Exclusive vector meson production at small x

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Outline

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

Exclusive light VM electroproduction

$$\gamma^*(\lambda_\gamma)\, p \to V(\lambda_V)\, p\,,$$

- studied in many experiments: from a few GeV at JLab to hundreds of GeV at the HERA collider. Prospects for experiments at future *ep* and *eA* colliders.
- VM decay, like $\rho^0 \to \pi^+\pi^-$, allows to access the helicity amplitudes $T_{\lambda_V \lambda_\gamma}$ (λ_γ, λ_V : polarizations of the virtual photon and the vector meson).
- Good HERA helicity analysis:
  ZEUS for $2 < Q^2 < 160$ GeV^2, $32 < W < 180$ GeV ($|t| < 1$ GeV^2), and H1 for $2.5 < Q^2 < 60$ GeV^2, $35 < W < 180$ GeV $(|t| < 3$ GeV$^2)$,
- Different theoretical approaches:
  - ◇ for $W \sim Q \gg \Lambda_{QCD}$: Collinear factorization in terms of GPDs
  - ◇ for $W \gg Q \gg \Lambda_{QCD}$: based on BFKL k_t- factorization in terms of UGD (and related to it the QCD dipole approach)

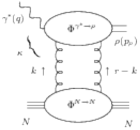
Collinear factorization for VM production:

- valid in all orders for longitudinal amplitude $T_{0,0}$ only !
- very large NLO corrections at small x [D.I., L.Szymanowski, G. Krasnikov]
  appearance of first BFKL energy log in hard coefficient function, NLO diagrams with gluonic exchange in the $t-$ channel
  (for DVCS – it starts from NNLO.)
- for transverse amplitude $T_{1,1}$ – no factorization (end-point singularities)

Modified collinear factorization by [P. Kroll, S. Goloskokov]:

- based on inclusion of Sudakov factors [Li, Sterman]
  description of $T_{\lambda_V \lambda_\gamma}$ with LO collinear GPDs and k_t- dependent light-cone WFs instead of collinear DAs
- end-point singularities for $T_{1,1}$ are suppressed
  successful phenomenology!
- Open questions:
  What this approach will give us at NLO?
  Can we generalize it to NLO without ambiguity?

Our approach: k_t- factorization



$$T_{\lambda_\rho\lambda_\gamma}(s;Q^2) \propto is \int \frac{d^2\underline{k}}{(\underline{k}^2)^2} \Phi^{\gamma^*(\lambda_\gamma)\to\rho(\lambda_\rho)}(\underline{k}^2,Q^2)\,\mathcal{F}(x,\underline{k}^2)\,, \quad x=\frac{Q^2}{s}$$

- based on BFKL: resummation of LLA (and NLA) energy logs
  $\mathcal{F}(x,\underline{k}^2)$ – unintegrated gluon distribution (UGD)
- $\Phi^{\gamma^*(\lambda_\gamma)\to\rho(\lambda_\rho)}(\underline{k}^2,Q^2)$- impact factor (IF).
- Our [Anikin, D.I., Pire, Szymanowski, Wallon] idea - to calculate IF in collinear factorization (using twist-2 and twist-3 DAs). Basic assumption (supported by the data and *a posteriori* by our calculation):
  physical mechanism – scattering of small size dipole, $\mathbf{r}\sim\mathbf{1/Q}$, on a target

- HERA data support the picture of small size dipole scattering for both longitudinal and transverse polarizations:
  - energy dependence: $d\sigma/dW \sim W^{\delta}$, $\delta_{\gamma^*(Q^2)p\to\rho p} \sim 0.8$, whereas for photoproduction $\delta_{\gamma p\to\rho p} \sim 0.22$
  - $t-$ dependence: $d\sigma/dt \sim e^{bt}$, $b_{\gamma^*(Q^2)p\to\rho p} \sim 5\ \mathrm{GeV}^{-2}$, for photoproduction $b_{\gamma p\to\rho p} \sim 10\ \mathrm{GeV}^{-2}$
  - no variation seen of T_{11}/T_{00} with W and t
  - hierarchy between helicity amplitudes, (predicted [D.I., R. Kirshner])

$$T_{00} \gg T_{11} \gg T_{10} \gg T_{01} \gg T_{-11}.$$

- small dipoles $\leftrightarrow$ collinear factorization and description in terms not light-cone WFs, but of DAs

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

- possibility to perform NLA resummation without ambiguity
  NLA $\gamma_L \to \rho_L$ IF by [D.I., M. Kotsky, A. Papa]

The BFKL resummation

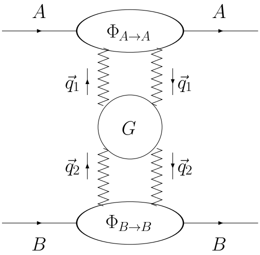
total cross section for $A + B \to X$: $\sigma_{AB}(s) = \frac{\mathcal{I}m_s\left(\mathcal{A}_{AB}^{AB}\right)}{s}$ $\Leftarrow$ **optical theorem**

◇ 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.

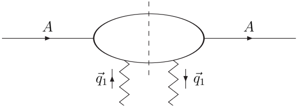
$$\mathrm{Im}_s(\mathcal{A}) = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^{\,2}} \Phi_A(\vec{q}_1, s_0) \int \frac{d^{D-2}q_2}{\vec{q}_2^{\,2}} \Phi_B(-\vec{q}_2, s_0) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0}\right)^{\omega} G_\omega(\vec{q}_1, \vec{q}_2)$$

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

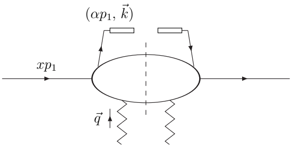
  $\longrightarrow$ determined through the **BFKL equation**
  [Ya. Balitsky, V. Fadin, E. Kuraev, L. Lipatov - LLA; V. Fadin, L. Lipatov - NLA]

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

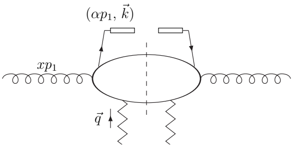
  $\longrightarrow$ known in the NLA just for few processes



example: forward identified hadron production



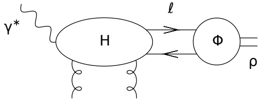
quark vertex



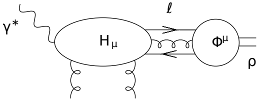
gluon vertex

[D.I., A. Papa]

IF for longitudinal and transverse V production



contribution of $q\bar{q}$ DA



contribution of $q\bar{q}G$ DA

- we assumed that both $Q, \underline{k} \gg \Lambda_{QCD}$ and calculated $\Phi^{\gamma^*_L \to \rho_L}$ and $\Phi^{\gamma^*_T \to \rho_T}$ IFs in leading power of its $1/Q$ expansion
- for $\Phi^{\gamma^*_L \to \rho_L}$ expansion starts from twist-2 ($\bar{y} \equiv 1 - y$)

$$\Phi^{\gamma^*_L \to \rho_L}(\underline{k}^2) = \frac{2\, e\, g^2\, f_\rho}{\sqrt{2}\, Q}\, \frac{\delta^{ab}}{2\, N_c} \int_0^1 dy\, \varphi_\parallel(y)\, \frac{\underline{k}^2}{y\, \bar{y}\, Q^2 + \underline{k}^2}$$

- for $\Phi^{\gamma^*_T \to \rho_T}$ – from twist-3.
- QCD gauge invariance $\longrightarrow \Phi(\underline{k}) \to 0$ at $\underline{k} \to 0$
  for transverse, twist-3 case, I will discuss important ideas behind our calculation.

twist-3 DAs

gauge invariant, light-cone, $z^2 \to 0$, matrix elements [P. Ball, V. Braun, Y. Koike, K. Tanaka] (DAs definitions, QCD EOM):

$$\langle \rho(p_\rho)|\bar\psi(z)\,[z,\,0]\,\gamma_\mu\gamma_5\psi(0)|0\rangle = \frac{1}{4} f_\rho\, m_\rho\, \varepsilon_\mu{}^{e_T^*\,p\,z} \int_0^1 dy\, e^{iy(p\cdot z)}\, g_\perp^{(a)}(y)$$

$$\langle \rho(p_\rho)|\bar\psi(z)\,[z,\,0]\,\gamma_\mu\psi(0)|0\rangle = f_\rho\, m_\rho \int_0^1 dy\, e^{iy(p\cdot z)} \left[p_\mu \frac{e^*\cdot z}{p\cdot z}\phi_\parallel(y) + e^*_{T\mu}\, g_\perp^{(v)}(y)\right]$$

In the axial gauge $A\cdot n = 0,\ n^2 = 0$, In this gauge the gluon field can be expressed in terms of field strength as follows

$$A_\alpha(y) = \int_0^\infty d\sigma\, e^{-\epsilon\,\sigma}\, n^\beta\, G_{\alpha\beta}(y+\sigma n)$$

which implies that the $(\bar q\, A\, q\ )$ correlators involving the gluon field A reads

$$\langle \rho(p_\rho)|\bar\psi(z)\gamma_\mu g A_\alpha(tz)\psi(0)|0\rangle = -p_\mu\, e^*_{T\alpha} m_\rho\, f_{3\rho}^V \int \frac{D\alpha}{\alpha_g}\, e^{i(p\cdot z)(\alpha_1+t\,\alpha_g)}\, V(\alpha_1,\alpha_2)$$

$$\langle \rho(p_\rho)|\bar\psi(z)\gamma_\mu\gamma_5 g A_\alpha(tz)\psi(0)|0\rangle = -ip_\mu \frac{\varepsilon_\alpha{}^{z\,p\,e_T^*}}{(p\cdot z)} m_\rho\, f_{3\rho}^A \int \frac{D\alpha}{\alpha_g}\, e^{i(p\cdot z)(\alpha_1+t\alpha_g)}\, A(\alpha_1,\alpha_2)\,.$$

Steps toward IFs

- an operator product expansion on the light cone, $z^2 \to 0$, which naturally gives the leading term in the power counting
- at $z^2 \to 0$ limit, any single diagram is given in terms of light-cone matrix elements without any Wilson line insertion between the quark and gluon operators, like

$$\langle V(p_V)|\bar{\psi}(z)\gamma_\mu \psi(0)|0\rangle \quad \text{and} \quad \langle V(p_V)|\bar{\psi}(z)\gamma_\mu A_\alpha(t\,z)\psi(0)|0\rangle \,,$$

- need to combine together contributions of quark–antiquark and quark–antiquark gluon diagrams in order to obtain a final gauge invariant result, using QCD EOM which relate DAs $g_\perp^{(v)}, g_\perp^{(a)}$ with $\phi_\parallel(y)$, $V(\alpha_1, \alpha_2)$, $A(\alpha_1, \alpha_2)$.
- in the axial gauge, $A \cdot n = 0$, $n^2 = 0$, one can not neglect completely an effect coming from the Wilson lines since the two light-cone vectors z and n are not equal to each other and thus, generically, Wilson lines are not equal to unity!
- in the axial gauge the contribution of each additional parton costs one extra power of $1/Q$, therefore a calculation can be organized in a simple iterative manner expanding the Wilson line.

At twist three level it is enough to consider the first two terms of such expansion

$$[z,0] = 1 + i\,g \int_0^1 dt\, z^\alpha A_\alpha(zt) + \mathcal{O}(A^2)$$

For instance, the quark–antiquark vector correlator:

$$\langle V(p_V)|\bar{\psi}(z)\gamma_\mu\psi(0)|0\rangle = \langle V(p_V)|\bar{\psi}(z)\gamma_\mu[z,0]\psi(0)|0\rangle$$

$$-ig\int_0^1 dt \langle V(p_V)|\bar{\psi}(z)\gamma_\mu z^\alpha A_\alpha(zt)\psi(0)|0\rangle$$

where we formally inserted the Wilson line in the r.h.s and performed its approximate subtraction.
It generates an additional contribution to the transverse IF!(in terms of $q\bar{q}G$ DAs)
Only taking it into account we got final gauge invariant result:

$$\Phi(\underline{k}) \to 0 \quad \text{at} \quad \underline{\mathrm{k}} \to 0$$

Decomposition of the impact factor into spin-non-flip and spin-flip part.

$$\Phi^{\gamma^*_T \to \rho_T}(\underline{k}^2) = \Phi^{\gamma^*_T \to \rho_T}_{n.f.}(\underline{k}^2)\, T_{n.f.} + \Phi^{\gamma^*_T \to \rho_T}_{f.}(\underline{k}^2)\, T_f \,,$$

The non-flip part is proportional to

$$T_{n.f.} = -(e_\gamma \cdot e^*_T)$$

whereas the spin-flip part involves

$$T_{f.} = \frac{(e_\gamma \cdot k_\perp)(e^*_T \cdot k_\perp)}{\underline{k}^2} + \frac{(e_\gamma \cdot e^*_T)}{2}$$

We use the notations

$$\alpha = \frac{\underline{k}^2}{Q^2}\,, \quad c_f = \frac{N_c^2}{N_c^2 - 1}\,, \quad \zeta_3^V = \frac{f^V_{3\rho}}{f_\rho}\,, \quad \zeta^A = \frac{f^A_{3\rho}}{f_\rho}$$

For the 3-parton, $q\bar{q}G$ contributions we obtain the result

$$\Phi^3 = -\frac{e\,g^2\,m_\rho\,f_\rho}{\sqrt{2}Q^2}\frac{\delta^{ab}}{2N_c}\left\{\Phi^{q\bar{q}g}(\alpha) + \Delta\Phi^3\right\}$$

with $\Phi^{q\bar{q}g}(\alpha) \to 0$ at $\alpha \to 0$, and "gauge non-invariant" term

$$\Delta\Phi^3 = -\frac{T_{n.f.}}{2}\int \frac{Dz}{\bar{z}_1\bar{z}_2 z_g}\left\{\zeta_3^V V(z_1,z_2)(z_1 - z_2) + \zeta_3^A A(z_1,z_2)(\bar{z}_1 + \bar{z}_2)\right\}$$

it appear due to our removal of diagrams with gluon radiation from the external lines (discussed also by Peter in his talk).
For the 2-parton, $q\bar{q}$ contributions we obtain

$$\Phi^2 = -\frac{e\,g^2\,m_\rho\,f_\rho}{\sqrt{2}Q^2}\frac{\delta^{ab}}{2N_c}\left\{\Phi^{q\bar{q}}(\alpha) + \Delta\Phi^2\right\}\,,$$

with $\Phi^{q\bar{q}}(\alpha) \to 0$ at $\alpha \to 0$

$$\Phi^{q\bar{q}}(\alpha) = \int\limits_0^1 dz\left\{T_{n.f.}\Phi^+(z)\frac{\alpha(\alpha + 2z\bar{z})}{z\bar{z}(\alpha + z\bar{z})^2} + T_{f.}\Phi^-(z)\frac{2\alpha}{(\alpha + z\bar{z})^2}\,,\right\}$$

where

$$\Phi^\pm(\alpha) = (2z-1)\left[h(z) - \tilde{h}(z)\right] \pm \frac{g_\perp^{(a)}(z) - \tilde{g}_\perp^{(a)}(z)}{4}\,,$$

whereas for $\Delta\Phi^2$ term we get

$$\Delta\Phi^2 = T_{n.f.}\int\limits_0^1 dz\left\{g_\perp^{(v)}(z) - \frac{\Phi^+(z)}{2z\bar{z}}\right\}\,.$$

Now we need to demonstrate that $\Delta\Phi^2$ and $\Delta\Phi^3$ cancel each other.

One can now separate from $\Delta\Phi^2$ the contribution $\Delta\Phi^2_a$ that is due to functions $\tilde{h}(z)$ and $\tilde{g}^a_\perp(z)$, which originates in our method from the Wilson lines insertion procedure,

$$\Delta\Phi^2 = \Delta\Phi^2_a + \Delta\Phi^2_b \,,$$

where

$$\Delta\Phi^2_a = T_{n.f.} \int_0^1 \frac{dz}{2z\bar{z}} \left\{ (2z-1)\tilde{h}(z) + \frac{\tilde{g}^{(a)}_\perp(z)}{4} \right\} .$$

after some transformation we got

$$\Delta\Phi^2_a = \frac{T_{n.f.}}{2} \int Dz \left\{ \zeta_3^V \frac{V(z_1,z_2)}{z_g^2} \ln\frac{z_1\bar{z}_1}{z_2\bar{z}_2} + \zeta_3^A \frac{A(z_1,z_2)}{z_g^2} \ln\frac{\bar{z}_1\bar{z}_2}{z_1 z_2} \right\} .$$

This is additional contribution that we have after our Wilson lines insertion procedure.

The second term of $\Delta\Phi^2$ can be reduced to the form

$$\Delta\Phi_b^2 = \frac{T_{n.f.}}{2}\int_0^1 dz \left\{ \ln(z)\, g^{\uparrow\downarrow}(z) + \ln(\bar{z})\, g^{\downarrow\uparrow}(z) \right\} .$$

where [V. Braun and coll.]

$$g^{\uparrow\downarrow}(z) = g_\perp^{(v)}(z) + \frac{1}{4}\frac{d}{dz} g_\perp^{(a)}(z) , \quad g^{\downarrow\uparrow}(z) = g_\perp^{(v)}(z) - \frac{1}{4}\frac{d}{dz} g_\perp^{(a)}(z) .$$

Then, we separate the WW and genuine twist 3 contributions to $\Delta\Phi_b^2$,

$$\Delta\Phi_b^2 = \Delta\Phi_b^{2\,WW} + \Delta\Phi_b^{2\,gen} ,$$

in accordance with

$$g^{\uparrow\downarrow}(z) = g^{\uparrow\downarrow\,WW}(z) + g^{\uparrow\downarrow\,gen}(z) , \quad g^{\uparrow\downarrow}(z) = g^{\uparrow\downarrow\,WW}(z) + g^{\uparrow\downarrow\,gen}(z) .$$

Using the explicit expressions for these functions in the WW limit

$$g^{\uparrow\downarrow\,WW}(z) = \int_z^1 \frac{du}{u}\phi_\parallel(u) , \quad g^{\downarrow\uparrow\,WW}(z) = \int_0^z \frac{du}{\bar{u}}\phi_\parallel(u) ,$$

one can easily found that the WW contribution to $\Delta\Phi_b^2$ vanishes,

$$\Delta\Phi_b^{2\,WW} = 0 .$$

In WW limit we got that IF is gauge invariant, as it should be!

We expressed $g^{\uparrow\downarrow\, gen}(z)$ and $g^{\downarrow\uparrow\, gen}(z)$ in terms of 3-partons DAs and found

$$\Delta\Phi_b^{2\,gen} = \frac{T_{n.f.}}{2} \int Dz \left\{ \zeta_3^V \frac{V(z_1,z_2)}{z_g} \left(\frac{z_1 - z_2}{\bar{z}_1 \bar{z}_2} - \ln \frac{z_1 \bar{z}_1}{z_2 \bar{z}_2} \frac{1}{z_g} \right) \right.$$
$$\left. + \zeta_3^A \frac{A(z_1,z_2)}{z_g} \left(\frac{\bar{z}_1 + \bar{z}_2}{\bar{z}_1 \bar{z}_2} - \ln \frac{\bar{z}_1 \bar{z}_2}{z_1 z_2} \frac{1}{z_g} \right) \right\}.$$

These results mean that

$$\Delta\Phi^2 = \frac{T_{n.f.}}{2} \int \frac{Dz}{z_g \bar{z}_1 \bar{z}_2} \left\{ \zeta_3^V V(z_1,z_2)(z_1 - z_2) + \zeta_3^A A(z_1,z_2)(\bar{z}_1 + \bar{z}_2) \right\}$$

and thus that the constant terms of 2-parton and 3- parton contributions cancel each other

$$\Delta\Phi^2 + \Delta\Phi^3 = 0\,.$$

Finally, our gauge invariant IF is given as a sum of two contributions

$$\Phi(\alpha) = -\frac{e\, g^2\, m_\rho\, f_\rho}{\sqrt{2} Q^2} \frac{\delta^{ab}}{2N_c} \left\{ \Phi^{q\bar{q}}(\alpha) + \Phi^{q\bar{q}g}(\alpha) \right\}$$

One can express it as a sum of WW and genuine contributions.

$$\Phi(\alpha) = \Phi(\alpha)^{WW} + \Phi(\alpha)^{gen}$$

Model for DAs

The first terms of the expansion of the three independent DAs have the form

$$
\begin{aligned}
\varphi_{\parallel}(y,\mu^2) &= 6y\bar{y}(1+a_2(\mu^2)\frac{3}{2}(5(y-\bar{y})^2-1))\,, \\
V(\alpha_1,\alpha_2;\mu^2) &= -5040\alpha_1\bar{\alpha}_2(\alpha_1-\bar{\alpha}_2)(\alpha_2-\alpha_1)\,, \\
A(\alpha_1,\alpha_2;\mu^2) &= -360\alpha_1\bar{\alpha}_2(\alpha_2-\alpha_1)(1+\frac{\omega^A_{\{1,0\}}(\mu^2)}{2}(7(\alpha_2-\alpha_1)-3))\,.
\end{aligned}
$$

The dependences on the renormalization scale μ^2 of the coupling constants a_2, $\omega^A_{\{1,0\}}$, $\zeta^A_{3\rho}$, and $\zeta^V_{3\rho}$ are given in [V. Braun and coll.]

α_s	0.52
$\omega^A_{\{1,0\}}$	-2.1
$\omega^V_{[0,1]}$	$28/3$
$a_{2,\rho}$	0.18 ± 0.10
$m_\rho\, f^A_{3\rho}$	$0.5 - 0.6\ 10^{-2}\,\mathrm{GeV}^2$
$m_\rho\, f^V_{3\rho}$	$0.2\ 10^{-2}\,\mathrm{GeV}^2$
$\zeta^A_{3\rho}$	0.032
$\zeta^V_{3\rho}$	0.013

Table: Coupling constants and Gegenbauer coefficients entering the $\rho-$meson DAs, at the scale $\mu_0 = 1$ GeV.

UGD models

In 2011 [I. Anikin, A. Besse, D.I., B. Pire, L. Szymanowski, S. Wallon]
we considered very simple assumption (denote here as [ABIPSW])

$$\mathcal{F}(x, \underline{k}) \sim \frac{\underline{k}^2}{\underline{k}^2 + M^2}$$

At $M = 1$ GeV, good description of HERA data.
In [A. Bolognino, F. Celiberto, D.I., A. Papa] arXive: 1808.02395 we study different UGD models:

- Gluon momentum derivative (Gluon mom.)

$$\mathcal{F}(x, \underline{k}^2) = \frac{dx\, g(x, \underline{k}^2)}{d \ln \underline{k}^2} \tag{1}$$

  of the collinear gluon density $g(x, \mu_F^2)$, taken at $\mu_F^2 = \underline{k}^2$.

- Igor Ivanov - Nikolaev (IN)
- Hentschinski-Salas-Sabio Vera (HSS)
- Golec-Biernat – Wüsthoff (GBW)
- Watt-Martin-Ryskin (WMR)

Golec-Biernat – Wüsthoff UGD

This model derives from the effective dipole cross section $\hat{\sigma}(x, \underline{r})$,

$$\hat{\sigma}(x, \underline{r}^2) = \sigma_0 \left\{ 1 - \exp\left(-\frac{\underline{r}^2}{4R_0^2(x)} \right) \right\} ,$$

through a reverse Fourier transform of the expression

$$\sigma_0 \left\{ 1 - \exp\left(-\frac{\underline{r}^2}{4R_0^2(x)} \right) \right\} = \int \frac{d^2\underline{k}}{\underline{k}^4} \mathcal{F}(x, \underline{k}^2) \left(1 - \exp(i\underline{k} \cdot \underline{r})\right) \left(1 - \exp(-i\underline{k} \cdot \underline{r})\right) ,$$

$$\mathcal{F}(x, \underline{k}^2) = \underline{k}^4 \sigma_0 \frac{R_0^2(x)}{2\pi} e^{-\underline{k}^2 R_0^2(x)} ,$$

with

$$R_0^2(x) = \frac{1}{\mathrm{GeV}^2} \left(\frac{x}{x_0} \right)^{\lambda_p}$$

and the following values

$$\sigma_0 = 23.03\,\mathrm{mb}, \qquad \lambda_p = 0.288, \qquad x_0 = 3.04 \cdot 10^{-4} .$$

The normalization σ_0 and the parameters x_0 and $\lambda_p > 0$ of $R_0^2(x)$ have been determined by a global fit to $F_2(x)$ in the region $x < 0.01$.

Transverse and longitudinal IFs have different collinear limits at $\underline{k} \to 0$:

- collinear limit is safe

$$\Phi^{\gamma^*_L \to \rho_L}(\underline{k}^2)/\underline{k}^2 \to const$$

- not safe for transverse non-flip – no collinear factorization

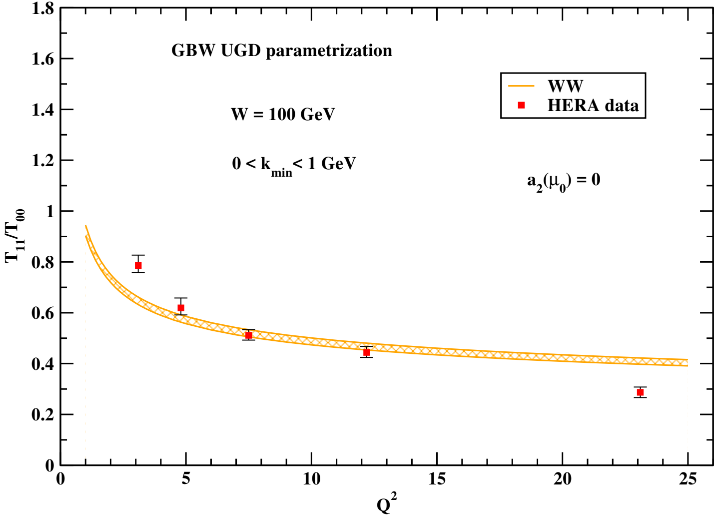
$$\Phi^{\gamma^*_T \to \rho_T}_{n.f.}(\underline{k}^2)/\underline{k}^2 \to \ln \underline{k}^2$$

- for photon helicity flip – collinear safe

$$\Phi^{\gamma^*_T \to \rho_T}_{f.}(\underline{k}^2)/\underline{k}^2 \to const$$

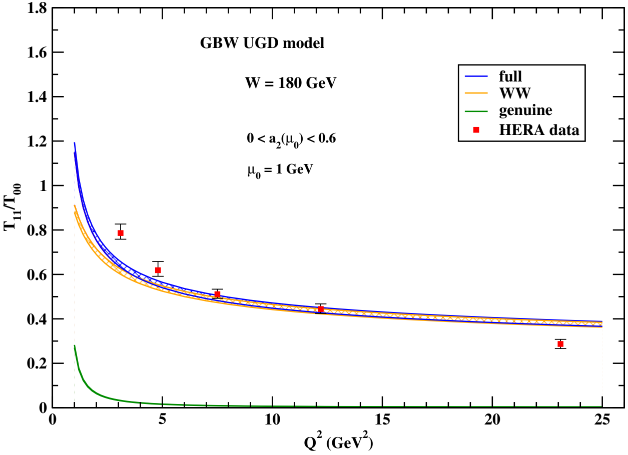
(related to gluon transversity GPD, and [Kolya Kivel] work – no end-point singularity for transverse double flip VM production.)

We study sensitivity of our prediction to the region of small $\underline{k}$, where our collinear factorization approach to IF may be not reliable, introducing a lower cutoff in $\underline{k}-$ integration.

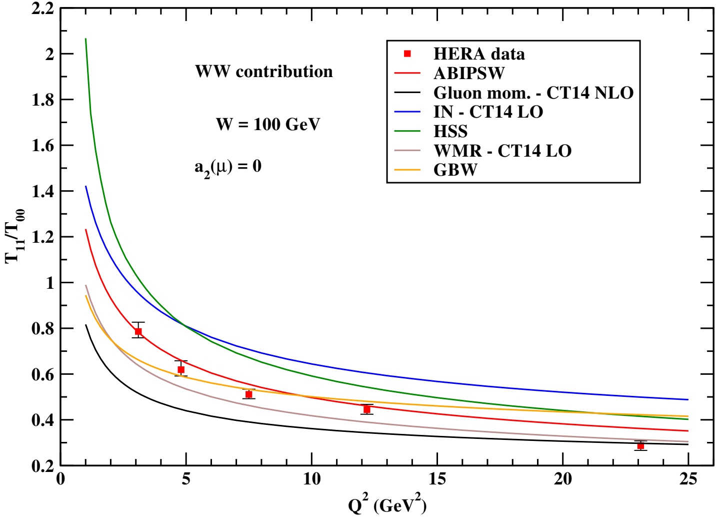


Q^2-dependence of the helicity-amplitude ratio T_{11}/T_{00} for the GBW UGD model at $W = 100$ GeV. The band is the effect of a lower cutoff in the κ-integration, ranging from 0. to 1 GeV. In the twist-2 DA we have put $a_2(\mu_0 = 1 \text{ GeV}) = 0$ and the T_{11} amplitude has been calculated in the WW approximation.

WW versus genuine twist-3, and variation of a_2 value



Sensitivity to $\underline{k}-$ shape of $\mathcal{F}(x, \underline{k})$



Conclusions...

- We considered small x VM elektroproduction in k_t- factorization.
- We obtain impact factor for $\gamma^*_T \to V_T$.

  Its calculation requires proper treatment of gauge link factor, even despite our use of the axial gauge.
- We demonstrate that T_{11}/T_{00} helicity amplitude ration is weakly sensitive to the physics encoded in DAs, whereas it depends strongly on the $\underline{k}-$ shape of UGD.
- Therefore, precise HERA data on T_{11}/T_{00} can be used to discriminate models of UGD.

...Outlook

- Description at NLA level. Need for calculation of $\gamma^*_T \to V_T$ impact factor with NLA accuracy.
  $\gamma^*_L \to V_L$ IF is known [D.I., M. Kotsky, A. Papa]
- Calculation in the QCD shockwave formalism: in order to study the onset of nonlinear effects in pA collisions.

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