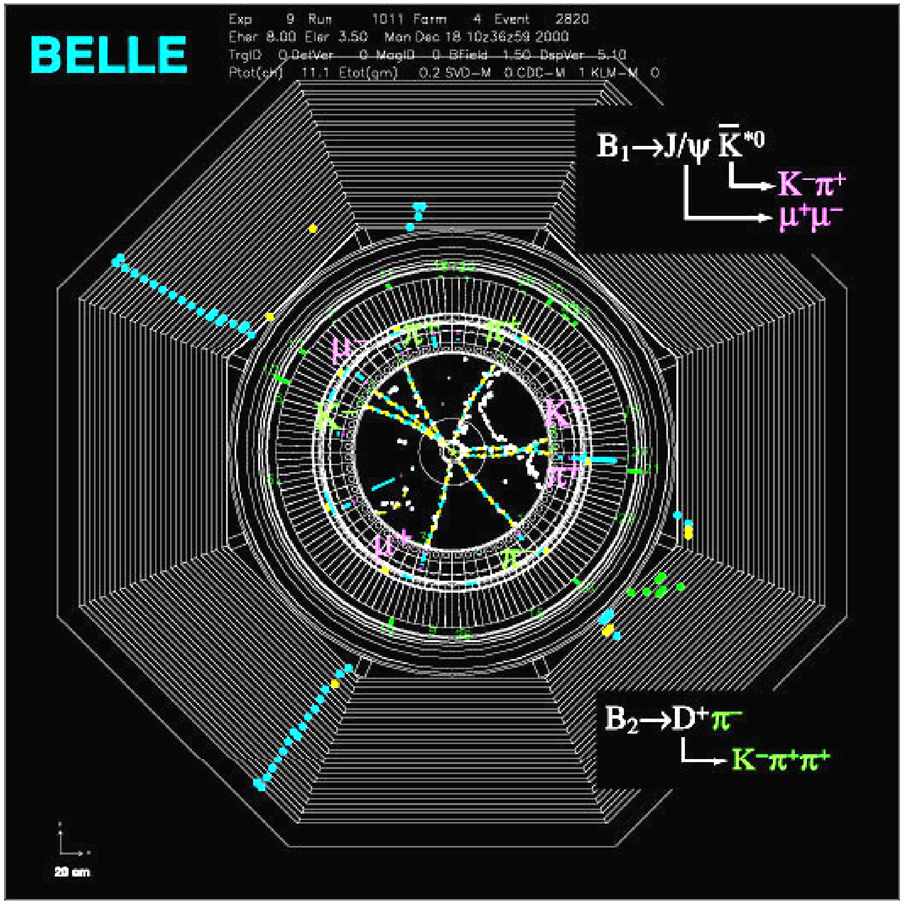
- very low angle e+e-
- Beam-gas/wall events - tracks not from beam spot in r or z

Trigger on simple event topology

- Time-Of-Flight coincidence
- Multiplicity of good tracks (from beam spot) – low pt cuts (100s of MeV/c)
- Calorimeter activity: global energy and clustered energy in relative coarse spatial bins
- Simple combinations

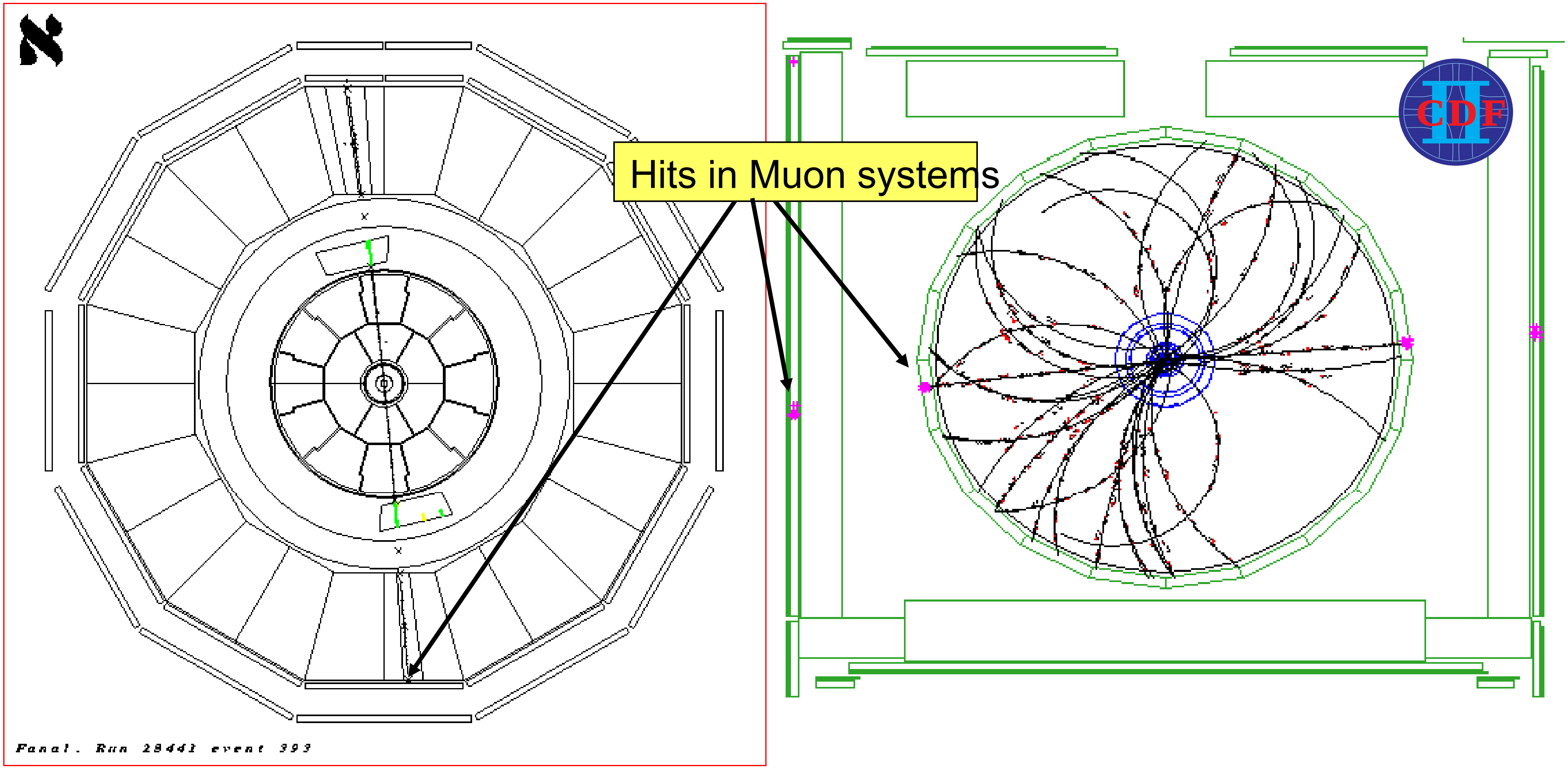
Time stamping

- Beam Xing << detector response times (few nsec vs 100-1000ns)



Very Clean Events

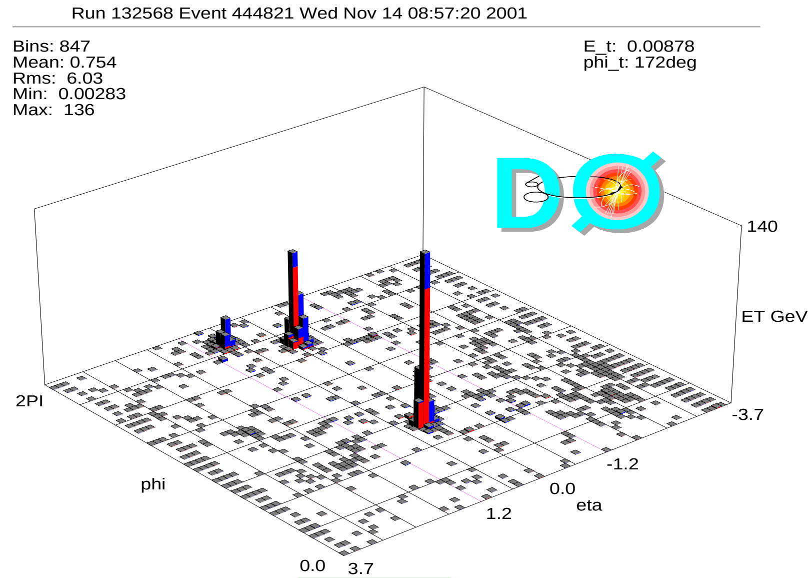
e^+e^- versus pp(pbar)



Aleph $Z \rightarrow \mu^+\mu^-$ Event
Only 2 Tracks

CDF $Z \rightarrow \mu^+\mu^-$ Event
Many Tracks over 500MeV/c

Signatures for pp(pbar) Triggering



Accept specific decays modes

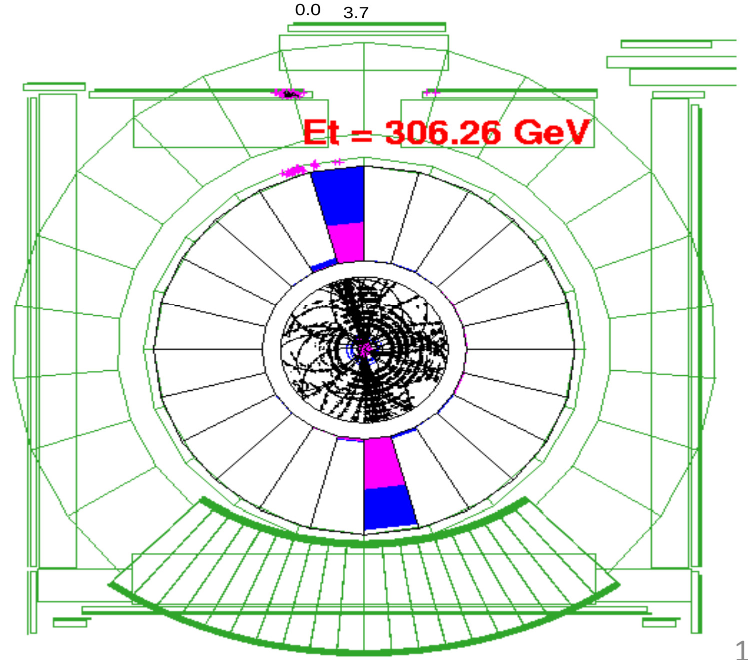
- High p_T leptons from W, Z, top, W/Z+Higgs QCD: High Et jets
- $\psi \rightarrow \mu\mu$, medium p_T leptons for B physics

Reject:

- Lower P_T objects (QCD)

Select on object/event kinematics:

- E_T in calorimeter tower, missing E_T
- μ P_T (+ track P_T)
- Track P_T (+ impact parameter/detached vertex)



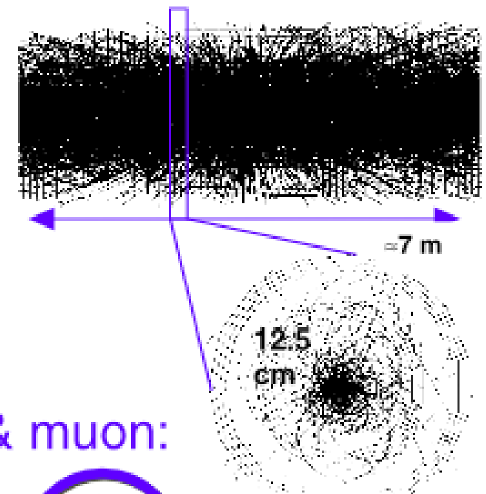
Trigger Strategies

- Select objects: muon, electron (photon), jet, track by applying threshold cuts in subsystem processors (custom hardware)
  - Tevatron – fine granularity and lots of E_T/P_T thresholds for different physics (eg top vs B's)
  - B-Factories , LEP – coarse granularity few thresholds
  - Hera – combination of above
- Track finding difference
  - Tevatron $\rightarrow$ Cut on P_T, good resolution and many bins
  - B-Factories, LEP and HERA $\rightarrow$Number and ϕ correlation of tracks above minimal P_T, z information to reject beam background
- Two strategies for combining objects:
  - CDF (and D0 muon) $\rightarrow$ fine Track match in subsystems, pass global count to decision logic. Complex subsystem logic, simpler final decision logic
  - B-Factories, LEP and HERA $\rightarrow$ Send counts in coarse geometric regions to global and do correlations there. Simpler subsystem logic, more complicated final decision

ATLAS and CMS Strategy

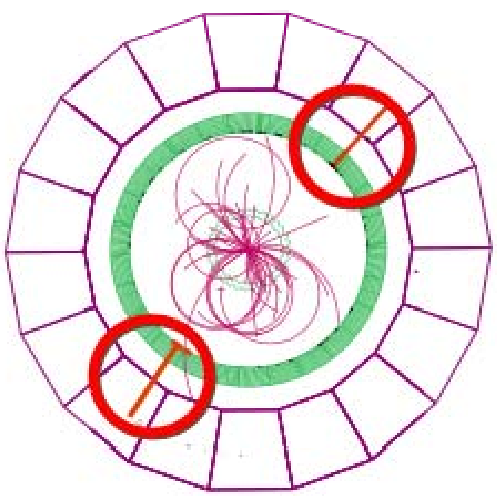
Level-1 : only calorimeters & muons ....

Compare to Central tracking at $L = 10^{34}$
(50 ns integration, ≈1000 tracks)



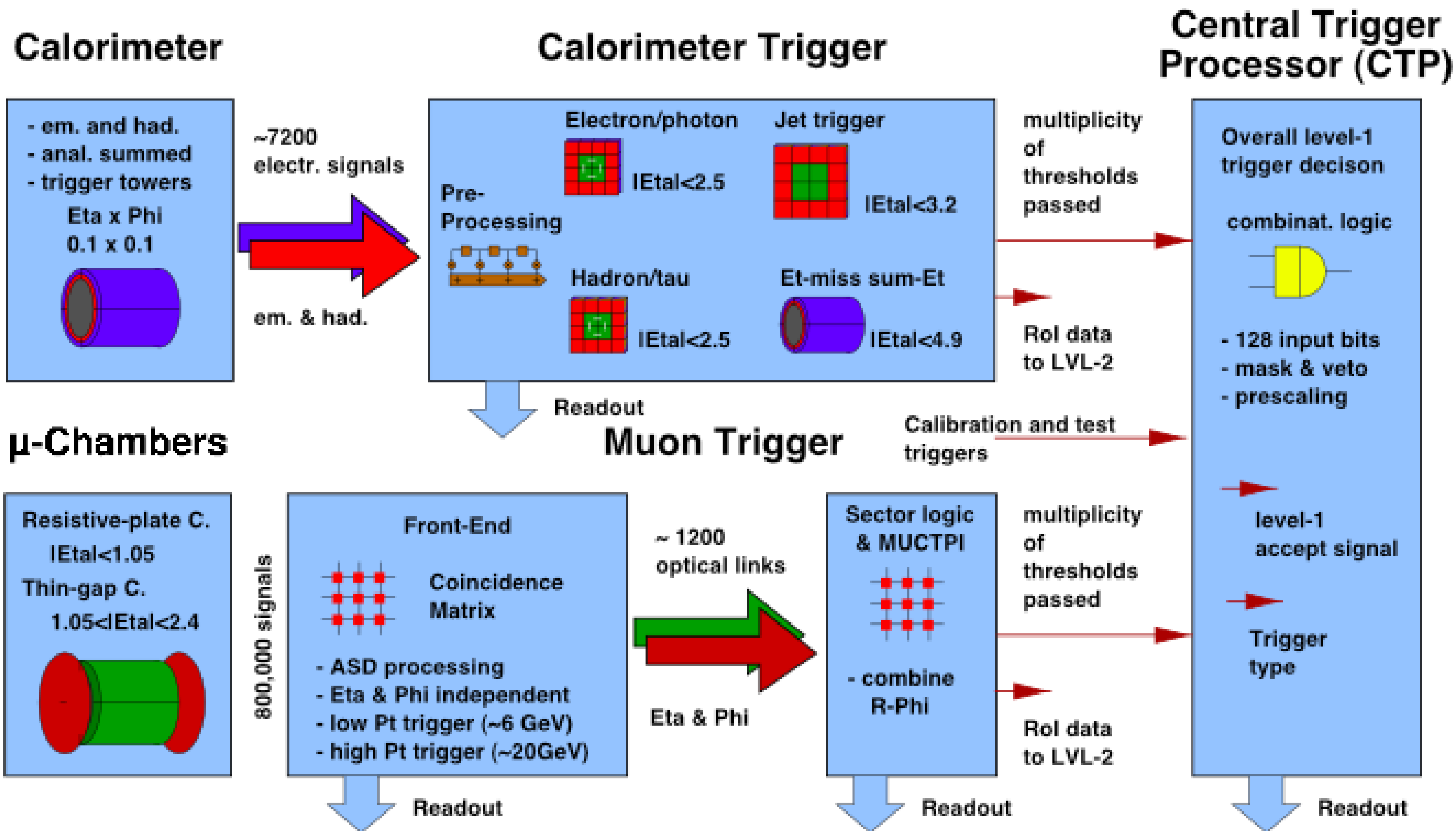
Algorithm Complexity
+
huge amount of data

Pattern recognition much easier on calo & muon:

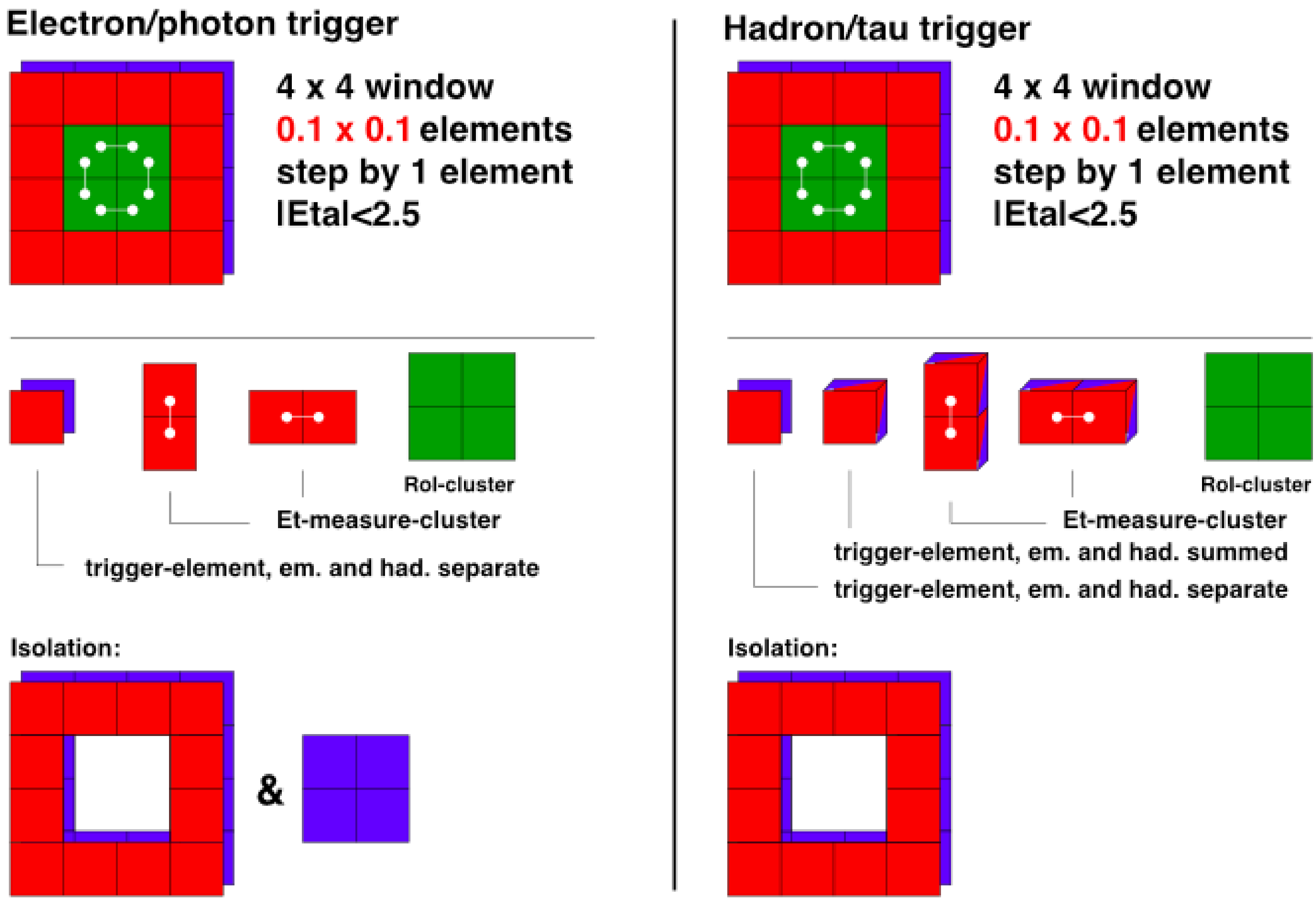


Complexity handled in software on CPUs

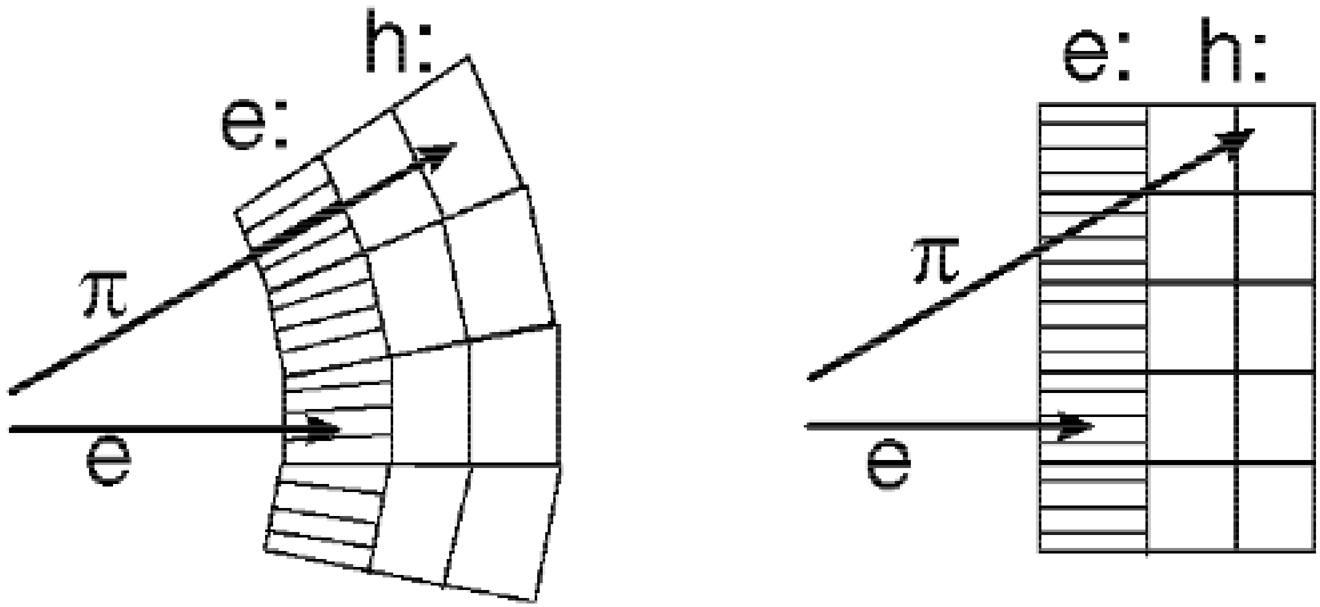
Trigger Flow : ATLAS Example



Example: ATLAS Calorimeter Trigger

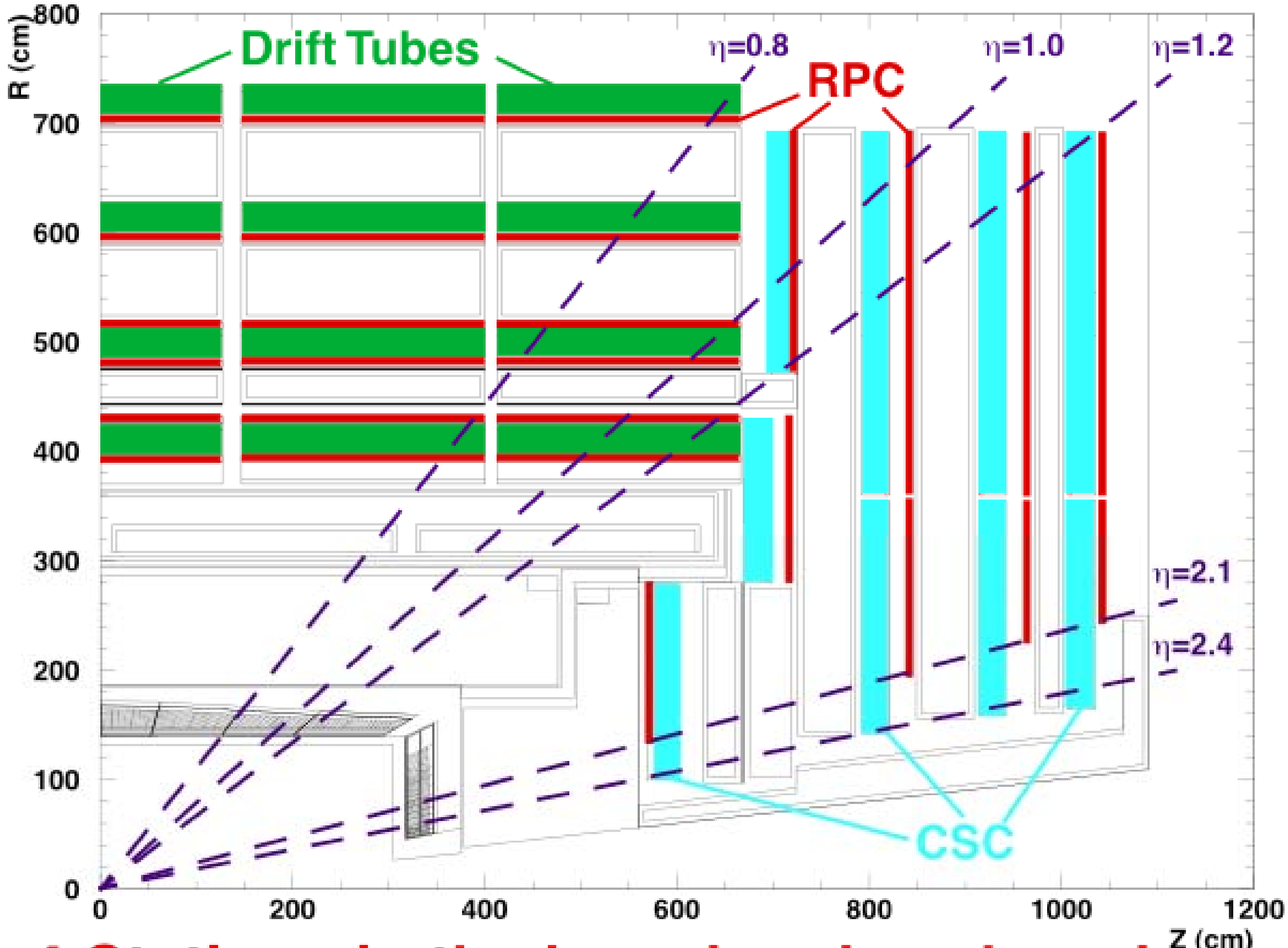


Note on Projective Geometry



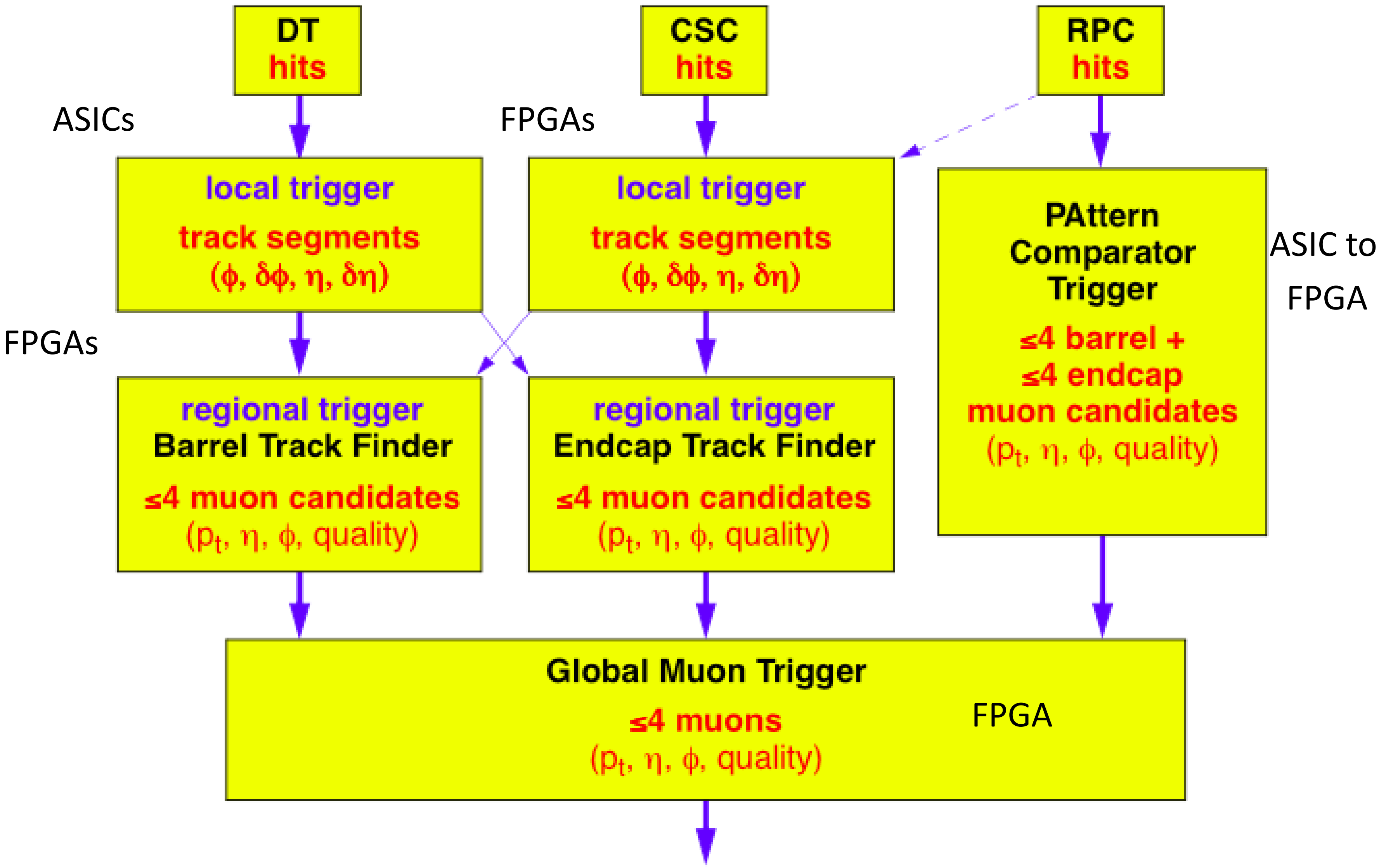
- Projective geometry is important
  - ZEUS: Used complicated cable mapping and pattern searches to reduce fake rate
  - ATLAS, CMS: Calorimeters are built projective
  - Mapping with muon system: Important for isolation

CMS Muon System



4 Stations in the barrel and each endcap

Example: CMS Muon Trigger



Multilevel Trigger Systems

Multi-Level Trigger Systems

High Efficiency ⟺ Large Rejection

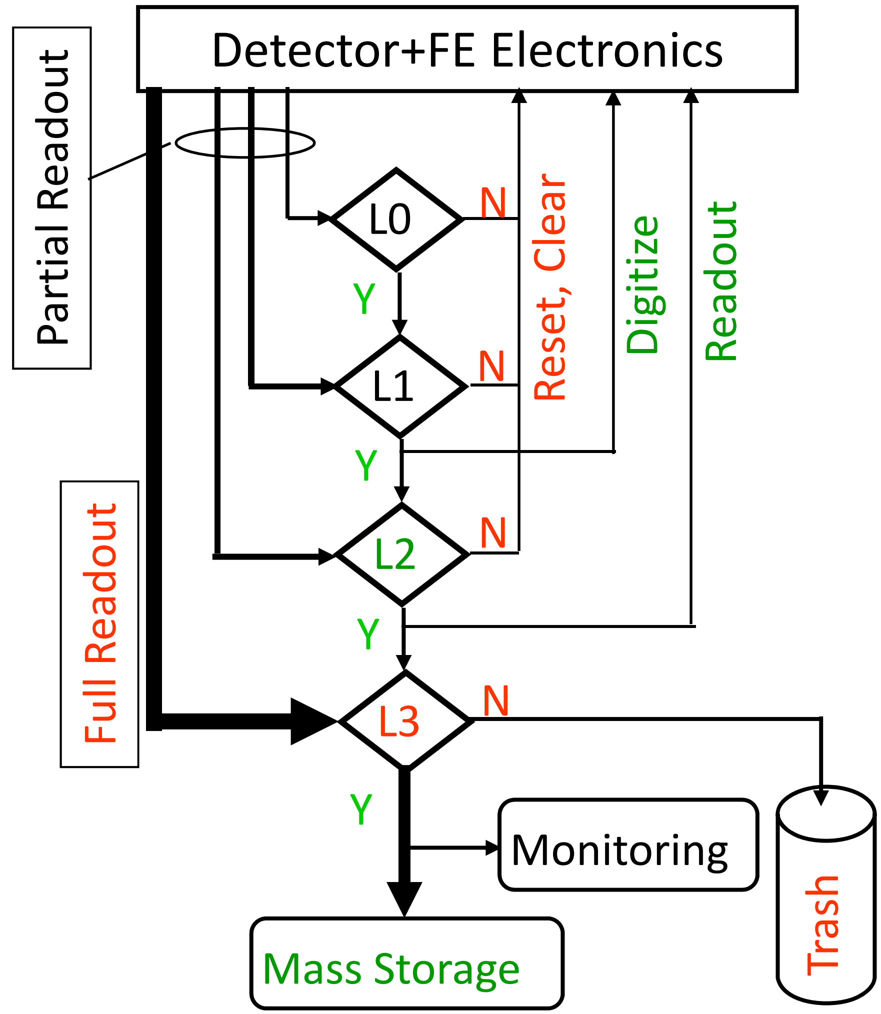
- Often can't achieve necessary rejection in a single triggering stage
- Reject in steps with successively more complete information

  L0 – very fast (<~bunch x-ing), very simple, usually scint. (TOF or Luminosity Counters)
  (Few expts use a L0 anymore)

  L1 – fast (~few μs) with limited information, hardware

  L2 – moderately fast (~10s of μs), hardware and sometimes software

  L3 – Commercial processor(s)



Example: CLEO II Trigger (ca 1989)

TOF (Cal) trigger (L0,L1,L2):

- discriminators on each bar (Σ 16 X-tals) and OR'd into 30(32) sectors
- >1 sector, 2 opposite, non-adjacent

BLT, TSP triggers (L1,L2):

- Count low P_T tracks (threshold algorithm) and determine charge (BLT)

PD trigger (L2):

- Vertex chamber path consistent with coming from beam spot

Hadron Trigger:

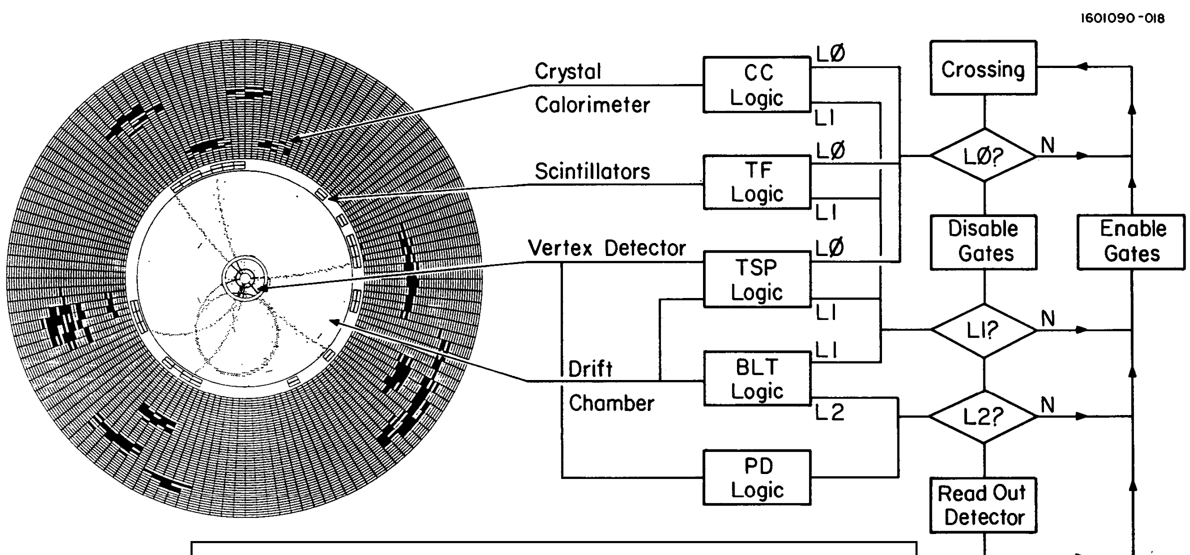
L0 TOF non-adjacent

L1 Three tracks

L2 Two PD tracks

Continuously gating sample and holds

Stage	Devices Used	Output	Execution Time	Dead Time
L0	Cal, TOF, VD	20kHz	<360ns	0
L1	Cal, DR, TOF, VD	20Hz	2.56ms	5%
L2	Cal, DR, VD	5Hz	50ms	0.10%
ReadOut	N.A.	5Hz	12ms	1.20%



C. Bebek et al NIM A302 (1991) 261

Example: D0 Run-1 (1991-95)

L0 Trigger (285kHz in,150kHz out)

- Beam hodoscopes

L1 Trigger (200Hz out)

- Single Cal trigger towers (4 thresh)
- Global E_T and missing E_T (EM, HAD)
- Muon chamber tracks
- No deadtime, exec. time <1 μs

L1.5(2) Trigger (100Hz out)

- Higher resolution muon chamber tracks
- TRD confirmation for electrons
- Execution time: up to 100μs

L2(3) Trigger (2Hz out)

- Farm of Vaxes running offline type code

D0 Trigger and DAQ System

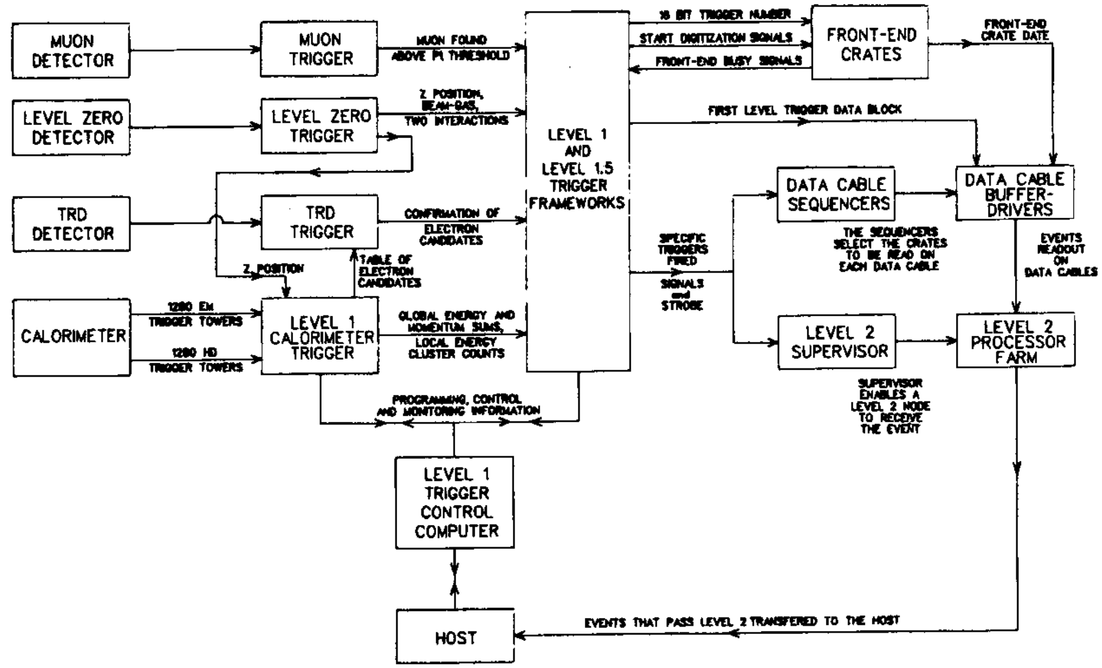


Fig. 67. Block diagram of the trigger and data acquisition system.

S. Abachi et al NIM A338 (1994) 185.

<u>Example</u>: CDF Run-1

Every 3.5μs (bunch spacing):

- Calorimeter Sample and Hold get reset
- Muon and CTC TDC get stop

L1 Trigger (285kHz in, 1.5kHz out)

- Trigger decision on fast output of Beam-Beam, Calorimeter, and Muon
- Execution <3.5μs ⇦ no dead-time

L1 Accept ⇦ stop gating detector

L1 Reject ⇦ continue gating detector

L2 Trigger (up to 50Hz out)

- Add CTC tracks and match to muon and Calorimeter clusters
- Execution 30-50μs ⇦ dead-time <10%

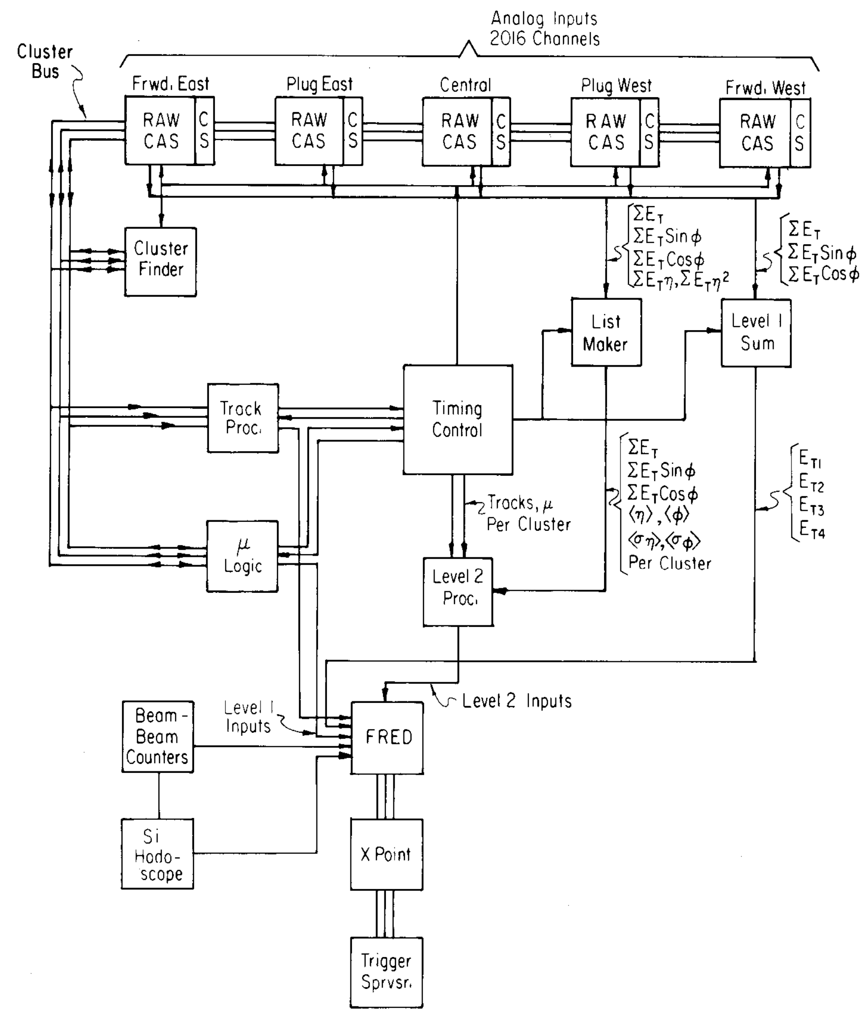
L1 Accept ⇦ digitize and readout

L1 Reject ⇦ resume gating detector

L3 Trigger (up to 5-8Hz out)

- Event size 300kB in, 100kB out
- Farm of SGIs running offline type code
- Readout ~3ms, Readout deadtime <10%

CDF Trigger System



D Amidei et al NIM A269 (1988) 51.

CDF/D0 L2 Trigger Strategy

Two stage process:

1. Reconstruct objects: muon, electron/photon, jet, tracks in pre-processors and pass object kinematics to central processing
   - Some input information will be the same as used at L1 (e.g. tracks from central tracker)
   - Remaining information will be newly formed (e.g. Silicon tracks with impact parameter measurement)
2. Assemble event in processor memory and run event filters much like a L3 trigger except on a very limited scale
   - Processor is custom VME module based on DEC Alpha chip
   - Filters written C/C++

CDF/D0 Run-1 L2 Implementation

CDF L2

- Drift Chamber Tracks
  - Digital pipeline finds tracks serially scanning 360° in ϕ
  - Eight P_T bins
  - Track P_T, ϕ_0 feed Cal and Muon matching hardware (15°, 5° match respectively)
  - Fast CMOS rams and AS TTL logic
- Other: Fine grain shower max info for electrons and Calorimeter Isolation trigger using analog NN chip
- Programmable processors (custom Fastbus) apply final event cuts:
  - 1A: Motorola bit slice
  - 1B: DEC Alpha
- Up to 64 different L2 triggers possible
- Other than track processor almost completely based on ECL logic

D0 L2

- No drift chamber tracking (no solenoid)
- 16 muon bits from finer matching
- L2 Triggers pre-requisite on L1 triggers
- Uses same global decision (L1 Framework) logic as L1

Pipelined Trigger Systems

What is a pipeline?

- A trigger pipeline is used to avoid trigger deadtime
  - Typically used in a collider environment where the accelerator RF provides a natural pipeline clock
  - Tight design constraints between trigger and FEE:
    - FEE pipeline must “buffer” events while waiting for trigger decision
    - Accomplished in one of two ways
      - FADC on input channels
      - Analog charge storage (AMUADC)
- Resulting system has no deadtime due to L1 trigger processing
  - Additional complication: synchronization

Trigger and FEE Pipelining : ZEUS, H1

Poor vacuum due to synchrotron radiation.
Large proton-beam background : $\sigma_{pp} >> \sigma_{ep}$
Beam-gas rate ~100kHz (10μs)

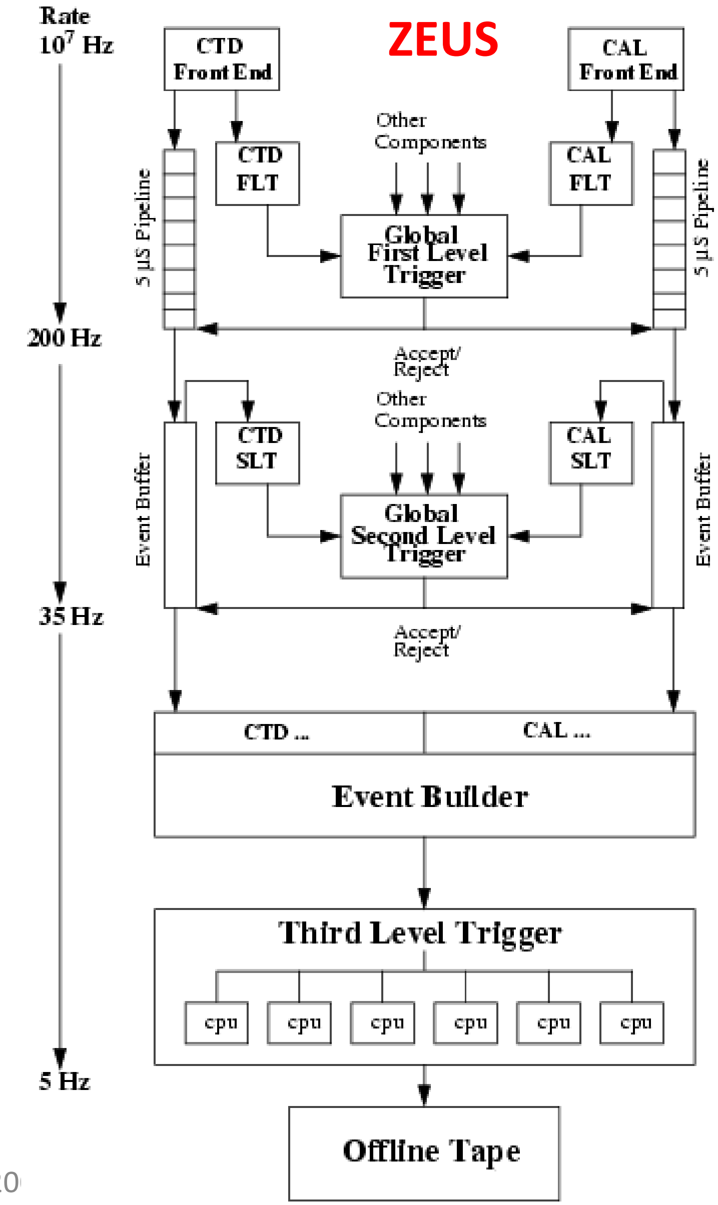
Bunch crossing rate 10.41MHz (96ns)
Can't make the decision in one step!
Solution is to pipeline the FEE and trigger.

<u>Three-Level Trigger</u>

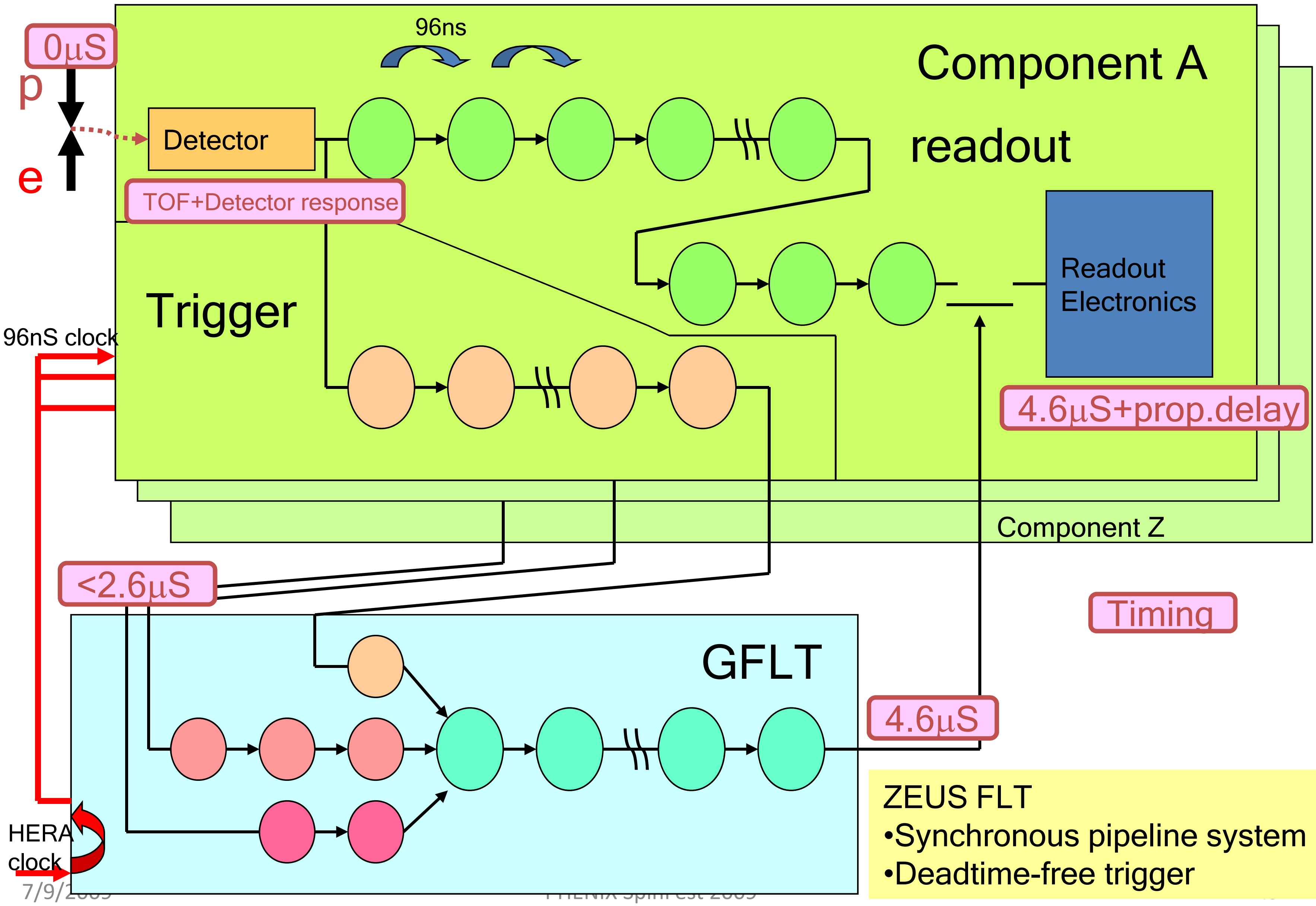
- **L1 (FLT)**: Hardware triggers
  starts readout (digitization)

- **L2 (SLT):** Software trigger with distributed processors
  starts event building

- **L3 (TLT):** Software trigger in a single processor
  starts data storage



ZEUS Pipelined Trigger



Rejecting Beam-Gas at HERA

- Timing of TOF hits (H1) rejects out of time events
- Track processors reject events with large impact parameter in r-ϕ and r-z planes to remove beam-wall and beam-gas backgrounds
- Example: Look for patterns in r/z across layers:
  - **Good tracks constant r/z**
  - **Tracks not from interaction region will have wrong pattern**

Zeus Track Z0 Finding

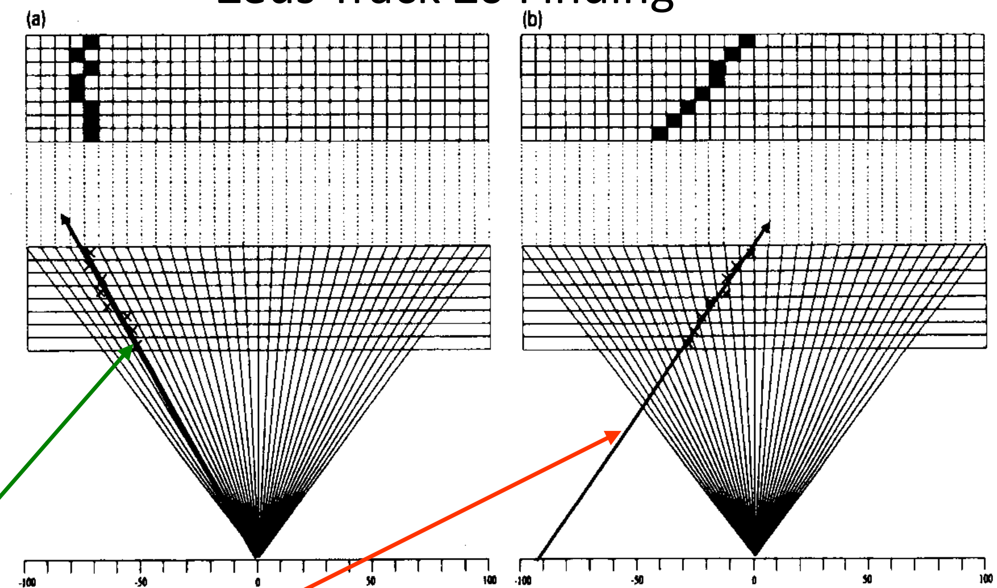
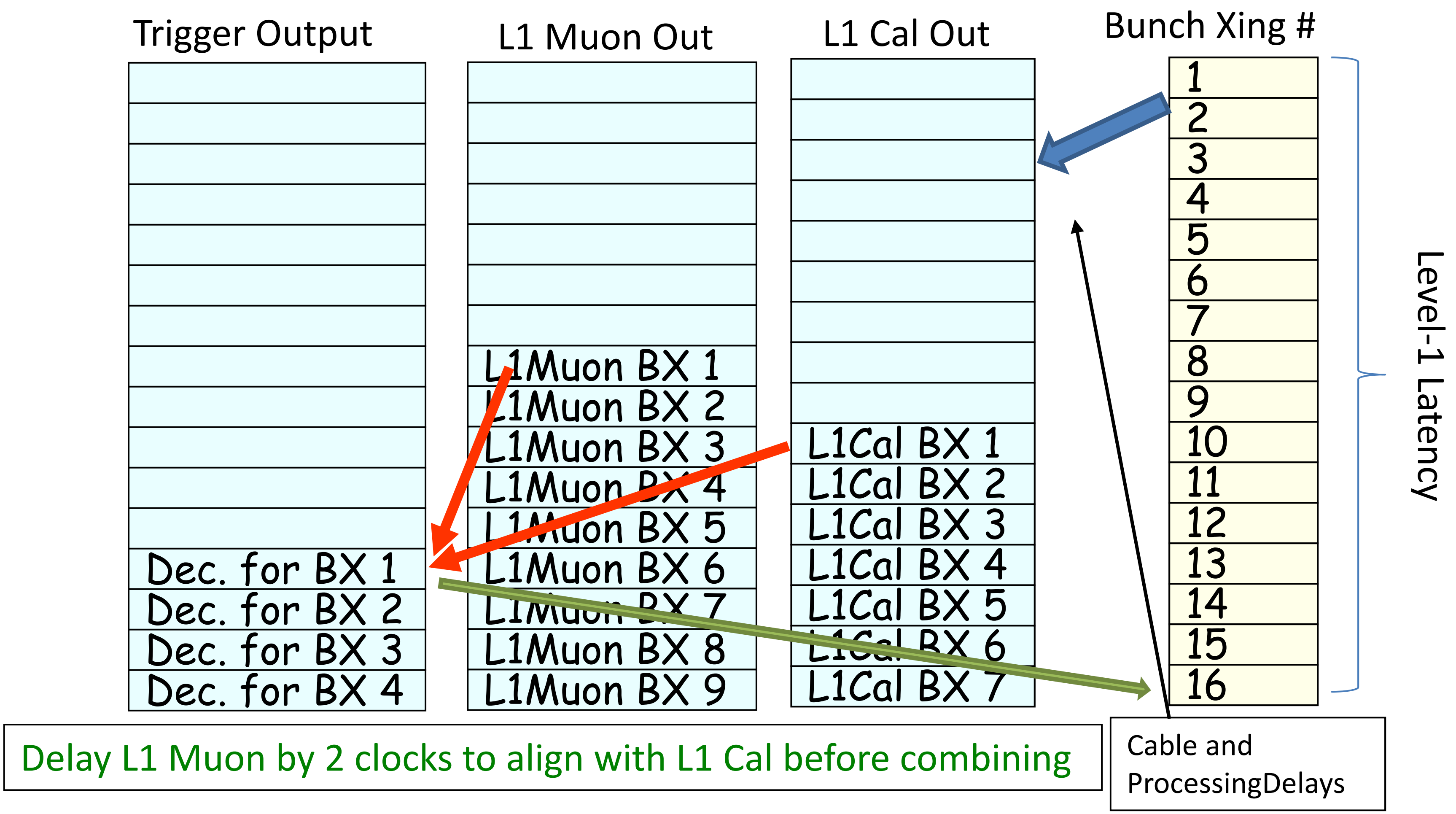


Fig. 2. The formation of the z/r table in the segment finding processor for (a) a track from the vertex region and (b) a track from outside the vertex region.

GP Heath et.al., NIMA 315(1992) 431.

Also can be effective for beam backgrounds at e+e- machines
(OPAL, M. Arignon etal NIM A313 (1992) 103.)

Pipeline Synchronization



Need to design in time alignment wherever L1 primitives come together

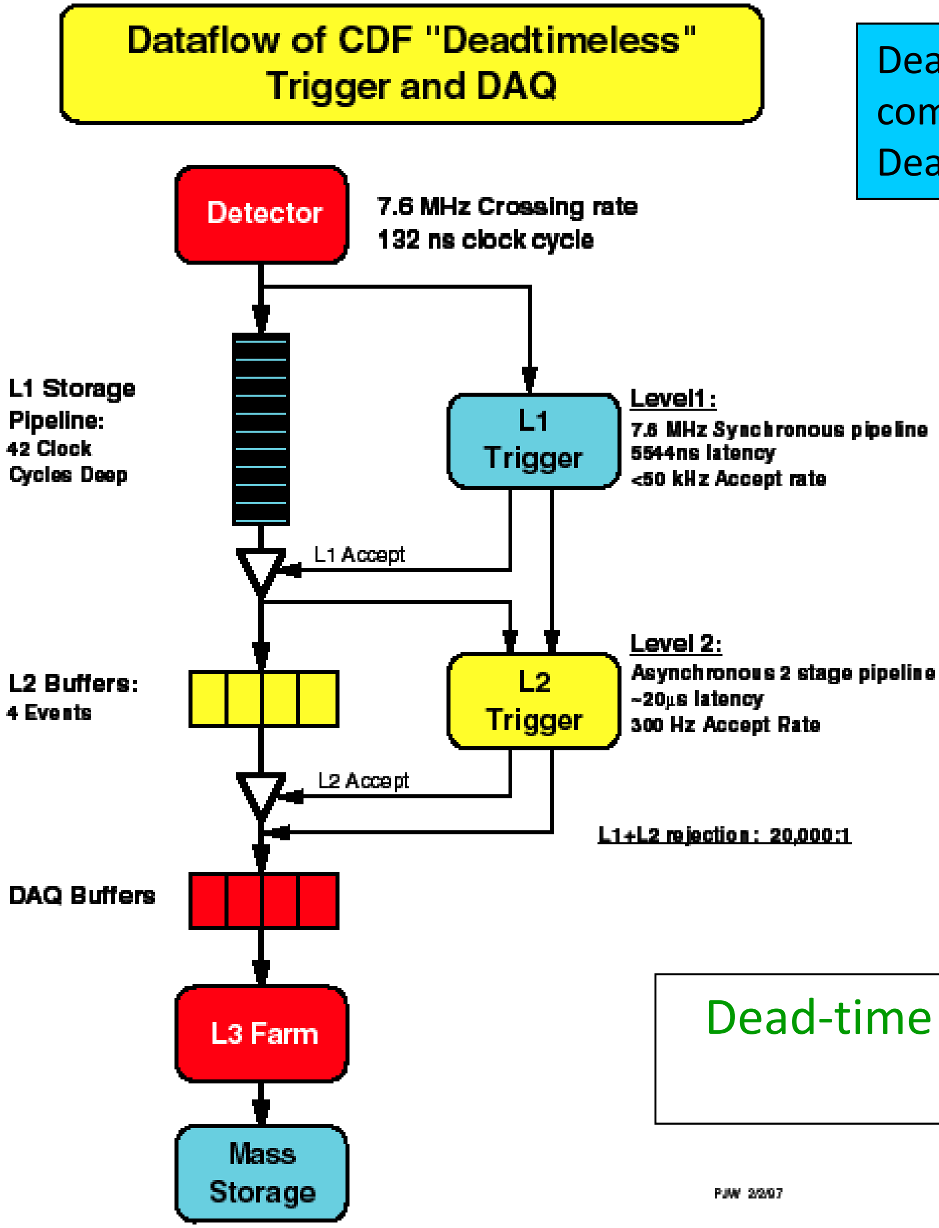
Bunch Crossing Counters

- **Critical for pipeline system design to provide method(s) of determining if pipelines are staying synchronized**
- Common method: bunch xing counters in each component which reset once per accel turn
  - Count fundamental clock even for unfilled buckets
  - CDF and D0: count 7.6MHz (132ns) clocks (0-158), actual number of beam x-ing per accelerator turn is 36 (104) for 396ns (132ns) accelerator operation (its actually a clock counter).
  - Distribute to each component: fundamental clock and beginning of turn marker, called bunch 0 (b0) at Tevatron

Bunch Crossing Checks

- CDF: bunch counter readout from each board into event data
  - Compare between boards in VME readout controller (PowerPC SBC). **Out of synch pull local error line.**
  - Compare between crates at event building time. Out of synch send error message
  - **Can miss occasional short term synch problems**
  - **Most frequent problem: errors in bunch counter logic on board**
- Zeus passes BX number along with data in L1 pipe to test synch at decision time
  - Some CDF components pass B0 mark: test every 21μs
- PHENIX distributes a common start for all FEE clock counters
  - Each FEE counts independently
  - Event and bunch crossing counters crosschecked in EvB

Deadtime in Pipelined Trigger



Deadtime cannot be incurred by L1 Trigger. Always complete before data comes off end of pipeline. L1 Deadtime → Broken System

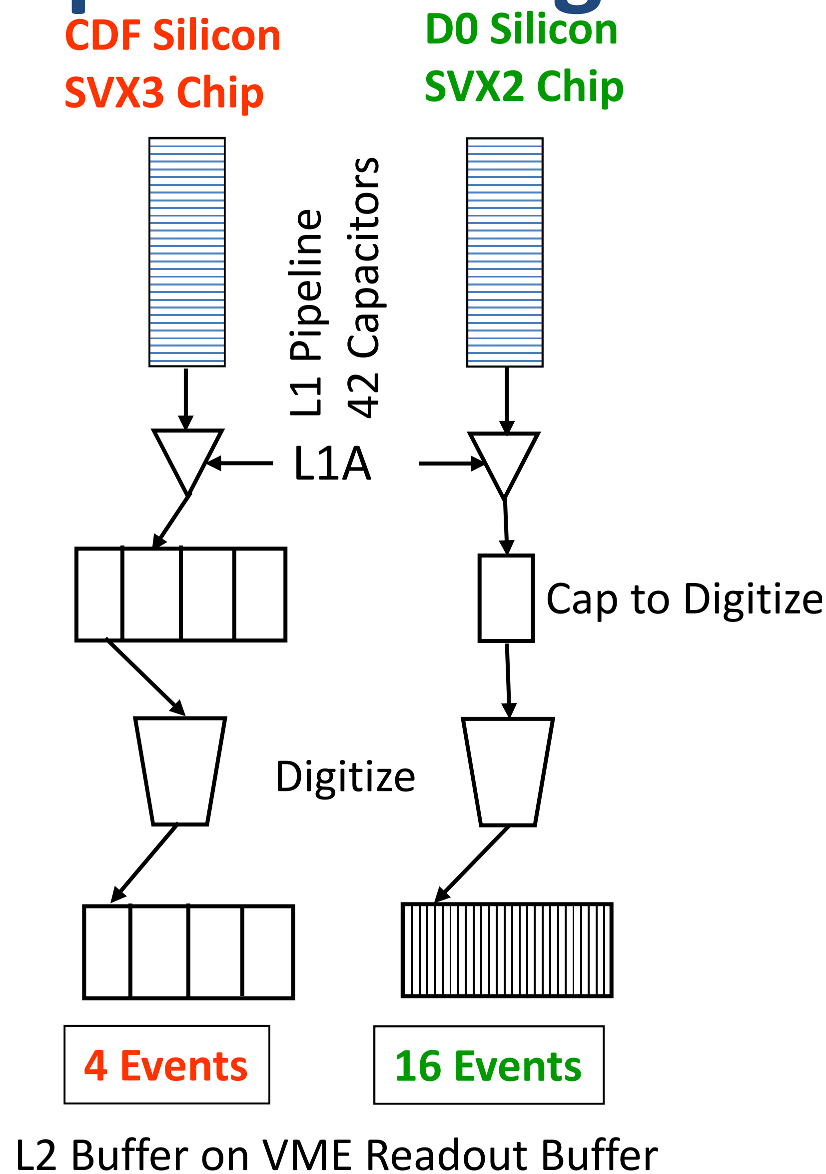
L2 incurs deadtime if all L2 buffers fill up before completing L2 decision. L1A must be held off.

Readout incurs deadtime if VRB buffers fill up → then L2 buffers will fill and L1A must be held off.
L3 incurs deadtime if the switch has no node to send output to. Again system backs up until L1A is stopped.

Dead-time is only incurred when all L2 buffers are full

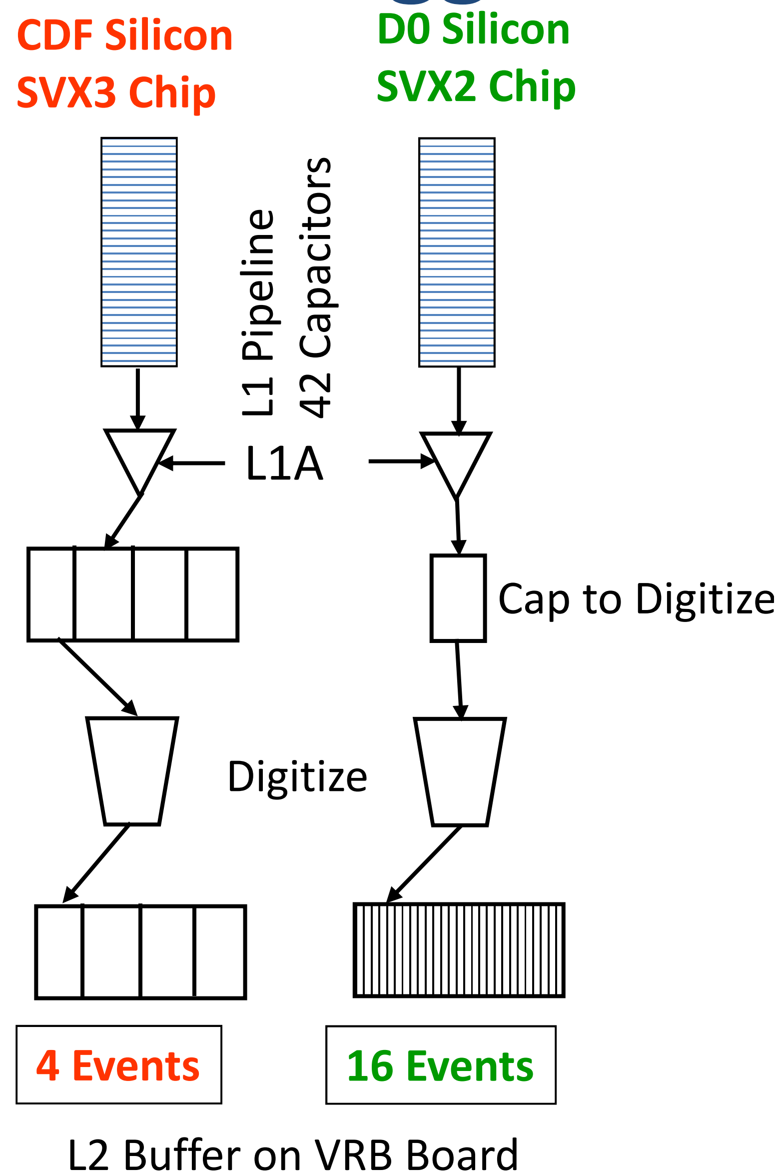
Detector FEE Affects Pipeline Design

- L1 pipelines implemented many ways: capacitor array, RAM, shift register (eg in FPGA), discrete FIFO
- L2 buffering also implemented many ways: capacitor array, RAM, discrete buffer chips
- CDF and D0 Si strip detectors use a capacitor array for the L1 pipeline and digitize on L1A
  - Capacitors are controlled as circular buffer.
  - 128 Channels on digitized sequentially
  - **CDF uses SVX3 chip: has 4 additional capacitors and skip logic that permit additional L1As during readout**
  - **D0 uses SVX2 chip: dead during digitization and readout (~10μs).**



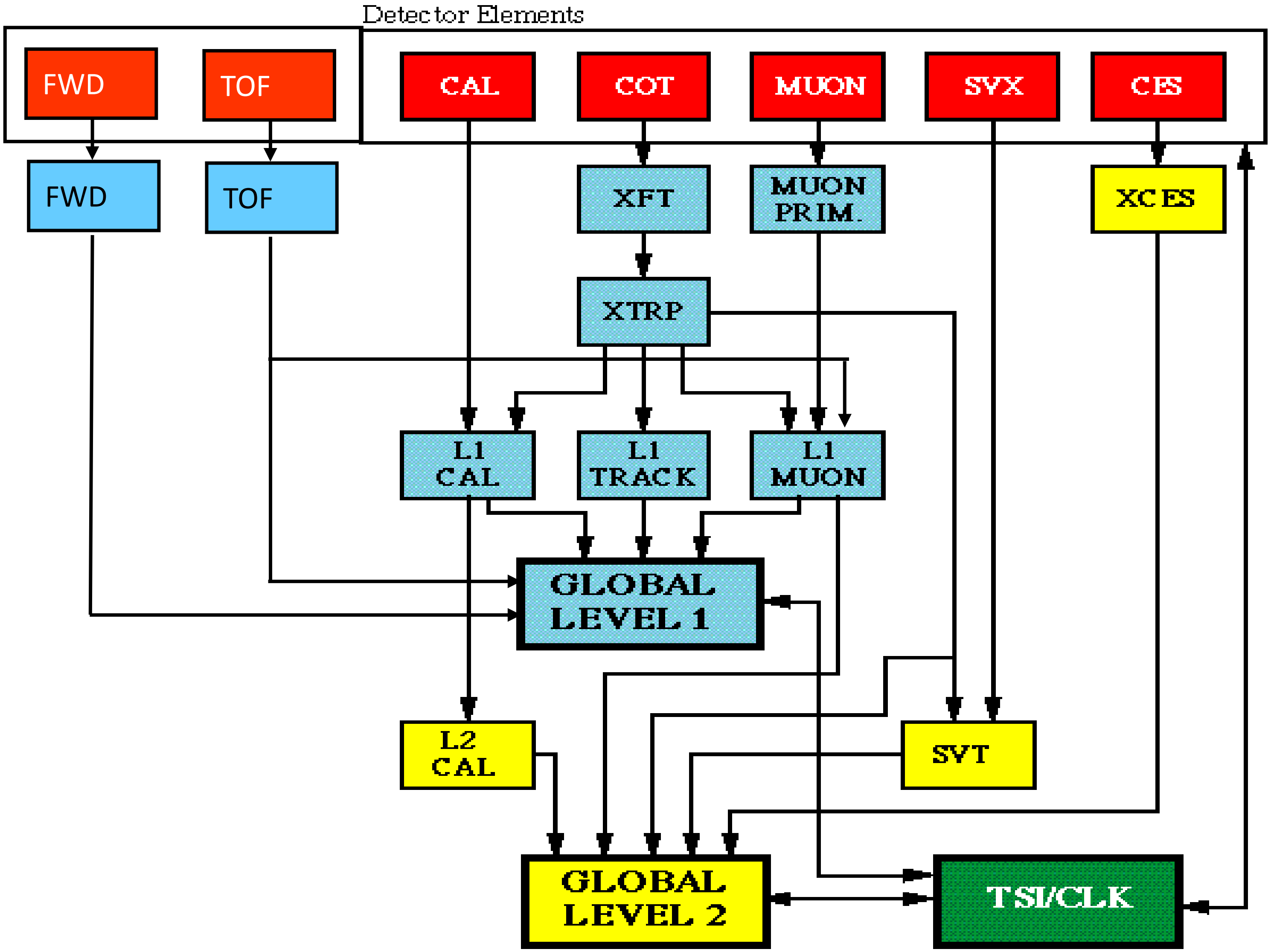
Impact of Si Readout on D0 Trigger

- Since D0 has SVX2 chip for Silicon and Fiber tracker readout, detector is dead for ~10ms after L1A
  - ➔ **Limit L1A to ~5-10kHz**
  - ➔ Queuing simulations show benefit from more VRB buffering
  - ➔ **With low L1 rate and more buffering, can take more time for L2 processing ~100μs**



Components of Modern Trigger Systems

CDF Trigger



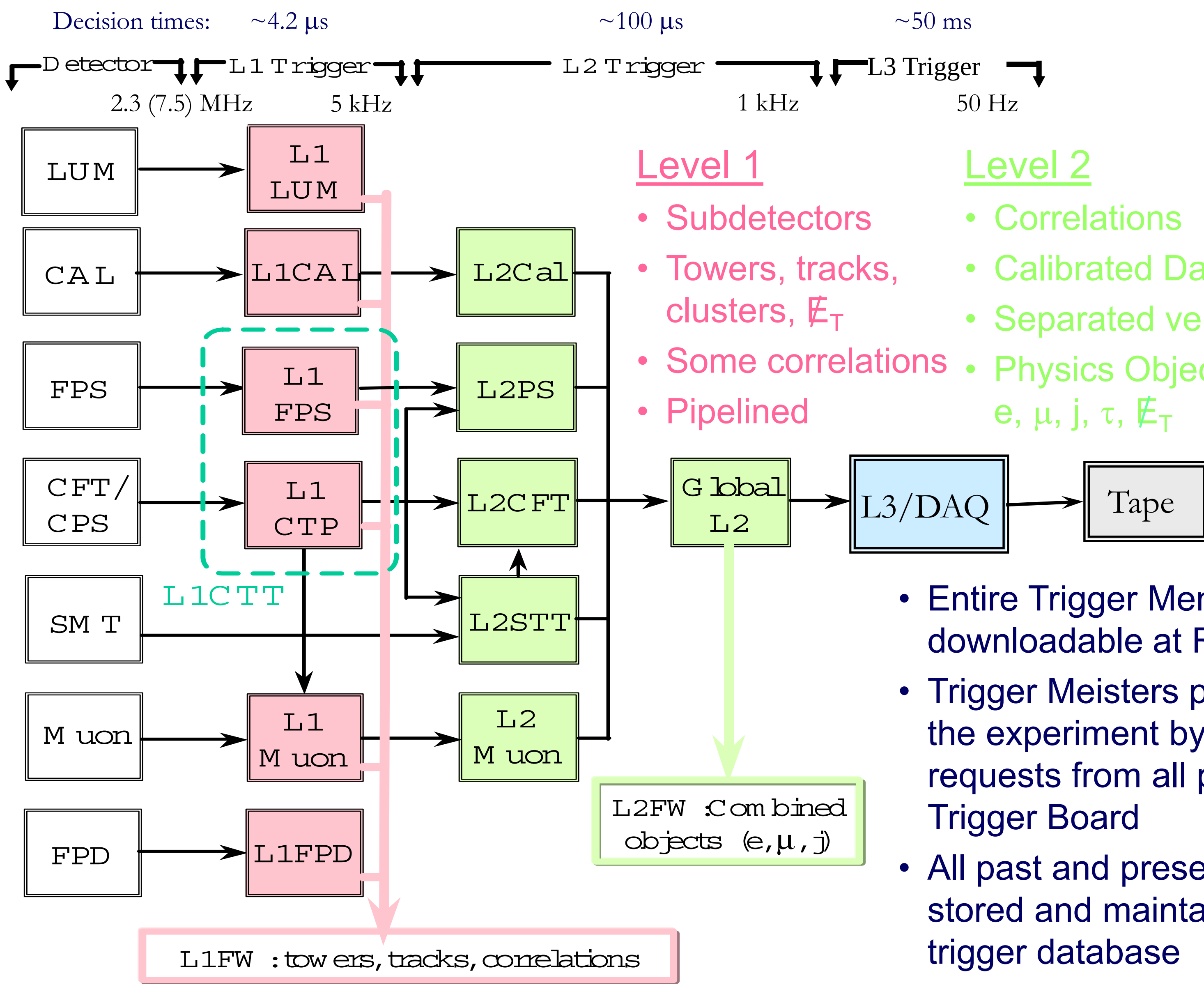
FE – 66 9U VME Crates

L1 – 15 9U VME Crates

L2 – 15 9U VME Crates

Trigger Supervisor 3 9U VME Crates

D0 Trigger System



Level 1
- Subdetectors
- Towers, tracks, clusters, $\not{E}_T$
- Some correlations
- Pipelined

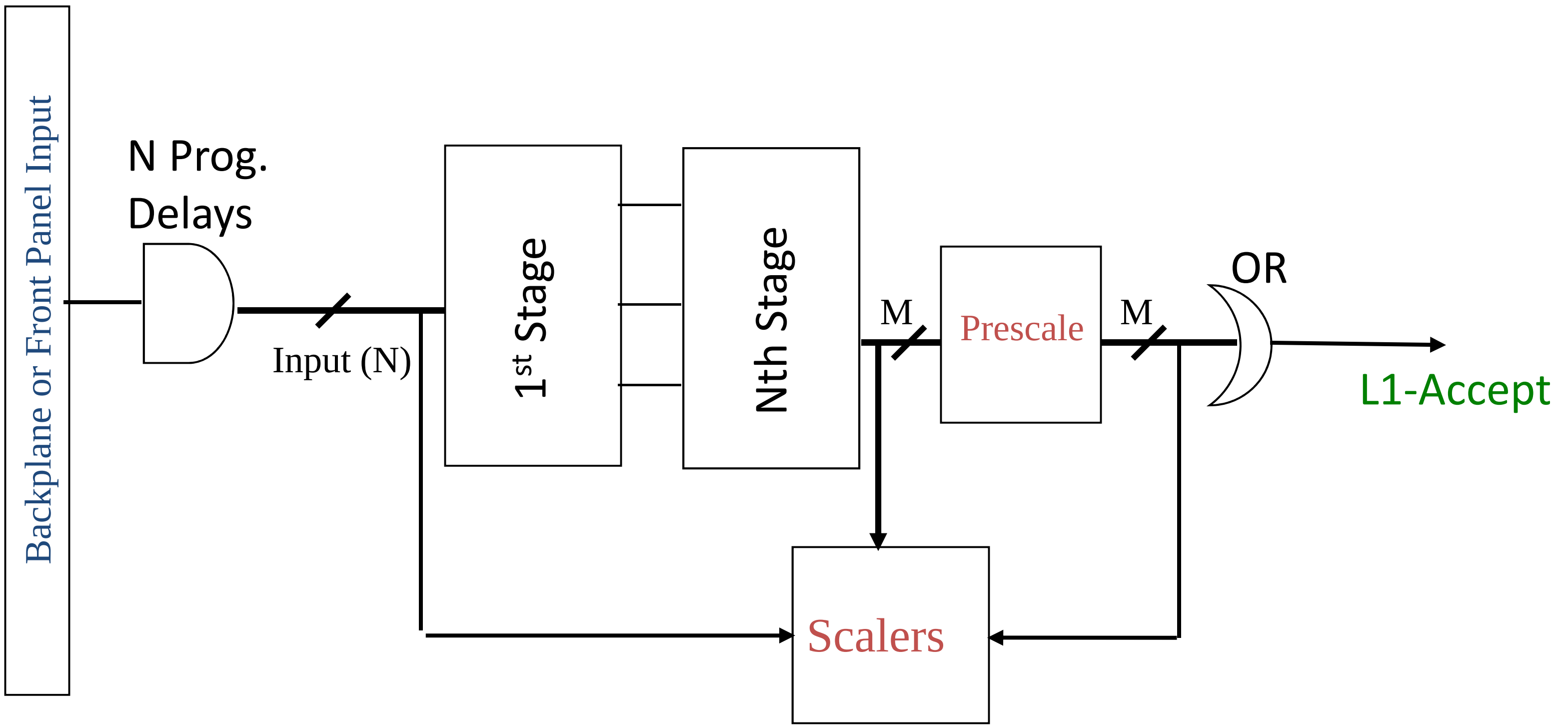
Level 2
- Correlations
- Calibrated Data
- Separated vertex
- Physics Objects e, μ, j, τ, $\not{E}_T$

Level 3
- Simple Reconstruction
- Physics Algorithms

- Entire Trigger Menu configurable and downloadable at Run start
- Trigger Meisters provide trigger lists for the experiment by collecting trigger requests from all physics groups in the Trigger Board
- All past and present trigger lists are stored and maintained in the dedicated trigger database

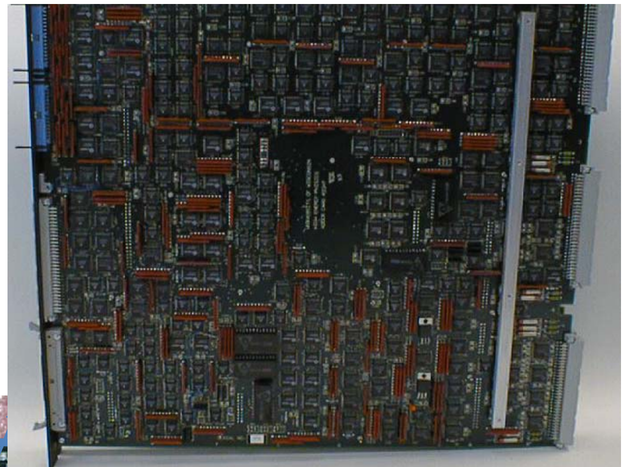
Global Decision Logic

Decision logic typically implemented in RAM - very flexible in allowed combinations
Combinations limited by software to configure the RAM
Can be arranged in several stages to allow more flexible combination
Prescale counters used for monitoring trigger and adjusting trigger rate
Scalers are used to count both inputs and outputs

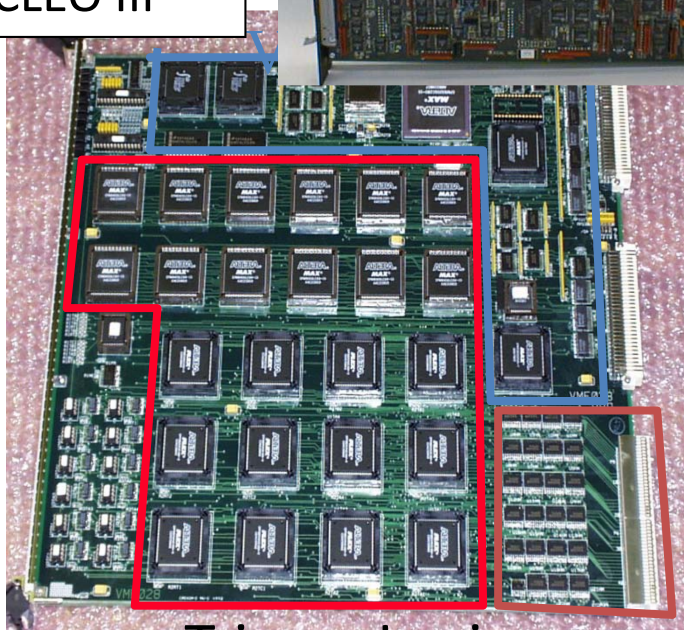


They all sort of look the same…

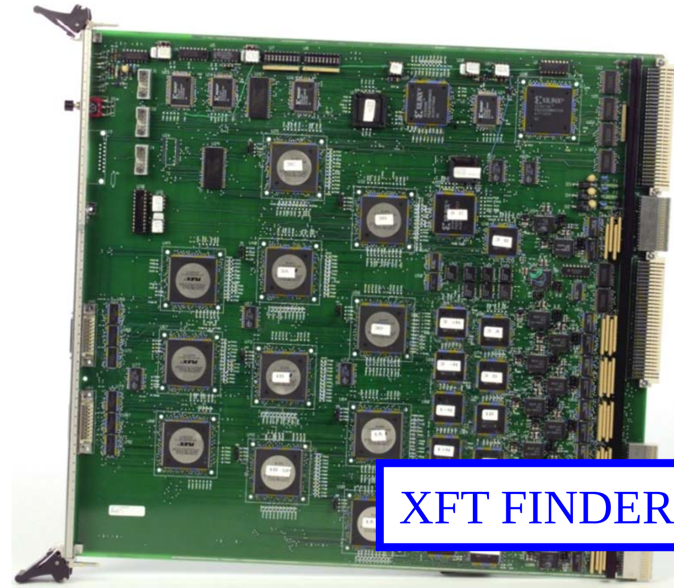
Zeus Calorimeter Trigger Adder Card



CLEO III



Trigger Logic



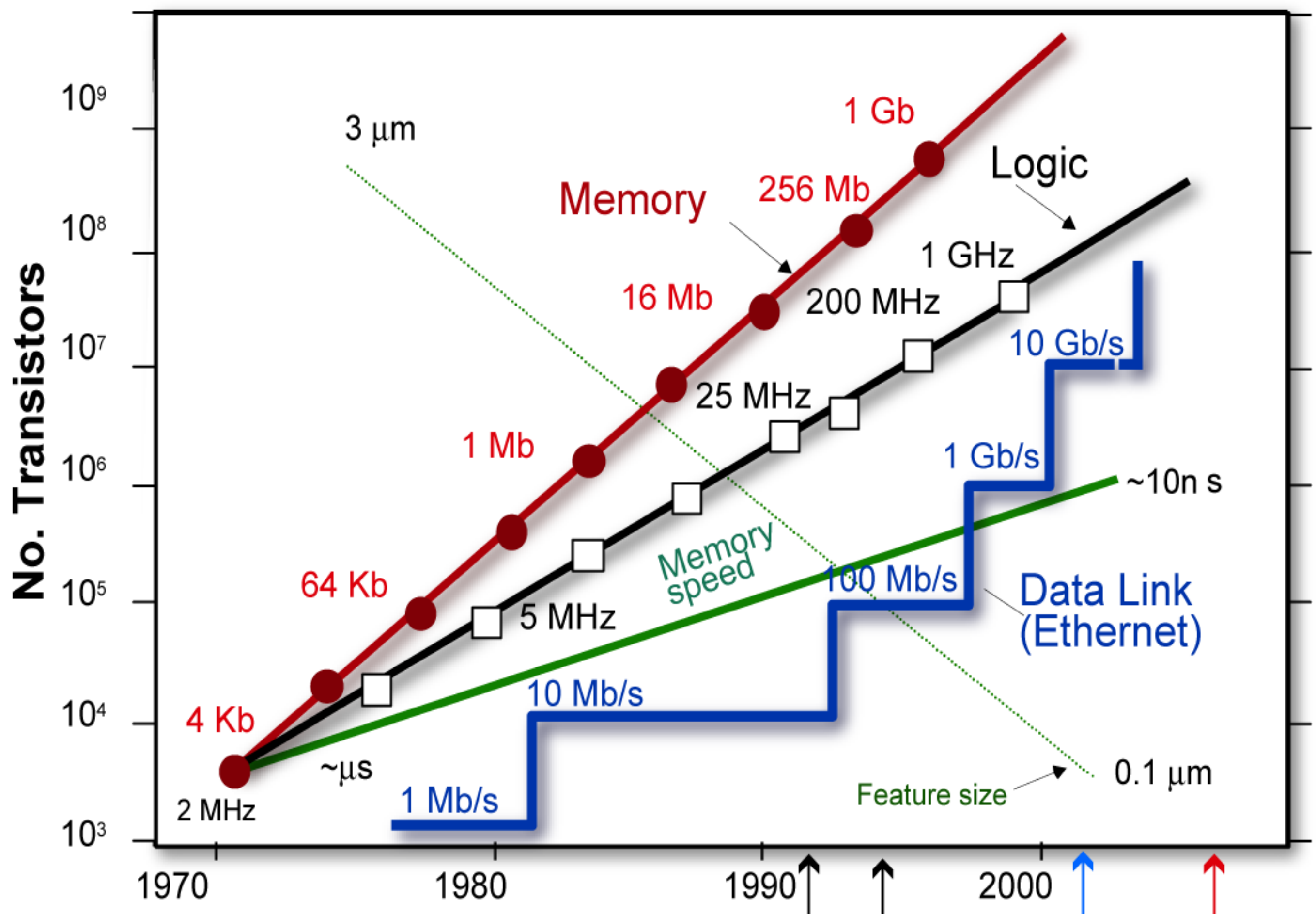
XFT FINDER - CDF

Babar

Track Segment Finder (x24)

Moore's Law

In 1965 Gordon Moore (Intel co-founder) observed that transistor densities on ICs were doubling every year.



S. Cittolin CERN/EP-CMD LECC Workshop 2002

Trigger Hardware Evolution

- Need to condense a large number of signals to a final decision in a very short time
- Premium on fast, high density processing, preferably re-programmable :
  - c 1980 – ECL (high power dissipation)
  - c 1990 – RAM, Shift registers, PALs, small CPLDs, gate arrays, multiple layers for complicated tasks
  - c 2000 – CPLDs, FPGAs, large RAM, FPGAs with embedded RAM ASICs see less use than in FE due to high initial cost
  - 2003+ Integration of high speed serial links, DSP cores with FPGAs
- Analog→Digital triggers:
  - 1988 CDF Cal trigger – analog summing, discriminators
    - Digitize after accept, hard to confirm trigger decision offline
  - 1990-92 D0, Zeus initial analog sum, digitize the final sum and thresholds
    - Readout of trigger data used for decision
  - 2000 CDF uses same digitized input for readout and Trigger in Calorimeter and Silicon (D0 too with Silicon)

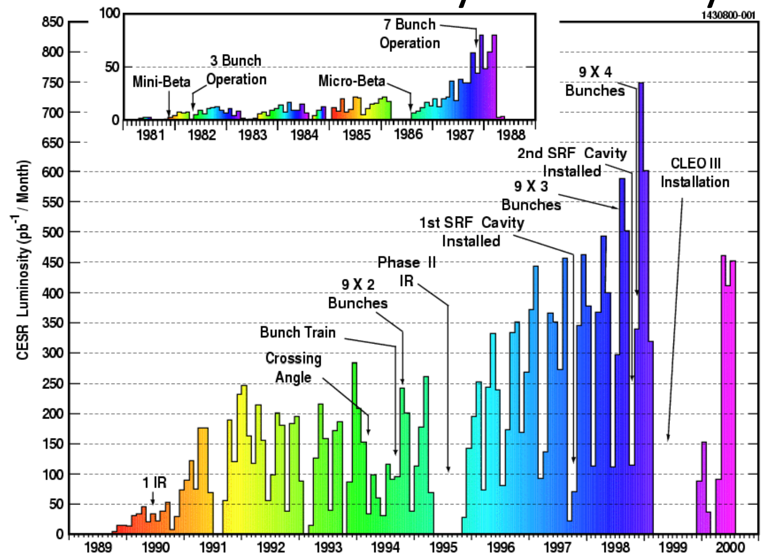
e^+e^- Luminosity Growth

- Luminosity at Upsilon(4S) has grown substantially over time:

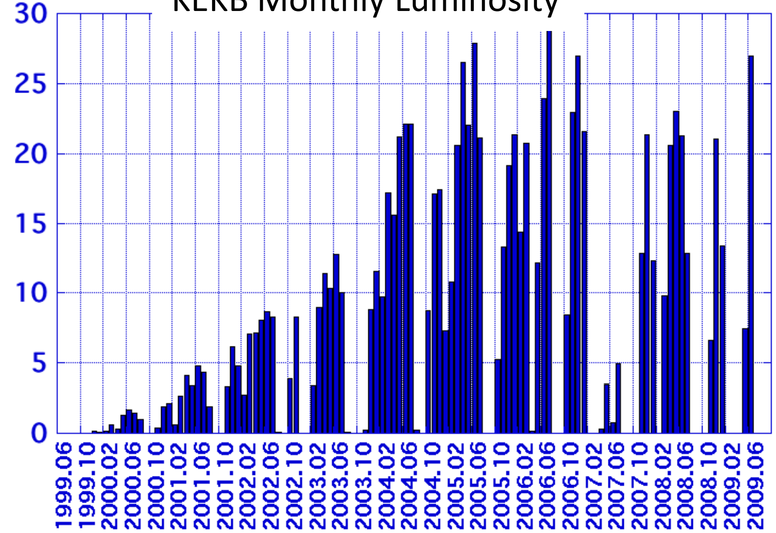
Accelerator	Year	Luminosity (fb^{-1}/month)
CESR (CLEO)	1982	0.010
CESR (CLEO)	1987	0.075
CESR (CLEO)	1992	0.250
CESR (CLEO)	1998	0.750
KEKB (Belle)	2006	30.0
PEP-II (Babar)	2006	17.0

- Factor of 25 from '82-'92
- Factor of 35 from '92-'02
- Close to a factor of 1000 in 20 years
- Luminosity doubles about every 2 years
- Slightly slower than Moore's law

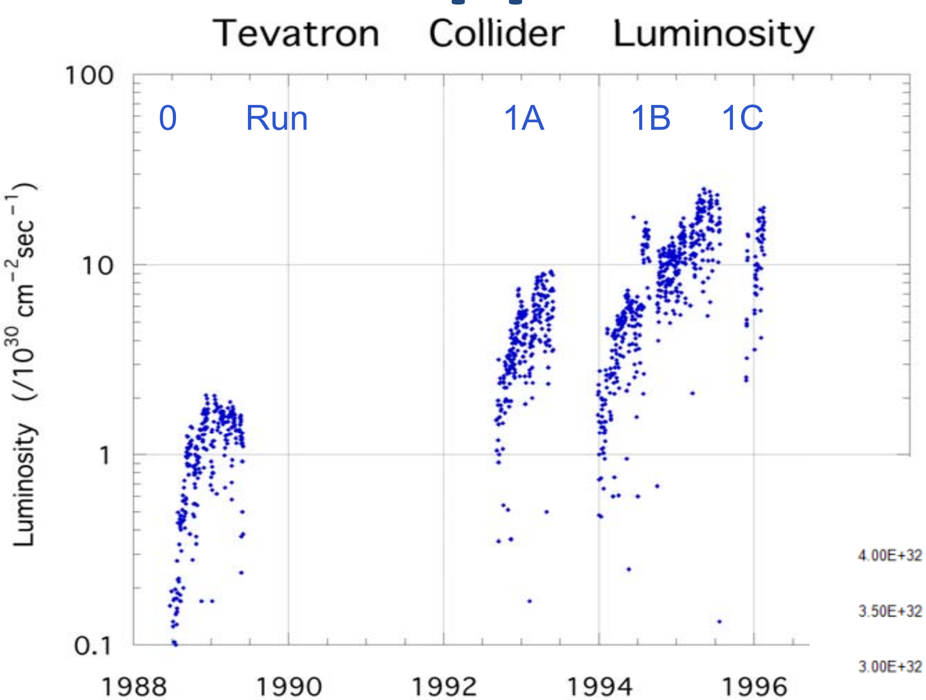
CESR Monthly Luminosity



KEKB Monthly Luminosity

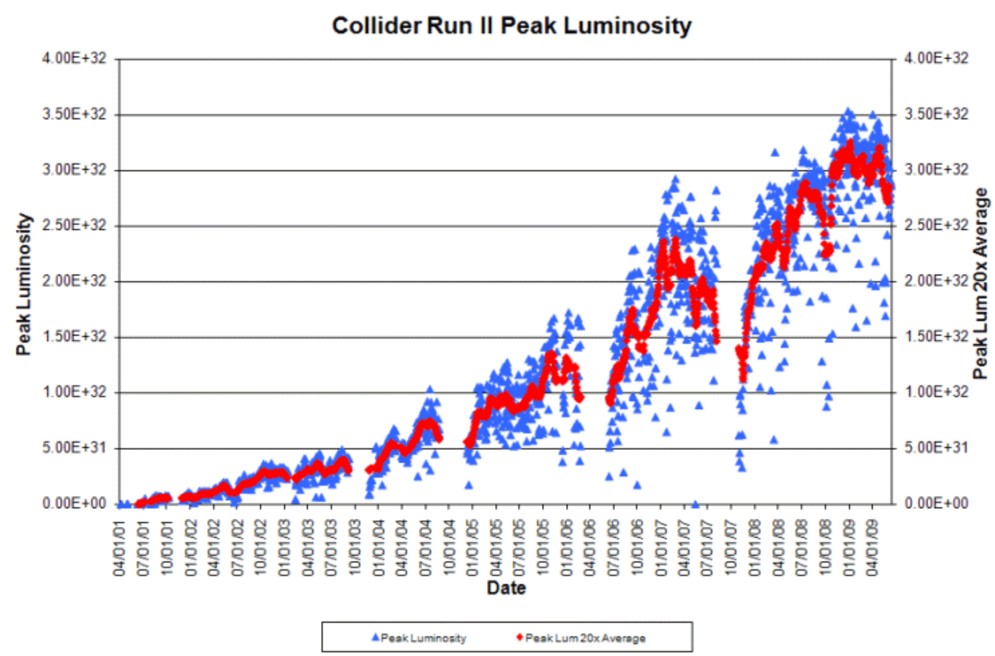


pp Luminosity Growth

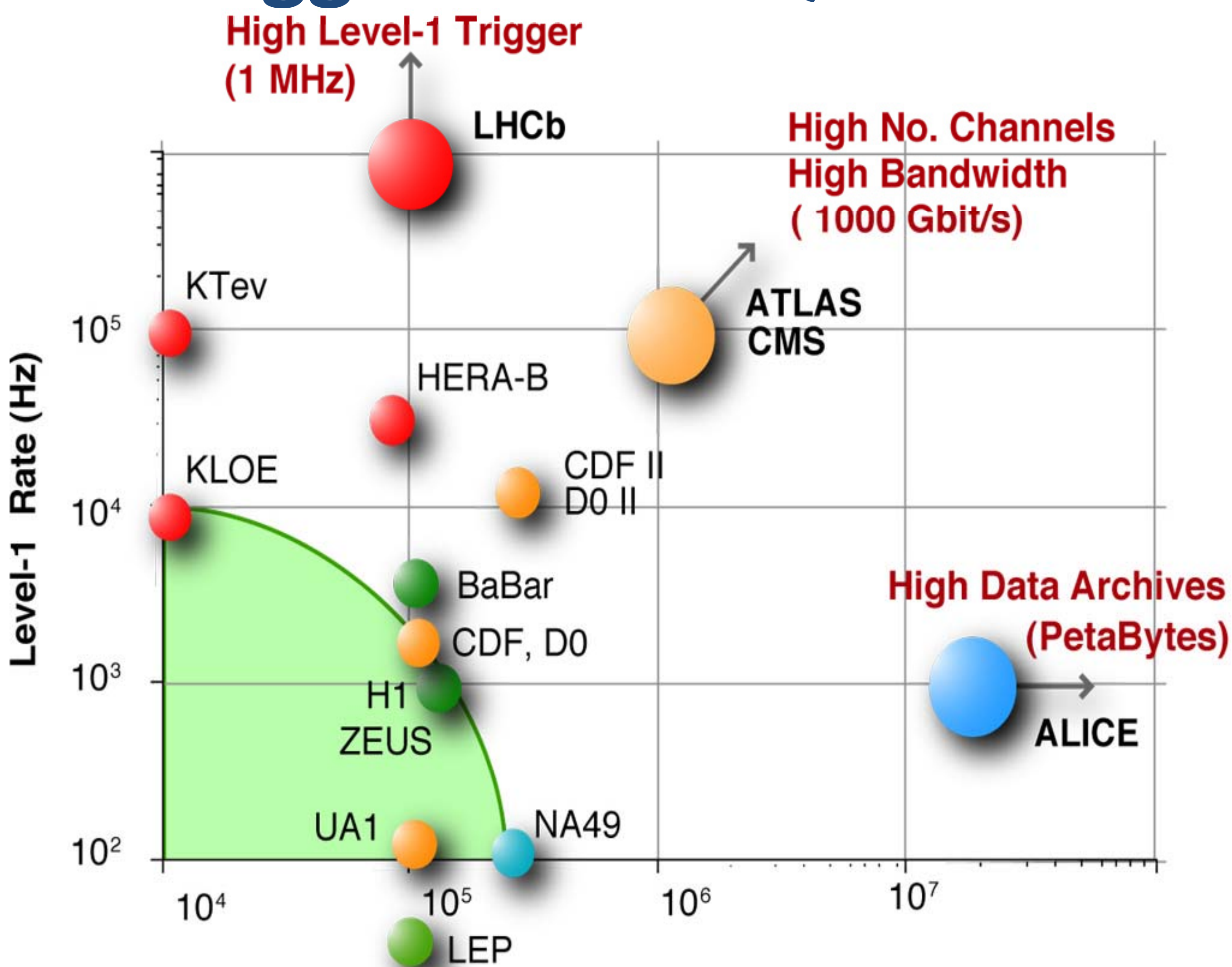


Accelerator	Year	Luminosity ($\mu b^{-1}s^{-1}$)
Tevatron (0)	1989	2.0
Tevatron (1A)	1993	9.0
Tevatron (1B)	1995	25.0
Tevatron (2A)	2002	36.0
Tevatron (2A)	2003	80.0
Tevatron (2B)	NOW	300
LHC	2009+	10,000

- Factor of ~10 in 10 years
  - Smaller than CESR
  - Trigger on lower p_T (expand B physics programs)
- Expect large increase going to LHC
  - Bigger than CESR to B-factory



Trigger and DAQ Trends



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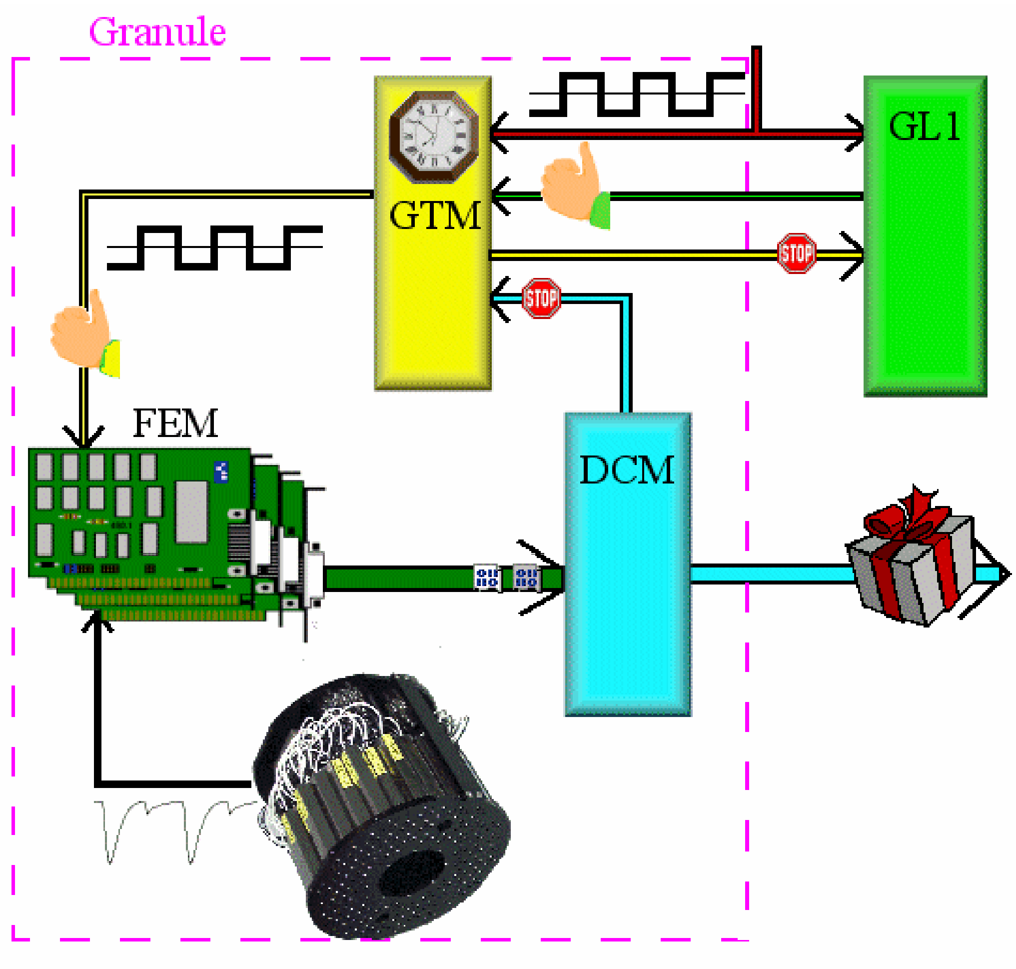
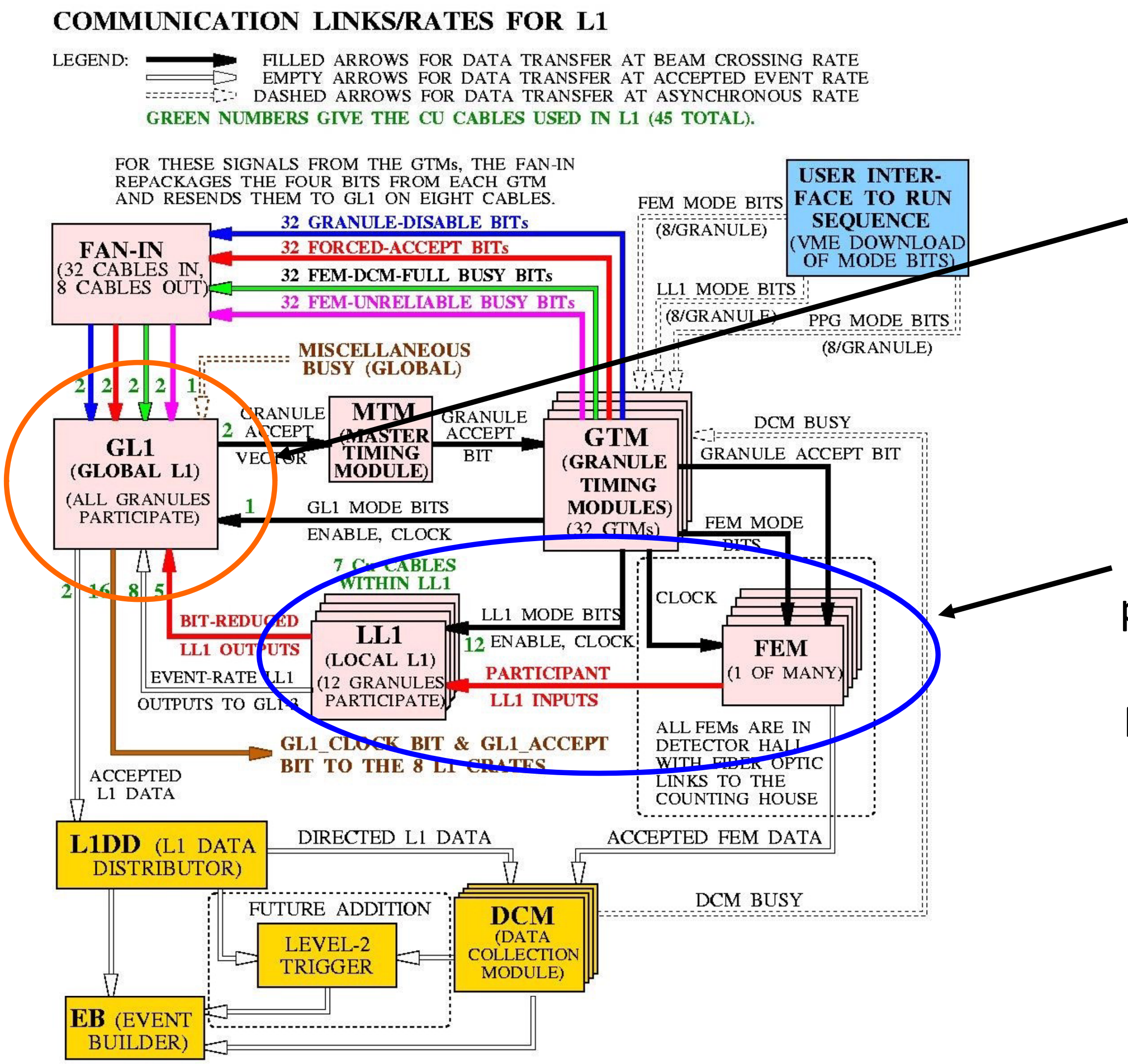
The PHENIX Trigger System

PHENIX Granules

- The PHENIX DAQ partitions the detector into granules.
  - A granules is the smallest possible readout element
  - Each granule receives timing information (clock, mode bits) from a GTM
  - The Level-1 accept is also distributed by the GTM
  - FEMs pipeline the data and send it up to DCM's on a valid L1 accept



The PHENIX Level-1 Trigger

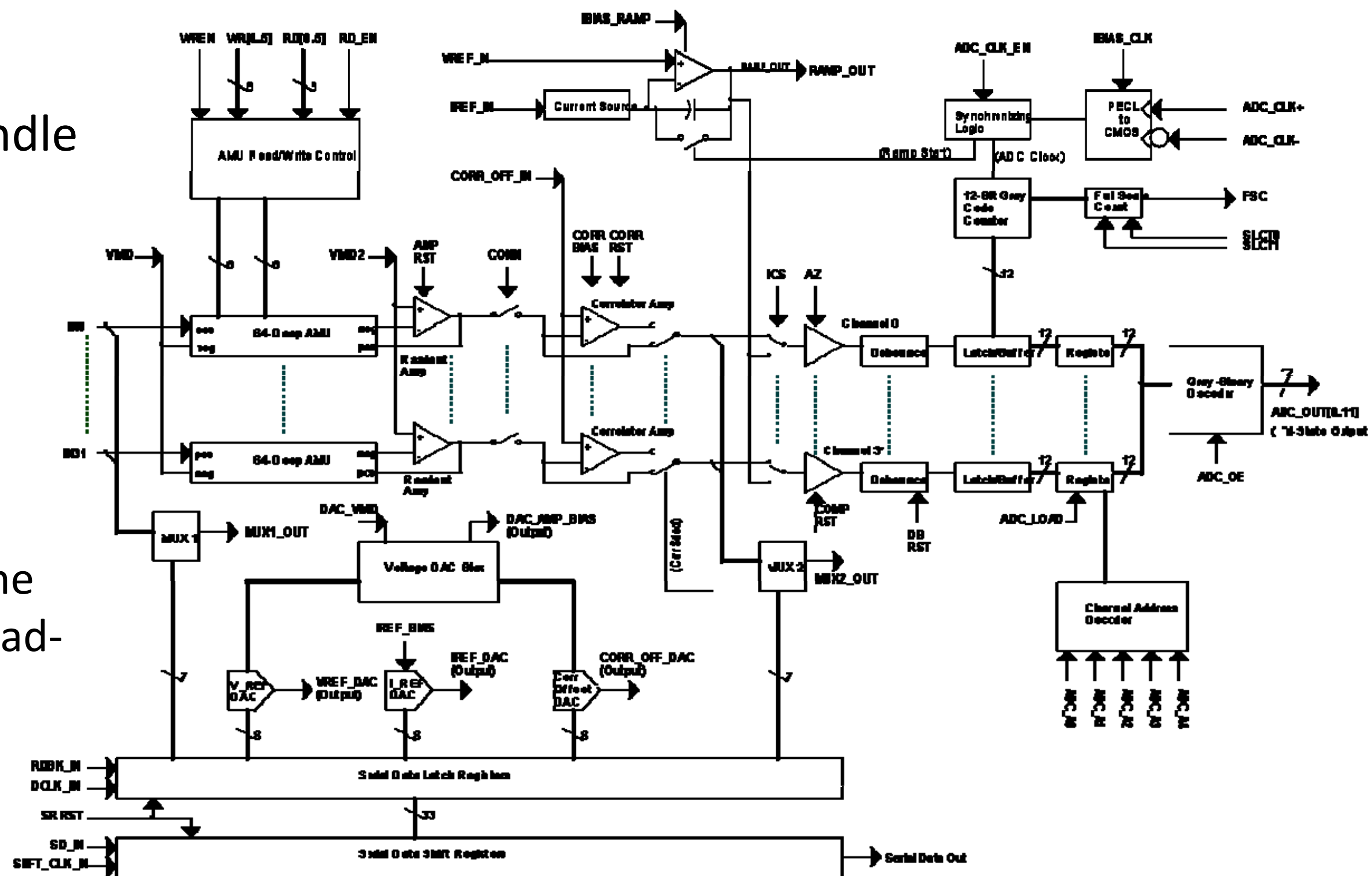


Global Level-1 manages the partitioned running of the detector.

Local Level-1 generates primitives from detector data received over optical fiber. Primitives are sent to GL1 for trigger decision.

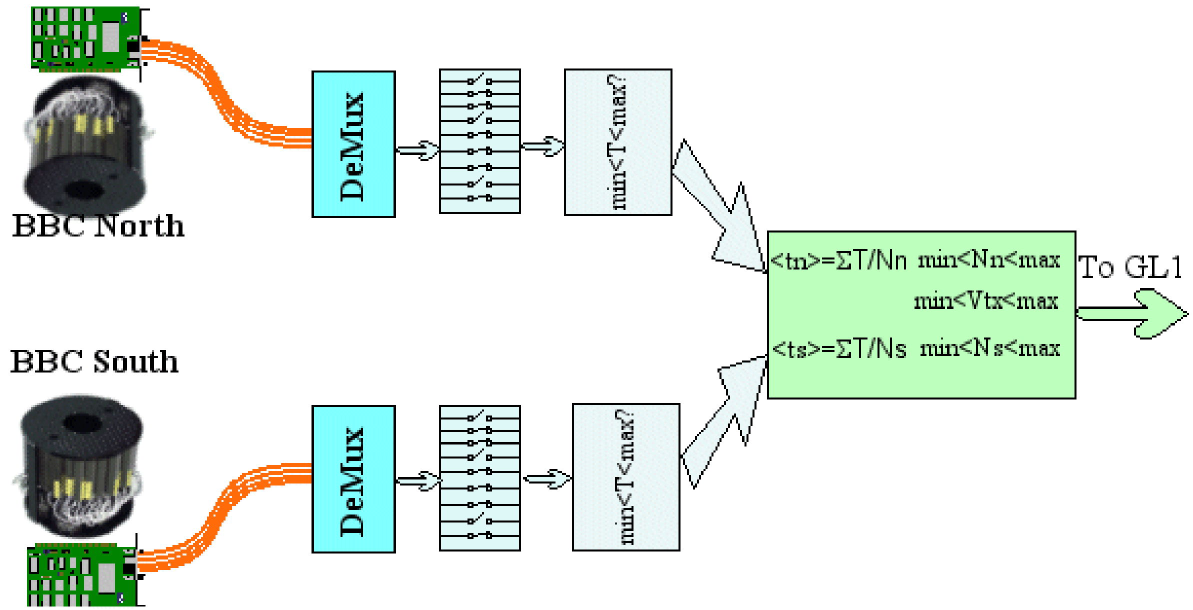
Pipelining (PHENIX AMUADC)

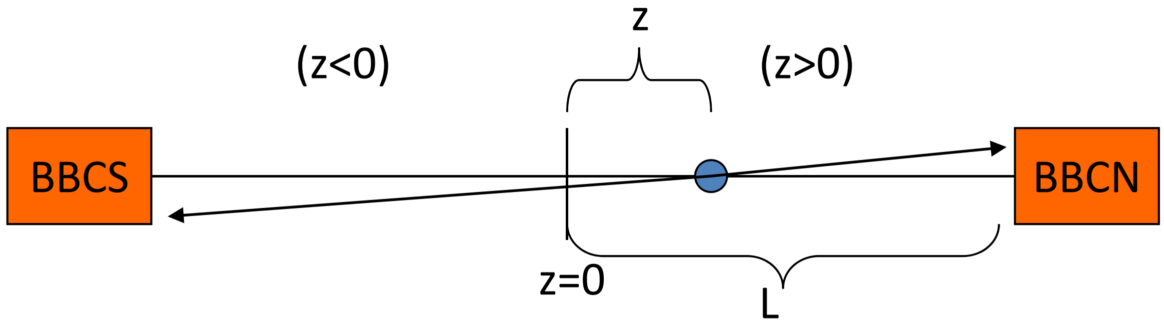
- PHENIX chose to develop a single custom ASIC to handle FEM pipelining
  - Analog memory storage
  - Heap manager
- Dead-4-4 on digitization
  - Minimal deadtime
  - Currently run Dead-4-16 due to FEM limitations
- PHENIX FEE also include 5 event buffer to mitigate readout deadtime



PHENIX BBC LL1 Trigger

1. Converts input bits into channel time values
2. Masks off bad channels
3. Checks time range for each channel
4. Determines number of hits in each arm
5. Calculates average arm time
6. For each arm checks if number of hits is in range
7. Checks if Vertex is in range
8. Result of the last two checks and FEM Unreliable signal are used as an input into 4->2 Look Up Table that creates 2 output bits for GL1.

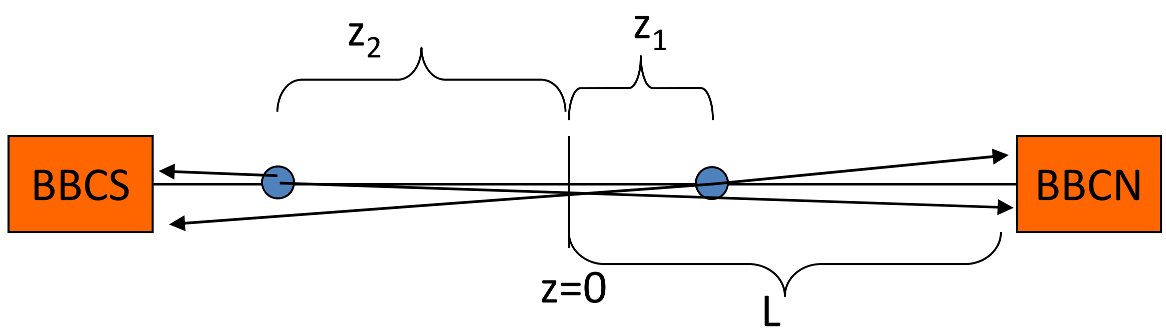




$$t_N = \frac{L - z}{c} \qquad t_S = \frac{L + z}{c} \qquad z_{VTX} = (t_S - t_N) \cdot \frac{c}{2} = (L + z - L + z) = z$$

BBC LL1 and Multiple Collisions

- What does the BBC LL1 do with multiple collisions



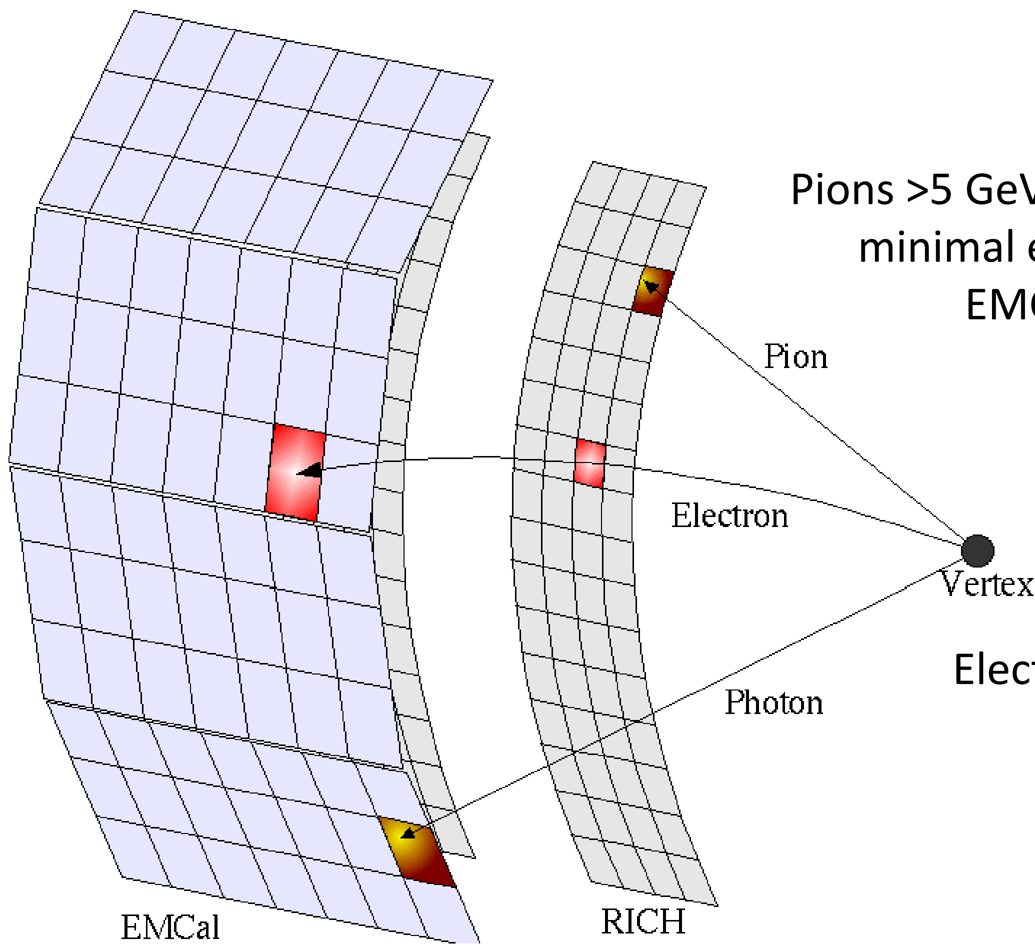
$$t_{N1} = \frac{L - z_1}{c} \qquad t_{S1} = \frac{L + z_1}{c} \qquad t_{N2} = \frac{L - z_2}{c} \qquad t_{S1} = \frac{L + z_2}{c}$$

$$t_N = \frac{1}{2}\frac{L - z_1 + L - z_2}{c} \qquad t_S = \frac{1}{2}\frac{L + z_1 + L + z_2}{c}$$

$$z_{VTX} = (t_S - t_N)\cdot\frac{c}{2} = \frac{1}{2}(z_1 + z_2)$$

– You <u>average</u> the two vertices
  - In general this is a weighted average depending on multiplicity

PHENIX ERT Trigger Algorithm

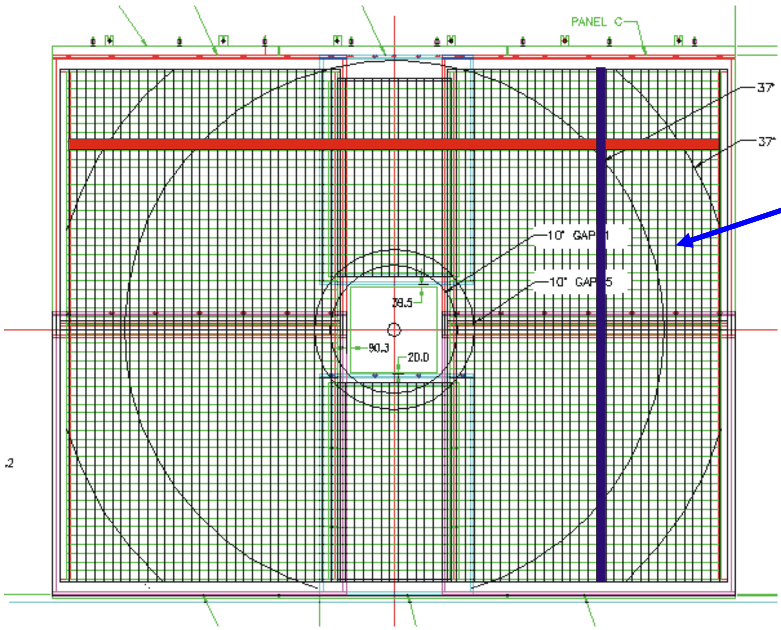


Pions >5 GeV/c fire RICH, minimal energy in EMCal.

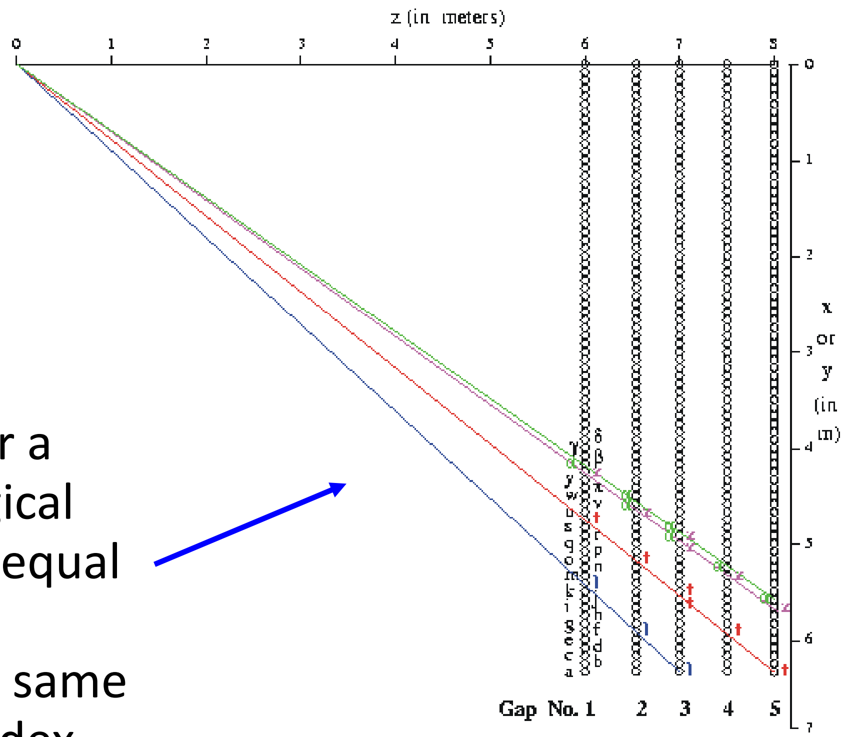
Photon trigger from EMCal cluster.

Electron trigger from EMCal/RICH matching.

MuID LL1 Trigger

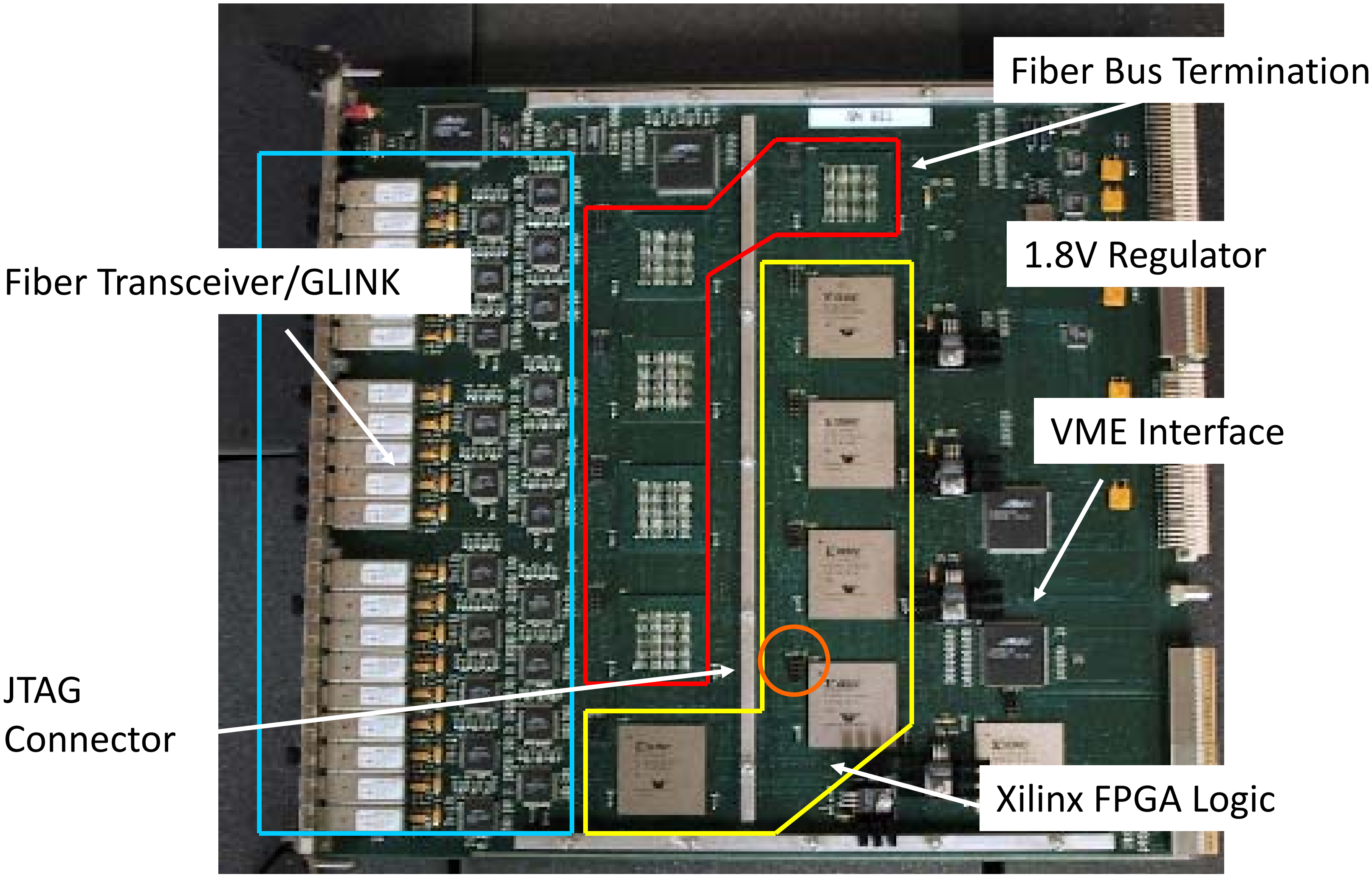


Logical tubes formed by OR of physical tubes across panels in each gap.

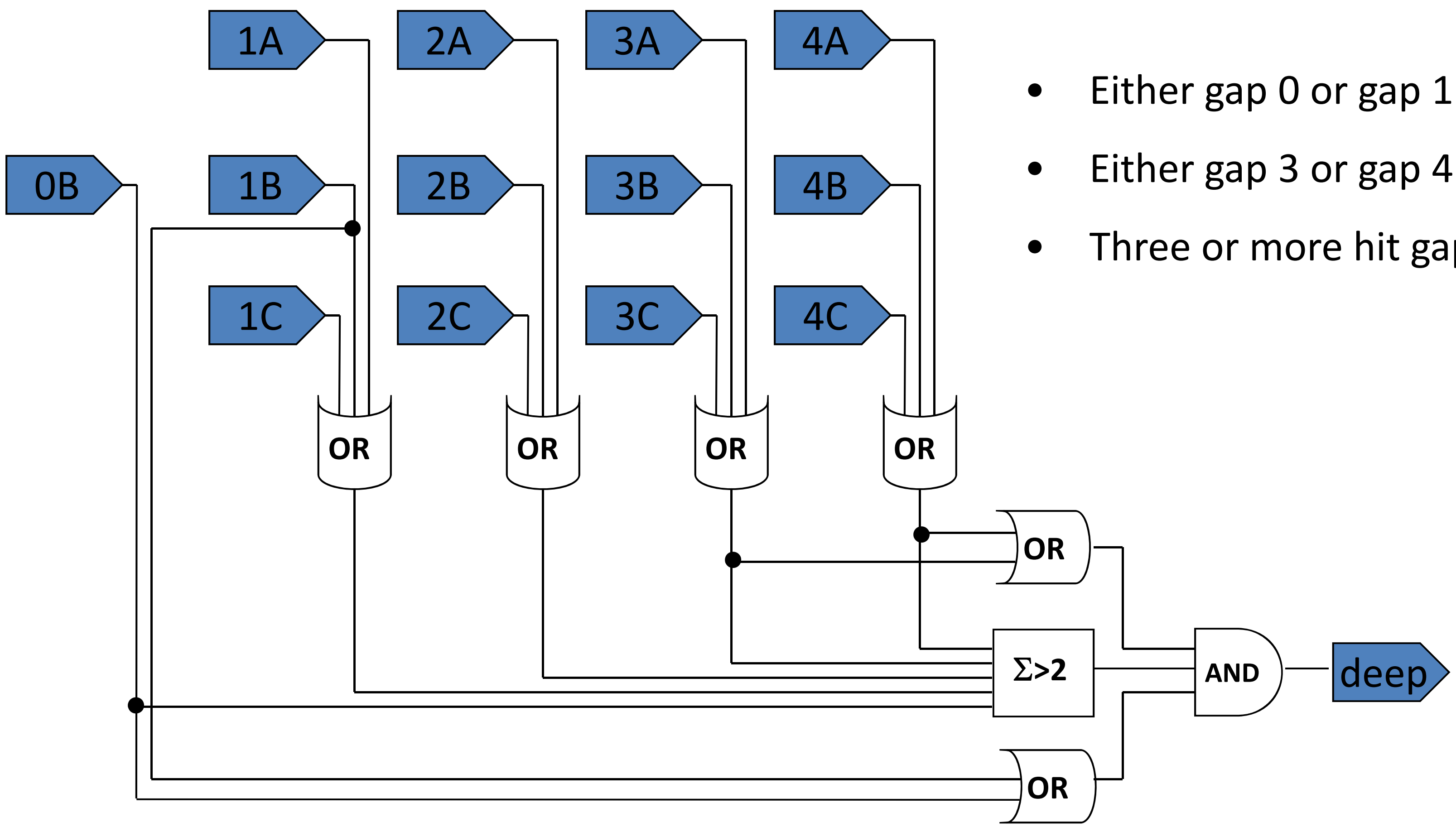


The most probable trajectory for a vertex muon striking a gap-1 logical tube is to continue on a path of equal *dx/dz* (vertical tubes) or *dy/dz* (horizontal tubes). Tubes w/ the same *dx/dz* (or *dy/dz*) get the same index.

"Generic" LL1 Board Design

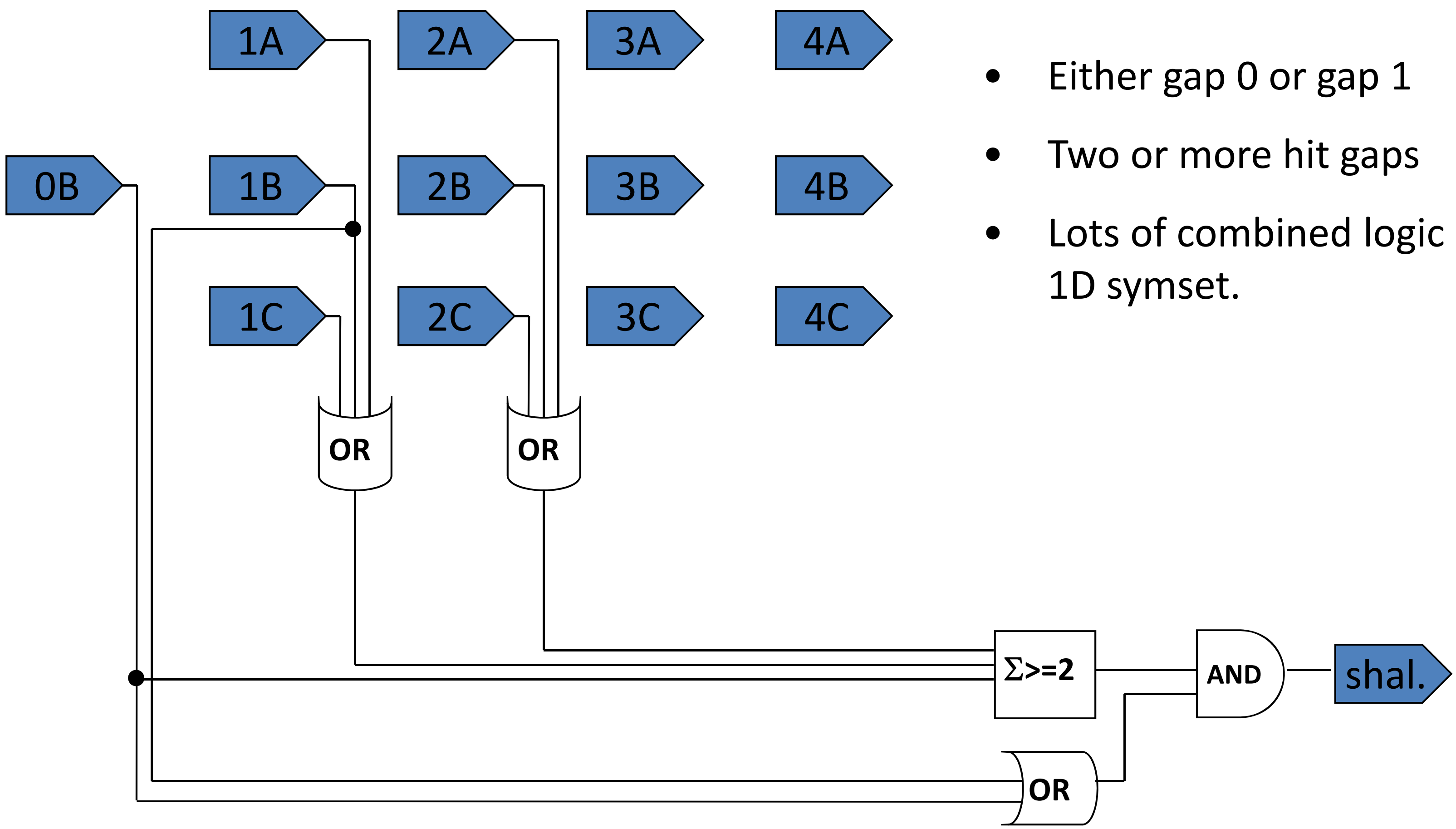


MuID LL1 Trigger Symsets (Deep)



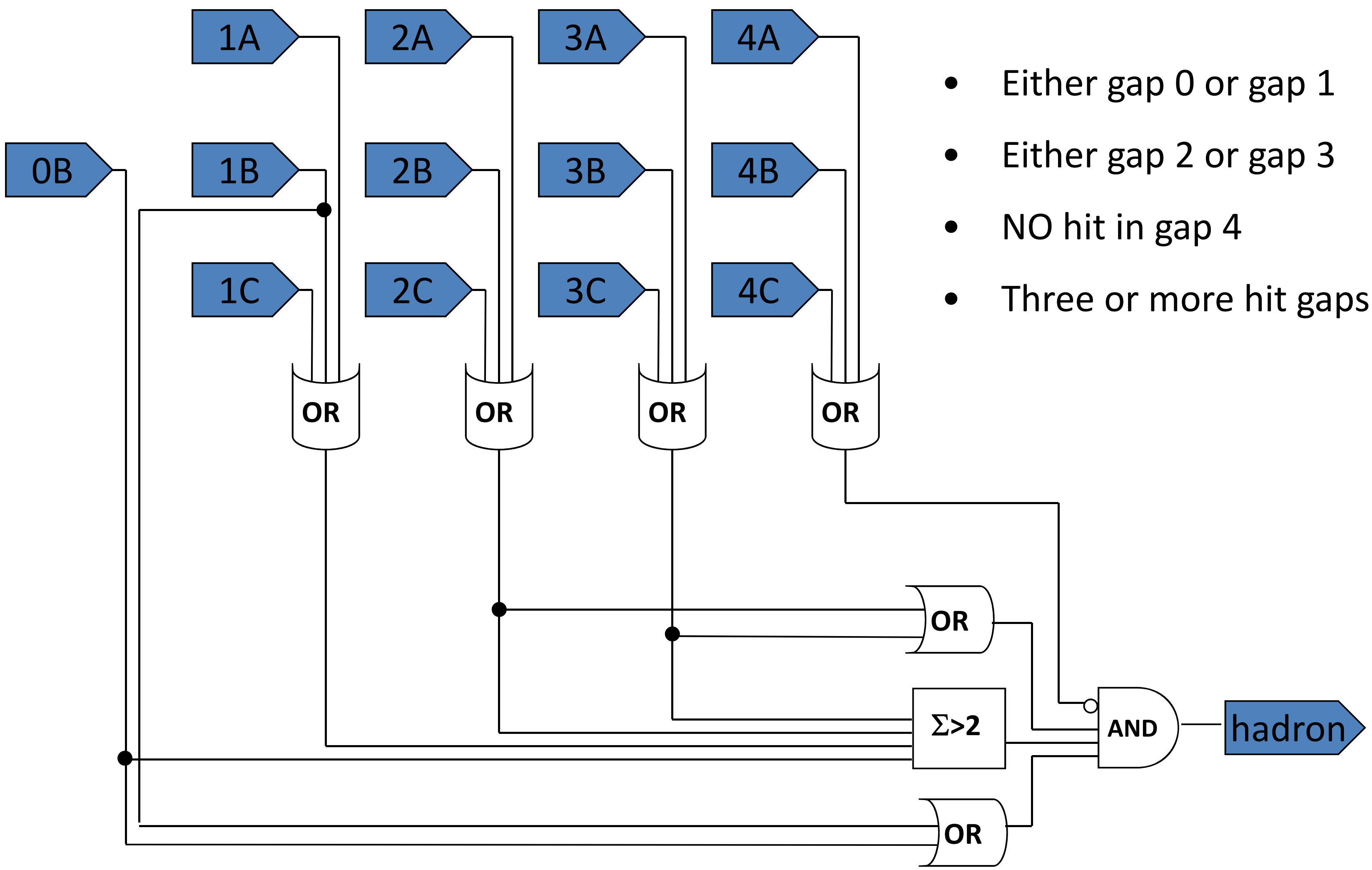
- Either gap 0 or gap 1
- Either gap 3 or gap 4
- Three or more hit gaps

MuID LL1 Trigger (Shallow, Run-4)



- Either gap 0 or gap 1
- Two or more hit gaps
- Lots of combined logic with 1D symset.

MuID LL1 Trigger (Hadron, Run-8)



- Either gap 0 or gap 1
- Either gap 2 or gap 3
- NO hit in gap 4
- Three or more hit gaps

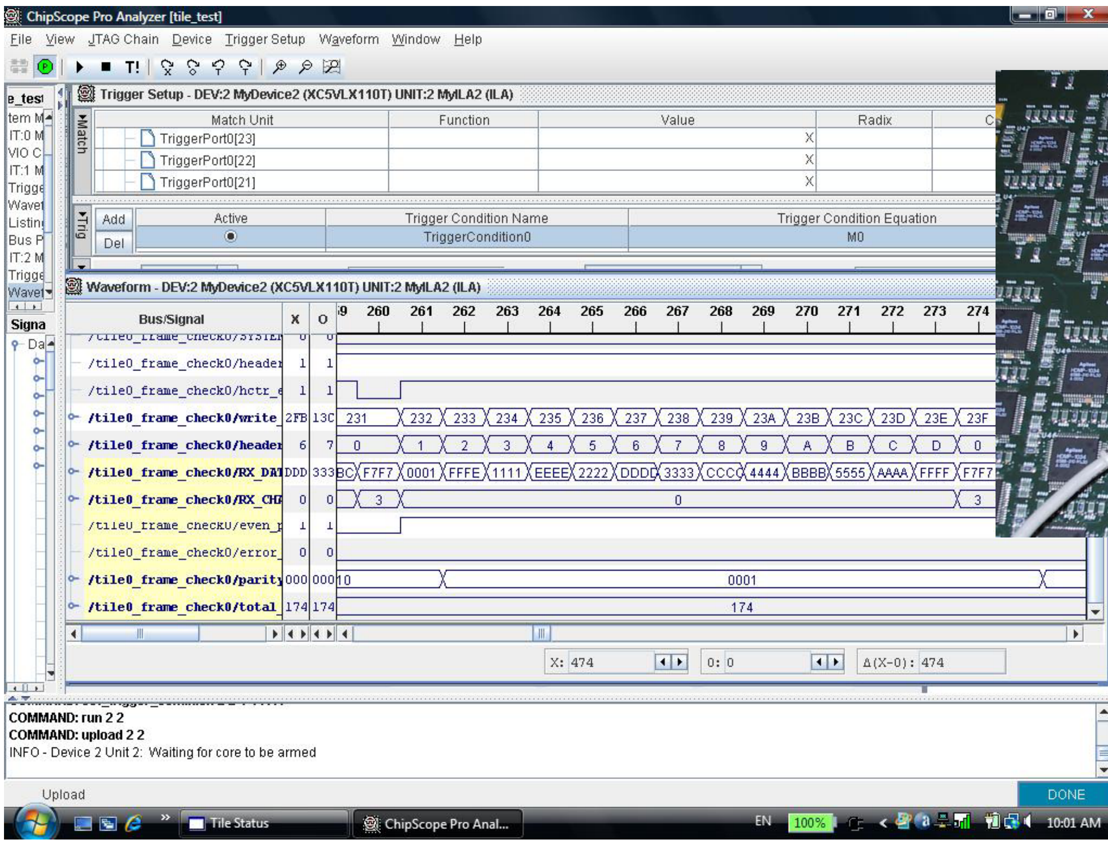
Trigger Programming

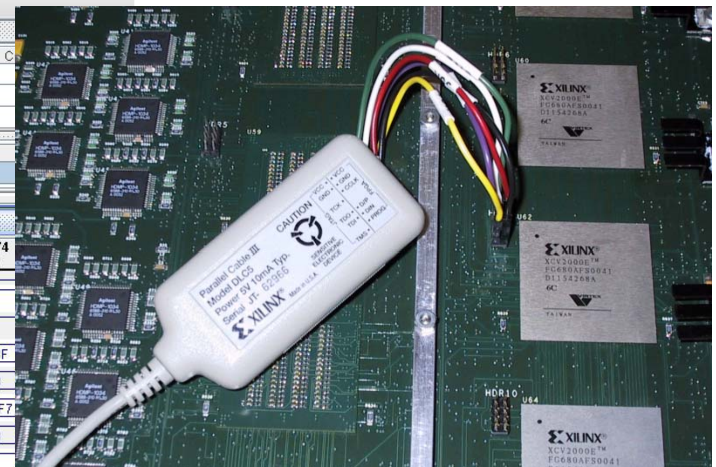
- The use of modern FPGA’s allows trigger algorithms to be programmed in higher level languages (VHDL, Verilog)
  - Easier to maintain
  - Easier to debug
  - Easier to simulate
  - Get more people involved!

```
entity muid_symset is
port(gap0: in std_logic; gap1: in std_ulogic_vector(16 downto 10); gap2:  in std_logic_vector (19 downto 7); gap3: in
std_logic_vector(22 downto 4); gap4: in std_logic_vector (25 downto 1);output: out std_logic; shallow: out std_logic);
end muid_symset;

architecture behavioral of muid_symset is

signal s1,s2,s3,s4,s_prime1,s_prime2,s_prime3,s_prime_shallow: std_logic;

--begin architecture declaration
begin

--Process input OR gates for each gap
s1 <= gap1(12) or gap1(13) or gap1(14);
s2 <= gap2(12) or gap2(13) or gap2(14);
s3 <= gap3(12) or gap3(13) or gap3(14);
s4 <= gap4(12) or gap4(13) or gap4(14);

--JGL 2/7/2005 back to sum of gates 0-4 > 2
s_prime1 <= (s1 and s2 and s3) or (s1 and s2 and s4) or (s2 and s3 and s4)
                or (s1 and s3 and s4) or (gap0 and s1 and s2) or (gap0 and s1 and s3)
                or (gap0 and s1 and s4) or (gap0 and s2 and s3) or (gap0 and s2 and s4)
                or (gap0 and s3 and s4);
--Either gap 3 or gap 4
s_prime2 <= (s3 or s4);

--Either gap 0 or gap 1central index
s_prime3 <= (gap0 or gap1(13));

--Process output
output <= (s_prime1 and s_prime2 and s_prime3);

--Shallow symset output
--
-- Modified to "hadron trigger" - 12/6/07 JGL
-- one hit in gaps 0, 1; one hit in gaps 2,3; no hits in gap 4
-- two of three hits in gap 0,1,2
--
s_prime_shallow <= (gap0 or gap1(13)) and (s2 or s3) and (not s4);
shallow <= ((gap0 and s2 and s3) or (s1 and s2 and s3) or (gap0 and s1 and s2) or (gap0 and s1 and s3)) and s_prime_shallow;

end behavioral;
```

FPGA Debugging

- Modern software tools allow for the integration of a configurable "software logic analyzer" into a design
  - Allows for complete debugging of complex designs!



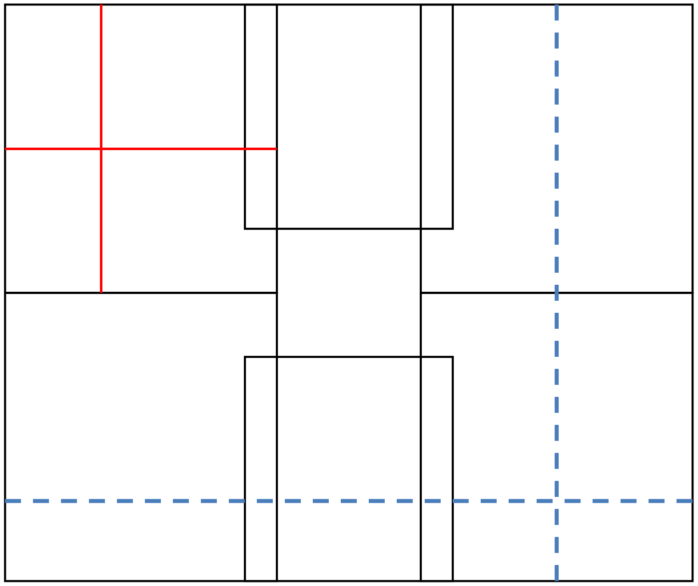


MuID LL1 Improvements (Run-10?)

- Investigate improving MuID LL1 rejection
  - Panel-based algorithm
    - No logical tubes
    - Reduced sensitivity to combinatoric background
    - Investigating if this can be implemented in existing hardware
      - Horizontal chips undergoing conversion, testing in Run-10…

Run-6 AuAu Data:

South 1 Deep rejection = 5.32874(33047)
South 1 Deep rejection (NEW) = 9.57841(18385)
South 1 Deep 1 Shallow rejection = 5.62329(31316)
South 1 Deep 1 Shallow rejection (NEW) = 11.3825(15471)
South 2 Deep rejection = 16.3752(10754)
South 2 Deep rejection (NEW) = 58.602(3005)
North 1 Deep rejection = 5.75393(30605)
North 1 Deep rejection (NEW) = 9.01685(19530)
North 1 Deep 1 Shallow rejection = 6.34111(27771)
North 1 Deep 1 Shallow rejection (NEW) = 11.2812(15610)
North 2 Deep rejection = 20.9692(8398)
North 2 Deep rejection (NEW) = 63.9895(2752)



Muon Trigger for W Physics @500GeV

Design Luminosity

$\sqrt{s}$ = 500 GeV σ=50mb

L = 2×10^{32}/cm^2/s

↓

Total X-sec rate = ~10MHz

DAQ LIMIT

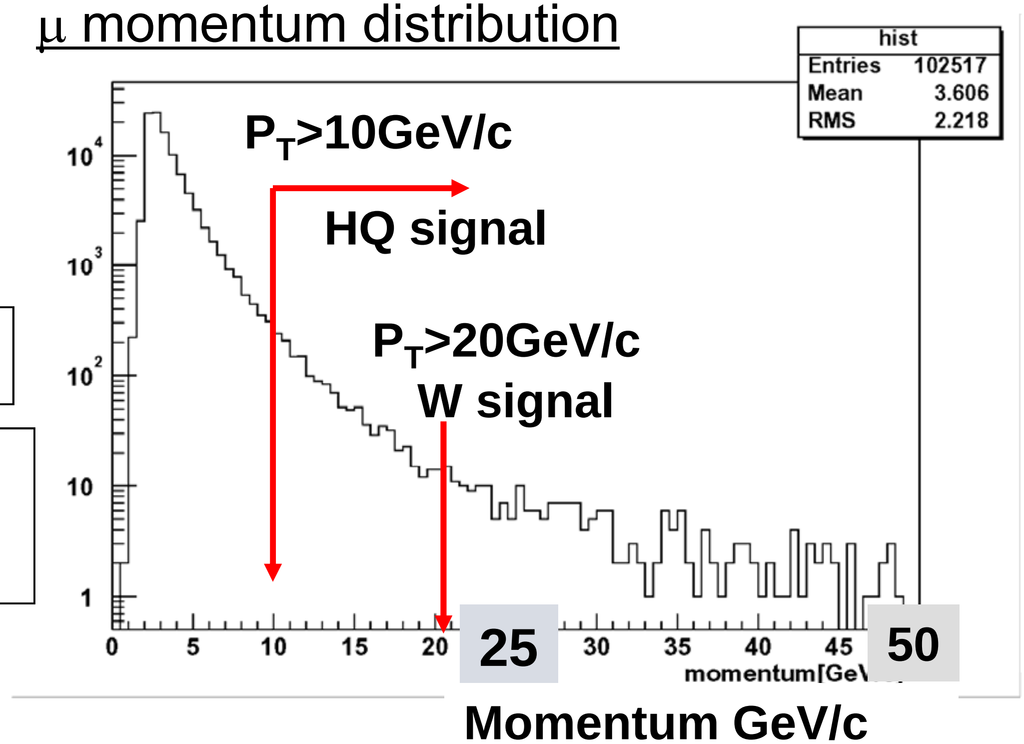
=1-2kHz (forμarm)

↓

Required RF

~ 10,000

μ momentum distribution



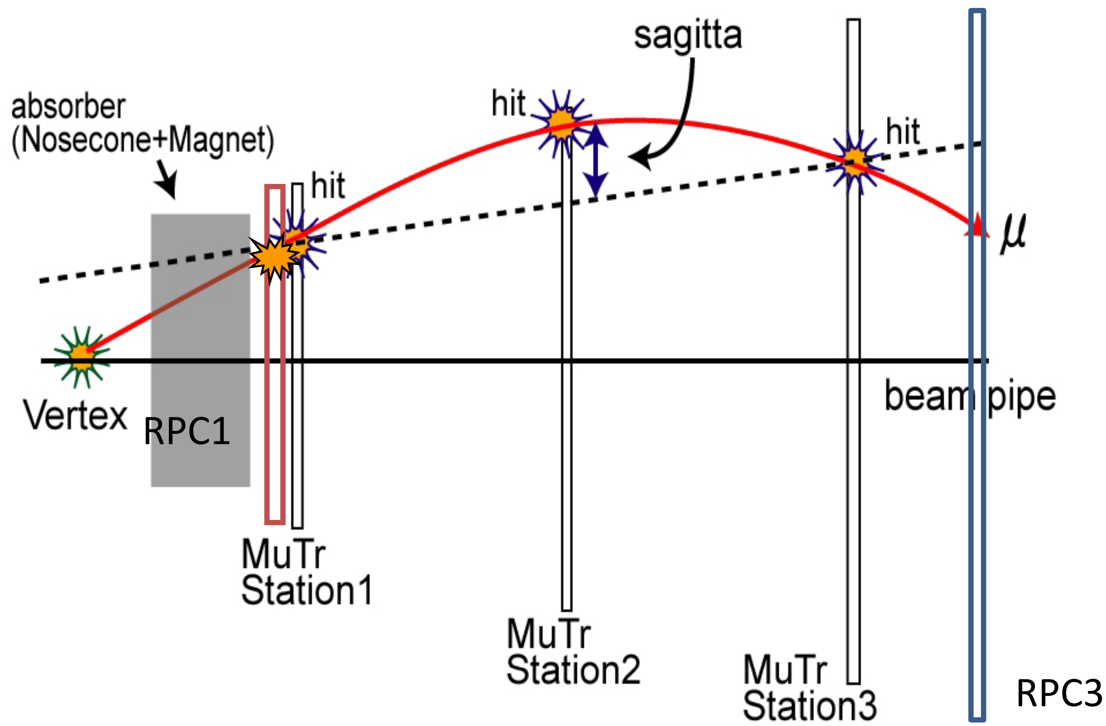
Need Momentum Selectivity in the LVL-1 Trigger!

PHENIX Muon Trigger Upgrade

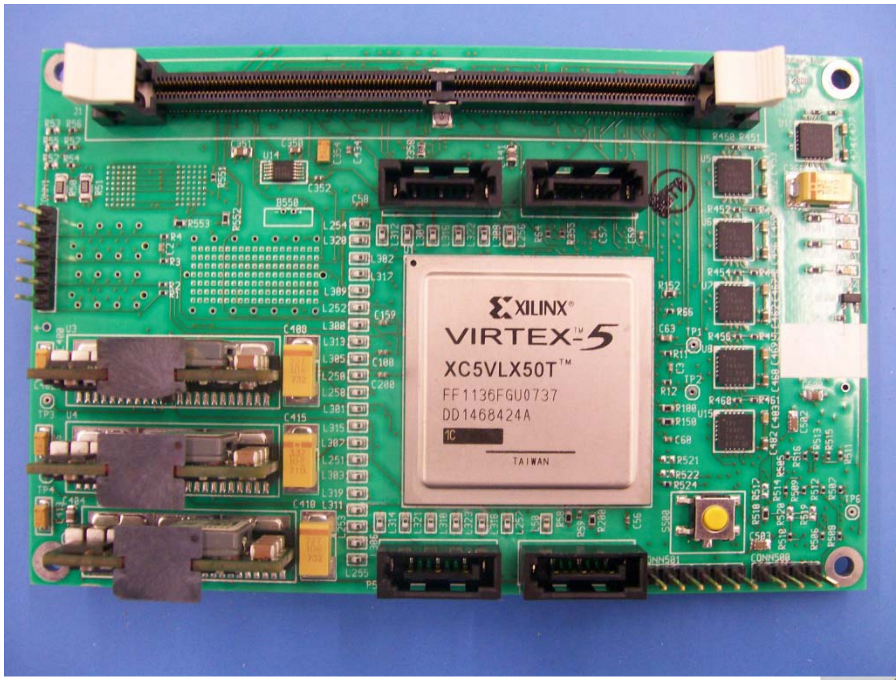
- Momentum selectivity through online sagitta measurement
  - Uses MuTR 1,2,3 and RPC1,3 planes

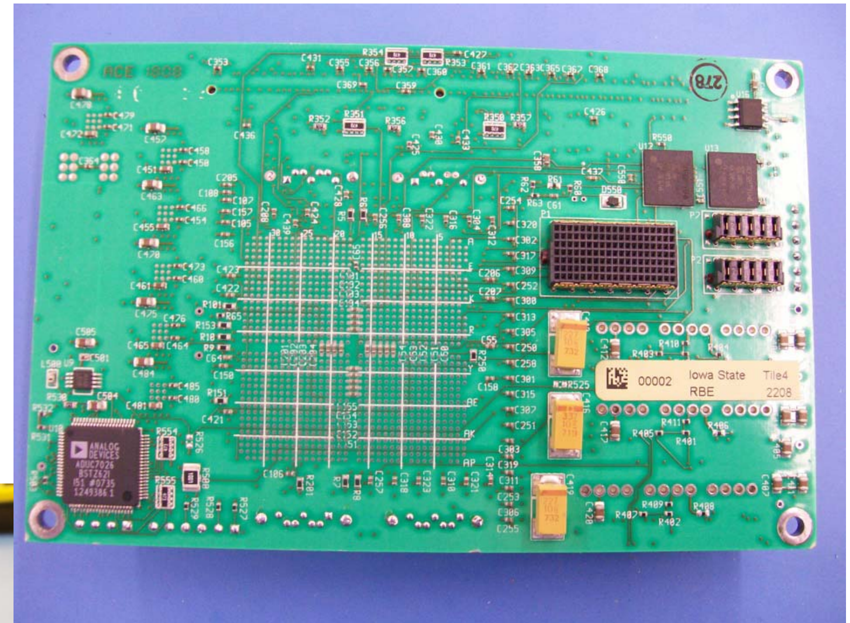
PHENIX LL1 decision time 40xBCLK (4μs)

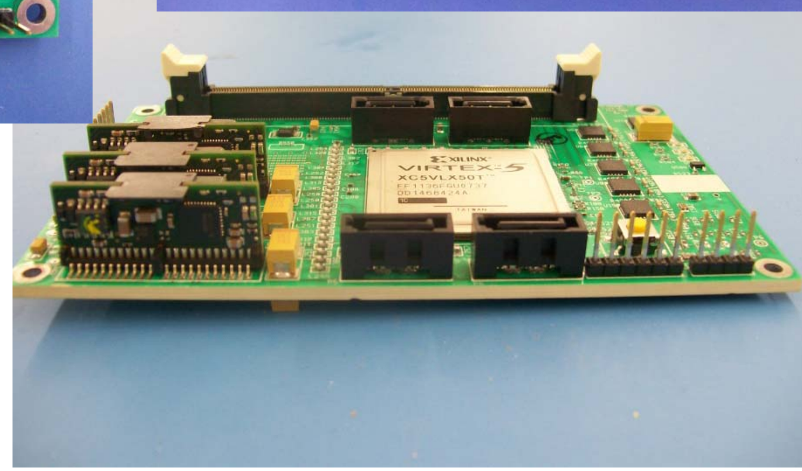
Implement trigger using fast, parallel logic on FPGA's



The LL1 Trigger Tile

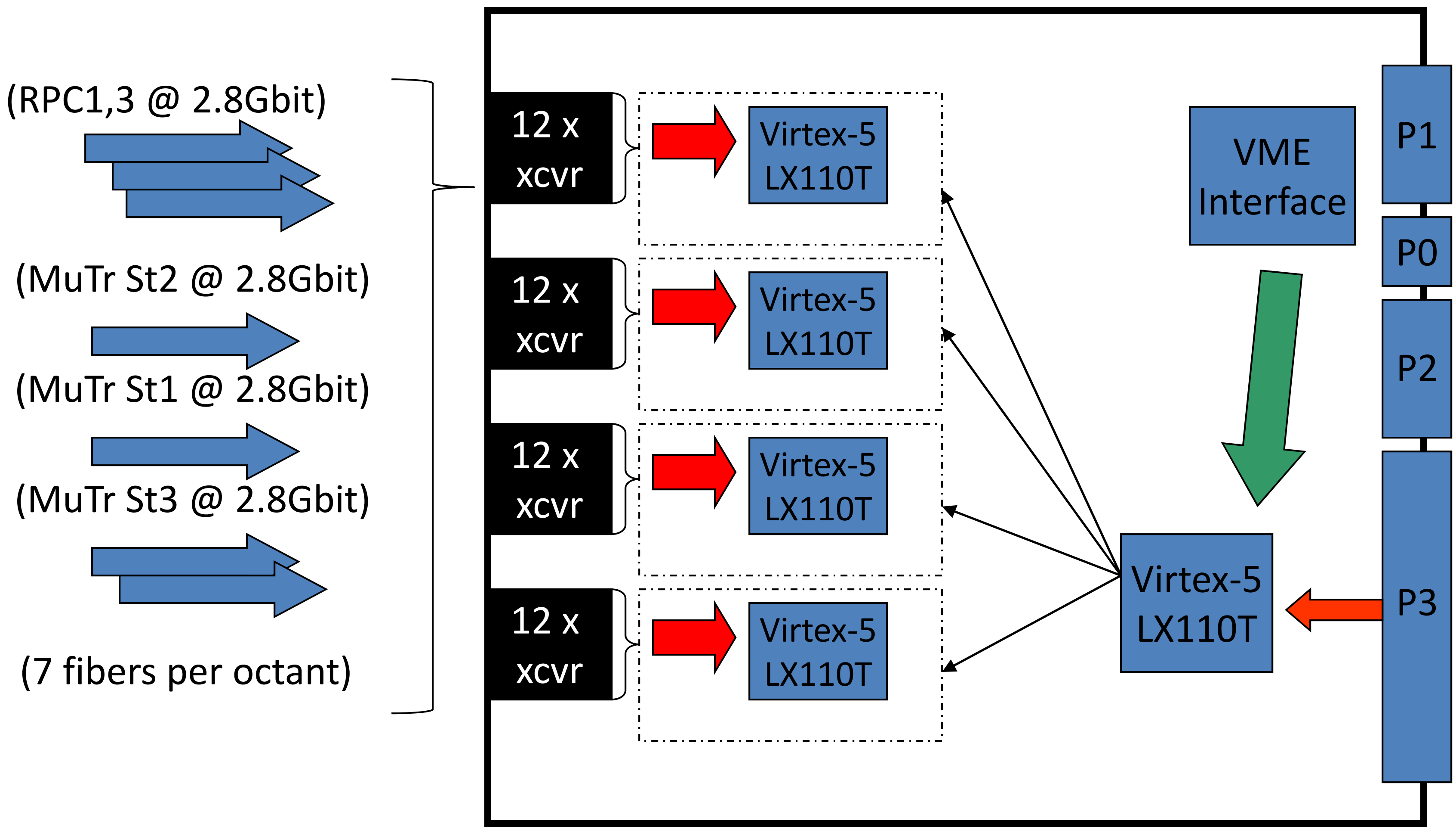




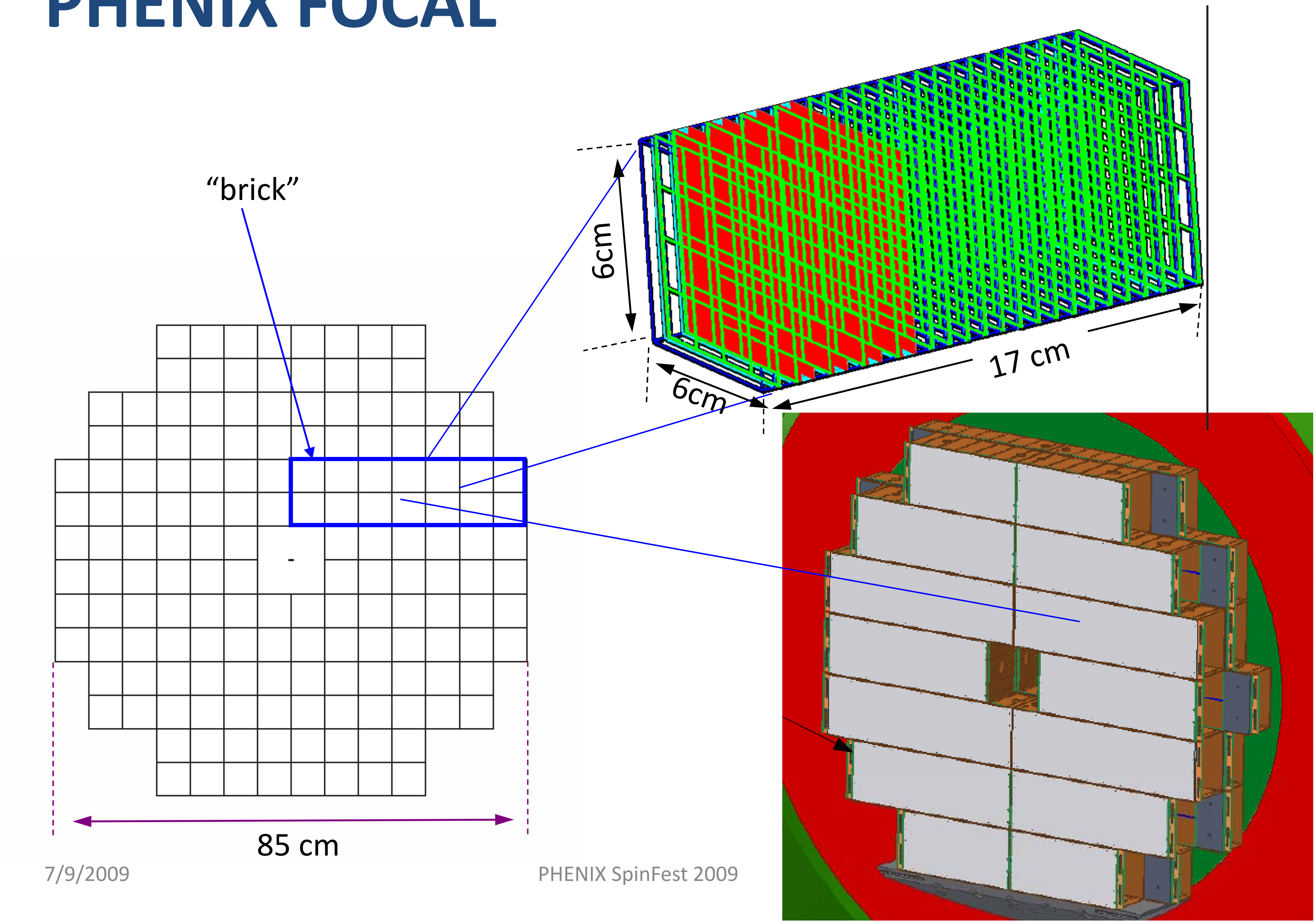


Muon Trigger Block Diagram

One board processes four trigger octants (one octant per tile).

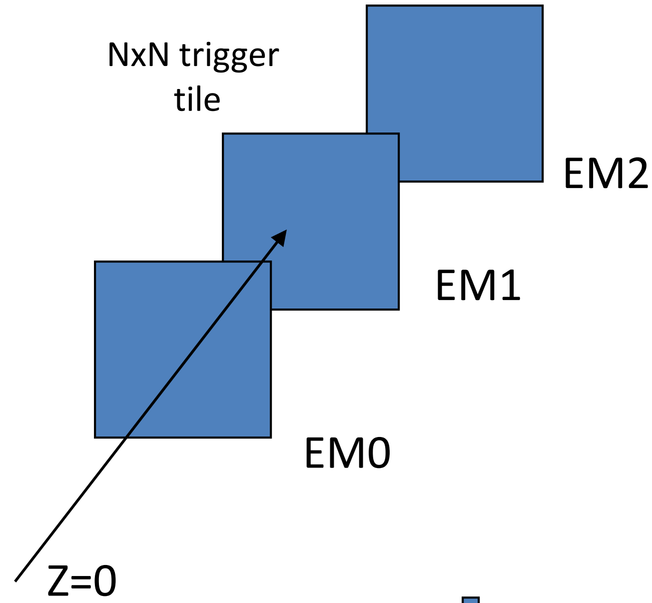


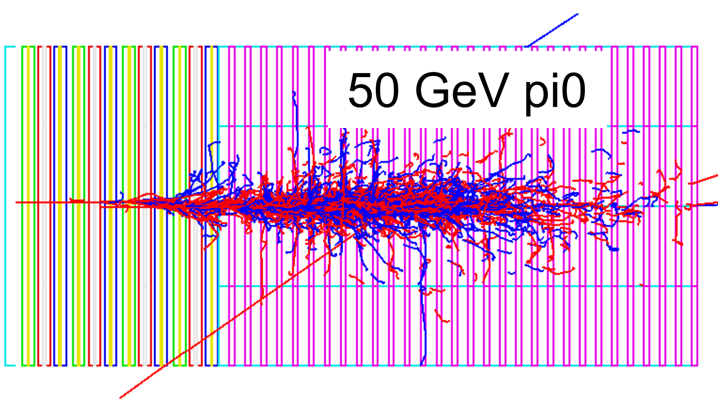
PHENIX FOCAL

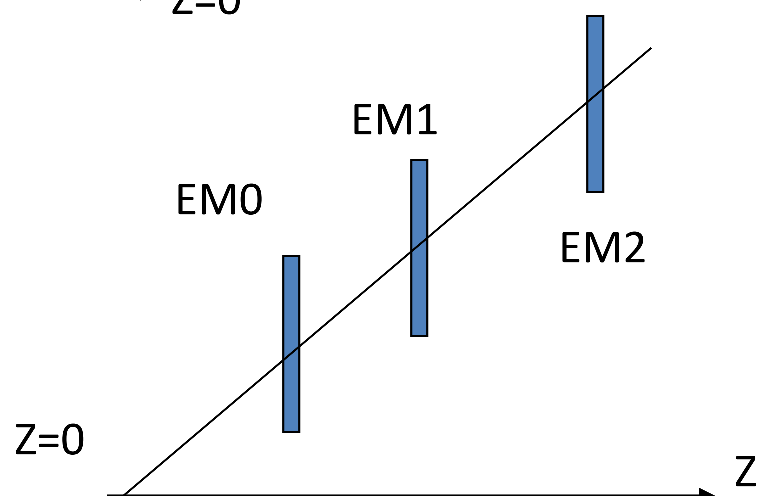


The FOCAL LL1 Trigger

- Algorithm starts by searching NxN (2x2, 4x4 or 4x4 overlapping) tiles in EM1 for tile with nonzero energy in pads
- Using z=0 and center of EM1 tile, project into EM0 and EM2
- Sum pad energy in EM0,EM1 and EM2
- Compare energy sum to threshold
  - Energy threshold scaled by pseudorapidity
  - Based on center of trigger tile in EM1 and assumes z=0 for vertex







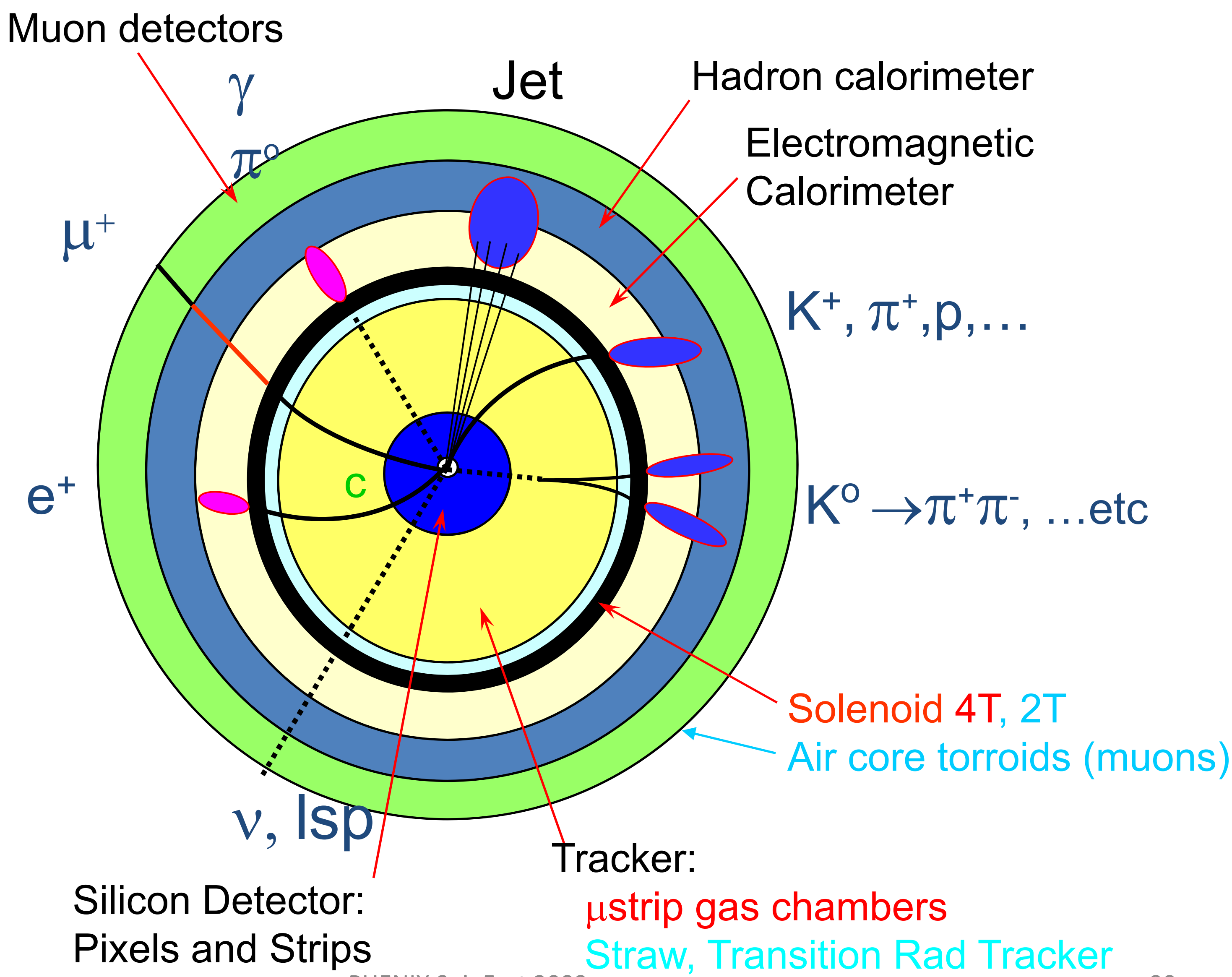
PHENIX Level-2 Trigger

- Sophisticated software trigger implementation within the Event Builder
  - Uses offline-compatible framework
    - Some special purpose objects for efficiency
  - Variety of triggers implemented
    - Dimuon, high-E_T cluster most useful
  - Used primarily for event filtering, not rejection
    - Data archiving bandwidth has kept pace with RHIC luminosity growth, no need to reject

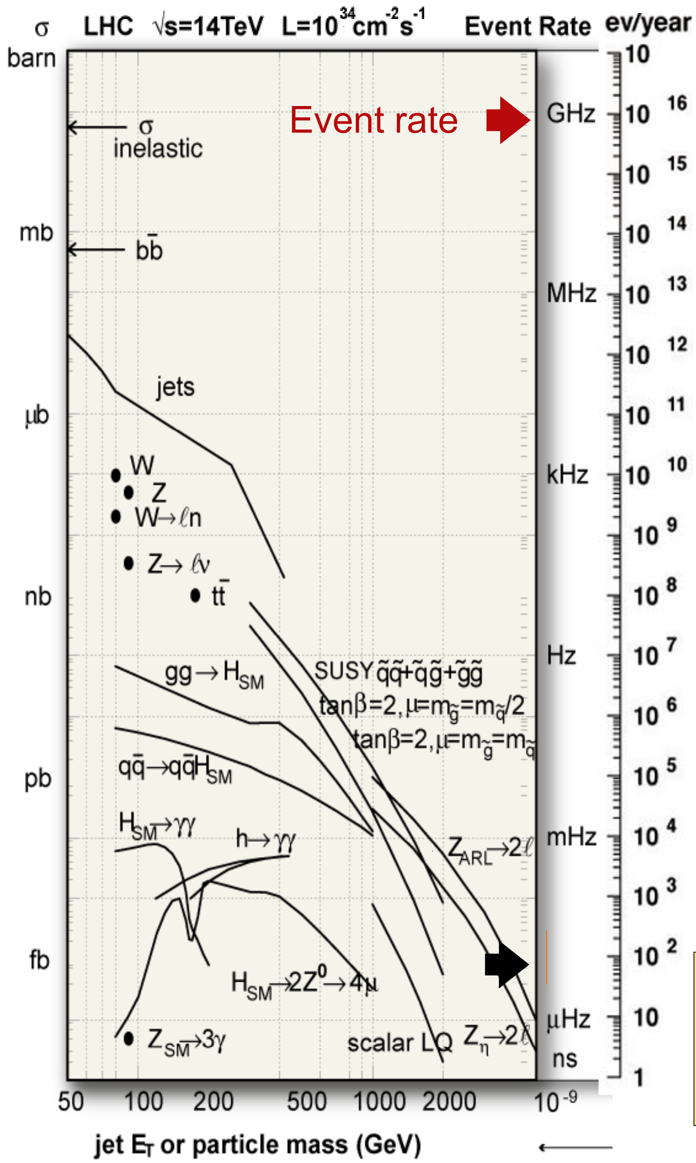
The (Near) Future

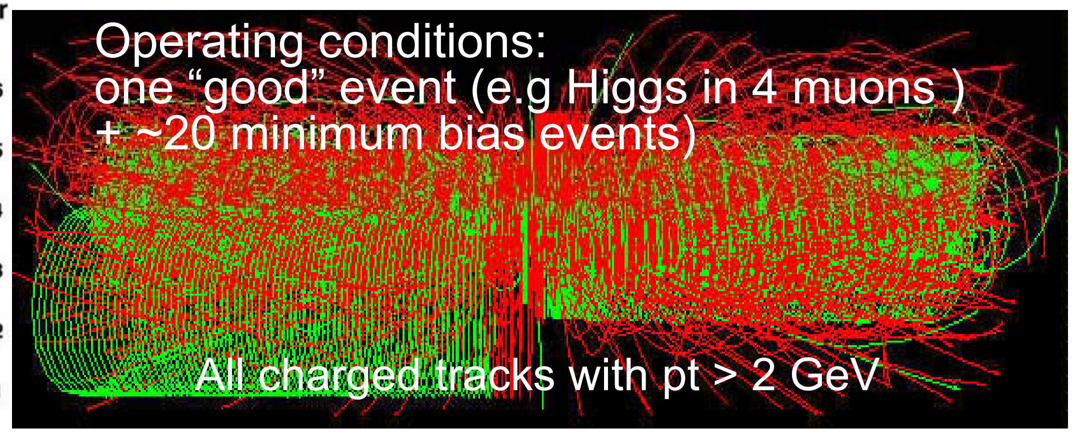
LHC Detector Schematic

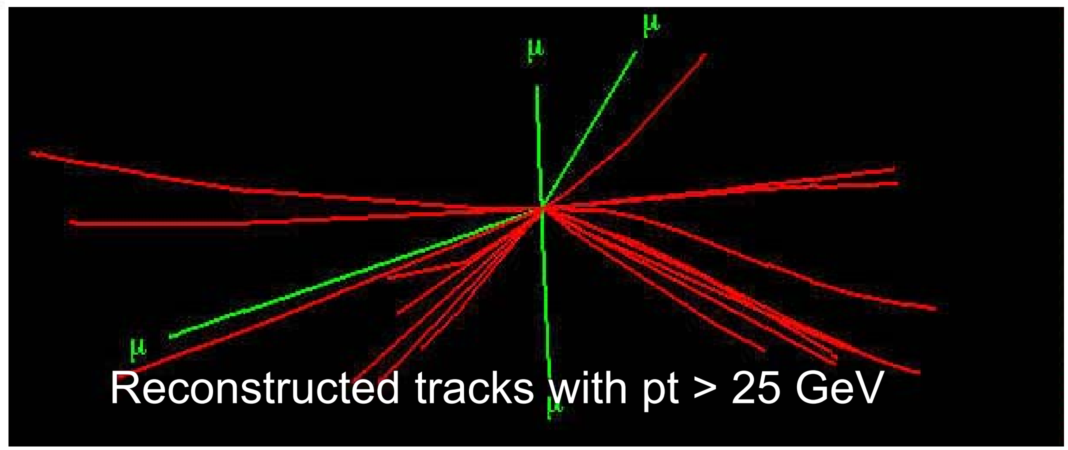
Key
CMS and ATLAS
CMS
ATLAS



pp Collisions at the LHC







Event size:	~1 MByte
Processing Power:	~X TFlop

S. Cittolin CERN/EP-CMD LECC Workshop 2002

ATLAS/CMS Trigger Rates

- Same challenges as Tevatron but higher energies, much higher luminosity $\rightarrow$more interactions/crossing (20-25)
- Cut on E_T and P_T to discriminate against QCD backgrounds
  - Higher E_T cuts than Tevatron needed
  - More boost $\rightarrow$don't loose efficiency
- Unprescaled High p_T trigger thresholds and rates:

	CDF L1		CDF L2		LHC L1	
	P_T Cut	Rate (HZ)	P_T Cut	Rate (Hz)	Pt Cut	Rate (Hz)
Single μ	4 GeV/c	280	12 GeV/c	25	20 GeV	10k
Single e	8 GeV	240	16 GeV	30	30 GeV	20k
Single γ	8 GeV	2400	18 GeV	60	30 (GeV)	20k
Single Jet	10 GeV	10K	90 GeV	10	300 (GeV)	200

CDF Rates for $2x10^{32} cm^{-2} s^{-1}$, scaled from $3x10^{31} cm^{-2} s^{-1}$ (no L2 μ)

LHC rates for $10^{34} cm^{-2} s^{-1}$, from N. Ellis, LECC Workshop 2002 at Colmar

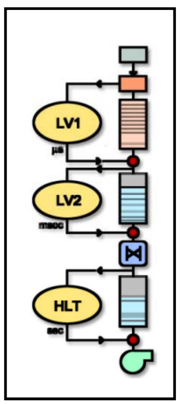
ATLAS and CMS Trigger Architecture

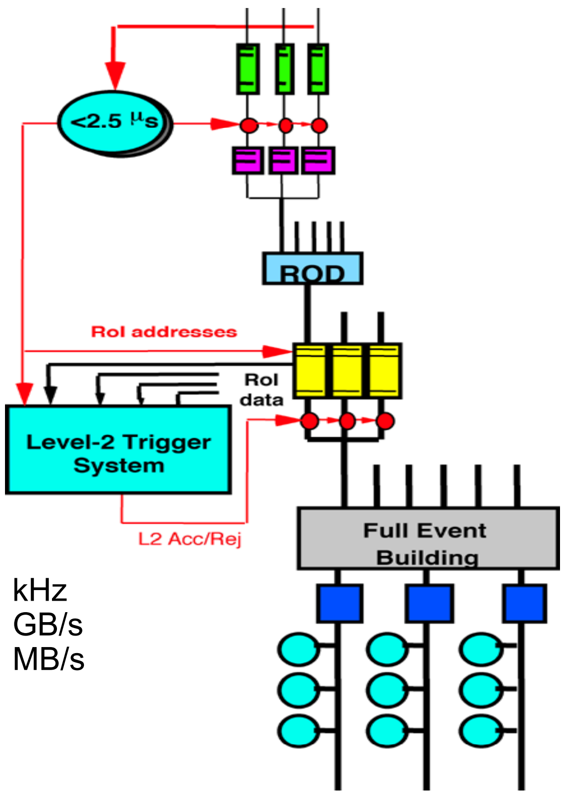
Large improvements in FPGA size, speed and link bandwidth

→Only L1 trigger in custom hardware

→No L2 trigger for CMS

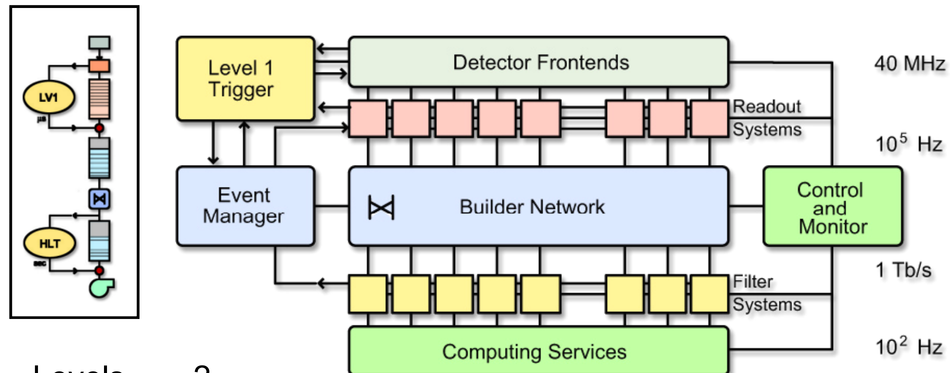
ATLAS





Levels	3	
LV-1 rate	100	kHz
Readout	10	GB/s
Storage	100	MB/s

CMS

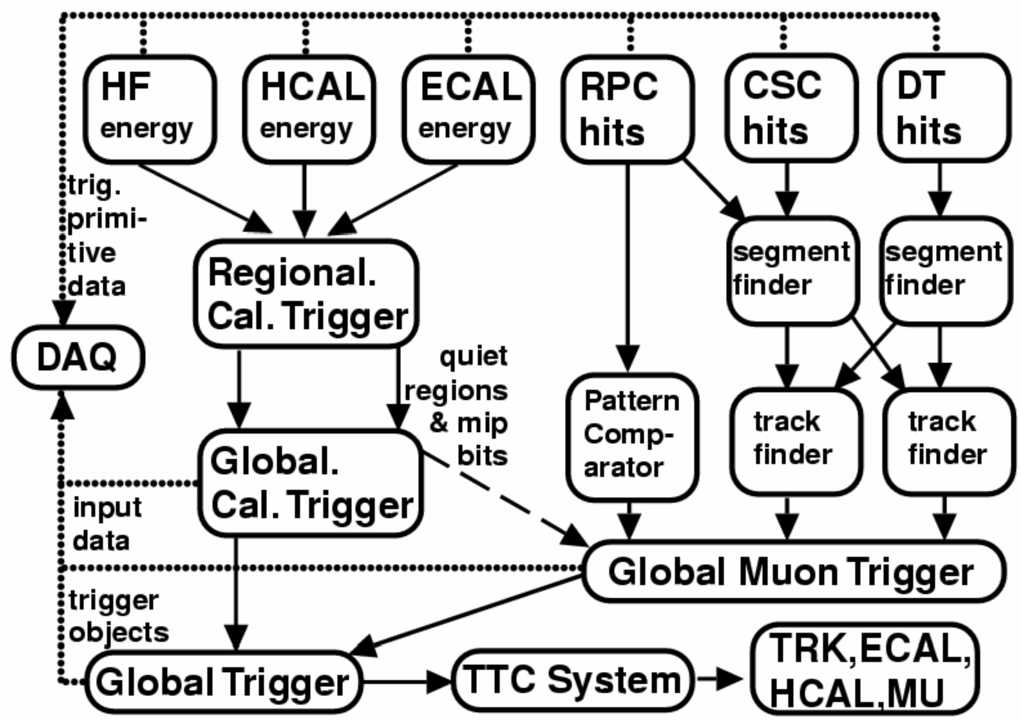


Levels	2	
LV-1 rate	100	kHz
Readout	100	GB/s
Storage	100	MB/s

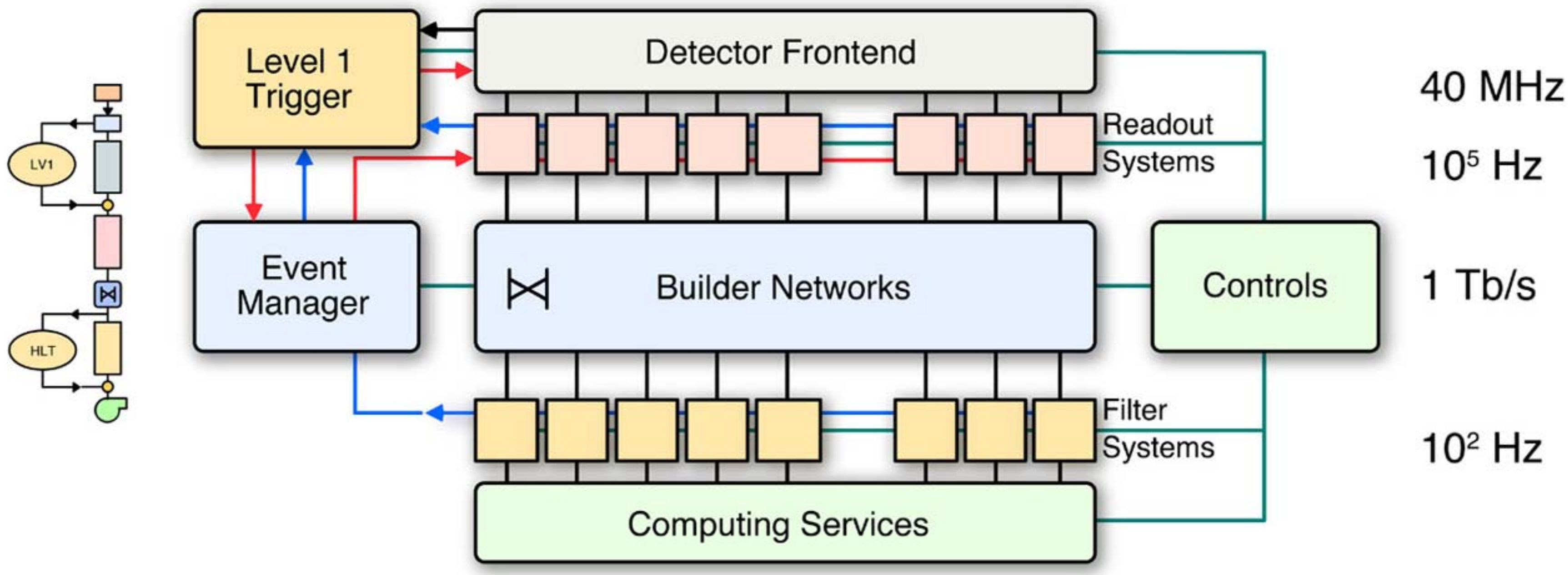
ATLAS/CMS L1 Trigger

- CMS and ATLAS L1 triggers both use data from Calorimeters and Muon detectors
  - No data from inner trackers – very high track density
  - E_T of clusters for e/γ/Jet triggers
  - Missing E_T for ν or SUSY LSP
  - P_T of Muon in flux return (CMS), air torroids (ATLAS)
- Same general functions as CDF/D0 Run 1 L1 Triggers
  - Better muon P_T
  - More sophisticated algorithms
  - Many more channels to handle

CMS L1 Trigger System



CMS DAQ/Trigger Structure



Collision rate	40 MHz
Level-1 Maximum trigger rate	100 kHz(*)
Average event size	≈ 1 Mbyte
Event Flow Control	≈ 10^6 Mssg/s

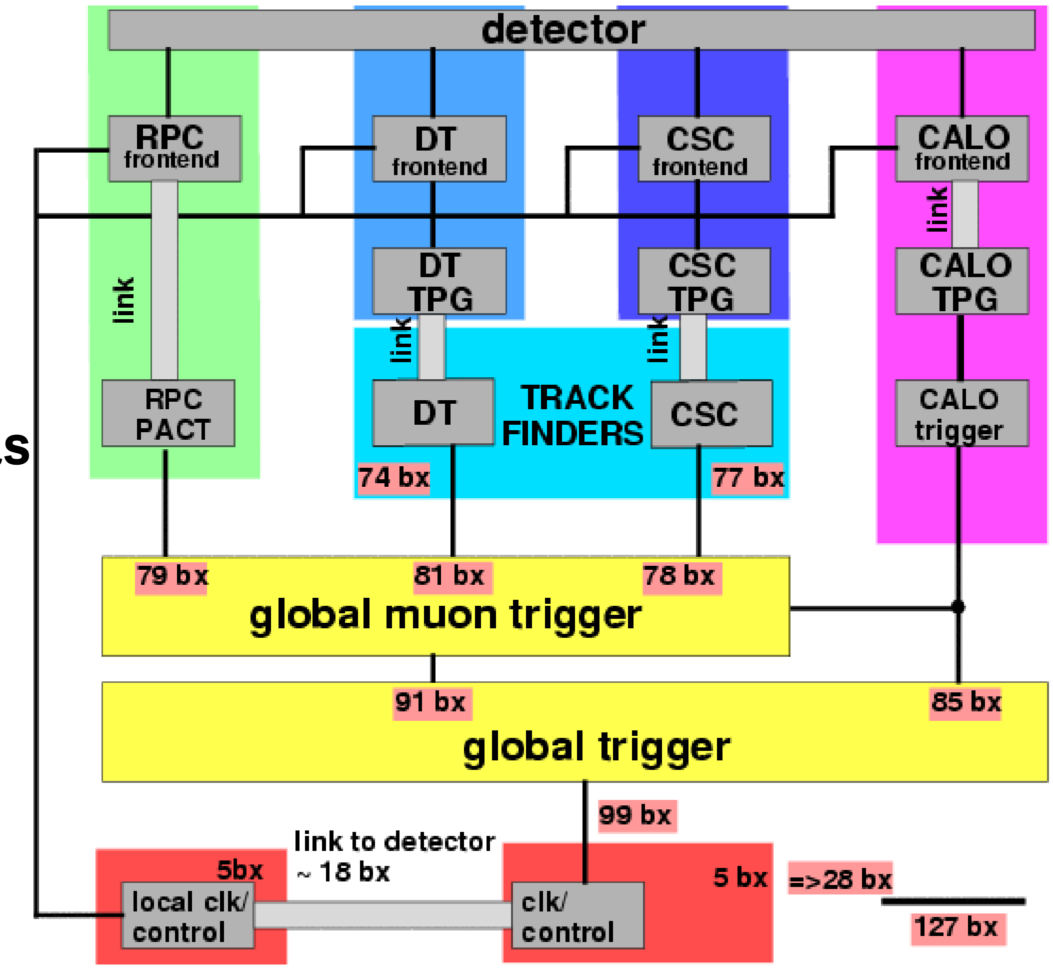
No. of In-Out units	≈ 500
Readout network bandwidth	≈ 1 Terabit/s
Event filter computing power	≈ 5 TFlop
Data production	≈ Tbyte/day
No. of PC motherboards	≈ Thousands

CMS L1 Latency

Budget of 128bx =3.2μs

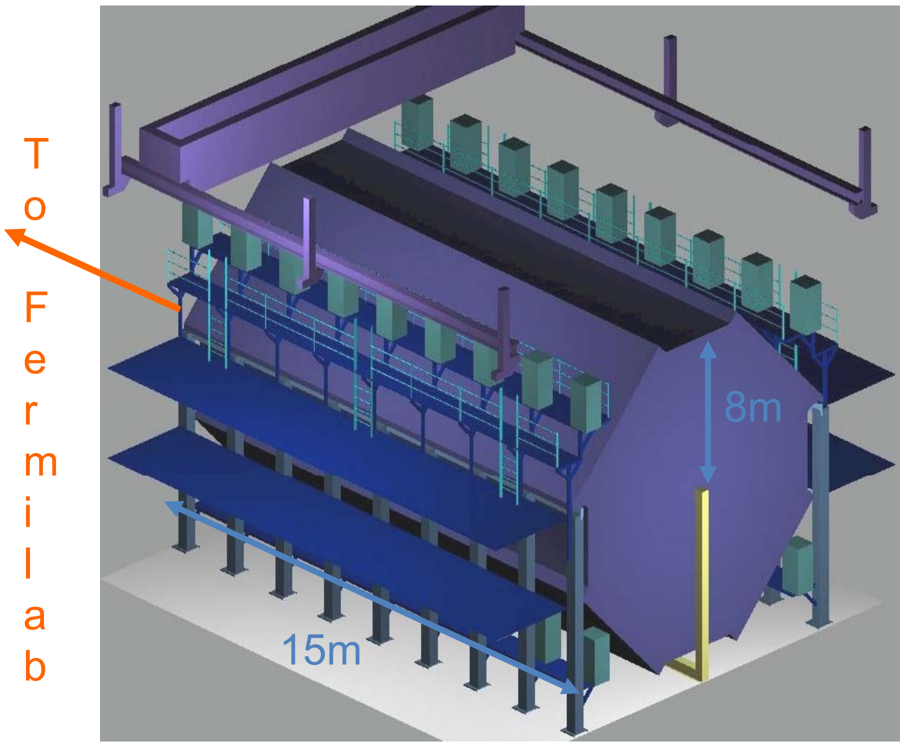
CDF/D0 (30-42bx) ~ 4-5.5μs

L1 latency currently dominated by cable/transmission delays.



Non-Traditional Trigger Systems

MINOS (Far Detector)

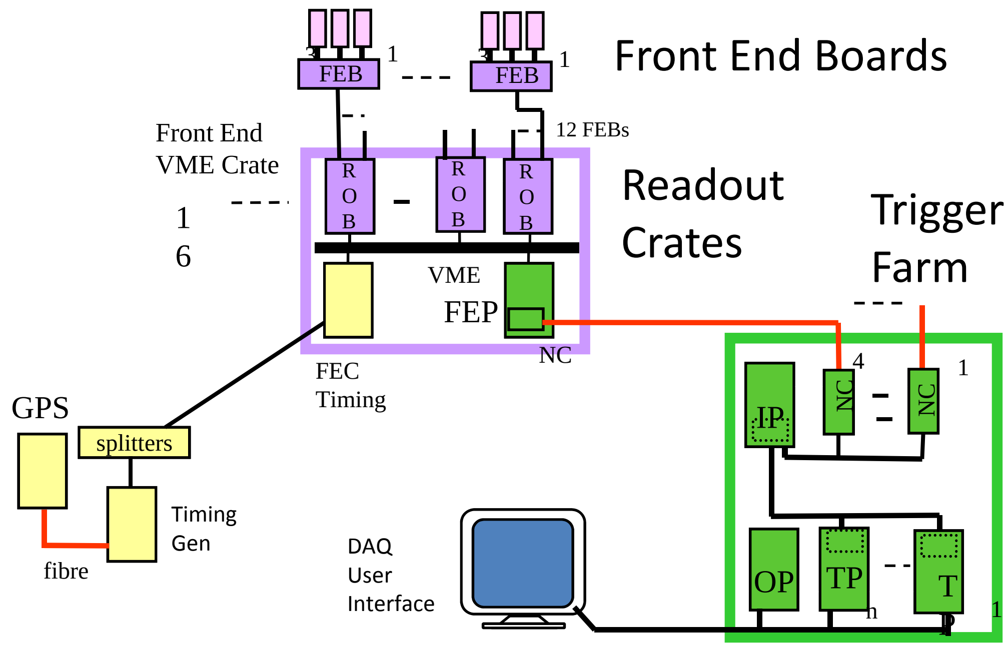


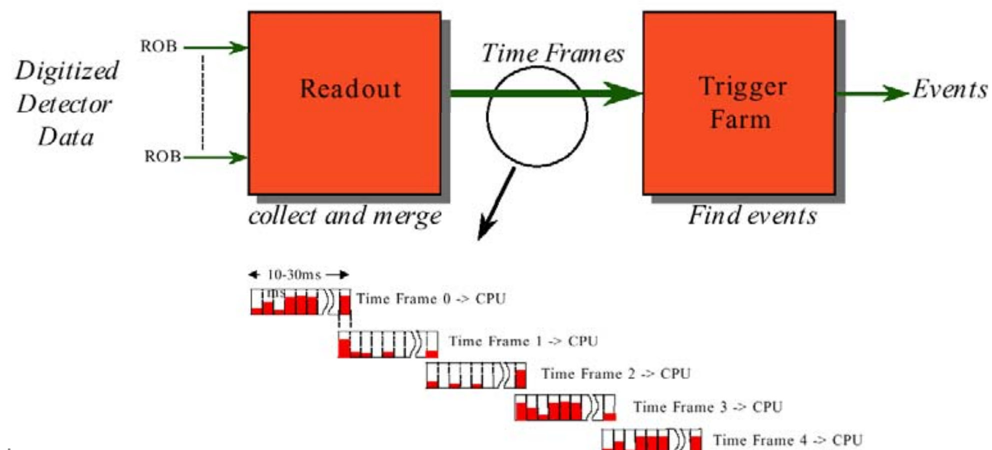
½ of the Far Detector

- Steel/Scintillator sampling calorimeter
  - 5.4 kt, 8m diameter, 31m long
  - 486 layers, each made of:
    - 1” steel
    - 1 cm plastic scintillator
  - Magnetized to ~1.5 T
- Design goals
  - $\nu_e/\nu_\mu/\pi$ discrimination
  - Good energy resolution
    - For both μ and showers
  - Good timing, both hit-to-hit and absolute
    - For particle direction and synching with Fermilab beam

MINOS Readout and Trigger

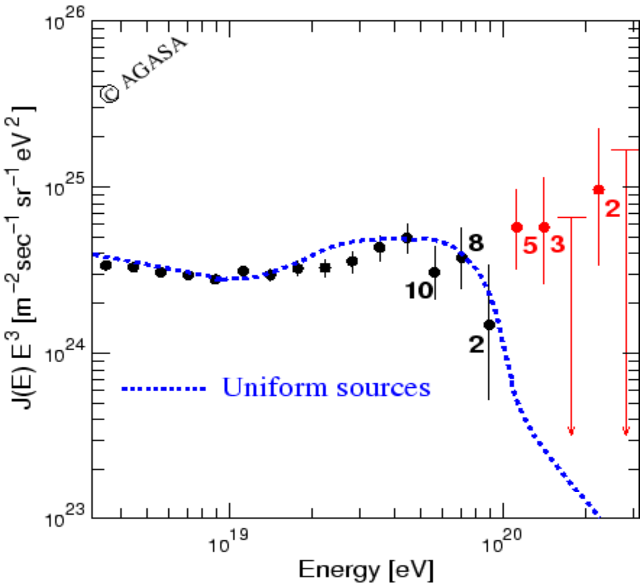
- Two detectors – near and far (730km separation)
- Time synch date <1ms (GPS)
- No hardware trigger
- Beam structure:
- ~10ms spill at ~1Hz
- 53MHz structure within spill
- Continuous digitization at 53MHz
- Readout into Trigger farm in overlapping ~4ms long frames of data
- Readout rate: 40MB/s

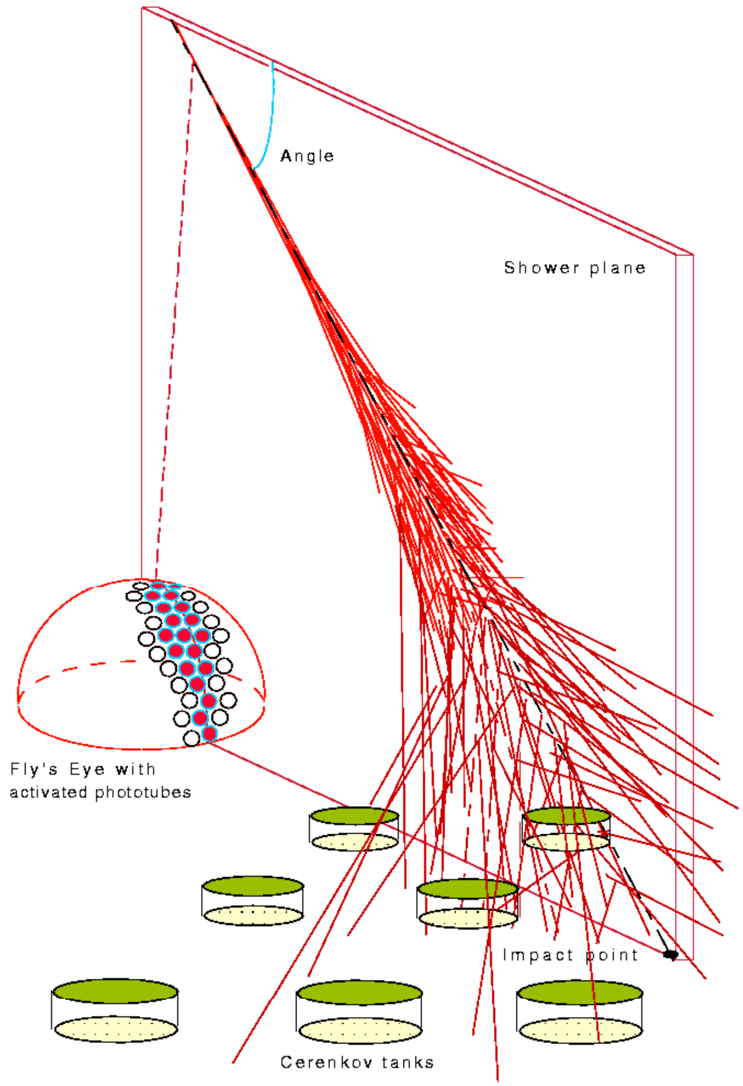




Pierre Auger Observatory

Search for Origin of cosmic rays with E>10^{20}eV





Rate ≈ 1 / km^2 / sr / century above 10^{20} eV!

Large scale detector:

- ✓ 1600 Cherenkov tanks, covering 3000 km^2
- ✓ 24 Fluorescence Detector telescopes

Auger Cerenkov Stations

- Highly distributed Particle physics detector
- Autonomous systems at each detector
  - Communicate via wireless technology
  - Timing via GPS (~10ns)
  - Cannot trigger globally
  - Two FADC (gain factor of 8) at 40MHz into buffer on each tube
- Backgrounds
  - PMT noise few kHz/PMT
  - Cosmics ~ 3kHz/station

Auger Trigger

Four level trigger

Locally: L1 in hardware – 100Hz out

Locally: L2 in μ-controller – 20Hz

Transmit 3Bytes to control center on L2A

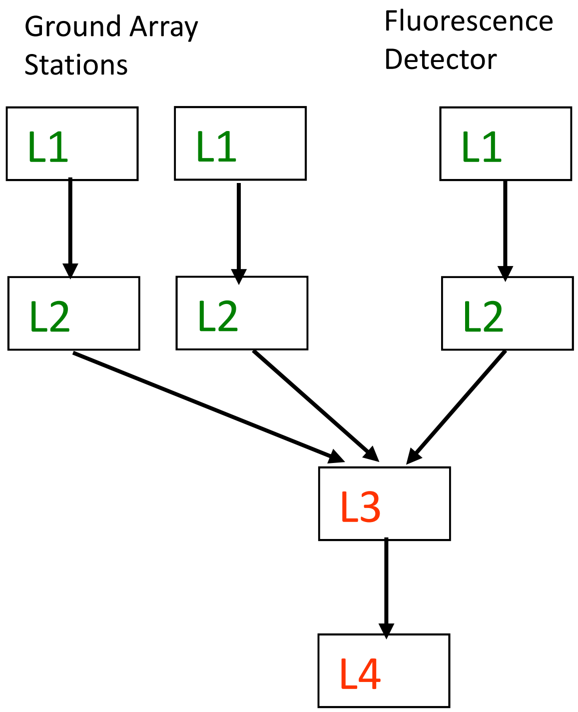
Globally: L3 and L4 in processors at control center

Data buffered locally to be retrievable after L3 even for un-triggered station

L1 Algorithm

Multiple time slices over threshold (e.g. 2 counts in low FADC range) in a sliding window (e.g. 4 time bins out of 240)

- Other algorithms look for single muons and Gamma Ray bursts
- Initially developed ASIC solution for low cost and power
- Decreasing FPGA costs: implemented in Altera ACEX EP1K100QI208-2, algorithm in VHDL.
- Online and running (2008)

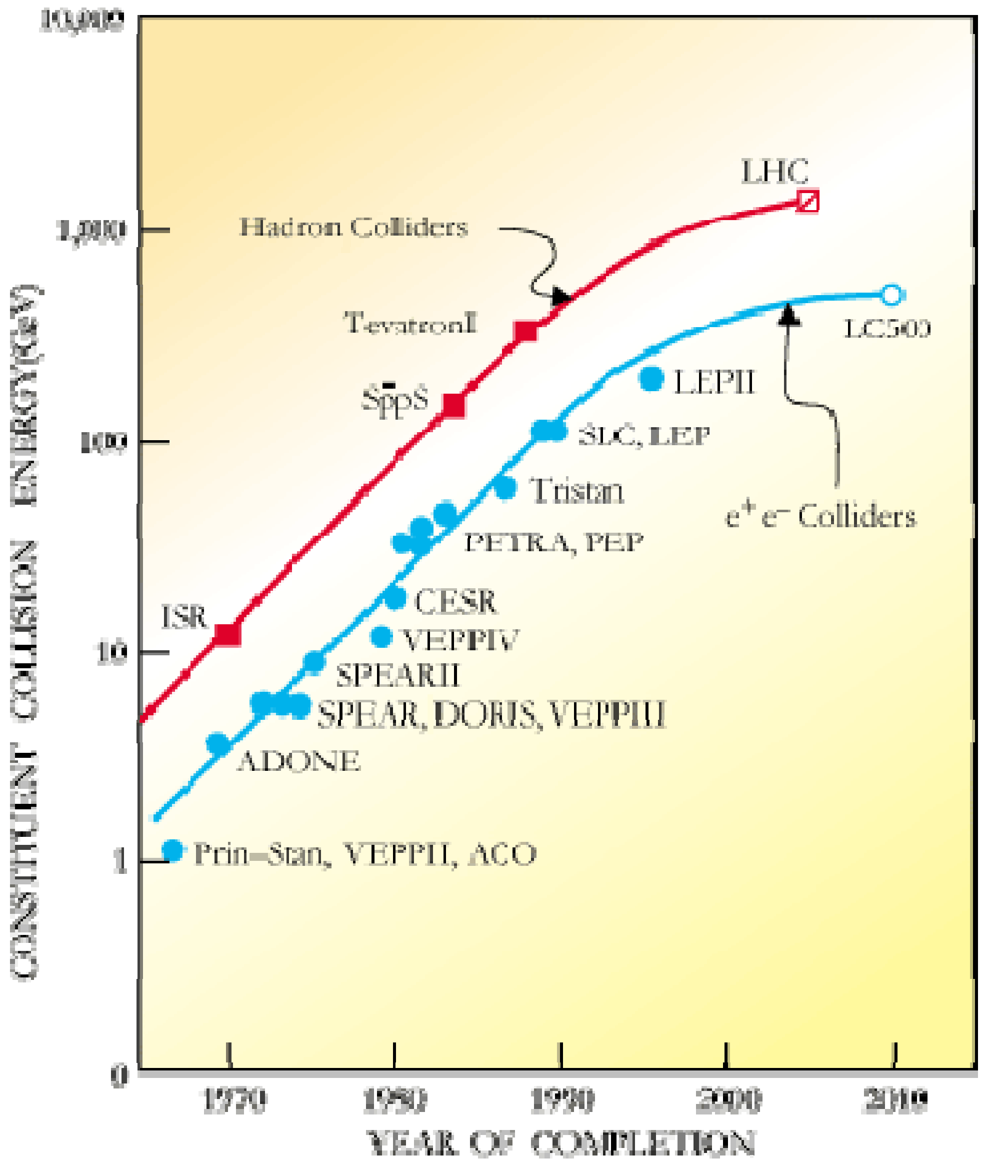


Send average of 500b/s from each ground station

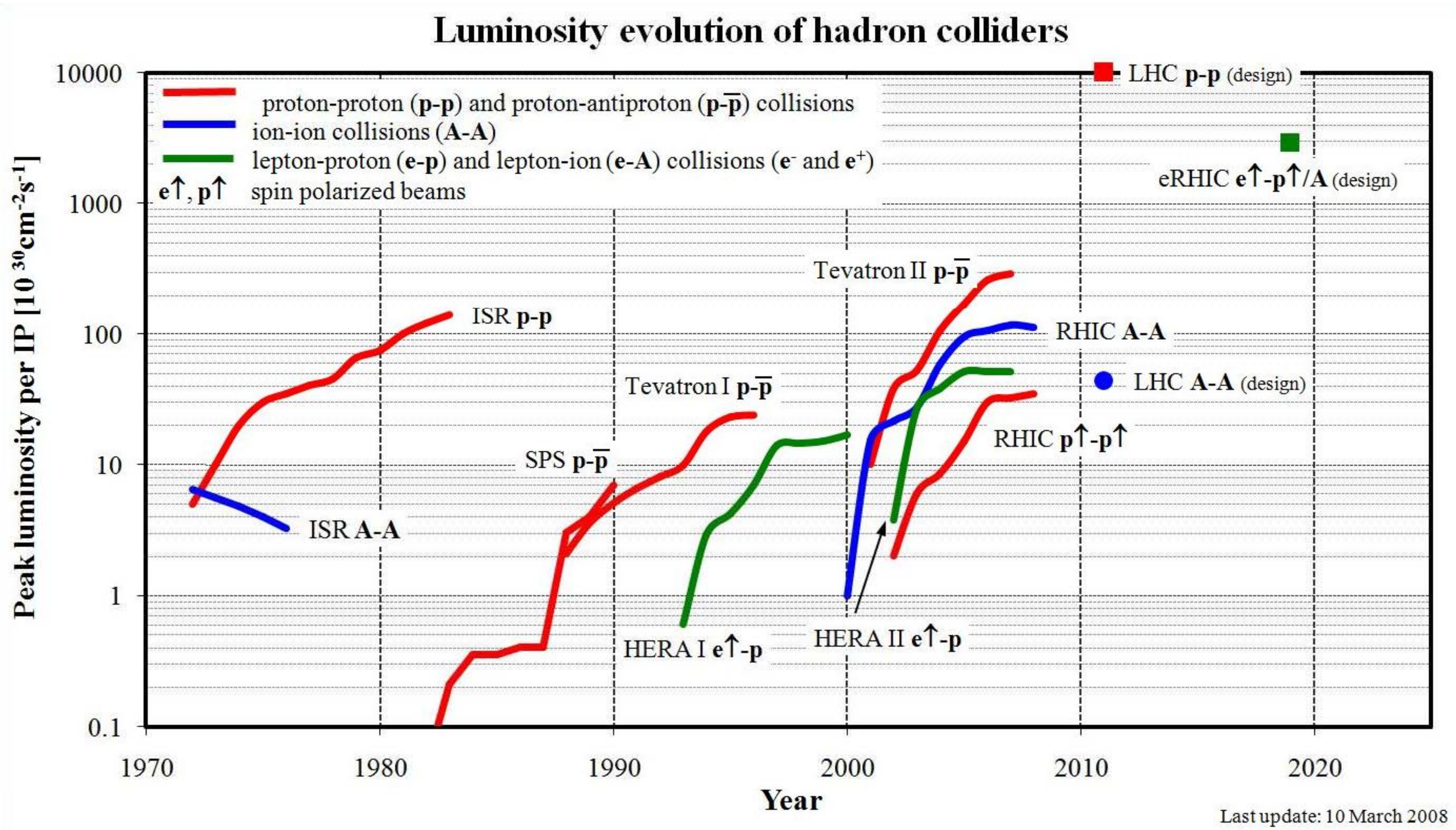
Future Accelerators

What will trigger systems look like in the future?

- Accelerator energy continues to grow… however rate of change may be decreasing
- Processing power, network bandwidth and storage media are all growing faster than increases in luminosity
- Trend is toward fewer (zero?) hardware levels
- Future Machines
  - Linear Collider (500-1000 GeV)
  - Muon Collider?
  - VLHC pp at 40-200 TeV
  - EIC (eA)



Luminosity Frontier



Linear Colliders

Low Beam X-ing Rate for Either Tesla or NLC

	Tesla	NLC
Rep Rate (Hz)	5	120
Bunch Spacing (ns)	337	1.4
Bunch/Pulse	2820	190
Pulse length (ms)	950	0.266
Average xing rate (kHz)	14	23

Triggerless (hardware) design (?)

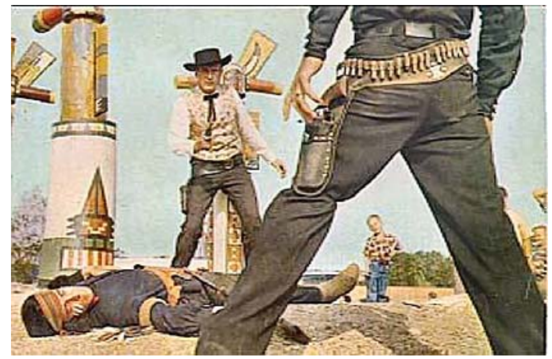
- Tesla conceptual detector: readout detector continuously to L3 farm

Parting Words…

- Trend in trigger design over the past 20 years has been towards greater complexity in hardware triggers
- With the increased capabilities (and decreased cost) of Ethernet, PCs, and Network switches, the use of custom hardware is decreasing
  - Corollary: HEP no longer is at cutting edge of electronics bandwidth
  - Usually still necessary at L1, avoided at L2/3
- The trend toward ASICs/custom hardware seems to have slowed
  - Economical only for very high volume (rare on trigger)
  - Use for special radiation environment (only first data formation for trigger)
  - Not as flexible in addressing unforeseen needs/desires

JL's Rules of Triggering

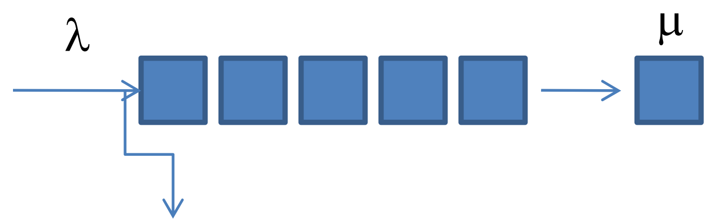
- "You have to trigger fast."
  - A late answer is a wrong answer



- "It's no good being fast if you're not accurate"
  - If you're not efficient, what's the point?

BACKUP

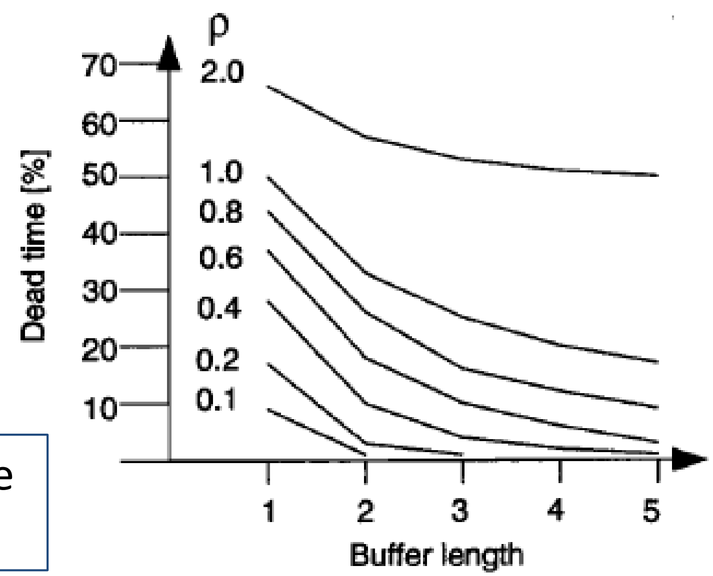
Queuing Theory



- Consider a system with:
  - exponential arrival times with average rate λ
  - exponential distribution of trigger service times with time constant μ (ratio $\rho = \lambda/\mu$)
  - A buffer depth N, where the system will produce dead time if the buffer becomes full

$$\tau = \frac{(1-\rho)\rho^N}{(1-\rho^{N+1})} \qquad \rho \neq 1$$

$$\tau = \frac{1}{N+1} \qquad \rho = 1$$



For ρ=1, if N=1 then deadtime = 50%. If N=5, the deadtime is reduced to 16%.

Recent Collider Detectors

Detector	Number of Channels	Silicon Part of Trigger?	Input Trigger Rate	Largest (Non) Physics Background
CLEO III	400K	No	L1: 72 MHz L2: 1 kHz Tape: <100 Hz	Electron pairs & $\gamma\gamma$
Belle	150K	Not Yet	L1: 50 MHz L2: 500 Hz Tape: 100 Hz	Electron pairs & $\gamma\gamma$ Beam-wall
BaBar	150K	No	L1: 25 MHz L3: 2 kHz Tape: 100 Hz	Electron Pairs & $\gamma\gamma$ Beam-Wall
H1, ZEUS	500K	No	L1: 10 MHz L2: 1 kHz L3: 100 Hz Tape: 2-4 Hz	Beam-gas
HERA-B	600K	Yes (L2)	L1: 10 MHz L2: 50 kHz L3: 500 Hz L4: 50 Hz Tape: 2 Hz	Beam-wire scattering Inelastics
Aleph, Opal, L3, Delphi	250-500k	No	L1: 45 kHz Tape: 15 Hz	Beam-gas
CDF (Run 2), **DØ** (Run 2)	750K-1M	Yes (L2)	L1: 7 MHz L2: 10-50 kHz L3: .3-1 kHz Tape: 50 Hz	QCD, pileup (multiple interactions)

Planned Experiments

	Type	L1 In (MHz)	L1 Out (kHz)	L2 Out (kHz)	Ev Size (kB)	Bandwidth RO (GB/s)	L3 Out (Hz)
ATLAS	pp	40	100	NA	1000	10	100
CMS	pp	40	100	100	1000	100	100
LHCb	pp	40	1000	1000	200	4	200
Minos	ν oscill	19ns RF for 8μs spill, rep rate ~1s				40MB/s	few

With increasing link and switch capabilities less selection in hardware

ATLAS L2: Regions of Interest

- L2 Trigger uses same data as goes to L3
- On L1 subsystems store regional information about decision
  - On L1A, pass to Region of interest builder in L2
  - Fetch complete detector data only for Regions of Interest (ROI). Data remains in buffers of readout system
  - Make fast decision in L2 Processor farm. Reduce rate by factor of 10
- ROI builder gathers packets from different parts of detector and align to same even. Then pass to farm.

An Example HLT/DAQ Implementation with Separate LVL2 and EF Networks