ISO-TDAQ school
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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)

Trigger concept in HEP

↗ In High Energy Physics

| Start the data acquisition | only when → | Identify the interesting process |

↗ What is "interesting"?
  ↗ Define what is signal and what is background
↗ Which is the final affordable rate of the DAQ system?
  ↗ Define the maximum allowed rate
↗ How fast the selection must be?
  ↗ Define the maximum allowed processing time

# 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
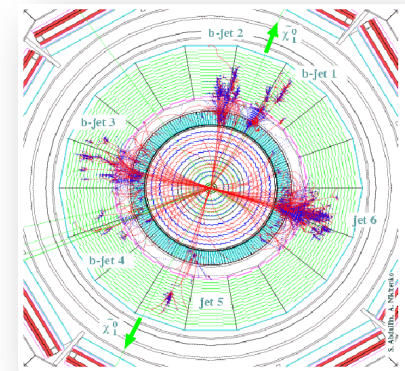
Trigger concept within collider experiments

↗ 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
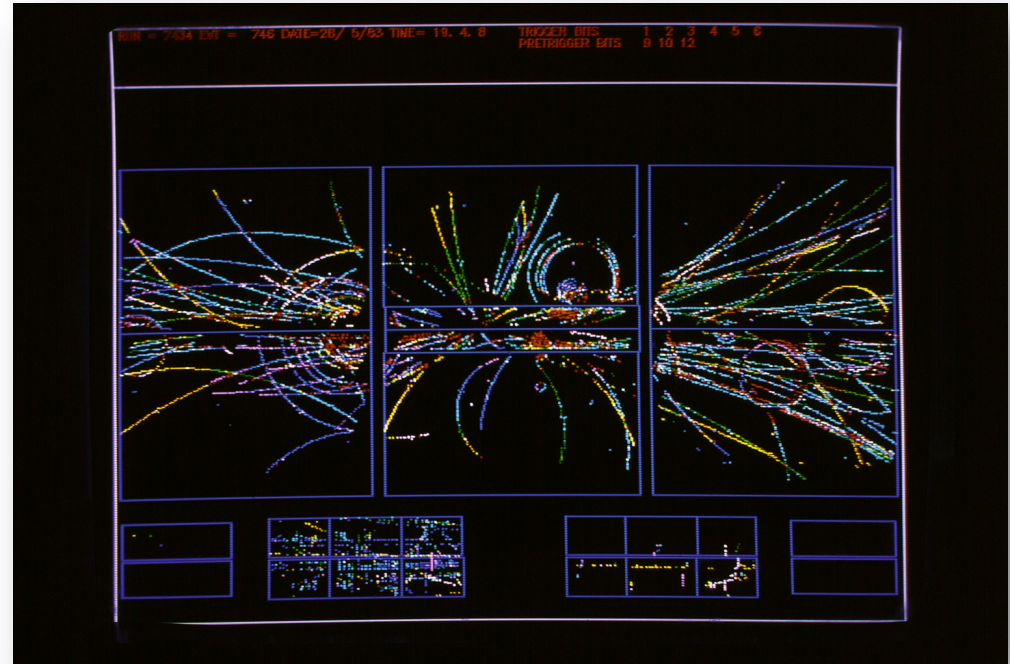

$$R = \mu \cdot f_{BC} = \sigma_{in} \cdot L$$

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

Multiple interactions per collision

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

↗ hadron colliders: each event contains more than one interaction
  ↗ LHC average 25 interactions per BC: added to the interaction of interest, there are a number of "**underlying events**"
  ↗ Additional interactions add superimposed information on the detectors, resulting in bigger and more complicated event **(pile-up)**. Event characteristics vary with luminosity so it's not a simple events rescaling but events with different number of muons, clusters,... must be managed
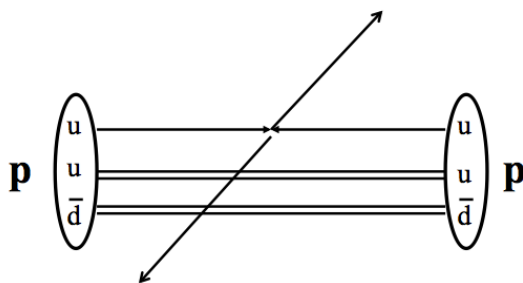
This has effects on:
  ❖ *the event-size, mainly when the number of readout channels is huge*
  ❖ *the trigger selection…..*
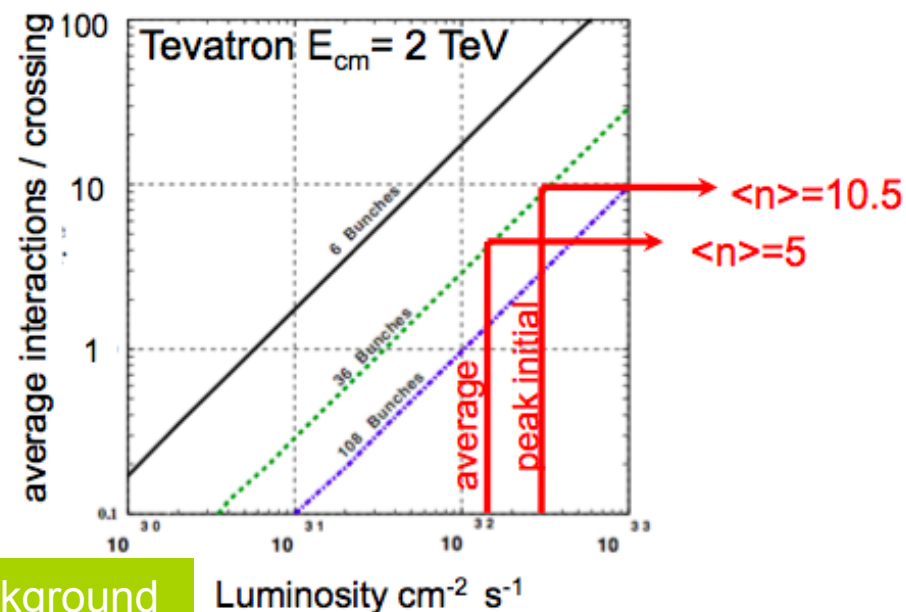
Trigger must be flexible to cope changes in L and background

The problem of the rate

colliders	BC time	collision rate	Design luminosity (cm^{-2} s^{-1})
LEP	22 μs	45 kHz	7 x 10^{31}
Tevatron	396-132 ns	2.5 - 7.6 MHz	4 x 10^{32}
LHC	25 ns	40 MHz	10^{34}

Maximum acceptable rate ~ O(100) Hz

↗ The crossing time defines an overall time constant for signal integration, DAQ and trigger

↗ Even at low luminosity colliders, the rate of the interactions is not affordable by any data taking system
  - ↗ 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

↗ 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

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

- ↗ 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 collider physics…

A trigger challenge: hadron collider experiments

↗ Production cross-sections span over many orders of magnitude (10 Tevatron, 12-13 LHC)

  ↗ Collision rate is dominated by non interesting physics

  ↗ Background discrimination is crucial

Total non-diffractive p-p cross section at LHC ($\sqrt{s}$=14 TeV) is ~ 70 mb

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

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
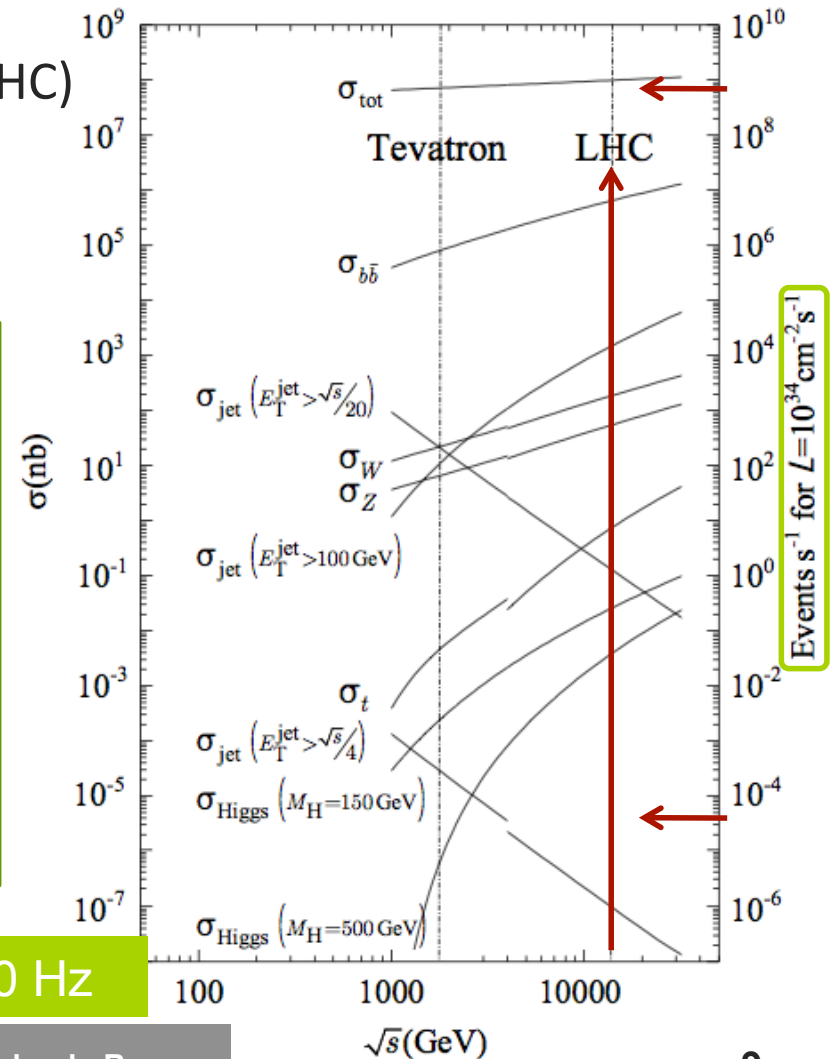
…and more requirements

↗ Multi-purpose experiments: the trigger must satisfy a **broad physics program, with no bias**
  - ↗ 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

Efficiency and dead-time

Which is the best filter?

↗ Goal of the trigger is to maximize the collection of data for physics process of interest
  ↗ Aim for high efficiency !

↗ $\varepsilon_{trigger} = N_{good\ (accepted)}/N_{good\ (produced)}$

  ↗ Selection must be optimized on the signal

  Next pages

  ↗ Trigger dead-time is source of inefficiency
    ↗ 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
    ↗ Use of multi-level triggers: filters in cascade!

  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
  ↗ Needs high efficiency, but rejection power can be comparatively modest

↗ **High-level**: 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

↗ 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

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

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

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

Trigger signatures in HEP
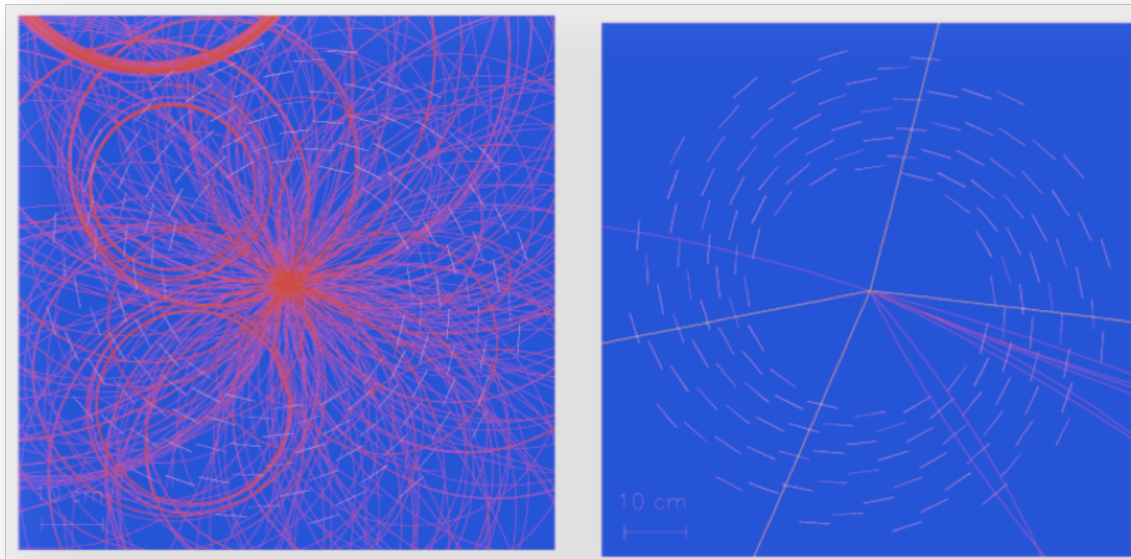
Simulated H-> 4μ event at LHC with and without soft collisions

Trigger signature given by high momentum muons

↗ **Signature**=one or more parameters used 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
   ↗ We first use intuitive criteria: fast and reliable

↗ Eventually combine more signals together following a certain trigger logic, giving **redundancy**.
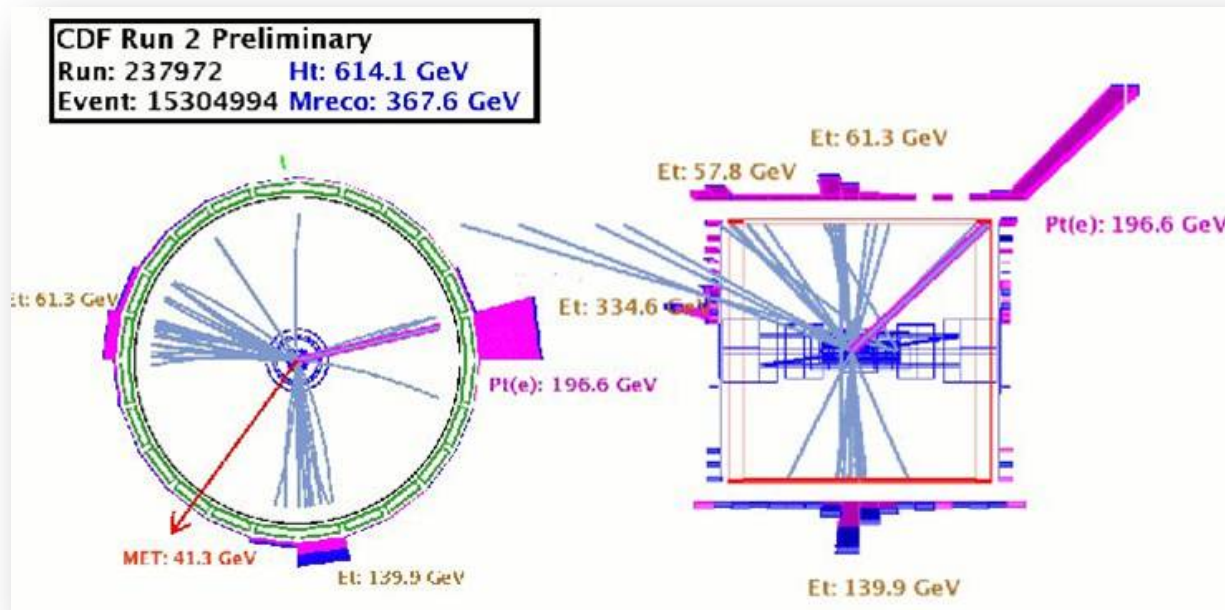
Selection criteria in HEP
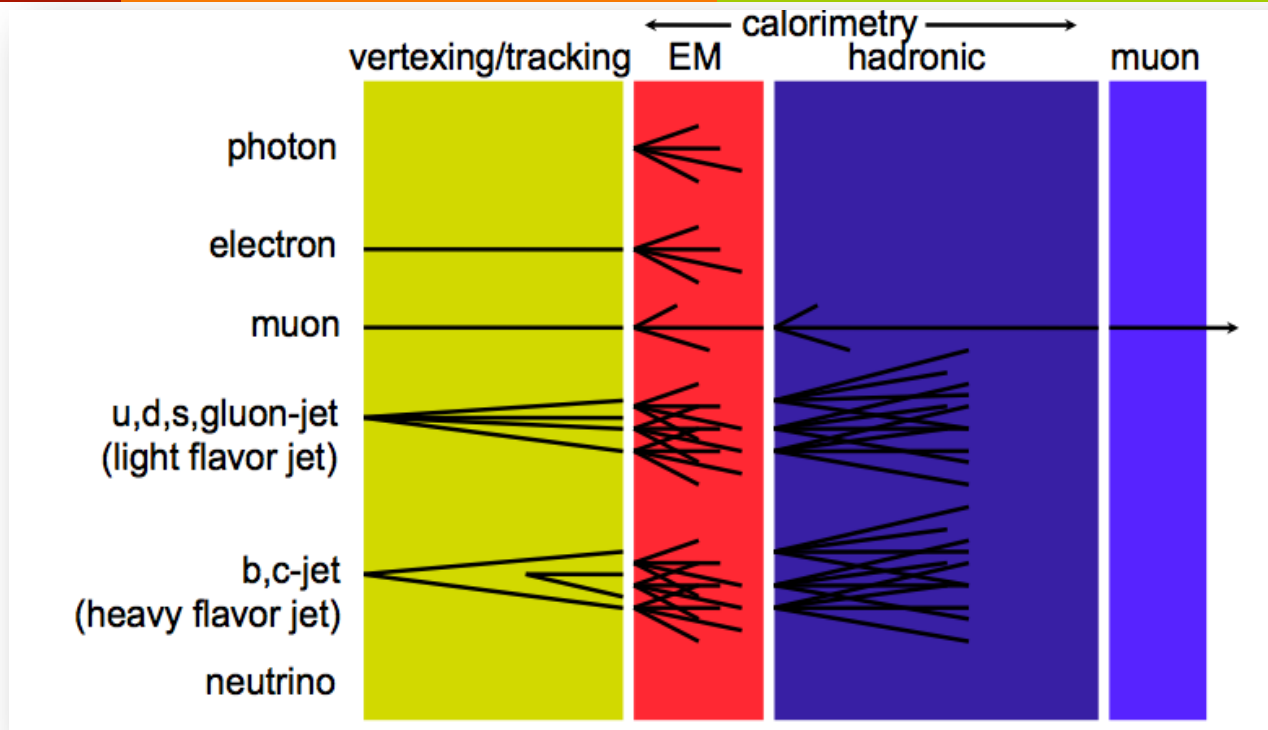
- ↗ Trigger selection is based on single/double particle signatures
  - ↗ Muon tracks, energy deposits in the calorimeters, tracks in the silicon detectors
- ↗ Usually detectors are segmented in a number of trigger regions
- ↗ The final trigger response is given by the logical combinations (AND, OR) of all/some of the inputs

Trigger criteria at colliders

↗ At collider experiments we apply thresholds on Energy or momentum of the identified particles: most used are **electrons and muons** which have clear signature

↗ **Shower shapes and isolation criteria** are also used to separate single leptons from jets

CDF Run 2 Preliminary
Run: 237972   Ht: 614.1 GeV
Event: 15304994 Mreco: 367.6 GeV

Et: 61.3 GeV
Et: 57.8 GeV
Pt(e): 196.6 GeV
Et: 61.3 GeV
Et: 334.6 GeV
Pt(e): 196.6 GeV
MET: 41.3 GeV
Et: 139.9 GeV
Et: 139.9 GeV

↗ In addition we use global variables, such **as total energy, missing energy** (for neutrino identification), **back-to-back tracks**, etc...

$$\mathbb{E}_T = -\left| \sum_{i=towers} E_i \cdot \hat{n}_T^i \right|$$

..and at hadron colliders

↗ 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 $E_{total} < E_{2\ beams} = E_{cm}$

↗ The bulk of the cross-sections from Standard Model processes are the presence of high-pT particles (hard processes)

  ↗ In contrast most of the particles producing minimum-bias interactions are soft (pT ~ 1 GeV)

  ↗ Large missing E_T can be sign of new physics
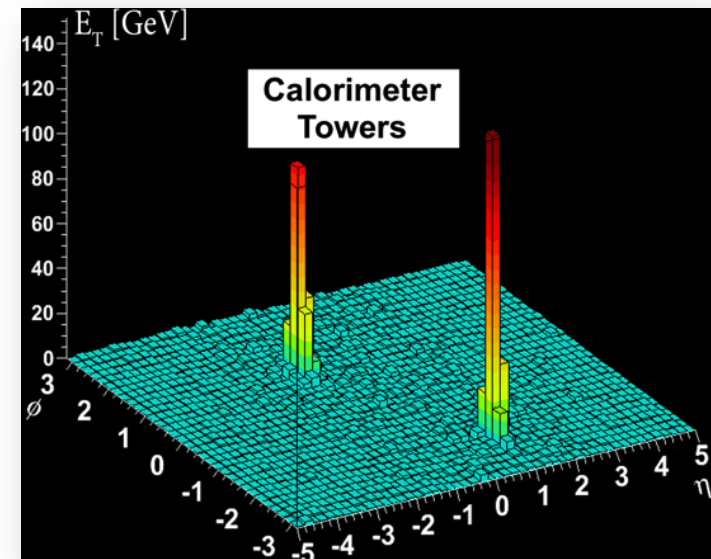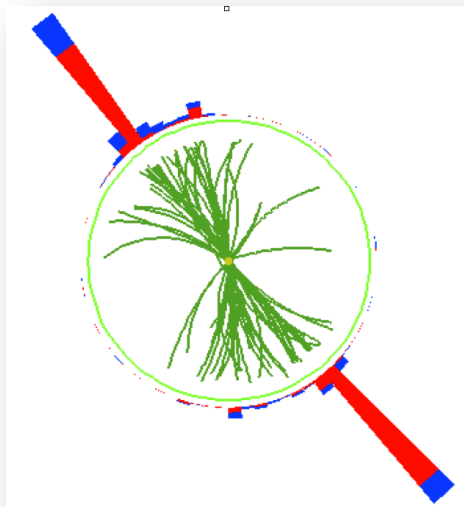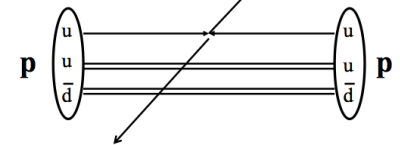
Example of multilevel trigger: ATLAS calorimeter trigger

- ↗ e, γ, τ, jets, E_{Tmiss}, 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 (signal is larger than 1 BC)
- ↗ High-Level trigger
  - ↗ Topological variables and tracking information for electrons from Inner Detectors
    - ↗ Cluster shape at L2
    - ↗ Jet algorithms at L3 (Event Filter)
  - ↗ Isolation criteria can be imposed to control the rate (reducing jet background at low energies thresholds)
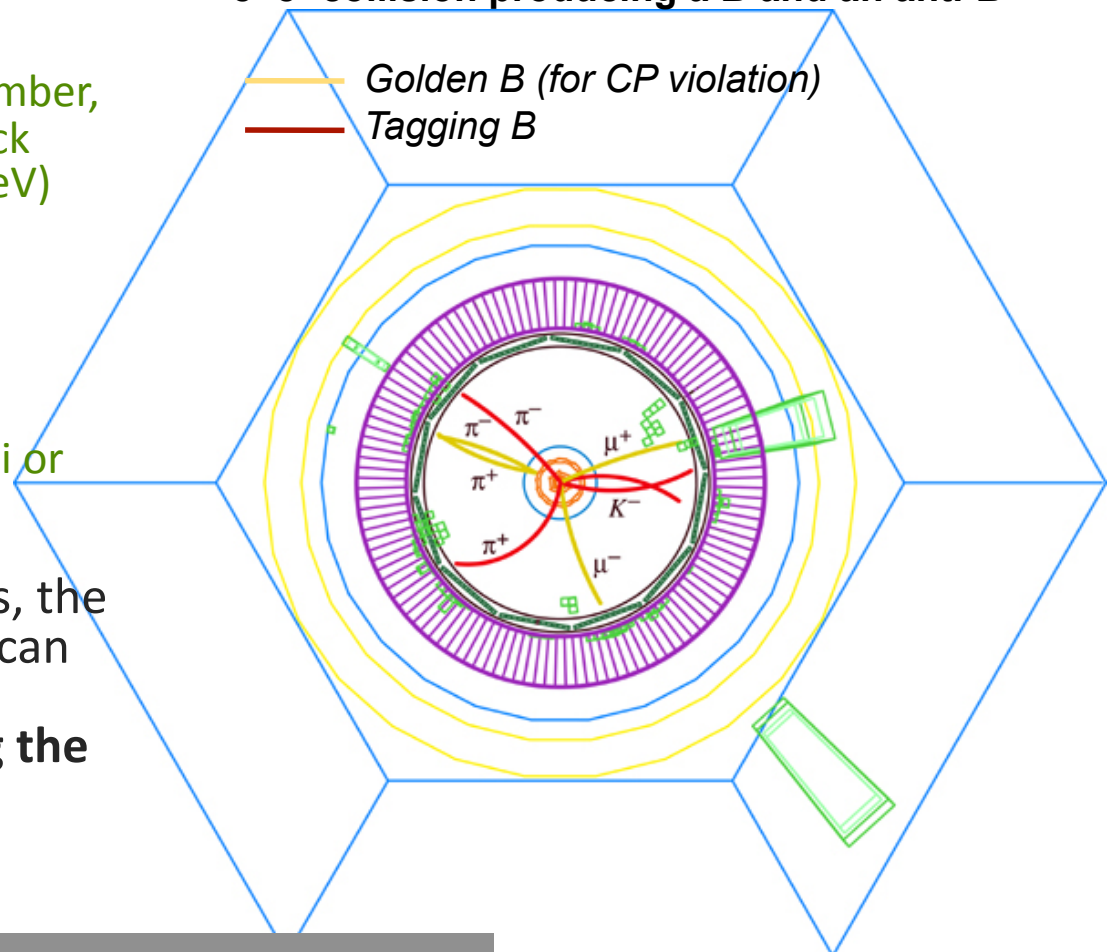

2009 SPLASH EVENT — HEC LAYER 1 — ATLAS Preliminary — Data — Prediction
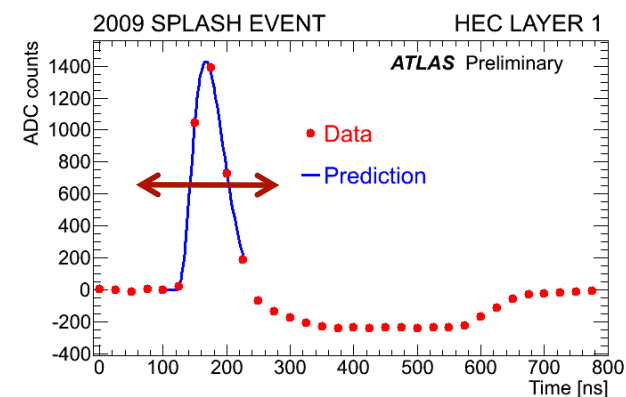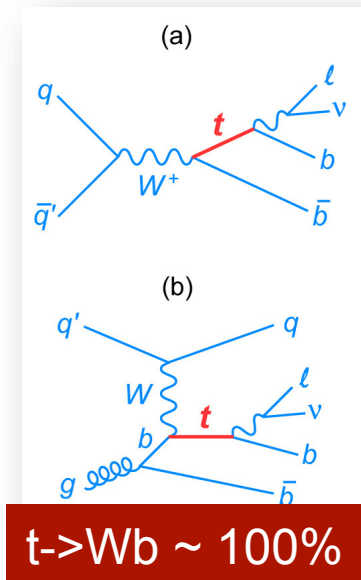
Level-1 clustering algorithm
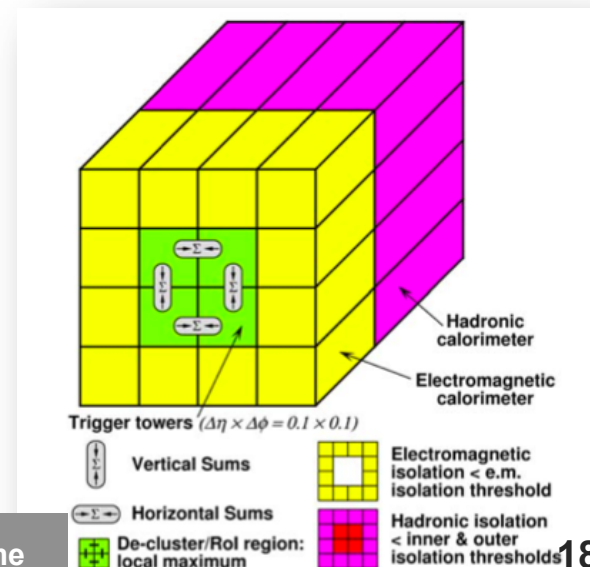
Trigger objects example: BaBar

- 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

- Search for topology
  - **number of objects**, optionally requiring separation cuts in phi or matching between tracks and clusters
- For some precise measurements, the crucial performance parameter can be not the efficiency, but the **systematic error in determining the efficiency**
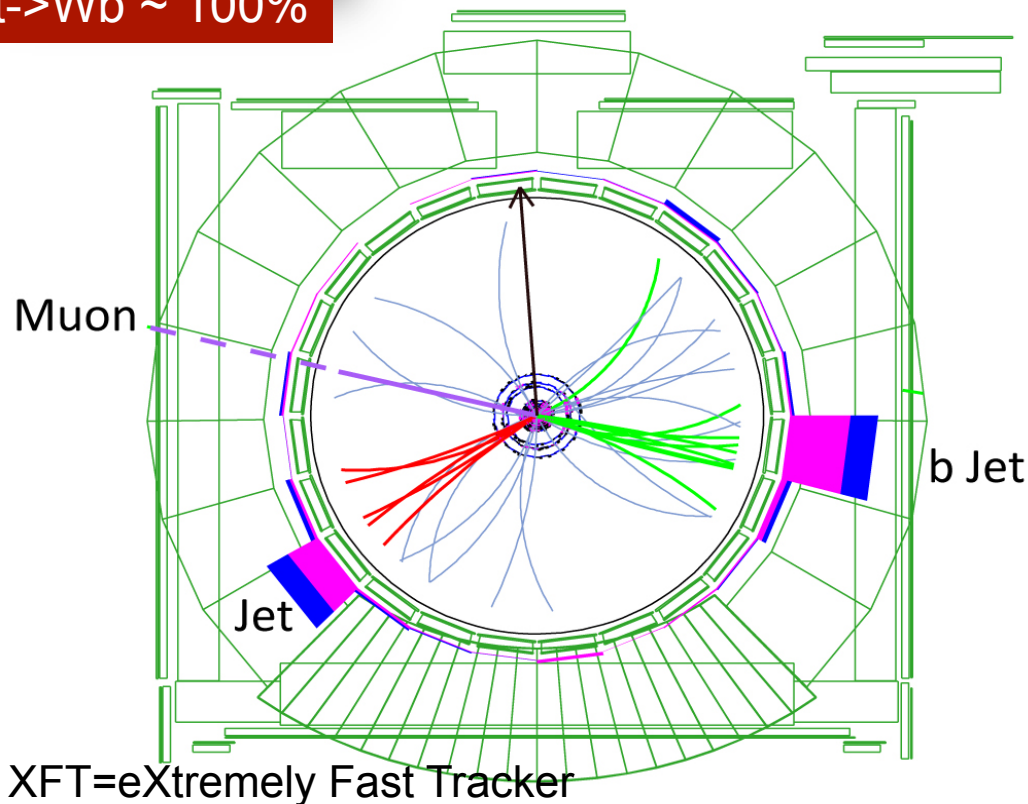
Golden event in the BaBar Detector
e+e- collision producing a B and an anti-B

Golden B (for CP violation)
Tagging B

(a)

q — t — ℓ, ν
W^+ — b
$\bar{q}'$ — $\bar{b}$

(b)

q' — q
W
b — t — ℓ, ν, b
g — $\bar{b}$

t->Wb ~ 100%

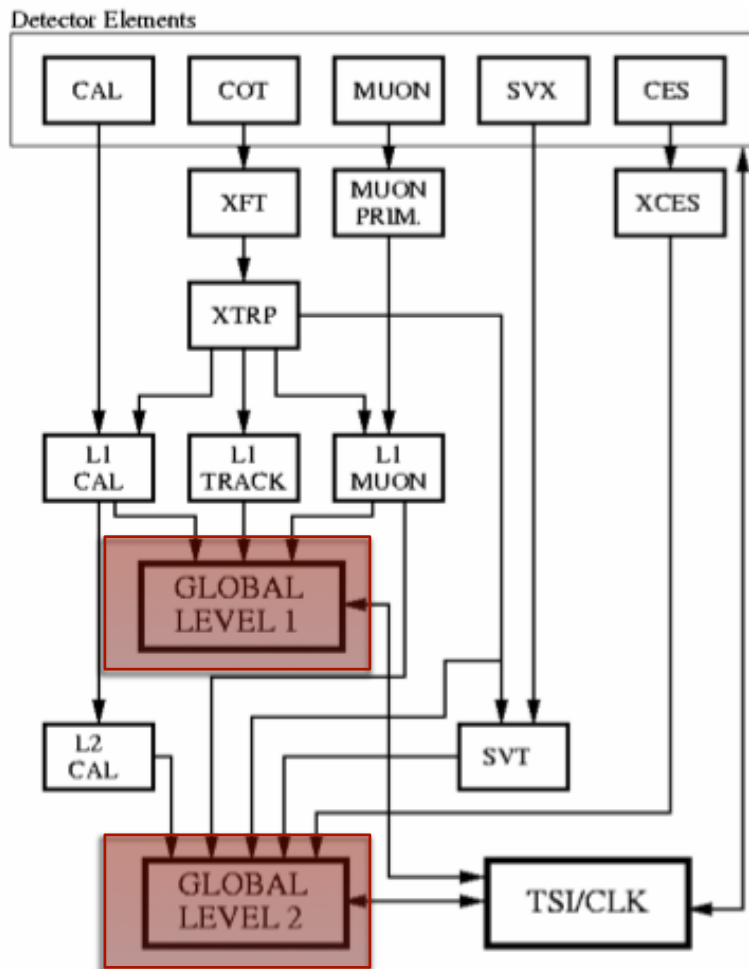missing Energy

Muon

Jet

b Jet

XFT=eXtremely Fast Tracker

CDF single top event

↗ Signal characterization:
  ↗ 1 high p_T lepton, in general isolated
  ↗ Large MET from 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 (Cal EM+HAD)
  ↗ Missing E_T, SumE$_T$
  ↗ Muon (Muon + XFT)

↗ Trigger objects at L2:
  ↗ L1 information
  ↗ SVT (displaced track, impact parameter)
  ↗ Jet cluster
  ↗ Isolated cluster
 ↗ Calorimeter ShowerMax

Trigger objects example: CDF

CDF single top event

- ↗ Signal characterization:
  - ↗ 1 high p_T lepton, in general isolated
  - ↗ Large MET from 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 (Cal EM+HAD)
  - ↗ Missing E_T, SumE_T
  - ↗ Muon (Muon + XFT)

- ↗ Trigger objects at L2:
  - ↗ L1 information
  - ↗ SVT (displaced track, impact parameter)
  - ↗ Jet cluster
  - ↗ Isolated cluster
  - ↗ Calorimeter ShowerMax (CES)

↗ Since p_T (or E_T) resolution is finite, and worst at level-1 (coarse granularity, $dp_T/p_T \sim 1\%$), the trigger efficiency depends on the real p_T

　　↗ For example some particles can be under threshold, failing the trigger, because their p_T is underestimated
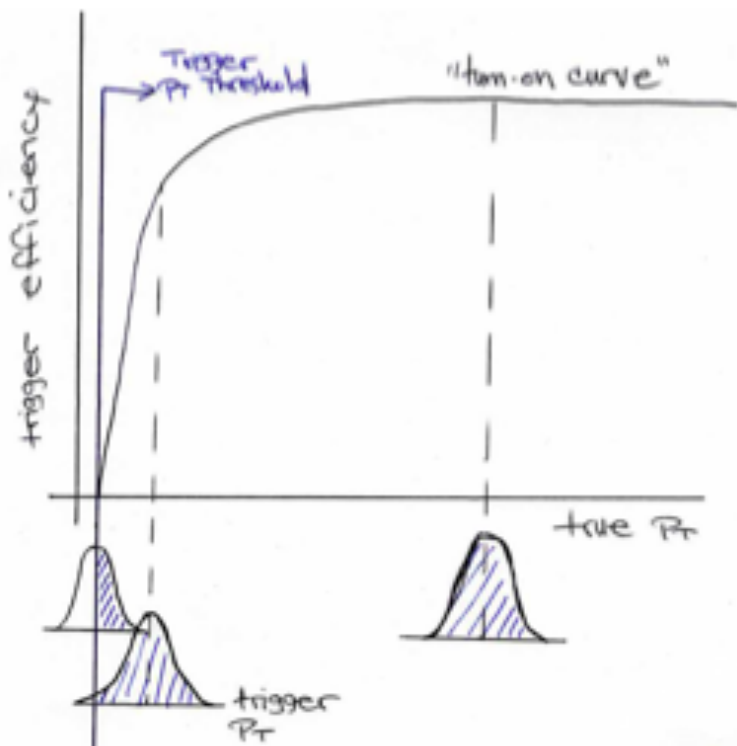

↗ The trigger efficiency as a function of the true p_T, measured with the offline reconstruction (resolution order of 0.1%), is described by the **turn-on curves**
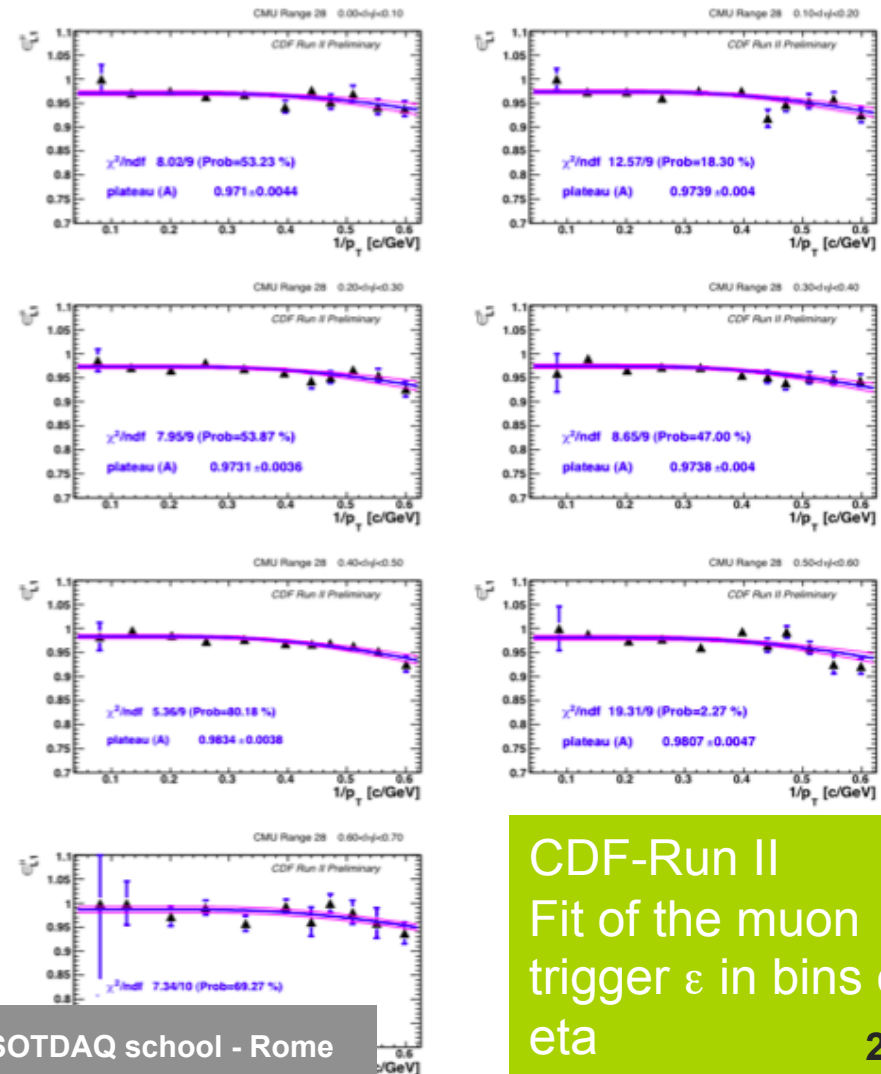
Trigger efficiency dependency

↗ 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 (to control the rate)

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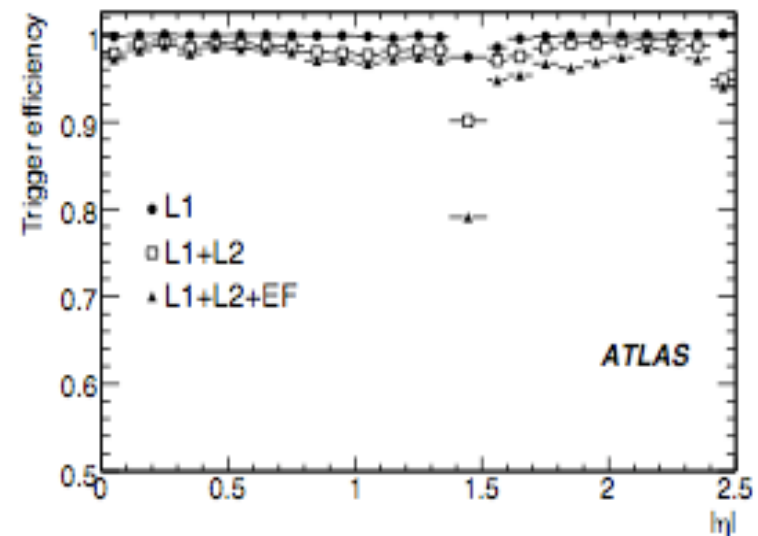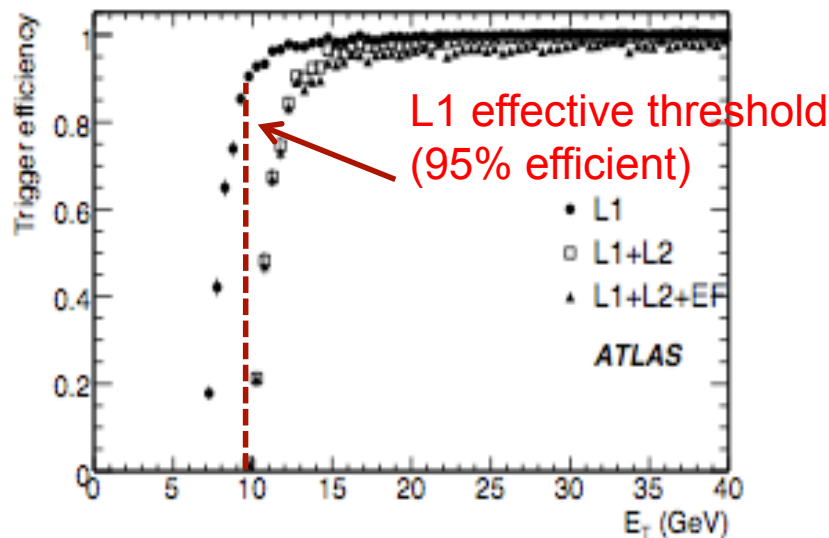
Parametrizing the trigger efficiency

↗ 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
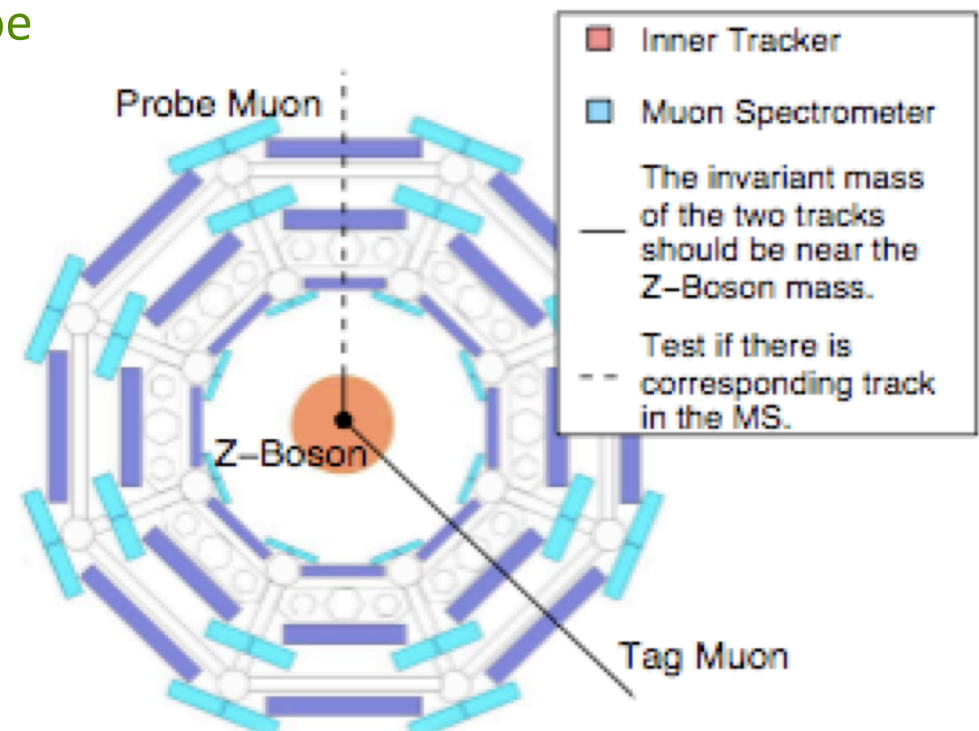Fit of the muon trigger ε in bins of eta

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
  ↗ We can use orthogonal triggers (not correlated, no bias)
  ↗ 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

Probe Muon

Inner Tracker

Muon Spectrometer

The invariant mass of the two tracks should be near the Z–Boson mass.

Test if there is corresponding track in the MS.

Z–Boson

Tag Muon

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
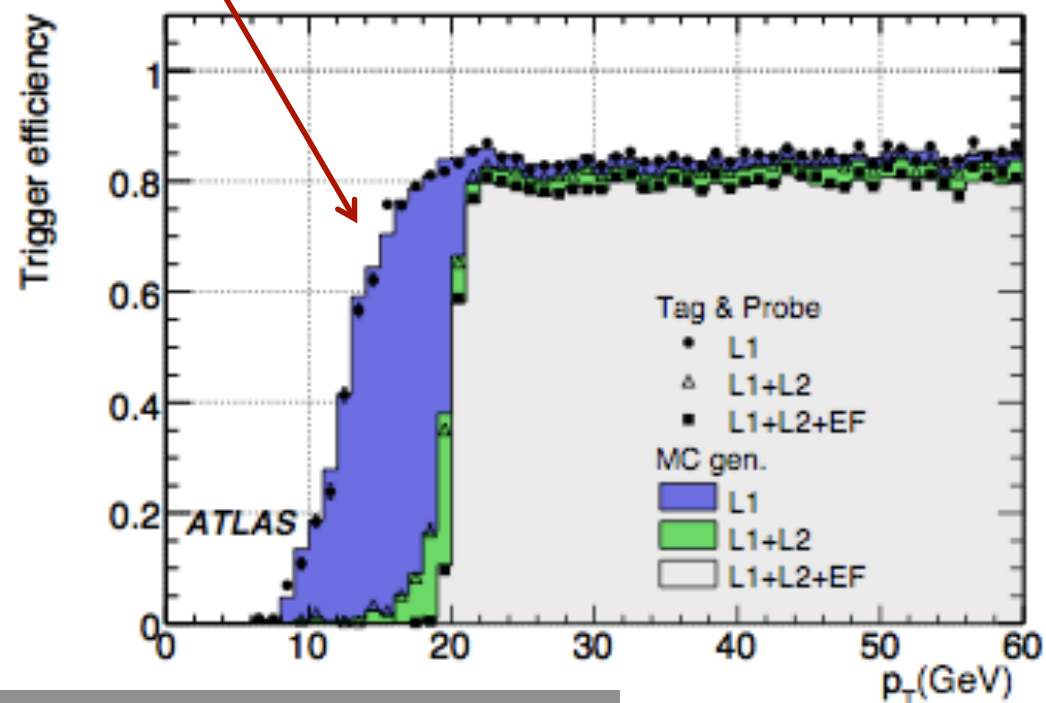
Rates allocation on trigger signatures

✓Target is the final allowed bandwidth (~200 Hz @ LHC)

✓Trigger rate allocation on each trigger item is 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 E_T/p_T range, of the estimated efficiency with the cross sections representing the main trigger source

↗ Large uncertainties due to detector response and jet cross-sections

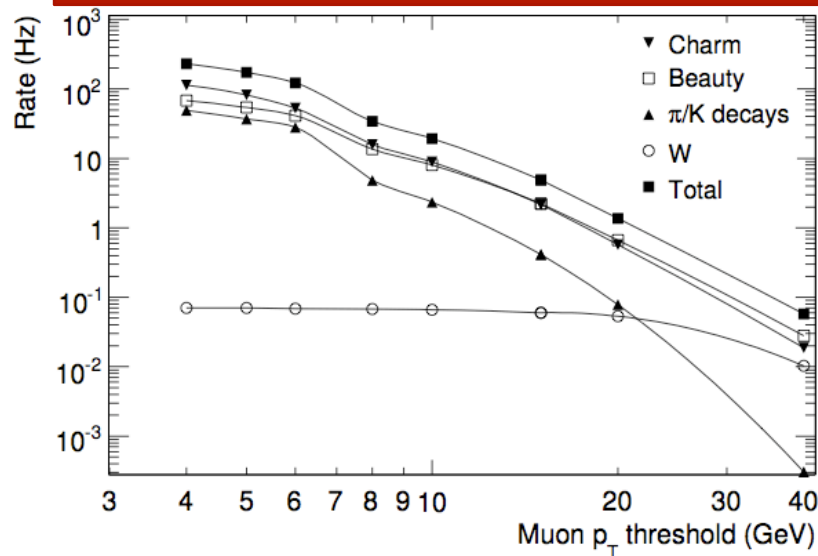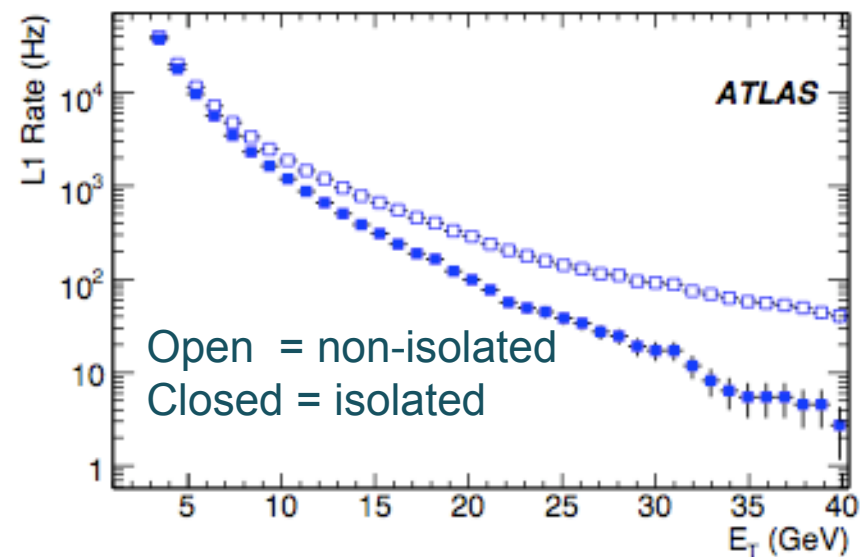 ↗ To be tuned with (early) data

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

Open = non-isolated
Closed = isolated

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

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 triggers 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)
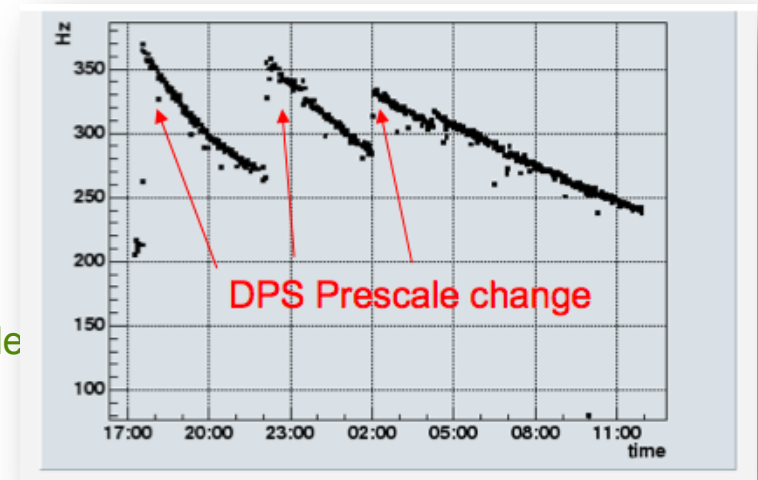
CDF: L2 rate during a run

A balance between physics interest and system bandwidth...

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 chain**

↗ A trigger chain includes a set of cut-parameters or instructions 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

A-tr

B-tr

C-tr

D-tr

E-tr

F-tr

My measure
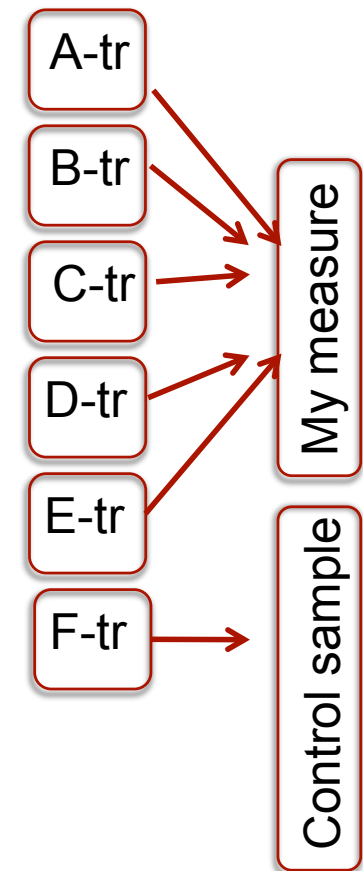
Control sample

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 increases, 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/γ and muon triggers are unprescaled, except EM3

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

Trigger Chain: Inclusive High-p_T Central Electron

- ↗ 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:

↗ 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 chains
  ↗ Di-lepton chains (ee, eμ, eτ)
  ↗ Several back-up triggers
  ↗ 15 separate L3 trigger chains in total

↗ A ttbar cross section analysis uses
  ↗ Inclusive high-p_T central e chains
  ↗ Inclusive high-p_T forward e chains
  ↗ MET + jet chains
  ↗ Muon chains

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