A Novel Technique for Studying the $Z$ Boson Transverse Momentum Distribution at Hadron Colliders

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Abstract

We present a novel method for studying the shape of the $Z$ boson transverse momentum distribution, $Q_T$, at hadron colliders in $pp/\bar{p}p \rightarrow Z/\gamma^* \rightarrow l^+l^-$. The $Q_T$ is decomposed into two orthogonal components; one transverse and the other parallel to the di-lepton thrust axis. We show that the transverse component is almost insensitive to the momentum resolution of the individual leptons and is thus more precisely determined on an event-by-event basis than the $Q_T$. Furthermore, we demonstrate that a measurement of the distribution of this transverse component is substantially less sensitive to the dominant experimental systematics (resolution unfolding and $Q_T$ dependence of event selection efficiencies) reported in previous measurements of the $Q_T$ distribution.

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1 Introduction

The shape of the $Z$ boson momentum distribution transverse to the beam direction ($Q_T$) at a hadron collider tests the predictions of quantum chromo dynamics (QCD), since non-zero $Q_T$ is generated through radiation from the initial state partons. A good understanding of electroweak vector boson production is important in precision measurements (e.g. top quark and $W$ boson mass) and in Higgs boson and new phenomena searches at hadron collider experiments. In many of these searches the signal and/or background processes involve electroweak vector bosons produced in association with jets.
At low $Q_T$ ($Q_T \ll Q$), where the emission of multiple soft gluons is important, calculations in fixed order perturbative QCD diverge. There exist resummation techniques, in which singular contributions from all orders of $\alpha_s$ are resummed to give a finite result. Resummation was first applied to the Drell-Yan process by Collins, Soper and Sterman (CSS) [1]. The resummation is carried out in impact parameter ($b$) space and includes a non-perturbative (NP) form factor that needs to be determined from data. Brock, Landry, Nadolsky and Yuan (BLNY) proposed the following parameterisation [2]:

$$S_{NP}(b, Q^2) = \left[ g_1 + g_2 \ln \left( \frac{Q}{2Q_0} \right) + g_1 g_3 \ln(100 x_i x_j) \right] b^2$$  \hspace{1cm} (1)

where $x_i$ and $x_j$ are the fractions of the hadron momenta carried by the initial state partons, $Q_0$ is an arbitrary scale set to 1.6 GeV and the parameters $g_i$ need to be fitted from data.

Using the BLNY NP form factor, the CSS formalism was able to describe simultaneously Tevatron Run I $Z$ data and lower $Q^2$ Drell-Yan data in a global fit of the parameters $g_i$ [2]. The $Q_T$ distribution at the Tevatron ($Q^2 \sim M_Z^2$) is sensitive to $g_2$ and insensitive to $g_1$ and $g_3$. A larger value of $g_2$ corresponds to a harder $Q_T$ distribution. The CSS formalism is implemented in the next to leading order (NLO) event generator ResBos [3]. In Run II the DØ Collaboration reported a $Q_T$ measurement in the di-electron channel with 1 fb$^{-1}$ of data [4]. For low $Q_T$ ($Q_T < 30$ GeV), the DØ data is, within the measurement uncertainties, well described by the CSS/BLNY formalism.

At low $Q_T$ the overall uncertainties were dominated by the parton distribution functions (PDFs) and the following experimental systematics [4]:

- Unfolding the $Q_T$ measurement to account for the resolution in the measurement of the $E_T$ of the electrons.
- Correcting for the $Q_T$ dependence of the overall event selection efficiency.

As a result of these substantial experimental systematics, the low $Q_T$ region was not much better measured in this 1 fb$^{-1}$ Run II analysis than in the 100 pb$^{-1}$ Run I analysis [5]. In both analyses, a measurement was made of $g_2$. The measurements: $0.59 \pm 0.06$ GeV$^2$ for Run I and $0.77 \pm 0.06$ GeV$^2$ for Run II, have comparable uncertainties $^1$.

An observable that is sensitive to the $Q_T$, but less sensitive to these experi-

\footnote{The DØ Run I and Run II measurements cannot be directly compared since they used different PDFs and the Run I measurement used the the Ladinsky-Yuan (LY) parameterisation [15] of the NP form factor as opposed to the BLNY parameterisation. Only the third term in $g_1 g_3$ is different and any shift in the fitted $g_2$ is far smaller than the uncertainties on these measurements.}
mental systematics would be beneficial. In this work, Monte Carlo studies of an optimal observable, \( a_T \), are presented. The \( a_T \) observable has previously been used in the selection of \( l^- l^+ \nu \bar{\nu} \) final states at LEP by the OPAL collaboration [6]. The UA2 Collaboration used a similar observable, \( p_T^Z \), which we refer to as \( b_T \), in a \( Q_T \) measurement [7].

### 2 Constructing the Observable

The measured \( Q_T \) is highly sensitive to the lepton \( p_T \) resolution. Our goal is to build an observable that is less sensitive to this resolution, whilst still sensitive to the \( Q_T \). We keep in mind the fact that collider detectors generally have far better angular resolution than calorimeter \( E_T \) or track \( p_T \) resolution.

![Fig. 1. A schematic representation in the transverse plane, of the construction of \( a_T \) and \( a_L \) in a typical leptonic \( Z \) decay. The hadronic recoil is expected to have equal and opposite transverse momentum to the \( Z \).](image)

For events with di-lepton azimuthal separation, \( \Delta \phi^{ll} > \frac{\pi}{2} \), the \( Q_T \) is decomposed into orthogonal components as follows (See figure 1):

- The thrust axis is defined as: \( \hat{t} = \frac{\vec{p}_T^{(1)} - \vec{p}_T^{(2)}}{|\vec{p}_T^{(1)} - \vec{p}_T^{(2)}|} \), where \( \vec{p}_T^{(i)} \) is the transverse momentum vector of lepton \( i \). The two leptons have equal momentum transverse to this axis.
- The transverse momentum vector of the di-lepton system, \( \vec{Q}_T = \vec{p}_T^{(1)} + \vec{p}_T^{(2)} \), is decomposed into components transverse to the axis, \( a_T = |\vec{Q}_T \times \hat{t}| \), and aligned with the axis, \( a_L = \vec{Q}_T \cdot \hat{t} \).

For events with \( \Delta \phi^{ll} < \frac{\pi}{2} \), \( a_T \) is set equal to the \( Q_T \), while \( a_L \) maintains the same definition for all values of \( \Delta \phi^{ll} \).

At low \( Q_T \), \( \Delta \phi^{ll} \sim \pi \), hence the uncertainty on \( a_T \) is approximately the uncertainty on the individual lepton \( p_T \)’s multiplied by the sine of a small angle. In contrast, the uncertainty on \( a_L \) (and thus also \( Q_T \)) is approximately...
the uncertainty on the individual lepton $p_T$’s multiplied by the cosine of a small angle.

An alternative observable is discussed, $b_T$, whose construction is identical to that of $a_T$ except that the decomposition is performed relative to the di-lepton perpendicular bisector axis:

$$\hat{b} = \frac{\vec{p}_{T(1)} - r \vec{p}_{T(2)}}{|\vec{p}_{T(1)} - r \vec{p}_{T(2)}|}$$

where $r = |\vec{p}_{T(1)}|/|\vec{p}_{T(2)}|$. The two leptons have equal acoplanarity with respect to this axis. In an event in which the leptons have equal $p_T$, the values of $a_T$ and $b_T$ are equal. No study is presented of the component longitudinal to the axis, $b_L$.

As discussed below, the relative sensitivity to lepton $p_T$ mis-measurement of $a_T$ and $b_T$ depends on the correlation between the lepton $p_T$ and its resolution.

3 Monte Carlo Simulation

Monte Carlo (MC) events are generated using PYTHIA [8], which treats at leading order (LO) the process $p\bar{p} \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-$ plus up to one jet, at a centre of mass energy of 1.96 TeV, and mass between 60 and 130 GeV. PYTHIA uses additional parton showering to simulate “soft” transverse momentum generation. Although this study is carried out with $Z \rightarrow \mu^+\mu^-$ events, the idea is applicable to studying the di-electron channel.

In order to simulate the imperfect muon $p_T$ resolution of a detector, Gaussian smearing of width 0.003 GeV$^{-1}$ is applied in $1/p_T$ to both muons, which is approximately the design muon $p_T$ resolution of the Run II DØ detector [9]. The design tracking resolution of other current and future hadron collider detectors; CDF, ATLAS and CMS [10–12] vary between $\approx 10^{-3}$ and $\approx 10^{-4}$ GeV$^{-1}$ depending on the track $p_T$ and pseudo-rapidity ($\eta$). We refer to the constant $\delta(1/p_T)$ form of the resolution $p_T$ dependence as muon-like. An alternative resolution dependence is studied; electron-like resolution with the form: $\delta p_T/p_T = 0.15/p^{1/2}$, which would be the form expected for a calorimeter-based measurement appropriate for electrons. Gaussian smearing is applied to the lepton azimuthal angle $\phi$ of width 0.0005 rad., which is the typical resolution of a detector.

In order to study the dependence of event selection efficiency on $Q_T$, $a_T$, $a_L$ and $b_T$, the following simple cuts are applied to the event sample. These are representative of the cuts typically applied to select $Z$ decays at a hadron collider.

- The di-muon invariant mass must be between 70 and 110 GeV.
- Kinematic cuts on both muons: $p_T > 15$ GeV and $|\eta| < 2$. 

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• An isolation cut on both muons: \( f_{iso} < 2.5 \, \text{GeV} \), where \( f_{iso} = \sum p_T(\Delta R < 0.2) \) and \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \) is the radius of a cone around the candidate muon. The sum is over all particles excluding both the candidate muon and any neutrinos.

**PYTHIA** is a LO event generator and is not expected to give a good description of the \( Q_T \) distribution in real data. The events are re-weighted in \( Q_T \) and \( Z \) rapidity \( (y) \) to match the prediction of ResBos using the default settings, which is in good agreement with DØ Run II data [4] in the region of low \( Q_T \) (\( Q_T < 40 \, \text{GeV} \)). Event samples are generated using ResBos, and the re-weighting procedure is carried out as follows:

- Two dimensional histograms in \( Q_T \) and \( |y| \) are produced for both the **PYTHIA** and ResBos event samples.
- Dividing the ResBos histogram by the **PYTHIA** histogram gives an *event-weight* histogram.
- The **PYTHIA** events are now given an *event-weight* based on their \( Q_T \) and \( |y| \) such that the distributions of these variables are the same as the ResBos prediction.

Hereafter, unless otherwise stated, MC refers to **PYTHIA** re-weighted to ResBos.

### 4 Sensitivity to Lepton \( p_T \) Mis-measurement

![Fig. 2](image_url)

(a) *muon-like*  
(b) *electron-like*

Fig. 2. Mean resolution, \( |X_{det} - X_{gen}|/X_{gen} \) for each of the observables, \( Q_T, a_T, a_L \) and \( b_T \) as a function of \( Q_{T_{gen}} \), with (a) *muon-like* resolution \( (\delta(1/p_T) = 0.003 \, \text{GeV}^{-1}) \) and (b) *electron-like* resolution \( (\delta p_T/p_T = 0.15/p^{1/2}) \).
Two quantities are defined: the smeared or detector level quantity, $X_{det}$, and the unsmeared or generator level quantity, $X_{gen}$, where $X$ corresponds to $Q_T$, $a_T$, $a_L$ or $b_T$.

Figures 2 (a) and 2 (b) show the mean resolution, $|X_{det} - X_{gen}|/X_{gen}$ as a function of $Q_{T gen}$ for muon-like and electron-like resolution respectively. It can be seen that for low to moderate values of $Q_T$ ($Q_{T gen} < 50$ GeV), $a_T$ and $b_T$ are significantly better measured than $a_L$ or $Q_T$. Either $a_T$ or $b_T$ are therefore particularly well suited to studying $Z$ production at low to moderate $Q_T$. In the region of low $Q_T$ ($Q_{T gen} < 15$ GeV), $a_T$ and $b_T$ have similar resolutions for either the (a) muon-like or (b) electron-like cases. At increasing $Q_T$, $a_T$ is more suited for (a), and $b_T$ more suited for (b). The construction of $a_T$ ensures that the acoplanarity angle to the thrust axis is smaller for the larger $p_T$ lepton which tends to have poorer resolution in the muon-like case. In the following sections, for brevity, we discuss the case of muon-like smearing.

## 5 Event Selection Efficiency Dependence

Figure 3 shows the dependence of the event selection efficiency (separately for the cuts on muon $|\eta|$, $p_T$ and isolation) on the generator level $Q_T$, $a_T$, $a_L$ and $b_T$. The cuts are applied in the following order: $|\eta|; p_T$; isolation. The efficiency dependence for each cut is calculated having applied all previous cuts. For large $Q_T$, the muons tend to be more central, increasing the $\eta$ cut efficiency. The same correlation is apparent for $a_T$ and $a_L$, although weaker than for $Q_T$.

The muon $p_T$ cut dependence on $a_T$ is flat in the range considered. Conversely large values of $a_L$, generate an asymmetry in the $p_T$‘s of the two muons and tend to push the lower $p_T$ muon below the cut threshold. The dependence on the isolation cut is substantially flatter for $a_T$ than for $a_L$. Large $a_L$ corresponds to a high $p_T$ hadronic recoil with a large fraction of its $p_T$ aligned along the thrust axis and thus possibly lying within the isolation cone of one of the two muons. There is no such dependence on $a_T$, since $a_T$ is the component of the recoil $p_T$ transverse to the thrust axis.

In summary, the efficiencies of the cuts on muon $|\eta|$, $p_T$ and isolation depend less strongly on $a_T$ than $Q_T$. The dependence of $b_T$ on each of the cuts is similar to that of $a_T$. 

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Fig. 3. The dependence of event selection efficiencies on the generator level (a) $a_T$, (b) $b_T$, (c) $a_L$ and (d) $Q_T$ in $Z \rightarrow \mu^+\mu^-$ MC events. The efficiencies $\epsilon_\eta$, $\epsilon_{p_T}$ and $\epsilon_{iso}$ (evaluated relative to the previous cut in the order; $|\eta|$, $p_T$, isolation) are shown separately for cuts on muon $|\eta|$, $p_T$ and isolation respectively. Note that the range of $Q_T$ shown in this figure is $\sqrt{2}$× larger than for $a_T$ and $a_L$.

6 Systematic Uncertainties on the Unfolded and Efficiency Corrected Distributions

Figure 4 compares (separately for $Q_T$, $a_T$, $a_L$ and $b_T$) the generator level distributions without selection cuts and the detector level distributions with selection cuts. The detector level $Q_T$ and $a_L$ distributions are substantially affected by the detector resolution and event selection efficiency. In contrast the distributions in $a_T$ and $b_T$ are almost completely unaffected.

In order to extract the underlying shape, the measured distributions would need to be unfolded for the detector resolution and corrected for the event selection efficiency with associated systematic uncertainties. These uncertain-
Fig. 4. Detector and generator level distributions for (a) $a_T$, (b) $b_T$, (c) $a_L$ and (d) $Q_T$. The detector level distributions are for Gaussian smearing in $1/p_T$ of width 0.003 GeV$^{-1}$, and all selection cuts are applied. The generator level distributions do not include selection cuts. The lower halves of each plot show the fractional differences.

ties would be substantially smaller for $a_T$ or $b_T$ than for $Q_T$ or $a_L$. In fact, for any realistic detector resolution, the measured $a_T$ or $b_T$ distribution describes the underlying distribution within a few percent without any unfolding or efficiency correction at all. The statistical sensitivity of $a_T$ or $b_T$ to the shape of the underlying $Q_T$ distribution is also enhanced by the lack of resolution smearing compared to $Q_T$. 
7 Uncertainties in Measurements of NP Phenomenological Parameters

In a “toy” MC measurement of the BLNY parameter $g_2$, we study both the sensitivity to systematic uncertainties and the statistical sensitivity of $a_T$, $a_L$, $Q_T$ and $b_T$. Figure 5 shows the PYTHIA (re-weighted to ResBos) prediction of the normalized $a_T$ distribution for two different values of $g_2$. The $a_T$ distribution is clearly sensitive to the value of $g_2$.

Event samples are generated using ResBos, for fifteen $g_2$ values from 0.54 to 0.82 (distributed around the world average, $g_2 = 0.68^{+0.07}_{-0.01}$ GeV$^2$) [2]. Using the re-weighting procedure described earlier, PYTHIA “MC samples” are produced corresponding to each of the $g_2$ values. An independent sample of 200k PYTHIA events is re-weighted to the central $g_2$ value and represents the experimental “pseudo-data” sample.

For each of the 15 MC templates, the pseudo-data vs MC $\chi^2$ is calculated. The function: $y = a(x-b)^2 + c$ is fitted to the $\chi^2$ as a function of $g_2$, and a best fit $g_2$ is determined as $b \pm a^{-1/2}$ where the uncertainty is statistical ($\Delta \chi^2 = \pm 1$).

This “toy” measurement of $g_2$ serves as an example analysis at an experiment. Free parameters in any NP model which affect the $Q_T$ could in principle be measured using this strategy.
7.1 Systematic Uncertainties

We study the systematic uncertainties on a fit to $g_2$. The following systematic variations are carried out. These are typical of the experimental uncertainties expected at a hadron collider although the size of the variations are chosen to give reasonable shifts in the fitted $g_2$:

- In the MC, the smearing constant ($\delta(1/p_T)$) is varied by a factor $\pm 1\%$ around a central value of $0.003$ GeV$^{-1}$.
- As a test of sensitivity to mis-measurement of the event selection efficiency dependencies on, $|\eta|$, $p_T$ and isolation, events in MC are given $\pm 10\%$ more weight for each muon with: $1 < |\eta| < 2$, $15 < p_T < 20$ GeV, or $1 < f_{iso} < 2.5$ GeV.
- In the MC, the $\phi$ smearing constant is varied by $\pm 10\%$.
- As a test of sensitivity to mis-modeling of final state radiation (FSR), events in MC are given $\pm 10\%$ more weight if the difference between the generator level $Z$ mass and the generator level di-lepton mass is greater than 1 GeV.

Table 1 shows the shifts (%) in the fitted $g_2$ for systematic variations in the MC.

|                  | $a_T$ | $a_L$ | $Q_T$ | $b_T$ |
|------------------|-------|-------|-------|-------|
| $p_T$ smearing $\pm 1\%$ | $-0.02$ | $\mp 11$ | $\pm 2.8$ | $\mp 0.03$ |
| $p_T$ $\pm 10\%$ | $\pm 0.2$ | $\pm 3.8$ | $\pm 1.4$ | $\pm 0.2$ |
| $f_{iso}$ $\pm 10\%$ | $\pm 0.3$ | $\pm 1.7$ | $\pm 0.59$ | $\pm 0.3$ |
| $|\eta|$ $\pm 10\%$ | $\pm 0.4$ | $\pm 11$ | $\pm 3.2$ | $\pm 0.4$ |
| $\phi$ smearing $\pm 10\%$ | $-0.01$ | $0.00$ | $0.00$ | $-0.02$ |
| FSR $\pm 10\%$ | $\mp 0.4$ | $\mp 0.96$ | $\mp 0.52$ | $\mp 0.4$ |

Table 1 shows the shifts in the fitted $g_2$ for the +ve and -ve systematic variations. For each of the variations, the shift in the fitted $g_2$ is substantially smaller using $a_T$ or $b_T$ than $Q_T$, and larger using $a_L$. In fact the only variation to which $a_T$ or $b_T$ are more sensitive is the $\phi$ smearing, but for any realistic detector $\phi$ resolution, the shift in $g_2$ is negligible.

7.2 Statistical Sensitivity

Simply discarding information from $a_L$ is not optimal in terms of the statistical sensitivity to the shape of the $Q_T$ distribution (and thus also the value of $g_2$). As well as the basic observables, $Q_T$, $a_T$ and $a_L$, the following ideas are
proposed as possible optimised combinations of $a_T$ and $a_L$:

- A weighted quadrature sum of $a_T$ and $a_L$ with more weight ($w$) given to $a_T$:
  $$Q_T^*(w) = \frac{1}{w} \sqrt{(w \cdot a_T)^2 + a_L^2}.$$  
- A 2D fit to $\frac{d^2\sigma}{da_T da_L}$.

Table 2

The binning and 1σ statistical uncertainties for each of the $g_2$ fits, for a range of $\delta(1/p_T)$.

| $\delta(1/p_T)$ (GeV$^{-1}$) | $Q_T$ | $a_T$ | $a_L$ | $Q_T^*(w = 5)$ | $\frac{d^2\sigma}{da_T da_L}$ | $b_T$ |
|-------------------------------|-------|-------|-------|----------------|-----------------------------|------|
| nbins range (GeV)             |       |       |       |                |                             |      |
| 0.0000 0-30                   | 1.4   | 2.2   | 2.4   | 1.9            | 1.4                         | 2.2  |
| 0.0003 0-20                    | 1.4   | 2.2   | 2.5   | 1.9            | 1.4                         | 2.2  |
| 0.0010 0-20                    | 1.8   | 2.2   | 3.6   | 1.9            | 1.6                         | 2.2  |
| 0.0030 0-20                    | 3.1   | 2.3   | 8.9   | 2.2            | 2.1                         | 2.2  |

The binning and 1σ statistical uncertainties for each of the fits is presented in Table 2. Since the relative statistical sensitivity of each of the observables depends on the detector resolution, the fit is performed for different widths of Gaussian smearing. All of the fits use equal width bins. For “perfect” resolution, a fit to $Q_T$ and the 2D fit have comparable statistical uncertainties. A fit to $a_T$ or $a_L$ alone is less statistically sensitive, as each contains information on only one component of the $Q_T$.

At larger $\delta(1/p_T)$, the sensitivity of $a_L$ is completely washed out by the smearing. For $\delta(1/p_T) = 0.003$ GeV$^{-1}$, $a_T$ alone gives better statistical precision than $Q_T$. Over the resolution range covered, $Q_T^*(w = 5)$ gives slightly better statistical precision than $a_T$ alone. Note that no attempt has been made to optimize the weight in $Q_T^*(w = 5)$ as a function of resolution, and $w = 5$ is a somewhat arbitrary choice. Clearly, for “perfect” resolution, $w = 1$ is the only sensible choice. Once experimental systematic uncertainties are taken into account, $a_T$ will need to be given more weight in any optimal combination of $a_T$ and $a_L$.

7.3 Sensitivity to Small-x Broadening

The NP form factor (Eq. 1) required an alteration, to describe deep inelastic scattering (DIS) data involving initial state partons with $x < 10^{-3}$ [13]. Berge et al. [14] suggested that if this (so-called small-x broadening) was observed
at the Tevatron in an exclusive high $|y|$ sample of $Z$ bosons, a broader Higgs (and $W, Z$) boson transverse momentum distribution could be expected at the LHC. The DØ Run II data on $Q_T$ [4] disfavoured this modification, although given the large uncertainties, the data was not particularly sensitive to such broadening. Even without taking into account the reduced systematic uncertainties, the optimised fits ($Q^*_T, d^2\sigma/d\alpha_Td\alpha_L$) described earlier would be more sensitive to such effects. Once systematic uncertainties are taken into account, the sensitivity is further enhanced relative to the $Q_T$.

7.4 Azimuthal Correlation Between the Recoil and the Leptonic Decay

The example $g_2$ measurement presented would be sensitive to the description by the MC event generator(s) of the azimuthal correlation between the hadronic recoil and the leptonic decay. A measurement of $d^2\sigma/d\alpha_Td\alpha_L$ could be used to study this correlation.

8 Conclusions

Using MC simulations we demonstrate the potential benefits of decomposing the $Q_T$ into two orthogonal components, $\alpha_T$ and $\alpha_L$. A measurement of the $\alpha_T$ distribution would be substantially less sensitive to two of the dominant experimental systematic uncertainties reported in previous $Q_T$ measurements: lepton $p_T$ or $E_T$ mis-measurement, and the $Q_T$ dependence of the event selection efficiencies. A slightly different variable $b_T$ is demonstrated to be similarly insensitive to these uncertainties. An optimal combination of $\alpha_T$ and $\alpha_L$, giving more weight to $\alpha_T$ gives, for any realistic detector resolution, better statistical sensitivity to the shape of the region of low $Q_T$. Two possibilities are proposed: a weighted quadrature sum of $\alpha_T$ and $\alpha_L$ or a fit to $d^2\sigma/d\alpha_Td\alpha_L$.

A measurement of $d^2\sigma/d\alpha_Td\alpha_L$ could potentially probe the azimuthal correlation between the $Z$ boson decay axis and the hadronic recoil. The partial differential cross sections; $d^2\sigma/d\alpha_TdQ$, $d^2\sigma/d\alpha_Tdy$ and $d^3\sigma/d\alpha_TdQdy$ could also be measured, taking advantage of the reduced systematic uncertainties on $\alpha_T$ compared with similar measurements of differential cross sections with respect to $Q_T$. Such distributions would be sensitive to small-$x$ broadening effects.
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