Summary of the Particle Physics and Technology Working Group

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Progress in particle physics has been tightly related to technological advances during the past half century. Progress in technologies has been driven in many cases by the needs of particle physics. Often, these advances have benefited fields beyond particle physics: other scientific fields, medicine, industrial development, and even found commercial applications.
The particle physics and technology working group of Snowmass 2001 reviewed leading-edge technologies recently developed or in the need of development for particle physics. The group has identified key areas where technological advances are vital for progress in our field, areas of opportunities where particle physics may play a principle role in fostering progress, and areas where advances in other fields may directly benefit particle physics. The group has also surveyed the technologies specifically developed or enhanced by research in particle physics that benefit other fields and/or society at large.

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1. Introduction

Particle physics research depends on and advances science and technology outside of particle physics. New developments in particle physics are inextricably intertwined symbiotically and causally with developments in science and technology. The list of advances in science and technology that are directly attributable to particle physics research is substantial and pervasive. The list of advances in technologies that have enabled progress in particle physics and that are needed for further progress is also extensive. The task of the Snowmass E7 working group on particle physics and technology was to survey and understand the connections between these two areas. This summary and the accompanying articles represent the findings of our studies.

2. Benefits from Particle Physics Technology

2.1. Overview

The attribution of major society-changing technological advances to particle physics is direct and straightforward to document. Some of these advances result from development of tools to perform the science, while others are derived from tools that enable particle physicists to collaborate in performing the science. An example of the former is the particle beam, which is used for medical treatment, biological research, materials research to produce new electronics chips and their manufacture. An example of the latter is the development of the world wide web (WWW). In these cases, as in the others documented below, the connection is neither peripheral nor derivative, but directly causal. The technology was developed by particle physicists and then used, basically as developed, to benefit society.

2.2. Particle Beams

1. Medicine

Perhaps the most commonly perceived benefits to society from particle physics are those derived from particle beam technology. Many lives have been saved from inoperable tumors through particle beam therapy. Physicians take advantage of the property of proton beams to deposit most of their energy as they slow down to precisely target cancerous areas. X-ray or gamma ray therapy results in damage to the skin and the tissue surrounding a tumor. Since a proton deposits less energy before it stops in the tumor, aporoton beam with precisely tuned energy causes less damage to skin and surrounding tissue.

Boron Neutron Capture Therapy (BNCT) introduces Boron-10 into a tumor and then exposes the tumor to neutrons. Boron-10 is a non-radioactive non-toxic isotope with a high cross section for capturing neutrons. Boron-10 becomes boron-11 in an excited state that fissions into an alpha particles and lithium ions, high-energy particles with a very short range. BNCT has the promise of little damage to surrounding tissue and the ability to precisely target tissue that has absorbed boron. New agents to provide selective boron delivery to tumors and determination of the optimal neutron energy make this a promising therapy. Until recently, the major hurdle had been the need to use a nuclear reactor for neutron generation. However, new developments in compact proton accelerators using lithium targets can provide the requisite neutron beam.

Proton beams are also used to make radio-pharmaceuticals. Examples are nuclear cardiograph products (heart perfusion agents, pharmacological stressors, and blood pool agents), general nuclear medicine products (studies of bone metastasis, lung function, brain perfusion, thyroid function, liver function, kidney function, and gallbladder function) other isotope products (iodine-131, iodine-123, xenon-133, gallium-67, indium-111, and other indium compounds), cancer imaging agents, imaging agents for infection, abscess and inflammation (white blood cell labeling), gallium imaging, and arteriosclerosis and thrombus imaging (for imaging plaque and thrombus formations).

2. Materials

Using accelerator technology from particle physics, neutron tubes create deuterium ions and accelerate them into deuterium or tritium targets to produce mono-energetic (2.5 or 14 MeV) neutrons. Unlike isotopic neutron generators, neutron tubes can be turned off and operated either in continuous or pulsed mode. Neutron tube applications include bulk materials analysis, detection of explosives, land mines, chemical weapons, and illicit drugs, as well as in-vivo measurement of human body composition. They also have applications in well logging and borehole geophysics applications.

About 95 percent of reactor waste is uranium that by itself does not require long-term, permanent storage. The remaining 5 percent is composed of more hazardous plutonium, other transuranics and highly radioactive fission products. Los Alamos and other U.S. Department of Energy (DOE) laboratories are studying accelerator transmutation of waste (ATW). ATW is processes hazardous waste with a high-power proton linear accelerator, a pyrochemical spent fuel treatment/waste cleanup system and a sub-critical waste burner based largely on existing nuclear technology, where it is fissioned into materials that pose mostly short-lived hazards. The fission process is controlled using neutrons produced by the accelerator's proton beam as it strikes a spallation target. The long-lived fission products capture neutrons and are converted into stable, non-hazardous materials. Because plutonium releases energy as it is destroyed by fission in the waste burner, the process can power itself. Only a fraction of the energy is needed to supply the ATW system. The rest can be sold to power companies. The destruction of plutonium also aids in non-proliferation.

The Spallation Neutron Source now under construction at Oak Ridge National Laboratory (ORNL) will advance materials science. This facility will use technology from particle accelerators such as an ion source, a linear accelerator, and an accumulator ring to produce a high intensity proton pulse that bombards a mercury target to produce a high flux pulse of neutrons. The neutron beams will be used to study the arrangement, motion, and interaction of atoms in materials. The goal of these studies is to provide improved materials for aircraft, cars, electronics, buildings and a wide variety of other applications where lighter and stronger materials are needed.

3. Ion Beams

Particle physics technology was used to develop ion implantation, a process by which ions are accelerated to a target at energies high enough (a few keV to MeV) to bury them below the target's surface. Ion implantation has become the standard means of doping the semiconductor elements of integrated circuits, because of its speed, accuracy, cleanliness, and controllability. Ion implantation of metal surfaces improves their wear, friction and corrosion properties. Ion implantation of specific tools is now preferred over other types of coating technologies because the ion implanted layer does not delaminate, require high processing temperatures to produce, nor add more material on the surface. Ion implantation is now used regularly for specific tools and equipment (e.g. to score dies for aluminum can pop-tops and artificial human joints).

Heavy Ion beams are a critical component of the program to develop fusion energy as an affordable and environmentally safe source of electrical power. Heavy ion beams are used in inertial containment fusion experiments to convey energy to heat a small ($\sim$ 1 cm) inertial fusion target for about (10^{-8}sec). The fusion target consists of an outer metal shell containing an inner spherical shell of frozen thermonuclear fuel. The heated outer shell emits intense X-rays that compress the fuel capsule to thousands of times its initial density and heat it, near the center, to thermonuclear temperatures. The resulting fusion reaction should produce about 100 times more energy than was supplied by the beams. Induction accelerators appear to have the highest practical efficiency for conveying energy to these inertial fusion targets.

4. Electron Beams

Electron beams are used for radiography, radiation therapy, and food sterilization. Electron beams are driving the frontier of the new generation of integrated circuits, constructed using nanolithography. Devices such as the "Nanowriter" of the Lawrence Berkeley National Laboratory (LBNL) are leading the way towards production of chips in the deep sub-0.1 micron feature size.

Electron beams are used to make synchrotron light sources that have made significant contributions towards developing new materials, advancing biological and medical science, and numerous other technological breakthroughs. Synchrotron light sources are used to study "quantum dots", tiny semiconductor crystals containing only a few hundred electrons, which can be used as miniature electronic switches or storage units in future, ultra-small electronics.

Synchrotron light sources are used to examine aspects of combustion and the operation of catalytic converters at the atomic level to study the chemical reactions and the catalyst aging process. They are used to study the dynamics of slip-stick friction on a molecular level to develop new materials that are either stickier or more slippery. They are used to observe the structure of tungsten filaments in incandescent light bulbs to improve their longevity and the coating of florescent light bulbs to improve their luminous efficiency. Synchrotron light sources are used to study the behavior of the phase transitions of high temperature superconducting materials.

Synchrotron light sources are used to study the structure of complex protein molecules in order to understand the details of their biological function. This is leading to new understandings in such areas as muscle physiology, how long proteins transfer nutrients and chemical messengers, the function of nerve cells, and the causes of Alzheimer's disease. Light sources are also used to study vibrations of biological molecules.

5. Superconductivity

Particle physics accelerators such as the Tevatron at the Fermi National Accelerator Laboratory (FNAL), HERA at the Deutsches Elektronen-Synchrotron (DESY) and the Large Hadron Collider (LHC) under construction at the European Organization for Nuclear Research (CERN) have been driving the development of superconducting magnets and their technology (i.e. superconducting wire and cables). Powerful superconducting magnets, with multi-Tesla fields, can be used for levitated transportation vehicles, energy storage and plasma confinement for fusion research. They are also used in magnetic resonance imaging (MRI), a technique to produce high quality images of the inside of the human body. MRI is based on the principles of nuclear magnetic resonance, which produces microscopic chemical and physical information about molecules.

2.3. Particle Physics Detectors

Particle physics detector technology has found direct application in medicine, astronomy, waste management, and many other areas. A good example of this is in the area of medical imaging, which has benefited from the use of particle physics technology in the areas of radiation detection, new detector materials, electronics and image reconstruction algorithms. The medical imaging market uses over 100 tons of particle physics-developed scintillator each year. Developments in particle physics of photo detectors and gaseous detectors are paving new advances. Recent examples are the achievement of 100-micron resolution and micro-pattern devices that provide for true 2-dimensional imaging applications. Medical imaging technology has also benefited from particle physics development of silicon detectors that offer very fast tracking and can be assembled into large structures as well as pixel-based silicon devices that provide very high spatial resolution. The latter also have commercial application in the camcorder market. Particle physics electronics advances in radiation-tolerant circuit design, signal processing and low noise circuits have also found medical applications.

2.4. Particle Physics Computing

The particle physics community has played a leading role in the reshaping of modern computing. Recently, the most widely known application of particle physics has been the World Wide Web, invented at CERN to address the needs of the widespread particle physics collaborations. Innovation in use of communication tools to enable collaboration continues today with developments in such areas as video conferencing technology.

Particle physics has also advanced computing technology through the development of parallel computing, first by the development of computers that could be linked together, followed by application of commercial CPU and network hardware in innovative structures to form massively parallel computing farms. These architectures and techniques have now been adopted by industry as the accepted methodology to advance computing power and form the basis of the most powerful computing facilities in the world today.

However, computing development in particle physics is always moving on towards the next challenge. The power of local combination of computers pales in comparison with the vision of combining computers worldwide to tackle the analysis challenges of the next generation of particle physics experiments. Particle physicists are making this vision real in the form of grid computing. Particle physics projects such as the Particle Physics Data Grid (PPDG) and the Grid Physics Network (GriPhyN) are developing a new class of advanced network-based applications involving coordinated use of distributed computers, high-speed networks, storage resources and sophisticated middleware collectively referred to as a “grid”. Much as operating systems have provided a unifying environment for processes on single computers, the “grid” architecture provides a unified approach to applications running on a network of widely separated computing systems. An important goal is the development of virtual data, the delivery to a large community of a (potentially unlimited) virtual space of data products derived from experimental data. In this virtual data space, requests can be satisfied via direct access and/or computation, with local and global resource management, policy, and security constraints determining the strategy used.

The techniques developed to analyze the existing particle physics experiments and those being developed to analyze the next generation of experiments, such as the LHC, have advanced the technologies of data handling and processing. LHC dataflow will equal about 5 PetaBytes (1 PetaByte = 1 Million GigaBytes). As described below in Section VI, the dataflow for the planned National Digital Mammography Archive (NDMA) is estimated to be 28 PetaBytes per year. Particle physicists in the National Scalable Cluster Project are undertaking the data processing for the NDMA pilot project. Techniques from particle physics are used to set up data infrastructure and data organization using parallel storage above the TeraByte level. This enables intensive data mining and statistical analysis using tools from particle physics. Data mining techniques are also being applied in the Neighborhood Information System in Philadelphia that combines census, economic, geographical, demographic and other Federal, State and Local data to produce studies of urban, suburban and rural migration and economic development that can guide policy-makers as to where resources are best placed.

The design of the next generation of particle accelerators is driving the need for the most advanced high performance computing tools be brought to bear on their design, optimization, technology development, and operation. The Scientific Discovery through Advanced Computing (SciDAC) accelerator modeling project is national research and development effort to establish a comprehensive Terascale simulation environment needed to solve the most challenging problems in accelerator science and technology. Research is focusing on developing high-quality, hybrid mesh generation for representing complex and evolving domains, high-order discretization techniques for improved numerical solutions, and adaptive strategies for automatically optimizing the mesh to follow moving fronts or to capture important solution features.

3. Silicon Detectors and Integrated Circuits

The tagging of b-quarks has proven to be the most important criteria in the searches for the top quark and Higgs bosons. Most of the background reactions to a Higgs boson signal are due to QCD final states which consists mostly of light quarks, while the Higgs decays predominantly into b-quarks. The precision to distinguish light and heavy quarks depends on the performance of the vertex detector. The study of the decay properties of Higgs bosons is a major challenge for the vertex detector system. The vertex detector will be used to measure the Higgs decay branching fraction into b and c quarks, gluons, and tau leptons. This measurement could have far-reaching consequences in the investigation of the electroweak symmetry breaking, since the expected branching fractions differ for Standard Model and its supersymmetric extension (MSSM). In an extended Higgs sector, the detection of charged Higgs bosons $e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b$ or $e^+e^- \to hA \to b\bar{b}b\bar{b}$ depends much on the performance of the vertex detector. Furthermore, several reactions in the MSSM will lead to b-quarks in the final state, for example $\tilde{t} \to b\tilde{\chi}^+ \to bW^+\tilde{\chi}^0$. The determination of the fundamental parameters in the MSSM depends as well on the b-tagging performance. The measurement of the small cross section of the reaction $e^+e^- \to b\bar{b}A \to b\bar{b}b\bar{b}$ leads to a determination of the $\tan\beta$ parameter in the MSSM. The b-tagging performance is typically measured as purity and efficiency. The goal is a high purity and high efficiency. Figure 1 shows an example of the achievable performance for a hadronic event sample $e^+e^- \rightarrow q\bar{q}$ for five flavors. The efficiency is defined as the ratio of simulated $b\bar{b}$ events after the selection and all simulated $b\bar{b}$ events, and the purity is defined as the ratio of simulated $b\bar{b}$ events after the selection and all selected events. Such a b-tagging performance will be achieved by a multi-layer vertex detector with a minimum of material and the innermost layer as close as possible at the interaction point.

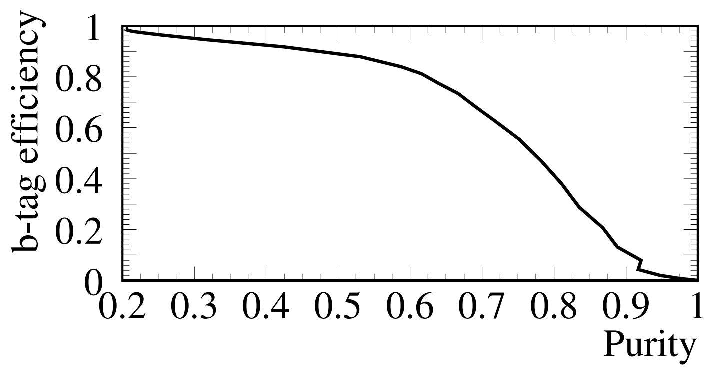

Figure 1: b-tagging performance.

3.1. Pixelated Silicon Detectors

Pixelated silicon detectors are important components of future experiments – LHC experiments, BTeV, and linear collider experiments. The interest is due to their ability to supply precision space coordinates in a dense track environment, and their high radiation tolerance. Pixelated detectors fall into three broad categories:

- monolithic pixel devices where each detector cell has its own readout circuitry manufactured on the same substrate as the sensor,
- hybrid pixel devices, similar to monolithic devices but using separate substrates for the sensor and electronics, and
- charge coupled devices (CCD's) where many cells share a single readout circuit, using a "bucket brigade" technique to pass charge from cell to cell.

CCD's offer smaller cell sizes, higher spatial precision, and lower mass, at the expense of readout speed. Monlithic designs offer higher readout speed without the need for bump bonding, but are less radiation tolerant than hyprids. Monolithic devices are still a subject of R&D [1].

1. Pixel Devices

High rate experiments use hybrid pixel devices [2]. These experiments include BTeV, Atlas, and CMS. The hybrid design allows the sensor and readout to be optimized independently, has been used in collider and fixed target experiments, and is the primary choice of future experiments.

The manufacture of standard sensors evolved from silicon strip techniques. Pads are created from n^+ material on a high resistivity n substrate. P-stops or p-spray is used to isolate the pads.

A group from the University of Hawaii has proposed an alternative sensor design called 3-D architecture [3]. Rather than planar electrodes, this design uses p and n electrodes that penetrate the entire substrate. The potential advantages are faster charge collection and higher radiation tolerance.

The pixel readout electronics are migrating from speciality radiation hard processes (DMILL, Harris, Honeywell) to commercial deep submicron processes [4]. Oxide thicknesses in deep submicron are tens of nanometers, and radiation induced charges are able to tunnel through and avoid being trapped. With design rules to complement this inherent radiation tolerance, chips have survived irradiation of more than 30 Mrad.

Reading out the tremendous amount of raw data from these devices is a major challenge. Perhaps the most ambitious scheme is BTeV's plan to use the pixel data in the first level trigger. The data rate from the detectors closest to the beam will exceed 200 Mbits/s [4].

2. CCD's

CCD's have been proven to work in a low rate environment [5]. For instance, the SLAC Large Detector (SLD) experiment was able to make very competitive measurements with only a fraction of the LEP data sample, based in part on the performance of the CCD-based vertex detector. The achieved 4 μm point resolution helped them reach a b-tagging greater than 60% with high purity [6].

The active region of the sensor is only about 20μ m thick in a CCD. This can be taken advantage of to thin the silicon, reducing the amount of material in the tracking volume. SLD achieved 0.4% of a radiation length per layer.

CCD's are the preferred technology for a detector at the next linar collider. Column-wise readout has been proposed to increase the readout rate by a factor of 100 or 1000. Further thinning of the silicon will reduce the radiation thickness to 0.06% radiation length per sensor [6], but require the silicon to be kept under tension to support itself (stretched silicon).

3. Mechanics and Cooling

To make use of the precision of the pixelated silicon detectors, their locations must be accurately known. This has been achieved by constructing precision machined mounting fixtures, accurate metrology during assembly, and painstaking alignment with tracks reconstructed in the detector [5].

Cooling of the detectors is needed not just to remove heat generated by the readout electronics, but also to achieve maximum radiation tolerance. It is intended to run hybrid pixel detectors at $-10°$C to $10°$C. The SLD CCD's were operated below 200 K by using liquid nitrogen boil-off, and enclosing the whole detector in a cryostat.

The mechanics and cooling challenges for the new detectors are great. This is certainly understood by the groups working on the detectors, but require considerable development.

3.2. Silicon Avalanche Photo-Diodes

The Avalanche Photo Diode (APD) [7] is one of the technologies most recently realized for particle physics application. APDs are planar p-n junction detectors. The primary electrons or holes, generated by incident light create many secondary electrons (or holes) in a high field region, all of which contribute to the photodiode current. Their invention goes back to the late 60s [8]. Work on APDs for particle physics started in 1987. Collaboration with industry and 10 years brought the technology to reality. Several more years of R&D and testing were needed to establish the technology before the readout of the electromagnetic calorimeter of CMS could be based on this technology. APDs are of particular interest because of their high quantum efficiency (QE) of over 90% and their large range of gain.

3.3. Three Dimensional Arrays

A new architecture of solid state particle detectors with a three dimensional geometry is being developed [9]. In normal planar sensors electrodes are confined to the silicon surface. In the new 3-D detectors P and N type electrodes extend from the surface deep into or all the way through the intrinsic bulk. The electrodes have aspect ratios exceeding 30 to 1. Manufacturing such 3-D structures is possible by using chemical etching in electric fields. The holes can then be filled with doped silicon and electrical contacts made on either side of the wafer surface. This process is analogous to integrated circuit fabrication methods, i.e. any read-out electronics could be build directly on the back of the sensor.

The technology is of particular interest to particle physics because of the much smaller collection distances: about 10 microns in 3-D sensors compared to hundreds of microns in planar sensors. As a result collection times are about one order of magnitude shorter, less than a nanosecond, and depletion voltages are lower by a factor of about 100. Bulk radiation damage causes an increase in the voltage required to fully deplete the detector and as the fields become high enough they can cause dielectric breakdown. The new 3-D detectors are thus much more tolerant to high radiation environments of particle physics experiments.

3.4. Future of Radiation Hard Electronics

The next generation of particle physics electronics technology is being prepared for the LHC, where custom integrated circuit technology allows placement of data buffering and first-level trigger filtering functions directly on the detectors themselves. However, there are complications in using the special industrial technologies required to resist the LHC radiation environment. Even the experimental caverns present dangers for the electronics, which must be at least “radiation tolerant”. Therefore, there is substantial effort being invested not only in the custom front-end designs in the high radiation areas but also in checking the radiation tolerance of many Commercial-Off-The-Shelf (COTS) components destined for placement in the caverns.

All of these challenges lead the electronics development teams to search for new solutions, working hand-to-hand with other research labs and with industry. Today there are a number of designs ready for production. Good examples are the ATLAS silicon tracker front-end chip that uses a 0.8 micron BiCMOS silicon on insulator (SOI) technology, which was specially developed to meet the challenges of the LHC environment. Its CMS equivalent, APV25, is implemented in a commercial 0.25 micron CMOS technology using a radiation-tolerant design technique developed for the LHC. Both function according to the target design specifications. In addition, complex, radiation-hard chips for the readout of pixel detectors of all LHC experiments are now available.

The next generation of hadron colliders may require more radiation tolerance or hardness than the LHC. For example, a possible upgrade of the LHC (SLHC) to a luminosity of $10^{35} cm^{-2} s^{-1}$ at the same energy as the LHC would increase the radiation levels by about a factor of 5-10. In addition, the hit occupancy of tracking detectors in an SLHC would also increase by a factor of 5-10. The most promising results in radiation hardness have recently been with 0.25 micron CMOS technology, which industry has begun to phase over into 0.13 and 0.08 micron feature sizes. However, industry may move to SOI technology. There may be difficult implications for analog design, device power and increased rates of Single Event Upsets.

The particle physics community will need to follow the trends in industry since the community lacks the volume to steer technology. However, particle physics needs often require access to more information about a specific device manufacturing process than commercial foundries usually give. In addition, adapting a technology for radiation tolerance requires an investment of many man-years of work. This limits the number of technologies that can be selected for adaptation. The low number of produced integrated circuits (relative to the industrial scale) means that the production cost of devices in the future will be dominated by design costs and not manufacturing.

4. Calorimeters and Crystals

4.1. Energy Flow in Calorimeter Design

At the linear collider, many processes have as backgrounds W and Z production. It will be important to be able to separate Ws and Zs according to their dijet masses. Therefore, the dijet mass resolution at the detector level must be on the order of a few GeV out of 100 GeV - a few percent. This depends mainly on the angular reconstruction, but it means that jet energies must be reconstructed to $\sim 30\%\sqrt{E}$. This has never been achieved by calorimeters built so far. What seems to be clear so far is that this will require:

1) energy flow algorithms in which reconstruction of jet components is optimized according to which detector subcomponent can do the best job, i.e., charged particles in the tracking system, photons in the electromagnetic calorimeter (ECAL), neutral hadrons in the hadron calorimeter (HCAL);

2) for both ECAL and HCAL, optimization on reconstruction of the shower, not necessarily for best energy resolution of single particles. This is a very different approach to calorimeter design compared to past efforts (like ZEUS);

3) 3-D reconstruction, not just in the transverse dimension, so extra longitudinal segmentation is desired over compensation. It is important to be able to identify the starting point in depth of the shower.

4) that the ECAL needs to have transverse segmentation on the order of the size of the Moliere radius and must be dense so that the longitudinal separation between hadronic and electromagnetic showers is large.

5) that the HCAL needs to be highly segmented both transversely and longitudinally in order to separate in 3-D nearby clusters in jets.

Development of such a calorimeter requires an integrated approach which includes other detector components and incorporates energy-flow algorithms in the design phase. Tracking can be optimized for, i.e., di-lepton measurements, and the ECAL can be optimized for photon reconstruction and energy measurement, but the HCAL will need to be optimized separately including the use of the tracker and ECAL in appropriate energy-flow algorithms. It may turn out that the cell size of the HCAL is so small that only a radically different readout system can be used - a digital readout of the HCAL for 1 cm^3 size cells has been proposed. A design approach is needed that can determine the optimal HCAL configuration, both in cell size and readout method. This approach is currently being undertaken by several groups working on e^+e^- linear collider detector development.

4.2. Advancements of Plastic/Organic Scintillators

Scintillators have been used traditionally in particle physics experiments in a variety of ways, ranging from timing and triggering to measurement of energy and momentum of particles. Over about the last 20 years, significant advances have been achieved in part through R&D for major detector construction and upgrade projects around the world and through generic funding through programs such as the small business innovative research (SBIR) program in the US. In the following, we restrict our discussion to organic plastic scintillation and waveshifter materials. The new advances include developments in scintillation and waveshifter materials, development of improved fiber-optic waveguide, and advances in photosensors. We provide a brief documentation of the strengths and challenges (weaknesses or downsides) to these advances and conclude the section with suggestions for further R&D that has generic applicability to a wide variety of particle physics experiments.

1. Scintillators for tracking: use of 3-hydroxyflavone, 3HF, as a secondary dye (with p-terphenyl, pTP, as the primary) in a polystyrene host material.

a. Strengths:

- Intramolecular proton transfer characteristic of 3HF in the excited state means very small self-absorption of light emission and hence long optical attenuation length.
- Emission maximum at $\lambda \sim 530$ nm is very good for transmission of the light in clear (undoped) polystyrene. This wavelength is also affords improved optical transmission in the presence of significant integrated radiation dose.
- Material is inexpensive at high purity.

b. Challenges:

- Fluorescence decay is modestly fast ($\tau \sim 7-8$ ns).

- Polystyrene material containing 3HF is susceptible to rapid optical degradation in the presence of UV and short-wavelength visible light.
- Radiation tolerance is modest, with noticeable effects after several hundred krads of integrated dose.
- To be useful for tracking - at low detected photon levels, a solid state photosensor is generally required such as VLPC or APD, or PMT with extended photocathode, preferably GaAsP if available otherwise GaAs or S20 but red extended.

2. Scintillators for calorimetry: use of Y11/K27 waveshifter in polystyrene host material to waveshift light from conventional scintillation materials such as SCSN-81 and BC-408.

a. Strengths:

- Very high efficiency among waveshifters.
- Material is environmentally very stable.
- Emission maximum at $\lambda \sim 500\,\text{nm}$ is good for transmission in clear (undoped) polystyrene, and also affords reasonable optical transmission in a high radiation field.
- Material is inexpensive at high purity.

b. Challenges:

- Fluorescence decay is quite slow in polystyrene ($\tau \sim 12 - 15\,\text{ns}$).
- Radiation tolerance is reasonable, with noticeable effects after several hundred krads of integrated dose.
- Emission wavelength requires the use of red-extended photocathodes on photosensors.

3. Multi-clad Optical Fiber: development of polystyrene fiber-optic wave guides with two claddings - the outermost having very low-refractive index or graded index.

a. Strengths:

- Outer cladding indices of $n = 1.42$ have been achieved, improving light trapping by total internal reflection by $\sim 70\%$ over conventional single-clad fibers for which $n = 1.49$ typically.
- The multi-clad structure is environmentally very stable and mechanically more robust than single-clad fibers.
- Excellent optical transmission. Attenuation lengths in the $8 - 11$ m range have been achieved for yellow green light in fibers of $830 - 940\,\mu\text{m}$ diameter.
- Material is relatively inexpensive for clear fiber. Material can be readily used for scintillating and/or waveshifter fibers - in which the core is doped with such materials as pTP+3HF or Y11/K27 or other combinations.

b. Challenges:

- No significant challenges. Multi-clad fiber is superior to single-clad fiber in all the ways that count: total internal reflection, optical transmission, and mechanical handling characteristics.
- At some molecular weights, the fiber can be more brittle and is thus less mechanically robust. The more brittle fiber has somewhat better optical transparency.

4. Solid-state photosensors, including VLPC, SSPM, HPD, and APD devices.

a. Strengths:

- VLPC: very high QE of about 75% across the visible spectrum; high gain of 10,000-50,000 depending upon structure; excellent gain dispersion; excellent high rate response; sub-nanosecond response time; pixel arrays available in groups of 8 (2 x 4 or 1 x 8 devices). Excellent for particle tracking using scintillating fibers.
- SSPM: similar to VLPC - slightly lower gain $\sim 10,000 - 15,000$, but equal or better in every other characteristic. High QE extends into the infrared to $\lambda > 20\,\text{mm}$, which is not generally useful for most particle physics applications. Excellent for particle tracking using scintillating fibers.

- HPD: capable of operation at room temperature and in high magnetic fields. Pixel readout with 19 channel, 61 channel and 73 channel designs available. Gains of several thousand with QE $\sim$ 15% using multi-alkali photocathode. A good choice for scintillation calorimetry operating in a magnetic field of several thousand Gauss or greater, and additionally for fiber tracking applications if care is taken in dealing with cross talk among pixels - mitigated if the tubes are operated with strong axial magnetic field.
- APD: capable of operation in high magnetic fields and with excellent QE for long-wave visible light (green). Modest gain (of several hundred) with operation in proportional mode and very high if operated in Geiger mode. A good choice for scintillation crystal electromagnetic calorimetry where light levels are high in the detector medium and for selected applications using fiber-optic detectors.

b. Challenges:

- VLPC: operate cryogenically in the range $6-9$ K depending upon device type. Large-scale integration requires careful design engineering and cryogenic support.
- SSPM: operate cryogenically at $5-6$ K. Large-scale integration requires careful design engineering and cryogenic support.
- HPD: in general, magnetic focusing is necessary if minimal cross talk among pixels is to be achieved.
- APD: Higher gains with fast recovery would be desirable while maintaining operation near room temperature at $\sim 0^\circ$C.

Given these excellent achievements, what should be the next steps taken in scintillator, waveshifter and photosensor R&D?

Fiber waveguide:

- Reduce the cladding index of the outer cladding further ($n < 1.4$) to improve light collection.
- Look for alternatives to PMMA as the inner cladding. PMMA serves as the optical and mechanical interface/bond between the core polystyrene and fluorinated acrylic outer claddings that are mechanically incompatible. However PMMA is the least radiation tolerant component of the fibers.
- Study other types of fiber waveguide structures besides the traditional step-index clad fibers.

Scintillator and waveshifter:

- Develop new materials with optical characteristics and fluorescence efficiency similar to Y11/K27, but with improved fluorescence decay time, about a few ns rather than the current $12-15$ ns value.
- Develop more environmentally robust alternatives to 3HF.
- Develop long-wavelength scintillators $\lambda > 570$ nm for which improved optical transmission in fiber and improved radiation tolerance in plastic host media might be possible.

Photosensors:

- Develop VLPC and SSPM with smaller pixel size, for example 0.5mm x 0.5mm, to accommodate tracking detectors built of smaller diameter fiber.
- Develop HPD with GaAsP transmission photocathodes to improve detector QE for long wavelength scintillator and waveguide materials. Current QE with multi-alkali photocathodes is typically $< 15\%$, whereas $\sim 40-45\%$ should be possible with GaAsP. Radiation tolerance of such cathodes should be studied to assess how applicable they are to certain experiments.
- Develop APD in pixel arrays and with high gain and fast recovery for tracking, calorimetry and other applications.

Many of these developments lend themselves naturally to R&D work at universities and smaller facilities - where student access to new techniques and detector development are possible and practical. In fact, some considerable R&D is already in progress on some of the above items, but a great deal more needs to be done. References on these and related topics can be found in several reviews [10, 11] and numerous conference proceedings [12, 13].

Table I Properties of Some Heavy Crystal Scintillators

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	$PbWO_4$
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	8.3
Melting Point (°C)	651	621	621	1280	1050	1123
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.12	0.9
Molière Radius (cm)	4.8	3.5	3.5	3.4	2.3	2.0
Interaction Length (cm)	41.4	37.0	37.0	29.9	21.8	18
Refractive Index^a	1.85	1.79	1.95	1.50	2.15	2.2
Hygroscopicity	Yes	slight	slight	No	No	No
Luminescence^b (nm) (at Peak)	410	560	420 310	300 220	480	500 500
Decay Time^b (ns)	230	1300	35 6	630 0.9	300	50 10
Light Yield^{b,c}	100	45	5.6 2.3	21 2.7	9	0.3 0.4
d(LY)/dT^{b,d} (%/°C)	~0	0.3	−0.6	−2 ~0	−1.6	−1.9
Price ($/cm^3)	1 to 2	2	2.5	2.5	7	2.5

a At the wavelength of the emission maximum.
b Top line: slow component, bottom line: fast component.
c Relative and measured with a PMT with a Bi-alkali cathode.
d At room temperature.

4.3. Lead Tungsten Crystals

A crystal calorimeter provides the best achievable energy and position resolutions for electrons and photons as well as good missing energy and jet energy resolutions, and thus maximizes physics discovery potential [14]. Table I lists the basic properties of commonly used heavy crystal scintillators: NaI(Tl), CsI(Tl), undoped CsI, BaF_2, bismuth gemanade ($Bi_4Ge_3O_{12}$, BGO) and lead tungstate ($PbWO_4$). All these crystals have been used in high energy or nuclear physics experiments. As a new material $PbWO_4$ crystals have, in the last ten years, attracted much attention in the high energy and nuclear physics community. They are now chosen by CMS and Alice at LHC, by BTeV at the Tevatron and by CLAS and PrimEx at CEBAF.

In the last six years significant R&D has been carried out by the CMS experiment in developing $PbWO_4$ crystals. Yttrium doped $PbWO_4$ crystals are currently produced in Bogoroditsk Techno-Chemical Plant (BTCP) in Tulla, Russia, and in the Shanghai Institute of Ceramics (SIC) Shanghai, China. A brief summary of their scintillation properties is given below. More detailed discussion on yttrium doped $PbWO_4$ crystals can be found in reference [15]. All samples shown in the plots in this section are CMS full size, which is 23 cm long tapered from $2.2 \times 2.2\text{cm}^2$ to $2.6 \times 2.6\text{cm}^2$.

As shown in Table I, an intrinsic advantage of lead tungstate crystal is its high density, short radiation length and small Molière radius. This makes a compact $PbWO_4$ calorimeter. The market price of mass produced $PbWO_4$ crystals is also relatively low. Combining these two features, a $PbWO_4$ crystal calorimeter is a cost effective detector. The blue scintillation generated by yttrium doped $PbWO_4$ crystals has a broad distribution with a peak at 420 nm. Their excitation and photo luminescence spectra and longitudinal light response uniformity are not affected by γ-ray irradiations. The longitudinal transmittance of yttrium doped $PbWO_4$ crystals approaches the theoretical limit, indicating very small residual absorption. Because of the birefringence [16, 17], the theoretical limit of SIC crystals grown along the c axis is about 3% lower than that of BTCP crystals grown along the a axis [15]. In case transmittance is to be used as a specification different numerical values should be used for crystals produced at SIC and BTCP. The radiation induced absorption in yttrium doped $PbWO_4$ crystals can be decomposed to two common color centers peaked at wavelength of 400 nm (3.07 eV) and 540 nm (2.30 eV) with widths of 0.76 and 0.19 eV respectively.

The blue scintillation of yttrium doped $PbWO_4$ crystals has short decay time. Figure 2 shows light output as a function of integration time. The ratio between light outputs integrated to 100

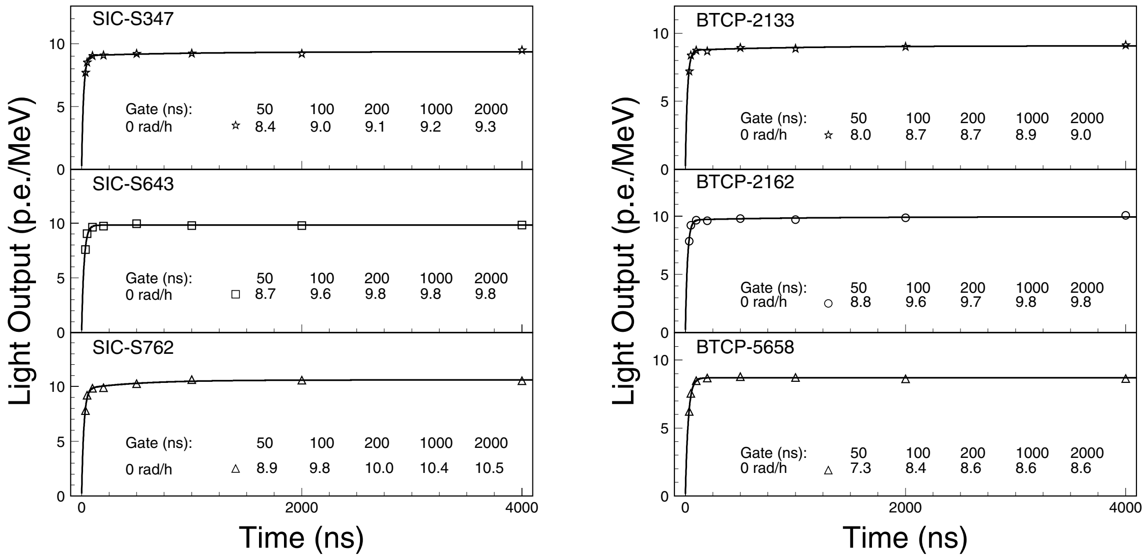

Figure 2: Light output of three SIC (Left) and BTCP (Right) samples is shown as a function of integration time.

and 1,000 ns is about 95%.

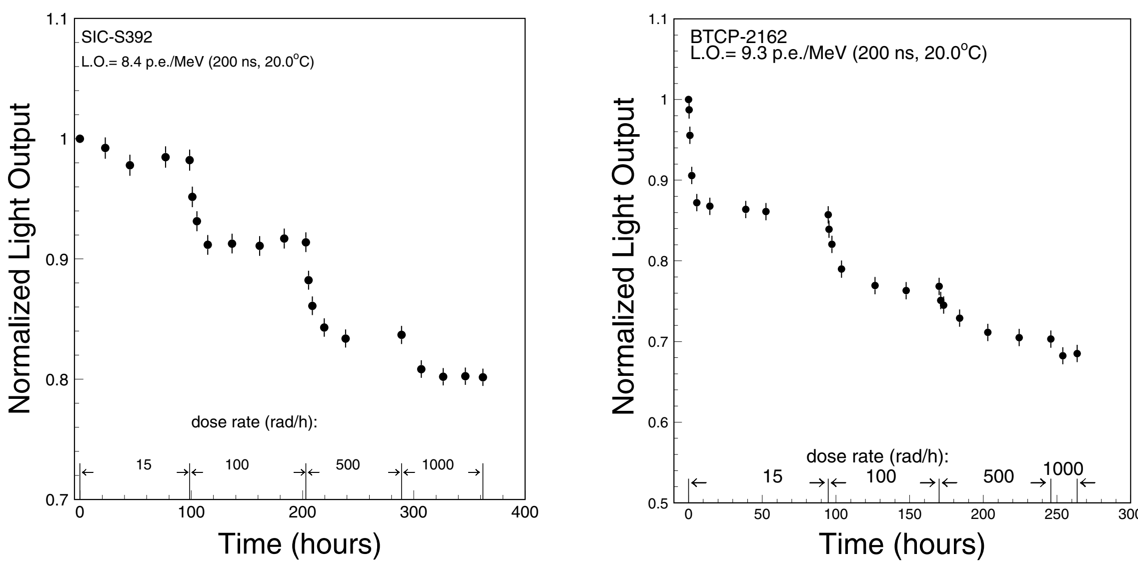

Figure 3: Normalized light output is shown as a function of time under irradiations for samples produced at SIC (Left) and BTCP (Right).

The yttrium doped $PbWO_4$ crystal has good radiation resistance. Figure 3 shows light output normalized to that before irradiation (solid dots with error bars) as a function of time under irradiation for samples produced at SIC and BTCP. Measurements were done step by step for different dose rates: 15, 100, 500 and 1,000 rad/h, as shown in these figures. The degradation of the light output shows a clear dose rate dependence, as discussed in reference [15]. At the maximum dose rate expected by CMS barrel calorimeter at LHC (15 rad/h), the loss of the light output is about 5 to 15%, which can be converted to 2 to 6% if irradiations were applied at the front (small) end of the crystal.

The yttrium doped $PbWO_4$ crystals chosen by CMS, however, have limited light output, about 10 p.e./MeV measured with a PMT of bi-alkali cathode. Recently, it is found that the light yield of $PbWO_4$ crystals may be increased by a factor of ten. Corresponding R&D work on $PbWO_4$ crystals of high lights yield can be found in these proceedings [18].

5. Trigger and Data Acquisition

5.1. Next Generation Trigger and Data Acquisition

Particle physics technology is being significantly advanced by the work on the new triggering and data acquisition (DAQ) systems for the LHC and BTeV. The LHCb trigger and data acquisition system must handle trigger rates approaching 1 MHz, while the ALICE experiment operating in ion-ion collision mode must handle very large event sizes. In the case of the ATLAS and CMS experiments, when the LHC operates in the pp collision mode at its nominal design luminosity of $10^{34} cm^{-2} s^{-1}$ an average of 25 events is expected to occur at each bunch crossing, while bunch crossings will occur at a rate of 40 MHz.

The LHC input rate of 10^9 interactions every second must be reduced by a factor of at least 10^7 to about 100 Hz, the maximum rate that can be archived by the on-line computer farm. CMS has chosen to reduce this rate in two steps. At the first level all data is stored for 3 μs, after which no more than 75 kHz of the stored events are forwarded to the High Level Trigger (HLT) system. This must be done for all channels without dead time. ATLAS also has a pipelined deadtimeless Level 1 trigger system with a latency of 2.5 μs. However, after a Level 1 Accept, regions of interest in the data are further analyzed by a second level of dedicated hardware processors that include tracking data before a rate of events reduced by an order of magnitude are transmitted to the processor farm.

For both CMS and ATLAS, the L1 system uses only coarsely segmented data from calorimeter and muon detectors, while holding all the high-resolution data in pipeline memories in the front-end electronics. During the Level 1 trigger processing time, decisions must be developed that discard a large fraction of the data while retaining the small portion coming from interactions of physics discovery potential. The large physical size of the detector and the short decision time present a series of technical and system challenges.

The ATLAS Level 3 and the CMS HLT are implemented as processing farms that are designed to achieve a rejection factor of 10^3 and about 100 events/second to mass storage. The last stage of High Level Trigger processing does reconstruction and event filtering with the primary goal of making data sets of different signatures on easily accessed media for further analysis by the world-wide physics community.

An important development to cope with the increasing complexity of online triggers is the implementation of fault-tolerant technology. The BTeV global Level 1 and Level 2/3 trigger systems employ processor farms using thousands of CPUs. The substantial challenge of availability of these systems is being met by a program to develop systems that are fault-tolerant, self-aware and fault adaptive. In such systems, faults are corrected as quickly as possible in a semi-autonomous manner using distributed and hierarchical monitoring and control.

Another industrial development that has important implications for the data acquisition of the LHC experiments and BTeV is the development of high bandwidth telecommunications switches. These devices allow the hundreds of buffers of LHC front-end readout electronics to be connected to the hundreds of processing compute nodes that must analyze the data being read out. The greater the bandwidth of these switches, the more data can be brought directly to the processing nodes for detailed analysis. The option to have an increasing fraction of commodity hardware in the readout network and data processing offers the opportunity for more easily scalable and supportable designs that can be augmented with additional straightforward purchases as the need for more processing increases.

After the LHC turns on, further evolution will be needed to cope with an upgraded higher luminosity LHC (SLHC) at CERN and BTeV at the Fermilab collider. Experiments should be able to move to a purely two-level trigger where the first level finds physics objects based on dedicated data and the higher levels are basically implemented in software processing the fully digitized data. More complex algorithms will migrate downstream to earlier levels in processing, including such tasks as finding displaced vertices. There should also be increasing use of commodity products and off-the-shelf technology. The amount of on-line processing power is increasing and real-time correction of data for calibration and other detailed effects is becoming practical. The end result will be a blurring of the distinction between on-line and off-line data processing, with the on-line data selection being quite close, if not identical to that of the off-line.

5.2. Applied Field Programmable Gate Arrays

The LHC experiments and BTeV are planning extensive use of Field Programmable Gate Arrays (FPGA). These devices offer programmable re-configurable logic, which has the flexibility trigger designers want in order to be able to alter algorithms to follow more closely the physics and detector performance as luminosity and beam conditions change. During the past decade there has been a remarkable improvement in FPGA speed and capacity, while the price has dropped. The enhanced performance of these devices is resulting in improved LHC level 1 trigger designs and is making possible the displaced vertex finding in BTeV.

Progress in FPGAs has been truly revolutionary. We can now expect to have access to reasonable cost FPGAs with 100,000 to millions of gates, on-chip RAM, and DSP support through fast-adders and dedicated multipliers)[19]. Clock rates now exceed 150 MHz. Use of these devices presents serious challenges in clock management, I/O, and power consumption. Further developments anticipated within the year are the inclusion of industry-standard processors such as the PowerPC and fully operational bit-serial self-clocking data transfer above 3 Gbps right on the FPGA. The inclusion of processors and data links in these devices offers many opportunities for particle physics electronics designers.

6. Computing

From the early days on particle physics had large compute and storage needs and the field realized quickly the potential and benefits brought by computing technology. Experimental and theoretical particle physics groups have employed massive computing to facilitate and enable their research as compute resources became both available and affordable. Initiatives of particle physics, development activities, and joint projects with information technology (IT) companies and groups have resulted in benefits beyond our own field and found their way into everybody's day-to-day life, like the world wide web (WWW).

6.1. Fault Tolerant Computing

Both theoretical and experimental groups have explored parallel computing to solve their large compute needs. The inherent event level parallelism in experimental data has made compute farms attractive solutions since the mid 80s. The current generation of experiments use compute farms with several hundred loosely clustered personal computers (PCs) to process their data. Next generation experiments, like BTeV, Atlas, and CMS, plan to expand the model further: to several thousand PCs and from the well defined single application of data processing to the more unpredictable stage of user analysis.

The increased performance and reduced cost of commodity compute technology allows solutions based on them to conquer places close to the detector that required custom solutions in the past. Integrated, PC based level 2 and 3 trigger systems, and the use of simple microprocessors, FPGAs, and Digital Signal Processing (DSP) chips for all kind of applications already on the detector are common in next generation experiments.

The next generation of experiments will use a huge number of processors, about 10,000 in the read-out and trigger system alone. The ability to record high quality analyzable physics data can no longer depend on all system being problem free, as this would result in low availability of the experiment. Fault detection and correction based solely on human monitoring and intervention is no longer an option either, as the experiments are extremely complex. To achieve high availability the experiment must be fault-tolerant, self-aware, and fault adaptive. As one of the first experiments, BTeV has identified fault-tolerance in the trigger system as an important issue. Together with computer engineering groups the experiment has developed a software architecture and formed a project to research and develop a solution [20]. BTeV plans a two tier hierarchical, distributed fault management system. The design and analysis environment will be used to develop failure detection and mitigation models, to simulate the behaviour of the system, and to analyze failures. The run time framework provides the actual fault-detection and failure mitigation.

6.2. Grid Computing

A major challenge of particle physics computing requirements in the next decade will be the Large Hadron Collider at CERN. The LHC experiments anticipate accumulating TeraBytes of data per day - PetaBytes per year. The resources needed to provide access and processing power for this vast amount of information will far outstrip the capabilities of traditional centralized computing resources.

A potential solution has emerged from the change in orientation of meta-computing activity from interconnected super-computers, towards a more general concept of a high-throughput computational grid. The name *Grid* comes from the ultimate goal of democratic computing - data and computation access as easy and available as using electricity from the power grid. You plug into a socket in the wall and you have instant, effortless access to power. Key requirements for such a system are services on demand, high reliability, dynamic data/computing distribution, transparent access to multi-PetaByte databases, and hidden complexity of the infrastructure. Implementing these goals will require a substantial extension to current national and international network and computing systems, both hardware and software. Following years of development among computer scientists, there has been a flurry of computational grid activity in high energy physics with two large projects in the US and several in Europe.

The driving force of the CERN-managed project in Europe, the DataGrid, is the need for mock data, simulation and analysis capability for each of the Large Hadron Collider experiments (ATLAS, CMS and LHCb) well ahead of LHC turn on. As part of a broader goal of the European Union, it is also an explicit part of the project to produce middleware, fabric and interfaces that are general enough to accommodate a broad range of scientific, industrial and commercial applications. The production of a truly global data grid is an excellent opportunity for HEP to continue to be a leader in world-changing technology transfer.

A grid project for a future linear collider will be an essential part of the international collaboration. Already today, a successful example for a first grid prototype exists. The grid of the D0 experiment at Fermilab enables world-wide data analysis on a day-to-day basis for both detector and Monte-Carlo (MC) data. The knowledge of the grid technology gained from the forefront of active experiments will be available for a future linear collider. In the example of the D0 experiment, MC event generation, detector simulation and event reconstruction are carried out in a standard framework. A user, somewhere in the world, can run a program to perform selection and analysis tasks on detector data and MC. Theses events are stored in files of similar event types. Analysis jobs are controlled by run control parameter (rcp) files.

The rcp files are handled by a data handling system that is independent of the format of the file. Each file has a unique identifier. The data is stored in several storage locations world-wide using hard disks and tape libraries. Analysis programs access the data via a file location catalogue. The catalogue contains all relevant information for data analysis, such as full processing history for MC data, run, configuration, luminosity and calibration data.

6.3. New Algorithms for Data Analysis

Particle physics experiments frequently encounter the need to separate events from different processes. When the signatures in the detector are very similar, information from several quantities needs to be combined to yield a good statistical separation. As experiments search for more rare processes, more sophisticated tools are needed to combine the information from the multivariate data and to separate those very similar signatures. In the past variables have been treated as independent and box cuts have been used. Likelihood distributions and neural networks (NN) have found limited acceptance thus far. The reluctance to employ these methods is due to the use of teaching by example and the separation being based on or including Monte Carlo artifacts instead of physics effects. The issue of machine learning has attracted interest not only in the mathematics and statistics community but also in computer science and IT companies (handwriting, text, voice, and image recognition). Recent theoretical advances have drawn attention to the use of kernel functions in learning systems. Support vector machines (SMV) [21] define a hyperplane between signal and background region as a vector function. This allows fast evaluation and classification of events. Finding this hyperplane involves solving a very large quadratic programming optimization problem. Sequential minimal optimization (SMO) is a convenient method to break this problem into a series of smaller quadratic programming problems. For particle physics needs, a less perfect but more simple way to find such a hyperplane is needed.

6.4. Data Warehouses and Data Mining

Particle physics experiments have large data volumes. Current experiments have accumulated hundreds of TeraBytes of data and will reach the PetaByte barrier during the next two years. To manage and analyze such large data volumes, new techniques and tools were needed. Data mining received much attention in the IT community during the 90s. Commercial relational databases found many new applications with some of the data volumes growing faster than capacity and bandwidth of storage devices. Data warehouses and data mining, pioneered by particle physics since the 80s, have provided solutions to such problems. Storage technology, in particular magnetic disk drives, have made tremendous advances over the past decades. Since 1997 the capacity of magnetic disks has been growing at 100% per year. Moreover, their cost is falling at an even faster rate by a factor of 2.3 per year. This development is of great benefit to particle physics, not only as it allows us to store and analyze more data but because this growth is faster than the increase in experimental data.

6.5. Scalable Clusters for Data Analysis

The National Scalable Cluster Project (NSCP) [22] started as a collaboration between particle physics and computer science. The project takes advantage of commodity processors and storage to research and build scalable clusters with large-scale storage. One such cluster at the University of Pennsylvania provides its compute and data management resources as a service to a large variety of projects and groups: The National Digital Mammography Archive (NDMA) generates tens of PetaBytes a year. The data arrive from a vast number of geographically distributed sources, similar to a particle physics collaboration. Secure data storage is a mandatory requirement of this project. The Neighborhood Information System for Philadelphia also benefits from the NSCP service. The project combines very diverse data from various Federal, State, and Local sources, like census, economic, geographical, demographic, etc. Access to the data is as diverse, with information hidden in the data being mined for all kind of social studies. NSCP is also part of the NSF Digital Government Program and is used to study ultra-large databases as part of the GriPhyN project.

6.6. Computing for Accelerator R&D

The National Energy Research Scientific Computing Center (NERSC) [23] provides high-performance computing tools and expertise to accelerate scientific discovery through advanced computing (SciDAT). The computing center is funded by the US Department of Energy . It has interdisciplinary teams of scientists and engineers working to understand and solve fundamental problems in science and engineering via advanced computing. Activities of those research teams range from developing numerical algorithms to solve mathematical equations describing internal combustion engines to data mining of biological information, simulation of climate models, and accelerator simulations for the next generation of particle physics colliders. The ability to simulate collider performance very precisely will allow to narrow the design paramaters and thus build a more efficient collider at a reduced costs. A study of the Superconducting Super Collider (SSC) showed that with detailed simulation of the collider performance design parameters like the aperture of the machine could indeed have been narrowed down.

7. R&D Programs

7.1. DOE's Advanced Detector Research Program

Following the recommendation of the 1998 High Energy Physics Advisory Panel (HEPAP) planning subpanel the Department of Energy has begun the Advanced Detector Research Program to fund detector research by university-based high energy physicists. The program has started with funding of approximately $500,000 per year with the hope that it will grow.

The program targets generic detector research which is promising but still too immature to be used in the near term. Awards can be for up to three years. After that time it is hoped that funding will be picked up by approved R&D or construction projects.

The first awards were made in 2001 to six investigators working on new ideas for silicon tracking detectors, photodetectors, calorimetry, and radio frequency detection of neutrinos. More information can be found at http://doe-hep.hep.net/.

8. Concluding Remarks

Particle physics has advanced because of technological improvements. Particle physics has also produced improvements in technology. Such improvements are not limited to particle physics but benefit other fields and society at large. Particle accelerators and detectors, designed and developed by our field and at the heart of particle physics experiments, have become standard tools in hospitals, food processing plants, and in the manufacturing of memory chips and microprocessors. Particle physics tends to push the limit of a technology for which it has found an application. The field has directly advanced many technologies or assisted in their improvements. Most notable are superconducting magnets where particle physics has the largest deployment and is leading R&D efforts. While particle physics was pushing computing in its early days, advances in IT technology are now driven by the commodity market and benefit our field greatly. A very visible remnant of HEP improvements to computing is the WWW.

8.1. R&D is Needed

Particle physics is the science of basic research of the fundamental forces and constituents of nature. To examine nature at smaller and smaller distances, Heisenberg's uncertainty principle needs to be overcome, and particles accelerated to higher and higher energies. Particle acceleration is based on the basic principles of electrostatic acceleration and electromagnetic guidance and focusing of the beam. Current accelerators make maximum use of today's technologies. To reach higher energies R&D is needed to advance technologies for both accelerators and detectors.

Technology R&D takes time. The time from discovering a technology for a particle physics application to the actual deployment is about 10 to 15 years. The environment inside a particle detector or accelerator is both harsh and complex. Each detector and accelerator is a unique irreplacable device. A small subsystem that is unreliable or not performing well can degrade an experiment to yield unusable data or require cost and time expensive replacements.

R&D will enable us to reach higher energies but also at reduced costs. However, this R&D effort needs to be spent before the conceptual design of the new collider or detector is made. A good example for such R&D is the effort of DESY for the TESLA project. In 1992 the laboratory started an R&D program to develop in collaboration with industry superconducting microwave cavity structures for a new linear collider. While superconducting accelerating cavities are ideally suited for the required small beam size and high beam power, the cost was considerably higher than conventional technologies. In 2001, when DESY wrote the technical design report of TESLA, the R&D program had resulted in a five times larger field gradient for the superconducting accelerating cavities in addition to a factor four reduction in cost per meter of accelerator.

8.2. The Future of Particle Physics and Technology

Particle physics is a field that benefits from new technology and new ideas. Particle physics has attracted new people because it has been a field of fast and dynamic research. HEP use of latest state-of-the technology has been an important factor in attracting the best people to the field. The people in HEP have become very specialized, since integrating new technologies takes a large effort. Our field must continue to apply modern technologies in the day-to-day research. We should increase technology R&D in our field so we can build and afford new experiments. Long-term R&D programs for particle acceleration and detection at both universities and laboratories are needed to guarantee the progress in particle physics.

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