High Level Trigger

Simone Gennai on Behalf of the CMS and ATLAS collaboration

Index

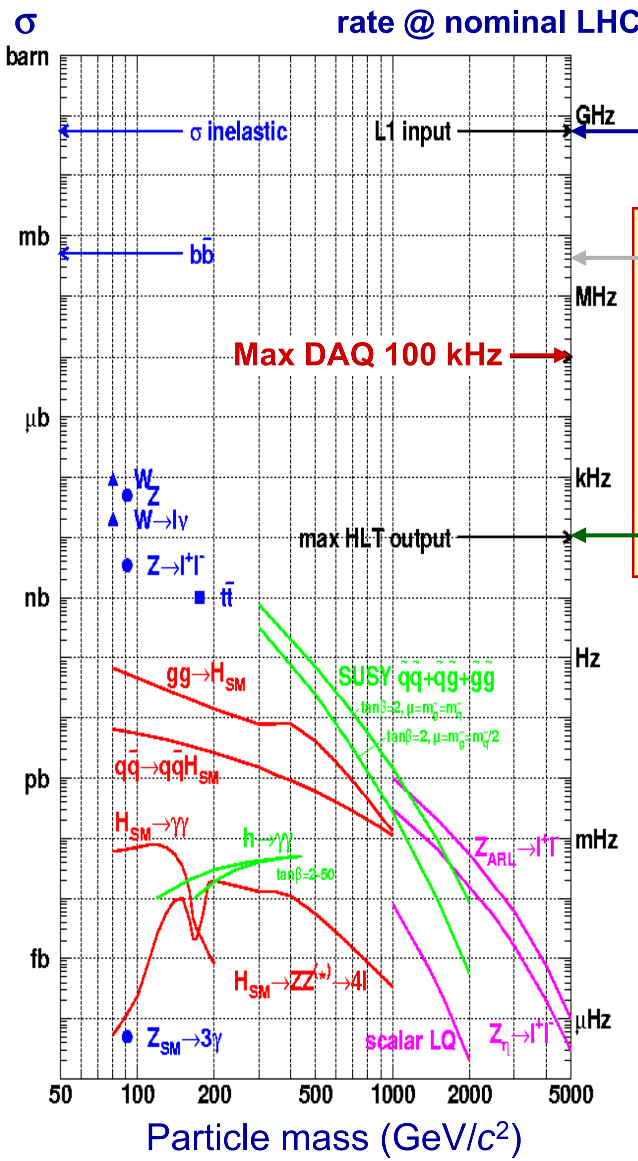
- This talk is a mixture of
  - old (but not complitely out) …
  - …new …
  - and “near-future” results

Apologies for information not anylonger up to date

- CMS and Atlas Trigger systems
  - L1 rates
  - HLT rates
  - HLT reconstruction
- A concrete example:the Tau trigger
- Trigger optimization and HLT exercise (CMS)

Special thanks to Francesca Sarri
for pointing me to the relevant documentation

LHC Event Rates



pp interactions

Pile-up

Machine Rate: 40 MHz

On-line trigger selection

Select 1:4x10⁵

Decide every 25 ns!

Acceptable storage rate: 100 Hz

Off-line analysis

Signals

CMS Trigger Architecture

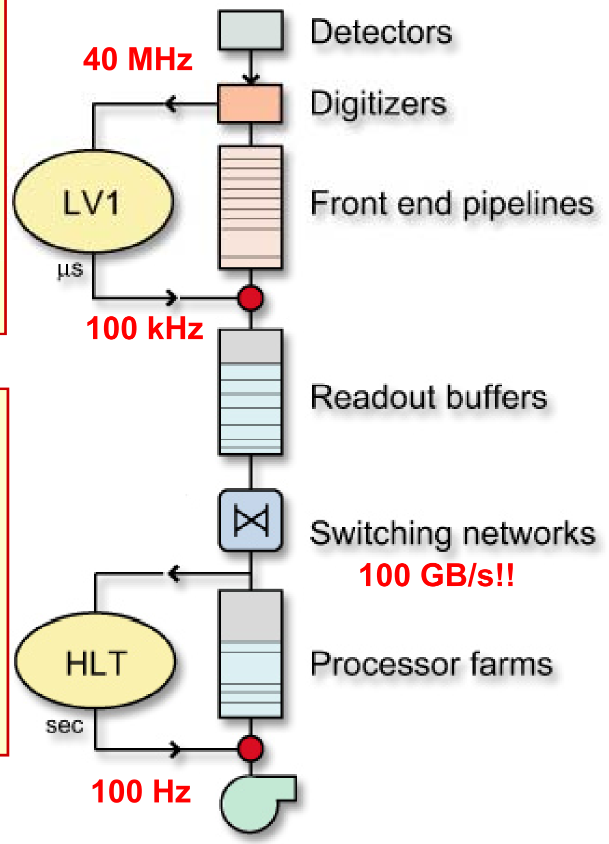
Start from 40 MHz → Decision every 25 ns

Too small even to read raw data
Selection in <u>multiple levels</u>, each taking a decision using only part of the available data

The <u>first level (L1)</u> is only feasible with dedicated, synchronous (clock driven) hardware

CMS choice: All further selection in a single phisical step (HLT)

Build full events and analyze them "as in offline"
Invest in networking (rather than in dedicated L2 hardware)



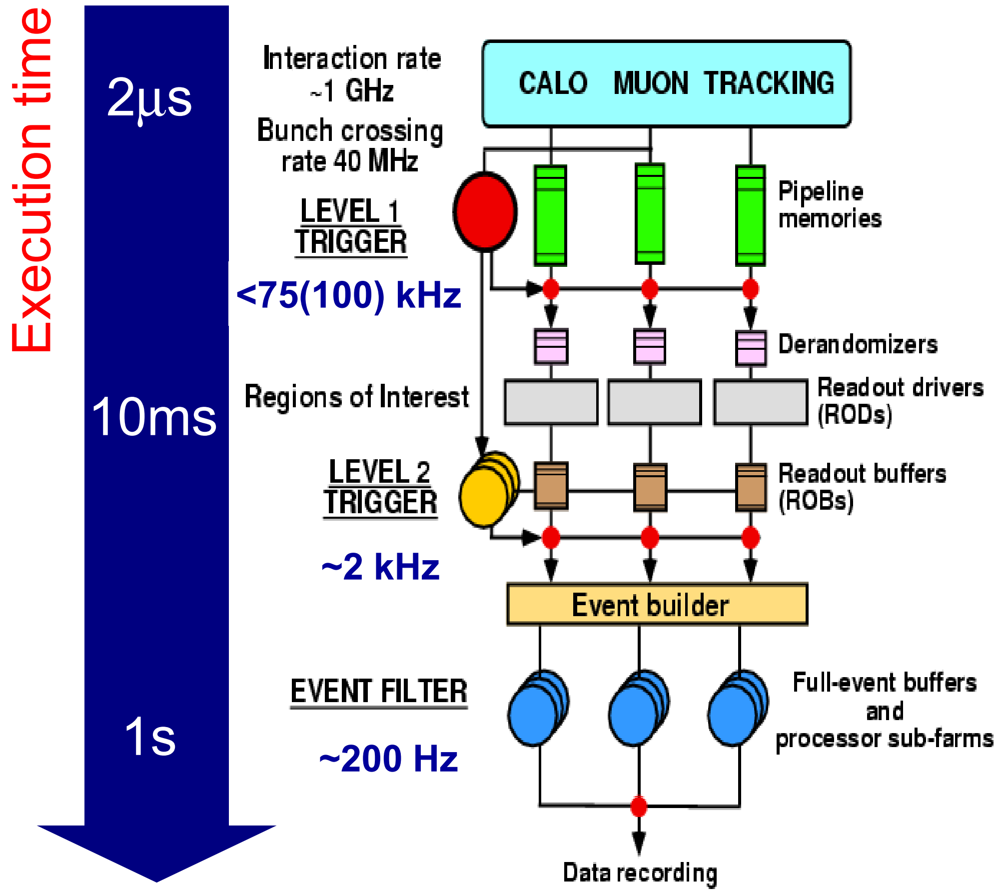
The ATLAS trigger

Level 1 (hardware):
Defines Regions of Interest (RoI).
Uses Calo cells and Muon chambers with reduced granularity.
e/γ, μ, τ, jet candidates.

High Level Trigger

Level 2 (software):
Seeded by LVL1 RoI.
Full granularity of the detector
Performs calo-track matching

Event Filter (software):
Offline-like algorithms.
Refines LVL2 decision
Full event building



TIER 0 mass storage

CMS HLT

- Run on farm of commercial CPUs: a single processor analyzes one event at a time and comes up with a decision
- Has access to full granularity information
- Freedom to implement sophisticated reconstruction algorithms, complex selection requirements, exclusive triggers…

Constraints:

- CPU time (Cost of filter farm)
  - Reject events ASAP: set up internal "logical" selection steps
    - L2: muon+ calorimeter only
    - L3: use full information including tracking
- Must be able to measure efficiency from data
  - Use inclusive selction whenever possible
    - Single/double object above pT/ET, etc.
  - Define HLT selection paths from the L1
- Keep output rate limited (obvious…)

Setting trigger tables

- HLT trigger paths start from corresponding L1 paths
- Thresholds are set distributing bandwidth to the various paths in order to maximize efficiencies
  - There can be significant overlaps
  - Iterative process
- Thresholds (and streams) will change with luminosity
  - And according to the physics of interest at the time of operation
  - Reference: 2×10^{33} cm^{-2} s^{-1} (and Pilot Run)
  - Evolution of selection with luminosity is a delicate issue, up to now studied in detail only for jet (with prescales)
  - It will be part of the CMS HLT Exercise

Example ofL1 Trigger Table

For L= $2x10^{33}$ $cm^{-2}s^{-1}$

Selections	Rates (KHz)
MU20	0.8
2MU6	0.2
EM25I	12.0
2EM15I	4.0
J200	0.2
3J90	0.2
4J65	0.2
J60+xE60	0.4
TAU25+xE30	2.0
MU10+EM15I	0.1
OTHERS (pre-Scales,calibration)	5.0
TOTAL	~25

Trigger	Level-1 Threshold (GeV)	Level-1 Rate (kHz)	Cumulative Level-1 Rate (kHz)
Inclusive $e\gamma$	22	4.2 ± 0.1	4.2 ± 0.1
Double $e\gamma$	11	1.1 ± 0.1	5.1 ± 0.1
Inclusive μ	14	2.7 ± 0.1	7.8 ± 0.2
Double μ	3	3.8 ± 0.1	11.4 ± 0.2
Inclusive τ	100	1.9 ± 0.1	13.0 ± 0.2
Double τ	66	1.8 ± 0.1	14.1 ± 0.2
1-,2-,3-,4-jets	150,100,70,50	1.8 ± 0.1	14.8 ± 0.3
H_T	300	1.2 ± 0.1	15.0 ± 0.3
E_T^{miss}	60	0.3 ± 0.1	15.1 ± 0.3
$H_T + E_T^{miss}$	200, 40	0.7 ± 0.1	15.3 ± 0.3
jet + E_T^{miss}	100, 40	0.8 ± 0.1	15.4 ± 0.3
$\tau + E_T^{miss}$	60, 40	2.7 ± 0.1	17.4 ± 0.3
$\mu + E_T^{miss}$	5, 30	0.3 ± 0.1	17.6 ± 0.3
$e\gamma + E_T^{miss}$	15, 30	0.7 ± 0.1	17.7 ± 0.3
μ + jet	7, 100	0.1 ± 0.1	17.8 ± 0.3
$e\gamma$ + jet	15, 100	0.6 ± 0.1	17.8 ± 0.3
$\mu + \tau$	7, 40	1.2 ± 0.1	18.4 ± 0.3
$e\gamma + \tau$	14, 52	5.4 ± 0.2	20.7 ± 0.3
$e\gamma + \mu$	15, 7	0.2 ± 0.1	20.7 ± 0.3
Prescaled			22.6 ± 0.3
Total Level-1 Rate			22.6 ± 0.3

Assume 50 KHz DAQ available + factor 3 safety

Example of HLT Reconstruction

- γ
  - L2: cluster ECAL deposits into "superclusters" and apply E_T threshold
  - L3: isolation in HCAL and tracker
- e
  - L2 common with γ
  - L2.5: match the supercluster with a track in the pixel detector
  - L3: isolation in HCAL and tracker, cut on E/p
- Jets
  - Iterative cone algorithm in calorimeters + energy corrections (non-linearity)
- MET
  - Vector sum of transverse energy deposit in calorimeters, incl. muons
- Muons
  - L2 muon reconstruction with improved pT resolution
  - L2.5 calorimeter isolation
  - L3 full information from SiStrip Tracker for further improvement on the pT resolution
- B-tagging
  - L2.5: impact parameter with pixel track stubs
  - L3: with regional track reconstruction
- Tau
  - See next slides in the talk

HLT Trigger Table

L= 2x10^{33} cm^{-2}s^{-1} (CMS Physics TDR v.2)

Trigger	HLT Threshold (GeV)	HLT Rate (Hz)
Inclusive e	26	23.5 ± 6.7
e-e	12, 12	1.0 ± 0.1
Relaxed e-e	19, 19	1.3 ± 0.1
Inclusive γ	80	3.1 ± 0.2
γ-γ	30, 20	1.6 ± 0.7
Relaxed γ-γ	30, 20	1.2 ± 0.6
Inclusive μ	19	25.8 ± 0.8
Relaxed μ	37	11.9 ± 0.5
μ-μ	7, 7	4.8 ± 0.4
Relaxed μ-μ	10, 10	8.6 ± 0.6
τ + E_T^{miss}	65 (E_T^{miss})	0.5 ± 0.1
Pixel τ-τ	—	4.1 ± 1.1
Tracker τ-τ	—	6.0 ± 1.1
τ + e	52, 16	< 1.0
τ + μ	40, 15	< 1.0
b-jet (leading jet)	350, 150, 55 (see text)	10.3 ± 0.3
b-jet (2nd leading jet)	350, 150, 55 (see text)	8.7 ± 0.3
Single-jet	400	4.8 ± 0.0
Double-jet	350	3.9 ± 0.0
Triple-jet	195	1.1 ± 0.0
Quadruple-jet	80	8.9 ± 0.2
E_T^{miss}	91	2.5 ± 0.2
jet + E_T^{miss}	180, 80	3.2 ± 0.1
acoplanar 2 jets	200, 200	0.2 ± 0.0
acoplanar jet + E_T^{miss}	100, 80	0.1 ± 0.0
2 jets + E_T^{miss}	155, 80	1.6 ± 0.0
3 jets + E_T^{miss}	85, 80	0.9 ± 0.1
4 jets + E_T^{miss}	35, 80	1.7 ± 0.2
Diffractive	40, 40	< 1.0
H_T + E_T^{miss}	350, 80	5.6 ± 0.2
H_T + e	350, 20	0.4 ± 0.1
Inclusive γ	23	0.3 ± 0.0
γ-γ	12, 12	2.5 ± 1.4
Relaxed γ-γ	19, 19	0.1 ± 0.0
Single-jet	250	5.2 ± 0.0
Single-jet	120	1.6 ± 0.0
Single-jet	60	0.4 ± 0.0
		119.3 ± 7.2

120 Hz

HLT Trigger Table

Selection	Physics coverage	$2x10^{33}$ $cm^{-2}s^{-1}$	Rates (Hz)
Electron	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top	e25i, 2e15i	~40
Photon	Higgs, SUSY, extra dim.	g60i, 2g20i	~40
Muon	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top, B-Physics	m20i, 2m10 2m6 with m_B /$m_{J/y}$	~50
Jets	SUSY, compositness, resonances	j400, 3j165, 4j110	~25
Jet & E_T^{miss}	SUSY, leptoquarks	j70 + xE70	~20
tau & E_T^{miss}	Extended Higgs models (e.g. MSSM), SUSY	t35 + xE45	~5
Others	pre-scales, calibration, …		~20
Total			~200

The rates for the HLT taken considering the EventFilter performances equal to those one of the OFFLINE.

TAU SOURCES AND INTEREST FOR PHYSICS

Standard Model:
- inclusive $W \rightarrow \tau\tau$ ($Z \rightarrow \tau\tau$) production
- QCD.

SM and MSSM Higgs:
- 100-150 GeV SM Higgs: qqH($\tau\tau$)
- A/H $\rightarrow \tau\tau$
- $H^+ \rightarrow \tau\nu$ ($m_H^+ < m_{top}$ and $m_H^+ > m_{top}$)

SUSY

Extra Dimensions

Etc. Etc.

A practical example: Tau trigger

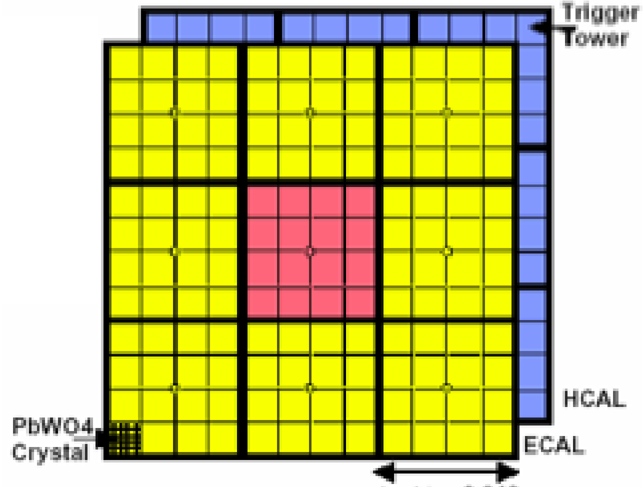
Calorimeter

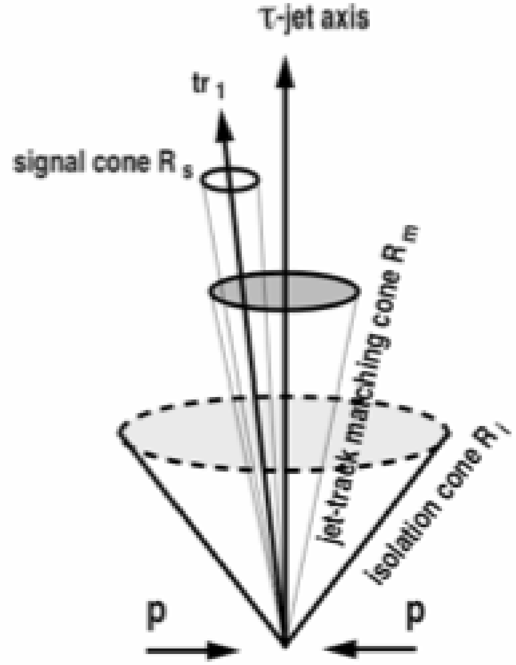
- Energy deposited in few cells:
  - narrow jets deposit and more collimated than QCD jets of the same energy

Tracker

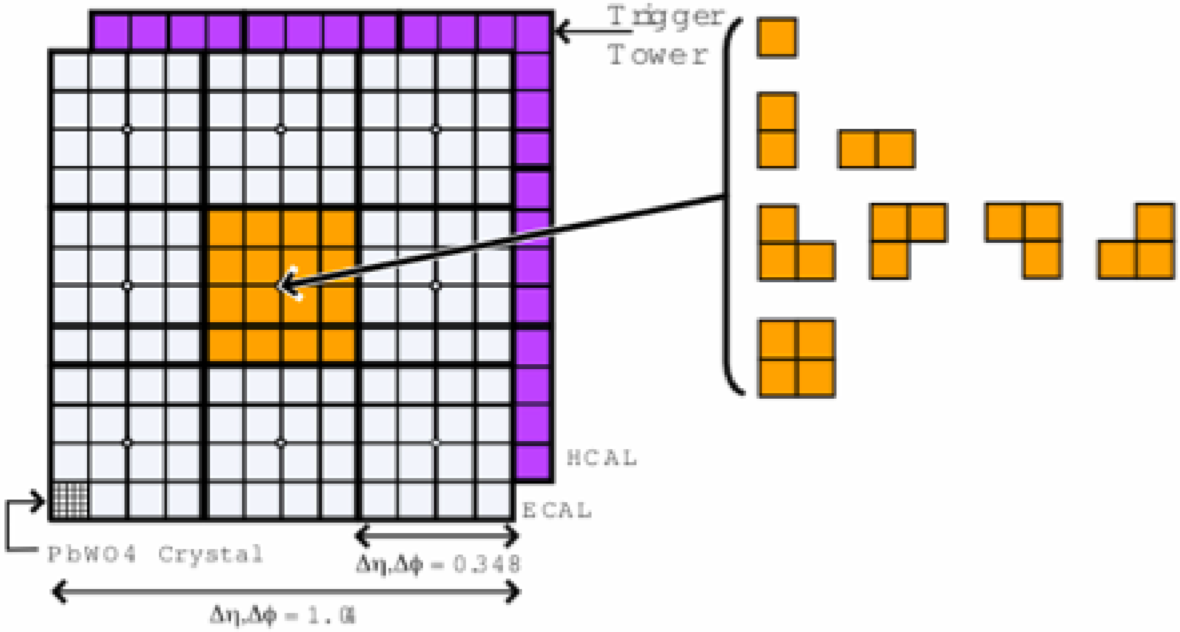
- Isolation criteria implemented with reconstructed tracks

Trigger rate is saturated by QCD 2jet events





L1 Tau trigger



Active towers patterns allowed for the tau jet reconstruction

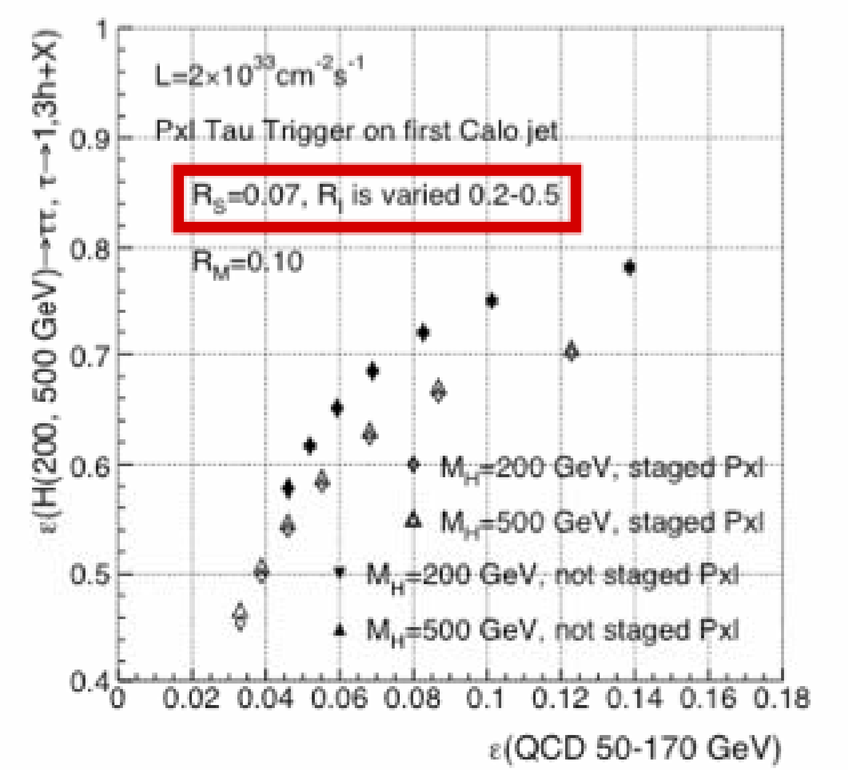
The Tau jet reconstruction is similar to a generic jet reconstruction with the additional use of a tau jet veto: the tau is accepted only if the active towers pattern is made of neighbour towers as shown above, as Tau jets are much more collimated than QCD jets at the same E_T.

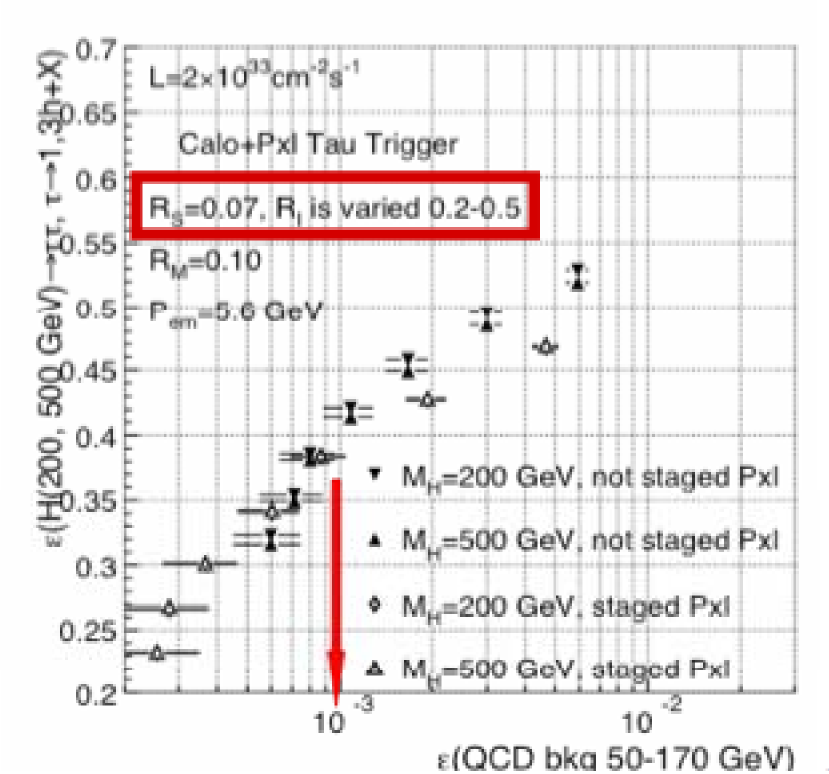
The performances have been computed on MSSM Higgs bosons, with a preselection at generator level.

Tau HLT

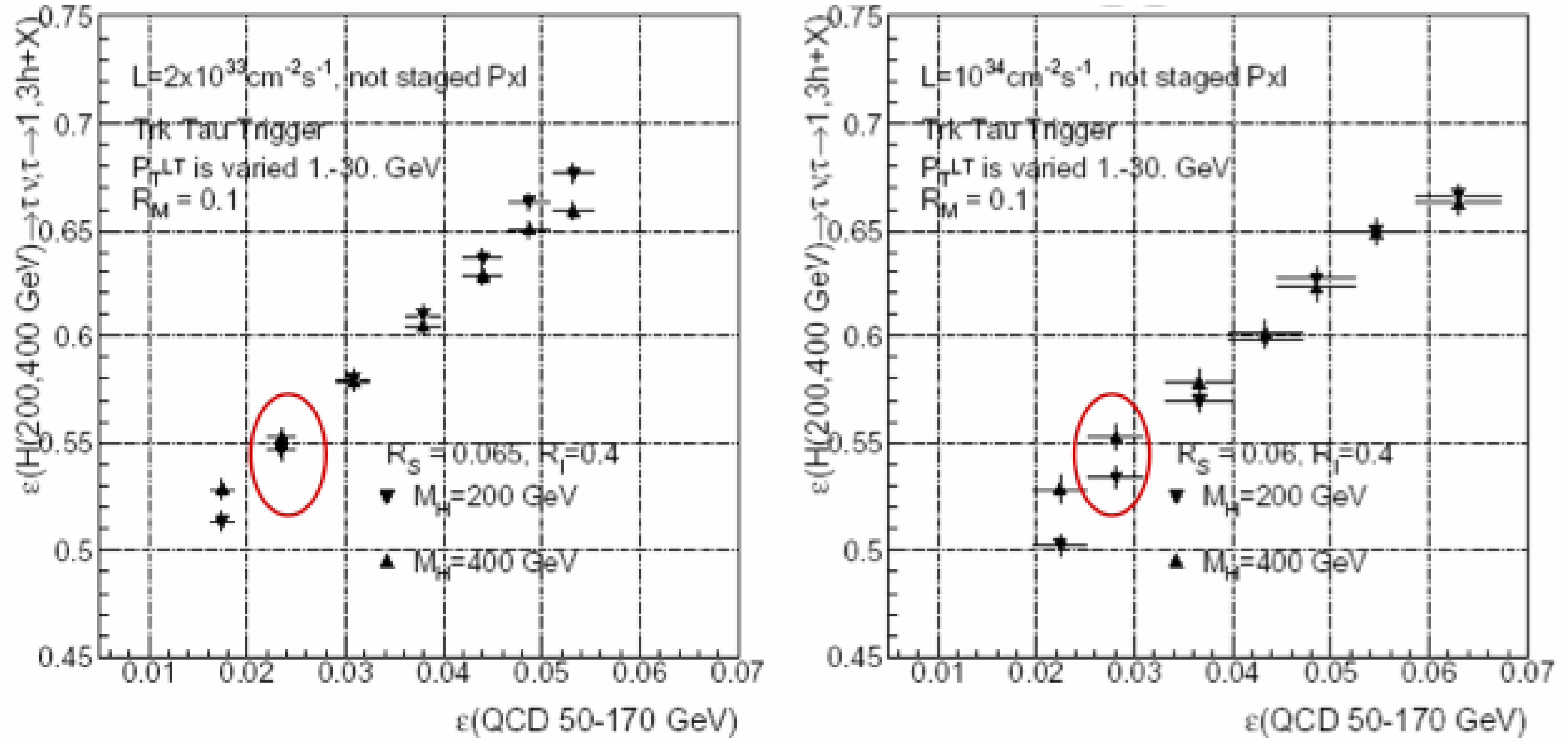
Tracks can be reconstructed with only the pixel layers or with also some microstrips layers. In the case of pixel only reconstruction, also the Level2 Calo isolation must be applied to get the final rate < 3 Hz.

(In the plot the Isolation Cone is varied from 0.2 to 0.5)





HLT for $H^{+} \to \tau\nu$ (CMS)



P_T of the leading track is varied from 1 to 30 GeV/c.

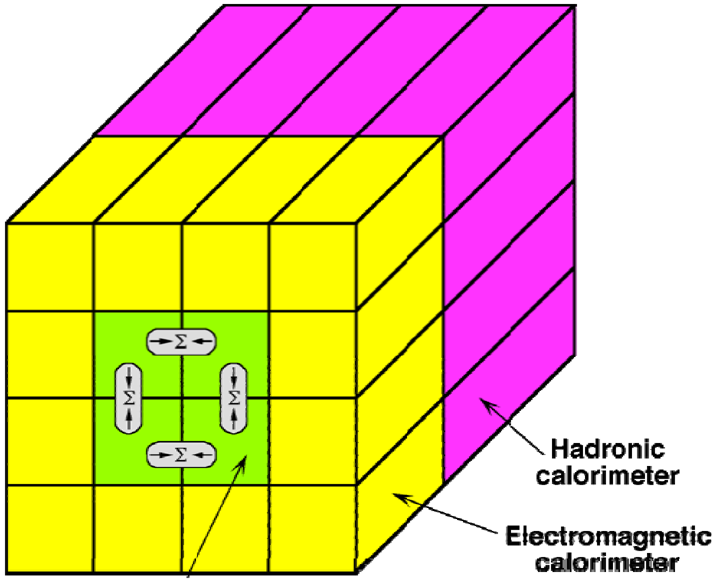
Background rejection by a factor ~ 30 can be achieved with signal efficiency of ~ 55% at both luminosities

(Off-line selection use a cut on P_T of leading track of about 80 GeV)

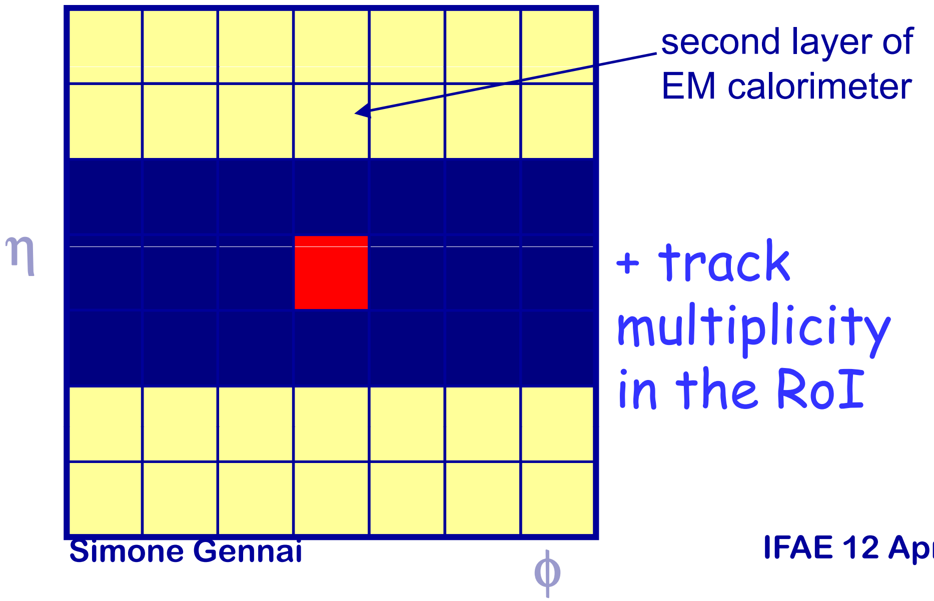
L1 Tau Trigger

as in the TDR

For | η|<2.5



LVL1 trigger:
look at 4X4 matrix of calorimetric towers ($\Delta\eta\Delta\phi$ = 0.1 x 0.1 each trigger tower).
E_T threshold for the central core (EM+Had) and isolation thresholds between core and 12 external towers for e.m. and had. calorimeters.



+ track multiplicity in the RoI

LVL2 trigger:
look at the shower shape in the 2nd layer of e.m. calorimeter and at the track multiplicity inside the RoI defined at LVL1.
Cut on the ratio between E_T contained in a 3x7 cell cluster and E_T in a 7x7 cell cluster and on track multiplicity

Tau Trigger

as in the TDR

LVL3 (Event Filter) :
look at the complete event.

- **number of reconstructed tracks, within DR = 0.3 of the candidate calorimeter cluster, between 1 and 3;**

- **cut on isolation fraction, defined as the difference between the E_T contained in a cone size of DR=0.2 and 0.1 normalized to the total jet E_T;**

- **cut on EM jet radius, an energy weighted radius calculated only in the e.m. calorimeter;**

- **cut on EM energy fraction, defined as the fraction of the total jet energy in the e.m. calorimeter;**

- **threshold on the p_T of the highest p_T track.**

TAU TRIGGER EVOLUTION: ATLAS case

For the LVL1 different RoI sizes are under study
(timing, resolution and efficiency,…)

LVL2 : Calorimeter based approach

(η,ϕ) from EMSamp2 Calo variables (more variables used than in the TDR)

Current approach

Tracking
(# of tracks, charge,…)

Final decision : matching of cluster and tracks, energy estimate

LVL2 :Tracking based approach

Perform tracking and obtain (η,ϕ)

New:studied for Very Low Lumi 10^{31} cm^{-2} s^{-1}

Calorimeter variables

Final decision : matching of cluster and tracks, energy estimate with energy flow

Under developing an EF tracking based algorithm.

The CMS HLT Exercise

The work of the OnSel group till the summer of 2007 ("HLT exercise") consists of:

- Implementing the L1 emulator and the HLT algorithms in CMSSW, and integrating them into consistent trigger paths
- Implementing pilot-run (with an emphasis on early physics, commissioning and monitoring triggers) menus
- Measuring the CPU-performance of the HLT

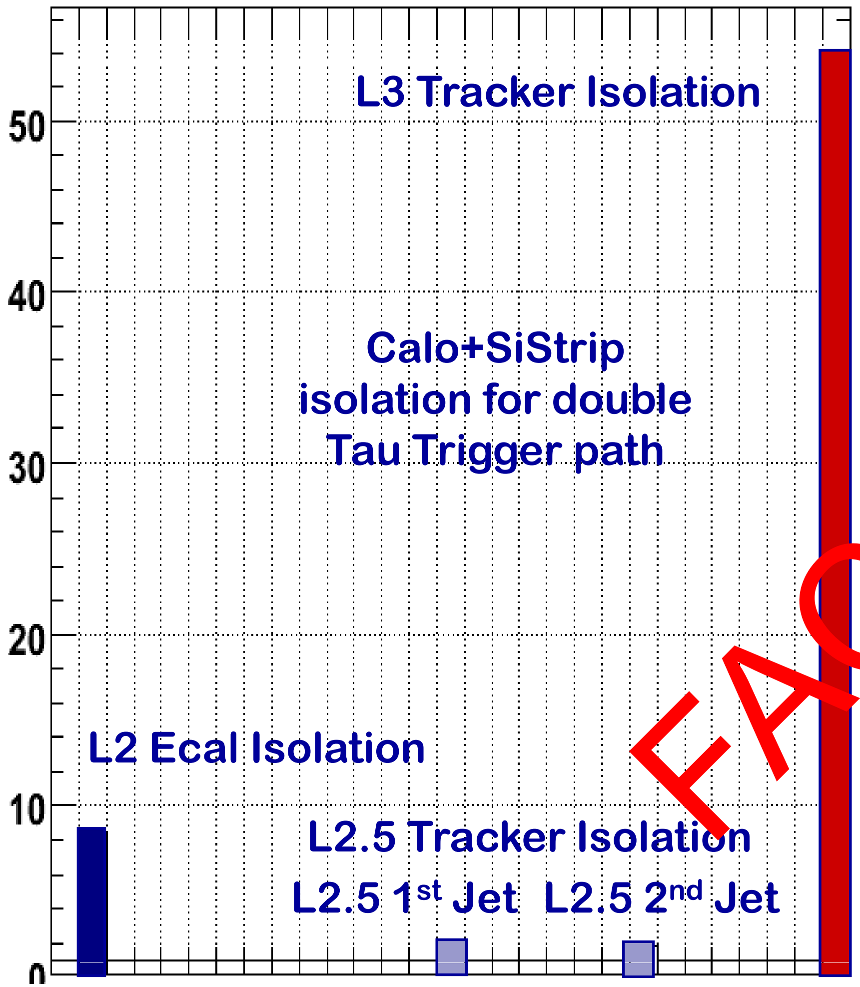
Example:

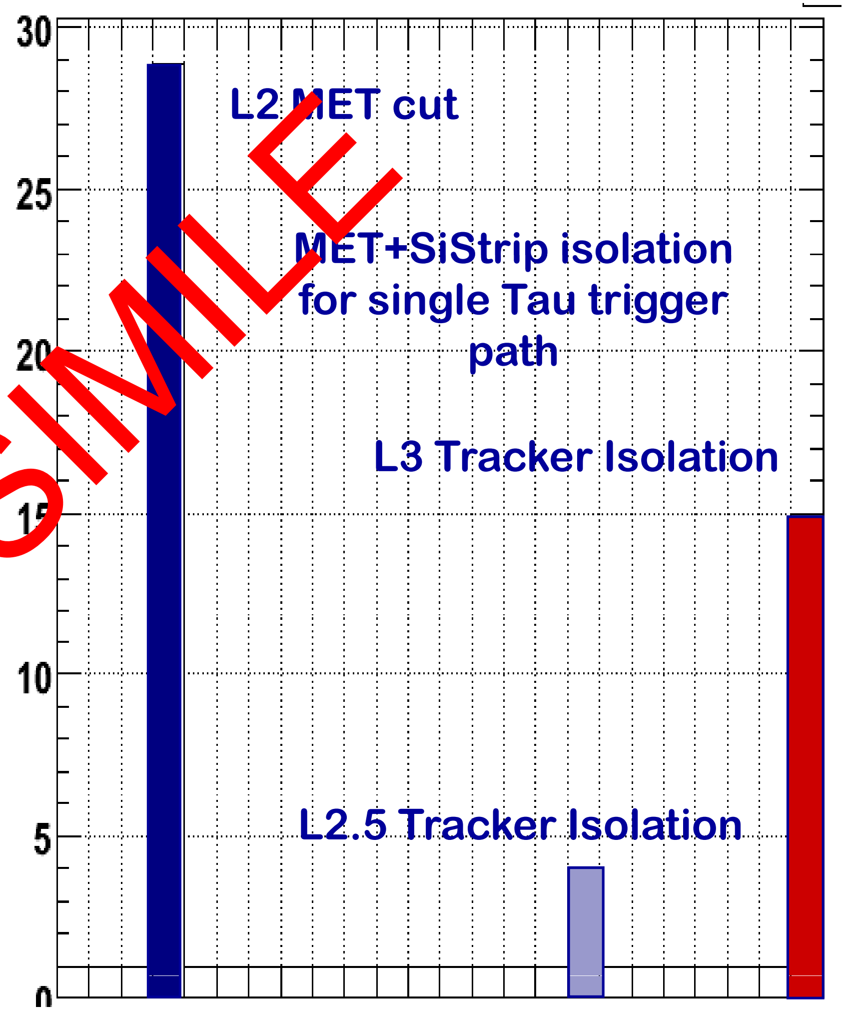
Trigger optimization and prospects for W $\rightarrow\tau$n with 100 pb^{-1} (few weeks of data taking at very low luminosity 10^{31}-10^{32} $cm^{-2}s^{-1}$)

Timing issue

- Up to the Physics TDR, the trigger performances were evaluated only in terms of Signal efficiency and background rejection
- As the Pilot run is approaching we have to optimize the timing performance.
  - 40 msec/Event is the “budget” we can spent at HLT
    - Reduce as soon as possible the bkg
    - Apply faster code than the one used in offline
    - Regional reconstruction and data unpacking becomes an Issue
- Some trigger paths have been partially re-designed in order to speed up the reconstruction and selection

Example of HLT filters





Trigger menu optimization, an example: W->$\tau\nu$

- Extract signal for most abundant source of t-leptons as early as possible. This requires a performant t and E_T^{miss} trigger from the very start!

  For L = 2x10[33], baseline plan is to trigger on τ25I + XE30 at LVL1 (for a rate of about 2 kHz) and to raise the thresholds to τ35i + xE45 at the HLT (for an output rate of about 5 Hz) .
- Measurment of W $\rightarrow\tau\nu$ / W $\rightarrow e\nu$ to confirm good understanding of trigger/reco/identification efficiencies
- E/p measurement in single-prong τ decay for calorimeter calibration.

Assumed that trigger chain is fully operational and that the detector operates more or less as expected (especially in terms of E_T^{miss} performance).

Efficiencies of ~ 80% for the t trigger and of ~ 50% for the id/reco of τ hadronic decays were assumed.

Expected rates for 100 pb^{-1}	W $\rightarrow \tau\nu$, $\tau\rightarrow$hadron	W $\rightarrow e\nu$	Z $\rightarrow \tau\tau$, 1$\tau\rightarrow$hadron
σ.B (pb)	11200	17300	1500
τ30i + xE35	~ 15000	~ 250000	~ 1300
τ20i + xE25	~ 60000	~ 560000	~ 3500

Conclusions

- Trigger at LHC is an integral part of the event selection
- CMS and ATLAS achieves a rejection factor of ~1000 at HLT from the L1 output
- HLT algorithms have the full event data available and no limitation on complexity, except for CPU time
- Inclusive triggers based on the presence on one or more objects above p_T/E_T thresholds are normally sufficient to get good efficiency on most signal
- More sophisticated selections are possible if necessary

The Trigger is not a static issue is always "pending".
It will be changed accordingly to the Luminosity and physics indication

References

- **CMS DAQ/HLT TDR, 2002, CERN-LHCC-2002-026**
  - Full study of HLT rates, timing, benchmark signal efficiencies
- **CMS Physics TDR Volume 1 (2006), CERN-LHCC-2006-001**
  - Detector performance, reconstruction
- **CMS Physics TDR Volume 2 (2006), CERN-LHCC-2006-021,**
  - Update of HLT rates and trigger tables (Appendix E)

- **ATL-COM-DAQ-2003-030**

BACKUP SLIDES

EFFECT OF TRIGGER SELECTIONS

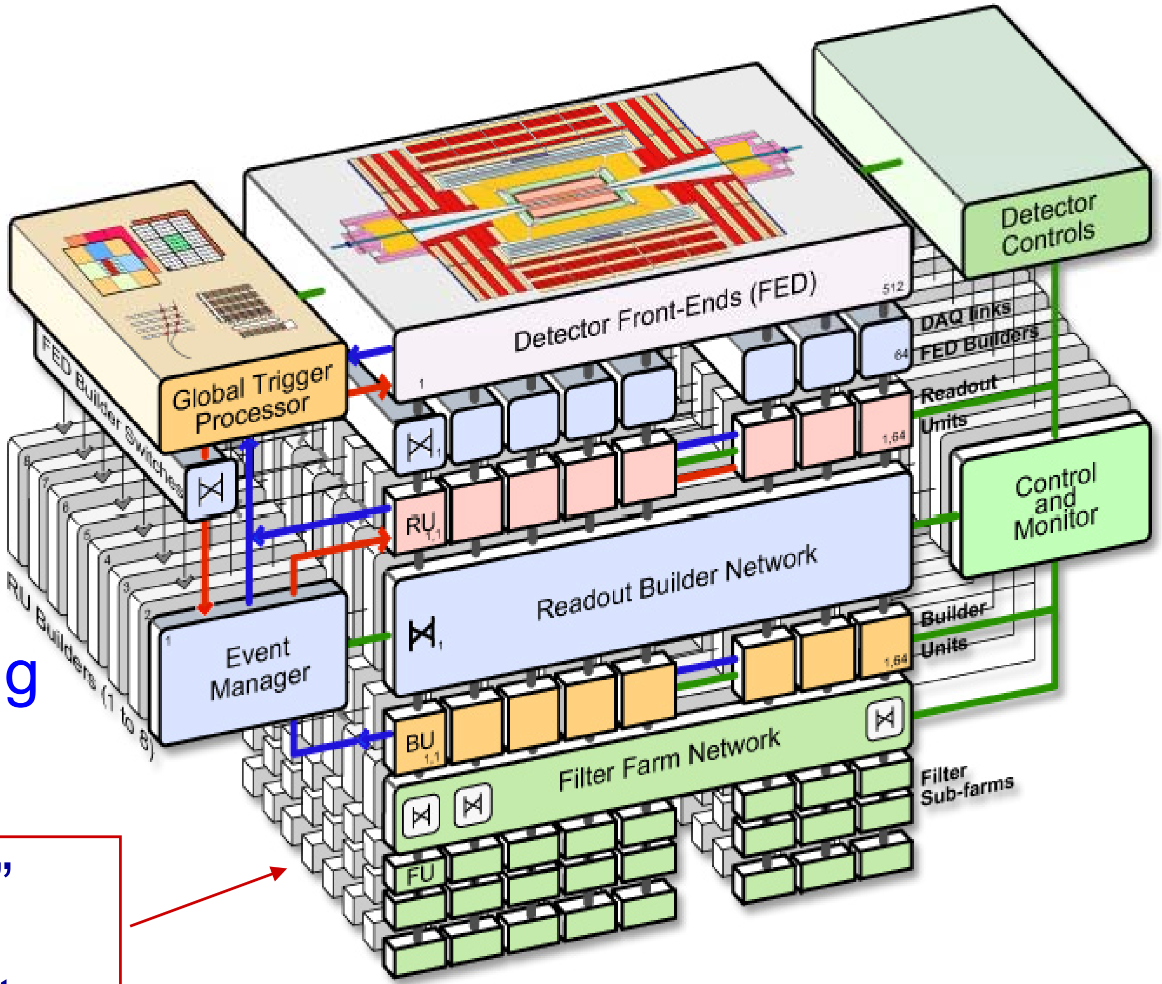
E_T core EM iso HAD iso

Cumulative Cuts Applied	$Z^0 \rightarrow \tau^+\tau^-$ With Pileup (%)	Jet Efficiency With Pileup (%)
L1:20/10/10	25.8±0.3	14.1±0.2
L2:0.9/4	53.5±0.9	15.3±0.6
L3:Number of tracks (1-3)	90.2±1.8	84.3±4.2
L3:Isolation fraction (<0.3)	81.7±1.7	64.8±3.5
L3:EM radius (<0.15)	76.9±1.6	55.0±3.1
L3:EM fraction (>0.6)	65.9±1.4	45.1±2.7
L3:P_T track 1 (>10)	46.5±1.1	17.3±1.5
L1:30/10/10	9.6±0.2	4.3±0.1
L2:0.9/4	55.7±1.5	15.8±1.0
L3:Number of tracks (1-3)	91.8±2.9	81.8±7.4
L3:Isolation fraction (<0.3)	86.0±2.8	65.7±6.3
L3:EM radius (<0.15)	82.4±2.7	59.5±5.9
L3:EM fraction (>0.6)	70.9±2.4	46.0±4.9
L3:P_T track 1 (>10)	52.0±2.0	19.7±2.9

DAQ

L1

Event building

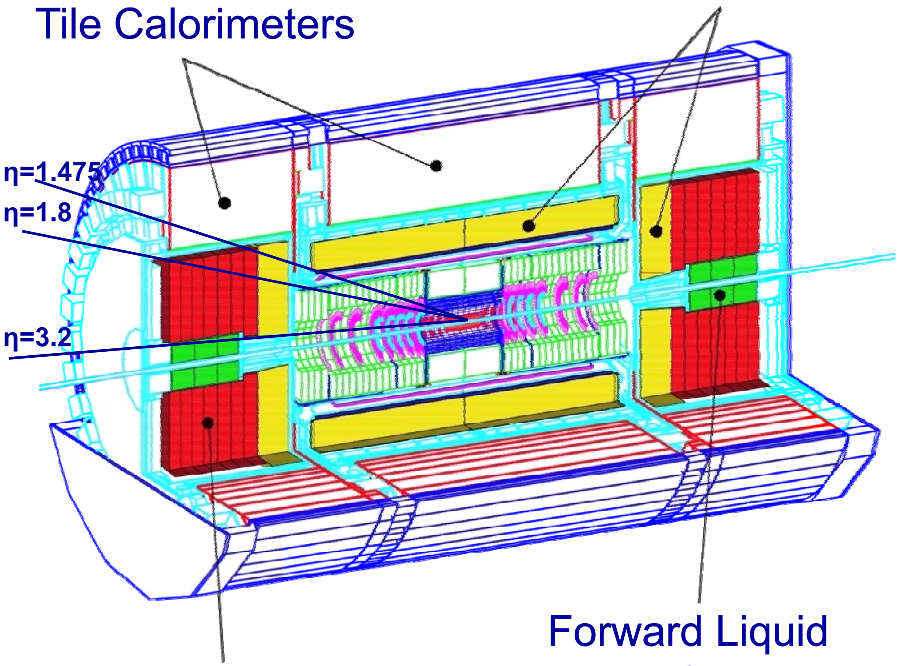


Modular, 8 "slices"

4 to be installed at startup

HLT farm (O(2000 CPU))

Sistema calorimetrico di



$$\frac{\sigma}{E} = \left(\frac{41.9\%}{\sqrt{E}} + 1.8\%\right) \oplus \frac{1.8}{E}$$

EM LAr $|\eta| < 3$:

Pb/LAr 24-26 X_0

3 sezioni longitudinali 1.2 λ

$\Delta\eta\times\Delta\varphi = 0.025 \times 0.025$ – 1% equal.

Central Hadronic $|\eta| < 1.7$:

Fe(82%)/scintillatore(18%)

3 sezioni longitudinali 7.2 λ

$\Delta\eta\times\Delta\varphi = 0.1 \times 0.1$

End Cap Hadronic $1.7 < \eta < 3.2$:

Cu/LAr – **4 sezioni longitudinali**

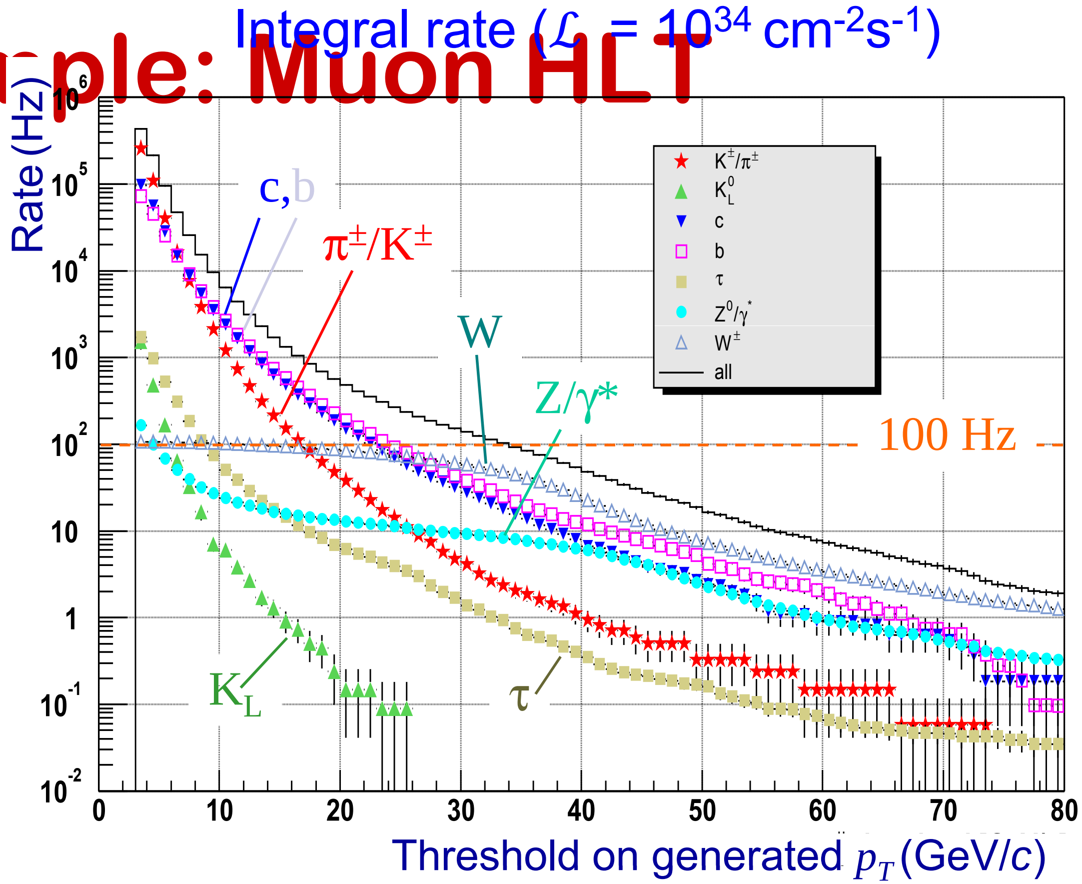
$\Delta\eta\times\Delta\varphi < 0.2 \times 0.2$

Forward calorimeter $3 < \eta < 4.9$:

EM Cu/LAr – HAD W/LAr

3 sezioni longitudinali

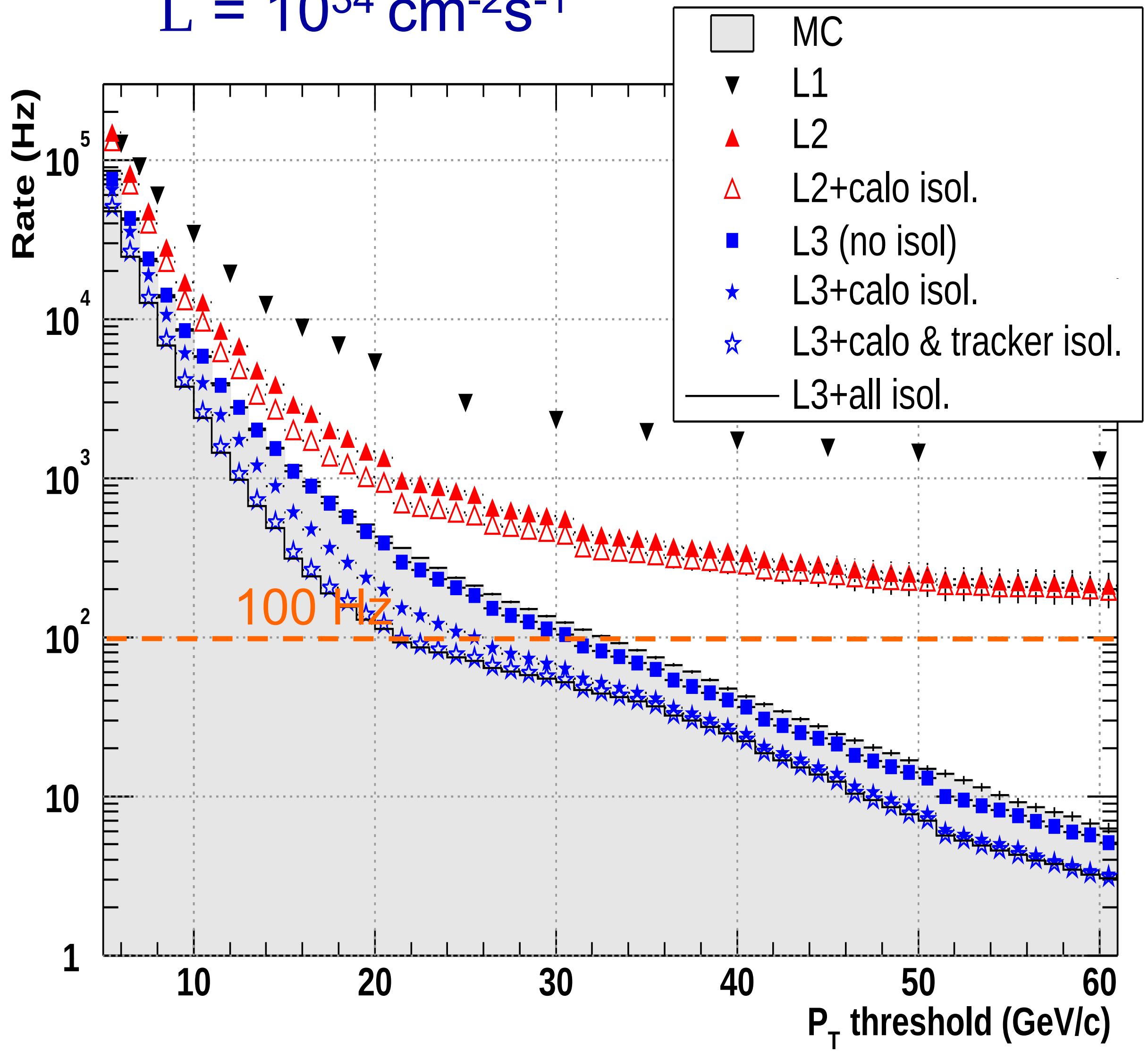
Example: Muon HLT



- **Key is to achieve the best p_T resolution (and suppress non-prompt muons and b,c decays)**

Single Muon Rates

$\mathcal{L} = 10^{34}\ cm^{-2}s^{-1}$



L2,L3 reduce the rate by improving the p_T resolution

- L2 is justified as it reduces the rate to allow more time for processing data from the tracker

Some HLT Efficiencies

At low luminosity, relative to events in detector acceptance:

$W \to e\nu$	68%
$W \to \mu\nu$	69%
$Z \to \mu\mu$	92%
$Z \to ee$	90%
$tt \to \mu+X$	72%
$H(115\ GeV) \to \gamma\gamma$	77%
$H(150) \to ZZ \to 4\mu$	98%
$H(120) \to ZZ \to 4e$	90%
$A/H(500\ GeV) \to 2\tau$	45%
$H^{+}(200\text{-}400) \to \tau^{+}\nu$	50%

Summary:

→ LVL1 and LVL2 selection (calo+tracks) emulated
for $W \rightarrow \tau\nu$ analysis

→ With rather soft selection ETmiss > 20 GeV + EMTauRoI > 20 GeV
estimated for 10^31:
60 Hz after LVL1
5 Hz after LVL2

→ For off-line analysis start with
S/B ~ 0.002 ~ 10^5 signal events accepted for 100pb-1
Increasing E_T^{MISS} threshold helps in the background rejection:
at 60 GeV threshold, supression 10^2-10^3 at 10% efficiency.

→ Offline tau selection has to do the final work to extract the signal.

Low luminosity provides unique opportunity to study low energy τ hadronic signatures in ATLAS (in view of SUSY) : important possibility to verify the understanding of tauID and E_T^{MISS} reco before attacking "New Physcics".