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HUNTING LOW-x DYNAMICS SIGNATURES IN DATA

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Dedicated to Jan Kwieciński in honour of his 65th birthday

About 10 years ago HERA has opened a new field of studies, namely that of low-x in QCD, initially via structure function measurements, and later with dedicated measurements of the hadronic final state. Theoretical guidance has turned out to be very important for these studies. The hunt for low-x effects in data has been a constant interplay between experiment and theory. This paper gives a personal account of a few examples which are directly related to the work of Jan Kwieciński and his collaborators.

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1. Introduction

The year of 1990 was very exiting: HERA and the H1 and ZEUS detectors were nearing their completion. HERA, the electron–proton collider with centre of mass system (CMS) energy of about 300 GeV, was programmed to be a machine that entered the uncharted new area of low-x physics, reaching values of x down to $10^{-4} - 10^{-5}$ in the deep inelastic scattering (DIS) regime. In fact at the start, before the arrival of the first data, HERA was not really fully appreciated as a low-x machine. The H1 experiment for example had only a rather simple detector for measuring electrons scattered under a small angle, covering the region of $Q^2 < 100$ GeV^2. It consisted of a lead scintillator calorimeter with medium granularity to measure the energy of electro–magnetic showers and a simple multi-wire proportional chamber to distinguish photons from electrons. Around 1990, however, the HERA community started to realize that there could be an interesting opportunity to explore this new low-x region. Much of the enthusiasm was generated through a workshop held at DESY in May 1990 on "low-x" physics [1]. It appeared that the parton density at low-x was essentially unconstrained by the available data, and could show interesting phenomena such as parton saturation effects or hotspots. As shown in Fig. 1, the theoretical tools at hand were the so called Altarelli–Parisi or DGLAP equations [2], and the at the time much less studied BFKL equation [3]. While the former perform an evolution in Q^2, the latter performs one in x and allows to predict the behavior of low-x phenomena. The interesting question at the time was whether the HERA data would be in the BFKL regime and show effects of so called BFKL dynamics. Later a combined equation (CCFM) [4] has been proposed which has the two other equations as it limits.

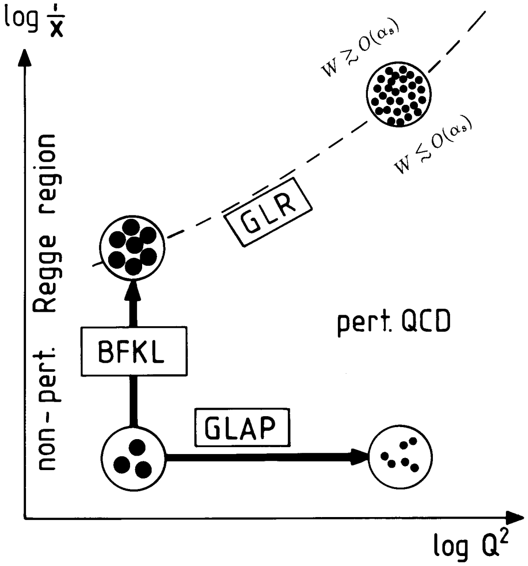

Fig. 1. The kinematic plane for DIS, with the QCD evolution equations and a line (GLR) where non-linear effects become important, leading eventually to the saturation regime.

Jan Kwieciński, who already had a good judgment on the expected interest in the HERA data and this physics, participated in this workshop talking about possible shadowing effects in future low-x data. Around that time he would join forces with the Durham group of Alan Martin and form what was to become the strong Durham–Kraków axis on studies of BFKL effects in the HERA data. It has certainly been a blessing to have people like Jan working in this field to facilitate the useful but absolutely essential cross talk between experiments and theorists in exploring the low-x regime, first at HERA, and then in other experimental environments. In this paper we give a few examples of the interplay between theory and experiment, and the progress in the last 10 years in this field.

2. Structure functions

The first and simplest measurable quantity in *ep* scattering is the inclusive structure function F_2. In the one-photon-exchange approximation, the differential electroproduction cross section is related to the structure function $F_2(x,Q^2)$ and the ratio $R(x,Q^2)$ of the cross sections for the longitudinally and transversally polarized virtual photons by

$$\frac{d^2\sigma(x,Q^2)}{dQ^2dx}=\frac{4\pi\alpha^2}{Q^4x}\left[1-y-\frac{Mxy}{2E}+\left(1-\frac{2m^2}{Q^2}\right)\frac{y^2\left(1+\frac{4M^2x^2}{Q^2}\right)}{2(1+R)}\right]F_2(x,Q^2)\,, \tag{1}$$

where M and m are the mass of the proton and the electron respectively, and E is the incident lepton energy. For the HERA kinematics by neglecting M and m this expression reduces to:

$$\frac{d^2\sigma}{dxdQ^2}=\frac{4\pi\alpha^2}{Q^4x}\left[1-y+\frac{y^2}{2(1+R)}\right]F_2(x,Q^2). \tag{2}$$

HERA delivered the first collisions to the experiments H1 and ZEUS in the summer of '92. In March 1993 at a workshop in Durham [5], which was the first one of a series that would later trigger the so called DIS conferences, I had the honour of showing for the first time to the world the F_2 measurement of the H1 experiment in the low-x range, namely for x down to 10^{-3}. The exciting news was that F_2 seemed to rise strongly with decreasing x, which came somewhat as a surprise. The file with the original plot of the preliminary data shown at the time has been lost in the mist of time, but a scanned version can be found in the Durham database and is shown in Fig. 2.

A few months before these data were revealed, namely in December 1992, Askew, Kwieciński, Martin and Sutton (AKMS) [7] submitted a paper where they actually predicted that F_2 would rise strongly in the low-x HERA regime by assuming that the dynamics is governed by the BFKL evolution equation. Be it that some cut-off parameters needed to be chosen, the agreement between data and calculations is very good, as is shown in comparison with published H1 and ZEUS data [8] in Fig. 3, taken from [9]. Although it came only a few months before the data was shown publically, they could not possibly have known that the data would actually show a rise. The simple reason was that we, the experimentalists, did not know it ourselves at that time. That period several groups in H1, lead by Max Klein, Witek Krasny and myself, were still working feverishly to get the data analysis finished. I believe the situation was similar in ZEUS.

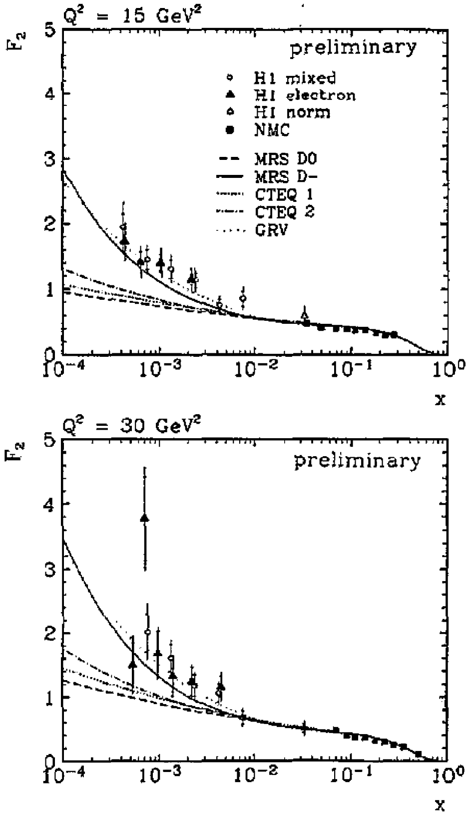

Fig. 2. The original preliminary data of the first structure function $F_2(x,Q^2)$ measurement at HERA, shown at the Durham93 workshop. Data are shown as function of x for different kinematical reconstruction methods and for two bins in Q^2. PDFs which were popular at the time are overlayed. Taken from [6].

Fig. 3 shows also the success of *e.g.* the GRV predictions [10], which were based on the more classical DGLAP evolution equations, taking the somewhat, at the time, unusual choice for starting the evolution (in Q^2) at a very low value of Q_0^2, namely around 0.3 GeV^2. This opened a strong debate, that started in earnest at this Durham Workshop, on whether or not the BFKL could be identified via F_2 measurements. Finally, after some years, there was a consensus that F_2 is probably a too inclusive measurement to study BFKL.

In the early fall of 1993 Alan Martin and Jan Kwieciński visited DESY for a month. There is a story that they found it difficult to have breakfast on the site and neighborhood during weekends, but there was one particular moment that they actually influenced the HERA operation indirectly.

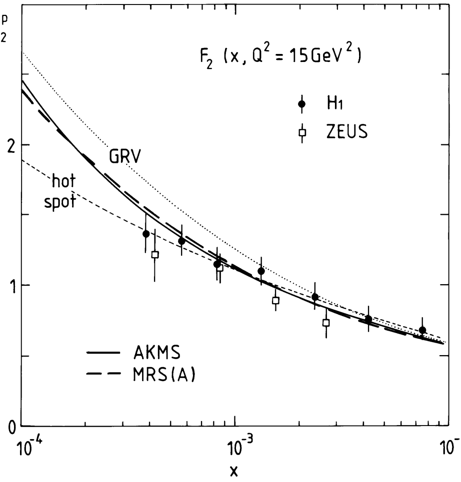

Fig. 3. Comparison of early HERA data from H1 and ZEUS with the calculations of AKMS and GRV.

One afternoon we were looking together at plots of the structure function and various predictions. Data, available at the time, reached Q^2 values down to about 8.5 GeV^2. This could perhaps be extended down to 5 GeV^2 in future, but the detector acceptance was certainly preventive to go any lower. Jan and Alan convinced us that it would be extremely important to try to measure down to lower values and to see if, how and when the rise would diminish.

This set for us the challenge to try to measure F_2 in that region. The idea was to shift the interaction point forward by roughly a meter, such that we would be able to see smaller scattering angles in the electron detector. Together with G. Rädel, and the support of J. Feltesse we could convince friend and foe that this might work. In order to give it a try such an exercise was finally allocated a generous two machine shifts at the very end of the 1993 run period in October. It worked surprisingly well and with only 2.5 nb^{-1} we could make a measurement. The Q^2 reach could be lowered from 8.5 to 4.5 GeV^2. Repeating the shifted vertex exercise for data runs in subsequent years allowed to reach values down to 1.5 GeV^2 (1994) and (with an upgraded detector) even down to 0.35 GeV^2 (1995). The ZEUS collaboration has installed around that time a beam-pipe calorimeter and could measure later down to even smaller values in Q^2. The 1994 H1 data (shifted and nominal low Q^2) are shown in Fig. 4. The message from the data is that below $Q^2 = 5$ GeV^2 the rise of F_2 with decreasing x is smoothly reduced, approaching for the lowest reachable values the almost flat expectation of $Q^2 = 0$.

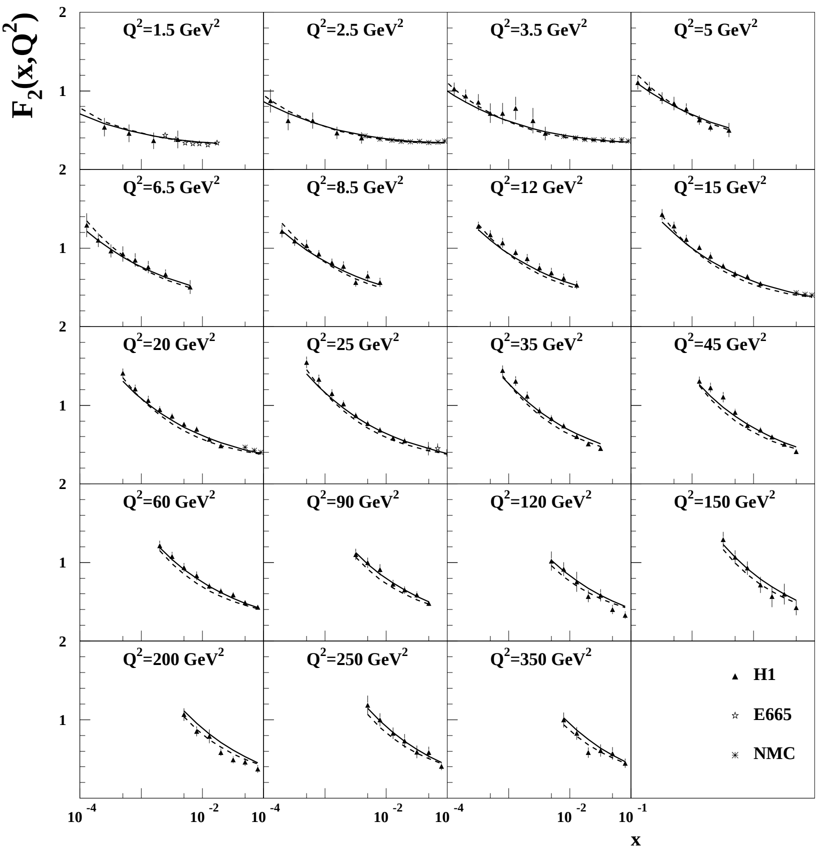

Fig. 4. Structure function data from 94, with unified BFKL+DGLAP calculations overlaid [13].

Generally models that attempt to describe this region of the data have experienced difficulties to account for all detailed aspects of these data. Kwieciński together with Badelek proposed a model [11] which has a mechanism that allows for a smooth transition of the vector dominance regime to the perturbative QCD regime. This model describes the data rather well as discussed in *e.g.* [12].

The Durham–Kraków group has continued on the line of proposing descriptions for the F_2 data, based either on the CCFM equations or with a unified DGLAP and BFKL description. An example of the latter is shown by the curves in Fig. 4; details are given in [13]. Generally the fits of such (rather complicated) unified formulae gave a somewhat better results than pure DGLAP fits, but the differences were not very large, illustrating that F_2 is indeed too inclusive to see BFKL effects clearly.

More sensitivity to BFKL or leading $\ln 1/x$ terms can be reached by studying the structure function g_1 in polarized *ep* scattering. Kwieciński and Ziaja [14] have calculated predictions from g_1 in the framework of the workshop on polarized *ep* scattering at HERA [15]. The reason that the effect is larger in polarized scattering is because here the structure functions depend on double logarithmic $\ln^2 1/x$ terms instead of single ones. The prediction is shown in Fig. 5: The upper dotted line is the DGLAP prediction while the solid line is a BFKL+DGLAP solution. For $x < 10^{-4}$ the difference between both predictions is larger than a factor two. Unfortunately it does not look that HERA will be polarized in future, but another project EIC, adding a electron linac or ring to RHIC, maybe be realized by 2010–2012 and could make a determinative measurement, if these predictions will not be spoiled by higher order corrections. A sadly missed chance for HERA, but one can look forward to such exciting measurements at BNL in future.

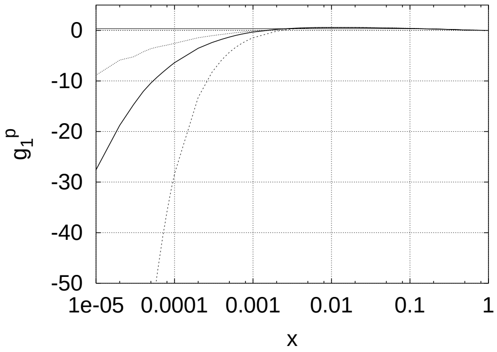

Fig. 5. Predictions for the polarized structure function g_1 at low-x, as explained in the text.

3. Final states

The search for less inclusive variables to study low-x effects naturally led to the study of hadronic final states in DIS. In 1992 Kwieciński, Martin and Sutton produced a paper discussing on how one could possibly isolate the "Lipatov $x^{-\lambda}$" behavior in deep inelastic scattering [16]. In LO the value of λ is expected to be around 0.5 for $\alpha_s = 0.2$. In fact at the same time Bartels, Loewe and myself have published a similar calculation [17], and both results were found to be in agreement. The idea is based on the Mueller–Navelet [18] process in hadron–hadron scattering, where two jets with medium to high E_T are tagged at a large rapidity distance, and the QCD evolution between the jets should behave according to the BFKL pomeron. In DIS the corresponding process is an event with a jet close to the outgoing proton direction and with an E_{T} close to the Q^2 value of the event. The idea is pictured in Fig. 6. Since in the HERA jargon the protons go "forward" these events are called "forward jet DIS events".

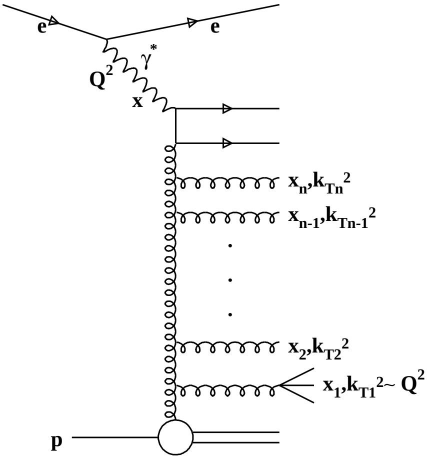

Fig. 6. Parton evolution in the ladder approximation. The kinematics of forward jets in DIS events are indicated.

It took until 1995 before a first measurement of the cross section of these events was published [19]. Typical selection cuts for such forward jets DIS events are $x_{\mathrm{jet}} > 0.035$, $0.5 < p^2_{\mathrm{jet}}/Q^2 < 2$, $7° < \theta_{\mathrm{jet}} < 20°$ and $p_{\mathrm{jet}} > 3.5$ GeV in the kinematic range $E'_e > 11$ GeV, $160° < \theta_e < 173°$ and $y > 0.1$. In H1 these measurements were made by three postdocs: J. Kurzhoefer, G. Contreras, and E. Lobodzinska. The latter worked for the Kraków group and was, therefore, close to the Kwieciński team. This was very useful for the interpretation of the measurements. The measurement is particularly difficult since jets have to be resolved close to the edge of the detector, and proton remnant debris must be avoided.

Already the early measurements showed that models based on LO matrix elements and parton showers could not account for the forward jet rate. More sophisticated data were published by both H1 and ZEUS in [20] and compared to the calculations of Kwieciński *et al.*, see *e.g.* Fig. 7 [21]. The results are generally in good agreement with the data but contain some parameters that must be tuned.

The data show a clear disagreement with fixed order calculations but can be described by BFKL based calculations. The calculations from the Durham–Kraków group include the so called consistency constraint. In 1998, after many years of very tedious calculations it was realized that the NLO

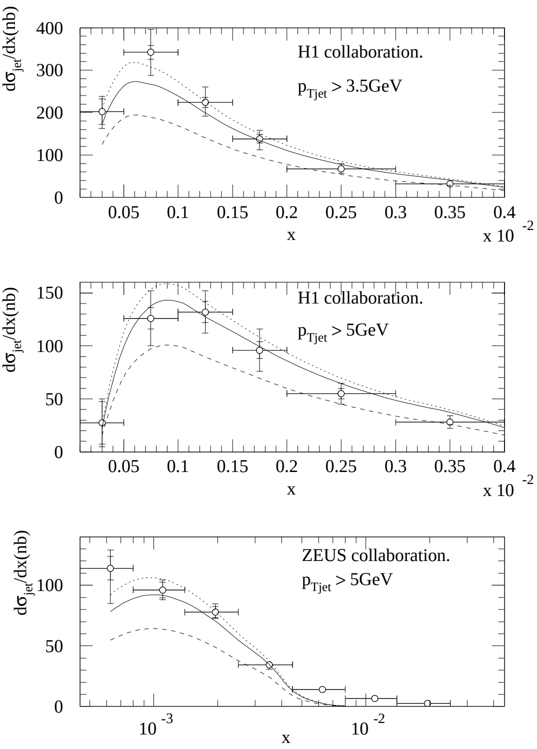

Fig. 7. Forward jet DIS cross section as a function of x. BFKL calculations including the consistency constraint are overlaid.

correction [22] to the BFKL kernel was quite large. However, a large part of this correction is kinematics which Jan could include in the calculations by applying this consistency constraint. This constraint tames the Lipatov exponent to values in the range of 0.2–0.3 rather than 0.5 as in LO.

Kwieciński and collaborators went also a step further and calculated cross sections for events with two forward jets and cross sections for forward single particles. In particular π^0's have the advantage that their showers in the calorimeter are less spread out and, therefore, somewhat easier to measure than jets in the forward region. A result of H1 published in 1999, derived by T. Wengler, is shown in Fig. 8 together with calculations of Kwieciński *et al.* Having these data one could use the forward jet *and* the single particle data simultaneously, *i.e.* fixing parameters to describe the forward jet data and having, therefore, more rigid predictions for the single particle cross sections. The Durham–Kraków team followed that principle and the resulting calculations give a good description of the single particle data, as shown in the figure.

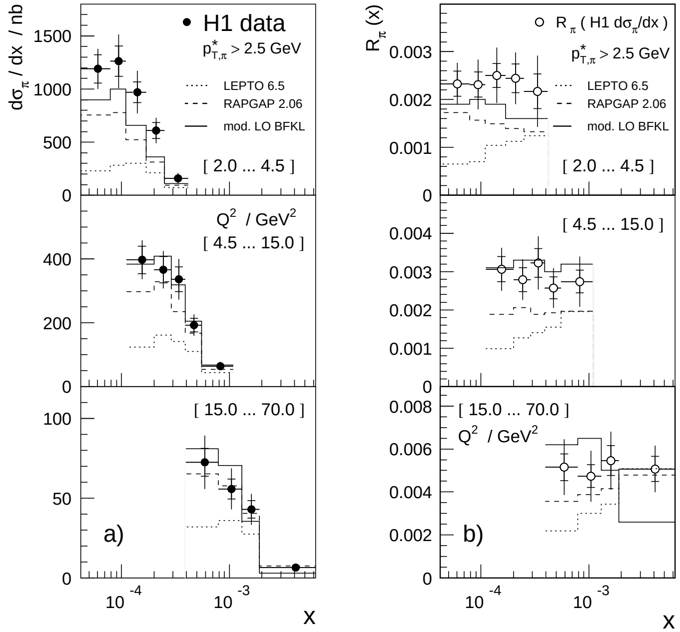

Fig. 8. Inclusive π^0 meson production cross sections as a function of x for different Q^2 regions.

What have we learned so far from these and other final state measurements? The final state measurements tailored for BFKL studies, such as forward jets and particles all show a similar feature: The data show that something extra on top of the fixed order matrix elements plus parton showers is needed. Adding a resolved photon component in the calculation, as proposed in [23], does not seem to be sufficient, as shown in Fig. 8 by the RAPGAP calculation.

However, one problem with HERA in general is that the ladder as shown in Fig. 6 may not be long enough. Bo Anderson [24] and collaborators calculated that the number of gluons emitted with $p_{\rm t} > 1.5$ GeV scales as $\ln(x_{\rm jet}/x)/2$, hence in the phase space available we typically have ladders with only 3–4 hard gluons which is a bit low for asymptotic BFKL formulae to be applied with confidence.

Hence the future of this field may lay in *ep* at HERA with an increased forward acceptance (*i.e.* accepting jets and particles to down to at least 1 degree away from the proton beam), or *ep* at increased energy such as THERA [25]. The first could be studied at the so called HERA-III phase, but its chances of being realized are still unclear. The latter is at best way in the future, beyond 2015. Closer to us is the LHC which thanks to its high energy and large coverage of detectors (at least 10 and perhaps 14 units in rapidity [26]) may become the place where new insight in low-x can be gained before the end of the decade. LHC is presently expected to start up in 2007.

4. BFKL in $e+e-$ colliders

In 1996 J. Bartels realized that the ideal environment for the study of BFKL would be the "pointlike" $\gamma^*\gamma^*$ scattering where both photons are off mass shell (say $Q^2 \simeq 10$ GeV^2). Such collisions can be realized in $ee \to eeX$ scattering *e.g.* at a future linear collider for which the first calculations were performed [27]. Such a collider is still rather far away in the future, hence we and others also studied the case for LEP [27, 28]. The disadvantage at LEP is that the maximum possible reach in $W_{\gamma^*\gamma^*}$, the hadronic invariant mass of the virtual photon system, is rather low, namely below 100 GeV. Hence the allowed phase space for BFKL evolution suffers in the same way as for HERA: the ladder is pretty short. However, even at LEP the original LO effects were predicted to be very large, the cross section including BFKL to be ten times larger than the one not including it and, therefore, we set out to try to measure this at LEP anyway.

As we were in the process of measuring this processes the "NLO BFKL" crisis came as mentioned earlier: the "Lipatov exponent" collapsed when the NLO calculations were completed. It did not stop M. Przybycien in OPAL to finalize the measurement we had started [29]. Also the L3 collaboration has put up an interesting result [30]. The experimental result of the $\gamma^*\gamma^*$ cross section, as measured by the OPAL collaboration, is shown in Fig. 9.

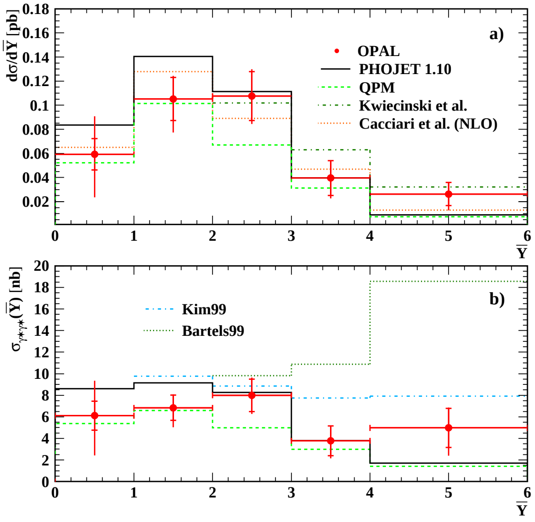

Fig. 9. The dependence of the $\gamma^*\gamma^*$ cross section on the variable $Y = \ln W/Q_1Q_2$.

The measurement does not show the strong rise as expected by the (by then disfavored) LO calculations, but in particular the L3 data suggests that there may be something more that the DGLAP NLO a the large values of $Y = \ln W/Q_1Q_2$. The results of Kwieciński and collaborators [31] which include the consistency constraint to partially emulate the BFKL higher order corrections, show a good agreement with the data.

Jan has also been closely connected to the QCD study group for the linear collider. Apart from producing inclusive $\gamma^*\gamma^*$ scattering predictions, we produced our only common paper together, with L. Motyka, in the context of these studies (apart from some working group summary papers), namely a study of the process $\gamma\gamma \to J/\psi J\psi$. This process [32], shown in Fig. 10 has the same characteristics as the inclusive $\gamma^*\gamma^*$ process, *i.e.* a strong rising cross section with $W_{\gamma\gamma}$ as shown in Fig. 10. The mass of the heavy vector mesons takes over the role of the Q^2, hence this process can be studied with real photons. We predict that an experiment at a 500 GeV e^+e^- linear collider should be able to measure the BFKL effect in this process provided muons can be measured down to at least 20 mrad.

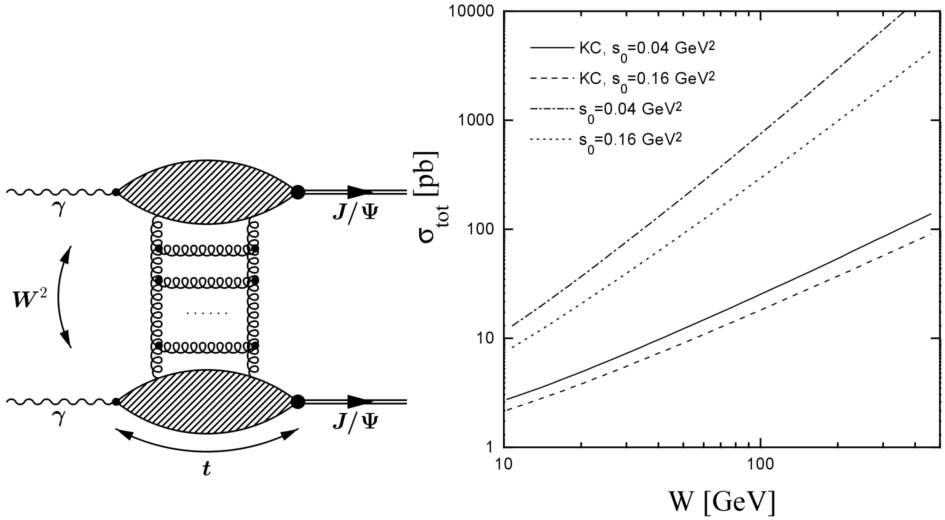

Fig. 10. The pomeron exchange mechanism for the process $\gamma\gamma \to J/\psi J\psi$ (left). Energy dependence of the cross section $\gamma\gamma \to J/\psi J\psi$. Upper curves are LO BFKL predictions while the two lower curves include the consistency constraint, both for two values of the cut-off (right).

5. Summary

Wherever we look we see some deviations from DGLAP type of calculations: Something more seems to be needed at small x. BFKL calculations can often accommodate for this effect, as we have seen in this small overview[1]. However, it often works, depending on the authors, due to special choices, using phenomenological approaches to the subleading terms, choosing fixed $\alpha_{\rm s}$, *etc.* Jan Kwieciński and his co-workers have established a framework of the consistency constraints which seems to perform a good job for all different BFKL signals studied. But in general the jury is still out on the question whether or not BFKL effects have actually been observed in the data.

It is obvious from this short account that Jan Kwieciński has played a pivotal part in the hunt for the BFKL in the last 10 years. It is a blessing for experimentalists to have a person such as Jan to rely upon for the theory discussion of the data. I hope Jan will pursue this effort in particular when the LHC turns on in less than 4 years from now as we all hope. Apart from hopefully settling the question on the electroweak symmetry breaking and possible discovering new physics beyond the standard model, particularly in the first days LHC will be mainly a QCD machine, allowing *e.g.* to study the Mueller–Navelet jets phenomena at high energies and large rapidity distances. Maybe finally the BFKL ladders will be long enough at this collider to settle the question on to $B_{\rm FKL}$ or not to $B_{\rm FKL}$. Good theory guidance will be imperative for such a project.

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