Probing BFKL dynamics, saturation and diffraction at hadronic colliders

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INT Workshop on Physics at the EIC, 10/02-11/16 2018, Seattle

Contents:

• Proton structure (quarks and gluons)
• BFKL dynamics (Forward and Mueller Navelet jets, jet gap jet)
• Jet gap jet in diffraction at the LHC
• Diffractive events: Pomeron structure, jet gap jets
• Photon induced processes
The HERA accelerator at DESY, Hamburg

HERA: ep collider who closed in 2007, about 1 fb$^{-1}$ accumulated

27.5 GeV  e  →  p  820 GeV

314 GeV

~ 350 collaborateurs, 15 pays

Laboratoire DESY
(Deutsches Elektronen Synchrotron)
Hambourg, Allemagne
**HERA kinematics**

- **Measurement of the** $e p \rightarrow e' X$ **cross section:** as a function of two
  independent variables $x$ and $Q^2$
- **Many methods available to measure** $x$ (momentum fraction of the
  proton carried by the interacting quark), or $Q^2$ (transfered energy
  squared) using scattered electron or hadron information

**Kinematic variables:**

- **Virtuality exchanged boson**
  
  $Q^2 = -q^2 = -(k - k')^2$

- **Bjorken scaling variable**
  
  $$x = \frac{Q^2}{2p \cdot q}$$
• Study the proton structure as a function of $x$ (Balitski Fadin Kuraev Lipatov evolution equation) or as a function of $Q^2$ (Dokshitzer Gribov Lipatov Altarelli Parisi)

• $Q^2$: Resolution power (like a microscope):

• $x$: momentum fraction of the proton carried away by the quark/gluon how does the gluon density increase at low $x$?
A picture of one electron-proton interaction

- One electron-proton interaction in the H1 detector: the electron is scattered and the proton is destroyed
- The electron probes the proton structure in terms of quarks and gluons
Measurement of the proton structure function $F_2$

- Measurement of the DIS cross section

$$\frac{d\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{2xQ^4} \left[(1 + (1 - y)^2)F_2(x, Q^2) - y^2F_L(x, Q^2)\right]$$

- Use these data to make QCD fits using NLO (or NNLO) Dokshitzer Gribov Lipatov Altarelli Parisi evolution equation and determine the proton structure in quarks and gluons → allows to predict cross section at Tevatron/LHC

- At low $x$: evolution driven by $g \rightarrow q\bar{q}$, at high $x$, $q \rightarrow qg$ becomes important

- Take all data for $Q^2 > \sim 4 \text{ GeV}^2$, to be in the perturbative QCD region

$$\frac{dF_2}{d\log Q^2} \sim \frac{\alpha_S}{2\pi} \left[P_{qg} \otimes g + P_{qq} \otimes \Sigma\right]$$
Kinematical domain at HERA

- Atlas and CMS
- Atlas and CMS rapidity plateau
- D0 Central+Fwd. Jets
- CDF/D0 Central Jets
- H1
- ZEUS
- NMC
- BCDMS
- E665
- SLAC

Resolving Power

Fraction of momentum
15 years of proton structure measurements at HERA

- Low $x$ and high gluon density: new field, main discovery at HERA
- 15 years of work: proton structure in terms of quarks and gluons: NLO QCD is working well!
- Missing transverse information (TMDs, GPDs...): to be performed at the EIC, also using Deeply Virtual Compton Scattering events
**Quark and Gluon extraction**

- Using the DGLAP evolution equation, obtain the quark and gluon densities in the proton as a function of $x$ and $Q^2$
- Method: Assume quark and gluon distributions at $Q_0^2 = 4 \text{ GeV}^2$ with some parameters, compute cross section for different $Q^2$ using DGLAP, and fit the parameters so that they describe the measured values
- Proton is gluon dominated at small $x$
A better understanding of the heavy ion structure

- Kinematical domain at the EIC
- The heavy ion structure is poorly known at low $x$ and also at high $Q^2$: similar situation as before HERA but for nuclei
- Similar gain in kinematical domain ($x$ and $Q^2$) for nuclei compared to HERA for the proton
- See E.C. Aschenauer at al., ArXiv:1708.05654
A better understanding of the heavy ion structure

- As an example: measure $eA \rightarrow eX$ cross section
- $eAu$ cross section measurement
- Very good precision expected: can we see new effects in QCD such as saturation (higher gluon density in heavy ions)
Looking for BFKL/saturation effects

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

\(\ln \frac{1}{x}\)

\(Q_s^2(Y)\)

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

Quarks, gluons

\(Q^2\)
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:

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

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

Comparison with H1 triple differential data

$d\sigma/dx\;dp_T^2\;dQ^2 - H1\;DATA$

5 < $Q^2$ < 10

12.25 < $p_T^2$ < 35.

$1.2 < r < 7.0$

$S4$

LL BFKL

NLO QCD

10 < $Q^2$ < 20

$0.6 < r < 3.5$

$S3$

20 < $Q^2$ < 85

$0.1 < r < 1.8$

5 < $Q^2$ < 10

35 < $p_T^2$ < 95.

$3.5 < r < 19.$

10 < $Q^2$ < 20

$1.8 < r < 9.5$

20 < $Q^2$ < 85

$0.4 < r < 4.8$

95 < $p_T^2$ < 400.

$9.5 < r < 80.$

$4.8 < r < 40.$

$1.1 < r < 20.$
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, Sabio-Vera, Chachamis...
Mueller Navelet jets: $\Delta \Phi$ dependence

- Study the $\Delta \Phi$ dependence of the relative cross section
- Relevant variables:

$$
\Delta \eta = y_1 - y_2 \\
y = \frac{y_1 + y_2}{2} \\
Q = \sqrt{k_1 k_2} \\
R = k_2/k_1
$$

- Azimuthal correlation of dijets:

$$
2\pi \left. \frac{d\sigma}{d\Delta \eta dR d\Delta \Phi} \right| \frac{d\sigma}{d\Delta \eta dR} = 1 + \frac{2}{\sigma_0(\Delta \eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta \eta, R) \cos(p \Delta \Phi)
$$

where

$$
\sigma_p = \int_{E_T}^{\infty} \frac{dQ}{Q^3} \alpha_s(Q^2/R) \alpha_s(Q^2 R) \\
\left( \int_{y<}^{y>} dy x_1 f_{eff}(x_1, Q^2/R) x_2 f_{eff}(x_2, Q^2 R) \right) \\
\int_{1/2-\infty}^{1/2+\infty} \frac{d\gamma}{2i\pi} R^{-2\gamma} e^{\tilde{\alpha}(Q^2) \chi_{eff}(p) \Delta \eta}
$$
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: $\sim 20\%$

- Mueller Navelet jets at NLL and saturation effects: Study in progress with F. Deganutti, T. Raben, S. Schlichtling
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 $y_{eff}$

$$y_{eff} = \Delta \eta \left( \int d\phi \cos(p\phi) \frac{d\sigma^{O(\alpha_s^3)}}{d\Delta\eta dy dQ dR d\Delta \Phi} \right)$$

$$\left( \int d\phi \cos(p\phi) \frac{d\sigma^{LL-BFKL}}{d\Delta\eta dy dQ dR d\Delta \Phi} \right)^{-1}$$

where $d\sigma^{O(\alpha_s^3)}$ is the exact $2 \to 3$ contribution to the $hh \to JXJ$ 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 $< 1.1-1.15$
Saturation effects at the LHC: Use pA data

- **Saturation effects:** need to go to low $x$, jets as forward as possible on the same side
- **Compare** pp and pA runs in order to remove many systematics

\[
x_p = \frac{k_1 e^{y_1} + k_2 e^{y_2}}{\sqrt{s}} \quad x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}}
\]

**final state:** $k_1, y_1 \quad k_2, y_2$

**scanning the wave functions:**

- $x_p \sim x_A < 1$
  - central rapidities probe moderate $x$
- $x_p$ increases $x_A$ ~ unchanged
- $x_p \sim 1, x_A < 1$
  - forward/central doesn’t probe much smaller $x$
- $x_p$ ~ unchanged $x_A$ decreases
- $x_p \sim 1, x_A \ll 1$
  - forward rapidities probe small $x$
Saturation effects at the LHC

- Suppression factor between pp and pA runs: estimated to be $1/2$ in CASTOR acceptance
- Important to get CASTOR in pA and low lumi pp data
- Study performed by Cyrille Marquet et al.; in progress by F. Deganutti, M. Hentschinski, T. Raben, S. Schlichting, CR
Jet gap jet cross sections

$\Delta \eta = \ln\left(\frac{x_1 x_2 s}{p_T^2}\right)$

- **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

\[
\frac{d\sigma^{pp \rightarrow XJJY}}{dx_1dx_2dp_T^2} = S \frac{f_{eff}(x_1, p_T^2)f_{eff}(x_2, p_T^2)}{16\pi} \left| A(\Delta \eta, p_T^2) \right|^2
\]

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

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

- $\alpha_s$: 0.17 at LL (constant), running using RGE at NLL
- **BFKL effective kernel $\chi_{eff}$**: determined numerically, solving the implicit equation: $\chi_{eff} = \chi_{NLL}(\gamma, \bar{\alpha} \chi_{eff})$
- **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:**

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

- **Reasonable description using BFKL NLL formalism**
**Full NLL calculation (in progress)**

- Combine NLL kernel with NLO impact factors (Hentschinski, Madrigal, Murdaca, Sabio Vera 2014)

- At NLO, impact factors are much more complicated!

NLL impact factors
- Mix loop momenta (not factorized)
- Involve jet distributions with two final states
- Contain complicated non-analytic progress
- Work in progress by D. Colferai, F. Daganutti, T. Raben

- Will lead to an improved parametrisation to be implemented in HERWIG
Understanding saturation? $F_L$ measurement at HERA

- Different impacts of saturation on longitudinal and transverse cross sections
- Important to measure $F_2$ and $F_L$ independently at HERA: unfortunately, the error bars were large

$$\frac{d\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{2xQ^4} \left[ (1 + (1 - y)^2)F_2(x, Q^2) - y^2F_L(x, Q^2) \right]$$
**$F_L$ measurement at the EIC**

- $F_L$ measurement in eA collisions
- High precision expected: important to probe saturation effects, and see different evolutions between $F_2$ and $F_L$
- This could be a clear indication of saturation!
Diffraction: DIS and Diffractive event at HERA
Definition of diffraction: example of HERA

- **Typical DIS event**: part of proton remnants seen in detectors in forward region (calorimeter, forward muon...)

- **HERA observation**: in some events, no energy in forward region, or in other words no colour exchange between proton and jets produced in the hard interaction

- **Leads to the first experimental method to detect diffractive events**: rapidity gap in calorimeter: difficult to be used at the LHC because of pile up events

- **Second method to find diffractive events**: Tag the proton in the final state, method to be used at the LHC (example of AFP project)
Diffractive kinematical variables

- Momentum fraction of the proton carried by the colourless object (pomeron): \( x_p = \xi = \frac{Q^2 + M_X^2}{Q^2 + W^2} \)

- Momentum fraction of the pomeron carried by the interacting parton if we assume the colourless object to be made of quarks and gluons:
  \[ \beta = \frac{Q^2}{Q^2 + M_X^2} = \frac{x_{Bj}}{x_P} \]

- 4-momentum squared transferred: \( t = (p - p')^2 \)
Parton densities in the pomeron (H1)

- Extraction of gluon and quark densities in pomeron: gluon dominated
- Gluon density poorly constrained at high $\beta$

![Graph showing parton densities](image-url)
Factorization breaking between $ep$ and $pp$

- Comparison between Tevatron CDF data and extrapolations from HERA
- Discrepancy due to survival probability
Factorization studies at HERA in Photoproduction

- Factorization is not expected to hold for resolved $\gamma$
- Observed by H1 but not by ZEUS; measurement to be done at the EIC?
Hard diffraction at the LHC

- **Dijet production:** dominated by $gg$ exchanges; $\gamma+$jet production: dominated by $qg$ exchanges
- **Jet gap jet in diffraction:** Probe BFKL
- **Three aims**
  - Is it the same object which explains diffraction in $pp$ and $ep$?
  - Further constraints on the structure of the Pomeron as was determined at HERA
  - Survival probability: difficult to compute theoretically, needs to be measured, inclusive diffraction is optimal place for measurement
Inclusive diffraction at the LHC: sensitivity to gluon density

- Predict DPE dijet cross section at the LHC in AFP acceptance, jets with $p_T >20$ GeV, reconstructed at particle level using anti-$k_T$ algorithm
- Sensitivity to gluon density in Pomeron especially the gluon density on Pomeron at high $\beta$: multiply the gluon density by $(1 - \beta)^\nu$ with $\nu = -1, ..., 1$
- Measurement possible with 10 pb$^{-1}$, allows to test if gluon density is similar between HERA and LHC (universality of Pomeron model)
- Dijet mass fraction: dijet mass divided by total diffractive mass ($\sqrt{\xi_1 \xi_2 S}$)

![Graph showing dijet mass fraction with different values of $\nu$]

**gluons**

$0.015 < \xi < 0.15$
Inclusive diffraction at the LHC: sensitivity to quark densities

- Predict DPE $\gamma^* + \text{jet}$ divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to quark density in Pomeron, and of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA
- Measurement of $W$ asymmetry also sensitive to quark densities
- Perform the diffractive/ultra-peripheral studies at the EIC
Jet gap jet events in diffraction

- Jet gap jet events in DPE processes: clean process, allows to go to larger $\Delta \eta$ between jets
- Can be studied at EIC: gaps between jets

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

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

$\int L dt = 300 \text{ pb}^{-1}$
Exclusive diffraction at the LHC (and the EIC)

- Many exclusive channels can be studied at medium and high luminosity: jets, $\chi_C$, charmonium, $J/\Psi$....

- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton: system completely constrained

- Central exclusive production is a potential channel for BSM physics: sensitivity to high masses up to 1.8 TeV (masses above 400 GeV, depending how close one can go to the beam)

- Very interesting channel at high mass sensitive to $\gamma\gamma\gamma\gamma$ anomalous couplings (via loops or resonances) (see S. Fichet, G. von Gersdorff, C. Royon, Phys. Rev.. D93 (2016) no.7, 075031; Phys. Rev. Lett. 116 (2016) no.23, 231801)

- Exclusive production can be studied both in $ep$ and $eA$ at the EIC
Search for $\gamma\gammaWW$, $\gamma\gamma\gamma\gamma$ quartic anomalous coupling at the LHC

- Study of the process: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1 TeV) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gammaWW$, $\gamma\gammaZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
exclusive production: SM contribution

- QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider $W$ loops at high $m_{\gamma\gamma}$
- At high masses ($> 200$ GeV), the photon induced processes are dominant
- Conclusion: Two photons and two tagged protons means photon-induced process
Motivations to look for quartic $\gamma\gamma$ anomalous couplings

- Two effective operators at low energies

\[
\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}
\]

- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charge particles

\[
\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}
\]

where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$ depends on the spin of the particle. This leads to $\zeta_1$ of the order of $10^{-14}$-$10^{-13}$

- $\zeta_1$ can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where $f_s$ is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$
One aside: what is pile up at LHC?

- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events
Search for quartic $\gamma\gamma$ anomalous couplings

- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...

\[ \sqrt{s} = 14 \text{ TeV} \]
\[ L = 300 \text{ fb}^{-1} \]
\[ \mu = 50 \]

\[ \zeta_1 = 10^{-12} \text{ GeV}^{-4} \]
\[ \zeta_2 = 10^{-13} \text{ GeV}^{-4} \]
Search for quartic $\gamma\gamma$ anomalous couplings

- No background after cuts for 300 fb$^{-1}$: sensitivity up to a few $10^{-15}$, better by 2 orders of magnitude with respect to “standard” methods
- Exclusivity cuts using proton tagging needed to suppress backgrounds
- For $Z\gamma$ production: gain of 3 orders of magnitude compared to usual LHC searches (looking for $Z$ decaying leptonically and hadronically)
Generalization - Looking for axion like particles
Search for axion like particles

- Production of axions via photon exchanges and tagging the intact protons in the final state complementary to the usual search at the LHC ($Z$ decays into 3 photons): sensitivity at high axion mass (spin 0 even resonance, width 45 GeV) - C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, ArXiv 1803.10835

- Complementarity with Pb Pb running: sensitivity to low mass diphoton, low luminosity but cross section increased by $Z^4$
Removing pile up: measuring proton time-of-flight

• Measure the proton time-of-flight in order to determine if they originate from the same interaction as our photon

• Typical precision: 10 ps means 2.1 mm
**Conclusion**

- **Inclusive structure function measurement:** well described by perturbative QCD, too inclusive to look for saturation/BFKL resummation effects
- **EIC:** ideal to understand better the ion structure
- **Use dedicated observables for BFKL/saturation effects:** very forward jets (HERA/EIC) and dijets (CASTOR in CMS for instance), Mueller Navelet jets (LHC), Jet gap jets (EIC/LHC)
- **Full implementation of BFKL NLL kernel including impact factors (in progress) for many jet processes at HERA, Tevatron, LHC and then EIC:** to be implemented in MC
- **Diffractive studies:** Pomeron structure in terms of quarks and gluons (LHC/EIC)
- **Photon exchange processes:** Exploratory physics at the LHC