Tidal-charged black holes @ the LHC

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Black Holes in a Violent Universe
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Summary

- A brief history...
- Brane-world black holes basics. Existence
- Accretion
- Evaporation
- Time evolution
- Black holes in the RS scenario
- Conclusions

A brief history...

- N. Dadhich, R. Maartens, P. Papadopoulos and V. Rezania, Phys. Lett. B **487**, 1 (2000):
  RS effective 4D Einstein equations admit tidal-charged black hole solutions
- R. Casadio and B. Harms, Int. J. Mod. Phys. A **17**, 4635 (2002):
  tidal charged micro-black holes may be long-lived (>>1 sec)
- S. Giddings and M. Mangano, Phys. Rev. D **78**, 035009 (2008):
  micro-black holes at LHC are no threat
- J.R. Ellis, G. Giudice, M.L. Mangano, I. Tkachev, U. Wiedemann, J. Phys. G **78**, 115004 (2008):
  LHC is safe!
- R. Plaga, arXiv:0808.1415:
  micro-black holes from 1-2 (not considered in 3-4) can cause catastrophe at LHC!
- R.Casadio, S. Fabi, B. Harms, and O. Micu, JHEP 1002:**079**, 2010:
  micro-black holes from 1-2 at the LHC are not bad

Brane-world black hole basics: Existence

Four dimensions:

Horizon radius: $R_{\mathrm{S}} \sim \frac{M}{M_{\mathrm{P}}^2}$

Compton length: $R_{\mathrm{C}} \sim \frac{1}{M}$

M = Black Hole mass

M_{P} = Planck mass

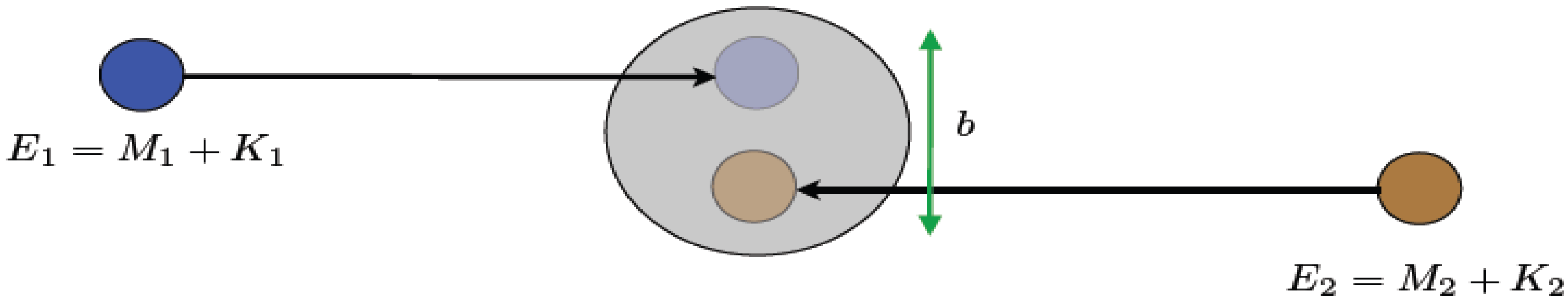
"Classicality" condition: $R_{\mathrm{S}} \gg R_{\mathrm{C}} \implies M \gg M_{\mathrm{P}} \simeq 10^{19}\,\mathrm{GeV}$

Extra dimensions:

$M_* \simeq 1\,\mathrm{TeV}$

Black Holes can exist with mass: $M \gg 1\,\mathrm{TeV}$

Brane-world black holes production



- Black hole forms if:

$$b < \frac{E_1 + E_2}{M_{(5)}^2} \sim \frac{M}{M_{(5)}^2} \sim R_H$$

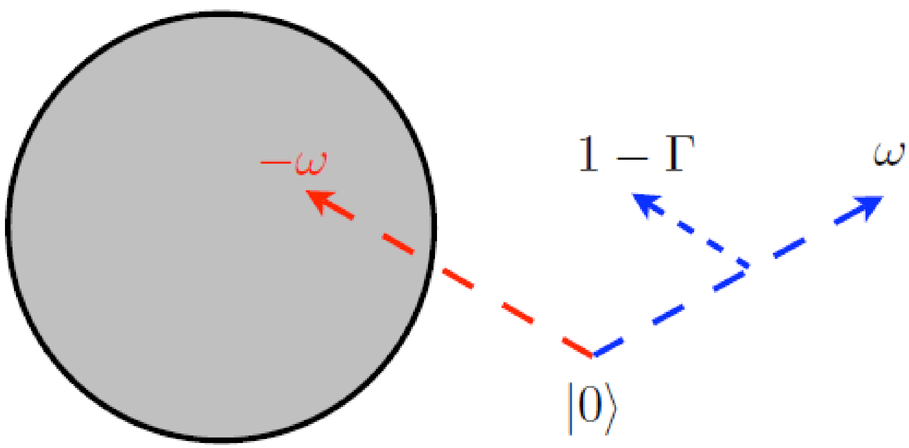
- 4D Cross section:

$$\sigma(E_1, E_2) \sim \pi R_H^2$$

- Numerically supported: H. Yoshino et al., Phys. Rev. D 71 (2005) 104028
- Numerical coefficients are model dependent!

Brane-world black holes. Evaporation

- Hawking evaporation $$\frac{dM}{d\tau} = -\mathcal{A}_{(D)} \sum_s \int_0^\infty \Gamma^{(s)}_{(D)}\, n^{(s)}_{(D)}\, \omega^{D-1}\, d\omega$$



- Grey body factors ➡ $\Gamma^{(s)}_{(D)}(\omega)$
- Horizon area ➡ $\mathcal{A}_{(D)}$
- # of available particles ➡ $n^{(s)}_{(D)}(\omega)$

- Area in 4 or D dimensions?
- Grey body factors?
- Canonical occupation # of particles?

$$n^{(s)}_{(D)}(\omega) = \frac{1}{e^{\beta\,\omega} \pm 1} \qquad \beta = \frac{1}{T_H} \sim R_H$$

Brane-world black holes. Evaporation

- Canonical ensemble:

$$n(\omega) \simeq \frac{1}{e^{\frac{M}{M_*^2}\omega} \pm 1}$$

Peak production at:

$$\omega \sim \frac{M_*^2}{M} \begin{cases} \ll M & \text{(astrophysical BH)} \\ \sim M & \text{(micro BH)} \end{cases}$$

Almost instantaneous decay by emision of a small number of particles!

$$n(\omega > M) > 0$$

→ Cutoff the integral at ω=M/2, or use the microcanonical # of particles!

Brane-world black holes. Evaporation

- Microcanonical # of particles.
  R. Casadio and B. Harms, Phys. Rev. D 58, 044014 (1998).

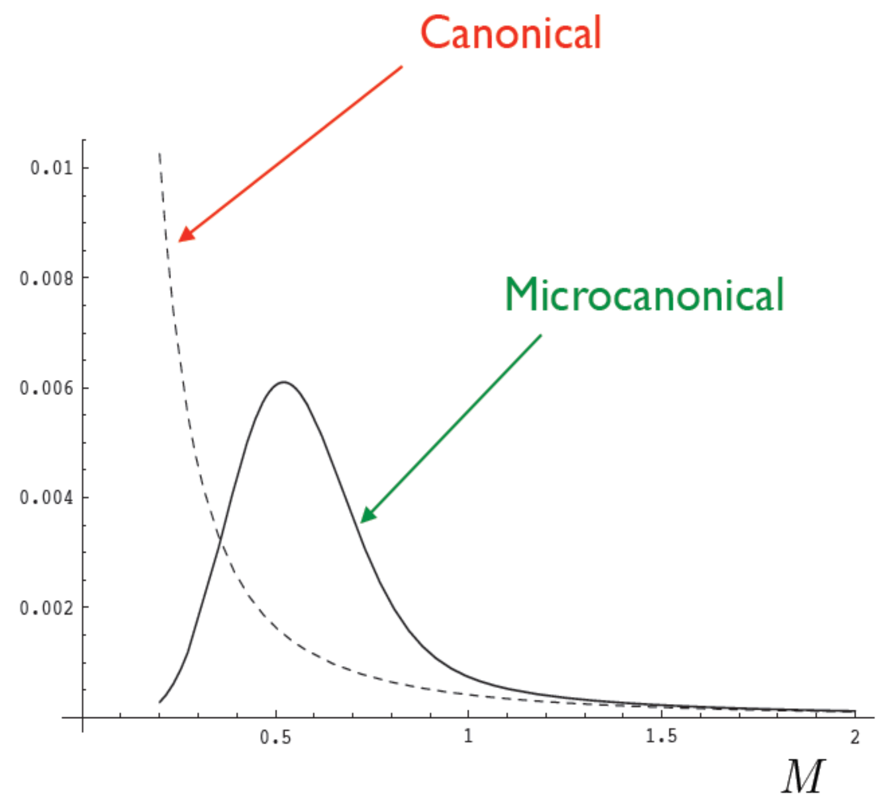
$$n(\omega) = B \sum_{n=1}^{[[M/\omega]]} \exp\left\{ \frac{S_{\mathrm{E}}(M - n\,\omega)}{\ell_{\mathrm{p}}\, M_{\mathrm{p}}} - \frac{S_{\mathrm{E}}(M)}{\ell_{\mathrm{p}}\, M_{\mathrm{p}}} \right\}$$

- S_E=Euclidean BH action
- $B \rightarrow$ deviations from area law

$$M \gg T_{\mathrm{H}} \sim \frac{M_{\mathrm{p}}^2}{M}$$

$$-\frac{dM}{d\tau} \simeq \frac{g_{\mathrm{eff}}\, M_{\mathrm{p}}^3}{960\,\pi\,\ell_{\mathrm{p}}\, M^2}$$

→ Hawking law



- *B*- determined using the large M limit!

Brane-world black holes. Accretion

- Subatomic accretion

$$\left.\frac{dM}{dt}\right|_{\rm acc} = \pi\, v\, \rho\, R_{\rm eff}^2$$

- v =Black hole velocity
- ρ =Medium average density
- $R_{\rm eff}$ =Rffective radius gravitaty overcomes EM force
- Black hole sweeps through matter and absorbs nuclei within capture radius

- Bondi accretion

- Black hole at rest absorbs nuclei with thermal velocity smaller than escape velocity
- Effective if

$$R_{\rm eff} \simeq 1\,\text{Å}$$

- Much more efficient!

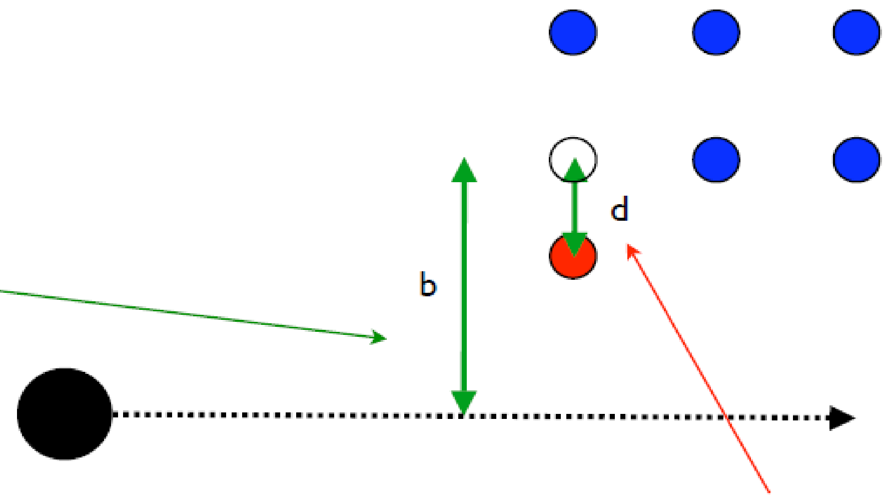
Please not on Earth!

Brane-world black holes. Accretion

- Newtonian capture radius

$$V_{\mathrm{G}} = \frac{1 - g_{tt}}{2} = \frac{1 + A}{2}$$

$$F_{\mathrm{G}} = - \left.\frac{\partial V_{\mathrm{G}}}{\partial r}\right|_{r=b-d}$$



$$F_{\mathrm{EM}} = -K\,d$$

Maximise $F_{\mathrm{EM}} = F_{\mathrm{G}}$ in d at fixed b

b

↓

R_{eff} = EM capture radius $(\gg R_{\mathrm{H}})$

Brane-world black holes. Time evolution

- Time evolution: subatomic accretion + evaporation

$$\begin{cases} \dfrac{dM}{dt} = \left.\dfrac{dM}{dt}\right|_{\rm acc} + \left.\dfrac{dM}{dt}\right|_{\rm evap} \\ \\ \dfrac{dp}{dt} = \dfrac{p}{M} \left.\dfrac{dM}{dt}\right|_{\rm evap} \end{cases}$$

- Check that we are not within Bondi accretion regime!

Brane world basics

L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 4690 (1999)
N. Dadhich, R. Maartens, P. Papadopoulos and V. Rezania, Phys. Lett. B **487**, 1 (2000)

- RS Metric:

$$\mathrm{d}s^2 = e^{-|y|/\ell} g_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu + \mathrm{d}y^2$$

Vary fundamental gravity scale! $M_{(5)}^3 \sim \kappa M_\mathrm{p}^2$

Newton law modifications in the range $M_{(5)} \simeq M_{ew} \simeq 1TeV$

5D Einstein equations → project on the brane → 4D effective metric

Tidal-charged black holes ← → other metrics

$$\mathrm{d}s^2 = -A\,\mathrm{d}t^2 + A^{-1}\,\mathrm{d}r^2 + r^2\left(\mathrm{d}\theta^2 + \sin(\theta)^2\,\mathrm{d}\phi^2\right)$$

$$A = 1 - \frac{2\,\ell_\mathrm{p}\,M}{M_\mathrm{p}\,r} - q\,\frac{M_\mathrm{p}^2\,\ell_\mathrm{p}^2}{M_{(5)}^2\,r^2}$$

Brane-world black hole metrics

R. Casadio, S. Fabi, B. Harms, O. Micu, JHEP **1002:097,** 2010. arXiv: 0911.1884.
R. Casadio, B. Harms, O. Micu, arXiv: 1003.2572.

Tidal black holes:

$$A = 1 - \frac{2\,\ell_{\rm p}\,M}{M_{\rm p}\,r} - q\,\frac{M_{\rm p}^2\,\ell_{\rm p}^2}{M_{(5)}^2\,r^2}$$

tidal charge parametrization

$$q \simeq \left(\frac{M_{\rm p}}{M_{(5)}}\right)^{\alpha}\left(\frac{M}{M_{(5)}}\right)^{\beta}$$

$$\beta > 0$$

Restrictions on the parameters:

- correct limiting cases,
- tidal term >> usual GR term
- black holes are 5 dimensional (the horizon radius is smaller than the length scale at which corrections to Newton's law have not been detected)
- condition of classicality.

Tidal charged black holes time evolution

Rapidly decaying solutions:

$0<\beta<1$ & $1.25<\beta$

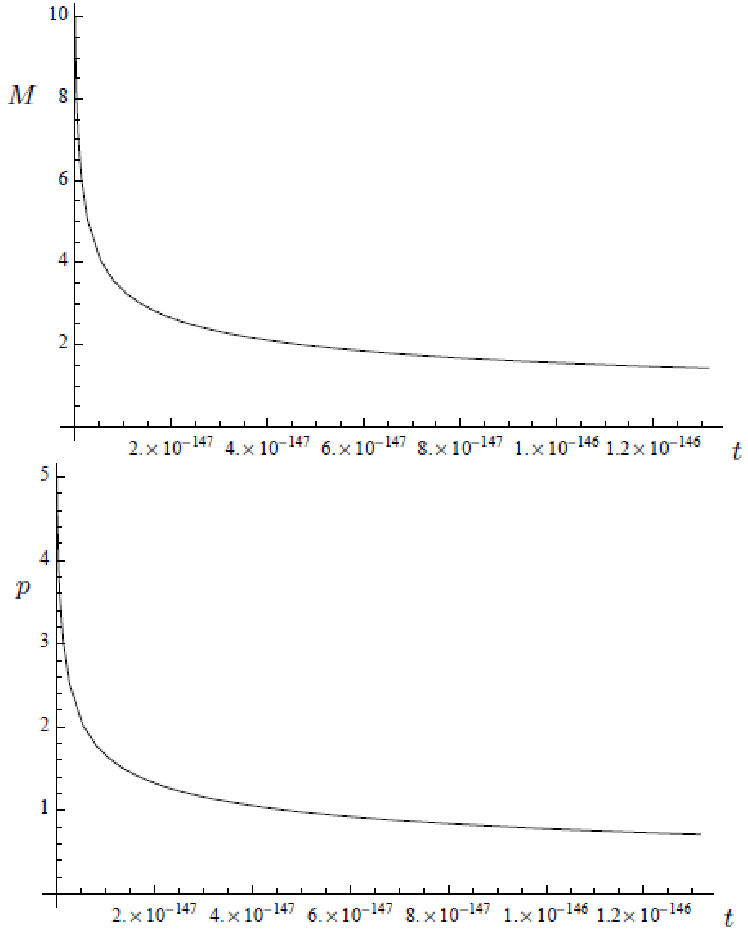


FIG. 3: Mass (in TeV/c^2) and momentum (in TeV/c) for $L = 1\,\mu\mathrm{m}$, $\beta = 0.5$, $\alpha = -1.5$, $M(0) = 10\,\mathrm{TeV}/c^2$ and $p(0) = 5\,\mathrm{TeV}/c$.

Growing solutions:

$1<\beta<1.25$

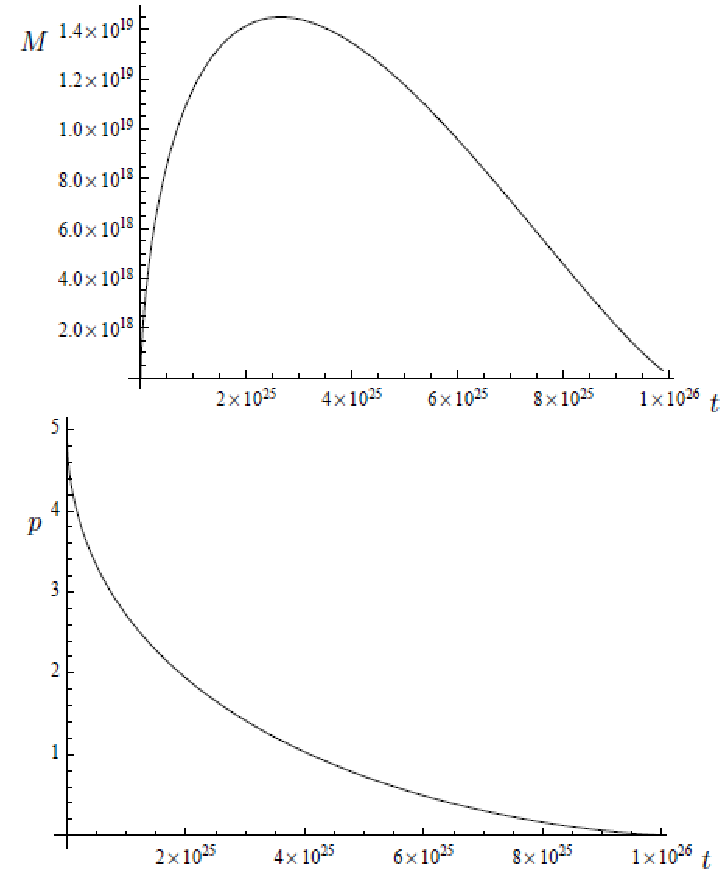


FIG. 4: Mass (in TeV/c^2) and momentum (in TeV/c) for $L = 44\,\mu\mathrm{m}$, $\beta = 1.25$, $\alpha = -1.8$, $M(0) = 10\,\mathrm{TeV}/c^2$ and $p(0) = 5\,\mathrm{TeV}/c$.

Tidal charged black holes time evolution

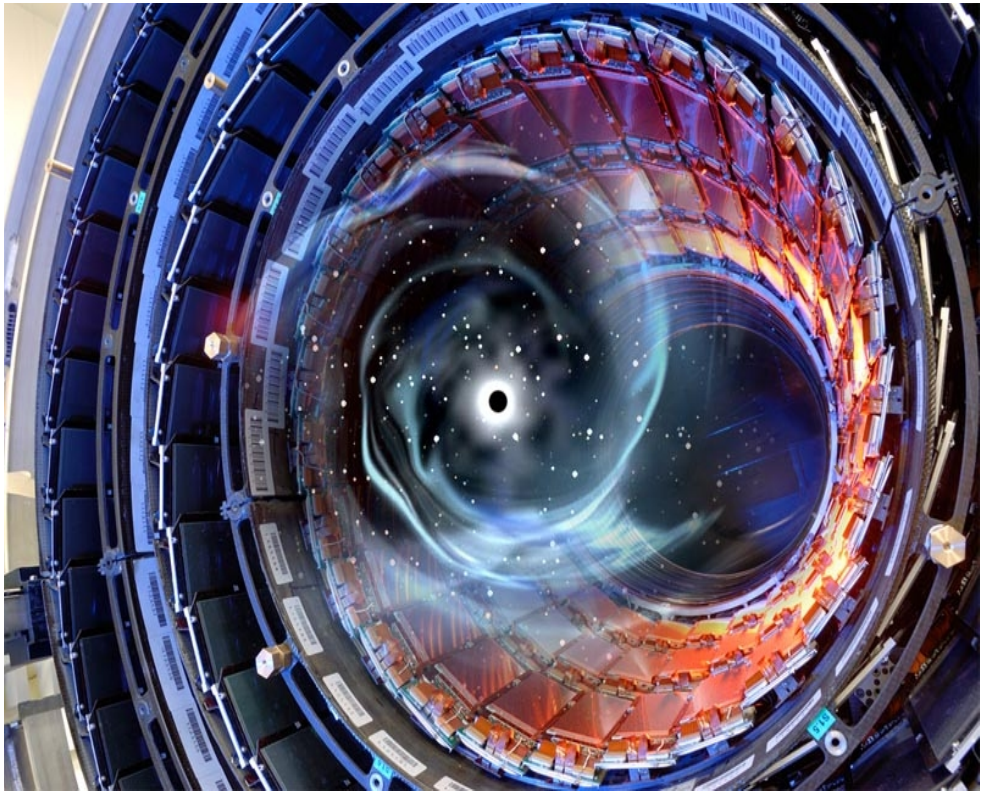
- Timevolution for black holes which are trapped within the Earth.

L (μm)	α	M_c (TeV/c^2)	$dM/dt\|_{t=0}$	M (kg)	R_{EM} (m)	R_H (m)
44	-1.44	$2 \cdot 10^{53}$	$2.8 \cdot 10^{-2}$	$4.0 \cdot 10^{-13}$	$1.3 \cdot 10^{-14}$	$9.0 \cdot 10^{-25}$
5.0	-1.50	$4 \cdot 10^{53}$	$1.1 \cdot 10^{-2}$	$1.9 \cdot 10^{-13}$	$6.5 \cdot 10^{-15}$	$2.0 \cdot 10^{-25}$
$1.0 \cdot 10^{-1}$	1.59	$1 \cdot 10^{51}$	$1.3 \cdot 10^{-3}$	$5.3 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$1.8 \cdot 10^{-26}$
$1.0 \cdot 10^{-2}$	-1.67	$1 \cdot 10^{54}$	$4.5 \cdot 10^{-4}$	$2.4 \cdot 10^{-14}$	$8.1 \cdot 10^{-16}$	$2.7 \cdot 10^{-27}$

TABLE V: Time evolution of black hole mass with critical mass M_c near upper bound for time equal to approximative age of the Universe and $\beta = 1.1$. Initial conditions are: $M(0) = 11\,\mathrm{TeV}/c^2$ and $p(0) = 0.0001\,\mathrm{TeV}/c$.

- Momentum is kept small enough so that the velocity is smaller than the escape velocity.
- Maximum atainable mass is obtained when parameters have such values that M_c is near its maximum allowed value $M_{\odot}$.
- The mass evolution is evaluated for 10^{18} s (a time equal to the present age of the universe from BH creation into the future).
- Maximum mass after that time is ~10^{-13} kg and horizon radius ~10^{-25}m.

Conclusions



Artistic view of a BH in the LHC detector, from Discovery news article „Man made (but very tiny) black holes possible!“ based on:

R. Casadio, S. Fabi, B. Harms, O. Micu; JHEP **1002:097,** 2010.

- Tidal charged BHs @ the LHC are possible in the RS scenario.
- BHs can decay instantly or be long lived and can escape from the detectors as missing energy.
- a) BHs with large initial momentum, escape the Earth and accretion turns off!
- b) BHs with small enough momentum be trapped in the Earth, mass still insignificant within 10^7 years.
- a) & b) => Doomsday will not happen because of BHs created @ LHC!
- One should take missing energy due to BHs production into account when analysing the LHC data!