Future physics: A personal view

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A personal view of the future of particle physics is presented.

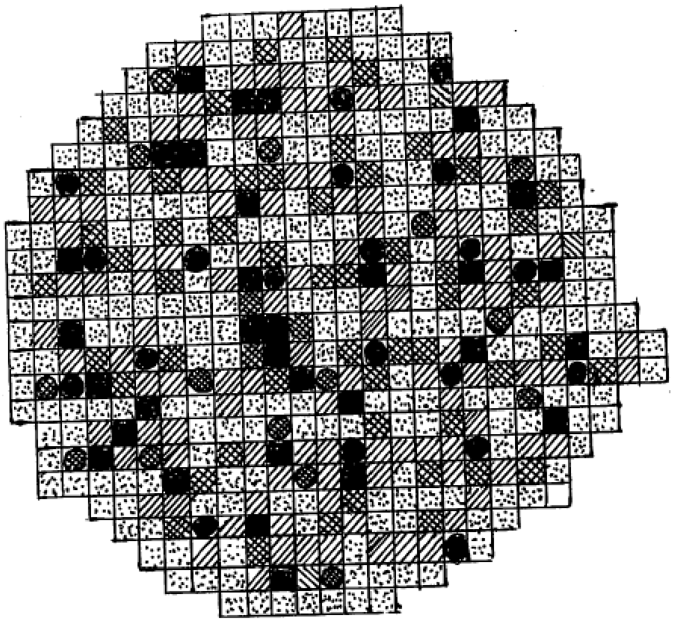
1. Introduction

It is a great pleasure to be back at an ISMD meeting, and to again meet so many old friends and colleagues, as well as members of the new generation. Because it has been a long time since I have been active in this field, this talk will not be a summary. I have instead chosen to touch briefly on a variety of topics of special interest to me. I will begin with a revisit of the parton model and continue with a look at the Higgs sector. This will be followed by a quick look at the problems of dark matter and dark energy, along with a few remarks regarding how future experimental programs might best address the above issues. Finally, I have added a few comments relevant to the material which was presented during the meeting.

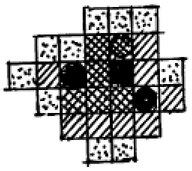
2. The Kindergarten Parton Model

To most people, the phrase "parton model" nowadays is almost synonymous with the phrase "inclusive distributions." But in principle there is, even at the original kindergarten level, much more to the parton model than that. A single energetic left-moving hadron is to be viewed as a configuration of many partons, each of which is labeled by its internal quantum numbers, its longitudinal fraction, and its location in the transverse impact plane. During its collision with a right-moving hadron (or lepton), the internal motion is frozen due to relativistic time dilation. Furthermore, Lorentz contraction of the valence components of the left-mover and right-mover means that the collision evolution is local in the impact plane until the momentum scale of the final-state evolution becomes of order the QCD scale, of order 1 GeV or so.

Because of this localization in the impact plane, I like to subdivide the transverse impact-plane into pixels, of diameter of order 0.2–0.3 fermi. To each pixel we may assign, event by event, a left-moving longitudinal



LEFT-MOVING CARBON NUCLEUS



LEFT-MOVING PROTON

■ $x \gtrsim 0.1$

▩ $0.1 \gtrsim x \gtrsim 0.03$

▨ $0.03 \gtrsim x \gtrsim 0.01$

⬚ $0.01 \gtrsim x \gtrsim 0.001$

x = longitudinal momentum fraction per nucleon

Fig. 1. Pixelized beams-eye views of impact- plane parton momentum fractions for a typical left-moving carbon ion and for a typical left-moving proton.

momentum fraction, a right-moving longitudinal-momentum fraction, a left-moving baryon number, etc. (Fig. 1). Consequently, each pixel can also be assigned a subenergy and a central rapidity for the collision products. Therefore the early stages of the evolution of the overall collision can be described in terms of the evolution of the sub-collisions occurring within the sundry pixels. I am tempted to label these pixels Vegas, because, as they often say, what happens in Vegas stays in Vegas. However this is not strictly true. While hard processes occur within Vegas, the information eventually does spread beyond.

When viewed this way, it is of course interesting to question whether, event-by-event, information regarding the distribution across the impact plane of the subenergies within the sundry pixels is reflected in the observed properties of the ultimate collision products. The answer is, of course, yes. Such effects are by now commonplace in noncentral heavy-ion collisions. The "hot" pixels, i.e. those containing large subenergies, typically comprise an almond-shaped region in the impact plane. This leads to azimuthal asymmetry of the collision products ("ellipticity") which is robust, event-by-event, with respect to longitudinal boosts of a few rapidity units (at LHC energies). The approximate boost invariance of this effect should be rather intuitively obvious, because qualitatively the impact-plane picture is itself quite robust with respect to moderate boosts of the left-moving and right-moving incident projectiles. All that is needed to defend this view is to argue that the distribution of produced entropy within a pixel is broad in rapidity, at least as broad as given, say, by Landau hydrodynamics. This boost-invariance of the initial-state configuration-dependence (e.g. ellipticity) goes by the name "ridge structure."

In the early days of the parton model, the hypothesis that all correlations are short-range in rapidity led to the notion of a universal central-rapidity plateau. This in turn led to the expectation that event-by-event configuration-dependent effects would be observable, if at all, in the fragmentation regions of the left and right movers. However, with the advent of QCD this is no longer true. We now see a dramatic rise in the gluon inclusive distribution at very small x, with a concomitant power-law rise in central multiplicities of produced hadrons. The opposite extreme of a Landau-like dependence of multiplicity on energy is at the least a credible option for phenomenology. If this hypothesis is defensible, it is easy to show that it leads to a significant amount of contrast in the distribution of entropy across the impact plane, even for typical central rapidities.

A reasonable starting point for this picture is to assign to a pixel the same entropy distribution (here assumed to be proportional to the final-state hadron multiplicity distribution) as for an electron-positron annihilation event occurring at the same cms energy as the pixel subenergy. I have scratched out an example of an LHC noncentral ion-ion collision with this assumption. It is shown in Fig. 2(a).

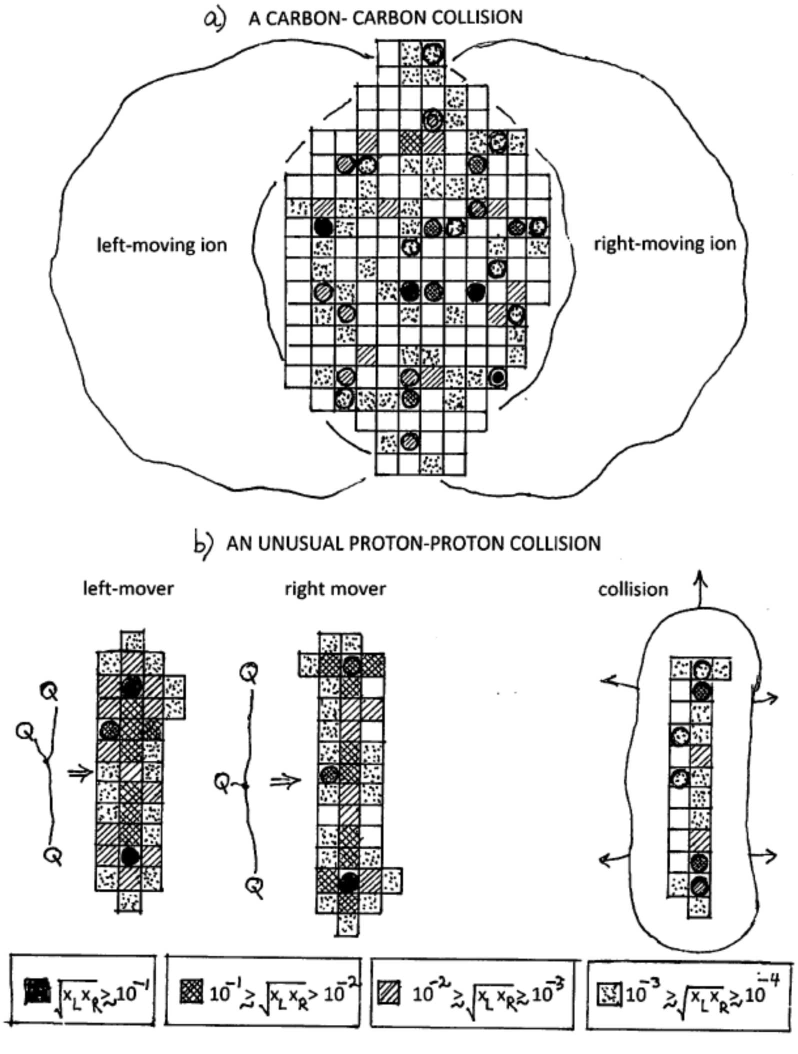


Fig. 2. Pixelized beams-eye views of the subenergy distribution in the impact plane for (a) a non-central carbon-carbon collision and for (b) an unusual LHC proton-proton collision.

Fred Goldhaber, Stan Brodsky, and I have explored an extreme example of configuration dependence [1]. It is shown in Fig. 2(b). Not infrequently the valence-quark configuration in the impact plane for an incident proton will be a compact diquark plus a quark connected by a color string. If both projectiles are in that configuration and are aligned, the hot pixels in the impact plane will lie along a line, and there should be not only high multiplicity but very large ellipticity and ridge structure.

Before moving on, I should emphasize that the above impact-plane picture has a long history, which I have not tried to cite. And present-day theoretical approaches, from BFKL to hydrodynamics to glasma [2], exploit the above ideas in one way or another. But I have included it here in kindergarten language because I believe its usefulness may still be undervalued. But there are problems. As I see it, the biggest problem with experimental searches for configuration dependence is that the theory is best expressed in terms of impact-plane properties, while the experiments are necessarily described in terms of the transverse momenta of the collision products within a given rapidity interval. There is a Fourier transform in between, which appears to create a serious barrier. We may need a good idea to effectively overcome this obstacle.

3. Family Symmetry and the Higgs Sector

Since the discovery at the LHC of the Higgs boson, I too have acquired a serious case of Higgsteria. It is wonderful how firm knowledge of the existence of the Higgs, even when its mass and properties were anticipated quite accurately years ago, can focus the mind and energize ones thinking about the problem. There is no good substitute for experimental facts.

For me, the focus has been on the role of the family group within the Higgs sector. I prefer the word "family" here. Long ago, Gell-Mann introduced a chiral $SU(3) \times SU(3)$ flavor group, with u, d, and s quarks forming a flavor triplet. The generalization appropriate nowadays is a chiral $SU(6) \times SU(6)$ flavor group, with the six quarks forming chiral sextet representations. Within this group is found not only the electroweak group, but also the chiral family group $SU(3) \times SU(3)$, with a family triplet, e.g., consisting of u, c, and t quarks.

Electroweak symmetry demands that d, s, and b also comprise a family triplet. And while it did not have to be so, the charged leptons e, μ, and τ also comprise a family triplet. Again electroweak symmetry demands that the three left-handed Dirac neutrino degrees of freedom are also family triplets. And we know that the photon, the gluons, the W's, and the Z are all family singlets.

But what about the Higgs sector? The default choice is that it consists of the "vanilla" Higgs, plus its three Goldstone-boson partners that are eaten by the W's and Z, and nothing more. This single electroweak doublet evidently is necessarily assigned to be family singlet. The MSSM extension, as do the majority of other more elaborate models, retains this assumption. To me this assignment of family singlet seems less than reasonable. After all, the notorious family-related problem of the origin of quark and lepton masses and mixings can be directly traced to the properties assigned to the Higgs sector itself. Why should the Higgs sector itself transform trivially under the family group?

It is not that the alternative option has not been explored. Serious technical difficulties were encountered long ago. However, much of that history precedes the important phenomenology associated with the very heavy top quark and with large neutrino mixing. Furthermore, the popularity of electroweak-scale SUSY also seems to have diluted efforts in this direction. But there exists at present very interesting work on the spontaneous breaking of family symmetry [3].

What are the simplest assignments for Higgs multiplets? On the electroweak side, it is singlet or complex doublet. On the family side, it is singlet, triplet, or octet/nonet. This gives six options to explore. I have chosen to assign the observed Higgs and its three Goldstone partners to components of an electroweak-doublet, family nonet. This option allows a Yukawa coupling to the quarks and leptons, and gives $4 \times 9 = 36$ Higgs degrees of freedom in all, 32 of which await discovery. I assume these 32 are heavier than the top quark but no heavier than, say, 1 TeV. A nomenclature and some basic properties of these particles (which predominantly decay, either directly or indirectly, final states containing top quarks plus jets) is given in Fig. 3.

In the absence of first and second generation masses and their concomitant mixings, working out the Higgs mechanism and the phenomenology of the production and decay of these sundry bosons is rather straightforward. Production of the new Higgs states via couplings to the W, Z, and photon appear to give yields too small to be easily detected at present at the LHC. However, certain "coset states" can be singly produced in quark-gluon subprocesses, leading to final states consisting of a top-antitop pair plus a first-generation quark. The same coset states turn out to easily account for the CDF top-antitop angular asymmetry observed a few years ago at Fermilab. Because of this, there have already been specific searches for such particles at the LHC [4, 5]. The bounds on the coupling constant are close to what I specify from the model, but do not appear to rule anything out yet.

On the theoretical side, there are at present serious deficiencies. The above phenomenology is defined in the limit of vanishing first and second

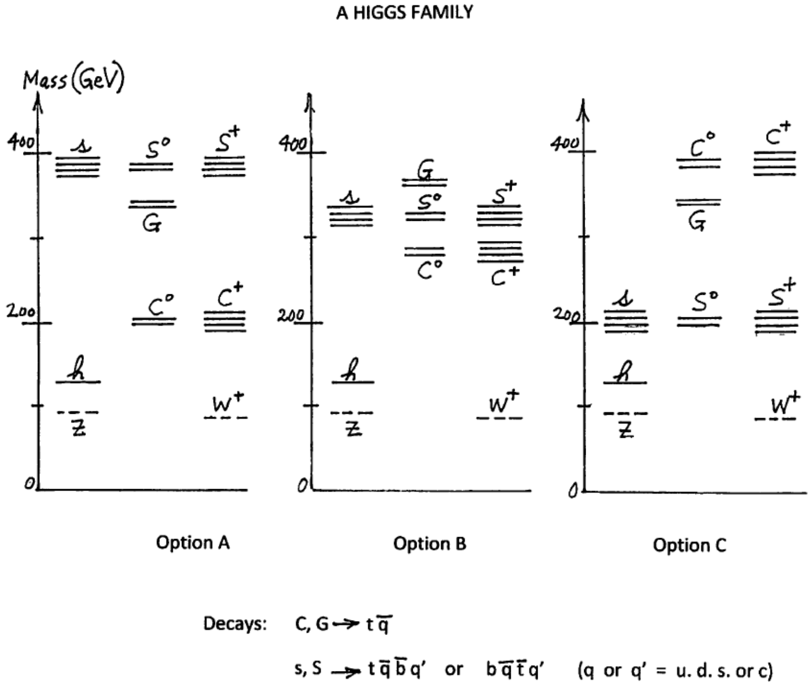


Fig. 3. Three candidate level schemes for the proposed electroweak-doublet, family nonet Higgs multiplet.

generation masses and mixings of the quarks and leptons. What I am looking for is a description in which these effects are generated by spontaneous breaking of the family symmetry group. For a while I thought I had such a model, at least for mixings of the second generation with the third. But I discovered mistakes - conceptual as well as algebraic. However, the parameter of difficulty is small: $(m_b/m_t)^2 \times V_{cb}$. So getting a satisfactory description is still a work in progress. But if there were to be success, I do not think that the LHC phenomenology of production and decay would be modified very much; the phenomenology sketched above, in my opinion, appears to be robust.

There is a message here to you, members of the QCD phenomenology community. The signal for these Higgs-sector candidates is buried in a large background of QCD top-antitop events. And the shape of the signal turns out to be not so different from the shape of the background [6]. Therefore there is a high premium on accurately controlling the background estimates. In addition, there is a second message. As the LHC upgrades energy and luminosity, most of the attention will rightfully be focused on searching for new physics at mass scales exceeding 1 TeV. What I anticipate is a lot of new physics on mass scales of order 200–500 GeV, but immersed in QCD background. This new-physics window deserves just as much scrutiny as the high-end region. In this regard, I was pleased to hear similar appeals from other speakers at this meeting, in particular by Patrick Meade and by Alan White.

4. Dark Matter and the Higgs Sector

Given the above approach, what seems to be essential for obtaining a satisfactory description of the Higgs sector — one that includes creation of the appropriate masses and mixings of quarks and leptons — is that it should include other family representations, in particular some that are electroweak-singlet. Such components of the Higgs sector – electrically neutral and colorless — appear to me to be attractive dark matter candidates. And it is not politically incorrect to assume that at least some of the members of this "dark Higgs sector" need not have large masses [7]. I myself have worked with others on elaborating this possibility [8].

While assuming a large Higgs sector might seem extravagant, I do not see it that way. For example, if one accepts $SO(10)$ grand unification (without SUSY) as a reasonable hypothesis, then it is reasonable that the 36 massive gauge bosons contained within the adjoint representation (all but the photon and the 8 gluons) get their masses via the Higgs mechanism. This puts 36 Goldstone modes into the Higgs sector, making it at least reasonable that those 36 are accompanied, at the very least, by a few dozen massive Higgs modes.

From the GUT point of view, I therefore find it reasonable to presume that, at the electroweak scale, the effective field theory of the Higgs sector may consist of a considerable number of shattered fragments which have descended down from the GUT scale, and have all the aesthetic deficiencies of its strong-interaction counterpart, namely the Gasser-Leutwyler effective action describing the hadronic sector of QCD. Consequently, I have spent this year contemplating what the Higgs sector might look like at the GUT scale, prior to its devastation via a sequence of symmetry breaking scales. There are of course many options. I have chosen to investigate orthogonal groups larger than $SO(10)$, and have settled for the moment on $SO(16)$. The 120 gauge bosons of that group break down into the 45 within the usual GUT $SO(10)$, plus 15 within the complementary "dark" $SO(6)$. All 15 "dark gluons" are by construction colorless, electrically neutral, and electroweak singlet. The remaining 60 gauge degrees of freedom are "coset" fields, which have both "dark" and "visible" properties. Almost all of these 120 bosons will have masses very large compared to the electroweak scale. But it is not impossible that there are some massless or almost massless "dark gluons," and/or others that have masses no larger than the electroweak scale.

For this to happen, the Higgs sector has to be quite large. There must be of order 100 Goldstone modes which are eaten by the large number of gauge bosons that do have mass. This suggests that there could be several hundred Higgs degrees of freedom in all. While from a bottoms-up point of view this may seem extravagant, one should keep in mind that from a top-down viewpoint a la string theory this is still modest. For example, the $E(8) \times E(8)$ heterotic string picture suggests the existence of many multiplets. Each one must have a dimensionality no smaller than 248.

The scenario I nowadays entertain contains 120 Higgs fields in the adjoint representation, plus another 256 "frame fields," which transform as vectors under the (spontaneously broken) "gauge $SO(16)$," as well as transforming as vectors under an auxiliary "frame $SO(16)$" (which is explicitly broken). This allows a lot of design flexibility, while keeping the fraction of Higgs fields which are massive relatively small. (I view this as a grotesque deformation of Occam's razor in action.) This notion of utilizing the frame field came to me via the work of Hong-Mo Chan and his collaborators on their "rotating mass matrix" description of fermion masses and mixings [9]. They create, via difficult-to-understand algorithms, an interesting and rather successful phenomenology of such masses and mixings, especially for the second generation. And underlying their ideas is a vision of the Higgs sector (largely unrealized in detail) in terms of such frame fields. As we will mention in the next section, the notion of frame fields also occurs in general relativity.

This is hardly the place to go further into this, which in any case is only work in progress. The reason I mention it at all is that I strongly believe that integration of family symmetry and its breaking (ideally only spontaneously) with Higgs-sector properties, and the integration of both with the dark-matter problem, is a fertile area for theoretical research. I find a lot of present theoretical phenomenology considerably more unfocused, as well as increasingly detached from the natural Big Picture architecture that hints from grand unification suggest.

5. Dark Energy and Darkness

Since retirement, the physics problem that has consumed me the most is that of dark energy. It is an ideal subject for a geriatric like me. Because I assume the default option of dark energy as due to a cosmological constant, all the direct data (a single number!) are in, and it is up to theory to do something about it. I have neither any excuse nor any motivation for procrastination. The two parameters of the Einstein-Hilbert action (Newton constant and cosmological constant) define two extreme distance scales — the Planck scale l_{Pl} of 10^{-33} cm and the Hubble scale H of 10^{28} cm. (The constant H is defined as $H^2 = \Lambda/3$.) All of phenomenologically relevant physics is bracketed by these very fundamental parameters. But taken together, these two parameters define an intermediate scale which is halfway in between, logarithmically speaking. This is the dark energy scale, defined by the value of the (negative) pressure possessed by regions of space (e.g. cosmic voids) whose spacetime curvature is dominated by the cosmological constant, and not by nearby matter. The numbers associated with this scale are 80 microns, or 2.4 meV, a scale associated with life itself.

I have become over the years quite persuaded that this is not the only intermediate scale induced by these two fundamental parameters. The other is what I call [10] the Zeldovich, or darkness, scale [11]. It is two thirds of the way from the cosmological scale to the Planck scale, logarithmically speaking. The value comes out somewhere around 10^{-12} cm, or 20 MeV. While the dark-energy scale is defined by vacuum pressure and vacuum energy, the darkness scale is defined (given that the idea makes sense!) by vacuum topology. By analogy with the density of vacuum energy that defines the dark-energy scale, the darkness scale is defined by a density of vacuum topological structures, roughly 10^{39} per liter.

This assertion is dependent on a certain version of general relativity called the MacDowell-Mansouri extension of the first-order Einstein-Cartan formalism. The Einstein-Cartan formalism replaces the 10 degrees of freedom (metric tensor) of the Einstein-Hilbert action with 40. It is a Yang-Mills gauge theory, with an $O(3,1)$ gauge group living in Minkowski spacetime. The gauge potentials, generally labeled ω, account for 24 degrees of freedom. These are supplemented by 16 frame fields (the "vierbein", generally labeled e) which are spacetime vectors as well as vector gauge-fields. The metric tensor of the usual (Einstein-Hilbert) textbook version is recovered in terms of a quadratic form in the vierbein fields. The Einstein-Cartan action depends on all 40 degrees of freedom. For most macroscopic applications, a few lines of computation exhibit the equivalence of the two formalisms. An exception occurs when Dirac particles are included in the gravitational action. Then it is imperative that the first-order Einstein-Cartan formalism be used [12].

The MacDowell-Mansouri extension of the first order formalism [13] generalizes the $O(3,1)$ gauge group to $O(4,1)$. The 16 vierbein variables e and the 24 gauge-potential variables ω are synthesized into the 40 gauge potentials A of the $O(4,1)$ group. A field strength F is constructed in the usual way, and an action, quadratic in the field strength F, is posited. When this, to my eyes, rather elegant form of the action is decomposed all the way back to the Einstein-Hilbert description, one finds three terms. One is the original Einstein-Hilbert term, and another is the cosmological-constant term (with necessarily a nonvanishing value, and with the correct sign, corresponding to a positive dark energy density). The third term is a well-known structure called the Euler or Gauss-Bonnet topological invariant. It is a quadratic form built from the Riemann curvature tensor, and its Lagrangian is a total time derivative. It therefore does not affect the Einstein field equations at all. However, what is interesting about this term is its coefficient, which is a pure number. That coefficient turns out to be the notorious factor of 10^{120} which pervades all discussions of the deep problems associated with dark energy.

In a formal sense, this Gauss-Bonnet term is the leading term when expanding out the MacDowell-Mansouri action. In a more practical sense, it is a totally irrelevant term. This ambivalence makes it hard to draw conclusions without pursuing the relevant issues more deeply. There is a rough QCD analogy. I think most of us believe that understanding the topological structure of the QCD vacuum is very important and fundamental. Even after decades of work, a small army of lattice QCD theorists still debate what that topological structure is: chromoelectric strings vs. monopoles vs. center vortices, etc., etc. Nevertheless, despite these deep unresolved issues, QCD phenomenology moves ahead, mostly unconcerned about the ultimate outcome.

Anyway, I choose to take this Gauss-Bonnet topological term seriously, and write its action in standard form, namely $S = 2\pi dN/dt$, with N an integer valued quantity. It is then possible to learn more about how N behaves in simple geometries, even without understanding in microscopic terms what it means. I find that, in FRW cosmology, this quantity is indeed extensive, and that in a cosmic void the density of topology or darkness, defined as $n = N/V$, is indeed proportional to HM_{Pl}^2. In the early universe, n was larger than that. It was Planckian when the universe was radiation-dominated, with a temperature of order 10 MeV. Likewise, upon adding a simple matter source to empty space, with nuclear matter density (proton, lead nucleus, neutron star), one finds that the darkness density varies in proportion to the inverse 9/2 power of the distance from the source. The darkness density becomes Planckian just outside the radius of the source, independent of the mass of the source.

These results, and other related issues, strongly suggest that at best the MacDowell-Mansouri action is an effective action, usable only at distance scales larger than the darkness scale of 10^{-12} cm. This does not mean that this formalism predicts that the Einstein equations of motion are invalid below that scale. It only means that the formalism itself is inappropriate to use at distance scales smaller than the darkness scale. A rough analogy might be QCD. Use of quarks and gluons to describe phenomena at distance scales large compared to the confinement scale is usually inappropriate. But this does not mean there is something fundamentally wrong with the QCD Lagrangian at such distance scales. And there are elements of the short-distance description, such as the weak and electromagnetic currents built from the quark fields, which can be used productively in the large-distance limit of the theory.

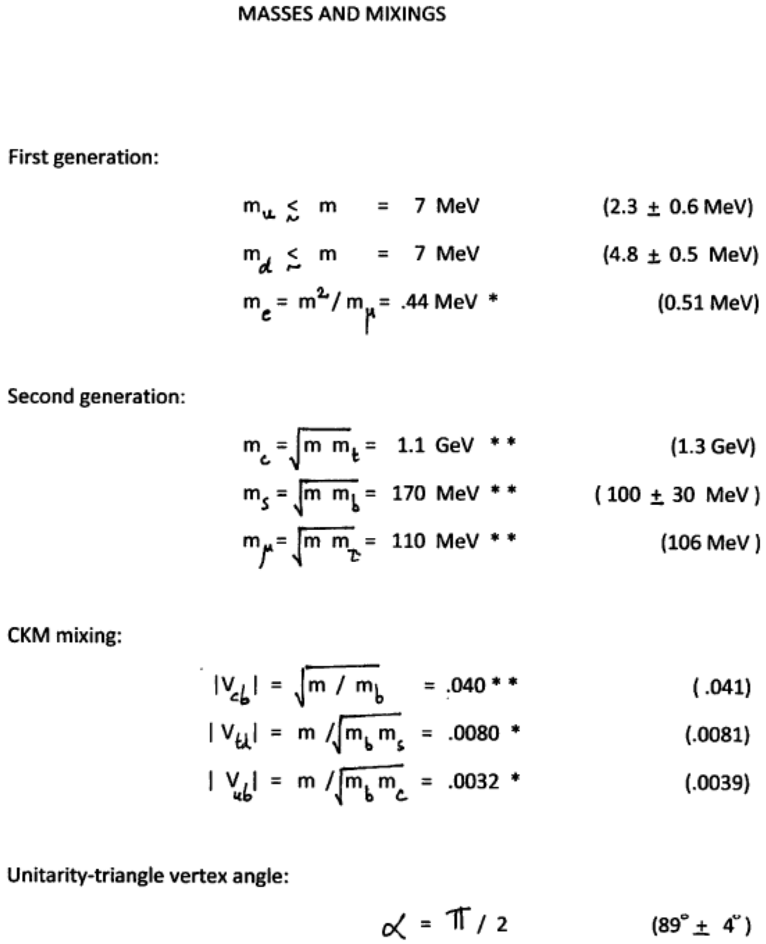
But the bottom line question is whether this concept of darkness can be put to work in other ways. I am tempted to speculate that there is a link to the confinement scale of QCD and the mass scale of the quarks and leptons. These scales did not in principle have to be close to the darkness scale. But they are. Perhaps the QCD vacuum texture somehow communicates with this gravitational topological vacuum texture. The QCD vacuum and the gravitational vacuum are in the same place at the same time, with arguably the same energy. Therefore, even a tiny coupling may persuade the two vacuum scales to converge to a common value. Likewise, the quark and lepton masses and mixings depend on the structure of the "Dirac sea" and of the Higgs vacuum condensate. So a similar argument may also apply in that case.

This line of argument provides me with a guidepost in my present search for patterns of symmetry breaking, etc. in the Higgs sector. I envisage an infrared, "darkness" scale characterized by a mass parameter m which controls first and second generation masses and mixings. Were this parameter m to be set to zero, all such effects vanish. In other words, many of the most difficult "family problems" resolve themselves, not at very high mass scales, but at mass scales no larger than the electroweak scale. While this is not at all what is anticipated by the vast majority of experts, I feel that the scenario I sketched out in the previous sections may just possibly be consistent with this notion. So I keep it in as a working hypothesis, which helps constrain the myriad of alternative scenarios that I face in dealing with the family problem.

I even have a candidate value for the small parameter — 7 MeV. I have created my own rough reconstruction of the aforementioned "rotating mass matrix" scheme of Hong-Mo Chan et al., with output values of masses and mixings as given in Fig. 4. In my version [10], this parameter m is explicit, and clearly plays a central role. In the original version [9] this low mass scale is also present, but in a less overt way.

6. Concluding Comments Beyond the QCD material

Most of this talk has not been hard science, but merely an outline of a personal belief system. The main features of this set of beliefs (or, more



MASSES AND MIXINGS

First generation:

$m_u \lesssim m \;=\; 7\ \text{MeV}$ (2.3 ± 0.6 MeV)

$m_d \lesssim m \;=\; 7\ \text{MeV}$ (4.8 ± 0.5 MeV)

$m_e = m^2/m_\mu = .44\ \text{MeV}$ * (0.51 MeV)

Second generation:

$m_c = \sqrt{m\, m_t} = 1.1\ \text{GeV}$ ** (1.3 GeV)

$m_s = \sqrt{m\, m_b} = 170\ \text{MeV}$ ** (100 ± 30 MeV)

$m_\mu = \sqrt{m\, m_\tau} = 110\ \text{MeV}$ ** (106 MeV)

CKM mixing:

$|V_{cb}| = \sqrt{m / m_b} = .040$ ** (.041)

$|V_{td}| = m/\sqrt{m_b m_s} = .0080$ * (.0081)

$|V_{ub}| = m/\sqrt{m_b m_c} = .0032$ * (.0039)

Unitarity-triangle vertex angle:

$\alpha = \pi / 2$ (89° ± 4°)

Fig. 4. Masses and mixings of quarks and leptons according to the electroweak-doublet, family-nonet model. The asterisks are "Michelin star" ratings, according to the quality (or lack thereof) of the theoretical arguments leading to the prediction.

respectably, working hypotheses) are as follows:

1. The problem of family symmetry (why three generations of quarks and leptons?) deserves as much detailed attention as, for example, the much more popular one having to do with the presence or absence of electroweak-scale supersymmetry.

2. A natural setting for addressing this problem is the issue of nontrivial family structure within the Higgs sector.

3. Given the reasonableness of an $SO(10)$ GUT, it is reasonable that the Higgs sector is quite large, with perhaps hundreds of degrees of freedom having masses below the GUT scale, and with a significant fraction being Goldstone. This feature makes it even more reasonable that nontrivial family multiplets of Higgs bosons exist.

4. It is not unreasonable to gauge the family group, thereby embedding the usual GUT $SO(10)$ within a larger unifying group. This opens up the possibility of the existence of a set of "dark gluons", which may be massless and/or nearly massless, with a concomitant "dark confinement" mass scale.

5. This also leads to a corresponding "dark sector" component of the Higgs sector, the members of which are also electroweak singlet, zero charge, and colorless. They, together with the "dark gluons," are candidates for the sector of the standard model responsible for dark matter. A significant fraction of this set of states may have masses no larger than the electroweak scale. Some might even be axion-like familons, with the extremely small mass scale appropriate to present-day axion searches.

6. The pattern of third generation masses suggests an origin connected to the GUT mass scale, because the sundry fermions get their masses via different group structures at the level of $SU(5)$: top via $5 \times (10 \times 10)$, bottom and tau via $5 \times (\bar{10} \times 5)$, Dirac neutrino via $5 \times (\bar{5} \times 1)$. However, the first and second generation masses are conjectured by me to come from a mechanism tied, either completely or largely, to an "infrared" scale, somewhere between a few Mev and tens of MeV. Explication of this mechanism will require, in all likelihood, a quite detailed understanding of nontrivial family multiplets beyond the one containing the recently discovered Higgs boson.

7. The origin of such a mysterious infrared scale may be tied to an equally mysterious "darkness" scale associated with topological structures within the "gravitational vacuum." This darkness scale might control not only the scale of quark and lepton masses, but also the value of the QCD confinement scale. It may also imply existence of dark matter degrees of freedom within the same mass scale.

8. Progress in developing the above ideas depends upon management of many details and the devils therein. In principle, the pattern of

masses and mixings may provide enough clues to allow data-driven progress. Many theorists, especially the landscapers, assert that there is no pattern at all, and that all of these mass and mixing parameters are determined anthropically. While I personally am sympathetic to anthropic reasoning and the multiverse hypothesis, this does not preclude the existence of a pattern. We should be very careful not to give up too soon. For better or worse, I do claim to see a pattern (Fig. 4) and try to build from it.

Many of the above items are not at all novel. Some are quite politically correct. Others will be regarded by most critics as rather outrageous. But, for better or worse, this is my personal belief system. I think that such belief systems at the individual level — even though they go far beyond the discipline of the scientific method — are a great asset. They energize us. They make us work much harder. But at the societal level, institutionalization of such belief systems is dangerous, both within science and beyond. I present mine not as advocacy, but as an encouragement to the community to maximize its tolerance of those viewpoints which do lack political correctness.

What do these beliefs have to say about the experimental future of our field?

1. There remains a high level of potential at the LHC for discovering members of the extended Higgs sector at the “low” mass scale of 200–500 GeV. This region deserves continued careful scrutiny.
2. If such states exist, they create an extremely strong case for an ILC.
3. A rich sector of dark-matter states with masses small compared to the electroweak scale invites a broad variety of non-accelerator searches (along with others at low-energy, high-intensity accelerators), with plenty of room for new creative ideas.

Were the political climate to improve to the level existing in, say, the 1970’s, existing technology would by itself guarantee a healthy future for many decades, perhaps culminating in a 100 TeV-scale proton-proton collider. The homework for such big initiatives should be done as soon as possible, so that if and when the politics improves, the field is ready to move ahead expeditiously.

I have in this talk wandered far afield from QCD phenomenology. Nevertheless, I need not elaborate here, of all places, on how central QCD remains in all of the above issues. It is our best quantum field theory. It is the underpinning of a large fraction of all particle-physics experiments. And it contains important fundamental features shared by other gauge theories —

including general relativity. Thorough, data-driven studies of QCD in all its aspects should never go out of fashion.

7. Acknowledgments

Thanks go to many colleagues at SLAC, Stanford, and elsewhere for much helpful criticism of these ideas. Thanks also go to Sergei Chekanov, Zack Sullivan, and their able assistants for organizing such an interesting and successful meeting.

8. Addendum

During the meeting, I could not help but react to the interesting material which was presented. In this addendum is a short summary of some primary reactions:

A. Underlying Events and Hole Fragmentation: Simulations of minimum-bias physics and of underlying-event structure have by now become very sophisticated. Nevertheless, there will always be room for improvement. With that in mind, it seems to me that a targeted approach is appropriate, with the individual targets being the dozen or so distinct regions of the lego plot present in a typical LHC hard-collision event (cf. Fig 5(a)). Most of these regions are already well-identified and studied. Beam fragmentation regions are challenging, but difficult to access experimentally. I suspect that a relatively underappreciated region is the "hole fragmentation" region, namely that portion of the lego plot which contained the initial state partons that participated in the hard process. In order to most expeditiously examine its properties and to compare with simulations, it would seem to be advantageous to place a hole fragmentation region in the barrel region of the detector, centered at zero rapidity (Fig. 5(b)). The trigger is a symmetric pair of "endwall jets."

B. Boosted Jets and Plumbing: There was considerable discussion of new physics searches involving "boosted jets." While well-isolated conventional jets can be defined as the contents within a circle of radius 0.7 in the lego plot, "boosted" configurations cannot. This "overlapping jet" problem requires more sophisticated approaches to the kinematics, some of which were on display during the meeting. Long ago I worked on this problem, and came up with a general method for untangling overlapping jets (SLAC-PUB-5593). Alas, it never received much attention. But I still think it has possible merit, and would like to see it applied, at the very least, to Monte Carlo data.

C. PDF's at very small x: During the meeting there was no discussion or display of PDF's at values of the deep-inelastic scaling variable $x \ll 10^{-4}$.

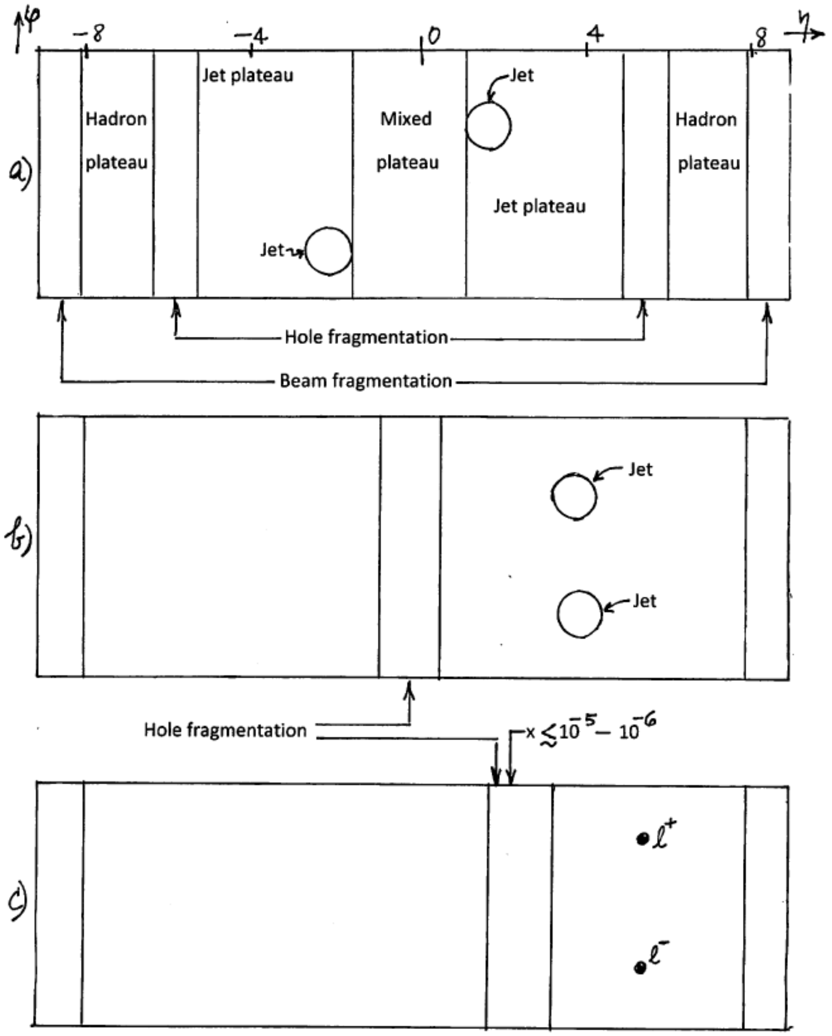


Fig. 5. Lego plots at the LHC energy scale for (a) a typical dijet event, for (b) a boosted dijet event appropriate for the detailed study of hole fragmentation, and for (c) probing parton distributions via the Drell-Yan process at values of $x < 10^{-5}$–10^{-6}.

Kinematically one can reach another factor of 10–100 at the LHC via "end-wall Drell-Yan dileptons" with masses in the 5–10 GeV range (Fig. 5(c)). After my talk, I learned that LHCb has published some data (LHCb-CONF-2012-013). But the resultant PDF's still deserve to be catalogued — it is an important frontier measurement.

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