Diffractive Vector Meson Production

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Overview

1. Dipole representation and diffractive factorisation
2. Exclusive vector meson production and high density QCD
3. The QCD Pomeron and $\gamma p \to VY$ high t and W
4. The Odderon
5. Conclusions and Outlook

Not covered

1. Off-diagonal distributions
2. Two Pomeron approach and Stochastic Vacuum Model
3. Production of pairs of mesons

Apologies . . .

Main goals

WHY?

- Proton structure, including off-diagonal partons
- Probe of the High Density QCD and partonic saturation
- The nature of the Pomeron (1 or 2?) and the Odderon
- Interplay between Soft and Hard
- Information on the meson structure

HOW?

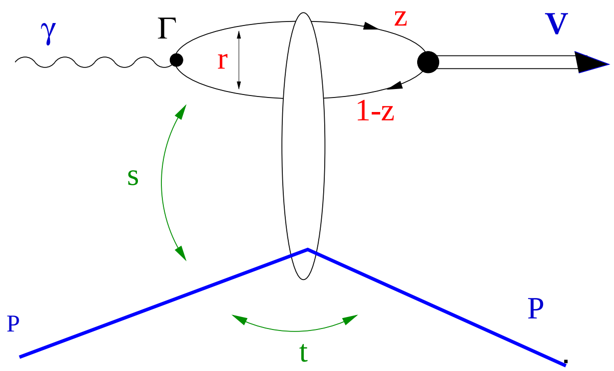
- Plenty of mesons: ρ^0, ω, ϕ, J/ψ, ψ', Υ,...
- Wide range of kinematical variables Q^2, W, t
- Observables: cross-sections, helicity structure, exclusive or with proton dissociation
- Very clean experimental signal

Ideal ground to get more insight into QCD

Dipole Representation

Diffractive scattering at high energies

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



Vector meson wave function Ψ_V

- $\Psi_V(r, z; \lambda\bar{\lambda})$, in some models factorised to $\psi(r)\phi(z)$
- Brodsky-Lepage: collinear parton momenta + distribution amplitudes
- Helicity of meson given by sum of quark helicities
- Beyond leading twist – all Dirac structures $\phi_V(z) = \int d^2 p_T \Psi_V(p_T, z)$

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

- Perturbative – chiral even and odd Γs
- Odd $\Gamma \sim m_q\, \sigma_{\mu\nu}$, m_q current mass?
- Chiral symmetry breaking by $\chi < \bar{q}q > \rightarrow$ hadronic part of photon, or constituent m_q?
- Distribution amplitudes $\phi_\gamma(z)$

Anatomy of VM Photoproduction

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

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

End-point singularities

Proof of diffractive factorisation holds for longitudinal photon and meson polarisation at high Q^2 [J. Collins]

For transverse mesons a helicity flip is necessary at high $Q^2 \longrightarrow$ supression by $1/Q^2$

In V_T production amplitude end-point singularities arise $G(z;\gamma g \to q\bar{q}g) \sim \frac{1}{z^2\bar{z}^2}$

$\int_{z_0} \Phi(z)G(z) \sim \log z_0$ for $\Phi(z) \sim z$ with $z_0 \sim \Lambda^2/Q^2$ or $z_0 \sim \Lambda^2/|t| \longrightarrow$ factorisation breaking

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Impact of the end-point enhancement on helicity flip and hard t-dependence [P. Hoyer, J.T. Lenaghan, K. Tuominen, C. Vogt]

1. End-point states have large invariant mass $\longrightarrow$ short-lived, non-conservation of helicity
2. Suppression of QCD radiation, even for large dipoles (Sudakov)
3. can $\Phi(z) \to$ const as $z\bar{z} \to 0$?
4. $\mathcal{A} \sim \int_{z_0} \Phi(z)G(z) \sim 1/z_0 \sim |t|/\Lambda^2$, a change of the scaling!
5. Explains the proton dissociative VM photoproduction data?

Another View on End-points

Note that $(p_T^2 + m_q^2)/z\bar{z} = M_X^2$ — large invariant mass of the $q\bar{q}$ state $\longrightarrow$ in conflict with assumptions of local parton-hadron duality [A. Martin, M.G. Ryskin, T. Teubner]

Cutting of the twist expansion may be misleading! [A. Ivanov, R. Kirschner]
Calculation modeling resummation of higher twists contribution at the end-points

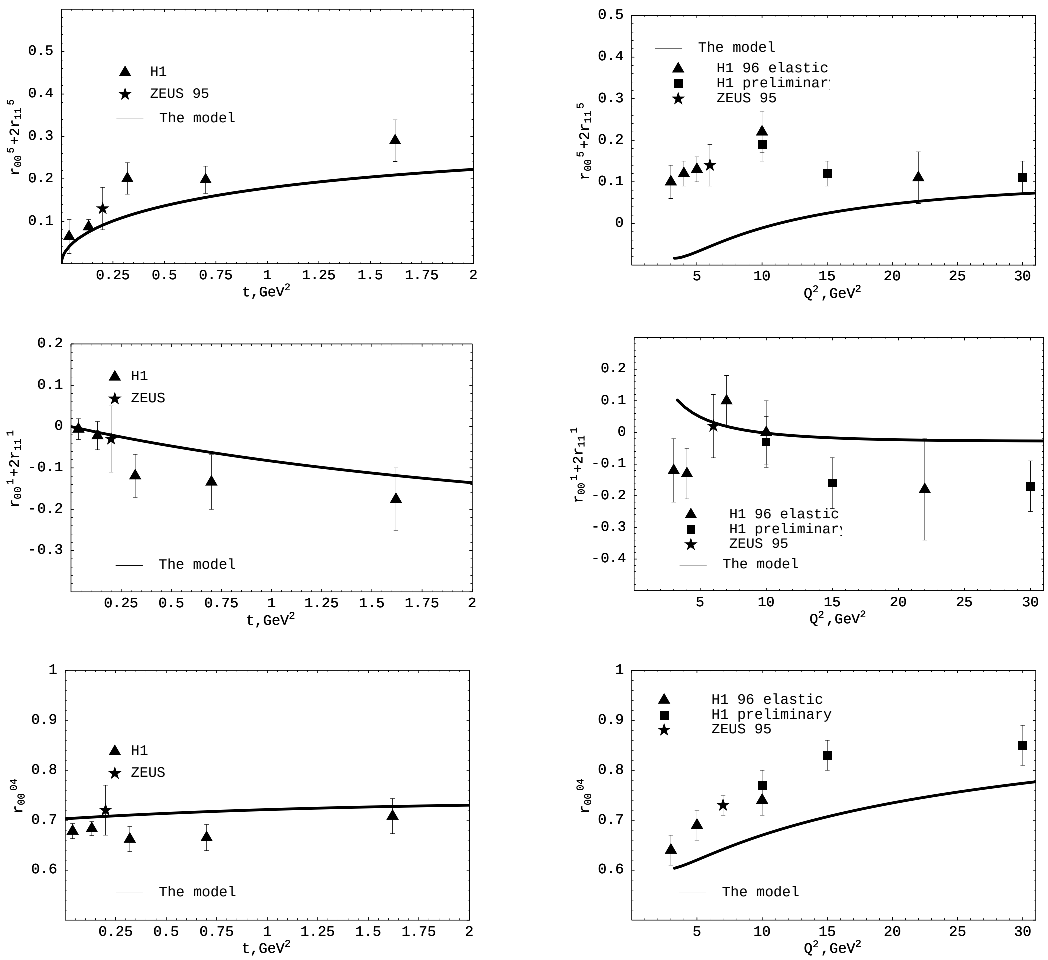
1. The hard part of the photon wave function is removed by the Borel transform $\Phi_V \sim \exp\left(-\frac{p_T^2+m_q^2}{M_V^2 z\bar{z}}\right)$; the helicity structure is kept unchanged
2. Tower of contributions $\sim \left(\frac{k^2}{Q^2 z\bar{z}}\right)^n$ to be resummed
3. Terms $\sim \log(k^2/Q^2)$ are absorbed into the generalised Bjorken evolution of t-channel parton exchange $gg \to q\bar{q}$
4. Contributions from gluon (hard) and quark distributions approximated by the gluon at the scale $z\bar{z}Q^2 \longrightarrow$ factorisation restored

Helicity Amplitudes in Electroproduction

Spin density matrix: $r^5_{00} + 2\, r^5_{11}$, $r^1_{00} + 2\, r^1_{11}$, r^{04}_{00}

[A. Ivanov, R. Kirschner]

t-dependence $\qquad$ Q^2-dependence



Reasonable description of data — not a fit

Unfolding the b-profile

Elements of the dipole S-matrix in the impact parameter plane for $\gamma^*(Q^2)p \to \rho p$
[S. Munier, A. Staśto, A. Mueller]

$$\mathcal{M}(x,\Delta,Q) = \sum_{h,\bar{h}} \int d^2\mathbf{r}\, dz\, \psi^{h,\bar{h}*}_{\gamma^*}(z,\mathbf{r};Q)\, A^{q\bar{q}-p}_{el}(x,\mathbf{r},\Delta)\, \psi^{h,\bar{h}}_{V}(z,\mathbf{r})$$

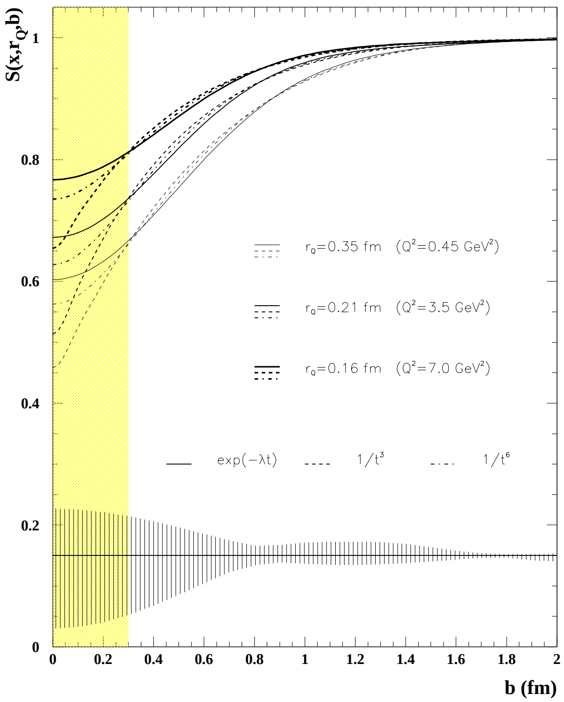
$$A^{q\bar{q}-p}_{el}(x,\mathbf{r},\Delta) = 2\int d^2\mathbf{b}\,[1 - S(x,\mathbf{r},\mathbf{b})]e^{i\mathbf{b}\Delta}$$

$$\langle S(x,r,b)\rangle_p = 1 - \frac{1}{2N(Q)\pi^{3/2}} \int d^2\Delta\, e^{-i\Delta\mathbf{b}} \sqrt{\frac{d\sigma}{dt}}$$

Real S-matrix, various wave functions were used
Assumptions about the high-t tail $d\sigma/dt \sim \exp(-B|t|)$, $d\sigma/dt \sim |t|^{-\alpha}$

Results

The profile

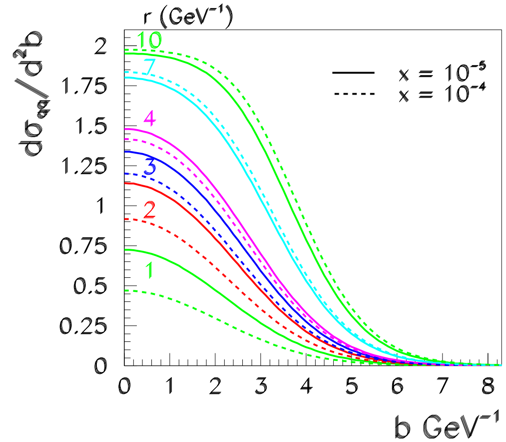


- Model independent results at large b
- Large uncertainty for $b < 0.3$ fm
- Estimate of the saturation scale
- $S = \exp(-r^2 Q_s^2/4)$ with $r \simeq \frac{2}{\sqrt{Q^2+M_V^2}}$
- $b = 0.3$ fm $\to Q_s^2 \simeq 1.2$ GeV^2
- $b = 1.0$ fm $\to Q_s^2 \simeq 0.2$ GeV^2

Saturation with b-dependence

Saturation model for $\gamma p \to J/\psi p$ [H. Kowalski and D. Teaney]
Dipole cross-section with colour transparency

$$\sigma_{q\bar{q}} = \frac{\pi^2}{N_c} r^2 \alpha_s(\mu^2) xg(x, \mu^2)$$



Probability of no-inelastic interaction on proton slice at z

$$P(b) = 1 - \frac{\pi^2}{N_c} r^2 \alpha_s(\mu^2) xg(x, \mu^2) \rho(b, z) dz$$

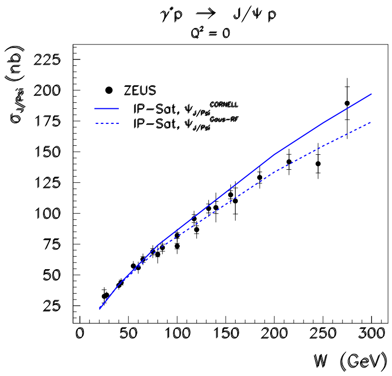
Elastic scattering $\to$ exponentiation with transverse profile $T(b) = \int \rho(b, z) dz$ (Gaussian)

$$\frac{d\sigma_{q\bar{q}}}{d^2b} = 2 \left[1 - \exp\left(-\frac{\pi^2}{2\, N_C} r^2 \alpha_s(\mu^2) xg(x, \mu^2) T(b) \right) \right]$$

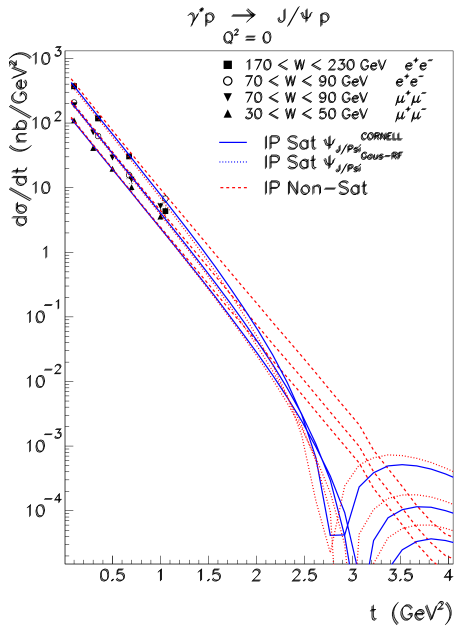
Comparison with data

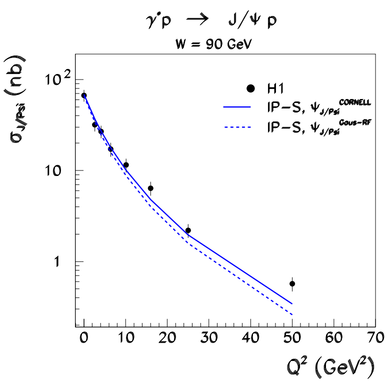
Model parameters constrained by F_2, F_2^{charm}

Profile $T(b) = \frac{1}{2\pi B}\exp(-b^2/2B)$ with $B \simeq 4.25$ GeV^2

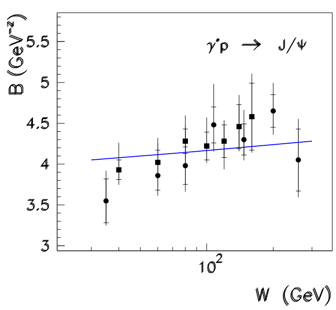


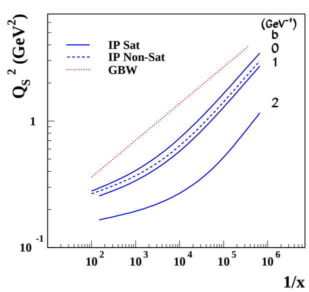
t-dependence





Good description, but small effects of saturation



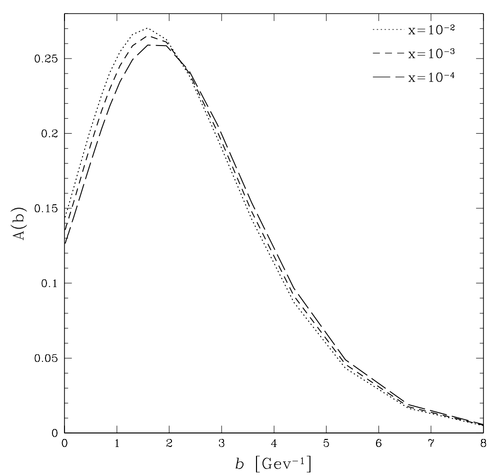


Elastic J/ψ from Balitsky-Kovchegov Equation

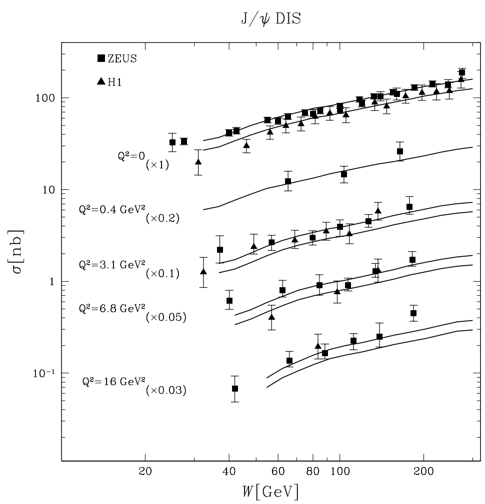
[E. Gotsman, E. Levin, M. Lublinsky, U. Maor, E. Naftali]

Nonlinear BK evolution equation is solved for the dipole scattering amplitude $N(r, Y, b)$
Presence of momentum transfer Δ leads to convolution of dipole-dipole scattering amplitude with the proton form-factor $S_p(b)$ in the dipole representation $\mathcal{A}(r, Y; b) = \int d^2b' N(r, Y; b') S_p(b - b')$

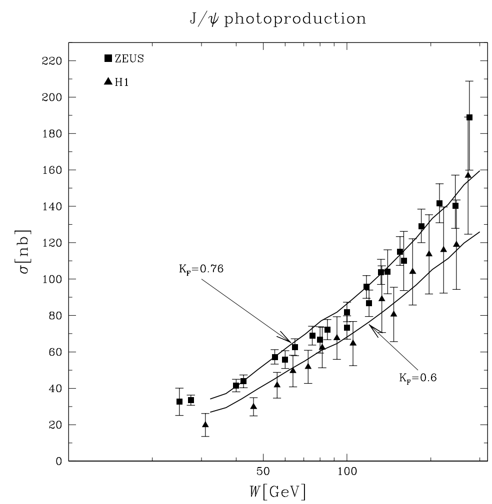
Peculiar profile



Q^2-dependence



W-dependence



Good description of data but

Little dependence on x but dip at $b \to 0 \leftrightarrow$ Saturation?

BFKL

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)

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

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

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

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 $Y \longrightarrow dP \sim \bar{\alpha}_s dY/2 \int_{k^2}^{q^2} \frac{dk'^2}{k'^2}$

$\Downarrow$

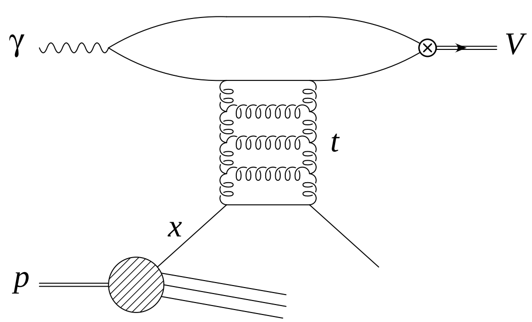
P (no emission) $= \exp(-\bar{\alpha}_s Y/2 \, \log(q^2/k^2))$

$\Downarrow$

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

$\Downarrow$

coupling to individual partons



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

Result of BFKL Evolution for LVM

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

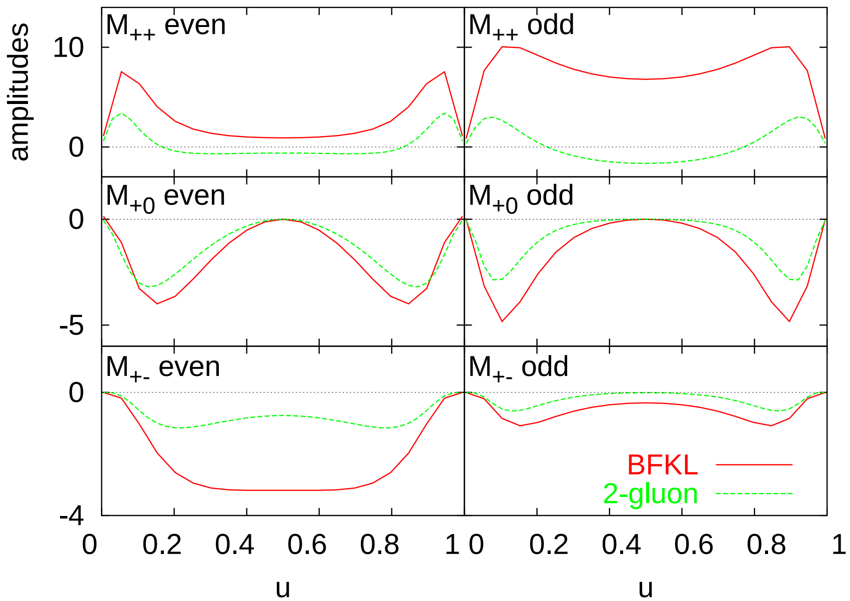
$$\times \sum_{n=-\infty}^{n=+\infty} \int_{-\infty}^{\infty} d\nu \frac{\nu^2 + n^2}{[\nu^2 + (n-1/2)^2][\nu^2 + (n+1/2)^2]} \frac{\exp[\chi_{2n}(\nu) z]}{\sin(i\pi\nu)}\; I_{-\frac{1}{2}-\frac{1}{2}}(\nu, 2n, q, u; 0)$$

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

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

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

Result of BFKL Evolution – Disentangled



2-gluon multiplied by factor of 3,

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

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

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

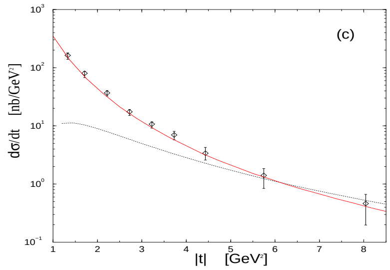
Pomeron intercept $\lambda \sim 0.4$

End-point divergences are removed in massless limit

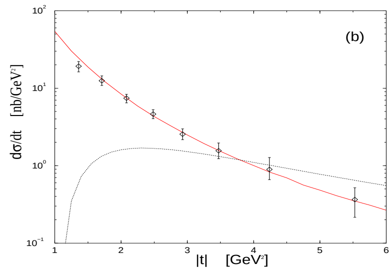
Photoproduction at high t

[J. Forshaw, G. Poludniowski]

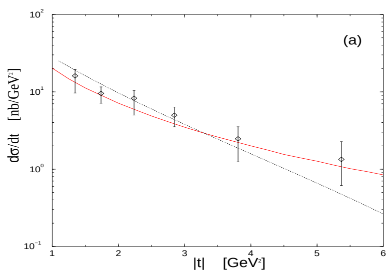
ρ



ϕ



J/ψ



Cross-sections – BFKL fit with 3 parameters, NR wave functions

Excellent description by BFKL, two-gluon fail badly

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

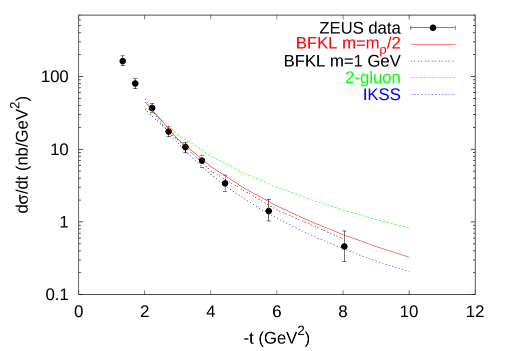
Corrections from higher conformal spins under control

ρ – beyond the NR approximation and SCHC [Enberg,Forshaw,LM,Poludniowski]

BFKL works well

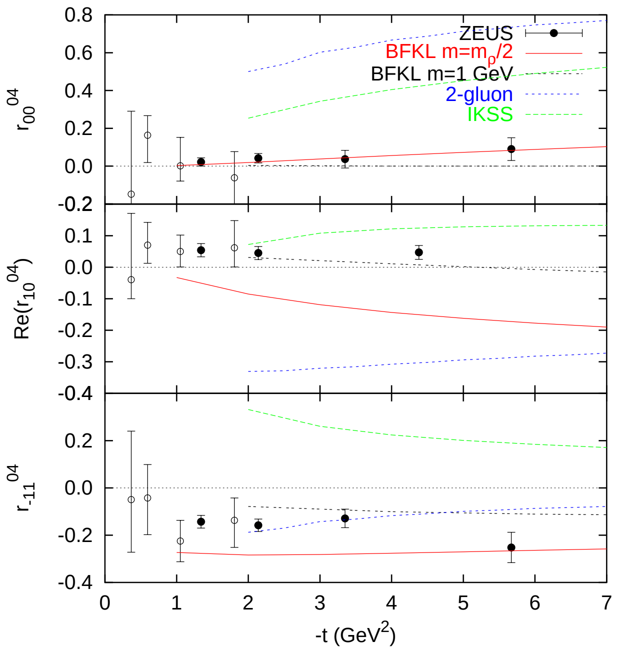
2-gluon with pert. γ-WF – fails

IKSS-2g, using non-pert. γ-WF-works



Spin Density Matrix in Photoproduction

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



Comparison of SDM: BFKL, IKSS and 2-g with perturbative γ

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

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

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

Neither conventional approach works for all r-s

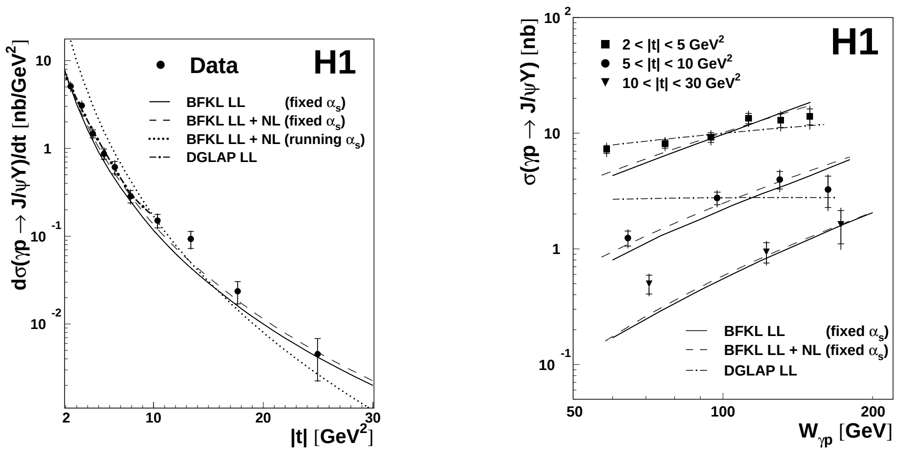
Asymptotically leading M_{+0} — too large without QCD evolution

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???

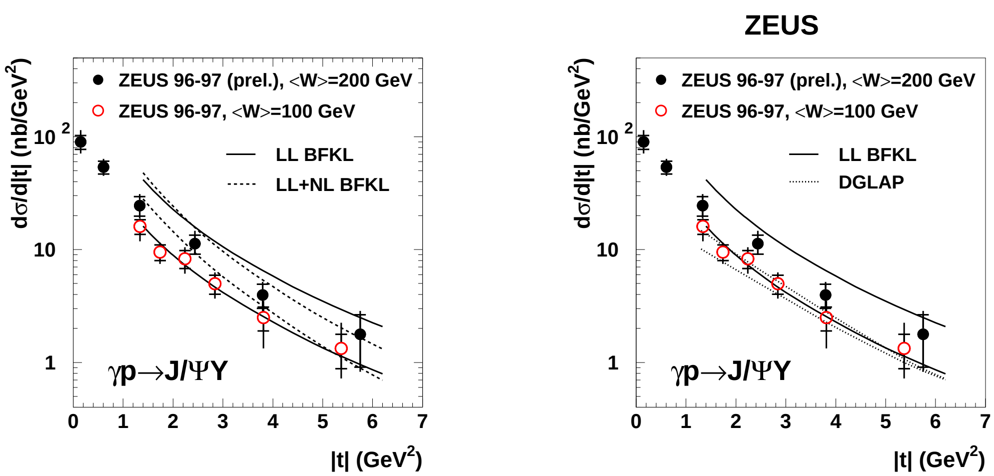
Reasons? Non-perturbative photon wave function? Meson wave function?
Rescattering suppressing large dipoles? Scattering of higher Fock components $q\bar{q}g$?

$\gamma p \to J/\psi + Y$: A Closer Look

H1 data



ZEUS data



- BFKL with fixed α_s gives reasonable description of data
- Energy dependence – best for BFKL+NL, worse for BFKL LL
- DGLAP fails to describe W-dependece at large t

The Odderon

[J. Bartels, J. Kwieciński and M. Praszałowicz]

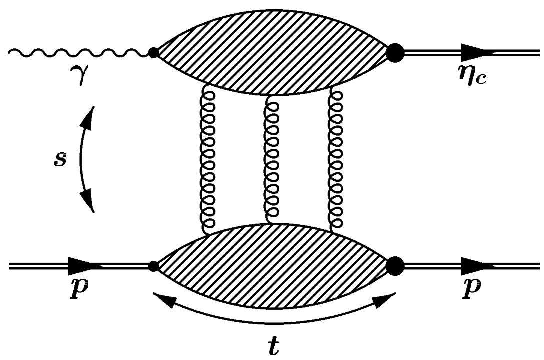
Intriguing object composed of 3 interacting Reggeized gluons with odd C-parity, evolution described by BKP equation

Perturbative Odderon may contribute to diffractive η_c photoproduction [O. Nachtmann; Czyżewski, Kwieciński, LM, Sadzikowski]

The 3-gluon exchange gets enhanced by the evolution, giving

$\sigma(\gamma p \to \eta_c p) \simeq 50$ pb and $\sigma(\gamma p \to \eta_c X) \simeq 60$ pb

(photoproduction) [J. Bartels, M. A. Braun, G. P. Vacca, D. Colferai]



Non-perturbative Odderon should contribute to the light C-even meson production:

[E.R. Berger, A. Donnachie, H.G. Dosch, W. Kilian, O. Nachtmann, M. Rueter]

Reaction	BDDKNR [nb]	H1 [nb]
$\gamma p \to \pi^0 N^*$	294 ± 150	< 38
$\gamma p \to f_2 N^*$	21 ± 10	< 16
$\gamma p \to a_2^0 N^*$	190 ± 100	< 96

But it does not! — WHY?

Conclusions and Outlook

1. Possibly, diffractive factorisation holds for production of both longitudinally and transversely polarised mesons

2. Exclusive production of vector mesons provides valuable information about High Density QCD, parton saturation, the nature of the Pomeron

3. Helicity observables provide stringent tests of models, in particular the BFKL description of $\gamma p \to VY$ has just become available and it describes well most observables

4. The Puzzle of Odderon

5. . . . and MUCH MORE to be expected