Resummed vector $Q_T$ distribution in DIS as a probe of small $x$ broadening effects

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Motivation

$Q_T$ distributions are important for studying properties of vector bosons (e.g. $W^\pm$, $Z^0$ and the Higgs at the LHC).
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Do conventional resummed predictions and $x$-independent NP corrections hold at small $x$? (BFKL?)
Motivation

Studies of event shape variables in DIS Breit current hemisphere suggest no significant \( x \)-dependent power corrections at relatively small \( x \) (except for jet broadening, whose \( x \)-dependence is not due to BFKL effects).
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However, semi-inclusive DIS $q_T$ (transverse energy) distribution appears to be broadened in impact parameter space, $b$, by a gaussian:

$$e^{-b^2 \rho(x)}, \quad \rho(x) \sim \frac{1}{x} \text{ at small } x.$$

e.g. S. Berge, P. M. Nadolsky, F. I. Olness, C.-P. Yuan, 2005

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**DIS at Born level:**

$$\gamma^*(q)\rightarrow e^-(l-q)$$

$$e^-(l)\rightarrow\gamma^*(q)\rightarrow r$$

$$p\rightarrow e^-(l-q)$$

**DIS standard variables:**

$$Q^2 = -q^2$$

$$x = \frac{Q^2}{2P\cdot q}$$

$$y = \frac{P\cdot q}{P\cdot l} = \frac{p\cdot q}{p\cdot l}$$
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DIS at Born level:

\[ Q^2 = -q^2 \]
\[ x = \frac{Q^2}{2P.q} \]
\[ y = \frac{P.q}{P.l} = \frac{p.q}{p.l} \]

$x$: momentum fraction of struck quark relative to proton.
Motivation

Breit frame: is the rest frame of $2xP + q$
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**Remnant hemisphere, $H_R$**: has same direction as the incoming quark direction.
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Why choose $H_C$?
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Why choose \( \mathcal{H}_C \)?

- Almost empty from non-perturbative remnants of the proton.
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Breit frame: is the rest frame of $2xP + q$

Current hemisphere, $\mathcal{H}_C$: has same direction as the photon current direction.
Remnant hemisphere, $\mathcal{H}_R$: has same direction as the incoming quark direction.

Why choose $\mathcal{H}_C$?

- Almost empty from non-perturbative remnants of the proton.
- Analogous to one hemisphere in $e^+e^-$.
Motivation
Comparison between DIS Breit frame and Hadron-Hadron collisions

Incoming leg 1
Hadron-Hadron collision
DIS Breit frame

Incoming leg 2

Outgoing leg

Vector Boson

$Q_T$ distribution

Matching

Conclusions and outlook
Leading Order $Q_T$ distribution

Number of events with $\left| \sum_{i \in H_C} \vec{k}_{Ti} \right| < Q_T$, for small $Q_T$, is:

$$\frac{\sigma}{\sigma_0} = \frac{\alpha_S}{2\pi} \left( -\frac{1}{2} C_F \ln^2 \frac{Q_T^2}{Q^2} - \frac{3}{2} C_F \ln \frac{Q_T^2}{Q^2} \right. + \left. \frac{P^{(0)}_{qq} \otimes q(x, Q^2)}{q(x, Q^2)} \ln \frac{Q_T^2}{Q^2} + \frac{C_1 \otimes q(x, Q^2)}{q(x, Q^2)} \right),$$

$q(x, Q^2) = \sum_{i}^{n_f} e_{q_i}^2 \left[ q_i(x, Q^2) + \bar{q}_i(x, Q^2) \right]$, (PDFs).

$P^{(0)}_{qq} : q \rightarrow q$ LO splitting function.

$q$ : column of PDFs (including gluon density).

$C_1$ : a row of regular functions (independent of $Q_T$), calculable in perturbation theory.
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$$\left. + \frac{P_{qq}^{(0)} \otimes q(x, Q^2)}{q(x, Q^2)} \ln \frac{Q_T^2}{Q^2} + \frac{C_1 \otimes q(x, Q^2)}{q(x, Q^2)} \right),$$

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Regular terms in $Q_T$ that tend to zero when $Q_T \rightarrow 0$ can be obtained from a DIS event generator, e.g. DISPATCH:

Restricting real emissions spoils the complete cancelation of infrared and/or collinear singularities between real and virtual contributions to Feynman diagrams.
The smallness of $\alpha_S$ is spoiled by the logarithms.
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Resummed $Q_T$ distribution

Result

\[
\frac{1}{\sigma_0} \frac{d\sigma}{dQ_T} = \frac{1}{q(x, Q^2)} \frac{d}{dQ_T} \left[ \left\{ q(x, Q_T^2) + \frac{\alpha_S}{2\pi} C_1 \otimes q(x, Q^2) \right\} \right]
\times e^{\gamma_E h} e^{-\{L g_1(\alpha_S L) + g_2(\alpha_S L) + \alpha_S g_3(\alpha_S L) + \ldots\} \frac{\Gamma(1 + h/2)}{\Gamma(1 - h/2)}}
\]

$L = \ln \frac{Q_T^2}{Q^2}$, $\gamma_E$: Euler constant, $\Gamma$: Euler Gamma function. $h$ and $g_i$ are functions of $\alpha_S L$.

The expansion of the above equation to $O(\alpha_S)$ gives exactly the leading order result.
Resummed cross-section does not have finite terms in $Q_T$ (important at large $Q_T$).
Matching

$M_2$ Matching Scheme

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Hence we add the resummed result and Monte Carlo result, and remove double counted terms (the Logs and constant $C_1$).
Matching
Comparison between Matched, resummed and MC results

Differential distributions

- Matched
- Resummed
- MC

$Q_T = 116$ GeV, $x = 0.304453$, $\sqrt{s} = 316$ GeV
Matching
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Motivation
Leading order $Q_T$ distribution
Resummed $Q_T$ distribution
Matching

Conclusions and outlook
Non perturbative correction to the distribution is a convolution with the gaussian, $e^{-kb^2}$. 
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$k$ is a constant (at large $x$ at least), and plausibly half of that in Drell-Yan.
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By comparing to small $x$ data, our plots should reveal any dependence of $k$ on $x$. 
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Outlook

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Need to understand low-$Q$ data.
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This observable is an excellent example of using HERA data for the LHC.