Electroproduction of light vector mesons

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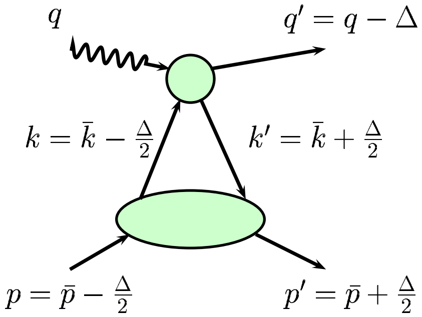
- Factorization of Vector meson leptoproduction .
- Model for GPDs.
- Modified PA for hard scattering amplitude
  - transverse degrees of freedom in wave function, hard subprocess ,
  -Sudakov suppression .
- Cross section in a wide energy range $5\text{GeV} < W < 75\text{GeV}$.
- SDME from HERMES, COMPASS to 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



$$k = ((\overline{x} + \xi)p_+, ...)$$

$$k' = ((\overline{x} - \xi)p_+, ...)$$

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

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

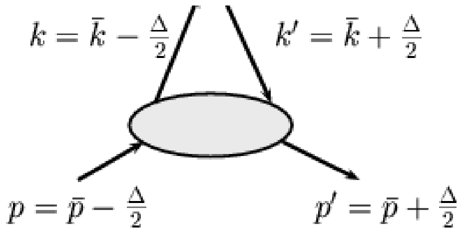
The process of VM production

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

Generalized Parton Distributions

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

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



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

$$H^g(\overline{x},0,0) = \overline{x}\,g(\overline{x}); \qquad \widetilde{H}^g(\overline{x},0,0) = \overline{x}\,\Delta g(\overline{x}) \tag{1}$$

Distributions $E^g(\overline{x},\xi,t)$, $(\tilde{E})$ 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

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

⋆ Gluon contribution (n=2) function.

$$h_g(\beta,0) \;= |\beta| g(|\beta|) \tag{3}$$

$$\Downarrow$$

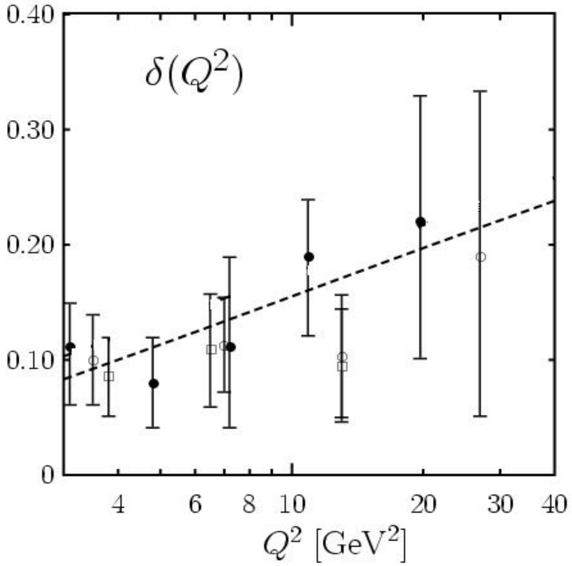
$$H^g(\overline{x},\xi,t) \;=\; \Big[\Theta(0\le\overline{x}\le\xi)\int_{\frac{\overline{x}-\xi}{1+\xi}}^{\frac{\overline{x}+\xi}{1+\xi}} d\beta + \Theta(\xi\le\overline{x}\le 1)\int_{\frac{\overline{x}-\xi}{1-\xi}}^{\frac{\overline{x}+\xi}{1+\xi}} d\beta\Big]\frac{\beta}{\xi}\, f(\beta,\alpha=\frac{\overline{x}-\beta}{\xi})$$

⋆ $h^q_{sea}(\beta,0) \;= g(|\beta|)\,\mathrm{sign}(\beta)$ - sea quark contribution (n=2).
– Similar form for sea quark but integral $\Theta(0\le\overline{x}\le\xi)$ is different .

⋆ $h^q_{val}(\beta,0) \;= g(|\beta|)\,\Theta(\beta)$ –valence contribution (n=1)

PDF t-dependence —Regge paramererization.

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



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

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

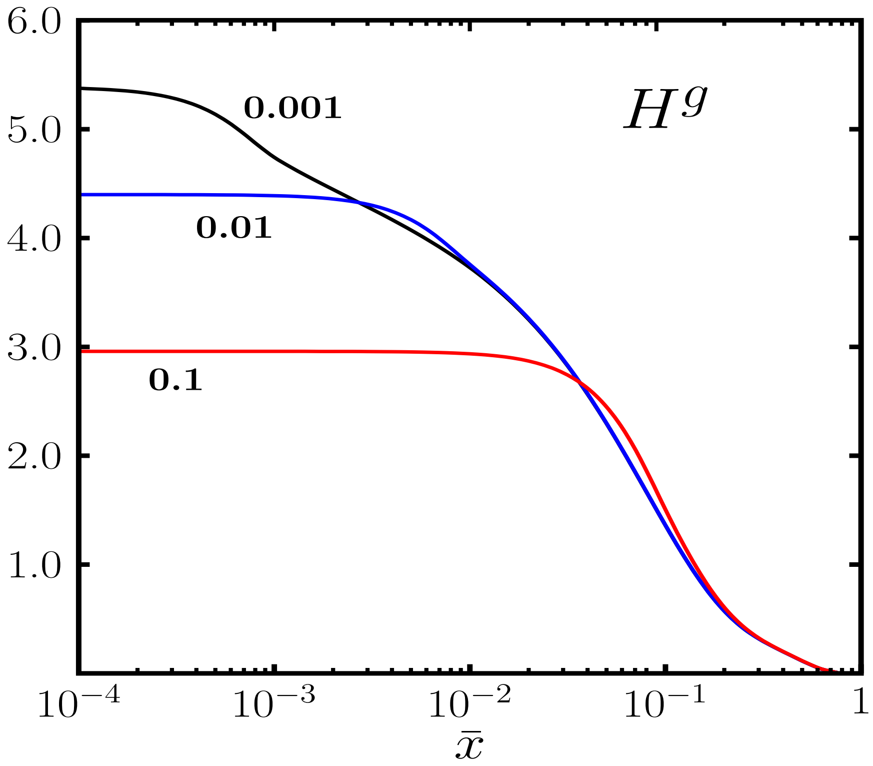
$$\alpha_g' \simeq 0.15\mathrm{GeV}^{-2}$$

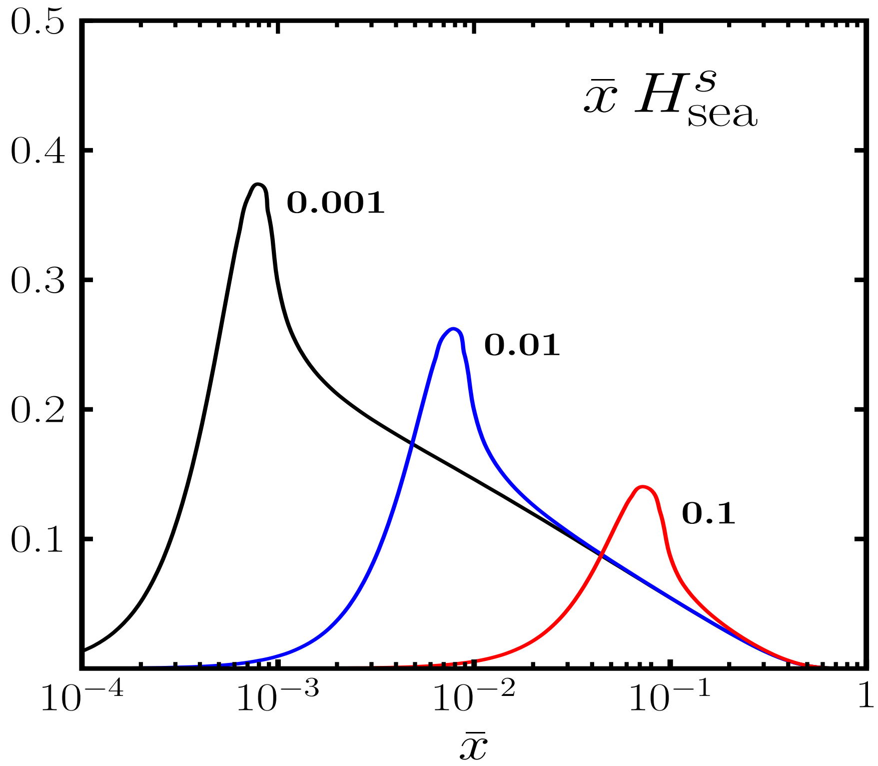
$$\delta_{sea} = \alpha_P(0) = 1 + \delta_g$$

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

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

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





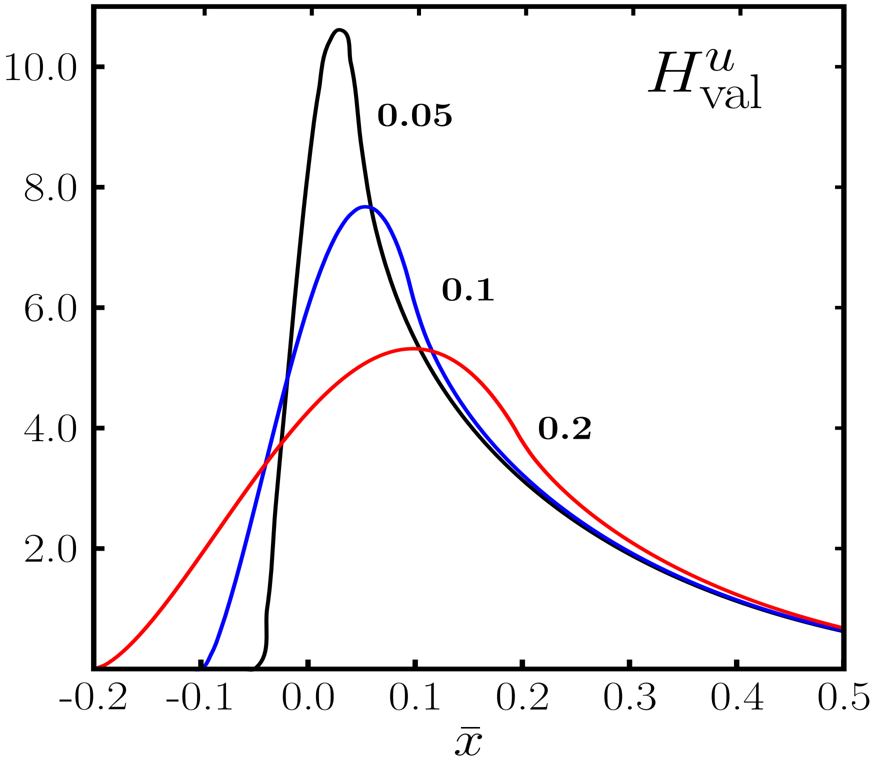
Model results for the H^g GPD at $t = 0$ and $Q^2 = 4\text{GeV}^2$. Lines- for $\xi = 10^{-3}, 10^{-2}, 10^{-1}$.

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

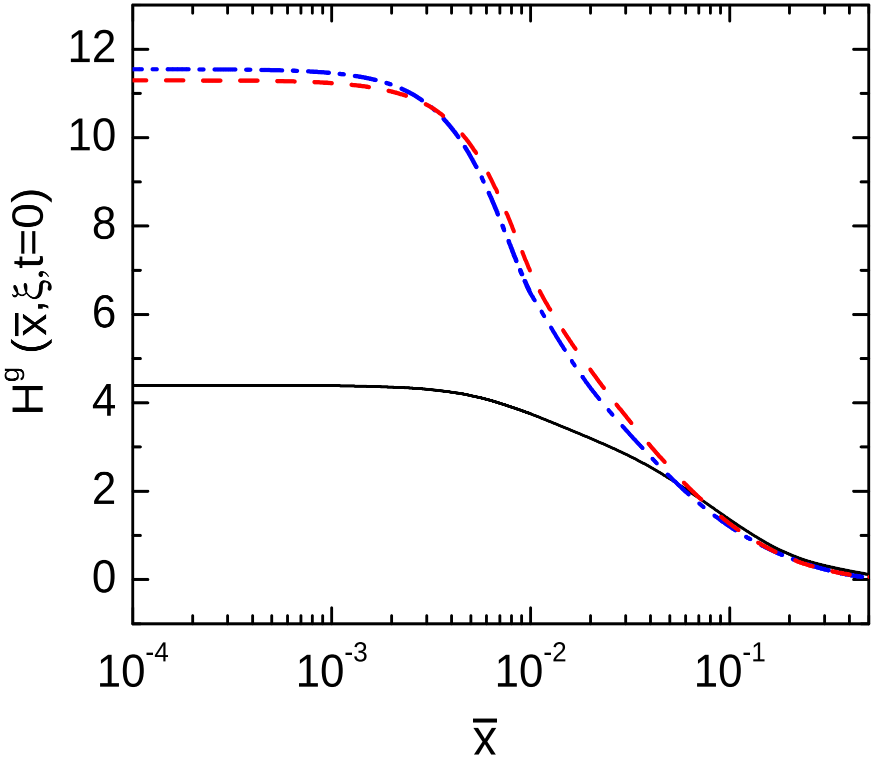
Simple model for u and d sea . Q^2 evolution of GPD

$$H^u_{sea} = H^d_{sea} = \kappa_s \, H^s_{sea}$$

The flavor symmetry breaking factor is from the PDFs fit $\kappa_s = 1 + 0.68/(1 + 0.52 \ln(Q^2/Q_0^2))$



H^u_{val} GPD at $t = 0$and $Q^2 = 4\text{GeV}^2$. Lines- for $\xi = 0.05, 0.1, 0.2$.



Evolution of gluon GPD for $\xi = 0.01$.
Black line- $Q^2 = 4\text{GeV}^2$; $Q^2 = 40\text{GeV}^2$
blue- Vinnikov code , red- our model

Modified PA for vector meson production

We calculate the $L \to L$ and $T \to T$ amplitudes – important in analyses of spin observales.

⋆ **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 $M_V = m_V/2$

$\star$ Structure of the amplitudes of vector meson production

$\gamma^*_\mu \to V'_\mu$ quark & gluons contributions

$$\begin{aligned}\mathcal{M}_{\mu'+,\mu+} &= \sum_a e_a\, B_a^V \\ &\times \Big\{ C_F \int_{-1}^{1} d\overline{x}\, H^a(\overline{x},\xi,t)\, F^a_{\mu',\mu}(\overline{x},\xi) \left[\frac{1}{\overline{x}+\xi-i\hat{\varepsilon}} + \frac{1}{\overline{x}-\xi+i\hat{\varepsilon}}\right] \\ &+ 2\,(1+\xi) \int_0^1 d\overline{x}\, \frac{H^g(\overline{x},\xi,t)\, F^g_{\mu',\mu}(\overline{x},\xi\,)}{(\overline{x}+\xi)(\overline{x}-\xi+i\hat{\varepsilon})} \Big\}\,. \end{aligned} \tag{5}$$

The hard scattering amplitudes-transverse quark motion

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

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

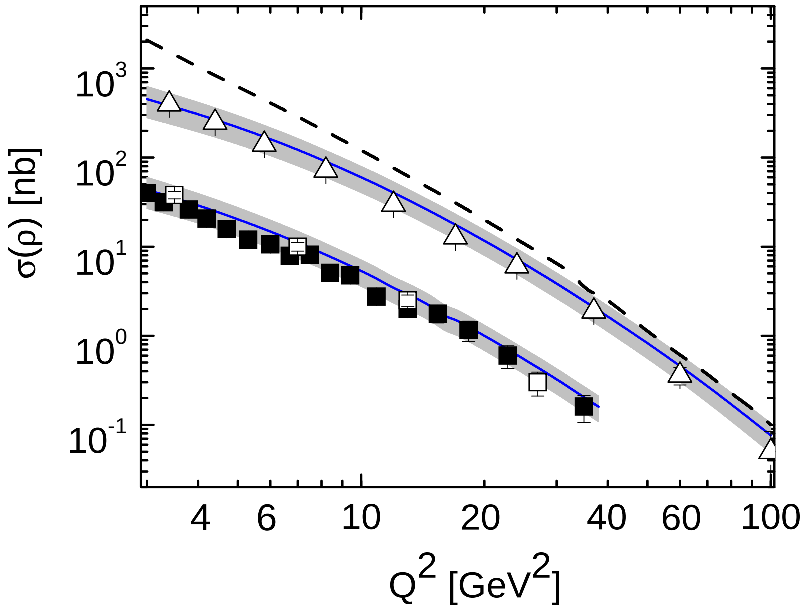
$f_{\rho L} = 0.209\mathbf{GeV},\ a_{\rho L} = 0.75\mathbf{GeV}^{-1}$ $\quad f_{\phi L} = 0.221\mathbf{GeV},\ a_{\rho L} = 0.7\mathbf{GeV}^{-1}$

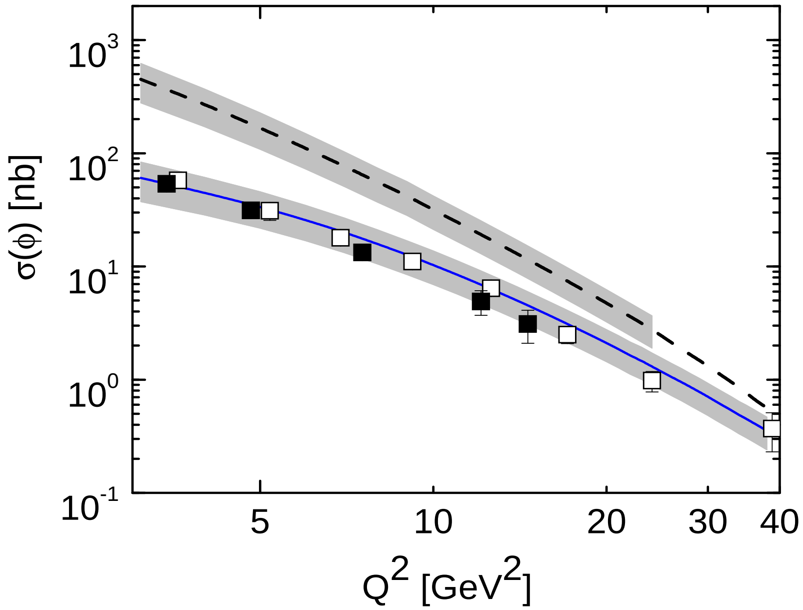
$f_{\rho L} = 0.167\mathbf{GeV},\ a_{\rho L} = 1.0\mathbf{GeV}^{-1}$ $\quad f_{\phi L} = 0.177\mathbf{GeV},\ a_{\rho L} = 0.95\mathbf{GeV}^{-1}$

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

Cross sections of VM production

Q^2 dependence of cross sections of ρ andϕ production at $W = 75$GeV. H1 and ZEUS data.



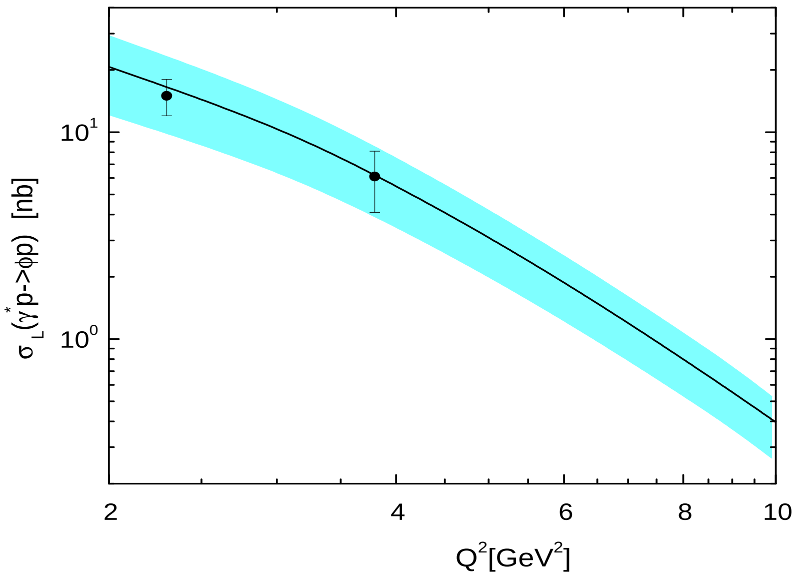


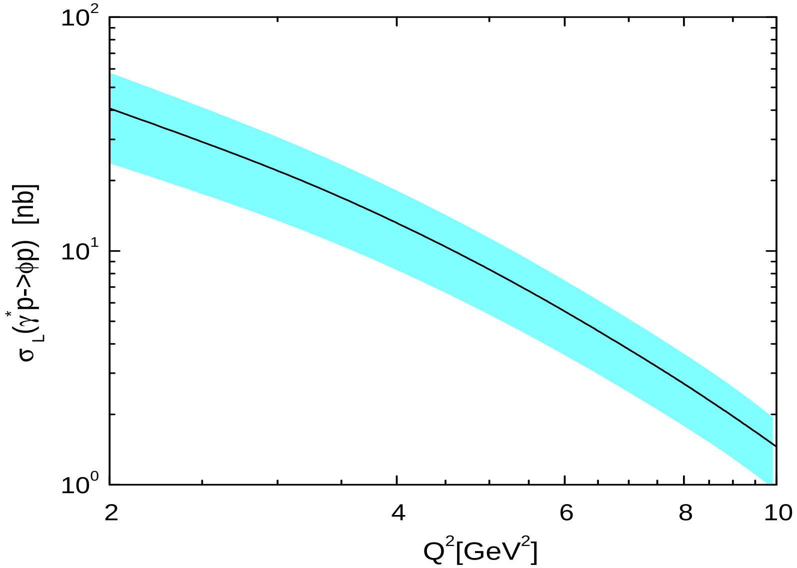
Cross sections of ρ production with errors from uncertainty in parton distributions at $W = 75$GeV/10 and $W = 90$GeV. Dashed line leading twist results.

Cross sections of ϕ production with errors from uncertainty in parton distributions at $W = 75$GeV. Dashed line leading twist results.

$\star$ Power corrections $\sim k_\perp^2/Q^2$ in propagators are important at low Q^2–1/10 suppression at $Q^2 \sim 3$GeV^2

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



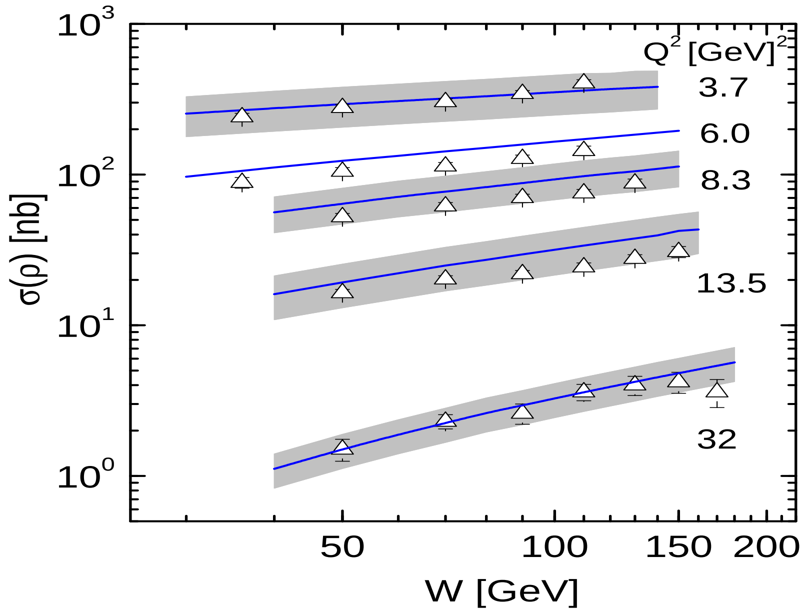


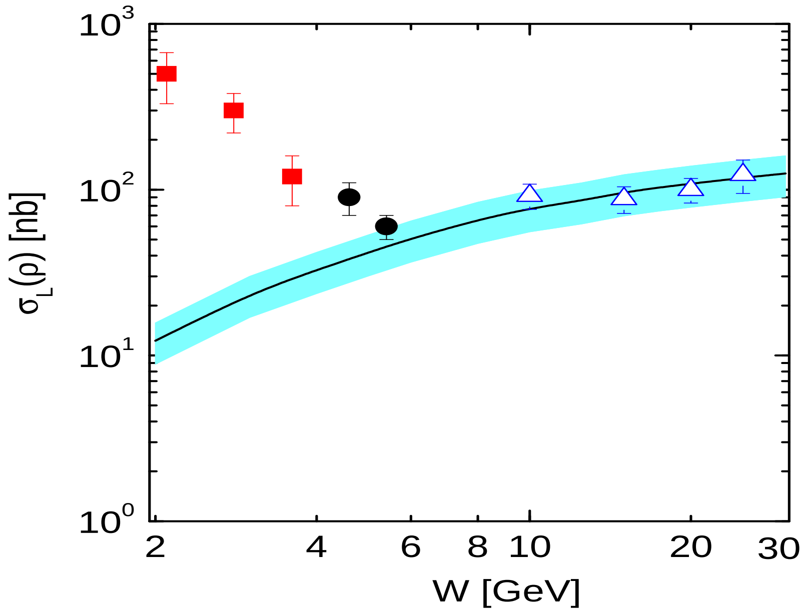
At HERMES energy $W = 5$GeV, full circle -preliminary HERMES data

Our predictions for COMPASS energy $W = 10$GeV

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

W dependence of ρ production cross section





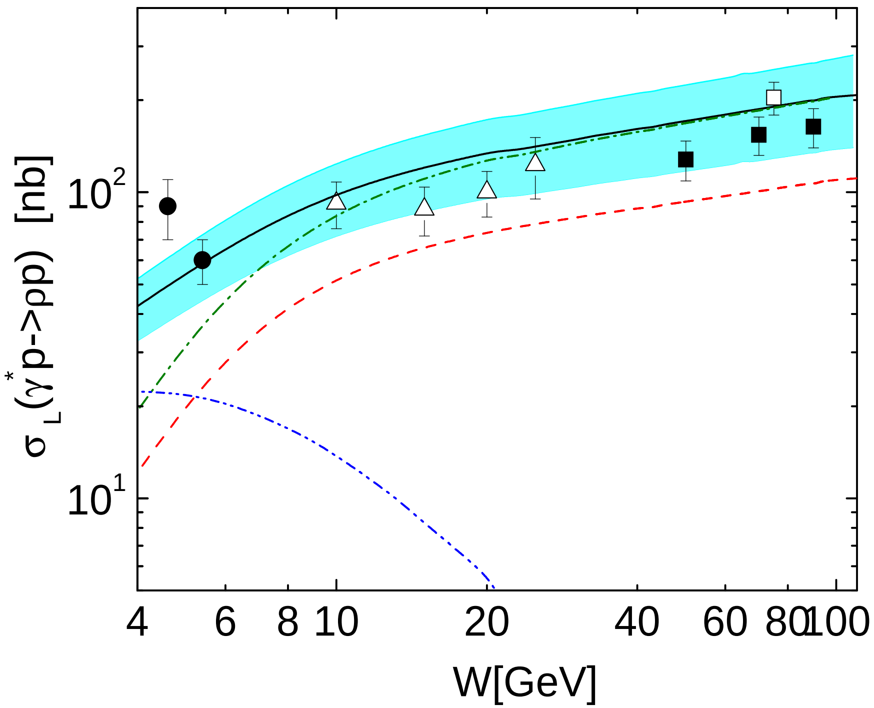
Cross sections of ρ production at different Q^2. New ZEUS data.

Red-squared estimated from CORNEL. Filed circles -HERMES. Open triangles -E665 data. $< Q^2 >= 4\text{GeV}^2$

At $W < 5\text{GeV}$ our results do not describe data. Most probably, observed grows cannot be explained by E –GPD contribution.

Other mechanisms should be important here.

Contributions to the ρ production cross section.



Full line- cross section.

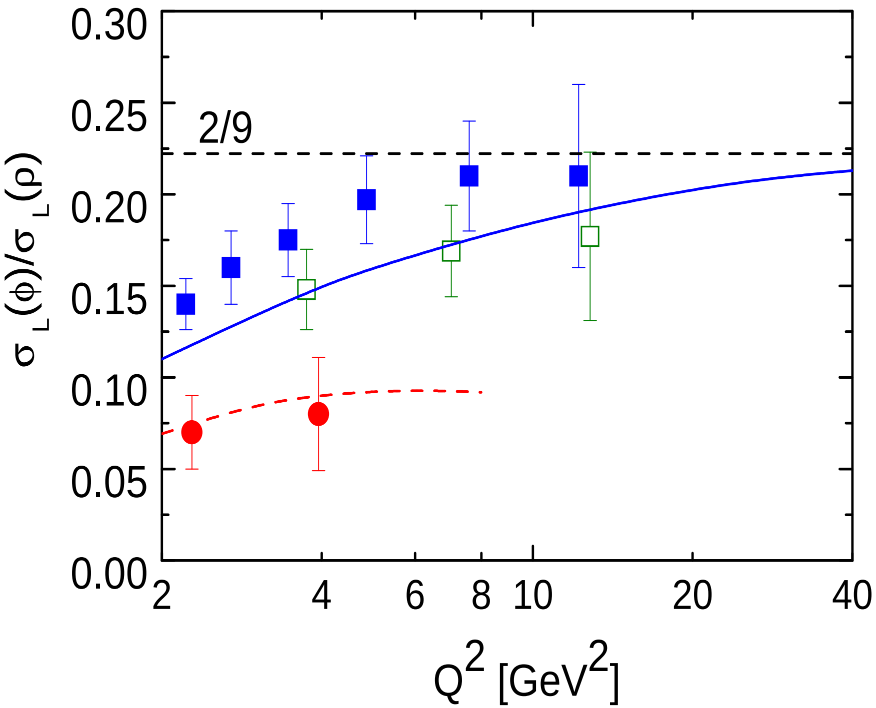
Red-gluon contribution

Green- gluon+ sea contribution.

Blue -Valence- gluon+sea interference

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 $\bar{s}$

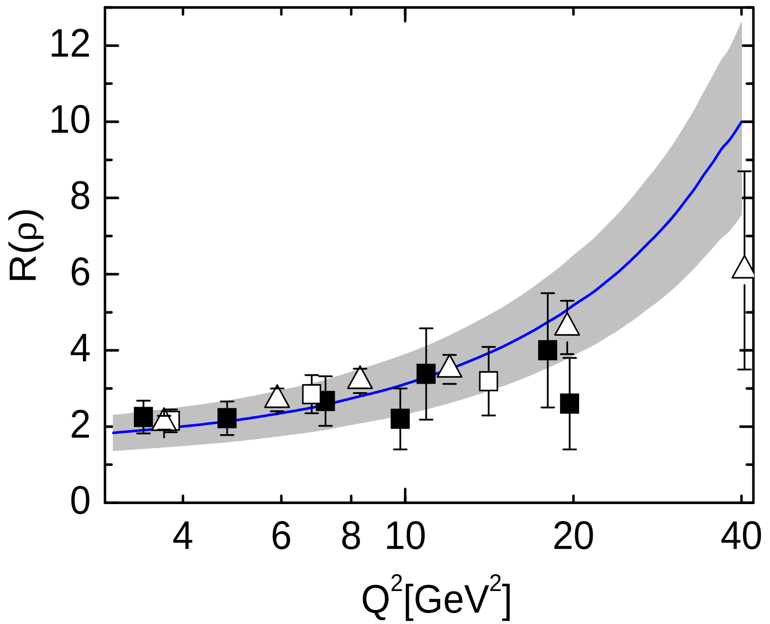
$$\bar{u}(x) = \bar{d}(x) = \kappa_s s(x)$$

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

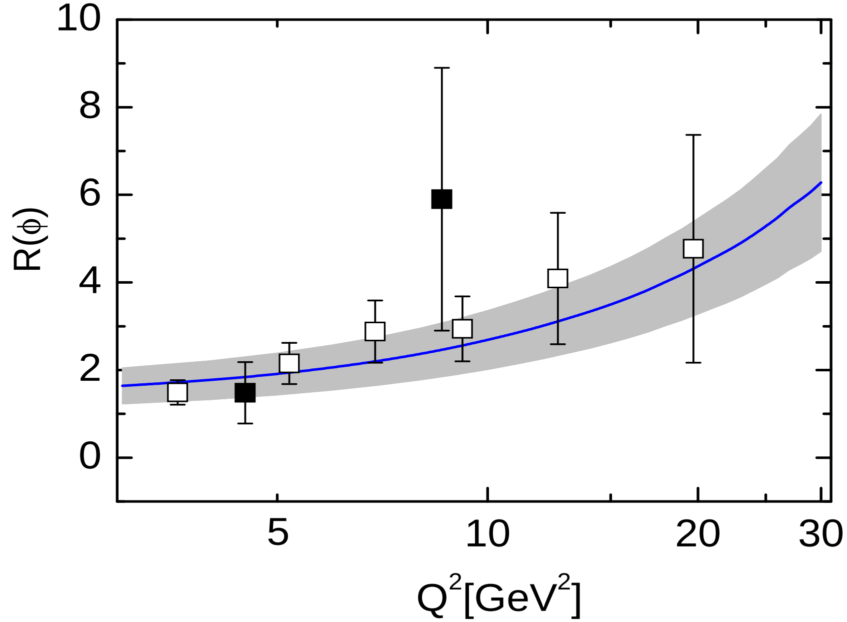
At HERMES energies we have valence quarks contribution which gives additional suppression of σ_ϕ/σ_ρ ratio.

Spin effects

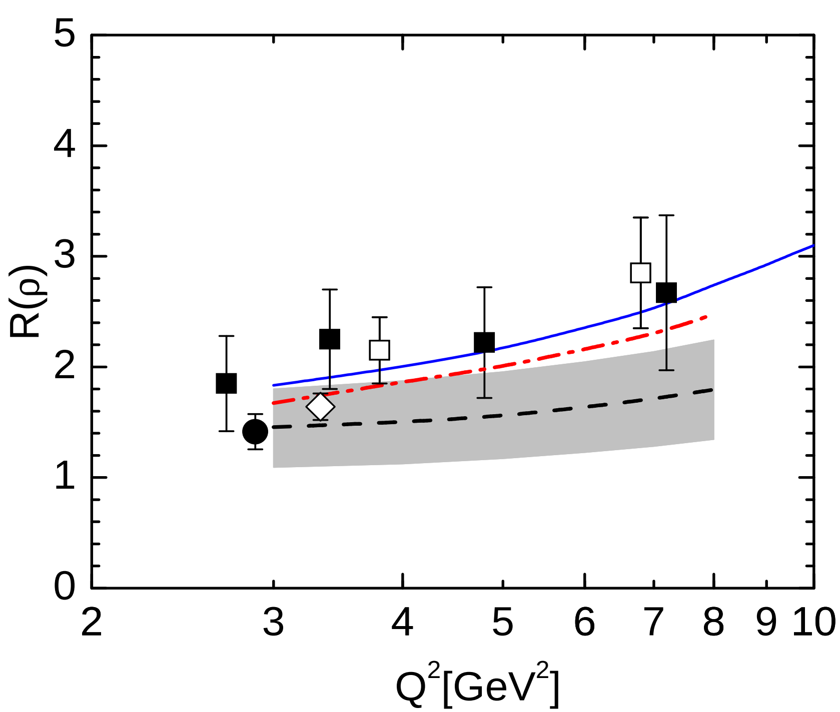
$$R(V) = \frac{\sigma_L(\gamma^* p \to V p)}{\sigma_T(\gamma^* p \to V p)}\,, \tag{8}$$



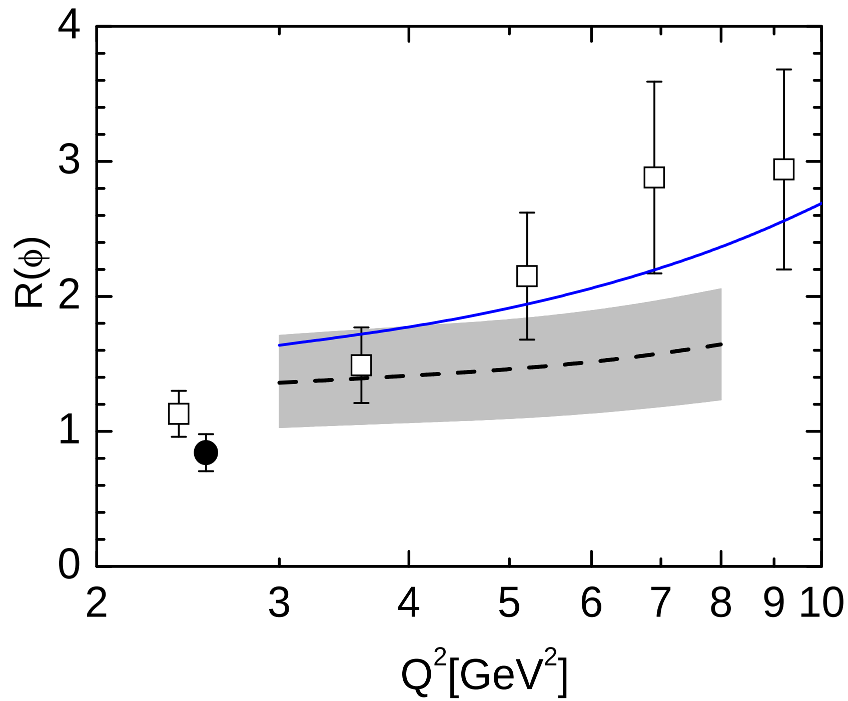
The ratio of longitudinal and transverse cross sections for ρ production versus Q^2 at $W \simeq 75$ GeV.



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



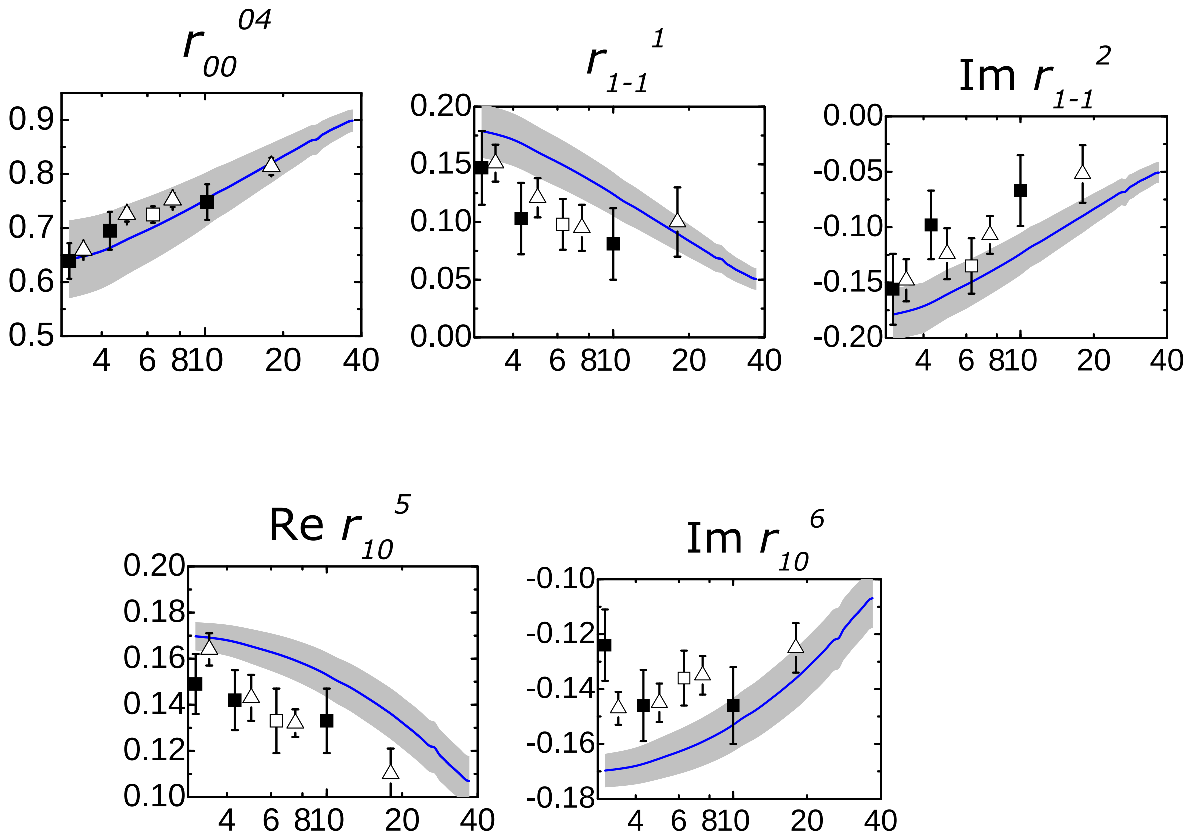
The ratio of longitudinal and transverse cross sections for ρ production at low Q^2 Blue line- HERA , red-COMPASS and black- HERMES.



The ratio of longitudinal and transverse cross sections for ϕ production at low Q^2 Blue line- HERA , black- HERMES.

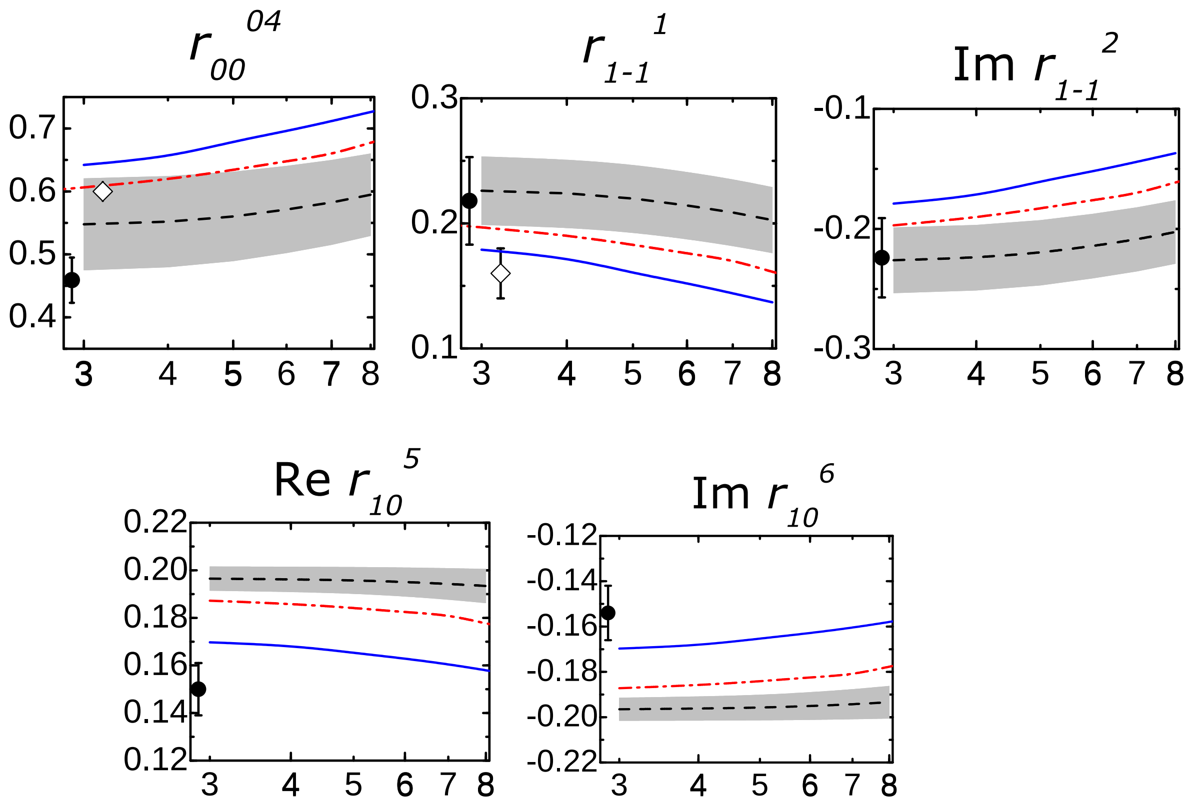
Squares- H1 and ZEUS data, open diamond- COMPASS, filled circles- HERMES.

Spin density matrix elements-ρ production at HERA



The SDME sensitive to LL and TT transitions via Q^2.

Spin density matrix elements-ρ production at energies from HERMES to HERA



The SDME sensitive to LL and TT transitions via Q^2.

Conclusion

- Modified PA which consider - transverse degrees of freedom and Sudakov suppressions was used to analyse light meson production.
- The GPD approach give fine description of cross section and spin observables for light VM production - Q^2 and W dependences . Power corrections $\sim k_\perp^2/Q^2$ in propagators are important.
- -Valence quarks contribute only for $W < 10$GeV: ρ cross section: at HERMES energies valence quarks - about 40%.
- Problems in handbag model found at low energies $W < 5$GeV
- R -ratio for ρ and ϕ production described well. Valence quark provide energy dependence or R at low energies
- Good description of of SDME in the range 5GeV $< W < 75$GeV .
- HERMES and COMPASS experimental results at $Q^2 > 3$GeV^2 on SDME are needed .
- Vector meson electroproduction-can be an excellent object to study GPDs.

  In different energy ranges, information about quark and gluon GPDs can be extracted from the cross section of the vector meson electroproduction.