Diffractive Vector Meson Production at Large Momentum Transfer

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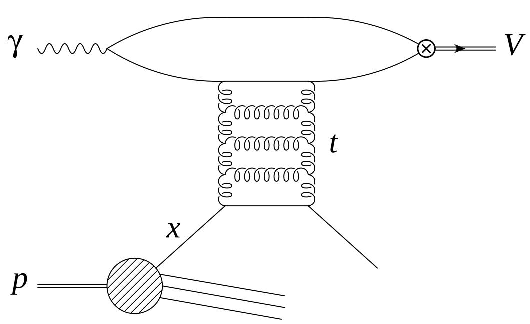
Overview and the Process Definition

[R. Enberg, J. Forshaw, LM, G. Poludniowski]

1. Dipole representation and diffractive factorisation
2. Photon and meson wave functions
3. BFKL evolution of the amplitudes
4. Results
5. Conclusions



Large γp collision energy $W \simeq 100$ GeV

Proton disintegration – but a rapidity gap is left between the proton remnant and the meson

Large momentum transfer $|t| = p_T^2 \sim 10$ GeV^2

Photon and meson polarisation – spin density matrix

WHY & HOW

WHY?

- Experimental data call for explanation
- Available: differential cross sections and spin density matrix elements
- Sensitive probe of the low-x dynamics
- Insight into photon and meson structure

HOW?

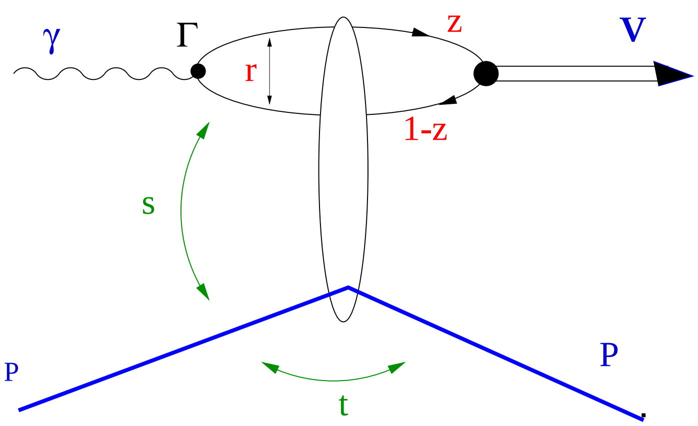
- Large momentum transfer + hard factorisation $\longrightarrow$ pQCD
- Diffractive process — model for colour singlet exchange
- Lowest order — 2 gluons but . . .
- Large n-loop corrections $\sim [\alpha_s \log(W^2/|t|)]^n$ $\longrightarrow$ BFKL resummation
- Meson and Photon wave functions have to be modelled

Dipole Representation

Diffractive scattering at high energies

$$\mathcal{M} \sim \int d^2\boldsymbol{k}\ \mathcal{G}(q,k)\ \Phi(p \to X)\ \Phi(\gamma \to V)$$

- long-living fluctuations: colour dipoles
- short interaction time
- parton energy $\sim z$ is conserved
- parton transverse positions do not change
- conservation of parton helicity



Wave Functions

- A wave function $\Psi(\boldsymbol{r}, z; \lambda\bar{\lambda})$ may be factorised to $\psi(r)\phi(z)$ when the hard process selects $r \to 0$, where $\phi(z) = \int d^2 p_T \Psi(p_T, z)$
- Brodsky-Lepage: collinear parton momenta + distribution amplitudes depending on longitudinal momentum fraction
- Helicity of meson given by sum of quark helicities
- Beyond leading twist – all Dirac structures

Photon wave function [Ivanov, Kirschner, Schäfer, Szymanowski]

- Perturbative – chiral even and chiral odd Driac structures Γ
- Odd $\Gamma \sim m_q \, \sigma_{\mu\nu}$, m_q current mass?
- Chiral symmetry breaking by $\chi < \bar{q}q >$ $\to$ hadronic part of photon and constituent quark mass m_q – we choose to represent the NP phenomena by the constituent mass
- Alternatively – distribution amplitudes for photon may be used

VM Photoproduction in Dipole Representation

$$\Phi_{\gamma V}(\boldsymbol{k},\boldsymbol{q}) \sim \sum_{\lambda,\bar{\lambda}} \int dz \int d^2\boldsymbol{r}\; \Psi_V^*(\boldsymbol{r},z)\; T(\boldsymbol{r},z;\boldsymbol{k},\boldsymbol{q})\; \Psi_\gamma(r,z)$$

The QCD dipole scattering amplitude $T(\boldsymbol{r},z;\boldsymbol{k},\boldsymbol{q})$ is hard, selecting small dipoles [J. Forshaw, P. Sutton]

$\Downarrow$

$$\Psi_V(\boldsymbol{r},z) \sim r^\alpha \phi_i(z) \qquad e^{i\boldsymbol{qr}u}\left(1-e^{-i\boldsymbol{kr}}\right)\left(1-e^{-i(\boldsymbol{q}-\boldsymbol{k})\boldsymbol{r}}\right) \qquad \Psi_\gamma(\boldsymbol{r},z) \sim K_0(mr) \text{ or } r\,K_1(mr)$$

Distribution amplitudes of twist 2, 3 and 4: $\phi_{||}$, $\phi_\perp$, $h_{||}^{(t)}$, $h_{||}^{(s)}$, $g_\perp^{(v)}$, $g_\perp^{(a)}$, g_3, h_3

Six helicity amplitudes, depending on polarisations (in and out) and chiral parity [D. Ivanov, R. Kirschner, A. Schäfer, L. Szymanowski]

Amplitude	Chiral even	Chiral odd
+0	Leading	$1/q^2$
++	$1/q$	$1/q$
+-	$1/q$	$1/q^3$

For virtual photons, additionally A_{00} and A_{0+}

Higher twist distribution amplitudes correspond to $q\bar{q}g, \ldots$ states

Pomeron Coupling

[Mueller and Tang, Bartels et al. Martin, LM, Ryskin]

IR divergence in quark-quark elastic scattering $A \sim \int d^2k/[k^2(q-k)^2]$

System of gluons with momenta $\boldsymbol{k}$ and $\boldsymbol{q}-\boldsymbol{k}$ acts as a colour antenna

The phase space for emissions $\sim$ rapidity $Y \longrightarrow dP \sim \bar{\alpha}_s dY/2 \int_{k^2}^{q^2} \frac{dk'^2}{k'^2}$

$\Downarrow$

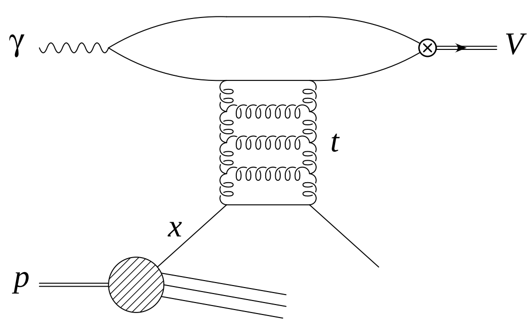
P (no emission) $= \exp(-\bar{\alpha}_s Y/2 \, \log(q^2/k^2))$

$\Downarrow$

Gluon reggeisation $\longrightarrow$ disappearance of the IR divergence $\longrightarrow k$ and $|q-k| \sim q \longrightarrow$ *small* Pomeron

$\Downarrow$

coupling to individual partons



$$\frac{d\sigma(\gamma p \to V X)}{dt\, dx_j} = \left(\frac{81}{16} G(x_j,t) + \sum_f [q_f(x_j,t) + \bar{q}_f(x_j,t)]\right) \frac{d\sigma(\gamma q \to V q)}{dt}$$

BFKL at all conformal spins

Colour singlet exchange $\mathcal{A}(q) = \int d^2\boldsymbol{k} \frac{1}{\boldsymbol{k}^2(\boldsymbol{q}-\boldsymbol{k})^2} \Phi_0^A(\boldsymbol{k},\boldsymbol{q})\, \Phi_0^B(\boldsymbol{k},\boldsymbol{q})$

The BFKL equation takes the form

$$\Phi^A(\boldsymbol{k},\boldsymbol{q};Y) = \Phi_0^A(\boldsymbol{k},\boldsymbol{q};Y) + \bar{\alpha}_s \int_0^Y dY' \int d^2\boldsymbol{k}'\, \mathcal{K}(\boldsymbol{k},\boldsymbol{k}',\boldsymbol{q};Y')\Phi^A(\boldsymbol{k}',\boldsymbol{q};Y')$$

Conformal invariance of the LL BFKL gives solution (in position space)

$$\mathcal{K}(\rho_1,\rho_2,\rho_1',\rho_2';Y) =$$

$$= \sum_{n=-\infty}^{n=\infty} \int_{-\infty}^{\infty} d\nu\, \frac{\nu^2+n^2/4}{[\nu^2+(n-1)^2/4][\nu^2+(n+1)^2/4]}\, E_{n,\nu}(\rho_1,\rho_2)\, E^*_{n,\nu}(\rho_1',\rho_2')\ \exp[\bar{\alpha}_s \chi_n(\nu) Y/2]$$

$$\mathcal{A}(\boldsymbol{q},Y) \sim \sum_{n=-\infty}^{n=\infty} \int_{-\infty}^{\infty} d\nu\, \frac{\nu^2+n^2/4}{[\nu^2+(n-1)^2/4][\nu^2+(n+1)^2/4]}\ (\Phi^A|E_{n,\nu})\ (E^*_{n,\nu}|\Phi^B)\ \exp[\bar{\alpha}_s \chi_n(\nu) Y/2]$$

$$\chi_n(\nu) = 4\mathrm{Re}\left(\psi(1) - \psi(1/2 + |n|/2 + i\nu)\right) \qquad \longrightarrow \text{the leading exponent for } n = 0$$

Result of BFKL Evolution for LVM

$$M_{++}^{\text{odd}} = \frac{C_V f_V^T}{4|q|} \int_0^1 du\; 6\, u(1-u)$$

$$\times \sum_{n=-\infty}^{n=+\infty} \int_{-\infty}^{\infty} d\nu \frac{\nu^2 + n^2}{[\nu^2 + (n-1/2)^2][\nu^2 + (n+1/2)^2]} \frac{\exp[\chi_{2n}(\nu) z]}{\sin(i\pi\nu)}\; I_{-\frac{1}{2}\,-\frac{1}{2}}(\nu, 2n, q, u; 0)$$

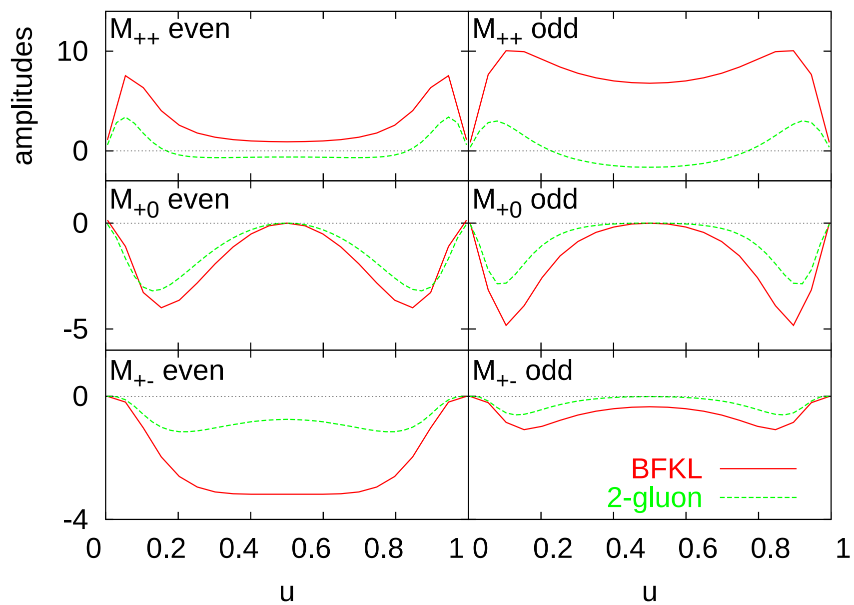
$$\begin{aligned} I_{\alpha\beta}(\nu, n, q, u; a) &= \frac{m}{2} \int_{C'-i\infty}^{C'+i\infty} \frac{d\zeta}{2\pi i} \Gamma(a/2-\zeta)\Gamma(-a/2-\zeta)\, \tau_q^{\zeta}\; (i\,\text{sign}\,(1-2u))^{\alpha-\beta+n} \\ &\times \left(\frac{4}{|q|}\right)^4 [\sin\pi(\alpha+\mu+\zeta)\;\; B(\alpha,\mu,q^*,u,\zeta)\, B(\beta,\widetilde{\mu},q,u^*,\zeta) \\ &- (-1)^n \sin\pi(\alpha-\mu+\zeta)\; B(\alpha,-\mu,q^*,u,\zeta)\, B(\beta,-\widetilde{\mu},q,u^*,\zeta)\;] \end{aligned}$$

$$B(\alpha,\mu,q^*,u,\zeta) = (-4u\bar{u})^{-(\mu+2+\alpha+\zeta)/2} \left(\frac{4}{q^*}\right)^{\alpha} 2^{-\mu} \frac{\Gamma(\mu+2+\alpha+\zeta)}{\Gamma(\mu+1)}$$

$${}_2F_1\left(\frac{\mu+2+\alpha+\zeta}{2}\,,\; \frac{\mu-1-\alpha-\zeta}{2}\,;\; \mu+1\,;\; \frac{1}{4u\bar{u}}\right)$$

BFKL-evolved Amplitudes

Differential amplitudes dM/du: 2-gluon and evolved



2-gluon multiplied by factor of 3,

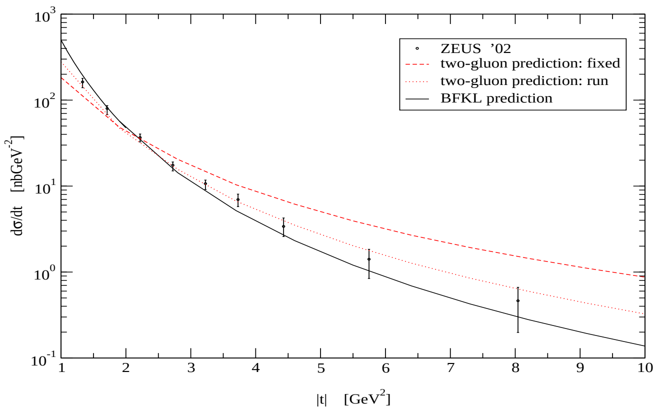
$\bar{\alpha}_s Y = 2.4$, $|t| = 10$ GeV^2

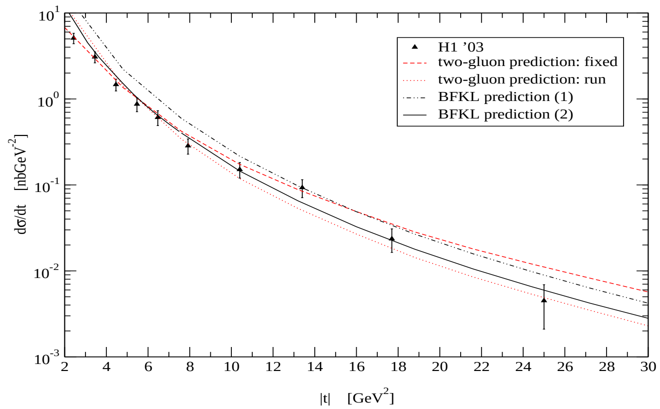
Relative enhancement of M_{++}^{odd}

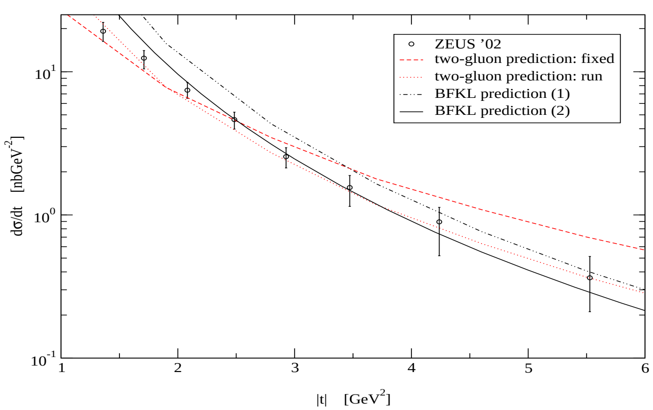
Pomeron intercept $\lambda \sim 0.4$

End-point divergences
do not appear
even in massless limit

$d\sigma/dt$ for ρ, ϕ and J/ψ







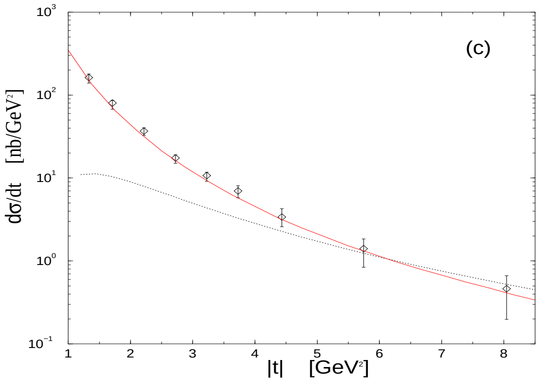
Predictions beyond nonrelativistic approximation

BFKL gives good fits

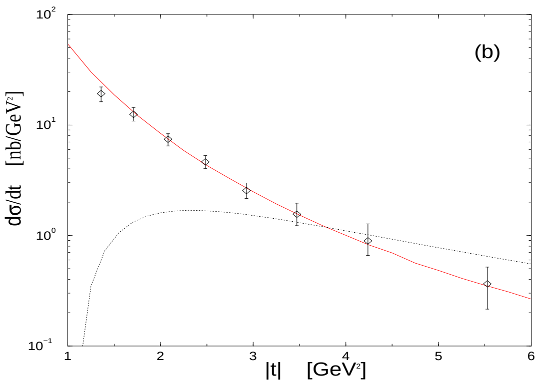
2-gluon approximation is slightly worse

Photoproduction at high t – Non-relativistic WF

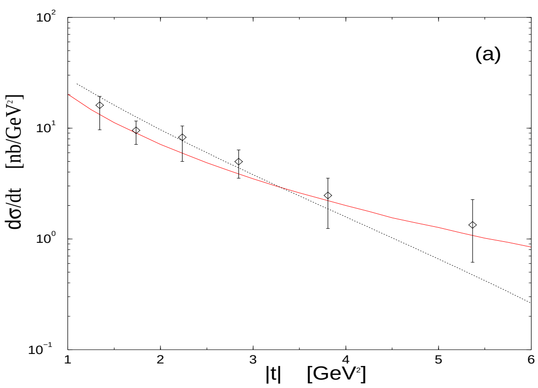
ρ



ϕ



J/ψ



[J. Forshaw, G. Poludniowski]

Non-relativistic wave functions

Cross-sections – BFKL fit with 3 parameters

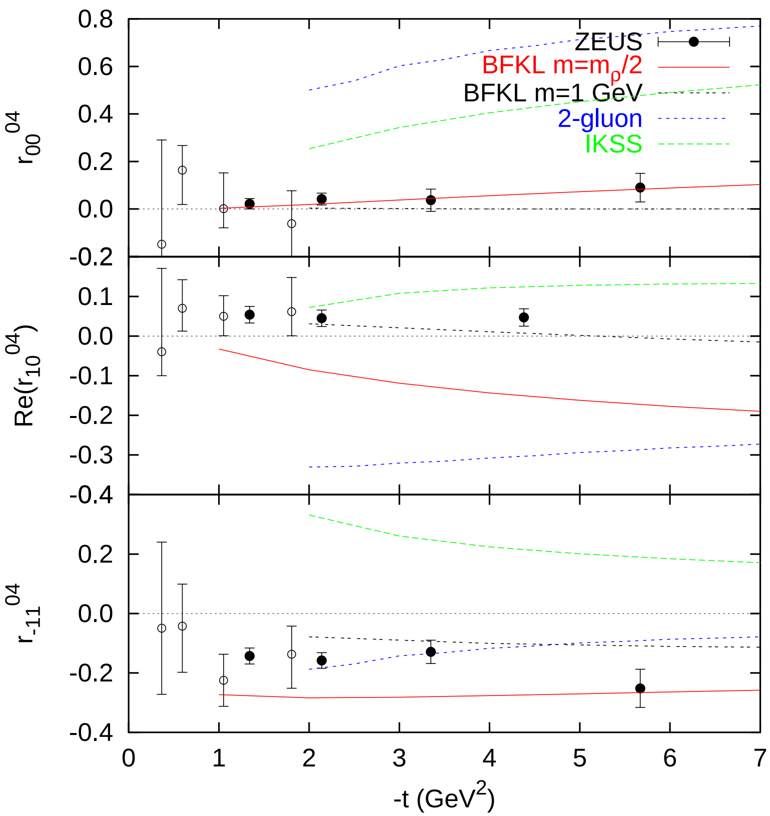
Excellent description by BFKL, two-gluon fail badly

S-channel helicity conservation – in conflict with data for ρ and ϕ

Corrections from higher conformal spins under control

Spin Density Matrix in ρ Photoproduction

SDM elements from: BFKL, IKSS and 2-gluon using perturbative γ



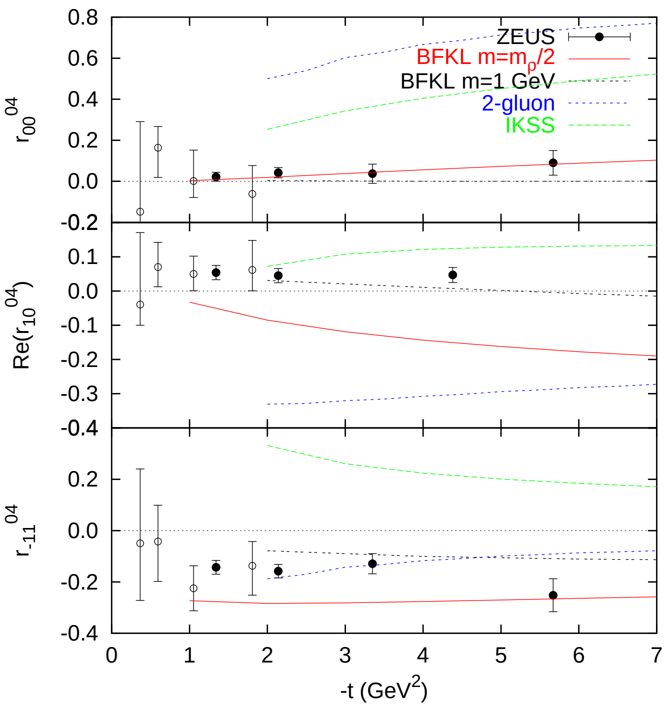
$$r_{00}^{04} \sim \langle |M_{+0}|^2 \rangle$$

$$r_{10}^{04} \sim \frac{1}{2}\langle M_{++}M_{+0}^* + M_{+-}M_{-0}^* \rangle$$

$$r_{-11}^{04} \sim \langle \mathrm{Re}\,(M_{++}M_{+-}^*) \rangle$$

No approach really works for all r-s
. . . but . . .

Spin Density Matrix in ρ Photoproduction 2



QCD evolution relatively supresses asymptotically leading M_{+0}

BFKL enhances M_{++} and gives about right magnitudes of all r-s but wrong sign of M_{+0} if realistic quark mass is used

A reasonable fit can be obtained with
$m_q \sim 1$ GeV $\longrightarrow$ interpretation???

Reasons? Sudakov form-factor? Non-perturbative photon wave function? Meson wave function? Rescattering suppressing large dipoles?
Scattering of higher Fock components $q\bar{q}g$?

Conclusions

1. The BFKL resummation scheme has been applied to diffractive VM photoproduction at large energy and momentum transfer
2. Differential cross-sections $d\sigma/dt$ for ρ, ϕ and J/ψ are sucessfully described within the same framework
3. BFKL description of spin density matrix is better than in other approaches (single flip amplitude is smaller) but it remains poor
4. The spin density matrix elements are found to depend on IR details in the t-range probed by experiments
5. Chiral odd contributions to the photon wave function are important
6. Improvements are possible (e.g. inclusion of Sudakov FF)