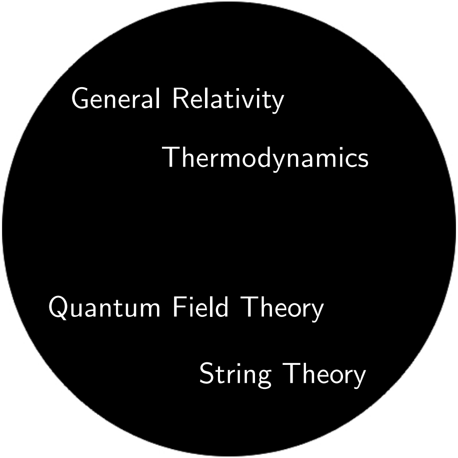
TeV-scale Black Holes

Sabine Hossenfelder

University of Arizona

SH, Ben Koch and Marcus Bleicher: hep-ph/0507138, hep-ph/0507140

Black Holes as Physics Meeting Point



Black Holes as Physics Meeting Point

General Relativity

Thermodynamics

Particle Physics

Quantum Field Theory

String Theory

Why Extra Dimensions

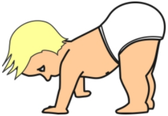
Why Extra Dimensions

Top down

Why Extra Dimensions

Top down

Bottom up

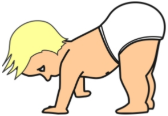


Why Extra Dimensions

Top down

Extra Dimensions

Bottom up

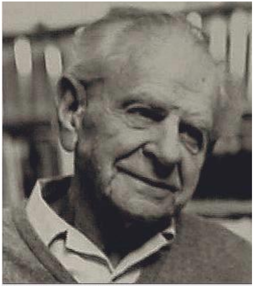


Why Extra Dimensions

Top down

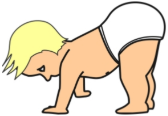
"Science may be described as the art of systematic over-simplification."

Extra Dimensions



Sir Karl Popper (1902-1994)

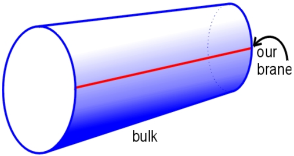
Bottom up



Karl Popper, The Observer, August 1982

The ADD-Model

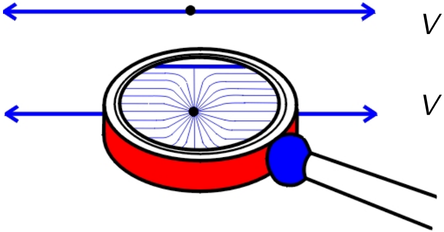
- $d + 3$ space like dimensions (bulk)
- Compactified to radius R
- Only gravitons are allowed into all dimensions
- SM particles bound to 3-dimensional submanifold (brane)



Arkani-Hamed, Dimopoulos and Dvali, Phys. Lett. B **429**, 263 (1998)
Antoniadis, Arkani-Hamed, Dimopoulos and Dvali, Phys. Lett. B **436**, 257 (1998)
Arkani-Hamed, Dimopoulos and Dvali, Phys. Rev. D **59**, 086004 (1999)

The ADD-Model

- $d+3$ space like dimensions (bulk)
- Compactified to radius R
- Only gravitons are allowed into all dimensions
- SM particles bound to 3-dimensional submanifold (brane)



$$V \sim \frac{1}{m_p^2}\frac{1}{r}$$

$$V \sim \frac{1}{M_f^{d+2}}\frac{1}{r^{d+1}} \to \frac{1}{M_f^{d+2}}\frac{1}{R^d}\frac{1}{r}$$

The ADD-Model

- $d+3$ space like dimensions (bulk)
- Compactified to radius R
- Only gravitons are allowed into all dimensions
- SM particles bound to 3-dimensional submanifold (brane)

\+ Solves hierarchy problem $m_p^2 = R^d M_f^{d+2}$

The ADD-Model

- $d + 3$ space like dimensions (bulk)
- Compactified to radius R
- Only gravitons are allowed into all dimensions
- SM particles bound to 3-dimensional submanifold (brane)
- \+ Solves hierarchy problem $m_p^2 = R^d M_f^{d+2}$
- Large radii $1/R \sim$ eV .. 10 MeV

Black Holes in Extra Dimensions

In large extra dimensions (ADD)

- Gravity stronger at small distances $\Rightarrow$ horizon radius larger
- For mass $M \sim 1$ TeV :

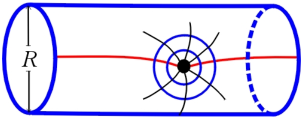
$$R_H \sim 2 \times 10^{-38}\text{fm} \quad \text{without} \quad R_H \sim 2 \times 10^{-4}\text{fm} \quad \text{with extra dim.}$$

Black Holes in Extra Dimensions

In large extra dimensions (ADD)

- Gravity stronger at small distances $\Rightarrow$ horizon radius larger
- For mass $M \sim 1$ TeV :

$$R_H \sim 2 \times 10^{-38}\text{fm} \quad \text{without} \quad R_H \sim 2 \times 10^{-4}\text{fm} \quad \text{with extra dim.}$$



Collider produced black holes

radius $R_H \ll R$

masses $\sim$ TeV

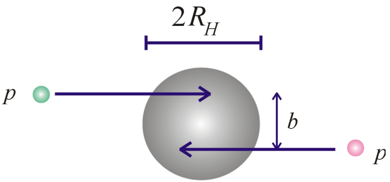
Black Holes in Extra Dimensions

In large extra dimensions (ADD)

- Gravity stronger at small distances $\Rightarrow$ horizon radius larger
- For mass $M \sim 1$ TeV :

$$R_H \sim 2 \times 10^{-38}\text{fm} \quad \text{without} \quad R_H \sim 2 \times 10^{-4}\text{fm} \quad \text{with extra dim.}$$

- At the LHC partons can come closer than their Schwarzschild horizon $\longrightarrow$ a black hole can be created!

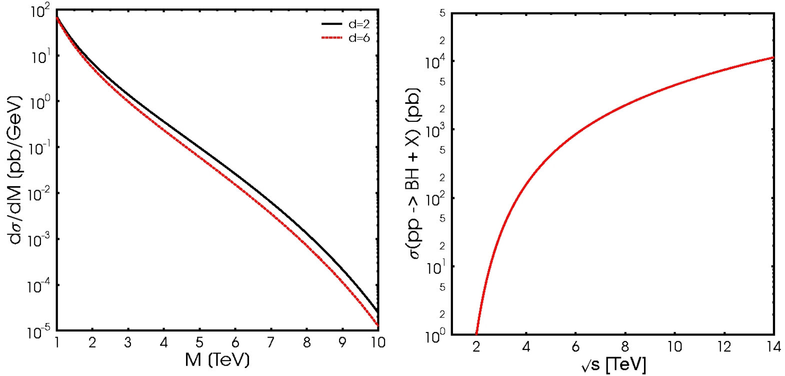


Dimopoulos and Landsberg, Phys. Rev. Lett. **87**, 161602 (2001)
Giddings and Thomas, Phys. Rev. **D 65** 056010 (2002)

Cross-section of Black Holes

- Cross section $\sigma \sim \pi R_H^2$ is function of $\sqrt{s}$
- Threshold $\Theta(M - M_{min})$, one expects $M_{min} \sim M_f$
- Model with colliding wave-packets in Aichelburg-Sexl geometry and examine spacetime for horizons
- Integrate over PDFs for hadron collisions

Production of Black Holes



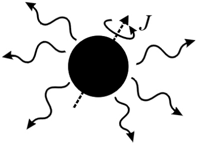
⟶ estimation yields $\approx 10^9$ black holes per year, one per second

Evaporation of Black Holes

The evaporation proceeds in 3 stages:

Evaporation of Black Holes

The evaporation proceeds in 3 stages:

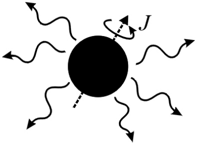


1. Balding phase: hair loss – the black hole radiates off angular momentum and multipole moments

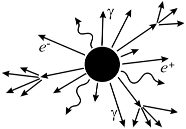
Evaporation of Black Holes

The evaporation proceeds in 3 stages:

1. Balding phase: hair loss – the black hole radiates off angular momentum and multipole moments



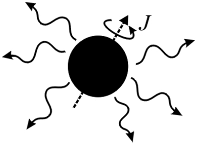
2. Hawking phase: thermal radiation into all particles of the standard model as well as gravitons
Black hole thermo: $T = \kappa/2\pi$ and $dS/dM = 1/T$



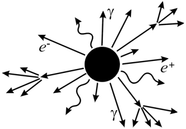
Evaporation of Black Holes

The evaporation proceeds in 3 stages:

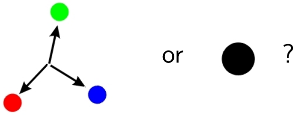
1. Balding phase: hair loss – the black hole radiates off angular momentum and multipole moments



2. Hawking phase: thermal radiation into all particles of the standard model as well as gravitons
   Black hole thermo: $T = \kappa/2\pi$ and $dS/dM = 1/T$

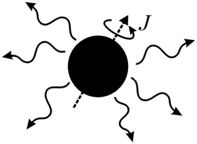


3. Final decay or remaining black hole relic

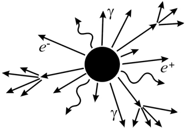


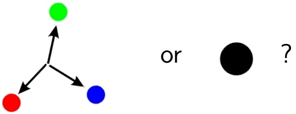
Evaporation of Black Holes

The evaporation proceeds in 3 stages:



1. Balding phase: hair loss – the black hole radiates off angular momentum and multipole moments
2. Hawking phase: thermal radiation into all particles of the standard model as well as gravitons
   Black hole thermo: $T = \kappa/2\pi$ and $dS/dM = 1/T$
3. Final decay or remaining black hole relic





Numerical investigation: black hole event generator CHARYBDIS

Tanaka *et al*, [arXiv:hep-ph/0411095]; Harris *et al*, [arXiv:hep-ph/0411022]

Why Black Hole Remnants

Information loss, modified gravity, hair ...

A simple argument:

- Compton-wavelength $\lambda \sim 1/E$, Schwarzschild-radius $R_H \sim E/m_p^2$
- R_H should not be $< \lambda$, because of the uncertainty principle

$\longrightarrow$ But would happens for black hole with $E < m_p$

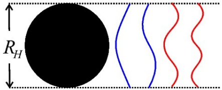
Why Black Hole Remanants

Information loss, modified gravity, hair ...

A simple argument:

- Compton-wavelength $\lambda \sim 1/E$, Schwarzschild-radius $R_H \sim E/m_p^2$
- R_H should not be $< \lambda$, because of the uncertainty principle

$\longrightarrow$ But would happens for black hole with $E < m_p$



Also:

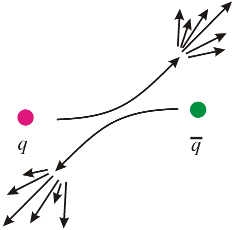
- Evaporation of $\lambda > R_H$ not possible
- Emission of $E \sim 1/\lambda$ larger than $M \sim R_H m_p^2$ is not possible

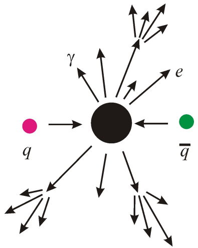
$\longrightarrow$ Evaporation stops when largest possible wavelength carries already too much energy

$\longrightarrow$ Black hole becomes stable at $M \sim m_p$

Observables of Black Holes

- Multi-jet like events
- Momentum cut-off at $\sim M_f$
- Thermal spectrum $\rightarrow$ yields d and M_f



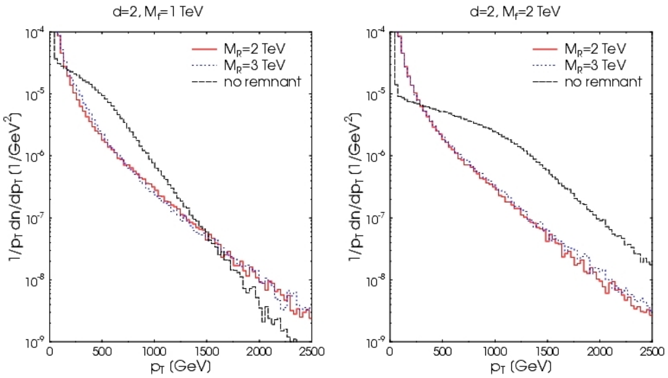


Observables of Black Holes

- Multi-jet like events
- Momentum cut-off at $\sim M_f$
- Thermal spectrum $\rightarrow$ yields d and M_f

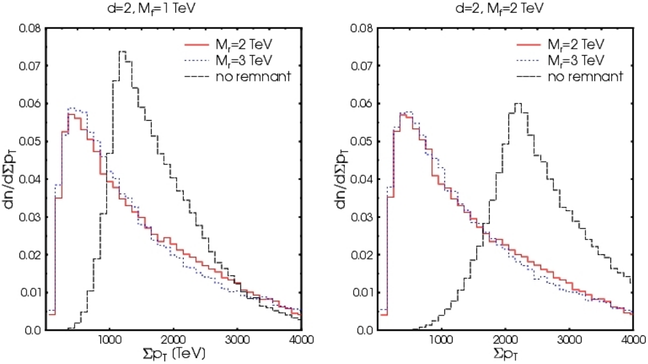
$\longrightarrow$ Are significantly modified through the formation of a remnant!

p_T-Spectrum of decay products before fragmentation



- Final decay makes an important contribution to p_T-spectrum
- Remnant production makes a significant difference
- After fragmentation, difference is less prominent but still present

$\sum p_T$-Spectrum of black hole event



- Missing p_T is increased in presence of remnants

Summary

- Effective models with extra dimensions quantify first effects beyond the standard model
- Black hole production will become important with strong gravitational effects
- Numerical tools for black hole events available
- New: Signatures of black hole event with possible remnant are significantly modified

$\longrightarrow$ Exciting test for the onset of quantum gravity

More details: hep-ph/0507138, hep-ph/0507140