ISO-TDAQ school
Ankara, 01/02/2010

Introduction to trigger

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Trigger concept

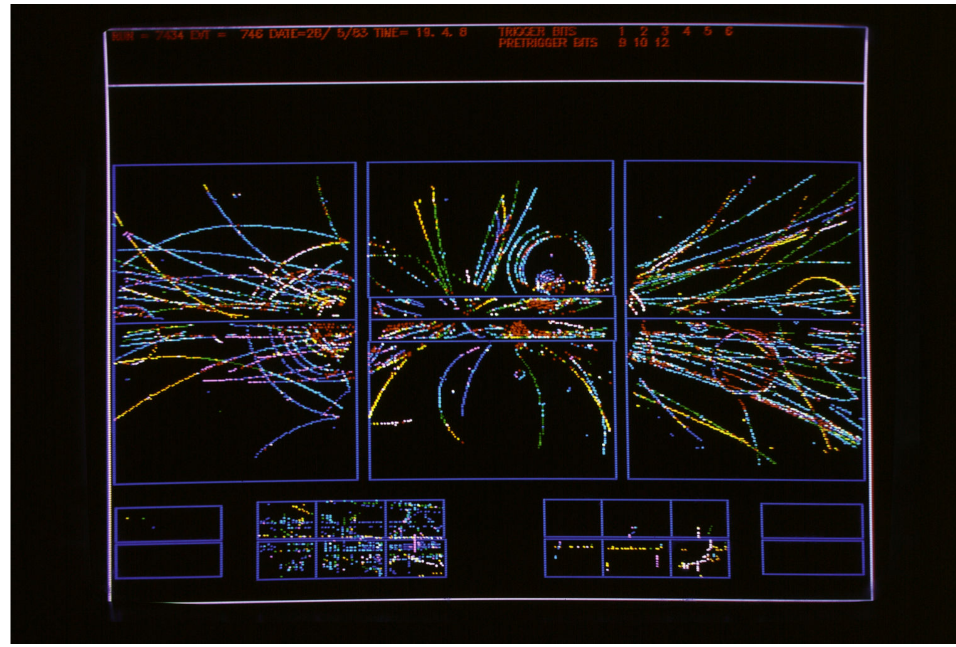
- From Mirriam-Webster dictionary:
  - something that acts like a mechanical trigger in initiating a process or reaction

- Trigger concept by an example: a photo camera
  - click the bottom to open the bolt and let the sensors operate → The trigger starts the photo process
  - take the photo only when you think the subjects are ready → First identify the interesting event
  - focus the image → Ensure the sensitivity to a parameter
  - only if there is enough light for your lenses (or add a flash light)
  - only if your hand is not shaking → Ensure a good synchronization

Digital signal saying yes or no (Interrupt signal)

Introduction to the trigger world (and words…)

- In HEP the trigger helps in identifying the interesting process, usually called "**event**"
- At the collider experiments, we have bunches of particles crossing at regular intervals and interactions occur during the **bunch crossings** (BCs)
  - Trigger must select the bunch crossing of interest for physics studies, containing the interesting interaction
  - Event is the recorded information from a given bunch-crossing



The problem of the rate

colliders	BC length	collision rate
LEP	22 us	45 kHz
Tevatron	396-132 ns	2.5 - 7.6 MHz
LHC	25 ns	40 MHz

Maximum acceptable rate ~ 100 Hz

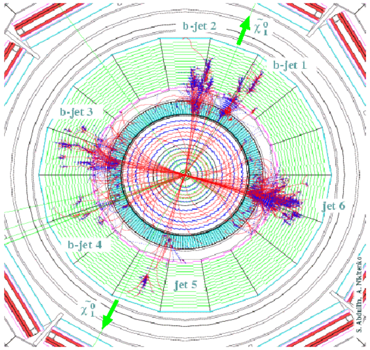
- Even at lower luminosity colliders, the rate of the interactions is not affordable by any data taking system
  - Don’t worry, not any interaction is interesting for our studies, most of them can be rejected

The trigger box is a filter that works at the input collision rate, but selecting only the interesting ones

trigger requirements in HEP, i.e. what we want from the trigger?

The role of the **trigger** is to make the online selection of particle collisions potentially containing interesting physics

- Robustness of the selection is required, since discarded events are lost forever (reliable)
- Strong background rejection
- High efficiency for benchmark physics processes
  - Not always both requirements can be realized: compromise between number of processors working in parallel and fastness of the algorithms - to make it affordable



Background rejection

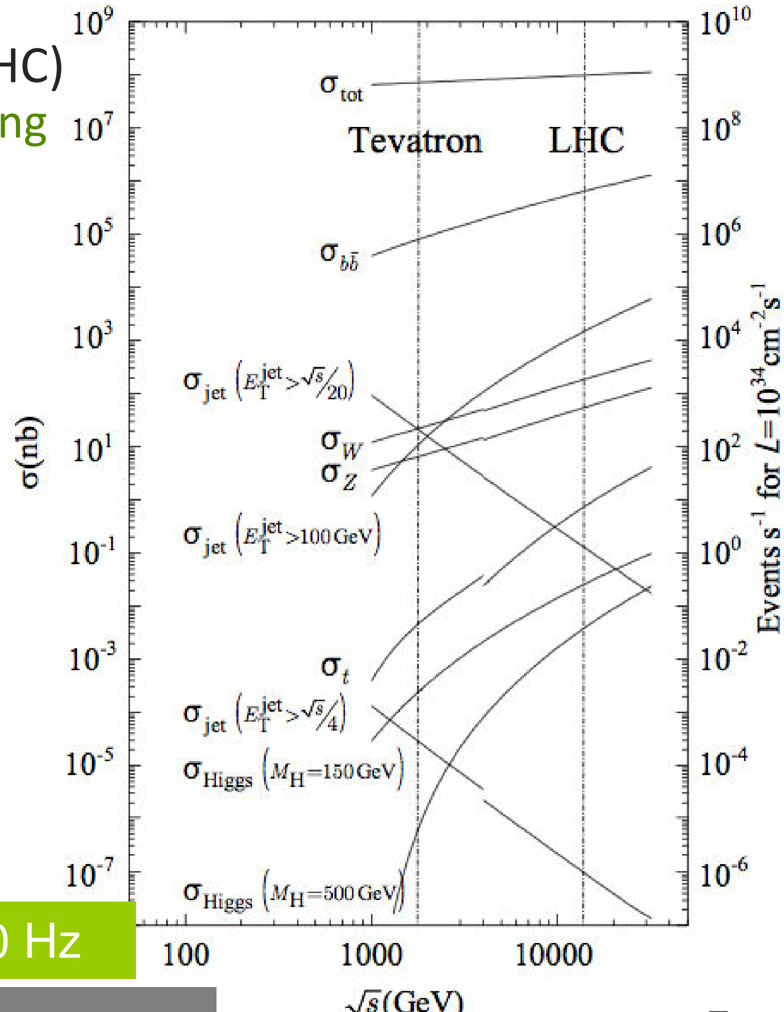
- Background rejection reduces the rate to match the DAQ capabilities (instrumental or physics background)
  - A strong link between the trigger and the DAQ system is required
  - The output rate is limited by the offline computing budget and storage capacity. Only a small fraction of production rate can be used in the analysis

- Sometimes backgrounds have rates much larger than the signal
  - Need to identify characteristics which can suppress the background
  - Need to demonstrate solid understanding of background rate and shapes

- Crucial for hadron colliders physics…

A trigger challenge: hadron collider experiments

- Production cross-sections span over many orders of magnitude (10 Tevatron, 12-13 LHC)
  - Collision rate dominated by non interesting physics
  - Background discrimination crucial



Total non-diffractive pp cross section at LHC √s=14 TeV is ~ 70 mb

Huge range of cross-sections and production rates (example with design L)

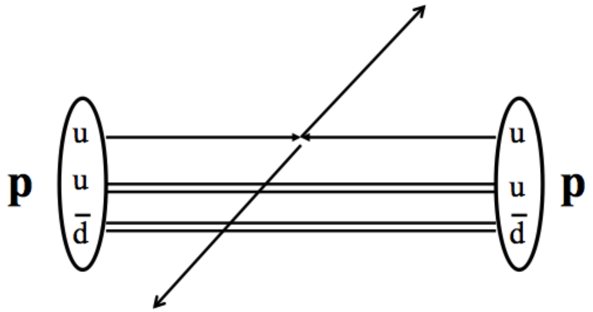
Beauty (0.7 mb)	– 10^3 Hz
W/Z (200/60 nb)	– 100 Hz
Top (0.8 nb)	– 10 Hz
Higgs - 150 GeV (30 pb)	– 0.1 Hz

Trigger must reduce event rates from GHz to ~200 Hz

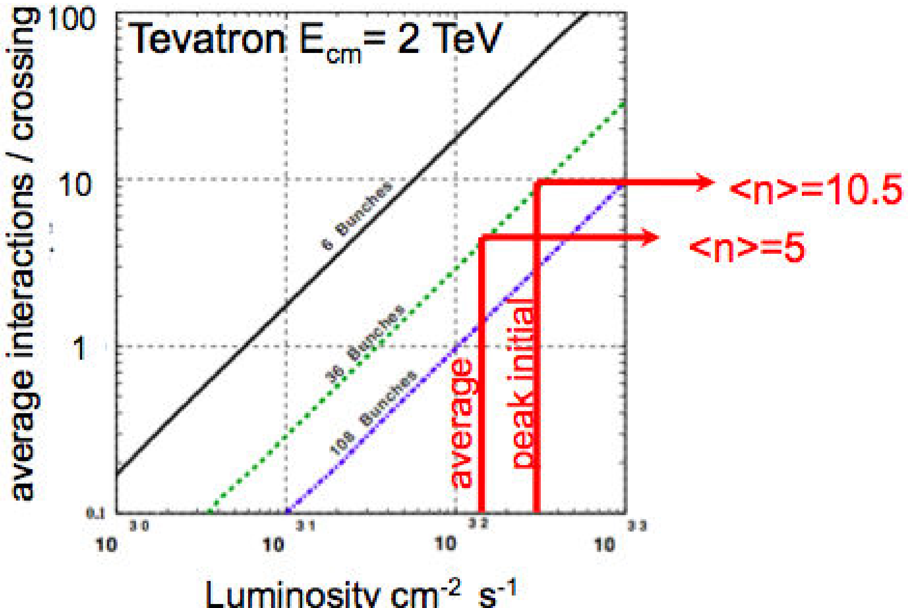
Multiple interactions per collision

- e+e- colliders: very small interaction rate (small cross-section), one event generally contains one single interaction (LEP-HERA)

- pp colliders: each bunch crossing contains more than one interaction
  - Added to the interaction of interest, there are a number of “underlying events”, often called **minimum bias** events (selected by any unbias trigger)
  - Additional interactions add superimposed information on the detectors, resulting in bigger and more complicated event (**pile-up**).



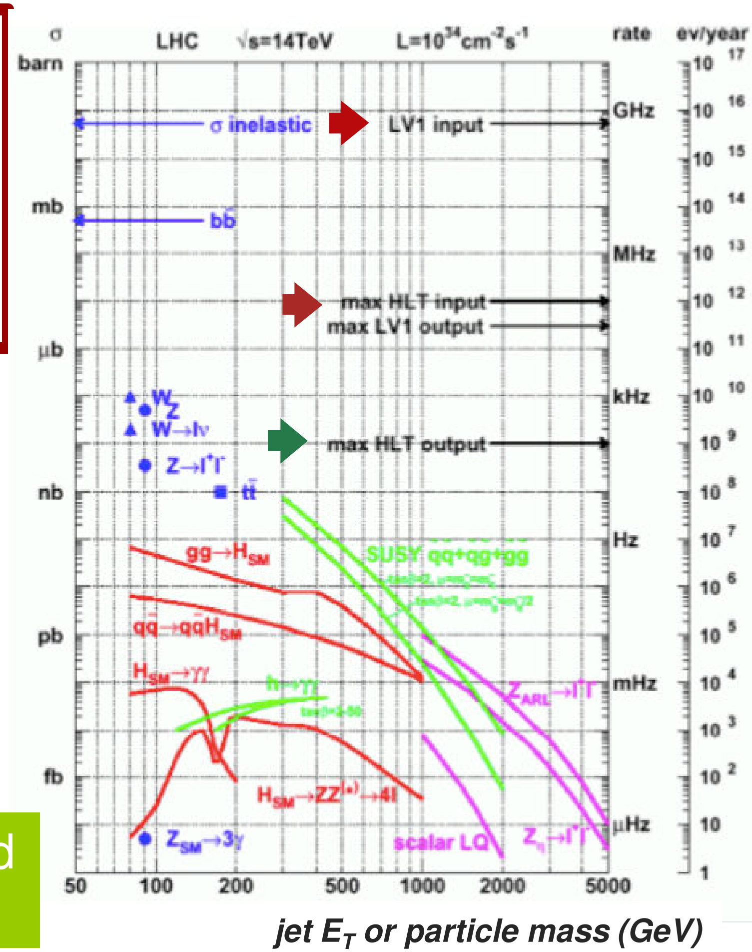
This has effects on:
- the event-size, mainly when the number of readout channels is huge
- trigger selection…..



Trigger interaction rate

R = $\mu \cdot f_{BC} = \sigma_{in} \cdot L$

L = instant. luminosity
f_{BC} = rate of bunch crossings
μ = average pp interactions/ BC



- LHC: σ $_{pp}$== ~ 70 mb, design L=10^{34} cm^{-2} s^{-1}
  - Average 25 interactions per BC
  - Event characteristics vary with luminosity, due to changes in pile-up, so it's not a simple events rescaling but events with different number of muons, clusters,... must be managed

Trigger must be flexible to cope changes in L and background

...more on hadron colliders

- Multi-purpose experiments: the trigger must satisfy a **broad physics program**
  - Main discovery channel (Higgs @LHC, top @Tevatron), with a precision EW program
  - Search for new phenomena
  - Tests of perturbative QCD
  - B physics

- **Pile-up** can be generated from data coming from nearby bunch-crossings, if the BC period is shorter than the detector acquisition time:
  - Detectors response must be faster than the BC period
  - More slow responses are allowed with peak finder algorithms

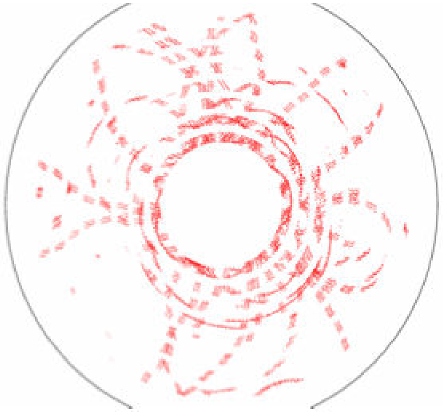
Rate dependency on Luminosity

- For a physics process, cross-section is not dependent on luminosity
- The trigger cross-section can change with Luminosity

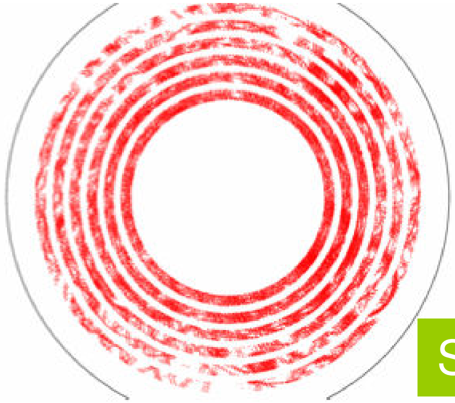
$$R = L\sigma = A + BL + CL^2 + DL^3$$

A = constant rate
B = constant sigma

- High purity triggers typically have C~D~0. Extra powers of L due to:
  - Overlapping objects from different interactions, more combinations of objects (fakes)
  - Worst resolution due to extra occupancy



Luminosity ~ 3E31



Luminosity ~ 4E32

Random Inelastic Interactions simulated in the CDF drift chamber (COT)

Solution: add information (stereo wires)

Efficiency and dead-time

- Goal of the trigger is to maximize the collection of data for physics process of interest
  - Aim for high efficiency !
- $\varepsilon_{trigger} = N_{good(accepted)}/N_{good(Produced)}$
  - One source of inefficiency is trigger dead-time!
    - Due to fluctuations, the incoming rate is higher than the processing one -> valid interactions are rejected due to system busy
    - Buffering incoming data could reduce dead-time
  - But dead-time always incurred if
    <incoming rate> > 1/<processing time> !

Next lesson

Use of multi-level triggers

To obtain high efficiency with large background rejection, trigger selection is organized in multiple levels

L1 = fast (~few μs) with limited information, hardware based
L2 = moderately fast (~10s to ms), hardware/software
L3 = Commercial processor(s)

- First-level: Rapid rejection of high-rate backgrounds without incurring (much) dead-time ⇒ Fast custom electronics used
  - Needs high efficiency, but rejection power can be comparatively modest
- High-level triggers: High overall rejection power to reduce output to mass storage to affordable rate ⇒ one or more Levels:
  - **Progressive reduction** in rate after each stage of selection allows use of more and more complex algorithms at affordable cost
  - Final stages of selection, running on computer farms, can use comparatively very complex (and hence slow) algorithms

LHC experiments

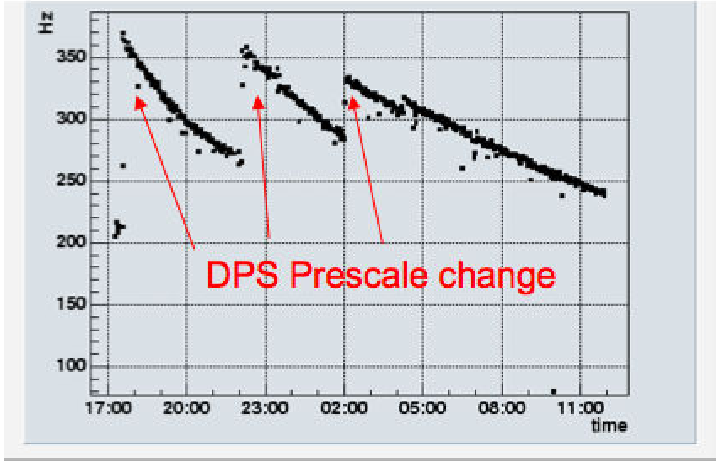
Exp.	No of Levels
ATLAS	3
CMS	2
LHCb	3
ALICE	4

Next lesson

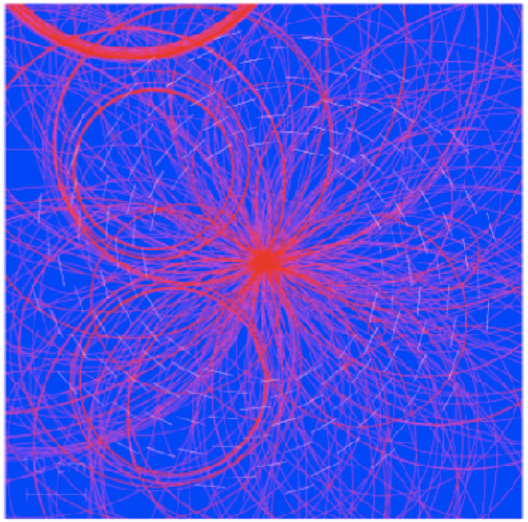
Different kind of triggers

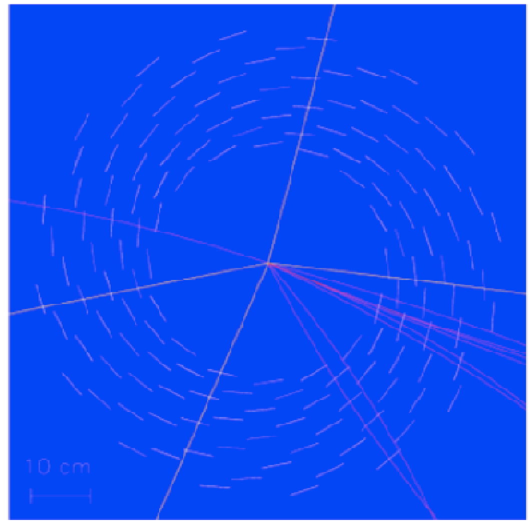
- The bulk of the selected events are those useful for the physics analysis, but the trigger must also ensure rates for
  - Instrumental and physics background studies
  - Detector and trigger efficiency measurement from data
  - Calibrations, tagging, energy scales
- Back-up triggers
  - Back-up is misleading…. These measurements are necessary for most of the analysis
  - Some large rate back-up triggers can be pre-scaled
- Pre-scaled triggers
  - Only a fraction N of the events satisfying the relevant criteria is recorded, where N is a parameter called pre-scale factor. This is useful for collecting samples of high-rate triggers without swamping the DAQ system
  - The pre-scale factor **can change** accordingly with the desired statistics and the system availability
  - Since trigger rate can change with Luminosity, **dynamic pre-scales** are sometimes used (reduce the pre-scales as Luminosity falls)

CDF L2 rate during a run



Trigger signatures in HEP





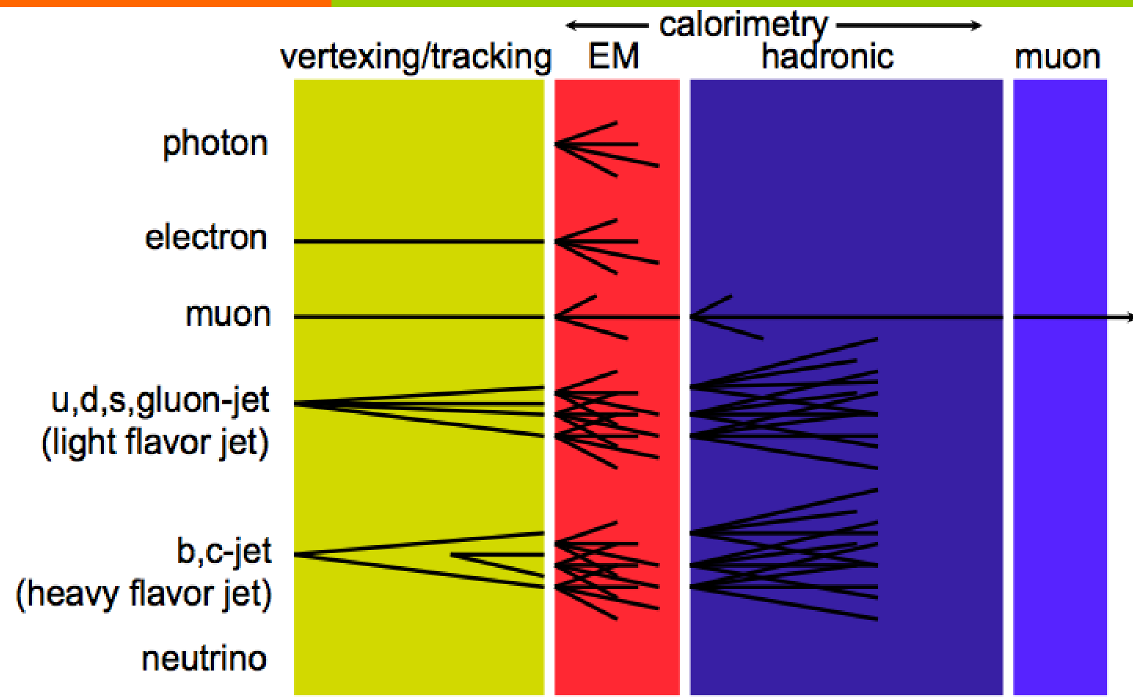
Simulated H-> 4μ event at LHC with and without min. bias events

- Signature=one or more parameters to use for discrimination, able to select "events" of potential interest for your studies
- The signature can be the amplitude of a signal passing a given threshold or a more complex quantity given by software calculation
  - First use intuitive criteria: fast and reliable
- Eventually combine more signals together following a certain trigger logic, giving redundancy.

Selection criteria in HEP

$\eta=-\ln(\tan(\theta/2))$

pseudorapidity



- Trigger selection in HEP is based on single/double particle signatures
  - Muon tracks, energy deposits in the calorimeters, tracks in the silicon detectors
- Usually detectors are segmented in a number of trigger regions in eta-phi
- The final trigger response is one of the logical combinations (AND, OR) of all or part of the inputs

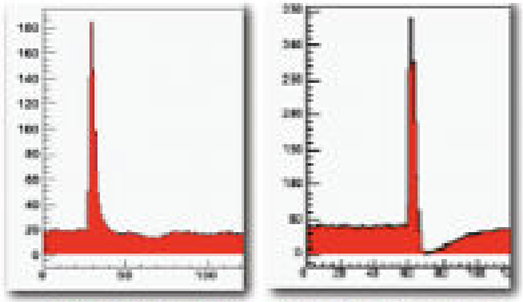
Trigger criteria at colliders

- At collider experiments we apply thresholds on transverse Energy (E_T) or transverse momentum (p_T): component of energy or momentum orthogonal to the beam axis
- Initial $p_T = 0$ and $E_{total} < E_{2\ beams} = E_{cm}$
- Shower shapes and isolation criteria are also used to separate single leptons from jets
- In addition we use global variables, such as total-energy, missing energy (for neutrino identification), back-to-back tracks, etc…
- At LHC
  - The bulk of the cross-sections for Standard Model processes are the presence of high-p_T particles
  - In contrast most of the particles producing minimum-bias interactions are soft (pT ~ 1 GeV)
  - Large missing ET can be sign of new physics

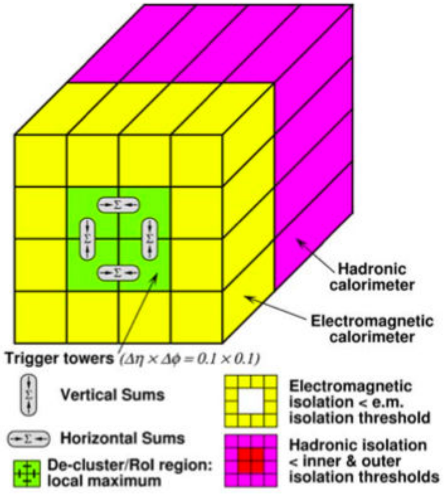
$$\not{E}_T = -\left| \sum_{i=towers} E_i \cdot \hat{n}_T^i \right|$$

Example of multilevel trigger: ATLAS calorimeter trigger

- e, γ, τ, jets, E_{tmis}s, ΣE_T
  - Various combinations of cluster sums and isolation criteria
- Level-1
  - Dedicated processors apply the algorithms, using programmable E_T thresholds
  - Peak finder for BC identification
  - Sliding-window technique to find clusters
- High-Level trigger
  - More topological variables and tracking information for electrons from Inner Detectors
    - Tower clustering at L2
    - Jet algorithms at L3 (Event Filter)
  - Isolation criteria can be imposed to control the rate (reducing jet background at low energies thresholds)



TileCal and LAr signals at trigger



Level-1 clustering algorithm

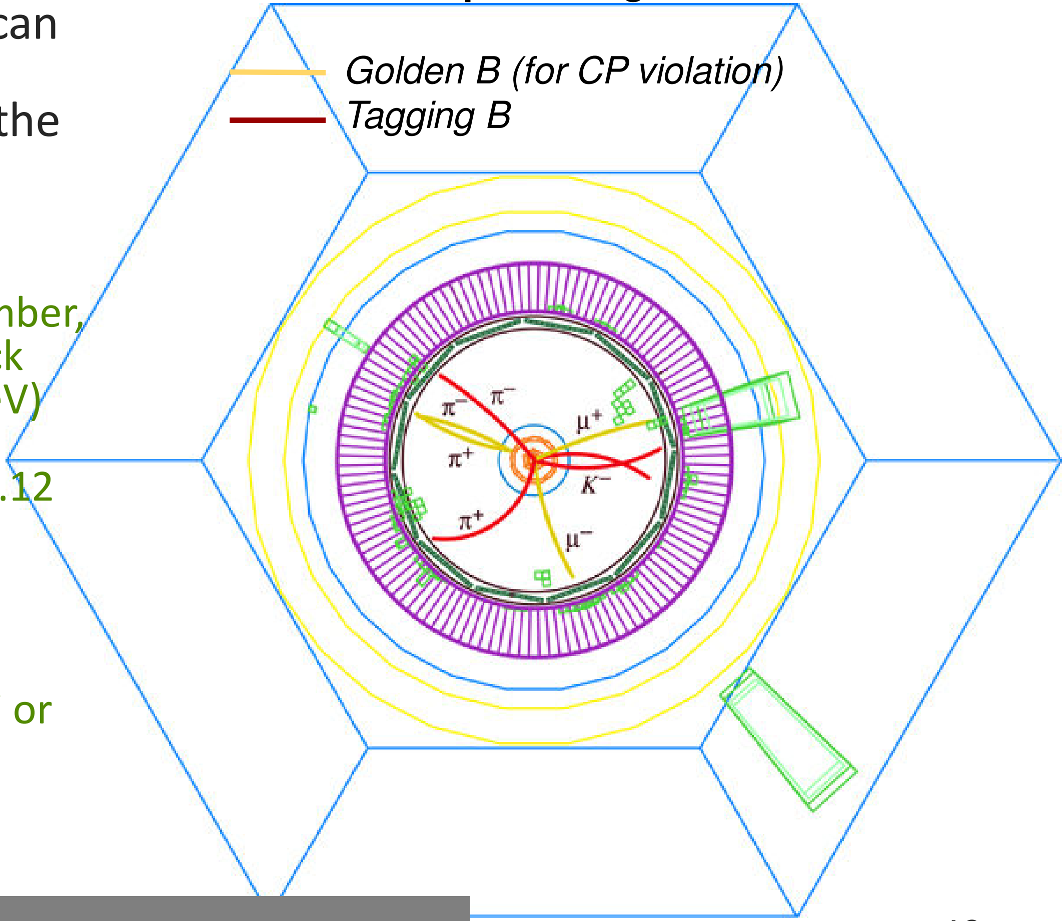
Trigger objects example: BaBar

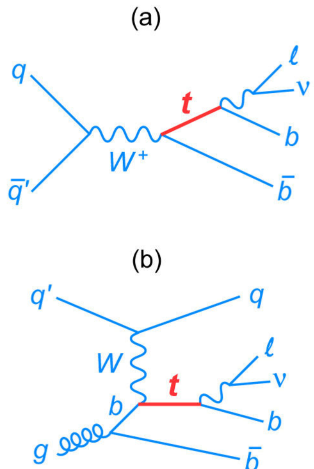
- For some precise measurements, the crucial performance parameter can be not the efficiency, but the systematic error in determining the efficiency

- Babar trigger objects:
  - charged tracks in the drift chamber, with different p_T cuts: long track (0.18GeV), short track (0.12 GeV)
  - E-m calorimeter clusters with different E_T cuts (minimum is 0.12 GeV efficient for mip muons)

- Search for topology
  - number of objects, optionally requiring separation cuts in phi or matching between tracks and clusters

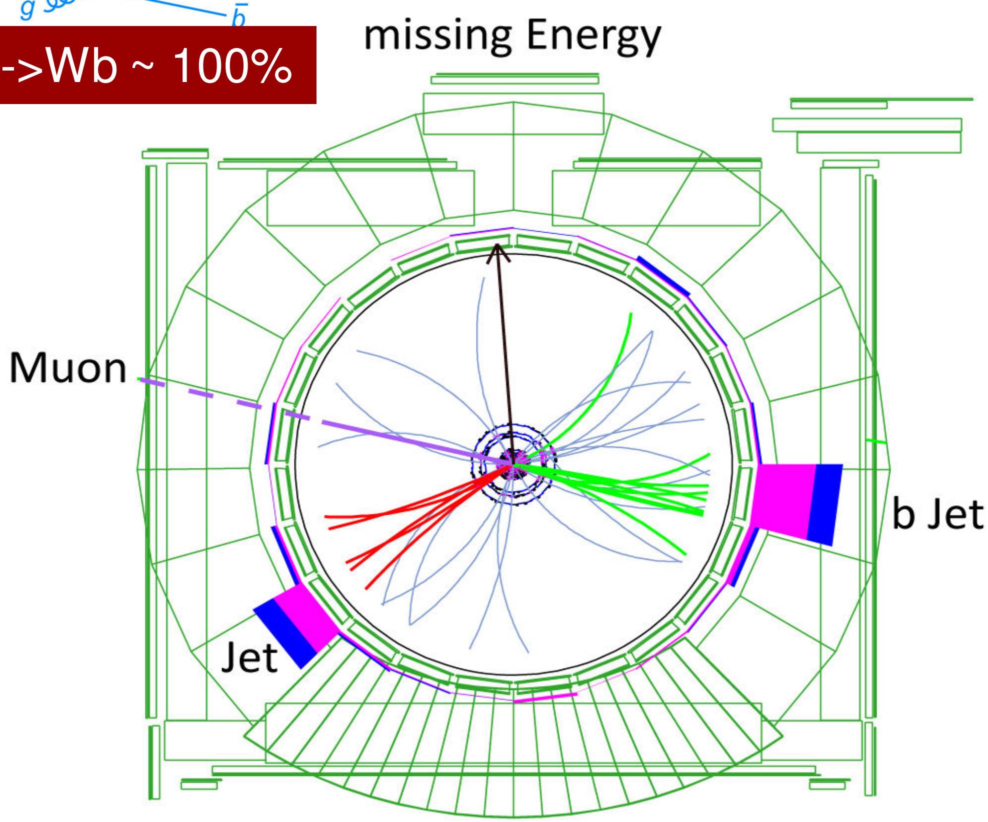
Golden event in the BaBar Detector
e+e- collision producing a B and an anti-B





Trigger objects example: CDF

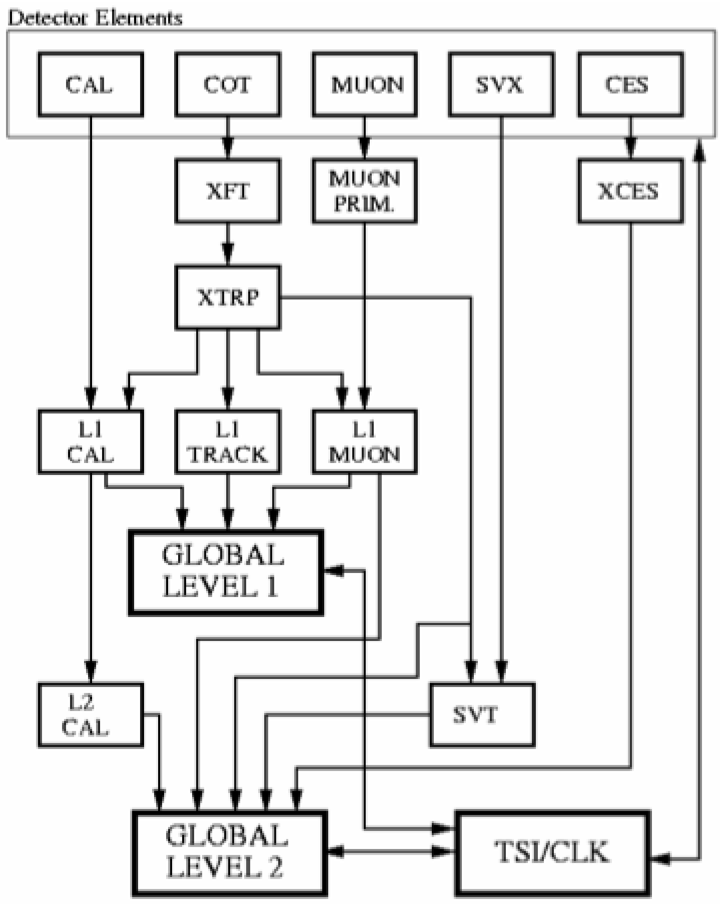
t->Wb ~ 100%



CDF single top event

- Signal characterization:
  - 1 high p_T lepton, in general isolated
  - Large MET from the high energy neutrino
  - 2 jets, 1 of which is a b-jets
- Trigger objects at L1
  - Central tracking (XFT p_T>1.5GeV)
  - Calorimeter
    - Electron (Cal +XFT)
    - Photon (Cal)
    - Jet (EM+HAD)
  - Missing Et, $SumE_T$
  - Muon (Muon + XFT)
  -
- Trigger objects at L2:
  - L1 information
  - SVT (displaced track, d_0)
  - Jet cluster
  - Isolated cluster
  - Calorimeter ShowerMax

Trigger objects example: CDF



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  - Calorimeter
    - Electron (Cal +XFT)
    - Photon (Cal)
    - Jet (EM+HAD)
  - Missing Et, $SumE_T$
  - Muon (Muon + XFT)
- Trigger objects at L2:
  - L1 information
  - SVT (displaced track, d_0)
  - Jet cluster
  - Isolated cluster
  - Calorimeter ShowerMax

Trigger efficiency

- Trigger design must ensure
  - high efficiency
  - no bias, providing the widest physics program
- Efficiency should be precisely known, since it enters in the calculation of the cross-sections
  - The orthogonality of the trigger requirements allows good cross-calibration of the efficiency

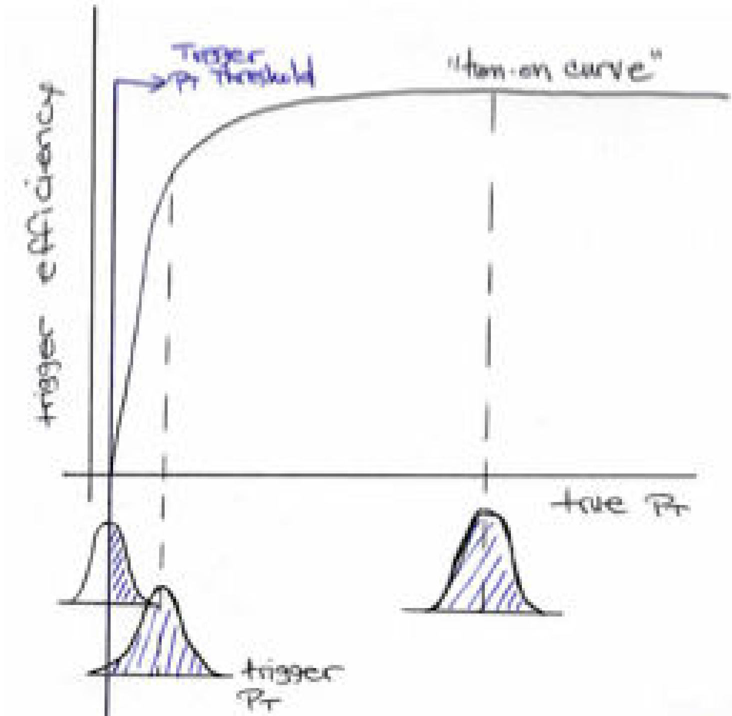
$$BR(\text{Signal}^{-}) = \frac{(N_{candidates} - N_{bg})}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{Bs} \cdot \int L dt}$$

$$\alpha \cdot \varepsilon_{\mathrm{total}} = \alpha \cdot \varepsilon_{\mathrm{Tracking}} \cdot \varepsilon_{\mathrm{Reco}} \cdot \varepsilon_{\mathrm{L1\text{-}Trig}} \cdot \varepsilon_{\mathrm{L2\text{-}Trig}} \cdot \varepsilon_{\mathrm{L3\text{-}Trig}} \cdot \varepsilon_{\mathrm{vertex}} \cdot \varepsilon_{\mathrm{analysis}}$$

Acceptable error on $\alpha\varepsilon$ can be around 10%

The turn-on curves

- Since pT resolution is finite, and worst at level-1 (coarse granularity, dp_T/p_T~1%), the efficiency is a function of the real p_T
  - For example some particles can be under threshold, failing the trigger, because their p_T is underestimated

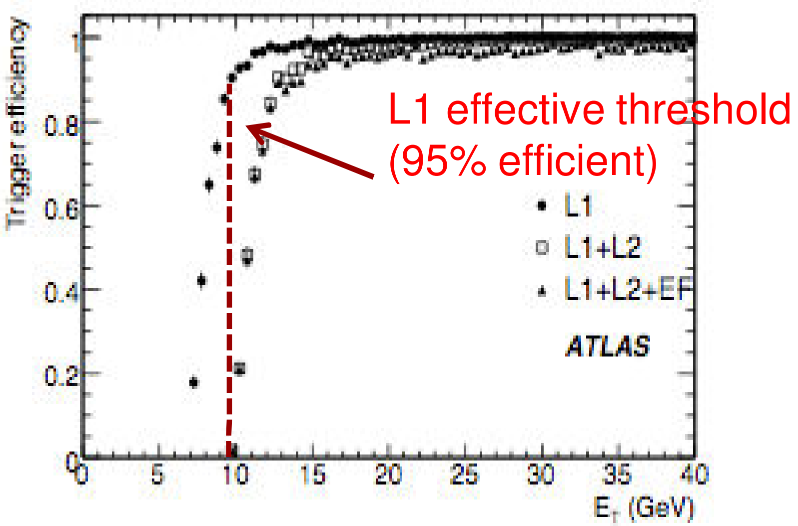


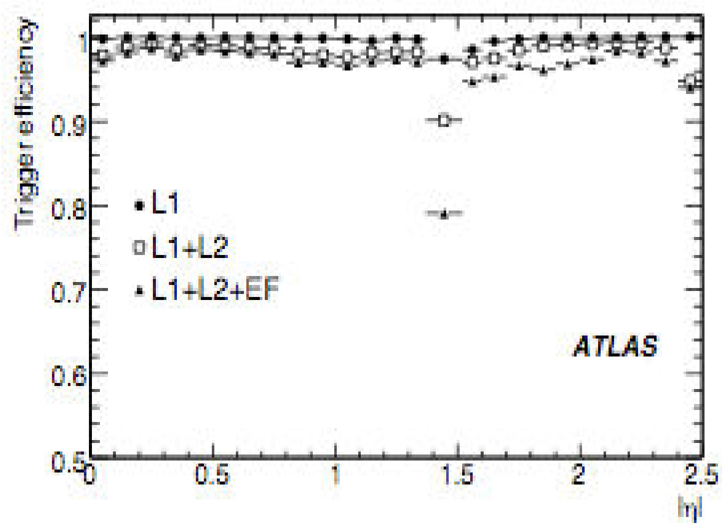
- The trigger efficiency as a function of the true p_T, measured with the offline reconstruction (resolution order of 0.1%), is described by the turn-on curves

Trigger efficiency dependency

- The design of a trigger system and the implementation of the selection algorithms must minimize the trigger efficiency dependency on p_T (E_T) and on geometrical acceptance (like η and ϕ)
- L1 Thresholds chosen so that efficiency is 95% of its maximum value

ATLAS: e10 trigger efficiency as a function of E_T and η (from Monte Carlo)



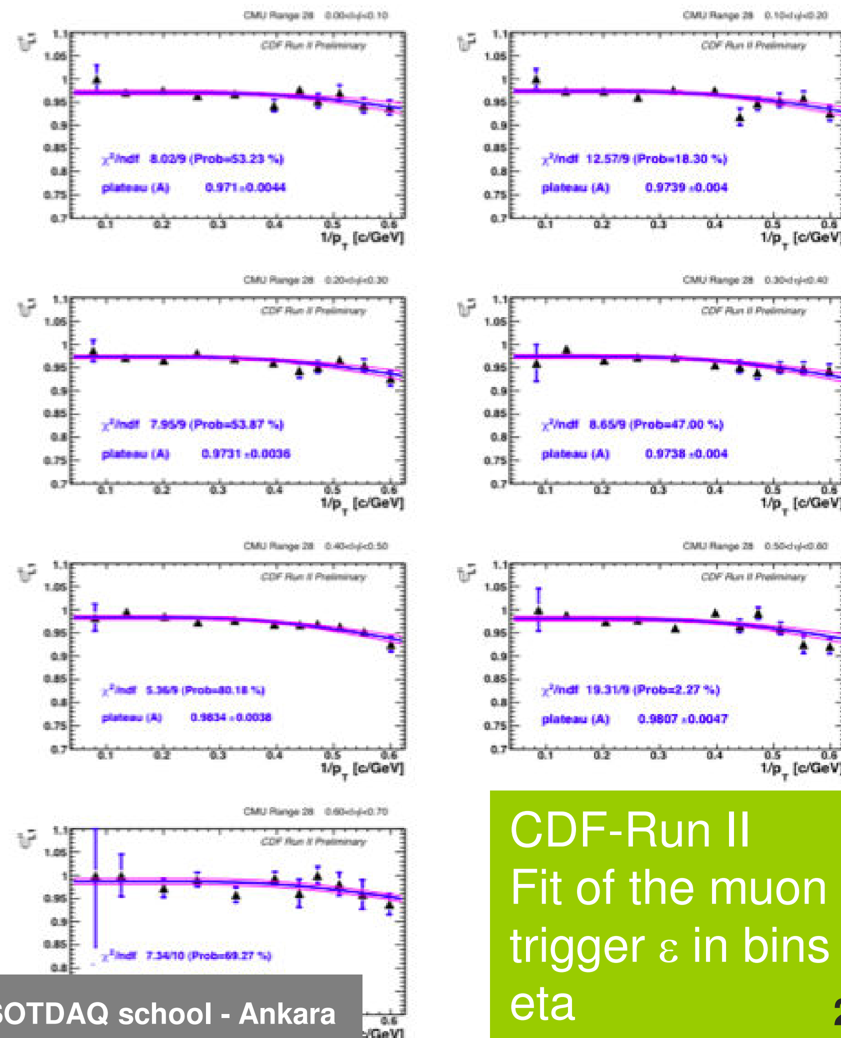


Parametrizing the trigger efficiency

- Trigger behavior, and thus the analysis sample, can change quickly due to important changes in
  - Detector
  - Trigger hardware
  - Trigger algorithms
  - Trigger definition

- The analysis must keep track of all these changes

- multi-dimensional study of the efficiency: $\varepsilon(p_T, \eta, \phi, run\#)$
  - Fit the turn-on curves for different bins of η, ϕ,
  - Actually fit the $1/p_T$ dependency since the resolution is gaussian in $1/p_T$



CDF-Run II
Fit of the muon trigger ε in bins of eta

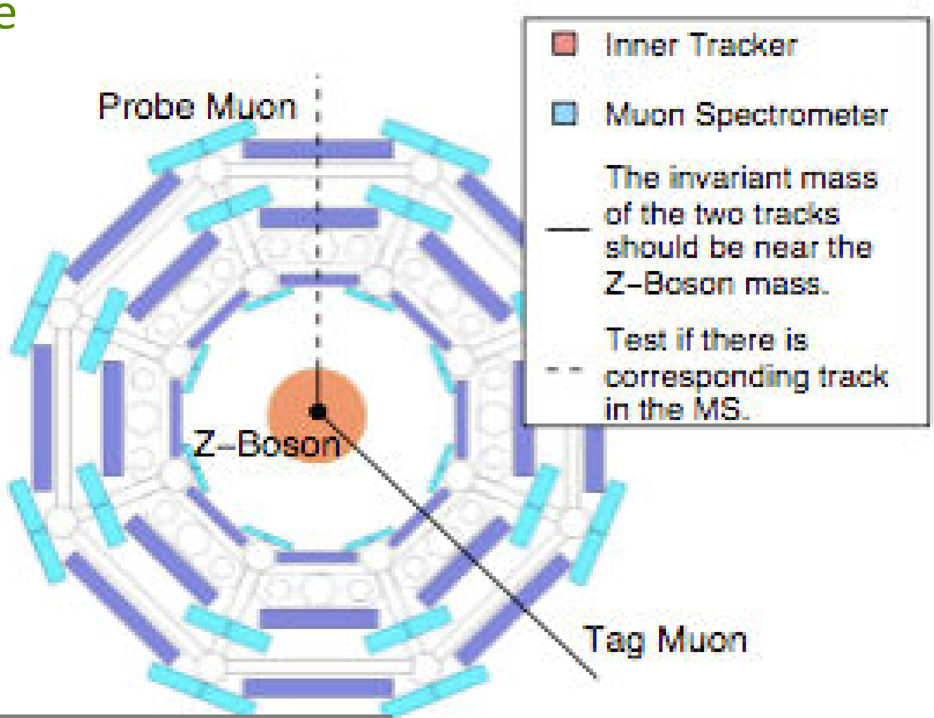
Trigger efficiency measurement (1)

$$\text{Efficiency} = \frac{\text{number of events that passed the selection}}{\text{number of events without that selection}}$$

- Basic idea: compare two cases in which the trigger selection is or is not applied
- For this purpose we use back-up triggers called **pass-through**
  - Do not apply the selection and calculate the denominator
- For HLT it's easily done using pass-through
  - $\text{Eff(L2MU10)} = \frac{\text{events passing L2MU10}}{\text{events passing L2MU10\_PASSTHROUGH}}$
- Level-1 trigger gives the biggest contribution to inefficiency because of the worst resolution
  - We don't know the absolute denominator
  - At the collider experiments can be measured with experimental technique called "Tag-and-Probe"

Trigger efficiency measurement (2)

- At colliders, "Tag and Probe" method is used where possible (mainly lepton triggers)
  - Clean signal sample (Z, J/ψ to leptons)
  - Select track that triggered the event (Tag)
  - Find the other offline track (Probe)
  - Apply trigger selection on Probe

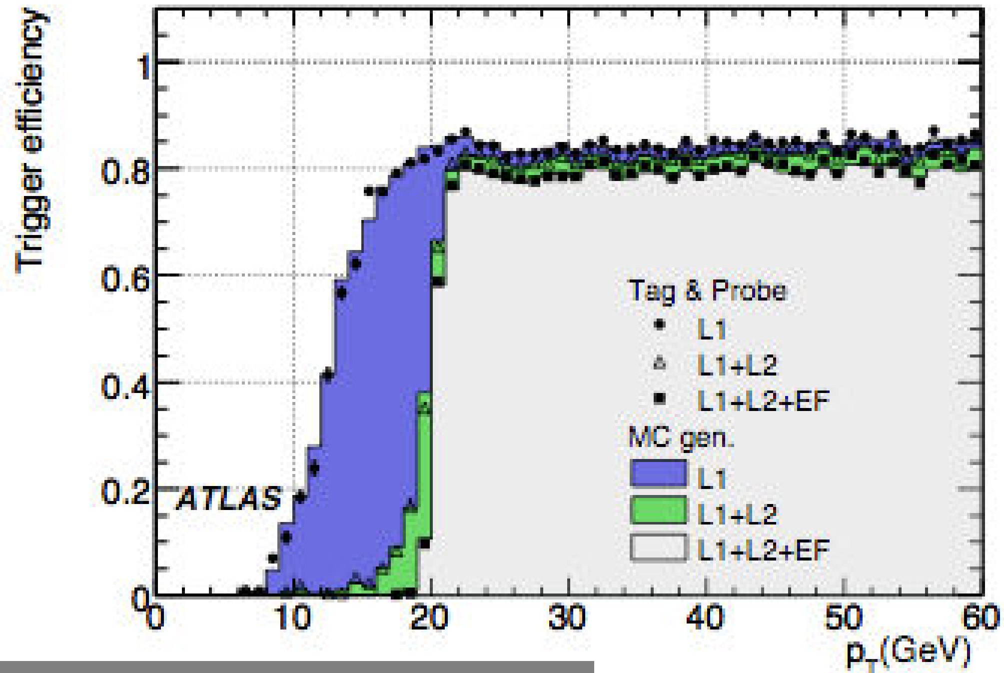


Use back-up triggers:
L1_LOWEST_THRESHOLD

Trigger efficiency measurement (3)

- To get the turn-on curve we bin the "probe" leptons by p_T (E_T)
  - Crucial is the study of the step region, in which efficiency changes very quickly
- The systematic uncertainties of the method are compared with Monte Carlo results, to understand possible bias coming from the sample used for the tag-and-probe method

ATLAS Muon trigger efficiency (with 1 fb^{-1}) from MC



A balance between physics interest and system bandwidth…

- High efficiency
- Low dead-time

Multilevel triggers
(…and other methods described in the next lesson)

Lower thresholds would be desirable, but the physics coverage must be balanced against considerations of the offline computing cost

- How accommodate broad physics program?
- And cope with increasing luminosity?

Organize trigger menus!

What is a trigger menu?

- A trigger menu is the list of our selection criteria
- Each item on the menu is a **trigger path**
- A trigger path includes a set of cut-parameters or instructions particular from each trigger level (L1+L2+L3..)
- An event is stored if one or more trigger chain criteria are met

How to do a trigger menu

- A well done trigger menu is crucial for the physics program
  - Multiple triggers serve the same analysis with different samples (going from the most inclusive to the most exclusive)
  - Ideally, will keep some events from all processes (to provide physics breadth and control samples)
  - Triggers for monitoring and calibration purpose have also to be foreseen, mostly to measure instrumental and physics background

- Efficiency measurement is ensured by the **redundancy** of selections, listed in the trigger menus

- The list must be sufficiently **flexible** to face possible variations of the environment (detectors, machine luminosity) and the physics program

- First look at the components……

Rates allocation on trigger signatures

- ✓Target is the final allowed bandwidth (~200 Hz @ LHC)
- ✓Trigger rate allocation on each trigger item based on
  - ✓Physics goals (plus calibration, monitoring samples)
  - ✓Required efficiency and background rejection
  - ✓Bandwidth consumed

- Trigger rates are calculated from large samples of simulated data, including large cross-section backgrounds (minimum-bias and QCD)
  - Large samples of background events are required (7 million non-diffractive events @ 70mb used as minimum-bias sample for 10^{31} cm^{-2} s^{-1} menu)

$$R_i = L \int_{p_{T\_inf}}^{p_{T\_cutoff}} \frac{d\sigma_i}{dp_T} \cdot \varepsilon(p_T)\, dp_T$$

Trigger Efficiency

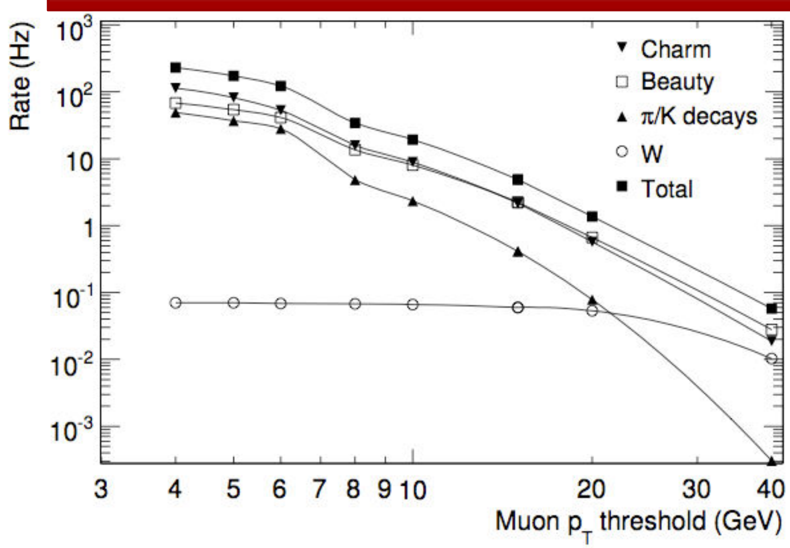
  - Given by convolution, over a given ET/pT range, of the estimated efficiency with the cross sections representing the main trigger source
- Large uncertainties due to detector response and jet cross-sections
  - To be tuned with (early) data

Expected ATLAS trigger rates @ LHC start-up $L=10^{31}\ cm^{-2}\ s^{-1}$

Muon trigger

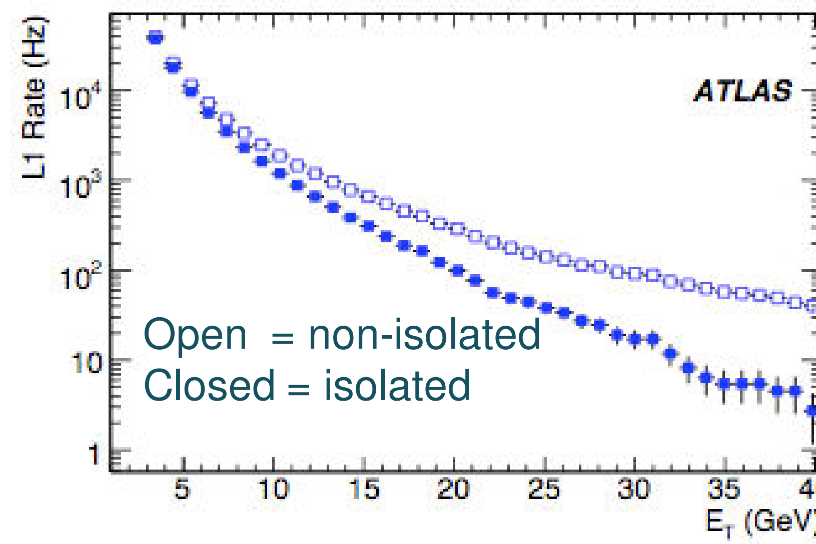
- Selection based on muon spectrometer only
- Largest source of muons are from b/c quarks and π/K in-flight decay

EF single muon trigger rate at start-up



Calorimeter trigger

Single e/γ L1 rates at start-up



- For E/p and jet calibration, the trigger has to guarantee SM channels as W, J/ψ, Drell-Yan, direct-γ production

Example of trigger menu flexibility

ATLAS trigger menu at start-up L=10^{31} cm^{-2} s^{-1}

- Level-1
  - low p_T thresholds and loose selection criteria (adding pre-scales to control rates)
  - deploy high thresholds and multi-objects triggers for validation (to be used as back-up triggers)
- HLT: running in pass-through mode for offline validation or with low thresholds
- As LHC luminosity reaches the design, complex signatures and higher p_T thresholds will be necessary to reach the physics goals

✓ Start-up trigger Menu contains ~130 Level-1 items and ~180 HLT selection chains
✓ e/□ and muon triggers are unprescaled, except

Object	L1 (Hz)	L2 (Hz)	EF (Hz)
Single-electrons	5580	176	27.3
Multi-electrons	6490	41.1	6.9
Multi-photons	common	2.9	< 0.1
Single-photons	common	33.4	9.1
Multi-Jets	221	7.9	7.9
Single-Jets	24.4	24.4	24.4
Multi-Fjets	2.7	2.7	2.7
Single-Fjets	3.7	3.7	3.7
Multi-bjets	common	12.9	2.6
Single-bjets	common	11.6	11.6
Multi-taus	465	14.5	12.4
Single-taus	148	32.9	22.3
Multi-muons	68.6	5.8	2.3
Single-muons	1730	204	21.8
Missing E_T	37.9	31.	3.8
Total E_T	6.3	6.3	1
Total Jet E_T	1.6	1.6	1.6
BPhysics	common	25	13
Muti-Object	5890	134	48
Minimum Bias	1000	10	10
Total	**12000**	**620**	**197**

Example of possible sharing of bandwidth

Trigger strategy @ colliders

- **Inclusive** triggers designed to collect the **signal** samples (mostly un-prescaled)
  - High-p_T e/μ/γ (p_T>20 GeV), jets (p_T>100 GeV)
  - Multi-object events: e-e, e-μ, μ-μ, e-τ, e-γ, μ-γ, etc… to further reduce the rate
- **Back-up** triggers designed to spot problems, provide control samples (often pre-scaled)
  - Jets (p_T>8, 20, 50, 70 GeV)
  - Inclusive leptons (p_T > 4, 8 GeV)
  - Lepton + jet

Inclusive trigger example: from CDF

Inclusive High-p_T Central Electron Trigger Path

- Level 1
  - EM Cluster $E_T > 8$ GeV
  - Rϕ Track $p_T > 8$ GeV
- Level 2
  - EM Cluster $E_T > 16$ GeV
  - Matched Track $p_T > 8$ GeV
  - Hadronic / EM energy < 0.125
- Level 3
  - EM Cluster $E_T > 18$ GeV
  - Matched Track $p_T > 9$ GeV
  - Shower profile consistent with e-

To efficiently collect W, Z, tt, tb, WW, WZ, ZZ, Wγ, Zγ, W', Z', etc…

Only one of these analysis needs to measure trigger efficiency, the others can benefit from one (use Standard Model Z,W)

Back-up trigger example: from CDF

Back-up Triggers for central Electron 18 GeV path:

- W_NOTRACK
  - L1: EMET > 8 GeV && MET > 15 GeV
  - L2: EMET > 16 GeV && MET > 15 GeV
  - L3: EMET > 25 GeV && MET > 25 GeV
- NO_L2
  - L1: EMET > 8 GeV && rϕ Track p_T > 8 GeV
  - L2: AUTO_ACCEPT
  - L3: EMET > 18 GeV && Track p_T > 9 GeV && shower profile consistent with e-
- NO_L3
  - L1: EMET > 8 GeV && rϕ Track p_T > 8 GeV
  - L2: EMET > 8 GeV && Track p_T > 8 GeV && Energy at Shower Max > 3 GeV
  - L3: AUTO_ACCEPT

- **Factorize efficiency into all the components:**
  - efficiency for track and EM inputs determined separately
  - separate contributions from all the trigger levels

- **Use resolution at L2/L3 to improve purity**
  - only really care about L1 efficiency near L2 threshold

Redundant trigger Example: from CDF

Inclusive, Redundant Inputs are helpful

- L1_EM8_PT8 feeds
  - Inclusive high-p_T central electron paths
  - Di-lepton paths (ee, eμ, eτ)
  - Several back-up triggers
  - 15 separate L3 trigger paths in total
- A ttbar cross section analysis uses
  - Inclusive high-p_T central e paths
  - Inclusive high-p_T forward e paths
  - MET + jet paths
  - Muon paths

Trigger menus must be

Inclusive:
Reduce the overhead for the program analysis

Redundant:
if there is a problem in one detector or in one trigger input, the physics is not affected (less efficiently, but still the measurement is possible)

Concluding remarks

- The trigger strategy is a trade-off between physics requirements and affordable systems and technologies
- Here we just reviewed the main trigger requirements coming from physics
  - High efficiency – low dead-time
  - Perfect knowledge of the trigger selection on signal and background
  - Flexibility and redundancy
- In the next section we will see how to implement such a system, still satisfying these requirements