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DIFFRACTION THEORY IN QCD AND BEYOND*

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Abstract

A study of the Pomeron in QCD is briefly outlined. Implications for the production of W^+W^- and Z^0Z^0 pairs are described and the possibility that the electroweak scale is a major strong-interaction threshold discussed. The application of Pomeron phase-transition theory to SU(5) dynamical symmetry breaking is suggested and the related "strong-interaction" properties of the photon briefly mentioned.

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1. INTRODUCTION

Diffraction, or the Pomeron, is a major theoretical challenge in QCD which cannot be attacked directly using either of the most familiar formulations of the theory—that is perturbation theory or lattice gauge theory. My attack[1] on the problem is based on the maximal exploitation of S-Matrix multiparticle Regge theory. I hope that this approach will ultimately be appreciated as a powerful technology which may also be useful for studying the spectrum of other gauge theories besides QCD. At the end of this talk I shall briefly describe a possible application to a particular[2] Grand Unified Theory which I believe is potentially very interesting (and which may even be relevant to recent high-energy phenomena observed in cosmic rays).

The talk will have four essentially distinct parts. I shall begin with a very brief review of my general program. I shall then describe the most immediate implications for electroweak collider physics—in particular the production of W^+W^- and Z^0Z^0 pairs. The possibility that there is an unexpectedly large cross-section for such pairs due to direct QCD production will be the focus. I shall then go on to discuss the possibility that the electro-weak scale is in fact a major threshold for the strong-interaction. Clearly the recent measurement[3] of a large real part at CERN encourages this speculation! Finally I shall describe how the complete picture of the Pomeron I advocate can be embedded in a unique unified theory in which Pomeron phase-transition theory may actually explain the (GUT) dynamical symmetry breaking. Effectively the photon becomes part of the Pomeron spectrum—a possibility which perhaps recent exotic cosmic ray phenomena actually point towards!![4]

2. MULTI-REGGE THEORY AND THE POMERON IN QCD

This topic is briefly reviewed in many of my publications[1] and a major review is in preparation. Here I shall simply outline the logical structure of the program I have been advocating for many years. The starting point is

A Multiparticle asymptotic dispersion relations[5] which have been developed from the full structure of "Axiomatic S-Matrix Theory"—with all evidence indicating that the relevant global analyticity properties are a consequence of the general framework of Axiomatic Field Theory.

B The dispersion relations allow the general formulation of multiparticle complex angular momentum theory[6] via Froissart-Gribov continuations, Sommerfeld-Watson representations, etc.

C Multiparticle unitarity equations continued into the complex angular momentum plane give the *reggeon unitarity* equations[6,7] which, for an even signature Regge pole "Pomeron", provide a general basis for the formulation of a Reggeon Field Theory (RFT) of the Pomeron.[8]

D The Critical Pomeron[9] is then derived as a reggeon "critical phenomenon" description of rising total cross-sections which is *unique* in satisfying all high-energy unitarity constraints.

E The final development of Pomeron RFT is the Super-Critical Pomeron phase[1] in which total cross-sections fall asymptotically but there is a Pomeron condensate and also a vector reggeon trajectory degenerate with that of the Pomeron.

F The connection with QCD is developed by first using **A** and **B** to develop the reggeon unitarity equations and corresponding RFT for (odd signature) vector reggeons.

G By matching vector RFT with perturbative reggeization calculations in spontaneously broken gauge theories a full RFT describing the high-energy behavior of spontaneously broken QCD can be developed.[1]

H The most important step comes next, that is the Super-Critical pomeron of **E** is identified[1] with QCD when the gauge-symmetry is spontaneously broken from SU(3) to SU(2). The Pomeron condensate is essentially identified with a winding-number condensate resulting from regularization of the quark sea.[10]

I Finally the restoration of SU(3) gauge symmetry is related to the Critical Pomeron. Connecting the RFT transverse momentum cut-off to the asymptotic freedom properties of spontaneously broken QCD shows[1] that the Critical Pomeron only occurs (for sure) in the special case that the asymptotic freedom constraint on the number of quarks is *saturated*.

K The conclusion is that a unitary, asymptotic, description of rising cross-sections in QCD requires "quark saturation"—that is the unrealistic possibility of sixteen quark flavors or the much more realistic possibility of

6 flavors of color triplet quarks plus 2 flavors of color sextet quarks.

3. ELECTROWEAK COLLIDER PHYSICS

Two flavors of color sextet quarks, if added to QCD, will produce a triplet of Goldstone boson massless "sextet pions" $\pi_6^{\pm}$, π_6^0 as a consequence of the breaking of the chiral $SU(2) \times SU(2)$ symmetry. In addition the sextet pions can provide[11] the electroweak Higgs sector so that the breaking of the chiral $SU(2) \times SU(2)$ symmetry simultaneously breaks the weak SU(2) gauge symmetry and gives mass to the $W^{\pm}$ and Z_0. In this case the longitudinal $W^{\pm}$ and Z^0 are effectively sextet pions and as a result[12]

W^+W^- and Z^0Z^0 pairs will be strongly produced by direct QCD interactions.

Note that the QCD interaction of sextet quarks is strong at the electroweak scale because

$$\alpha_s^6(Q^2) \sim \frac{C^6}{C_3}\alpha_s^3(Q^2) \qquad C_{6,3} \equiv \text{Casimir}$$
$$\equiv \frac{5}{2}\alpha_s(Q^2)$$

More specifically pure gluon interactions will produce W^+W^- (and Z^0Z^0) pairs immediately above threshold as illustrated in Fig. 1. Since gluon interactions are dominantly represented by the Pomeron at high-energy it is as if

W^+W^- (and Z^0Z^0) pairs are produced "out of the Pomeron".

To determine additional properties of the production process the best we can do[12] is exploit the similarity between sextet pions and normal pions in their Goldstone boson properties. That is we try to extrapolate W^+W^- (and Z^0Z^0) pair production from low-energy $\pi^+\pi^-$ (and $\pi^0\pi^0$) production.

The magnitude and energy dependence of the cross-sections for $pp\pi^+\pi^-$ and $\bar{p}p \to \bar{p}p\pi^+\pi^-$ is shown in Fig. 2. (As an aside we note that the cross-sections are equal, within experimental error, at all energies—suggesting, perhaps, a surprising dominance of gluon production processes.) At high-energies it is possible to apply a very simple chiral scaling argument[12] to the diffractive production process to give

$$\begin{aligned}\sigma_{\substack{\bar{p}p \to \bar{p}pW^+W^- \\ (+\text{ soft hadrons})}} &\sim \left(\frac{f_{\pi_3}}{f_{\pi_6}}\right)^2 \sigma_{\bar{p}p \to \bar{p}p\pi^+\pi^-} \\ &\sim \left(\frac{0.09}{250}\right)^2 \times (0.6 \text{ mb}) \\ &\sim 70 \text{ pb.}\end{aligned}$$

At high energies we expect both cross-sections to be almost entirely diffractive (we know this to be the case experimentally for the $\pi^+\pi^-$ cross-sections) and so 70 pb is a reasonable estimate for the W^+W^- cross-section at high energy. However, the $\pi^+\pi^-$ cross-sections are almost energy independent from just above threshold. If the W^+W^- cross-section behaves similarly then, 70 pb could also be a reasonable estimate of the low-energy cross-section.

In fact at least two $W + 2$ jet events have been observed[13] at CERN with very large transverse momentum and with the right two-jet mass to be interpreted as W^+W^- pairs. The corresponding cross-section would be three orders of magnitude larger than that expected in the standard model. From Fig. 3 it is clear that the large $p_\perp$ cross section(which is entirely given by the $W + 2$ jet events) should be 1–2% of the total W cross-section. This is just the 70 pb order of magnitude that we have estimated above.

We can obtain a crude picture of the full range of kinematic properties that we expect for W^+W^- pair production by scaling up the corresponding $\pi^+\pi^-$ production properties. Since we are only just above threshold we anticipate that m_W/m_π (rather than f_{π_6}/f_{π_3}) is a more appropriate rescaling and this is what we have used in Figs.4–6. To obtain "W^+W^-" distributions we have actually used five events—the two UA1 W-pair candidates referred to above, one UA2 W-pair candidate and two UA1 events that were (initially at least) considered as possible Z^0-pair candidates (ignoring the $W^\pm$-Z^0 mass difference we clearly expect the same kinematic properties for both W^+W^- and Z^0Z^0 pairs).

From Figs. 4–6 it is apparent that, qualitatively at least, the production of vector meson pairs at CERN (if that is what has been seen) could be that expected from the hadronic production of sextet pion pairs. Perhaps we have indeed seen the first evidence that the electroweak scale is a QCD (that is sextet color) scale and that the full fermion structure which I have argued to be needed for a complete, theoretically consistent, description of the Pomeron in QCD is actually present.

3. THE ELECTROWEAK THRESHOLD AND THE LARGE REAL PART

I have emphasized that the sextet quark QCD interaction is still strong at the electroweak scale—in order of magnitude we have

$$100 \text{ GeV for sextet quarks} \sim 100 \text{ MeV for triplet quarks.} \tag{3.1}$$

I also anticipate that there will be many bound-states—new "hadrons"—composed of sextet quarks. The lightest may well be "mixed" baryons—containing a sextet quark and two triplet quarks. Because of the strong-coupling involved we might expect substantial cross-sections for this new sector. Perhaps then the sextet quark mass-scale, or equivalently the electroweak scale, is a major new threshold for the strong-interaction as we know it.

It is clearly very tempting to consider that the large real part for the elastic $\bar{p}p$ amplitude measured at CERN is an indication of an electro-weak threshold effect. Many speakers[14] at this conference have argued that the result

$$\text{“}\rho \sim 0.24\text{”} \tag{3.2}$$

suggests a new threshold effect. Indeed it seems to me that since (3.2) gives a clear violation of the elementary derivative dispersion relation[15] (for the elastic amplitude $A(s,t)$)

$$\text{Re}\left[\frac{A(s,t)}{s}\right] \sim \frac{d}{d\ln s}\left[\frac{\text{Im}A(s,t)}{s}\right]\left(1+O\left(\frac{1}{\ln s}\right)\right), \tag{3.3}$$

we must be seeing some sort of threshold effect. (The derivative dispersion relation is immediate for any simple angular-momentum plane description of high-energy behavior.)

We have also heard at this conference[16] that initial observations at the Fermilab Tevatron do not seem to indicate any dramatic rise in the general inelastic cross-section. Certainly not anything in the region of 30–40 mb as some of the dispersion relation fits[14,17] to ρ that we have been shown indicate. It might, however, be significant that there is not as yet any indication on the magnitude of either the diffractive or the elastic cross-sections. Both might still be substantially larger than expected.

Apparently there are indications[18] from cosmic ray observations that diffractive effects do indeed have a significant threshold between the CERN $S\bar{p}pS$ energies and the Tevatron collider. In particular Centauro and Mini-Centauro events seem to be diffractive production processes with thresholds around $\sqrt{s} \sim$ 1–2 TeV. Recall also that the finite mass sum rule[19] implies that any major increase in the diffractive cross-section should ultimately be accompanied by a similar increase in the elastic cross-section, and vice versa. So it is certainly natural for the diffractive and elastic cross-sections to separately increase significantly faster than the general inelastic cross-section. Indeed since the elastic cross-section has already increased substantially more than the diffractive cross-section from the ISR to the $S\bar{p}pS$ energy range, the finite mass sum rule (which is well-satisfied at the ISR) actually suggests that a corresponding increase in the diffractive cross-section is imminent.

We have already noted that sextet quarks are (pair-) produced by gluons, so we expect them to be produced in very high-energy "gluon excitation processes" and in particular during diffractive excitation processes. That is the exchange of a QCD Pomeron ("made of gluons") should, at very high energy, lead to the (presumably copious) diffractive production of sextet hadrons which could be seen, perhaps, for the first time at CDF. It would be very nice, of course, to find a link between the properties of sextet hadron production and those of centauro events but we will not explore this possibility here.

In general terms it seems to me that a consistent view of what is seen (or hinted at) in all existing data is—

$10\ \text{GeV} \lesssim \sqrt{s} \lesssim 100\ \text{GeV} \leftrightarrow$ "high-energy" Pomeron theory for triplet quark QCD interactions

$100\ \text{GeV} \lesssim \sqrt{s} \lesssim\ ?$ $\leftrightarrow$ sextet quark sector emerges out of the Pomeron".

This implies, of course, that the Pomeron will be more complicated for some energy range and will only be truly asymptotic way above the electroweak scale!!

4. GRAND UNIFICATION AND POMERON PHASE-TRANSITION THEORY

In QCD the Critical Pomeron phase-transition involves[1] the spontaneous breaking of the SU(3) gauge symmetry which therefore is at the point of occurring dynamically when the theory is saturated with quarks. Note that this implies that *the cross-section rises asymptotically because gluons are almost deconfined!*

In a higher gauge group the analogous critical point (determined by the possibility of adding a Higgs sector while preserving asymptotic freedom) occurs for less than the maximum number of flavors. Therefore

saturation with fermions may break the gauge symmetry dynamically.

I should briefly mention my belief that the physical phenomenon produced by adding many fermions (which are effectively massless at high-energy) is the enhancement of instanton interactions. Such interactions combine with the ("massless") fermion sea to produce[10] a "winding-number condensate" which can actually be identified with the Pomeron condensate of Pomeron phase-transition theory.

There is an essentially unique unified theory which is asymptotically free and contains the $SU(3) \times SU(2) \times U(1)$ sector of the Standard Model together with the sextet quark content required for the $SU(2) \times U(1)$ symmetry breaking discussed above. This is[2] SU(5) gauge theory with the (left-handed) fermion content

$$5 \oplus 15 \oplus 40 \oplus 45^{*}. \tag{4.1}$$

This set of representations is entirely contained in the 144 representation of SO(10) and so it might be that we should study an SO(10) theory directly. However, the SU(5) theory given by (7.10) is actually saturated with fermions and so we expect a Super-Critical Pomeron phase to occur. In this case a winding-number condensate will effectively break the gauge-symmetry to $SU(3) \times SU(2) \times U(1)$. (Chiral symmetry breaking of the sextet SU(2) symmetry then leaves $SU(3) \times U(1)$ as the residual symmetry.) It seems therefore that the fermion saturation mechanism described by a Pomeron phase-transition may be the dynamical mechanism behind GUT dynamical symmetry breaking.

An intriguing aspect of this kind of unification is that the photon can be regarded as part of the "Pomeron spectrum" in the theory. Of course, the electromagnetic coupling is so weak at low energy that the photon appears to be associated with a much weaker interaction than the Pomeron. However, if all of the fermions in (4.1) (apart from the known low-energy fermions) enter the theory between the electroweak-scale and the GUT symmetry-breaking scale as we anticipate, then the energy-dependence of the SU(3) × SU(2) × U(1) couplings must qualitatively be as illustrated in Fig. 7. (This is because we expect the winding-number condensate to develop at a mass-scale well above all fermion mass-scales where all fermions are effectively massless. Also both the SU(3) and SU(2) couplings will be non-asymptotically free in the energy-range above the fermion mass-scale and before the SU(5) gauge symmetry is restored.) We have no real estimate of the energy scales involved in Fig. 7. However, it is clear that there should be an energy range where the SU(5) symmetry is not restored but the electromagnetic interaction is strong and any photon-Pomeron equivalence should be manifest. Perhaps this is related to the speculation[4] that for $E \sim$ 10–100 TeV the photon radically changes its interaction with matter—the normal electromagnetic interaction being replaced by a diffractive-like interaction. Apparently this would explain many exotic cosmic-ray phenomena (including the apparent absence of π^0's in Centauro events)!

REFERENCES

1. For a complete set of references see A. R. White, "The Pomeron in QCD", Argonne preprint ANL-HEP-PR-87-92—contribution to the Review Volume "Hadronic Multiparticle Production", edited by P. Carruthers, to be published by World Scientific Publishing Co.

2. K. Kang and A. R. White, Journal of Modern Physics **A2**, 409 (1987).

3. UA4 Collaboration, D. Bernard *et al.*, CERN preprint CERN/EP 87-147 (1987).

4. F. Halzen, P. Hoyer and N. Yamdagni, Phys. Lett. **B190**, 211 (1987).

5. H. P. Stapp and A. R. White, Phys. Rev. **D26**, 2145 (1982), H. P. Stapp, in Structural Analysis of Collision Amplitudes, Les Houches Lectures, edited by R. Balian and D. Iagolnitzer (North-Holland, New York, 1976).

6. A. R. White, in Structural Analysis of Collision Amplitudes, Les Houches Lectures, edited by R. Balian and D. Iagonitzer (North-Holland, New York, 1976).

7. V. N. Gribov, Y. Ya Pomeranchuk and K. A. Ter Martirosyan, Phys. Rev. **B139,** 184 (1965).

8. V. N. Gribov, Sov. Phys. JETP **26,** 414 (1968); H. D. I. Abarbanel, J. B. Bronzan, R. L. Sugar and A. R. White, Phys. Repts. **21C**, 119 (1975).

9. A. A. Migdal, A. M. Polyakov and K. A. Ter Martirosyan, Zh. Eksp. Teor. Fiz. **67,** 84 (1974); H. D. I. Abarbanel and J. B. Bronzan, Phys. Rev. **D9**, 2397 (1974).

10. N. S. Manton, Ann. Phys. **159,** 220 (1985).

11. W. J. Marciano, Phys. Rev. **D21,** 2425 (1980); E. Braaten, A. R. White and C. R. Willcox, Journal of Modern Physics **A1,** 693 (1986).

12. A. R. White, Mod. Phys. Letts. **A2,** 397 (1987).

13. UA1 Collab., C. Albajar *et al.*, Phys. Lett. **B193**, 389 (1987).

14. A. Martin has emphasized this particularly, CERN preprint, to appear.

15. J. D. Jackson, Scottish Universities Summer School Lectures (1973), J. B. Bronzan, G. L. Kane and U. P. Sukhatme, Phys. Lett. **49B,** 272 (1974).

16. Informal remarks by G. Giacomelli and K. Goulianos.

17. Contributions by P. Kluit and K. Kang.

18. K. Goulianos, these proceedings and in Proceedings of the Workshop on Physics Simulations at High Energies, Madison (1986) published by World Scientific Publishing Co.

19. Y. Akimov *et al.*, Phys. Rev. **D14,** 3148 (1976), M. B. Einhorn, J. Ellis and J. Finkelstein, Phys. Rev. **D5,** 2063 (1972); A. I. Sanda, Phys. Rev. **D6**, 280 (1972).

FIGURE CAPTIONS

Fig. 1 Multi-gluon production of sextet pions and hence W^+W^- and Z^0Z^0 pairs.

Fig. 2 Energy dependence of $\sigma_{pp\to pp\pi^+\pi^-}$ and $\sigma_{\bar{p}p\to\bar{p}p\pi^+\pi^-}$.

Fig. 3 p_T dependence of UA1 production of W's.

Fig. 4 Comparison of rapidity dependence of "W^+W^- events" with low-energy pion pairs.

Fig. 5 Comparison of mass dependence of "W^+W^- events" with rescaled low energy pion pairs.

Fig. 6 Comparison of the $p_\perp$ dependence of "W^+W^- events" compared with rescaled low-energy pion pairs.

Fig. 7 Qualitative evolution of SU(3) × SU(2) × U(1) gauge couplings in the SU(5) unified theory.

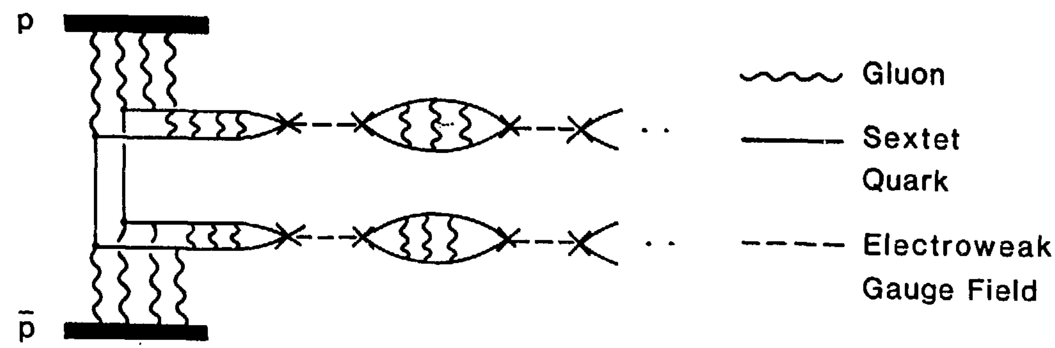
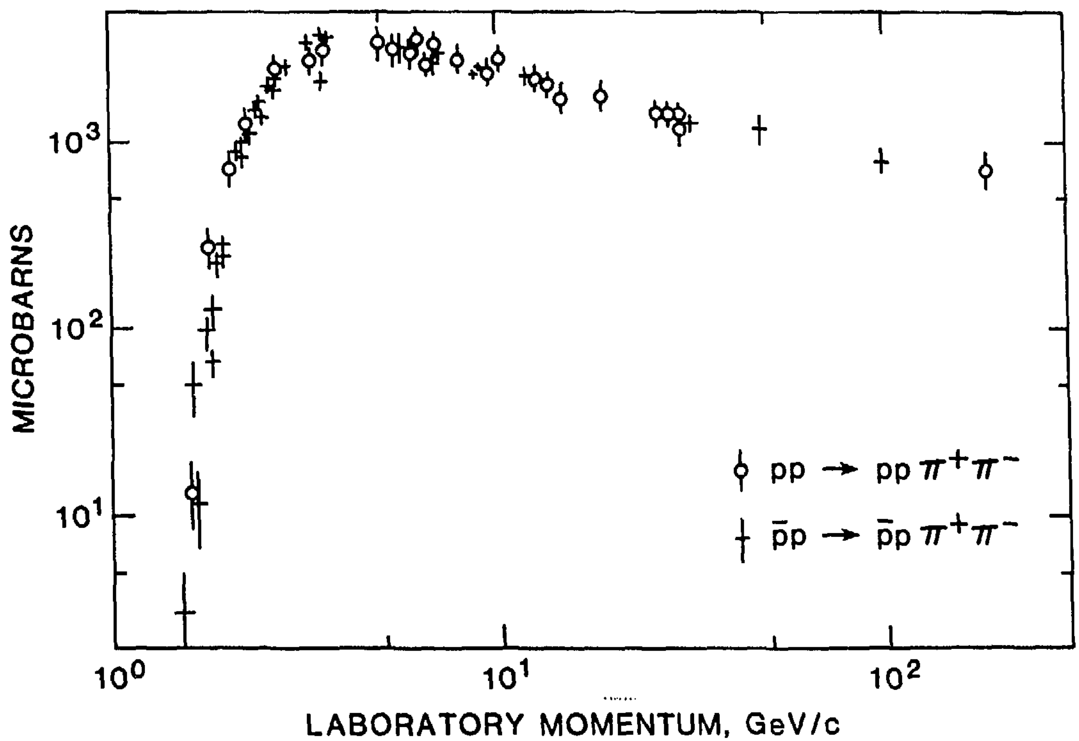


Fig. 1



MICROBARNS
10^3
10^2
10^1
10^0
10^1
10^2
LABORATORY MOMENTUM, GeV/c
$pp \rightarrow pp\,\pi^+\pi^-$
$\bar{p}p \rightarrow \bar{p}p\,\pi^+\pi^-$

Fig. 2

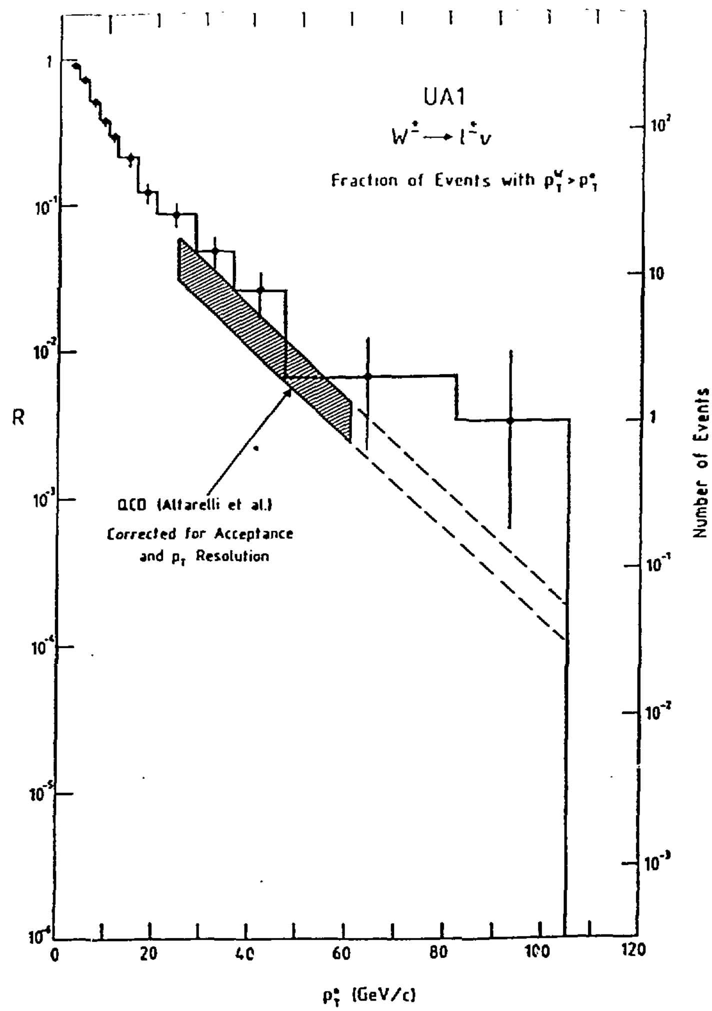

UA1
W± → l±ν
Fraction of Events with $p_T^W > p_T^*$
QCD (Altarelli et al.)
Corrected for Acceptance
and p_T Resolution
R
Number of Events
p_T^* (GeV/c)

Fig. 3

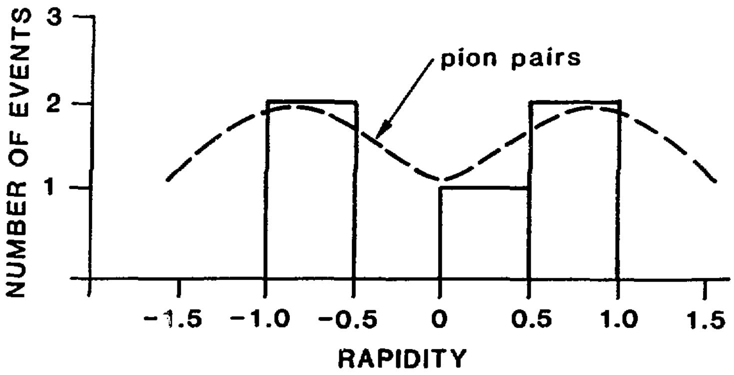


Fig. 4

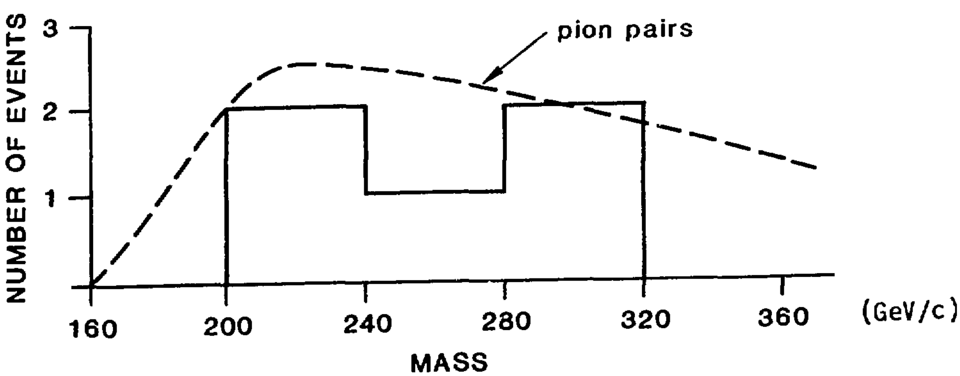

pion pairs
NUMBER OF EVENTS
3
2
1
160
200
240
280
320
360
(GeV/c)
MASS

Fig. 5

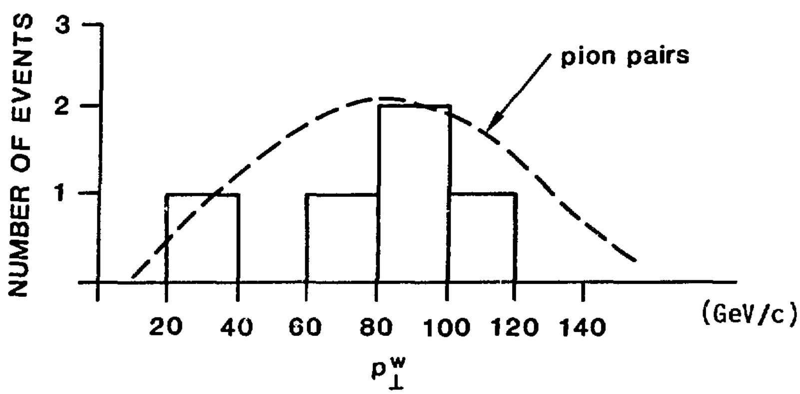

NUMBER OF EVENTS
3
2
1
pion pairs
20
40
60
80
100
120
140
(GeV/c)
$p_\perp^w$

Fig. 6

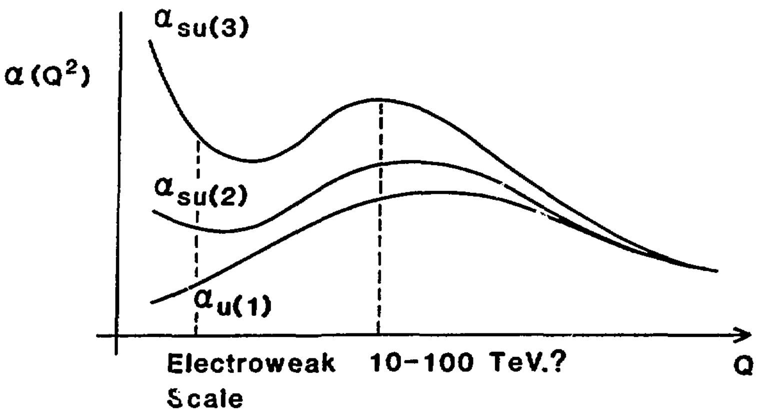

$\alpha_{su(3)}$
$\alpha(Q^2)$
$\alpha_{su(2)}$
$\alpha_{u(1)}$
Electroweak
Scale
10-100 TeV.?
Q

Fig. 7