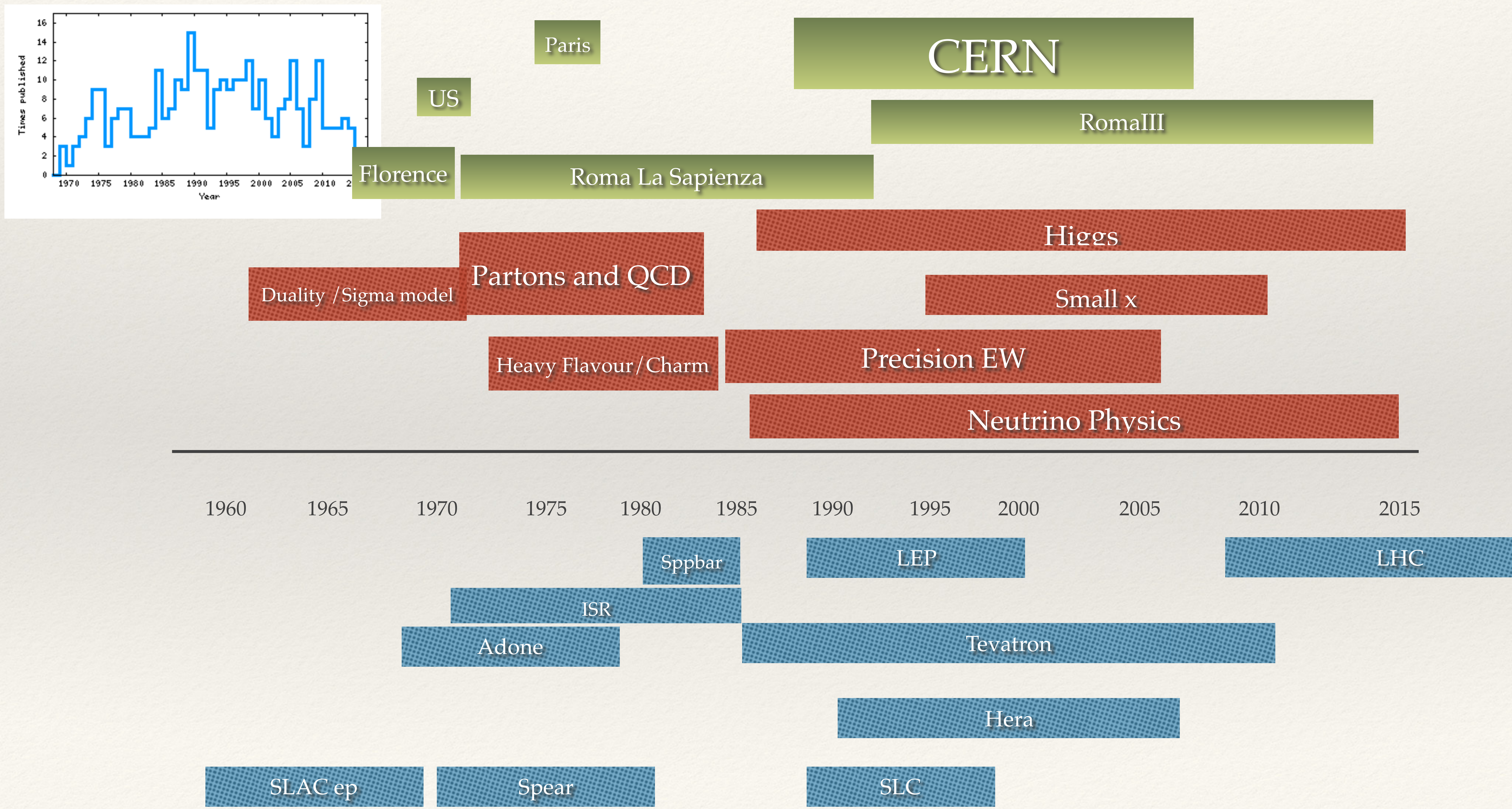
La Thuile — March 2016

Remembering Guido Altarelli

Keith Ellis
IPPP Durham

Life in the vanguard of science



Top papers

1. **"Vacuum polarization effects of new physics on electroweak processes"**
G. Altarelli and R. Barbieri.
10.1016/0370-2693(91)91378-9
Phys. Lett. B **253**, 161 (1991). 500+

2. **"The Anomalous Gluon Contribution to Polarized Leptoproduction"**
G. Altarelli and G. G. Ross.
10.1016/0370-2693(88)91335-4
Phys. Lett. B **212**, 391 (1988). 500+

3. **"Vector Boson Production at Colliders: A Theoretical Reappraisal"**
G. Altarelli, R. K. Ellis, M. Greco and G. Martinelli.
10.1016/0550-3213(84)90112-3
Nucl. Phys. B **246**, 12 (1984). 500+

4. **"Leptonic Decay of Heavy Flavors: A Theoretical Update"**
G. Altarelli, N. Cabibbo, G. Corbo, L. Maiani and G. Martinelli.
10.1016/0550-3213(82)90226-7
Nucl. Phys. B **208**, 365 (1982). 500+

5. **"Partons in Quantum Chromodynamics"**
G. Altarelli.
10.1016/0370-1573(82)90127-2
Phys. Rept. **81**, 1 (1982). 500+

6. **"Large Perturbative Corrections to the Drell-Yan Process in QCD"**
G. Altarelli, R. K. Ellis and G. Martinelli.
10.1016/0550-3213(79)90116-0
Nucl. Phys. B **157**, 461 (1979). 500+

7. **"Asymptotic Freedom in Parton Language"**
G. Altarelli and G. Parisi.
10.1016/0550-3213(77)90384-4
Nucl. Phys. B **126**, 298 (1977). 5000+

8. **"Octet Enhancement of Nonleptonic Weak Interactions in Asymptotically Free Gauge Theories"**
G. Altarelli and L. Maiani.
10.1016/0370-2693(74)90060-4
Phys. Lett. B **52**, 351 (1974). 500+

- A different world—UK enters the common market in 1973.
- I was in Rome from 1972-1975 and from 1982-1984.
- Guido and I wrote papers together from 1974-1985.

Bottom Papers?

1. G. Altarelli, R. K. Ellis and R. Petronzio, "Radiative Corrections to $e^+e^- \to \mu^+\mu^-$ Near a Narrow Vector Resonance," Lett. Nuovo Cim. **13** (1975) 393. <10

Radiative Corrections to $e^+e^- \to \mu^+\mu^-$ near a Narrow Vector Resonance.

G. ALTARELLI, R. K. ELLIS (*) and R. PETRONZIO

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 2 Maggio 1975)

In this note we evaluate the forward-backward asymmetry in $e^+e^- \to \mu^+\mu^-$ in the vicinity of a narrow resonance such as the recently discovered (1) $\psi(3100)$ or the $\psi'(3700)$. Since we assume that the ψ and ψ' are pure $J^P = 1^-$ states, this asymmetry is due to radiative corrections. We consider only the case of nonpolarized beams. Although it is likely that the ψ and ψ' are coupled to leptons via the photon, it is entirely equivalent for our purposes to assume an effective universal vector coupling of the form $gR^\mu(\bar{e}\gamma_\mu e + \bar{\mu}\gamma_\mu\mu)$ with $g^2/4\pi = \tilde{\alpha}$ for ψ and $\tilde{\alpha}'$ for ψ'. The computation of the cross-section to order α^3 in pure quantum electrodynamics has been presented in ref. (2,3). Near a narrow resonance terms proportional to $\tilde{\alpha}$ can become comparable or larger than terms of order α. We therefore calculate the cross-section to third order in both α and $\tilde{\alpha}$. The diagrams which give significant contributions are shown in Fig. 1. In view

(*) Royal Society European Exchange Fellow.

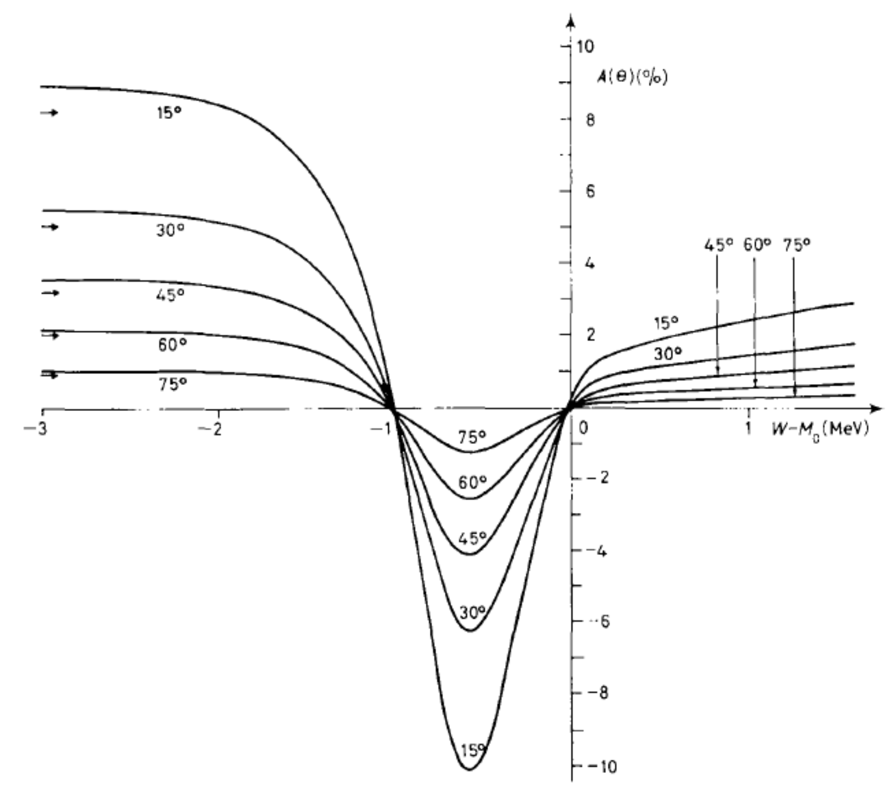


Fig. 2. – Plot of the asymmetry $A(\theta) = \sigma_A(\theta)/\sigma_S(\theta)$ expressed in percent against $W - M_0$, for various values of the centre-of-mass angle θ. The parameters were chosen as follows: $M = 3098$ MeV, $\Gamma = 77$ keV, $\Gamma_e = 5$ keV, $\tilde{\alpha} = 3\Gamma_e/M_0$ and $\Delta E/E = 20\,\%$. The arrows indicate the pure QED values. Comparison of the asymmetry with experimental data would require that both $\sigma_A(\theta)$ and $\sigma_S(\theta)$ be convoluted with the machine resolution function.

How I came to be in Rome

- “Bird of Passage”, Autobiography of Professor Sir Rudolph Peierls, (Professor in Oxford), pg. 318


Rudolph Peierls

“Often the problems raised by the students are far removed from the scientific ones. Keith Ellis, for example, had made a good start, working with Jack Paton on a problem in particle physics and then decided to leave after the end of his first year.

He explained that he had spent a vacation in Italy and had become so fascinated with Italian life and language that he had the urge to spend time there.
It turned out there was no girlfriend behind this as we had first suspected.
(….)

I got in touch with Italian friends who arranged for him to join a research group in Rome. His research scholarship was transferred and his father agreed to help him with the higher cost of living. He did complete a good thesis there, and when I ran into him afterwards in an American University I was told by his professor that he was doing well…."


Eduardo Amaldi

An extraordinary collection of talent in Rome

- 1972-1975 a the birth of the standard model
- La Sapienza-theorists
  - Altarelli, Buccella, Cabibbo, Gatto, Maiani, Martinelli, Parisi, Petronzio, Preparata,Testa
- LNF Frascati,
  - Greco, Etim Etim,Panchieri,Srivastava,Touschek

Life before DGLAP

In the deep-inelastic scattering of a lepton off a hadron one measures the Fourier transform of the commutator of electromagnetic or weak currents. We define the standard structure functions as follows:

$$\frac{1}{2\pi}\int dy\, e^{iq\cdot y}\langle p|[J_\mu(a;\tfrac{1}{2}y), J_\nu(b;-\tfrac{1}{2}y)]|p\rangle$$
$$=\frac{p_\mu p_\nu}{m\nu}F_2^{(a,b)}(\nu,q^2)-\frac{g_{\mu\nu}}{m}F_1^{(a,b)}(\nu,q^2)$$
$$+i\frac{\epsilon_{\mu\nu\sigma\lambda}p_\sigma q_\lambda}{2m\nu}F_3^{(a,b)}(\nu,q^2)+\cdots, \quad (1)$$

- Operator product expansion Wilson 1969.

$$J_\mu(a;\tfrac{1}{2}y)J_\nu(b;-\tfrac{1}{2}y)=\tfrac{1}{2}g_{\mu\nu}\left(\frac{\partial}{\partial y}\right)^2\frac{1}{y^2-i\epsilon y_0}\sum_{n=0}^{\infty}\sum_i C_{i,1}^{(n)}(a,b;y^2-i\epsilon y_0)\,O^i_{\mu_1\cdots\mu_n}(0)y^{\mu_1}\cdots y^{\mu_n}$$
$$+\frac{1}{y^2-i\epsilon y_0}\sum_{n=0}^{\infty}\sum_i C_{i,2}^{(n)}(a,b;y^2-i\epsilon y_0)\,O^i_{\mu\nu\mu_1\cdots\mu_n}(0)y^{\mu_1}\cdots y^{\mu_n}$$
$$+\tfrac{1}{2}i\epsilon_{\mu\nu\sigma\lambda}\frac{\partial}{\partial y^\lambda}\frac{1}{y^2-i\epsilon y_0}\sum_{n=0}^{\infty}\sum_i C_{i,3}^{(n)}(a,b;y^2-i\epsilon y_0)\,O^i_{\sigma\mu_1\cdots\mu_n}y^{\mu_1}\cdots y^{\mu_n}+\cdots.$$

DIS in asymptotically free theories.

- Coefficient functions (Moments of the structure function) satisfy a renormalization group equation.

$$\left(\mu\frac{\partial}{\partial\mu}+\beta(g)\frac{\partial}{\partial g}-\gamma^{n}(g)\right)\tilde{C}^{(n)}(q^2/\mu^2,g)=0\ ,$$

$$\int_0^1 dx\, x^n F^{\mathrm{NS}}(x,Q^2)\underset{Q^2\to\infty}{\sim} C_{\mathrm{NS}}^{(n)}(\ln Q^2)^{-A_{n+2}^{\mathrm{NS}}}\ , \qquad (42)$$

where

$$A_n^{\mathrm{NS}}=\frac{3C_2(R)}{22C_2(G)-8T(R)}\left(1-\frac{2}{n(n+1)}+4\sum_{k=2}^{n}\frac{1}{k}\right) \qquad (43)$$

and

$$Q_2=-q^2\ .$$

In the "red, white, and blue" quark model [H $=$SU(3)], we have

$$C_2(G)=3,$$
$$C_2(R)=\tfrac{4}{3}, \qquad (44)$$
$$T(R)=\tfrac{3}{2}\ .$$

2. Bjorken scaling is violated by finite powers of logarithms. These logarithmic violations are readily calculated in terms of the γ matrix evaluated in second-order perturbation theory. Here

Life before the AP equation

- “In spite of the relative simplicity of the final results, their derivation, although theoretically rigorous, is somewhat abstract and formal, being formulated in the language of renormalisation group equations for the coefficient functions of the local operators which appear in the light cone expansion for the product of two currents.” (AP, Nuclear Phys. B)

Georgi Politzer Phys. Rev. D9 (1974) 416
685
Gross-Wilczek, Phys. Rev. D9 (1974) 980
1131

The Altarelli-Parisi Eqn.

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE.

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ABSTRACT : A novel derivation of the Q^2 dependence of quark and gluon densities (of given helicity) as predicted by Quantum Chromo-dynamics is presented. The main body of predictions of the theory for deep inelastic scattering on either unpolarized or polarized targets is reobtained by a method which makes only use of simplest tree diagrams and is entirely phrased in parton language with no reference to the conventional operator formalism.

LPTENS 77/6
March 1977

* On leave of absence from the Istituto di Fisica dell' Università di Roma.
** On leave of absence from the Laboratori Nazionali di Frascati
++ Laboratoire propre du C.N.R.S. associé à l'Ecole Normale Supérieure et à l'Université de Paris-Sud.
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Anatomy of a splitting function

- "In our paper a particular emphasis was devoted to prove that splitting functions are a property of the theory and do not depend on the process."
- Time ordered perturbation theory.
- Physical gauge

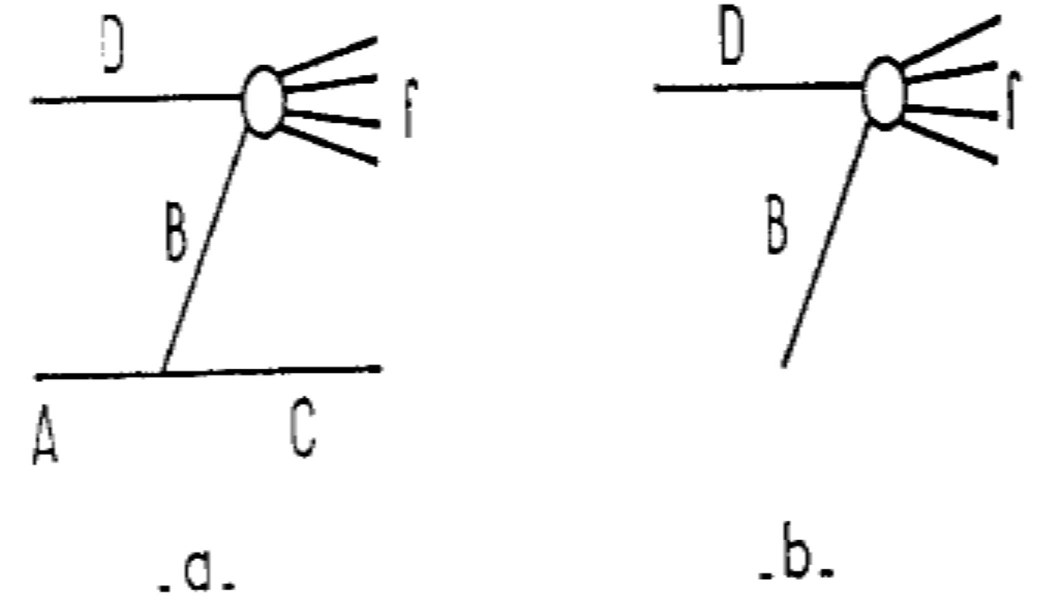


FIG. 1

The two processes are related by :

$$d\sigma_a = d\mathcal{P}_{BA}(z)\, dz\, d\sigma_b$$

Before 1977

- At least to the west of the iron curtain, there was very little understanding of the graphs summed up by the renormalisation group equation.
- Post-AP it was clear that these were ladder diagrams, but only in a physical gauge.

Old Fashioned Pert. Theory.

- Old-fashioned perturbation theory, (obtained by integrating over the Energy component of normal perturbation theory).
- Energy denominators, as in Non-relativistic QM.
- On-shell particles
- Momentum is conserved, but energy is not.

we obtain:

$$d\mathcal{P}_{BA}(z)\,dz = \frac{E_B}{E_A}\,\frac{g^2\left|V_{A\to B+C}\right|^2}{(2E_B)^2(E_B+E_C-E_A)^2}\,\frac{d^3k_c}{(2\pi)^3(2E_C)}$$

$$k_A = \left(P;\, P,\, \vec{0}\right)$$

$$k_B = \left(zP + \frac{p_\perp^2}{2zP};\, zP,\, \vec{p}_\perp\right)$$

$$k_C = \left((1-z)P + \frac{p_\perp^2}{2(1-z)P};\, (1-z)P,\, -\vec{p}_\perp\right)$$

Calculating the splitting functions

Fig. 2. The quark gluon vertex which determines P_{Gq} and P_{qq}. The form of the vertex is $ig\bar{q}_{\mathrm{C}}\gamma^{\mu}t^{a}q_{\mathrm{A}}B^{a}_{\mu}$ with $\mathrm{Tr}\,t^{a}t^{b} = \frac{1}{2}\delta^{ab}$.

- Helicity conservation argument tells you that the amplitude vanishes as $p_T \to 0$, (actually as $\sqrt{p_T}$)
- Care must be taken that the sum is only over the transverse gluon states.

$$\sum_{\mathrm{pol}} \epsilon^{*}\epsilon \to \delta^{ij} - \frac{k^{i}_{\mathrm{B}}k^{j}_{\mathrm{B}}}{k^{2}_{\mathrm{B}}} \qquad (i, j = 1, 2, 3)\,.$$

$$P_{\mathrm{BA}}(z) = \tfrac{1}{2}\, z(1-z) \overline{\sum_{\mathrm{spins}}} \frac{|V_{\mathrm{A}\to\mathrm{B}+\mathrm{C}}|^{2}}{p^{2}_{\perp}} \qquad (z < 1)\,,$$

Concern about the publication of the AP paper

- My recollection was that Guido was concerned about the suitability for publication of the AP paper.
- After all, at some level it was just an inverse Mellin transform of known results.

$$\frac{\mathrm{d}M_n^{\mathrm{NS}}(t)}{\mathrm{d}t} = \frac{\alpha(t)}{2\pi} A_n^{\mathrm{NS}}\, M_n^{\mathrm{NS}}(t) \,,$$

$$\frac{\mathrm{d}q^{\mathrm{NS}}(x,t)}{\mathrm{d}t} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{\mathrm{d}y}{y}\, q^{\mathrm{NS}}(y,t)\, P\!\left(\frac{x}{y}\right)$$

$$\int_0^1 \mathrm{d}z\, z^{n-1} P(z) = A_n^{\mathrm{NS}} \,.$$

- Hence the focus on the results for G_1 which was a relatively new and unconfirmed result.

M. Gaillard and B. W. Lee, Phys.Rev.Lett., 33, 108 (1974).
G. Altarelli and L. Maiani, Phys.Lett., B52, 351 (1974)

Δ I=1/2 rule

- In the decay K->ππ, 450 times more likely to have isospin I=0, rather than I=2.
- $\mathrm{Re}(A_0/A_2) \approx 22.5$.
- It had been suggested by Ken Wilson that strong interaction effects on weak operators could cause this.
- With the discovery of asymptotic freedom, one could actually do the calculation

$$(\text{W-exch})_{\Delta S \neq 0} = \alpha M_W^{-2} \sum_k C_k \left(\ln \frac{M_W^2}{m^2} \right)^{d_k} \langle f | O_k(0) | i \rangle$$

- ΔI=1/2 and ΔI=3/2 operators have different fermionic symmetry properties.
- In their paper Altarelli and Maiani found a factor 4-6 for the standard model, and even larger factors for other models of the weak interactions.
- Modern assessment is that perturbative running from the electroweak scale to a few GeV, contributes about a factor 2 to this ratio. The remaining factor of about 10 comes from non-perturbative physics, 1212.1474

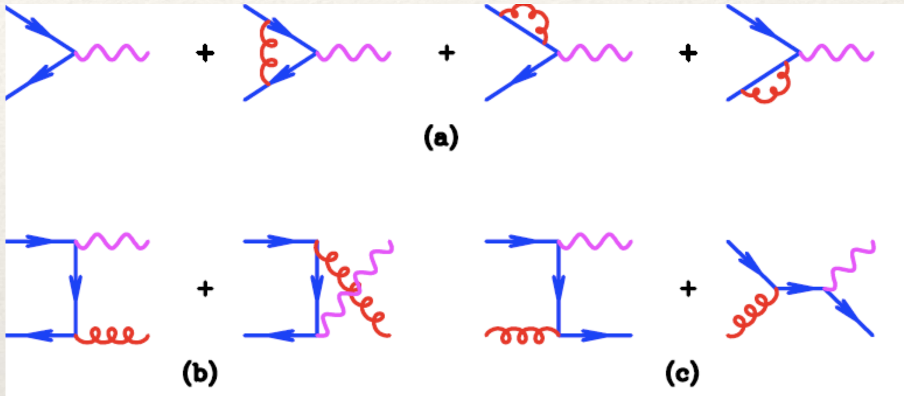
Corrections to Drell-Yan

- The principle benefit of QCD is that it gives a procedure for systematically improving the predictions using perturbation theory.

- Altarelli et al. was the first attempt to apply this to hadronically induced processes.

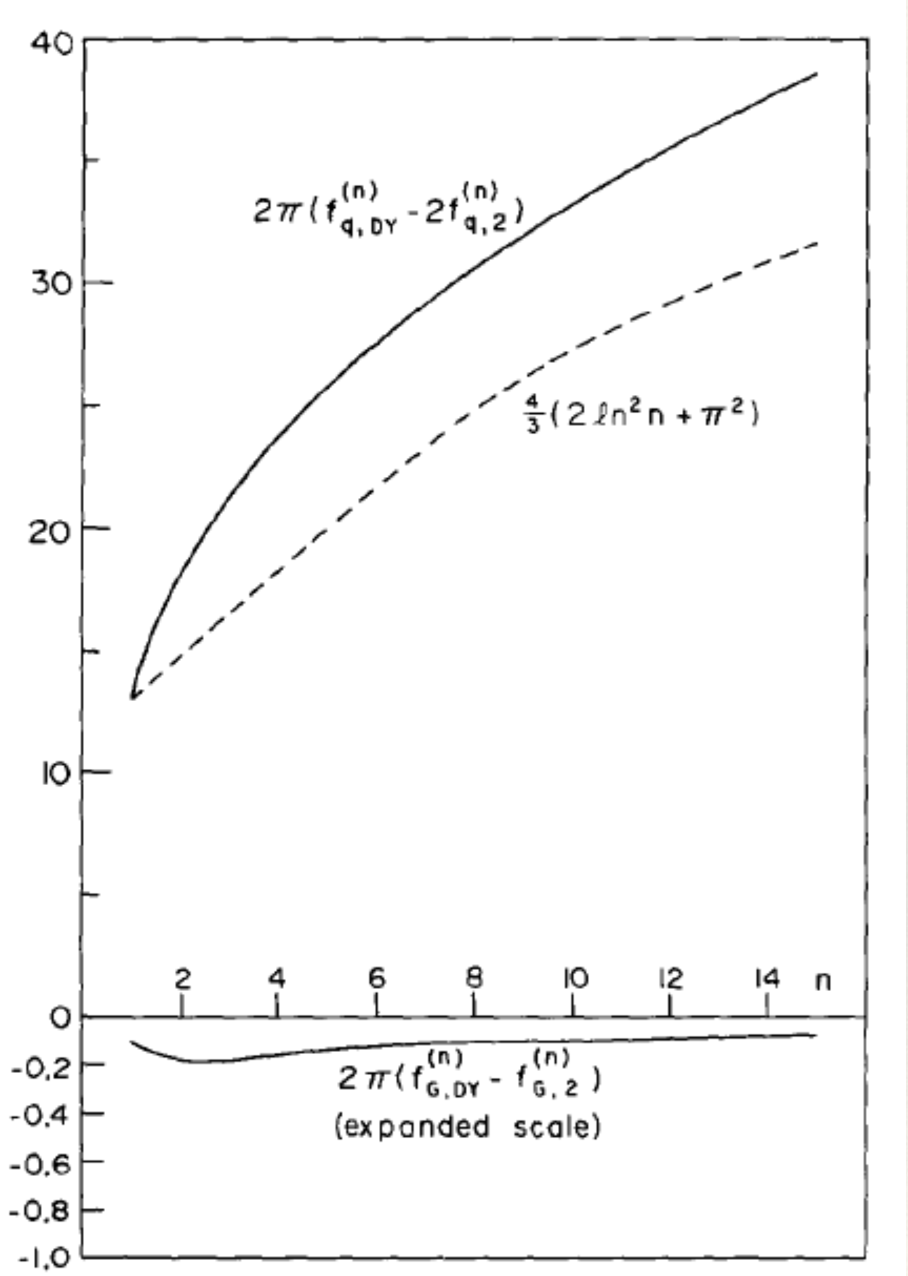
- Two bites at the cherry

Diagrams for NLO prediction



Corrections to Drell- Yan (the K-factor)

$$\alpha_s(f_{q,\mathrm{DY}} - 2f_{q,2})$$
$$= \frac{\alpha_s}{2\pi}\frac{4}{3}\left[\frac{3}{(1-z)_+} - 6 - 4z + 2(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1+\tfrac{4}{3}\pi^2)\,\delta(1-z)\right].$$



- Taking the notional value $\alpha\_s/(2\pi)=1/20$ we see that the corrections are not small.
- Helpful in accommodating data.
- Since in a coloured quark theory a red quark can only annihilate with an anti-red quark suppression by 3
- Feynman-Field recalculation at Caltech.

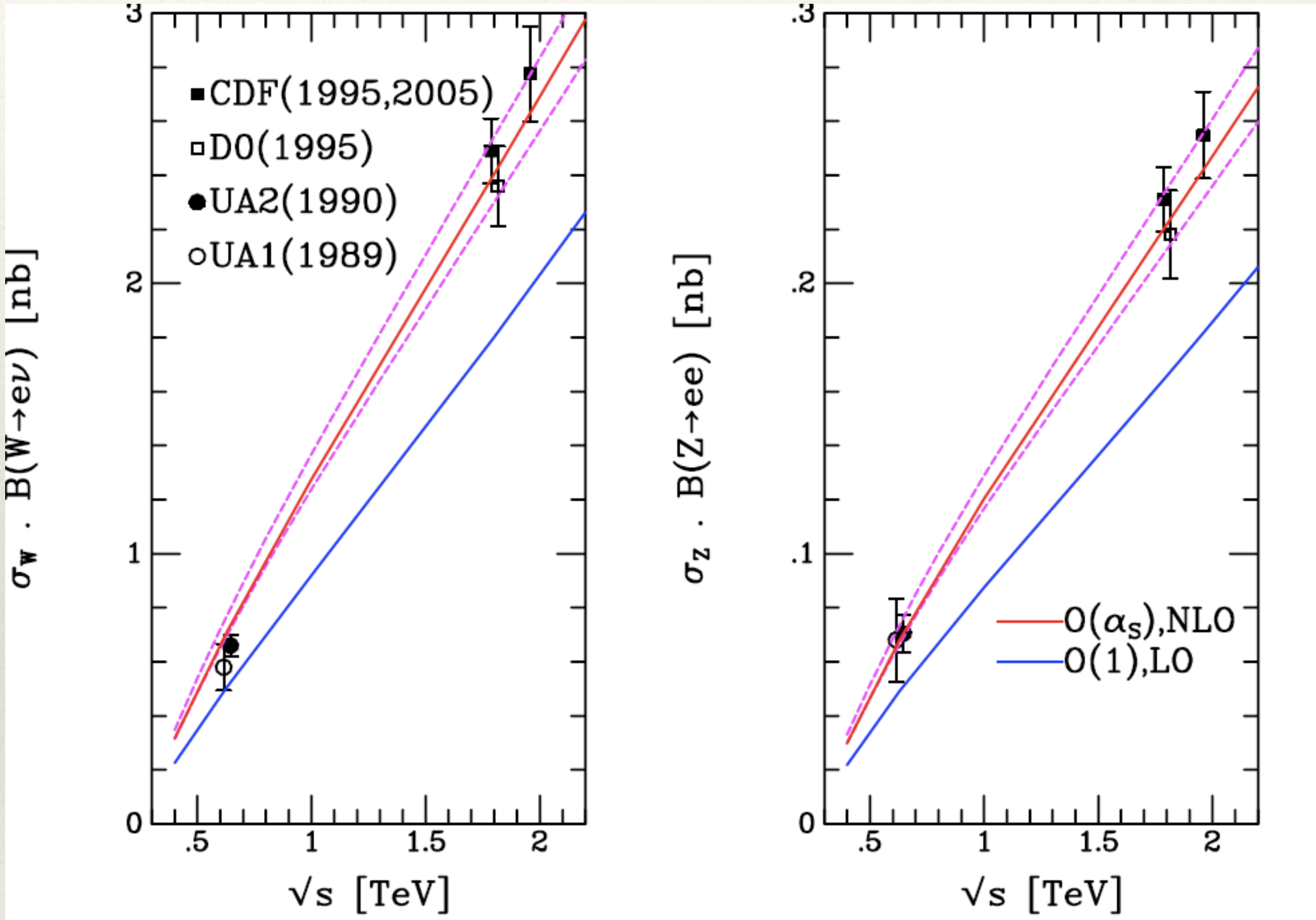
Drell-Yan type processes (γ*,W,Z)

QCD provides a systematic way of improving the calculations of cross sections

$$\hat{\sigma}(z) = \delta(1-z) + \frac{\alpha_s}{2\pi} f_1(z) + \left(\frac{\alpha_s}{2\pi}\right)^2 f_2(z) + \ldots$$

by expanding in the small coupling α_S. Corrections are large at $O(\alpha_S)$ but needed to needed to achieve agreement with data.

(α_S^2 corrections also known and lead to a further modest increase.)



Moral: at least next-to-leading order (NLO) corrections are needed.

Chania, Crete 1980

- Nonleading QCD Effects for Weak Nonleptonic Amplitudes
- Understood the subtleties of dimensional reduction.

QCD NON-LEADING CORRECTIONS TO WEAK DECAYS AS AN APPLICATION OF REGULARIZATION BY DIMENSIONAL REDUCTION

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Received 23 February 1981

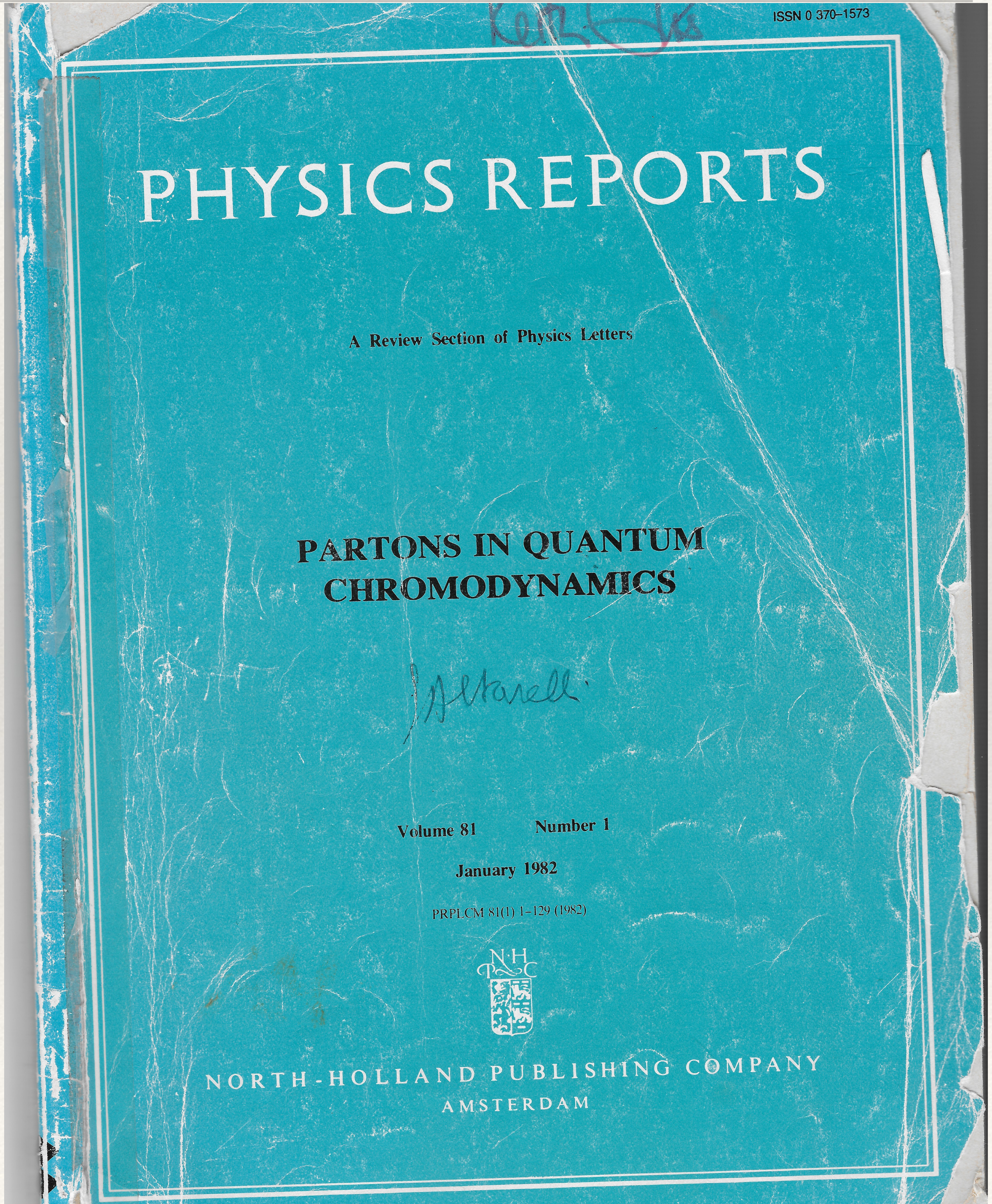
With thanks to Guido Martinelli

“L’orso bianco”

With thanks to Guido Martinelli

Partons in Quantum Chromodynamics

- The definitive text for the 80-90's on QCD.
- As you can see my copy is much used (and abused).
- Written, for the most part, in the library at CERN as a visitor.
- By an unacknowledged author!



The Altarelli cocktail

- The calculation of the splitting functions rapidly gave rise to shower Monte Carlos
- Importantly these give a good description of collinear emission, but seriously underestimate events at large p_T
- Monojet events — the standard model is dead (1984)?
- Eventually explained as a “cocktail” of Z+jet events, misidentified electron, Z->tau tau events….at St. Vincent an early version of this conference.

Language

- Almost from the beginning we talked in Italian.
- Royal Society
- i poli (polli).
- "the normal Evolution Equation"
- Il senso del gioco

Radiative Corrections to $e^+e^- \to \mu^+\mu^-$ near a Narrow Vector Resonance.

G. ALTARELLI, R. K. ELLIS (*) and R. PETRONZIO

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 2 Maggio 1975)

In this note we evaluate the forward-backward asymmetry in $e^+e^- \to \mu^+\mu^-$ in the vicinity of a narrow resonance such as the recently discovered (1) $\psi(3100)$ or the $\psi'(3700)$. Since we assume that the ψ and ψ' are pure $J^P = 1^-$ states, this asymmetry is due to radiative corrections. We consider only the case of nonpolarized beams. Although it is likely that the ψ and ψ' are coupled to leptons via the photon, it is entirely equivalent for our purposes to assume an effective universal vector coupling of the form $gR^\mu(\bar{e}\gamma_\mu e + \bar{\mu}\gamma_\mu\mu)$ with $g^2/4\pi = \tilde{\alpha}$ for ψ and $\tilde{\alpha}'$ for ψ'. The computation of the cross-section to order α^3 in pure quantum electrodynamics has been presented in ref. (2,3). Near a narrow resonance terms proportional to $\tilde{\alpha}$ can become comparable or larger than terms of order α. We therefore calculate the cross-section to third order in both α and $\tilde{\alpha}$. The diagrams which give significant contributions are shown in Fig. 1. In view

(*) Royal Society European Exchange Fellow.

Letters

- Estimation of Cabibbo and Letter from Cabibbo
- My thesis was supervised by Guido and Luciano Maiani
  "To this last paper also contributed Keith Ellis, a Scottish PhD student of Cabibbo, who was to stay with us in Rome for a few years, eventually speaking a very good Italian and fully understanding the roman way of living." GA 1106.3189
- I had a very chequered post-doc career (six post-docs!); at every stage Guido wrote letters of recommendation for me.
- So it was a great pleasure to return the favour, in supporting his nomination for the Sakurai Prize, (although I had the impression that the tail was wagging the dog).

Fermilab

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Joseph Lykken,
Chair, 2011 Sakurai Prize Committee
MS 106
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Batavia, IL 60510

Dear Joe,

It is a great pleasure to support the nomination of Guido Altarelli for the Sakurai Prize. Guido has been an influential and authoritative figure in our field from the invention of the Standard model in the early seventies until the present day.

Although the jewel in the crown of his production is the Altarelli-Parisi (AP) equation, it is my opinion that his achievements over the years would merit the award of the Sakurai prize, even if the AP paper had never been written.

I am referring in particular to his work transverse momentum distributions in Drell-Yan processes, a key element of distinction between the parton model and QCD; to his work on higher order corrections to the Drell Yan process (where I was a co-author) that calculated the first K factor; to his work on the small x evolution of the structure functions that emphasizes the tempering role that momentum conservation has on the growth of parton distributions at small x. I am also referring to his work on the interpetation of precision electroweak data from LEP, that provides important constraints on physics beyond the standard model. I am referring to his work on the Delta I = 1/2 rule, showing that hard QCD effects were responsible for part of the enhancement. Also noteworthy is his work on neutrino mixing based on the flavor group A_4, that provides an appealing explanation for the tri-bimaximal structure of the neutrino mixing matrix. The tri-bimaximal structure provides a convenient lowest order prediction for the observed structure of the neutrino mixing matrix. Lastly, I am referring to his work on the polarized structure function, suggesting that a sizeable fraction of the spin of the proton is carried by the gluons. Although Nature appears not to have availed herself of this possibility it remains an extremely elegant solution.

Guido's work on the Altarelli-Parisi equation was tremendously influential; the new result of that paper was the calculation of splitting functions for polarized targets. But much more importantly the work of Altarelli and Parisi gave a physical picture, which allowed the union of the parton model with QCD. Prior to the appearance work of AP the treatment of deep inelastic scattering was done using the operator product expansion and the renormalization group. However, at the time there was little understanding of the classes of diagrams that were summed by the renormalization group, or of the importance of a physical gauge to simplify the QCD treatment. The simple physical picture of the AP paper begged the question of the extension to other processes such as Drell-Yan that ultimately led to proofs of factorization.

I believe that his intensely physical approach, communicated through his papers, and perhaps more importantly through his influence on students and junior collaborators, has had a profound effect on our field. I am happy to recommend the award of the Sakurai prize without reservation.

Yours sincerely,

R Keith Ellis

R. Keith Ellis

- Students
  - Keith Ellis
  - Guido Martinelli
  - Barbara Mele
  - Marco Ciuchini
  - Roberto Franceschini
  - Emilio Gabrielli
  - Sandro Ambrosiano
  - +many younger collaborators

Roma-La Sapienza

- “Triste e’ quel discepolo che non superi il suo maestro”
- Another reason to be sad that Guido is no longer with us.