Triggering on Higgs at the LHC

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Outline

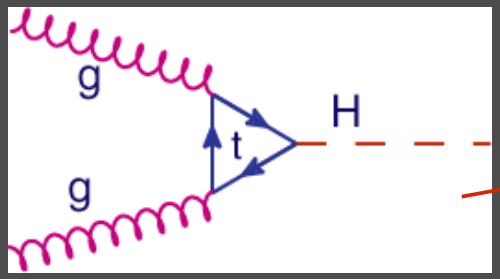
- What do we want to trigger on?
- Why is it so difficult?
- How do trigger systems work?
- Trigger efficiency

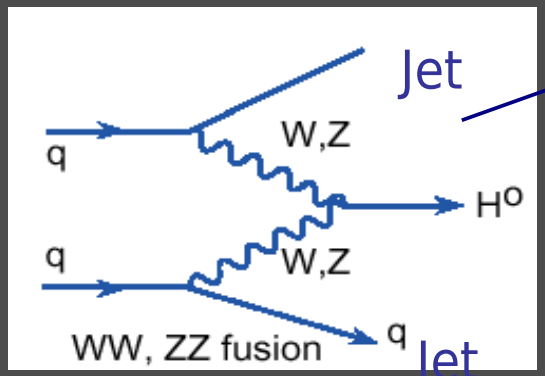
I will not describe trigger designs in detail but I will present the general concepts/ideas that one student needs to know to do physics

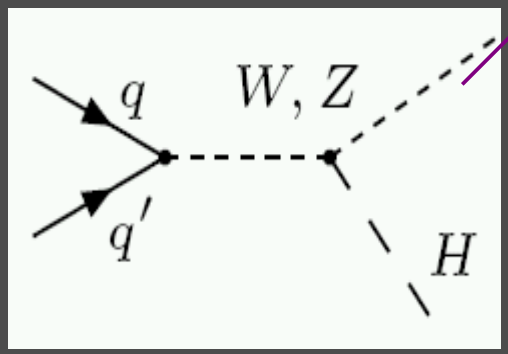
Examples from ATLAS/CMS triggers mainly

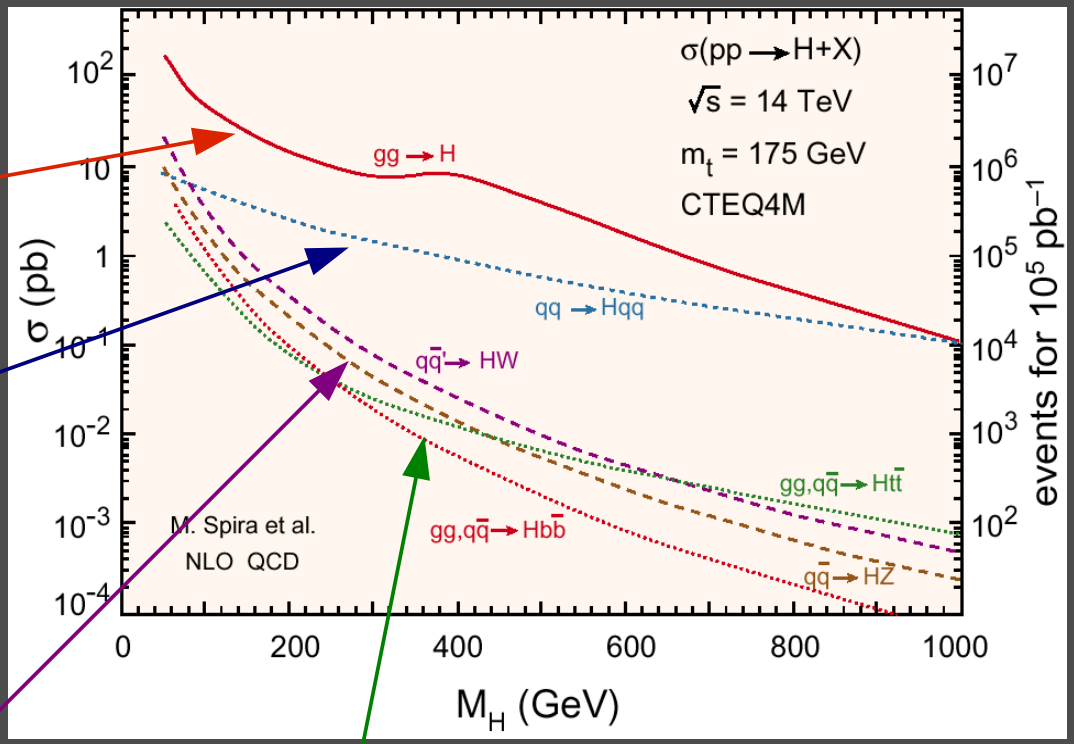
What do we want to trigger on?

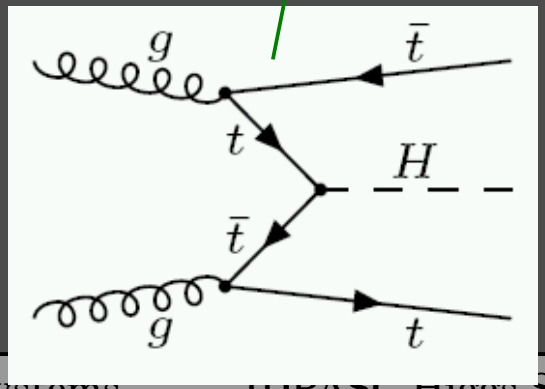
Higgs production









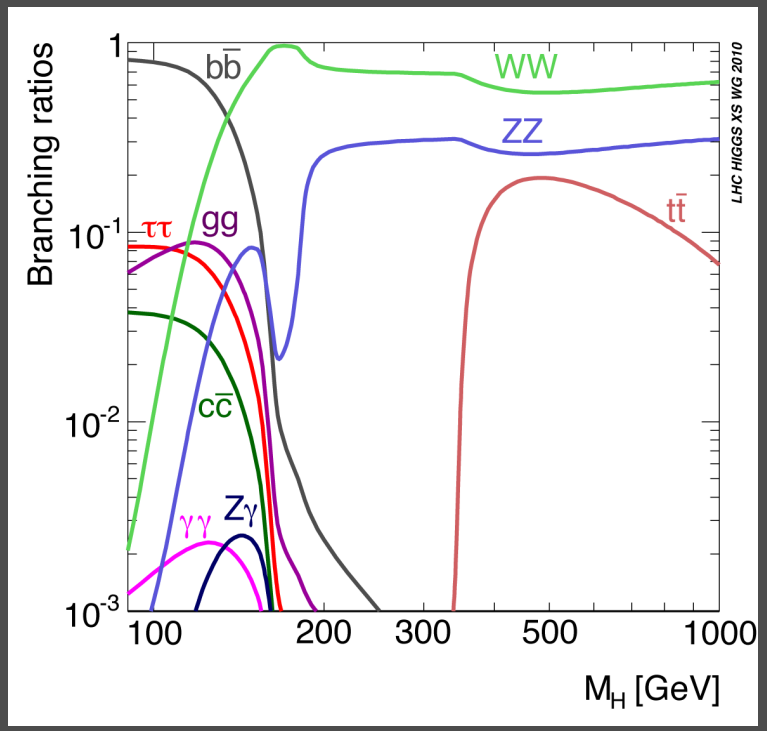


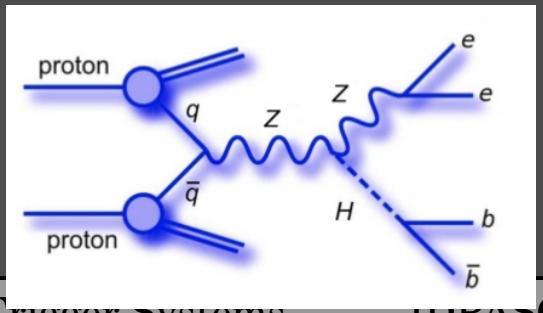
Higgs decays in the SM

Decay branching ratios depend on the Higgs mass

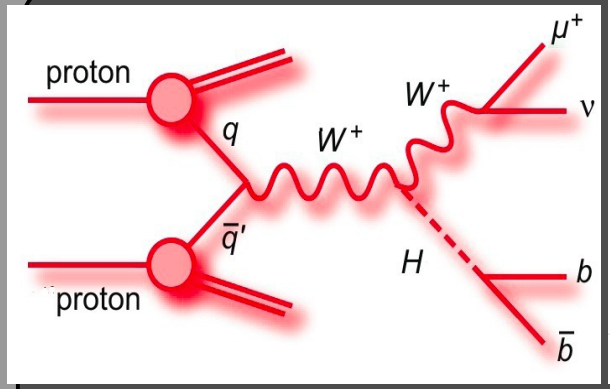
- Low mass range:
  - H→bb dominates
  - H→ττ second most important
  - H→γγ has very small BR
- Larger masses:
  - WW dominates
  - ZZ second most important

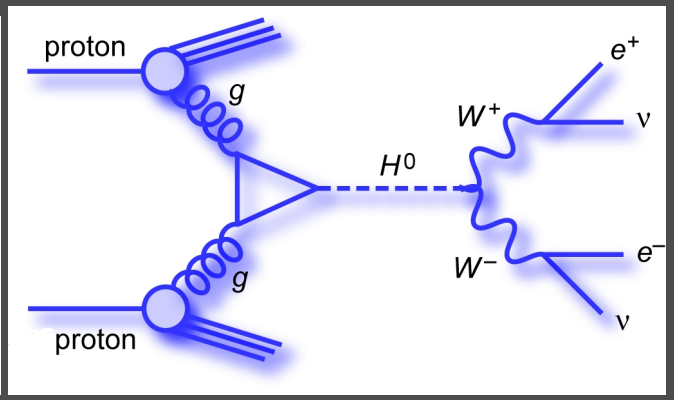
Higgs search channel: normally, it means a production mechanism + a particular decay mode

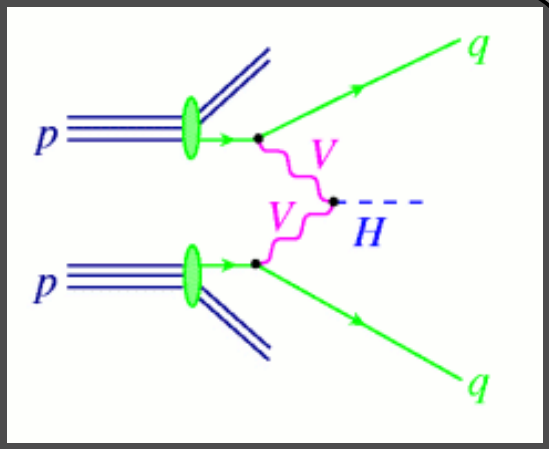




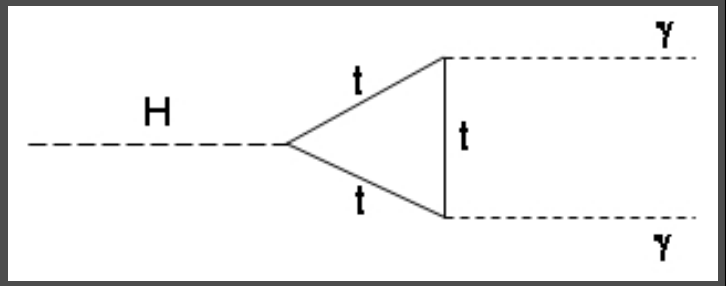
Signatures





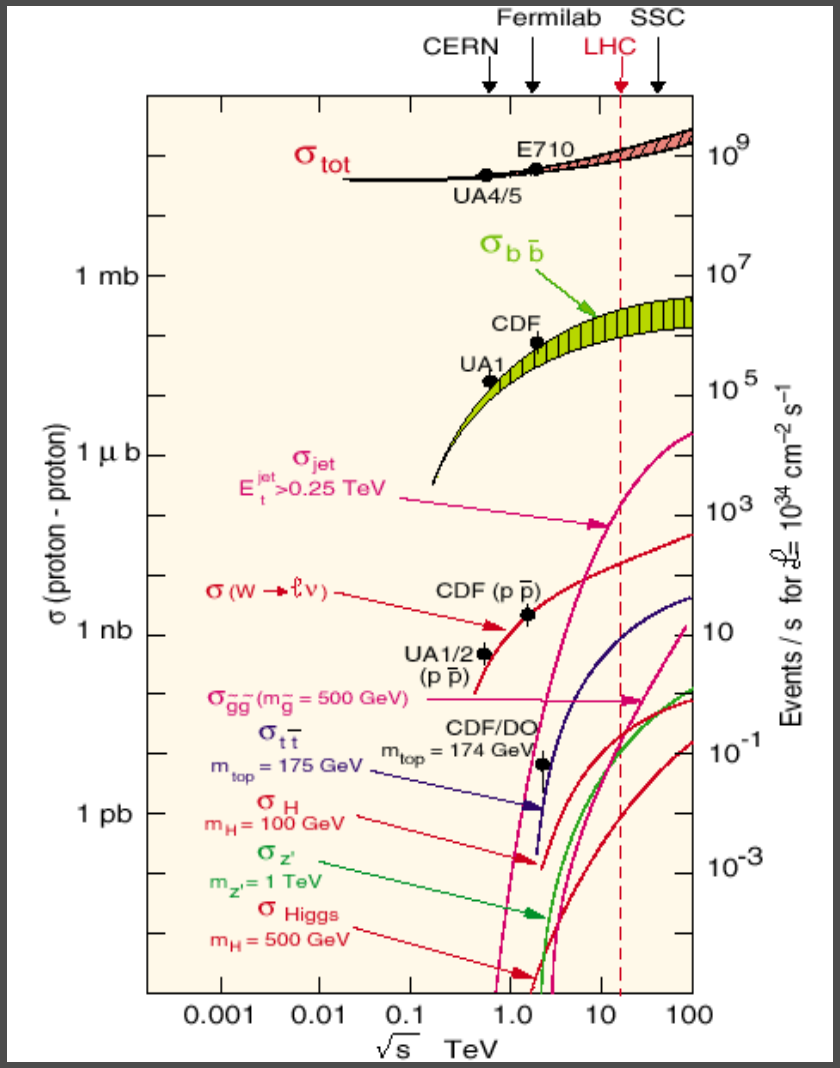


- Final state particles: e, μ, τ, ν, quarks, γ
- Provide the signatures to search for:
  - High p_T leptons: e, μ, τ,
  - High p_T jets or b-jets
  - Photons
  - Missing transverse energy (from scaping neutrino)



Why is it so difficult to identify them?

Production cross sections at LHC



- The total production cross section at LHC is:
  - ~ 10^3 × σ(bb)
  - ~10^7 × σ(W→μν)
  - ~10^8 × σ(tt)
  - σ(di-jet) for jets with E_T > 7 GeV is ~ 50% of σ(tot)
  - ~5x10^{10} × σ(H) (m_H ~ 100 GeV)
- Most of the collisions are not interesting at all
- Need to select the important ones

Be inclusive: keep all the interesting events (not only Higgs!)

Interaction rate

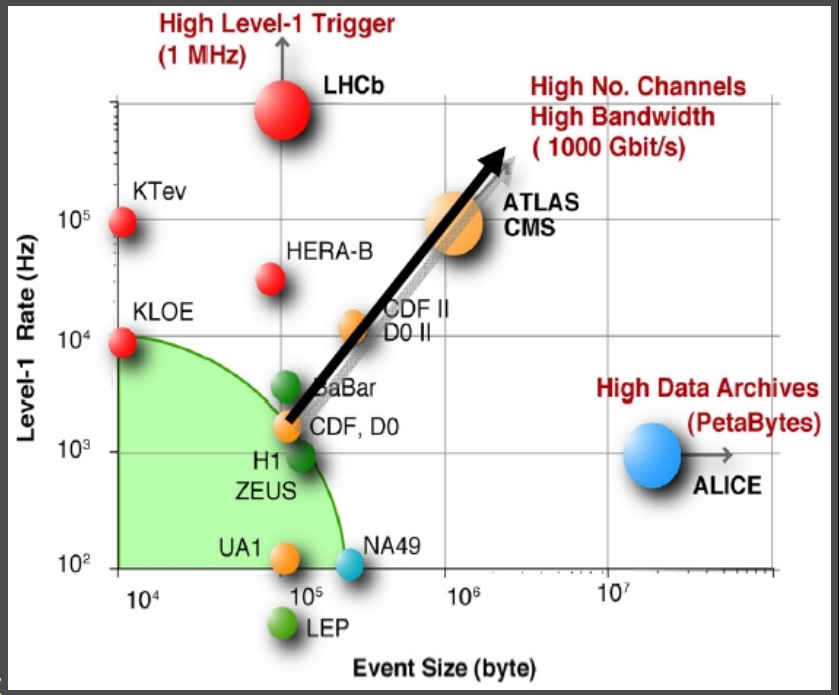
$$R = \mu \cdot f_{BC} = \sigma_{in} \cdot L$$

- L = instant. luminosity
- f_{BC} = bunch crossing frequency
- μ = average pp interactions/ BC

At the LHC

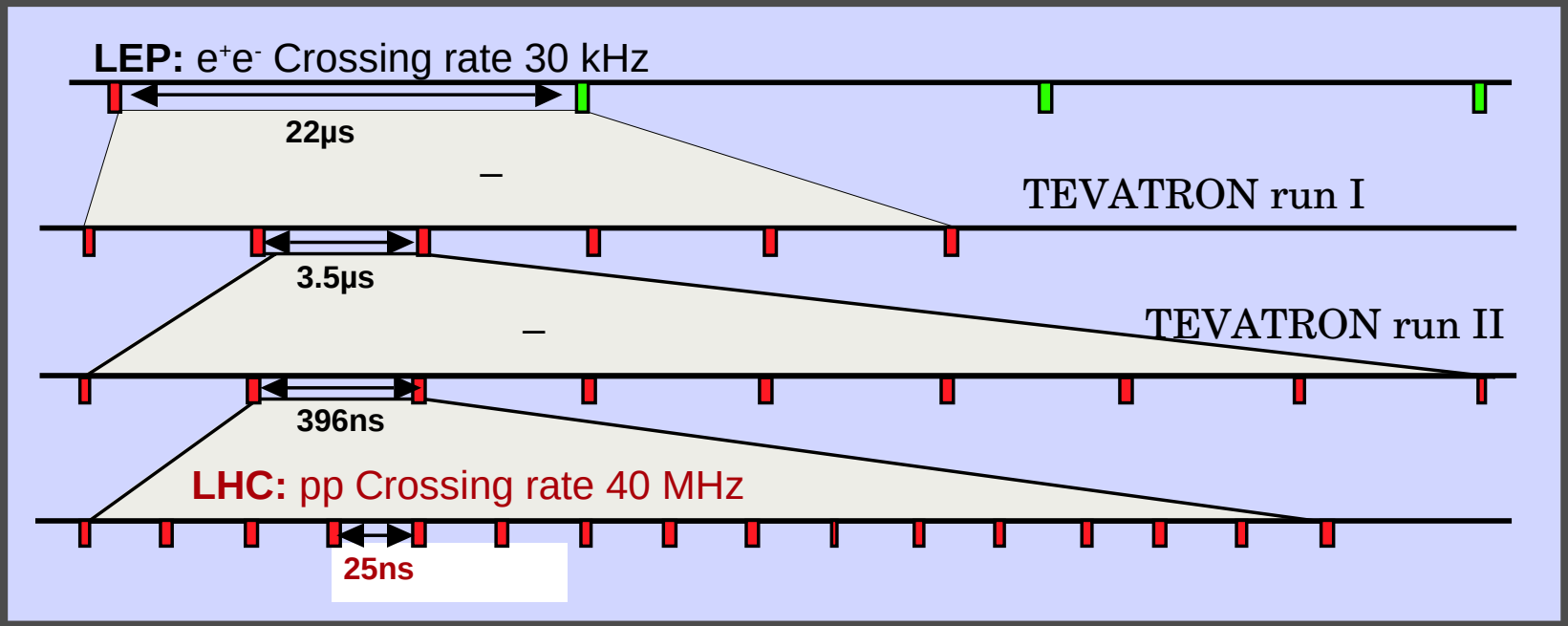
- $L = 10^{34}\ cm^{-2}s^{-1}$
- 25 interactions per bunch crossing
- Total bunch crossing rate ~ 40 MHz
  - Interaction rate ~ 1 GHz
- Storage capabilities: ~ 200 Hz

The trigger system must reduce the rate selecting the interesting events



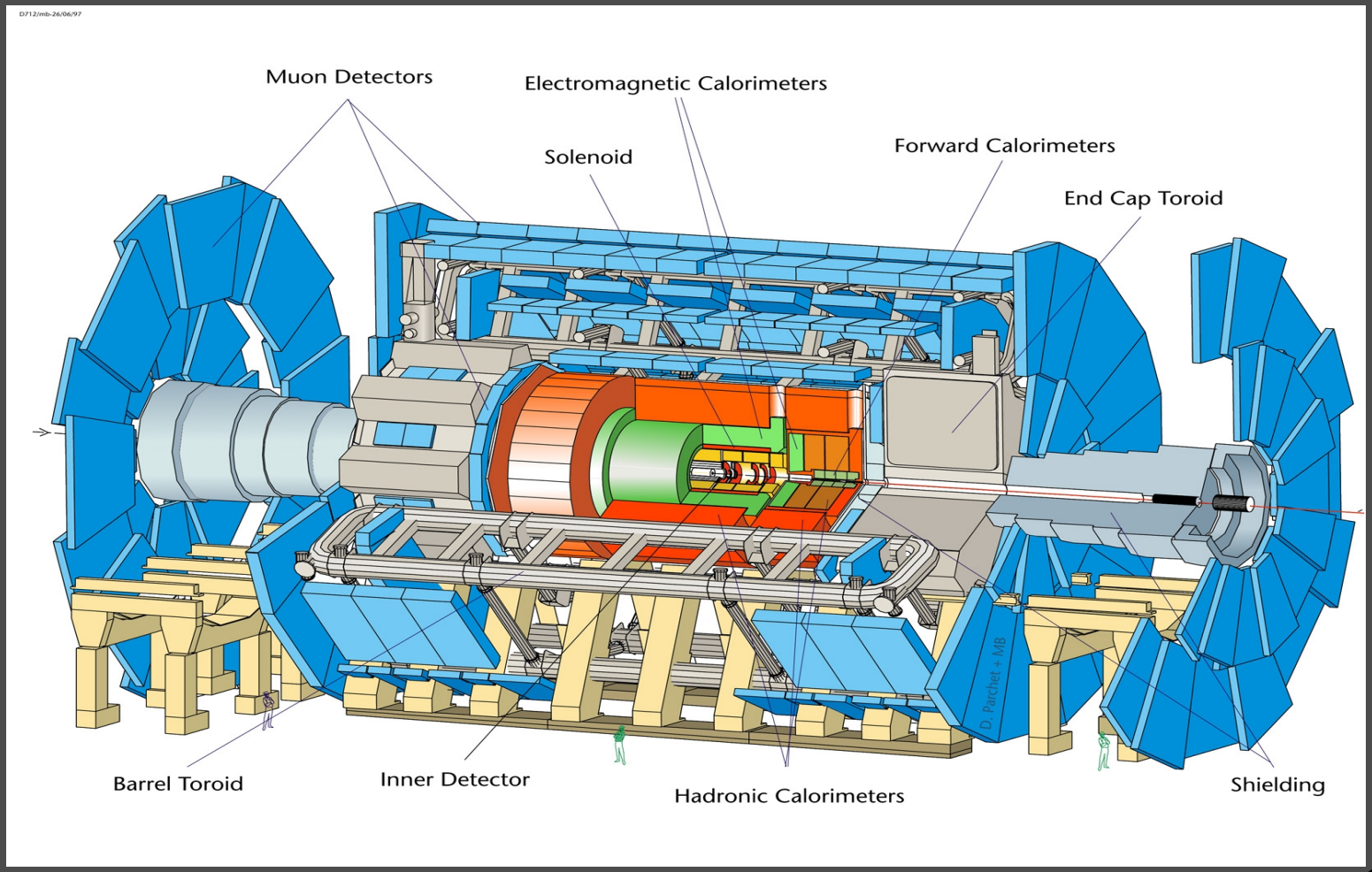
Bunch crossing rate

- LHC will have ~3600 bunches
  - And same length as LEP (27 km)
  - Distance between bunches: 27km/3600=7.5m
  - Distance between bunches in time: 7.5m/c=25ns



Time of flight

c=30cm/ns, so in 25ns s=7.5m



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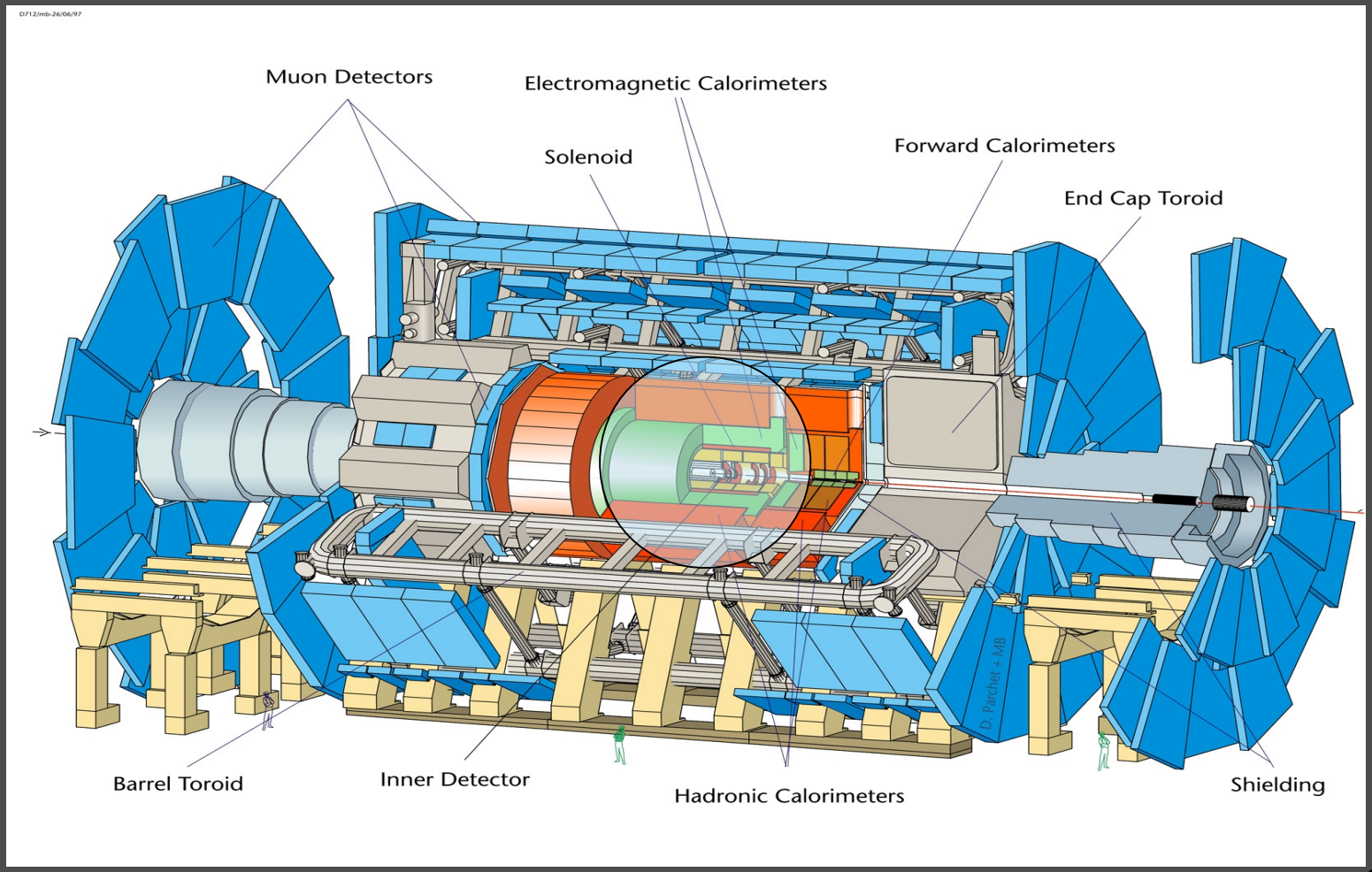

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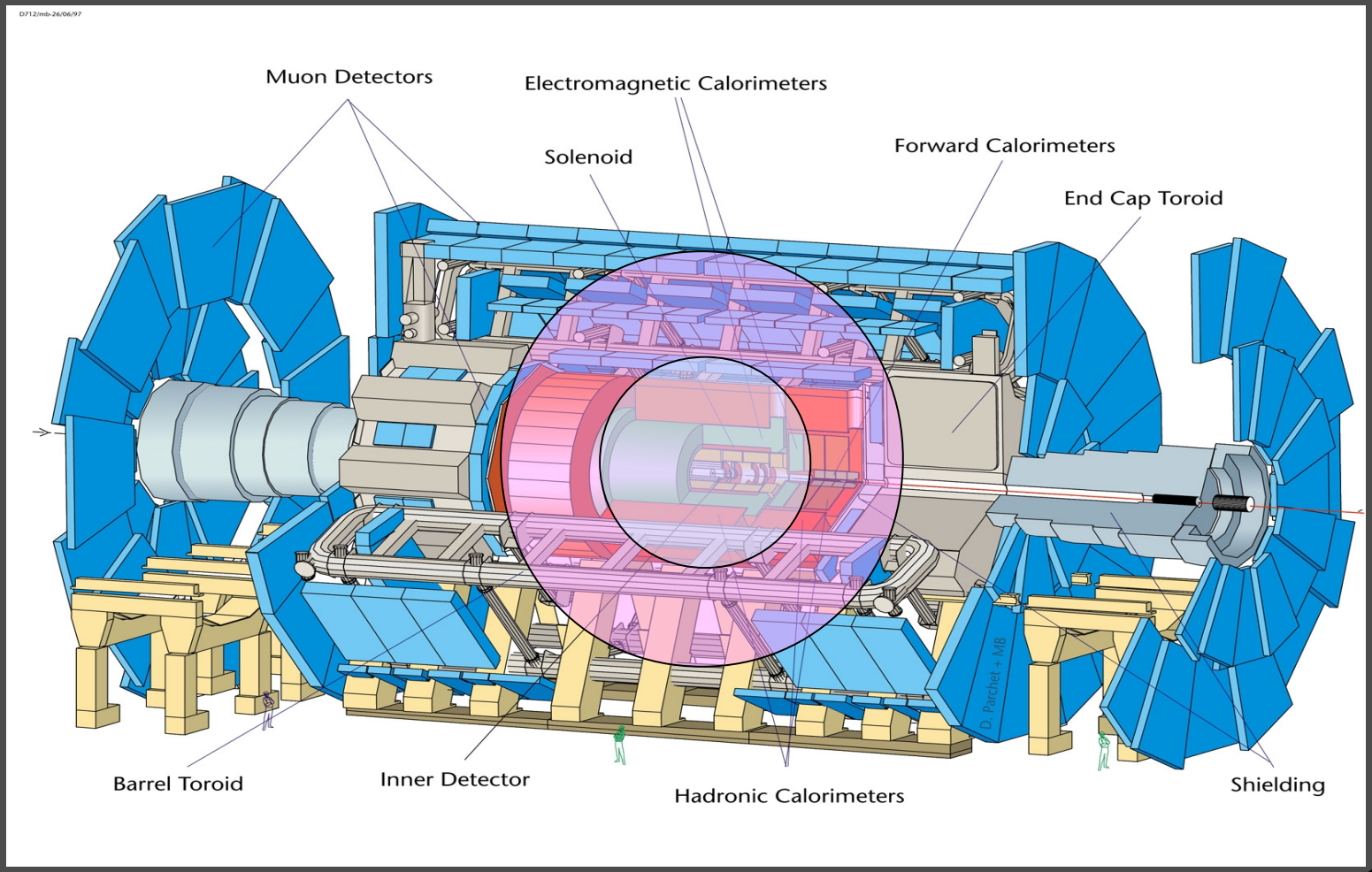

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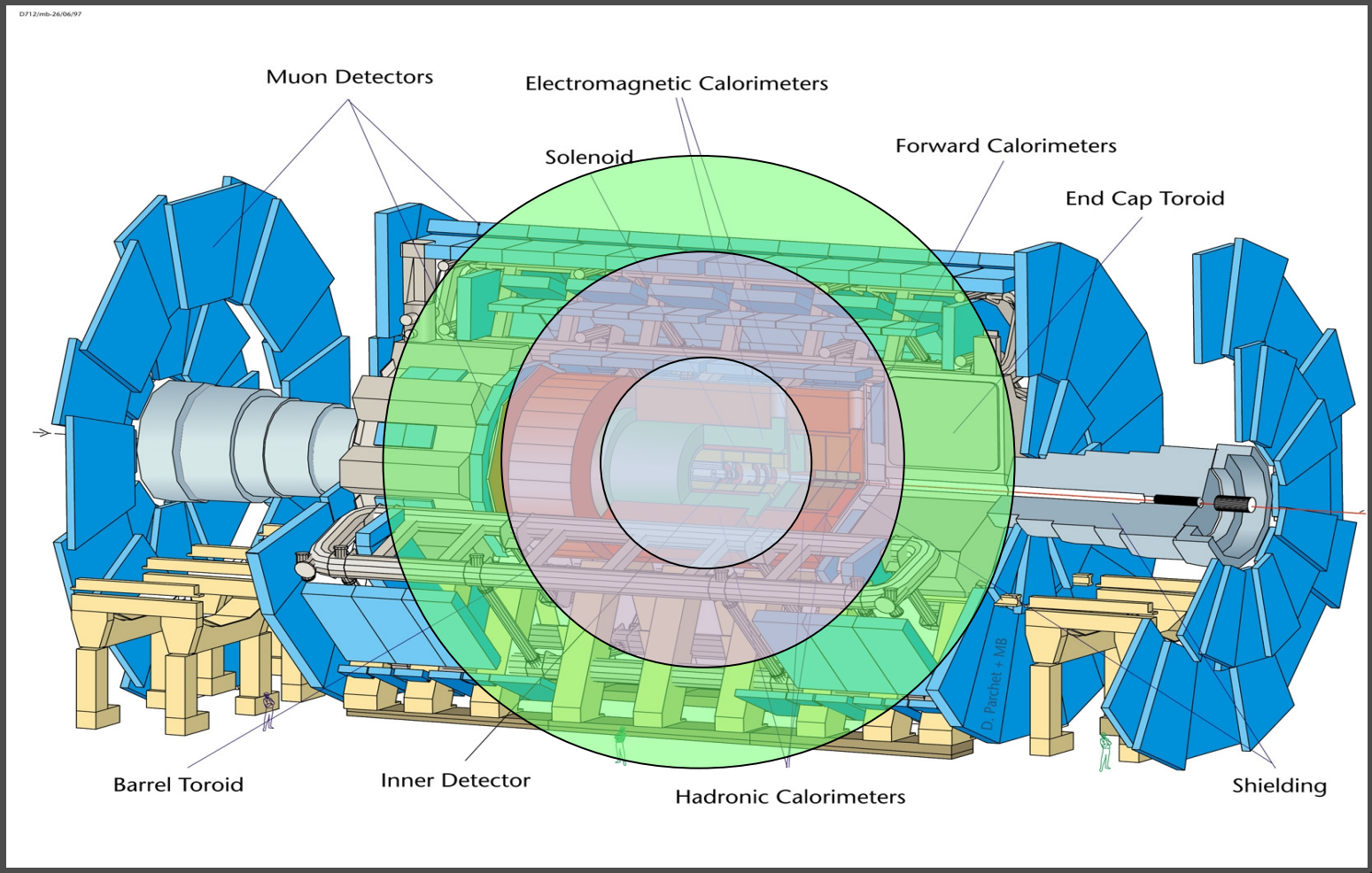
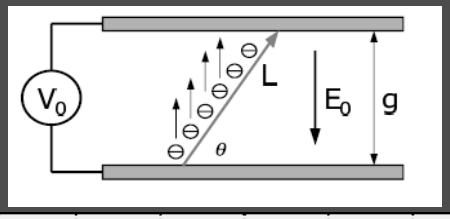
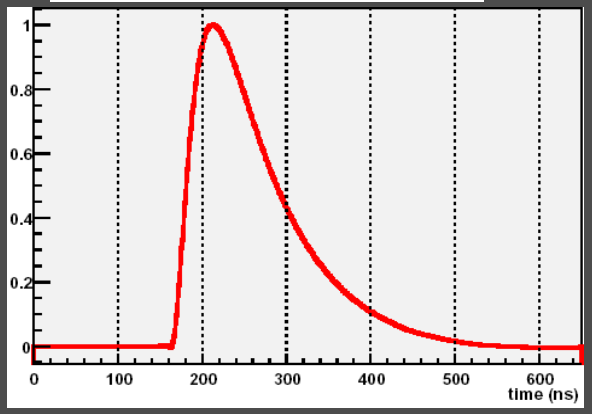
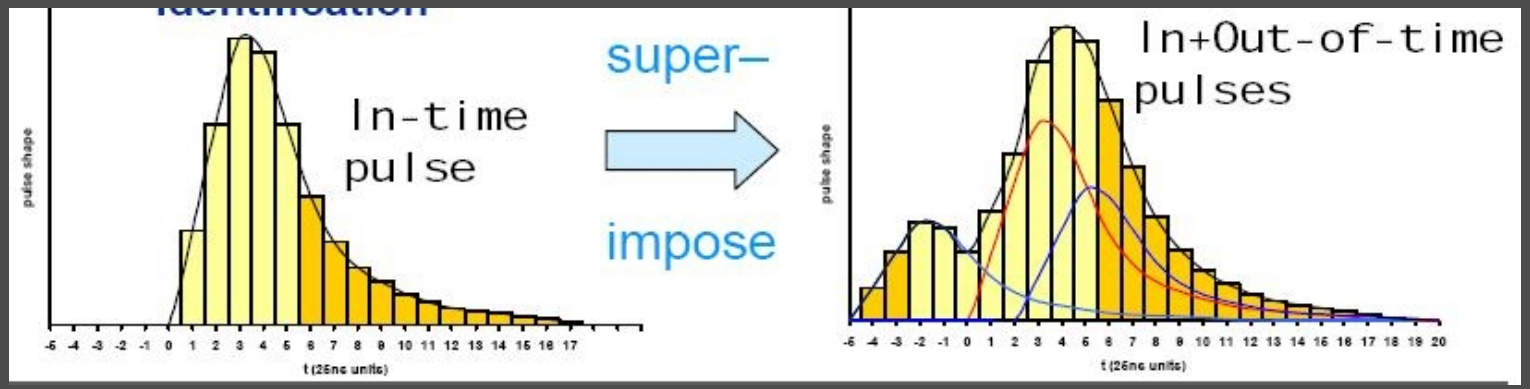


Out of time pile-up

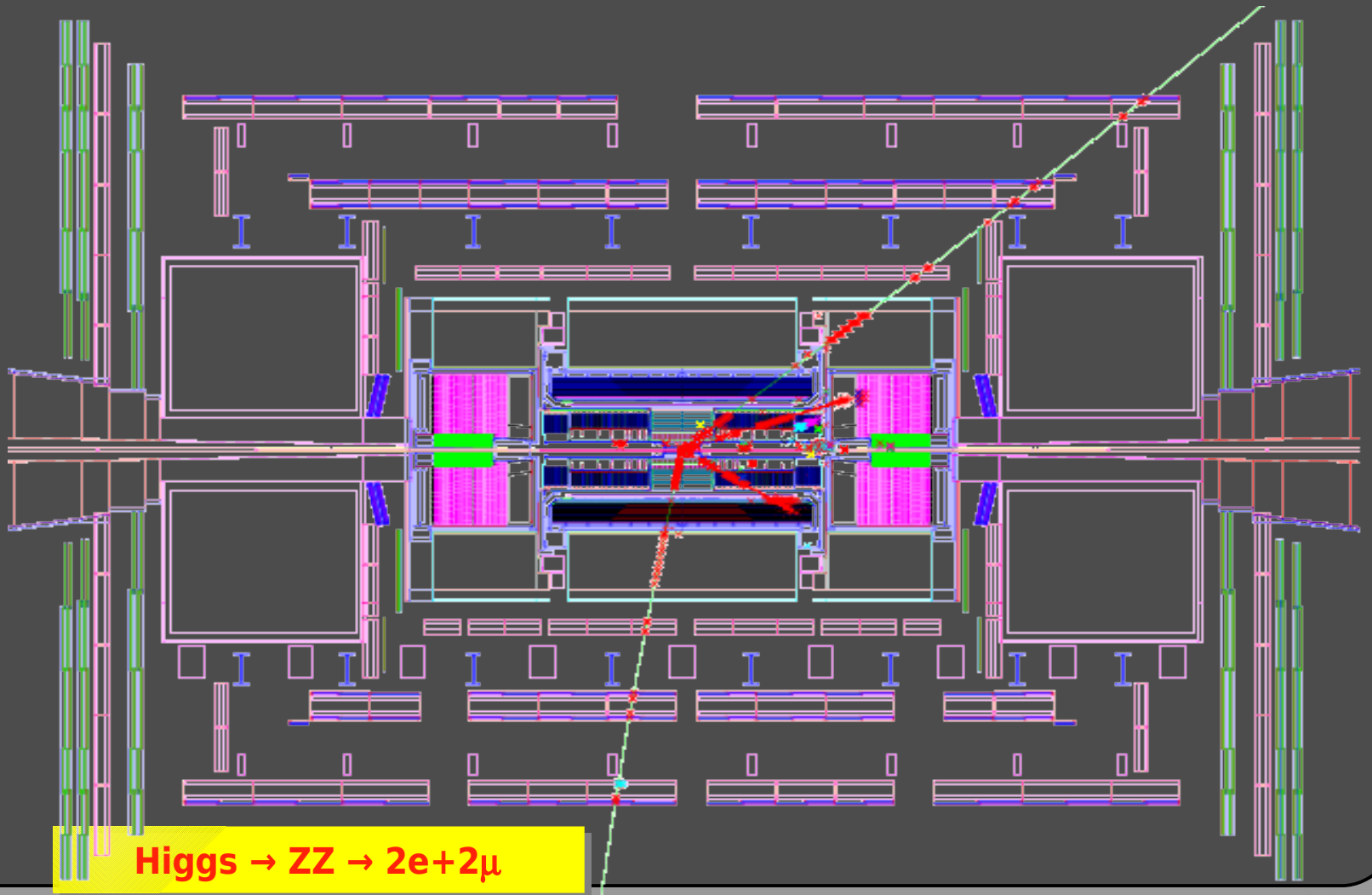
- Long detector response/pulse shapes:
  - "Out-of-time" pile-up: left-over signals from interactions in previous crossings
  - Need bunch-crossing identification
  - Sinchronize detectors better than 25 ns!





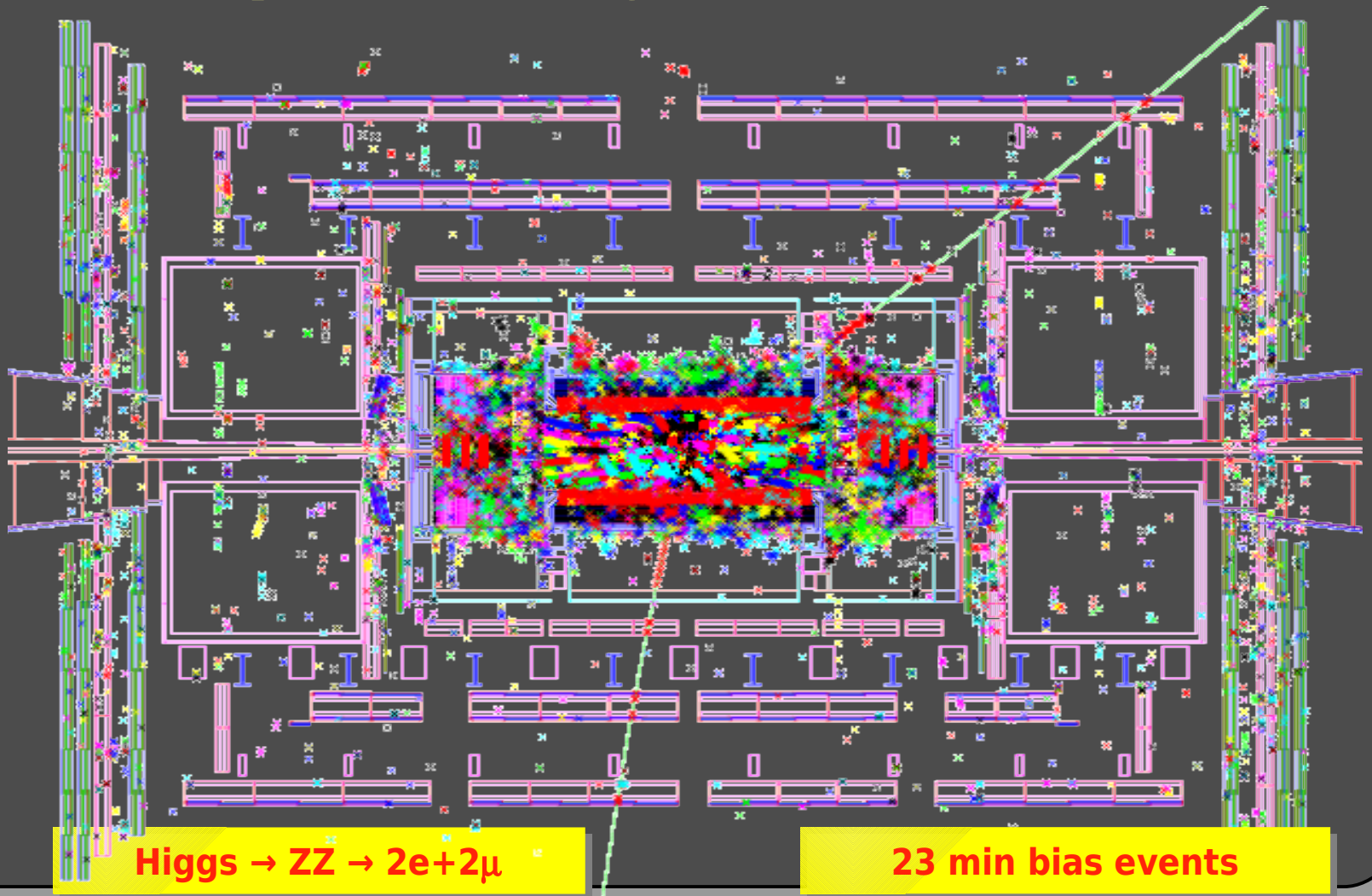


In-time pile-up



In-time pile-up

- 23 interactions per bunch crossing

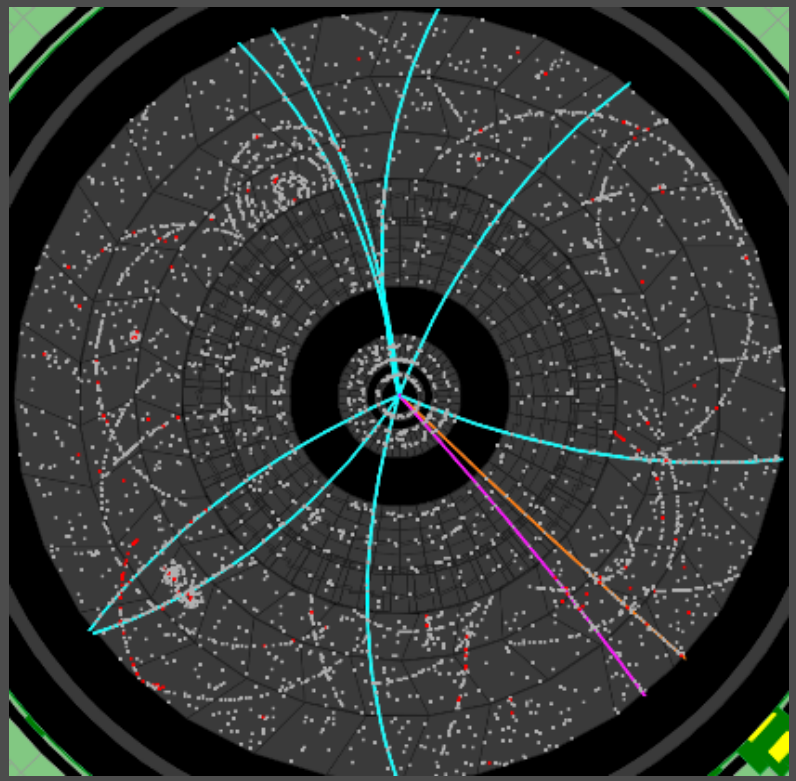


Rate and luminosity relation

- Cross sections of physics processes do not depend on luminosity
- Trigger rates do depend on it:

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

  - A = cte. Rate
  - B = constant sigma
  - High purity triggers have C, D ~0.
  - Extra terms due to
    - Objects from different interactions
    - More fakes
    - Worse resolution due to high occupancy



Impact on detector design

- LHC detectors must have fast response
  - Avoid integrating over many bunch crossings ("pile-up")
  - Typical response time : 20-50 ns
    - integrate over 1-2 bunch crossings
    - pile-up of 25-50 min-bias events
    - very challenging readout electronics
- LHC detectors must be highly granular
  - Minimize probability that pile-up particles be in the same detector element as interesting object
    - large number of electronic channels
- LHC detectors must be radiation resistant:
  - high flux of particles from pp collisions $\rightarrow$high radiation environment e.g. in forward calorimeters

Trigger/DAQ challenges

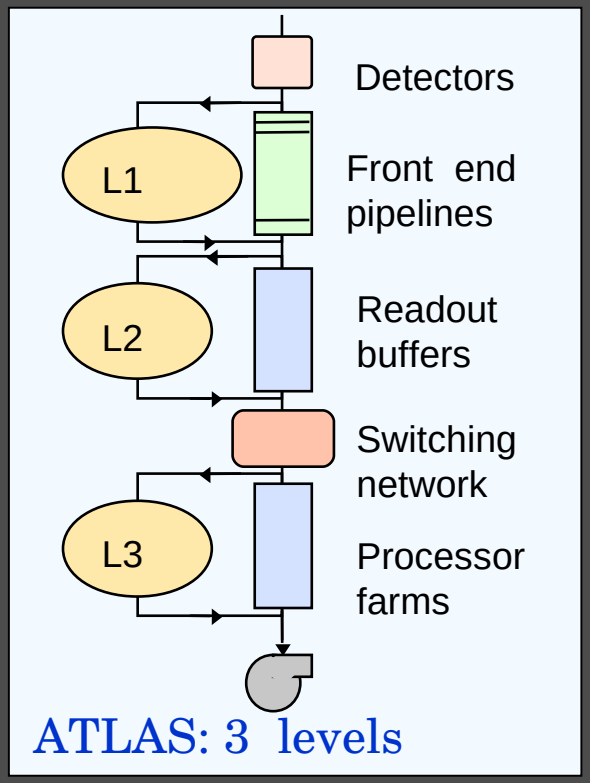
- N (channels) ~ O(10^8); ≈20 interactions every 25 ns
  - need huge number of connections
  - need information super-highway
- Need to synchronize detector elements to (better than) 25 ns
  - Calorimeter information should correspond to tracker info
- In some cases: detector signal/time of flight > 25 ns
  - integrate more than one bunch crossing's worth of information
  - need to identify bunch crossing...
- Can store data at ≈ 100 Hz
  - need to reject most interactions
- It's On-Line (cannot go back and recover events)
  - Robustness and reliability are essential!
  - need to monitor selection

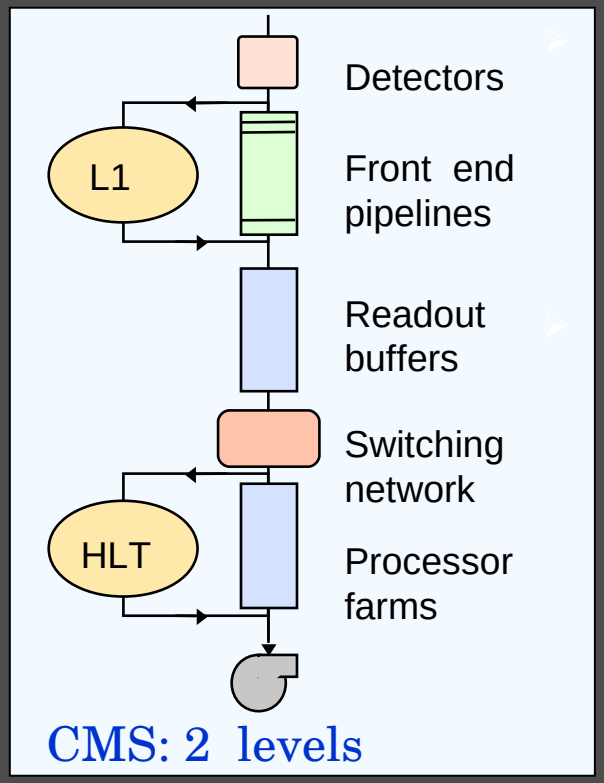
How does the trigger to select interesting events so fast?

- Trigger achitectures
  - L1 triggers
  - HLT designs
- Trigger menus

Trigger architectures

- To obtain high efficiency and large background rejection, the trigger systems are organized in steps

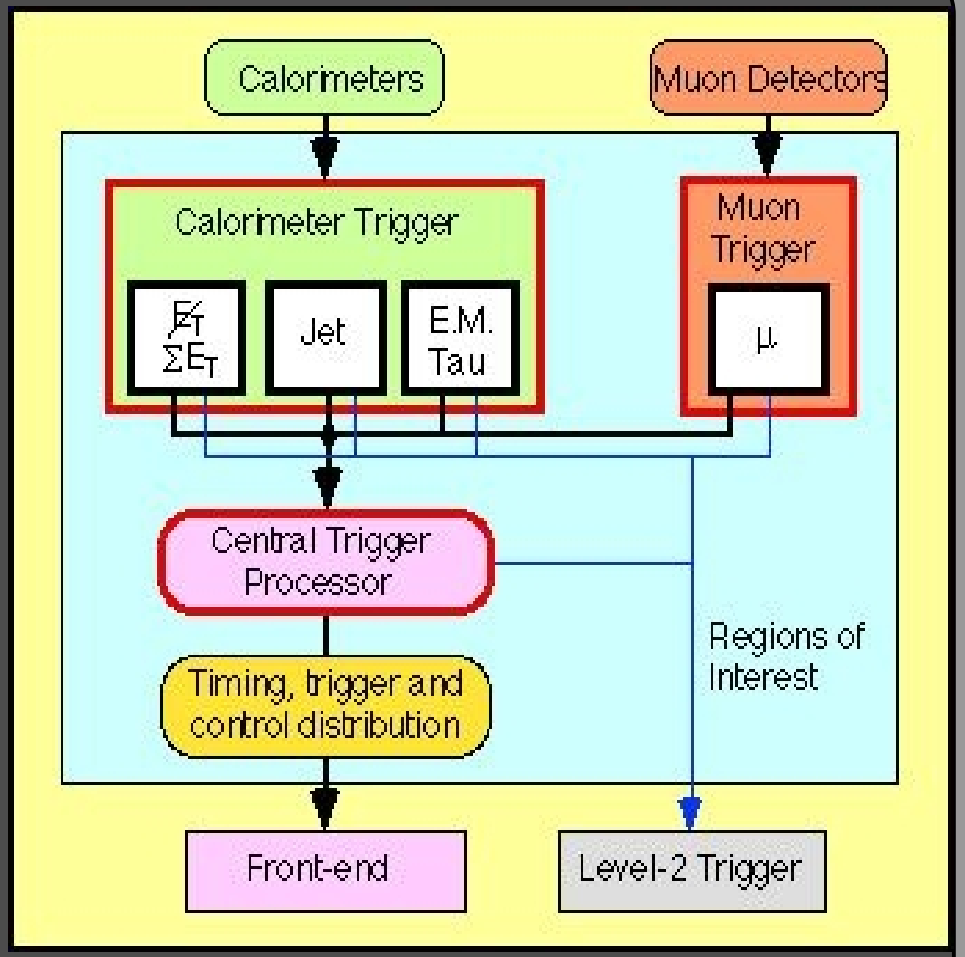




- First level: decision taken in ~μs
  - Need fast customs electronics
- High level triggers
  - Progressive reduction in rate
  - Final steps run on computer farms
  - May use complex algorithms

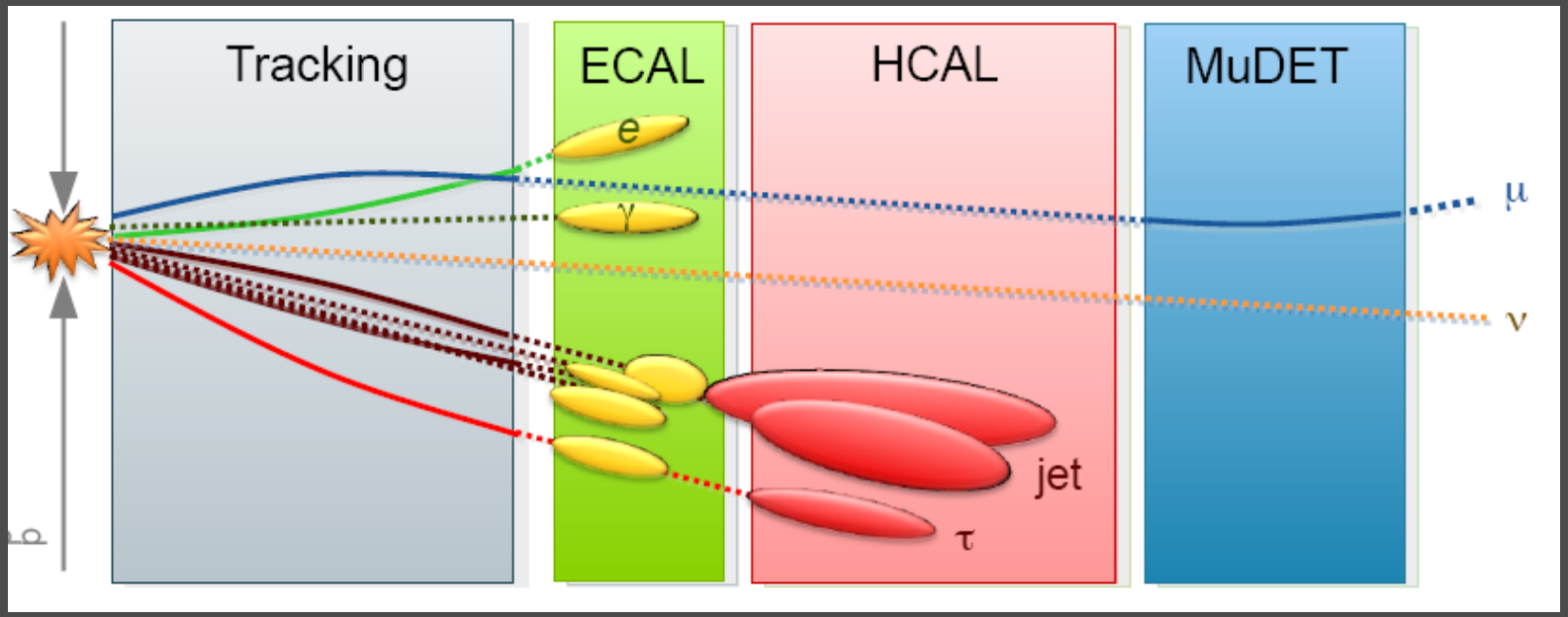
First level trigger

- Custom dedicated processors
- Reduced granularity
- Basic calibrations (if available at all)
- Use calorimeter & muon chambers (no tracking)
  - Smaller number of electronic channels
  - Faster pattern recognition



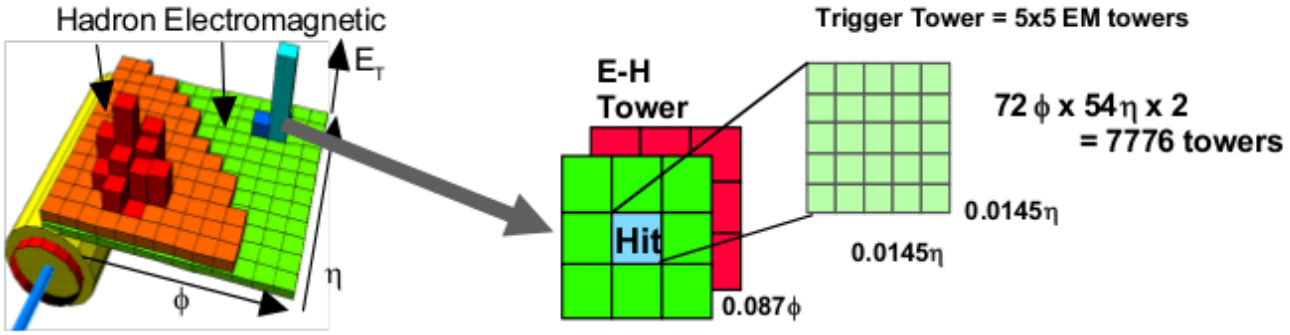
Example from ATLAS (CMS has a similar design)

Particle identification



- Use properties of the objects to separate them from background:
  - e,γ from jets: shower shape variables, no hadronic energy, track/no track, isolation
  - μ from jets: good track in tracking+muon chambers, isolation
  - τ from jets: few tracks, shower shape conditions, isolation
  - Jets from jets: jet energy scale

Example: e/γ L1 trigger at CMS



$E_T(\square) + \max E_T(\square) > E_T^{min}$

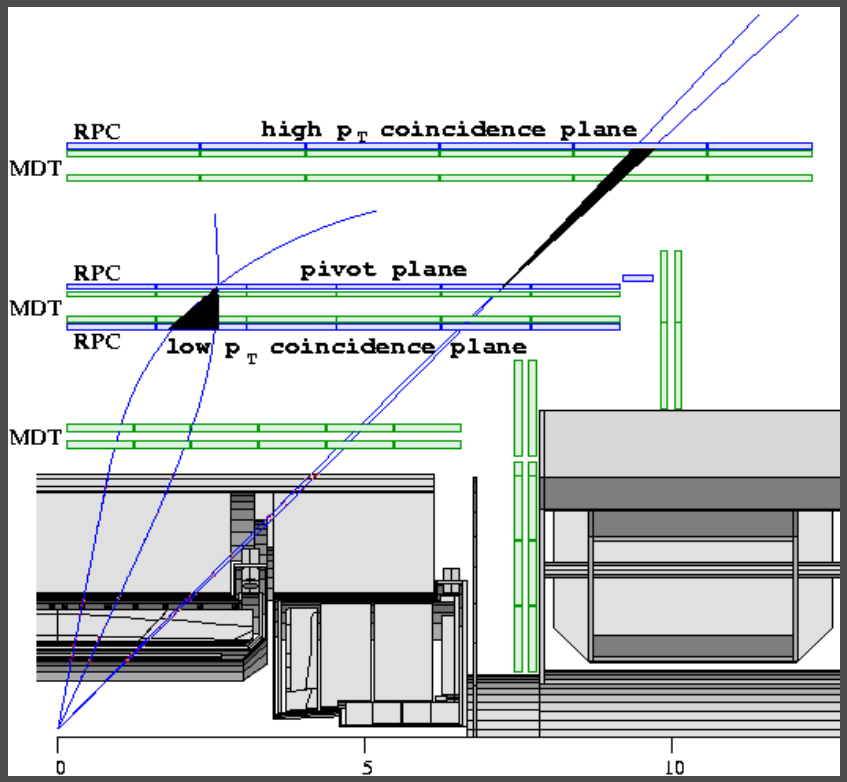
$E_T(\square) / E_T(\square) < HoE^{max}$

At least 1 $E_T(\square, \square, \square, \square) < E_{iso}^{max}$

Fine-grain: ≥1($\square\square\square\square$) > $R\ E_T^{min}$

→ Isolated "e/γ"

Example: ATLAS L1 μ trigger

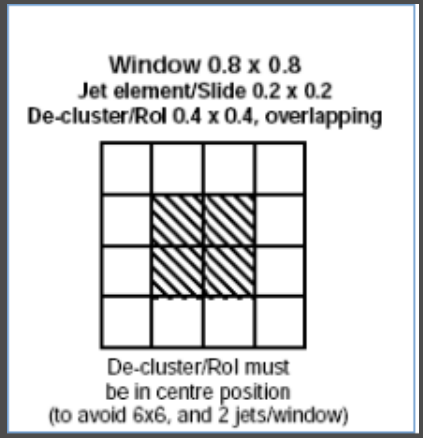


- Asume: track from primary interaction point
- 3 low p_T and 3 high p_T thresholds
- For each hit in pivot plane:
  - Search for muon tracks in a p_T interval around threshold value ⇔ coincidences in a region of the 1st/3rd planes
- Coincidences processed in parallel

Example: jet & τ triggers at ATLAS

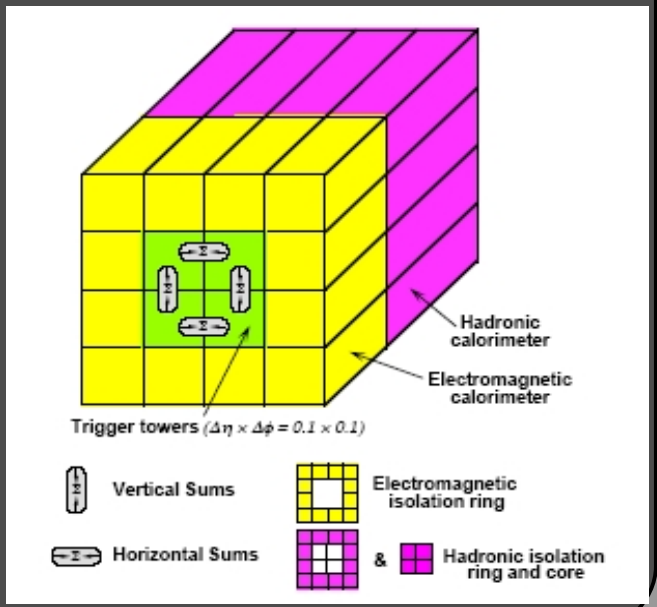
Jets

- Jet element: 0.2x0.2 in η,ϕ (sum in depth)
- Sliding window of 4x4 jet elements
- Conditions:
  - The central cluster is a local E_T maximum
  - The cluster passes E_T threshold



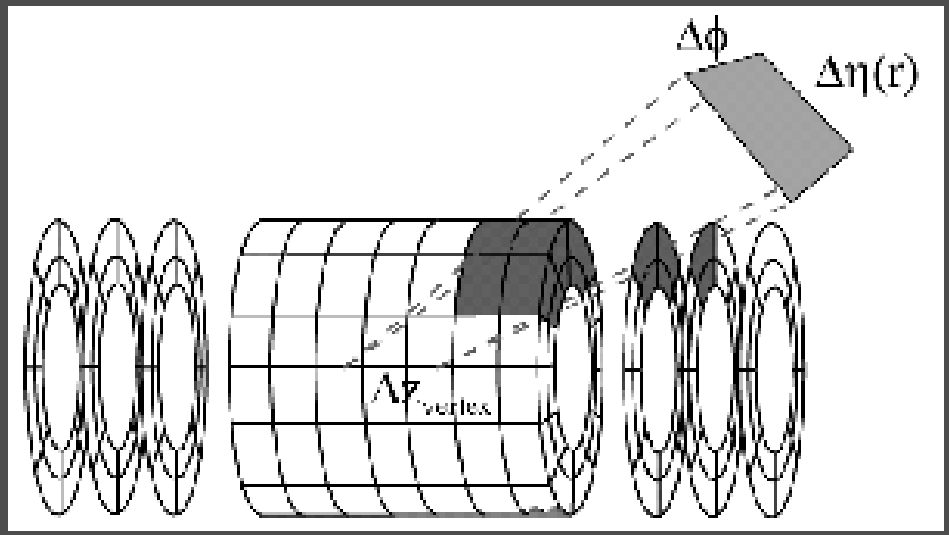
Tau:

- Calculates the following quantities & imposes thresholds
  - 2x1 towers energy sums (EM+Had): most energetic should pass E_T threshold
  - Had/EM isolation energies
  - Cluster center must be a local E_T maximum



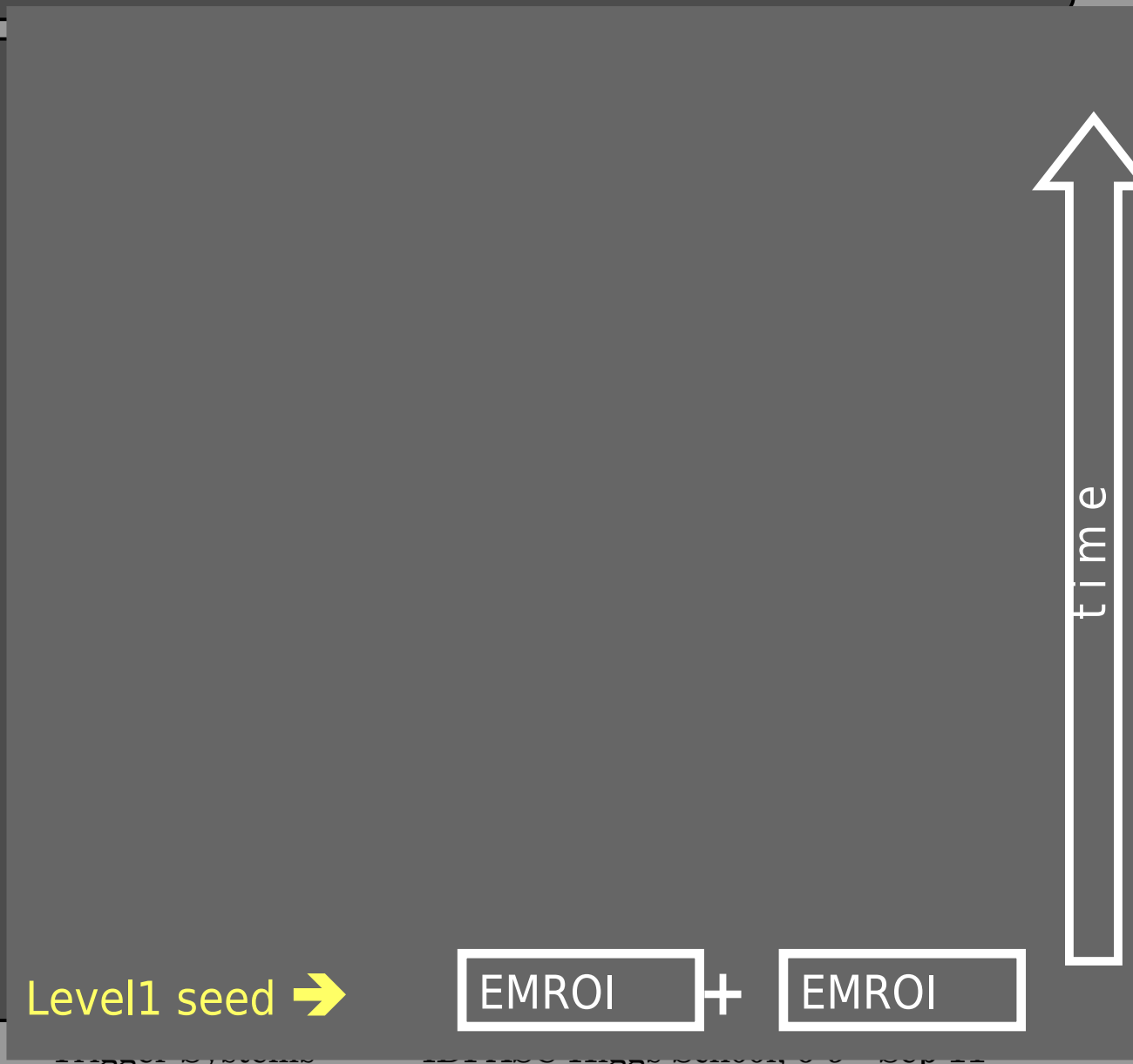
High level triggers

- More complex (offline-like) algorithms
  - If more than one: each level runs more refined (slower) algorithms
  - In some cases run offline algorithms directly
- Full granularity available
- Refined calibrations (usually not the final ones)
- Reconstruct Regions of Interest around L1 seed
  - In ATLAS: L2 uses RoIs
    but EF may use full event
    scan (for jets, E_T^{miss})



Early rejection

- Execute a sequence of algorithms
  - Validate step by step
  - Confirm intermediate steps
  - Reject event as soon as possible
- Similar in ATLAS & CMS
  - Different implementations



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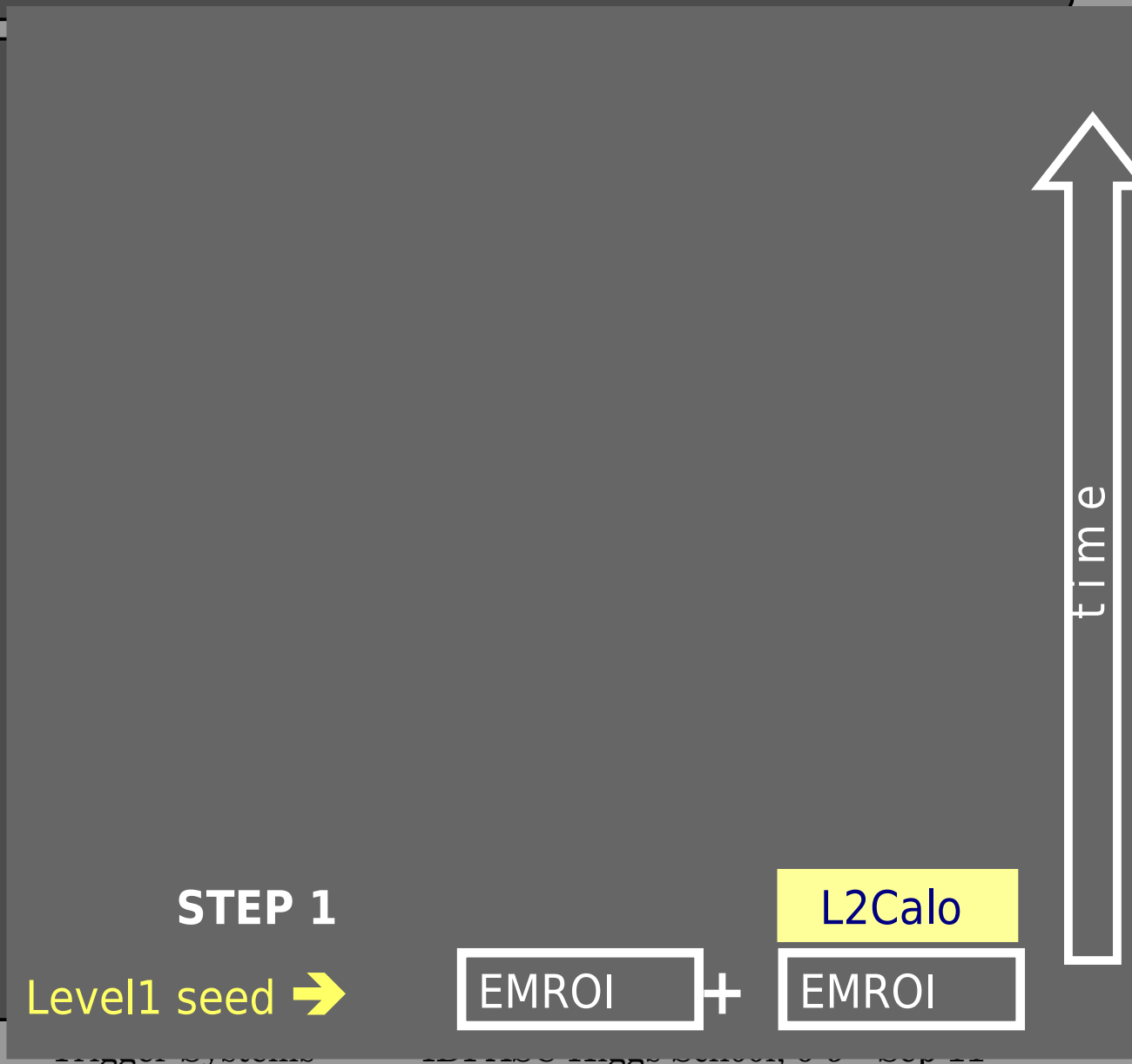

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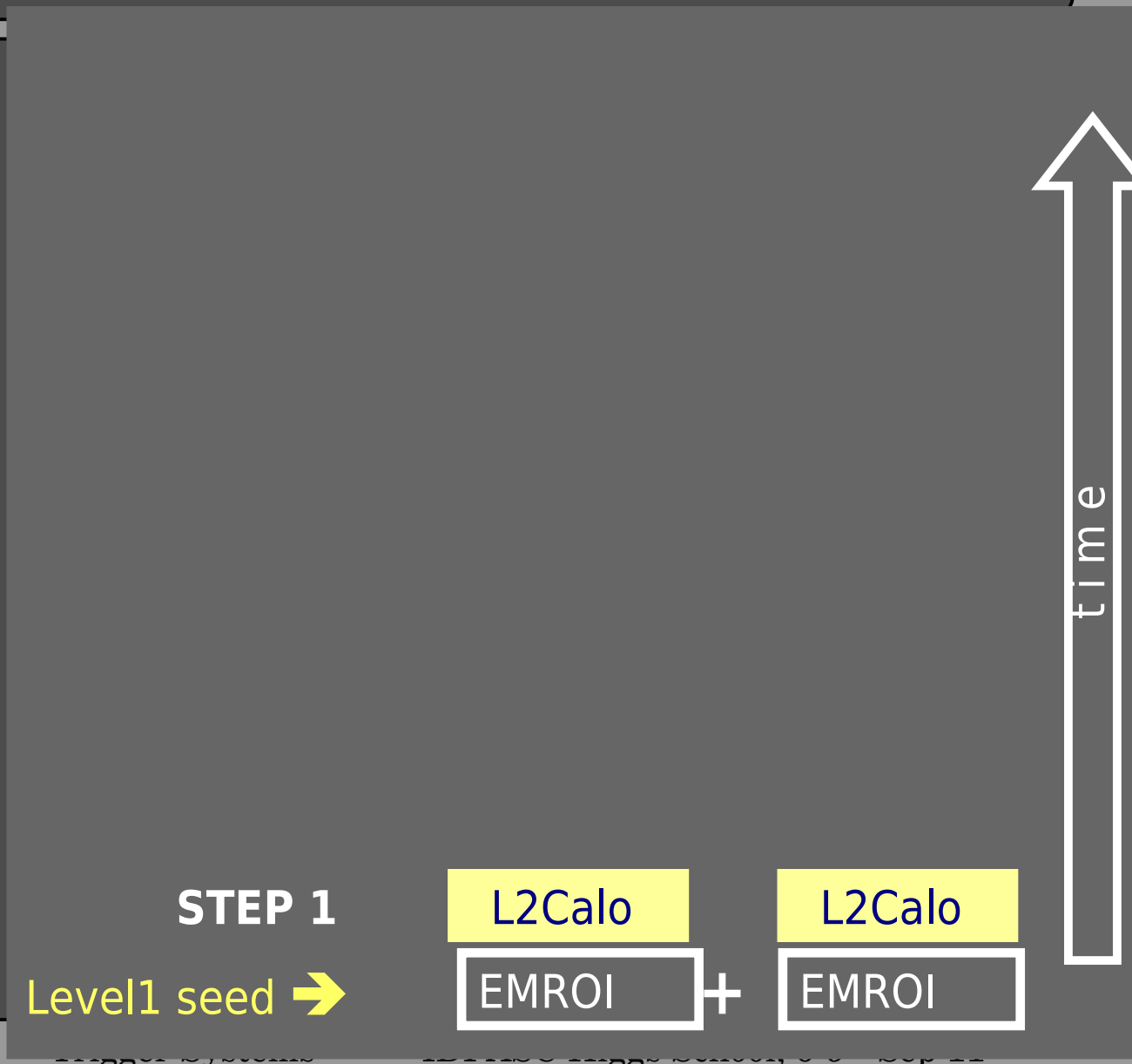

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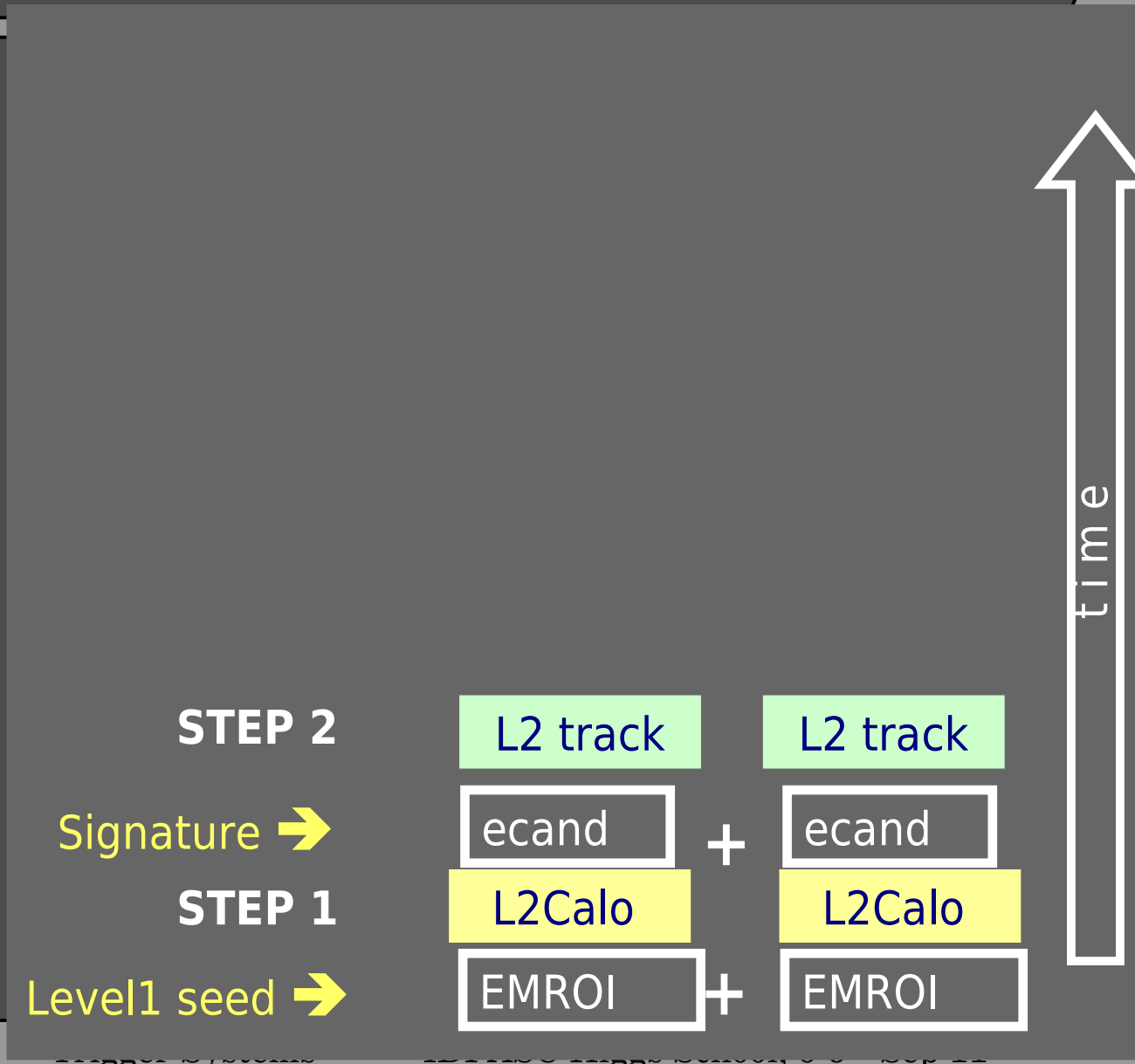

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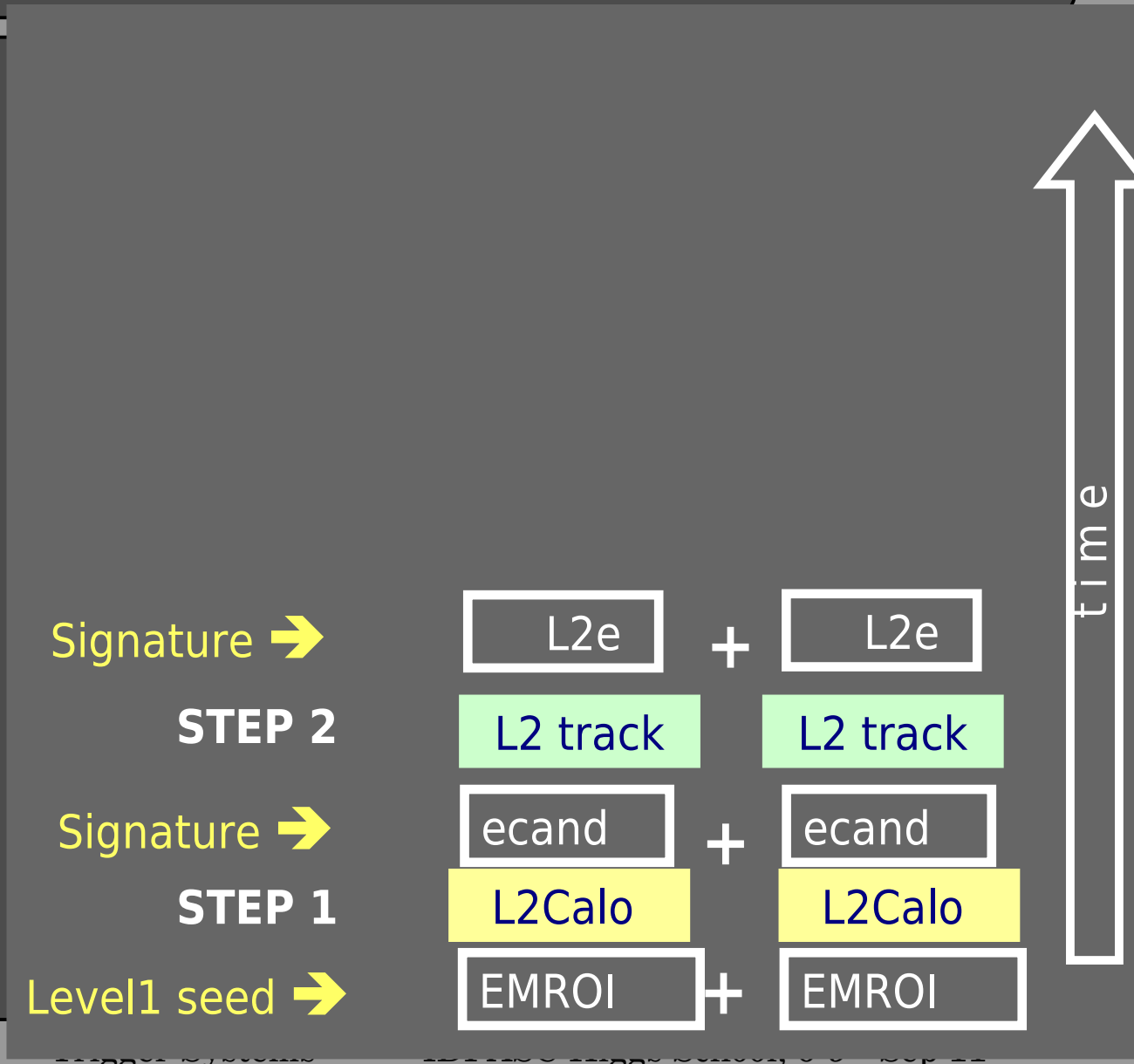

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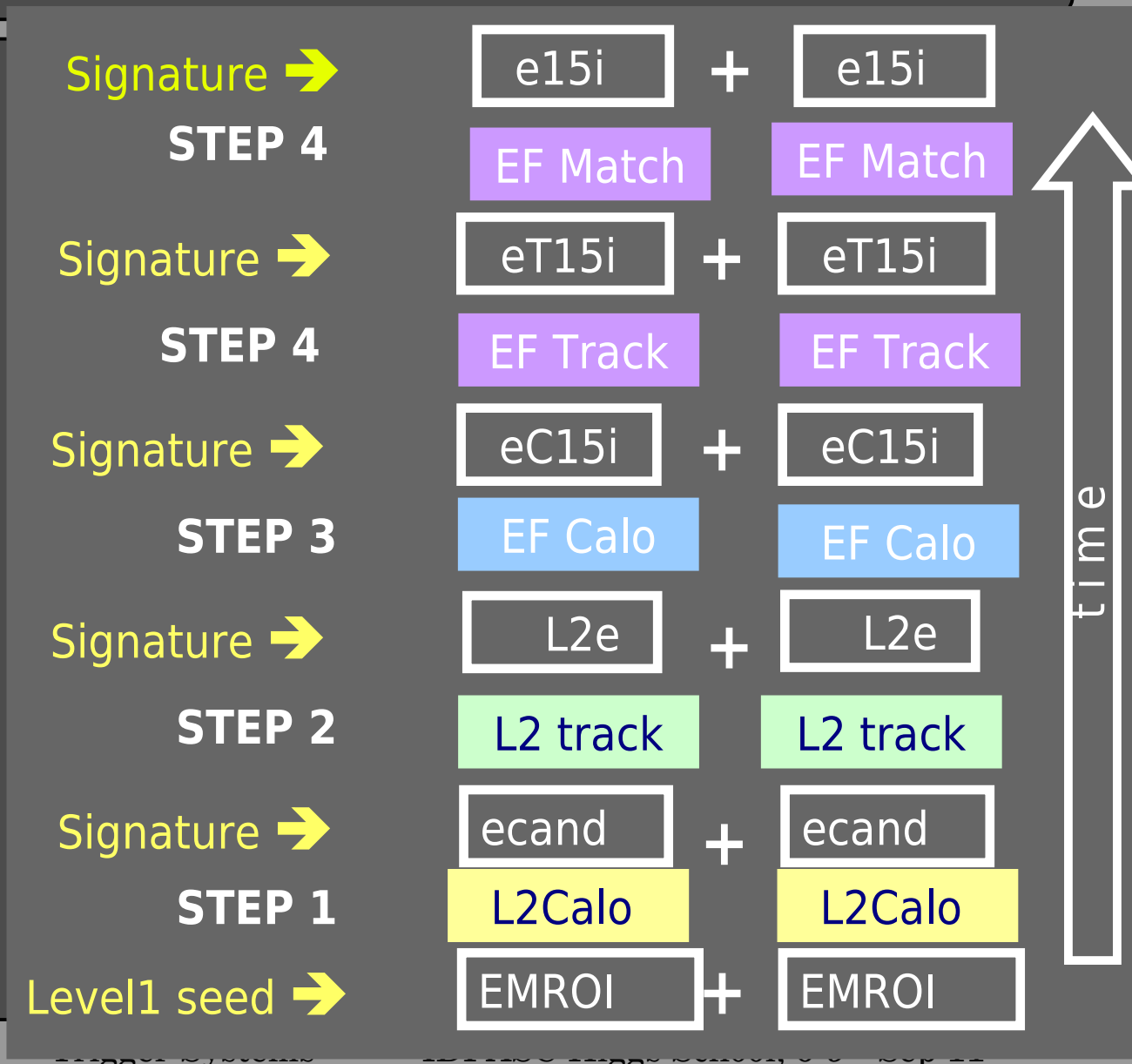
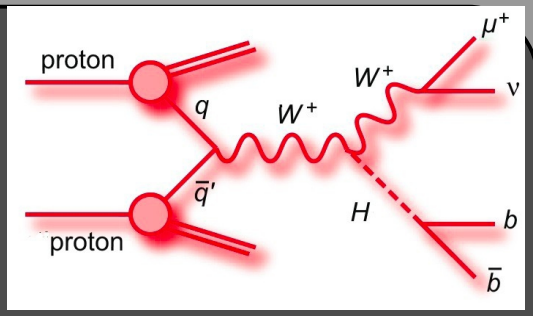


Trigger Menus

Trigger menu

- A trigger menu is the list of selection criteria
  - Each item is a trigger chain (or path) made of several criteria and E/p_T thresholds
  - An event is stored if one or more trigger chain criteria are met



Trigger	L1 Item	L1 Rate	L2 Rate	EF Rate
mu20				25
2mu10				3
2mu4_Jpsi/Upsilon/B mumu				15
e20_medium1				
2e12_medium	2EM7	4000		
e10_medium_mu6				
g80_loose				
2g20_loose				1.5
tau100_medium				3
2tau29_medium1	2TAU11	2500	30	4
tau29_medium_xs80				4
tau29_loose_xs45_3J10				8
tau16_loose_e15_tight				3
tau16_loose_mu15				5
j75_xe55	J50_XE20	500		
ht400				
j250				
fj100				

Lepton triggers for: SM(W,Z,top etc..), H->WW/ZZ, Exotics (Z',W'), SUSY

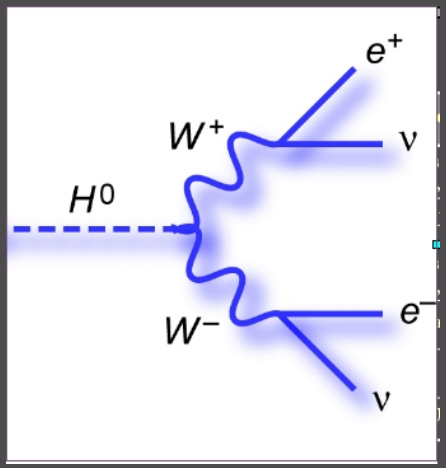
Low mass di-muon trigger for B-physics

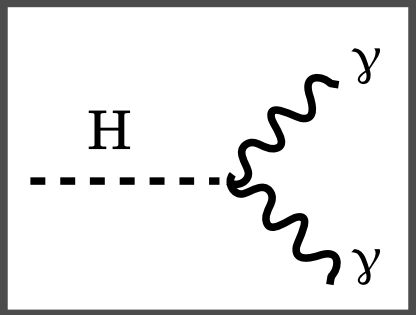
Photon triggers for: H->gamma gamma, exotics, SM (direct photon)

Tau for: Z->tau tau, H->tau tau, SUSY Higgs

SumEt and MissingEt for SUSY

Jets + b-Jet for SUSY, exotics (q*), SM (jet measurements), top



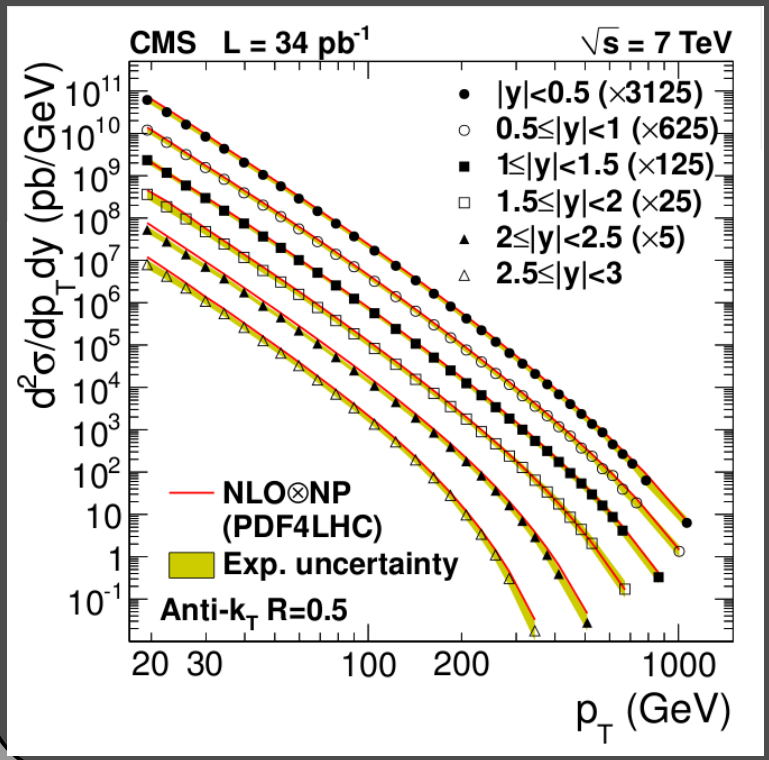


Trigger menu

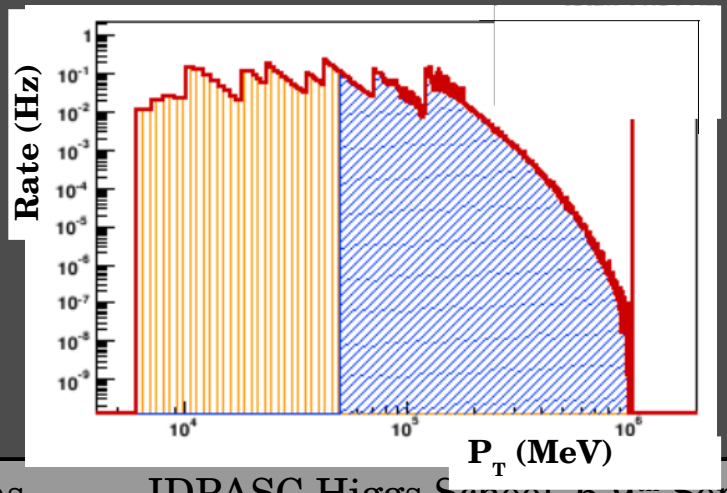
- A good trigger menu is essential for physics analysis
  - Multiple triggers needed for the same analysis
  - Triggers for monitoring, calibration and control samples
- If necessary triggers are not foreseen in advance, data is lost!
  - Implies involvement of all communities: physics, detectors, performance, ...
- ATLAS/CMS are multipurpose experiments
  - Inclusive: select expected and unexpected events!
- Trigger efficiency measurement is ensured by redundancy of selections
- The list must be flexible to face variations of the environment
  - Luminosity, detector problems, ...
- Fixed bandwidth: balance of different interests

Prescales

- When the rate becomes too large:
  - Increase thresholds
  - Prescale: only 1 out of X accepted events is indeed kept
- Example: jet trigger:



- σ_{jet} falls 10 orders of magnitude!
- Need jets in all p_T bins
- Several thresholds with different prescales

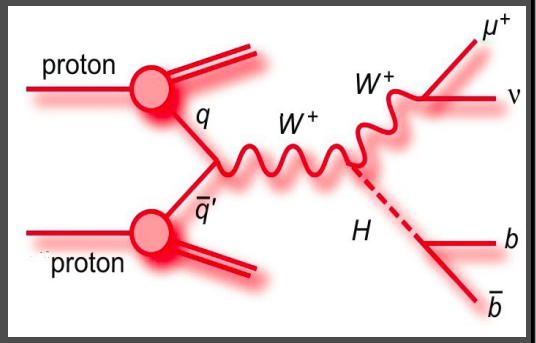


Understanding the trigger system: performance measurements

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

$$\sigma \cdot BR = \frac{N_{cand} - N_{backg}}{A \cdot \epsilon_{total} \cdot \int Ldt}$$



$$A \cdot \epsilon_{total} = A \cdot \epsilon_{Track} \cdot \epsilon_{Muon} \cdot \epsilon_{L1-Trig} \cdot \epsilon_{L2-Trig} \cdot \epsilon_{L3-Trig} \cdot \epsilon_{Analysis}$$

Efficiency = fraction of the interesting events that pass the trigger

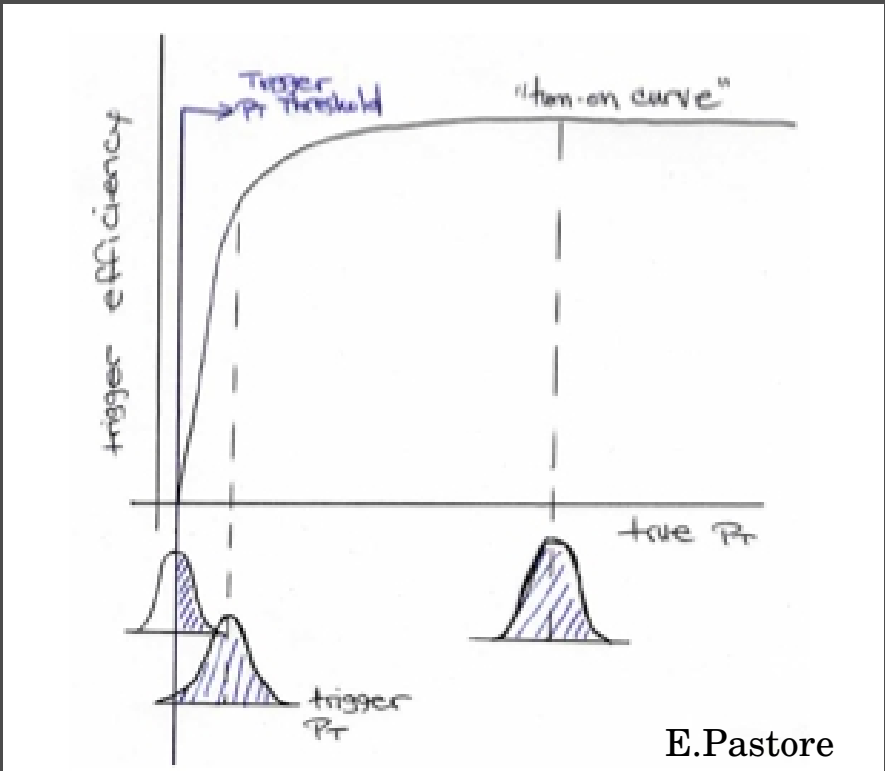
- Methods to measure efficiency
  - Orthogonal trigger
  - Bootstrap
  - Tag and probe

Trigger turn on curves

- Finite p_T resolution
  - worst at level-1 due to coarse granularity, dpT/pT~1%
- the efficiency is a function of the real p_T

- Turn on curve = trigger efficiency as a function of the true p_T, measured with the offline reconstruction

- The trigger efficiency is a function of η, ϕ, pT, run #, ...



E.Pastore

Trigger efficiency measurements

Orthogonal triggers:

- Use triggers that look at different detector information from the one under study. Example
  - Muon trigger + close track activity to measure jet calorimeter trigger efficiency
    - This sample will be biased towards more heavy-flavor jets (from b-hadron semileptonic decay) than light-quark jets; may be what you want!
    - or it is a possible pitfall if not what you want, and measure the incorrect trigger efficiency

Random triggers, minimum bias triggers

- Select events just requiring some detector activity
- Only work for objects with very large cross sections

Pass-through:

- Run your trigger to flag events but not to select
- Useful for the HLT efficiencies

Tag and probe method

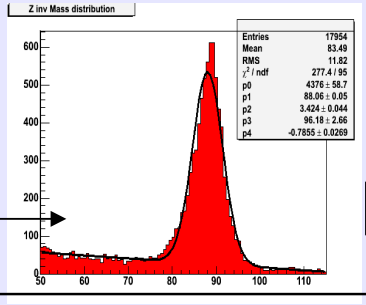
- Identify a resonance decaying to the particle we want to study (ej. $J/\psi \to \mu\mu$, $Z \to \mu\mu$, $Z \to ee$, $K_s^0 \to \pi\pi$, $\Lambda \to Kp$, ...)
  - Resonance products should have a p_T close to the one we want to study
- Impose conditions on one of the daughter tracks
  - Clean up background
  - Count number of decays (fit to a mass peak)
- Use the other daughter track as unbiased particle for testing
  - Impose selection requirements and count number of decays after selection
- The efficiency can be extracted from the total number of resonance particles reconstructed before and after

Example: e trigger efficiency

Determine electron trigger efficiencies with real data using a Z→ee sample

a) Run the HLT. Store events offline. Determine the number of Z by a fitting procedure (after reconstruction).

SINGLE TRIGGER : e25i

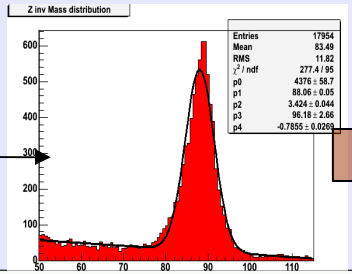
Trigger → offline → 

-Diagnostic sample-

N_1^Z events

b) Tag (online) the events with 2 or more clusters satisfying the e25i cuts

DOUBLE TAG: 2e25i

Trigger → offline → 

-Tagged sample-

N_2^Z events

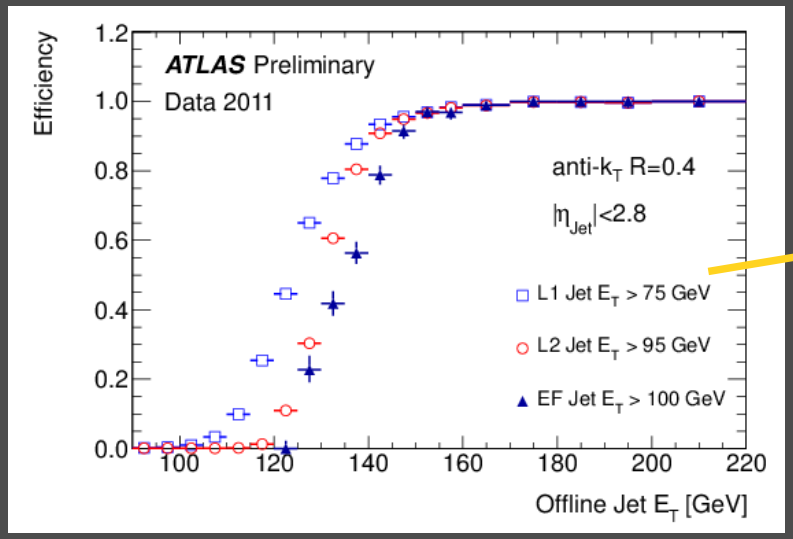
$$N_1^Z = \varepsilon_z^{rec}(2\varepsilon_e^{trig} - \varepsilon_e^{trig\,2})N_0^Z + B_1$$

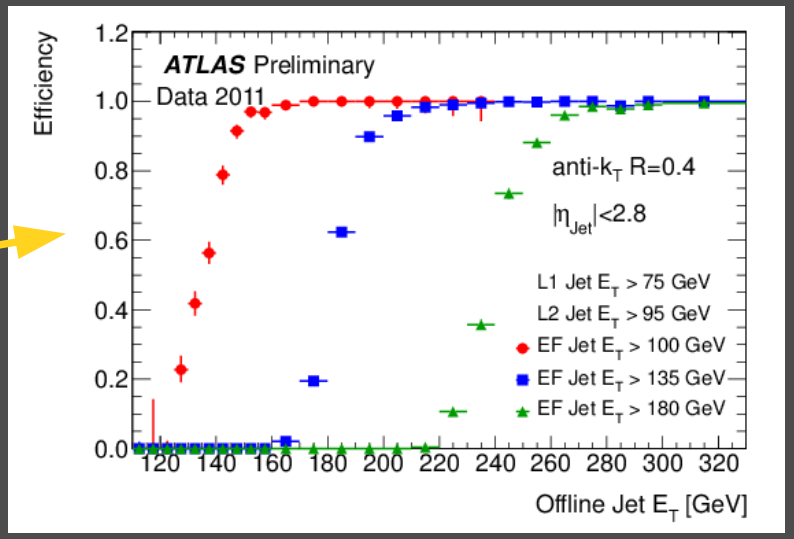
$$N_2^Z = \varepsilon_z^{rec}\varepsilon_e^{trig\,2}N_0^Z + B_2$$

$$\varepsilon^{trig} = \frac{2(N_2^Z - B_2)}{(N_2^Z - B_2) + (N_1^Z - B_1)}$$

Bootstrap method

- Use less restrictive trigger sample to determine efficiency of more restrictive one
  - Example from ATLAS: use a lower jet trigger chain to study the efficiency of other jet triggers with higher threshold





  - Be careful: ensure your trigger has reached the plateau to have an unbiased selection

Conclusions and remarks

- Trigger systems are necessary to select the interesting events from the non-interesting ones in real time
  - Reduce the rate to manageable value
- The LHC extreme conditions impose difficult challenges to the detectors and Trigger/DAQ systems
- Trigger systems should be flexible to select even unknown interesting signals and adapt to the detector conditions
  - Trigger menus
  - Different trigger levels: faster (simpler)--> slower (elaborated)
- The trigger system introduces biases in the analysis
  - Important to ensure that available triggers are adequate for you analysis
  - Measure the trigger efficiency accurately

Acknowledgements

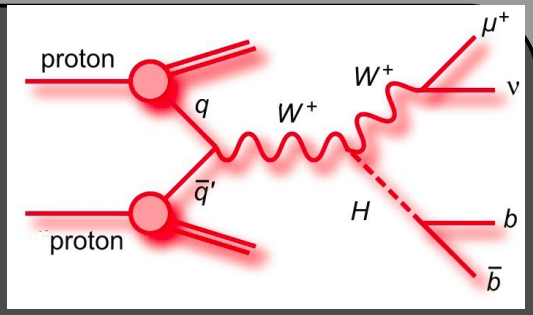
Material

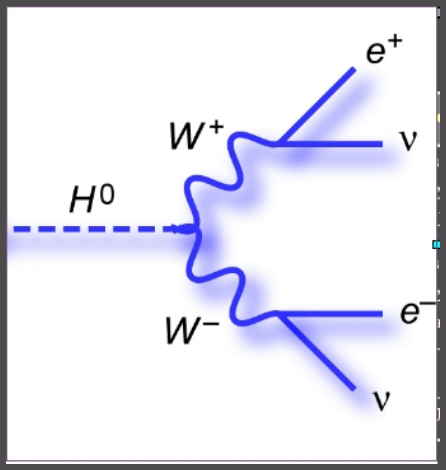
- Preparing these slides I took material from:
  - E. Pastore, ISO TDAQ School 2010, Ankara.
  - P. Sphicas, SLAC Summer Institute, 2006.
  - I. Ahmed, First School on LHC Physics, 2009.
  - R. Van Kooten, Hadron Collider Physics Summer School, 2010, Fermilab.
  - J. Boyd, Hadron Collider Physics Summer School 20011, Geneva.

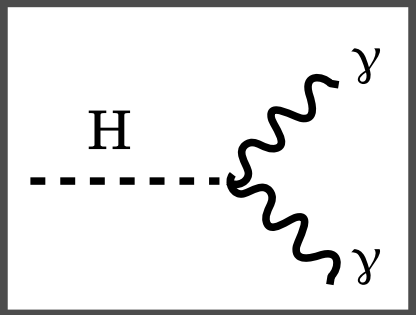
Trigger signatures

- Inclusive signatures: high p_T objects

Object	Examples of physics coverage
Electrons	Higgs , new gauge bosons, extra dimensions, SUSY, W, top
Photons	Higgs, extra dimensions, SUSY
Muons	Higgs , new gauge bosons, extra dimensions, SUSY, W, top
Jets	SUSY, compositeness, resonances
Jet+missing E_T	SUSY, leptoquarks
Tau+missing E_T	Extended Higgs models, SUSY

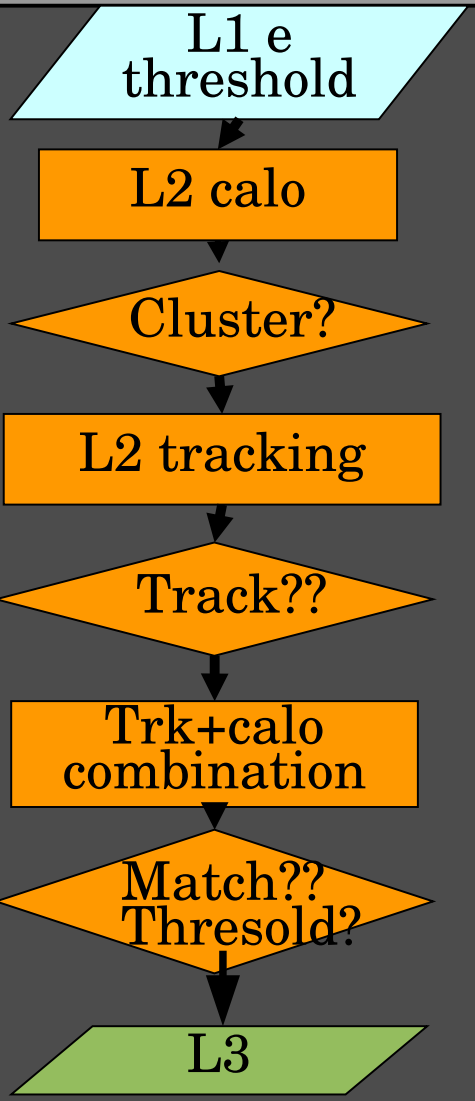






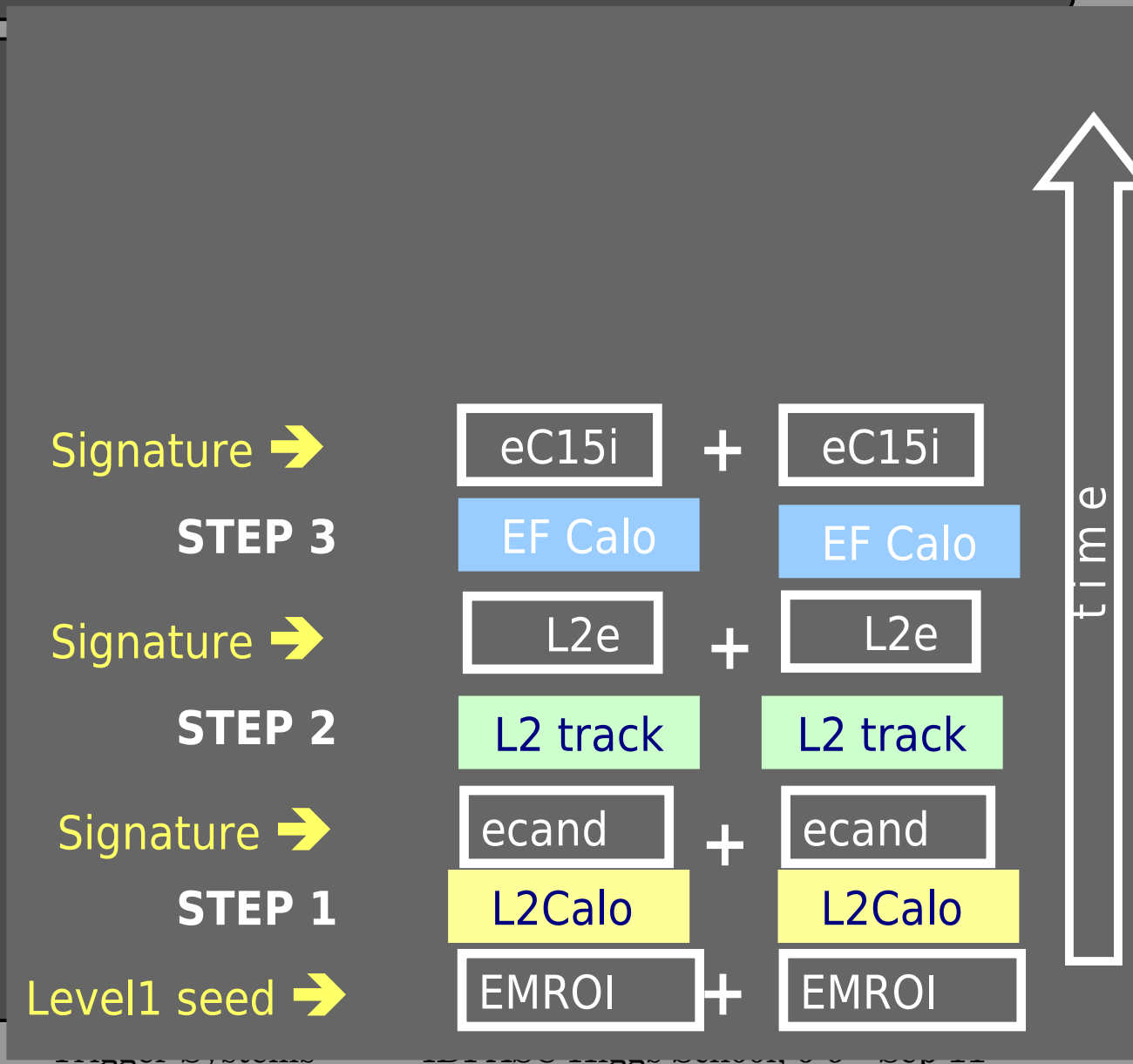
Trigger chain

- Trigger chain
  - Made of several steps at different levels
  - Reconstruction of variables
  - Conditions and E/p_T thresholds
- Use properties of the object to identify it from the background



Early rejection

- Execute a sequence of algorithms
  - Validate step by step
  - Confirm intermediate steps
  - Reject event as soon as possible
- Similar in ATLAS & CMS
  - Different implementations



LHC Status

2011 data taking

- Integrated luminosity: 2.55 fb^{-1} recorded at ATLAS
  - Luminosity used in the H→bb analysis: 1.04 fb^{-1}
- Peak luminosity: 2.37×10^{33} $cm^{-2}s^{-1}$
- Average pile-up: $\langle\mu\rangle = 6.2$
- Continue run till end 2012. Then shutdown for upgrade