Trigger and Data Acquisition

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Academic Training Lecture
Friday, May 13

Outline

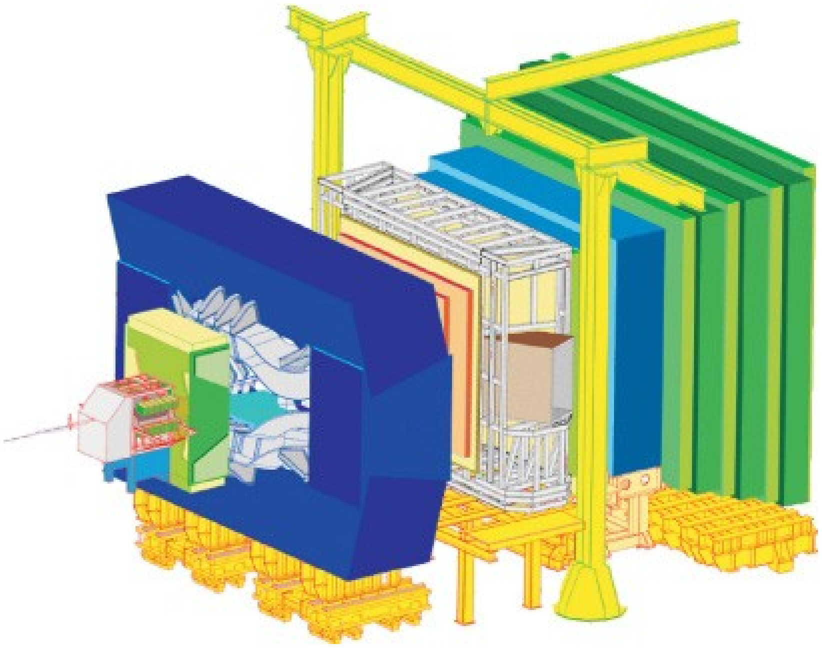
- Introduction
- Basic concepts of DAQ
- Trigger for (hadron) colliders
- Comparison of LHC trigger/DAQ systems

More material
International School of Trigger and Data Acquisition 2011
2010 Hadron Collider Physics Summer School

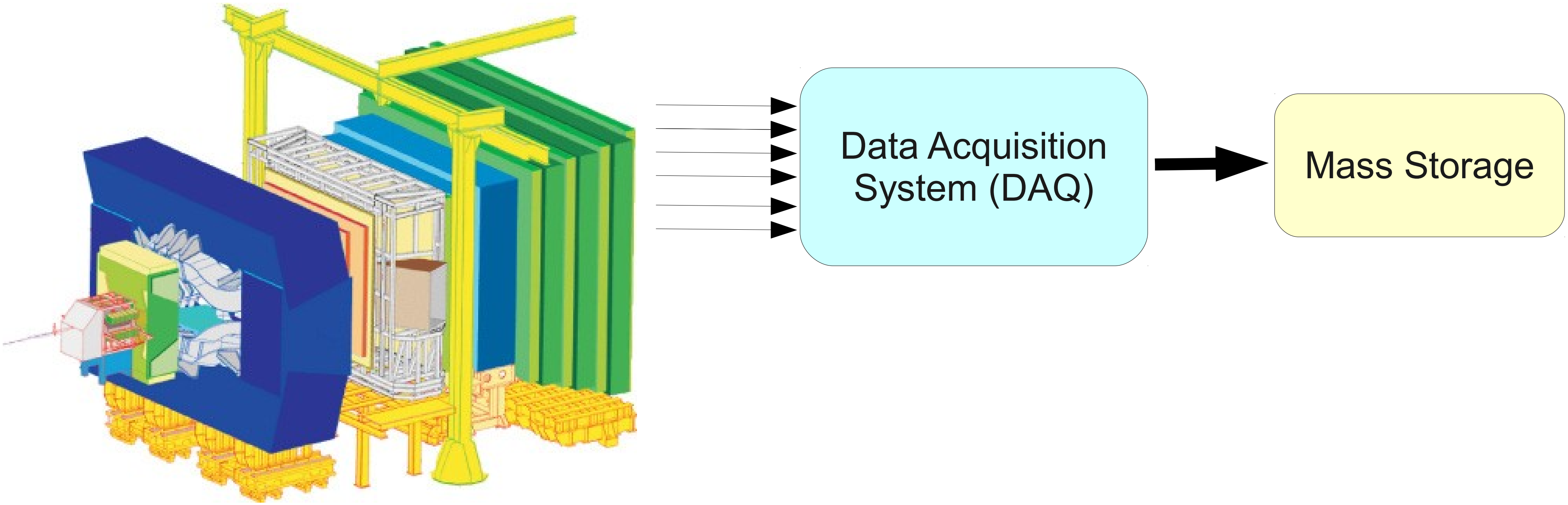
Many figures and plots are taken from the lectures

Introduction

DAQ and Trigger Defined

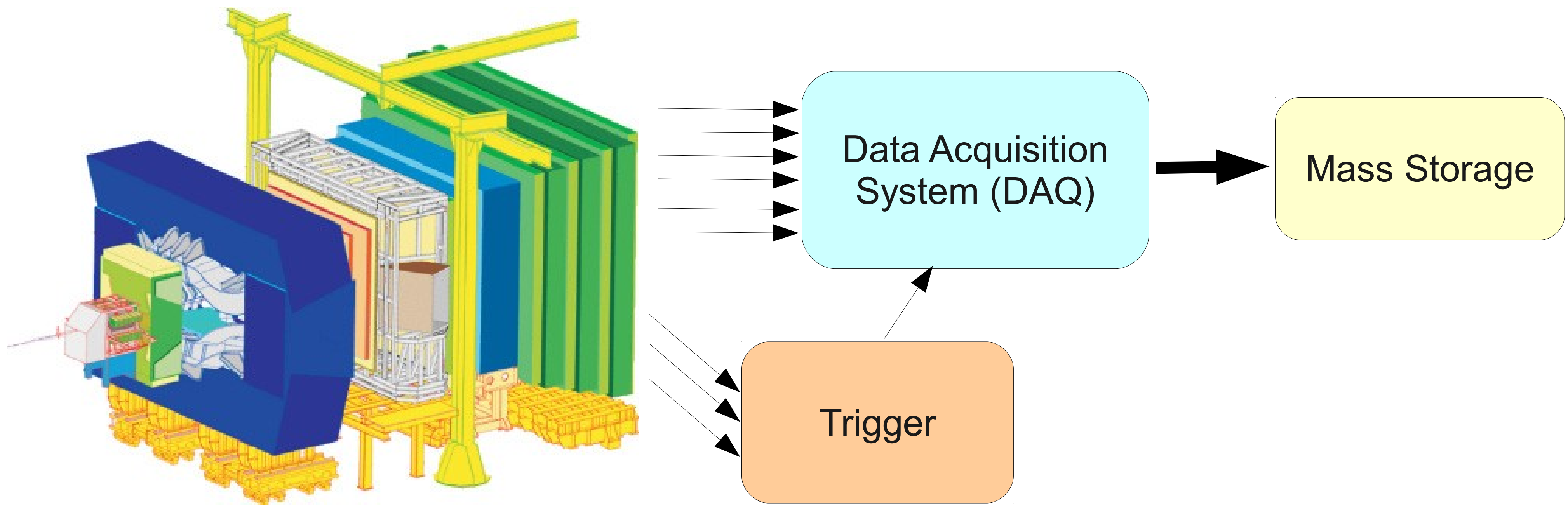


DAQ and Trigger Defined



DAQ is responsible for collecting data from detector systems and recording them to mass storage for offline analysis

DAQ and Trigger Defined



DAQ is responsible for collecting data from detector systems and recording them to mass storage for offline analysis

Trigger is responsible for real-time selection of the subset of data to be recorded

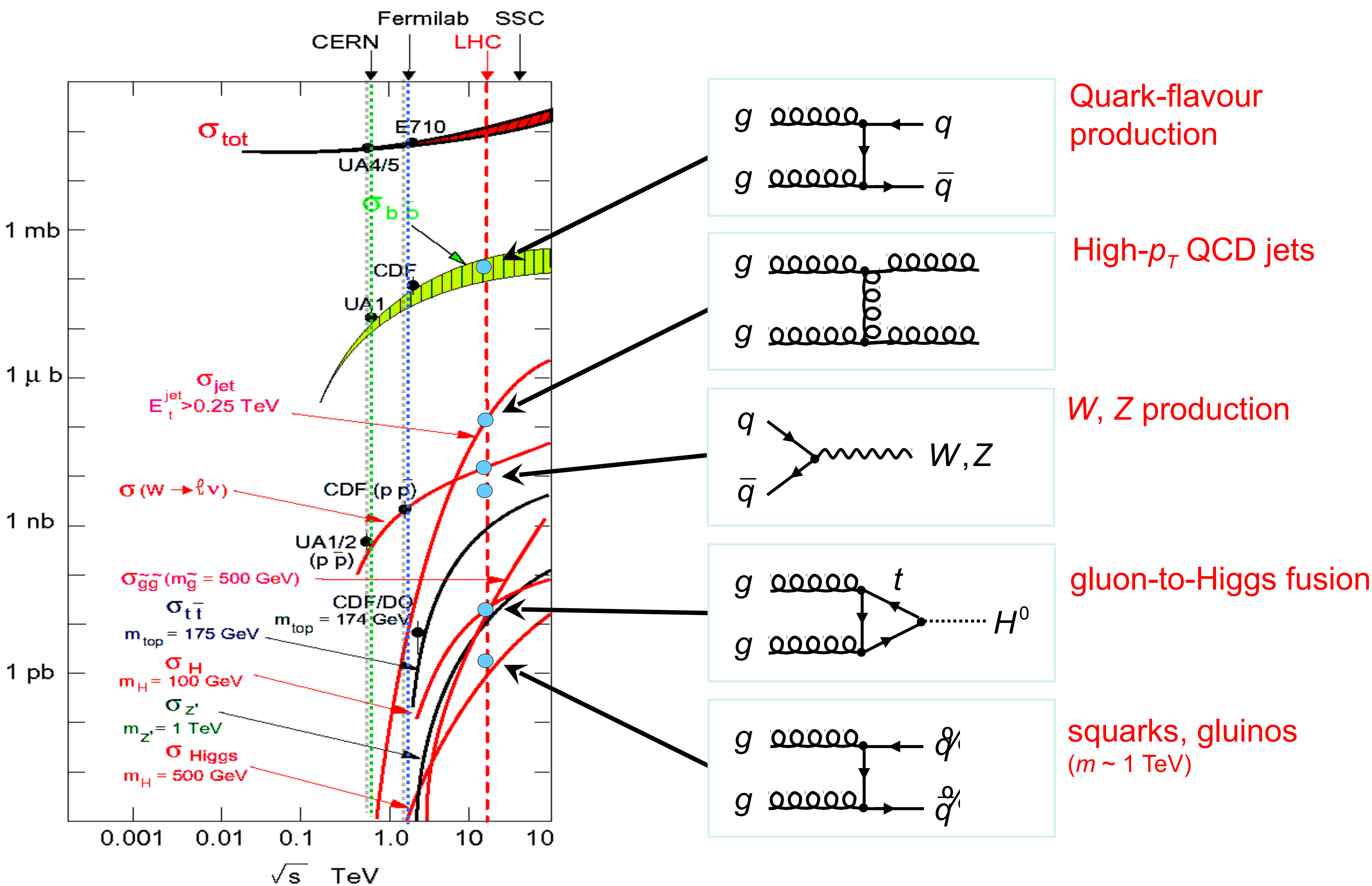
Why use a Trigger?

In any collider experiment, data rates are too high to fully process and record with current technologies
– essential to reduce rates, typically by factor 10^4-10^5

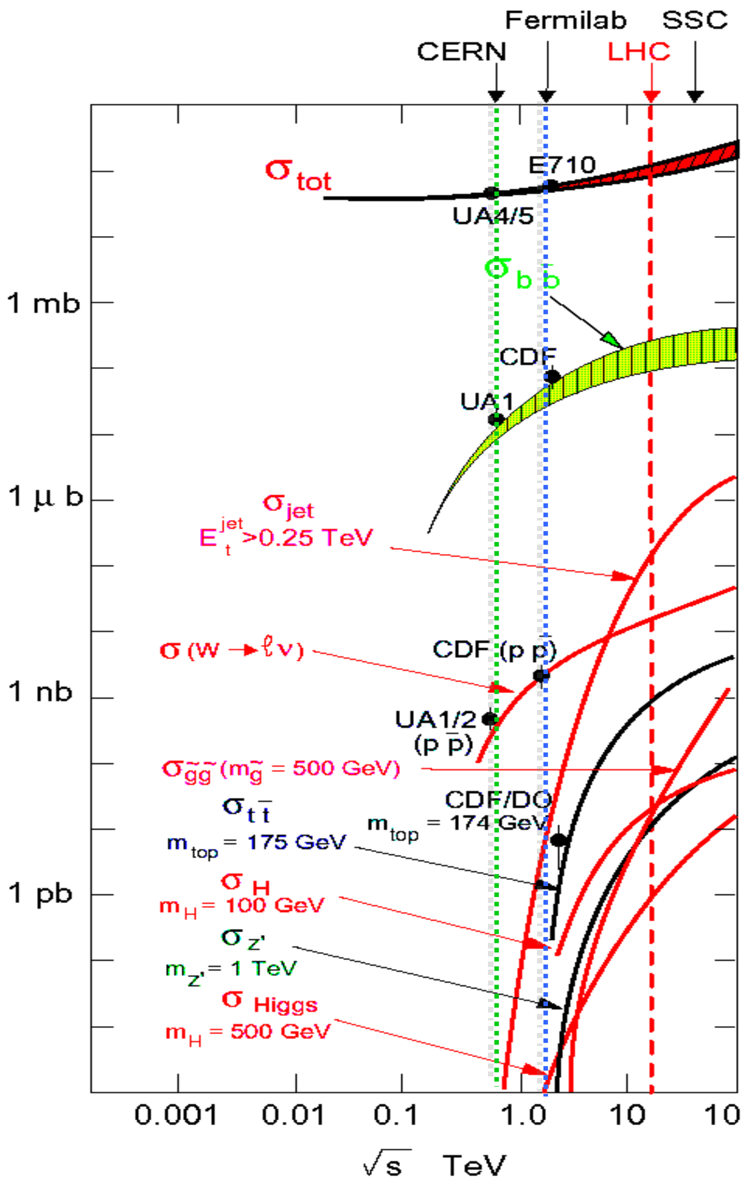
	Bunch Crossing Rate	Event size	Trigger Rate Output	Data rate without trigger (PB/year*)	Data rate with trigger (PB/year*)
LEP	45 kHz	~ 100 kB	~ 5 Hz	O(100)	O(0.01)
Tevatron	2.5 MHz	~ 250 kB	~ 50-100 Hz	O(10 000)	O(0.1)
HERA	10 MHz	~ 100 kB	~ 5 Hz	O(10000)	O(0.01)
LHC	40 MHz	~ 1 MB	~ 100-200 Hz	O(100 000)	O(1)

* Assume 50% accelerator duty cycle

Hadron Collider Challenge



Hadron Collider Challenge



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
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	150
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
$Z'(1\ \mathrm{TeV})$	0.05	0.5
$\tilde{g}\tilde{g}(1\ \mathrm{TeV})$	0.05	0.5
H (120 GeV)	0.04	0.4
H (180 GeV)	0.02	0.2

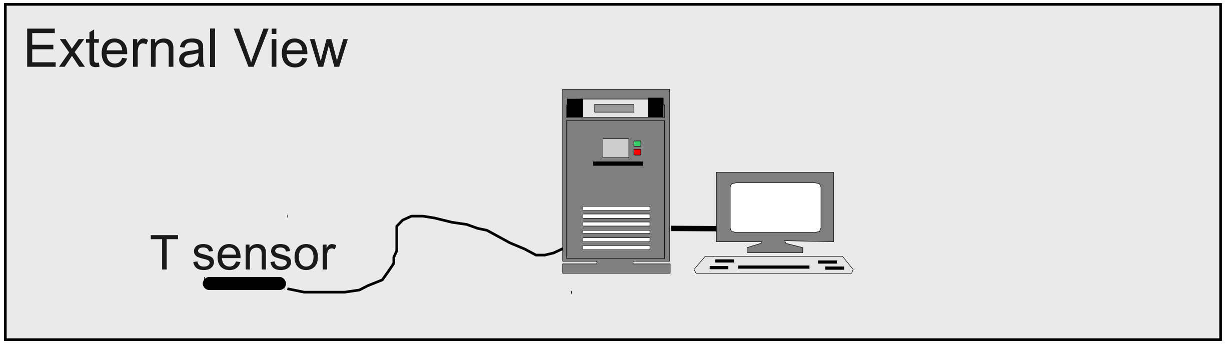
Conversions:

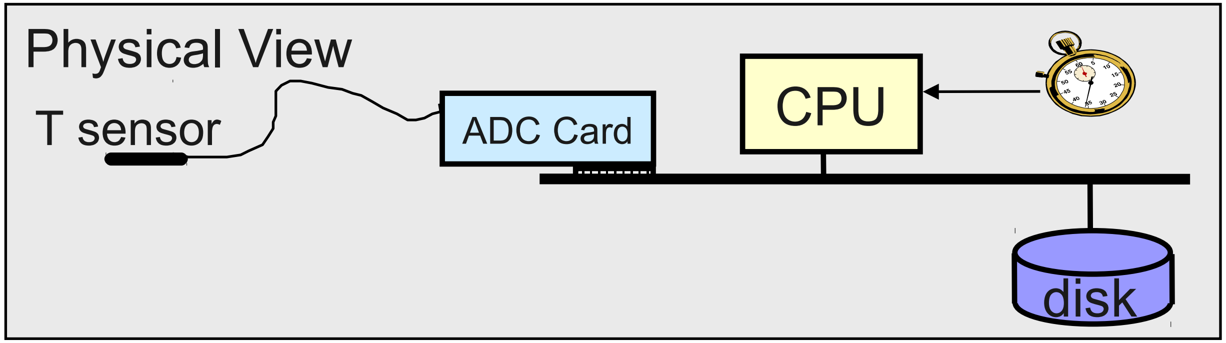
$1\ \mathrm{pb}^{-1} = 10^{36}\ \mathrm{cm}^{-2}$

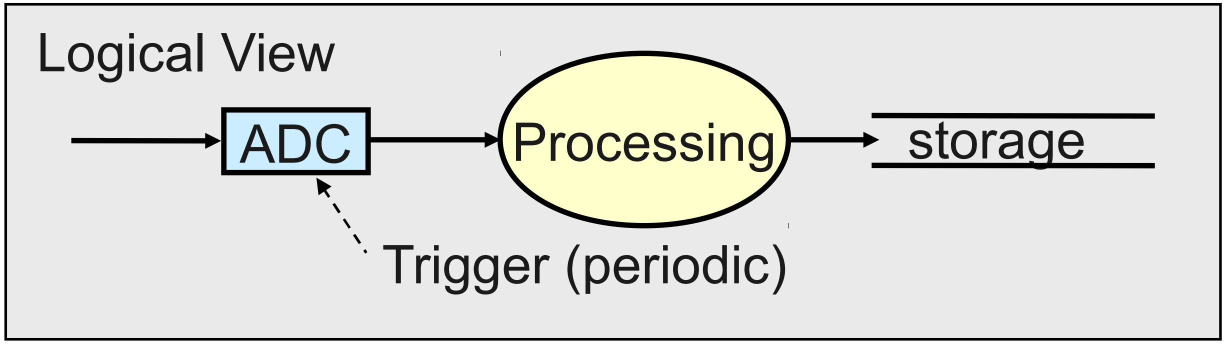
$15\ \mathrm{nb} \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} = 150\ \mathrm{Hz}$

DAQ Basics

Simple DAQ System







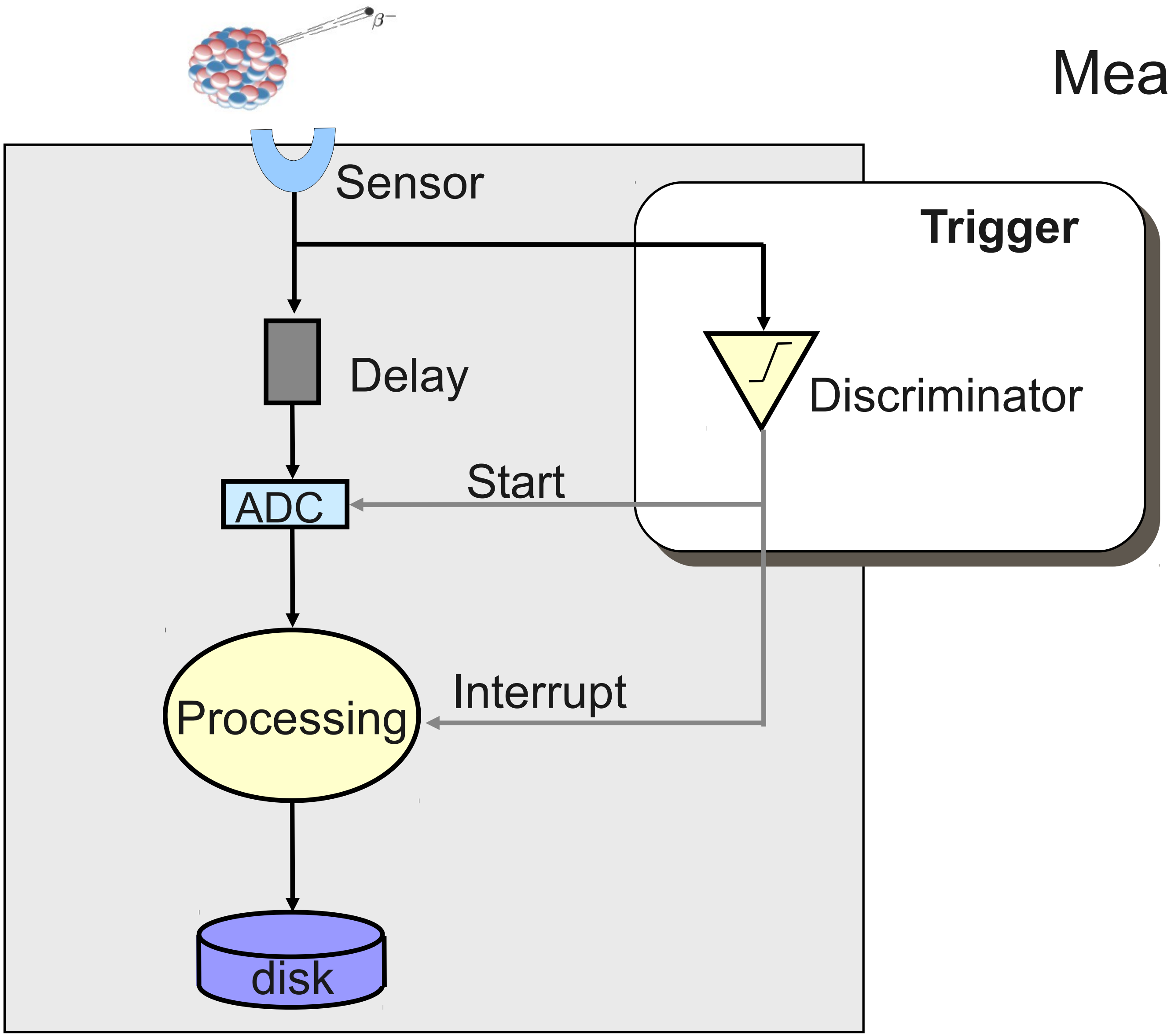
System to measure temperature at fixed rate

Analog-to-digital converter (ADC) digitizes signal

PC does readout and records data to disk

Rate limited by conversion, readout and data recording
If τ=1ms, max rate is 1 kHz

Adding a Trigger



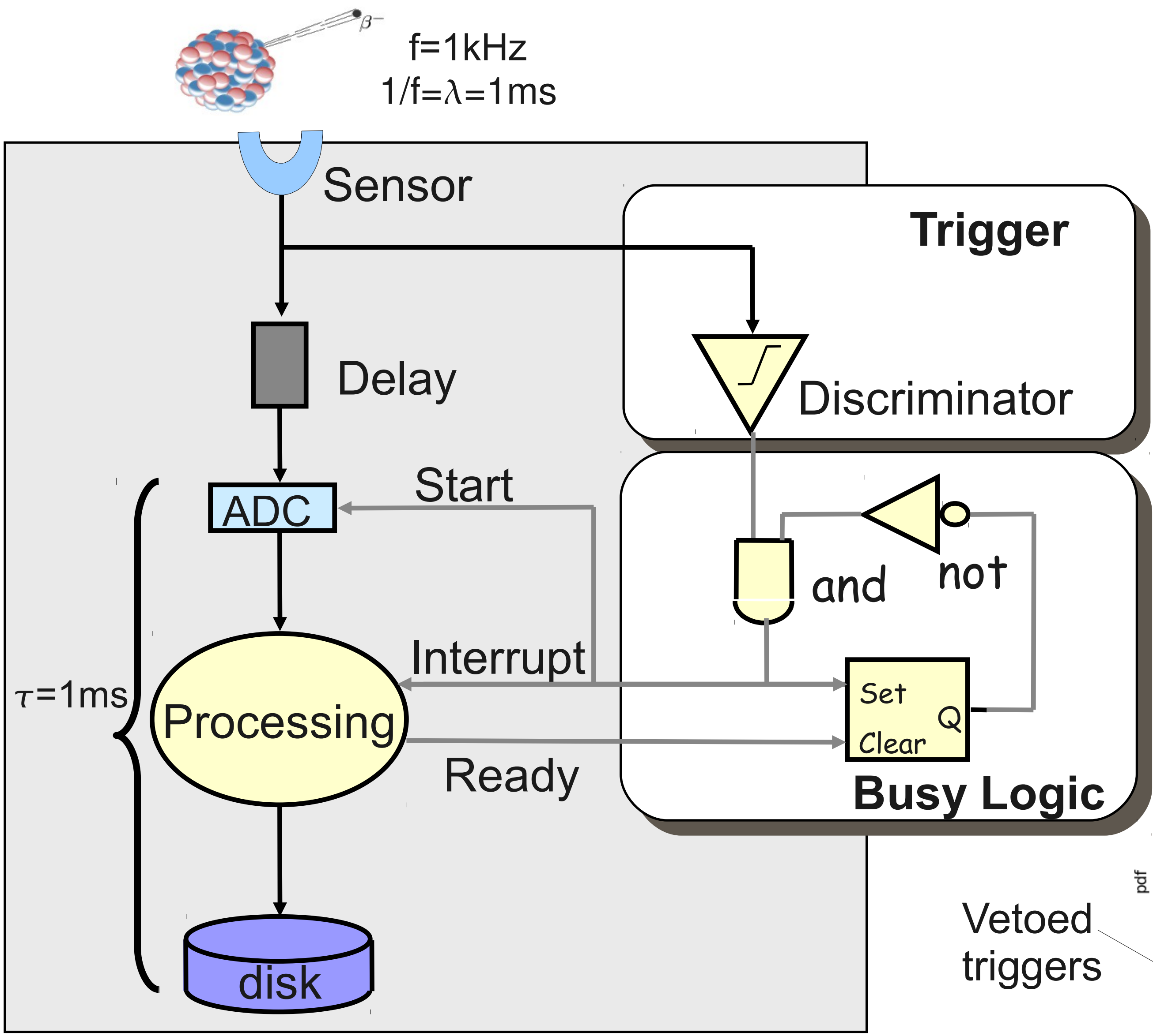
Measurement of β decays

With unpredictable signal, we need a physics based trigger

Delay of signal to ADC needed to synchronize with trigger signal (Trigger Latency)

Delay can be a long cable in simplest cases

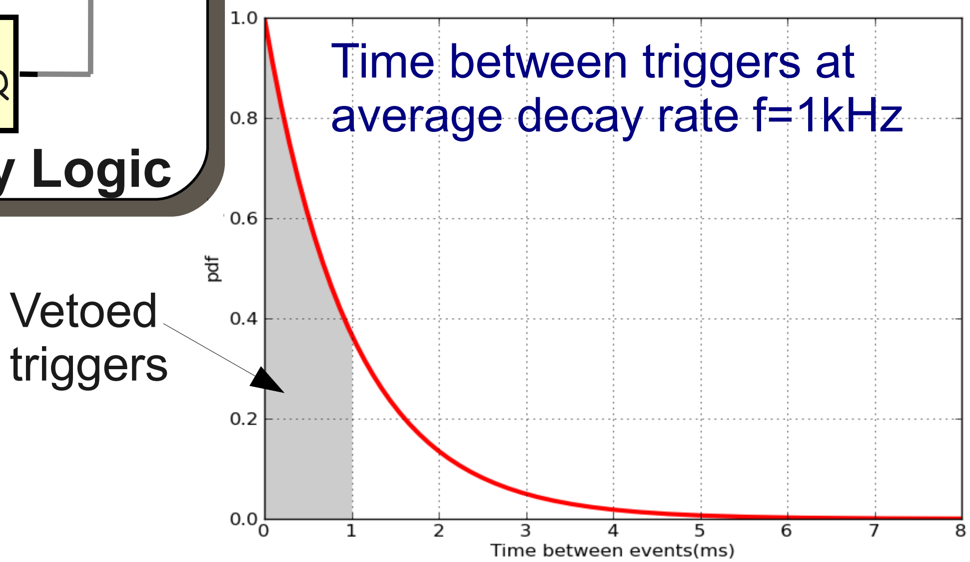
Introducing "Busy" in System



With stochastic process, new signals can arrive while system is still processing

Busy logic prevents this

No longer able to process 1 kHz of rate (deadtime)

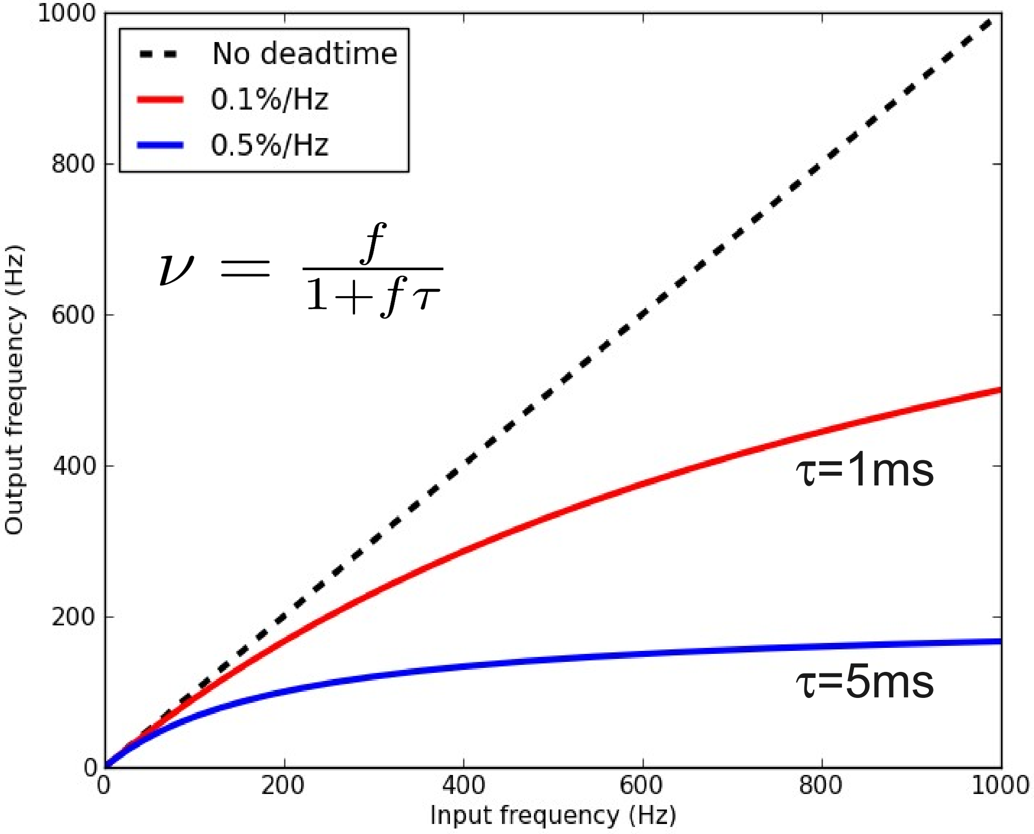


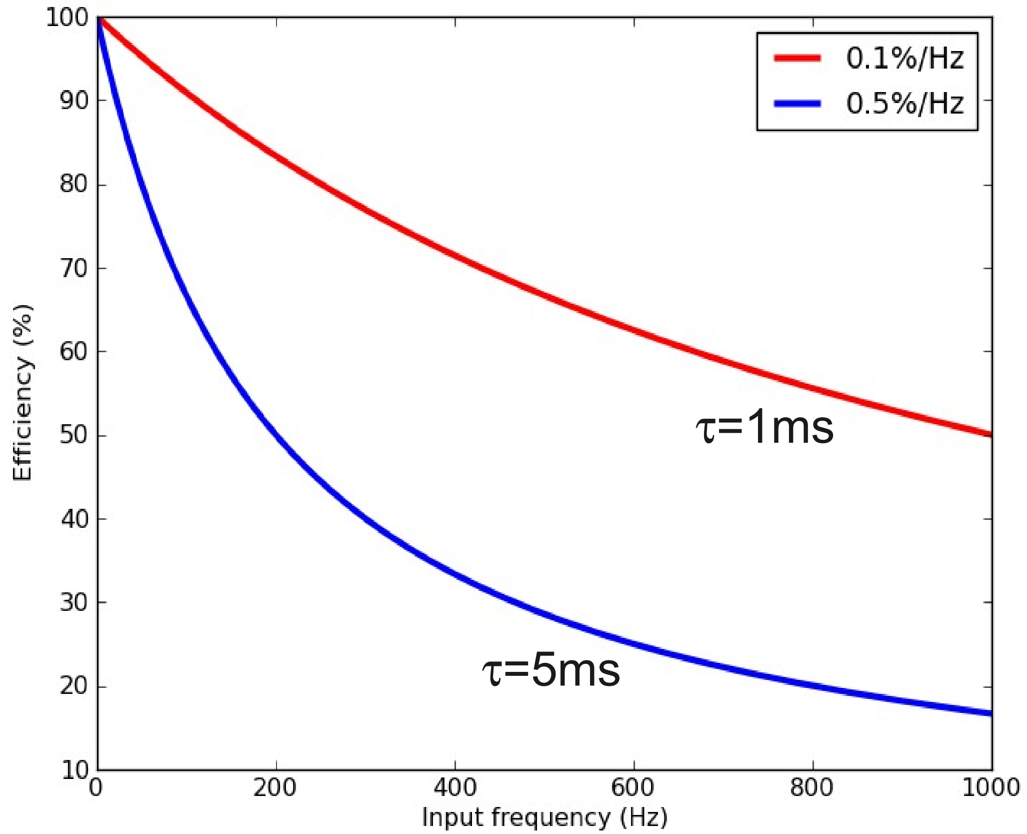
Deadtime

At output rate ν, the system will only be accept (1-ντ) of triggers

$$\nu = f(1-\nu\tau) \Rightarrow \nu = \frac{f}{1+f\tau} < f$$

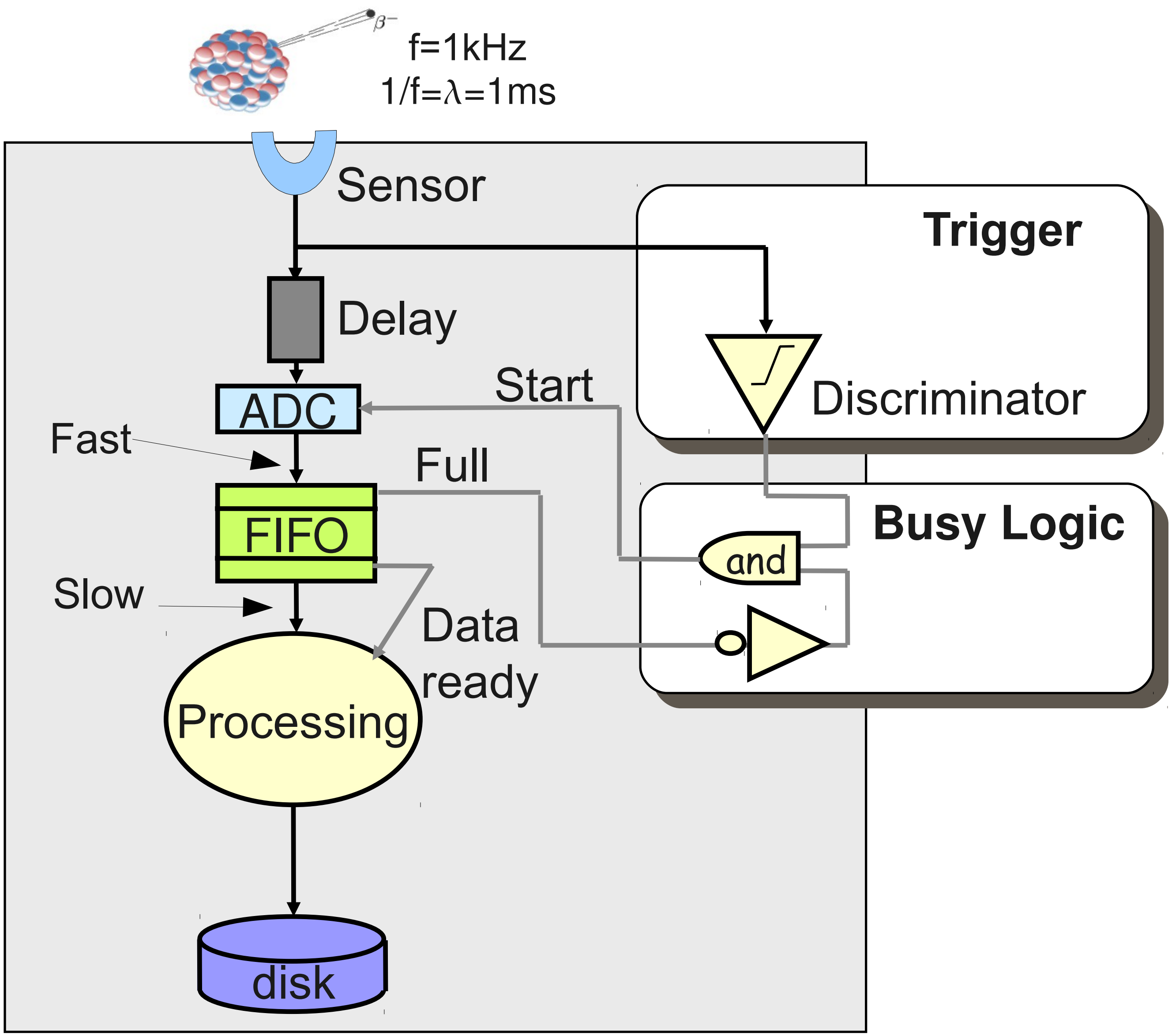
f input rate
τ readout time





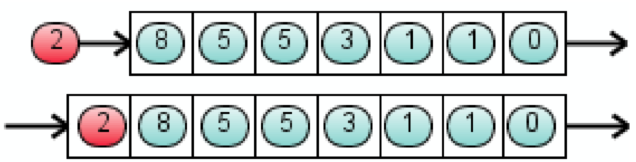
Unless readout time<<time between triggers,
we will have very inefficient system – normally highly undesirable

Derandomizing Buffer



Smooth out fluctuations (derandomize) by introducing an fast, intermediate buffer

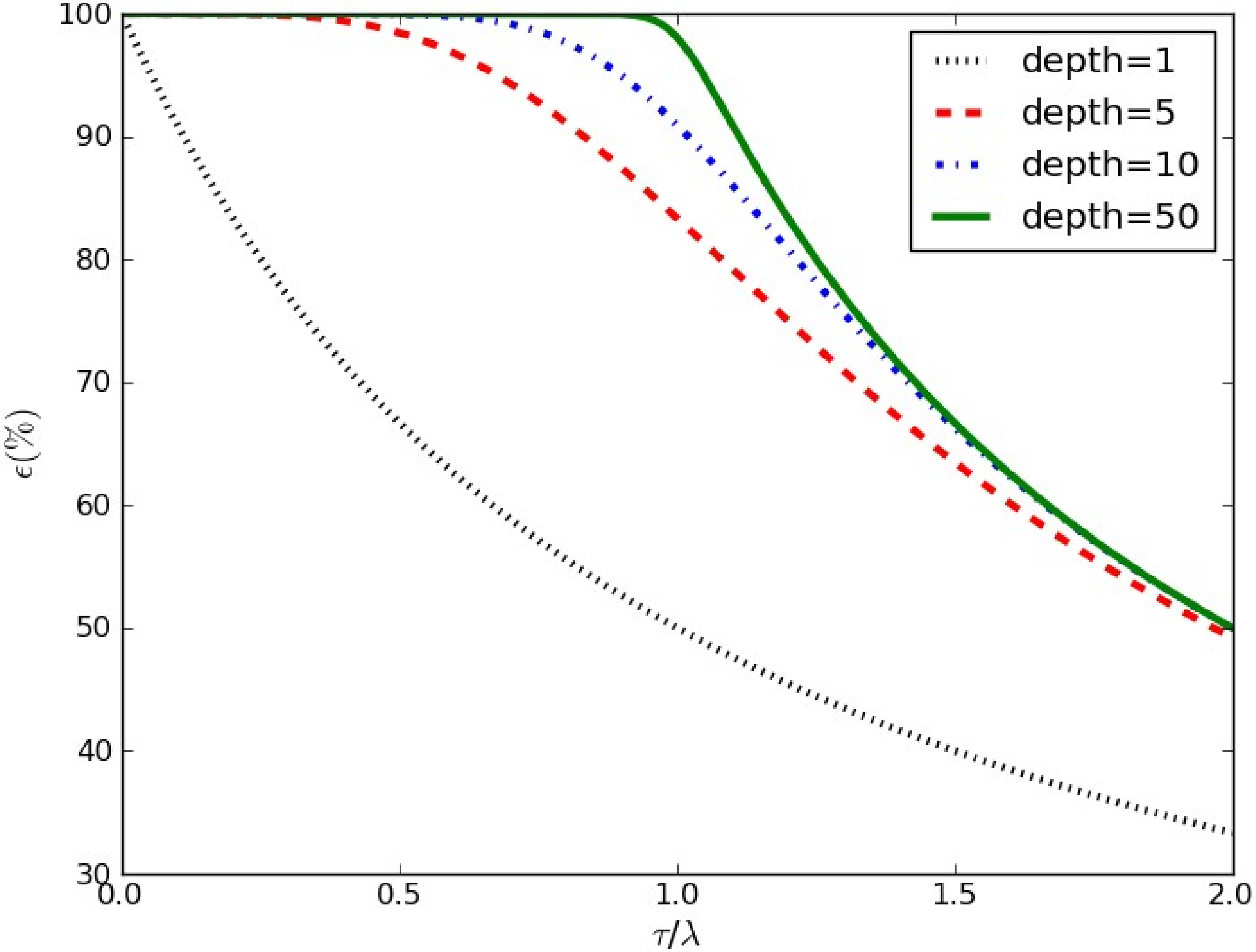
Organized as a queue First-In, First-Out (FIFO)



Decouples the fast front-end (ADC) from slow readout

Deadtime with Derandomizer

τ_{ADC}~0 ms $\tau_{readout}$=1 ms

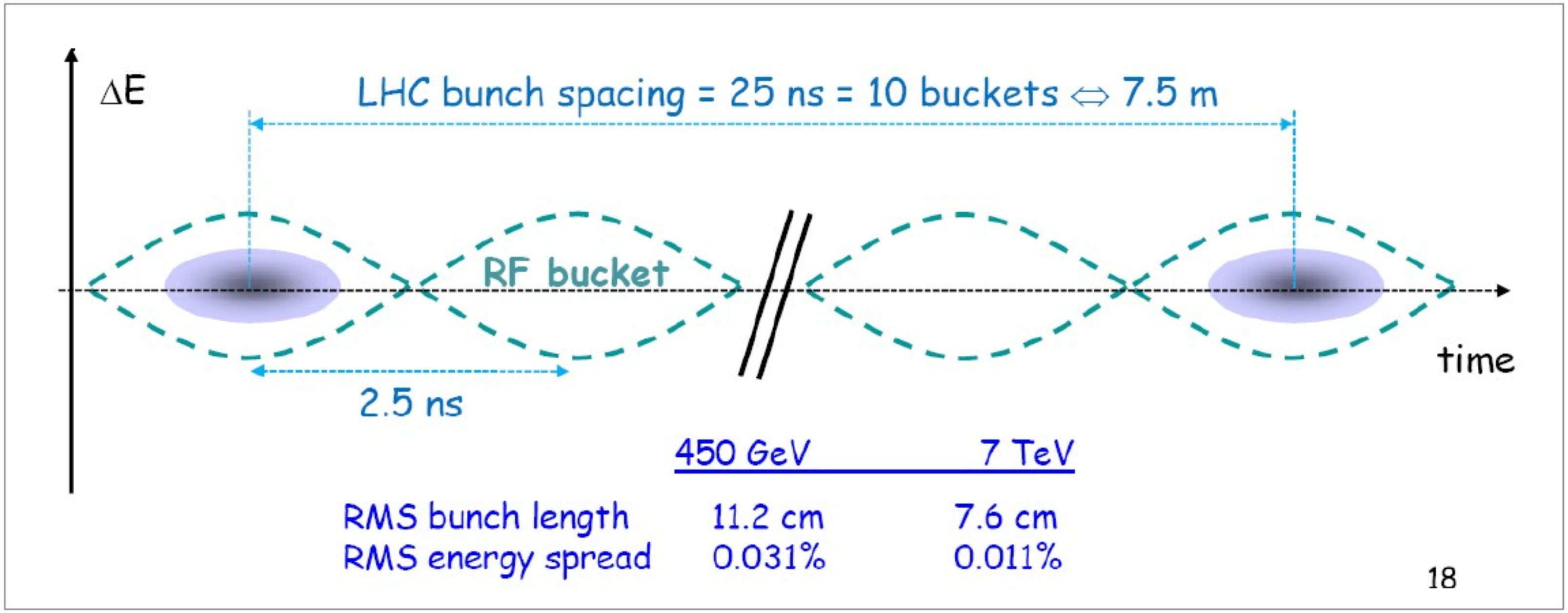


With moderate sized buffer we can retain good efficiency up to f~1/$\tau_{readout}$

Avoids having to over-design the full DAQ system

DAQ in Collider Mode

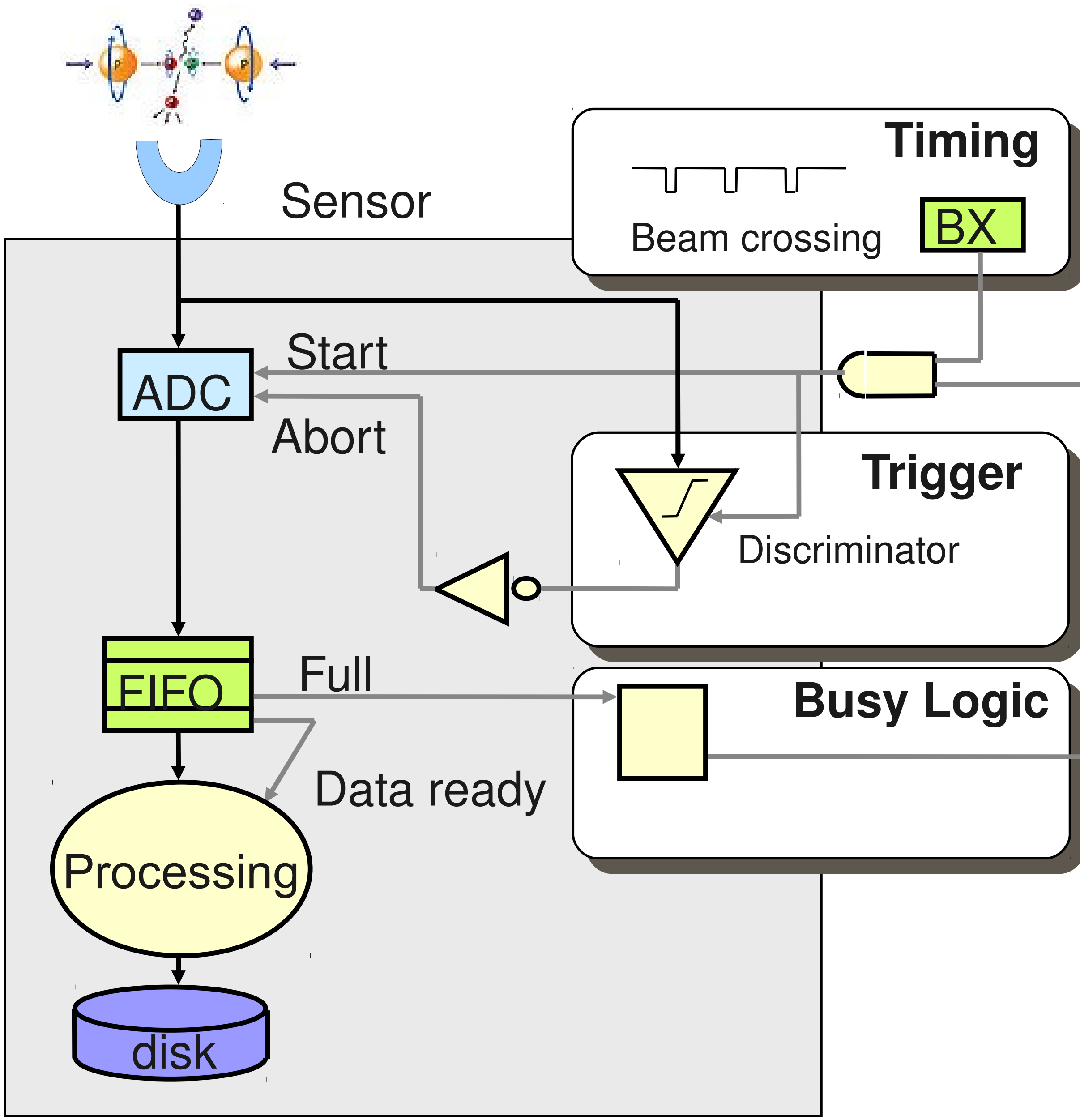
At a collider we know when collision occur



Collider Parameters

	LEP	HERA	PEP-II/KEKB	Tevatron	LHC	ILC
Particles collided	e^+e^-	ep	e^+e^-	$p\bar{p}$	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

DAQ with Bunched Beams



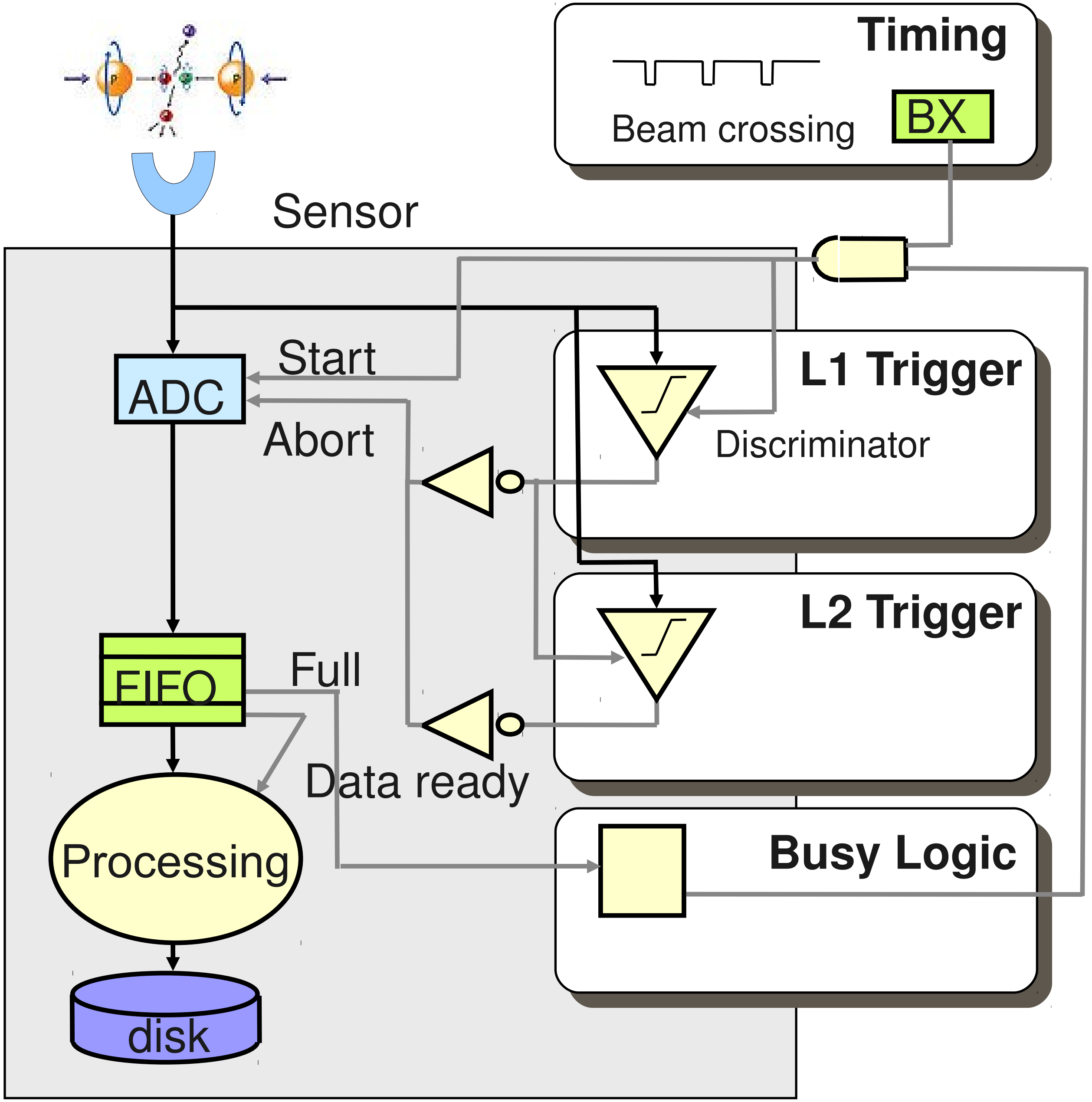
ADC now synchronous with beam crossing

Trigger rejects events

Still need FIFO as trigger output still stochastic

No trigger deadtime if trigger latency below beam crossing interval

Multi-Level Trigger



For complicated triggers latency can be long

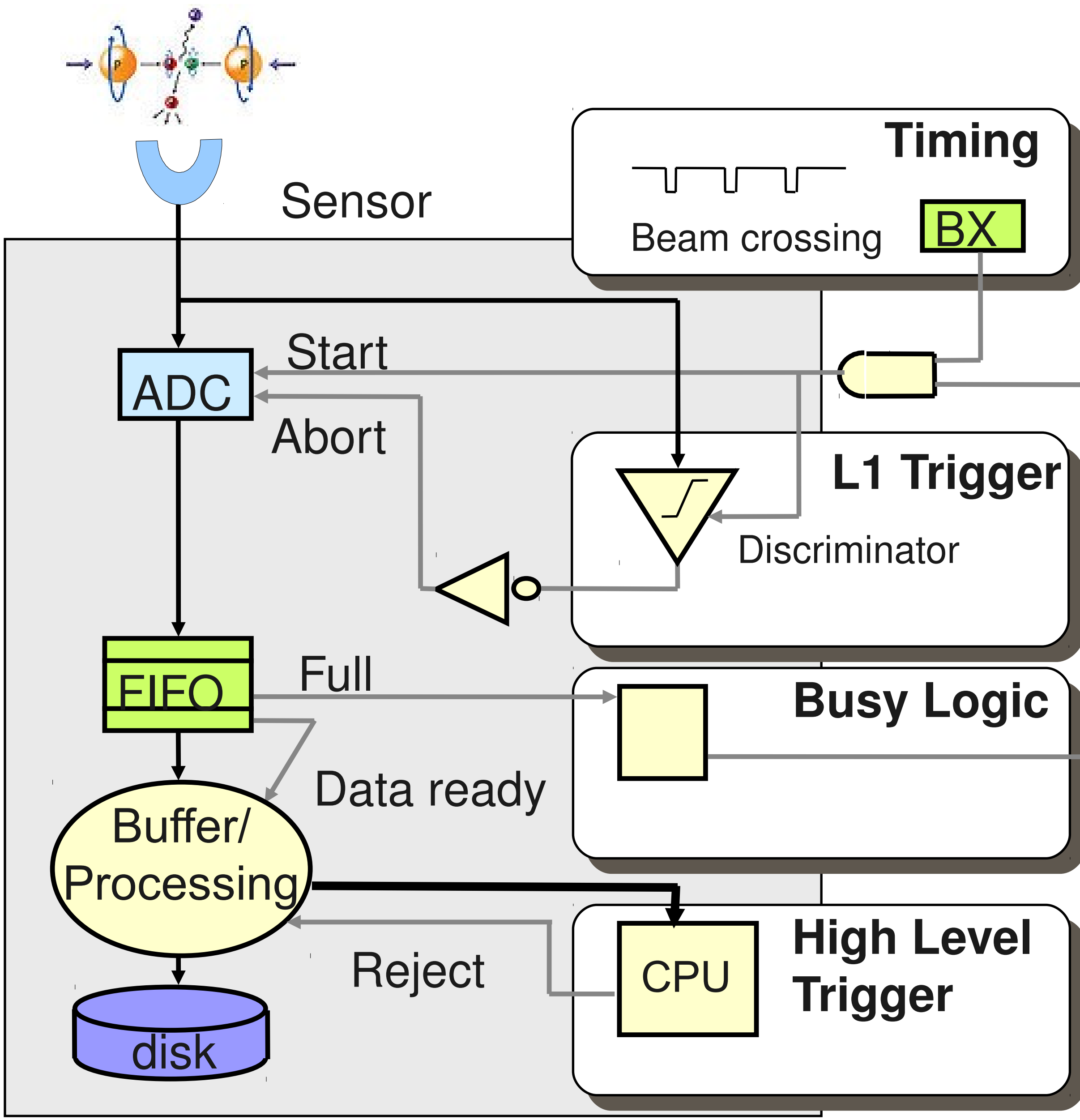
- if $\tau_{trig} > \tau_{BX}$, deadtime>50%

Split trigger in several levels with increasing complexity and latency

All levels can reject events

- with $\tau_{L1} < \tau_{BX}$, trigger deadtime only $\nu_{L1} \cdot \tau_{L2}$

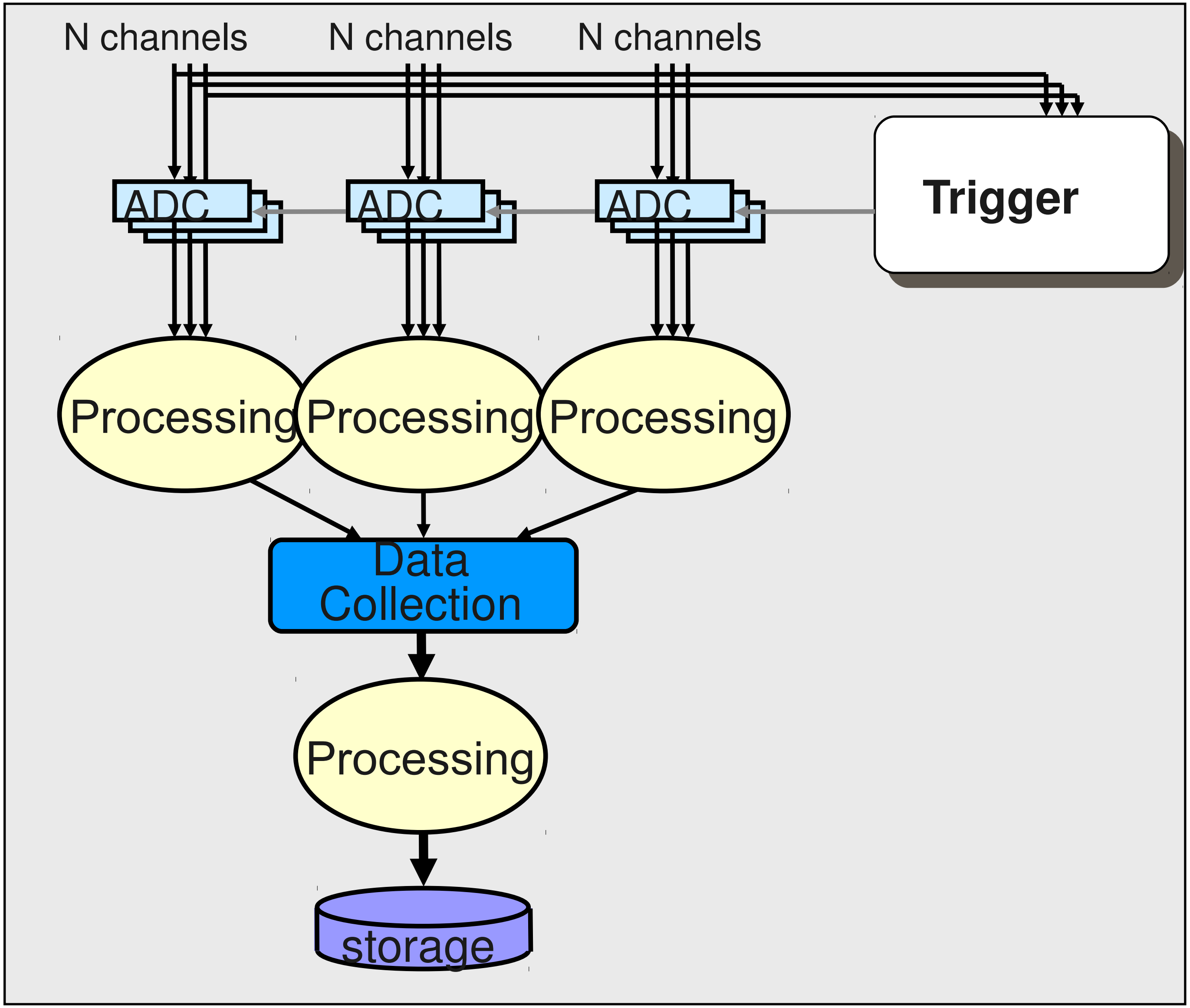
Multi-Level Trigger



For optimal data reduction can add trigger level between readout and storage (High-level trigger)

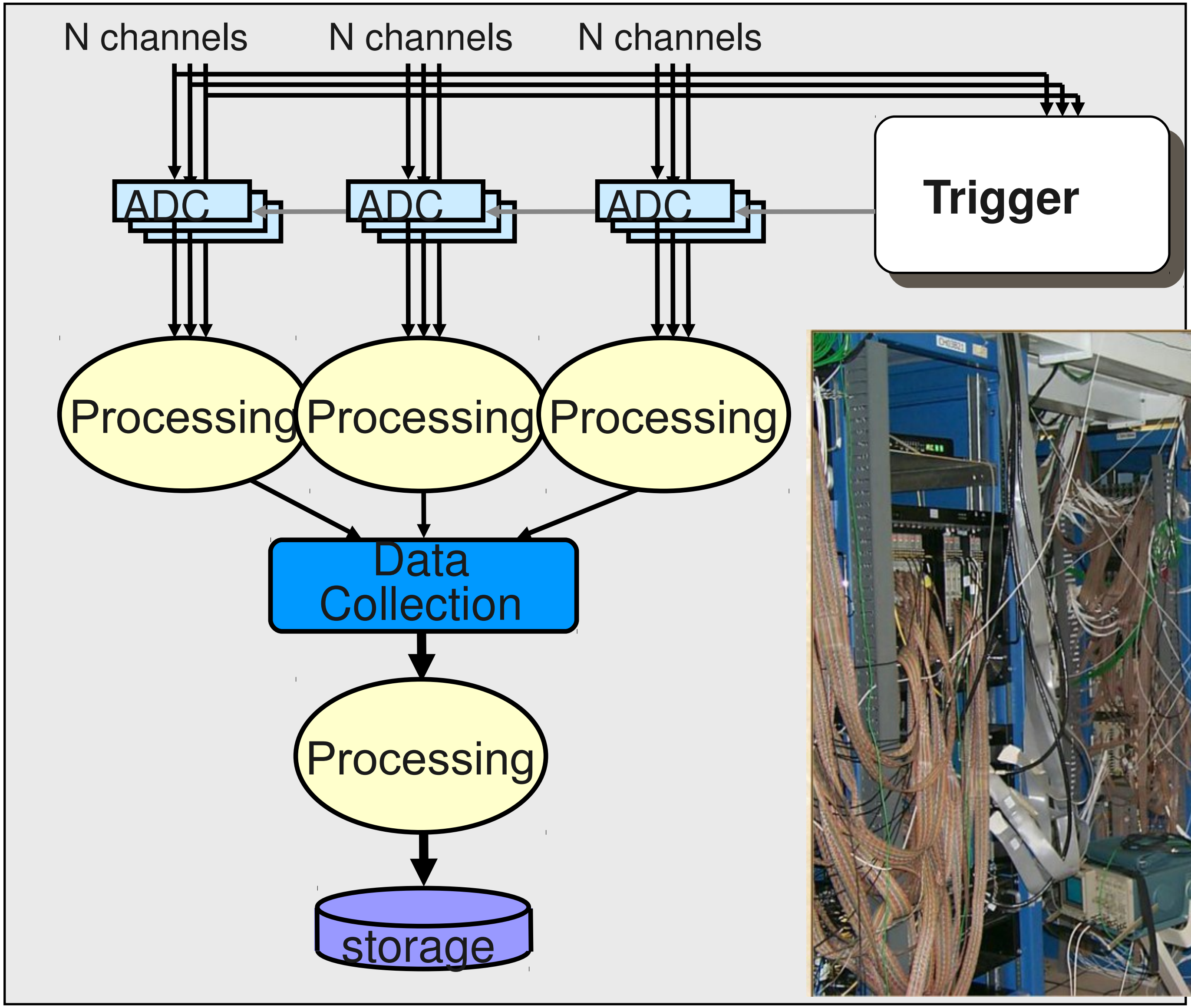
Has accessed to some/all processed data

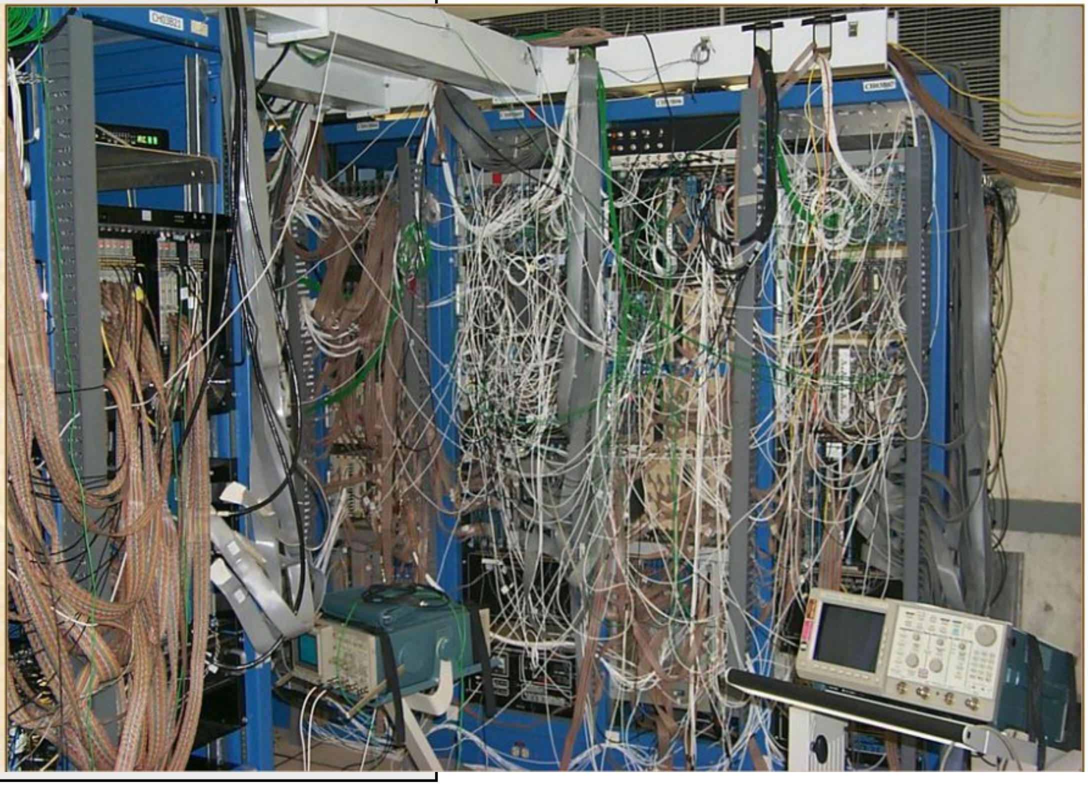
Scaling up



Increasing the system, complexity starts to enter

Scaling up

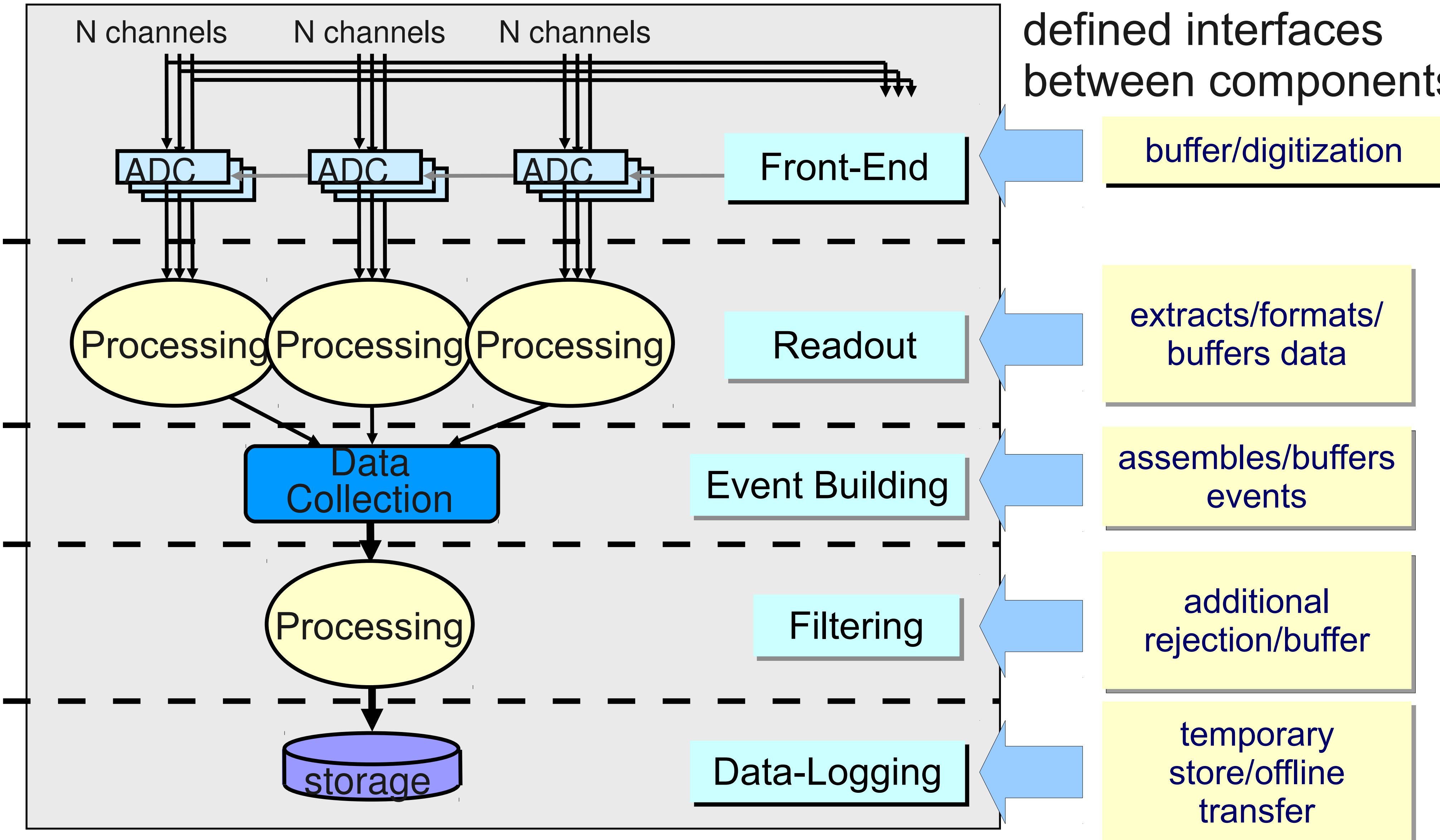




Increasing the system, complexity starts to enter

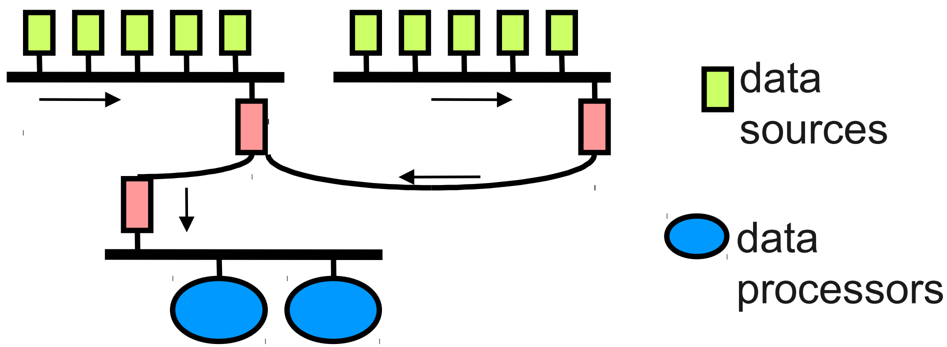
Scaling up

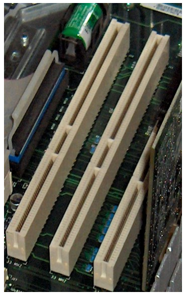
Need to impose structure with well-defined interfaces between components

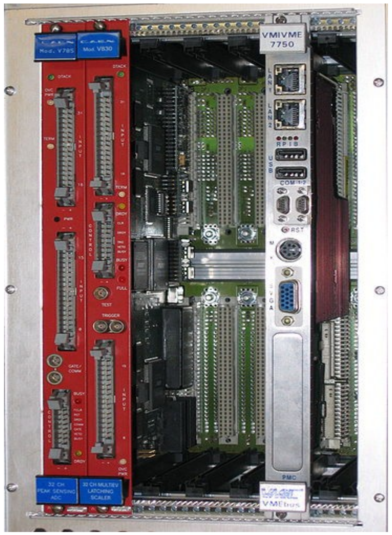


Scaling the Readout Bandwidth

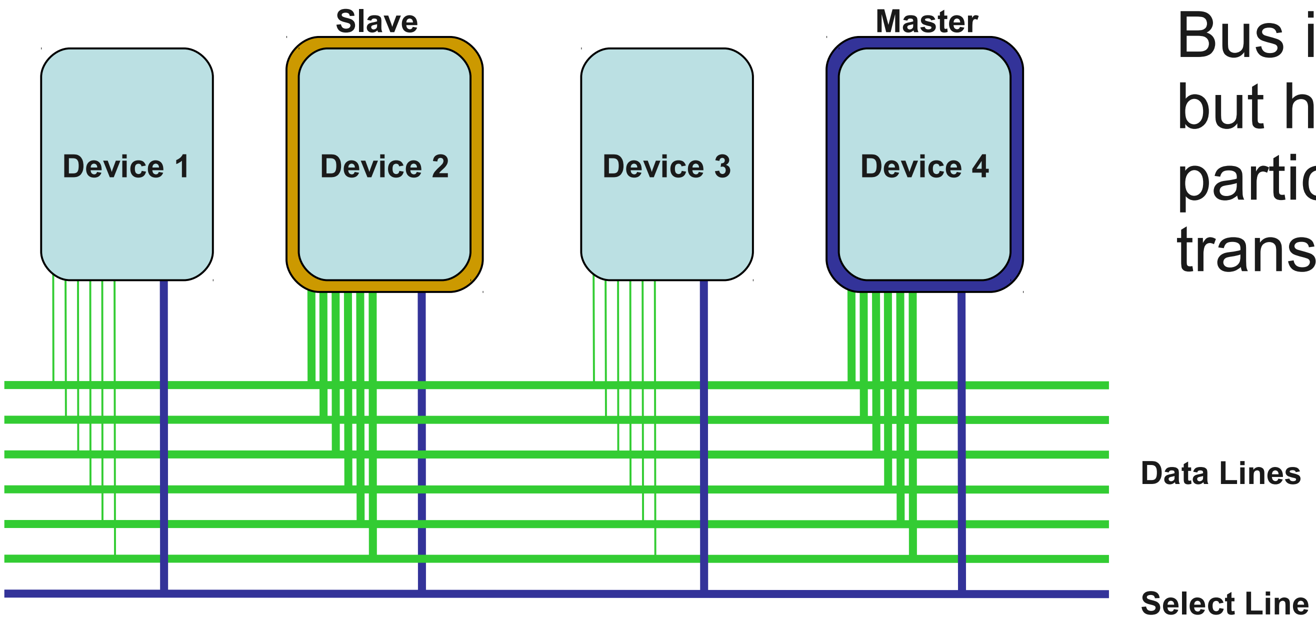
Can use bus to collect data into one place







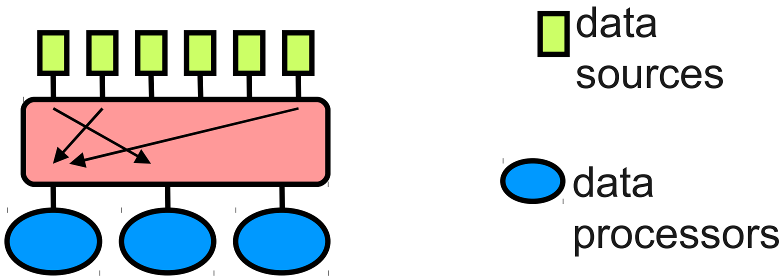
Set of electrical lines shared between all devices
- need a arbitration mechanism



Bus is simple to implement, but has limited bandwidth, particularly for long transmission lengths

Network

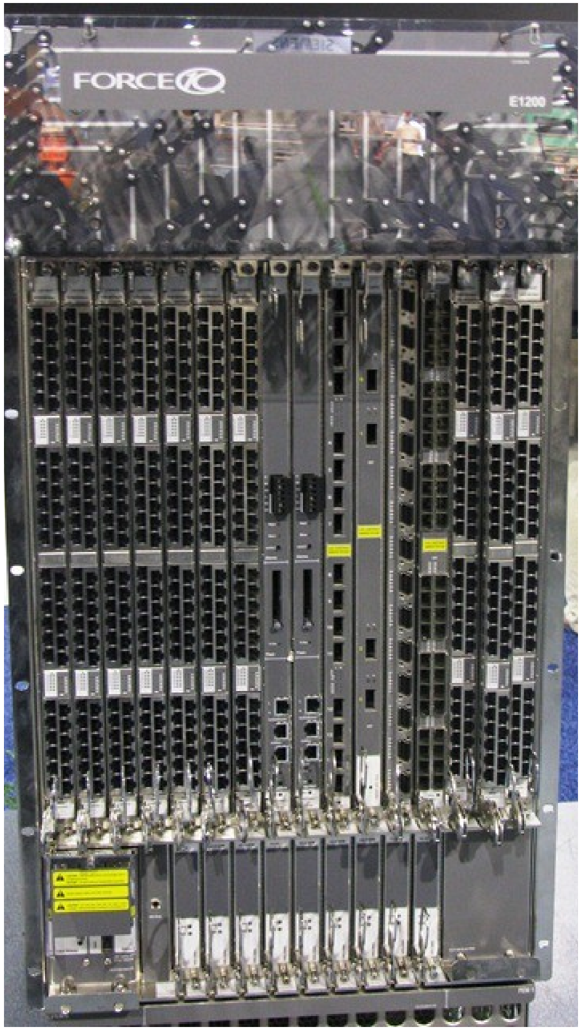
Alternative is to use network
Devices can talk to other devices in parallel



Communication is done with messages
In switched network, switches move messages between devices

Thanks mainly to growth of telecom and internet industry, large commercial switches now available
- used in all LHC experiments

1260 port switch



Triggers at Colliders

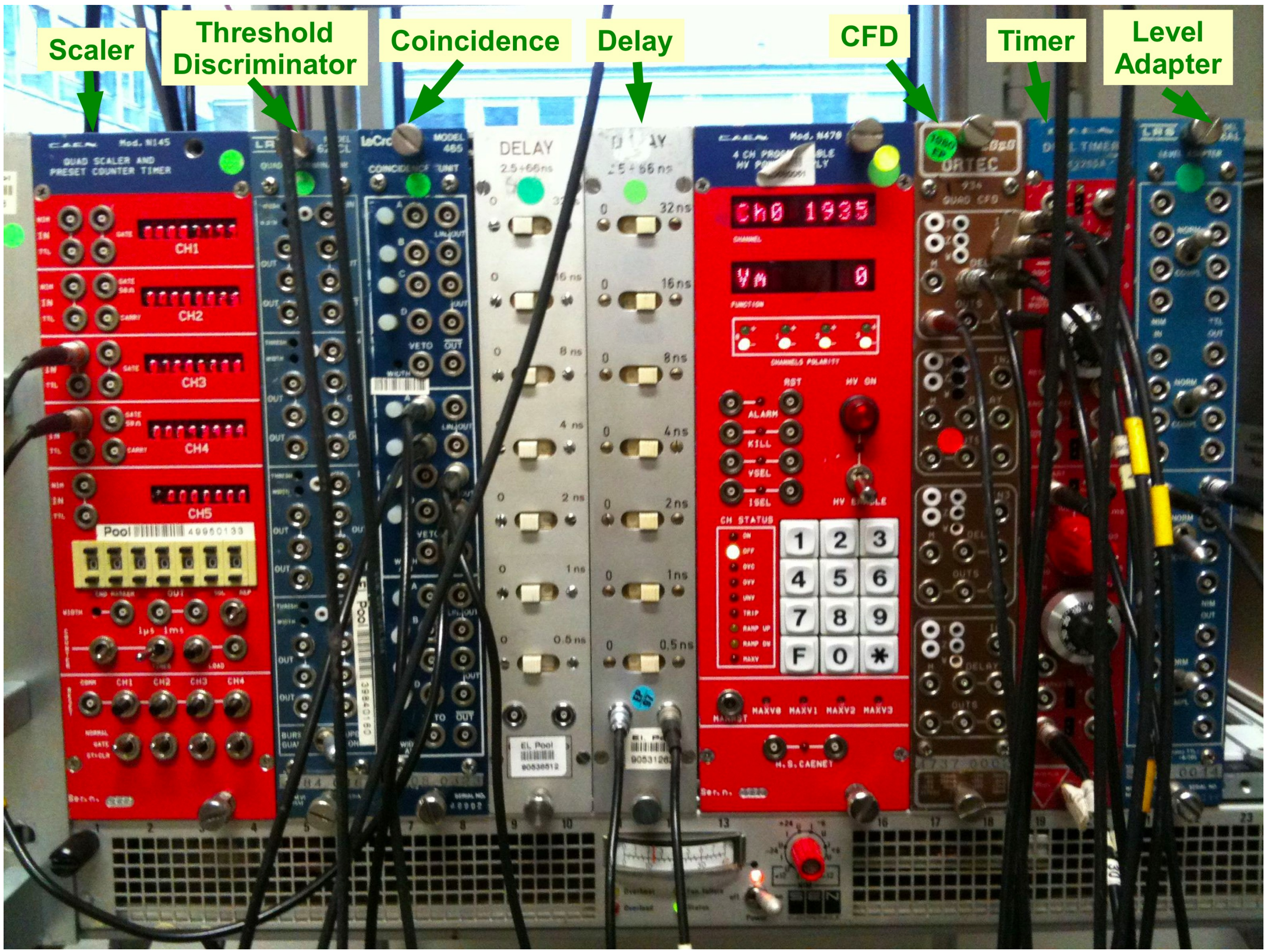
Trigger Requirements

- Low latency
  - Need to avoid deadtime and expensive buffers
  - Particularly important for first level trigger
- Large rejection factor
  - Rejections of 10^4-10^5 common
- High efficiency
  - Any events rejected are lost for ever
  - Efficiency should also be measurable
- Be affordable
- Flexible
  - Cannot foresee all possible signals

Will often require part of the detector
to be designed for use in trigger
 - chambers with fast response, for instance

L1 Trigger

First level(s) of trigger need latencies O(1-10) μs
- need to use fast electronics



For smaller systems existing electronics modules convenient for doing quick setup and modifications

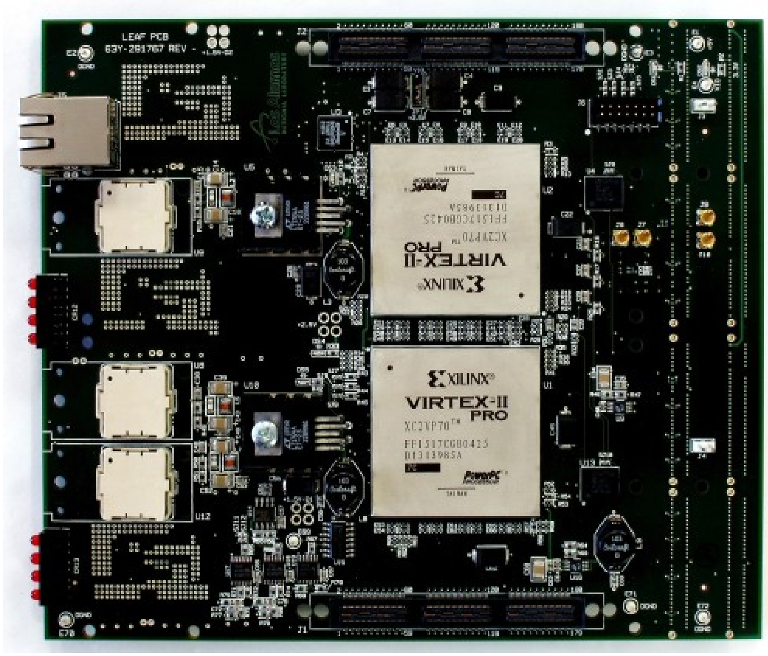
Even at the LHC it is occasionally used

L1 Trigger Electronics

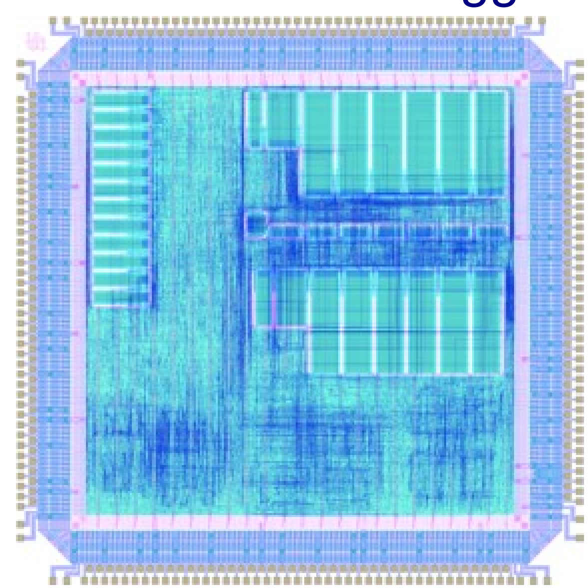
For large scale applications need custom-made electronics

- Application-specific integrated circuits (ASICs)
  Very fast and radiation tolerant if needed
- Field programmable gate arrays (FPGAs) or similar
  Still very fast (100+ MHz)
  Algorithms can be changed after installation!
- High speed/bandwidth communication
  Serial links (1+ Gbit/s, copper or optical)
  Massive backplanes for exchange data between boards

CMS Calo trigger algorithm card

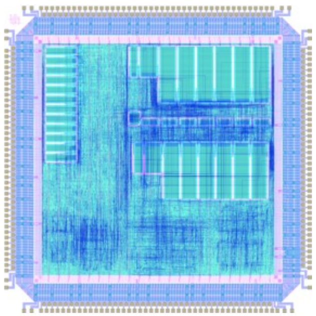


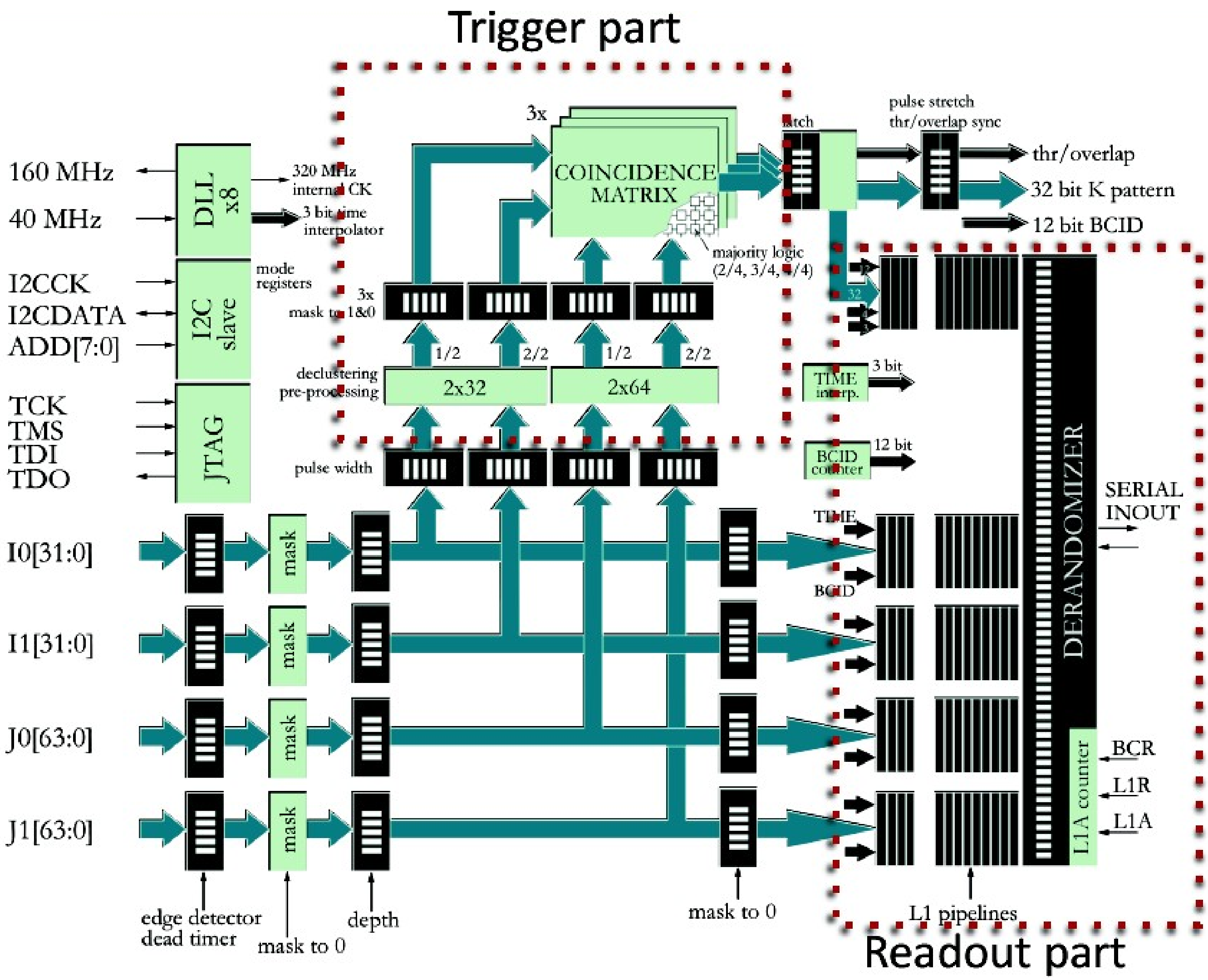
Coincidence matrix ASIC
for ATLAS muon trigger



Example Triggger ASIC Logic

ATLAS Muon Barrel Trigger ASIC





Trigger output

Readout output

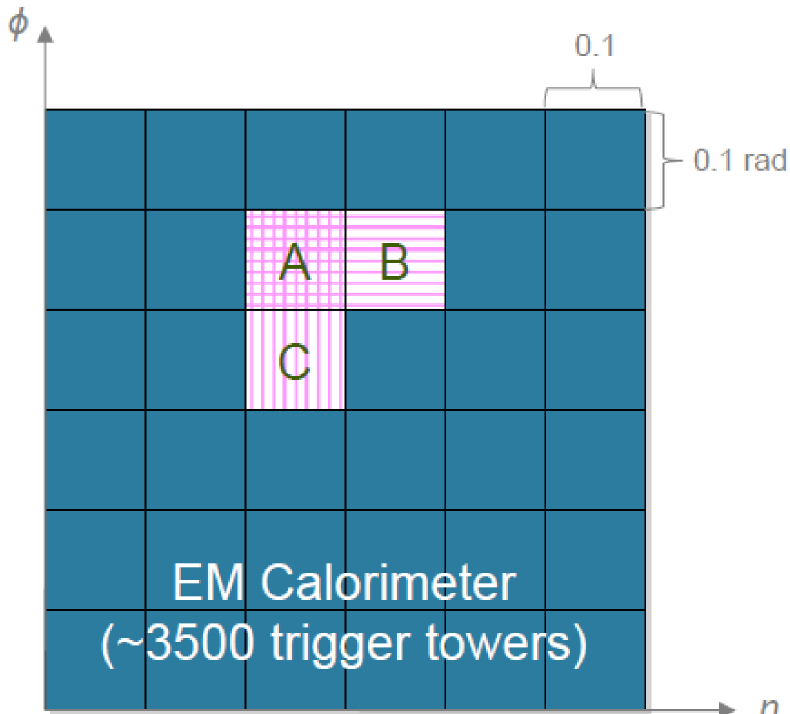
Digital inputs from detector

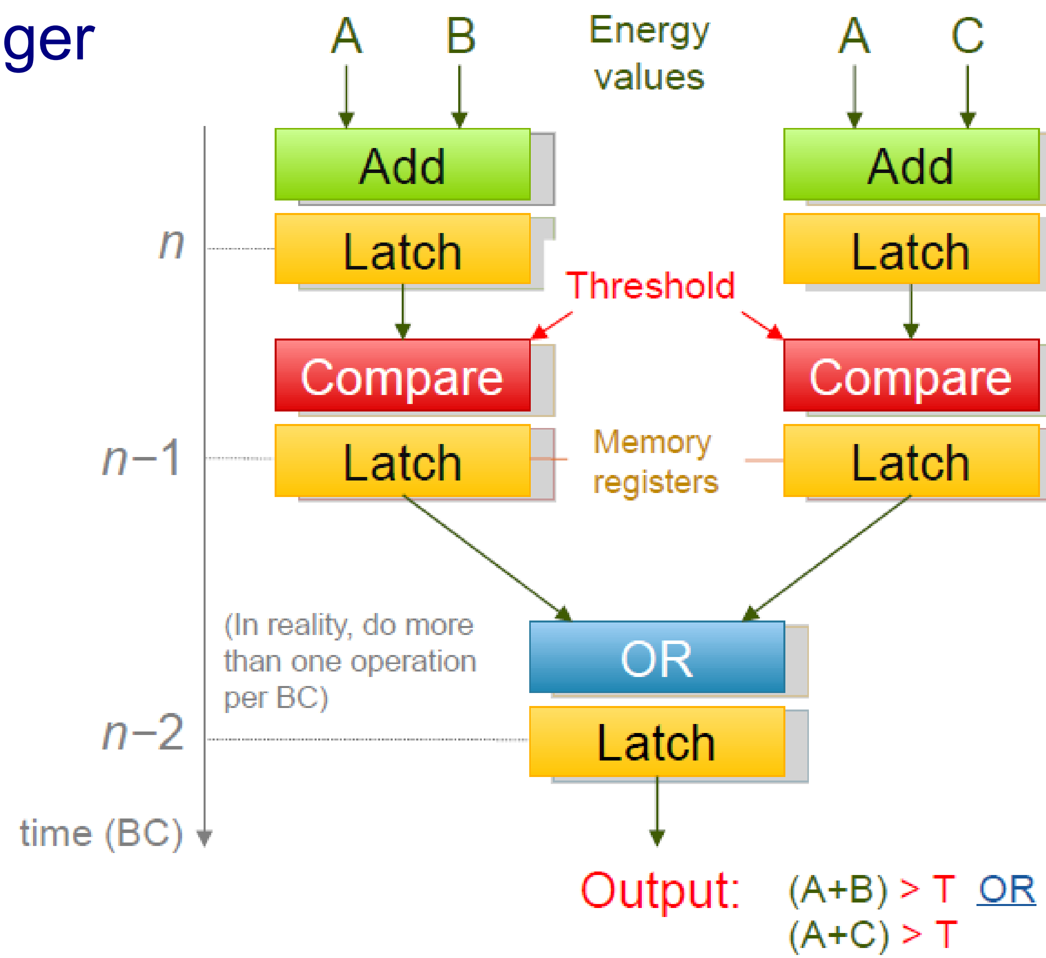
Input: synchronization signals

Pipelined and Parallel Trigger

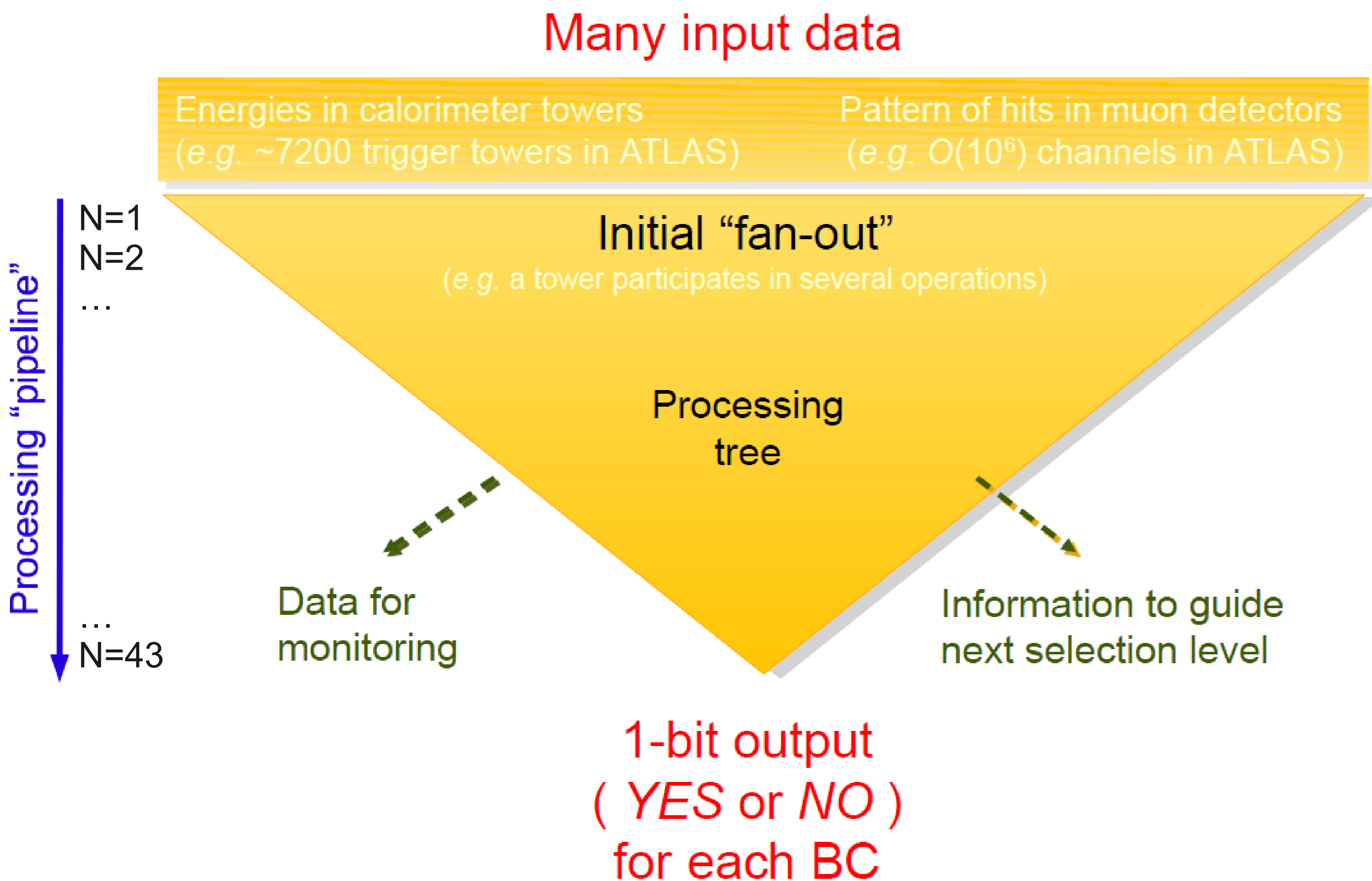
With bunch spacing<1μs cannot process only one event at a time
- Multiple processing steps, events flowing from step to step (pipeline)
- Parallel processing of different inputs as much as possible

Example L1 calorimeter trigger

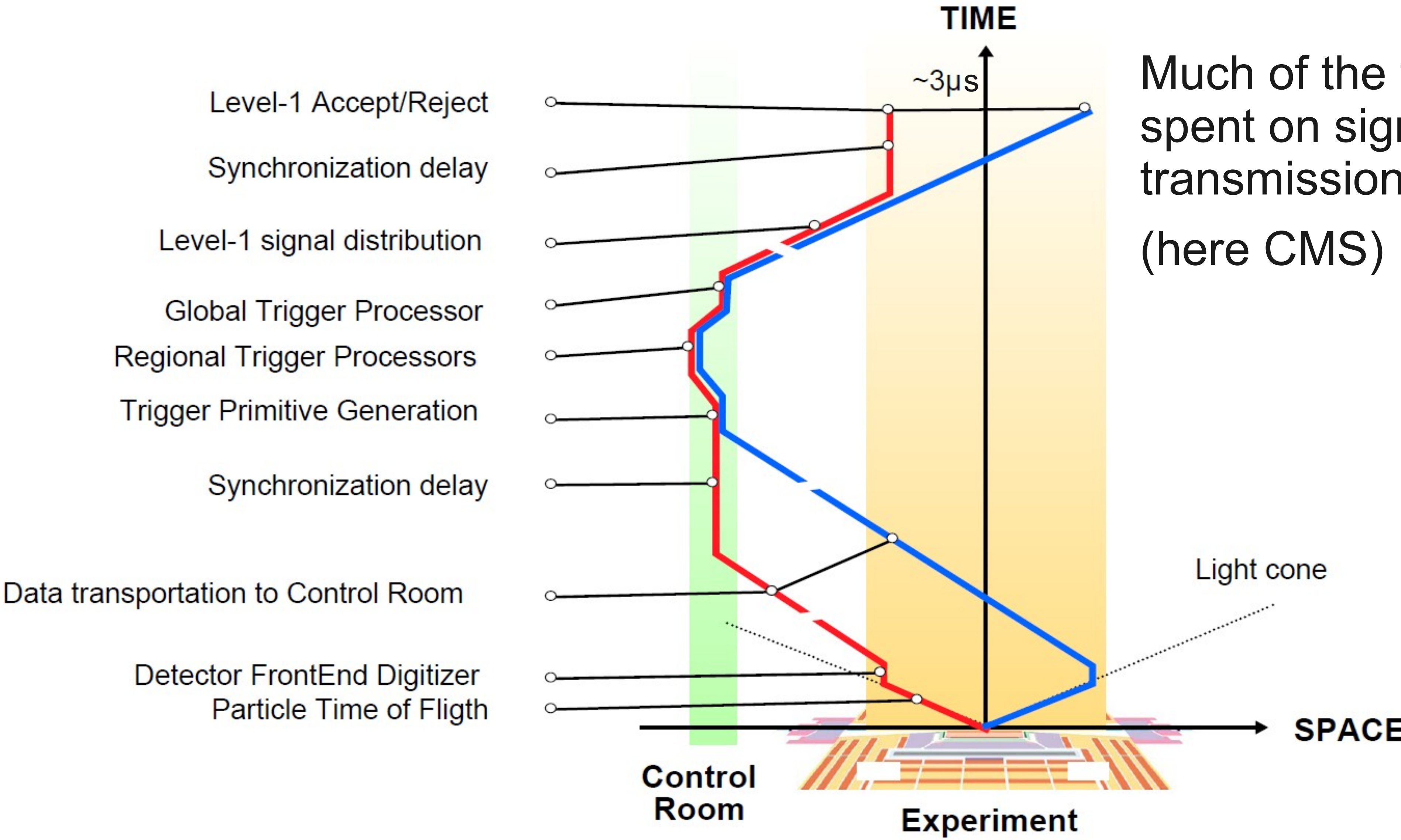




L1 Dataflow


Many input data
Energies in calorimeter towers
(e.g. ~7200 trigger towers in ATLAS)
Pattern of hits in muon detectors
(e.g. O(10^6) channels in ATLAS)
Initial "fan-out"
(e.g. a tower participates in several operations)
Processing tree
Data for monitoring
Information to guide next selection level
Processing "pipeline"
N=1
N=2
…
…
N=43
1-bit output
(YES or NO)
for each BC

L1 Latency

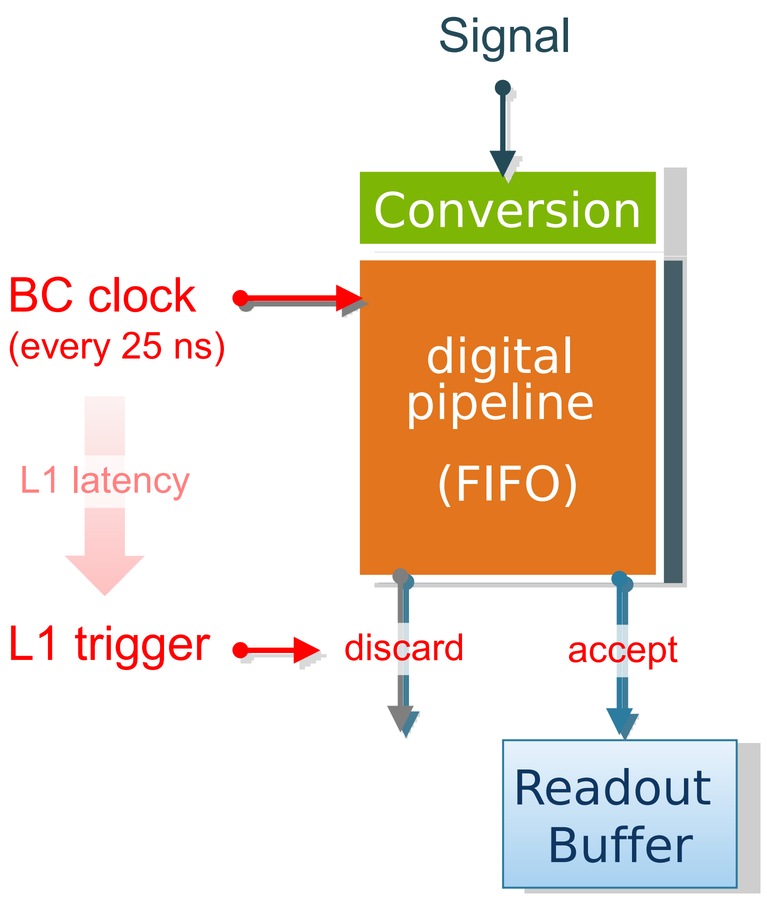


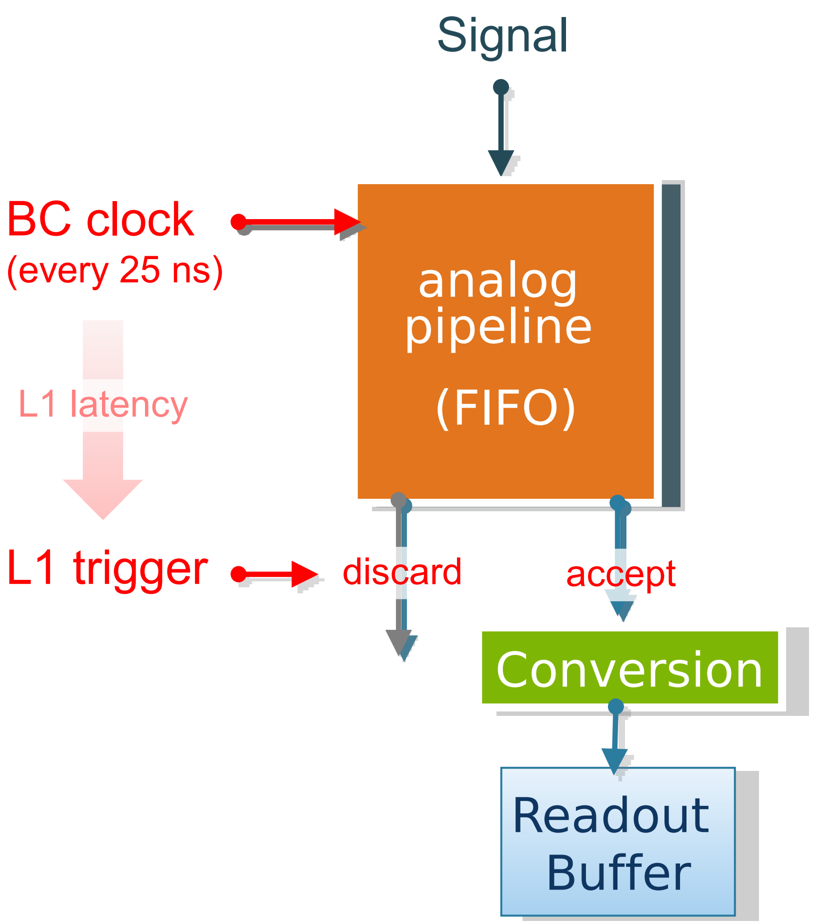
Much of the time spent on signal transmission

(here CMS)

Pipelined Frontends

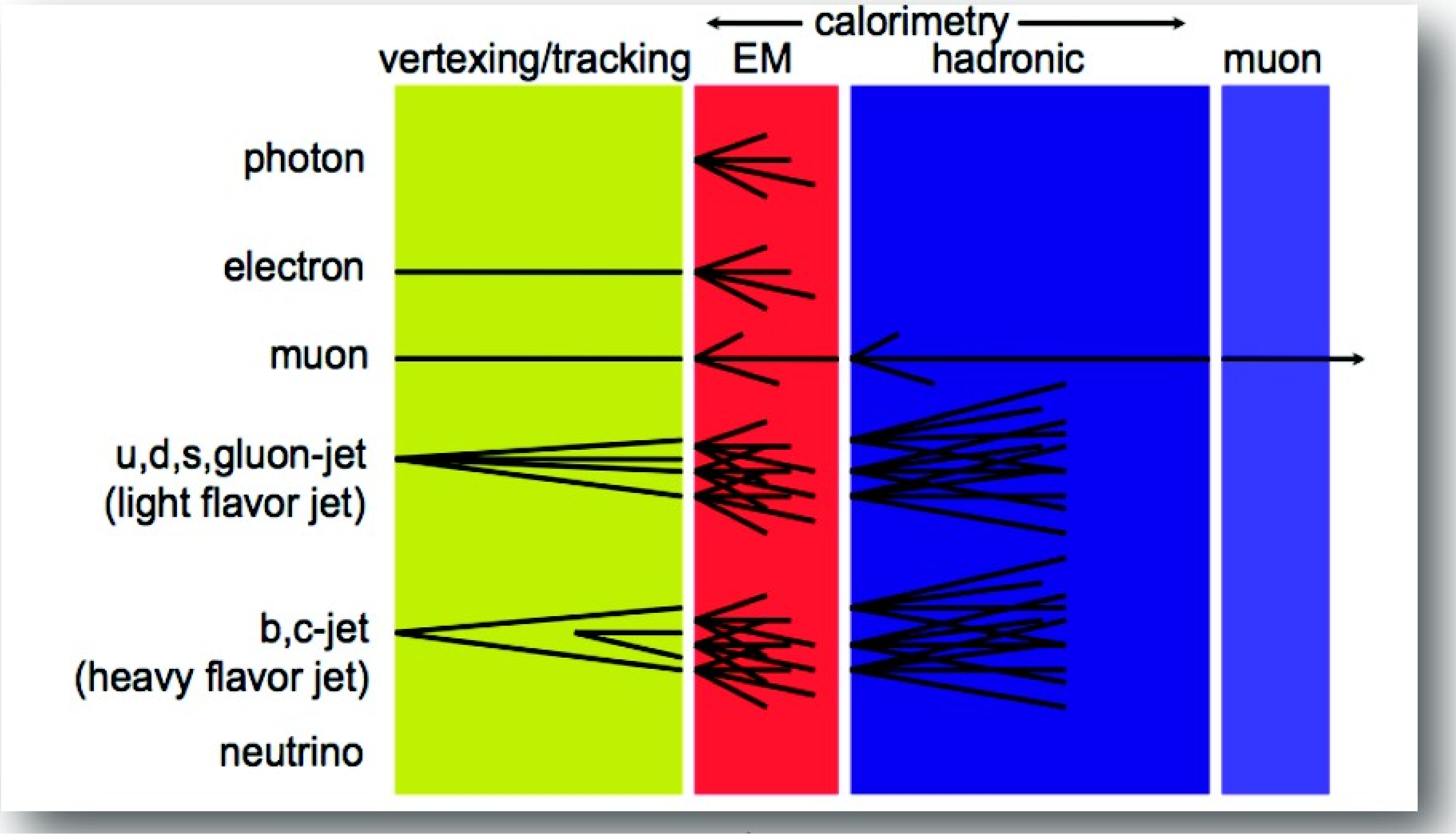
During L1 processing data for all bunch crossings buffered
Use pipeline in data path for holding data
 - many variations (analog/digital, on/off detector)
Length of pipeline determines maximum L1 latency



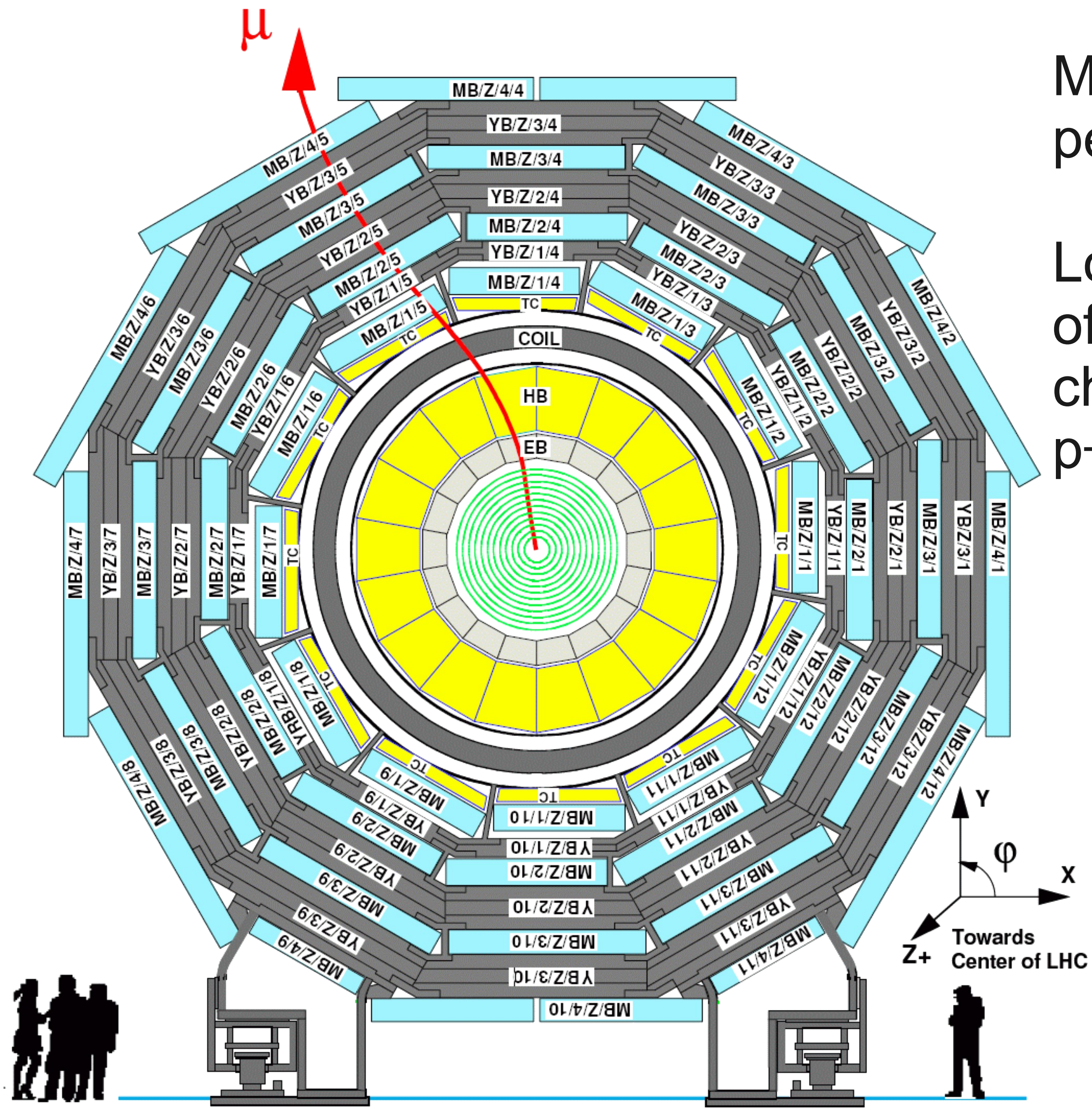


What to Trigger on

Multiple signatures for different physics signals



L1 Muon Trigger



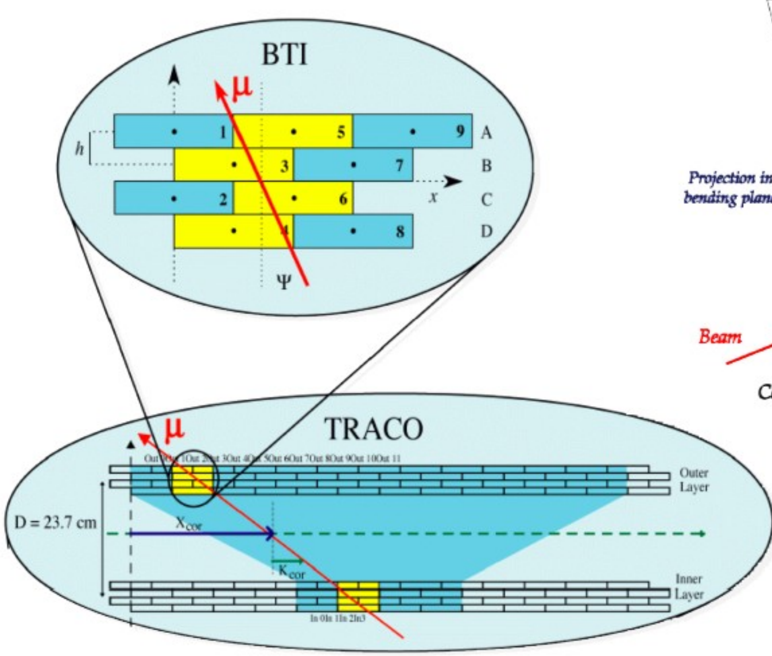
Mostly only muons penetrate calorimeter

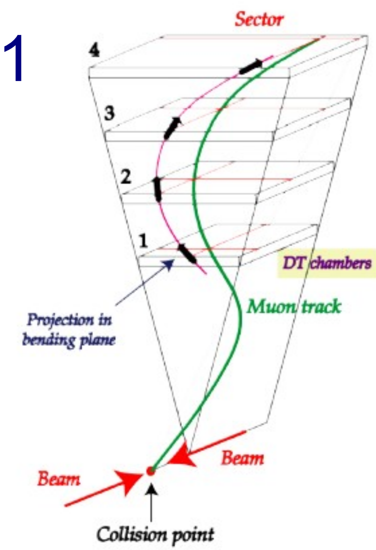
Look for coincidences of hits in muon chambers and measure p_T from bending in field

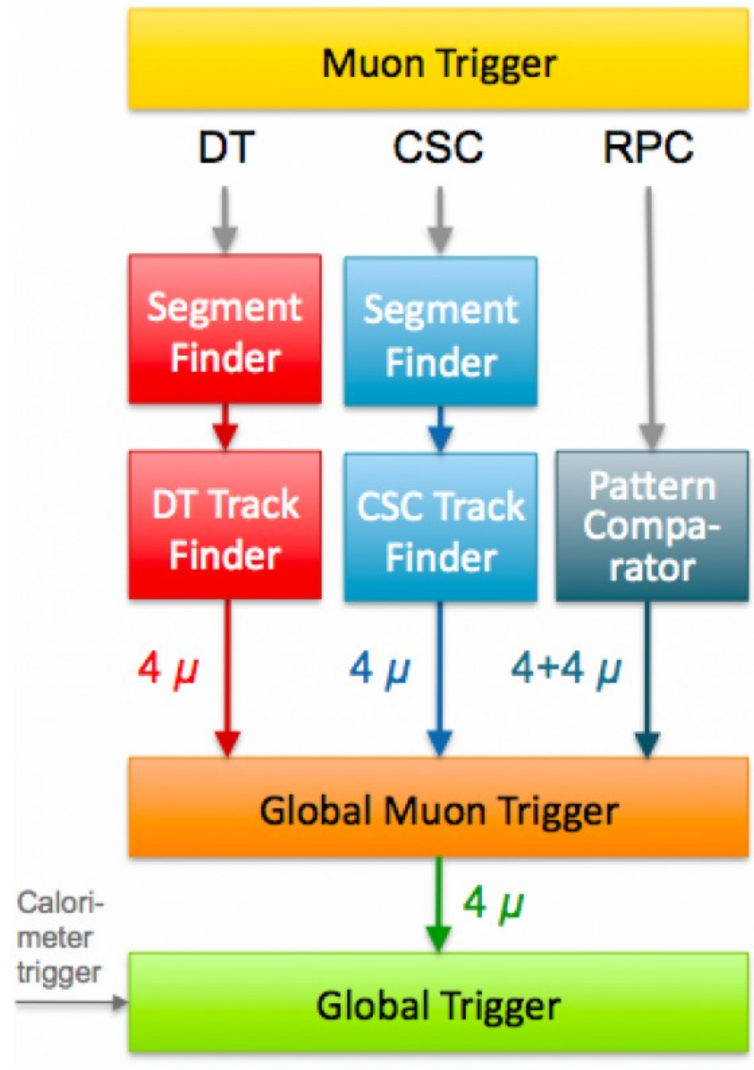
L1 Muon Trigger

Reconstruct segments in each muon chamber
Combine segments to form track
and measure p_T (rough)

Example: CMS Muon L1







Calorimeter Trigger

Calorimeter essential source of
L1 triggers at hadron colliders
- electrons, photons, jets
  taus (thin jets)
- also global quantities like
  energy sum or missing energy

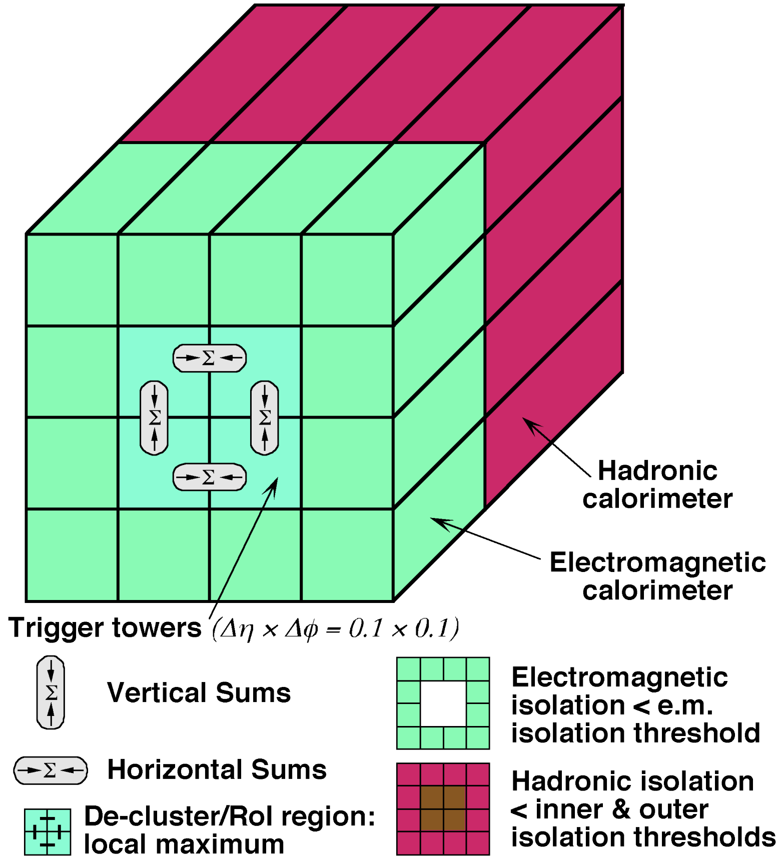
Example: ATLAS L1 e/γ trigger

Cells summed to towers of 0.1x0.1 in ηxϕ
(EM and hadron towers separate)

Search in 4x4 overlapping, sliding window

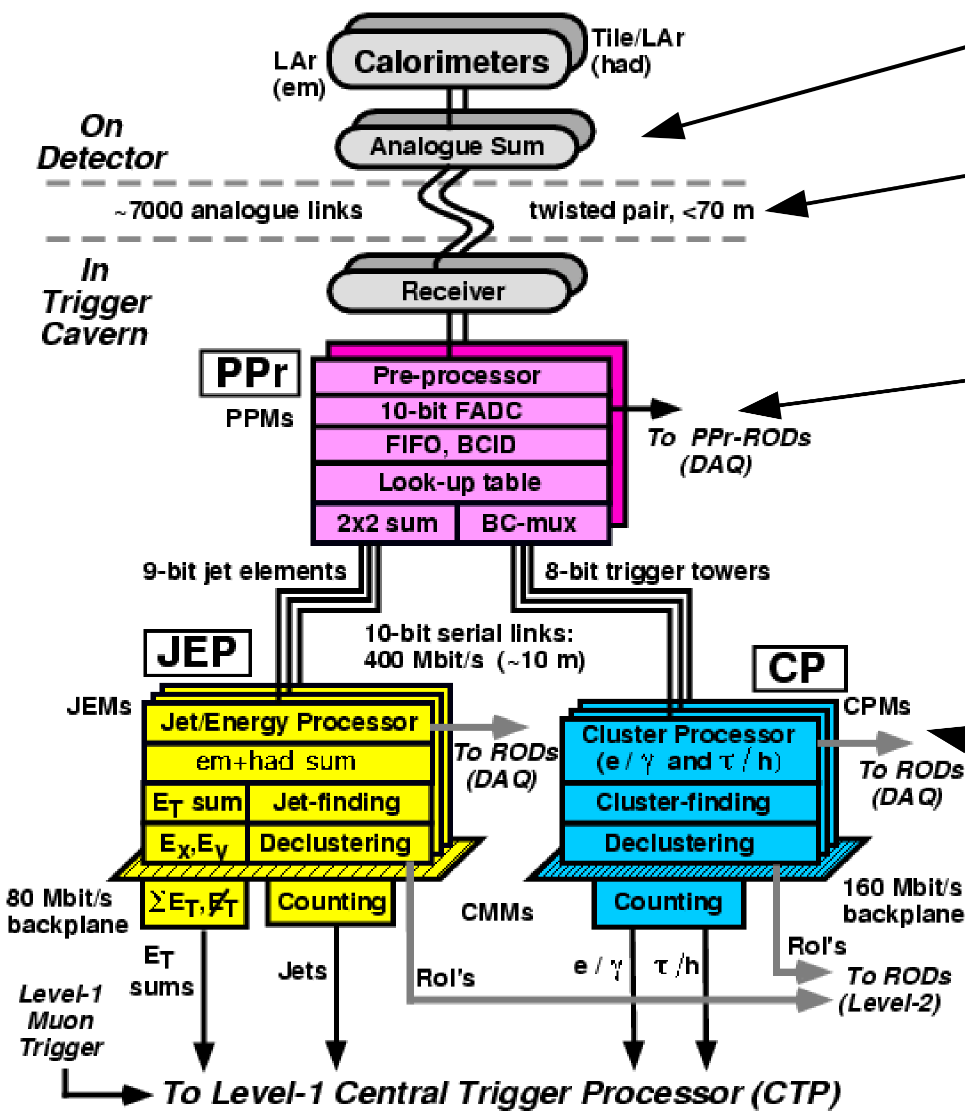
Cluster local maximum in window

Possible to require isolation
(Max energy in EM ring around or
in hadronic towers behind)



Calorimeter Trigger Processing Steps

ATLAS L1 calorimeter trigger



Calorimeter cells in analog sum on detector

Transmitted to underground counting room

Signal timing adjusted, signal digitized and converted to tower E_T (*ADC* and *ASICs*)

Cluster identification and isolation requirement (in *FPGA*)

ATLAS Calorimeter Trigger

Level-1 Calorimeter Pre-processor crate

Analogue trigger cables received in electronics cavern

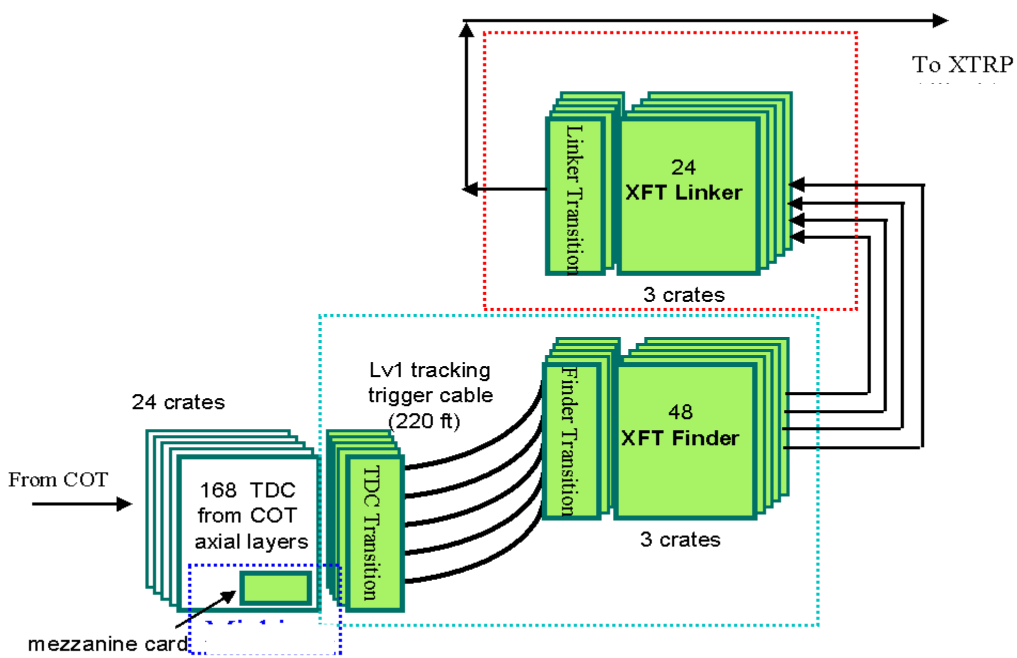
In total 27 VME crates in the full L1 calorimeter trigger

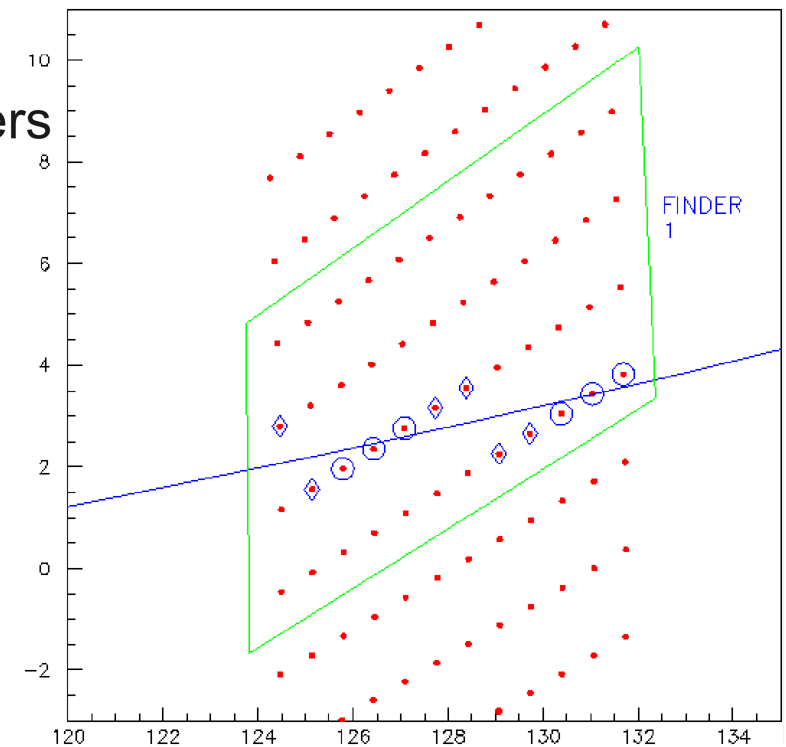
L1 Track Trigger

Can reconstruct tracks in main tracking detector
- primarily use case is to confirm electrons and muon triggers
- also possible use as seed for later triggers

Example: CDF eXtremely Fast Tracker (XFT)

Drift chamber hits digitized in two time bins
Segments identified from hit patterns in 4 layers
Segments linked into tracks with p_T threshold





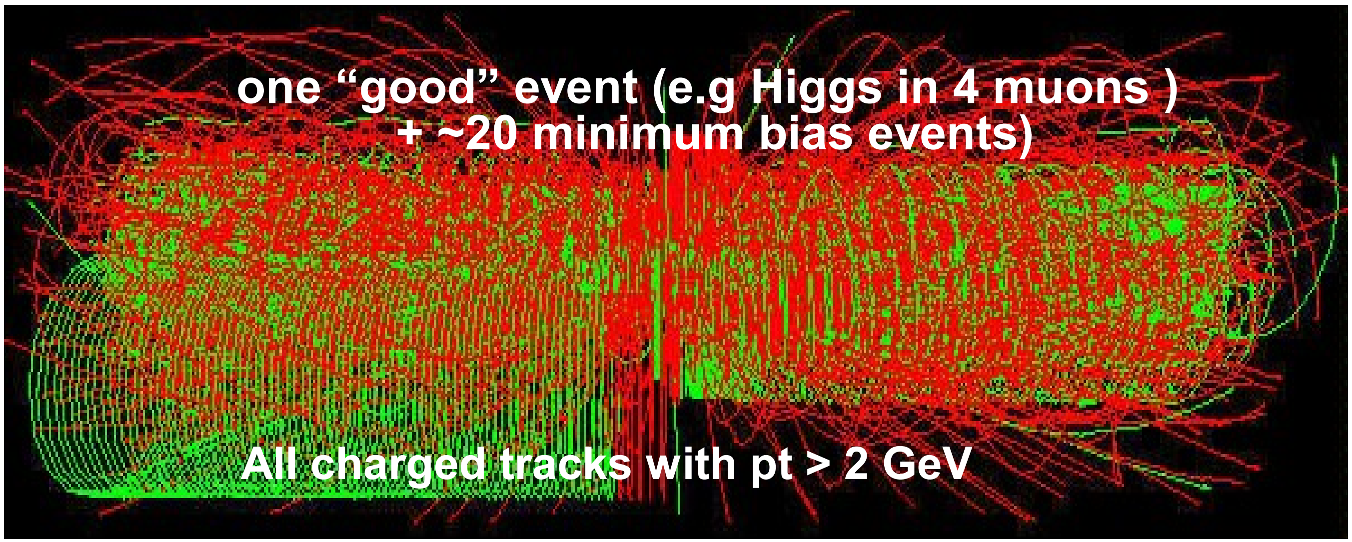
Mostly done with pattern matching

minimal threshold pt 1.5 GeV

L1 Track Trigger at LHC?

No LHC experiment uses track trigger at first trigger level

Difficult to process an LHC event in few μs:



Transmitting all data at full 40 MHz rate requires high amount of electrical power

It is being studied for LHC/detector upgrades
- can be used for isolation requirement or matching with $e^{\pm}$ or $\mu^{\pm}$

ATLAS: Do full tracking between L1 and L2 (75 kHz input rate)
CMS: Track trigger with upgraded tracking detectors (phase 2) requires ability to only readout hits from "high" p_T tracks
LHCb: Already doing tracking at ~1 MHz in software

Global/Central Trigger

Multiple sources of L1 triggers combined in one place for final decision of "accept" or "reject" (global/central trigger)
- also includes busy logic

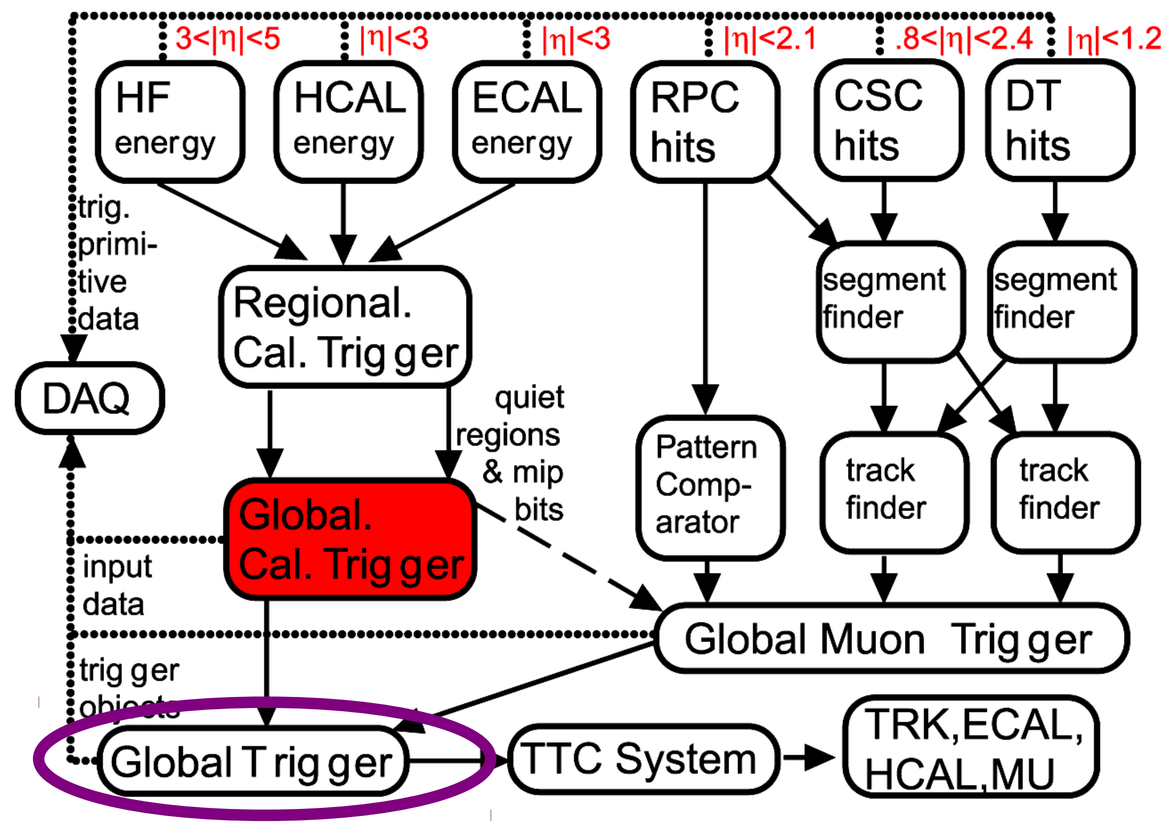
Can either be big OR of input triggers, require combinations of certain trigger objects or even some topological cuts

Example:

Pass event if:
- 1 muon with p_T>20 GeV, or
- 2 muons with p_T>5 GeV, or
- 1 electron with p_T>7 GeV and 1 muon with p_T>5 GeV, or
- 1 muon above 15 GeV and no jet within $\Delta\phi$ of 0.2 rad,

...

Example: CMS L1 Trigger

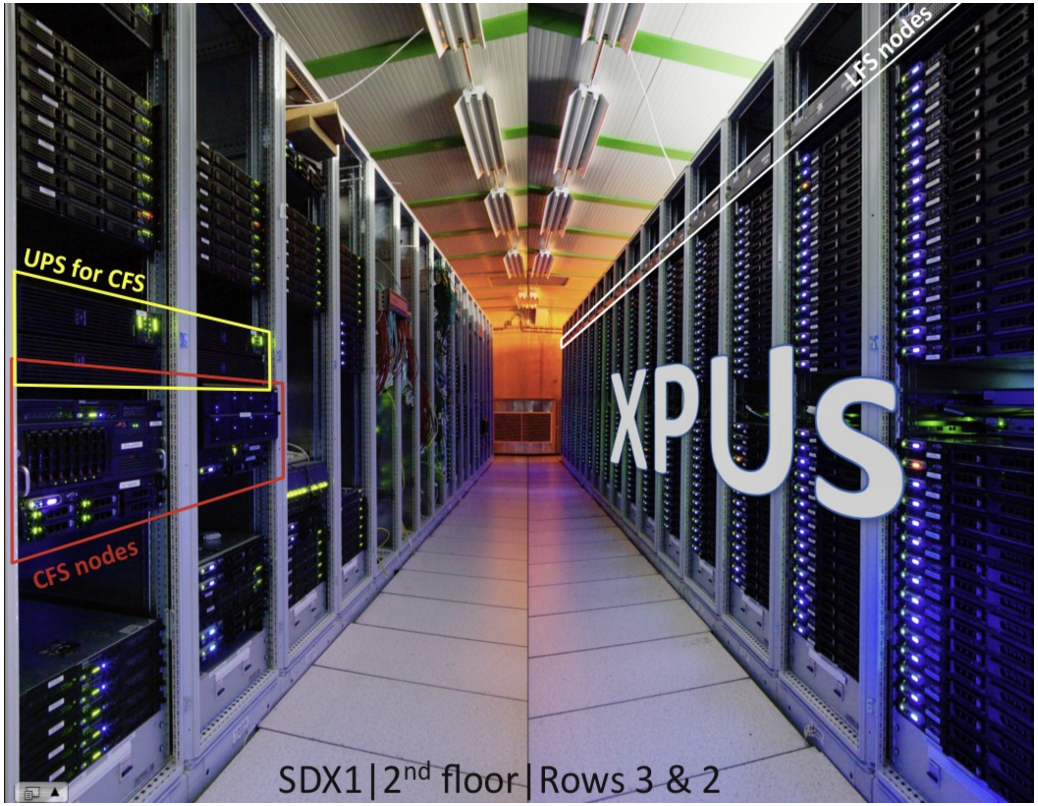


Event Filtering (HLT)

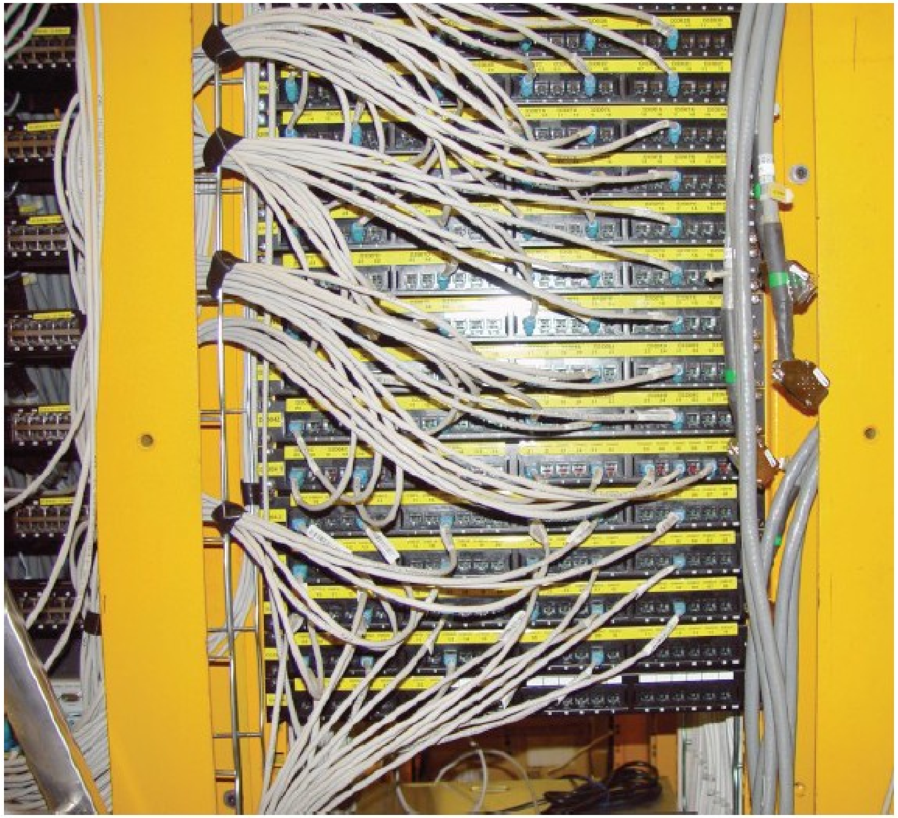
Final selection in software triggers using large commercial PC farms
- acces to full granularity and offline reconstruction-like algorithms
- extremely flexible
- slow (1-100+ ms latency), so use many PCs at the same time

Events are independent, so trivially parallelizable on PC cluster

ATLAS HLT farm:



LHCb readout switch:



HLT Processing

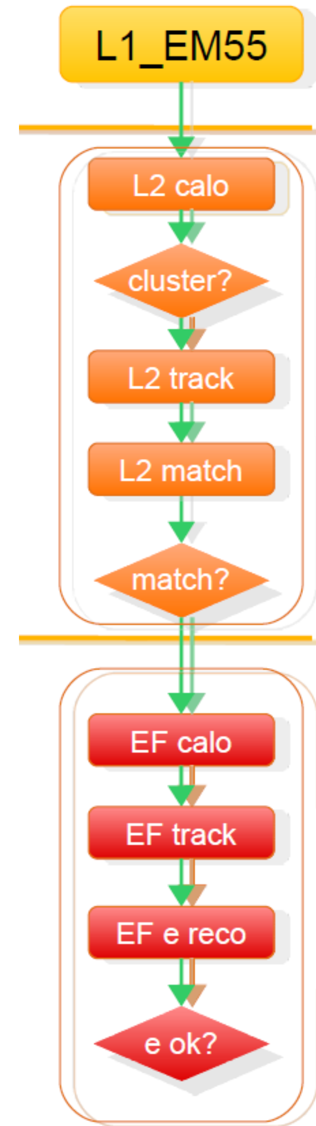
5-100 kHz input rate requires fast algorithms
Processing is typically done multiple steps:

Start by confirming L1 results

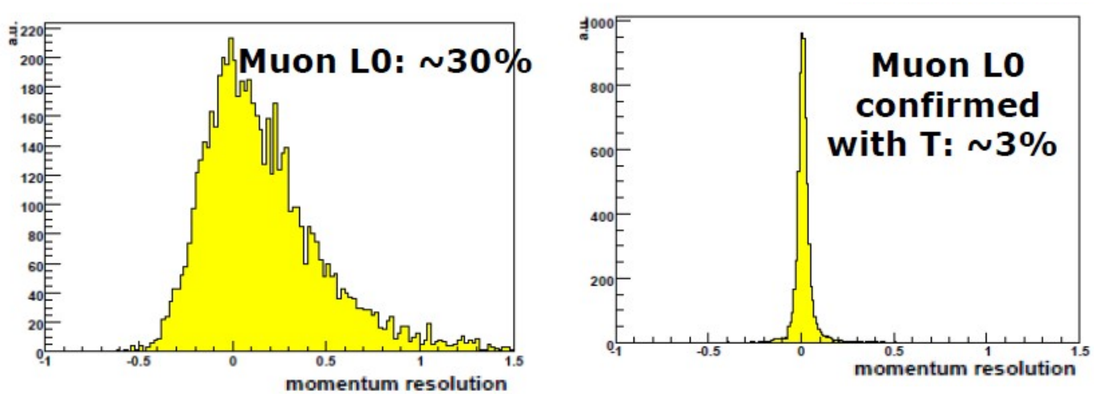
- Only process data in region where L1 found “object”
  - * ATLAS also only reads out detector in region of interest (RoI) at L2 (reduce data traffic)
- Use full granularity of detector readout
- Combine with info from other detectors (trackers)
- reject events as soon as algorithm step fails

Fullscale event reconstruction to find specific B-decay, all jets, etc. is done at lower rates

ATLAS electron trigger



LHCb muon trigger



Trigger Menu (or List or Table)

Each physics signature will one or more "trigger lines" to select it
Collection of trigger lines is "trigger menu" which defines all of the physics the experiment wants to collect events for

Illustrative example of a trigger menu

signature	Level-1	Level-2	Level-3
e20	L1_e15	L2_e20	EF_e20
2e15	L1_2e10	L2_2e15	EF_2e15
mu20	L1_mu20	L2_mu20	EF_mu20
2mu15	L1_2mu10	L2_mu15	EF_mu15
j100	L1_j50	L2_j80	EF_j100
2j50	L1_2j30	L2_2j40	EF_2j50
3j30	L1_3j20	L2_3j25	EF_3j30
j30_met50	L1_j20_met40	L2_j25_met50	EF_j25_met50
....	...	...	...

Trigger Line

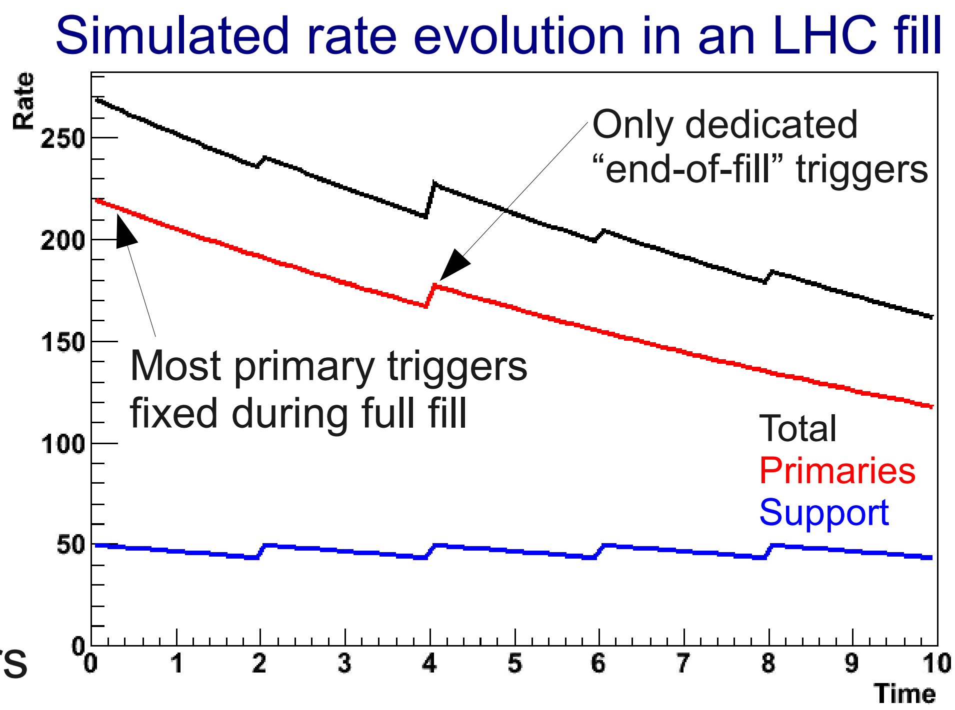
Typical to have several hundred trigger lines at hadron collider

Trigger menu varies with luminosity and time

Prescaled Triggers

Not all triggers need to be recorded at full rate

- often want to just sample low E_T events
- some triggers might just be too high rate



Use prescale for trigger lines

Example:

- prescale of 50 for "e10" line
  records 2% of 10 GeV electron triggers
- prescale of 1 for "e20" line
  Records all 20 GeV electron triggers

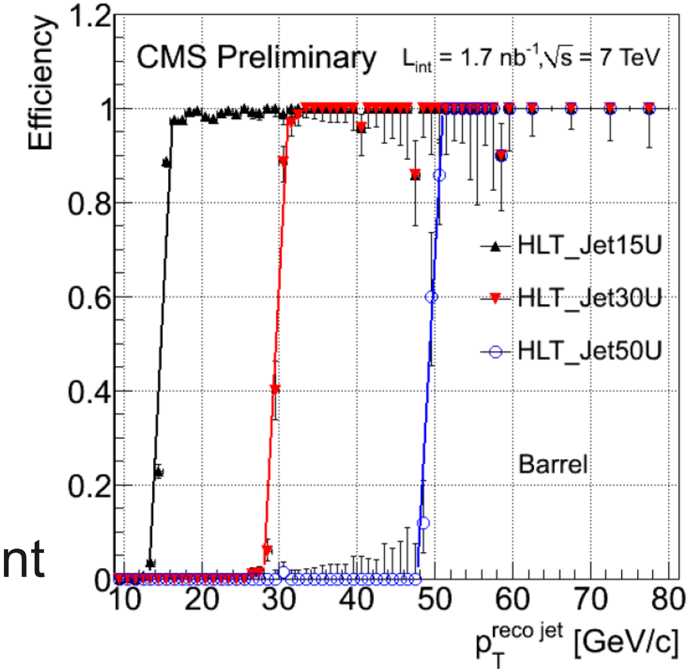
Prescales should be done early to avoid unnecessary rates
Normally implemented in global trigger logic

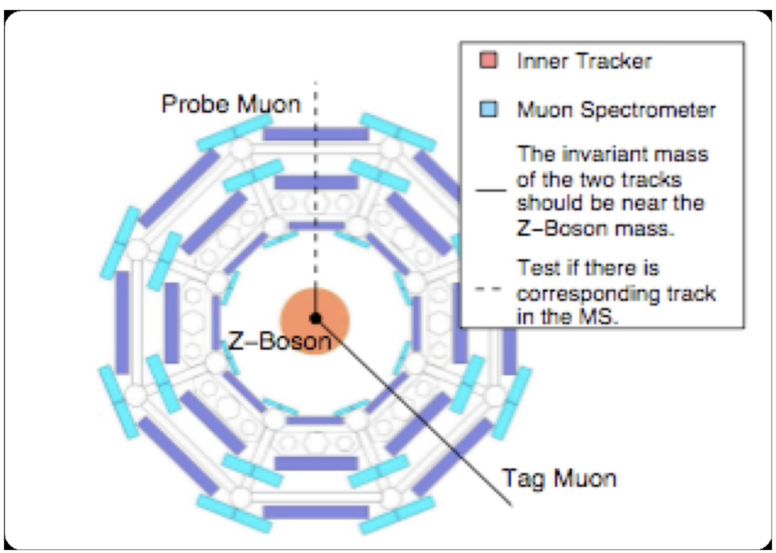
Trigger Efficiencies

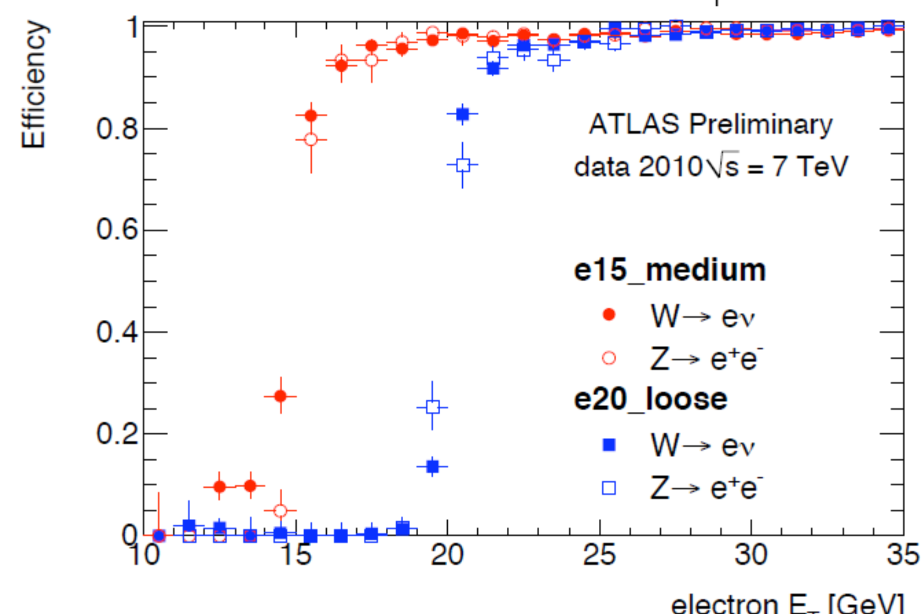
Does the trigger record all signal events?

Different ways to measure trigger efficiency

- "tag-and-probe"
  Trigger on 1 particle from resonance and measure how often 2nd particle is triggered
- "Boot-strap"
  Use looser (prescaled) trigger line
- "Orthogonal" trigger
  Trigger on one physics signature, measure a different
- Simulation





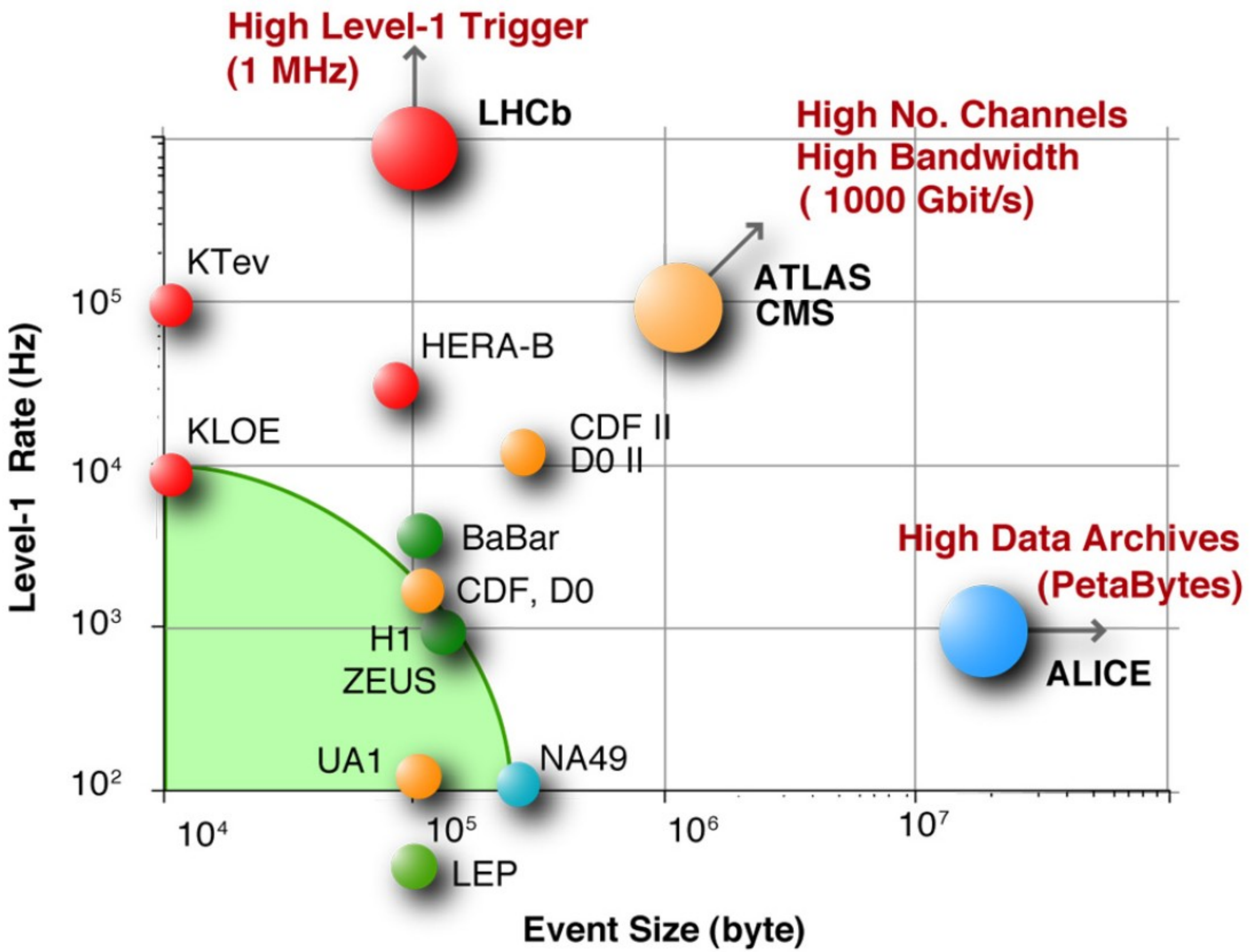


Have to include trigger lines for measuring efficiencies

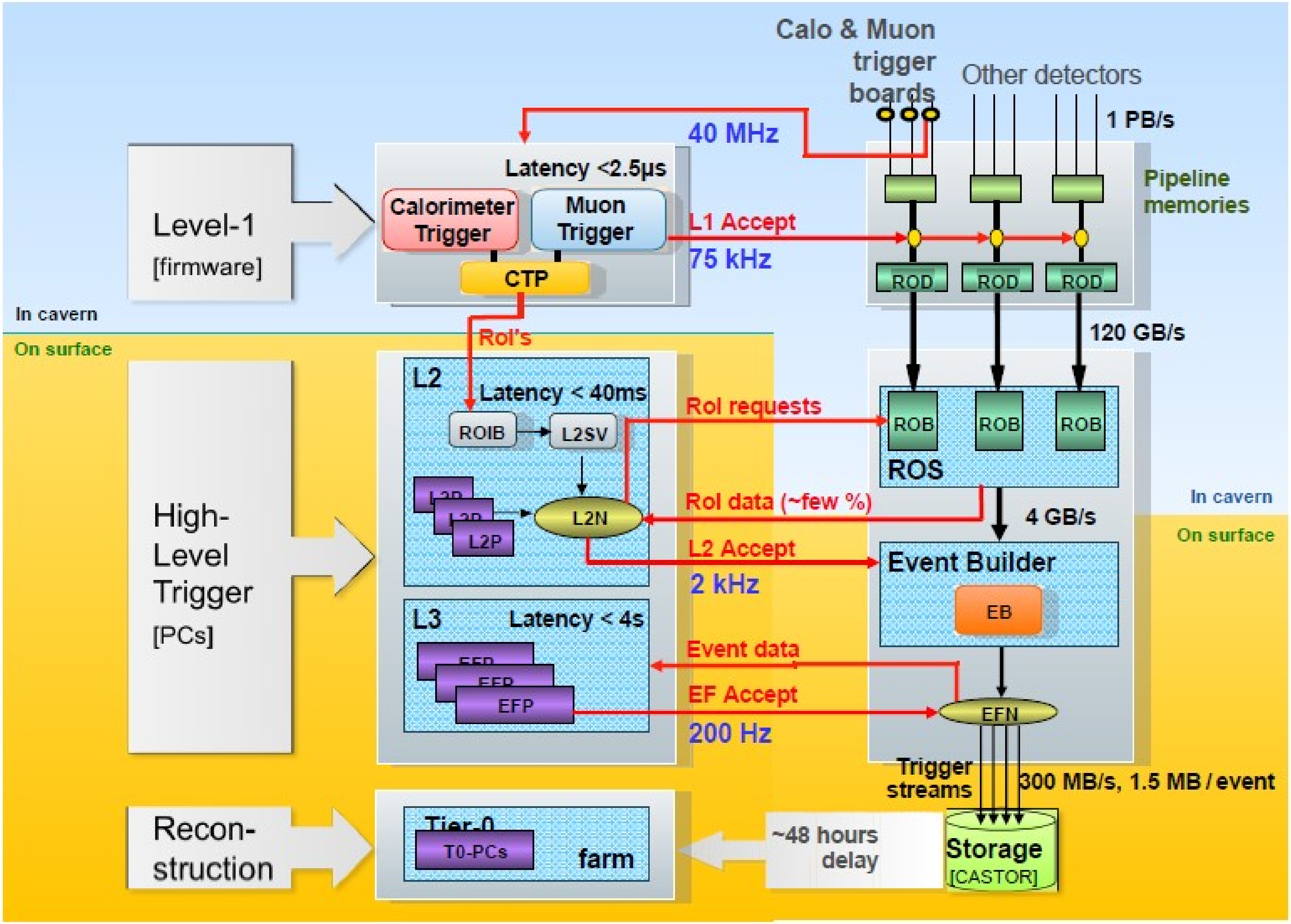
Trigger/DAQ at the LHC

Trigger/DAQ Comparison

LHC trigger/DAQs are order of magnitude larger than before



The ATLAS Trigger/DAQ System

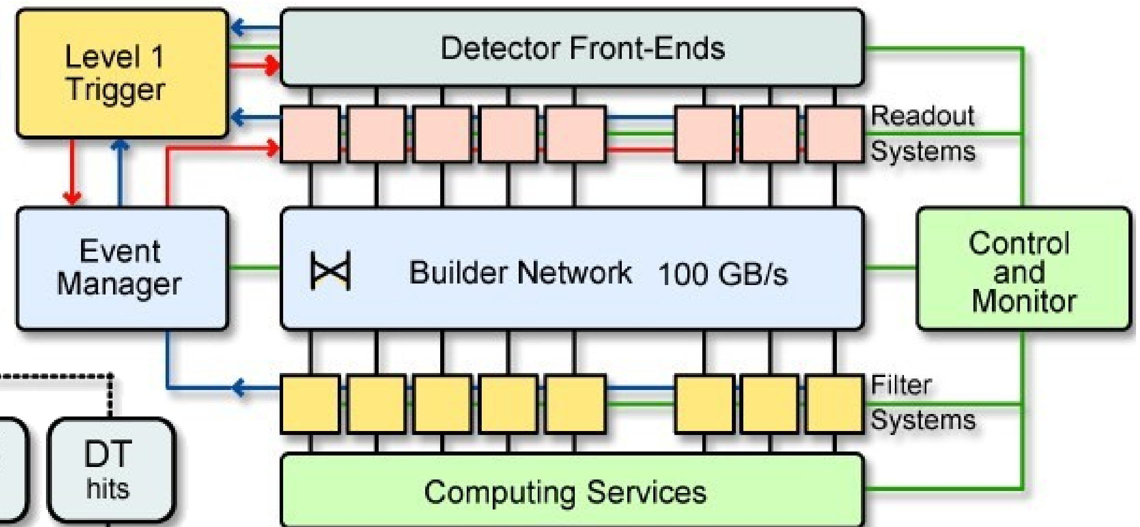


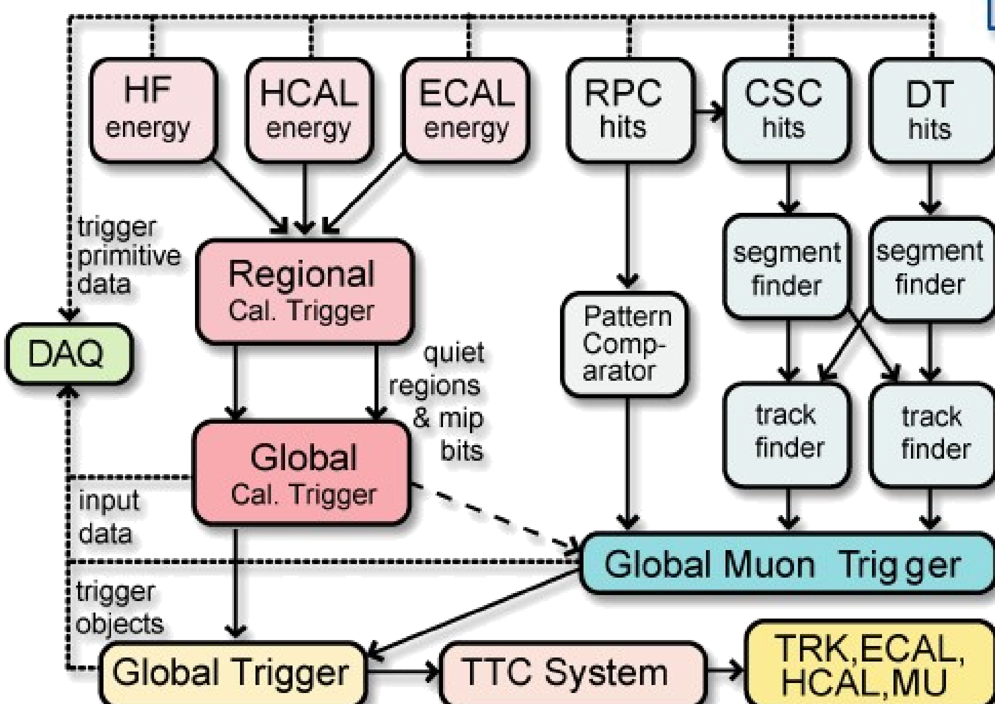
The CMS Trigger/DAQ System

Overall Trigger & DAQ Architecture: 2 Levels

Level-1 Trigger:

- 3.2 μs latency
- 100 kHz output



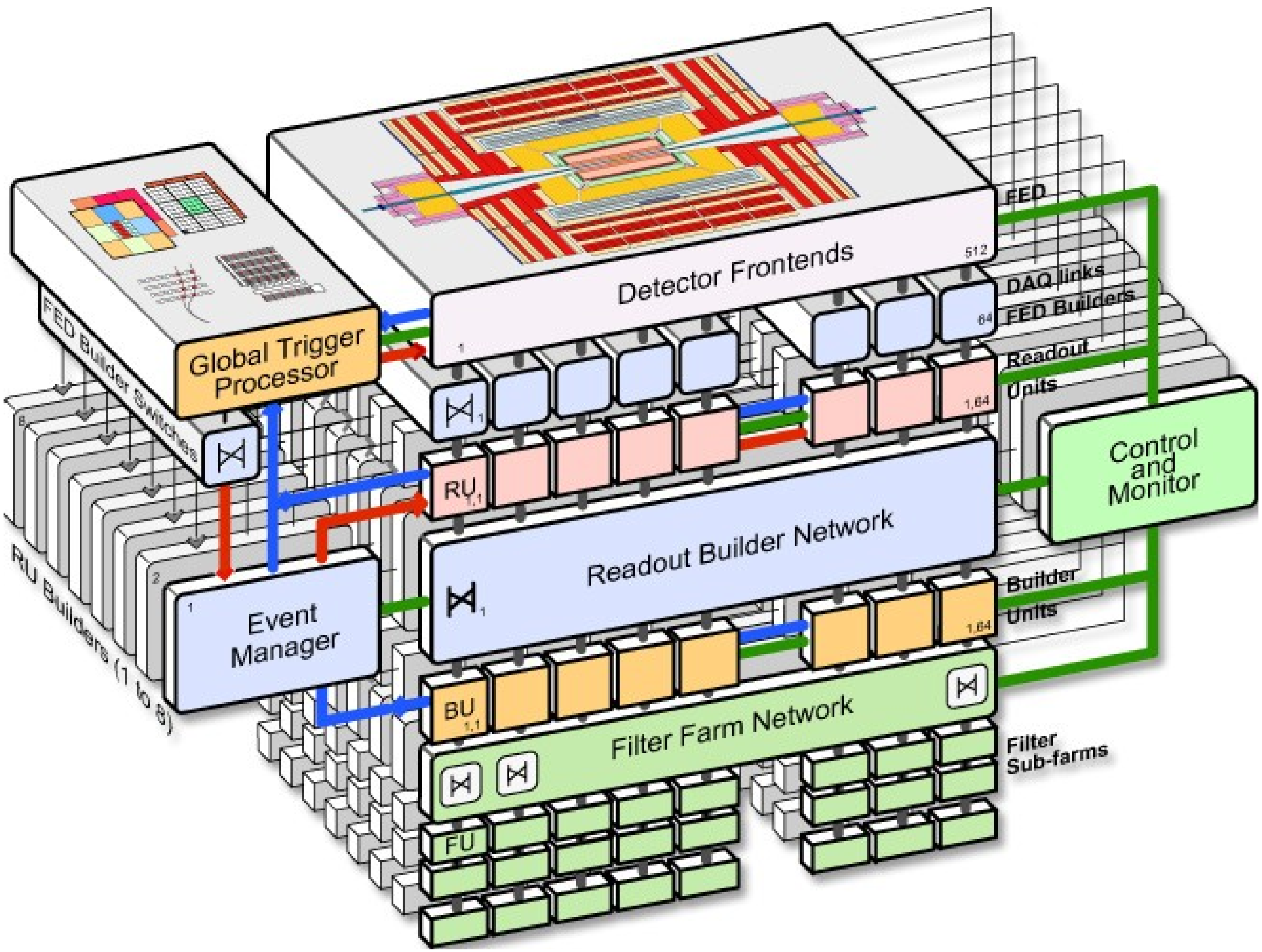


DAQ/HLT:

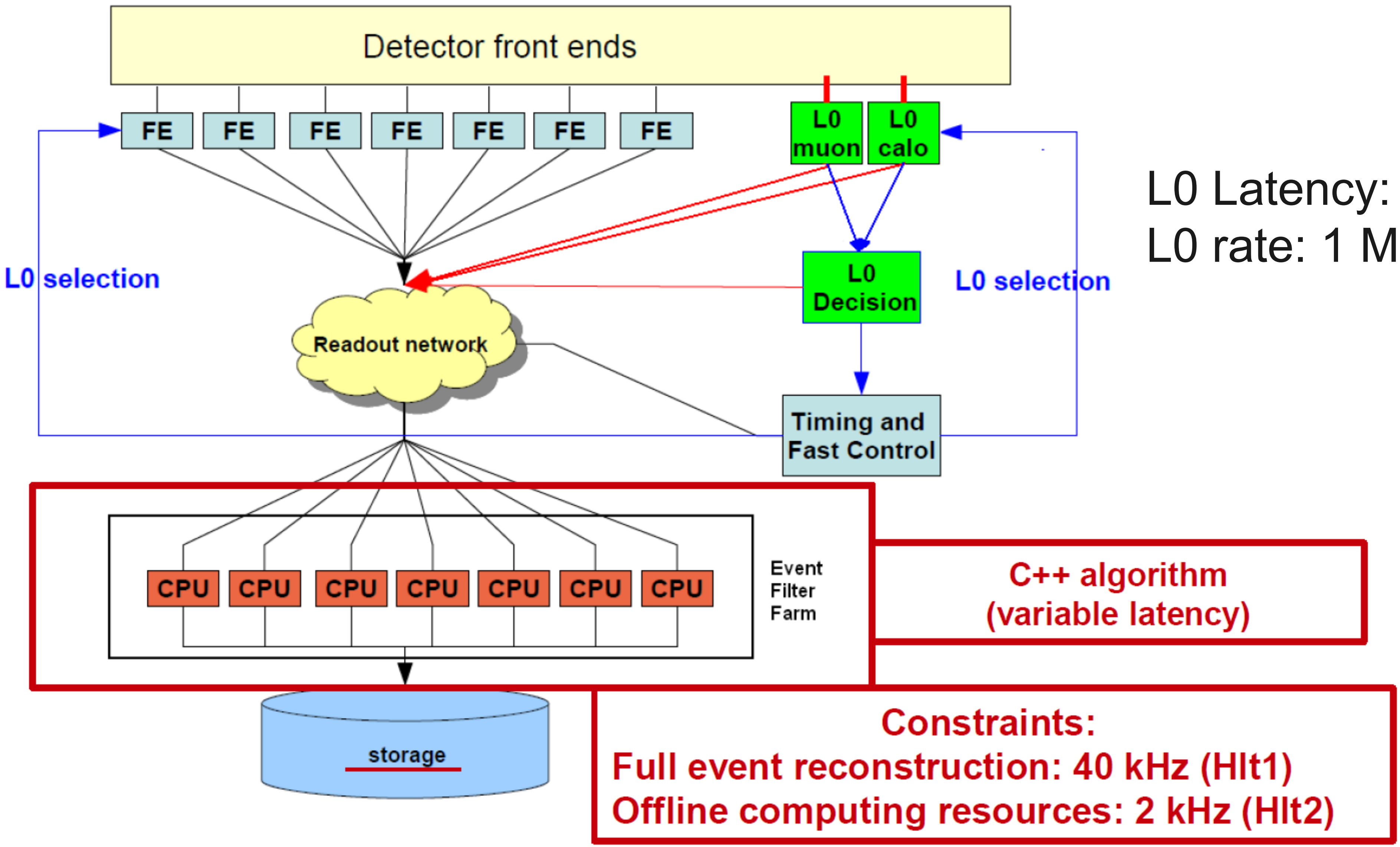
- Event building at full L1 rate
- Average event size: 1 MB
- Average HLT time: 50 ms
- Output rate: 100-300 Hz

CMS "3D" Event Builder

Event building and filtering done in 8 independent "slices" to facilitate 100 kHz rate



LHCb DAQ System



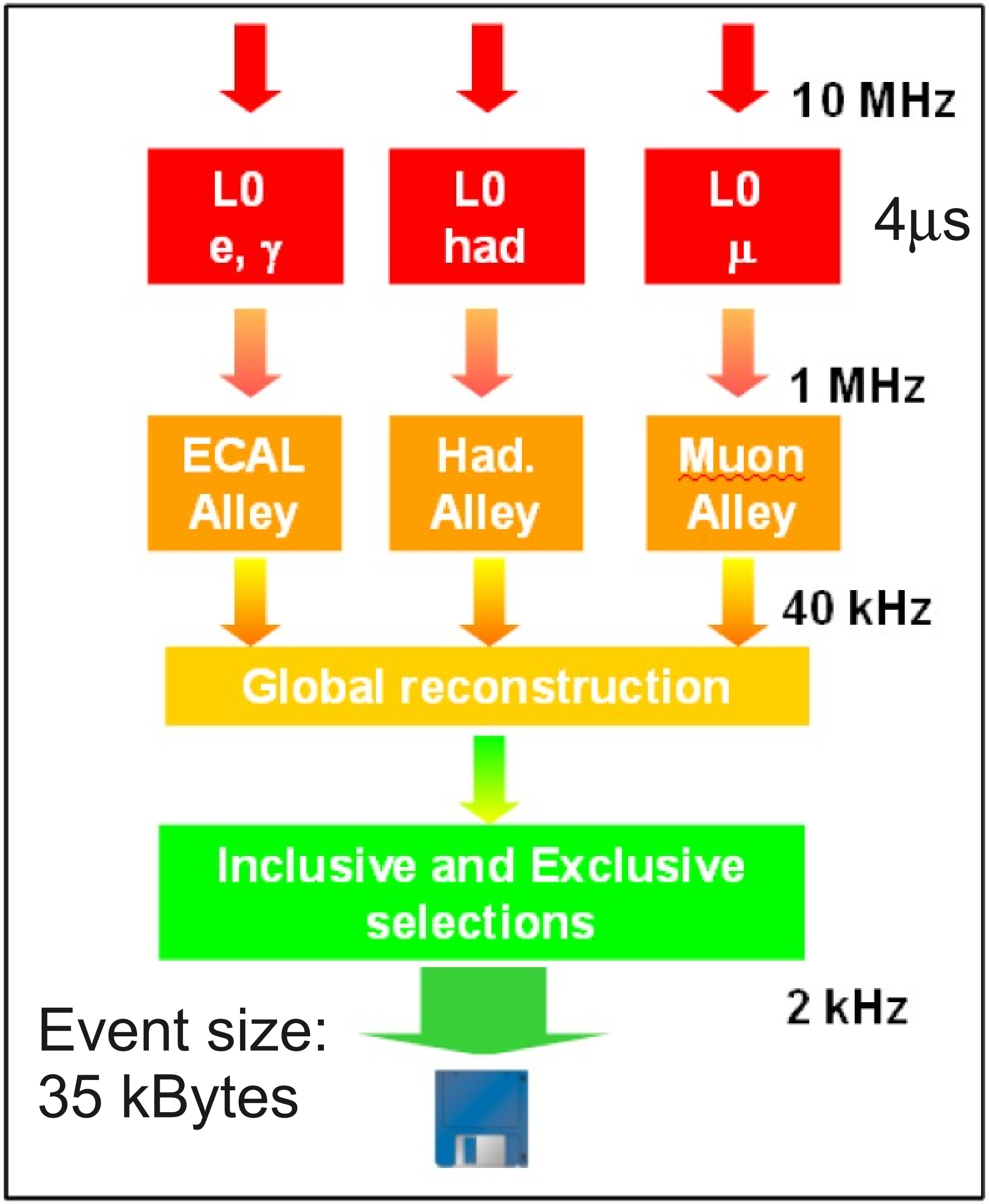
L0 Latency: 4μs
L0 rate: 1 MHz

LHC-b Trigger System

Level-0 (hardware): High E_T / p_T candidates

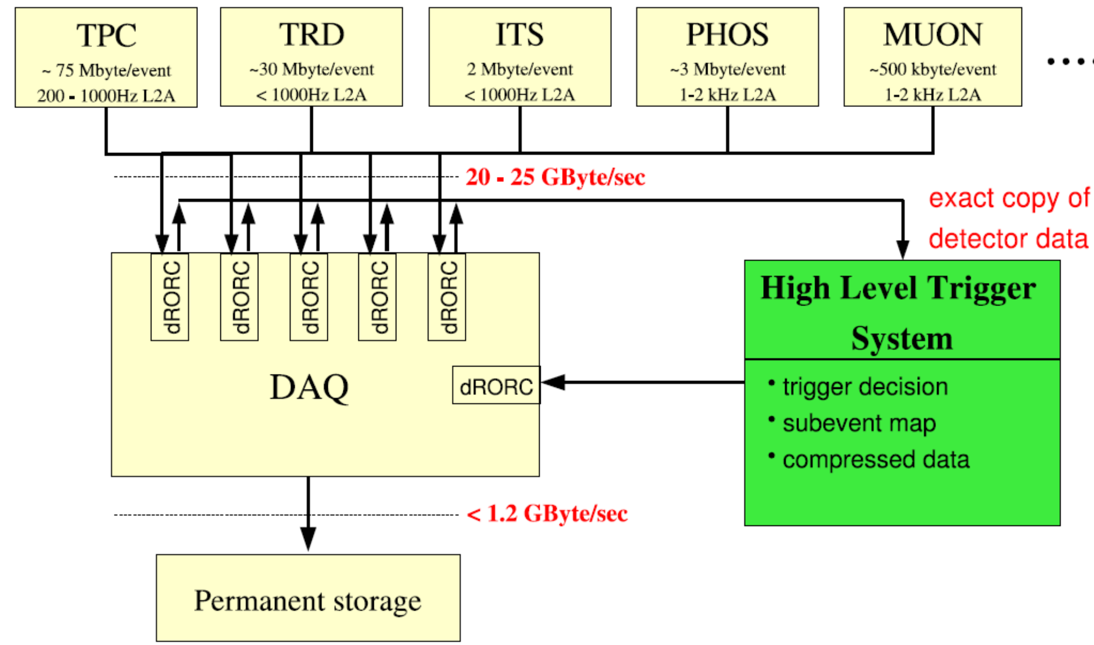
HLT1 (software):
- Partial Reconstruction on ROIs to confirm L0 candidates
- Use VELO for IP filter
- Add extra tracks

HLT2 (software):
- Full Reconstruction of event
- RICH available for PID
- Few tracks (inclusive)
- All tracks (exclusive)



ALICE Trigger/DAQ System

ALICE has different constrains:
- Low rate (max 8 kHz of Pb+Pb)
- Very large events (>40 Mbytes)
- Slow detector (TPC ~ 100 µs)



HLT process data in parallel
with event building
Also does event compression

3 levels of hardware triggers:

Collision

L0: Trigger detectors detect collision (V0/T0, PHOS, SPD, TOF, dimuon trigger

L1: select events according to
- centrality (ZDC, ...)
- high-pt di-muons
- high-pt di-electrons (TRD)
- high-pt photons/pi0 (PHOS)
- jets (EMCAL, TRD)

L2: reject events due to past/future protection

HLT rejects events containing
- **no J/psi, Y**
- **no D0**
- **no high-pt photon**
- **no high-pt pi0**
- **no jet, di-jet, γ-jet**

0 1.2 6.5 88 t [µsec]

LHC Trigger/DAQ Comparison

Caution: my attempt at getting somewhat comparable numbers

	ATLAS	CMS	LHCb	ALICE
"L1" Latency [μs]	2.5	3.2	4	1.2/6/88
Max "L1" output rate [kHz]	75	100	1000	~2
Frontend readout bandwidth [GBytes/s]	120	100	40	25
Max HLT avg. latency [ms] (upgrade with luminosity)	L2: 40 EF: 1000	50 (in 2010)	20	
Event building bandwidth [GBytes/s]	4	100	40	25
Trigger output rate [Hz]	~200	~300	~2000	~50
Output bandwidth [MBytes/s]	300	300	100	1200
Event size [MBytes]	1.5	1	0.035	Up to 20

Some of these are evolving due to computing upgrades

Summary

- Challenge to design efficient trigger/DAQ for LHC
  - Very large collision rates (up to 40 MHz)
  - Very large data volumes (tens of MBytes per collision)
  - Very large rejection factors needed ($>10^5$)
- Pipelined readouts and fast, parallel custom electronics enable triggers to work at 25 ns collision spacing
- Large networking switches allow high-rate/volume event building
- Large parallel commercial PC farm used to process events with advanced algorithms and high rejections

Next challenge is to design system for SLHC with higher particle densities and larger data volumes