SUMMARY
MUON DETECTION WORKING GROUP

NOEL R. STANTON[1]
Physics Department, Kansas State University
Manhattan, KS 66506 USA

1. INTRODUCTION

1.1 The Muon Working Group

The areas of concentration of the Muon Working Group[2] reflected its composition: about half of the group was interested primarily in extending the capability of existing general purpose colliders (CDF, D0). Smaller numbers of people were interested in B physics with general purpose colliders at the SSC and LHC, with SSC fixed target experiments, and with dedicated forward colliders.

1.2 Why Muons?

Good muon tagging, and possibly also muon triggering, is essential for studying CP violation in $B_i \to J/\psi X$, $J/\psi \to \mu^+\mu^-$; as a flavor tag, with the semimuonic decay $B \to \mu^+ X$ or $\overline{B} \to \mu^- X$ tagging the flavor of the partner; for studying the physics of the semimuonic B decays themselves; and for looking for really rare decays like $B \to \mu^+\mu^-$.

1.3 How to Identify Muons

Some simple ideas involved in muon identification are illustrated in Fig. 1. If particles traverse an absorber of thickness x, the probability for a hadron to pass through without interacting is $\exp(-x/\lambda)$, where λ is the collision length. The thicker the absorber, the better the hadron rejection, as long as the muon is energetic enough to get through the absorber. Note however that for a central detector, where $p \approx p_T$, the typical p_T's useful for B physics (~ 2 GeV/c) do not permit very thick absorbers[3].

Just detecting a particle on the other side of an absorber is usually insufficient for good muon identification. The detected particle could be a low-energy survivor of a hadron interaction (punch through); or it could be a real muon, but not the track of interest (mismatch); or, it could have come from another source entirely, having avoided passing through the absorber. Ideally, the position, direction, arrival time, and momentum of the exiting particle should match those expected from the entering one. However, such desirable redundancy must be balanced against detector size and cost.

Even if the particle entering the absorber is unambiguously identified as a muon, it might

[1]Co-convener D.A. Hedin.

[2]The following presentations were given: Vaia Papadimitriou, 'CDF Muon Upgrades'; Tom LeCompte, 'CDF Problems and Cures'; Ken Johns, 'D0 Muon Triggers'; Dave Hedin, 'D0 Muons, Central Region'; Vladimir Glebov, 'D0 Muons, Forward Region'; Norbert Neumeister, 'Muons in CMS'; Patty McBride, 'Muons in SDC'; Gloria Corti, 'Muons in E771 and SFT'; Al Abashian, 'Resistive Plate Chambers'; Mohammad Mohammadi, 'GEM Muon System'; Valery Kubarovsky, 'SDC Muon System'.

[3]For iron, $\lambda \approx 0.11$ m, and 1 GeV of energy loss occurs in about 1.2 m.

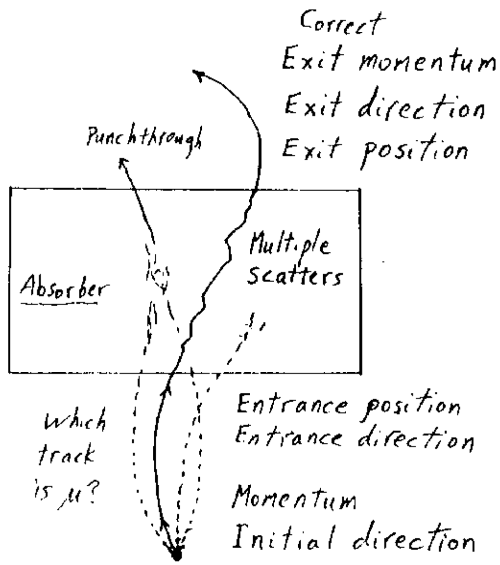

Figure 1. How to identify muons.

be a pion or kaon which decayed in flight before it could interact in the absorber. Compact detectors, in which the flight distance from production point to absorber is small, have an advantage in reducing false muon ID from this source.

2. FIXED TARGET B EXPERIMENTS

The chief disadvantage of fixed target experiments for high-statistics B physics is the reduced production cross section at lower $\sqrt{s}$. However, there are also some distinct advantages which compensate at least partially for this handicap at SSC or LHC energies.

1. It is easy to get good geometrical acceptance, ~ 0.8 for $B \to \mu X$, ~ 0.6 for $B \to J/\psi X$, with $J/\psi \to \mu^+\mu^-$.
2. Because of the large Lorentz boost, there is little loss in $B \to \mu X$ efficiency for thick absorbers; 10-20 GeV of energy loss is no problem.
3. B's are 'high p_T' physics for $\sqrt{s}$ typical of fixed target experiments, and this can be used to great advantage in hardware triggers or offline selection. An extreme example: Fermilab E653, in a 600 GeV/c π^- beam with an offline muon p_T cut of 1.5 GeV/c, achieved a factor of 50,000 in background rejection.
4. Muon p_T triggers are not hard, and dimuon mass triggers are possible.

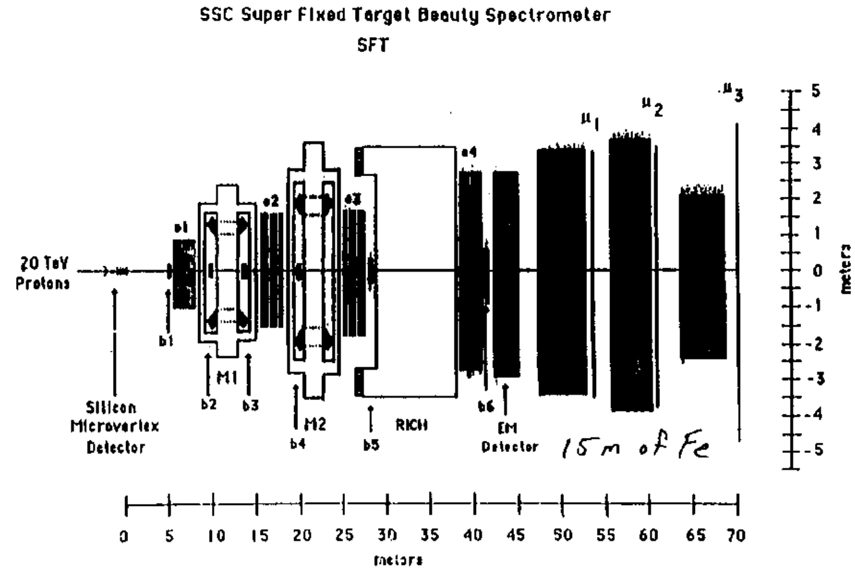

Figure 2. Layout of the proposed SFT spectrometer.

An example of one such experiment, the SFT (Super Fixed Target) detector proposed for a 20 TeV proton beam at the SSC, is shown in Fig. 2. It has a muon p_T trigger, and 15 m of iron absorber.

An important advantage of fixed target experiments over central colliders for B physics is the fact that p and p_T are not the same; one gets two background rejection factors, not one. The average muon momentum $\hat{p}_\mu$ in $B \to \mu X$ is >> $\hat{p}_\mu$ for centrally produced π, K decays to muons, and in addition $\hat{p}_{T\mu}$ in $B \to \mu X$ is >> $\hat{p}_{T\mu}$ for μ' s from such π's and K's. The expected discrimination for SFT is illustrated in Fig. 3. Requiring $p_\mu > 20$ GeV/c is already worth a factor of 10 in π, K rejection, and a modest p_T cut of 1.5 GeV/c gives a total rejection of $\times 1000$ against π, K and $\times 40$ against charm.

Some parameters of SFT and of the proposed LHB detector at LHC are compared in Table 1.

For fixed target experiments, muon ID and muon-based triggers are relatively easy and quite powerful. However, because of the small $B\bar{B}$ cross section it is not clear that FT experiments can afford to use only muons from $B \to J/\psi X$ for CP studies, or only muons from $B \to lX$ for tagging; the corresponding electron channels are also needed for statistics. Unfortunately, these electron channels appear to be a good deal more difficult than the muon ones.

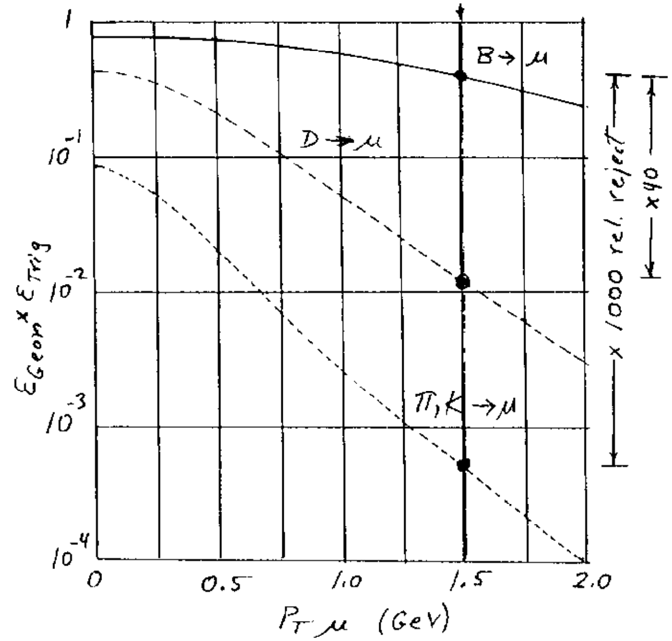

Figure 3. Product of geometrical and trigger efficiencies for B's in SFT, and for background muons from π, K decays and charm, as a function of the minimum allowed $p_{T\mu}$. A momentum cut of $p_\mu > 20$ GeV/c has already been imposed.

Table 1. Some parameters of SFT and LHB.

	Single μ		Dimuon
Parameter	SFT	LHB	SFT
Muon coverage	2 - 75 mr	< 100 mr	2 - 75 mr
π, K decay distance	40 m	30 m	40 m
Absorber thickness	15 m	6 m	15 m
Minimum p_μ (GeV/c)	20 GeV/c	10 GeV/c	20 GeV/c
Minimum $p_{T\mu}$	1.5 GeV/c	1.2 GeV/c	1.0, 0.5 GeV/c
Muon geom. effic. $\epsilon_{g\mu}$	0.82	?	0.68
Muon trigger effic. $\epsilon_{T\mu}$	0.45×BR	?	0.95
$\epsilon_{g\mu} \cdot \epsilon_{T\mu}$	0.37×BR	0.45×BR	0.65
π, K rejection	$\sim$ 2000	> 100	?
$c\bar{c}$ rejection	$\sim$ 100	?	?
Tagging effic. $\epsilon_{\mu Tag}$	—	—	0.8×BR

3. FORWARD COLLIDERS

One such proposed forward collider experiment, COBEX at LHC[4], is sketched schematically in Fig. 4. Of necessity, the beam pipe passes through the muon range filter, which cannot be as thick as those for SSC and LHC fixed target experiments. Forward collider experiments lie between the kinematic regimes of fixed target and central colliders: p_μ and $p_{T\mu}$ are still separately effective in reducing backgrounds, but less so than for fixed target. The COBEX proponents require an additional impact parameter requirement to get sufficiently low trigger rate; this costs an additional factor of about 0.13 for reconstruction efficiency.

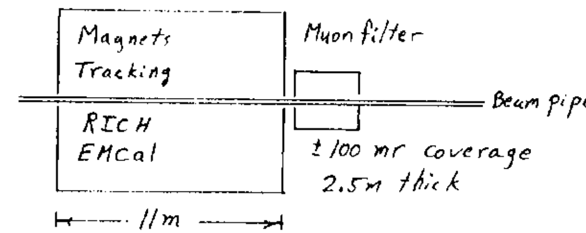

Figure 4. Cartoon of the proposed COBEX detector at LHC.

4. UPGRADED CENTRAL COLLIDERS: CDF AND D0

Upgraded existing central colliders are certainly proving grounds for future B experiments. It is also interesting to know how well they could compete with dedicated B experiments when the upgrades are complete.

4.1 CDF

The CDF muon system and the upgrades planned for it are discussed in detail in the paper by T. LeCompte and V. Papadimitriou. Muon detection in the central region (pseudorapidity$|\eta| < 0.8$) is shown schematically in Fig. 5, and the evolution of the detector is illustrated in Fig. 6. For the muon system, these consist of increasing the absorber thickness (Central Muon Upgrade) and η coverage (Central Muon Extension) in the central region, and moving the forward muon system closer to increase angular coverage and decrease the potential π, K decay path. There will also be upgrades to the CDF rate capability and to the silicon tracking.

Difficulty was encountered with the Central Muon Extension during the last CDF run with backsplash from the beam pipe and forward calorimeter. This backsplash bypassed the absorber and produced an unacceptably large trigger rate. The cure was a beam pipe of lower mass, and tighter timing of the muon scintillators.

[4]There was unfortunately no COBEX expertise available, so that the forward collider option is less fully developed than the others in this report.

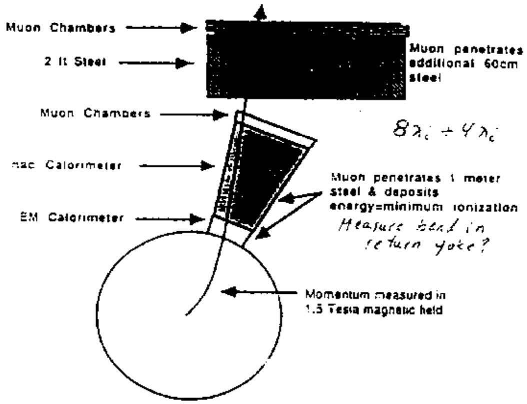

Figure 5. Sketch of CDF muon detection in the central region.

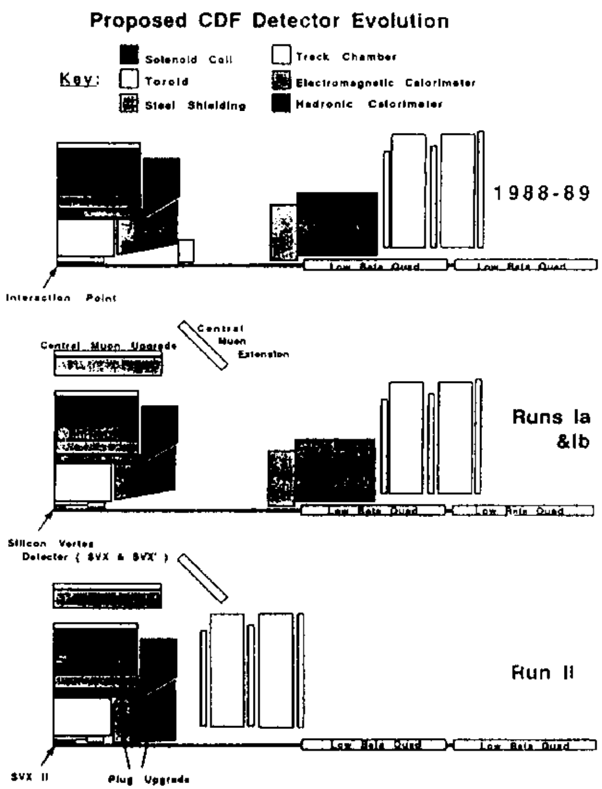

Figure 6. Evolution of CDF.

Table 2. Comparison of CDF and D0 parameters for $B \to \mu X$.

	CDF			D0
Parameter	Run Ia (now)	Run III (M.I.)	B physics takeover	Run III (M.I.)
$\|\eta\|$ for muons	< 0.55	< 1.0	< 2.8	< 3.4
π, K decay dist.	1.5 m	1.5 m	1.5 m	0.7 m
Filter thickness	12λ	8-12λ	8-12λ	10-18λ
Min. $p_{T\mu}$ (GeV/c)	~ 7.5	6.0 3.0+IP ?	5.0? 3.0+IP ?	4.0
Geom. effic. $\epsilon_{g\mu}$ (η, ϕ)	0.10	0.25	0.50	0.60
Trig. effic. $\epsilon_{T\mu}$	0.01×BR	0.025×BR	0.025×BR	0.027×BR
$\epsilon_{g\mu} \cdot \epsilon_{T\mu}$	0.001×BR	0.006×BR	0.012×BR	0.016×BR
Punchthru (online) fraction (offline)	0.20 < 0.05	0.20 < 0.05	0.20 < 0.05	
π, K decay fraction	0.50	0.25	0.35	< 0.05 tot
$c\bar{c}$ BG after cuts	< 0.15	—	—	0.10
$B \to \mu X$ per year	0.5M	150M	300M	~ 400M

Table 3. Comparison of CDF and D0 parameters for $B \to J/\psi X$, with $J/\psi \to \mu^+\mu^-$, plus a muon away-side tag.

	CDF			D0
Parameter	Run Ia (now)	Run III (M.I.)	B physics takeover	Run III (M.I.)
$\|\eta\|$ for muons	< 0.55	< 1.0	< 2.8	< 3.4
π, K decay dist.	1.5 m	1.5 m	1.5 m	0.7 m
Filter thickness	12λ	8-12λ	8-12λ	10-18λ
Min. $p_{T\mu}$ (GeV/c)	3.0, 1.5	2.0	1.5	3.0
Geom. effic. $\epsilon_{g\mu}$ (η, ϕ)	0.25	0.35	0.42	0.75
Trig. effic. $\epsilon_{T\mu}$	0.014	0.014	0.03 ?	0.12
$\epsilon_{g\mu} \cdot \epsilon_{T\mu}$	0.0035	0.005	0.012	0.09
Away-side μ tag ϵ_{tag}	0.1×BR	0.4×BR	0.5×BR	0.53×BR
$\epsilon_{g\mu} \cdot \epsilon_{T\mu} \cdot \epsilon_{tag}$	3.5×10^{-4}×BR	2×10^{-3}×BR	6×10^{-3}×BR	5×10^{-2}×BR

5. GENERAL-PURPOSE COLLIDERS AT LHC AND SSC

Distributions in p_T and η for muons from B decay at LHC energy are shown in Fig. 9. B's are very much low-p_T physics, with the peak of the muon p_T distribution at about 1.5 GeV/c.

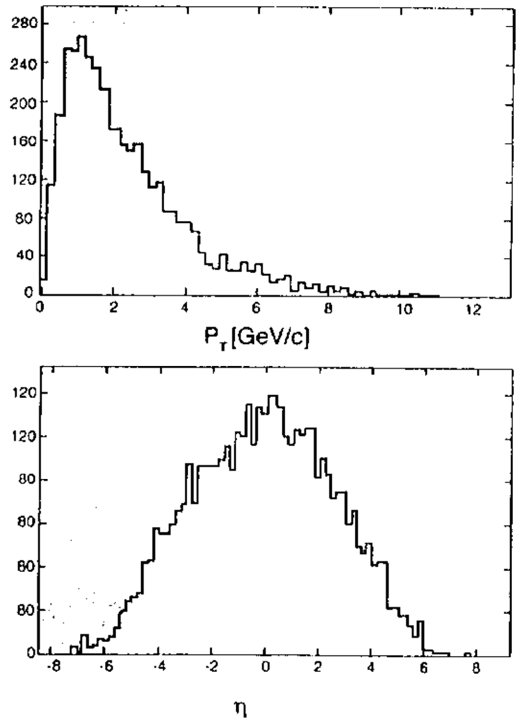

Figure 9. Expected distributions in p_T and η for muons from B decay at LHC energy.

5.1 SDC and GEM at SSC

B physics has not had high priority in planning for GEM and SDC, and thinking about how to use low-luminosity ($\sim 10^{33}$) initial running for B physics is just beginning. As with central colliders at lower energy, an important issue is how to trigger at an acceptable rate on muons of relatively low p_T. The results of one such study for SDC by D.P. Coupal is reproduced in Fig. 10. Coupal limited his study to b quarks produced with $p_T > 10$ GeV/c; this leaves an estimated 250μb out of a total SSC $b\bar{b}$ cross section of 1-3 mb. For this preselection, Fig. 10 shows the relative acceptance for 1μ, 2μ, and 3μ triggers as a function of p_T for $B \to J/\psi K^0_s$, $J/\psi \to \mu^+\mu^-$, tagged by $\overline{B} \to \mu^- X$. Tracks with $p_T < 5$ GeV/c will barely penetrate the SDC calorimeter and toroid. The acceptance for triggering on three muons with $p_T > 5$ GeV/c is about the same as that for one muon with $p_T > 20$ GeV/c, about 2% of that for no p_T requirement.

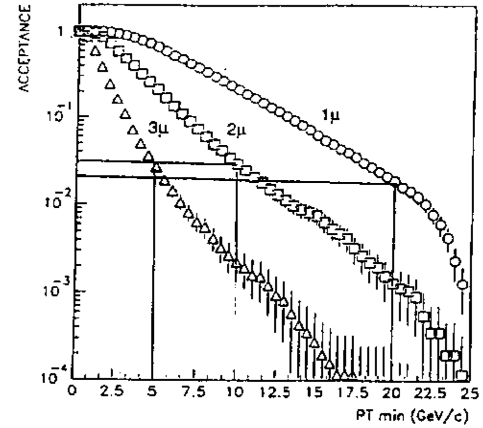

Figure 10. Relative acceptance in SDC for $|\eta| < 2.5$ for 1μ, 2μ, and 3μ triggers, as a function of p_T, from $B \to J/\psi K^0_s$, $J/\psi \to \mu^+\mu^-$, tagged by $\overline{B} \to \mu^- X$.

The muon trigger concept of GEM is illustrated in Fig. 11; muons are tracked in a magnetic field in air after they emerge from the calorimeter. GEM will be able to trigger on single muons or dimuons with $p_T > 10$ GeV/c and $|\eta| < 2.5$, and to tag B jets with muons with $p_T > 15$ GeV/c.

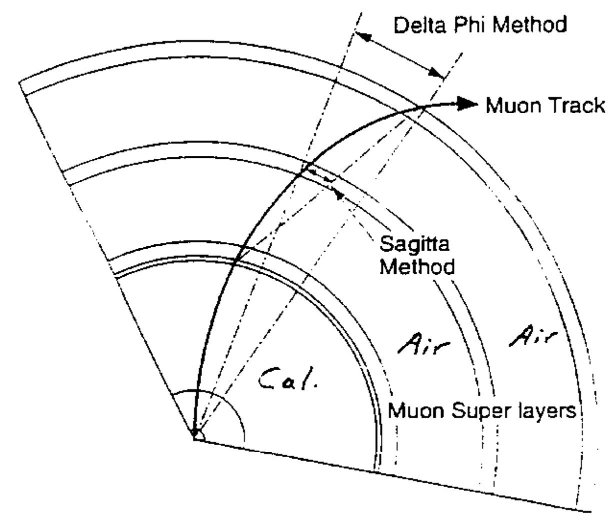

Figure 11. Level 1 muon trigger concept for GEM.

5.2 CMS at LHC

The Compact Muon Spectrometer (CMS) proposed for LHC (Fig. 12) is optimized for muon identification. As shown in Fig. 13, the detector has considerable redundancy, including multiple momentum measurements, and tight ϕ coverage with no gaps for $|\eta| < 2.5$. The CMS proponents have done substantial planning for doing B physics in the early running (luminosity $\sim 10^{33}$), and have carefully studied resolution, backgrounds, and calibration of the dilution factor. They will be able to do trimuons with $p_T < 4$ GeV/c or dimuons with $p_T < 5$ GeV/c with a 100 Hz trigger rate at that luminosity, and then turn up the p_T threshold as luminosity increases. For the trimuon option and an integrated luminosity of 10^4 pb^{-1}, CMS can obtain about 5.6×10^6 events per year of $B \to J/\psi K^0_s$, $J/\psi \to \mu^+\mu^-$ with an away-side muon tag, giving errors on $\sin(2\beta)$ of 0.06 to 0.09.

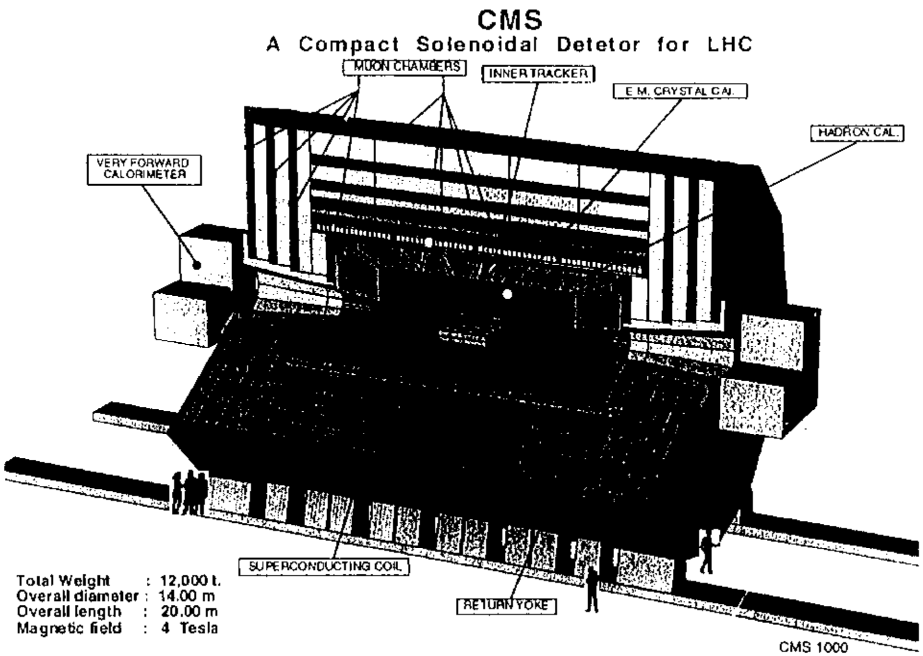

Figure 12. The proposed CMS detector for LHC.

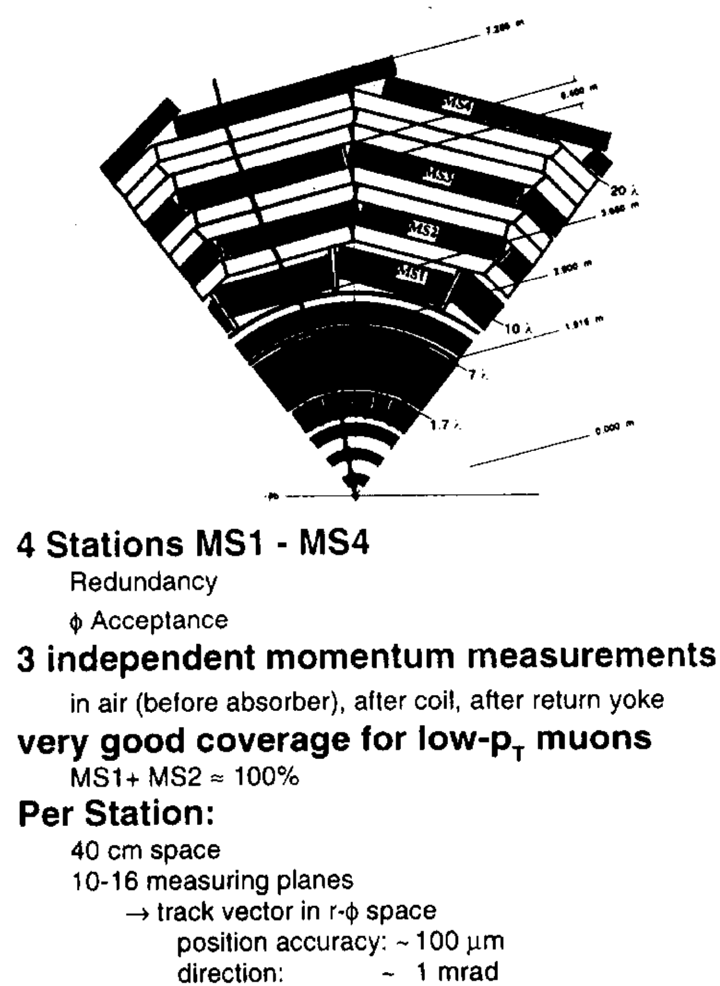

Figure 13. Muon detection in CMS.