On-line Selection in the CMS Experiment

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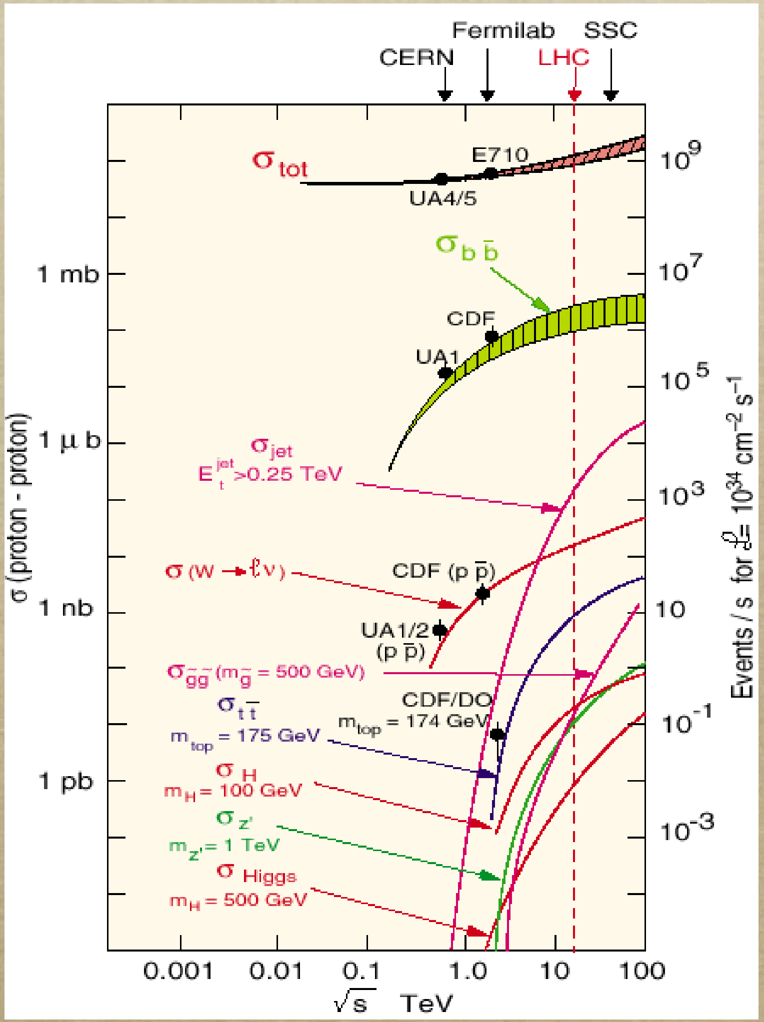
Outline:
- *Physics requirements.*
- *Trigger strategy.*
- *Physics objects selection.*
- *Performance & Conclusions.*

Only luminosity of 2×10^{33} is considered.

Trigger Requirements

pp Cross Section and Events Rate

- *$\sqrt{s}$ = 14 TeV*
- *Luminosity = $2x10^{33}$ $cm^{-2}s^{-1}$ (2007)*
  10^{34} $cm^{-2}s^{-1}$ (by 2010)
- *Interactions/xing = 5 @ $2x10^{33}$*
  20 @ 10^{34} $cm^{-2}s^{-1}$
- ***σ(pp)** inelastic = 80mb*
- *Interaction rate = 140 MHz @ $2x10^{33}$*
  700 MHz @ 10^{34}
- Δt = *25ns*

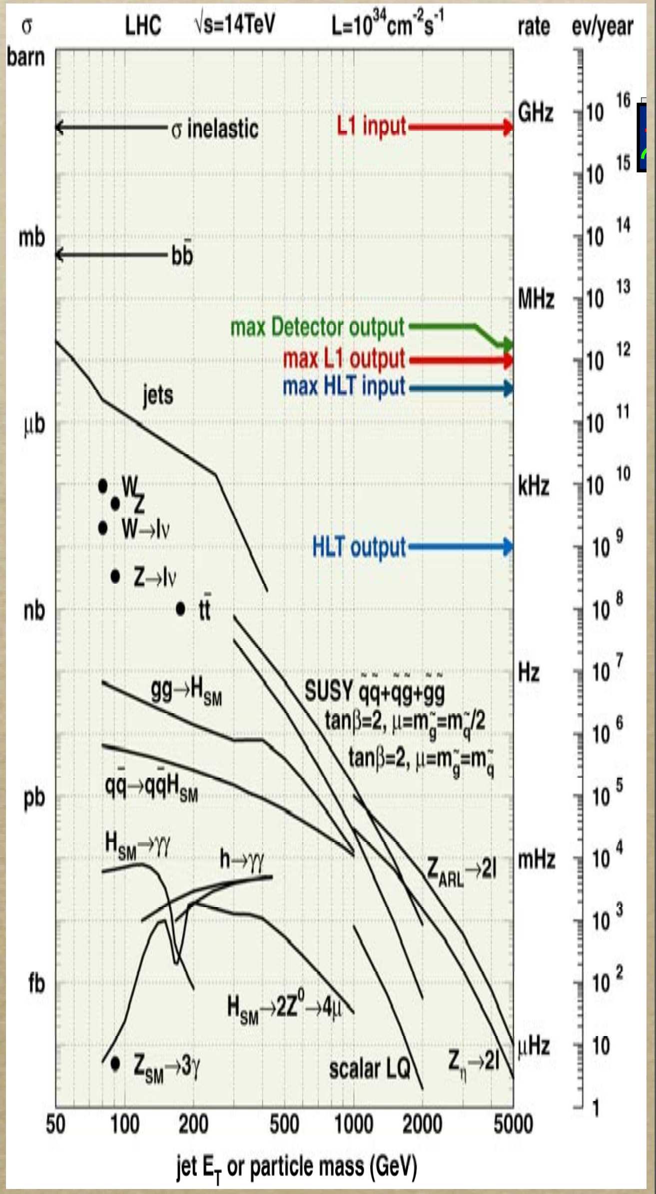


High event rate dominated by minimum bias events.

Physics requirements

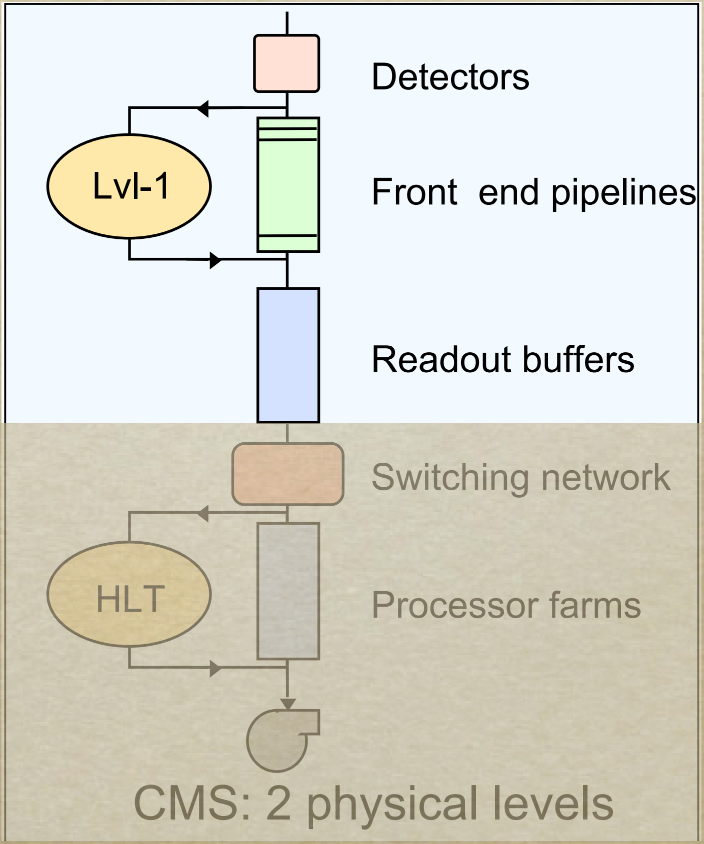
Trigger requirements are driven by physics:

- *Maximize signal efficiencies for interesting physics signatures.*
- *Share the available bandwidth among all possible HLT streams.*
- *Flexibility to adapt to change in running conditions.*
- *Possibility to compute trigger efficiencies from data.*
- *Dedicated streams for detector calibration & DQM.*



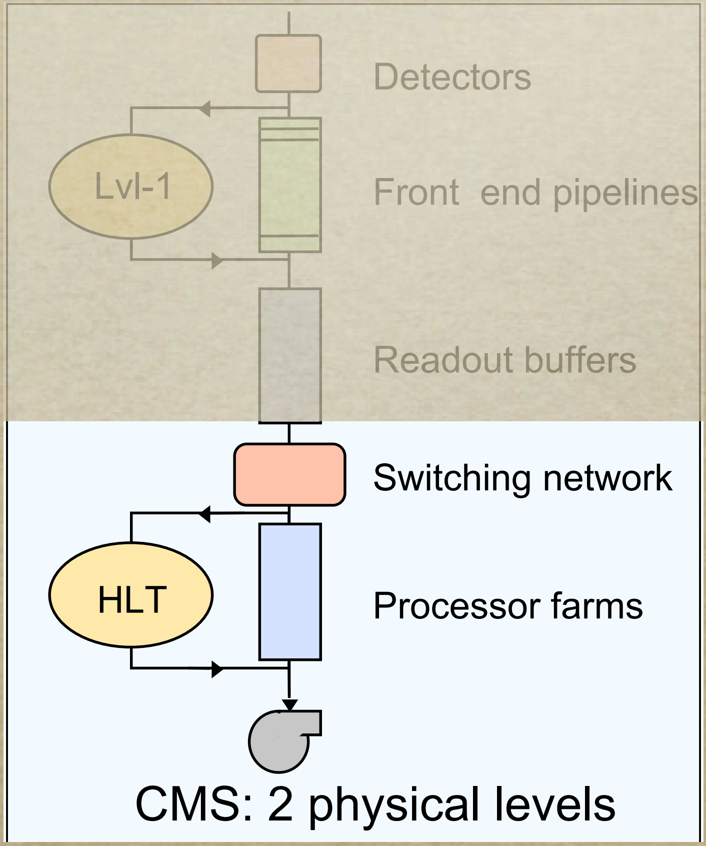
Level-1 Trigger

- *Input rate 40 MHz*
- *can store 3μs data in pipelines (~ 120 continuous crossings):*
  - *< 1μs for reading and processing.*
  - *~ 2μs latency to transfer the information (FE->L1T).*
- *Only process data from calorimeters and muons chambers.*
- *This data is only coarse granularity, i.e. lower resolution.*
- *100 KHz L1 output at full designed performance (assuming a data size =1Mb/b.c.).*
- *High rejection factor (~400).*



High Level Trigger

- *Data stored in commercial random-access memories.*
- *Limitation on storage ability and reconstruction: maximum output rate 100-150Hz to be written on disk.*
- *About 1000 dual-CPU processors receiving data from about 700 FE modules at a sustained bandwidth of 100kHz×1Mb =100GB/s.*



Trigger Strategy

HLT Optimization

Multi-level selection strategy and reconstruction on demand:

- *There is one single HLT entity (the HLT farm).*
  - *Nevertheless selection is optimized: reconstructed only parts of the events that can be used for fast selection.*
- *electron/photon example*
  - *Level-2: based on calorimeter information only.*
  - *Level-2.5: partial track information (pixel match to the electromagnetic cluster)*
  - *Level-3: full tracks information.*
- *Partial event reconstruction starting from Level-1 information: the muon track is extrapolated from the muon system to the inner tracker only in a region of interest pointed by the Level-1.*
- *Use well defined L1 conditions (i.e. no volunteers) for well defined efficiencies.*

Level-1 trigger table

Trigger	Level-1 Threshold (GeV)	Level-1 Rate (kHz)	Cumulative Level-1 Rate (kHz)
Inclusive $e\gamma$	22	3.9 ± 0.3	3.9 ± 0.3
Double $e\gamma$	11	1.0 ± 0.1	4.6 ± 0.3
Inclusive μ	14	2.5 ± 0.2	7.1 ± 0.3
Double μ	3	4.0 ± 0.3	11.0 ± 0.4
Inclusive τ	100	2.2 ± 0.2	12.9 ± 0.5
Double τ	60	3.0 ± 0.2	14.9 ± 0.5
1-,2-,3-,4-jets	150,100,70,50	2.2 ± 0.2	15.8 ± 0.5
H_{T}	275	2.0 ± 0.2	16.2 ± 0.5
$E_{\mathrm{T}}^{\mathrm{miss}}$	60	0.4 ± 0.1	16.3 ± 0.5
$H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$	200, 40	1.1 ± 0.1	16.6 ± 0.5
jet + $E_{\mathrm{T}}^{\mathrm{miss}}$	100, 40	1.1 ± 0.1	16.7 ± 0.5
$\tau + E_{\mathrm{T}}^{\mathrm{miss}}$	60, 40	2.7 ± 0.2	18.8 ± 0.5
$\mu + E_{\mathrm{T}}^{\mathrm{miss}}$	5, 30	0.3 ± 0.1	19.0 ± 0.6
$e\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$	15, 30	0.5 ± 0.1	19.1 ± 0.6
μ + jet	7, 100	0.2 ± 0.1	19.1 ± 0.6
$e\gamma$ + jet	15, 100	0.6 ± 0.1	19.2 ± 0.6
$\mu + \tau$	7, 40	1.2 ± 0.1	19.8 ± 0.6
$e\gamma + \tau$	15, 60	2.6 ± 0.2	20.5 ± 0.6
$e\gamma + \mu$	15, 7	0.2 ± 0.1	20.5 ± 0.6
Prescaled			22.3 ± 0.6
Total Level-1 Rate			22.3 ± 0.6

Luminosity of $2\times10^{33}cm^{-2}s^{-1}$

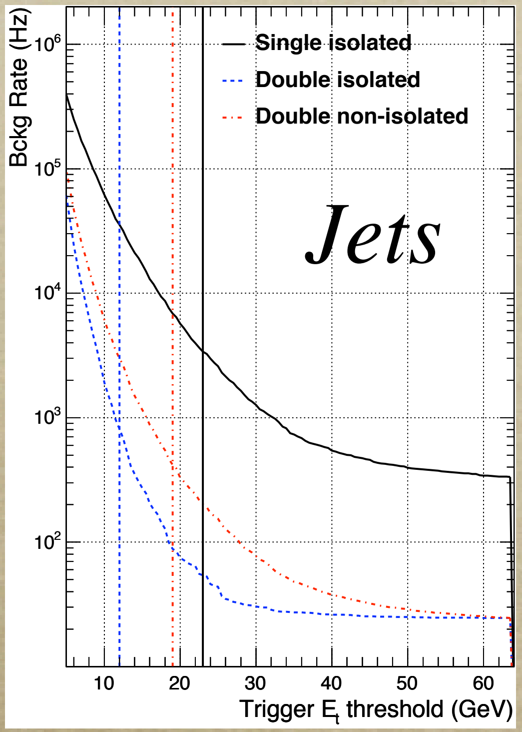
Include safety margin!

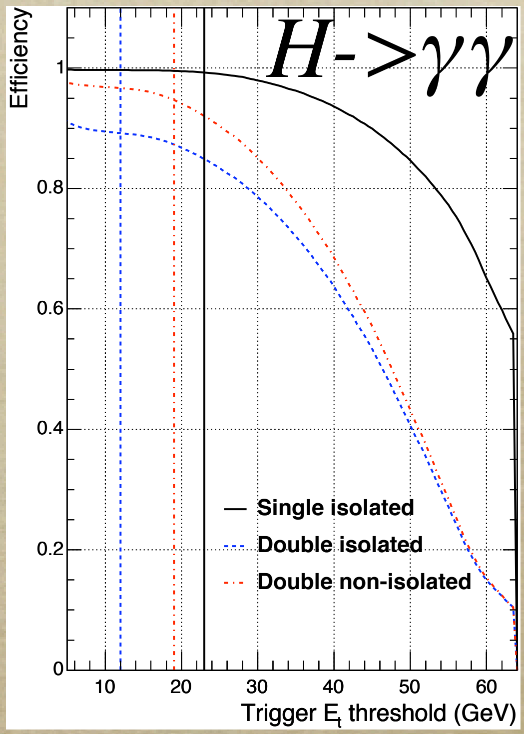
Trigger Objects and Selection

Electron/Photon

✓ *Different types of energy deposition with increasingly tighter cuts on isolation: isolated, non-isolated and unidentified.*

✓*Three streams output from L1: single isolated, double isolated, double non-isolated.*



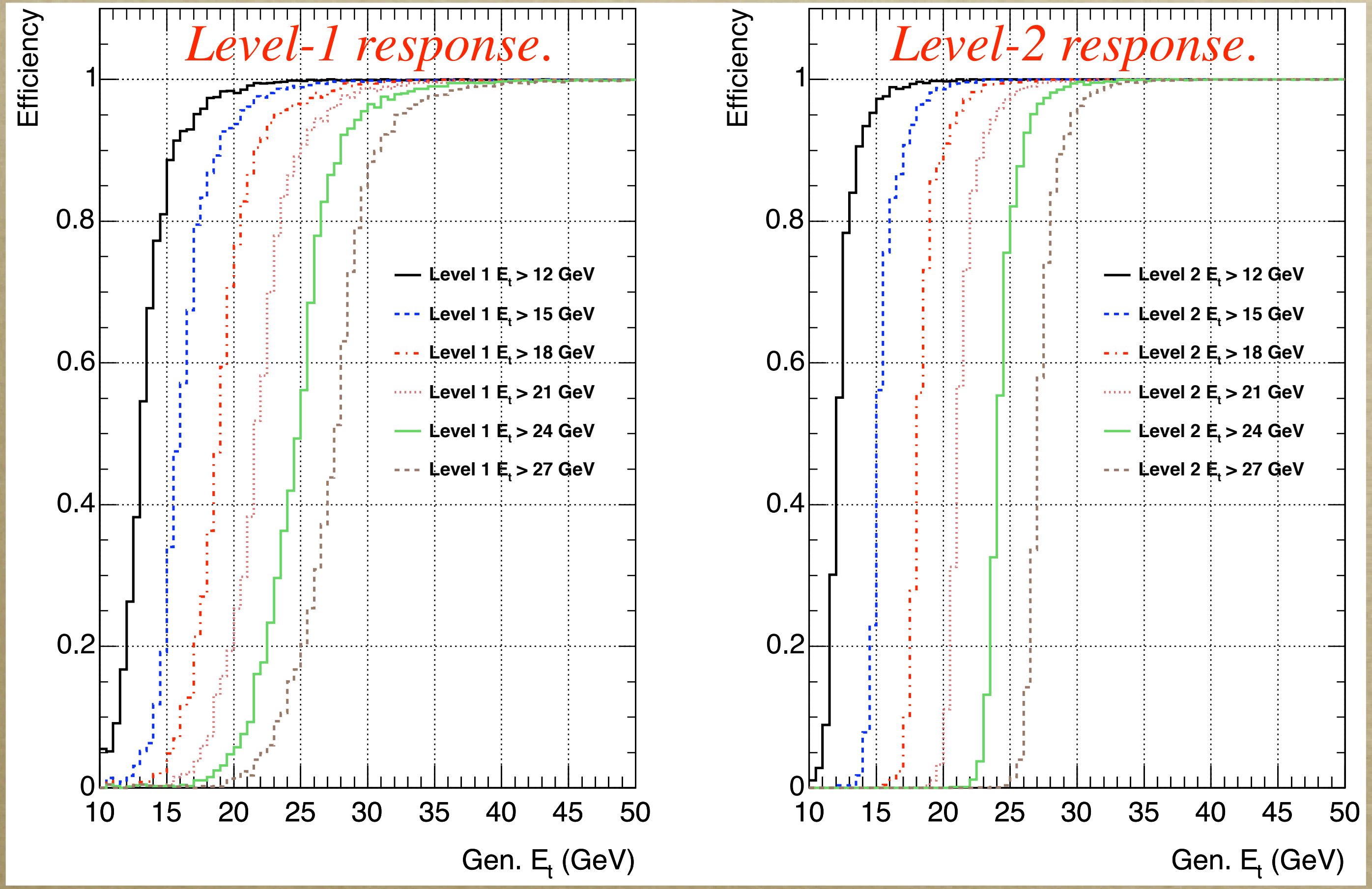


Efficiencies:

Signal Process	Single isolated	Double isolated	Double non-isolated	Total
$H \to \gamma\gamma$ ($M_H = 120$ GeV)	99.3%	89.2%	94.7%	99.7%
$H \to ZZ \to e^+e^-e^+e^-$ ($M_H = 120$ GeV)	90.8%	89.5%	79.5%	96.5%
$Z \to e^+e^-$	93.5%	81.0%	85.1%	97.1%
$W \to e\nu$	89.8%	2.7%	2.0%	90.0%

Electron/Photon (Level-2)

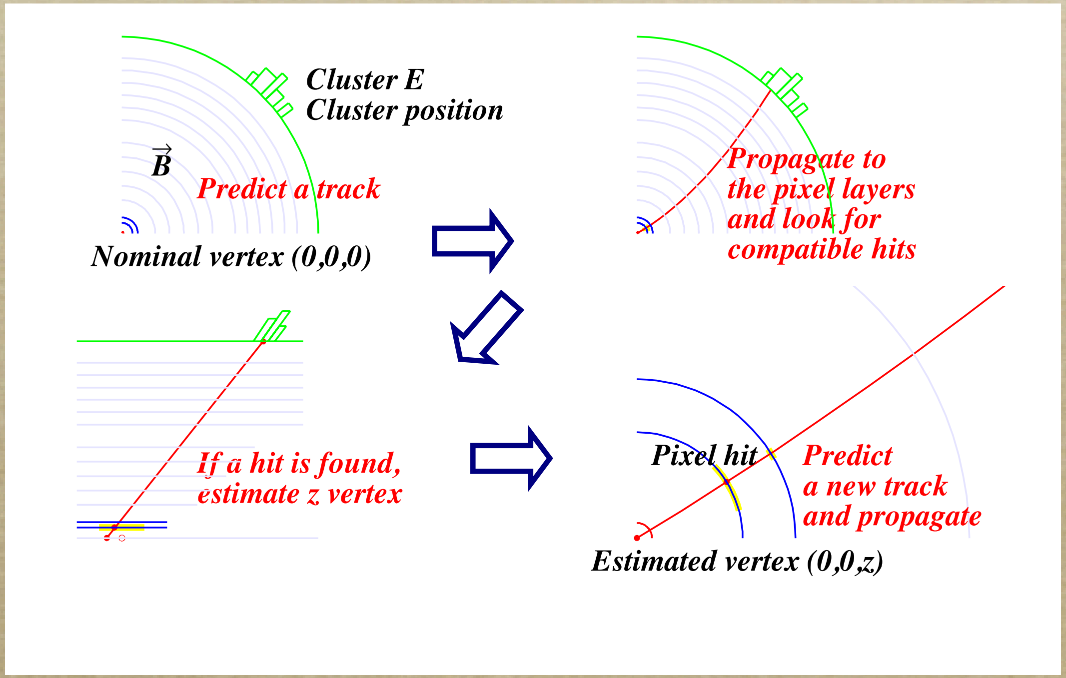
Level-2 confirms Level-1 decision.



- ✓ *At Level-2 electromagnetic clusters are reconstructed improving the resolution (sharper turn-on curves).*
- ✓ *Efficiencies computed with respect to electrons/ photons generated in the fiducial ECAL volume and matching a trigger candidate (~100% efficiency).*

Electrons (Level-2.5)

- ✓ *Partial use of tracking information.*
- ✓ *Fast!*
- ✓ *High rate reduction.*
- ✓ *Photon candidates pass the level 2.5 regardless of the pixel information.*

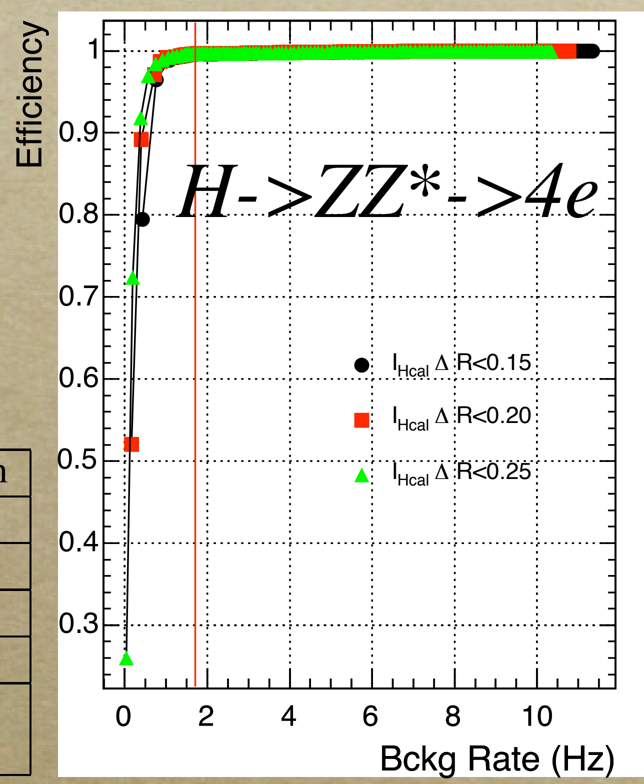


Electrons (Level-3)

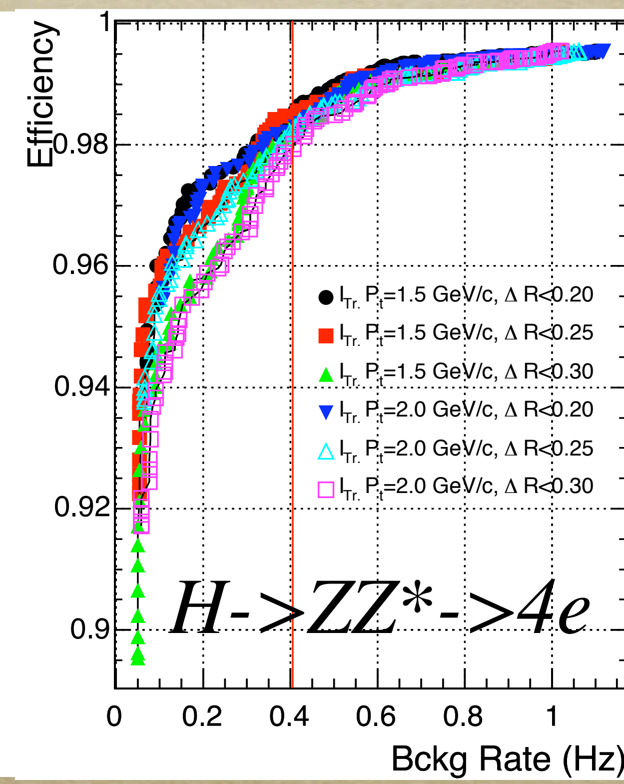
- ✓ *Full tracking information available.*
- ✓ *Isolation variables based on ECAL, HCAL, TRACKER information.*
- ✓ *Significant improvements w.r.t DAQ TDR.*

Background rejection vs. signal efficiency

HCAL Isolation



TRACK Isolation



Variable	Single electron	Double electron
$\lvert\eta\rvert$	< 2.5	< 2.5
E_t	> 26 GeV	> 12 GeV
HCAL Isolation	< 3 GeV	< 9 GeV
Track Isolation	< 0.06	< 0.4
E/P (Barrel)	< 1.5	–
E/P (Endcaps)	< 2.45	–

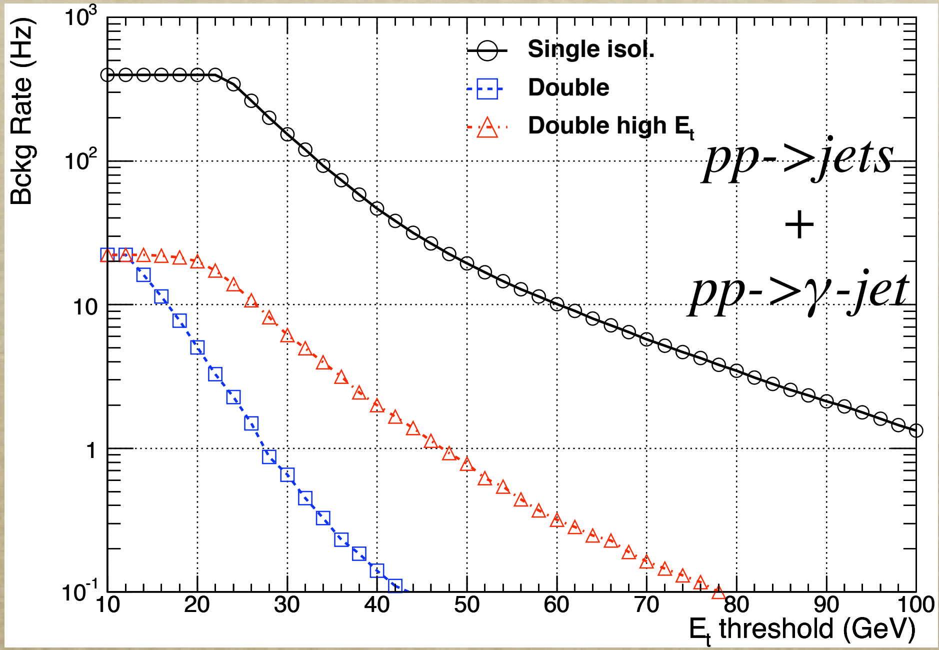
Photons (Level-3)

✓ *Photons have a large background coming from decays of high Et particles (π^0).*

✓ *Isolation criteria and Et cuts allow to reject a big fraction of this background.*

✓ *Nevertheless there is interesting data below 80 GeV (efficiencies studies, calibration studies, background studies for H->$\gamma\gamma$).*

✓ *Prescaling below the 80 GeV is a solution.*



Variable	Single photon	Double photon
$\lvert\eta\rvert$	< 2.5	< 2.5
E_t	> 80 GeV	$> 30, 20$ GeV
Track isolation	$= 0$	< 3
HCAL isolation (Barrel) HCAL isolation (Endcaps)	< 6 GeV < 4 GeV	< 8 GeV < 6 GeV
ECAL Isolation	< 1.5 GeV	< 2.5 GeV

Electron/photon Trigger Rates

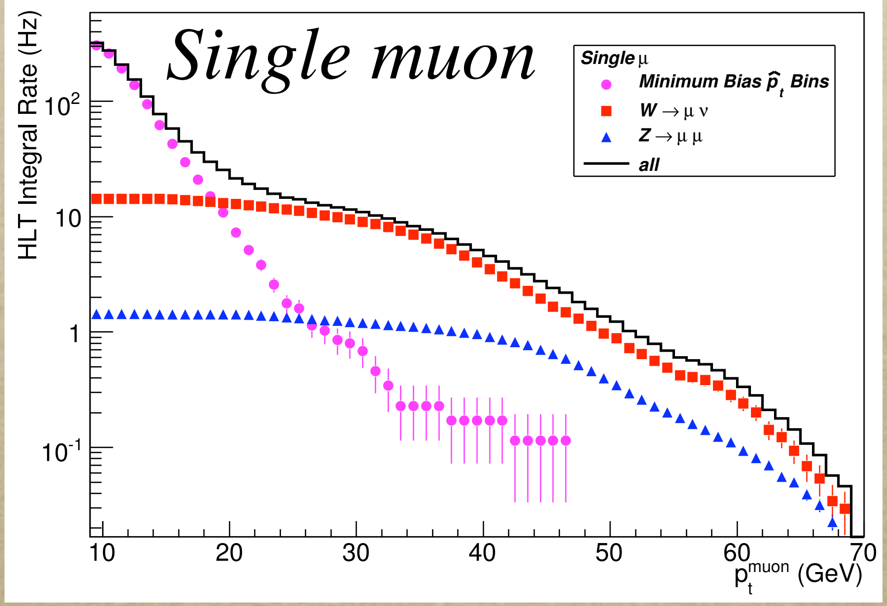
~20 Hz in DAQ TDR, i.e. 20% of the total rate!

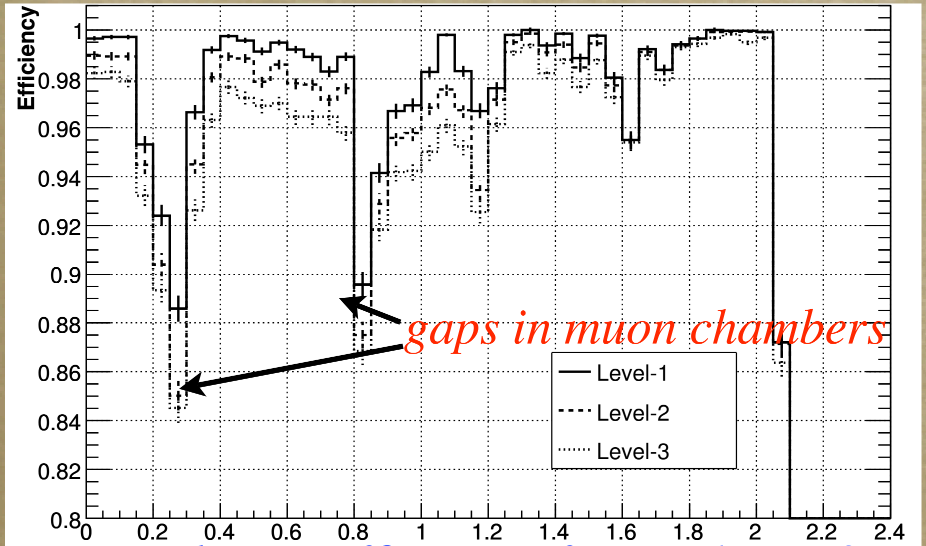
	Signal	LO	NLO	Background		Total
Single electron (E_t >26 GeV)	$W \to e\nu$ $Z \to e^+e^-$	9.8 Hz 1.3 Hz	(11.6 Hz) (1.5 Hz)	Jets	9.4 Hz	21 Hz
Double electron (E_t^1, E_t^2 >12 GeV)	$Z \to e^+e^-$	1.1 Hz	(1.3 Hz)	Jets	0.8 Hz	1.9 Hz
Single photon (E_t >80 GeV)	γ + jet	2.1 Hz		Jets	1.4 Hz	3.5 Hz
Double photon (E_t^1 >30, E_t^2 >20 GeV)		~0 Hz		Jets γ + jet	1.9 Hz 0.4 Hz	2.3 Hz
Total:		13.3 Hz			13.9Hz	27.2 Hz

- *Possible improvements without much degradation of the signal efficiencies are possible if needed.*
- *General improvement with respect to the DAQ TDR.*

Muon Streams

✓ *Level-1: match DT, CSC and RPC tracks segments.*
✓ *Level-2: stand-alone muon (with seed from Level-1) pointing to interaction vertex + Pt cut and calorimeter isolation.*
✓ *Level-3: full tracker information (seed from Level-2). At least 5 silicon hits (pixel or strips) + track isolation.*





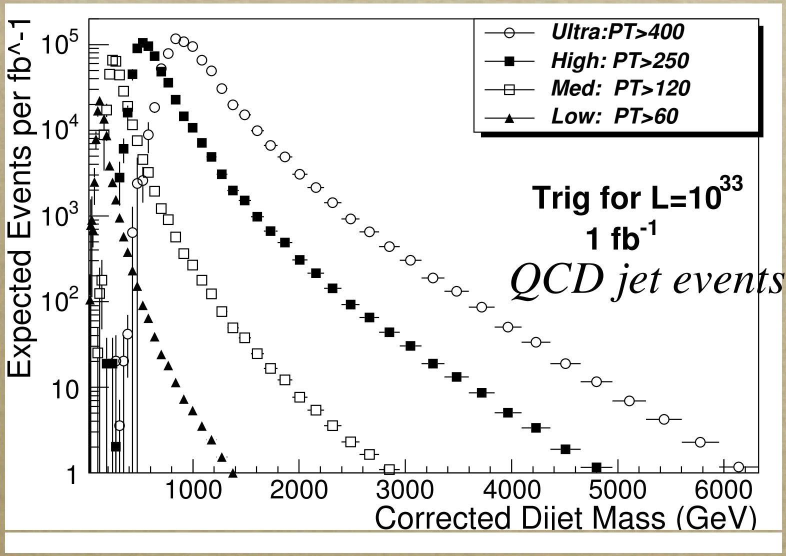
Cumulative efficiency from L1 to L3

✱ Trigger	Threshold (GeV)	Rates (Hz)		
		Enriched-μ sample	$W \longrightarrow \mu\nu$	$Z \longrightarrow \mu\mu$
Inclusive μ	19	10.9 ± 0.8	13.4 ± 0.3	1.5 ± 0.0
Relaxed μ	37	5.1 ± 0.5	5.7 ± 0.1	1.1 ± 0.0
μ-μ	7, 7	3.4 ± 0.4	—	1.3 ± 0.0
Relaxed μ-μ	10, 10	7.1 ± 0.5	—	1.4 ± 0.0

✱ *Relaxed=no requirement on isolation.*

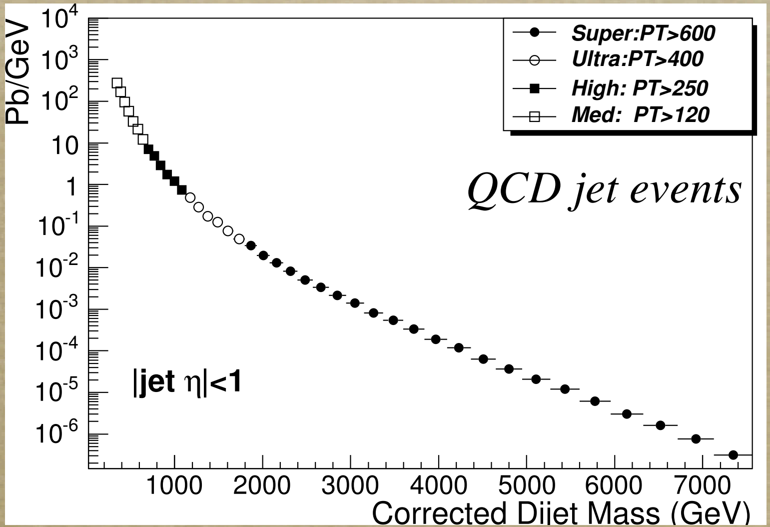
Single Jet Triggers

✓HLT jets: iterative seed jet cone algorithm. It helps reducing low Et jets from pileup and noise.
✓ Jet energy response varies with eta; energy scale corrections are implemented.



✓ Total output ~ 10Hz divided in ***at least*** three <u>overlapping</u> streams with different Et thresholds and proper <u>prescale factor</u>.

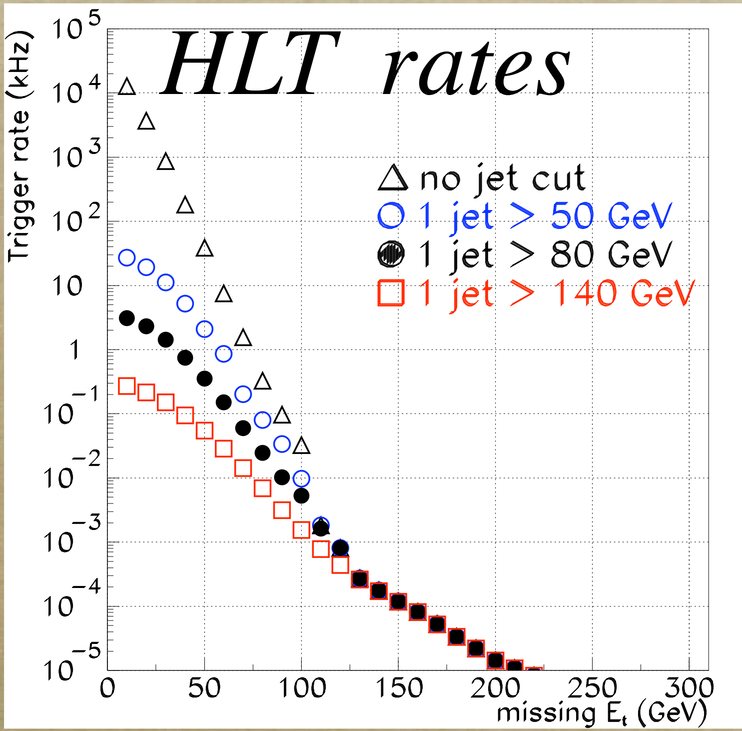
✓ Level-1 threshold designed such that at the HLT threshold, the efficiency is ~95%. This guarantees that most of the collected data can be used in analyses.



✓ Large di-jet mass spectrum (up to 6 TeV) is covered by the combination of these triggers.
✓From the regions where at least one trigger is fully efficient, the di-jet mass spectrum can be reconstructed.

Missing Et

- ✓*Calorimeter information is used to measure the missing Et.*
- ✓ *Negative vector sum of energies (above a given threshold) in all the calorimeter towers.*
- ✓*Large background from inclusive di-jet production where one jet is not well measured, use phi-correlation to reject this background.*



τ-lepton Trigger (I)

- ✓*The level-1 rate is dominated by QCD jets.*
- ✓*Single and double τ triggers optimized for SUSY searches (H^0->$\tau\tau$).*
- ✓*HLT τ-jets are reconstructed by the calorimeters in a region given by the Level-1.*

Level-1 rates from QCD jets background

$\hat{p}_T$, GeV/c	cross section, fb	Rate, kHz		
		single τ	double τ	single or double τ
30-50	1.56×10^{11}	0.04	0.08	0.12
50-80	2.09×10^{10}	0.59	0.70	1.19
80-120	2.94×10^{9}	1.32	0.75	1.65
120-170	5.00×10^{8}	0.46	0.16	0.48
170-230	1.01×10^{8}	0.10	0.03	0.10
230-300	2.39×10^{8}	0.02	0.007	0.021
total rate		2.53	1.73	3.56

- ✓*After the jets are reconstructed, τ-jet tagging is performed.*
- ✓*In order to contain the rate, two jets have to be tagged.*

τ-lepton Trigger (II)

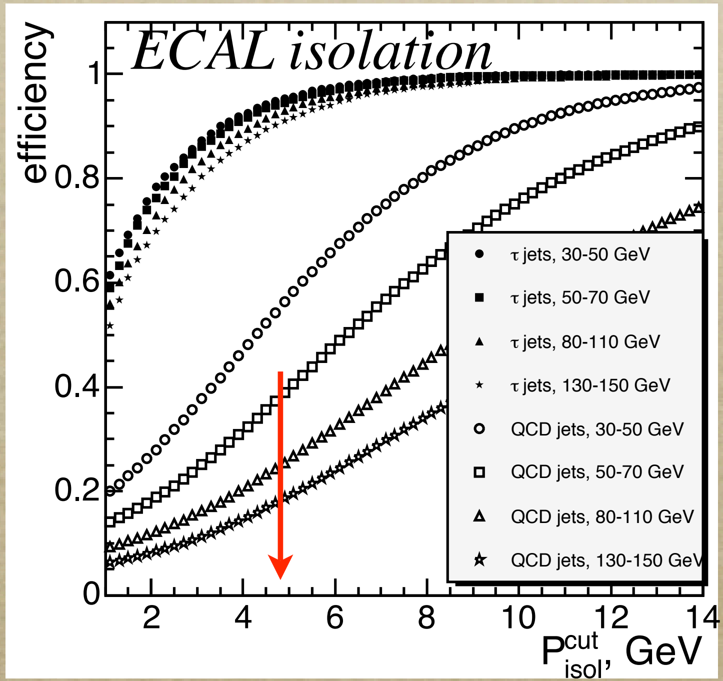
Types of τ-jet tagging used at the HLT:

$$P_{isol} = \sum_{\Delta R<0.40} E_T - \sum_{\Delta R<0.13} E_T$$

I) ECAL isolation: performs sum of the transverse energy in a cone . A veto region around the jet direction is excluded from the sum.

II) Pixel Isolation: isolation in the pixel detector is performed by reconstructing tracks with consistent hits in all pixel layers.

III)Track Isolation: isolation is performed using full track information only in a region defined around the calorimeter jet direction.

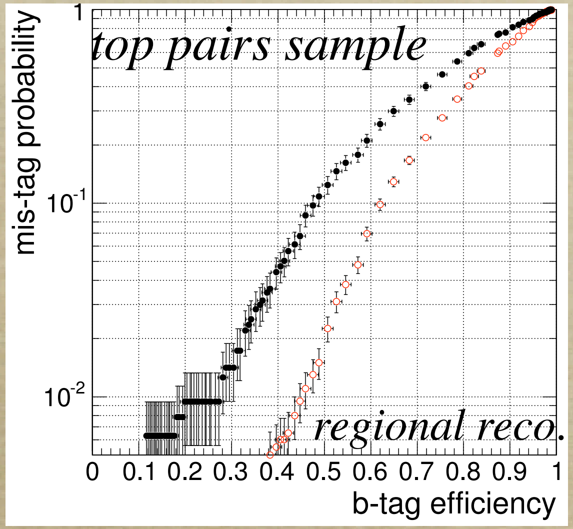


HLT Streams	*Rate (Hz)*
Ecal+Pixel double τ	*4.1*
Tracker double τ	*6.0*

b-Jet Tagging

✓ *Important topic for many physics studies (MSSM Higgs, top, etc.)*

✓ *$c\tau$ = 450 μm gives large impact parameters w.r.t. the production vertex. Very useful to reject background.*



LEVEL-2.5:

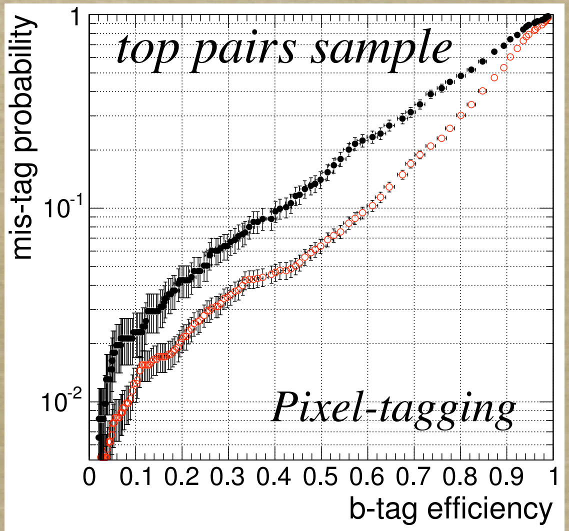
- *Optimized for speed (work at 1kHz).*
- *Fast track reconstruction performed in the pixel detector only.*
- *Poor momentum resolution with subsequent deterioration of the sensitivity for transverse impact parameter.*
- *Fake rate ~10%.*

LEVEL-3:

- *Must pass Level-2.5*
- *Full track reconstruction in a region of interest identified as a b-jet from Level-2.5.*
- *Good momentum resolution.*

b-jets efficiency vs. light jets rejection.

b-jets efficiency vs. c-jets rejection



Additional Triggers

- *Triggers on forward physics can be exploited taking advantage of the unprecedented pseudorapidity coverage of CMS + TOTEM detectors.*
- *An Ht trigger: sum of jet corrected transverse energy (Et>5 GeV) in the region η<5 with the Pt (>5GeV) of HLT muons and the missing Et. This trigger is combined with other HLT objects.*
- *Acoplanar di-jet and jet + MEt triggers (ex. SUSY searches): thanks to the topology constraint a lower energy threshold can be implemented.*
- *Many cross-triggers (combination of different basic HLT objects) are under investigation. These triggers profit from relatively low rate and take advantage of the correlation between the objects to reduce the thresholds applied to the basic (single, double) triggers.*

Additional triggers (cont.)

- *E_t^{miss} + X where X = Ht or Jet(s) or lepton: this triggers allowes to access E_t^{miss} enhanced data, for example:*
  - *E_t^{miss} + jets: important for SUSY searches has the additional advantage of a reduced threshold on the jets objects.*
  - *E_t^{miss} + l: exploit the presence of W bosons or top with a low Pt threshold on the lepton.*
- *e+μ: useful for SUSY searches, Higgs decays (ex. H->ττ) lepton number violation studies etc. Also in this case a reduction in the single electron threshold can be achieved.*

Summary and Conclusions

HLT menu @ 2×10^{33}

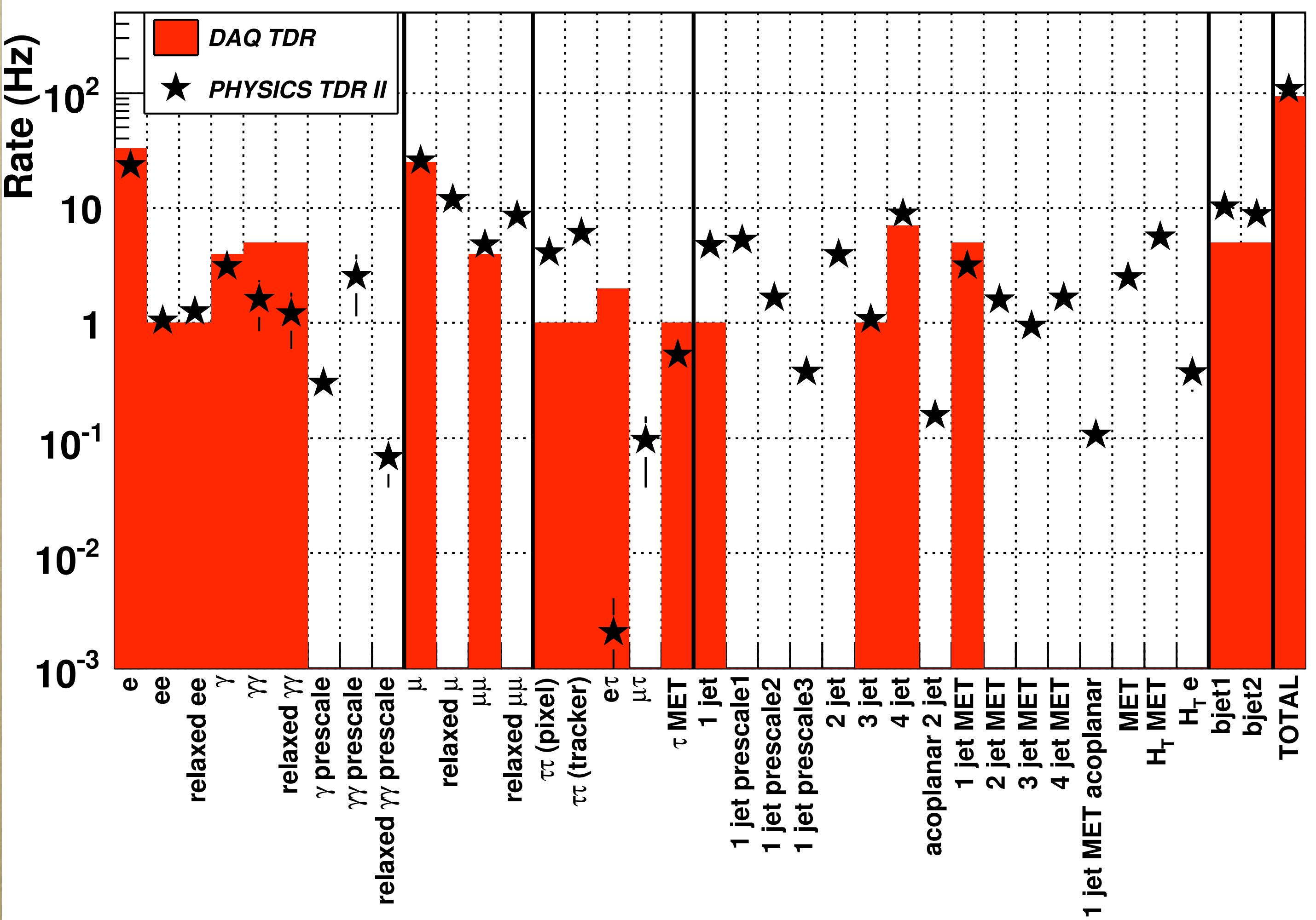
Trigger	Level-1 bits used	Level-1 Prescale	HLT Threshold (GeV)	HLT Rate (Hz)
Inclusive e	2	1	26	23.5 ± 6.7
e-e	3	1	12, 12	1.0 ± 0.1
Relaxed e-e	4	1	19, 19	1.3 ± 0.1
Inclusive γ	2	1	80	3.1 ± 0.2
γ-γ	3	1	30, 20	1.6 ± 0.7
Relaxed γ-γ	4	1	30, 20	1.2 ± 0.6
Inclusive μ	0	1	19	25.8 ± 0.8
Relaxed μ	0	1	37	11.9 ± 0.5
μ-μ	1	1	7, 7	4.8 ± 0.4
Relaxed μ-μ	1	1	10, 10	8.6 ± 0.6
$\tau + E_T^{miss}$	10	1	65 (E_T^{miss})	0.5 ± 0.1
Pixel τ-τ	10, 13	1	—	4.1 ± 1.1
Tracker τ-τ	10, 13	1	—	6.0 ± 1.1
$\tau + e$	26	1	52, 16	< 1.0
$\tau + \mu$	0	1	40, 15	< 1.0
b-jet (leading jet)	36, 37, 38, 39	1	350, 150, 55 (see text)	10.3 ± 0.3
b-jet (2^{nd} leading jet)	36, 37, 38, 39	1	350, 150, 55 (see text)	8.7 ± 0.3
Single-jet	36	1	400	4.8 ± 0.0
Double-jet	36, 37	1	350	3.9 ± 0.0
Triple-jet	36, 37, 38	1	195	1.1 ± 0.0
Quadruple-jet	36, 37, 38, 39	1	80	8.9 ± 0.2
E_T^{miss}	32	1	91	2.5 ± 0.2
jet + E_T^{miss}	32	1	180, 80	3.2 ± 0.1
acoplanar 2 jets	36, 37	1	200, 200	0.2 ± 0.0
acoplanar jet + E_T^{miss}	32	1	100, 80	0.1 ± 0.0
2 jets + E_T^{miss}	32	1	155, 80	1.6 ± 0.0
3 jets + E_T^{miss}	32	1	85, 80	0.9 ± 0.1
4 jets + E_T^{miss}	32	1	35, 80	1.7 ± 0.2
Diffractive	Sec. 0.3	1	40, 40	< 1.0
$H_T + E_T^{miss}$	31	1	350, 80	5.6 ± 0.2
$H_T + e$	31	1	350, 20	0.4 ± 0.1
Inclusive γ	2	400	23	0.3 ± 0.0
γ-γ	3	20	12, 12	2.5 ± 1.4
Relaxed γ-γ	4	20	19, 19	0.1 ± 0.0
Single-jet	33	10	250	5.2 ± 0.0
Single-jet	34	1 000	120	1.6 ± 0.0
Single-jet	35	100 000	60	0.4 ± 0.0
Total HLT rate				119.3 ± 7.2

Still work in progress!

Thresholds chosen to obtain a final output rate consistent with the bandwidth capability.

HLT performance

Many new triggers available with respect to the DAQ TDR.



Conclusions

- *Extensive studies on the HLT selection and the Trigger Paths are currently being studied in CMS.*
  - *The scenario described concerns the luminosity scenarion of* $2x10^{33}$ *cm*$^{-2}$ *s*$^{-1}$.
  - *L1 output rate 50 KHz*
  - *An HLT output rate of 100-150 Hz is expected.*
- *These studies are carried out with full simulation and pileup contribution.*
- *The Level-1 background is dominated by strong interactions.*
- *Series of prescaled triggers are introduced for efficiency measurements.*
- *Factor of 3 in rate has been used as safety margin in the determination of the prescaling factors.*
- *Many types of cross-triggers are being studied: they allow to exploit low threshold on the basic trigger objects.*
- *General improvements have been obtained with respect to the DAQ-TDR.*
- *Lots of work still on-going.*

Backup Slides

MC Samples

Sample description	**Cuts (Momenta in GeV/c)**	**Cross section (mb)**	**# of events**	**HLT rate (Hz)**
Minimum bias with in-time pile-up; <# of interactions>= 5	—	79.3	50 000 000	—
QCD	$\hat{p_T} \in [15, 20]$	1.46×10^{0}	49 491	
QCD	$\hat{p_T} \in [20, 30]$	6.32×10^{-1}	49 244	
QCD	$\hat{p_T} \in [30, 50]$	1.63×10^{-1}	49 742	
QCD	$\hat{p_T} \in [50, 80]$	2.16×10^{-2}	99 486	
QCD	$\hat{p_T} \in [80, 120]$	3.08×10^{-3}	96 238	
QCD	$\hat{p_T} \in [120, 170]$	4.94×10^{-4}	99 736	
QCD	$\hat{p_T} \in [170, 230]$	1.01×10^{-4}	99 226	
QCD	$\hat{p_T} \in [230, 300]$	2.45×10^{-5}	99 481	
QCD	$\hat{p_T} \in [300, 380]$	6.24×10^{-6}	98 739	
QCD	$\hat{p_T} \in [380, 470]$	1.78×10^{-6}	46 491	
QCD	$\hat{p_T} \in [470, 600]$	6.83×10^{-7}	47 496	
QCD	$\hat{p_T} \in [600, 800]$	2.04×10^{-7}	48 986	
QCD	$\hat{p_T} \in [800, 1000]$	3.51×10^{-8}	45 741	
Partial total			930 099	55.3 ± 6.9
$W \longrightarrow e\nu$	1 electron with $\lvert\eta\rvert < 2.7, p_T > 25$	7.9×10^{-6}	3 944	9.7 ± 0.2
$Z \longrightarrow ee$	2 electrons with $\lvert\eta\rvert < 2.7, p_T > 5$	8.2×10^{-7}	4 000	1.4 ± 0.0
$pp \longrightarrow \text{jet(s)} + \gamma$, $\hat{p_T} > 30\,\text{GeV/c}$	jet: $p_T > 20$, γ: $p_T > 30$	2.5×10^{-6}	4 000	1.0 ± 0.0
$W \longrightarrow \mu\nu$	1 muon with $\lvert\eta\rvert < 2.5, p_T > 14$	9.8×10^{-6}	4 000	14.0 ± 0.3
$Z \longrightarrow \mu\mu$	2 muons with $\lvert\eta\rvert < 2.5, p_T > 20, 10$	7.9×10^{-7}	2 941	1.5 ± 0.0
$pp \longrightarrow \mu + X$	1 muon with $p_T > 3$	2.4×10^{-2}	839 999	25.5 ± 1.2

pp Cross-section