Quantum Black Holes at the LHC

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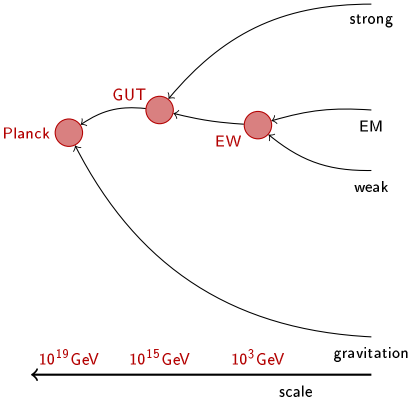
Outline

1. Motivation
   - Low scale quantum gravity
   - Black hole formation
2. Quantum black holes
   - QBH vs semi-classical BH
   - Continuous mass spectrum
   - Discrete mass spectrum
3. Possible decay modes
   - Classification of QBHs
   - Branching ratios

Low scale quantum gravity



- Is there one fundamental interaction?
- Planck mass: energy scale at which quantum gravitational effects become important!

$$M_P = \sqrt{\frac{\hbar c}{G_N}}$$

- Dimensional analysis: $M_P \sim 10^{19}\,\text{GeV} \rightarrow$ really?

Low scale quantum gravity

Quantum gravity effects at a much lower energy scale?
In case of extra dimensions:

$$S \sim \int d^4x \, d^{d-4}x' \sqrt{-g} \left(M^{d-2} \mathcal{R} + \cdots \right)$$

large volume $\rightarrow$ $M_P^2 = M^{d-2} V_{d-4}$ where M_P is the effective Planck scale in 4-dim.

Models of low scale quantum gravity

- *ADD*: large extra dimensions
- *RS*: warped extra dimension

Quantum gravity effects relevant at lower energies $\rightarrow$ prediction of microscopic black hole formation in particle collisions

Black hole formation

classical BHs: well understood in GR (symm. matter distribution)
In particle collisions? Einstein equations can't be solved exactly.

→ **Hoop conjecture** (Kip Thorne): black holes with horizons form when and only when an energy E gets compacted into a region whose circumference in every direction is $2\pi r_s$.

Formation of classical black holes (BHs) in High-Energy collisions

classical BHs in limit of very large CoM energy with non zero impact parameters (Eardley & Giddings, following works of D'Eath & Payne)

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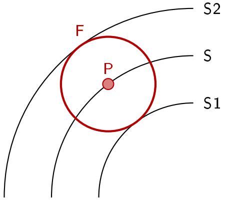
Black hole formation



- compact spacelike two-surface in space-time (outgoing null rays perpendicular to the surface are not expanding)
- areas of both, S_1 and S_2, less than of S $\rightarrow$ S closed trapped surface

Formation of semi-classical black holes

semi-classical formulation, closed trapped surface

$$\sigma \approx \pi r_s^2 \,, \; r_s\,(M_{BH}) = M_D^{-1} \left[\frac{M_{BH}}{M_D}\right]^{\frac{1}{1+n}} \left[\frac{2^n\,\pi^{(n-3)/2}\,\Gamma(\frac{n+3}{2})}{n+2}\right]^{\frac{1}{1+n}}$$

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Quantum black holes (QBH)

Semi-classical BH

- thermal object
- decay via Hawking radiation into many particle final state
- geometrical cross section:

$$\sigma = \pi r_s^2$$

- formation unlikely since $M_{BH} \gg M_P$

QBH

- $M_{BH} \sim$ TeV, non-thermal
- decay into only a few particles
- extrapolation from geometrical cross section
- interpretation as short-lived state

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QBH cross section - Continuous mass spectrum

Parton-level cross sections for QBH production (implemented in new version of BlackMax)

$$\sigma^{pp}(s, x_{min}, n, M_D) \equiv \int_0^1 2z\mathrm{d}z \int_{\frac{x_{min} M_D}{y^2 s}}^1 \mathrm{d}u \int_u^1 \frac{\mathrm{d}v}{v} \times$$

$$\times F(n)\pi r_s^2(us, n, M_D) \sum_{ij} f_i(v, Q) f_j(u/v, Q)$$

- n: number extra dimensions
- $z \equiv b/b_{max}$: rescaled impact parameter
- $F(n)$: form factor
- u, v: momentum fractions of incoming partons
- r_s: Schwarzschild radius
- $x_{min} = M_{BH}^{min}/M_D$
- i,j: parton species
- f_i,f_j parton distribution functions
- Q: scale of momentum transfer

Schwarzschild radius

ADD (Arkani-Hamed, Dimopoulos, and Dvali)

Choice of number of extra dimensions $n = 0$ to 7

$$r_s\left(us, n, M_D\right) = k\left(n\right) M_D^{-1} \left[\frac{\sqrt{us}}{M_D}\right]^{1/(1+n)}$$

$$k(n) \equiv \left[2^n \sqrt{\pi}^{n-3} \frac{\Gamma\left[\left(3+n\right)/2\right]}{2+n}\right]^{1/(1+n)}$$

RS (Randall and Sundrum)

Number of extra dimensions is fixed to be equal to 1;

$$r_s = M_D^{-1} \left(\frac{2M_{BH}}{3\pi M_D}\right)^{1/2}$$

where M_D is the reduced Planck mass

QBH cross section - Discrete masses

existence of minimal length → quantized QBH masses

Individual cross sections for QBH production

$$\sigma^{pp}_{QBH}(s, M_{BH}, n, M_D) = \pi r_s^2(M_{BH}^2, n, M_D) \times$$
$$\times \int_0^1 2zdz \int_{\frac{(M_{BH})^2}{y(z)^2 s}}^1 du \int_u^1 \frac{dv}{v} F(n) \sum_{\text{partons i, j}} f_i(v, Q) f_j(u/v, Q)$$

Total cross sections for QBH production

$$\sigma^{pp}_{tot}(s, n, M_D) = \sum_{M_{BH}} \sigma^{pp}_{QBH}(s, M_{BH}, n, M_D)$$

Schwarzschild radius

ADD

$$r_s(M_{QBH}^2, n, M_D) = k(n) M_D^{-1} [M_{BH}/M_D]^{1/(1+n)}$$

as in continuous case

$$k(n) \equiv \left[2^n \sqrt{\pi}^{n-3} \frac{\Gamma\left[\left(3+n\right)/2\right]}{2+n} \right]^{1/(1+n)}$$

In RS, we still find

$$r_s = M_D^{-1} \left(\frac{2 M_{BH}}{3\pi M_D} \right)^{1/2}$$

Classification of QBHs

QBH states according to representations $\mathrm{SU(3)_c}$ and $\mathrm{U(1)_{em}}$

$p_i + p_j \to QBH_c^q$ defined by mass, spin & gauge charges

Color multiplets of QBHs

$$3 \times \bar{3} = 8 + 1 \qquad 3 \times 8 = 3 + \bar{6} + 15$$

$$3 \times 3 = 6 + \bar{3} \qquad 8 \times 8 = 1 + 8 + 8 + 10 + \overline{10} + 27$$

- confinement? $\Lambda_{QCD}^{-1} \gg \mathrm{M_P}^{-1}$
- Nine possible em charges
  0, $\pm 1/3$, $\pm 2/3$, $\pm 4/3$, ± 1
- spin factors for massless particles using Clebsch-Gordon coefficients

	0	1/2	1
0	0	1/2	1
1/2		0 , 1 1 : 3	1/2 , 3/2 1 : 2
1			0 , 1 , 2 2 : 3 : 7

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Branching ratios

Restrictions on symmetries

1. Lepton flavor, quark flavor, B-L, Lorentz invariance conserved
2. Lepton flavor violated, everything else conserved
3. Quark flavor violated, everything else conserved
4. quark and lepton flavor violated, B-L conserved
5. everything violated except Lorentz invariance

Incidental $U(1)_{em}$ charge of $4/3$ an weighed by spin factors:

QBH created by two up-quarks

$$QBH(u,u,4/3) \to u + u : \quad \overset{\text{color}}{(6+3)} \times \overset{\text{spin}}{(1+3)} = 36$$

$$QBH(u,u,4/3) \to l^+ + \bar{d} : \quad \overset{\text{color}}{(3)} \times \overset{\text{spin}}{(1+3)} = 12$$

Specific final states

Most final states: jets back to back → large background, but specific final states, e.g. QBH $\rightarrow \gamma + \gamma$, easy to identify at LHC:

- Sum over production cross section of contributing QBHs (calculation automated in MC integration algorithm)
- Consideration of all existing QBH masses
- Multiplication with suitable branching ratio

Calculation rule for specific final state

$$\sigma_{\text{QBH}\rightarrow\text{final state}} = \sum_{\text{initial states}} \sum_{\text{masses}} \sigma_{\text{initial state}\rightarrow\text{QBH}_{\text{mass}}} \times \text{BR}_{\text{final state,model}}$$

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Conclusions and outline

- QBHs with continuous mass spectrum implemented into new version of BlackMax[1].
- Cross sections for specific final states for QBHs with discrete masses can be found in arXiv:1209.4618 [hep-ph].
- Sizable cross sections, depending on magnitude of Planck scale, considered final state and SM background.
- As expected, discrete cross sections $<$ continuous ones.
- Although same possible final states, nature of discrete and continuous QBHs very different.
- Extension of QBH model considering supersymmetric particle productions in progress

[1] BlackMax: A black-hole event generator with rotation, recoil, split branes and brane tension, Phys. Rev. D (Vol.77, No.7), arXiv:0711.3012 [hep-ph]

Thanks

Thanks for your attention!