Trigger and Data Analysis (I)

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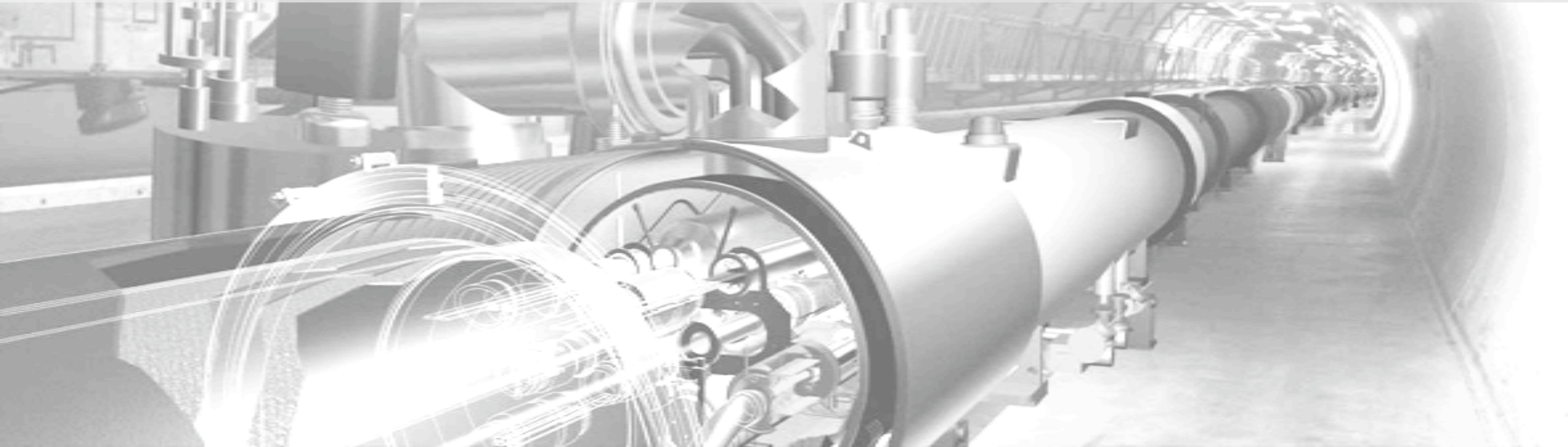

Lecture Themes

I. Introduction and Challenges

II. Trigger and Data Acquisition Basics

III. Trigger Selection at the LHC

today

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tomorrow

IV. More in Depth: ATLAS *e*/*γ* Trigger

V. Jet and Muon Triggers

VI. Trigger/DAQ Commissioning

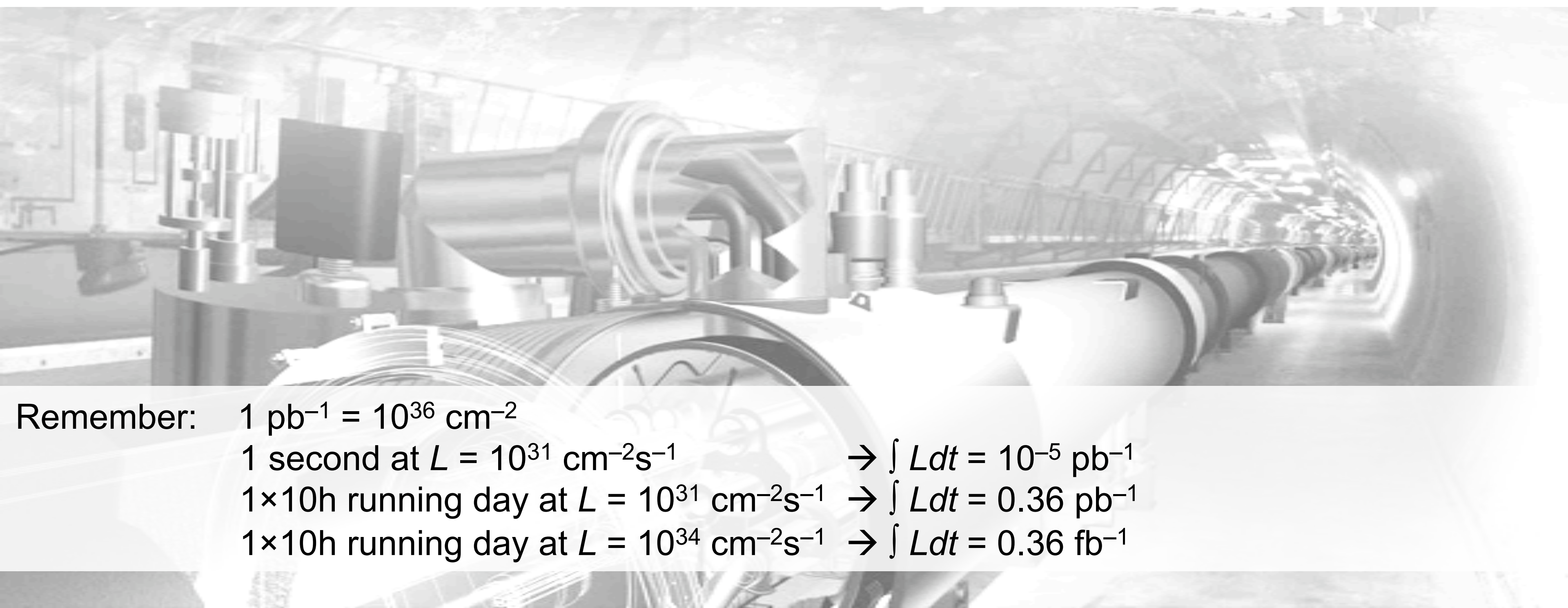
VII. Trigger-Aware Data Analysis

Will concentrate on LHC – ATLAS/CMS/LHCb

- the near future of most of us
- most challenging and state-of-the-art
- that's what I know best (ATLAS)

However, will also briefly review LEP (complementary) and Tevatron cases

Introduction – Challenges



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

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

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

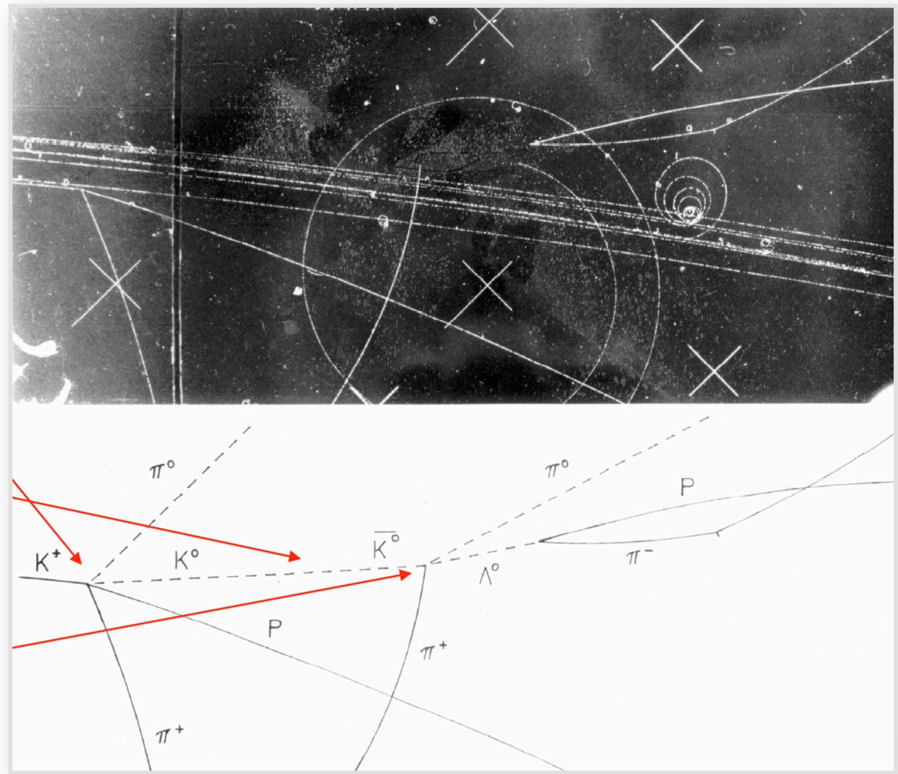
1×10h running day at $L = 10^{34}\ cm^{-2}s^{-1}$ → $\int L dt = 0.36\ fb^{-1}$

Early Accelerator Expts: Bubble Chambers

[page from: Babukhadia *et al.* "Triggering in Particle Physics Experiments", IEEE Nuclear Science Sypmosium, 10 Nov 2002]

Bubble Chambers, Cloud Chambers, etc

- DAQ was a stereo photograph
- Effectively no Trigger:
  - Each expansion was photographed (based on accelerator cycle)
  - High-level trigger was human (scanning teams)
- Slow repetition rate (observe only most common processes)
- Later some triggering attempts with higher repetition rate (> 40 Hz)



K^0 mixing event, Graham Thompson, 1971
(careful, this is fixed target – example for photograph only!)

Emulsions still used in some experiments (*e.g.* CHORUS, DONUT)

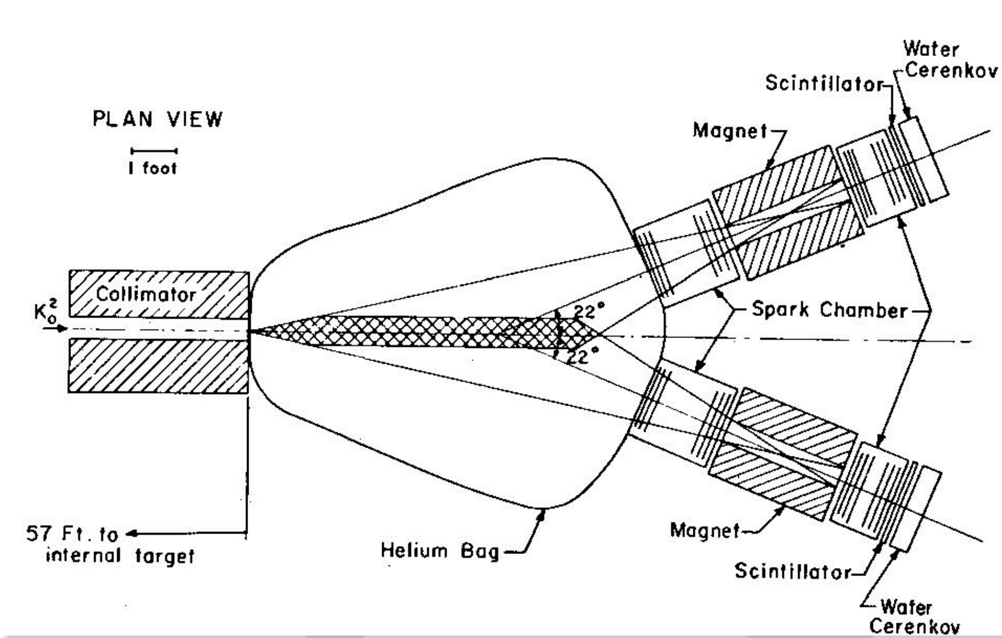
- Events selected with electronically readout detectors → scanning of emulsion seeded by external tracks

Early Fixed Target Trigger

[page from: Babukhadia *et al.* "Triggering in Particle Physics Experiments", IEEE Nuclear Science Sypmosium, 10 Nov 2002]

Cronin-Fitch *et al.* experiment 1964 – discovery of *CP* violation

- K_L mesons produced from protons bombarding Be target
- Two arm spectrometer with Spark Chambers, Chernkov counters and Trigger scintillators
- Spark chambers require fast (~20ns) HV pulse to develop spark, followed by triggering camera to photograph tracks
- Trigger on coincidence of Scintillators and Water Cherenkov counters
- Only one trigger level
- Dead-time incurred while film advances

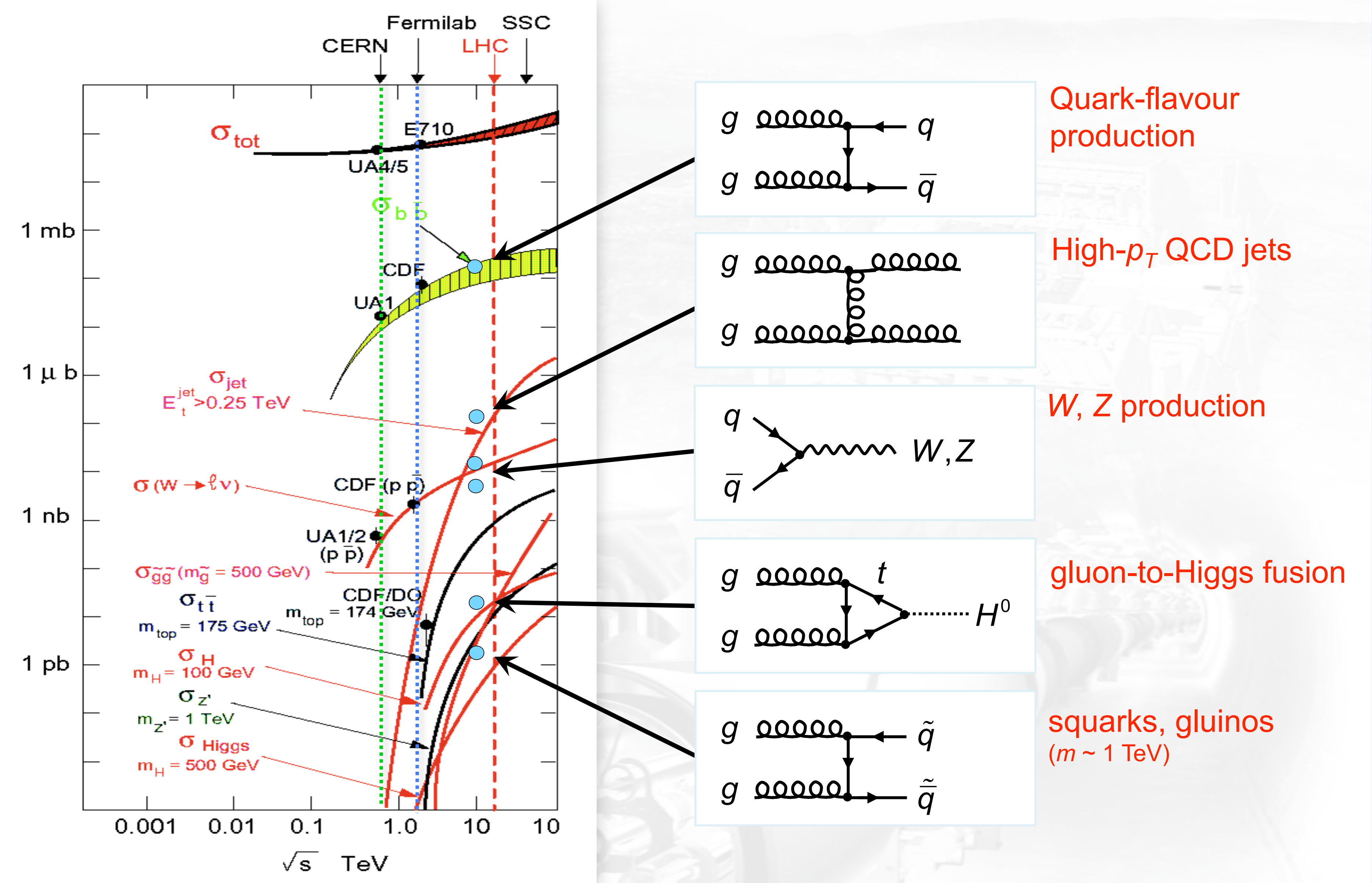


Jim Cronin

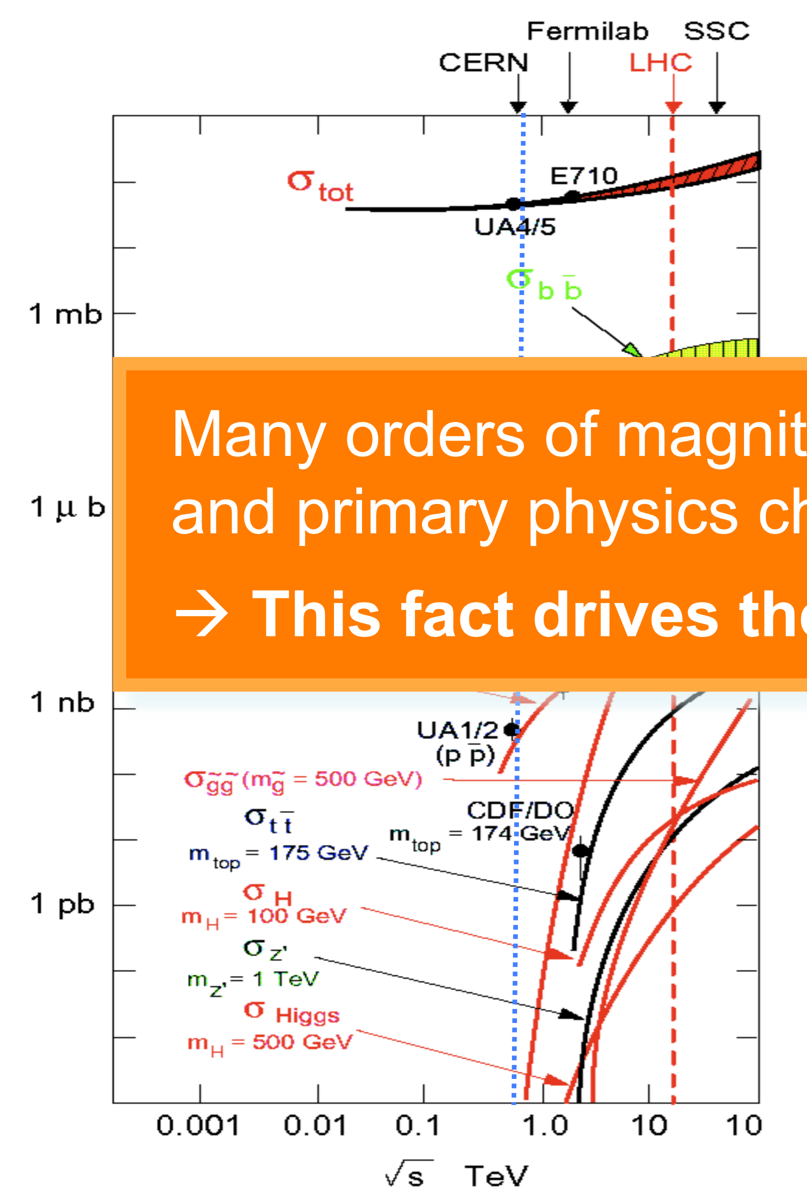
Val Fitch

Measurement of opening angle of pion tracks and their invariant mass to spot $K_L \rightarrow \pi\pi$ decay

pp(bar) Cross Sections



pp(bar) Cross Sections



Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34}$ cm^{-2}s^{-2}
Inelastic	10^8	10^9
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.5
H (120 GeV)	0.04	0.4
H (180 GeV)	0.02	0.2

Many orders of magnitude between QCD background and primary physics channels

→ **This fact drives the detector and *trigger* design**

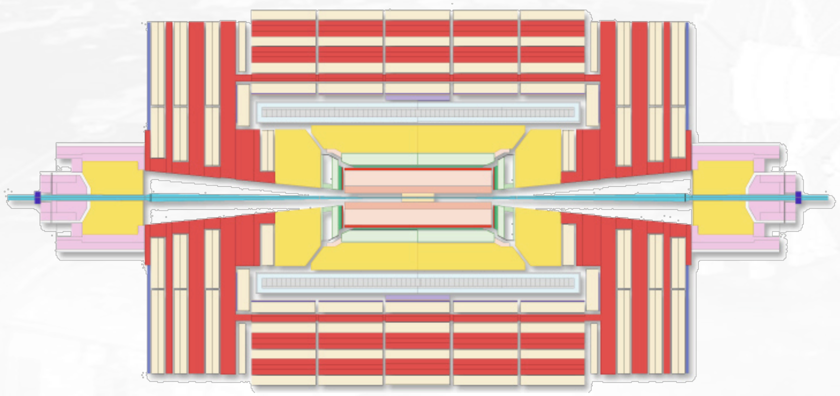
Recall: $1\,\text{pb}^{-1} \triangleq 10^{36}\,\text{cm}^{-2}$

$\Rightarrow 15\,\text{nb} \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1} =$

$15\,\text{nb} \times 10^{-2}\,\text{pb}^{-1}\text{s}^{-1} = 150\,\text{Hz}$

The Trigger is a Function of

T(



) = Accept / Reject

Event data and Apparatus
Physics channel and Parameters

Look at (almost) all bunch crossings, select most interesting one, collect all detector information and store it for offline analysis (do this for a reasonable amount of money)

Slide taken from from Alessandro Cardini, INFN-Cagliari, 2006

What is the Problem ?

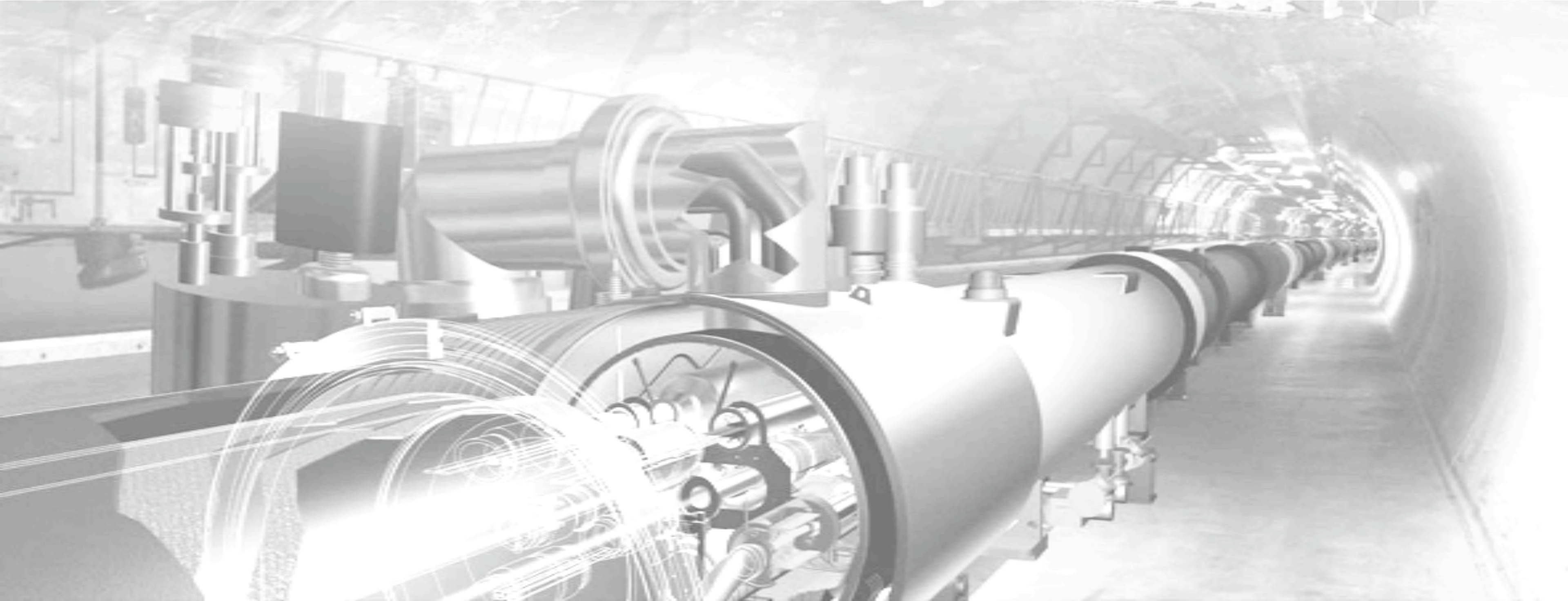
Cannot (*and do not want to*) register all events

“Old physics” occurs more often than new physics

New physics buried under tons of old physics

[Following pages give examples and numbers for ATLAS/CMS]

[Inspired by C. Leonidopoulos, Jan 5, 2008]



Why not keep all events ?

How many event do we keep ?

- ➠ About 200 Hz (somewhat varying with luminosity)

Why only so few ? → Resources

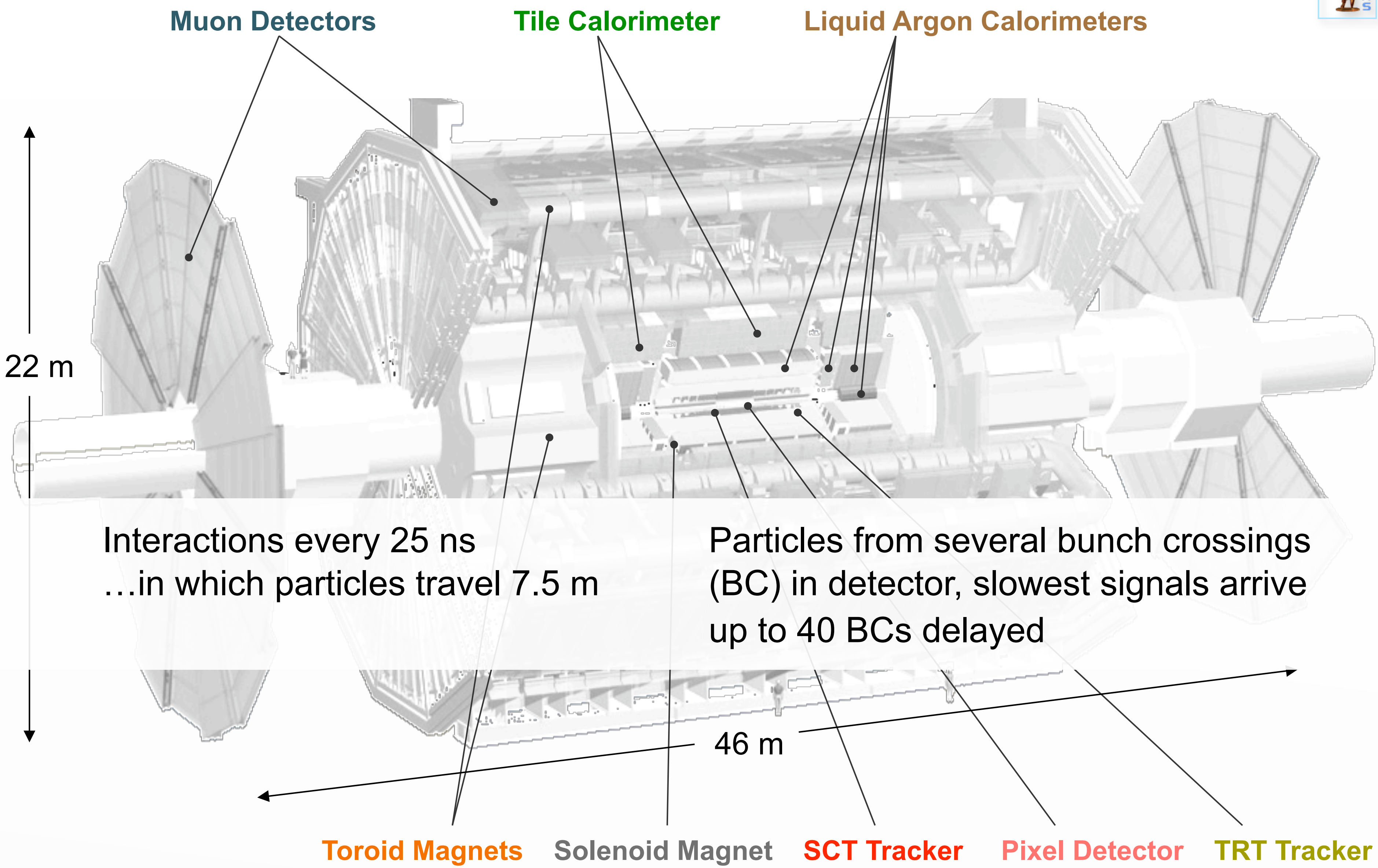
For ~1.5 MB raw event size + about same amount derived data

- ➠ Up to 4300 TB (~1 MCHF) a year per experiment (multiplied for distributed analysis)
- ➠ For about 10 sec / event offline processing time, need 2000 CPUs to keep up

"Interesting physics" occurs mostly at rates of 10, 1 or < 0.1 Hz

- ➠ We are only interested in a tiny fraction of the events produced
- ➠ Do want to **keep all of those**, and **reject most of the others**
- ➠ However, low-mass flavour physics – although being "old" is still very interesting !

→ First Trigger Challenge: **efficient signal selection and background rejection down to low p_T**



Interactions every 25 ns
…in which particles travel 7.5 m

Particles from several bunch crossings (BC) in detector, slowest signals arrive up to 40 BCs delayed

LHC and Physics Challenges

40 MHz bunch crossing rate

- 25 ns = 7.5 m between bunches

New physics buried under old physics

- About 1 GHz interaction rate at $L = 10^{34}$ cm^{-2}s^{-1}

High charged multiplicity

- About 1000 tracks per event → 10^{12} tracks per second rate at $L = 10^{34}$ cm^{-2}s^{-1}
- ➠ Need several trigger levels if tracking must be used for trigger decision

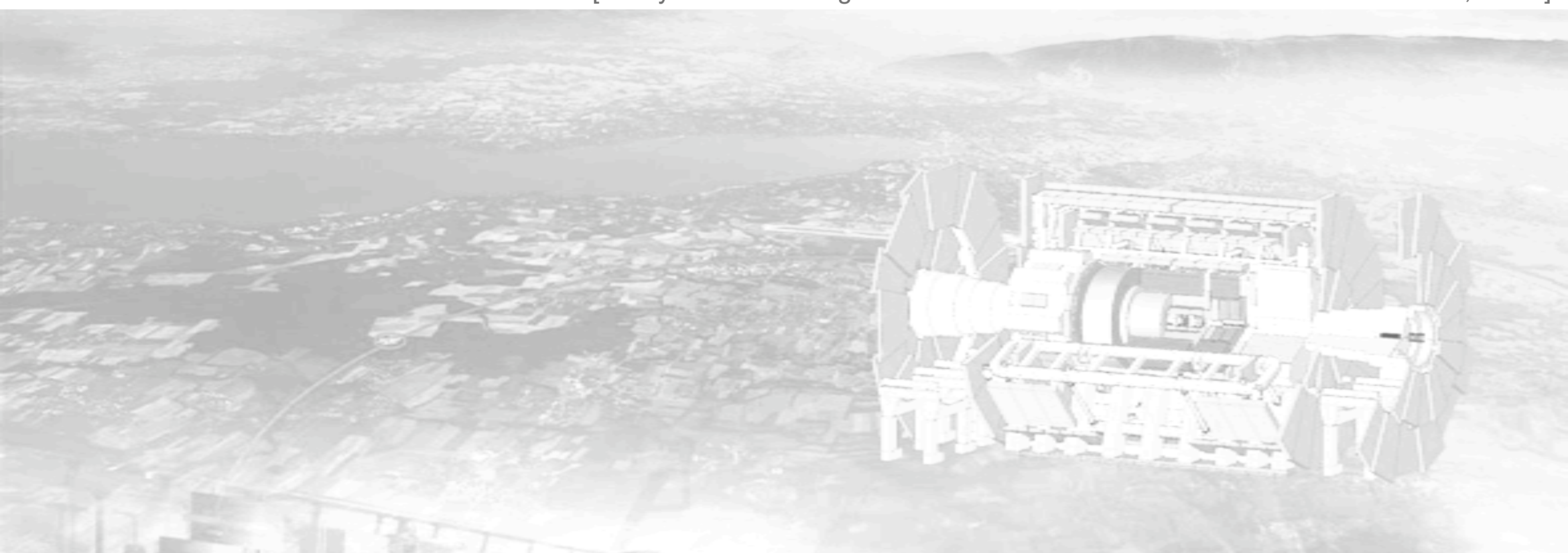
Fit best possible physics cocktail in available bandwidth

- ➠ Use as much as possible the entire detector for trigger decision

→ Second Trigger Challenge: **fast decision, more than one trigger level for decision refinement**

Trigger and Data Acquisition – Basics

[Many of the following slides taken from N. Ellis' excellent Columbia lecture, 2009]



Trigger-DAQ Systems

T/DAQ system:

- **Selects particle interactions** that are potentially of interest for physics analysis (*trigger*)
- **Collects the data** from the detector systems, **puts them into a suitable format**, and **records them** in permanent storage with efficient data compression (*DAQ*)

Basic DAQ requirements are:

- Provide online services (*e.g*. Run Control system, data quality monitoring)
- Keep record of conditions (book-keeping)
- Avoid data corruption or data loss, and check data sanity
- Be robust against imperfection in the detector and associated electronic systems
- Minimising dead-time (see later)

Terminology: *Dead-Time*

What is **dead-time**?

➠ Fraction of time where valid interactions could not be recorded for various reasons

Dead time from a number of sources has a typical total of up to *O*(10%)

- Readout and trigger dead-time (see next slides)
- Operational dead-time (*e.g.* time to start/stop runs, detector configuration)
- T/DAQ down-time (*e.g.* following computer failure)
- Detector down-time (*e.g.* following high-voltage trip)

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

Given the investment in the accelerators and the detectors for a modern HEP experiment, it is clearly important to keep dead-time to a minimum!

A Simple Example for a TDAQ System

Consider Time-of-Flight (ToF) measurement using a scintillation-counter telescope read out with Time-to-Digital Converter chips (TDC – think of multi-channel stop watch)

- Figure on next slide omits details (discriminators, dead-time logic)

Start with "traditional" approach (as one might implement using, *e.g.*, off-the-shelf electronic modules plus a DAQ computer)

- This case is still common, *e.g.* in small test setups

Discuss limitations of this model

- Then see how we can improve on it

Of course, a big HEP experiment has an enormous number of sensor channels (up to $O(10^8)$ at LHC), *compared to 3* in the example!

- However, the principles are the same as we will see later

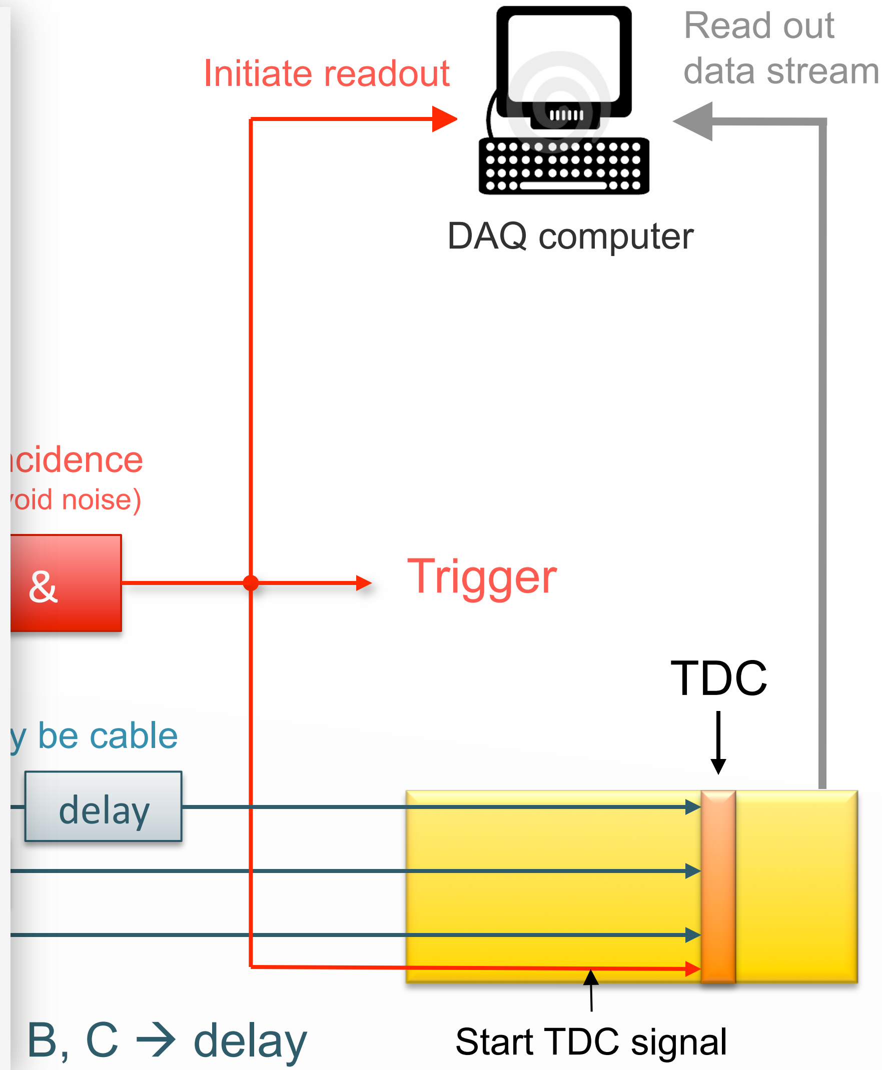
A Simple Example for a TDAQ System

Need very fast trigger decision

- The TDC requires a "start" signal that arrives before the signals that we wish to digitise
- The situation is similar with traditional Analogue-to-Digital Converters (ADCs) that require a "gate" during which the signal to be digitised must arrive

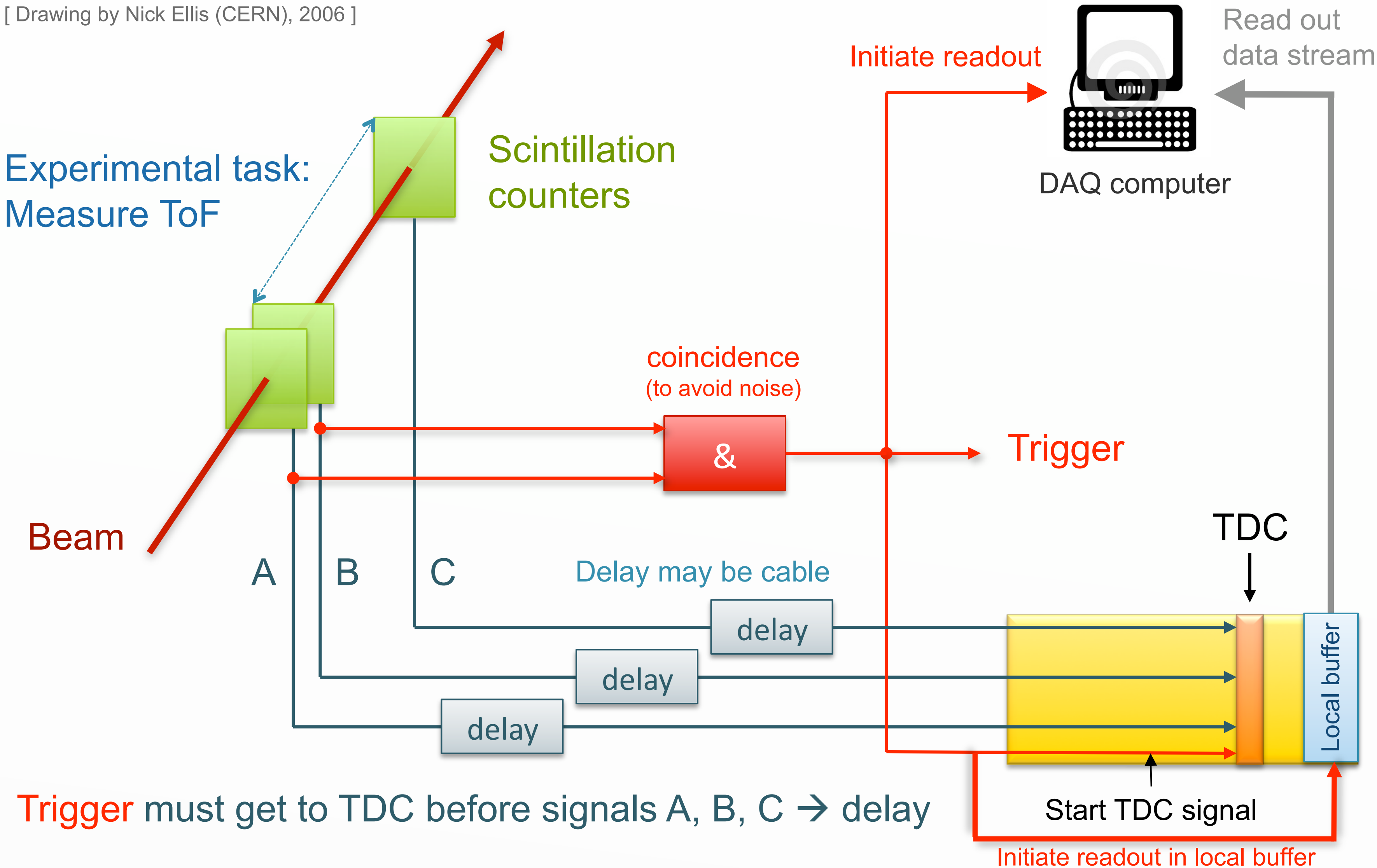
Readout from TDCs to the computer is quite slow — implies significant dead time if the trigger rate is high

- This becomes much more important in larger systems where many channels have to be read out for each event (readout time multiplied by number of channels)



Same Example with Fast Local Readout

[Drawing by Nick Ellis (CERN), 2006]

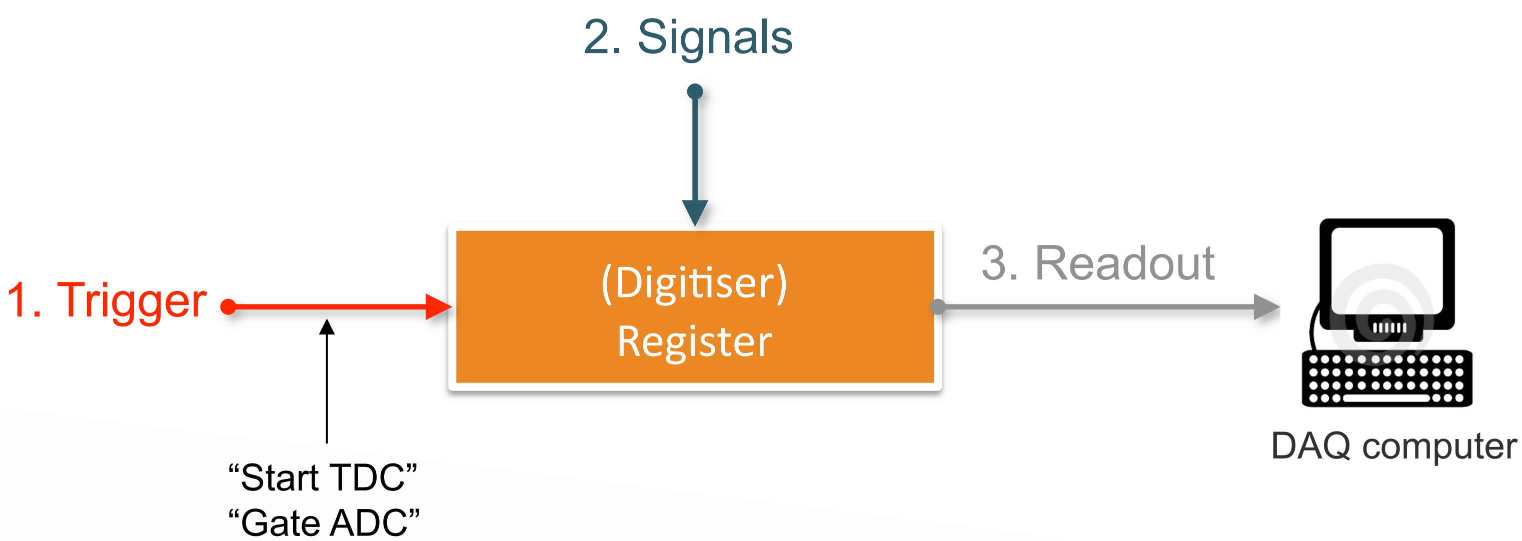


Trigger must get to TDC before signals A, B, C → delay

Traditional Readout Schema

[Drawing by Nick Ellis (CERN), 2006]

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



Sequence of action:

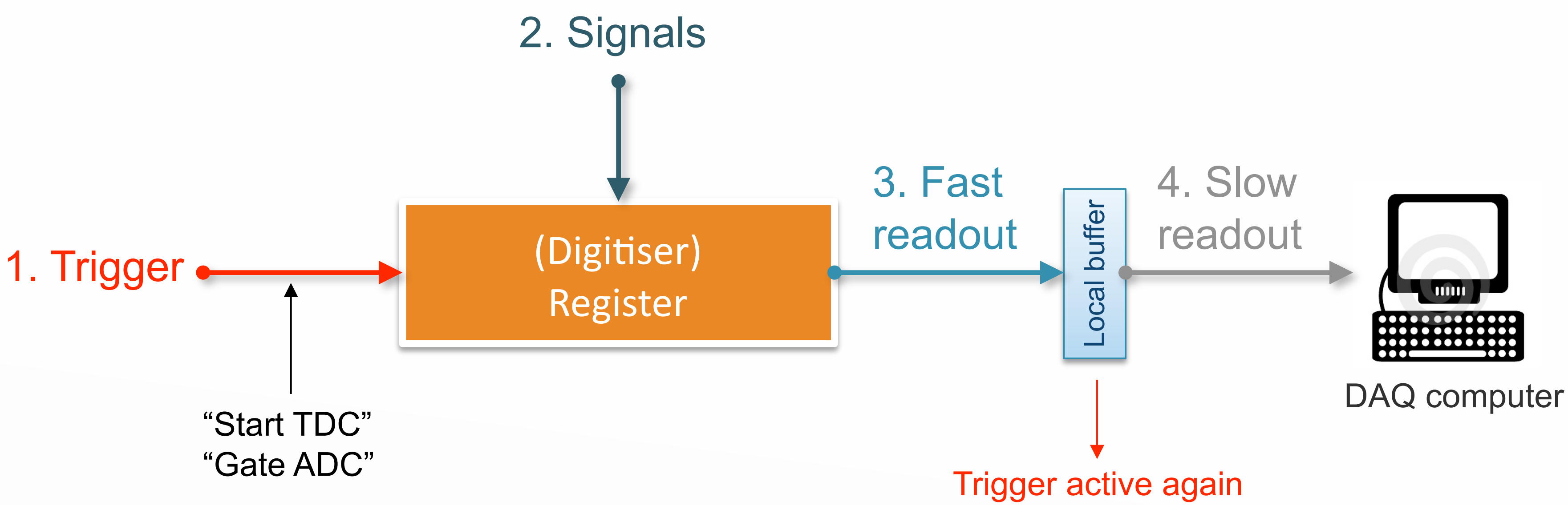
1. Arrival of trigger
2. Arrival of detector signals, followed by digitisation and storage in a TDC data register
3. Readout into DAQ computer

Since no new trigger accept until full readout, dead-time is product of trigger rate and readout time

Local Memory Buffer Schema

[Drawing by Nick Ellis (CERN), 2006]

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



Sequence of action:

3. Fast readout into local memory buffer, reducing dead-time
4. Slow readout into DAQ computer

Local buffers make readout speed independent of size of system

Note: fast trigger still needed – trigger decision must be taken before detector signals arrive !

Multi-level Triggers

It is often not possible to simultaneously meet the physics requirements (high efficiency, high background rejection) and 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 triggers, where the first level has short latency, high efficiency, but only modest rejection power

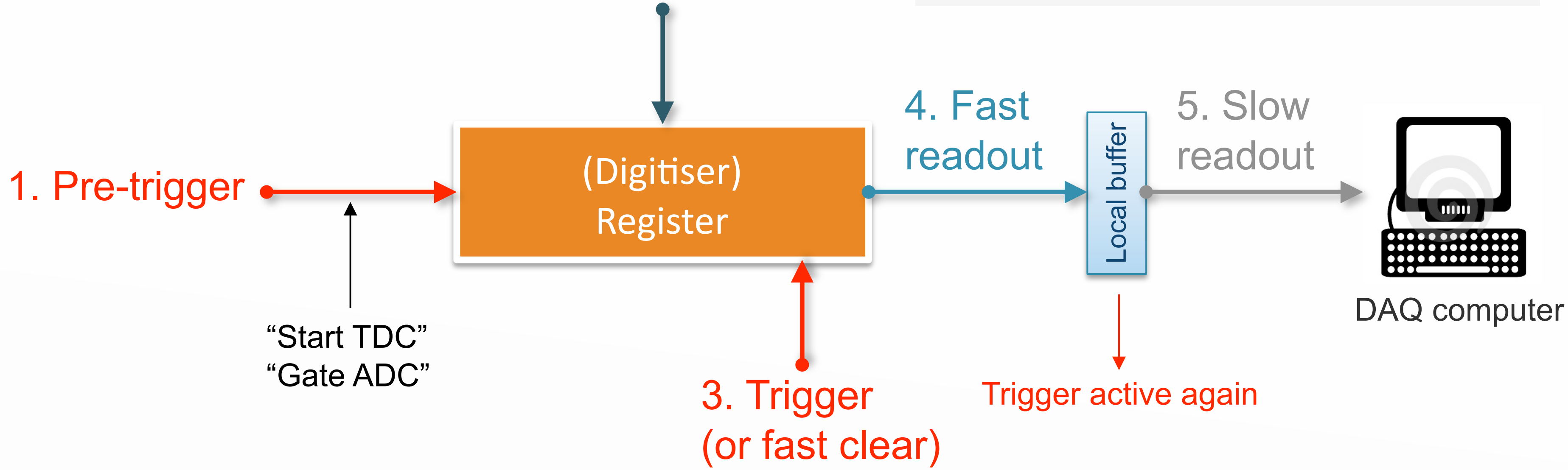
Further background rejection comes from higher trigger levels, which can be slower (*i.e.* may have larger latency)

The very fast first stage of the trigger is sometimes called "pre-trigger" — it may be sufficient to signal the presence of minimal activity in the detectors at this stage

Pre-trigger & Fast Clear with Local Buffer

[Drawing by Nick Ellis (CERN), 2006]

Readout dead-time:
trigger rate × **local** readout time
Plus trigger dead-time:
pre-trigger rate × trigger latency



Sequence of action:

3. Higher-level trigger latency defined by time it takes to accept or reject event (fast clear)

Pre-trigger decision (very simple & fast criteria) still has to come before detector signals

Main trigger decision taken later, accompanied by dead-time

Further Improvements

Idea of multi-level triggers can be extended beyond two levels

- Efficiency for desired physics must be high at all levels → rejected events are lost forever
- Initial levels must be fast, but can have modest rejection → can reject at later levels
- Final levels must strongly reject, but can be slower, thanks to rejection at earlier levels

Total dead-time is trigger dead-time summed over all trigger levels

- S_{level} = trigger rate out of previous level × trigger latency for this level
- Readout dead-time: final trigger rate × local readout time

Implicit assumptions in the above

- All trigger levels are completed before readout starts → long dead-time for some events
- This long dead-time can be avoided by reading out to intermediate storage all events passing the initial stages of trigger selection after that, further triggers can be accepted (in parallel with the execution of the later stages of trigger selection on the first event)

Still need pre-trigger available by the time the signals from the detector arrive at the digitizers !

Collider Experiments

Particles in the counter-rotating colliding beams are **bunched**

- Bunches cross at regular intervals leading to interactions → here denoted ***event***
- Trigger selects bunch-crossings of interest for physics analysis, *i.e.* those containing interactions of interest (an event can contain multiple interactions)

LEP: e^+e^- collider

- CM energy ~ 200 GeV
- Peak $L = 10^{32}$ cm^{-2}s^{-1}
- BC period: 22 μs

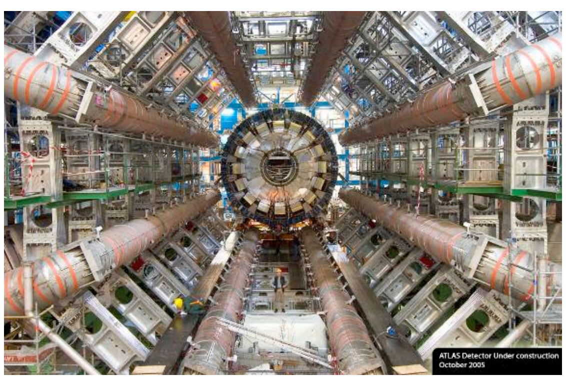
Tevatron: $p\bar{p}$ collider

- CM energy ~ 2 TeV
- $L = 3.5\times10^{32}$ cm^{-2}s^{-1}
- BC period: 396 ns

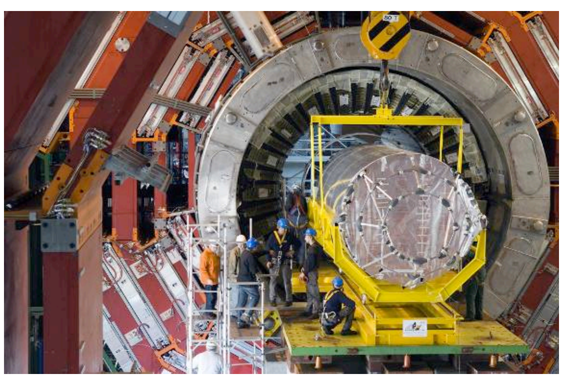
LHC: pp collider

- CM energy 14 TeV
- $L = 10^{34}$ cm^{-2}s^{-1}
- BC period: 25 ns

ATLAS



CMS



LHCb

… and also ALICE !

Terminology: *Pile-up*

In e^+e^- colliders, the interaction rate is very small compared to the bunch-crossing rate (because of the low e^+e^- cross-section)

- Generally, selected events contain just a single interaction (LEP and HERA)

In contrast, at the LHC at design luminosity, each bunch-crossing will on average contain about 25 interactions

- The interaction of interest, *e.g*. the one that produced $H \rightarrow ZZ^* \rightarrow e^+e^-\mu^+\mu^-$, will be recorded together with ~25 other proton–proton interactions
- These *other interactions* are often called "minimum-bias" interactions, *i.e.*, the ones that would be selected by a trigger that selects interactions in an (almost) unbiased way

Terminology: *Exposure Time*

Particle detectors do not have an infinitely fast response time

- This is analogous to the *exposure time* of a camera
- If the exposure time is shorter than the bunch-crossing period, the event will contain only information from the selected bunch crossing
- Otherwise, the event will contain activity (if any) from neighbouring bunches in addition
- In e^+e^- colliders, *e.g.* LEP, such activity was very unlikely — this allowed the use of slow detectors such as the Time-Projection Chamber
- The same is true in ALICE due to the low luminosity for heavy-ion running at LHC

At LHC, despite a short (25 ns) bunch-crossing period (*i.e.* 40 MHz rate), there will be activity in essentially all bunch crossings (BCs)

- Some detectors, *e.g.* ATLAS silicon tracker, achieve an exposure time of less than 25 ns, but many do not
- For example, signals from the ATLAS liquid-argon calorimeter extend over many BCs
  → so need to read out several BC, "readout frame"

Using the BC Signal as Pre-trigger

If the time between bunch crossings is reasonably long, one can use the clock that signals when bunches cross as the pre-trigger

- The first-level trigger can then use the time between bunch crossings to make a decision
- For most crossings, the trigger will reject the event by issuing a fast clear
- In such cases, no dead-time is introduced
- Following an accept signal, dead-time will be introduced until the data have been read out (or until the event has been rejected by a higher-level trigger)

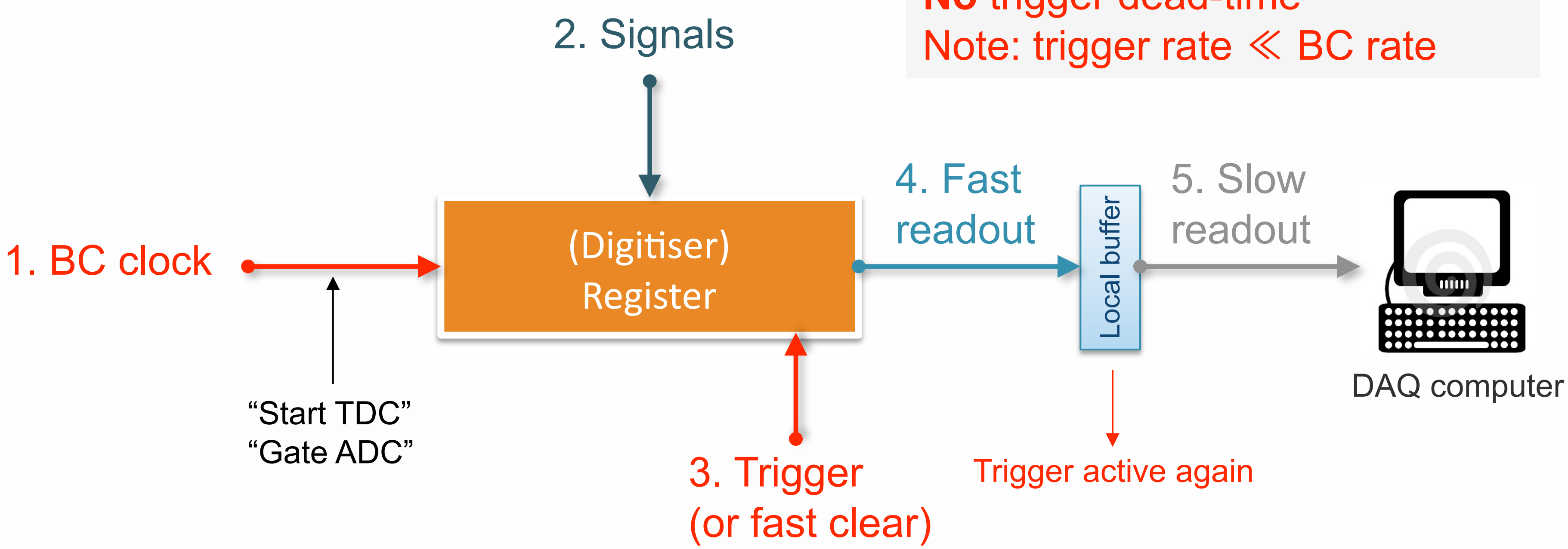
This model was used at LEP

- Bunch crossing interval 22 μs (11 μs in 8-bunch mode) allowed comparatively complicated trigger processing (latency of few μs)

Bunch Crossing Clock & Fast Clear

[Drawing by Nick Ellis (CERN), 2006]

Readout dead-time:
trigger rate × **local** readout time
No trigger dead-time
Note: trigger rate ≪ BC rate



Sequence of action:

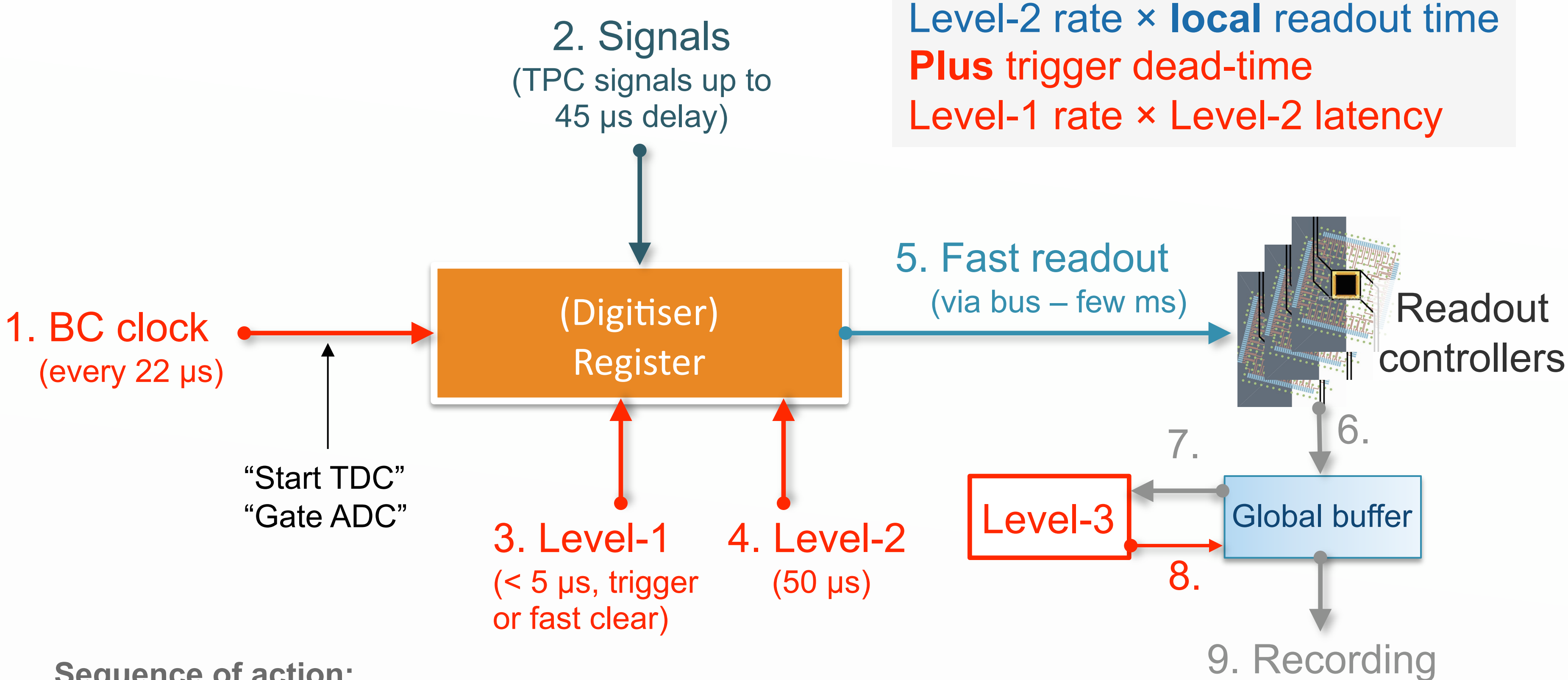
1. Use clock that signals when bunches cross as pre-trigger (if long enough BC period)
3. First-level trigger can then use time between bunch-crossings to make decision

No first-level trigger dead-time because decision is made during bunch intervals with no interactions

LEP Model (here ALEPH)

[Drawing by Nick Ellis (CERN), 2006]

Readout dead-time:
Level-2 rate × **local** readout time
Plus trigger dead-time
Level-1 rate × Level-2 latency



Sequence of action:

3. Two trigger levels with different sophistication before fast (bus-based) readout to local buffer in ROC, and subsequently send over bus to event builder → final EB computer sees full data rate
6. One more trigger level (using fully built event) to pass before accept of event

A few Numbers (from DELPHI – LEP)

Illustrative numbers from LEP-2:

L1 rate:	~ 500 – 1000 Hz (instrumental)
L2 rate:	= 6 – 8 Hz
L3 (SW) rate:	= 4 – 6 Hz
L2 latency:	= 39 μs (22 μs effective: frozen during 1 BC)
Local readout time	= ~ 2.5 ms
Recorded data rate	= few Hz × *O*(100 kB/event) ≈ few 100 kB/sec*

Readout dead-time:
Level-2 rate × **local** readout time
Plus trigger dead-time
Level-1 rate × Level-2 latency

→

Readout dead-time:
7 Hz × 2.5 ms = 1.8%
Plus trigger dead-time
750 Hz × 22 μs = 1.7%
} 3.5%

*small enough compared to maximum of ~40 MB/sec on VME bus

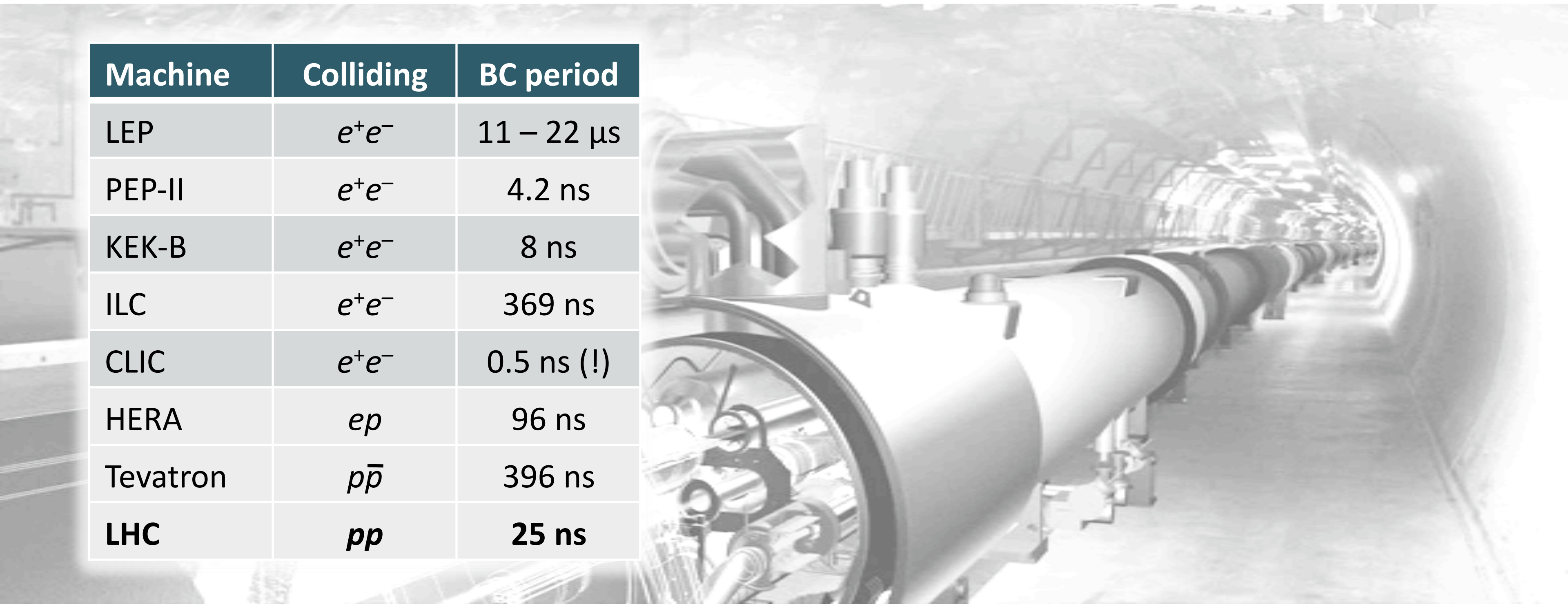
Towards the LHC

If time between BC too short for trigger decision, need new concepts

➠ “Pipelined” readout and L1 trigger processing

If data rates after L1 are still very high, also need new ideas for higher trigger levels and DAQ

➠ Event building based on data networks and switches rather than data buses



Machine	Colliding	BC period
LEP	e^+e^-	11 – 22 μs
PEP-II	e^+e^-	4.2 ns
KEK-B	e^+e^-	8 ns
ILC	e^+e^-	369 ns
CLIC	e^+e^-	0.5 ns (!)
HERA	ep	96 ns
Tevatron	$p\bar{p}$	396 ns
LHC	$\boldsymbol{pp}$	**25 ns**

Pipelined Readout

[Drawing by Nick Ellis (CERN), 2006]

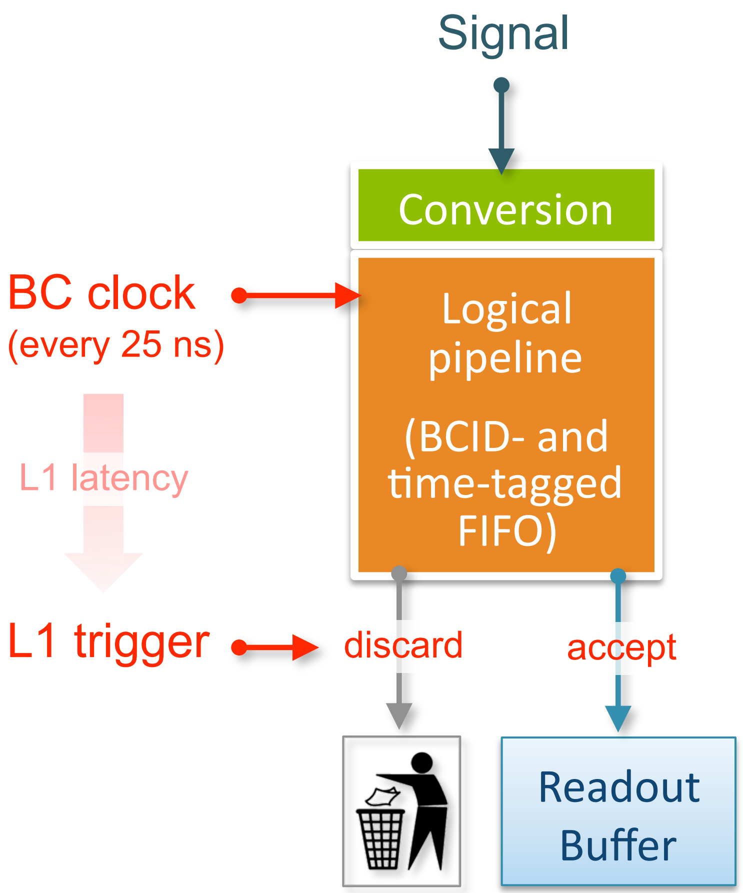
The information from each BC, for each detector element, is retained during the latency of the L1 trigger (few μs)

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)

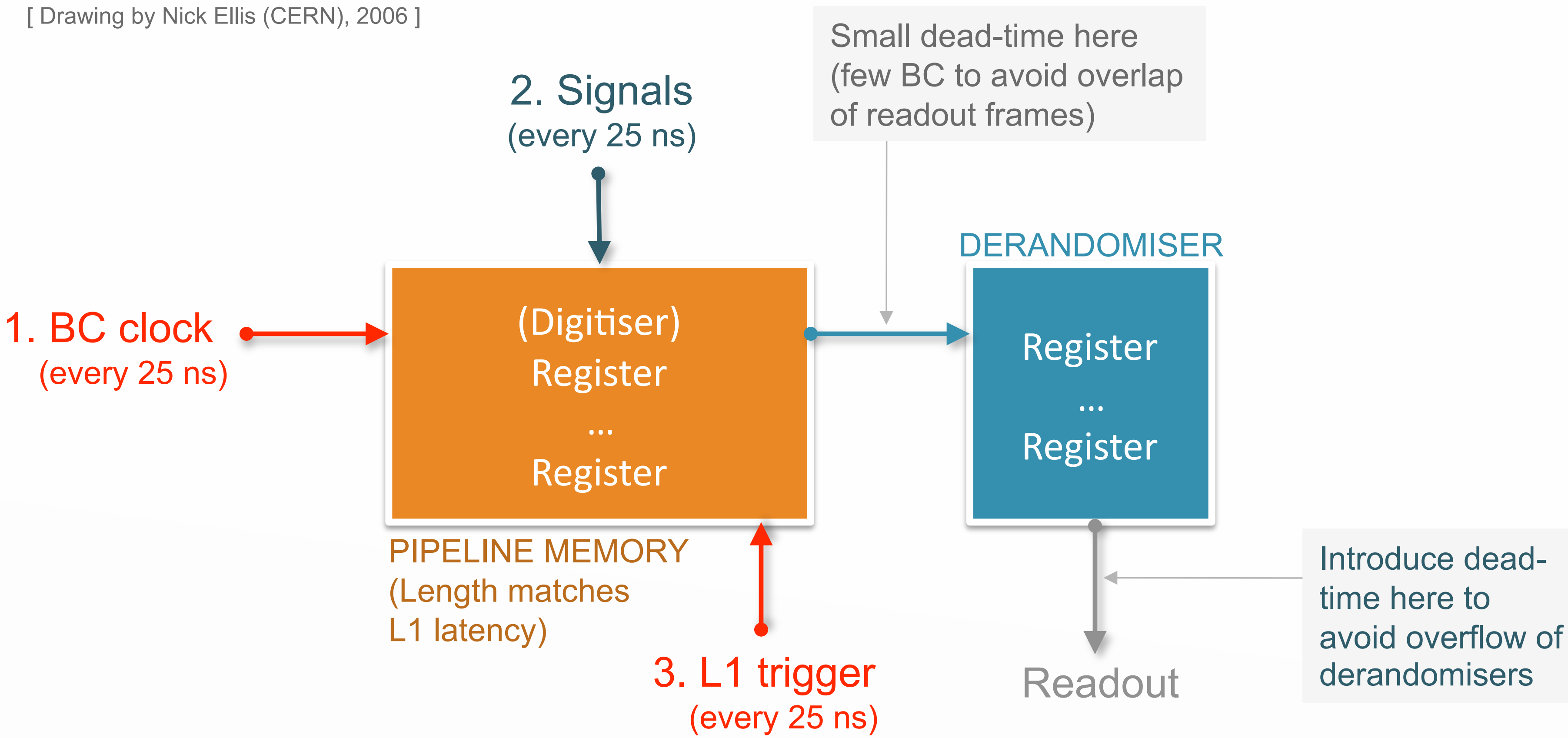
Data reaching end of pipeline is either discarded (large majority of events) or accepted by trigger

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



Pipelined Readout (here LHC)

[Drawing by Nick Ellis (CERN), 2006]



Comments:

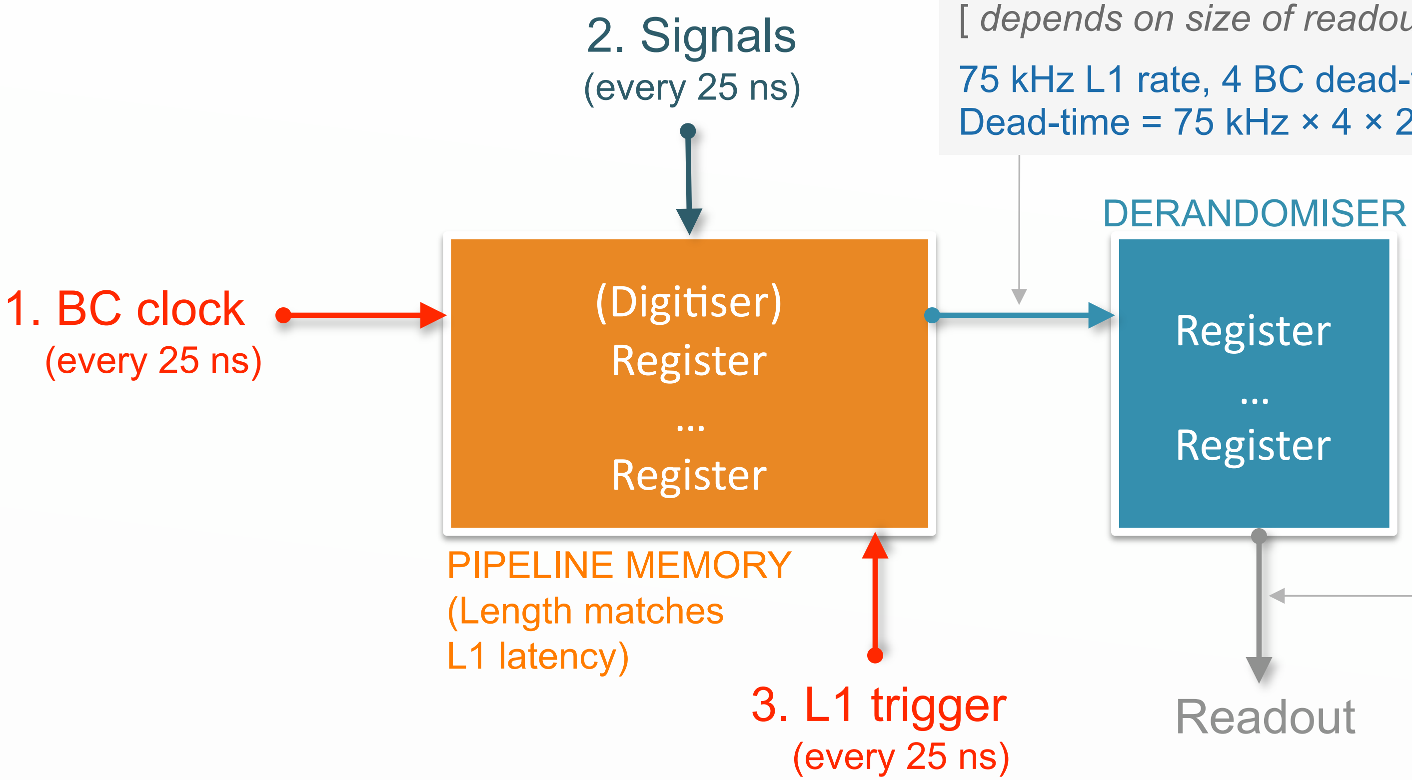
- **Digitiser and pipeline are driven by 40 MHz BC clock**
- L1 decision at each BC → concurrent L1 event processing through L1 pipeline
- "Derandomiser" memory buffers events coming at uncertain rate into well-defined readout rate

Dead-time (here ATLAS)

[Drawing by Nick Ellis (CERN), 2006]

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%

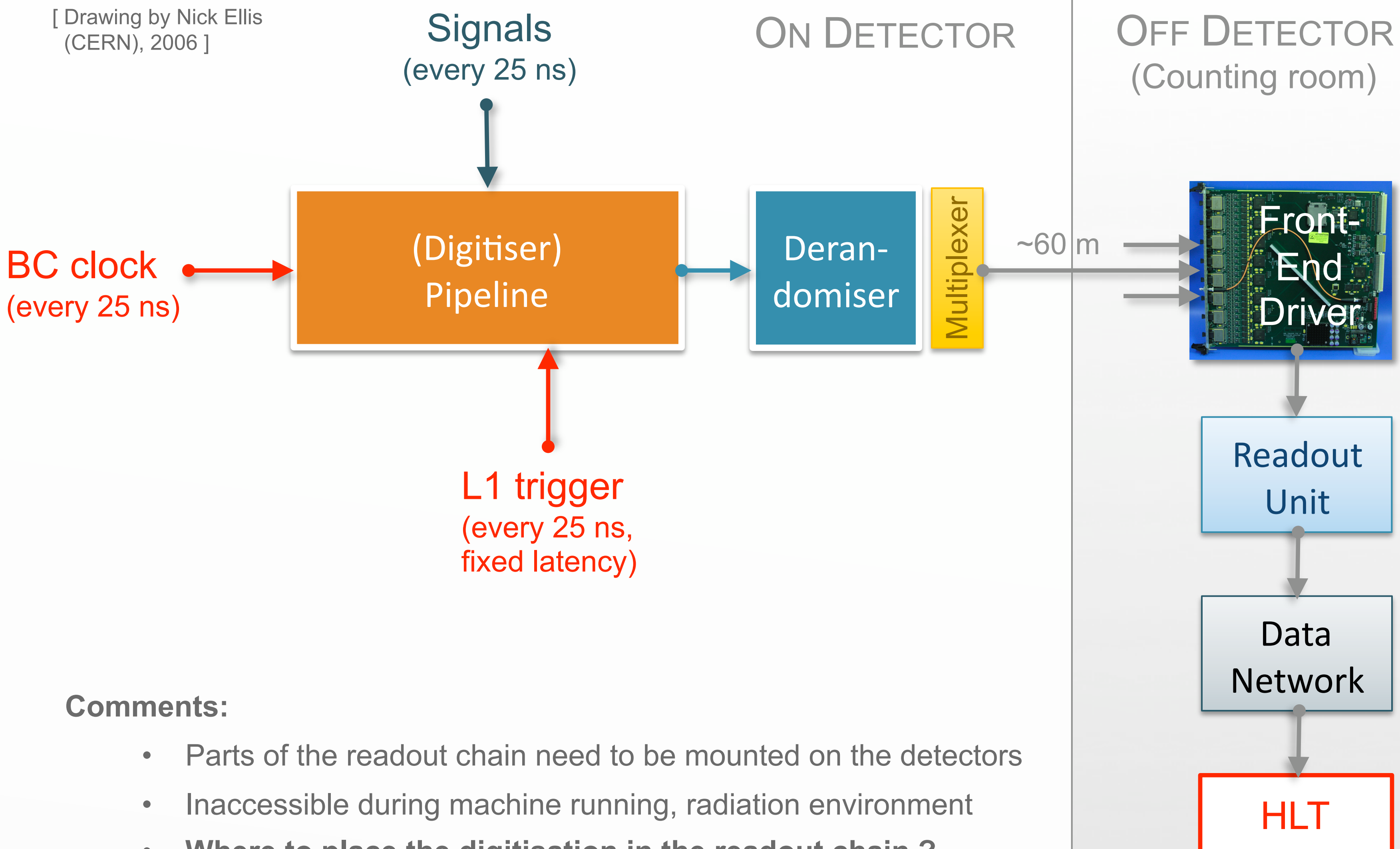


Dead-time (2)
[*depends on size of derandomiser and drain speed*]

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

On/Off-Detector Readout (here CMS)

[Drawing by Nick Ellis (CERN), 2006]

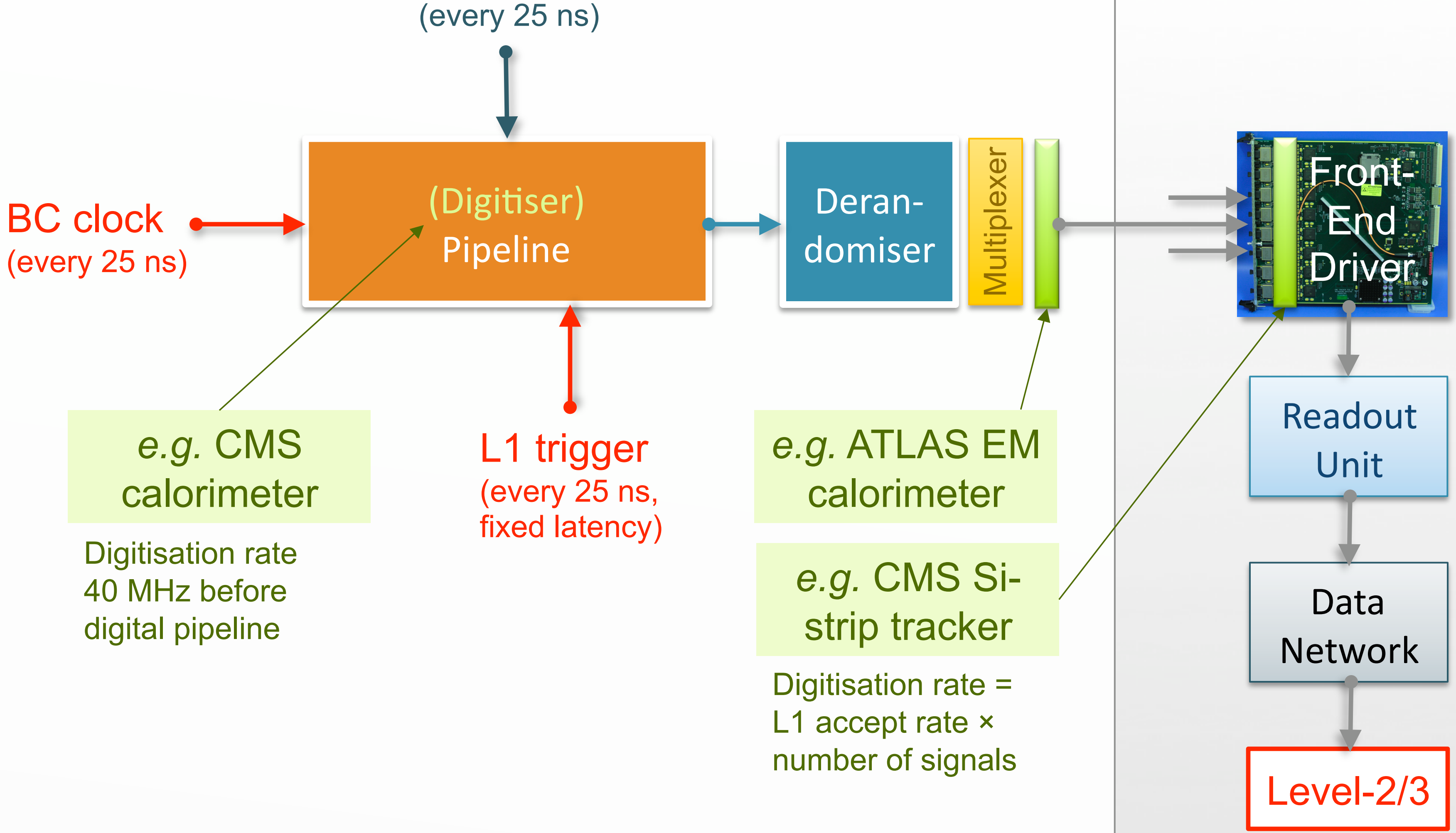


Comments:

- Parts of the readout chain need to be mounted on the detectors
- Inaccessible during machine running, radiation environment
- **Where to place the digitisation in the readout chain ?**

Digitisation Options

[Drawing by Nick Ellis (CERN), 2006]



Pipelined Level-1 Trigger

The L1 trigger has to deliver a new decision every BC, but the trigger latency is much longer than the BC period

- L1 trigger must concurrently process many events

➠ Can be achieved by "pipelining" the processing in custom trigger processors built using modern digital electronics

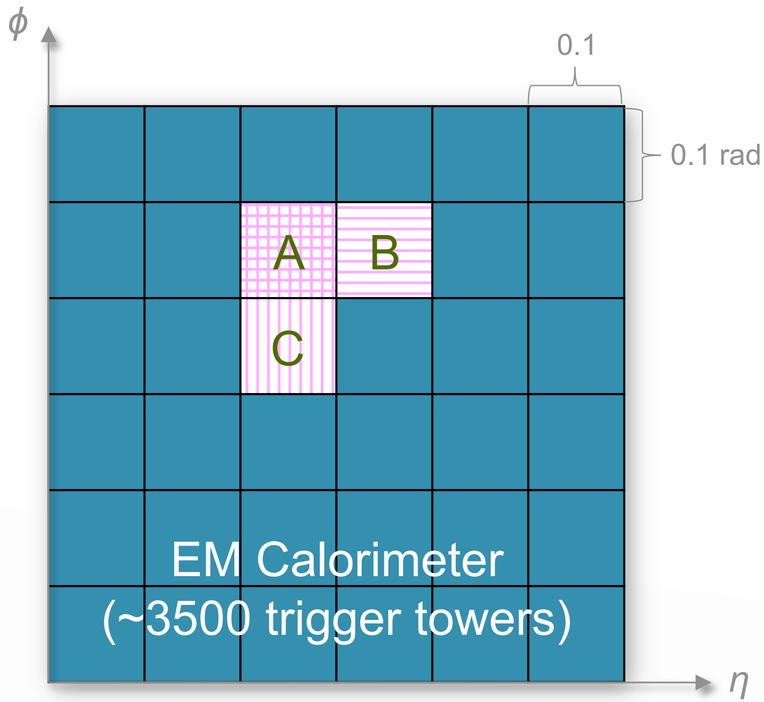
1. Break processing down into a series of steps, each of which can be performed within a single BC period
2. Many operations can be performed in parallel by having a separate processing logic for each one

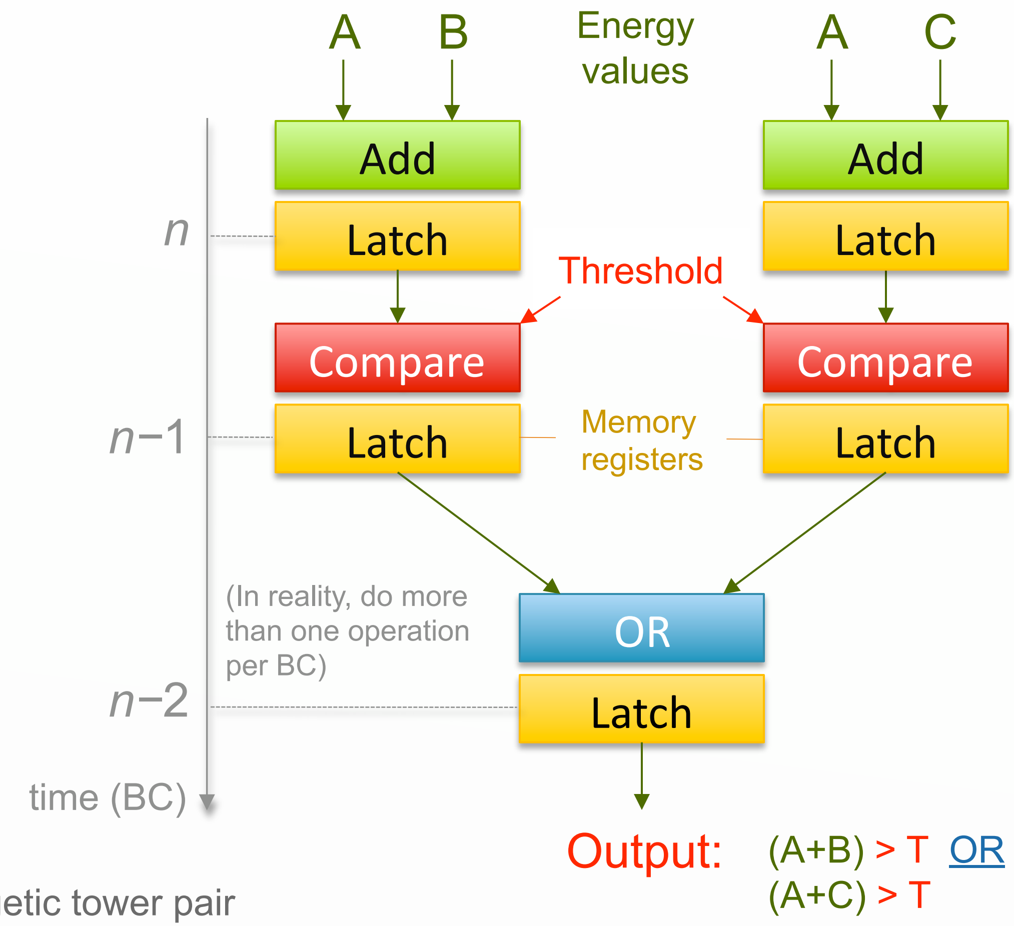
Note that the latency of the trigger is fixed

- Determined by the number of steps in the calculation plus the time taken to move signals and data to and from the components of the trigger system

Pipelined Level-1 Trigger (here ATLAS)

[Drawing by Nick Ellis (CERN), 2006]

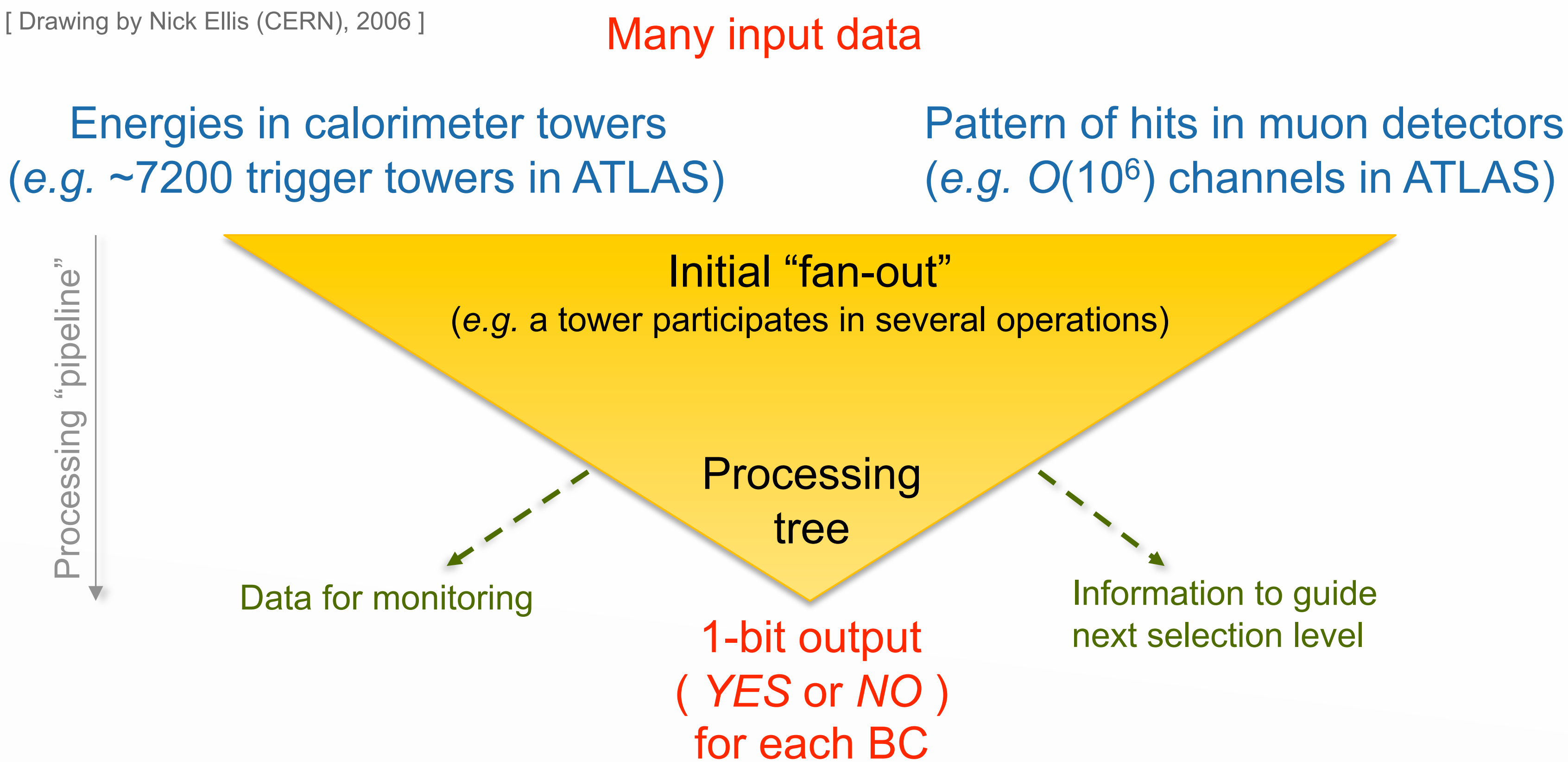




Comments:

- Task: accept any sufficiently energetic tower pair
- In each 25 ns period, data from one layer of 'latches' are processed, and the results are captured in the next layer of latches.
- Parallel processing for all towers (don't know energy deposits in advance)

Level-1 Data Flow



Comments:

- Amount of data to be handled varies along the progress of the processing pipeline
- Initially it expands wrt. digitisation level due to signature overlap: input data is fanned out to several processing elements
- The amount of data decreases as one moves further down the processing tree

Higher Level Triggers at the LHC

Data are transferred to large buffer memories after a Level-1 accept

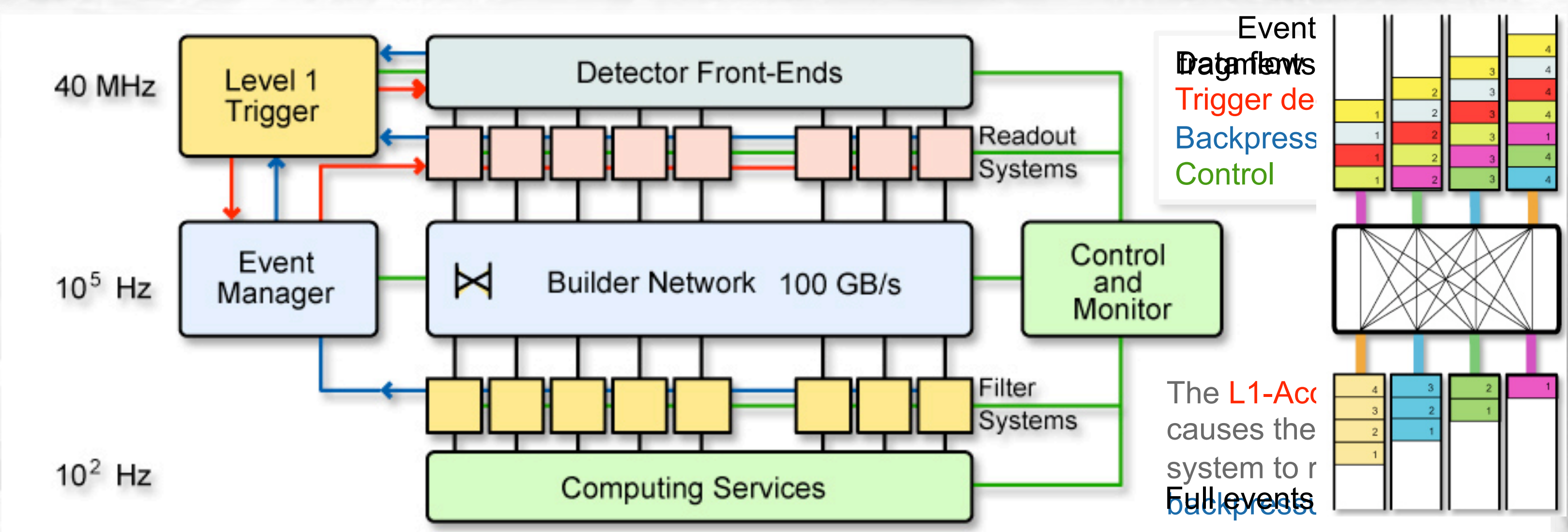
➠ The subsequent stages should not introduce further dead-time

The data rates at the HLT/DAQ input are still massive

- ~1 MB event size at ~100 kHz event rate → 100 GB/s data rate (*i.e.* 800 Gbit/s)

This is far beyond the capacity of the bus-based event building of LEP

- Use network-based event building to avoid bandwidth bottlenecks



No node in the system sees the full data rate — each Readout System covers only a part of the detector — each Filter System deals with only a fraction of the events

HLT and DAQ: Concepts

The massive data rate after L1 poses problems even for network-based event building — different solutions have been adopted to address this

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

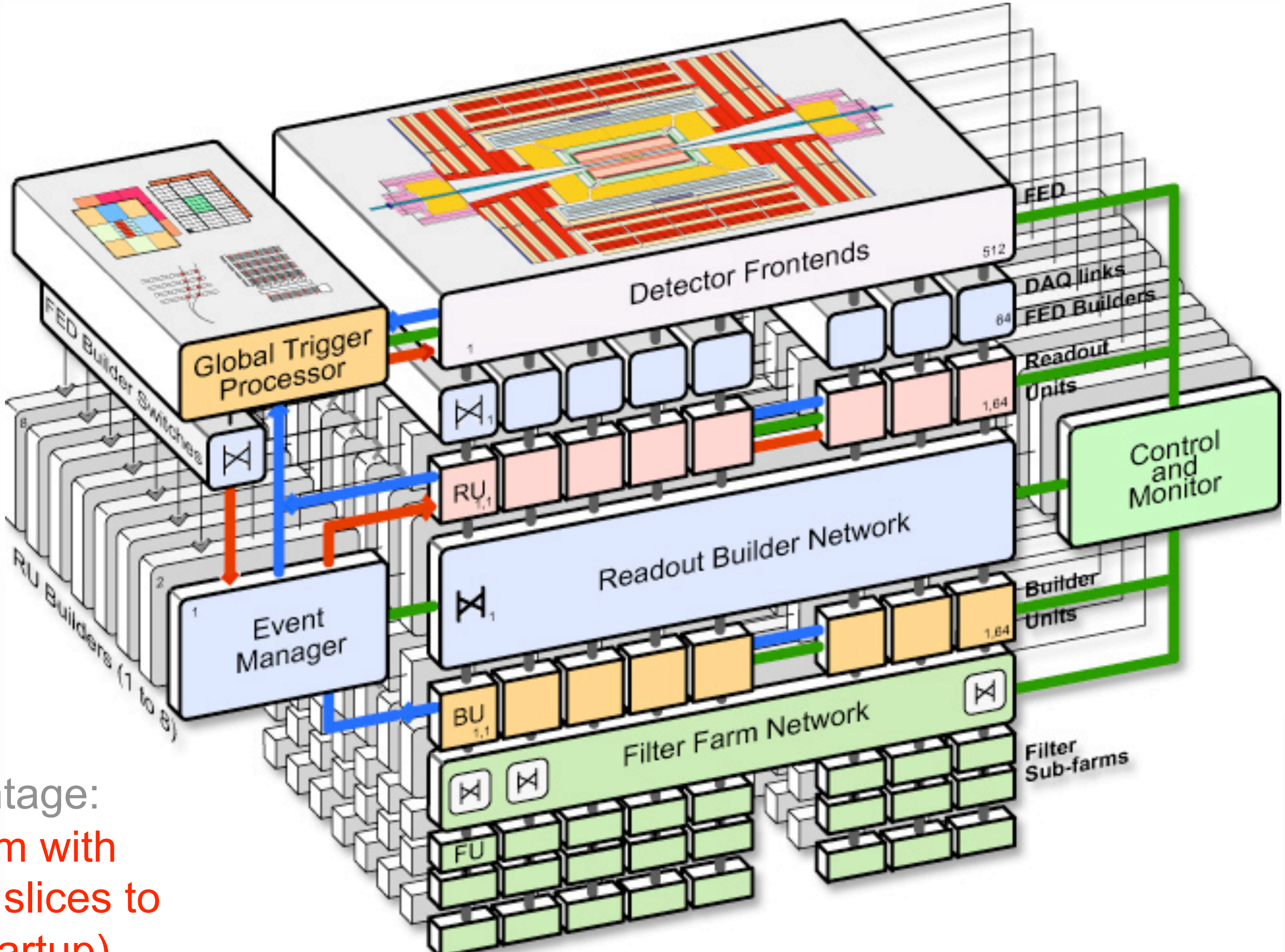
- Requires large total network bandwidth (→ cost), but avoids need for a very large single network switch

In ATLAS, the Region-of-Interest (RoI) mechanism is used to access the data selectively – only move data needed for Level-2 processing

- 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 Slicing Concept – 3D Event Builder

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



Additional advantage:
extensible system with rising funding (4 slices to be installed at startup)

Selective Readout Concepts

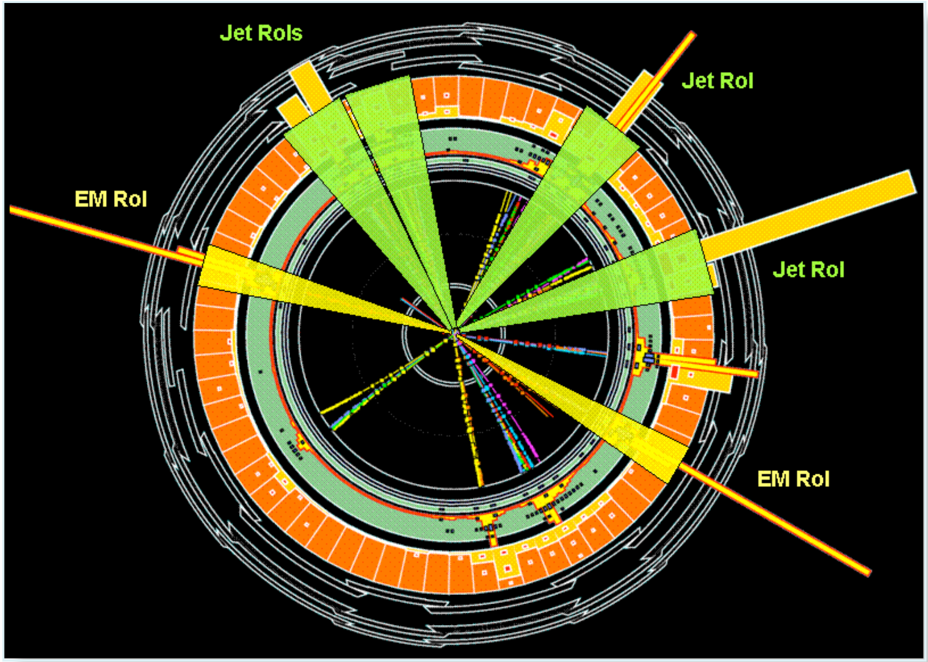
Two concepts are used to select data subsets from the readout systems

Region-of-Interest concept (ATLAS, LHCb):

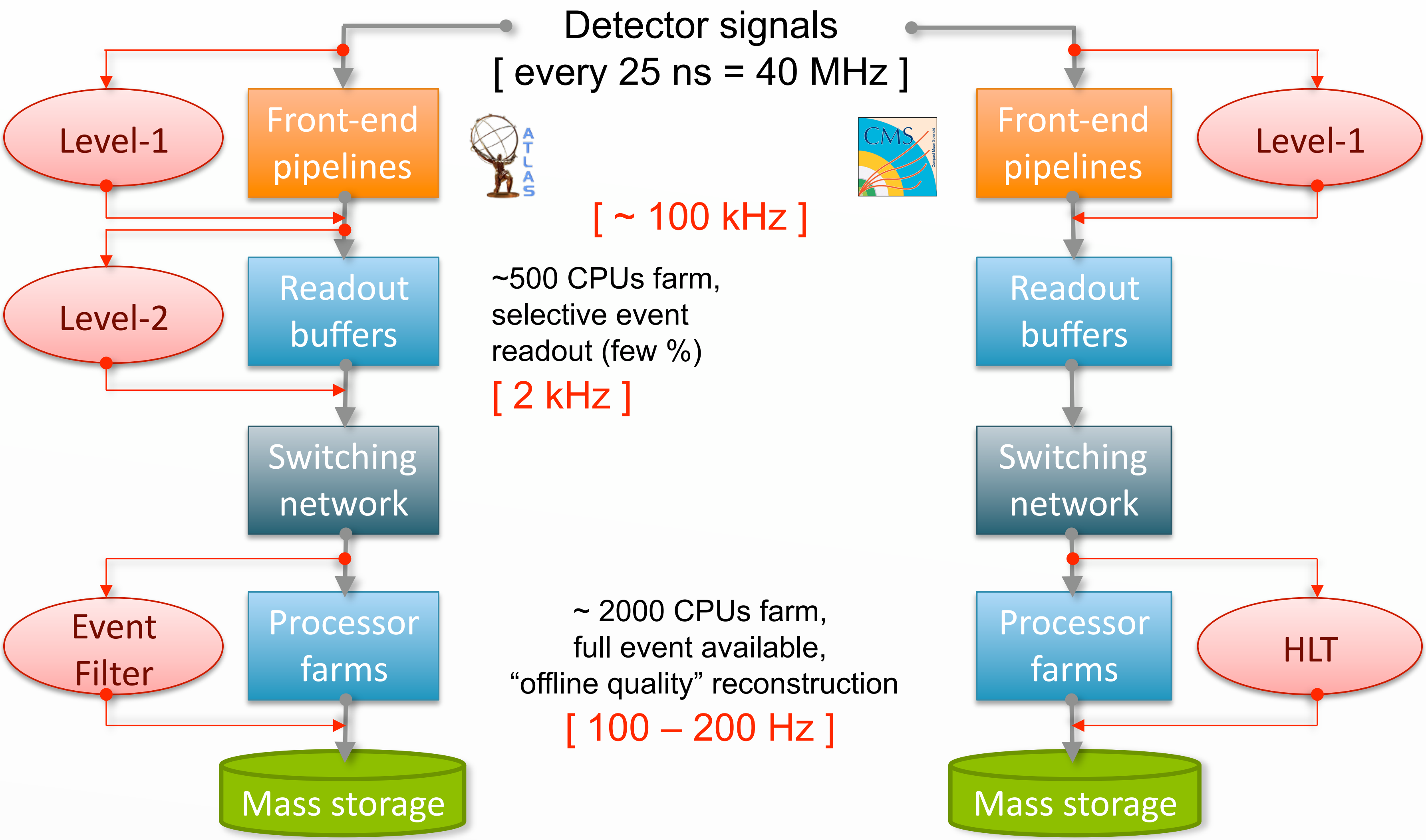
- L1 indicates the geographical location of candidate objects, *e.g.* EM clusters
- L2 only accesses data from RoIs, small fraction of total data

Sequential-selection concept (ATLAS, CMS):

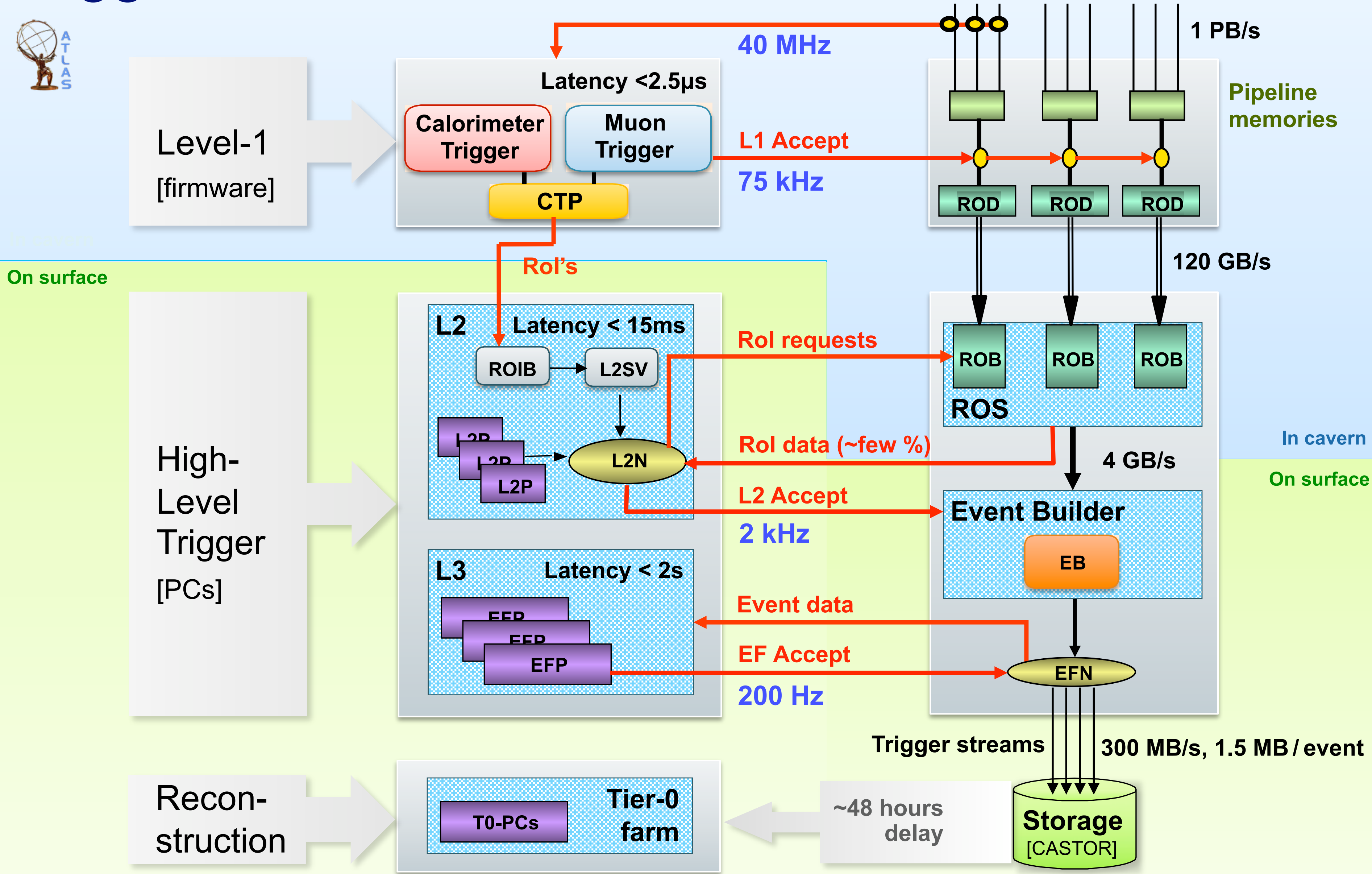
- Data are accessed by L2 initially only from a subset of detectors (*e.g.* muon systems and calorimeters)
- Many events rejected without accessing, *e.g.*, inner detector



ATLAS and CMS HLT Concepts



Trigger & Data Flow



HLT Logic

In the HLT, each trigger line corresponds to a series of algorithms

- **Early accept mechanism** (*e.g.* H1 in early HERA)
  - As soon as the decision to keep an event is made by one trigger, the event is accepted and the remaining trigger lines are not evaluated
- **Early reject mechanism** (*e.g.* ATLAS)
  - All trigger lines are evaluated step-wise and in parallel
  - If a line fails, it is stopped → the event is rejected if all trigger lines fail at given step
  - In case of a trigger accept, all trigger lines have been evaluated (this is useful for the study of combined triggers, in particular in case of prescales → see later)

ATLAS distinguishes “feature extraction” and “hypothesis” algorithms

- *Feature extraction* retrieves detector data from readout buffers and reconstructs physics quantities/objects. Smart caching makes sure that objects already reconstructed by one algorithm can be reused by all others.
- *Hypothesis algorithms* apply the actual trigger cuts, and may stop a trigger line

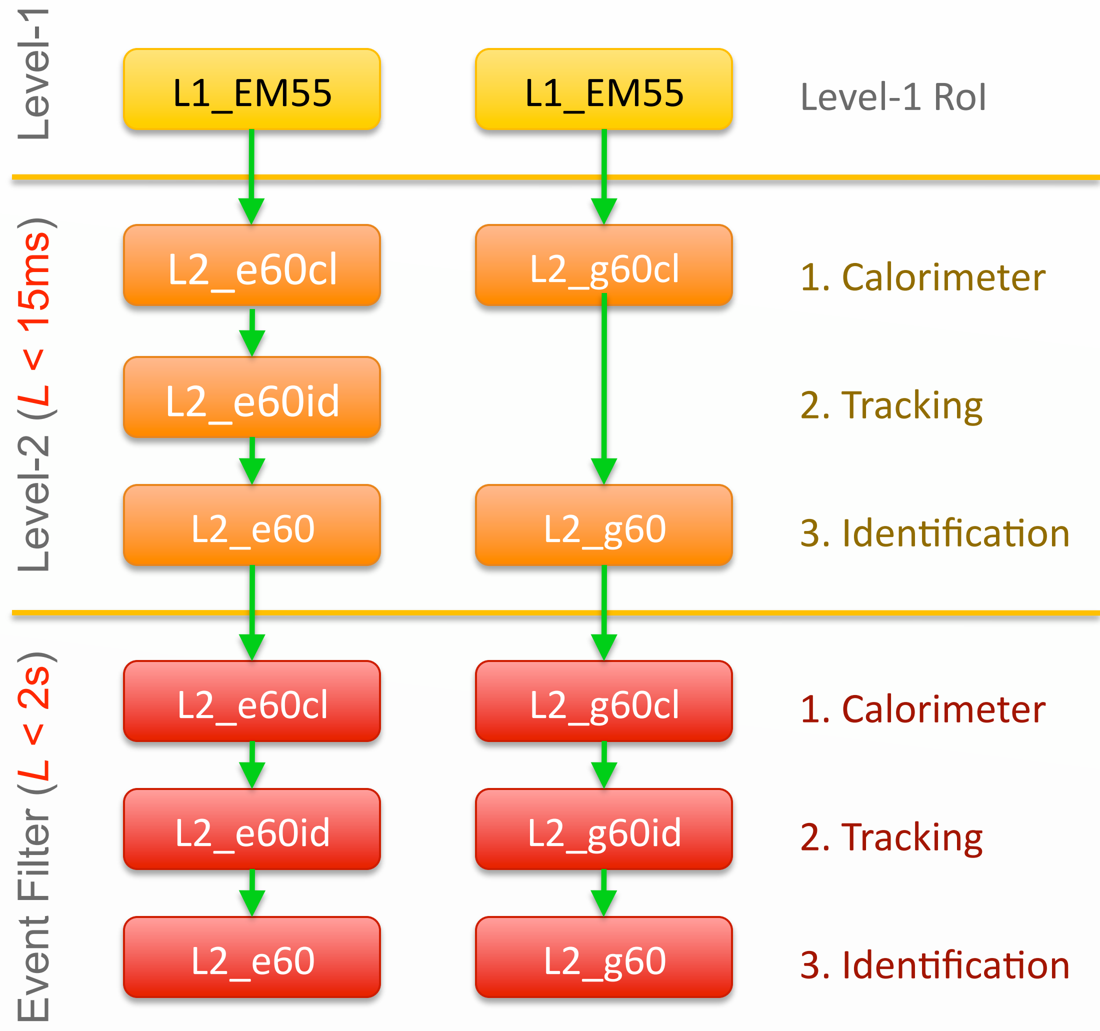
HLT Trigger Lines

Example for “e60” and “g60” signature chains in ATLAS

The early reject algorithm benefits from separating HLT algorithms into steps

- Each one requesting additional detector data or performing reconstruction, followed by a hypothesis algorithm
- As soon as one steps is unsuccessful, the trigger line is stopped

Compare to full event reconstruction *O*(10s) per event



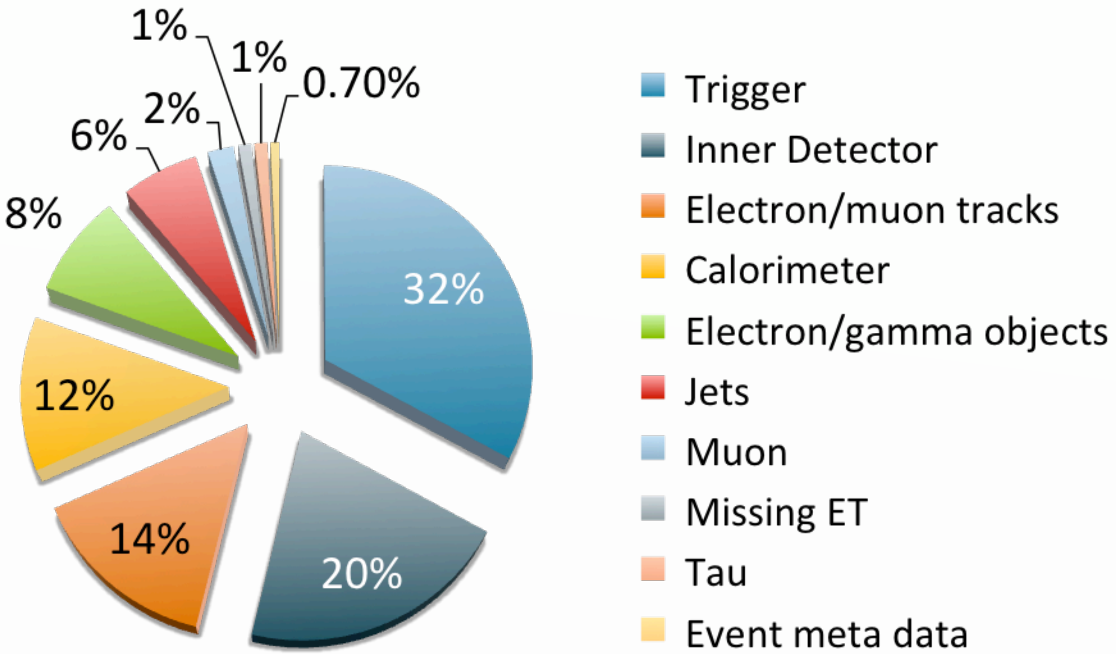
HLT Features

In addition to the trigger decision (of all lines and at all levels, before and after prescaling → see later), the reconstructed physics objects (features) of the trigger are stored as (substantial) part of the event data

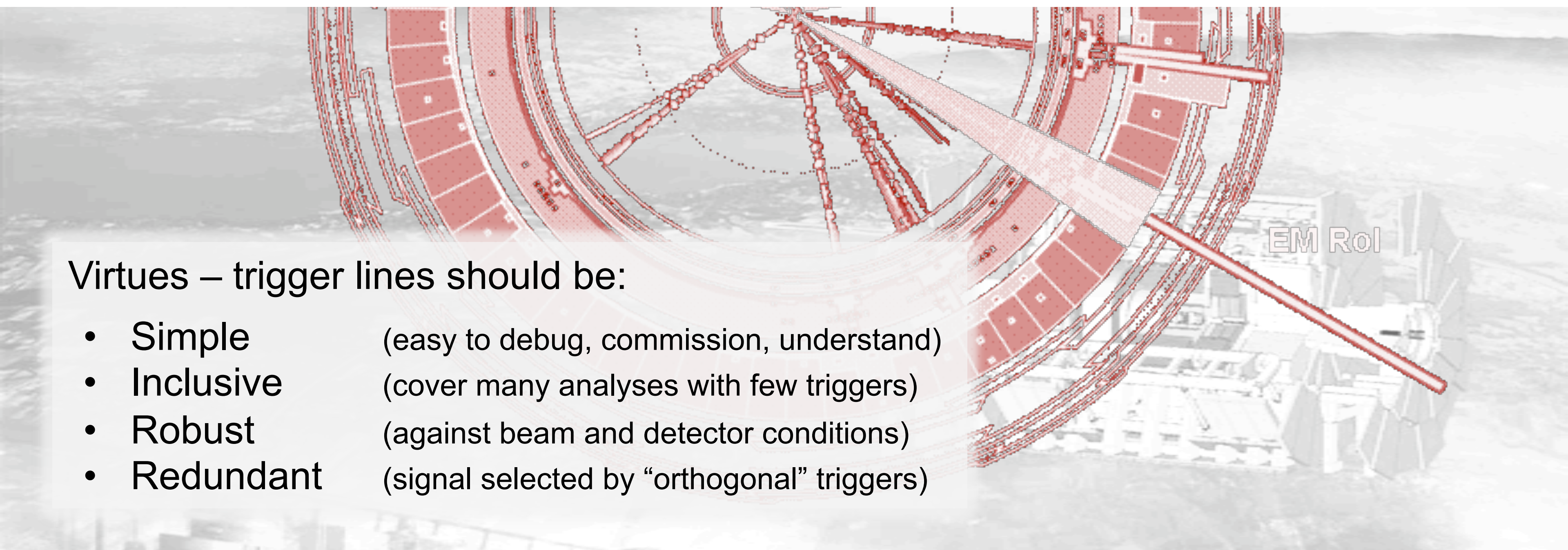
- This is **mandatory** for the offline study of trigger reconstruction, decision, the determination of the trigger efficiency and systematic effects

Factions of total size (167 kB/event) in ATLAS AOD for simulated top events

Biggest contribution (32%) by trigger features !



Trigger Selection at the LHC



Virtues – trigger lines should be:

- Simple (easy to debug, commission, understand)
- Inclusive (cover many analyses with few triggers)
- Robust (against beam and detector conditions)
- Redundant (signal selected by "orthogonal" triggers)

Pillars of the LHC Physics Programme

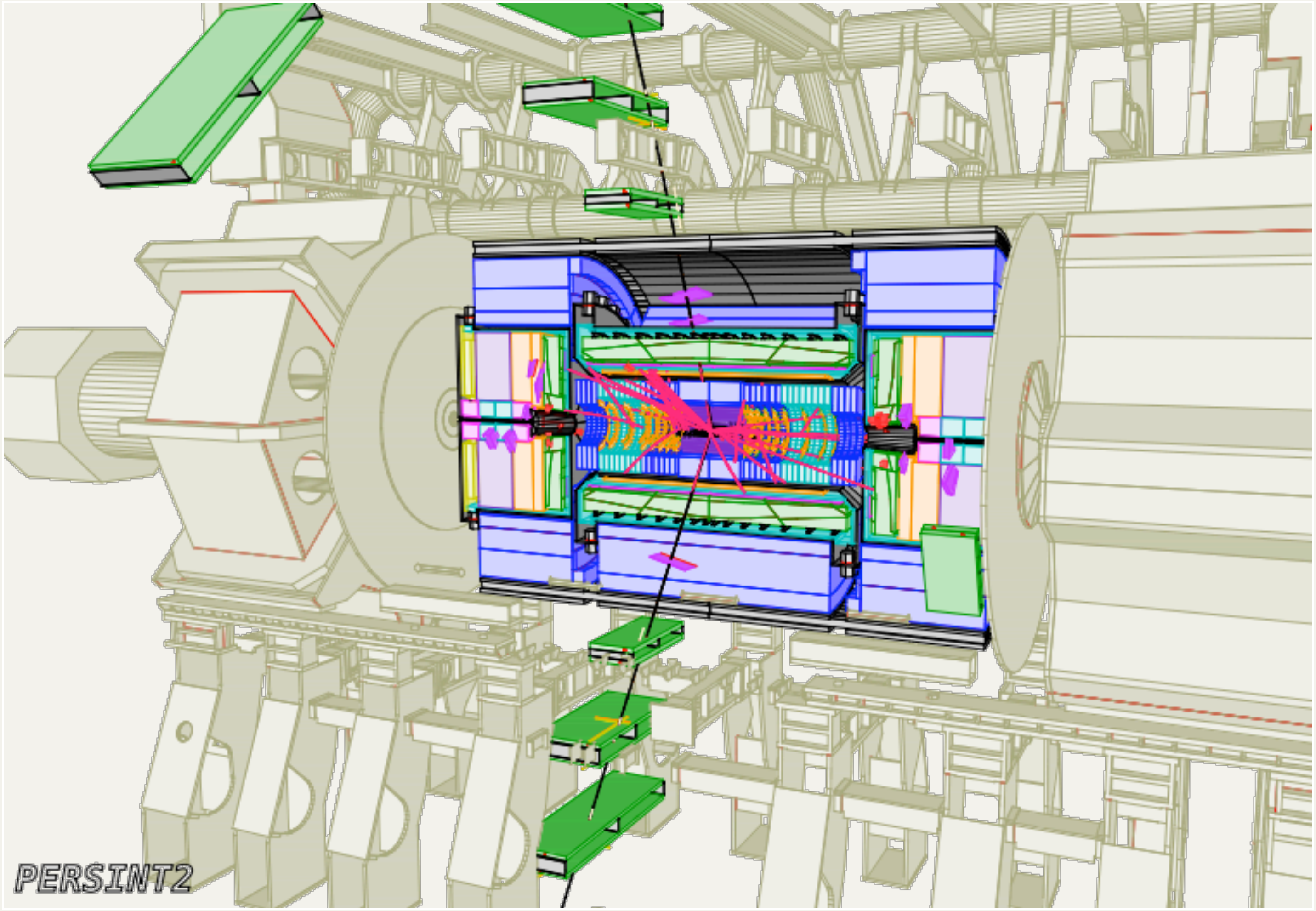
1. **Mass**
   - Search for the Higgs Boson
2. **Electroweak unification**
   - Precision measurements (M_W, m_{top}) and tests of the Standard Model
3. **Hierarchy in the TeV domain**
   - Search for Supersymmetry, Extra dimensions, Higgs composites, …
4. **Flavour**
   - *B* mixing, rare decays and *CP* violation as tests of the Standard Model

Triggers in the general-purpose proton–proton experiments, ATLAS and CMS, will have to retain as many as possible of the events of interest for the diverse physics programmes of these experiments

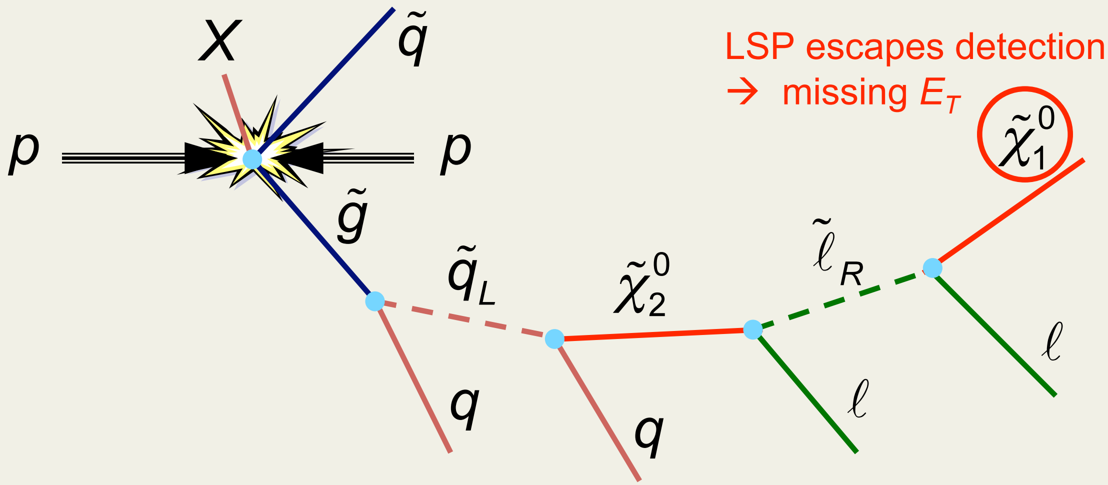
N.b. selections often need to be made at analysis level to suppress backgrounds, so focus especially on events that must be retained !

Simulated Z → $\mu\mu$ event in **ATLAS**

Expect 10,000 of these events in first 10 pb^{-1}(and 10 times more $W \rightarrow e\nu$) recorded



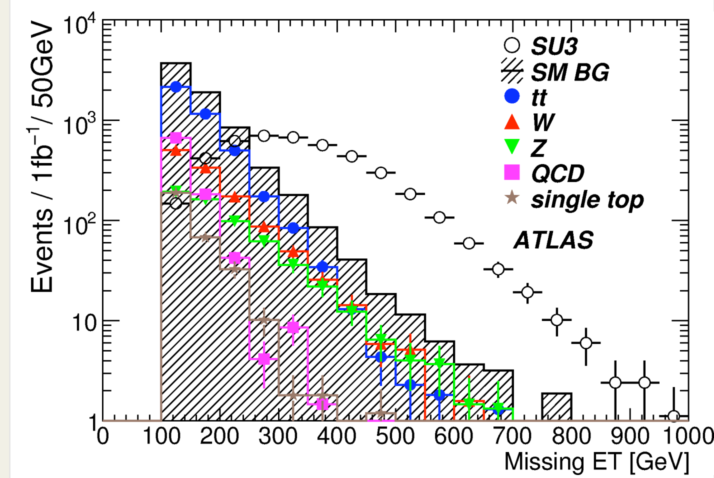
MET would be generated by stable neutralinos in SUSY



"Typical" SUSY decay chain at the LHC – assuming *R*-parity conservation

SUSY can also be *R*-parity violating

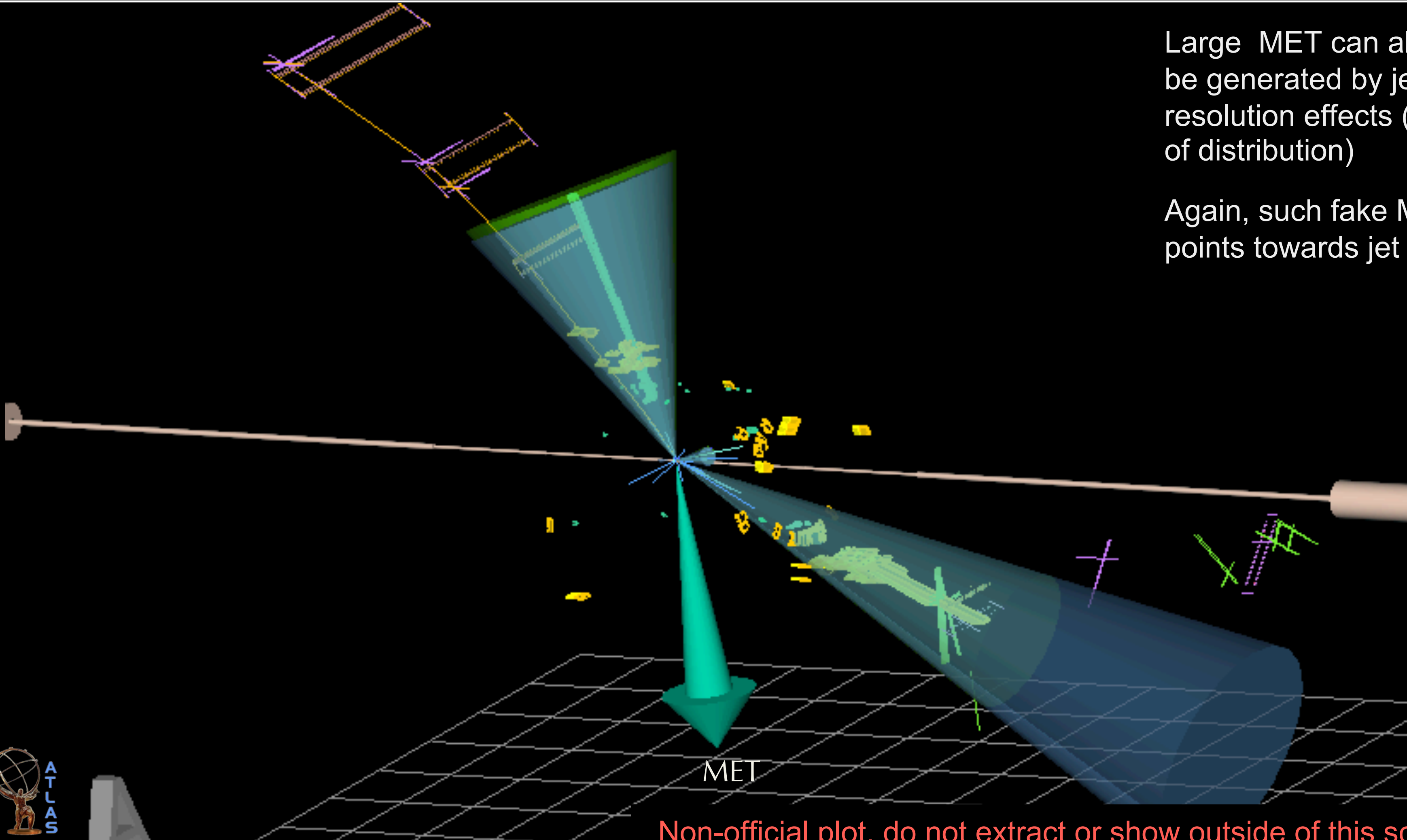
Some SUSY models predict particles with very long lifetime



Distribution of MET in SUSY and background events

Fake MET can be generated by resolution effects

Simulated di-jet event (ATLAS)



Large MET can also be generated by jet resolution effects (tails of distribution)

Again, such fake MET points towards jet axi

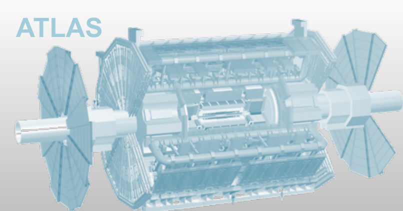
Non-official plot, do not extract or show outside of this school

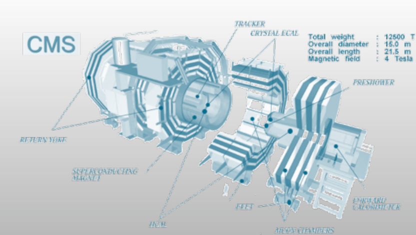
Constraints – ATLAS & CMS

Need to reduce the event rate to a manageable level for data recording and offline analysis

- $L = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ → 1 GHz interaction rate ("interesting" rate *O*(100 Hz))
- The size of the events is very large, *O*(1 MB)
  - Huge number of detector channels, high multiplicity of events
- Recording and subsequently processing offline, *O*(100) Hz event rate per experiment with *O*(1) MB event size requires major computing resources
- Hence, only a tiny fraction $O(10^{-7})$ of proton–proton collisions can be selected

Have to balance needs of maximising coverage for a very diverse physics programme and reaching acceptable (*i.e.* affordable) recording rates





Constraints – LHCb

LHCb, dedicated to studying *B*-physics, faces similar challenges to ATLAS and CMS

It will operate at a comparatively low luminosity (~2×10^{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

The event size is comparatively small (~35 kB)

- Fewer detector channels
- Less occupancy due to lower luminosity

However, there is a very high rate of beauty production

- Given cross section of ~500 μb, $b\bar{b}$ production rate ~100 kHz

The trigger must therefore search for specific *B* decay modes that are of interest for the physics analysis (aim to record ~2 kHz event rate)

Constraints – ALICE

The heavy-ion experiment ALICE is particularly demanding for DAQ

The total interaction rate will be much smaller than in the *pp* experiments

- $L \sim 10^{27}\ cm^{-2}s^{-1} \rightarrow R \sim 8000$ Hz for Pb–Pb collisions

Trigger selects “minimum-bias” and “central” events (rates scaled down to total ~40 Hz), and events with di-leptons (~1 kHz with only part of the detector read out)

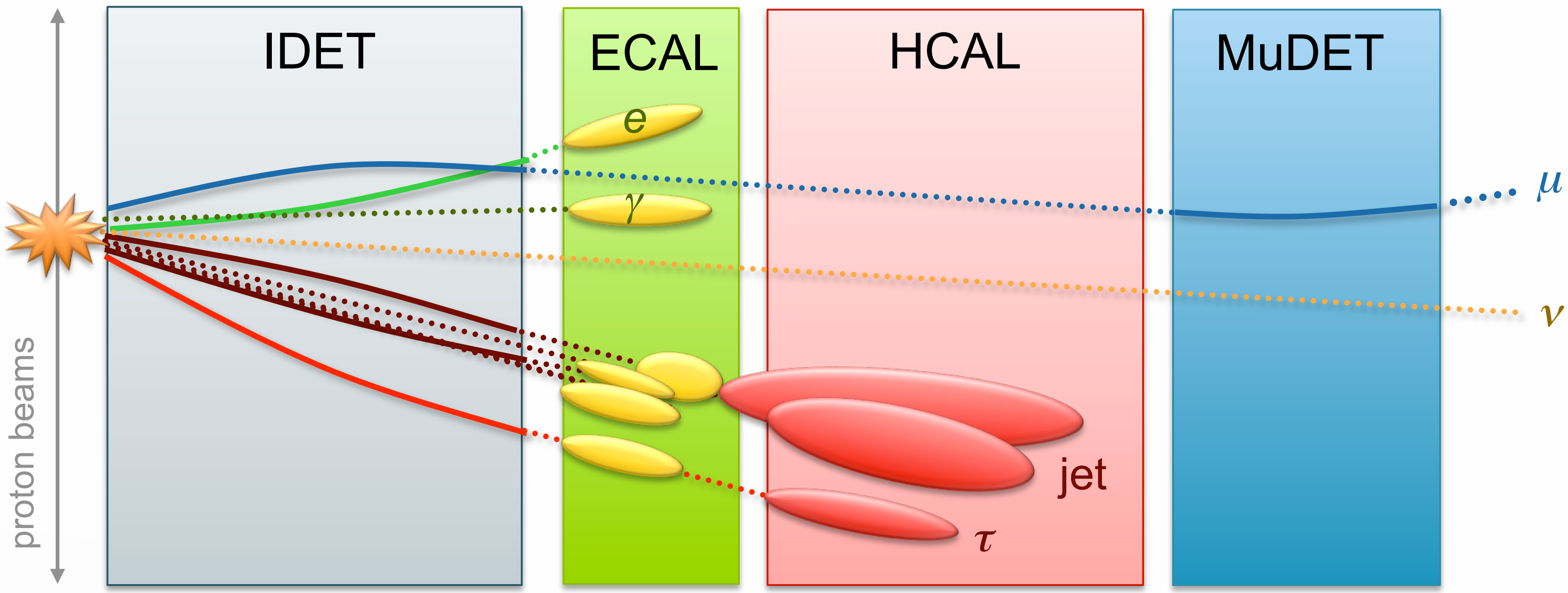
However, huge event size due to high particle multiplicity in Pb–Pb collisions at LHC energy

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

Even more than in the other experiments, the volume of data to be stored and subsequently processed offline will be massive

- Data rate to storage ~1 GB/s (limited by what is possible / affordable)

Trigger Signatures



Features distinguishing new physics from the bulk of the SM cross-section

- Presence of high-p_T objects from decays of heavy particles (min. bias <p_T> ~ 0.6 GeV)
- More specifically, the presence of isolated high-p_T leptons or photons
- The presence of known heavy particles (*W*, *Z*)
- Missing transverse energy (either from high-p_T neutrinos, or from new invisible particles)

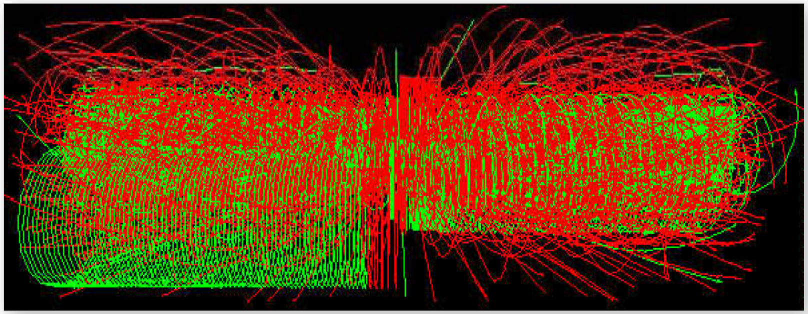
Which Detectors Participate in Trigger ?

In Muon Detector and Calorimeters we encounter low occupancy and pattern recognition is straightforward ☺

- Simple reconstruction algorithms → fast
- Small amount of data
- Can take "regional" decisions

Not so in the Inner Detectors… ☹

- Complicated events
- Complex reconstruction algorithms → slow
- Huge amount of data
- Need to link to other detectors for additional information



CMS event display of a $H \to 4\mu$ simulation at $L = 10^{34}$ cm^{-2}s^{-1}

Level-1 Signatures at Hadron Colliders

High-p_T muons

- Identified beyond calorimeters; need p_T cut to control rate from $\pi^+/K^+ \rightarrow \mu\nu$ and $b/c \rightarrow \mu\nu$

High-p_T photons

- Identified as narrow EM calorimeter clusters; need cut on E_T; cuts on isolation and hadronic-energy veto reduce strongly rates from high-p_T jets

High-p_T electrons

- Same as photon

High-p_T taus (decaying to hadrons)

- Identified as narrow cluster in EM+hadronic calorimeters

High-p_T jets

- Identified as local cluster in EM & hadronic calorimeter — need to cut at very high p_T to control rate (jets are dominant high-p_T process)

Large missing E_T or scalar E_T sum

Level-1 Trigger "Menu"

Illustrative Level-1 trigger menu for LHC at high luminosity

The full menu includes many additional signatures

Signature	Transverse Momentum	Approximate rate
≥ 1 μ	> 20 GeV	11 kHz
≥ 2 μ	> 6 GeV	1 kHz
≥ 1 e or γ	> 30 GeV	22 kHz
≥ 2 e or γ	> 20 GeV	5 kHz
≥ 1 jet	> 290 GeV	200 Hz
≥ 1 jet	> 100 GeV and $E_{T,miss}$ > 100 GeV	500 Hz
≥ 3 jet	> 130 GeV	200 Hz
≥ 4 jet	> 90 GeV	200 Hz

"Trigger menu"

- Typically, trigger systems select events according to a list of selection criteria → "*menu*"
- An event is selected by the trigger if one or more of the criteria are met
- Different criteria may correspond to different signatures for the same physics process
- The menu has to cover the physics channels to be studied, plus additional event samples required to complete the analysis

High-Level Trigger Menu

Illustrative HLT menu for LHC at 2×10^{33} cm^{-2}s^{-1} luminosity (CMS)

Refinement of Level-1 selection criteria and additional signatures

Signature	Approximate rate
≥ 1 μ > 19 GeV or ≥ 2 μ > 7 GeV	29 Hz
≥ 1 γ > 80 GeV or ≥ 2 γ > 40, 25 GeV	9 Hz
≥ 1 e > 29 GeV or ≥ 2 e > 17 GeV	34 Hz
≥ 1 τ > 86 GeV or ≥ 2 τ > 59 GeV	4 Hz
≥ 1 jet ≥ 180 GeV and $E_{T,\text{miss}}$ > 123 GeV	5 Hz
≥ 1 jet > 657 GeV or ≥ 3 jets > 247 GeV or 4 jets > 113 GeV	9 Hz
Others (e/γ-jet, b-jets, etc.)	7 Hz

Total of ~ 100 Hz (large uncertainties), large fraction of interesting physics

- Need to balance physics coverage against offline computing cost

HLT Efficiency for Physics

Expected CMS results for HLT menu at 2×10^{33} cm^{-2}s^{-1} luminosity

Channel	Efficiency (in detector accept.)
$W \rightarrow e\nu$	67 % (fid: 60 %)
$W \rightarrow \mu\nu$	69 % (fid: 50 %)
$tt \rightarrow \mu+X$	72 %
H(115 GeV) $\rightarrow \gamma\gamma$	77 %
H(160 GeV) $\rightarrow WW^* \rightarrow 2\mu$	92 %
H(150 GeV) $\rightarrow ZZ^* \rightarrow 4\mu$	92 %
A/H(200 GeV) $\rightarrow 2\tau$	45 %
H^+(200 – 400 GeV) $\rightarrow \tau\nu$	58 %
SUSY (≈ 0.5 TeV squarks/gluinos)	≈ 60 %

LHCb also expects good (fiducial) efficiencies for primary physics modes

- 40% (total) for $B_s \rightarrow D_s^+\pi^-$, 70% for $B_s \rightarrow J/\psi(\mu\mu)\phi$, 40% for $B \rightarrow K^*\gamma$
- 1 billion fully contained (decay-unbiased) B mesons for 2 fb^{-1} from inclusive trigger

High-Level Trigger Menu

Illustrative HLT menu

Signature	Approximate rate

A realistic trigger menu contains many more lines:

- Prescaled low-p_T lines for physics, background studies (pile-up – also use random BC triggers), and to measure turn-on curves
- “Pass-through” lines to monitor L1 and HLT performance (*e.g.* to check isolation requirements in L1)
- “Orthogonal triggers” to study trigger reconstruction and efficiencies (*e.g.* check electron track-matching with photon trigger)
- Redundant triggers to increase robustness and efficiency
  → if two triggers *A* and *B* uncorrelated, $\varepsilon_{combined} = (1 - \delta_A \delta_B)$

Electron-Photon Trigger

How it Really Looks Like

Signature	Level-1 Item	Level-1 Pre-scale	Level-1 Rate [kHz]	HLT Sel-ection	HLT Pre-scale	HLT Rate [Hz]	Motivation
e5	EM3	60	0.7	medium	1	4.8 ± 0.2	$J/\Psi \to ee$, $Y \to ee$, Drell-Yan
2e5	2EM3	1	6.5	medium	1	6	$J/\psi \to ee$, $Y \to ee$, Drell-Yan
Jpsiee	2EM3	1	6.5	medium	1	1	$J/\psi \to ee$, $Y \to ee$
e10	EM7	1	5.0	medium	1	21	$e^{\pm}$ from b,c decays, E/p studies
γ10	EM7	1	5.0	medium	100	0.6 ± 0.1	$e^{\pm}$ direct photon cross-section, e-no-track trigger
e10_xe30	EM7_XE30	1	0.2	medium	1	0.3 ± 0.3	access low p_T-range for $W \to e\nu$
2γ10	2EM7	1	0.5	loose	1	< 0.1	di-photon cross-section
2e10	2EM7	1	0.5	loose	1	0.4 ± 0.2	$Z \to e^+e^-$
Zee	2EM7	1	0.5	loose	1	< 0.1	$Z \to e^+e^-$
2e12i_L33	2EM7	1	0.5	tight	1	< 0.1	trigger for L$\sim 10^{33}$ cm^{-2} s^{-1}
γ15	EM13	1	0.7	medium	10	1.3 ± 0.1	$e^{\pm}$ direct photon cross-section
e15_xe20	EM13_XE20	1	0.2	loose	1	1.0 ± 0.4	access low p_T-range for $W \to e\nu$
2g17i_L33	2EM13I	1	0.1	tight	1	< 0.1	trigger for L$\sim 10^{33}$ cm^{-2} s^{-1}
γ20	EM18	1	0.3	loose	1	5.4 ± 0.2	direct photons, jet calibration using γ-jet events, high-p_T physics,check tracking eff.
e20_passL2	EM18	1	0.3	loose	200	< 0.1	check L2EF performance
e20 passEF	EM18	1	0.3		125	0.1	check L2EF performance
em20_passEF	EM18	1	0.3		750	0.5 ± 0.1	check HLT performance
em20i_passEF	EM18I	1	0.1		300	0.5 ± 0.1	check L1 isolation
e22i_L33	EM18I	1	0.1	tight	1	1.2 ± 0.1	trigger for L$\sim 10^{33}$ cm^{-2} s^{-1}
γ55_L33	EM18	1	0.3	tight	1	1.2 ± 0.1	trigger for L$\sim 10^{33}$ cm^{-2} s^{-1}
em105_passHLT	EM100	1	1		1	1.0 ± 0.1	New physics, check for possible problems
γ150_passHLT	EM100	1	1		1	< 0.1	check for possible problems in express stream

Table 5: Summary of triggers for the first physics run assuming a luminosity of L$\sim 10^{31}$ cm^{-2} s^{-1}. For each signature rates and the motivation for this trigger are given.

[CERN-OPEN-2008-020]

and tomorrow…

Lecture Themes

I. Introduction and Challenges

II. Trigger and Data Acquisition Basics

III. Trigger Selection at the LHC

today

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tomorrow

IV. More in Depth: ATLAS *e*/*γ* Trigger

V. Jet and Muon Triggers

VI. Trigger/DAQ Commissioning

VII. Trigger-Aware Data Analysis