CATFISH: Black Hole Simulation at CMS

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On behalf of

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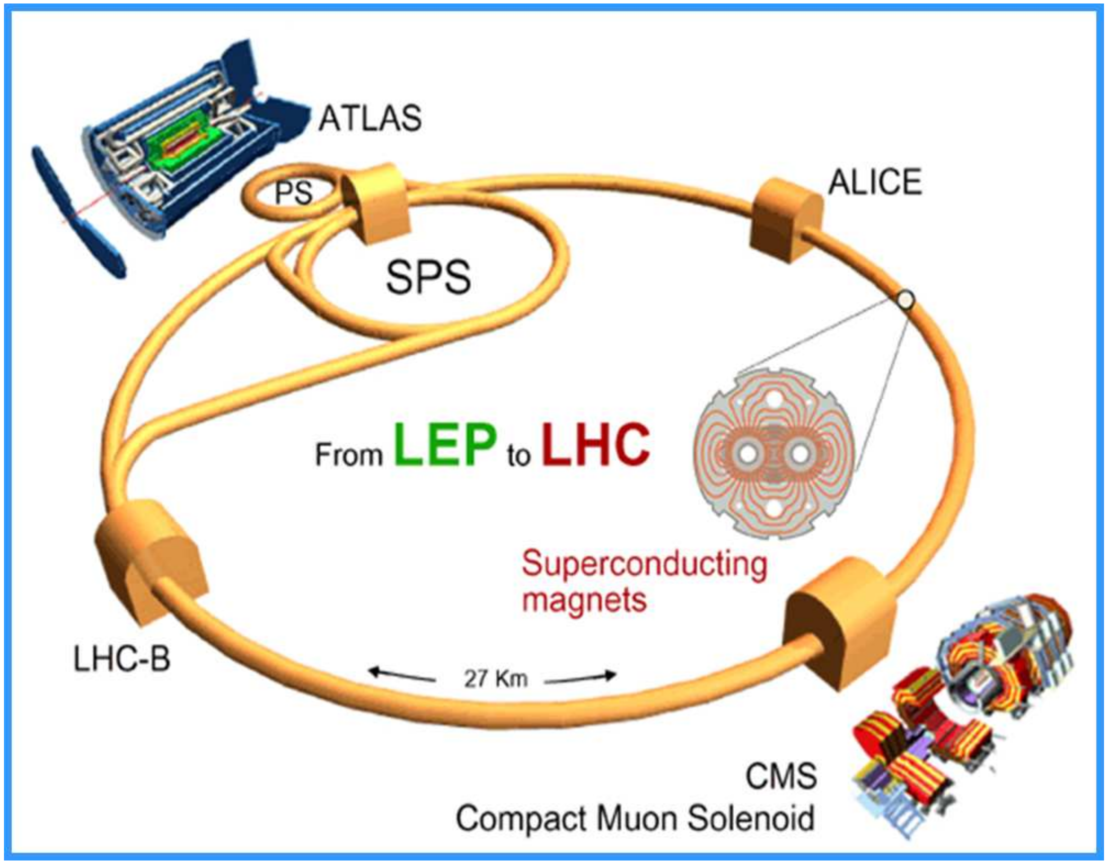
Introduction

- 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 $M_\star \sim 1$ 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 $\sqrt{s} = 14\ TeV$

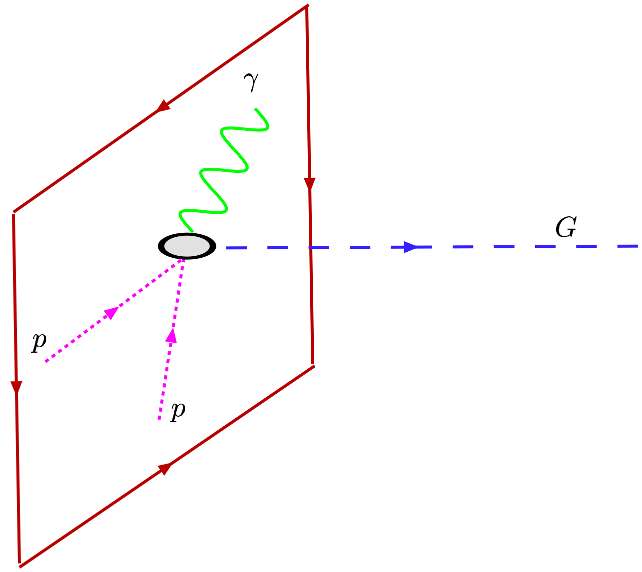


- CMS Collaboration: 1050 physicists with 82 institutes in 38 countries

  ↪ BH production is one of the physics goals in CMS

Extra Dimensions

- In large extra dimensions at the TeV energy scale, Gravitons can propagate in the $n = D - 4$ extra dimensions

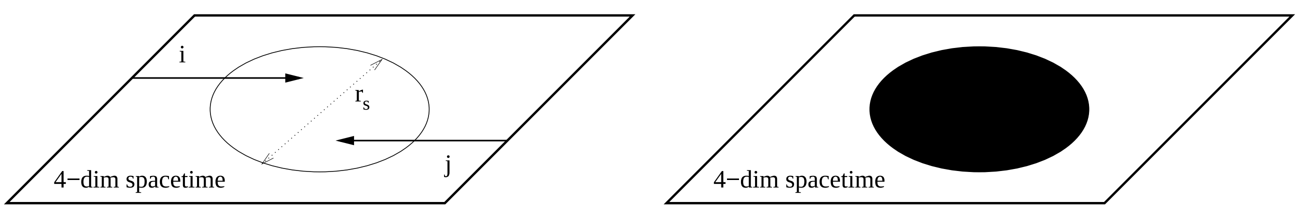


- The BH is characterized by the Schwarzschild radius

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

  - $M_\star \sim TeV$ is fundamental Planck scale

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

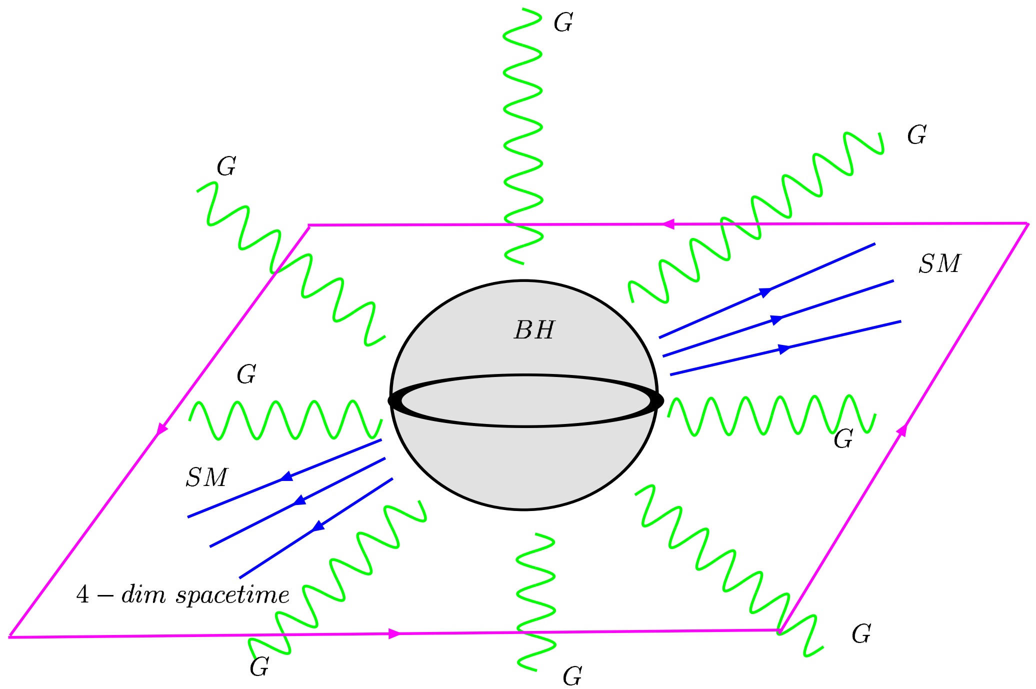


Hawking's Evaporation

- 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 Calculation

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

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

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

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

  - $x_m = M^2_{BH(min)}/s$, $s = M_\star^2$ **and** Q **= the momentum transfer**
  - f_i, f_j **= Parton Distribution Function (PDF)**

- **At CLIC ($e^+ - e^-$ collider), beamstrahlung smears the collision energy unlike Muon Collider**

- **At 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})**

CATFISH: New MC Generator

- We introduce a new MC generator so called CATFISH

  CATFISH (Collider grAviTational FIeld Simulator for black Holes)

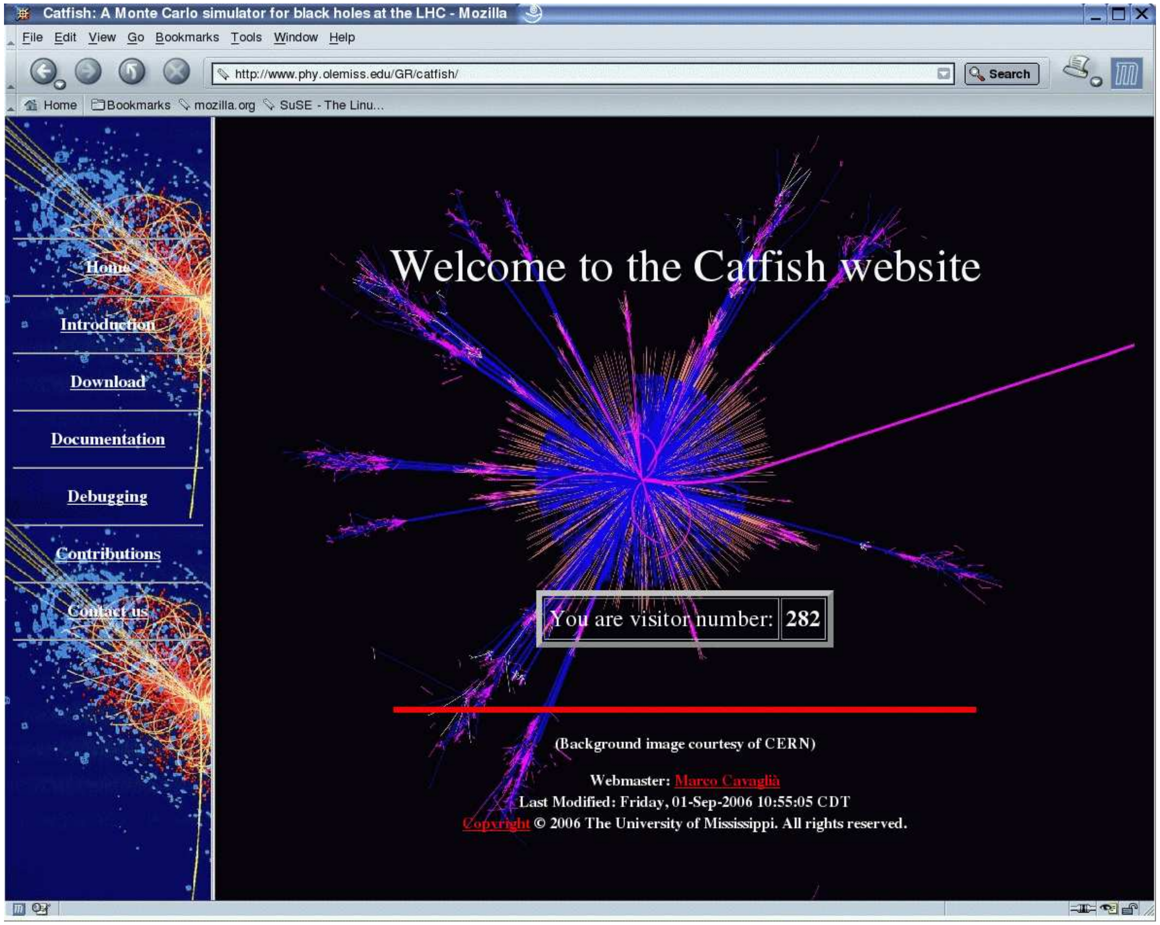
- New features of CATFISH compared to other BH generators :

  - 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 Website



- **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: New MC Generator...

- CATFISH has been submitted to JHEP with arXiv:hep-ph/0609001

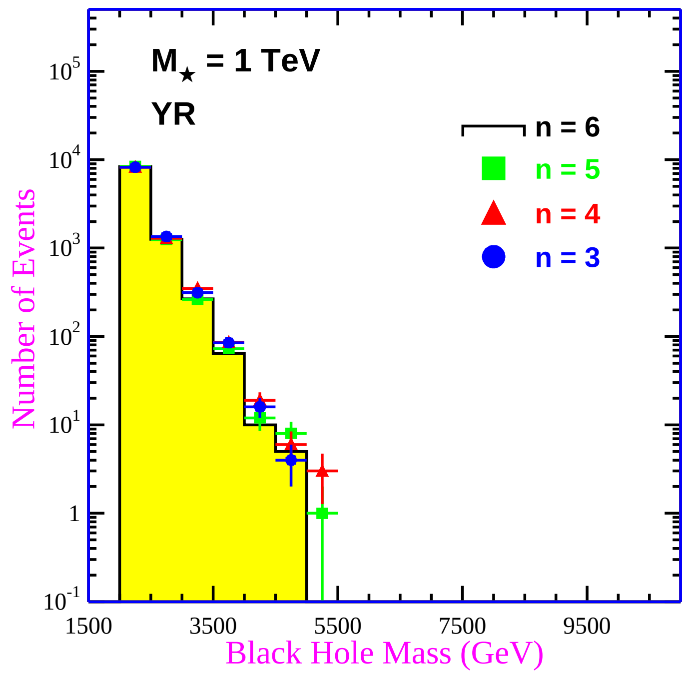
- The physics of BH is determined using a set of external parameters :
  - Fundamental Planck scale ($M_\star$)
  - Number of large extra dimensions (n)
  - Gravitational loss at formation
  - Minimum BH mass at at formation (M_{min})
  - Quantum BH mass threshold at evaporation (Q_{min})
  - Number of quanta at the end of BH decay (n_p)
  - Minimum space time length (α)...etc

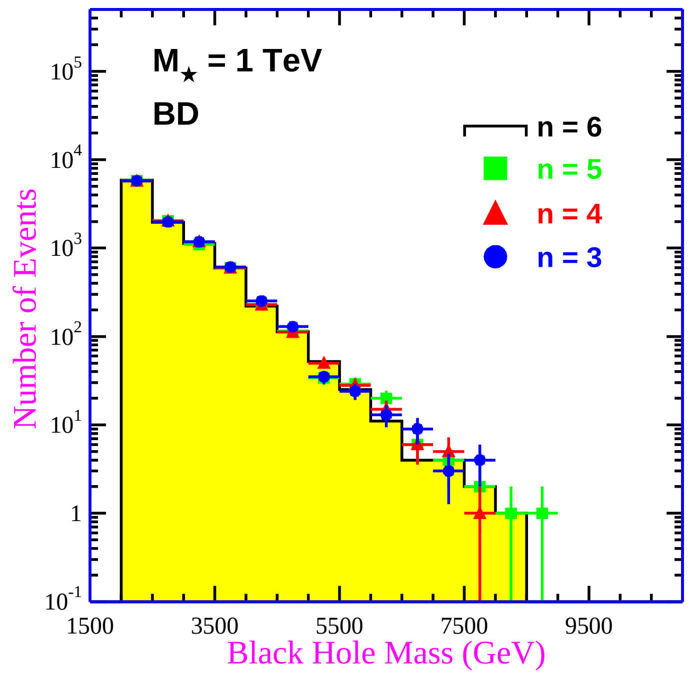
    $\hookrightarrow$ All parameters are listed in a single input file

- The CATFISH pre-compiled code is available in Linux and Mac

BH Mass

- BH Mass distribution for fundamental Planck scale $M_\star = 1$ TeV, $n_p = 2$

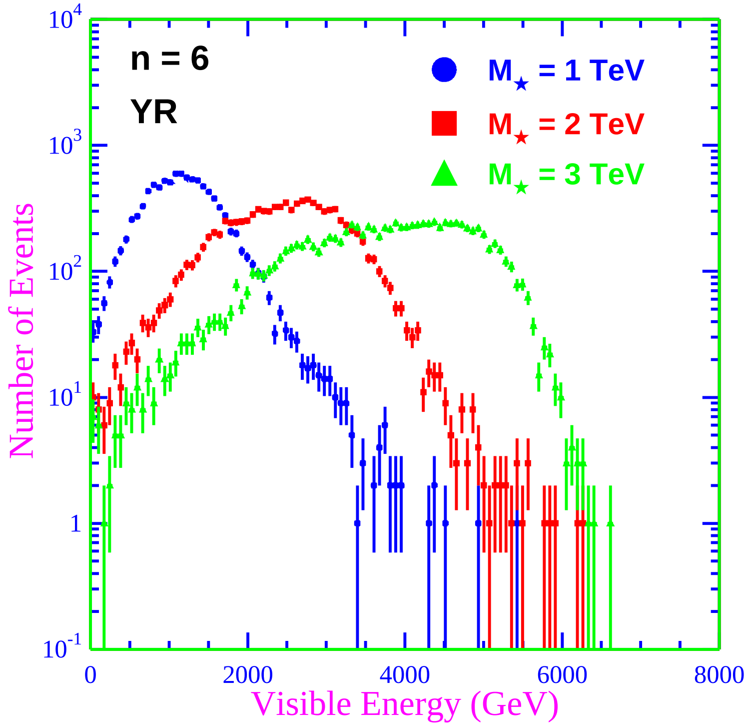


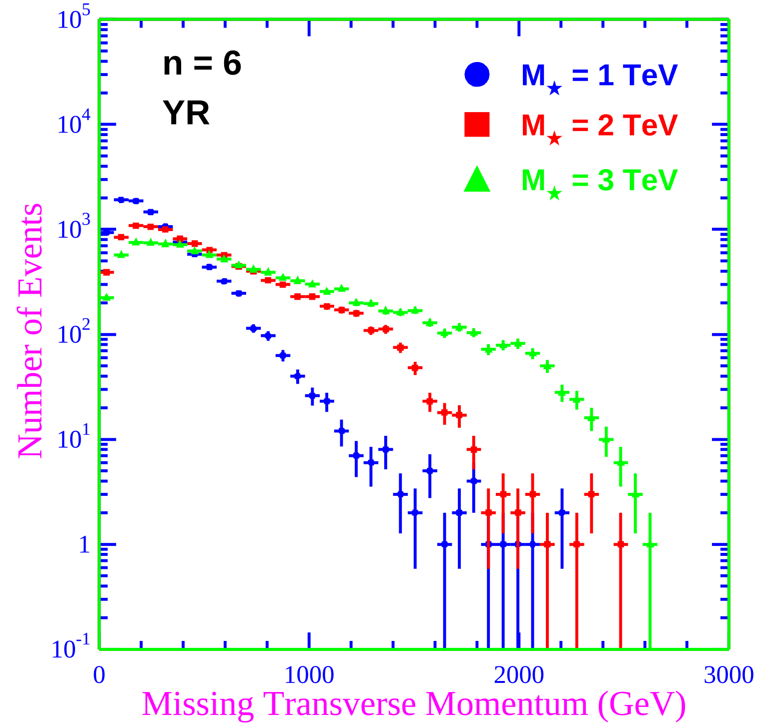


- $n = D - 4$ extra dimensions (3,4,6,..)
- (left) Black Disk model (BD) $\Longrightarrow$ no Gravitons loss
- (right) Yoshino-Rychkov TS model (YR) $\Longrightarrow$ with Gravitons loss
- The YR (BD) model is considered as lower (upper) bounds on M_{BH}
  $\hookrightarrow$ M_{BH} depends on the impact parameter

Effects of Fundamental Scale

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

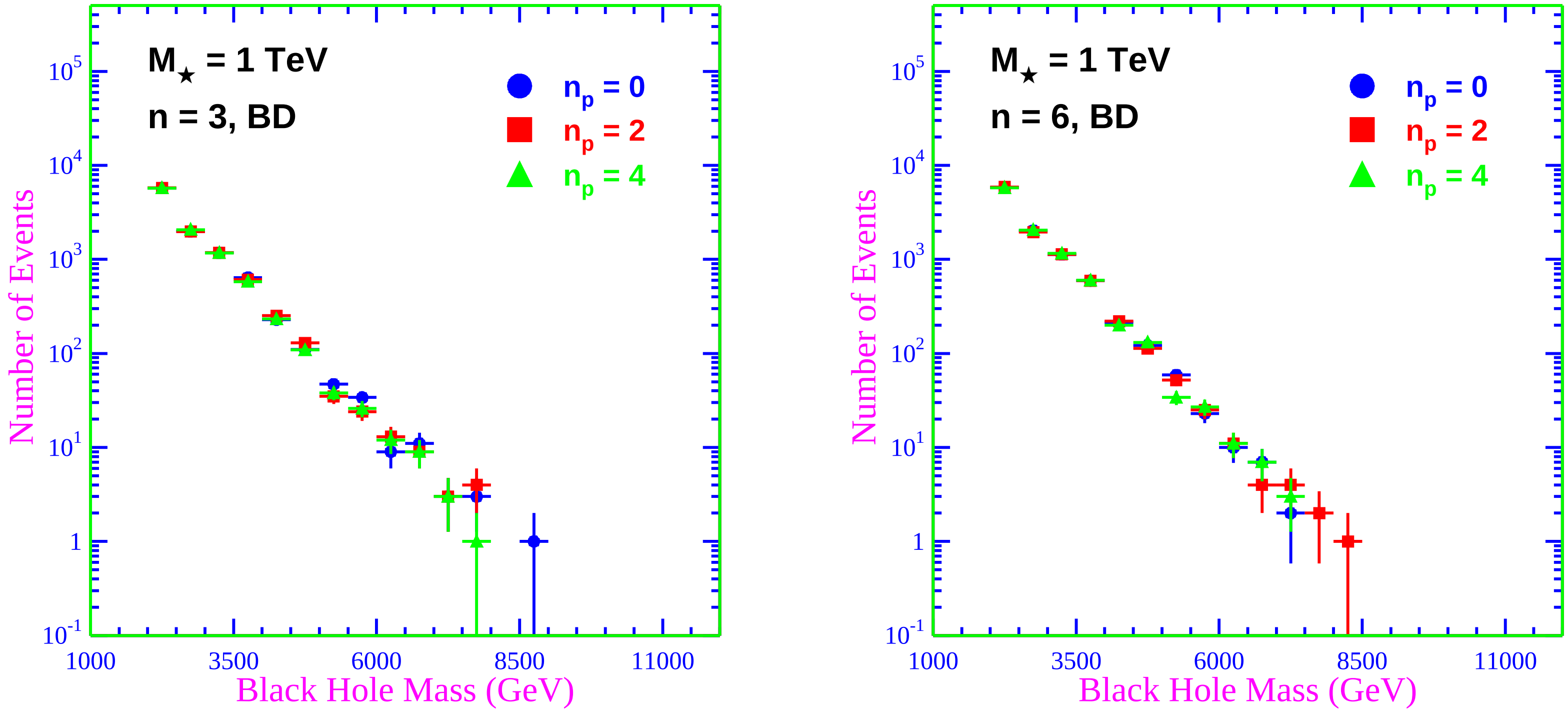




- Increasing $M_\star$ leads to higher M_{min} ($M_{min} = 2M_\star$) :
  - Larger visible energy in Hawking phase
  - Larger missing transverse momentum
- If BHs are observed at LHC $\Longrightarrow$ $M_\star$ could be measured to a certain degree of precision

Effects of Final BH Decay

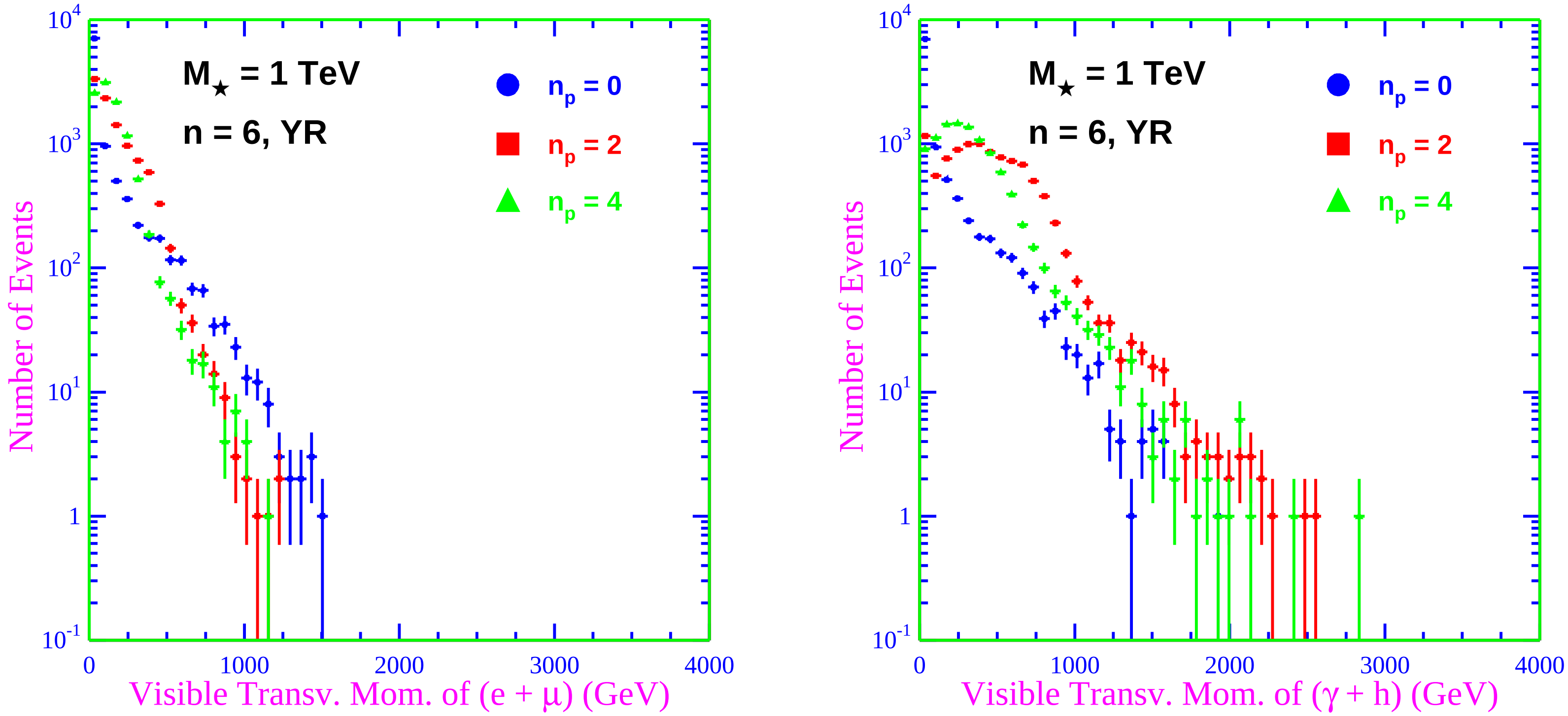
- BH Mass distribution for $M_\star = 1$ TeV, (n =3, 6), BD



- 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 $M_\star = 1$ TeV, n = 6, YR**

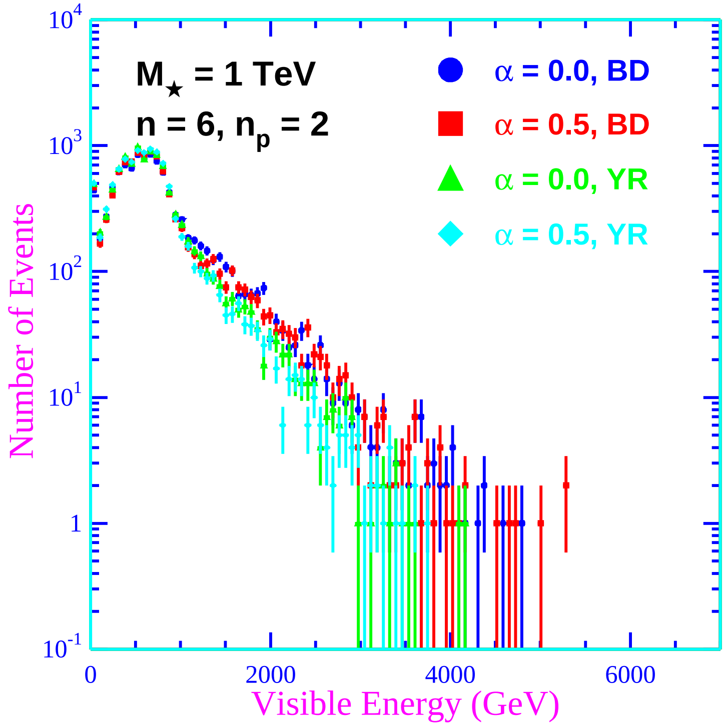


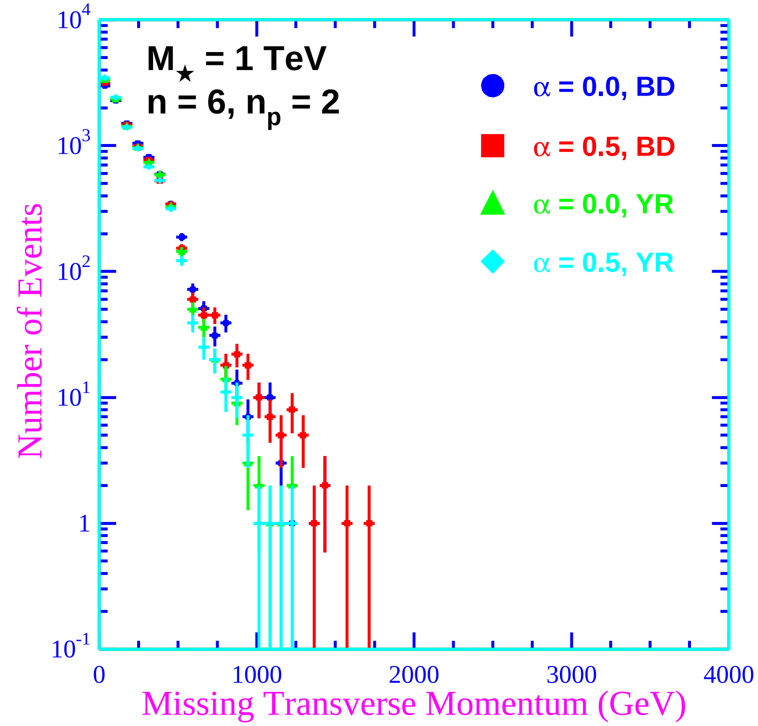
- **Quanta emissivities in Hawking phase are different wrt n_p**
  - **(left) Visible transverse momentum of (e + μ)**
  - **(right) Visible transverse momentum of (γ + hadron)**

  $\hookrightarrow$ **Experimentally it is almost impossible to distinguish between models**

Effects of Minimum Spacetime Length

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

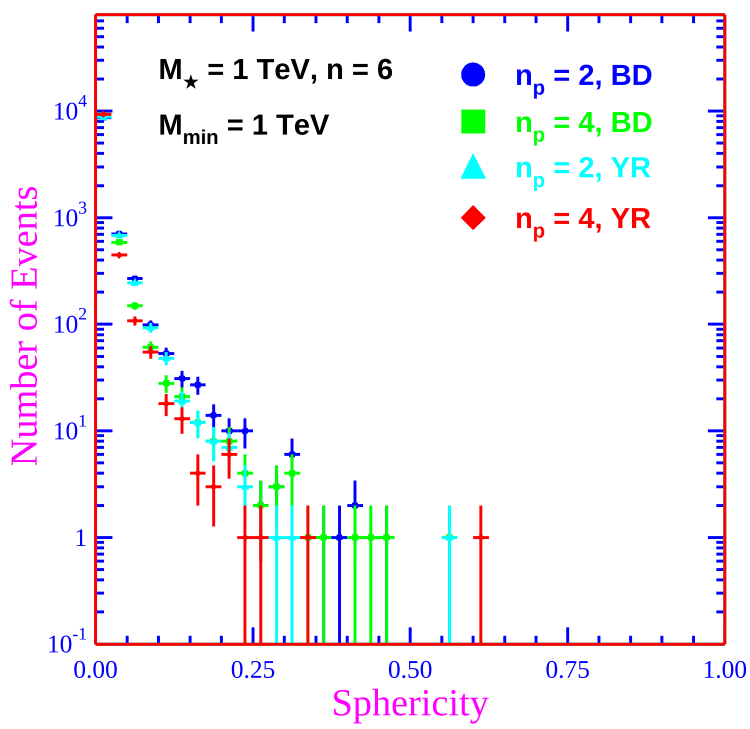


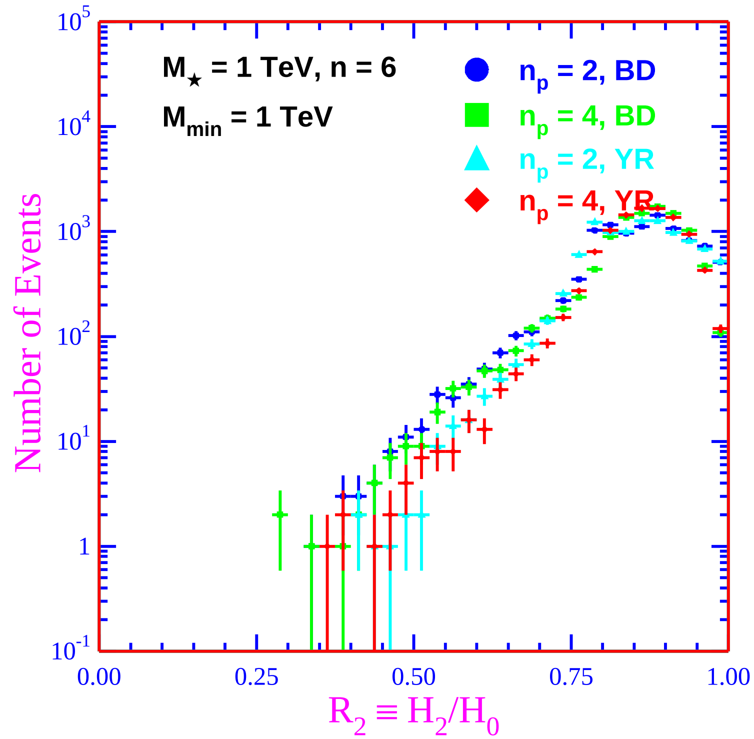


- The effect of a small distance cut-off shows no significant differences in :
  - (left) total visible energy
  - (right) total missing transverse momentum
- To observe of minimum length effects at LHC $\Longrightarrow$ needs a fine tuning in α

BH Events Shape

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

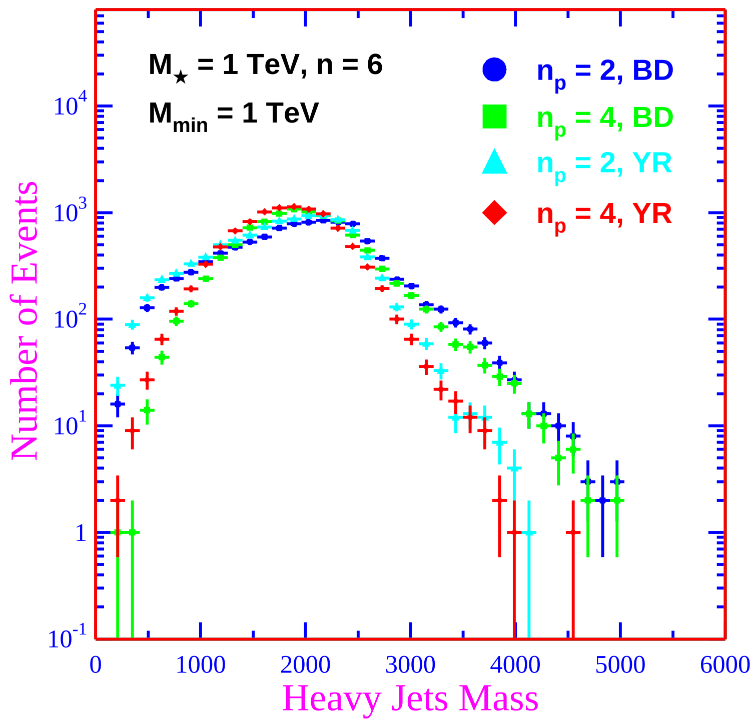


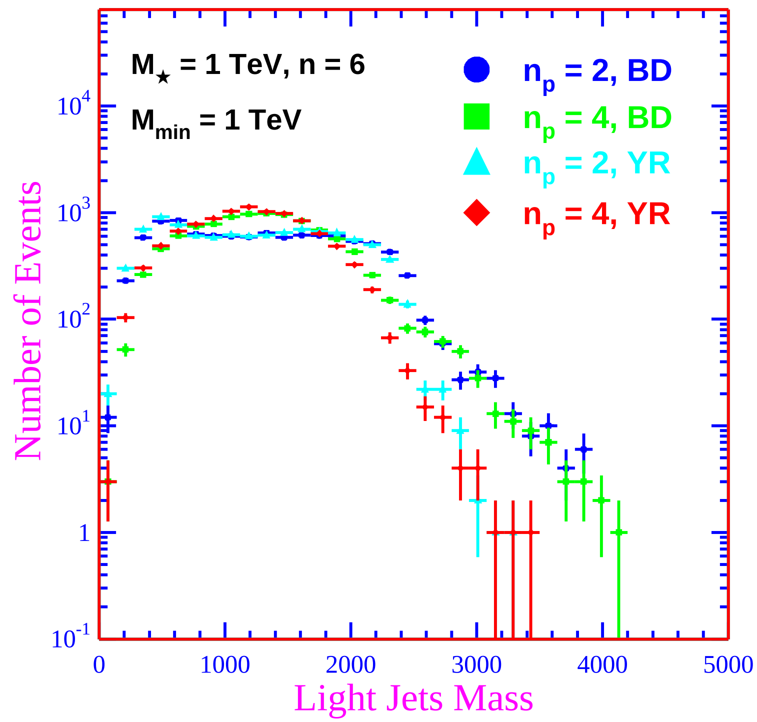


- Experimentally one needs to distinguish between BH events shape with $q\bar{q}$ events as BH-background (back-to-back events shape)
  - (left) Sphericity BH events shape, $\rightarrow S > 0.30$ (depends on M_{min})
  - (right) Fox-Wolfram moment, $\rightarrow R_2 < 0.50$

Jets Mass

- 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

Summary

- 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}
  $\hookrightarrow$ M_{BH} depends on the impact parameter
- If BHs are observed at LHC $\hookrightarrow$ $M_\star$ could be measured to a certain degree of precision $\hookrightarrow$ 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