CATFISH: Black Hole Simulation at CMS

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On behalf of
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• The observable astronomical BH encourages us to explore miniature BH production in laboratories

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

• Much effort has been made to predict BH production in fundamental Planck scale of $M_* \sim 1 \text{ TeV}$

• Such BH formation could be experimentally observed at the LHC detectors, such as CMS and ATLAS

• This talk is mainly focused on a new MC simulation of BH that is currently available to use
LHC Detectors

- **LHC:** $p - p$ collisions with **CM-energy $\sqrt{s} = 14 \text{ TeV}$**

- **CMS Collaboration:** 1050 physicists with 82 institutes in 38 countries

  $\leftarrow$ **BH production is one of the physics goals in CMS**
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

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

- \( M_* \sim TeV \) is fundamental Planck scale.

If the impact parameter \( b < r_s \), → 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 Calculation

- BH cross section can be estimated from the geometrical cross section (Black Disk)

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

- LHC \((p-p\text{ collider})\), we need to consider its cross section at the parton level (hampered by parton distributions)

\[ \sigma_{pp \rightarrow BH} \approx \sum_{ij} \int_{x_{m}}^{1} dx \int_{x}^{1} dy f_{i}(y, Q) f_{j}(x/y, Q) \sigma_{ij \rightarrow BH}(x, s, n) \]

  - \(x_{m} = M_{BH(min)}^{2}/s, \ s = M_{*}^{2}\) and \(Q = \) the momentum transfer
  - \(f_{i}, f_{j} = \) Parton Distribution Function (PDF)

- At CLIC \((e^{+} - e^{-}\text{ collider})\), beamstrahlung smears the collision energy unlike Muon Collider

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

\[ \sigma_{\mu\mu \rightarrow BH} \approx \sigma_{BH}(s, n) \] (it does not depend on the minimum \(M_{BH}\))
CATFISH: New MC Generator

- We introduce a new MC generator so called CATFISH
  - CATFISH (Collider grAviTational FIeld Simulator for black Holes)

- New features of CATFISH compared to other BH generators:
  - CATFISH is more flexible and user friendly
  - It includes different final BH decay modes with possibility of remnant formation either charged or neutral
  - It includes Graviton field emissivities
  - The missing energy is not only due to the neutrinos but also Gravitons, BH remnant and inelastic effect during BH formation

- CATFISH is available with PYTHIA interface at the moment
  - we plan to add HERWIG interface in the future version
• CATFISH is well documented and available for public
  http://www.phy.olemiss.edu/GR/catfish/

• CATFISH authors: M. Cavaglià, R. Godang, L. Cremaldi, D. Summers
CATFISH has been submitted to JHEP with arXiv:hep-ph/0609001

The physics of BH is determined using a set of external parameters:

- Fundamental Planck scale ($M_\star$)
- Number of large extra dimensions ($n$)
- Gravitational loss at formation
- Minimum BH mass at formation ($M_{\text{min}}$)
- Quantum BH mass threshold at evaporation ($Q_{\text{min}}$)
- Number of quanta at the end of BH decay ($n_p$)
- Minimum space time length ($\alpha$)...etc

All parameters are listed in a single input file

The CATFISH pre-compiled code is available in Linux and Mac
BH Mass distribution for fundamental Planck scale $M_* = 1$ TeV, $n_p = 2$

- $n = D - 4$ extra dimensions (3,4,6,..)

- (left) Black Disk model (BD) $\Rightarrow$ no Gravitons loss

- (right) Yoshino-Rychkov TS model (YR) $\Rightarrow$ with Gravitons loss

- The YR (BD) model is considered as lower (upper) bounds on $M_{BH}$

$\leftarrow M_{BH}$ depends on the impact parameter
Effects of Fundamental Scale

- Visible energy and missing transverse momentum for $n = 6$, $n_p = 4$, YR

![Graph showing visible energy and missing transverse momentum for $n = 6$, $n_p = 4$, YR with varying $M_\star$ values: $M_\star = 1$ TeV, $2$ TeV, and $3$ TeV.](image)

- Increasing $M_\star$ leads to higher $M_{\min}$ ($M_{\min} = 2M_\star$):
  - Larger visible energy in Hawking phase
  - Larger missing transverse momentum

- If BHs are observed at LHC $\implies M_\star$ could be measured to a certain degree of precision
• BH Mass distribution for $M_\star = 1$ TeV, ($n = 3, 6$), BD

The initial BH mass is obviously unaffected by the detail of final decay

- (left) We vary number of quanta at the end of BH decay for $n = 3$
- (right) We vary number of quanta at the end of BH decay for $n = 6$

This is a nice consistency check of CATFISH code
Effects of Final BH Decay...

- **Visible Transverse Momentum** for $M_* = 1$ TeV, $n = 6$, YR

![Graphs showing visible transverse momentum distributions](image)

- **Quanta emissivities in Hawking phase** are different wrt $n_p$
  - (left) Visible transverse momentum of ($e + \mu$)
  - (right) Visible transverse momentum of ($\gamma +$ hadron)

  → Experimentally it is almost impossible to distinguish between models
Effects of Minimum Spacetime Length

- Visible energy and missing transverse mom. for $n = 6$, $n_p = 2$, $\alpha = 0, 0.5$

\[ M_\star = 1 \text{ TeV} \]
\[ n = 6, n_p = 2 \]

- The effect of a small distance cut-off shows no significant differences in:
  - (left) total visible energy
  - (right) total missing transverse momentum

- To observe of minimum length effects at LHC $\rightarrow$ needs a fine tuning in $\alpha$
BH Events Shape

- BH events are expected to be highly spherical due to the spherical nature of Hawking evaporation process

Experimentally one needs to distinguish between BH events shape with $q\bar{q}$ events as BH-background (back-to-back events shape)

- (left) Sphericity BH events shape, $\rightarrow S > 0.30$ (depends on $M_{\text{min}}$)
- (right) Fox-Wolfram moment, $\rightarrow R_2 < 0.50$
Heavy and light jets mass are one of the BH signatures

- **These plots include initial and final state radiation**
  - BD model produces more massive BH than YR model (on average)

  - Heavy jets mass distribution → BH formation process
  - Light jets mass distribution → BH final process
CATFISH produces consistent results compared to the other generators. It has some new features and is user friendly.

The initial BH mass is obviously unaffected by the detail of final decay.

The YR (BD) model is considered as lower (upper) bounds on $M_{BH}$.

$M_{BH}$ depends on the impact parameter.

If BHs are observed at LHC, $M_x$ could be measured to a certain degree of precision. New discoveries are waiting to be explored!

BH events show a highly spherical shape as we expected.

Heavy and light jets mass show a consistency of BH signature.

All BH signatures are consistent with CATFISH results.