Proceedings of the DIS'2004, Štrbské Pleso, Slovakia

THE NUCLEON'S GLUONIC TRANSVERSE SIZE: FROM EXCLUSIVE J/ψ PHOTOPRODUCTION TO HIGH–ENERGY PP COLLISIONS

M. STRIKMAN
Pennsylvania State University, University Park, PA 16802, U.S.A.

C. WEISS
Theory Group, Jefferson Lab, Newport News, VA 23606, U.S.A.

We summarize what is known about the transverse spatial distribution of gluons in the nucleon and its x–dependence from exclusive J/ψ photo/electroproduction in ep fixed–target and collider experiments (HERA H1 and ZEUS). This information can be used to predict the impact parameter dependence of the cross section for certain hard QCD processes (dijet production) in $\bar{p}p$ and pp collisions at the Tevatron and LHC.

The parton picture of the nucleon deals not only with the distribution of partons with respect to longitudinal momentum, but also with their spatial distribution in the transverse plane. The latter aspect, which was investigated by Gribov in a general context [1], is receiving new attention in connection with the recent interest in generalized parton distributions (GPD's). The spatial distribution of partons in the transverse plane can be resolved in hard exclusive processes, in which the nucleon is observed in the final state, with an invariant momentum transfer $t \ll \mu^2$ (μ^2 is the hard scale characterizing the process). Examples include the photoproduction of heavy quarkonia (J/ψ), or the hard electroproduction of light mesons or real photons (deeply virtual Compton scattering). At the same time, the transverse spatial distribution of partons plays an important role in the description of hard QCD processes in hadron–hadron collisions at high energies [2]. This concept thus provides a means by which information gained in ep scattering experiments can be used to make predictions for $\bar{p}p$ and pp collisions at the Tevatron and the LHC.

The generalized parton distributions parametrize the non-diagonal matrix elements of the twist–2 QCD quark and gluon operators between nucleon states. In the simplest case, when the momentum transfer between the nucleon states has only a transverse component, $\boldsymbol{\Delta}_\perp$, the generalized gluon distribution, $H_g(x,t)$, with $t \equiv -\boldsymbol{\Delta}_\perp^2$, can be interpreted as the elastic nucleon form factor for gluons with longitudinal momentum fraction x, with $H_g(x, t=0) = g(x)$ the usual gluon density. One can represent this form factor as the Fourier transform of a function of a transverse coordinate, $\boldsymbol{\rho}$,

$$H_g(x, -\boldsymbol{\Delta}_\perp^2) \;=\; \int d^2\rho \; e^{i(\boldsymbol{\Delta}_\perp \boldsymbol{\rho})} \; g(x,\rho) \qquad\qquad (\rho \equiv |\boldsymbol{\rho}|). \tag{1}$$

This function describes the spatial distribution of gluons with longitudinal momentum fraction x in the transverse plane [3]. Its integral over the transverse coordinate

© Institute of Experimental Physics SAS, Košice, Slovakia

gives back the total gluon density,

$$\int d^2\rho\, g(x,\rho) \;=\; g(x). \tag{2}$$

In particular, the average "gluonic transverse size" of the nucleon is related to the slope of the generalized gluon distribution at $t = 0$,

$$\langle \rho^2 \rangle \;\equiv\; \frac{\int d^2\rho\, g(x,\rho)\, \rho^2}{\int d^2\rho\, g(x,\rho)} \;=\; 4\, \frac{\partial}{\partial t} \left[\frac{H_g(x,t)}{H_g(x,0)} \right]_{t=0}. \tag{3}$$

This quantity allows for an intuitive physical interpretation, and can be compared with other measures of the 2–dimensional size of the nucleon, for example, with $2/3$ times the 3–dimensional electric or axial charge radius squared of the nucleon.

The gluonic transverse size of the nucleon is expected to grow with decreasing longitudinal momentum fraction, x. Different physical mechanisms are responsible for this growth in different regions of x. At $x \to 1$, $\langle \rho^2 \rangle$ vanishes because the t–dependence of the generalized gluon distribution disappears if one parton carries the entire longitudinal momentum of the nucleon (Feynman mechanism). When x is decreased below the valence region, a distinctive increase of $\langle \rho^2 \rangle$ is caused by pion cloud contributions to the gluon density, which set in for $x < M_\pi / M_N$ [4,5]. Finally, when x is decreased further, the transverse size grows due to the random walk character of successive emissions in the partonic ladder (Gribov diffusion) [1].

The transverse spatial distribution of gluons also changes with the scale, μ^2, as a result of DGLAP evolution. For μ^2 sufficiently large compared to the transverse spatial resolution, $\mu^2 \gg 1/(\Delta\rho)^2$, the parton decays happen locally in transverse position. Looking at the ρ–distribution at some fixed x, one finds that that it shrinks with increasing μ^2. The reason is that, as μ^2 increases, the distribution becomes sensitive to the input distribution (at the initial scale) at higher values of x, where it is concentrated at smaller transverse distances [2].

Most of the experimental information about the transverse spatial distribution of gluons in the nucleon comes from exclusive J/ψ photoproduction, $\gamma + N \to J/\psi + N$. At the leading twist level, the amplitude for this process is proportional to the generalized gluon distribution in the nucleon, with $\mu^2 \sim (\text{size of } \bar{c}c)^{-2} \approx 3\,\text{GeV}^2$, and $x \sim (\text{mass of } \bar{c}c)^2 / W^2$ for sufficiently large $W \equiv \sqrt{s}$ (for smaller energies the "skewedness" of the gluon distribution, $x_1 \neq x_2$, becomes important) [6]. In this approximation the t–dependence of the generalized gluon distribution can directly be inferred from the measured t–dependence of the differential cross section.

Exclusive J/ψ photoproduction has been studied in a number of fixed–target experiments: Cornell at $E_\gamma = 11.8$ GeV [7], SLAC at $E_\gamma = 19$ GeV [8], CERN NA14 at $\langle E_\gamma \rangle = 90$ GeV [9], and FNAL E401/E458 at $\langle E_\gamma \rangle = 100$ GeV [10] (in this experiment also the recoiling proton was detected). Fig. 1 shows the t–dependence of the differential cross section measured in the FNAL E401/E458 experiment. An exponential fit $d\sigma/dt \propto e^{Bt}$ gives $B = 3.26 \pm 1.30\ \text{GeV}^{-2}$. In order to extract the gluonic transverse size of the nucleon one should correct for the finite size of the produced $\bar{c}c$ system, which leads to an additional "smearing" in the transverse plane and accounts for approximately $0.3\,\text{GeV}^{-2}$ of the observed B value [6]. Subtracting this contribution we obtain the estimate

$$\langle \rho^2 \rangle \;\approx\; 0.24\,\text{fm}^2 \qquad\qquad (x \sim 10^{-1}). \tag{4}$$

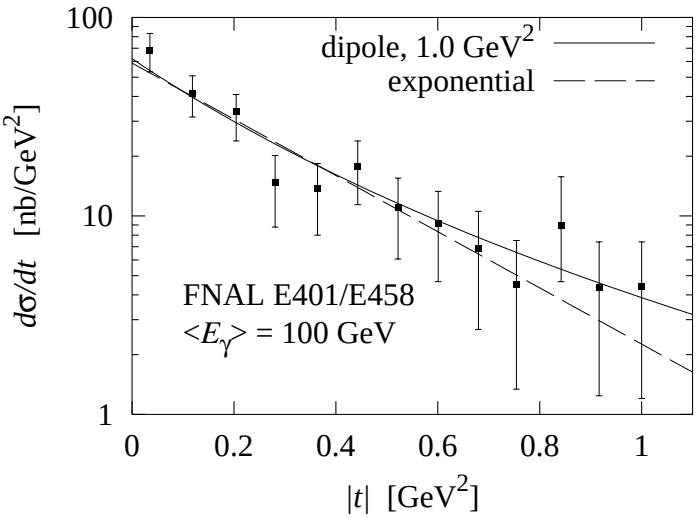

Figure 1. The t–dependence of the differential cross section for exclusive J/ψ photoproduction measured in the FNAL E401 / E458 experiment [10]. Dashed line: Exponential fit $e^{3.26t/\mathrm{GeV}^2}$. Solid line: Dipole parametrization $(1 - t/1.0\,\mathrm{GeV}^2)^{-4}$.

One expects the t–dependence of the generalized gluon distribution at $x \geq 10^{-1}$ to be similar to the nucleon's axial form factor [5]. The reason is that, like the axial form factor, the generalized gluon distribution for $x > M_\pi/M_N$ does not receive contributions from the nucleon's pion cloud [4,5]. The t–dependence should thus be well described by the dipole parametrization (see Ref.[11] for a review)

$$H_g(x,t) \;\propto\; (1 - t/m_g^2)^{-2}, \qquad m_g^2 \;=\; 1.1\,\mathrm{GeV}^2 \qquad (x \sim 10^{-1}). \quad (5)$$

This corresponds to a gluonic transverse size of the nucleon of

$$\langle \rho^2 \rangle \;=\; 8/m_g^2 \;\approx\; 0.28\,\mathrm{fm}^2 \qquad (x \sim 10^{-1}), \quad (6)$$

consistent with the estimate (4). The dipole parametrization (5) implies a t–dependence of the differential cross section as $(1 - t/1.0\,\mathrm{GeV}^2)^{-4}$, where the 10% decrease in the mass parameter accounts for the finite size of the $\bar{c}c$ system (see above). This form describes well the E401/E458 data, see Fig. 1. It also describes the t–dependence of the data at much lower energies [7,8]; see Ref. [5] for details. In particular, in this way the observed decrease of the B parameter in exponential fits to the low–energy data can be explained as the result of sampling the dipole form factor at larger $|t| > |t_{\mathrm{min}}|$, where its logarithmic slope becomes smaller.

J/ψ photoproduction near threshold ($E_\gamma = 8.2$ GeV) will be investigated at Jefferson Lab Hall A with the 11 GeV electron beam [12]. An interesting question is whether the two–gluon exchange mechanism will still be applicable in this region, or whether a coherent multi–parton reaction mechanism will take over [13]. This issue will be crucial also for interpreting the data on sub–threshold J/ψ photoproduction off nuclei expected from the E-03-008 experiment at Jefferson Lab Hall C.

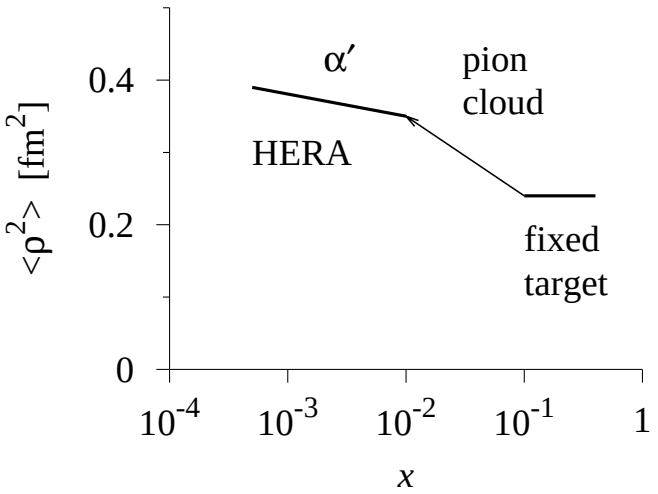

Figure 2. Schematic illustration of the x–dependence of the gluonic transverse size of the nucleon, $\langle\rho^2\rangle$. The increase between $x \sim 10^{-1}$ and $x \sim 10^{-2}$ can be attributed to the contribution of the nucleon's pion cloud to the gluon density.

J/ψ photoproduction has also been studied extensively by the H1 and ZEUS experiments at the HERA collider. The effective x values in the generalized gluon distribution here are $x \sim 10^{-2} - 10^{-3}$. The t–dependence of the measured differential cross section in both experiments is well described by the exponential form, e^{Bt}. H1 quotes a value of $B = 4.73 \pm 0.25^{+0.30}_{-0.39}$ GeV^{-2} for data averaged over the range $40 < W < 150$ GeV [14]. The recent ZEUS analysis of J/ψ electroproduction data reports a value of $4.72 \pm 0.15 \pm 0.12$ GeV^{-2} for the combined data in the range $2 < Q^2 < 100$ GeV^2, with no noticeable Q^2 dependence [15]. The previous ZEUS photoproduction data suggested a somewhat smaller value, $B = 4.15 \pm 0.05^{+0.30}_{-0.18}$ GeV^{-2} at $W = 90$ GeV [16]. Correcting again for the finite size of the $\bar{c}c$ system, we estimate the gluonic transverse size of the nucleon as

$$\langle\rho^2\rangle \approx 0.35\,\mathrm{fm}^2 \qquad (x \sim 10^{-2} - 10^{-3}). \tag{7}$$

This is about 30% larger than the estimate (4) at $x \sim 10^{-1}$.

The increase in the nucleon's gluonic transverse size between fixed–target and collider energies can be explained as the result of the contribution of the nucleon's pion cloud to the gluon distribution $g(x,\rho)$ at distances $\rho \sim 1/M_\pi$, which is suppressed for $x > M_\pi/M_N \sim 10^{-1}$ but becomes noticeable around $x \sim 10^{-2}$. It was estimated in Ref. [4] that this results in an increase of the gluonic transverse size of the nucleon of

$$\langle\rho^2\rangle_{\text{pion cloud}} \approx 0.06\,\mathrm{fm}^2, \tag{8}$$

which is roughly consistent with the difference between the estimates (7) and (4), (6). The H1 and ZEUS experiments have measured also the change of the logarithmic t–slope of the cross section with the CM energy, α', over the W range

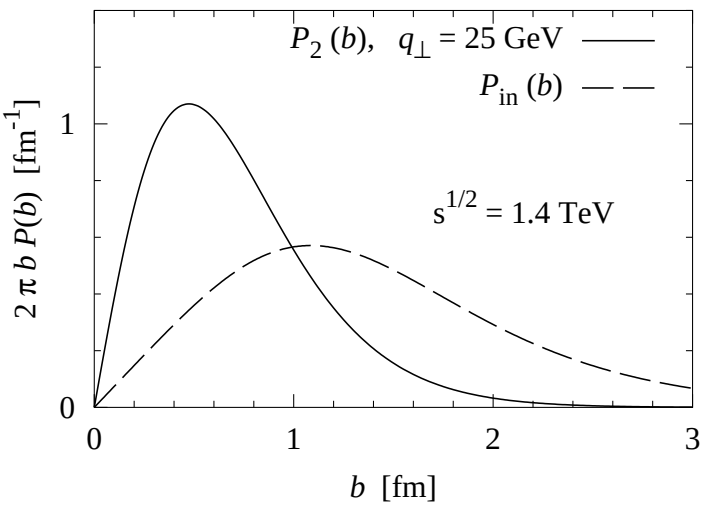

Figure 3. Solid line: Probability for producing a hard dijet ($q_\perp = 25$ GeV) in pp collisions at LHC, $P_2(b)$ of Eq. (10), as a function of the pp impact parameter, b. Dashed line: Probability distribution for generic inelastic events, $P_{\rm in}(b)$. Shown are the radial distributions, $2\pi b P(b)$.

covered in these experiments. In our context this parameter can be interpreted as the change of the nucleon's gluonic transverse size with $\ln(1/x)$,

$$\frac{1}{4}\,\frac{\partial\,\langle\rho^2\rangle}{\partial\ln(1/x)} \;=\; \alpha'. \tag{9}$$

The H1 photoproduction data estimates a value of $\alpha' = 0.08 \pm 0.17$ GeV^{-2} [14]; the new ZEUS analysis of electroproduction data quotes $0.07 \pm 0.05(\mathrm{stat})^{+0.03}_{-0.04}(\mathrm{syst})$ GeV^{-2} [15]. Thus, the variation of $\langle\rho^2\rangle$ in the range $x \sim 10^{-3} - 10^{-2}$ is rather small, and the extrapolation to the region $x \sim 10^{-1}$ does not match with the value extracted from the fixed target data. This indicates that the change in $\langle\rho^2\rangle$ indeed happens rather suddenly between $x \sim 10^{-1}$ and $x \sim 10^{-2}$, as implied by the pion cloud mechanism. Fig. 2 schematically illustrates this scenario.

The information about the transverse spatial distribution of gluons gained from the study of exclusive processes in ep scattering can be used to make predictions for certain characteristics of $\bar{p}p$ and pp collisions at high energies (Tevatron, LHC). In particular, one can predict the probability for the production of a hard dijet at zero rapidity by a gluon–gluon collision, depending on the impact parameter of the underlying pp collision, b [2].

$$P_2(b) \;=\; \int d^2\rho_1 \int d^2\rho_2\; \delta^{(2)}(\boldsymbol{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2)\; \frac{g(x,\rho_1)}{g(x)}\;\frac{g(x,\rho_2)}{g(x)}, \tag{10}$$

where $x = 2q_\perp/\sqrt{s}$ is the momentum fraction of the colliding gluons, with $q_\perp$ the transverse momentum of the dijet. Fig. 3 shows $P_2(b)$ for dijets with $q_\perp = 25$ GeV in pp collisions at the LHC ($\sqrt{s} = 14$ TeV), as obtained from the parametrization of

$g(x,\rho)$ of Ref. [2], which is based on the dipole parametrization (5) and incorporates the information about the x–dependence of $\langle\rho^2\rangle$ shown in Fig. 2. This b–distribution is much narrower than the corresponding distribution for generic inelastic events (i.e., with no condition on hard processes), $P_{\rm in}(b)$, which can be inferred from the impact parameter representation of the amplitude for pp elastic scattering. The reason is that the cross section for generic inelastic events is dominated by collisions of soft partons, whose transverse spatial distribution is much wider than that of the hard partons required to make the dijet. Conversely, this means that requiring the presence of a hard dijet (e.g., by way of a trigger) amounts to a "filter" for central pp collisions at high energies [2]. This possibility is of considerable practical importance. In particular, it allows systematic studies of the approach to the unitarity ("black body") limit in central pp collisions, which would manifest itself in certain modifications of particle production at forward/backward rapidities. Such studies could be performed with the CMS/TOTEM detectors at LHC. Finally, we note that the transverse spatial distribution of large–x partons plays an important role also in the diffractive production of Higgs bosons at LHC [17].

The ideas presented here were developed in collaboration with L. Frankfurt. We thank E. Chudakov for interesting discussions. This work was supported by the US Department of Energy contract DE-AC05-84ER40150, under which the Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility. The work of C. W. was partly supported by Deutsche Forschungsgemeinschaft (Heisenberg Fellowship).

References

1. V. N. Gribov, arXiv:hep-ph/0006158 .
2. L. Frankfurt, M. Strikman and C. Weiss, Phys. Rev. D **69**, 114010 (2004).
3. M. Burkardt, Int. J. Mod. Phys. A **18**, 173 (2003); Phys. Rev. D **66**, 114005 (2002). P. V. Pobylitsa, Phys. Rev. D **66**, 094002 (2002).
4. M. Strikman and C. Weiss, Phys. Rev. D **69**, 054012 (2004)
5. L. Frankfurt and M. Strikman, Phys. Rev. D **66**, 031502 (2002).
6. L. Frankfurt *et al.*, Phys. Rev. D **57**, 512 (1998). L. Frankfurt *et al.*, JHEP **9902**, 002 (1999); JHEP **0103**, 045 (2001).
7. B. Gittelman *et al.*, Phys. Rev. Lett. **35**, 1616 (1975).
8. U. Camerini *et al.*, Phys. Rev. Lett. **35**, 483 (1975).
9. R. Barate *et al.* [NA14 Collaboration], Z. Phys. C **33**, 505 (1987).
10. M. Binkley *et al.*, Phys. Rev. Lett. **48**, 73 (1982).
11. V. Bernard, L. Elouadrhiri and U. G. Meissner, J. Phys. G **28**, R1 (2002).
12. E. Chudakov *et al.*, JLAB-TN-01-007
13. S. J. Brodsky *et al.*, Phys. Lett. B **498**, 23 (2001).
14. C. Adloff *et al.* [H1 Collaboration], Phys. Lett. B **483**, 23 (2000).
15. [ZEUS Collaboration], arXiv:hep-ex/0404008; A. Bruni, these proceedings.
16. S. Chekanov *et al.* [ZEUS Collaboration], Eur. Phys. J. C **24**, 345 (2002).
17. L. Frankfurt, M. Strikman and C. Weiss, in preparation.