Monika Wielers

Rutherford Appleton Laboratory

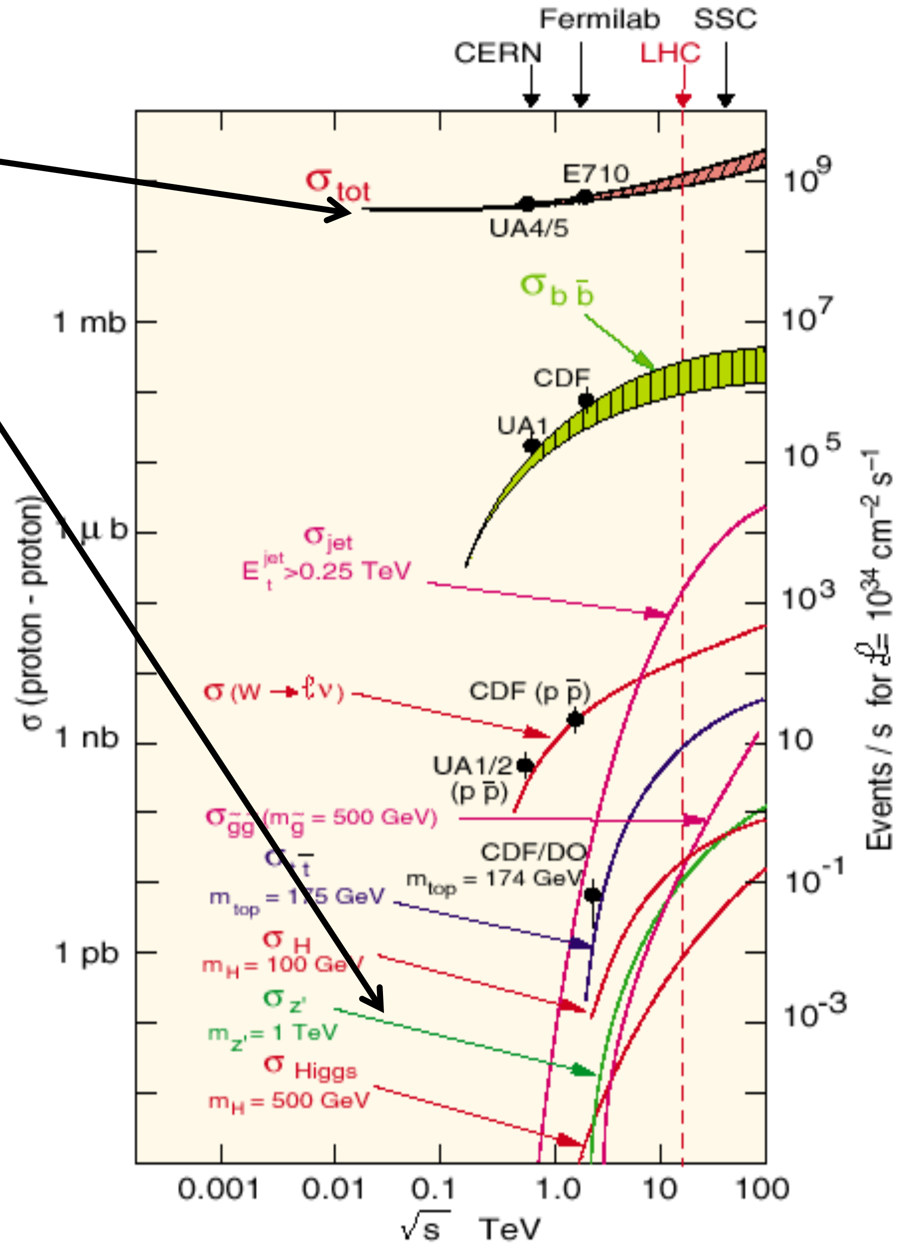
- Lecture 3
  - Trigger

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 to minimise deadtime (reject as fast as possible)
- Today we’ll learn more how the trigger looks
  - Again we take ATLAS as an example

Why do I need a trigger at the LHC?

- Huge incoming rate of mainly “uninteresting” collisions
- Impossible to save all collisions
  - Would result in O(100000) PetaByte or O(1000) Exabyte per year of data per experiment
    - For comparison: 5 Exabytes: All words ever spoken by human beings.
- Impossible to reconstruct and analyse
- Need a system to select only the interesting event



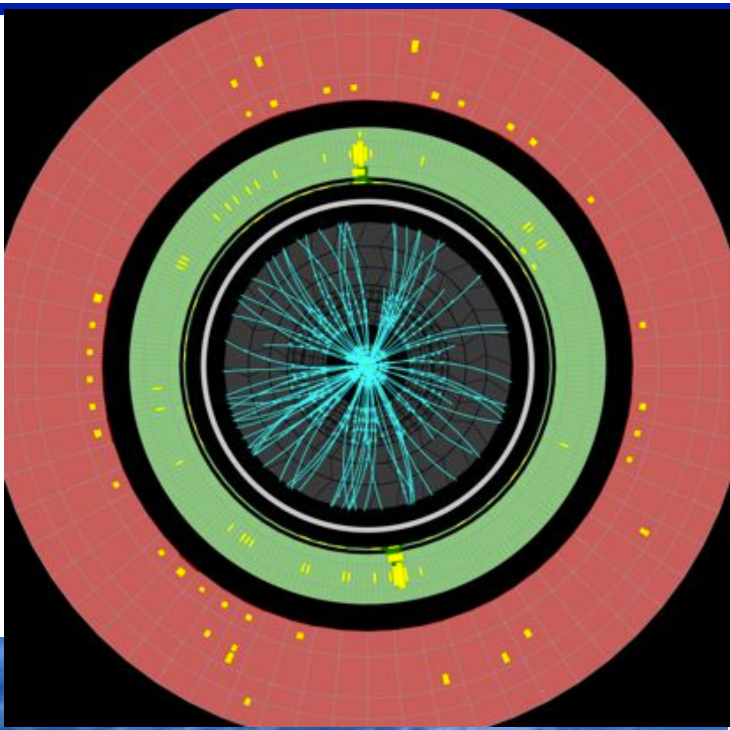
Trigger = Rejection

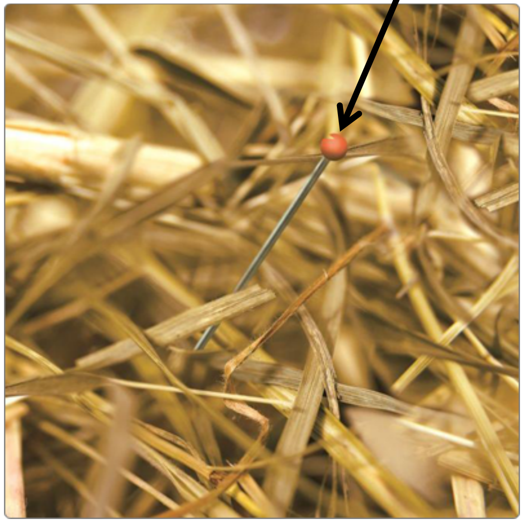
- Problem: We must analyse and reject most collisions prior to storage
- Solution: Trigger
  - Fast processing
  - High rejection factor: $10^4 - 10^5$
  - High efficiency for interesting physics

- Note as the incoming rate is now that high, the trigger itself is a ‘severe’ physics decision
- Make sure your favourite physics channel is selected with high efficiency
  - Amount of data we can write out is limited and many trigger/ physics analyses will compete with you

Example: H→γγ

- Roughly one light (125 GeV) Higgs for every 10,000,000,000 pp interactions
- H→γγ is rare decay with BR ~10^{-3}
- Approx. 1 H→γγ per 10,000,000,000,000 interactions
- Make sure you select them all….



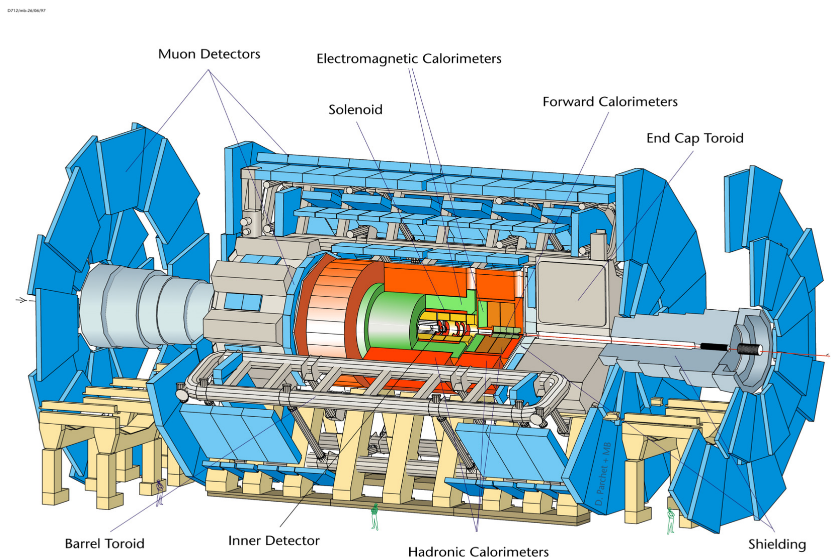


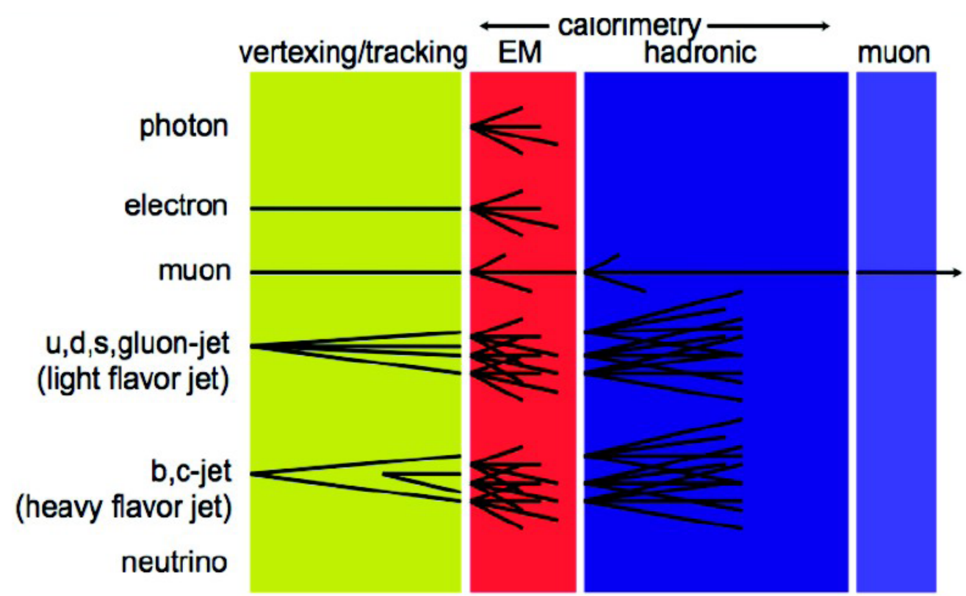
Other Challenges

- Accelerator and Detector
  - Bunch crossing frequency of 20 (40) MHz currently (design)
  - LHC produces now up to ~30 overlapping p-p interactions every 50 ns. Every 50ns LHC flushes detector with ~1000-2000 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
  - Any events thrown away is lost for ever!

How do I select interesting collisions

- Need to identify the different particles produced
- 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)





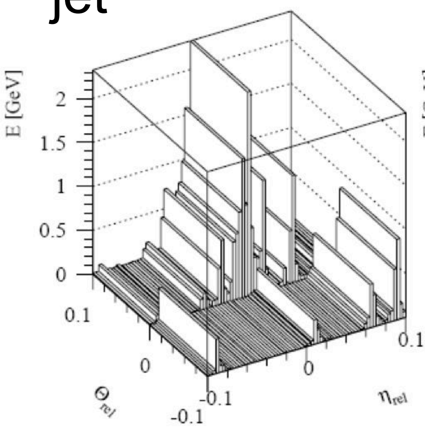
How do I select interesting collisions

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

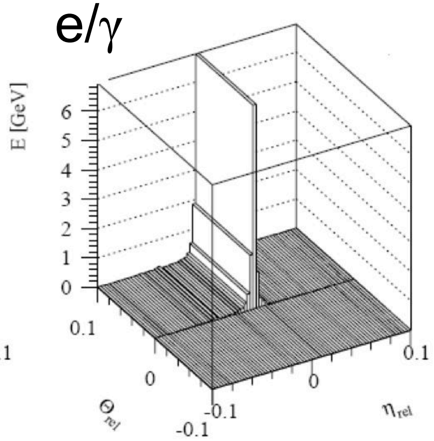
Detector feature
(deposit in EM calorimeter)

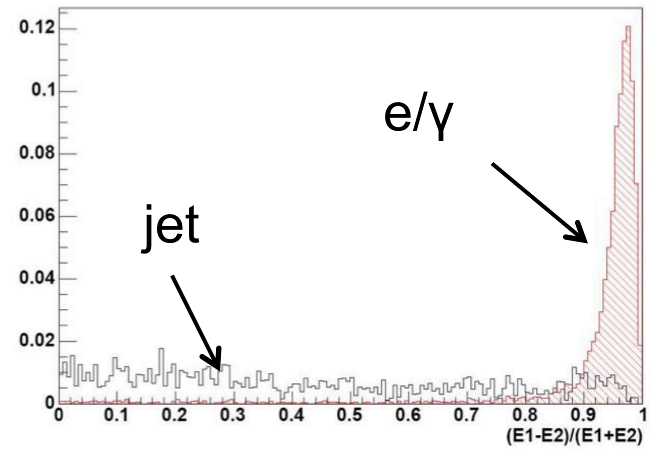
Trigger quantity

jet



e/γ





- Example: Electrons
  - Is the E_T high enough?
  - Does the cluster shape is similar to that of an electron/photon?
  - Is only little energy deposited in the hadronic calorimeter?
  - Is there a well matched track pointing to the cluster?
  - Is the electron isolated?

To decide if you want to keep certain events

- Use the identified particles above given (transverse) energy thresholds
  - Isolated electron, muon and photons,
  - τ-, central- and forward-jets, jets from b-decays
  - Events with missing E_T, missing E_T significance
- You can select events according to a combination of the above signatures
  - E.g. one electron and one muon, 4 jets etc
- The set of triggers or trigger items to be run online is called Trigger Menu

- Let's look at this in more 'technical' terms using ATLAS as an example

Trigger Design (ATLAS)

design
currently

Trigger

Three logical levels

40 MHz
20 MHz

~ μs

L1 - Fastest: Only Calo and Muon (hardwired)

75 kHz
< 75kHz

~ ms

L2 - Local: L1 refinement + track association

~ kHz
5 kHz

~ sec.

EF - Full event: "Offline" analysis

~ 200-300 Hz
300-1000 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

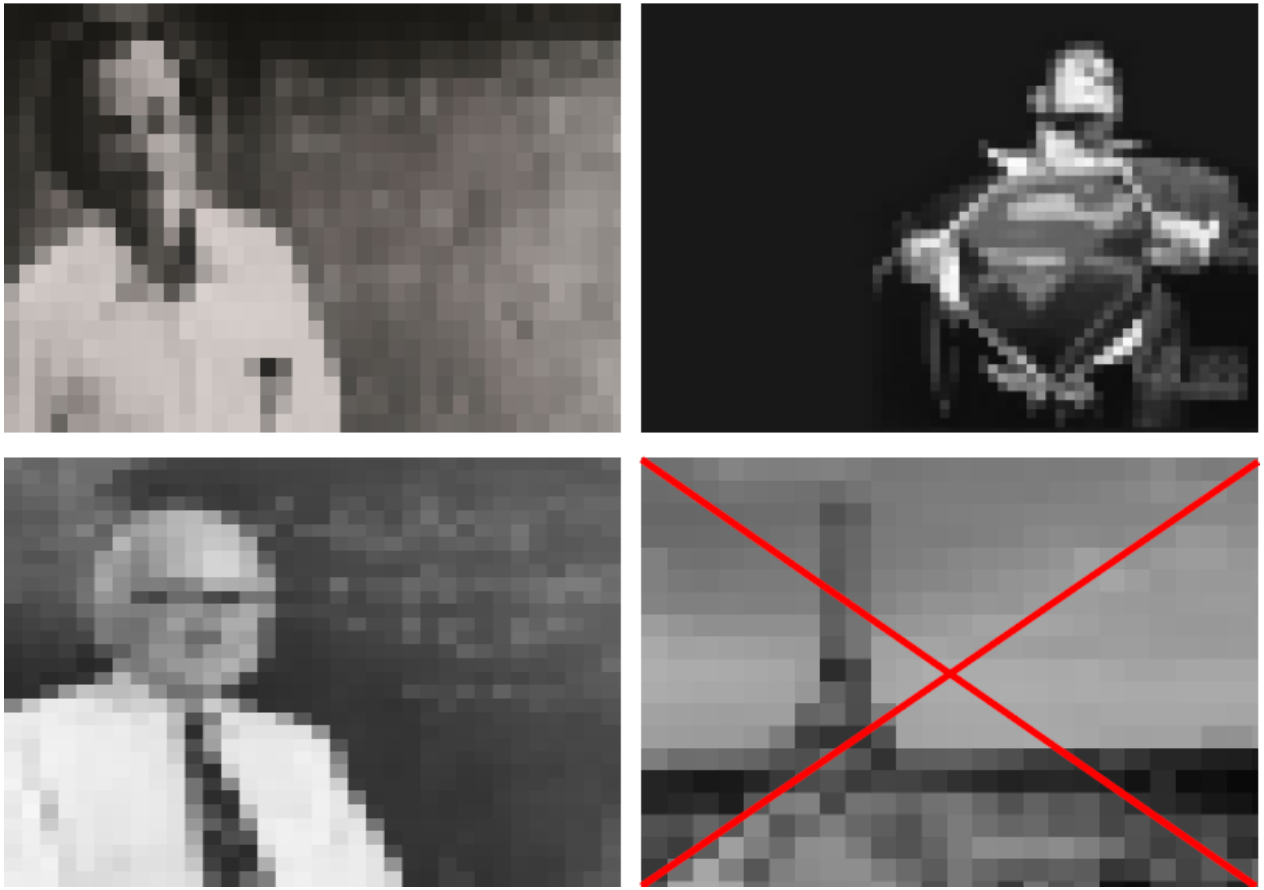
Example: Higgs

- L1
  Coarse granularity

Example: Higgs

- L2

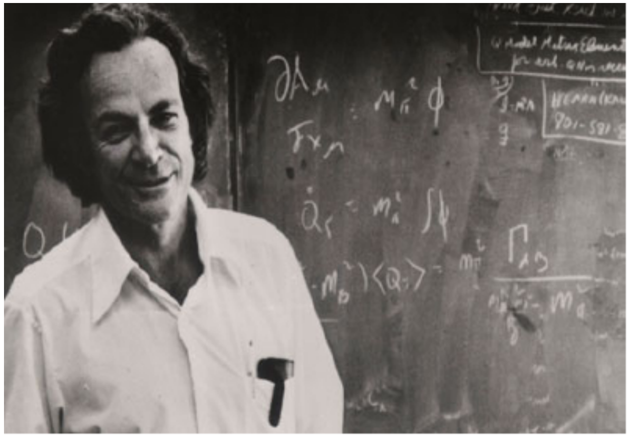
  Improved reconstruction, improved ability to reject events

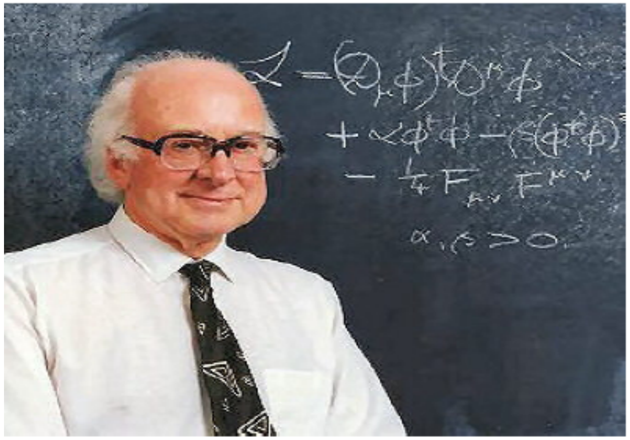
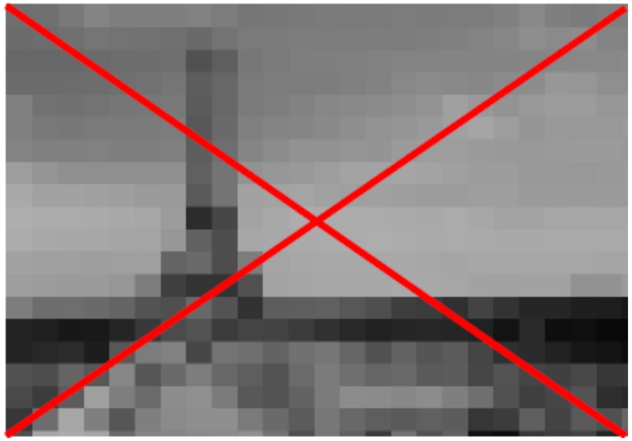


Example: Higgs

- EF

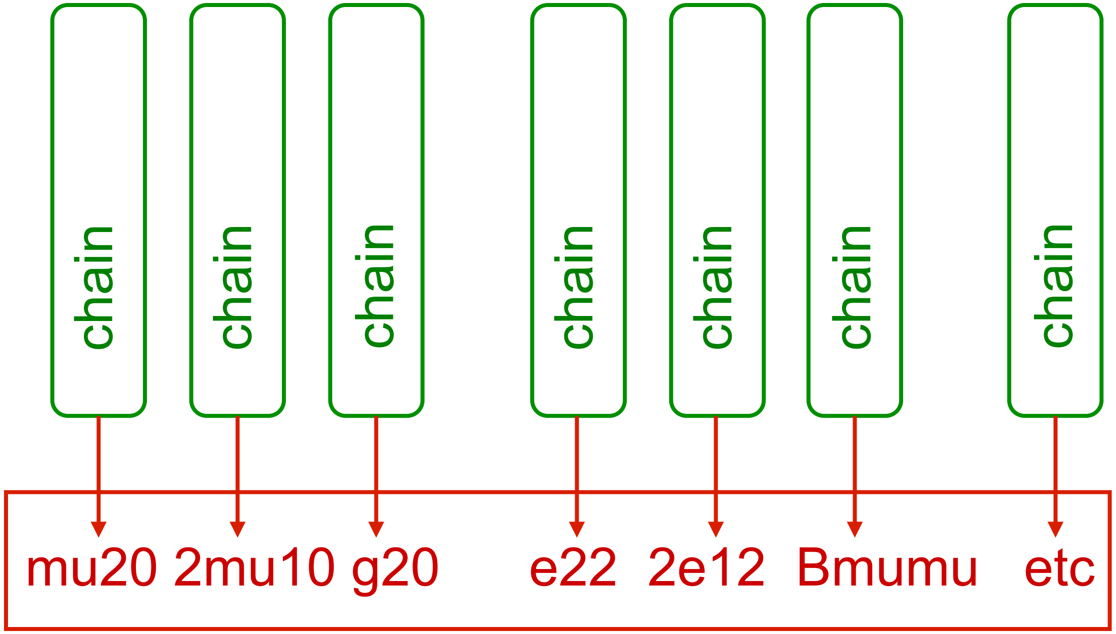
  high quality reconstruction, improved ability to reject events



Selection chain / trigger path

- Select particle candidate based on some given identification criteria, e.g. electron, muon, jet…) above given energy (or transverse energy (E_T)
- For each trigger / signature there is a chain of processing steps for each trigger level (L1, L2, EF) (in CMS called "trigger path")
  - E.g: reconstruct cluster, identify electron, reconstruct track, identify $e^{\pm}$
- Examples
  - One electron with E_T>22GeV
  - 2 muons with E_T> 10GeV
  - 2 jets and missing E_T
  - B meson decaying into 2 muons (apply invariant mass cut)



- Based on these we base the online selection (Trigger Decision)

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
  - Event is stored if one or more trigger items are passed
- Currently we run 500-700 triggers online!


Today's Specials


Electrons

e24 (24 electron raviolis) £7.95

2e12 (2 12 oz electron steaks) £9.95

Muons

Mu24 (24 dl muon soup) £5.95

2mu10 (2 pizze 10cm ⃠) £7.95

Jets

4j50 (4 jet pancakes) £8:95

J500 (500g grilled jet fish) £16:95

Mixed triggers

J50_ETmiss50 (yummy jet with missing french fries) £10:95

Tau40_e20 (tau salad with electrons) £8.95

Trigger item

- 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
    - Example: trigger for efficiency extraction, trigger to select samples for data-driven background subtraction
    - Also used for physics measurements if you can't keep all of them

What makes up a Menu

- Physics triggers (typically take all of them)
  - e.g. mu24 (one muon with E_T>24GeV, 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/offline 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 can do in the offline analysis

Delayed stream / data parking

- Delayed stream (ATLAS), data parking (CMS) implies you do not reconstruct the data directly after data taking but whenever you 'have time'
  - Useful if you have the capacity to write out more data, but do not have the capacity to reconstruct them offline
  - Save additional 100-200 Hz in ATLAS and 350 Hz in CMS
- Example: samples not used for searches such as B-physics, low-p_T physics

Example for physics triggers

Object	Trigger (ATLAS)	Trigger (CMS)	Physics Signature
Muon	1μ > 24 GeV	1μ > 24	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top
	2μ > 13 GeV	1μ > 17 + 1μ > 8	
Electron	1e > 25 GeV	1e > 27	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top
	2e > 15 GeV	1e > 17, 1e > 8	
Photon	1γ > 120 GeV	1γ > 150	Higgs (SM, MSSM), extra dimensions, SUSY
	2γ > 20 GeV	1γ > 22 + 1γ > 36	
Jet	1j > 360 GeV	1j > 320	SUSY, compositeness, resonances
	4j > 80 GeV	4j > 50	

Plus many more mixed triggers: 4 jets > 45, 1 tagged as b-jet, Jet > 170 + E_T^{miss}>80 GeV, Tau > 27 + E_T^{miss}> 50

Plus topological triggers: B-physics: 2μ>6GeV with invariant mass near the B mass

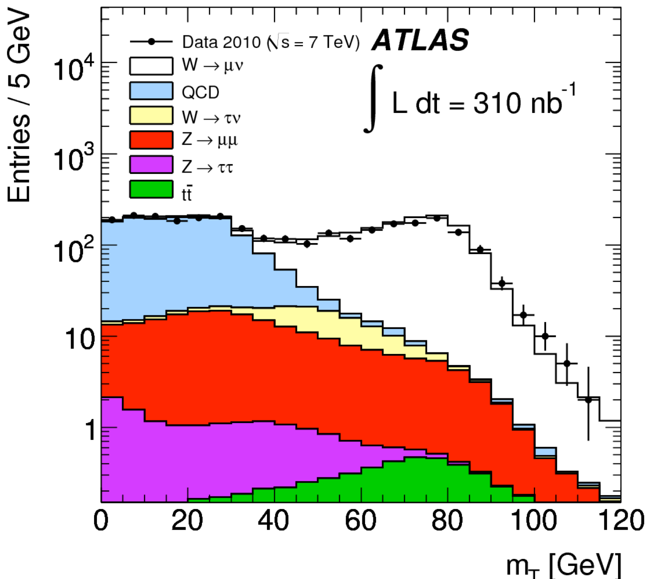
Plus, plus, plus

How to design a trigger

- First understand the physics you want to do
  - Which are the particles in your final state and how high is their E_T?
- Figure out how to select the data
  - Figure out if there is already a trigger in place which does the job well
    - No need to design a new one if it’s already covered
  - If not, try to think up a new trigger
    - Can you combine several particles into one trigger, e.g. muon + 2 bjets?
    - Can you take advantage of the topology of your event, e.g. invariant mass, back-to-back topology?
    - Also keep in mind that the trigger reconstruction is not as good as the offline one and your selections need to be looser
- Figure out if also other analyses might profit from your trigger
  - The more analyses there are the more likely you can get more of the bandwidth

Example: W cross section measurement

- How do I reconstruct W's in the offline?
  - Select events containing 1 electron or muon with high transverse energies (E_T > 25 GeV)
  - Select events with high missing transverse energy (E_T^{miss} > 20 GeV)
  - Calculate transverse mass
    - $M_T^2 = (E_{T,1} + E_{T,2})^2 - (\vec{p}_{T,1} + \vec{p}_{T,2})^2$
  - Extract background and subtract
  - Count events and convert in cross section
    - $\sigma(\text{signal}) = \dfrac{(N_{\text{cand}} - N_{\text{bkg}})}{\alpha \cdot \varepsilon_{\text{trig}} \cdot \varepsilon_{\text{offline}} \cdot \int L\,dt}$



- Trigger can select these events selecting high energetic electrons or muons and/or via E_T^{miss}
  - So what should I choose?

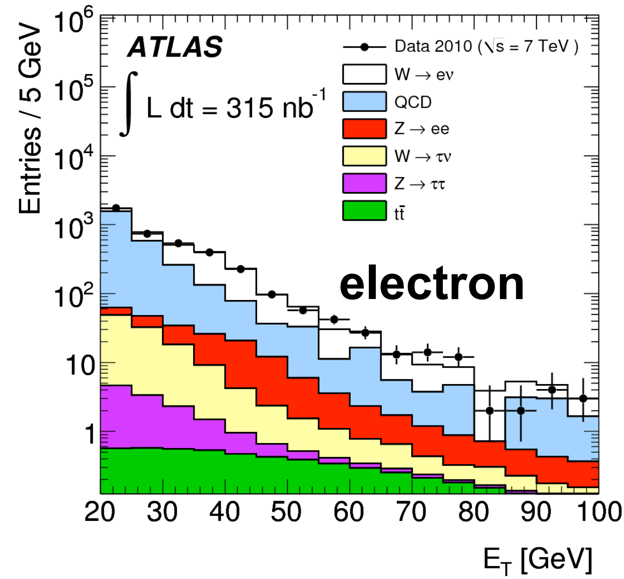
Example: Trigger for measuring W cross section

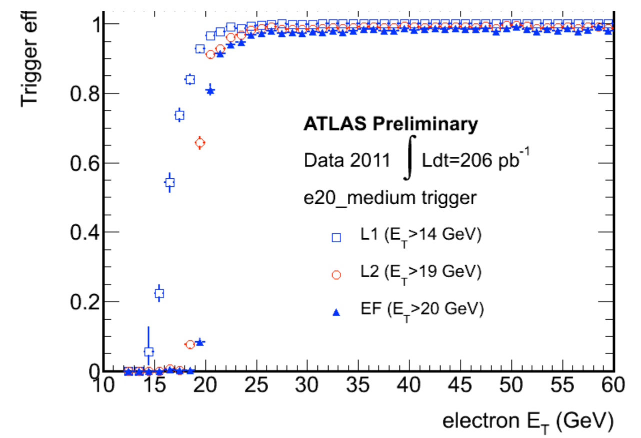
- E_T of the electrons and muons
  - Selection of E_T>20-30 GeV e/μ's will keep most of the W's

➡ Select events containing one high p_T e/μ

- Next: check the turn-on – trigger efficiency w.r.t. offline E_T near the trigger threshold
  - E.g. $e^{\pm}$-trigger with E_T = 20 GeV threshold (e20) efficient for offline E_T > 22 GeV, plateau for E_T > 25 GeV

  ➡ Trigger threshold few GeV lower than what you want in offline anbalysis (resolution effect)





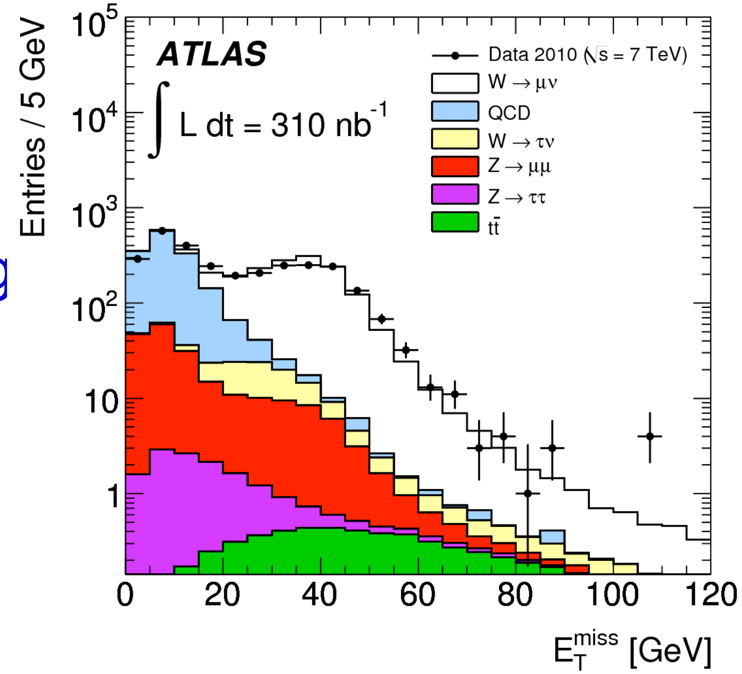
- Check the rate:
  - At luminosities of $L=8\times10^{33}$ $cm^{-2}s^{-1}$ for $\sqrt{s}$ = 8 TeV: Rate ≈ 500 Hz

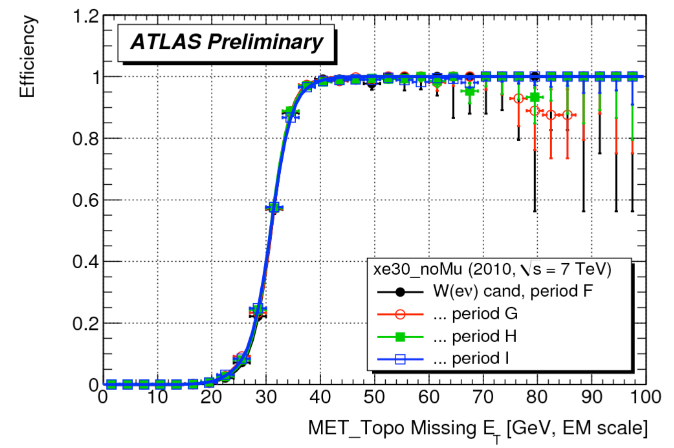
  ➡ Hmmm that's too much, need higher thresholds and tighter selection

  ➡ Currently we use isolated trigger with tighter selection and E_T>25GeV (Rate: 100Hz)

Example: Trigger for measuring W cross section

- And if the rate is still too high?
  - Even tighter selection (typical lower eff)
  - Even higher E_T
- Could we in addition ask for high missing E_T in the event?
  - Promising for E_T^{miss}>30 GeV
- Let's look at turn-on for E_T^{miss} > 30GeV
  - Efficient at offline E_T^{miss} > 40 GeV
- Rate:
  - ~5 kHz at L=8×10^33 cm^-2s^-1
  - Need to combine with e/μ
    - Electron with $E_T(e^{\pm})$ > 25 GeV + E_T^{miss} > 30 GeV: 30Hz
  - But now less analyses can use this trigger… perhaps rather higher E_T?
    - Best compromise needed…





What other triggers do I need: background trigger

- Now I e.g. select events with:
  - isolated electron with $E_T > 25$ GeV
  - unisolated electron with $E_T > 25$ GeV and E_T^{miss}>30GeV
- I need to estimate the background under my signal
  - Often done via cut-reversal (ABCD) method
- Need sample of events selected without or only loose electron selections,
  - e.g. need e25_loose (rate: 160 Hz)
  - Do not need all of them, so you can prescale by e.g. a factor of 100
    - Enough events for the analysis

	Pass $e^{\pm}$ identif.	Fail $e^{\pm}$ identif.
Low E_T^{miss}	A **(bkg enriched)**	B **(mainly bkg)**
High E_T^{miss}	C **(Signal + bkg)**	D **(bkg enriched)**

What other triggers do I need: efficiency extraction

- 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 as your trigger might have introduced a bias
- Need an unbiased measurement of trigger and offline efficiency

Methods for trigger efficiency measurements

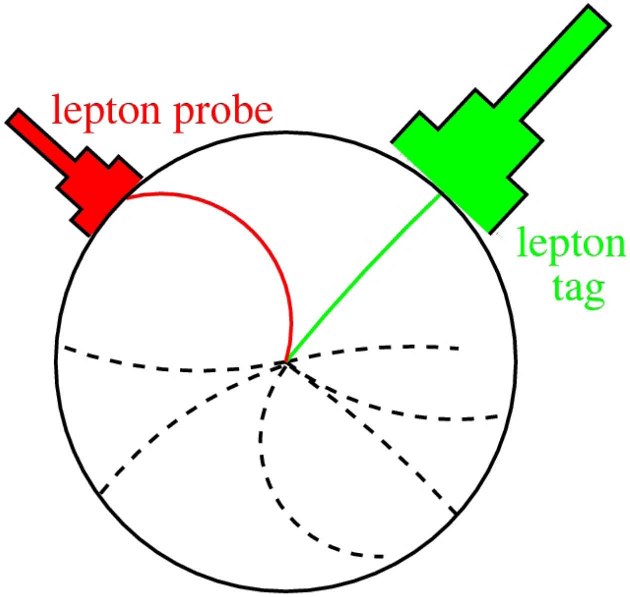
- Random sample of pp collisions
- Bootstrapping via pass-through triggers
  - Use looser trigger, e.g. apply only L1 selection, but nothing at L2

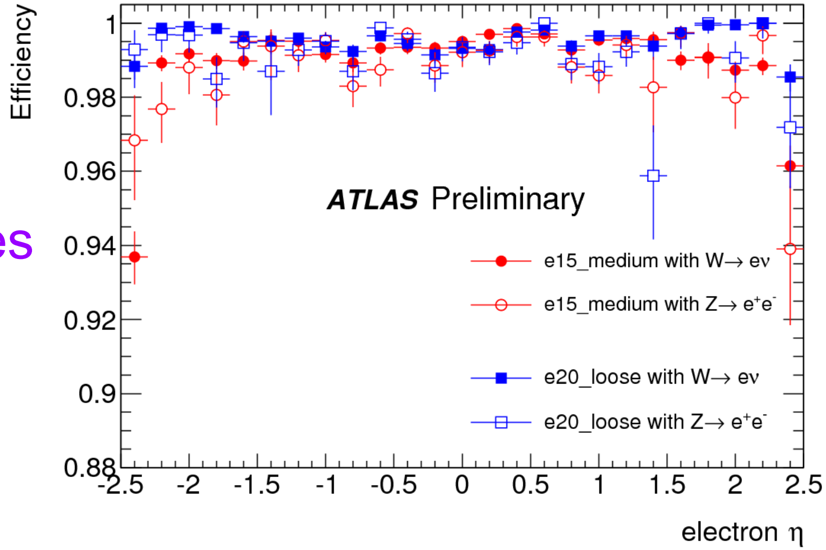
$$\varepsilon(\text{L2 mu20}) = \frac{\text{events passing L2 mu20}}{\text{events passing L2 mu20 in pass} - \text{through}}$$

  - 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 electron trigger efficiency
  - Method might suffers from your topology (you might select more (less) crowded events)
- Use simulations
  - MC must very well describe the data

Efficiency Measurement

- Use well-known physics processes and do "tag & probe"
  - $Z\rightarrow ll$, $J/\Psi\rightarrow ll$: trigger only on one leptons
    - Most precise way to calculate efficiencies
  - $W\rightarrow l\nu$: trigger on missing E_T
- 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



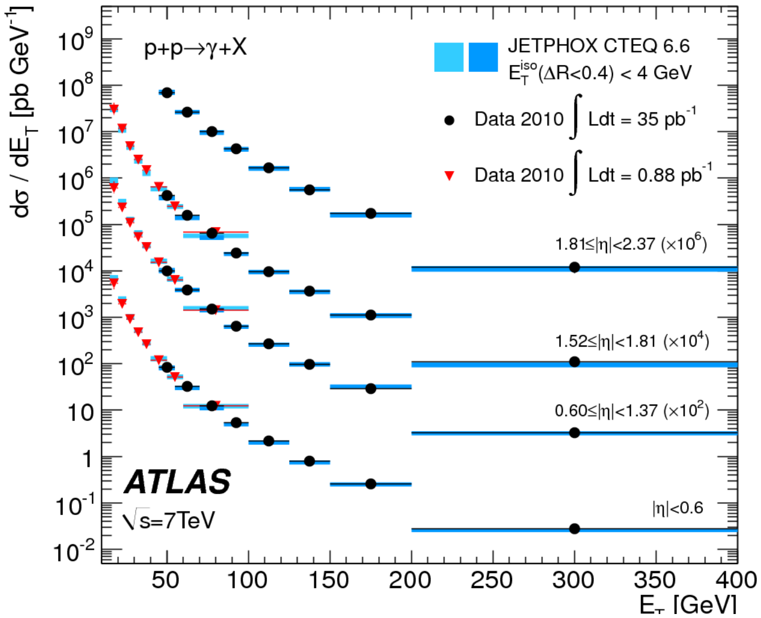


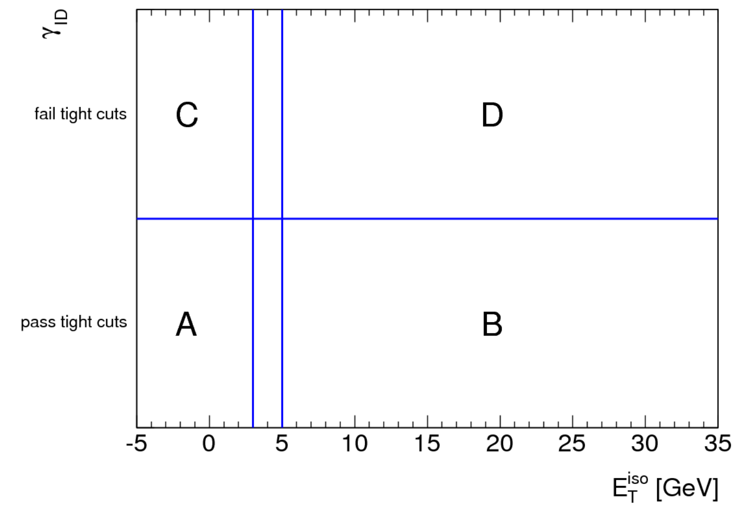
Summary: triggers for W cross section measurement

- Trigger to select signals
  - electron/muon with $E_T > 25$ GeV
  - electron/muon with $E_T > 25$ GeV and E_T^{miss}>30GeV
- Trigger needed for background subtractions
  - Prescaled trigger loosely selecting electron/muon with $E_T >$ 25 GeV
- Triggers for efficiency extraction
  - Electron/muon with $E_T > 25$ GeV (use the electrons from Z decays)
  - E_t^{miss} and cluster in electro-magnetic calo to measure offline efficiency

Example 2: Measurement of direct photon production

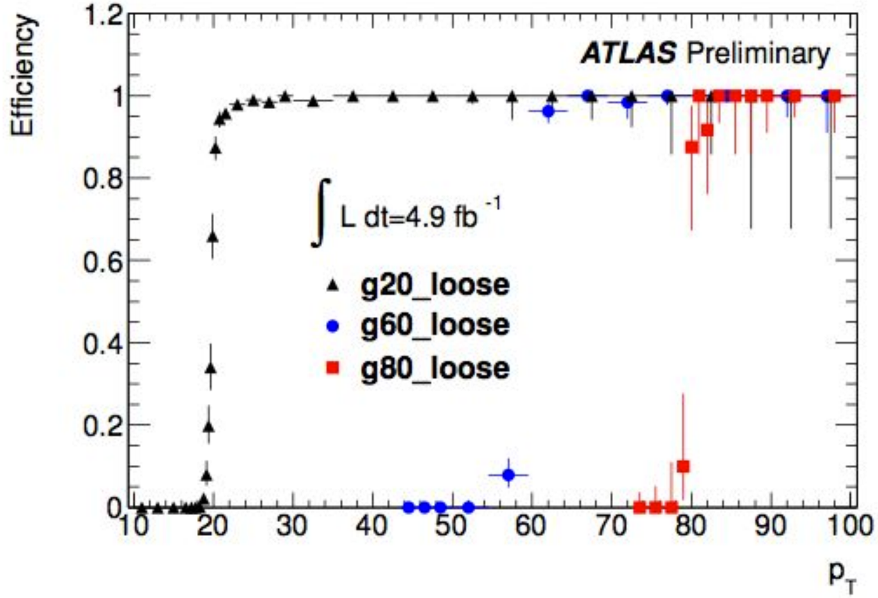
- Measure spectrum starting with E_T > 15 GeV
- Can't keep all the collisions with photons at low E_T
  - Use prescaled triggers
    - g10, g20, g40, g60, etc until rate low enough
  - prescale each trigger to give ~1Hz rate
- Trigger for background extraction
  - If photons loosely selected, can use same sample to extract the background from jets faking γ's
    - Identification criteria vs isolation





Example 2: Measurement of direct photon production

- Efficiency
  - Initially we used bootstrapping
    - use photon candidates selected by L1 only, measure photon efficiency w.r.t. L1
    - Use unbiased sample e.g. minimum bias to measure L1 efficiency
    - $\varepsilon_{Trigger} = \varepsilon_{L1} \bullet \varepsilon_{HLT}$
    - Advantage: 2-step approach results in less overall statistics needed due to high rejection at each trigger level
  - Since recently we can also use Z->eeγ events (tag & probe)



With increasing luminosity (more pileup)

- With increasing luminosity we have to be even more selective and throw away more of potentially interesting candidates
  - Cannot rely so much any more on single particle triggers
    - Rate of W->lv at $\sqrt{s}$ = 14 TeV L=10^{34} $cm^{-2}s^{-1}$ is ~ 100Hz
  - Single object triggers need to increase threshold
  - Need to have more combined triggers using identified particles
  - Need to have more topological trigger, select events with W/Z candidates, back-to-back signatures, etc.
- With increasing pileup
  - Larger occupancies in the detector
  - Identification criteria can become more ‘fuzzy’
  - Time to execute event can take longer
  - Events become larger (problem for event storage)
- To keep the performance of the detector a lot of components need to be upgraded in Trigger and DAQ
- We are working on this now for LHC restart in 2015 and also beyond

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 path)
  - Trigger menu
  - Efficiency extraction and turn-on

Backup

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 x 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

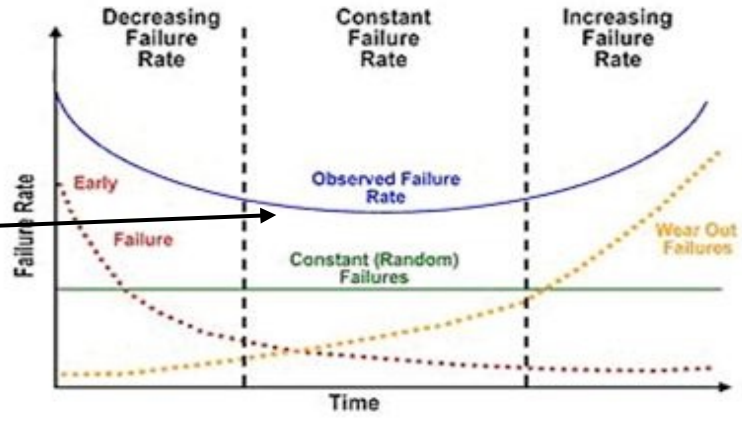


Figure 1: Failure rate versus t

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)