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Remarks on punchthrough in the CMS Muon System

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Abstract
This paper is intended to be a working document containing various remarks concerning hadronic shower punchthrough in the CMS Muon System. It is going to be updated continuously following results of simulations and related discussions.

1. Introduction

1.1. CMS geometry

There are two critical regions in the CMS detector where we need to concentrate our considerations:
- MB/0/1 chamber where the amount of the absorber is the smallest
- barrel/endcap corner where the cable paths open some roads for energy leakage

At the moment we concentrate only on the first one. The amount of absorber in front of MB/0/1 at η=0 in the CMS Letter of Intent was equal to 10.1 λ. In the Technical Proposal it was reduced to 9.4 λ. Recently it was proposed to remove the absorber between the coil and MB/0/1 previously used as a calorimeter tail catcher (TC). This would reduce further the absorber thickness down to 8.1 λ (see Fig. 1).

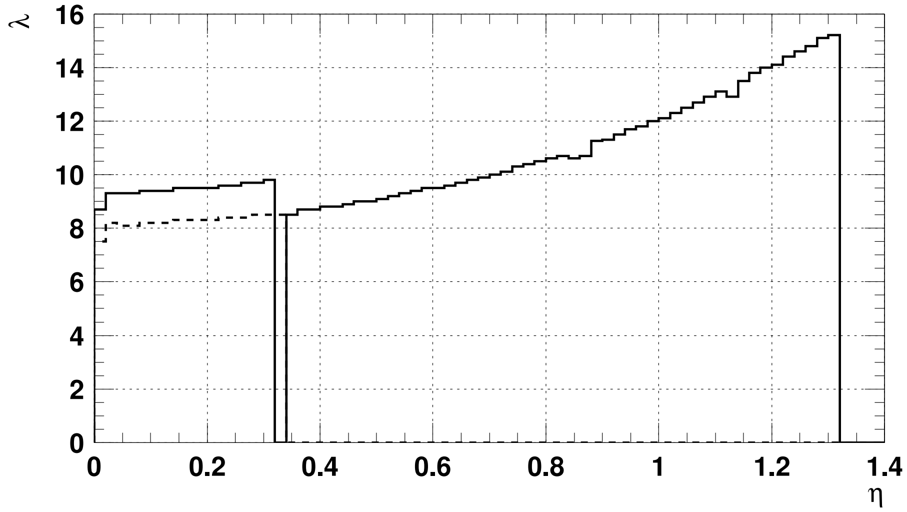

Fig. 1. Absorber thickness in nuclear interaction length λ with and without the TC

1.2. Effects of punchthrough

Hadronic shower punchthrough can affect the Muon System in various ways. One needs to consider the following items:

- Random hits rate [Hz/cm^2] and its influence on chamber performance, pattern recognition and momentum measurement
- Increase of the trigger rate due to random punchthrough hits
- Increase of the trigger rate due to punchthrough tracks
- Increase of the trigger rate because of the p_t overestimation for a muon accompanied by a jet (b- and c-quark decays)
- Mismeasurement of p_t for a muon accompanied by a jet (t→b→J/ψ→2μ, stop→Z→2μ)
- Fake muon tags of b-jets

We are going to discuss them one by one in consecutive sections.

2. Random hits rate

The rates of hits in muon chambers presented in the CMS Technical Proposal were calculated [CMS TN/93-106] before the TP geometry was fixed. Therefore they reflect the LOI design which has 10.1 λ at η=0. These rates for various components are given in Fig. 2 and Tab. 1.

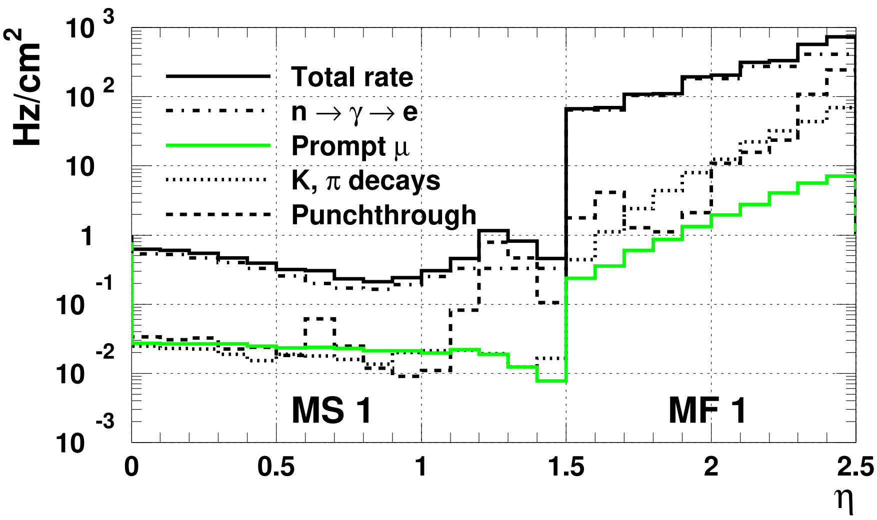

Fig. 2. Background rates in muon chambers

Tab. 1. Rates of hits @ CMS TN/93-106

source	rate [Hz/cm^2]
n → γ → e	0.60
prompt μ (b, c decays)	0.03
μ from π, K decays	0.03
punchthrough	0.03
total	0.69

One can try to extrapolate these numbers to 9.4 λ and 8.1 λ using results of the RD5 experiment. Punchthrough probability measured by RD5 is given in Tab. 2. It is seen that ratio of punchthrough rates for 8.1 λ and 10.1 λ increase with decreasing momentum. From previous studies (see also Fig. 5) it is known that punchthrough rate is dominated by low momentum (a few GeV) part. Therefore, to be on the safe side, one can assume factor 10 in rate extrapolation from 10.1 λ to 8.1 λ. The results of such a simple extrapolation is given in Tab. 3 and denoted as “TP × 10“. Total rate was obtained assuming that the rates from other sources are not changed.

Tab. 2. Punchthrough probability measured by RD5 for B=3T

Momentum of π^-	8.1 λ	9.4 λ	10.1 λ	8.1/10.1
30 GeV	0.113	0.0357	0.0197	5.7
50 GeV	0.201	0.0767	0.0527	3.8
100 GeV	0.389	0.1640	0.1035	3.8
200 GeV	0.622	0.3230	0.2270	2.7
300 GeV	0.768	0.4910	0.3770	2.0

Another way to estimate punchthrough is a parametrization developed by Roger Mc Neil [GEM Note 92-193]. It was tuned using precise GEANT simulation and it was checked to agree with the RD5 data within a factor 2. Numbers obtained with this parametrization are only slightly higher than those from TP and the simple extrapolation.

Tab. 3. Punchthrough and total rate [Hz/cm^2] extrapolated form 10.1 λ to 8.1 λ

	TP	TP × 10	parametrization		
	10.1 λ	~8.1 λ	8.1 λ	9.4 λ	10.1 λ
punchthrough	0.03	0.30	0.39	0.12	0.06
total	0.69	0.96	1.05	0.78	0.72

In summary, removing the TC can increase significantly the single rate due to punchthrough, but this is not a dominant factor. The total single rate remains of the order of 1 Hz/cm^2 which is considered as very comfortable.

3. Trigger rate due to random hits and tracks

Another problem which might be caused by punchthrough is increase of the muon trigger rate. This can happen due to three reasons:

- random hits in muon chambers can be by chance aligned along a possible muon track;
- a real punchthrough particle (also a muon) can be created during the evolution of a hadronic shower and sometimes it can cross more than one muon station;
- random hits in muon chambers can be by chance aligned with hits from a real muon in such a way that the muon track looks more straight — in such a case the muon momentum will be overestimated.

The third one is especially important when the muon is accompanied by a jet, e.g. in the case of b-quark decay. This case we treat separately in Sec. 4. In this section we consider only minimum bias events without looking at correlations between the particles at the vertex.

The parametrization mentioned in Sec. 2. turned out to be not precise enough for this task and we used full GEANT+FLUKA simulation. FLUKA was chosen because it was shown [Z.Phys C69, 415 (1996)] that it reproduce the RD5 data on punchthrough significantly better than GHEISHA. The CMS detector was described by CMSIM 101 package. The RPC trigger was simulated in detail using the MRPC software.

Since it is crucial to optimize the energy cutoffs in such a simulation we list all the used cuts in Tab. 4. Approximate time needed to simulate one particle or one event in given in Tab. 5.

Tab. 4. GEANT cuts used in the simulation

particle or process	GEANT name	far from the muon chambers	close to the muon chambers	inside the muon chambers
γ	CUTGAM	100 MeV	10 MeV	10 keV
e	CUTELE	100 MeV	10 MeV	10 keV
n	CUTNEU	1 MeV	1 MeV	1 MeV
hadrons	CUTHAD	1 MeV	1 MeV	100 keV
μ	CUTMUO	10 MeV	10 MeV	100 keV
e $\rightarrow$ bremsstrahlung	BCUTE	10 MeV	10 MeV	10 MeV
$\mu \rightarrow$ bremsstrahlung	BCUTM	10 MeV	10 MeV	10 MeV
e $\rightarrow$ δ-rays	DCUTE	off	off	10 keV
$\mu \rightarrow \delta$-rays	DCUTM	off	off	10 keV
$\mu \rightarrow$ pair production	PPCUTM	10 MeV	10 MeV	10 MeV

Tab. 5. Simulation time at SHIFTCMS

μ	$<\pi> \in$ 1-100 GeV	π = 100 GeV	π = 1 TeV	min. bias event
0.04 s	2.2 s	1 min.	5 min.	1 min.

At high luminosity the first level muon trigger must reduce the 1 GHz primary rate of pp collisions down to several kHz. Thus the required rejection factor is of the order of 10^5-10^6. In order to measure this factor looking how the trigger acts on minimum bias events one would need to simulate at least 10^8 events. This would require about **two centuries of CPU time**. Thus, it is absolutely impossible to generate enough statistics simulating minimum bias events. Instead we have chosen to simulate single hadrons.

Spectrum of hadrons in minimum bias events has been recently parametrized in CMS TN/95-150. Trying to simulate hadrons according to this spectrum one would immediately meet the same troubles with CPU time as in the case of full minimum bias events. Therefore we have generated hadrons of $p_t \in$ 1-100 GeV with a flat distribution of $\log_{10}(p_t)$. One event took on average ~2.2 s which allowed us to simulate 355 000 hadrons using "only" 9 CPU days. 1679 of simulated hadrons caused a trigger (see Tab. 6). The hadrons were generated with $\phi \in (0, 2\pi)$ and $\eta \in (-0.25, 0.25)$ i.e. within the TC acceptance. The following mixture was generated: 31.62% of π^+, π^-, 5.32% of K^+, K^-, K^0_L, K^0_S, 3.87% of p, $\bar{p}$, n, $\bar{n}$. The sample contains also those events where the hadron decayed into μ before the calorimeter.

Tab. 6. Statistics of simulated hadrons

	λ	events simulated	triggered	fraction
with TC	9.4	215 000	803	0.37%
without TC	8.1	140 000	876	0.63%

Momentum (p_t^{hadron}) distributions of hadrons causing a trigger and distribution of momentum given by the trigger ($p_t^{trigger}$) are shown in Fig. 3. As expected, higher p_t hadrons have higher probability to produce punchthrough. However the trigger answer $p_t^{trigger}$ distribution is rather flat with a peak at 5 GeV.

This is because the trigger algorithm is based on 4 muon stations for $p_t > 5$ GeV whereas only the first two stations are used below this threshold. Thus any punchthrough event which has no hits in station 3 or 4 cannot have $p_t > 5$ GeV assigned by the trigger. Since most of the punchthrough events cannot reach station 3 they are "suppressed" below 5 GeV. This is well illustrated in Fig. 4a.

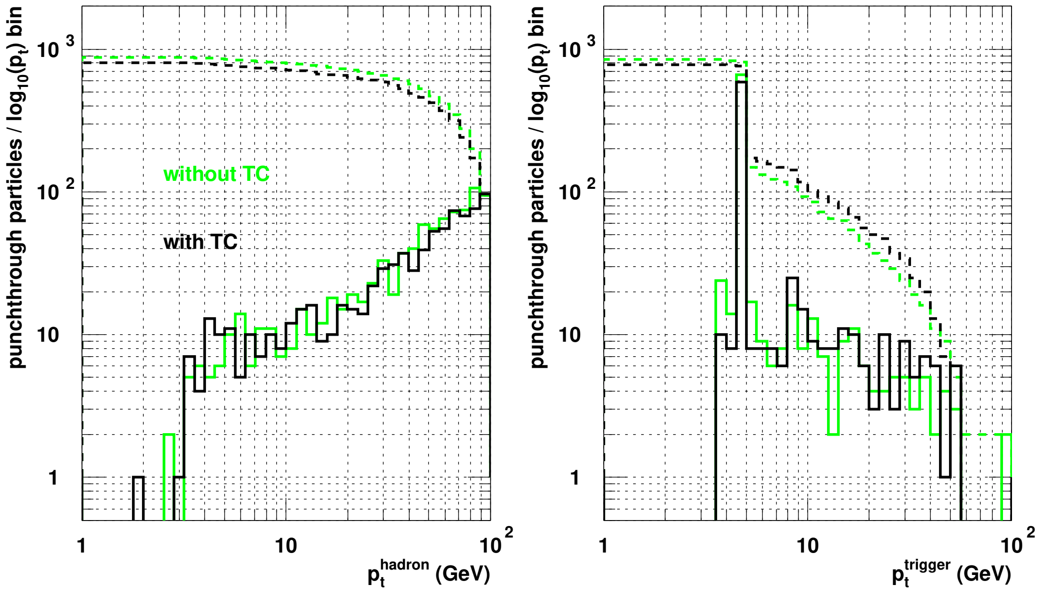

Fig. 3. Differential (solid line) and integral (dashed line) spectra of hadrons causing a trigger and distributions of trigger answers $p_t^{trigger}$

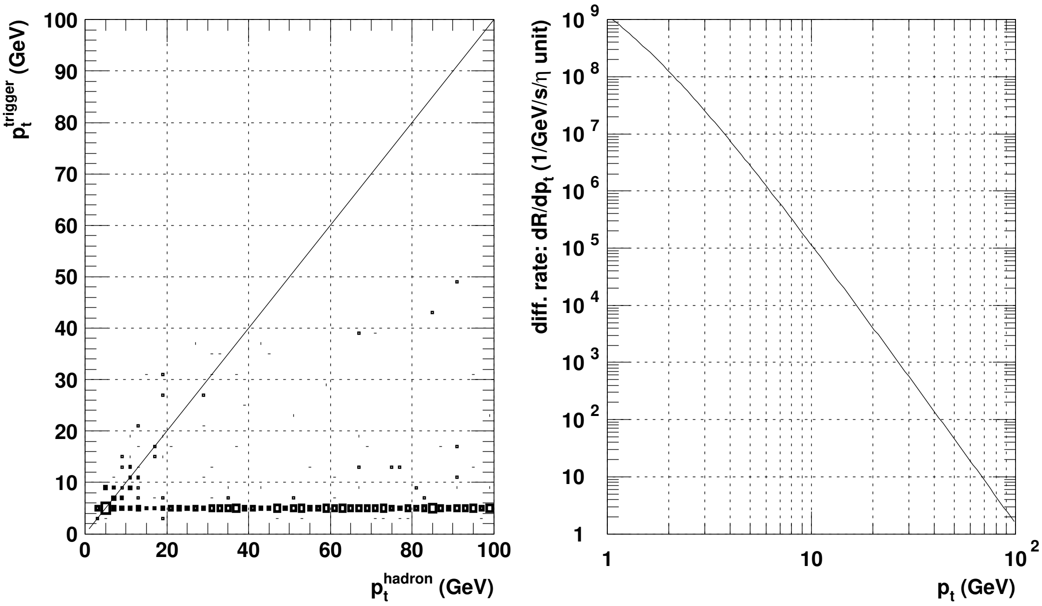

Fig. 4. a) Correlation of trigger answer and hadron momentum.
b) Hadron rate expected in LHC minimum bias events at L=10^{34}cm^{-2}s^{-1}

Expected p_t spectrum of hadrons produced at LHC, shown in Fig. 4b, is given by the function [CMS TN/95-150]:

$$\frac{dR_{expected}}{dp_t}\left[\frac{\text{Hz}}{\text{GeV}\cdot\eta\text{-unit}}\right] = f(p_t) = 1.1429\times10^{10}\cdot\left(p_t^{1.306}+0.8251\right)^{-3.781}$$

We have simulated flat distribution in $\log_{10}(p_t)$:

$$\frac{dN}{d\log_{10}(p_t)} = \frac{N}{\Delta_l} = \mathrm{const}$$

where N is the total number of generated hadrons and $\Delta_l = \log_{10}(100\ \mathrm{GeV}) - \log_{10}(1\ \mathrm{GeV}) = 2$.
This can be transformed into

$$\frac{dN}{dp_t} = \frac{dN}{d\log_{10}(p_t)} \cdot \frac{d\log_{10}(p_t)}{dp_t} = \frac{N}{\Delta_l} \cdot \frac{1}{p_t \cdot \log_e 10}$$

Number of particles can be converted into rate by a weight function $w(p_t)$:

$$\frac{dR}{dp_t} = w(p_t) \cdot \frac{dN}{dp_t}$$

In the case of the generated hadron distribution this reads:

$$f(p_t) = w(p_t) \cdot \frac{N}{\Delta_l \cdot p_t \cdot \log_e 10}$$

From here we can calculate the weight function $w(p_t)$:

$$w(p_t) = f(p_t) \cdot \frac{\Delta_l}{N} \cdot p_t \cdot \log_e 10$$

This weight function has been applied to the distributions from Fig. 3 and the result is shown in Fig. 5. It is seen that the contribution from low p_t hadrons dominates. Punchthrough probability is higher for high hadron momenta, but the rate of low p_t hadrons is high enough to overcompensate this effect.

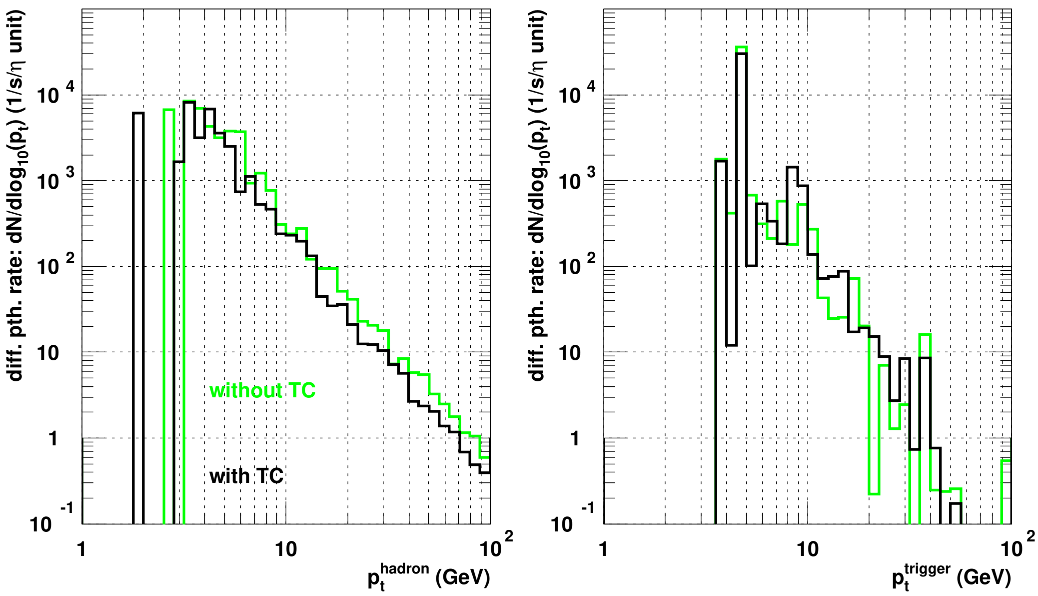

Fig. 5. Weighted spectra of hadrons causing a trigger and distributions of trigger answers $p_t^{trigger}$

In order to obtain the trigger rate as a function of the p_t^{cut} threshold, the distributions from Fig. 5b have been integrated. The result is shown in Fig. 6a. Rate due to prompt muons (those from c- and b-quark decays) is shown for comparison. Finally, the ratio of rates without and with the TC is plotted in Fig. 6b. It is seen that there is no significant difference between the rate in the two cases.

It is worth to mention why the probability of a trigger due to punchthrough was almost twice higher without the TC in the raw sample whereas at the end of the analysis the difference turned out to be negligible. This is because the raw distribution (flat in $\log_{10}(p_t)$) enhances high p_t part of the spectrum in respect to the minimum bias distribution. Punchthrough effects which are more prominent at high p_t are also enhanced in this way. However, transformation to the minimum bias distribution gives them a very low weight, thus suppressing significantly the effect.

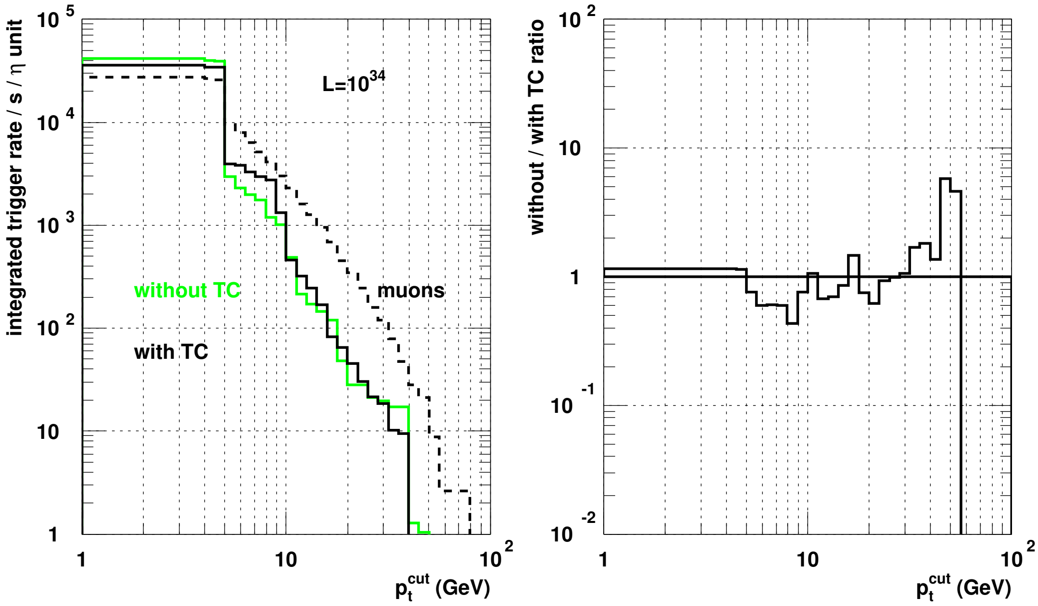

Fig. 6. a) Single muon trigger rate due to prompt muons and punchthrough (including π and K decays)
b) Ratio of single muon trigger rates due to punchthrough without and with the TC.

Another interesting comment is that the requirement of more then two muon stations above 5 GeV is absolutely crucial in punchthrough reduction. The punchthrough rate which dominates over prompt muons at low p_t is rapidly falling down by an order of magnitude due to this requirement.

In conclusion one can say that removal of the TC does not increase significantly the rate of the RPC based muon trigger. It would be still interesting, however, to see how the Drift Tube trigger is effected.

4. Trigger p_t overestimation for a muon in a jet

As it was shown in the TP and CMS TN/94-282 the dominant single muon trigger "background" are low p_t prompt muons which momenta were overestimated by the trigger logic. The trigger rate due to this effect has been calculated with a detailed simulation of the RPC based trigger applied to single muons in a "bath" of random hits (see CMS TN/94-138 for details). The effect, however, might be enhanced if we take into account the fact that the muons from c- and b-quark decays are always accompanied by jets.

In order to study this effect a sample of $b\bar{b}$ events with p_t^{jet} > 3 GeV was generated with PYTHIA 5.7. Only events with a muon having a chance to cross the TC were selected using cuts of $p_t(\mu)$ > 3 GeV and $|\eta(\mu)|$ < 0.28. 20 000 such events were analysed. In those events we have selected all particles having a chance to give punchthrough in the TC region, i.e. hadrons with p_t(had) > 3 GeV and $|\eta(\text{had})|$ < 0.28. In the total sample of 20 000 events we have found 5849 such particles. All those particles (muons and hadrons) were tracked through the CMS using CMSIM / GEANT simulation. It was done for the geometry without the TC. Hadronic shower developments was simulated in detail by GEANT / FLUKA. The RPC trigger algorithm was simulated with CMSIM / MRPC software.

Momentum spectra of selected muons and hadrons are plotted in Fig. 7. Spatial correlations of leading muons and associated hadrons are shown in Fig. 8. The two-jet structure of events is clearly seen.

The trigger algorithm was applied for two cases: single muons (without any additional particles) and for full events containing the muons and hadrons from associated jets. Results are shown in Fig. 9 and Fig. 10.

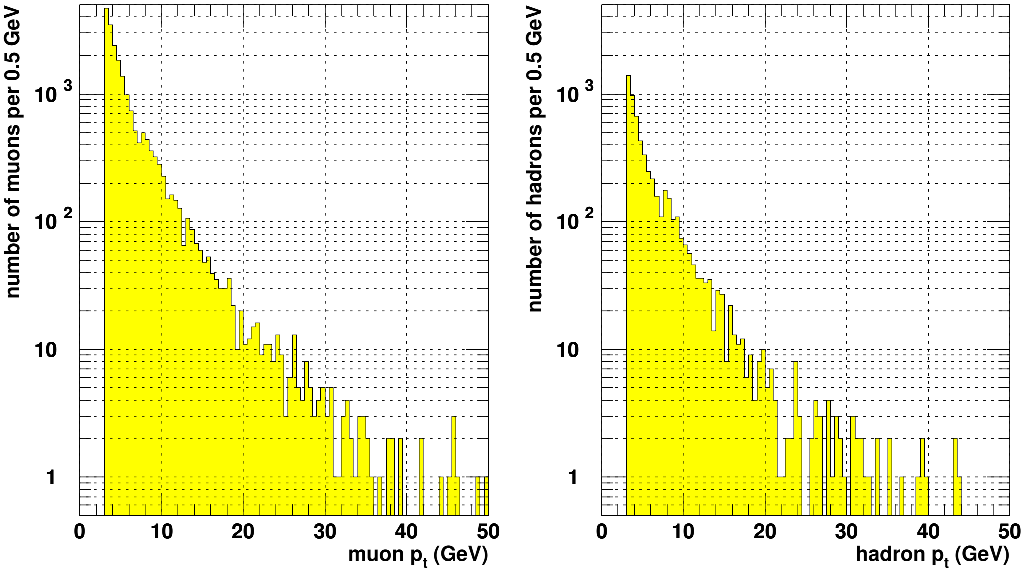

Fig. 7. Spectra of selected muons and hadrons in $b\bar{b}$ events.

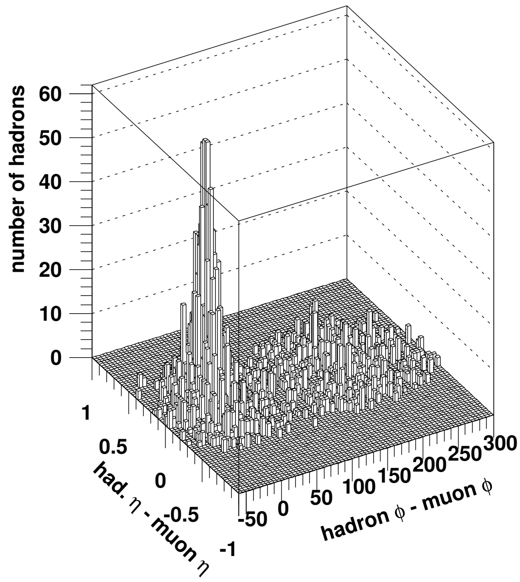

Fig. 8. Position of a hadron in respect to the leading muon.

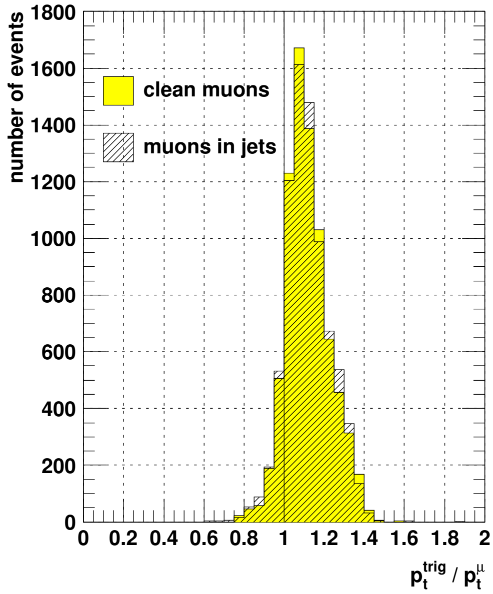

Fig. 9. Ratio of muon momentum measured by the trigger p_t^{trig} to the real p_t^{μ} in the case of single muons and muons accompanied by hadrons in jets.

Fig. 9 shows the ratio of muon momentum measured by the trigger p_t^{trig} to the real p_t^{μ}. The trigger algorithm is optimised in such a way that the distribution is not centered at 1. Events are grouped possibly close to 1 on its right side. This is because the final goal of the trigger is a p_t cut, not a measurement. An important observation for our study is that the two distributions, for single muons and for muons in jets, are very similar. It means that the presence of jets around muons does not disturb significantly the trigger momentum measurement.

This conclusion is confirmed by Fig. 10 which shows spectra of real muon momentum p_t^{μ} and momentum measured by the trigger p_t^{trig}. Most of the muons with p_t < 3.6 GeV do not cause a trigger because they are

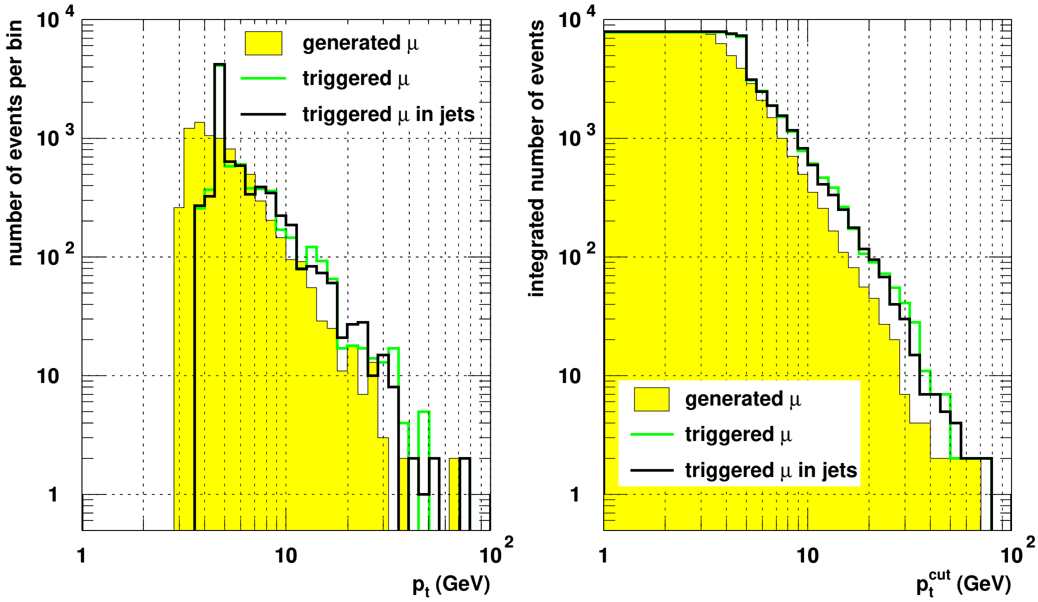

Fig. 10. Spectra of real muon momentum and momentum measured by the trigger in the case of single muons and muons accompanied by jets.

not able to reach the second muon station. A peak at 5 GeV in the p_t^{trig} distribution has the same origin as the one in Fig. 3b described in Sec. 3. — the trigger algorithm is changed from 2 to 4 stations. If a muon does not reach the third station it cannot have assigned p_t > 5 GeV even if his track has rather low curvature. Again the distributions for single muons and muons in jets do not differ significantly.

One can conclude that the presence of jets around muons, inevitable in the case of $c\bar{c}$ and $b\bar{b}$ events, does not influence significantly the RPC trigger performance. The study presented in this section was done for the geometry without the TC. Adding the TC could only decrease the possible effect of jets. Therefore one can conclude that the TC is irrelevant for the behaviour of the RPC trigger in case of muons coming from b- and c-quark decays.

5. Mismeasurement of p_t for a muon in a jet

Apart from the trigger, hadronic punchthrough may also affect pattern recognition in muon chambers and, in consequence, the momentum measurement. This should not be crucial for relatively “soft” physics, like the one involving b-quarks, because the measurement precision in the low p_t domain is given mainly by the Inner Tracker. It might be dangerous, however, when objects heavier then 100 GeV are involved. Fortunately in most of the channels when precise measurement of high p_t is required, muons are isolated. There are however a few exceptions.

$t \rightarrow b \rightarrow J/\psi \rightarrow 2\mu$

This channel is important because it should give the best precision for the top mass measurement.

stop→Z→2μ

Here highly boosted Z produce 2 nearby muons which most probably remain inside the stop jet.

Other channels of this kind should be identified.

6. Fake muon tags of b-jets

In many interesting physics channels one needs to tag jets by muons in order to suppress the huge QCD background. Such a tag can be faked by a muon created during the development of a hadronic shower within the jet. Probability of such a fake tag is presumably not very high but having in mind rather large rejection factors needed, one has to simulate carefully this effect. Physics channels which potentially might be affected should be identified.

7. Status and plans

As of today the study described in Sec. 2., Sec. 3. and Sec. 4. can be considered as finished. Their results cannot justify the need for the TC because its influence was found to be negligible. The study was done for the RPC trigger but in principle the Drift Tube trigger, based on several layers per station, should be even more resistant to this kind of background.

It is not yet proven, however, that the precise momentum measurement will not be affected by punch-through if there is no TC. This should be studied by detailed simulation, especially in the difficult cases described in Sec. 5. and Sec. 6.

The simulation should be done in three steps:
- generation of a sample of events
- tracking through the CMS with CMSIM / GEANT / FLUKA
- full muon reconstruction including pattern recognition and momentum fit

We need to ask Physics Group to help us in the first step. As a result we should have a library of generated events for all the channels in question, in the form of CMKIN ntuples, compatible with CMSIM input. The second part might be CPU consuming, but it is rather straightforward. The third step, the most sophisticated one, requires a lot of expertise and can be done only by Padova group responsible for the track reconstruction in Drift Tubes.