Polarized vector meson production in semi-inclusive DIS

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Based on: X.S. Jiao, K.B. Chen, Phys. Rev. D105, 054010 (2022)

K.B. Chen, Z.T. Liang, Y.K. Song, S.Y. Wei, Phys. Rev. D102, 034001 (2020)

Contents

- Introduction
- Kinematics and structure functions for $eN \to eVX$
- Parton model results and the spin alignment
- Summary

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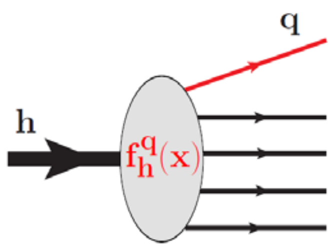
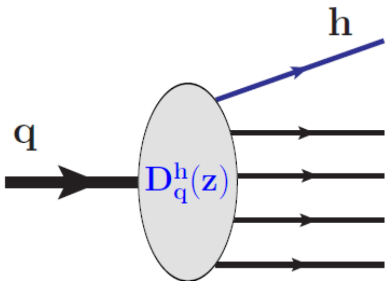
PDFs and FFs

Parton distribution functions (**PDFs**)



Hadron structure

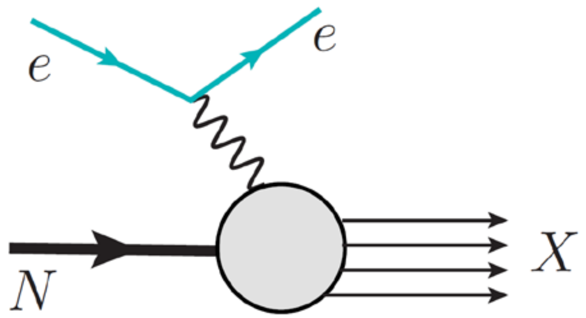
Fragmentation functions (**FFs**)



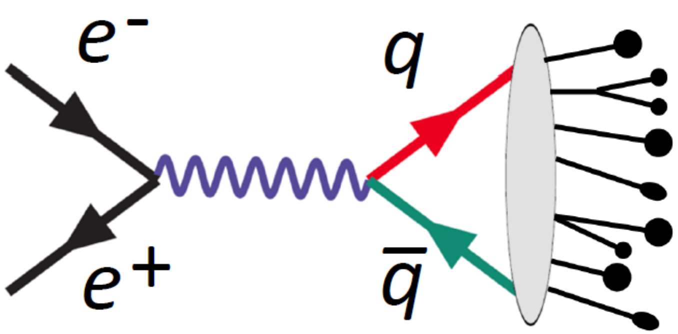
Hadronization mechanism

Parton momentum distribution inside a hadron

Hadron momentum distribution inside a parton jet



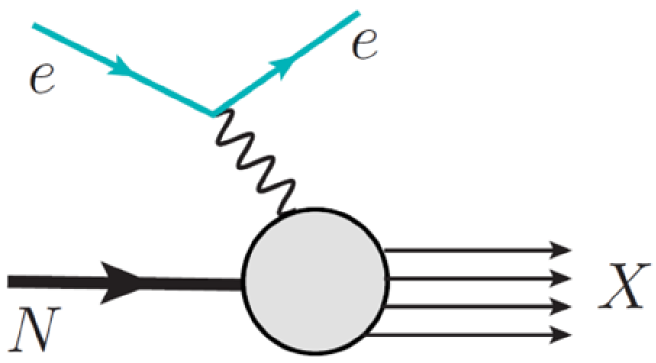
Lepton-nucleon deep inelastic scattering (DIS)



e^+e^- annihilation to hadrons

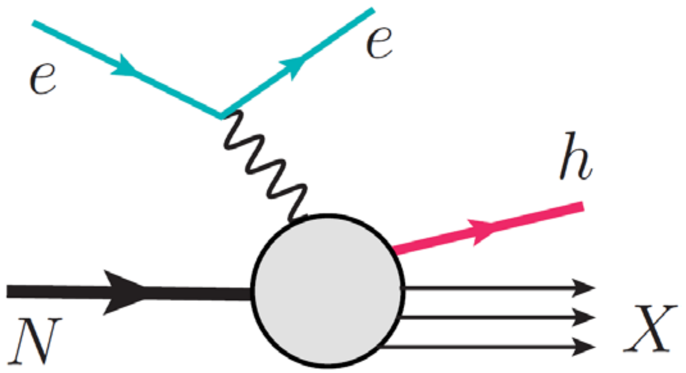
Introduction

Semi-inclusive DIS (SIDIS)



Inclusive DIS

- One dimensional imaging of the nucleon
- Without fragmentation functions
- Target spin asymmetries



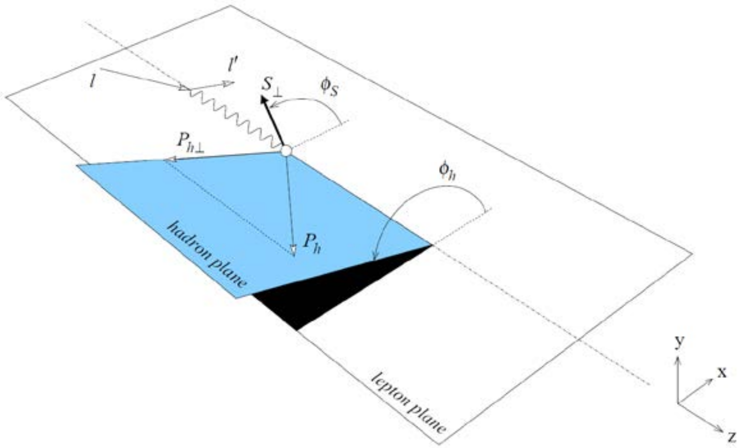
SIDIS

- Three dimensional imaging of the nucleon
- Accessing fragmentation functions
- Azimuthal and/or spin asymmetries

More abundant physical contents!

Introduction

■ **Semi-inclusive DIS (SIDIS)**

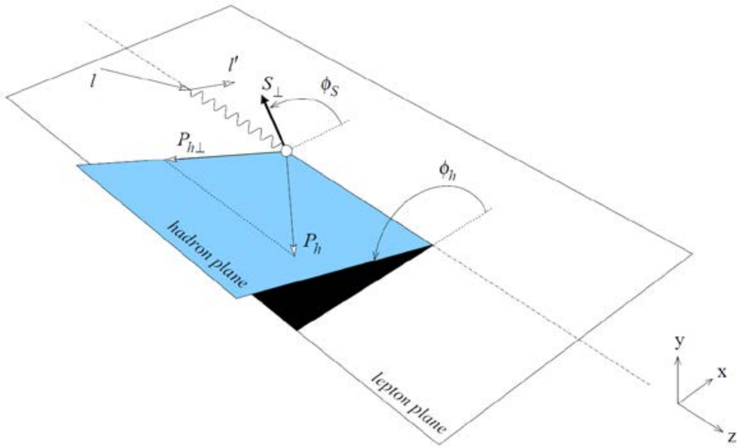


A. Bacchetta *et al.*, JHEP 02, 093 (2007)

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$
$$\Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$
$$+ \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$
$$+ S_{\parallel}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$
$$+ S_{\parallel}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$
$$+ |\boldsymbol{S}_{\perp}|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+ \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$
$$+ |\boldsymbol{S}_{\perp}|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

Introduction

Semi-inclusive DIS (SIDIS)



A. Bacchetta *et al.*, JHEP 02, 093 (2007)

$P_{h\perp} \ll Q$: TMD factorization applies.

Structure functions are expressed by the convolution of TMD PDFs and FFs.

$F_{UU,T} \sim f_1 \otimes D_1$ — Number density

$F_{LL} \sim g_{1L} \otimes D_1$ — Helicity

$F_{UT,T}^{\sin(\phi_h-\phi_S)} \sim f_{1T}^{\perp} \otimes D_1$ — Sivers

$F_{LT}^{\cos(\phi_h-\phi_S)} \sim g_{1T} \otimes D_1$ — Worm-gear

} $\otimes$ Unpolarized FF

$F_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1 \otimes H_1^{\perp}$ — Transversity

$F_{UU}^{\cos 2\phi_h} \sim h_1^{\perp} \otimes H_1^{\perp}$ — Boer-Mulders

$F_{UL}^{\sin 2\phi_h} \sim h_{1L}^{\perp} \otimes H_1^{\perp}$ — Worm-gear

$F_{UT}^{\sin(3\phi_h-\phi_S)} \sim h_{1T}^{\perp} \otimes H_1^{\perp}$ — Pretzelosity

} $\otimes$ Collins FF

$\vdots$

Introduction

- **The polarization of the produced hadron**

  Vector meson production

  $\Longrightarrow$ New polarization dependent TMD FFs

Quark pol.	Hadron pol.	Chiral-even: T-even	Chiral-even: T-odd	Chiral-odd: T-even	Chiral-odd: T-odd
U	U	$D_1 \quad D^\perp \quad D_3$		E	
	L		$D_L^\perp$		
	T		$D_{1T}^\perp \quad D_T \quad D_T^\perp \quad D_{3T}^\perp$		$E_T^\perp$
	LL	$D_{1LL} \quad D_{LL}^\perp \quad D_{3LL}$		E_{LL}	
	LT	$D_{1LT}^\perp \quad D_{LT} \quad D_{LT}^\perp \quad D_{3LT}^\perp$		$E_{LT}^\perp$	
	TT	$D_{1TT}^\perp \quad D_{TT}^\perp \quad D_{TT}'^\perp \quad D_{3TT}^\perp$		$E_{TT}^\perp$	
L	U		$G^\perp$		
	L	$G_{1L} \quad G_L^\perp \quad G_{3L}$			E_L
	T	$G_{1T}^\perp \quad G_T \quad G_T^\perp \quad G_{3T}^\perp$			$E_T'^\perp$
	LL		$G_{LL}^\perp$		
	LT		$G_{1LT}^\perp \quad G_{LT} \quad G_{LT}^\perp \quad G_{3LT}^\perp$	$E_{LT}'^\perp$	
	TT		$G_{1TT}^\perp \quad G_{TT}^\perp \quad G_{TT}'^\perp \quad G_{3TT}^\perp$	$E_{TT}'^\perp$	
T	U				$H_1^\perp \quad H \quad H_3^\perp$
	L			$H_{1L}^\perp \quad H_L \quad H_{3L}^\perp$	
	T(∥)			$H_{1T} \quad H_T^\perp \quad H_{3T}$	
	T(⊥)			$H_{1T}^\perp \quad H_T'^\perp \quad H_{3T}^\perp$	
	LL				$H_{1LL}^\perp \quad H_{LL} \quad H_{3LL}^\perp$
	LT				$H_{1LT} \quad H_{1LT}^\perp \quad H_{LT}^\perp \quad H_{LT}'^\perp \quad H_{3LT} \quad H_{3LT}^\perp$
	TT				$H_{1TT}^\perp \quad H_{1TT}'^\perp \quad H_{TT}^\perp \quad H_{TT}'^\perp \quad H_{3TT}^\perp \quad H_{3TT}'^\perp$

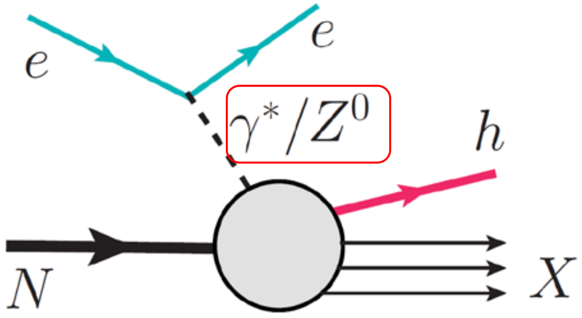
72 TMD FFs for polarized vector meson production

Chen, Yang, Wei and Liang, PRD94, 034003 (2016)

- **Electroweak contributions at high energy**

  Parity violating SIDIS

  $\Longrightarrow$ New structure functions



See e.g.,

Boer, Jakob and Mulders,

NPB 564, 471 (2000)

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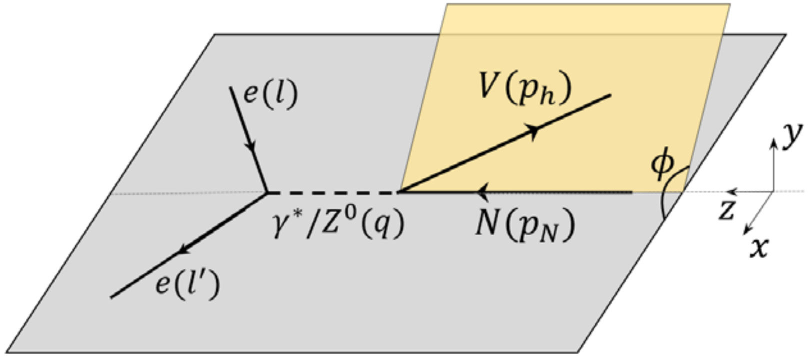
Kinematics and structure functions for $eN \to eVX$

The process

$$e(l) + N(p_N) \to e(l') + V(p_h, S) + X$$

V: Vector meson (spin 1)



$$d\sigma = \frac{2\alpha_{em}^2}{sQ^4} A_r L_r^{\mu\nu}(l,l') W_{r,\mu\nu}(q,p_N,p_h,S) \frac{d^3 l' d^3 p_h}{2E_{l'} 2E_h}, \quad (r = \gamma\gamma, ZZ, \gamma Z)$$

$$L_{\gamma\gamma}^{\mu\nu}(l,l') = 2(l^\mu l'^\nu + l^\nu l'^\mu - g^{\mu\nu} l\cdot l')$$

$$L_{ZZ}^{\mu\nu}(l,l') = c_1^e L_{\gamma\gamma}^{\mu\nu}(l,l') - 2ic_3^e \varepsilon^{\mu\nu l l'}$$

$$L_{\gamma Z}^{\mu\nu}(l,l') = c_V^e L_{\gamma\gamma}^{\mu\nu}(l,l') - 2ic_A^e \varepsilon^{\mu\nu l l'}$$

$$A_{\gamma\gamma} = e_q^2,$$

$$A_{ZZ} = \frac{Q^4}{[(Q^2+M_Z^2)^2 + \Gamma_Z^2 M_Z^2]\sin^4 2\theta_W} \equiv \chi,$$

$$A_{\gamma Z} = \frac{2e_q Q^2(Q^2+M_Z^2)}{[(Q^2+M_Z^2)^2 + \Gamma_Z^2 M_Z^2]\sin^2 2\theta_W} \equiv \chi_{\rm int},$$

$$Q^2 = -q^2, \quad x = \frac{Q^2}{2p_N\cdot q}, \quad y = \frac{p_N\cdot q}{p_N\cdot l}, \quad z_h = \frac{p_N\cdot p_h}{p_N\cdot q}, \quad s = (p_N + l)^2$$

$$W_{\gamma\gamma}^{\mu\nu}(q,p_N,p_h,S) = \sum_X \delta^4(p_N + q - p_h - p_X) \langle p_N | J_{\gamma\gamma}^\mu(0) | p_h, S; X\rangle \langle p_h, S; X | J_{\gamma\gamma}^\nu(0) | p_N\rangle$$

$$W_{ZZ}^{\mu\nu}(q,p_N,p_h,S) = \sum_X \delta^4(p_N + q - p_h - p_X) \langle p_N | J_{ZZ}^\mu(0) | p_h, S; X\rangle \langle p_h, S; X | J_{ZZ}^\nu(0) | p_N\rangle$$

$$W_{ZZ}^{\mu\nu}(q,p_N,p_h,S) = \sum_X \delta^4(p_N + q - p_h - p_X) \langle p_N | J_{ZZ}^\mu(0) | p_h, S; X\rangle \langle p_h, S; X | J_{\gamma\gamma}^\nu(0) | p_N\rangle$$

Kinematics and structure functions for $eN \to eVX$

General form of the hadronic tensor

$$W_{ZZ}^{\mu\nu}(q,p_N,p_h,S) = W_{ZZ}^{S\mu\nu}(\text{symmetric}) + iW_{ZZ}^{A\mu\nu}(\text{antisymmetric})$$

$$= \sum_{\sigma,i} W_{\sigma i}^{S}\ h_{\sigma i}^{S\mu\nu} + i\sum_{\sigma,j} W_{\sigma j}^{A}\ h_{\sigma j}^{A\mu\nu}$$

$$+ \sum_{\sigma,k} \tilde{W}_{\sigma k}^{S}\ \tilde{h}_{\sigma k}^{S\mu\nu} + i\sum_{\sigma,l} \tilde{W}_{\sigma l}^{A}\ \tilde{h}_{\sigma l}^{A\mu\nu}$$

Scalar coefficients — Basic Lorentz tensors (BLTs)

Hermiticity:

$$W_{ZZ}^{*\mu\nu} = W_{ZZ}^{\nu\mu}$$

Current conservation:

$$q_\mu W_{ZZ}^{\mu\nu} = q_\nu W_{ZZ}^{\mu\nu} = 0$$

h: Parity even, $\hat{\mathcal{P}} h^{\mu\nu} = h^{\mu\nu}$

$\tilde{h}$: Parity odd, $\hat{\mathcal{P}} \tilde{h}^{\mu\nu} = -\tilde{h}^{\mu\nu}$

σ: polarizations, U, V, LL, LT, TT

- ***Unpolarized BLTs***

$$h_{Ui}^{S\mu\nu} = \{g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2},\quad p_{Nq}^{\mu} p_{Nq}^{\nu},\quad p_{Nq}^{\{\mu} p_{hq}^{\nu\}},\quad p_{hq}^{\mu} p_{hq}^{\nu}\}$$

$$\tilde{h}_{Ui}^{S\mu\nu} = \{\varepsilon^{\{\mu q p_N p_h} p_{Nq}^{\nu\}},\quad \varepsilon^{\{\mu q p_N p_h} p_{hq}^{\nu\}}\}$$

$$h_{U}^{A\mu\nu} = p_{Nq}^{[\mu} p_{hq}^{\nu]}$$

$$\tilde{h}_{Ui}^{A\mu\nu} = \{\varepsilon^{\mu\nu q p_N},\quad \varepsilon^{\mu\nu q p_h}\}$$

$$p_q^\mu \equiv p^\mu - \frac{p\cdot q}{q^2} q^\mu$$

$$q \cdot p_q = 0$$

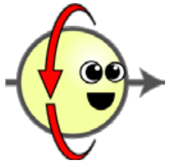
Kinematics and structure functions for $eN \to eVX$

Spin dependence

$S = 1/2$

2 × 2 spin density matrix: $\rho = \frac{1}{2}(1 + \vec{S} \cdot \vec{\sigma})$

Polarization vector: $S^\mu = (0, \vec{S}_T, \lambda)$, $\vec{S}_T = (S_T^x, S_T^y)$



$S = 1$

3 × 3 spin density matrix: $\rho = \frac{1}{3}\left(1 + \frac{3}{2}\vec{S} \cdot \vec{\Sigma} + 3T^{ij}\Sigma^{ij}\right)$, $\Sigma^{ij} = \frac{1}{2}(\Sigma^i\Sigma^j + \Sigma^j\Sigma^i) - \frac{2}{3}\delta^{ij}\boldsymbol{I}$.

Polarization vector: $S^\mu = (0, \vec{S}_T, \lambda)$

Polarization tensor: $\mathbf{T} = \frac{1}{2}\begin{pmatrix} -\frac{2}{3}S_{LL} + S_{TT}^{xx} & S_{TT}^{xy} & S_{LT}^x \\ S_{TT}^{xy} & -\frac{2}{3}S_{LL} - S_{TT}^{xx} & S_{LT}^y \\ S_{LT}^x & S_{LT}^y & \frac{4}{3}S_{LL} \end{pmatrix}$.

S_{LL}

$S_{LT}^\mu = (0, S_{LT}^x, S_{LT}^y, 0)$

$S_{TT}^{x\mu} = (0, S_{TT}^{xx}, S_{TT}^{xy}, 0)$

A. Bacchetta and P.J. Mulders, PRD62, 114004 (2000)

Kinematics and structure functions for $eN \to eVX$

- ***Polarized BLTs***

The polarized BLTs can be constructed from the unpolarized ones by multiplying with the polarization dependent scalars.

$$h_{Vi}^{S\mu\nu} = \{[\lambda, (p_{h\perp}\cdot S_T)]\tilde{h}_{Ui}^{S\mu\nu}, \quad \varepsilon_\perp^{p_h S_T} h_{Uj}^{S\mu\nu}\}$$

$$\tilde{h}_{Vi}^{S\mu\nu} = \{[\lambda, (p_{h\perp}\cdot S_T)]h_{Ui}^{S\mu\nu}, \quad \varepsilon_\perp^{p_h S_T} \tilde{h}_{Uj}^{S\mu\nu}\}$$

$$h_{Vi}^{A\mu\nu} = \{[\lambda, (p_{h\perp}\cdot S_T)]\tilde{h}_{Ui}^{A\mu\nu}, \quad \varepsilon_\perp^{p_h S_T} h_{U}^{A\mu\nu}\}$$

$$\tilde{h}_{Vi}^{A\mu\nu} = \{[\lambda, (p_{h\perp}\cdot S_T)]h_{U}^{A\mu\nu}, \quad \varepsilon_\perp^{p_h S_T} \tilde{h}_{Uj}^{A\mu\nu}\}$$

$$\begin{pmatrix}\text{Polarization}\\ \text{dependent BLTs}\end{pmatrix} = \begin{pmatrix}\text{Polarization}\\ \text{dependent scalars}\end{pmatrix} \times \begin{pmatrix}\text{Unpolarized}\\ \text{BLTs}\end{pmatrix}$$

81 independent BLTs in total

K.B. Chen, W.H. Yang, S.Y. Wei and Z.T. Liang, Phys. Rev. D94, 034003 (2016)

$$\begin{Bmatrix} h_{LLi}^{S\mu\nu} \\ \tilde{h}_{LLi}^{S\mu\nu} \\ h_{LL}^{A\mu\nu} \\ \tilde{h}_{LLi}^{A\mu\nu} \end{Bmatrix} = S_{LL} \begin{Bmatrix} h_{Ui}^{S\mu\nu} \\ \tilde{h}_{Ui}^{S\mu\nu} \\ h_{U}^{A\mu\nu} \\ \tilde{h}_{Ui}^{A\mu\nu} \end{Bmatrix}$$

$$h_{LTi}^{S\mu\nu} = \{(p_{h\perp}\cdot S_{LT})h_{Ui}^{S\mu\nu}, \quad \varepsilon_\perp^{p_h S_{LT}} \tilde{h}_{Uj}^{S\mu\nu}\}$$

$$\tilde{h}_{LTi}^{S\mu\nu} = \{(p_{h\perp}\cdot S_{LT})\tilde{h}_{Ui}^{S\mu\nu}, \quad \varepsilon_\perp^{p_h S_{LT}} h_{Uj}^{S\mu\nu}\}$$

$$h_{LTi}^{A\mu\nu} = \{(p_{h\perp}\cdot S_{LT})h_{U}^{A\mu\nu}, \quad \varepsilon_\perp^{p_h S_{LT}} \tilde{h}_{Uj}^{A\mu\nu}\}$$

$$\tilde{h}_{LTi}^{A\mu\nu} = \{(p_{h\perp}\cdot S_{LT})\tilde{h}_{Ui}^{A\mu\nu}, \quad \varepsilon_\perp^{p_h S_{LT}} h_{U}^{A\mu\nu}\}$$

$$h_{TTi}^{S\mu\nu} = \{S_{TT}^{p_h p_h} h_{Ui}^{S\mu\nu}, \quad \tilde{S}_{TT}^{p_h p_h} \tilde{h}_{Uj}^{S\mu\nu}\}$$

$$\tilde{h}_{TTi}^{S\mu\nu} = \{S_{TT}^{p_h p_h} \tilde{h}_{Ui}^{S\mu\nu}, \quad \tilde{S}_{TT}^{p_h p_h} h_{Uj}^{S\mu\nu}\}$$

$$h_{TTi}^{A\mu\nu} = \{S_{TT}^{p_h p_h} h_{U}^{A\mu\nu}, \quad \tilde{S}_{TT}^{p_h p_h} \tilde{h}_{Uj}^{A\mu\nu}\}$$

$$\tilde{h}_{TTi}^{A\mu\nu} = \{S_{TT}^{p_h p_h} \tilde{h}_{Ui}^{A\mu\nu}, \quad \tilde{S}_{TT}^{p_h p_h} h_{U}^{A\mu\nu}\}$$

Kinematics and structure functions for $eN \to eVX$

The cross section in terms of structure functions

$$\frac{d\sigma}{dxdydz_h d\psi d^2 p_{h\perp}} = \frac{\alpha_{\rm em}^2}{xyQ^2}\left(\mathcal{W}_U + \lambda \mathcal{W}_L + |S_T|\mathcal{W}_T + S_{LL}\mathcal{W}_{LL} + |S_{LT}|\mathcal{W}_{LT} + |S_{TT}|\mathcal{W}_{TT}\right)$$

$$A(y) = y^2 - 2y + 2,$$
$$B(y) = 2(2-y)\sqrt{1-y},$$
$$C(y) = y(2-y),$$
$$D(y) = 2y\sqrt{1-y},$$
$$E(y) = 2(1-y).$$

$$\mathcal{W}_U = A(y)W_U^T + E(y)W_U^L + B(y)(\sin\phi \tilde{W}_{U1}^{\sin\phi} + \cos\phi W_{U1}^{\cos\phi}) + E(y)(\sin 2\phi \tilde{W}_U^{\sin 2\phi} + \cos 2\phi W_U^{\cos 2\phi}) + C(y)W_U + D(y)(\sin\phi \tilde{W}_{U2}^{\sin\phi} + \cos\phi W_{U2}^{\cos\phi}),$$

$$\mathcal{W}_L = A(y)\tilde{W}_L^T + E(y)\tilde{W}_L^L + B(y)(\sin\phi W_{L1}^{\sin\phi} + \cos\phi \tilde{W}_{L1}^{\cos\phi}) + E(y)(\sin 2\phi W_L^{\sin 2\phi} + \cos 2\phi \tilde{W}_L^{\cos 2\phi}) + C(y)\tilde{W}_L + D(y)(\sin\phi W_{L2}^{\sin\phi} + \cos\phi \tilde{W}_{L2}^{\cos\phi}),$$

$$\begin{aligned}\mathcal{W}_T = {}& \sin\phi_S[B(y)W_{T1}^{\sin\phi_S} + D(y)W_{T2}^{\sin\phi_S}] + \sin(\phi+\phi_S)E(y)W_T^{\sin(\phi+\phi_S)} \\ & + \sin(\phi-\phi_S)[A(y)W_T^{T,\sin(\phi-\phi_S)} + E(y)W_T^{L,\sin(\phi-\phi_S)} + C(y)W_T^{\sin(\phi-\phi_S)}] \\ & + \sin(2\phi-\phi_S)[B(y)W_{T1}^{\sin(2\phi-\phi_S)} + D(y)W_{T2}^{\sin(2\phi-\phi_S)}] + \sin(3\phi-\phi_S)E(y)W_T^{\sin(3\phi-\phi_S)} + \cos\phi_S[B(y)\tilde{W}_{T1}^{\cos\phi_S} + D(y)\tilde{W}_{T2}^{\cos\phi_S}] \\ & + \cos(\phi+\phi_S)E(y)\tilde{W}_T^{\cos(\phi+\phi_S)} + \cos(\phi-\phi_S)[A(y)\tilde{W}_T^{T,\cos(\phi-\phi_S)} + E(y)\tilde{W}_T^{L,\cos(\phi-\phi_S)} + C(y)\tilde{W}_T^{\cos(\phi-\phi_S)}] \\ & + \cos(2\phi-\phi_S)[B(y)\tilde{W}_{T1}^{\cos(2\phi-\phi_S)} + D(y)\tilde{W}_{T2}^{\cos(2\phi-\phi_S)}] + \cos(3\phi-\phi_S)E(y)\tilde{W}_T^{\cos(3\phi-\phi_S)},\end{aligned}$$

$$\mathcal{W}_{LL} = A(y)W_{LL}^T + E(y)W_{LL}^L + B(y)(\sin\phi \tilde{W}_{LL1}^{\sin\phi} + \cos\phi W_{LL1}^{\cos\phi}) + E(y)(\sin 2\phi \tilde{W}_{LL}^{\sin 2\phi} + \cos 2\phi W_{LL}^{\cos 2\phi}) + C(y)W_{LL} + D(y)(\sin\phi \tilde{W}_{LL2}^{\sin\phi} + \cos\phi W_{LL2}^{\cos\phi}),$$

Kinematics and structure functions for $eN \to eVX$

$$\begin{aligned}
\mathcal{W}_{LT} = {} & \sin\phi_{LT}[B(y)\tilde{W}_{LT1}^{\sin\phi_{LT}} + D(y)\tilde{W}_{LT2}^{\sin\phi_{LT}}] + \sin(\phi+\phi_{LT})E(y)\tilde{W}_{LT}^{\sin(\phi+\phi_{LT})} \\
& + \sin(\phi-\phi_{LT})[A(y)\tilde{W}_{LT}^{T,\sin(\phi-\phi_{LT})} + E(y)\tilde{W}_{LT}^{L,\sin(\phi-\phi_{LT})} + C(y)\tilde{W}_{LT}^{\sin(\phi-\phi_{LT})}] \\
& + \sin(2\phi-\phi_{LT})[B(y)\tilde{W}_{LT1}^{\sin(2\phi-\phi_{LT})} + D(y)\tilde{W}_{LT2}^{\sin(2\phi-\phi_{LT})}] + \sin(3\phi-\phi_{LT})E(y)\tilde{W}_{LT}^{\sin(3\phi-\phi_{LT})} \\
& + \cos\phi_{LT}[B(y)W_{LT1}^{\cos\phi_{LT}} + D(y)W_{LT2}^{\cos\phi_{LT}}] + \cos(\phi+\phi_{LT})E(y)W_{LT}^{\cos(\phi+\phi_{LT})} \\
& + \cos(\phi-\phi_{LT})[A(y)W_{LT}^{T,\cos(\phi-\phi_{LT})} + E(y)W_{LT}^{L,\cos(\phi-\phi_{LT})} + C(y)W_{LT}^{\cos(\phi-\phi_{LT})}] \\
& + \cos(2\phi-\phi_{LT})[B(y)W_{LT1}^{\cos(2\phi-\phi_{LT})} + D(y)W_{LT2}^{\cos(2\phi-\phi_{LT})}] + \cos(3\phi-\phi_{LT})E(y)W_{LT}^{\cos(3\phi-\phi_{LT})}
\end{aligned}$$

$$\begin{aligned}
\mathcal{W}_{TT} = {} & \sin(\phi-2\phi_{TT})[B(y)\tilde{W}_{TT1}^{\sin(\phi-2\phi_{TT})} + D(y)\tilde{W}_{TT2}^{\sin(\phi-2\phi_{TT})}] + \sin 2\phi_{TT}E(y)\tilde{W}_{TT}^{\sin 2\phi_{TT}} \\
& + \sin(2\phi-2\phi_{TT})[A(y)\tilde{W}_{TT}^{T,\sin(2\phi-2\phi_{TT})} + E(y)\tilde{W}_{TT}^{L,\sin(2\phi-2\phi_{TT})} + C(y)\tilde{W}_{TT}^{\sin(2\phi-2\phi_{TT})}] \\
& + \sin(3\phi-2\phi_{TT})[B(y)\tilde{W}_{TT1}^{\sin(3\phi-2\phi_{TT})} + D(y)\tilde{W}_{TT2}^{\sin(3\phi-2\phi_{TT})}] + \sin(4\phi-2\phi_{TT})E(y)\tilde{W}_{TT}^{\sin(4\phi-2\phi_{TT})} \\
& + \cos(\phi-2\phi_{TT})[B(y)W_{TT1}^{\cos(\phi-2\phi_{TT})} + D(y)W_{TT2}^{\cos(\phi-2\phi_{TT})}] + \cos 2\phi_{TT}E(y)W_{TT}^{\cos 2\phi_{TT}} \\
& + \cos(2\phi-2\phi_{TT})[A(y)W_{TT}^{T,\cos(2\phi-2\phi_{TT})} + E(y)W_{TT}^{L,\cos(2\phi-2\phi_{TT})} + C(y)W_{TT}^{\cos(2\phi-2\phi_{TT})}] \\
& + \cos(3\phi-2\phi_{TT})[B(y)W_{TT1}^{\cos(3\phi-2\phi_{TT})} + D(y)W_{TT2}^{\cos(3\phi-2\phi_{TT})}] + \cos(4\phi-2\phi_{TT})E(y)W_{TT}^{\cos(4\phi-2\phi_{TT})}
\end{aligned}$$

$$\begin{aligned}
A(y) &= y^2 - 2y + 2, \\
B(y) &= 2(2-y)\sqrt{1-y}, \\
C(y) &= y(2-y), \\
D(y) &= 2y\sqrt{1-y}, \\
E(y) &= 2(1-y).
\end{aligned}$$

- 81 structure functions (SFs) in total
- 39 SFs are space reflection odd
- 45 tensor polarization dependent SFs

Contents

- Introduction
- Kinematics and structure functions for $eN \to eVX$
- Parton model results and the spin alignment
- Summary

Parton model results and the spin alignment

The hadronic tensor in terms of TMD PDFs and FFs

TMD factorization applies at $P_{h\perp} \ll Q$:

$$W_{ZZ}^{\mu\nu} = 2z_h \int d^2k_{iT} d^2k_{fT} \delta^2(\vec{k}_{iT} - \vec{k}_{fT} - \vec{p}_{h\perp}/z_h) \mathrm{Tr}[\hat{\Phi}(x, k_{iT}) \Gamma_q^\mu \hat{\Xi}(z_h, k_{fT}, S) \Gamma_q^\nu]$$

$$\Gamma_q^\mu = \gamma^\mu (c_V^q - c_A^q \gamma_5)$$

The TMD parton correlators:

$$\hat{\Phi}_{ij}(x, k_{iT}) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3} e^{ixp_N^+\xi^- + ik_{iT}\cdot\xi_T} \langle p_N | \bar{\psi}_i(0) \psi_j(\xi^-, \xi_T) | p_N \rangle$$

$$\hat{\Xi}_{ij}(z_h, k_{fT}, S) = \sum_X \int \frac{d\eta^+ d^2\eta_T}{2z_h(2\pi)^3} e^{-i\eta^+ p_h^-/z_h - i\eta_T\cdot k_{fT}} \langle 0 | \psi_i(0) | p_h, S; X \rangle \langle p_h, S; X | \bar{\psi}_j(\eta^+, \eta_T) | 0 \rangle$$

For unpolarized nucleon:

$$\hat{\Phi} = \frac{1}{2}(\Phi_\alpha \gamma^\alpha - \tilde{\Phi}_\alpha \gamma_5 \gamma^\alpha + \Phi_{\alpha\beta} i\sigma^{\alpha\beta}\gamma_5) + \cdots$$

$$\Phi^\alpha = \bar{n}^\alpha f_1(x, k_{iT}) + \cdots$$

$$\Phi^{\alpha\beta} = -\frac{1}{M_N} \bar{n}^\alpha \tilde{k}_{iT}^\beta h_1^\perp(x, k_{iT}) + \cdots$$

Parton model results and the spin alignment

For polarized vector meson production: $\hat{\Xi} = \frac{1}{2}(\Xi_\alpha \gamma^\alpha + \tilde{\Xi}_\alpha \gamma_5 \gamma^\alpha + \Xi_{\alpha\beta} i\sigma^{\alpha\beta}\gamma_5) + \cdots$

$$\Xi^\alpha = n^\alpha \left(D_1 + \frac{\tilde{k}_{fT} \cdot S_T}{M_h} D_{1T}^\perp + S_{LL} D_{1LL} + \frac{k_{fT} \cdot S_{LT}}{M_h} D_{1LT}^\perp + \frac{S_{TT}^{k_f k_f}}{M_h^2} D_{1TT}^\perp \right) + \cdots$$

$$\tilde{\Xi}^\alpha = n^\alpha \left(\lambda_h G_{1L} + \frac{k_{fT} \cdot S_T}{M_h} G_{1T}^\perp + \frac{\tilde{k}_{fT} \cdot S_{LT}}{M_h} G_{1LT}^\perp - \frac{\tilde{S}_{TT}^{k_f k_f}}{M_h^2} G_{1TT}^\perp \right) + \cdots$$

$$\Xi^{\alpha\beta} = -\frac{n^{[\alpha} \tilde{k}_{fT}^{\beta]}}{M_h} (H_1^\perp + S_{LL} H_{1LL}^\perp) + n^{[\alpha} S_T^{\beta]} H_{1T} + \frac{n^{[\alpha} k_{fT}^{\beta]}}{M_h} \left(\lambda_h H_{1L}^\perp + \frac{k_{fT} \cdot S_T}{M_h} H_{1T}^\perp \right)$$

$$- n^{[\alpha} \tilde{S}_{LT}^{\beta]} H_{1LT} - \frac{n^{[\alpha} \tilde{S}_{TT}^{k_f \beta]}}{M_h} H_{1TT}'^\perp - \frac{n^{[\alpha} \tilde{k}_{fT}^{\beta]}}{M_h} \left(\frac{k_{fT} \cdot S_{LT}}{M_h} H_{1LT}^\perp + \frac{S_{TT}^{k_f k_f}}{M_h^2} H_{1TT}^\perp \right) + \cdots$$

Ten tensor polarization dependent TMD FFs at twist-2.

Parton model results and the spin alignment

The hadronic tensor results:

$$W_{ZZ}^{\mu\nu} = \frac{2z_h}{x}\mathcal{C}\Big\{(c_3^q g_\perp^{\mu\nu} + ic_1^q\varepsilon_\perp^{\mu\nu})f_1\mathcal{G}_1 - (c_1^q g_\perp^{\mu\nu} + ic_3^q\varepsilon_\perp^{\mu\nu})f_1\mathcal{D}_1 + 2c_2^q h_1^\perp\Big[\frac{\alpha_T^{\mu\nu}(\tilde{k}_{iT}, S_T)}{M_N}H_{1T} + \frac{\alpha_T^{\mu\nu}(k_{iT}, S_{LT})}{M_N}H_{1LT}$$
$$+ \frac{\alpha_T^{\mu\nu}(\tilde{k}_{iT}, k_{fT})}{M_N M_h}\Big(\lambda_h H_{1L}^\perp + \frac{k_{fT}\cdot S_T}{M_h}H_{1T}^\perp\Big) + \frac{\alpha_T^{\mu\nu}(k_{iT}, S_{TT}^{k_f})}{M_N M_h}H_{1TT}'^\perp + \frac{\alpha_T^{\mu\nu}(k_{iT}, k_{fT})}{M_N M_h}\mathcal{H}_1\Big]\Big\}.$$

$$\alpha_T^{\mu\nu}(a_T, b_T) \equiv a_T^{\{\mu}b_T^{\nu\}} - (a_T\cdot b_T)g_\perp^{\mu\nu}$$

$$\mathcal{C}[wfD] = x\int d^2k_{iT}d^2k_{fT}\delta^2(\vec{k}_{iT} - \vec{k}_{fT} - \vec{p}_{h\perp}/z_h)wf(x, k_{iT})D(z_h, k_{fT})$$

$$\mathcal{D}_1 \equiv D_1 + \frac{\tilde{k}_{fT}\cdot S_T}{M_h}D_{1T}^\perp + S_{LL}D_{1LL} + \frac{k_{fT}\cdot S_{LT}}{M_h}D_{1LT}^\perp + \frac{S_{TT}^{k_f k_f}}{M_h^2}D_{1TT}^\perp,$$
$$\mathcal{G}_1 \equiv \lambda_h G_{1L} + \frac{k_{fT}\cdot S_T}{M_h}G_{1T}^\perp + \frac{\tilde{k}_{fT}\cdot S_{LT}}{M_h}G_{1LT}^\perp - \frac{\tilde{S}_{TT}^{k_f k_f}}{M_h^2}G_{1TT}^\perp,$$
$$\mathcal{H}_1 \equiv H_1^\perp + S_{LL}H_{1LL}^\perp + \frac{k_{fT}\cdot S_{LT}}{M_h}H_{1LT}^\perp + \frac{S_{TT}^{k_f k_f}}{M_h^2}H_{1TT}^\perp.$$

Parameters for weak, electromagnetic and interference contributions

	A_r	$L_r^{\mu\nu}$	$W_r^{\mu\nu}$
ZZ	χ	c_1^e, c_3^e	c_1^q, c_2^q, c_3^q
γZ	$\chi_{\rm int}$	c_V^e, c_A^e	c_V^q, c_V^q, c_A^q
$\gamma\gamma$	e_q^2	1, 0	1, 1, 0

Parton model results and the spin alignment

The structure functions

$$W_U^T = c_{11}^{\rm ew}\mathcal{C}[f_1 D_1],$$
$$W_U = c_{33}^{\rm ew}\mathcal{C}[f_1 D_1],$$
$$W_U^{\cos 2\phi} = 2c_{12}^{\rm ew}\mathcal{C}[w_2 h_1^\perp H_1^\perp],$$
$$\tilde{W}_L^T = -c_{13}^{\rm ew}\mathcal{C}[f_1 G_{1L}],$$
$$\tilde{W}_L = -c_{31}^{\rm ew}\mathcal{C}[f_1 G_{1L}],$$
$$W_L^{\sin 2\phi} = -2c_{12}^{\rm ew}\mathcal{C}[w_2 h_1^\perp H_{1L}^\perp],$$
$$W_T^{T,\sin(\phi-\phi_S)} = c_{11}^{\rm ew}\mathcal{C}[\bar{w}_1 f_1 D_{1T}^\perp],$$
$$W_T^{\sin(\phi-\phi_S)} = c_{33}^{\rm ew}\mathcal{C}[\bar{w}_1 f_1 D_{1T}^\perp],$$
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$$\tilde{W}_T^{\cos(\phi-\phi_S)} = c_{31}^{\rm ew}\mathcal{C}[\bar{w}_1 f_1 G_{1T}^\perp],$$
$$W_T^{\sin(\phi+\phi_S)} = c_{12}^{\rm ew}\mathcal{C}[w_1 h_1^\perp(\bar{w}_0 H_{1T}^\perp - 2H_{1T})],$$
$$W_T^{\sin(3\phi-\phi_S)} = c_{12}^{\rm ew}\mathcal{C}[w_3 h_1^\perp H_{1T}^\perp],$$
$$W_{LL}^T = c_{11}^{\rm ew}\mathcal{C}[f_1 D_{1LL}],$$
$$W_{LL} = c_{33}^{\rm ew}\mathcal{C}[f_1 D_{1LL}],$$

$$W_{LL}^{\cos 2\phi} = 2c_{12}^{\rm ew}\mathcal{C}[w_2 h_1^\perp H_{1LL}^\perp],$$
$$W_{LT}^{T,\cos(\phi-\phi_{LT})} = -c_{11}^{\rm ew}\mathcal{C}[\bar{w}_1 f_1 D_{1LT}^\perp],$$
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$$W_{TT}^{\cos 2\phi_{TT}} = c_{12}^{\rm ew}\mathcal{C}[w_0' h_1^\perp(\bar{w}_0 H_{1TT}^\perp - 2H_{1TT}'^\perp)],$$
$$W_{TT}^{\cos(4\phi-2\phi_{TT})} = c_{12}^{\rm ew}\mathcal{C}[w_4 h_1^\perp H_{1TT}^\perp].$$

$$\bar{w}_0 = -\frac{k_{fT}^2}{M_h^2}, \qquad w_0' = -\frac{k_{iT}\cdot k_{fT}}{M_N M_h},$$
$$w_1 = -\frac{\hat{h}\cdot k_{iT}}{M_N}, \qquad \bar{w}_1 = -\frac{\hat{h}\cdot k_{fT}}{M_h},$$
$$w_2 = \frac{2(\hat{h}\cdot k_{iT})(\hat{h}\cdot k_{fT}) + k_{iT}\cdot k_{fT}}{M_N M_h},$$
$$w_2' = \frac{(\hat{h}\cdot k_{iT})(\hat{h}\cdot k_{fT}) + k_{iT}\cdot k_{fT}}{M_N M_h},$$
$$\bar{w}_2 = \frac{2(\hat{h}\cdot k_{fT})^2 + k_{fT}^2}{M_h^2},$$
$$w_3 = \frac{-1}{M_N M_h^2}[4(\hat{h}\cdot k_{fT})^2(\hat{h}\cdot k_{iT}) + k_{fT}^2(\hat{h}\cdot k_{iT}) + 2(\hat{h}\cdot k_{fT})(k_{iT}\cdot k_{fT})],$$
$$w_4 = \frac{1}{M_N M_h^3}\{k_{fT}^2[k_{iT}\cdot k_{fT} + 4(\hat{h}\cdot k_{fT})(\hat{h}\cdot k_{iT})] + 4(\hat{h}\cdot k_{fT})^2[k_{iT}\cdot k_{fT} + 2(\hat{h}\cdot k_{fT})(\hat{h}\cdot k_{iT})]\}.$$

$$c_{11}^{\rm ew} = c_1^e c_1^q \chi + c_V^e c_V^q \chi_{\rm int} + e_q^2,$$
$$c_{12}^{\rm ew} = c_1^e c_2^q \chi + c_V^e c_V^q \chi_{\rm int} + e_q^2,$$
$$c_{13}^{\rm ew} = c_1^e c_3^q \chi + c_V^e c_A^q \chi_{\rm int},$$
$$c_{31}^{\rm ew} = c_3^e c_1^q \chi + c_A^e c_V^q \chi_{\rm int},$$
$$c_{33}^{\rm ew} = c_3^e c_3^q \chi + c_A^e c_A^q \chi_{\rm int}.$$

Parton model results and the spin alignment

The structure functions

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$$W_{LL}^T = c_{11}^{\rm ew}\mathcal{C}[f_1 D_{1LL}],$$
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$$W_{LT}^{T,\cos(\phi-\phi_{LT})} = -c_{11}^{\rm ew}\mathcal{C}[\bar{w}_1 f_1 D_{1LT}^\perp],$$
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$$W_{TT}^{\cos(4\phi-2\phi_{TT})} = c_{12}^{\rm ew}\mathcal{C}[w_4 h_1^\perp H_{1TT}^\perp].$$

- 27 nonzero SFs at the leading twist
- 15 tensor polarization dependent SFs
- 13 new SFs exist only when considering weak interaction

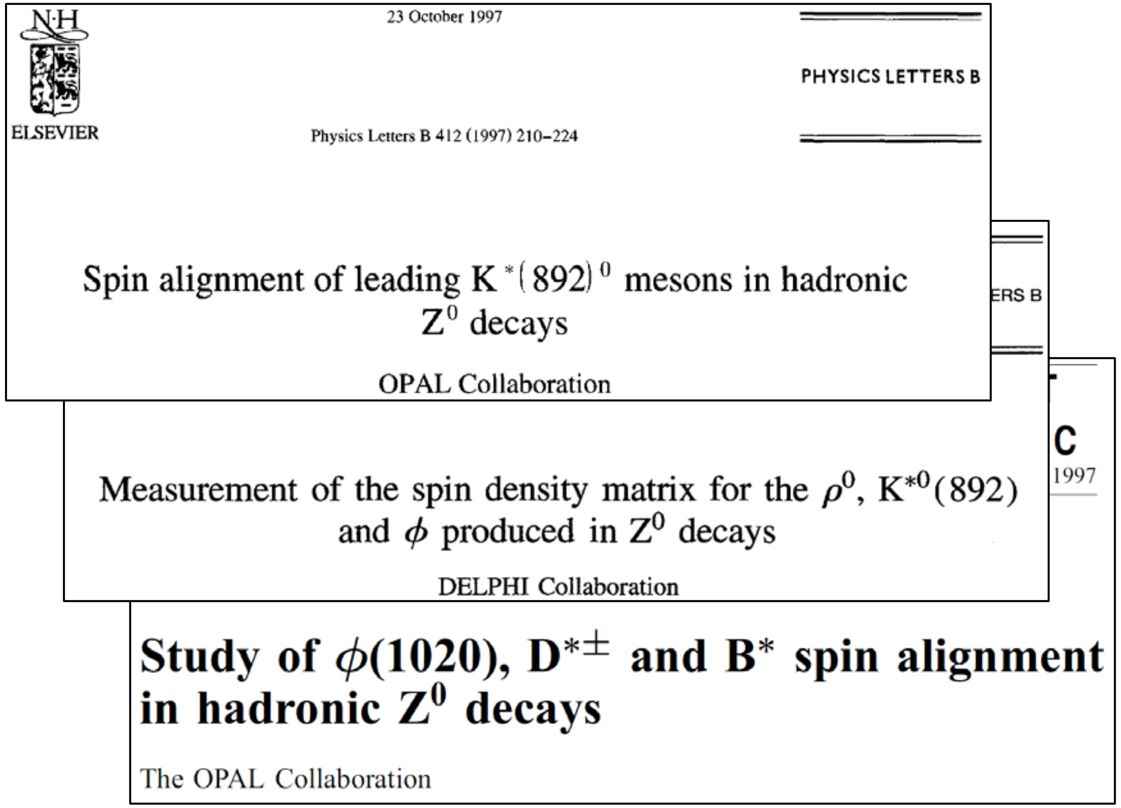
$$c_{11}^{\rm ew} = c_1^e c_1^q \chi + c_V^e c_V^q \chi_{\rm int} + e_q^2,$$
$$c_{12}^{\rm ew} = c_1^e c_2^q \chi + c_V^e c_V^q \chi_{\rm int} + e_q^2,$$
$$c_{13}^{\rm ew} = c_1^e c_3^q \chi + c_V^e c_A^q \chi_{\rm int},$$
$$c_{31}^{\rm ew} = c_3^e c_1^q \chi + c_A^e c_V^q \chi_{\rm int},$$
$$c_{33}^{\rm ew} = c_3^e c_3^q \chi + c_A^e c_A^q \chi_{\rm int}.$$

Parton model results and the spin alignment

The spin alignment of the vector meson

ρ_{00} gives the relative intensity of mesons in helicity 0 state

- **In e^+e^- annihilation:**


23 October 1997

PHYSICS LETTERS B

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Physics Letters B 412 (1997) 210–224

Spin alignment of leading $K^*(892)^0$ mesons in hadronic Z^0 decays

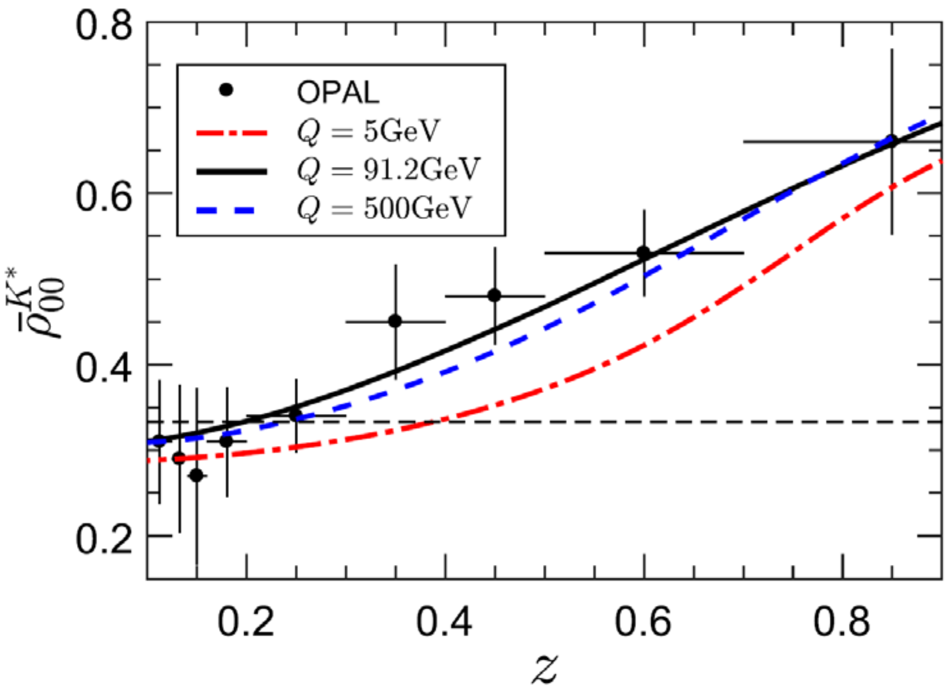
OPAL Collaboration

Measurement of the spin density matrix for the ρ^0, $K^{*0}(892)$ and ϕ produced in Z^0 decays

DELPHI Collaboration

Study of $\phi(1020)$, $D^{*\pm}$ and B^* spin alignment in hadronic Z^0 decays

The OPAL Collaboration



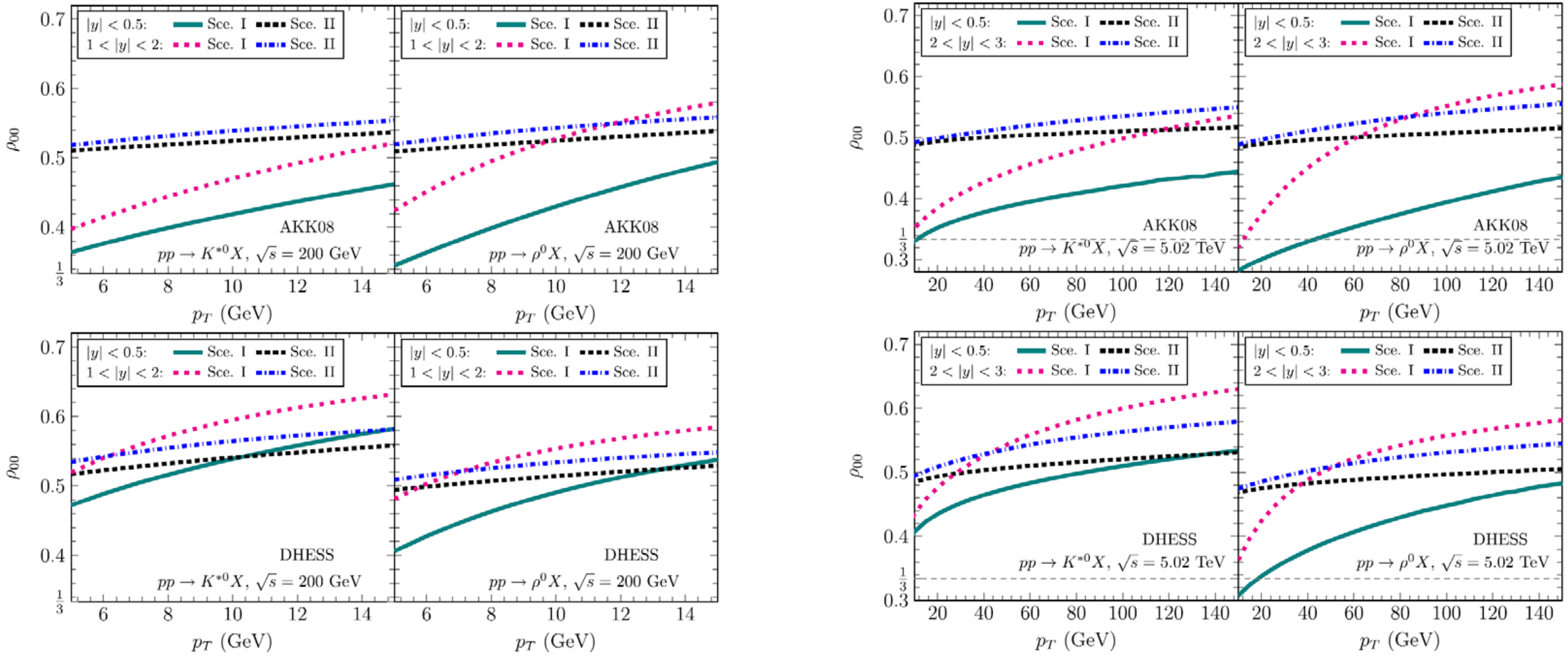
General features:

- Independent of the polarization of the fragmenting quark
- Weak energy dependence

K.B. Chen, W.H. Yang, Y.J. Zhou and Z.T. Liang, Phys. Rev. D95, 034009 (2017)

The spin alignment of the vector meson

- **In pp collision:**



K.B. Chen, Z.T. Liang, Y.K. Song, S.Y. Wei, Phys. Rev. D102, 034001 (2020)

Parton model results and the spin alignment

The spin alignment of the vector meson

- **In SIDIS:**

$$\rho_{00}^{V} = \frac{1}{3} - \frac{\mathcal{W}_{LL}}{3\mathcal{W}_{U}} = \frac{1}{3}\left\{1 - \frac{[c_{11}^{\rm ew}A(y) + c_{33}^{\rm ew}C(y)]\mathcal{C}[f_1 D_{1LL}] + 2c_{12}^{\rm ew}E(y)\mathcal{C}[w_2 h_1^{\perp} H_{1LL}^{\perp}]\cos 2\phi}{[c_{11}^{\rm ew}A(y) + c_{33}^{\rm ew}C(y)]\mathcal{C}[f_1 D_1] + 2c_{12}^{\rm ew}E(y)\mathcal{C}[w_2 h_1^{\perp} H_1^{\perp}]\cos 2\phi}\right\}.$$

ϕ integrated →

$$\langle \rho_{00}^{V}\rangle = \frac{1}{3} - \frac{(c_{11}^{\rm ew}A(y) + c_{33}^{\rm ew}C(y))\mathcal{C}[f_1(x,k_{iT})D_{1LL}(z_h,k_{fT})]}{3(c_{11}^{\rm ew}A(y) + c_{33}^{\rm ew}C(y))\mathcal{C}[f_1(x,k_{iT})D_1(z_h,k_{fT})]}$$

Take Gaussian form for TMDs:

$$f_1(x,k_{iT}) = f_{1q}(x)\frac{1}{\pi\Delta_f^2}e^{-\vec{k}_{iT}^2/\Delta_f^2},$$

$$D_1(z_h,k_{fT}) = D_{1q}^{K^{*0}}(z_h)\frac{1}{\pi\Delta_D^2}e^{-\vec{k}_{fT}^2/\Delta_D^2},$$

$$D_{1LL}(z_h,k_{fT}) = D_{1LLq}^{K^{*0}}(z_h)\frac{1}{\pi\Delta_{LL}^2}e^{-\vec{k}_{fT}^2/\Delta_{LL}^2}.$$

$p_{h\perp}$ integrated →

$$\langle \bar{\rho}_{00}^{K^{*0}}\rangle = \frac{1}{3} - \frac{[c_{11}^{\rm ew}A(y) + c_{33}^{\rm ew}C(y)]f_{1q}(x)D_{1LLq}^{K^{*0}}(z_h)}{3[c_{11}^{\rm ew}A(y) + c_{33}^{\rm ew}C(y)]f_{1q}(x)D_{1q}^{K^{*0}}(z_h)}$$

Only depends on the **collinear part** of the TMDs

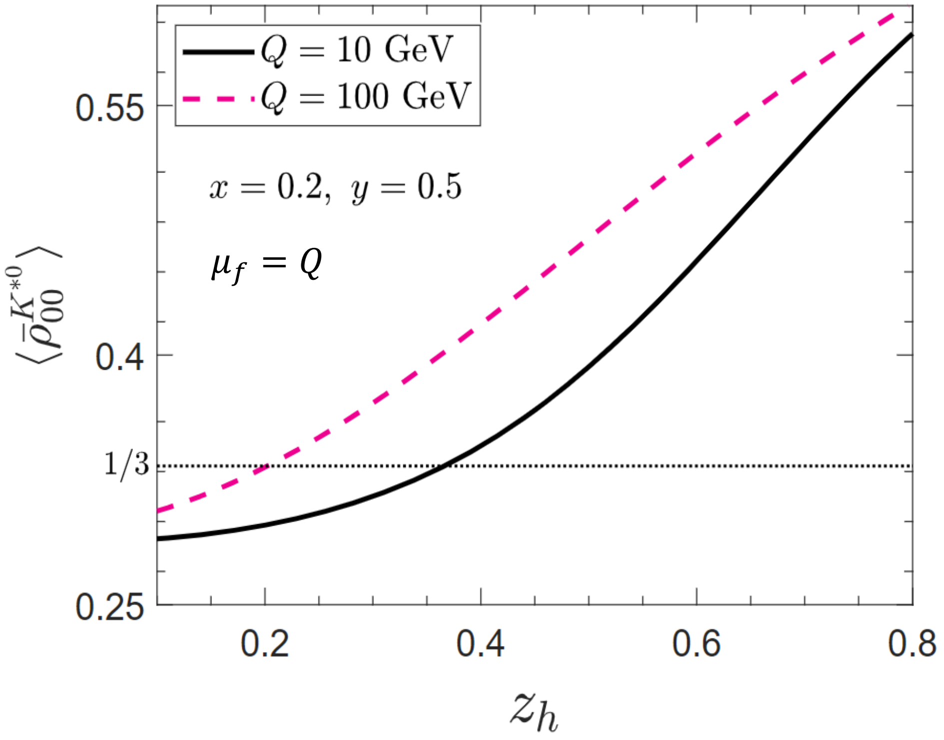
$f_{1q}(x)$: CTEQ14 NLO

$D_{1q}^{K^{*0}}(z_h)$, $D_{1LLq}^{K^{*0}}(z_h)$: K.B. Chen et al., *PRD102, 034001 (2020)*

Parton model results and the spin alignment

The spin alignment of the vector meson

- **In SIDIS:**

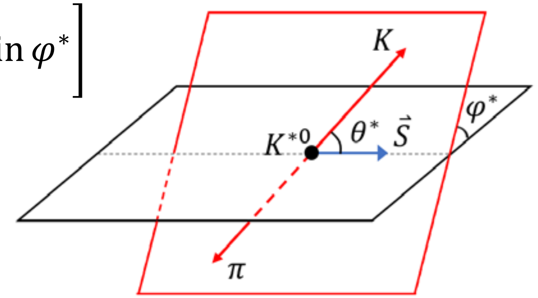


A rough numerical estimate of the spin alignment for K^{*0} production

- $\langle \bar{\rho}_{00}^{K^{*0}} \rangle$ deviates from 1/3 at both low and high Q
- $\langle \bar{\rho}_{00}^{K^{*0}} \rangle$ increases monotonically with z_h
- Scale dependence is relatively small

$$W(\cos\theta^*, \varphi^*) = \frac{3}{4\pi}\Big[\frac{1-\rho_{00}}{2} + \frac{3\rho_{00}-1}{2}\cos^2\theta^* - \mathrm{Re}\rho_{1-1}\sin^2\theta^*\cos 2\varphi^* - \frac{1}{\sqrt{2}}\mathrm{Re}(\rho_{10}-\rho_{0-1})\sin 2\theta^*\cos\varphi^* + \mathrm{Im}\rho_{1-1}\sin^2\theta^*\sin 2\varphi^* + \frac{1}{\sqrt{2}}\mathrm{Im}(\rho_{10}-\rho_{0-1})\sin 2\theta^*\sin\varphi^*\Big]$$

$$W(\cos\theta^*) = \frac{3}{4}[1-\rho_{00}+(3\rho_{00}-1)\cos^2\theta^*]$$



K. Ackerstaff et al., Z. Phys. C 74, 437 (1997)

Possible measurements at EicC, EIC, JLab ...

Summary

- We make a kinematic analysis for polarized vector meson production SIDIS. Considering the parity violating effects, the cross section is expressed by 81 structure functions.
- We give a parton model calculation in TMD factorization. There are 27 nonzero SFs at the leading twist; 15 tensor polarization dependent SFs; 13 new SFs generated by weak interaction.
- A rough numerical estimate of the spin alignment for K^{*0} production is given.

Thank you for your attention!