A-Exam: The Rare $B_s \to \mu^+\mu^-$ decay and tanβ

Walter Hopkins

Physics Department, Cornell University.

The rare B decay of $B_s \to \mu^+\mu^-$ is a promising decay channel to find beyond the Standard Model (BSM) physics because flavor changing neutral current (FCNC) decays are suppressed in the Standard Model (SM). In the SM this decay isn't possible at tree level and can have a box diagram (Figure 1) or a penguin diagram (Figure 2) as the highest contributing diagrams. Both these diagrams are suppressed due to the CKM coupling of the top to the strange quark (thus an off diagonal term of the CKM matrix). Diagrams that are mediated by the charm and up quarks are suppressed by the GIM mechanism. The SM diagrams are also helicity suppressed because the B_s is a spin zero particle, and thus the muons should have opposite helicity (chirality since the muon energy in this decay is significantly greater than the muon mass), which is not what the interactions require.

This channel thus has very low SM contribution and excesses could be attributed to beyond the SM physics. Particularly in super symmetry (SUSY) this process can be enhanced and dramatically depends on tanβ^6 for large tanβ (tanβ is the ratio of the two SUSY Higgs VEV's). An example diagram for such a process is shown in Figure 3.

Theoretical Background: SUSY and tanβ

Supersymmetry is a group of models which is meant to solve the electroweak hierarchy problem by introducing bosonic super partners of fermions and fermionic super partners for

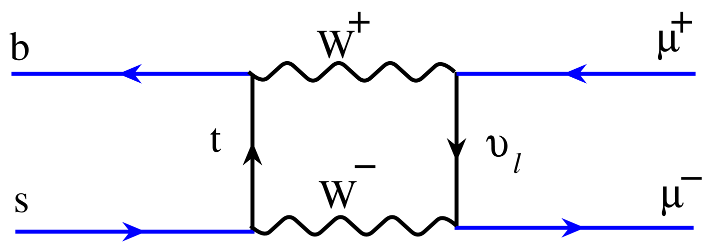

FIG. 1: Feynman Box Diagram for $B_s \to \mu^+\mu^-$

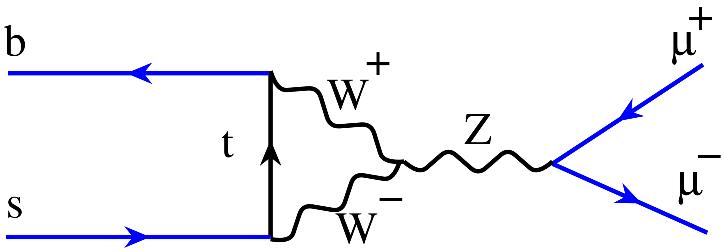

FIG. 2: Feynman Penguin Diagram for $B_s \to \mu^+\mu^-$

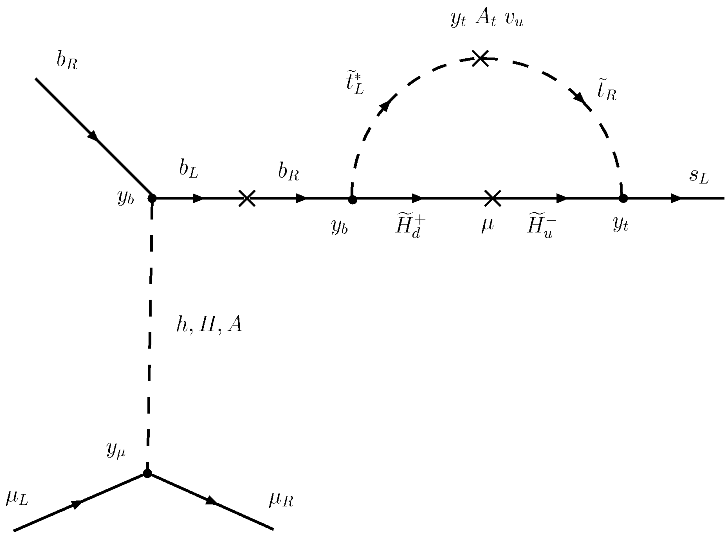

FIG. 3: Feynman Penguin Diagram for $B_s \to \mu^+\mu^-$

gauge bosons. In this section I will briefly discuss what tanβ is and why the $B_s \to \mu^+\mu^-$ decay could be enhanced by tanβ^6 in the Minimal Supersymmetric Standard Model.

In this model there are charged and neutral Higgs fields along with their super partner Higgsinos. You have a Higgs field that couples to up type quark fields and another that couples to down type quark fields and leptons. These two up and down Higgs will have different VEV's and tanβ is given by the ratio of these two VEV's:

$$tan\beta = \frac{v_u}{v_d} \tag{1}$$

All the quark and lepton masses depend on these VEV's and the Yukawa couplings in the following way:

$$m_u = \sqrt{2} y_u v sin\beta \tag{2}$$

and

$$m_d = \sqrt{2} y_d v cos\beta \tag{3}$$

where $v^2 = v_u^2 + v_d^2$. If tanβ is large we know that sin$\beta \sim 1$ and thus tan$\beta \sim \frac{1}{\cos\beta}$ which results in the Yukawa couplings for the top quark, bottom quark and muon:

$$y_b = \frac{m_b}{\sqrt{2}v} tan\beta \tag{4}$$

$$y_t = \frac{m_t}{\sqrt{2}v} \tag{5}$$

$$y_\mu = \frac{m_\mu}{\sqrt{2}v} tan\beta \tag{6}$$

When considering the diagram in figure 3 these are exactly the Yukawa couplings that are relevant. The two vertices involving bottom quarks will have tanβ dependence while the the muon vertex will also yield a tanβ, thus resulting in a tanβ^6 dependence in the cross section.

Leptonic B_s decay channels

There are two other channels one can consider when studying leptonic B_s decays: $B_s \rightarrow e^+e^-$ and $B_s \rightarrow \tau^+\tau^-$. In this section I will explain why the dimuon channel is the most promising channel for finding evidence of beyond the Standard Model physics.

$B_s \rightarrow e^+e^-$

The SUSY diagram shows that the dilepton decay of the B_s is mediated by the Higgs. The Higgs coupling constants to fermions is proportional to the fermion masses, which in the case of electrons would be about 200 times smaller than for muons. This results in factor of 200 suppression of the diagram shown in Figure 3. There are also experimental difficulties with using electrons, which involve the dielectron invariant mass. Electrons are more likely to lose momentum due to bremsstrahlung which could complicate electron track reconstruction. Muons are not as susceptible to bremsstrahlung because their mass is significantly larger than the electron mass.

$B_s \to \tau^+\tau^-$

The Yukawa couplings for the τ is larger than for the muon but detection of such decays are much more challenging experimentally. τ's have a much shorter lifetime than the muon ($c\tau = 87\mu m$ compared to $c\tau = 659m$), which requires detailed knowledge of the τ's decay products. These decay products will always involve at least a ν_τ which will result in MET, which will cause less accurate B_s reconstruction due to lack of neutrino longitudinal momentum information. There are many decay channels for the τ, of which nearly 40% of the decays would also have two neutrinos as final particles, which would have to be studied to properly reconstruct the B_s. In a e^+e^- collider this channel may be more feasible since you wouldn't have to deal with parton distribution functions (PDF's) and could reconstruct the longitudinal neutrino momentum, and thus properly reconstruct the invariant mass of the τ's. The error on the invariant mass however would still be larger than in the $\mu^+\mu^-$ case.

Search for $B_s \to \mu^+\mu^-$ at the LHC

Due to the higher instantaneous luminosities and energy of the LHC when compared to the Tevatron, the LHC is expected to produce about 50 times more $b\bar{b}$ pairs ($\mathcal{O}(10^{14})$ $b\bar{b}$ pairs per second at a luminosity of 10^{34} cm^{-2}s^{-1}) than the Tevatron [1]. The cross section at $\sqrt{s}$=14 TeV at the LHC would be approximately 500 μb [2] compared to the Tevatrons 20 μb. This is an important improvement because this B_s decay is so rare and current results from CDF and D0 are limited by statistics. This increase is due to the increase in bunch crossing time, collision energy, and luminosity. The experiments at the LHC, ATLAS, CMS, and LHCb, will continue the search for excesses in $B_s \to \mu^+\mu^-$ events. ATLAS and CMS are general purpose solenoidal detectors that were built with the search for the Higgs in mind, but due to their muon and pixel tracker systems they have the possibility to improve our current measurements of this rare B decay. LHCb is a fixed target experiment that focuses on b physis and thus will be especially suited for this measurement/search. I will focus on the subdetectors that will be important for this analysis: the tracking system and the muon tracking system.

ATLAS

This analysis will mostly rely on the inner tracker, for secondary vertex identification, and the muon tracking system and dimuon trigger, for muon identification.

The trigger is required just as in any other high luminosity hadron collider to reduce the flow of data from the MHz range to the Hz range. ATLAS and CMS will both use a level one dimuon trigger for potential B_s events. The trigger p_t threshold will be determined depending on the instantaneous luminosities expected at the LHC but will probably be around 3-6 GeV.

The inner tracker of ATLAS consists of a pixel detector, a semiconductor tracker, and a transition radiation tracker. The pixel detector will be essential at identifying the secondary vertices of the B_s. The ATLAS pixel detector has 80 million channels spread across three barrel layers, allowing for 3 space points for track reconstruction, and six end layers (three in the positive z direction and three in the negative z direction). This yields a $R\phi$ resolution of 12 micron and a resolution of 60 micron in the z direction as well as a $|\eta| < 2.5$ coverage [3]. This is a significant improvement from the CDF silicon tracker system, which has a $|\eta| < 2$ coverage, approximately 722,000 read out channels, and a $R\phi$ resolution of 35 micron [4, 5].

The ATLAS semiconductor tracker uses silicon strips whereas the CDF outer tracker (COT) is a drift chamber. Typically silicon strip trackers have a better resolution than drift chambers (such as the CDF COT) but the drift chambers can use more hits for track reconstruction. The ATLAS silicon strip detector $R\phi$ resolution is about 16 micron while the Rz resolution is 580 micron. The hit resolution of the CDF COT, in comparison, is 146 micron [6, 7] thus in ATLAS there is clearly a greater focus on high p_T physics. Figure 4 shows the p_T and impact parameter resolution for muons in the inner detector.

The muon system at CDF is a patchwork of different muon systems, however ATLAS was designed with accurate muon detection as a primary goal, and with the muon system intended to run independently. ATLAS has a greater $\eta < 2.7$ coverage than CDF ($\eta < 1.5$) as well as a greater muon trigger coverage [8, 9]. CDF also mainly uses drift tubes for the muon reconstruction while ATLAS uses monitored drift tubes (MDT), resistive plate chambers (RPC), thin gap chambers (TGC), and cathode strip chambers (CSC). The RPC's and TGC's are especially useful for triggering due to their fast time response.

ATLAS is expected to be able to measure SM events at 30 fb^{-1}, which could have been collected in less than a year under the original LHC luminosity. The instantaneous luminosity however has been lowered by two orders of magnitude until 2012, at which point 1 fb^{-1} would have been collected. CDF would have collected approximately 15 fb^{-1} by 2012 (if it is still running). However ATLAS still has an acceptance advantage since they could set similar limits with 100 pb^{-1} that CDF set with 2 fb^{-1}.

CMS

CMS, like ATLAS is a general purpose detector which can be useful for B-physics. CMS and ATLAS have similar geometries and subdetector. CMS however uses a different electromagnetic calorimeter as well as a different magnetic field. CMS however has a similar silicon based tracking system (excluding the transition tracker).

CMS will use a di-muon trigger, just as ATLAS and CDF, with a p_t threshold of 3 GeV at low luminosity. This threshold is 1.5 GeV (2.0 GeV) for CMU-CMU (CMU-CMX) di-muons at CDF.

The occupancy at high luminosities will cause difficulties in finding secondary vertices from B_s hadrons unless a high resolution can be achieved with the pixel detector, the inner most tracking detector. The CMS pixel detector consists of three layers in the barrel region and two disks in both the +z and -z direction, which in total yield 66 million read out channels. This CMS pixel detector has a higher z resolution (17 micron) but approximately the same $R\phi$ resolution as the ATLAS pixel detector. The CMS pixel detector has an $|\eta| < 2.2$ coverage [10], which is achieved with four instead of the six layers in ATLAS.

Outside the pixel detector CMS also has a silicon strip detector consisting of $\sim$10 million read out channels. The silicon tracker has both stereo and mono layers that in total give a $|\eta| < 2.2$ coverage. Stereo layers can more accurately measure position because they are essentially two mono layers glued together with a small pitch between the strips. The combined p_T and impact parameter resolution as a function of pseudo-rapidity is shown in figure 5. Both CMS and ATLAS have similar track reconstruction efficiencies of about 98-100% over most of the η range, which is very similar to CDF's track reconstruction efficiency.

The muon detectors at CMS use the same detector subsystems as ATLAS, namely CSC's, RPC's, and Drift tubes (figure 6). The CMS Muon system has a slightly lower $\eta < 2.4$

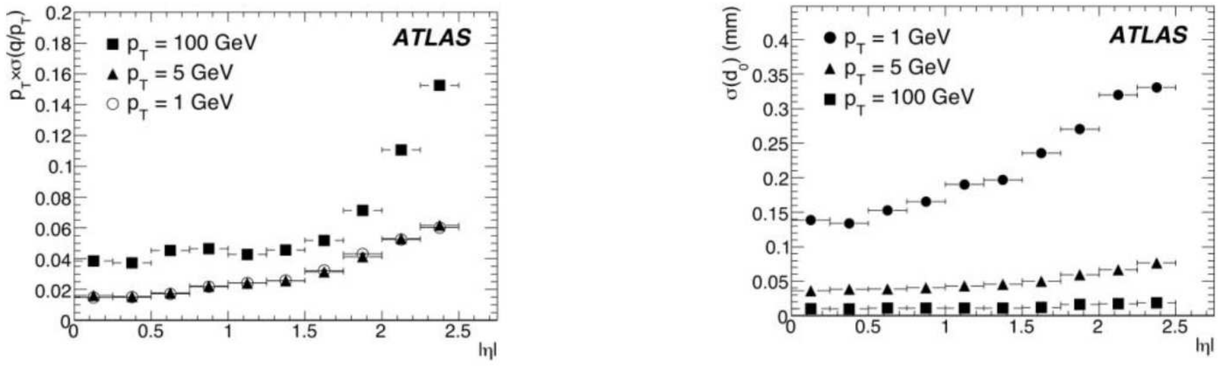

FIG. 4: p_T (left) and impact parameter (right) resolutions for ATLAS Inner tracker

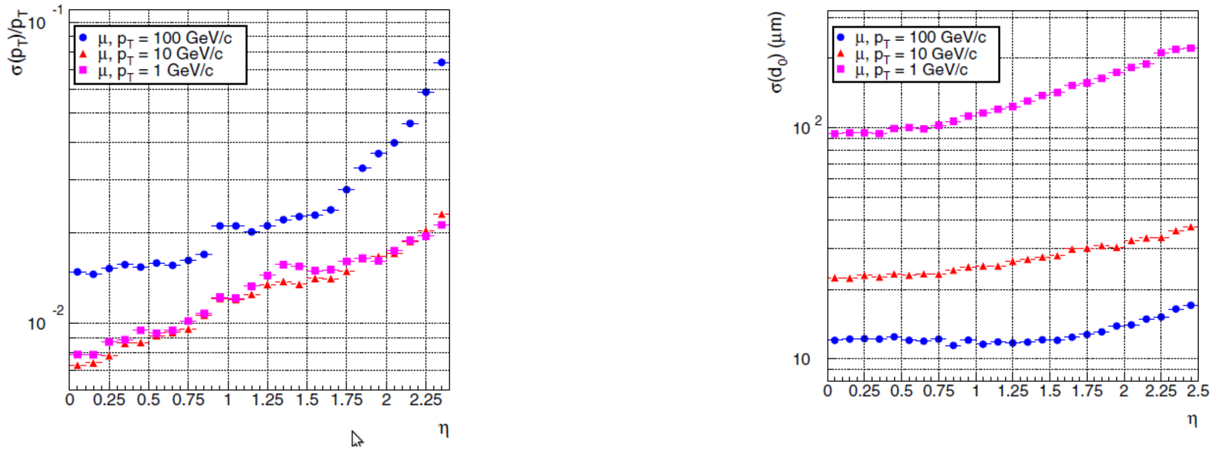

FIG. 5: p_T (left) and impact parameter (right) resolutions for CMS Tracker (Pixel and Silicon Strip combined)

coverage with the barrel part of the muon system extending to $\eta < 1.2$ and the end cap having $0.9 < \eta < 1.2$ range. The drift tubes have a hit resolution of 190 micron, while the CSC's have a $R\phi$ resolution of about 100-240 micron, both of which are an improvement over CDF's CMU resolution of 250 micron in the drift direction. The RPC's are mainly used for timing information to reconstruct muons to the correct bunch crossing and have order cm spatial resolution. The overall momentum resolution of the entire muon system (disregarding the contribution due to the tracking system) is between 8 and 15 % for muons with momentum of approximately 10 GeV, which is slightly lower than ATLAS's 2-3% p_T resolution.

Overall CMS and ATLAS will provide similar performance for the $B_s \to \mu^-\mu^+$. With 1

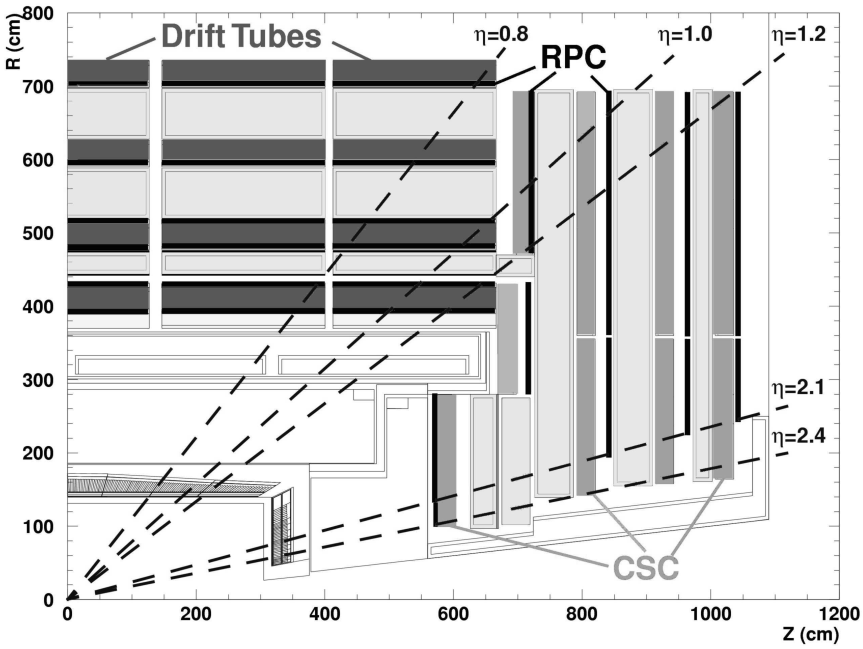

FIG. 6: CMS Muon system

fb^{-1} at 14 TeV CMS should be able to set a limit of 1.9 x 10^{-8} for the $B_s \rightarrow \mu^- \mu^+$ branching fraction at 95% confidence level, which is approximately 1.5 times better than the current CDF limit of 3.3 x 10^{-8} for 3.7 fb^{-1}.

LHCb

Unlike CMS, ATLAS, and CDF LHCb is not a general purpose detector and was specifically built for B physics. LHCb also differs from the other experiments mentioned in this paper because it is a fixed target experiment and thus will have at most half the luminosity of ATLAS and CMS. The fixed target setup allows for greater B acceptance, since the B production cross section is peaked in the forward direction, and it allows for highly boosted b quarks, which travel longer distances and thus make secondary vertex identification easier. The geometry of LHCb, which has to be different from the ATLAS, CMS, and CDF solenoidal geometries, is shown in figure 7. LHCb will run at lower luminosities (2-5 * 10^{32} $cm^2 s^{-1}$) to help with B hadron identification by lowering the tracker occupancy [11]. The relevant subsystems for the $B_s \rightarrow \mu^- \mu^+$ analysis will be the vertex locator (VELO), the tracker, and the muon system.

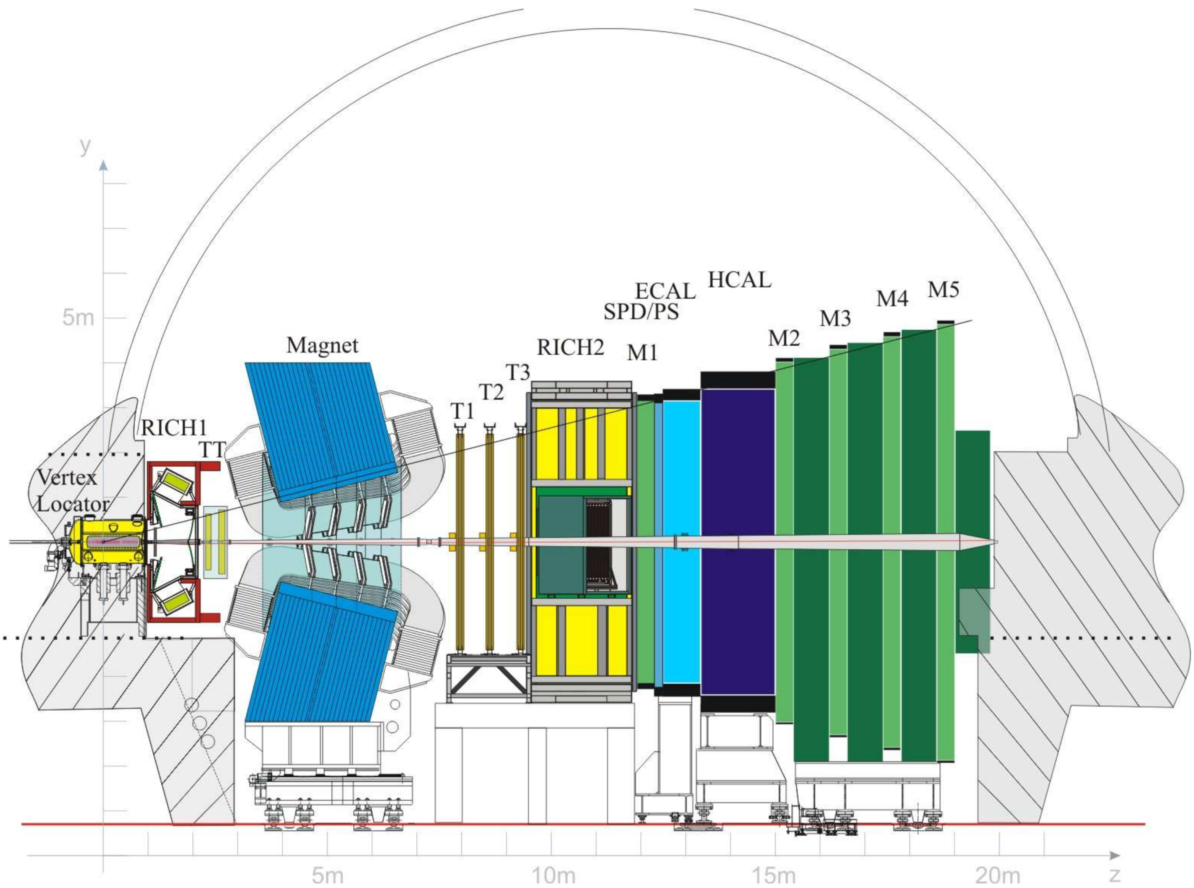

FIG. 7: LHCb detector

The maximum LHCb trigger output rate is a factor of 10 higher than that of ATLAS and CMS (100kHz), which is significantly higher than the level 1 trigger output of CDF.

Secondary vertex identification is done with the VELO, which has a spacial resolution of 12 micron ($R\phi$) and 135 micron (z) [12]. However due to the forward geometry, the B mesons now have a decay length of approximately 10 mm making secondary vertex finding significantly easier, even with high luminosities.

Tracking at LHCb is done with the four silicon tracking stations, one upstream of the dipole magnet and three downstream of the magnet. The tracker has a momentum resolution of 0.4% up to a momentum of 200 GeV and a spacial resolution of about 50 micron. Unlike the solenoidal geometries of the ATLAS, CMS, and CDF tracking isn't done inside the constant magnetic field. The change of the particle path after entering the magnet will allow for momentum measurements.

Muons are identified by five muon systems one of which is in upstream of the calorimeters,

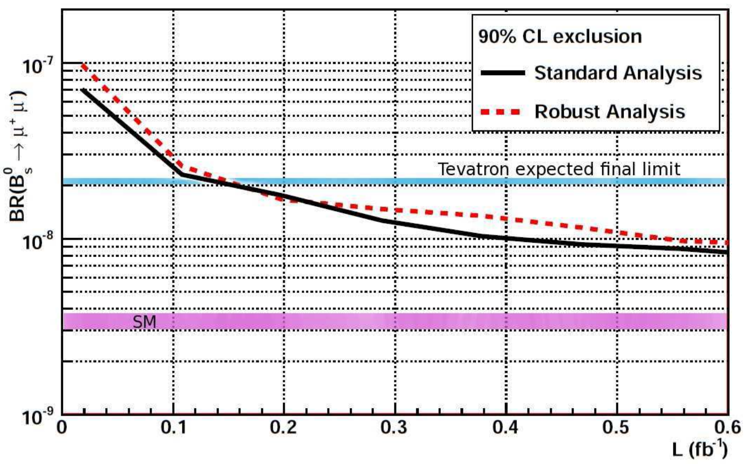

FIG. 8: Expected limits for LHCb at $\sqrt{s}$ = 8 TeV and L=2x10^{32}cm^{2}s^{-1}. The Tevatron line assumes 8 fb^{-1} per experiment [13].

while the rest are further downstream and are interleaved with iron muon filters. The outer four muon stations are multi-wire proportional chambers (MWPT) while the innermost station, due to the higher rate at this location, consists of triple-GEM detectors. RPC's are also used in the most upstream muon station. A consequence of the forward design is that the rates of particle along the pp line are high in the muon systems when compared to solenoidal experiments where only high p_T muons (for example the threshold for muons in CDF is ∼1 GeV) reach the muon system. The geometry also makes different requirements for the muon trigger system. With ATLAS, CMS, and CDF only a certain section of the muon system is required for the muon trigger, but in LHCb all muon stations are required for a level 0 muon trigger since a muon from a secondary vertex would traverse all the stations while other particles would stop in the calorimeters or even in some of the more upstream stations.

All the LHCb detector systems and its forward geometry allows LHCb to be able to collect many B_s decays with comparatively little luminosity (Figure 8). Even with the new low energy and low luminosity (which is the luminosity LHCb intended to run at) LHCb should be able to compete with the CDF set limits before 2012. The final expected invariant mass resolution and number of events for the three different LHC experiments is given in table for luminosities of 10 fb^{-1} for ATLAS and CMS and 2 fb^{-1} for LHCb.

Parameter	**ATLAS**	**CMS**	**LHCb**
$\sigma_{\mu\mu}$[MeV]	67	43	20
N_{sig}	7	6	30
N_{bkg}	20	14	183

---

[1] Natalia Panikashvili. The atlas b-physics program. *Nucl. Phys. B - (Proc. Suppl.)*, 185:201 – 206, 2008.

[2] T. Speer. Prospects for b physics at cms. *Nucl. Phys. B - (Proc. Suppl.)*, 163:159 – 164, 2007.

[3] Jens Weingarten. Results from the commissioning of the atlas pixel detector with cosmics data. *Nucl Instr. and Meth. A*, In Press, Corrected Proof:–, 2009.

[4] Gino Bolla. Status of the cdf silicon detector. *Eur. Phys. J. C*, 33:1020–1022, Jul 2004.

[5] Petra Merkel. The cdf silicon detector upgrade and performance. *Nucl. Instr. and Meth. A*, 501(1):1 – 6, 2003.

[6] Y. Unno. Atlas silicon microstrip semiconductor tracker (sct). *Nucl. Instr. and Meth. in Phys. Res. A*, 453(1-2):109 – 120, 2000.

[7] T. Affolder. Cdf central outer tracker. *Nucl. Instr. and Meth. in Phys. Res. A*, 526(3):249 – 299, 2004.

[8] J. Dubbert. First experience with the atlas muon spectrometer. *Nucl. Instr. and Meth. in Phys. Res. A*, 581(1-2):507 – 510, 2007.

[9] A. Artikov. Design and construction of new central and forward muon counters for cdf ii. *Nucl. Instr. and Meth. in Phys. Res. A*, 538(1-3):358 – 371, 2005.

[10] Alessia Tricomi. Performances of the atlas and cms silicon tracker. *Eur. Phys. J C*, 33, 2004.

[11] Fabio C. D. Metlica. The lhcb detector and triggers. *Nuclear Physics B (Proc. Suppl.)*, 2007.

[12] Olaf Behrendt. The lhcb vertex locator. *Nucl. Instr. and Meth. in Phys. Res. A*, 598(1):61 – 63, 2009.

[13] Marc-Olivier Bettler. The lhcb analysis for b_s to mu^+mu^-. 2009.