# *Single-spin azimuthal asymmetry in exclusive electroproduction of $\phi$ and $\omega$ vector mesons on transversely polarized protons*

**W. Augustyniak**

Andrzej Soltan Institute for Nuclear Studies, Warsaw, Poland

on behalf of HERMES Collaboration

witold.augustyniak@fuw.edu.pl

- **Introduction & Motivations**
- **Rudiments**
- **$A_{UT}$ and other observables**
  - **Definition of $A_{UT}$**
  - **Determination of $A_{UT}$ in experiment**
  - **Determination of $A_{UT}$ from GPDs theory**
- **Theoretical models with GPDs used for calculations of $A_{UT}$**
- **Conclusions**

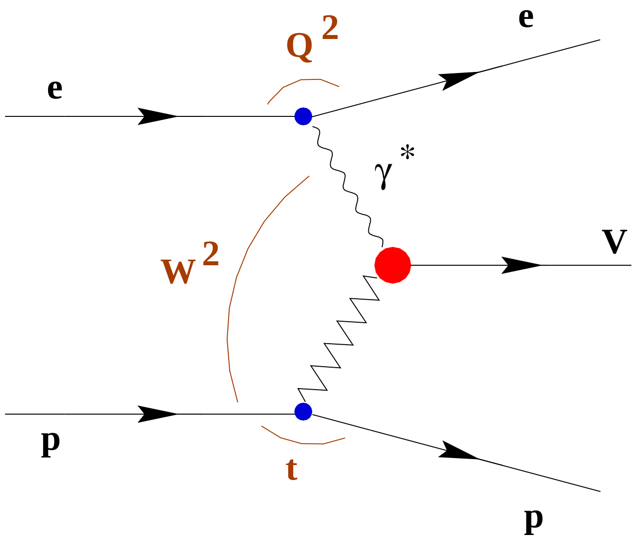
## Introduction

- **The hard exclusive electro-production of $\phi$ and $\omega$ vector mesons was studied with the HERMES spectrometer at the DESY laboratory by scattering 27.6 GeV positron and electron beams off a transversely polarized hydrogen target. The single-spin azimuthal asymmetry with respect to the transverse proton polarization was measured.**
- **The experiment with polarized target gives us the possibility to select interesting for the theory, in our case GPDs, processes. Here, the observation will be focused on the process with proton (target) changing polarization.**
  **In the language of GPDs theory our studies with polarized target are related to the $E(x_B, \xi, Q^2)$ distribution.**

# Introduction & GPDs Motivations

- The transverse target polarization asymmetry $A_{UT}$ for exclusive electroproduction of light vector mesons is related to the imaginary part of an interference term between the two GPDs $H$ and $E$.
- The parton-polarization-independent function $H$ can be extracted from the unpolarized cross section for electroproduction of vector mesons. Therefore, $A_{UT}$ provide an information about $E$.
- The transverse target spin polarization in exclusive VM production has the advantage to be one of rare observables where asymmetry depend on the helicity-flip $E^{q,g}$.
- In some models the total angular momenta carried by $u$ and $d$ quarks enter directly as free parameters in parametrization of $E^q(x, \xi)$.

# $e + p \rightarrow e' + p' + V$: Rudiments



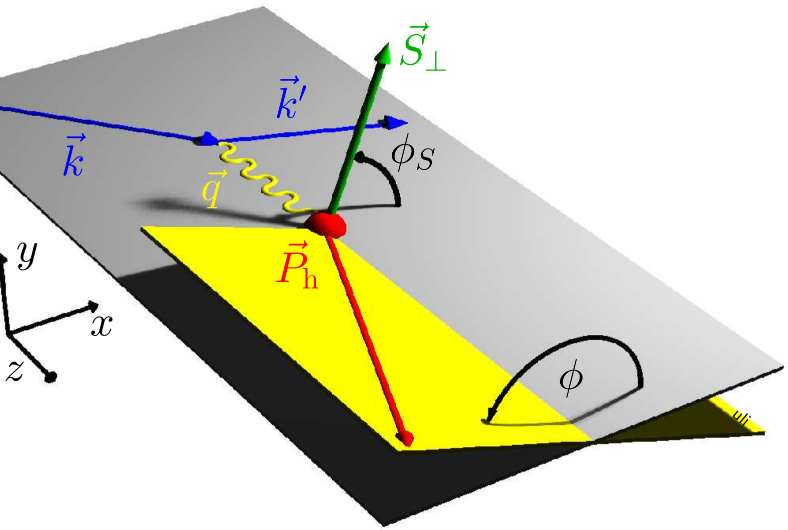

**Kinematics:**

- $\nu$= 5 $\div$ 24 GeV, $< \nu >$ = 13.3 GeV,
- $Q^2$ = 1.0 $\div$ 7.0 GeV$^2$, $< Q^2 >$ = 2.3 GeV$^2$
- W = 3.0 $\div$ 6.5 GeV, $<$ W $>$ = 4.9 GeV,
- $x_{Bj}$ = 0.01 $\div$ 0.35 $< x_{Bj} >$ = 0.07
- $t'$ = (t-$t_{min.}$)
  $t'$ = 0 $\div$ 0.4 GeV$^2$, $< t' >$ = 0.13 GeV$^2$

- In one photon approximation $\equiv \gamma^* + p \longrightarrow p' + V$
- The amplitude of this process can be factorized:
  $A = \Phi^*_{\gamma^* \rightarrow q\bar{q}} \otimes A_{q\bar{q}+p \rightarrow q\bar{q}+p} \otimes \Phi_{q\bar{q} \rightarrow V}$.
  In these three steps the interaction time $(q\bar{q})$ with target is shorter than $\gamma^*$ fluctuation and formation of VM. (Collins,Frankfurt and Strikman Phys.Rev D56(1997)2982)
- $\gamma^* + p \longrightarrow \phi + p'$ : with transversely pol. target is good tool to study Transverse Target Spin Asymmetry
  - The detected decay products: $\phi \longrightarrow K^+ + K^-$ and $\omega \longrightarrow \pi^+ + \pi^0 + \pi^-$ are used for identification of VM.
  - The scattering and production planes are easy defined.

# Definition of the azimuthal angles

TRENTO CONVENTION




$$\cos\phi = \frac{(\vec{q}\times\vec{v})\cdot(\vec{k}\times\vec{k}')}{|\vec{q}\times\vec{v}|\cdot|\vec{k}\times\vec{k}'|}, \quad \sin\phi = \frac{[(\vec{k}\times\vec{v})\cdot\vec{q}]\cdot|\vec{q}|}{|\vec{k}\times\vec{q}|\cdot|\vec{q}\times\vec{v}|},$$

$$\cos\phi_S = \frac{(\vec{q}\times\vec{S})\cdot(\vec{k}\times\vec{k}')}{|\vec{q}\times\vec{S}|\cdot|\vec{k}\times\vec{k}'|}, \quad \sin\phi_S = \frac{[(\vec{k}\times\vec{S})\cdot\vec{q}]\cdot|\vec{q}|}{|\vec{k}\times\vec{q}|\cdot|\vec{q}\times\vec{S}|},$$

The angle $\phi$ between the lepton-scattering plane and the VM production plane.

Relation between the azimuthal angles in the selected frames:

$$F^{q\perp S}(S_T, S_L, \phi, \phi_S) = \mathcal{R}(\theta,\gamma)F^{k\perp S}(P_T, P_L, \psi, \psi_S),$$

where: $\sin(\theta) = \gamma(1-y-\frac{1}{4}y^2\gamma^2)/(1+\gamma^2), \quad \gamma = 2x_B M_p/Q.$

$$S_T = \frac{P_T\cos(\theta)}{\sqrt{1-\sin(\theta)^2\sin\phi_S^2}}.$$

# Main definitions and relations

M.Diehl, S. Sapeta

hep-ph/0503023

$$\left[\frac{\cos\theta}{1-\sin^2\theta\,\sin^2\phi_S}\right]^{-1}\left[\frac{\alpha_{\rm em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_B}{x_B}\,\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_B\,dQ^2\,d\phi\,d\phi_S}\bigg|_{P_L=0}$$

$$= \text{ terms independent of } P_T$$

$$- \frac{P_T}{\sqrt{1-\sin^2\theta\,\sin^2\phi_S}}\Bigg[\sin\phi_S\;\cos\theta\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\,\sigma_{+0}^{+-}$$

$$+\sin(\phi-\phi_S)\left(\cos\theta\,\mathrm{Im}\,(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{1}{2}\sin\theta\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right)$$

$$+\sin(\phi+\phi_S)\left(\cos\theta\,\frac{\varepsilon}{2}\,\mathrm{Im}\,\sigma_{+-}^{+-}+\frac{1}{2}\sin\theta\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right)$$

$$+\sin(2\phi-\phi_S)\left(\cos\theta\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\,\sigma_{+0}^{-+}+\frac{1}{2}\sin\theta\,\varepsilon\,\mathrm{Im}\,\sigma_{+-}^{++}\right)$$

$$+\sin(2\phi+\phi_S)\,\frac{1}{2}\sin\theta\,\varepsilon\,\mathrm{Im}\,\sigma_{+-}^{++}$$

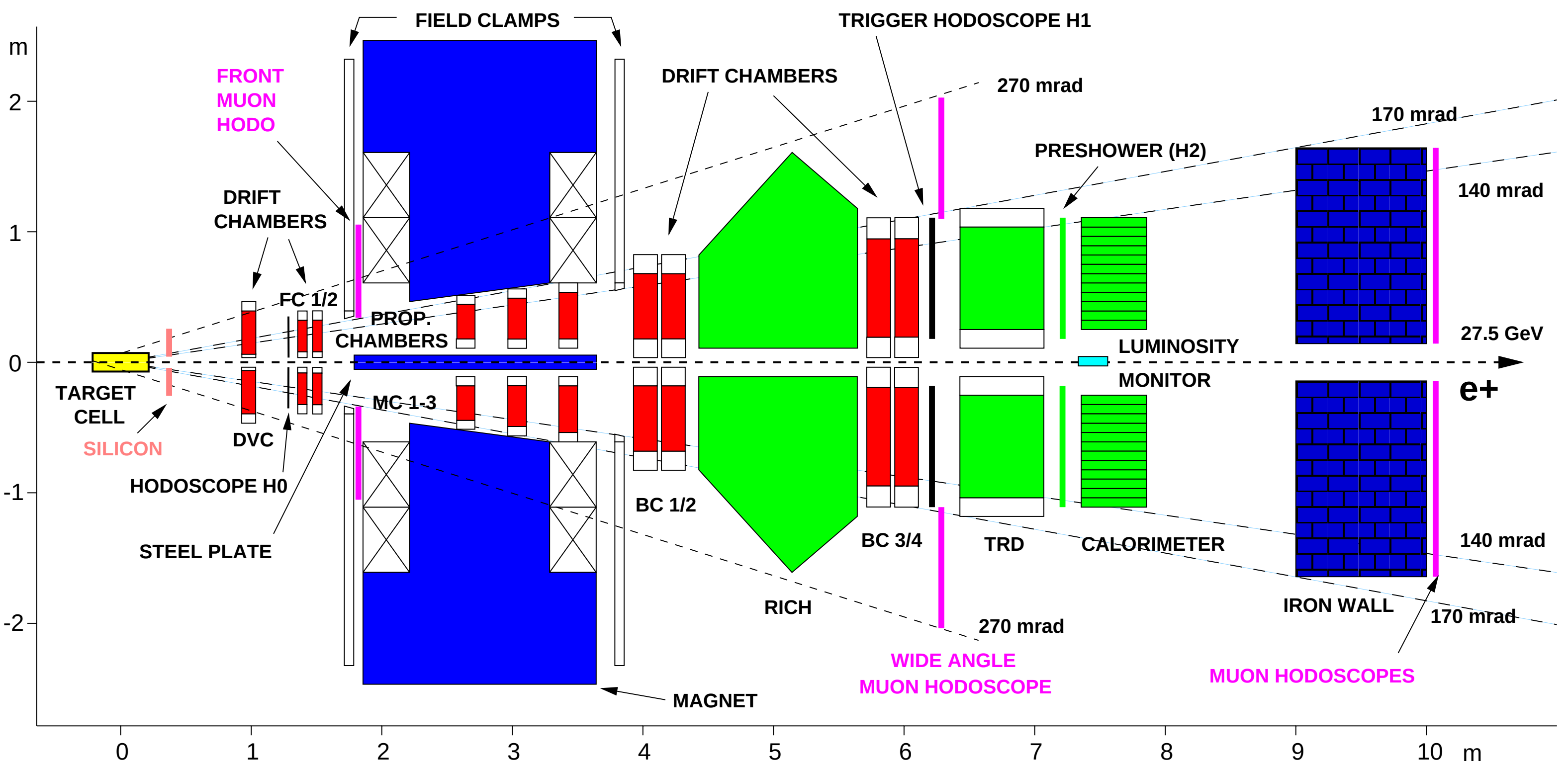
$$+\sin(3\phi-\phi_S)\;\cos\theta\,\frac{\varepsilon}{2}\,\mathrm{Im}\,\sigma_{+-}^{-+}\Bigg]$$

$$A_{UT}\sim\cos\theta\ \mathrm{Im}\,(\ \sigma_{++}^{+-}+\epsilon\sigma_{00}^{+-}\ )$$

where: $\sigma_{mn}^{ij}(Q^2,x_B)$ are cross sections or interference terms with indices: (i, j) describing polarization of the protons (p and p′) as well as (m,n) - polarization of ($\gamma^*$ and VM),

$\epsilon$ - ratio of longitudinal to transverse photon flux

# HERMES SPECTROMETER



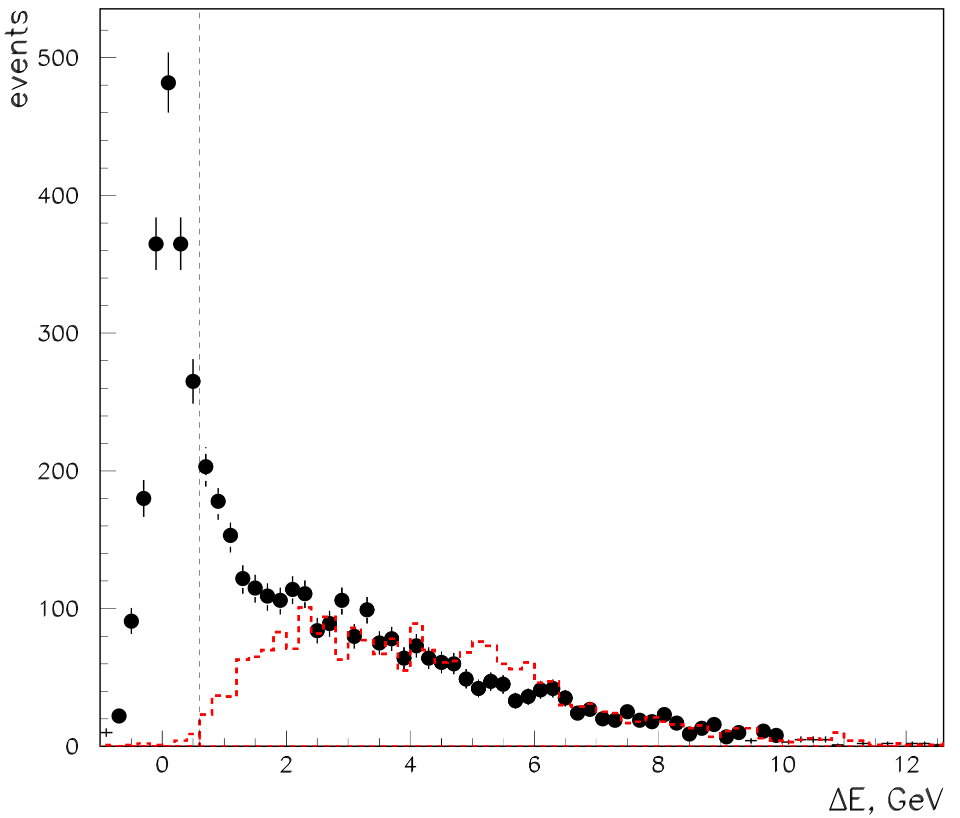

- **Acceptance:** $|\Theta_x| < 170$ **mrad, 40** $< |\Theta_y| < 140$ **mrad,**
- **Resolution** $\delta$**p/p** $< 1\ \%$, $\delta\Theta < 0.6$ **mrad,**
- **Positron identification efficiency above 99% , hadron average is 99%,**
- **Contamination of hadrons (positrons) in the positron (hadron) sample - below 0.01% (0.6%)**
- **Good separation pions, kaons, protons and other hadrons for momenta between 2- 15 GeV,**
- **Average target polarization (02-05)** $\sim$ **72 %.**

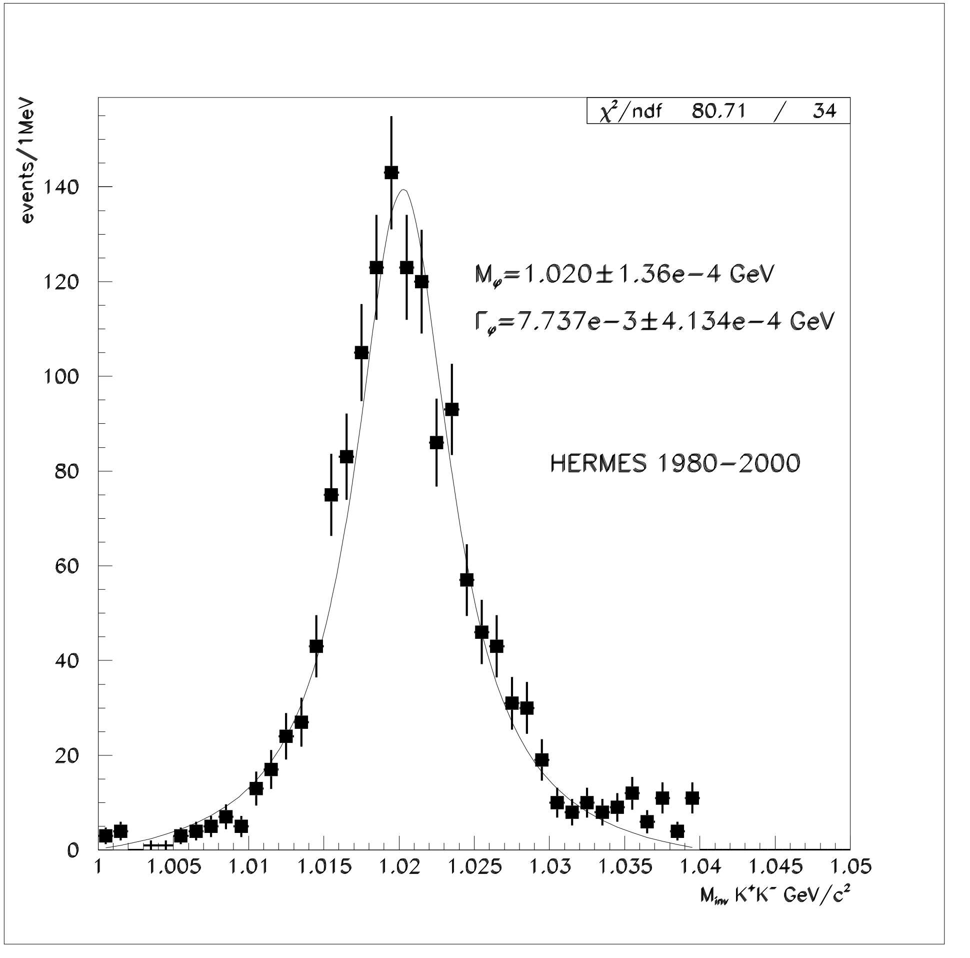
# Exclusive $\phi$ Meson Production

$$e + p \to e' + p' + \phi \to K^+ K^-$$

The exclusive events were selected using

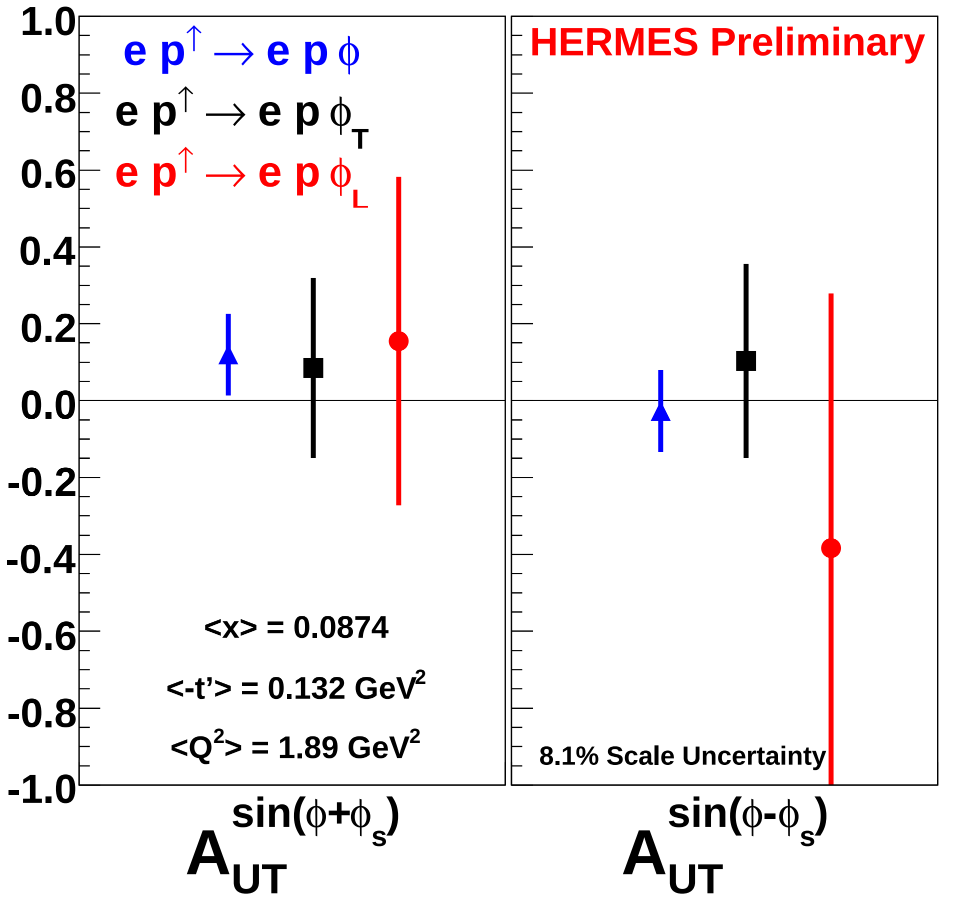
the missing energy spectra $\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$.




The background was simulated by code MC PYTHIA.

# $A_{UT}$ for $\phi$ vector mesons

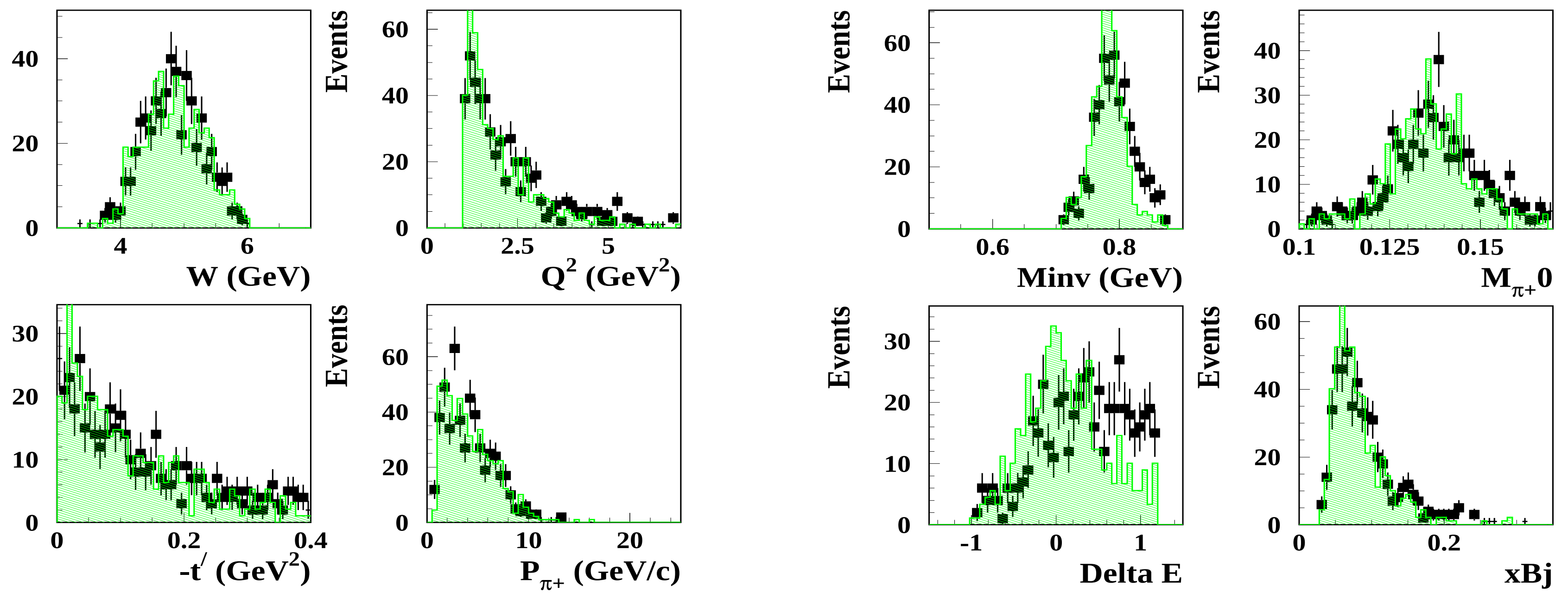



Third and second ($A_{UT}$) moments for $\phi$ mesons.

**Used cuts for idenetyfied particles $e^{\pm}$, $K^{+}$, $K^{-}$ :**

- **'Fiducial' cut**
- **Cut for opening angle of decaying $\phi$ meson**
- **Cut for $P_{\phi} > 7.5$ GeV/c**
- **Kinematical cuts $Q^2 >$1GeV, $-t' < 0.5$ GeV$^2$, W$>$ 5GeV.**

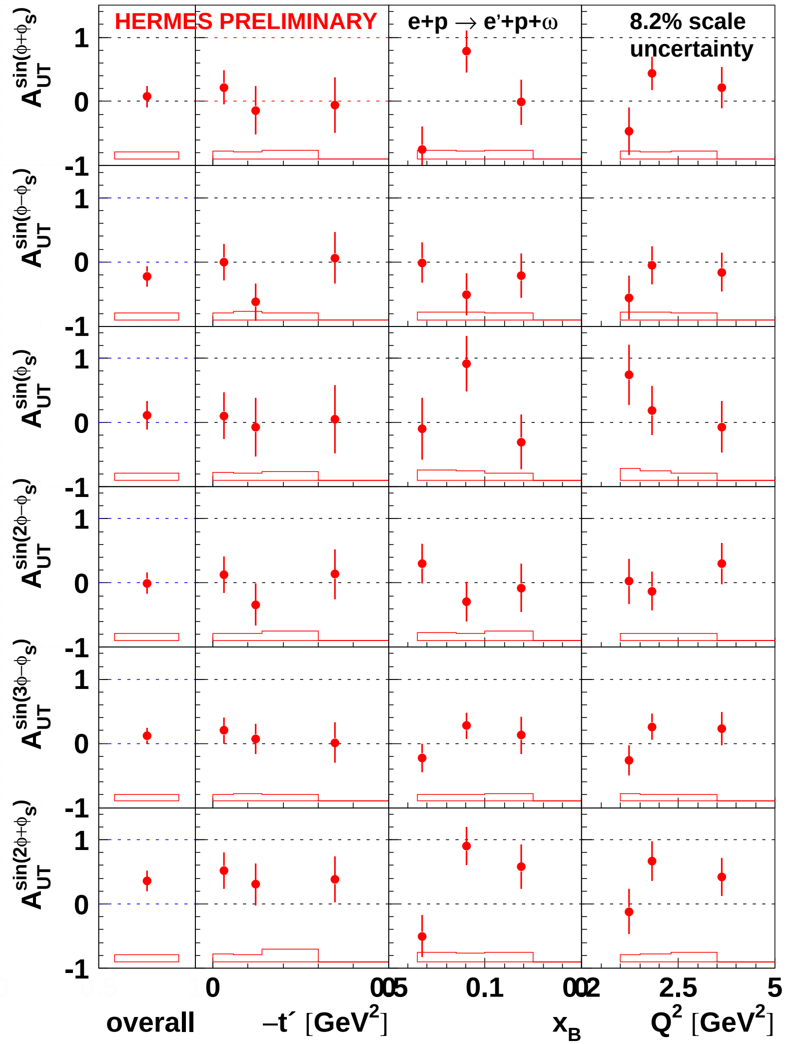
# Main observables for $\omega$




**Distributions of several kinematic variables from data on exclusive $\omega$ meson leptoproduction (black squares) compared to PYTHIA simulated spectra (dashed areas). Simulated spectra were normalized to the data.**

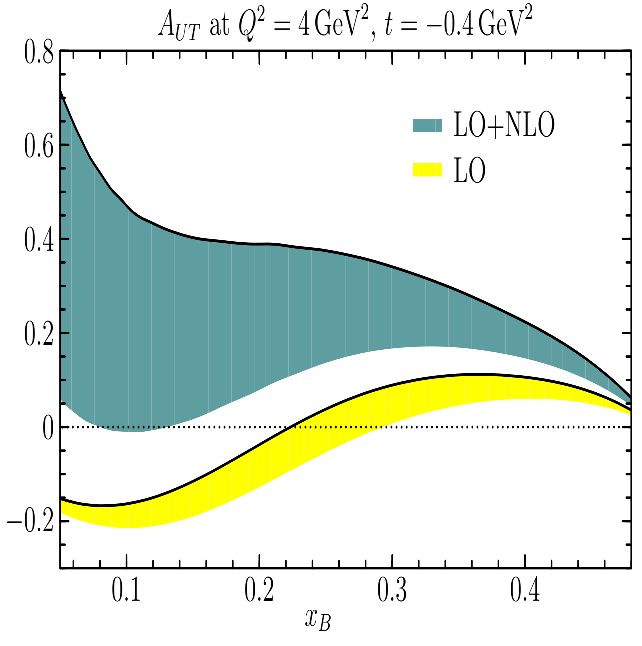
**The exclusive $\omega$ vector mesons were indetyfied by invariant mass spectra: $M^{\omega}(h^{+},h^{-},\pi^{0})$, $M^{\pi^0}(\gamma,\gamma)$ as well as $\Delta$E spectrum.**

# $A_{UT}$ for $\omega$




**The moments of A$_{UT}$ for $\omega$ as functcion of $-t'$, $x_B$ and $Q^2$ after background subtraction. Statistical uncertainties are shown as error bars. Red boxes at the bottom of each plot represent the systematic uncertainties.**

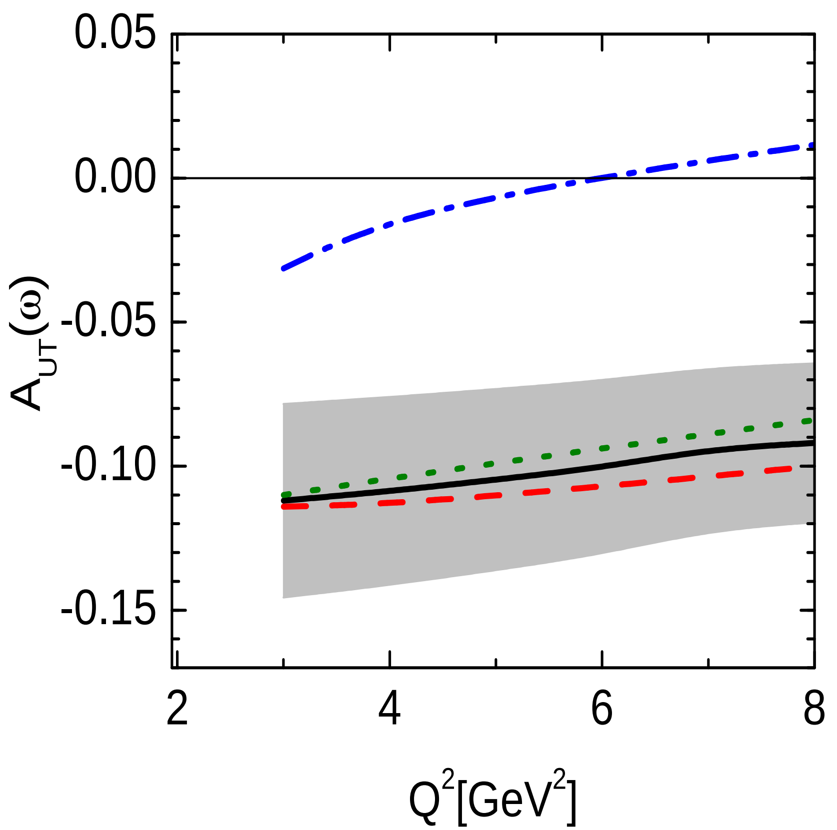
# Theory, models, predictions for $A_{UT}^{\omega}$




M. Diehl and W. Kugler, Eur.Phys.J.C**52**,933(2007) [arXiv:0708.1121 [hep-ph]],calculations.
$A_{UT}$ as function of $x_B$. (Calculations for $\sigma_{00}^{+-}$)
The bands correspond to the range of the factorization scale parameter $2 < \mu < 4$ GeV.

# $A_{UT}$ and GPDs

$$A_{UT} = -2\frac{\text{Im}[\mathcal{M}^*_{+-,++}\mathcal{M}_{++,++} + \epsilon\text{Im}[\mathcal{M}^*_{0-,0+}\mathcal{M}_{0+,0+}]}{\Sigma_{\nu'}[|\mathcal{M}_{+\nu',++}|^2 + \epsilon|\mathcal{M}_{0\nu',0+}|^2]},$$



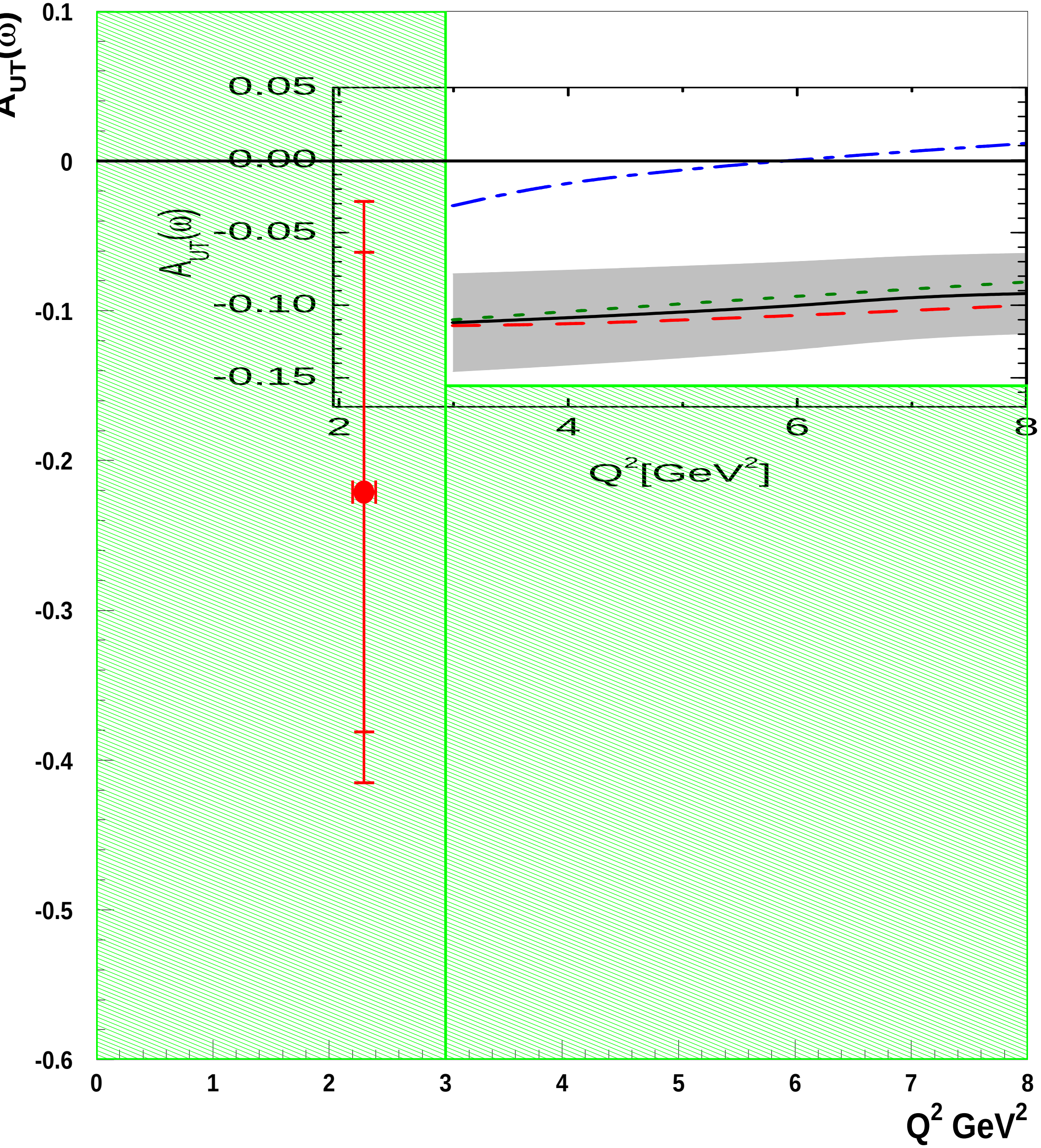

S.V.Goloskokov and P.Kroll
hep-ph/0809412

Important characteristics of G.K. model:

Introduce the quark transverse momenta with model regulation : $\frac{1}{dQ^2} \Rightarrow \frac{1}{dQ^2+k_\perp^2}$.

Include Sudakov effect in b space.

# $A_{UT}$ results for $\omega$




$A_{UT}$: experimental value and theoretical predictions. The theoretical predictions done by GK model. The solid, dashed, dotted and dash-dotted lines represent the results for different variants. The shaded band indicates the theoretical uncertainty for one variant. The other variants have similar uncertainties.

# Conclusions

- **The value of A$_{UT}$ for the $\phi$ meson is close to zero. It confirms the model expectation that $E^g$ and $E^{see}$ distributions in the HERMES kinematics is negligible.**
- **The value of A$_{UT}$ in the case of $\omega$ is negative. The sign is related to weight factors flavor structure of $\omega$ vector meson and agrees with predictions of (GK) model.**

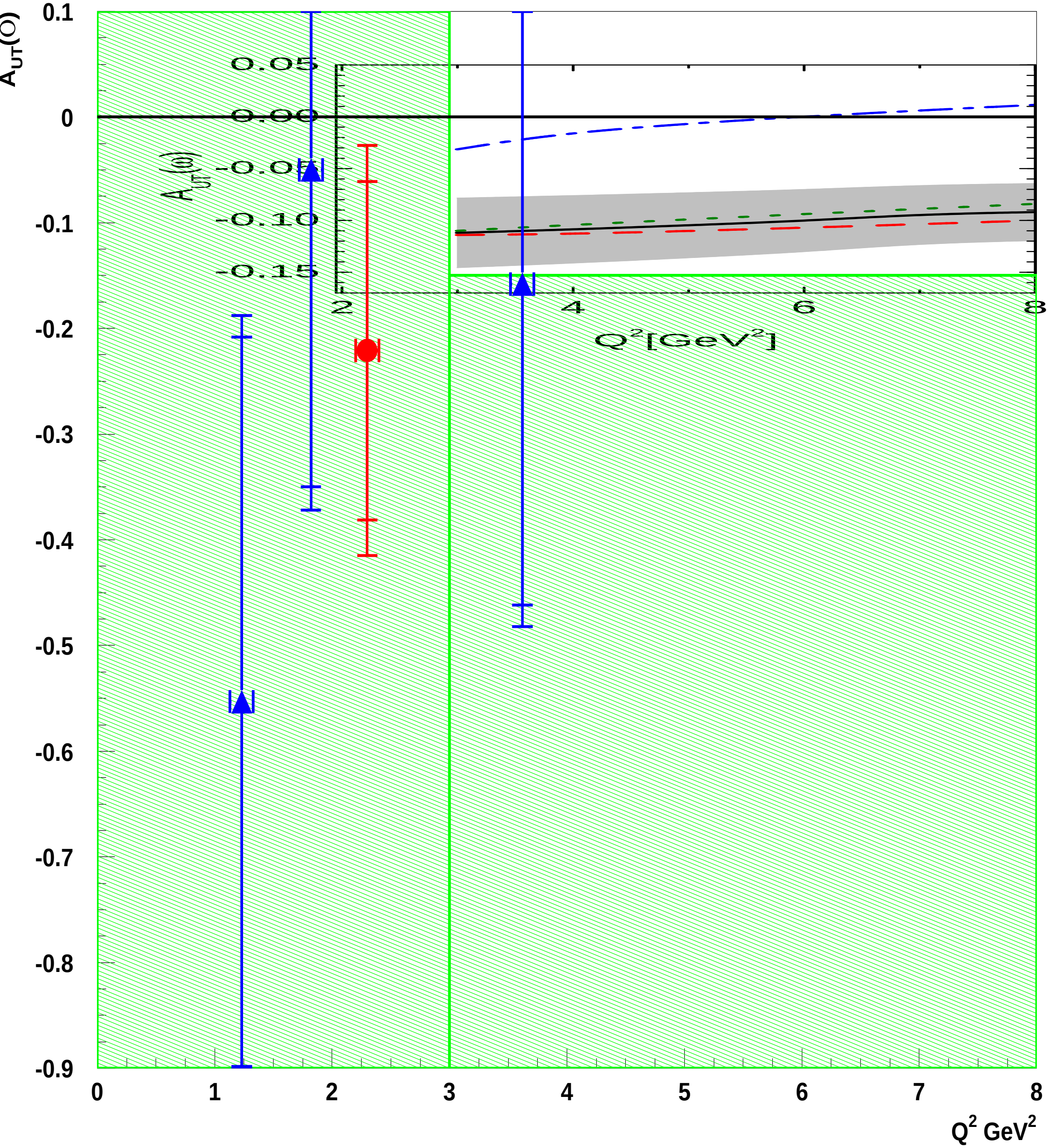
# ADDITIONAL SLIDES

# Introduction

**The hard exclusive electro-production of $\phi$ and $\omega$ vector mesons was studied with the HERMES spectrometer at the DESY laboratory by scattering 27.6 GeV positron and electron beams off a transversely polarized hydrogen target. The single-spin azimuthal asymmetry with respect to the transverse proton polarization was measured. The exclusive reaction e + p $\longrightarrow$ V + p$'$ or equivalent $\gamma^*$ + p $\longrightarrow$ V + p$'$ consist in a complex set of processes. The processes indexed by the polarization of virtual photon and vector meson as well as by the proton polarization before and after the reaction are seen in the experiment as a sum of processes and interference contributions of two processes. It was observed that processes are ordered by certain hierarchy starting from the strong processes like $\gamma^*_L \longrightarrow$ V$_L$, $\gamma^*_T \longrightarrow$ V$_T$ without the spin-flip of the proton up to the weak processes with the spin-flip of proton and transition with change of helicity like $\gamma^*_T \longrightarrow$ V$_L$.**

**Some of weak processes are seen only as an interference with the strong process. The experiment with polarized target gives us the possibility to select interesting for the theory, in our case GPDs, such processes. Here the observation will be focused on the process with proton (target) changing polarization. In the language of GPDs theory our studies with polarized target are related with the $E(x_B, \xi, Q^2)$ distribution.**

# $A_{UT}$ results for $\omega$




$A_{UT}$: experimental values and theoretical predictions as function of $Q^2$.

The experimental results indicated by black markers were determined in the bins defined by values: 1.0, 1.5, 2.3 and 7.0 GeV$^2$. The red point corresponds the full bin: 1.0 - 7.0 GeV$^2$.

The theoretical predictions done by (GK), arXiv:0809.4126[hep-ph] . The solid, dashed, dotted and dash-dotted lines represent the results for different variants The shaded band indicates the theoretical uncertainty for variant one. The other variants have similar uncertainties.

# $A_{UT}$ and GPDs

$$A_{UT} = -2\frac{\text{Im}[\mathcal{M}^*_{+-,++}\mathcal{M}_{++,++} + \epsilon\text{Im}[\mathcal{M}^*_{0-,0+}\mathcal{M}_{0+,0+}]}{\Sigma_{\nu'}[|\mathcal{M}_{+\nu',++}|^2 + \epsilon|\mathcal{M}_{0\nu',0+}|^2]},$$

$$\mathcal{M}_{\mu,+,\mu+}(V) = \frac{e}{2}\{\sum_a e_a \mathcal{C}_V^{aa}\langle H\rangle^g_{V\mu} + \sum_{ab}\mathcal{C}_V^{ab}\langle H\rangle^{ab}_{V\mu}\},$$

$$\mathcal{M}_{\mu,-,\mu+}(V) = -\frac{e}{2}\frac{\sqrt{(-t)}}{M+m}\{\sum_a e_a \mathcal{C}_V^{aa}\langle E\rangle^g_{V\mu} + \sum_{ab}\mathcal{C}_V^{ab}\langle E\rangle^{ab}_{V\mu}\},$$

$$\langle F\rangle^g_{V\mu} = \sum_\lambda \int_0^1 d\bar{x}\mathcal{H}^{Vg}_{\mu\lambda,\mu\lambda}(\bar{x},\xi,Q^2,t=0)F^g(\bar{x},\xi,t),$$

$$\langle F\rangle^{ab}_{V\mu} = \sum_\lambda \int_{-1}^1 d\bar{x}\mathcal{H}^{Vab}_{\mu\lambda,\mu\lambda}(\bar{x},\xi,Q^2,t=0)F^{ab}(\bar{x},\xi,t),$$

$$\mathcal{H}^{Vab}_{\mu\lambda,\mu\lambda} = \int d\tau d^2b\hat{\Psi}_{V\mu}(\tau,-\mathbf{b})\hat{\mathcal{F}}(\bar{x},\xi,\tau,Q^2,\mathbf{b})$$

$$\mathbf{x}\alpha_s(\mu_R)\exp[-S(\tau,\mathbf{b},Q^2)],$$

$$\Psi_{Vj}(\tau,\mathbf{k}_\perp) = 8\pi^2\sqrt{2N_C}f_{Vj}(\mu_F)a^2_{Vj}[1 + B_1^{Vj}(\mu_F)C_1^{3/2}(2\tau-1)$$

$$+B_2^{Vj}(\mu_F)C_2^{3/2}(2\tau-1)]\exp[-a^2_{Vj}\mathbf{k}^2_\perp/(\tau\bar{\tau})].$$

S.V.Goloskokov and P.Kroll hep-ph/0809412

Important characteristics of G.K. theory:

Introduce the quark transverse momenta with model regulation: $\frac{1}{dQ^2} = \frac{1}{dQ^2+k_\perp^2}$.

The weight factors comprise the flavor structure of VM: $C_\omega^{uu} = C_\omega^{dd} = \frac{1}{\sqrt{2}}$, $C_\phi^{ss} = 1$,

F(=H,E),

$\hat{F}$ - hard scattering kernel

Sudakov effect in b space.

Parameters of wave function.

# Main definitions and relations

M.Diehl, S. Sapeta

hep-ph/0503023

$$\left[\frac{\cos\theta}{1-\sin^2\theta\,\sin^2\phi_S}\right]^{-1}\left[\frac{\alpha_{em}}{8\pi^3}\frac{y^2}{1-\varepsilon}\frac{1-x_B}{x_B}\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_B\,dQ^2\,d\phi\,d\phi_S}\bigg|_{P_L=0}$$

$$= \text{ terms independent of } P_T$$

$$- \frac{P_T}{\sqrt{1-\sin^2\theta\,\sin^2\phi_S}}\Big[\sin\phi_S\,\cos\theta\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\,\sigma_{+0}^{+-}$$

$$+\sin(\phi-\phi_S)\Big(\cos\theta\,\mathrm{Im}\,(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{1}{2}\sin\theta\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\Big)$$

$$+\sin(\phi+\phi_S)\Big(\cos\theta\,\frac{\varepsilon}{2}\,\mathrm{Im}\,\sigma_{+-}^{+-}+\frac{1}{2}\sin\theta\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\Big)$$

$$+\sin(2\phi-\phi_S)\Big(\cos\theta\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\,\sigma_{+0}^{-+}+\frac{1}{2}\sin\theta\,\varepsilon\,\mathrm{Im}\,\sigma_{+-}^{++}\Big)$$

$$+\sin(2\phi+\phi_S)\,\frac{1}{2}\sin\theta\,\varepsilon\,\mathrm{Im}\,\sigma_{+-}^{++}$$

$$+\sin(3\phi-\phi_S)\,\cos\theta\,\frac{\varepsilon}{2}\,\mathrm{Im}\,\sigma_{+-}^{-+}\Big]$$

$$A_{UT} \sim \cos\theta\ \mathrm{Im}\ (\ \sigma_{++}^{+-} + \epsilon\sigma_{00}^{+-}\ )$$

where: $\sigma_{mn}^{ij}(Q^2, x_B)$ are cross sections or interference terms with indices: (i, j) describing polarization of the protons (p and p′) as well as (m,n) - polarization of ($\gamma^*$ and VM),

$\epsilon$ - ratio of longitudinal to transverse photon flux