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THE LEP TRAIL TO NON-PERTURBATIVE QCD*

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When giving a summary talk, one always faces a difficult choice. Either she makes a very personal selection of what to present, and integrates it with more material, so as to produce a coherent presentation (and NOT give a summary at all!), or she sticks to some sort of accountant-like report of the various parallel-session presentations (and she ends up with a possibly dull talk).

I find the first alternative more attractive. However, on one hand it doesn't do any justice to at least part of the speakers and, on the other, it is difficult to prepare a proper talk in the few hours available between the last parallel talk and the summary one (not to mention the long-lasting social dinner and its excellent wine).

All in all, I have opted for what I hope to be a reasonable compromise: reporting from all the speakers, but trying to frame the various presentations into some kind of common path.

"Path" being indeed the proper word, because the theme I have chosen is the California gold rush in 1849.

The gold mine of present-day QCD is, of course, a full theoretical calculation also including what is today referred to as "non-perturbative physics" and usually parametrized and/or fitted to data rather than derived from first principles.

After twelve years of running of LEP, and endless tests of QCD (or, rather, of its perturbative regime) we are in a situation akin to the one of the United States around mid-nineteenth century. The eastern part, up to the Missouri-Mississippi river, has been colonized. Our understanding of (and confidence in) perturbative QCD is on a very firm ground. A few wild spots may of course still remain, but by far and large this is now friendly territory.

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Figure 1: The California-Oregon trail, and its alternatives, from the Missouri river to the West Coast.

However, far away, in California, we know the ultimate prize to lie in wait: to be able to make theoretically sound predictions for what we now generically refer to as non-perturbative physics.

"Young men attracted to California's golden opportunities in 1849 faced two major problems. Finding gold was the second. The first was getting there." [1] These young men endured a dangerous four to six month long trip along the so-called California Trail (see Fig. 1). The ultimate goal was clear in their mind. How to get there much less.

It seems to me the path to understanding non-perturbative QCD might live a similar situation. For the trip to California, more than a single trail was traveled, as people tried different options, shortcuts and cutoffs. In the same way, at least two regions of QCD are at present being intensely studied in the intent of better understanding how to reach the final goal. They are the power corrections and the beyond-next-to-leading calculations, and they can be thought of as the North-West pass and the South-West pass route of the path to California.

Before describing in some detail the recent results obtained in these two fields, I should however dedicate some time to more limited, but nonetheless important, aspects which are being studied, and to some experimental results obtained so far.

Let us start at the lower end of the energy spectrum. Graziano Venanzoni [2] reported on experimental results on $\sigma(e^+e^- \to hadrons)$ at centre-of-mass energies below 5 GeV. The precise determination of such a cross section has considerable importance for the physics at much larger energies. In fact, it enters, via the so-called hadronic contribution to the vacuum polarization, the evolution of the electromagnetic coupling $\alpha_{em}(Q^2)$, and consequently the precision physics at LEP1 and LEP2 energies.

Venanzoni also put forward the suggestion of using radiative events at DAΦNE to measure the $e^+e^- \to hadrons$ cross section at different centre-of-mass energies, rather than performing a machine-driven energy scan as customary.

Remaining in the few-GeV energy region, Saverio Braccini [3] reported on the experimental study of resonant states in $\gamma\gamma$ collisions at LEP. Quite interestingly, an e^+e^- collider at high energy can be turned into a powerful tool for performing a hadron collider-like scan of the various states which can be produced in photon-photon collisions. In particular, it has been possible - among other results - to set limits on glueball candidates and to perform analyses of the charmonium states.

Vittorio Del Duca [4] also reported about photon collision studies at LEP. In this case the photons are taken virtual, so as to set a scale hard enough for perturbative QCD to be applicable. The process under consideration is

$$e^+ + e^- \quad \longrightarrow \quad e^+ + e^- + \underbrace{\gamma^* + \gamma^*}_{\llcorner\!\longrightarrow \text{ hadrons}} \tag{1}$$

The speaker and his collaborators have evaluated next-to-leading (NLO) QCD corrections for this process, so as to provide a more reliable theoretical prediction, and therefore a better benchmark against which to compare the experimental results. In this way it will be easier to understand if signals of “BFKL dynamics” are visible in the data. They have found that NLO corrections can be sizeable and should be properly included, but the data are still too sketchy to allow a conclusion about BFKL to be drawn.

A difficult and obscure argument (but not because of this less important and interesting) was discussed by Lorenzo Vitale [5], namely colour reconnections and Bose-Einstein Correlations. These effects are due to the fact that when we have many coloured particle in the final state, like four quarks from W boson decays at LEP2, phenomena related to the quantum uncertainty principle can take place. For instance, since the W decay time is much shorter than the typical hadronization time, we can have a superposition of the two W’s hadronization regions. Hence we can no longer assume they hadronize independently. For all the details the reader is of course addressed to Vitale’s proceedings. Suffice here to say that the conclusion of the extremely complex experimental analyses performed is that the variables studied so far do not have the necessary sensitivity to test the various models for colour reconnections proposed, and no significant effect has been observed. As far as Bose-Einstein Correlations (BEC) are concerned, there is evidence for the existence of the intra-BEC (i.e. correlations within the decay products of a single W) kind, but no signal for the inter-BEC one.

The topics I have summarized so far are somewhat unrelated with each other. They show how varied the studies of QCD can be, and how many spots worth studying always remain even when the main frontier of the research moves forward. I now wish instead to describe in some more detail the topics I consider to represent the mainstream of the westward path to the gold mines.

But first, we must of course carefully make sure we are on the correct path: Günther Dissertori [6] presented an extensive list of experimental measurements and checks on the strong coupling α_s. It plays of course a very important role and can be measured in many different reactions studied at LEP: from very inclusive ones, like the total hadron production rate, to more exclusive ones like the various shape variables. Daniele Bonacorsi [7] also addressed the issue of testing the agreement between theory and experiment, showing comparisons of many distributions for multi-hadronic final states measured at LEP with the theoretical predictions, in many cases produced by MonteCarlo event generators.

In both cases the comparisons are very successful. Hadronic distributions can be matched to a high degree of accuracy by MonteCarlo predictions. While it is true that MonteCarlo models are usually tuned to (a subset of) the data themselves, the widespread agreement does however ensure overall consistency of the theoretical picture. Moreover the precision of the data is good enough to exclude some of the more simplified models, in favour of the ones which include finer details of QCD like, for instance, colour coherence.

The various determinations of α_s extracted from LEP measurements also show a high degree of internal consistency and good agreement with the world average from other experiments. All in all, LEP has brought about a sizeable improvement in the accuracy with which we know α_s, the single largest error on the final measurement being now due to the theoretical uncertainty. Indeed, we have for instance $\alpha_s(M_Z) = 0.1181 \pm 0.0007$ (expt)± 0.003 (theo) from τ decay measurements and $\alpha_s(M_Z) = 0.1181 \pm 0.0036$ (expt) $\pm$ 0.0052 (theo) from shape variables analyses. Both of these results compare very well with the world average, at present $\alpha_s(M_Z) = 0.1184 \pm 0.0031$, and show how big a contribution LEP has given to this determination.

In all these measurements and comparisons, two main obstacles have to be overcome to obtain accurate and meaningful tests. Since we are always comparing an experimental result to a perturbative series in α_s, it is of course essential to make sure that this series gives a reliable account of the "true" theoretical prediction. Our result may instead be approximate on two counts: the series might be poorly converging, and non-perturbative contributions might have been neglected. These are exactly the two problems that have been tackled in the talks I am now going to summarize.

Massimilano Grazzini [8] and Andrea Banfi [9] reviewed the two items which I consider to represent the frontier of today's QCD. Albeit distinct, these two issues represent the two ways we are trying to open our road to a more comprehensive understanding of QCD and of its non-perturbative region.

On one hand, it is of course very important to have the perturbative series under good control. The more exclusive an observable is, the more one can learn from it. But the price to pay is that theoretical calculations become usually more difficult. Until a few years ago next-to-leading calculations (i.e. usually one-loop) were the state of the art. In the last couple of years, however, a great deal of progress has been made towards next-to-next-to-leading (NNLO) predictions. They are particularly important because, if a reliable result in perturbation theory starts being available at NLO, a reliable estimate of the error of the prediction can only be achieved at NNLO. The basic ingredients of a NNLO calculation are *i*) NNLO parton distributions; *ii*) two-loop amplitudes; *iii*) knowledge of the IR behaviour of tree-level and one-loop amplitudes at $\mathcal{O}(\alpha_s^2)$. Most of these are now becoming to be available. The talk of Grazzini gives a full reference list and describes some of the first applications of NNLO technology.

On the other hand, it is easily understandable how useless it can be to push to very

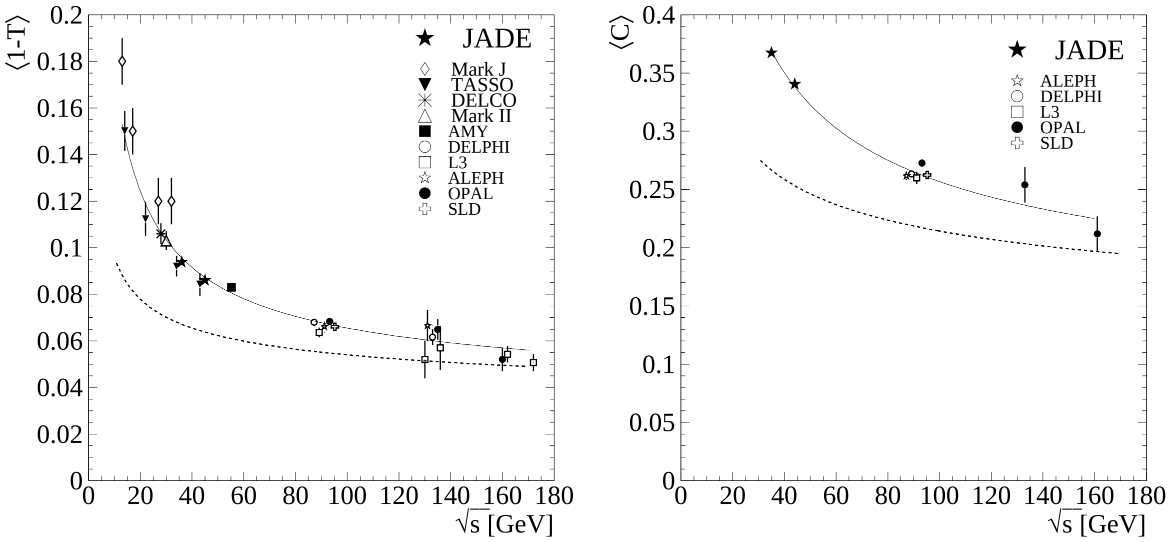

Figure 2: Experimental results for the average value of 1−Thrust and the C-parameter, compared to a purely perturbative prediction (dashed line) and to a calculation also including a power correction term (solid line), see eq. 2.

high accuracy the calculation of a perturbative series, when much more is left which perturbation theory cannot account for. Andrea Banfi started by making clear how important non-perturbative power corrections can be for phenomenology, by showing the plots in Fig. 2. In this figure we can see experimental results for the average value of 1−Thrust and the C-parameter, as a function of the centre-of-mass energy $\sqrt{s}$. One can clearly see the perturbative prediction, given by the dashed line, to fail to describe the data. On the other hand, the inclusion of a power correction of the form

$$\langle 1-T\rangle = \langle 1-T\rangle_{\mathrm{PT}} + \frac{C_T}{\sqrt{s}}, \tag{2}$$

with $C_T \sim 1$ GeV, clearly fits very well the data points. Very similar plots can be obtained for other variables like, for instance, the C-parameter and the heavy-jet mass. An interesting aspect is that, say, the C-parameter results can be fitted with a coefficient $C_C \sim 4$ GeV, and the ratio C_C/C_T can be correctly predicted within a universality hypothesis for $1/Q$ power corrections. The fact that such a hypothesis appears to work, at least at this accuracy level, opens the way for a theoretically rigorous treatment, which tries to explain many observables within a unified framework. One way of parametrizing this universal "building block" is by defining a universal coupling in the infrared region via dispersion relations. The universality hypothesis can be seen to have some shortcomings, and can be somehow extended by introducing a "shape function", that can be used to model non-perturbative effects on many different distributions, and not only mean values.

The important point I wish to stress once more is that these treatments of power corrections are not purely phenomenological, but rather try to stick to rigorous theory as much as possible. The approach is usually that of looking for process independent behaviour, and only as a last resort parametrize incalculable parts in terms of as few as possible measured parameters. The ultimate hope, of course, is to be eventually able to calculate also these quantities from first principles.

I wish to conclude with a quote from Paolo Di Vecchia at Moriond QCD 1995. Paolo concluded his talk on the applications of the Seiberg-Witten duality approach to the non-perturbative region by saying (I quote from memory):

> THERE ARE TWO WAYS OF STUDYING NON-PERTURBATIVE QCD:
> THERE ARE PEOPLE WHO STUDY QCD-INSPIRED MODELS;
> AND THERE ARE PEOPLE WHO STUDY THEORIES DIFFERENT FROM QCD!

In that context he was - I think - cautioning that results were indeed being obtained, but in theories that were not the real QCD.

In the present context, I wish people will more and more concentrate on trying to provide theoretically sound solutions for the non-perturbative problems in real QCD, rather than being tempted to make use of *ad hoc* phenomenological models and short-cuts.

LEP, and its huge collection of high precision data, has certainly played a pivotal role in allowing QCD and its phenomenology to make the transition from a tentative strong interaction theory to a well defined and widely accepted environment, where precision calculations and comparisons are possible. Equally accurate data will be very useful in the future to test the solutions for the non-perturbative region we may come up with. Since no new machine capable of producing them will be available any time soon, it is imperative we try to save the LEP results for future use, in a form where the bias from present-day knowledge of non-perturbative processes is as small as possible.

Acknowledgments. I wish to thank the Organizers for the invitation and Fabrizio Fabbri, who shared the convening of this parallel session and explained to me the details of many experimental results. I am also mostly grateful to all the speakers for their efforts and availability. Needless to say, the responsibility for how this Summary was framed only rests with me.

References

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