Black Hole Production in High Energy Collisions

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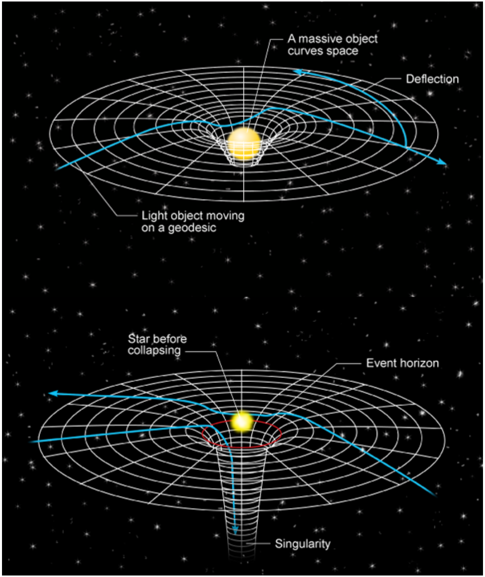
Einstein's General Theory of Relativity

- Gravity is nothing more than the curvature of spacetime

- A collapsing star can form a dense and massive region with infinite curvature a **singularity**



Solution of Einstein's Gravitational Field Equations

Einstein's equation

Gravity=Energy-Momentum

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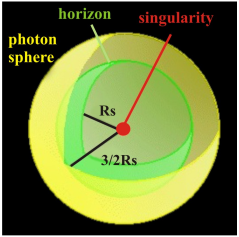

Schwarzschild black hole [1]

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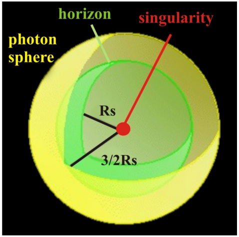

Schwarzschild black hole [1]

- Hawking radiation temperature⇒ $T_H = \frac{1}{8\pi M}$

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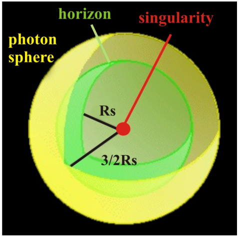

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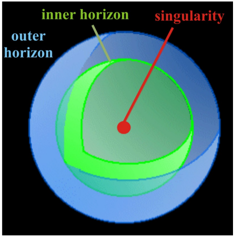

Reissner Nordstrom black hole [2]

- Hawking radiation temperature⇒ $T_H = \frac{1}{8\pi M}$

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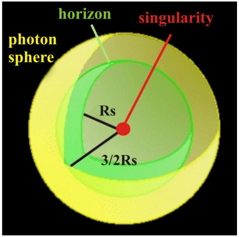

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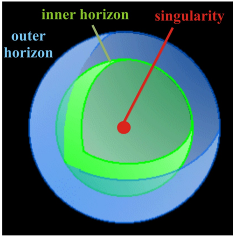
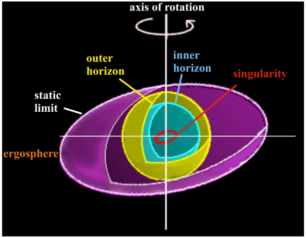


Reissner Nordstrom black hole [2]



Kerr black hole [3]

- Hawking radiation temperature⇒ $T_H = \frac{1}{8\pi M}$

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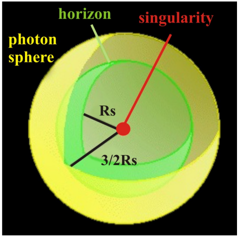

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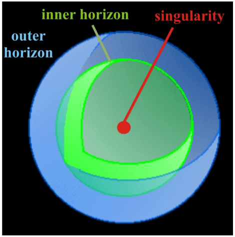

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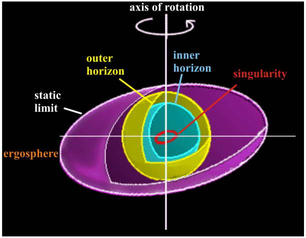


Kerr black hole [3]

- Hawking radiation temperature$\Rightarrow$ $T_H = \frac{1}{8\pi M}$
- The minimum necessary energy for producing black hole in high energy collisions $\Rightarrow$ $M_p \sim 10^{19}$ GeV

Hierarchy Problem

$$F_{em} = \kappa \frac{q_1 q_2}{r^2} \qquad F_{gravity} = G \frac{m_1 m_2}{r^2}$$

- $F_{gravity} = 10^{-36} F_{em}$, why is gravity very weak?

Maybe it's not!

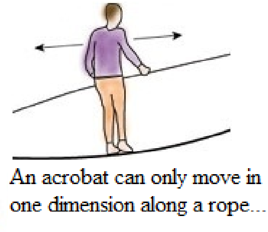
But how?

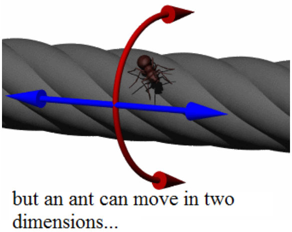
- **A**rkani, **D**imopoulos and **D**vail (ADD model) Phys. Lett. B 429, 263(1998).

Large extra dimensions

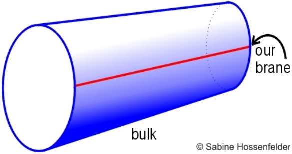
Extra Dimensions

1. Our $(3+1)$ dimensional world is embedded in a higher dimensional universe





2. The n space-like dimensions which compactified into radius R

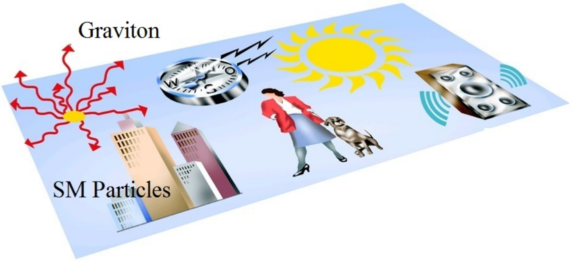


Dilution of Gravitational Force

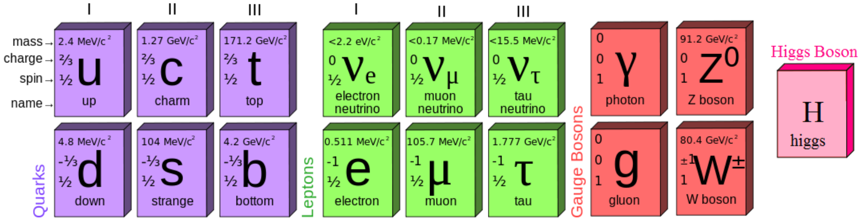
Newton's gravitational constant in 4D

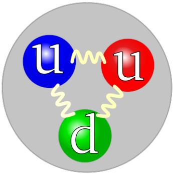
$$G_4 = \frac{G_{4+n}}{V_n} \qquad M_4 = \frac{1}{\sqrt{8\pi G_4}}$$

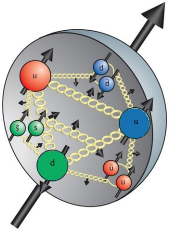
- $V_n \to \infty \quad \Rightarrow \quad G_4 \to 0 \quad \Rightarrow \quad M_4 \to \infty$
- Gravitational force is diluted due to the presence of extra dimensions
- $M_{4+n} \sim 1\text{TeV}$



Standard Model Particles on the Brane



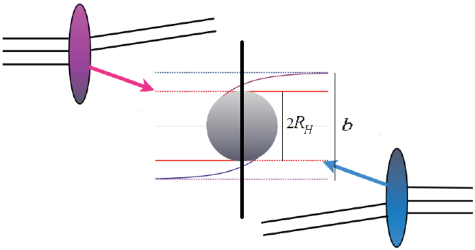




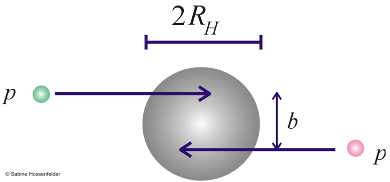
proton

Recipe for Black Hole Production

- Collision of two protons with energy E_{cm}



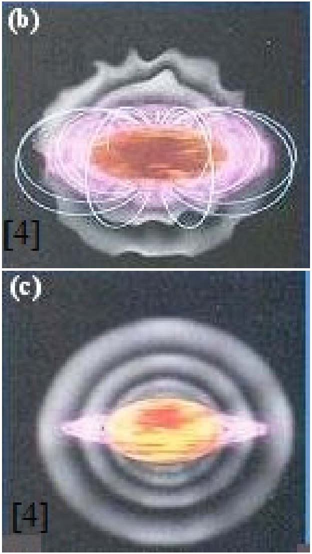
- In terms of hoop conjecture a black hole forms when $b \leq 2R_h$



Balding Phase and Spindown Phase

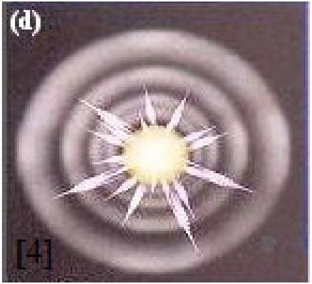
- **Balding phase**
  loses 'hair' and multipole moments, mainly by gravitational radiation

- **Spindown phase**
  loses angular momentum, mainly by Hawking radiation

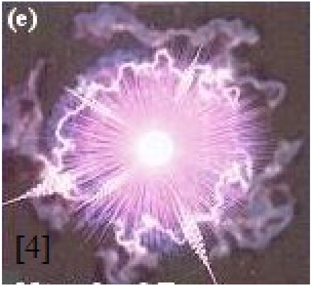


Schwarzschild Phase and Planck Phase

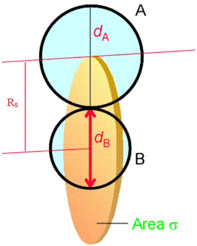
- **Schwarzschild phase**
  loses mass by Hawking radiation, temperature increases



- **Planck phase**
  mass and/or temperature reach Planck scale



Black Hole Production Cross Section



- The relevant geometrical cross section along collision axis is, $\sigma = \pi R_s^2(E)$

- The total black hole production cross section in pp collision is

$$\sigma_{pp\to BH+X} = \frac{1}{s}\sum_{ij}\int_{M^2_{BH,min}}^{s} dM^2_{BH}\int_{x_1,min}^{1}\frac{dx_1}{x_1} f_i(x_1,Q^2)f_j(x_2,Q^2)\hat{\sigma}_{ij\to BH+X}$$

x_1 and $x_2 = M^2_{BH}/(x_1 s)$ are the momentum fractions of the initial partons

Black Holes in Accelerators : LHC

- Extremely unstable,
  Lifetime $\sim 10^{-25}$ seconds
- Large multiplicity of the produced particles
- Flavor blindness
- Number of produced black holes

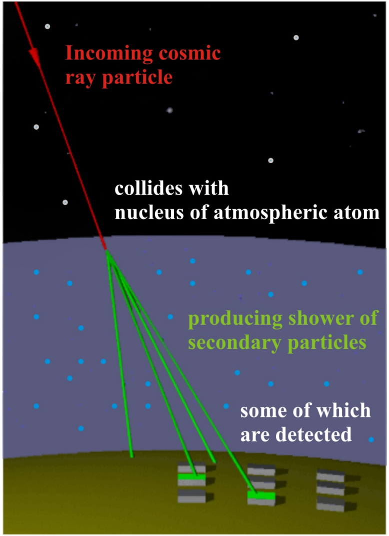
$$N_{BH_{signal}} = \mathcal{L}_{LHC} \times \sigma(pp \to BH + X) \times Br(BH \to signal)$$

$\sim 10^7$ per year for $E_{cm} = 14$ TeV if $M_P = 1$ TeV

LHC can be a black hole factory!

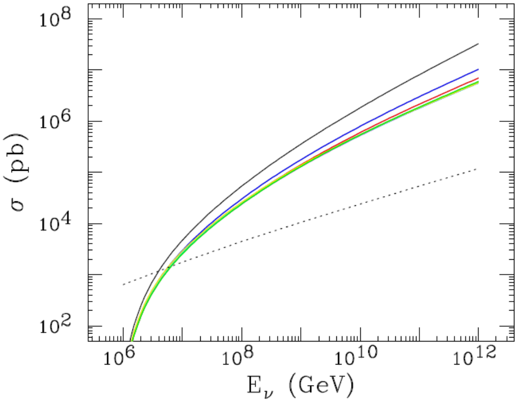
Black Holes by Ultra High Energy Cosmic Rays

- Ultra High-Energy Cosmic Rays (UHECRs) are particles of unknown origin and identity (protons? light atomic nuclei?) reaching the Earth from outer space
- Cosmic rays are the nature free colliders $E_{cm} = 100$ TeV
- Black holes can be continuously created in the Earth's atmosphere by the collision of UHECRs with nuclei of oxygen, carbon, nitrogen and other elements present in the atmosphere



Ultra High Energy Cosmic Ray Flux

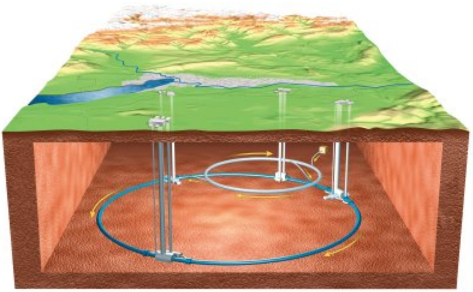
- **Ultra high energy cosmic neutrinos** can produce hundreds of black hole before the LHC begins operation
- **Flux** of high energy cosmic νs is very low



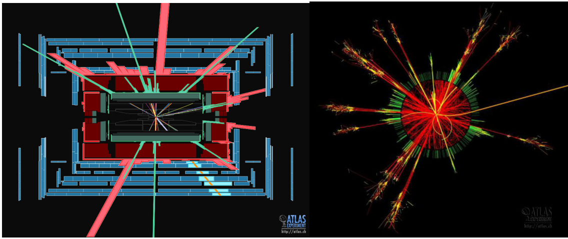
Cross sections $\sigma(\nu N \to BH)$ for $n = 1, ..., 7$ extra dimensions from above. The dotted curve is for the SM process $\sigma(\nu N \to \ell X)$ [5]

Black Hole Discovery Potential, ATLAS Simulation

- New constrain in Planck mass ~ 3.5 TeV



- Simulated production of a black hole in ATLAS detector.



BlackMax Event Generator

- The most inclusive event generator 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 now official software at CERN

How Does BlackMax Work?

- 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

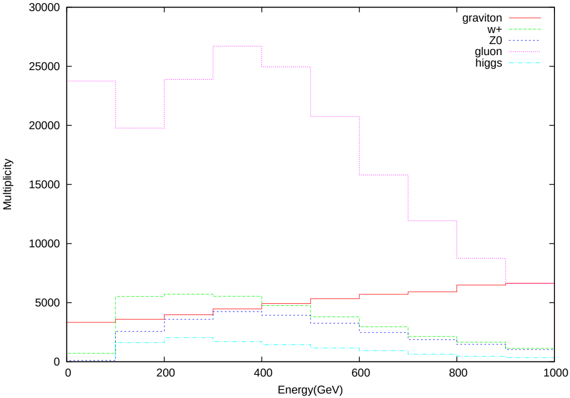
BlackMax Input

BlackMax[6] input setting

- Number of simulations:100000
- incoming particle:proton-proton
- Center of mass energy of incoming particle:50TeV
- tensionless nonrotating black hole
- Parton distribution function (PDF) set:cteq6
- Minimum mass:5TeV

BlackMax Output

Multiplicity of particles by type



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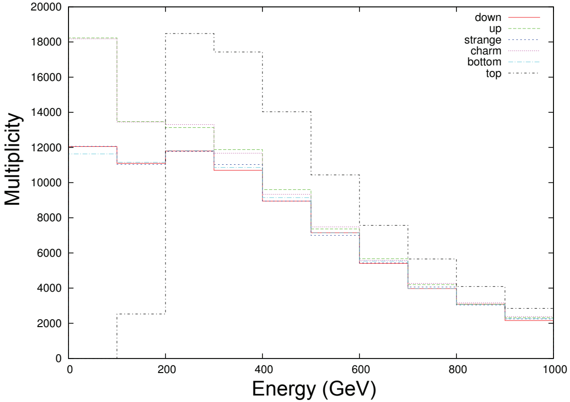

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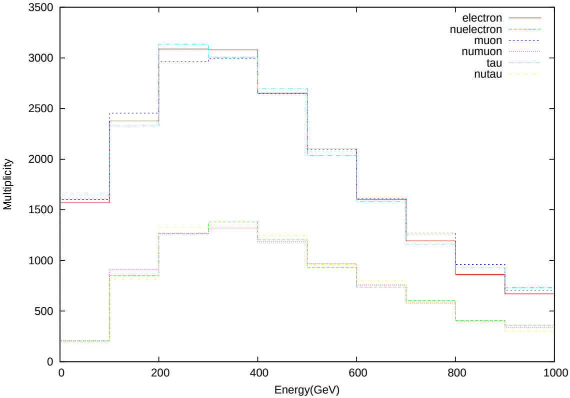
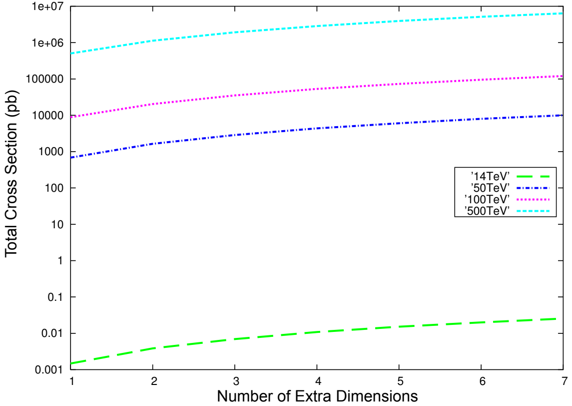


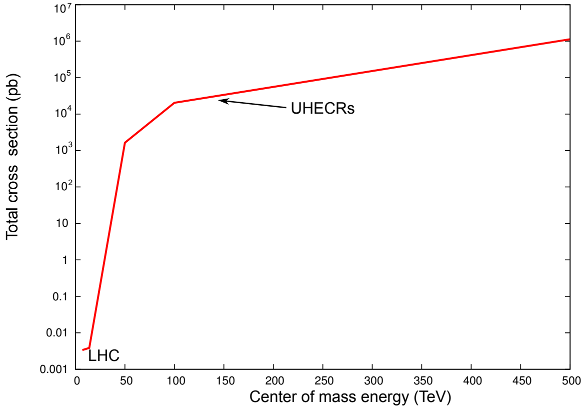
BlackMax Output

BH cross section vs Number of Extra Dimensions



BlackMax Output

BH cross section vs Energy for $(d = 2)$

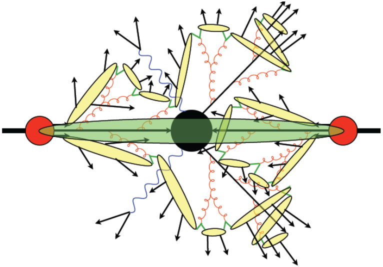


Conclusions

1. Gravity may be strong, but appear weak, because it is leaking into extra dimensions!
2. If gravity is strong, micro black holes may be produced in the LHC
3. Large cross section if Planck mass ~ 1 TeV
4. Black hole decay not well understood: early phases, time variation, Planck-scale remnant ....
5. Hawking radiation depends on the number of degrees of freedom of each particle, as a result we got the higher multiparity for quarks and gluon in compare with other particles

General Aims

1. **The phenomenology of black hole production** in accelerators and in cosmic rays
2. Extend current or invent new **simulations** (where and if needed) for subsequent particle shower formation and evolution
3. Investigate the differences of other Event generators like CHARYBDIS from BlackMax in all stages of the simulation
4. Interfacing to a parton shower and hadronization generator (PYTHIA or HERWIG)
5. As the output, the generator gives the Standard Model particles with their energy, linear and angular momentum distributions
6. **Analysis** of Pierre Auger Observatory data



1. Parton collision
2. Black hole formation and evaporation
3. Parton shower and hadronization
4. Hadron decay

"It's black, and it looks like a hole.
I'd say it's a black hole."

Bibliography

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- De-Chang Dai, Cigdem Issever, Eram Rizvi, Glenn Starkman, Dejan Stojkovic, Je Tseng *The BlackMax Manual A black-hole event generator with rotation, recoil, split branes, and brane tension*, (2009) arXiv:0902.3577v1 [hep-ph] http://blackmax.hepforge.org