Physics with Black Hole Systems of Known Mass at a Muon Collider

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On behalf of

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Introduction

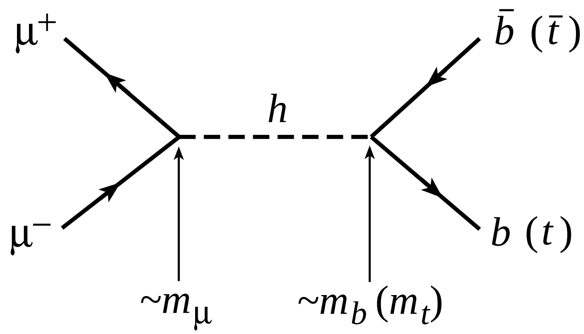
- **Unique features of a Muon Collider ($\mu^+ - \mu^-$):**

  (Barger, Berger, Gunion, Han 1996)

  - **Bremsstrahlung radiation effect is negligible (scales by m_μ^{-4})**

  - **Direct s-channel coupling to Higgs boson resonances is 40,000 $(m_\mu/m_e)^2$ greater for $(\mu^+\mu^- \to h)$ than for $(e^+e^- \to h)$**

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



  - **Beam energy resolution is not limited by beamstrahlung smearing, such that the beam energy resolution $\sigma_{\sqrt{s}} \leq \Gamma_h^{total}$**

Neutral Higgs Bosons Search

- At Muon Collider, there are 3 possible techniques for searching heavy neutral higgs bosons: H^0 (CP-even) and A^0 (CP-odd)

1. Scan for s-channel Higgs : 250 GeV $< m_{H^0/A^0} <$ 500 GeV; $tan\ \beta > 3$
2. Bremsstrahlung Tail : Good for higher $tan\ \beta$
3. H^0, A^0 and H^+H^- Production : for very heavy Higgs bosons ($\sim$ 10 TeV)

(We focus only the first two techniques)

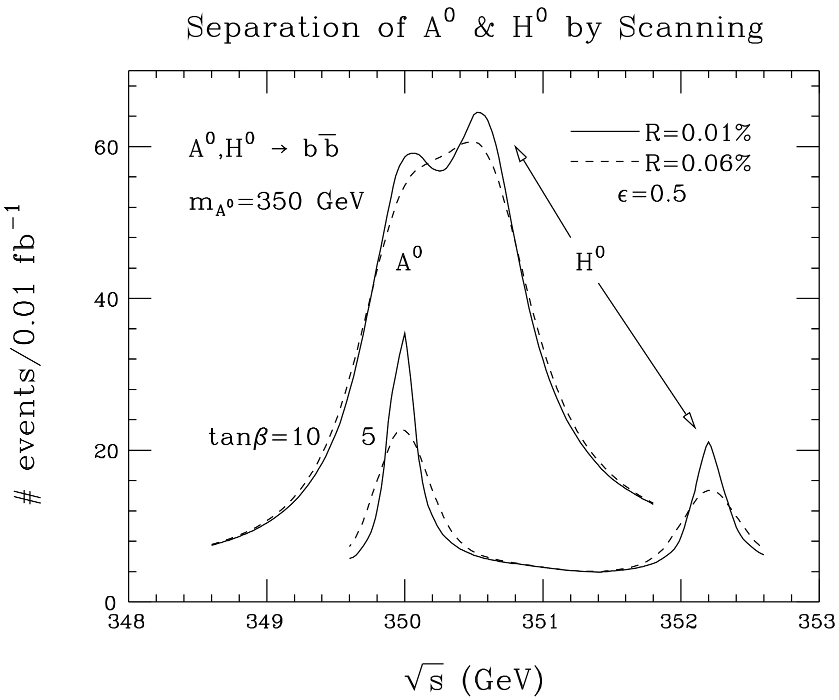
- Supersymmetry parameter $tan\ \beta \equiv v_2/v_1$, where v_1, v_2 is the vacuum expectation values of neutral members of Higgs doublet of MSSM

- In MSSM, the heavy Higgs bosons are largely degenerate $\Longrightarrow$larger values of $tan\ \beta$ heighten this degeneracy: ($tan\ \beta$=5, 10 and 20)

Scan for s-Channel Higgs

- **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 with $\Gamma_{H^0,A^0} \sim 0.1 - 0.6$ GeV**

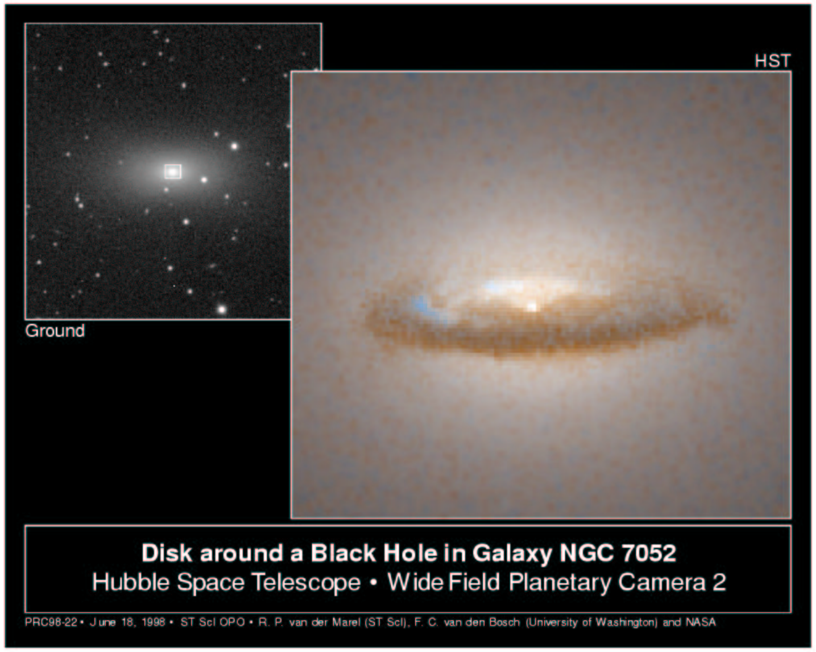
- **Muon Collider with sufficient energy resolution might be the only possible means for separating out these states: with $R = 0.01\%$ and $R = 0.06\%$**

Black Holes Motivation

- **We have observed Astronomical Black Holes (BH):**

  Hubble uncovers dust disk around a massive Black Hole

  3,700 light-year-diameter dust disk

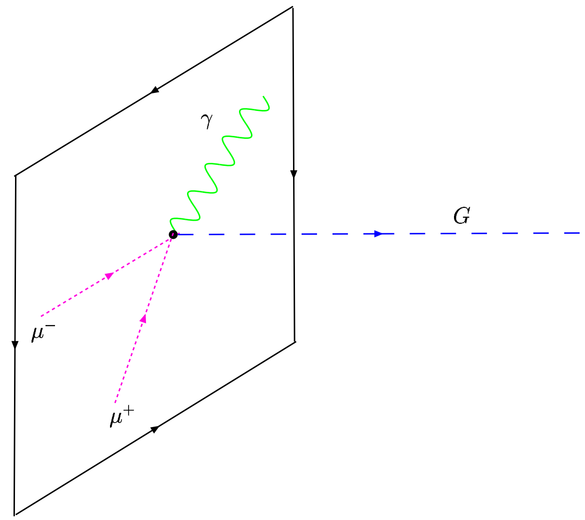


- **The observable astronomical BH encourages us to explore miniature BH production in a Laboratory**

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

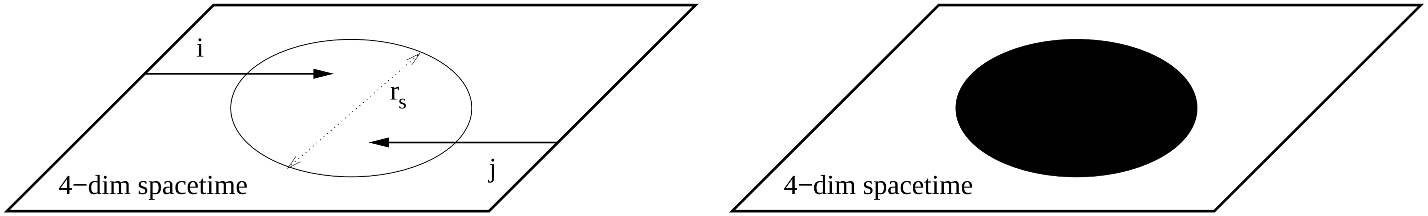


- The BH is characterized by the Schwarzschild radius

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

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

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

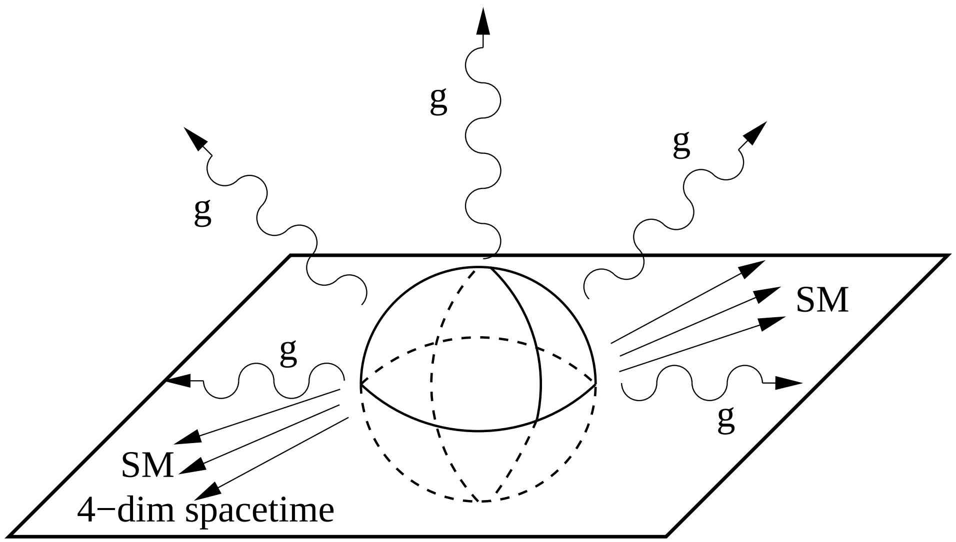


Hawking's Evaporation

- **After Black Hole formed it will decay via Hawking evaporation process (Hawking radiation)**
- **The Black Holes emits into two modes :**

1. **Along the brane (brane mode): Standard Model fields**
2. **Into the extra dimensions (bulk mode): gravitons (invisible)**

- **Hawking radiation**



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)

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

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

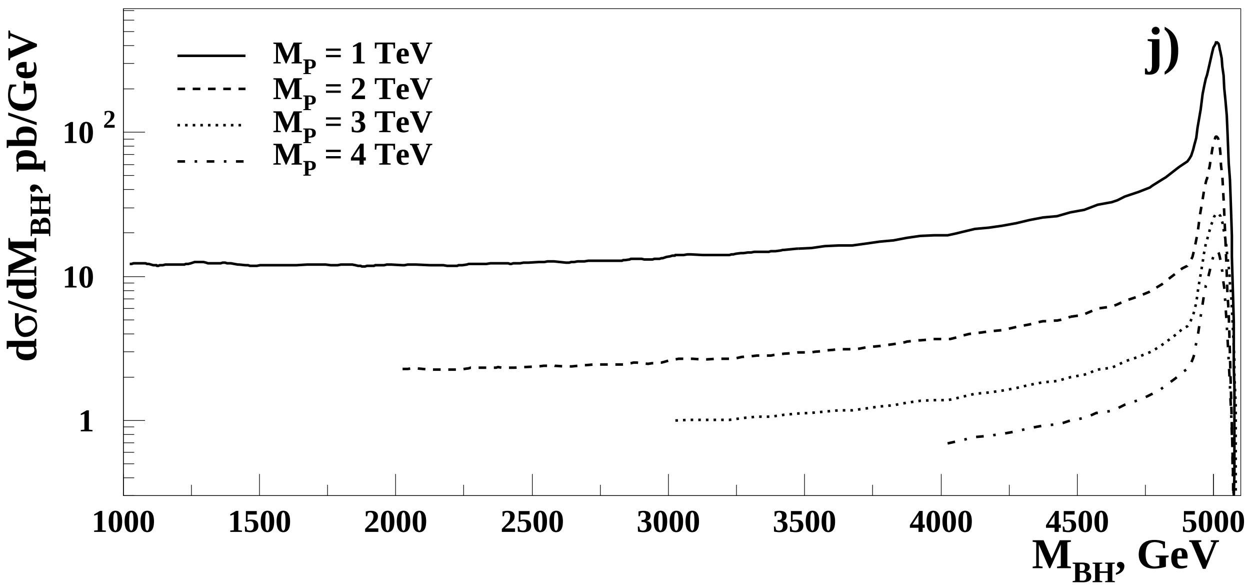
- Muon Collider ($\mu^+ - \mu^-$ collider), the BH cross section is relatively simple

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

Cross Section at CLIC

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

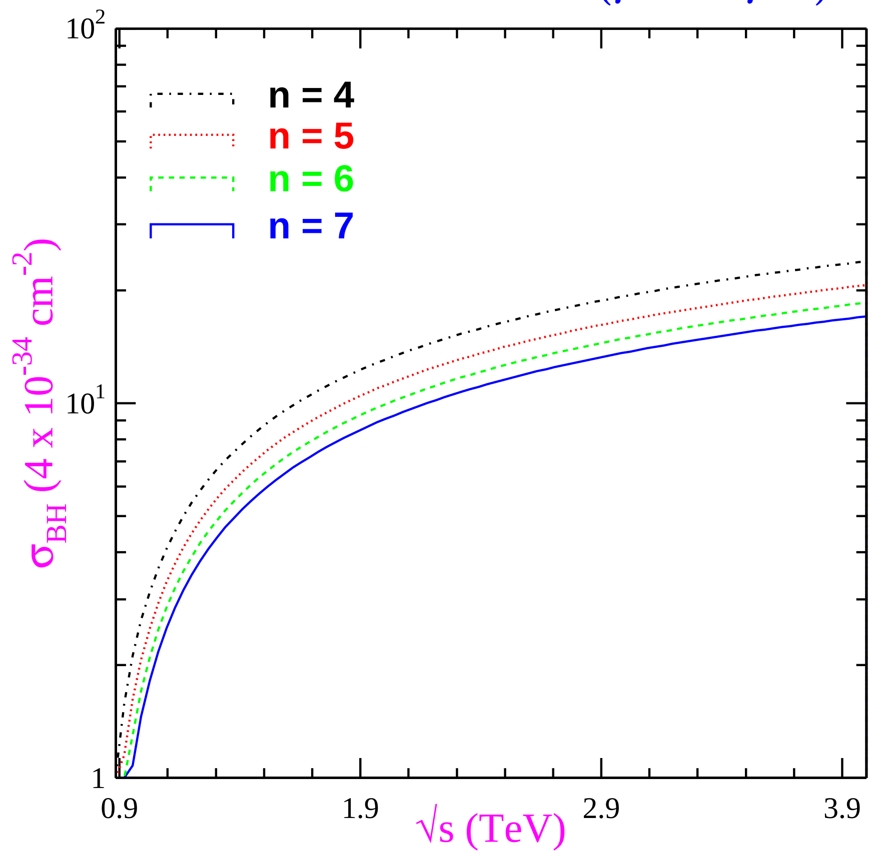
  Courtesy of Landsberg and Dimopoulos (hep-ph 0204031)



- 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**

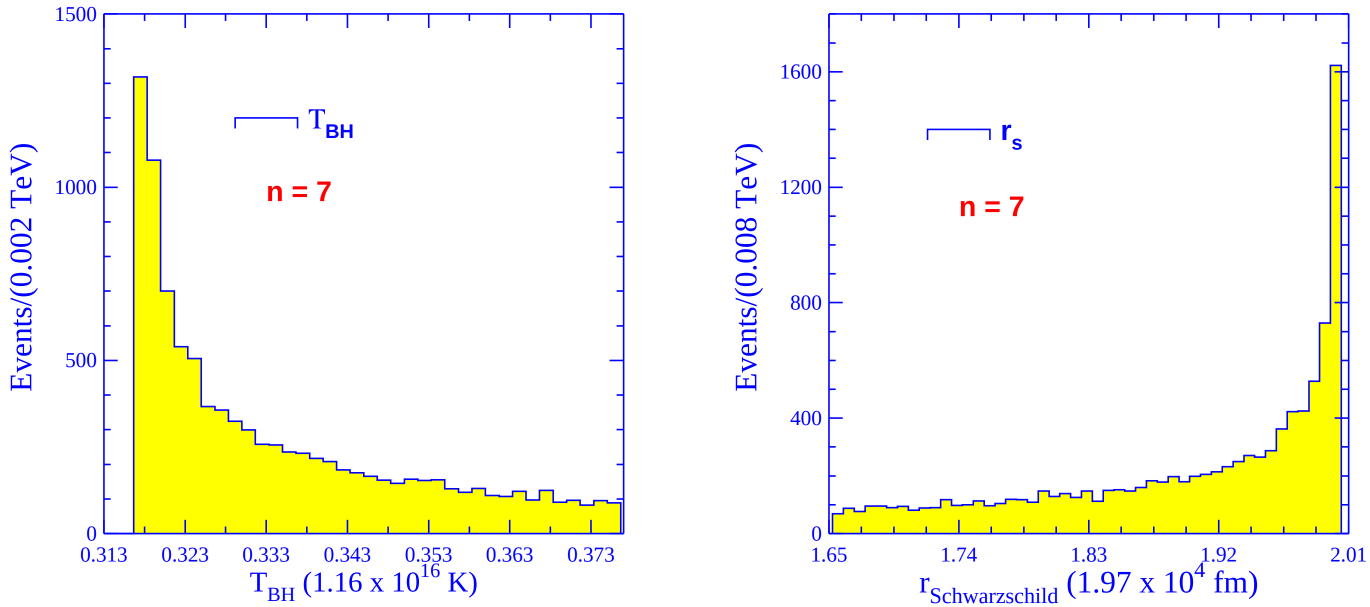
  $\Longrightarrow \tau_{BH} \sim 10^{-27}s$

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

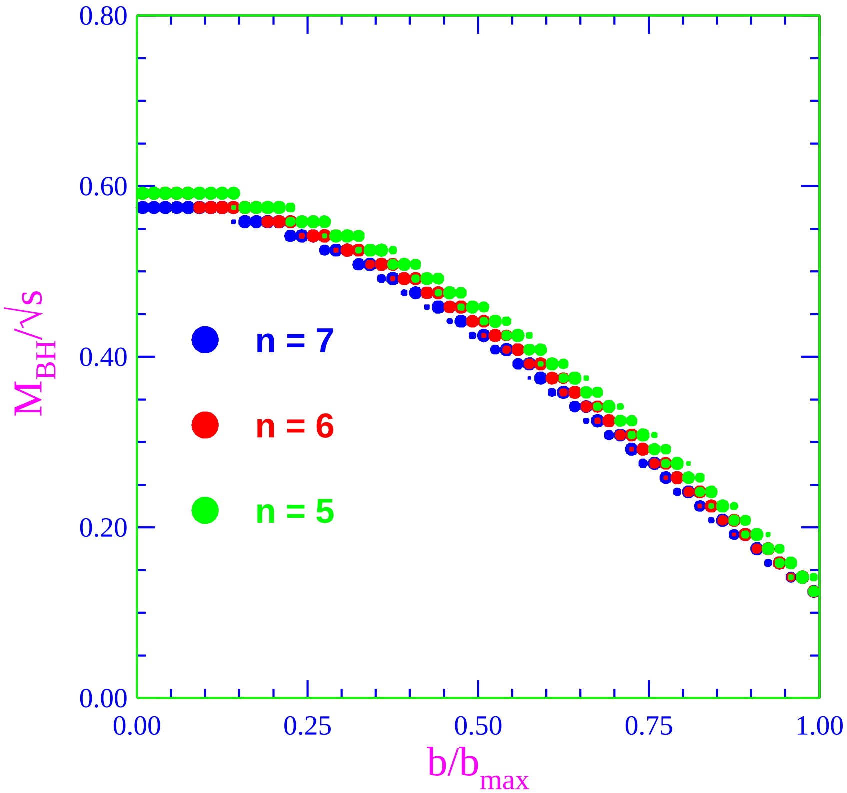


- The higher CM-energy (or the higher extra dimension),

  $\Longrightarrow$ 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

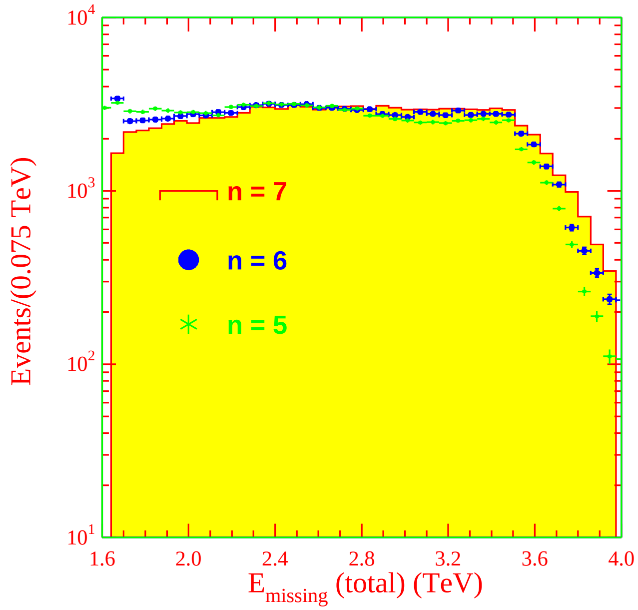
  [We use Yoshino and Nambu's model (PRD 67, 2003)]

Total Missing Energy

- Total missing energy (E_{miss}^{Total}) provides a signature of un-observed gravitons and neutrinos that are emitted ($E_{miss}^{Total} = 2.7$ TeV)
  - $E_{miss}^{Total} = E_{miss}^{Formation} + E_{miss}^{Evaporation}$
  - $E_{miss}^{Evaporation} = \sum_i N_i E_i$

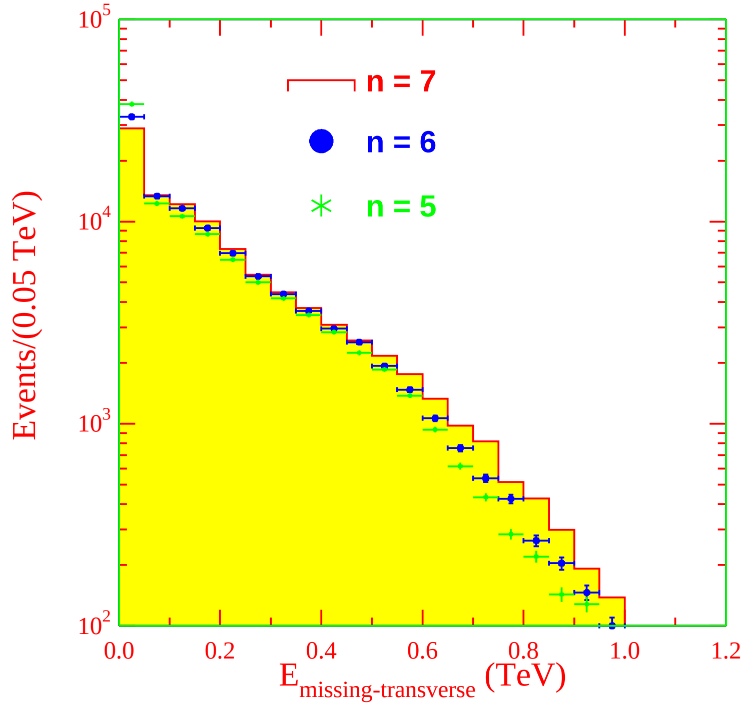
    N_i = number of un-observed particles (neutrinos and gravitons)

    E_i = its corresponding missing energy at evaporation process



Transverse Missing Energy

- Transverse missing energy ($\not\!\!E_T$) is coming from the transverse momentum of neutrinos and gravitons ($\not\!\!E_T = 190$ GeV)
  - Note that we assume all gravitons emit in brane modes
  - $\not\!\!E_T$ distribution with different extra dimensions



BH Signatures

- What are the BH signatures experimentally ?

1. Large cross section rate determined by the dimensionality of the extra dimensions (Giddings & Thomas 2002)

   $\Longrightarrow$ we have a relatively high cross section $\sim$ 7 nb

2. Large missing energy (Cavaglia, Das & Maartens, 2003)

   $\Longrightarrow$ we have $E_{miss}^{Total} \sim$ 2.7 TeV

3. Visible transverse missing energy (Giddings & Thomas 2002)

   $\Longrightarrow$ we have $E_T \sim$ 190 GeV

4. The typical ratio of hadron to lepton in the evaporation process is 7:1

5. The typical ratio of hadron to photon is 60:1

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 transverse missing energy help us to explore gravitons, extra dimensions, Hawking radiation and quantum remnants