School on QCD, low x, Saturation and Diffraction
Enrico Predazzi

- **I.   Diffraction: an overview from its origin**
- **II. From basic kinematics to Regge poles**
- **III. Historical Interlude**
- **IV. Regge poles resurrected**
- **V. Unitarity effects in the b representation (if possible)**

Diffraction: an overview from its origin*

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*What's past is prologue (Shakespeare)

PRELIMINARIES & GENERALITIES

- **Diffraction: a pretty old and well established subject (on both accounts, theoretical as well as experimental)**

- **Good old wave properties**

A puzzling reference: "Leonardo da Vinci – An Artabras Book" – Reynal & Co in Association with William Marrow & Co. – N.Y. – Chapter *Leonardo Opticis*- Domenico Argentieri (pag. 405) says:

"*I made a great discovery in the transcription … of Gian Battista Venturini which was in the Reggio Emilia Library. The text shows clearly that Leonardo observed diffraction phenonena but gave a wrong interpretation*"

- There seems to be an explicite construction in a code by Leonardo da Vinci (1452-1519): He probably performed some kind of experiment but had no hint about the theoretical implications.

The gesuit father Francesco Grimaldi (Bologna, 1618-1663) in his posthumous treatise Physics Mathesis de Lumine, Coloribus et Iride (1665) is the first to use the word Diffraction when he says:

Lumen propagatur seu diffunditur non solum directe, refracte ac reflexe sed etiam quodam quarto modo **diffracte**

(Light propagates and diffuses not only directly, refractively and reflectively but also in a fourth way, diffractively)

Joseph Fraunhofer (1787-1826)
and **Augustin Fresnel** (1788-1827)
give the first mathematical
formulation of the different regimes of
diffraction working out the
approximate solutions of
the general formulation to reconstruct
e.m. images due to
Gustav R. Kirchhof (1824-1887).

Diffraction plays a central role in e.m. (obeying a system of linear [Maxwell] differential equations for which the superposition (Huygens) principle applies)

Analogies with D. exist in Q.M. due to its wave nature.

The analogy is complete in the case of elastic scattering when the internal structure of the interacting system does not come into play.

The inelastic diffractive excitations are peculiar Q.M. phenomena connected directly to the complexity of the internal degrees of freedom.

In this sense, hadronic D. represents a highly non trivial extension of a macroscopic phenomenon into the microscopic world

Various regimes of Diffraction

Suppose a beam of wave length $\lambda = 2\pi/k$ crosses a hole in a screen or (which turns out to be the same), meets an obstacle of linear (average) dimension R and one has to reconstruct the image on a screen (fig.)

We assume that the short walelength condition

$$kR \gg 1 \qquad\qquad (1)$$
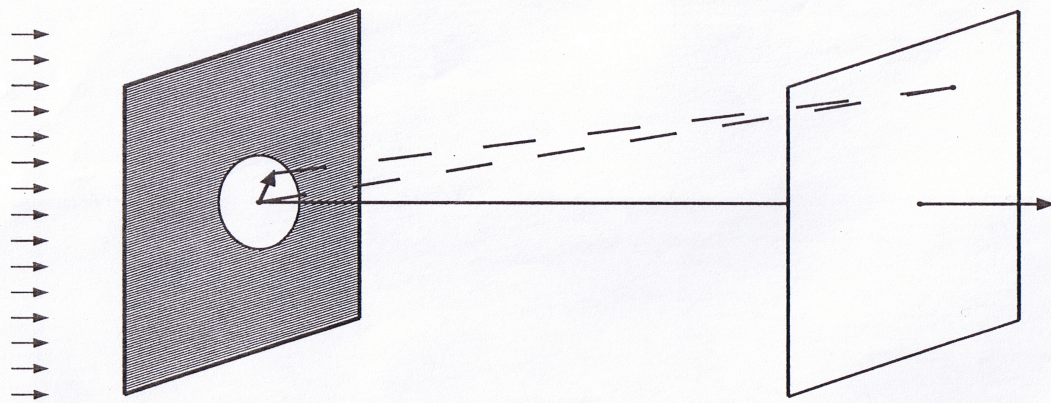
is always satisfied

Fig. 2.1. Diffraction of a plane wave by a hole in a screen.

Fraunhofer diffraction

- When the distance D between the obstacle and the screen is very large

  so that

  $$kR^2/D \ll 1 \qquad\qquad (2)$$

we are in the Fraunhofer regime

Fresnel Regime

- When

$$kR^2/D \approx 1 \qquad (3)$$

we are in the Fresnel regime

Geometrical Optics

- Finally, when

$$kR^2/D \gg 1 \qquad\qquad (4)$$

we are in the geometrical optics limit

LAYOUT OF THE TALK

- **1) Diffraction in particle physics**
- **2) Conventional particle diffraction**
- **3) From soft to hard diffraction**
- **4) Conclusions**

1) Diffraction in (high energy) particle physics

According to QM, a particle is endowed with a de Broglie wavelength and the short wavelength condition is always satisfied once we are in an energy range of the order of 1 GeV given that the hadron's dimensions are of the order of the Fermi. Thus, diffraction is expected to play a prominent role in particle physics (and it does, see figure 1).

Diffraction in nuclei and proton

QCD, lowx, Saturation and
Diffraction
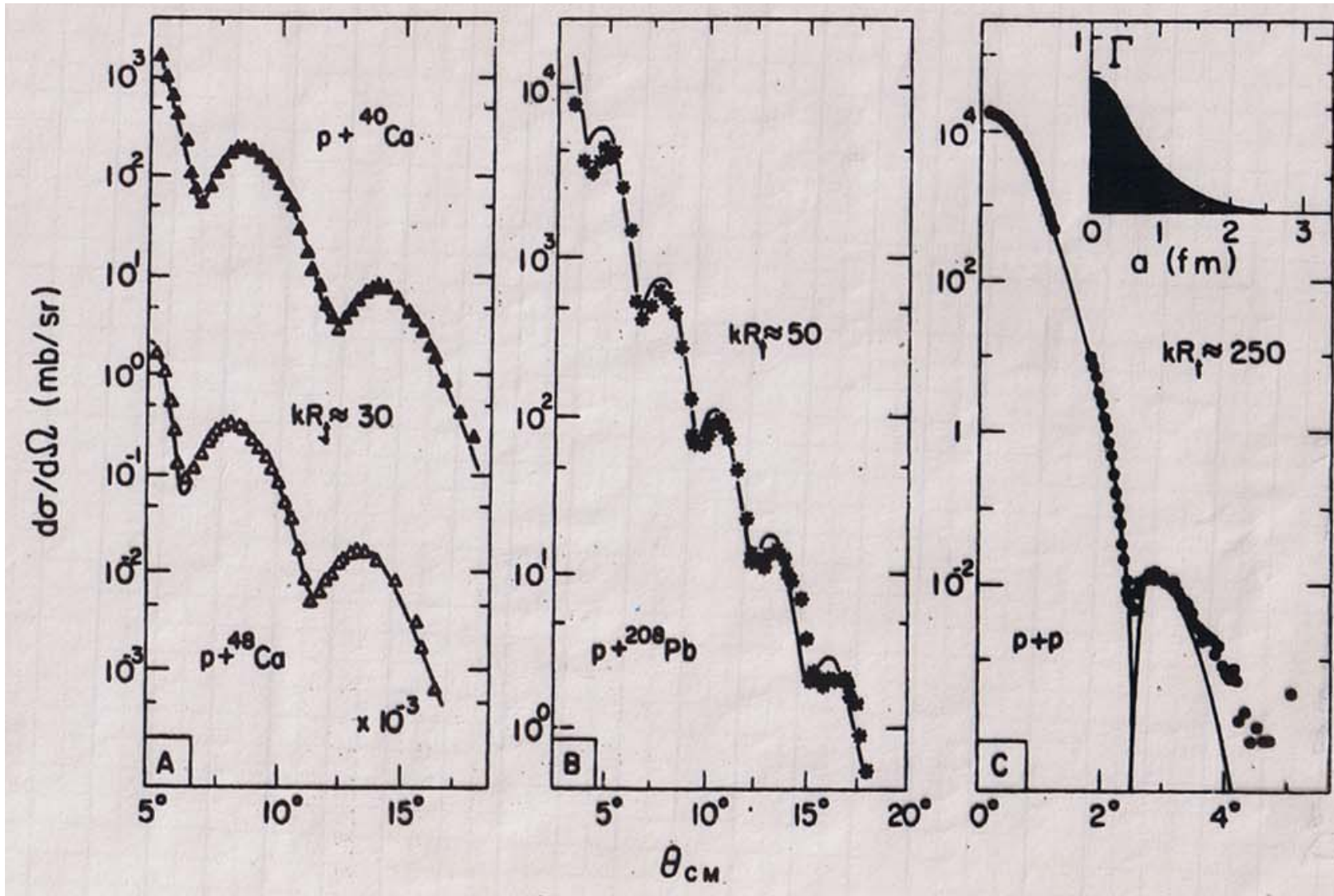
In (high energy) particle physics we are always in a Fraunhofer regime.

Consider the (most unfavourable) case of LHC as an example. In this case:

$\sqrt{s} \approx 15$ TeV, R ≈ 1 fm and D ≈ 1 cm

so that

$k\ R^2/D \approx 10^{-6}$

In the case of the Intersecting Storage Ring (ISR)

where $\sqrt{s} \approx$ 50 GeV, we would have had

$$k\ R^2/D \approx 10^{-9}$$

Whenever in the Fraunhofer regime,

the solution to the problem of diffraction takes on a rather simple form reminiscent of the geometry of the problem

If

$$\Gamma(\mathbf{b}, s)$$

(**b** being the usual impact parameter)

is the **profile function**; the scattering amplitude takes the form

$$f(\mathbf{q}, s) = (1/2\pi) \int \Gamma(\mathbf{b}, s) \exp(i \, \mathbf{b} \cdot \mathbf{q}) \, d\mathbf{b} \quad (4)$$

where **q** is the momentum transfer.

Analyzing the optical limit and the diffraction of the highest energy e.m. waves simulated by the collision of perfectly conducting spheres, T. T. Wu has come to the appalling conclusion that… "applied to the Maxwell regime, …*diffraction describes e.m. waves over at least 18 orders of magnitude from the Edison-Hertz to the Hera wavelengths*".

2) **Conventional particle diffraction**

Diffraction in particle physics is credited to have its origin from the Russian school of Landau and many names are to be associated to it: L. D. Landau, L. Y. Pomeranchuk, E. Feinberg, A. I. Akhiezer, A. Sitenko, V. N. Gribov

in my opinion, to date, the best definition of diffraction in particle physics remains the one given by Good and Walker in 1960; they write:

"…a phenomenon is predicted in which a high energy particle beam undergoing diffraction scattering from a nucleus will acquire components corresponding to various products of the virtual dissociations of the incident particle…"

and they predict

"These diffraction-produced systems would have a characteristic *extremely narrow distribution in transverse momentum and* would have *the* same *quantum numbers of the initial particles*"

This definition is not totally unambiguous but it is perfectly viable in most situations (and it applies both to soft and hard diffraction). It also perfectly agrees with the experimental results (figure).
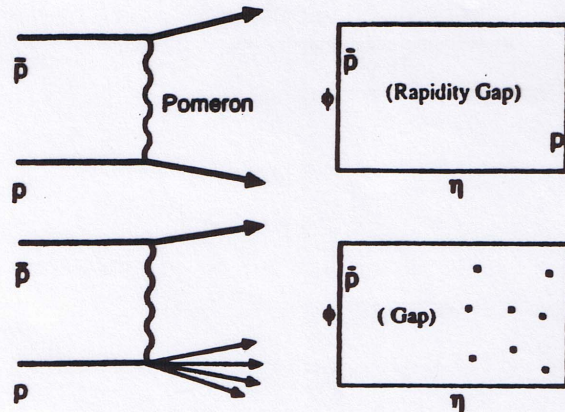
Diffraction in nuclei and proton
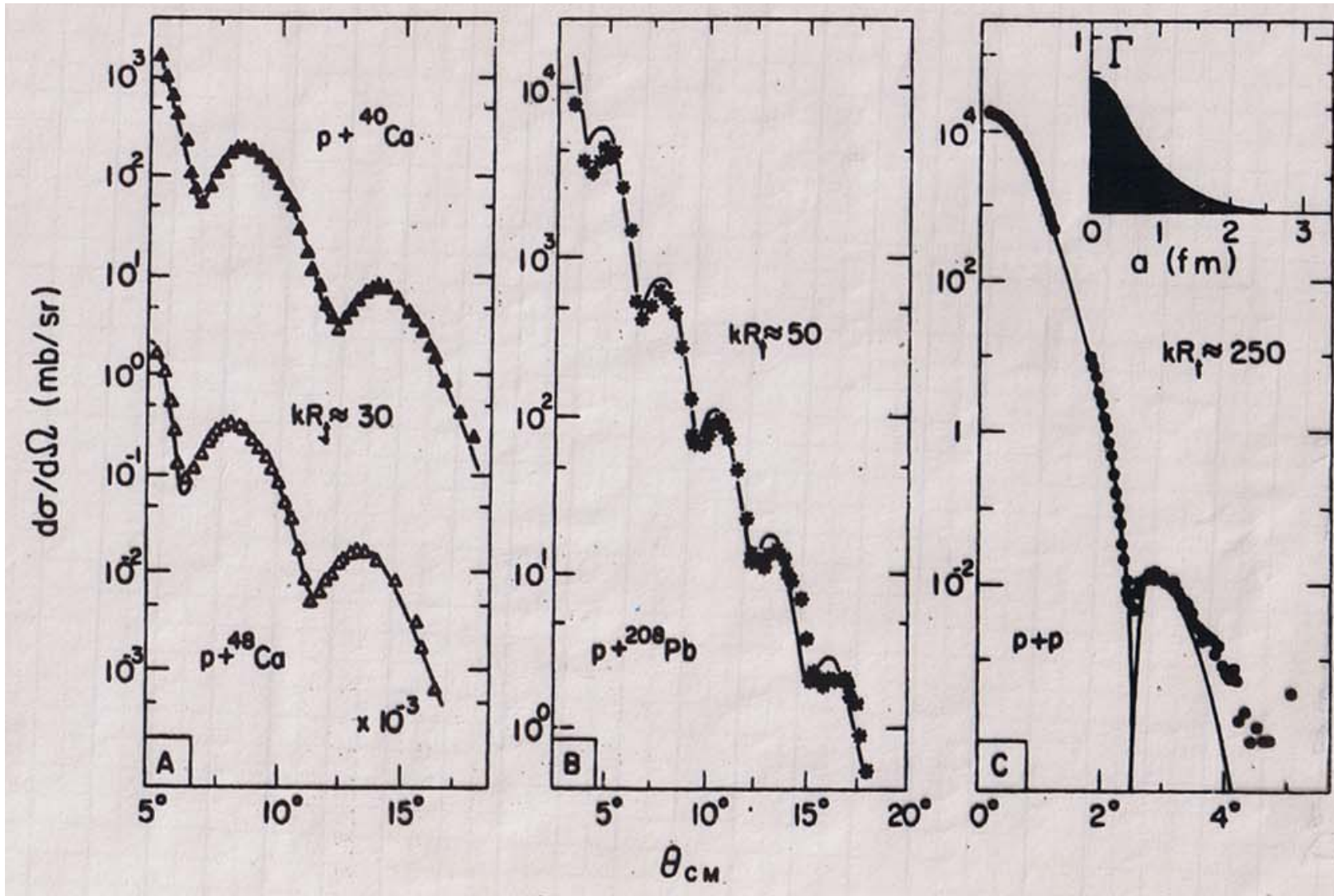
A valuable alternative and equivalent definition has been proposed first by Bjorken and uses the notion of **rapidity gaps** which have been variously verified to exist at the Tevatron and at HERA (we do not expect LHC to behave differently).
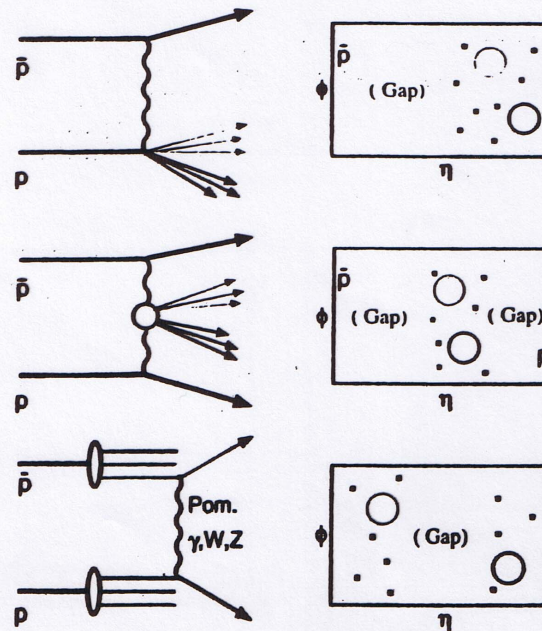
Rapidity Gaps

Soft Processes:

Pomeron

(Rapidity Gap)

Elastic Scattering

(Gap)

Single Diffraction

Hard Processes (jet production):

(Gap)

Hard Single Diffraction

(Gap)   (Gap)

Hard Double Pomeron

Pom.
γ,W,Z

(Gap)

Hard Color-Singlet

Rapidity gap events
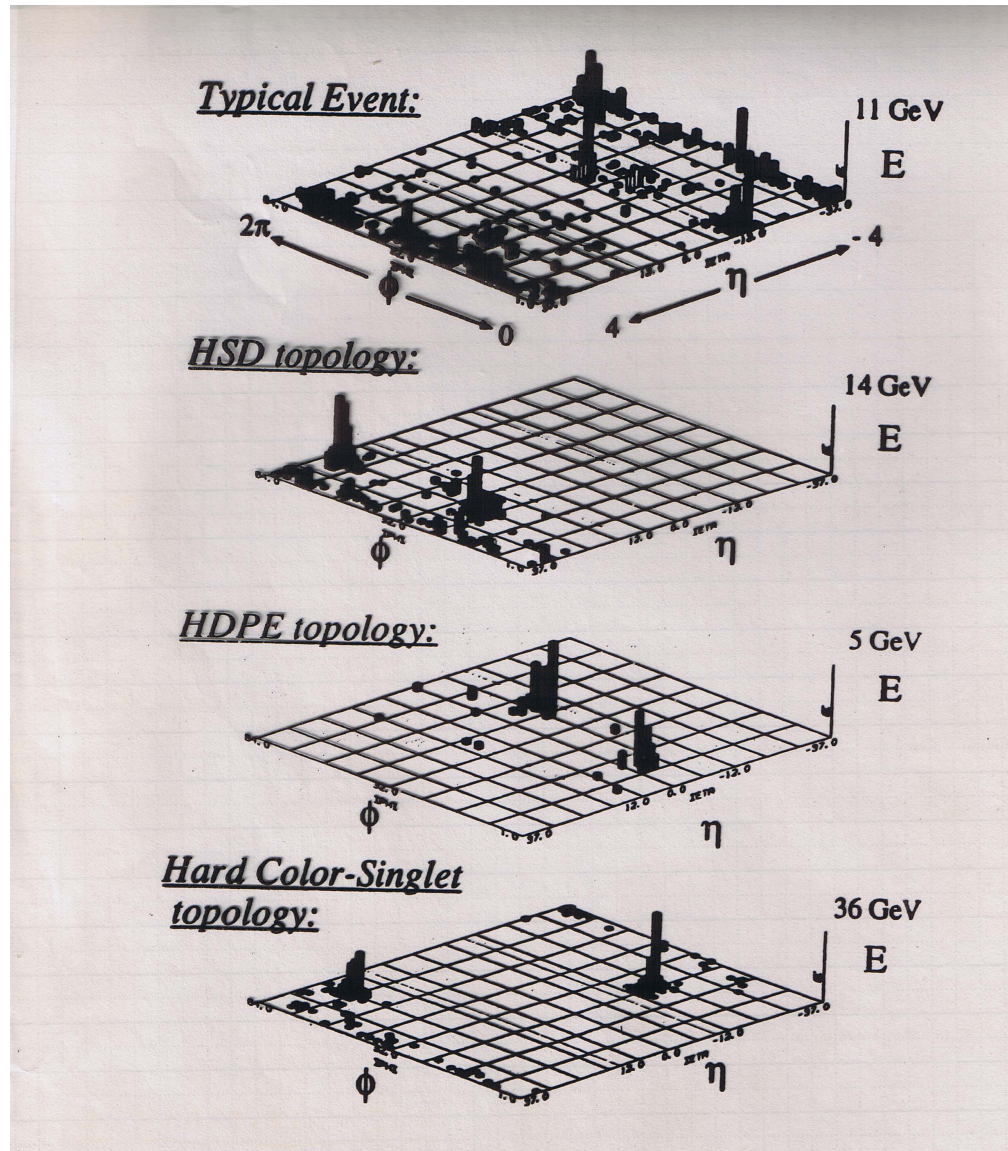
- According to the previous definition, we will say that: **diffraction occurs (and dominates in the high energy domain) when no exchange of quantum numbers takes place between the initial and the final state, i.e. when the reaction is of the kind**

- $\quad$ a + b $\longrightarrow$ a* + b* $\qquad$ (5)

- (where a* and b* have the same quantum numbers of a and b respectively)

This definition covers all cases in which diffraction has been verified to occur:

1) **Elastic scattering (a*=a, b*=b)**

2) **Single diffraction (a*=a and b* decays in many final particles but its Q.N. are still the same as b)**

3) **Double diffraction (also a* decays in many final particles but its Q.N. are the same as a)**

In these cases, (figure 2) the quantity exchanged between initial and final state is called

POMERON
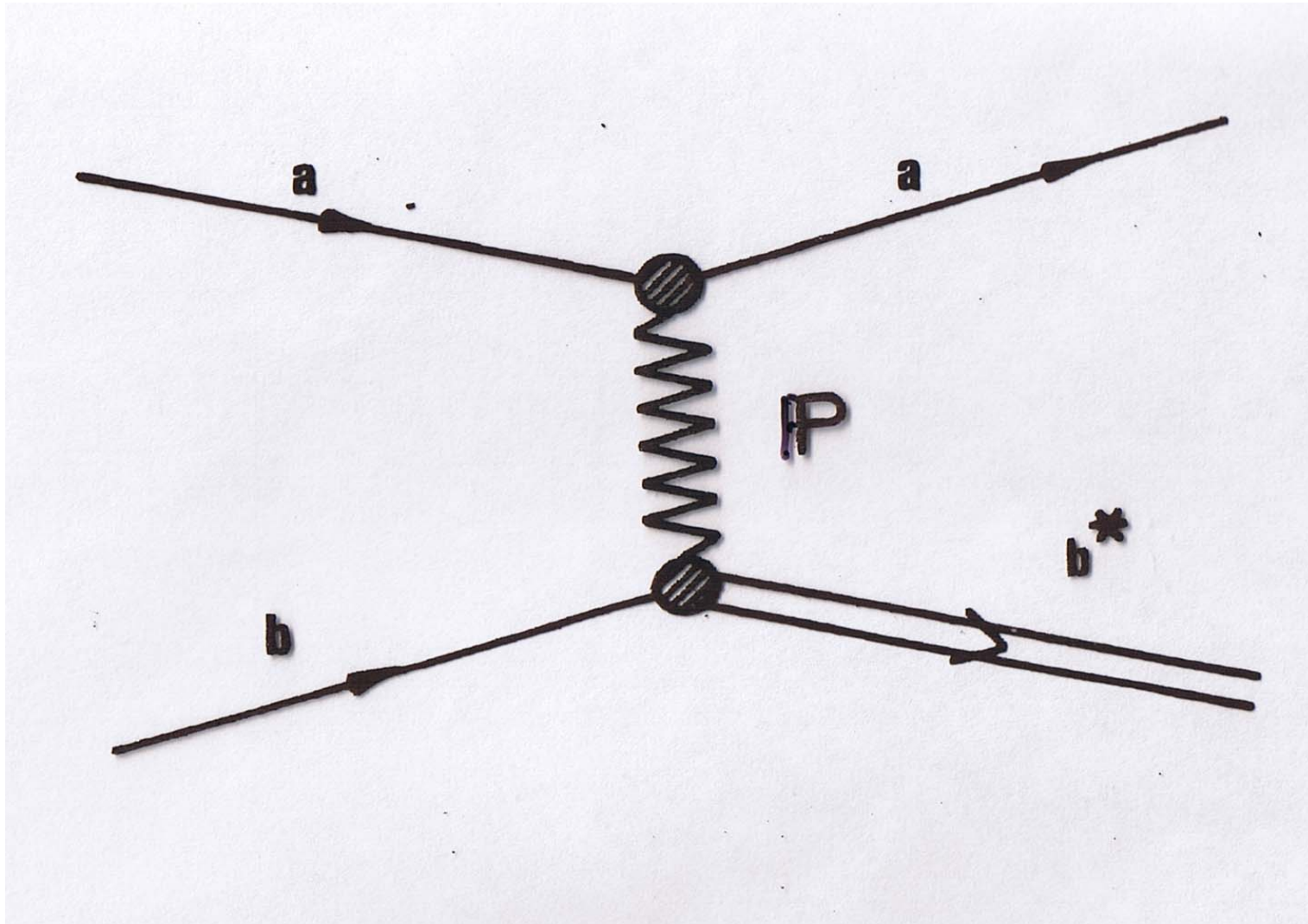
It is a matter of heated discussion not only whether the Pomeron is unique (see Landshoff) but whether it exists at all. Here we propose that **Pomeron exchange is *synonimous of exchange of no quantum numbers except, possibly, spin and parity*** (this appears to be a safe though little operational definition of the Pomeron).

We will list only a few of the many consequences of conventional (or soft) diffraction:

1) *Steep angular distributions (at small transverse momenta) like in optics*

2) *Rising with energy of total cross sections and of optical point*

3) *Shrinking of forward peak with energy (i.e. increase of slopes)*

(See figure 3)

p-p elastic

PROTON-PROTON ELASTIC SCATTERING
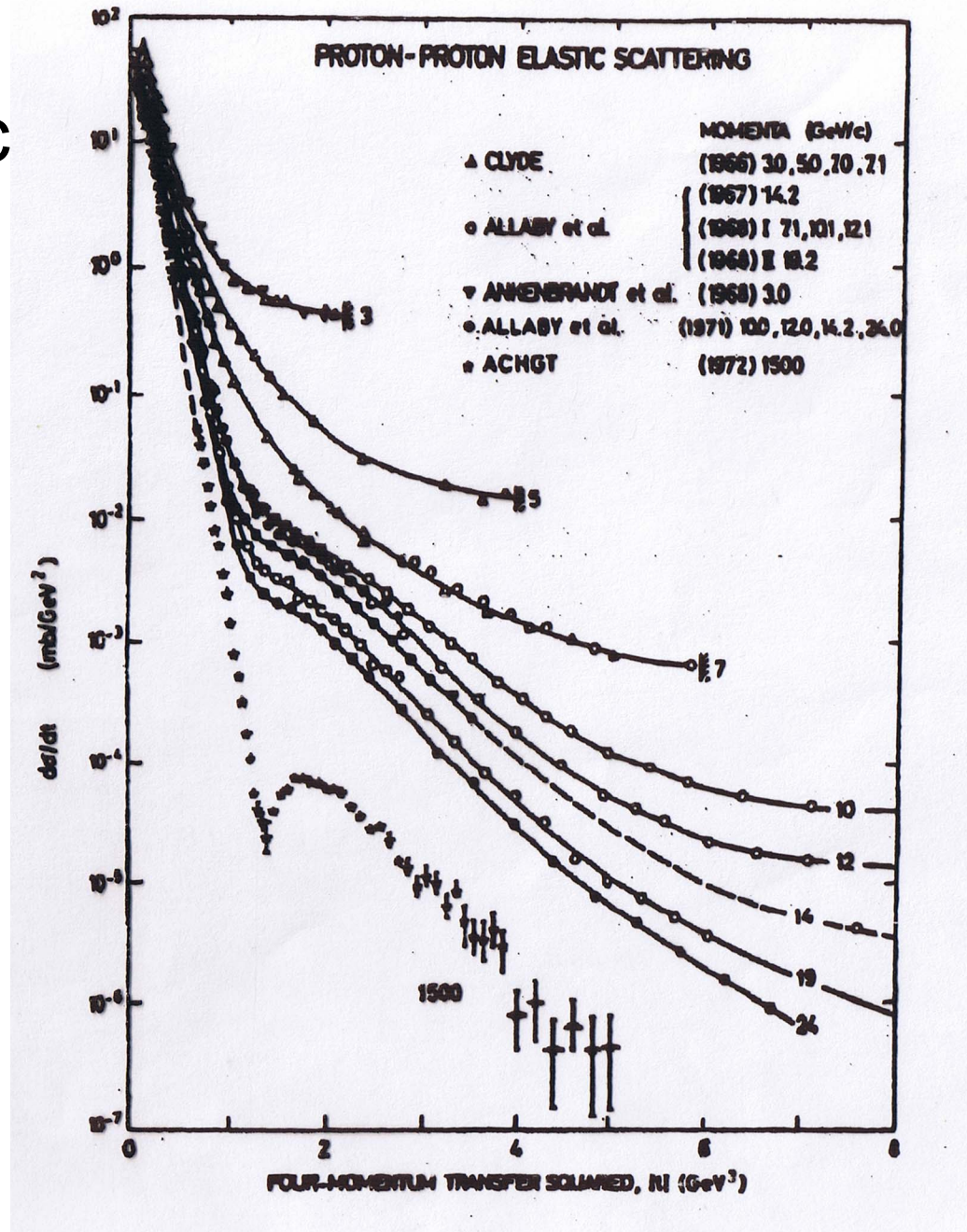
QCD, lowx, Saturation and
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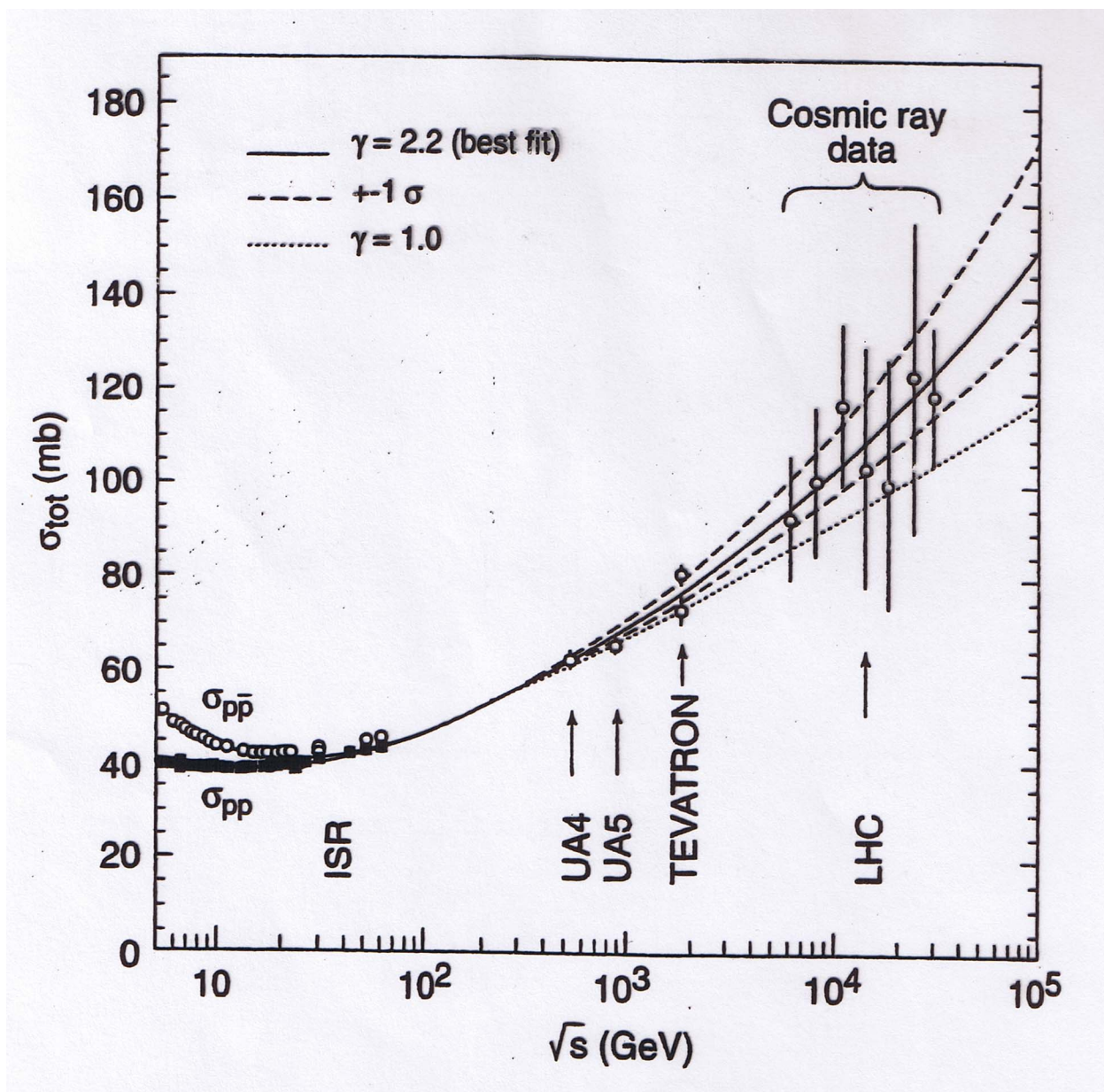
- As we shall see, all these properties (and more) are qualitative features of Regge poles
- Conversely, it is not true (at my eyes) that the whole of high energy particle physics is quantitively representable by Regge poles (but a good deal is)

In spite of many successes, it has remained essentially impossible to go beyond the frame of phenomenology in soft diffraction and perform actual and hard calculations.

The reason, in modern language, is that **soft diffraction lies in the realm of non perturbative QCD.**

This situation led, in the seventies, to a slow diminution of interest in soft diffraction.

3) From soft to hard diffraction

Somewhat unexpectedly, the turn for the revival of interest in diffraction came from the new hadronic fashion of the Seventies, *Deep Inelastic Scattering* (**figure 4**) where the composite structure of the hadrons was proved beyond doubts in **Inclusive lepton hadron collisions**

$$\ell(k) + h(p) \longrightarrow \ell(k') + X \qquad (6)$$

where **X** is an unresolved system of particles
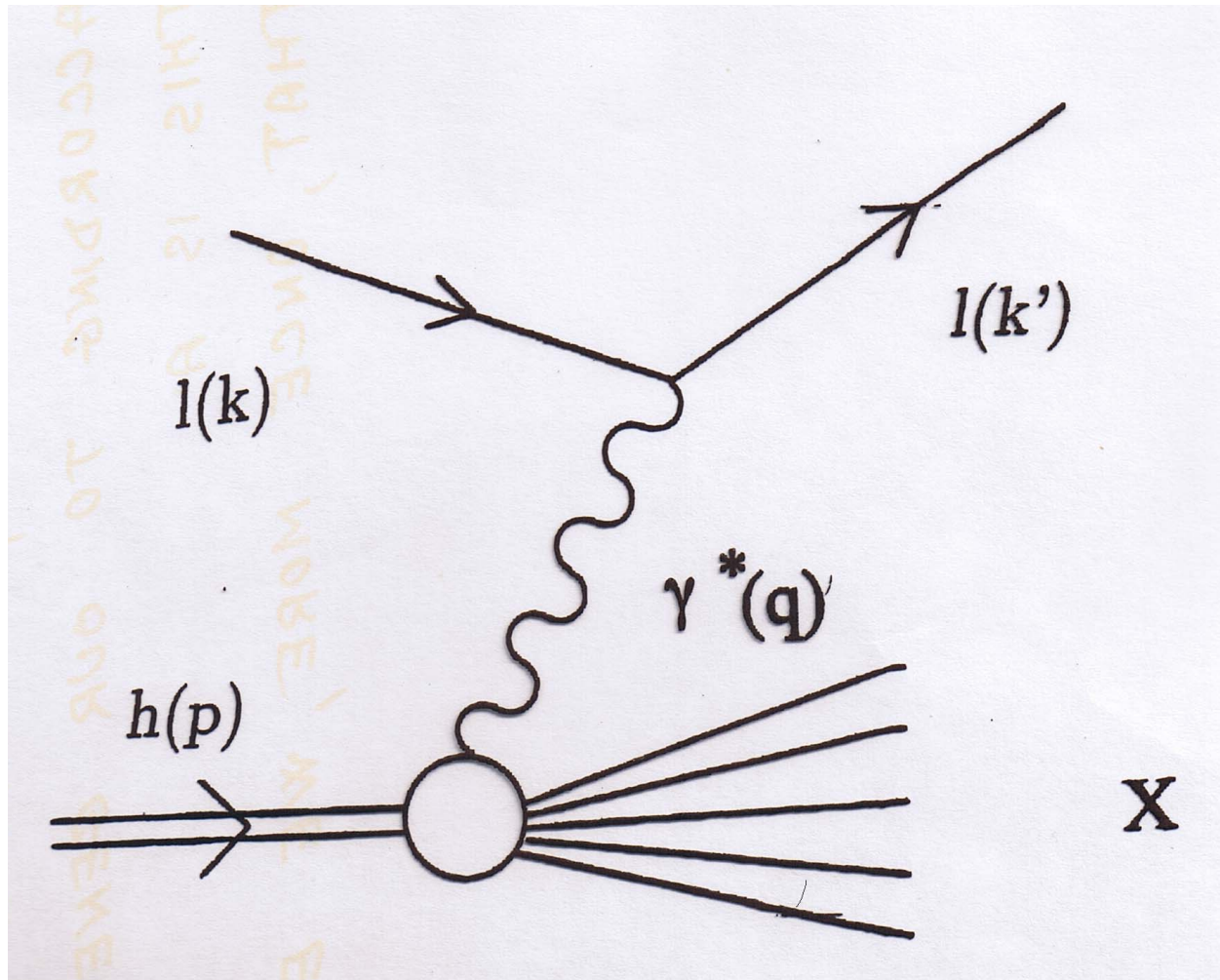
Like in any quasi-three body reaction, 3 independent variables are needed; these are often chosen as

$v = p \cdot q / m = E - E'$

$Q^2 = -q^2 = -(k - k')^2 > 0$

$x = Q^2 / 2 \, p \cdot q = Q^2 / 2 \, m \, v$

$0 \leq x \leq 1$

The *DIS regime* obtains when

$v \gg |Q| \gg m$

and

x is fixed

QCD, lowx, Saturation and Diffraction

From these experiments, Bjorken argued the existence of partons (to be identified with quarks and gluons) with a revival (60 years after)of the celebrated Rutherford analysis of the Geiger Marsden experiment proving the compositeness of the atom. Through many complex developments, QCD came of age, a new field of hadronic high energy (hard) diffraction was born

when Ingelman and Schlein suggested to investigate the seminclusive reaction

$$\ell(k) + h(p) \longrightarrow \ell(k') + h'(k') + X \qquad (7)$$

When hadron h' is the same as h, we are back to the case a diffractive reaction according to our definition (see figure 5) where the diffractive part is

$$\gamma^* + p \longrightarrow p' + X \qquad (8)$$

provided X has the same QN as the off shell photon γ (can be a vector meson or a vectorial quasiparticle)

4 Conclusions

It remains a rapidly expanding field; the literature (books and papers) about diffraction In general and hard diffraction in particular have grown tremendously in recent years and the field is still rapidly expanding.
The reader is urged to consult specialized books on the subject. In particular, let me recommend:

- **E. LEADER and E. PREDAZZI**

  An introduction to gauge theories and modern particle physics (Cambridge Press 1994)

- **V. BARONE and E. PREDAZZI**

  High energy particle diffraction (Springer Texts and monographs in physics) ISBN 3-540-42107-6 (2002)