International Journal of Modern Physics A
Vol. 20, No. 15 (20 June 2005) 3409–3412


World Scientific
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# Resolution of Nearly Mass Degenerate Higgs Bosons and Production of Black Hole Systems of Known Mass at a Muon Collider

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The direct s-channel coupling to Higgs bosons is 40000 times greater for muons than electrons; the coupling goes as mass squared. High precision scanning of the lighter $h^0$ and the higher mass $H^0$ and $A^0$ is thus possible with a muon collider. The $H^0$ and $A^0$ are expected to be nearly mass degenerate and to be CP even and odd, respectively. A muon collider could resolve the mass degeneracy and make CP measurements. The origin of CP violation in the $K^0$ and $B^0$ meson systems might lie in the the $H^0/A^0$ Higgs bosons. If large extra dimensions exist, black holes with lifetimes of $\sim 10^{-26}$ seconds could be created and observed via Hawking radiation at the LHC. Unlike proton or electron colliders, muon colliders can produce black hole systems of known mass. This opens the possibilities of measuring quantum remnants, gravitons as missing energy, and scanning production turn on. Proton colliders are hampered by parton distributions and CLIC by beamstrahlung. The ILC lacks the energy reach.

*Keywords*: Higgs Boson, Black Hole, Extra Dimensions, Hawking Radiation.

## 1. Introduction

A $\mu^+\mu^-$ collider with 4 TeV center-of-mass (CM) energy has unique and prominent features to probe the Higgs boson physics and produce microscopic black holes of known CM energy in super-Planckian events [1]. Muons emit 2 billion times less bremsstrahlung radiation then electrons $((m_\mu/m_e)^4)$. This makes the muon collider [2] very attractive: 1) The possibility of precision measurements of the Higgs and supersymmetric particles using rings; 2) The possibility of the separation of a higher Higgs boson doublet by scanning s-channel production; 3) Production of black hole (BH) systems (initially radiated gravitons plus BH) of known mass without the limitations of parton distributions or beamstrahlung smearing [3].

## 2. Heavy Higgs Bosons

The Higgs discovery will likely occur at Large Hadron Collider (LHC) experiments such as the Compact Muon Solenoid (CMS) [4]. The next critical challenge in high-energy physics will be to differentiate between the Standard Model (SM) Higgs

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boson and the Minimal Supersymmetric Standard Model (MSSM) Higgs boson. In the context of MSSM, the important Higgs parameters are $m_{A^0}$ and $tan\ \beta$, where $tan\ \beta$ is the ratio of the vacuum expectation values of the Higgs doublet. In the first-order approximation, the Higgs decay width is small compared to the mass resolution for large $tan\ \beta$. Furthermore, the higher mass Higgs bosons, $H^0/A^0$, may be nearly mass degenerate. The LHC and the ILC may fail to separate them.

For the s-channel Higgs process of narrow resonances, energy resolution is an important consideration. A muon collider with sufficient energy resolution (R = 0.01% and/or 0.06%) might be the only possible means for separating the two higher mass Higgs bosons, $H^0$ and $A^0$. The s-channel Higgs resonance would be found by scanning in $\sqrt{s}$ using a small step ($\sigma$). Using sufficient energy resolution, the line shape of a Breit-Wigner resonance and the Higgs width could be deduced. Figure 1 shows the $H^0$ and $A^0$ resonances for $tan\ \beta = 5$ and 10, including the $b\bar{b}$ continuum background[5]. It is clear the resonances are overlapping for the larger value of $tan\ \beta$. With R = 0.01%, the two distinct resonance peaks are clearly visible, although, the peaks are smeared out for R = 0.06%.

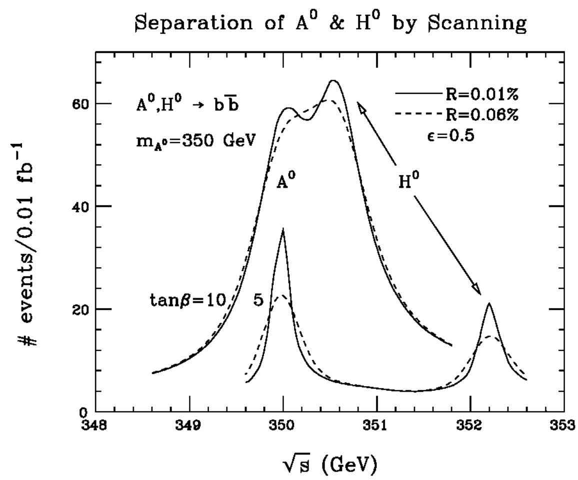


Fig. 1. Separation of heavy Higgs bosons $H^0$ and $A^0$ for the $b\bar{b}$ final state event rate as a function of $\sqrt{s}$ for $m_{A^0} = 350$ GeV and $tan\ \beta = 5$ and 10. Courtesy of J. F. Gunion, Ref. 5.

## 3. Black Holes Production

BH production at colliders depends on the value of the fundamental Planck scale $M_{Pl}$, which determines the energy where the gravitational interaction becomes strong. If this fundamental energy scale is as low as the TeV scale, BHs can be produced in future colliders such as the LHC, CLIC, and the muon collider. BH production at the LHC depends on parton distributions. BH production at the CLIC is smeared by beamstrahlung. These effects introduce extra unknowns into the physics of BH formation. Unlike the LHC and the CLIC, the muon collider could produce BH systems of known energy with a simple cross section.

The properties of BHs at the muon collider are completely determined by the BH mass and angular momentum. In this paper we will restrict our discussion to BHs with vanishing angular momentum for simplicity. In a scenario with $n$ large flat extra dimensions, the cross section of BH formation at the muon collider is roughly the geometrical cross section

$$\sigma_{\mu\mu\to BH}(E) = F\frac{1}{M_{Pl}^2}\left[\frac{8\Gamma\left(\frac{n+3}{2}\right)}{(2+n)}\frac{\sqrt{s}}{M_{Pl}}\right]^{\frac{2}{n+1}}, \tag{1}$$

where $F$ is a form factor which depends on the model. The semiclassical approach suggests that if the impact parameter is less than the Schwarzschild radius corresponding to a BH with mass $M_{BH} = \sqrt{s}$, a BH is formed. After formation, the BH evaporates semiclassically in a time $\sim 10^{-26}\,s$ through emission of Hawking radiation[6]. The BH emits SM fields on the brane and gravitational quanta in the extra-dimensional bulk.

For totally elastic processes, the mass of the BH is equal to the CM energy of the collision. For inelastic collisions, some of the CM energy is not trapped into the BH. An indicator of the energy trapped by the horizon is given in Ref. 7. The trapped energy monotonically decreases with the impact parameter from a maximum value of about 60% of the CM energy (head-on collision) to zero (maximum impact parameter $b_{max}$). Figure 2 shows the correlation between the $M_{BH}/\sqrt{s}$ and the impact parameter ratio $b/b_{max}$ for different numbers of large extra dimensions. The energy trapped by the horizon decreases with more dimensions.

The BH cross section for a muon collider is shown in Fig. 3 as a function of the collider CM energy. The typical BH cross section at a 4 TeV muon collider is of order of a few $nb$. By using the lower bound of the integrated luminosity, $\mathcal{L}_{\mu^+\mu^-} = 10^{33}\,(cm^{-2}s^{-1})$, the BH production rate is about 7 BHs/s.

## 4. Black Hole Experimental Signatures

BH experimental signatures at the muon collider are large production cross section, events with large missing total/transverse energy ($E_T$), and high $E_T$ jets. If the BH leaves no remnant, the expected total missing energy for a 4 TeV collision is about 2.7 TeV. This missing energy is essentially due to gravitons propagating in the extra-dimensional bulk, plus a few gravitons and neutrinos on the brane. Assuming an isotropic distribution of emitted gravitons in the bulk and a four-body final decay for the BH, the missing transverse energy due to the transverse momentum of the gravitons and neutrinos on the brane is about 190 GeV. The typical hadron to photon (lepton) ratio of BH decay is about 60:1 (7:1).

## 5. Summary and Acknowledgments

A muon collider is fundamental to study the direct s-channel Higgs boson and differentiate between the $A^0$ and $H^0$. BH production at a 4 TeV CM energy muon

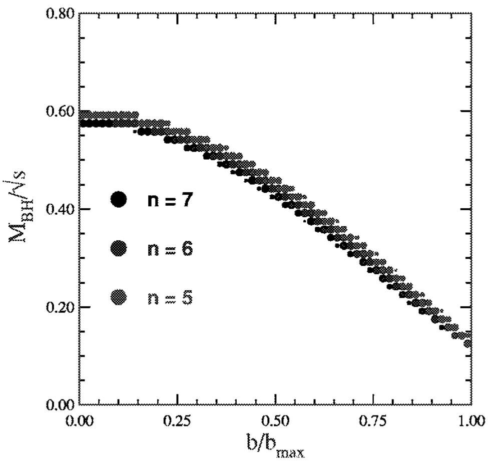


Fig. 2. The correlation between the horizon mass, $M_{BH}/\sqrt{s}$, and the impact parameter ratio, $b/b_{max}$, for $n = 5, \ldots 7$ large extra dimensions.

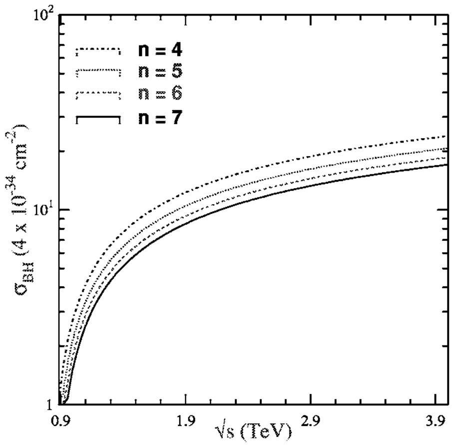


Fig. 3. The BH cross section produced at a muon collider as a function of the CM energy for $n = 4, \ldots 7$ large extra dimensions.

collider does not suffer from beamstrahlung smearing and unknown factors of parton production. Unlike proton or electron colliders, muon colliders can produce black hole systems of known mass. These unique features open the possibilities of measuring BH quantum remnants, bulk graviton emission, and Hawking radiation on the brane.

The authors would like to thank the Muon Collider Collaboration. This work was supported in part by the U.S. Department of Energy contract DE-FG05-91ER40622.

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