COLLOQUIA: LaThuile11

Heavy quarks, from discovery to precision

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Summary. — The discoveries of the heavy quarks are briefly reviewed, with a focus on the role played by Mario Greco in the interpretation of the experimental observations, and on his contributions to heavy quark precision phenomenology.

PACS `12.38.-t` – Quantum chromodynamics.
PACS `14.40.Pq` – Heavy quarkonia.
PACS `14.65.-q` – Quarks.

1. – Mario's charm

In November 1974 two experimental groups simultaneously announced the discovery of a new resonance. The collaboration led by Sam Ting [1] at the Brookhaven National Laboratory and the one led by Burton Richter [2] at the Stanford Linear Accelerator Laboratory agreed on all the key characteristics of the new particle, but its name. Since the latter is not consequential, we shall rather focus here on its mass, at $3\,\mathrm{GeV}$ significantly larger than previously observed hadronic resonances and—more importantly—its total width, estimated at less than $1.3\,\mathrm{MeV}$ in [2], a surprisingly small value for a hadronic resonance. Appelquist and Politzer [3] and De Rujula and Glashow [4] are credited with the first interpretation of the new particle (eventually called J/ψ) as a bound state of the previously unobserved charm quark and its antiquark. The relatively large mass of the new quark ($\sim 1.5\,\mathrm{GeV}$), together with the asymptotic freedom property of QCD, could elegantly explain the very small observed width.

Mario Greco was 33 years old and en route to SLAC for a seminar when the news of the discovery broke. Once at destination he was able to gather the available details, notably the mass of the resonance, and forward them to Frascati, where the observation could immediately be confirmed by the ADONE e^+e^- collider [5]. Mario then flew to Mexico City for a planned visit, and once there he learnt about the discovery of the ψ' through the local press. In collaboration with C. A. Dominguez he quickly published a paper [6] (fig. 1). Working within the Extended Vector Meson Dominance (EVMD) approach [7], and using the scarce experimental data available about the new ψ_n resonances, they were able to derive their total contribution to hadron production in e^+e^- collisions.

Charm, EVDM and Narrow Resonances in e⁺e⁻ Annihilation.

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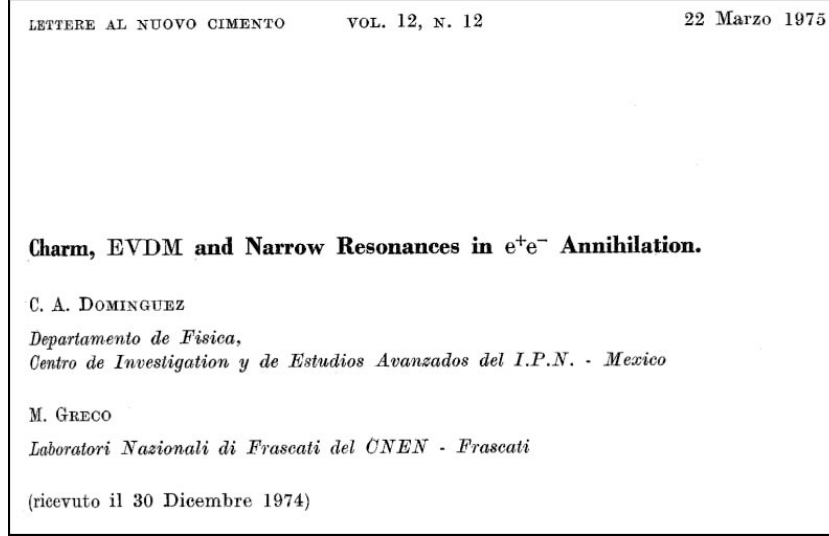
(ricevuto il 30 Dicembre 1974)

Fig. 1. – The front page of the Dominguez-Greco [6] paper interpreting the observation of the J/ψ as a charm-anticharm vector bound state. The typo in the title, EV**D**M rather than EV**M**D (a clear indication of how hectic those times must have been), bears fortunately no relation with the accuracy of the paper.

They wrote

$$R = \frac{\sigma(e^+e^- \to \gamma \to \text{hadrons}) + \sigma(e^+e^- \to \psi_n \to \text{hadrons})}{\sigma(e^+e^- \to \gamma \to \mu^+\mu^-) + \sigma(e^+e^- \to \psi_n \to \mu^+\mu^-)}$$

(1)
$$= R_{\text{normal}} + R_{\text{charm}} \simeq 2.5 + 1.2 = 3.7.$$

The resulting increment for the R ratio was in fair agreement with experimental data, and allowed them to interpret the newly observed resonances: "*...one is naturally led to think of the new narrow resonances as charm-anticharm vector mesons*".

2. – Mario's beauty

A few years later it was the turn of another quark to make its appearance in the form of a new resonance. In 1977 the collaboration led by Leon Lederman observed a peak around $9.5\,\text{GeV}$ in the structure of the dimuon spectrum in $400\,\text{GeV}$ proton-nucleus collisions at the Fermilab [8]. This was quickly interpreted as a bottom (or beauty)-antibottom bound state. Shortly thereafter, Mario Greco applied again [9] duality ideas [7, 10-14] to this discovery. These ideas led to simple relations for the electronic widths of vector mesons

(2) $$\Gamma_\rho^{e\bar{e}} : \Gamma_\omega^{e\bar{e}} : \Gamma_\varphi^{e\bar{e}} : \Gamma_\psi^{e\bar{e}} : \Gamma_\Upsilon^{e\bar{e}} = 9 : 1 : 2 : 8 : 2(8),$$

where the last term in the equation above is related to the electric charge of the bottom quark having the value $-1/3(2/3)$. Choosing the value $-1/3$ leads to the prediction $\Gamma_\Upsilon^{e\bar{e}} \simeq 1.2\,\text{keV}$. This, in turn, allows one to estimate the production cross section of the Υ, for which Mario obtained a value in good agreement (within a factor of two) with the

TABLE I. – *The predictions of ref.* [9] *for the electronic widths of bottom-antibottom bound states, compared to modern experimental results.*

$\Gamma^{e\bar{e}}$ (keV)	Υ	Υ'	Υ''
Mario Greco [9]	1.2	0.65	0.55
PDG [15]	1.34	0.61	0.44

experimental measurement. He could therefore conclude that the charge $-1/3$ for the bottom quark was favoured by the available data: "*Our results suggest that the charge of the new constituent quark is likely* $-1/3$".

A by-product of this analysis were the predictions for the values for the leptonic widths of the Υ and the higher resonances, at the time unknown. Table I compares the predictions in [9] with the modern measured values. Obviously, not a bad job.

3. – Top discovery

After these two discoveries almost twenty years elapsed before the sixth quark was finally observed. The CDF collaboration at the Fermilab Tevatron collider published at first initial evidence [16] for the top quark in 1994, and followed up in 1995 with the definitive observation [17]. This last paper was also presented [18] in the 1995 edition of the La Thuile conference, one of the very first public announcements of the definitive discovery of the top quark.

The very large mass, of the order of 175 GeV, at which the top quark was finally observed would have been perhaps surprising only a few years earlier when, without any other experimental guidance, one could have expected a top quark only marginally heavier than the heavy quarks already discovered. However, by the time of the CDF discovery, a lot more information was available through the precision fits of the Standard Model parameters performed at LEP. In particular, it had become clear (see, *e.g.*, fig. 2, taken from [19]) that the top quark was going to be very heavy, with a mass of the order of 150 GeV, and a residual uncertainty that, in 1994, was probably of the order of ± 20–30 GeV. This indirect evidence for the value of the top mass was one of the main contributions of LEP to the experimental landscape, and it was possible because of a huge amount of theoretical and phenomenological work directed at improving the predictions. As an example of Mario Greco's contribution to this collective effort I'd like to mention two of his many papers on radiative corrections for LEP physics, refs. [20] and [21], which extensively reviewed and systematized electromagnetic corrections to Bhabha scattering at the Z^0 pole.

4. – "Precision" physics in heavy quarks and quarkonium

After the time of discoveries comes of course that of more accurate measurements and, out of necessity, more refined theoretical predictions, usually in the form of next-to-leading order (NLO) and resummed calculations. I wish to mention in particular two contributions of Mario Greco to this endeavour.

On of them is the first complete and systematic NLO calculation of heavy quarkonium total cross sections in hadronic collisions [22] within the then recently developed Non-Relativistic QCD (NRQCD) formalism [23]. This work capped a series of papers
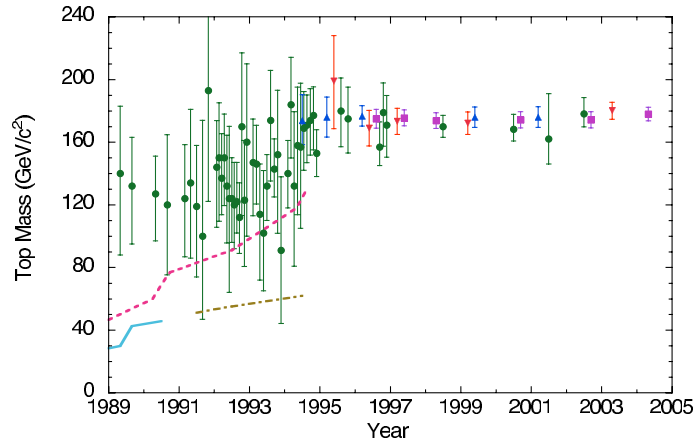
Fig. 2. – (Colour on-line) The evolution in time of the top mass value extracted from electroweak precision fits at LEP (green circles), together with the actual measurements at the Tevatron (red and blue triangles, magenta squares). Taken from ref. [19], page 24, fig. 16.

on heavy quarkonium that Mario and I wrote together, the first of them, on the role of resummed fragmentation contributions in the production of J/ψ at the Tevatron [24], as part of my doctoral thesis. Twenty years after its discovery, the J/ψ was still providing theorists with a lot of work, the focus having shifted to a detailed understanding of its production mechanism and to accurate evaluations of its cross sections, a quest that still goes on today.

A second contribution of Mario to precision phenomenology is the large transverse momentum resummation of heavy quark production in hadronic collisions [25], a paper that we wrote together in 1993 and my first foray into QCD. At the time I was a graduate student in Pavia. Mario, who eventually spent three years there, had just moved from a position with the INFN (the Italian Institute for Nuclear Physics) to a professorship in the University. He suggested that I look into combining the results of an article he had written a few years earlier with Aversa, Chiappetta and Guillet, the full set of higher-order QCD corrections to parton-parton scattering processes [26], with those from a paper from Mele and Nason [27], which calculated the boundary conditions of the fragmentation functions of massless partons into a massive quark. Together with the evolution kernels from Altarelli-Parisi [28] and Curci-Furmanski-Petronzio [29], these ingredients were what was needed to perform the resummation to next-to-leading logarithmic level of the cross section for heavy quark production at large transverse momentum. The availability of all the building blocks did not make the job look less daunting. Mario put me in touch with Jean-Philippe Guillet and with Paolo Nason (and later Michel Fontannaz), who kindly provided us with codes they had written for other projects but which contained the necessary ingredients. Then, patiently and with a keen understanding of what the correct outcome had to look like, he helped me make sense of a few thousand lines of CAPITALISED Fortran 77 code and eventually obtain physically meaningful results.

This work, also a part of my PhD thesis, has successively evolved into the so-called FONLL calculation [30] of heavy quark production, a formalism where the fixed order calculation at NLO [31] is matched with the resummed one from [25] and, at the same time, non-perturbative information extracted from LEP data is employed in predictions of
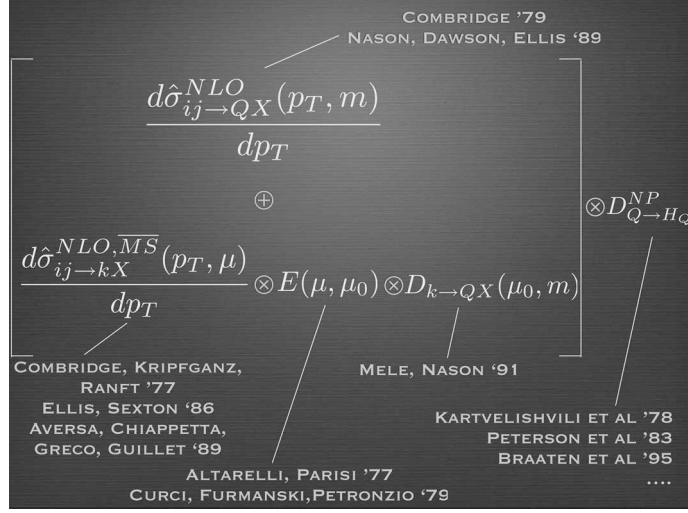
Fig. 3. – Schematic view of "previous art" used in the FONLL formalism, showing the authors of the main ingredients that enter the calculation.

heavy hadrons spectra in hadronic collisions. A schematic view of the FONLL calculation, in the form

$$\text{(3)} \qquad \mathrm{d}\sigma_{H_Q}^{FONLL} = \left[\mathrm{d}\sigma_Q^{NLO} \oplus \mathrm{d}\sigma_Q^{res}\right] \otimes D_{Q \to H_Q}^{non\text{-}pert},$$

where $\oplus$ denotes a "matched" sum and $\otimes$ a convolution, is given in fig. 3. It shows how FONLL draws from a large amount of previous work in QCD, achieving a remarkable synthesis. Eventually, this synthesis also proved to be quite effective, as it was shown capable of describing well heavy quark production in a number of different experiments, from ep collisions at HERA, to pp and $p\bar{p}$ at RHIC and the Tevatron and, more recently and almost 20 years after it was first introduced, pp collisions at the LHC.

5. – Conclusions

The history of heavy quarks is now almost forty years long, and Mario Greco's career spanned all of it. His work has given many contributions to our present understanding, and in these proceedings I could only describe briefly some of it.

The very much abridged story of these forty years started here with the discovery of the fourth quark, charm. It may be easy, today and from the heights of our six known quarks, the heaviest of them with potential links to new physics beyond the electroweak scale, to take this fourth, barely "heavy" quark almost for granted. This would however mean doing injustice to the revolutionary proposal of Glashow, Iliopoulos and Maiani [32] which in 1970, introducing the charm quark, presciently captured the lepton-hadron symmetry which is now a cornerstone of the Standard Model. Indeed, its importance did not quite go unnoticed at the time, and Collins, Wilczek and Zee [33] could for instance write, in 1978 and before the Nobel prize effectively sealed the paternity of the Standard Model, "...we specialize to the standard sequential Weinberg-Salam-Glashow-Iliopoulos-Maiani model of weak interactions...".

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I wish to thank the Organisers of La Thuile conference for inviting me to give this talk. More importantly, I wish to thank Mario for the physics he has taught me and for the attitude towards physics that I have tried to learn from him. It has been a privilege to be his student and collaborator, and a real pleasure to work with him.

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