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Optimisation
of the
Forward Muon System Geometry

G. Wrochna[1]
CERN

Abstract

The study presented is a continuation of the work described in [1] and [2]. Various possible configurations of the forward muon chambers are discussed in terms of momentum resolution and matching of tracks measured in the muon system and in the inner tracker. A new layout proposed to avoid the gap between MF1 and MS1 is also examined.

1 Configuration of Cathode Strip Chambers

The momentum resolution curves presented in the CMS LOI assumed that the muon measurement can be simulated by two superlayers per station, each having an $r\varphi$ resolution of 100μm. Actually Cathode Strip Chambers (CSC) proposed for the forward region can perform better. The question however is, what is the optimal layout of the forward region taking into accont momentum resolution, track matching quality, technical feasibility and overall cost. The main parameters under discussion are:

- lever arm of MF1,
- number of layers per station,
- $r\varphi$ resolution of single layer,
- single layer efficiency.

The general CMS detector geometry described in the Status Report [3] has been used (see Fig. 1). The following resolutions have been assumed for the vertex, tracker and barrel muon chambers:

	$r\varphi$	r, z	
vertex	20 μm	5.3 cm	
Silicon tracker mono-layers	15 μm	12.5 cm	$/\sqrt{12}$
Silicon tracker stereo-layers	15 μm	0.1 cm	
MSGC tracker mono-layers	60 μm	12.5 cm	$/\sqrt{12}$
MSGC tracker stereo-layers	60 μm	0.1 cm	
MS 1-4	200 μm	0.2 cm	

The material of the barrel muon chambers was simulated with 2×4 gas volumes per stations, each 1 cm thick, separated by 1 mm aluminium walls. In the case of the forward chambers, 5 mm thick gas volumes where interleaved with 22 mm thick honeycomb plates. This geometry version is switched on in the CMSIM program [4] by IMVERS=904 or 906 for 4 and 6 layers per station respectivly. The main parameters of version 904 are compared below with the LOI version 901.

version	layers / MF1	layers / MF2-4	$\sigma(r\varphi)$	layer efficiency
901	2	2	100 μm	95 %
904	2×4	4	70 μm	80 %

[1] on leave of absence from Institute of Experimental Physics, Warsaw University, Poland

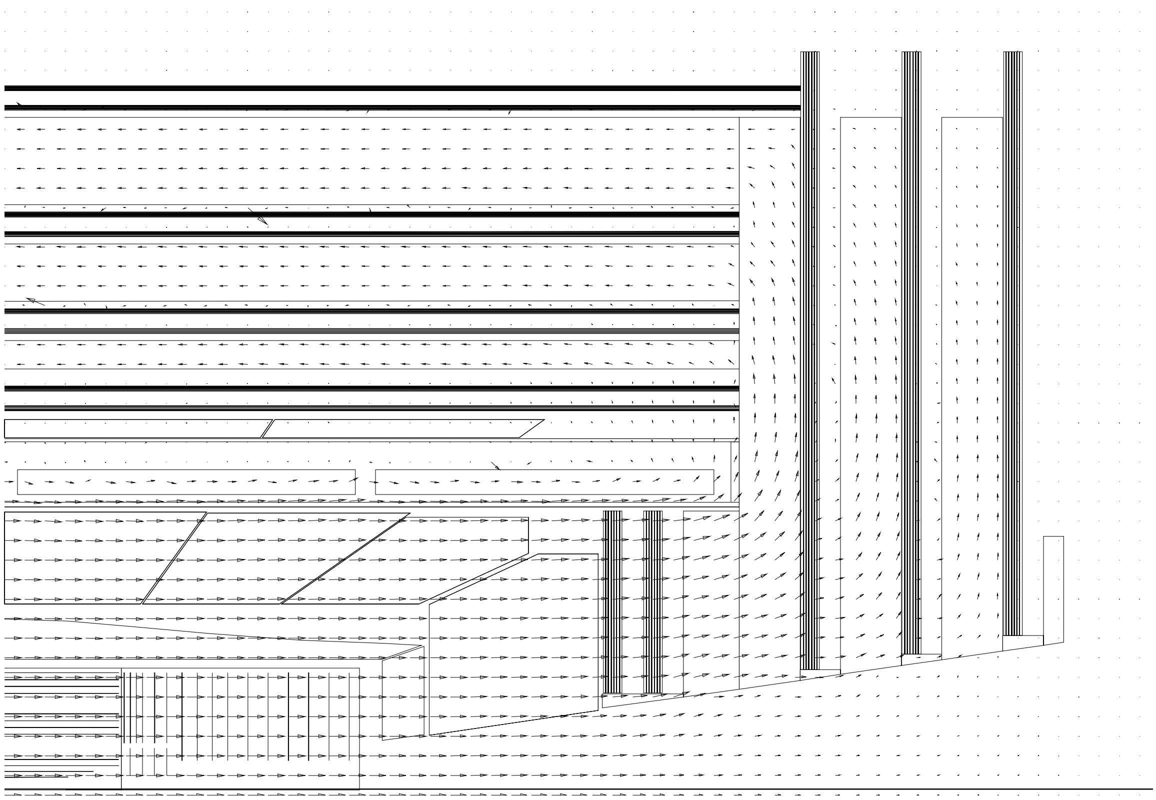

Figure 1: Simulated CMS layout (version 906).

1.1 Comparison of the LOI (901) and the actual (904) versions

The performance of the two versions has been compared in terms of momentum resolution. The track fitting has been done using the GEANE package [5] incorporated into the CMSIM program [6, 4]. The obtained transverse momentum resolution is plotted in Fig. 2 for both the muon system alone and for the full CMS including the inner tracker. As expected, the resolution of the new version is better, although the difference is significant only for the highest momenta in case of a stand alone measurement.

1.2 Varying CSC parameters

Station MF1 in CMS is placed at the turning point of the magnetic field. Therefore it plays a crucial role in momentum measurement. This is also the place where the density of tracks is highest. Taking this into account one can consider improving its performance by doubling the number of layers. At the same time the measurement lever arm is twice larger. Version 904 contains by default double MF1. Its first part is called MF0. One can disable it from the simulation by commenting out two corresponding lines in the TITLE file. Comparison of momentum resolutions achieved using single (4 layers) and double (2×4 layers) MF1 is presented in Fig. 3. No significant difference is observed, except the last point at $\eta = 2.45$. At this angle tracks miss the first part of MF1 so it is rather acceptance then resolution problem.

Next parameter in question is number of layers per station. The 4 and 6 layer solutions (versions 904 and 906) are compared in Fig. 4. Again no significant difference is observed.

Spatial resolution of CSC can be as good as 50 μm per layer [7]. However it depends strongly on the incident angle and magnetic field. Moreover measurement accuracy can be affected by alignment errors, not taken into account explicitly in this study. Thus it is interesting to know how a worsening of the overall spatial precision changes the momentum resolution. Three values of $\sigma(r\varphi) = 50$, 70, and 100 μm are compared in Fig. 5. One cannot see any difference between 50 and 70 μm. Only the stand alone measurement at very high p_t is affected by rising $\sigma(r\varphi)$ up to 100 μm. One can conclude that the overall spatial precision (including Lorentz effect and alignment errors) should not exceed 100 μm, but there is no reason to make it better than 70 μm.

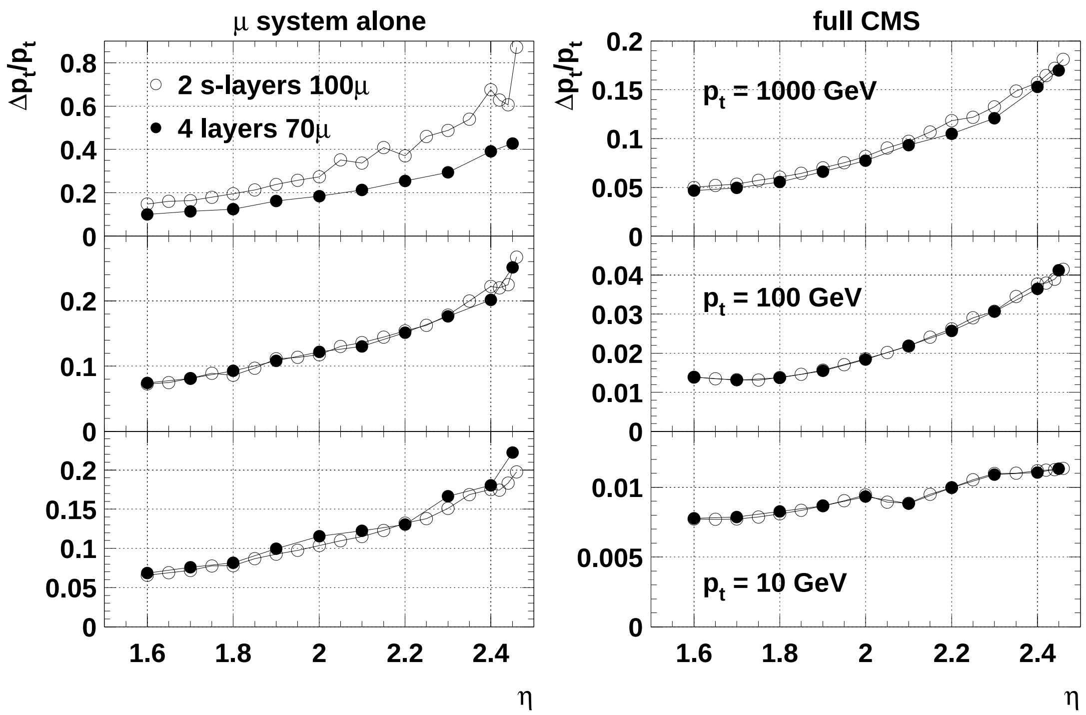

Figure 2: Momentum resolution for the improved CMS forward muon system (version 904, full circles) compared to the LOI version (901, open circles).

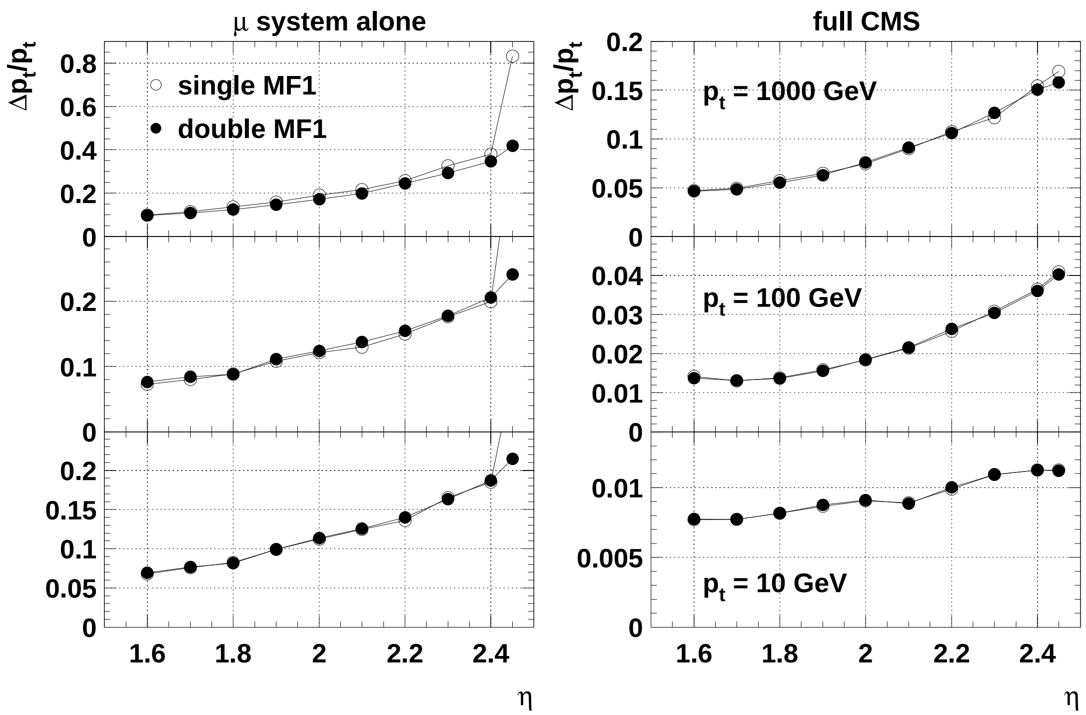

Figure 3: Momentum resolution with single (4 layers, 35 cm lever arm) and double (8 layers, 70 cm lever arm) MF1.

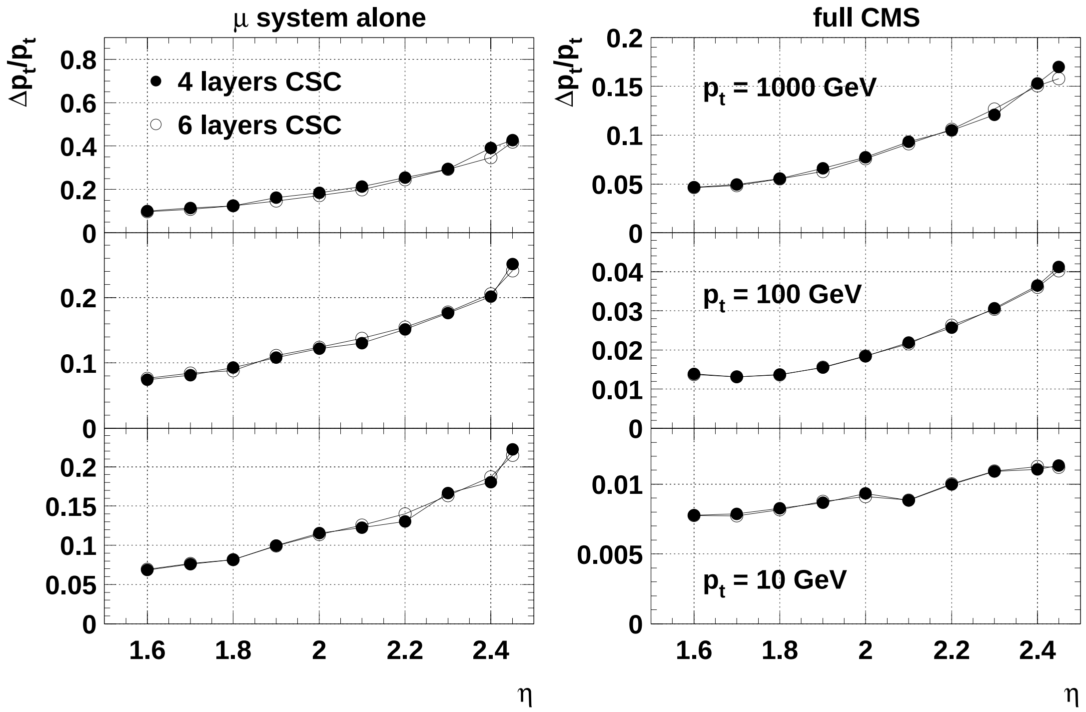

Figure 4: Momentum resolution with 4 and 6 layers CSC (version 904 and 906 respectivly).

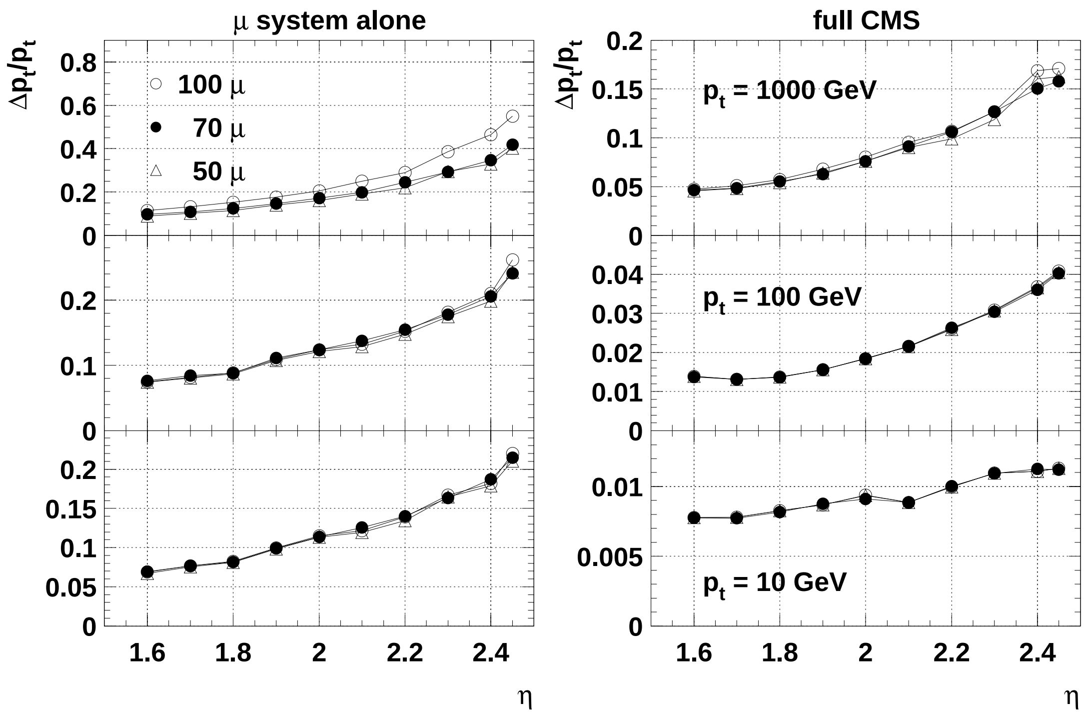

Figure 5: Momentum resolution for various $\sigma(r\varphi)$ per layer.

The last parameter studied here is the single layer efficiency. A chamber is certainly more then 95 % efficient but e.g. δ-electrons produced by a muon can deteriorate the measurement significantly. Results of the RD5 experiment [8] show that such mismeasured points can be recognized and removed from the overall fit. Therefore this effect can be considered as a certain loss of the single layer efficiency. On avereage about 12 % of the points will not survive a 3σ cut. If a δ or bremstrahlung electron has an energy high enough to develop a shower, the whole station can be lost. This effect has not been simulated explicitly in this study. It has been taken into account only in the sense that the single layer efficiency has been reduced to 80 %. Since this number is not very precise it is important to know how the overall momentum resolutions depends on this value. Three values 100, 80 and 50 % are compared in Fig. 6. No difference between 80 and 100 % is observed. This means that 4 layers per station provide enough redundancy. The situation becomes different when the efficiency goes down to 50 %. Now, at high p_t, the momentum resolution is worse and the fit is unstable; this can be seen from point to point fluctuations.

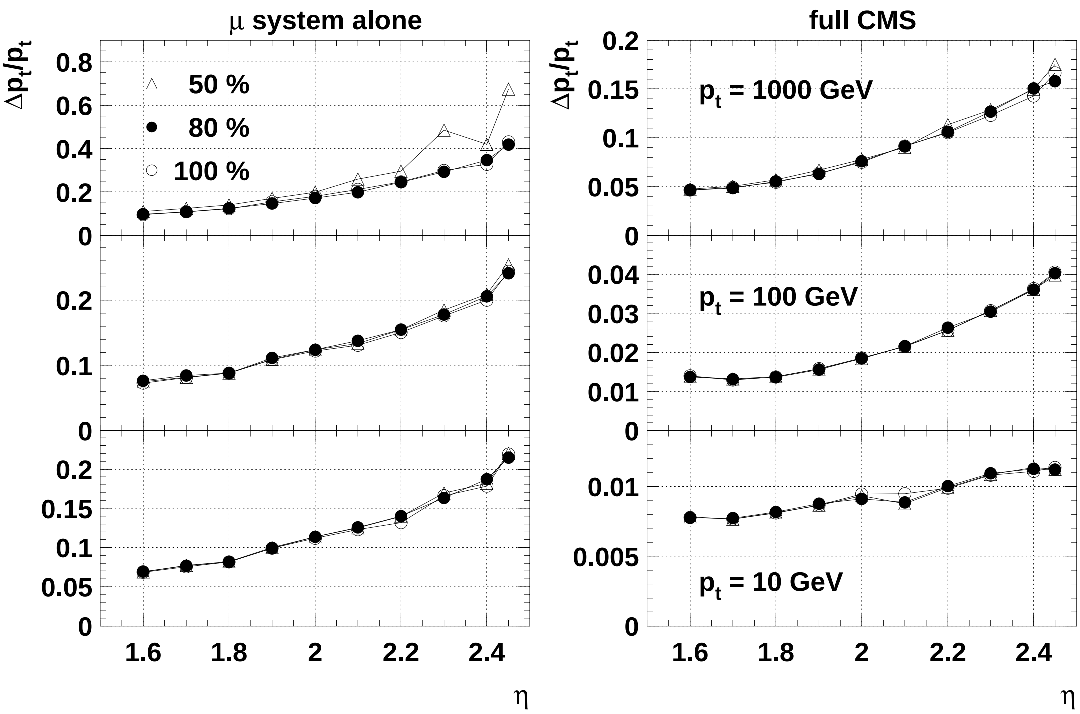

Figure 6: Momentum resolution for various single layer efficiencies.

1.3 Conclusions

All the above variations do not change the overall momentum resolution. They affect only the stand alone measurement. This measurement is needed mainly for extrapolation of tracks down to the inner tracker. Once the proper track is selected among all candidates in the tracker one can use the full power of CMS to perform momentum measurement. Therefore one can expect that the stand alone momentum resolution is not the most relevant parameter. In the next section we are going to study directly the quality of matching tracks measured by the muon system and the inner tracker.

2 Track matching

It has been shown already in the CMS LOI that all charged tracks with $p_t > 2$ GeV can be recognised in the tracker with an efficiency of better than 90 % even when they are part of energetic jets. In the muon system the occupancy is low and track recognition is easy, providing the particle reaches the muon system at all. The main difficulty is to match the track observed in the muon station with the proper candidate in the inner tracker. The matching should be done in the full parameter space, namely in momentum as well as in position. Therefore accuracy of measuring all the parameters should be well balanced. It seems that the present design having very poor resolution in r (wires ganged over 5 cm) compared to $\sigma(r\varphi) < 100\mu$m is not ideal. On the other hand, very high $r\varphi$ precistion is needed to provide good momentum resolution. Momentum resolution is crucial in the case of the most demanding situation, namely a muon inside a jet. Tracks inside a jet are all close together in space, but they are well separated in momentum. Therefore in this case the momentum matching is more selective than the spatial one.

In order to give some more quantitative estimation of the matching performance the matching procedure has been tested with two samples of muons within jets. The b-quark originated jets of $p_t^{jet} > 20$ GeV and $p_t^{jet} > 1$ TeV have been generated[2] using ISAJET 7.2. All mesons and barions containing b-quarks have been forced to decay into muons. Only muons with $p_t > 4$ GeV observed in the muon system have been used. Charged tracks with $p_t > 0.2$ GeV observed in the tracker have been considered as candidates for matching if they were in a 5 degree cone around the muon. A typical high p_t event is shown in Fig. 7. Distribution of η and p_t spectrum of generated muons is plotted in Fig. 8. Numbers of muons and candidate pairs in the sample are listed below:

ISAJET events	$p_t^{jet} > 20$ GeV $\lvert\eta^{jet}\rvert < 2.4$		$p_t^{jet} > 1$ TeV $1.0 < \lvert\eta^{jet}\rvert < 2.4$	
statistics:	5000 events:	per event:	1000 events:	per event:
all particles:	1592606	318.52	778463	778.46
particles ($p_t > 0.2$ GeV):	150092	30.02	117905	117.91
all muons:	4574	0.92	1159	1.16
muons ($p_t > 4$ GeV):	2659	0.53	1089	1.09
		per muon:		per muon:
all pairs:	91925	34.57	130569	119.90
pairs ($angle < 5$ degree):	4458	1.68	14308	13.14

Having two pieces of track, one in the muon system, the second one in the inner tracker, one can use several strategies for matching. For example one can extrapolate both tracks to a common plane and check the difference in momentum and position. In the present study a different method has been used, namely an overall fit through all the hits belonging to the two tracks. In this case all the information available is used and therefore this method provides the most powerful tool for selecting the right combinations among all candidates. From the simulation we know beforehand which combination is the right one. This gives us the possibility to estimate the matching efficiency. A simple χ^2 cut has been used as a matching criterium. We call "lost muon" a real muon which did not pass the cut. We call "ghost" a wrong combination which was nevertheless succefully fitted with a χ^2 below the cut value.

We have tested the procedure for two extreme versions of the forward muon detector:

detector version:	"optimistic"	"pessimistic"
layers in MF1:	6+6	4
layers per MF2-4:	6	4
wire ganging:	3×2.5 mm	20×2.5 mm
$r\varphi$ resolution per layer:	70 μm	200 μm

The χ^2 distribution of real muons and ghosts is shown separately in Fig. 9 for the "optimistic" version. The χ^2/NDF values for real muons are, as expected, concentrated around 1, whereas ghosts have usually much higher χ^2/NDF values.

[2] The 1 TeV region is certainly not interested from the point of view of b-quark physics. We used 1 TeV b-jets here for purely technical reasons in order to push the system to its limits.

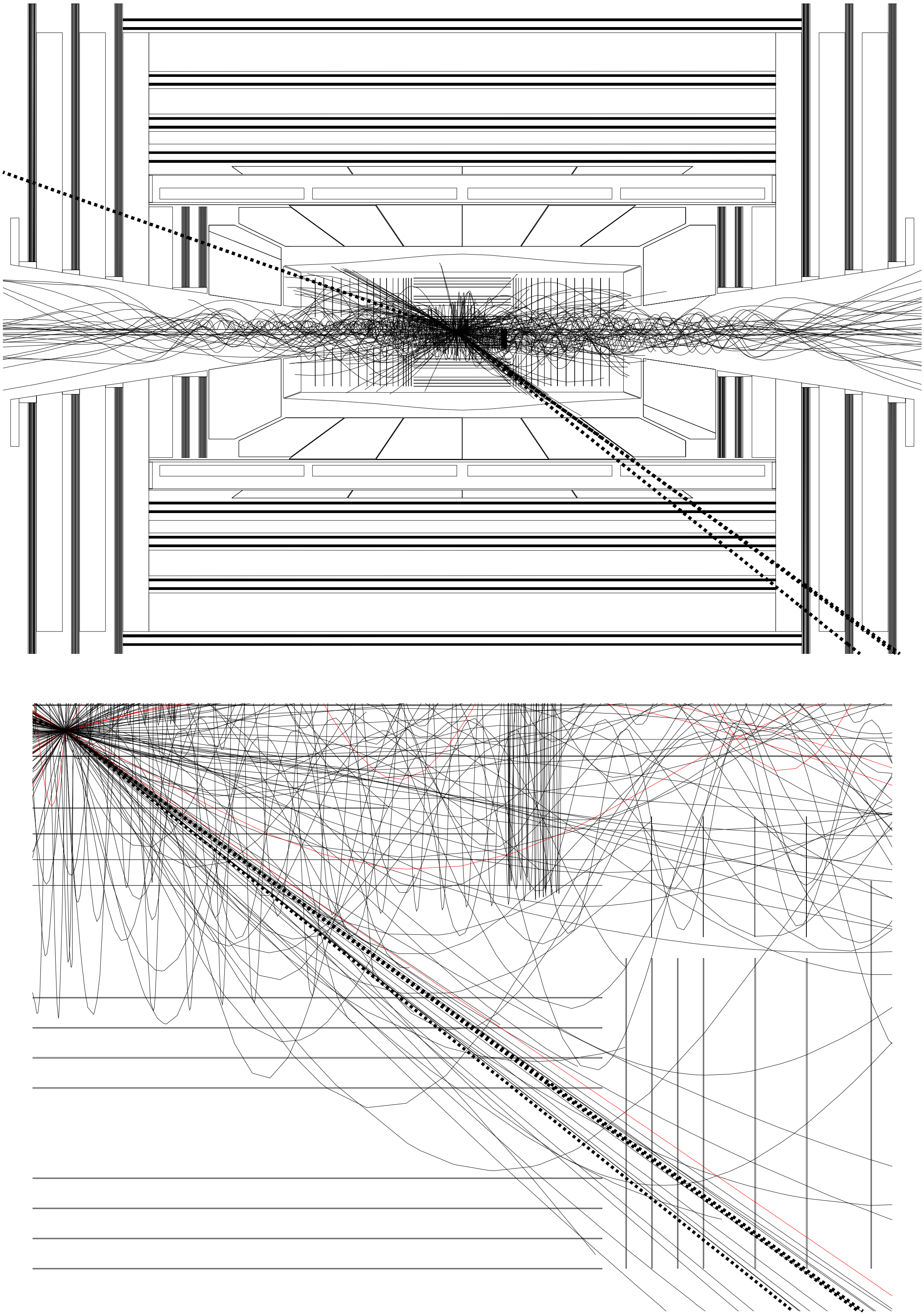

Figure 7: A typical event with muons (thick, dashed lines) within a jet of $p_t^{jet} = 1$ TeV.

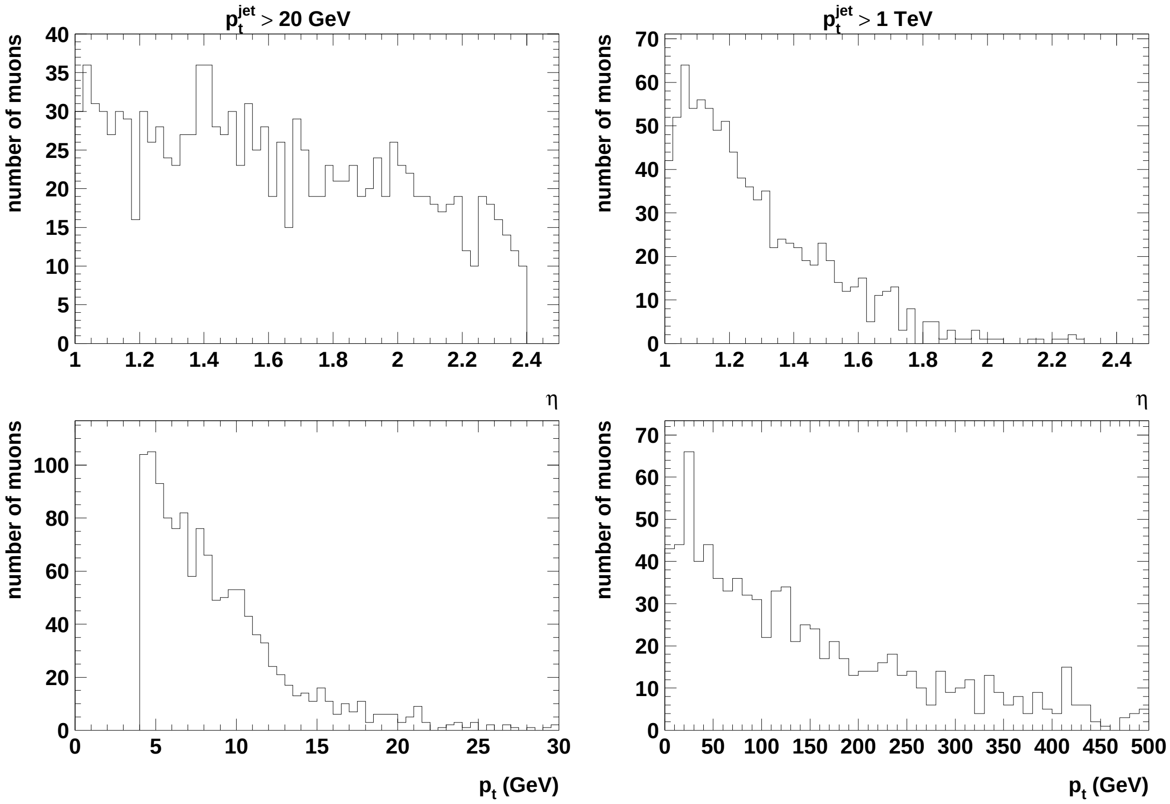

Figure 8: Distribution of η and p_t spectrum of generated muons.

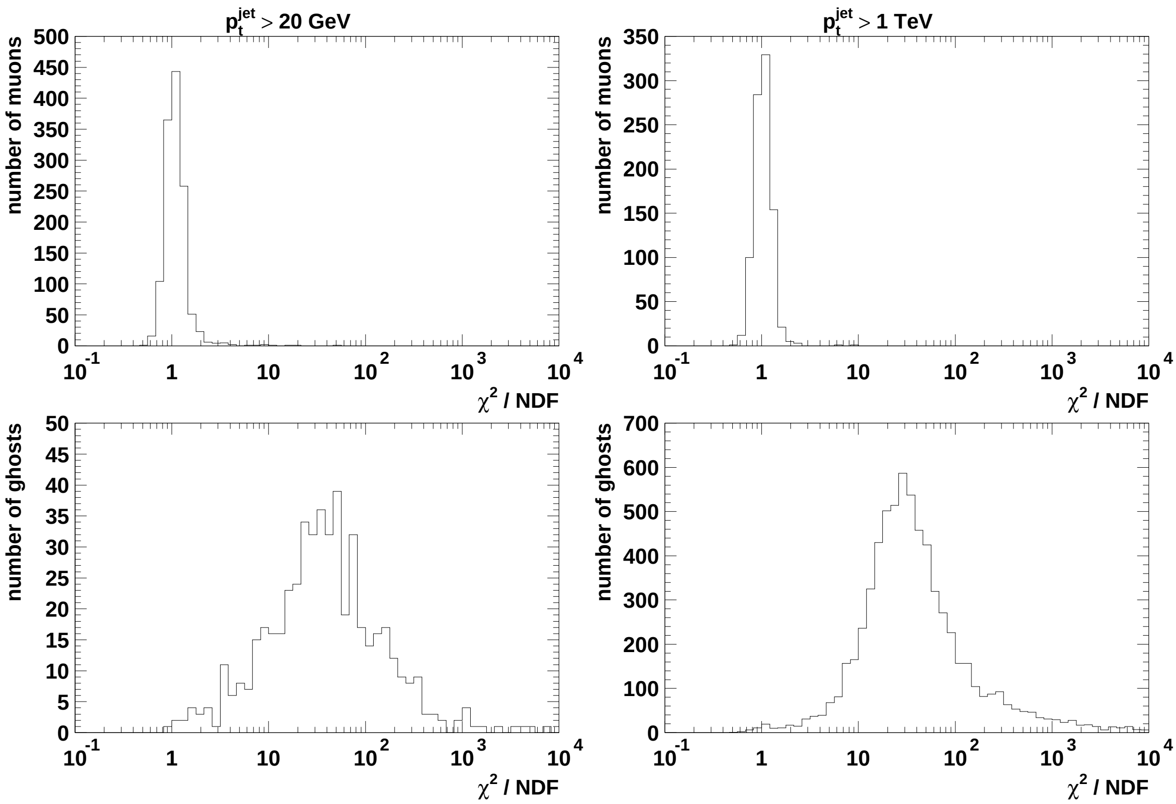

Figure 9: The χ^2 distribution of real muons and ghosts.

An optimal cut can be choosen looking at Fig. 10 which shows how the number of lost muons and ghosts depends on the cut value. It seems that the optimum is where the lost muons curve begin to flatten i.e. ≈ 3 for low p_t jets and ≈ 2 for high p_t jets.

In the same figure one can compare the matching performance of the "optimistic" (full line) and the "pessimistic" (dotted line) version of the detector. Let us first discuss the case of low p_t jets shown in Fig. 10a. The number of ghosts is roughly the same for both detector versions, whereas more muons are lost for a given χ^2 cut in the "optimistic" version. Obviously one should not draw an absurdal conclusion that the worse detector is better than the other one. The right explanation of the paradox is that "optimistic" version imposes stronger constraints which are more difficult to be fulfilled. After adjusting the cut value for each version, both give the same result: 1.5 % of lost muons and 1.5 % of ghosts in the sample. Anyway, the result is very good. Unfortunately it is not very conclusive, because it is not sensitive to the changes of the detector parameters under discussion.

In case of high p_t jets the number of ghosts is higher, because there are more candidates for matching in the narrow jet cone. Thus keeping the number of lost muons at the level of ≈ 1 % one gets ≈ 7 % of ghosts. No significant difference between the two detector versions is seen.

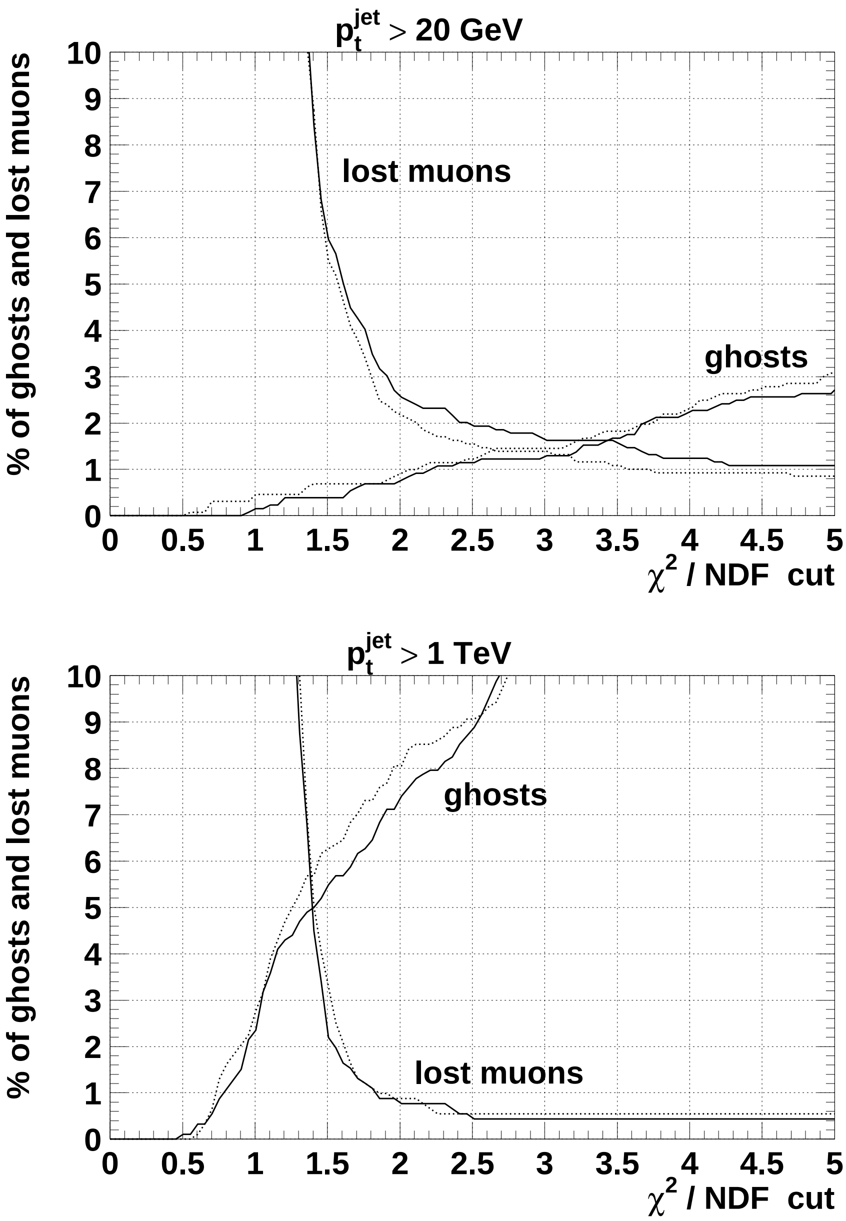

Figure 10: Percentage of lost muons and ghosts for the "optimistic" (full line) and the "pessimistic" (dotted line) version of the Forward Muon System.

Let us now have a look at the origin of the lost muons and ghosts in the low p_t sample. Fig. 11 shows their η and p_t distributions, assuming χ^2/NDF cut at 3.5 for the "optimistic" detector. Lost muons spectra (upper graphs) reflects the generated muons spectra and nothing can be deduced about the detector quality. In case of ghosts (black histograms) statistics is too small to draw any conclusion. Therefore we have also plotted (white, lower histograms) all the wrong combinations for which the fit was performed without failure, no matter how big is the χ^2. Those are potential candidates for ghosts, since in the case of very bad matching the fit simply fails because of numerical reasons.

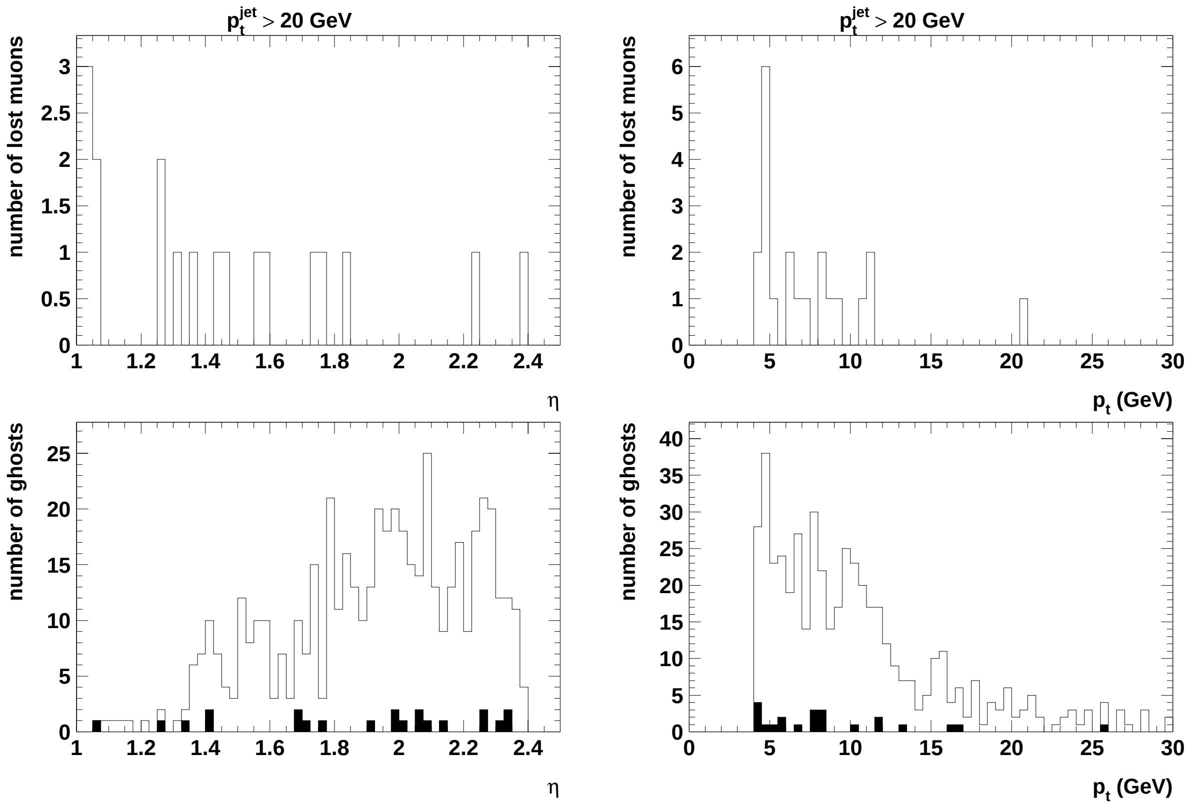

Figure 11: Distributions of lost ($\chi^2/NDF > 3.5$ or fit failure) muons (upper figures), all wrong combinations (lower figures, white histograms), and ghosts ($\chi^2/NDF < 3.5$, black histograms).

One can see that the number of wrong combinations begin to grow around $\eta = 1.4$, i.e. in the gap between MS1 and MF1. However the situation is even worse for higher η. In general the matching is much more diffcult in the forward region. There are at least three contributions to this effect:

- $\int B \times dl$ along the track is lower,
- multiple scattering is larger, because for a given p_t the total momentum decreases with η,
- having a fixed resolution in r the angular resolution is worse for higher values of η.

Another way to check the matching quality is to select the best (lowest χ^2/NDF) combination for every muon seen in the muon system. The table below shows how many times the right combination was chosen:

sample:	$p_t^{jet} > 20$ GeV		$p_t^{jet} > 1$ TeV	
version:	"optimistic"	"pessimistic"	"optimistic"	"pessimistic"
right combination	99.2 %	98.8 %	97.4 %	96.9 %
wrong combination	0.3 %	0.5 %	2.6 %	3.1 %
none (lost)	0.5 %	0.6 %	0.0 %	0.0 %

Good matching results for the two extreme cases of low and high p_t muons comes from the complementarity of matching in space and in the momentum. At low p_t multiple scattering deteriorates the spacial matching accuracy but excellent momentum resolution enables unambigous matching of momenta. On the other hand at very high p_t where the momentum resolution is rather poor, free of multiple scattering straight line tracks can be perfectly matched in space.

3 Filling the gap between MS1 and MF1

The impact of the gap between MS1 and MF1 on the momentum resolution was discussed in detail in the technical note [2]. It can be even more dangerous for the trigger. Either we switch this area off, or the whole trigger rate will be dominated by low p_t muons mismeasured in the gap. Maybe it is not difficult to fill the gap with a thin RPC layer. However if we want to have a complementary trigger system (e.g. CSC based) one needs to install here a full muon station.

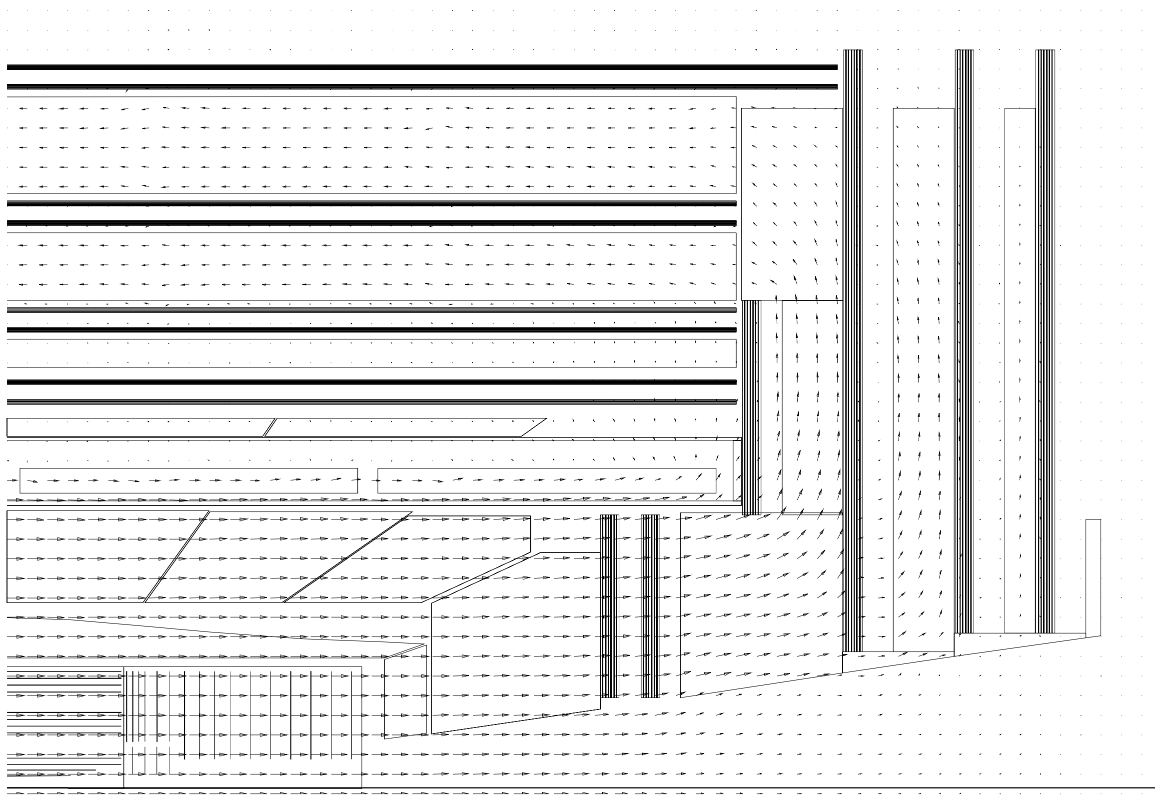

Figure 12: Proposal of rearranging the Forward Muon System to avoid the gap between MS1 and MF1.

A first attemp to rearrange forward area to avoid the gap has been done recently by the CMS Detector Integration Group [9]. The new design is shown in Fig. 12. At a first glance the design looks very promising. The first muon station has now full η coverage. The absorber layer between MS1 and MS2 is nonmagnetic, hence MS2 sees the full $\int B \times dl$ similarly to MS1. For high p_t the MS1/MS2 system provides a long lever arm for measurement of the bending angle. Usage of nonmagnetic material close to the coil can also decrease forces acting on the criostat. At the same time the overall shape of the magnetic field does not change very much and especially the field inside the muon chamber is similar to that in the old design. In detail, momentum resolutions for the old and new design are compared in Fig. 13. It is seen that the bump caused be the gap disappears whereas the resolution in the rest of the detector remains the same.

Summarizing, the new design seems to be very atractive, but its technical feasibility still needs to be proven.

4 Conclusions

Simple methods used in this study do not allow us to draw strong conclusions about the design of the muon system. It has been found that details of the layout and parameters of the forward muon chambers have little impact on the momentum resolution and track matching performance. However one should keep in mind that the study was based on the assumption that pattern recognition is perfect, i.e. all hits are unambigously grouped into tracks. In reality pattern recognition is a problem in itself, probably more complicated than track matching and fitting. Therefore the results presented here should not be considered as a definitive answer. They can only suggest where one can expect problems and show limits of what one can achieve. This way they prepare a ground for more detailed study including full pattern recognition.

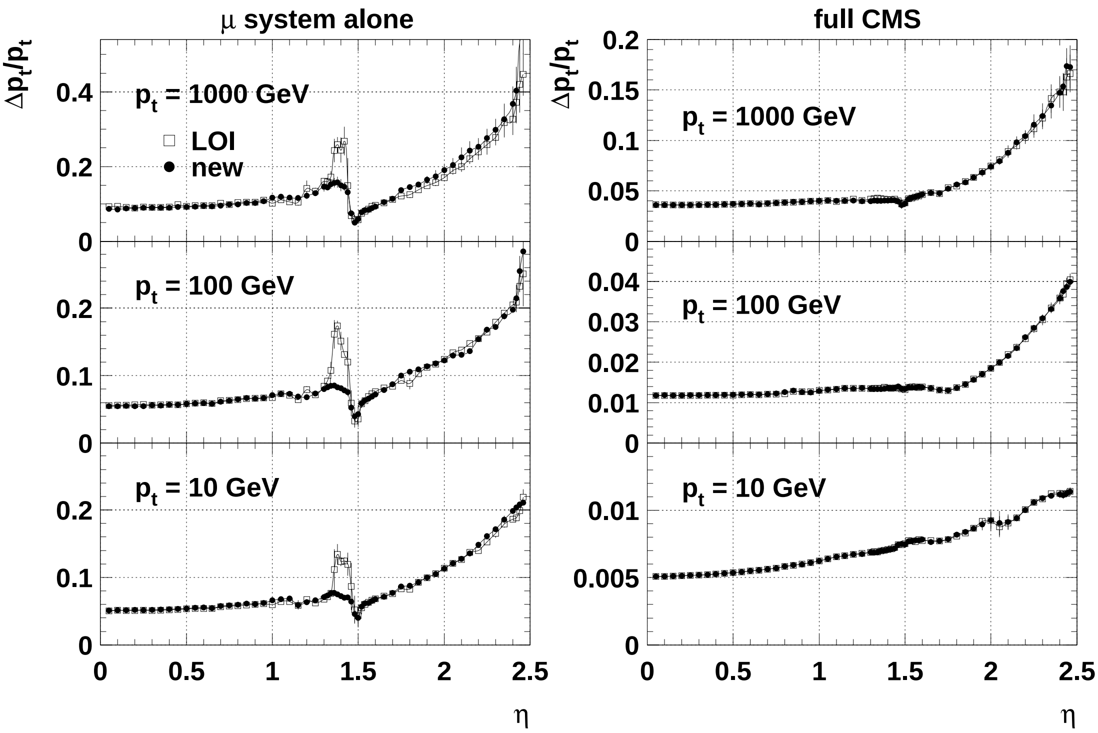

Figure 13: Momentum resolution for the new proposal (see Fig. 12) compared to that for the LOI version of the Forward Muon System (Fig. 1).

Acknowledgments

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