CMS TN/94-200
Draft of July 16, 1994

Proposal of Unified Criteria for Muon Trigger Studies

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Abstract

A set of criteria for comparison of various muon trigger algorithms is proposed. It concerns definition of basic variables, input data (particle rates etc), and the way the results are ported for further analysis.

Introduction

The aim of this paper is to propose unified criteria for examining performance of various muon trigger systems in CMS. Such a unification concerns the following items:

- input data (particle rates etc)
- definition of variables to be calculated (simulated)
- the way the results are ported for further analysis
- bench mark physics processes.

In this paper we concentrate on the technical issues leaving aside question of bench mark processes.

1 Input data

1.1 Charge particle rates

It has been shown in [1] that the muon trigger rate in CMS is dominated by prompt muons (mainly form b and c quark decays). Only at low p_t and high η muons from π and K decays take over. Other sources can be neglected in the first approximation.

Rates of prompt muons and hadrons at the vertex have been studies and parametrised in [1]. An improved version of the parametrisations one can find in [2]. The rates do not varry significantly with rapidity, hence the dependence on η is neglected in the proposed parametrisations. The rates below are given for the luminosity 10^{34} cm^{-2}s^{-1}.

Prompt muons

$$\frac{dN}{d\eta dp_t} = a \exp \frac{-(x-\mu)^2}{2\sigma^2}$$

where $x = log_{10}\, p_t$ [GeV] and,

$$a = 0.134 \times 10^7, \quad \mu = -0.593, \quad \sigma = 0.371 \quad \text{for} \quad 0.1 < p_t < 1.$$

$$a = 0.230 \times 10^7, \quad \mu = -1.570, \quad \sigma = 0.565 \quad \text{for} \quad 1. < p_t < 100.$$

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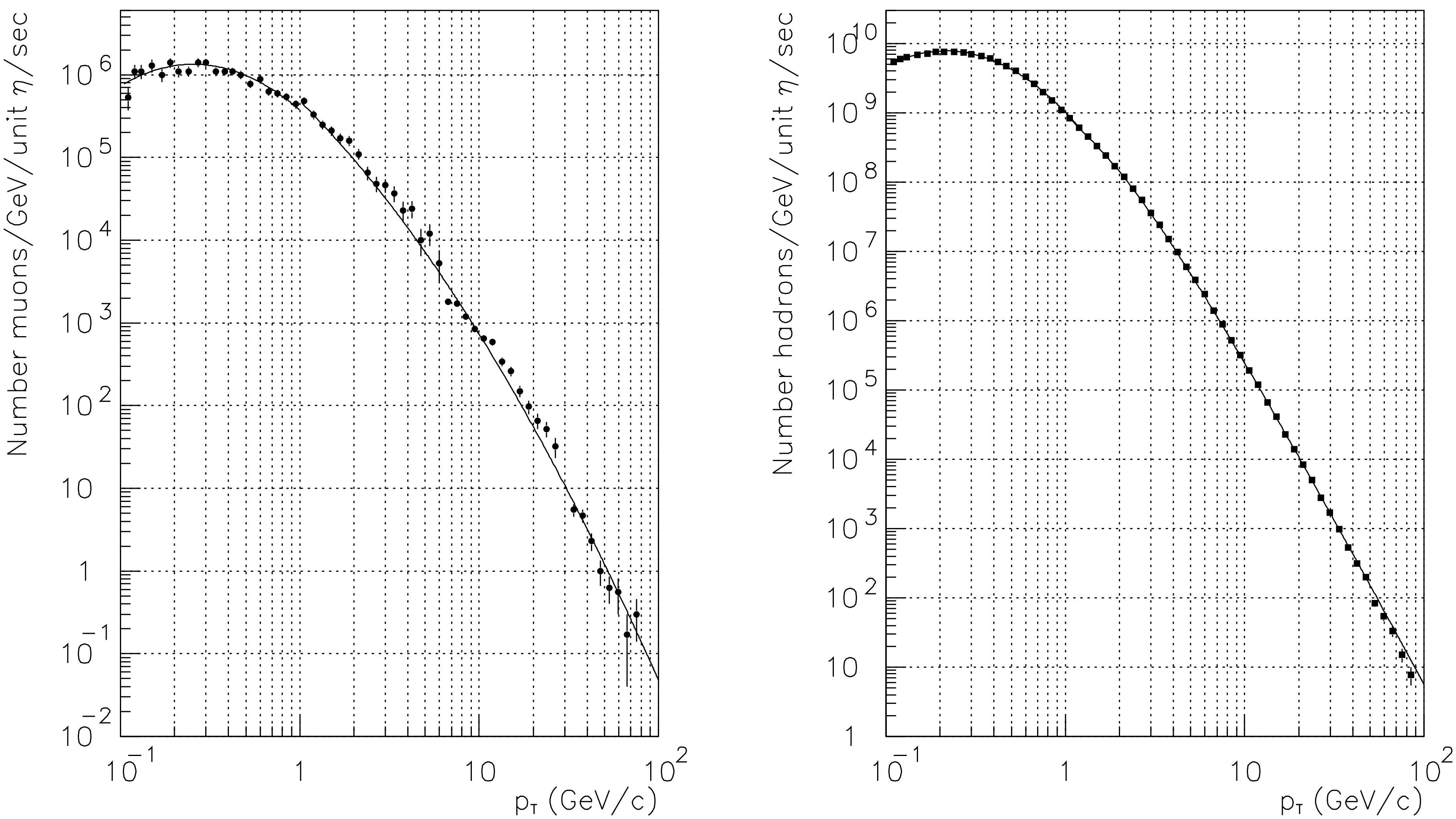

Figure 1: Prompt muon and hadron rates at the vertex – raw data and parametrisaton.

Prompt hadrons

$$\frac{dN}{d\eta dp_t} = \begin{cases} a \exp \frac{-(x-\mu)^2}{2\sigma^2} & 0.1 < p_t < 1. \\ (1 + a_3 x + a_4 x^2) \exp(a_1 + a_2 x) & 1. < p_t < 100. \end{cases}$$

where $x = log_{10}\, p_t$ [GeV] and,

$$a = 0.780 \times 10^{10}, \quad \mu = -0.664, \quad \sigma = 0.329$$

$$a_1 = 20.75, \quad a_2 = -12, \quad a_3 = 3.3, \quad a_4 = 34.1$$

Muons from π and K decays

The above rates of hadrons are dominated by pions and kaons. Knowing these rates one can easily calculate rates of muons from π and K decays. Now dependence on η must be introduced, because one needs to convert p_t to p and calculate a decay path in the inner cavity of CMS. The cavity is a cylinder 7 m long, having 2.6 m diameter.

1.2 Particle generation

In practice generation of paticles according to the parametrised spectra given above is impossible. The rates are decreasing with p_t so rapidly that one need to simulate millions of a few GeV particles in order to have some 100 GeV ones in the sample. The usefull method is to generate particles with flatter spectrum (e.g. flat in $\log p_t$) and apply in further analysis a proper weight taken from the above parametrisations.

1.3 Neutral particle rates

Neutral particle fluxes have been studied in [3]. With the best invented shielding the fluxes (kHz/cm^2) are the following:

η		1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
MF1	n	0.0	0.0	0.0	20.6	43.9	86.9	185.1	345.5
	γ	0.0	0.0	0.0	19.3	30.0	57.0	119.5	158.4
MF2	n	2.0	0.2	2.7	8.9	36.4	85.5	187.5	315.1
	γ	0.6	0.8	3.2	6.3	14.7	29.8	58.3	73.8
MF3	n	3.5	1.3	2.7	8.6	27.2	74.2	170.1	301.9
	γ	2.2	0.8	1.5	5.3	9.0	24.8	51.2	71.9
MF4	n	0.0	5.3	6.6	13.3	29.6	89.7	186.7	296.4
	γ	0.0	1.9	2.3	4.6	11.0	18.4	30.9	49.1
z [cm]		50.0	150.0	250.0	350.0	450.0	550.0	650.0	712.5
MS4	n	2.0	2.0	2.4	2.0	2.1	2.7	3.5	2.3
	γ	0.4	1.1	1.1	1.6	1.3	1.9	1.6	1.4

Fluxes in places not mentioned in the table can be neglected. In order to calculate rates of hits in trigger chambers (in Hz/cm^2) one needs to multiply the above fluxes by the efficiency (sensitivity) of the given chamber to neutrons ϵ_n and gammas ϵ_γ. At the moment we assume

$$\epsilon_n = 0.0005 \quad \text{and} \quad \epsilon_\gamma = 0.005$$

The rates obtained with these values are shown in Fig. 2.

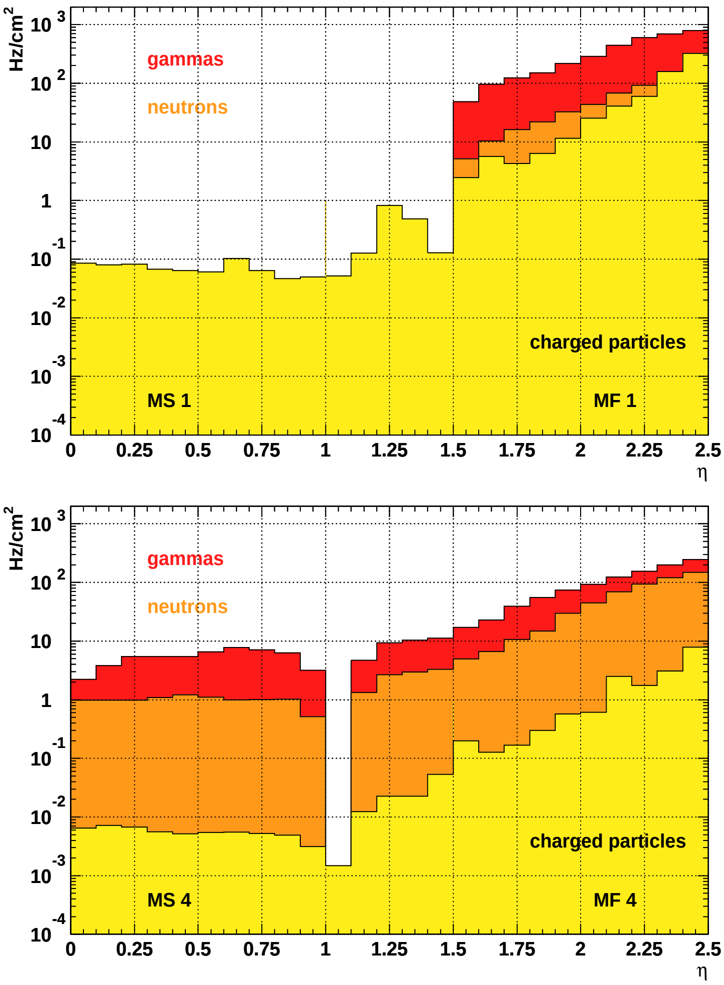

Figure 2: Hit rates in the muon stations due to charged and neutral particles.

2 Variables to be calculated

2.1 Basic definitions

Trigger efficiency $\varepsilon(\eta, p_t)$

Probability that the muon having given p_t and η will be accepted for the given trigger setting.

Transverse momentum cut p_t^{cut}

The p_t value for which efficiency reach 90 %

$$\varepsilon(\eta, p_t = p_t^{cut}) \equiv 0.9$$

Cut purity (or "sharpness") $s(\eta_{min}, \eta_{max}; p_t^{cut})$

Fraction of trigger particles truly have $p_t > p_t^{cut}$ i.e. particles useful for offline analysis (see Fig. 3).

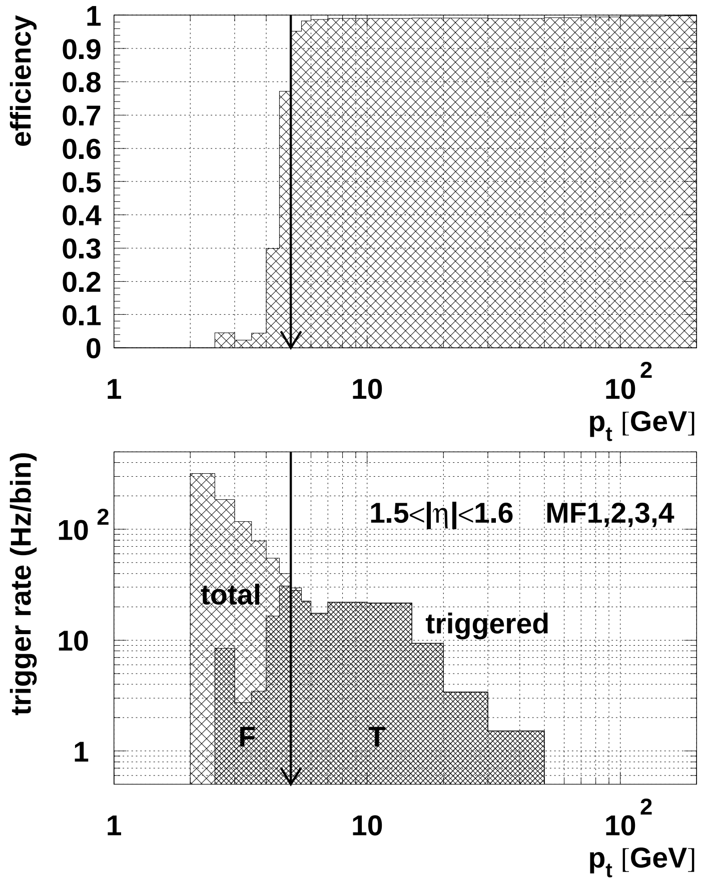

Figure 3: Example of purity calculations: $s = T/(T+F)$, where T and F stands for the number of triggered events to be true and false with $p_t > p_t^{cut}$ respectivly.

2.2 Calculation

Studying a given trigger algorithm one should define trigger configuration (set of hit patterns, opening cone, etc.) corresponding to various values of p_t^{cut}. Typicaly the configuraion will depend also on η. Thus for every p_t^{cut} and η one should:

- calculate efficiency curves $\varepsilon(\eta, p_t^{cut}; p_t)$,
- convolute them with parametrised muon rate $R(\eta, p_t) = dN/d\eta dp_t$ in order to calculate trigger rates $r(\eta_{min}, \eta_{max}; p_t^{cut})$

$$r(\eta_{min}, \eta_{max}; p_t^{cut}) = \int_{\eta_{min}}^{\eta_{max}} \int_{p_t^{min}}^{p_t^{max}} R(\eta, p_t)\varepsilon(\eta, p_t) dp_t d\eta,$$

- calculate purity of the cuts $s(\eta_{min}, \eta_{max}; p_t^{cut})$

$$s(\eta_{min}, \eta_{max}; p_t^{cut}) = \frac{\int_{\eta_{min}}^{\eta_{max}} \int_{p_t^{cut}}^{p_t^{max}} R(\eta, p_t)\varepsilon(\eta, p_t) dp_t d\eta}{\int_{\eta_{min}}^{\eta_{max}} \int_{p_t^{min}}^{p_t^{max}} R(\eta, p_t)\varepsilon(\eta, p_t) dp_t d\eta}$$

.

In case of CMS any muon trigger will stay in the range:

$$\eta_{min} \geq -2.5\ , \quad \eta_{max} \leq 2.5\ , \qquad p_t^{min} \geq 1\ \text{GeV}.$$

In principle $p_t^{max} = \infty$ but the rate is decreasing so rapidly with p_t that e.g. taking $p_t^{max} = 400$ GeV couses the rate to be underestimated by $\approx 4\%$ only. Integration should be done rather carefuly because both ε and R varry very fast with p_t. Too large bins may lead to completly wrong results.

2.3 Criteria

In principle efficiency curves can be used for comparison of different trigger algorithms. However looking at an efficiency curve it is hard to judge whether the trigger performance is good enough or not. Also comparison of rates does not give the final answer because one would like to know which fraction of the given rate is due to incorrectly recognised muons. Therefore the purity of cuts s seems to be the best tool for such a comparision.

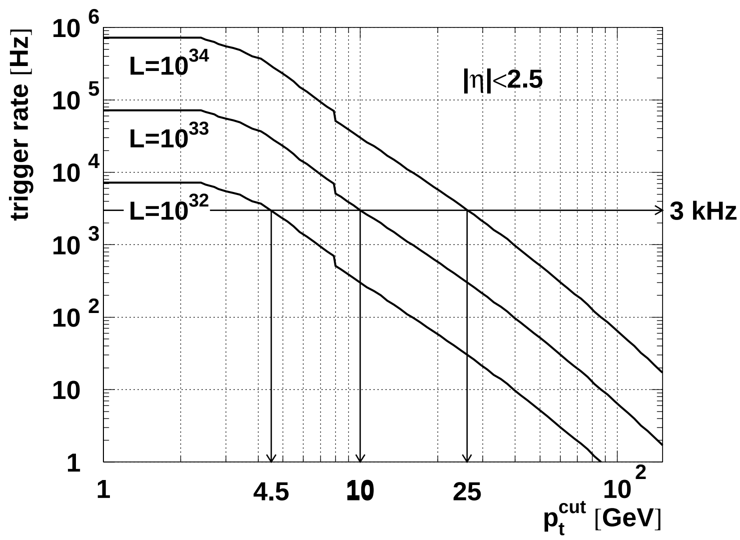

Figure 4: RPC/PPC trigger rates for the luminosities expected at LHC: 10^{32}, 10^{33}, and 10^{34} cm^{-2}s^{-1}, for $|\eta| < 2.5$

Let us consider the single muon trigger first. Let us assume that the acceptable output rate for $|\eta| < 2.5$ is 3 kHz (exact values are not crucial for our discussion). One can see from Fig. 4 that for the luminosities expected at LHC the optimal p_t cuts are the following:

luminosity	p_t cut
10^{32} cm^{-2}s^{-1}	4.5 GeV
10^{33} cm^{-2}s^{-1}	10 GeV
10^{34} cm^{-2}s^{-1}	25 GeV

This means that single muon trigger should perform well down to the lowest p_t allowed by muon energy loss in calorimeters. Concerning high p_t limit one can define two safety margins:

operational - taking into account uncertainty of extrapolation from lower energies and accuracy of simulation; in this region a trigger should preserve its full performance, say $s > 50\%$,

exceptional - in case of something unexpected; a trigger should still work, but its performence may be compromised, say $s > 10\%$.

Let us arbitrarily assume a rate increase factor of 6 for both margins. From Fig. 5 one can find corresponding p_t cuts.

safety margin	rate factor	cut purity	minimal p_t^{cut}	maximal p_t^{cut}
normal operation	1	$s > 50\%$	4.5 GeV	25 GeV
operational margin	6	$s > 50\%$	25 GeV	50 GeV
exceptional margin	6·6	$s > 10\%$	50 GeV	100 GeV

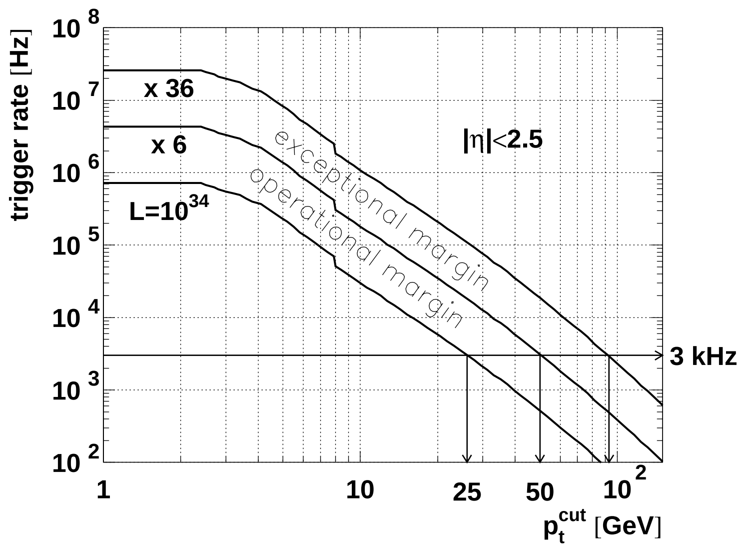

Figure 5: *Operational* and *exceptional* safety margins of the RPC/PPC trigger ($L = 10^{34}$ cm^{-2}s^{-1}, $|\eta| < 2.5$)

From the above table one can derive criteria to be fulfiled by every CMS single muon trigger:

$s > 50\%$	for $p_t^{cut} < 50$ GeV
$s > 10\%$	for $p_t^{cut} < 100$ GeV

Double muon trigger and combined muon-calorimeter trigger cannot be considered regardless specific physics channels. Therefore it escapes the scope of this paper.

2.4 Stability and safety of algorithms

An important feature of a trigger algorithm is its stability. Results of an algorithm should not change under small variations of its parameters or small changes of the environment, eg.

- adding or removing of a few patterns (in case of pattern based algorithms),
- expected misalignment of the chambers ($\sim$ a few mm),
- local distortions of the magnetic field,
- noisy or dead single channels.

This kind of changes are expected during normal operation and therefore the trigger performance should stay within the *operational* safety margin.

A class of phenomena falling into the *exceptional* margin is by definition more difficult to define. We can only list a few examples of working conditions much worse then expected:

- charge particle rate is much higher,
- charge particle momenta spectrum is different from the expected one,
- machine background (beam halo) is much higher,
- noise or neutral particle rate is much higher,
- magnetic field is significantly lower.

One should be able to keep the trigger performance within the *exceptional* margin only by:

- reprogramming trigger processors,
- limiting η range or rising p_t cut.

2.5 Comparison of simulation results

In order to enable direct comparison one should provide the following plots for each considered solution:

- trigger efficiency $\varepsilon(p_t)$ plot in a log-log scale for various p_t^{cut} and several η intervals

$$10^{-5} < \varepsilon < 1 \ , \quad 1 \text{ GeV} < p_t < 150 \text{ GeV}$$

- trigger rate $r(p_t^{cut})$ plot in a log-log scale for the full η range covered by the given algorithm

$$1 \text{ Hz} < r < 10^7 \text{ Hz} \ , \quad 1 \text{ GeV} < p_t < 150 \text{ GeV}$$

- map (e.g. contour plot) of *purity* $s(\eta, p_t)$

$$0 < |\eta| < 2.5 \ , \quad \text{linear scale}$$

$$1 \text{ GeV} < p_t < 150 \text{ GeV} \ , \quad \text{log scale.}$$

One should assume luminosity 10^{34} cm^{-2}s^{-1} and particle rates as described in Section 1.

In addition one should run parameters given below and notice for which value of each parameter the trigger performace escape the criteria defined at the end of Section 2.3.

parameter	nominal value	critical value
misalignment of chambers	0 mm	
local distortion of the magnetic field	0 T	
fraction of dead channels	0	
fraction of "always on" channels	0	
charge particle rate increase factor	1	
neutral particle rate increase factor	1	
electronics noise	0 Hz/channel	
chamber noise	0 Hz/cm^2	
magnetic field value	4 T	

The charge and neutral particle rate increase factor refer to the rates defined in Section 1.

3 Porting results for further analysis

Behaviour of the muon trigger system should be simulated on several levels. In order to check carefuly a given design in presence of noise, background, and pile-up effects full event detail simulation is necessary. This is however very time consuming and one cannot study this way rare physics processes. Therefore various parametrisations are needed. It would be very useful if parametrisations of variuos trygger subsystems are compatible with each other. A set of examples is presented in the following sections.

3.1 Step efficiency curves

The p_t cuts of the first level trigger cannot be perfectly sharp and therefore some fraction of muons with $p_t < p_t^{cut}$ is accepted. These muons should be rejected later, in the off-line analysis. Sharp off-line cuts can be however applied only in this part of phase space which is accesible for muons. For example if a muon trigger is based on the first two muon stations one needs to know its acceptance $\alpha(\eta, p_t)$, namely the probability that a muon with a given η and p_t can reach the second muon station. The routine MUONAC in the CMSIM package [4] (CMZ path MUON/UTIL/MUONAC) provides a parametrisation of this variable for the LOI version of the CMS detector [5] (see Fig. 6). The routine contains tabulated values of $\alpha(\eta, p_t)$ and performes an interpolation making use of CERNLIB E104 routine FINT. More details one can find in [6].

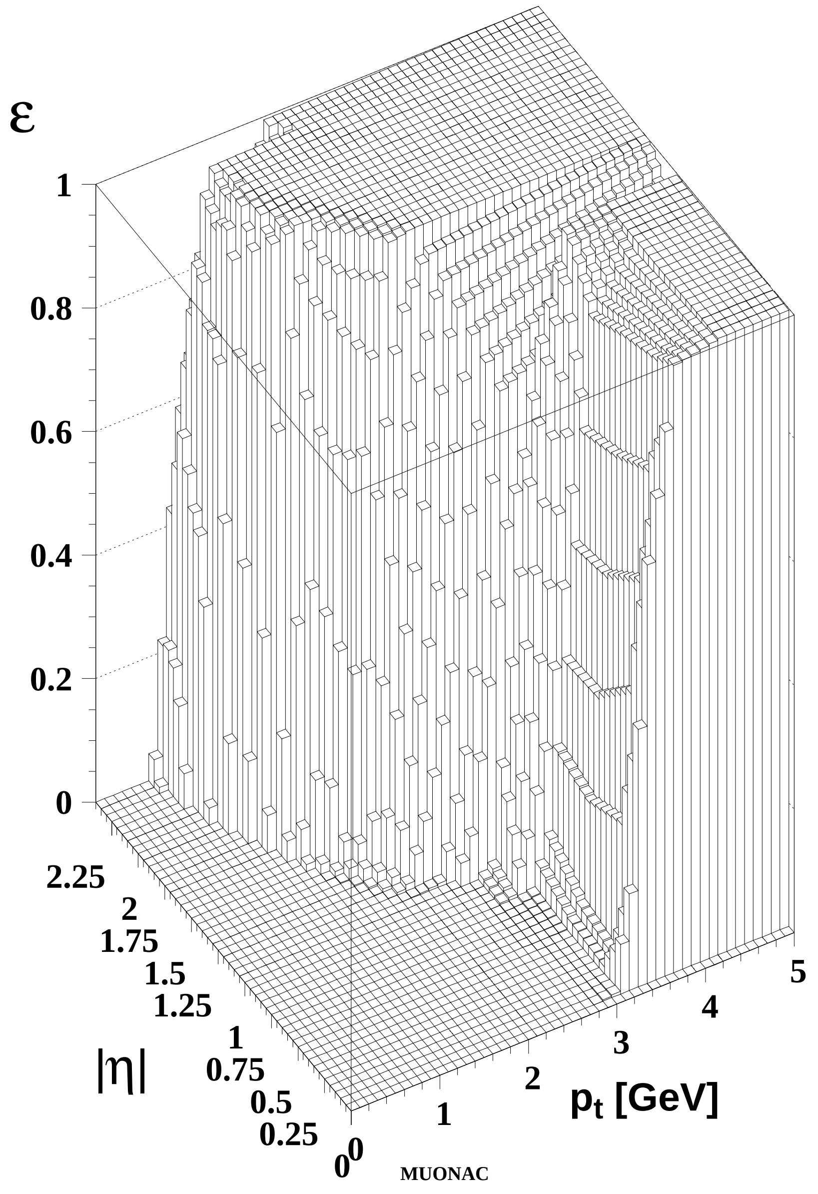

Figure 6: Muon trigger acceptance $\alpha(\eta, p_t)$ based on two muon stations.

3.2 Parametrised efficiency curves

It has been proposed in [1] to use the error function

$$erf(x) = \int_{-\infty}^{x} e^{-\frac{x^2}{2}}$$

for parametrisation of efficiency curves. The idea is shown in Fig. 7. Every efficiency curve $\varepsilon(p_t)$ corresponding to a certain p_t^{cut} has two parameters: μ and σ.

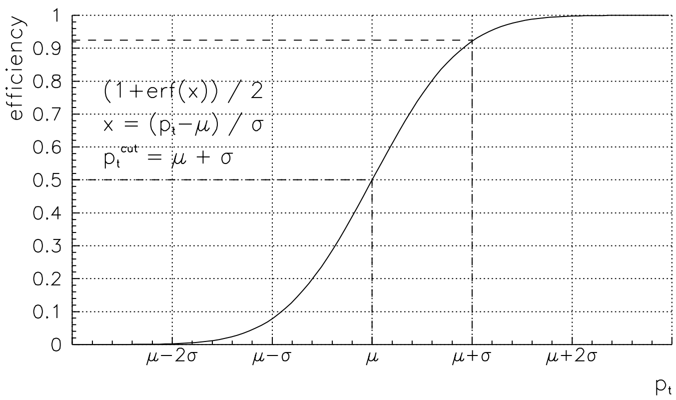

Figure 7: Principle of efficiency curve parametrisation using error function.

One can eliminate μ using the relation $p_t^{cut} \approx \mu + \sigma$. Then the σ vs p_t^{cut} relation can be plotted. It turned out to be a straight line which again enable an easy parametrisation. Thus a full set of efficiency curves for a given η interval can be characterised by only two nubers, offset and slope of the $\sigma(p_t^{cut})$. An example of such a procedure is shown in Fig. 8.

One has to look carefuly whether the parametrisation reproduce correctly low p_t tail for $\varepsilon < 10^{-3}$. In same cases better results can be obtained if the normal integral is replaced by the lognormal one. This is formaly done by substituting $\log(p_t)$ in place of p_t.

3.3 Full event simulation

In order to study technical details of trigger algorithms one has to perform full event simulation including noise, background, and pile-up effects. The MTRIG program is an already existing example. It has been oryginaly written for studying the RPC/PPC trigger, but large part of the program is rather general. Espacialy the I/O part, structure of banks, interface to the core of the CMSIM program and some utility routines (like parametrisations mentioned above) can be used for other triggers as well. Detailed description of the program one can find in [7].

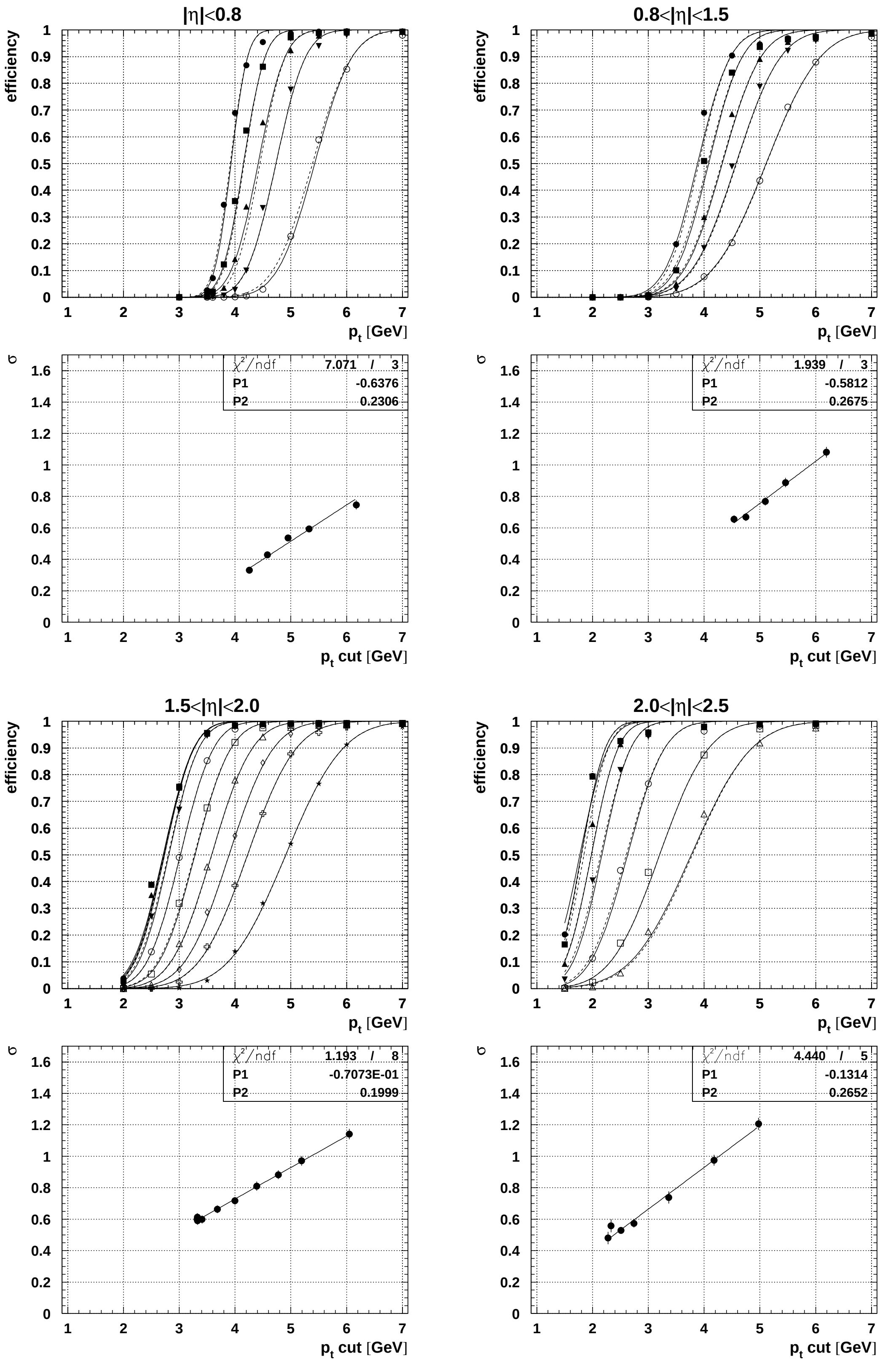

Figure 8: Example of efficiency curves parametrisation.

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