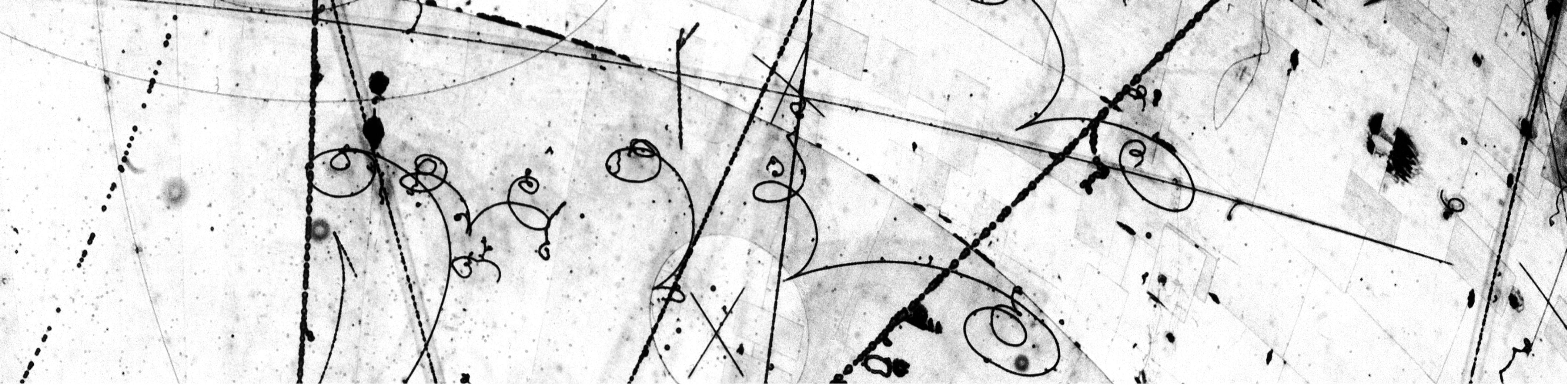
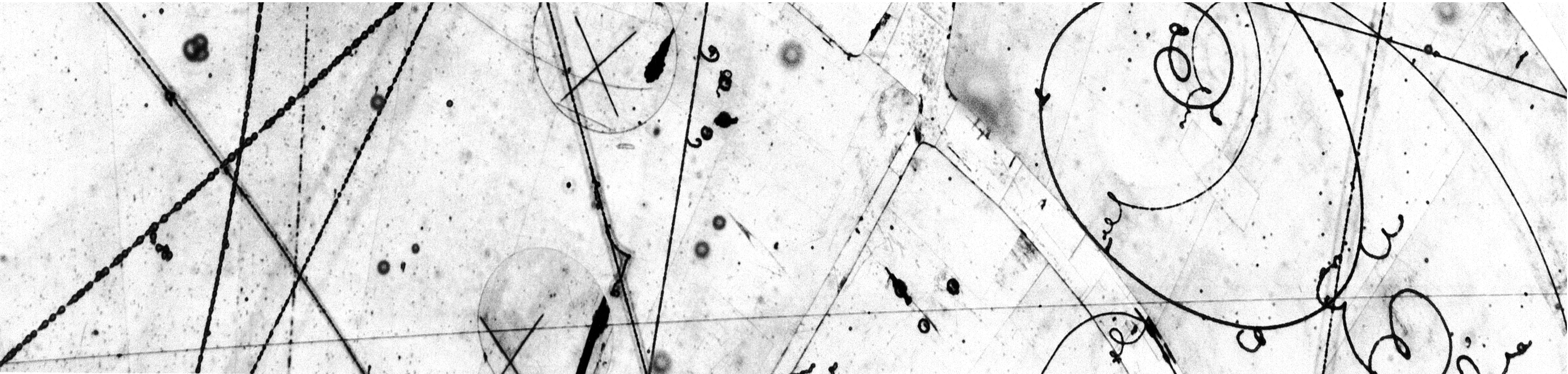
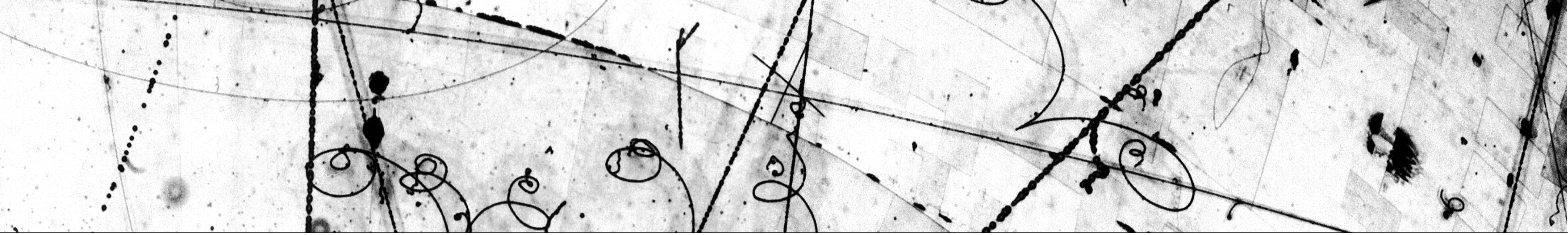


Trigger and Data Acquisition (I)

Brigitte Vachon (McGill)

HCPSS 2010



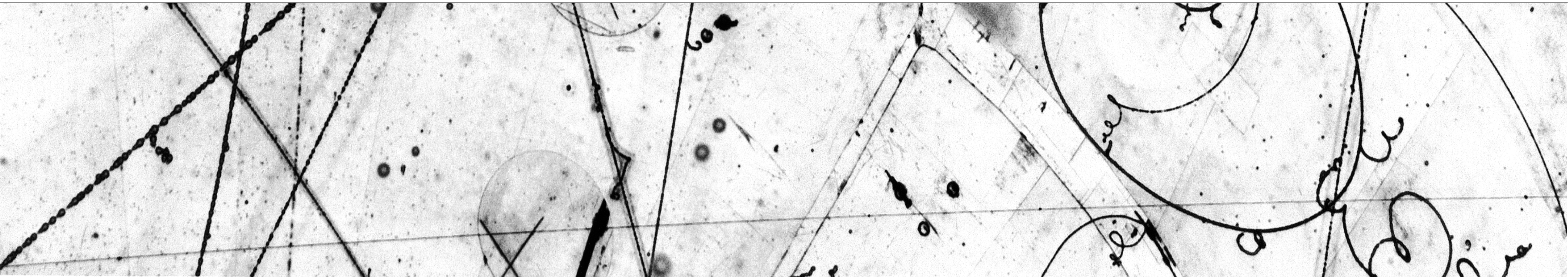


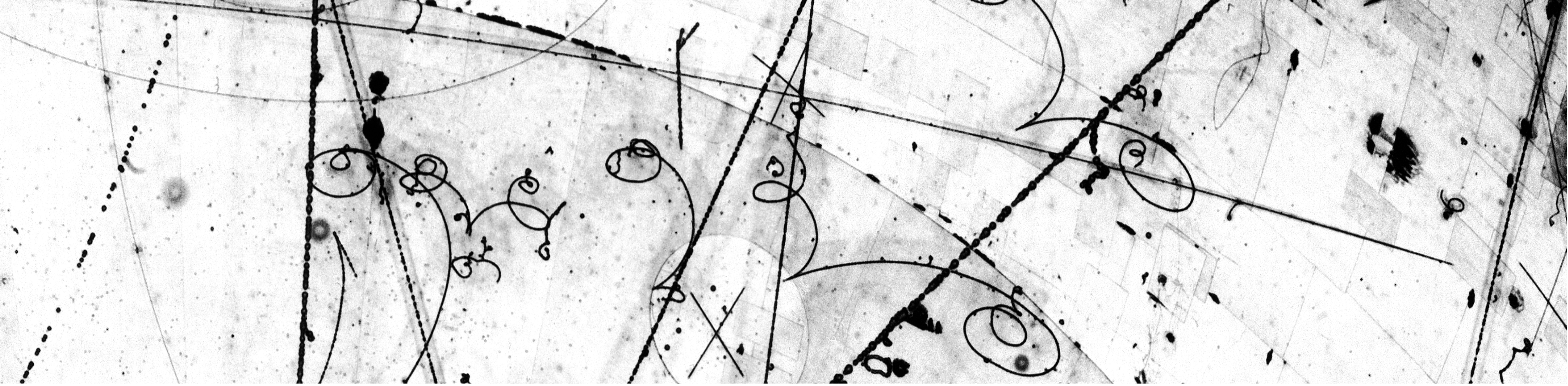
Part-I

- Introduction
- Trigger and Data Acquisition Basics

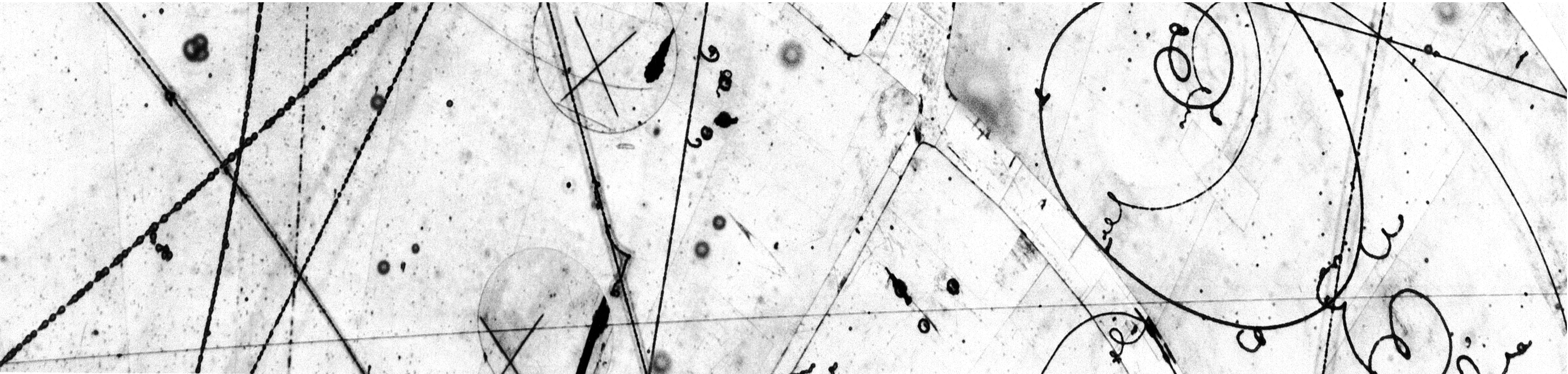
Part-II

- System Commissioning
- Trigger Selection
  - Electron and Jets
  - Muons
  - Secondary vertex
- Trigger Menu Design





Introduction



References and Useful Information

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H.P. Beck, "*Triggering at high luminosity colliders*", New J. Phys. 9 (2007) 334.

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G. Broijmans, "*Triggering at Hadron Colliders*", Lectures at HCPSS, 9-18 August 2006, FNAL.

L. Babukhadia *et al.* "*Triggering in Particle Physics Experiments*", IEEE Nuclear Science Symposium short course, 10 Nov 2002.

R. Fernow, "*Introduction to experimental particle physics*", Cambridge University Press, March 1986, ISBN 052130170X.

R. Frühwirth, M. Regler, R.K. Bock, H. Grote and D. Notz, "*Data Analysis Techniques for High-Energy Physics*", Cambridge University Press, 2rd Edition, August 200 , ISBN 0521635489.

<u>Useful shortcuts</u>:

1 $pb^{-1} = 10^{36}\ cm^{-2}$

1 second at $L = 10^{31}\ cm^{-2} s^{-1}$ $\Rightarrow \int L dt = 10^{-5}\ pb^{-1}$

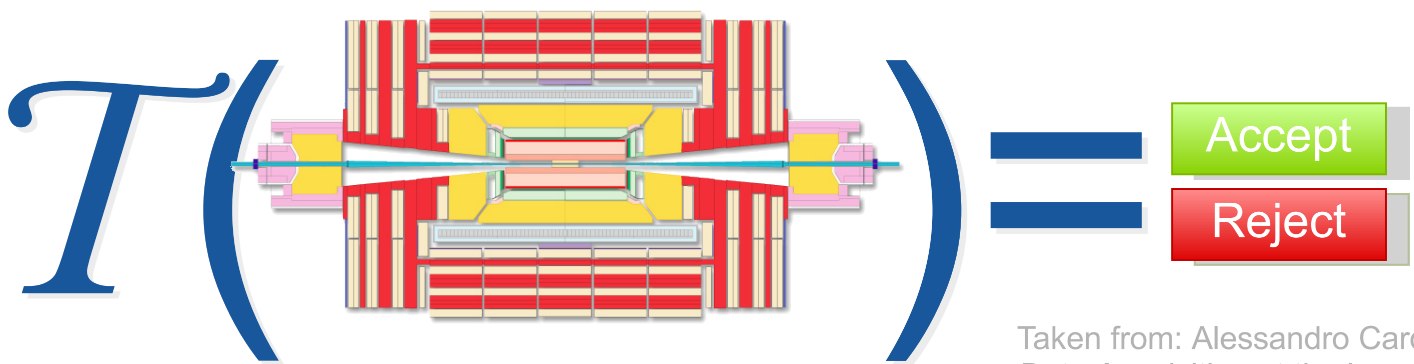
1 x 10h running day at $L = 10^{31}\ cm^{-2} s^{-1}$ $\Rightarrow \int L dt = 0.36\ pb^{-1}$

1 x 10h running day at $L = 10^{34}\ cm^{-2} s^{-1}$ $\Rightarrow \int L dt = 0.36\ fb^{-1}$

Physics rates: 10 nb x $10^{34}\ cm^{-2} s^{-1}$ = 10 nb x $10^{2}\ pb^{-1} s^{-1}$ = 100 Hz

Definitions

The *trigger* of an experiment is the system that decides, in real-time, which subset of data is to be readout by the detector and archived for offline analysis.



Taken from: Alessandro Cardini, " *Trigger and Data Acquisition at the Large Hadron Collider* ", Italo-Hellenic School of Physics, June 2006.

The *Data AcQuisition* (DAQ) system collects the data from the different parts of the detector, converts the data in a suitable format and saves it to permanent storage.

Example of a trigger in Nature

Video from BBC One Life Program http://www.bbc.co.uk/life

Why do we need a trigger?

	Bunch Crossing Rate	Event size	Trigger Rate Output	Data rate without trigger (PB/year*)	Data rate with trigger (PB/year*)
LEP	45 kHz	~ 100 kB	~ 5 Hz	O(100)	O(0.01)
Tevatron	2.5 MHz	~ 250 kB	~ 50-100 Hz	O(10 000)	O(0.1)
HERA	10 MHz	~ 100 kB	~ 5 Hz	O(1 000)	O(0.01)
LHC	40 MHz	~ 1 MB	~ 100-200 Hz	O(100 000)	O(1)

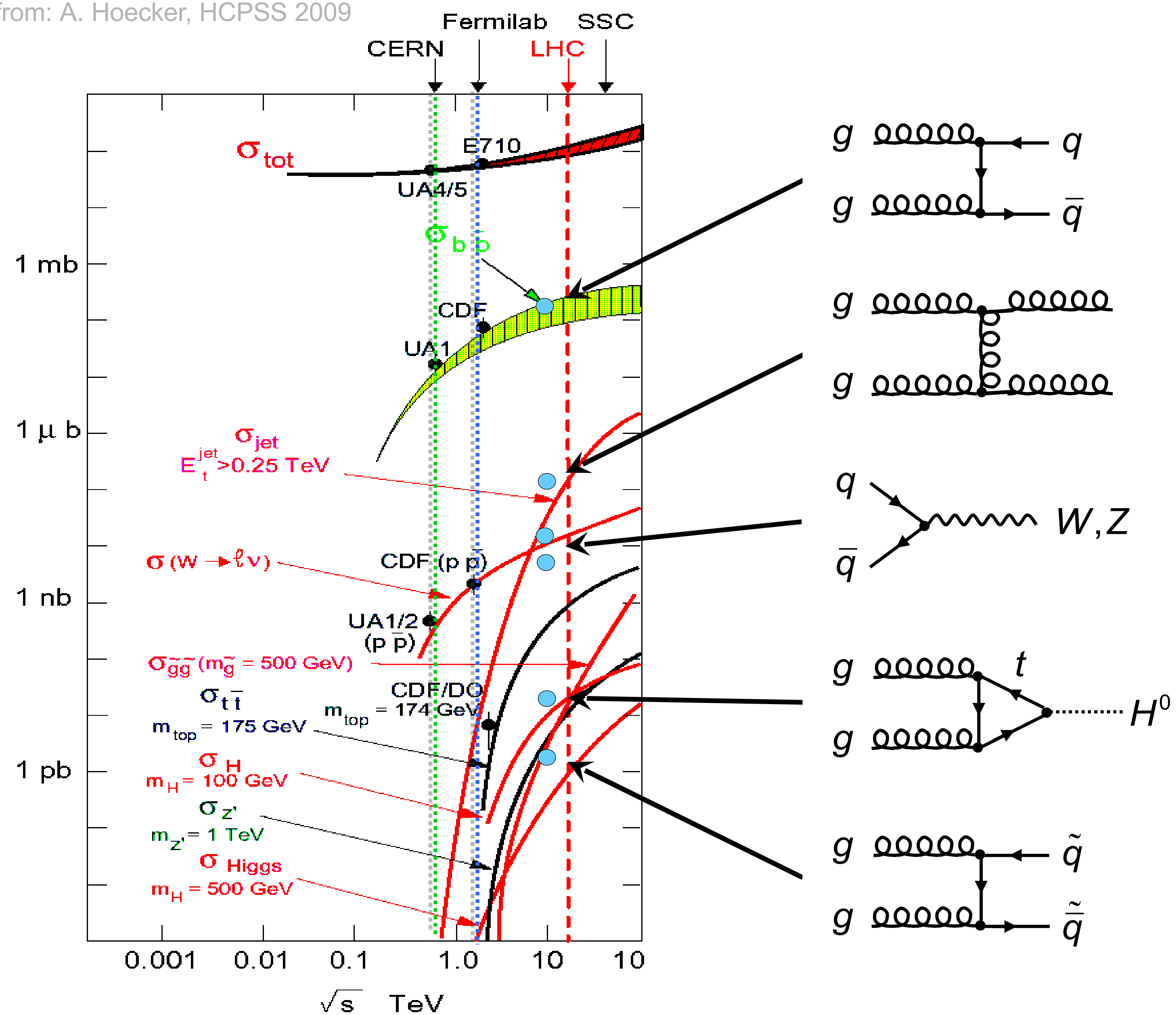
* Assume 50% accelerator duty cycle

Too much data to be archived (and re-processed offline)

- Cannot sustain data throughput with current technology
- **Too costly!**

Why do we need a trigger?

Slide from: A. Hoecker, HCPSS 2009



Quark-flavour production

High-p_T QCD jets

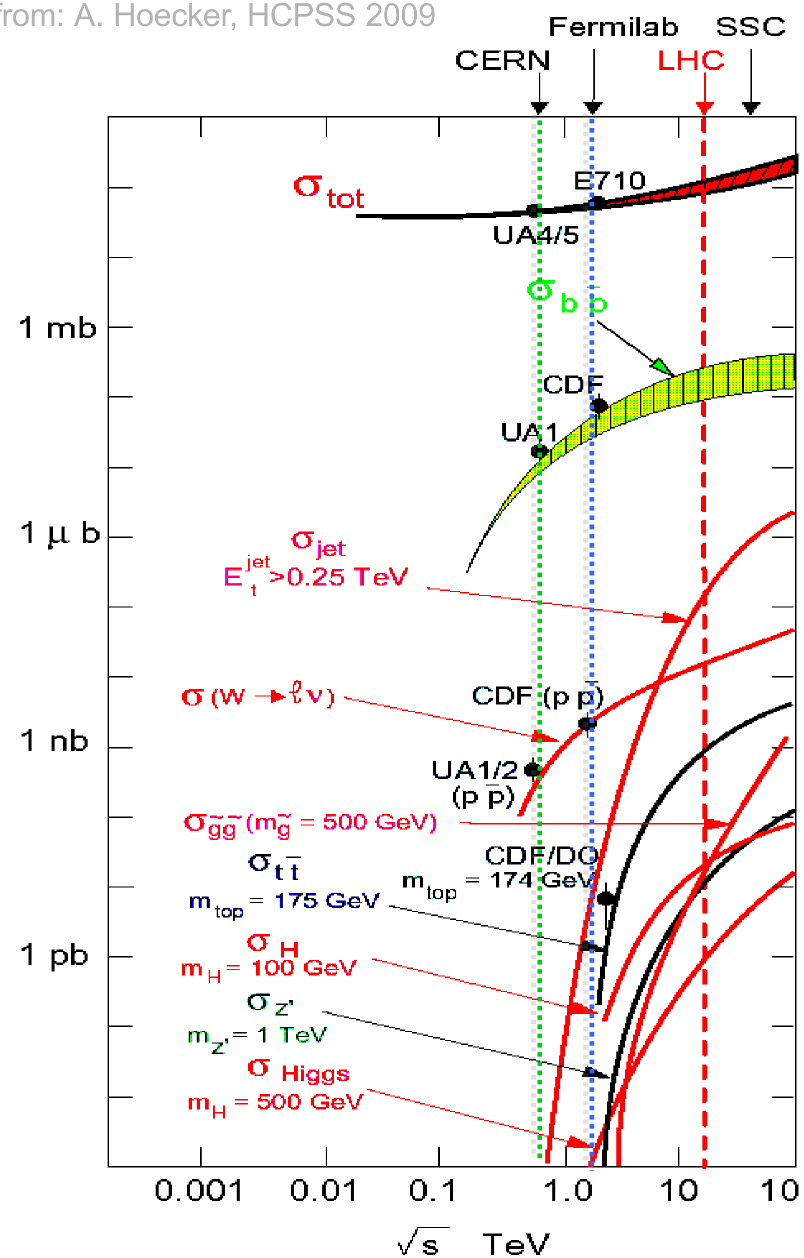
W, *Z* production

gluon-to-Higgs fusion

squarks, gluinos
(m ~ 1 TeV)

Why do we need a trigger?

Slide from: A. Hoecker, HCPSS 2009



Process	Cross-section (nb) at 14 TeV CM energy	Production rates (Hz) at L = 10^{34} cm^{-2} s^{-1}
Inelastic	10^8	10^9
$b\bar{b}$	$5x10^5$	$5x10^6$
$W \rightarrow l\, \nu$	15	150
$Z \rightarrow l\, l$	2	20
$t\,\bar{t}$	1	10
Z' (1 TeV)	0.05	0.5
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.5
H (120 GeV)	0.04	0.4
H (180 GeV)	0.02	0.2

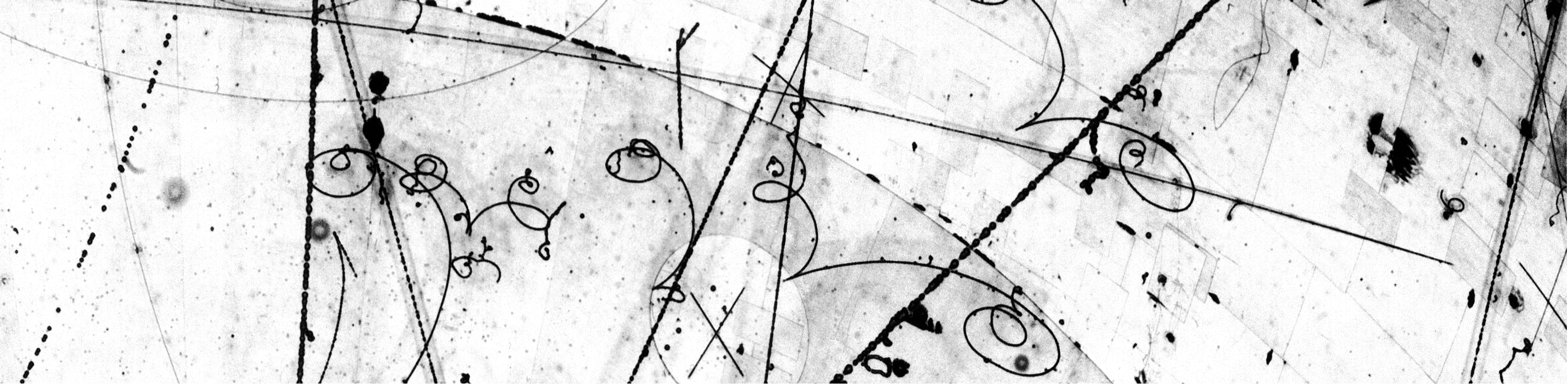
Trigger/DAQ Requirements

The Trigger must

- select with high efficiency signal(s) of interest.
  - need to be able to precisely calculate trigger efficiency.
  - avoid biases affecting physics results.
  - REJECTED EVENTS ARE LOSS FOREVER!
- achieve high background rejection
  - reduce rate to match DAQ and offline computing capabilities.
- be affordable
  - limited custom electronics and computing power imply that trigger algorithms must be design to have a fast execution time.

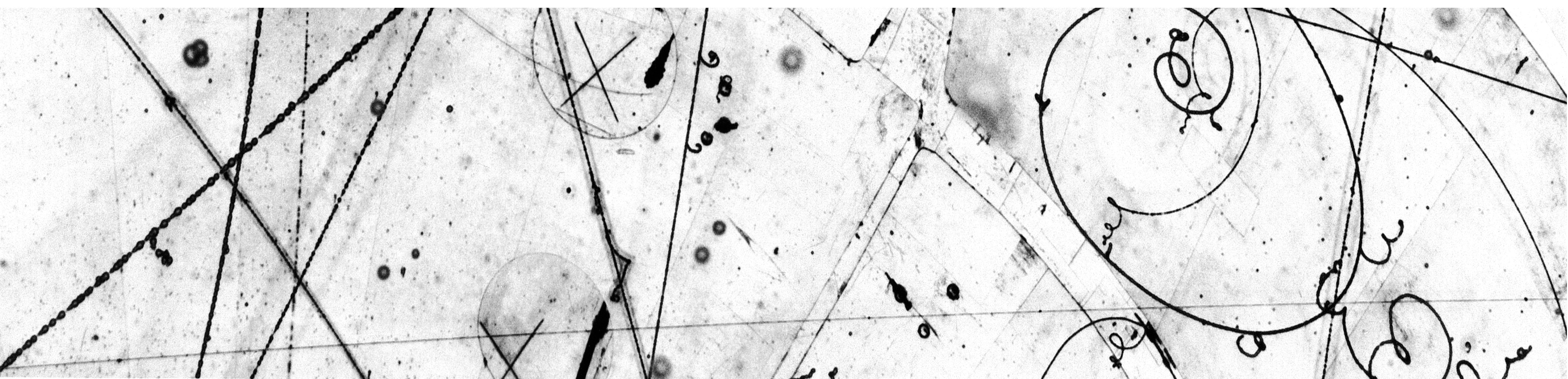
The DAQ system must

- provide online services (run control system, data flow monitoring, detector controls, etc.)
- keep record of data-taking and detector conditions
- avoid data corruption and data loss, check data integrity
- be robust against varying data taking conditions and detector/electronics problems
- provide flexibility to record data in different configuration (commissioning, calibration, physics data-taking)
- minimize dead-time (see later)
- be affordable



Trigger and DAQ Basics

[many of the diagrams/slides taken from Nick Ellis and Andreas Hoecker]



Dead-time

"Dead-time" is the fraction of time an experiment cannot record data.

Sources of dead-time:

- Read-out and trigger dead-time (see next slide)
- Operational dead-time (ex. start/stop data-taking periods)
- T/DAQ downtime (ex. Computer failure)
- Detector downtime (ex. Following a high-voltage trip)

Note that trigger dead-time logic is ***required*** to prevent triggering on another event before the detector is fully read-out!

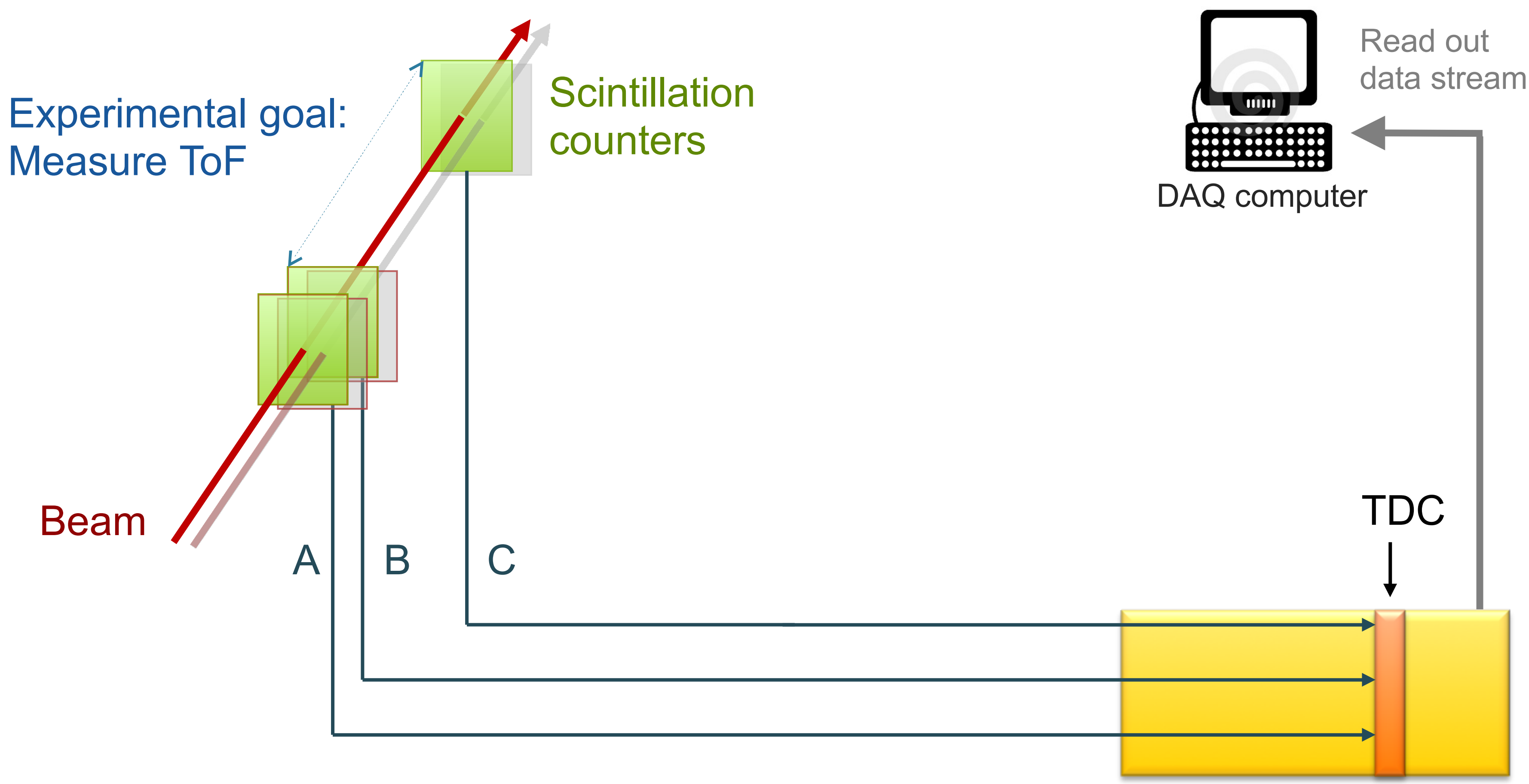
The T/DAQ system must be designed to minimize dead-time
(typically < $\mathcal{O}(10\%)$)

- fully capitalize on important investment in detectors/accelerators
- achieve physics goals in timely manner

A Simple T/DAQ System

[Drawing by Nick Ellis]

Consider an experiment designed to measure the time-of-flight (ToF) of particles passing through scintillation counters and readout with Time-to-Digital Converter (TDC) electronics.



[Simplified diagram omitting many details such as dead-time logic, discriminators, etc.]

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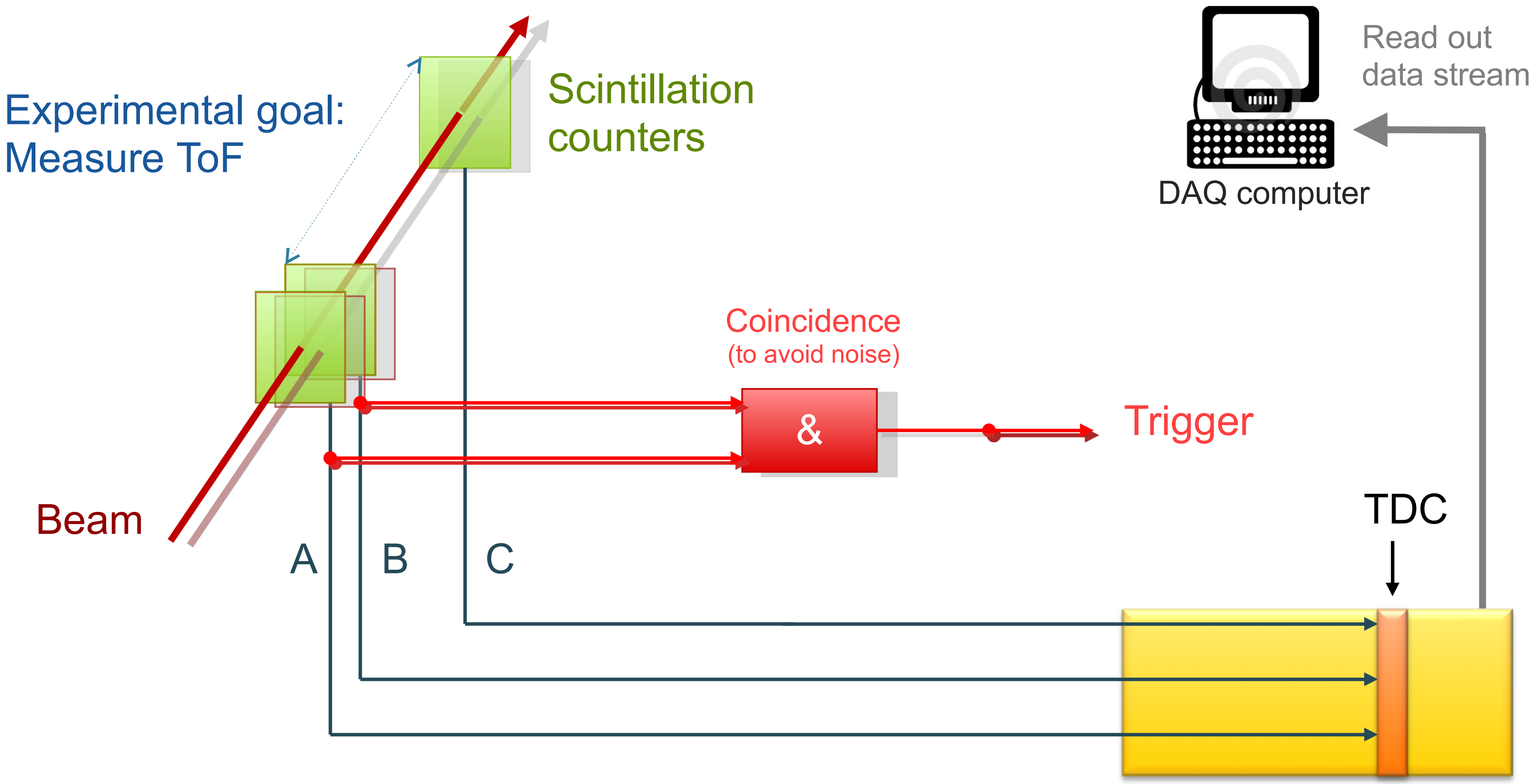

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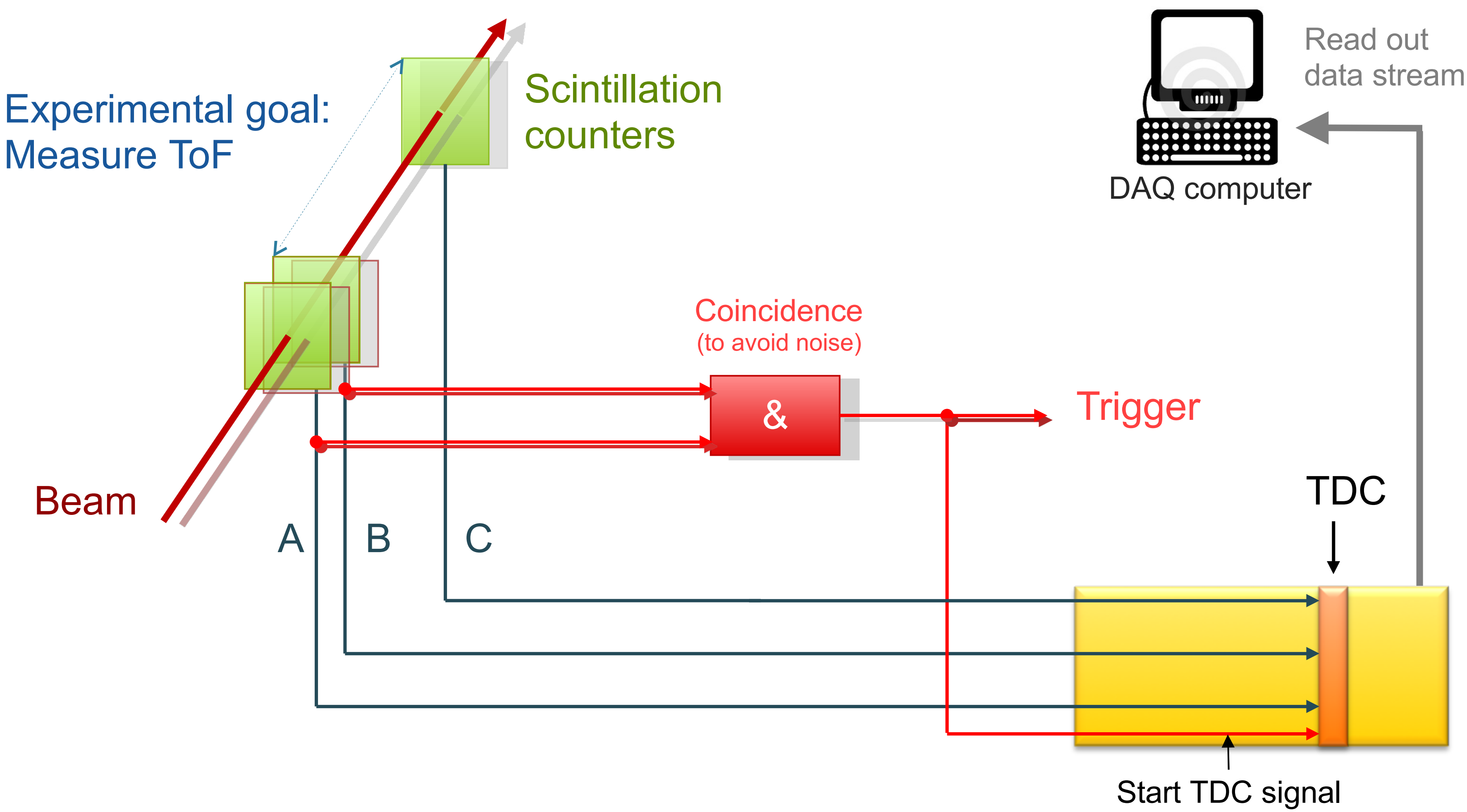

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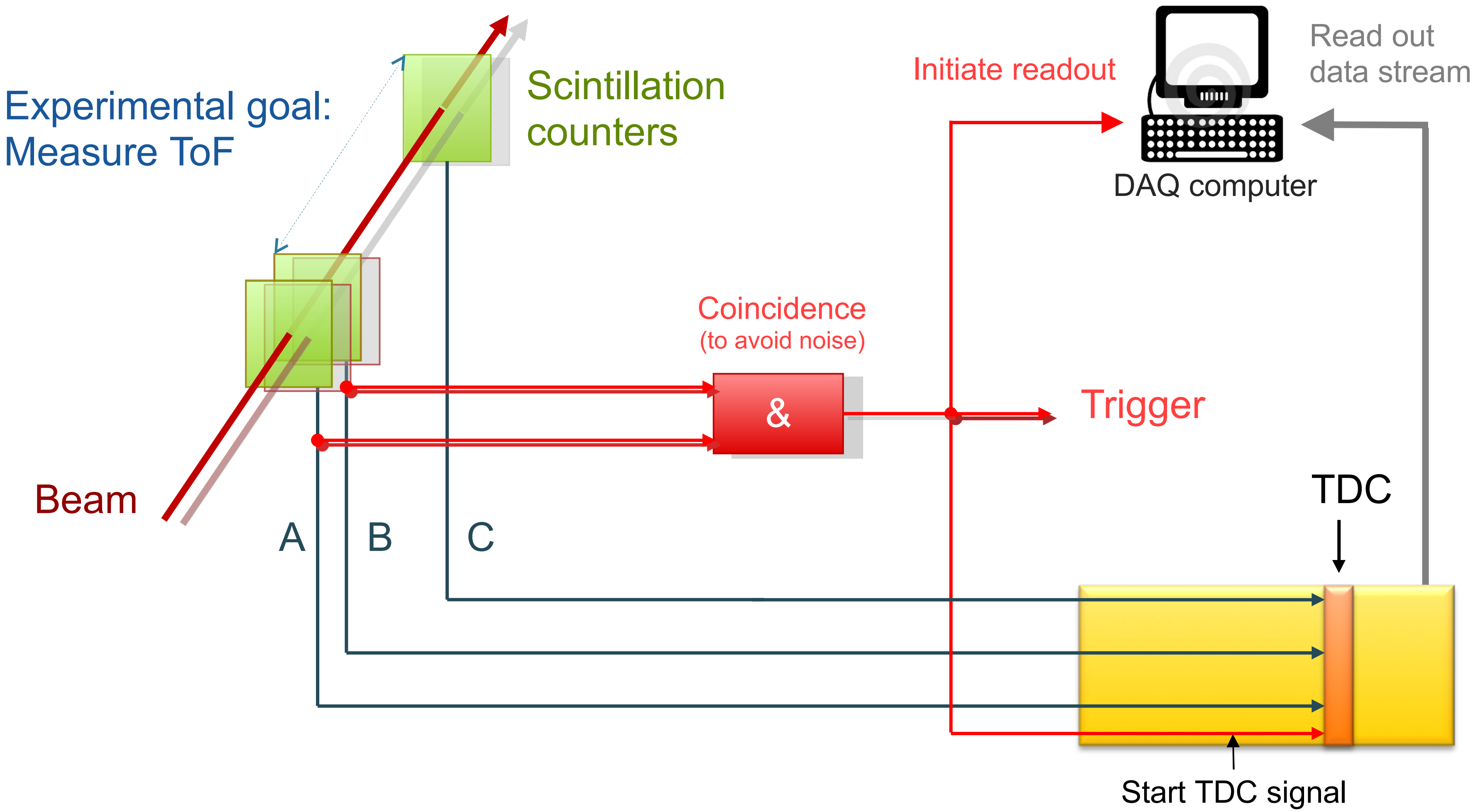

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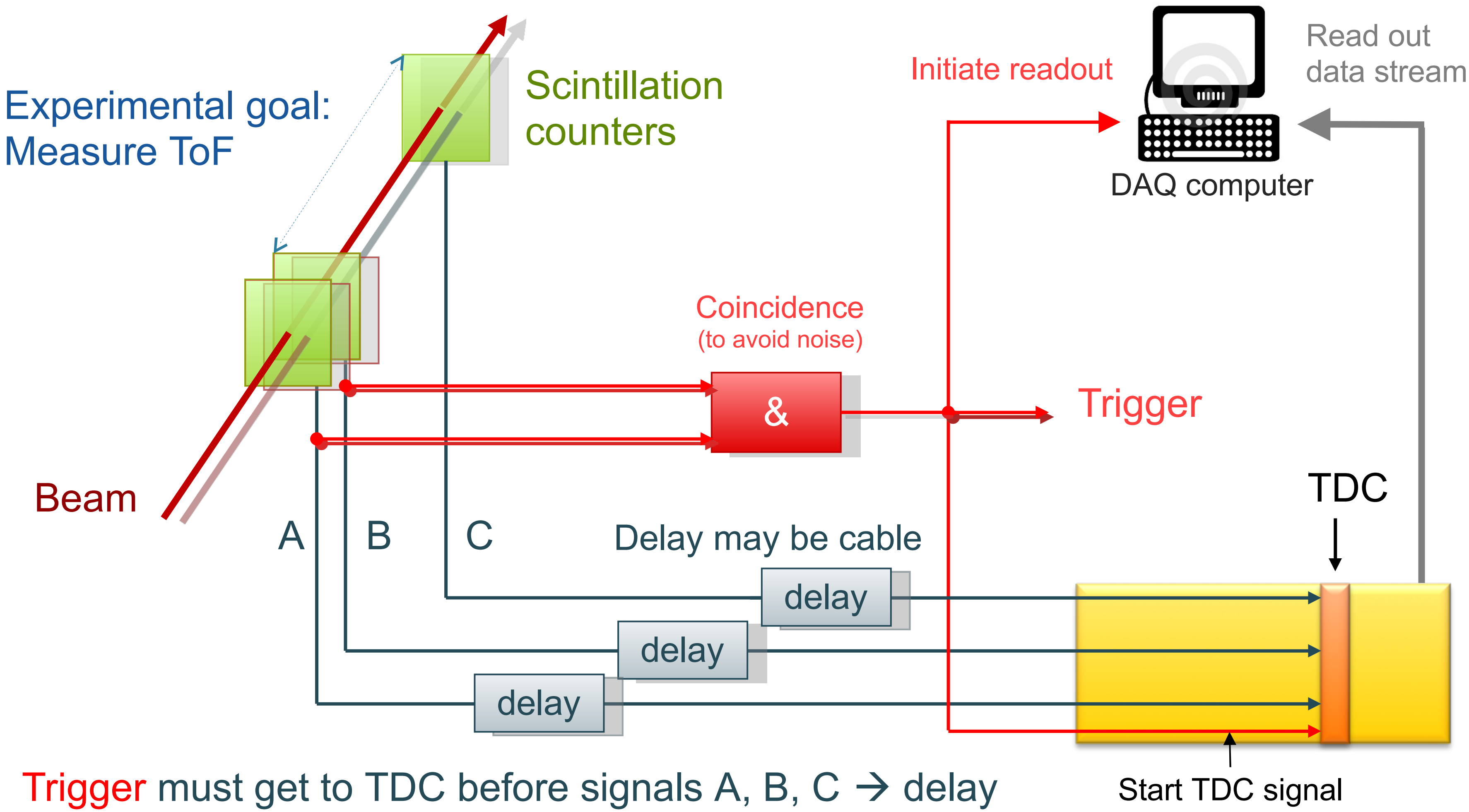


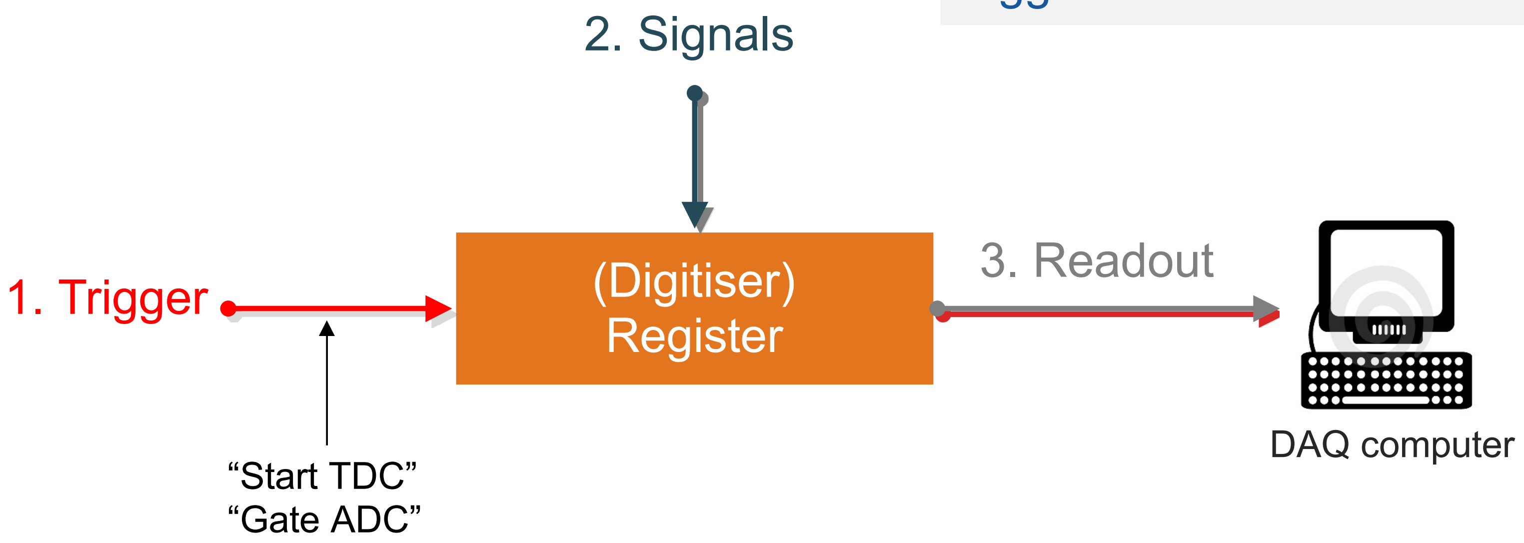
Trigger must get to TDC before signals A, B, C → delay

[Simplified diagram omitting many details such as dead-time logic, discriminators, etc.]

A Simple T/DAQ System

[Drawing by Nick Ellis]

Readout dead-time:
trigger rate × **full** readout time



A Simple T/DAQ System

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Readout dead-time:
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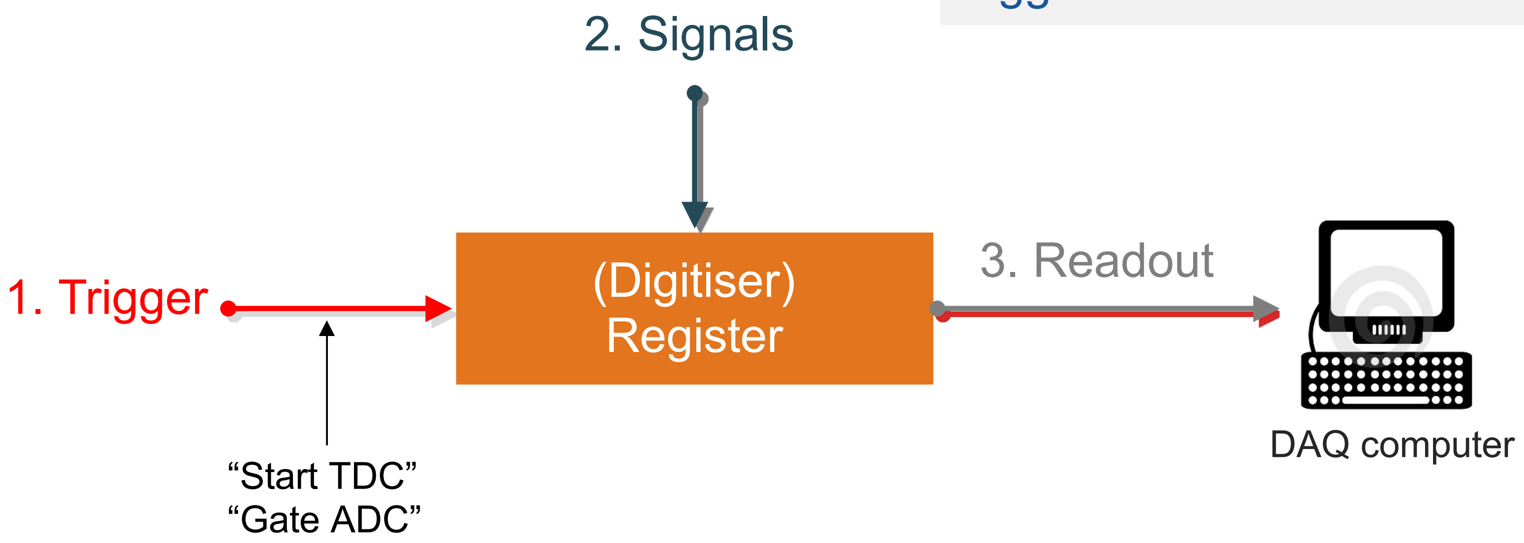
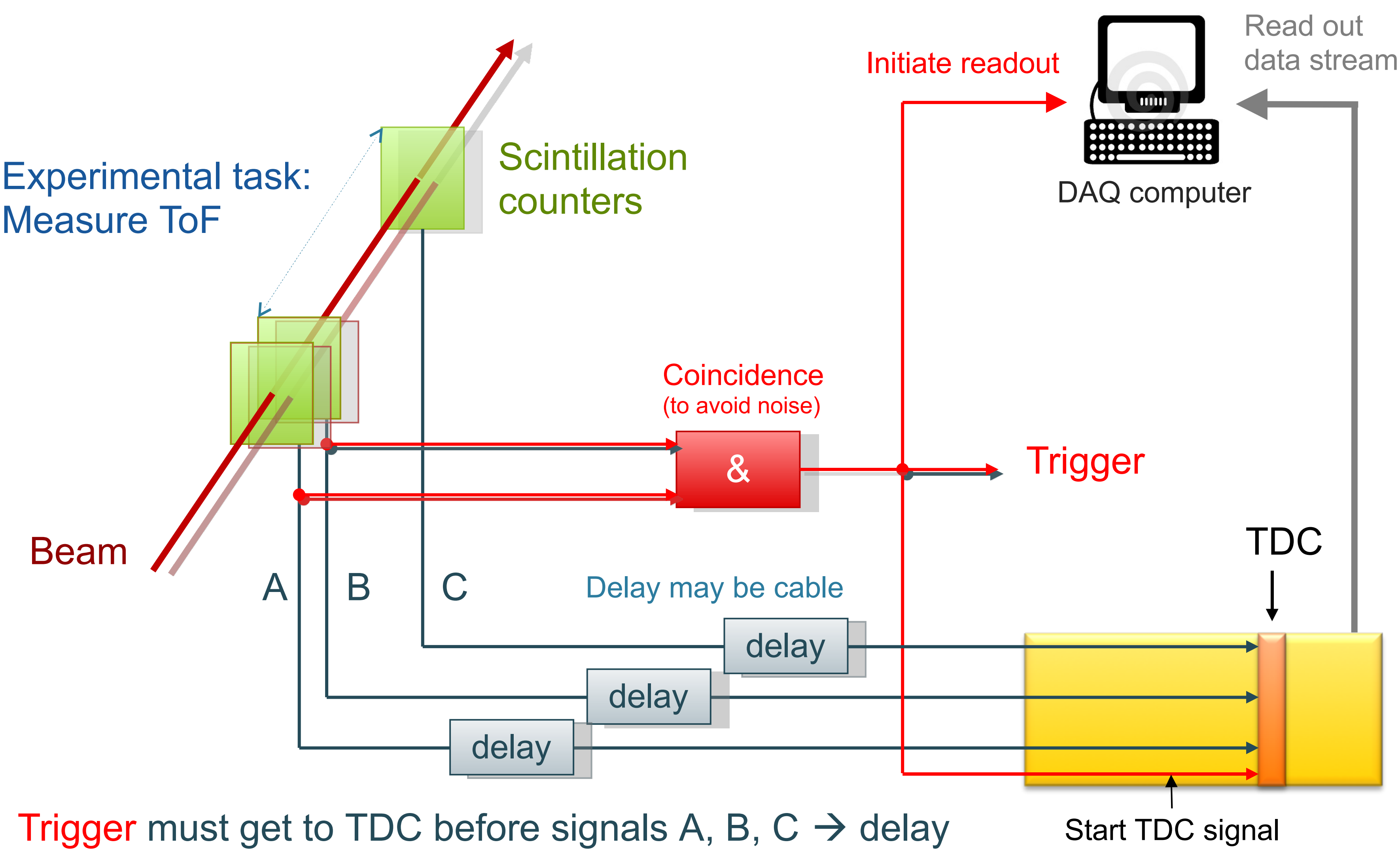


<u>Limitations:</u>

- Trigger decision must be made very quickly to "start" TDC before detector signals arrive.
- TDC readout to DAQ computer quite slow.
  - Significant dead-time if trigger rate is high

Fast Local Memory Readout

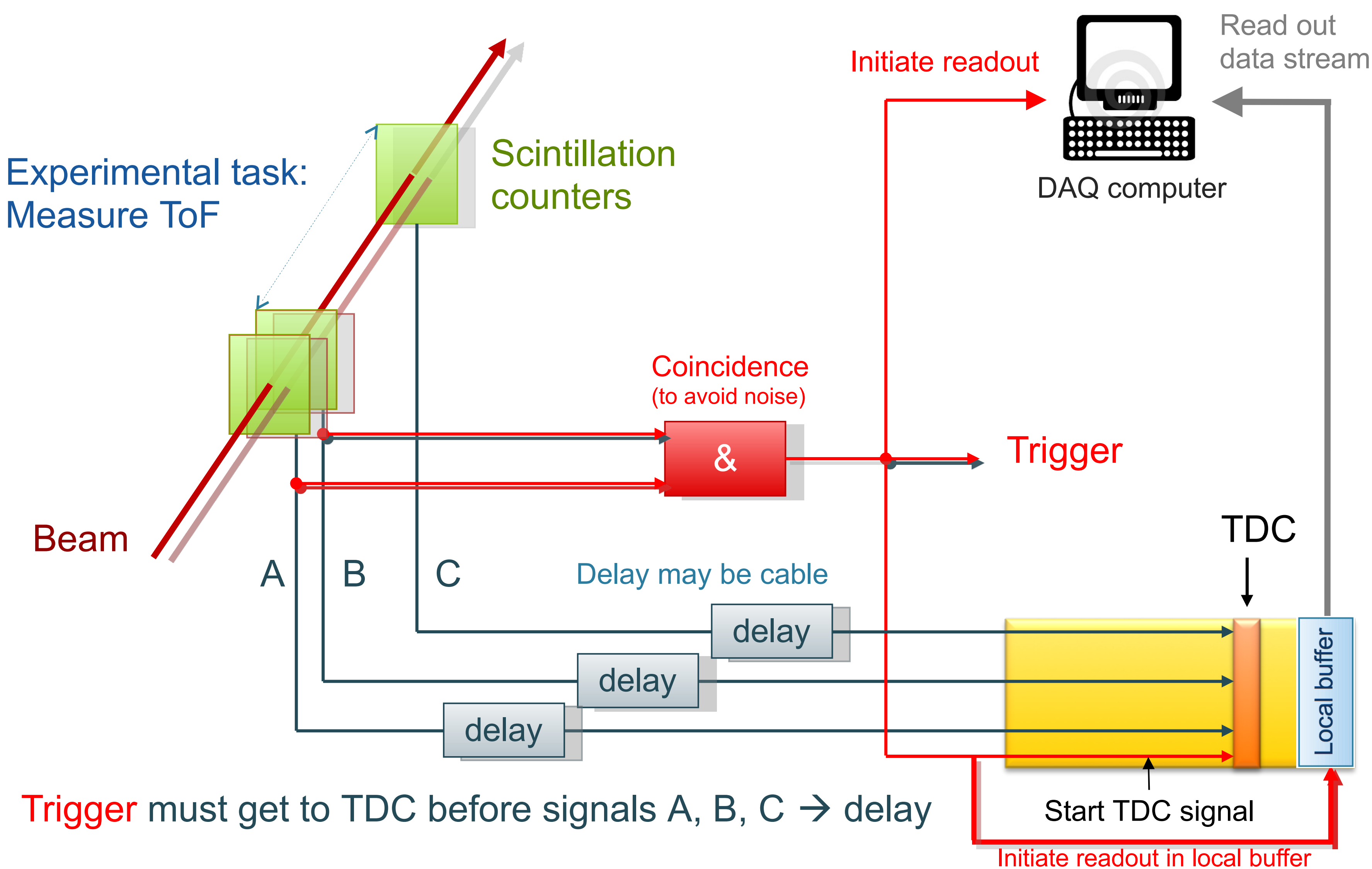
[Drawing by Nick Ellis]



Trigger must get to TDC before signals A, B, C → delay

Fast Local Memory Readout

[Drawing by Nick Ellis]

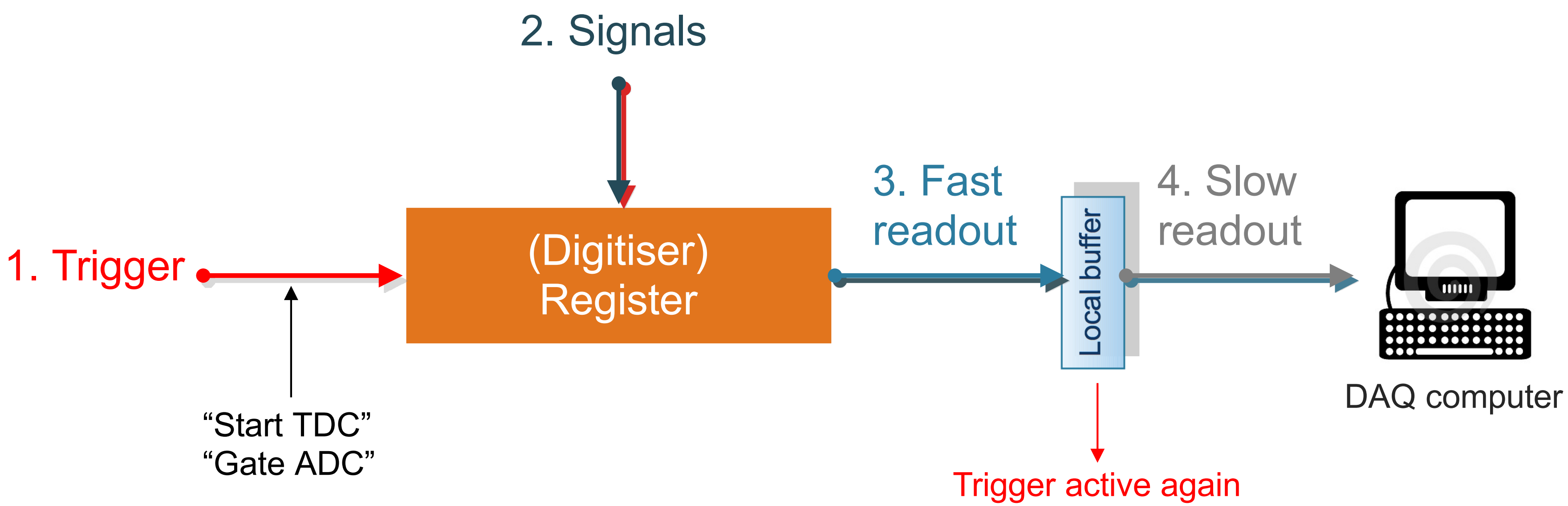


Trigger must get to TDC before signals A, B, C → delay

Fast Local Memory Buffer

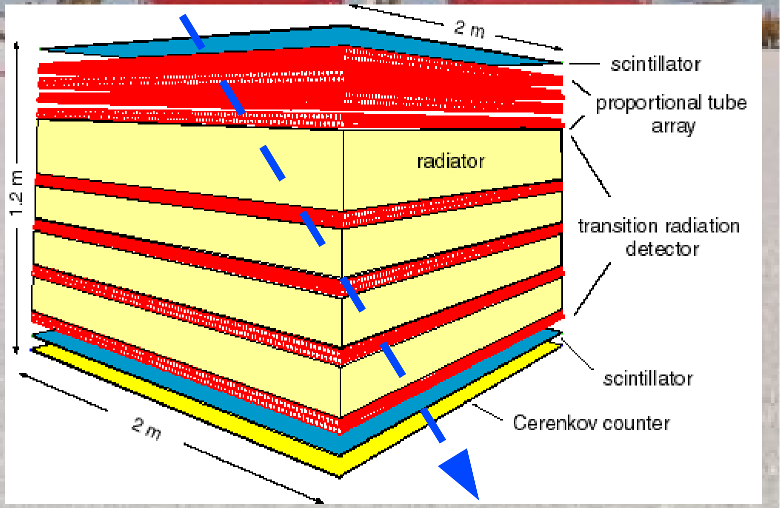
[Drawing by Nick Ellis]

Readout dead-time:
trigger rate × **local** readout time



Example: TRACER experiment

The Transition Radiation Array for Cosmic Energetic Radiation (TRACER) is a balloon-born experiment to measure the composition of cosmic ray nuclei.

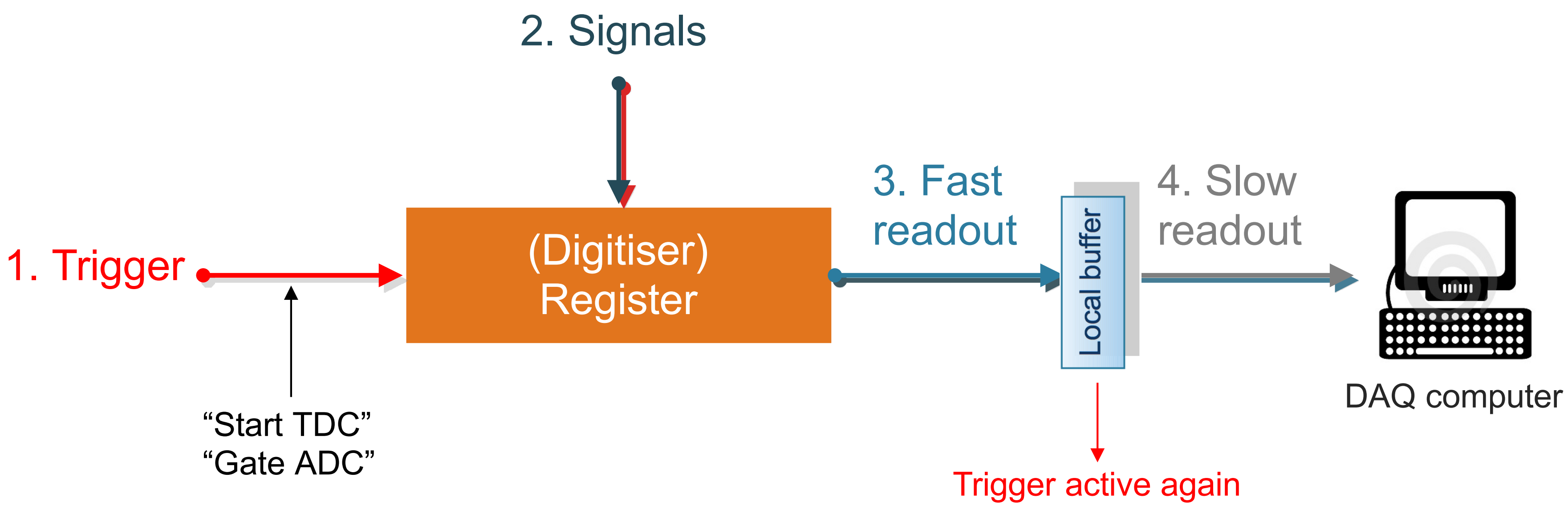


Trigger requires coincidence of two scintillator planes
Trigger rate ~ 60-100 Hz

Fast Local Memory Buffer

[Drawing by Nick Ellis]

Readout dead-time:
trigger rate × **local** readout time



<u>Limitations:</u>

- Trigger decision must be made very quickly to "start" TDC before detector signals arrive.
  - Not possible to apply complex selection criteria

Multi-level trigger

Often cannot achieve requirements of high signal efficiency and high background rejection with an extremely short trigger "*latency*" (i.e. time to form trigger decision and distribute it to digitisers).

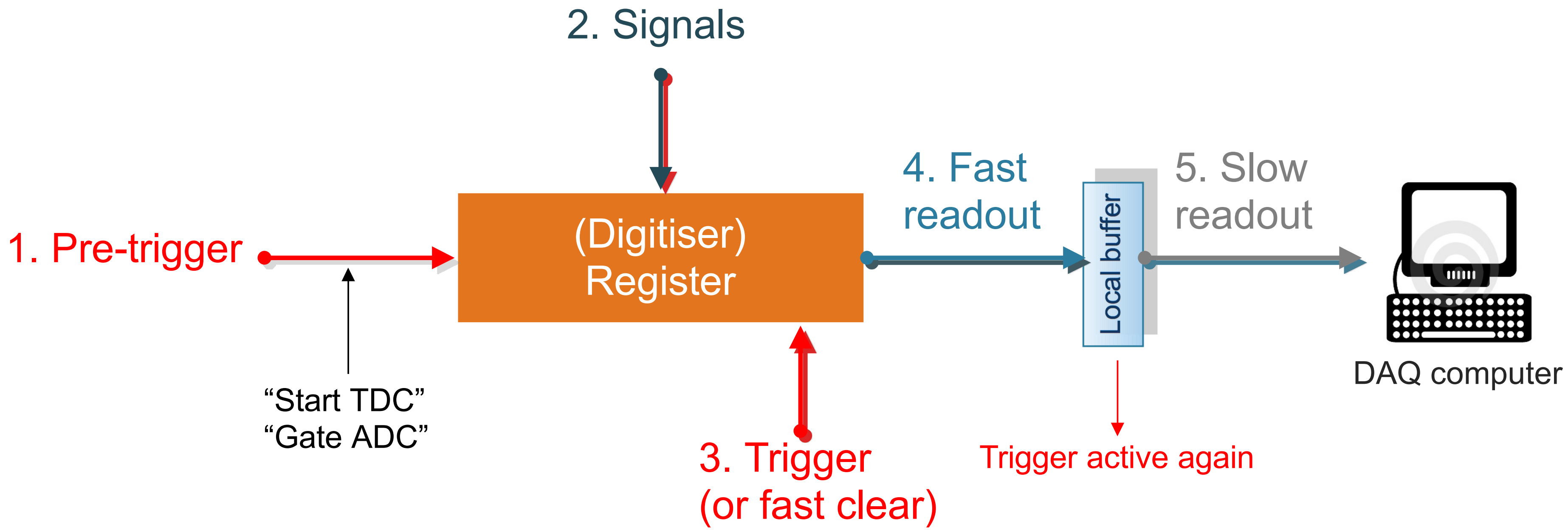
Need to introduce the concept of ***multi-level trigger***:

- first trigger level has very short latency, high signal efficiency but modest background rejection
  - Sometimes called "pre-trigger"
  - May be sufficient to just signal presence of minimal activity in detector
- subsequent trigger level(s) achieve high background rejection, with typically larger latency.

Multi-level trigger

[Drawing by Nick Ellis]

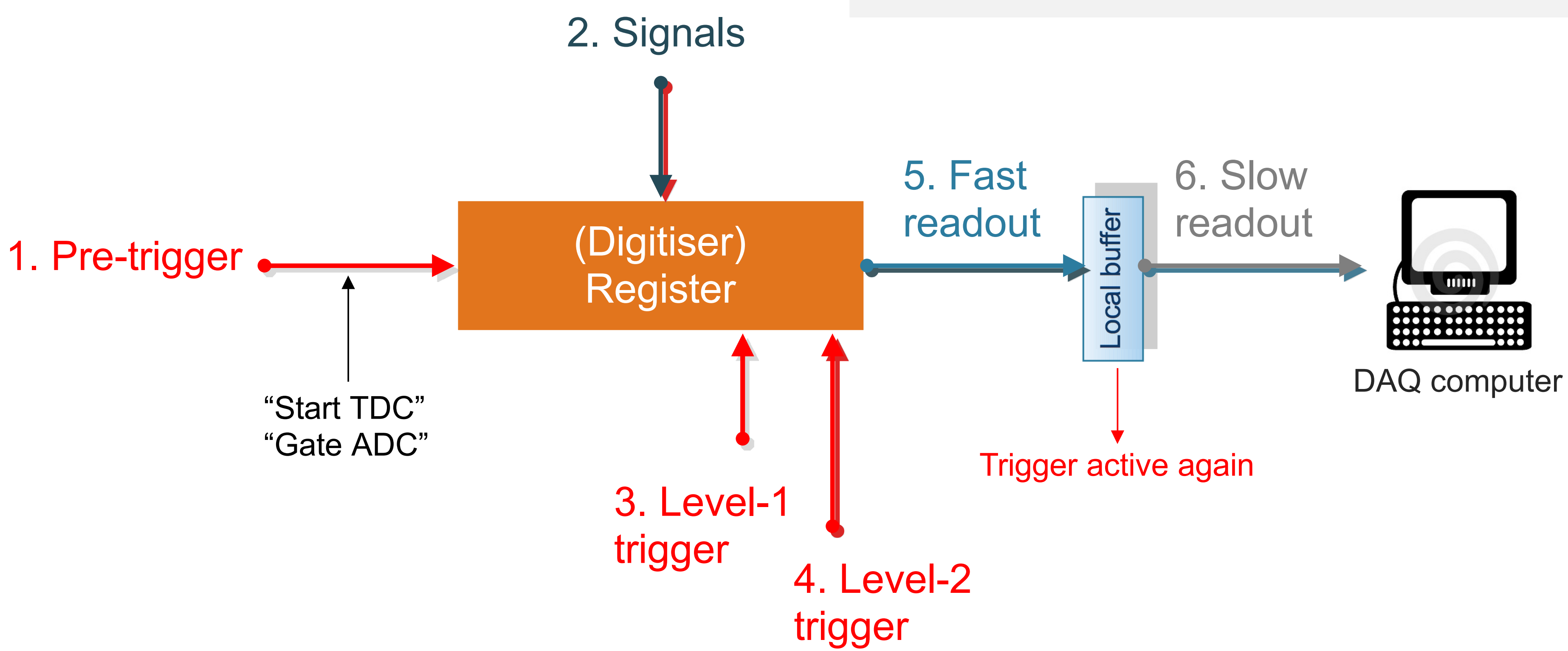
Readout dead-time
[trigger rate × **local** readout time]
+
Total trigger dead-time
[pre-trigger rate × trigger latency]



Multi-level trigger

[Drawing by Nick Ellis]

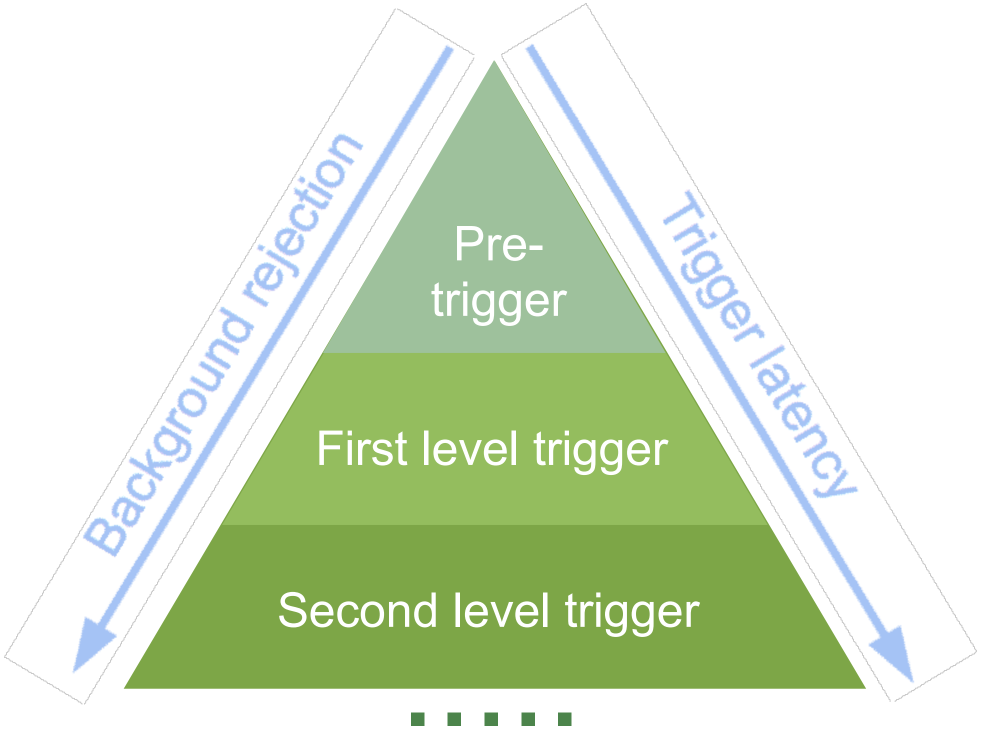
Readout dead-time
[L2 trigger rate × **local** readout time]
+
trigger dead-time
[(pre-trigger rate × L1 latency) +
(L1 rate x L2 latency)]



Multi-level trigger

Can extend the idea of multi-level trigger to more than two levels

Need to keep a high efficiency for signal events at all trigger levels



Total deadtime = (total trigger deadtime) + (readout time)

$$= \left(\sum_{i=2}^{N} R_{i-1} \times L_i\right) + \left(R_N \times T_{\mathrm{LR}}\right)$$

R_i = Rate after i^{th} level

L_i = Latency of i^{th} level

T_{LR} = Local readout time

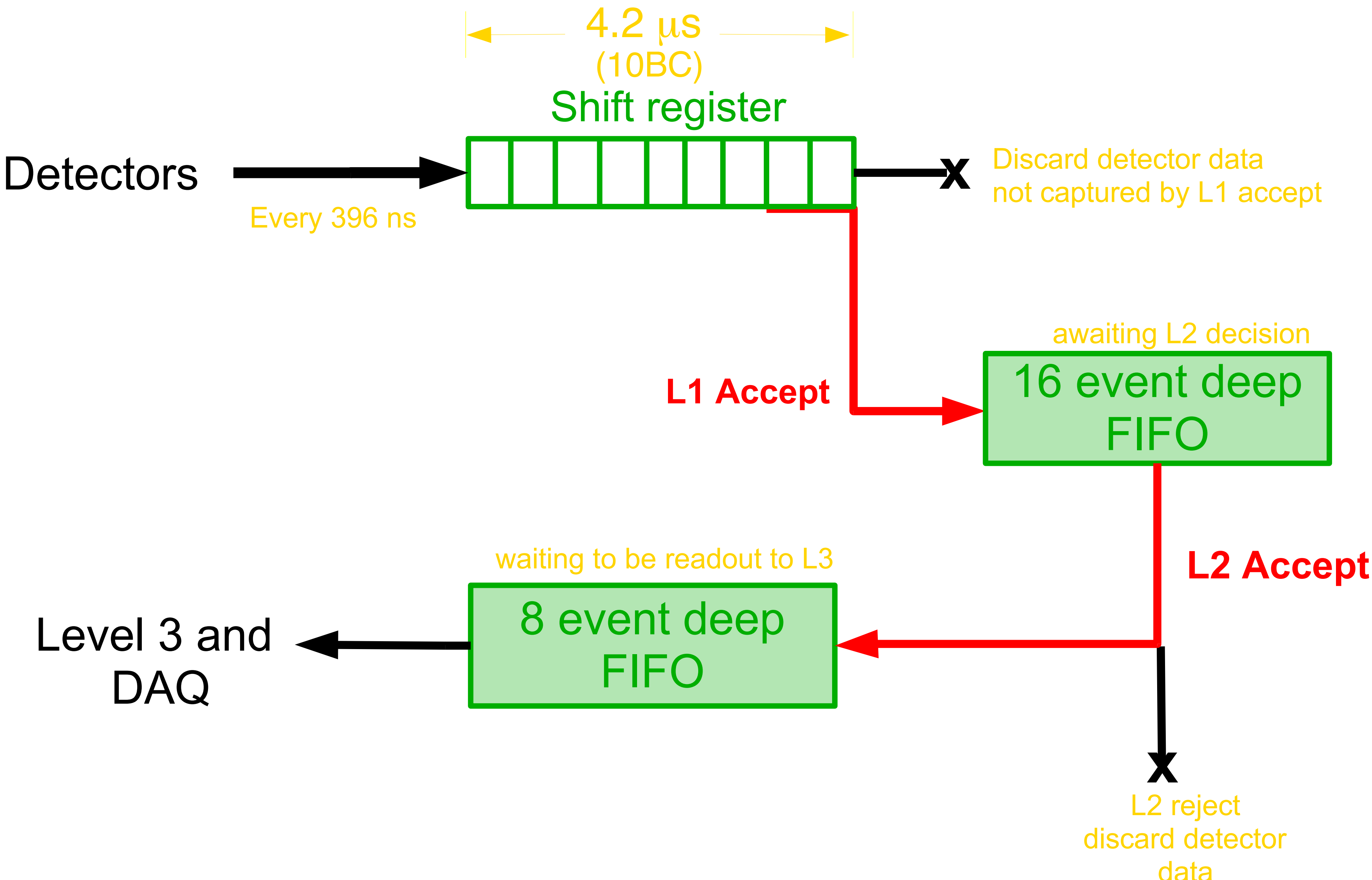
Further Improvements

Limitations:

All trigger levels must be completed before readout starts, which implies long deadtime for events passing the first (fast) trigger levels.

> Deadtime can be reduced by reading out to intermediate storage all events passing the initial stages of trigger selection, after that, low-level triggers can be accepted in parallel with the execution of later stages of trigger selection on the first event.

Readout Buffering (DØ)



Further Improvements

Limitations:

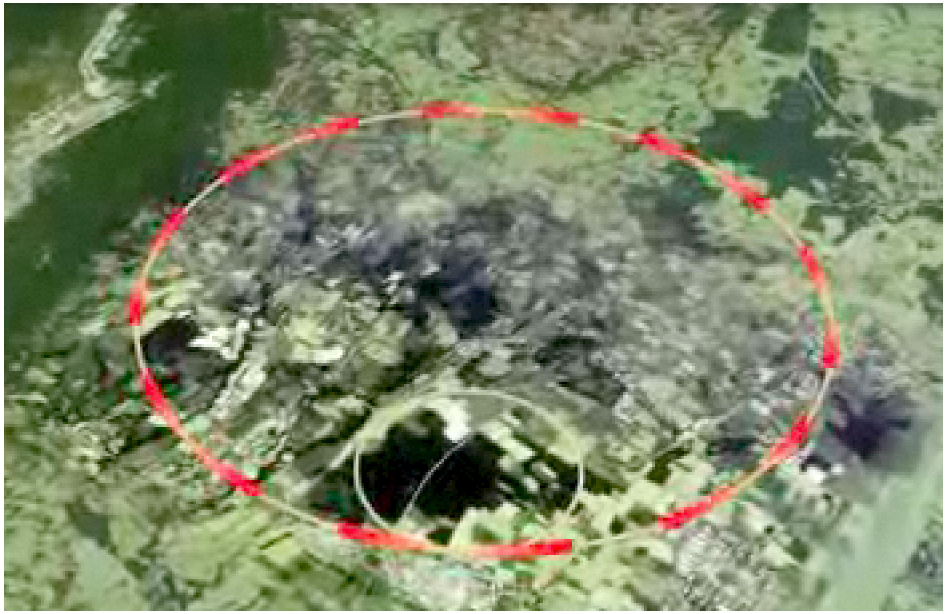
All trigger levels must be completed before readout starts, which implies long deadtime for events passing the first (fast) trigger levels.

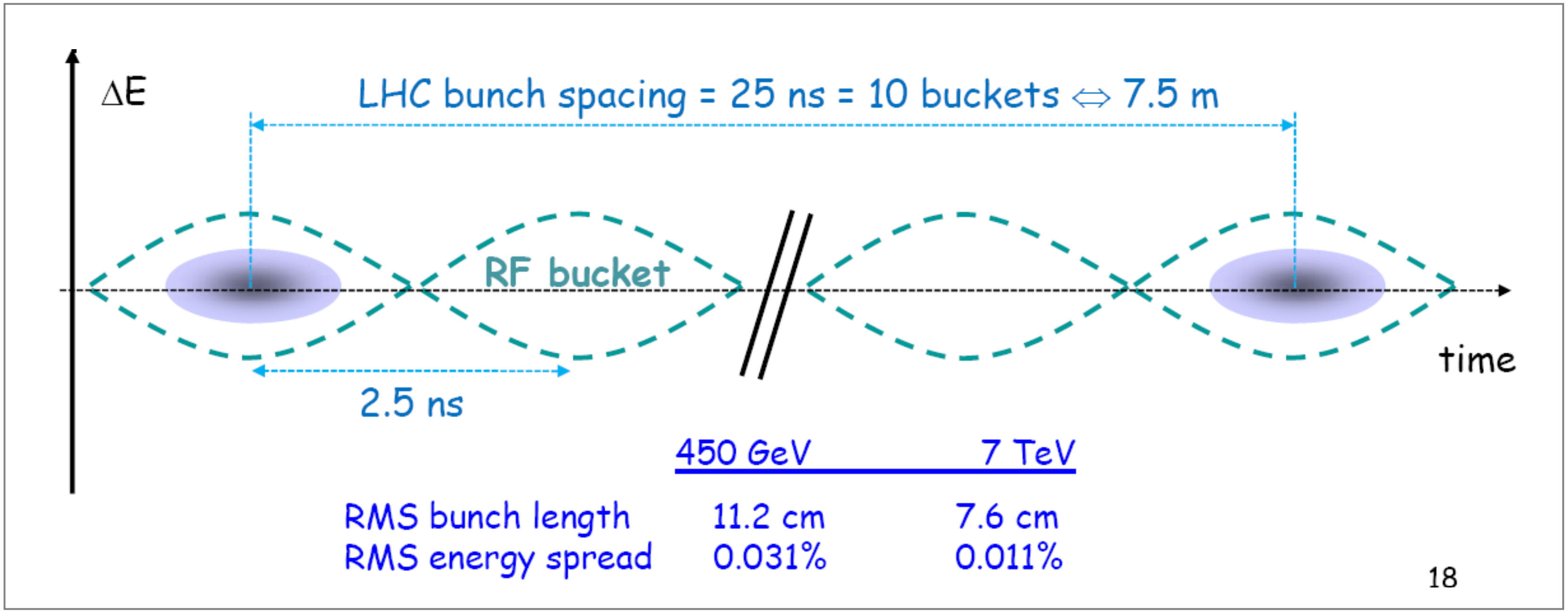
Deadtime can be reduced by reading out to intermediate storage all events passing the initial stages of trigger selection, after that, low-level triggers can be accepted in parallel with the execution of later stages of trigger selection on the first event.

Pre-trigger decision must be available before detector signals arrive to the digitizers.

This limitation can be avoided in collider experiments with bunched beams of particles.

Bunched Beams at Colliders





Collider parameters

	LEP	HERA	PEP-II/KEKB	Tevatron	LHC	ILC
Particles collided	e^+e^-	ep	e^+e^-	pp	pp	e^+e^-
Date of operation	1989-2000	1992-2007	1999-2008 / 1999-now	1987-now	2009-now	TBD
Max beam energy [GeV]	104.6	30 (e) / 920 (p)	8x3.5 / 9x3.1	980	7	250
Luminosity [10^{30} cm^{-2} s^{-1}]	16 (Z) / 100	75	21083 / 12069	402	10 000	20000
Time between collisions [ns]	22000	96	4.2/8	396	25	300
Number of bunches	4	189 (e) / 180 (p)	1732 / 1585	36	2808	2625
Number of particles / bunch (10^{10})	45	3 (e) / 7(p)	5.2 (e^-) 8 (e^+) / 5.7 (e^-) 6.4(e^+)	26(p) / 9($\bar{p}$)	11.5	2

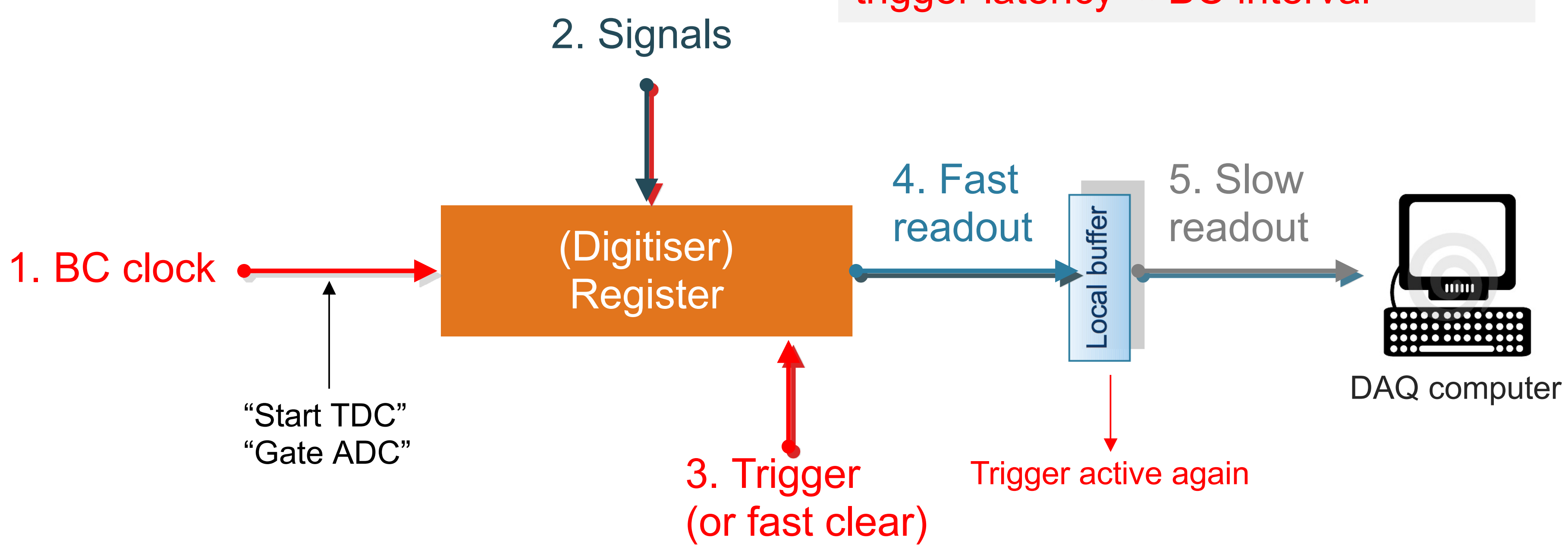
PDG

Bunch crossing as pre-trigger

[Drawing by Nick Ellis]

Readout dead-time:
trigger rate × **local** readout time

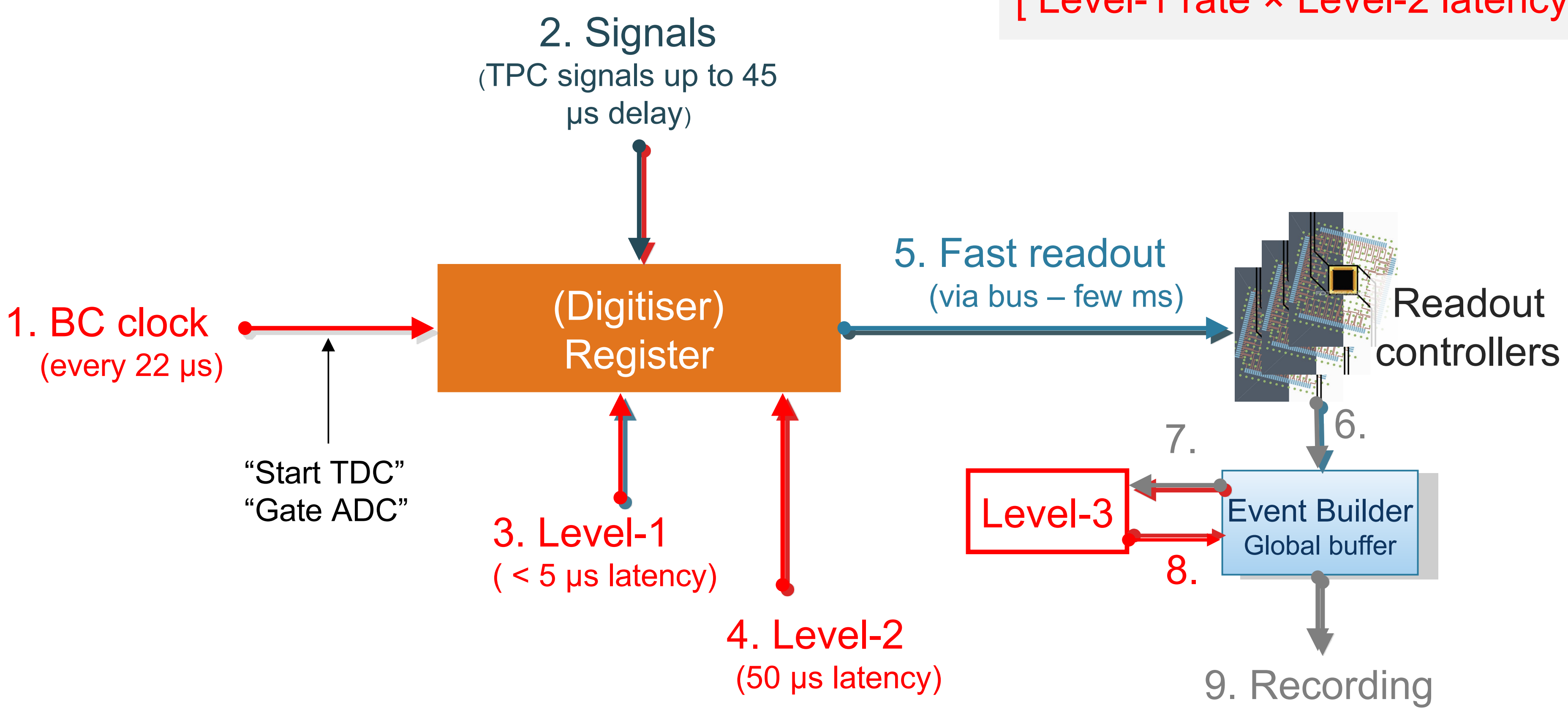
No trigger dead-time if
trigger latency « BC interval



LEP Example (ALEPH)

[Drawing by Nick Ellis]

Readout dead-time
[Level-2 rate × **local** readout time]
+
trigger dead-time
[Level-1 rate × Level-2 latency]



LEP Example (DELPHI)

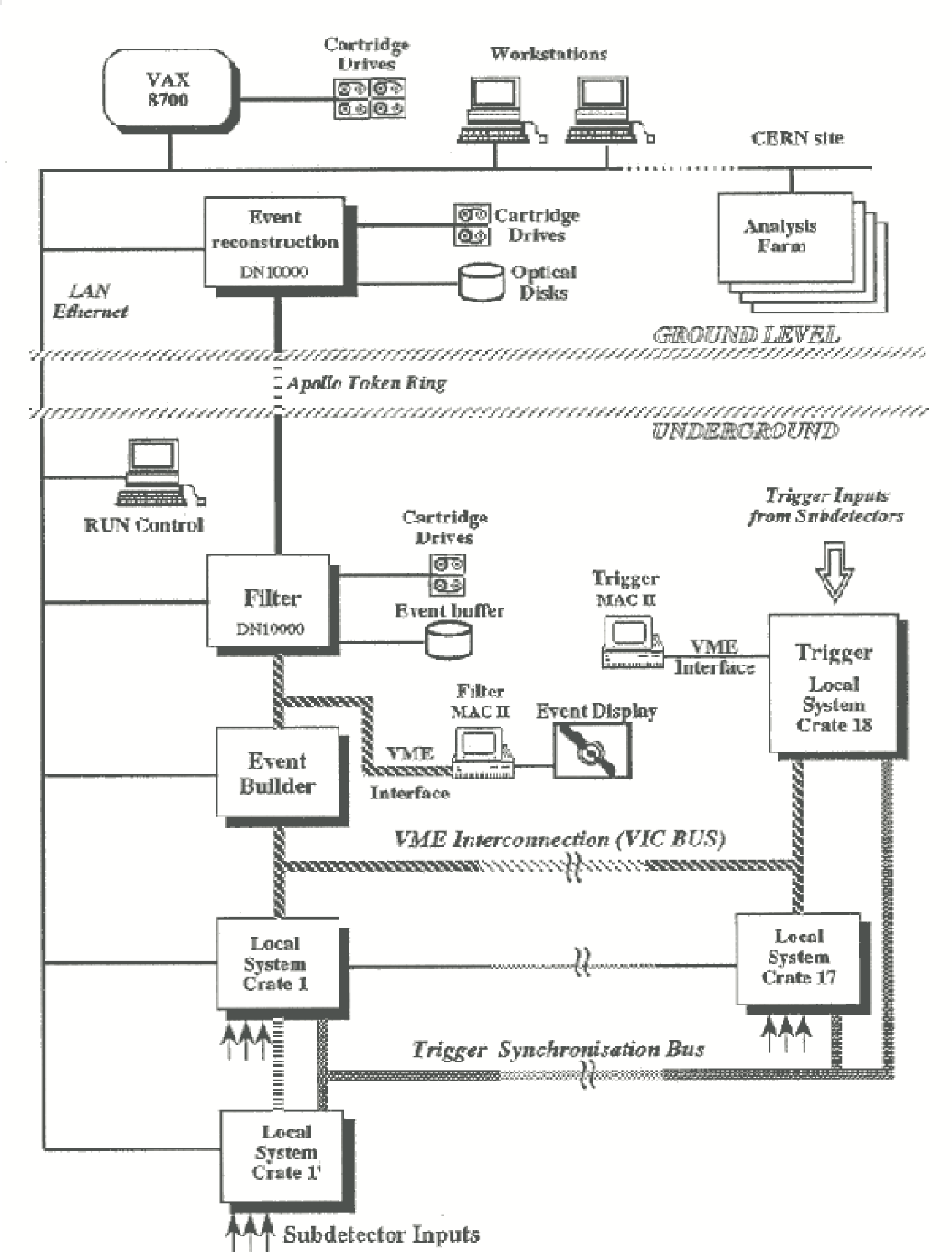
Level-1 rate	~ 500 – 1000 Hz (instrumental bkg?)
Level-2 rate	6-8 Hz
Level-3 rate	4-6 Hz
Level-2 latency	38 μs (1 BC lost → effective latency of 22 μs)
Local readout time	~ 2.5 ms
Recorded data rate	few Hz x *O*(100 kB/event) ≈ few 100 kB/sec [less than maximum of ~40 MB/sec on VME bus]

Readout dead-time
[Level-2 rate × **local** readout time]
+
trigger dead-time
[Level-1 rate × Level-2 latency]

Readout dead-time
[7 Hz × 2.5 ms = 1.8%]
+
trigger dead-time
[750 Hz × 22 μs = 1.7%]

} 3.5%

LEP Example (OPAL)



Data rate throughput:

few Hz x O(100 kB/event) ≈ few 100 kB/s

[less than maximum of ~40 MB/s on VME32 bus]

Bus-based data movement and event building.

Limitations of LEP T/DAQ

The first level trigger decision must be available between bunch crossings.

- Not possible if bunch crossing is too short.
- Need to introduce the concepts of
  - ***pipelined readout***
  - ***pipelined/parallel Level-1 processing***

Bus-based event building and DAQ.

- Not possible for large data rates
- Need to use ***data networks and switches***

Collider parameters

	LEP	HERA	PEP-II/KEKB	Tevatron	LHC	ILC
Particles collided	e^+e^-	ep	e^+e^-	pp	pp	e^+e^-
Date of operation	1989-2000	1992-2007	1999-2008 / 1999-now	1987-now	2009-now	TBD
Max beam energy [GeV]	104.6	30 (e) / 920 (p)	8x3.5 / 9x3.1	980	7	250
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PDG

Pipelined Readout

[Drawing by Nick Ellis]

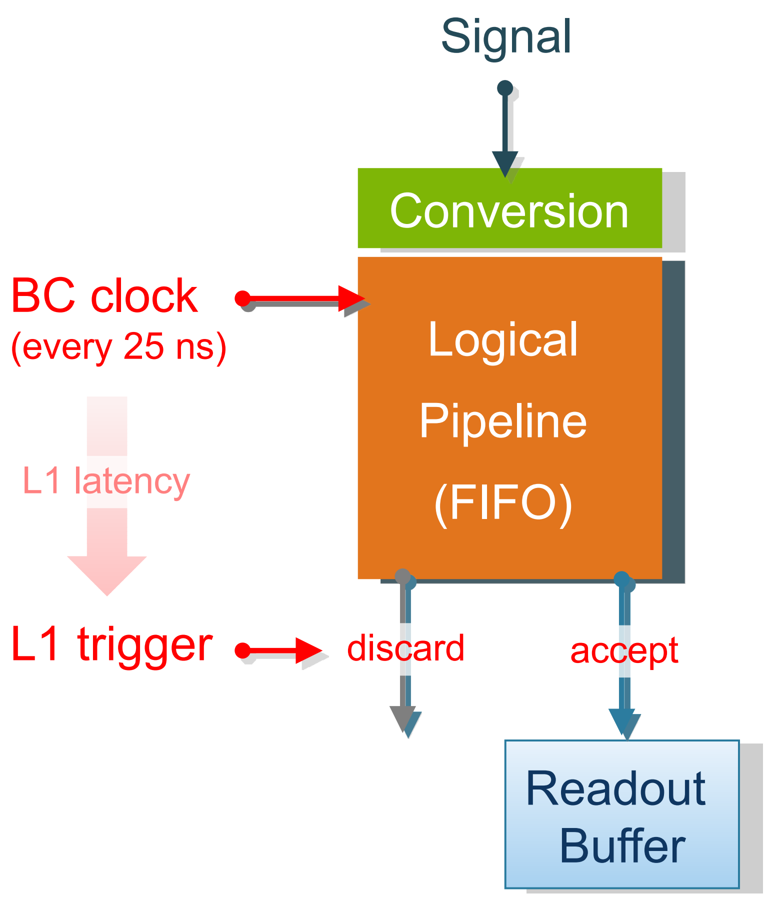
The information from each BC, for each detector element, is retained during the latency of the L1 trigger (few μs)

The information retained may be in several forms

- Analogue level (held on capacitor)
- Digital value (*e.g.* ADC result)
- Binary value (*i.e.* hit / no hit)

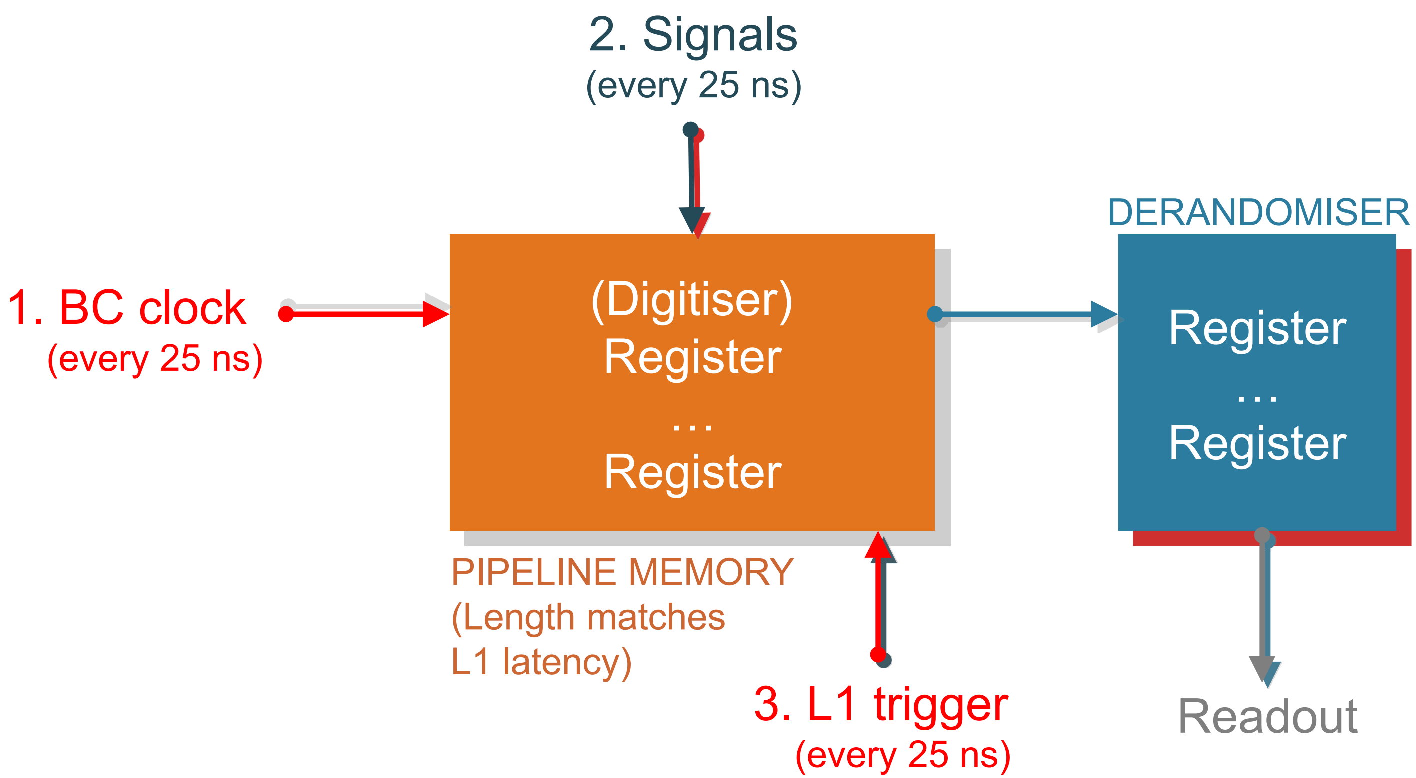
Data reaching end of pipeline is either discarded (large majority of events) or accepted by trigger

Pipelined readout already used at HERA and Tevatron, NA48, BABAR, …



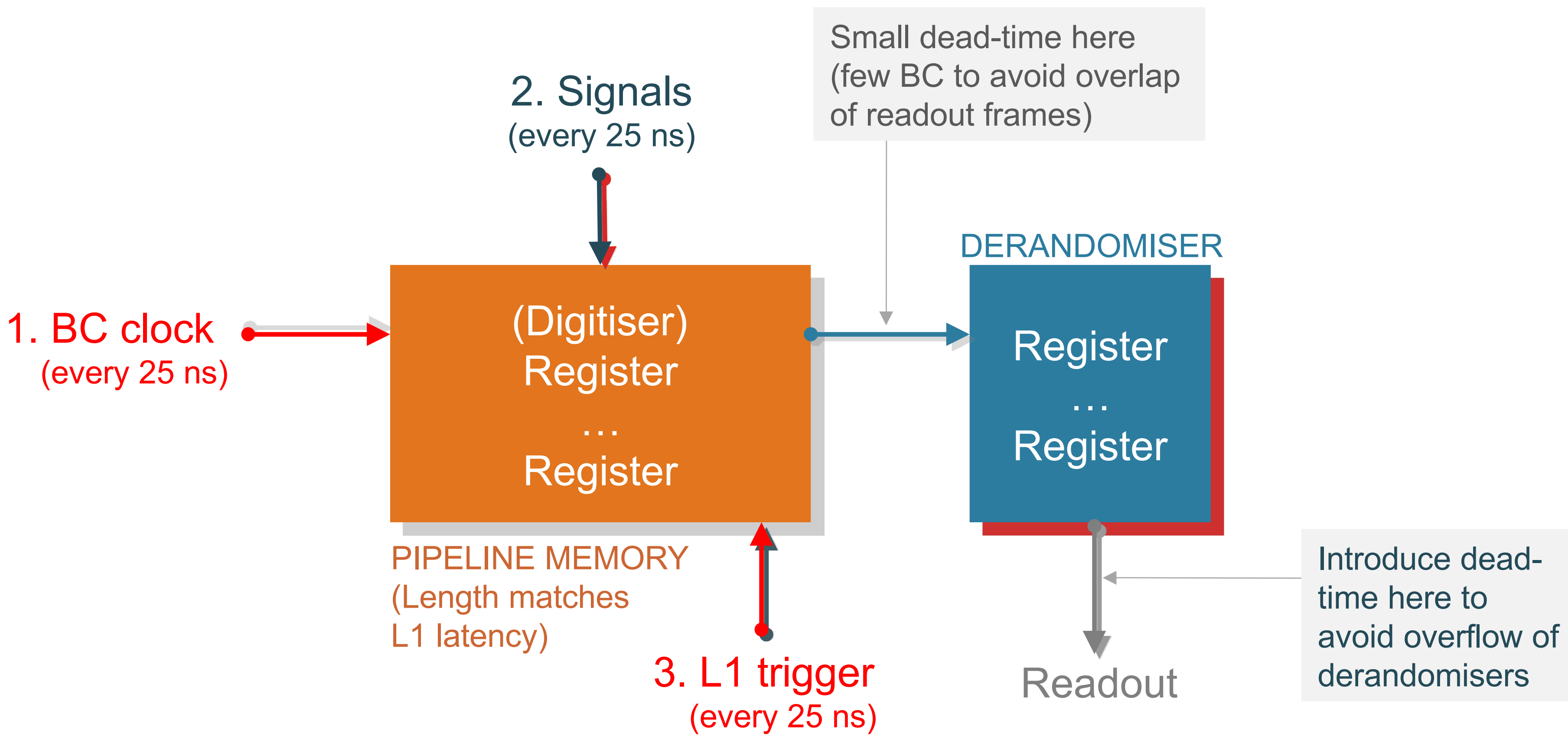
Pipelined Readout (LHC)

[Drawing by Nick Ellis]



Pipelined Readout (LHC)

[Drawing by Nick Ellis]

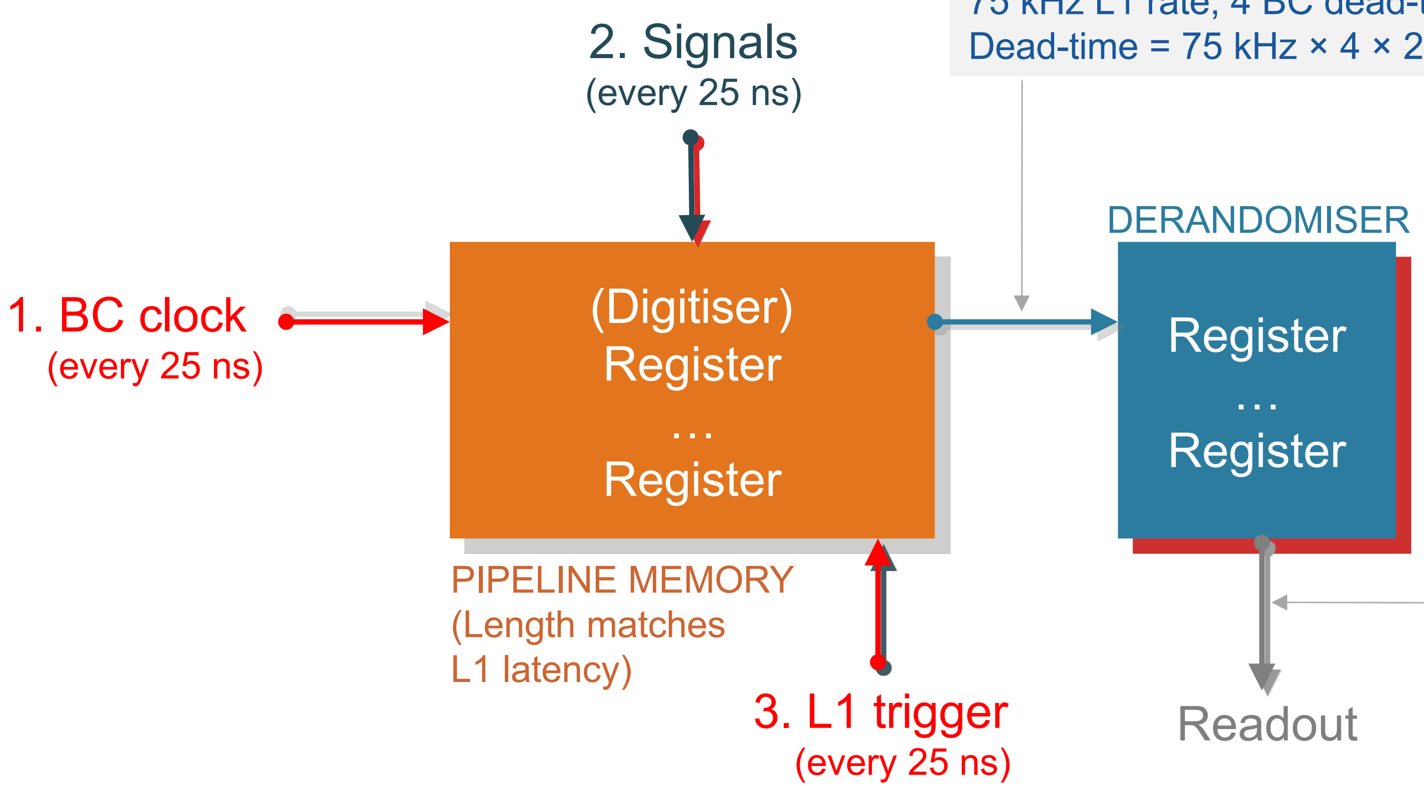


Pipelined Readout (ATLAS)

[Drawing by Nick Ellis]

Dead-time (1)
[*depends on size of readout frame*]

75 kHz L1 rate, 4 BC dead-time
Dead-time = 75 kHz × 4 × 25 ns = 0.75%

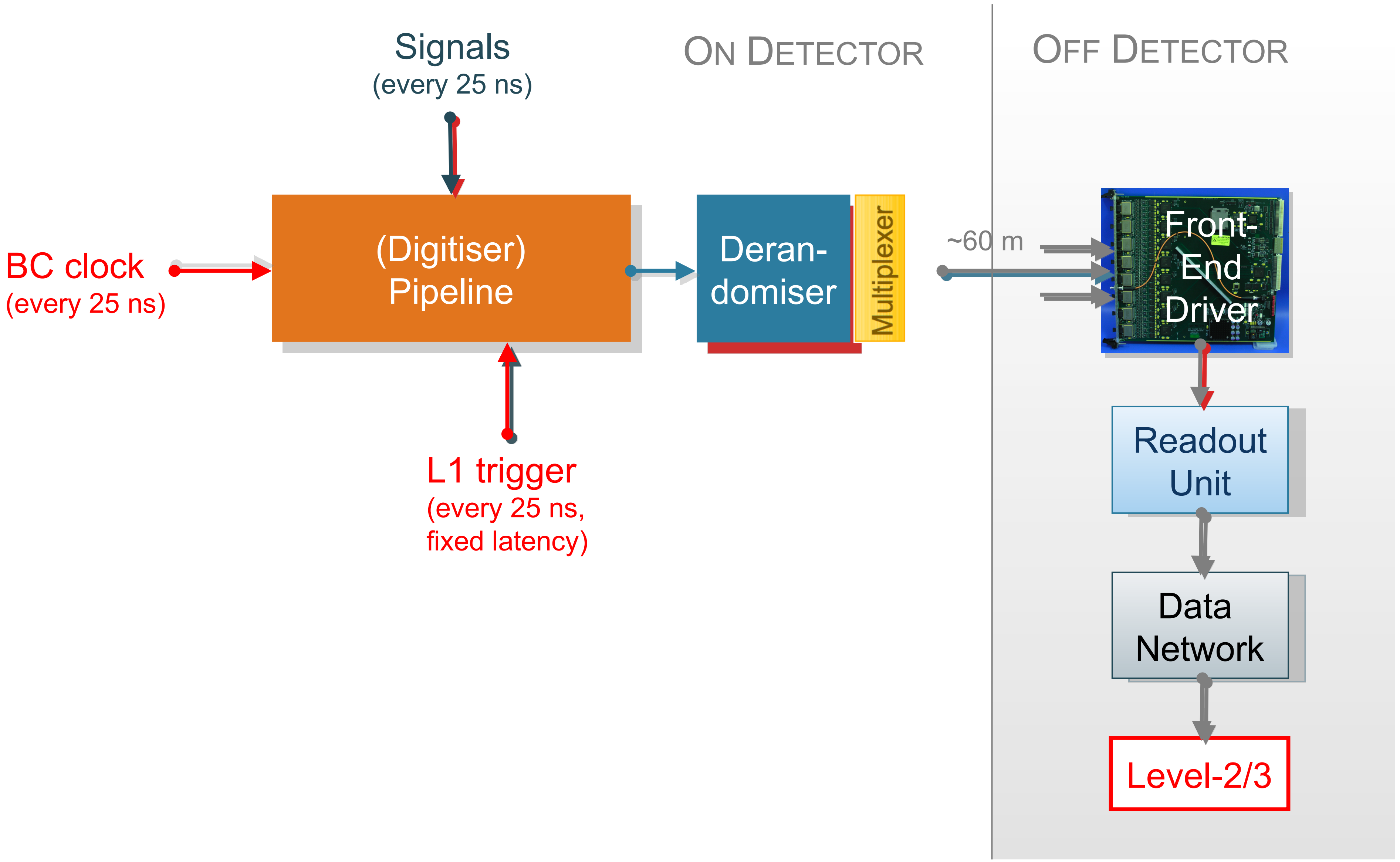


Dead-time (2)
[*depends on size of derandomiser and drain speed*]

Require dead-time
< 1% at 75 kHz
(< 6% at 100 kHz)

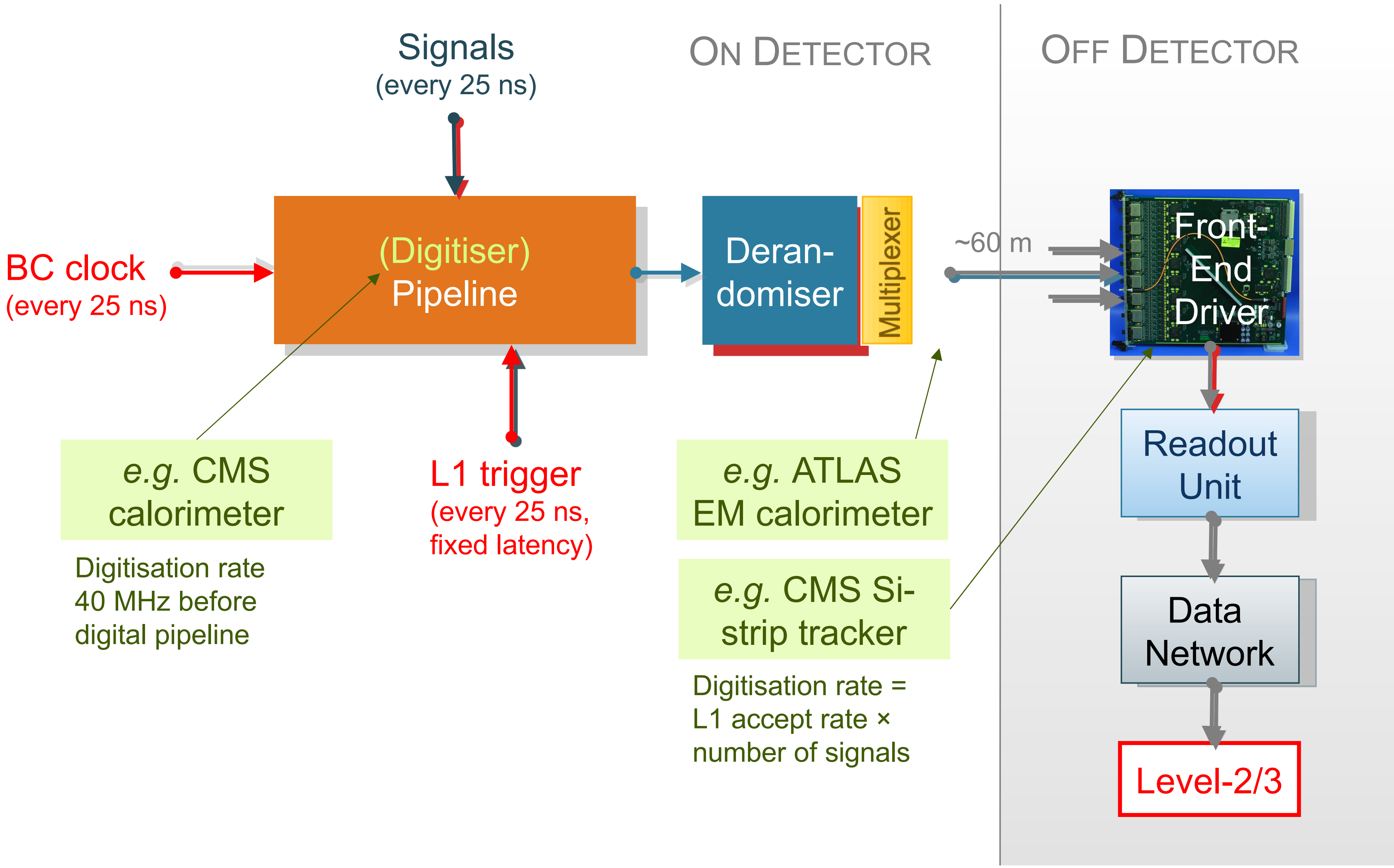
Readout Location (CMS)

[Drawing by Nick Ellis]



Readout Location

[Drawing by Nick Ellis]



Pipelined/parallel Level-1 Trigger

Level-1 trigger must provide trigger decision for every bunch crossing but trigger latency is much longer than bunch crossing period.

➡ Level-1 must concurrently process many events

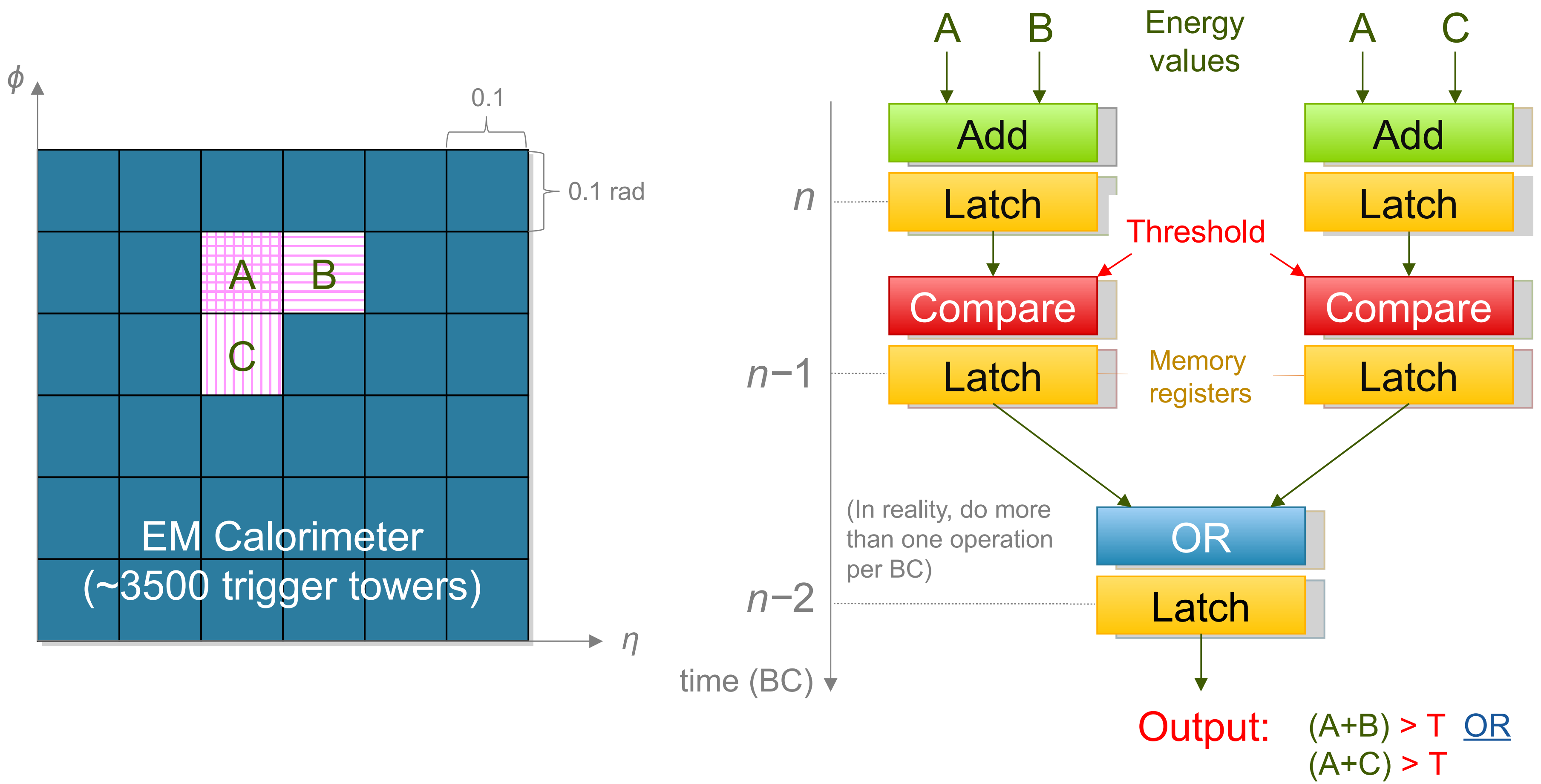
Solution: Design pipelined level-1 system using modern digital electronics

- Break down processing into series of simple steps that can be performed within a bunch crossing.
- Perform many operations in parallel using separate processing logic for each calculation

Note: Latency of Level-1 trigger is fixed and determined by the number of steps (and time for dataflow)

Pipelined/parallel Level-1 Trigger (ATLAS)

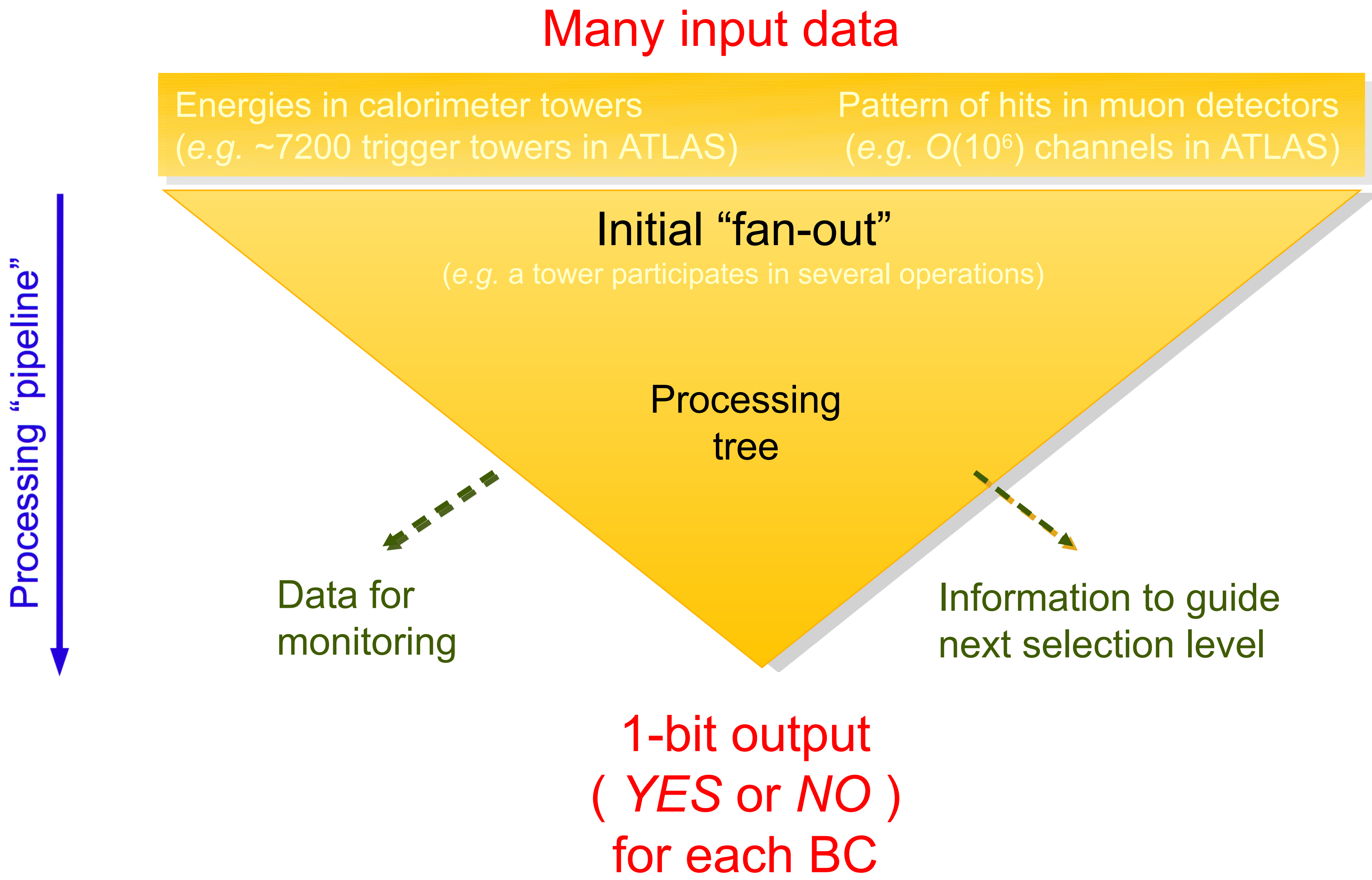
Example task: Determine if a pair of towers exceeds a threshold



[Drawing by Nick Ellis]

Level-1 Dataflow

[Drawing by Nick Ellis]



Limitations of LEP T/DAQ

The first level trigger decision must be available between bunch crossings.

- Not possible if bunch crossing is too short.
- Need to introduce the concepts of
    - ***pipelined readout***
    - ***pipelined/parallel Level-1 processing***

Bus-based event building and DAQ.

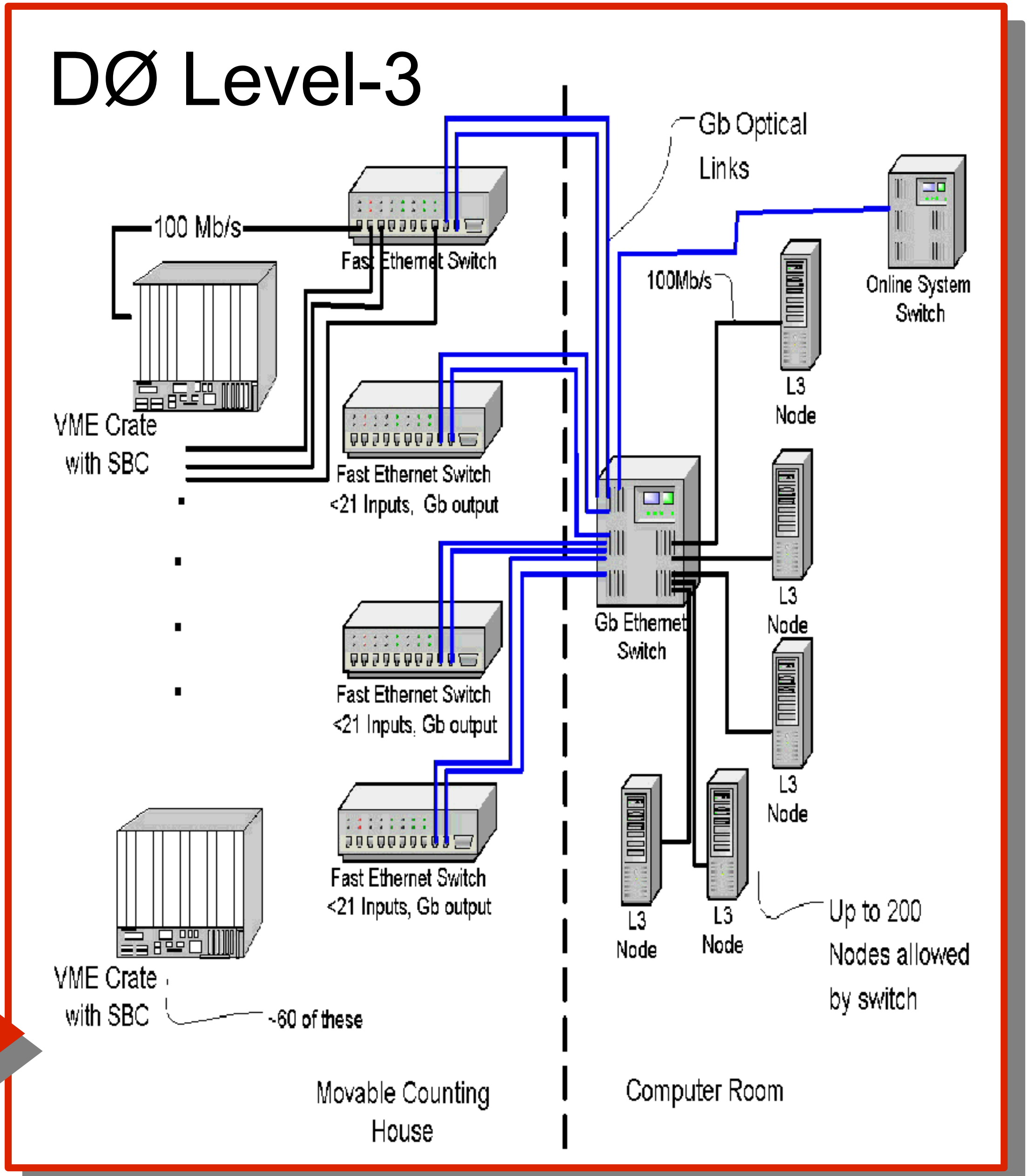
- Not possible for large data rates
- Need to use ***data networks and switches***

High Level Trigger / DAQ

Trigger systems with large data rates throughput cannot rely on a bus-based event building and filtering like at LEP.

Tevatron: ~ 250 MB/s
LHC: 100 GB/s

Maximum rate of
VME64 bus ~ 80 MB/s



Solution:

Use network-based event building and high level trigger(s).

High Level Trigger / DAQ

At LHC, the large data rate throughput after Level-1 poses problems even for a network-based event building. Two approaches have been developed:

In CMS, the event building is factorized into a number of "slices" each of which sees only a fraction of the rate.

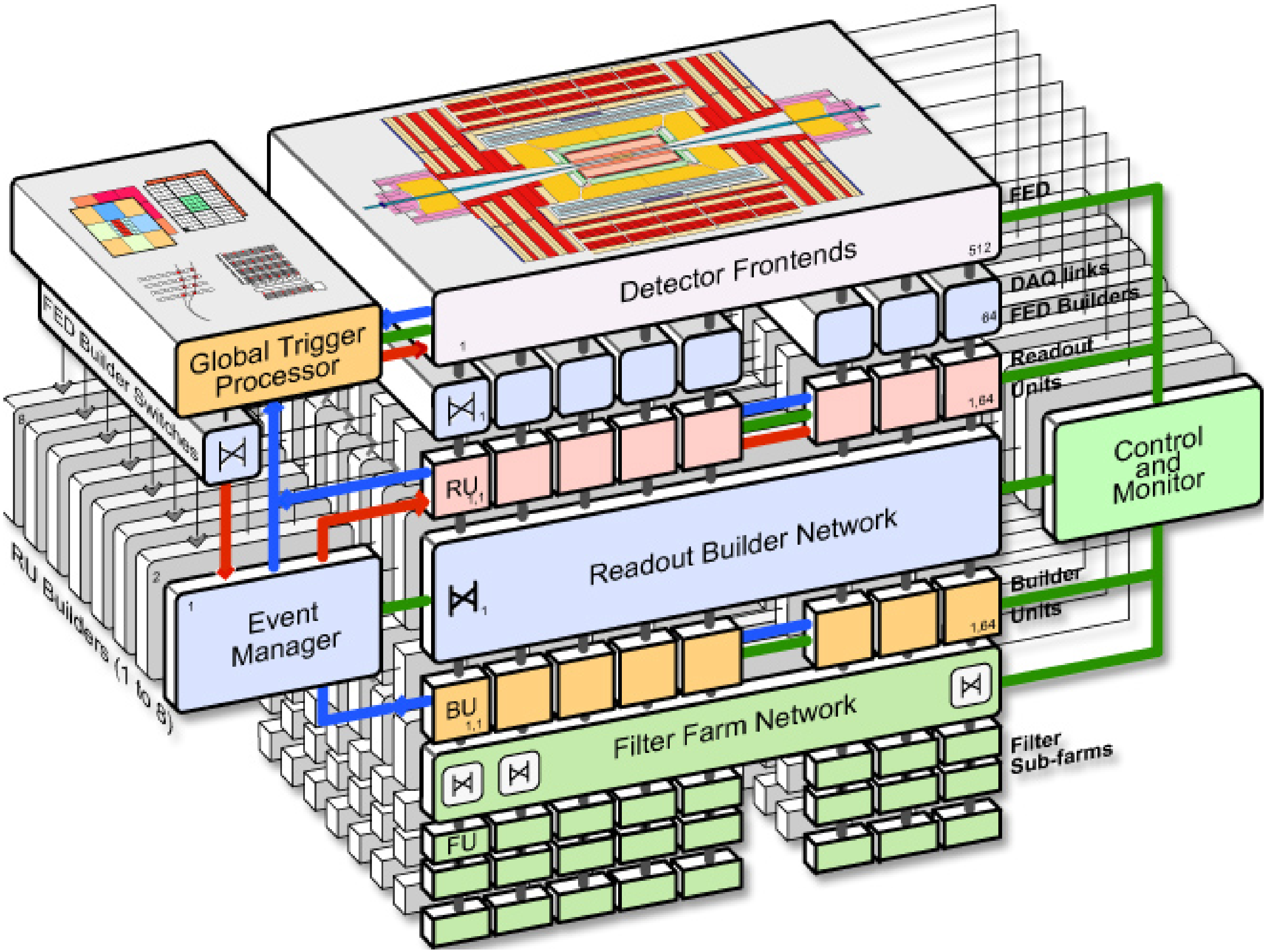
- Still requires large total network bandwidth, but avoids need for a very large single network switch
- Size of the system is easily scalable (ex. when additional funding is available)

In ATLAS, the amount of data to be move is reduced using a selective readout in a Region-of-Interest (RoI).

- Reduces by a substantial factor the amount of data that needs to be moved from the readout systems to the processors
- Implies relatively complicated mechanisms to serve the data selectively to the Level-2 trigger processors → more complex software

CMS "3D Event Builder"

Eight slices:
each slice sees only
1/8th of the events

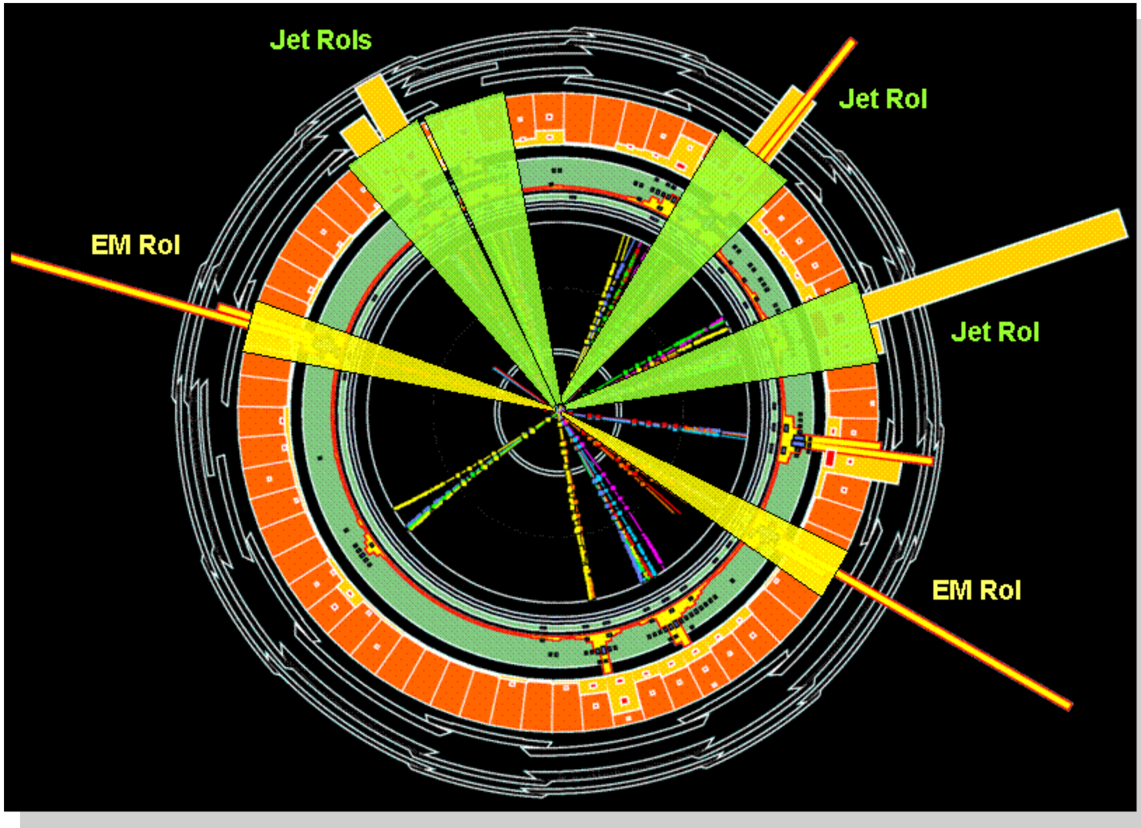


ATLAS Selective Readout Concept

Two concepts are used to select subsets of data from the readout systems

Region-of-Interest concept:

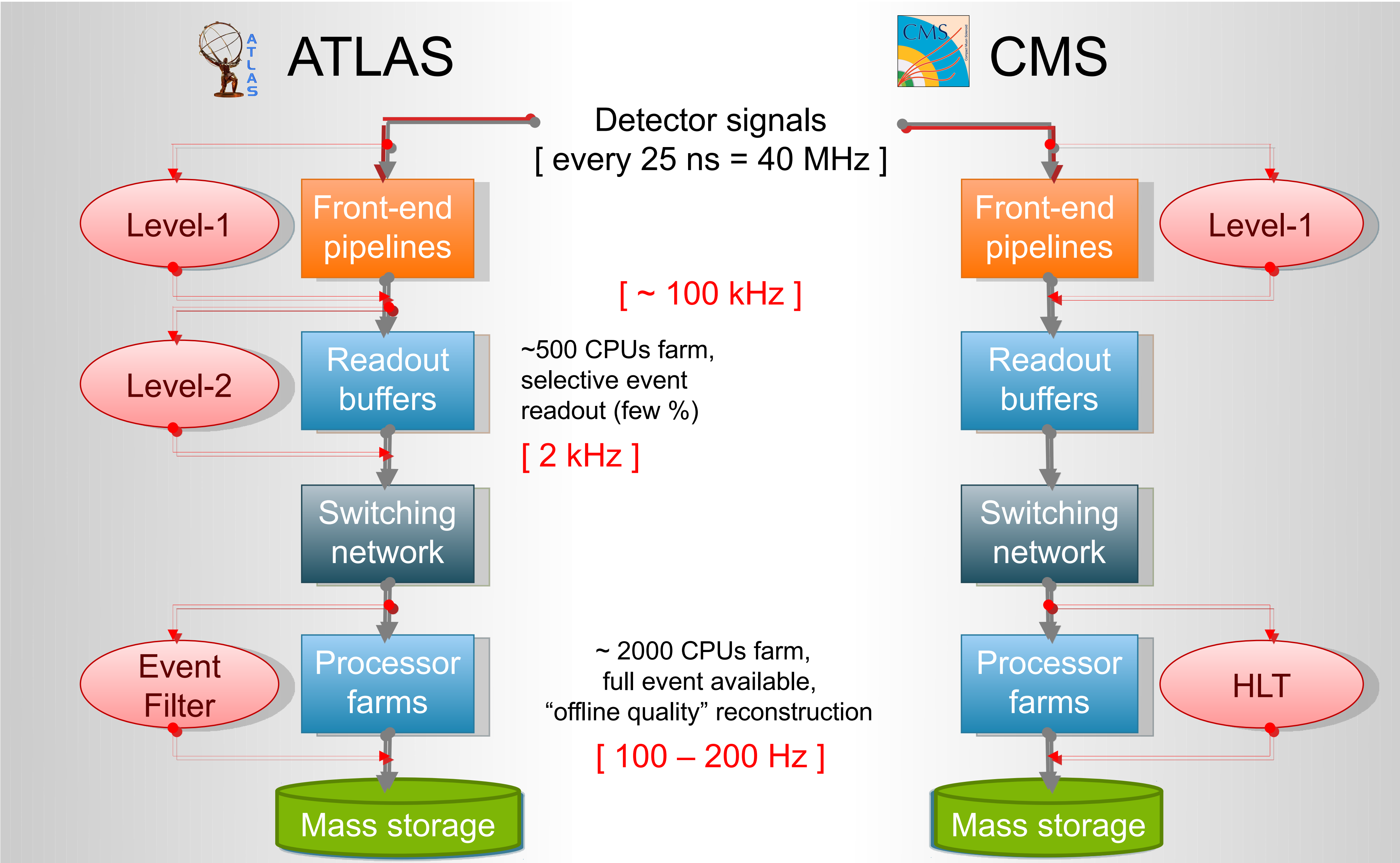
- L1 indicates the geographical location of candidate objects, *e.g.* EM clusters
- L2 only accesses data from RoIs, small fraction of total data



Sequential-selection concept:

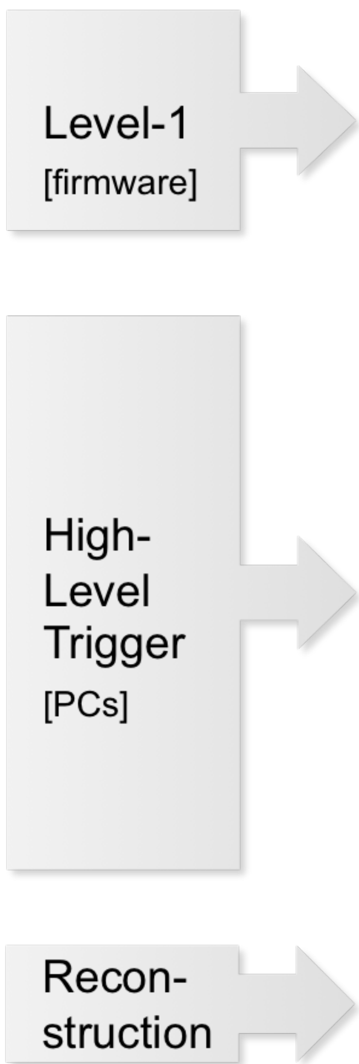
- Data are accessed by L2 initially only from a subset of detectors (*e.g.* muon systems and calorimeters)
- Many events rejected without accessing, *e.g.*, inner detector

HLT/DAQ Comparison

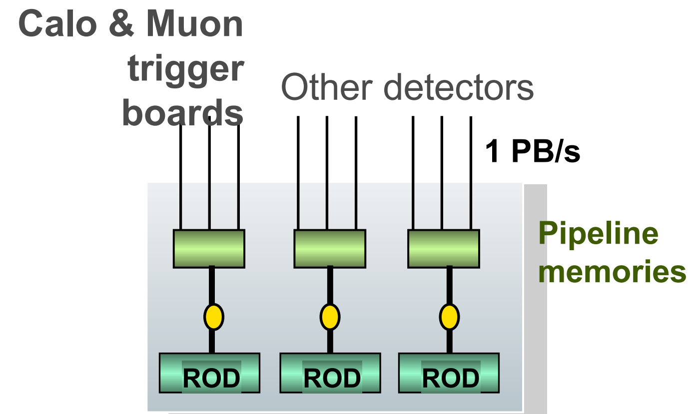


Trigger and Data Flow (ATLAS)

Trigger and Data Flow (ATLAS)



Trigger and Data Flow (ATLAS)

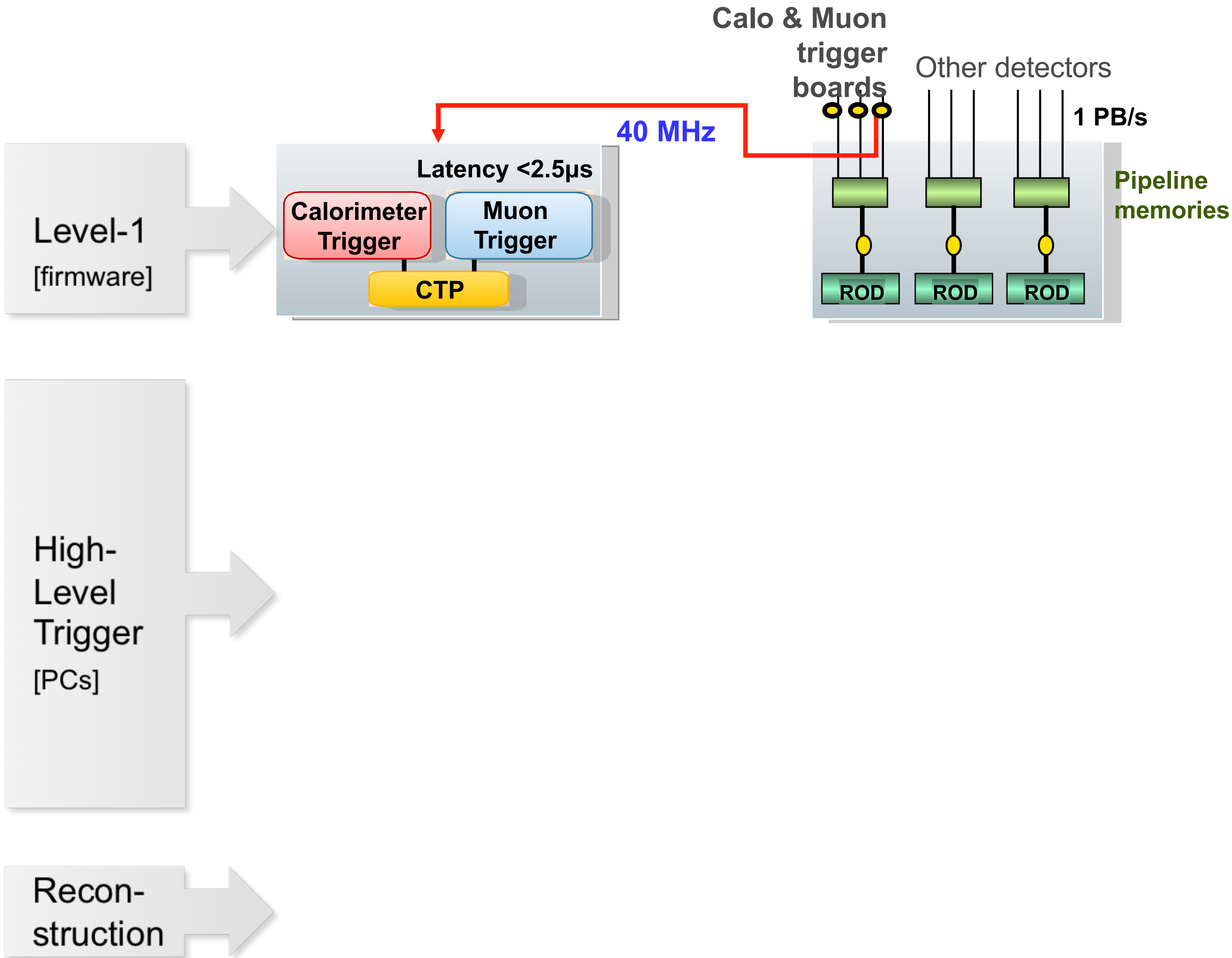


Level-1
[firmware]

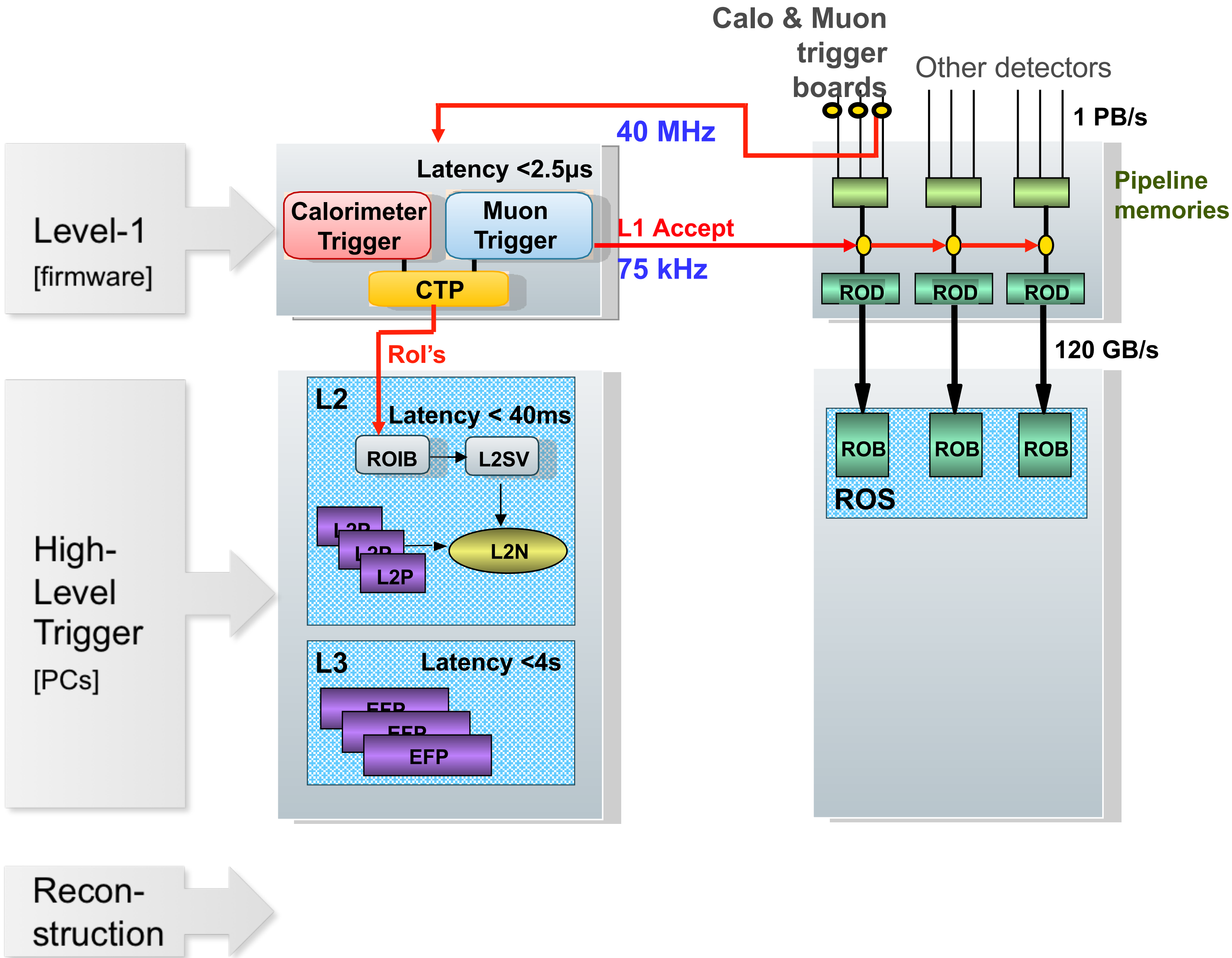
High-Level Trigger
[PCs]

Recon-struction

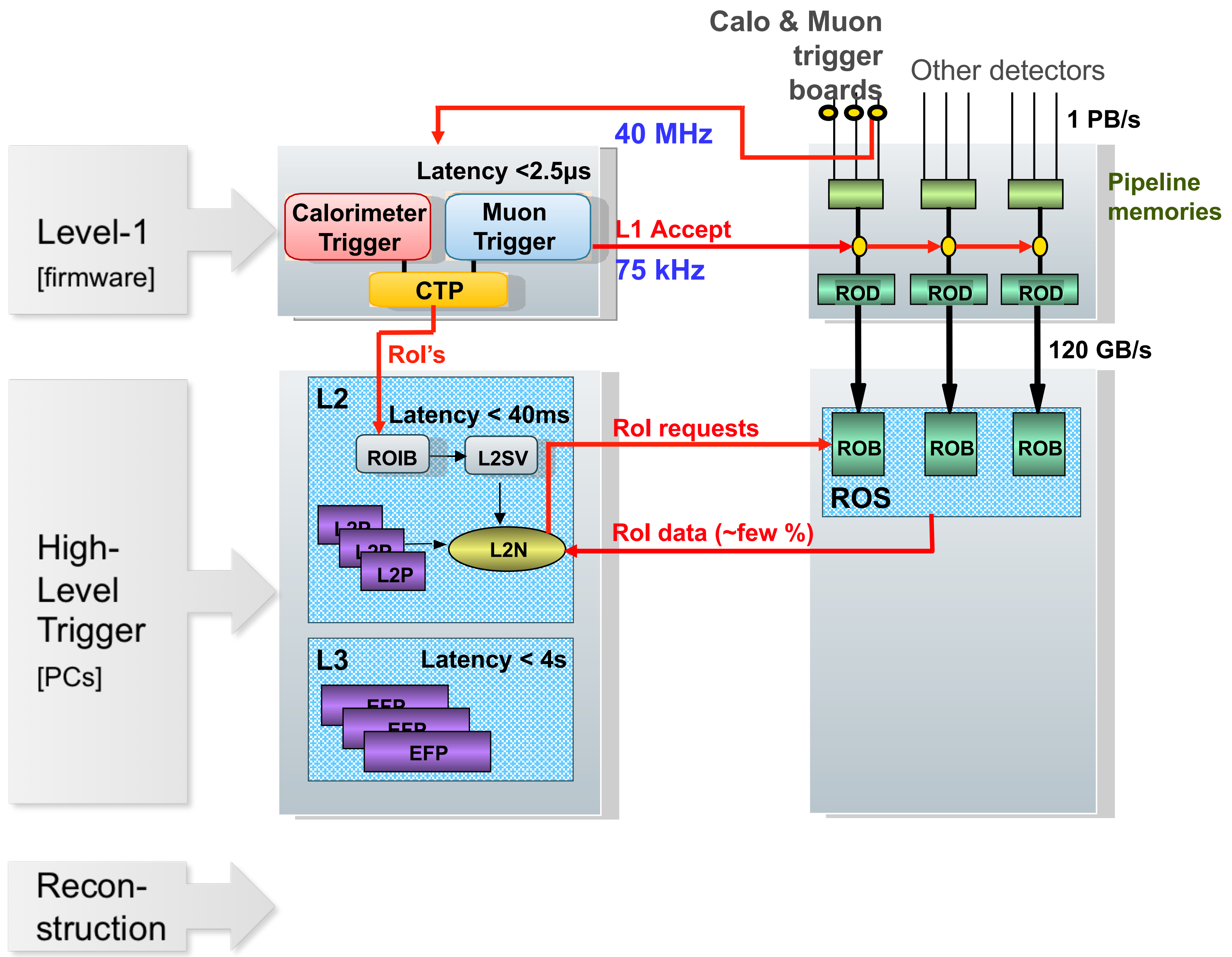
Trigger and Data Flow (ATLAS)



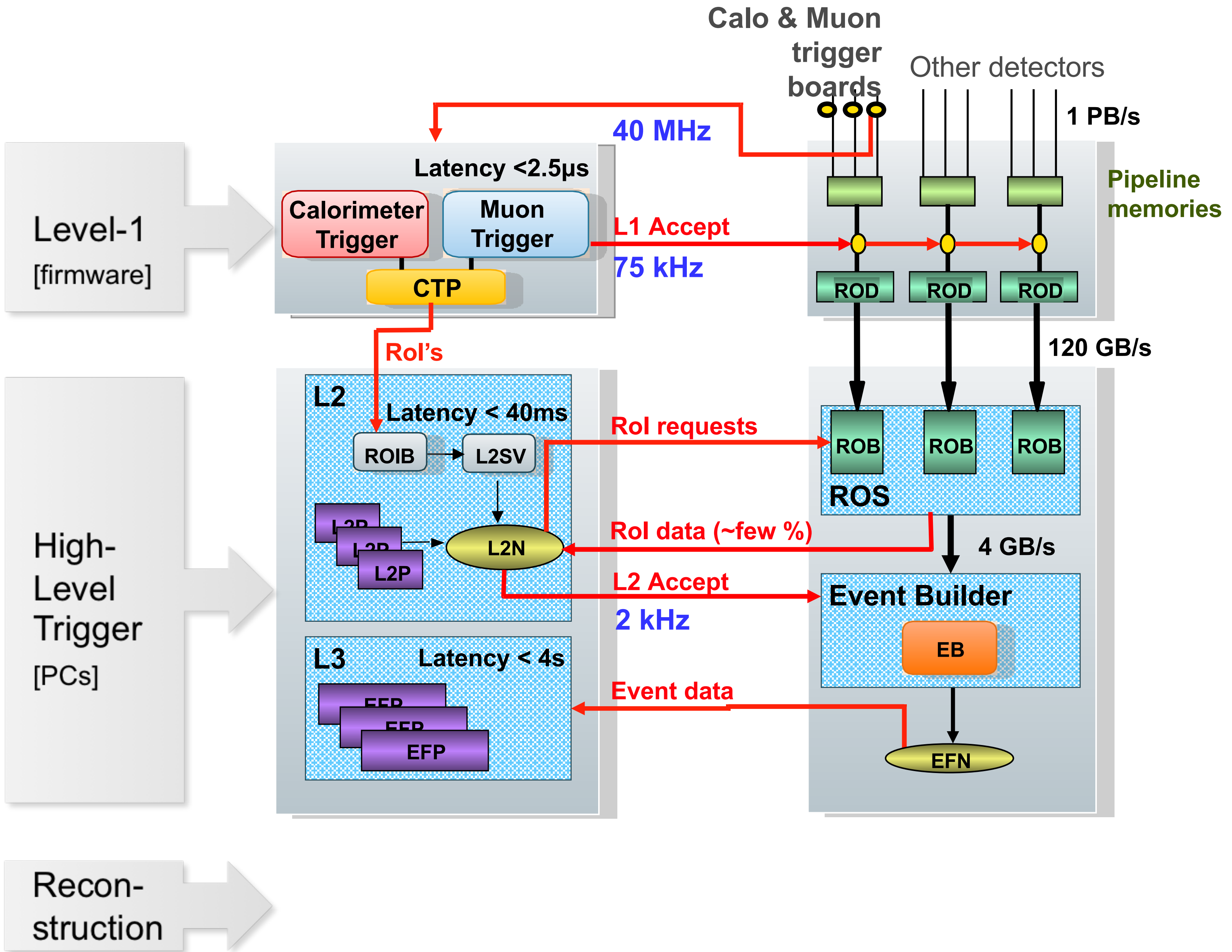
Trigger and Data Flow (ATLAS)



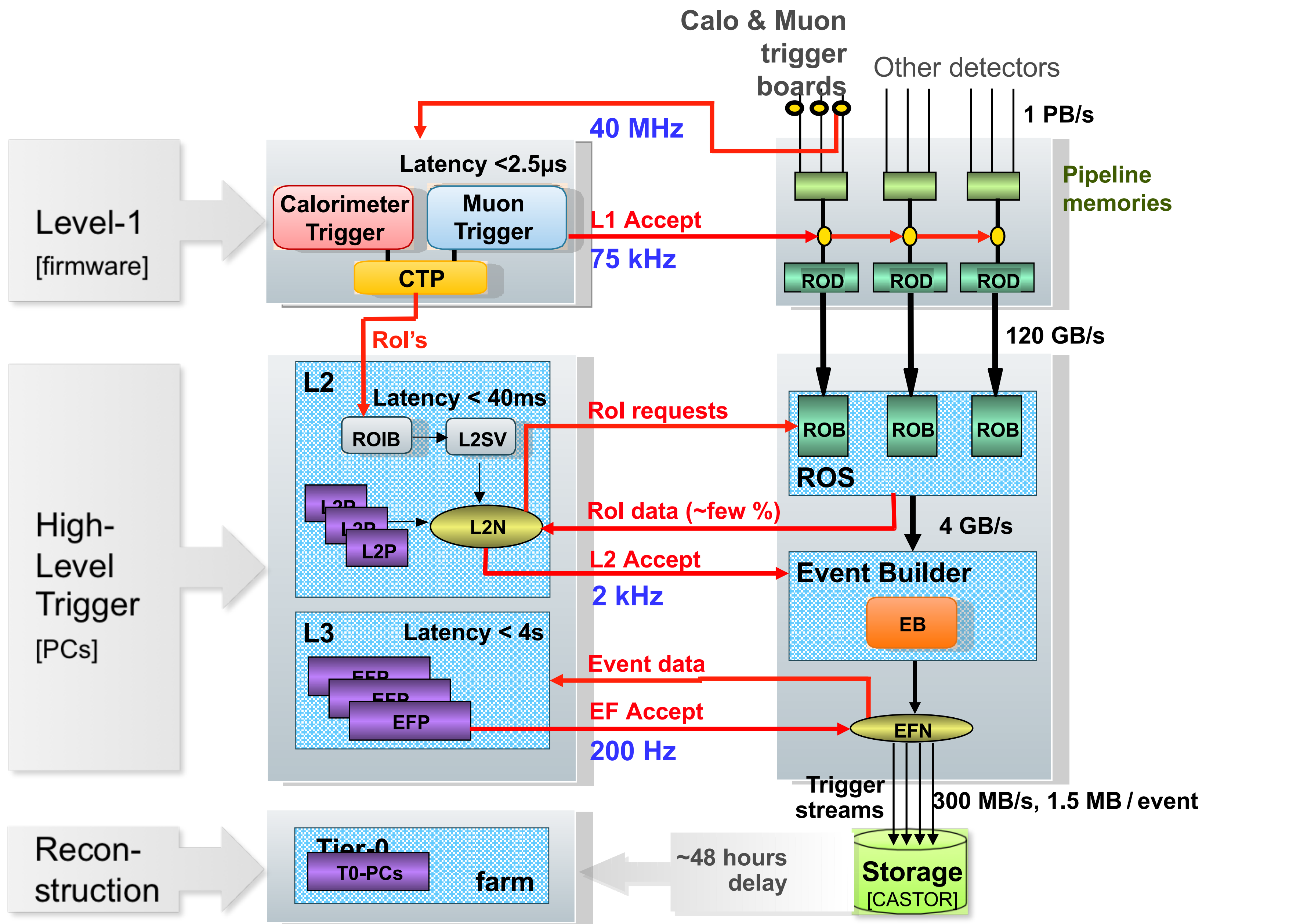
Trigger and Data Flow (ATLAS)



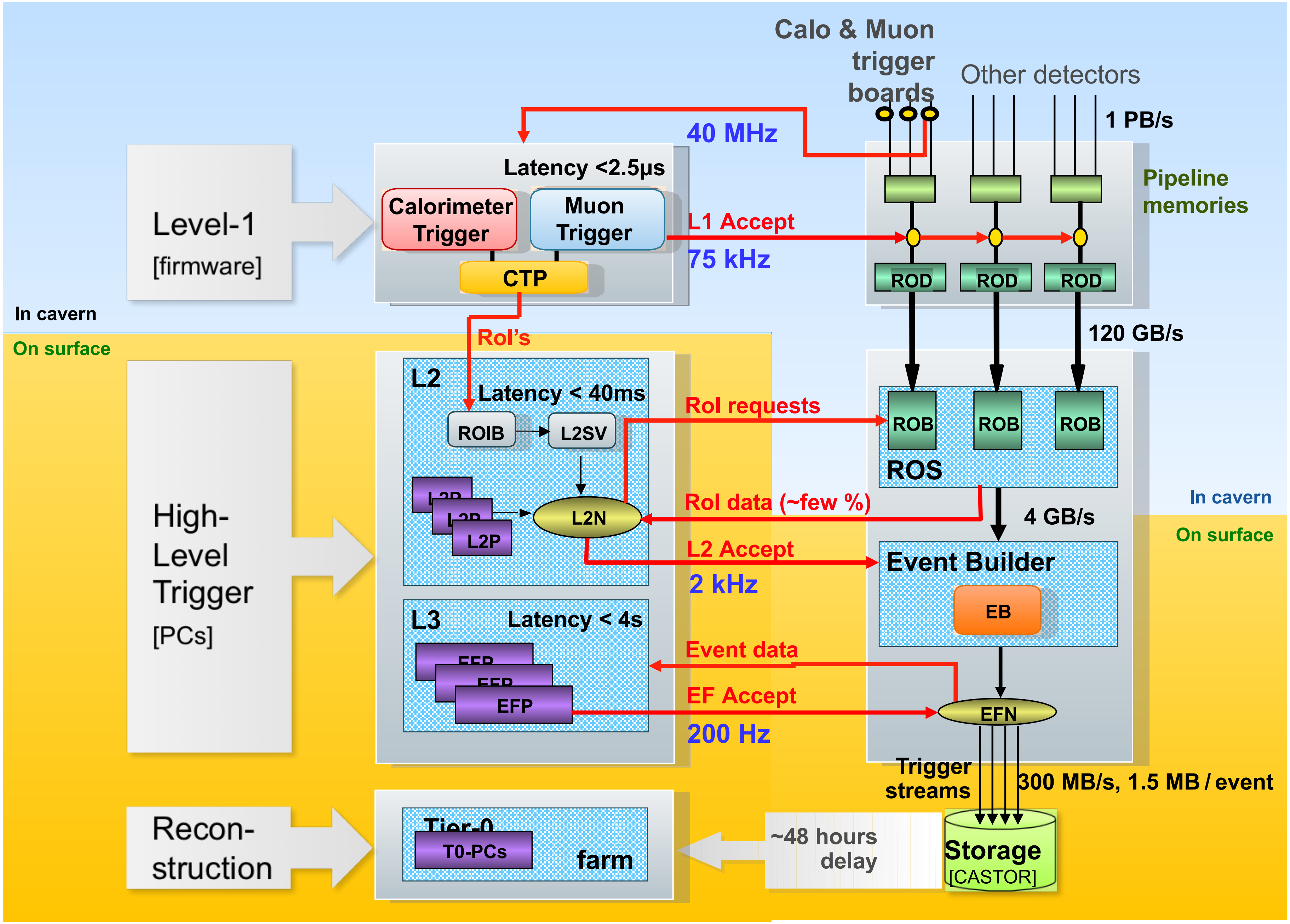
Trigger and Data Flow (ATLAS)



Trigger and Data Flow (ATLAS)



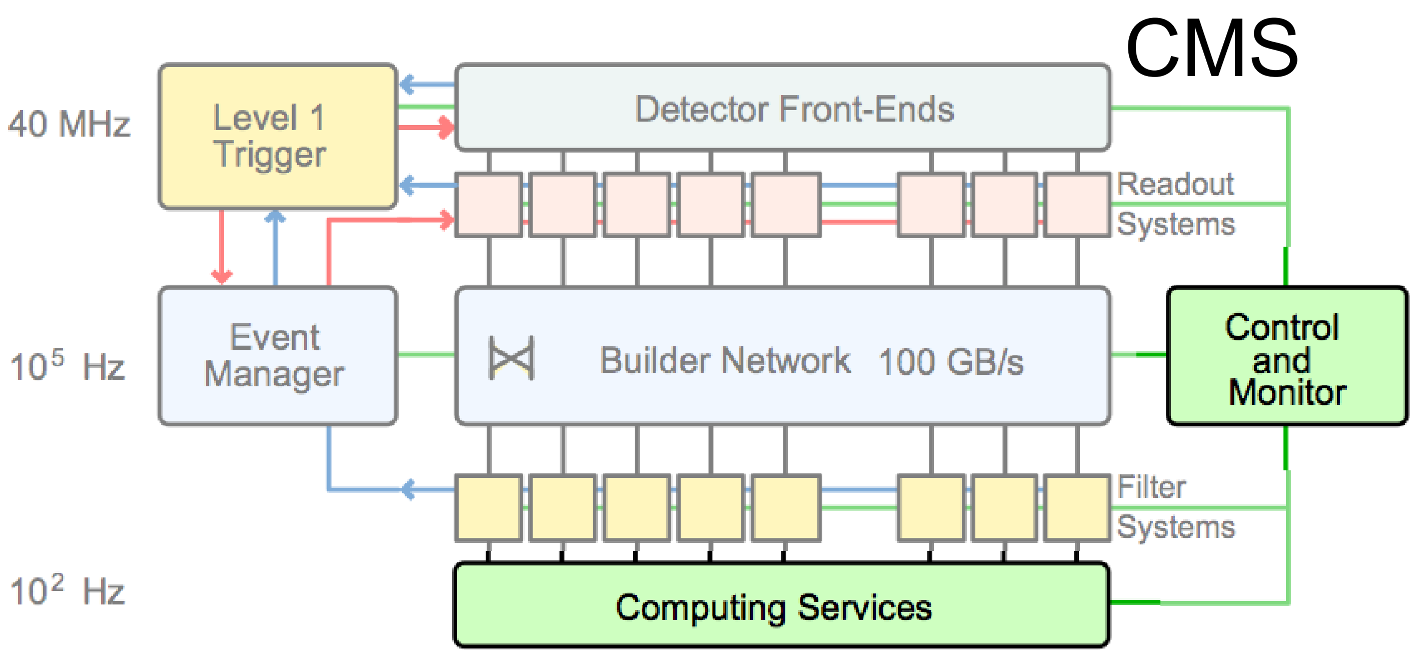
Trigger and Data Flow (ATLAS)



Control and monitoring

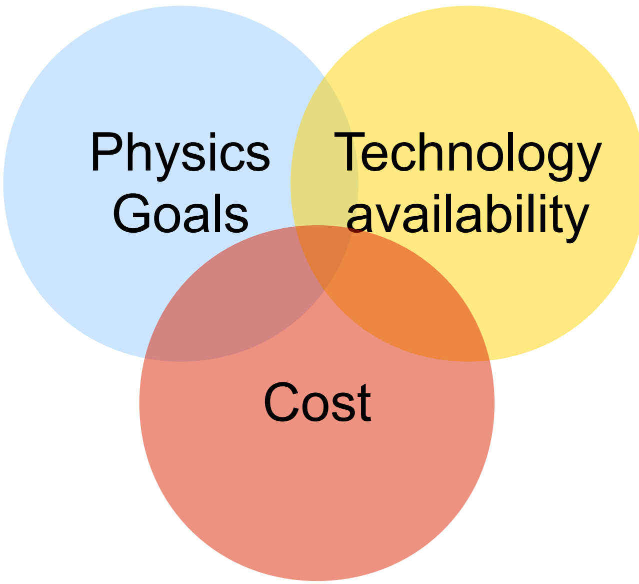
In addition to the basics Trigger and DAQ components discussed so far, a complete system also requires additional services:

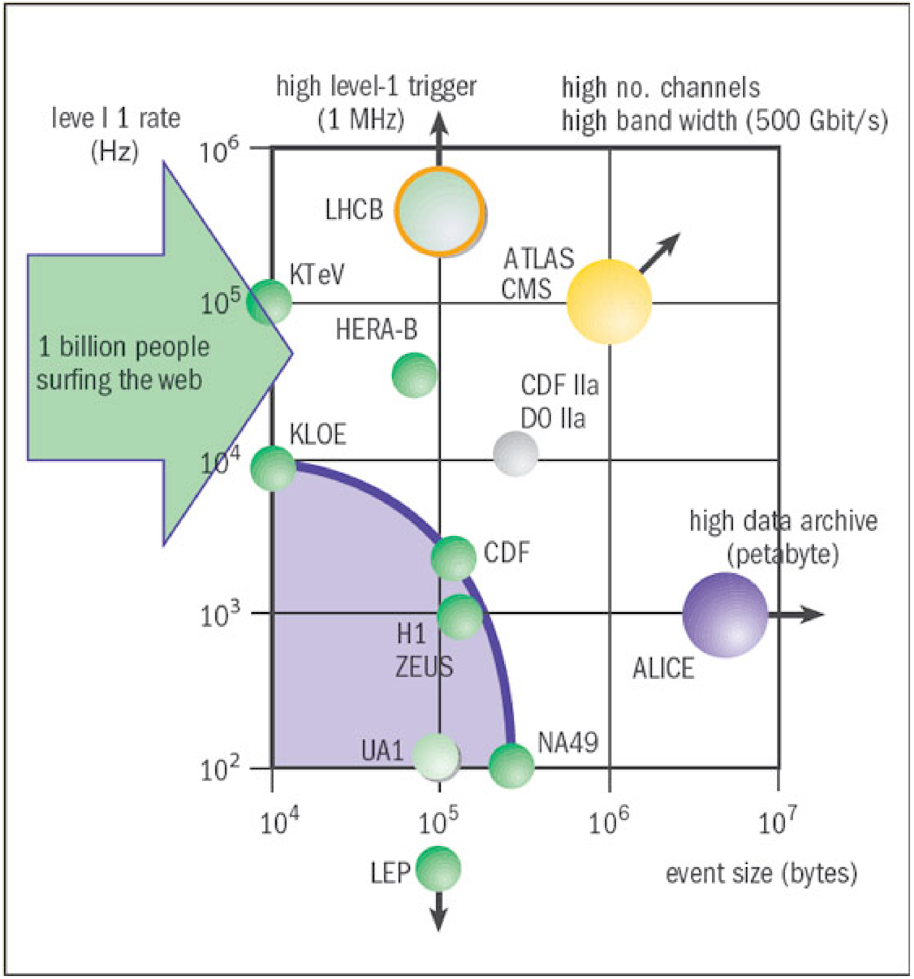
- Detector control system and network
- Readout control system
- Trigger/DAQ control system and network
- Run control and monitoring system
- Peripheral computing services (file server, databases, resource and account management, log message collector, etc.)
- etc.



T/DAQ Design Constraints

Considerations when designing a trigger and DAQ system:





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T/DAQ Design Constraints

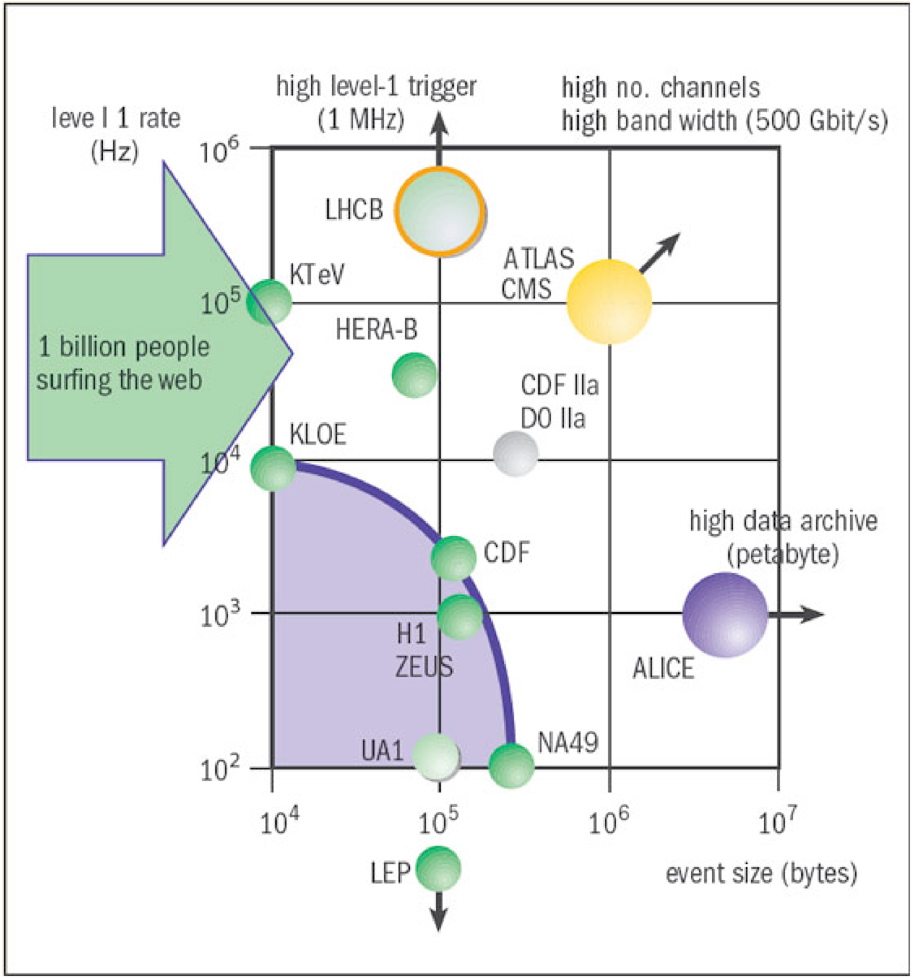
ATLAS/CMS

Huge number of detector channel and high multiplicity of events
- Large event size *O*(1) MB

Recording and processing of *O*(100) Hz event rate at *O*(1) MB/event requires major computing infrastructure

Can only select $O(10^{-7})$ of pp collisions

Must balance needs for wide physics coverage with acceptable (i.e. affordable) Recording rates



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T/DAQ Design Constraints

LHCb

Operates at a comparatively low luminosity ($\sim 2\times10^{32}$ cm^{-2} s^{-1}), giving an overall proton–proton interaction rate of ~20 MHz

- Chosen to maximise the rate of single-interaction bunch-crossings

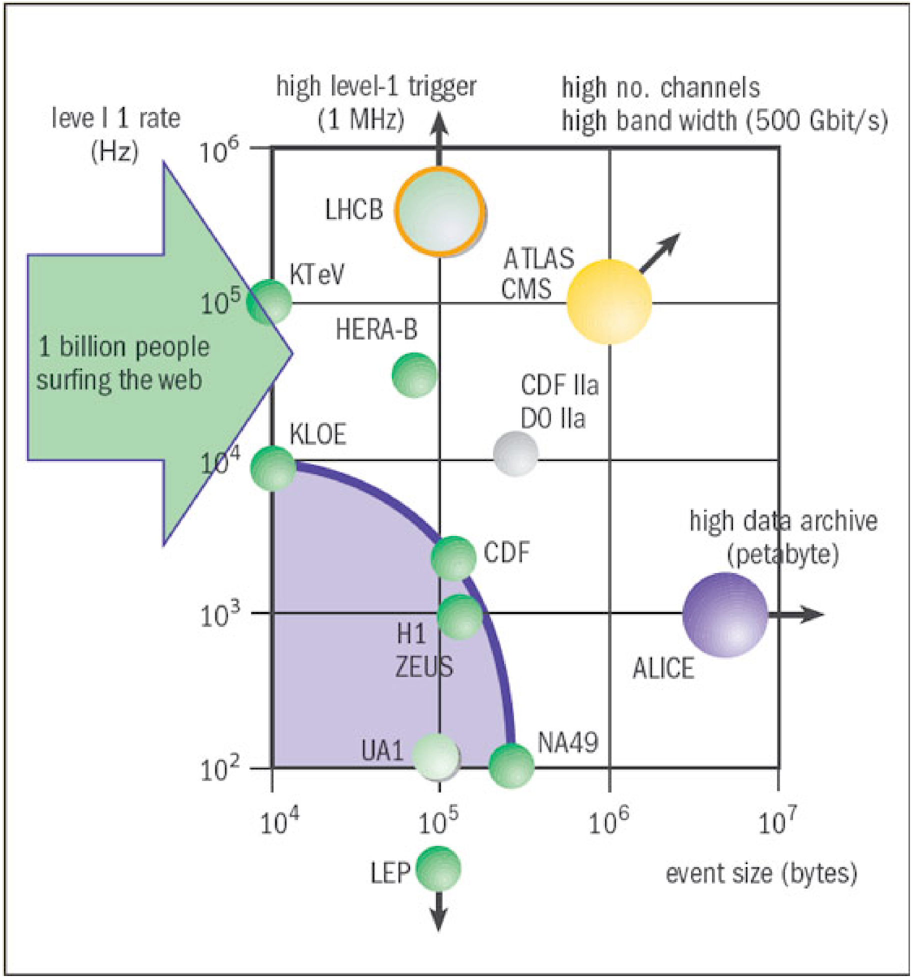
Event size comparatively small (~ 35 kB/evt)

- few detector channels
- less occupancy

However, high rate of beauty production

- $b\bar{b}$ production rate ~ 100 kHz

Trigger must identify specific B decay modes that are of interest for physics analysis (~ 2 kHz event rate)



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T/DAQ Design Constraints

ALICE

Total interaction rate much smaller than in Pp experiments

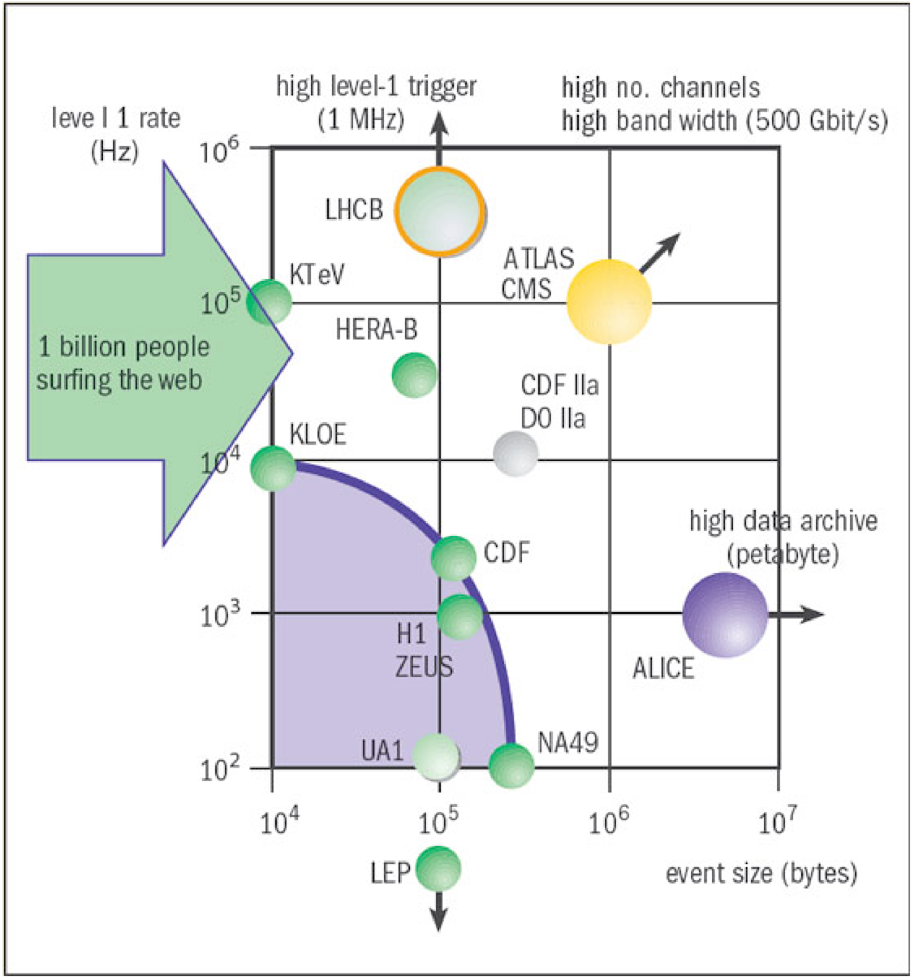
- $L \sim 10^{27}$ cm^{-2}s^{-1} ➔ R ~ 8 kHz for Pb-Pb collisions

However, huge event size due to high particle multiplicity

- Up to O(10,000) charged particles in central region
- Event size up to ~ 40 MB when full detector is read out

Volume of data to be stored and processed offline will be massive

- limited by what is possible/affordable



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Discussion Session

Topic for the discussion session tomorrow:

Discuss what will be the main challenges and possible solutions in the design of a trigger and DAQ system for the following colliders:

SLHC

$L = 10^{35}$ cm^{-2} s^{-1}

$\sqrt{s}$ = 14 TeV

BC = 50 ns

An average of 500 pile-up events!

ILC

$\sqrt{s}$ = 500-1000 GeV

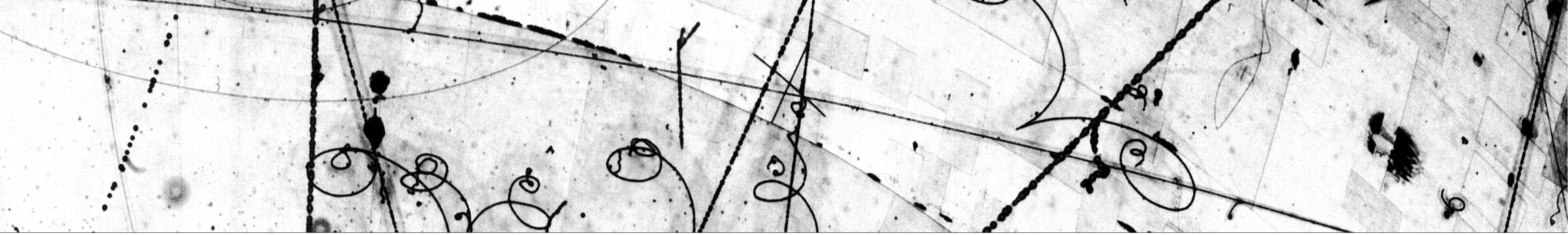
$L = 10^{34}$ cm^{-2} s^{-1}

Beams: Train of 2625 bunches within 970 μs with bunch spacing of 370 ns
A new bunch train every 200 ms

Discussion Session

Topic for the discussion session tomorrow:

Estimate the total buffer memory of your experiment



Part-I

- Introduction
- Trigger and Data Acquisition Basics

Part-II

- System Commissioning
- Trigger Selection
  - Electron and Jets
  - Muons
  - Secondary vertex
- Trigger Menu Design