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MORIOND ELECTROWEAK 2006: THEORY SUMMARY

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A concise look at the big picture of particle physics, including the status of the Standard Model, neutrinos, supersymmetry, extra dimensions and cosmology. Based upon the theoretical summary presented at the XLIst Rencontres de Moriond on Electroweak Interactions and Unified Theories, La Thuile, 11-18 March 2006.

1 Dancing in the Dark

"It's promising for the future. The important matches are coming."

– *Zinédine Zidane*

The irony and frustration of particle physics today is that simultaneously we know so much and so little. The Standard Model (SM) has successfully predicted hundreds of new phenomena, observed and confirmed in detail by a triumphant progression of experiments. Our understanding and technical grasp of the Standard Model has matured greatly, mostly as a result of the intimate interaction of theory with experiment. This mature understanding has guided our speculative frameworks for physics Beyond the Standard Model (BSM). These frameworks are well-motivated. They have impressive explanatory potential for fundamental mysteries not addressed by the Standard Model. Most BSM frameworks make dramatic predictions for discoveries at the Large Hadron Collider (LHC).

Yet, as of the middle of 2006, we are very much in the dark as to what is the larger picture that subsumes the Standard Model. Dozens of experiments, which could have yielded clear signals of new physics, have instead shown only Standard Model physics to within ever–shrinking error bars. Some recent discoveries are clearly not explained by the SM: neutrino oscillations, dark matter, and the accelerating expansion of the universe. But these discoveries, singly or collectively, do not point unambiguously to their BSM resolution.

2 Discovering the Standard Model

The Standard Model predicts a wealth of new particle physics phenomena. It is misleading to refer to experimental observations of these phenomena as "tests" of the Standard Model. The first observation of a new particle, particle property, interaction, decay or symmetry violation is a discovery, not a test. Detailed measurements of new phenomena have the potential to reveal discrepancies with the Standard Model, but just as importantly they force us to develop a deeper and more concrete understanding of the Standard Model itself.

2.1 Top physics

Experiments in Tevatron Run I discovered a new strongly pair-produced heavy state which decays promptly to a W and a b-jet. Now experiments in Run II are discovering the properties of this new particle, how it fits into the Standard Model, and clues to its potentially unique role in particle physics. During the past year, the charge, spin, and $V-A$ coupling of this particle have been directly measured, confirming its identity as top [1].

The mass of top is now measured with an accuracy of $\pm 1.5\%$ in a single experiment [2]. This has two important consequences. First, we can extract with greater precision the virtual top contributions to electoweak radiative corrections, giving us greater sensitivity to the radiative effects of new physics, including the Higgs. Second, we have discovered that the mass of the top quark, in its natural units of $v/\sqrt{2}$, is equal to one: $\lambda_t = 0.99 \pm 0.01$. This is a striking result, certainly as striking as the much ballyhooed unification of the SM gauge couplings, which requires the additional assumption of TeV supersymmetry to achieve similar precision. As far as I know, no theoretical model has been suggested which can explain this fact, which is made even more bizarre by the large hierarchies of SM fermion masses in general.

2.2 B physics

Results from BaBar and Belle continue to have a great impact on at least three fronts:

- First observations of processes which could have $\mathcal{O}(1)$ contributions from new physics.
- Over-constraining the CKM model of flavor and CP violation.
- Challenging (and thus improving) our understanding of strong interaction and heavy quark physics, including lattice QCD.

Progress along these three fronts is correlated. The prediction of B decays, for example, requires a combination of electroweak physics, perturbative QCD, and nonperturbative QCD, further complicated by multiple scales. Similar challenges occur in the charm and kaon sectors [3]. Exclusive decays involve hadronic form factors which are estimated using unquenched lattice QCD. As reported [4,5] at Moriond, lattice uncertainities for exclusive B and charm decays are now on the order of 10%, as cross-checked in the data itself. These are expected to improve to 5%, and in some cases the order 1% accuracy which is already obtained in kaon sector [6].

For the exclusive hadronic decays $B \to K\pi$ and $B \to \pi\pi$, $SU(3)$ isospin relations can be used to make consistency checks in which hadronic uncertainties are minimized. The first step is to use an isospin analysis of the various $B \to \pi\pi$ modes to extract some hadronic parameters from data. Then $SU(3)$ isospin, with known factorizable $SU(3)$-breaking corrections, is used to make predictions for ratios of $B \to K\pi$ rates. For one such ratio the agreement between prediction and data is good. For another ratio, one which is sensitive to electroweak penguins, the agreement is poor. This "$K-\pi$" puzzle could be a hint of new physics in the aforementioned electroweak penguins [7] or it may reflect a misunderstanding of QCD. An improved analysis announced at Moriond still finds a discrepancy [8].

The basic theory of inclusive B decays is an effective hamiltonian approach[9] using an operator product expansion:

$$\langle f|H_{eff}|i\rangle = \frac{G_F}{\sqrt{2}}\lambda_{CKM}\sum_k C_k(\mu)\langle f|Q_k(\mu)|i\rangle \ , \tag{1}$$

where the Wilson coefficients $C_k(\mu, \alpha_s)$ are the scale-dependent couplings of the interactions induced by the operators Q_k. Higher order operators are suppressed by powers of the small quantity Λ_{QCD}/m_b. Recent successes of this method include[10,11] the determination of the sign of C_7 in the inclusive rare decays $b \to s\ell^+\ell^-$.

However our theoretical handle on inclusive B decays is still far from satisfactory. For example, inclusive $B \to X_s\gamma$ decays are among the most sensitive channels for supersymmetry and other new physics. The NLO theoretical prediction for the inclusive branching fraction has about a 10% uncertainty, which is comparable to the current experimental uncertainty[10]. To compare with the future data sets, we need a NNLO calulation, reducing the renormalization scheme-dependence on the (poorly measured) charm quark mass, and dealing with the effects of the 1 GeV scale $m_b - 2E^{\gamma}_{min}$ created by the analysis cuts[12].

The situation is especially challenging for the inclusive semileptonic decays used to extract the CKM element V_{ub}. Here the kinimatic cuts used to separate $b \to u$ from $b \to c$ cause a breakdown of the operator product expansion, which is patched up by introducing "shape functions" to resum nonperturbative physics. It is thus not surprising that in the latest global fits[13] of B physics data to the Standard Model, the largest inconsistency seems to come from the inclusive determination of $|V_{ub}|$. This may indicate a problem either with the central value (too large) or the estimated errors (too small).

The most dramatic moment of the Moriond conference was the surprise announcement by the DZero collaboration of the first two-sided bound on the $B^0_s - \bar{B}^0_s$ mass difference ΔM_s[14]. This was followed shortly after the conference by a CDF measurement[15] with remarkable 2% accuracy:

$$\Delta M_s(\text{CDF}) = 17.33^{+0.42}_{-0.21}(\text{stat.}) \pm 0.07(\text{syst.})\ \text{ps}^{-1} \ . \tag{2}$$

It is exciting to observe this variety of matter-antimatter oscillations never before seen. After Moriond a number of global data fits, using also various lattice QCD inputs, have attempted to estimate the Standard Model prediction for ΔM_s. The latest fit[13] gives:

$$\Delta M_s = 20.9 \pm 2.6\ \text{ps}^{-1} \ . \tag{3}$$

If we remove the problematic inclusive $|V_{ub}|$ determination from the analysis, the prediction becomes

$$\Delta M_s = 19.4 \pm 2.5\ \text{ps}^{-1} \ . \tag{4}$$

This is good agreement, but it is embarrassing that the (data-assisted) theory error is 5 times the CDF experimental error!

The CDF and DZero analyses also provide strong constraints on new physics. Together with the first branching ratio for the rare decay $B \to \tau\nu$, reported by Belle shortly after Moriond[5], this follows a pattern of first observations of the dwindling number of channels in which $\mathcal{O}(1)$ signals of new physics could have been hiding.

To understand the significance of measuring ΔM_s, we first classify models of new physics according to how they affect flavor physics:

- **CMFV:** These are models in which the only source of quark flavor violation is the CKM matrix, and the only low dimension operators contributing to flavor transitions are those

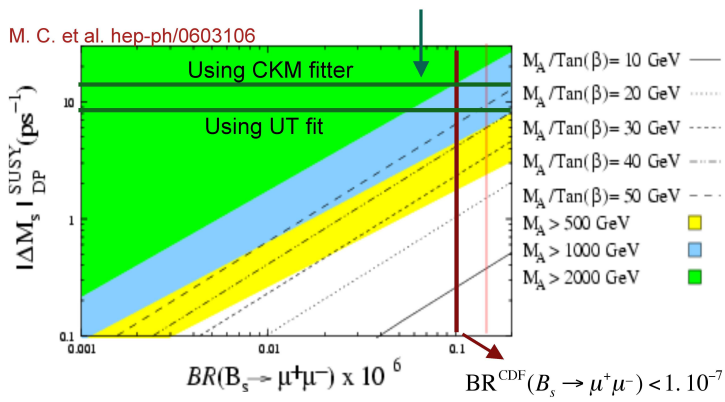

Figure 1: MFV SUSY models outside of the thick solid lines are excluded. From hep-ph/0603106.

present already in the SM. This is called Constrained Minimal Flavor Violation [16]. Examples include minimal supergravity models with low or moderate $\tan\beta$, and models with a universal large extra dimension.

- **MFV:** Same as above, except there are some new relevant operators. This is called Minimal Flavor Violation [17]. Examples include SUSY models with large $\tan\beta$, where the new relevant operators are Higgs penguins.

- **NMFV:** There are new operators involving the third generation quarks, and these are flavor-diagonal up to small rotations with roughly the same hierarchies as in the CKM matrix. This is Next-to-Minimal Flavor Violation [18]. The quasi-alignment is an attractive way to solve the flavor problems that appear in frameworks such as Little Higgs, topcolor, and warped extra dimensions.

- **GFV:** These are models with both new operators and new sources of flavor violation. This is called General Flavor Violation [19]. Examples include most of the MSSM parameter space, and almost any BSM model that you can think of, before you start worrying about flavor constraints.

CMFV models predict the same relations among flavor parameters as the SM [20], thus the CMFV prediction for ΔM_s is the same as the SM prediction quoted above. For MFV, the most interesting case is SUSY with large $\tan\beta$. Double Higgs penguins interfere destructively with the SM contribution, reducing ΔM_s by an amount which is potentially enhanced by $(\tan\beta/M_A)^4$. At the same time, the rare decay $B_s \to \mu^+\mu^-$ is enhanced by as much as $(\tan\beta/M_A)^6$. As it happens, the constraints on such models from ΔM_s are comparable at the moment to those from the CDF and DZero upper limits [21,22] on $B_s \to \mu^+\mu^-$. An improved CDF limit on this branching fraction was announced at the time of Moriond:

$$Br(B_s \to \mu^+\mu^-) < 8 \times 10^{-8} \text{ (90\% CL)}, \quad < 1.0 \times 10^{-7} \text{ (95\% CL)} . \tag{5}$$

Figure 1 shows the predictions [23] for $Br(B_s \to \mu^+\mu^-)$ and the (negative) contribution to ΔM_s, for a sample of the large $\tan\beta$ MFV SUSY parameter space. Obviously the model space is beginning to be nontrivially constrained. Better constraints are expected from improvement in the Tevatron $Br(B_s \to \mu^+\mu^-)$ upper bound, to 2×10^{-8} or lower. It has also been suggested [24] that the slightly high SM value for ΔM_s, as well as the slightly high SM value for $Br(B_u \to \tau\nu)$ compared to the Belle result, are emerging signals of large $\tan\beta$ SUSY. If so, Tevatron and LHC results will provide definitive confirmation.

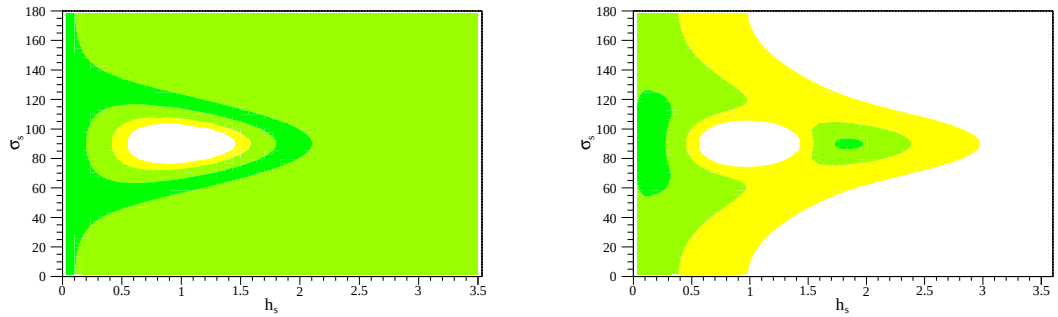

Figure 2: Allowed range for NMFV parameters h_s, σ_s using the data before (left) and after (right) the ΔM_s measurement. The dark/medium/light areas have CL > 0.90, 0.32, and 0.05, respectively. From hep-ph/0604112.

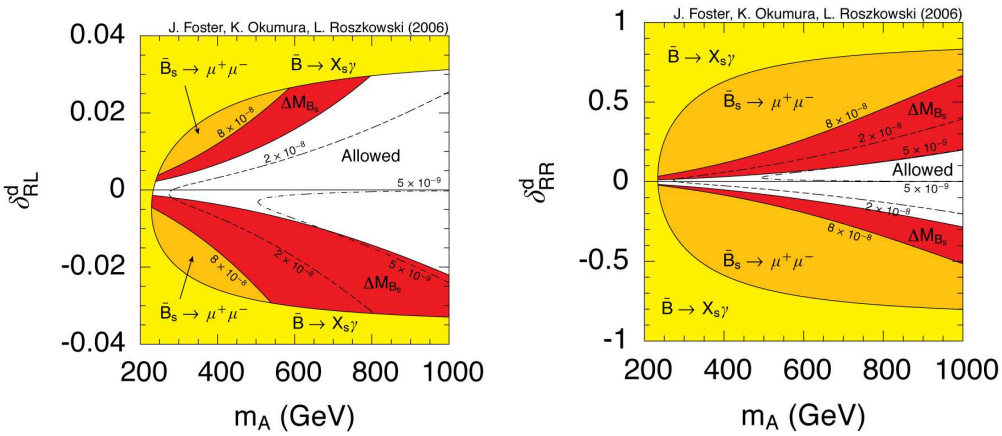

Figure 3: Contour plots showing the limits on the GFV supersymmetry parameters δ^d_{RL} and δ^d_{RR} for varying m_A and fixed $\tan\beta = 40$, $\mu = -A_u = 500$ GeV, and a common squark/gluino mass of 1 TeV. From hep-ph/0604121.

As seen in Figure 2, NMFV models are significantly contrained by the measurement of ΔM_s, but $\mathcal{O}(1)$ new sources of flavor violation are still allowed [25]. LHCb will provide the definitive probe of these models, by measuring (among other things) the time dependent CP asymmetries in B^0_s decays.

For GFV models, the new results on ΔM_s are quite constraining on a large piece of the general parameter space [26]. In some cases the ΔM_s constraint, even though it includes the large theory error bar from the SM prediction, is much more constraining than the current upper bound on $Br(B_s \to \mu^+\mu^-)$. This is shown in Figure 3. It is interesting to note that the preliminary versions of these plots were produced during the week of Moriond, showing once again the remarkably tight coupling between theory and experiment in this field.

3 The SciFi Channel

Moving beyond the Standard Model, let us contemplate the opening titles of a popular program on The SciFi Channel:

- The Cylons were created by man.
- They evolved.
- They rebelled.
- There are many copies.

- And they have a plan.

This is a perfect outline to review the history and status of BSM theory.

3.1 The models were created

If you attended Moriond circa 1983, you recall that BSM theory consisted of supersymmetry, grand unification, and technicolor. The technical and phenomenological status of these models was primitive. The BSM community was compact, and did not include the even smaller detached cults of "neutrino" and "particle-astro" people.

3.2 They evolved

During the intervening 20+ years, there has been enormous development in BSM theory. String theory took over the BSM high ground, at first discouraging phenomenological progress, but ultimately stimulating it with new ideas and powerful technical insights. Supersymmetry models became much more sophisticated, detailed and ambitious, creating a framework with the potential to describe everything from Higgs to unification to dark matter to inflation to baryogenesis. Technicolor was badly mauled by electroweak precision data, but revived with help from AdS/CFT and other technical advances [27].

3.3 They rebelled

Despite this progress, the BSM community has been increasingly unsettled. After 30 years, SUSY is still not discovered, which is surprising given the golden opportunities from LEP, the Tevatron, B physics, electric dipole moment measurements, etc. Meanwhile the mysteries of flavor, as we have already seen above, have gotten worse, compounded by the even deeper mystery of how (or if) gravity couples to vacuum energy.

Many theorists responded by moving in directions orthogonal to the traditional main line of BSM development. There was an explosion of model building invoking various scenarios with extra dimensions. The extra dimensions could be infinitely large but hidden, very large (10 fm to 0.1 mm), large (1/TeV), or tiny ($1/10^{16}$ GeV) but warped [28]. They have been invoked to solve the hierarchy problem, break SUSY [29], explain dark matter [30], explain some hierarchies of fermion masses [31,32], and even to explain the accelerating expansion of the universe [33]. None of these models are as robust and well-developed as traditional SUSY, but in many cases they are compatible and complementary with SUSY models, as well as with other frameworks like Little Higgs [34] or technicolor.

The most dramatic examples of BSM theory rebellion are the Higgsless models and split-SUSY. The Higgsless models [35] use extra heavy gauge bosons, instead of a Higgs, to unitarize the scattering of longitudinal W's and Z's. While generic examples of such models are already ruled out by electroweak precision data, they are a warning that Nature may have chosen a more obscure path to electroweak symmetry breaking than we have yet imagined. Split-SUSY enthusiasts throw out the baby and play with bathwater, creating models [36] which explain dark matter and unification, have nice flavor properties, but give up on explaining the origin or stability of the electroweak scale.

3.4 There are many copies

Despite wildly differing theoretical inputs and philosophies, many BSM models end up with similar phenomenological outputs. This is because nearly all of these models are trying to do the same three things:

Figure 4: With BSM models, as with Cylons, there are many copies.

- Explain electroweak symmetry breaking.
- Explain dark matter.
- Avoid being ruled out by constraints from current data[37].

Thus most BSM models have a WIMP dark matter candidate; other heavy exotics can decay to this WIMP, leading to the prediction of dramatic missing energy signatures at colliders. To avoid constraints from electroweak precision data, from data on flavor violation, and other low energy precision measurements, BSM models choose from three strategies:

- The new states are very heavy (multi-TeV).
- There are conspiracies to cancel electroweak radiative corrections and/or flavor violating effects.
- A conserved parity requires all of the new particles to be pair-produced (suppressing radiative corrections and providing a stable WIMP), and the model is Minimal Flavor Violating or at least NMFV.

The third strategy is the most attractive, leading to a variety of SUSY models, Little Higgs with T-parity, and Universal Extra Dimensions. It will be quite challenging at the LHC to tell these models apart (see Figure 4). This is true even if we restrict to just SUSY models[38].

3.5 And they have a plan

The plan is not to replace the Standard Model. The plan is rather to discover the larger more explanatory framework in which the SM is embedded. I expect that discoveries of the next ten years will teach us as much about the Standard Model itself as what lies beyond it.

4 The Big Picture

The big picture[39] of BSM physics is illustrated in Figure 5. The vertical direction represents energy scale; shown are the "TeV scale" characterized by the new physics responsible for electroweak symmetry breaking, and the "string unification" scale, defined as the scale where one begins to have a unified description of quantum gravity with the gauge interactions of the SM. We do not know the scale of unification even to within an order of mangitude, nor do we know to what extent it involves gauge coupling unification, grand unification, flavor unification, or superstrings. Our best guess is that some combination of all these elements is involved.

If unification occurs in any form, then there must be highly sophisticated dynamical mechanisms which convert the simple unified theory at ultra high energies into the messy junk that

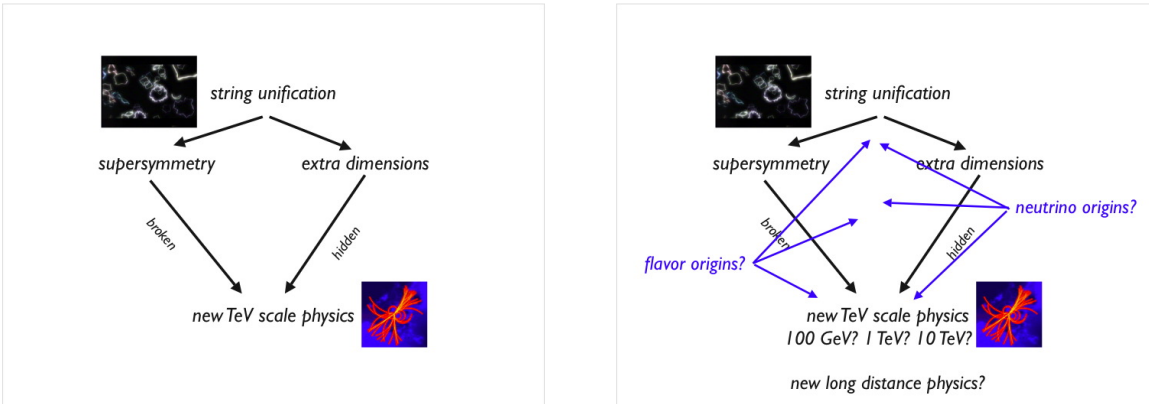

Figure 5: The big picture of physics Beyond the Standard Model.

we observe in experiments. These are shown in the figure as the mechanisms that break supersymmetry and hide extra dimensions. It has also been suggested that the messiness we observe at accessible energies is due mostly to initial conditions, selecting from a vast "landscape" of possible vacua. This possibility involves strong cosmological assumptions whose plausibility I find hard to evaluate.

Even with the caveats just mentioned, the left panel of Figure 5 displays an elegant picture that is well-motivated and widely believed. However the right panel is a more honest depiction of our current state of ignorance. We know that neutrinos have mass, but the physics responsible for this may lurk anywhere in a 15 order of magnitude energy range. This is also true *a fortiori* for the origin [40] of the complicated flavor structure of the Standard Model.

To see better where we stand, we can break down our ignorance about one subject, neutrinos, into a set of concrete questions [41]:

- What energy scales and symmetries are involved in the orgin of the PMNS masses and mixings?
- How are these related to the CKM matrix?
- Are the masses Dirac or Majorana?
- Is the mass hierarchy normal, inverted or quasi-degenerate?
- What is the absolute scale of neutrino masses?
- Are there light sterile neutrinos? If so, are they eV of keV?
- What is the relation to dark matter?
- What is the value of θ_{13}?
- Is there CP violation in the lepton sector? If so, are the CP phases Dirac or Majorana or both?
- Is there lepton flavor violation apart from Majorana masses?
- How are neutrinos related to leptogenesis/baryogenesis?

The prospects for neutrino physics in the next decade are very promising. One can imagine, through a combination of proposed accelerator and non-accelerator based experiments, piecing together an exciting story of neutrino origins. For example, such a story could tie supersymmetry at the LHC to observations of novel lepton flavor violation plus neutrinoless double beta decay, and a discovery of an inverted neutrino mass hierarchy. In this case we could develop a compelling theory of leptogenesis. Many similar stories were discussed at Moriond [41–48].

5 TeV Cosmology

The WMAP three year results [49] arrived during the week of Moriond. These add yet more independent evidence for the reality of dark matter. The rival MOND explanation of galaxy rotation curves [33] appears to be under serious attack from both small scale data (dwarf galaxies) and large scale data (galaxy cluster collisions). WIMPS and axions are both well-motivated dark matter candidates, and both are getting constrained by direct searches [50,51]. Of course direct and indirect searches are affected by astrophysical uncertainties about the local density of dark matter and how it is distributed in the galaxy, so a positive signal is more informative than a negative one.

The LHC collider provides a golden opportunity to manufacture and study WIMP dark matter in the laboratory. My guess is that dark matter will turn out to consist of several different components, just as visible matter does, and that a thermal relic WIMP will be an important part of the story.

Still there are many challenges for understanding WIMP dark matter. Neutralino dark matter from SUSY is the best understood case, but here we know that the relic density estimates are strongly dependent on details of the model. Thus, for example, it is certainly not sufficient just to scan over the CMSSM parameter space [52]. Other SUSY dark matter candidates need to be taken seriously [53]. Alternatives to SUSY, such as Universal Extra Dimensions and Little Higgs with T parity, are still baby models which will become more sophisticated over time; their WIMP relic density estimates will evolve accordingly.

One of our great ambitions for the LHC/ILC era should be to uncover the hard details of TeV cosmology. At present, the earliest clear signpost of our cosmological history is from the MeV scale, the time of primordial big bang nucleosynthesis (BBN). Particle physics data implies that a quark deconfinement transition happened at higher temperatures, around 170 MeV. We expect to greatly increase our knowledge of this transition during the next decade, but not necessarily to obtain any strong links to cosmology. Astrophysical data gives us hints about a much earlier period of primordial inflation, but these hints are clouded and ambiguous, much as are the hints of gauge/grand/string unification in particle physics.

We strongly suspect that there was some kind of phase transition at a temperature around 100 GeV, associated with electroweak symmetry breaking. Combining results from LHC, ILC and other experiments, we have a good chance of pinning down the details of this transition, and its relation to baryogenesis/leptogenesis [54]. Similarly, we suspect that at least one thermal relic stable WIMP froze out during this same era of TeV cosmology. Combining results from LHC, ILC and other experiments on the nature of this WIMP and its interactions, we should be able to compute its relic density under a a variety of cosmological assumptions. As happened with BBN, a successful linkup between these advances from particle physics and those from dark matter searches and cosmological data could provide a sturdy TeV signpost for cosmology.

Such a breakthrough may be essential for pushing on to understand inflation and other features of our earliest cosmological development. This necessity is illustrated by noncanonical cosmological histories like the "Slinky", which are nearly canonical from BBN time on, but wildly different at earlier times [55,56].

Particle physics may also play a crucial role in unraveling the mystery of "dark energy". This

depends, however, on what is the actual source of the current accelerating expansion. There seem to be four general possibilities:

- The Friedmann-Robertson-Walker approximation is breaking down [57].
- The Friedmann equation is modified due to extra dimensions or modified gravity [33].
- There is a tiny cosmological constant.
- There is a dynamically evolving quintessence field.

In every case but the first it seems that particle physics input will be essential.

6 The LHC Era

"Never trust a theorist."

– *Samuel C.C. Ting*

At Moriond there was palpable excitement about the advent next year of the LHC. Those of us who need to abide by U.S. Dept. of Energy travel rules have already made our reservations to attend Moriond 2009, where we expect the first LHC discoveries to be announced [58]. What will be found is anybody's guess, and if history is any guide, even the most enlightened theorists will benefit from a few sharp jolts of reality. One thing that we do know for sure is that the LHC will open a window on a new world, even for Standard Model physics. Understanding the Standard Model at 14 TeV is our most immediate challenge [59], and one for which close interaction between theorists and experimentalists will be required.

Acknowledgments

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