EPS - HEPP Prize, 27 July 2015

Recollections from the early days of QCD in the 70's

Guido Altarelli
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I was very happy, surprised and grateful when this highly prestigious Prize was announced to me.

I most warmly thank Prof. Lohse (Chair) and all the Members of the EPS - HEPP Board for this great honour

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Claudia-Elisabeth Wulz

The Prize refers to works done some 40 years ago.
Thus, some telegraphic historical introduction is appropriate

I start with a grateful tribute
to my most important teachers

Bruno Touschek

Raoul Gatto

Nicola Cabibbo

DIS is nearly 50 years old!

VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

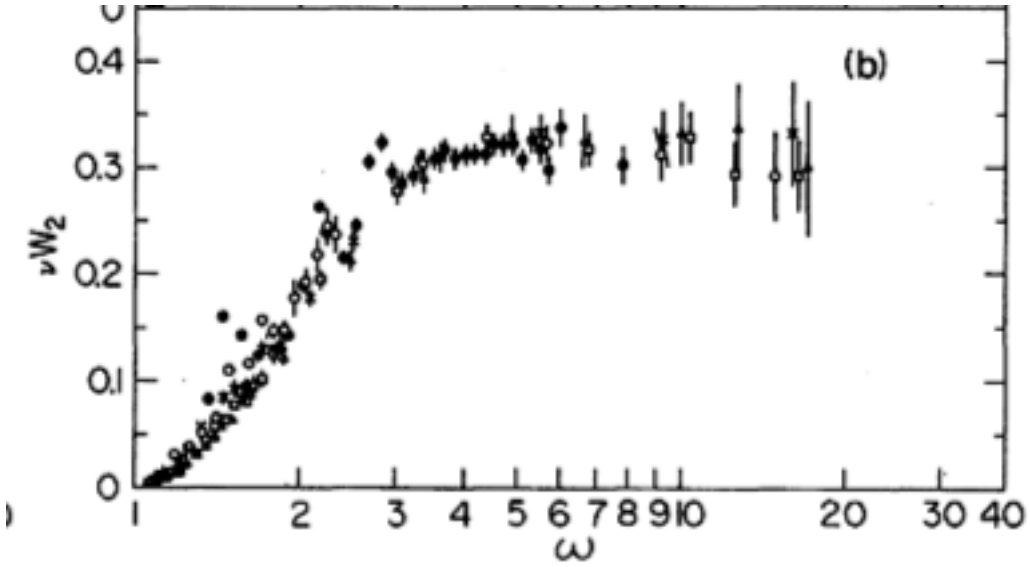
M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)

Results of electron-proton inelastic scattering at 6° and 10° are discussed, and values of the structure function W_2 are estimated. If the interaction is dominated by transverse virtual photons, νW_2 can be expressed as a function of $\omega = 2M\nu/q^2$ within experimental errors for $q^2 > 1$ $(\mathrm{GeV}/c)^2$ and $\omega > 4$, where ν is the invariant energy transfer and q^2 is the invariant momentum transfer of the electron. Various theoretical models and sum rules are briefly discussed.

1969: first evidence of approximate Bjorken scaling



From spectroscopy in the '60's constituent coloured quarks where established, at least as a mathematical book keeping

The "naive" parton model of Feynman, Bjorken.... was formulated on an intuitive basis

$F\gamma p = 4/9\ u(x) + 1/9\ d(x) + \ldots\ldots$

In DIS quarks and their quantum numbers reappear as partons

Why don't they get out? Confinement?

The great problem: build a field theory understanding of the parton model

1972: birth of QCD

Very important works on the way to QCD

Parton model

Bjorken
Paschos
Feynman
•••••

Quarks

Gell-Mann
Zweig
Greenberg
•••••

Short distance

Wilson
Brandt-Preparata
•••••

Ren. Group.

Gell-Mann-Low
Callan-Symanzik
•••••

QCD field theory

Fritzsch-Gell-Mann-Leutwyler
•••••

Asymptotic freedom

't Hooft
•••••

One can say that the application of QCD started with the Nobel winner papers by Gross & Wilczek and by Politzer in 1973

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

Since a few years in our group we were studying hard processes in the parton model (with approximate scaling)

Asymptotic properties of virtual Compton amplitudes in the ladder model
Guido Altarelli, H.R. Rubinstein (New York U.). Nov 1969. 9 pp.
Published in **Phys.Rev. 187 (1969) 2111-2119**

Deep inelastic processes in ladder models.
Guido Altarelli, L. Maiani (Rome U.). 1973.
Published in **Nucl.Phys. B51 (1973) 509-534**

Deep-inelastic one-particle inclusive processes in the parton model.
Guido Altarelli (Rome U.), L. Maiani (Rome, ISS). 1973.
Published in **Nucl.Phys. B56 (1973) 477-492**

a $\lambda\phi^3$ field theory model for scaling

The Nucleon as a bound state of three quarks and deep inelastic phenomena.
Guido Altarelli (Rome U.), N. Cabibbo (CERN & Rome U. & INFN, Rome), L. Maiani (Rome, ISS & INFN, Rome), R. Petronzio (Rome U.). Aug 1973.
Published in **Nucl.Phys. B69 (1974) 531-536**

the nucleon is described in terms of constituent quarks, each of them with a parton structure. This idea is still viable.

After Gross&Wilczek and Politzer we focussed on studying the implications of QCD

OCTET ENHANCEMENT OF NON-LEPTONIC WEAK INTERACTIONS IN ASYMPTOTICALLY FREE GAUGE THEORIES

G. ALTARELLI
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L. MAIANI
Lab. di Fisica, Istituto Superiore di Sanità, Rome, Italy
and Ist. Naz. di Fisica Nucleare, Sezione Sanità, Rome, Italy

Received 22 June 1974

Octet enhancement of weak non leptonic amplitudes is found to occur in asymptotically free gauge theories of strong interactions, combined with unified weak and e.m. interactions. The order of magnitude of the enhancement factor for different models is discussed.

This is an important paper (together with the work by M. K. Gaillard and B. W. Lee, Phys. Rev. Lett. 33(1974)108)

It was the first calculation of QCD corrections to the coefficients of the Wilson expansion in the product of two weak currents

Application to charm decay of the QCD-improved non leptonic weak Hamiltonian

ENHANCEMENT OF NON-LEPTONIC DECAYS OF CHARMED PARTICLES

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*Laboratoire de Physique Théorique de l'Ecole Normale Supérieure, Paris, France**
Istituto di Fisica dell'Università, Roma, Italy

N. CABIBBO
Istituto di Fisica dell'Università, Roma, Italy
CERN, Genève, Switzerland

L. MAIANI
*Laboratoire de Physique Théorique de l'Ecole Normale Supérieure, Paris, France**
Laboratori di Fisica, Istituto Superiore di Sanità, Roma, Italy

Received 14 October 1974

before charm was discovered!!

The theory of scaling violations, in Mellin moment terms, was applied to total neutrino cross sections

Volume 63B, number 2 PHYSICS LETTERS 19 July 1976

CHARMED QUARKS AND ASYMPTOTIC FREEDOM IN NEUTRINO SCATTERING

G. ALTARELLI, R. PETRONZIO
Istituto di Fisica, Roma, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy

and

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 24 March 1976

Asymptotic freedom and charm production are both important ingredients for a theoretical analysis of neutrino cross sections. We study in detail the Q^2 dependence of integrated quantities like cross sections, y-distributions and $\langle x \rangle$ values. Deviations from scaling are quite substantial in the present energy range.

This paper contributed to downgrading the "y-anomaly" from a signal of new physics (right-handed charged currents) down to a charm threshold + QCD-logs effect

The evolution equations

a French paper!

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

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G. PARISI ***

Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

Received 12 April 1977

$$\frac{dq^i(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{q^i q^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{q^i G}\left(\frac{x}{y}\right)\right] \qquad (22)$$

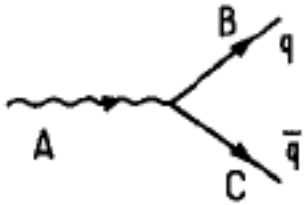
$t = \ln Q^2/\mu^2$

$$\frac{dG(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{Gq^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{GG}\left(\frac{x}{y}\right)\right] \qquad (23)$$

The QCD evolution equations hand-written by me on the '77 preprint

In our paper, formulated in parton language, with running coupling, the splitting functions are derived directly from the QCD vertices, making clear they are the same for all processes (factorisation).

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



$$\sum_{\text{pol}} |V_{q\to G+q}|^2 = \frac{2p_\perp^2}{z(1-z)} \frac{1+(1-z)^2}{z} C_2(R)$$

$$P_{Gq}(z) = C_2(R) \frac{1+(1-z)^2}{z} \qquad P_{qq}(z) = C_2(R) \frac{1+z^2}{1-z} \qquad (z<1)$$

$$P_{qq}(z) = C_2(R) \left[\frac{1+z^2}{(1-z)_+} + \tfrac{3}{2}\,\delta(z-1) \right]$$

The polarized splitting functions were also derived with the same method

$$\frac{dq^i(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{q^i q^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{q^i G}\left(\frac{x}{y}\right)\right] \qquad (22)$$

$$\frac{dG(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{Gq^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{GG}\left(\frac{x}{y}\right)\right] \qquad (23)$$

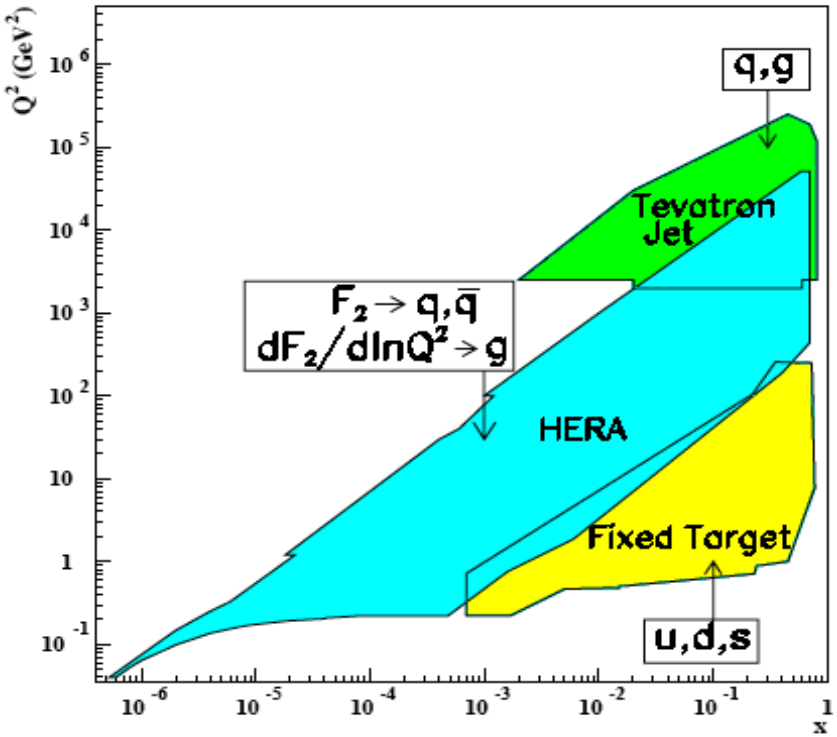
The derivatives at x only involve data at y > x

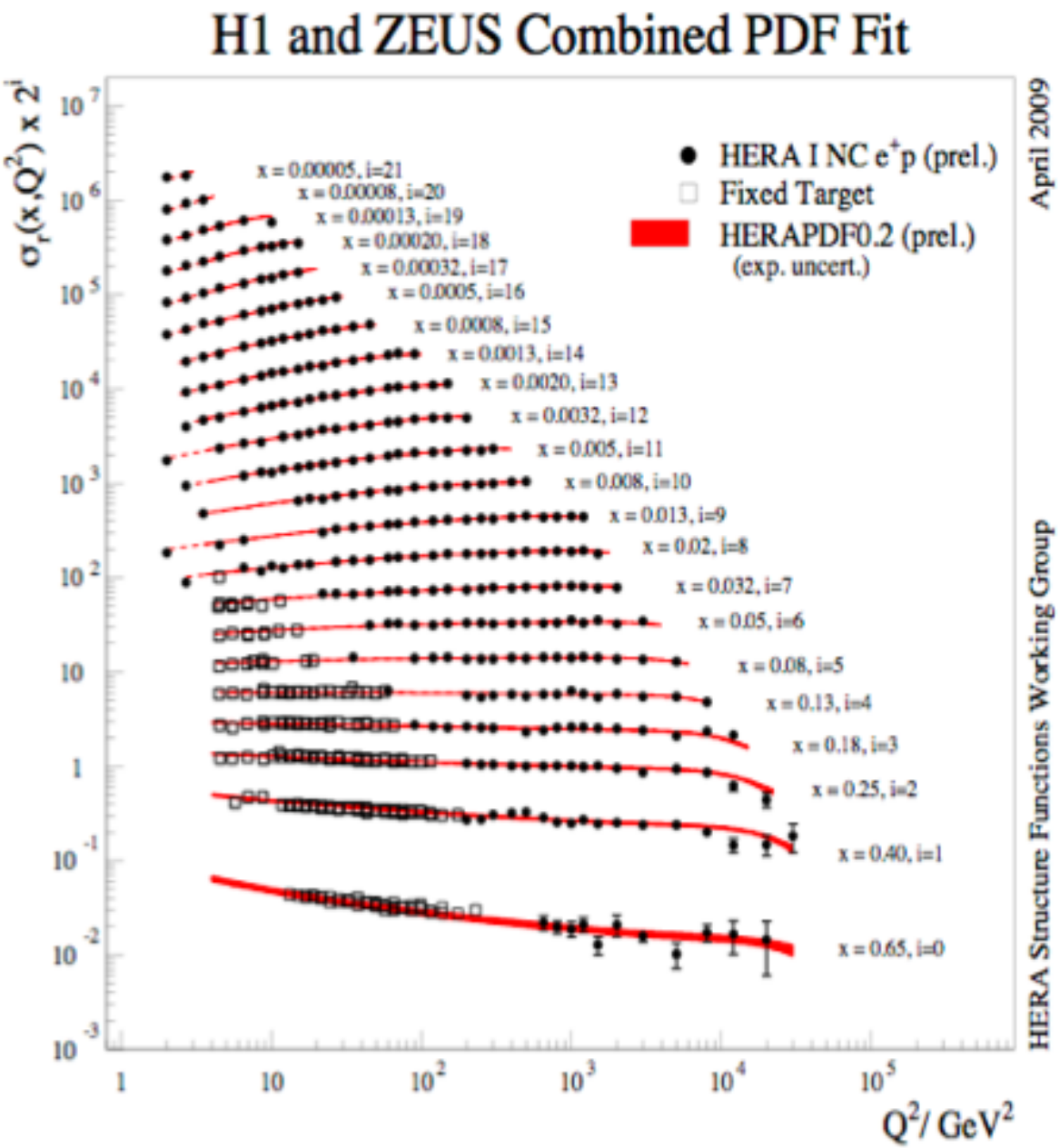
While moments need data at all x, here the unmeasured region at small x (where densities are large) does not enter

A probabilistic language for the branching at LO
(building up parton showers in event generators}

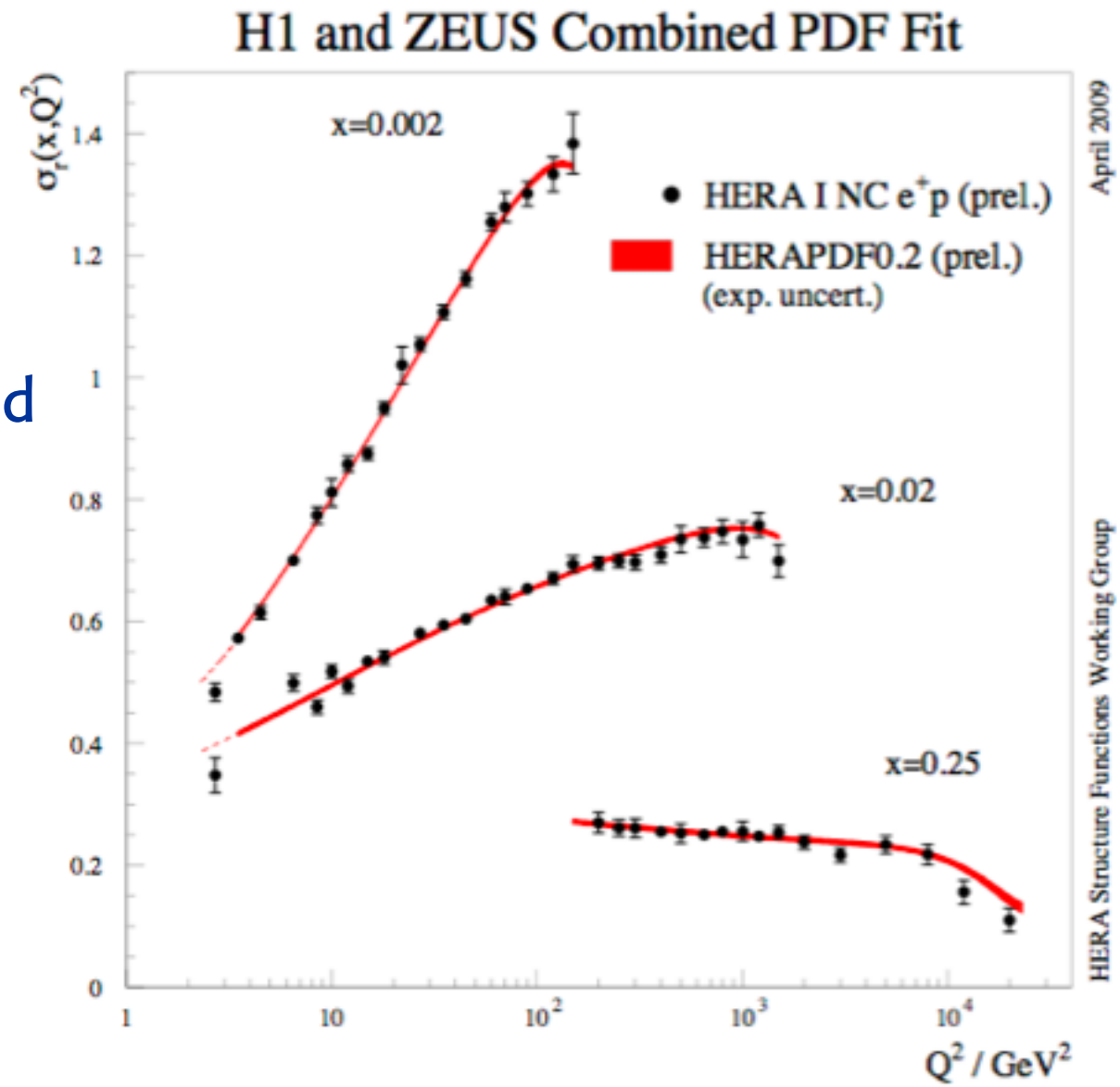
Great progress in the DIS data over the years culminated at HERA

Proton Structure Function $F_2(x,Q^2)$





This is how the scaling violations are compared with QCD evolution in 2015 after 46 years



I conclude by most warmly thanking again the EPS-HEPP Board for the Prize
and all of you for your attention