

Theoretical summary talk of QCD 2002

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Abstract. This is a summary of the talks on QCD, not including QCD at finite temperature or density (which are discussed elsewhere) presented at the QCD 2002 meeting held at IIT, Kanpur. I have attempted to give only an overview of the talks since the details may be found in the individual contributions.

Keywords. Quantum chromodynamics; resummation; gauge theories.

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1. Introduction

This summary will cover the theoretical talks presented at the QCD 2002 meeting held at IIT, Kanpur from November 18–22, 2002. However this talk will not cover the $T \neq 0$ and $\rho \neq 0$ talks as well as discussions of lattice QCD given at the meeting – these will be discussed in the summary by Rajeev Bhalerao.

The meeting had, apart from the review talks, a very wide variety of contributed papers covering many diverse subjects all purporting to come under the general ambit of quantum chromodynamics. For convenience these talks are roughly divided into the following classes:

- Perturbative QCD
- Resummations
- Effective field theories
- Topological aspects of field theories
- Formal developments in gauge theories
- Nuclear physics issues.

The above division is somewhat arbitrary and done mainly to have some basic organizing principle in discussing the various talks. In many cases a particular talk could well have been placed in a different category.

I will discuss each of these in turn.

2. Perturbative QCD

The search for new physics at future colliders like the LHC necessitates a clear understanding of known physics at these colliders. Soper [1] discussed various scenarios for direct

and indirect searches at the LHC. Direct searches involve, for example, looking for the production of a squark–anti squark pair in a pp collision. In an indirect search, we look for the standard decay channel of $p + p \rightarrow W^+W^- + X$ and compare with a standard physics prediction to check if it matches the predicted cross-section. In both cases, one uses the fact that

$$d\sigma \approx \sum_{a,b} \int_0^1 d\xi_A \int_0^1 d\xi_B f_{a/A}(\xi_A, \mu) f_{b/B}(\xi_B, \mu) d\hat{\sigma}^{ab}(\mu). \quad (1)$$

The parton distribution functions $f_{a/A}$ as well as the partonic cross-section $d\hat{\sigma}$ have been calculated to next to leading order (NLO) for many processes. In the direct searches one calculates the cross-section using the above formula whereas in indirect searches, one looks for discrepancies from the above formula for known particle production.

Another area where one can look for new physics is in jet cross-sections. If there exists a new interaction at some scale Λ , then one can look for new physics, both at scales below as well as above Λ . In the former, one looks for a virtual production of a new particle which decays into one or more jets. One can also look for resonance production or threshold effects at $E = M/2$, where M is the mass of the new particle. In the latter where we are above the scale of new physics, one looks for new types of interaction terms in the Lagrangian, which change, for example, the one-jet and two-jet inclusive cross-sections.

The recent surge of interest in extra dimensions has its effect on QCD predictions at colliders. Thus, if the extra dimensions are rolled up into a little ball of size R , then a quark or gluon is point-like when viewed by a probe with wavelength $\lambda \gg R$ but not when viewed by a probe of wavelength $\lambda \lesssim R$. This suppresses the one-jet cross-section by a form factor .

What is the evidence of new physics, at least in relation to QCD, till now? In measurements of the inclusive jet cross-section at the Tevatron at Fermilab, QCD works up to the highest E_T probed so far.

The D0 data for dijet production at large E_T shows no signs of new physics. However, CDF reported a distinct excess at large E_T which was not seen at D0 and neither D0 nor CDF saw any discrepancy in the dijet angular correlation. However, these discrepancies were finally settled by tweaking the parton distributions, which we will discuss later in more detail.

Any search for new physics at colliders involves a careful estimate of known theoretical errors. The errors appear from many sources:

- The calculations typically are carried out to order α_s^2 and α_s^3 . However the order α_s^4 terms are not necessarily small.
- There are power suppressed corrections of the form Λ_1/E_T and Λ_2^2/E_T^2 coming from hadronization corrections, transverse momentum effects and so on. Rough estimates suggest $\Lambda \lesssim 10$ GeV at Fermilab. This would be significant for jets at Fermilab but not probably for jets at the LHC.
- Parton distribution errors – these arise because for say, $x < 0.3$, we know parton distribution functions (PDF) to be around 10% and therefore jet cross-sections to be about 20%. In fact for larger x values, our knowledge of the gluon distribution is very poor. One approach to quantifying theoretical errors would be to provide PDFs with errors though this is harder than one thinks. There are recent CTEQ PDFs which do provide error estimates.

There are many ways of reducing theoretical errors. The first and most obvious is to do the NNLO calculations for various processes. This is a highly technical subject and enormous progress has been made in recent years. Errors due to PDFs can be reduced by providing error estimates as already mentioned. Another place where errors creep in are in jet definitions in hadron–hadron collisions. Infra-red safe algorithms are not always easy to define and some work needs to go into this.

Finally, it is not enough to do fixed order perturbation theory. Depending on the process one is looking at as well as the phase space region one is studying, it is often necessary to resum large logs. This brings us to the subject of resummations.

3. Resummations

Resummations are needed to supplement fixed order calculations when large logs appear in perturbative QCD calculations [2]. These are of various kinds.

- Scale changes as in evolution of parton distributions through different Q^2 values. Such resummations which involve summing the series $\sum_n \alpha_s^n \ln(Q^2)$ is done through a NLO kernel using the renormalization group. The DGLAP equations are a restatement of this fact. The limiting factor here is the partial information about the kernel at N³LO.
- If we produce a heavy particle (of mass M) in the final state, one may want to know its transverse distribution. At higher orders, these produce large logs of the form $\ln^2(p_T^2/M^2)$ which need to be summed $\sum_n [\alpha_s^n \ln^2(p_T^2/M^2)]$. Techniques for this have been known for a long time.
- In many processes at both HERA and Tevatron, and eventually at LHC, large logs appear at small Bjorken x – these have to be summed $\sum_n \alpha_s^n \ln(1/x)$. This is typically done through the BFKL program. However, [2] points out that small x resummation may not be very important at the LHC.
- There is also a large x problem. These appear when terms of order $\ln^{2n}(1-x)$ appear and need to be summed, near $x \rightarrow 1$. This, in fact, is expected to be a more serious issue at the LHC than the small x resummation.

NLO corrections to ultra-high energy neutrino–nucleon scattering was presented in [3]. It was pointed out that these corrections are not very small as earlier believed, mainly due to the rising gluon distributions at ultra-low Bjorken x . A careful analysis of extending the known parton distributions into the very low x and very large Q^2 region was presented and the effects of reaching the saturation region at very low x were discussed. It was shown that this region contributes very little to the overall size of the cross-section.

4. Effective field theories

Chiral perturbation theory was discussed in [4]. This is the effective field theory of strong interactions at low energies ($\ll 1$ GeV). This employs the non-linear realization of chiral symmetry in the QCD Lagrangian

$$SU(N_f)_L \times SU(N_f)_R \rightarrow SU(N_f)_V,$$

when the quark condensate has a non-zero value. The basic idea is to start with the non-linear sigma model, work out loops (in this non-renormalizable theory) and absorb the divergences into appropriately introduced counter-terms in the Lagrangian at a particular order. The parameters in the Lagrangian are fixed using a single known process and then used to predict other processes.

Chiral perturbation theory has been successful in calculating scattering amplitudes for $\pi\pi \rightarrow \pi\pi$ and $\pi K \rightarrow \pi K$ to fairly high accuracy. The nucleon sector however is far more complicated although results exist for baryon masses, magnetic moments and πN scattering in a limited domain of validity.

More work is also needed in putting chiral perturbation theory on the lattice, and in performing calculations in this formalism at finite T and large N_c .

Some issues in the subject of the chiral quark model was introduced in [5]. This is an effective meson theory inspired by large N_c QCD. The idea once again is to model the effective meson theory using the chiral symmetry of QCD. The starting point happens to be the bosonized Nambu–Jona–Lasinio model. This produces baryons as chiral solitons and mesons are generated from the Bethe–Salpeter equation. This model can be used to obtain structure functions from the Compton amplitude. There is presently qualitatively good agreement with data for the pion structure functions, as also for nuclear form factor, the nucleon structure function F_2 and the polarized structure functions for the proton, g_1 and g_2 . Since the soliton is a localized object, the computed structure functions are frame-dependent and therefore a particular frame has to be picked – which is taken to be the infinite momentum frame. Furthermore, usual DGLAP evolution has to be invoked to sum the usual $\ln Q^2$ terms and give energy dependence to these structure functions.

A model of dihyperons (2 color-neutral 3-quark states) using a chiral dielectric model was presented in [6]. The model contains quarks and gluons, a dielectric (which is the gluon field) and pseudoscalar mesons. It exhibits confinement and chiral invariance and the model has been solved in the mean field approximation to calculate the dihyperon wave function and mass. The mass turns out to be very sensitive to the assumed glueball mass, and is in the range of 2070–2140 MeV. However, as yet, there is no experimental evidence of these six quark states.

A discussion of nuclear effects on the deeply inelastic scattering of electrons, muons and neutrinos on nucleon and nuclear effects was presented in [7]. Various nuclear effects were discussed, including those of Fermi motion, nucleon binding and so on. These effects are also important as inputs in cross-section calculations in neutrino oscillation experiments (for example, in atmospheric neutrino interactions with ^{16}O , ^{12}C).

An integrated approach was presented to study three types of reactions: Quasi-elastic reactions like $\nu_\mu + n \rightarrow \mu^- + p$, inelastic reactions like $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$ or $\mu^- + n + \pi^+$, and deeply inelastic scattering experiments like $\nu_\mu + N \rightarrow \mu^- + X$. This approach has been used to study how nuclear effects modify the standard sum rules like Callan–Gross, GLS etc.

Precise knowledge of nuclear structure functions is essential in modern experiments like A – A and e – A collisions, as in RHIC, EIC and LHC. Unfortunately the method presented in [7] is not suitable at energies above a few GeV. It would be interesting if these methods could be generalized to be applicable at the energies of relevance at today’s colliders.

The issue of the strangeness content of the proton was addressed in [8]. By strangeness content it is meant, specifically, the matrix element $\langle p | \bar{s} \Gamma s | p \rangle$ where the contribution when Γ is 1 or $\gamma_\mu \gamma^5$ is calculated. The sigma and the $SU(3)$ singlet axial matrix element are

found from the trace anomaly and QCD sum rules. The role of anomalies in maintaining flavour symmetry in the presence of large differences in quark masses is discussed and a strong case is made for dispensing with the need for an intrinsic strange quark component in the proton wave function.

5. Topological aspects of field theories

The rich topological structure of non-Abelian gauge theories (NAGT) is now a well-studied field. Instantons and monopoles have become the bread and butter stuff of the topological sector of NAGT.

In this, there were two presentations at this meeting. In [9] it was shown that the non-Abelian ($SO(3)$) gauge field configurations can be completely characterized by certain gauge invariant vector fields. In particular, the topological or monopole charge is characterized by the curl of an Abelian vector potential that is pure gauge. Moreover, the non-Abelian gauge field can be used to capture the topological aspects of the theory without recourse to any Higgs field. Thus, within this framework, the 't Hooft–Polyakov monopole potential is rederived and the magnetic charge is obtained without reference to a Higgs field.

In [10], it was pointed out in a similar approach as above, that vortex and monopole configuration of one-half winding number are present in Yang–Mills theory. These arise from smooth Yang–Mills potentials, and are shown to be generic configurations, unlike the integral winding number configurations of the 't Hooft–Polyakov monopole.

6. Formal aspects of gauge theories

The very technically challenging issue of using interpolating gauges to define non-covariant gauges starting from covariant ones, was discussed in [11]. The importance of a careful treatment of boundary conditions was pointed out since the boundary conditions needed to maintain gauge invariance as the interpolating parameter is varied, and depends very sensitively on the variation of the parameter. Details may be seen in the contribution above.

7. Nuclear physics studies

Some results on scattering of K^+ on $N = Z$ nuclei was presented in [12]. Studies of the nuclear core using K^+ has the advantage that K^+ has a long mean free path below 800 MeV/c. A 15% change in the expected $\sigma_{\text{eff}}^{K^+N}$ is observed which is attributed to the fact that the nucleon core swells while the vector–meson cloud shrinks during the process ('breathing mode'). Using this knowledge, it was found that all the data from ${}^6\text{Li}$ to ${}^{40}\text{Ca}$ fitted nicely, if σ^{K^+N} was reduced at lower energies and increased at higher energies.

8. Conclusions

The meeting was the second such meeting held in India (the first was at the Institute of Mathematical Sciences, in 1998) which brought together all practitioners of QCD in its various forms (perturbative, non-perturbative, topological, finite temperature and density

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including QGP etc.). The earlier meeting had been a purely Indian affair whereas the scope of this meeting was much broader and involved many foreign participants. One of the things that this meeting showed was that there is substantial activity of QCD in India and such meetings are very useful in bringing together people for discussions and setting up collaborations. This is particularly important for a subject like QCD since the number of practitioners in any one place is usually barely one or two and such meetings provide a meeting place where new projects could be discussed and started. I think the momentum created by this meeting should not be allowed to lapse and one such meeting perhaps every alternate year should be held on a regular basis.

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