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THE VIIth BLOIS WORKSHOP: THEORY SUMMARY AND FACTORIZATION ISSUES *

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Abstract

Workshop presentations on elastic and diffractive scattering and other recent advances in hadron physics are summarized. The role of "factorization" in determining parton properties of the pomeron is particularly discussed.

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1 Introduction

Theory presentations at this workshop have covered a wide range of topics. In addition to the traditional topics of elastic and diffractive scattering, we have had a variety of interesting talks coming under the broad umbrella of "Recent Advances in Hadron Physics". These have included review talks on lattice gauge theory, techniques for high-order perturbative QCD calculations, strong interaction effective field theories, the current status of QED and the construction of theories beyond the Standard Model. While I shall briefly describe some topics covered, a "review of reviews" is in no way a substitute for the original reviews which also appear, of course, in this same volume.

Amongst the more traditional topics I will cover are: BFKL physics - higher-order corrections and jet cross-sections; unitarity and eikonal screening - mainly in deep-inelastic diffraction but also in soft diffraction; elastic scattering phenomenology - including real parts, the pomeron intercept and small-t oscillations. I will also discuss the role of "factorization", i.e. both Regge pole factorization and perturbative QCD factorization theorems in the definition of a pomeron structure function and in the formulation of a "parton model" description of diffractive hard physics. I will focus on "one gluon versus two gluons" as illustrating the issues involved.

2 QCD on the Lattice

The "coming of age" of lattice gauge theory, as he called it, was reviewed by G. Kilcup. This maturity is an outcome of many years of improving techniques, algorithms etc. Particularly notable is the relatively recent improvement of lattice perturbation theory via tadpole summation. This process leads to the scaling of the Wilson link variable by $U_\mu \longrightarrow U_\mu/U_0$ where U_0 is the mean-field value. The consequences have included impressive results for the Υ spectrum and spin-splittings. A very accurate value for α_s is obtained

$$\alpha_{\overline{MS}}\,(M_Z) \;=\; 0.1174\;(\pm 0.0024)$$

Since this is more accurate than any other existing "measurement" it surely focusses attention on the assumptions made in refining lattice QCD to this level.

Other new results include values for the strange quark mass. Wilson and staggered fermions give different results, i.e.

$$m_s(\overline{MS}\,, 2GeV) = 100 \pm 21 MeV \quad \text{and} \quad 68 \pm 12 MeV$$

respectively. Clearly there is a remaining need to improve lattice perturbation theory for fermions. Currently a number of groups are working on this problem and several ideas have been proposed, although no method has yet been universally adopted. Kilcup also presented new results for the glueball spectrum, including

$$M_{0^{++}} = 1630 \pm 60 \pm 80 MeV, \quad M_{2^{++}} = 2400 \pm 10 \pm 120 MeV$$

3 Recent Advances in Perturbative QCD Calculations

Perturbative QCD is now applied to a wide range of high-energy jet, photon, heavy quark and weak vector boson production processes. Such processes also inevitably provide the background in searches for new physics and so a detailed understanding of the "known physics" involved is crucial. This is, perhaps, most clearly the case for higher-order contributions to jet physics. As D. Kosower reviewed, the calculation of next-to-leading order QCD contributions has become a forefront theory industry. At next-to-leading order and beyond, sophisticated techniques are essential just to handle the enormous number of diagrams, the large amount of vertex algebra in each diagram and the complexity of loop integrals with large powers of the loop momentum in the numerator. "String-based rules" for organizing diagrams etc. have been particularly successful. The spinor helicity method and supersymmetry decompositions have also been used very effectively.

Most recently, the string-based rules have been superseded by "unitarity-based" rules. "Cut-containing" parts of amplitudes are determined by sewing together on-shell tree amplitudes via unitarity integrals. An explicit dispersion relation is not used, instead the sewing procedure is used only to determine the integral functions that can appear in a given amplitude, along with their coefficients. The restricted number of functions that can appear actually implies that in some cases cut-free pieces are also determined by the sewing process. In supersymmetric theories, for example, entire amplitudes are determined. In general, the remaining (real part) ambiguity of possible "rational pieces" is determined by collinear limits and/or dimensional regularization. Kosower summarized, by noting that a variety of hard calculations have been completed using these techniques and "two loops is the next frontier".

4 Effective Field Theories in Strong Interactions

Effective field theories are constructed by combining symmetry considerations with a power counting algorithm relevant to the kinematic regime studied. The subject was reviewed by M. Wise.

The first example considered was chiral perturbation theory for nucleon-nucleon interactions. Pion exchange is the lowest-order interaction, but a problem arises. Iteration of this interaction leads to ultra-violet divergences which generate a leading-order counter term which should be suppressed according to the power counting algorithm used. As a result the consistency of the formalism is in doubt.

The next effective field theory reviewed was NRQCD. Here an expansion in powers of "v/c" gives surprising predictions for quarkonium production/decay because suppressed powers of v/c can be enhanced by factors of $1/\alpha_s$. The separation of color singlet and octet contributions via an operator product expansion has to be treated with particular care when "end-point" higher-order contributions are involved. In general a careful study of end-point phenomena provides an understanding of the failures of "octet production". Successes of the "octet mechanism" were described in separate talks by G. Zhao and J. Lee.

The third example discussed by Wise was heavy quark effective theory. In this case the limit $m_Q \to \infty$, with v fixed, breaks both spin and flavor symmetries. The remaining light quark spin symmetry can be used to obtain mass differences, sum rules, etc. for heavy quark hadrons. Such sum rules were discussed in detail by M. Bander. In particular Bander noted that a sum rule for heavy meson decay widths works well for charmed quark mesons and even kaons can be successfully treated as heavy quark hadrons!

5 Other QCD Topics

Other "non-diffractive" QCD talks included the following.

- A very interesting all-orders discussion of ultra-violet renormalons in QED (with some discussion of QCD) was presented by T. Lee. He considered the effective charge and showed that, at all orders, the strength of the singularity is independent of the number of exchanges.
- C. Ji suggested that a factorization prescription provided by light-cone quantization might allow perturbative QCD to be used to study exclusive processes at intermediate energies.
- Techniques developed for studying the nucleon-nucleon force were reviewed by R. Vinh Mau.
- Features of multiplicity distributions, including the kinds of pattern recognition that can be used, were reviewed by I. Dremin.
- T. Muta described the four loop calculation of the QCD β-function
- Polarized deep-inelastic scattering was discussed by both Muta and S. Troshin.
- Low-energy form factors were discussed by W. Buck.
- Inclusive B meson decays were considered by Y. Keum while semileptonic B decays were discussed by D. Hwang.

6 The Current Status of Quantum Electrodynamics

T. Kinoshita described how low-energy, high precision, experiments now provide very accurate measurements of the anomalous magnetic moments of the electron and the muon, as well as the hyperfine structure of muonium. He pointed out that the "best measurement" of α_{em} is obtained by demanding the theoretical consistency of measurements of the anomalous magnetic moment of the electron. The result is

$$\alpha_{em}(a_e) = 137.03599993(52)$$

which is an accuracy of 3.8×10^{-9}. Soon α_{em} will be directly measured to an accuracy better than 10^{-9} and the question of whether this fundamental constant is truly universal will be become a significant issue.

7 Beyond the Standard Model

Possible deviations from the Standard Model were the focus of several talks.

7.1 SUSY at the Tevatron

C. S. Kim considered whether the excess jet cross-section seen [1] by CDF at large E_T can be explained by virtual SUSY effects. After including one-loop corrections in the running of α_s and the appropriate modification of parton distributions, Kim concludes that the the CDF effect is too large to be a SUSY effect.

7.2 Large x and Q^2 at HERA

The large x and Q^2 events [2] seen at HERA were discussed by P. Ko. He argued that if R-parity violation is allowed within the minimal supersymmetric standard model, these events can be interpreted as s-channel "stop" production.

7.3 Model Construction

General strategies for extending the Standard Model were reviewed by P. Frampton. He emphasized the need for motivation and testability. As illustrative examples he considered the Left-Right model as explaining the chirality of quarks and leptons, the "331" model as providing an understanding of the existence of three generations, and the SU(15) model as an example which accomodates light leptoquarks without producing proton decay.

8 BFKL Physics

8.1 NLO and the Effective Action

The completion of the calculation of next-to-leading-order corrections to the BFKL kernel was described by L. Lipatov. There are three components of the kernel -

[1] the Regge trajectory of the gluon, [2] the reggeon-reggeon-particle vertex and
[3] the four-reggeon interaction.

NLO corrections to [1] and [2] have been known for several years. The corrections to [3] arise from the production of pairs of gluons (and quarks) separated by a finite rapidity gap.

They are very complicated and have taken a long time to calculate.

Lipatov further described how a gauge-invariant effective lagrangian can be constructed for gluon-reggeon interactions. The production of finite rapidity multi-gluon states can be included in the effective lagrangian, although the NLO results have not yet been derived this way. Additional properties of multi-reggeon states, including the odderon, were also discussed.

There is no doubt that the NLO calculation is a historic contribution to understanding small-x and Regge limit physics in QCD. Not surprisingly, many important questions remain, including the following, some of which will surely be answered soon.

1) What is the new BFKL pomeron intercept, i.e. the new leading eigenvalue?
2) How does the scale that appears in α_s contribute to small-x evolution?
3) What do the NLO corrections tell us about the kinematic range of validity of BFKL physics.
4) Is there any role for conformal symmetry at NLO? In particular, what is the relationship the NLO kernel obtained[3] via t-channel unitarity which, in impact parameter space, is the fourth power of a logarithm of a simple harmonic ratio?

8.2 Jet Physics

BFKL jet production was discussed by V. Kim. When considering dijet production at large rapidity separation, there is an issue as to whether BFKL effects should be included in the parton distributions. Is this double counting? Kim argued that including BFKL in the parton distributions used could explain the small x_T anomaly found by CDF (when data at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1800$ GeV are compared).

9 Eikonal Screening and Unitarity Corrections

The eikonal model is commonly used as an approximation to s-channel unitarity. It was used by several speakers to discuss screening in DIS diffraction and vector meson production.

9.1 Vector Meson Production

U. Maor used a two radii model of the proton to discuss screening corrections to diffractive vector meson production. The values of the radii were chosen to fit the data for ψ diffractive production. Amongst the conclusions are

1) α'_{eff} decreases with Q^2
2) a dip in $\frac{d\sigma}{dt}$ is predicted
3) screening corrections decrease the increase with Q^2 of the pomeron intercept.

Eikonal screening and unitarity, in the context of the general issue of separating hard and soft diffraction, was discussed by V. Petrov. He argued that the HERA data on vector meson production can be fit without the addition of any "hard pomeron" trajectory. The approach to asymptopia is simply delayed at larger Q^2.

9.2 Unitarity Limits In Impact Parameter Space

It was argued by E. Predazzi that diffractive diisociation of a highly virtual photon is predominantly a soft process and that unitarity effects should be as important as in hadronic reactions. Predazzi proposed an impact parameter analysis to detect the onset of "unitarity effects" in the data. The expected effects are most pronounced when alaysed this way. In particular, $\Delta_{eff}(b)$ is predicted to be significantly reduced at small b.

When the energy and impact parameter dependence of the eikonal are factorized, the increase of the cross-section with energy is directly felt at all impact parameters. As a result the unitarity limit is rapidly approached. As was discussed by M. Gay Ducatti, vector meson production at HERA is actually well-fit by such a model. In this case, the unitarity bound is indeed being rapidly approached.

9.3 Diffractive Phenomenology

Unitarity corrections to the large mass diffractive cross-section (i.e. the "triple-pomeron" cross-section) were discussed by C. Tan. If the whole cross-section is fit to the triple pomeron formula with $\alpha_{\mathbb{P}}(0) > 1$ then unitarity problems with energy dependence quickly appear. Eikonal screening can be employed to avoid this and can, perhaps, be used as a basis for "pomeron flux renormalization" phenomenology. However, since very strong screening corrections are invoked, the Regge pole factorization property is lost and, as we discuss further below, the basis for a parton model analysis of the pomeron is also lost.

The eikonal model does not include "unitarity corrections" which occur over partial (finite) rapidity ranges away from the ends of the rapidity interval. A simple example of such processes is multiple diffraction. Another example is the appearance of heavy quark states. Tan refers generically to all such processes as "flavoring". Flavoring can be incorporated phenomenologically by allowing the pomeron intercept to be rapidity-interval dependent. A successful phenomenology can be developed with the Regge pole factorization property of the pomeron retained.

A full phenomenological analysis of diffraction employing secondary Regge trajectories has not yet been carried out (although H1 do subtract the contribution of secondary trajectories when extracting the diffractive cross-section [4]). In fact one would expect comparable phenomenological success to that obtained via flavoring, since including secondary Regge trajectories will produce an effective rapidity-dependent intercept.

10 Elastic Scattering Phenomenology

10.1 The Pomeron Intercept

The soft pomeron intercept $\alpha_{\mathbb{P}}(0)$ plays an important role in HERA diffractive phenomenology. Is the well-known Donnachie-Landshoff result the best fit to all high-energy data? This question was discussed by K. Kang

Inconsistencies amongst data sets suggest that a "filtering" process should be applied. In this process the complete set of all data points is fit first and those data points which are more than 2σ away from the fit determined. These data points are removed and the fit is again performed. This time the data points that are more than 1σ away from the fit are removed. Finally the remaining data points are refit. The vital point is to determine whether the parameters of the fit remain stable during the filtering process.

Kang argued that the Donnachie-Landshoff fit, with exchange-degenerate non-leading trajectories, is unstable under the filtering process. If exchange degeneracy is not imposed, a fit is obtained that is stable under filtering. The resulting pomeron intercept is

$$\alpha_{\mathbb{P}}(0) \;=\; 1.0964 \quad +0.0115/-0.0091$$

which is somewhat higher than the 1.08 of the Donnachie-Landshoff fit.

A phenomenology based on the use of two pomeron poles, as an approximation to the BFKL pomeron, was described by L. Dakhno. This leads to

$$\alpha_{\mathbb{P}}^{(1)} \;=\; 1.29\;, \qquad \alpha_{\mathbb{P}}^{(2)} \;=\; 1.00$$

giving a better fit to the BFKL "hard pomeron" intercept.

10.2 The Real Part

The UA4/2 results for small t scattering, and the related result for the real part of the hadronic amplitude, continue to provoke discussion. To extract the real part it is essential that the hadronic amplitude can be parametrized by a simple exponential.

Both P. Gauron and O. Selyugin argued that the UA4/2 results suggest the differential cross-section actually has very small scale oscillations on top of the exponential behavior. This would, of course, invalidate the conventional extraction of the real part. Gauron suggested such oscillations could be a manifestation of the Auberson-Kinoshita-Martin zeroes that are required by general asymptotic theorems. In conventional models of the elastic scattering diffraction peak the AKM zeroes are simply manifest in the familiar diffraction pattern of dips and maxima which are established experimentally. These represent "oscillations" which are present with a period set by normal hadronic scales. If the oscillations suggested by Gauron and Selyugin are indeed present they indicate the exsatence of a completely new hadronic scale. The period in $\sqrt{|t|}$ is $\approx$ 20 MeV.

A related subject was discussed by M. Block. He considered the real part zero that A. Martin has recently argued should be present in models of the kind conventionally used to fit current data. In the "QCD inspired" eikonal model discussed by Block this zero actually appears at much larger $|t|$ and is, as would surely be generally expected, simply related to the normal diffraction pattern.

Block also noted that the anomalous magnetic moment of the nucleon is always ignored when the real part is extracted via Coulomb interference with the electromagnetic interaction. He estimated that when this effect is taken into account the $\bar{p}p$ real part is lowered by $\approx$ 0.0075 while the pp real part should be raised by the same amount. This shift is significant since it is comparable to the error quoted by UA4/2 on their result. Regarded as a theoretical uncertainty, the effect can be minimized by splitting the interference region into two parts and extracting two experimentally independent results.

11 Factorization and the Pomeron Structure Function

Finally, I would like to discuss a central theoretical issue which is now being confronted experimentally. Can the QCD parton model be extended to the pomeron? The simplest possibility, which comparison of HERA and Tevatron data already seems to rule out[6], would be that the pomeron is like a hadron and has a universal structure function that can be measured in DIS and transported to hadron hard diffraction as illustrated in Fig. 1. In fact, since the pomeron is a virtual exchange, we expect it to be different to a normal hadron. To discuss this we first distinguish two basic "factorization" concepts that are involved.

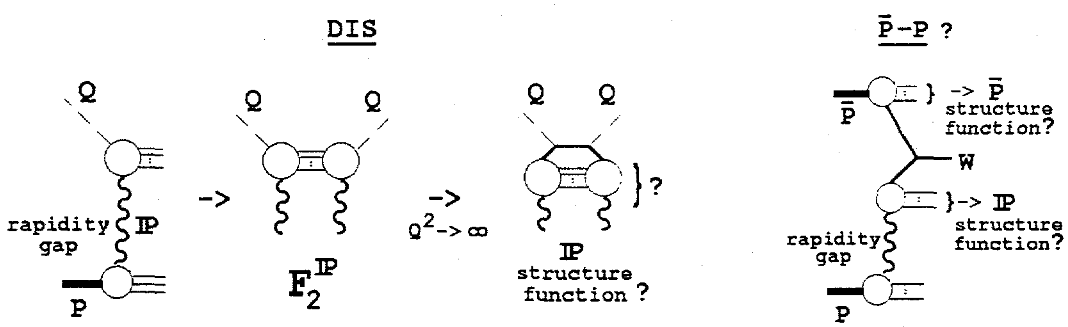

Fig. 1

11.1 Regge Pole Factorization

This follows theoretically from the J-plane continuation of t-channel unitarity discussed in my talk. If the pomeron is (approximately) a Regge pole, the factorization of residues ensures that the first stage of Fig. 1 giving $F_2^{\mathbb{P}}$ is well-defined. (Experimentally it is straightforward to subtract the contribution of secondary reggeons.)

It is not generally appreciated, but that there are two fundamental theoretical reasons why the pomeron should be a Regge pole. Firstly, multi-pomeron t-channel states are well-defined and multiparticle t-channel unitarity (i.e. reggeon unitarity) is satisfied only if the pomeron is a Regge pole. More physically, perhaps, if the parton model has it's origin in infinite momentum quantization (as we discuss below) the pomeron will be a direct manifestation of the "universal wee parton distribution" in a hadron. Wee parton universality requires Regge pole factorization for the pomeron [5].

11.2 Factorization Theorems and the "QCD Parton Model"

Factorization theorems provide a basis for the application of perturbative QCD. If Q^2, say, is a large scale such that $\alpha_s(Q^2)$ is small, perturbation theory can be consistently used provided any infra-red divergences that appear can be factorized into parton distributions. This leads to the familiar "QCD parton model" for inclusive production, i.e. (symbolically) $\sigma \sim \int f_a f_b \, \sigma_{ab}$ where σ_{ab} is a parton cross-section and f_a and f_b are parton distributions. Applying the renormalization group to the factorization process leads to an evolution equation for the parton distributions. Note that factorization theorems, and therefore the QCD parton model, apply only to the leading power in Q^2 (leading-twist).

For Fig. 1 to hold in it's entirety, a QCD factorization theorem must be valid at large Q^2 when $F_2^{\mathbb{P}}$ is defined by Regge factorization. At present there is no indication that both factorization properties can be simultaneously satisfied within QCD. Perturbatively, the pomeron appears as two (reggeized) gluon exchange and is not a Regge pole. Alternatively, one would not expect that a conventional factorization proof applies for the full "off-shell" non-perturbative pomeron.

Regge pole factorization can, perhaps, be by-passed by defining [7] an inclusive DIS cross-section in which the initial proton is required to go forward (if there are no massless particles a rapidity gap must appear at high-energy). At large Q^2 this cross-section may satisfy a factorization theorem and provide a perturbative basis for describing some properties of DIS diffraction. However, since the lowest-order perturbative contribution to the pomeron (i.e. the rapidity gap cross-section) would be two gluon exchange, it is apparent phenomenologically (from the scaling violations in particular) that non-leading twist terms must be equally important in the current experimental cross-section [8]. As a result, it seems that this formulation of a leading-twist "QCD parton model" for diffraction can at best be relevant experimentally at much higher Q^2. (Note that it is also unlikely that the formalism can be extended to hadron scattering.)

11.3 The Infinite Momentum Frame Parton Model

There are strong indications that in processes involving final state hadrons, where a-priori a QCD factorization theorem is much more difficult to prove, some form of the parton model is valid significantly beyond the leading-twist approximation. Most notable is the success of dimensional counting rules in elastic scattering [9] and even, perhaps, the constituent quark model itself [10]. If a broader form of the parton model is valid in QCD we may expect, as we now discuss, that it will be directly visible in the parton properties of the pomeron.

The original parton model formulated by Feynman, Gribov and others, was indeed a broader concept, in many respects, than the "QCD parton model" we have described above. It was based on the (superficial) simplicities of infinite momentum frame quantization. At infinite momentum the constituents of a theory are apparently exposed directly without the complications of the vacuum being present. If the vacuum is non-trivial, as it is of course in QCD, the "wee partons" (with vanishingly small momentum fraction) must somehow carry the vacuum properties of the theory, including confinement and chiral symmetry breaking. This is a very strong requirement which may well not be satisfied in QCD. To carry vacuum properties, the wee partons must certainly be the same in all hadrons (Feynman proposed that the wee distribution should be that of a critical phenomenon). If the pomeron is produced by the interactions of universal wee partons it will also be universal and so will have the regge pole factorization property [5].

In my talk I discussed breaking the SU(3) gauge symmetry of QCD to SU(2). In this case, the Regge pole nature of the pomeron is directly related to the presence of a universal infra-red divergent component of both hadrons and the pomeron. A "reggeon condensate" is produced which is responsible for hadron vacuum properties and, in a sense, is the simplest possible universal wee-parton distribution. If the full gauge symmetry is restored the wee parton distribution (when it is independent of the $k_\perp$ cut-off) is that of the Critical Pomeron. I described how the special properties of the wee parton component lead to the single gluon dominance of the DIS pomeron structure function seen in the H1 analysis [4]. Single gluon dominance will also occur in hadronic hard diffraction. However, the wee parton component of the pomeron plays an even more crucial role. As illustrated in Fig. 2, this component must couple to the hadron state whose hard constituent produces the W. Thus a new hadron structure function is involved, distinct from that appearing in normal parton model processes. In this sense, the $\bar{p}p$ part of Fig. 1 does not hold. However, a more subtle parton model may nevertheless be at work.

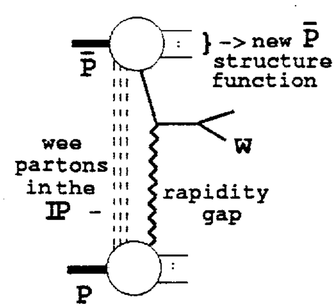

Fig. 2

It is my belief that the picture of the pomeron I presented will eventually be understood as signifying the validity of a deeper form of the parton model in QCD, beyond that of leading-twist factorization theorems. The immediate issue is whether a two-gluon or single gluon picture of the hard component of the pomeron is most successful experimentally.

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