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# Trigger, DAQ and FPGAs

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Slides available at:

http://www.hep.ph.ic.ac.uk/~tapper/lecture.html

# Overview

Lectures on how data gets from the detector onto disk (examples from CMS)

- Trigger  - decide which collisions yielded something interesting
- Data Acquisition System - how you get all the signals from the detector
- FPGAs - fast, programmable digital electronics

# Introduction

- Aim - gentle overview - not too much detail

- Outline

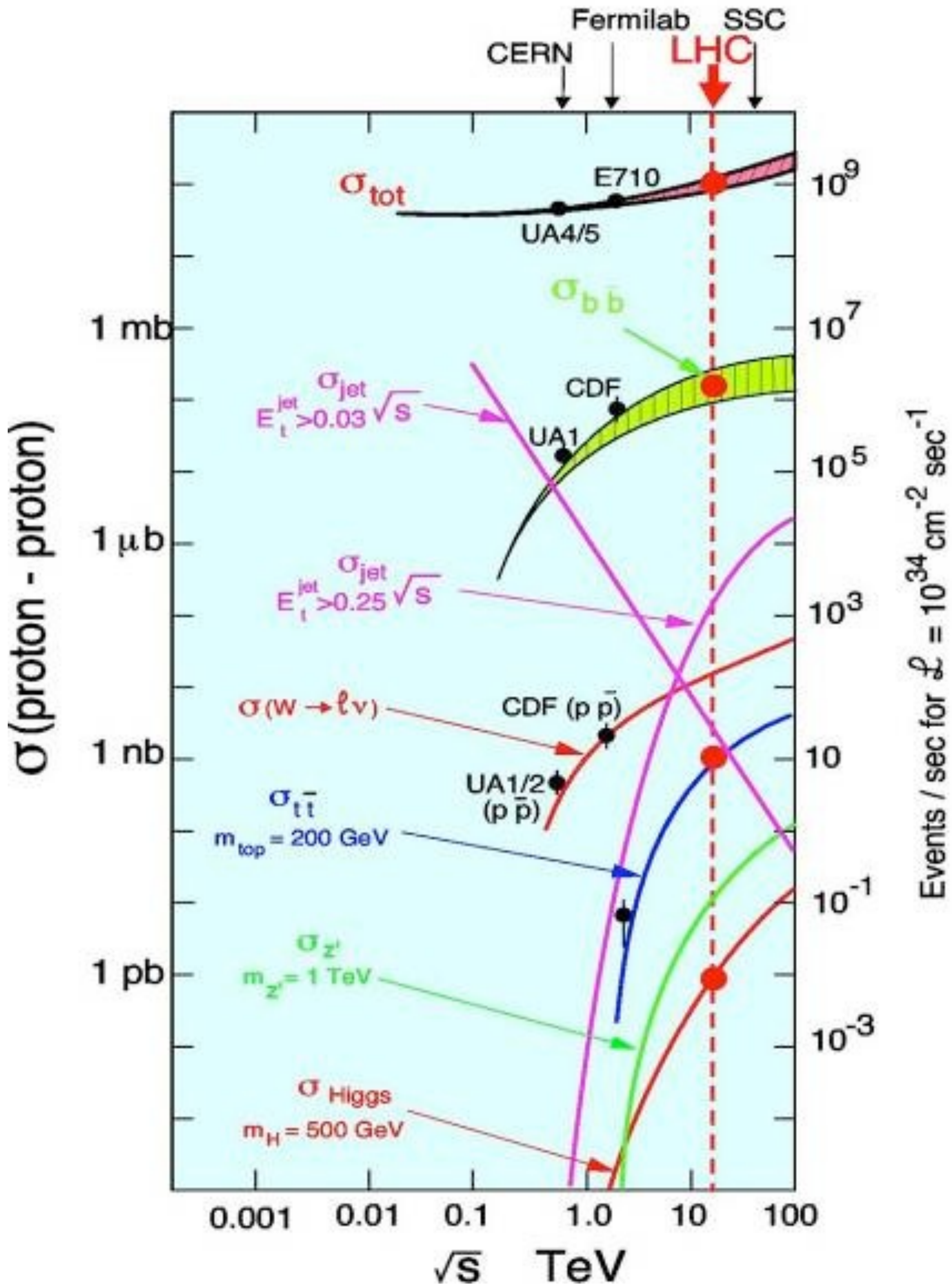
  – Motivation and some important concepts
  – Historical overview highlighting how challenges have driven development in the past
  – Case study: CMS
  – Practical advice (!)

# Introduction

- Further reading and disclaimers
  - For details (rates, bandwidths anything with numbers basically) read Ricardo's ATLAS trigger seminar
    - http://www.pp.rhul.ac.uk/~goncalo/scratch/talks/talks.html
  - For HL-LHC and more on CMS commissioning
    - http://www.hep.ph.imperial.ac.uk/~tapper/talks/Imperial-CMS-Trigger-09.pdf
  - For upgrade to CMS trigger
    - https://cds.cern.ch/record/1556311
  - Apologies in advance for bias towards collider experiments
  - I will say nothing about what happens after you decide to keep an event

# What and why?

- Enormous data rate:
  - 40 MHz * 1-2 MB
  - > 60 TB/s
  - Can't write this to tape!
- Just throw away events randomly?
  - Tiny cross sections for Higgs and new physics
  - Selection 1:$10^{11}$
- All online
  - Can't go back and fix it.
  - Don't screw up!



# Challenges and constraints

- Constraints on trigger come from
  - Accelerator: Bunch crossing rate, pile-up and multiple interactions, beam-gas interactions
  - Physics: What is required to make the decision to keep or reject an event? Simple objects like electrons and jets, track finding, matching objects together....
  - Output: How much data can you write to tape? How much can you reconstruct at an acceptable rate?

# Some important definitions

- Good trigger will capture it's design physics and anything unexpected and reject common processes
- Deadtime
  - Trigger is not live for some reason so cannot take data
- Prescaling (downscaling)
  - Take every nth event that fires your trigger
  - Adjust n to allowed bandwidth
- Pass-through events (mark and pass)
  - Randomly select an event and allow it to pass the trigger regardless of any criteria
  - Useful to study and validate trigger systems

# History…

# The first trigger?

- Blackett pioneered a technique to trigger the camera of cloud chambers (and got the Nobel prize for this and other work)
- Just missed out on discovering the positron in 1932
- Stevenson and Street used this to confirm the discovery of the muon in 1937
- Can measure momentum and ionisation (~$1/\beta^2$)
- Derive mass of particle - not electron or proton

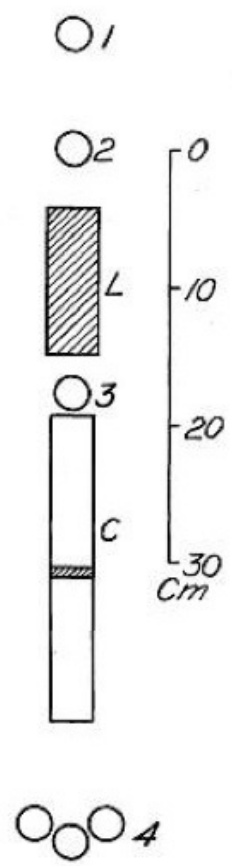


FIG. 1. Geometrical arrangement of apparatus.

# Bubble chambers

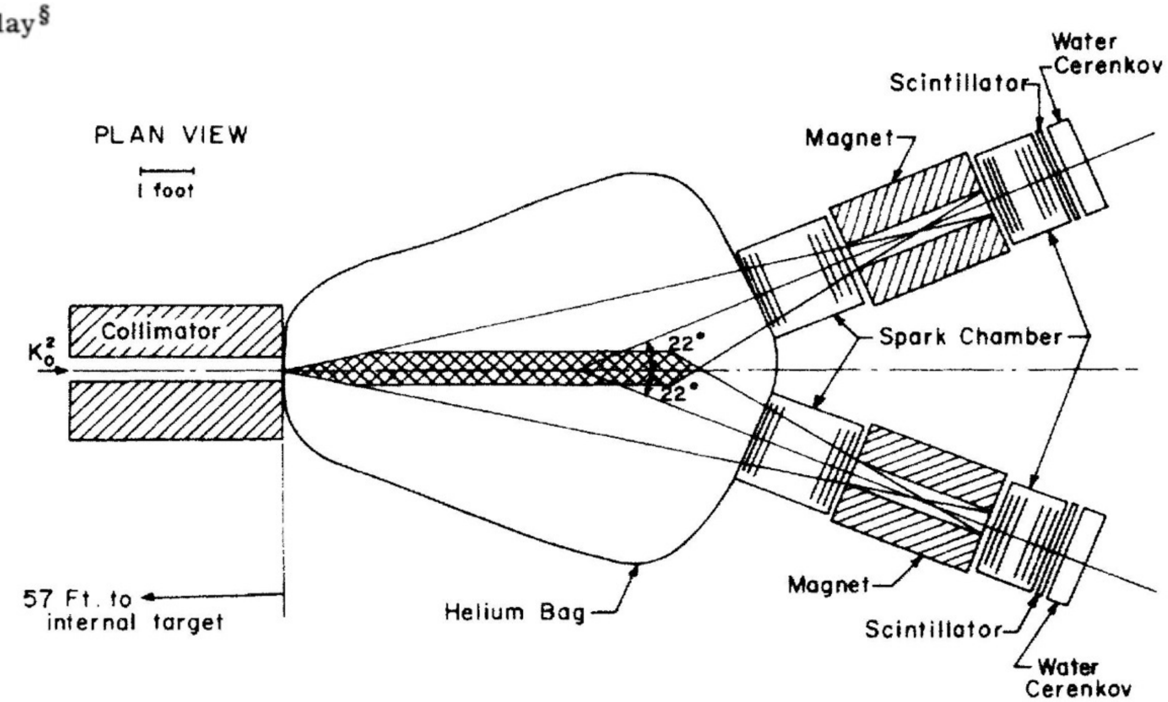
- Accelerator gave a low-level trigger
  - Each expansion photographed
- DAQ was photographs
- Offline selection was human (looking at photographs)
- Only the most common processes observed
- Need to scan a huge number of photographs

# Fixed-target experiments

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2$\pi$ DECAY OF THE $K_2^0$ MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)




- Real physics triggers around in the ‘60s
- Discovery of CP violation
- Experiment triggered on coincidence of scintillators and Cerenkov detectors
- Small effect that they would not have seen otherwise ($10^{-3}$)
- High dead time while detectors read out

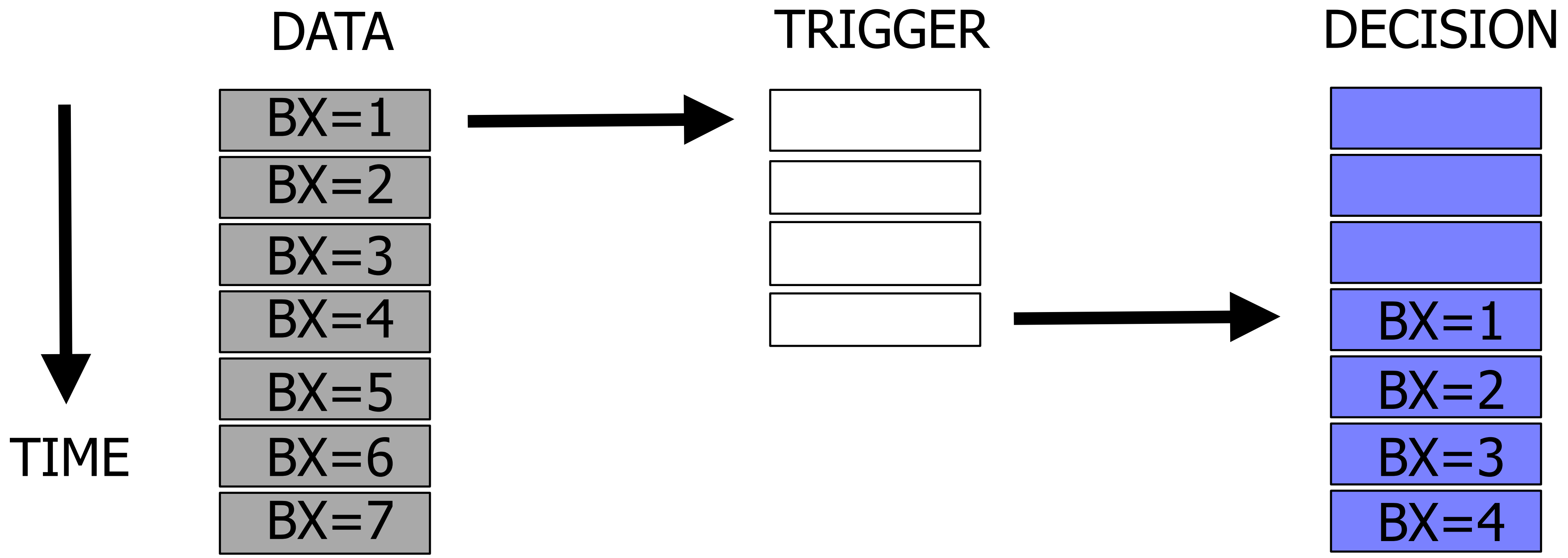
# HERA



- 1992 - 2007
- Crossing rate 10 MHz (96 ns) very challenging
- Dominated by beam-gas interactions
- First use of pipelined trigger logic →

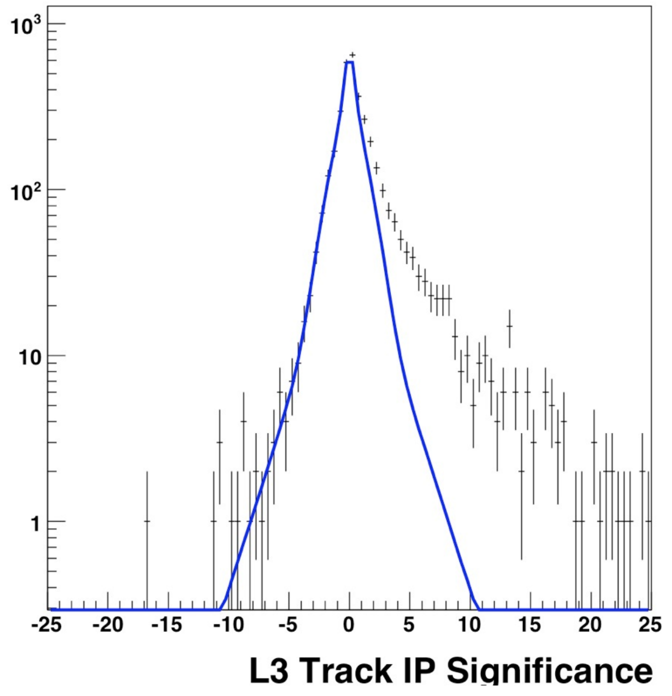
# Pipelined trigger logic

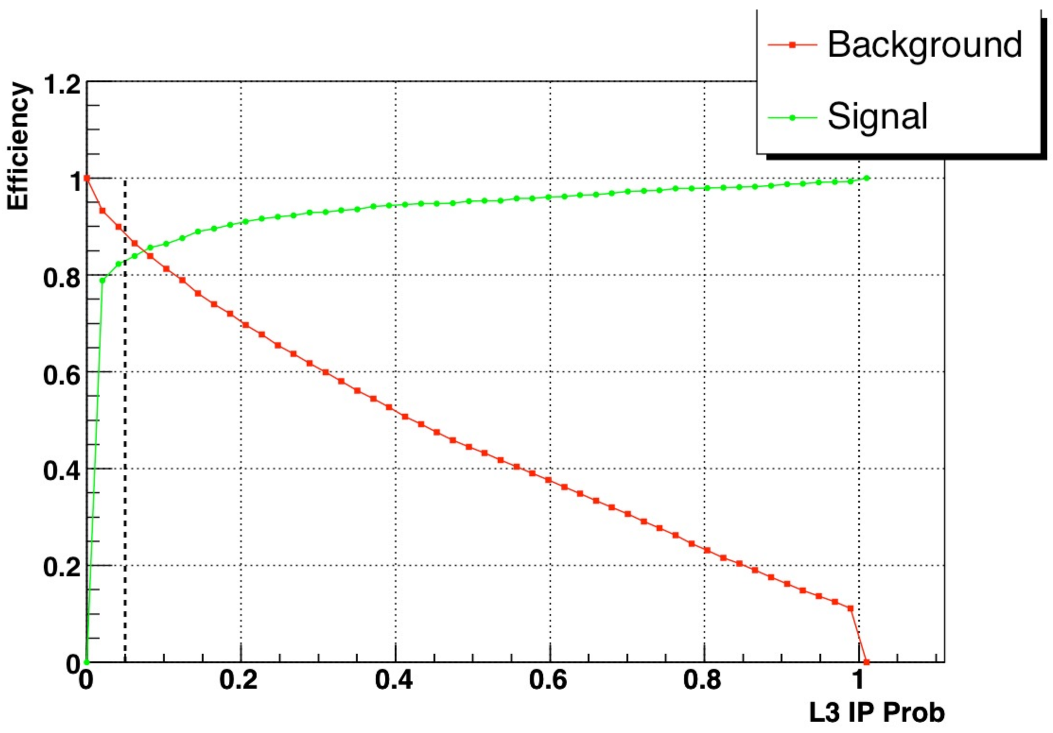
- Data stored in detector front-end pipeline
  - Pipelines deep enough for X BXs where X can be 100s
- Trigger analyses data and makes decision
- Decision used to signal readout or not
- Must give decision every BX to be dead time free
- Must have fixed latency (no iterative algorithms)



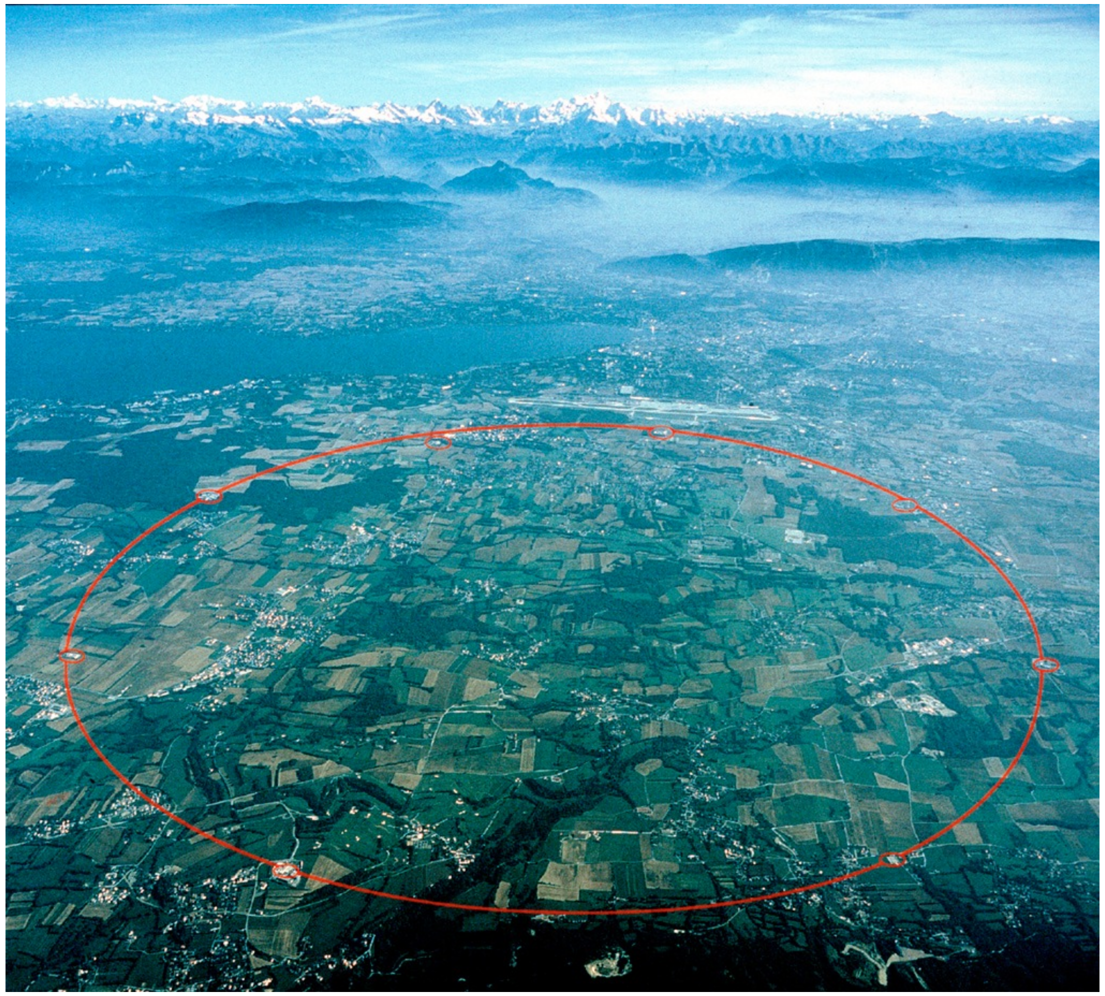
# Tevatron and tracking triggers

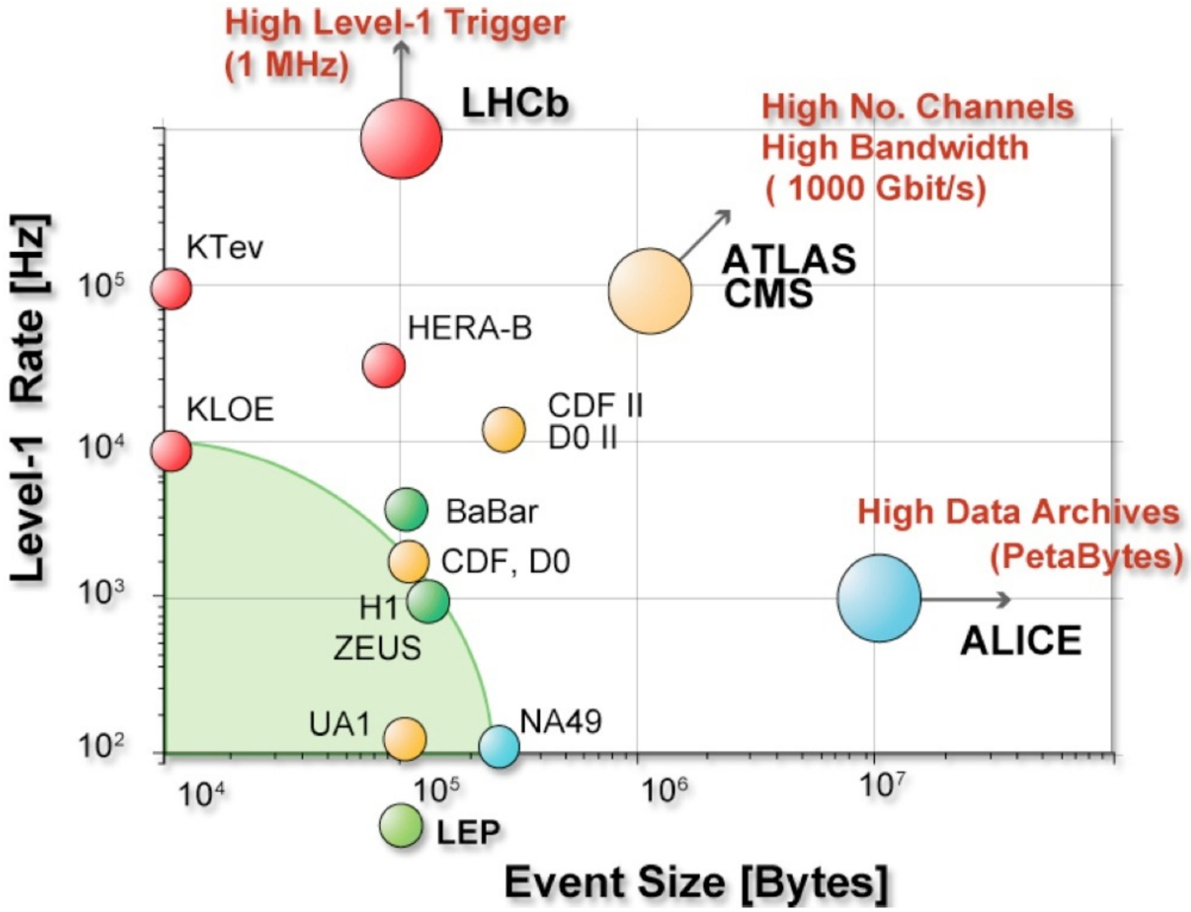
- Bunch spacing 396 ns
- Not as challenging as other colliders
- Challenge is to trigger B physics at an acceptable rate
- Huge amount of work went into developing tracking triggers
- Impact parameter Level 3 (software) trigger to select events with long-lived particles
- Developed at Imperial
- LHCb now use Boosted Decision Trees extensively



# The LHC experiments



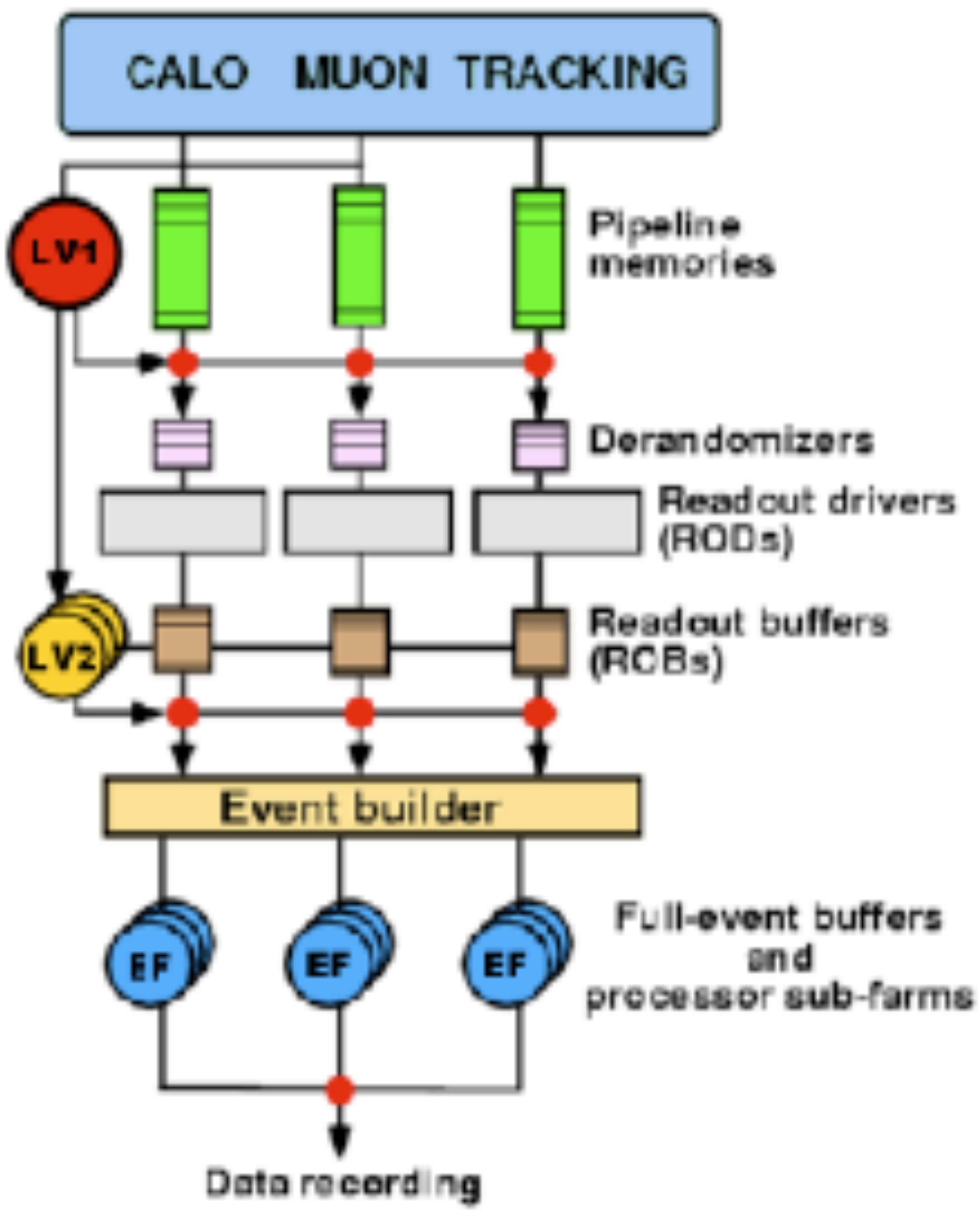




- Bigger detectors
- 40 MHz crossing rate

  → order of magnitude more challenging

# Typical trigger design




- Three levels
- Level 1: hardware and firmware
  - Cannot keep up with bunch crossing rate
  - Pipelined and dead-timeless
- Level 2: composite of hardware and software
  - Can have hardware pre-processing
  - Can be regional processing
- Level 3: software
  - Farms of PCs
  - Full detector information
  - Close to offline algorithms

# FPGAs


- FPGAs have been around in trigger systems for a while
- Latest large FPGAs give a huge amount of flexibility and are used in the LHC experiments
- Revolutionised trigger systems since the logic (algorithms) do not need to be fixed when the board is produced
- Can change the algorithms running in hardware, in light of better detector understanding, even physics discoveries
- Much more detail from Andrew

# Hardware algorithms

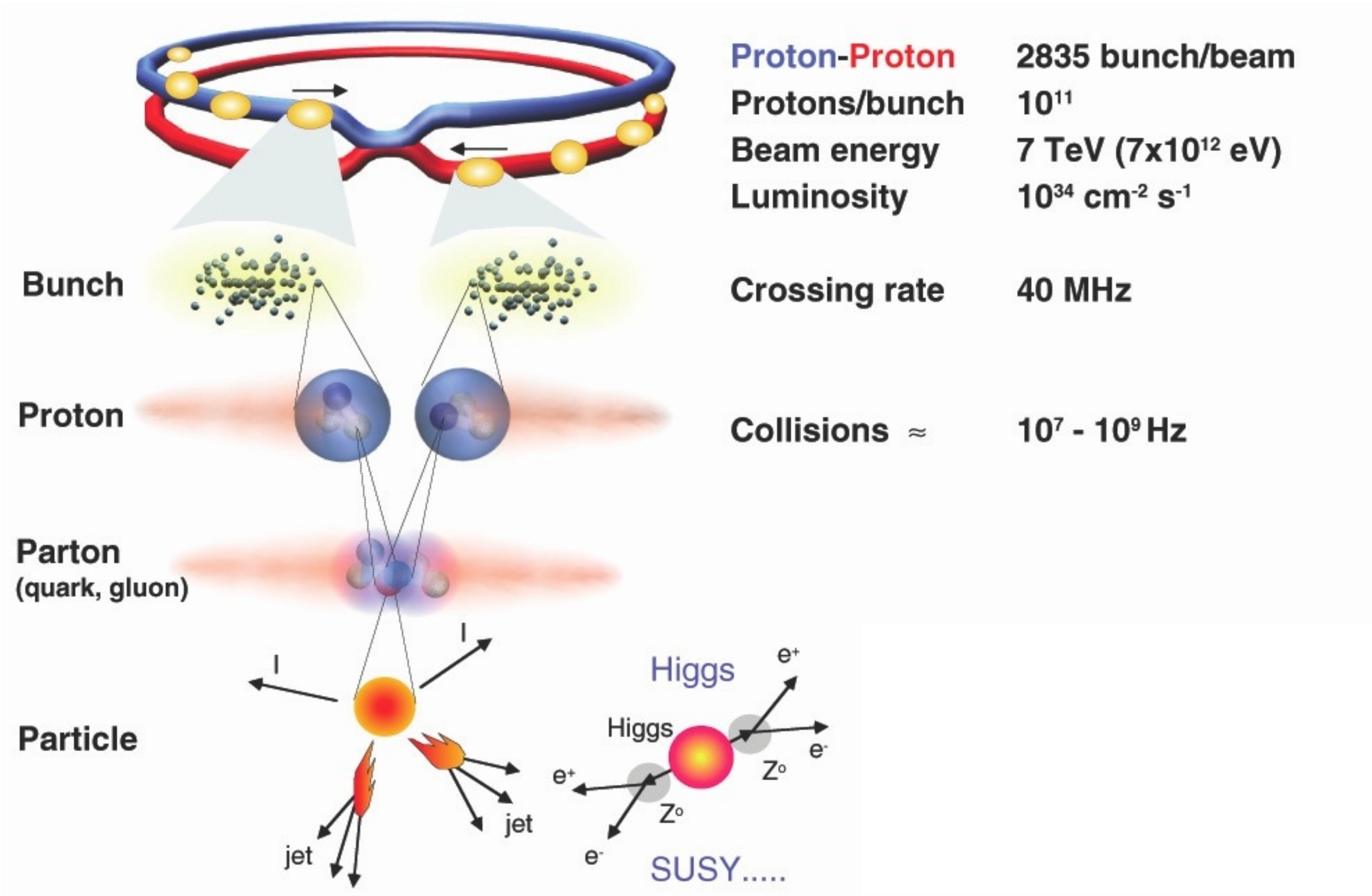
- Hardware is well suited to simple questions
- Cut out simple high-rate backgrounds
  - QCD at Tevatron and LHC
  - Beam-gas at HERA
- Capabilities are limited
  - Can extract objects like electrons, jets etc.
  - Can match and correlate these objects
- High speed and dead-timeless
- More difficult to modify algorithms
- Possible algorithms tied to detector geometry

# Software triggers and algorithms

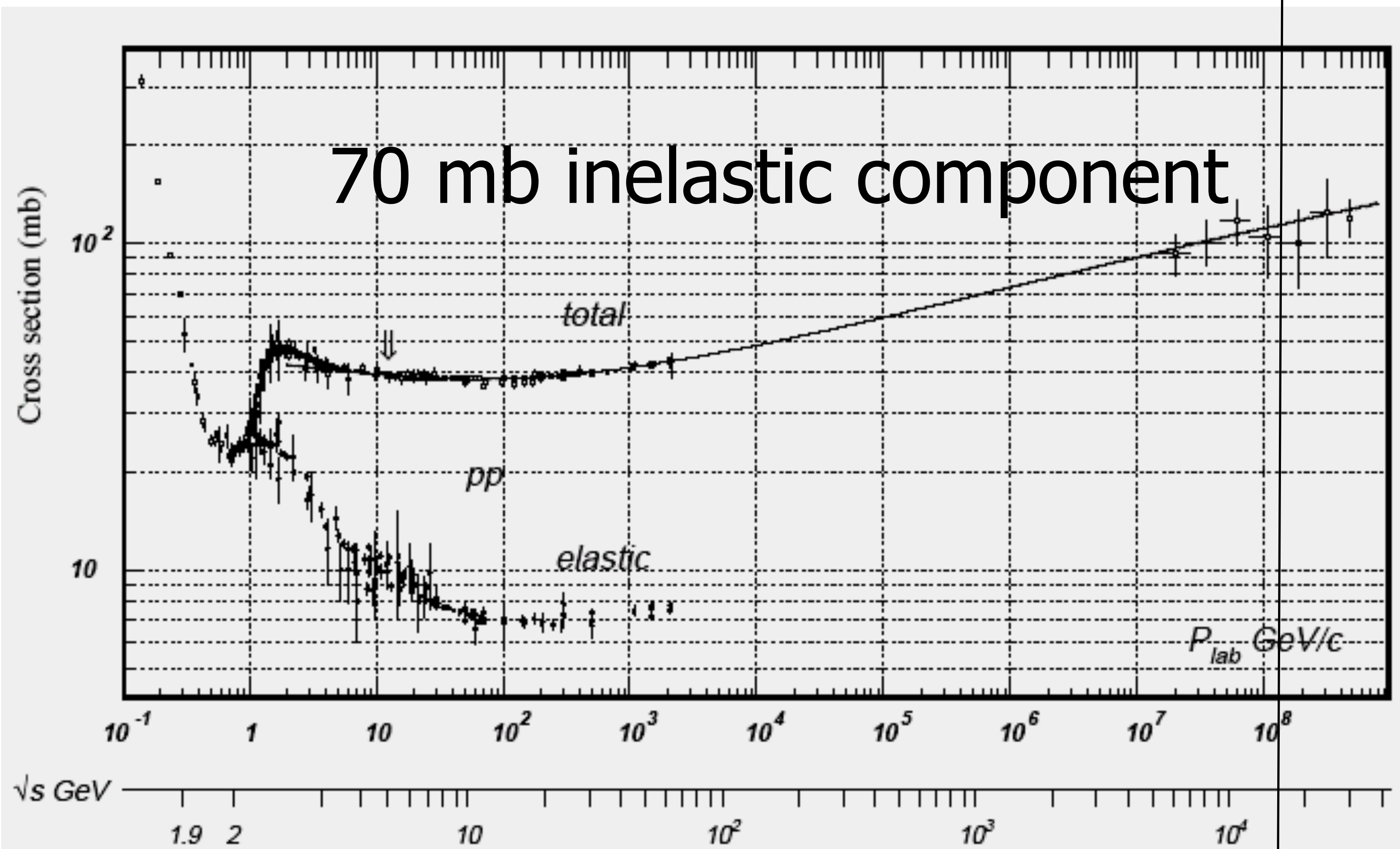
- Hardware not well suited to complex algorithms with data from different detectors
- Track and vertex finding for example
  - Loop over hits and search
  - Iterative algorithms
- Software triggers are well suited to complex algorithms where full granularity data from the whole detector is necessary
- Higher level triggers are farms of PCs
- Distributed systems can have 1000s of nodes to be controlled

# CMS and the LHC

# The Large Hadron Collider



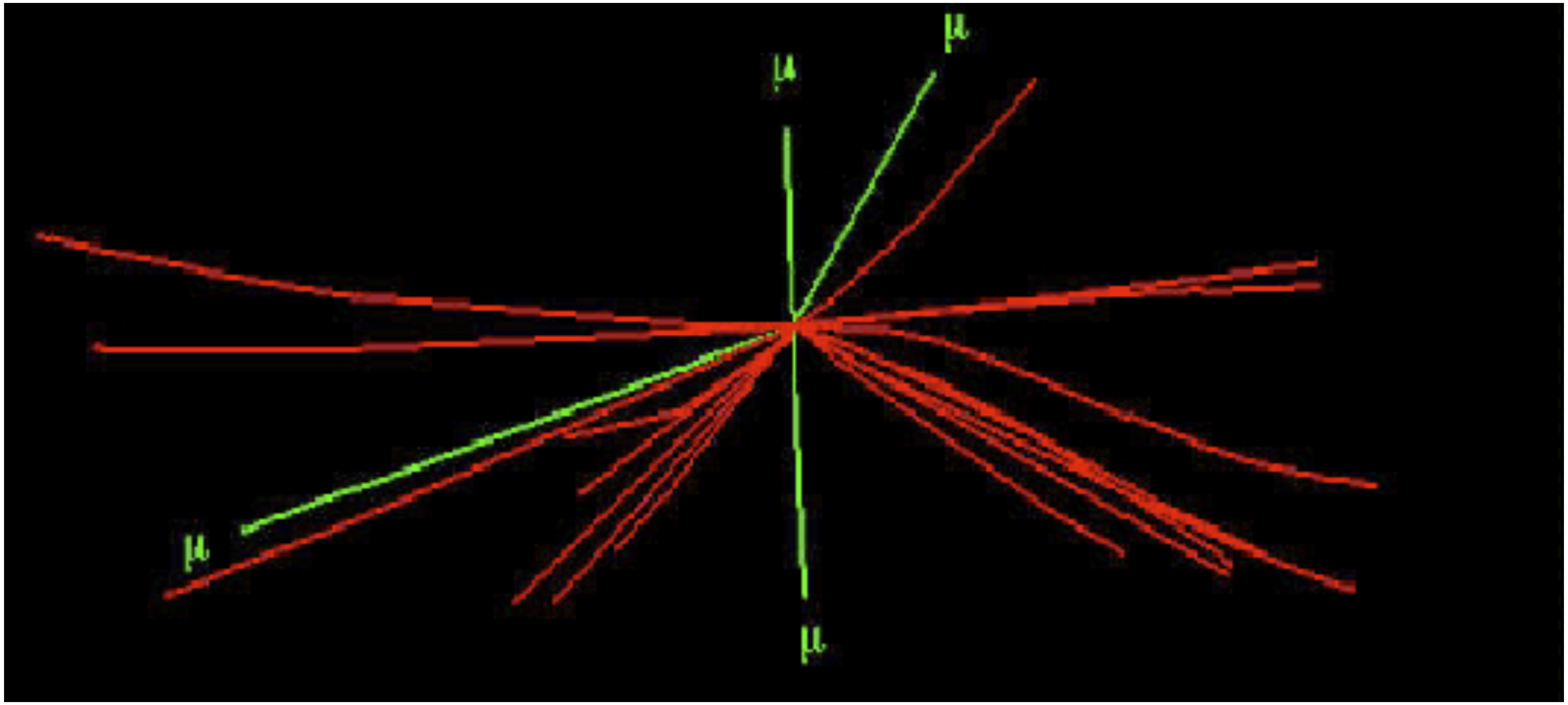
# LHC challenges: data rate




- $L = 10^{34}\ cm^{-2}\ s^{-1} = 10^{7}\ mb^{-1}$ Hz
- $\sigma_{inel}$ (pp) ≈ 70 mb
  → **Event Rate = 7 x 10⁸ Hz**
- $\Delta t$ = 25 ns = 25 x $10^{-9}$ $Hz^{-1}$
  → **Events/25ns =7 x 2.5 = 17.5**
- Not all bunches full (2835/3564)
  → **Events/crossing = 23**

- At full LHC luminosity we have 22 events superimposed on any discovery signal
- $10^9$ events per second x typical event size of 1-2 Mbytes >> TByte/sec
- Enormous data rate. Need super-fast algorithms to select interesting events while suppressing less interesting events

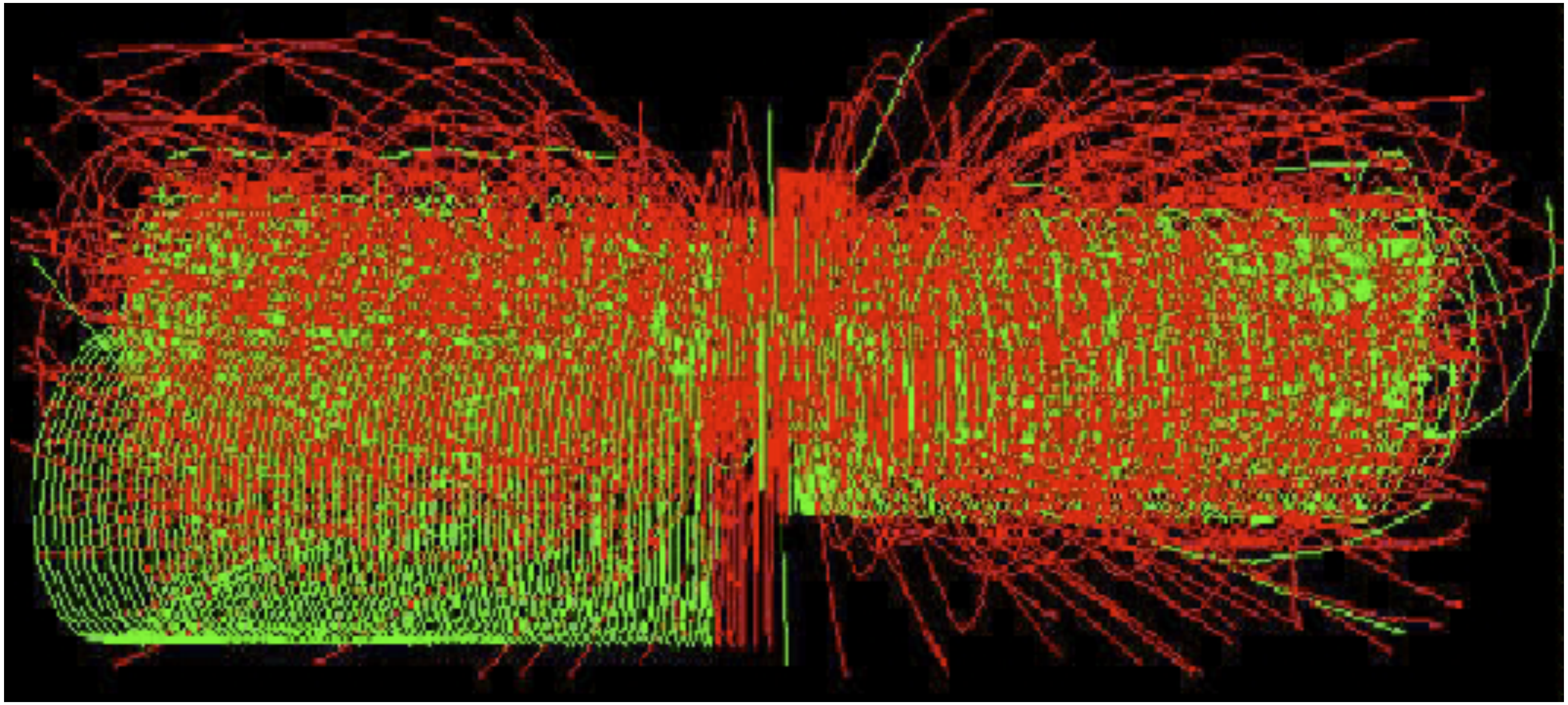
# LHC trigger challenges - pile-up




Higgs -> 4μ

- We want to select this type of event for example Higgs to 4 muons....

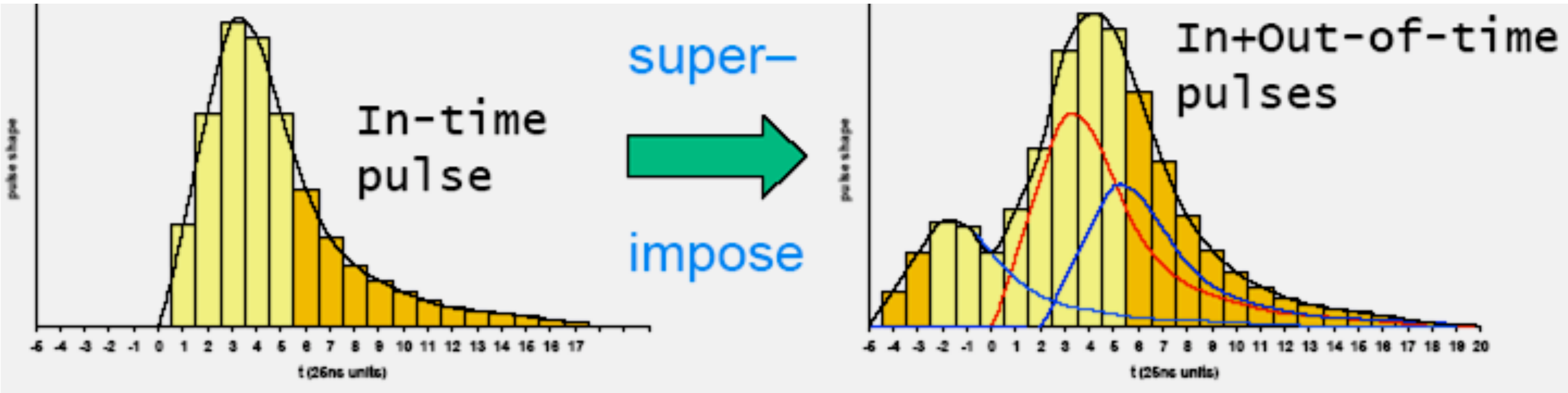
# LHC trigger challenges - pile-up



Higgs -> 4μ +30 MinBias

- We want to select this type of event for example Higgs to 4 muons....
  - which has this superimposed on it……
- Sophisticated algorithms necessary

# LHC trigger challenges - pile-up



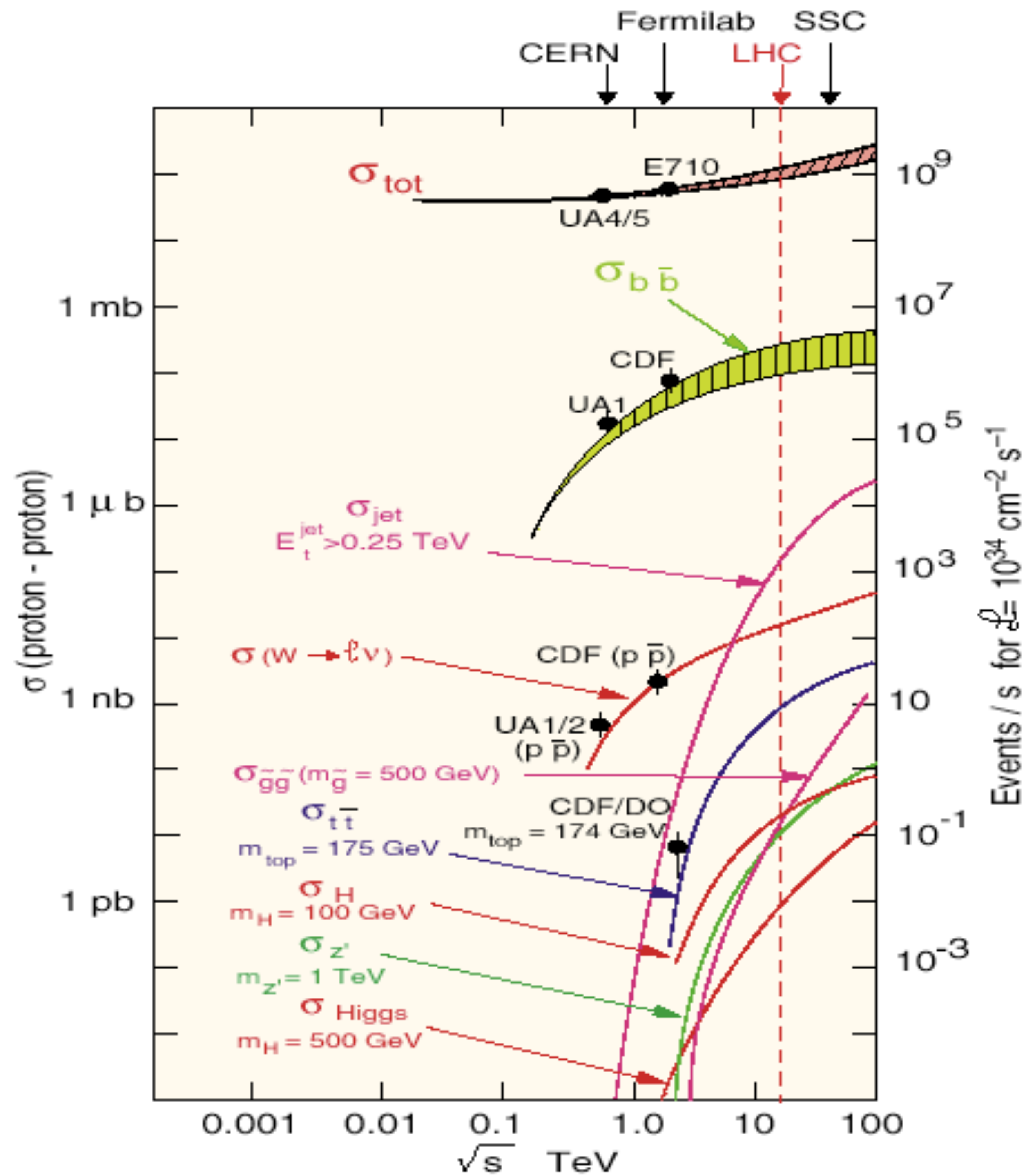

- In-time pile up: Same crossing different interactions
- New events come every 25 nsec → 7.5 m separation
- Out-of-time pile up: Due to events from different crossings
- Need a to identify the bunch crossing that a given event comes from

# LHC challenges: needle in a haystack

- QCD cross sections are orders of magnitude larger than electroweak or any exotic channels

- Event rates:
  - Inelastic: $10^9$ Hz
  - $W \rightarrow l\nu$ : 100 Hz
  - t-tbar:10 Hz
  - H(100 GeV): 0.1 Hz
  - H(600 GeV): 0.01 Hz

- $\Rightarrow$ Need to select events at the 1:$10^{11}$ level



# From the trigger design report

- High efficiency for hard scattering physics at the LHC
- Processes like
  - top decays, $H \rightarrow \gamma\gamma$, $H \rightarrow 4l$, W-W, SUSY...
- Need to efficiently reconstruct decay products from intermediate W and Z bosons
    - Sets scale for single lepton triggers from W decay $P_T > 40$ GeV
- For $H \rightarrow \gamma\gamma$
  - Sets scale for di-photon trigger of $P_T > 20$, 15 GeV
- Benchmark is that muon and isolated electron must have efficiency > 50% for W decays

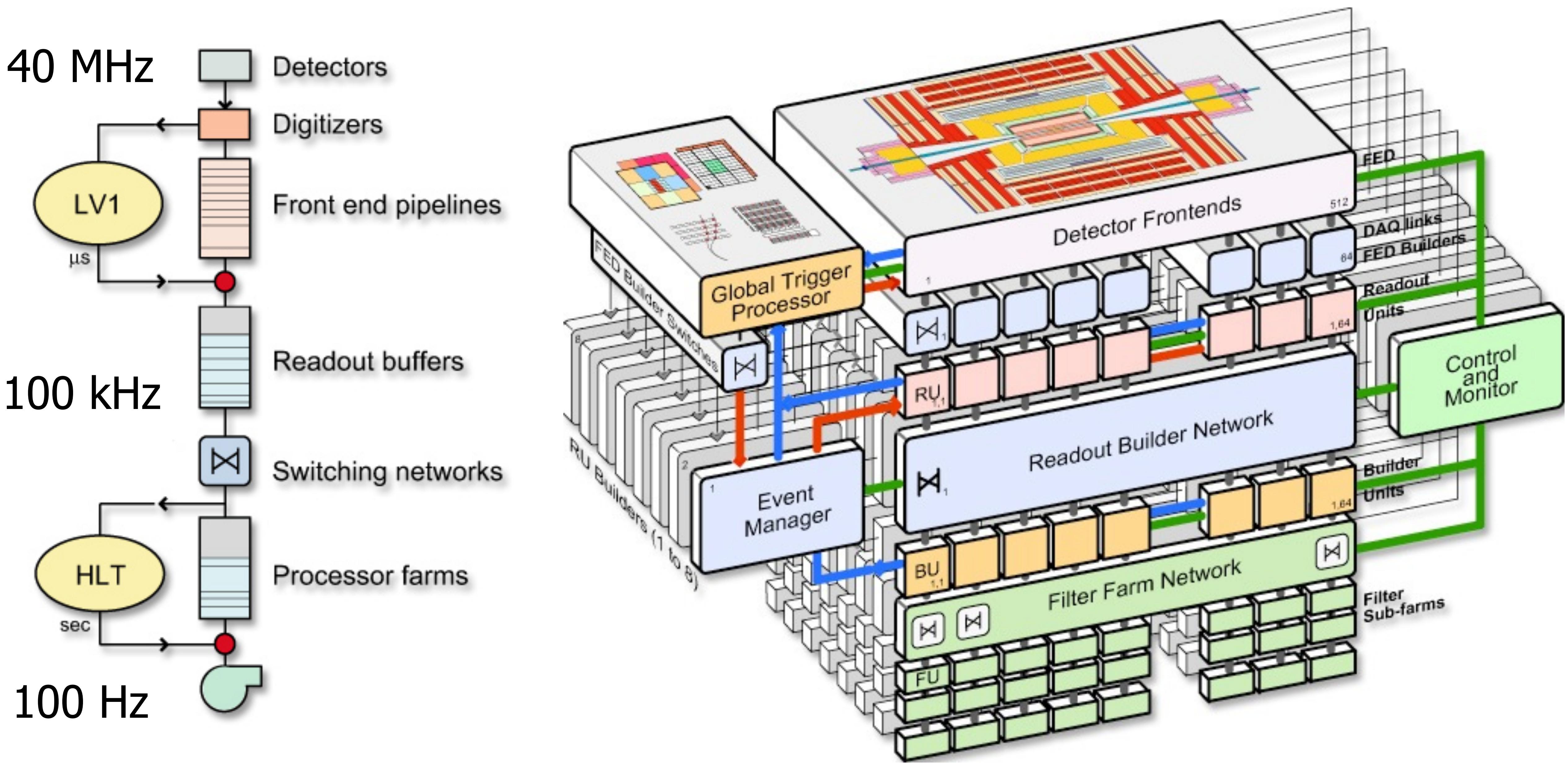
# From the trigger design report

- Requirements
  - Leptons and jets $|\eta|<2.5$ with high efficiency above some PT threshold
  - Single lepton triggers with high efficiency (>95%) $|\eta|<2.5$ $P_T>40$ GeV
  - Di-lepton triggers with high efficiency (>95%) $|\eta|<2.5$ $P_T>20$, 15 GeV
  - Di-photons similar to di-leptons
  - Jets continuous over $|\eta|<5$ for single and multi-jet topologies. High efficiency required for high-$E_T$ jets
  - Missing $E_T$ with threshold around 100 GeV

# Backgrounds

- What drives the rate for each type of trigger?
- Electrons and photons
  - High-$E_T$ $\pi^0$ from jet fragmentation and direct photon processes
- Muons
  - Mis-measurement of low $P_T$ muons
  - Hadronic decays
  - Punch through from jets
- Jets
  - Mis-measurement of low $E_T$ QCD jets
- Tau
  - Narrow QCD jets fake hadronic tau decays
- Missing $E_T$
  - All sorts of mis-measurement, machine backgrounds etc.

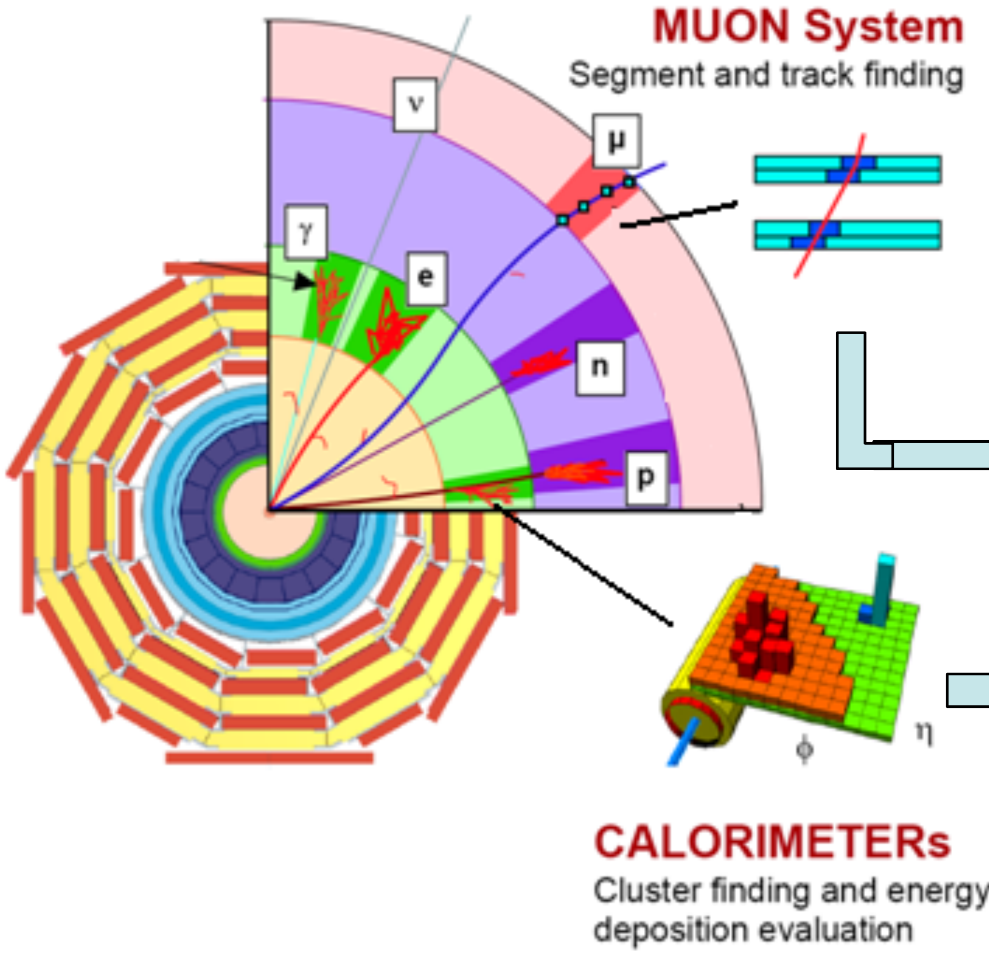
# CMS trigger and DAQ

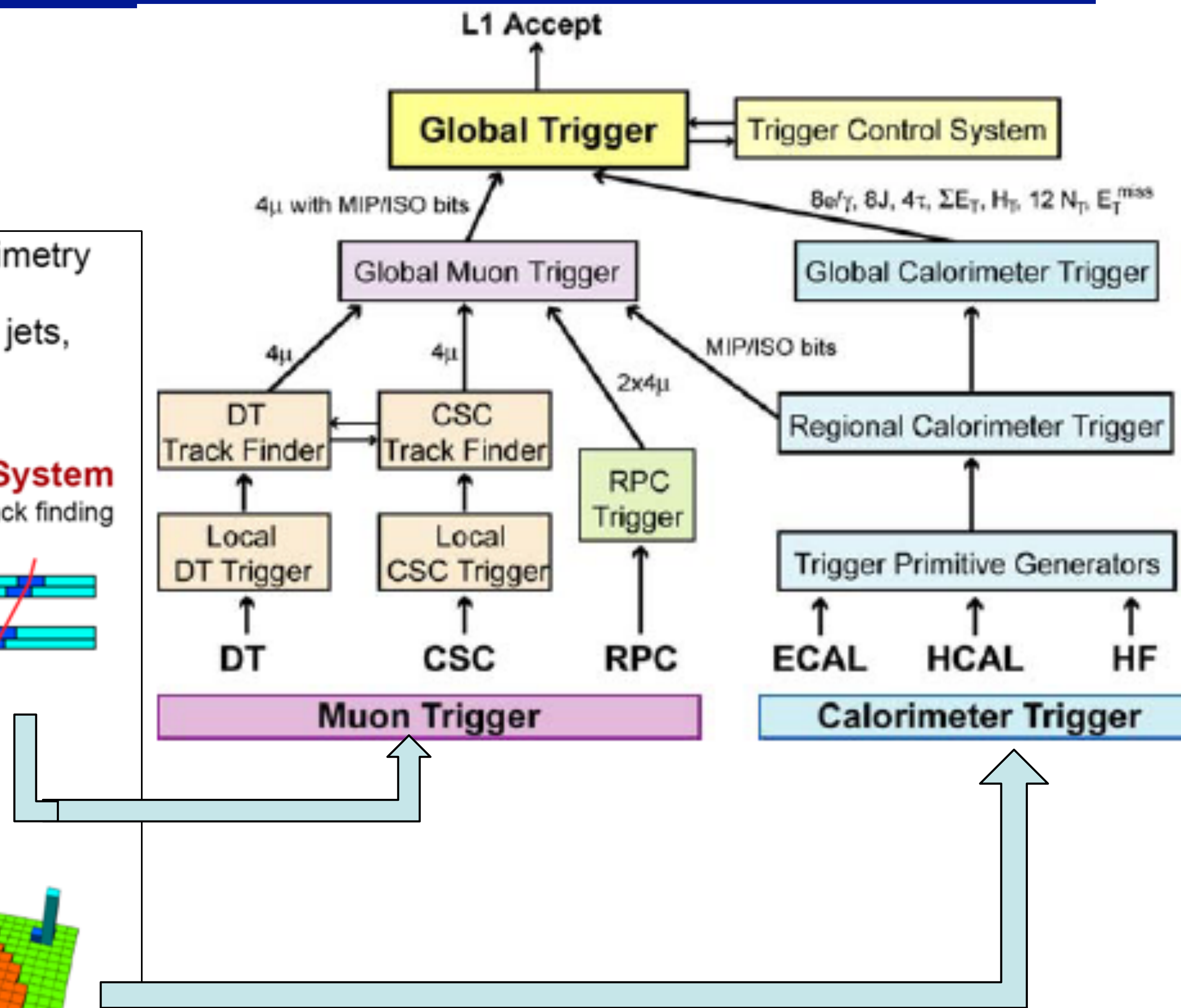


# CMS Level 1 Trigger

**New data every 25 ns**
**Decision latency ~ μs**

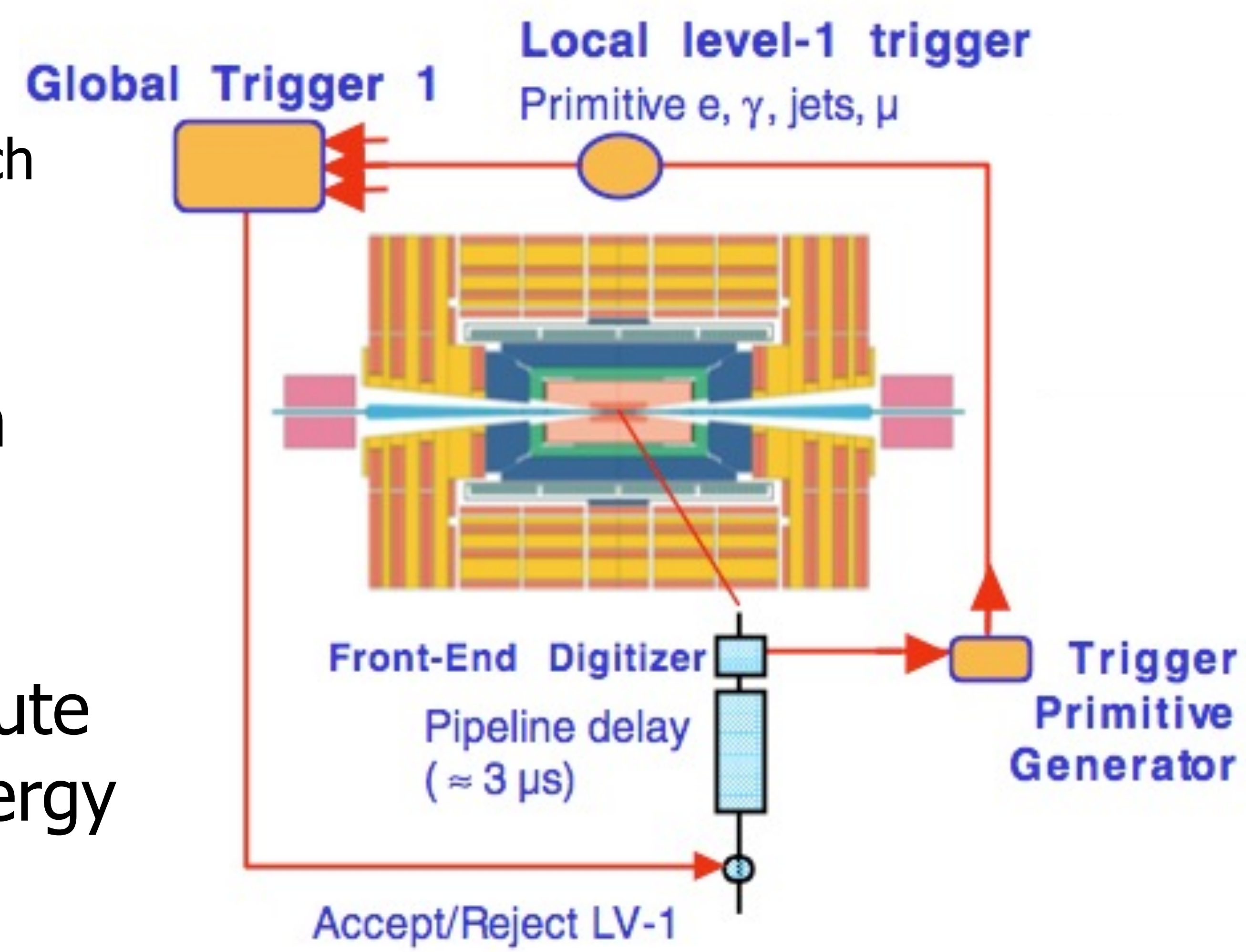
Use prompt data (calorimetry and muons) to identify:
High $p_t$ electron, muon, jets, missing $E_T$



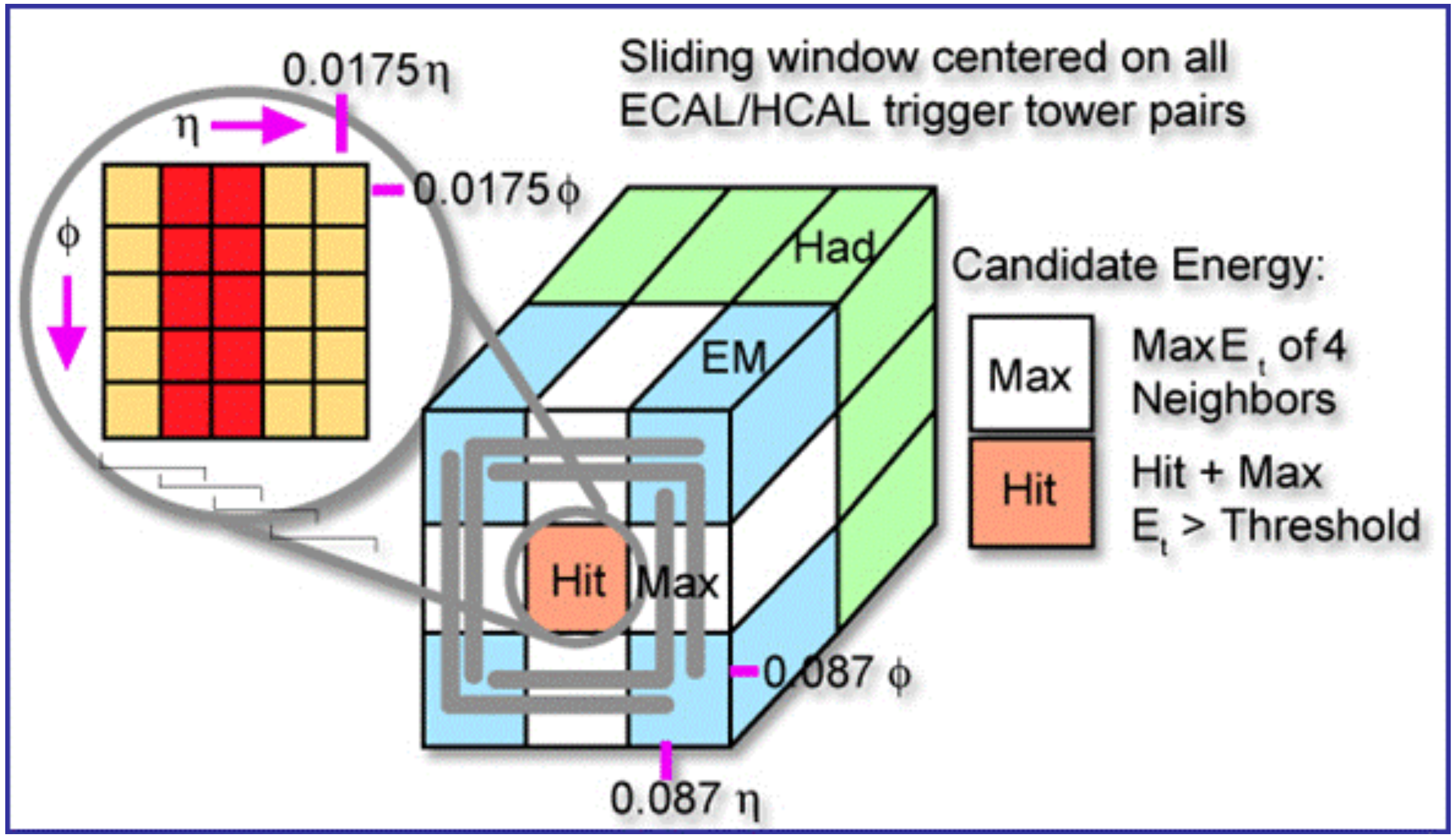
# The CMS Level 1 Trigger

- Detector data stored in front-end pipelines
  - Pipelines deep enough for 128 bunch crossings (3.2μs)
- Trigger decision derived from trigger primitives generated on the detector
- Trigger systems search for isolated e, γ, μ, jets and compute the transverse and missing energy of the event
- Event selection algorithms run on the global triggers
  - Must give a trigger decision every 25ns.



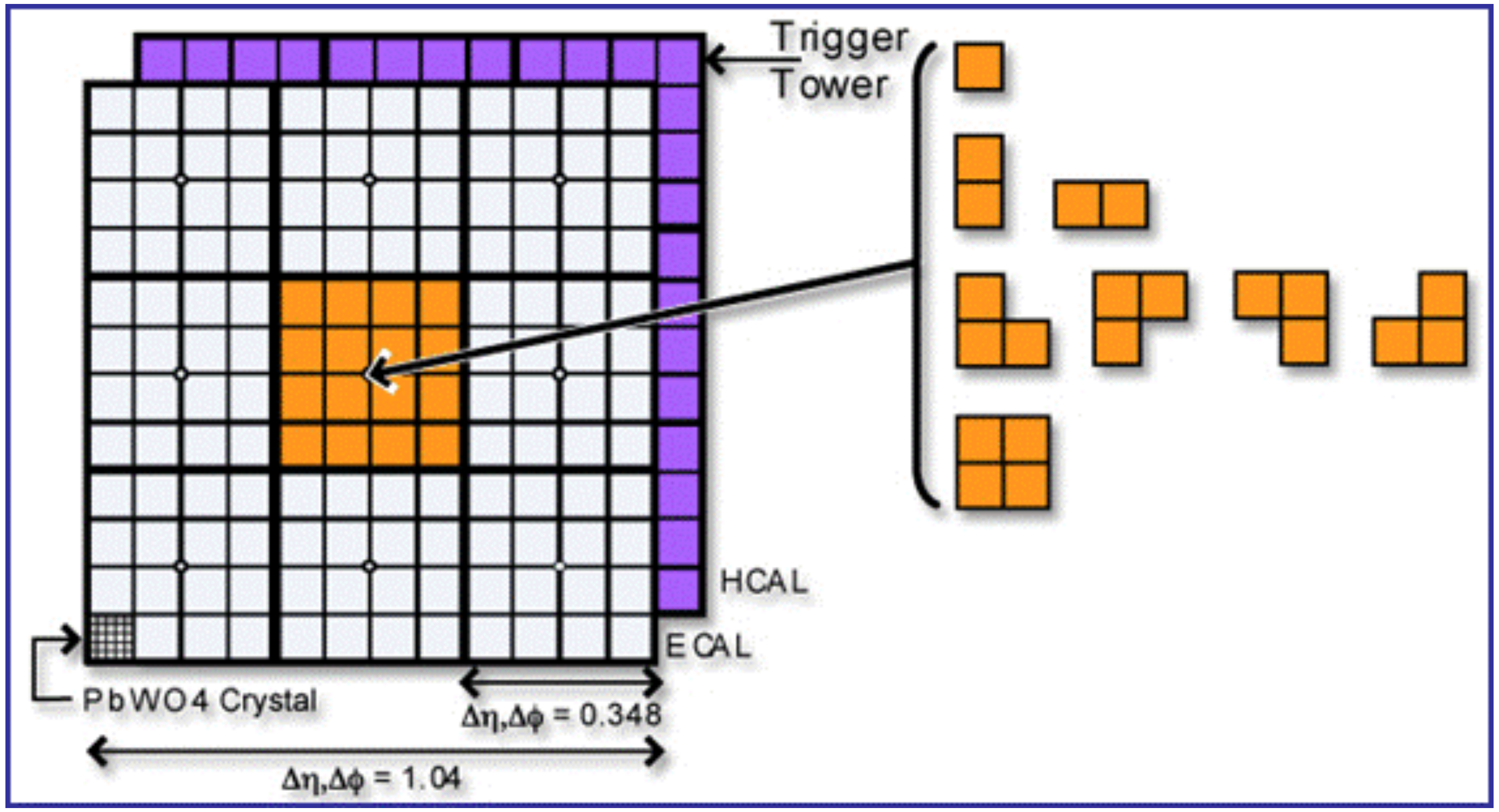
# Electron trigger algorithm

- Trigger tower is 5x5 PbWO4 crystals
- Sliding window of 3x3 trigger towers to find local maxima
- Electron ID requirements
  - Large fraction of $E_T$ deposited in 5x2 crystal region (>90%) and HCAL/ECAL veto (<5%) in central trigger tower
  - Greater than threshold $E_T$ in central + maximum neighbouring trigger tower
  - Isolation criterion: at least one "quiet corner" (towers<1.5 GeV) and vetos for all towers



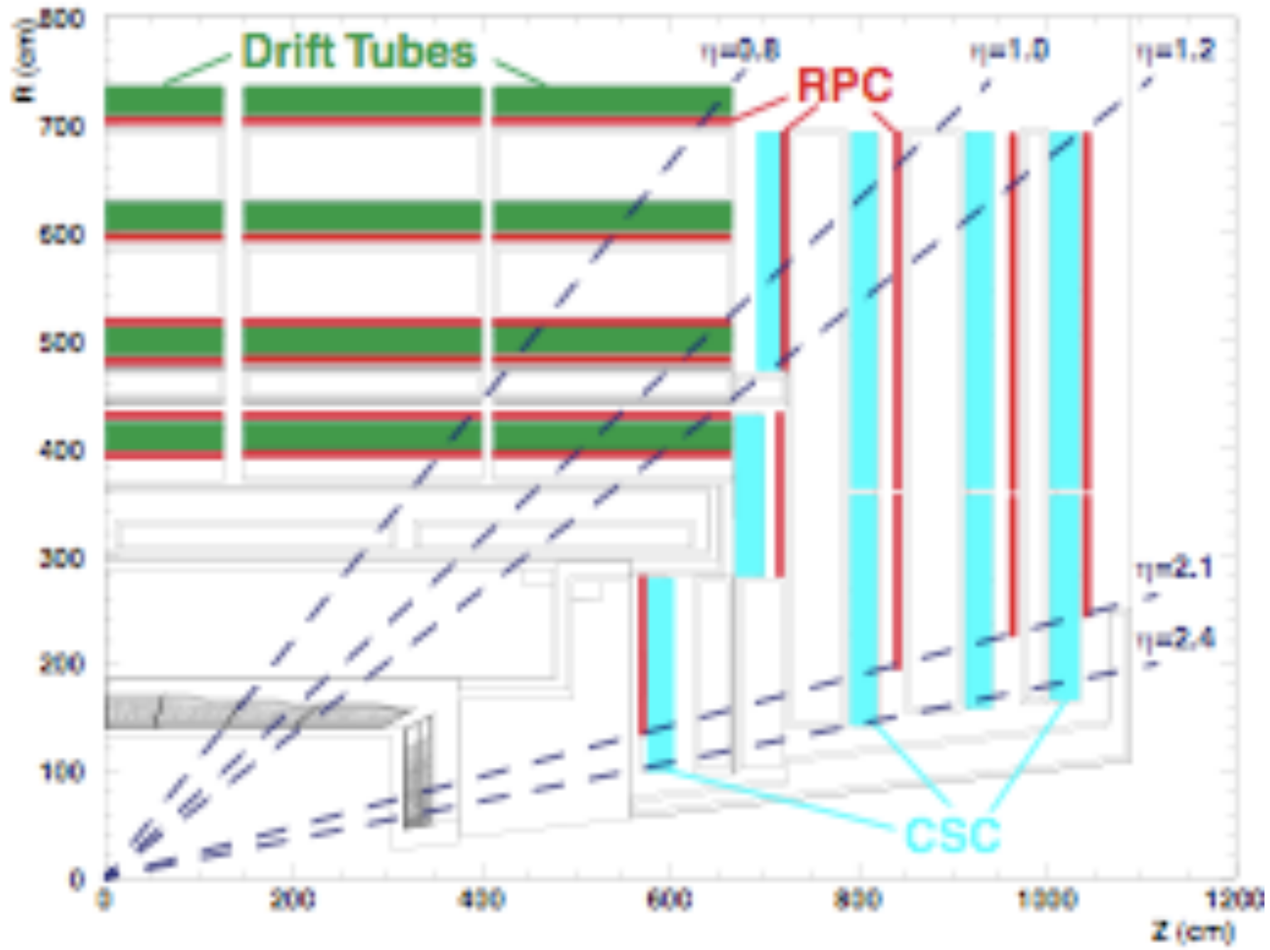
# Jet trigger algorithm

- Trigger region is 4x4 trigger towers (20x20 PbWO4 crystals in ECAL)
- Sliding window of 3x3 regions to find local maxima: cone (square) jet algorithm
- Sum all $E_T$ in 3x3 region window
- Tau veto bit set if none of patterns are found in region (trigger tower $E_T$>3 GeV)
- Jet is marked as tau-jet if tau veto is not set for all 9 regions



# L1 muon trigger

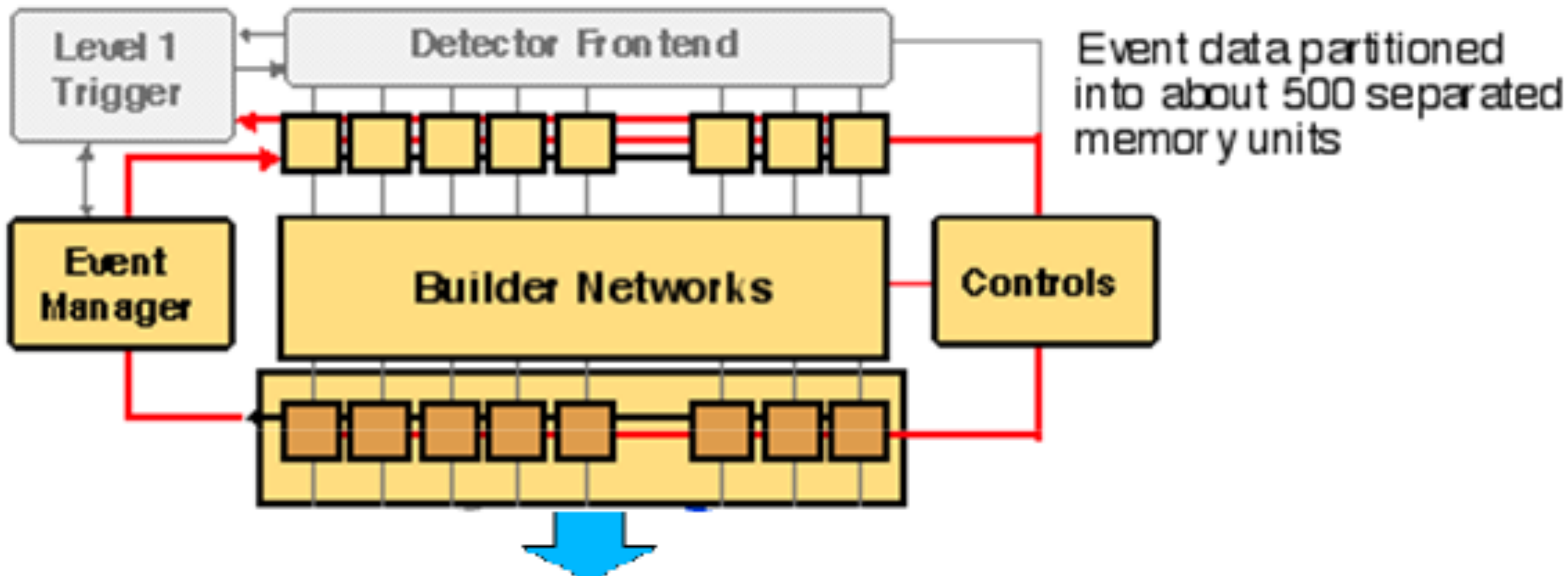
- Combination of three
- technologies
  - Drift tubes
  - Cathode strip chambers
  - Resistive plate chambers
    - For triggering only
  - Redundant
  - Complementary technologies
  - Geometric overlap




- Tracks from different systems combined in the Global Muon Trigger
  - Combination uses optimal information from each system and is less sensitive to backgrounds, noise, etc.

# CMS High Level Trigger

L1 Input rate ≈ 40 MHz
L1 latency: 3.2 μs
L1  Output rate: 100 kHz




L2 and L3 merged into
High Level Trigger (HLT)

100kHz input rate
~2000 CPUs
~40 ms average per event

Farm of processors
ONE event, ONE processor
- High latency (larger buffers)
- Simpler I/O
- Sequential programming

The HLT  accesses full full granularity event information seeded by L1 objects

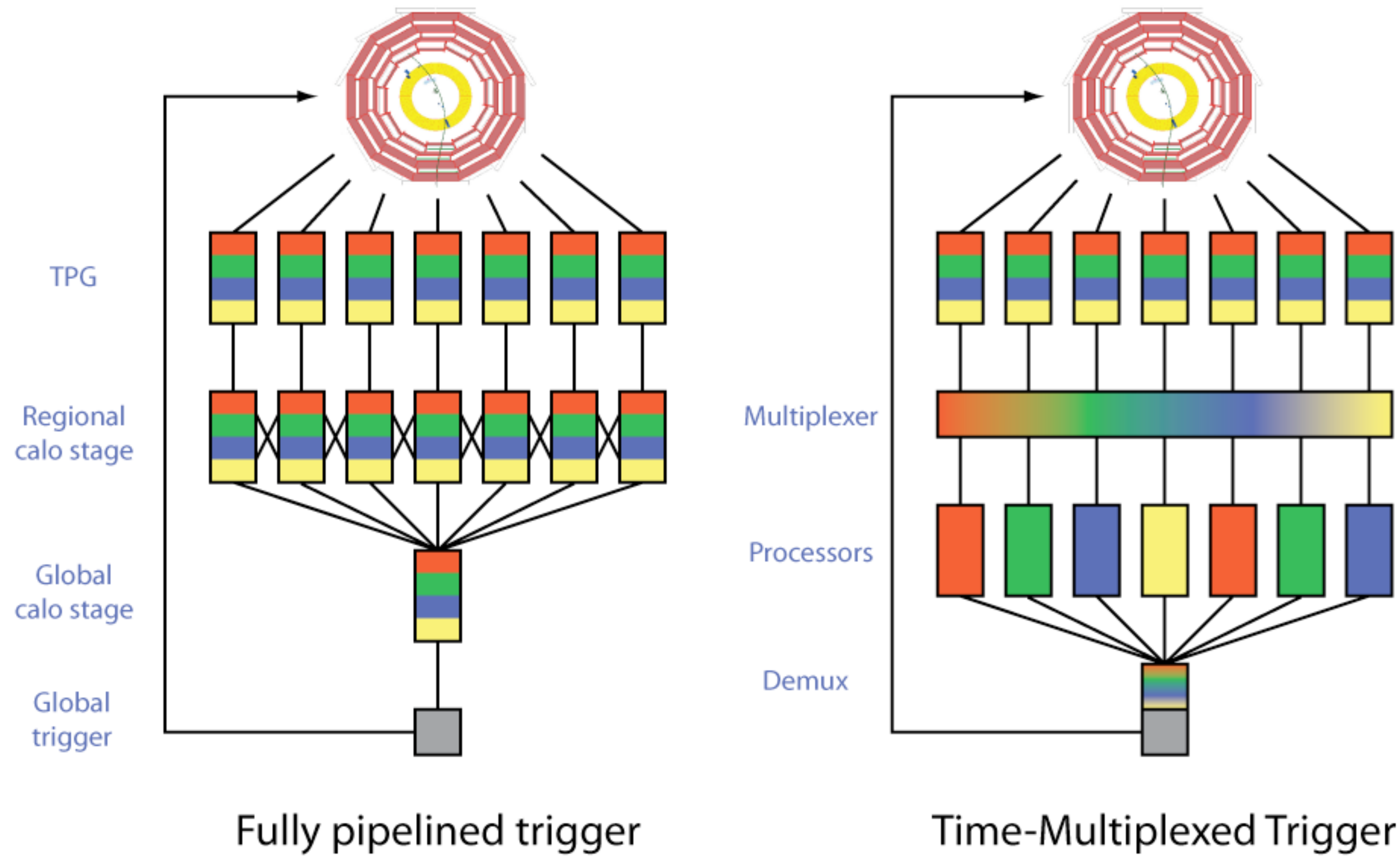
# The future

- Triggers driven by physics needs and accelerator environment

- Easy future: ILC
  - No trigger!
  - 200 μs between trains
  - Buffer and readout everything

- Difficult future: HL-LHC
  - Up to 200 interactions per bunch crossing
  - Need to keep trigger thresholds as LHC
  - Need to incorporate tracking into hardware algorithms

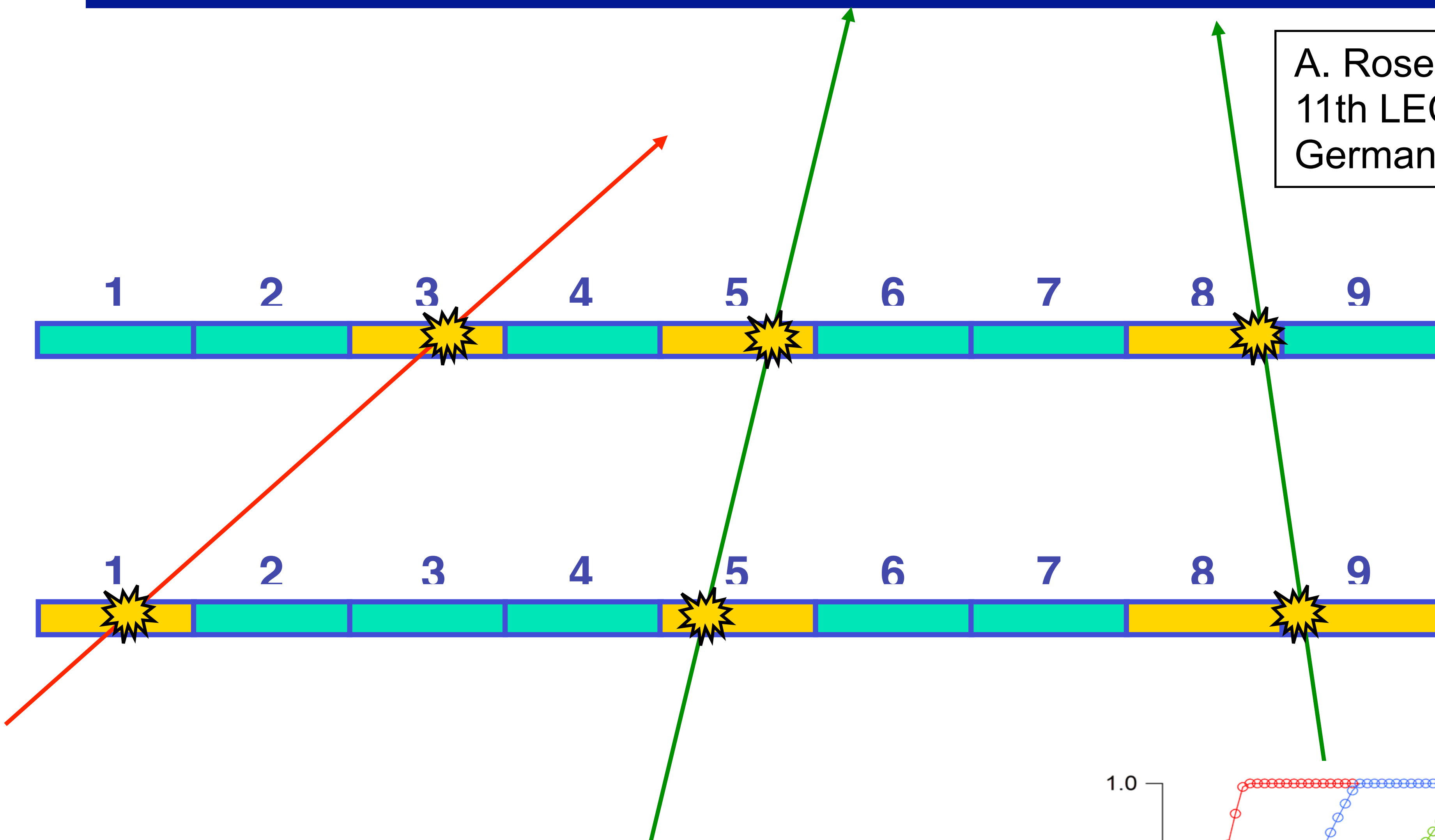
# Time Multiplexed Trigger



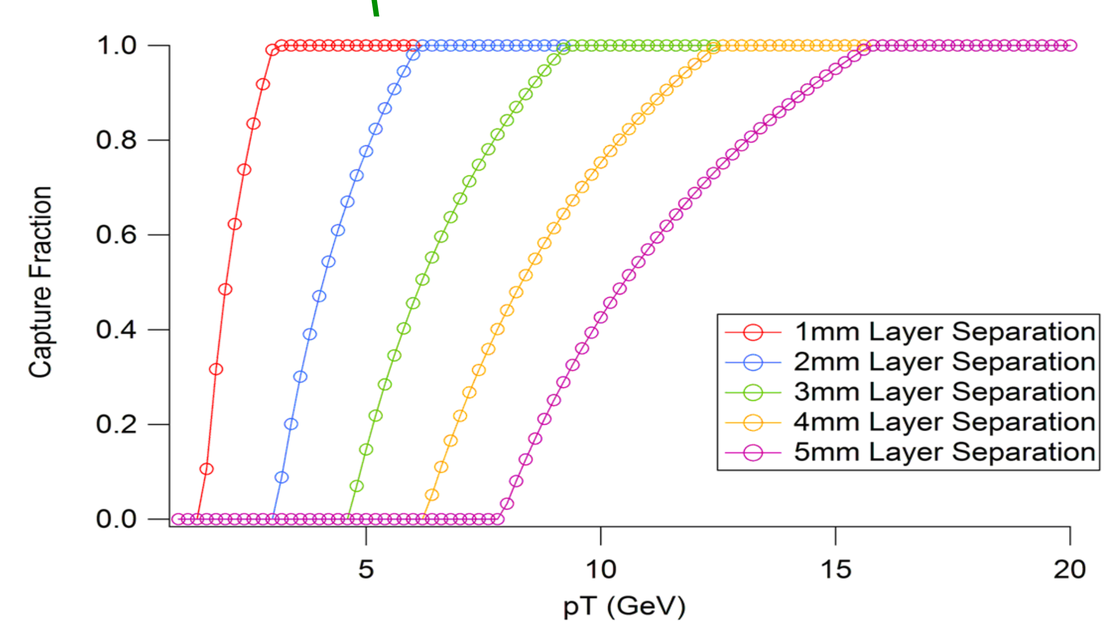

- Choice for CMS calorimeter trigger upgrade

# Hardware Tracking Trigger

A. Rose, C. Foudas, J. Jones & G. Hall, 11th LECC Workshop, Heidelberg, Germany (2005).

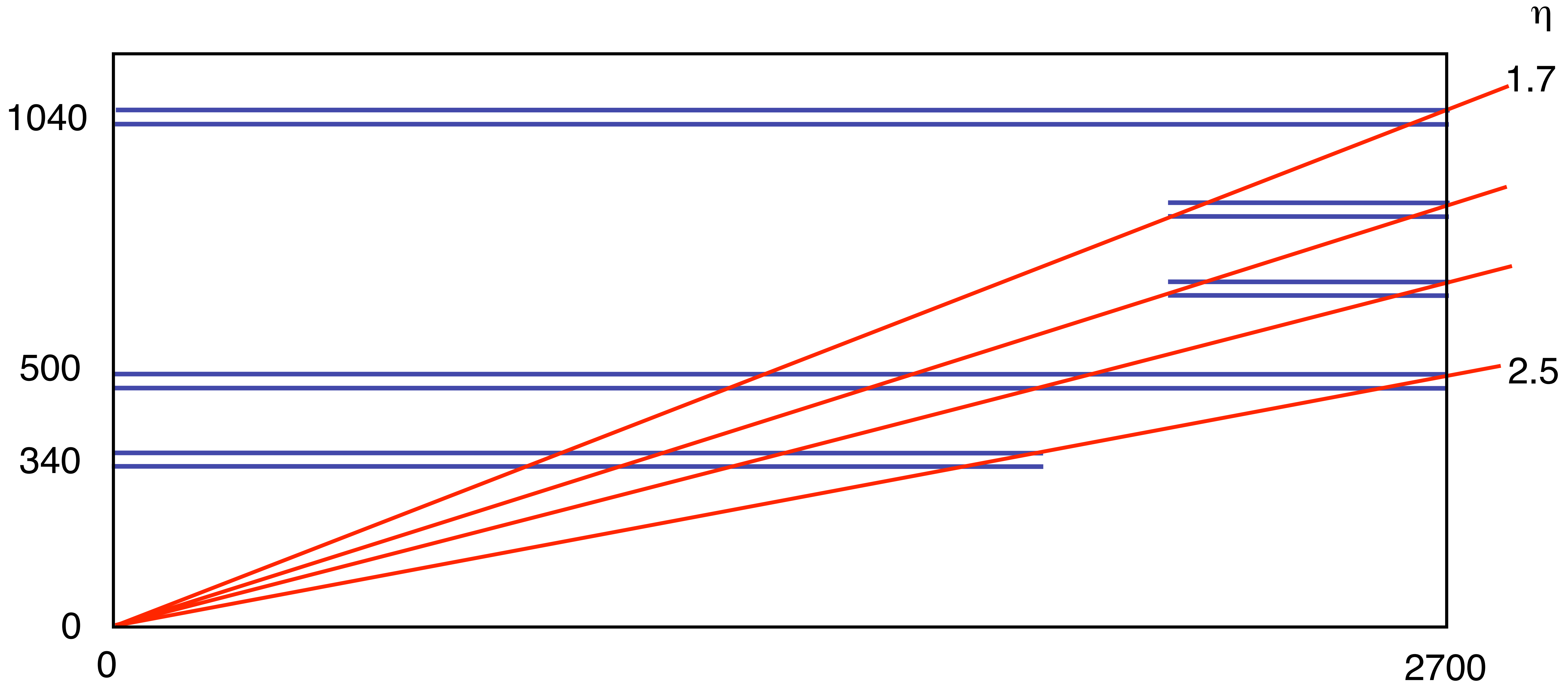



- Pixel spacing and separation of layers gives an implicit min $P_T$ cut on track stubs



# Hardware Tracking Trigger

- Design for CMS HL-LHC upgrade (out of date now)



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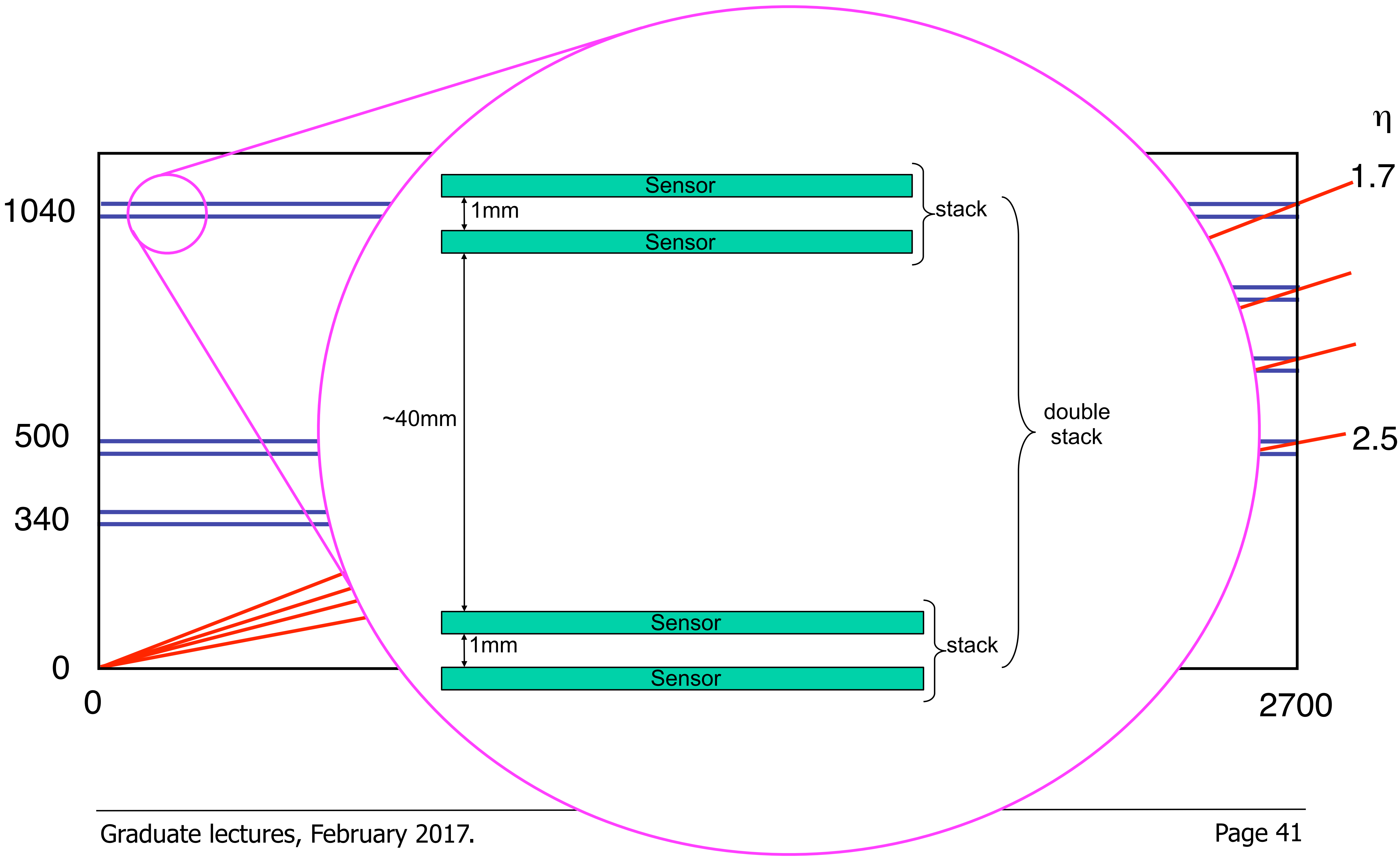
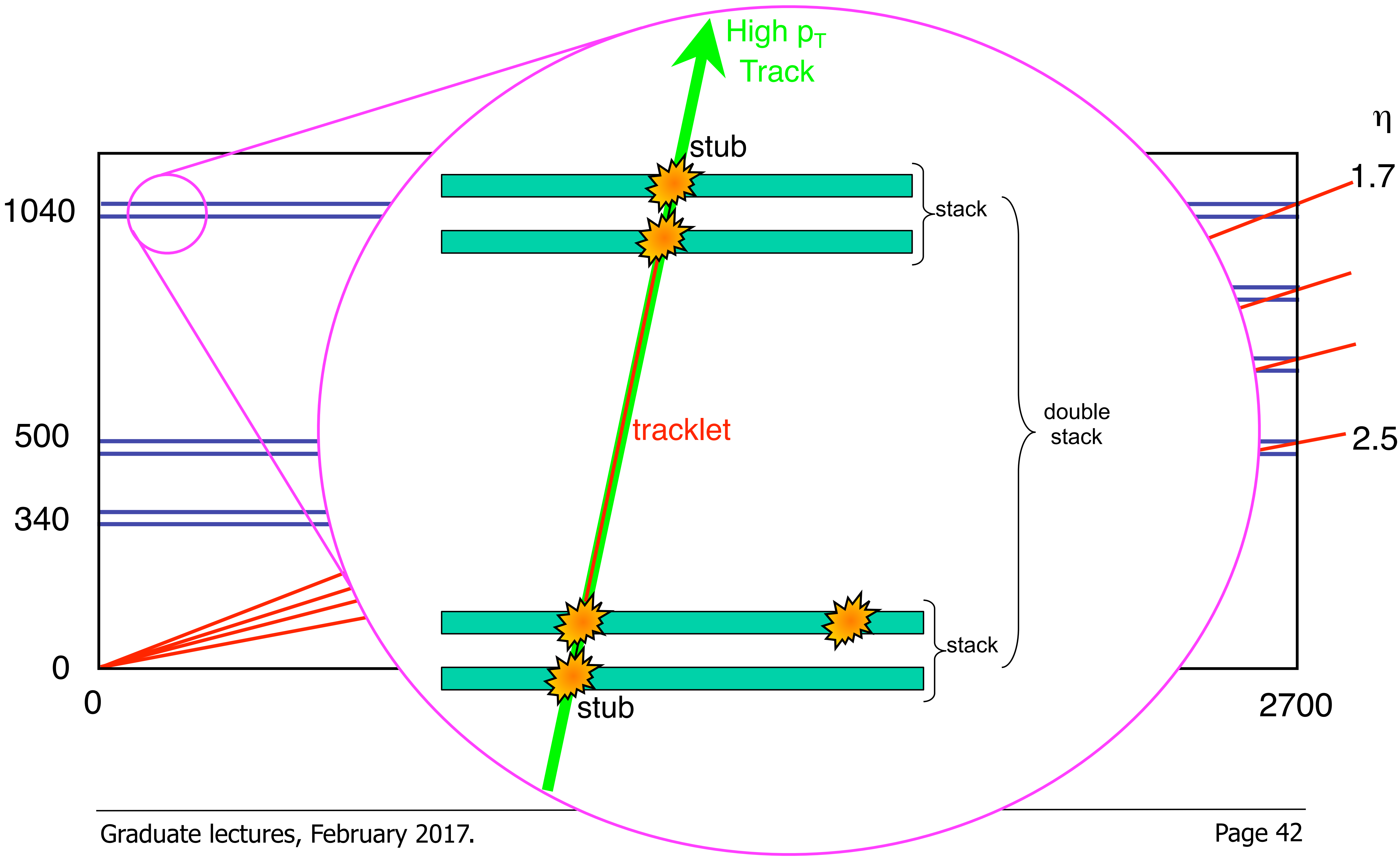


# Hardware Tracking Trigger



# Advice...

# Practical advice

- You might well have to design a trigger for some physics channel you are interested in
- Not as unusual as you might imagine!
- Some things to remember....

# Practical advice

- Generally
  - Keep it as simple as possible
  - Easy to commission
  - Easy to debug
  - Easy to understand

# Practical advice

- Generally
  - Be as inclusive as possible
  - One trigger for several similar analyses
  - Your trigger should be able to discover the unexpected as well as the signal you intended it for!

# Practical advice

- Generally
  - Make sure your trigger is robust
  - Triggers run millions of times a second so any strange condition WILL occur, make sure you are prepared for it
  - Detectors don't work perfectly ever! make sure your trigger is immune to detector problems
  - Beam conditions change - be prepared

# Practical advice

- Generally
  - Build in redundancy
  - Make sure your signal can be selected by more than one trigger
  - Helps to understand biases and measure efficiencies
  - Also for safety, if rates are too high or there's some problem you still get your events

# Practical advice

- Finally
  - Taking your signal events is only part of the game
  - You might well also need background samples
  - You will need to measure the efficiency of your trigger using a redundant trigger path
  - You will need to know if it works! Monitoring.

# Summary

- Trigger is essential at colliders
- Must have a huge rejection of unwanted events if we are to see low cross section processes
- Trigger is not there to do analysis, just get the events written to tape at an acceptable rate
- This was a very simple, conceptual discussion
- In real life there are many more details to consider