From LHeC to LHC and back: the issue of forward jets

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MOTIVATIONS

• Multiple Interactions usually studied in context of hadron – hadron collision

• One can study this issues also using DIS

• Unique possibility to investigate the amount of MI dependence on $Q$ at very low $x$

• One could more clearly disantangle: multiple interactions, rescatterings effects of $kt$ shower
Problem of MI in p-p

\[
\frac{d\sigma}{dp_{\perp}^2} = \sum_{i,j} \int dx_1 \int dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}}{dp_{\perp}^2}
\]

Cross-section diverges

Color screening

\[
\frac{d\hat{\sigma}}{dp_{\perp}^2} \propto \frac{\alpha_S^2(p_{\perp}^2)}{p_{\perp}^4} \rightarrow \frac{\alpha_S^2(p_{\perp0}^2 + p_{\perp}^2)}{(p_{\perp0}^2 + p_{\perp}^2)^2}.
\]
Multiple Interactions in DIS

Small coupling suppressed

“Resolved photon”

- DGLAP approach but strict ordering broken,
  pt of jet > Q
Multiple Interactions in DIS-forward jets

Problems with description using standard DGLAP

What is the impact of MI on forward jets cross section?

Substantial effect in the lowest pt bin

Ratio of forward jets with and without MI
Setup $Q = 3$ GeV, $x = 0.0001$
Multiple Interactions in DIS-forward jets

Problems with description using standard DGLAP

What is the impact of MI on forward jets cross section?

Enhancement in the lowest x bin
Forward jets at LHC
MI vs high energy factorisation

possible configuration for multijet activity in collinear approach

possible configuration for multijet activity in high energy factorisation approach
SETUP

On-shell
Large longitudinal momentum fraction $x_1 p_1$
No $k_t$

Off-shell
Low longitudinal momentum fraction $x_2 p_2$
$k_t$
Jet production at the LHC

central jets

x1 >> x2

forward jet

Mueller, Tang, Webber, Royon, Marquet, Peschanski,...

remnant

remnant

μgg -> qq
• gg -> gg
• qg -> qg

Phase space opening for large energies

Unique coverage of large rapidities

Physics of hard processes with multiple hard scales

And highly sensitive to parton dynamics at x2 -> 0 and x1 -> 1
Polar angles small but far enough from beam axis
Measure: energy flow, spectra of jets

central detector

forward detector

CMS Coll, CERN-LHCC-2006-001; CMS PAS FWD-08-001 (2008);
CMS Coll, CERN-LHCC-2006-001; CMS PAS FWD-08-001 (2008);
HIGH ENERGY LIMIT QCD

\[ f(x, k^2) \] - sum up diagrams -

- takes into account logs of hard scale and of energy

\[ \sigma \]

Calculated by taking appropriate polarisation sum for incoming off-shell gluon

\[ Y \sim \ln 1/x \sim \text{total energy} \]

\[ s \sim \text{s-square of total energy} \]

\[ \partial_Y f(Y, k^2) = K_{BFKL} \otimes f(Y, k^2) \]

Lipatov, Fadin, Kuraev “77
Ciafaloni ’89, Catani, Fiorani, Marchesini.

possible nonlinear extensions to account for dense partonic systems
Consistent resumption both logs of rapidity and logs of hard scale

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

Φa/A → a ̂σ → g

Φg*/B

Deak, Jung, Hautmann & K JHEP(2009) 121

◊ φa near-collinear, large- x; φg* k⊥-dependent, small- x
◊ ̂σ off-shell continuation of hard-scattering matrix elements
HARD SCATTERING CROSS SECTIONS $qg \rightarrow qg$

- Matrix elements for fully exclusive events with forward jets
- Both quark and gluon channels found to be important for realistic phenomenology

\[
\mathcal{M}_{qg \rightarrow qg} = g^4 \left( \frac{k_1 k_2}{k_1 p_2} \right)^2 \left[ \frac{(N_c^2 - 1)}{4N_c^2} \frac{(k_1 p_2)^2 + (p_2 p_3)^2}{(k_1 p_4)(p_3 p_4)} + \frac{C_1 C_A}{2C_F} \frac{(k_1 p_2)^2 + (p_2 p_3)^2}{(k_1 p_4)(p_3 p_4)} \times \left( \frac{(p_3 p_4)(k_1 p_2)}{(k_1 p_3)(p_2 p_4)} + \frac{(k_1 p_4)(p_2 p_3)}{(k_1 p_3)(p_2 p_4)} - 1 \right) \right]
\]

- In collinear limit reduce to standard matrix elements
- Gauge invariant with respect to incoming gluon
**BEHAVIOR AT LARGE $k_T$ qg CHANNEL**

$k_T = \text{transversal momentum of incoming gluon} = \text{transverse momentum carried away by extra jets}$

$k_T/Q_T \to 0$ leading order process

- **$C_F^2$ term qg channel**
  
  - $Q_T^4 \frac{d \hat{\sigma}}{d \varphi d Q_T^2}$
  
  - $\varphi = 1$
  
  - $\varphi = 1.5$
  
  - $\varphi = 2$

- **$C_A C_F$ term qg channel**
  
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  - $\varphi = 1$
  
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  - $\varphi = 2$

- **dynamical cut-off at $k_T \sim Q_T$ set by coherence effects**

- **non-negligible terms from finite $k_T$ tail**

Such hard emission is not possible at LO DGAP parton shower. High energy approach allows for it.
GLUON DENSITY FROM CCFM

Equation based on strong ordering in angle and coherence effects at high energies. Interpolates between DGLAP and BFKL.

\[ p = \frac{q}{1 - z} \]
\[ z = \frac{x_i}{x_{i-1}} \]
\[ \bar{p} = \frac{\bar{q}}{1 - z} \]

\[ \xi = \frac{z_i p_i^2}{x_i^2 E} \]

Implemented in CASCADE Monte Carlo (H. Jung)

Sudakov form factor. No branching.

\[ \mathcal{A}(x, k, \bar{p}) = \bar{\alpha}_s \int_x^1 dz \int \frac{d^2p}{\pi p^2} \theta(\bar{p} - zp) \Delta_s(\bar{p}, zp) \]

Non-Sudakov form factor. Regularizes 1/z singularity
• We can calculate the convolution formula for the cross section using a Monte Carlo generator and study jet observables.
• Look for small-x dynamics effects at forward calorimeter.

We can study two jet correlations:

- one jet in the central rapidity region \(-2 < |y| < 2\) \(pt > 10\text{GeV}\)
- the other in the forward rapidity region \(3 < |y| < 5\) \(pt > 10\text{GeV}\)
kt of incoming gluons and coherence allows for harder spectrum

CASCADE uses CCFM like parton showers which are not ordered in $k_t$

Multiple interactions model in some regions mimics high energy factorization
Larger energy flow in central region predicted by CASCADE and MPI-PYTHIA.
Larger energy flow in central region predicted by CASCADE and MPI-PYTHIA
Lower energy flow in more forward region
Conclusions

- LheC offers possibility to study physics of forward jets, MI at unique level
- We performed study of forward jets at LHC
- Interesting similarities and differences between high energy factorization and MI model
- Diagrams are different but $k_t$ dependent
  - Parton shower allows for hard jets
- More studies are to be done