QCD HARD PROCESSES IN $\bar{p}p$ COLLISION

Jiro KODAIRA
Department of Physics
Hiroshima University
Hiroshima 730
Japan

Some aspects of Quantum Chromodynamics (QCD) at short distance are reviewed. The vector boson productions in $\bar{p}p$ collision are discussed with special emphasis on the soft gluon effects. The jets at large p_T and the jet activities associated with vector bosons are also briefly mentioned.

1. Introduction

Quantum Chromodynamics (QCD) at short distance has been one of the main topics in the high energy physics.[1] It is now well established that the hadron interactions at short distance can be consistently described by the QCD improved parton model. Especially the new data[2] from the CERN-SPS-Collider have provided a further confirmation of the theory in a new energy regime. Today's interests in QCD at high energies are two-fold. Firstly we can expect that an even more stringent test of QCD will be made at much higher energies. Secondly QCD processes like jets will be the dominant backgrounds for "new phenomena" which are expected[3] to occur at 100 GeV - 1 TeV energy scale from various theoretical considerations.

In general, making a quantitative prediction of QCD is quite difficult in spite of the fact that there is no doubt in the qualitative agreement of the theory with experiments. The reason is that even if the short distance behavior of QCD is quantitatively described, the large distance non-perturbative effects still elude a systematic analysis. The theoretical predictions sometimes depend explicitly on the phenomenological model for the non-perturbative regions. On the other hand even in the short-distance parts, there still exist several issues such as the "K-factor", the excitation of heavy flavors, the effects of multi-gluon radiations, etc.

In this talk I will focus on some aspects of the perturbative QCD in $\bar{p}p$ collision. The Drell-Yan process for the vector boson (W, Z, "γ", ···) productions will be reviewed with special emphasis on the p_T distributions. Jet productions at large p_T and jet activities produced in association with vector boson are also briefly discussed. Other various aspects of the theory including the important problems of the hadronization will not be discussed.[4)]

2. Drell-Yan Process for Vector Boson Production

2a Inclusive Production

The total and the rapidity differential cross section are predicted by the QCD improved parton model[1)] through the Drell-Yan mechanism. Schematically, the parton model (rapidity y) cross-section is given by

$$\frac{d\sigma}{dy} \sim \frac{1}{s} \sum_{a,b} \int_{x_1}^{1} \frac{d\xi_1}{\xi_1} \int_{x_2}^{1} \frac{d\xi_2}{\xi_2} f_a(\xi_1, Q^2) f_b(\xi_2, Q^2) \hat{\sigma}_{ab}(\alpha_s(Q^2)) , \tag{1}$$

where f_a are the parton distributions and a, b run over parton species. s is the total C.M. energy and $Q^2 = M_V^2$ for the vector boson V. Although Eq.(1) assumes a very simple form, it already has some subtleties. After the proof[5)] of the factorized form of Eq.(1), the higher order corrections to the parton sub-processes $\hat{\sigma}_{ab}$ has been calculated[6)] and proved not to be negligible. Inclusion of the higher order effects increases the naive parton model prediction by the so-called K-factor[7)] which generally depends on the energy and also the rapidity y. Therefore the "zeroth" order prediction for this process should be written as,

$$\frac{d\sigma}{dy} \sim \frac{K}{s} \sum_{a} \int_{x_1}^{1} \frac{d\xi_1}{\xi_1} \int_{x_2}^{1} \frac{d\xi_2}{\xi_2} f_a(\xi_1, Q^2) f_{\bar{a}}(\xi_2, Q^2) , \tag{2}$$

where K is the K-factor. At smaller energies the correction is extremely large and the resummation technique must be applied to make a meaningful prediction.[8)] The resummation of such large corrections leads to the result $K \sim 2$ at fixed target energies. On the other hand, the size of the $O(\alpha_s)$ correction at the collider energies is about 30% ($K \sim 1.3$). This decrease in the size of the radiative corrections is mainly due to the decrease in the size of the running coupling constant α_s. Therefore at higher energies, more reliable predictions we can get. However when s becomes large with Q^2 fixed, we will encounter another aspect, namely small $\tau(= Q^2/s)$ problem.[9),10),11)] For example the weak boson production at TeV collider requires the parton distribution functions at values of $\sqrt{\tau} \sim 10^{(-2 \sim -4)}$. This problem has been recently discussed by several authors.[12)] It is very important to use an appropriate structure function which is valid also at this region.[10),11)]

Now we can give the theoretical prediction by using Eq.(2) with some theoretical uncertainties related to different choices of the structure functions, Λ and the scale in α_s. The recent analyses in Ref.9) give the following predictions for the total production cross section of weak bosons at $\sqrt{s}$ = 540 GeV.

$$\sigma^{W^++W^-} = (4.2 \,{}^{+1.3}_{-0.6}) \text{ nb} , \quad \sigma^{Z^0} = (1.3 \,{}^{+0.4}_{-0.2}) \text{ nb} . \tag{3}$$

The error in Eq.(3) refers to the uncertainties mentioned above. Multiplying Eq.(3) by the branching ratio into electrons which are given by, if m_{top} = 40 GeV and α_s/π = 0.04,

$$B(W \to e\nu) = 0.089 , \quad B(Z^0 \to e^+e^-) = 0.032 ,$$

we get the following values.

$$(\sigma B)_{W\to e\nu} = (370 \,{}^{+110}_{-60}) \text{ pb} , \quad (\sigma B)_{Z^0\to ee} = (42 \,{}^{+12}_{-6}) \text{ pb} .$$

These values are to be compared with the experimental data,[13)]

$$(\sigma B)_W = 530 \pm 80 \pm 90 \text{ pb} , \quad (\sigma B)_Z = 71 \pm 24 \pm 13 \text{ pb} \quad \text{UA1}$$

$$(\sigma B)_W = 530 \pm 100 \pm 100 \text{ pb} , \quad (\sigma B)_Z = 110 \pm 40 \pm 20 \text{ pb} \quad \text{UA2} .$$

Fig.1 shows[9)] the theoretical predictions for the total cross-section against the C.M. energy for the productions of W and hypothetical vector bosons with their masses. Note that the two cross-sections (one is for pp, another is for $p\bar{p}$) are almost the same due to the sea quark dominance at high energies.

2b Semi-Inclusive Process —— p_T Distribution ——

The transverse momentum distribution in the Drell-Yan process is of great interest. When the transverse momentum of the vector boson (Q_T) is large ($Q_T \sim Q$), the cross section is well described by the standard QCD improved parton model, i.e. the low order terms in the perturbative series can reliably predict the cross-section. On the other hand when $Q_T^2 \ll Q^2$, the low order perturbative expansion does not make sense because the appearance of large logarithms $\ln^n Q^2/Q_T^2$ at each order of α_s clearly breaks the perturbative expansion. This large logarithmic correction is produced by the emission of soft gluons. The compensation between real emission of gluons and virtual contributions is not complete since the real gluon phase space is limited by a condition on Q_T. Since the soft gluon radiation is characteristic of QCD (presence of gauge bosons) and most of the cross-section is at small Q_T, it is important problem from both theoretical and practical point of view. In order to get a meaningful answer, these large logarithms must be resummed to all orders.

After the pioneering work of Ref.14), much progress has been made.[15)-22)] A great amount of theoretical analyses, which has been accumulated recent years, has provided a consistent framework on this subject. The techniques to sum up the large logarithms to all orders are developed and all logarithms are now under theoretical control. Based on these developments we can give a precise prediction for the complete transverse momentum distributions. Of course, some non-perturbative effects, namely intrinsic transverse momentum and possible initial state interaction[23)], come into play especially at very small Q_T. At smaller energies it is difficult to separate the soft gluon effects from the above effects. However at higher energies it is expected that we can see the soft gluon effects clearly.

The resummation of soft gluon effects can be done systematically in the impact parameter space (b-space).[15)] The general result for the Q_T cross section is [19),20)]

$$\frac{1}{\sigma}\frac{d\sigma}{dQ_T^2} = \frac{1}{4\pi}\int d^2\vec{b}\, e^{-i\vec{b}\cdot\vec{Q}_T}\,\hat{\sigma}(b) + Y(Q_T^2, Q^2) \ . \tag{4}$$

$Y(Q_T^2, Q^2)$ is a regular function of Q_T at $Q_T = 0$. The cross-section in b space factorizes into two structure functions, F, and an effective quark (Sudakov) form factor, exp $T(b, Q^2)$, which contains all the informations from the soft gluons. $\hat{\sigma}(b)$ is written as

$$\hat{\sigma}(b) = R(b^2)\exp T(b, Q^2) \ ,$$

and

$$T(b, Q^2) = -\int_{(b_0/b)^2}^{Q^2} \frac{dq^2}{q^2}\{\ln\frac{Q^2}{q^2}A(\alpha_s(q^2)) + B(\alpha_s(q^2))\} \ , \tag{5}$$

$$R(b^2) = \{F_q(b_0/b)F_{\bar{q}}(b_0/b) + (q \leftrightarrow \bar{q})\}(1 + O(\alpha_s(b_0^2/b^2)) \ ,$$

where $b_0 = 2e^{-\gamma_E}$. A and B can be calculated perturbatively. The general structure of the exponent T will be [19),20)]

$$T(b) = \sum_{n=1}^{\infty} \sum_{m=0}^{n+1} d_{nm} B^m L^{-n} ,$$

where $B = \ln b^2Q^2$ and $L = \ln Q^2/\Lambda^2$. The behavior of the cross-section for $Q_T \simeq 0$ and $Q^2 \to \infty$ is controlled by a saddle point in the integration over b. It turns out that the sensible approximation is given by taking the following limit; $L \to \infty$ with B/L fixed. Therefore in order to have the lowest approximation one must calculate A to the order α_s^2 and B to the order α_s. (β function is calculated to order α_s^2.) The neglected terms are suppressed by a factor of L^{-1}. The calculation gives,

$$A = \frac{C_F}{\pi} \alpha_s + \frac{C_F}{2\pi^2} K\alpha_s^2 ,$$

$$B = - \frac{3C_F}{2\pi} \alpha_s ,$$

where

$$K = C_G(\frac{67}{18} - \frac{\pi^2}{6}) + N_F T_F(- \frac{10}{9}) .$$

K has been calculated in Ref.20) and 21). Note that the perturbative expansion is performed at two scales b and Q, therefore the above approximation is valid for $Q^2 \gtrsim \frac{1}{b^2} \gtrsim \Lambda^2$.

Qualitative features of the cross-section are easily found from Eqs.(4) and (5). The effective form factor exp T provides a strong cut off at large b. This Sudakov type suppression becomes stronger as Q^2 increases. Since the non-perturbative effects are important only at large b, the whole of the cross -section is dominated by the short distance effects if Q^2 is large enough. This property is one of the most important results of the soft gluon physics. This behaviour is shown in Fig.2 schematically.

In order to make a quantitative prediction, we must perform the integration in Eq.(4). Here as usual we got involved in various nuisances. The integration is from b = 0 to ∞ although the result presented above is sensible in the region $\frac{1}{Q^2} \lesssim b^2 \lesssim \Lambda^2$. There is practically no problem in the integration from 0 to 1/Q due to the kinematical factor b from $d^2\vec{b}$. The region $b \gtrsim 1/\Lambda$

is more of a problem. In this region the perturbative result itself is not reliable and some non-perturbative effects would dominate unless Q^2 is large enough to make suppression in this region. There have been proposed some methods to control this region. The usually adopted procedures are i) smearing by an intrinsic transverse momentum[20] and ii) freezing of the coupling constant someway[9] and iii) both[19]. There may be "K-factor" also in this process. Finally the parametrizations of the structure functions introduce some uncertainties into the numerical results. These problems are discussed in detail in the recent papers Ref.9) and 24). In Fig.3 is shown[24] the contribution of each term in Eq.(5) to the cross sections for the W production in $\bar{p}p$ at $\sqrt{s}$ = 630 GeV. In this result the smearing method proposed in Ref.19) is used and the structure function is DO2[25] (Duke and Owens Set 2 with Λ = 0.4 GeV). It is discussed that in the region $6 < Q_T < 16$ GeV the result is not sensitive to the non-perturbative effects and so give a reliable prediction[24]. In their analyses, only the soft gluon regions are discussed. Therefore the results are correct for small Q_T. The authors in Ref.9) successfully join the cross-section at large Q_T to that at small Q_T including the soft gluon effects to all orders. They used a different method to control the large b region. The coupling constant is freezed such as $\alpha_s(q^2) = [\beta_0 \ln (q^2 + a\Lambda^2)/\Lambda^2]^{-1}$ including the heavy quark thresholds properly. a is a parameter. No smearing device is introduced. The results are insensitive to a for $Q_T^2 \gtrsim 1$ GeV^2 and $a\Lambda^2 < 1$ GeV^2. The normalized cross-section $R = (d\sigma/dQ_T dy)/(d\sigma/dy)|_{y=0}$ for the W-production are exemplified in Fig.4[9] with the data of the UA1 and UA2 groups.[13] Duke-Owens (Gluck-Hoffmann-Reya)[26] structure functions are used in Fig.4a(4b). In these predictions the term K in Eq.(5) is not included since the effect of K can roughly be reproduced by changing Λ by a factor of about 1.5. It should be noticed in Fig.4 that the predictions are much more sensitive to Λ than to the parametrization of the structure functions. Therefore when one tries to extract the value of Λ from these processes it is important to include K.[19),20] And in fact, the inclusion of K is required from theoretical point of view as discussed before. Note also that the results at large Q_T are subject to some theoretical uncertainties related to the choice of the scale in α_s which can be removed by calculating the $O(\alpha_s^2)$ terms completely. From the above analyses, I conclude that the new data at collider energies have given a clear evidence for the soft gluon effects and provided an essentially new test of QCD. There are many processes to which the soft gluon resummed formula can be applied. For example, the momentum spectrum of lepton from W decay is recently discussed in Ref.27) and 28) with successful results. The Drell-Yan processes at ISR energies are recently reanalized in Ref.29) including the soft gluon effects. It is claimed that the data are completely consistent with the theoretical expectations without any appreciable intrinsic transverse momentum.

3. Large Transverse Momentum Phenomena

3a Jet Production at Collider

Jet production is one of the clean evidence for the QCD improved parton model.[30] As discussed in the previous sections, the widely separated two or more jets production and in general, so-called large p_T phenomena can be predicted reliably by the low order QCD perturbation theory. The new data from CERN SPS for jet phenomena has added a further confidence for QCD. In this section I review the well-known analyses[31] just for "sceptics".

Jet production is calculated by the similar formula to Eq.(1),

$$d\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1,Q^2) f_b(x_1,Q^2) d\hat{\sigma}_{ab}(\alpha_s(Q^2)) \ . \tag{6}$$

The scale Q^2 which enters in α_s and structure functions is expected to be of the order of p_T^2. We must await a complete calculation of the next leading terms to fix the scale exactly. It is interesting to note that numerically the parton sub-process cross-sections behave almost the same for any a, b as shown in Fig.5a[32] by three lines and in Fig.5b[33] by the area between the two broken lines. Also shown are the data for the angular distributions of jet from UA1 and UA2. By making use of this fact, the formula Eq.(6) can be approximated as follows.

$$d\sigma = \int dx_1 dx_2 F(x_1, Q^2) F(x_2, Q^2) d\hat{\sigma}(\alpha_s(Q^2)) \ , \tag{7}$$

where $d\hat{\sigma}$ is the universal function and F is the effective structure function. F is given by

$$F(x, Q^2) = G(x, Q^2) + \frac{4}{9}[q(x, Q^2) + \bar{q}(x, Q^2)] \ . \tag{8}$$

The waight in the right hand side of Eq.(8) comes from the fact that the approximate ratios of the parton cross-sections are

$$d\hat{\sigma}_{qq} : d\hat{\sigma}_{ag} : d\hat{\sigma}_{gg} \approx 1 : (9/4) : (9/4)^2$$

due to the color factors. Now we can compare the $F(x, Q^2)$ from the jet production data with the theoretical expectation using the low energy ν data. This is done in Fig. 6.[32),33)] The value $Q^2 = 2000\ GeV^2$ is used as the typical scale for jet productions. The nice agreements are obtained. However it should be kept in mind that there remain several theoretical uncertainties. For instance, the perturbative results are ambiguous within a factor of two or so because the "K-factor" in this process has not yet been obtained and no exact scale is known as discussed before. These are due to the lack of the complete calculation of the next leading orders although there are partial results.[34)]

In general, also for large p_T phenomena there remain several important calculations. Especially taking into account the fact that the QCD processes could be a dominant background for "New Phenomena", much works should be done such as i) higher order corrections, ii) many jets process e.g. four jets production, iii) double parton scattering process[35)], etc.

3b Jet Activity Associated with Vector Boson

In section 2 the weak boson productions are discussed and the agreement between the theory and the experiment is shown. It is of some interest to see the final hadronic structure associated with the weak bosons since we may get a deeper understanding of the hadronic interactions and also a further check of the perturbative structure of QCD. Recently this problem is discussed in Ref.36) and 37). The cross-section for the V(vector boson W or Z^0) plus n jets production can be calculated in the standard framework of perturbative QCD as far as the kinematical regions where the soft singularities are not negligible are avoided. Among the many interesting predictions related to this process is the jet multiplicity distribution. The jet multiplicity distribution is defined as[36)]

$$f_n = \frac{R_n}{1+\sum_{\ell=1} R_\ell},$$

where $R_n = \sigma(V + nJets)/\sigma(V)$. The predictions for $W(Z^0)$ plus n jets are shown[36)] in Fig.7 with the data. In this calculation the cuts $p_T^{jet} \geq p_T^{min} = 6$ GeV/c and $r \equiv \sqrt{(\Delta\phi^2+\Delta\eta^2)} > r_{min} = 1$ (where ϕ is the azimuthal angle and η is the pseudorapidity) are adopted. It may be premature to say anything about the apparent discrepancy for the Z^0.[37)] These kind of analyses should be forwarded in order to extract "new singals" from the experimental data.

4 Conclusions

The hadron physics at short distance has entered upon a new situation since the beginning of the experiment at CERN SPS. The new data have given clear and further indications in favor of QCD as an underlying theory of the strong interactions. For large p_T phenomena the various analyses show an excellent agreement between the theory and the experiment. One of the important theoretical progress of recent years has been the development of the framework of the resummation of soft gluon effects to all orders. The theoretically reliable predictions have provided a new test of QCD at small Q_T regions. The numerical analyses have shown a beautiful agreement with the data.

On the other hand I would like to stress that there are many issues which should be investigated. Reducing the theoretical uncertainties for the QCD process would be one of the next jobs for theorists in order to have a much firmer confidence for QCD and to estimate the QCD backgrounds correctly for possible new physics. The higher order calculations for the two jets production and a new estimate for multijets process should be completed before the construction of new $\bar{p}$-p and/or p-p colliding machines.[11),38)]

Finally, why does the nature respect the theory (QCD and also Glashow-Weinberg-Salam theory) so gently? The answer could be "The nature is so simple" and/or "The human being is so clever".

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Figure Captions

Fig.1. Total cross-sections for the production of W and hypothetical vector bosons (M = 200, 500, 1000 GeV).
Solid line is for $p\bar{p}$ collisions and dashed line for pp collisions. (Structure function is DO1.) Ref.9)

Fig.2. Qualitative behaviors of $\hat{\sigma}(b)$ and $d\sigma/dQ_T^2$ when Q^2 increases.

Fig.3. Transverse momentum distribution of W at $\sqrt{s}$ = 630 GeV. Dashed-dotted line corresponds to the $T(b, Q^2)$ which includes only the first term in A. Dashed line; without K. Solid line is the full "lowest order" prediction of the soft gluon resummed formula. Ref.24)

Fig.4. Normalized cross-section $R = (d\sigma/dQ_T dy)/(d\sigma/dy)$ at rapidity y = 0 with the data using the structure function of DO(4a) and the structure function of GHR(4b). Ref.9)

Fig.5. Angular distributions of parton sub-processes with the UA1 data (5a) and the UA2 (5b). Ref.32) and 33)

Fig.6. Effective structure functions F in jet productions predicted by QCD. Ref.32) and 33)

Fig.7. Jet multiplicity distributions for W and Z production. QCD predictions are indicated by the horizontal solid (using DO1 structure functions) and dashed (using DO2) lines. Ref.36)

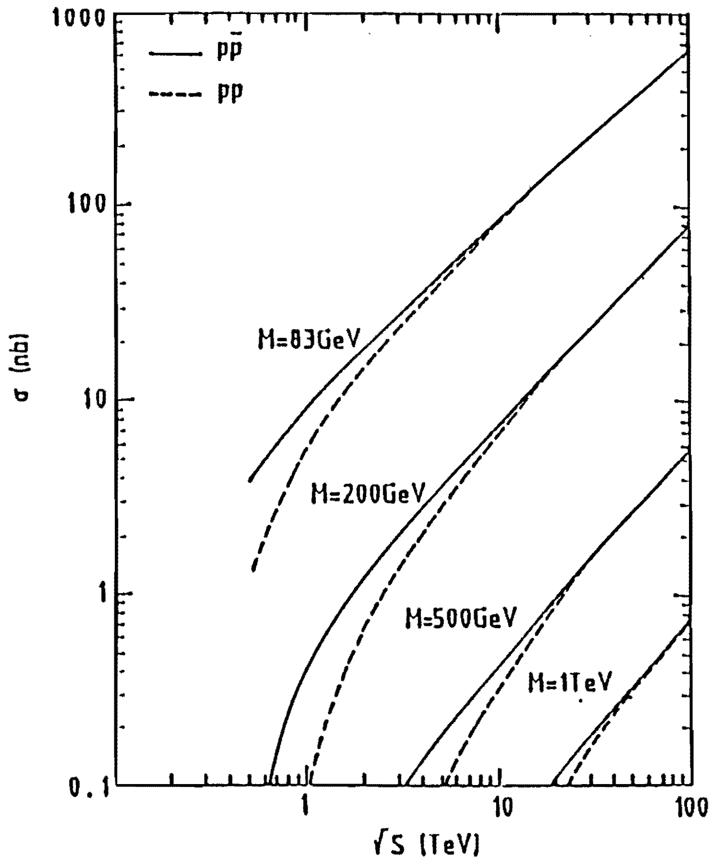


Fig.1

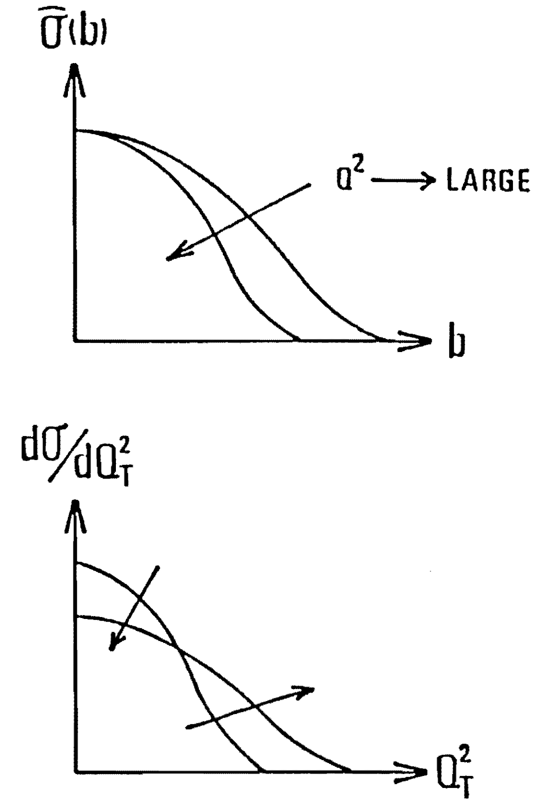


Fig.2

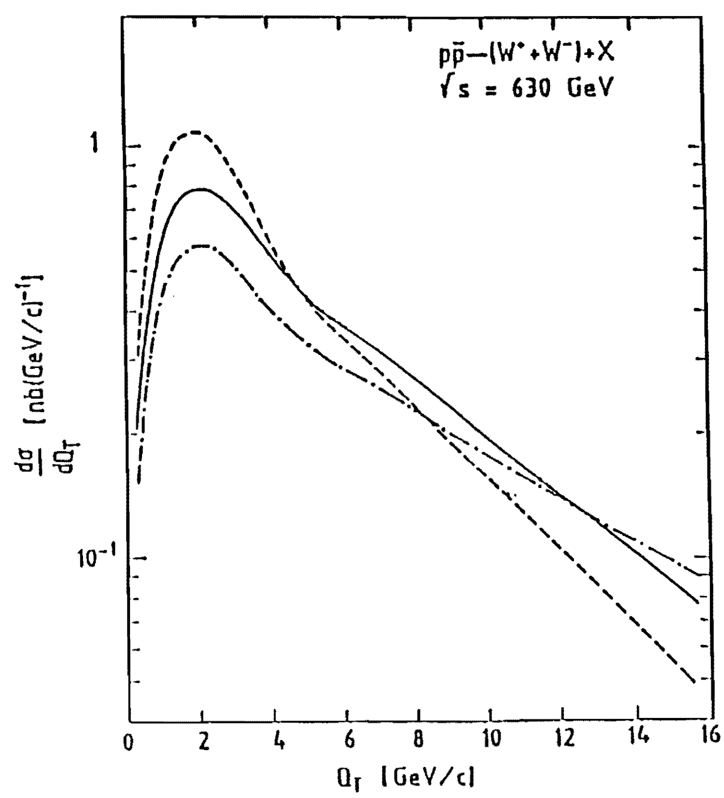


Fig. 3

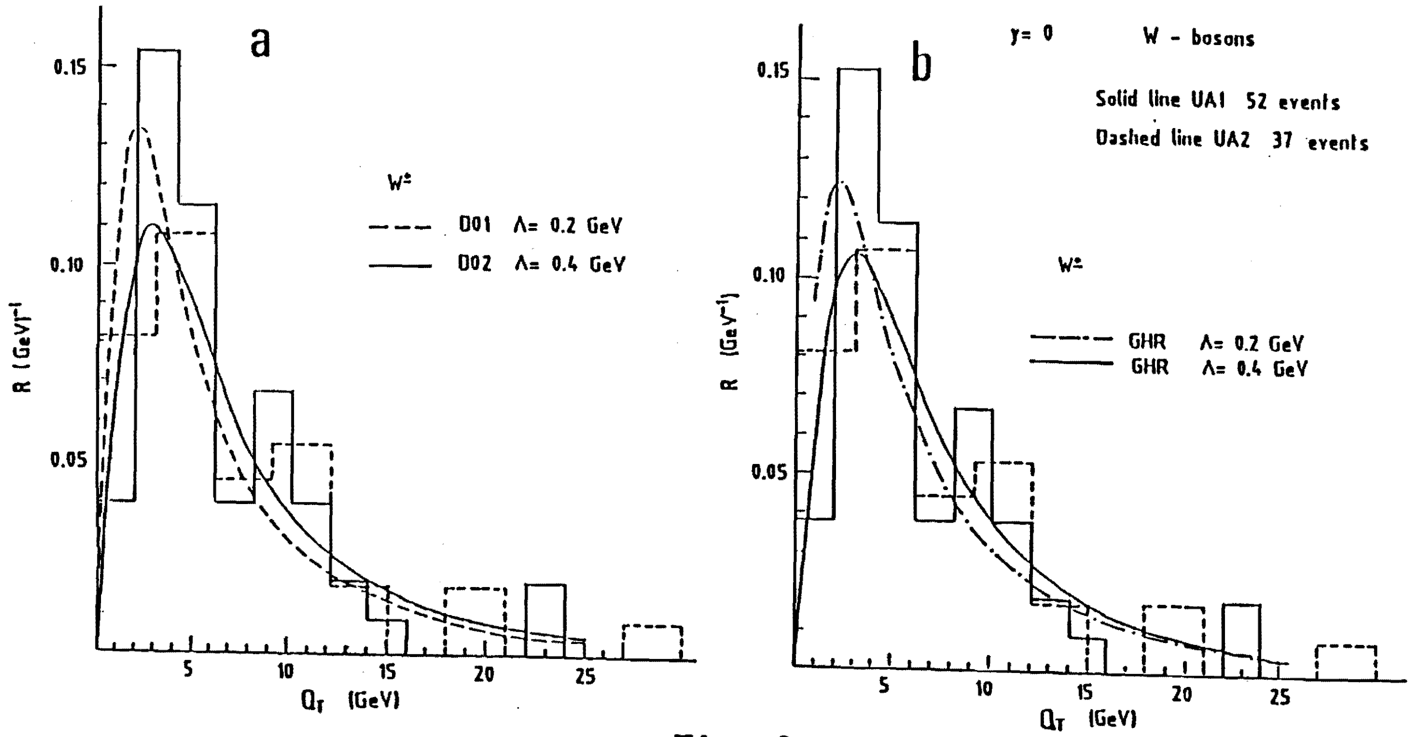

a
R (GeV)$^{-1}$
$W^{\pm}$
D01 Λ= 0.2 GeV
D02 Λ= 0.4 GeV
Q_T (GeV)
b
y= 0
W - bosons
Solid line UA1 52 events
Dashed line UA2 37 events
R (GeV^{-1})
$W^{\pm}$
GHR Λ= 0.2 GeV
GHR Λ= 0.4 GeV
Q_T (GeV)

Fig.4

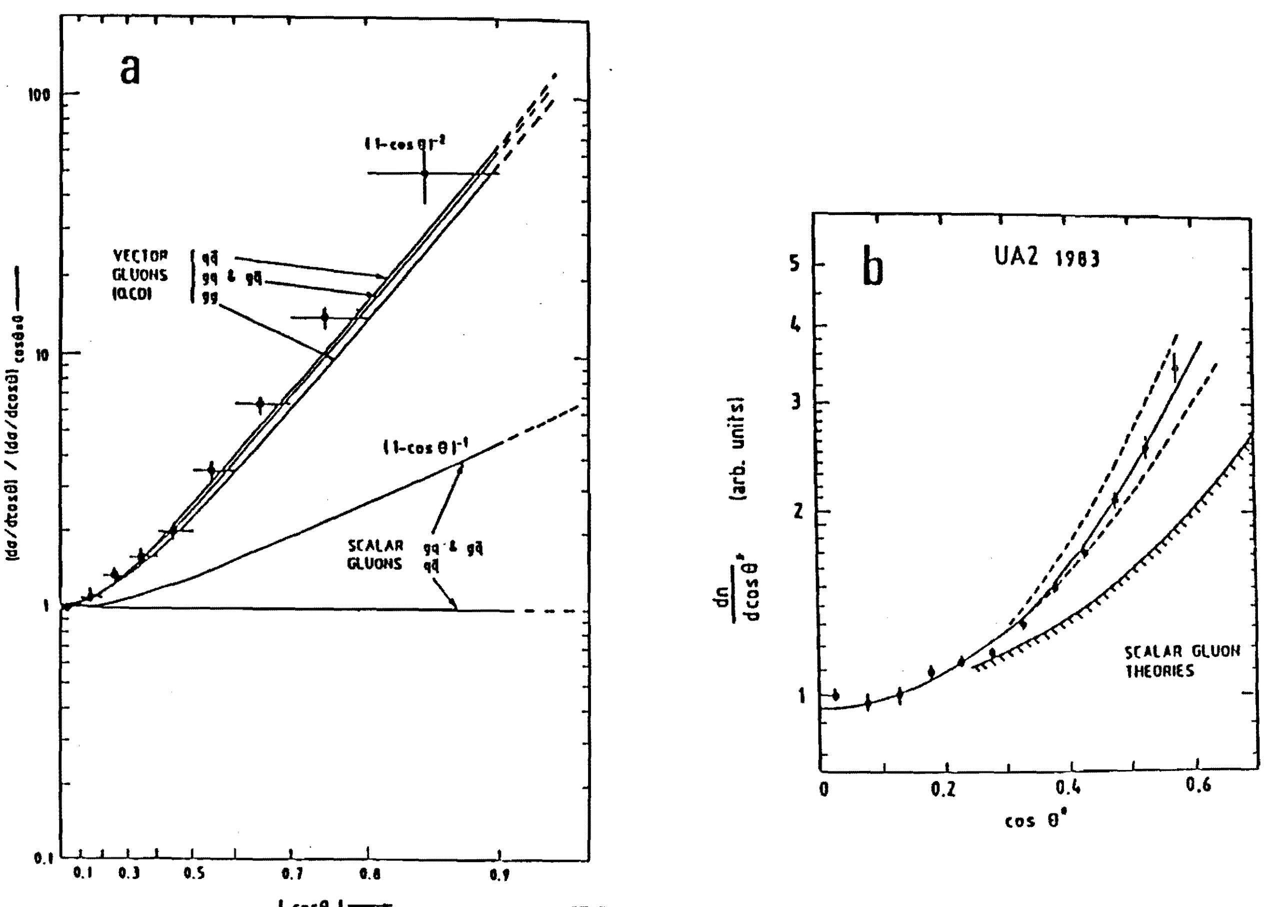
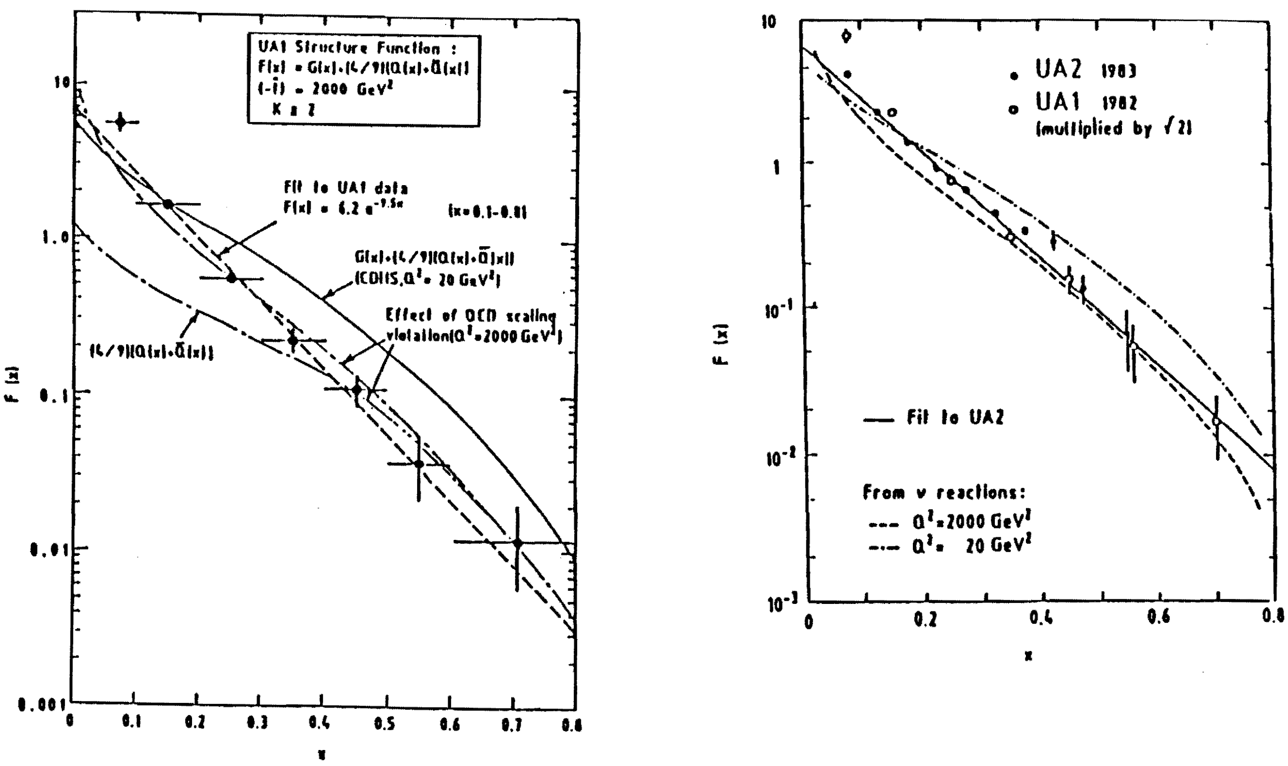
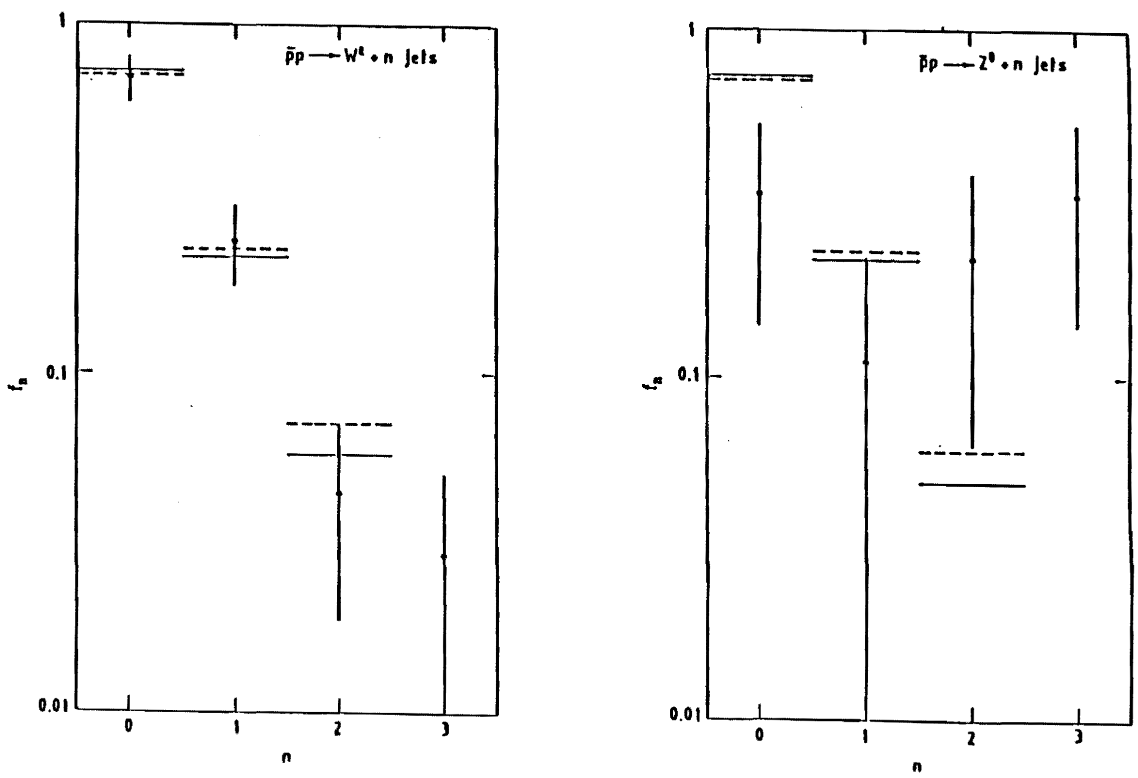

a
$(1-\cos\theta)^{-2}$
VECTOR GLUONS (QCD)
$q\bar{q}$
qq & $q\bar{q}$
gg
$(1-\cos\theta)^{-1}$
SCALAR GLUONS
qq & $q\bar{q}$
$q\bar{q}$
$(d\sigma/d\cos\theta)$ / $(d\sigma/d\cos\theta)_{\cos\theta=0}$
$|\cos\theta|$
b
UA2 1983
$\frac{dn}{d\cos\theta^*}$ (arb. units)
SCALAR GLUON THEORIES
$\cos\theta^*$

Fig.5



UA1 Structure Function :
F(x) = G(x)+(4/9)(Q(x)+Q̄(x))
(-t̂) = 2000 GeV²
K = 2
Fit to UA1 data
F(x) = 6.2 e^{-9.5x}
(x=0.1-0.8)
G(x)+(4/9)(Q(x)+Q̄(x))
(CDHS, Q² = 20 GeV²)
Effect of QCD scaling violation (Q²=2000 GeV²)
(4/9)(Q(x)+Q̄(x))
F(x)
x
UA2 1983
UA1 1982
(multiplied by √2)
Fit to UA2
From ν reactions:
Q²=2000 GeV²
Q²= 20 GeV²

Fig. 6



p̄p → W± + n jets
p̄p → Z⁰ + n jets
f_n
n

Fig. 7