Exclusive vector meson (photo)production and low x dynamics

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Why exclusive diffractive VM (photo)production?

- Unique sensitivity to gluon distribution of the target: gluon density squared.
- Semi-hard scale: can treat perturbatively even in photo-production for heavier mesons.
- In ep DIS possibility to control the scale through the photon virtuality.
- Test the universality of dynamics between different VM.
- Momentum transfer dependence allows to access the impact parameter profile of the interaction radius.
Low x/dipole - type approaches to exclusive VM production

In the proton rest frame: the formation time of dipole is much longer than the interaction time with the target. Allows to factorize the process.

Lowest order: non-relativistic approximation to J/\psi wave function

\[
\frac{d\sigma}{dt} \left( \gamma^* p \rightarrow J/\psi \ p \right) \bigg|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \left[ \frac{\alpha_s(Q^2)}{Q^4 xg(x, Q^2)} \right]^2 \left( 1 + \frac{Q^2}{M_{J/\psi}^2} \right)
\]

\[
\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4, \quad x = (Q^2 + M_{J/\psi}^2)/(W^2 + Q^2)
\]

In principle need to take into account skewed gluon distribution.

Effectively, multiplicative factor taken into account

\[
R_g = \frac{2^{2\lambda+3} \Gamma(\lambda + \frac{5}{2})}{\sqrt{\pi} \ \Gamma(\lambda + 4)} \quad \text{with} \quad \lambda(Q^2) = \partial [\ln(xg)] / \partial \ln(1/x)
\]

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Low x/dipole - type approaches to exclusive VM production

Jones, Martin, Ryskin, Teubner

‘NLO’ improvement: including transverse momentum dependence in the gluon distribution integrated with the hard factor

\[
\left[ \frac{\alpha_s(Q^2)}{Q^4} x g(x, Q^2) \right] \to \int_{Q_0^2}^{(W^2-M_{\psi}^2)/4} \frac{dk_T^2}{Q^2(Q^2 + k_T^2)} \frac{\alpha_s(\mu^2)}{Q^2 Q_0^2} \frac{\partial}{\partial k_T^2} \frac{x g(x, k_T^2) \sqrt{T(k_T^2, \mu^2)}}{x g(x, Q_0^2) \sqrt{T(Q_0^2, \mu^2)}} \ln \left( \frac{Q^2 + Q_0^2}{Q^2} \right)
\]

Sudakov form factor:

\[
T(k_T^2, \mu^2) = \exp \left[ -\frac{C_A \alpha_s(\mu^2)}{4\pi} \ln^2 \left( \frac{\mu^2}{k_T^2} \right) \right]
\]

\[
T = 1 \quad \text{for} \quad k_T^2 \geq \mu^2
\]

No additional gluons with transverse momenta larger than \( k_T \) are emitted in the process

t- distribution modeled in this approach:

\[
\sigma \sim \exp(-Bt)
\]

\[
B(W) = (4.9 + 4\alpha' \ln(W/W_0)) \quad \text{GeV}^{-2}
\]

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Exclusive production of vector mesons in the dipole approach

Nikolaev, Zkharov; Strikman, Frankfurt, Rogers; Levin et al; Munier, Mueller, AS; Motyka, Kowalski, Watt; Berger, AS; Armesto, Rezaean; Lappi, Mantysaari, Schenke;...

cross section

\[ \frac{d\sigma}{dt} = \frac{1}{16\pi} |A(x, \Delta, Q)|^2 \]

amplitude

\[ A(x, \Delta, Q) = \sum_{h,h'} \int d^2r \int dz \Psi_{h,h'}(r, z, Q^2) N(x, r, \Delta) \Psi_{h,h'}^V(r, z) \]

dipole cross section

\[ \sigma_{\text{dip}}(x, r) = \text{Im } i N(x, r, \Delta = 0) \]

dipole amplitude

\[ N(x, r, \Delta) = 2 \int d^2b \, N(x, r, b) \, e^{i\Delta \cdot b} \]

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\( \rho, \Phi, J/\psi, \gamma \) production

r dipole size
b impact parameter
\( \Delta \) momentum transfer

z, (1 − z) fraction of the longitudinal momentum of the photon carried by the quark(anti-quark)
Low $x$ - type approaches to exclusive VM production

Bautista, Fernandez Tellez, Hentschinski

\[
\Im \mathcal{M}_T^{\gamma^* p \rightarrow V p} (W, 0) = \alpha_s(M \cdot Q_0) \int_{\frac{1}{2} - i\infty}^{\frac{1}{2} + i\infty} \frac{d\gamma}{2\pi i} \int_0^{1} \frac{dz}{4\pi} \hat{g}(x, \frac{M^2}{Q_0^2}, \frac{M^2}{M^2}, Q_0, \gamma) \cdot \Phi_{V, T}(\gamma, z, M) \cdot \left(\frac{M^2}{Q_0^2}\right)^\gamma
\]

Dipole amplitude obtained from the BFKL unintegrated gluon distribution

\[
G(x, k^2, M) = \frac{1}{k^2} \int_{\frac{1}{2} - i\infty}^{\frac{1}{2} + i\infty} \frac{d\gamma}{2\pi i} \hat{g}(x, \frac{M^2}{Q_0^2}, \frac{M^2}{M^2}, \gamma) \left(\frac{k^2}{Q_0^2}\right)^\gamma
\]

\[
\sigma_0 N(r, x) = \frac{4\pi}{N_c} \int \frac{d^2 k}{k^2} \left(1 - e^{ik \cdot r}\right) \alpha_s G(x, k^2)
\]

Vector meson photoproduction impact factor obtained from the dipole model in coordinate space

\[
\Phi_{V, T}(\gamma, z, M) = \frac{4\pi}{N_c} \int d^2 r \int \frac{d^2 k}{(k^2)^2} \left(1 - e^{ik \cdot r}\right) \left(\frac{k^2}{M^2}\right)^\gamma (\Psi^* \Psi)_T (r)
\]

t- distribution modeled in this approach

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Low x dipole amplitude: including saturation

Glauber-Mueller parameterization often used; includes nonlinear effects

Motyka,Kowalski,Watt; ‘b-Sat model’

\[
N_{GM}(r, b; Y = \ln 1/x) = 1 - \exp\left(-\frac{\pi^2}{2N_c}r^2xg(x, \eta^2)T(b)\right)
\]

\[
T(b) = \frac{1}{8\pi}e^{\frac{-b^2}{2BG}}
\]

Can be obtained from low x nonlinear equation: Balitsky - Kovchegov equation

\[
\frac{dN(r_{01}, b_{01}, Y)}{dY} = \frac{\alpha_s N_c}{\pi} \int \frac{d^2r_2r^2_{01}}{r^2_{20}r^2_{12}} \left[ N(r_{20}, b_{01} + \frac{r_{12}}{2}, Y) + N(r_{12}, b_{01} - \frac{r_{20}}{2}, Y) 
- N(r_{01}, b_{01}, Y) - N(r_{20}, b_{01} + \frac{r_{12}}{2}, Y)N(r_{12}, b_{01} - \frac{r_{20}}{2}, Y) \right]
\]

- Typically BK solved in a local approximation: without impact parameter dependence. Successful description of variety of data.
- Can be solved (at least numerically) relatively easily.
- Generates the saturation scale that divides the dense and dilute regime.

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What about spatial distribution?

**Usual approximation:**

\[ N(r, b, Y) = N(r, Y) \]

- The target has infinite size.
- Local approximation suggests that the system becomes more perturbative as the energy grows.
- But this cannot be true everywhere (IR in QCD)

**Impact parameter profile**
What about spatial distribution?

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Impact parameter profile

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Solving impact parameter dependent BK equation

\[
\frac{dN(r_{01}, b_{01}, Y)}{dY} = \frac{\alpha_s N_c}{\pi} \int \frac{d^2r_2 r_{01}^2}{r_2^2 r_{12}^2} \left[ N(r_{20}, b_{01} + \frac{r_{12}}{2}, Y) + N(r_{12}, b_{01} - \frac{r_{20}}{2}, Y) \right.
\]
\[
- N(r_{01}, b_{01}, Y) - N(r_{20}, b_{01} + \frac{r_{12}}{2}, Y)N(r_{12}, b_{01} - \frac{r_{20}}{2}, Y) \right]
\]

Initial condition Glauber-Mueller type: \(N^{(0)} = 1 - \exp(-c_r r^2 \exp(-c_b b^2))\)

Without impact parameter dependence

Dipole amplitude as a function of dipole size (arbitrary units)

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Solving impact parameter dependent BK equation

\[
\frac{dN(r_{01}, b_{01}, Y)}{dY} = \frac{\alpha_s N_c}{\pi} \int \frac{d^2r_2}{r_{20}^2 r_{12}^2} \left[ N(r_{20} + \frac{r_{12}}{2}, Y) + N(r_{12} - \frac{r_{20}}{2}, Y) 
- N(r_{01} + \frac{r_{12}}{2}, Y) - N(r_{01} - \frac{r_{20}}{2}, Y) \right]
\]

Initial condition Glauber-Mueller type:

\[ N^{(0)} = 1 - \exp(-c_r r^2 \exp(-c_b b^2)) \]

Without impact parameter dependence

Dipole amplitude as a function of dipole size (arbitrary units)

With impact parameter dependence

\[ Q_s^{-1}(Y_2) \quad Q_s^{-1}(Y_1) \]

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Initial condition Glauber-Mueller type:

Without impact parameter dependence

\[ N^{(0)} = 1 - \exp(-c_r r^2 \exp(-c_b b^2)) \]

With impact parameter dependence

\[
\frac{dN(r_{01}, b_{01}, Y)}{dY} = \frac{\alpha_s N_c}{\pi} \int \frac{d^2 r_2 r_{01}^2}{r_2^2 r_{12}^2} \left[ N(r_{20}, b_{01} + \frac{r_{12}}{2}, Y) + N(r_{12}, b_{01} - \frac{r_{20}}{2}, Y) \right] \\
- N(r_{01}, b_{01}, Y) - N(r_{20}, b_{01} + \frac{r_{12}}{2}, Y) N(r_{12}, b_{01} - \frac{r_{20}}{2}, Y) \]

Golec-Biernat,AS; Berger,AS;

Dipole amplitude as a function of dipole size (arbitrary units)

Glauber-Mueller form is not conserved under low x evolution

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Impact parameter profile of the interaction region

- Saturation for small impact parameters
- No saturation for large impact parameters (system is still dilute)
- Initial impact parameter profile is not preserved
- Power tail in b is generated, this is due to perturbative evolution and lack of confinement effect.
Angular correlations present in the solution

Amplitude larger for aligned configurations of the dipole

Could be relevant for the angular sensitive observables

Sensitivity through diffractive dijet in photoproduction/DIS

Hatta, Xiao, Yuan; Altinoluk, Armento, Beuf, Rezaeian;

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Initial condition and cutoff for large dipoles

At \( x_0 = 0.01 \) use Glauber-Mueller formula:

\[
N(r, b, Y_0 = \ln 1/x_0) = 1 - \exp\left(-\frac{\pi^2}{2N_c}r^2 xg(x, \eta^2)T(b)\right) \quad T(b) = \frac{1}{8\pi}e^{\frac{-b^2}{2B_G}}
\]

with parameters from Kowalski, Motyka, Watt \( B_G = 4 \text{ GeV}^{-2} \quad \langle b^2 \rangle = 2B_G \)

Need to implement the cutoff to regulate large dipole sizes, mimic confinement:

\[
K = dx_0^2 \bar{\alpha}_s \frac{x_{01}^2}{x_{02}^2x_{12}^2} \Theta\left(\frac{1}{m^2} - x_{02}^2\right)\Theta\left(\frac{1}{m^2} - x_{12}^2\right)
\]

Cutoff: \( m \simeq 1/\sqrt{2B_G} \sim 350 \text{ MeV} \quad \sqrt{2B_G} \simeq 2.83 \text{ GeV}^{-1} \)

Cutoff included both in the evolution kernel and in the GM initial condition. Refit the inclusive HERA data for \( F_2 \)

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Evolved solution for the dipole amplitude

Profile in b: Solid line KMW, dashed lines BK with running coupling and cuts
Small x evolution leads to the broader distribution in impact parameter
Change of shape with decreasing x

Dipole Size: 1.00 (GeV$^{-1}$) | cos(phi): 0.0 | Delta Y: 4.0 | max Y: 8.0

FIG. 7: Dipole scattering amplitude as a function of the impact parameter for fixed dipole size and dipole orientation θ = π/2.

The solid lines represent the model (8) used in [45]. The dashed lines correspond to the solution of the BK equation with the kernel (15), m = 0.35 GeV. The dashed - dotted line represents the initial conditions at Y = 0 (x$_0$ = 0.01) also taken from model in [45].

FIG. 8: The value of the average squared width ⟨b$^2$⟩, defined in Eq. (17), as a function of rapidity for fixed value of the dipole size r. We compared the value of ⟨b$^2$⟩ extracted from the solution to the BK equation with the value obtained from model (8). The model (8) gives almost constant width, independent of rapidity, which is to be expected. On the contrary, in the case of the BK equation the width clearly increases with rapidity. For the rapidities considered here, we observe that it is almost a linear growth, with slightly faster increase at the highest values of rapidity ∼ 6–8 along with mild dependence of the slope on the value of the dipole size.

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**Exclusive process: photo(production) and DIS**

\[ J/\psi, \phi \]

exclusive production; comparison with HERA data

Integrated(over t): good description of the energy dependence

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Experimental data are from [1, 3, 6, 7].

3.2 Calculations based on the dipole model. Experimental data are from [3, 6].

Figure 7: The t-distribution of the differential cross section and production: normalization systematically underestimated especially at low scales.

Energy dependence is reasonably described.

ρ production: normalization systematically underestimated especially at low scales. Energy dependence is reasonably described.

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Correction from skewedness

\( \gamma^* p \to p p \)

\( \gamma^* p \to J/\psi p \)

with skewed corr.

w/o skewed corr.

Effect of correction from skewed gluon distribution non-negligible

\[
R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + \frac{5}{2})}{\Gamma(\lambda + 4)}
\]

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Differential cross section

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The value of $B_D$ is closely related to the transverse size of the interaction region which is a combination of the size of the VM and the size of the gluon hot-spot in the proton.

In the case of the lighter mesons it is the first one which prevails.

For heavier mesons, it is the larger size of the gluon distribution in the proton. Thus it does not depend on $Q^2$ that much.

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\[ \frac{d\sigma}{dt} \sim e^{-B_D |t|} \]

Original b-Sat model has flat dependence

Intercept controlled by the initial profile in b, slope controlled by the mass regulator in the kernel.

Trend of the data nicely reproduced.

\[ B_D (\text{GeV}^{-2}) \]

on the lower side: more non-perturbative corrections

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Reasonable description of the diffractive slope from dynamical prediction based on BK evolution with cutoff

By making mass regulator smaller, the slope can be increased

Functional dependence on energy could help determine type of cutoff: sharp or exponential

\[ B_D(W = 29.8 \text{ GeV}) = 4 \text{ GeV}^{-2} \]

\[ B_D(W = 706 \text{ GeV}) = 6.7 \text{ GeV}^{-2} \]
Summary and outlook

- Exclusive diffractive VM production using solution to the impact parameter dependent BK equation.

- Coupling no longer regularized by saturation only. Need cuts on large dipoles. Large sensitivity to this regularization.

- Extra corrections: skewed gluon distribution, non-perturbative modification to the photon wave function.

- Exclusive diffraction of vector mesons, good description of data, in bins of $t, W, Q$, especially for heavier vector mesons. Lighter VM overall shape is reproduced, normalization is not well reproduced.

- Energy dependence of the diffractive slope generated by the model, depends on the phenomenological parameters, mainly set by the cutoff on the large dipoles.

- Looking forward to the more measurements of the energy dependence of $t$-distribution for $J/\psi$ from LHC.