PROCEEDINGS OF SCIENCE

Concluding remarks

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Some remarks on the 40$^{\text{th}}$ anniversary of QCD, "QCD–XL"

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1. Phenomenological Background

In the early 1960's the particle garden has started to turn into jungles. The baryons and mesons known at the time fell into symmetric families of multiplets (octuplets, decuplets) sharing two quantum numbers (spin and parity), but differing in an ordered way in mass, charge, baryon number and strangeness. The mathematical group to fit this complex situation — $SU(3)$, the unitary group of dimension 3 — was proposed independently by Gell-Mann and Ne'eman and named by Gell-Mann "The Eightfold Way".

At the end of one plenary session on strange-particle physics, Gell-Mann strode to the microphone: "*If the information I've heard is really right, then our speculation might have some value, and we should look for the last particles, called, say, Omega-minus*" (1962). Ω-baryon was discovered in 1964 by a team of physicists from Brookhaven, the University of Rochester and Syracuse University using the 80-inch bubble chamber at Brookhaven's AGS. The discovery of *Omega* was the *Alpha* of the New Times — the first true "Ahaa!" of the Quark Model. (The final — decisive — "Ahaa!" came with the discovery of the 4th quark 10 years later.)

2. Theoretical Background

On the theory side, that was a 3D decade: one of Despair, Distrust and Diversions.

Back in 1958, Freeman Dyson (the great man who has always argued that "it is better to be wrong than to be vague") professed that "*the correct meson theory will not be found in the next hundred years*".

The depth of despair can be gauged by the famous punch-line belonging to Lev Landau: "*the Hamiltonian method for strong interactions is dead and must be buried, although of course with deserved honor* (1960). This harsh statement resulted from a traumatic experience that followed the discovery of "nullification" of the effective interaction strength in Quantum Electrodynamics (aka "Moscow zero"). In 1954 Abrikosov and Khalatnikov, equipped by Landau's idea of "leading logarithmic approximation", have performed the first calculation of the running electric charge and running electron mass in QED and found that the effective interaction strength *increases catastrophically* at large momentum scales (small distances) [1].

Landau had a good reason to believe that this phenomenon applies to effective coupling in any Quantum Field Theory (QFT). Actually, the initial calculation contained a wrong sign so that the authors have obtained a "QCD-ish" beta-function! For a couple of weeks Landau and Pomeranchuk enthusiastically discussed with their pupils a beautiful physical picture of charge disappearing when you probe the electron closer and closer to its "core"... The picture has been developed of what we call now *asymptotic freedom*. The error was found (B. Ioffe and A. Galanin) and the write-up of the paper corrected (before publication). The blow was so hard that Isaak Pomeranchuk undertook a three-year-long profound search (1955-58) which has lead him to conclude that QED-ish behavior of the coupling was a general, seemingly inevitable property of any QFT.

Recall that it is the vacuum polarization electron loop in the photon polarization operator that makes the effective charge run with virtuality. As any QFT amplitude, this loop is analytic in the momentum transfer, $t = k^2$. In the crossing channel, the momentum transfer t turns into the annihilation energy (s), and the imaginary part of the loop is proportional to the cross section of production of the fermion pair. The latter got to be positive (unitarity), and this dictates the sign of the logarithm in the running coupling, thus making the "asymptotically free" behavior look impossible. As a result, the 'Moscow zero" seemed to be an inevitable direct consequence of causality (analyticity), relativistic crossing and unitarity.

Not having much trust in microscopic dynamics, in the late 50's–60's theorists undertook a flanking maneuver. The emphasis was put on studying properties of the scattering matrix, as well as on abstracting general structure of a theory of strong interactions that would be able to embed many (an infinite number of) particles — hadrons and hadron resonances.

This path has lead to understanding of many a deep features of relativistic dynamics:

- Detailed scrutiny of the relativistic scattering theory (Pomeranchuk theorem. Froissart bound),
- Exploration of Analytic properties of scattering amplitudes (Dispersion relations),
- Crossing as specific feature of relativistic theory,
- "Bootstrap" and the birth of String Theory (Veneziano amplitude),
- Unitarity and its analytic continuation into crossing channels (Mandelstam),
- Growth of the hadron interaction radius with collision energy as a consequence of Unitarity, Causality and Relativity (Gribov).

The Gribov–Regge theory of complex angular momenta [2] left the following milestones on the road to understanding hadron interactions at very high energies:

- Analytic continuation of partial wave amplitudes onto complex values of the angular momentum,
- Singularities of these partial waves drive the high energy behavior of scattering amplitudes in the crossing channel,
- "Pomeron" as the leading singularity in the vacuum channel,
- Interacting Pomerons as the first example of intrinsic dynamical instability "in the infrared",
- "Scaling regime", and the breakthrough in the theory of second order phase transitions [3].

3. QCD

— *a Lagrangian field theory model in which quark fields are coupled symmetrically to a neutral vector "gluon" field*. These are words from the paper "Advantages of the Color Octet Gluon Picture" [4]. Its abstract read: "It is pointed out that there are several advantages in abstracting properties of hadrons and their currents from a Yang–Mills gauge model based on colored quarks and color octet gluons."

Among Fritzsch–Gell-Mann–Leutwyler commandments were:

- The quarks come in three "colors", but all physical states and interactions are supposed to be singlets with respect to the SU of color.
- Thus, we do not accept theories in which quarks are real, observable particles; nor do we allow any scheme in which the color non-singlet degrees of freedom can be excited.
- Color is a perfect symmetry.
- (We should mention that even if there is a fourth "charmed" quark u' in addition to the usual u, d and s, there are still three colors and the principal conclusions set forth here are unaffected.)

Describing the advantages of having 8 gluons rather than 1, the authors have listed the following reasons:

1. the gluons are now just as fictitious as the quarks
2. hint as to why Nature selects color singlets
3. no mixing between the usual SU_3 and the color SU_3 groups
4. "the bare coupling constant is zero" (referring to Politzer, Gross & Wilczek 1973 preprints)
5. axial anomaly and the absence of the 9th massless pseudoscalar meson in the chiral limit

A number of hints from high energy phenomenology could have been added to the list. Namely, the fact that in high energy hadron interaction processes inelastic breakup dominates over elastic scattering hinted at proton being a loosely bound compound object (constituent quarks). Limited transverse momenta of produced hadrons, rare appearance of large-k_t fluctuations, was signaling the weakness of interaction at small relative distances (asymptotic freedom). Practical constancy with energy of total hadron interaction cross sections, Feynman rapidity plateau in the distribution of produced hadrons hinted at vector (spin 1) nature of the mediating field, should one dare to have applied the notion of a mediating elementary particle to strong interactions (gluon).

Quote/Unquote

If we accept the stronger abstractions like exact asymptotic Bjorken scaling, we may have to assume that the propagation of gluons is somehow modified at high frequencies *to give the transverse momentum cutoff.*

Actually, the authors did not have to accept such a "stronger abstraction": already at that time it had been understood that the Bjorken scaling scaling could not hold exactly in a QFT with dimensionless coupling constant [5].

Likewise a modification at low frequencies *may be necessary so as to confine the quarks and antiquarks permanently inside the hadrons.*

Very well may be. This remains an open question, after all these years.

So, the microscopic dynamics underlying the physics of hadrons was formulated in its entirety and complexity. Thanks to QCD, the QFT has re-established itself as an adequate approach to the multitude of problems of hadrons and their interactions. The 40 years that followed were devoted to applications.

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4. QCD on the move

QCD is on the move. But the driving motivations have changed. No-one is interested any longer in “checking” QCD. Now the goal is to learn how to apply it, to precise, to go broader and get deeper. “Bump Hunting” is still an actuality, as it was in pre-QCD epoch. As well as looking for unconventional objects, one looks for unconventional behavior by putting QCD into extreme conditions like HI collisions.

Physics of hadrons has never been simple. And will never be. At the same time, an explosive progress in analytic calculations of multi-leg QFT amplitudes and multi-loop corrections in recent years provides reappearing themes, motives, constructs, of striking simplicity. Could it be that the deep structure of the underlying QFT dynamics is actually simpler than one dared to think?

Having claimed upper hand in hadron physics 40 years ago, QFT has now a good chance to amuse us with a new breakthrough. It should arise from a deeper scrutiny of the algebraic structure of its most symmetric child — the $N=4$ Super-Symmetric Yang-Mills (SYM) model.

$N=4$ SYM has a good chance to be a *fully solvable* (integrable) field model. Recent theoretical developments hint at an intriguing possibility that this QFT, super-conformally invariant at the quantum level, may admit an all loop solution for anomalous dimensions of its composite operators [6]. QCD would benefit a lot from such a solution, since QCD and $N=4$ SYM share the gluon sector.

The gluon radiation probability has, in general, two terms: “classical” and “quantum”:

$$\mathscr{P}(x)_{A\to A+g(x)} = \frac{C_A\alpha_s}{\pi}\left\{\frac{1-x}{x} + \mathscr{O}(x)\right\}. \tag{4.1}$$

The second — “quantum” — term, vanishes in the small gluon energy limit as $\mathscr{O}(x)$ and is different for different emitters A. At the same time, the first — “classical” — term is *universal* with respect to intrinsic quantum properties of participating objects and the nature of the underlying scattering process: it is only classical movement of the “charged particle” A that matters. It is the essence of the celebrated Low–Burnett–Kroll theorem [7] which states that soft gluon radiation has in fact *classical nature*. It is independent of the quantum state of the radiating parton system, and does not change it. The Eq. 4.1 holds in *all orders* in perturbation theory (provided the “physical scheme” for the QCD coupling is chosen) [8].

Taken globally, the rôle of fermion and scalar fields present in the Lagrangian of the model consists of canceling effects of “quantum” gluons. As a result, quantum corrections manifest themselves neither in the running of the coupling ($\beta(\alpha)\equiv 0$), nor in parton multiplication (no second term in the one-loop anomalous dimension Eq. 4.1).

A complete solution of the $N=4$ SYM QFT should provide us one day with a *one-line-all-order* description of the major part of the QCD parton dynamics.

References

[1] L.D. Landau, A.A. Abrikosov and I.M. Khalatnikov, Dokl. Akad. Nauk SSSR **95** (1954) 497, 773, 1177.

[2] V.N. Gribov, “Strong interactions of hadrons at high emnergies: Gribov lectures on”, Cambridge Univ. Pr., Yu.L. Dokshitzer, J. Nyiri, (ed.), 2009, 477 p.

[3] A. Polyakov, “A view form the Island”, arXiv: hep-th/9211140.

[4] M. Gell-Mann, G. Fritzsch and H. Leutwyler, Phys. Lett. **B47** (1973) 365.

[5] V.N. Gribov and L.N. Lipatov, Sov. J. Nucl. Phys. **15** (1972) 438, 675.

[6] A.V. Belitsky, V.M. Braun, A.S. Gorsky and G.P. Korchemsky, Int. J. Mod. Phys. **A 19** (2004) 4715.

[7] F.E. Low, Phys. Rev. **110** (1958) 974; T.H. Burnett and N.M. Kroll, Phys. Rev. Lett. **20** (1968) 86.

[8] Yu.L. Dokshitzer and G. Marchesini, Phys. Lett. **B646** (2007) 189.