Introduction to trigger concepts

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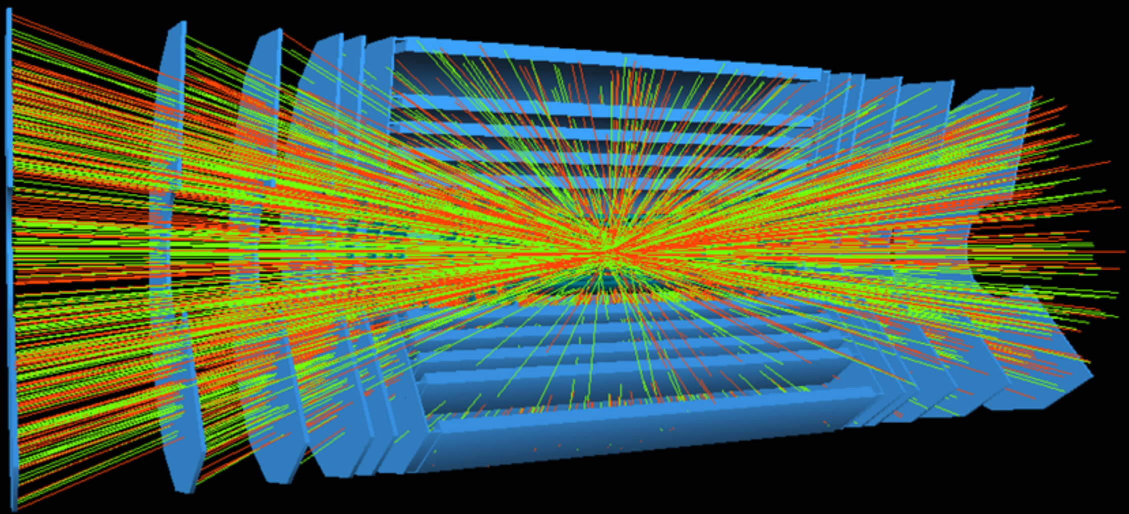
Outline

- Two lectures dedicated to describe the main trigger concepts

- Introduction to trigger concept
  - Why using a trigger
  - Interface to a DAQ system
  - How measuring trigger efficiencies
  - Many examples

- Elements to build up a trigger system
  - From a very simple system…
  - … to a more complex one, with many levels
  - Dead-time
  - Optimal devices for a fast trigger
  - Selectivity of a complex system
  - How technology helps

The data deluge



- In many systems, like particle physics or astronomy experiments, to store all the possibly relevant data provided by the sensors is UNREALISTIC and often becomes also UNDESIRABLE
- Three approaches are possible:
  - Reduced amount of data (packing and/or filtering) → ***Trigger!***
  - Faster data transmission and processing

As easy as….

- Crucial for selecting specific features within widely extended systems
- With limited amount of time
- With limited resources

The trigger concept

Digital signal saying YES or NO

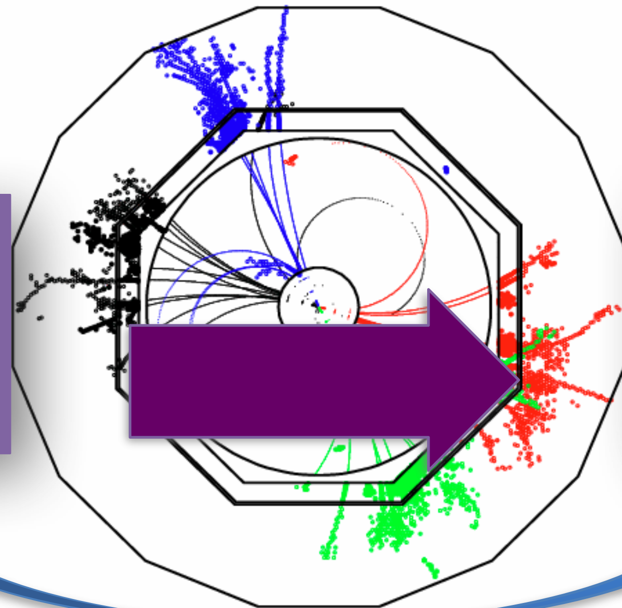
- It's like deciding to take a very good photo in Rio de Janeiro:
  - **click the button** to open the bolt and let the sensors operate
    - take the photo only when you think the **subjects** are ready → The trigger starts the photo process
    - **focus** the image → First identify the interesting event
    - only if there is enough **light** for your lenses (or add a flash light) → Ensure the sensitivity to parameters
    - only if your hand is not **shaking** → Ensure a good synchronization

Trigger concept in HEP

Event has interesting features

Identify the interesting process

Trigger



Event is recorded…

Start the data acquisition

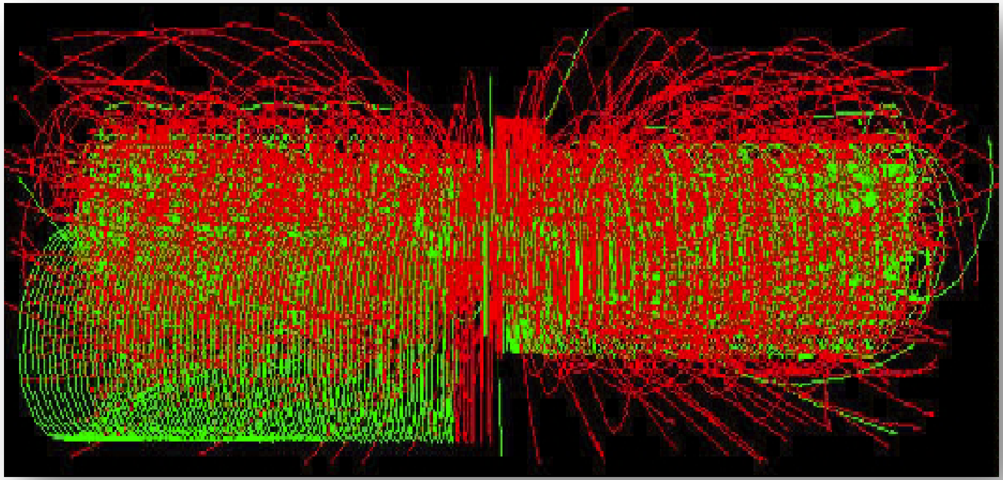
DAQ

with time constraints

- 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

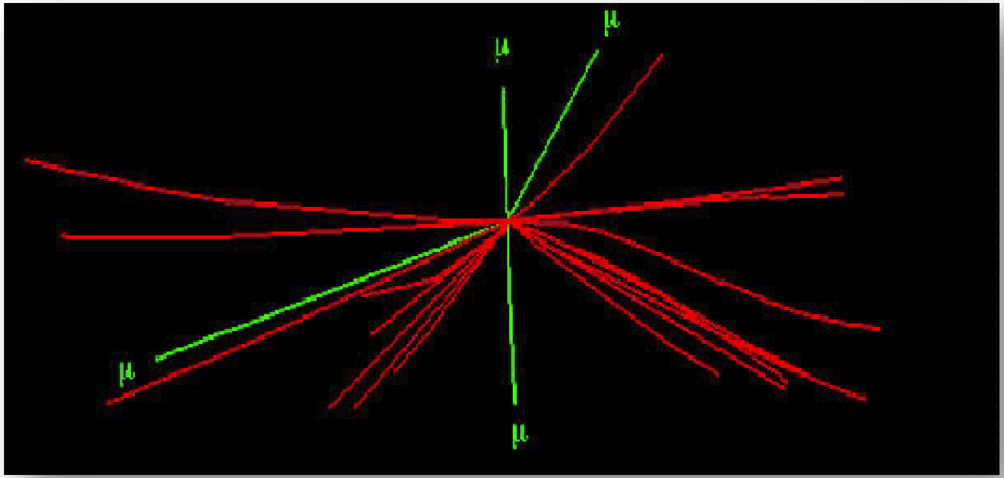
Which is a good trigger for the Higgs Boson?

All tracks



+30 MinBias

Only high-pt tracks



Higgs -> 4μ

Simulate the signal events **Higgs → 4μ** as it appears at the LHC (with soft collisions coming from the p-p interactions)

The trigger signature is given by **high momentum muons** (at least one)

Which is the expected trigger rate?

The expected event rate is derived from the physics process (x-section times Luminosity)

$$R = \sigma_{in} \times L$$

LHC: the trigger challenge!

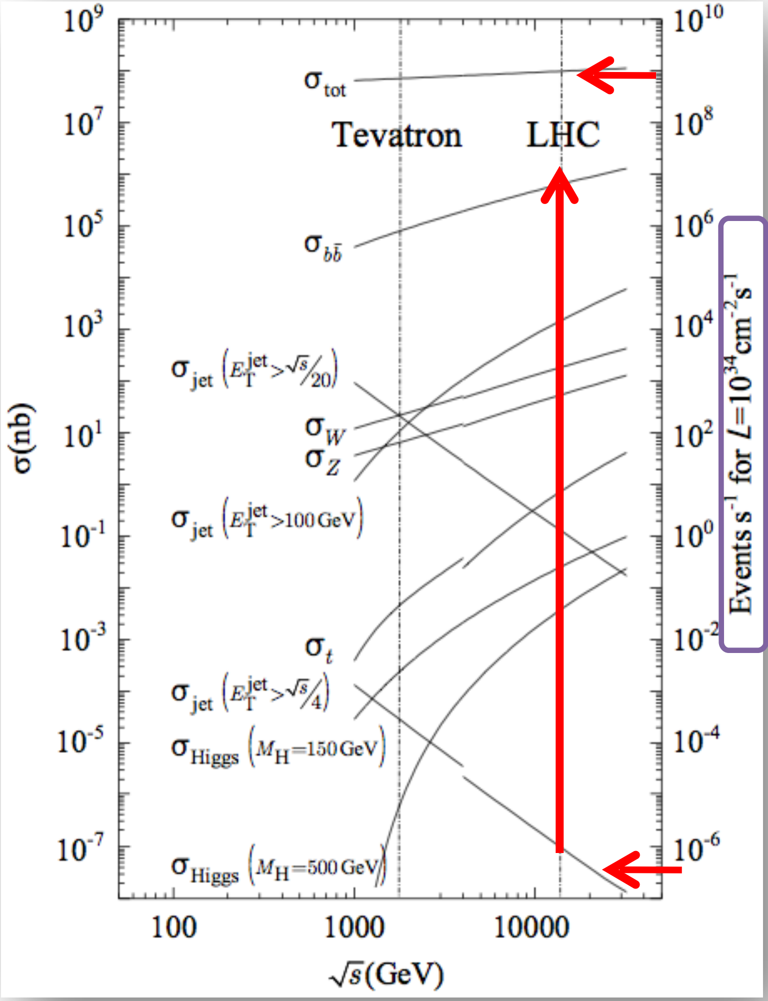
Total non-diffractive p-p cross section is **70 mb**

Total trigger rate is ~ GHz!!!

Huge range of cross-sections and production rates at design:

Beauty (0.7 mb)	– 1000 Hz
W/Z (200/60 nb)	– 100 Hz
Top (0.8 nb)	– 10 Hz
Higgs - 125 GeV (30 pb)	– 0.1 Hz

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



- The final rate is often dominated by not interesting physics
- The trigger accepts events with features similar to the signal

Background discrimination is crucial

Which is the affordable trigger rate?

- **The Data Acquisition system collects data and write it to disk**
- With limited capabilities, mainly for money and dimensions
  - Limited computing power (available for online and offline processing)
  - Limited storage capabilities
- Given the **size** of one typical measurement/event, the maximum allowed trigger rate is due to

$$R_{DAQ} = R_T^{max} \times S_E$$

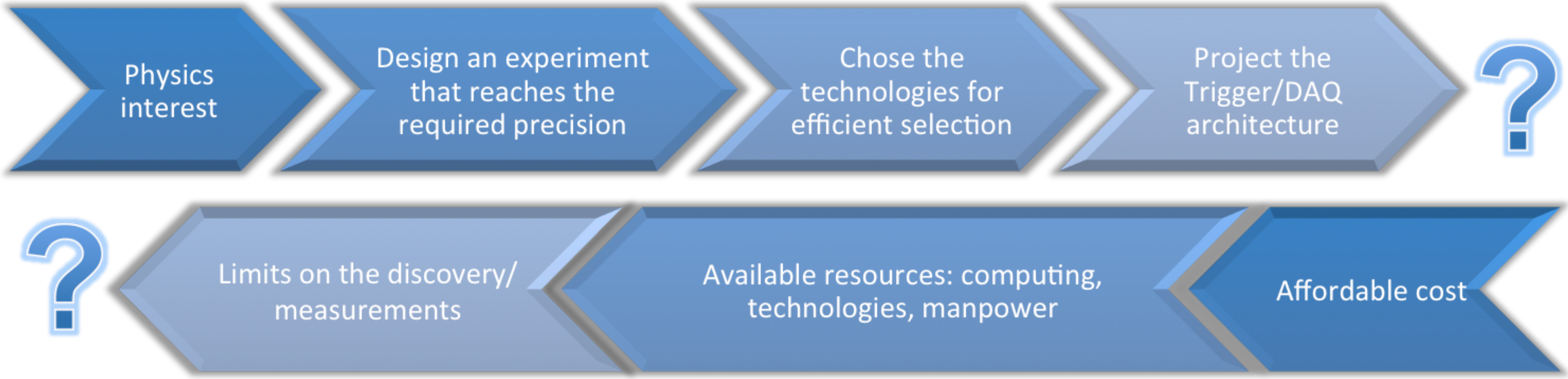
DAQ rate

Maximum Trigger rate

Event size

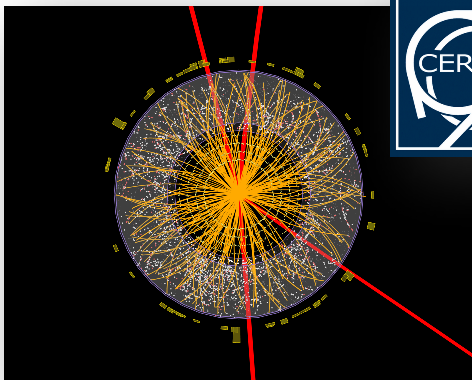
How many particles in the event?
How many FE channels?

The trigger connections



The trigger system design is connected to physics requirements and technologies capabilities: it needs that the experts on each field work together to **maximize** the available resources

Not always need to reduce the rate



- **LHC – ATLAS**

- Project started in 1996
- Technology chosen in 2000
- Start data-taking 2008

- Full p-p collision rate: 40 MHz
- Average event size: 1.5 MB
- Full data rate: ~60 PB/s

- Defined physics channels
- Complex trigger: reduces 7 orders of magnitudes to 200 Hz

- Affordable DAQ rate: ~300 MB/s -> 200 Hz
- Data distribution (GRID)

- **SKA (Square Km Array)**

- Project started in 2011
- Technologies under evaluation now
- Start operations in 2024

- Photograph the sky continuously
- 1.12 PB/s of photons collected

- EXASCALE system 10^{18} operations for correlation and imaging
- **Simple correlator : 10 TB/s**
- **Total Internet Traffic ≈ 8 TB/s in 2010**

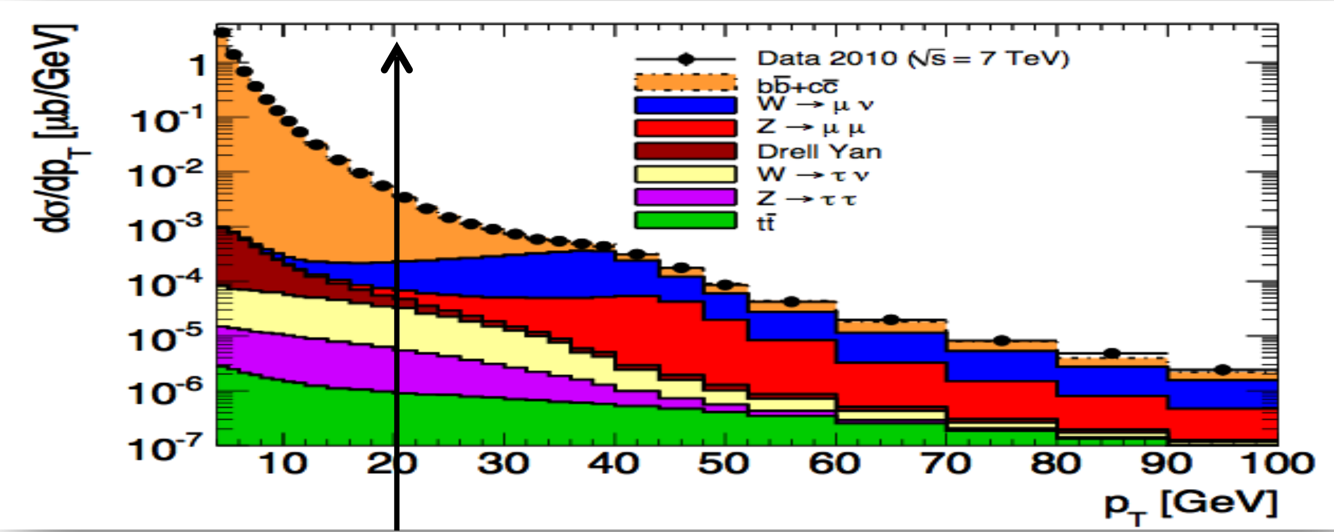
- Required large computing power
- Big-data and cloud-computing drive market

Which is the best filter?

Trigger requirements

Trigger requirements: *background rejection*

Inclusive single muon p_T spectrum



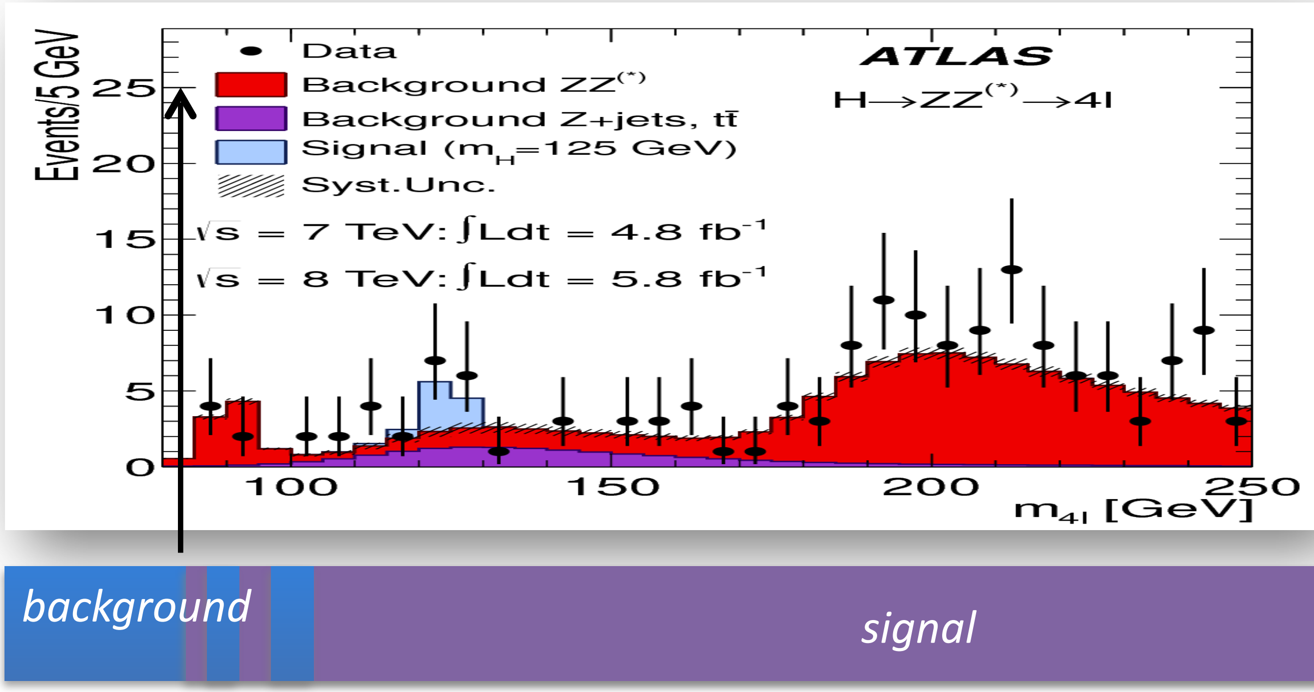
muon p_T — *background* | *signal*

$$\mathbf{Rej_{bkg} = 1 - N_{bad(accepted)}/N_{bad\ (produced/expected)}}$$

- **Background rejection** (Rate control)
  - Instrumental or physics background
    - Need to identify **characteristics** which can suppress the background
    - Need to demonstrate solid **understanding** of background rate and shapes
  - Backgrounds sometimes are known with great uncertainties: make your trigger **flexible and robust**

Trigger requirements: *signal efficiency*

4-leptons invariant mass, selected events for H→ZZ→4l



muon p_T

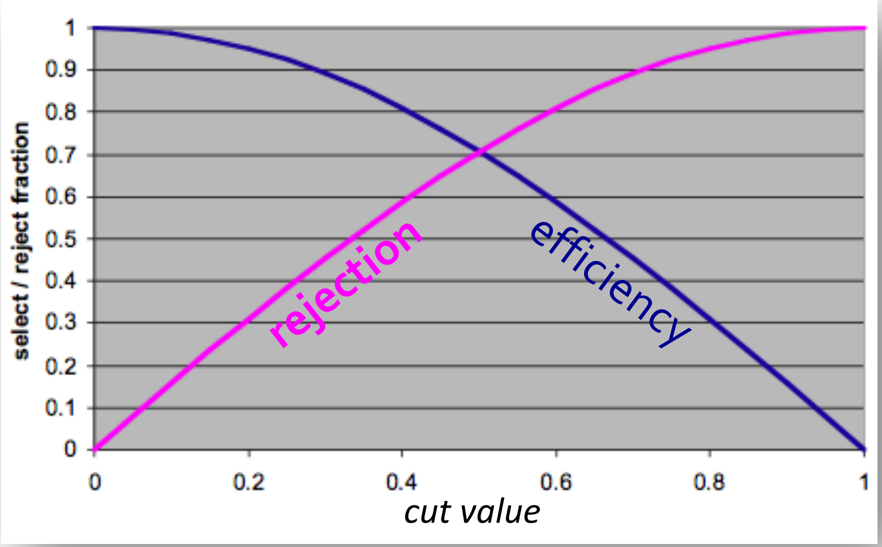
- **Signal efficiency**:

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

- Maximize the acceptance
  - Good design of the architecture
- Optimize the selection
  - The selection must be optimized on the signal

...with compromises?

- If any of the two requirements cannot be realized**, refine your selection**!
  - Change the parameters, eventually with more complex ones, but still remain **fast**!
  - Additional compromises between
    - number of processors working in parallel and
    - fastness of the algorithms



- Whatever criteria you choose, discarded events are lost for ever!
- So, check that your trigger system:
  - Is not biasing your measurement
    - Discovery experiments: use inclusive selections
    - Precision experiments: use well known selections
  - Is reliable
    - Do you trust your trigger? If not, add control samples!

Ensure good efficiency with...

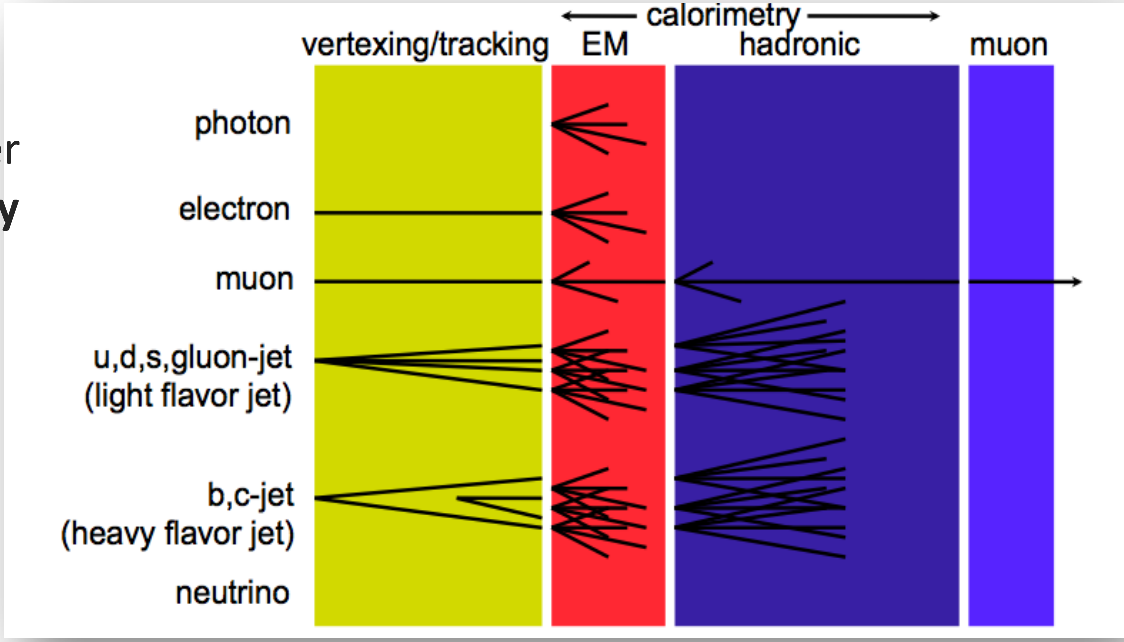
Robustness! Win against the unexpected!

- **Flexibility**: to cope changes in conditions 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 trigger rates independent from the detector and the collider performance
  - Different backgrounds can change the event shape and dimension, so the result of your trigger selection
- **Selectivity**
  - Good granularity and good resolution of the parameters to ensure good rejection of the unwanted background

And now let's go to details and examples

Trigger signatures

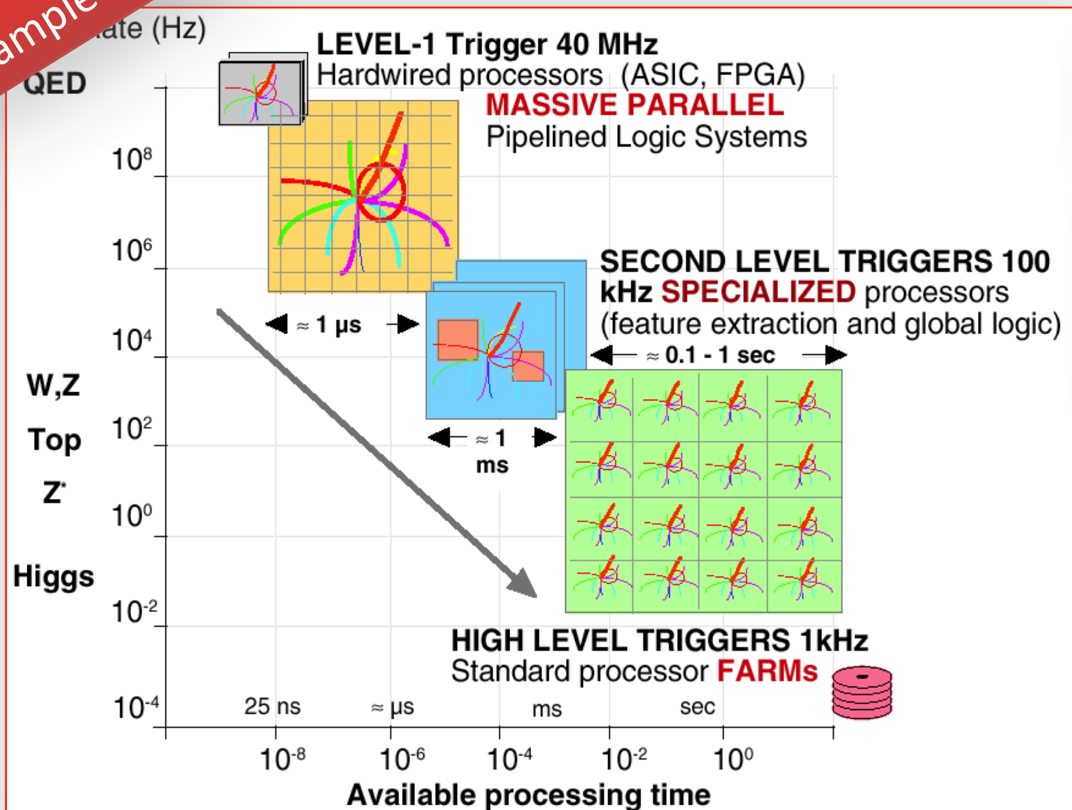
- **Signature** = a collection of parameters used for discrimination
  - Can be the amplitude of a signal passing a given **threshold** or a more complex quantity given by software calculations
- We first use intuitive criteria: **be fast and reliable!**
  - Use clear/simple signatures
    - i.e.: apply thresholds on: muon momenta, energy deposits in the calorimeters, good quality tracks in the tracker detectors….
- Eventually combine more signals together following a certain trigger logic (AND/OR), giving **redundancy**



Use of multi-level trigger

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

Example for LHC



Architectural view

L1: Inclusive trigger

L2: Confirm L1, inclusive and semi-incl., simple topology, vertex rec.

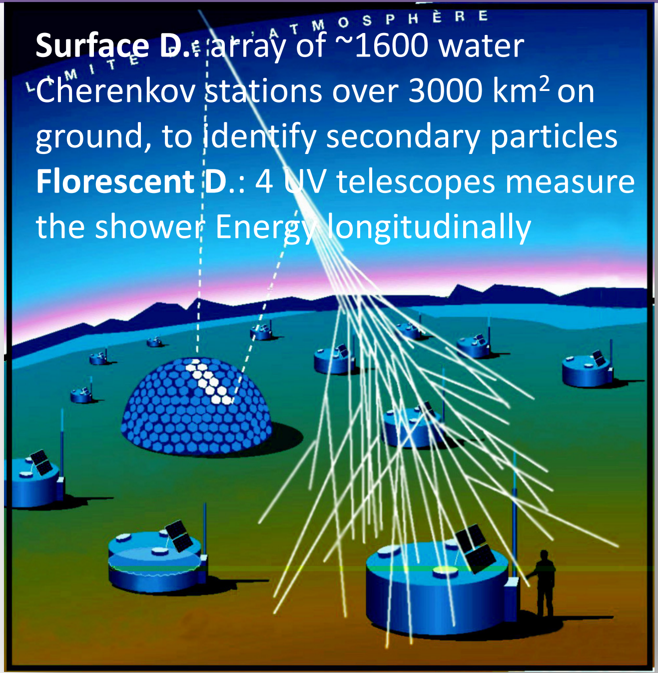
L3: Confirm L2, more refined topology selection, near offline

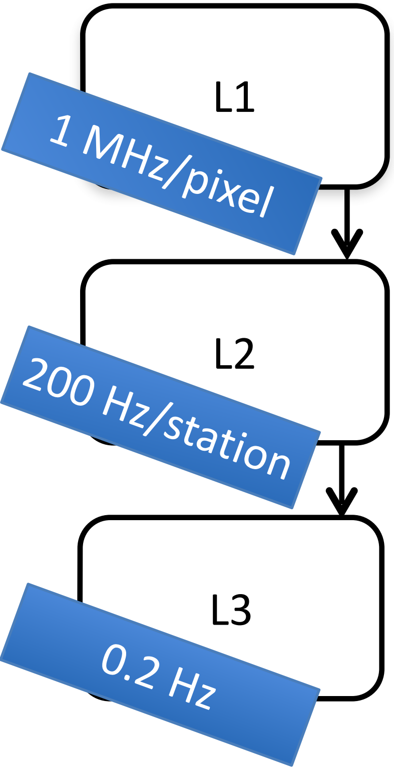
Logical view

In the next trigger lesson we will learn how to implement it

Simple signatures: Auger observatory

- **Detect air showers generated by cosmic rays above 10^{17} eV**
  - Expected rate $< 1/km^2/century$. Two large area detectors
- On each detector, a 3-level trigger operates at a wide range of primary energies, for both vertical and very inclined showers

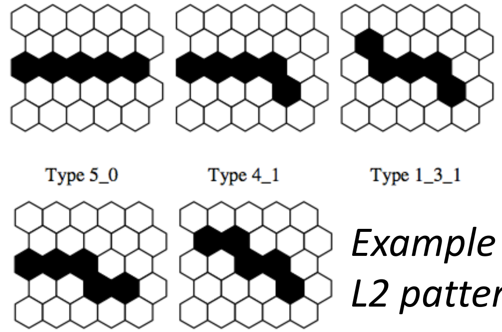




L1: (local) decides the pixel status (on/off)
- ADC counts > **threshold**
- ADC digitizes any 100 ns (**time** resolution)
- ADC values stored for 100 μs in **buffers**
- **Synchronized** with a signal from a GPS clock

L2: (local) identifies track segments
- Geometrical criteria with recognition algorithms on programmable patterns

L3: (central) makes spatial and temporal correlation between L2 triggers



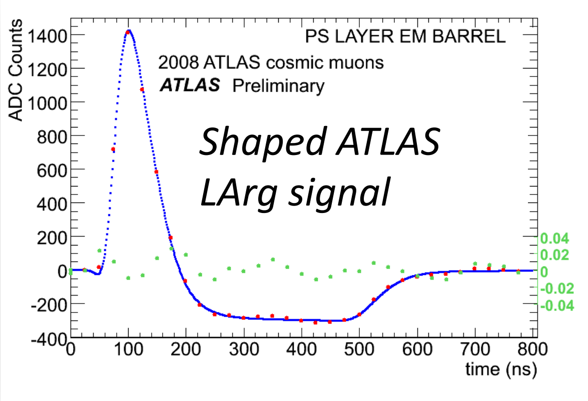
Example of L2 patterns

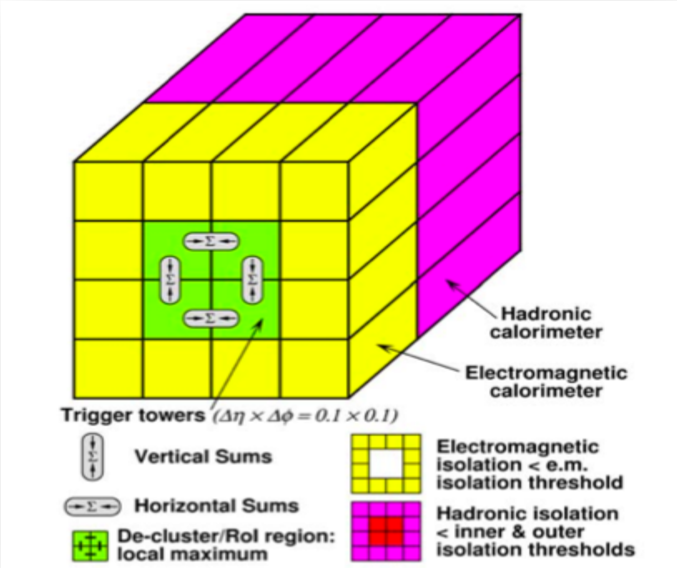
One event ~ 1MB → 0.2 MB/s bandwidth needed for the DAQ system

Multiple signatures: the ATLAS calorimeter trigger

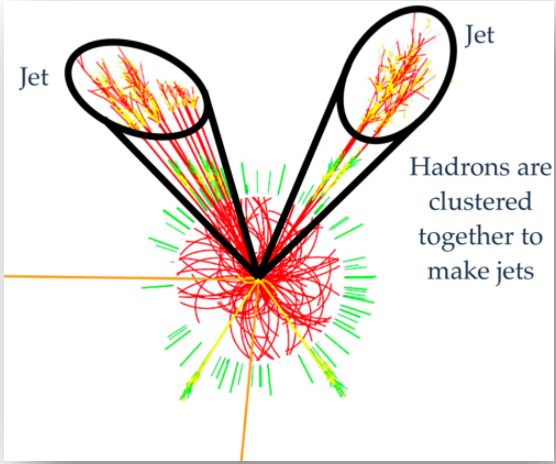
- Identify high energy e, γ, τ, jets, missing E_T, ΣE_T

  - 1: Dedicated Front-End electronics
    - Front-End of cells sends shaped analog signals



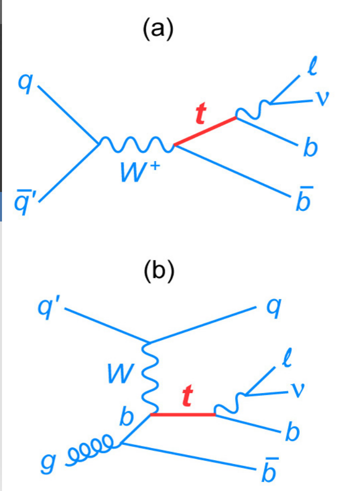


  - 2: Level-1 trigger
    - Dedicated **processors** apply simple cluster algorithms over cells and programmable E_T thresholds

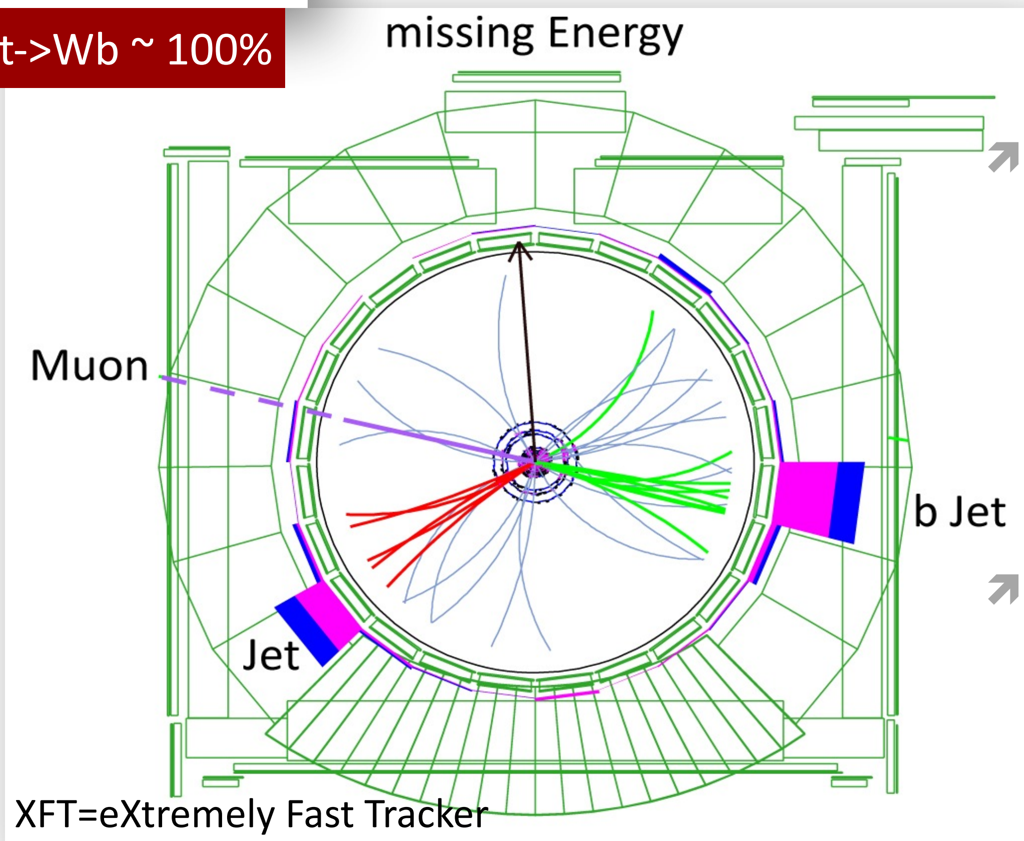


  - 3: High-Level triggers
    - **Topological** variables and **tracking** information
      - e/jet separation using cluster shapes
      - e/γ separation using tracking
    - **Isolation** criteria

Multi objects trigger: CDF



t->Wb ~ 100%



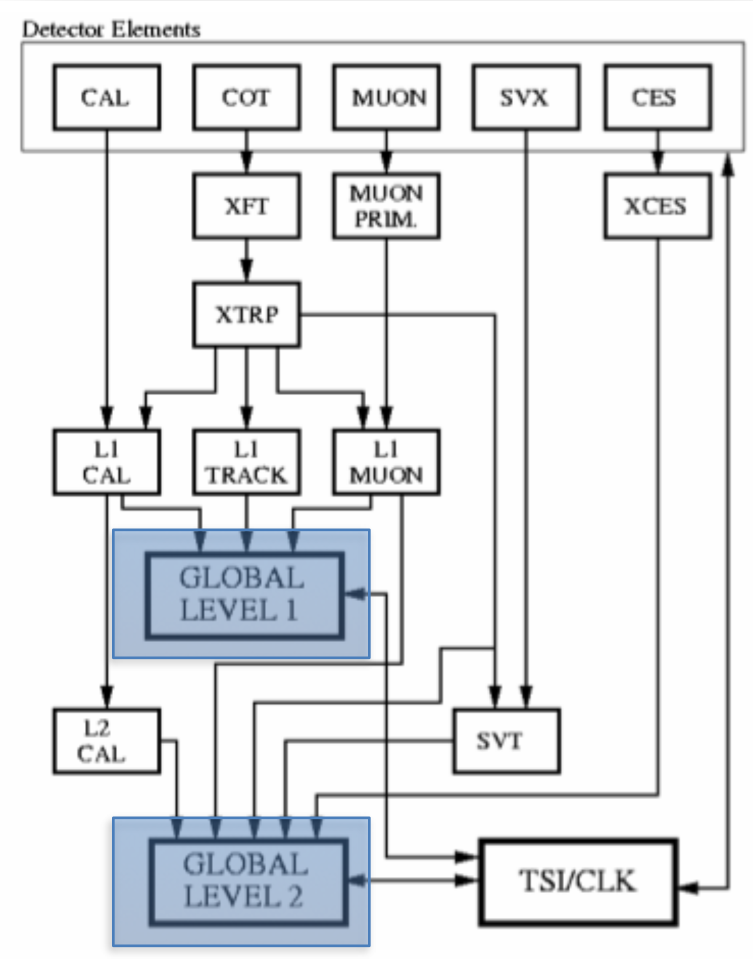
XFT=eXtremely Fast Tracker

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)

Multi objects trigger: 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)

The trigger efficiency is a parameter of your measurement

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

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

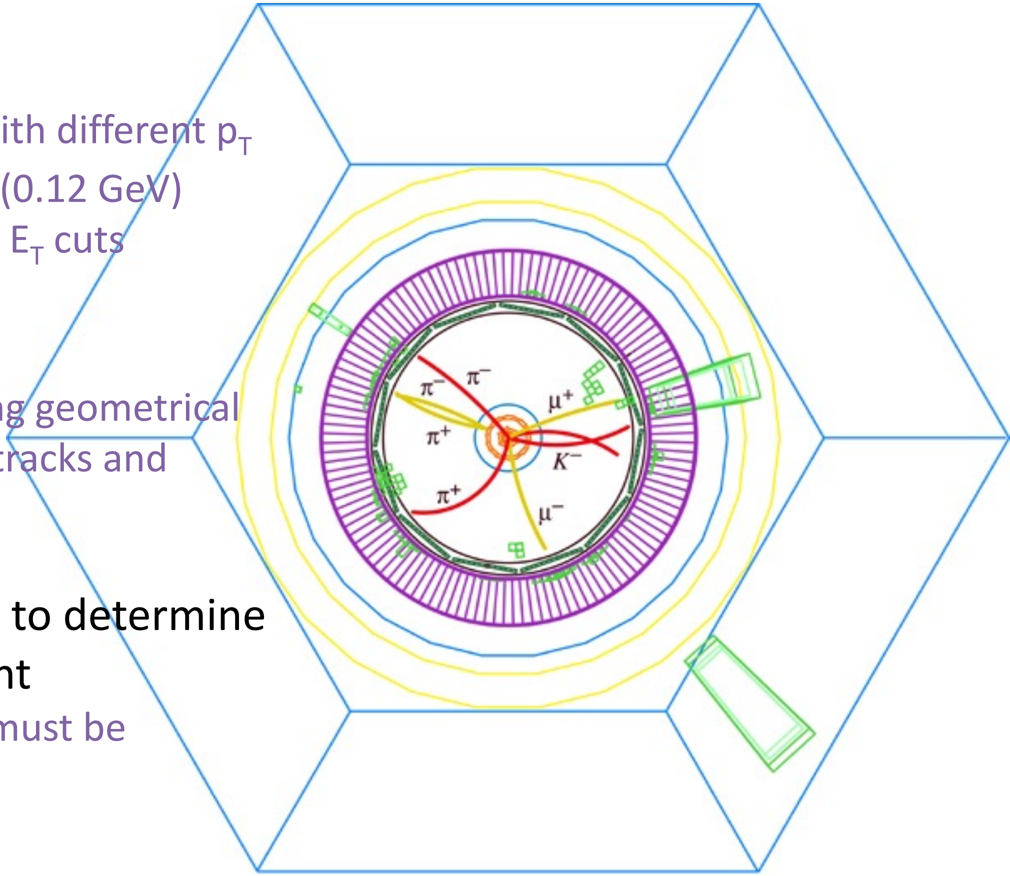
- Trigger efficiency must be precisely known, since it enters in the calculation of the cross-sections
  - For some precise measurements, the crucial performance parameter is not the efficiency, but the **systematic** error on determining it
- Different **independent** trigger selections allows good cross-calibration of the efficiency
  - Besides your "physics" triggers, foresee additional **back-up triggers**

Trigger for precision measurements: BaBar

- Goal: reduce systematic errors on the measurement of CP violating parameters

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

Golden B (for CP violation)
Tagging B



- 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 in the trigger itself

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 the different rates between applying and not applying the selection
  - It's crucial to select the correct **sample without biases**
- For High-level triggers, the efficiency is easily measured using back-up triggers called **pass-through**
  - A trigger that does not include the selection

L2 muon at 10GeV

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

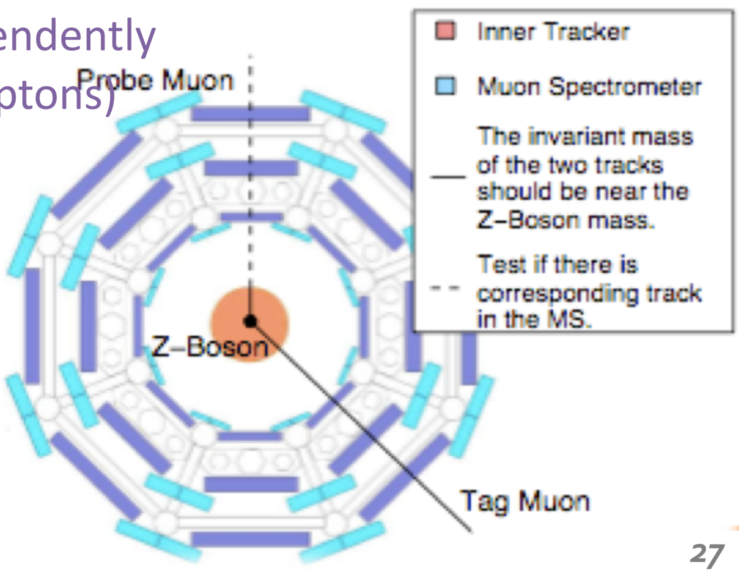
Trigger efficiency measurement (2)

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

- For L1, we don't know the absolute denominator; different methods are used

1. Calculate the efficiency **relatively** to another trigger selection
   - Compare independent triggers (not correlated, of course)

2. At the collider experiments, use experimental technique called **"Tag-and-Probe"**
   - Use a known physics process which can be independently selected, very clean (like the Z-boson decay into leptons)
   - Select the track that triggered the event (**Tag**)
   - Find the other offline track (**Probe**)
   - Apply offline the trigger selection on Probe

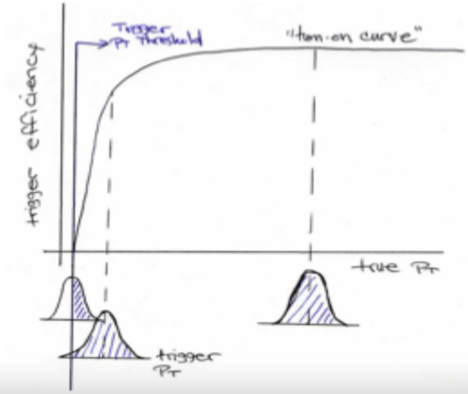


Use back-up triggers:
L1_LOWEST_THRESHOLD

Trigger efficiency measurement (3)

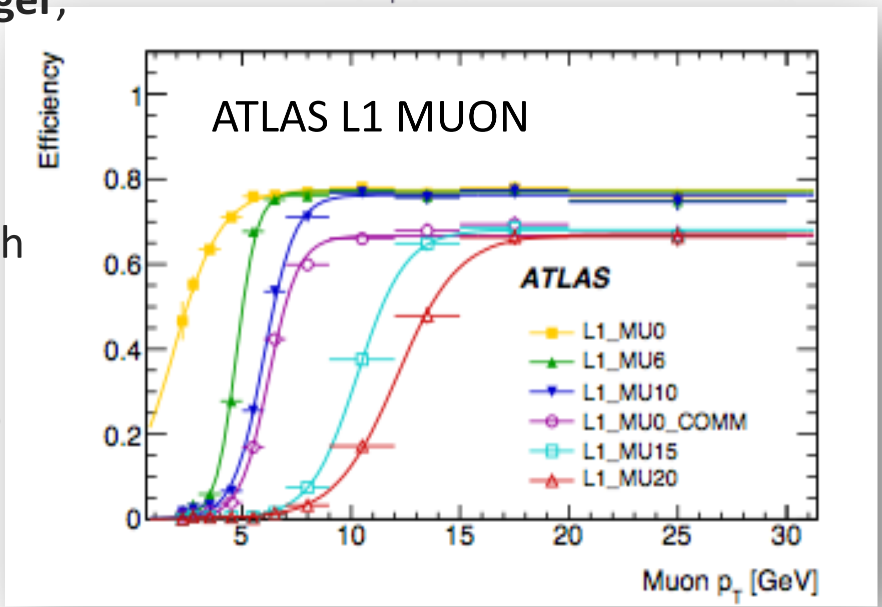
The dependency of ε on the threshold value (measured offline with the maximum resolution) is described by the turn-on curves

- The capability of controlling the rate depends on the **resolution** on the trigger parameter
  - For example some particles can be under threshold, failing the trigger, because their trigger parameter is underestimated



- The worst allowed resolution is **at level-1 trigger**, which has coarse granularity
  - Example: $\delta p_T/p_T$ can be up to 30%

- Crucial is the study of the **step region**, in which efficiency changes very quickly and contamination from background can be important (soft particles are often abundant!)
  - If **quick**, better background suppression
  - If **slow**, can be better extrapolated and systematic error can be reduced

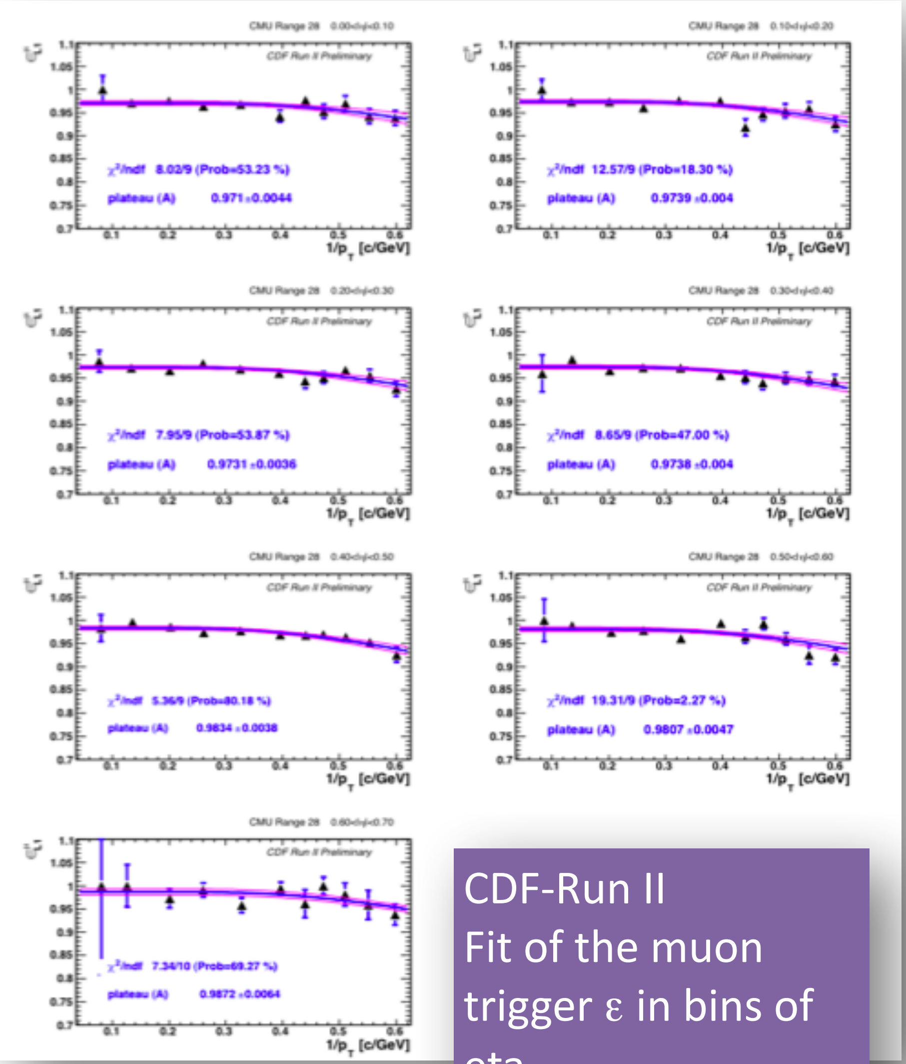


Parametrizing the trigger efficiency

- 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: $\varepsilon(p_T, \eta, \phi, run\#)$
  - 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

How many trigger signatures?

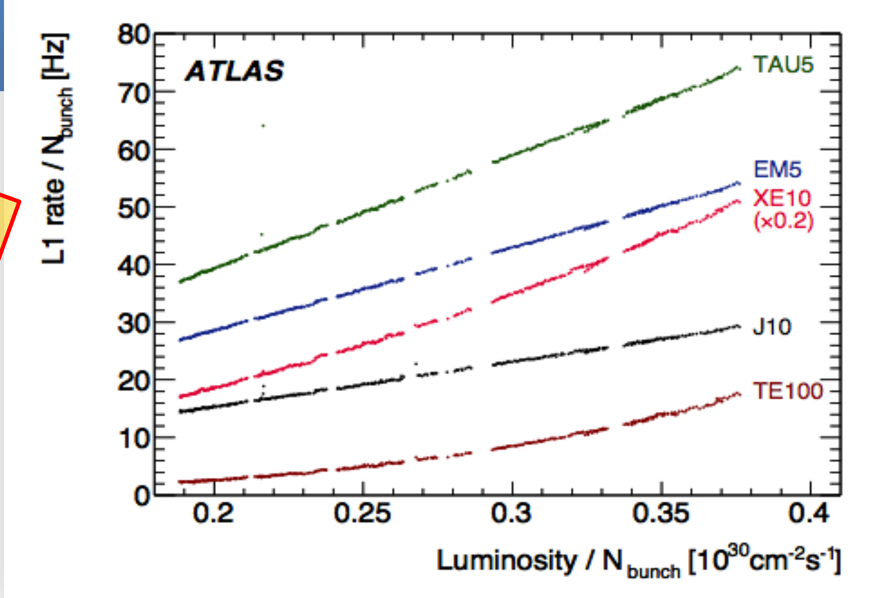
- Physics triggers
  - **Discovery experiments**: multiple inclusive selections ensure wide open windows to look at
  - **Precision experiments**: multiple triggers for multiple measurements
- Calibration triggers
  - Detectors calibrations
  - Detectors and trigger efficiency measurements
  - Tagging efficiency
  - Energy scale measurements
- Background triggers
  - Instrumental and physics background
  - Better description of the background can be extrapolated from data than from Monte Carlo
  - Understand resolutions, including the under-threshold population
- Monitor triggers
  - To monitor the trigger itself (remember, lost events are lost for ever!)

Bulk of the selected events!

Rate allocations of the trigger signatures

- ✓The target is the final allowed DAQ bandwidth
- ✓The rate allocation on each trigger signature based on
  - ✓Physics goals (plus calibration, monitoring samples)
  - ✓Required efficiency and background rejection
  - ✓Bandwidth consumed

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



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

Trigger Efficiency

Extrapolate the expected trigger rates:

- For trigger design and commissioning: use large samples of simulated data, including large cross-section backgrounds
  - 7 million of non-diffractive events used in the ATLAS trigger design
  - Large uncertainties due to detector response and background cross-sections: apply **safety factors**, then tuned with data
- During running (at colliders), (some) rates can be extrapolated to higher Luminosity

Physics interest vs system bandwidth…

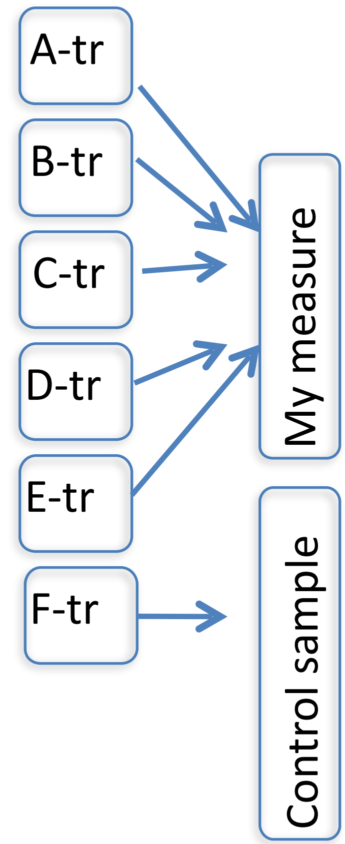
Lower thresholds would be desirable, but the physics coverage must be balanced against considerations of the offline computing cost

- **How accommodate a broad physics program?**
- **And cope with increasing rates?**

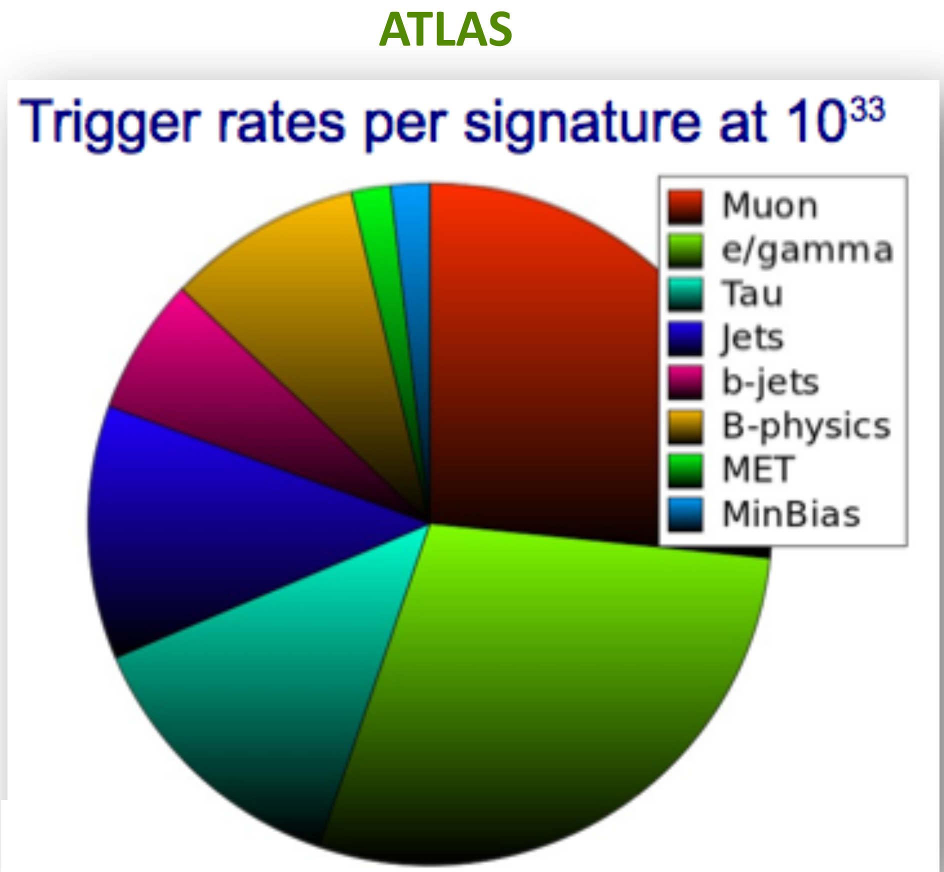
Organize trigger menus!

Design a trigger menu

- The list of our selection criteria must be
  - **Redundant** to ensure the efficiency measurement
  - Sufficiently **flexible** to face possible variations of the environment (detectors, machine luminosity) and the physics program
- 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, it will keep **some events from all processes** (to provide physics breadth and control samples)



Trigger strategy @ colliders: ATLAS menu

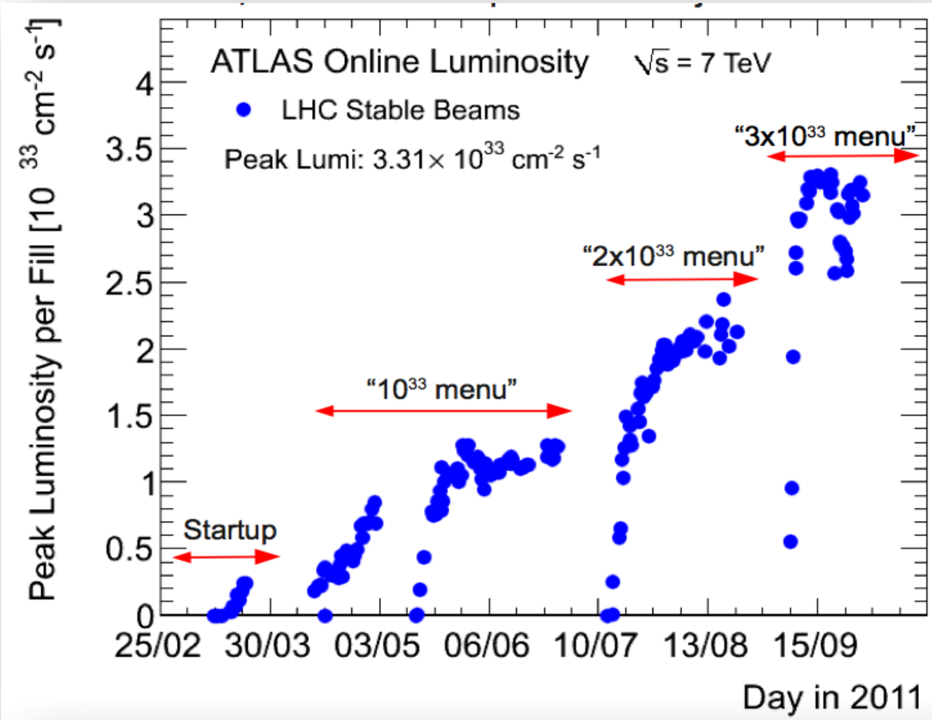


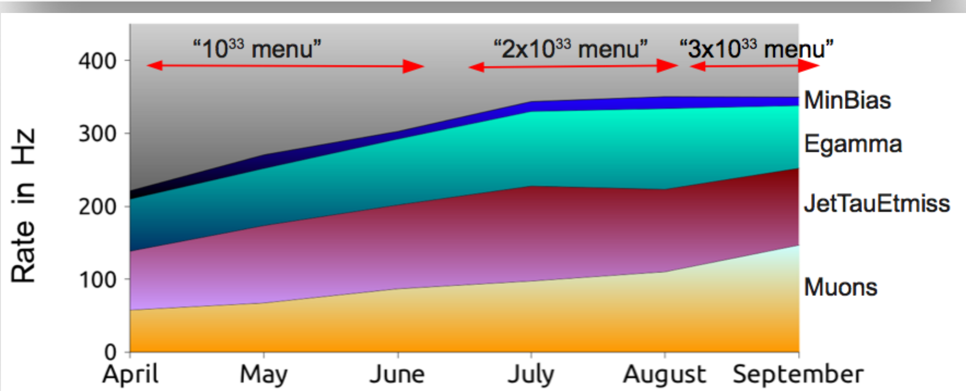
- Inclusive triggers to collect the **signal samples**
  - Single high-p_T
    - e/μ/γ (p_T>20 GeV)
    - jets (p_T>100 GeV)
  - Multi-object events
    - e-e, e-μ, μ-μ, e-τ, e-γ, μ-γ, etc… to further reduce the rate
- **Back-up triggers** designed to spot problems, provide control samples (often pre-scaled)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

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	5×10^{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 menu flexibility: commissioning of the ATLAS trigger





- ATLAS **start-up in 2008**: $L=10^{31}$ 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 increasing LHC luminosity
  - Complex signatures and higher p_T thresholds are added to reach the physics goals
  - Maintain stable trigger conditions for important physics results (for conferences)
  - Mostly keep the same balance between physics streams (electrons, muons, jets, minimum-bias)

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)

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

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

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
  - 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
  - High efficiency – rate control
  - Perfect knowledge of the trigger selection on signal and background
  - Flexibility and redundancy
- In the next lecture, we will see how to implement such a system, still satisfying these requirements