TeV scale gravity at the LHC

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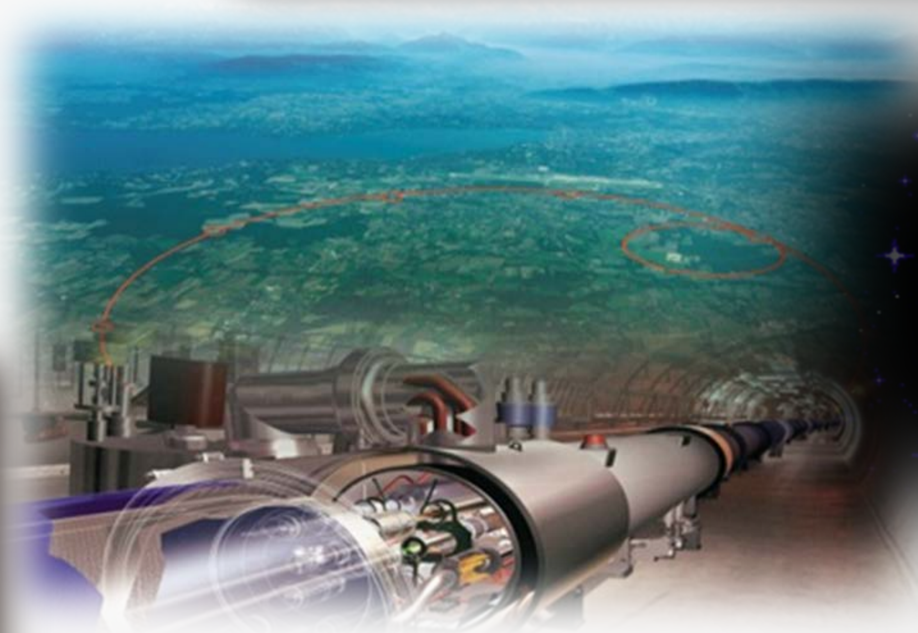
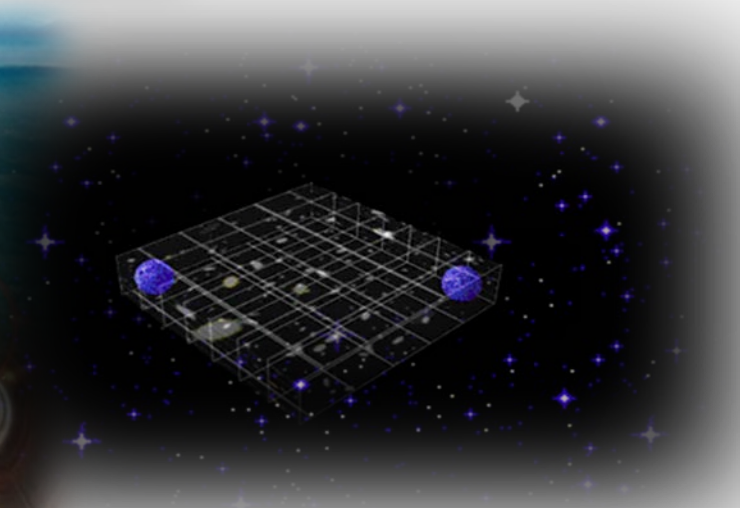
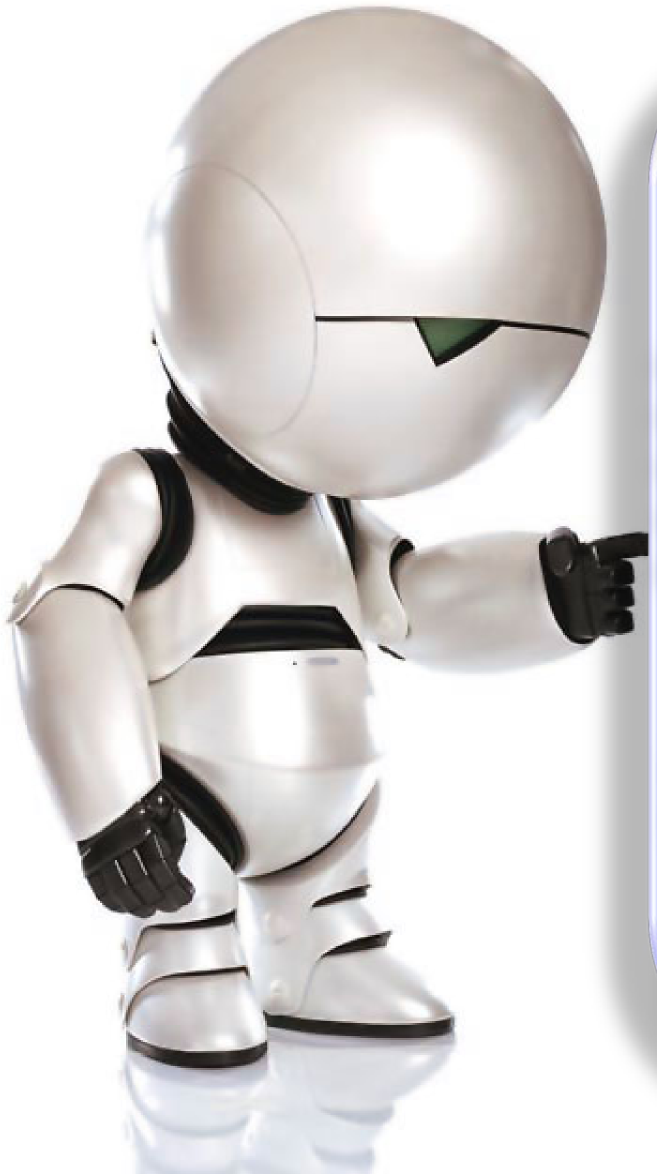




PHENO 2012
7-9 May 2012
University of Pittsburgh

University at Buffalo
The State University of New York

Outline



- **Higher dimensional black holes: theory and phenomenology**

  - Higher dimensional solutions
  - Characteristic Hawking radiation
  - Interaction with the brane - friction
  - Recoil effect due to radiation
  - Effects of the brane tension

i) Black holes in accelerators: LHC
ii) Black holes by cosmic rays

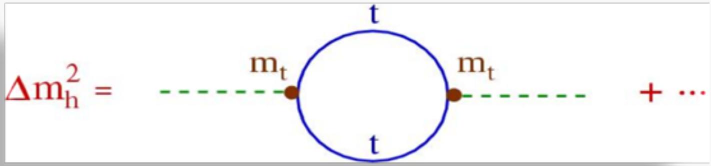
- Black Max: event generator

The need for physics beyond the SM

- **Validity of SM is probably limited to energies up to 1 TeV**

- **Radiative corrections to the Higgs mass:**

$$\Delta m_h^2 \approx \Lambda^2 \frac{3(2m_W^2 + m_Z^2 + m_h^2 - 4m_t^2)}{32\pi^2 v^2}$$



- **If SM is valid all the way to M_{Pl} , i.e. $\Lambda \approx M_{Pl}$, then a rather fine-tuned cancellation must take place (about 1 part in 10^{17})**

- **If physics beyond the SM is to solve the hierarchy problem, it has to come not far above the TeV scale**

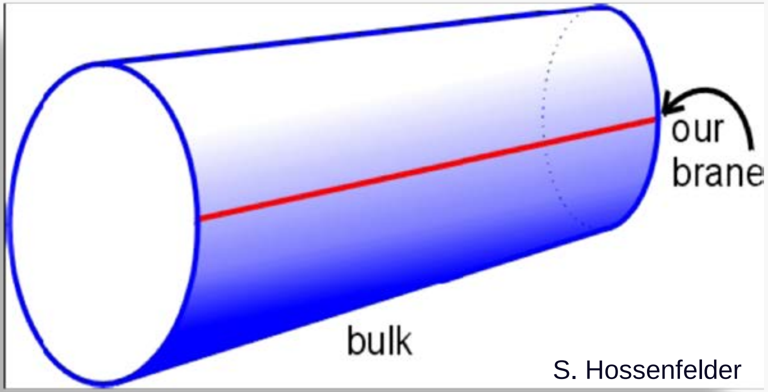
1. *Supersymmetry*

2. *Strong (TeV scale) quantum gravity*

Strong gravity: ADD model

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

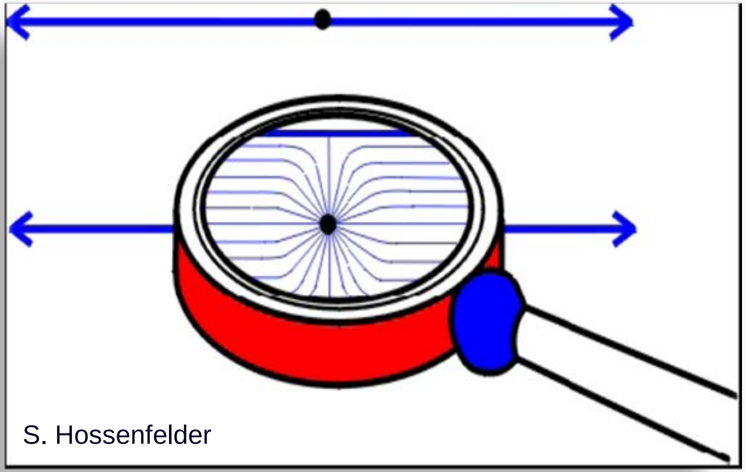
- Our universe consists of:
- 3+n space-like dimensions (bulk)
- n dimensions compactified to radius R

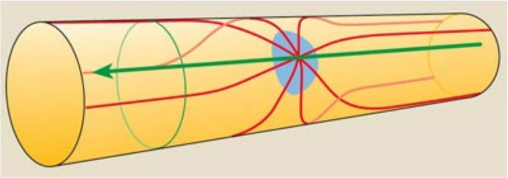


- ***Only gravitons are allowed to propagate in all dimensions***
- ***SM particles are bound to 3-dim submanifold (brane)***

In this framework:

- Gravity is as strong as the other interactions
- But gravitational force is diluted due to the presence of extra dimensions





Weak gravity is only an illusion for an observer located on the brane

Fundamental gravity can be as strong as the electroweak force

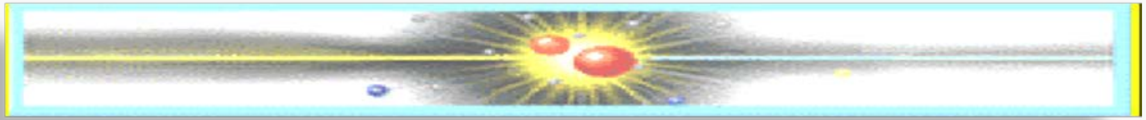
If $M_* = 1TeV = 10^3 GeV$

We can talk about non-perturbative quantum gravity effects in accelerators → Mini Black Holes

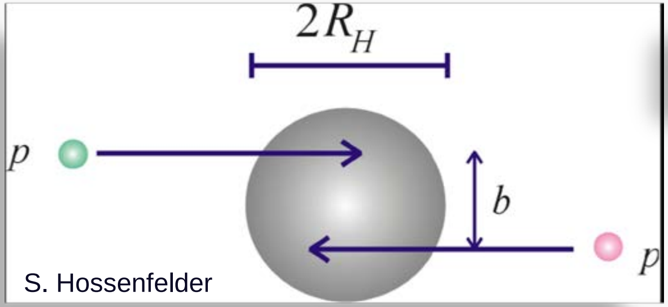
Black holes in accelerators

Particle accelerator (e.g. Large Hadron Collider):

Collision of two particles with COM energy E_c



If an impact parameter *b* is smaller than $2R_H$ for a given E_c



Trans-Planckian energies

Black hole with a mass M ~ Ec forms!

- The total black hole production cross section in pp collison is:

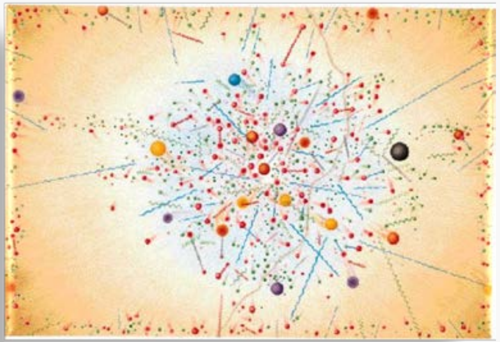
$$\sigma(pp \rightarrow BH) = \Sigma_{ij} \int_{\tau_{\min}}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} \hat{\sigma}_{ij}(\tau s) f_i(x) f_j(\frac{\tau}{x})$$

- The sum runs over all partons in the proton

$$\hat{\sigma}_{ij} = \pi R_H^2$$

- $\sqrt{s}$ is the proton-proton COM energy
- f_i are the parton distribution functions
- x_i is the momentum fraction carried by an i-th parton
- $\sqrt{\tau} = \sqrt{x_i x_j}$ is the momentum transfer
- $M_{\min} = \sqrt{\tau_{\min} s} \approx M_*$ is the minimal energy needed to form a black hole

Large Hadron Collider → CERN



LHC: E_c =14 TeV

$$\sigma(M) \approx \pi R_H^2$$

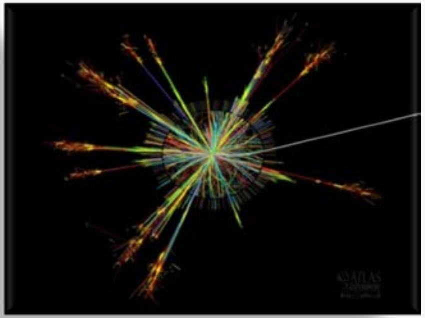
Numerical estimates:

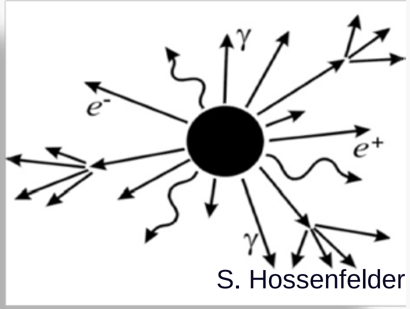
10^7 black holes per year if M_* =1 TeV

LHC - black hole factory!

Life-time of a small black hole very short :

TeV black hole lives 10^{-27} seconds
→ disappears almost instantaneously





- Number of particles emitted equal to black hole entropy: $S = \frac{n+1}{n+2}\frac{M_{BH}}{T_{BH}}$
- e.g. 5 TeV black hole emits of the order of 30 particles

BH event may have a distinct signature in accelerators!

Higher dimensional black hole solutions

Schwarzschild-like solution (non-rotating)

Tangherlini, 1963

$$ds^2 = -(1-\frac{r_H^{1+n}}{r^{1+n}})dt^2 + (1-\frac{r_H^{1+n}}{r^{1+n}})^{-1}dr^2 + r^2 d\Omega_{2+n}^2$$

n: the number of extra dimensions

Kerr-like solution (rotating): 5D

Myers and Perry, 1986

$$ds^2 = d\gamma^2 + \frac{r^2\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2$$

$$d\gamma^2 = -dt^2 + (r^2+a^2)\sin^2\theta d\phi^2 + (r^2+b^2)\cos^2\theta d\psi^2 + \frac{r_0^2}{\rho^2}(dt + a\sin^2\theta d\phi + b\cos^2\theta d\psi)^2$$

$$\rho^2 = r^2 + a^2\cos^2\theta + b^2\sin^2\theta$$

$$\Delta = (r^2+a^2)(r^2+b^2) - r_0^2 r^2$$

Two parameters of rotation: a and b

Five-dimensional rotating black holes: theory

V. Frolov, D. Stojkovic, **Phys.Rev.D67**:084004,2003; **Phys.Rev.D68**:064011,2003

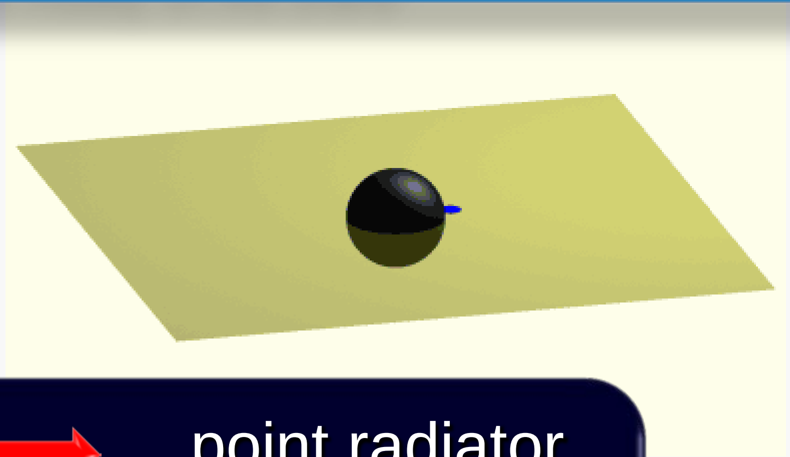
	4D black hole	5D black hole
Parameters	**M, a**	**M, a, b**
Killing Vectors	$\partial_t, \partial_\Phi$	$\partial_t, \partial_\Phi, \partial_\Psi$
Killing Tensor	**Yes**	**Yes**
Scalar field separation of variables	**Yes**	**Yes**
Higher spin fields separation of variables	**Yes**	**?**
Decoupling	**Yes**	**?**
Stable circular orbits	**Yes**	**No**
Superradiance	**Yes**	**Yes**
Algebraically special	**Yes**	**Yes**
Two principle null congruencies (PNC)	**Yes**	**Yes**
Petrov class D	**Yes**	**Yes**
PNC is shear free	**Yes**	**No**

Timescale: 30 years

Timescale: 2 months

Where do black holes mostly radiate? Brane or Bulk?

R. Emparan, G. Horowitz, R. Myers, **Phys. Rev. Lett.** 85 499 (2000)
"Black holes radiate mostly on the brane"



$\lambda_T > R_S$ → point radiator

→ s-mode dominant → radiates equally in all directions

Number of degrees of freedom much larger on the brane ?
(60 SM particles vs. 1 graviton)

Where do black holes mostly radiate? Brane or Bulk?

Objection 1:

# of degrees of freedom of gravitons in the N+1-dimensional space-time is:

$$\mathscr{N} = (N+1)(N-2)/2 \Longrightarrow N = 9, \quad \mathscr{N} = 35$$

Objection 2:

- LHC: non-zero impact parameter → most of the black holes will be rotating
- Rotating black holes → superradiance → graviton emission dominant

V. Frolov, D. Stojkovic, **Phys. Rev. Lett.** 89:151302 (2002)

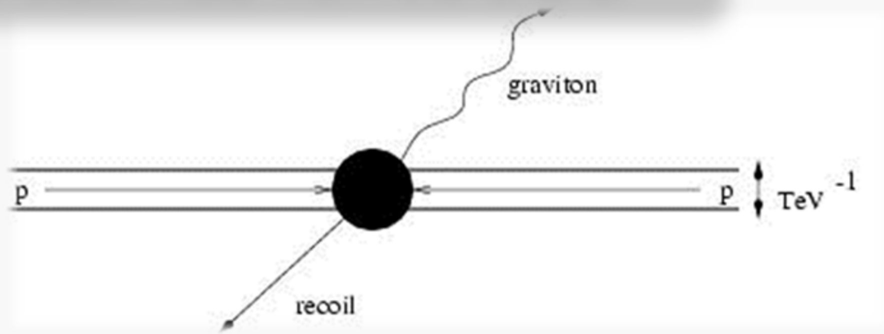
Black holes radiate mostly OFF the brane !

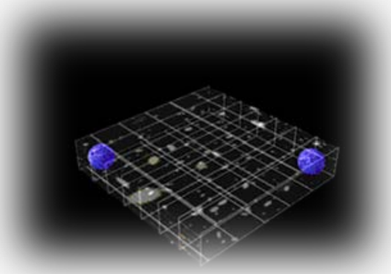
At least as long as they are rotating fast

Recoil Effect

V. Frolov, D. Stojkovic, **Phys. Rev. Lett.** 89:151302 (2002)

Any particle emitted in the bulk can cause a recoil of the black hole from the brane





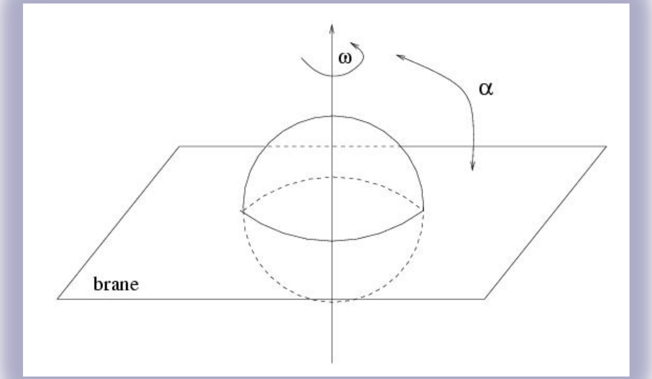
Recoil due to Hawking radiation can be very significant for small black holes (energy of emitted particles comparable to the mass of the black hole)

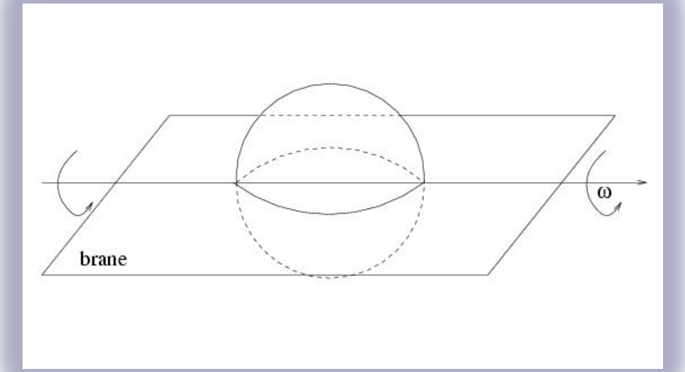
Consequences:

i) black hole radiation would be suddenly terminated
ii) observer located on the brane would register apparent energy non-conservation

Friction between the black hole and the brane

V. Frolov, D. Fursaev, D. Stojkovic, **CQG,** 21:3483 (2004)
D. Stojkovic, **Phys. Rev. Lett.** 94: 011603 (2005)





Rate of loss of the angular momentum

$$\dot{J} = \pi \sigma a R_H \cos^2 \alpha$$

$\alpha = \pi / 2 \Rightarrow \dot{J} = 0$ **final stationary equilibrium configuration is:**

$$J_{bulk} = 0$$

$$\tau \approx (G \sigma \cos^2 \alpha)^{-1}$$

Evaporation of a black hole off of a tense brane

D. Dai, N. Kaloper, G. Starkman, D. Stojkovic, **Phys.Rev.D75:**024043,2007

$$ds^2 = -(1-\frac{r_H^3}{r^3})dt^2 + (1-\frac{r_H^3}{r^3})^{-1}dr^2 + r^2\{d\theta^2 + \sin^2\theta[d\phi^2 + \sin^2\phi(d\chi^2 + B\sin^2\chi d\psi^2)]\}$$

6D black hole on a co-dimension 2 brane

$$B = 1 - \frac{T}{2\pi M_*^4}$$

deficit angle

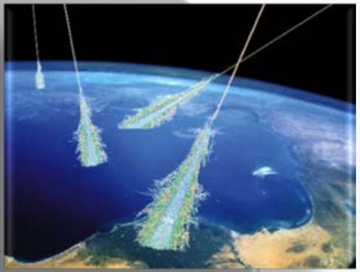
$$r_H = \frac{r_s}{B^{1/3}}$$

horizon radius

- Finite brane tension modifies the standard results
- Increasing tension increases the horizon radius
- Power carried away into the bulk diminishes

Black Holes from Cosmic Rays

J. Feng, A. Shapere, **Phys. Rev. Lett.** 88:021303 (2002)



- **Cosmic rays are Nature's free collider**
- Observed events produce COM energy of 100 TeV
- If $M_* \approx 1\text{TeV}$ (quantum gravity energy scale), then

small black holes can be produced in the atmosphere

- Proposed mechanism:

- neutrino-nucleon scattering deep in the atmosphere

Cosmic neutrinos

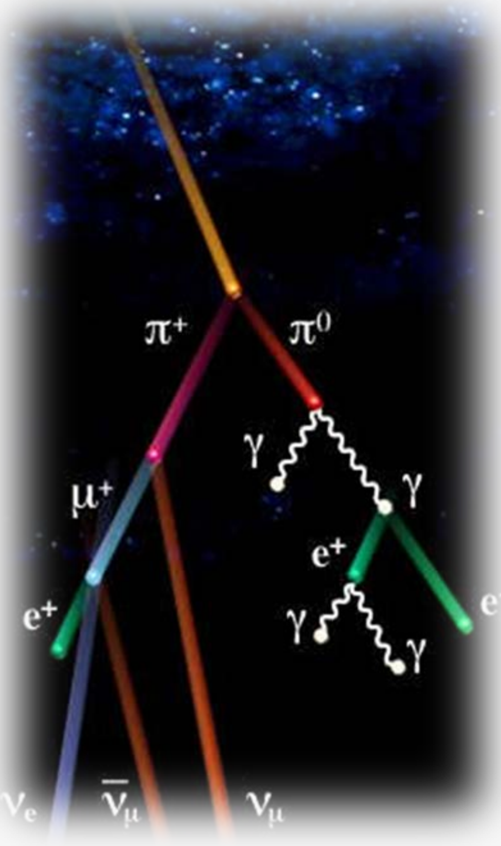
• **Cosmic protons scatter off the cosmic microwave background to create ultra-high energy neutrinos**

$$p+\gamma_{CMB} \to n+\pi^{+} \to n+\mu^{+}+\nu$$

• **These neutrinos enter Earth's atmosphere**

• **They have very weak SM interactions**

• **Dominant interaction:** $\nu N \to BH + X$



•The total black hole production cross section in neutrino-nucleon scattering is:

$$\sigma(\nu N \rightarrow BH) = \Sigma_i \int dx \hat{\sigma}_i(xs) f_i(x\tilde{Q})$$

• The sum runs over all partons in the nucleon

$$s = 2m_N E_\nu \qquad E_{CM} = \sqrt{s}$$

• f_i are the parton distribution functions

• $\tilde{Q}$ is momentum transfer

$$\hat{\sigma} = \pi R_H^2$$

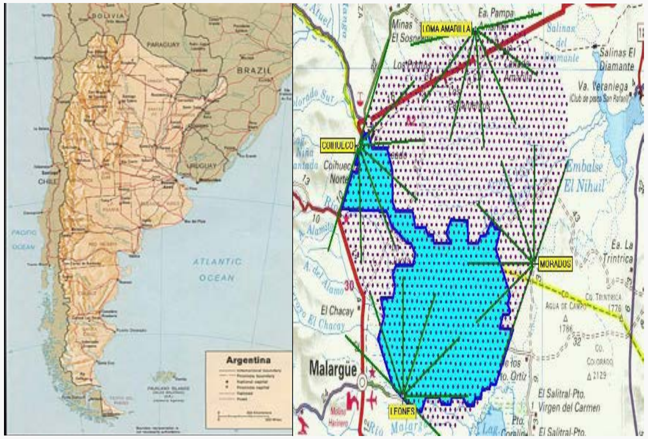
• The cross section for black hole production is found to be several orders of magnitude higher than the SM cross section for $\nu N \rightarrow \nu L + X$ if $M_* \approx$1-10TeV

Auger Observatory

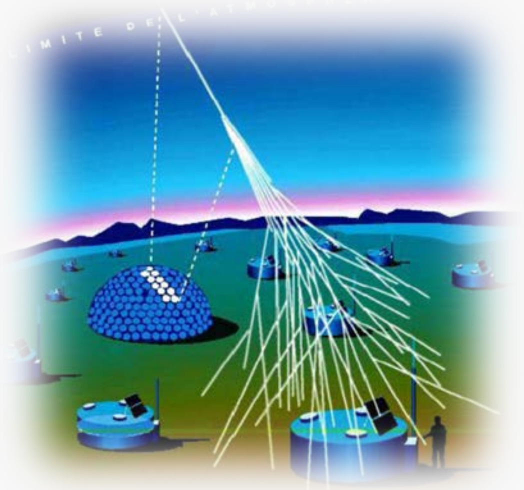
Pierre Auger

- **Best current setup for cosmic ray studies (also IceCube)**

- Located in Argentina (Pampa Amarillas)



- **1600 Water Cerenkov ground arrays**
- **4 air fluorescence telescopes**
- **spread over 3000 km^2**



• Numerical estimates:

- Auger can detect ~ 100 black holes in 3 years (i.e. BEFORE the LHC data become available)

• This could be the first window into extra dimensions

• USA Today version:

"Dozens of tiny black holes may be forming right over our heads... A new observatory might start spotting signs of the tiny terrors, say physicists Feng and Shapere. They're harmless and pose no threat to humans."

Eight years after…

Auger has reported some interesting results but NO black hole events!

Are TeV scale gravity models already excluded?

Karl Popper (1902-1994)

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

Karl Popper, The Observer, August 1982

Model Building

- Some things have their natural habitat in the "grand desert“ that is destroyed by a low scale gravity

- Like proton stability, neutrino masses...

$$\tau_{proton} = m_{proton}^{-1} \left(\frac{M_{Pl}}{m_{proton}} \right)^4$$

- **Low scale quantum gravity implies very fast proton decay!**

Saving Proton

Gaging the baryon number

- One way out is to gauge the baryon number
  → promote a $U(1)_B$ into a gauge symmetry

- **Problems:**

- **Baryogenesis**
  - Before: "We exist → proton must be stable"
  - After: "We exist → proton must be unstable"

- **To avoid a new long range interaction,** $U(1)_B$ **must be broken down to some discrete gauge symmetry**

- **Arranging for anomaly cancellation**

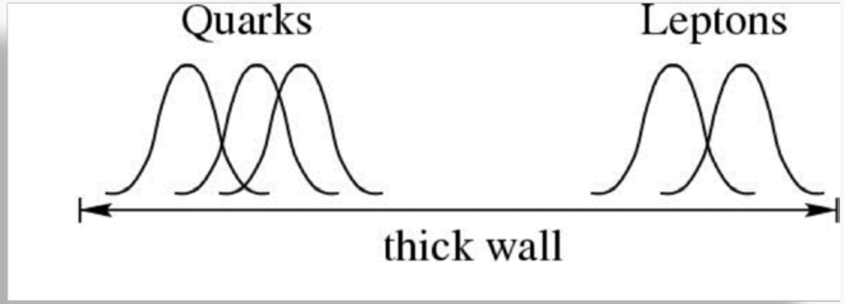
- **Gauge couplings unification**

- **So far, gauging the baryon number has not proved very attractive!**

An alternative: Split Fermions

*N. Arkani-Hamed, M. Schmaltz, **Phys. Rev. D 61**:033005 (2000)*

• In order to suppress a direct QQQL coupling we must separate quarks form leptons



• Quarks and leptons are localized at different points on a thick brane
• Or alternatively, on different branes

• The model yields exponentially small coupling (wave function overlap) between quarks and leptons

• Dangerous QQQL interaction is suppressed

- The propagator between fermions which are separated in extra dimensions (in the high energy and high momentum transfer limit) is

$$P_{extra} \approx P_4 e^{-d^2/\sigma^2}$$

d: separation between the quarks and leptons
σ: the width of the fermion wave function

- The propagator has the usual 4-dim form except that the coupling is suppressed by the exponentially small wave function overlap

- Suppression factor of $e^{-d^2/\sigma^2} \approx 10^{-26}$ (which can be achieved for a rather modest hierarchy of $d \approx 10\sigma$)

completely saves the proton!

Consequences: the price we to have pay

D. Stojkovic, G. Starkman, D. Dai, **Phys. Rev. Lett.** 96, 041303 (2006)

- Spatial separation between the quark and lepton wave functions successfully suppresses proton decay

- However, this implies strong consequences for cosmic ray neutrino scattering off the atmosphere

- The correct black hole production cross section in collisions of neutrinos with each quark in a nucleon is not $\hat{\sigma} = \pi R_H^2$

- The correct cross section is divided by the large suppression factor of

10^{52}

Large suppression factors enter the total production cross section

$$\sigma(\nu N \to BH)$$

and render the corresponding probability for the black hole production by cosmic neutrinos *completely uninteresting* for the Auger Observatory!

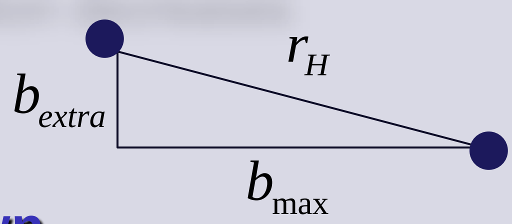
Non-observation of BH events at the Auger likely has no implications for the LHC

Implications of split fermions for the LHC

D. Dai, D. Stojkovic, G. Starkman, **Phys.Rev.D73**:104037,2006

- Neutron-antineutron oscillations are described by **uddudd** operator
- Limits on $n\bar{n}$ oscillations require splitting between **u** and **d** quarks
- **Consequences**
- As the separation between quarks increases, the maximum 3+1-dim impact parameter that results in black hole creation decreases

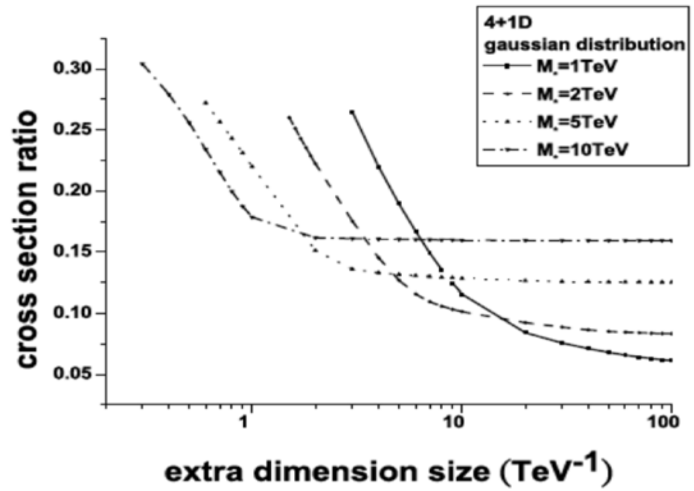
$$b_{\max} = \sqrt{r_H^2 - b_{extra}^2}$$

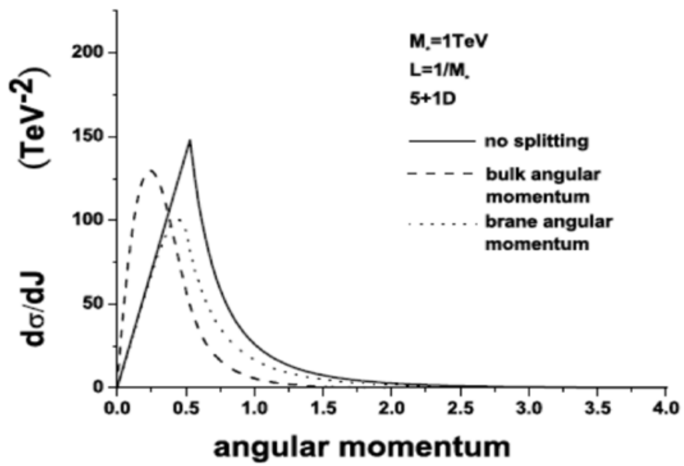


- **the production cross section goes down**
- **the bulk component of angular momentum grows**

Implications of split fermions for the LHC

1. the production cross section goes down
2. the bulk component of angular momentum grows





$$\sigma_{split} / \sigma_{non-split}$$

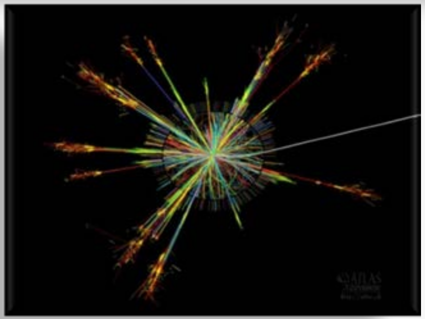
- The decline ceases when the size of the extra dimension exceeds the size of the black hole
- Bulk component of angular momentum is of the same order as brane component
- Main contribution comes from uu and dd collisions

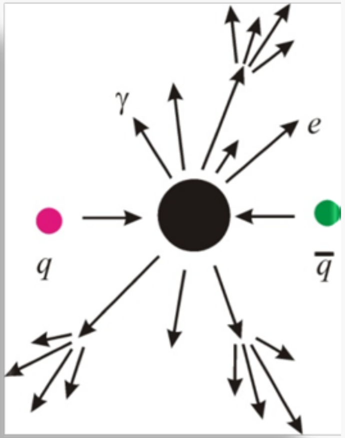
Black Max

"BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension"
D. Dai, G. Starkman, D. Stojkovic, C. Issever, E. Rizvi, J. Tseng
Phys.Rev.D77:076007,2008

- The most comprehensive tool to study quantum gravity effects
- Based on phenomenologically realistic models, thus offering most realistic predictions for hadron-hadron colliders.
- Includes all of the black-hole greybody factors known to date
- Incorporates: the effects of black-hole rotation, splitting between the fermions, non-zero brane tension and black-hole recoil
- The generator is interfaced with Herwig and Pythia and is now official software at CERN

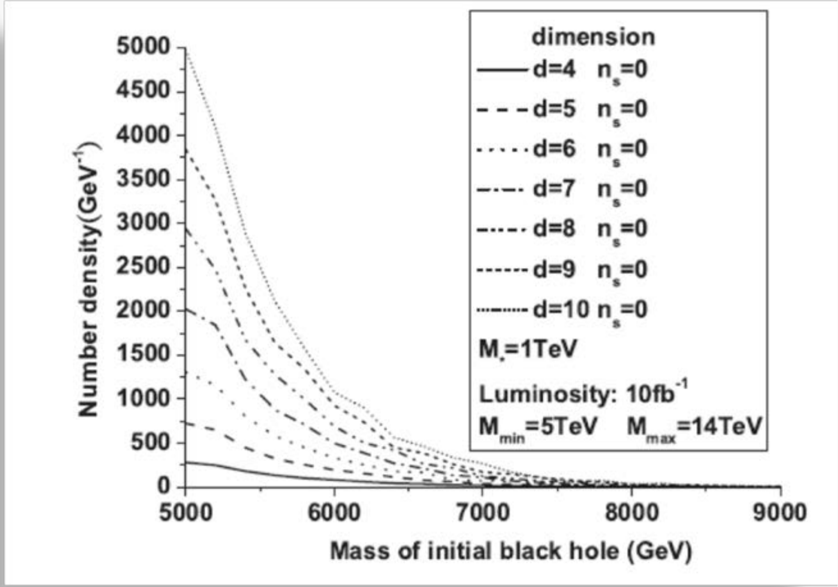
Black Max procedure



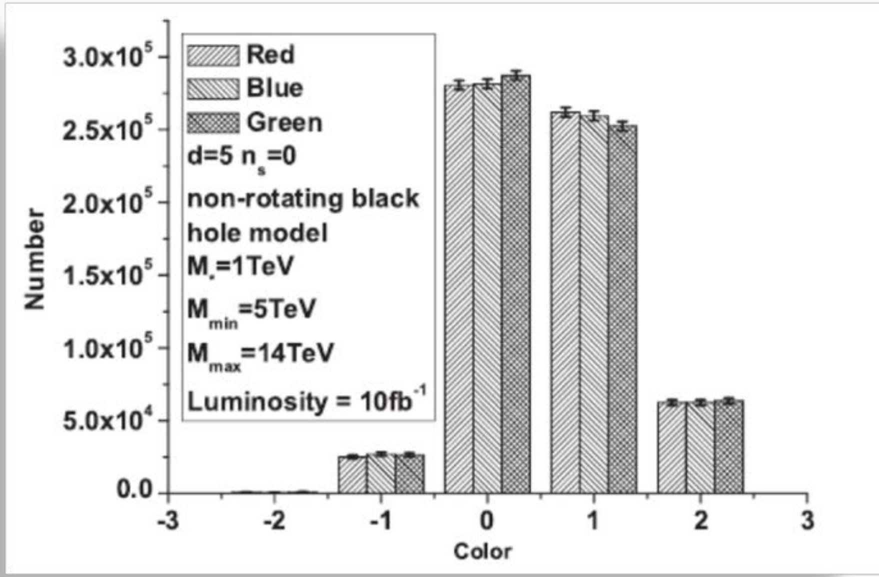


- The generator requires a well defined input, e.g. two colliding partons, which is obtained from the known parton distribution functions of a proton
- Then the probability for a black hole production is calculated with the basic characteristics of a formed black hole, like its mass, angular momentum, electromagnetic and color charge
- Next, the decay pattern via Hawking radiation is computed
- As the output, the generator gives the Standard Model particles with their energy, linear and angular momentum distributions

Black Max output



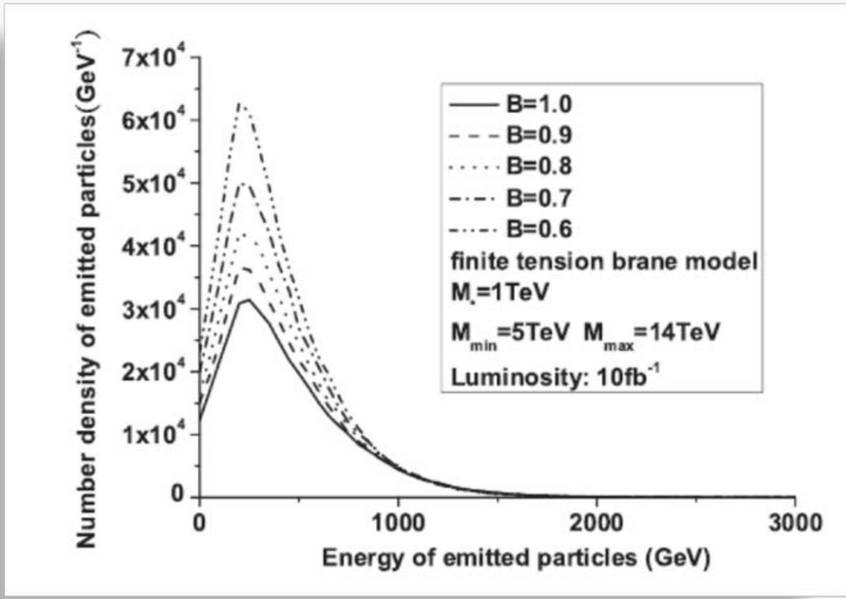
Mass distribution of initial black holes for various numbers of extra dimension.



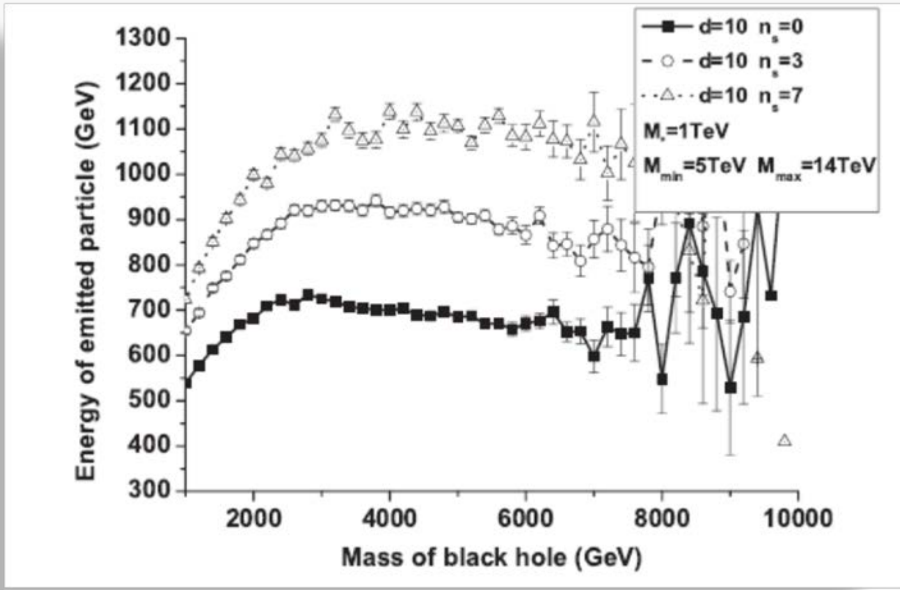
Initial color distribution of the created black holes

BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension.
D. Dai, G. Starkman, D. Stojkovic, C. Issever, E. Rizvi, J. Tseng
Phys.Rev.D77:076007,2008

Black Max output



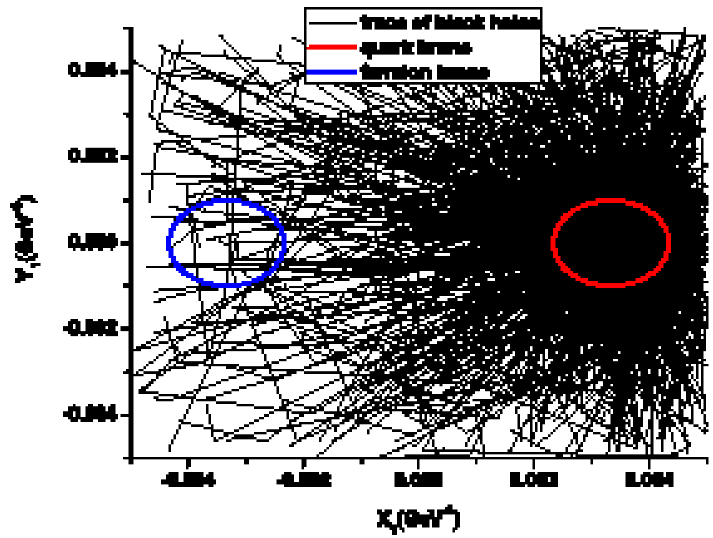
Energy distribution of emitted particles for black holes on a nonzero tension brane



Average energy of the particles emitted in split branes versus the mass of the black hole at the time of emission.

BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension.
D. Dai, G. Starkman, D. Stojkovic, C. Issever, E. Rizvi, J. Tseng
Phys.Rev.D77:076007,2008

Black Max output



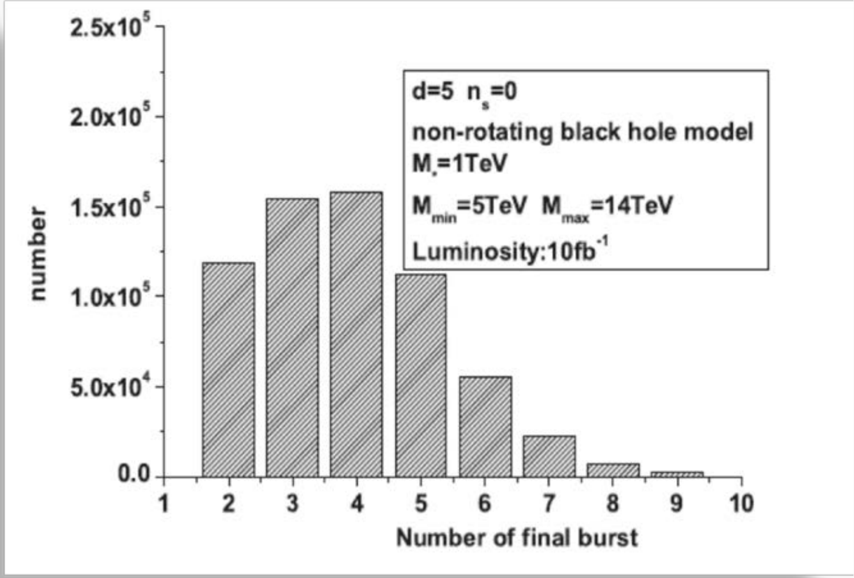
Black hole recoil in the split brane scenario

- black lines are black holes traces
- red circle is a quark brane
- blue circle is a lepton brane

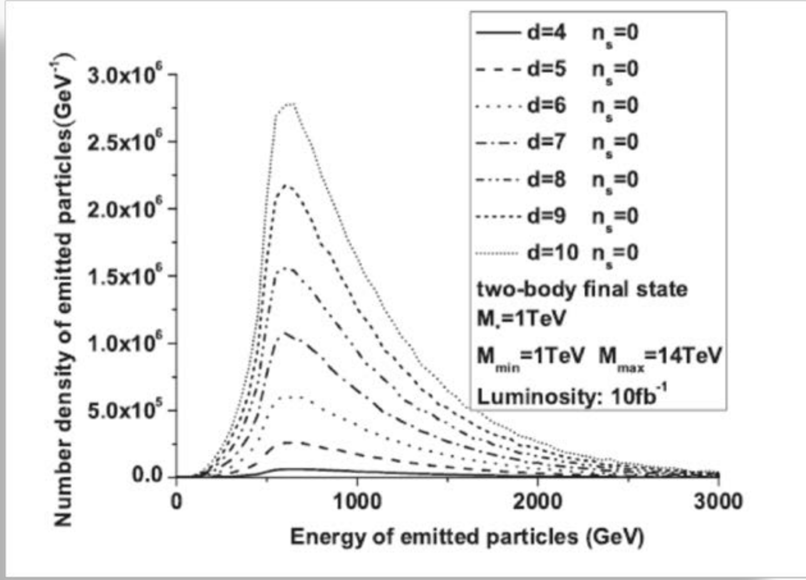
BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension.
D. Dai, G. Starkman, D. Stojkovic, C. Issever, E. Rizvi, J. Tseng
Phys.Rev.D77:076007,2008

Black Max output

$$P_2 = \frac{\sum_{n=0}^{2} \frac{1}{n!}\langle N\rangle^n}{e^{\langle N\rangle}}$$



Number of particles emitted in the final burst (when the black hole mass is about M_*)



Energy distribution of emitted particles for L. Randall's "two-body final states"

BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension.
D. Dai G. Starkman D. Stojkovic C. Issever E. Rizvi J. Tseng
Phys.Rev.D77:076007,2008

ATLAS and CMS use BlackMax

Search for Microscopic Black Hole Signatures at the Large Hadron Collider
The CMS Collaboration
e-Print: **arXiv:1012.3375**

Search for strong gravity signatures in same-sign dimuon final states
The ATLAS Collaboration
e-Print: **arXiv:1111.0080**

ATLAS and CMS intensively use Black Max

- **Newest limit (2012): minimal black hole mass > 5 TeV**

Conclusions

- Fine tuning in the SM may imply strong gravity at aTeV scale

- If gravity is strong, we can expect non-perturbative quantum gravity effects at soon available energies in accelerators

- Like mini black hole production

- Our knowledge about higher dimensional BH improved significantly

HOWEVER:

- The weakest link in TeV scale gravity models $\rightarrow$ fast proton decay

- Realistic models with stable proton:
  Some of the channels for black hole production are strongly suppressed

Auger $\neq$ LHC

THANK YOU