Fermi National Accelerator Laboratory

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Particle Physics

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"PARTICLE PHYSICS"

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INTRODUCTION

1. THE STANDARD MODEL - SYNTHESIS AND OVERVIEW

Within the last two decades, particle physics has achieved a synthesis of the knowledge of the fundamental forces which is called the Standard Model (SM). The SM describes all known phenomena in terms of a limited number of basic constituents and fundamental interactions. There are only a finite number of arbitrary parameters in the SM, which are put in "by hand".

1.1 The SM Constituents

The SM constituents are classified first as matter (spin 1/2 fermions) or as energy (spin 1 gauge bosons). Matter is itself subdivided into leptons, which have only electroweak (EW) interactions, and quarks which also interact strongly. Both quarks and leptons recur in 3 known "generations". The members of each generation are copies of the basic generation. A chart of the SM constituents is shown in Table 1. The number of generations and the masses of the members of the generations are put in by hand. One should note that the top quark is not yet discovered. It is assumed to be simply a sequential quark in the third generation EW quark doublet. The "flavor" labels refer to approximately conserved quantum numbers such as isospin and strangeness.

Energy is organized in terms of the 3 basic interactions which have different couplings. All interactions appear to obey a "gauge principle" which specifies the interaction by demanding invariance under local gauge transformation. The interactions are quantum chromodynamics (QCD), which governs the interaction between colored gluons and quarks, quantum electrodynamics (QED), which governs the interactions between photons and charged leptons and quarks, and EW interactions, which determine the interactions between W and Z bosons and the weakly "charged" doublets of quarks and leptons. Gauge interactions are renormalizable, which means that perturbative calculations of reaction rates can be made which are finite to all orders in the coupling constants.

Table 1
The SM Constituents

	GENERATIONS			**CHARGE Q**	
MATTER (SPIN 1/2)	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$ $\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $\begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix}$	LEPTONS QUARKS
	QUANTA	**FORCE**	**COUPLING**		
ENERGY (SPIN 1)	g	QCD	α_s		
	γ	QED	α		
	W,Z	EW	α_w		

The weak and QED interactions are "unified" in that the coupling constants for the 2 gauge groups are related. Using experimental values for G_F, the Fermi decay constant and θ_W, the Weinberg angle, the masses of the gauge bosons are predicted.

$$\begin{aligned} G_F &\sim g_W^2 / M_W^2 \\ e &\sim g_W \\ &= g_W \sin(\theta_W) \\ M_W &\sim e / \sqrt{G_F} \sim 90\,GeV \end{aligned} \tag{1}$$

It must also be noted that the SM posits the existence of a fundamental scalar particle, the Higgs boson. This object allows one to have a renormalizable theory of weak interactions with massive gauge bosons, Z and W. The Higgs is also thought to be responsible, via interaction with the fermions comprising matter, for the generation of all mass. The masses acquired by the W, Z and fermions are acquired by their interaction with the vacuum condensation of the Higgs field. The situation is similar to that of a photon in a superconductor which acquires mass in interacting with that medium. In the case of the Higgs field, the particle mass is generated when a massless particle travels in the vacuum filled with the Higgs condensate background field. The examination of the exact mechanism for the breaking of EW symmetry is one of the most pressing problems in particle physics.

1.2 SM Forces

All forces in the SM arise from the coupling of energy to matter. The forces are specified by requiring that the physics be the same regardless of the phase conventions adopted at local space-time points. This gauge principle specifies the interactions and leads to "non Abelian" couplings among the gauge bosons. For example, gluons have color and W/Z have weak charge. Color is the "charge" in QCD. These two "charges" are expected to be exactly conserved. Other conservation laws such as lepton number, baryon number, or quark flavor do not arise from a gauge principle and are thus suspected not to be rigorously conserved.

A familiar example is QED where local phase invariance implies the gauge replacement.

$$\partial_\mu \rightarrow \partial_\mu - ie\, A_\mu \tag{2}$$

This replacement requires the interaction of a photon gauge field A^μ with the fermions.

$$\begin{aligned} &\overline{\Psi}\left(\partial_\mu - m\right)\Psi \rightarrow \\ &\mathrm{H_{int}} = -ie\left(\overline{\Psi}\gamma_\mu\Psi\right)A^\mu \\ &\quad\;\; = j_\mu A^\mu \end{aligned} \tag{3}$$

One implication is that the interactions are nonlinear because there are couplings between the gauge bosons. The situation is similar to that in general relativity (GR) which is the classical gauge theory defined by requiring local invariance under arbitrary coordinate transformations. This invariance requires the existence of the gravitational field with specified and universal coupling to mass. GR is nonlinear because gravitational energy has mass and, hence, gravitates. Gravity is presently outside the SM. However, the similarities of GR to the SM forces, e.g. universal couplings, lead one to hope for the eventual unification of all the basic forces of nature.

The coupling constants are functions of the energy scale at which they are viewed; the coupling constants "run". This behavior is familiar in QED vacuum polarization. The bare charge of QED is altered by virtual e^+e^- pairs in the vacuum. Therefore, the effective charge is a function of the distance scale probed. The QED coupling increases (vacuum screening), while the QCD coupling decreases (asymptotic freedom) with energy.

Because of the "running" behavior, it is important to examine the energy dependence of the three coupling constants. Remarkably, their extrapolation converges at a very high mass scale (Grand Unified Theory, GUT). This behavior leads to the speculation that the three forces are unified at high energies. A GUT would also, presumably, connect the quarks and leptons, and naturally explain the quantization of electric charge. Since a gauge theory contains only one coupling constant per group, there is universal coupling of all group elements and the transitions among them.

A GUT also predicts relations between coupling constants of the subgroups to which the GUT is broken at low energies. Thus, the relationship between e and g_W, θ_W, is specified, and the experimental result is successfully predicted. The GUT might also explain the fact that nature contains mostly matter and not antimatter, and that the entropy ratio of matter to energy is $\sim 10^{-10}$. Experimental data on the coupling constants implies a GUT mass scale of $\sim 10^{15}$ GeV. Note that this mass is far below the scale where gravity becomes strong, the Planck mass of 10^{19} GeV, indicating that new physics may appear in the interval.

1.3 Parameters in the SM, Unsolved Problems

There are many experimentally determined parameters in the SM. For example, the quark, the lepton and gauge boson masses are shown schematically in Fig. 1. Since the quarks are not asymptotically free particles (the colorless $\bar{q}q$ and qqq hadrons are), the mass of a quark is a somewhat ill-defined quantity. A schematic idea of the spread in values of light quark masses is indicated in Fig. 1.

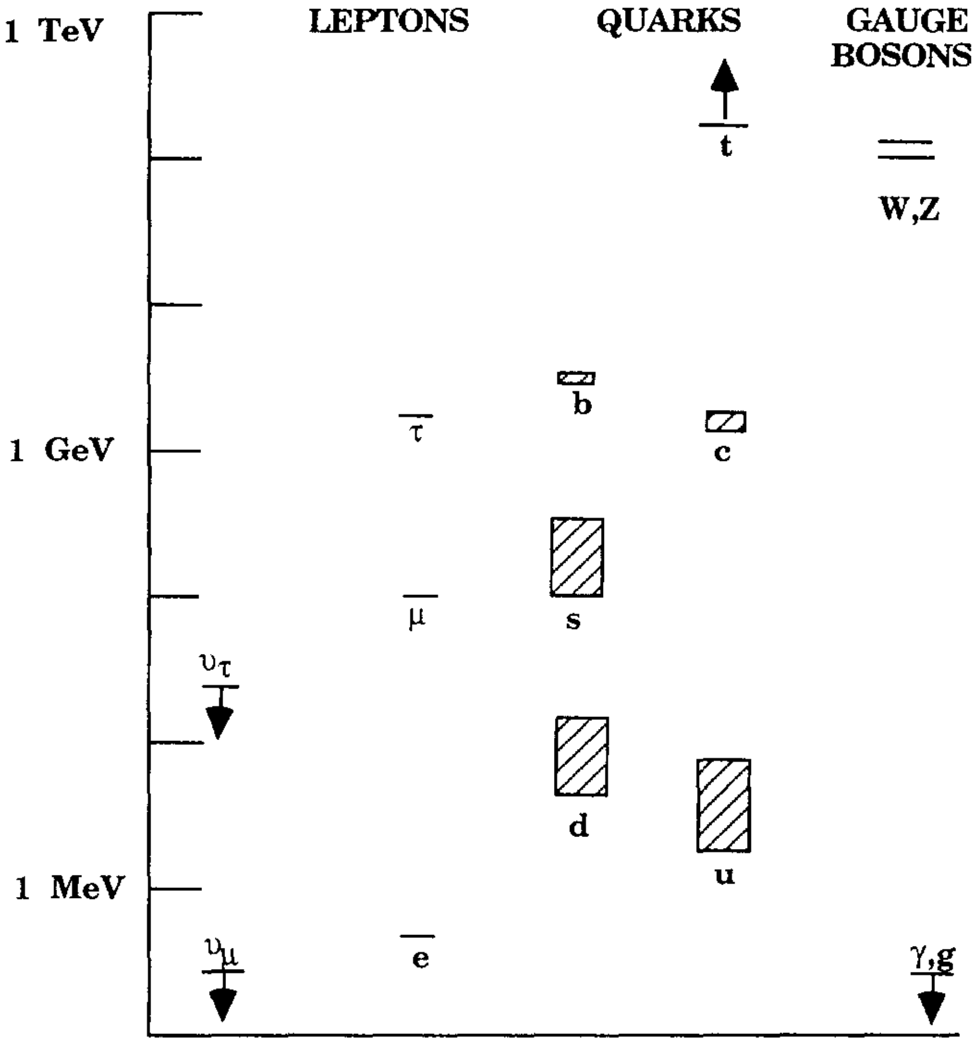

FIG 1. Masses of the SM constituents.

The weak eigenstates relevant to decays of particles are not the same as the strong flavor eigenstates shown in Table 1 which characterize particle production. In general, there is a unitary matrix connecting the strong and weak quark eigenstates: the Cabbibo-Kobayashi-Maskawa (CKM) matrix. The measured matrix elements exhibit fascinating regularities but, at present, they cannot be calculated theoretically. In fact, CP violation in the SM is allowed and arises from complex values of the CKM matrix elements. A parametrization of the CKM matrix in terms of four parameters is shown in Fig. 2.

$$\begin{array}{cccc} \mathrm{A}\ldots & & & \\ \end{array}$$

FIG. 2. A representation of the CKM matrix in terms of 4 parameters.

The neutrino masses are defined to be zero. There is no compelling reason. If the masses were non-zero, the three neutrino generations shown in Table 1 above would mix in analogy to the CKM quark mixing matrix. Clearly, the search for neutrino mass is a high priority activity in particle physics.

1.4 QCD Calculational Implications

Aside from these fundamental parameters, much of the SM relys on data from experiments. In particular, experiments are done with hadrons, bound states of quarks and antiquarks. In principle, the spectrum and quantum numbers of these bound states should be calculable.

In practice, the running of the strong coupling constant implies that QCD becomes very strong at large distances. This in turn means that quarks and gluons are permanently confined (unobservable) and that perturbation theory is not applicable in most calculations.

Particle physics calculations as applied to hadrons require strong coupling field theoretic techniques. In this respect, a strong connection to statistical mechanics is evident. The theory of QCD is cut off by formulating it on a mesh with finite spacing (limited momentum) in a "lattice gauge theory". The numerical problems are formidable and massively parallel computing is used to calculate the bound state spectrum, and other quantities which require a nonperturbative approach. For example, a phase transition to a new state of matter, the "quark-gluon plasma", is predicted by using these techniques.

2. ACCELERATORS AND OTHER FACILITIES

Particle physics is a worldwide occupation which takes place in a wide variety of facilities. The primary focus for experimental particle physics has traditionally been based at accelerators of ever-increasing energy. This growth in energy will, naturally, have some intrinsic limits. Hence, other avenues for particle physics may gain in importance in the future.

The program discussed below constitutes a broad based attack on the validity of the SM. It is focused on the outstanding problems alluded to in Section 1.3 which constitute the "frontier" issues in particle physics. The locations and energies of the accelerator facilities operating at the highest energies are shown in Table 2.

2.1 Accelerator Based Particle Physics

There are two broad categories of particle physics experiments: fixed target experiments where a beam of accelerated particles strikes a stationary target, and collider experiments, wherein beams of particles collide head-on. The former type of experiment is unrivalled in the study of low rate interactions, while the latter is the technique of choice in exploring high mass scales since all the energy in such a collision is available for particle production.

2.1.1 Fixed Target Experiments

Fixed target experiments are currently in progress at several facilities in Russia, Europe, Japan, and the USA. Secondary beams of particles of different types are the exclusive purview of fixed target experiments. Examples include photon, muon, pion, kaon, and neutrino beams.

The "strong force" between hadrons is now recognized as a complicated residual "van der Waals" force. Thus, efforts have shifted to studies of the more fundamental interactions between constituents. Scattering at large momentum transfer is used to select interactions between the quarks and gluons. The energy scale at which QCD becomes strong and, hence, unmanageable by perturbative techniques, is $\Lambda \sim 0.2\,GeV$. Thus, operation at transverse momenta far in excess of this scale makes the interpretation of experiments reliable.

Table 2

Experimental Facilities at Accelerators

Type	Location	Name Energy	CM Energy $\sqrt{s}$ (GeV)	Experiments
Fixed Target	KEK, Japan	12 GeV	2.5 + 2.5	[Spectroscopy (QCD)
	BNL, USA	AGS 33 GeV	4.0 + 4.0	ν Beams (ν Mass, Mixing)
	SLAC, USA	50 GeV	4.9 + 4.9	K Beams ($\not{C}\not{P}$, Rare Decays)
	Serpukhov, Russia	76 GeV	6.0 + 6.0	e,γ Beams
	CERN, Switzerland	SPS 450 GeV	14.6 + 14.6	c,b Production (CKM Elements)
	Fermilab, USA	Tevatron 800 GeV	19.4 + 19.4	e,μ,ν Beams (Structure Functions)]
e^+e^- Collider	Beijing, China	BEPS	2 + 2	$c\bar{c}$ Spectroscopy
	Cornell, USA	CLEO	8 + 8	$b\bar{b}$ Spectroscopy
	KEK, Japan	Tristan	30 + 30	Jet Phenomena
	CERN, Switzerland	LEP	50 + 50	Z Properties
	SLAC, USA	SLC	50 + 50	Z Properties
ep Collider	DESY, Germany	HERA	30 + 820 (157 + 157)	Proton Structure Function c,b Production
$\bar{p}p$,pp Collider	BNL, USA	RHIC	200 + 200	Quark-Gluon Plasma
	CERN, Switzerland	S$\bar{p}$pS	310 + 310	[QCD Jets
	Fermilab, USA	TeV Collider	900 + 900	W/Z/γ Properties
				b Spectroscopy
				t Search
				New Phenomena Search]

[ ] Indicates a set of common experimental topics studied at all corresponding facilities.

Searches for neutrino mass are an active part of research using neutrino beams. Searches for the origin of CP violation, which is allowed for ≥ three generations, are also carried out. Thus far CP violation has only been observed in kaon decays. Second and third generation heavy quarks possess a rich spectroscopy (CKM matrix element determination), and in addition their production dynamics, which are assumed to be calculable, provide interesting QCD tests. Since the strong coupling constant decreases at higher mass, perturbation theory is expected to describe heavy quark states well.

Experiments with incident electrons, muons, and neutrinos also provide sources of valuable data through "deep inelastic scattering" experiments which measure the distribution of quarks and gluons within the nucleon. Lepton beam results are easily interpreted since leptons are pointlike and do not have QCD interactions. Since these parton distributions are, as yet, not calculable, these experiments provide essential data including the spin degree of freedom.

2.1.2 e^+e^- Collider Experiments

Heavy quarks form quark-antiquark bound states, in analogy to the electron-positron bound states of positronium. These states occur at mass scales with respect to Λ such that QCD perturbation theory may be expected to work. The explication of the spectroscopy of the bound state systems is a vital test of QCD.

These bound states are observed and are studied for charm quarks (charmonium) and for bottom quarks. In addition, at center of mass (cm) energies slightly above the bound states, almost pure sources of quark/antiquark pairs become available, when strong decay into heavy meson pairs becomes energetically possible. Thus, these experiments are also major contributors to the knowledge of the spectroscopy of the mesons containing heavy quarks.

At elevated cm energies, the EW bosons are formed. The Z is formed resonantly, and thus e^+e^- collisions are a clean source of Z decay products. Very precise EW tests are performed at these Z "factories", which yield accurate determinations of EW parameters. When the energy of LEP is increased, W pairs will be produced, this opening the study of the self-coupling between gauge bosons. As noted above, nonlinear interaction among gauge bosons is a basic feature of the fundamental forces.

2.1.3 ep Collider Experiments

At present, the distribution of quarks and gluons in the proton is determined experimentally. The data come from lepton-proton scattering with fixed proton targets, and neutrino, electron, and muon incident beams.

The range of such experiments is limited by the cm energy. Recently, an ep colliding beam accelerator has become operational. The goal of experiments at this facility is to extend the range of measurements of the proton structure function and, of course, to search for new and unexpected phenomena. The ep collisions will also be sources of hadrons containing b quarks.

2.1.4 pp Collider Experiments

The proton is a composite object and can be thought of as a "broad band" beam of quarks, antiquarks and gluons of different momenta specified by structure functions. Therefore, $pp / p\bar{p}$ colliders are capable of simultaneous studies of many aspects of current investigations in particle physics. Examples include QCD studies in multijet phenomena, $W / Z / \gamma$ production and decay properties, heavy flavor (B) production dynamics and decay spectroscopy, searches for the top quark, and searches for new phenomena outside the SM.

The strong coupling versions of QCD lead one to expect phase transitions in matter at elevated temperatures and energy densities. At extreme temperatures a "quark-gluon plasma" in a "deconfined" phase should exist. Several experiments will search for this new phase of matter in the future.

2.1.5 Applications

Accelerators have also been fruitful facilities in their applications to areas outside particle physics. The large-scale use of superconductivity was pioneered in accelerators for high energy physics. Large-scale high vacuum and distributed control systems are another outgrowth of accelerator "technology transfer". Electron accelerators are used as synchrotron light sources. These new facilities are heavily subscribed to by materials and solid state physicists at many locations throughout the world.

In addition, there are numerous examples of medical applications. First, the detectors used in particle physics are widely used in medicine, for example, a PET detector. High field magnets similar to those built for accelerators are used in MRI imaging. Finally, accelerators themselves are used in treatment. Examples include electron, neutron and proton irradiation, where proton beams of variable energy allow precise doses to be placed deep in the body with minimal damage to intervening tissues.

2.2 Non-Accelerator Particle Physics

Cosmic rays extend up to energies which are still inaccessible at the accelerator facilities given in Table 2. Therefore, it is natural to search for new phenomena at the highest cosmic ray energies. It is also true that the SM, and its possible extensions, have been incorporated into the allied field of cosmology.

As noted in Section 1.2, a GUT relates the 3 basic couplings. Since the strong interactions are what distinguishes quarks from leptons, it is clear that a GUT implies that quarks and leptons are connected. Therefore, protons will decay and baryon conservation, which was put in by hand, is not required. Baryon nonconservation and CP violation are, in fact, required to explain the photon-to-matter entropy ratio which is observed.

Several experiments have been set up to search for proton decay, all without success to date. They have set useful limits, and since they are located deep underground in order to minimize cosmic ray backgrounds, are active neutrino "observatories". Detectors of this type, for example at Kamioka in Japan , Gran Sasso in Italy, and IMB and Soudan in the USA, detected the neutrino pulse from supernova SN1987A.

They have also been able to detect neutrinos from the sun, following the pioneering work at the Homestake mine in the USA. Other specialized detectors which measure the neutrino flux more directly have recently become active at Baksan in Russia and at Gran Sasso (GALLEX) in Italy.

If the neutrino mass is non-zero, then different generations will mix in analogy to the CKM quark mixing. Neutrino beams from accelerators can be directed towards the distant underground observatories. Such long baseline neutrino oscillation experiments will push down the limits on the neutrino masses. A finite neutrino mass might relate to the postulated existence of "dark matter".

3. MAPPING THE SM CONSTITUENTS ONTO THE DETECTORS

Detectors in particle physics are ideally used to measure the position and momentum of all the constituents of the SM emanating from a collision and to distinguish among them ("particle identification"). In principle, a perfect detector would measure and identify all the particles in both the initial and final states of a collision. The design of the detectors is dictated by the characteristic interactions which the SM constituents participate in. The categories are shown in Table 3 explained below.

3.1 Confinment and Jets - Quarks and Gluons

As mentioned in Section 1, quarks and gluons carry color and interact strongly. Confinement means that quarks and gluons are not asymptotically free states. They appear in detectors as collimated "jets" of hadrons moving near the direction and with roughly the momentum of the parent q or g. Finely segmented calorimeters measure the positions and energies of these ensembles of particles and thus one may infer the properties of the q or g parent.

Table 3

Detection/Identification Methods

TOPOLOGY	DETECTOR	PARTICLE
Jet of Hadrons	Calorimeter	u, c, t → Wb d, s, b g
No Interactions	Calorimeter	ν_e, ν_μ, ν_τ
Electromagnetic Shower	Calorimeter	e, γ
Only Ionization Interactions	Muon Absorber	$\mu, \tau \rightarrow \mu\nu\nu$
Decay with $c\tau \gtrsim 100\mu m$	Si Tracking	s, c, b

3.2 Hermiticity and Neutrinos

Leptons, by definition, interact only via the EW interaction. In particular, neutrinos are uncharged, and only interact weakly. Therefore, they pass through a calorimeter system which absorbs and detects all strongly and electromagnetically interacting particles.

The presence of neutrinos is thus signaled by the existence of the "missing energy" which they carry off. Since the initial state energy is well defined, (for example in a symmetric pp collider it is twice the beam energy), the energy taken away by noninteracting neutrinos may be inferred using "hermetic" calorimeters.

3.3 Charged Leptons and EM Interactions

Charged leptons interact electromagnetically (EM) via the forces specified by QED. Extremely relativistic photons and electrons interact with a calorimeter medium by pair production or bremmstrahlung. The resulting EM cascades yield a characteristic signature.

Therefore, a calorimeter can be used to perform e/γ particle id by measuring the characteristic EM shower.

The muon is unstable, with a lifetime, $(c\tau)$ ~ 658 m. Therefore, it can be measured before it decays. Muons are "heavy electrons", sequential second generation leptons identical to electrons save for mass. This large mass means the acceleration of a muon is much reduced with respect to an electron and this in turn causes the muon EM cascade to occur only at much higher energies than the e cascade. For example, muons at energies $\lesssim$ 300 GeV ionize the detection medium, thereby leaving a minimum ionizing particle, or MIP, signal in particle detectors. This signal is the basis for muon identification.

3.4 W, Z, τ and Decays

The W and Z gauge bosons decay into final states containing either lepton or quark pairs. The cleanest experimental signatures are the decays, $W \to \ell + \nu$ and $Z \to \ell^+ + \ell^-$. Final states containing quarks, such as $W^+ \to u + \overline{d} \to Jet1 + Jet2$ are subject to large backgrounds.

The τ lepton often decays into final state leptons, for example $\tau \to \mu + \overline{\nu}_\mu + \nu_\tau$. Since the τ has a lifetime of $(c\tau) \sim 200\mu m$, an additional experimental signature for it is the existence of both a secondary decay vertex (see Section 3.5) and a primary production vertex.

3.5 Displaced Secondary Vertices

All the elementary constituents except electrons, states composed of u and d quarks and massless neutrinos are unstable. The leptons typically decay leptonically, for example, $\mu \to e + \overline{\nu}_e + \nu_\mu$ and the decay widths scale as the available energy to the fifth power. This means that the muon can be considered stable during its detection, while the τ has a lifetime $\sim 200\mu m$ and must be detected by its decay products.

The separation of light (u-d) from heavy (s-c-b-t) quark states can be accomplished by detection of the secondary vertex. The quarks decay semileptonically, for example, $s \to u + \ell^- + \overline{\nu}_\ell$. The strange hadrons, e.g. K_S, have lifetimes $(c\tau)$ ~ cm, while c and b quark decays lead to lifetimes, $(c\tau) \sim 200\mu m$.

The top quark appears to be unusually massive. Assuming this as yet undiscovered particle is simply a heavy sequential quark, the favored decay mode is $t \rightarrow W^+ + b$. The large mass implies that top id is performed by observation of the final state decay products.

4. A MODEL $pp/\bar{p}p$ COLLIDER DETECTOR

The characteristic interactions of the SM constituents are used in their detection as outlined above. Fixed target detectors are often special purpose instruments optimized to do a particular type of physics, for example K_L decays. Collider detectors tend to be general purpose instruments designed to simultaneously study a large variety of reactions. For this reason, a hadron collider detector can be discussed "generically". Generally, the backgrounds and trigger strategies are more challenging at a hadron collider than at an e^+e^- collider. A schematic of a typical detector is shown in Fig. 3. Detectors for e^+e^- colliders are rather similar in layout, although the issues of triggering are easier due to the lower levels of "soft" backgrounds and the lower interaction rates. However, reaction rates are larger at hadron colliders.

4.1 Soft Backgrounds

The probability for an inelastic interaction to occur is set by the magnitude of the total inelastic cross-section. At a cm energy of 40 TeV, the pp inelastic cross section is ~ 100 mb = 10^{-25} cm^2. The overwhelming majority of these interactions are soft, consisting of produced hadrons with limited transverse momentum ,$\langle P_t \rangle \sim \Lambda$. The number of pions produced increases slowly with cm energy , $\sqrt{s}$, with a mean $< n > \sim \ell n(\sqrt{s})$. The secondary particles are distributed according to single particle one dimensional phase space, with a density of ~ 6 pions/unit of rapidity, y,

$$\text{Single particle phase space} \quad = \quad \begin{aligned} & d^4 p\, \delta(p^2 - m^2) \\ & \sim dy\, dp_t^2 \end{aligned} \qquad (4)$$

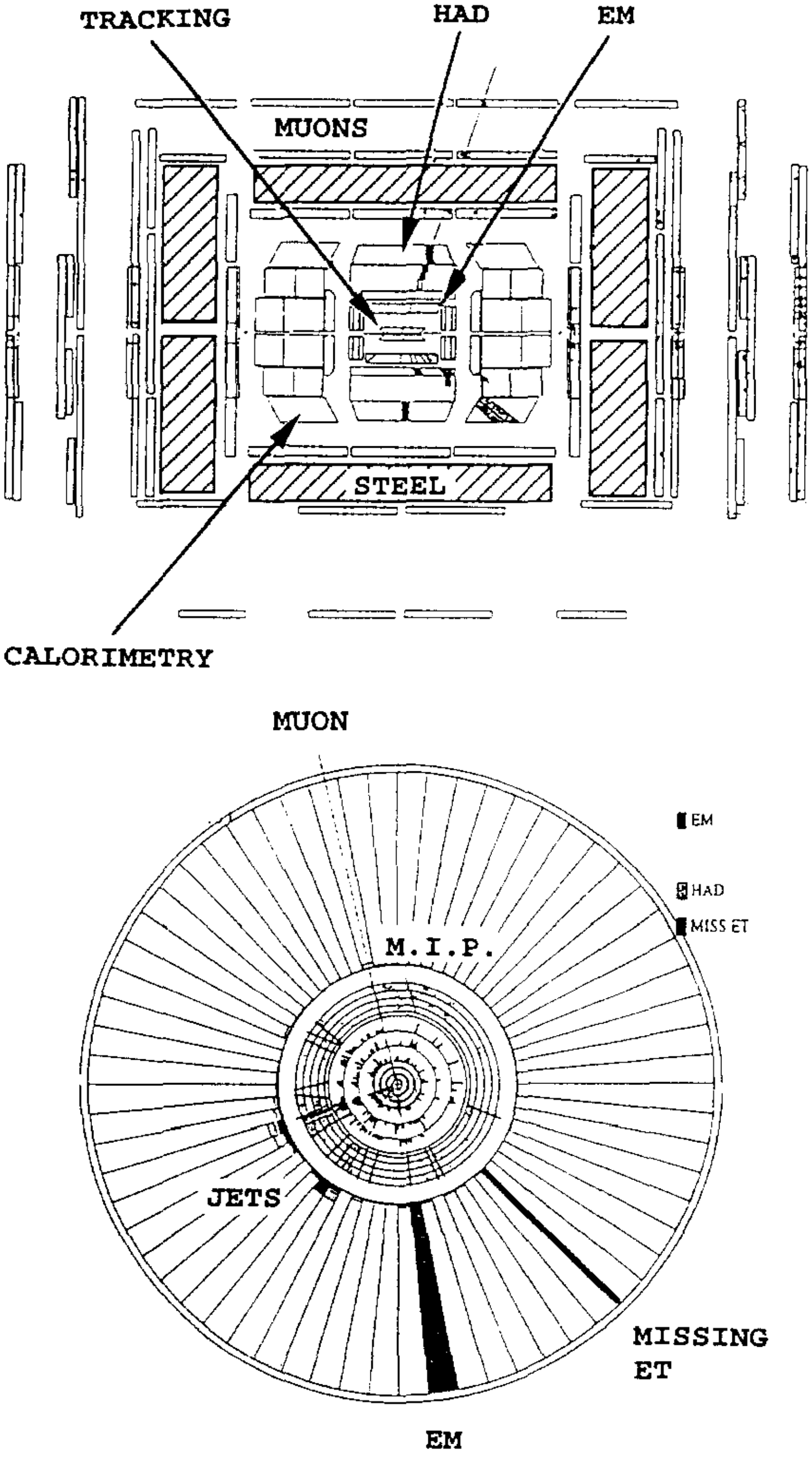

FIG 3. A typical p$\bar{\text{p}}$ collider detector showing tracking, calorimetry, and muon detectors. Charged tracks and EM and HAD energy deposits are shown in the lower figure.

These "soft" events are due to strong, non-perturbative QCD interactions. The collisions of interest occur at large transverse momentum, since they probe the small distance behavior of the interactions. Therefore, the detection, triggering, and data acquisition strategy adopted for these detectors puts an emphasis on high P_t interactions.

4.2 Magnetic Analysis

Typically, the detector provides a volume of magnetic field, often of a solenoidal nature. A uniform magnetic field causes all charged particles to move on helical paths, with radii of curvature which are determined by the particle momentum and charge. Thus, determination of the particle trajectory in the field volume determines the charge, momentum, position, and angle of all the secondary charged particles produced in the collision.

4.3 Si Inner Tracker

Since b and c quarks and the τ leptons have lifetimes of order 200 μm. an inner detector consisting of strips of Si with a pitch of ~ $50\mu m$ is is often employed as the first detector element encountered by a secondary particle after it exits the vacuum pipe containing the incident beams.

The Si detector pitch is well matched to the lifetimes of the particles. The Si detector also serves as the initial element in a tracking system which measures the particle trajectory in the magnetic field.

4.4 Outer Tracker

The Si elements are fairly expensive. For that reason, most tracking systems employ different detector technologies at larger radii. Gas filled wire chambers, or scintillating fiber detectors are two possible options. The size of these outer trackers is roughly matched to the decay length scale implied by the decays of s quarks. For example, $(c\tau)$ for the K_S meson is ~ 2.5 cm.

Therefore, the complete tracking system allows the experimenter to perform particle identification, or id, on the s, c, and b quarks, and the τ lepton. The e and μ charged leptons are measured and, by extension, the leptons from τ, W, and Z decays. Note that longer lived objects, such as K^+ mesons, will be unlikely to decay within the tracking volume and will not, therefore, be positively identified.

4.5 Calorimetry

The next system encountered by the exiting particles is usually the calorimeter. Particles there cascade in a dense medium and deposit their energy. The calorimeter is segmented transversely so that this system measures, destructively, the position and energy of all particles, both charged and neutral. The achievable transverse position resolution is limited by the intrinsic transverse spread of EM and hadronic cascades. The medium can be either completely active (crystals) or interspersed heavy absorber plates with active detection layers (sampling calorimetry). Particle id is provided by the tranverse and longitudinal segmentation of the calorimetry and the corresponding differences in cascade development of the different incident particles.

4.5.1 EM Compartment

In most applications the calorimeter system is also segmented longitudinally. The first compartment encountered is typically Pb or some other high Z element that induces e and photon cascades via the EM interaction. Since hadrons interact differently, the first, or EM, compartment is used to identify e / γ. The tracking system is then used for e / γ separation.

The depth of the EM compartment is sufficient to contain the EM shower. That depth is typically ~ 20 radiation lengths or ~ 12 cm in Pb. By comparison, the ratio of e shower probability to hadron interaction probability is ~ 30 in Pb, so that most hadrons will not even interact in the EM compartment. This difference in interaction length scales, and a corresponding difference in the transverse size of the EM and hadronic cascades, is the basis of clean e / γ particle id.

4.5.2 HAD Compartment

The EM compartment is followed by a hadronic, HAD, compartment. Its role is to absorb the energy of all the hadrons which impinge. The scale for hadronic interactions defines the size of the calorimeter system. For example, ~ 10 nuclear absorption lengths (or 167 cm of Fe) are needed to absorb most of the hadronic energy. .

The HAD compartment is used to measure the angles of the hadrons, and their energies. The "missing energy" in the final state supplies a measure of the neutrino energy as mentioned previously.

Muons will typically deposit only ionization energy in the calorimeter. Thus, a particle which acts like a MIP, can be identified provisionally as a muon.

4.6 Muon Detection

Detectors external to the calorimetry are often employed to provide independent muon identification and a redundant measurement of the muon position and momentum. This redundancy is similar to that provided by the two measurements of an electron momentum: by tracking in a magnetic field and by the EM compartment of the calorimetry.

Redundant muon information is supplied by a second magnetic analysis of the muon after most of the secondary particles in the interaction are removed by absorbtion in the calorimeter. This analysis may occur either in air or in a solid steel electromagnet. Wire chambers surrounding the magnetic volume provide the kinematic determination.

4.7 Trigger and DAQ

Since the total cross-section is large and the cross-sections for the physics of interest are small, the trigger is composed of several redundant requirements. The ratio of all events to the events of primary interest may be as small as 10^{-12}. In the presence of backgrounds of this magnitude, redundant measurement and particle id are absolutely necessary. The situation of e^+e^- interactions is more relaxed.

The systems described above are designed to supply coarse information very rapidly. That information is used in a hierarchy of triggers which select events of interest. This hierarchy is designed to reduce the inclusive inelastic rate of typically 100 MHz to a rate logged to permanent medium (e.g. magnetic tape) of a few Hz. Clearly, the trigger cannot accomplish this prodigy (reduction by a factor 10^8) in one step. Often three successively slower but more incisive trigger levels are used where the slower triggers are protected from high rates by the fast but loose lower level triggers.

4.8 Analysis

Often, crude analysis of complete events consisting of the full granularity of information supplied by the detector is part of the highest level of triggering. Thus, triggering and data acquisition (DAQ) merge smoothly into offline analysis of the events.

Typically, a complete event is assembled from the individual detector systems by the DAQ system and loaded into a high level workstation. The highest level trigger may consist of simplified analysis of these events on an extensive farm of such workstations. Offline analysis of the events stored on permanent medium is often performed on the same sort of farm.

5. OTHER EXPERIMENTAL TECHNIQUES

Detectors are designed to address specific physics issues. Some detector systems may be of a more specialized nature than the generic detectors for collider experiments which were discussed in the previous two Sections.

All detectors utilize the interactions of the particles of interest with a detecting medium. In the previous Sections ionization in the tracking system, EM/hadronic cascades in the calorimetric media, and energy loss in the muon system were discussed. Much of the discussion in this Section deals with particle id in additional detection systems or measurements.

5.1 Ionization Detectors

Ionization refers to the interaction of incident charged particles with the atomic electrons of a detecting medium. The energy loss by ionization varies with velocity as $1/v^2$ for slow incident particles. As v → c the ionization loss approaches a minimum, a MIP.

Tracking detectors use the detected ionization to determine a point on the charged particle trajectory as discussed above. If the actual value of the energy loss is measured several times, the velocity is determined. Knowing the momentum from the curvature of the path in a magnetic field, the mass of the particle may be inferred. Therefore, ionization detectors can be used for slow particle id if many samples of the ionization are made.

5.2 PMT, Scintillator

Scintillating plastics coupled to photomultiplier tubes (PMT) are used to measure the particle time of flight between two sets of counters to sub nanosecond accuracy. The measurement of time over a fixed distance is a velocity measurement. Thus, scintillation counter arrays are also useful in particle id for slow particles.

5.3 Slow n detection

Neutrons can be easily detected by measuring the proton recoils from an elastic np interaction. The recoil protons take up a significant fraction of the neutron energy (1/2 on average). Thick scintillation counters can supply the proton targets and detect the recoil protons via their large ionization losses in the plastic.

5.4 Cerenkov Detectors

A charged particle which exceeds the velocity of light in a medium of index of refraction n, $v > c/n$, emits a Mach cone of radiation. This is called the Cerenkov effect. Cerenkov counters consist, typically, of a gas filled vessel outfitted with mirrors to collect the emitted light in the gas, and PMT to convert the light into a usable signal.

The angle of the emitted light, θc, is determined by $\beta = v / c$ and n, $\cos(\theta c) = 1 / \beta n$. Clearly, a measurement of the angle of the emitted light is a measure of the particle velocity. Such counters are called ring (from the Mach cone angle image) imaging Cerenkov counters (RICH). Cerenkov counters are another tool used in particle id.

5.5 TRD Detectors

A Transition Radiation Detector (TRD) may be thought of as utilizing the diffraction pattern arising from the radiation of a Cerenkov detector of finite length. The interference of the radiation at the exit and entry points of a thin foil yields a pattern at very forward angles. In addition, the radiation is in the x-ray frequency range, with an intensity which is proportional to $\gamma = 1 / \sqrt{1 - \beta^2}$. Therefore, the TRD is a device which is also used for particle id of very relativistic particles. Note that the TRD is a complementary detector to those, like the Cerenkov counter, which lose discrimination power as $\beta \to 1$.

6. FUTURE PLANS

The SM has been very successful, but it is widely felt to be incomplete. Even within the SM, the Higgs boson, the fundamental scalar responsible for the W and Z masses and the masses of all matter (fermions), has not yet been found. The Higgs may be thought of as a convenient mnemonic for the fact that the origin of the spontaneous breakdown of EW symmetry has not been explored. A single neutral Higgs is simply the most compact way of satisfying the constraints on the SM imposed by all presently existing data.

Clearly, the exploration of spontaneous EW symmetry breaking is a high priority for the field of particle physics. The energy when the weak interactions become strong can be estimated by looking at the S wave amplitude for $e^+ + e^- \to WW$. Partial wave unitarity requires that the cm energy not exceed ~ 1.6 TeV. Therefore, one may be assured that some new phenomena MUST arise to restore unitarity.

$$A_o(ee \to WW) \sim \frac{\alpha_W}{4\pi}\left(s / M_W{}^2\right)$$

$$A_o(ee \to WW) \leq 1 \Rightarrow M_H < \sqrt{\frac{4\pi}{\alpha_W}}\, M_W \;\; \sim 1.6\, TeV \tag{5}$$

Additional pressing issues have to do with the ad hoc (and hence incomplete) nature of the SM. The CKM matrix, CP violation, and possible neutrino masses are all in need of a more fundamental explanation.

6.1 New Facilities

In order to attack these frontier issues, new facilities are under construction or are planned. The highest priority new facility is the new hadron collider, the LHC at CERN. The main scientific goal of this machine is to search for the Higgs boson. Since this object is very weakly coupled to ordinary matter, the events of interest are very rare. They may constitute only 1 in 10^{12} of all pp interactions even at multi TeV energies.

Therefore, high energy hadron colliders emphasize high luminosity operation. For the detectors, the challenges due to high luminosity operation are the unprecedented field of radiation in which they must operate, the speed required of the detectors (time between interactions ~ 25 nsec), and the complexity of the trigger and DAQ systems. As an example, the widespread use of commercially available fiber-optic transmission lines is envisioned in several of these new detectors.

In the context of the SM, the CKM elements are merely parameters. The fact that ≥ 3 generations will allow a unitary CKM matrix with complex elements means that CP violation is allowed in the SM, but its origin is not understood. In fact, CP violation has only been seen so far in the K system (mesons containing s quarks). Violations of CP are also expected in the B system (mesons containing b quarks). In addition, several CKM matrix elements are experimentally determined most easily in the study of B decays. For these reasons, e^+e^- B factories are under design in Europe, the USA, Japan, and elsewhere.

In addition, expanded underground facilities are proposed. To probe small neutrino masses, long baseline oscillation experiments, with accelerator produced neutrino beams directed to existing or proposed underground detectors, are planned. As a corollary, the underground detectors will continue the study of solar and astronomical (e.g. supernovae) neutrino sources.

6.2 Old Questions

The goal of these new experiments is to answer some of the most basic problems contained within the successes of the SM. What is the mechanism of EW symmetry breaking? How do the weak interactions become strong? What is the origin of fermion masses? What is the nature of the EW vacuum? Why are there 3 generations? What is responsible for the regularities in the masses of the generations? What is the origin of the CKM matrix? What explains the regularities in the matrix elements? Why is CP symmetry violated? Is there a CKM matrix for neutrinos? Do neutrinos have a mass? Is there a GUT scale? If so, why are protons stable (within experimental errors)? What is the relationship of gravity to the other 3 fundamental gauge interactions?

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GLOSSARY

Baryon: Half integral spin hadron made up of qqq valence quarks.

Boson: Integral spin particle.

Calorimeter: A device which provides a signal proportional to the energy of the particle incident upon it.

Charge quantization: Electrical charge is observed to come in quanta of e- the electron charge.

Confinement: Since α_s increases with distance, quarks and gluons are hypothesized not to propagate as asymptotic free particle states .

CP symmetry: A symmetry of interactions under the combined parity and charge conjugation operation.

cV: A measure of energy. An electron dropping through a potential of 1 volt requires 1 cV increment of energy.

Fermion: Half integral spin particle.

Flavor: Approximately conserved quantum numbers of quarks, e.g. strangeness.

g_W : Weak coupling constant analogous to e in QED.

Gauge symmetry: A symmetry arising from requiring that physics be independent of the phase convention chosen at arbitrary spacetime points.

Generations: The replication basic quark/lepton EW doublet pair.

Gluon: The quantum of QCD.

Hadron: A strongly interacting colorless composite of quarks which is asymptotically free.

Higgs boson: A hypothesized particle whose non-zero vacuum expectation field value gives rise to the masses of all fermions and bosons.

Lepton: Fermion without color (QCD interactions).

Lifetime: A characteristic time for the exponential decay of unstable particles.

Luminosity: The quantity which when multiplied by a cross-section gives the reaction rate.

Mass: A parameter defined by the response of a particle to external forces.

Meson: Integral spin hadron made up of $q\bar{q}$ valence quarks.

Neutrino: Uncharged lepton, assumed to be massless.

"onium": Bound states of heavy quarks and antiquarks.

Photon: The quantum of QED.

QCD: Quantum theory of quarks and gluons.

QED: Quantum theory of leptons and photons.

Quarks: Fermions with color (QCD interactions).

Rapidity: A variable, y, which defines longitudinal velocity and is invariant under Lorentz transformations, $\tanh(y) = (P_{11}/E)$.

Spin: The intrinsic, quantized angular momentum possessed by SM constituents.

Renormalization: A technique in quantum field theory whereby calculational infinites are absorbed into finite observables such as mass.

Structure function: Experimentally determined distribution of momenta of constituents within a composite bound state (e.g. proton).

Universality: Identical couplings of all matter to energy, as seen in gravity, QCD, and EW interactions.

Vacuum: A complex quantum medium propagation in which is thought to generate the masses of all matter and energy.

W, Z: The quanta of the EW force.