Studies of forward jets and production of $Z$, $W$ within high energy factorisation approach

Krzysztof Kutak (DESY)

In collaboration with: M. Deák (DESY), F. Hautmann (Oxford), H. Jung (DESY)
I. INTRODUCTION

High-$p_T$ production at the LHC

- Phase space opening up for large $\sqrt{s}$
- Unique coverage of large rapidities (calorimeters+proton taggers)

- Physics of hard processes with multiple hard scales and highly sensitive to parton dynamics at $x \rightarrow 0$
polar angles small but far enough from beam axis

- measure azimuthal plane correlations

\[ p_\perp \gtrsim 20 \text{ GeV}, \quad \Delta \eta \gtrsim 4 \div 6 \]

central + forward detectors

azimuthal plane

X. Aslanoglou et al., CERN-CMS-NOTE-2008-022 (2008)]
Multi-scale problem ⇒

⇒ all-order summation of high-energy logarithmic corrections long recognized to be necessary for reliable QCD predictions

Mueller & Navelet, 1987; Del Duca, Peskin & Tang, 1993; Stirling, 1994

efforts toward improved Monte Carlos / semi-analytic approaches

Andersen, arXiv:0906.1965; Andersen and Sabio Vera, 2003;
Andersen, Del Duca, Frixione, Schmidt and Stirling, 2001;
Schwennsen, hep-ph/0703198; Bartels, Sabio Vera and Schwennsen, 2006;
Ewerz, Orr, Stirling and Webber, 2000; Orr and Stirling, 1998

• DIS case ⇒

• neither PYTHIA Monte Carlo nor NLO calculations are able to describe forward jet ep data

High-energy factorization at fixed transverse momentum

\[ \frac{d\sigma}{dQ_T^2 d\phi} = \sum_a \int \phi_{a/A} \otimes \frac{d\hat{\sigma}}{dQ_T^2 d\phi} \otimes \phi_{g^*/B} \]

needed to resum consistently both logs of rapidity and logs of hard scale

\[ (a) \]

Figure 1: (a) Factorized structure of the cross section; (b) a typical contribution to the \( gg \) channel matrix element.

\[ (b) \]

\[ \diamond \phi_a \text{ near-collinear, large-x; } \phi_{g^*} \text{ } k_{\perp}\text{-dependent, small-x} \]

\[ \diamond \hat{\sigma} \text{ off-shell continuation of hard-scattering matrix elements} \]

Catani et al., 1991; Ciafaloni, 1998

Deák, Jung, Hautmann & K, in progress
II. PARTON DISTRIBUTIONS BY SHOWERING METHODS

\[ d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \, \alpha_S(q^2) \, P(z) \, \Delta(q^2, q_0^2) \]

\[ \leftrightarrow \text{collinear, incoherent emission} \]

\[ \diamond \text{ Soft emission} \rightarrow \text{interferences} \rightarrow \text{ordering in decay angles} \]

\[ \leftrightarrow \text{gluon coherence for } x \sim 1 \]

\[ \text{ex.: Herwig, new Pythia} \]

\[ \diamond \text{Gluon coherence for } x \ll 1 \Rightarrow \text{corrections to angular ordering:} \]

\[ \leftrightarrow \text{MC based on } k_\perp\text{-dependent unintegrated pdfs and MEs} \]
**K⊥-DEPENDENT PARTON BRANCHING**

- MC for NLO QCD evolution at unintegrated level

- CCFM gluon branching eq. (leading-logarithmic)

\[
G(x, k_T, \mu) = G_0(x, k_T, \mu) + \int \frac{dz}{z} \int \frac{dq^2}{q^2} \Theta(\mu - zq) \\
\times \Delta(\mu, zq) \quad P(z, q, k_T) \quad G(\frac{x}{z}, k_T + (1 - z)q, q)
\]

\[\text{Sudakov unintegr. splitting}\]

\[\xrightarrow{\alpha_1} \quad \xrightarrow{\alpha} \quad \xrightarrow{\text{implemented in CASCADe MC (H. Jung)}}\]

\[
P \xrightarrow{\alpha} \text{p} \quad \rightarrow \quad P \xrightarrow{\alpha_1} \text{xp} \\
\]

\[\xrightarrow{\text{p}} \quad \xrightarrow{+} \quad \xrightarrow{+} \quad \text{..}\]
III. HARD SCATTERING CROSS SECTIONS

- Matrix elements for fully exclusive events with forward jets
  
  \[ [\text{Deák, Hautmann, Jung, & K, 2009}] \]

- Both quark and gluon channels found to be important for realistic phenomenology

\[ Q_T = \text{final-state transverse energy (in terms of two leading jets } p_T \text{’s)} \]

\[ C_F^2 \text{ term } qg \text{ channel} \]
\[ C_A C_F \text{ term } qg \text{ channel} \]

\[ \frac{Q_T^4 \, d \sigma}{d \varphi \, d Q_T^2} \]

\[ \begin{align*}
  \varphi = 1 & : \quad 5 \times 10^{-3} \quad 1 \times 10^{-3} \\
  \varphi = 1.5 & : \quad 3 \times 10^{-3} \quad 2 \times 10^{-3} \\
  \varphi = 2 & : \quad 1 \times 10^{-3} \quad 1 \times 10^{-2}
\end{align*} \]

\[ \begin{align*}
  \varphi = 1 & : \quad 4 \times 10^{-2} \quad 2 \times 10^{-2} \\
  \varphi = 1.5 & : \quad 3 \times 10^{-2} \quad 3 \times 10^{-3} \\
  \varphi = 2 & : \quad 2 \times 10^{-2} \quad 2 \times 10^{-3}
\end{align*} \]

\[ \triangleright C_F C_A \text{ contribution to } qg \text{ dominates large } s/Q_T^2 \text{ (constant at large energy)} \]
BEHAVIOR AT LARGE $k_\perp$

$k_T$ = transverse momentum carried away by extra jets

$k_T/Q_T \to 0$ leading order process

\[ C_F^2 \text{ term qg channel} \]

\[
\frac{Q_T^4}{dQ_T^2} \frac{d\sigma}{d\varphi dQ_T^2} \quad \text{for} \quad \varphi = 1, 1.5, 2
\]

\[ C_A C_F \text{ term qg channel} \]

\[
\frac{Q_T^4}{dQ_T^2} \frac{d\sigma}{d\varphi dQ_T^2} \quad \text{for} \quad \varphi = 1, 1.5, 2
\]

[Deák, Hautmann, Jung, & K, in progress]

- dynamical cut-off at $k_T \sim Q_T$ set by coherence effects
- non-negligible terms from finite $k_T$ tail
Jet Nr.1: $-2 < y < 2 \ p_\perp > 20\text{GeV}$
Jet Nr.2: $3 < y < 5$ and $4 < y < 6.6 \ p_\perp > 20\text{GeV}$

$k_T$ of incoming gluon allows for harder spectrum
- non-negligible terms from finite $k_T$ tail
• in our approach we consider only flavour nonsinglet
  • PYTHIA cross checks that flavour singlet contribute
    less in a forward region
PRODUCTION OF Z/W BOSONS

- background for BSM processes
  - luminosity measurements, calibration of detectors

[Deák, Schwennsen; Baranov, Lipatov, Zotov]

- hard scale provided by mass of $Z/W$
  - $k_T$ of incoming gluons might be relevant for $W/Z$ $p_{\perp}$ spectra
ANGULAR CORRELATIONS AND $p_\perp$ SPECTRUM

$$\Delta \phi_{Zhb} = \text{ang}(p_{Z\perp}, \max(p_{b\perp}, p_{\bar{b}\perp}))$$

- forbidden at LO region in collinear factorisation can be evaded in LO high energy factorisation
- difference in $p_\perp$ spectrum due to missing higher order terms in collinear calculation
Conclusions

- Correlations of high-$p_T$ probes across large rapidity intervals will be explored with forward detectors at the LHC to unique level

- Branching methods based on $u$-pdfs and $k_{\perp}$-MEs useful to
  - simulate high-energy parton showers
  - investigate possibly new effects from QCD physics
  - calculate background for BSM physics