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

Romulus Godang
University of Mississippi

August 26-31, 2004
DPF Meeting, Riverside, CA

On behalf of
R. Godang, M. Cavaglia, D. Cline, L. Cremaldi, and D. Summers
Neutrino Factory/Muon Collider Collaboration
Introduction

- Unique features of a Muon Collider ($\mu^+ - \mu^-$):
  
  - Bremsstrahlung radiation effect is negligible (scales by $m_{\mu}^{-4}$) so it does not limit their circular acceleration to reach multi-TeV energies.
  
  - Direct s-channel coupling to Higgs boson resonances is $40,000 \left(\frac{m_{\mu}}{m_e}\right)^2$ greater for $(\mu^+\mu^- \to h)$ than for $(e^+e^- \to h)$

\[
\Rightarrow R_{higgs}^{(\mu^+\mu^-)} \gg R_{higgs}^{(e^+e^-)}
\]

- Beam energy resolution is not limited by beamstrahlung smearing, i.e. choosing $\delta E/E = R \sim 0.003\%$ for $m_{h(SM)} \leq 120$ GeV such that the beam energy spread $\sigma \sqrt{s} \leq \Gamma_{h}^{\text{total}}$.

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

Romulus Godang
University of Mississippi

August 26-31, 2004
DPF Meeting, Riverside, CA
Heavy Neutral Higgs Bosons

- In MSSM, the heavy Higgs bosons are largely degenerate
  large values of $\tan\beta$ heighten this degeneracy

- The Higgs boson cross section in $s$-channel:

$$\sigma_h(\sqrt{s}) = \frac{4\pi \Gamma(h \to \mu\bar{\mu}) \Gamma(h \to X)}{(s-m_h^2)^2 + m_h^2 \Gamma_{tot}^2} \implies \sigma \sqrt{s} = (2 \text{ MeV}) \left( \frac{R}{0.003\%} \right) \left( \frac{\sqrt{s}}{100 \text{ GeV}} \right)$$

- For the larger $\tan\beta$ the resonances are clearly overlapping
  (only separated by 1 or 2 GeV)

- Muon Collider with sufficient energy resolution might be the only possible
  means for separating out these states: with $R = 0.01\%$ and $R = 0.06\%$
Motivation

- We have observed Astronomical Black Holes (BH):
  Hubble uncovers dust disk around a massive Black Hole
  3,700 light-year-diameter dust disk

- The observable astronomical BH encourages us to explore
  miniature BH production in a Laboratory

- BH production in Lab could be the most promising signal of
  TeV-scale quantum gravity
• In large extra dimensions at the TeV energy scale, Gravitons can propagate outside the three-brane.

• The BH is characterized by the Schwarzschild radius

\[ r_s = \frac{1}{\sqrt{\pi} M_{pl}} \left[ \frac{8 \Gamma \left( \frac{n+3}{2} \right)}{(2+n)} \right]^{\frac{1}{n+1}} \left( \frac{M_{BH}}{M_{pl}} \right)^{\frac{1}{n+1}} \]

○ \( M_{pl} \sim \text{TeV} \) is fundamental Planck scale

• If the impact parameter \( b < r_s \), \( \rightarrow \) an Event Horizon is formed
Cross Section

- BH cross section can be estimated from the geometrical cross section (black disk)

\[ \sigma_{ij \rightarrow BH} \approx \pi r_s^2 = \frac{1}{M_{pl}^2} \left[ \frac{M_{BH}}{M_{pl}} \left( \frac{8 \Gamma \left( \frac{n+3}{2} \right)}{(2+n)} \right) \right]^{\frac{2}{n+1}} \]

- LHC (proton-proton collider), we need to consider its cross section at the parton level (hampered by parton distributions)

\[ \sigma_{pp \rightarrow BH} \approx \sum_{ij} \int_{x_m}^1 dx \int_{y}^1 dy f_i(y, Q) f_j(x/y, Q) \sigma_{ij \rightarrow BH}(x, s, n) \]

- \( x_m = M_{BH(min)}^2/s \), \( s = M_{pl}^2 \) and \( Q \) = the momentum transfer

- \( f_i, f_j \) = Parton Distribution Function (PDF)

- For \( (e^+ - e^- \) collider) like CLIC, beamstrahlung smears the collision energy, and the NLC lacks the energy reach

- Muon Collider \( (\mu^+ - \mu^- \) collider), the BH cross section is relatively simple

\[ \sigma_{\mu\mu \rightarrow BH} \approx \sigma_{BH}(s, n) \] (it does not depend on the minimum \( M_{BH} \))
- BH Cross Section of 5 TeV \((e^+ - e^-)\) collider at CLIC

  Courtesy of Landsberg and Dimopoulos (hep-ph 0204031)

- The extra dimension \(n = 4\)

- The CM-energy \(\sqrt{s} = 5\ TeV\)

- The beamstrahlung-corrected energy spectrum for CLIC machine is peaking at the nominal energy (5 TeV)
• BH Cross Section for 4 $TeV$ ($\mu^+ - \mu^-$)

\[ \frac{d^2 \sigma}{d^2 \Omega} (4 \times 10^{-34} \text{cm}^{-2}) \]

\[ \sqrt{s} \text{ (TeV)} \]

• $n = D - 4$ extra dimensions

• $\sqrt{s} = 4 \text{ TeV CM-energy} \Rightarrow \sigma_{BH} \sim 7 \text{ nb}$

• Using $\mathcal{L}_{\mu^+\mu^-} \sim 10^{33} (cm^{-2}s^{-1}) \Rightarrow$ BH production rate $\sim 7 \text{ BH/s}$

\[ \Rightarrow \tau_{BH} \sim 10^{-27} s \]
• BH decay depends on Hawking temperature and is proportional to the inverse radius.

• Hawking temperature of (n+4)-dimensional BH:

\[ T_H = M_{pl} \left[ \frac{M_{pl}}{M_{BH}} \frac{n+2}{8 \Gamma \left( \frac{n+3}{2} \right)} \right]^{\frac{1}{n+1}} \frac{n+1}{4 \sqrt{\pi}} = \frac{n+1}{4 \pi r_s} \text{ where } r_s \text{ is Schwarzschild radius} \]

• The higher CM-energy (or the higher extra dimension), \( \implies \) the heavier and the colder BH
Horizon Formation

- Horizon formation of CM-energy of 4 TeV with impact parameter $b$

- The energy trapped by the horizon is a function of the impact parameter.

- For head-on collision, $\sim 60\%$ of CM-energy trapped by the horizon.

- When extra dimension increases $\Rightarrow M_{BH}/\sqrt{s}$ decreases

  [We use Yoshino and Nambu's model (PRD 67, 2003)]
Total missing energy ($E_{\text{miss}}^{Total}$) provides a signature of un-observed gravitons and neutrinos that are emitted

- $E_{\text{miss}}^{Total} = E_{\text{miss}}^{\text{Formation}} + E_{\text{miss}}^{\text{Evaporation}}$

- $E_{\text{miss}}^{\text{Evaporation}} = \sum_i N_i E_i$
  
  $N_i =$ number of un-observed particles (neutrinos and gravitons)
  
  $E_i =$ its corresponding missing energy at evaporation process

Missing momentum-transverse ($E_T$) is in order of 190 GeV
Muon Collider is a good place to study a direct s-channel Higgs boson, and to differentiate between $A^0$ and $H^0$

Muon Collider at 4 $TeV$ is a suitable place for producing miniature Black Holes with no beamstrahlung smearing

Muon Collider provides a relatively high and constant cross section of BH

\[
\sigma_{\mu\mu \rightarrow BH} \approx \sigma_{BH}(s, n) \quad \text{(only depend on CM-energy and extra dimensions)}
\]

- $\sigma_{BH} \sim 7$ $nb$, using $[L_{\mu^+\mu^-} \sim 10^{33}(cm^{-2}s^{-1})]$ \Rightarrow BH \text{ production rate } \sim 7$ BH/s ($\tau_{BH} \sim 10^{-27}s$)

BH system (BH + gravitons) produced at rest with known mass

Missing energy and missing $E_T$ help us to explore gravitons, extra dimensions, Hawking radiation and quantum remnants