

## Justifying the QCD parton model

G. VENEZIANO<sup>(1)</sup>(<sup>2</sup>)

<sup>(1)</sup> *Theory Division, CERN - CH-1211 Geneva 23, Switzerland*

<sup>(2)</sup> *Collège de France - 11 place M. Berthelot, 75005 Paris, France*

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**Summary.** — I will focus my attention on the two papers I wrote with Roberto and Daniele Amati on justifying the QCD-improved parton model, a very basic tool used every day to estimate a variety of processes involving strong (as well as possibly other) interactions. While doing so, I will also touch on other occasions I had to work—or just interact—with Roberto during more than 30 years of our respective careers.

### 1. – Outline

Here is a schematic outline of my talk:

- Fall 1977
- The QCD factorization theorem
- A conference at Caltech
- A digression on strings and grand-unification
- Roberto and the GGI

### 2. – Fall 1977

In spite of my poor (or perhaps I should say “selective”) memory I remember very well my first encounter with Roberto in September-October 1977. I had been at CERN for a little over one year and had been offered a 5-year staff position. Roberto had just arrived as a new fellow. It so happened that we were both living in a housing complex called Les Vertes Campagnes, in Gex, France. One day we bumped into each other near the local supermarket (perhaps not accidentally since he probably knew my face) and he introduced himself.

That was the beginning of a long friendship soon extended to the families. Our respective daughters, Chiara and Erika, were about the same age (one-year then). I remember, in later years, picking up Erika (on my way back home from CERN) at their new home near Saint Genis, where the two girls had spent the afternoon together after the CERN kindergarden.

Scientific interactions at CERN/TH started soon after, since we found out we had strongly overlapping interests in physics. Roberto was well informed, of course, of the research that had been going on in Rome, in particular about the very important work of Altarelli and Parisi. As to myself, around 1976 I had left, not without regrets, the Dual Resonance Model (by then already interpreted as a string theory) in favor of QCD. I had entered the QCD door via large- $N$ , following up on 't Hooft's 1974 papers on the large- $N$  expansion of QCD.

Two papers that came out in 1977 had attracted my attention:

- The already mentioned Altarelli-Parisi (later DGLAP) reformulation of scaling violations in deep inelastic scattering (DIS) reinterpreting anomalous dimensions as moments of splitting functions having a clear physical meaning;
- The Sterman-Weinberg approach to QCD jets claiming that perturbative QCD (PQCD) can make solid predictions for infrared and collinear-safe quantities (such as the two-jet cross-section in  $e^+e^-$  collisions for suitably defined jets).

Trying to combine both ideas led us quickly to an important breakthrough.

### 3. – Justifying the QCD parton Model (1978)

Together with Daniele Amati we asked ourselves whether those recent developments could allow for a derivation of a QCD-corrected parton model for generic hard processes for which, unlike the case of deep inelastic lepton-hadron scattering, no operator product expansion derivation was available.

To this purpose we had to show that collinear (mass) singularities, when present, can be lumped into some universal quantities such as structure and fragmentation functions. These cannot be calculated in PQCD, have to be measured in one process, but then can be used elsewhere. Instead, their  $Q^2$ -evolution would be calculable through DGLAP (or DGLAP-like for fragmentation functions) equations, together with the infrared and collinear-safe process-dependent part. In a relatively short time we wrote two papers (see fig. 1) I am still (and I believe Roberto was) very proud of.

The technique we applied made heavy use of general theorems on infrared and mass singularities due to T. Kinoshita (1962) and to T.D. Lee and M. Nauenberg (1964). We were facing strong competition from an American group (Harvard-MIT-Caltech) and one member of that Collaboration (H. Georgi) was visiting CERN/TH (see their acknowledgement in fig. 2 to the three of us and to Álvaro de Rújula).

Another “selective” recollection of mine was that Georgi, at some point, was claiming that factorization was badly broken (*i.e.*, not just by power-suppressed terms) at some loop order. We told him that, in our opinion, this was not the case and, eventually, he agreed with us. Thus our papers came to the same conclusion. Eventually, also thanks to work by Al Mueller and others, the QCD-parton model was rigorously (at least by physicists standards) established.

### Relating Hard QCD Processes Through Universality of Mass Singularities

D. Amati, R. Petronzio, G. Veneziano (CERN)

Mar 1978 - 19 pages

**Nucl.Phys. B140 (1978) 54-72**  
(1978)

DOI: [10.1016/0550-3213\(78\)90313-9](https://doi.org/10.1016/0550-3213(78)90313-9)  
CERN-TH-2470

#### Abstract (Elsevier)

Hard QCD processes involving final jets are studied and compared by means of a simple approach to mass singularities. This is based on the Lee-Nauenberg-Kinoshita theorem and on a rather subtle use of gauge invariance in hard collinear gluon bremsstrahlung. One-loop results are easily derived for processes involving any number of initial quarks and/or currents. The method greatly simplifies the computation of higher-order loops at the leading log level and our preliminary results allow us to conclude that the crucial features encountered at the one-loop level will persist. We are thus able to relate different hard processes and to show that suitable ratios of cross sections, being free from mass singularities, can be computed perturbatively, as usually assumed in QCD-inspired parton models. We are also able to relate our universal leading mass singularities to leading scaling violations and to extend therefore the results of the operator product expansion method to processes outside the range of the light-cone analysis. Some delicate points caused by confinement-related singularities (e.g., narrow resonance poles) are also discussed.

### Relating Hard QCD Processes Through Universality of Mass Singularities. 2.

D. Amati, R. Petronzio, G. Veneziano (CERN)

Jul 1978 - 21 pages

**Nucl.Phys. B146 (1978) 29-49**  
(1978)

DOI: [10.1016/0550-3213\(78\)90430-3](https://doi.org/10.1016/0550-3213(78)90430-3)  
CERN-TH-2527

#### Abstract (Elsevier)

Extending previous techniques we obtain at all orders the factorization of mass singularities for every hard QCD process. These appear in a universal factor that can be reabsorbed into the standard parton density. Thus suitable ratios of cross sections can be computed by a perturbative expansion in the running coupling constant. Moreover, at the leading log level we obtain, after explicit cancellation of infrared divergences, the scaling violation of the operator product expansion.

Fig. 1. – Titles and abstracts of the two papers by APV justifying the QCD parton model.

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**Factorization and the parton model in QCD**

R.Keith Ellis<sup>1, \*</sup>

Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics,  
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Howard Georgi<sup>2, \*</sup>, Marie Machacek<sup>2, \*</sup>

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

H.David Politzer<sup>3, \*</sup>, Graham G. Ross<sup>3, \*</sup>

California Institute of Technology, Pasadena, CA 91125, USA

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Some of this work has been done while one of us (H.G.) was a guest at CERN. We gratefully acknowledge useful conversations with many colleagues in the CERN theory division, particularly D. Amati, A. De Rújula, R. Petronzio and G. Veneziano.

Fig. 2. – The paper of our American competitors with an acknowledgement to us and A. de Rújula.

### A Simple Algorithm for QCD Jets

K. Konishi, A. Ukawa, G. Veneziano (CERN)

Jun 1978 - 6 pages

Phys.Lett. **78B** (1978) 243-248  
(1978)

DOI: [10.1016/0370-2693\(78\)90015-1](https://doi.org/10.1016/0370-2693(78)90015-1)  
CERN-TH-2509

#### Abstract (Elsevier)

A proposal is made, giving multiparticle (parton) spectra inside quark and gluon jets in terms of the tree diagrams of an effective field theory. The resulting "jet calculus" satisfies many consistency checks. A first sample of applications is given.

### On the Transverse Spread of QCD Jets

K. Konishi (Rutherford), A. Ukawa, G. Veneziano (CERN)

Oct 1978 - 6 pages

Phys.Lett. **80B** (1979) 259-264  
(1979)

DOI: [10.1016/0370-2693\(79\)90212-0](https://doi.org/10.1016/0370-2693(79)90212-0)  
CERN-TH-2577

#### Abstract (Elsevier)

Recent QCD results on two-particle longitudinal spectra inside quark and gluon jets are extended to the case of a fixed relative transverse momentum  $q_T$  with  $\Lambda \ll q_T \ll 2Q$ . Broad  $q_T$  distributions, especially for gluon jets, are obtained which smooth out automatically the perturbative result and whose integrated versions scale in  $\eta \approx \log(2q_T \text{Max } \Lambda) / \log(Q/\Lambda)$ .

### Probing the Transverse Momentum Structure of {QCD} Jets

R.Keith Ellis (MIT, LNS), R. Petronzio (CERN)

Oct 1978 - 6 pages

Phys.Lett. **80B** (1979) 249-254  
(1979)

DOI: [10.1016/0370-2693\(79\)90210-7](https://doi.org/10.1016/0370-2693(79)90210-7)  
CERN-TH-2571

#### Abstract (Elsevier)

Large logarithms are resummed to give QCD predictions for the differing transverse momentum structure of quark and gluon jets.

Fig. 3. – Titles and abstracts of separate papers by Roberto and by myself (and our respective collaborators) on QCD jets.

**3'1. *Playing with jets.*** – In between those two papers with Roberto and Daniele I also collaborated with K. Konishi and A. Ukawa on jet-branching and transverse spreading (the so-called jet calculus which represents the starting point of future QCD-based Monte Carlo for jet hadronization).

Also Roberto got interested in that kind of problems and worked on it in collaboration with Keith Ellis (see fig. 3). Our collaboration had turned into a sound competition and I remember my feeling of having missed perhaps the most striking application of those results when I saw the paper by Roberto and Keith.

**3'2. *A Conference at Caltech.*** – In 1979 both Roberto and I were invited to give talks at a QCD Conference at Caltech. It was an important event with the participation of important people like Wilczek and Feynman. The latter was in a joking mood, perhaps not so atypical of him. He was teasing Wilczek by quoting Politzer, Gross and ... "a third guy" for asymptotic freedom (to which Wilczek in his talk retaliated by quoting Tomonaga, Schwinger and ... "a third guy" for the 1965 Nobel prize for QED) and he also referred in a very flattering way to Roberto and myself's talks. I remember that he played with names by referring to us as "Veneziano and Petronziano" ...

After his talk I congratulated him and he replied something like: "well, you liked it because I treated you so well". Anyway he invited me to have a beer since he wanted to understand better the jet-branching business. I started to do my best to explain it but then he stopped me saying: "but then you cheated me: what you did is just Altarelli-Parisi!" to which of course I tried to argue we had gone a little further. In his talk he was speaking about a "fraying jet". I did not know the meaning of fraying (it means "che si sfilaccia") so I asked him and he replied "you see is just what your shirt is doing" pointing at it. Was it indeed? I do not know... perhaps he was joking as usual.

## Constraints From String Unification

R. Petronzio (Munich, Max Planck Inst.) , G. Veneziano (CERN)

Jun 1987 - 11 pages

Mod.Phys.Lett. A2 (1987) 707

DOI: [10.1142/S0217732387000872](https://doi.org/10.1142/S0217732387000872)

CERN-TH.4776/87, MPI-PAE-PTH-60/87

### Abstract (WSP)

The incorporation of a standard model with  $n$  generations and softly broken  $N = 1$  supersymmetry in a string theory of the heterotic type implies relations among the string scale, the compactification scale, the Planck mass and various couplings. We study these constraints, including running effects through two loops, and obtain severe limitations on possible consistent string unifications by requiring string loops not to be totally out of control.

Fig. 4. – Our paper on unification and string theory.

## 4. – Some ten years later

Almost 10 year later we wrote another paper together: the 1st string revolution (1984) had taken place and gravity had become part of the game for particle theorists. We wrote a rather simple paper where we tried to put together the so-called “anti-unification” idea of Maiani, Parisi and Petronzio with the one of grand<sup>2</sup> unification (I put a square to indicate that, unlike in usual Grand-Unification, in string theory also gravity is unified with the other three fundamental interactions).

By then, Roberto was back in Rome (Tor Vergata) heading for a brilliant career in scientific research and management. As member, for a few years, of INFN’s “Consiglio di Valutazione Interna (CVI)” I could witness his skills as deputy director under Enzo Iarocci. It was pretty obvious to me that he would become the next director of INFN.

Incidentally, Roberto once confessed to me that he had been quite disappointed by not having been offered a permanent position at CERN after having been there as a fixed-term staff member. He even knew that in the tough decision we had to make, I had voted for his competitor. But never took this personally against me.

## 5. – Roberto and the GGI

As I stressed recently at the Giuseppe Marchesini Memorial Conference (19.05.2017) we owe the birth of the Galileo Galilei Institute (GGI) in 2005 mostly to three colleagues (two of them no longer with us):

Pino Marchesini (then head of INFN’s Gruppo IV), for his vision, and stubborn optimism;

Roberto Casalbuoni (then head the Florence INFN Section) for taking care so well of all the local logistics;

And last but not least to Roberto (then President of INFN) for pushing through and sealing off successfully the project.

Shortly after the launch of GGI Roberto made a nice gesture towards me. He asked me to become a sort of general supervisor of the GGI workshops. I had to attend a substantial fraction of each workshop and come out with comments and suggestions about its implementation. INFN would rent for me an apartment in Florence for the duration of the contract (that went on for almost 5 years) and a small salary. It was for me a nice and interesting experience to be back to my hometown (left forty years earlier) for extended periods.

**6. – Our last encounter**

The last time I met him (just outside a supermarket in St. Genis) he looked great and as full of energy as ever. It must have been shortly before the tragedy. . . News of his terrible accident, and then of his passing away, came as a real shock to the whole high energy community. We lost a great physicist, a very capable and dedicated science-policy leader and, above all, a dear friend to so many of us.

Thank you Roberto for all you have given us!