QCD, Theoretical issues.

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Abstract

Today's QCD problems, prospects and achievements are reviewed.

1   Introduction: QCD in 13 puzzles

Exploring the gap between small- and large-distance-dominated phenomena remains the challenge for quantum chromodynamics. QCD is the strangest construction in the history of modern physics. Practically nobody doubts today that it **is** the microscopic theory of strong interactions; at the same time we are practically as vague in addressing the basic questions of this Field Theory as we were 25 years ago.

Puzzle of

Objects: quarks/gluons are the Truth   *but*   hadrons are the Reality.

Rules: sacred   *but*   absent. The QCD Lagrangian is a beautiful construction. At the microscopic level, *bal tosif, bal tigra* [1]. No initiative is allowed, as in a FSU "administrative economy". When it comes to the macroscopic hadron world, on the contrary, no rules seem to exist. As in a market economy, what matters is not the quality of the product, but whether you manage to fool your customer into buying it.

Responsibility: gluons are essential   *but*   quarks dominate. The non-Abelian gluon self-interaction is crucial for asymptotic freedom and thus for causing an infrared instability. However, the hadron world as we know it remains persistently quark-driven.

Scales: finite interaction radius   *but* $m_{gluon} \equiv 0$. No field-theoretical mechanism is known that would protect a theory possessing a strictly massless gluon field from developing long-range forces.

Binding, Relativity, Multiplicity: we deal with strongly interacting practically massless particles, hence one could expect many-body ($N \gg 1$) relativistic ($1-v \ll 1$) dynamics, *but* we see additive quarks, surprising successes of the non-relativistic valence quark model.

Goals & Means: We aim at describing a colourless world in terms of propagation and interaction of coloured quarks and gluons. Strictly speaking, we do not know how to do it consistently, that is how to properly define gluon degrees of freedom, even within perturbation theory. The problem of "Gribov copies" is there and remains unsolved.

Perturbation: $\alpha_s(Q^2)$ is small *but* often all orders are essential. Depending on the problem under consideration, the true perturbative expansion parameter is often enhanced by power(s) of $\log Q^2$.

Evolution: Quantum Field Theory *but* classical probabilities.

Freedom: quarks imprisoned *but* fly away for about 10^3 fm these days.

Confinement: Inevitable *but* elusive. Certain global characteristics of multi-hadron production in hard processes, such as inclusive energy spectra of light hadrons (pions, all charged) in jets, multiplicity hadron flows in the inter-jet regions, show no sign of hadronisation effects.

Coupling: "Strong interactions" *but* $\left\langle \frac{\alpha_s}{\pi} \right\rangle_{\text{infrared.}} \sim 0.2$.

"Confinement? What's the problem? Hasn't it been solved long ago by W. [the name may vary]?" — would be a mean theoretician's response. As a reflection of this attitude, the authors of experimental papers dealing with hadroproduction increasingly often tend to equate QCD with Monte Carlo hadron generators. Not only does time cure: it also tends to put out of focus, for the sake of psychological protection, difficult problems that have resisted head-on theoretical attacks for far too long. We may appreciate the former property of time; we'd better be alarmed by the latter.

Vladimir Gribov, a brilliant physicist and a strong character, had enough curiosity, motivation and stamina to pursue a non-stop 20-year study of QCD confinement, till that night of August 13, 1997, when he passed away.

The founder and the leader of the renouned "Leningrad school of theoretical physics", Gribov belongs to the generation of physicists, now almost extinct, who did not take the Quantum Field Theory (QFT) for granted. Thus he was able to raise heretic questions, putting under scrutiny the very basics of the QFT as we (think we) know it. Let me list for you some of them:

- Are the three approaches — secondary quantisation, Feynman diagrams, functional integrals — really equivalent?

- Does classical topology play any rôle in QFT?

- Can Euclidean rotation be justified and thus a statistical system substituted for QFT in the case of infrared unstable dynamics?

- How should an ultraviolet renormalization programme be carried out in a theory where the physical states do not resemble the fundamental fields the Lagrangian is made of?

- Whether the Dirac picture of the vacuum, with negative-energy levels being occupied and the positive-energy ones being kept empty, applies to quarks?

- How to bind together massless particles?

- Shouldn't the electro-weak symmetry breaking scale and the QCD scale be related with one another by a pion which is an electro-weak point-like Goldstone and, at the same time, a quark-antiquark bound state from the QCD point of view?

In general, the confinement problem is a problem of understanding and describing the physical states of a Field Theory with (unbroken) non-Abelian gauge symmetry. There can be many confinements, that is many solutions to the non-Abelian instability. The core observation made by V.N. Gribov was that *the* confinement, that is confinement in the world we live and experiment in, is largely determined by the fact that practically massless quarks are present in the theory.

Gribov's ideas remain to be discovered, understood and developed.

2   Small x and Confinement (Heron vs. Pomeron)

A message from DIS 97, Chicago:

A rare thing is more damaging to empirical science than an improper name. In perturbative QCD we may discuss the BFKL *approximation*, the BFKL *equation*, BFKL *dynamics* but should restrain from talking about a "BFKL or Hard Pomeron". There are two reasons for that. First of all, the Pomeron (Gell-Mann's name for the Gribov vacuum pole or vacuum singularity) is a reserved word... More importantly, the very term "Hard Pomeron" is nonsensical.

- **Pomeron:** a leading high-energy contribution to elastic hadron scattering amplitudes driven by the leading singularity in the t-channel (complex) angular momentum ω.

- **Hard:** determined by small distances, and therefore perturbatively controllable.

These two word simply don't merge, since the position and the nature of the leading singularity in ω is entirely off the books of perturbative QCD.

2.1   BFKL and confinement

"I am but mad north-north-west:
when the wind is southerly I know
a hawk from a handsaw."

Hamlet, Prince of Denmark

The fact that the behaviour of DIS structure functions at fixed Q^2 and $x \to 0$ is an entirely *non*-perturbative phenomenon, was recently demonstrated, beyond any reasonable doubt, by Camici & Ciafaloni and by A. Mueller.

In Mueller's paper [2] an estimate is given of the range of x beyond which the perturbative treatment (operator product expansion, OPE) breaks down due to diffusion into the small-transverse-momentum (strong interaction) region. Numerically,

$$Y = \ln x^{-1} \ll (2\alpha_s(Q_0))^{-3},$$

with Q_0 the *minimal* of the two scales, to which high energy $s \propto 1/x$ is applied. This leaves no hope for *predicting* the x-behaviour of the initial parton distributions at virtualities as low as 1–2 GeV, and, therefore, the x-behaviour of the DIS structure functions.

Camici and Ciafaloni have shown in [3], in a very nice physically transparent way, that the position and the nature of the leading complex-angular-momentum singularity (Pomeron) depend crucially on the behaviour of the QCD coupling α_s in the infrared region. Read: have non-perturbative origin.

This does not mean that the BFKL analysis and results are nice but irrelevant. We have to come to terms with the fact that the BFKL-predicted increase of cross sections with energy is of little relevance for DIS structure functions. However, in special circumstances it remains a perfectly sound and unquestionable QCD prediction which should be seen experimentally.

Instead of the "BFKL Pomeron" we may say the BFKL **HER**on, a temporary **H**igh-**E**nergy **R**egime of increasing *small* interaction cross sections of *small* hadronic objects.

2.2 Next-to-leading BFKL dynamics

The next-to-leading analysis of the BFKL problem is about to be completed. The necessary ingredients have been computed, in recent years, in a series of highly technical works by Camici, Ciafaloni, Fadin, Kotsky, Lipatov, Quartarolo. What remains to be done is to deduce how the BFKL equation is modified beyond leading logarithms, whether the Regge-Gribov factorisation is respected, how the coupling runs in the BFKL kernel, how much down the energy-growth exponent (the "BFKL intercept") goes. These questions are not easy to answer, even though all the next-to-leading corrections, to this and that, are known. To put it simple, a severe "ideological" problem remains of how to *formulate* the improved answer. For example, the very notion of the BFKL exponent λ is elusive: how to quantify *"asymptotic behaviour"* of a *non-asymptotic* amplitude? (The true asymptotia, as we know, is the soft = non-perturbative Pomeron.)

Let us present the behaviour of the forward amplitude (total cross section) for the scattering of two objects with small sizes $p_t^{-1} \ll 1\text{fm}$ at invariant energy $\hat{s}$ as

$$\text{Heron}(\hat{s}, p_t^2; 0) \propto \left(\frac{\hat{s}}{p_t^2}\right)^{\lambda(\alpha_s(p_t^2))}.$$

(The third argument of H is the momentum transfer along the BFKL-ladder, $t = 0$ for the forward scattering amplitude.)

A *preliminary* result for the Heron "intercept" 1997 is [4]

$$\lambda^{1997}(\alpha_s) = \lambda^{1976}(\alpha_s) \cdot \left(1 - 3.4N_c\frac{\alpha_s}{\pi} - 0.15n_f\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right).$$

Numerically,

$$\lambda = 0.5 \quad \rightarrow \quad \lambda = 0.2 \qquad \text{for } \alpha_s = 0.15 \quad (?)$$

If we close our eyes on the inapplicability of the BFKL Heron to DIS structure functions and boldly translate the next-to-leading BFKL correction into the DIS anomalous dimension, weird results may follow. As was demonstrated by Blümlein & Vogt[1], the gluon splitting yields negative probability, structure functions (a gluon-driven F_L in the first place) start decreasing at small x, and the like [5]. Not that the BFKL-corrected anomalous dimension adopted by B&V was free of criticism [6]. What seems to me a more important shortfall is asking a wrong question. Let DIS SF rest in peace!

The crisis is over. Back to work.

2.3   Two large-and-equal scales

In *ep*-scattering we look at forward jet production (Mueller-Navelet jets) with jet transverse momentum $p_t^2 \simeq Q^2$. This is a two-large-scale problem, and the corresponding cross section should increase with the boson–jet pair energy as

$$d\sigma^{\text{MN}} \propto \text{Heron}(\hat{s}, Q^2; 0), \qquad \hat{s} = Q^2 x_{jet}/x_{Bjorken} \gg Q^2 .$$

In *pp*-scattering we may discuss at least two options. The first is *inclusive* production of a high-invariant-mass pair of jets with large (and comparable) transverse momenta, $s \gg \hat{s} = (p_1 + p_2)^2 \gg p_t^2$. In this case we expect

$$d\sigma^{\text{incl.}} \propto \text{Heron}(\hat{s}, p_t^2; 0) .$$

If we impose a condition of having a *rapidity gap* between the jets, then for rapidities large enough so as to eliminate the Sudakov-suppressed one-gluon exchange, we should have

$$d\sigma^{\text{gap}} \propto \left(\text{Heron}(\hat{s}, p_t^2; -p_t^2)\right)^2 .$$

(Recall, the last argument of the Heron amplitude is the momentum transfer; here $t \approx -p_t^2$.) The latter "double-diffractive" process is a unitarity-shadow of the former (total, inclusive) one.

The Heron may also be searched for in $\gamma\gamma$ collisions in conditions similar to *pp*, as well as in double-hard double-diffractive processes like the "dream process" $\gamma\gamma \rightarrow J/\psi + J/\psi$,

$$d\sigma_{\gamma\gamma \rightarrow J/\psi J/\psi}^{\text{frwrd.,excl.}} \propto \left(\text{Heron}(\hat{s}, m_c^2; 0)\right)^2 .$$

Two comments are due concerning experimental BFKL searches, one optimistic, another rather pessimistic.

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[1] The subject field of the Johannes Blümlein's email message read "suicide of small-x physics"

2.3.1 Mueller-Navelet experiment and "BFKL at hadron level".

ZEUS exercises some caution before claiming that the BFKL-predicted increase of MN-jet cross section is observed experimentally [7]. This caution is well grounded but may be slightly exaggerated. As I understand, it stems from the observation that the standard cascade-type generators (Lepto, Herwig) exhibit an alarmingly large mismatch between the parton- and hadron-level cross sections.

However, this does not necessarily imply that the lacking hadron-level BFKL prediction is really necessary. The very idea of jet finding algorithms was to keep the correspondence between the parton and hadron ensembles. The fact that the MC generators fail to preserve this correspondence may be simply due to their inability to properly estimate the parton level cross section: they can produce the MN-events only as improbable fluctuations.

Indeed, a starting point for BFKL in the MN-experiment is the α_s^2 QCD matrix element. For small values of Bjorken x, production of a forward jet with $p_\perp^2 \sim Q^2$ is accompanied by two more quark jets with transverse momenta of the same order, coming from the Boson-Gluon-Fusion box. None of the standard MC generators based on the logarithmic DGLAP evolution picture ever pretended to embody such high-order configurations with 3 partons at the same hardness scale (corresponding to the two-loop correction to the coefficient function).

Therefore, MC models are likely to be responsible for the mismatch between parton- and hadron-level results, not the physics, which is the BFKL physics in this case.

2.3.2 Azimuthal de-correlation as a sign of the BFKL dynamics.

Accompanying gluon radiation in the production of two jets with large p_t has a double-logarithmic nature. It consists of gluons with transverse momenta distributed logarithmically from small $k_{ti}^2 \ll p_t^2$ up to $k_{ti}^2 \sim p_t^2$ at a given rapidity (energy log) and uniformly in rapidity (angular log). In the inclusive two-jet cross section the double-logs disappear (real and virtual gluons with $k_{ti}^2 \ll p_t^2$ cancel). The result can be expressed in terms of (an imaginary part of) the single-logarithmic forward amplitude known as BFKL.

Studying the $\hat{s}$ dependence of the two-jet cross section, $\hat{s} = x_1 x_2 s$ (keeping the x_1, x_2 fixed as to factor out the initial parton distributions) is a straight road to verifying the BFKL dynamics. However, the cancellation of small-$k_\perp$ gluons mentioned above is not present in less inclusive quantities such as the distribution in the total transverse momentum of the two triggered jets, or in the azimuthal angle between the jets, in particular in the back-to-back region, $\Delta\phi = \pi - \phi_{12} \ll 1$. Sudakov form factor suppression broadens the $\Delta\phi$–distribution. Moreover, this broadening (azimuthal de-correlation) increases with $\hat{s}$ roughly as

$$\frac{d\sigma}{d\phi} \propto (\Delta\phi)^{-1+N_c \frac{\alpha_s}{\pi} \ln \frac{\hat{s}}{p_\perp^2}} .$$

The $\hat{s}$–dependent part of the de-correlation is due to the dynamical suppression of soft gluon emission at "large angles", that is within the broad rapidity interval between the jets. Since in two-jet production at large $\hat{s}$ one-gluon exchange dominates, this coherent radiation is determined by the colour charge of the t-channel exchange, i.e. by that of the gluon. Hence,

the N_c factor in the radiation intensity. It is related with QCD Reggeization of the *gluon* and has little to do with the vacuum-exchange dynamics, that is with the BFKL phenomenon.

There is a hope to see the BFKL-motivated energy dependence of the first *moments* of the ϕ_{12}–distribution, in which the back-to-back region is suppressed [8,9]. This is not impossible. However, the necessity of hunting down single-log effects in the presence of double-logs in the differential distribution makes one feel suspicious about this option of visualising the BFKL dynamics.

2.4   0- and 1-scale diffractive (quasi-elastic) processes

The following HERA chart illustrates the transition from 0– to 1–hard-scale processes:

$\sigma_{\text{tot}}(\gamma p)$	Pomeron
$\sigma_{\text{D}}(\gamma p)$	$[\text{Pomeron}]^2$
$\sigma_{\text{tot}}(\gamma^* p)$	$G(x, Q^2)$
$\sigma_{\text{D}}(\gamma^* p)$	$G^2(x, Q^2)$
$\sigma(\gamma^{(*)} p \to J/\psi + p^*)$	$[G(x, m_c^2)]^2 \to [G(x, Q^2)]^2$
$\sigma(\gamma^{(*)} p \to 2\text{jets}(k_t) + p^*)$	$[G(x, k_t^2)]^2 \to [G(x, Q^2)]^2$

In the second block the rôle of a hard scale may be played by the initial photon virtuality Q^2, a heavy quark mass, or large *transverse momenta* inside a diffractively produced system. (Notice that a large *invariant mass* of the latter does not qualify.)

In the two last cases γp and $\gamma^* p$ (DIS) stand on an equal footing. With increasing photon virtuality, Q^2 may take over from the quark mass or the jet transverse momentum as the hardness argument determining the scale of the gluon distribution.

Here there is no room for the Heron amplitude which applies to the scattering of **two** small objects:

The energy dependence of total (inclusive) cross sections are, for the

scattering of $\begin{cases} \text{Large on Large:} & \textbf{Pomeron,} \\ \text{Small on Large:} & \textbf{Gluon} \text{ (in the proton),} \\ \text{Small on Small:} & \textbf{Heron.} \end{cases}$

The energy dependence of diffractive cross sections are, for the

scattering of $\begin{cases} \text{Large on Large:} & (\textbf{Pomeron})^2, \\ \text{Small on Large:} & (\textbf{Gluon})^2, \\ \text{Small on Small:} & (\textbf{Heron})^2. \end{cases}$

There is an interesting option to ensure two small scales, and thus to approach BFKL dynamics, namely by studying diffractive processes, e.g. $\gamma p \to \rho + p^*$ at sufficiently large

momentum transfer t. Forshaw and Ryskin have recently verified that a finite momentum transfer $|t|$ suppresses large-distance-directed diffusion and thus keeps the BFKL gluon system under perturbative control. For example, one can expect the two-gluon exchange to turn into a fully-fleshed Heron in the $s/t \gg 1$ limit of (double-) diffraction processes with $|t| >$ few GeV^2,

$\gamma p \to \gamma^{(**)} + p^{(*)}$	$2g \to [\text{Heron}(\hat{s}, 0; t)]^2$

where $\gamma^{(**)} = \gamma,\ \rho,\ J/\psi, Z^0$, whatever.

3 Coherence and the Nucleus as Colorometer

Our field has emerged as a result of the digression: natural philosophy $\to$ physics $\to$ quantum physics $\to$ elementary particle physics. The older generation participated in the next step, elementary particle physics $\to$ high energy physics. In the past 20 years we have witnessed the final split

high energy physics $\to \begin{cases} \text{soft physics} \\ \text{hard physics} \end{cases}$.

It is about time to restore the integrity of the subject. **Coherence** is the key-word for re-integrating *soft* and *hard* physics into *high energy physics.*

You can smell new **quasi-classics** in the air when you hear discussions of high gluon densities (hot spots), disoriented chiral condensates, percolating strings, quark-gluon plasmas, the effective colour field of a nucleus, etc. What remains to be done is to condense this smell into a marketable fragrance.

High-energy hadron-scattering phenomena may be more *classical* than we use to think they are. To illustrate the point let us look into Scattering phenomenon and High Energies.

3.1 Scattering

V.N. Gribov produced an argument in favour of Scattering in the Quantum Field Theory framework being an inch closer to Classical Scattering than, paradoxically, that in Quantum Mechanics. He addressed the question "Why does the total cross section rise in the first place?"

Total cross sections of classical potential scattering are typically infinite. For example, the tail of the Yukava potential, $V(r) = \mu \exp(-\mu r)/r$, produces small-angle scattering which makes $\sigma_{tot} = \infty$.

What keeps σ_{tot} finite in quantum mechanics, as we know, is the impossibility to separate a go-straight wave from a diffracted one in the case of too small a scattering angle, $p_\perp = p\theta < 1/\rho$.

QFT, however, gives us such an option by introducing *inelastic diffraction.* The final

state being different from the initial one, the QM argument breaks down, and large impact parameters start contributing to the total cross section. The latter increases with energy due to the decrease of $t_{\min}$ with s.

3.2 High Energies

The hadron as a QFT object is a coherent sum of various configurations. The quantum portrait of a projectile, its field fluctuation, stays frozen in the course of interaction at high energies, so that each fluctuation scatters independently [10]. The total interaction cross section, for example, emerges as a classical (incoherent) sum of cross sections of different configurations inside the projectile hadron h, each of which interacts with its private σ. Introducing the corresponding distribution [11], we may write

$$\sigma_{\text{tot}}^h = \langle \sigma \rangle_h \equiv \int d\sigma\, \sigma \cdot p_h(\sigma)\,.$$

The issue of coherence comes onto the stage when we turn from the total cross sections to more subtle phenomena, **diffraction** being rightfully the first among many.

Let us repeat, an incident proton is a coherent sum of different field fluctuations. Talking hadrons, they are $p \to \pi^+ n \to p$, $p \to K^+\Lambda \to p$, etc. Switching to the quark language, we may talk about three valence quarks at various relative distances, with a correspondingly suppressed or enhanced gluon field between them, that is to picture the proton as being virtually squeezed or swollen. As was noticed by Feinberg and Pomeranchuk, if all the configurations inside the projectile interacted *identically* with the target, such interaction would not induce *inelastic diffraction*. Indeed, in this case the interaction Hamiltonian preserves the coherence of the initial state which, therefore, would scatter elastically but would not break apart producing small-mass diffractive states. In other words, inelastic diffraction is sensitive to the σ-*distribution*. The dispersion of the latter can be directly measured in diffraction on nuclei [12]

$$\left.\frac{\sigma(hA \to h^*A)}{\sigma(hA \to hA)}\right|_{t=0} = \frac{\langle \sigma^2 \rangle_h}{\langle \sigma \rangle_h^2} - 1\,.$$

In general, high energy scattering off nuclear targets provides indispensable tools for studying the internal structure of hadrons.

3.2.1 Proton-penetrator.

The A-dependence of inelastic diffraction gives a classical example of the use of the nucleus as a *colorometer*. If an incident hadron (p, π) *always* interacted strongly with the target in central collisions, inelastic diffraction would be peripheral and therefore its cross section would grow as $A^{1/3}$ (total absorption being an example of an "identical interaction"). Experimentally (FNAL, ISR), $\sigma_D \sim A^{0.8}$. This shows that there are *small* configurations inside the proton that penetrate the nucleus. It is not easy to visualise such a configuration ("penetrator") using the hadronic fluctuation picture. However, it is readily understood in the

quark language: tightly placed valence quarks with abnormally small gluon field between them, due to quasi-local compensation of the colour charge.

The interaction of such fluctuations with the target stays under the jurisdiction of pQCD. Theoretically, there is a nice tool for describing the interaction of a simpler projectile, that is a tight colourless $q\bar{q}$ pair:

$$\sigma(q\bar{q}, A) = \frac{\pi^2}{3} b^2 \alpha_s(b^{-2}) \, xG_A(x, b^{-2}) \, .$$

It relates the interaction cross section of a quark and an antiquark at small relative transverse distance b (inside a real/virtual photon or a meson) with the gluon distribution in the target [13]. Its application to the A- and s-dependence of shadowing, to colour transparency phenomena, and many other intriguing subjects marked the beginning of QCD "Geometric colour optics", the name of the game invented by Frankfurt and Strikman.

3.2.2   Proton-perpetrator.

Thus, diffraction and transparency phenomena can be employed to study squeezed, penetrating hadrons. Their opposite members — swollen hadrons — can also be visualised in scattering on nuclei.

Contrary to the penetrator, the proton-perpetrator should willingly interact with the target. In such configurations "strings" are pulled, colour (or, pion) fields are stronger than typical, the vacuum is virtually broken. So, one can expect an enhanced yield of antiquarks pre-prepared to be released when coherence of the projectile is destroyed. Perpetrators can take responsibility for a bunch of puzzling phenomena observed in pA and ion-ion (AB) collisions, such as baryon stopping, the increase of the Λ/p ratio (Kharzeev) and an amazingly large relative yield of *antibaryons*.

To enhance the rôle of non-typical configurations one should look at the *tails* of various distributions. In particular, by looking into events with *very large* E_t in ion-ion collisions one may see unusual percolated nuclei consisting of merged nucleons, instead of the much too familiar nucleon gas. The quark-gluon plasma state is usually thought to be formed in the collision, which provides a melting pot for individual nucleons. A large E_t-yield is considered to be a sign of the phase transition into such a state, in the course of the collision. Alternatively, very large E_t may be looked upon as a *precondition* for the collision, rather than the result of it: to observe a larger than typical transverse energy yield, we catch the colliding nuclei in rare, confinement-perpetrating, virtually melted configurations a'la the desired plasma state.

In such configurations the yield of Drell-Yan lepton pairs should be higher (extra pions, or antiquarks, around); the reduced yield of J/ψ (heavy traffic) is to be expected.

3.3 Praising J/ψ — a boarder-guard

Heavy onia remain a pseudo-perturbative tool for probing strong interaction dynamics, and a source of surprises at the same time. One of the striking puzzles is offered by the comparison of *medium-dependent* transverse momentum broadening of Drell-Yan pairs, J/ψ and Υ observed in pA collisions: $\ell^+\ell^- : J/\psi : \Upsilon \simeq 1 : 2 : 8$. Future explanation of this puzzle should shade light on the production mechanism of vector $Q\bar{Q}$ onia.

The cross section for J/ψ production in pp collisions is a long-standing problem: the pQCD treatment based on the gluon-gluon fusion into J/ψ plus the final-state gluon, $gg \to J/\psi + g$, is way off.

To avoid an extra α_s-cost the so-called "octet mechanism" was suggested based on producing a colour-*octet* $c\bar{c}$ which then gets rid of colour by radiating off "a soft, non-PT gluon", for free. This quite popular picture, however, misses one essential point: According to the renouned Low-Barnet-Kroll theorem, soft radiation does not change the state of the radiating system. In other words, soft radiation does not carry away quantum numbers. Colour is no exception: paradoxical though it may sound, soft gluons cannot blanch the octet $c\bar{c}$ into a white J/ψ.

Physically, soft gluons are radiated *coherently* by the colour charges involved, and enter the stage, formally speaking, long after the J/ψ formation time. Technically, a soft gluon, that is one with the characteristic logarithmic energy spectrum $d\omega/\omega$, sits, colour-wise, in an *antisymmetric* f_{abc} configuration with its two partners. However, to form a C-odd J/ψ state one needs a *symmetric* d_{abc} colour coupling instead. This is the reason why in the decay channel, $J/\psi \to ggg$, none of the gluons is allowed to be soft: in the small energy domain one has the $\omega d\omega$ distribution rather than the classical $d\omega/\omega$.

There is no doubt that J/ψ is not an entirely small-distance object, not a pure non-relativistic Coulomb $c\bar{c}$ system. Therefore the idea of introducing into the game new non-perturbative matrix elements, in other words, large-distance configurations in the J/ψ field wave function (Braaten et al) is well grounded. What makes me feel uneasy, however, is an accompanying (hopefully, unnecessary) chant of the free-of-charge soft-gluon blanching of the system, which sounds too much like a free lunch.

4 QCD checks 1997

Let me start by citing George Sterman at the DIS conference in Chicago last spring:

> "The study of quantum chromodynamics and the investigation of hadronic scattering are the most challenging problems in quantum field theory that are currently accessible in the laboratory."

4.1   QCD in danger

A decade after the JADE collaboration, which pioneered the e^+e^- jet studies at PETRA, was dissolved, impressive new JADE results have appeared. Reanalysis of the old data was necessitated by the new jet measure (broadening), new jet finder (Durham) and new wisdom (confinement $1/Q$ effects in jet shape observables, see below).

Have a look at few citations from "A study of Event Shapes and Determination of α_s using data of e^+e^- Annihilation at $\sqrt{s}$=22 to 44 GeV", and you will agree that the paper could have been rightfully submitted to a journal on Archaeology.

> "The retrieval of the data eleven years after shutdown of the experiment turned out to be <u>cumbersome</u> and finally <u>incomplete</u>."
>
> "... <u>missing data sets</u> of about 250 events around 22 GeV and about 450 events around 44 GeV. In addition, the original files containing information about the luminosity of different running periods <u>could not be retrieved</u>..."

Even the Acknowledgement section sounds alarming:

> "We thank the DESY computer centre for copying old IBM format tapes to modern data storage devices before the shutdown of the DESY-IBM. We also acknowledge the effort... to <u>search for</u> files and tapes..."

Hadron physics is forever, because today's devotion to high energies is *temporary*. High energies let us watch the vacuum being excited and think about it for some (Lorentz-dilatated) time. Once the vacuum structure has been understood (the most important and the most difficult step still to make), hadron physics will turn back to small and medium energies.

Anyone willing to revisit celebrated ISR data? Forget it! What makes the old experiments dead as a doornail?

1. the data is gone;

2. the tapes are kept somewhere, but cannot be read out (the recording media have changed);

3. the data can be retrieved but nobody remembers how the information storage was organised: the students who knew are no longer around.

To make you shiver, just imagine a similar fate awaiting the LEP-1 data! We will never have anything comparable with the Z-hadron-physics-factory in the future. No one has enough imagination to foresee what sort of questions theoreticians will fancy in ten years from now. It will be a major catastrophe for the field if a well organised representative set of pre-processed LEP-1 data is not available in the future, for theoreticians to probe new ideas against the wealth of hadronic LEP-1 information. A special task force should be established at CERN to carry out the project.

4.2   Basic stuff

George Sterman again:

> "Perturbative methods have been found to be surprisingly, sometimes *amazingly,* flexible, when the *right questions* are asked."

I took the liberty to emphasise the two ingredients crucial for the discussion that follows, which are: "amazing" and "right questions".

LEP and SLAC e^+e^- experiments have reached a high level of sophistication. These days they talk about identified particles in perfectly identified (heavy quark, light quark, gluon) jets. Theoretical expectations of gluon jets being softer and broader are verified, even an elusive C_A/C_F ratio is now well in place. Extracting gluon jets from three-jet events is a tricky business which involves choosing a proper event-geometry-dependent hardness scale to describe the gluon subjet (see, in particular, [14]); e^+e^- annihilation events with gluon jet recoiling against heavy $Q\bar{Q}$ flying into the opposite hemisphere, though rare, provide a bias-free environment for studying glue [15].

The HERA experiments are catching up, the global properties of the struck quark jet (inclusive energy spectra and the scaling violation pattern, KNO multiplicity fluctuations, etc.) converging with those of quark jets seen in e^+e^- [16,17]. What makes the HERA jet studies even more exciting, is an ability to scan through the moderate (and small) Q^2 range in order to shed some light onto the transition between hard and soft phenomena.

A comparative study of the yield of different hadron species in quark and gluon jets is underway. Gluon jets are reportedly richer with baryons (as was expected from the times of hadronic Υ decays). The yield of η and η' mesons in gluon jets is also under focus (L3, ALEPH). The numbers are still uncertain. For example, the relative excess of Λ hyperons was reported from almost none [18] up to 40% [19]. There is no doubt that in the near future the situation will be clarified[2].

From the theoretical side, one warning is due. According to the present-day wisdom, the production of accompanying hadrons with *relatively small* momenta in jets is always *"gluonic"*: it is driven by multiple radiation of soft gluons off the primary hard quark/gluon parton which determining the nature of the jet. The gluon radiation being *universal,* so should be the relative abundance of different hadron species in the "sea".

From this point of view, the difference in the yield of hadrons should be there only in the leading-parton fragmentation region: hadron fragmentation of the valence quark can differ from that of a gluon. So, the crucial question is: whether the differences between the quark- and gluon-initiated jets is concentrated near the tip of the jet. If it is not, that would be evidence for (unexpected) gluon density effects in the dynamics of hadronisation.

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[2]I remember hearing during the conference of a 100% Λ–excess, but failed to find any documented evidence.

4.3 Subtleties

The effects of QCD coherence in hadron flows **in** and **in-between** jets are well established experimentally. Gluon coherence inside jets leads to the so-called "hump-backed" plateau in one-particle inclusive energy spectra. A quantitative theoretical prediction known as the "MLLA-LPHD prediction" was derived in 1984. It has survived the LEP-1 scrutiny; more recently, it has been confirmed by a detailed CDF analysis [20]; these days it is seen also at HERA[16].

This QCD prediction has two ingredients.

MLLA stands for the "modified leading log approximation" of pQCD and represents, in a certain sense, the resummed next-to-leading-order approximation. This step is necessary for deriving *asymptotically correct* predictions concerning multiple particle production in jets. This means that the MLLA parton-level predictions become exact in the $W^2 \to \infty$ limit.

LPHD (local parton-hadron duality) is a hypothesis rather than a solid QCD prediction. It was based on the idea of soft confinement, motivated by the analysis of the space-time picture of parton multiplication, and stated that observable spectra of hadrons should be mathematically similar to the calculated spectrum of partons (the bulk of which are relatively soft gluons).

Experiment does respect LPHD [21].

What makes the story really surprising is that the perturbative QCD spectrum is mirrored by that of the pions (which constitute 90% of all charged hadrons produced in jets), even at momenta below 1 GeV! Moreover, the ratios of particle flows in the inter-jet regions in various multi-jet configurations, which reveal the so-called "string" or "drag" effects also respect the parameter-free pQCD predictions based on the coherent soft gluon radiation picture. These observables are dominated, at present energies, by junky pions in the 100–300 MeV momentum range!

Is there any sense in applying the quark-gluon language at such low scales? What this tells us is that the production of hadrons is driven by the strength of the underlying colour fields, the perturbative gluon radiation probability being a mere tool for quantifying the latter.

There is no need to experimentally verify the MLLA, that is to check quantum mechanics for ca 200 SF/Z^0 (LEP-1). However, it is not difficult to imagine *a world* without "LPHD". The QCD string is a nice image for encoding the structure of the basic underlying hadronisation pattern (Feynman hot-dog). What the experimental verification of LPHD tells us, is that hadronisation is an amazingly soft phenomenon. As far as the global characteristics of final states are concerned, such as inclusive energy and angular distributions of particle flows, there is no visible re-shuffling of particle momenta when the transformation from coloured quarks and gluons to blanched hadrons occurs. This means that the QCD string is not a dynamical object, in a sense: it does not *pull*. It could, if there were no light quarks around.

4.4 Some nasty theoretical remarks

Disproving QCD is no longer in fashion. We are now at the stage of trying to understand QCD and learn to apply it to a broader range of phenomena. To this end we should ask "proper questions" and use proper tools to avoid confusion.

It is not experimentors' fault that the present-day theory is not smart enough to extract valuable information from a given experimental observation. Therefore I had better restrain myself from listing "improper questions" (IQs). But let me mention one famous case: the long-standing problem of the (W+1-jet) to (W+0-jet) Tevatron ratio may belong to the IQ-club. The ratio (W+1-jet)/(W+all) would be a safer quantity to check against the fixed-order QCD prediction.

Two examples of the necessity of "proper tools".

There seems to be a problem with electro-production of large-p_t jets. However, in the region $p_\perp^2 \gg Q^2$ HERA becomes a "Tevatron" with a virtual photon substituted for one of the protons. Hence, a proper tool here would be merging the parton structure of the proton with that of the virtual photon. (A general plea: you don't have a proper Monte-Carlo $\neq$ QCD fails!)

Another example is the E706 finding of very broad distributions over the total transverse momentum of $\pi^0\pi^0$, $\pi^0\gamma$ and $\gamma\gamma$ pairs at Fermilab. The observed phenomenon is similar to that known for almost 20 years in the Drell-Yan pair production. The proper tool here would be all-order double logarithmic Sudakov form factor effects as a substitute for the claimed large intrinsic transverse momentum, $\langle k_t \rangle > 1$ GeV [22].

5 ICS observables and Confinement

The much debated problem of power uncertainties in the perturbative expansion (the concept of renormalons pioneered by G. 't Hooft and A. Mueller) has mutated, all of a sudden, into brave attempts to *quantify* power-behaving contributions to various Infrared and Collinear safe (ICS) observables. This field was initiated and is being pursued by Korchemsky and Sterman, Akhoury and Zakharov, Beneke and Braun, Nason and Seymour, Shifman, Vainstein and Uraltsev, Marchesini and Webber, and many others.

The notion of ICS pQCD predictions ascends to Sterman and Weinberg. ICS are the observables that do not contain logarithms of collinear and/or infrared cutoff μ in pQCD calculations, and therefore have a finite $\mu \to 0$ limit. The contribution of small momentum scales to such quantities should therefore be proportional to $(\mu^2/Q^2)^p$ with $p > 0$, modulo logarithms.

Simply by examining Feynman diagrams, one can find the powers p for different observables. This information is already useful: it tells us how (in)sensitive to confinement physics a given observable is. For example, one can compare the performance of different jet finding algorithms in this respect to see that hadronisation corrections to jet rates defined with use of the Durham jet-finder are expected to be smaller ($1/Q^2$) than those for the JADE algo-

rithms $(1/Q)$[23]. More ambitious a programme aims at the *magnitudes* of power-suppressed contributions to hard cross sections/jet observables.

In the last two or three years first steps have been made towards a joint technology for triggering and quantifying non-perturbative effects in "Euclid-translatable" cross sections (vacuum condensates) and, at the same time, in the essentially Minkowskian characteristics of hadronic final states. In the systematic approach known as the "Wise Dispersive Method" (WDM) [24] new dimension-full parameters $A_{2p,q}$ emerge that normalise genuine non-perturbative contributions to dimensionless ICS observables V,

$$\delta^{(\mathrm{NP})} V \;=\; \sum_{q=0}^{q_m} \rho_q^{(V)} \left(\ln \frac{Q^2}{\mu^2} \right)^q \cdot \frac{A_{2p,q}}{(Q^2)^p} + \ldots$$

Perturbative analysis (PT) provides the observable-dependent factors $\rho_q^{(V)}$ and the leading power p. The non-perturbative (NP) parameters A are expressed in terms of log-moments of the "effective coupling modification"

$$A_{2p,q} \;=\; \frac{C_F}{2\pi} \int_0^\infty \frac{dm^2}{m^2} (m^2)^p \left(\ln \frac{m^2}{\mu^2} \right)^{q_m - q} \delta\alpha_{\mathrm{eff}}(m^2) \,,$$

where p is half-integer or $q > 0$. For different observables, $q_m = 0, 1, 2$. (If $q_m > 0$, the contributions combine so as to produce an answer that does not depend on the arbitrary parameter μ.)

The moments of $\delta\alpha_{\mathrm{eff}}(m^2)$ converge at m^2 of the order of Λ_{QCD}^2. The function α_{eff} is related to the standard QCD coupling via the dispersive integral,

$$\alpha_s(k^2) = \int_0^\infty \frac{dm^2 \, k^2}{(m^2 + k^2)^2} \, \alpha_{\mathrm{eff}}(m^2) \,; \quad \alpha_{\mathrm{eff}}(m^2) = \frac{\sin(\pi D)}{\pi D} \alpha_s(m^2) \,, \;\; D \equiv \frac{m^2 \, d}{dm^2} \,.$$

It is thought to be a universal function that characterises, in an effective way, the strength of the QCD interaction all the way down to small momentum scales. Given this universality, it becomes possible to *predict* the ratios of the Q^{-2p} contributions to observables belonging to the same class p.

Those who believe that a school of little fish can be mistaken for a baby-whale, are aware of mounting evidence in favour of the notion of an infrared-finite QCD coupling[3]. Phenomena range from simple estimates of hadron interaction cross sections in the Low-Nussinov two-gluon model of the Pomeron, all the way up to a detailed sophisticated analysis of meson properties in the framework of the "relativised" potential model of Godfrey and Isgur [25].

Of primary interest are ICS jet-shape observables many of which exhibit the $1/Q$ leading power corrections, $p = \frac{1}{2}$. These include the thrust T, the so called C-parameter, invariant jet masses, the jet broadening B (ln$Q$–enhanced). The energy-energy correlation function in e^+e^- annihilation, EEC(χ), also contains the $1/Q$ confinement contribution (away from the back-to-back region, $\chi \neq \pi$).

A crucial question is that of marrying PT and NP contributions. At the PT level, only the first few orders of the α_s expansion are available, for most observables up to the next-to-leading α_s^2 order. This fact is not too disappointing: a full knowledge of the PT expansion

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[3]A certain irony is necessary since little can be rigourously proved in the game.

would be of little help anyway. Indeed, the series diverge factorially, so that an intrinsic uncertainty of the sum of PT terms is at the level of that very same power Q^{-2p} (infrared renormalon ambiguity).

The price offered in [26] for resolving this ambiguity was the introduction of a matching infrared scale μ_I, above which the coupling is well matched by its famous logarithmic PT expression. The genuine NP $1/Q$ effects can then be expressed in terms of the effective magnitude of the coupling in the infrared region, $\bar{\alpha}_0$,

$$\bar{\alpha}_0(\mu_I) \equiv \frac{1}{\mu_I} \int_0^{\mu_I} dk \, \alpha_s(k^2) \, .$$

Experimental analyses carried out by ALEPH, DELPHI, H1, JADE and OPAL have demonstrated consistency between power terms in the *mean values* of $1-T$, M^2 and, to a lesser extent, B. They pointed at the value for $\bar{\alpha}_0(2\text{GeV})$ in the ball-park of 0.5–0.54[4].

It is clear that the data at *smaller* Q^2 are more sensitive to power effects. Hence, a potential advantage of HERA and the necessity of revisiting JADE and TASSO data. "Parasitic" radiative LEP-1 events $e^+e^- \to Z^0 + \gamma$ also provide a nice opportunity for studying jet shapes at reduced hardness scales. The L3 collaboration has it all, but, for the time being, has conservatively restricted itself to comparison with the MC models only [27].

The most exciting result has emerged from the recent ALEPH study of the thrust *distribution* in the energy range from 14 up to 180 GeV [28]. The quality of the two-parameter fit of the form [26]

$$\frac{d\sigma}{dT}(T) \; = \; \left(\frac{d\sigma}{dT}\right)_{\text{PT}} (T - A/Q) \, ,$$

proves to be *better* than that of the fits that incorporate MC-generated hadronisation effects! The expression in the right-hand-side is the all-order resummed perturbative spectrum *shifted* by A/Q, that very same NP correction term that appears in the mean, $\langle 1 - T \rangle$. The ALEPH result is

$$\bar{\alpha}_0 \; = \; 0.529 \pm 0.002 \pm 0.0034 \, , \quad \text{with } \alpha_{\overline{\text{MS}}}(M_Z^2) \; = \; 0.1194 \pm 0.0003 \pm 0.0035 \, .$$

A free fit to the power in the form

$$\langle 1 - T \rangle = c_1 \alpha_s(Q^2) + c_2 \alpha_s^2(Q^2) \; + \; \frac{\text{const}}{Q^P},$$

with c_1 and c_2 the known PT coefficients, yielded $P \; = \; 0.98 \pm 0.19$, in accord with the theoretical expectation.

It would be premature, however, to celebrate the success of the PT-motivated approach to the NP-physics outlined above. Experimental studies do not yet incorporate the latest theoretical findings. First is the so-called Milan factor, the two-loop renormalisation effect that multiplies the $1/Q$ power terms by the factor 1.8 (for three active quark flavours) [29].

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[4]OPAL came up with a smaller value, the reason being an implementation of a strongly reduced scale of the PT contribution, as substitute for part of the power effect. An experimental verification of the renormalon phenomenon, if you wish.

The good news is that this factor is universal. In spite of this, its inclusion may affect the fits.

On top of it, in the studies of the *jet broadening* (H1, JADE) the wrong relation $\rho_1^{(B)} = \rho_0^{(1-T)}$, instead of the correct $\rho_1^{(B)} = \frac{1}{2}\rho_0^{(1-T)}$, was being used (stemming from an unfortunate misprint in the theoretical paper). Moreover, an improved PT description of the B-distribution is now available [30] and should be implemented.

These reservations do not undermine the main amazing finding that a pure perturbative analysis is capable of predicting the power of the Q-dependence and the magnitude of genuine confinement effects in hard observables in general, and in jet shapes in particular.

With the notion of an infrared-finite coupling gaining grounds, we shall be able to speculate about the characteristic QCD parameter,

$$\frac{\alpha_s}{\pi} \simeq 0.16\,, \qquad \text{versus} \quad \frac{\alpha_{\text{crit}}}{\pi} = \frac{1}{C_F}\left(1 - \sqrt{\frac{2}{3}}\right) \approx 0.137\,,$$

being sufficiently small to allow the application of perturbative language, at least semi-quantitatively, down to small momentum scales. At the same time, it appears to be sufficiently large to activate the Gribov super-critical light-quark confinement mechanism [31].

6 Conclusions

6.1 Theory

QCD is an infrared-unstable theory. Physical states are Swedish miles[5] away from the fundamental objects making up the QCD Lagrangian. In such circumstances we had better be sceptical and put under Cartesian scrutiny our field-theoretical concepts and tools. In particular, we expect quark and gluon Green's functions to have weird analytic properties as they ought to describe *decaying* objects, in a rather unprecedented way. This fact makes the concept of "Euclidean rotation" far from secure and, in principle, undermines the familiar statistical mechanics substitute for Minkowskian field theory (read: lattice).

To understand the structure of the QCD vacuum and that of hadrons in the real world, we have to address the general problem of binding massless particles. The Gribov super-critical confinement remains, at present, the only dynamical mechanism proposed for that.

The 13 puzzles will stay with us for a while longer.

6.2 Phenomenology

The quantitative theory of hadrons, which theoreticians ought to be looking for, gets more and more restricted by the findings of our experimenting colleagues. The news is, that

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[5]1 Swedish mile = 10 km

the small-distance (pQCD) approach, using quarks and gluons, works too often too well. Hadronisation effects, when viewed *globally* seem to behave surprisingly amicably: they either stay *invisible* (inclusive energy and angular hadron spectra) or can be quantified (power effects).

A pQCD-motivated technology for triggering and quantifying genuine non-perturbative (confinement) effects is under construction. These effects show up as power-behaving contributions to Infrared/Collinear-Safe observables, and jet shapes in particular. From within perturbation theory the leading powers can be detected, and the *relative* magnitude of power terms predicted. The absolute values of new dimensional parameters, which we find phenomenologically these days, can be related to the shape of the effective interaction strength (effective QCD coupling) in the infrared region, $\langle \alpha_s/\pi \rangle \sim 0.2$.

6.3 Experiment ("what am I doing this for?")

The epoch of basic QCD tests is over. Today's quest is to understand hadron structure via hadron interactions. The major goal is to study the interface between small and large distances.

The best laboratory for that is "almost-photo-production" at HERA, that is the interaction of small-virtuality photons, $0 < Q^2 < 4\,\mathrm{GeV}^2$, or so, with protons and, hopefully, nuclei.

Diffraction phenomena also target smaller-than-typical hadronic states (e.g., t- and Q^2–dependence of vector meson photo/electro-production).

Studying Drell-Yan pairs, J/ψ and Υ in pp ($p\bar{p}$), pA and AB interactions remains a top priority. In addition to the total production cross sections and the p_t–distributions, various correlation experiments are extremely informative (a famous example being the NA 50 study of the J/ψ yield as a function of accompanying hadronic activity, E_T, in ion-ion collisions).

Jet studies looking for differences in hadron abundances between quark- and gluon-initiated jets should be pursued. Similarity of the yield of hadrons of different species in q and g jets in the "sea" region, if confirmed, would be of major importance for understanding hadronisation dynamics.

Differential jet rates and internal jet-substructure of jets in hard interactions also provide a handle on the soft-hard interface, when one increases jet resolution (by decreasing y_{cut}). To look for genuine confinement effects in such observables, special care should be taken to preserve, as much as possible, the correspondence between parton and hadron ensembles at the perturbative level. To this end the recently proposed modified Durham jet finder, the so-called Cambridge jet algorithm, will have to be used.

6.4 Overall

QCD is on the move, and the pace is good.

Acknowledgements

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