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LVL1 trigger systems for LHC experiments

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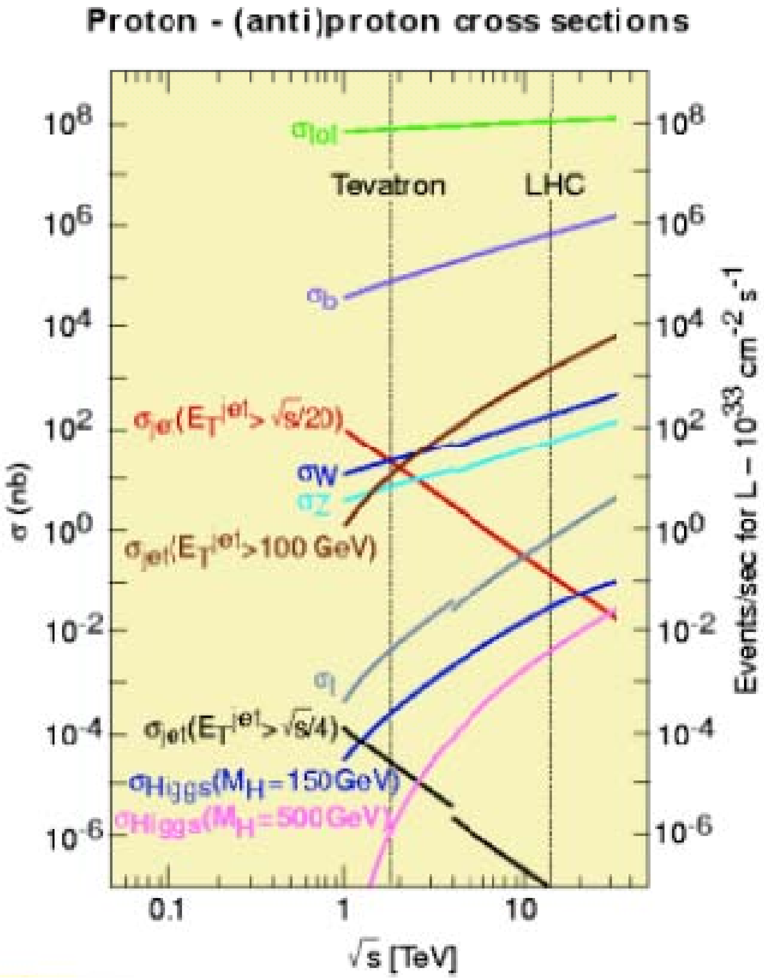
Thanks to M. Dellavalle and A. Satta

outline

- LHC requirements
- ATLAS and CMS LVL1 trigger strategy
  - Calorimeter trigger
  - Muon trigger
- Some notes on LHCb

Global requirements



- p-p collider √s= 14 TeV
- Bunch crossing rate 40 MHz (**25 ns bunch spacing**)
  - 80% of bunched will be filled, effective bunch crossing rate 32 MHz
- Two luminosity scenarios:
  - Low Luminosity: L=2x10^{33} first 2 years after start-up, 10 fb^{-1}/year
  - High Luminosity: L=10^{34} 100 fb^{-1}/year
- Average interactions per bunch crossing: 17.3 for HL and 3.5 for LL
  - **10^9 Hz collision rate**
- Total non-diffractive cross section ~ 70 mb
- Huge range of cross-sections and rates (HL)
  - B production 0.7 mb – 7 10^6 Hz
  - W/Z production 200/60 nb – 2/0.6 kHz
  - Top 0.8 nb – 80 Hz
  - Higgs (150 GeV) 30 pb – 3 Hz

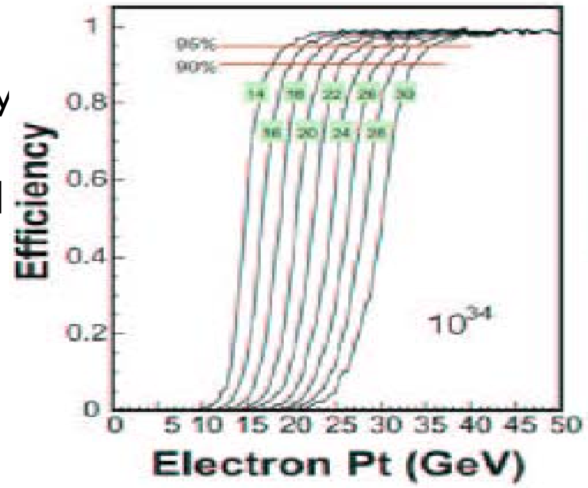
Level 1 trigger strategy

Objects	Physics Measurments	Trigger chains	
electrons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top	**e25i, 2e15i**	**~20 kHz**
photons	Higgs (SM, MSSM), extra dimensions, SUSY	**γ60i, 2γ20i**	
muons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top	**μ20i, 2μ10**	**~10 kHz**
Jets	SUSY, compositeness, resonances	**j400, 3j165, 4j110**	**~200 Hz**
Jet + missing E_T	SUSY, leptoquarks	**j70 + xE70**	
Tau + missing E_T	Extended Higgs models (e.g. MSSM), SUSY	**τ35 + xE45**	**~500 Hz**

- Selection is based on inclusive high pT physics, with low multiplicity (single/di-objects)
  - SM physics overlap with Tevatron and "known" NP (MSSM)
  - Sensitive to unpredicted new physics
- Allow reasonable safety factors in the accepted rates to account for physics (cross-sections, cavern and other bkg) and detector (performance) uncertainties
- Must ensure rates for monitoring and calibration/energy scale
  - Instrumental and physics bkg (cavern and others not completely known)
  - Detector efficiency from data
  - Selection algorithm performances

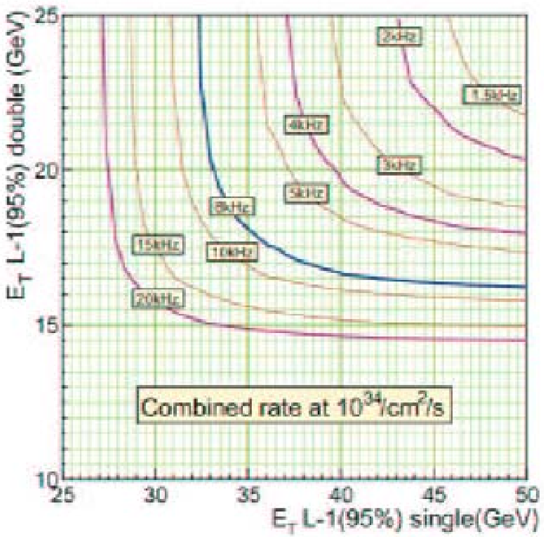
L1 bandwidth optimization

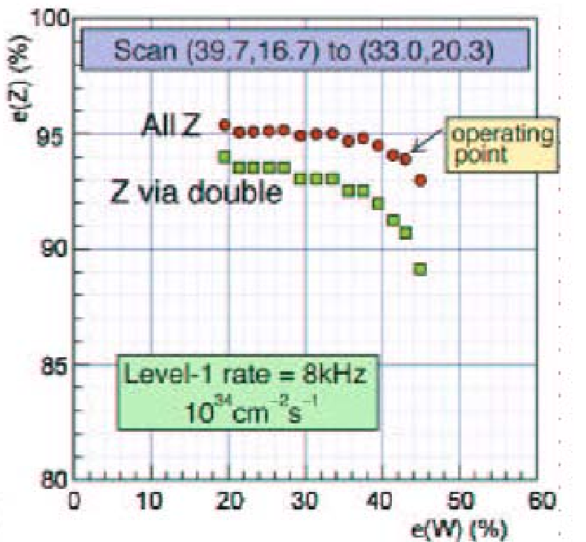
- Allocation of bandwidth across different objects
  - Equally divided across e/γ, mu, tau-jets and comb-jets
  - SF=3: Low Luminosity 4 kHz/obj, 8 kHz High Luminosity



- Turn-on curves: effective requirements on pT defined as the value at which L1 trigger is 95% efficient

- Determination of thresholds for single/double objects
  - Optimal operating point must be chosen in the single vs double space at given rate. Based on efficiency optimization (e/mu/tau, no jets)





Example for e/γ trigger using W->eν vs Z->ee

Example of L1 trigger tables

Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
inclusive isolated electron/photon	29	3.3	3.3
di-electron/di-photon	17	1.3	4.3
inclusive isolated muon	14	2.7	7.0
di-muon	3	0.9	7.9
single τ jet	86	2.2	10.1
di-τ-jet	59	1.0	10.9
1-jet, 3-jet, 4-jet	177, 86, 70	3.0	12.5
jet * E_T^{miss}	88 * 46	2.3	14.3
electron * τ-jet	19 * 45	0.8	15.1
minimum bias (calibration)		0.9	16.0
TOTAL			16.0

Low luminosity trigger table

Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
inclusive isolated electron/photon	34	6.5	6.5
di-electron/di-photon	19	3.3	9.4
inclusive isolated muon	20	6.2	15.6
di-muons	5	1.7	17.3
single τ-jet trigger	101	5.3	22.6
di-τ-jets	67	3.6	25.0
1-jet, 3-jets, 4-jets	250, 110, 95	3.0	26.7
jet * E_T^{miss}	113 * 70	4.5	30.4
electron * τ-jet	25 * 52	1.3	31.7
muon * τ-jet	15 * 40	0.8	32.5
minimum bias (calibration)		1.0	33.5
TOTAL			33.5

High luminosity trigger table

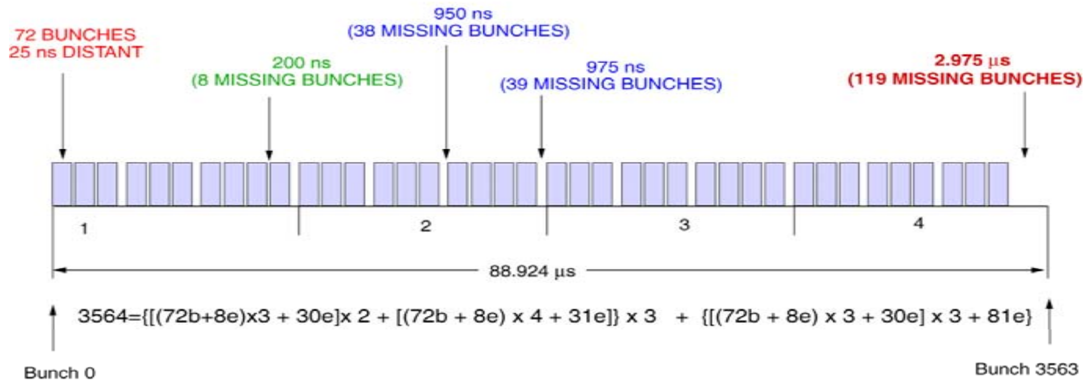
- Thresholds at which efficiency of the trigger il 95% of its maximum value
- 1 kHz allocated to minimum-bias events which will be used for calibration and monitoring
- Only muon trigger has low enough threshold for B physics (B->μμ)

CMS latest results dec. 2006

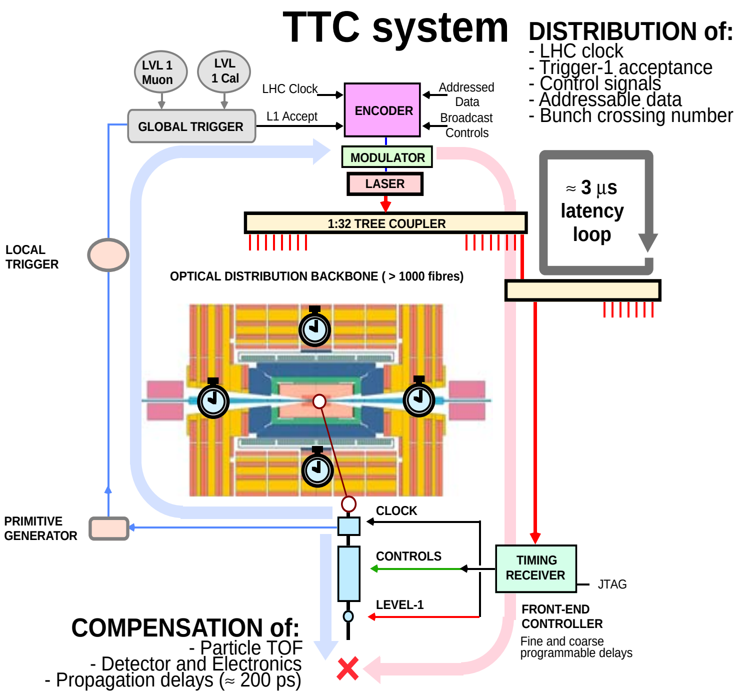
LHC Level-1 systems requirements

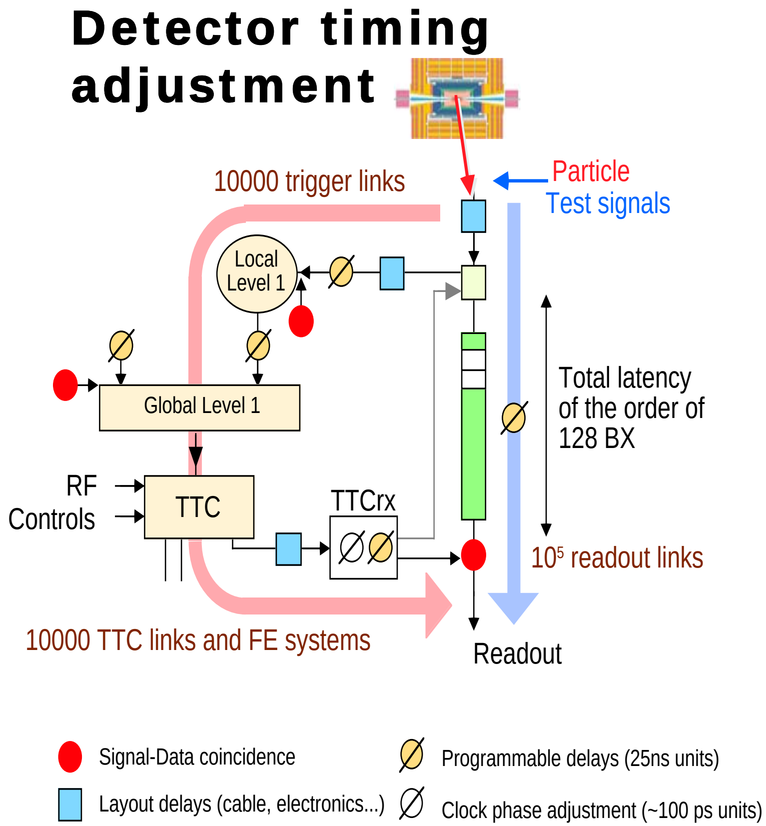
- Rate reduction of 10^4-10^5
- Data identification with Bunch Crossing Number (absolute synchronization)
  - Logic decisions are taken by custom hardware systems (FPGAs and ASICs) @40 MHz
  - Data held in pipelines, with a fixed latency
  - Fast dectector responses and data movement
- BC identification is crucial
- Redondance of selection criteria (“trigger menus”) leads to high trigger efficiency and the possibility to measure it from the data
- Must be sufficiently flexible to face possible variations of LHC luminosity, one order of magnitude at least
  - Event characteristics vary with luminosity, due to changings in pile-up, so it's not a simple events rescaling but events with different number of muons, clusters,... must be managed

LHC bunch structure



Trigger timing and adjustment

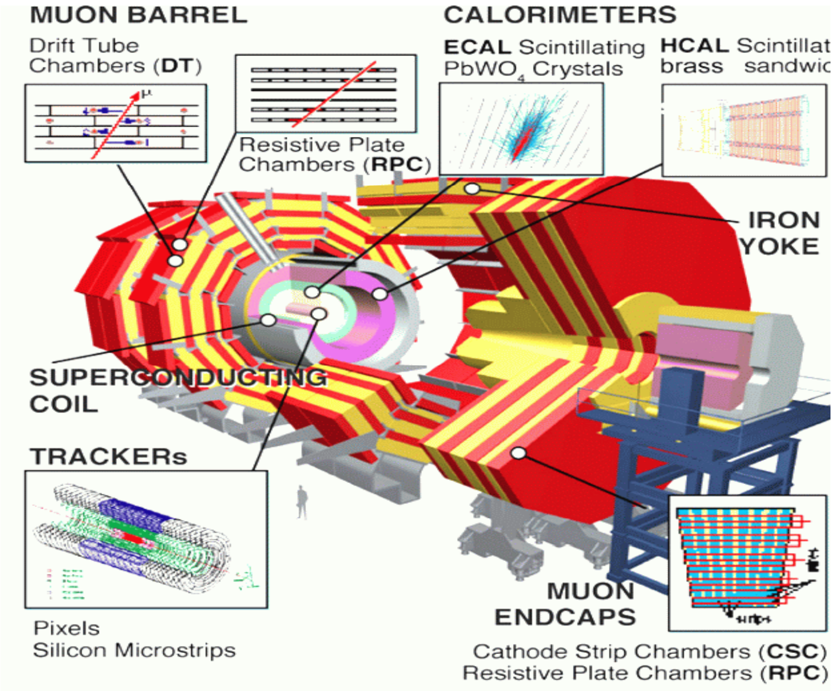


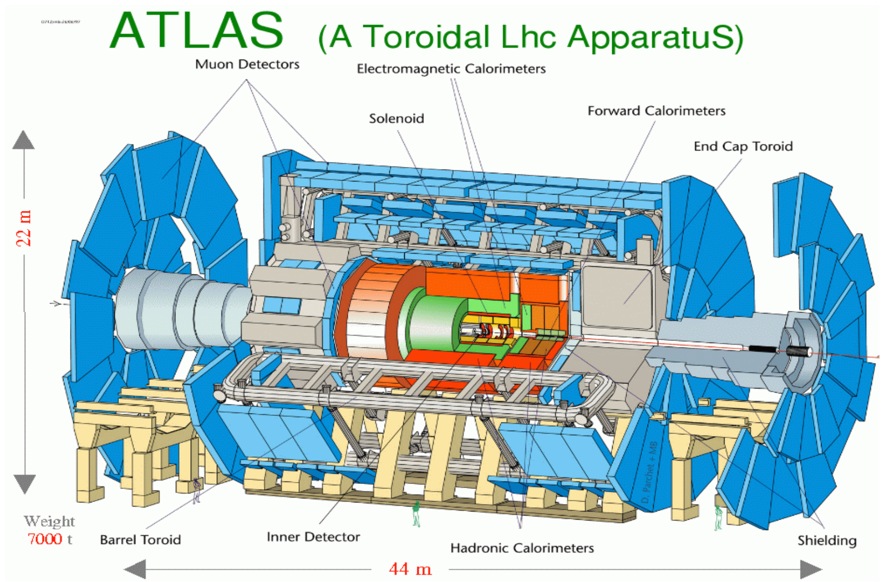


- signals propagated in all the system (TTC system)
  - Bunch Crossing Number
  - Level 1 Accept Number
- Synchronization
  - Detector pulse w/collision at IP
  - Trigger data w/readout data
  - Different detector trigger data w/each other

ATLAS/CMS: design principles

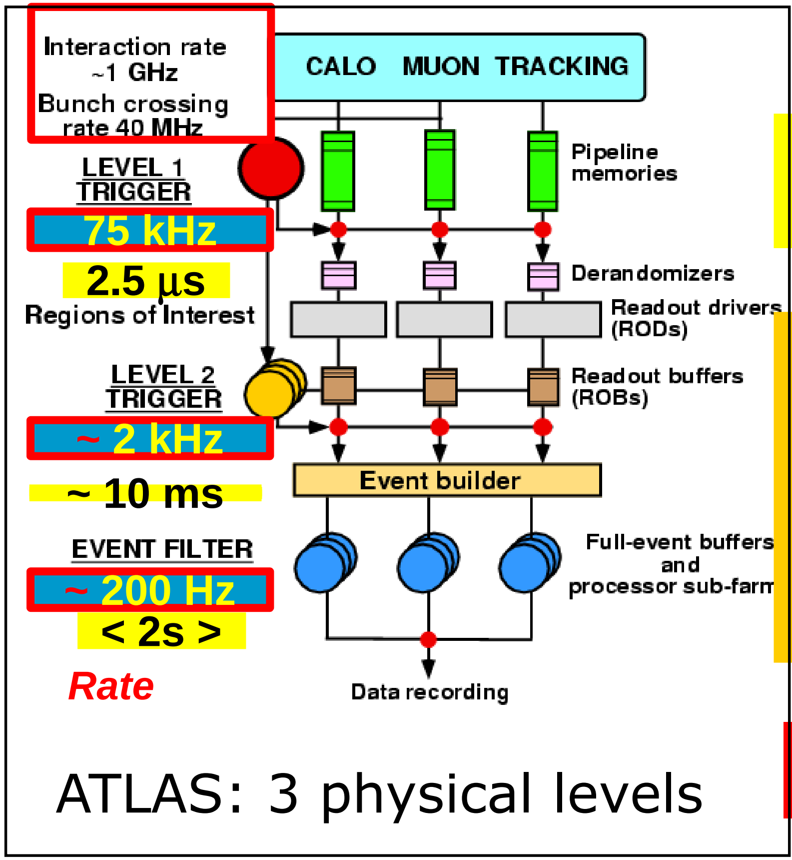
- Magnetic field structure
  - ATLAS: 2 Tesla solenoid + Toroids (barrel + 2 end-cap)
  - CMS: 4 Tesla solenoid
- Muon system
  - ATLAS: air-core toroid, minimizing MS, fast dedicated trigger detectors (RPC/TGC, 10 ns)
  - CMS: focus on high bending, instrumented return yoke, 2 independent trigger systems
- Calorimetry: sampling/homogenous
- Trigger architecture
  - ATLAS: minimizes data flow across levels and use of multi-tier Trigger/DAQ architecture
  - CMS: invests on commercial technologies for processing and communication (Terabit/s networks)





ATLAS/CMS: Trigger overview

- Different division of resources for processors and bandwidths



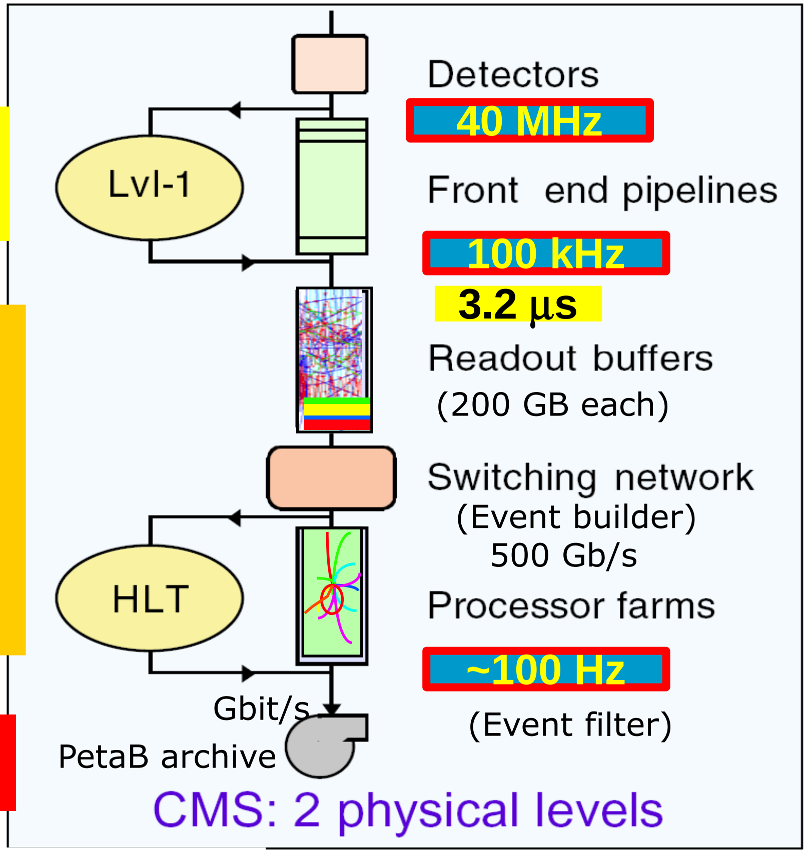
Level-1

Hardware

High Level Triggers (HLT)

Software

Event: 1 MB (1 TB/day)



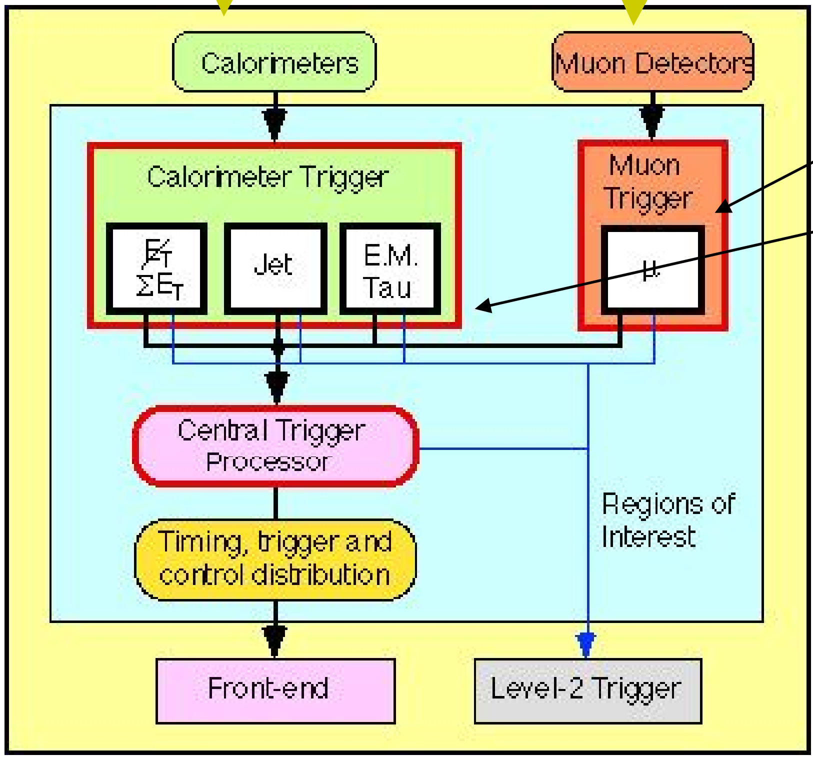
Region of interest: 2/event

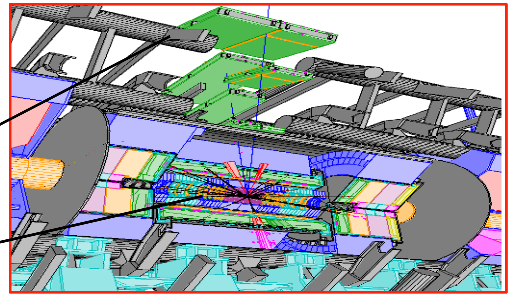
HLT partial event reconstruction

ATLAS: level 1 trigger

ECAL:Liquid Argon
HCAL:Tile/LAr

Barrel: RPC
Endcap:TGC





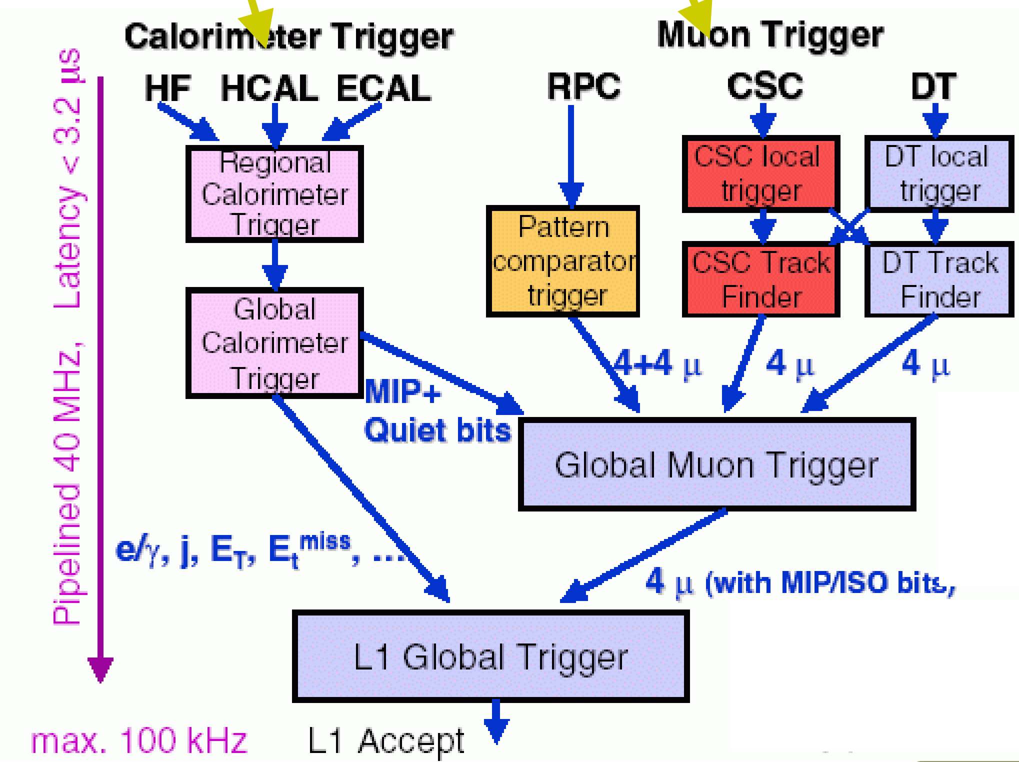
CTP makes the final decision based on multeplicities, using pT thresholds and global energy variables

- Accept calo+muon region-of-interest of each candidate found and their multiplicity
- **256 trigger items**, combinations of one or more trigger inputs
- The dead-time generated after each L1A can be specified for each item

CMS level1 trigger

ECAL: lead-Tungstate Crystals
HCAL: sc+cupper absorber plates
HCAL Forward: sc+steel absorber plates

Barrel: Drift Tubes
EndCaps: Cathod Strip Chambers
Barrel + EndCaps: RPC (for BC identification)



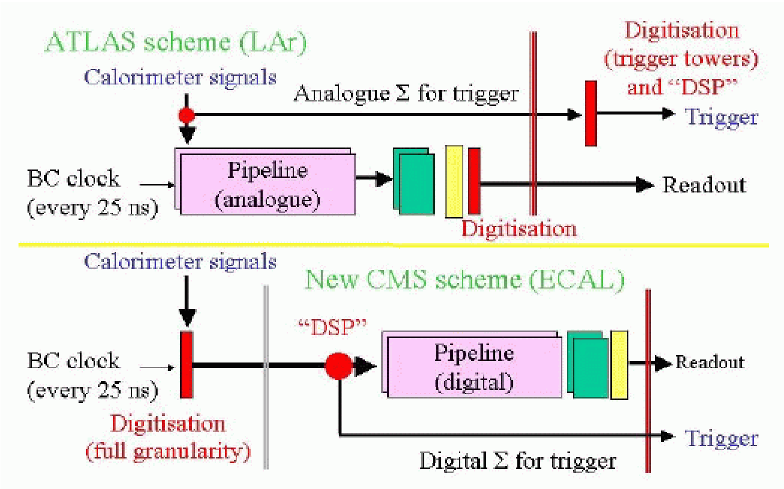
The Global Muon Trigger receives 4 muons candidate of maximum p_T, selects the best quality candidates (n.of hits, matched track segments, responses by the 3 detectors)
$\Delta\eta x \Delta\phi$ = 0.35x0.35 rad

The Global Calorimeter Trigger selects the best 4 e,γ (separately single and not), τ and jets. It calculates the total E_T and the E_T missing vector

The Global Trigger

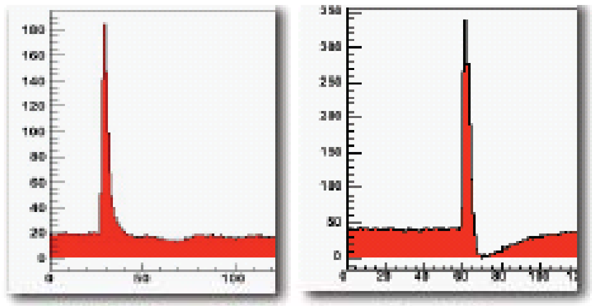
- Accepts calo+muon **sorted** objects
- Synchronizes matching sub-systems
- Computes up to **128 trigger** algorithms in parallel
- Global trigger objects includes eta-phi position, used by HLT to start reconstruction

ATLAS/CMS calorimeter trigger

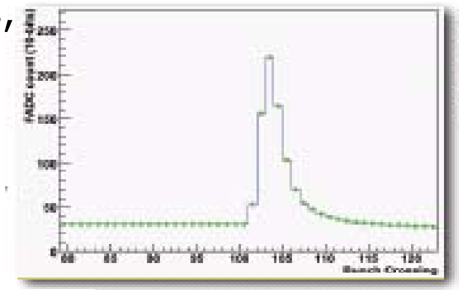


- **CMS**: on-detector electronics digitizes analogue signals, trigger towers formed off-detector by digital summation
- **ATLAS**, before digitization, a weight is applied to the pulse over bins of sinTheta to produce the approximate ET value (dynamic range of the energy pulse is reduced, 10-bit precision)

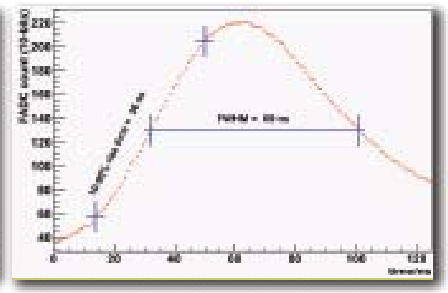
- Peak finder for **BC-identification**
- ET conversion using LUT: 8-bit ET, scaling is linear up to 255 GeV
- Dedicated processors apply the algorithms, using programmable thresholds
- **Sliding window** technique to find candidate tower
- Et is the **sum of ECAL and HCAL** contributions, in order to provide sharp turn-on curves with the true ET of the particles



TileCal and LAr signals at trigger

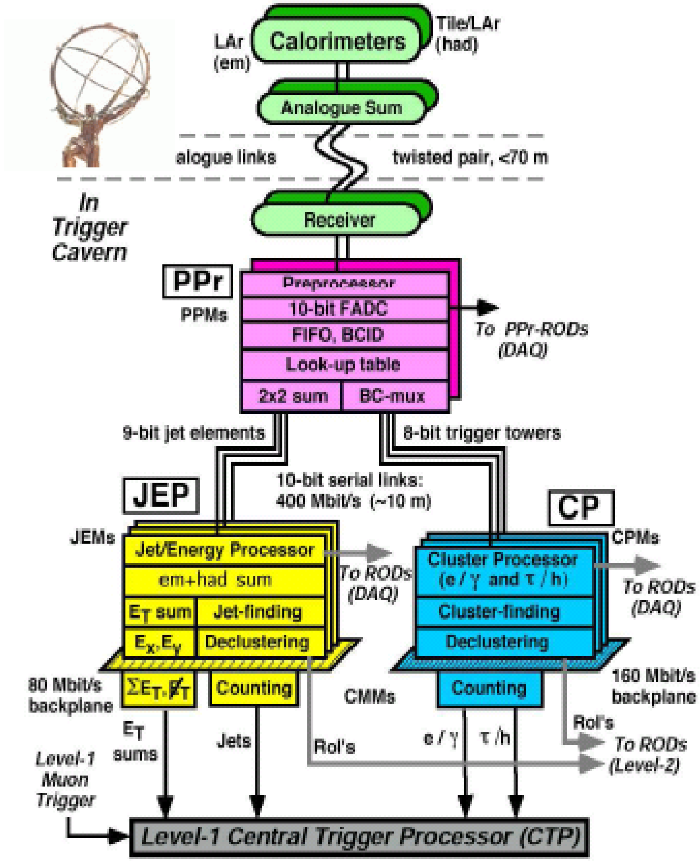


Pulse as digitised



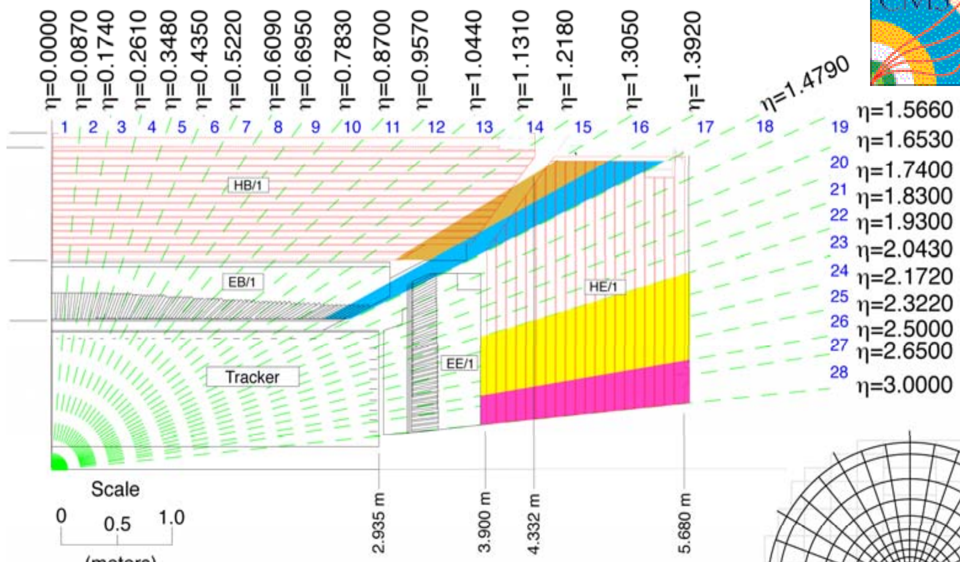
PPM 1-ns timing scan

Calorimeter trigger primitives



ATLAS

- ~7200 projective trigger towers
- Trigger towers $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
- ET summations: Acceptance coverage: $|\eta|=4.9$ (FCAL)
- 32 threshold bits + 3 multiplicity bits are sent to CTP



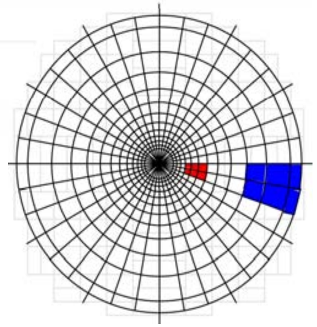
Segmentation (4176 trigger towers)

Barrel: 5x5 ECAL crystals towers $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$

EndCap: growing eta dimensions : 10 to 25 crystals per Tower

HCAL: follows the ECAL geometry

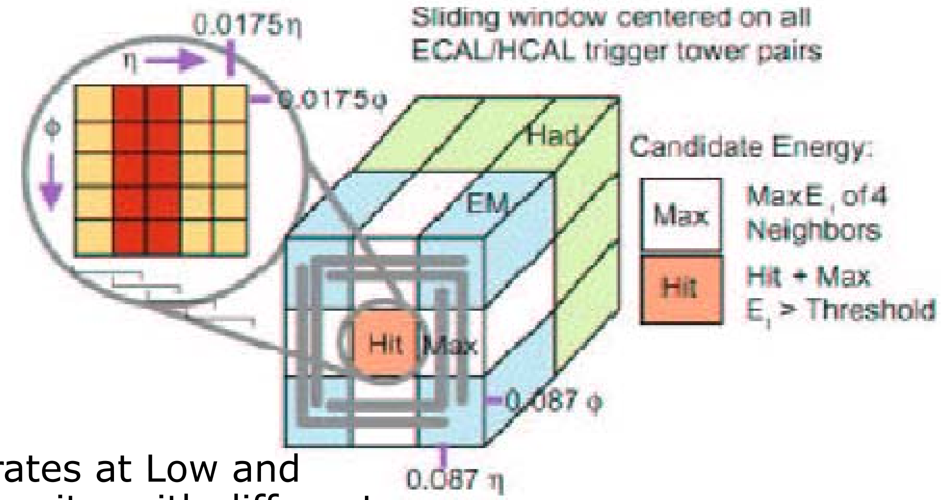
HF: used only for seamless jets and missing E_T, coarser segmentation in ϕ



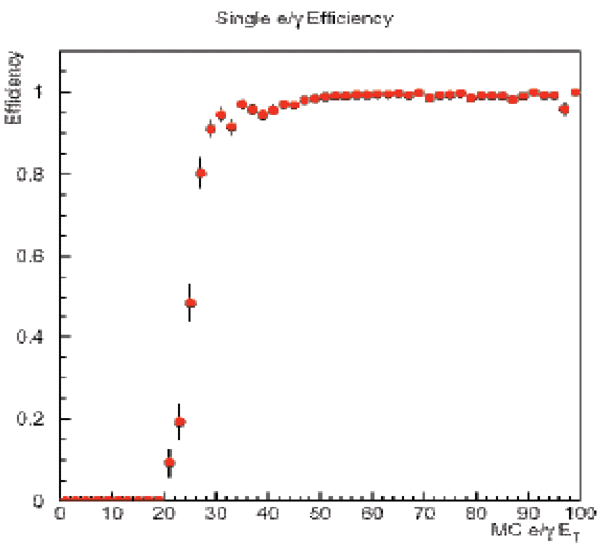
CMS

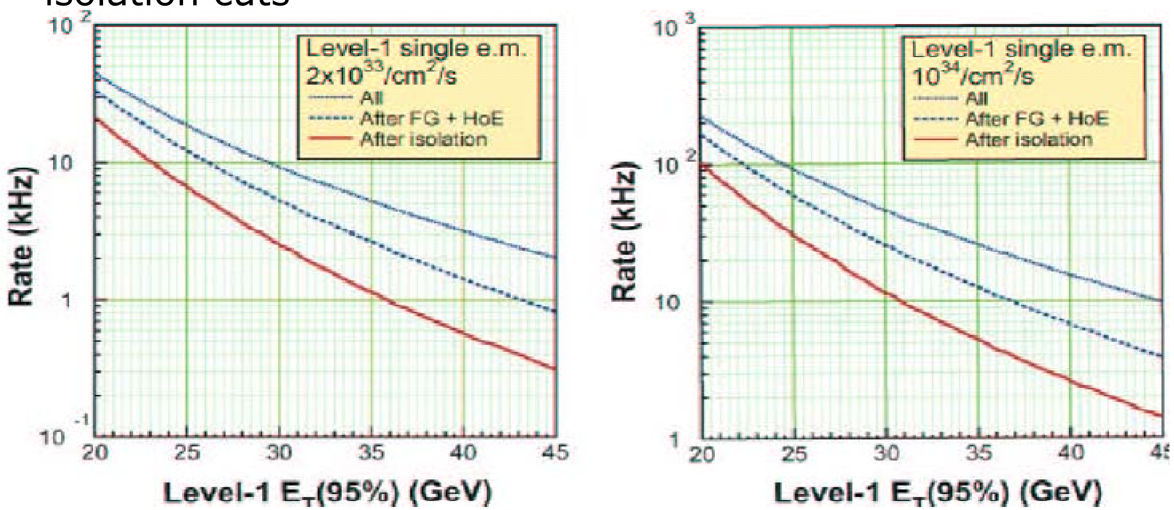
CMS: e/γ trigger

- 3 x 3 trigger towers sliding window
- ET of the hit trigger tower is the sum of central values + 4 highest neighbors
- **Isolation:** 2 separated streams based on longitudinal and lateral shower profile:
  - **"fine-grain" FG veto**: strip structure inside the tower (1x5), highest energy strip >90% of the total energy. Noise and pileup contamination to 2%
  - Ehad/Eem < 5%



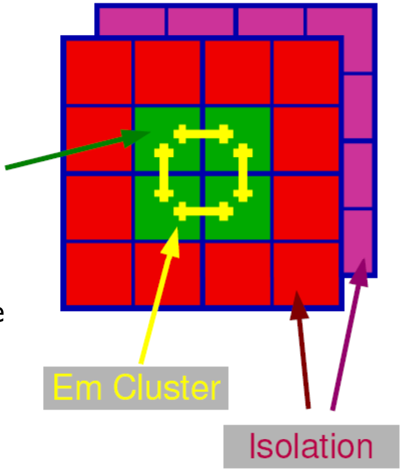
Expected rates at Low and High luminosity, with different isolation cuts





25 GeV cut: 95% at 31 GeV, 1.9 kHz expected

ATLAS: single e/γ trigger



Moliere radius in lead ~1 cm: e/g leave energy in one tower. Cluster energy in 2 contiguous towers

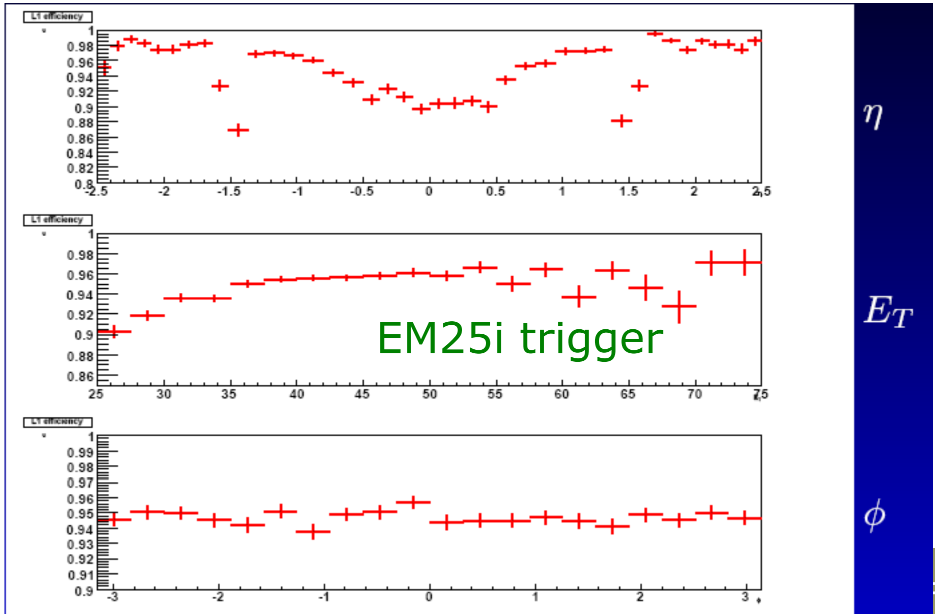
e/γ and tau/hadron trigger

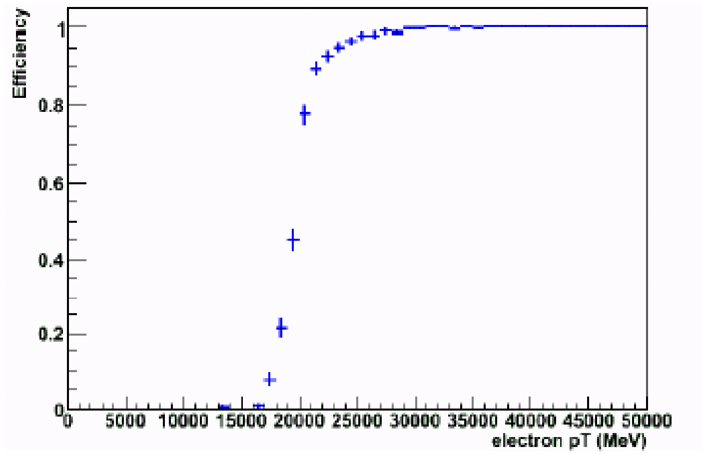
Trigger towers Δη x Δφ = 0.1 x 0.1

Acceptance coverage: |η|=2.5 (ID and LAr)

16 thresholds:

- Cluster RoI: 2x2-towers region (EM+Had)
- Cluster ET: summed 4 overlapping 2x1 towers with energy > threshold
- EM Isolation: Energy in the 12 adjacent cells < threshold
- Had isolation: Energy in 16 cells < threshold

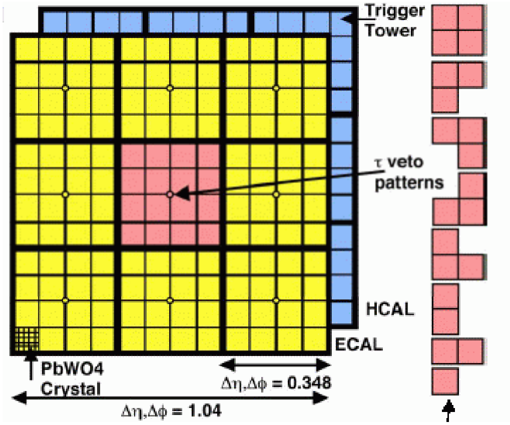


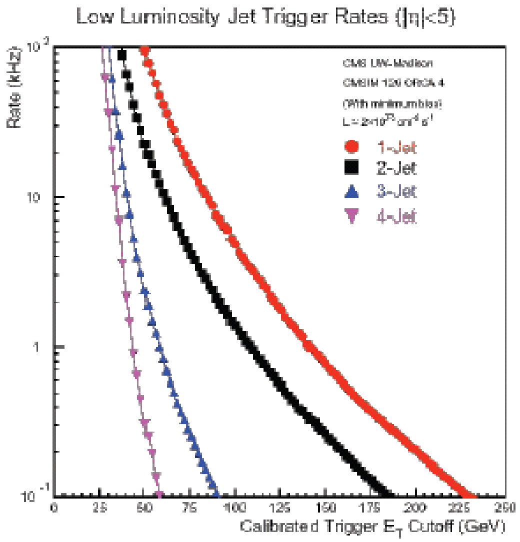


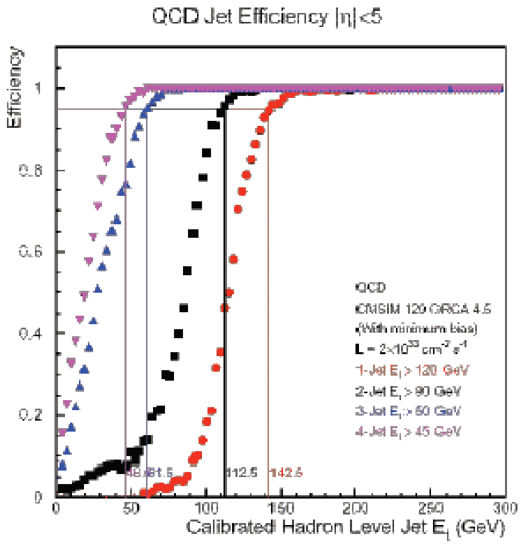
Single e 25 GeV: 96.7 %, ~ 6 kHz

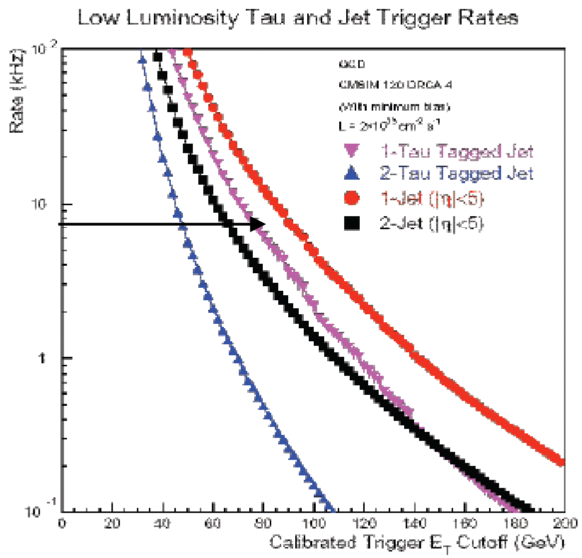
CMS: Jet and tau trigger

- 12x12 towers sliding window
- Central ET greater than 8 neighbors and over threshold to suppress noise
- Tau vetos pattern: narrow clusters from single and 3-prong decays of taus, with charged pions deposits in the HCAL (distinguished by electrons)





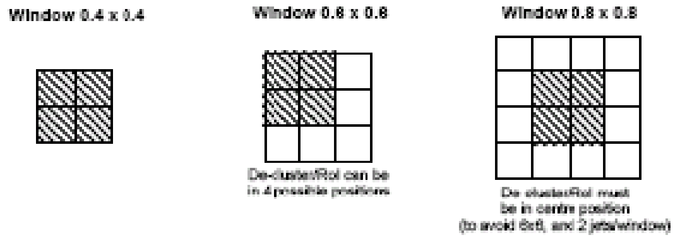




- **Single jet at 120 GeV**: 2.2 kHz, 95% @ 143 GeV
- **Dijet at 90 GeV**: 2.1 kHz, 95% @ 113 GeV

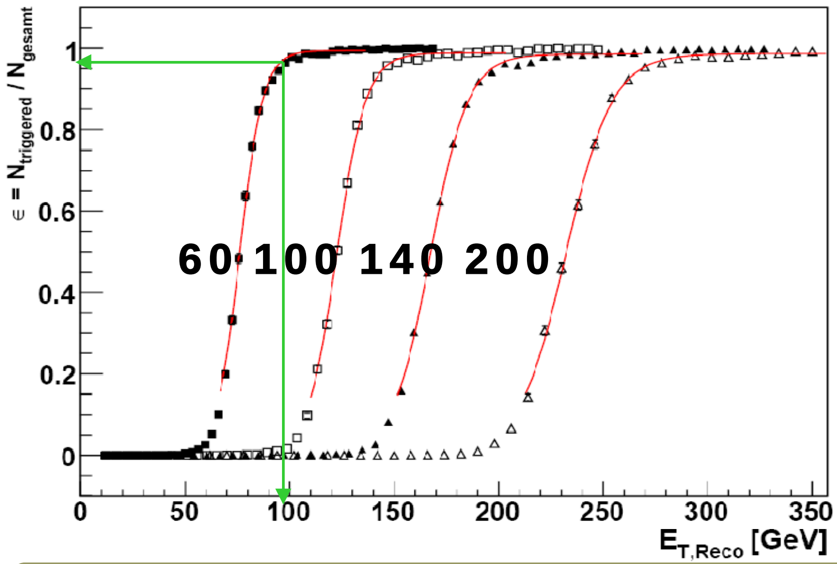
Single tau at 80 GeV: 6.1 kHz

ATLAS: Jet trigger



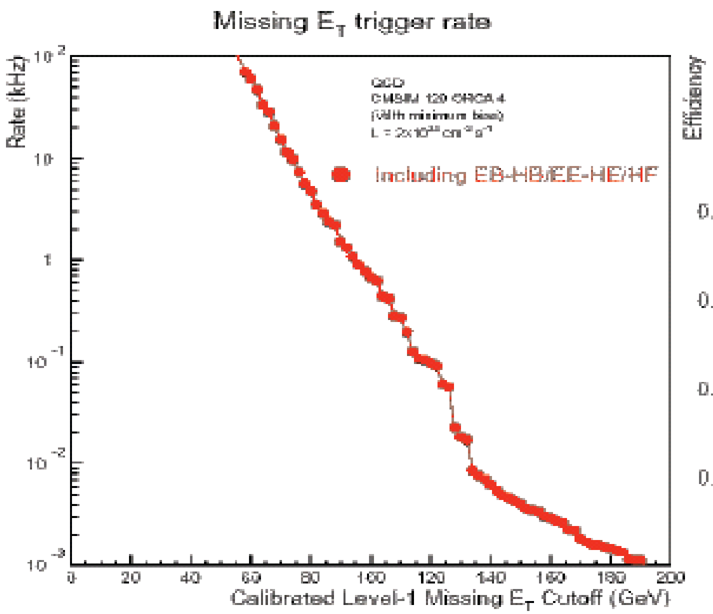
Jet trigger
Trigger towers $\Delta\eta \times \Delta\varphi = 0.2 \times 0.2$
Acceptance coverage: $|\eta|=3.2$ (endcap)
8 thresholds:
- Jet RoI: 2x2-towers region (EM+Had)
- Jet windows: summed 2, 3 or 4 jet element with energy > threshold

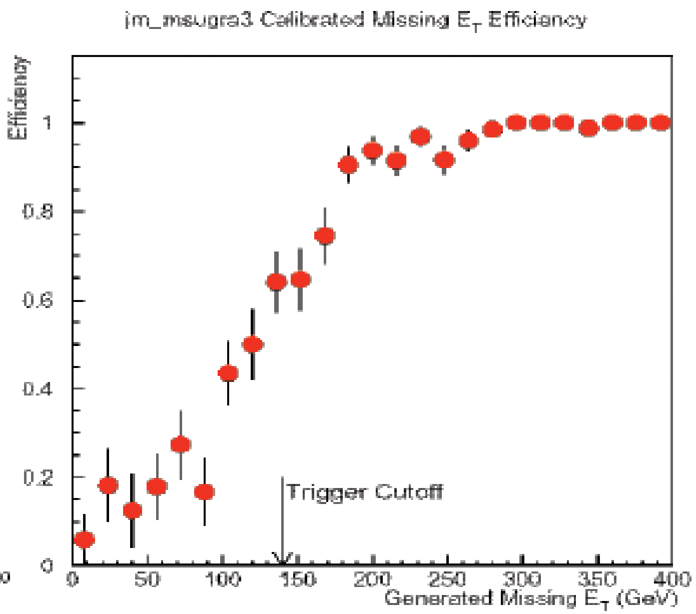
- rate foreseen on L1: R ~ O(100) Hz
- choice of Level 1 thresholds and prescales under study
  - distribute rate as equal as possible among the jet E_T-spectrum
  - keep the thresholds as constant as possible through runtime-> adjustment to increasing luminosities by prescales



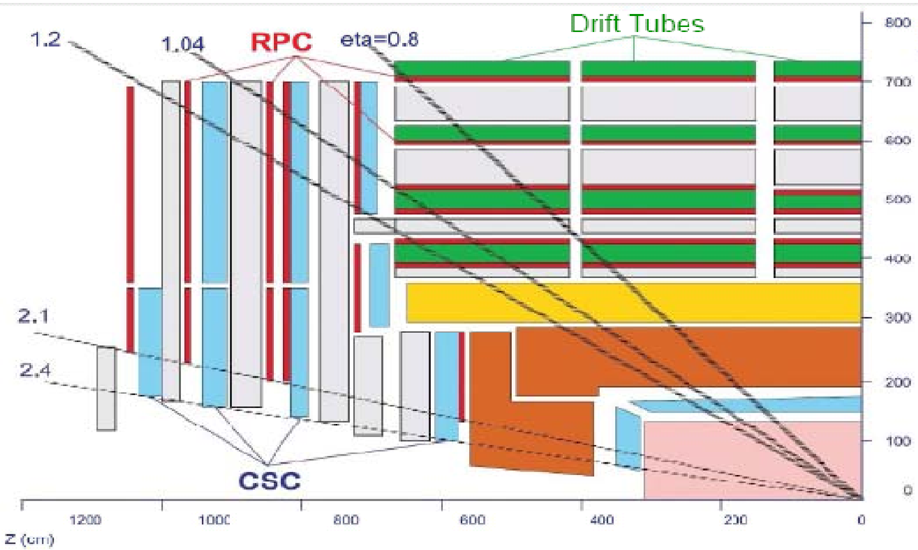
CMS: transverse E trigger

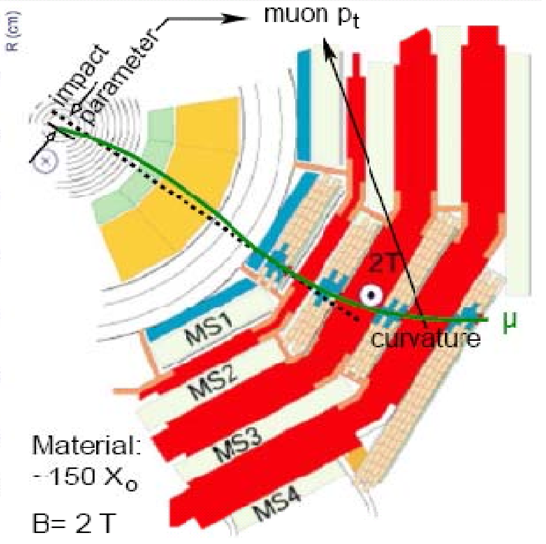
- ET and missing-ET triggers : transverse energy sums, defined by a threshold and a prescaling factor
- The HT trigger: scalar sum of ET of jets above a given threshold (typically 10 GeV)
  - Less sensitive to noise and pileup effects
  - Can capture high jet multiplicity events (fully hadronic top decays, hadronic decays of squarks and gluinos), with single jet energies below the jet-trigger thresholds
- Quiet and MIP bits used by the muon trigger
  - Quiet: computed when ET in the calorimeter regions are below a given threshold
  - MIP: Quiet + at least one HCAL tower with fine grain bit ON

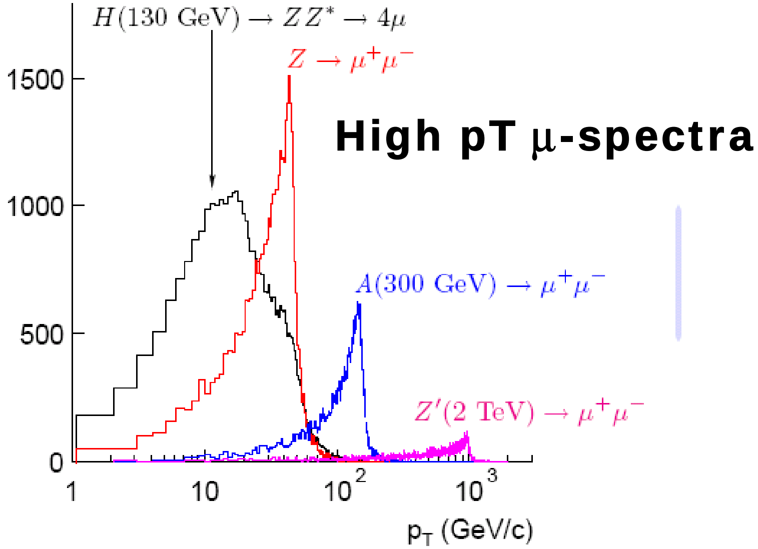




ATLAS/CMS Muon trigger



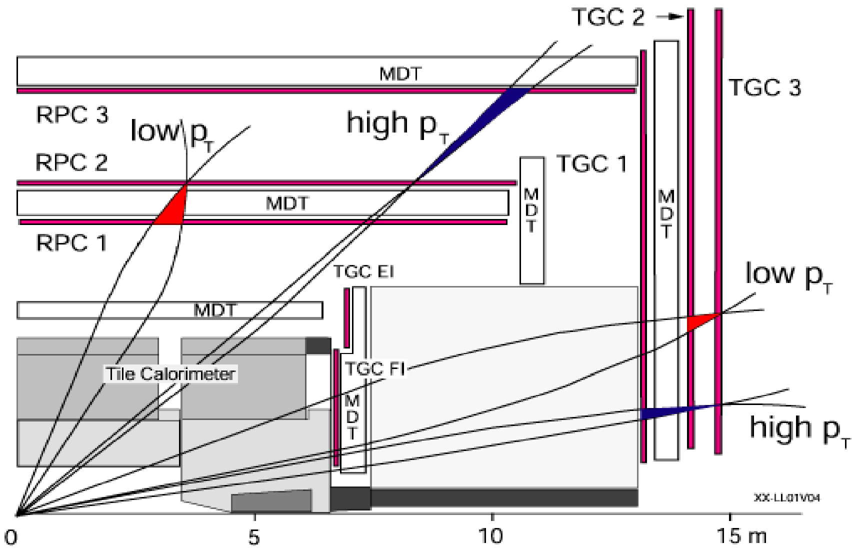


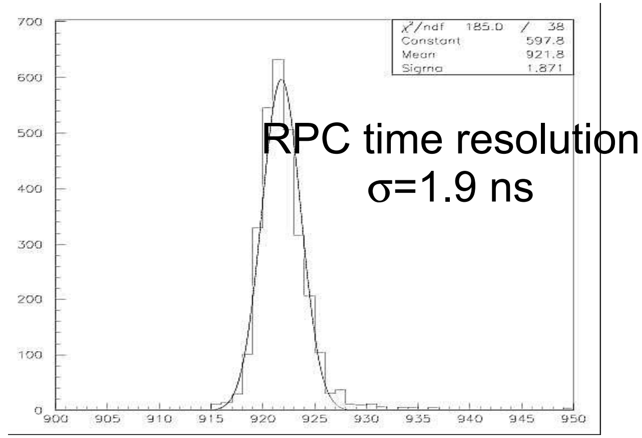


- Different bending planes in ATLAS & CMS
- Low pT systems for B-physics study
- Italian responsibility in both experiments

ATLAS: muon trigger

Momentum is defined with track deviation from an infinite momentum muon (Coincidence Windows)

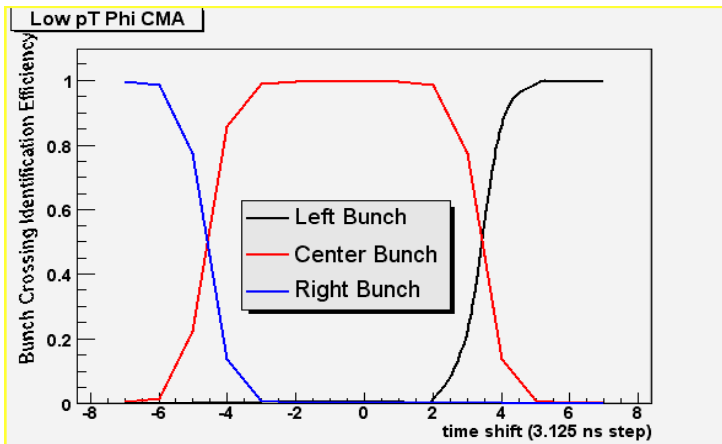




Fast and high redundancy system

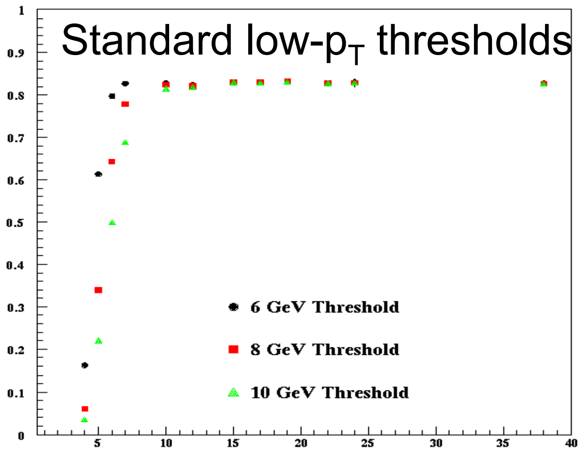
- Wide pT-threshold range: 2 separate systems: **low pt and high** pt trigger
- Safe Bunch Crossing Identification
- Strong rejection of fake muons (induced by noise and physics background) using algorithms on 2 views
- 1/8 BC interpolator to measure RPC timing hit
- Requirement for cosmic-ray and beam-halo triggers included in design

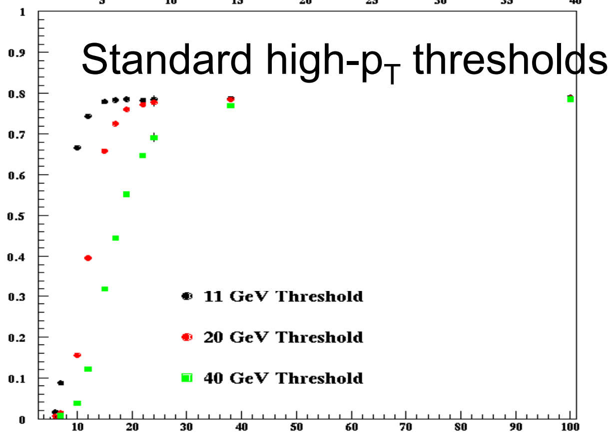
BC Identification efficiency vs pipeline delay (test-beam data)

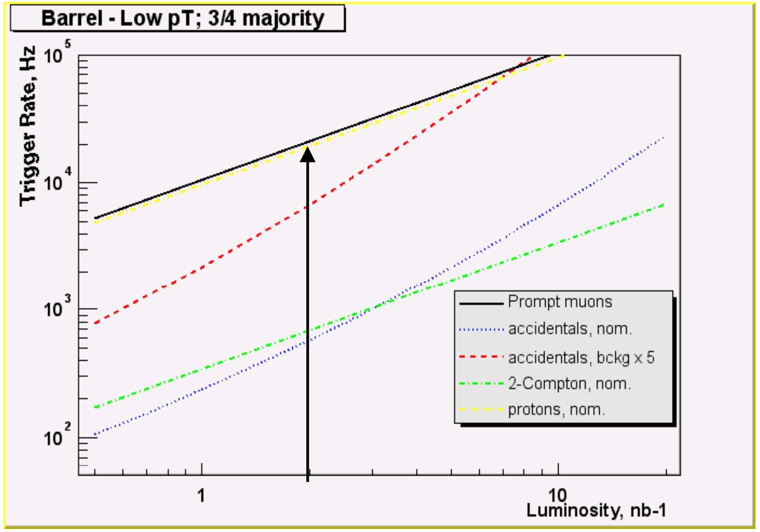


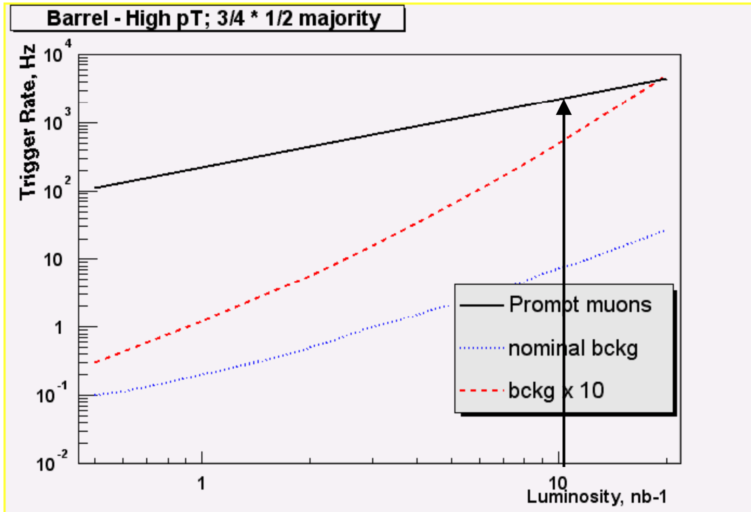
ATLAS: muon trigger performance

- Due to the air-toroid structure, the study of cavern background is mandatory
- Low pT system more sensitive to accidental background due to less redundancy



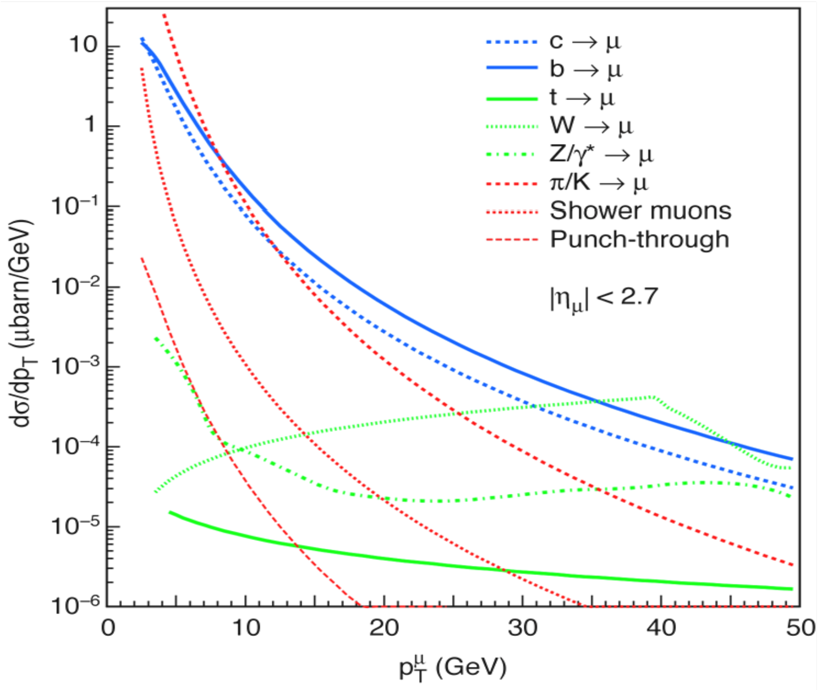






ATLAS: Muon Trigger rates

Inclusive μ cross-section @ LHC
(prompt μ and π/K decay)

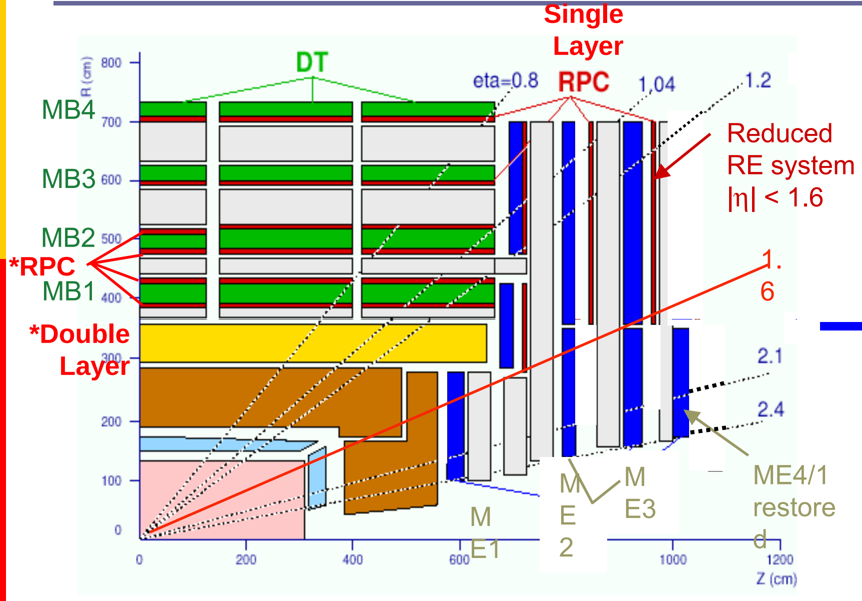


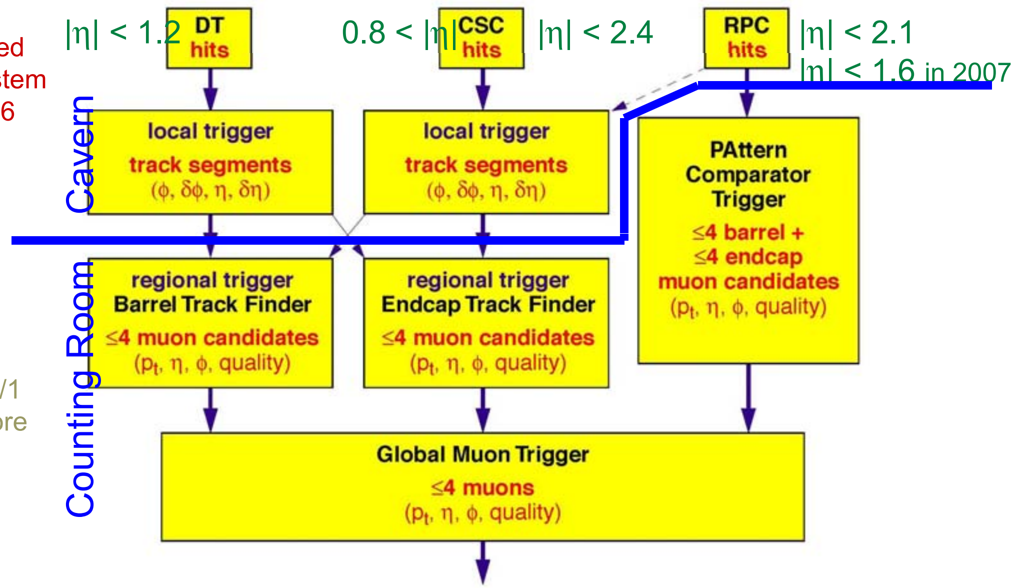
$$R_i = L \int_{p_{T\_inf}}^{p_{T\_cutoff}} \frac{d\sigma_i}{dp_T} \varepsilon(p_T)\, dp_T$$

Level-1 Efficiency

Muon sources	11 GeV 10^{34}	20 GeV 10^{34}
π/K	7420 Hz	3540 Hz
b	2330 Hz	760 Hz
c	1100 Hz	340 Hz
W	28 Hz	26 Hz
t	Negligible	Negligible
Sum	12 kHz	4.7 kHz

CMS: L1 muon trigger



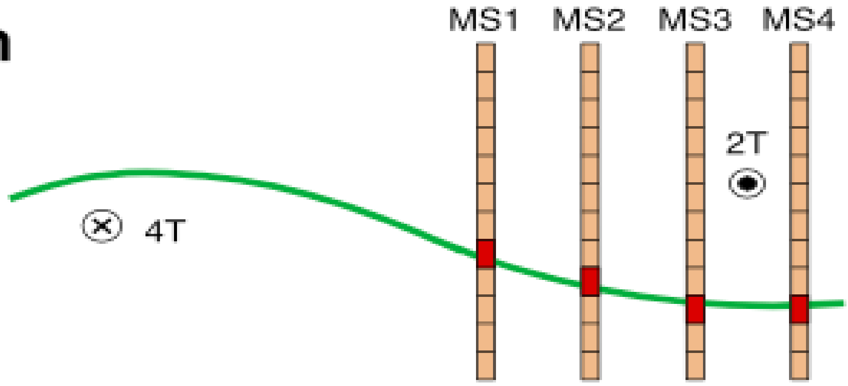


- Muon system, stations interleaved with the iron yoke of the return flux
  - DT, outside the magnet coil, in the Barrel
    - 4 stations, 2-3 SL each, 1 SL=4 staggered layers of tubes
  - CSC, in the endcap
    - 3 stations, 6 layers of CSC each
  - RPC, in the Barrel and endcap, dedicated to BC-identification

CMS: muon trigger primitives

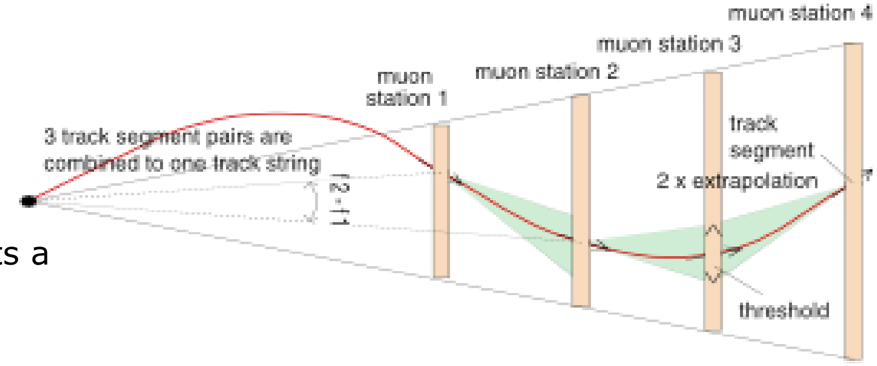
RPC pattern recognition

- Pattern trigger logic (PACT)
  - Many possible hits patterns assigned to each pT (and direction), due to dE/dx fluctuations and MS. Each pattern identifies a pT threshold
  - Time coincidence of hits in predefined patterns required on 3/4 to 4/6 stations, which gives the **BC assignment**



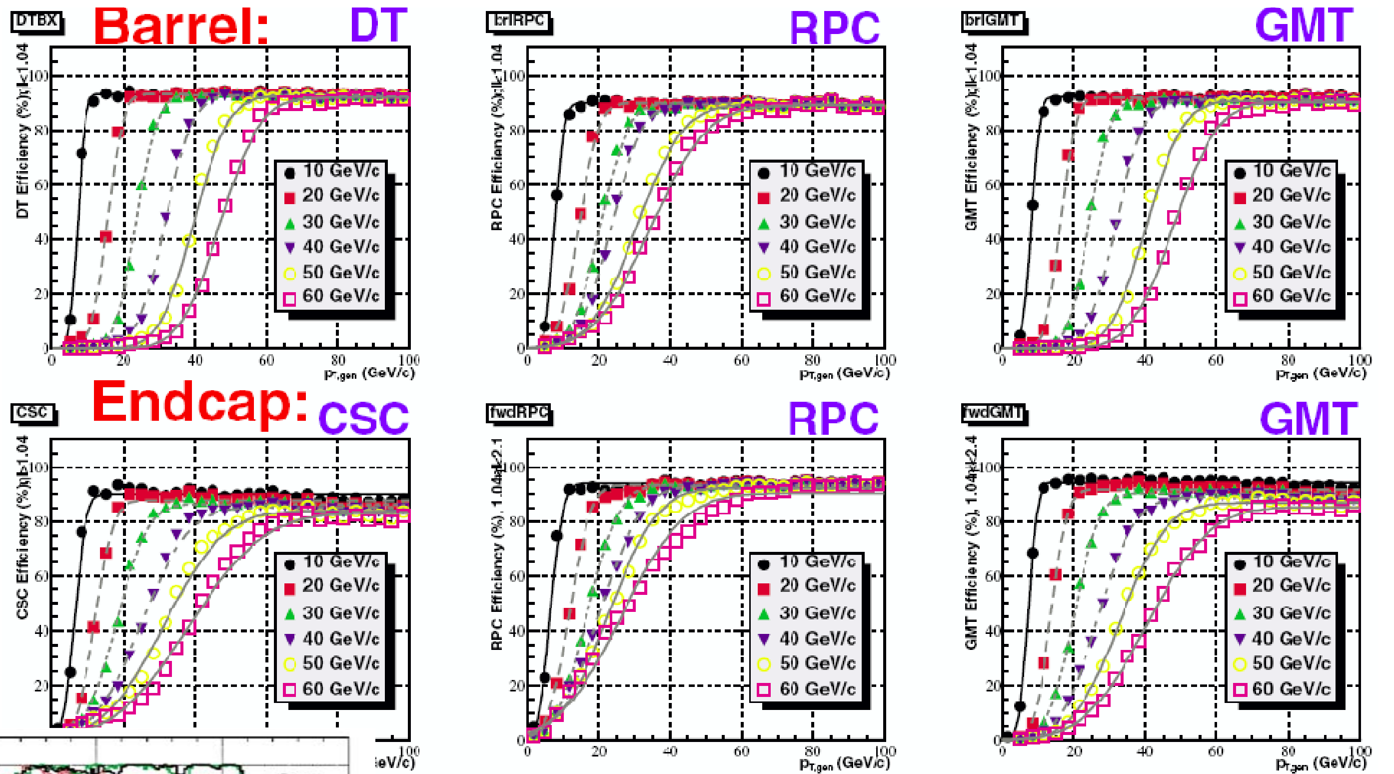
DT and CSC track finding:

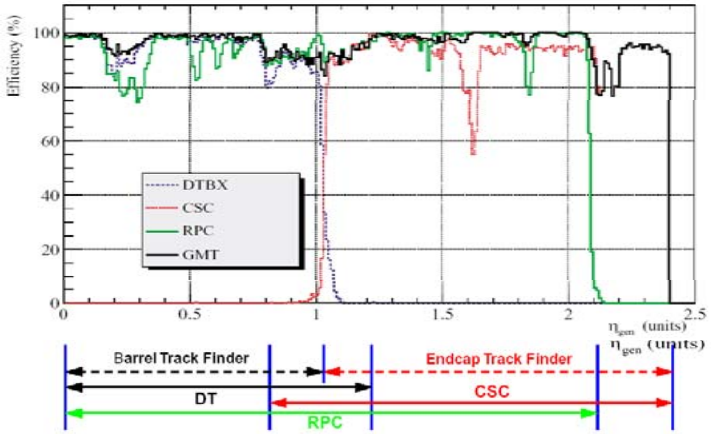
- Finds hit/segments
- Combines vectors
- Formats a track
- Assigns p_t value



- DT: 3-out-of-4 hits in each superlayer, fits a straight line within angular acceptance. Segments are correlated using angular distance form the IP
- CSC: segments in both views, then correlated: cathode strips on bending, anode dedicated to BC identification

CMS: muon trigger turn on

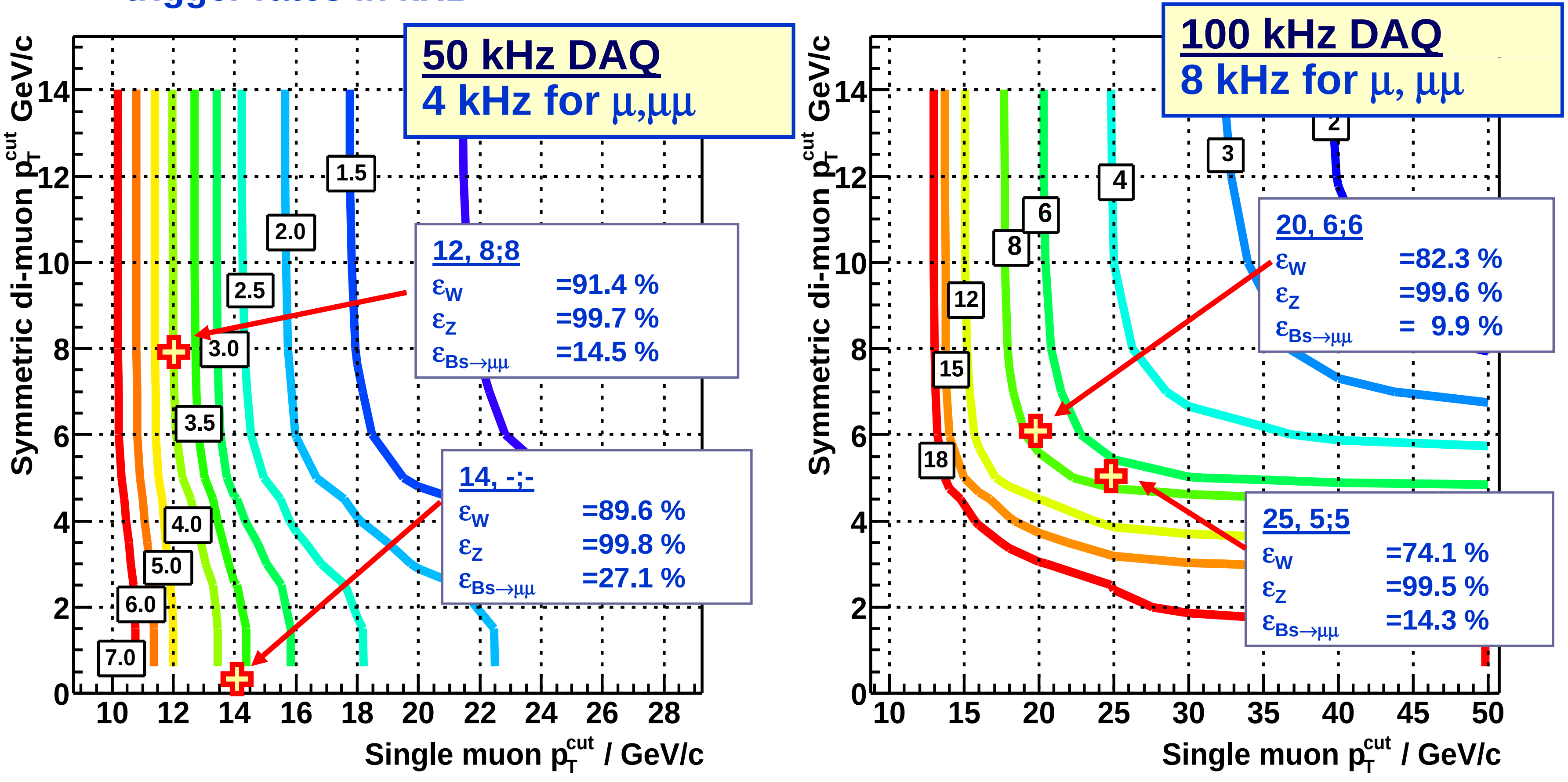




Global muon trigger: fake muon bkg reduced <0.2%

CMS: L1 muon trigger rates

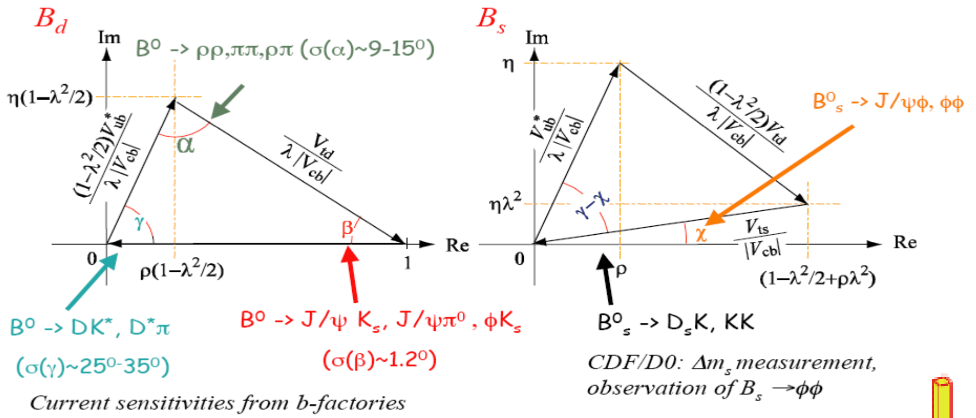
trigger rates in kHz |η| < 2.1



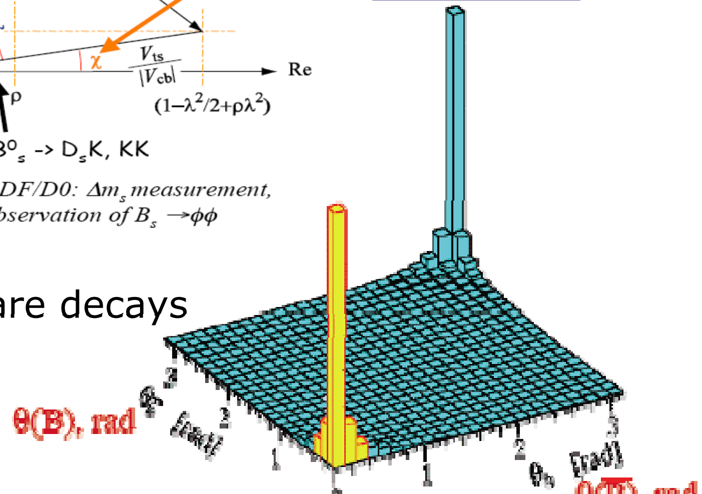
✚ working points selected as examples

L = 2×10^{33}cm^{-2}s^{-1} **L = 10^{34}cm^{-2}s^{-1}**

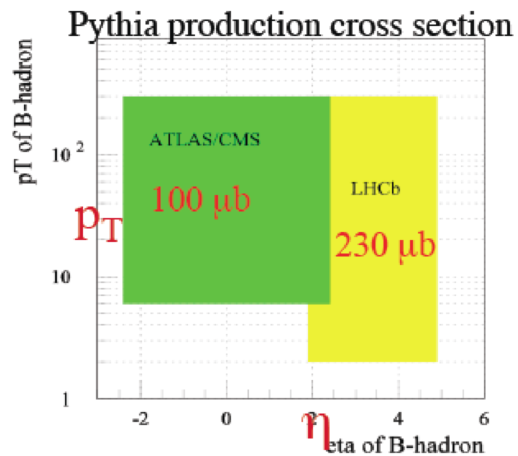
LHCb



- Designed to make precision measurements of CPV and rare decays in the B system ($\sigma(\gamma) < 10$ degree)
  - Large $\sigma_{\beta\beta}$ ~500 μb, but $\sigma_{\beta\beta}/\sigma_{\tau o\tau}$ ~ 5×10^{-3}
  - Interesting **B decays BR ~ 10^{-5}**
- Nominal luminosity: **2×10^{32}** $cm^{-2}\,s^{-1}$ (10-50 times lower than ATLAS/CMS)
  - dominated by single p-p /low occupancy events
  - 2 fb-1/year -> 10^{12} bb produced/year
  - Expected 'visible' rate: **10 MHz** (given by low L and LHC bunch structure)
    - bb: ~ 100 kHz (whole B-decay within acceptance ~15 kHz)
    - cc: ~ 600 kHz
- Multitude of trigger requests (excl. and incl.):
  - Excl: Signals to over-constrain the unitary triangle
  - Excl: Measurement of the purity of the B-tagging
  - Incl.:Calibration, alignments and systematic studies
  - Incl.:Unbiased control samples

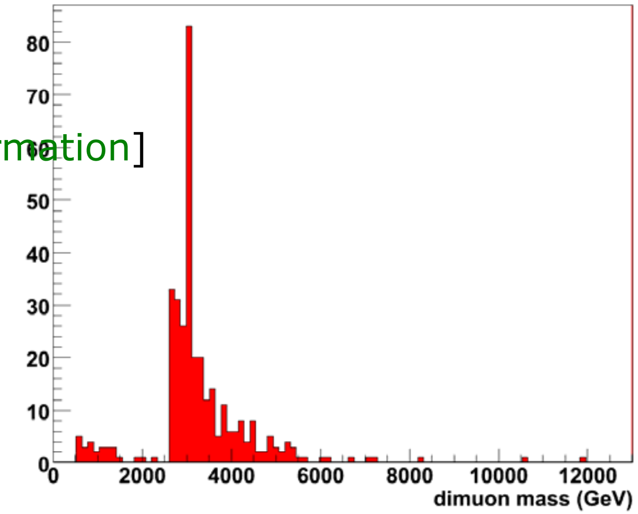


Forward peaked, correlated bb pair production

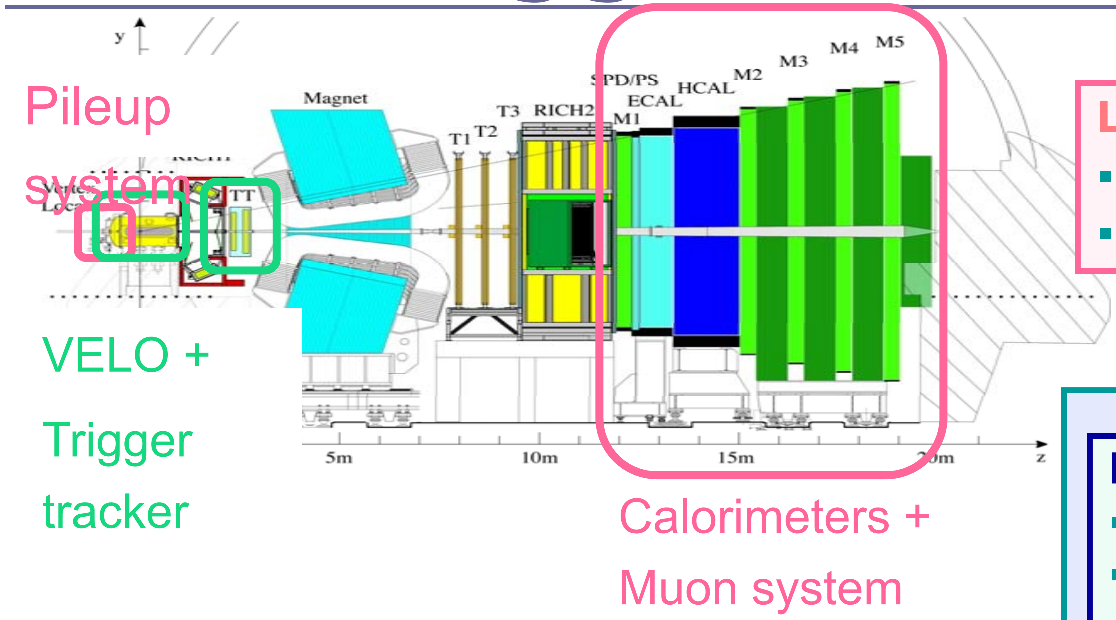


LHCb: trigger strategy

- Exclusive triggers : 'hot' physics eg. $B_s \to D_s h$, $B_s \to \phi\phi$, $B^0 \to J/\psi\ K_S$, $B^0 \to D^* \pi$, $B_{(s)} \to h^+ h^-$, $B^0 \to K^* \mu^+ \mu^-$, $B^0 \to D^0\ K^*$, $B_s \to \mu^+ \mu^-$, $B_s \to J/\psi\ \phi$, $B_s \to \phi\gamma$
- Inclusive triggers → Data mining:
  - Inclusive single-muon (900Hz) [independent of signal type]
    - Sample triggered independent of signal type – unbiased on the signal side
    - Signal trigger efficiencies, beauty content ~60%
  - Inclusive di-muon (600Hz) [selected without lifetime information]
    - Clean mass peaks for alignment, momentum (B field) calibration
    - Proper time resolution using prompt J/ψ events
  - Inclusive D* (300Hz) [selected without RICH information]
    - Clean signal of $D^{*+} \to D^0(K^- \pi^+)\pi^+$
    - Measure PID performance as a function of momentum
    - Charm content ~20%



LHCb trigger overview



10 MHz

L0: high p_T + track multiplicity

- synchr. (40 MHz), fixed 4 μs latency
- custom boards, commercial compon.

1 MHz

HLT inclusive: refine p_T + IP

- latency: 1 ms (max 50 ms)
- event buffers
- interface to Gbit Eth. readout networks

Full detector information

HLT full reconstruction

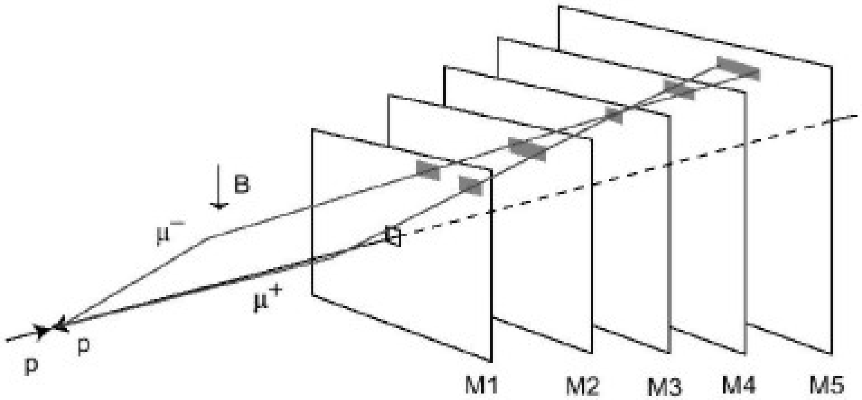
- Full detector: ~ 40 kb / evt (50 GB/s)

≤ 2 KHz

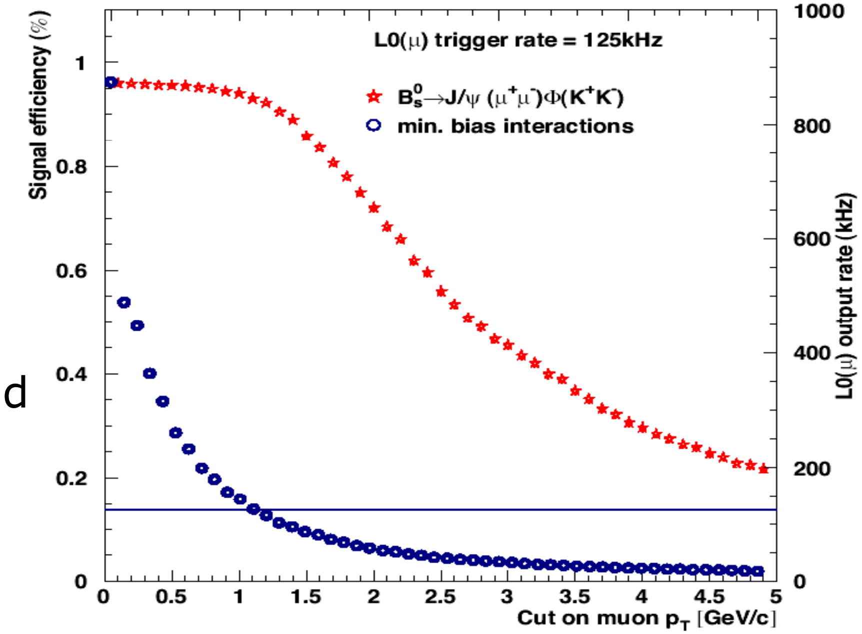
Single PC farm
~1600 CPUs

- Open geometry, excellent tracking capability
- Selection of B mesons using pT and impact parameter (IP) of the B decay (related to high mass and long lifetime of the b-quark)
  - Hardware trigger (L0): selection of events with at least one high ET object, reject complex events and beam-halo

LHCb: level-0 muon trigger

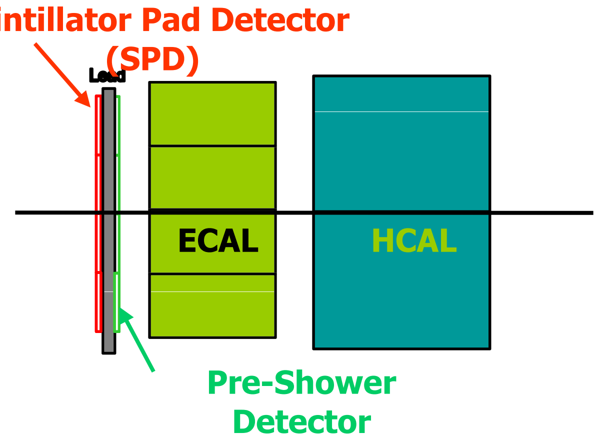


- Detectors: 1368 MWPC + 12 3-GEM for hottest region
- Five projective stations, with graduated segmentation (26k logical pads)
- Strategy: search of track on four layers and <u>check compatible hits on the fifth</u>
- Decision: send the two highest pT candidates in the chambers (Δp/p ~ 20%)
- **Typical Performance: ~88% efficiency on B->J/ψ(μμ)X**



LHCb: level-0 calorimeter trigger

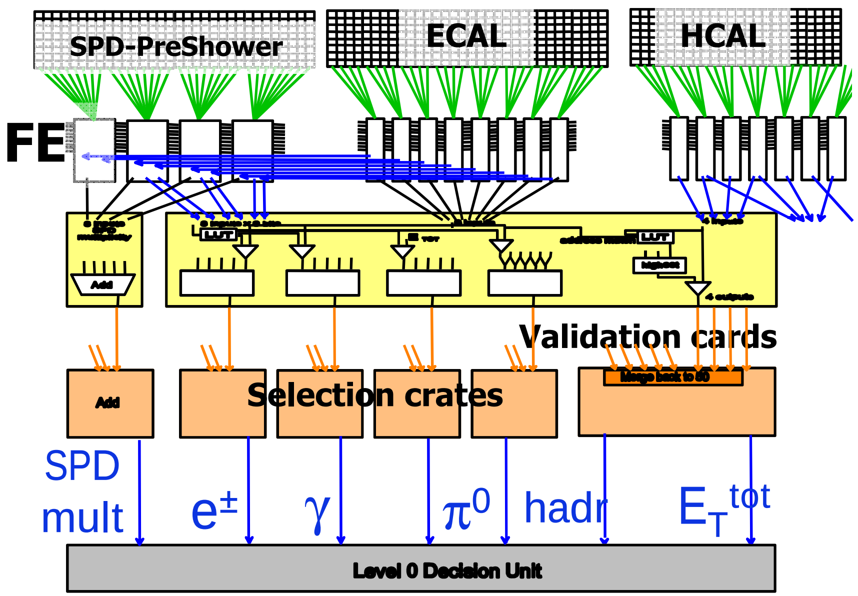
- Calorimeter
  - ECAL: Shashlik technology (lead/fibers r/o by WLS fibers), l=25, 8-bit ET
  - HCAL: iron/scintillating tiles (8-bit ET per cell)
  - Scintillator PAD (SPD) for neutral/charged separation
  - Preshower (PS) for e/π separation



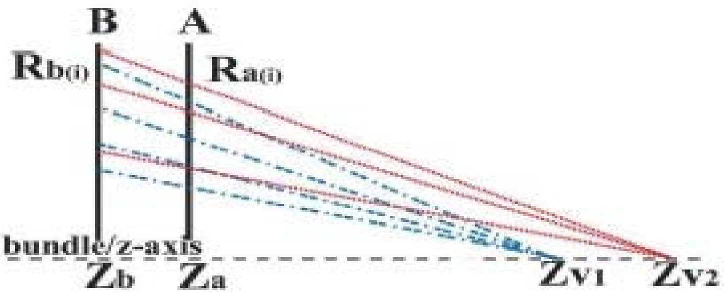
- Strategy: look for two highest ET candidates of each type (>3 GeV)
  - **PID** by HCAL+ECAL and SPD+PS

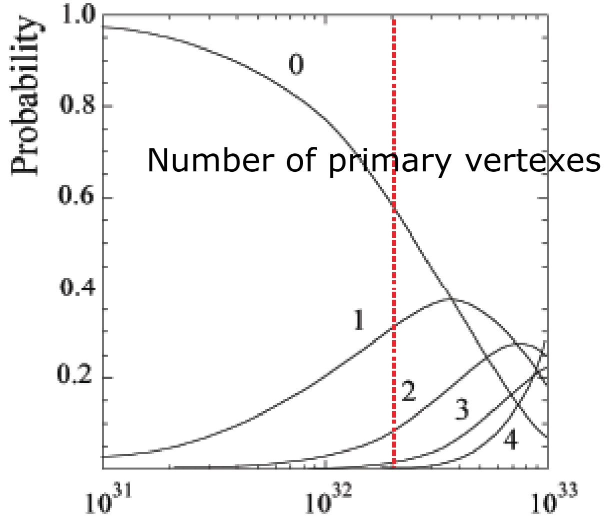
- Also sent to L0: total calorimeter ET and SPD track multiplicity

- **Typical Performance: 30-50% efficiency on hadronic channels for about 700 kHz bandwidth**

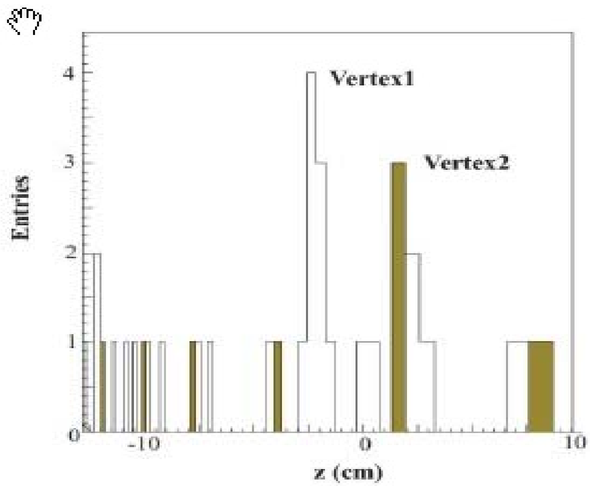


LHCb: level-0 pile-up system



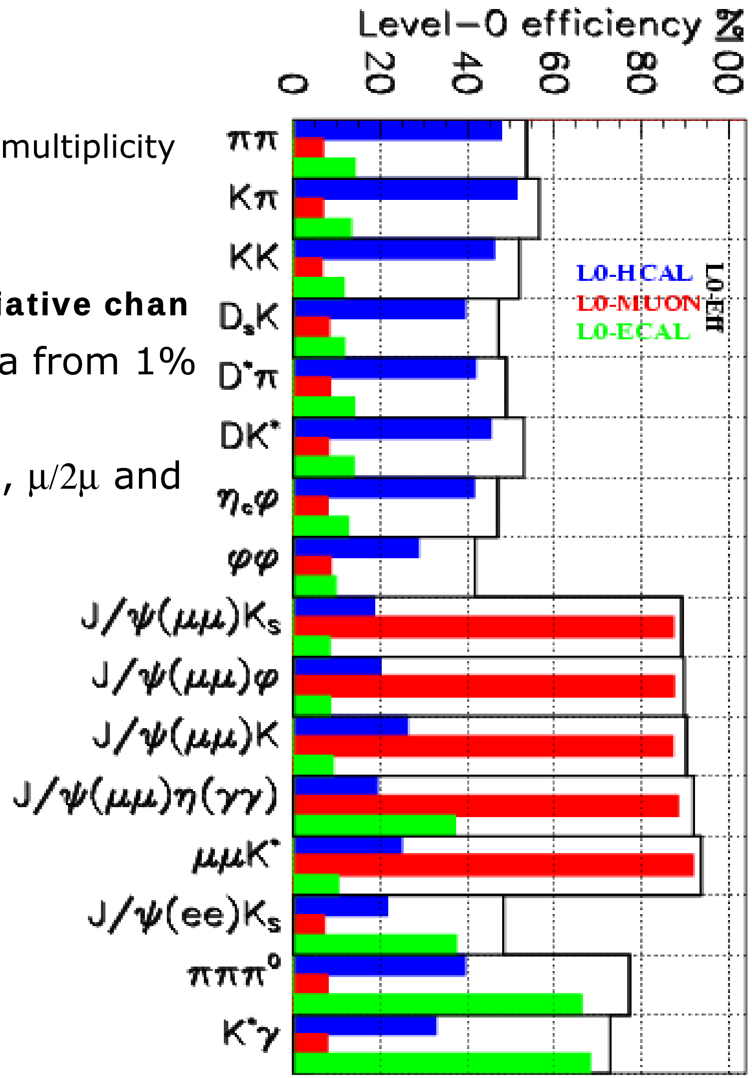


- Used to suppress events with multiple primary interactions within one bunch crossing (reducing event size, required bandwidth and offline analysis)
- Two dedicated silicon disks in the backward direction ($\eta<0$) reconstruct the longitudinal position of the IP
- Strategy
  - perform all combinatorial combinations of hits, find the most probable position (primary vertex) and mask all hits belonging to it
  - The height of the **secondary peak** gives the secondary vertex multeplicity, used to select the event
- **Typical performance: 60% efficiency identifying double interactions with 95% purity**



LHCb level-0: Decision and performance

- OR combination of
  - single objects thresholds, to exclude min. bias
  - global variables, to exclude combinatorics (total ET, track multiplicity in the 2nd vertex, pile-up and SPD multiplicity)
- Expected efficiency for a given channel
  - **~50% for hadrons, ~90% for muons, ~70% for radiative chan**
- The level-0 trigger enhances the bb content of the data from 1% to 3%: expected rates are **bb 30 kHz, cc 106 kHz**
- L0 hadron trigger mainly occupy the bandwidth (60%), $\mu/2\mu$ and $e/\gamma/\pi0$ about 20% each



Type	Threshold (GeV)	Rate (kHz)
Hadron	3.6	705
Electron	2.8	103
Photon	2.6	126
π^0 local	4.5	110
π^0 global	4.0	145
Muon	1.1	110
Di-muon	1.3	145