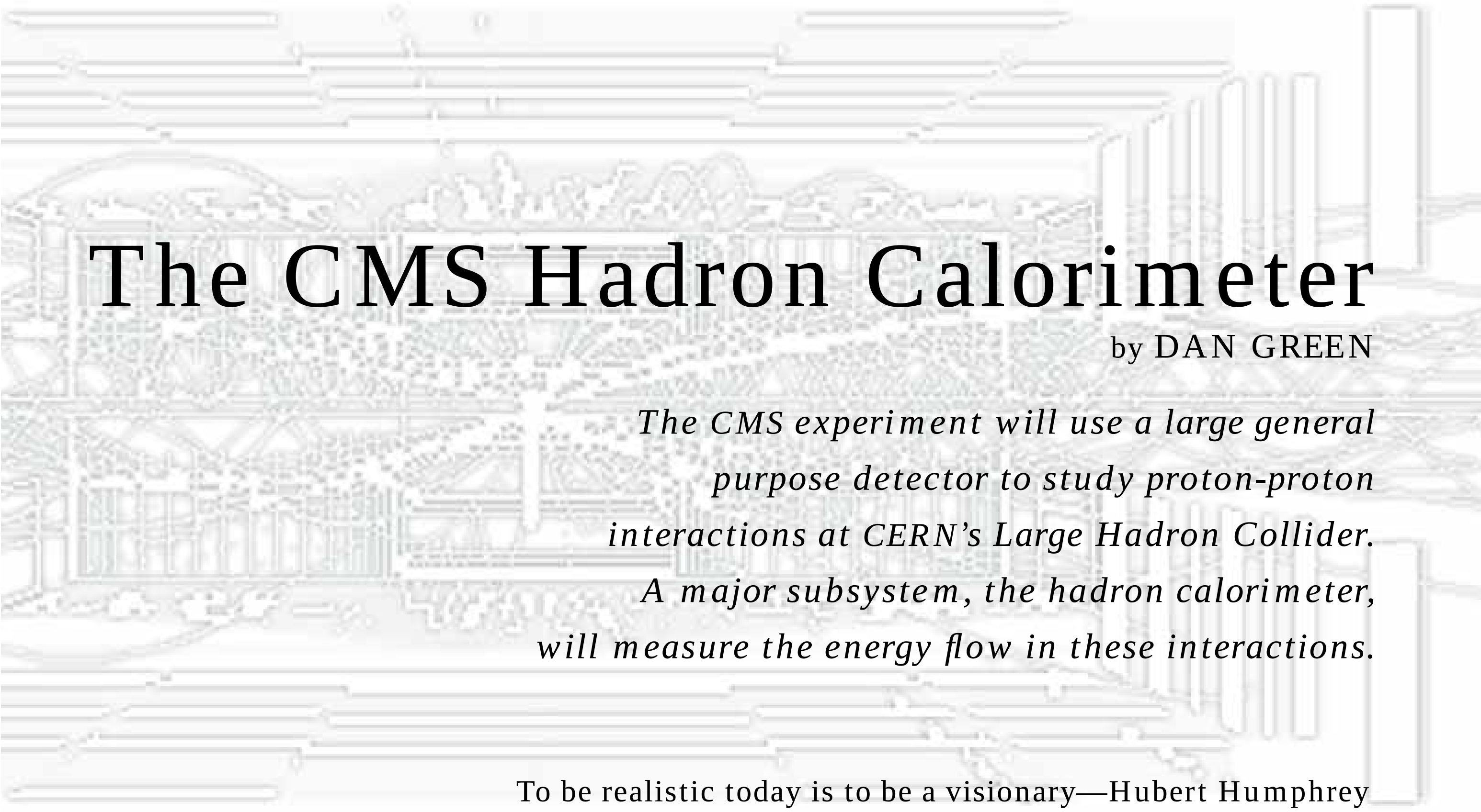


The CMS Hadron Calorimeter

by DAN GREEN

The CMS experiment will use a large general purpose detector to study proton-proton interactions at CERN's Large Hadron Collider. A major subsystem, the hadron calorimeter, will measure the energy flow in these interactions.

To be realistic today is to be a visionary—Hubert Humphrey
White House Conference on International Cooperation

THE COMPACT MUON SOLENOID (CMS) collaboration consists of about 1650 high-energy physicists from 150 institutions scattered around the globe whose collective goal is to take the next discovery step at the "energy frontier." The U.S. part of this collaboration, which formed in response to the 1993 demise of the Superconducting Super Collider, includes about 300 physicists from 40 institutions. Our challenge is to participate successfully in what are arguably the first truly global scientific experiments.

The CMS detector is a general purpose detector. When voyaging into the unknown, it is best to be ready for anything. In the case of CMS, where we do not know exactly what we will find, we must be prepared by building a detector capable of measuring all the known fundamental particles to good accuracy.

The particles of matter are categorized as leptons and quarks. The fundamental force carriers are the photon of electromagnetism; the weak force carriers, W and Z; and the strong force carriers, the gluons. Quarks interact strongly and thus evolve into hadrons—strongly interacting particles such as the pion and proton. The leptons are either charged or neutral. The neutral leptons, called neutrinos, interact so weakly that they escape direct detection. At every moment, for example, billions of solar neutrinos are traversing our bodies without our notice and without causing us harm. We infer the production of neutrinos in a reaction by the energy that they carry off undetected, which shows up in the detector as an imbalance in the momentum. Since particle detection is extremely difficult at small angles to the incoming beams, only the energy imbalance transverse to the beams can be measured.

W. Wu

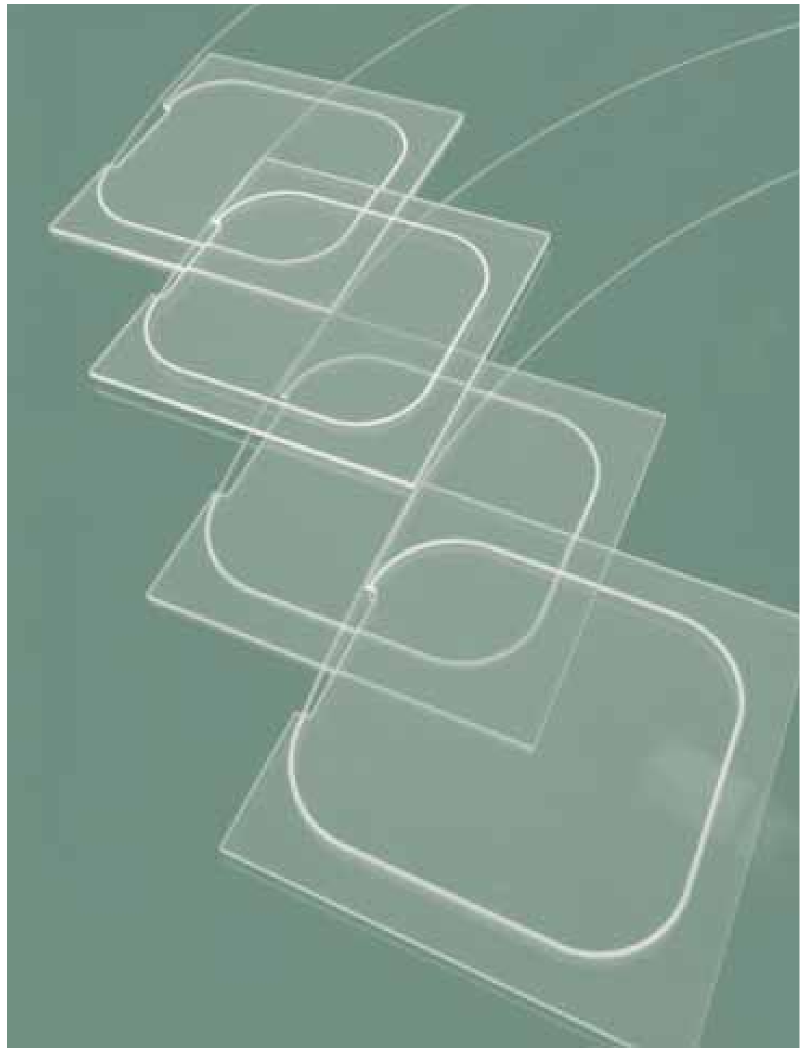
Dan Green, left, and Prof. Xuan Zhu of the Chinese Academy of Sciences discuss potential collaboration on CMS between the United States and Chinese groups.

The CMS detector is organized into specialized subdetectors. I will concentrate on the hadron calorimeter—referred to by George Trilling as "nearly hermetic"—in part because U.S. groups have a major role in designing and building it. The purpose of this calorimeter is to measure the energies and directions of all strongly interacting particles —the quarks and gluons—produced in an interaction. The term "hermetic" means that nearly all secondary particles are observed. If this is true, then missing transverse energy in the final state implies the production of a noninteracting particle. Therefore, the detectors must be fully active, without "dead" or inactive regions.

The objects actually observed are not the fundamental particles themselves, which are hidden from our view, but "jets" of ordinary particles. These ensembles of hadrons are emitted as a tightly collimated spray with almost the same direction and energy as the parent quark or gluon. It is these jets which are detected in the calorimeter subsystem. A high-energy jet might attain an energy of 1 trillion electron volts (1 TeV). That energy is 40 billionths of a calorie; therefore, we cannot simply measure the temperature rise in the calorimeter because it is infinitesimal.

The method we use is to convert the energy to mass, à la Einstein, and thus to produce many secondary particles. These particles, in turn, produce tertiary particles. In a fashion analogous to the geometric growth of bacteria, the number of particles in the calorimeter increases rapidly in a cascade of interactions until the "food"—in this case the energy needed to produce new particles—runs out. At that point, multiplication stops. The particles in turn ionize the active detecting medium, and the resultant rapid pulse of deposited energy is measured. Since the number of produced particles is proportional to the incident energy, E, what amounts to counting these particles gives us a measure of the energy.

The statistical fluctuations in the number of particles produced means that the fractional energy error, dE/E, is proportional to $1/\sqrt{E}$. Note that the performance improves with energy, which explains why calorimetry becomes an important tool in high-energy experiments. To be fair, any nonuniformity of manufacturing or performance has the result that the



The tile and wavelength-shifting fiber active elements of the hadron calorimeter detector for CMS. (Courtesy Fermilab Visual Media Services)

mean energy measured in different parts of the detector varies. This effect causes an error, dE/E, that goes as a constant and thus dominates the high-energy behavior of the detector. It is this error that the CMS calorimeter group has worked to reduce to as low a value as possible.

The groups who are working to design and build the CMS hadron calorimeter (HCAL) come from China, Hungary, India, Italy, Russia and Dubna member states, Spain, Turkey, and the United States. Over the past four years we have formed a team with the goal of not only designing and building it, but also installing it in CMS during 2003 and 2004, and using it for physics beginning in 2005. The diversity and geography of the hadron calorimeter groups requires special effort to unify the team. Once the design is complete, it must be tested in beams of particles, and the ones most accessible to all the HCAL groups are at CERN in Geneva, Switzerland. The planning, execution, and analysis of these test beam runs amount to a small international experiment in itself, and it is an enviable accomplishment that the HCAL groups have run every year since 1994.

The calorimeter itself is deployed in five distinct pieces: a barrel at wide angles to the incident beams; two endcaps at intermediate angles; and two forward detectors at small angles. These pieces are the responsibility of different subgroups.

The hadron calorimeter is immersed in a 40 kG magnetic field, which is used to deflect charged particles and thus measure their momentum in other CMS subsystems. As a consequence, HCAL must be built of non-magnetic materials, such as copper. As a result of concerted efforts, the HCAL community has adopted many solutions in common such as the optics and transducers in the barrel and the two endcaps. Because the forward detector system is exposed to high radiation, it requires different solutions; however, we have adopted a common front-end electronics and a common readout system for all of HCAL which will simplify the work of building and commissioning it.

As seen above, we have achieved an almost hermetic design. The active element is a scintillator tile which emits light in the blue. That light is absorbed and shifted to the green by a wavelength shifting (WLS) fiber rather than a conventional light pipe. By using a WLS to "cool" the scintillator light, we can reduce the dead area dramatically, leading to the required performance.

The search for the origin of mass, which is the primary goal of LHC experimentation, requires the study of rare processes. Thus, very high beam fluxes are needed, which means that the hadron calorimeter must endure unprecedented radiation doses. In the barrel and endcaps, scintillator will continue to function; however, the forward detectors will be exposed to up to 1 billion rads, and a different

The CMS prototype hybrid photodetector (top) and a schematic of the pixel readout (bottom). This device functions in the 40 kG field of CMS where a conventional phototube cannot. (Courtesy Fermilab Visual Media Services)

technology is needed. To compare it to everyday life, we all absorb a yearly dose of 0.2 rads from cosmic rays, and a dose of 300 rads is lethal. Because the dose of the forward detectors is high, their optics are made out of pure quartz, which is also used for reactor windows.

In the 40 kG field of CMS, conventional transducers, such as photomultiplier tubes,will not function, so the HCAL community has found and tested other technologies. The device shown on this page is a new hybrid combining a normal photocathode with a silicon diode acting as the anode. The resulting signals must be compactly processed and sent off the HCAL detector to remote counting rooms. In this case, we adopted the solutions of the telecommunications industry and converted the digitized signals back to light for transmission along fiber optic cables. These solutions are again chosen to maintain the hermetic character of HCAL.

The dispersed HCAL community is doing its work more or less in concert using new computing and networking technologies such as electronic mail, teleconferencing, and the World Wide Web. For example, we assembled a 530-page Technical Design Report using everyone's input—which is nothing unusual—but in the process, a "virus" was picked up. After some frantic efforts, it was finally eradicated.

In the future, global efforts will become the norm as we ask deeper questions and thus attack harder problems. As the introductory quote illustrates, this is a practical fact of our scientific life. It is the science that is our pole star, and it guides us toward a global community. Indeed, the rewards go beyond science. The personal pleasures of meeting and working together with scientists from many cultures make all the challenges stimulating and ultimately even satisfying.