Exclusive vector meson production in the QCD shockwave approach

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in collaboration with

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Outline

Motivation

HARD PROCESSES, $s \sim Q^2 \gg \Lambda^2_{QCD}$, like DIS at $x \sim 1$, inclusive jets production, . . . , also hard exclusive reactions like DVCS, exclusive VM production

- ◇ leading twist QCD collinear factorization: DGLAP evolution equation, PDFs
- ◇ similar for exclusive processes: GPDs and it DGLAP evolution, DA for mesons and ERBL evolution equation.
- ◇ neglect power corrections (suppressed by additional $\sim 1/Q$) and resummation of logs: $\sim \alpha_s^n \ln^n Q^2$ (LO), $\sim \alpha_s \alpha_s^n \ln^n Q^2$ (NLO), . . .

SEMIHARD PROCESSES, $s \gg Q^2 \gg \Lambda^2_{QCD}$

- small x DIS and DIS-like processes:
  DIS and exclusive processes at $x \ll 1$, forward inclusive hadron production $pA \to h + X$, . . . ,
- inclusive $\gamma^*(Q_1^2)\gamma^*(Q_2^2) \to X$, Mueller-Navelet jets, $pp \to J_1 + X + J_2$, . . .

- ◇ leading order in $1/s$ expansion and resummation of energy logs $\sim \alpha_s^n \ln^n s$ (LLA) and $\sim \alpha_s \alpha_s^n \ln^n s$ (NLA)
- ◇ **BFKL approach**: at LLA, NLA ; **main concept – Reggezied gluon**
- ◇ **QCD shockwave formalism** (known also as CGC picture): at LLA and NLA; **main concept – dipole scattering** , BK-JIMWLK - evolution equation

The BFKL resummation

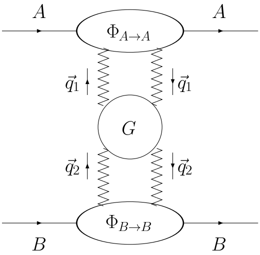
total cross section for $A+B\to X$: $\sigma_{AB}(s)=\frac{\mathcal{I}m_s\left(\mathcal{A}_{AB}^{AB}\right)}{s}$ $\Leftarrow$ optical theorem

- Pomeron channel: $t=0$ + singlet colour representation in the t-channel
- Regge limit: $s\simeq -u\to\infty$, t not growing with s

- **BFKL resummation**:

  leading logarithmic approximation (LLA): $\alpha_s^n(\ln s)^n$

  next-to-leading logarithmic approximation (NLA): $\alpha_s^{n+1}(\ln s)^n$



- $\mathrm{Im}_s\left(\mathcal{A}_{AB}^{AB}\right)$ factorization:

  convolution of the **Green's function** of two interacting Reggeized gluons with the **impact factors** of the colliding particles.

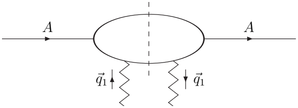
$$\mathrm{Im}_s\left(\mathcal{A}\right)=\frac{s}{(2\pi)^{D-2}}\int\frac{d^{D-2}q_1}{\vec{q}_1^{\,2}}\Phi_A(\vec{q}_1,s_0)\int\frac{d^{D-2}q_2}{\vec{q}_2^{\,2}}\Phi_B(-\vec{q}_2,s_0)\int_{\delta-i\infty}^{\delta+i\infty}\frac{d\omega}{2\pi i}\left(\frac{s}{s_0}\right)^{\omega}G_\omega(\vec{q}_1,\vec{q}_2)$$

- **Green's function** is **process-independent**

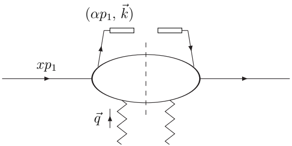
$\longrightarrow$ determined through the **BFKL equation**
[Ya.Ya. Balitsky, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

- **Impact factors** are **process-dependent**

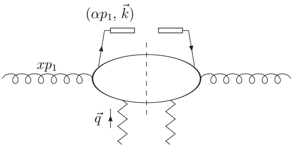
$\longrightarrow$ known in the NLA just for few processes



example: forward identified hadron production



quark vertex

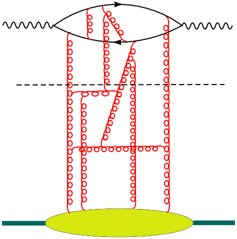


gluon vertex

[D.Yu. Ivanov, A. Papa (2012)]

Shockwave framework

for DIS:



The Sudakov expansion:

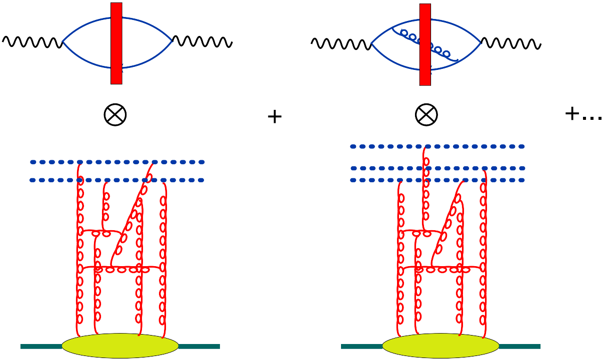
$$p^\mu \equiv p^+ n_1^\mu + p^- n_2^\mu + p_\perp^\mu, \quad n_1 \cdot n_2 = 1$$

separation in slow and fast gluons in the light-cone gauge $An_2 = 0$:

$$\mathcal{A}^\mu = A_\eta^\mu + b_\eta^\mu \quad , b_\eta^\mu(z) = b_\eta^-(\vec{z}\,)\,\delta(z^+)\,n_2^\mu.$$

b_η^μ external shockwave field

factorization in impact factors and dipole operators



eikonal quark scattering in terms of the high-energy Wilson line operator

$$U^{\eta}_{\vec{z}} \equiv \mathcal{P} \exp \left[ig \int_{-\infty}^{+\infty} dz^+ b^-_{\eta}(z) \right].$$

and in LLA the dipole

$$\begin{aligned} & \left[\mathrm{Tr}(U_1^{\eta} U_2^{\eta\dagger}) - N_c \right] (\vec{p}_1, \vec{p}_2) \\ \equiv & \int d^d\vec{z}_1 d^d\vec{z}_2 \, e^{-i(\vec{p}_1\cdot\vec{z}_1)-i(\vec{p}_2\cdot\vec{z}_2)} \left[\mathrm{Tr}(U^{\eta}_{\vec{z}_1} U^{\eta\dagger}_{\vec{z}_2}) - N_c \right], \end{aligned}$$

and in NLA the double dipole operators

$$\begin{aligned} & \left[\mathrm{Tr}(U_1^{\eta} U_3^{\eta\dagger}) \mathrm{Tr}(U_3^{\eta} U_2^{\eta\dagger}) - N_c \mathrm{Tr}(U_1^{\eta} U_2^{\eta\dagger}) \right] (\vec{p}_1, \vec{p}_2, \vec{p}_3) \\ \equiv & \int d^d\vec{z}_1 d^d\vec{z}_2 d^d\vec{z}_3 \, e^{-i(\vec{p}_1\cdot\vec{z}_1)-i(\vec{p}_2\cdot\vec{z}_2)-i(\vec{p}_3\cdot\vec{z}_3)} \\ \times & \left[\mathrm{Tr}(U^{\eta}_{\vec{z}_1} U^{\eta\dagger}_{\vec{z}_3}) \mathrm{Tr}(U^{\eta}_{\vec{z}_3} U^{\eta\dagger}_{\vec{z}_2}) - N_c \mathrm{Tr}(U^{\eta}_{\vec{z}_1} U^{\eta\dagger}_{\vec{z}_2}) \right], \end{aligned}$$

Shockwave vs BFKL

- both approaches resum LLA and NLA logs of energy
- but shockwave scheme includes also nonlinear effects, therefore, one can study the onset of nonlinear saturation regime.
- NLO kernels: BFKL [Fadin, Lipatov]; shockwave [Balitski, Chirilli]
- In linear limit both approaches should be equivalent. The kernels are related to each other, up to transformation that redistributes rad. corrections between the BFKL kernel and the impact factors [Fadin, Papa].
- need to prove equivalence of NLA resummation at the level of physical observables.

Exclusive VM production

$$\gamma^* p \to Vp, \quad \gamma^* A \to VA,$$

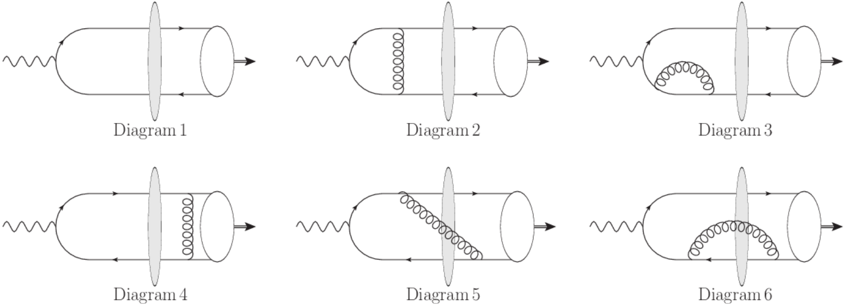
- well measured by H1 and ZEUS at HERA at small x
- HERA data support the picture of small size dipole scattering (energy dependence, $t-$ dependence) for both longitudinal and transverse polarizations
- small dipoles $\leftrightarrow$ collinear factorization and description in terms not light-cone WFs, but of DAs

$$< V_L(p_V)|\bar{\psi}(z)\gamma^\mu\psi(0)|0 >_{z^2\to 0} = f_V p_V^\mu \int_0^1 dx\, e^{ix(p_V\cdot z)}\varphi(x,\mu_F).$$

- possibility to calculate NLA corrections without ambiguity
- recent results of [Boussarie, Grabovsky, Szymanowski, Wallon] for $\gamma^* \to q\bar{q}$ in the shockwave approach.

Exclusive VM production in NLO

Diagrams were calculated using the effective shockwave Feynman rules



$$\mathcal{A} = \mathcal{A}_{LO} + \mathcal{A}_{NLO}$$

The leading order impact factor:

$$\begin{aligned}
\mathcal{A}_{LO}^{\eta} \equiv & -\frac{e_V\, f_V\, \varepsilon_\beta}{N_c} \int_0^1 dx\, \varphi\left(x, \mu_F\right) \int \frac{d^d \vec{p}_1}{(2\pi)^d} \frac{d^d \vec{p}_2}{(2\pi)^d} \\
\times & \left(2\pi\right)^{d+1} \delta\left(p_V^+ - p_\gamma^+\right) \delta\left(\vec{p}_V - \vec{p}_\gamma - \vec{p}_1 - \vec{p}_2\right) \\
\times & \Phi_0^\beta\left(x, \vec{p}_1, \vec{p}_2\right) \left[\mathrm{Tr}(U_1^\eta U_2^{\eta\dagger}) - N_c\right] \left(\vec{p}_1, \vec{p}_2\right).
\end{aligned} \quad (1)$$

$\eta = \ln s / Q^2$

$$\Phi_0^+(x) = \frac{2x\bar{x}\left(p_V^+\right)^2}{\left[\left(\bar{x}\vec{p}_1 - x\vec{p}_2\right)^2 + x\bar{x}Q^2\right]},$$

where $\bar{x} \equiv 1 - x.$, ε_β is the photon polarization vector, f_V is the meson coupling, e_V is an effective electric quark charge which takes into account the flavor content of the meson.

at NLO both the dipole and the double dipole operators contribute

$$\mathcal{A}^{\eta}_{NLO} \equiv -\frac{e_V f_V \varepsilon_\beta}{N_c}\int_0^1 dx\,\varphi\left(x,\mu_F\right)\int \frac{d^d\vec{p}_1}{(2\pi)^d}\frac{d^d\vec{p}_2}{(2\pi)^d}\frac{d^d\vec{p}_3}{(2\pi)^d}$$
$$(2\pi)^{d+1}\,\delta\left(p_V^+ - p_\gamma^+\right)\delta\left(\vec{p}_V - \vec{p}_\gamma - \vec{p}_1 - \vec{p}_2 - \vec{p}_3\right)$$
$$\times\frac{\alpha_s\Gamma\left(1-\epsilon\right)}{(4\pi)^{1+\epsilon}}\left\{\left(\frac{N_c^2-1}{N_c}\right)\Phi_1^\beta(x,\,\vec{p}_1,\,\vec{p}_2)\left[\mathrm{Tr}(U_1^\eta U_2^{\eta\dagger}) - N_c\right](\vec{p}_1,\,\vec{p}_2)\,(2\pi)^d\,\delta\left(\vec{p}_3\right)\right.$$
$$\left. + \Phi_2^\beta\left(x,\,\vec{p}_1,\,\vec{p}_2,\,\vec{p}_3\right)\left[\mathrm{Tr}(U_1^{\eta\dagger}U_3^{\eta\dagger})\mathrm{Tr}(U_3^{\eta\dagger}U_2^{\eta\dagger}) - N_c\mathrm{Tr}(U_1^\eta U_2^{\eta\dagger})\right](\vec{p}_1,\,\vec{p}_2,\,\vec{p}_3)\right\}.$$

we calculate $\Phi_1^\beta\left(x,\,\vec{p}_1,\,\vec{p}_2\right)$ and $\Phi_2^\beta\left(x,\,\vec{p}_1,\,\vec{p}_2,\,\vec{p}_3\right)$ showing that all divergences (collinear and rapidity) cancel.

Divergences and evolution equations.

- Collinear divergensy is removed due to VM DA renormalization, which gives the counterterm to the NLO dipole contribution

$$\tilde{\Phi}_1^{\beta}(x,\mu_F) = -\int_0^1 dz\,\mathcal{K}(z,x)\left[\frac{1}{\epsilon} + \ln\left(\frac{\mu_F^2}{\mu^2}\right)\right]\Phi_0^{\beta}(z).$$

  where

$$\mathcal{K}(x,z) = \frac{1-x}{1-z}\left(1+\left[\frac{1}{x-z}\right]_+\right)\theta(x-z) + \frac{x}{z}\left(1+\left[\frac{1}{z-x}\right]_+\right)\theta(z-x) + \frac{3}{2}\,\delta(z-x).$$

  is ERBL- kernel.

- the counterterm for rapidity divergence

$$\tilde{\Phi}_2^{\beta}(\eta,\alpha,\vec{p}_1,\vec{p}_2,\vec{p}_3) = -\frac{\mu^{2-d}}{\Gamma(1-\epsilon)\pi^{1+\epsilon}}\ln\left(\frac{e^{\eta}}{\alpha}\right)$$
$$\times\int d^d\vec{k}_1 d^d\vec{k}_2\,\delta(\vec{p}_V-\vec{p}_\gamma-\vec{k}_1-\vec{k}_2)$$
$$\times\mathcal{H}(\vec{p}_1,\,\vec{p}_2,\,\vec{p}_3,\,\vec{k}_1,\,\vec{k}_2)\,\Phi_0^{\beta}(x,\,\vec{k}_1,\,\vec{k}_2)\,.$$

  is due to BK-JIMWLK evolution for the dipole operator.

Conclusions...

- We obtain the complete NLO impact factor for $\gamma_L^* \to V_L$ and $\gamma_T^* \to V_L$ transitions in the sockwave framework and in general kinematics.
- Possibility for precision studies of small-x and saturation physics of nucleon and nuclei in exclusive VM photo- and electroproduction (LHC, HERA, EIC, ...)

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...Outlook

- production of transversly polarized meson, V_T, (in terms of twist 3 DAs)
- Comparison to NLA BFKL calculation [D.I. and A. Papa; D.I., M. Kotsky, A. Papa]:
  full NLO BFKL for forward amplitude $\gamma^*\gamma^* \to VV$
- implementation of numerics and phenomenology for exclusive electroproduction in *ep* and *eA* experiments, as well as photoproduction at large *t* in ultraperipheral *pA* collisions.

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