Monika Wielers

Rutherford Appleton Laboratory

- Lecture 3
  - Trigger
  - Current trends/developments

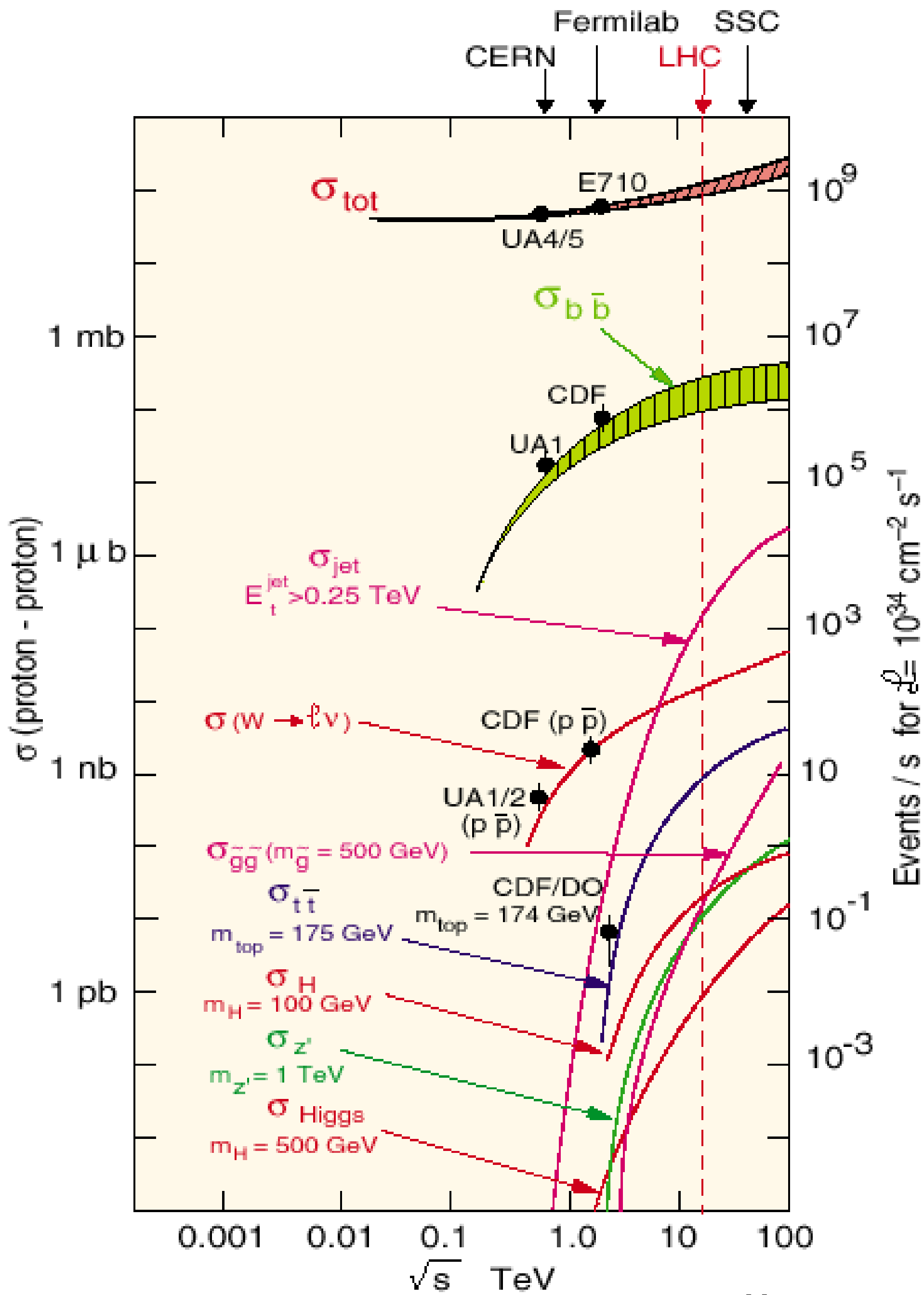
Reminder from last time

- Last time we look at various examples of a data acquisition system
- We looked at the data acquisition system of ATLAS and at the dataflow (transport of event information from collision to mass storage)
- We learned what a trigger is
  - Tells you when is the “right” moment to take your data
  - Decides very rapidly what output to keep if you can’t keep all of it. The decision is based on some ‘simple’ criteria
  - Can be done in several levels (L1 – L2 – EF)
- Today we’ll learn more how the trigger looks
  - Again we take ATLAS as an example

Challenge 1: Physics

- Cross sections for most processes at the LHC span ~10 orders of magnitude
- LHC is a factory for almost everything: t, b, W, Z…
- But: some important signatures have small branching ratios (e.g. $H \rightarrow \gamma\gamma$, BR ~$10^{-3}$)

Process	Production Rate 10^{34} cm^{-2}s^{-1}
inelastic	~1 GHz
bbbar	5 MHz
$W \rightarrow l\nu$	150 Hz
$Z \rightarrow l\nu$	15 Hz
ttbar	10 Hz
Z'	0.5 Hz
H(120) SM	0.4 Hz



Other Challenges

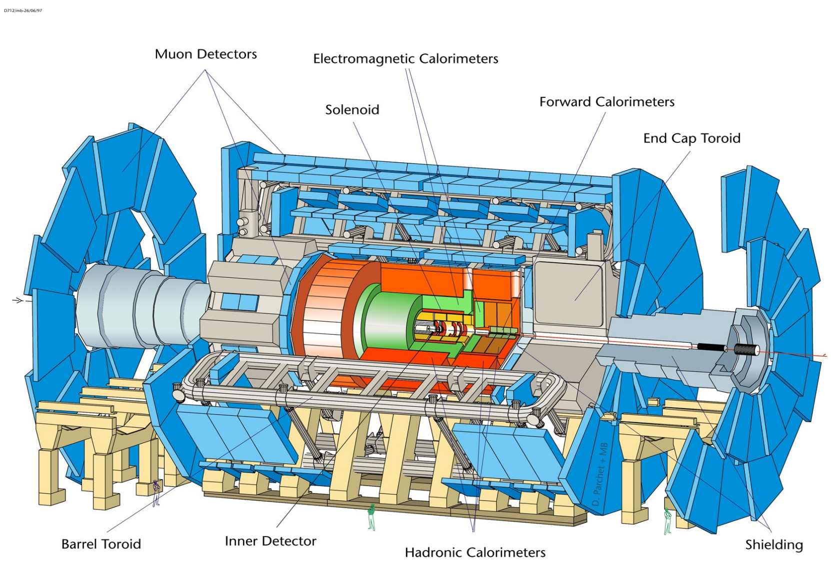
- Accelerator and Detector
  - Bunch crossing frequency of 40 MHz
  - LHC produces ~25 overlapping p-p interactions every 25 ns at design luminosity (in 2011 we had already up to ~20 ‘pile-up’ events with 50s bunch spacing)
  - At 10^{34} $cm^{-2}s^{-1}$ every 25ns LHC flushes detector with ~1400 particles
- Some detectors need > 25ns to readout their channels and integrate more than one bunch crossing's worth of information (e.g. LArg readout takes ~400ns)
  - need to identify bunch crossing...
- It's on-line (cannot go back and recover events)
  - need to monitor selection - need very good control over all conditions

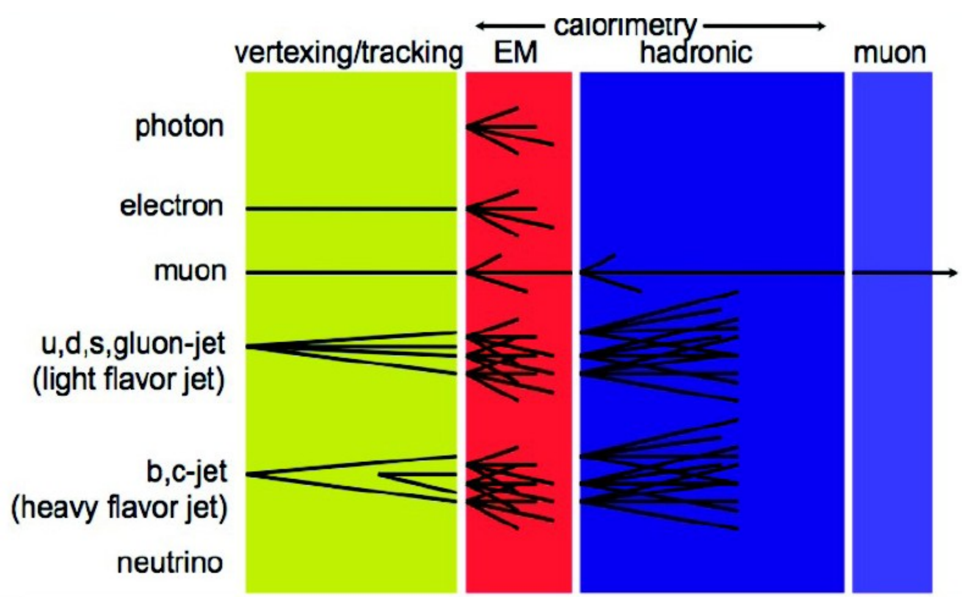
Trigger motivations

- For many physics analyses, aim is to obtain as high statistics as possible for a given process
  - We cannot afford to handle or store all of the data the detector can produce!
- To obtain best use of the limited trigger bandwidth
  - Must select the required physics
    - with good/high efficiency
    - Means to monitor efficiency
    - In robust and reliable way
    - in shortest possible time (and lowest cost)
  - Must throw away less interesting events
  - But note must get it right - any good events thrown away are lost for ever!
- Goal
  - Achieve highest efficiency for interesting events
  - Keep trigger rate as low as possible

Identification of different physics signals

- Needs to be done at trigger level
- Of course can't be a good as what you can do in offline due to timing constraints
- Trigger selections based on particle signatures
  - Muon tracks, energy deposits in the calorimeter (distinguish electro-magnetic (EM) and hadronic)

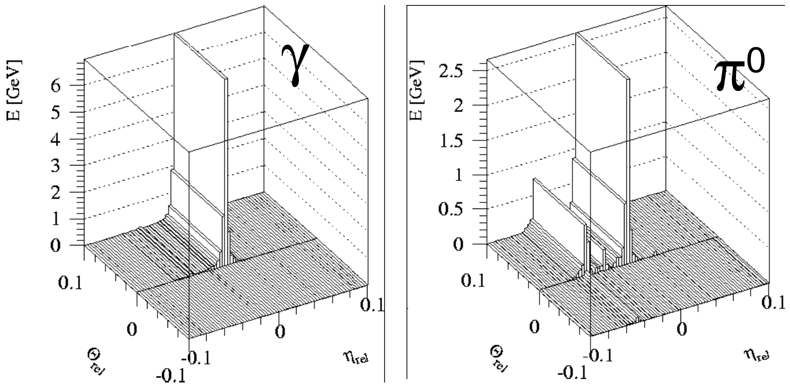




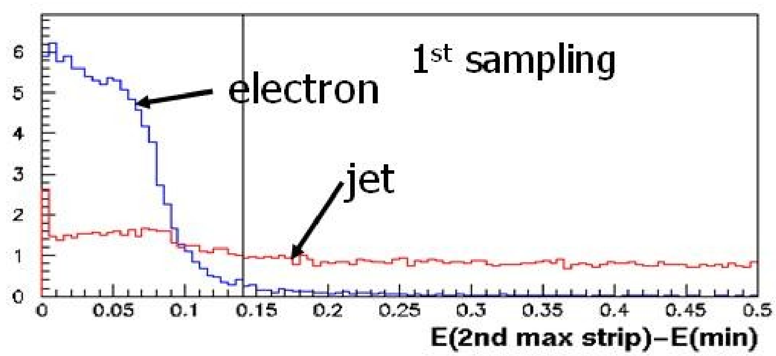
Identification

- Run reconstruction algorithms and calculate variables which can be used for identification

Detector feature



Level-2 trigger quantity



- Use these trigger quantities as input to decide if you want to keep event

Trigger strategy

- The trigger selection looks for events with:
  - Isolated leptons and photons,
  - τ-, central- and forward-jets
  - Events with missing E_T, missing E_T significance
- You can select events according to a combination of the above signatures
- Need to select signatures with small background

Trigger Design (ATLAS)

40 MHz

Trigger

Three logical levels

~ µs — **L1 - Fastest: Only Calo and Muon (hardwired)**

<75 kHz

~ ms — **L2 - Local: L1 refinement + track association**

~ kHz

~ sec. — **EF - Full event: “Offline” analysis**

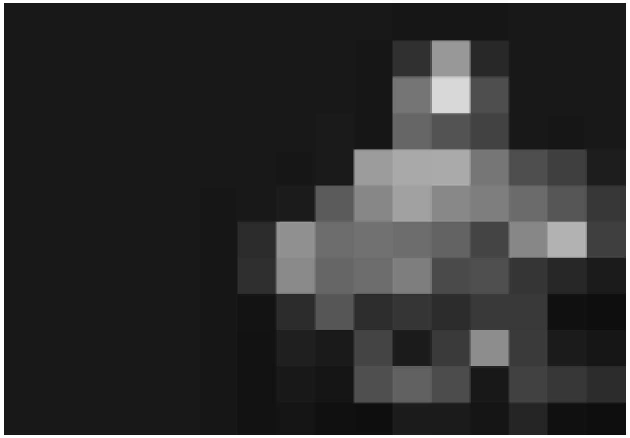
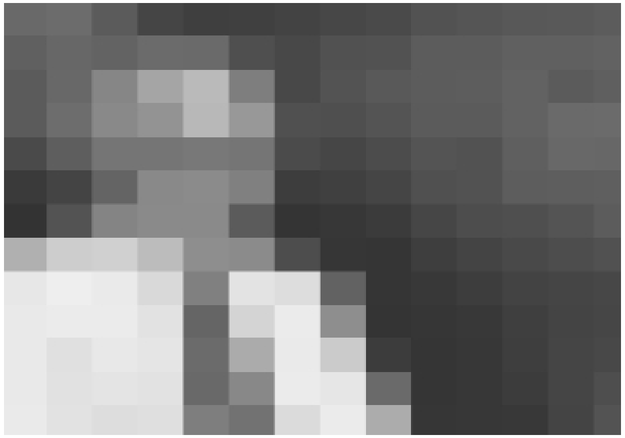
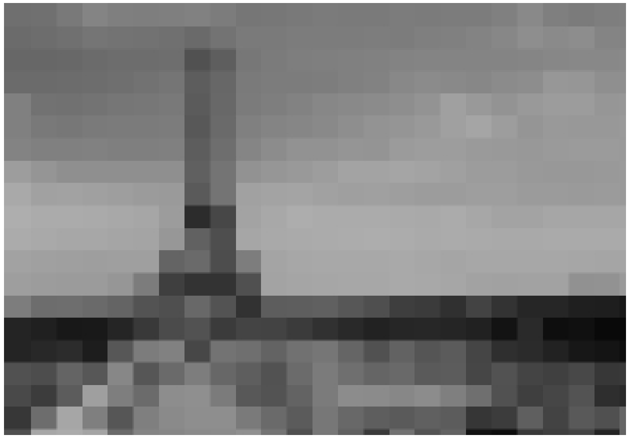
~ 200-300 Hz

- 3-level trigger hierarchy: L1 – L2 – EF (Event Filter) in ATLAS
  - 2-3 levels in other LHC exps.
- Use multi-level trigger to reduce dead-time and reject “uninteresting” events asap
- L1 is hardware trigger
  - Only calo and muons
  - Use reduced calo granularity
- L2 (software)
  - Fast selection algorithms depending on input object
  - Identify objects using “simple” criteria
- EF (software)
  - offline reconstruction-like algorithms

Example: Higgs

- L1

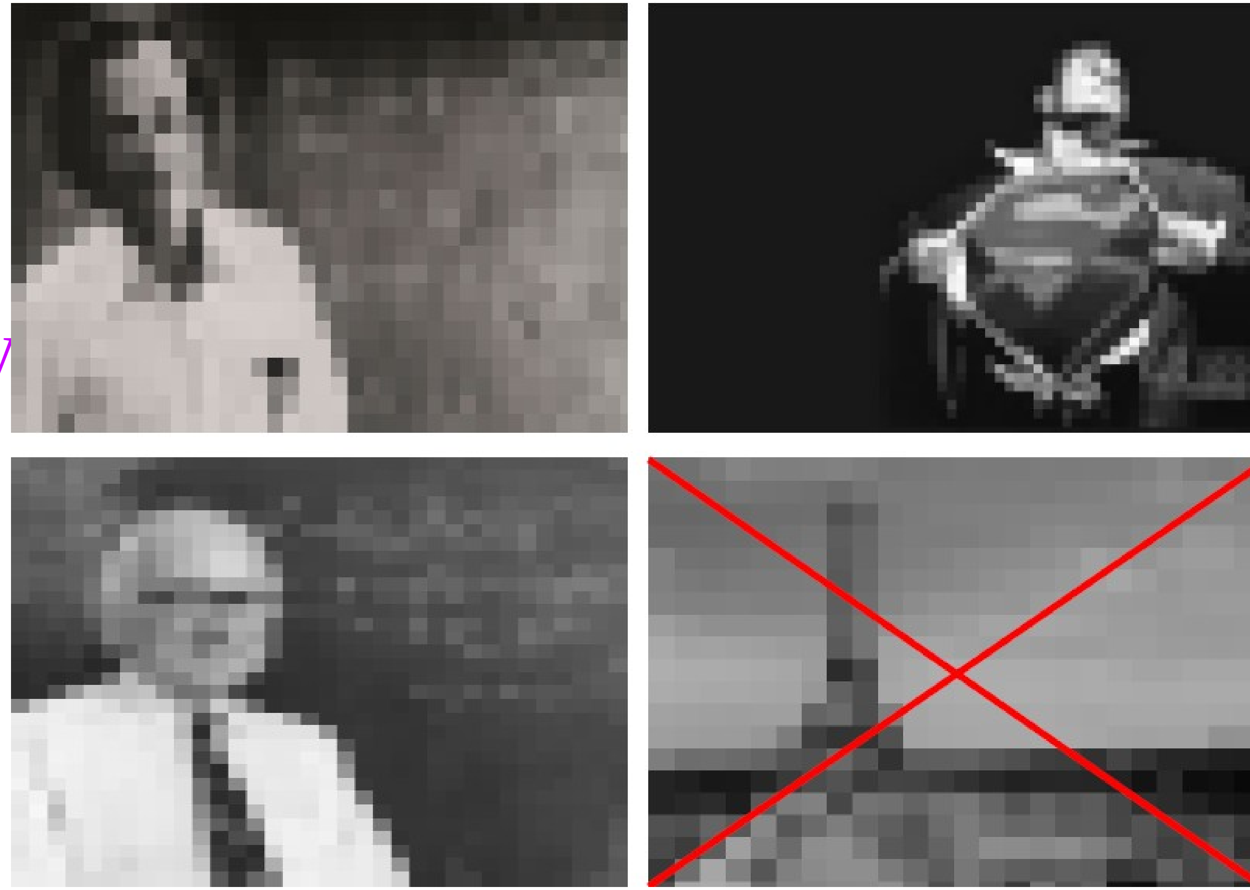
  Coarse granularity

Example: Higgs

- L2

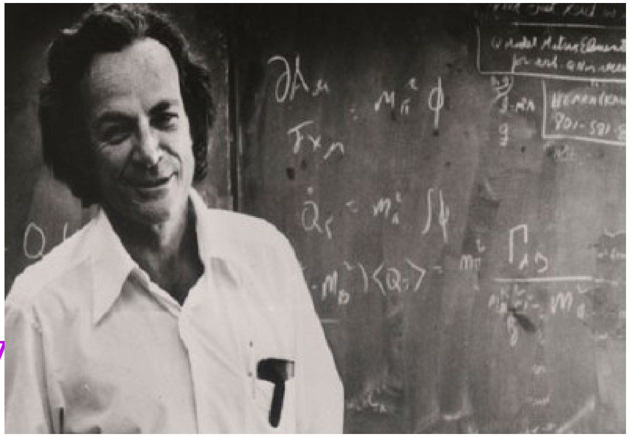
  Improved reconstruction, improved ability to reject events

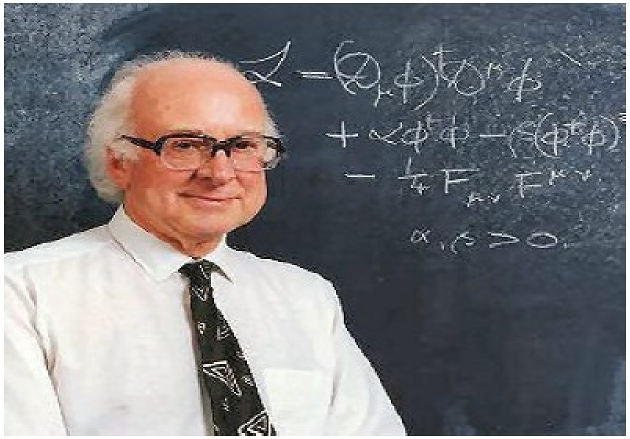


Example: Higgs

- EF

  high quality reconstruction, improved ability to reject events



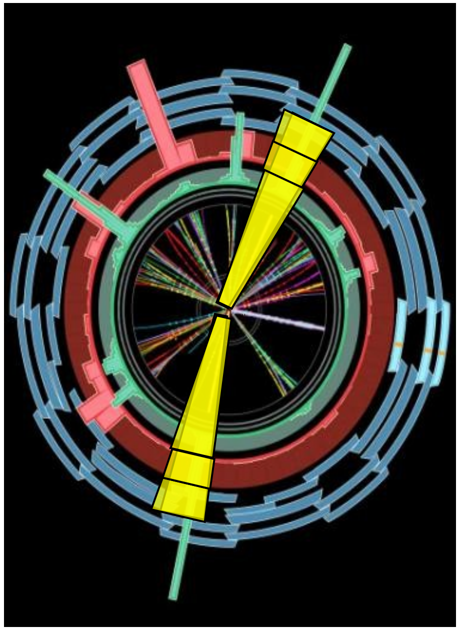


Trigger design: L1

- L1 reduce trigger rate to ~75 kHz
- L1 trigger has a very short time budget
  - 2.5 μs - much of this used up in cable delays!
- Detectors used must provide data very promptly, must be simple to analyse
  - Coarse grain data from calorimeters
  - Fast parts of muon spectrometer (I.e. not precision chambers)
  - NOT Inner detector - too slow, too complex
    - Although LHCb does use some tracking data from their VELO detector to veto events with more than 1 primary vertex
    - And CMS and ATLAS both considering a L1 Track Trigger for a future upgrade (~2020)

HLT Trigger Design: L2 and EF

- Reduce trigger rate to few kHz at L2, 200-300Hz at EF
- L2 trigger has a short time budget
  - On average ~40 ms at L2, ~4 s at EF in ATLAS
    - Note, for Level-1 the time budget is a hard limit for every event, for the High Level Trigger it is the average that matters, so some events can take several times the average, provided they are a minority
- Full detector data is available, but to minimise resources
  - Limit the data accessed
  - Only unpack detector data when it is needed
  - Use information from L1 to guide the process
    - Region of Interest (RoI)
  - Use dedicated fast algorithms at L2, offline-like algorithms at EF
  - Stepwise reconstruction

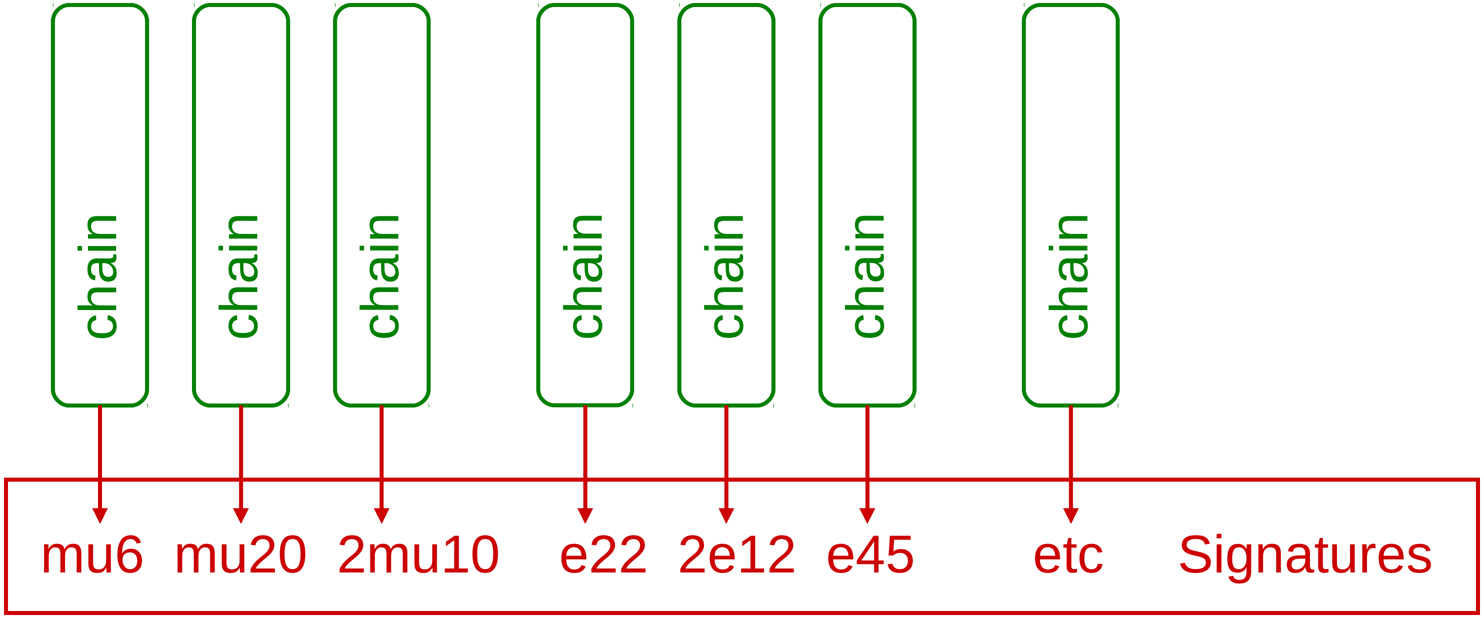


Precision w.r.t. offline

- Precision of L2 - similar caveats as L1
  - Emphasis on very fast algorithms with reasonable accuracy
  - Do not apply many corrections which may be applied off-line
  - Calibrations and alignment are not as precise as offline ones
- Precision of EF
  - Better than L2, but still a bit worse than offline
    - Calibration and alignment comes from the time of data-taking, offline will improve with time
    - Some time consuming elements not run (e.g. for bremsstrahlung recovery for electrons

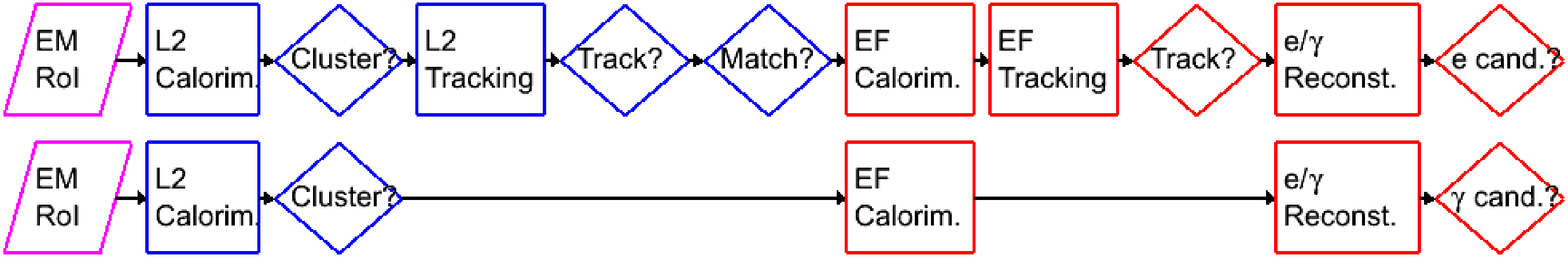
Selection chain

- Reject as fast as possible
- Signature = candidate of given particle type based on some given identification criteria, e.g. electron, muon, jet…) above given energy (or transverse energy (E_T)
  - Based on these we select "events" of interest for your studies
- For each signature there is a chain of processing steps for each trigger level (L1, L2, EF) (in CMS called "trigger path")



Selection chain: Example e/γ

- Steps
  - Cluster reconstruction and e/g identification
  - Track reco for electron and calculation of track quality and track cluster position matching
  - Decision based on “narrowness“ of EM calorimeter cluster plus for electrons track quality and track-cluster position differences
  - Reconstruction and decision steps are interleaved
  - If decision is negative, stop processing and look at next RoI in the event
  - Very similar at L2 and EF



How to organise all the different triggers

- What is needed
  - Accommodate all trigger items needed to cover the physics programme
  - cope with changing luminosities
  - Be able to add triggers if needed (e.g. new triggers upon discovery of new particles)
- Prepare a "trigger menu"
  - defines all of the physics we want to do at our experiment
  - Each trigger item is defined by trigger chains (can contain one or more chains)
  - Event is stored if one or more trigger items are passed
- In hadron collider experiments you typically define few 100 triggers per menu

Trigger item

- Trigger item consist of
  - Set of interesting signatures (electrons, muons, taus, jets, photons, missing E_T)
  - Examples
    - One electron with E_T>22GeV (e22_medium)
    - 2 muons with E_T>10GeV (2mu10)
    - 2 jets and missing E_T (2j50_xe20)
    - B meson decaying into 2 muons (apply invariant mass cut) (Bmumu)
- Each trigger item can be prescaled, thus only a fraction of the events satisfying the criteria for given trigger item is recorded. This fraction is determined by the prescale factor
  - Typically used for trigger which are not the main ones and for which it is enough to select only a part of the produced events

What makes up a menu

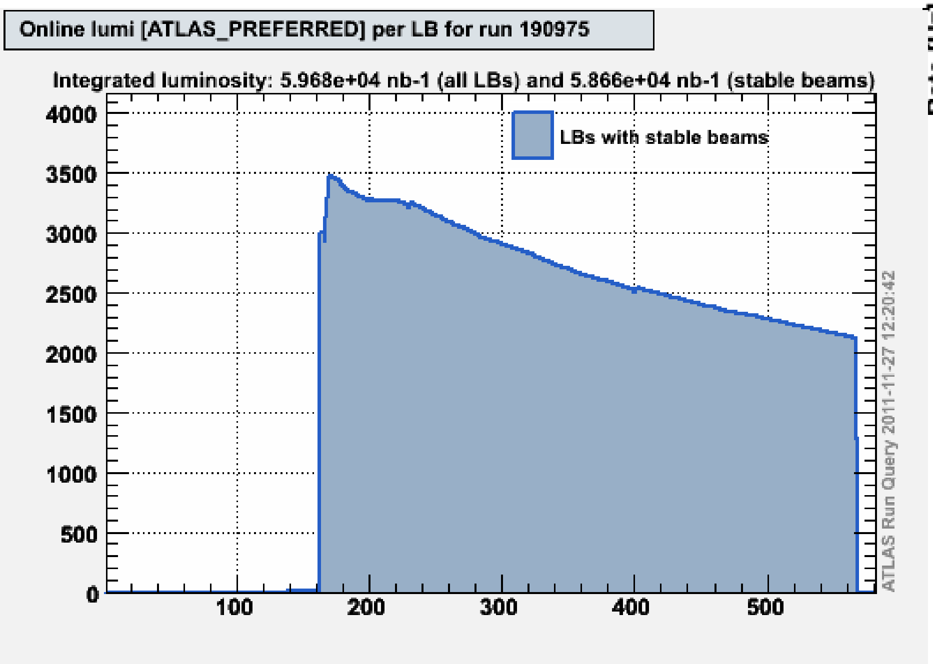
- Physics triggers (typically take all of them)
  - e.g. mu20 (one muon with E_T>20GeV, useful for many analysis from SM to searches for new particles (Higgs, Susy, …)
  - Obviously most of the trigger bandwidth is used for these
- Supporting trigger (typically prescaled)
  - Needed to understand (support) your physics analysis for e.g.
    - Measure trigger efficiency
    - Understand your backgrounds
  - Calibration Triggers
    - E.g. select events selected by L1 only
  - Monitoring triggers
    - E.g. select $Z \rightarrow ll$ events
- Putting the "correct" menu together is a must as this determines the physics we select for offline analysis

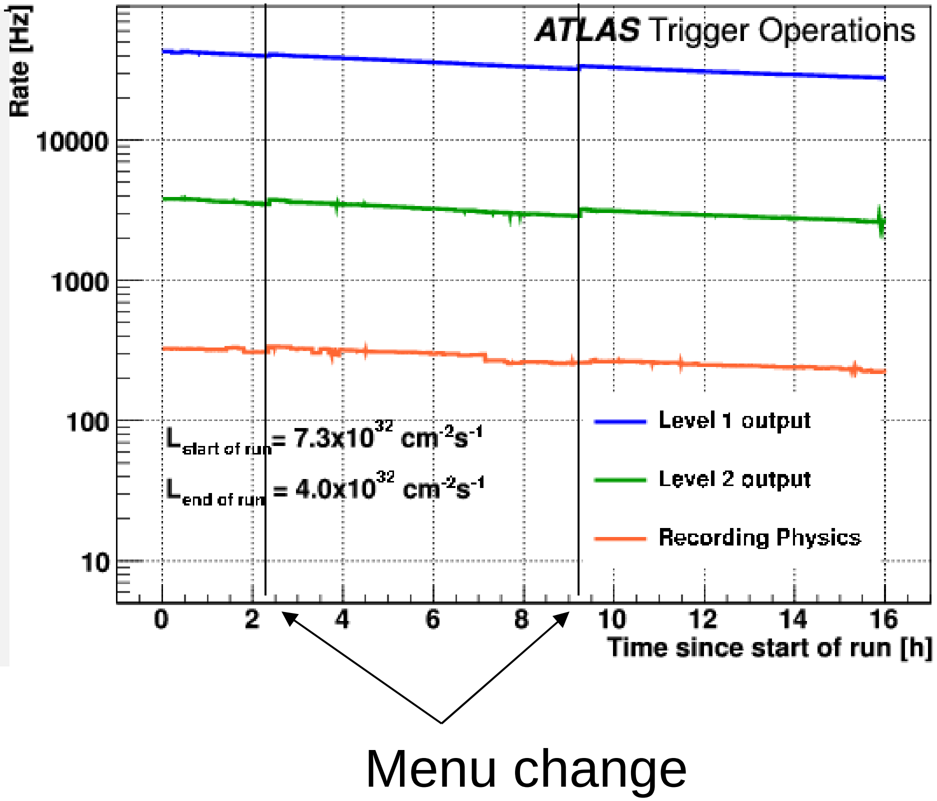
Example for physics triggers

Objects	Physics signatures
Electron 1e>25, 2e>15 GeV	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top
Photon 1γ>60, 2γ>20 GeV	Higgs (SM, MSSM), extra dimensions, SUSY
Muon 1μ>20, 2μ>10 GeV	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top
Jet 1j>360, 3j>150, 4j>100 GeV	SUSY, compositeness, resonances
Jet >60 + $E_T$miss >60 GeV	SUSY, leptoquarks
Tau >30 + $E_T$miss >40 GeV	Extended Higgs models, SUSY

Menu changes

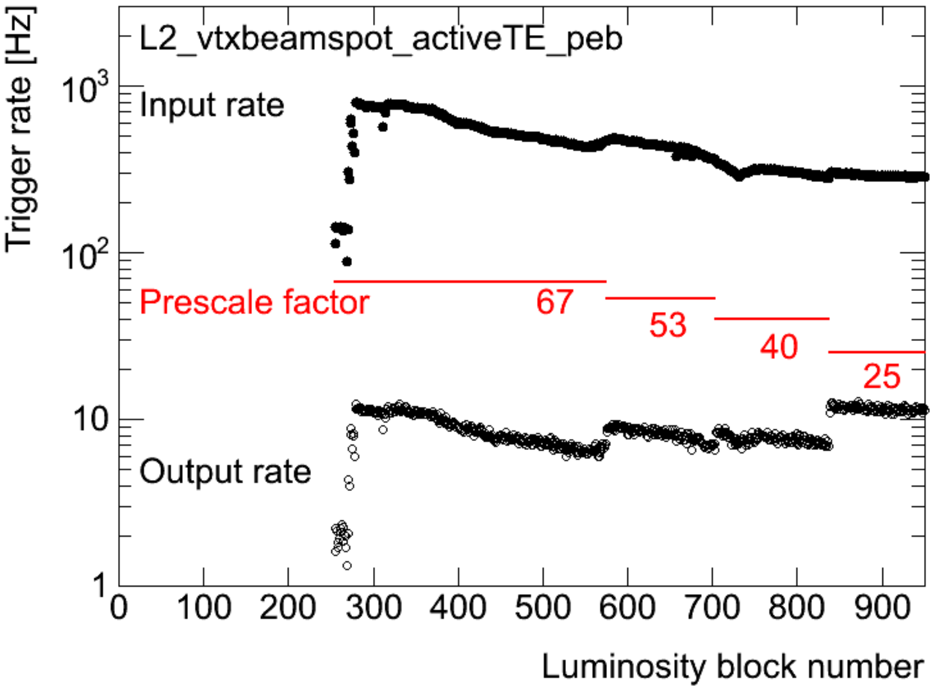
- Menus are typically changed during time LHC provides collisions as luminosity drops
  - Ensures the bandwidth is used in an optimal way
  - change rate of prescaled triggers





Prescale changes

- Example: beamspot trigger at L2 (tells us where collisions happen)
- trigger is off before collisions from LHC arrive
- As the beam intensity falls, the input rate drops by almost a factor of 4. The prescale factor is reduced
- keep the output rate between about 6 to 12 Hz.

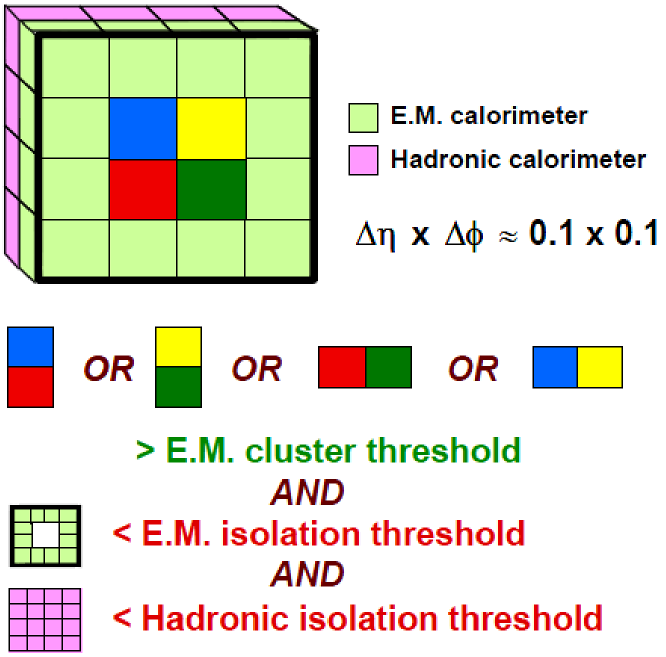


Trigger Selections

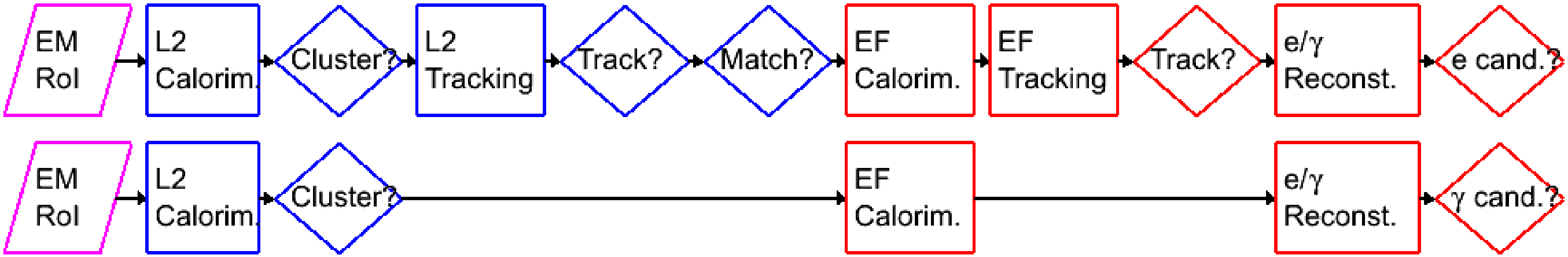
- Some example on how particles are selected in the trigger
  - Electron and photons
  - Muons

Electron and Photon Trigger: L1

- Coarse granularity
  - ~ 7200 trigger tower with a granularity of $\Delta\eta\times\Delta\varphi = 0.1\times0.1$ (note in EM calo readout cell granularity is $\Delta\eta\times\Delta\varphi = 0.003\text{-}0.006\times0.1$ in 1st layer, 0.025×0.025 in 2nd layer and 0.05×0.05 in 3rd layer)
  - Distinguish EM and HAD tower
- Algorithm
  - Run cluster finding using the energy in 4×4 towers
  - Search for local maximum
  - Retain cluster (composed of 2 towers) with max E_T value
  - Calculate isolation variables: EM and hadronic
- Selection based on multiplicities and thresholds use E_T, EM_{ISO}, HAD_{ISO}



Electron and Photon Trigger: L2 and EF



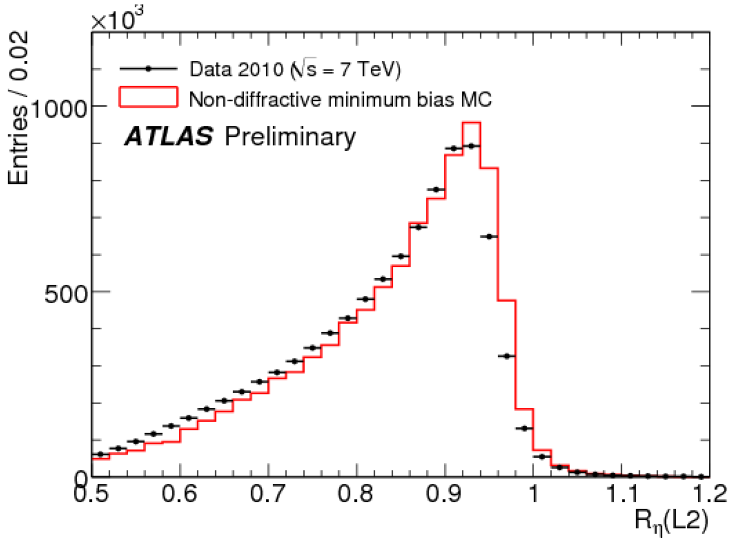
- Cluster reconstruction and e/g identification
- Track reco for electron and calculation of track quality and track cluster position matching
- Decision based on “narrowness“ of EM calorimeter cluster plus for electrons track quality and track-cluster position differences

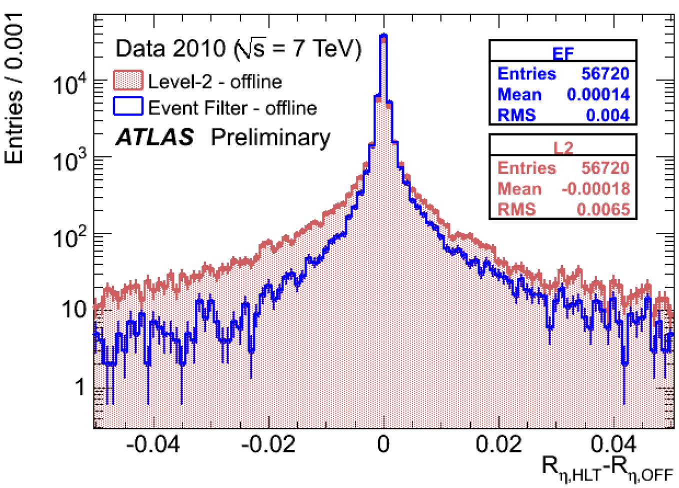
Electron and Photon Trigger: L2 and EF

- Example: shape of electron candidate in the 2nd EM layer (in $\eta\times\varphi$ space)

$$R_{\text{eta}} = \frac{E(0.075\times0.175)}{E(0.175\times0.175)}$$

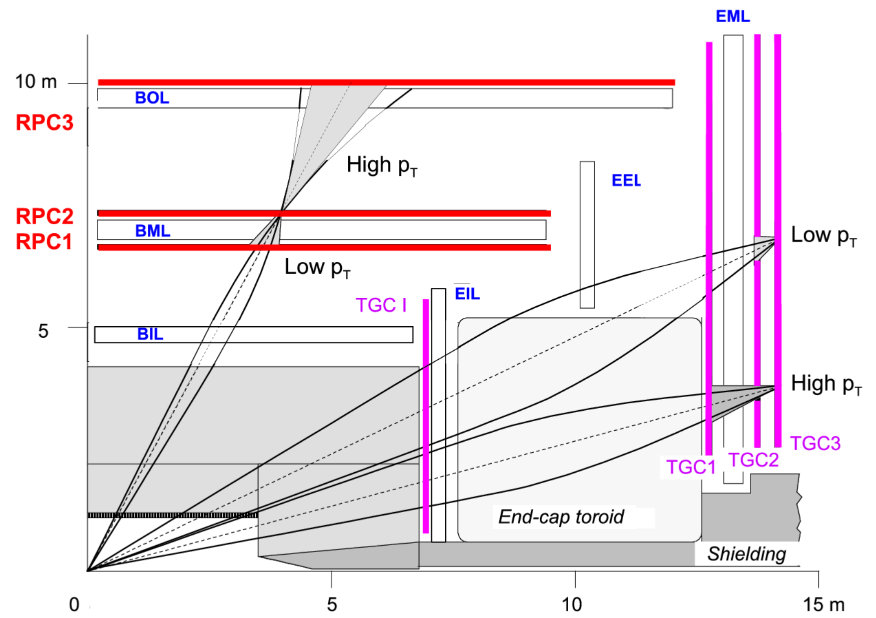
  - Note, >70% of the energy of e/γ is deposited in 2nd layer
  - Ratio is used to select electron and photon candidates
  - Ratio $\rightarrow$ 1 for e/γ as most of the energy is found in 0.075×0.125
- Precision for calculating this variable is better at EF than at L2





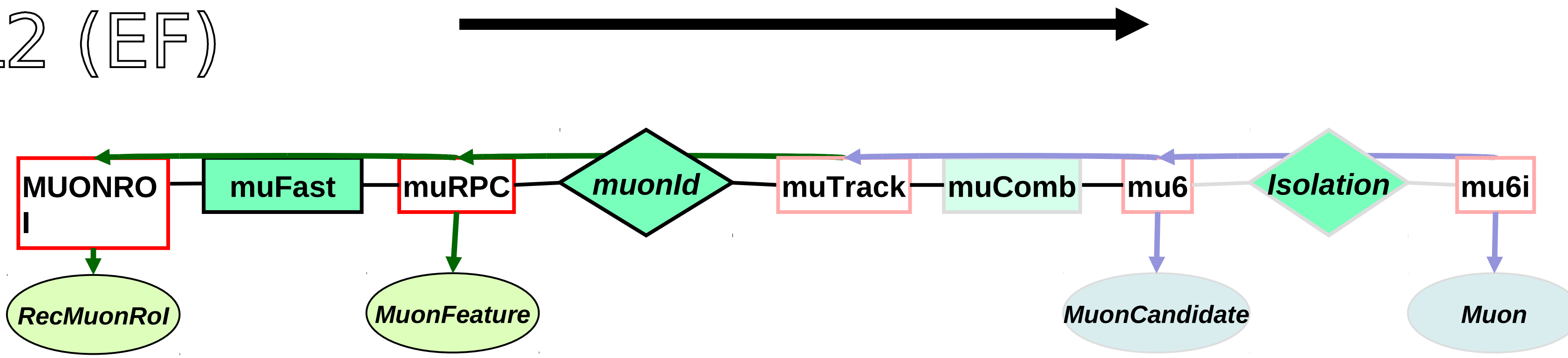
Muon Trigger: L1

- Dedicated muon trigger chambers with good time resolution:
- Search for patterns of hits consistent with muons coming from interaction point
- Three trigger stations in each region, require coincidence of hits in different stations within a road (size depends on p_T)
  - Number of coincidences required depends on p_T

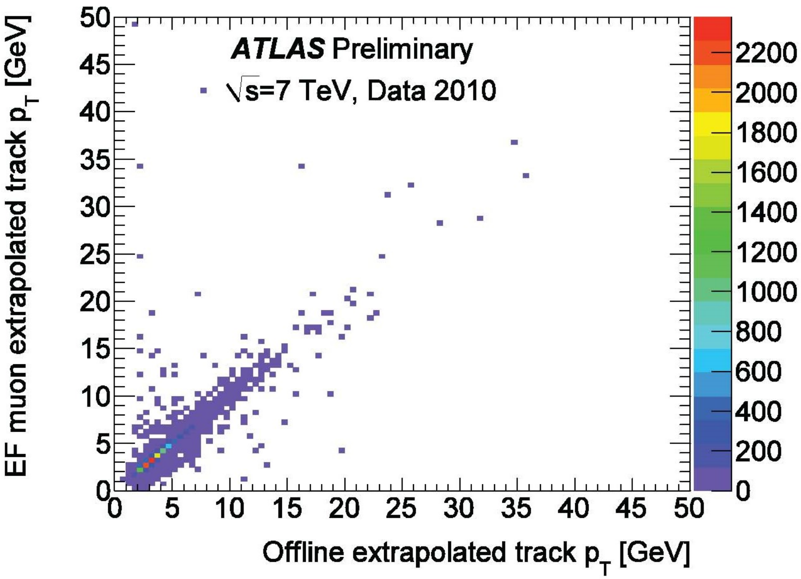


Muon Trigger: HLT

L2 (EF)



- Steps
  - Muon reconstruction done in muon detector first, then track reconstruction in inner detector and then tracks are combined
  - Selection based on p_T
- Example: EF vs offline p_T



Trigger Efficiency

- Trigger efficiency needs to be precisely measured since it enters in the calculation of the cross-sections

$$\varepsilon_{\text{trig}} = \frac{\text{Number of events passing trigger selection}}{\text{Number of events without trigger selection}}$$

- Trigger efficiency is usually measured w.r.t. offline, such that

$$\sigma(\text{signal}) = \frac{(N_{\text{cand}} - N_{\text{bkg}})}{\alpha \cdot \varepsilon_{\text{trig}} \cdot \varepsilon_{\text{offline}} \cdot \int L dt} \text{ with } \varepsilon_{\text{trig}} = \varepsilon(\text{L1}) \cdot \varepsilon(\text{L2}) \cdot \varepsilon(\text{EF})$$

- Your trigger is used to collect your data
  - You cannot blindly use your data to study efficiency
- Need an unbiased measurement of trigger efficiency

Trigger efficiency measurements

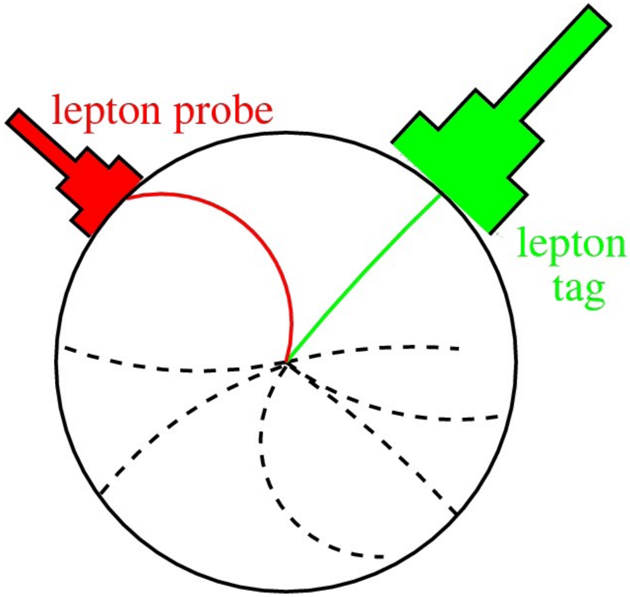
- Random sample of pp collisions
- Bootstrapping via pass-through triggers
  - Use looser trigger, e.g. apply only L1 selection, but nothing at L2

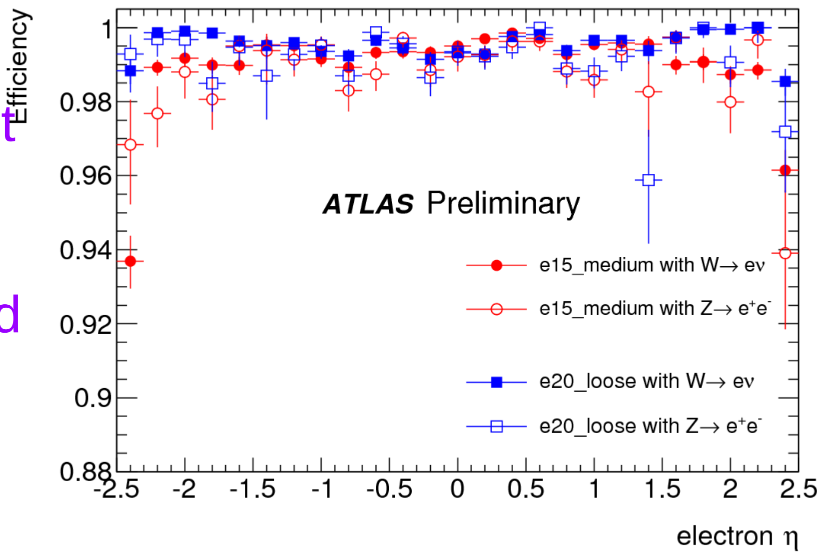
$$\varepsilon(\text{L2 mu20}) = \frac{\text{events passing L2 mu20}}{\text{events passing L2 mu20 in pass} - \text{through}}$$

  - Drawback: you might measure the efficiency of your signal plus some background
- Use "orthogonal" trigger
  - Trigger on certain particle type in the event, measure another one
    - For example use muon triggered events to measure jet trigger efficiency
  - Method might suffers from your topology (you might select more (less) crowded events)
- Use simulations
  - MC must very well describe the data

Trigger Efficiency Measurement

- Use well-known physics processes and do "tag & probe"
  - $Z \rightarrow ll$, $J/\Psi \rightarrow ll$: trigger only on one electrons
  - $W \rightarrow l\nu$: trigger on missing E_T
  - Most precise way to calculate efficiencies
- Example: $Z \rightarrow ee$ tag and probe
  - Trigger on one of the electrons
  - Select offline events with 2 good electrons which have an invariant mass around the Z mass
  - "tag" electron: well identified, coincides with electron which triggered event
  - "probe" electron: check if this one passed or failed the trigger selection

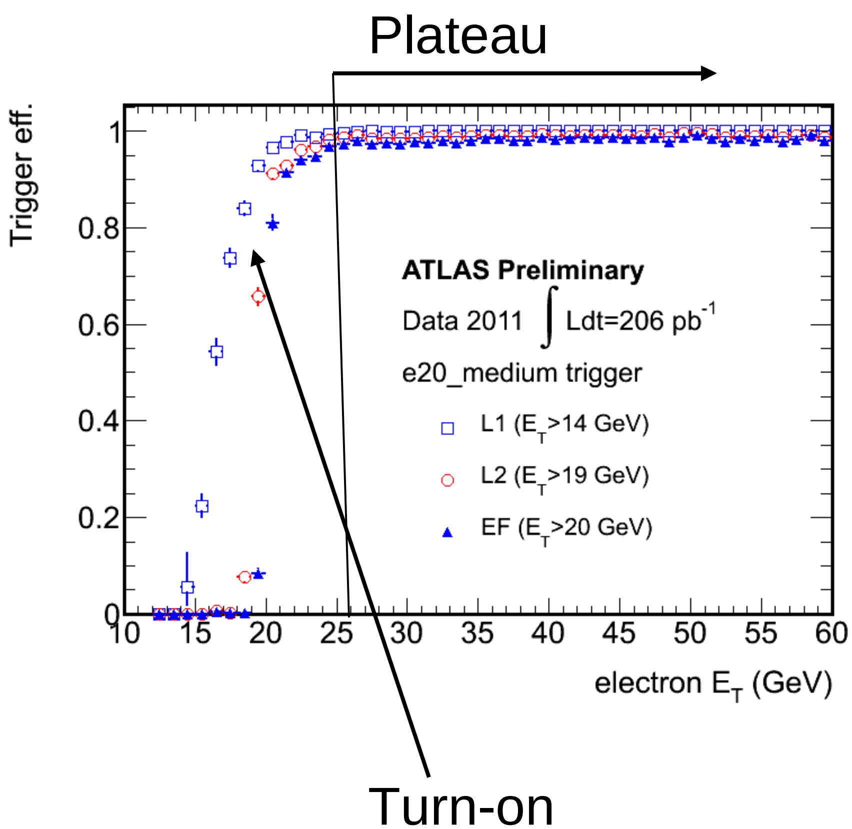




Turn-on and plateau

- The trigger efficiency is usually measured as a function of the true p_T (E_T)
  - Often referred to as a trigger "turn-on" curve
- Since p_T (or E_T) resolution is finite, the trigger efficiency depends on the real (offline) p_T
  - E.g. some particles can be below threshold because p_T is underestimated
- As resolution worse at L1, typically use lower p_T threshold at L1 and then tighten threshold cut at L2 and EF
- Even when flat, the efficiency may not be 100%
  - Important to consider in the analysis

Example: Electron Turn-on



With increasing luminosity (more pileup)

- Larger occupancies in the detector
- Trigger algorithms perform worse
  - Identification criteria needs changing
  - Purity gets worse (rate goes up) or efficiency drops
  - Thresholds need to be raised
- Events become larger
  - Problem for event storage
  - Need to shuffle more data through DAQ system
- HLT needs to work harder
  - E.g. to do tracking at higher occupancies, algorithms need more time
- To keep the performance of the detector a lot of components need to be upgraded in Trigger and DAQ

Trends / recent developments

- Use GPUs
  - Abbreviation for Graphics Processing Units
  - Act as co-processors for CPUs
  - Operate at Teraflop level
    - Flop: number of floating point operations per second
  - Originally used for graphics applications, now fully programmable
  - Work well for data parallel operations but not good for memory access and serial operations
- In HEP could become very useful for data unpacking and some of our algorithms
- 1st Teraflop chips soon available on the market

LHC upgrade

- We are investigating running at even higher luminosities of **5×10^{34} $cm^{-2}s^{-1}$** which is 5 x design lumi = 5 × more pileup
- Trigger and DAQ need to be heavily upgraded for this scenario.
  - Probably Tracker information need to be added to the trigger at L1
  - Calorimeter L1 triggers need to work with finer granularities in order to be able to be more selective using e.g. better isolation cuts or adding shape cuts
- Event size will grow due to detector upgrades (more channels) and more pile-up
- DAQ needs substantially higher data throughput

Real Life

- A lot of hardware components become old …
  - System reliability decreases
    - It makes sense to replace PCs every 4 years
    - It make sense to replace network equipment every 7 years
    - Custom hardware is usually kept longer… but of course it also starts breaking…

General behaviour of hardware components

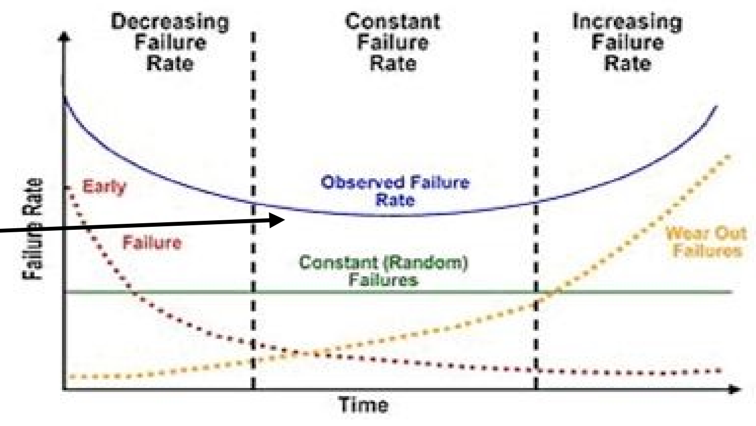


Figure 1: Failure rate versus t

Trigger Upgrade Projects

- Upgrade technology for very high lumi
  - Larger state of the art FPGA devices
    - Larger granularity needed
    - The trigger needs to cope with more channels
  - More modern link technology to interconnect processing boards
    - Multi Gigabit serial links
  - Use of Telecommunication technology (uTCA crates with customised backplanes)

DAQ upgrade projects

- Increase bandwidth of Event Builder
  - New Readout links
    - Possibly with standard protocols
    - Connect directly to industrial network technology (TCP/IP?)
  - Event builder switch network
    - Move to 10Gb/Ethernet
  - HLT farm
    - Higher multi-core machines
    - Use of GPUs
- Specific DAQ problem: backwards compatibility
  - Not all sub-systems do the upgrade at the same time
  - Old and new readout systems need to co-exist
    - This prevents the possibility of radical changes (and unfortunately radical improvements are not feasible even though technical possible)

Summary

- Showed how the trigger works at LHC
  - Selection using several trigger levels with increasing amount of detail and precision
  - Trigger strategy is trade-off between physics requirements and affordable systems and technologies
- Introduction to
  - sequence of selection and decision steps (chains)
  - trigger menu
  - Efficiency extraction and turn-on