Neutrino Bounds on Astrophysical Sources and New Physics

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- Introduction: neutrino and hadron shower Characteristics
- Neutrino acceptances and exposures: hadronic and electromagnetic
- Bounds on the high energy neutrino flux
- Model-independent bounds on new physics interactions
- Implications for TeV-scale gravity
- Conclusions

Work done with: Luis Anchordoqui, Jonathan Feng and Alfred Shapere
Phys. Rev. D **66**, 103002 (2002) [hep-ph/0207139].

Shower characteristics

Neutrino showers

- Long interaction length $>$ any atmospheric depth $\Rightarrow$ showers above detector
- Large EM component
- Curved front
- Signal spread in time (μs)

Hadron showers

- Short Interaction length ~ 40 g/cm^2 $\Rightarrow$ shower maximum high in the atmosphere ($X_{\rm max} \sim 800 - 900$ g/cm^2)
- EM component damped in $\sim 40 - 60$ g/cm^2 $\Rightarrow$ only muons survive at ground
- Flat shower front (> 100 km)
- Short signal (ns)

Neutrino exposure: basic relations

Exposure

$$\mathcal{E}(E_{\rm sh}) \approx \int_0^T dt \int_0^{h_{\rm max}} (A\Omega)_{\rm eff}(E_{\rm sh}, t)\, \frac{\rho_{\rm atm}(0)}{\rho_{\rm water}}\, e^{-h/H}\, dh$$

T = total observation time of the detector

$h_{\rm max} = 15\ {\rm km}, \quad H \approx 8\ {\rm km}$

Effective aperture

P. Billoir, in *Venice 1999, Neutrino telescopes*, Vol. 2, p. 111

$$(A\Omega)_{\rm eff}(E_{\rm sh}, t) \equiv \int_{\theta_{\rm min}}^{\theta_{\rm max}} A(t)\, \mathcal{P}(E_{\rm sh}, \theta, t)\, 2\pi\, \sin\theta\, d\theta$$

$A(t)$ = detector area

$\mathcal{P}(E_{\rm sh}, \theta, t)$ = probability that a shower (energy $E_{\rm sh}$, zenith angle θ) triggers the detector

Neutrino exposure: ground arrays

Hadronic showers (*e.g.*, $\nu N \to \nu X$)

- At ground level, muon component ($\sim$ 10-20% of $E_{\rm sh}$) enhances triggering over EM showers
- At higher $E_{\rm sh}$ hadronic exposure for AGASA for 1.5×10^8 s of livetime between December 1995 and November 2000, based on results from searches for deeply penetrating showers N. Inoue [AGASA Collaboration], *Proc. 26th International Cosmic Ray Conference (ICRC 99)*, eds. D. Kieda, M. Salamon, and B. Dingus, Salt Lake City, Utah, 1999, Vol. 1, p. 361.
- For lower $E_{\rm sh}$, AGASA hadronic exposure obtained by scaling down Auger exposure by factor of 30 (ratio of surface areas). *ask about where is auger hadronic exposure, and about closeness of tanks.*

Electromagnetic Showers (*e.g.*, $\nu_e N \to e X$)

- Adopt effective aperture at Auger K. S. Capelle, J. W. Cronin, G. Parente and E. Zas, Astropart. Phys. **8**, 321 (1998) reduced by ratio of surface areas (factor of 30). This reproduces AGASA's bounds on ν_e fluxes to within 20%.

Neutrino exposure: fluorescence detectors (FD)

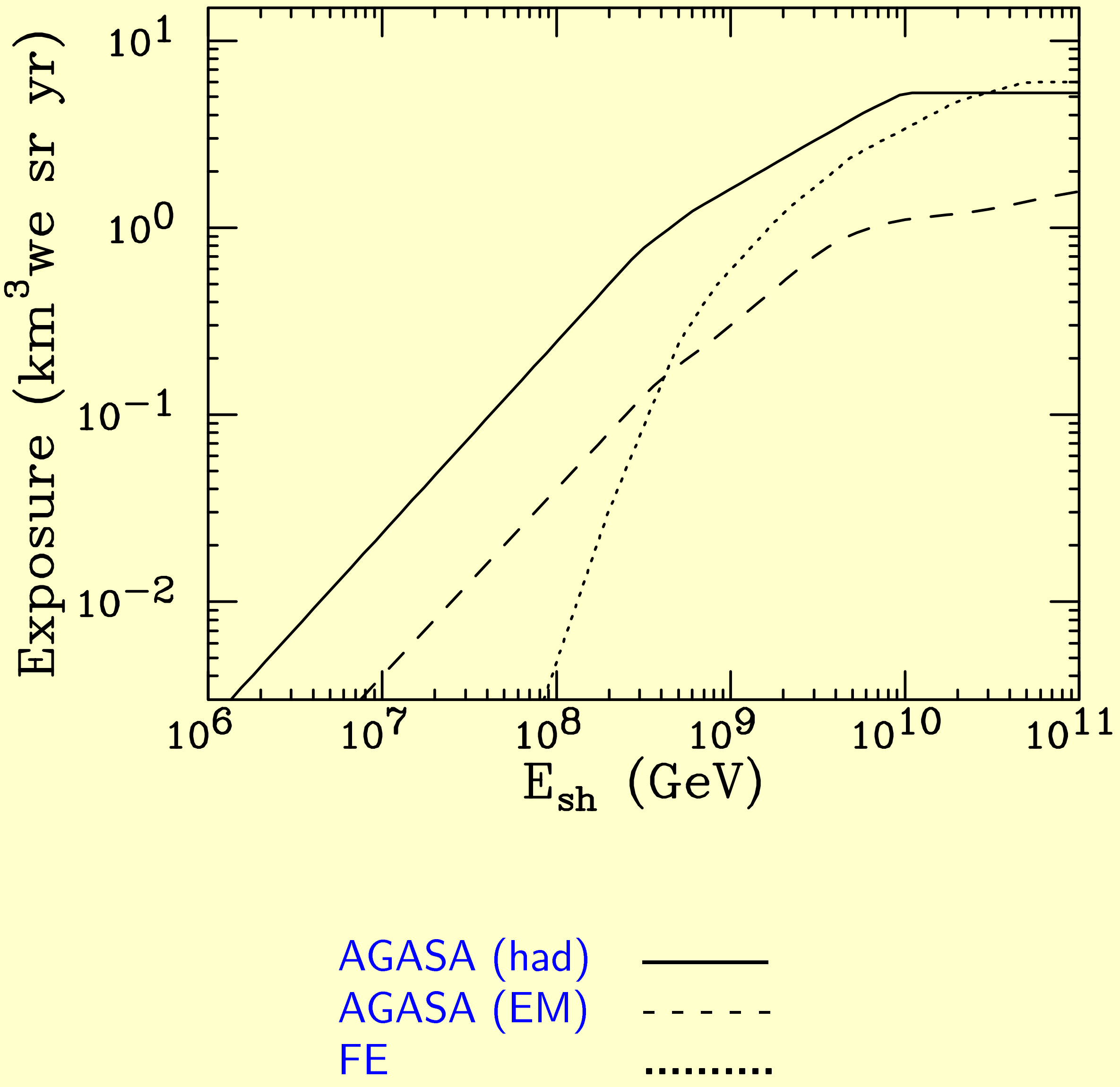
Hadronic and EM similar

- FD's sensitive to total EM activity along shower axis
- Because $\pi^{\pm}$ mostly interact before decay, 80-90% of energy in hadronic showers is EM
- Adopt total FE exposure for both hadronic and EM showers from a total of five running periods ("epochs") (1983-1992) as reported in

  R. M. Baltrusaitis *et al.*, Nucl. Instrum. Meth. A **240** (1985) 410; R. M. Baltrusaitis *et al.*, Nucl. Instrum. Meth. A **264** (1988) 87. D. J. Bird *et al.* [HIRES Collaboration], Astrophys. J. **424** (1994) 491.

- The additional periods enhance the first-epoch FE exposure by a factor of 3.

Total exposures



Results of searches for deeply penetrating QH showers

AGASA Collaboration

- Searched for QH showers with $X_{\max} \geq 2500$ g/cm^2
- $X_{\max}$ determined by
  - fit to lateral distribution of charged particles at ground level
  - fit to curvature of shower front
- expected hadronic backg'd 1.72 events
- only one event with $X_{\max}$ clearly $>$ 2500 g/cm^2

Fly's Eye

- $X_{\max}$ determined by 3-parameter fit to charged particle density
- 5000 events, 11 years, no neutrino candidates
- combined data imply upper bound of 3.5 neutrino-induced events at 95% CL

Working equations for bounds

Event rate

$$N = \sum_{i,X} \int dE_i \, N_A \, \frac{d\Phi_i}{dE_i} \, \sigma_{iN\to X}(E_i) \, \mathcal{E}_{iX}(E_i)$$

- $i = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
- $d\Phi_i/dE_i =$ source flux of neutrino species i.
- $\mathcal{E}_{iX}(E_i) =$ appropriate exposure measured in cm^3 we sr · time.

Exposures for SM processes

- 20% of energy → hadronic recoil
- Examples for AGASA (charged current)

$$\begin{aligned} \mathcal{E}_{\nu_e X}(E_{\nu_e}) &= \min\{\mathcal{E}_{\rm had}(0.2E_{\nu_e}) + \mathcal{E}_{\rm EM}(0.8E_{\nu_e}), \mathcal{E}_{\rm sat}\} \\ \mathcal{E}_{\nu_\mu X}(E_{\nu_\mu}) &= \mathcal{E}_{\rm had}(0.2E_{\nu_\mu}) \end{aligned}$$

- Examples for Fly's Eye (charged current):

$$\begin{aligned} \mathcal{E}_{\nu_e X}(E_{\nu_e}) &= \mathcal{E}(E_{\nu_e}) \\ \mathcal{E}_{\nu_\mu X}(E_{\nu_\mu}) &= \mathcal{E}(0.2E_{\nu_\mu}) \end{aligned}$$

- Neutral current RHS $= \mathcal{E}_{\rm had}(0.2E_{\nu_i})$ (AGASA), $\mathcal{E}(0.2E_{\nu_i})$ (FE)

Bounds on astrophysical neutrino fluxes

Model-independent local bounds

- Previous bound valid bin by bin

$$\sum_{i,X} \int_\Delta dE_i \, N_A \, \frac{d\Phi_i}{dE_i} \, \sigma_{iN \to X}(E_i) \, \mathcal{E}_{iX}(E_i) \; < 3.5 \;,$$

- Choose logarithmic interval small enough where

$$\frac{d\Phi_i}{dE_i} \, \sigma_{iN \to X}(E_i) \, \mathcal{E}_{iX}(E_i) \sim E_i^\alpha \longrightarrow$$

$$\int_{\langle E_i \rangle e^{-\Delta/2}}^{\langle E_i \rangle e^{\Delta/2}} \frac{dE_i}{E_i} \, E_i \, \frac{d\Phi_i}{dE_i} \sigma_{iN \to X}(E_i) \, \mathcal{E}_{iX}(E_i) =$$

$$\langle \sigma_{\nu_i N \to X}(E_i) \rangle \, \langle \mathcal{E}_{iX}(E_i) \rangle \, \langle E_i \, d\Phi_i / dE_i \rangle \frac{\sinh \delta}{\delta} \, \Delta$$

$$\delta = (\alpha + 1)\Delta/2$$

- Since $\sinh \delta/\delta > 1$, → conservative local bound

$$N_A \sum_{i,X} \langle \sigma_{\nu_i N \to X}(E_i) \rangle \, \langle \mathcal{E}_{iX}(E_i) \rangle \, \langle E_i d\Phi_i / dE_i \rangle$$

$$< 3.5/\Delta$$

Bounds on astrophysical neutrino fluxes (cont'd)

Model-independent local bounds (continued)

- Take $\Delta = 1$, and total mixing

$$\langle E_i d\Phi_i/dE_i \rangle = \frac{1}{6} \langle E_\nu d\Phi_\nu/dE_\nu \rangle$$

and use SM cross sections to obtain model-independent local upper bound on total ν flux at 95% CL.

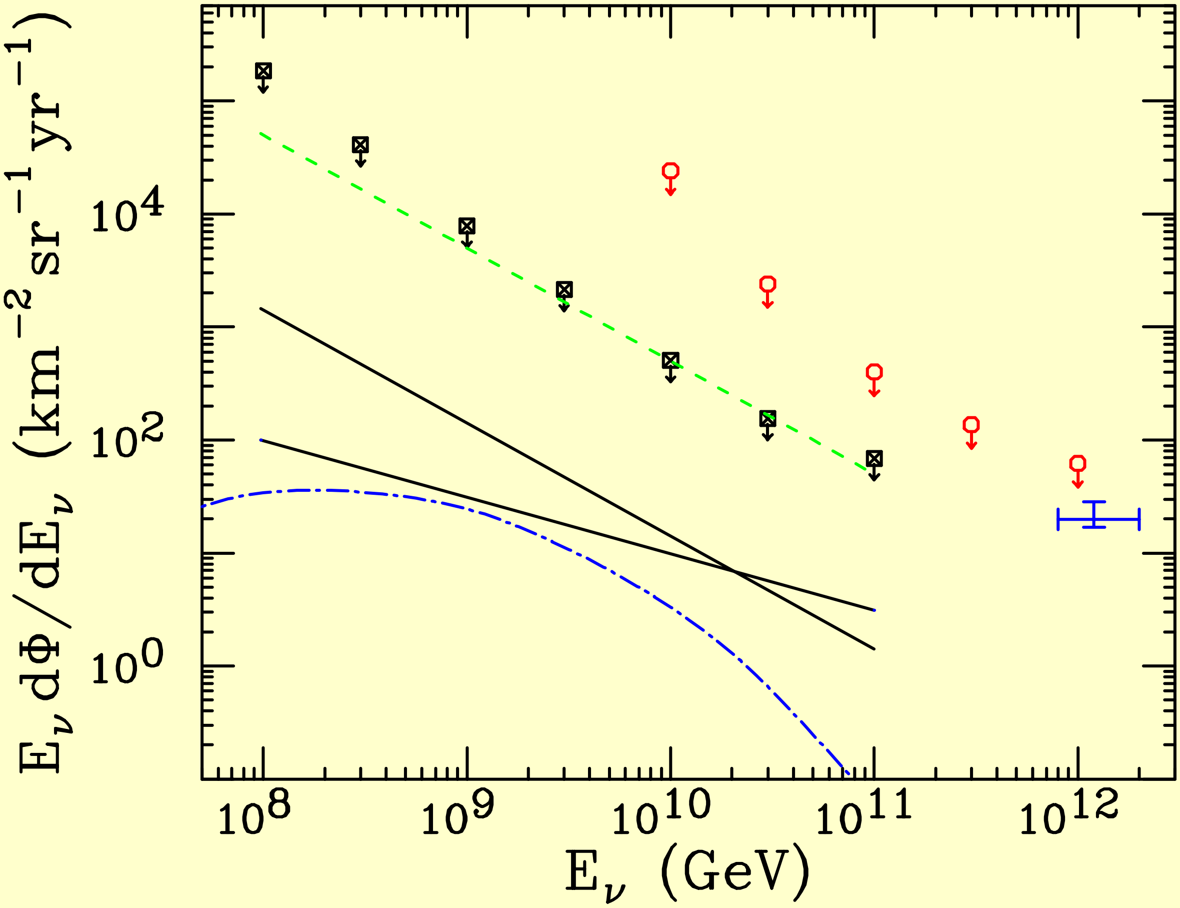
Global bounds assuming particular flux behavior

- Illustrative choices

$$\frac{d\Phi_\nu}{dE_\nu} = J_0 \left(\frac{E_\nu}{E_0}\right)^{-\gamma} \;, \gamma = 1.5 \text{ or } 2.0$$

- Can now integrate and obtain bounds over entire energy range for each γ.

Graphical summary of flux bounds



■	Model independent (this work)
──	Assumed power law ($\gamma = 1.5, 2.0$) (this work)
╌╌╌╌	RICE (ν_e, assumes $\gamma = 2$) I. Kravchenko *et al.*, astro-ph/0206371.
○	GLUE ($\nu_e + \nu_\mu$) P. W. Gorham *et al.*, astro-ph/0102435.
-.-.-.-.	Cosmogenic flux (Protheroe-Johnson) Astrop. Phys. **4**, 253 (1996)
+	Required for Z-burst Fodor, Katz, Ringwald, hep-ph/0203198

Weiler, Phys. Rev. Lett. **49**, 234 (1982); Astropart. Phys. **11**, 303 (1999);

Fargion et al, Astrophys. J. **517**, 725 (1999)

RICE and GLUE

Radio Ice Čerenkov Experiment:

searches for radio pulses from EM showers created by electron neutrino collisions in ice.

Goldstone Lunar Ultra-high energy neutrino Experiment:

searches for microwave Čerenkov pulses from EM showers induced by neutrinos in the Moon's rim.

Bounds on neutrino cross sections

Assume Protheroe-Johnson flux

- Input nucleon spectrum E^{-2}, cutoff energy $10^{12.5}$ GeV, source evolution $(1+z)^4$ as a minimum
- Expected event rate at AGASA and FE with SM cross section $\sim$ 0.02/yr
- Keep new physics flavor-blind, negligible EM component
- Illustrate with two cases for new physics

  (1) $y = E_{\rm sh}/E_\nu = 1$: all energy into shower. Example: TeV scale black hole production. D'Eath, Payne, Phys. Rev. D **46**, 694 (1992).

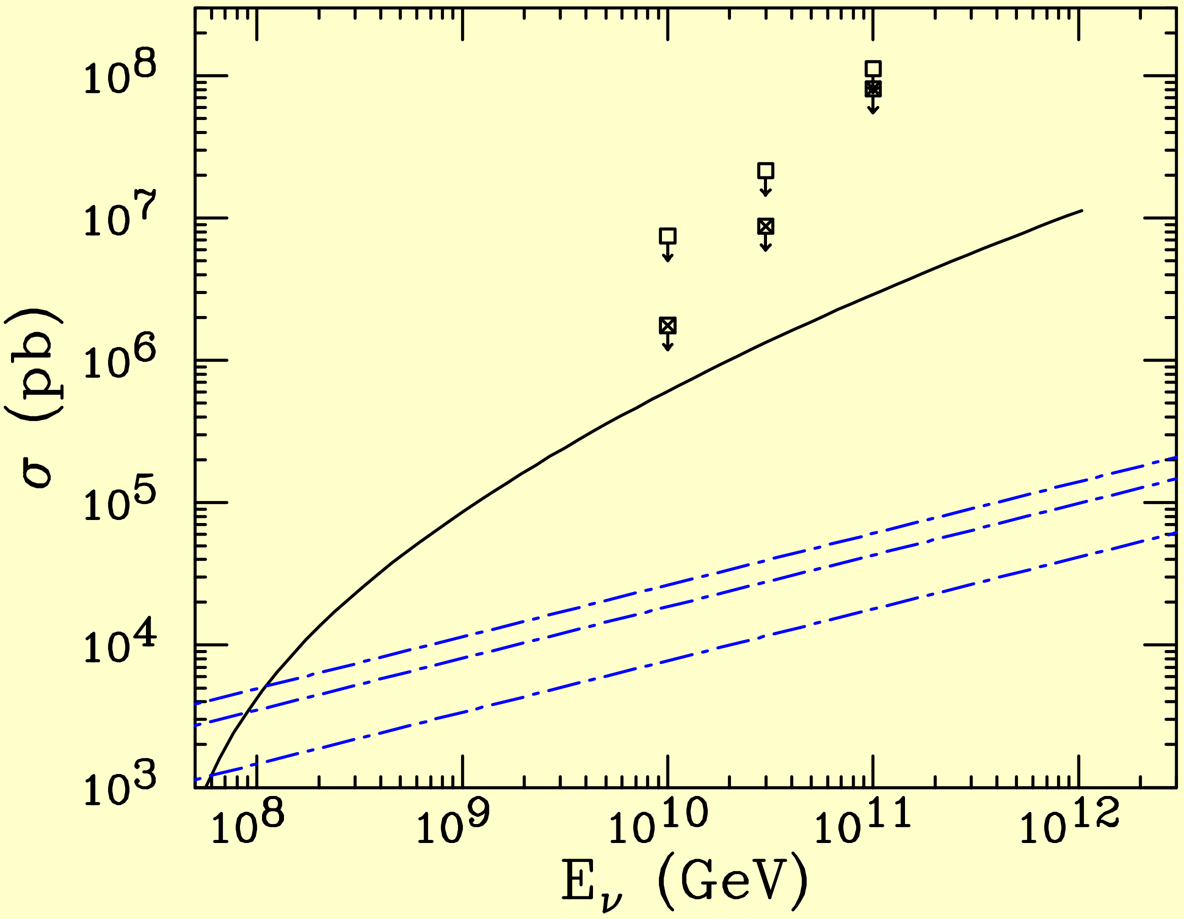
  (2) $y = 0.1$: leading particle effect. Example: KK graviton exchange in NC interaction Kachelriess, Plumacher, hep-ph/0109184.

- Model-independent condition on cross section is now

$$N_A \left<\sigma_{\nu N \to X}(E_\nu)\right> \left<\mathcal{E}(yE_\nu)\right> \left<E_\nu d\Phi_\nu/dE_\nu\right> < 3.5$$

averaged over an energy interval of 1 e-folding.

Summary of νN cross section bounds



☐ Model-independent $y = 0.1$

■ Model-independent $y = 1$

—— BH production σ for $n = 7,\ x_{\min} = 5$
$M_D = 1.1$ TeV.

-.-.-.-.-. SM total, CC, NC σ

νN cross section bounds (cont'd)

Comparison to previous bounds C. Tyler, A. V. Olinto and G. Sigl, Phys. Rev. D **63**, 055001 (2001) [hep-ph/0002257] (TOS)

- Updated exposure → gain factor of 9
- Cosmogenic flux source cutoff energy of $10^{12.5}$ *vs.* $10^{11.5}$ in TOS (just at cutoff CR energy) → gain factor of 4
- 95% CL limits→ lose factor of 4

→ net improvement on bounds by about order of magnitude

Implications for TeV-scale gravity

Extra dimensions

- General idea: our 4-dimensional universe is embedded in a larger geometry with n extra spatial dimensions
- Compactify on n-torus, common radius R
- Regaining Newton's law at distances large compared to R implies

$$M_{\rm Pl}^2 = 8\pi\ M_D^{2+n}\ R^n$$

  with M_D related to the $(4+n)$-dimensional Planck mass
- Exciting possibility: R is large enough so that $M_D \sim 1$ TeV I. Antoniadis, Phys. Lett. B **246**, 377 (1990); J. D. Lykken, Phys. Rev. D **54**, 3693 (1996) [hep-th/9603133]; N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429**, 263 (1998) [hep-ph/9803315]
- Striking implication: existence of tower of massive gravitons (KK)

Bounds on M_D

Tabletop Gravity

Newtonian gravity good down to 0.2 mm Hoyle et al., PRL86 (2001) 1418 → for $n = 1$ $M_D >$ 5000 TeV: uninteresting

Astrophysics

For $n = 2(3)$ limits on rate of supernova cooling through KK graviton emission require $M_D > 10(600)$ TeV Cullen-Perelstein, PRL83 (1999) 268; Hannestad-Raffelt, PRL87 (2001) 051301; hep-ph/0110067

Accelerator experiments

- LEP – direct graviton emission (single photons, Z's): for $n = 4(6)$, $M_D > 870(610)$ GeV L3 Collaboration, PLB470 (1999) 281
- Tevatron – virtual KK graviton exchange in e^+e^- and $\gamma\gamma$ production: $M_D > 1.0 - 1.2$ TeV, *depending on brane tension cutoff*

Black holes

- Proposal that collapse to TeV-scale BHs occurs in high energy particle collisions Banks, Fischler, hep-th/9906038; Emparan, Horowitz, Myers, Phys. Rev. Lett. **85**, 499 (2000) [hep-th/0003118]; Giddings, Katz, J. Math. Phys. **42**, 3082 (2001) [hep-th/0009176]; Giddings, Thomas, hep-ph/0106219; Dimopoulos,Landsberg, Phys. Rev. Lett. **87**, 161602 (2001) [hep-ph/0106295].
- These evaporate primarily to SM particles
- Parton-parton cross section is $\sim$ geometric $\hat{\sigma} \simeq \pi r_s^2$, where Schwarzschild radius

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

Black hole production by neutrinos in cosmic rays

- Can initiate deep quasi-horizontal showers far above SM rate Feng, Shapere, Phys. Rev. Lett. **88**, 021303 (2001) [hep-ph/0109106]

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

  Cross section depends on

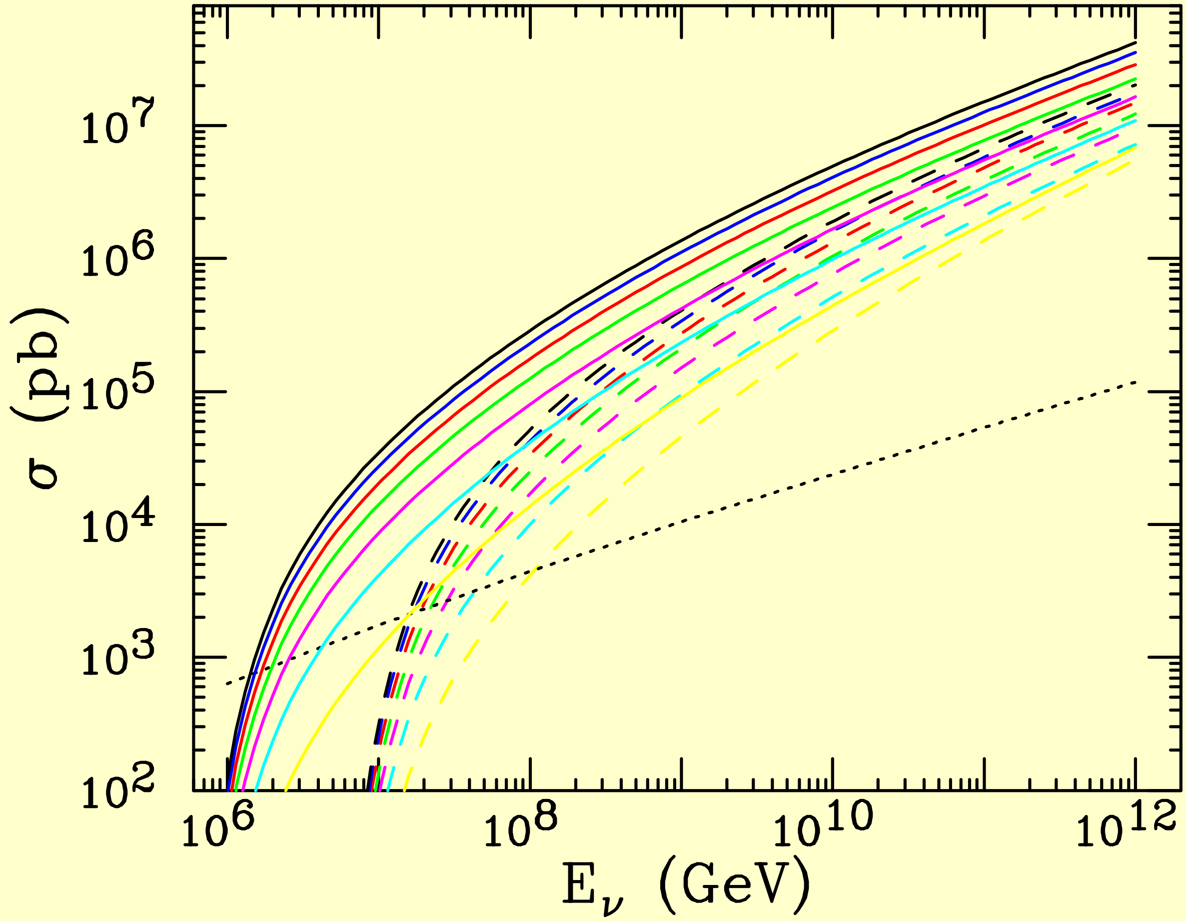
  $$x_{\min} \equiv M_{\mathrm{BH}}^{\min}/M_D$$

- $x_{\min}$ related to validity of classical description of BH: the entropy

  $$S = f(n)\left(\frac{M_{\mathrm{BH}}}{M_D}\right)^{\frac{2+n}{1+n}}$$

  so that for $S \gtrsim 10$, require $x_{\min} \simeq 3$.

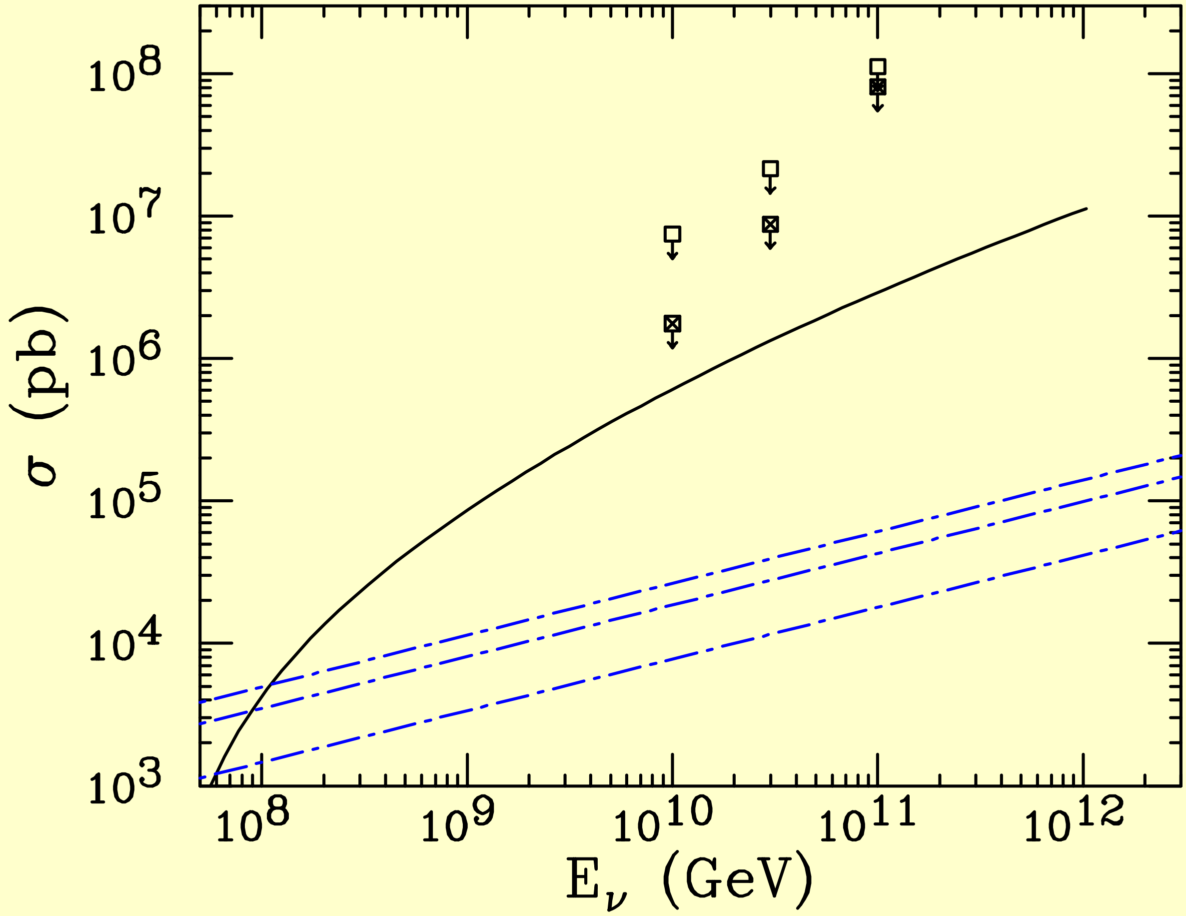
Some sample cross sections



BH cross sections for $n = 1, \ldots 7$ from bottom
Solid lines: $x_{\min} = 1$
Dashed lines: $x_{\min} = 3$
Dotted line: SM

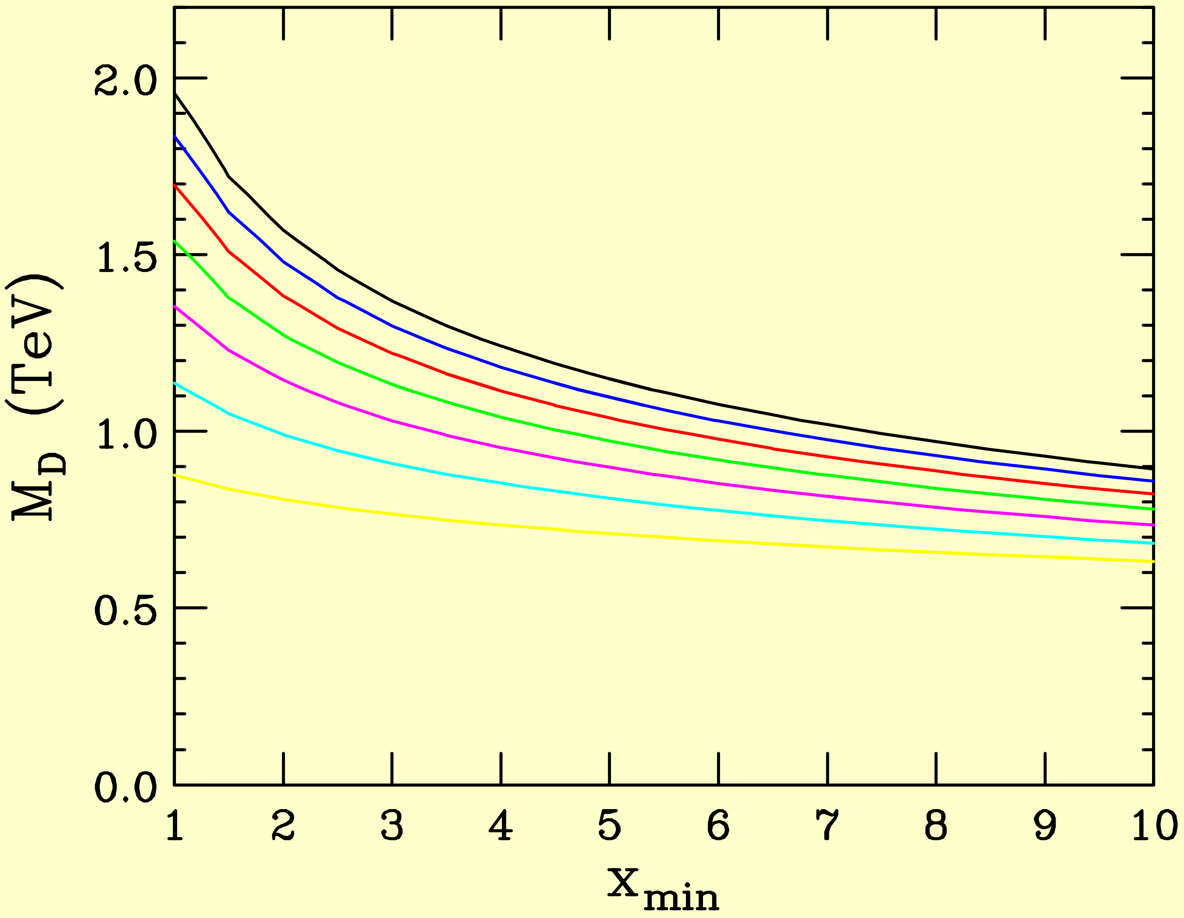
Bounds on TeV-scale gravity

- Total exposure + cosmogenic flux + σ $\longrightarrow$ expected event rates for different value of $x_{\min}$ and M_D
- Requiring that event rate satisfy the 95% CL bound $\longrightarrow$ determine lower bound on M_D for each $x_{\min}$



Bounds on TeV-scale gravity (cont'd)

Can now generate 95% exclusion plot in $M_D\!-\!x_{\min}$ space, $n = 1\ldots7$ from bottom.



For example, for $n = 6(7)$, $x_{\min} = 3$, so that entropy ≥ 20, obtain $M_D \geq 1.30\ (1.40)$.

Comparison with D0 Collaboration bounds

- These are obtained from 95% CL upper bounds on anomalous 4-point functions generating $\gamma\gamma$ or e^+e^- pairs. B. Abbott *et al.* [D0 Collaboration], Phys. Rev. Lett. **86**, 1156 (2001) [arXiv:hep-ex/0008065].

- The 4-pt function arises through virtual KK graviton s-channel intermediate states. Giudice, Rattazzi, Wells, Nucl. Phys. B **544**, 3 (1999); Han, Lykken and Zhang, Phys. Rev. D **59**, 105006 (1999); Hewett, Phys. Rev. Lett. **82**, 4765 (1999).

- Sum diverges, so need cutoff introduced as brane-softening factor Λ - expect $\Lambda \leq M_D$.

  M. Bando *et al*, Phys. Rev. Lett. **83**, 3601 (1999); M. Bando, T. Noguchi, arXiv:hep-ph/0011374; H. Murayama, J. D. Wells, arXiv:hep-ph/0109004.

Table 1: Lower limits on M_D at 95% CL in TeV.

Λ/M_D	$M_{D,\rm min}$ (TeV)		
	$n = 4$	$n = 6$	$n = 7$
0.5	0.80	0.63	0.58
0.6	0.88	0.76	0.73
0.7	0.95	0.89	0.88
0.8	1.01	1.01	1.04
0.9	1.07	1.14	1.21
1.0	1.13	1.26	1.38

- For $\Lambda < M_D$, present bounds $1.3 - 1.4$ TeV exceed Tevatron bounds ~ 1 TeV.

Summary of results and conclusions

- New bounds obtained on the cosmic neutrino flux from existing limits on quasi-horizontal deeply developing showers, taking into account the combined exposures of the AGASA and Fly's Eye experiments. Results significantly strengthen existing limits.

- They also present severe constraints on top-down models where the cascade decay of exotic elementary X particles or topological defects are responsible for the events detected with energies $\gtrsim 10^{11}$ GeV. This is because neutrinos are typically a significant component in X decays, and have a hard spectrum extending up to $M_{\rm GUT} \sim 10^{16}$ GeV, and our bounds are typically exceeded when the proton flux from top-down models is normalized to the observed spectrum.

- Complete neutrino exposure was combined with the flux of cosmogenic neutrinos, to derive model-independent upper bounds on the neutrino-nucleon cross section. These bounds strengthen existing limits by roughly one order of magnitude.

Summary of results and conclusions (cont'd)

- Considered TeV-scale gravity models to study BH production. Upper bounds on the neutrino-nucleon cross section implied lower limits on the fundamental Planck scale, which represent the best existing limits on TeV-scale gravity for $n \geq 5$ extra spatial dimensions.