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Looking for BFKL/saturation effects

Looking for BFKL effects (x-resummation) at HERA/LHC in dedicated final states

BFKL: Balitski Fadin Kuraev Lipatov
DGLAP: Dokshitzer Gribov Lipatov Altarelli Parisi

Quarks, gluons
Forward jet measurement at HERA

- Full BFKL NLL calculation used for the BFKL kernel, available in S3 and S4 resummation schemes to remove the spurious singularities (modulo the impact factors taken at LL)

- Equation:

\[ \frac{d\sigma_{T,L}^{X \rightarrow JX}}{dx_J dk_T^2} = \frac{\alpha_s(k_T^2)\alpha_s(Q^2)}{k_T^2 Q^2} f_{eff}(x_J, k_T^2) \]

\[ \int \frac{d\gamma}{2i\pi} \left( \frac{Q^2}{k_T^2} \right)^\gamma \phi_{T,L}^\gamma(\gamma) e^{\bar{\alpha}(k_T Q) \chi_{eff}[\gamma, \bar{\alpha}(k_T Q)] Y} \]

- Implicit equation: \( \chi_{eff}(\gamma, \alpha) = \chi_{NLL}(\gamma, \alpha, \chi_{eff}(\gamma, \alpha)) \) solved numerically
Comparison with H1 triple differential data

\[ \frac{d\sigma}{dx\, dp_T^2} \, dQ^2 - H1 DATA \]

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**5 < Q^2 < 10**

- 1.2 < r < 7.0
- 0.6 < r < 3.5
- 0.1 < r < 1.8

**10 < Q^2 < 20**

- 3.5 < r < 19.
- 1.8 < r < 9.5
- 0.4 < r < 4.8

**20 < Q^2 < 85**

- 9.5 < r < 80.
- 4.8 < r < 40.
- 1.1 < r < 20.
Mueller Navelet jets

Same kind of processes at the Tevatron and the LHC

- Same kind of processes at the Tevatron and the LHC: Mueller Navelet jets
- Study the $\Delta \Phi$ between jets dependence of the cross section:
- See papers by Papa, Murdaca, Wallon, Szymanowski, Ducloue...
Mueller Navelet jets: $\Delta \Phi$ dependence

- Study the $\Delta \Phi$ dependence of the relative cross section
- Relevant variables:
  \[
  \Delta \eta = y_1 - y_2 \\
y = (y_1 + y_2)/2 \\
Q = \sqrt{k_1 k_2} \\
R = k_2/k_1
  \]

- Azimuthal correlation of dijets:
  \[
  2\pi \frac{d\sigma}{d\Delta \eta dR d\Delta \Phi} / \frac{d\sigma}{d\Delta \eta dR} = 1 + \frac{2}{\sigma_0(\Delta \eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta \eta, R) \cos(p \Delta \Phi)
  \]
  where
  \[
  \sigma_p = \int_{E_T}^{\infty} \frac{dQ}{Q^3} \alpha_s(Q^2/R) \alpha_s(Q^2 R) \\
  \left( \int_{y_1}^{y_2} dy x_1 f_{eff}(x_1, Q^2/R) x_2 f_{eff}(x_2, Q^2 R) \right) \\
  \left( \int_{1/2+\infty}^{1/2-\infty} d\gamma R^{-2\gamma} e^{\tilde{\alpha}(Q^2) x_{eff}(p) \Delta \eta} \right)
  \]
Mueller Navelet jets: $\Delta \Phi$ dependence

- $1/\sigma d\sigma/d\Delta \Phi$ spectrum for BFKL LL and BFKL NLL as a function of $\Delta \Phi$ for different values of $\Delta \eta$, scale dependence: $\sim 20\%$
Effect of energy conservation on BFKL equation

- BFKL cross section lacks energy-momentum conservation since these effects are higher order corrections

- Following Del Duca-Schmidt, we substitute $\Delta \eta$ by an effective rapidity interval $y_{eff}$

\[
y_{eff} = \Delta \eta \left( \int d\phi \cos(p\phi) \frac{d\sigma^{O(\alpha_s^3)}}{d\Delta \eta dydQdRd\Delta \Phi} \right)
\]

\[
\left( \int d\phi \cos(p\phi) \frac{d\sigma^{LL-BFKL}}{d\Delta \eta dydQdRd\Delta \Phi} \right)^{-1}
\]

where $d\sigma^{O(\alpha_s^3)}$ is the exact $2 \rightarrow 3$ contribution to the $h h \rightarrow J X J$ cross-section at order $\alpha_s^3$, and $d\sigma^{LL-BFKL}$ is the LL-BFKL result

- To compute $d\sigma^{O(\alpha_s^3)}$, we use the standard jet cone size $R_{cut} = 0.5$ when integrating over the third particle’s momentum
Mueller Navelet cross sections: energy conservation effect in BFKL

- Effect of energy conservation on BFKL dynamics
- Large effect if jet $p_T$ ratios not close to 1: goes closer to DGLAP predictions, needs jet $p_T$ ratio $< 1.1-1.15$
ATLAS “jet veto” measurement: sign of BFKL?

- Select events with two high $p_T$ jets, well separated in rapidity by $\Delta y$
- Veto on additional jet activity (with $k_T > Q_0$, with $Q_0 \gg \Lambda_{QCD}$) between the two jets
- Measure the “gap” fraction: dijet events with veto/total dijet events
• Compute the probability $P_T$ that the total energy emitted outside the jet cone is less than $E_{out}$

$$
\partial_T P_T(\Omega_\alpha, \Omega_\beta) = -\int_{C_{out}} \frac{d^2 \Omega_\gamma}{4\pi} \frac{1 - \cos \theta_{\alpha\beta}}{(1 - \cos \theta_{\alpha\gamma})(1 - \cos \theta_{\gamma\beta})} P_T(\Omega_\alpha, \Omega_\beta)
+ \int_{C_{in}} \frac{d^2 \Omega_\gamma}{4\pi} \frac{1 - \cos \theta_{\alpha\beta}}{(1 - \cos \theta_{\alpha\gamma})(1 - \cos \theta_{\gamma\beta})} \left( P_T(\Omega_\alpha, \Omega_\gamma) P_T(\Omega_\gamma, \Omega_\beta) - P_T(\Omega_\alpha, \Omega_\beta) \right)
$$

• Numerical solutions are available (Hatta and Ueda, 2009)
• Good agreement between prediction and ATLAS data (black points when the most forward and backward jets are selected and $E_{out}=20$ GeV)

• Plot as a function of $\Delta y$ between jets in different jet $p_T$ bins

• Green band: renormalisation and factorisation scale uncertainties (between $2p_T$ and $p_T/2$); yellow band: uncertainties related to sub-leading logs
Jet gap jet cross sections

- **Test of BFKL evolution:** jet gap jet events, large $\Delta \eta$, same $p_T$ for both jets in BFKL calculation
- **Principle:** Implementation of BFKL NLL formalism in HERWIG Monte Carlo (Measurement sensitive to jet structure and size, gap size smaller than $\Delta \eta$ between jets)
**BFKL formalism**

- **BFKL jet gap jet cross section**: integration over $\xi, p_T$ performed in Herwig event generation

$$
\frac{d\sigma^{pp\to XJJY}}{dx_1 dx_2 dp_T^2} = S \frac{f_{\text{eff}}(x_1, p_T^2) f_{\text{eff}}(x_2, p_T^2)}{16\pi} |A(\Delta\eta, p_T^2)|^2
$$

where $S$ is the survival probability (0.1 at Tevatron, 0.03 at LHC)

$$
A(\Delta\eta, p_T^2) = \frac{16N_c\pi\alpha_s^2}{C_F p_T^2} \sum_{p=-\infty}^{\infty} \int \frac{d\gamma}{2i\pi} \frac{[p^2 - (\gamma - 1/2)^2]}{[(\gamma - 1/2)^2 - (p - 1/2)^2]} \exp \left\{ \frac{\alpha_s N_C}{\pi} \chi_{\text{eff}} \Delta\eta \right\} 
\frac{[\gamma - 1/2)^2 - (p + 1/2)^2]}{(\gamma - 1/2)^2 - (p + 1/2)^2}
$$

- $\alpha_S$: 0.17 at LL (constant), running using RGE at NLL
- **BFKL effective kernel $\chi_{\text{eff}}$**: determined numerically, solving the implicit equation: $\chi_{\text{eff}} = \chi_{\text{NLL}}(\gamma, \bar{\alpha} \chi_{\text{eff}})$
- **S4 resummation scheme used** to remove spurious singularities in BFKL NLL kernel
- **Implementation in Herwig Monte Carlo**: needed to take into account jet size and at parton level the gap size is equal to $\Delta\eta$ between jets
- **Herwig MC**: Parametrised distribution of $d\sigma/dp_T^2$ fitted to BFKL NLL cross section (2200 points fitted between $10 < p_T < 120$ GeV, $0.1 < \Delta\eta < 10$ with a $\chi^2 \sim 0.1$)
Comparison with D0 data

- **D0 measurement:** Jet gap jet cross section ratios as a function of second highest $E_T$ jet, or $\Delta \eta$ for the low and high $E_T$ samples, the gap between jets being between -1 and 1 in rapidity.

- **Comparison with BFKL formalism:**

\[
Ratio = \frac{BFKL \ NLL \ Herwig}{Dijet \ Herwig} \times \frac{LO \ QCD \ NLOJet++}{NLO \ QCD \ NLOJet++}
\]

- **Reasonable description using BFKL NLL formalism**
Predictions for the LHC

- Weak $E_T$ and $\Delta \eta$ dependence
- Large differences in normalisation between BFKL LL and NLL predictions
Jet gap jet events in diffraction

- Study BFKL dynamics using jet gap jet events
- Jet gap jet events in DPE processes: clean process, allows to go to larger $\Delta \eta$ between jets
Jet gap jet events in diffraction

- Measure the ratio of the jet gap jet to the dijet cross sections: sensitivity to BFKL dynamics
- As an example, study as a function of leading jet $p_T$
- Advantage: ratio close to 10% (no survival probability), very clean events since jets not “polluted” by remnants

$$\text{ratio} = \frac{\sigma(\text{DPE JGJ})}{\sigma(\text{DPE Jets})} \times \frac{\sigma(\text{DPE LO Jet++})}{\sigma(\text{DPE NLO Jet++})}$$

- 2$^{nd}$ leading jet $p_T > 20$ GeV
- $0.012 < \xi_{\text{AFP}} < 0.14$
- $\Delta \eta_j > 3.0 \quad |\eta_g| > 1.0$

$\int L \cdot dt = 300 \text{ pb}^{-1}$
Conclusion

• Full implementation of BFKL NLL kernel for many jet processes at HERA, Tevatron and LHC

• Forward jets at HERA: DGLAP NLO fails to describe HERA data, good description of data using BFKL NLL formalism

• Mueller Navelet jets: Larger decorrelation expected for BFKL formalism, unfortunately suffers a lot of corrections introduced when ones imposes the conservation of energy in the BFKL formalism (see Phys. Rev. D79 (2009) 034028)

• Jet veto measurements in ATLAS: mainly not related to BFKL resummation effects

• Jet gap jets:
  – NLL BFKL cross section implemented in HERWIG
  – Fair description of D0 and CDF data
  – Jet gap jet events in diffraction: clean tests of BFKL, modulo the survival probability (and its dependence on kinematics)
BFKL formalism: resummation over conformal spins

- Study of the ratio $\frac{d\sigma/dp_T(\text{all } p)}{d\sigma/dp_T(p=0)}$
- Resummation over $p$ needed: modifies the $p_T$ and $\Delta\eta$ dependences...