
BRIGHTER
FUTURE

Collider luminosity is the key to particle physics discoveries. Fermilab and labs around the world have spared no effort in increasing their collider luminosities.

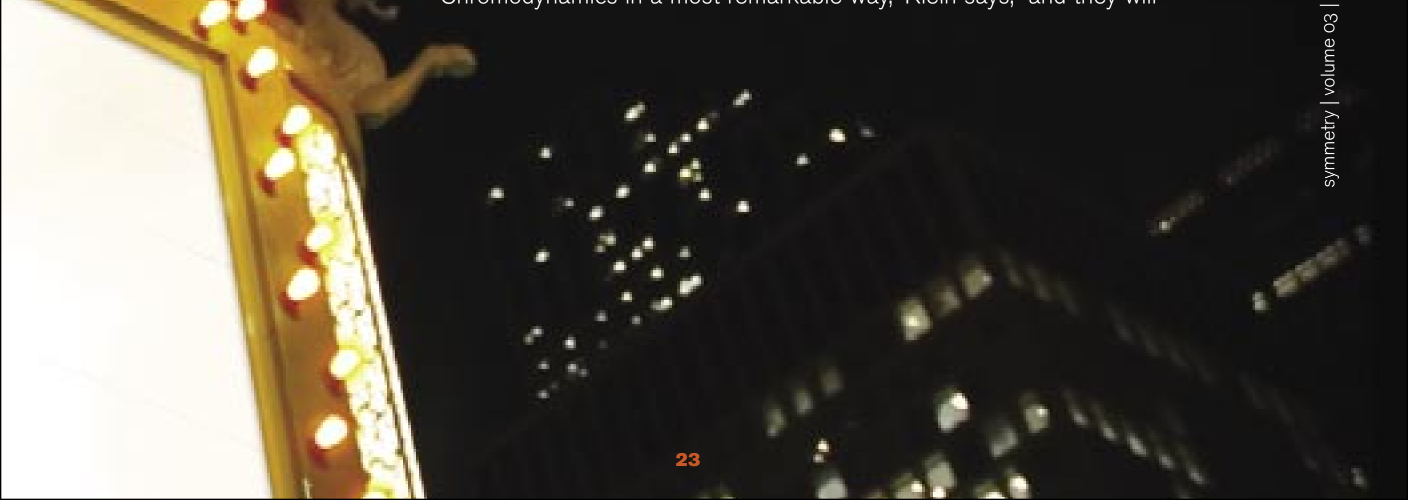
By Siri Steiner and Mike Perricone

There's a bright light at the end of the accelerator tunnel for PEP-II at SLAC, KEKB in Japan, HERA at DESY, and the venerable Tevatron at Fermilab. It's the bright light of glowing, growing luminosity from particle collisions in the United States, Asia, and Europe, beckoning high-energy physicists around the globe toward new realms of discovery.

At Japan's KEKB electron-positron collider, until just recently, the integrated luminosity (a measure of the total number of collisions produced) has been doubling approximately every 14 months—which, along with a record peak luminosity in December 2005, promises bountiful results for the Belle *B*-factory, studying decays of *B* mesons. "Luminosity is to experimenters what mother's milk is to babies," says Belle co-spokesperson Stephen Olsen of the University of Hawaii. "When they are deprived of it, they are surly and unhappy. When they are getting their fill they are happy and smiley. These days, Belle experimenters are a pretty happy lot."

Operations at the PEP-II electron-positron collider at SLAC were halted in October 2004 during an overall lab shutdown following an electrical accident. Since operations resumed in April 2005, the accelerator and *B*-factory have been humming. Says the BaBar experiment co-spokesperson David MacFarlane: "The achievement of the new record peak luminosity at the beginning of October, breaking the previous Run 4 record from May 2004, and the corresponding new records for shift and 24-hour integrated data samples very clearly demonstrates that PEP-II has not only restored full operation but is once more aggressively pushing along the planned path towards higher luminosity."

At DESY in Germany, upgrades have doubled the luminosity for the electron-proton HERA collider over the levels of 2000. In 2004-05 alone, HERA delivered nearly double the integrated luminosity that it did during the entire span of 1992-2000. HERA is the world's first electron-proton collider, with a mission of resolving the substructure of protons and the strong interaction of quarks as is mediated by gluons. "The prospects for the forthcoming run, which will start in February this year and end in the summer of 2007, are that within these 1.5 years the [integrated] luminosity delivered will be doubled," says Max Klein, spokesperson of the H1 detector experiment at HERA. "The results of HERA have advanced Quantum Chromodynamics in a most remarkable way," Klein says, "and they will



thus be of crucial importance when the data at the LHC will have to be analyzed, and searches will be pursued at the TeV scale of energy."

Culminating an extensive upgrade project of more than two years at Fermilab, the Tevatron proton-antiproton collider posted a series of peak luminosity records during 2005, thanks to major improvements in available antiprotons. What experimenters really want is integrated luminosity: a consistent number of collisions maintained and added up over the long haul. Average integrated luminosity per week at the Tevatron has more than tripled since January 2003, from approximately seven inverse picobarns (the measure of integrated luminosity representing the total number of collisions) to nearly 23 inverse picobarns; average peak luminosity has increased by nearly a factor of six. "It required lots of hard work from all across the lab," says Jeff Spalding, manager of the upgrade effort. "But in the last three months of 2005 we've seen a higher integrated luminosity than all of Run I combined [1992-96]. And that's pretty darn impressive."

Taking a cue from billiards

Particle physics at colliders is strikingly similar to shooting pool (a.k.a. pocket billiards): the greater the number of collisions created, the greater the likelihood of success–and of moving on to a bigger game with higher stakes.

But while one billiard ball classically colliding with another billiard ball always adds up to two billiard balls, the near-light-speed quantum environment of $E=mc^2$ changes the picture completely for particle collisions. "Imagine a car crash," says Steve Holmes, Associate Director for Accelerators at Fermilab. "Two 2,500-pound Minis run into each other and, instead of a fender rattling to the pavement, a 6,500-pound Hummer pops out."

Which is exactly what happened when collisions of protons and antiprotons (each with a mass of about 1 GeV/c^2) produced the first observation of the top quark (mass of about 175 GeV/c^2, roughly equivalent to the mass of a gold nucleus), reported by Fermilab in 1995.

Fermilab was able to produce this relic particle of the early universe because the Tevatron collider is the world's most powerful accelerator, recreating conditions that existed a trillionth of a second after the big bang. "One could almost say that we are bringing extinct states of matter back into existence," says Roger Dixon, head of Fermilab's Accelerator Division. "We're looking back to a time when only simple things existed, like quarks and gluons."

In particle physics, as in life, the simplest things are often the rarest, and they take the most looking. "It's hard to say what we'll find until it happens," says Holmes. "But the more collisions we produce, the better the chance we have of finding something rare." How rare? "It is possible," says Fermilab theorist Chris Quigg, "that we will find something that changes our perception of the universe for good."

Numbers game

The Tevatron itself represents an earlier time. When completed in 1983, the four-mile ring represented the world's largest assembly of superconducting magnet technology. It also led the world in collision energy, and will continue to hold that lead at two trillion electronvolts (2 TeV) until CERN turns on the Large Hadron Collider at 14 TeV. Until then, the Tevatron's challenge is to squeeze the maximum number of particle collisions across the smallest achievable area over the longest possible span of time. "We try to push more particles through a smaller beam area to make oncoming particles collide," says Dixon.

The resulting measurement is a wacky-looking term, such as 171E30 cm^{-2} sec^{-1}–which the Tevatron produced on January 6, 2006, as one of a series of world records for "initial luminosity," a snapshot of the likely number of collisions (in this case, 171×10^{30}) per second if the beams had a cross-section of one square centimeter. "Integrated luminosity," totaling up the snapshots over a longer period of time, is the measure prized by experimenters seeking to feed their need for data in their quest for discoveries.

Totaling up luminosity gets a little tricky because of the units, which use the concept of a "barn," an area of 10^{-24} cm^2, based on the typical nucleus cross section. Picobarns are 10^{-12} barns, and femtobarns are 10^{-15} barns. Luminosity is rated in collisions per cross sectional area so luminosities measured in inverse picobarns (collisions per 10^{-36} cm^2) are not as

Fermilab's Tevatron collider has tripled its luminosity since 2003.

Photo: Reidar Hahn, Fermilab

bright as luminosities in inverse femtobarns (collisions per 10^{-39} cm^2).

Tevatron luminosity depends on having roughly equal numbers of protons and antiprotons in the colliding beams. Producing protons is easy, by particle physics standards: remove the electrons from hydrogen and you have single protons. Producing antiprotons is not easy, by any standard: colliding beams of protons with a fixed target made of nickel, with every million collisions producing about 18 antiprotons. Ultimately, Tevatron luminosity depends on the number of antiprotons available for collisions.

Upping the upgrade stakes

When Fermilab completed four years and $260 million in upgrades to its accelerators and detectors, and turned on Collider Run II at the Tevatron in March 2001, the progress on luminosity was sluggish. The lab received less-than-glowing reviews in the national and international science press, along with signs of dissatisfaction from its funding agency, the US Department of Energy. Changes were needed. Spalding had come to the Accelerator Division to help formulate an upgrade plan just before Dixon's arrival to head up the division in January 2003. "He's like a really good chess player," says Dixon. "Always thinking one step ahead." Spalding saw the first priority as producing a steady supply of antiprotons, or "pbars," in maximum quantities with minimum losses. "Antiprotons are not easy to come by," says Dave McGinnis, a former head of the lab's Antiproton Source department. "The heart of the issue was simple: make more, collect more, and cool them faster so we can build antiproton beams quickly and maintain them."

Producing, collecting, cooling

The three-part upgrade strategy focused on increasing the antiproton production rate; providing a third stage of antiproton cooling (concentrating the beam) with the Recycler storage ring; and increasing the transfer efficiency of antiprotons to the Tevatron. The plan was put together by Spalding, the upgrade manager, and McGinnis, the leader of Accelerator Systems. There were five main areas:

Antiproton production—The antiproton creation and collection rates were increased, decreasing the time it takes to collect enough of them (a process called stacking) in Fermilab's Accumulator storage ring. Furthermore, the rate at which those antiprotons are transferred to the Recycler ring was increased. Storing fewer antiprotons in the Accumulator at any one time saves time and increases efficiency.

Slip-stacking protons—In the past year the implementation of a technique called slip-stacking effectively doubled the number of protons that the Main Injector ring delivers to the antiproton-producing target. Protons travel around the Main Injector ring in small bunches. Slip-stacking allows extra bunches of protons to be slipped in beside bunches already circulating the Main Injector.

Recycler e-cooling—A flurry of luminosity records has been closely related to the full integration of the Recycler antiproton storage ring into the antiproton supply chain. The Recycler has the capability to store more antiprotons than the Accumulator and to "cool" antiproton beams thanks to electron cooling: a continuous, high-intensity beam of electrons in the Recycler manipulates the speed of individual antiprotons and produces denser antiproton bunches. Fermilab has become the first lab to use electron cooling at high energy. First operational in the fall of 2005, electron cooling has helped luminosity to nearly triple in two years.

Tevatron beam position monitors—A team from the Accelerator and Computing Divisions upgraded the electronics and software for the 240 beam position monitors (BPMs) in the Tevatron, which help prevent the beam drifting too close to a wall and causing losses. The electronics were replaced with modern signal-processing equipment; old BPM cables were reused for Tevatron antiproton signals; and computer equipment was updated.

Controlling collisions—Premature ("parasitic") collisions in the Tevatron waste antiprotons and reduce luminosity at the detectors. Stainless steel electrostatic separators create an electric field that pulls the protons and antiprotons in opposite directions toward the outside of the beam pipe as they orbit. When Run II began, parasitic collisions claimed 30 to 35 percent of the antiprotons in the beams. With new separators, losses to parasitic collisions have fallen to less than 3 percent.

Bright beam, bright prospects

There is no time like the present for Fermilab to make big news with its luminosity upgrades. The LHC will be turning on at CERN in 2007, with physics results to follow. Boosting the Tevatron luminosity enhances Fermilab's chances for discoveries and its chances to continue playing the game at higher stakes.

"We know that the LHC will assume the high-energy frontier once it is operational, but we also know that discoveries are the best way to position ourselves at the forefront of the field and help us to secure future projects," says Fermilab Director Pier Oddone. "The Fermilab luminosity upgrades will take us there."

And like the Tevatron, other particle colliders are operating at higher and higher luminosities to nourish experimenters' appetite for the data that brings discoveries.