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

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On behalf of

R. Godang, M. Cavaglia, D. Cline, L. Cremaldi, and D. Summers

Neutrino Factory/Muon Collider Collaboration

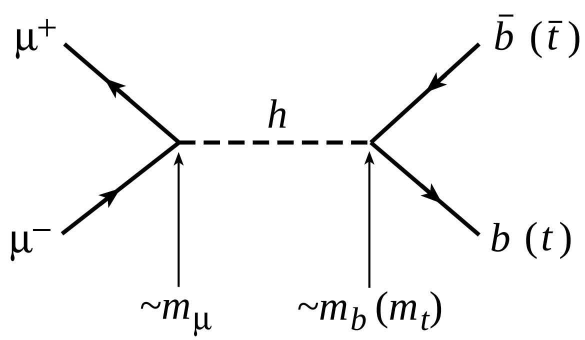
Introduction

- Unique features of a Muon Collider ($\mu^+ - \mu^-$):

  - Bremsstrahlung radiation effect is negligible (scales by m_μ^{-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 $(m_\mu/m_e)^2$ greater for $(\mu^+\mu^- \rightarrow h)$ than for $(e^+e^- \rightarrow h)$

$$\Longrightarrow R_{higgs}^{(\mu^+\mu^-)} \gg R_{higgs}^{(e^+e^-)}$$



  - 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 $\sigma_{\sqrt{s}} \leq \Gamma_h^{total}$

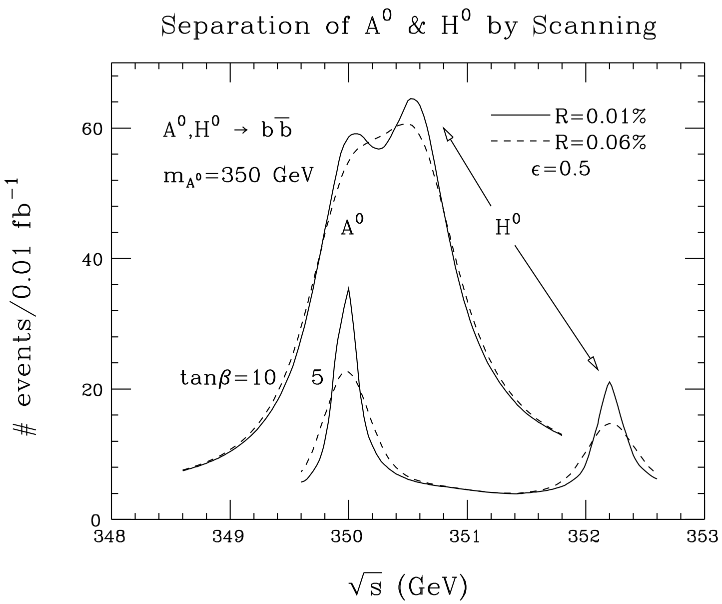
Heavy Neutral Higgs Bosons

- **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:**

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



- **For the larger $tan\beta$ the resonances are clearly overlapping**

  (only separated by 1 or 2 GeV)

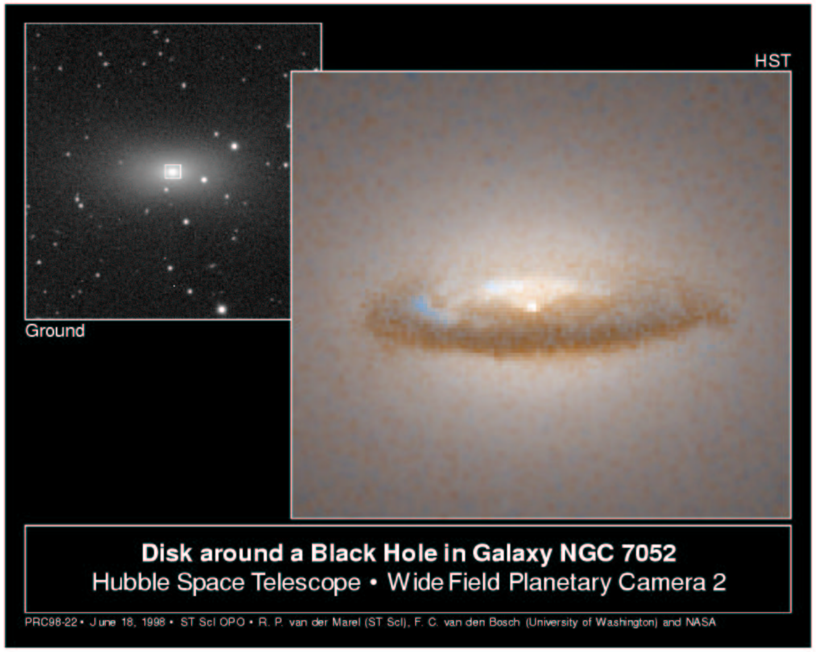
- **Muon Collider with sufficient energy resolution might be the only possible means for separating out these states: with $R = 0.01\%$ and $R = 0.06\%$**

Motivation

- We have observed Astronomical Black Holes (BH):

  Hubble uncovers dust disk around a massive Black Hole

  3,700 light-year-diameter dust disk

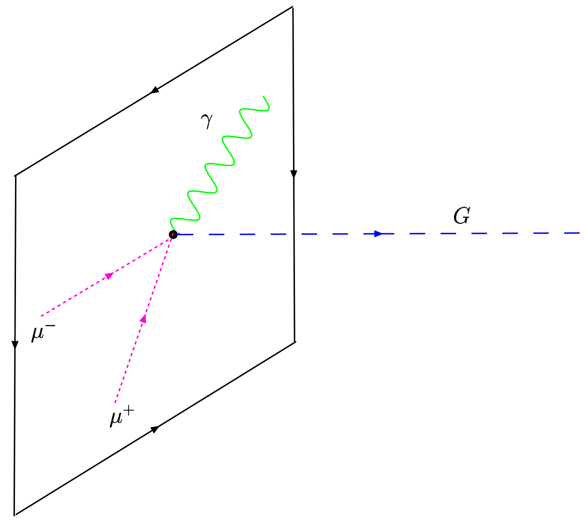


- The observable astronomical BH encourages us to explore miniature BH production in a Laboratory

- BH production in Lab could be the most promising signal of TeV-scale quantum gravity

Extra Dimensions

- In large extra dimensions at the TeV energy scale, Gravitons can propagate outside the three-brane

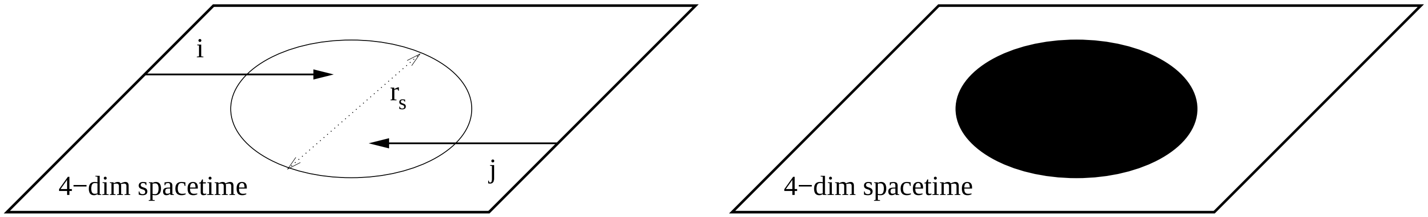


- The BH is characterized by the Schwarzschild radius

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

  - ◦ $M_{pl} \sim TeV$ is fundamental Planck scale

- If the impact parameter $b < r_s$, $\longrightarrow$ an Event Horizon is formed



Cross Section

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

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

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

$$\sigma_{pp\to BH} \approx \sum_{ij}\int_{x_m}^{1} dx \int_x^1 \frac{dy}{y} f_i(y,Q) f_j(x/y,Q)\sigma_{ij\to BH}(x,s,n)$$

  - $x_m = M_{BH(min)}^2/s$, $s = M_{pl}^2$ 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

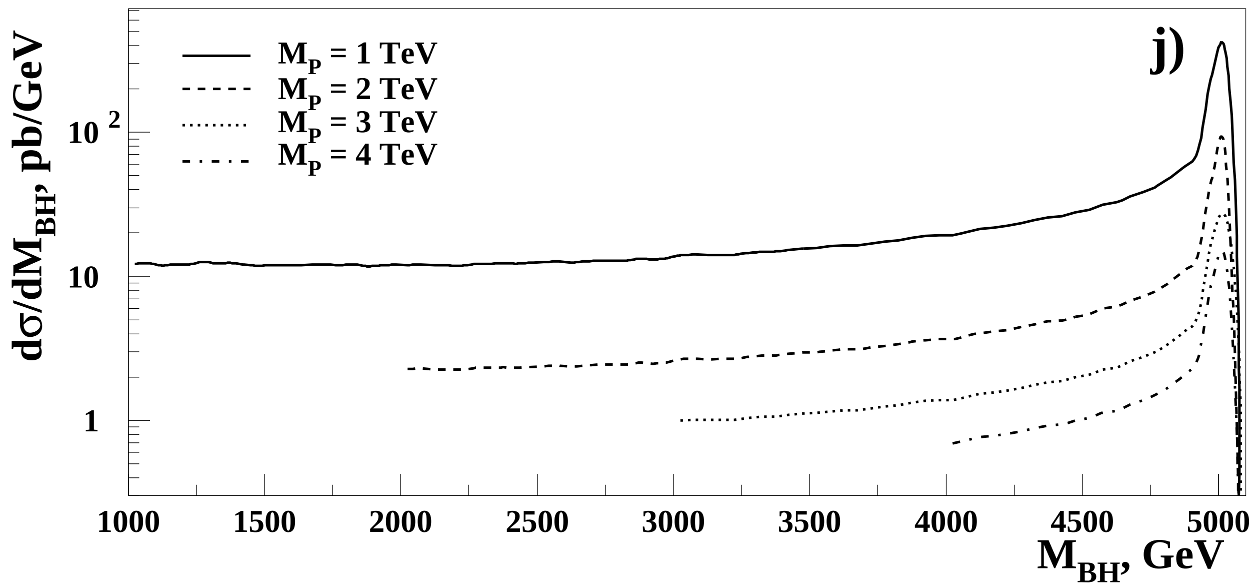
- Muon Collider ($\mu^+ - \mu^-$ collider), the BH cross section is relatively simple

$\sigma_{\mu\mu\to BH} \approx \sigma_{BH}(s,n)$ (it does not depend on the minimum M_{BH})

Cross Section at CLIC

- BH Cross Section of 5 TeV ($e^+ - e^-$) collider at CLIC

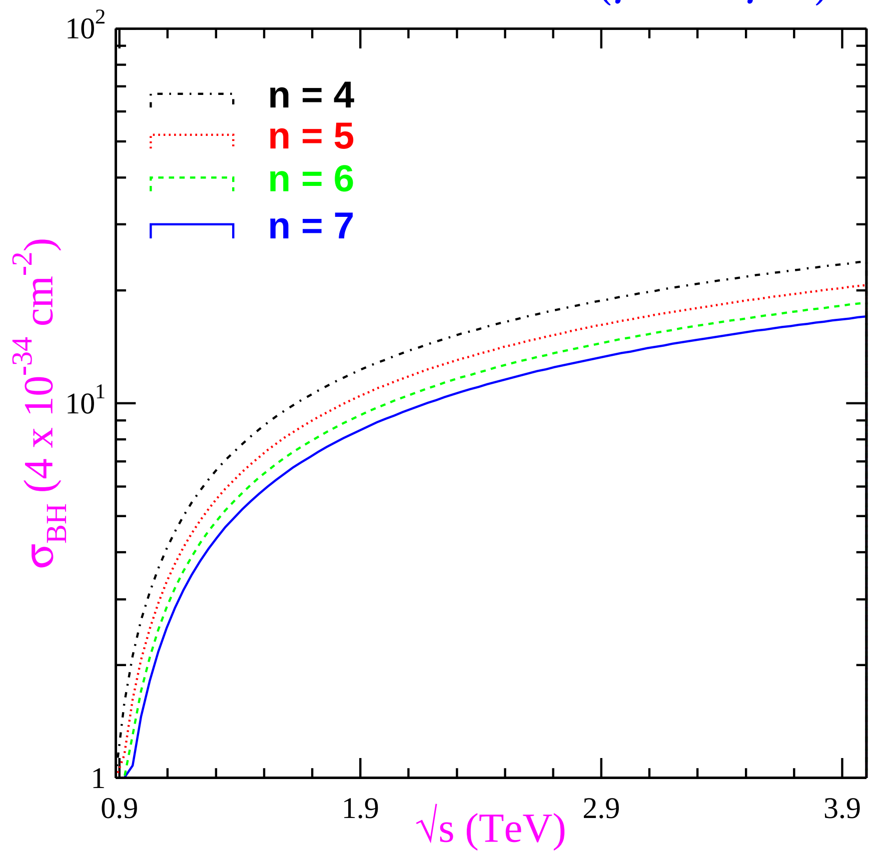
  Courtesy of Landsberg and Dimopoulos (hep-ph 0204031)



- 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)

Cross Section at Muon Collider

- **BH Cross Section for $4\ TeV\ (\mu^+ - \mu^-)$**



- $n = D - 4$ **extra dimensions**

- $\sqrt{s} =$ **4 TeV CM-energy** $\Longrightarrow \sigma_{BH} \sim 7\ nb$

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

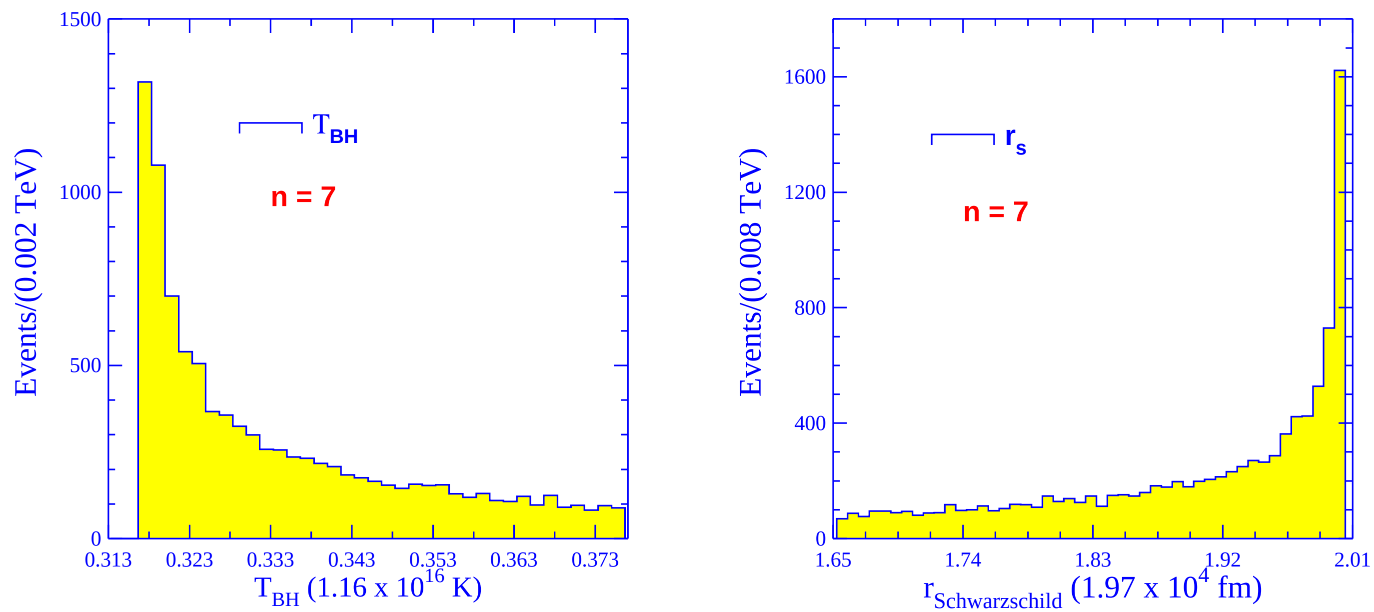
  $\Longrightarrow \tau_{BH} \sim 10^{-27}s$

Temperature and Radius

- BH decay depends on Hawking temperature and is proportional to the inverse radius

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

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

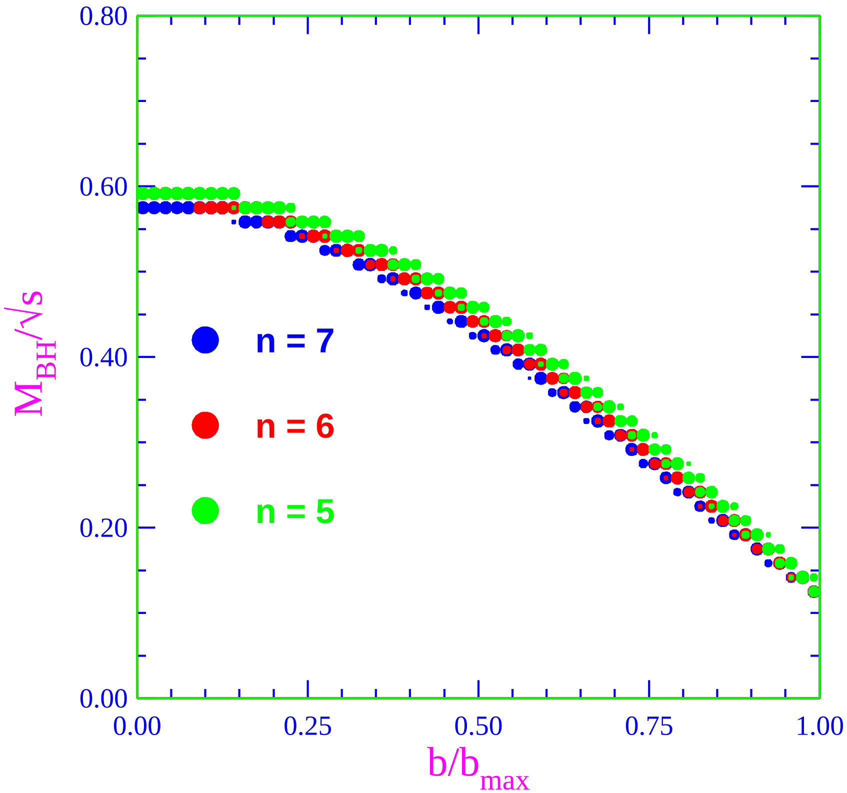


- The higher CM-energy (or the higher extra dimension),

  $\Longrightarrow$ 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 $\Longrightarrow$ $M_{BH}/\sqrt{s}$ decreases

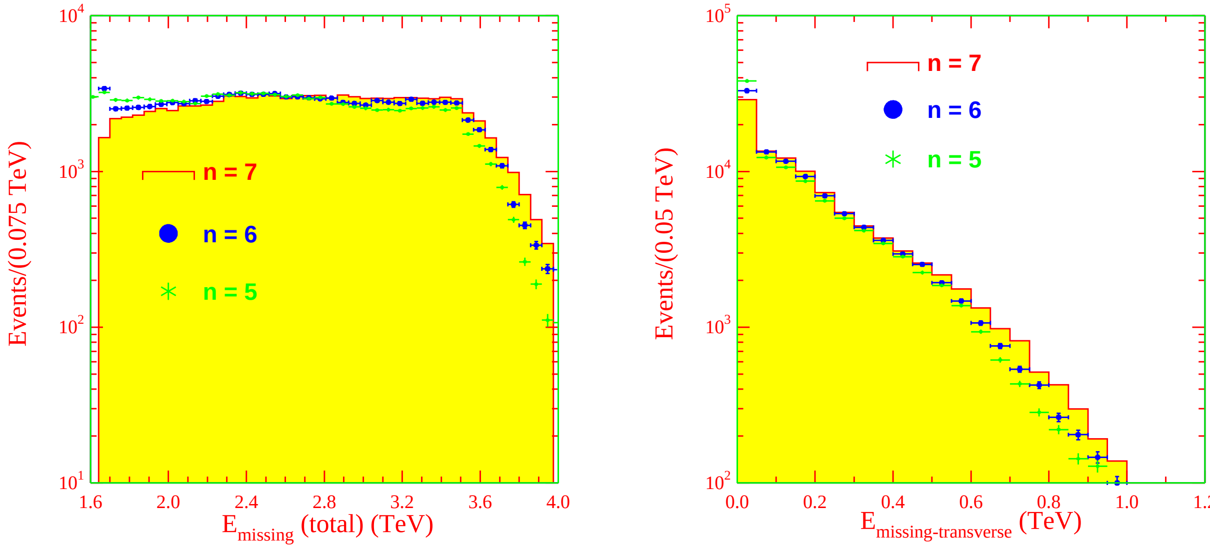
  [We use Yoshino and Nambu's model (PRD 67, 2003)]

Missing Energy

- Total missing energy (E_{miss}^{Total}) provides a signature of un-observed gravitons and neutrinos that are emitted
  - $E_{miss}^{Total} = E_{miss}^{Formation} + E_{miss}^{Evaporation}$
  - $E_{miss}^{Evaporation} = \sum_i N_i E_i$

    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 $190\ GeV$



Summary

- 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

  $\sigma_{\mu\mu \to BH} \approx \sigma_{BH}(s, n)$ (only depend on CM-energy and extra dimensions)

  - $\sigma_{BH} \sim 7\ nb$, using $\left[\mathcal{L}_{\mu^+\mu^-} \sim 10^{33}(cm^{-2}s^{-1})\right]$

    $\Longrightarrow$ BH 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