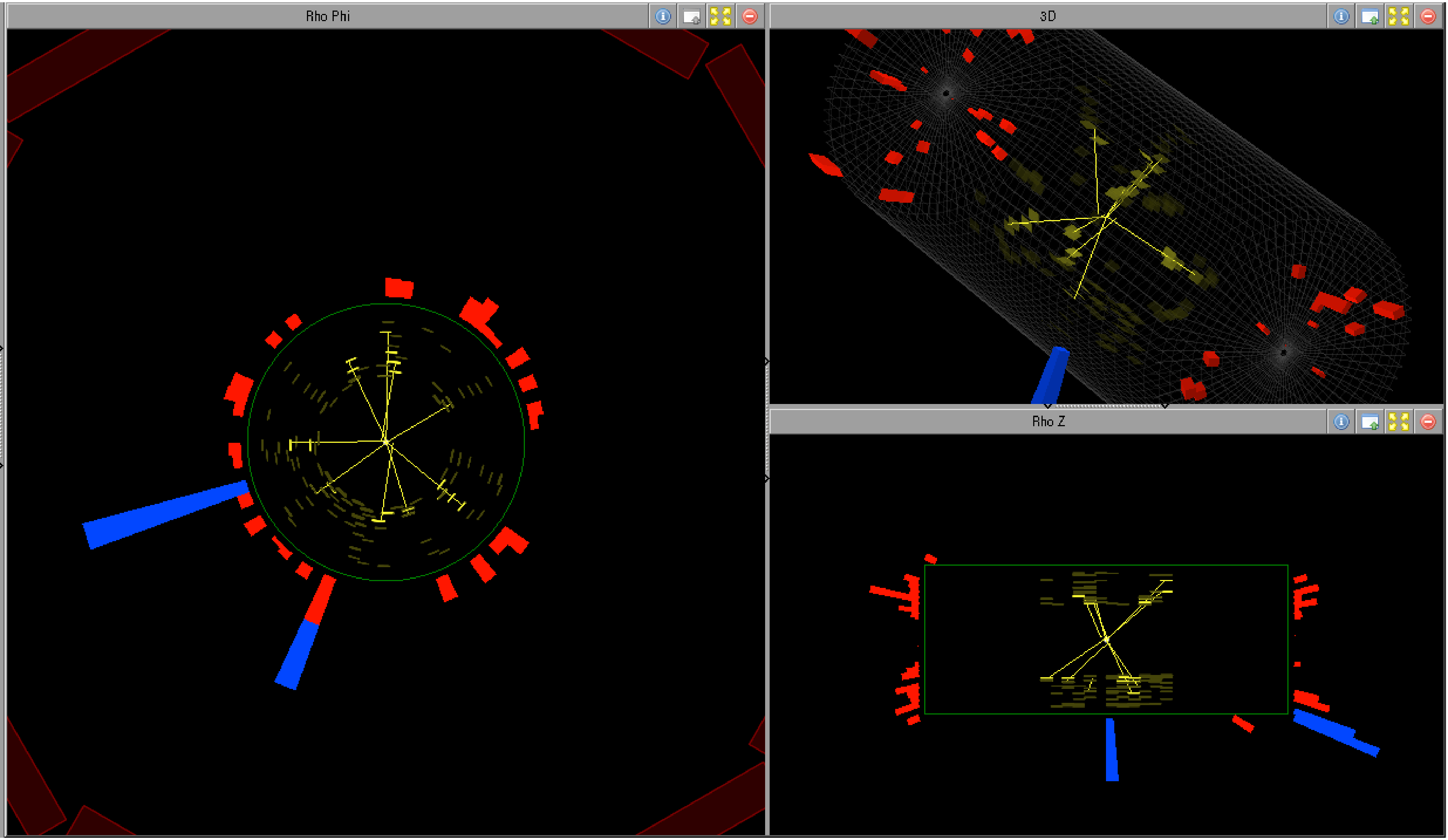
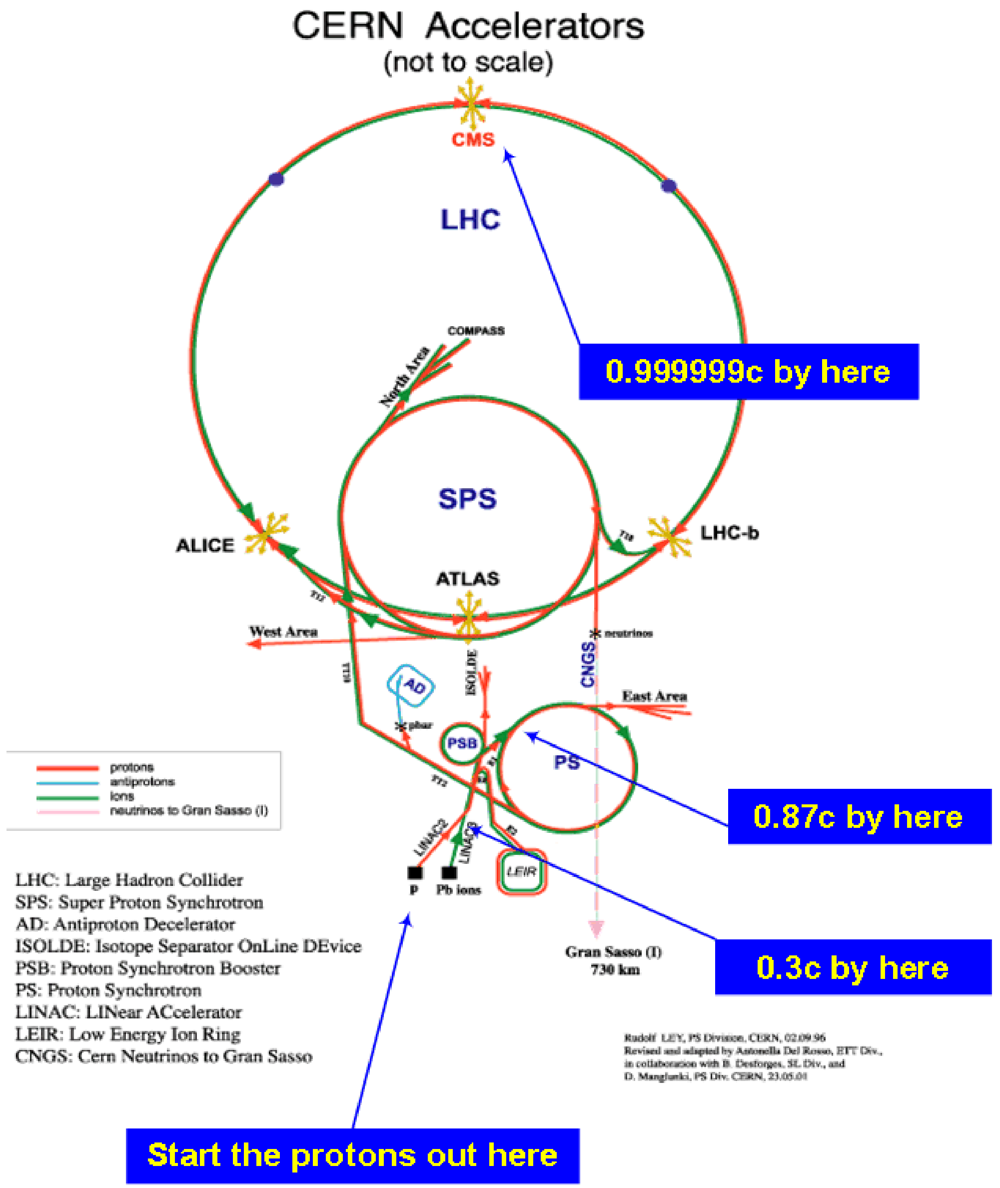
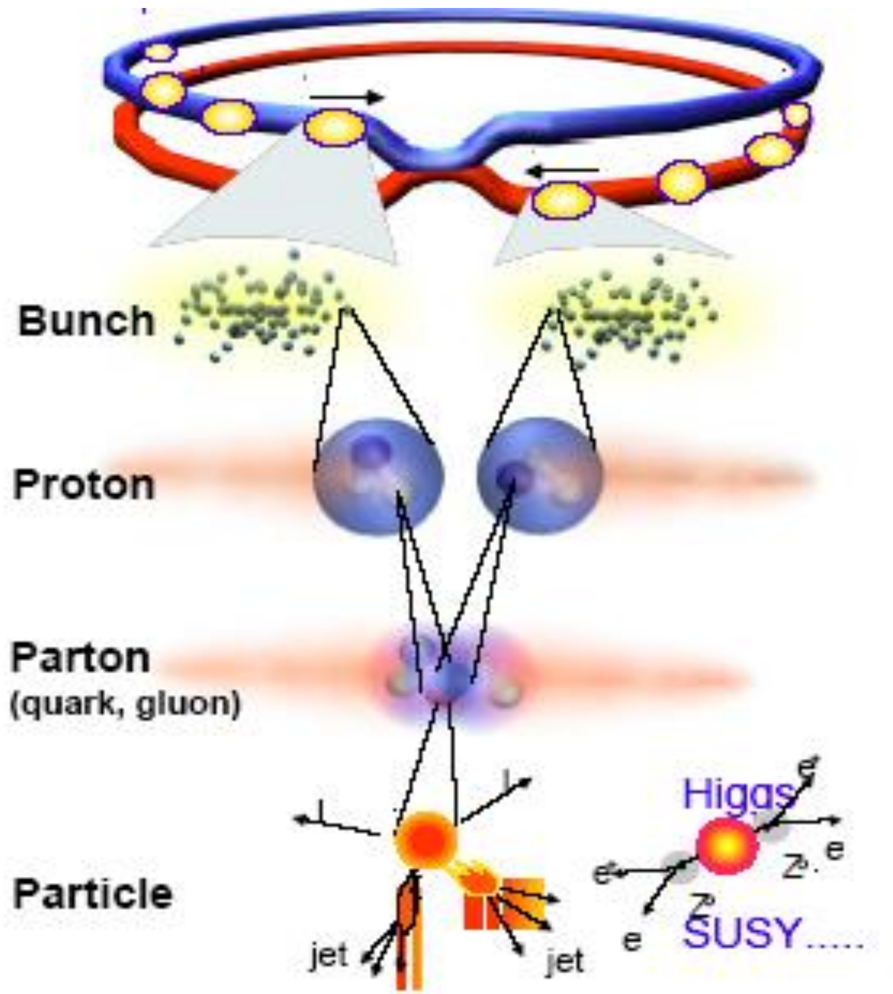
Triggering at LHC




CERN Accelerators
(not to scale)
CMS
LHC
COMPASS
North Area
SPS
ALICE
ATLAS
LHC-b
West Area
ISOLDE
CNGS
neutrinos
AD
pbar
East Area
PSB
PS
LINAC2
LINAC3
LEIR
p
Pb ions
Gran Sasso (I)
730 km
protons
antiprotons
ions
neutrinos to Gran Sasso (I)
LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso
0.999999c by here
0.87c by here
0.3c by here
Start the protons out here

Collisions



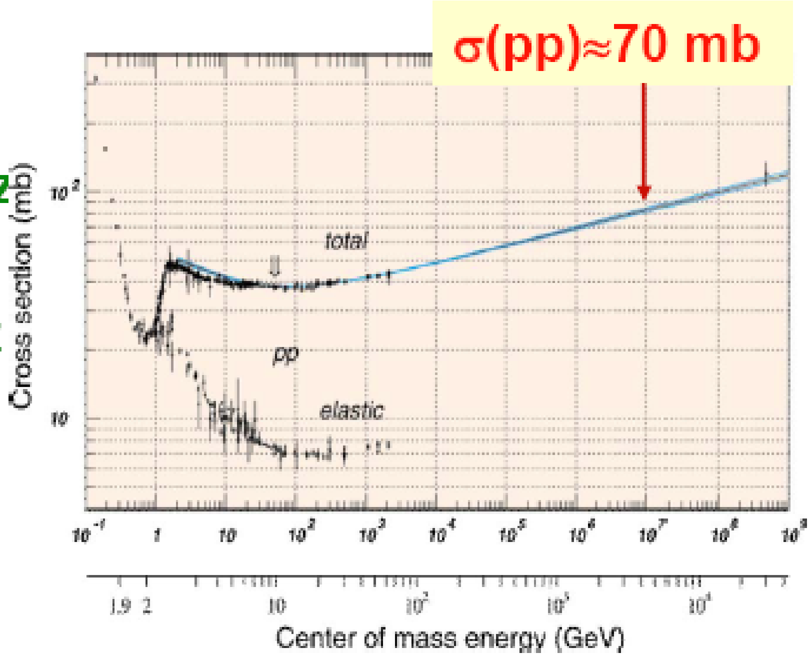
Proton - Proton	2804 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	$10^{34} cm^{-2}s^{-1}$
Crossing rate	40 MHz
Collision rate ≈	10^{7}-10^{9}

New physics rate ≈ .00001 Hz

Event selection:
1 in 10,000,000,000,000

PP Interactions

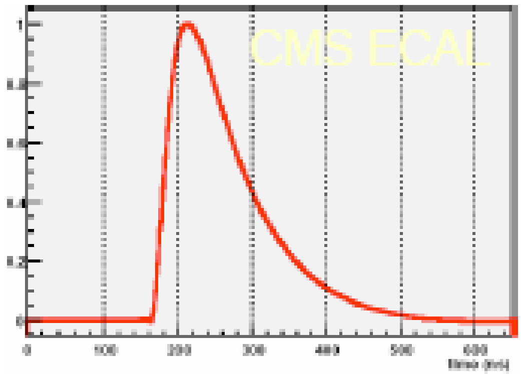
- **# of interactions/crossing:**
  - **Interactions/s:**
    - **Lum = 10^{34} $cm^{-2}s^{-1}$=$10^7 mb^{-1}Hz$**
    - **σ(pp) = 70 mb**
    - **Interaction Rate, R = $7x10^8$ Hz**
  - **Events/beam crossing:**
    - **Δt = 25 ns = $2.5x10^{-8}$ s**
    - **Interactions/crossing=17.5**
  - **Not all p bunches are full**
    - **2835 out of 3564 only**
    - **Interactions/"active" crossing = 17.5 x 3564/2835 = 23**

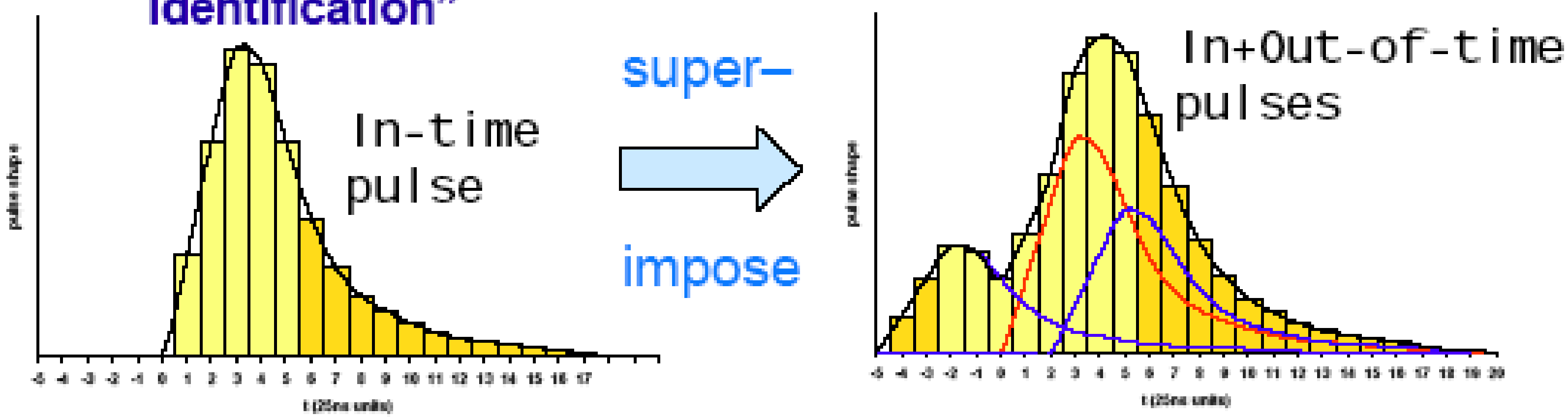


Issues

- In time pile up
- Out of time pile up
- Finite speed of particles

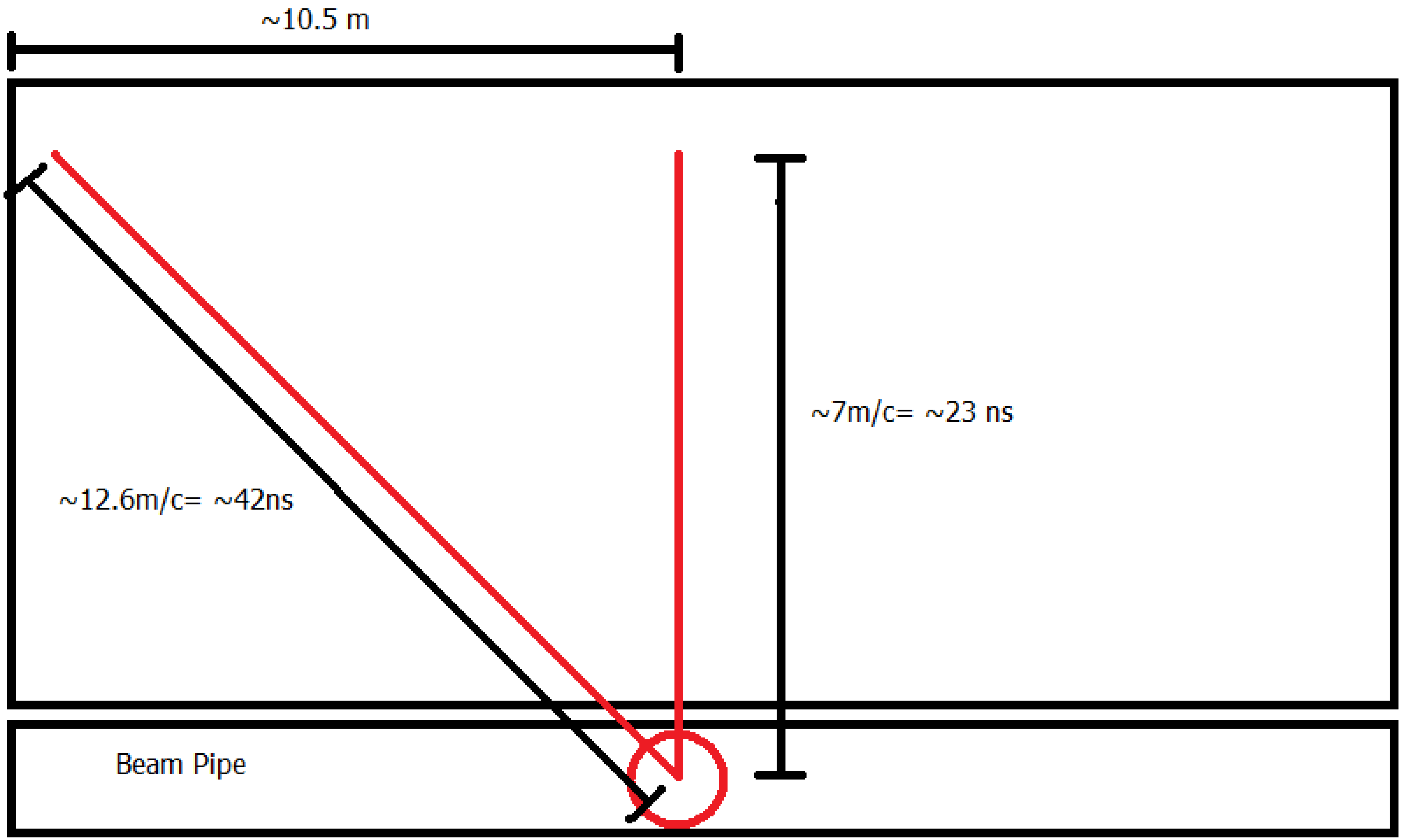
- “In-time” pile-up: particles from the same crossing but from a different pp interaction
- Long detector response/pulse shapes:
  - “Out-of-time” pile-up: left-over signals from interactions in previous crossings
  - Need “bunch-crossing identification”





Spicas

Time of Flight



Cost of Storage

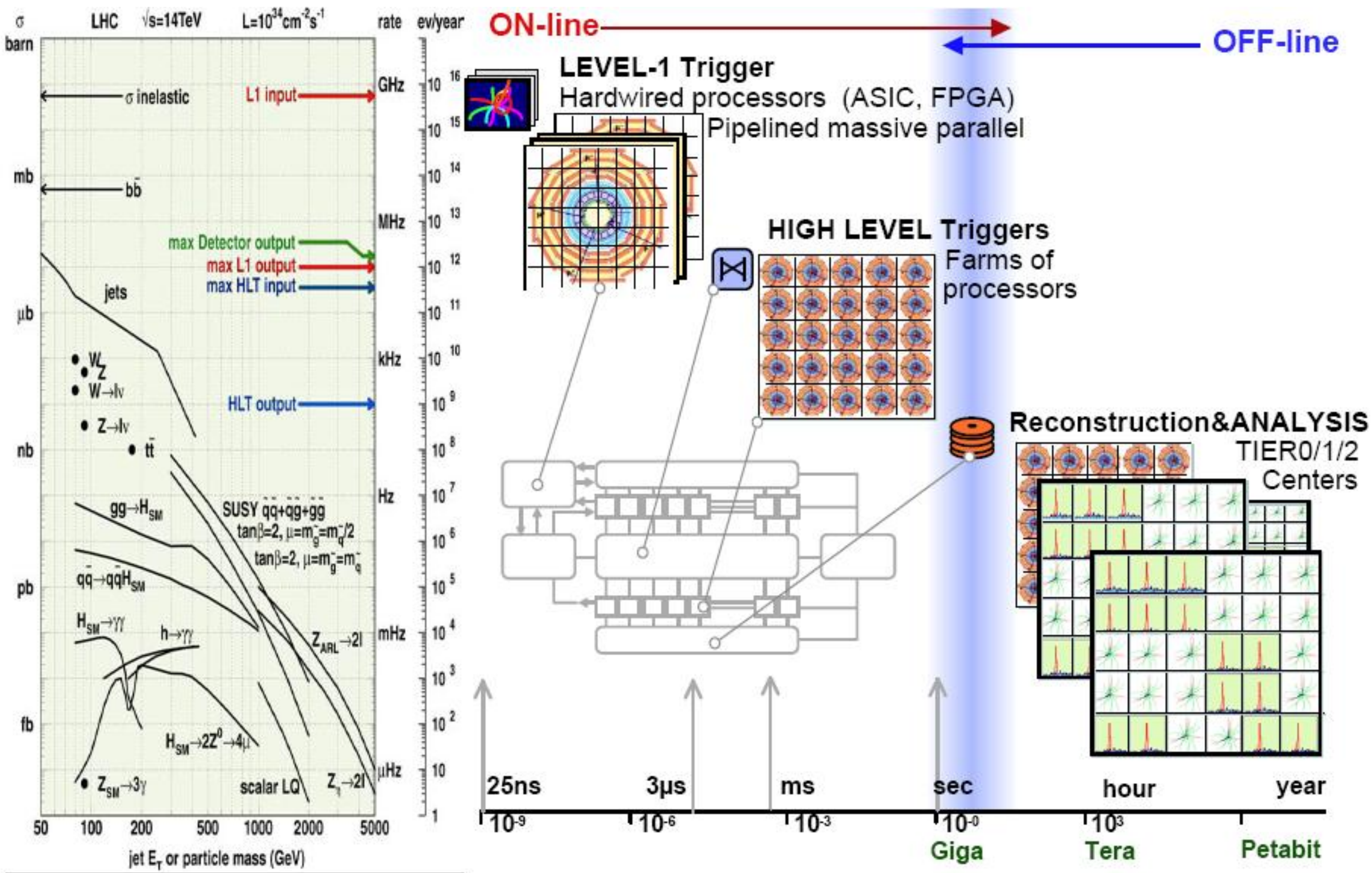
CMS outputs ~10 Pb/s of Data

Can’t store all of this on disk.

Concept of Trigger

- Mostly interested in high Pt events
- Most events are uninteresting (low Pt)
- Therefore we discard them
- Helps alleviate storage issues by removing data
- Helps alleviate previously discussed issues through parallelization and buffering

- N (channels) ~ O(10^7); ≈20 interactions every 25 ns
  - need huge number of connections
  - need information super-highway
- Calorimeter information should correspond to tracker info
  - need to synchronize detector elements to (better than) 25 ns
- In some cases: detector signal/time of flight > 25 ns
  - integrate more than one bunch crossing's worth of information
  - need to identify bunch crossing...
- Can store data at ≈ 10^2 Hz
  - need to reject most interactions
- It's On-Line (cannot go back and recover events)
  - need to monitor selection


σ barn
LHC √s=14TeV L=10^34 cm^-2 s^-1
rate ev/year
σ inelastic
L1 input
bb̄
max Detector output
max L1 output
max HLT input
jets
HLT output
W Z
W→lν
Z→lν
tt̄
gg→H_SM
SUSY q̃q̃+q̃g̃+g̃g̃
tanβ=2, μ=m_g̃=m_q̃/2
tanβ=2, μ=m_g̃=m_q̃
qq̄→qqH_SM
H_SM→γγ
h→γγ
Z_ARL→2l
H_SM→ZZ^0→4l
Z_SM→3γ
scalar LQ
Z_η→2l
mb
μb
nb
pb
fb
GHz
MHz
kHz
Hz
mHz
μHz
50 100 200 500 1000 2000 5000
jet E_T or particle mass (GeV)
ON-line
OFF-line
LEVEL-1 Trigger
Hardwired processors (ASIC, FPGA)
Pipelined massive parallel
HIGH LEVEL Triggers
Farms of processors
Reconstruction&ANALYSIS
TIER0/1/2
Centers
25ns
3μs
ms
sec
hour
year
10^-9
10^-6
10^-3
10^-0
10^3
Giga
Tera
Petabit

Spicas

Overview of Data Flow

- CMS Output ~$8*10^7$ channels.
- Assume 32 bits per number stored.
- 40 MHz collision rate.

So ~$8*10^7$ *4 bytes * 40 MHz = ~10 Pb/s

Lose about 3 orders of magnitude to 0 suppression.

Remove another 3 by triggering.

Output to of events tape is ~300Hz * 1Mb

L1 Hardware Triggers

- **Physics facts:**
  - pp collisions produce mainly hadrons with P_T~1 GeV
  - Interesting physics (old and new) has particles (leptons and hadrons) with large transverse momenta:
    - $W \rightarrow e\nu$: $M(W)=80$ GeV/c^2; $P_T(e) \sim 30\text{-}40$ GeV
    - H(120 GeV)$\rightarrow\gamma\gamma$: $P_T(\gamma) \sim 50\text{-}60$ GeV
- **Basic requirements:**
  - Impose high thresholds on particles
    - Implies distinguishing particle types; possible for electrons, muons and "jets"; beyond that, need complex algorithms
  - Typical thresholds:
    - Single muon with P_T>20 GeV (rate ~ 10 kHz)
      - → Dimuons with P_T>6 (rate ~ 1 kHz)
    - Single e/γ with P_T>30 GeV (rate ~ 10-20 kHz)
      - → Dielectrons with P_T>20 GeV (rate ~ 5 kHz)
    - Single jet with P_T>300 GeV (rate ~ 0.2-0.4 kHz)

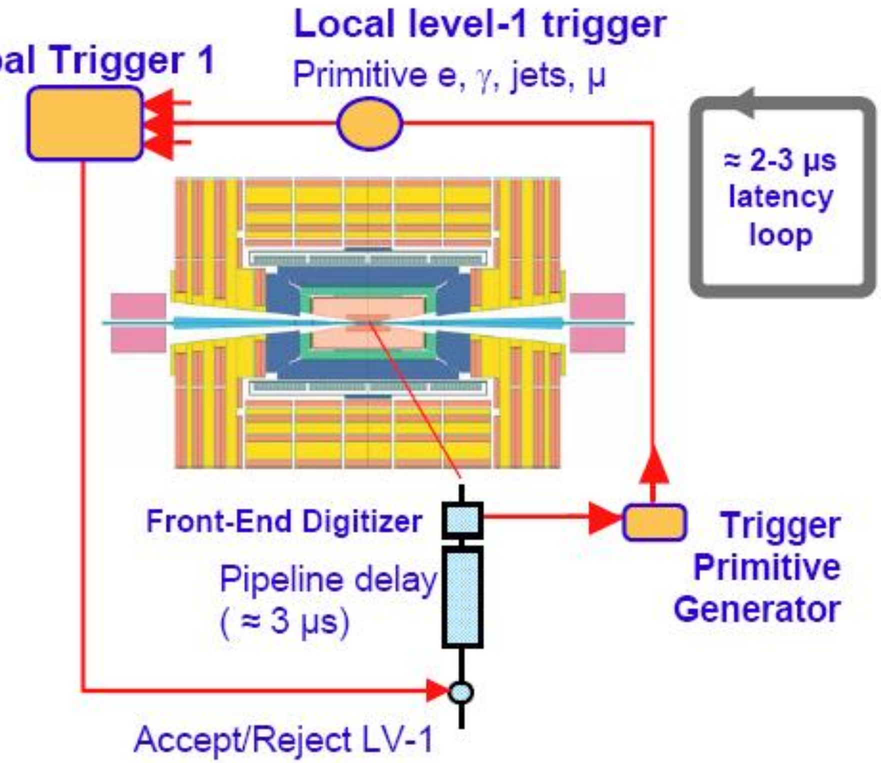
Table E.11: The Level-1 Trigger Menu at $\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ İndividual and cumulative rates are given for the different trigger paths and selected kinematic thresholds.

Trigger	Level-1 Threshold (GeV)	Level-1 Rate (kHz)	Cumulative Level-1 Rate (kHz)
Inclusive $e\,\gamma$	22	3.9 ± 0.3	3.9 ± 0.3
Double $e\,\gamma$	11	1.0 ± 0.1	4.6 ± 0.3
Inclusive μ	14	2.5 ± 0.2	7.1 ± 0.3
Double μ	3	4.0 ± 0.3	11.0 ± 0.4
Inclusive τ	100	2.2 ± 0.2	12.9 ± 0.5
Double τ	60	3.0 ± 0.2	14.9 ± 0.5
1-,2-,3-,4-jets	150,100,70,50	2.2 ± 0.2	15.8 ± 0.5
H_{T}	275	2.0 ± 0.2	16.2 ± 0.5
$E_{\mathrm{T}}^{\mathrm{miss}}$	60	0.4 ± 0.1	16.3 ± 0.5
H_{T} + $E_{\mathrm{T}}^{\mathrm{miss}}$	200, 40	1.1 ± 0.1	16.6 ± 0.5
jet + $E_{\mathrm{T}}^{\mathrm{miss}}$	100, 40	1.1 ± 0.1	16.7 ± 0.5
τ + $E_{\mathrm{T}}^{\mathrm{miss}}$	60, 40	2.7 ± 0.2	18.8 ± 0.5
μ + $E_{\mathrm{T}}^{\mathrm{miss}}$	5, 30	0.3 ± 0.1	19.0 ± 0.6
$e\,\gamma$ + $E_{\mathrm{T}}^{\mathrm{miss}}$	15, 30	0.5 ± 0.1	19.1 ± 0.6
μ + jet	7, 100	0.2 ± 0.1	19.1 ± 0.6
$e\,\gamma$ + jet	15, 100	0.6 ± 0.1	19.2 ± 0.6
$\mu + \tau$	7, 40	1.2 ± 0.1	19.8 ± 0.6
$e\,\gamma + \tau$	15, 60	2.6 ± 0.2	20.5 ± 0.6
$e\,\gamma + \mu$	15, 7	0.2 ± 0.1	20.5 ± 0.6
Prescaled			22.3 ± 0.6
Total Level-1 Rate			22.3 ± 0.6

Combining Triggers/Readout

- Each Element (Silicon, Ecal, ect) must read out full event data.
- Data continues to flow down a series of parallel pipes.
- Trigger for each element stored as logic bit and enters global logic circuits.
- If event selected, then data from event is sent on to HLT.

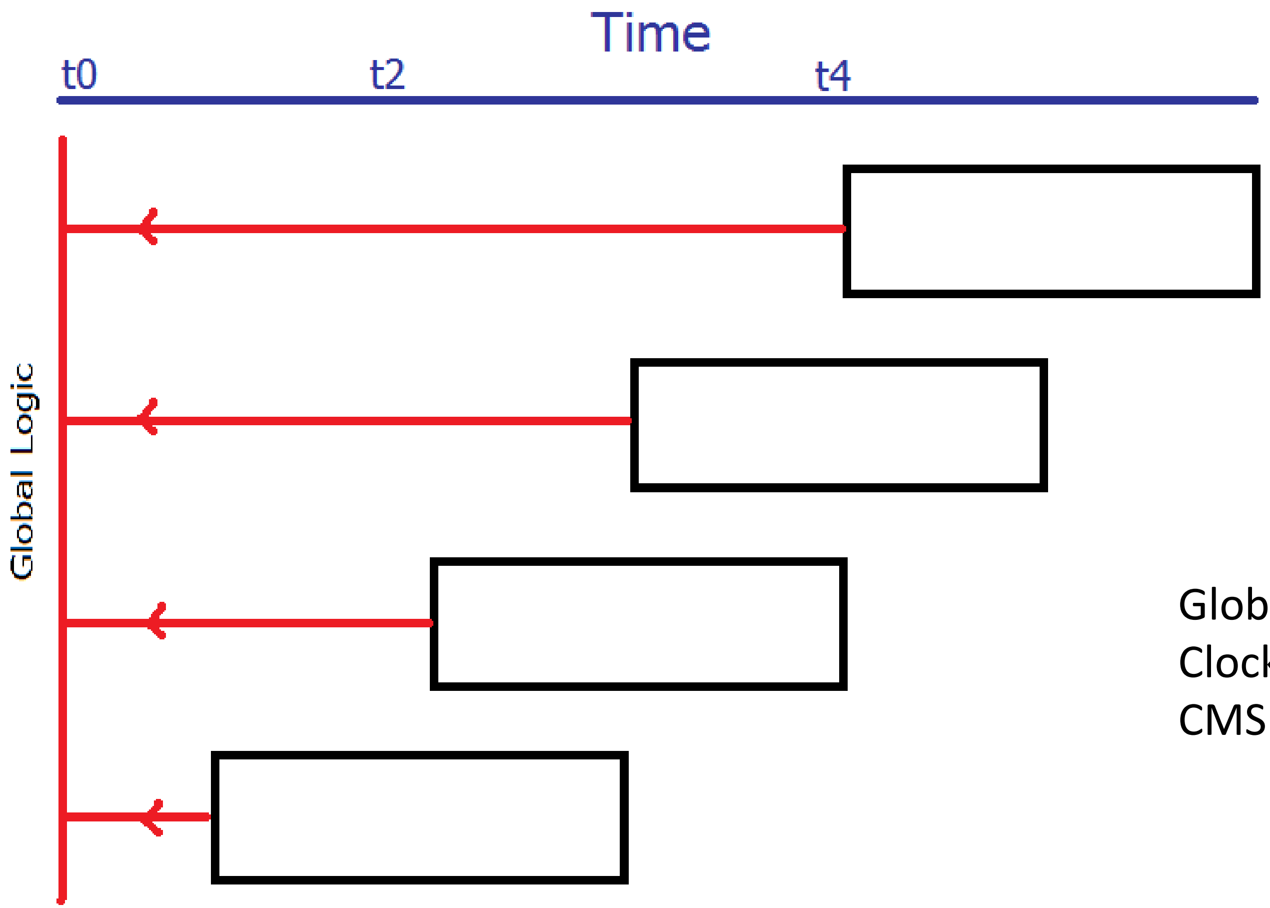
- **Synchronous 40 MHz digital system**
  - Typical: 160 MHz internal pipeline
  - Latencies:
    - Readout + processing: < 1μs
    - Signal collection & distribution: ≈ 2μs
- **At Lvl-1: process only calo+μ info**



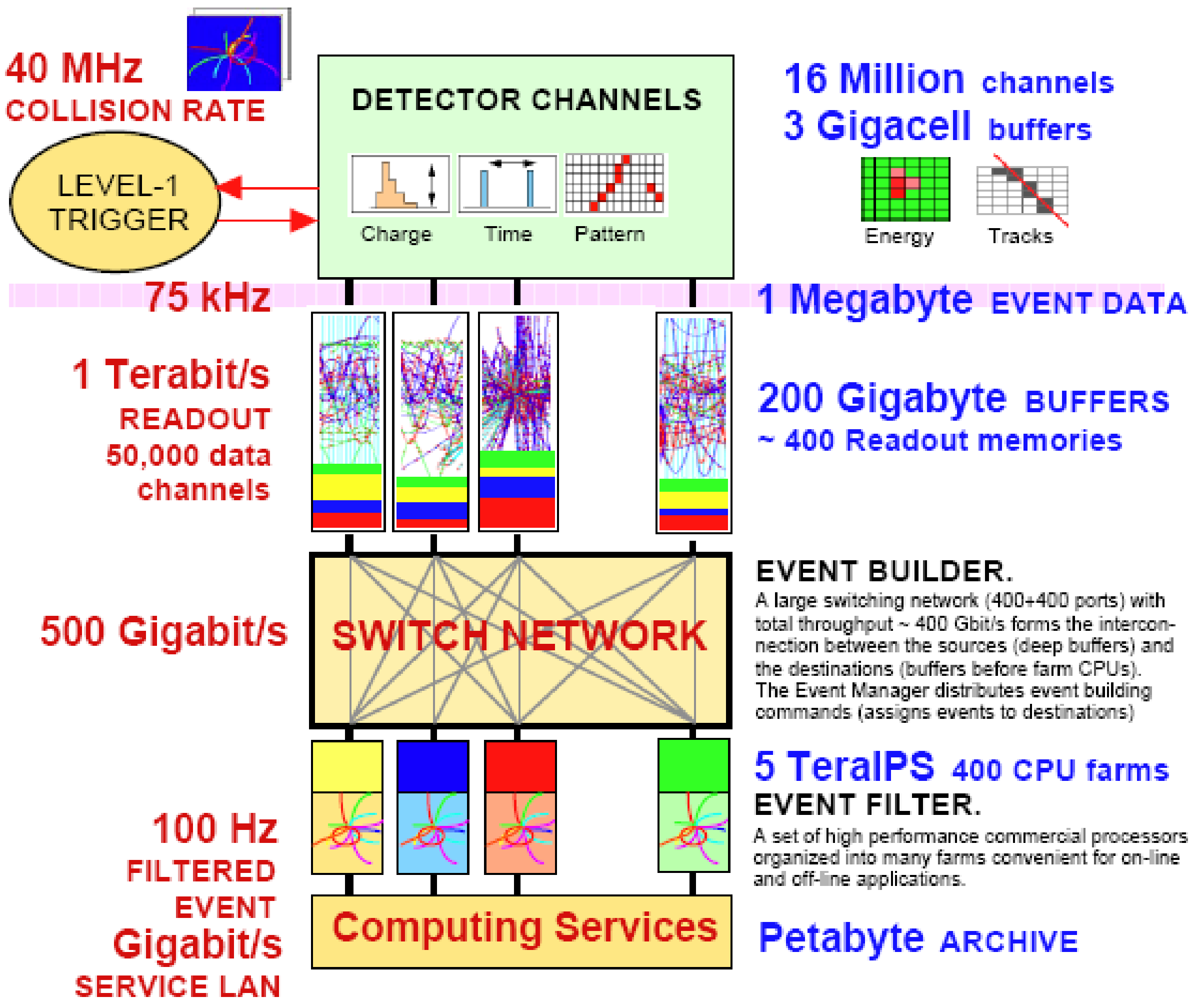
- A very large OR-AND network that allows for the specification of complex conditions:
  - 1 electron with P_T>20 GeV OR 2 electrons with P_T>14 GeV OR 1 electron with P_T>16 and one jet with P_T>40 GeV…
  - The top-level logic requirements (e.g. 2 electrons) constitute the "trigger-table" of the experiment
    - Allocating this rate is a complex process that involves the optimization of physics efficiencies vs backgrounds, rates and machine conditions

      → More on this in the HLT part

DAQ/Buffers

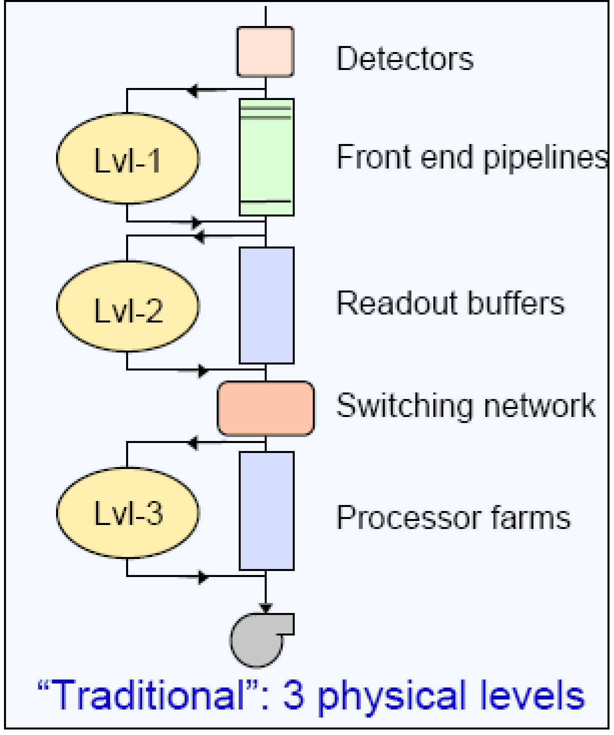


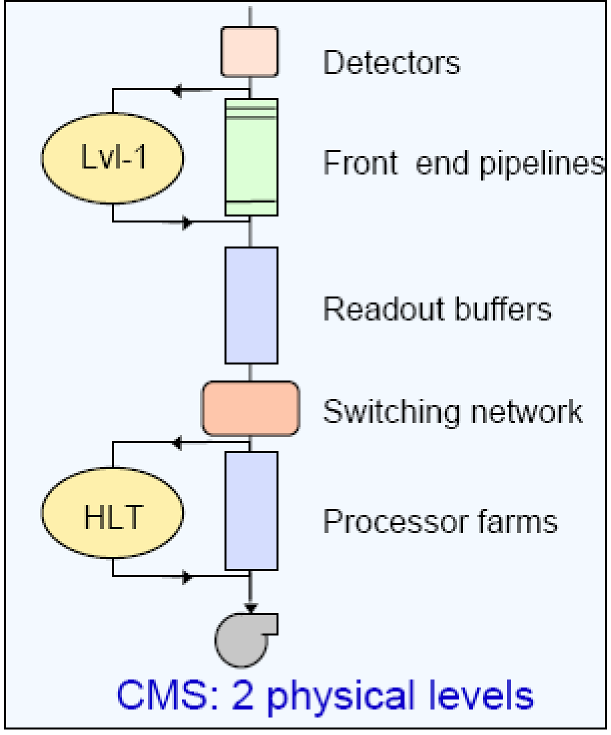
Global Logic
Clocked to 25 ns
CMS timing.


40 MHz
COLLISION RATE
LEVEL-1
TRIGGER
DETECTOR CHANNELS
Charge
Time
Pattern
16 Million channels
3 Gigacell buffers
Energy
Tracks
75 kHz
1 Megabyte EVENT DATA
1 Terabit/s
READOUT
50,000 data
channels
200 Gigabyte BUFFERS
~ 400 Readout memories
500 Gigabit/s
SWITCH NETWORK
EVENT BUILDER.
A large switching network (400+400 ports) with total throughput ~ 400 Gbit/s forms the interconnection between the sources (deep buffers) and the destinations (buffers before farm CPUs).
The Event Manager distributes event building commands (assigns events to destinations)
5 TeraIPS 400 CPU farms
EVENT FILTER.
A set of high performance commercial processors organized into many farms convenient for on-line and off-line applications.
100 Hz
FILTERED
EVENT
Gigabit/s
SERVICE LAN
Computing Services
Petabyte ARCHIVE

L2 Trigger

- **Level-1 trigger: reduce 40 MHz to 10^5 Hz**
  - **This step is always there**
  - **Upstream: still need to get to 10^2 Hz; in 1 or 2 extra steps**





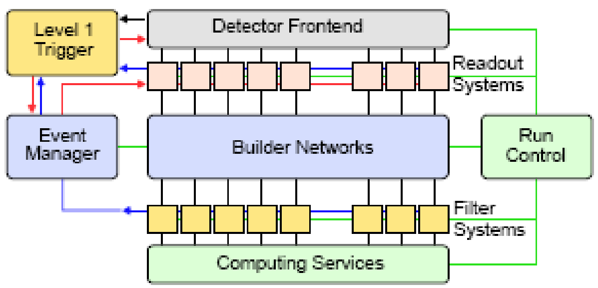
High Level Trigger (CMS)/ L3 Trigger (ATLESS has more?)

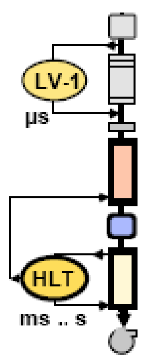
- Two solutions:
  - Decrease rate by using a Level-2 farm (ATLAS)
    - → Thus, two farms: a Level-2 and Level-3 farm
  - Build a system that can do 800 Gb/s (CMS)
    - → Thus, a single farm

Remember, the detector designs for Atlas were finalized over 10 years ago. Although relying on predictions of Moore's Law and other advances in technology, ATLAS took a conservative approach and did not want to rely on being able to handle the bandwidth at the cpu farm level.

CMS started a little later and took a less conservative approach…

CMS



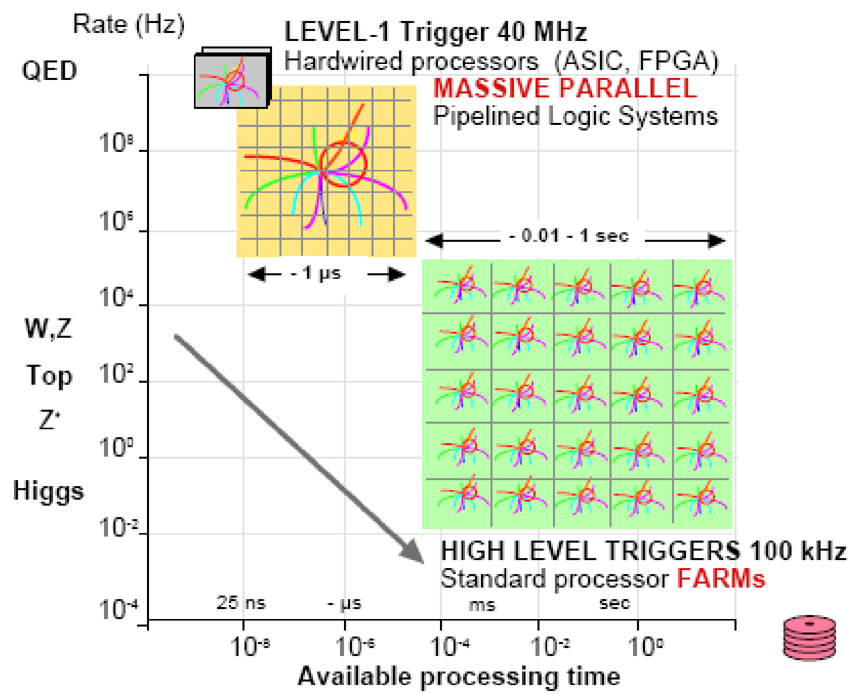


40 MHz

10^5 Hz

1000 Gb/s

10^2 Hz



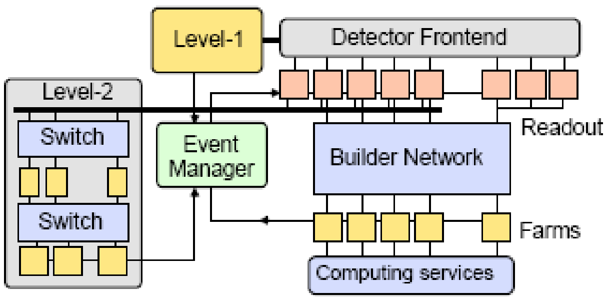
- Reduce number of building blocks
- Rely on commercial components (especially processing and communications)

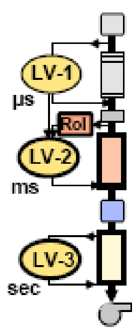
Table E.8: Comparison of HLT bandwidth given to various trigger paths calculated in this study with the DAQ TDR. See text for details on different kinematic cuts and changes in the HLT algorithms.

Trigger	DAQ TDR Rate (Hz)	New Rate (Hz)
Inclusive e	33.0	23.5 ± 6.7
e-e	1.0	1.0 ± 0.1
Relaxed e-e	1.0	1.3 ± 0.1
Inclusive γ	4.0	3.1 ± 0.2
γ-γ	5.0	1.6 ± 0.7
Relaxed γ-γ	5.0	1.2 ± 0.6
Inclusive μ	25.0	25.8 ± 0.8
μ-μ	4.0	4.8 ± 0.4
τ + $E_{\mathrm{T}}^{\mathrm{miss}}$	1.0	0.5 ± 0.1
τ + e	2.0	< 1.0
Double Pixel τ	1.0	4.1 ± 1.1
Double Tracker τ	1.0	6.0 ± 1.1
Single jet	1.0	4.8 ± 0.0
Triple jet	1.0	1.1 ± 0.0
Quadruple jet	7.0	8.9 ± 0.2
jet + $E_{\mathrm{T}}^{\mathrm{miss}}$	5.0	3.2 ± 0.1
b-jet (leading jet)	5.0	10.3 ± 0.3
b-jet (2^{nd} leading jet)	5.0	8.7 ± 0.3

ATLAS

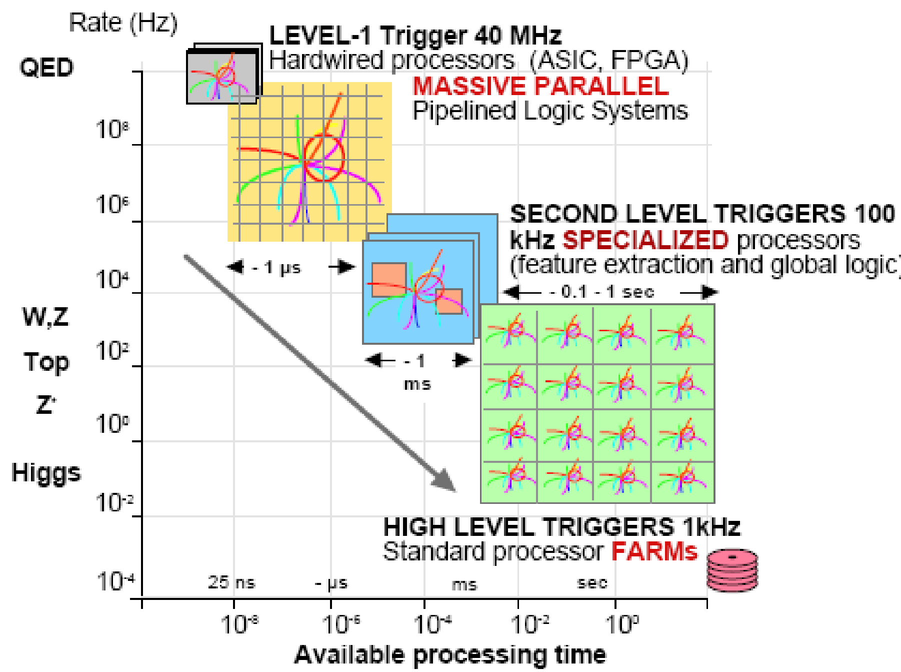
- **Additional processing in LV-2: reduce network bandwidth requirements**





40 MHz
10^5 Hz
10^3 Hz
10 Gb/s

10^2 Hz



Output

The output rate is ~300 Hz

Output event size is ~1 Mb

The size of each event is made as compact as possible while preserving information.

Output rate will can be increased in software as cost of storage goes down.

Citations

Primary

- Paris Spicas Presentation
- Frank Wuerthwein Presentation

Secondary (good reading but not directly used in this presentation)

- "Triggering at Hadron Colliders." Brooijmans, Gustaaf
- "Triggering at CMS." Smith, Wesley
- CMS TDR