CLNS 02/1796
hep-ph/0207357
July 30, 2002

MORIOND QCD 2002: THEORETICAL SUMMARY

M. NEUBERT[a]
F.R. Newman Laboratory for Elementary-Particle Physics
Cornell University, Ithaca, NY 14853, USA

Abstract:

I summarize highlights of the theory talks presented at the 37th Rencontres de Moriond on QCD and High Energy Hadronic Interactions.

1 Preface

During this conference we heard many impressive talks on a vast variety of subjects. Although QCD is a mature field, very significant progress is still being made. Understanding QCD is not just an academic challenge but impacts on almost all aspects of high-energy physics. In particular, it is a prerequisite for precise measurements of many Standard Model parameters, such as the gauge couplings α_s and α, fermion and boson masses, flavor-changing couplings, and the CP-violating phase of the CKM matrix. Understanding QCD is also important for searches for physics beyond the Standard Model, both via the direct production of new particles and using precision measurements at low energy. Last but not least, QCD is our playground for exploring strongly coupled gauge theories; lessons learned here will help in understanding other strongly coupled theories (i.e., almost any New Physics model, perhaps even gravity).

In this talk I will focus on three sectors of QCD research: core QCD (pQCD, resummation, power corrections, factorization), multi-body problems in QCD (saturation, unitarization, heavy ions), and searches for New Physics and CP violation. Rather than repeating all 39 theory talks of this conference, I will try to put things in perspective and focus on a few recent developments. I apologize to all those whose interesting contributions are only briefly mentioned here because of space (time) limitations.

[a]Supported by the National Science Foundation under Grant PHY-0098631

2 Hard-Core QCD (rated R)

Precise calculations of physical cross sections in QCD pose several theoretical challenges. Recently, significant progress has been made on various fronts, pushing the limits of what is state-of-the-art to a new level of sophistication. Research in this area has focused on three directions: multi-loop amplitudes, resummation of large logarithms, and non-perturbative power corrections. Although rather different in their technicalities, these three major directions go together and form the basis of most precision calculations in QCD, as indicated in Figure 1.

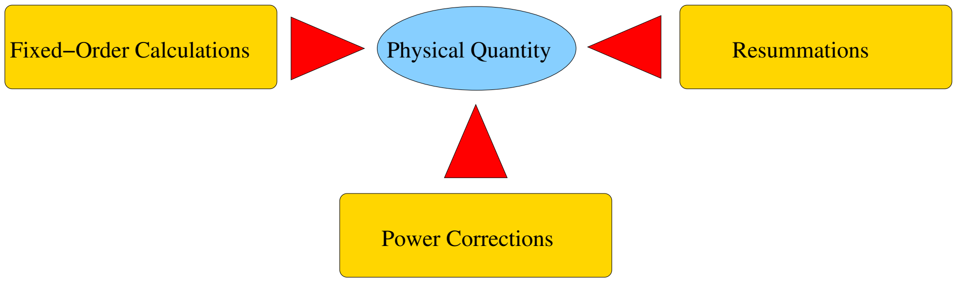

Figure 1: Multi-loop amplitudes, resummation of large logarithms, and non-perturbative power corrections form the basis of modern QCD calculations.

2.1 Scattering Amplitudes Beyond Leading Order

Controlling the scale dependence (and, more generally, the dependence on the choice of the renormalization scheme) in the prediction for a QCD amplitude requires that the calculations be performed beyond the leading order. This requires exact multi-loop calculations of Feynman diagrams. There has been impressive progress in recent years in the calculation of multi-parton scattering amplitudes at next-to-leading order (NLO) and beyond. Examples include jets in e^+e^- and hadron collisions, Higgs production, Drell–Yan production, etc. The challenges faced in such calculations were discussed by Oleari. They are the evaluation of (many) two-loop diagrams, the need for next-to-next-to-leading order (NNLO) splitting functions, the handling of real emissions (soft and collinear cancellations), and finally the implementation of hadronization effects using Monte Carlo generators, also discussed by Weinzierl.

An important example of a NNLO calculation is the inclusive Higgs production at hadron colliders, which was reviewed by Kilgore and Grazzini. The cross section for this process increases strongly when going from leading to NLO, and so a NNLO calculation is required to see whether or not a reliable prediction can be obtained. Such a NNLO calculation becomes feasible after introducing an effective vertex for the Hgg coupling (with the top loop integrated out). The result shows that perturbation theory converges better than expected based on previously available partial resummations. Fortunately, it appears that there is now a reliable prediction for this important discovery process.

2.2 Resummations

While exact multi-loop calculations are indispensable for obtaining precise predictions, in many cases they are insufficient due to the presence of widely separated mass scales. Such scales typically arise when experimental cuts restrict phase space, or when heavy particles are involved. Physical quantities are infrared safe, but large logarithms can arise as a result of incomplete infrared cancellations near phase-space boundaries. Such logarithms lead to a breakdown of fixed-order perturbation theory, making it necessary to resum an infinite number of terms in the perturbation series. While the leading double logarithms are under good control, Salam pointed out that the resummation of the NLO single logarithms still poses significant theoretical challenges. As an example he discussed so-called "non-global" observables, which measure gluon emission only in part of the event. In this case the approximation of independent emissions implies suppression only of primary emissions in the current hemisphere. But for a correct resummation of single logarithms one must also suppress energy-ordered large-angle secondary emissions. Accounting for the non-global logarithms thus needs a change of philosophy.

A semi-numerical method for the computation of single-logarithmic effects due to multiple gluon radiation was suggested by Zanderighi, who presented new predictions for several event-shape distributions (thrust major, oblateness, 3-jet resolution). Novel effects can also arise from the interplay of different types of logarithms. Kulesza explained how the simultaneous resummation of recoil and threshold logarithms in electroweak boson production leads to an interplay of Sudakov suppression and enhancement.

2.3 Power Corrections

Unfortunately, physics doesn't stop with partons, and the presence of hadronization effects complicates our understanding of QCD observables, as indicated in Figure 2. This is what adds the spice to the life of QCD phenomenologists.

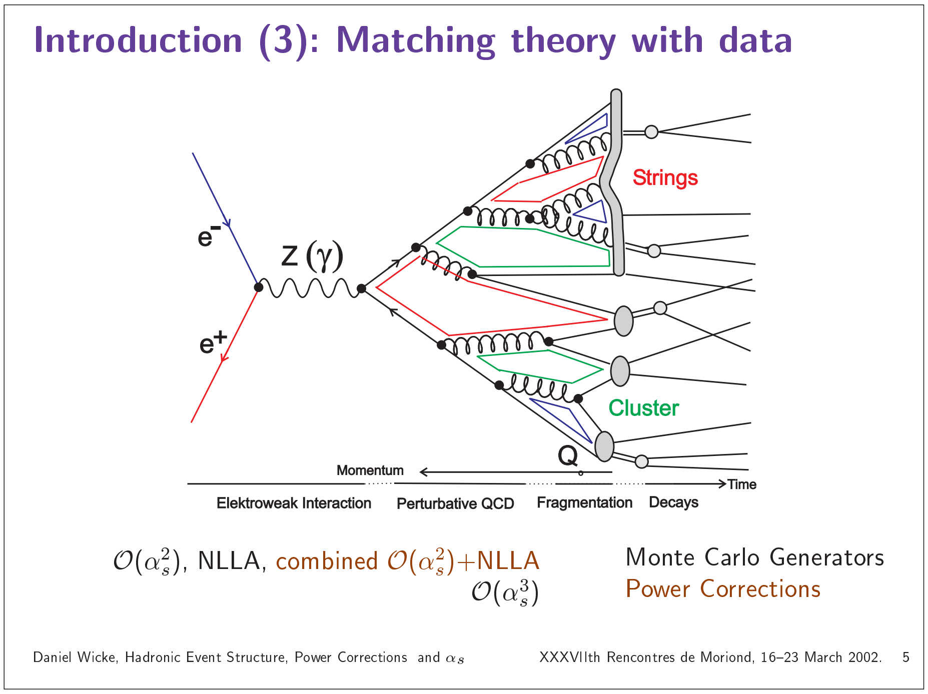

Figure 2: An artistic view of hadronization effects, taken from Wicke's talk.

There are contributions to scattering amplitudes not seen at any (finite) order in perturbation theory. Such non-perturbative effects are often power suppressed by a large scale $\sim (\Lambda/Q)^n$. In simple cases, they can be included using the operator product expansion (OPE), which provides a systematic parameterization of power corrections in terms of matrix elements of local operators. Examples include moments of structure functions discussed by Alekhin, and a gauge-dependent $\langle A^2\rangle/Q^2$ correction in lattice determinations of α_s mentioned by Quintero, which is a lattice artifact that must be subtracted before taking the continuum limit.

There is evidence for an interplay of perturbative terms and power corrections in the sense that often power corrections are found to diminish if higher-order perturbative corrections are included. In general, however, power corrections cannot be made arbitrarily small, and an estimate of their effects is often the limiting factor in theoretical predictions. Much effort is currently being devoted to more systematic studies of power corrections in cases where no local OPE can be applied. For many years, the method of choice was based on the renormalon calculus, by means of which one can study the renormalization-group mixing of (certain) terms of different power in $1/Q$. This method has been applied rather successfully to event shapes in e^+e^- annihilation, which as Marchesini reviewed can be fitted (within large errors) in terms of only two parameters: $\alpha_s(M_Z)$ and $\alpha_0(\mu_I)$. Both Marchesini and Salam stressed, however, that event shapes in deeply inelastic scattering (DIS) are not just a simple extension of e^+e^- but pose additional problems. For instance, the question about the universality (i.e., process independence) of the hadronic parameter $\alpha_0(\mu_I)$ arises. Another interesting application, presented by Qiu, employs the b-space method of Collins, Soper and Sterman to estimate the non-perturbative contribution to resummation formulae for heavy boson production, using a new extrapolation to the large-b region.

More recently, significant progress has been made toward a systematic analysis of power corrections for observables that do not admit an expansion in local operators. Factorization theorems provide a separation of different energy scales (hard, collinear, soft, ultrasoft) to all orders of perturbation theory. Traditionally, they are derived by an analysis of Feynman diagrams using the method of regions. The example of factorization in heavy-quark fragmentation was discussed by Cacciari and Corcella. Another example (which I would have discussed if I had not been convinced to give the summary talk) is the QCD factorization approach to hadronic B-meson decays developed by Beneke, Buchalla, Sachrajda and myself. Alternatively, factorization theorems can be derived by constructing effective field theories for soft and collinear fields. Examples in the context of non-relativistic QCD were presented by Zhang and Vairo. Although not discussed at this conference, I consider the recent development of the soft-collinear effective theory by Bauer, Pirjol and Stewart a significant step forward. This theory has potential applications in many areas of QCD phenomenology. Another interesting development was presented by Gardi, who made the conjecture of a factorization formula for the moments of the structure function $F_2(x, Q^2)$, which is believed to be valid beyond leading power.

2.4 Other Topics

Let me finish this section by mentioning several other interesting talks, which were not related to perturbative QCD. Igi presented a new look at an old subject, the large-s behavior of the π–N cross section, using finite-energy sum rules. Semi-classical quantization of effective string theories and Regge trajectories were studied in great detail by Baker. Tung presented a new generation of parton distribution functions, with uncertainties from the global QCD fit taken into account. New results on Fierz transformations and bosonization were discussed by Jäckel, while Arleo summarized constraints on quark energy loss from Drell–Yan data.

3 QCD in Many-Body Systems (rated *PG-13*)

While exact perturbative calculations are only possible for very simple processes involving few partons, new challenges are met when one attempts to understand the properties of hadronic, nuclear or quark matter.

3.1 Non-perturbative Effects on Structure Functions

Kulagin emphasized that the structure functions of nuclei are not simply multiples of nucleon structure functions, but that several novel effects must be taken into account. These are, in particular, the shadowing effect at small x, nuclear binding and off-shell corrections at intermediate x, and nuclear motion (Fermi motion) at large x. Constraints on nuclear gluon shadowing obtained from DIS data were pointed out by Salgado.

Liuti argued that, at large x and low Q^2 ($W^2 < 2.5\,\mathrm{GeV}^2$), structure functions can no longer be described by standard pQCD evolution, but instead exhibit significant scaling and duality violations. A "semi-hard" cluster mass distribution was introduced, describing the rescattering of the proton remnant ($p \to$ cluster $\to$ partons).

Very interesting effects occur at low x and/or very large A, where saturation and unitarization corrections become important. As Iancu pointed out, parton distributions rise strongly at small x. A linear evolution à la BFKL or DGLAP can explain the rise but leads to inconsistencies such as violation of unitarity. At high density, non-linear effects should limit the growth.

Capella, Kaidalov, Ferreiro and Salgado have suggested a hybrid approach to DIS and diffraction, in which Regge theory is combined with pQCD. Properties of this model were discussed by Kaidalov and Ferreiro. Unitarity is restored by including multi-pomeron exchange. For instance, in *ep* collisions the virtual photon dissociates into a $(q\bar{q})$ fluctuation, which for small transverse size is described by pQCD (color dipole), but for large size is described by Regge phenomenology. This model provides a good description of the HERA data for $F_2(x, Q^2)$.

An alternative approach discussed by Steffen links gluon saturation to unitarity in a model based on the functional integral approach, which relates the transition amplitude to correlation functions of Wilson loops. In that way a unified description of *pp*, $\gamma^* p$ and $\gamma\gamma$ reactions can be obtained.

3.2 The Color-Glass Condensate

A very interesting formal development discussed by Iancu, Itakura and Kharzeev is that of an effective theory, derived from QCD, for (very) high-density gluonic systems at (very) small x. Saturation occurs when the interaction probability becomes $O(1)$, i.e., for $Q^2 < Q_S^2(x)$ with a saturation scale given by $Q_S^2(x) = \alpha_s N_c \cdot (x\, G(x, Q^2)/\pi R_A^2)$. A crucial observation, stressed by Iancu, is that $Q_S^2(x) \sim A^{1/3} x^{-C\alpha_s}$ with a coefficient $C > 0$. It follows that the saturation scale becomes perturbative in the formal limit where $A \to \infty$ and/or $x \to 0$. One then enters a semi-classical regime of weak coupling and large occupation numbers. The high-density gluons correspond to classical color fields in the effective theory, which are radiated by fast-moving partons. In other words, the fast partons are "frozen" in some random color configuration, which the authors have called a "color glass" (in analogy with spin glasses).

Some predictions of this theory have been discussed by Itakura. The gluon distribution in transverse phase space saturates for small $k_\perp$ and falls off over a region $Q_S < |k_\perp| < Q_S^2/\Lambda$, yielding geometric scaling, i.e., $\sigma_{\mathrm{tot}}^{\gamma^* p}(x, Q^2) \to f(Q^2 R_0^2(x))$. Scaling holds over a wide region $0.045 < Q^2 < 450\,\mathrm{GeV}^2$, since $Q_S/\Lambda \sim$ 5–20 is a large scale. Predictions for hadron production at RHIC (multiplicity and rapidity distributions) were presented by Kharzeev.

In the discussion sessions there was much controversy about the phenomenological applications of these ideas, mainly related to the fact that the shadowing corrections predicted by the color-glass theory are larger than those seen in the data. The question was raised whether this might be "a beautiful theory, which however fails when applied to present data"? Future will tell. In my opinion one cannot overemphasize the importance of having first-principles predictions in some limit of QCD, even if this limit is not so close to reality. Therefore, work on the color glass theory is certainly worth pursuing.

3.3 Chiral Phase Transition in χPT

The temperature dependence of the chiral condensate, the order parameter of chiral symmetry breaking, can be studied in chiral perturbation theory using the virial expansion and unitarization, as pointed out by Pelaez. He observes a "paramagnetic effect" (reduction of the critical temperature T_c when going from $n_f = 2$ to $n_f = 3$ light flavors) and a "ferromagnetic effect" (reduction of T_c for $m_q \neq 0$). These analytical results are consistent with lattice computations.

3.4 Other Topics

There were several other interesting presentations related to heavy-ion physics. Pierog discussed the role of screening corrections in numerical simulations. Baryon-number transfer was discussed by Shabelski, while Sousa presented predictions for the baryon and anti-baryon yields obtained in the dual parton model. Finally, Sarcevic presented detailed calculations of prompt photon production for RHIC and LHC.

4 QCD in Flavor Physics and New Physics Searches (rated *General Audience*)

The last few years have seen a revolution in B physics. At this year's spring conferences, BaBar and Belle (and CLEO) have presented yet another round of exciting results, such as updated precision measurements of $\sin 2\beta$, measurements of mixing-induced and direct CP violation in $B \to \pi^+\pi^-$ decays, measurements of (and limits on) direct CP asymmetries in several decay modes, updated results for rare charmless and radiative decays, and last but not least new precision determinations of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$. This wealth of experimental information has triggered a steady improvement of the theoretical tools that allow us to interpret these data in terms of Standard Model parameters. This is non-trivial, because the physics of hadronic weak decays is to a large extent the physics of hadronic bound states.

4.1 Unitarity Triangle

The experimental knowledge about the smallest entries in the CKM matrix (V_{ub} and V_{td}) can be summarized by displaying the unitarity relation $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$ as a triangle in the complex $(\bar\rho, \bar\eta)$ plane. As is well known, CP violation results from $\bar\eta \neq 0$ and so corresponds to a non-vanishing area of the triangle. The so-called "standard constraints" on the apex of the unitarity triangle come from measurements of CP violation in K–$\bar K$ mixing (parameter ϵ_K), $|V_{ub}/V_{cb}|$ in semileptonic decays of B mesons, the neutral B-meson mass differences $\Delta m_{d,s}$ in $B_{d,s}$–$\bar B_{d,s}$ mixing, and $\sin 2\beta$ in $B \to J/\psi\, K_S$ decays. A summary of the resulting constraints is shown in the first plot in Figure 3. With the exception of the $\sin 2\beta$ measurement, the standard analysis is limited by large theoretical uncertainties, which dominate the widths of the various bands in the figure. These uncertainties enter via the calculation of hadronic matrix elements.

With the new data of BaBar and Belle, it is possible to construct the unitarity triangle using novel methods based on charmless hadronic B decays. They are afflicted by smaller hadronic uncertainties and hence provide powerful new tests of the Standard Model, which can complement the standard analysis. The resulting constraints on $(\bar\rho, \bar\eta)$ are independent of B–$\bar B$ and K–$\bar K$ mixing. They are in this sense orthogonal to the standard analysis. Specifically, one combines information from semileptonic B decays, CP-averaged branching fractions in $B^\pm \to (\pi K)^\pm$ decays, and the time-dependent CP asymmetry in the decays $B \to \pi^+\pi^-$. The result of such an analysis, using present data, is shown in the second plot in Figure 3.

There are four allowed regions, two of which remain if we use the information that the measured value of ϵ_K requires a positive value of $\bar\eta$. One of these regions (dark shading) is close to the standard fit. This agreement is highly non-trivial, since with the exception of

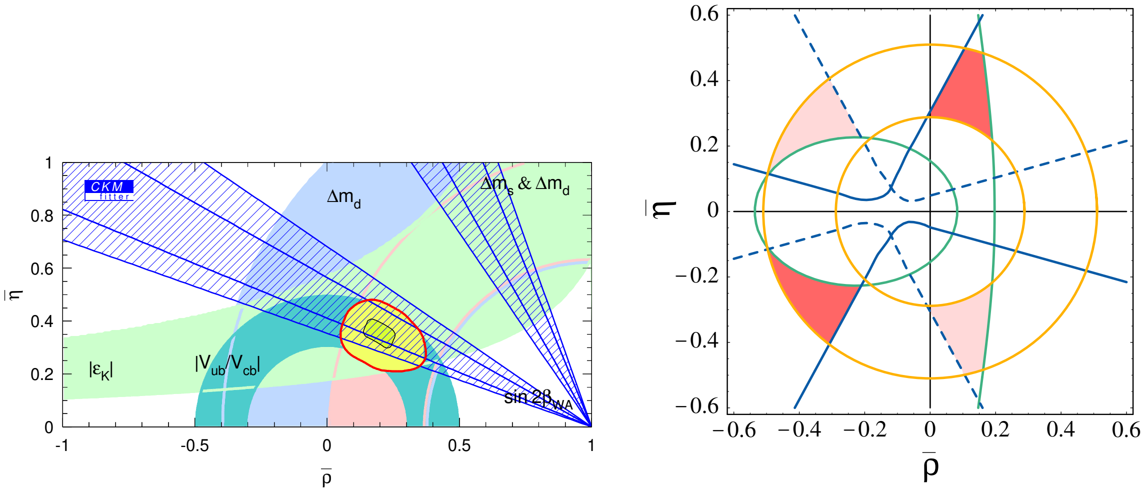

Figure 3: Left: Standard constraints on the apex $(\bar{\rho}, \bar{\eta})$ of the unitarity triangle. Right: Allowed regions in the $(\bar{\rho}, \bar{\eta})$ plane obtained from a novel construction of the unitarity triangle.

$|V_{ub}|$ none of the standard constraints are used in this construction. Interestingly, there is a second allowed region (light shading) which would be consistent with the constraint from ϵ_K but inconsistent with the constraints derived from $\sin 2\beta$ and $\Delta m_s/\Delta m_d$. Such a solution would require a significant New Physics contribution to B–$\bar{B}$ mixing.

4.2 Anomalous Magnetic Moment of the Muon

If you type "FITS SUPERSYMMETRY LIKE A GLOVE" in Google, you find an article published in the science section of the New York Times on Feb. 9, 2001, which is entitled *Tiniest of Particles Pokes Big Hole in Physics Theory.* There we find the following modest statements by some leading physicists:

"The most natural meaning of this kind of indication," Dr. Marciano said, "would be supersymmetry." The observed change in frequency, he said, "fits supersymmetry like a glove."

"It would mean that in describing the world, we would need to add to the equations of the Standard Model," Dr. Wilczek said. "And those additions make the whole thing much prettier, more unified and more beautiful."

And best of all: *"It could lead to a whole deeper understanding of how reality is put together", Dr. Gabrielse said.*

Unfortunately, by now the supersymmetrists have once again to find a reason why SUSY does *not* give a sizable contribution to an observable, since the $(g_\mu - 2)$ anomaly has essentially disappeared with a sign mistake! As everybody knows, the contraction of two ϵ-tensors is proportional to the determinant of the space-time metric: $\epsilon_{\mu\nu\alpha\beta}\, \epsilon^{\mu\nu\alpha\beta} = 24 \det(g^{\mu\nu})$. Since we live in 1 time and 3 spatial dimensions (or so we think), this number is -24. In FORM, this quantity is $+24$ (as explained on p. 14 of the tutorial), and there the trouble begins … (and my polemics stops).

What is left after the dust has settled is a hard QCD problem, since the main uncertainty in the calculation of $a_\mu = (g_\mu - 2)/2$ comes from hadronic contributions such as light-by-light scattering, discussed by Czarnecki. The relevant diagrams shown in Figure 4 are dominated by soft physics and thus cannot be computed reliably. The corresponding uncertainty makes up for a large portion of the difference $a_\mu^{\rm exp} - a_\mu^{\rm th} = (202 \pm 151_{\rm exp} \pm 100_{\rm th}) \cdot 10^{-11}$. While the double and single chiral logarithms in this estimate are sort of under control, the non-logarithmic

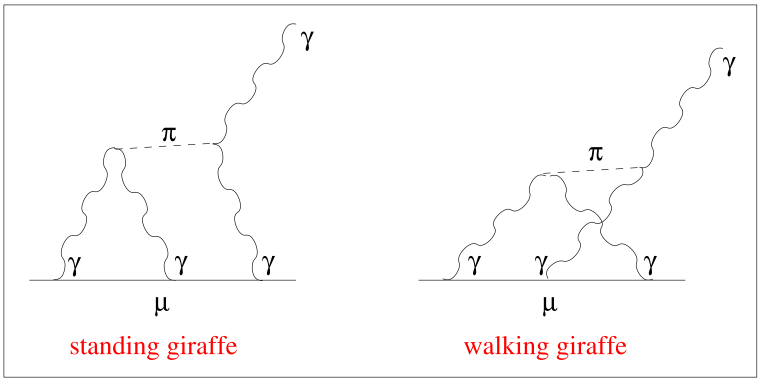

Figure 4: "Giraffe diagrams" entering the light-by-light scattering contribution to the anomalous magnetic moment of the muon.

contribution to light-by-light scattering is largely model dependent. To improve the situation would require a better control over the $\pi\gamma^*\gamma^*$ form factor, which was discussed by Dorokhof and Praszalowicz.

4.3 Black Holes at Future Colliders

Even a QCD conference can nowadays not avoid having a talk on extra dimension. While his presentation was totally unrelated to QCD, Landsberg presented perhaps the most fancy transparencies seen at this conference. If his claim that the LHC will turn out to be a black-hole factory is correct, this machine should be renamed the *Large Hole Producer (LHP)*.

5 Fromages et Desserts

As at any good meeting, a couple of surprises were presented and lively discussed at this conference. I therefore finish with my list of three 3σ effects.

The measurement of the weak mixing angle in deep-inelastic neutrino scattering presented by NuTeV, $\sin^2\theta_W = 0.2277 \pm 0.0016$, deviates by 3σ from the value obtained from the global electroweak fit. If this discrepancy is real (i.e., if it cannot be explained by some underestimated hadronic uncertainty), it could be explained in terms of a left-handed coupling g_L lower than predicted by the Standard Model, whereas the right-handed coupling g_R appears to be about right.

Belle has reported two anomalies at this conference. The first is the observation of a near maximal direct CP asymmetry in $B \to \pi^+\pi^-$ decays, $A_{\rm CP} = 0.94\,^{+0.25}_{-0.31} \pm 0.09$. This is a factor 3 larger than even the most optimistic theoretical predictions. The second Belle anomaly is equally surprising. They see a large direct CP asymmetry in $B^\pm \to \pi^\pm K_S$ decays, $A_{\rm CP} = 0.46 \pm 0.15 \pm 0.02$, which deviates from zero by about 3σ. However, in the Standard Model these decays are almost pure penguin processes and so lack the required amplitude interference, which could result is a large direct CP asymmetry. The Standard Model expectation is $A_{\rm CP} < 3\%$.

If only one of these three 3σ effects will turn out to be real, then perhaps Moriond 2002 will be remembered as the conference where the Standard Model begun to collapse.

Acknowledgments

I wish to thank the organizers of Moriond QCD for the invitation to present this summary talk, and many of my colleagues (you know who you are) for great times on (and off!) the slopes of Les Arcs.