

Vector meson electroproduction within GPD approach.

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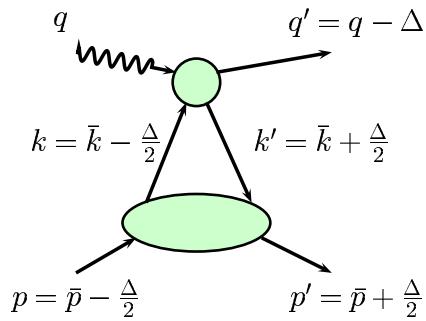
Plan

- Factorization of Vector meson leptoproduction .
- Model for GPDs.
- Modified PA for hard scattering amplitude
 - transverse degrees of freedom in wave function, hard subprocess ,
 - Sudakov suppression .
- LL cross section in a wide energy range $5\text{GeV} < W < 75\text{GeV}$.
- TT transition amplitude-small x - gluon contribution at HERA energies.

Factorization of Vector Mesons production amplitude

- Large Q^2 - factorization into a hard meson photoproduction off partons, and GPDs. (LL)

Radyushkin, Collins, Frankfurt Strikman



$$k = ((\bar{x} + \xi)p_+, \dots)$$

$$k' = ((\bar{x} - \xi)p_+, \dots)$$

$$k \neq k'; \quad \xi \sim \frac{x_B}{2 - x_B}$$

$L \rightarrow L$ transition - predominant. Other amplitudes are suppressed as powers $1/Q$

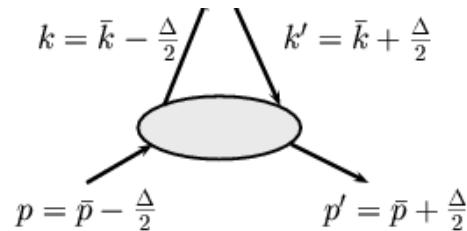
The process of VM production

- ϕ production (gluon&strange sea)
- ρ production (gluon&sea&valence quarks)

Generalized Parton Distributions

D.Mueller, 1994; Ji, 1997; Radyushkin, 1997

$$\xi = \frac{(p - p')^+}{(p + p')^+}, \quad \bar{x} = \bar{k}^+/\bar{p}^+, \quad t$$



$$\begin{aligned} \langle p'\nu' | \sum_{a,a'} A^{a\rho}(0) A^{a'\rho'}(\bar{z}) | p\nu \rangle &\propto \int_0^1 \frac{d\bar{x}}{(\bar{x} + \xi - i\varepsilon)(\bar{x} - \xi + i\varepsilon)} e^{-i(\bar{x} - \xi)p \cdot \bar{z}} \\ &\times \left\{ \frac{\bar{u}(p'\nu') \not{u}(p\nu)}{2\bar{p} \cdot n} H^g(\bar{x}, \xi, t) + \frac{\bar{u}(p'\nu') i \sigma^{\alpha\beta} n_\alpha \Delta_\beta u(p\nu)}{4m \bar{p} \cdot n} E^g(\bar{x}, \xi, t) \right. \\ &+ \left. \frac{\bar{u}(p'\nu') \not{u}\gamma_5 u(p\nu)}{2\bar{p} \cdot n} \tilde{H}^g(\bar{x}, \xi, t) + \frac{\bar{u}(p'\nu') n \cdot \Delta \gamma_5 u(p\nu)}{4m \bar{p} \cdot n} \tilde{E}^g(\bar{x}, \xi, t) \right\}. \end{aligned}$$

$$H^g(\bar{x}, 0, 0) = \bar{x} g(\bar{x}); \quad \tilde{H}^g(\bar{x}, 0, 0) = \bar{x} \Delta g(\bar{x}) \quad (1)$$

Distributions $E^g(\bar{x}, \xi, t)$, (\tilde{E}) determine mainly proton spin-flip – **not essential for unpolarized proton target at low x .**

Modelling the GPDs

The double distributions for GPDs Radyushkin '99 .

- simple for the double distributions

$$f_i(\beta, \alpha, t') = h_i(\beta, t') \frac{\Gamma(2n_i + 2)}{2^{2n_i+1} \Gamma^2(n_i + 1)} \frac{[(1 - |\beta|)^2 - \alpha^2]^{n_i}}{(1 - |\beta|)^{2n_i+1}}, \quad (2)$$

- ★ Gluon contribution (n=2) function.

$$h_g(\beta, 0) = |\beta|g(|\beta|) \quad (3)$$

↓

$$H^g(\bar{x}, \xi, t) = \left[\Theta(0 \leq \bar{x} \leq \xi) \int_{\frac{\bar{x}-\xi}{1+\xi}}^{\frac{\bar{x}+\xi}{1+\xi}} d\beta + \Theta(\xi \leq \bar{x} \leq 1) \int_{\frac{\bar{x}-\xi}{1-\xi}}^{\frac{\bar{x}+\xi}{1-\xi}} d\beta \right] \frac{\beta}{\xi} f(\beta, \alpha = \frac{\bar{x} - \beta}{\xi})$$

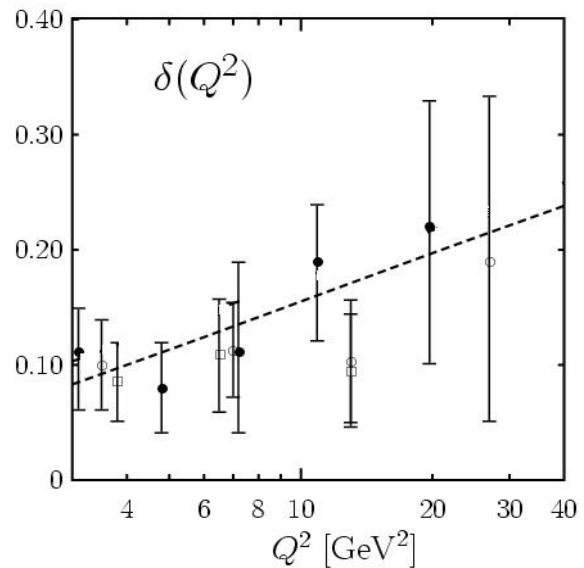
- ★ $h_{sea}^q(\beta, 0) = g(|\beta|) \operatorname{sign}(\beta)$ - sea quark contribution (n=2).

- Similar form for sea quark but integral $\Theta(0 \leq \bar{x} \leq \xi)$ is different .

- ★ $h_{val}^q(\beta, 0) = g(|\beta|) \Theta(\beta)$ – valence contribution (n=1)

PDF t -dependence —Regge paramerization.

$$h_i(\beta, t) = e^{b_0 t} \beta^{-(\delta_i(Q^2) + \alpha'_i t)} (1 - \beta)^5 \sum_{i=0}^3 c_i \beta^{i/2} \quad (4)$$



$$\alpha_i(t) = \alpha_i(0) + \alpha'_i t$$

$$\delta_g(Q^2) = \alpha_P(0) - 1 = .1 + .06 \ln \frac{Q^2}{4\text{GeV}^2}$$

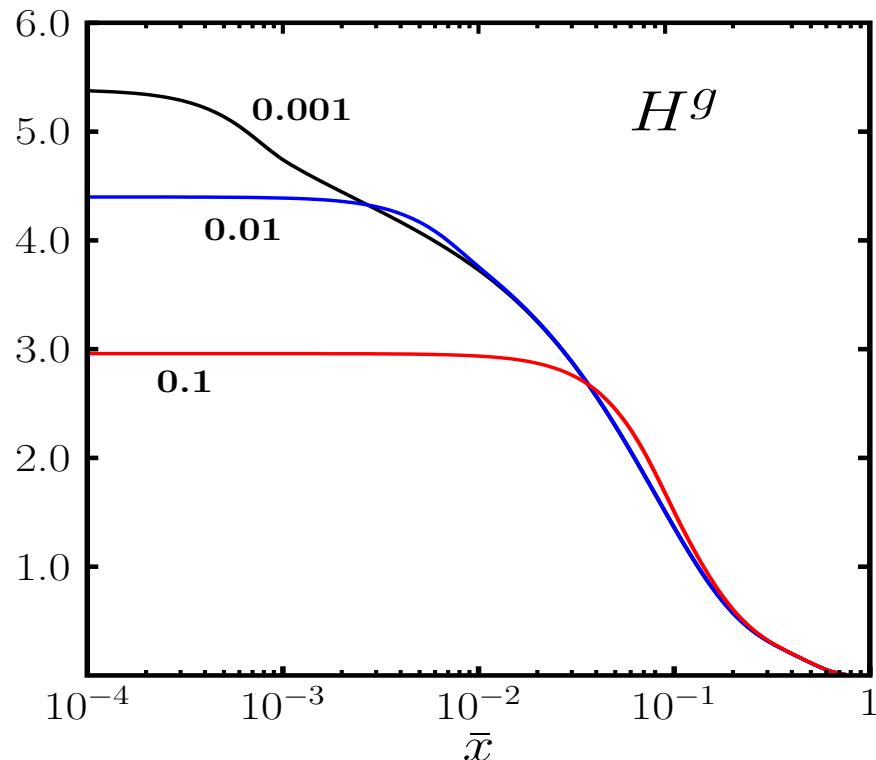
$$\alpha'_g \simeq 0.15 \text{GeV}^{-2}$$

$$\delta_{sea} = \alpha_P(0) = 1 + \delta_g$$

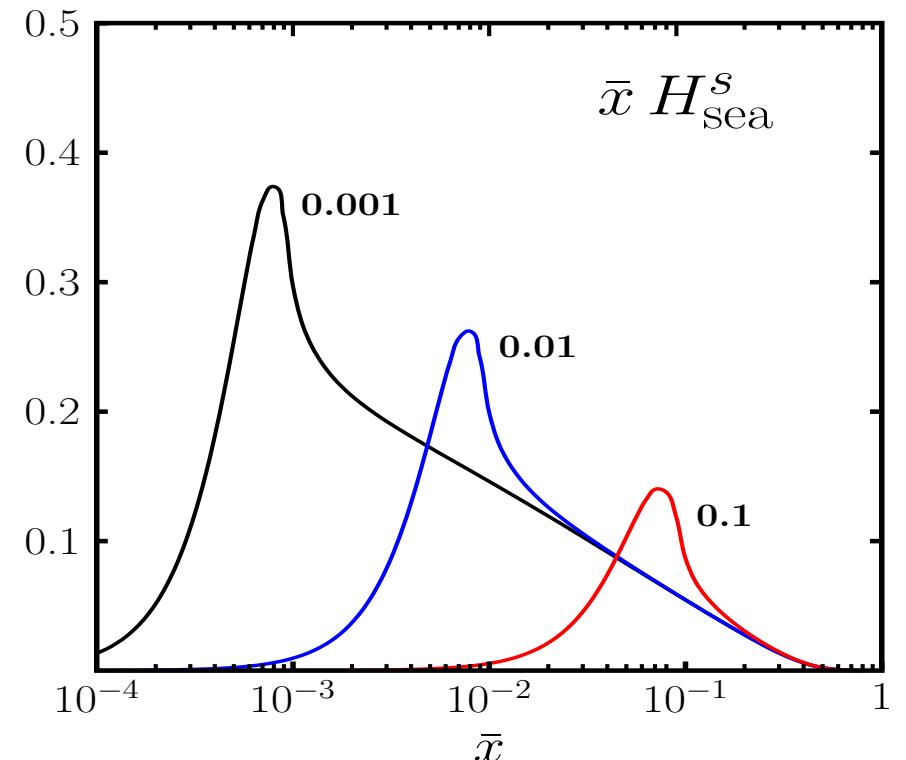
$$\delta_{val} = \alpha_{val}(0) \sim 0.48; \alpha'_{val} = 0.9 \text{GeV}^{-2}$$

$\sigma_L \sim W^{4\delta_g(Q^2)}$ —High energies —HERA

★ Results for gluon and sea GPDs - CTEQ6 parameterization of PDFs (n=2)



Model results for the H^g GPD at $t = 0$ and $Q^2 = 4\text{GeV}^2$. Lines- for $\xi = 10^{-3}, 10^{-2}, 10^{-1}$.



Model results for the xH^s GPD at $t = 0$ and $Q^2 = 4\text{GeV}^2$ for $\xi = 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}$.

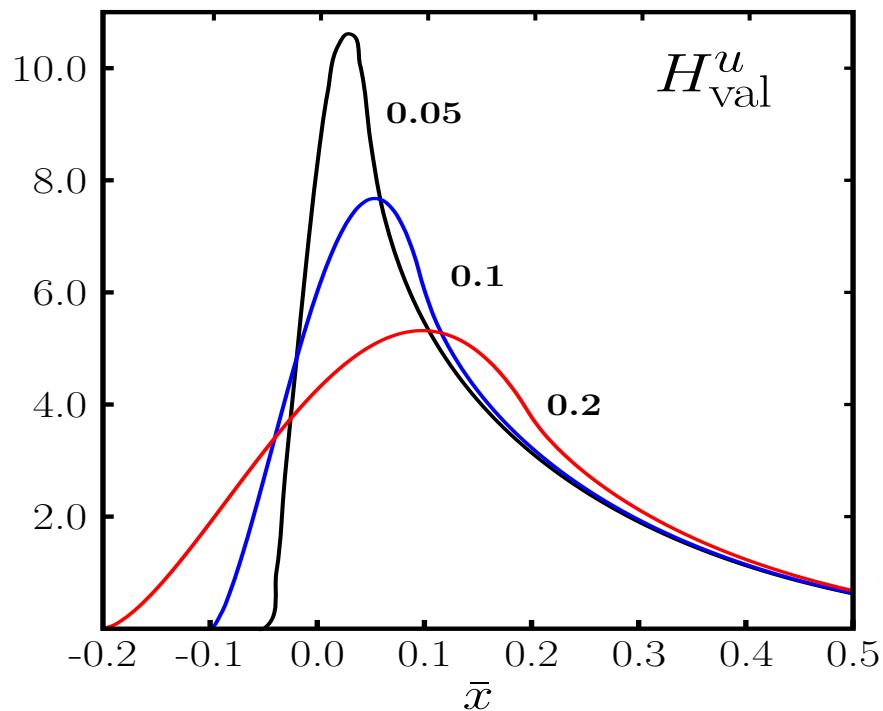
Simple model for u and d sea .

$$H_{sea}^u = H_{sea}^d = \kappa_s H_{sea}^s$$

The flavor symmetry breaking factor is from the fit if CTEQ6M PDFs

$$\kappa_s = 1 + 0.68/(1 + 0.52 \ln(Q^2/Q_0^2))$$

Valence quark- (n=1) .



H_{val}^u GPD at $t = 0$ and $Q^2 = 4\text{GeV}^2$

Modified PA for vector meson production

We calculate the $L \rightarrow L$, $T \rightarrow T$ and $T \rightarrow L$ amplitudes – important in analyses of spin observables.

★ Wave function

The k - dependent wave function is used

$$\hat{\Psi}_V = \hat{\Psi}_V^0 + \hat{\Psi}_V^1.$$

$$\hat{\Psi}_V^0 = (\not{V} + m_V) \not{\epsilon}_V \phi_V(k, \tau).$$

$$\hat{\Psi}_V^1 = [\frac{2}{M_V} \not{V} \not{\epsilon}_V \not{K} - \frac{2}{M_V} (\not{V} - m_V)(\epsilon_V \cdot K)] \phi'_V(k, \tau).$$

J. Bolz, J. Körner and P. Kroll, 1994

- $\hat{\Psi}_V^0$ - leading twist wave function -L polarized meson
- $\hat{\Psi}_V^1$ - higher twist wave function -T polarized meson
- V is a vector meson momentum and m_V is its mass
- ϵ_V is a meson polarization vector and K is a quark transverse momentum
- M_V is a scale in the $\hat{\Psi}_V^1$. We use $M_V = m_V/2$

★ Structure of the amplitudes of vector meson production

$$\begin{aligned}
& \gamma_\mu^* \rightarrow V'_\mu \text{ quark \& gluons contributions} \\
\mathcal{M}_{\mu'+,\mu+} &= \sum_a e_a B_a^V \\
&\times \left\{ C_F \int_{-1}^1 d\bar{x} H^a(\bar{x}, \xi, t) F_{\mu',\mu}^a(\bar{x}, \xi) \left[\frac{1}{\bar{x} + \xi - i\hat{\varepsilon}} + \frac{1}{\bar{x} - \xi + i\hat{\varepsilon}} \right] \right. \\
&\left. + 2(1 + \xi) \int_0^1 d\bar{x} \frac{H^g(\bar{x}, \xi, t) F_{\mu',\mu}^g(\bar{x}, \xi)}{(\bar{x} + \xi)(\bar{x} - \xi + i\hat{\varepsilon})} \right\}. \tag{5}
\end{aligned}$$

The hard scattering amplitudes-transverse quark motion

$$F_{\mu',\mu}^{a(g)}(\bar{x}, \xi) = \frac{8\pi\alpha_s(\mu_R)}{\sqrt{2N_c}} \int_0^1 d\tau \int \frac{d^2\mathbf{k}_\perp}{16\pi^3} \phi_{V\mu'}(\tau, k_\perp^2) f_{\mu',\mu}^{a(g)}(\mathbf{k}_\perp, \bar{x}, \xi, \tau) D. \tag{6}$$

$$\phi_V(\mathbf{k}_\perp, \tau) = 8\pi^2 \sqrt{2N_c} f_V a_V^2 \exp \left[-a_V^2 \frac{\mathbf{k}_\perp^2}{\tau \bar{\tau}} \right]. \tag{7}$$

$$f_{\rho L} = 0.209 \text{GeV}, \quad a_{\rho L} = 0.75 \text{GeV}^{-1} \quad f_{\phi L} = 0.221 \text{GeV}, \quad a_{\rho L} = 0.7 \text{GeV}^{-1}$$

$D \sim \frac{1}{(k_\perp^2 + \tau Q^2) \dots}$ - contains power corrections $\sim k_\perp^2/Q^2$.

The full amplitudes of vector meson lepto production (leading twist)

$$\begin{aligned}
 \mathcal{M}_\phi &= e \frac{8\pi\alpha_s}{N_c Q} f_\phi \langle 1/\tau \rangle_\phi \frac{-1}{3} \left\{ \frac{1}{2\xi} I_g + C_F I_{\text{sea}} \right\}, \\
 \mathcal{M}_\rho &= e \frac{8\pi\alpha_s}{N_c Q} f_\rho \langle 1/\tau \rangle_\rho \frac{1}{\sqrt{2}} \left\{ \frac{1}{2\xi} I_g + \kappa_s C_F I_{\text{sea}} + \frac{1}{3} C_F I_{\text{val}}^u + \frac{1}{6} C_F I_{\text{val}}^d \right\}, \\
 \mathcal{M}_\omega &= e \frac{8\pi\alpha_s}{N_c Q} f_\omega \langle 1/\tau \rangle_\omega \frac{1}{3\sqrt{2}} \left\{ \frac{1}{2\xi} I_g + \kappa_s C_F I_{\text{sea}} + C_F I_{\text{val}}^u - \frac{1}{2} C_F I_{\text{val}}^d \right\}
 \end{aligned} \tag{8}$$

The integrals:

$$\begin{aligned}
 I_g &= 2 \int_0^1 d\bar{x} \frac{\xi H^g(\bar{x}, \xi, t')}{(\bar{x} + \xi)(\bar{x} - \xi + i\epsilon)}, \\
 I_{\text{sea}} &= 2 \int_0^1 d\bar{x} \frac{\bar{x} H_{\text{sea}}^s(\bar{x}, \xi, t')}{(\bar{x} + \xi)(\bar{x} - \xi + i\epsilon)}, \\
 I_{\text{val}}^a &= 2 \int_{-\xi}^1 d\bar{x} \frac{\bar{x} H_{\text{val}}^a(\bar{x}, \xi, t')}{(\bar{x} + \xi)(\bar{x} - \xi + i\epsilon)}.
 \end{aligned} \tag{9}$$

Different combinations of valence quark GPDs. **Valence quark contribution** $u^{val} \sim 2d^{val}$

$$\begin{aligned}
 \phi: & \text{ val}=0; \\
 \rho: & \sim 5/6 d^{val}; \\
 \omega: & \sim 9/6 d^{val}
 \end{aligned}$$

The impact parameter space

In calculation

- We consider **Sudakov** suppression of large quark-antiquark separations where **factorization breaks down**. These effects **suppress contributions from the end-point regions** too.
- Since the **Sudakov** factor is exponentiate in the impact parameter space- we have to work in this space.

The gluonic contributions to the helicity amplitudes for vector-meson electroproduction read

$$\begin{aligned}\mathcal{M}_{\mu'+,\mu+} &= \mathcal{M}_{\mu'+,\mu+}^H + \mathcal{M}_{\mu'+,\mu+}^{\tilde{H}}, \\ \mathcal{M}_{\mu'+,\mu+}^H &= \frac{e}{\sqrt{2N_c}} \mathcal{C}_V \int d\bar{x}d\tau f_{\mu'\mu}^+ H^g(\bar{x}, \xi, t) \\ &\times \int d^2\mathbf{b} \hat{\Phi}_{V\mu'}(\tau, b^2) \hat{D}(\tau, Q, b) \alpha_s(\mu_R) \exp[-S(\tau, b, Q)].\end{aligned}\tag{10}$$

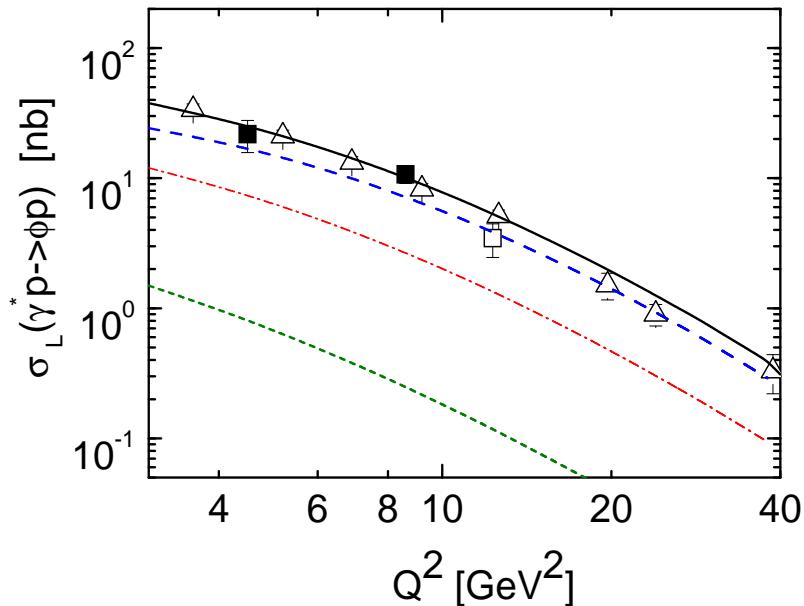
(11)

Similar- for \tilde{H}

The renormalization scale μ_R is taken to be the largest mass scale appearing in the hard scattering amplitude, i.e. $\mu_R = \max(\tau Q, \bar{\tau} Q, 1/b)$.

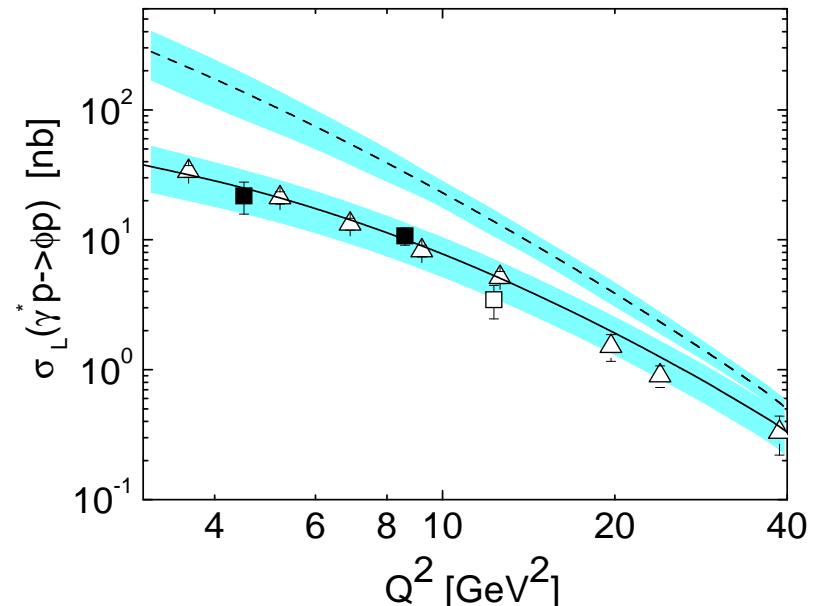
LL amplitudes and cross sections

Q^2 dependence of longitudinal cross sections of ϕ production at $W = 75\text{GeV}$. H1 and ZEUS data.



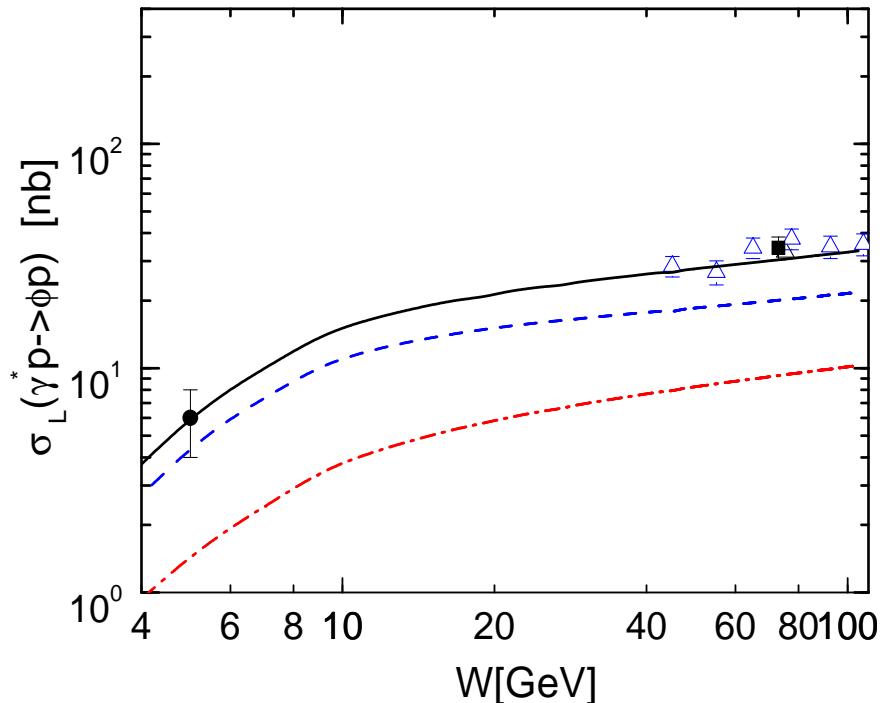
Full line cross section, dashed blue-gluon, dashed-dot red - gluon-strange interference, green- strange contribution.

- ★ The gluon-strange quark interferences < 40% than the gluon contribution at HERA energies .
- ★ Power corrections $\sim k_\perp^2/Q^2$ in propagators are important at low Q^2 - $1/10$ suppression at $Q^2 \sim 3\text{GeV}^2$



Cross sections with errors from uncertainty in parton distributions. Dashed line- leading twist result.

Energy dependence of longitudinal cross sections of ϕ production.



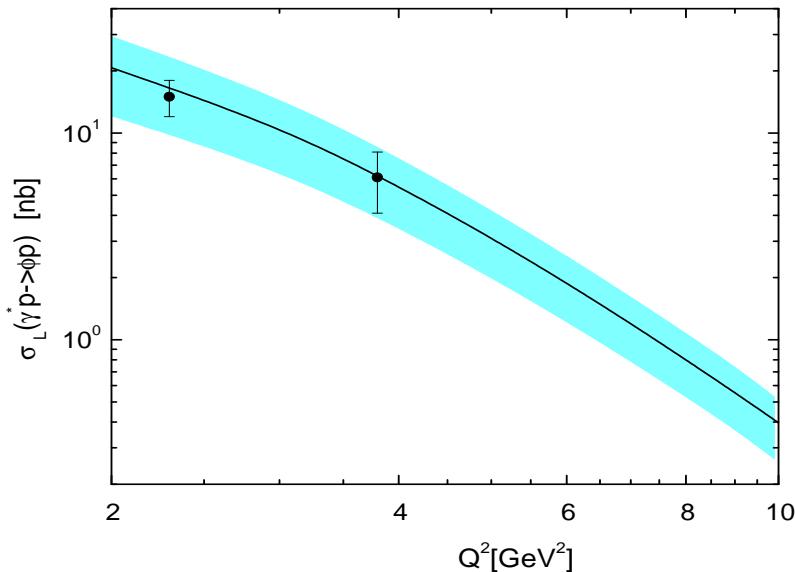
Amplitudes contribution at $Q^2 = 3.8 \text{ GeV}^2$. Full line cross section, dashed blue- gluon contribution, dashed-dot- red - gluon-strange interference.

The longitudinal cross section at HERA (Δ) are recalculated from $\gamma^* P$ cross section. HERMES-preliminary.

At HERMES energies.

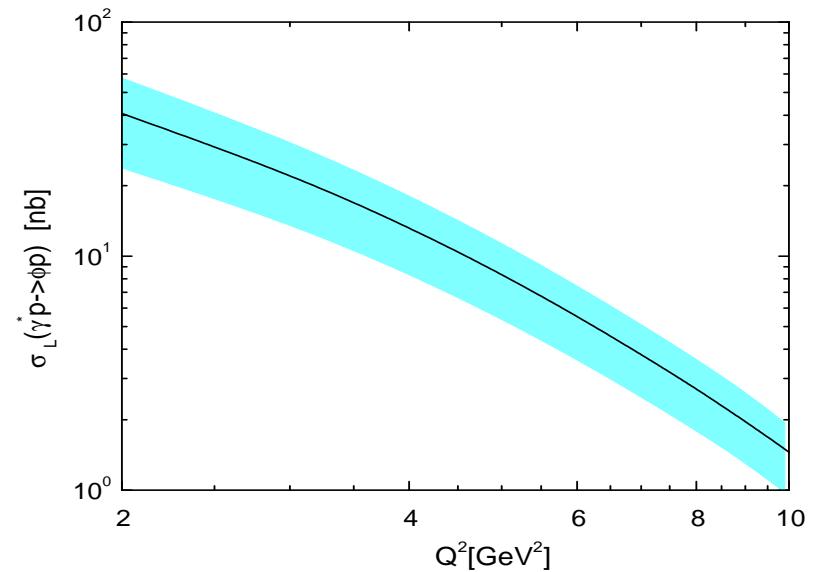
- ★ The contribution of gluon real part is essential.
 - ★ The gluon-strange quark interference is about 40% with respect to gluon contribution.
- At COMPASS energies contribution of gluon real part is about gluon-strange interference.
- At higher energies gluon Re part contribution is negligible

Q^2 dependence of longitudinal cross sections of ϕ production.



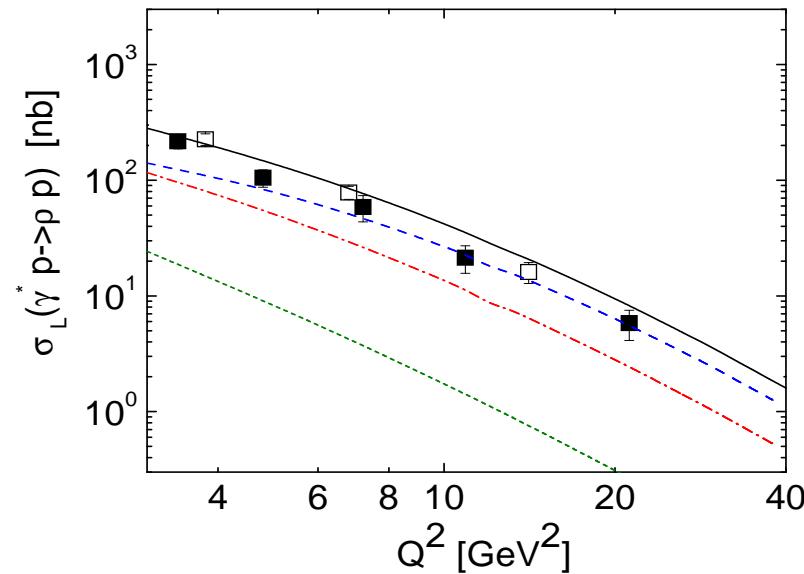
At HERMES energy $W = 5\text{GeV}$, full circle -preliminary HERMES data

- HERMES data are described fine.
- Predictions for COMPASS should be fine too.

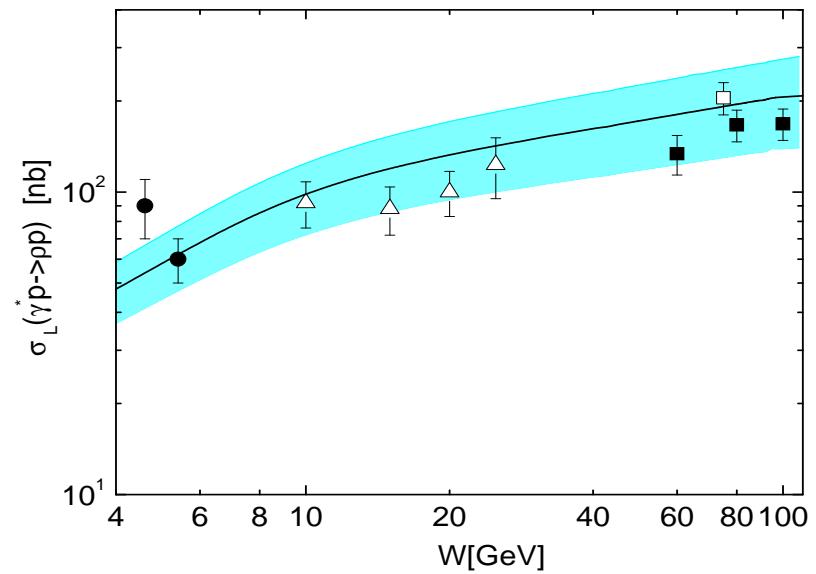


Our predictions for COMPASS energy $W = 10\text{GeV}$

Cross section for ρ production for our gluon and quark-sea + valence distributions

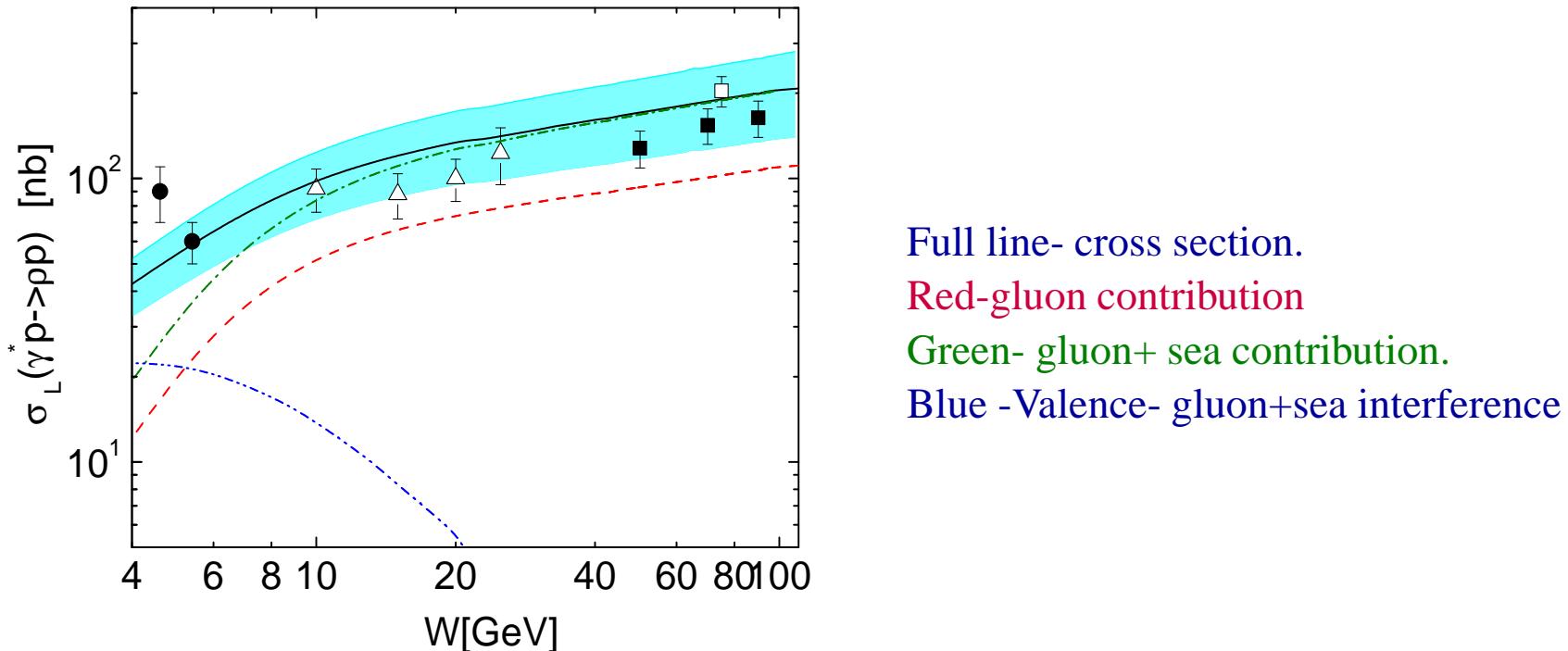


Longitudinal cross sections of ρ production at $W = 75\text{GeV}$ with errors from uncertainty in parton distributions



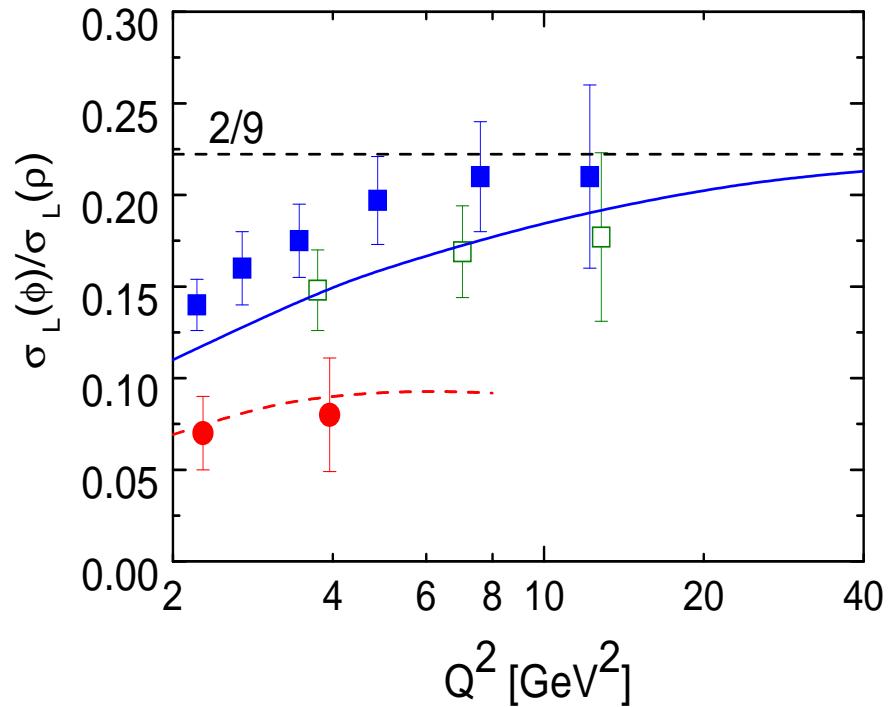
Our results for energy dependence at $Q^2 = 4\text{GeV}^2$. Data are from H1, ZEUS, E665 and HERMES

Contributions to the ρ production cross section.



At HERMES energies we have valence quarks contribution which decrease rapidly at energies higher 5GeV^2 .

Ratio of cross sections of ϕ/ρ production.



Show strong violation of $\sigma_\phi/\sigma_\rho = 2/9$ at HERA energies and low Q^2 is caused by the flavor symmetry breaking between \bar{u} and \bar{s}

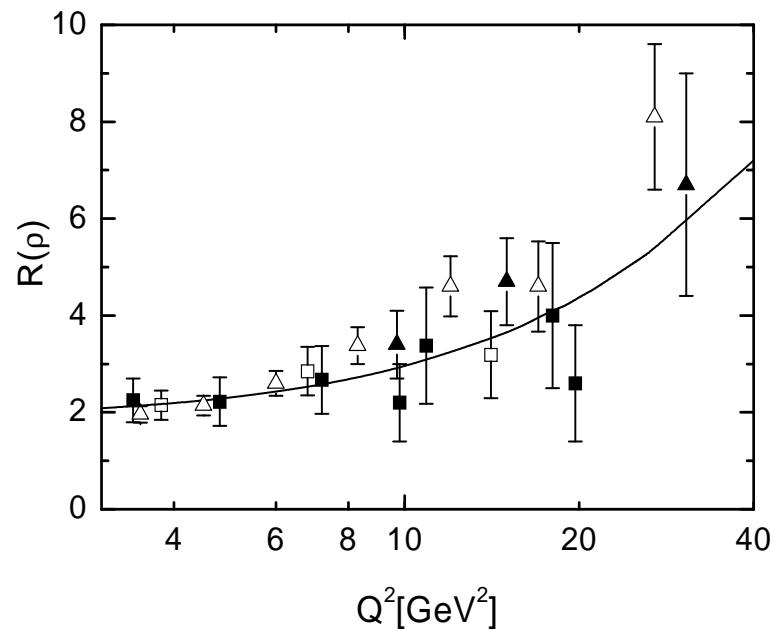
$$\bar{u}(x) = \bar{d}(x) = \kappa_s s(x)$$

Q^2 dependence of σ_ϕ/σ_ρ at HERA is determined by κ_s factor completely.

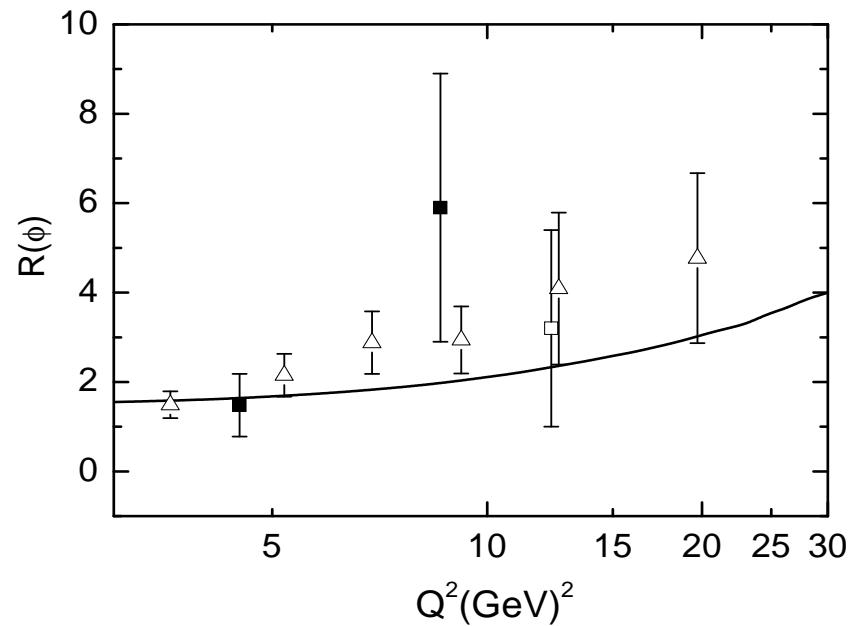
At **HERMES** energies we have **valence quarks contribution** which gives additional suppression of σ_ϕ/σ_ρ ratio.

Amplitudes for transversally polarized photons-gluons@small x

$$R(V) = \frac{\sigma_L(\gamma^* p \rightarrow Vp)}{\sigma_T(\gamma^* p \rightarrow Vp)}, \quad (12)$$

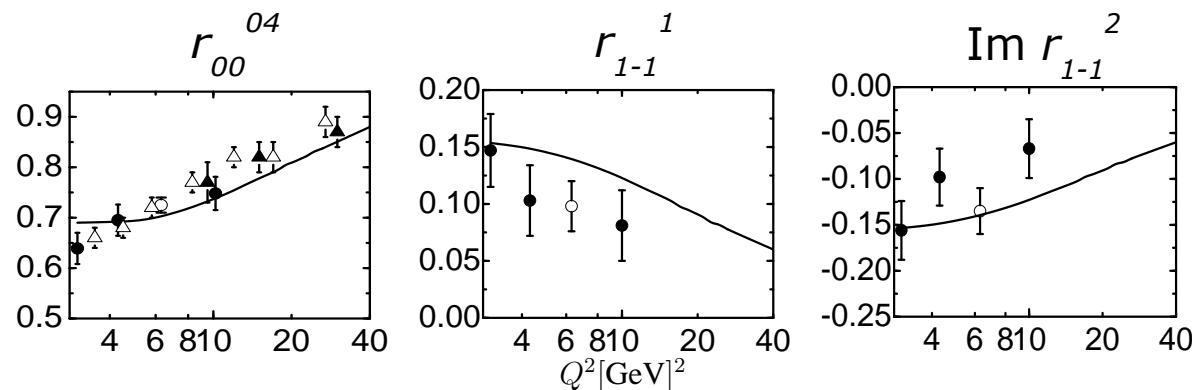


The ratio of longitudinal and transverse cross sections for ρ production versus Q^2 at $W \simeq 75 \text{ GeV}$.

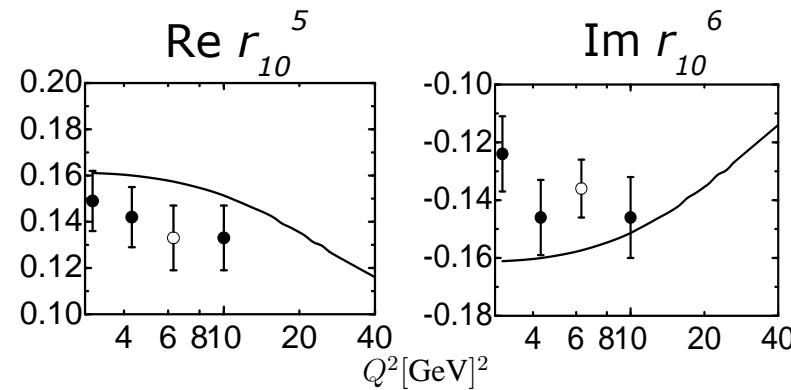


The ratio of longitudinal and transverse cross sections for ϕ production versus Q^2 at $W \simeq 75 \text{ GeV}$.

Spin density matrix elements



The SDME sensitive to LL/TT ratio.



The SDME sensitive to $LL - TT$ interference.

Conclusion

- Modified PA which consider - transverse degrees of freedom and Sudakov suppressions was used to analyse light meson production.
- The GPD approach give reasonable description of cross section and spin observables for light VM production . Power corrections $\sim k_\perp^2/Q^2$ in propagators are extremely important.
- - the gluonic contribution plays an essential role for all energies $W > 5\text{GeV}$ in vector meson electroproduction.
-the gluon-sea interference is about 30(50)% for ϕ (ρ) production.
- -Valence quarks contribute only for $W < 10\text{GeV}$:
 ρ cross section: at HERMES energies valence quarks - about 40% .
at COMPASS about 10% .
To $\omega \sim 65\%$ at HERMES.
- Analyses of SDME -information about $\gamma \rightarrow V$ hard amplitudes.
- HERMES and COMPASS experimental results at $Q^2 > 3\text{GeV}^2$ on SDME are extremely important .
- Vector meson electroproduction-can be an excellent object to study GPDs .