ISO-TDAQ school
Krakow, 01/02/2012

An introduction to the trigger

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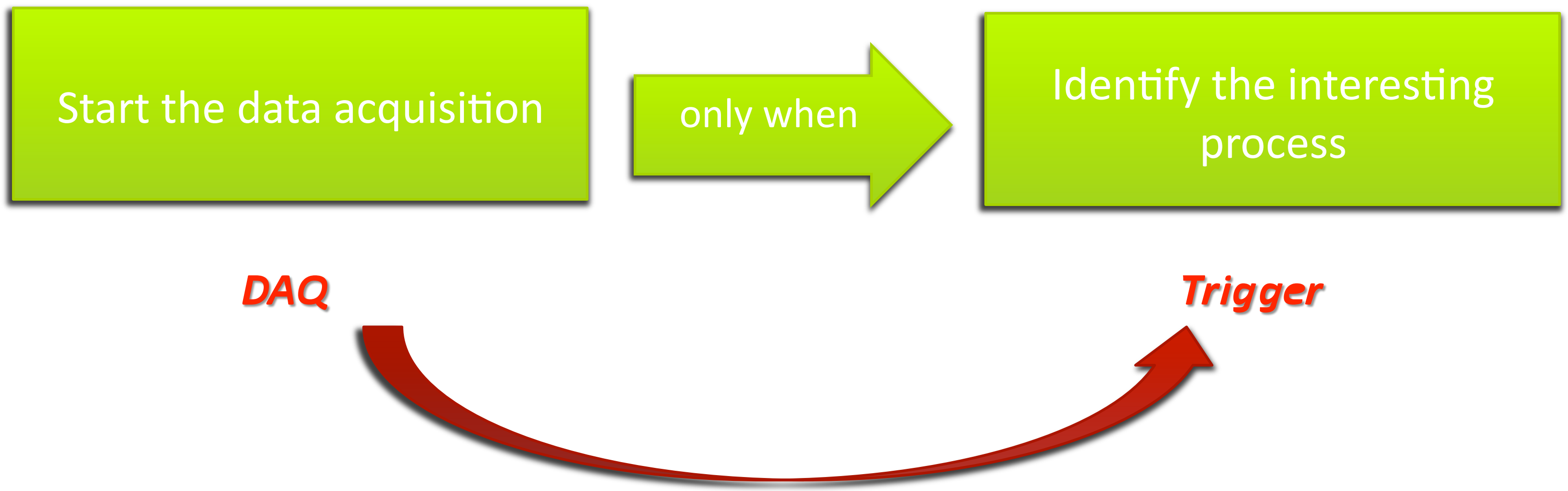
Trigger concept

- 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
  - only if there is enough light for your lenses (or add a flash light) → Ensure the sensitivity to a parameter
  - only if your hand is not shaking → Ensure a good synchronization

Digital signal saying yes or no (Interrupt signal)

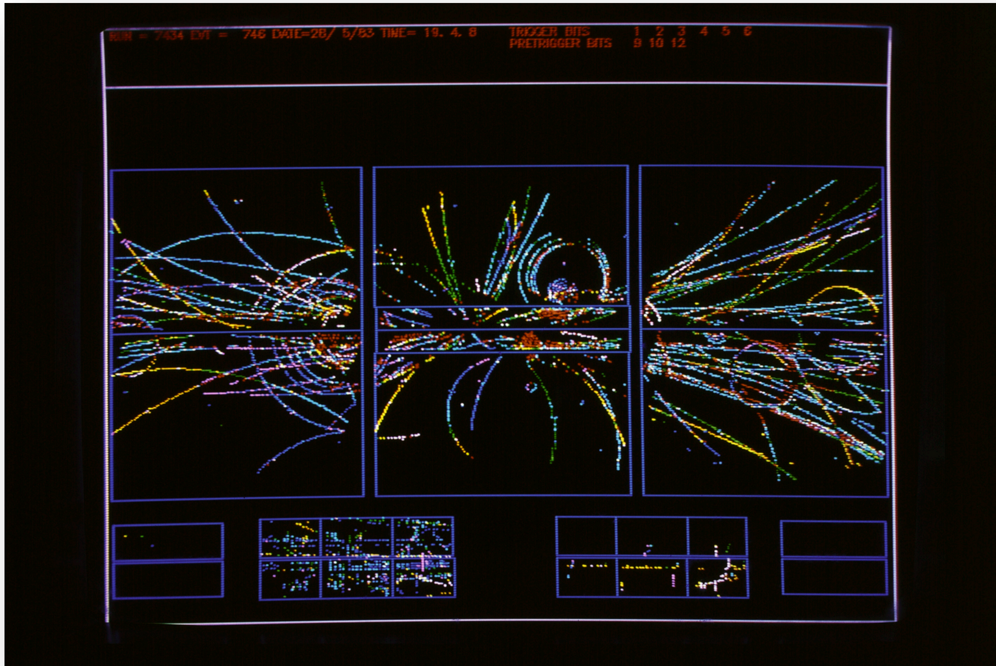
Trigger concept in HEP



- 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 for collider experiments

- At the collider experiments, we have bunches of particles crossing at regular intervals and interactions occur during the bunch-crossings (BCs)
  - **Event**: the trigger selects the bunch crossing of interest for physics studies, and all the information from the detectors corresponding at that given BC are recorded



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

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

L = Instant. luminosity
f_{BC} = Rate of bunch crossings
μ = Average (pp) interactions / BC

The problem of the rate

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

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

25 * 40 MHz ≈ 70 mb *10/nb
≈ **1GHz**

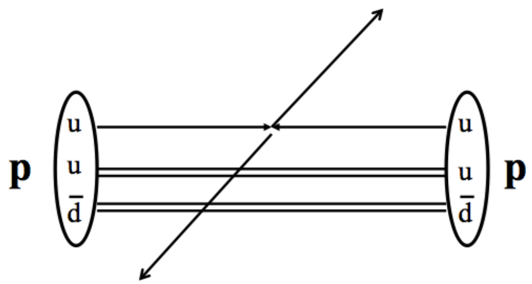
Maximum acceptable rate
~ O(100) Hz

- 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…..

Multiple interactions per collision

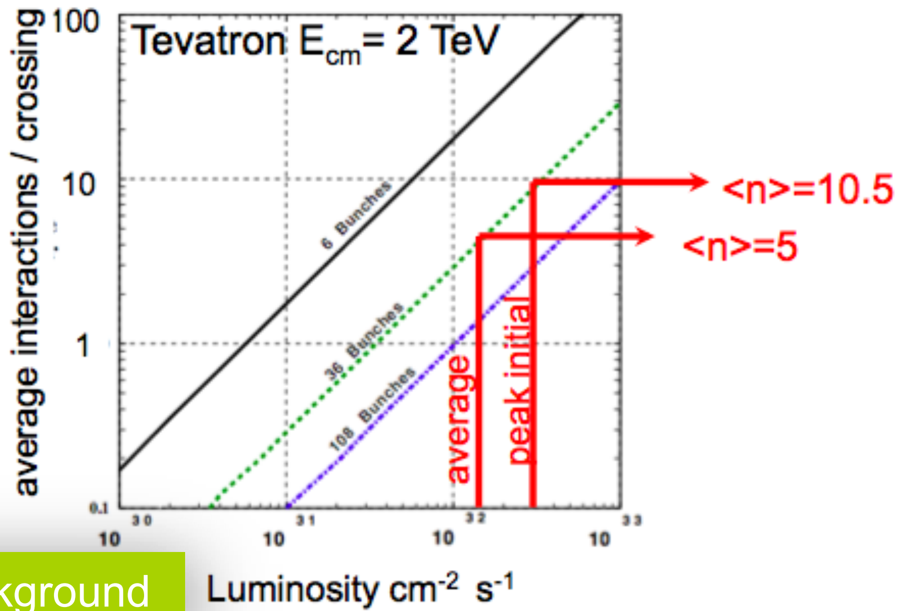
- e+e- colliders
  - very small interaction rate (small cross-section), one event generally contains one single interaction (LEP-HERA)

- 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

A trigger challenge: hadron colliders

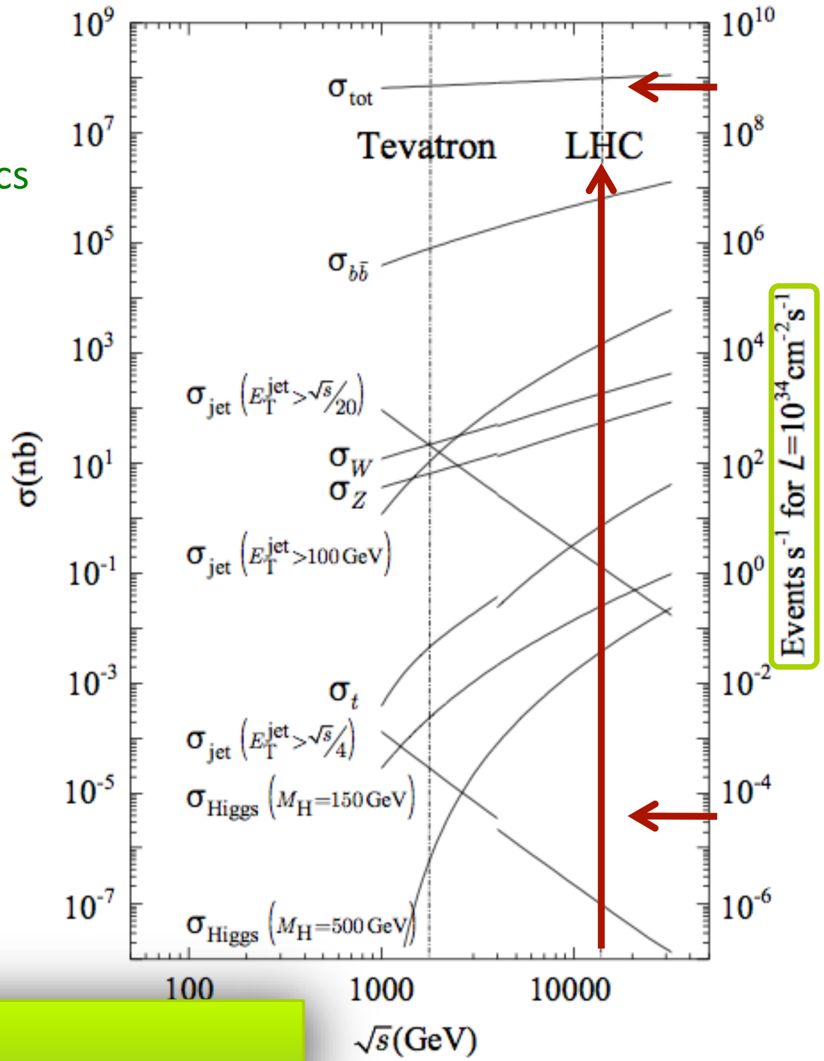
- Production cross-sections span over many orders of magnitude (10 Tevatron, 12-13 LHC)
  - Collision rate is dominated by non interesting physics
  - Background discrimination is crucial

Total non-diffractive p-p cross section at LHC (√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

$$\frac{\sigma_{tot}}{\sigma_{H(500\,\mathrm{GeV})}} \approx \frac{100\,mb}{1\,pb} \approx 10^{11}$$



Trigger must reduce event rates from GHz to ~200 Hz

Trigger requirements in HEP
(i.e. what do we want to maximize in the trigger?)

- **Background rejection** (Rate control)
  - Instrumental or physics background
  - 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

Which is the best filter?

- **Signal efficiency**: Goal of the trigger is to maximize the collection of data for physics process of interest

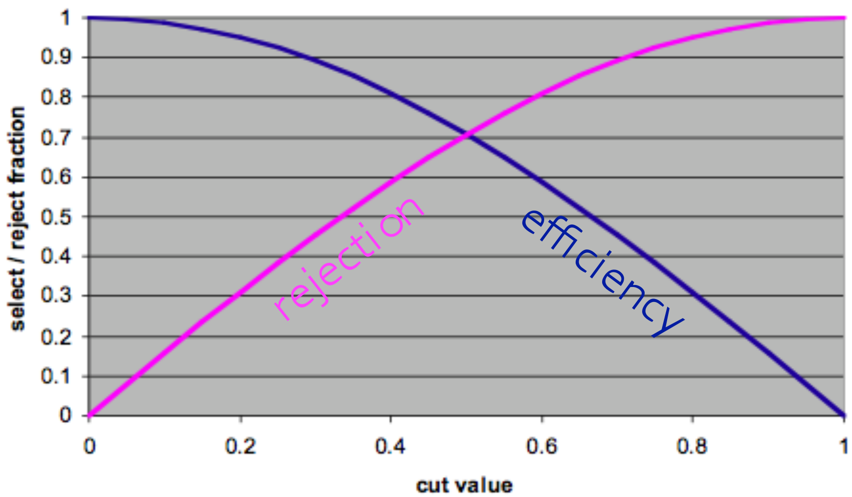
$$\varepsilon_{trigger} = N_{good\,(accepted)} / N_{good\,(produced)}$$

  - Maximize the acceptance
    - Good design of the architecture
      - Use of multi-level triggers: filters in cascade!
  - Optimize the selection
    - Selection must be optimized on the signal

...with compromises

- Not always both requirements can be realized: a compromise between number of processors working in parallel and fastness of the algorithms - to make it affordable

- As selection criteria are tightened
  - Background rejection improves
  - But selection efficiency decreases



- Whatever criteria you choose, discarded events are lost for ever!
- So, be careful that your trigger
  - Is not biasing your measurement
    - Discovery experiments: use inclusive selections
    - Precision experiments: use well known selections
  - Is reliable

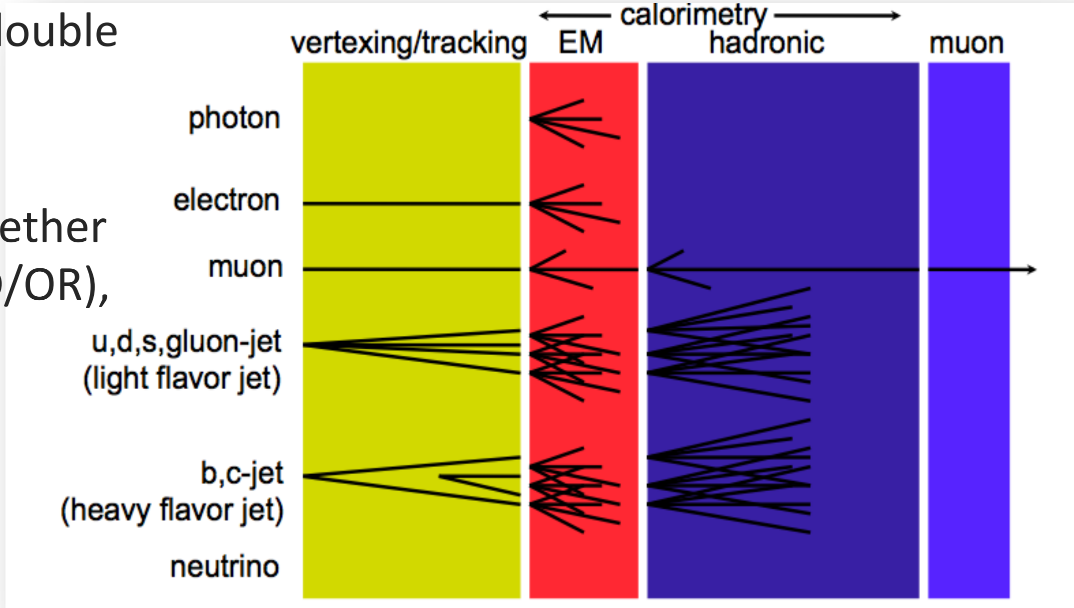
Ensure good efficiency with…

Robustness! Win against the unexpected!

- **Flexibility**: to cope changes in Luminosity and background
  - Programmable thresholds, high granularity to maintain uniform performance, able to follow changes of luminosity, beam-size and vertex position, able to reach physics results also after 10 years of data taking
- **Redundancy**: to make rates independent from the detector and the machine performance
  - Different background and pile-up change event shape and dimension
- **Selectivity**
  - Good granularity and good resolution of the parameters to ensure good rejection of the unwanted background

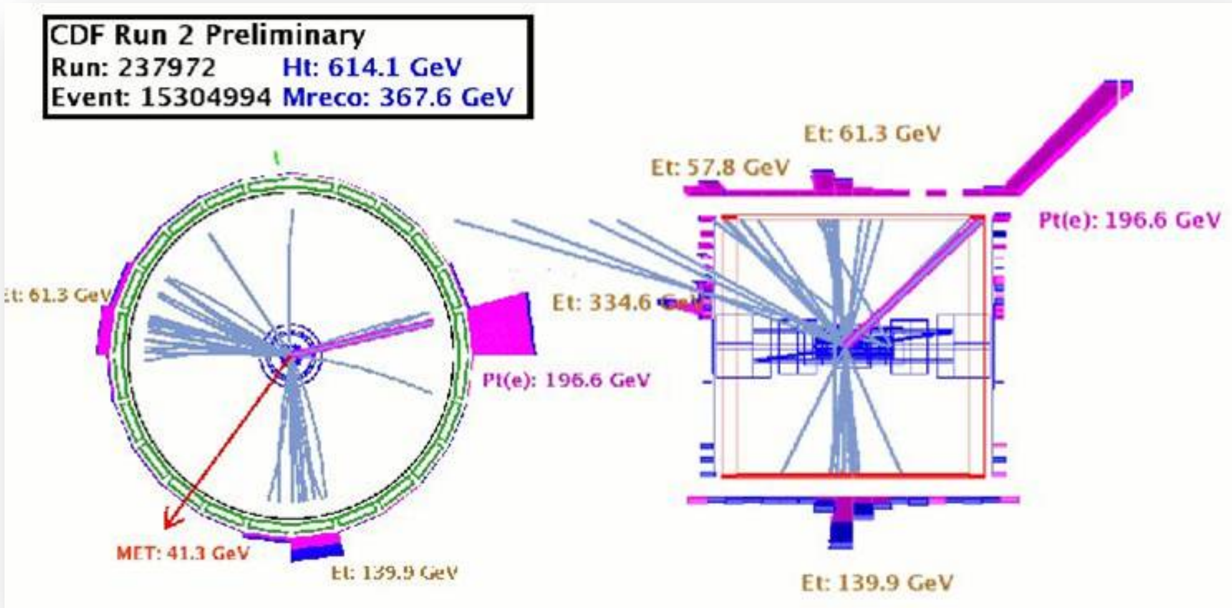
Trigger signatures

- **Signature** = collection of parameters used for discrimination
- 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
  - Muon tracks, energy deposits in the calorimeters, tracks in the silicon detectors….
- Trigger selection is based on single/double particle signatures
- Eventually combine more signals together following a certain trigger logic (AND/OR), giving **redundancy**
  - Different signatures -> one analysis
  - Different analysis -> one signature



Trigger criteria at colliders

- Apply thresholds on energy/momentum of the identified particles: most used are **electrons and muons** which have a clear signature
- **Shower shapes and isolation criteria** are also used to separate single leptons from jets

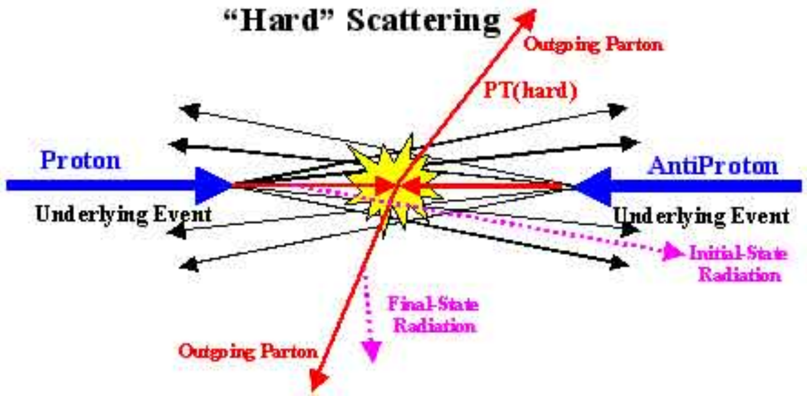


$$\not{E}_T = -\left| \sum_{i=towers} E_i \cdot \hat{n}_T^i \right|$$

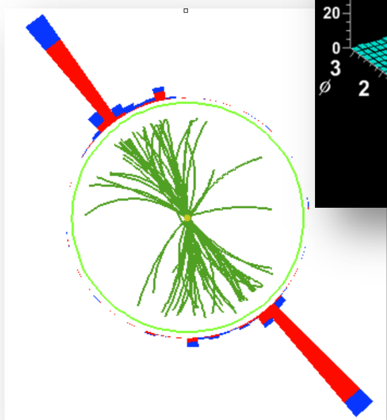
- In addition, global variables such **as total energy, missing energy** (for neutrino identification), **back-to-back tracks**, etc…

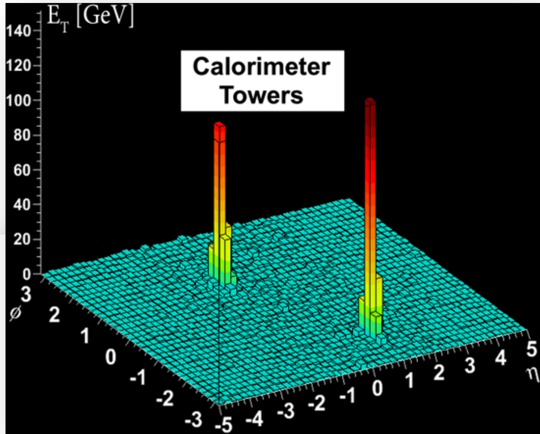
..and at hadron colliders

- Apply thresholds on **transverse Energy E_T** (or transverse momentum **p_T**), which is the component of energy (or momentum) orthogonal to the beam axis
  - **Initial $p_T = 0$**
  - **$E_{total} < E_{2\ beams} = E_{cm}$**

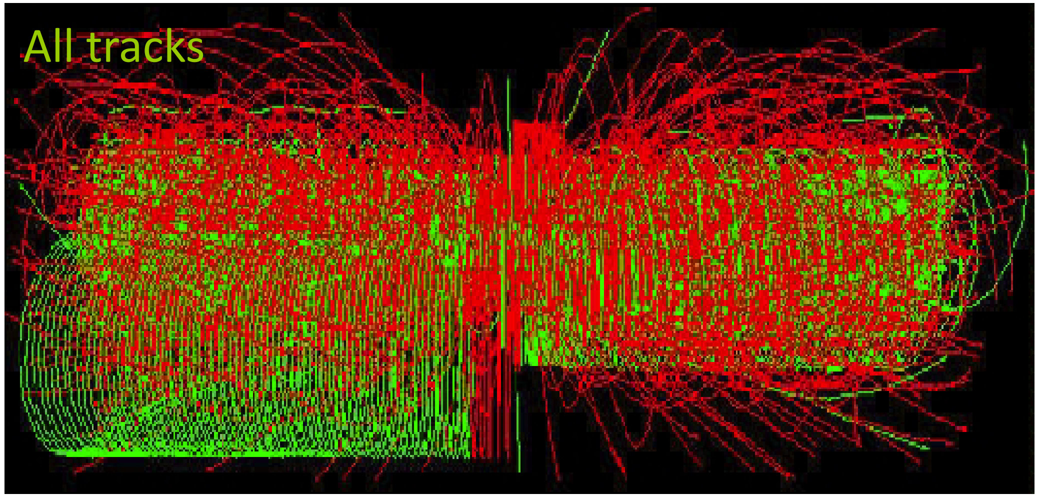


- The bulk of the cross-sections from Standard Model processes are the presence of **high-p_T particles** (**hard processes**)
  - In contrast most of the particles producing (minimum-bias) interactions are soft (p_T ~ 1 GeV)
  - Large missing E_T can be sign of new physics

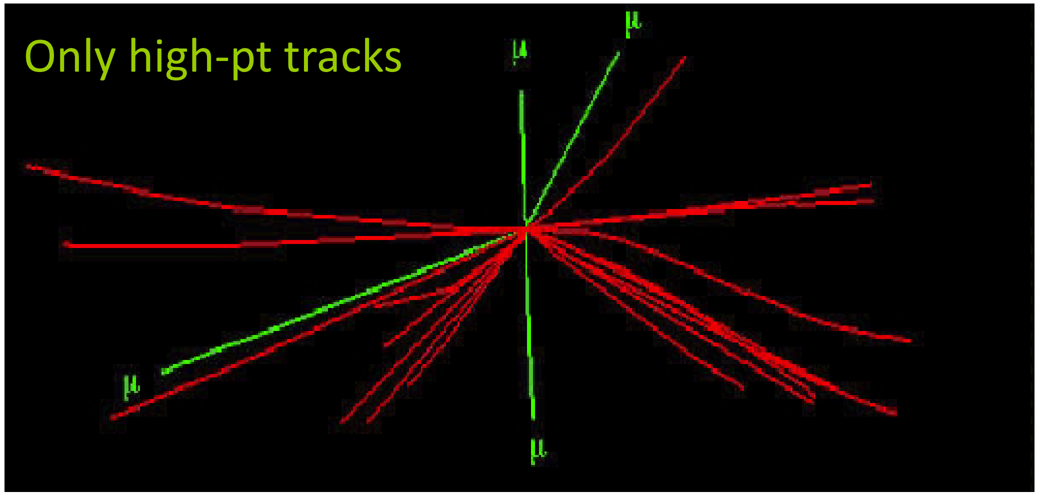




A simple trigger for the Higgs Boson



+30 MinBias



Higgs -> 4μ

Simulated **H→ 4μ** event at LHC with and without soft collisions

Trigger signature given by **high momentum muons**

Use of multi-level triggers

- To obtain high efficiency with large background rejection, the trigger selection is organized in multiple steps

  - **First-level** = fast (~few μs) with limited information and simple algorithms (hardware)
  - **Higher levels** = moderately fast (~10s to ms), hardware/software, can use comparatively very complex (hence slow) algorithms

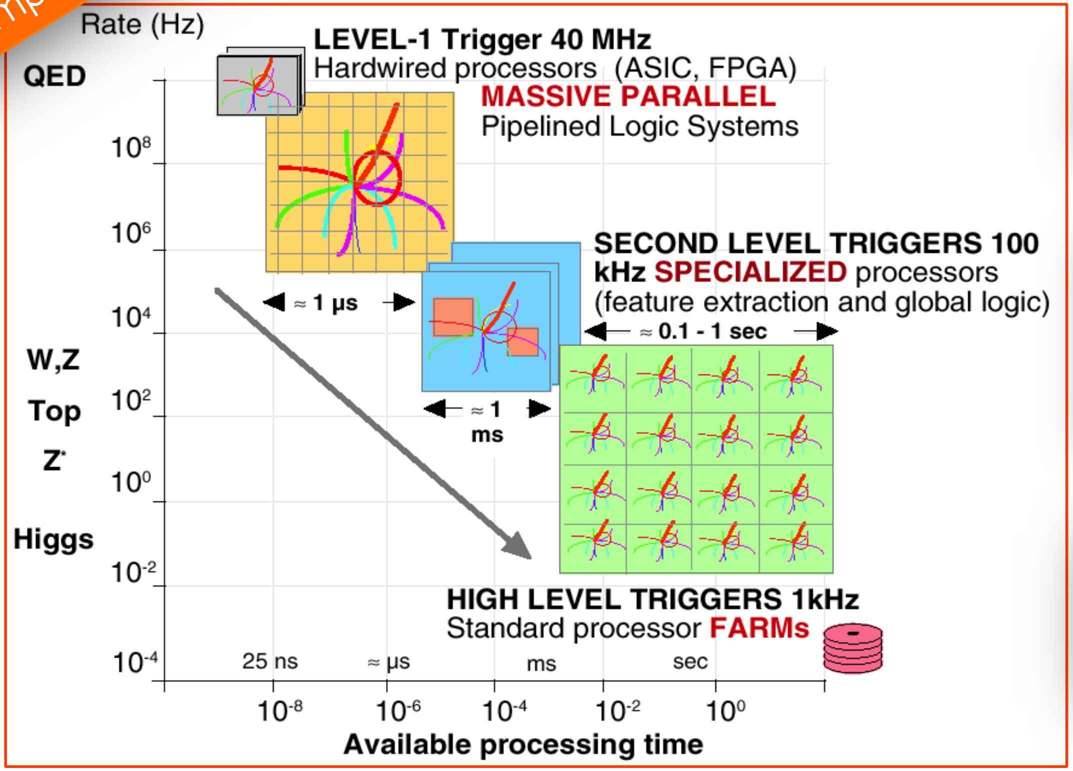
LHC experiments

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

Next lesson

Trigger selections

Example for LHC



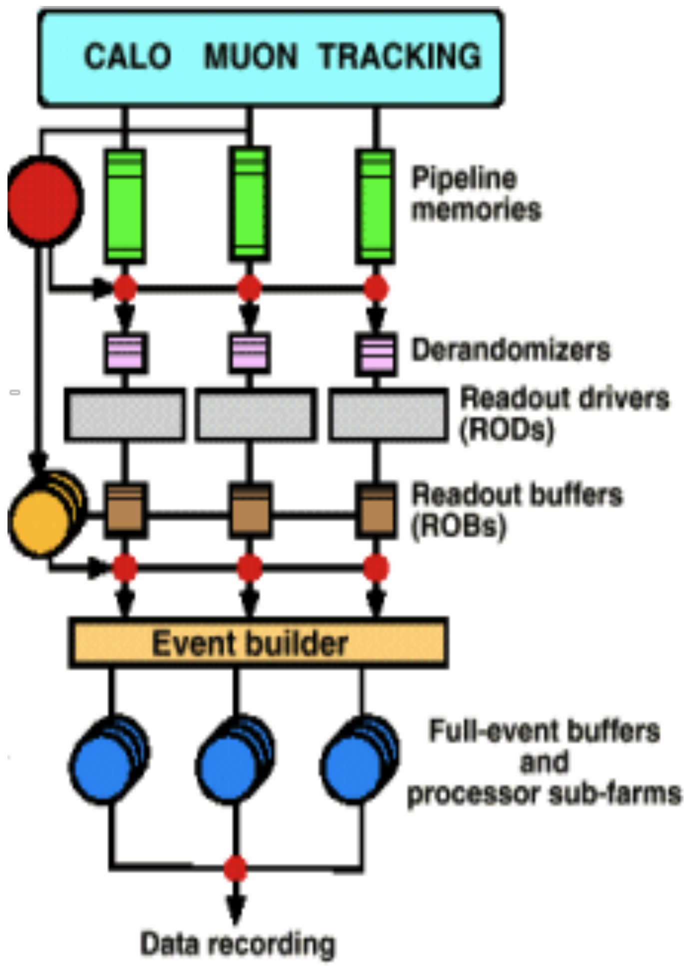
Inclusive trigger

Confirm L1, inclusive and semi-incl., simple topology, vertex rec.

Confirm L2, more refined topology selection, near offline

Different levels, different information

- First-level selection
  - **Coarse granularity** data from detectors, mostly aimed at lepton identification
    - Hadron and EM calorimeters for electrons/γ/jets
    - Muon chambers
    - Usually does not need to access data from the inner-tracking detectors (only if the rate can allow it)

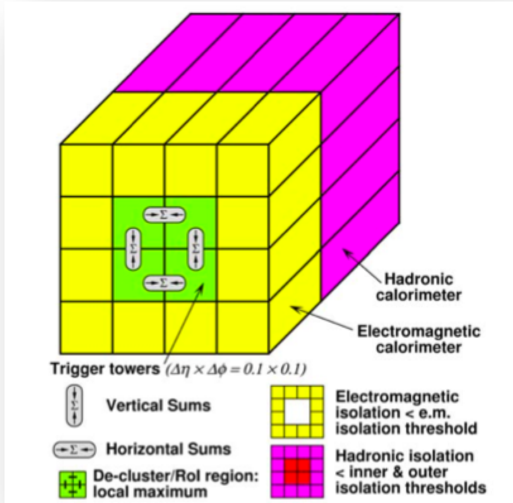


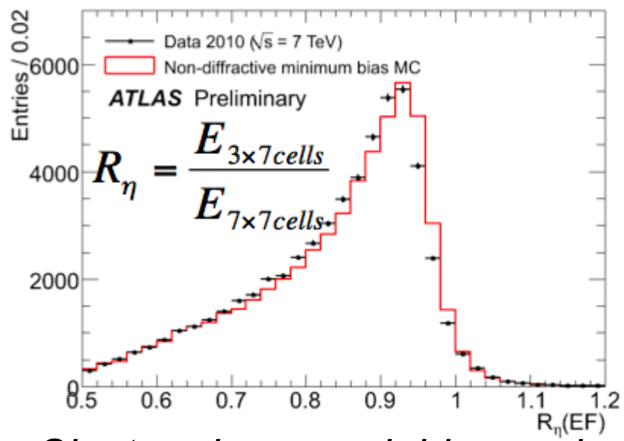
- HLT must be selective
  - Can be separated into levels
    - Level-2 accessing only a part of the event
    - Level-3 accessing the full event
  - Full-precision and full-granularity calorimeter information
  - High-precision readout from the muon detectors
  - Fast tracking in the inner detectors (for example to distinguish e/γ)

Example of multilevel trigger: ATLAS calorimeter trigger

- e, γ, τ, jets, $E_T$miss, ΣE_T
  - Various combinations of cluster sums and isolation criteria
- Level-1
  - Dedicated **processors** apply simple 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)

Level-1 clustering algorithm





Cluster shape variable used in HLT for e/γ selection

The trigger efficiency is a parameter of your measurement

- Efficiency should be precisely known, since it enters in the calculation of the cross-sections
  - For some precise measurements, the crucial performance parameter is not the efficiency, but the **systematic** error in determining it
  - The independence of the trigger selections allows good cross-calibration of the efficiency

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

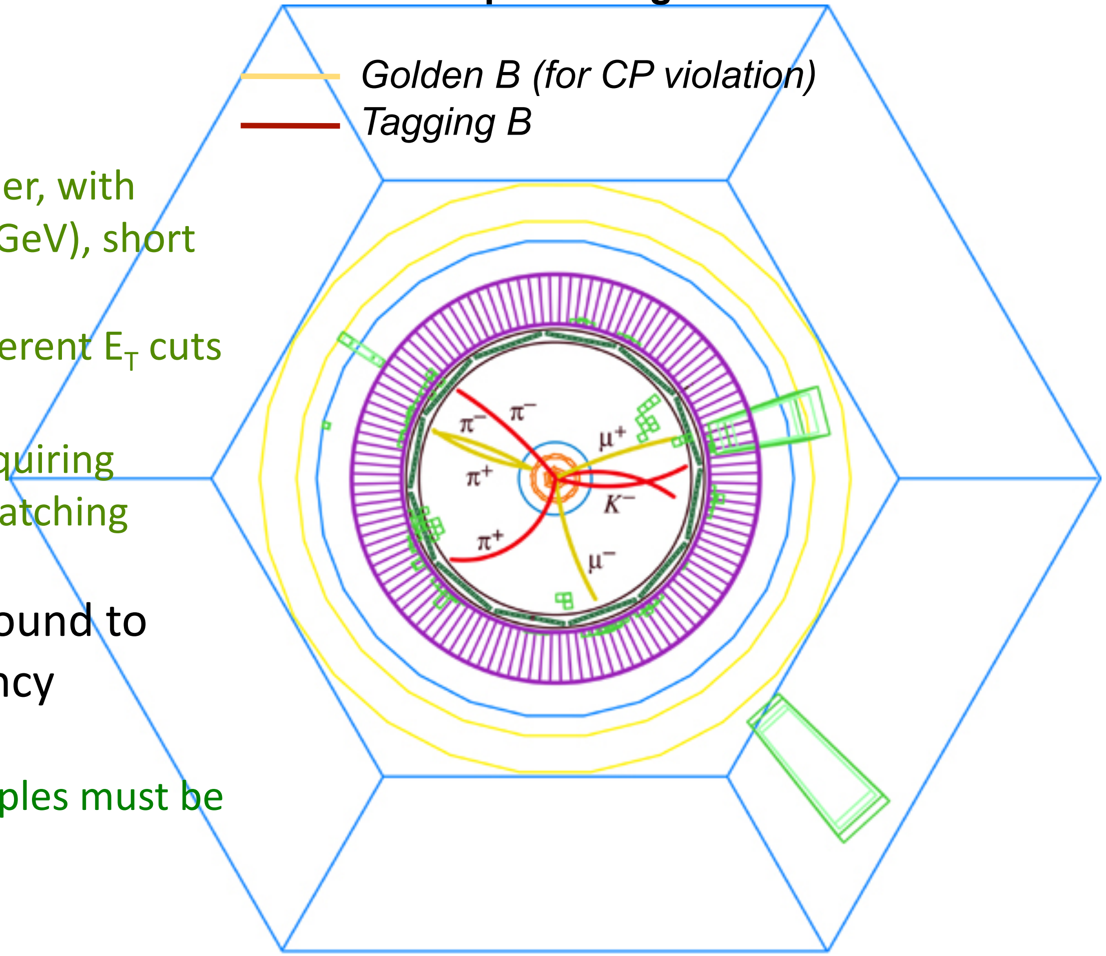
$$\alpha \cdot \varepsilon_{\text{total}} = \alpha \cdot \varepsilon_{\text{Tracking}} \cdot \varepsilon_{\text{Reco}} \cdot \varepsilon_{\text{L1-Trig}} \cdot \varepsilon_{\text{L2-Trig}} \cdot \varepsilon_{\text{L3-Trig}} \cdot \varepsilon_{\text{vertex}} \cdot \varepsilon_{\text{analysis}}$$

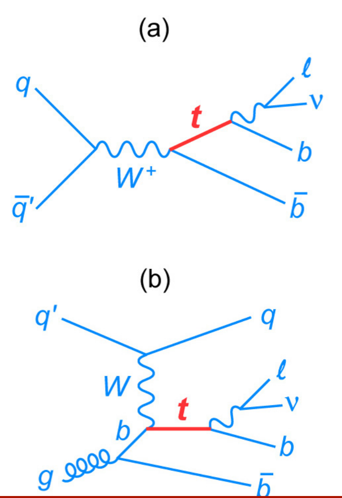
Trigger objects example: BaBar

- For some precise measurements, the crucial performance parameter is 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)
  - **EM calorimeter clusters** with different E_T cuts
- Search for topology
  - **number of objects**, optionally requiring geometrical separation cuts or matching between tracks and clusters
- Deep studies on signal and background to determine the error on the efficiency measurement
  - The selection of background samples must be foreseen

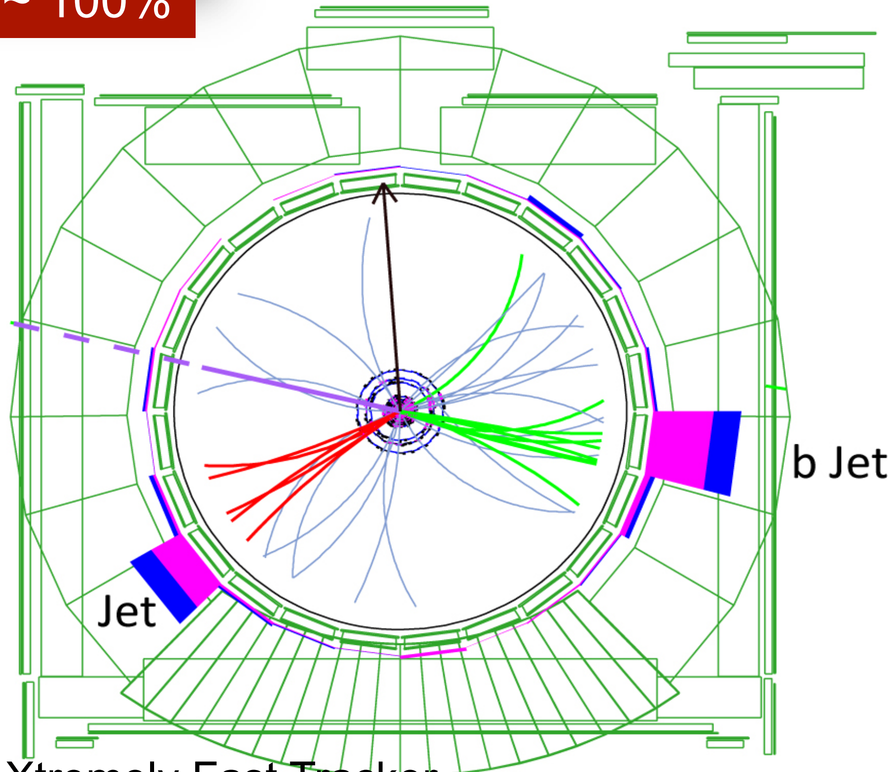
Golden event in the BaBar Detector
e+e- collision producing a B and an anti-B





t->Wb ~ 100%

Trigger objects example: CDF

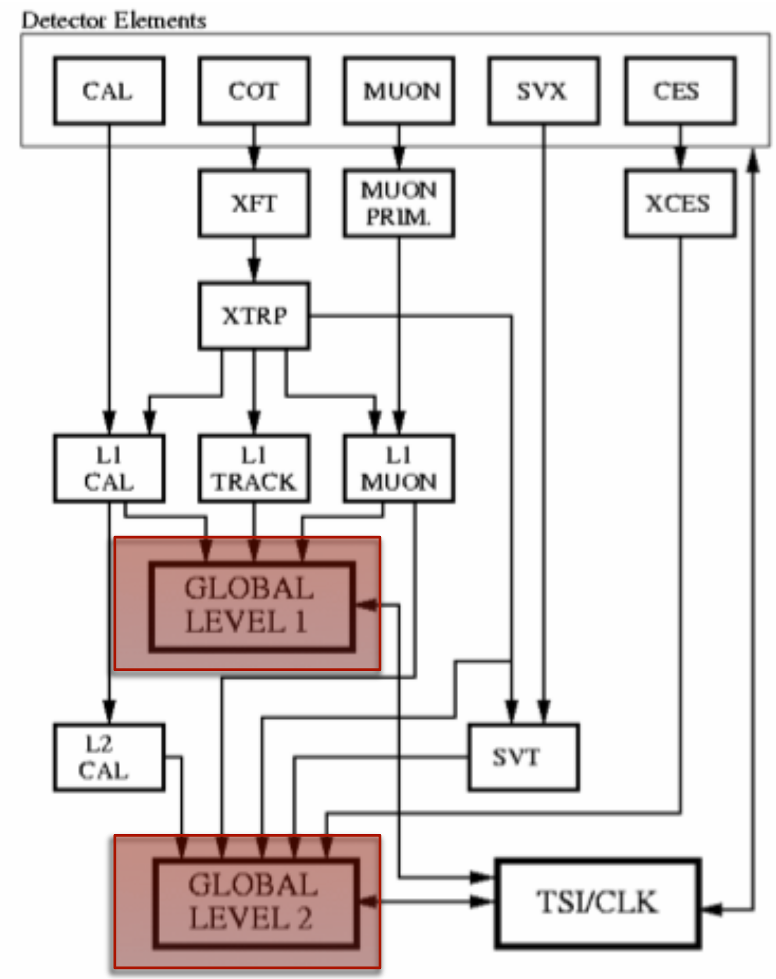


XFT=eXtremely Fast Tracker

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 (CES)

Trigger objects example: CDF



CDF single top event

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    - Electron (Cal +XFT)
    - Photon (Cal)
    - Jet (Cal EM+HAD)
  - Missing E_T, SumE_T
  - Muon (Muon + XFT)

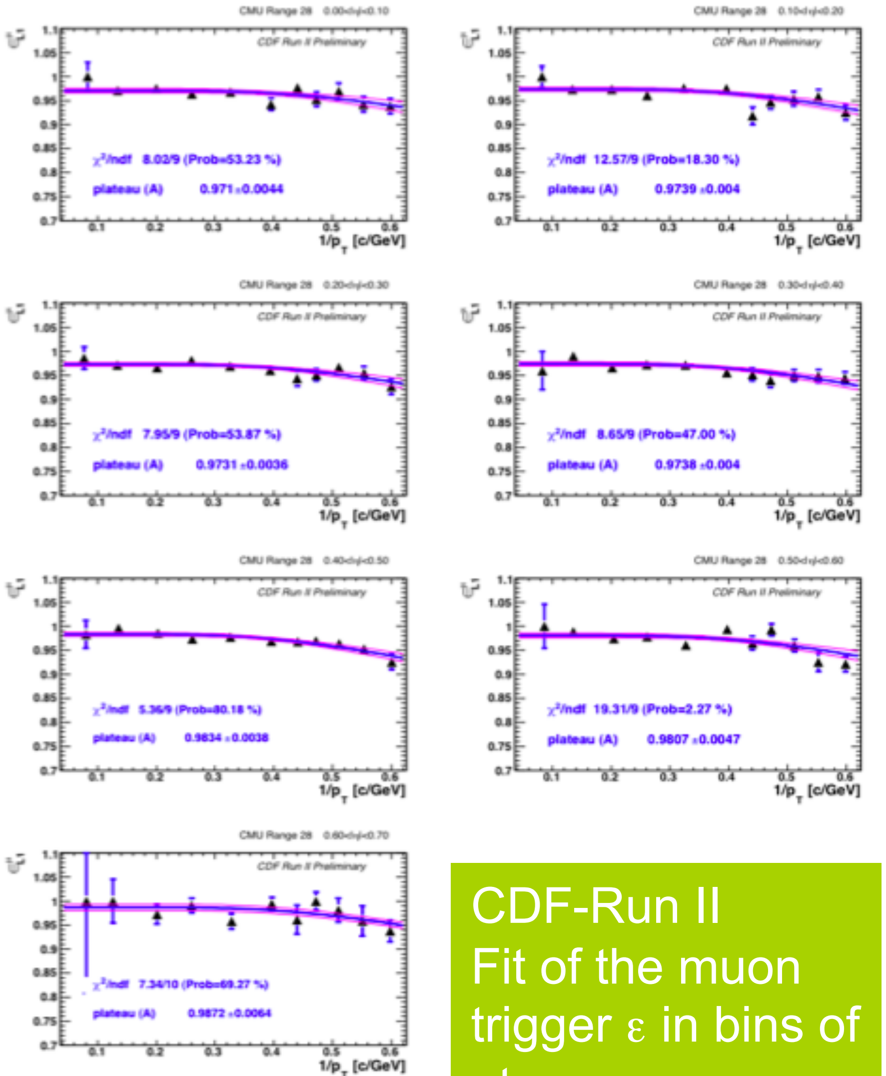
- Trigger objects at L2:
  - L1 information
  - SVT (displaced track, impact parameter)
  - Jet cluster
  - Isolated cluster
  - Calorimeter ShowerMax (CES)

Parametrizing the trigger efficiency

- The 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: $\varepsilon(p_T, \eta, \phi, \text{run\#})$
  - Fit the turn-on curves for different bins of η, ϕ, p_T
  - 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 and is not applied
  - It's crucial to select the correct **sample without biases**

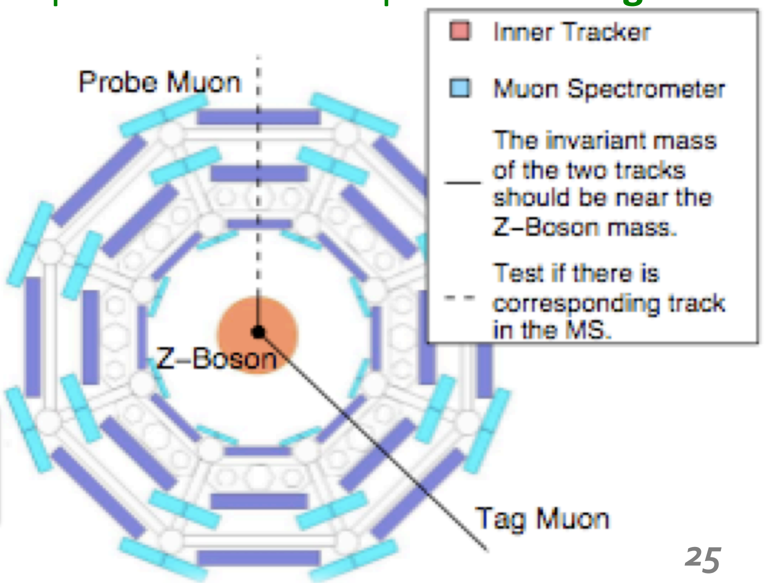
- For HLT it's easily done using back-up triggers called **pass-through**
  - Do not apply the selection and calculate the denominator

$$\text{Eff(L2MU10)} = \frac{\text{events passing L2MU10}}{\text{events passing L2MU10\_PASSTHROUGH}}$$

Trigger efficiency measurement (2)

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

- For Level-1, we don't know the absolute denominator, so different methods are used:
  - Compare independent (orthogonal) triggers (not correlated, mainly minimum-bias)
    - Calculate the efficiency relative to another trigger selection
  - At the collider experiments can be measured with an experimental technique called **"Tag-and-Probe"** (mainly for lepton triggers)
    - Helps in defining an unbiased sample (no background included)
    - 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

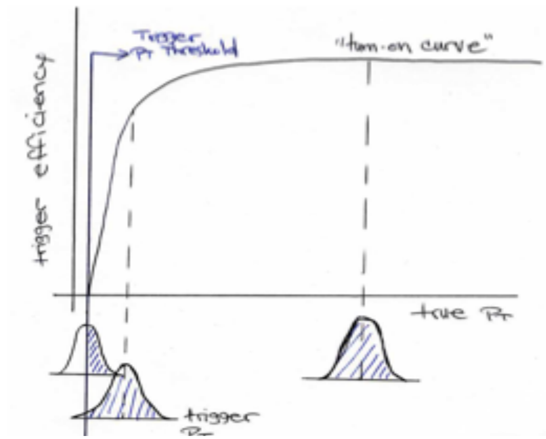


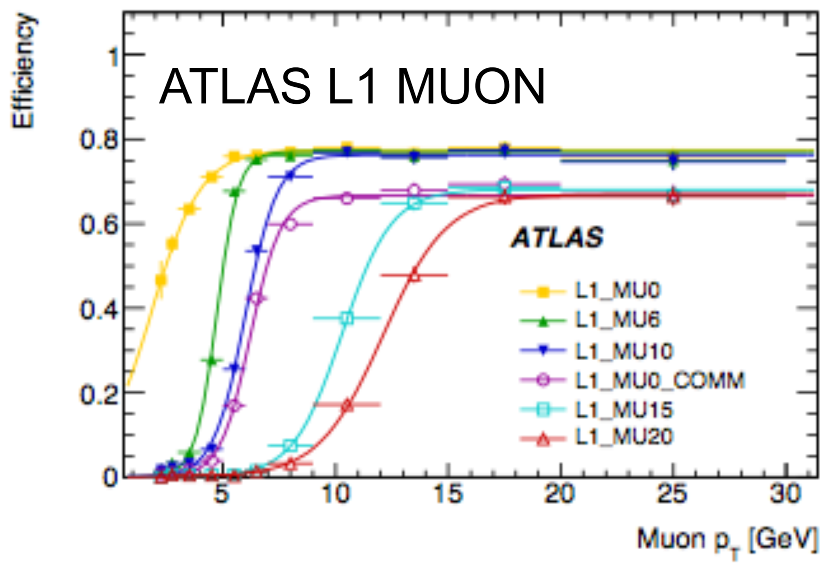
Use back-up triggers:
L1_LOWEST_THRESHOLD

Trigger efficiency measurement (3)

The dependency of ε on the true p_T/E_T (measured offline with max resolution, order 0.1%) describes the **turn-on curves**

- The capability of rate depends on the p_T (or E_T) resolution of the trigger system
  - For example some particles can be under threshold, failing the trigger, because their p_T is underestimated
- Worst resolution is **at level-1**: coarse granularity, $\delta p_T/p_T$ can be up to 30%
- Crucial is the study of the **step region**, in which efficiency changes very quickly and contamination from background is important (soft particles are abundant!)
  - If quick, better background suppression
  - If slow, can be better extrapolated and systematic error can be reduced





Rates allocation of the trigger signatures

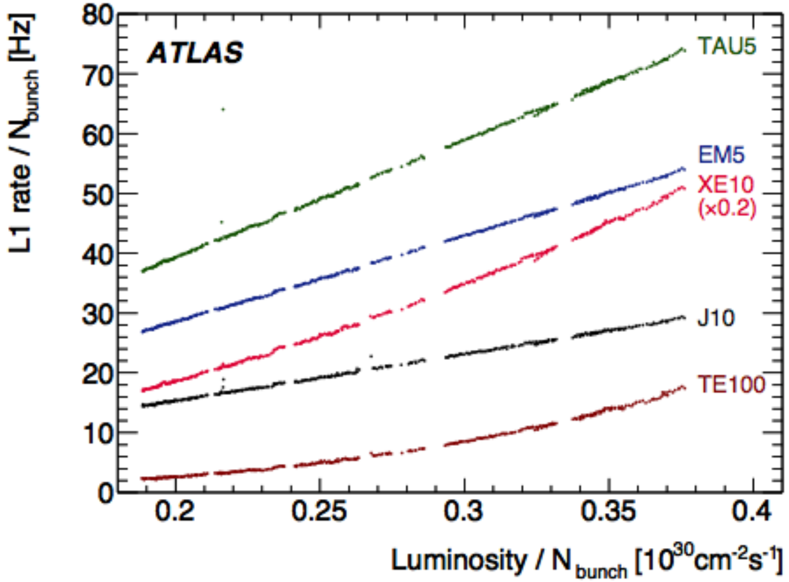
- ✓Target is the final allowed bandwidth (~200 Hz @ LHC)
- ✓Trigger rate allocation on each trigger item is based on
  - ✓Physics goals (plus calibration, monitoring samples)
  - ✓Required efficiency and background rejection
  - ✓Bandwidth consumed

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

Trigger Efficiency

Expected trigger rates:

- For design and during commissioning, are calculated from large samples of simulated data, including large cross-section backgrounds
  - 7 million of non-diffractive events @70mb used for 10^{31} $cm^{-2} s^{-1}$ in ALTAS
  - Large uncertainties due to detector response and jet cross-sections: apply safety factors, then tuned with data
- During running, extrapolation from data to higher Luminosity



Rates scale linearly with luminosity, but linearity is smoothly broken due to pile-up

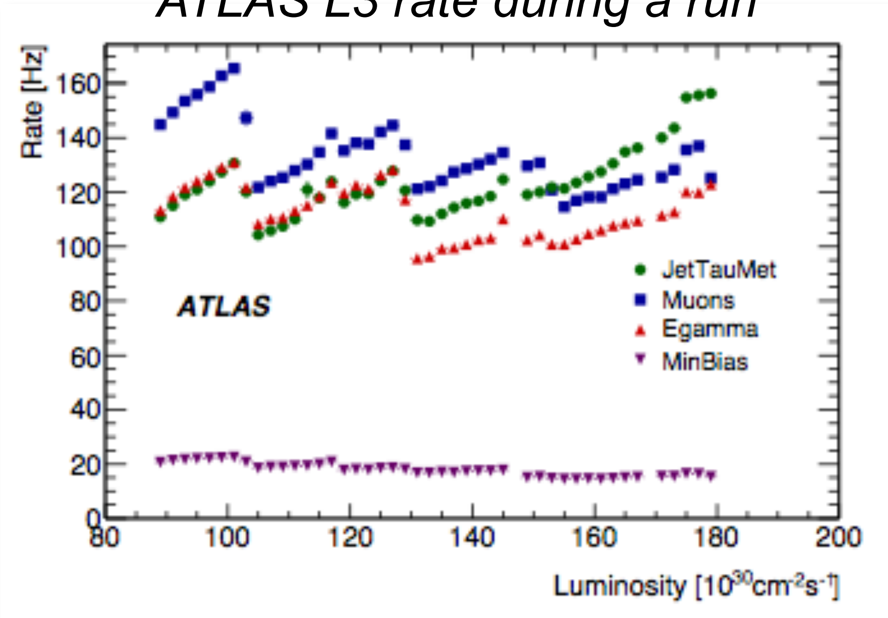
Different kind of triggers

- 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 mandatory 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 criteria is recorded. This is useful for collecting samples of high-rate triggers without swamping the DAQ system
  - Since trigger rate changes with Luminosity, **dynamic pre-scales** are sometimes used (reduce the pre-scales as Luminosity falls)

ATLAS L3 rate during a run



Minimum-bias triggers provide control triggers on the collision (soft QCD events), usually pre-scaled

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 a broad physics program?
- And cope with increasing luminosity?

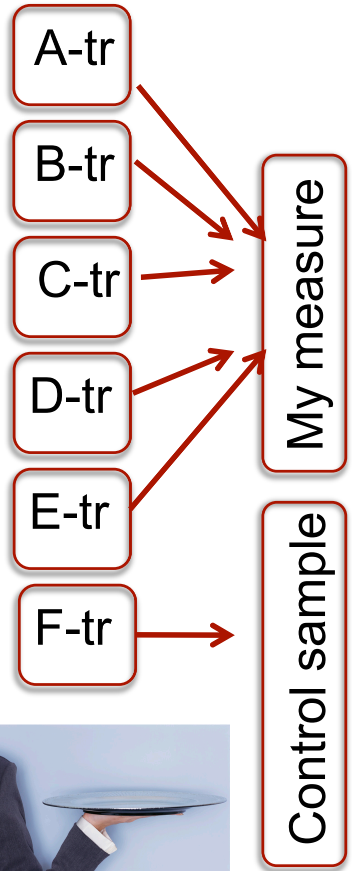
Organize trigger menus!

Design 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..)
  - Each chain has its own bandwidth allocation
  - An event is stored if one or more trigger chain criteria are met

- 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)

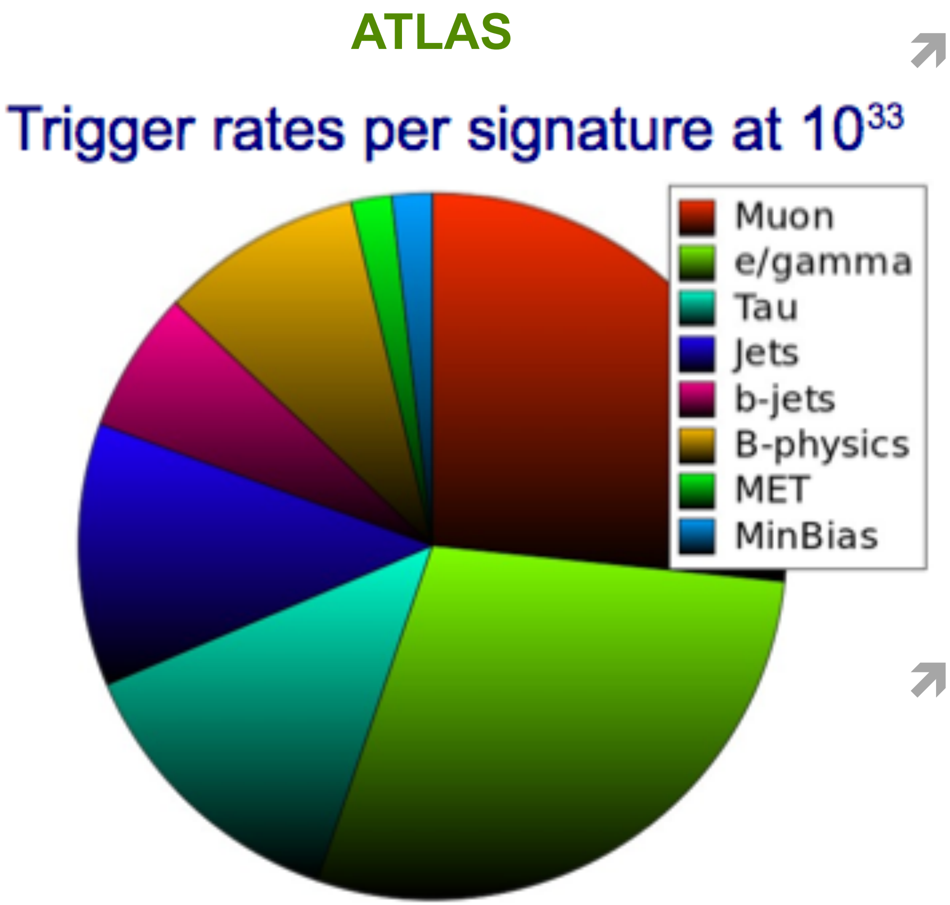
- The list must be
  - **Redundant** to ensure the efficiency measurement
  - Sufficiently **flexible** to face possible variations of the environment (detectors, machine luminosity) and the physics program



Priority List for >300 Hz

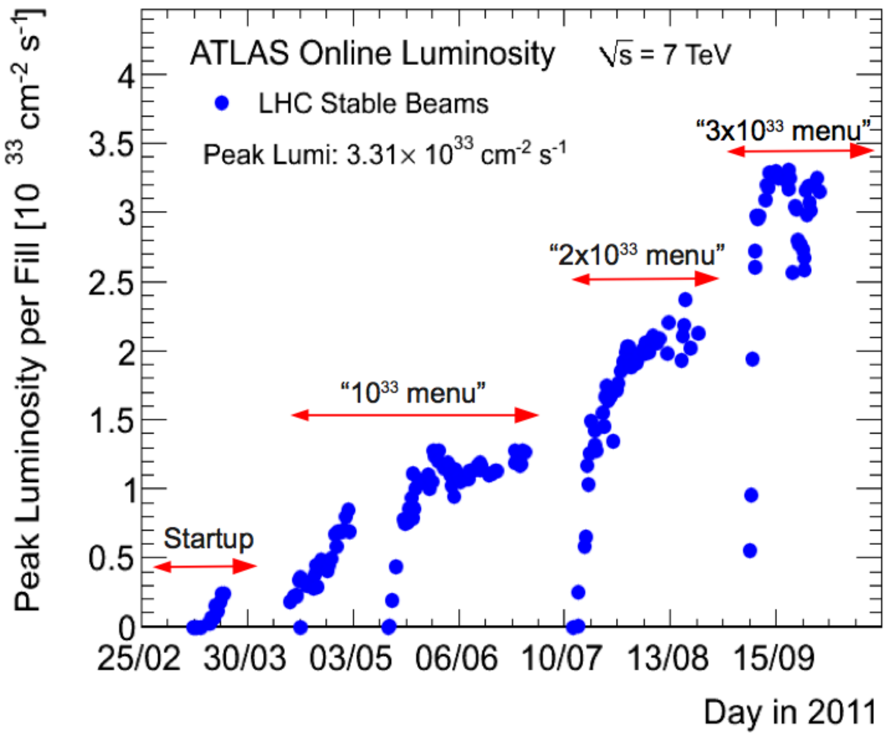
Chain		Unique rate L1 (Hz)	Unique rate L2 (Hz)	Unique rate EF (Hz)	*Sorted by* Problem level
EF_xe60_verytight_noMu	SUSY/Exotics	0	0	0.5	EF (pileup)
EF_j100_a4tc_EFFS_ht400	SUSY	0	0	2.5	EF
EF_4j45_a4tc_EFFS	SUSY/SM	0	0	2	EF
EF_5j30_a4tc_EFFS		0	5	3	EF
EF_j240_a10tc_EFFS	Exotics/SM	0	0	1	EF
EF_tau29_loose1_xs45_loose_noMu_3L1J10	Higgs	0	40	5	EF
EF_b10_medium_4j30_a4tc_EFFS	Top/Higgs	0	4	10	EF
EF_2mu4_BmumuX	B-physics	0	7	0.9	EF
EF_2mu4_Jpsimumu		0	6	1.7	EF
EF_mu4mu6_DiMu		0	25	6.5	EF
EF_mu4mu6_DiMu_DY20	SM	0	10	5?	EF
EF_2MUL1_l2j30_HV_allMS	Exotics	0	?	?	EF
EF_mu20i_medium	$5x10^{33}$ prep.	0	15	3	EF
EF_mu18_MG_medium	Many	0	0	60	EF
EF_mu18_medium		0	0	60	EF
EF_e60_loose	(Exotics)	0	5	7	EF,client
EF_mu15/18/22_njX?	SUSY/??	100	10	?	EF,non-validated
EF_g22_hiptrt?	Exotics	0	?	< 1?	non-validated
EF_e15_medium_xe40_noMu	SUSY/Exotics	310	70?	1.3	L2 (pileup)
EF_j55_a4tc_EFFS_xe55_medium_noMu_dphi2j30xe10		70	210	1.5	L2
EF_e10_medium_mu6_topo_medium	Higgs	1200	9	1	L1
EF_tau20_medium_e15_medium	Higgs	3700	10	1	L1
EF_xe60_tight_noMu	SUSY	680?	150?	1	L1,L2 (pileup),EF
EF_e10_medium_mu6	Higgs/SUSY	1200	75	10	L1, EF
EF_l2j30_Trackless_HV_L1MU6	Exotics	1500?	0.5	0.5	L1
Total extra rate		6500	600	100	Peak at 3×10^{33}

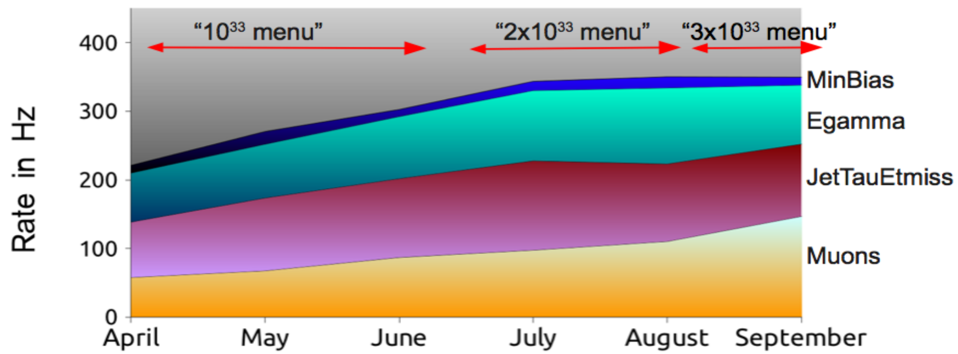
Trigger strategy @ colliders



- Inclusive triggers are designed to collect the **signal samples** (mostly un-prescaled)
  - Single 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

Example of trigger menu flexibility





- ATLAS **start-up**: L=10^{31} cm^{-2} s^{-1}
  - **Level-1**: Low p_T thresholds and loose selection criteria
    - In the meanwhile, 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
- Trigger menu **evolved** in several steps with LHC peak luminosity
  - Complex signatures and higher p_T thresholds are added to reach the physics goals
  - Stable condition for important physics results (summer or winter conferences)
  - Mostly kept same balance between physics streams

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 pT > 8 GeV
  - L2: **AUTO_ACCEPT**
  - L3: EMET > 18 GeV && Track pT > 9 GeV && shower profile consistent with e-
- NO_L3
  - L1: EMET > 8 GeV && rϕ Track pT > 8 GeV
  - L2: EMET > 8 GeV && Track pT > 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)

Summarizing….

- The trigger strategy is a trade-off between physics requirements and affordable system power and technologies
  - A good design is crucial – then the work to maintain optimal performance is easy
- Here we just reviewed the main trigger requirements coming from physics
  - Perfect knowledge of the trigger selection on both signal and background
  - Flexibility and redundancy ensure a reliable system
- In particular, for hadron colliders like LHC, the trigger performance is crucial for discovery or not discovery new physics that can be easily lost if we don't think of it in advance!
- In the next section we will see how to implement such a system, still satisfying these requirements
  - Design an architecture with low dead-time, in which each step of the selection must accomplish requirements on speed and rate suppression

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