EXTRA DIMENSIONS

Jonathan Feng

UCI QuarkNet
Associate Teachers Institute
23 August 2002

The Standard Model

Triumphs: explains LOTS of data

- EM force tested to 10^{-8}
- Weak force tested to 10^{-3}
- Strong force tested to 10^{-2}

So what's wrong with the Standard Model?

- Higgs boson not found
- Masses not understood
- Not enough CP violation
- No explanation of dark matter

  ⋮

- NO GRAVITY!

Why not include gravity?

Many deep problems, but one is easy to understand:

To unify, forces must have equal strength.

Gravity is *very* weak.

The weakness of gravity

Consider 2 protons 1 cm apart:

$$F_{\mathsf{EM}} = \frac{q^2}{r^2} = \frac{(4.8 \times 10^{-10}\ \mathsf{esu})^2}{(1\ \mathsf{cm})^2}$$

$$= 2.3 \times 10^{-19}\ \mathsf{dynes}$$

$$F_{\mathsf{grav}} = G_N \frac{m^2}{r^2} = 6.7 \times 10^{-8}\ \mathsf{cm}^3\ \mathsf{g}^{-1}\ \mathsf{s}^{-2}$$

$$\times \frac{(1.7 \times 10^{-24}\ \mathsf{g})^2}{(1\ \mathsf{cm})^2}$$

$$= 1.9 \times 10^{-55}\ \mathsf{dynes}$$

Gravity is 10^{36} times weaker!

Illustrations

- Magnet vs. Earth

A magnet can lift a paper clip against the gravitational pull of the entire Earth.

- Earth and moon

Suppose there were $10^{18}+1$ protons for every 10^{18} electrons on both the Earth and moon. Bye-bye, moon!

EM is negligible in astronomy only because matter is *extraordinarily* close to neutral.

So gravity is very weak.

Or maybe it isn't. For example, if the charges of the electron and proton were 10^{20} times smaller, electromagnetism would appear weak also.

Gravity could be weak because the masses ('gravitational charges') of all elementary particles are unusually small.

"Unusually small" — compared to what?

Dimensional analysis

All fundamental quantities should be of order 1 when expressed in terms of fundamental constants.

We know 3 fundamental constants:

Special relativity: speed of light c
Gravity: Newton's constant G_N
Quantum mechanics: Planck's constant h

These uniquely define one mass, one length, and one time:

$$M_{\text{Planck}} = \sqrt{\frac{hc}{G_N}} \approx 10^{18}\ \text{GeV}/c^2$$

$$l_{\text{Planck}} = \ldots\ldots \approx 10^{-33}\ \text{m}$$

$$t_{\text{Planck}} = \ldots\ldots \approx 10^{-43}\ \text{s}$$

All observed masses are $\lesssim 200$ GeV, and so are unusually small compared to M_{Planck}.

The gauge hierarchy problem

Gravity is weak $\Leftrightarrow m_{\text{proton}} \ll M_{\text{Planck}}$

Both are equally good interpretations.

Why is this? No one knows.

This is the *gauge hierarchy problem*, one of the central problems of particle physics.

Its solutions almost all require new particles and interactions (beyond the Higgs boson) at the LHC and other experiments.

Aside

Dimensional analysis is invalidated by symmetries.

Consider a soap bubble: it's length and width are identical to high accuracy.

Why? Rotational symmetry.

The gauge hierarchy problem has a similar solution, called *supersymmetry*, which predicts partner particles for all known particles.

Supersymmetry relates fermions (spin 1/2, 3/2) to bosons (spin 0, 1, 2).

Extra dimensions

Proposal: maybe gravity isn't weak, and the particles aren't light.

Gravity only seems weak because it's diluted by propagating in small extra dimensions.

4D, 5D, etc. are hard to envision. Consider lower-dimensional examples:

• Garden hose. This looks 1D from far away, but is 2D to a small insect.

• Table top. This looks 2D from far away, but close up, we see it has a small 3rd dimension. (We must 'identify' the top and bottom so we wrap around, as with the garden hose.)

Force law

Suppose there are 2 large dimensions, and one small one of length L. What is the force between two particles separated by distance r?

- $r \ll L$ (3D) $\Rightarrow F_{\text{grav}} \sim 1/r^2$ ("3D")

- $r \gg L \Rightarrow F_{\text{grav}} \sim 1/r$ ("2D")

More generally, in $(3+n)$ spatial dimensions, $F_{\text{grav}} \sim 1/r^{2+n}$.

Force unification

Assume EM propagates in only 3D, but gravity propagates in more.

Can gravity become strong where the electromagnetic and weak forces unify, around 10^{-16} cm?

The required length of the extra dimension is

$$L \sim 10^{\frac{32}{n}-19} \text{ m}$$

n	L
1	10^{13} m
2	mm
3	10 nm
4	10^{-11} m
6	10 fm

For $n = 1$, Newton's Law would be wrong on solar system length scales. This is not possible.

However, for $n = 2$, $1/r^2$ would be modified at distances below 1 mm. This is still possible.

How to discover new dimensions

1. Tests of Newton's $1/r^2$ law at short distances.

2. New collider signals at the Tevatron and LHC.

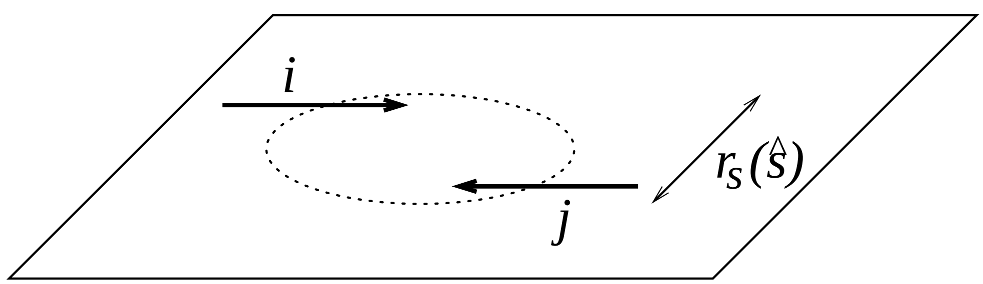
Events: $q\bar{q} \rightarrow \gamma \rightarrow e^{+}e^{-}G$

Gravitons would evade detection, lead to strange missing energy events.

3. Microscopic black holes

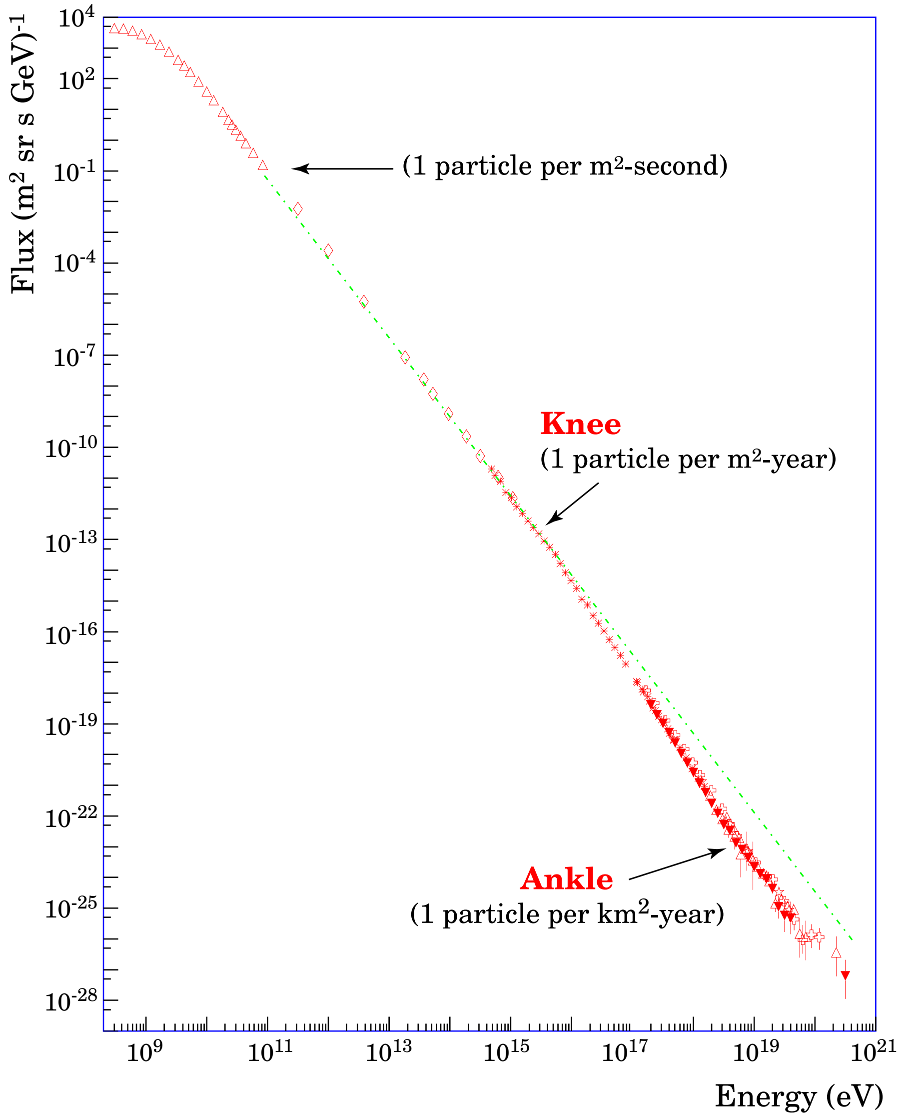
With extra dimensions, a TeV mass particle experiences gravity and all other forces with the same strength.

$E = mc^2 \Rightarrow$ In collisions with center-of-mass energy $E \sim$ TeV, gravity becomes strong, black holes form.



Particles must pass close to each other at high energy to concentrate a large energy within a small space.

Good places to look: colliders, cosmic rays.

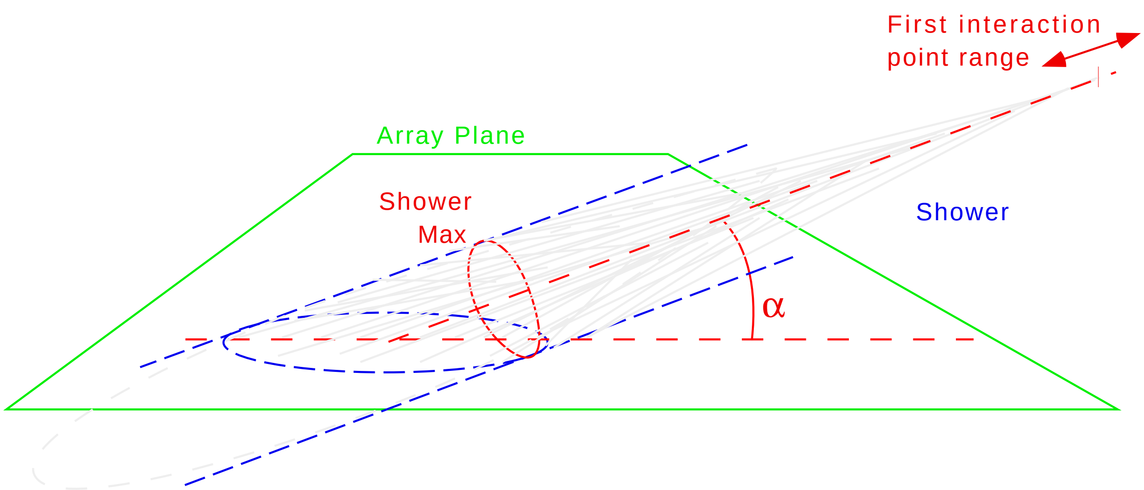


The energy frontier: $\sqrt{s} = \sqrt{2m_{\text{proton}}E}$

$$E \sim 10^{19}\ \text{eV} \Rightarrow \sqrt{s} \sim 100\ \text{TeV}$$

Microscopic black holes

- are 10^{-16} cm wide
- decay through Hawking radiation in 10^{-27} s
- would initiate a few showers per minute in the Earth's atmosphere



Cosmic ray detectors (Auger, etc.) may see 10-100 black holes in the next few years.

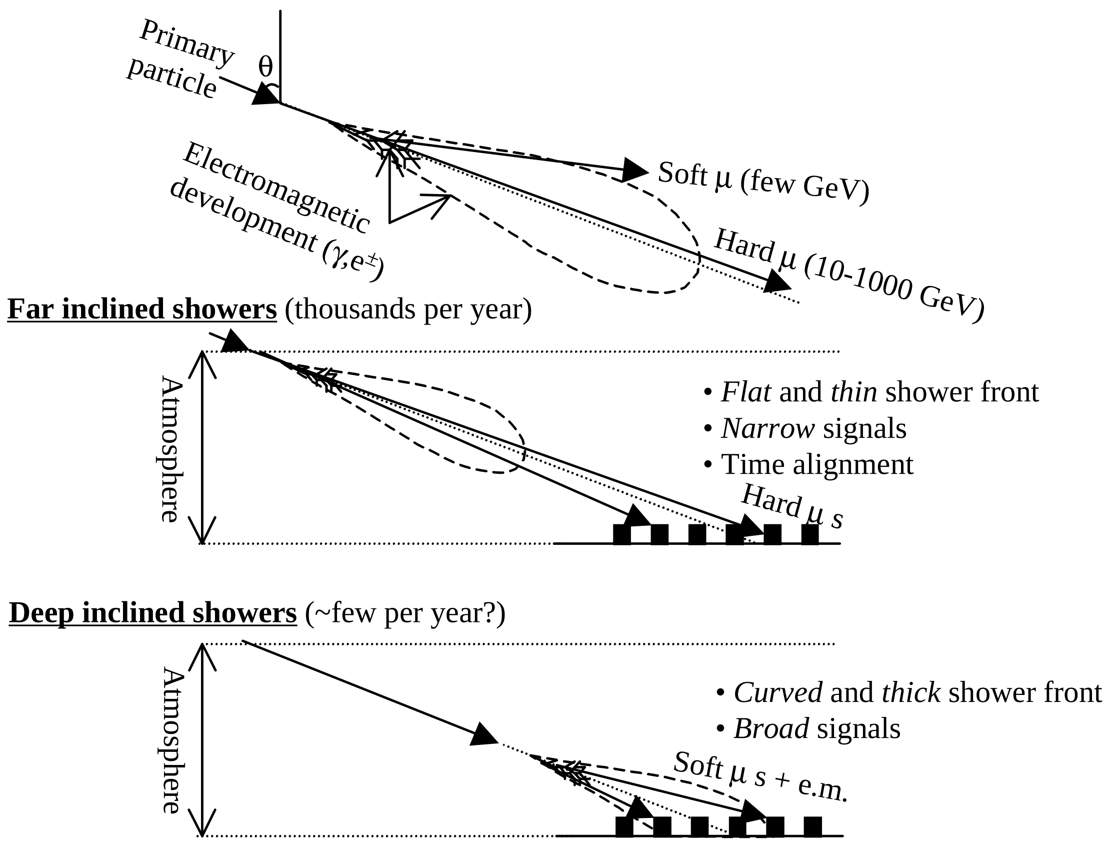


FIG. 6. Schematic representation of a UHE air shower, and of its placement with respect to the ground and the Auger array. A "far inclined" shower is likely to be due to a hadronic cosmic ray, whereas a "deep inclined" shower can only be caused by a neutrino.