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## **Perspectives in High-Energy Physics**

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# Perspectives in High-Energy Physics<sup>1</sup>

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**Abstract.** I sketch some pressing questions in several active areas of particle physics and outline the challenges they present for the design and operation of detectors.

## INTRODUCTION

My assignment at the 1999 ICFA Instrumentation School is to survey some current developments in particle physics, and to describe the kinds of experiments we would like to do in the near future and illustrate the demands our desires place on detectors and data analysis. Like any active science, particle physics is in a state of continual renewal. Many of the subjects that seem most fascinating and most promising today simply did not exist as recently as twenty-five years ago. Other topics that have preoccupied physicists for many years have been reshaped by recent discoveries and insights, and transformed by new techniques in accelerator science and detector technology. To provide some context for the courses and laboratories at this school, I have chosen three topics that are of high scientific interest, and that place very different demands on instrumental techniques. I hope that you will begin to see the breadth of opportunities in particle physics, and that you will also look beyond the domain of particle physics for opportunities to apply the lessons you learn here in Istanbul.

I begin with the remarkable neutrino, a subatomic particle that our instruments must be able to detect both by its presence and by its absence, depending on the circumstances. In particular, I note the interest in observing and characterizing neutrino oscillations in order to determine the properties of the neutrinos, and describe some of the new instruments contemplated to do that. Then I will talk about physics at the high-energy frontier, focusing on what we hope to learn from

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the top quark in the next set of experiments at Fermilab's Tevatron Collider. Third, I will tell you some of the ways we hope to explore the landscape of spacetime, and explore some of the signs we might find that the three-plus-one dimensions of ordinary experience are not the whole story. My treatment of all of these will be schematic; in a single lecture, my intent is to raise questions and present a wide range of challenges and opportunities.

## NEUTRINO PUZZLES

Neutrinos are tiny subatomic particles that carry no electric charge, have (almost) no mass, move (nearly) at the speed of light, and hardly interact at all. They are among the most abundant particles in the Universe. As you listen to this lecture, inside your body are more than 10 million ( $10^7$ ) relic neutrinos left over from the Big Bang. Each second, some  $10^{14}$  neutrinos made in the Sun pass through you. In one tick of the clock, about a thousand neutrinos made by cosmic-ray interactions in Earth's atmosphere traverse your body. Other neutrinos reach us from natural sources, including radioactive decays of elements inside the Earth, and artificial sources, such as nuclear reactors.

Our awareness of neutrinos started with a puzzle in 1914 that led to an idea in 1930 that was confirmed by an experiment in 1956. Today, neutrinos have become an important tool for particle physics and astrophysics, and fascinating objects of study that may yield important new clues about the basic laws of Nature.

### The First Neutrino Puzzle

There was a neutrino puzzle even before physicists knew there was a neutrino. Natural and artificial radioactivity includes nuclear beta ( $\beta$ ) decay, observed as



where  $\beta^-$  is the old-fashioned name for an electron and  ${}^A_Z$  stands for the nucleus with  $Z$  protons and  $A - Z$  neutrons. Examples are tritium  $\beta$  decay,



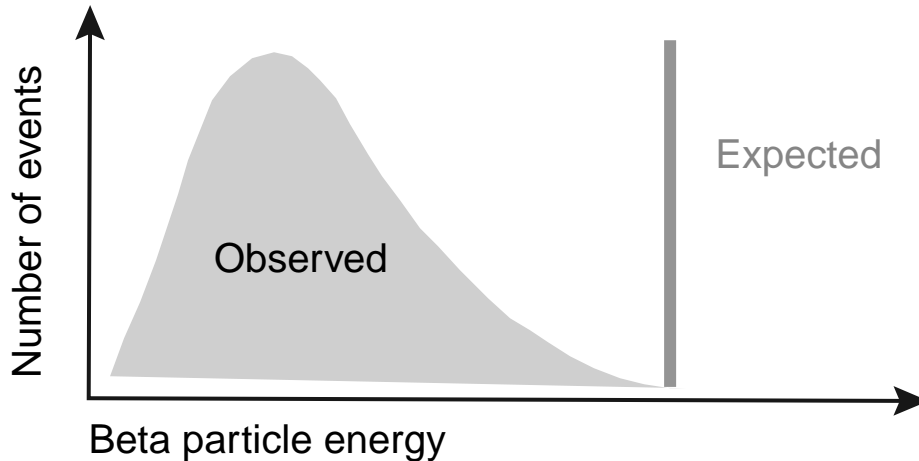
neutron  $\beta$  decay,



and  $\beta$  decay of Lead-214,



For two-body decays, the Principle of Conservation of Energy & Momentum says that the  $\beta$  particle, or electron, should have a definite energy, indicated by the

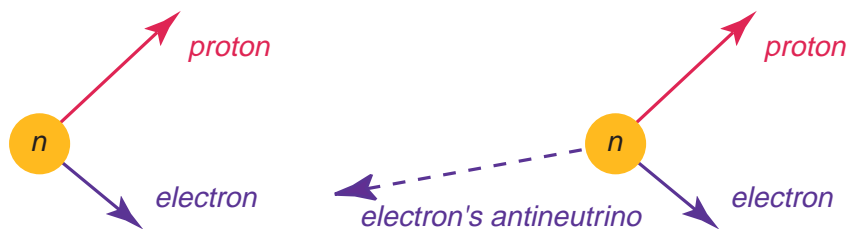


**FIGURE 1.** Expectations and reality for the beta decay spectrum.

spike in Figure 1. What was observed was very different: in 1914, James Chadwick (later to discover the neutron) showed conclusively [1] that in the decay of Radium B and C ( $^{214}\text{Pb}$  and  $^{214}\text{Bi}$ ), the  $\beta$  energy follows a continuous spectrum, as shown in Figure 1.

How could we account for this completely unexpected behavior? Might it mean that energy and momentum are not uniformly conserved in subatomic events?<sup>4</sup> Although Chadwick did not discover the neutron until 1932, we can use a little chronological license to sharpen our puzzle by considering a cartoon of neutron  $\beta$  decay. The continuous  $\beta$  spectrum means that, in general, the products of the decay of a stationary neutron will not have balanced momenta (zero net momentum), as shown in the left-hand frame in Figure 2. For the products of a system at rest to drift off in some direction flies in the face of physical intuition, though we have to concede that at the time, physicists' intuition was still largely derived from macroscopic experience.

<sup>4</sup>) Niels Bohr was willing to consider this possibility.



**FIGURE 2.** (Left) Apparent nonconservation of energy and momentum in neutron beta decay; (Right) Pauli's solution to the nonconservation of energy and momentum: a nearly massless, neutral, penetrating particle that we know as  $\bar{\nu}_e$ .

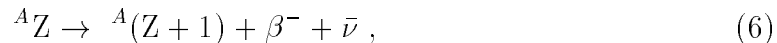
## The Neutrino Conjectured and Observed

The  $\beta$ -decay energy crisis tormented physicists for years. On December 4, 1930, Wolfgang Pauli addressed an open letter<sup>5</sup> to a meeting on radioactivity in Tübingen. Pauli could not attend in person because his presence at a student ball in Zurich was “indispensable.” In his letter, Pauli advanced the outlandish idea of a new, very penetrating, neutral particle of vanishingly small mass. Because Pauli’s new particle interacted very feebly with matter, it would escape undetected from any known apparatus, taking with it some energy, which would seemingly be lost. The balance of energy and momentum would be restored, as shown in the right-hand frame of Figure 2, by the particle we now know as the electron’s antineutrino. The proper decay scheme for the neutron is thus



Pauli’s new particle was indeed a “desperate remedy,” but it was, in its way, very conservative, for it preserved the principle of energy and momentum conservation and with it the notion that the laws of physics are invariant under translations in space and time. The hypothesis fit the facts; after the discovery of the neutron in 1932, Fermi named the new particle the neutrino, to distinguish it from the neutron, and constructed his four-fermion theory of the weak interaction. Experimental confirmation of Pauli’s neutrino had to wait for dramatic advances in technology.

Detecting a particle as penetrating as the neutrino required a large target and a copious source of neutrinos. In 1953, Clyde Cowan and Fred Reines [4] used the intense beam of antineutrinos from a fission reactor



and a heavy target (10.7 ft<sup>3</sup> of liquid scintillator) containing about 10<sup>28</sup> protons to detect the reaction



Initial runs at the Hanford Engineering Works were suggestive but inconclusive. Moving their apparatus to the stronger fission neutrino source at the Savannah River nuclear plant, Cowan and Reines and their team made the definitive observation of inverse  $\beta$  decay in 1956 [5].

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<sup>5</sup>) Pauli’s letter (in the original German) is reproduced in Ref. [2]. For an English translation, see pp. 127-8 of Ref. [3]. It begins, “Dear Radioactive Ladies and Gentlemen, I have hit upon a desperate remedy regarding . . . the continuous  $\beta$ -spectrum . . .” Pauli concluded, “For the moment I dare not publish anything about this idea and address myself confidentially first to you. . . I admit that my way out may seem rather improbable *a priori* . . . Nevertheless, if you don’t play you can’t win . . . Therefore, Dear Radioactives, test and judge.” Pauli’s neutrino, together with the discovery of the neutron, also resolved a vexing nuclear spin-and-statistics problem.

## Three Families of Leptons

In addition to the electron ( $e$ ) and its neutrino ( $\nu_e$ ), we now recognize two other pairs of pointlike, spin- $\frac{1}{2}$  particles that are not affected by the strong interaction:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L . \quad (8)$$

These particles are known as leptons, from the Greek  $\lambda\epsilon\pi\tau\acute{o}\varsigma$  = thin, inspired by the small mass of the electron, muon, and their neutrinos compared with the mass of the proton and neutron, the lightest of the baryons (from the Greek  $\beta\alpha\rho\acute{\upsilon}\varsigma$  = heavy).<sup>6</sup>

The muon neutrino is created in charged pion decay,

$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad \text{and} \quad \pi^- \rightarrow \mu^- \bar{\nu}_\mu , \quad (9)$$

and neutrino beams produced at accelerators are overwhelmingly muon neutrinos. The two-neutrino experiment carried out at Brookhaven National Lab in the early 1960s [6] demonstrated that the neutrinos produced in pion decays do not initiate inverse  $\beta$  decay, so that  $\nu_\mu$  is distinct from  $\nu_e$ .

The DONUT (Direct Observation of NU-Tau) Experiment [7] under analysis at Fermilab is a three-neutrino experiment. Using a prompt neutrino beam in which decays of the charmed-strange meson

$$D_s^+ \rightarrow \begin{cases} \tau^+ \nu_\tau \\ \downarrow \\ \bar{\nu}_\tau + \text{anything} \end{cases} \quad (10)$$

provide the  $\nu_\tau$  source, the experimenters aim to observe the reaction

$$\nu_\tau N \rightarrow \tau + \text{anything}. \quad (11)$$

I expect to see results from DONUT in the year 2000.

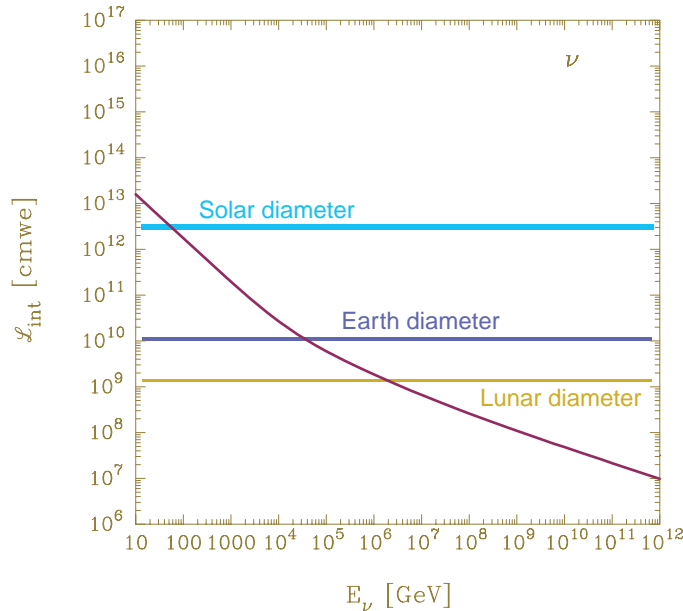
## Neutrino Beams and Detectors

Neutrinos traverse vast amounts of material. The fission antineutrinos detected by Cowan, Reines, and their collaborators have an inverse  $\beta$ -decay cross section  $\sigma(\bar{\nu}_e p \rightarrow e^+ n) \approx 10^{-43} \text{ cm}^2$ . Accordingly, their interaction length,

$$\mathcal{L}_{\text{int}} = \frac{1}{\sigma(\bar{\nu}_e p \rightarrow e^+ n) N_A (Z/A) \bar{\rho}} , \quad (12)$$

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<sup>6)</sup> We would not choose the same names today, knowing that the tau lepton is twice as massive as the proton ...



**FIGURE 3.** Interaction lengths for neutrino interactions on an isoscalar nucleon target (from Ref. [8]).

where  $N_A = 6.022 \times 10^{23} \text{ cm}^{-3}$  is Avogadro's number,  $\bar{\rho}$  is the specific gravity of the target, and  $Z/A$  is the proton fraction of the target nucleons, is very long. It corresponds to about  $1.7 \times 10^{19} \text{ cm}$  of water, or a column density of  $1.7 \times 10^{10}$  kilotonnes per square centimeter. On average, a fission neutrino would traverse more than four light-years of lead—the distance from Earth to  $\alpha$ -Centauri—before interacting. At higher energies, the cross section for the inclusive reaction  $\bar{\nu}_e p \rightarrow e^+ + \text{anything}$  grows—at first  $\propto E_\nu$ , then more slowly—so the interaction length decreases. The high-energy dependence of the  $\nu N$  interaction length is shown in Figure 3. The interaction length of a 100-GeV neutrino is approximately 25 million kilometers of water, or about 230 Earth diameters. If you should stand in Fermilab's neutrino beam, only one neutrino in  $10^{11}$  will interact in your body.

What are the consequences of the great interaction length? First, there is the missing-energy signature for neutrinos. Second, there is the difficulty of detecting neutrino interactions. Third—because the other known particles all interact more than neutrinos do—we have the possibility of preparing filtered neutrino beams, which we shall discuss in a moment. Fourth, because neutrinos can penetrate great columns of matter, whereas electromagnetic radiation is blocked by a few hundred grams of material, it is appealing to consider the promise of neutrino astronomy for peering into the hearts of dense structures or looking back at the state of the universe before recombination of ions and electrons into neutral atoms.

At high-energy accelerators, neutrinos are tertiary products of collisions

$$p + \text{Target} \rightarrow \text{many } \pi, K, \quad (13)$$



followed by the decays

$$\pi \rightarrow \mu\nu_\mu, \quad K \rightarrow \mu\nu_\mu, \quad (14)$$

in an evacuated decay space up to a kilometer long. The decay region is followed by an earthen shield, perhaps made denser by the inclusion of blocks of iron or steel, that absorbs photons, surviving mesons, and other hadrons, and ranges out many of the muons. At Fermilab, the total length of the neutrino beam line is about 3 km.

In the most recent study of deeply inelastic neutrino scattering at Fermilab, 800-GeV protons from the Tevatron deliver  $10^{10}$  neutrinos in 5 pings over 2.5 seconds each minute, spread over the 100 ft<sup>2</sup> face of the NuTeV Detector. The detector is made up of 690 T of iron, scintillator, and drift chambers. Events are studied from a “fiducial volume” of 390 T. The  $10^{10}$  neutrinos per minute produce about 10 – 20 events that are recorded for off-line analysis. Experiments of this kind give us our best look at the interior of the proton, and reveal its quark structure in exquisite detail [9].

## Neutrino Mass

*Neutrinos are very light.* No one has ever weighed a neutrino. The best kinematical determinations set upper bounds [10] on the dominant neutrino species emitted in nuclear beta decay ( $m_{\nu_e} \lesssim 15 \text{ eV}/c^2$ ), charged-pion decay ( $m_{\nu_\mu} < 0.19 \text{ MeV}/c^2$  at 90% CL), and  $\tau$ -lepton decay ( $m_{\nu_\tau} < 18.2 \text{ MeV}/c^2$  at 95% CL). Although there are prospects<sup>7</sup> for improving these bounds—and the measurement of a nonzero mass would constitute a real discovery—they are sufficiently large that it is of interest to consider indirect (nonkinematic) constraints from other quarters.

If neutrino lifetimes are greater than the age of the Universe, the requirement that neutrino relics from the Big Bang not overclose the Universe leads to a constraint on the sum of neutrino masses. For relatively light neutrinos ( $m_\nu \lesssim$  a few  $\text{MeV}/c^2$ ), the total mass in neutrinos,

$$m_{\text{tot}} = \sum_i \frac{1}{2} g_i m_{\nu_i}, \quad (15)$$

where  $g_i$  is the number of spin degrees of freedom of  $\nu_i$  plus  $\bar{\nu}_i$ , sets the scale of the neutrino contribution to the mass density of the Universe,  $\rho_\nu = m_{\text{tot}} n_\nu \approx 112 m_{\text{tot}} \text{ cm}^{-3}$ . If we measure  $\rho_\nu$  as a fraction of the critical density to close the Universe,  $\rho_c = 1.05 \times 10^4 h^2 \text{ eV}/c^2 \text{ cm}^{-3}$ , where  $h$  is the reduced Hubble parameter, then

$$\Omega_\nu \equiv \frac{\rho_\nu}{\rho_c} = \frac{m_{\text{tot}}}{94 h^2 \text{ eV}/c^2}. \quad (16)$$

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<sup>7</sup>) Some of these prospects were reviewed at  $\nu$ Fact '99 in Lyon by Alvaro De Rújula, Ref. [11].

An assumed bound on  $\Omega_\nu h^2$  then implies a bound on  $m_{\text{tot}}$ . A very conservative bound results from the assumption that  $\Omega_\nu h^2 < 1$ : it is that  $m_{\text{tot}} < 94 \text{ eV}/c^2$ .

Recent observations<sup>8</sup> suggest that the total matter density is considerably smaller than the critical density, so that  $\Omega_m \approx 0.3$ . If we fix  $\Omega_\nu < \Omega_m$  and choose the plausible value  $h^2 = 0.5 \pm 0.15$ , then we arrive at the still generous upper bound  $m_{\text{tot}} \lesssim 19 \text{ eV}/c^2$ . Taking into account the best (and model-dependent) information about the hot- and cold-dark-matter cocktail [13] needed to reproduce the observed fluctuations in the cosmic microwave background, it seems likely that cosmology limits  $m_{\text{tot}} \lesssim$  a few  $\text{eV}/c^2$ . It is worth remarking that the cosmological desire for hot dark matter has been on the wane.

If neutrinos were exactly massless, neutrino physics would be simple. There would be no pattern of masses to explain, no neutrino decays, no mixing among lepton generations, and no neutrino oscillations. The only question would be Why?

If neutrinos do have masses, the electroweak theory has more unexplained parameters: the neutrino masses, three mixing angles, and a CP-violating phase. Neutrinos may decay, and neutrinos can oscillate from one electroweak species to another.

## Neutrino Oscillations<sup>9</sup>

In the quantum world, particles are waves. If neutrinos  $\nu_1, \nu_2, \dots$  have different masses  $m_1, m_2, \dots$ , each neutrino flavor may be a mixture of different masses. Let us consider two species for simplicity, and take

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}. \quad (17)$$

If neutrinos are emitted with a definite momentum  $p$ , the wave functions corresponding to the two mass eigenstates evolve with different frequencies. As a consequence, a beam born as pure  $\nu_\mu$  may evolve a  $\nu_e$  component with time. If the neutrino momentum is large compared with the neutrino masses,  $p \gg m_i$ , then the probability for a  $\nu_e$  component to develop in a  $\nu_\mu$  beam after a time  $t$  is

$$P_{\nu_e \leftarrow \nu_\mu}(t) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 t}{4p} \right). \quad (18)$$

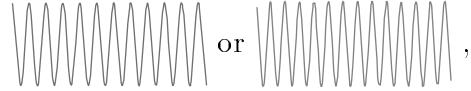
Measuring the propagation distance  $L = ct$ , approximating the neutrino energy as  $E \approx pc$ , and using the conversion factor  $\hbar c \approx 1.97 \times 10^{-13} \text{ MeV m}$ , we can re-express

$$\sin^2 \left( \frac{\Delta m^2 t}{4p} \right) \approx \sin^2 \left( 1.27 \frac{\Delta m^2}{1 \text{ eV}^2} \cdot \frac{L}{1 \text{ km}} \cdot \frac{1 \text{ GeV}}{E} \right). \quad (19)$$

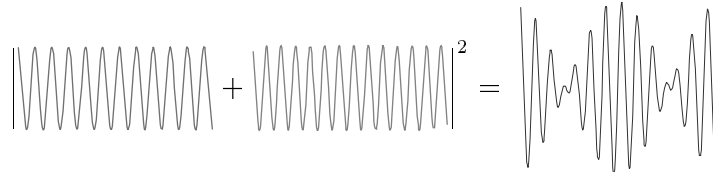
<sup>8)</sup> For a review and interpretation of recent observations, see Ref. [12].

<sup>9)</sup> For a review of the essentials, see [14].

Arising as it does from a slight frequency mismatch, neutrino flavor oscillation is analogous to the beat-frequency phenomenon observed when two tuning forks with *almost* the same pitch are sounded at the same time. If the forks are sounded individually, producing waves



we might find it difficult to distinguish the pitches. But when we sound them together, the sound intensity



swells and fades periodically because the two sound waves are different, reflecting the physical difference between the two tuning forks.

The probability that a neutrino born as  $\nu_\mu$  remain a  $\nu_\mu$  at distance  $L$  is

$$P_{\nu_\mu \leftarrow \nu_\mu}(L) = 1 - \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m^2}{1 \text{ eV}^2} \cdot \frac{L}{1 \text{ km}} \cdot \frac{1 \text{ GeV}}{E} \right). \quad (20)$$

The probability for a  $\nu_\mu$  to metamorphose into a  $\nu_e$ ,

$$P_{\nu_e \leftarrow \nu_\mu} = \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m^2}{1 \text{ eV}^2} \cdot \frac{L}{1 \text{ km}} \cdot \frac{1 \text{ GeV}}{E} \right), \quad (21)$$

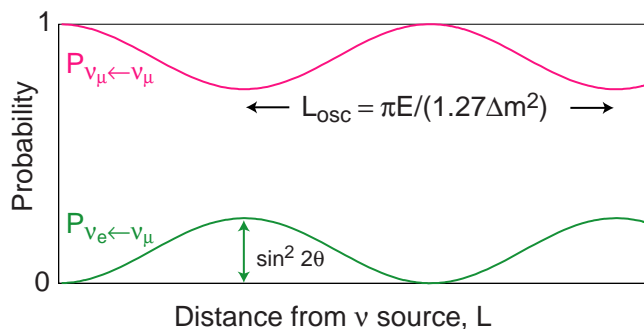
depends on two parameters related to experimental conditions:  $L$ , the distance from the neutrino source to the detector, and  $E$ , the neutrino energy. It also depends on two fundamental neutrino parameters: the difference of masses squared,  $\Delta m^2 = m_1^2 - m_2^2$ , and the neutrino mixing parameter,  $\sin^2 2\theta$ . The amplitude of the probability oscillations is given by  $\sin^2 2\theta$ , as shown in Figure 4; the wavelength of the oscillations is

$$L_{\text{osc}} = \frac{\pi}{1.27} \cdot \frac{E}{1 \text{ GeV}} \cdot \frac{1 \text{ eV}^2}{\Delta m^2} \text{ km} = 2.48 \frac{E}{1 \text{ GeV}} \cdot \frac{1 \text{ eV}^2}{\Delta m^2} \text{ km}, \quad (22)$$

and the oscillation probability is greatest at a distance  $L_{\text{max}} = (k + \frac{1}{2})L_{\text{osc}}$ , where  $k$  is an integer.

Many experiments have now used natural sources of neutrinos, neutrino radiation from fission reactors, and neutrino beams generated in particle accelerators to look for evidence of neutrino oscillation.<sup>10</sup>

<sup>10)</sup> For summaries of the current evidence about neutrino oscillations, see Ref. [15].



**FIGURE 4.** Evolution of a  $\nu_\mu$  beam of energy  $E$  depends on the intrinsic parameters  $\Delta m^2$  and  $\sin^2 2\theta$ , and on the experimental conditions characterized by  $L$  and  $E$ .

The nuclear burning that powers the Sun produces neutrinos as well as light and heat [16]. Overall, a network of reactions we may summarize as

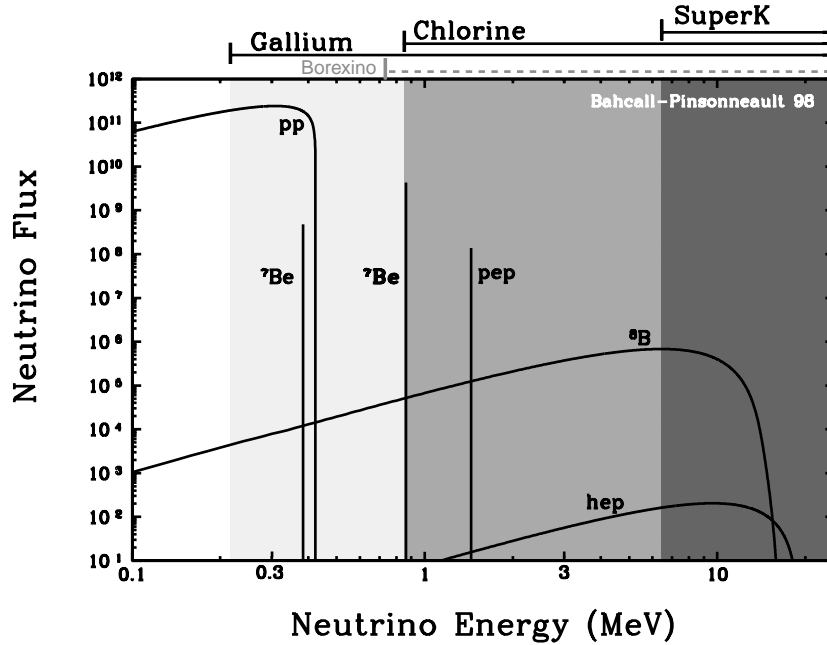


leads to the spectrum of neutrinos<sup>11</sup> shown in Figure 5. Because solar neutrinos interact so feebly, they can only be detected in a very massive target and detector. The Super-Kamiokande Detector in Japan consists of 50 000 tonnes of pure water viewed by 11 000 photomultiplier tubes to detect Cherenkov light. It is sited 1 km under a mountain, under 3 kmwe. The great advantage of the Super-K detector is that it detects neutrino interactions  $\nu_e + n \rightarrow p + e^-$  in real time, and determines the neutrino direction from the electron direction. Super-K has demonstrated that the brightest object in the neutrino sky is the Sun, which proves that nuclear fusion powers our star. The disadvantage of the water-Cherenkov technique (see Figure 5) is that it is only sensitive to the highest-energy solar neutrinos.

Five solar-neutrino experiments report deficits with respect to the predictions of the standard solar model: Kamiokande and Super-Kamiokande using water-Cherenkov techniques, SAGE and GALLEX using chemical recovery of germanium produced in neutrino interactions with gallium, and Homestake using radiochemical separation of argon produced in neutrino interactions with chlorine. These results suggest the oscillation  $\nu_e \rightarrow \nu_x$ .

Cosmic rays that interact in Earth's atmosphere produce neutrinos in the decays of pions, kaons, and muons, in the approximate proportions  $\nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e :: 2 : 2 : 1 : 1$ . Five atmospheric-neutrino experiments report anomalies in the arrival of muon neutrinos: Kamiokande, IMB, and Super-Kamiokande using water-Cherenkov techniques, and Soudan II and MACRO using sampling calorimetry. The most striking result is the zenith-angle dependence of the  $\nu_\mu$  rate reported last year by Super-K [20,21], which is shown in Figure 6. The electron-like events follow the Monte Carlo simulation, but the muon-like events exhibit a deficit that is

<sup>11)</sup> The standard solar model is described in Ref. [17]. A wealth of information is available on John Bahcall's home page at <http://www.sns.ias.edu/~jnb>.



**FIGURE 5.** The spectrum of neutrinos from the  $pp$  chain predicted by the standard solar model. The neutrino fluxes from continuum sources ( $pp$  and  ${}^8\text{B}$ ) are given in units of number per  $\text{cm}^2$  per second per MeV at one astronomical unit. The line fluxes ( $pep$  and  ${}^7\text{Be}$ ) are given in number per  $\text{cm}^2$  per second. The detection thresholds for several solar neutrino experiments are indicated at the top of the figure. The figure is from Ref. [18], updated using the data from Ref. [19].

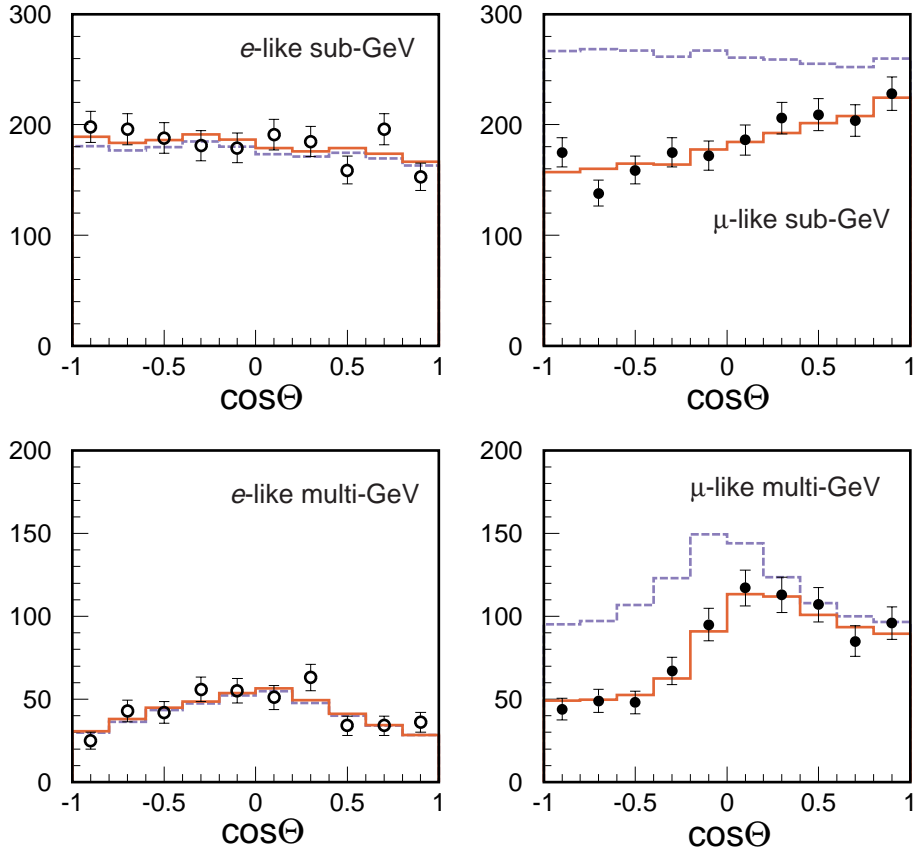
most pronounced for upward-coming neutrinos, *i.e.*, those for which the flight path is longest, up to 13000 km. These results suggest the oscillation  $\nu_\mu \rightarrow \nu_\tau$  or  $\nu_s$ . Auxiliary information disfavors the sterile-neutrino ( $\nu_s$ ) interpretation.

The atmospheric- and solar-neutrino anomalies are both disappearance phenomena. A single experiment reports the appearance of neutrinos that would not be seen in the absence of neutrino oscillations. The LSND experiment [22] reports the observation of  $\bar{\nu}_e$ -like events is what should be an essentially pure  $\bar{\nu}_\mu$  beam produced at the Los Alamos Meson Physics Facility, suggesting the oscillation  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ . This result has not yet been reproduced by any other experiment.

A host of experiments have failed to turn up evidence for neutrino oscillations in the regimes of their sensitivity. These results limit neutrino mass-squared differences and mixing angles. In more than a few cases, positive and negative claims are in conflict, or at least face off against each other. Over the next five years, many experiments will seek to verify, further quantify, and extend these claims.

## The Ultimate Neutrino Source?

Our colleagues working to assess the feasibility of very-high-energy muon colliders have given us the courage to think that it may be possible, not too many years in



**FIGURE 6.** Comparison of Monte Carlo simulations (dashed curves) and measurements for events initiated in the Super-Kamiokande detector by cosmic-ray  $\nu_e + \bar{\nu}_e$  ( $\circ$ ) and  $\nu_\mu + \bar{\nu}_\mu$  ( $\bullet$ ). The solid lines show the effects of  $\nu_\mu \rightarrow \nu_\tau$  oscillations.

the future, to accumulate  $10^{20-21}$  (or even  $10^{22}$ ) muons per year. It is very exciting to think of the possibilities that millimoles of muons would raise for studies in fundamental physics.

From the perspective of a muon collider, the 2.2- $\mu$ s lifetime of the muon presents a formidable challenge. But if the challenge of producing, capturing, storing, and replenishing many unstable muons can be met, the decays

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e, \quad \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e \quad (24)$$

offer delicious possibilities for the study of neutrino interactions and neutrino properties [23–25]. We would have at our disposal for the first time not only neutrino beams of unprecedented intensity, but also controlled beams rich in high-energy electron neutrinos. In a *Neutrino Factory*, the composition and spectra of intense neutrino beams will be determined by the charge, momentum, and polarization of the stored muons. The beam from a  $\mu^+$  storage ring contains  $\bar{\nu}_\mu$  and  $\nu_e$ , but no  $\nu_\mu$ ,  $\bar{\nu}_e$ ,  $\nu_\tau$ , or  $\bar{\nu}_\tau$ . The neutrino spectra are given by

$$\frac{d^2 N_{\bar{\nu}_\mu}}{dx d\Omega} = \frac{x^2}{2\pi} [(3 - 2x) - (1 - 2x) \cos \theta], \quad \cos \theta = \hat{p}_\nu \cdot \hat{s}_\mu, \quad (25)$$

and

$$\frac{d^2 N_{\nu_e}}{dx d\Omega} = \frac{3x^2}{\pi} [(1 - x) - (1 - x) \cos \theta], \quad (26)$$

where  $x = 2E_\nu/E_\mu$  measures the neutrino energy and  $\hat{s}_\mu$  specifies the muon's spin direction.

At the energies best suited for the study of neutrino oscillations—tens of GeV, by our current estimates—the muon storage ring is compact. We could build it at one laboratory, pitched at a deep angle, to illuminate a laboratory on the other side of the globe with a neutrino beam whose properties we can control with great precision. By choosing the right combination of energy and destination, we can tune future neutrino-oscillation experiments to the physics questions we will need to answer, by specifying the ratio of path length to neutrino energy and determining the amount of matter the neutrinos traverse. Although we can use each muon decay only once, and we will not be able to select many destinations, we may be able to illuminate two or three well-chosen sites from a muon-storage-ring neutrino source. That possibility—added to the ability to vary the muon charge, polarization, and energy—may give us just the degree of experimental control it will take to resolve the outstanding questions about neutrino oscillations.

*The Detector Challenge.* To distinguish oscillations among  $\nu_e$ ,  $\nu_\mu$ ,  $\nu_\tau$ , and a possible fourth, “sterile,” neutrino  $\nu_s$  that does not experience weak interactions, we require a target *cum* detector of several kilotonnes—perhaps several tens of kilotonnes—that can distinguish electrons, muons, and taus, and measure their charges. This is a straightforward requirement for the muons, but the short-lived (0.3 picosecond)  $\tau$  and the eager-to-shower electron are more difficult to deal with.

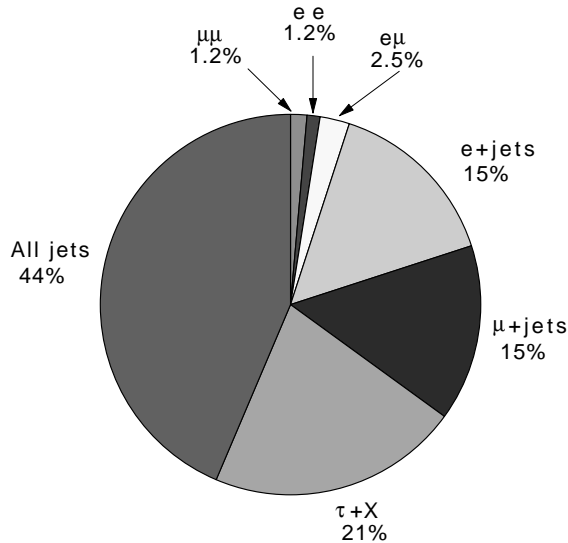
## WHAT CAN WE LEARN FROM THE TOP QUARK?

Top is a most remarkable particle, even for a quark.<sup>12</sup> A single top quark weighs 175 GeV/ $c^2$ , about as much as an atom of gold. But unlike the gold atom, which can be disassembled into 79 protons, 79 electrons, and 118 neutrons, top seems indivisible, for we discern no structure at a resolution approaching  $10^{-18}$  m. Top's expected lifetime of about 0.4 yoctosecond ( $0.4 \times 10^{-24}$  s) makes it by far the most ephemeral of the quarks. The compensation for this exceedingly brief life is a measure of freedom: top decays before it experiences the confining influence of the strong interaction. In spite of its fleeting existence, the top quark helps shape the character of the everyday world.

The discovery experiments were carried out at Fermilab's Tevatron, in which a beam of 900-GeV protons collides with a beam of 900-GeV antiprotons. Creating

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<sup>12)</sup> See Ref. [26] for a general introduction.



**FIGURE 7.** Branching fractions for prominent decay modes in  $t\bar{t}$  production.

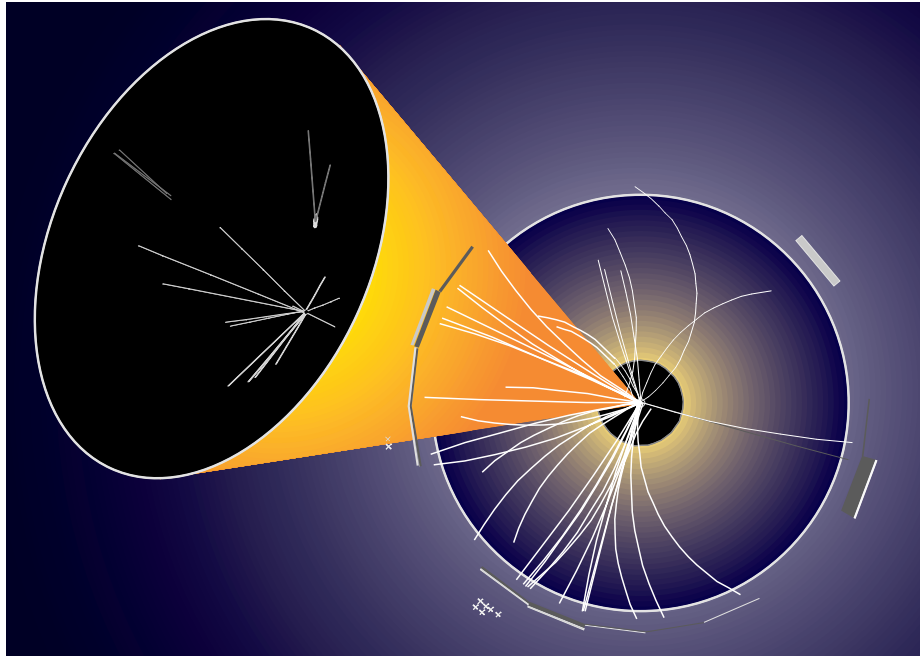
top-antitop pairs in sufficient numbers to claim discovery demanded exceptional performance from the Tevatron, for only one interaction in ten billion results in a top-antitop pair, through the reaction

$$\bar{p}p \rightarrow t \bar{t} + \dots \quad (27)$$

$$\left. \begin{array}{l} \downarrow \\ \downarrow \\ \downarrow \end{array} \right\} \begin{array}{l} \rightarrow W^- \bar{b} \\ \rightarrow W^+ b \end{array}$$

Observing traces of the disintegration of top into a  $b$ -quark and a  $W$ -boson, the agent of the weak interaction, required highly capable detectors and extraordinary attention to experimental detail. Both the  $b$ -quark and the  $W$ -boson are themselves unstable, with many multibody decay modes. The  $b$ -quark's mean lifetime is about 1.5 ps. It can be identified by a decay vertex displaced by a fraction of a millimeter from the production point, or by the low-momentum electron or muon from the semileptonic decays  $b \rightarrow ce\nu$ ,  $b \rightarrow c\mu\nu$ , each with branching fraction about 10%. The  $W$  boson decays after only 0.3 ys on average into  $e\bar{\nu}_e$ ,  $\mu\bar{\nu}_\mu$ ,  $\tau\bar{\nu}_\tau$ , or a quark and antiquark (observed as two jets of hadrons), with probabilities 1/9, 1/9, 1/9, and 2/3. The characteristic modes in which  $t\bar{t}$  production can be sought are shown with their relative weights in Figure 7. Dilepton events ( $e\mu$ ,  $ee$ , and  $\mu\mu$ ) are produced primarily when both  $W$  bosons decay into  $e\nu$  or  $\mu\nu$ . Events in the lepton + jets channels ( $e, \mu + jets$ ) occur when one  $W$  boson decays into leptons and the other decays through quarks into hadrons. Another challenge to experiment is the complexity of events in high-energy  $\bar{p}p$  collisions. The top and antitop are typically accompanied by scores of other particles. The discovery experiments scanned  $10^6$  events per second.

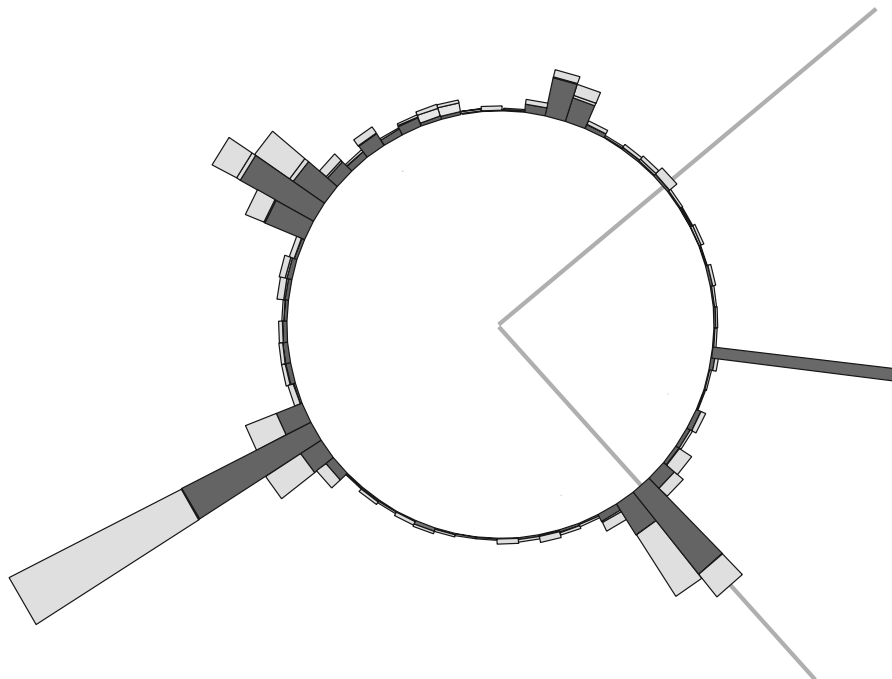




**FIGURE 8.** A pair of top quarks reconstructed in the CDF experiment at Fermilab. Each top decays to a  $W$  boson and a  $b$  quark. The tower pointing east-southeast in the wide view identifies a positron from  $W^+$  decay; the inset shows displaced decays of two  $b$  particles.

Each detector is an intricate apparatus operated by an international collaboration of about 450 physicists. The tracking devices, calorimeters, and surrounding iron for muon identification occupy a volume about three stories high and weigh about 5000 tons. The Collider Detector at Fermilab (CDF), a magnetic detector with solenoidal geometry, profited from its high-resolution silicon vertex detector (SVX) to tag  $b$ -quarks with good efficiency. The DØ Detector (D-Zero) had no central magnetic field, emphasizing instead calorimetric measurement of the energies of produced particles. A top event from the CDF detector, shown in Figure 8, displays the power of the silicon vertex detector to resolve secondary  $b$  decays at only a small remove from the production vertex. The DØ event pictured in Figure 9 shows one  $W$  boson reconstructed from a muon plus missing energy, and a second  $W$  reconstructed from two jets.

*The Detector Challenge.* To select top-quark events with high efficiency, and to measure them effectively, require the ability to decide quickly which few of the  $10^7$  events per second in Tevatron Run 2 ( $10^8$  per second at the LHC) are interesting; excellent  $b$  tagging, resolving secondary vertices within a few tenths of a millimeter of the collision point in a hostile high-radiation environment; efficient lepton identification and measurement of both electron and muon momenta, even for leptons in jets; calorimetry that provides good jet-jet invariant mass resolution



**FIGURE 9.** A pair of top quarks reconstructed in the DØ experiment at Fermilab. This end view shows the final decay products: two muons (thin lines at northeast and southeast), a neutrino (east), and four jets of particles.

and a reliable measurement of missing transverse energy; a hermetic detector.

For the moment, the direct study of the top quark belongs to the Tevatron. Early in the next century, samples twenty times greater than the current samples should be in hand, thanks to the increased event rate made possible by Fermilab's Main Injector and upgrades to CDF and DØ. Boosting the Tevatron's energy to 1 TeV per beam will increase the top yield by nearly 40%. Further enhancements to Fermilab's accelerator complex are under study. A decade from now, the Large Hadron Collider at CERN will produce tops at more than ten thousand times the rate of the discovery experiments. Electron-positron linear colliders or muon colliders may add new opportunities for the study of top-quark properties and dynamics. In the meantime, the network of understanding known as the standard model of particle physics links the properties of top to many phenomena to be explored in other experiments.

How can we expect new experiments to extend our knowledge of the top quark?<sup>13</sup> Tevatron Run 2, to begin in March 2001, is to accumulate  $2 \text{ fb}^{-1}$  of integrated luminosity. We anticipate a determination of the top mass to  $\pm 3 \text{ GeV}/c^2$  in Run 2,  $\pm 1 \text{ GeV}/c^2$  with  $30 \text{ fb}^{-1}$  in Run 2<sup>bis</sup> or in LHC experiments. Combined with a

<sup>13)</sup> The home page of the Fermilab *thinkshop* on top-quark physics for Run 2 of the Tevatron, at <http://lutece.fnal.gov/thinkshop/>, contains many useful links. See also the surveys in Refs. [27] and [28].

measurement of the  $W$ -boson mass to  $\pm 40$  MeV/ $c^2$ , this measurement will make it possible to infer the Higgs-boson mass with increased precision. It is now possible to begin asking how precisely top fits the profile of anticipated properties in its production and decay. It should be possible to determine the  $t \rightarrow bW$  coupling in single-top production:  $\pm 10\%$  in Run 2,  $\pm 5\%$  in Run 2<sup>bis</sup>. One of the exploratory goals of the new round of experiments will be to search for  $t\bar{t}$  resonances, rare decays, and deviations from the expected pattern of top decays. Finally, it may prove possible to begin to probe the ephemeral lifetime of top. On the theoretical front, the large mass of top encourages us to think that the two problems of mass may be linked at the electroweak scale.

## Top Matters!

It is popular to say that top quarks were produced in great numbers in the fiery cauldron of the Big Bang some fifteen billion years ago, disintegrated in the merest fraction of a second, and vanished from the scene until my colleagues learned to create them in the Tevatron. That would be reason enough to care about top: to learn how it helped sow the seeds for the primordial universe that evolved into our world of diversity and change. But it is not the whole story; it invests the top quark with a remoteness that veils its importance for the everyday world.

The real wonder is that here and now, every minute of every day, the top quark affects the world around us. Through the uncertainty principle of quantum mechanics, top quarks and antiquarks wink in and out of an ephemeral presence in our world. Though they appear virtually, fleetingly, on borrowed time, top quarks have real effects.

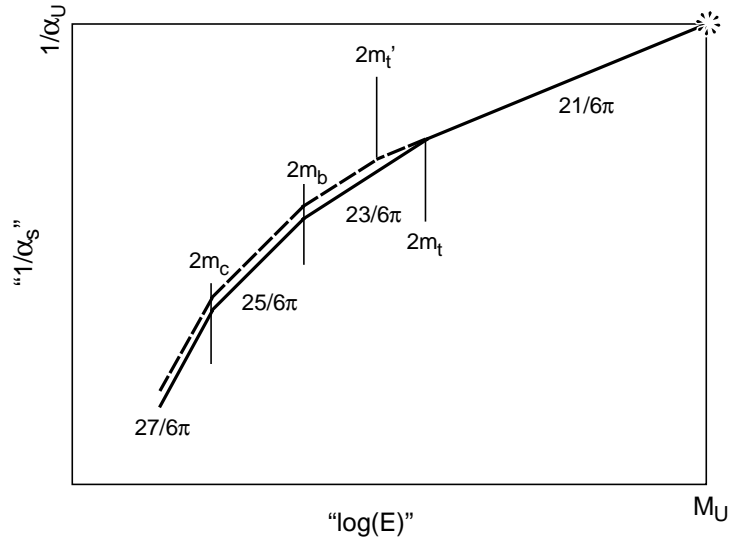
Quantum effects make the coupling strengths of the fundamental interactions—appropriately normalized analogues of the fine-structure constant  $\alpha$ —vary with the energy scale on which the coupling is measured. The fine-structure constant itself has the familiar value  $1/137$  in the low-energy (or long-wavelength) limit, but grows to about  $1/129$  at the mass of the  $Z^0$  boson, about  $91$  GeV/ $c^2$ . Vacuum-polarization effects make the effective electric charge increase at short distances or high energies.

In unified theories of the strong, weak, and electromagnetic interactions, all the coupling “constants” take on a common value,  $\alpha_U$ , at some high energy,  $M_U$ . If we adopt the point of view that  $\alpha_U$  is fixed at the unification scale, then the mass of the top quark is encoded in the value of the strong coupling  $\alpha_s$  that we experience at low energies.<sup>14</sup> Assuming three generations of quarks and leptons, we evolve  $\alpha_s$  downwards in energy from the unification scale.<sup>15</sup> The leading-logarithmic behavior is given by

$$1/\alpha_s(Q) = 1/\alpha_U + \frac{21}{6\pi} \ln(Q/M_U) \ , \quad (28)$$

<sup>14</sup>) All the important features emerge in an  $SU(5)$  unified theory that contains the standard-model gauge group  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ . The final result is more general.

<sup>15</sup>) The strategy is explained in Ref. [29].



**FIGURE 10.** Two evolutions of the strong coupling constant  $\alpha_s$ . A smaller value of the top-quark mass leads to a smaller value of  $\alpha_s$ .

for  $M_U > Q > 2m_t$ . The positive coefficient  $+21/6\pi$  means that the strong coupling constant  $\alpha_s$  is smaller at high energies than at low energies. This behavior—opposite to the familiar behavior of the electric charge—is the celebrated property of asymptotic freedom. In the interval between  $2m_t$  and  $2m_b$ , the slope  $(33 - 2n_f)/6\pi$  (where  $n_f$  is the number of active quark flavors) steepens to  $23/6\pi$ , and then increases by another  $2/6\pi$  at every quark threshold. At the boundary  $Q = Q_n$  between effective field theories with  $n-1$  and  $n$  active flavors, the coupling constants  $\alpha_s^{(n-1)}(Q_n)$  and  $\alpha_s^{(n)}(Q_n)$  must match. This behavior is shown by the solid line in Figure 10. The dotted line in Figure 10 shows how the evolution of  $1/\alpha_s$  changes if the top-quark mass is reduced. A smaller top mass means a larger low-energy value of  $1/\alpha_s$ , so a smaller value of  $\alpha_s$ .

To discover the dependence of  $\Lambda_{\text{QCD}}$  upon the top-quark mass, we calculate  $\alpha_s(2m_t)$  evolving up from low energies and down from the unification scale, and match:

$$1/\alpha_U + \frac{21}{6\pi} \ln(2m_t/M_U) = 1/\alpha_s(2m_c) - \frac{25}{6\pi} \ln(m_c/m_b) - \frac{23}{6\pi} \ln(m_b/m_t). \quad (29)$$

Identifying

$$1/\alpha_s(2m_c) \equiv \frac{27}{6\pi} \ln(2m_c/\Lambda_{\text{QCD}}), \quad (30)$$

we find that

$$\Lambda_{\text{QCD}} = e^{-6\pi/27\alpha_U} \left(\frac{M_U}{1 \text{ GeV}}\right)^{21/27} \left(\frac{2m_t \cdot 2m_b \cdot 2m_c}{1 \text{ GeV}^3}\right)^{2/27} \text{ GeV}. \quad (31)$$

Thanks to QCD, we have learned that the dominant contribution to the light-hadron masses is not the masses of the quarks of which they are constituted, but the energy stored up in confining the quarks in a tiny volume.<sup>16</sup> Our most useful tool in the strong-coupling regime is lattice QCD. Calculating the light hadron spectrum from first principles has been one of the main objectives of the lattice program, and important strides have been made recently. In 1994, the GF11 Collaboration [31] carried out a quenched calculation of the spectrum (no dynamical fermions) that yielded masses that agree with experiment within 5–10%, with good understanding of the residual systematic uncertainties. The CP-PACS Collaboration centered in Tsukuba has embarked on an ambitious program that will soon lead to a full (unquenched) calculation [32].

Neglecting the tiny “current-quark” masses of the up and down quarks, the scale parameter  $\Lambda_{\text{QCD}}$  is the only mass parameter in QCD. It determines the scale of the confinement energy that is the dominant contribution to the proton mass. To a good first approximation,

$$M_{\text{proton}} \approx C \Lambda_{\text{QCD}}, \quad (32)$$

where the constant of proportionality  $C$  is calculable using techniques of lattice field theory.

We conclude that, in a simple unified theory,

$$\frac{M_{\text{proton}}}{1 \text{ GeV}} \propto \left( \frac{m_t}{1 \text{ GeV}} \right)^{2/27}. \quad (33)$$

This is a wonderful result. Now, we can’t use it to compute the mass of the top quark, because we don’t know the values of  $M_U$  and  $\alpha_U$ , and haven’t yet calculated precisely the constant of proportionality between the proton mass and the QCD scale parameter. Never mind! The important lesson—no surprise to any twentieth-century physicist—is that the microworld does determine the behavior of the quotidian. We will fully understand the origin of one of the most important parameters in the everyday world—the mass of the proton—only by knowing the properties of the top quark.<sup>17</sup>

## WHAT IS THE DIMENSIONALITY OF SPACETIME?

Ordinary experience tells us that spacetime has  $3 + 1$  dimensions. Could our perceptions be limited? That is the question raised allegorically in *Flatland*, a Victorian fable published in 1880 by a British schoolmaster, Edwin Abbott Abbott (1839 – 1926), and still widely available [34].

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<sup>16)</sup> An accessible essay on our understanding of hadron mass appears in Ref. [30].

<sup>17)</sup> For a fuller development of the influence of standard-model parameters on the everyday world, see Ref. [33].

Like any question that tests our preconceptions and unspoken assumptions, “What is the dimensionality of spacetime?” is a legitimate scientific question, to which we should return from time to time. It is given immediacy by recent theoretical work. For its internal consistency, string theory requires an additional six or seven space dimensions, beyond the  $3 + 1$  dimensions of everyday experience. Until recently it has been presumed that the extra dimensions must be compactified on the Planck scale, with a compactification radius

$$R_{\text{unobserved}} \simeq \frac{1}{M_{\text{Planck}}} = \frac{1}{1.22 \times 10^{19} \text{ GeV}/c^2} = 1.6 \times 10^{-35} \text{ m} . \quad (34)$$

Part of the vision of string theory is that what goes on in the small curled-up dimensions does affect the everyday world: excitations of the Calabi–Yau manifolds determine the fermion spectrum, for example.<sup>18</sup>

The great gap between the electroweak scale of about  $10^3$  GeV and the Planck scale of about  $10^{19}$  GeV gives rise to the hierarchy problem of the electroweak theory [36]. The conventional approach to new physics has been to extend the standard model to understand why the electroweak scale (and the mass of the Higgs boson) is so much smaller than the Planck scale. A novel approach that has evolved over the past two years is instead to *change gravity* to understand why the Planck scale is so much greater than the electroweak scale [37]. Now, experiment tells us that gravitation closely follows the Newtonian force law down to distances on the order of 1 mm. Let us parameterize deviations from a  $1/r$  gravitational potential in terms of a relative strength  $\varepsilon_G$  and a range  $\lambda_G$ , so that

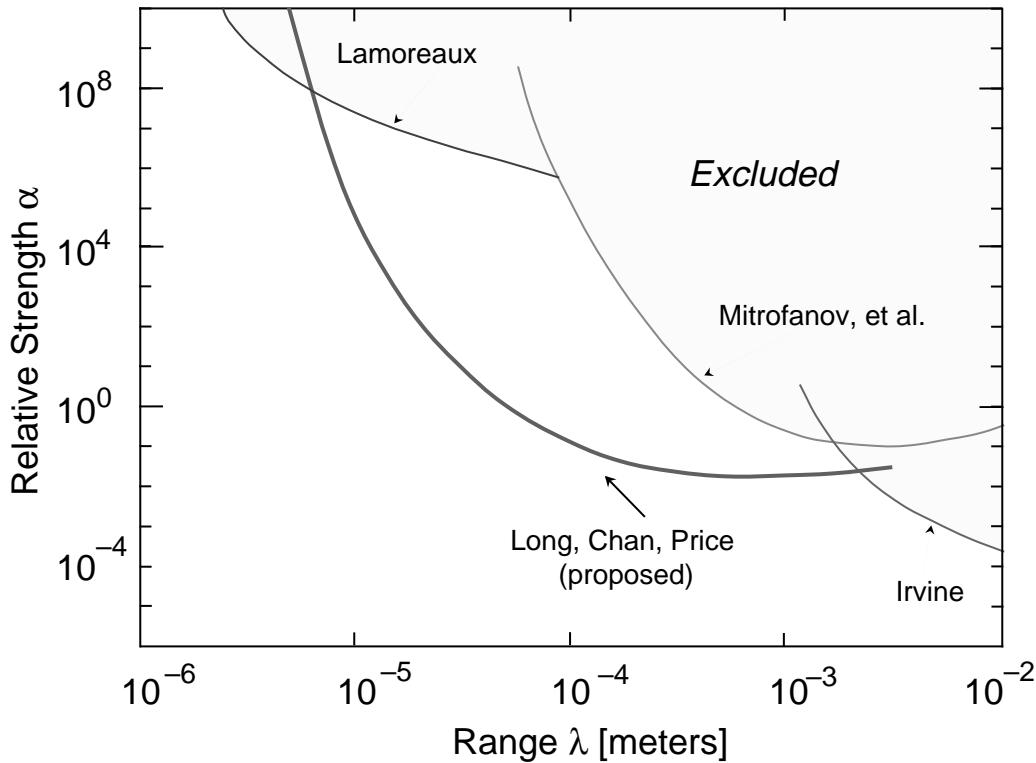
$$V(r) = - \int dr_1 \int dr_2 \frac{G_{\text{Newton}} \rho(r_1) \rho(r_2)}{r_{12}} [1 + \varepsilon_G \exp(-r_{12}/\lambda_G)] , \quad (35)$$

where  $\rho(r_i)$  is the mass density of object  $i$  and  $r_{12}$  is the separation between body 1 and body 2. Elegant experiments that study details of Casimir and Van der Waals forces imply bounds on anomalous gravitational interactions, as shown in Figure 11. Below about a millimeter, the constraints on deviations from Newton’s inverse-square force law deteriorate rapidly, so we are free to consider changes to gravity even on a small but macroscopic scale.

That is precisely the possibility raised by the interesting new idea that some extra dimensions of spacetime might be—relatively speaking—large.<sup>19</sup> The new idea is to consider that the  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  standard-model gauge fields, plus needed extensions, reside on  $3 + 1$ -dimensional branes, not in the extra dimensions, but that gravity can propagate into the extra dimensions. How does this hypothesis change the picture? The dimensional analysis (Gauss’s law, if you like) that relates Newton’s constant to the Planck scale changes. If gravity propagates not only in

<sup>18)</sup> For a gentle introduction to the aspirations of string theory, see Ref. [35].

<sup>19)</sup> For an enthusiastic overview, see Marcus Chown, “Five and Counting . . .,” *New Scientist* **160**, No. 2157 (24 October 1998), <http://www.newscientist.com/ns/981024/fifth.html>.



**FIGURE 11.** Experimental limits on the strength  $\varepsilon_G$  (relative to gravity) versus the range  $\lambda_G$  of a new long-range force, together with the anticipated sensitivity of a new experiment based on small mechanical resonators [38].

the 3+1 dimensions of Minkowski space, but also in  $n$  extra dimensions with radius  $R$ , then

$$G_{\text{Newton}} \sim M_{\text{Planck}}^{-2} \sim M^{\star -n-2} R^{-n}, \quad (36)$$

where  $M^{\star}$  is gravity’s true scale. The correlation between  $M^{\star}$  and the size  $R$  of the  $n$  large extra dimensions is given in Table 1 for some representative cases. Could the extra dimensions be quasimacroscopic? One large extra dimension seems excluded, since gravity within the solar system obeys Newton’s force law in three (not more) spatial dimensions.<sup>20</sup> Notice that if we boldly take  $M^{\star}$  to be as small as  $1 \text{ TeV}/c^2$ , then the scaling law (36) requires the radius of the extra dimensions to be smaller than about 1 mm, for  $n \geq 2$ .<sup>21</sup> Deviations on the millimeter scale are allowed by current knowledge of gravity on short distances, but will be challenged soon.

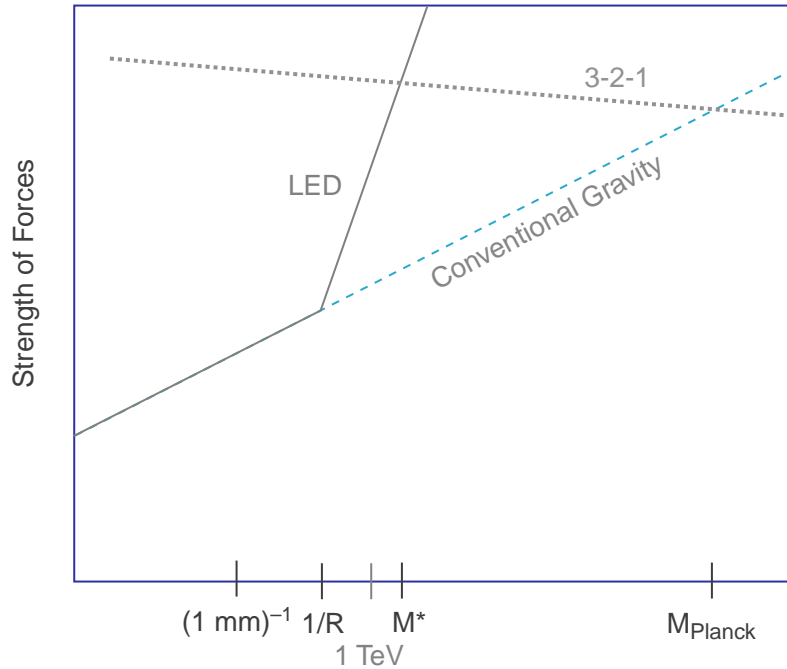
If we use the four-dimensional force law to extrapolate the strength of gravity from low energies to high, we find that gravity becomes as strong as the other

<sup>20)</sup> The semimajor axis of Pluto’s orbit is about  $6 \times 10^{12}$  m.

<sup>21)</sup> Other observational constraints [39] suggest that it is more prudent to choose  $M^{\star} \approx 10 - 100 \text{ TeV}/c^2$ , for which at least three large extra dimensions are required to alter gravity on the millimeter scale.

**TABLE 1.** Radius  $R$  of  $n$  large extra dimensions for low values of the scale  $M^*$  of gravity.

	$n = 1$	$n = 2$	$n = 3$	$n = 6$
$M^* = 1 \text{ TeV}/c^2$	$10^{13} \text{ m}$	$10^{-3} \text{ m}$	$10^{-8} \text{ m}$	$10^{-14} \text{ m}$
$M^* = 10 \text{ TeV}/c^2$	$10^{10} \text{ m}$	$10^{-5} \text{ m}$	$10^{-10} \text{ m}$	$10^{-15} \text{ m}$
$M^* = 100 \text{ TeV}/c^2$	$10^7 \text{ m}$	$10^{-7} \text{ m}$	$10^{-12} \text{ m}$	$10^{-16} \text{ m}$



**FIGURE 12.** One of these extrapolations (at least!) is false.

forces on the Planck scale, as shown by the dashed line in Figure 12. If the force law changes at an energy  $1/R$ , as the large-extra-dimensions scenario suggests, then the forces are unified at an energy  $M^*$ , as shown by the solid line in Figure 12. What we know as the Planck scale is then a mirage that results from a false extrapolation: treating gravity as four-dimensional down to arbitrarily small distances, when in fact—or at least in this particular fiction—gravity propagates in  $3 + n$  spatial dimensions. The Planck mass is an artifact, given by  $M_{\text{Planck}} = M^*(M^*R)^{n/2}$ .

Extra dimensions seen by standard-model particles cannot be larger than about  $1 \text{ TeV}^{-1} \approx 10^{-19} \text{ m}$ , or we would already have probed them at LEP2, HERA, and the Tevatron. We will see in a moment that future collider experiments can examine two or more large extra dimensions with a low gravitational (string) scale  $M^*$ .

Although the idea that extra dimensions are just around the corner—either on the submillimeter scale or on the TeV scale—is preposterous, it is not ruled out by observations. For that reason alone, we should entertain ourselves by entertain-



**TABLE 2.** Sensitivities to large extra dimensions, expressed as 95% CL upper limits on the radius  $R$  of  $n$  extra dimensions (from Ref. [41]).

	$n = 2$	$n = 4$	$n = 6$
LEP2	$4.7 \times 10^{-4}$ m	$1.9 \times 10^{-11}$ m	$6.9 \times 10^{-14}$ m
Tevatron Run 1	$1.1 \times 10^{-3}$ m	$2.4 \times 10^{-11}$ m	$5.8 \times 10^{-14}$ m
Tevatron Run 2	$3.9 \times 10^{-4}$ m	$1.4 \times 10^{-11}$ m	$4.0 \times 10^{-14}$ m
Large Hadron Collider	$3.4 \times 10^{-5}$ m	$1.9 \times 10^{-12}$ m	$6.1 \times 10^{-15}$ m
1-TeV polarized linear collider	$1.2 \times 10^{-5}$ m	$1.2 \times 10^{-12}$ m	$6.5 \times 10^{-15}$ m

ing the consequences. Any particle can radiate a graviton into extra dimensions. An extradimensional graviton is only gravitationally coupled, and so will not interact in the detector: the gravitons go off into extra dimensions and are lost. Their signature is missing energy,  $\cancel{E}_T$ . These processes, individually tiny, may be observable because the number of excitable modes is very large. Many authors [39] have considered the gravitational excitation of a tower of Kaluza–Klein modes in the extra dimensions, which would give rise to a missing (transverse) energy signature in collider experiments [40]. We call these excitations *provatons*, after the Greek word  $\pi\rho\acute{o}\beta\alpha\tau\omicron$  for a sheep in a flock. For proton-antiproton collisions, the experimental signatures include  $\bar{p}p \rightarrow \text{jet} + \cancel{E}_T$  (parton + graviton), and  $\bar{p}p \rightarrow \ell^+\ell^- + \cancel{E}_T$  ( $\ell^+\ell^-$  + graviton).

*The Detector Challenge.* To establish a jet +  $\cancel{E}_T$  signature at a hadron collider, we require a hermetic detector with well-controlled  $\cancel{E}_T$  tails to establish and quantify the missing-energy signature; highly efficient rejection of cosmic-ray and accidental triggers; the ability to reject triggers originating from jet mismeasurements; and control over physics backgrounds, including  $Z^0$  + jets and  $W^\pm$  + jets. The experimental sensitivity to provatons depends on collider energy, luminosity, and species, and the number of large extra dimensions.

A representative analysis of the constraints that may be inferred from anomalous single photon production at  $e^+e^-$  colliders and from monojet production at hadron colliders if no signal is seen is shown in Table 2. If a missing-energy signal is found, it will be a challenge to distinguish an extradimensional signal from the classic  $R$ -parity-conserving signature for supersymmetry. We should be so lucky!

## The Outlook for Extra Dimensions

We are only beginning to explore the possible implications of almost-accessible extra dimensions. Among the fascinating new worlds to explore are the Randall–Sundrum mechanism for localizing gravity in an extra dimension (in the vicinity of a brane or domain wall) [42], and the speculation of Arkani-Hamed and Schmaltz that the fermion mass hierarchy reflects fermion wave packets separated in an extra dimension [43]. The characteristic missing-energy signature of a Kaluza–Klein

excitation will be hard to distinguish from other new physics. We need to think in more detail about the backgrounds and optimal search techniques. The search for large extra dimensions reinforces the informative metaphor of a collider and its detectors as an ultramicroscope. Are extra dimensions large enough to see? It is also interesting to consider what might we observe above the threshold for exciting extra dimensions. Although the basic concepts that underlie these speculations have a sound basis in string theory, most of the scenarios put forward so far have more to do with storytelling than with theoretical rigor. However, it is plain that our inability to disprove at once the outlandish idea of large extra dimensions is a measure of the potential for experimental surprises, and an indication of Nature's capacity to amaze us!

## FINAL THOUGHTS

To a great degree, the progress of particle physics has followed from progress in accelerator science and instrumentation. There is no substitute for experiment, and experiment requires inventions in both hardware and software and continuous innovation in analysis. The slogan, "Yesterday's sensation is today's calibration and tomorrow's background,"<sup>22</sup> embodies both the challenge and the opportunity of advances in experimental technique.

In the middle of the revolution we are experiencing—indeed, making—in our conception of Nature, when we deal with fundamental questions about our world, including

*What are the symmetries of Nature, and how are they hidden from us?*

*Are the quarks and leptons composite?*

*Are there new forms of matter, like the superpartners suggested by supersymmetry?*

*Are there more fundamental forces?*

*What makes an electron an electron, a neutrino a neutrino, and a top quark a top quark?*

*What is the dimensionality of spacetime?*

we cannot advance without new instruments that extend our senses and allow us to create—and understand—new experience far beyond the realm of everyday human experience.

I wish you a productive two weeks in Istanbul, and hope that what you learn about instrumentation, the spirit of experimentation, and the habits of mind necessary to make detectors act as reliable extensions of our senses will open new horizons for you and for science.

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<sup>22)</sup> I believe that this formulation is due to V. L. Telegdi.

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