Production of W and Z bosons in off-shell gluon-gluon fusion

Nikolay P. Zotov

(SINP, Lomonosov Moscow State University)

in collaboration with
S.P. Baranov (Lebedev Physics Institute, Moscow)

A.V. Lipatov (SINP, Lomonosov Moscow State University)

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O U T L I N E

1. **Introduction and motivations**
2. **Theoretical framework**
3. **Numerical results**
4. **Conclusions**

1. Introduction and motivations

Our consideration of the production of electroweak gauge bosons W, Z in hadron-hadron collisions is is starting from several points. First, predictions of the k_T-factorization approach supplemented with the BFKL-like gluon dynamics agree well with the experimental data on the number of heavy quark production processes at the HERA and Tevatron colliders:

S.P. Baranov, A.V. Lipatov, N.Z., Yad. Fiz. 67 (2004) 859;

A.V. Lipatov, N.Z., Phys. Rev. D73 (2006) 114018, D75 (2007) 014028.

It is important that these predictions were based on the off-shell matrix elements $\gamma g^* \to Q\bar{Q}$ or $g^* g^* \to Q\bar{Q}$. At this point we have tested the consistency of that k_T-factorization approach.

Our next step is to investigate the processes at high scales (around 100 GeV). So the inclusive Higgs hadroproduction at Tevatron and LHC energies has been investigated:

A.V. Lipatov, N.Z., Eur. Phys. J. C44 (2005) 559,

where the main contribution also comes from the off-shell gluon-gluon fusion. It was demonstrated that using of the CCFM-evolved unintegrated gluon densities results to the predictions which are very close to the NNLO pQCD ones.

Now we turn to the inclusive electroweak gauge boson production.

At the leading order (LO) QCD, the $W^{\pm}$ and Z^0 bosons are produced via quark-antiquark annihilation $q + \bar{q}' \to W/Z$.
Here, an important component of the calculations are the unintegrated quark distributions. At present, these distributions are only available in the Kimber-Martin-Ryskin (KMR) scheme:

M.A. Kimber, A.D. Martin, M.G. Ryskin, Phys. Rev. D63 (2001) 114027;

G. Watt, A.D. Martin, M.G. Ryskin, Eur. Phys. J. C31 (2003) 73.

This contrasts with the gluon-induced processes where the market of unintegrated gluon densities is much richer.

Way out: consider higher-order partonic subprocess, gluon-gluon fusion. Gluon splitting $g \to q\bar{q}$ is regarded as part of hard subprocess rather than parton evolution. Then, the problem of quark densities is reduced to gluon densities. Tested for prompt photons:

S.P. Baranov, A.V. Lipatov, N.Z. Phys. Rev. D77 (2008) 074024.

We calculate off-shell m.e. of the $g^* + g^* \to q + \bar{q}' + W/Z$ subprocess and then operate in terms of the u.g.d. only. In this way the different non-collinear evolution schemes can be applied and tested (in future).

However, since the gluons are only resposible for the appearance of the sea but not valence quarks, the conribution from the valence quarks should be calculated separately. Having in mind that the valence quarks are only important at large x, this contribution can be taken into account within the collinear scheme based on the $q + g^* \to W^\pm/Z^0 + q'$ and $q + \bar{q}' \to W^\pm/Z^0$ m.e. convoluted with the on-shell valence quark and/or off-shell gluon densities.

Of course, this approach can only work if the sea quarks appear from the last step of the gluon evolution - then we can absorb this last step of the gluon ladder into a hard m.e.. But this method does not apply to the quarks comming from the earlier steps of the evolution. However, it is not evident in advance whether the last gluon splitting dominates or not. One of the goals of that study is to clarify this point, to what extent the quark contributions can be reexpressed in terms of the gluon contributions.

At the same time, by considering the higher order matrix elements we take into account the terms not containing large logarithms, i.e., the terms not included in the evolution equations. Within our scheme, we get a numerical estimate of the corresponding contributions.

2. Theoretical framework

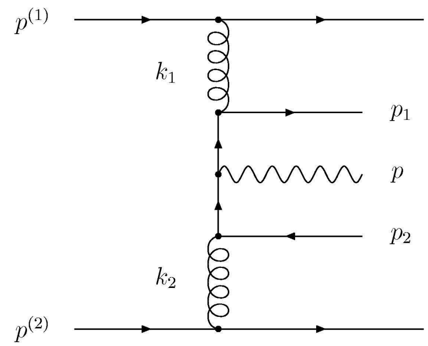

Figure 1: *Kinematics of the* $g^* + g^* \to W^\pm/Z^0 + q + \bar{q}'$ *subprocess.*

The kinematical variables are shown in Fig. 1. We used Sudakov decopmosition for them.

There is the gauge invariant set of eight diagrams (see Fig. 2), which describes the partonic subprocess $g^* g^* \to q\bar{q}' W/Z$ at the leading order in α_s and α.
The summation on the $W^\pm/Z^0$ polarization was carried out by covariant formula

$$\sum \epsilon^\mu(p)\epsilon^{*\,\nu}(p) = -g^{\mu\nu} + \frac{p^\mu p^\nu}{m^2}.$$

In the case of initial off-shell gluon we used known now the BFKL prescription:

$$\epsilon_i^\mu(k)\epsilon_i^{*\,\nu}(k) = \frac{k_{iT}^\mu k_{iT}^\nu}{\mathbf{k}_{iT}^2}.$$

The last formula converges to the former after azimuthal angle averaging in the $k_T \to 0$ limit. The evaluation of the traces of eight m.e. was done using the algebraic manipulation system FORM. The usual method of squaring of m.e. results in enormously long output. This technical problem was solved by applying the method of so called orthogonal amplitudes:

R.E. Prange, Phys. Rev. 110 (1958) 240.

We start from the leading order $\mathcal{O}(\alpha)$ subprocess $q + \bar{q}' \to W/Z$, and then divide it into several contributions which correspond to the interactions of valence quarks $q_v(x, \mathbf{k}_T^2, \mu^2)$, sea quarks appearing at the last step of the gluon evolution $q_g(x, \mathbf{k}_T^2, \mu^2)$, and sea quarks coming from the earlier steps $q_s(x, \mathbf{k}_T^2, \mu^2)$. Here we use the specific property of the KMR scheme which enables us to discriminate between the various components of the quark densities.

The KMR approach represents an approximate treatment of the parton evolution mainly based on the DGLAP equation and incorporating the BFKL effects at the last step of the parton ladder only, in the form of the properly defined Sudakov formfactors $T_q(\mathbf{k}_T^2, \mu^2)$ and $T_g(\mathbf{k}_T^2, \mu^2)$. These formfactors already include logarithmic loop coorections. Also, there are nonlogarithmic corrections which result in the K-factor

A. Kulesza, W.J. Stilling, Nucl. Phys. B555 (1999) 279.

on the cross section $K(q + \bar{q}' \to W/Z) \simeq \exp\left[C_F \pi \alpha_s(\mu^2)/2\right]$ with $C_F = 4/3$ and $\mu^2 = \mathbf{p}_T^{4/3} m^{2/3}$.

In this approximation, the unintegrated quark and gluon distributions are given by

$$f_q(x,\mathbf{k}_T^2,\mu^2) = T_q(\mathbf{k}_T^2,\mu^2)\frac{\alpha_s(\mathbf{k}_T^2)}{2\pi}\times$$
$$\times\int\limits_x^1 dz\left[P_{qq}(z)\frac{x}{z}q\left(\frac{x}{z},\mathbf{k}_T^2\right)\Theta\left(\Delta - z\right) + P_{qg}(z)\frac{x}{z}g\left(\frac{x}{z},\mathbf{k}_T^2\right)\right], \quad (1)$$

$$f_g(x,\mathbf{k}_T^2,\mu^2) = T_g(\mathbf{k}_T^2,\mu^2)\frac{\alpha_s(\mathbf{k}_T^2)}{2\pi}\times$$
$$\times\int\limits_x^1 dz\left[\sum_q P_{gq}(z)\frac{x}{z}q\left(\frac{x}{z},\mathbf{k}_T^2\right) + P_{gg}(z)\frac{x}{z}g\left(\frac{x}{z},\mathbf{k}_T^2\right)\Theta\left(\Delta - z\right)\right], \quad (2)$$

The function $f_q(x,\mathbf{k}_T^2,\mu^2)$ in Eq. (1) represents the total quark distribution. Modifying Eq. (1) in such a way that only the first term is kept and the second term omitted, we switch the last gluon splitting off, thus excluding the $q_g(x,\mathbf{k}_T^2,\mu^2)$ component. Taking the difference between the quark and antiquark densities we extract the valence quark component $q_v(x,\mathbf{k}_T^2,\mu^2) = f_q(x,\mathbf{k}_T^2,\mu^2) - f_{\bar q}(x,\mathbf{k}_T^2,\mu^2)$.

Summing up, we consider the following partonic subprocesses: gluon-gluon fusion $g^* + g^* \to W/Z + q + \bar{q}'$, with which the $q_g + \bar{q}_g$ annihilation is replaced; valence and sea quark-gluon scattering $q_v + g^* \to W/Z + q'$ and $q_s + g^* \to W/Z + q'$, with which the $q_v + \bar{q}_g$ and $q_s + \bar{q}_g$ annihilation is replaced; and quark-antiquark annihilation $q + \bar{q}' \to W/Z$ including both valence q_v and sea q_s quark components.

The contribution to the cross section of $W^\pm/Z^0$ hadroproduction from the off-shell gluon-gluon fusion in the k_T-factorization approach can be written as

$$\sigma(p\bar{p} \to W^\pm/Z^0\, X) = \sum_q \int \frac{1}{256\pi^3 (x_1 x_2 s)^2} |\bar{\mathcal{M}}(g^* g^* \to q\bar{q}'\, W^\pm/Z^0)|^2 \times$$
$$\times f_g(x_1, \mathbf{k}_{1T}^2, \mu^2) f_g(x_2, \mathbf{k}_{2T}^2, \mu^2) d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 d\mathbf{p}_{1T}^2 \mathbf{p}_{2T}^2 dy dy_1 dy_2 \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi} \frac{d\psi_1}{2\pi} \frac{d\psi_2}{2\pi},$$

where $f_g(x, \mathbf{k}_T^2, \mu^2)$ is the u.g.d. in a proton, $|\bar{\mathcal{M}}(g^* g^* \to q\bar{q}'\, W^\pm/Z^0)|^2$ is the off-mass shell m. e., ϕ_1, ϕ_2 are the azimuthal angles of the incoming gluons and ψ_1, ψ_2 are the azimuthal angles of the final state quark and antiquark, respectively.

Significant theoretical uncertainties are connected with the choice of the F. and R. scales. We took $\mu_R = \mu_F = \mu = \xi|\mathbf{m}_T|$**.**

We varied the scale parameter ξ **between** $1/2$ **and 2 about the default value** $\xi = 1$**.**

The charmed quark mass was set to $m_c = 1.5$ **GeV.**

For completeness, we set $m_W = 80.403$ **GeV,** $m_Z = 91.1876$ **GeV,** $\sin^2\theta_W = 0.23122$ **and use LO formula for the strong coupling constant** $\alpha_s(\mu^2)$ **with** $n_f = 4$ **active quark flavours at** $\Lambda_{\rm QCD} = 200$ **MeV, such that** $\alpha_s(M_Z^2) = 0.1232$**.**

The m.e of subprocess $g^*g^* \to q\bar{q}'\,W^\pm/Z^0$ **have been calculated independently**

M. Deak, F. Schwennsen, JHEP 0809 (2008) 035.

3. Numerical results

The solid, dashed and dotted histograms in Fig. 3 represent the contributions from the $g^* + g^* \to W^\pm/Z^0 + q + \bar{q}'$, $q_v + g^* \to W^\pm/Z^0 + q'$ and $q_v + \bar{q}'_v \to W^\pm/Z^0$ subprocesses. The dash-dotted histograms represent the sum of the contributions from the $q_s + \bar{q}'_s \to W^\pm/Z^0$, $q_s + g^* \to W^\pm/Z^0 + q'$ and $q_v + \bar{q}'_s \to W^\pm/Z^0$ subprocesses.

We find that the contribution from the valence quark-antiquark annihilation is important at the Tevatron but yields only about few percent at the LHC energy.

The gluon-gluon fusion is unimportant at the Tevatron ($\sim 1\%$ to the total cross section), but becomes important at higher energies (up to $\sim 25\%$ at the LHC) and has to be taken into account at the LHC.

Quite a significant fraction (nearly 50%) of the calculated cross section at both the Tevatron and the LHC conditions comes from the q_s

quark component.

Figs. 4 and 5 display a comparison between the calculated differential cross sections $d\sigma/dp_T$ and the experimental data

B. Abbott et al. (D∅ Collab.), Phys. Rev. D61 (2000) 032004;
Phys. Lett. B513 (2001) 292;
B. Affolder et al. (CDF Collab.), Phys. Rev. Lett. 84 (2000) 845.

at low p_T ($p_T < 20$ GeV), and in the full p_T range. For comparison, we also show the predictions based on the simple $2 \to 1$ quark-antiquark annihilation subprocess (dotted histograms), with all quark components summed together. The difference between the results can probably be attributed to the terms not containing large logarithms. The predictions of the 'subprocess decomposition' scheme lie by about a factor of 1.25 higher and show good agreement with the data.

4. Conclusions

- **We have presented the results of calculations of inclusive W/Z hadroproduction at high energies in the framework of k_T-factorization QCD approach with the $g^*g^* \to q\bar{q}W/Z$ off-mass shell m.e..**
- **We have used the "decomposition scheme" based on the unintegrated gluon densities obtained from the Kimber-Martin-Ryskin prescription.**
- **We have shown that the dominant contribution comes from the sea quark interactions $q_s + \bar{q}'_s \to W/Z$, $\bar{q}'_s + q_v \to W/Z$ and $q_s + g^* \to W/Z + q'$.**
- **We found that these subprocesses are mainly due to the quarks emerging from the earler steps of the parton evolution (rather than from the last gluon splitting).**
- **We conclude that the quarks constitute an important component of the parton ladder, not negligible even at the LHC energies and not reducible to the gluon component.**

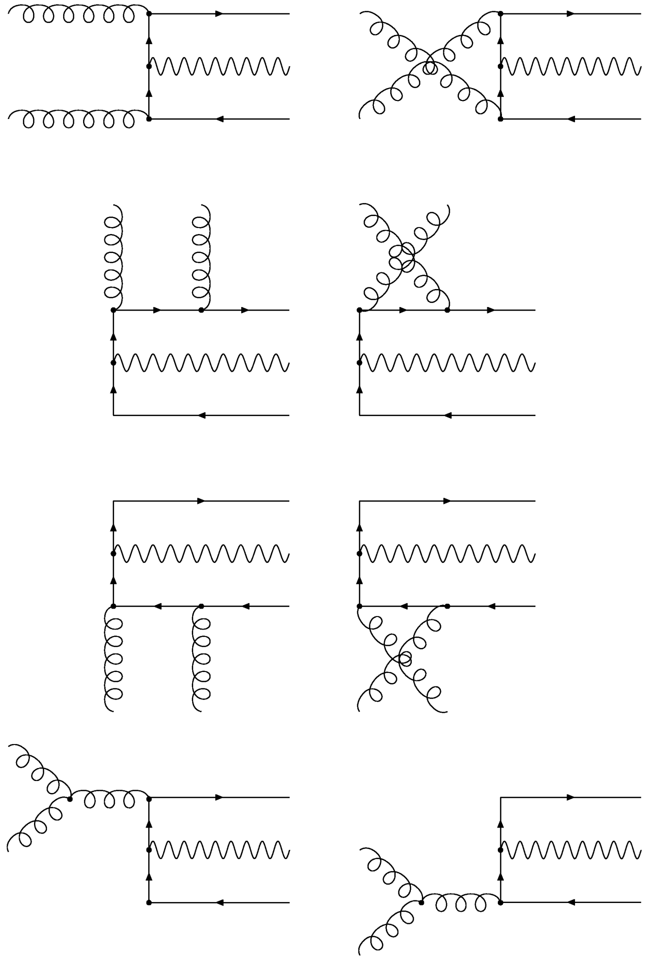

Figure 2: *Feynman diagrams of the partonic subprocess* $g^*g^* \to q\bar{q}'W/Z$.

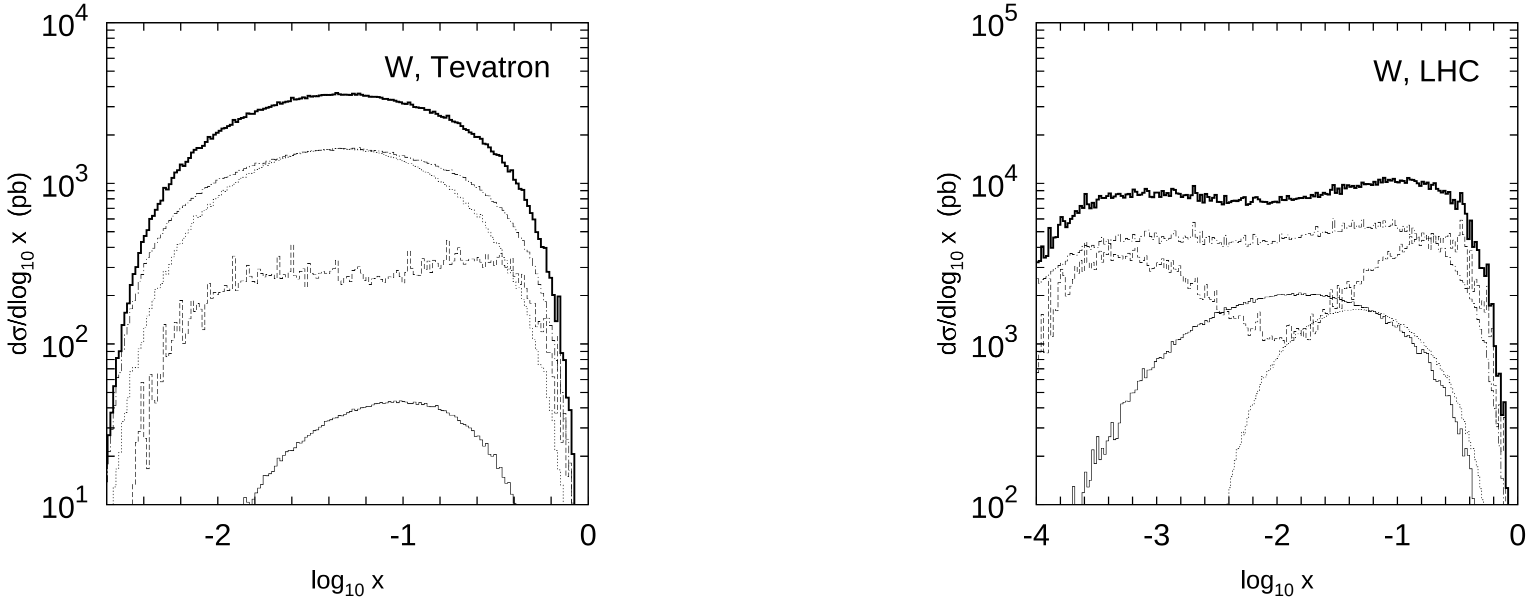

Figure 3: *Different contributions to the inclusive* $W^{\pm}$ *boson production at the Tevatron (left panel) and LHC (right panel) conditions. The solid, dashed and dotted histograms correspond to* $g^* + g^* \to W^{\pm}/Z^0 + q + \bar{q}'$, $q_v + g^* \to W^{\pm}/Z^0 + q'$ *and* $q_v + \bar{q}'_v \to W^{\pm}/Z^0$ *subprocesses. The dash-dotted histograms - the "reduced sea" component. The thick solid histograms - the sum of all contributions.*

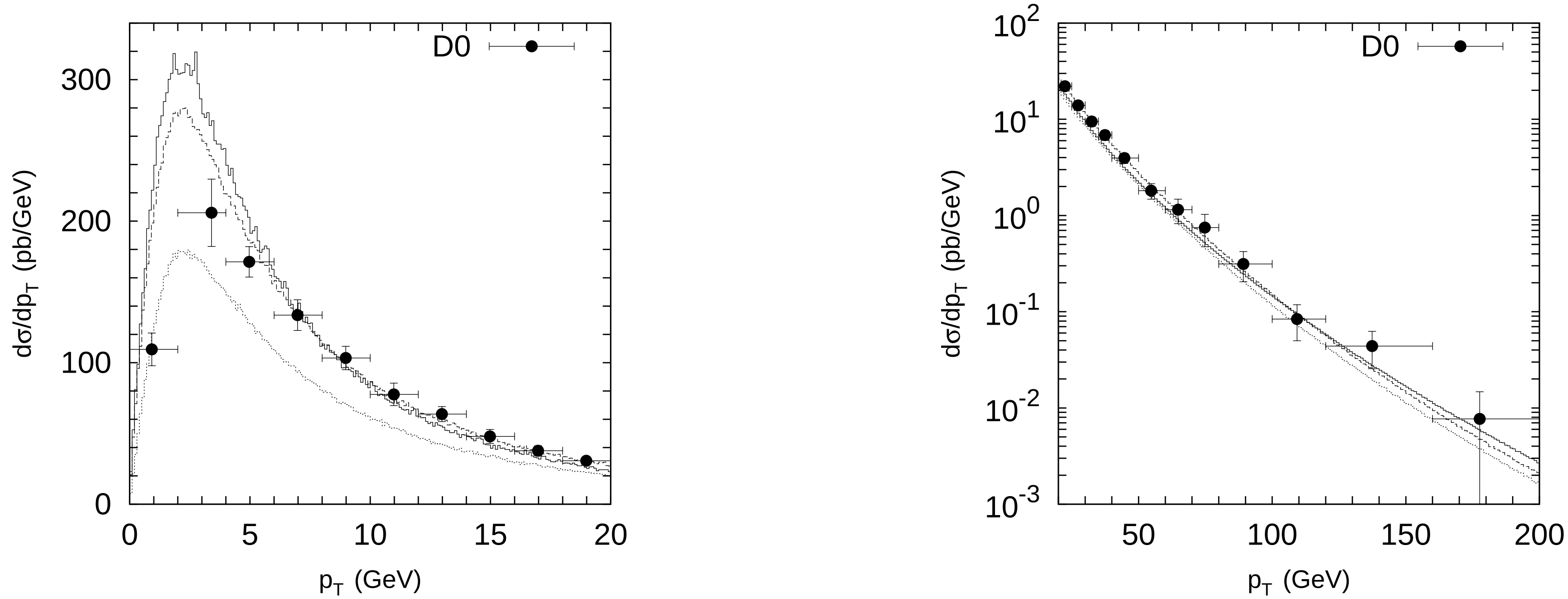

Figure 4: *Transverse mometum distribution of the* $W^{\pm}$ *boson production at* $\sqrt{s} = 1800$ *GeV. Solid histograms - the calculations in the "decomposition" scheme (all contributions described in the text are taken into account). Dashed histograms correspond to the simple* $2 \to 1$ *quark-antiquark annihilation subprocess with all quark components summed together. Dotted histograms correspond to the simple* $2 \to 1$ *quark-antiquark annihilation subprocess without* K*-factor. The cross sections times branching fraction* $f(W \to l\nu)$ *are shown.*

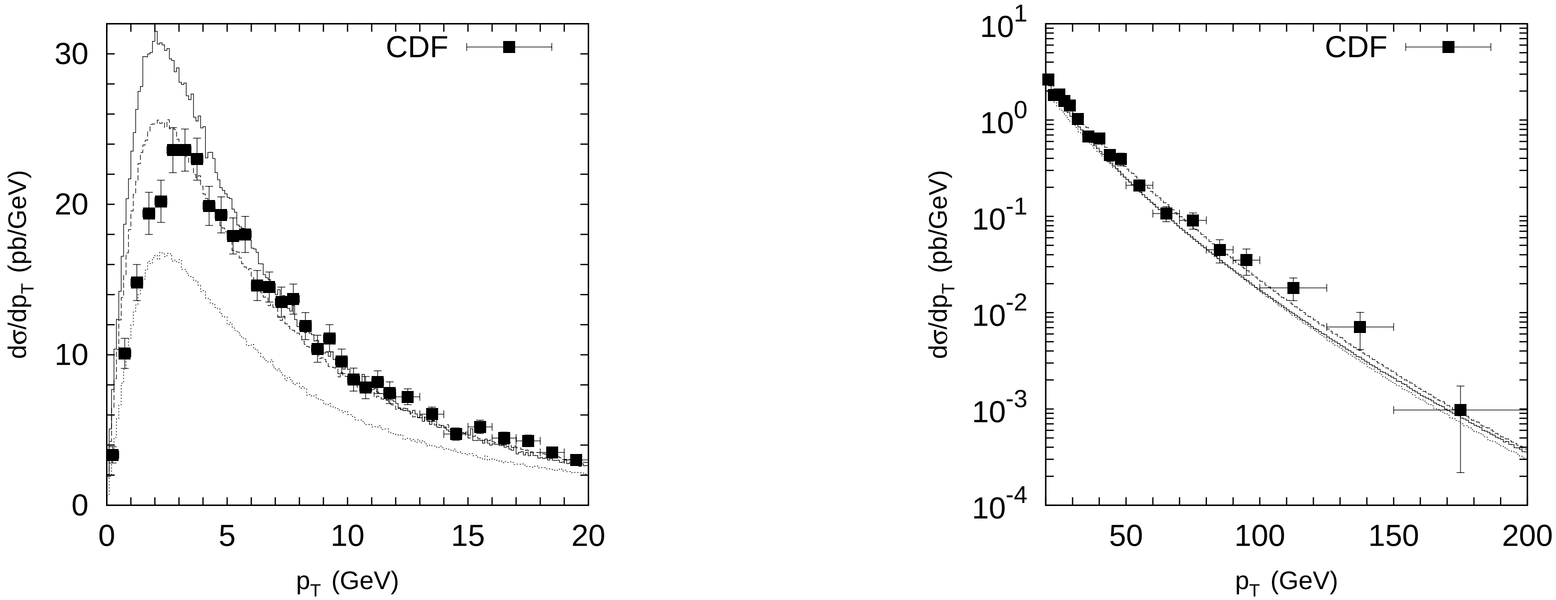

Figure 5: *Transverse mometum distribution of the Z^0 boson. Notation of the histograms is as in Fig. 4*