Universita' degli Studi di Napoli Federico II, 16.April 2010

Black Holes on Branes: their creation on colliders

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I. What kind of worlds are suitable to generate mini black holes (BH) and what to make them of?

II. If the suitable Worlds are higher-dimensional then what type of BH one can expect to detect?

III. Where do mini BH disappear? What are decay remnants?

IV. Subtleties!

Static Black Holes in our 3+1 world

$$ds^2 = U(r)dt^2 - \frac{1}{U(r)}dr^2 - r^2 d\Omega_2^2$$

Area gauge

Black Hole when its mass inside its horizon

$$U(r_h) = 0$$

Schwarzschild (1916)

$$U_{Sch}(r) = 1 - \frac{2G_N M}{r} \qquad 2G_N M = \frac{2M}{M_{Pl}^2} \equiv r_g$$

It gives the exact Newton law for gravitational potential g_{00}

First implications on

J. Michell, Phil. Trans. Roy. Soc., 74 (1784) 35-74
P.-S. Marquis de Laplace, Exposition du syst`eme du Monde, 1796.

An object of mass m propelled vertically upwards (with velocity v) from the surface of a mass M with radius r can only escape from the gravitational pull if

$$\frac{1}{2}mv^2 > \frac{GMm}{r}\,. \tag{3.1}$$

If r decreases, v must be larger if the object is to escape. The radius at which escape is only just possible even if travelling at the speed of light is found by setting $v = c$. Hence we obtain

$$r = \frac{2GM}{c^2}\,, \tag{3.2}$$

exactly as Schwarzschild derived using the later relativistic theory.

Reissner-N”ordstrom (1916)

$$U_{R-N}(r) = 1 - \frac{2G_N M}{r} + \frac{G_N Q^2}{r^2} \qquad r_g = G_N M\left(1 \pm \sqrt{1 - \frac{Q^2 M_{Pl}^2}{M^2}}\right)$$

For particles/partons

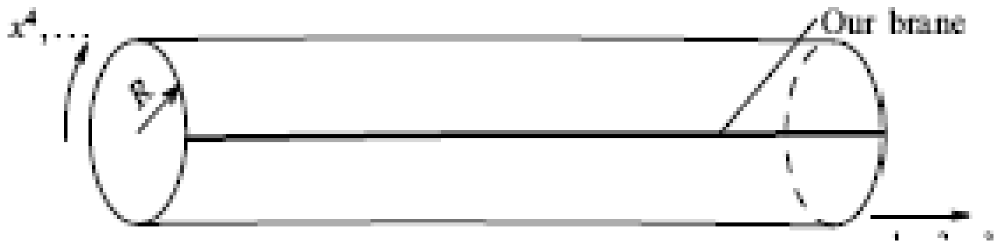
$$M \sim 1GeV \qquad Q^2 \sim e^2 \sim 0.1 \qquad \frac{M^2}{M_{Pl}^2} \sim 10^{-38} \lll Q^2 \Rightarrow \boxed{U_{R-N}(r) \neq 0}$$

No horizon in 3+1 ! **No BH description for SM hadrons**

Extra dimensions

And how to realize?

- Extra dimensions may be small, compact to stay invisible: gravity background – curvature of extra-dim space, may be not essential.



- On a torus: Fourier expansion, tower of massive KK states for graviton

$$m^2_{KK} = {}^{(4)}p^2 \equiv \omega^2 - {}^{(3)}\mathbf{p}^2 = \frac{\mathbf{n}^2}{R^2} .$$

- Gravity in the bulk but matter on a brane at a point in extra dim.

Size of extra dimensions

Planck scale transmutation due to large volume of extra dimensions

$M_{Pl}^2 = 8\pi \bar{M}_{Pl}^2$ $\qquad$ $\bar{M}_{Pl}^2 = M_*^{n+2}(2\pi R)^n$ $\qquad$ $M_{Pl} \simeq 10^{16} TeV \Rightarrow M_* \simeq 1 TeV$

Gravity - in 4 dim and in (4+n) dim

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n = 1

$R \sim 10^{15}$ cm;

No!

n = 2

$R \sim 0.1$ cm

No!

Table-top exp.!

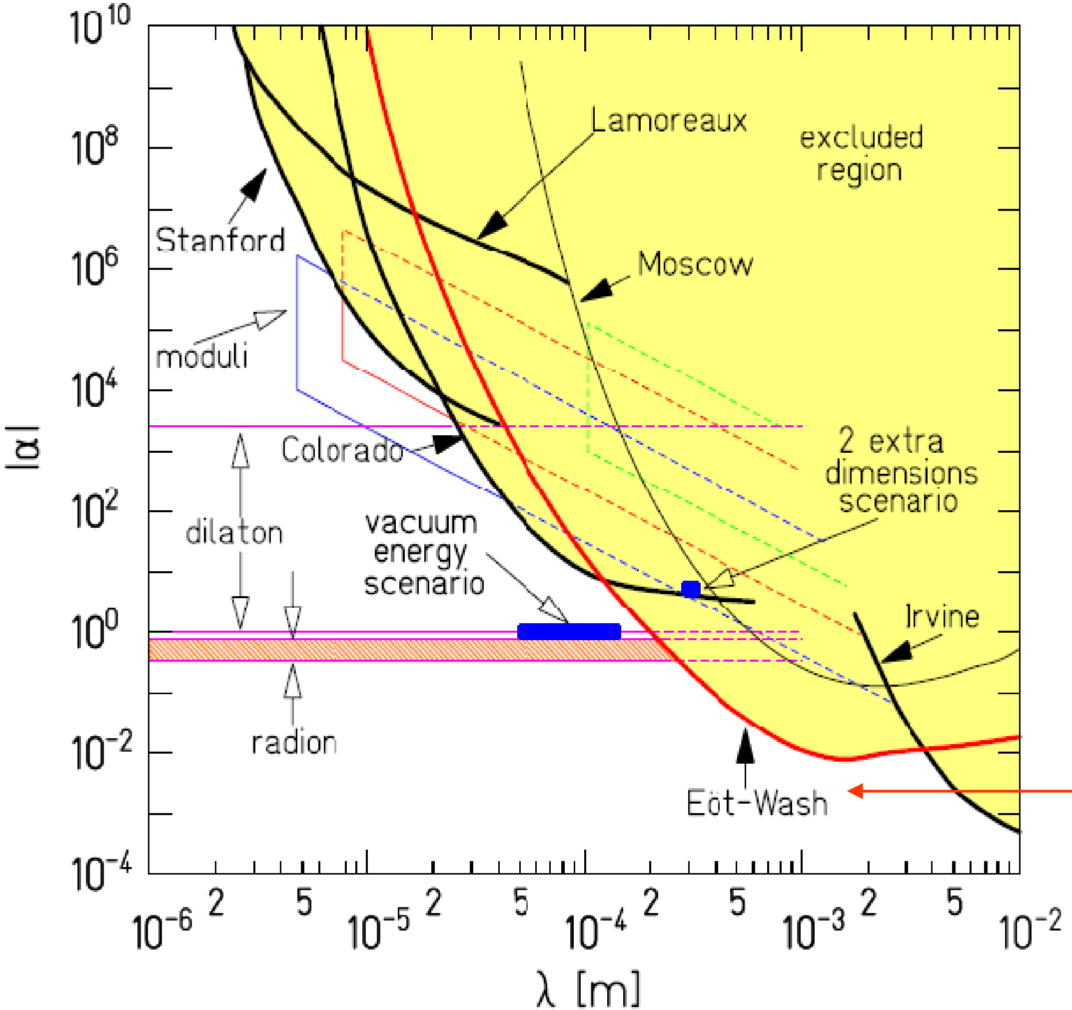
Modified Newton law

n = 1

$$V(\vec{x}) = \begin{cases} -\frac{4}{3}\frac{G_N M}{r}, & r \gg R; \\ -\frac{M}{6\pi^2 M_*^3 r^2}, & r \ll R. \end{cases}$$

$$n > 1 \qquad V(r) \sim \int d^{3+n}q \frac{M}{M^{2+n}q^2} \sim -\frac{M}{M^{2+n}r^{n+1}} \qquad r \ll R$$

- Spectrum of KK gravitons $\longrightarrow$ modification of the Newton law at short distances

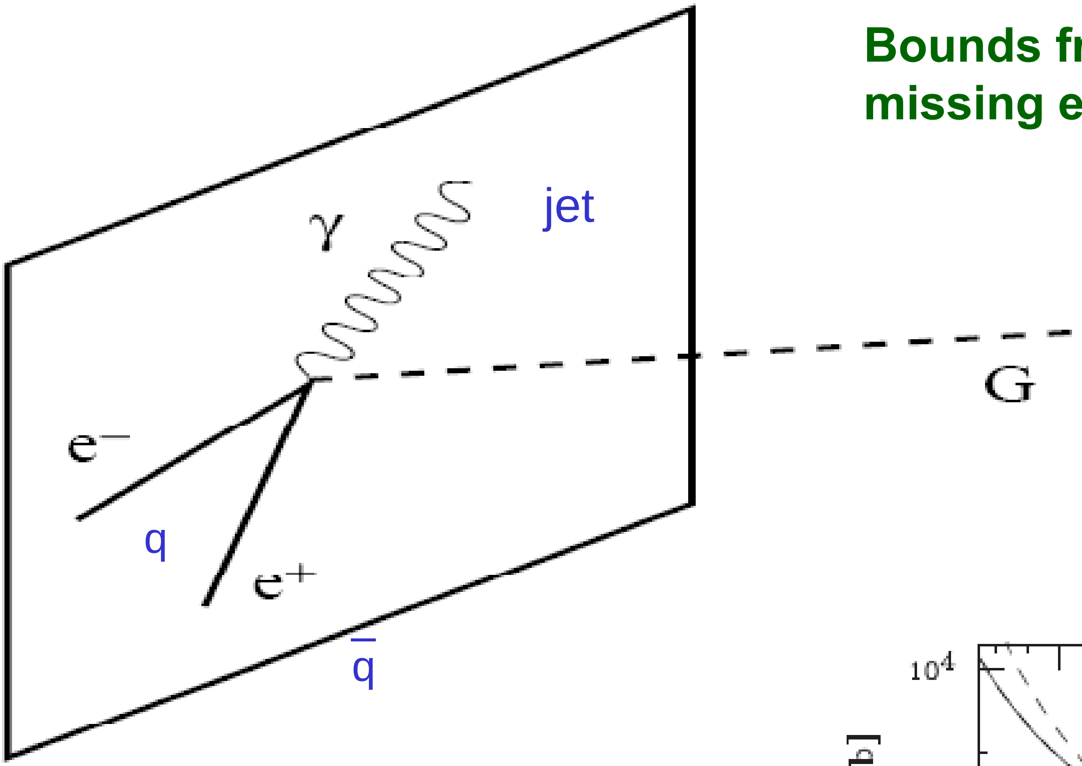


$$V(r) = -\frac{G_N m}{r}\left(1 + \alpha\, e^{-\frac{r}{\lambda}}\right)$$

$$\boxed{\lambda < 10\mu m\,(95\%CL)}$$

Regions in the $\alpha - \lambda$ plane excluded by table top searches for deviations from Newtonian gravity

Bounds from collider physics: missing energy events

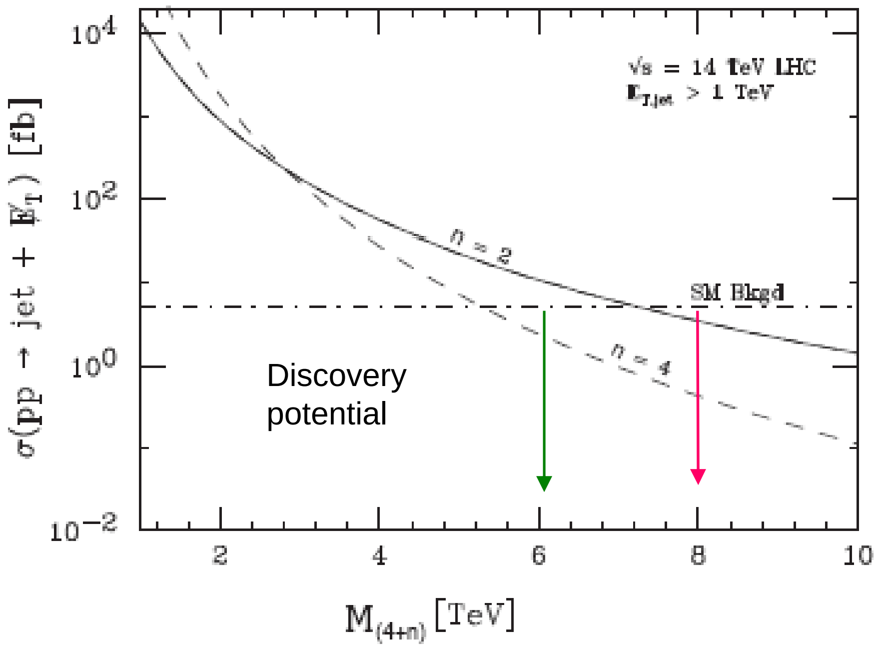


graviton

$$\sigma(e^+e^- \to \gamma + \not{E}_T) \sim \frac{\alpha}{M_{Pl}^2} N(E) \sim \frac{\alpha}{E^2}\left(\frac{E}{M}\right)^{n+2}$$

$$q\bar{q} \to \text{jet} + \not{E}_T,$$

$N(E)$ is the number of KK gravitons with masses below E



Search for Large Extra Dimensions in the Production of Jets and Missing Transverse Energy in p¯p Collisions at √s = 1.96 TeV

KK scenario

$$\bar{M}_{Pl}^2 = M_*^{n+2}(2\pi R)^n$$

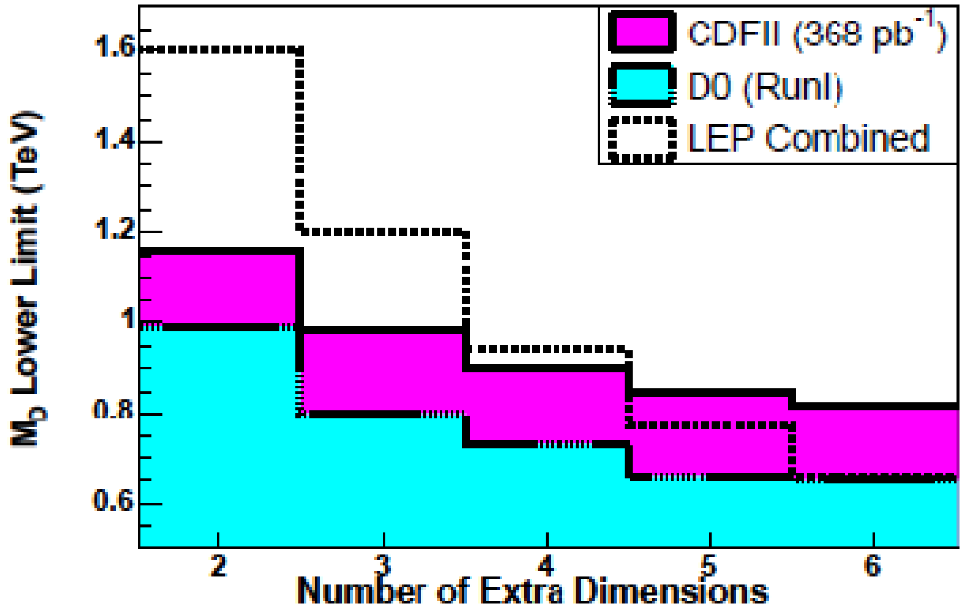


FIG. 3: Comparison of 95% CL lower limits on M_D based on the Run II CDF and Run I DØ results with LEP combined results.

CDF Collaboration Phys.Rev.Lett.97:171802,2006

Search for Large Extra Dimensions via Single Photon plus Missing Energy Final States at sqrt(s) = 1.96 TeV

KK scenario

$$\bar{M}_{Pl}^2 = M_*^{n+2}(2\pi R)^n$$

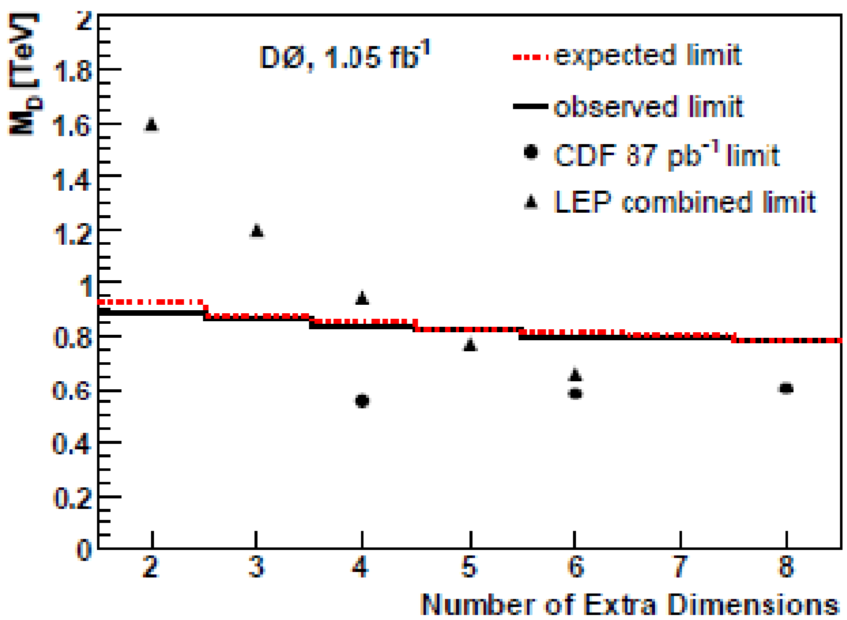
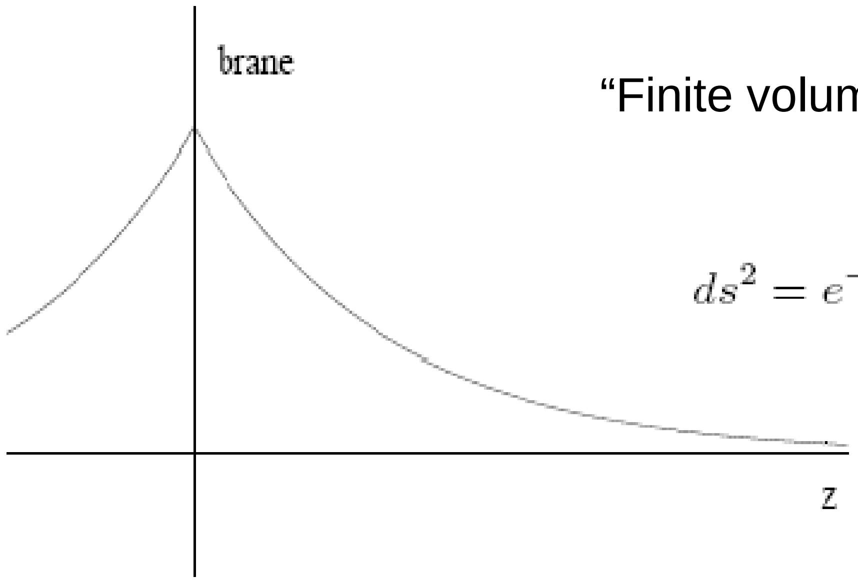


FIG. 3: Expected and observed lower limits on M_D for LED in the $\gamma + \not{E}_T$ final state. CDF limits with 87 pb^{-1} of data [3], and the LEP combined limits [6] are also shown.

D0 Collaboration Phys.Rev.Lett.101:011601,2008

One brane + gravity in the bulk

<u>L.Randall and R.Sundrum (II)</u>



"Finite volume of extra dimensions" $\sim$1/k

$$ds^2 = e^{-2k|y|}[\eta_{\mu\nu} + h_{\mu\nu}(x)]dx^\mu dx^\nu - dy^2$$

Modified Newton law

Massless graviton is localized around the brane!

KK gravitons form continuum spectrum

$$V(\bar{x}) = \begin{cases} -\frac{G_N M}{r}\left(1 + \frac{2}{3k^2r^2} + \mathcal{O}(1/r^3)\right), & r \gg 1/k; \\ -\frac{M}{6\pi^2 M_*^3 r^2}, & r \ll 1/k. \end{cases}$$

Exp.

$$k > 0.02eV \simeq 1/10\mu m$$

Black Hole metric? U(r) = 1+ 2 V(r)

Synthesis of KK and RSI

Low energy supergravity $AdS_5 \times S^{(5)}$

For an easy estimation $S^{(5)} \rightarrow T^{(5)} = \left[\times S^{(1)} \right]^5$

$$M_*^8 \cdot L^5 \frac{1}{k} = M_{Pl}^2; \quad \longrightarrow \quad L = \sqrt[5]{\frac{M_{Pl}^2 \cdot k}{M_*^8}} < 1\mathrm{fm}$$

if $M_* \sim 1TeV$ $\quad k > 0,02eV$ $\quad M_{Pl} = 10^{16}TeV$

Higher-dimensional Black Holes

Static BH $$ds^2 = U(r)dt^2 - \frac{1}{U(r)}dr^2 - r^2 d\Omega_{n-1}^2$$

Schwarzschild-Tangherlini $$\boxed{U_{Sch-Tan}(r) = 1 - \frac{r_g^{n+1}}{r^{n+1}}}$$

$$r_g = \frac{1}{\sqrt{\pi} M_*} \left(\frac{8\Gamma(\frac{n+3}{2})}{(n+2)} \frac{M}{M_*} \right)^{1/(n+1)} \Bigg|_{n=(1,...7)} \leq \frac{1}{M_*} \left(\frac{M}{M_*} \right)^{1/(n+1)}$$

Evidently for any particles with masses $M < M_* \sim 1TeV$

their horizon is less than the Plank scale $r_g < 1/M_*$

Therefore SM particles by no means can be considered as classical BH, their apparent horizons can be only treated in Quantum Gravity approach

Only the objects with $M \gg M_* \sim 1TeV$ $r_g \gg 1/M_*$

can be considered as true classical black holes: **M > 3-5 TeV?**

From bulk to brane

If the matter is located on a brane then the Sch.-Tan. metric is generated by a point-like particle at r = 0 whereas we want to deal with matter distribution on the brane to proceed to 3+1 dim world

Let's introduce cylindrical coordinates $r, \theta \to \rho = r\cos\theta,\ z = r\sin\theta$

Does it exist a matter distribution which provides the interpolation of a section of S-T geometry at z = 0 at intermediate distances to asymptotical Reisner-N"ordstrom geometry?

$$U_{brane}(\rho, z=0)\Big|_{\rho \gg r_g} \overset{?}{\simeq} 1 - \frac{2G_N M}{\rho} + \frac{G_N Q^2}{\rho^2} - \frac{r_g^{n+1}}{\rho^{n+1}}$$

This conjecture has not yet been justified by any proof !
But for Q = 0!? N. Dadhich et al. 2000 ??

Anyways the last "tidal" term will certainly dominate over R-N one even for n= 1 and for $M \gg M_* \sim 1TeV$

could trigger black hole formation

BLACK HOLE PRODUCTION

- BH forms if the impact parameter *b* is comparable to the Schwarzschild radius r_s of a BH of mass *E*.

- The Thorn's hoop conjecture gives a rough estimate for classical geometrical cross-section

$$\sigma(1+1 \to \mathrm{BH}) \sim \pi\ r_S^2$$

$$r_S^2 \sim \frac{M_{BH}}{M_D^2}$$

Hoop conjecture and trapped surface

According the D-dimensional version of this conjecture if a total amount of matter mass M is compressed into a spherical region of radius R, a black hole will form if R is less than the corresponding Schwarzschild radius

$$R < R_{S,D}(E) = \left(\Omega_n \frac{G_D E}{c^4}\right)^{\frac{1}{n+1}},$$

D = 4 +n total dimension

the trapped surfaces do form when $b \lesssim R_{S,D}$, and have the area of the order $\sim R^2_{S,D}$, where $R_{S,D}$ is the horizon radius given by (19) (see below).

Trapped surface

- A trapped surface is a two dimensional spacelike surface whose two null normals have zero convergence (Neighbouring light rays, normal to the surface, must move towards one another)

- **Th. (Hawking-Penrose)** A spacetime $(M; g)$ with a complete future null infinity which contains a closed trapped surface must contain a future event horizon, the interior of which contains the trapped surface

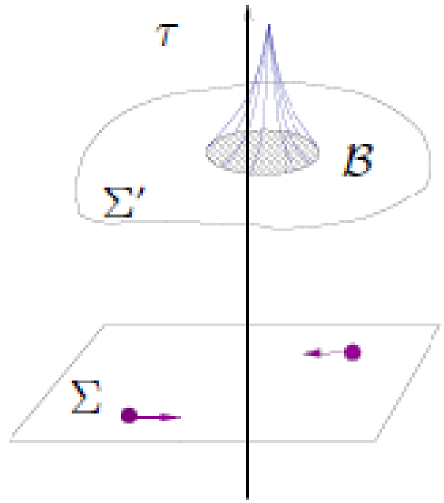
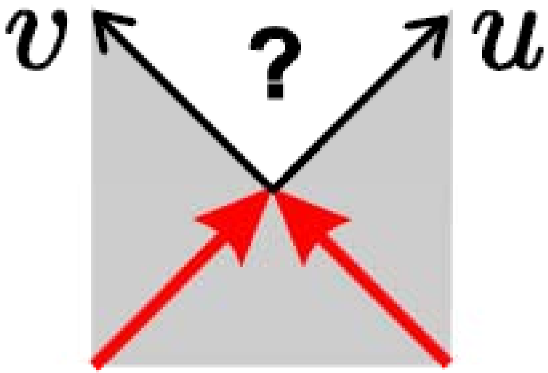
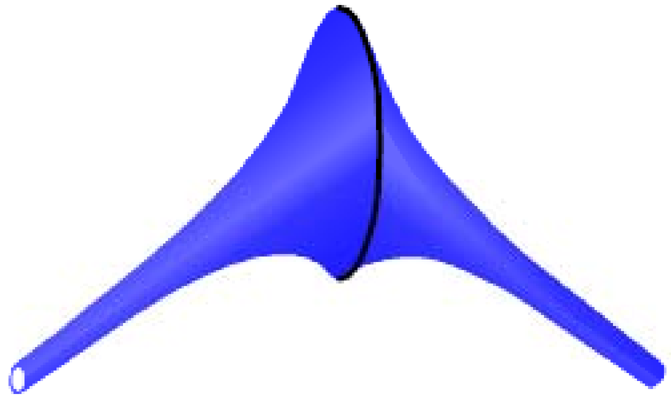


Figure 2: A slice Σ at $\tau = t$ is an initial slice with particles and a slice Σ' at $\tau = t'$ is a slice with a black hole $\mathcal{B}$. Null geodesics started from the shaded region do not reach null infinity.

Shock waves,

Penrose, D'Eath, Eardley, Giddings, …





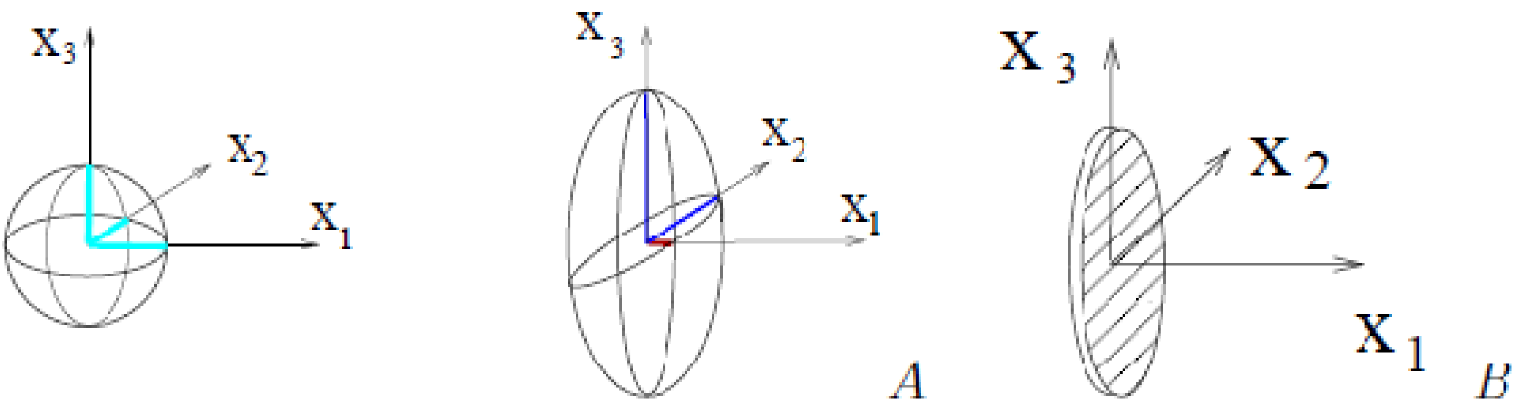
Classical geometric cross-section $\sigma \propto \pi r_s^2$

$$b \leq r_S \propto E^{1/D-3}$$

$$D = 7 \quad \sigma \propto 100\, pb$$

Boosting to shock waves

large Lorentz boost factor $\gamma = 1/\sqrt{1 - v^2/c^2}$.



Aichelburg-Sexl (AS) metric

$$ds^2 = -2dUdV + dX_i^2 + F(X)\delta(U)dU^2,$$

i = 2,3,…n+2

$$V = (X^0 + X^1)/\sqrt{2},\ U = (X^0 - X^1)/\sqrt{2}.$$

take $m \to 0$ and hold p fixed,

Green function of the $D-2$-dimensional Laplace equation

$$\Delta_{R^{D-2}} F = -\frac{2p\sqrt{2}}{M_{Pl}^{D-2}}\delta^{(D-2)}(X).$$

$$\boxed{F(X) = \frac{p2\sqrt{2}}{(D-4)\Omega M_{Pl,D}^{D-2}}\frac{1}{\rho^{D-4}}}$$

where $\rho^2 = (X^2)^2 + ...(X^{D-1})^2$. For D=4 the shape is

$$F(X) = -\frac{p\sqrt{2}}{\pi M_4^2}\ln\frac{\rho}{\varepsilon}$$

breaks down far away from the moving particle, more precisely at transverse distances from the source which are of the order of

$$\ell \sim r_h(m)/\sqrt{1-v^2}. \tag{17}$$

At these distances the field lines will spread out of the null transverse surface orthogonal to the direction of motion. But for $b << \ell$ one can use the shock wave field to extract the information about the black hole formation to the leading order in m/p. These

Thus commonly used evidence for black hole formation in collisions of particles comes from the study of the collision of two Aichelburg-Sexl shock waves. It is assumed that there is a solution interpolating between two shock waves and BH. However with this argument there is a problem that space time with a shock wave is not asymptotically flat. The AS metric has also a naked singularity at the origin which is an artifact of point-like mass distribution and does not appear for a boson star metric

Numerical evidence:
black holes do form at high velocities in boson star collisions

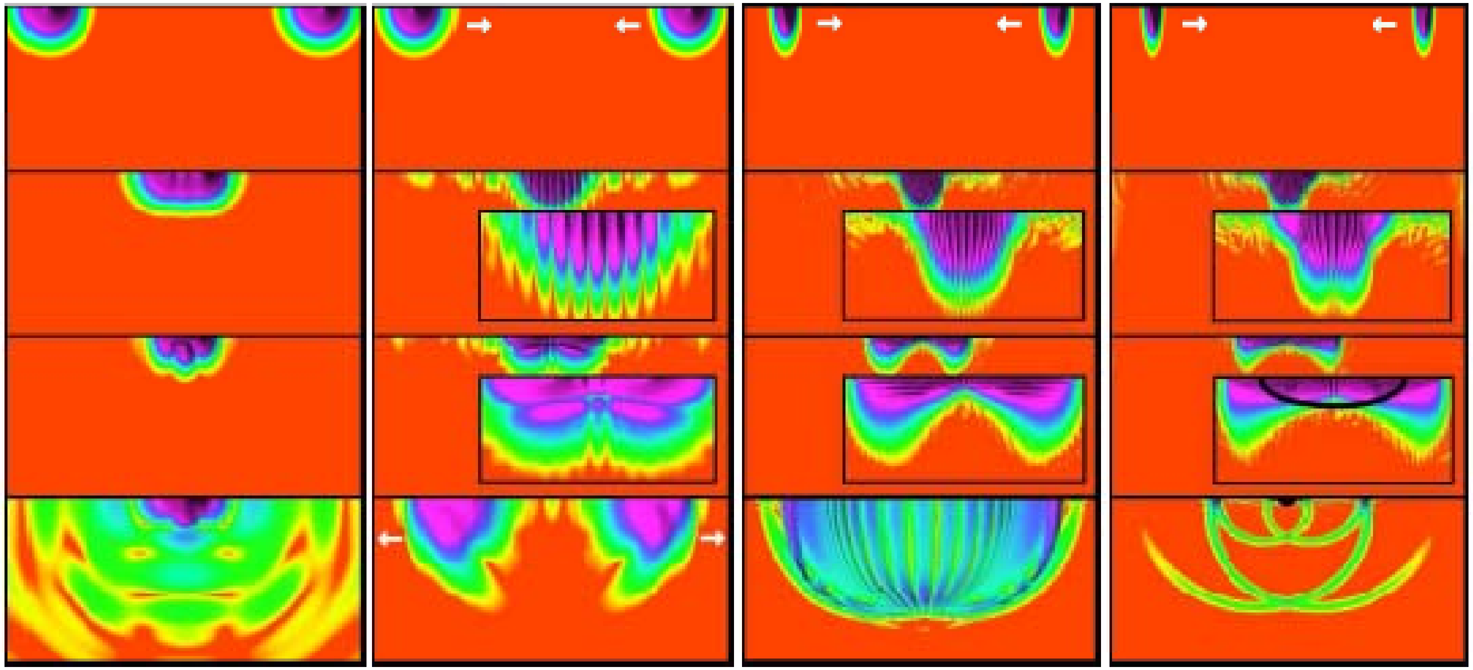


FIG. 1: The magnitude $|\phi|$ of the scalar field for collisions with $\gamma = 1, 1.15, 2.75$ and 4 (left to right). The axis of symmetry is coincident with the top edge of each panel. Four times are shown in each sequence ($t/M_0 = [0, 4390, 4500, 7480]$ for $\gamma = 1$, $[0, 254, 297, 469]$ for $\gamma = 1.15$, $[0, 141, 172, 313]$ for $\gamma = 2.75$ and $[0, 137, 168, 309]$ for $\gamma = 4$): the top panel is $t = 0$, the second panel down is when the boson stars first completely overlap, the third panel is shortly afterwards when $|\phi|$ reaches a first local maximum due to gravitational focusing, and the fourth panel is at a late time after the collision. The insets, where present, are zoom-ins of the central interaction regions. For the $\gamma = 4$ case, a black hole forms near the time of panel 3—the black line in the corresponding inset shows the shape of the apparent horizon then. In the fourth panel of this figure, the black semi-circle is the excised region inside the black hole; the small size of this compared to the apparent horizon in the previous figure is a coordinate effect—the proper area of the horizon grows with time.

Matthew W. Choptuik[1] and Frans Pretorius[2] **arXiv:0908.1780**

BH creation in PP collisions: parton picture

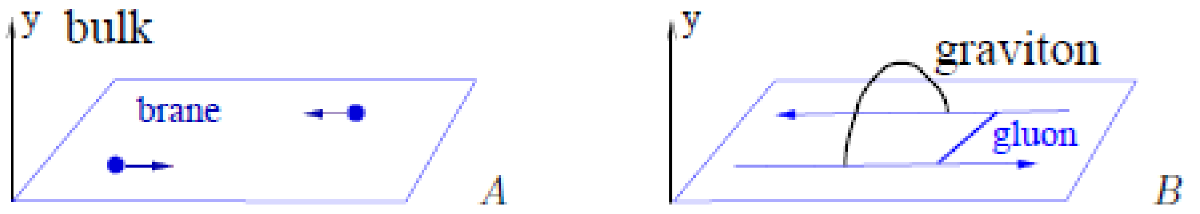


Figure 1: A. Colliding particles on the brane. B. D-dimensional graviton and 4-dimensional gluon exchanges.

$$\sqrt{s} >> E_{Pl}, \qquad l_B = \frac{\hbar c}{E} \quad << \quad r_g < 1/M_*$$

Parton collisions may produce BH assisted by their shock waves (not nucleon neither heavy ion collisions as a whole)

$$\sigma_{pp\to BH}(s,n) = \sum_{ij} \int_0^1 2z dz \int_{x_m}^1 dx \int_x^1 \frac{dx'}{x'} f_i(x',Q) f_j(x/x',Q)\, F\, \sigma_{BD}(xs,n)\,, \qquad (1)$$

where $f_i(\cdot, Q)$ are the PDFs with four-momentum transfer squared Q [20, 21] and z is the impact parameter normalized to its maximum value. The cutoff at small x is $x_m = M_{min}^2/(sy^2(z))$, where $y(z)$ and M_{min} are the fraction of CM energy trapped into the BH and the minimum-allowed mass of the gravitational object, respectively. F is a form factor. The total cross section for the BD model is obtained by setting $F = 1$ and $y^2(z) = 1$. The momentum transfer is usually set to be M_{BH}

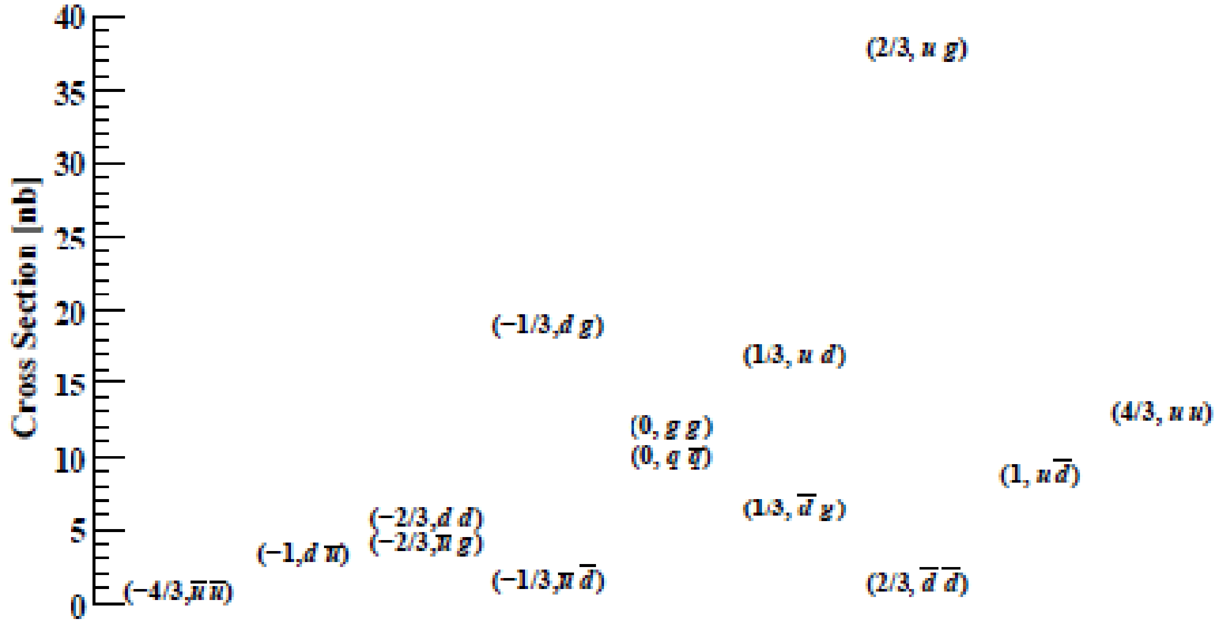


Figure 1: Cross section spectrum for quantum black holes of different electric charge and parton progenitors.

Douglas M. Gingrich :0912.0826

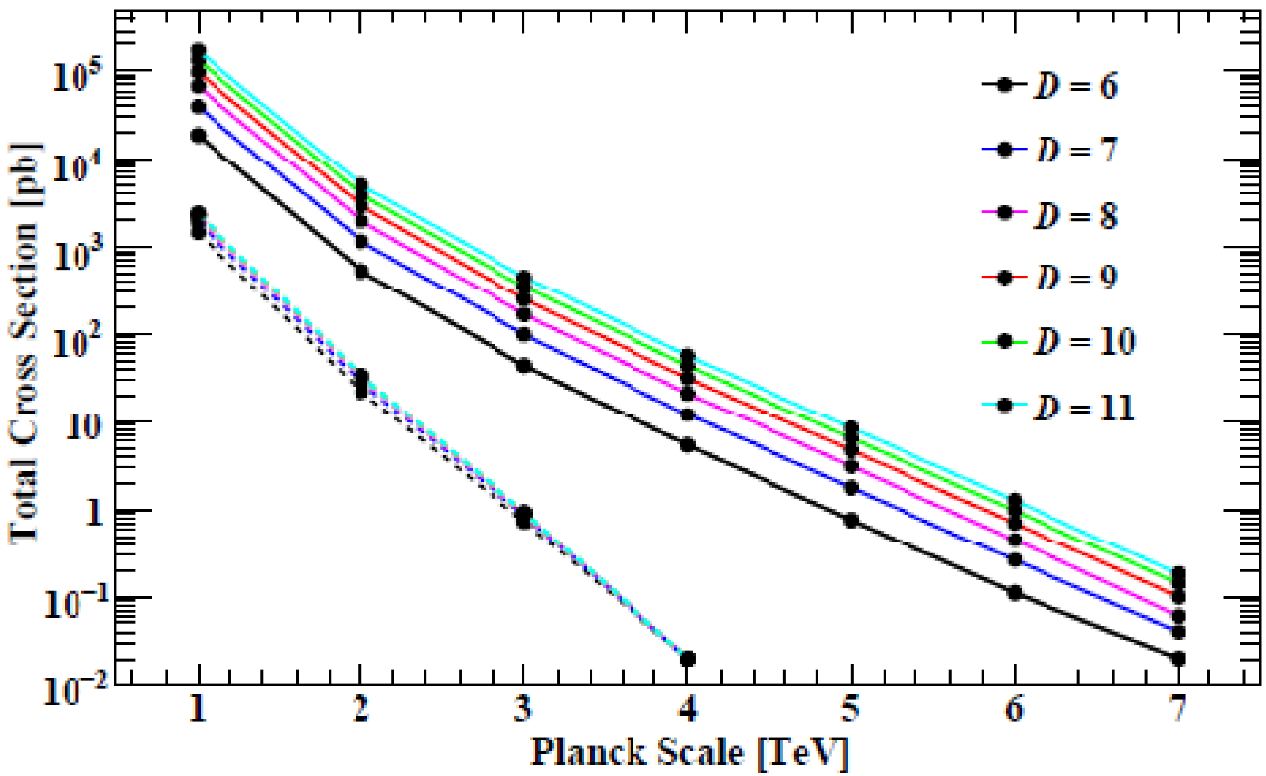


Figure 2: Total proton-proton cross section for different number of dimensions D and different fundamental Planck scales. The solid lines are totally inelastic cross sections and the dashed lines are trapped surface cross sections.

Balding phase. When first formed, the black hole is very asymmetrical – both its gravitational and other fields have very high multipole moments. However, a stationary black hole has no "hair" – that is, to become stationary, the black hole must shed its higher multipole moments through a process termed *balding*. In the $E \gg M_D$ limit, this is an essentially classical process, which takes place on a characteristic time scale . $t \sim R_S$.. At the same time, the black hole should shed any charges carried by particles with large charge to mass ratios, through an analog of the Schwinger process; this is expected to include color and electric charge.

Spindown phase. After balding the black hole is classically stable, but as predicted by Hawking, will continue to decay quantum-mechanically. A rotating black hole first decays by preferentially shedding its angular momentum, in *spindown*.

A basic parameter for higher dimensional black holes is the evaporation time scale

$$t_H \sim M_D^{-1}(E/M_D)^{(D-1)/(D-3)} \ . \qquad ($$

Remark

The **no-hair theorem** postulates that all black hole solutions of the Einstein-Maxwell equations of gravitation and electromagnetism in general relativity can be completely characterized by only three *externally* observable classical parameters: mass, electric charge, and angular momentum. All other information (for which "hair" is a metaphor) about the matter which formed a black hole or is falling into it, "disappears" behind the black-hole event horizon and is therefore permanently inaccessible to external observers

Black hole decay - evaporation

$$T_H = \frac{k}{2\pi} = \frac{1}{4\pi}\,\frac{1}{\sqrt{|g_{tt}\,g_{rr}|}}\left(\frac{d|g_{tt}|}{dr}\right)_{r=r_H} = \frac{(n+1)}{4\pi\, r_H}\,,$$

in terms of the black hole's surface gravity *k*

Table 2. Horizon radius and temperature of the Schwarzschild-Tangherlini black hole as a function of the number of extra dimensions, for $M_* = 1\,\mathrm{TeV}$ and $M_{BH} = 5\,\mathrm{TeV}$ [12]

n	1	2	3	4	5	6	7
r_H (10^{-4} fm)	4.06	2.63	2.22	2.07	2.00	1.99	1.99
T_H (GeV)	77	179	282	379	470	553	629

Schwarzschild phase. There has been greater focus on the details of this theoretically-simplest stage, where the black hole is non-rotating and decays via Hawking radiation. Power spectra, relative emission rates of different particle species, etc. are largely determined by the fact that such a black hole emits essentially thermally, at an instantaneous temperature determined by its mass:

$$T_H = \frac{D-3}{4\pi R_S} \propto M^{-1/(D-3)}$$

Planck phase. When the black hole reaches the mass scale $M \sim M_D$, all known physics breaks down and predictions cannot be made: this is the fully quantum gravitational realm. Conversely, to the extent to which we can see experimental signatures from this phase, we will learn about the dynamics of quantum gravity. This is thus the most interesting phase. One might in general expect emission of a few particles

The experimental signatures of BH decay:

a) Hadronic to leptonic activity of 5 : 1

b) High multiplicity

c) High sphericity

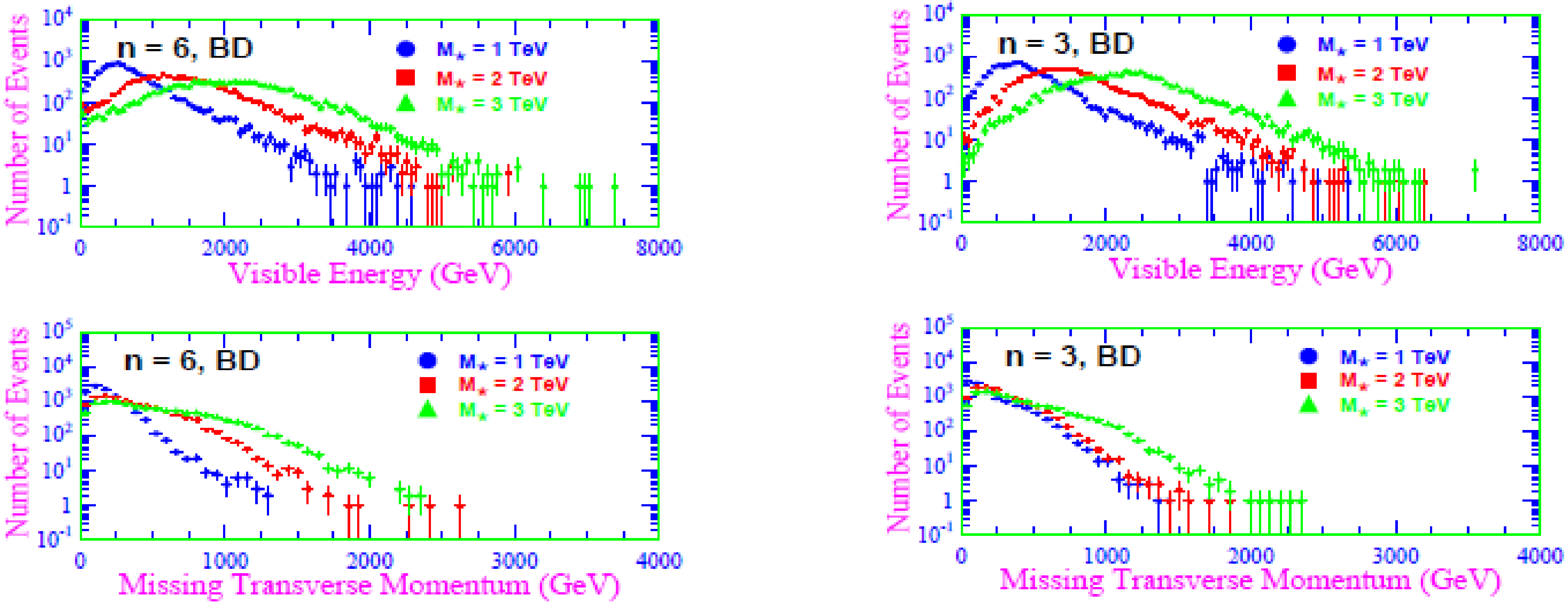
d) Visible transverse energy ~ 30% of the total energy

e) Emission of few hard visible quanta at the end of evaporation phase

f) Suppression of hard perturbative scattering processes

The CATFISH generator Fortran Monte Carlo generator

M.Cavaglia et al. 0707.0317



A handful of BH events shows a large amount of transverse momentum up to several TeV, depending on the value of the fundamental scale and the number of extra dimensions. In the absence of a BH remnant, this missing transverse momentum is due to the emission of gravitons and other invisible quanta (e.g. neutrinos) in the various evolutionary phases of the BH (formation,

The discovery reach for mini black holes with the ATLAS Detector at the LHC

ATL-PHYS-PROC-2009-024

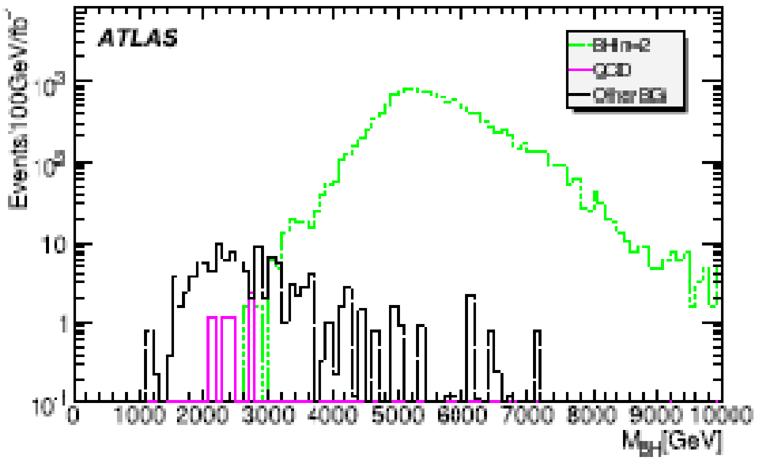


Figure 6: Reconstructed mass of black hole

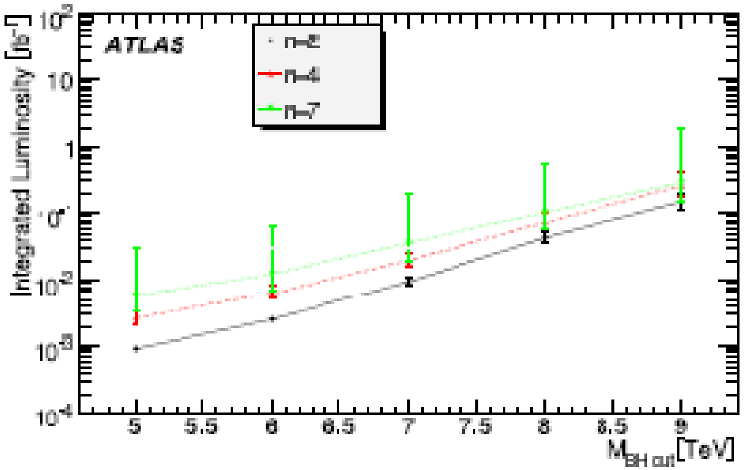


Figure 7: Discovery potential for black hole with the multi-object selection

only a few pb^{-1} are needed to discover black hole of minimum mass

of 5 TeV [for M_D = 1 TeV]. With 1 fb^{-1}, 8 TeV black holes could be discovered.

Subtleties

Bulk BH vs. Brane BH

Einstein 5

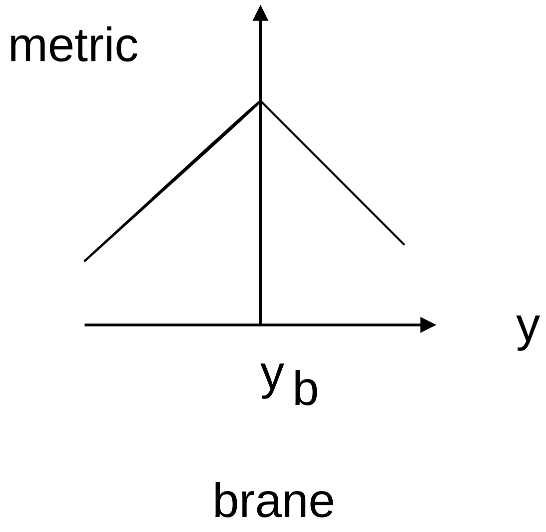
$$ {}^{(5)}G_{AB} = \frac{{}^{(5)}T_{AB}}{\kappa_5}; \Rightarrow {}^{(5)}R = -\frac{2}{3}\frac{{}^{(5)}T}{\kappa_5}; \quad \kappa_5 \equiv M_*^3, $$

Energy-momentum tensor

$$ {}^{(5)}T_{AB} = g_{AB}\Lambda_5 + \delta_A^\mu \delta_B^\nu S_{\mu\nu}\delta(y - y_b); \quad S_{\mu\nu} \equiv \lambda g_{\mu\nu} + \tau_{\mu\nu}. $$

Einstein 5 → SMS 4

$$ {}^{(5)}G_{\mu\nu} = G_{\mu\nu} - \partial_y K_{\mu\nu} + g_{\mu\nu}\partial_y K + K K_{\mu\nu} - 2K_\mu^\sigma K_{\sigma\nu} - \frac{1}{2}g_{\mu\nu}(K^2 + K_{\sigma\rho}K^{\rho\sigma}); $$



Orbifold ⟷ **R-S II**

Gaussian normal coordinates

Israel-… matching conditions

$$g_{\mu\nu}(y_b + y) = g_{\mu\nu}(y_b - y);$$

$$K^{+}_{\mu\nu} = -K^{-}_{\mu\nu} = -\frac{1}{2\kappa_5}(S_{\mu\nu} - \frac{1}{3}g_{\mu\nu}S).$$

Conformal Weyl tensor

$$R_{ABCD} = \frac{1}{N+2}(g_{AC}R_{BD} - g_{AD}R_{CB} + g_{BD}R_{AC} - g_{BC}R_{AD}) -$$

$$-\frac{1}{(N+2)(N+3)}(g_{AC}g_{BD} - g_{AD}g_{BC})R + C_{ABCD};$$

SMS (Shiromizu-Maeda-Sasaki) equation

$$\boxed{G_{\mu\nu} =} \frac{2}{3\kappa_5}\left({}^{(5)}T_{\mu\nu} - g_{\mu\nu}\left({}^{(5)}T_{55} + \frac{1}{4}\,{}^{(5)}T\right)\right) - KK_{\mu\nu} + K^{\sigma}_{\mu}K_{\sigma\nu} + \frac{1}{2}g_{\mu\nu}(K^2 - K^{\sigma\rho}K_{\sigma\rho}) - E_{\mu\nu}$$

$$\boxed{= \frac{\Lambda}{\kappa}g_{\mu\nu} + \frac{1}{\kappa}\tau_{\mu\nu} + \frac{1}{\kappa\lambda}\Sigma_{\mu\nu} - E_{\mu\nu},}$$

Gravity from the bulk

$$\Sigma_{\mu\nu} = \frac{1}{4}\Big(- 2\tau\tau_{\mu\nu} + 6\tau^{\sigma}_{\mu}\tau_{\sigma\nu} + g_{\mu\nu}(-3\tau^{\sigma\rho}\tau_{\sigma\rho} + \tau^2)\Big). \qquad E_{\mu\nu} \equiv {}^{(5)}C^{5}_{\mu5\nu}$$

Conservation law $\quad \nabla^{\rho}\tau_{\rho\mu} = 0 \implies \nabla^{\rho}E_{\rho\mu} = \nabla^{\rho}\Sigma_{\rho\mu},$

$$\boxed{\Lambda = \frac{1}{2}(\Lambda_5 + \frac{\lambda^2}{6\kappa_5}); \quad \kappa \equiv \frac{6\kappa_5^2}{\lambda},}$$

Brane is flat $\quad \Lambda_5 = -\frac{\lambda^2}{6\kappa_5};\ \lambda = \pm\sqrt{6\kappa_5\Lambda_5};\ \kappa_5 \equiv M_*^3.$

Solution

static vacuum,

$$\mathcal{E}_{\mu\nu} = -\left(\frac{q}{\widetilde{M}_{\mathrm{p}}^2}\right)\frac{1}{r^4}\left[u_\mu u_\nu - 2r_\mu r_\nu + h_{\mu\nu}\right] .$$

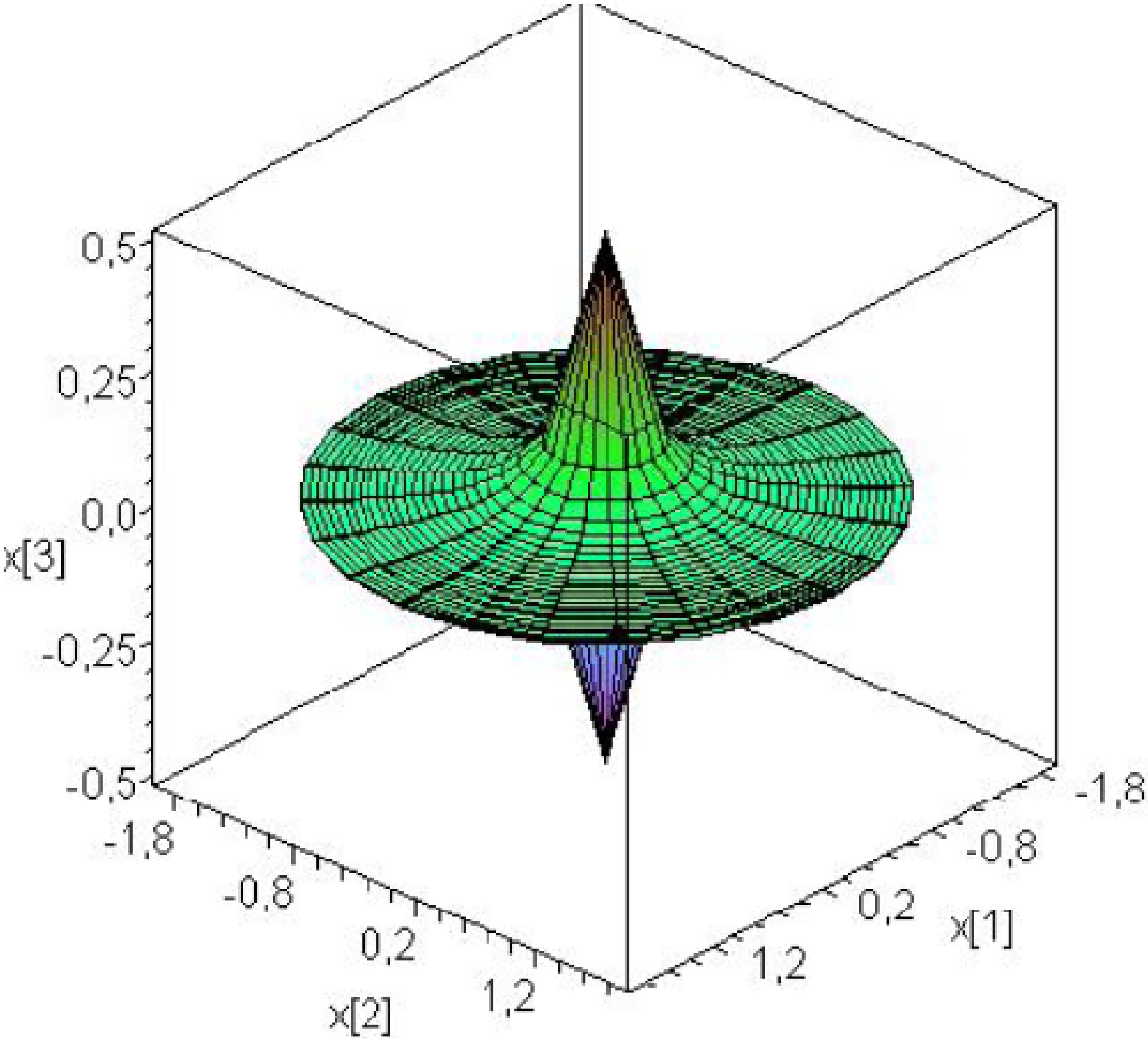
$$-g_{tt} = (g_{rr})^{-1} = 1 - \left(\frac{2M}{M_{\mathrm{p}}^2}\right)\frac{1}{r} + \left(\frac{q}{\widetilde{M}_{\mathrm{p}}^2}\right)\frac{1}{r^2}$$

$q = Q\widetilde{M}_{\mathrm{p}}^2$ *is a dimensionless tidal charge*

Where from Q? From 5th dimension!

But this solution is accompanied by spreading out the matter to the bulk!

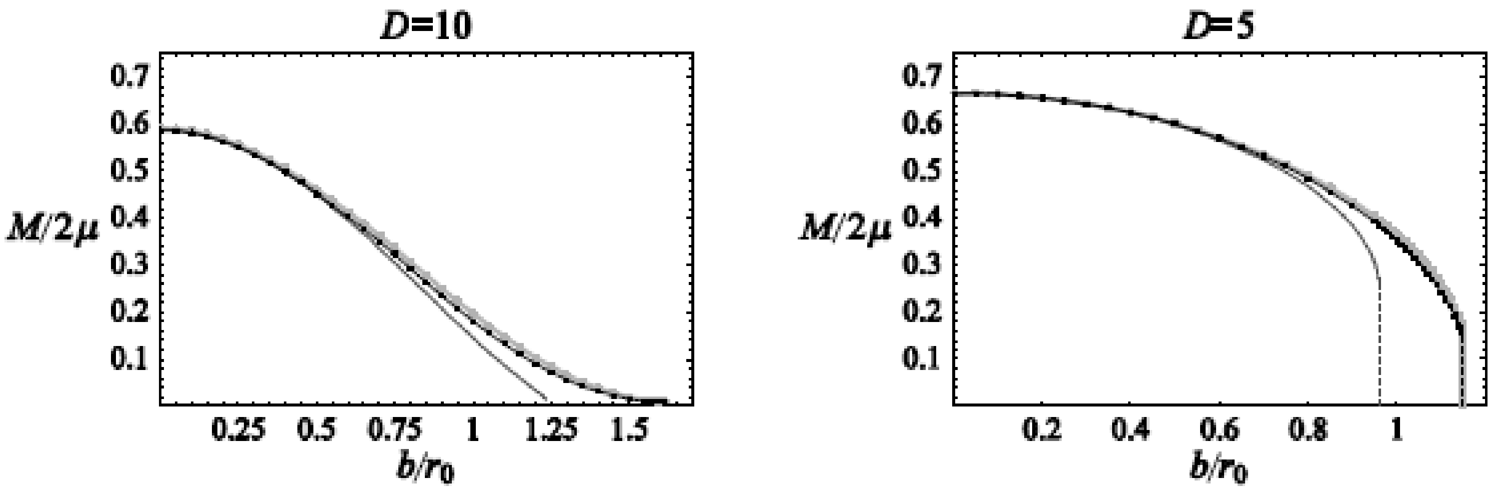
Andrianov – Kurkov solution



Back-up slides

Danger of BH blowing up, is it viable?

Inelasticity



The ratio of the mass of the BH to the initial energy of the collision as a function of the impact parameter divided by r_{sh} (the Schwarzschild radius)

Eardley, Yoshino, Randall

CHARYBDIS: A Black Hole Event Generator

The generator also has an option to allow the black hole temperature to vary as the decay progresses and is designed for simulations with either p-p or p-p.

CHARYBDIS only attempts to model in detail the Hawking evaporation phase which is expected to account for the majority of the mass loss. To provide a further simplification only non-spinning black holes are modelled. This is perhaps a less good approximation but comparison with the 4D situation suggests that most of the angular momentum will be lost in a relatively short spin-down phase [185]. The balding phase is difficult to model and is neglected—this is equivalent to the assumption that $M_{BH} = \sqrt{\hat{s}}$ in spite of the evidence that this will not necessarily be the case. A related assumption is that the cross section calculation assumes F_n of equation (3.6) is equal to unity (i.e. the parton-level cross section is assumed to be πr_S^2).

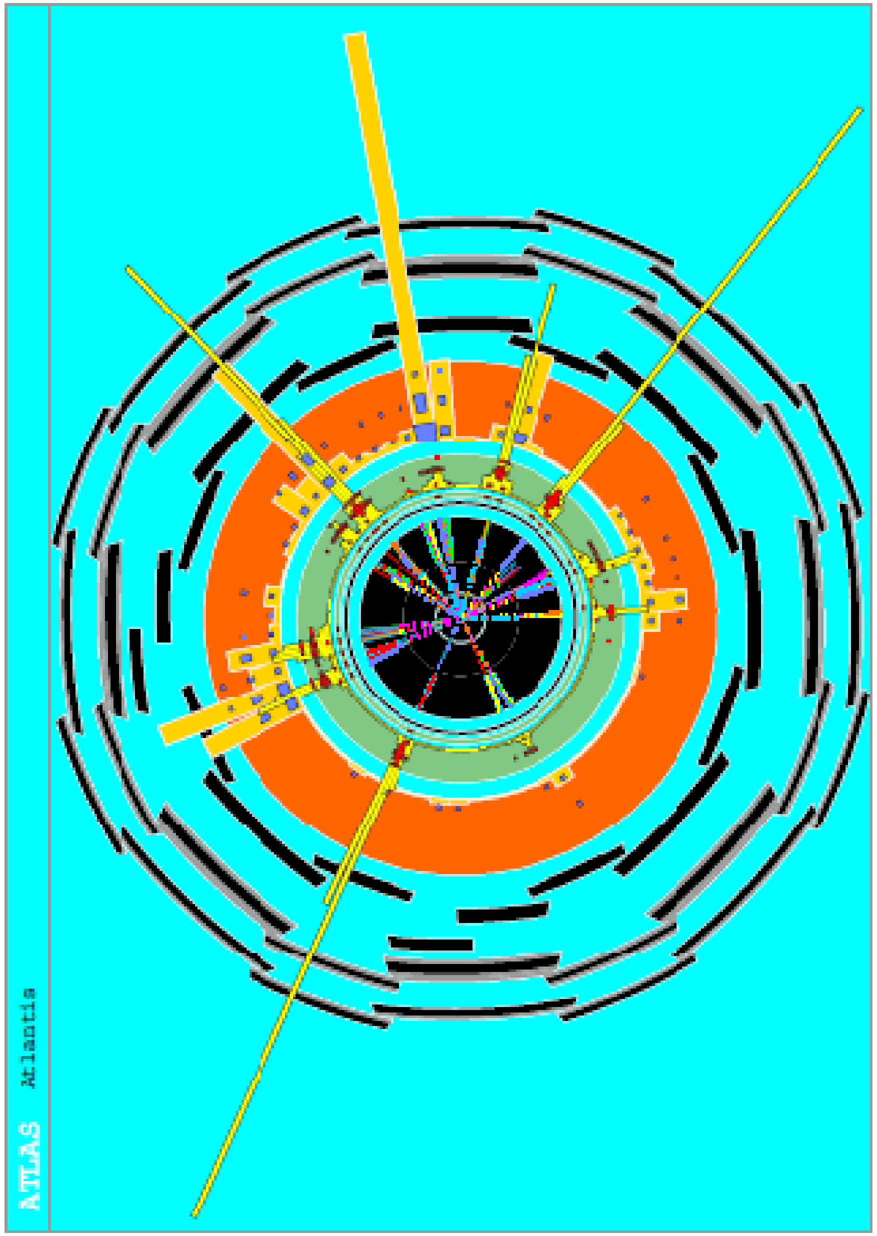


Figure 5.1: Sample event display (details in text).

TABLE VI: Lower limits on the fundamental energy scale $\overline{M}_{4+n}$ (in TeV) corresponding to the R-limits of Table V. Multiply limits on $\overline{M}_{4+n}$ by the factor $M/\overline{M}_{n+4}$ given in the second row to obtain limits on the parameter M used in our previous papers [11, 12].

n	1	2	3	4	5	6	7
$M/\overline{M}_{n+4}$	2.32	2.98	3.46	3.82	4.10	4.32	4.51
Neutrino Signal							
SN 1987A	7.4×10^2	8.9	0.66	1.18×10^{-1}	3.5×10^{-2}	1.44×10^{-2}	7.2×10^{-3}
EGRET γ-ray limits							
All cosmic SNe	3.4×10^3	28.	1.65	2.54×10^{-1}	6.8×10^{-2}	2.56×10^{-2}	1.21×10^{-2}
Cas A	7.7×10^2	14.5	1.24	2.34×10^{-1}	7.0×10^{-2}	2.80×10^{-2}	1.37×10^{-2}
PSR J0953+0755, RX J185635–3754	4.58×10^3	54.0	3.46	0.54	0.14	5.10×10^{-2}	2.30×10^{-2}
Neutron-star excess heat							
PSR J0952+0755	1.61×10^5	7.01×10^2	25.5	2.77	0.57	0.17	6.84×10^{-2}

S.Hannestad, G.G.Raffelt

Supernova and neutron-star limits on large extra dimensions Phys.Rev.D67:125008,2003

TABLE I: Upper limits on the compactification radius R (in m) and corresponding lower limits on the fundamental energy scale $\bar{M}_{4+n}$ (in TeV), for $N_{NS} = 7 \times 10^8$ and T=30 MeV. We show for comparison, in parentheses, the limits obtained by Hannestad & Raffelt in Ref. [5], as they would be obtained for a distance to the NS of 0.12 kpc.

n	1	2	3	4	5	6	7
R	3.9×10^{-4} (7.7)	3.8×10^{-10} (5.3×10^{-8})	4.2×10^{-12} (1.1×10^{-10})	4.7×10^{-13} (5.5×10^{-12})	1.3×10^{-13} (9.2×10^{-13})	5.4×10^{-14} (2.8×10^{-13})	2.9×10^{-14} (1.2×10^{-13})
$\bar{M}_{4+n}$	7.8×10^4 (2.9×10^3)	4.5×10^2 (3.8×10^1)	1.9×10^1 (2.6)	2.2 (4.3×10^{-1})	4.7×10^{-1} (1.2×10^{-1})	1.47×10^{-1} (4.3×10^{-2})	5.9×10^{-2} (1.9×10^{-2})

Gamma rays from the Galactic bulge and large extra dimensions Phys.Rev.Lett.92:111102,2004

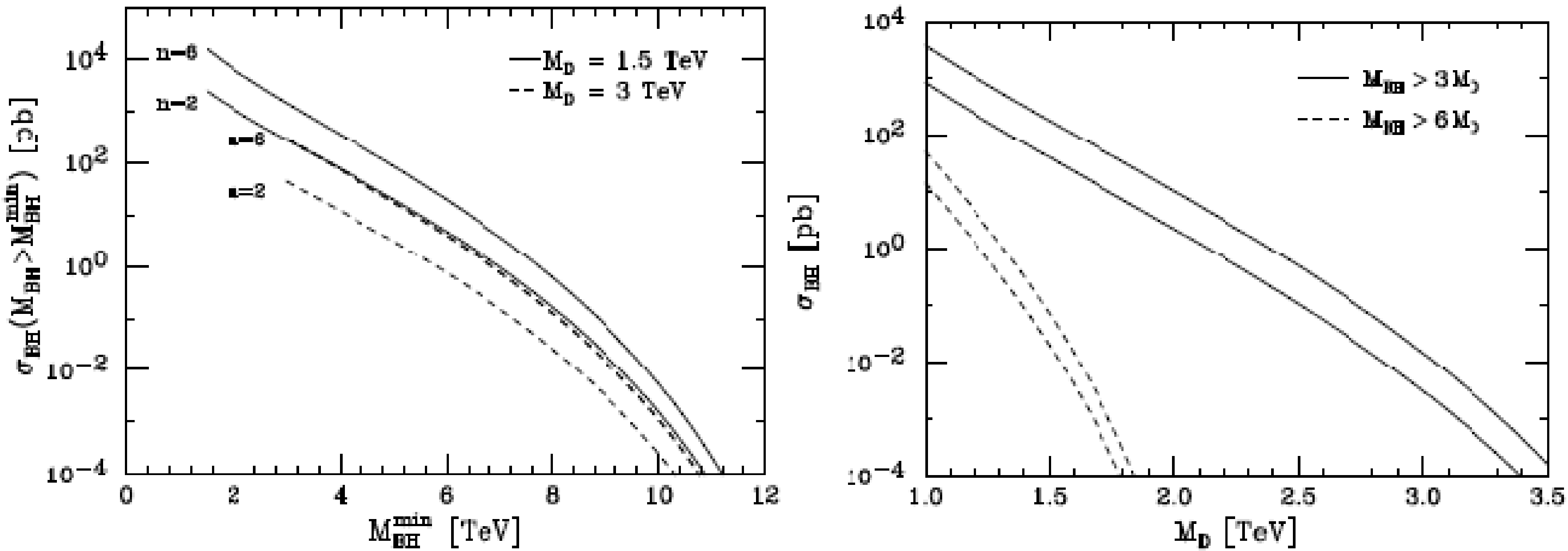


Figure 8: Black-hole production cross-section as a function of (left panel) minimum black-hole mass and (right panel) the gravity scale M_D.

BH decays

1. Balding phase: the black hole radiates away the multipole moments it has inherited from the initial configuration, and settles down in a hairless state. A certain fraction of the initial mass will also be lost in gravitational radiation.
2. Evaporation phase: it starts with a spin down phase in which the Hawking radiation [9] carries away the angular momentum, after which it proceeds with the emission of thermally distributed quanta until the black hole reaches the Planck mass (replaced by the fundamental scale M_G in the models we are considering here). The radiation spectrum contains all the Standard Model particles, which are emitted on our brane, as well as gravitons, which are also emitted into the extra dimensions. It is in fact expected that most of the initial energy is emitted during this phase into Standard Model particles [7] although this conclusion is still being debated (see, e.g. Ref. [20]).
3. Planck phase: once the black hole has reached a mass close to the effective Planck scale M_G, it falls into the regime of quantum gravity and predictions become increasingly difficult. It is generally assumed that the black hole will either completely decay in some last few Standard Model particles or a stable remnant be left which carries away the remaining energy [19].

Charged particles

$$ds^2 = -g(R)dT^2 + g(R)^{-1}dR^2 + R^2 d\Omega_{D-2}^2,$$

$$g(R) = 1 - \left(\frac{R_{S,D}(m)}{R}\right)^{D-3} + \frac{Q^2}{R^{2(D-3)}}, \qquad Q^2 = \frac{8\pi G_D q^2}{(D-2)(D-3)}.$$

If electromagnetic field can propagate in D dimensions

The D-dimensional charged version of the Aichelburg-Sexl metric :

$$ds^2 = -2dUdV + dX_i^2 + F(|X|)\delta(U)dU^2,$$

$$F(\rho) = \begin{cases} -8G_4 p \ln\rho - \frac{2a_4}{\rho}, & (D=4), \\ \frac{16\pi G_D p}{(D-4)\Omega_{D-3}\rho^{D-4}} - \frac{2a_D}{(2D-7)\rho^{2D-7}}, & (D \geq 5), \end{cases}$$

$$a_D = \frac{2\pi(4\pi G_D p_e^2)}{(D-3)} \frac{(2D-5)!!}{(2D-4)!!} \quad (D \geq 4)$$

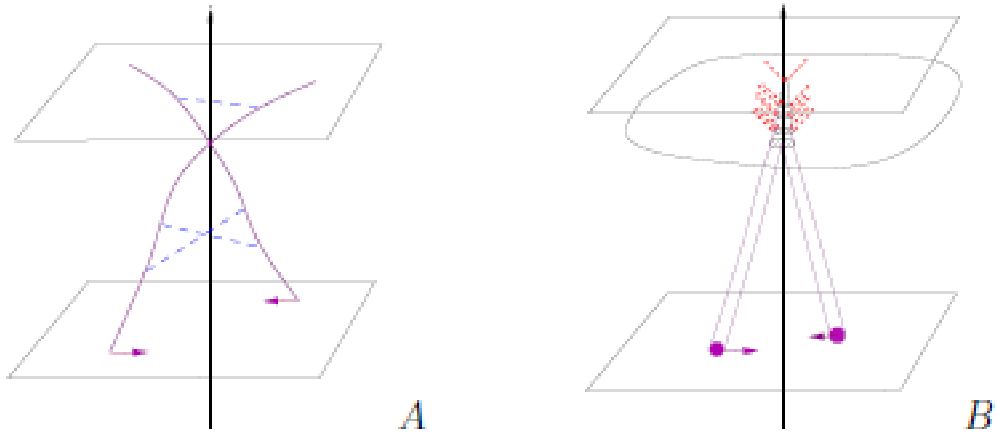


Figure 8: A. Ultra relativistic colliding particles with a large impact parameter. Blue lines represent the graviton exchange. B. Colliding particles with a small impact parameter and mass/energy enough to produce BH. Red dot lines represent BH evaporation.

BH production in the collision of two particles can also seen as a violation of the unitary in the $2 \to 2$ elastic channel. Indeed, let us consider a scattering amplitude in two channels system,

$$\mathcal{A} = \begin{pmatrix} \mathcal{A}_{2p\to 2p} & \mathcal{A}_{2p\to BH} \\ \mathcal{A}_{BH\to 2p} & \mathcal{A}_{BH\to BH} \end{pmatrix} \tag{32}$$

$\mathcal{A}_{2p\to 2p}$ is the elastic scattering amplitude and $\mathcal{A}_{2p\to BH}$ is the inelastic one. The unitary condition means that

$$2\mathrm{Im}\mathcal{A}_{2p\to 2p} = |\mathcal{A}_{2p\to 2p}|^2 + |\mathcal{A}_{2p\to BH}|^2 \tag{33}$$

The **no-hair theorem** postulates that all black hole solutions of the Einstein-Maxwell equations of gravitation and electromagnetism in general relativity can be completely characterized by only three *externally* observable classical parameters: mass, electric charge, and angular momentum. All other information (for which "hair" is a metaphor) about the matter which formed a black hole or is falling into it, "disappears" behind the black-hole event horizon and is therefore permanently inaccessible to external observers

THE NO HAIR THEOREM

(1) The Schwarzschild solution is the unique, static, spherically symmetric solution in the case of pure gravity in the absence of any other field.[3] This non-rotating black hole is stable and parametrized by its mass.

(2) The Kerr solution is the unique stationary axisymmetric solution in the case of pure gravity.[4] This rotating black hole is stable and characterized by its angular momentum and mass.

(3) For the theory that gravity is coupled to the electromagnetic field, the spherically symmetric solution must be the Reissner-Nordstrom metric. This non-rotating charged black hole is stable and characterized by its mass and charge,’ whereas, the stable axisymmetric rotating black hole solution must belong to the Kerr-Newman family and be characterized by its angular momentum, mass and charge.[6]

(4) For the case that gravity is minimally coupled to those massless scalars or massive bosons of spin zero, one or two, there is no non-vanishing field of massless scalars, or of massive bosons in the exterior of the black hole.’

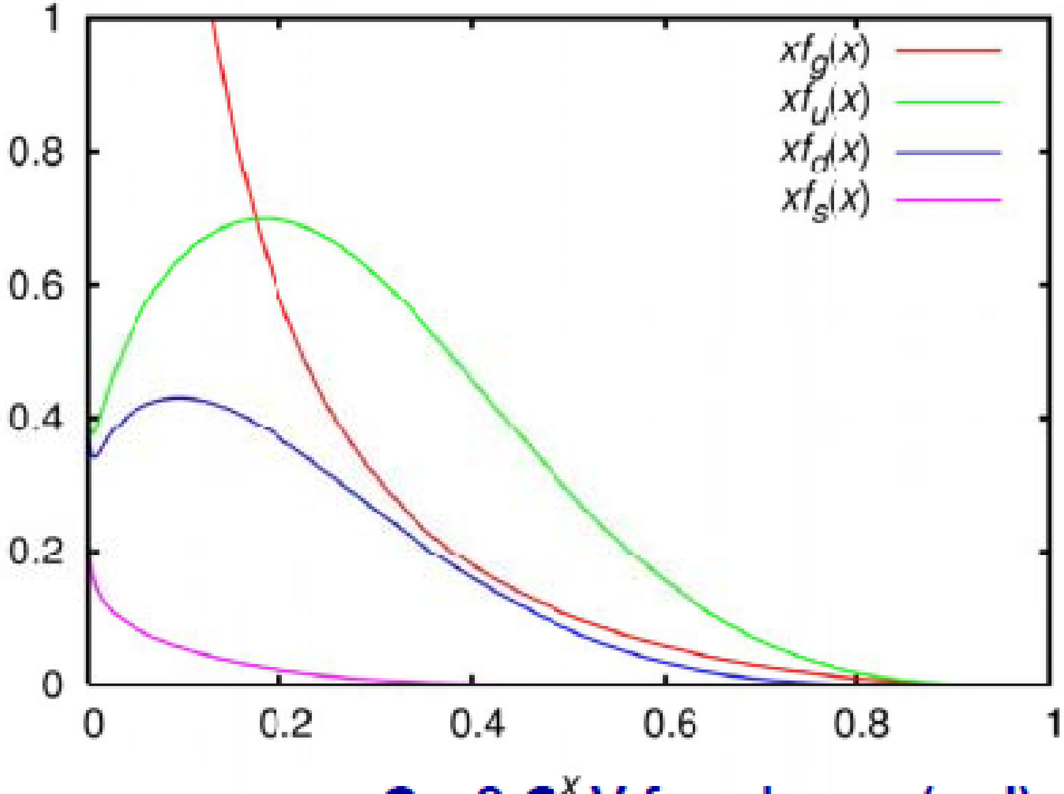
(5) The theory according to which gravity is coupled to a spin one-half fermionic field, cannot give a non-vanishing fermionic field exterior to the black hole.*

(6) For the case of a scalar field that is conformal coupled to gravity, a black hole solution has a non-trivial scalar field,• • but this is unstable to a radial perturbation and is expected to decay to the Schwarzschild or Reissner-Nordstrom solution.”

(7) A discrete family of solutions with non-trivial $SU(2)$ Yang-Mills field strength has been found numerically in the case of non-abelian gauge fields coupled to gravity,• • but these solutions are unstable[12] to a growing radial perturbation and are expected to decay to the Schwarzschild solution.

Parton Distribution Functions

$$\sigma_{pp\to X} \propto \sum_{ij} \int dx_1 \int dx_2 f_i(x_1) f_i(x_2) \sigma_{ij\to X}(x_1, x_2)$$



***Q* = 2 GeV for gluons (red), up (green), down (blue), and strange (violet) quarks**