TeV Scale Gravity and Black Hole Production in UHECR

- Motivation
- TeV Scale Gravity & Extra-Dimensions
- Black Hole Production & Multiplicity

Motivation

- Ultra-high energy cosmic rays (cosmic neutrinos) may create micro-scopic black holes -> evaporate -> hadronic shower, muon, tau...
- the fundamental Planck scale at which gravity becomes comparable in strength to other forces may be far below 10^19 GeV, leading to a host of potential signatures for high energy physics
- Hierarchy Problem -> what is the intrinsic fundamental scale

TeV Scale Gravity & Extra Dimensions Model

In D = 4 + n dimensions, gravity is described by the Einstein action

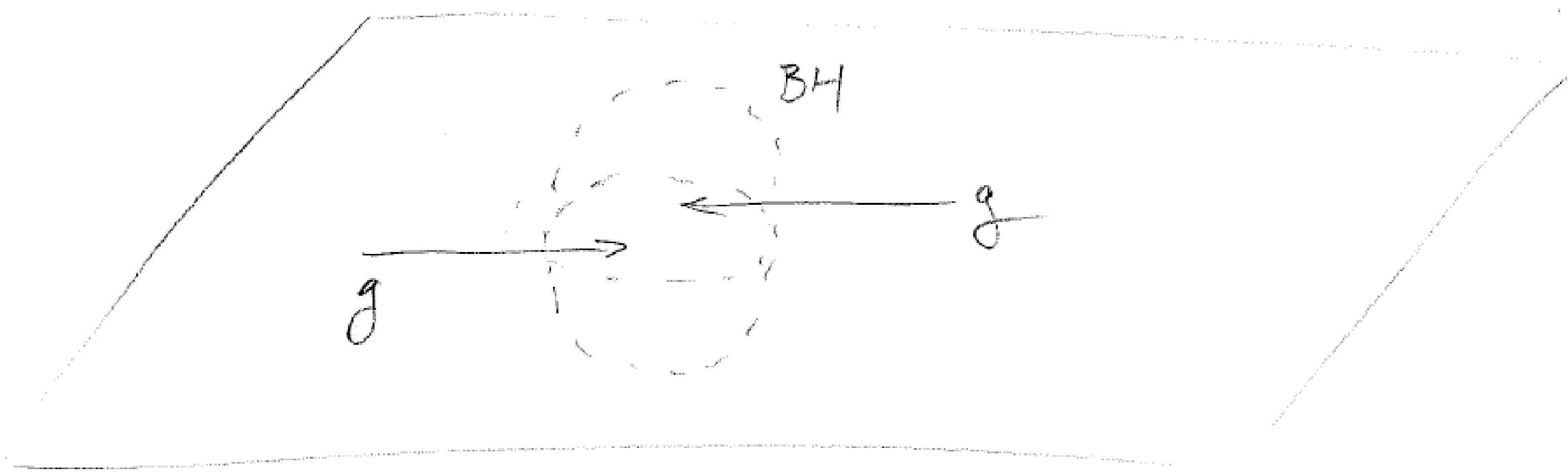
$$S_E = \frac{1}{8\pi G_D} \int d^{4+n}x \sqrt{-g}\, \tfrac{1}{2}\mathcal{R}$$

$$\frac{1}{8\pi G_D} = \frac{M_D^{2+n}}{(2\pi)^n}$$

Constraints About the Theory

- n=1 excluded by solar system tests of Newtonian gravity
- astrophysical bound on supernova cooling and neutron star heating
  - ✦ n=2 $M_D \gtrsim 600$ TeV
  - ✦ n=3 $M_D \gtrsim 10$ TeV
- collider searches for perturbative graviton effects & cosmic ray bounds on black hole production (e.g. AGASA)
  - ⋆ $M_D \gtrsim 1.3 - 1.8$ TeV for $n \geq 4$

Basic picture



$$\sigma \sim r_{schw}^2 \sim \frac{1}{M_p^2}\left(\frac{E}{M_p}\right)^{\frac{2}{1+n}}$$

Black Hole Production

Black holes produced in parton collisions are typically far smaller than the length scales of the extra dimensions. These black holes are then well-approximated by (4+n)-dimensional solutions. The Schwarzschild radius for a (4+n)-dimensional black hole with mass M_{BH} and vanishing charge and angular momentum is

$$r_s(M_{\mathrm{BH}}^2) = \frac{1}{M_D}\left[\frac{M_{\mathrm{BH}}}{M_D}\right]^{\frac{1}{1+n}}\left[\frac{2^n \pi^{\frac{n-3}{2}}\Gamma\left(\frac{3+n}{2}\right)}{2+n}\right]^{\frac{1}{1+n}}$$

Geometric Black Hole Production cross section with i, j parton collision

$$\hat{\sigma}(ij \to \mathrm{BH})(\hat{s}) = \pi r_s^2(\hat{s})$$

Evidence from analyses of axisymmetric and off-axis classical collisions, an analysis in a simple model framework, and a string calculation suggests that this picture is valid semi-classically and is not subject to large corrections. Modifications for nonvanishing angular momentum and spinning black holes have also been found to be small.

Voloshin has argued that the cross section could be suppressed by the factor e^{-I} , where the action is

$$I = \frac{S}{n+1} = \frac{4\pi\, M_{\mathrm{BH}}\, r_s}{(n+1)(n+2)}$$

with S the black hole entropy. This implies vanishing cross sections in the classical limit, contrary to the evidence noted above.

The neutrino-nucleon scattering cross section is

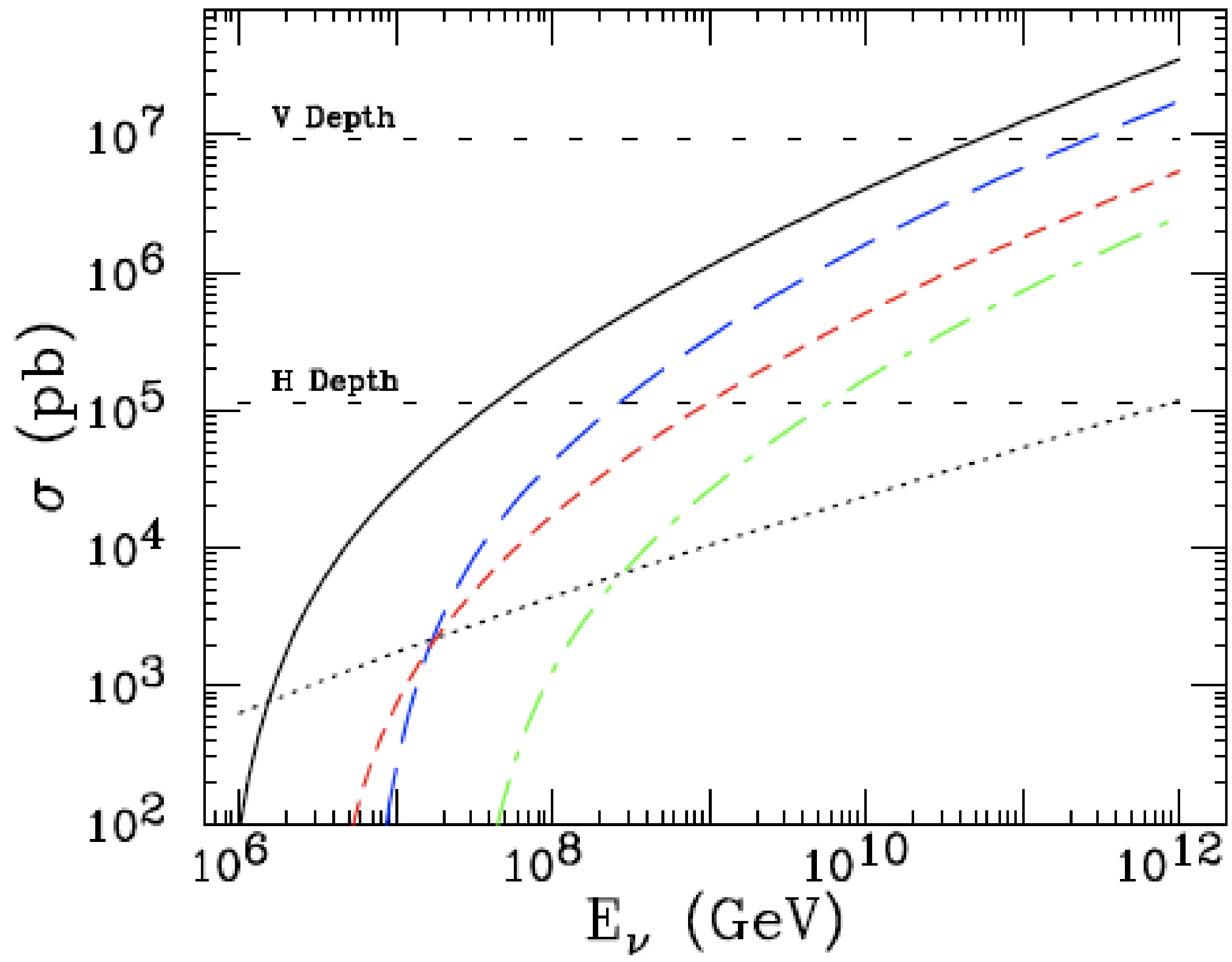
$$\sigma(\nu N \to \mathrm{BH}) = \sum_i \int_{(x_{\min} M_D)^2/s}^{1} dx\, \hat{\sigma}_i(xs)\, f_i(x, Q)$$

$$x_{\min} \equiv M_{\mathrm{BH}}^{\min}/M_D \gtrsim 1 \qquad\qquad s = 2 m_N E_\nu$$

Using the CTEQ5 parton distribution functions.

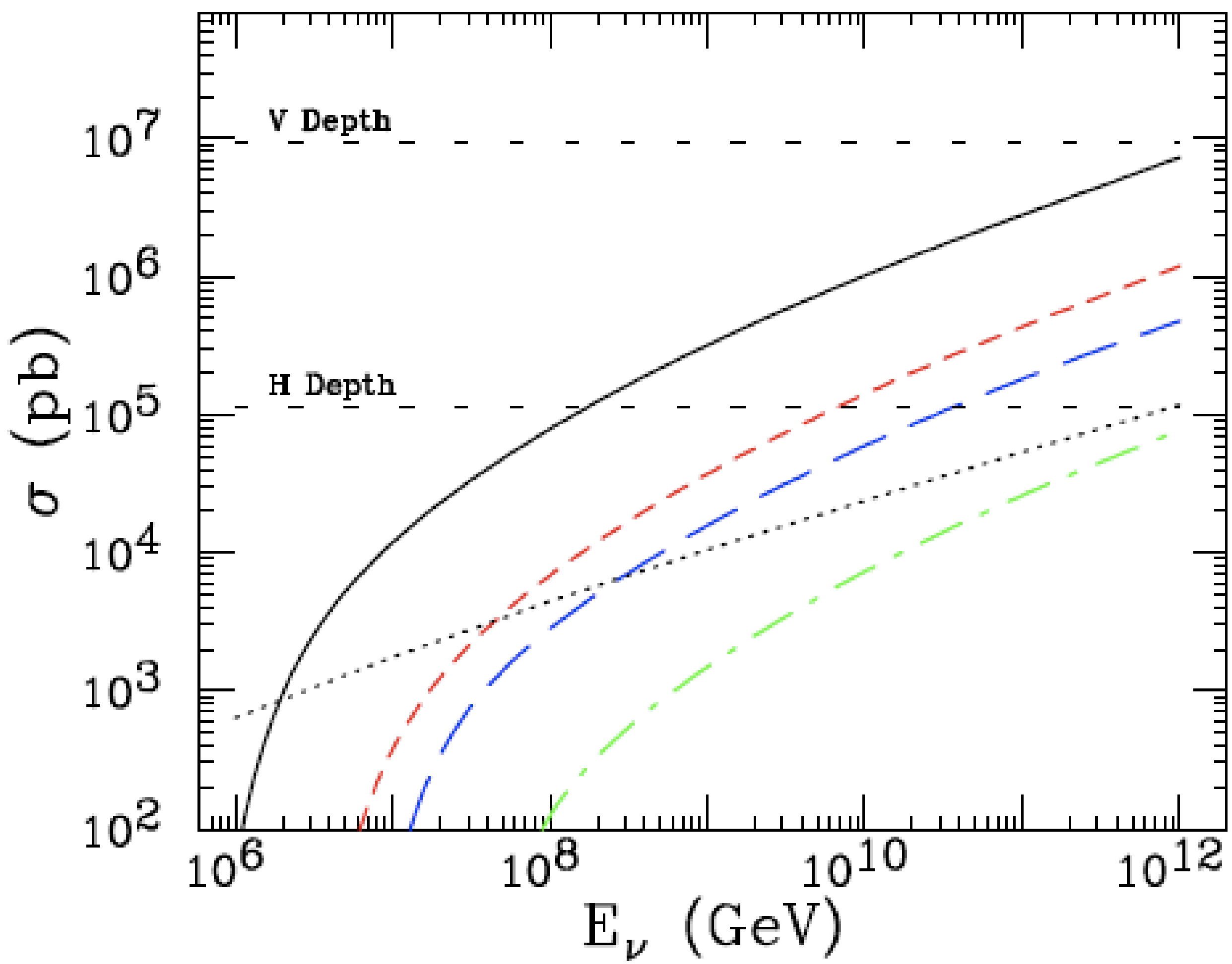
The cross section is highly insensitive to choice of momentum transfer Q, and uncertainties at low x.

parton cross sections πr_s^2



Cross sections $\sigma(\nu N \rightarrow BH)$ for $n = 6$, and $(M_D, x_{min}) = (1$ TeV, $1)$ (solid), (1 TeV, 3) (long dash), (2 TeV, 1) (short dash), (2 TeV, 3) (dot-dash). The dotted curve is the SM cross section $\sigma(\nu N \rightarrow \ell X)$.

parton cross sections $\pi r_s^2 e^{-I}$



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Icecube Implication

the neutrino's interaction length in Earth is

$$L = 1.7 \times 10^7 \text{ km} \left(\frac{\text{pb}}{\sigma} \right)$$

The center of IceCube is at a depth of roughly 1.8 km. A neutrino reaching this point horizontally passes through 150 km of Earth. The cross sections corresponding to neutrino interaction lengths equal to these two lengths, that is, the horizontal and vertical depths of IceCube, are also given in figure.

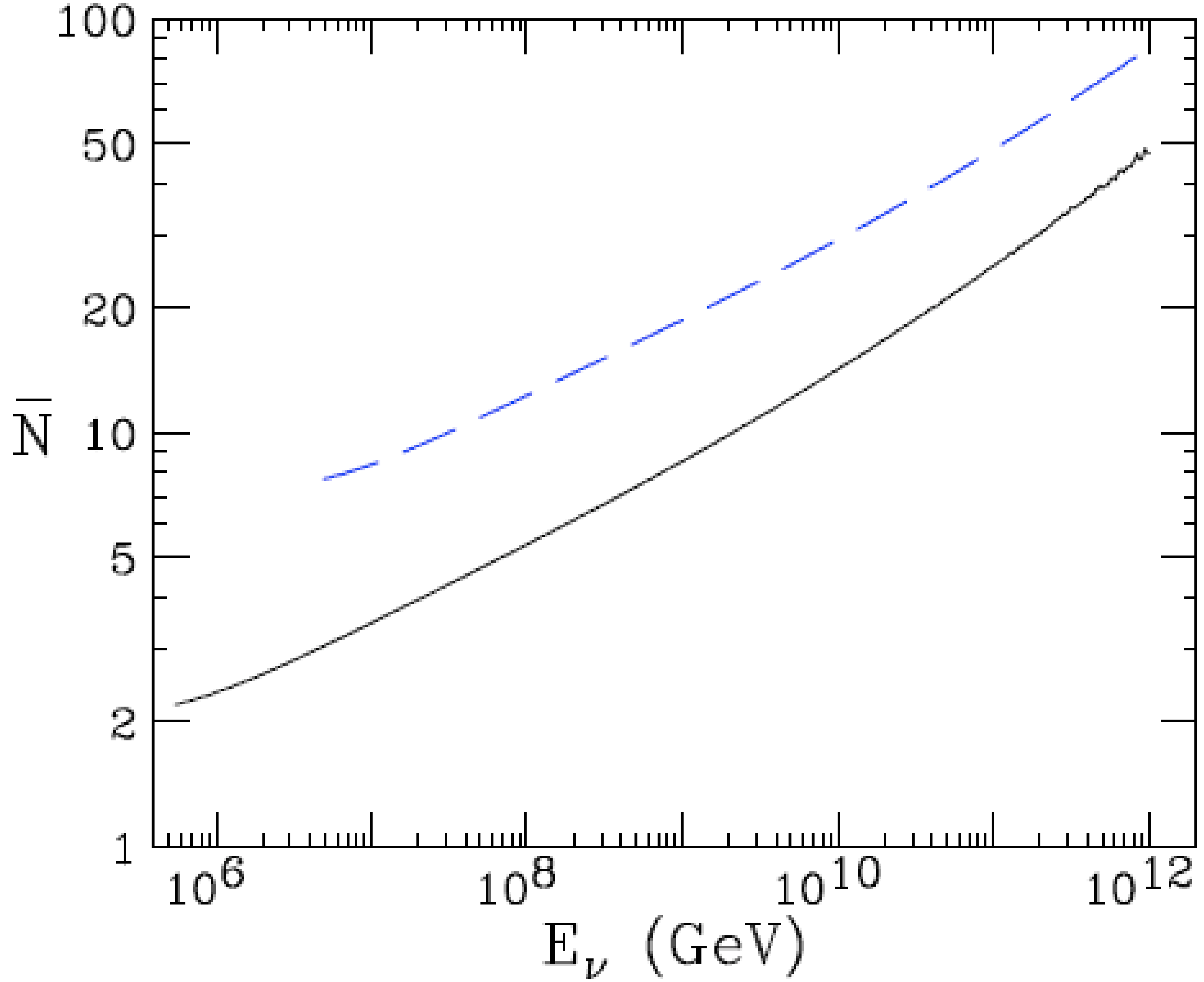
mini-Black Hole Evaporation

These black holes evaporate with rest lifetime of order $\mathrm{TeV}^{-1} \sim 10^{-27}$ s. Even though highly boosted, they decay before accreting matter. They evaporate in a thermal distribution with temperature $T_H = (1+n)/(4\pi r_s)$

$$\langle N \rangle \approx \frac{M_{\mathrm{BH}}}{2T_H} = \frac{2\pi}{1+n}\left[\frac{M_{\mathrm{BH}}}{M_D}\right]^{\frac{2+n}{1+n}}\left[\frac{2^n \pi^{\frac{n-3}{2}}\Gamma\left(\frac{3+n}{2}\right)}{2+n}\right]^{\frac{1}{1+n}}$$

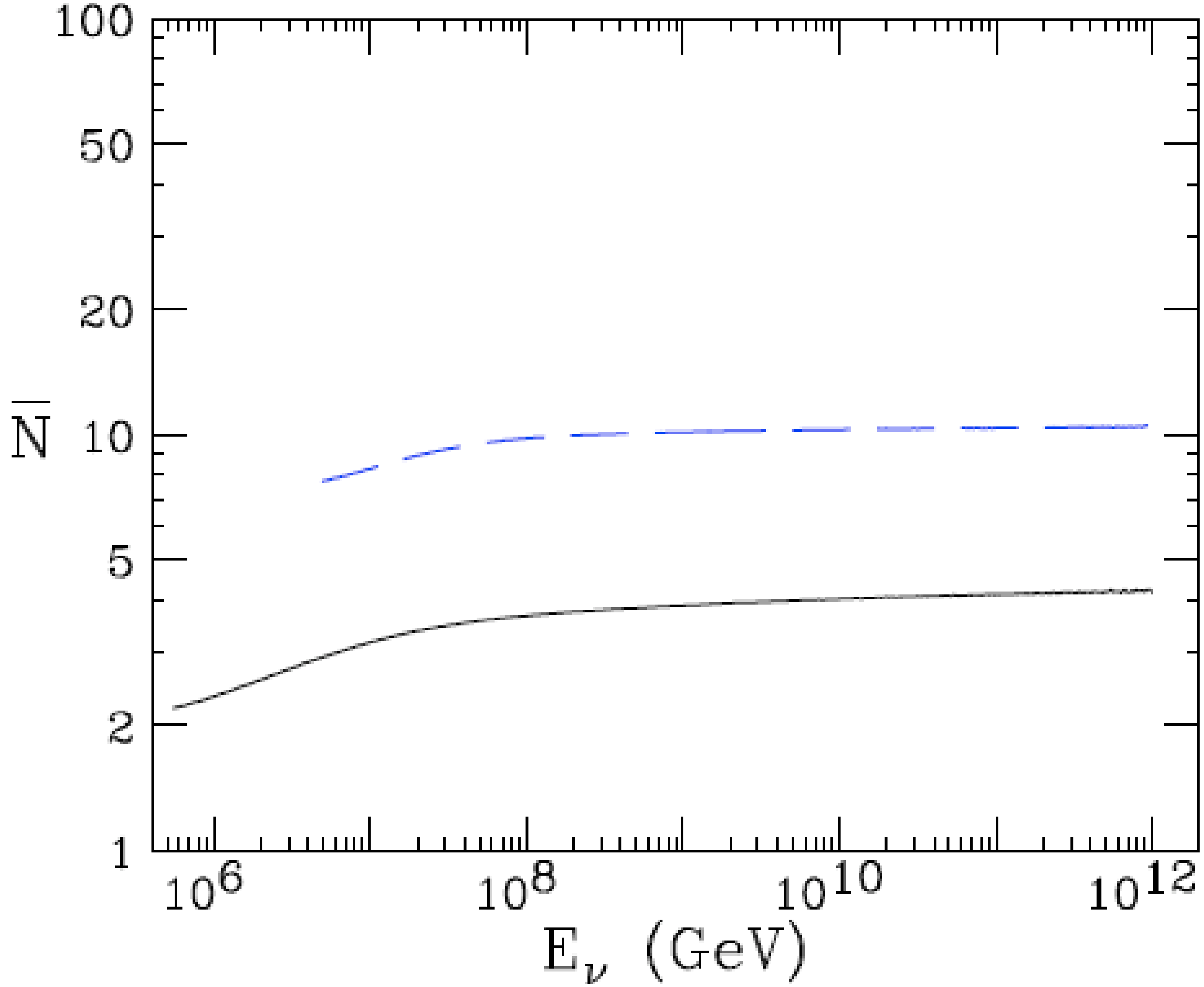
$$\overline{N} = \frac{1}{\sigma}\sum_i \int_{(x_{\mathrm{min}} M_D)^2/s}^{1} dx \,\langle N \rangle\, \hat{\sigma}_i(xs)\, f_i(x, Q)$$

Neglecting particle masses, the decay products are distributed according to the number of degrees of freedom: quarks (72), gluons (16), charged leptons (12), neutrinos (6), W and Z bosons (9), photons (2), Higgs bosons (1), and gravitons (2). We neglect the possibility of other low mass degrees of freedom, such as right-handed neutrinos and supersymmetric particles. About 75% of the black hole's energy is radiated in hadronic degrees of freedom, while the probability of any given decay particle being a muon (or a tau) is approximately 3%.



Weighted multiplicities $\overline{N}$ for $n = 6$, $M_D = 1$ TeV,

and $x_{\min} = 1$ (solid) and 3 (long dash).



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Reference

- arXiv: hep-ph/0107057v2
- arXiv: 0806.3381v2.pdf
- arXiv: 0808.4087v1.pdf
- Steven Giddings, Lecture Notes on *Gauge Theory* at UCSB