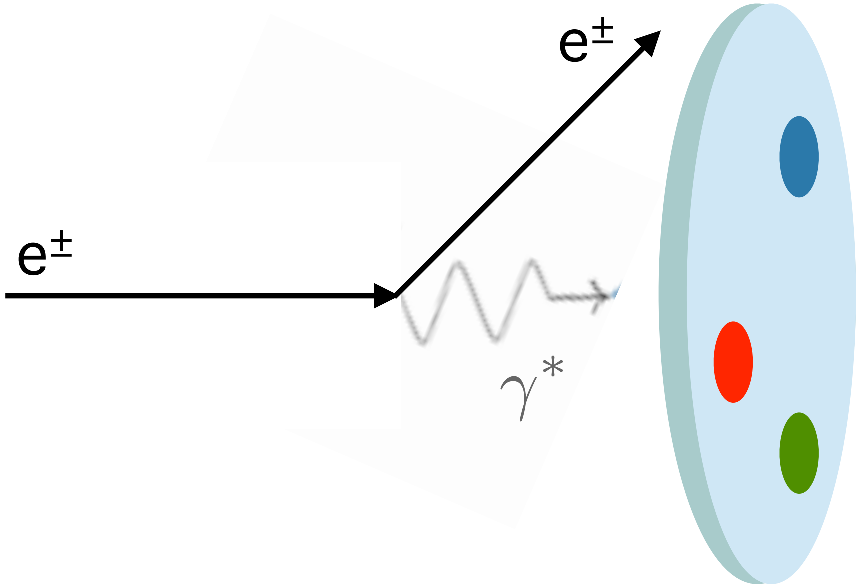
Possibilities for learning about the nucleon spin structure with positrons and electrons

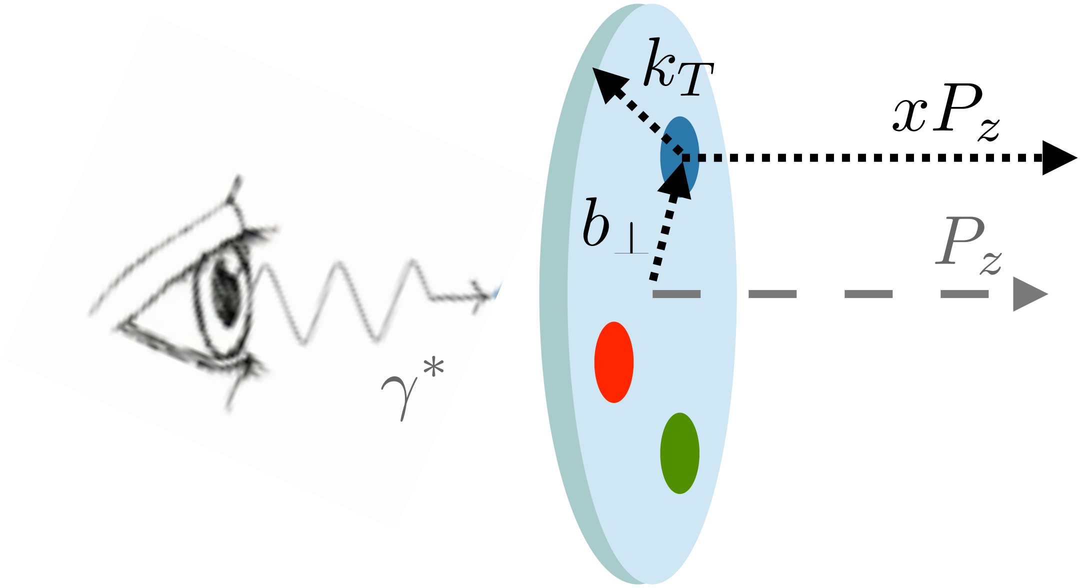
Charlotte Van Hulse
University of the Basque Country

JPos17
Jefferson Lab
12-15 Sep. 2017

Structure of the nucleon

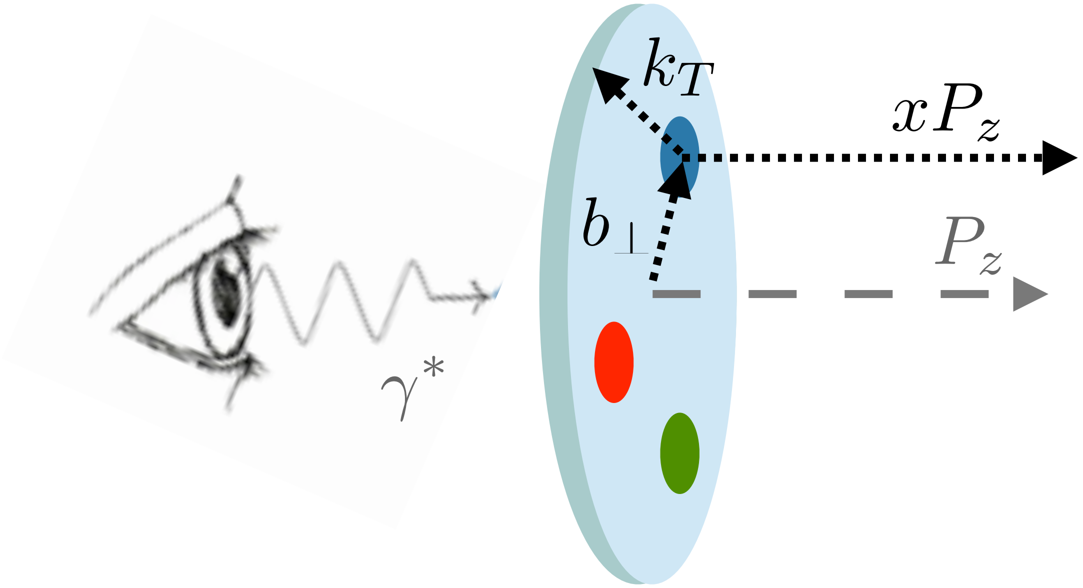


Structure of the nucleon



Structure of the nucleon

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

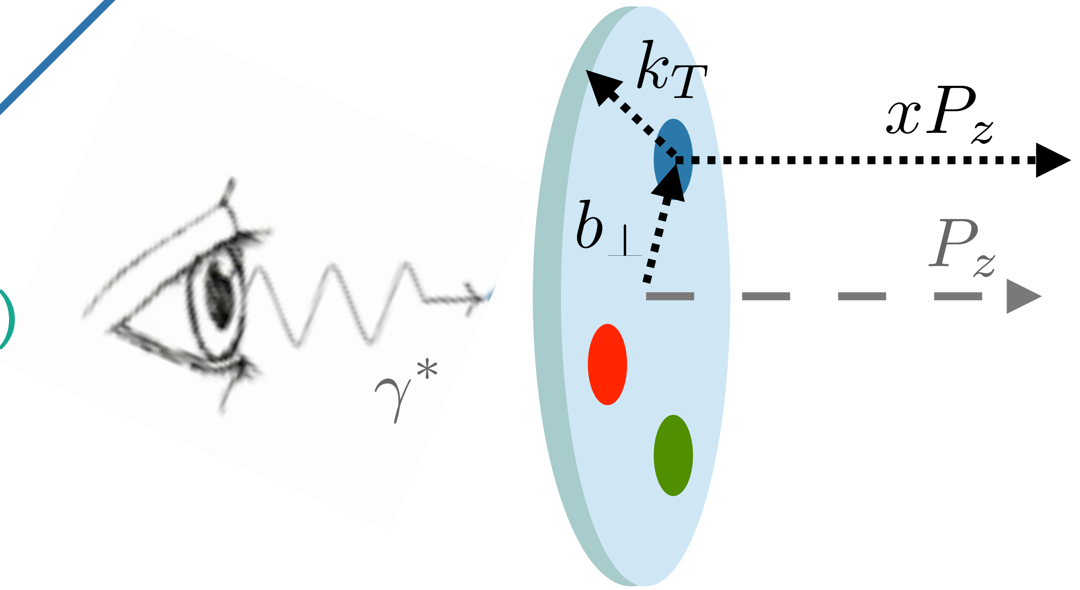


Structure of the nucleon

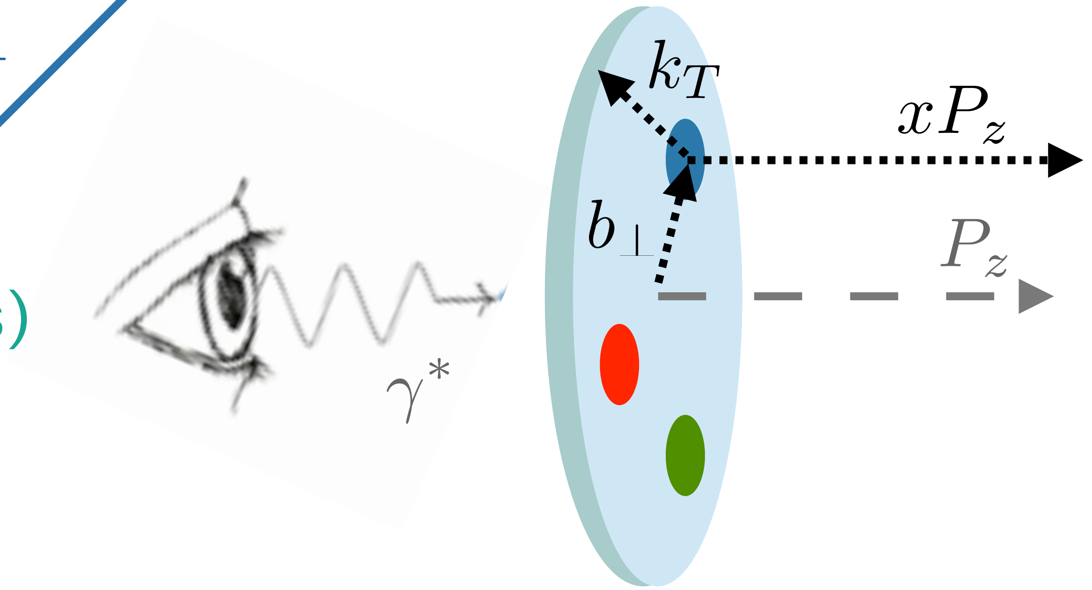
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent PDFs (TMDs)



Structure of the nucleon



Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent PDFs (TMDs)

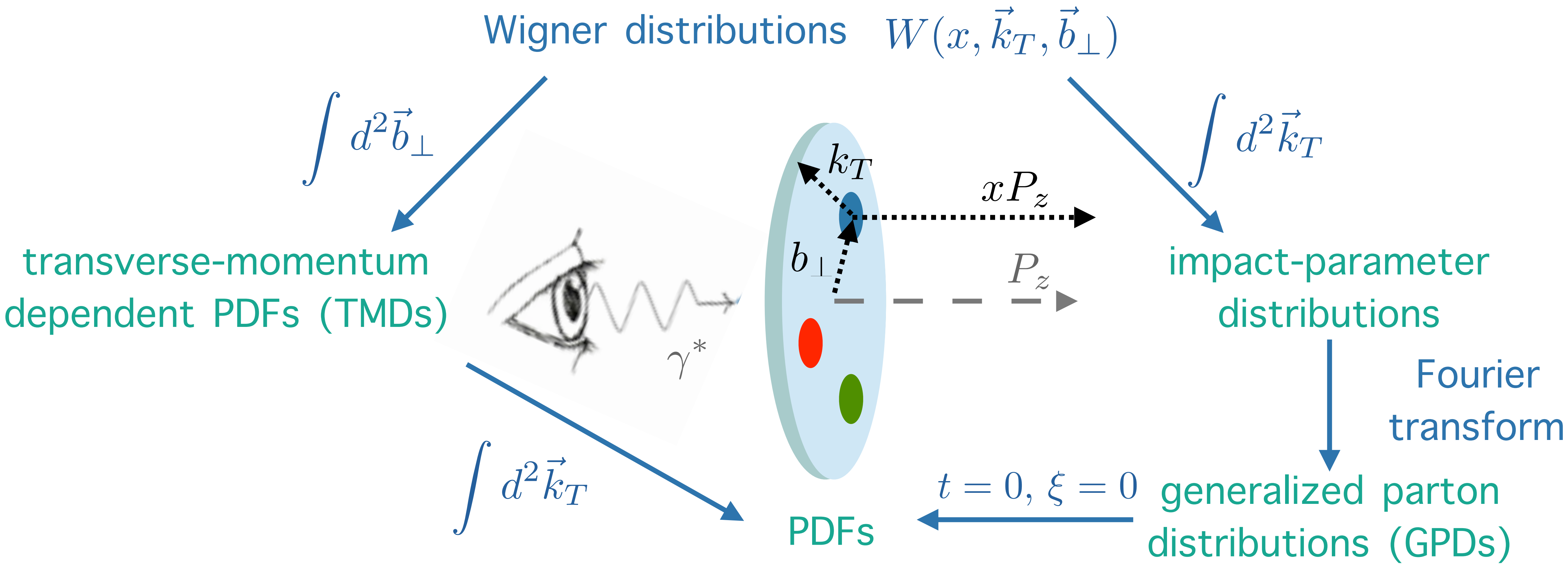
$\int d^2\vec{k}_T$

impact-parameter distributions

Fourier transform

generalized parton distributions (GPDs)

Structure of the nucleon



Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent PDFs (TMDs)

$\int d^2\vec{k}_T$

impact-parameter distributions

Fourier transform

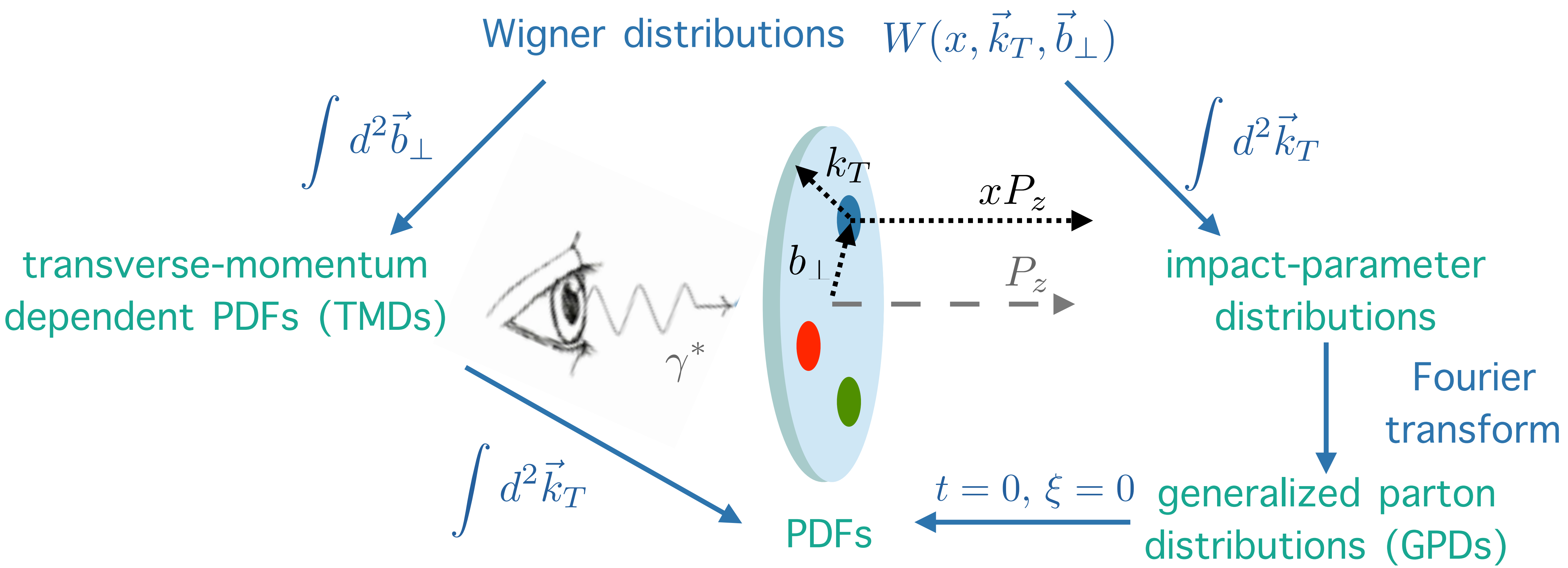
generalized parton distributions (GPDs)

$t = 0,\ \xi = 0$

PDFs

$\int d^2\vec{k}_T$

Structure of the nucleon



Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent PDFs (TMDs)

$\int d^2\vec{k}_T$

impact-parameter distributions

Fourier transform

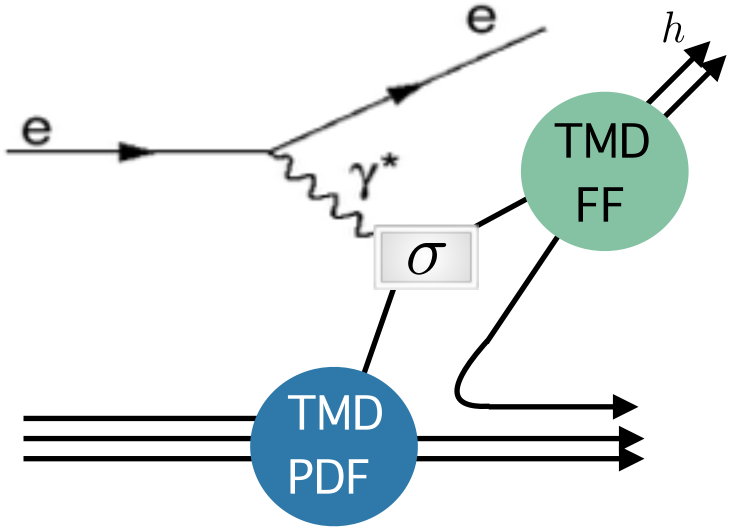
generalized parton distributions (GPDs)

$t = 0,\ \xi = 0$

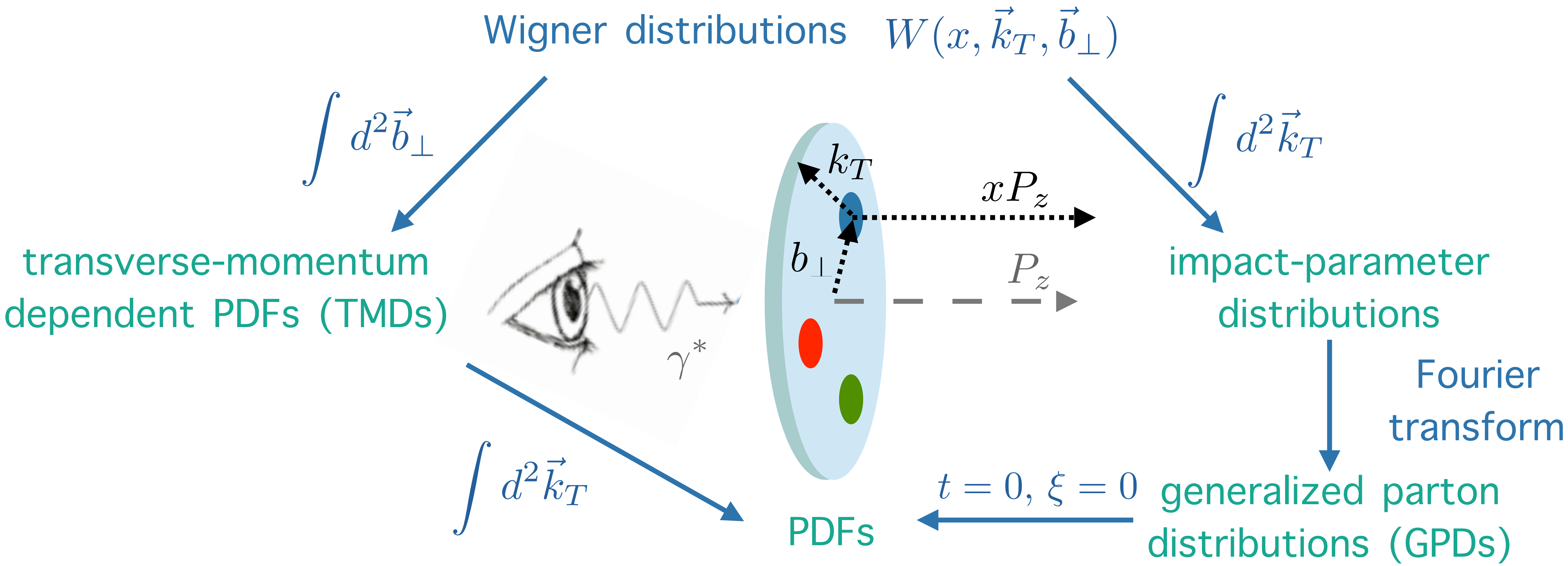
$\int d^2\vec{k}_T$

PDFs

semi-inclusive deep-inelastic scattering (DIS)



Structure of the nucleon



Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

$\int d^2\vec{k}_T$

transverse-momentum dependent PDFs (TMDs)

impact-parameter distributions

Fourier transform

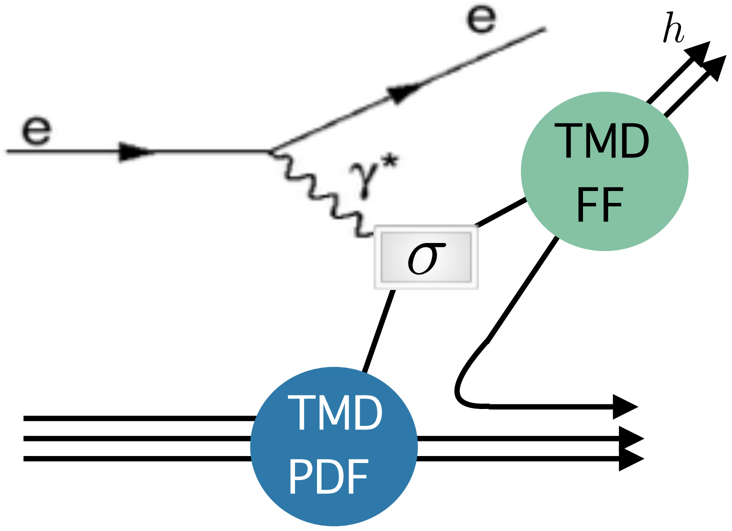
$\int d^2\vec{k}_T$

PDFs

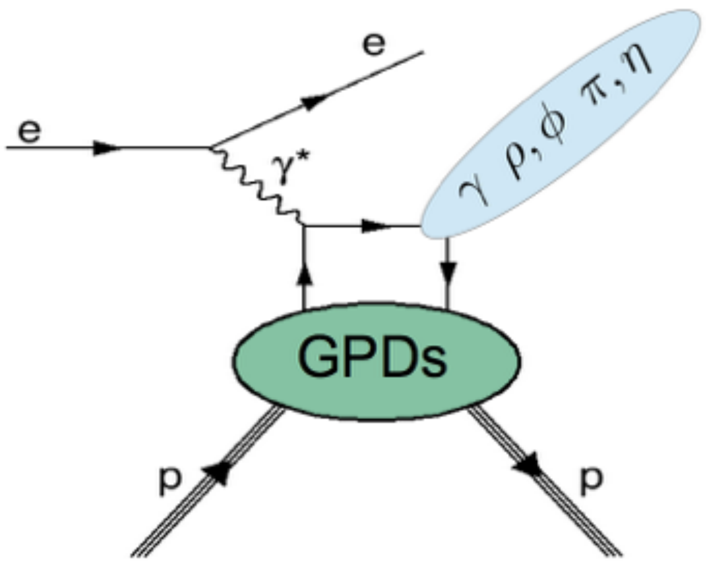
$t = 0,\ \xi = 0$

generalized parton distributions (GPDs)

semi-inclusive deep-inelastic scattering (DIS)

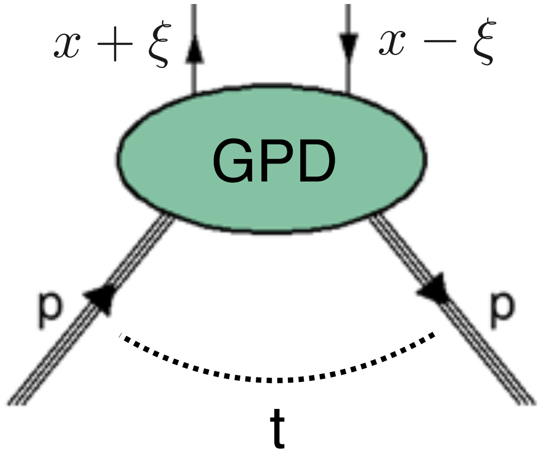


hard exclusive reactions



Deeply virtual Compton scattering and beam-charge asymmetries

GPDs and DVCS



- x=average longitudinal momentum fraction
- 2ξ=average longitudinal momentum transfer
- t=four-momentum transfer squared

quark-helicity conserving twist-2 GPDs

$H(x,\xi,t)$	$E(x,\xi,t)$	spin independent
$\tilde{H}(x,\xi,t)$	$\tilde{E}(x,\xi,t)$	spin dependent
nucleon helicity conservation	nucleon helicity flip	

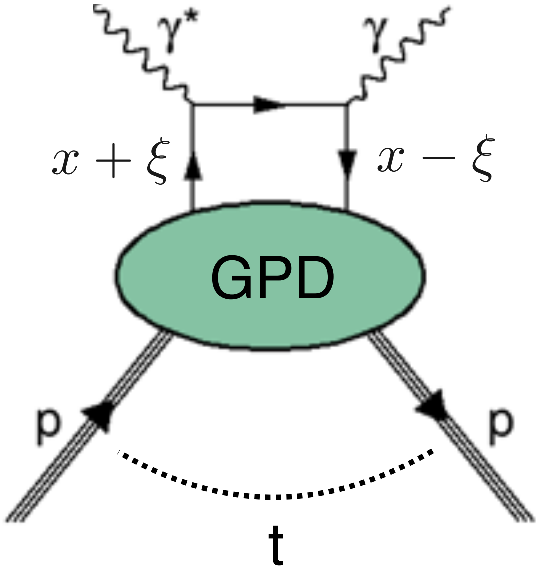
quark-helicity flip twist-2 GPDs

$H_T(x,\xi,t)$	$E_T(x,\xi,t)$
$\tilde{H}_T(x,\xi,t)$	$\tilde{E}_T(x,\xi,t)$

$$J = \lim_{t\to 0} \frac{1}{2} \int_{-1}^{1} dx\, x \left[H(x,\xi,t) + E(x,\xi,t)\right]$$

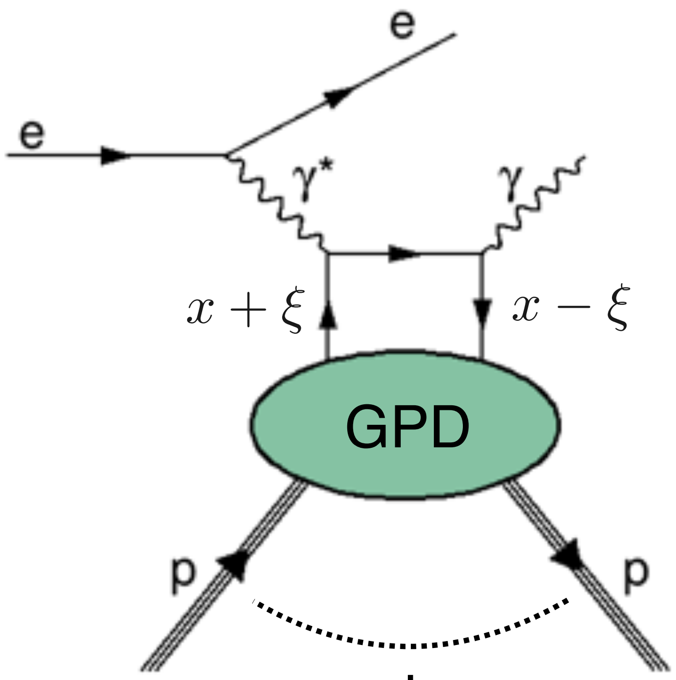
X. Ji, Phys. Rev. Lett. 78 (1997) 610

GPDs and DVCS



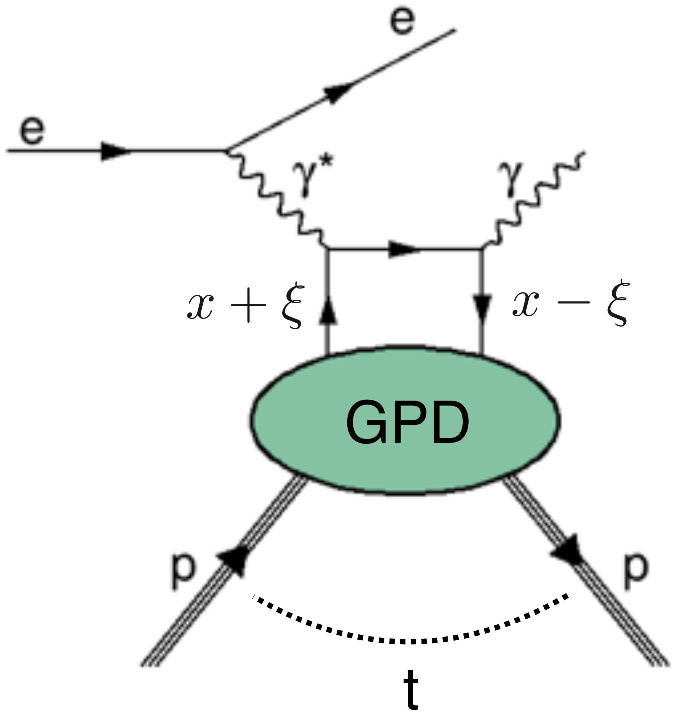
DVCS

GPDs and DVCS

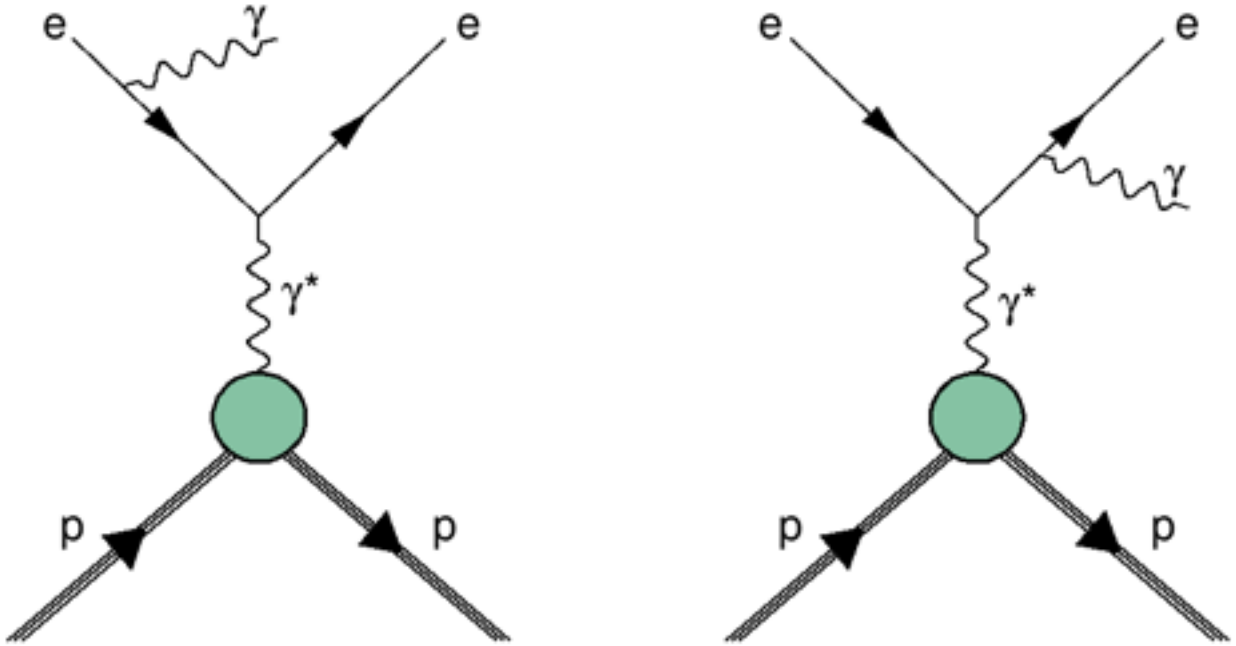


t
DVCS

GPDs and DVCS

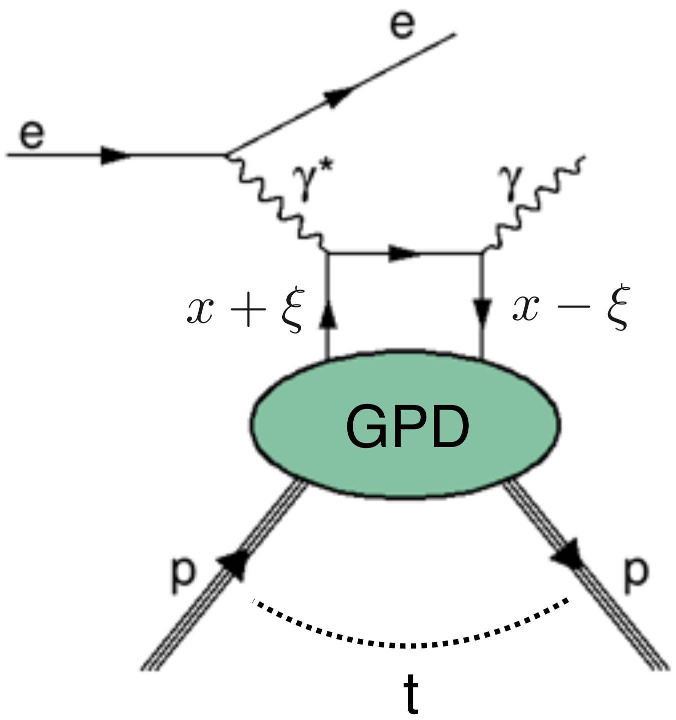


DVCS

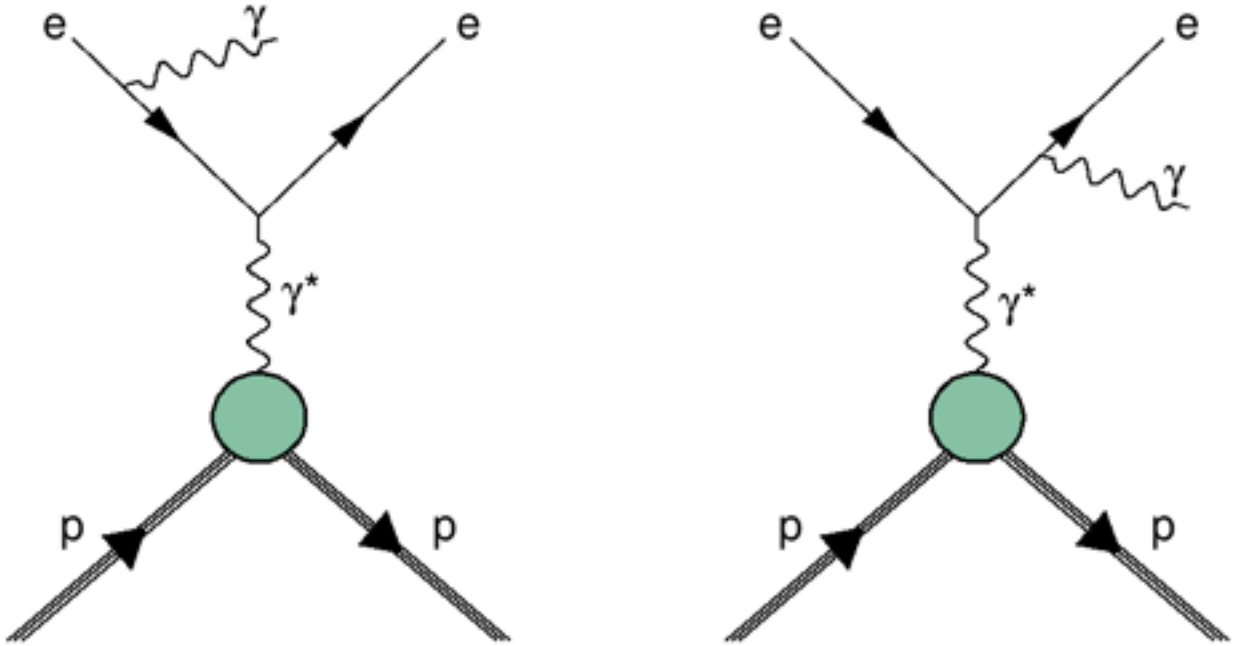


Bethe-Heitler

GPDs and DVCS



DVCS



Bethe-Heitler

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH}$$

DVCS cross section

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH}$$

Unpolarized nucleon
Longitudinally polarized lepton beam

DVCS cross section

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{DVCS}\tau^*_{BH} + \tau^*_{DVCS}\tau_{BH}$$

Unpolarized nucleon
Longitudinally polarized lepton beam

$$|\tau_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{2} c_n^{BH} \cos(n\phi) \right\}$$

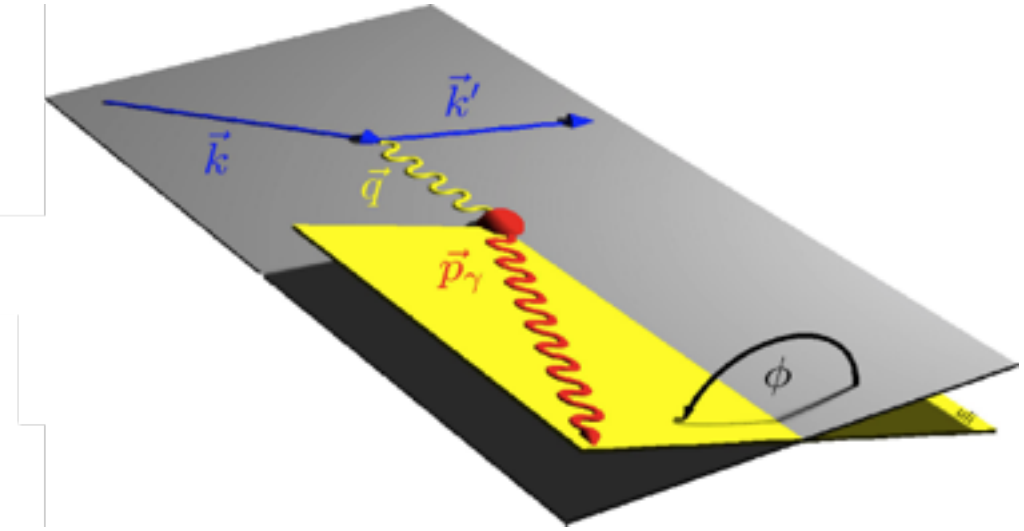
calculable with knowledge Pauli & Dirac form factors

$$|\tau_{DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + \lambda\, s_1^{DVCS} \sin(\phi) \right\}$$

coefficients: bilinear in GPDs

$$\mathcal{I} = \frac{-e_l\, K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right\}$$

coefficients: linear in GPDs



DVCS cross section

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{DVCS}\tau^*_{BH} + \tau^*_{DVCS}\tau_{BH}$$

Unpolarized nucleon
Longitudinally polarized lepton beam

$$|\tau_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{2} c_n^{BH} \cos(n\phi) \right\}$$

calculable with knowledge Pauli & Dirac form factors

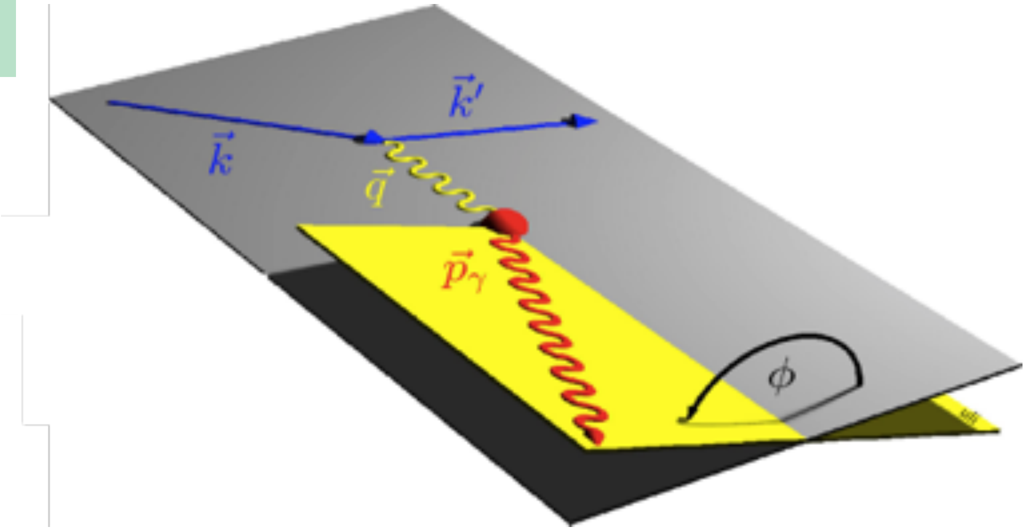
$$|\tau_{DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + \lambda\, s_1^{DVCS} \sin(\phi) \right\}$$

coefficients: bilinear in GPDs

$$\mathcal{I} = \frac{-e_l\, K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right\}$$

coefficients: linear in GPDs

beam
polarization



DVCS cross section

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH}$$

Unpolarized nucleon
Longitudinally polarized lepton beam

$$|\tau_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{2} c_n^{BH} \cos(n\phi) \right\}$$

calculable with knowledge Pauli & Dirac form factors

$$|\tau_{DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + \lambda\, s_1^{DVCS} \sin(\phi) \right\}$$

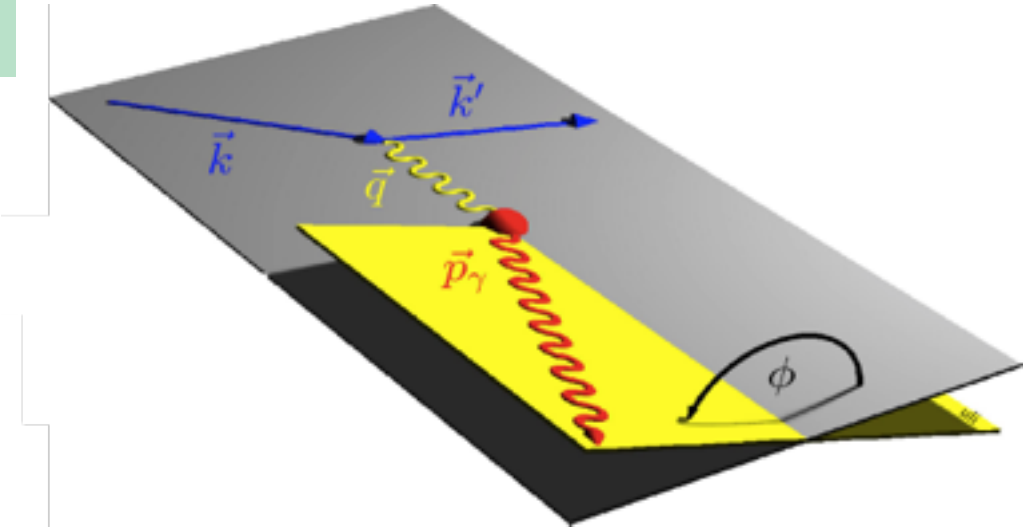
coefficients: bilinear in GPDs

$$\mathcal{I} = \frac{-e_l K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right\}$$

coefficients: linear in GPDs

beam charge

beam polarization



DVCS cross section

$$\mathcal{I} = \frac{-e_l\, K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right\}$$

$c_1^{\mathcal{I}} \propto \Re M^{1,1}$

$s_1^{\mathcal{I}} \propto \Im M^{1,1}$

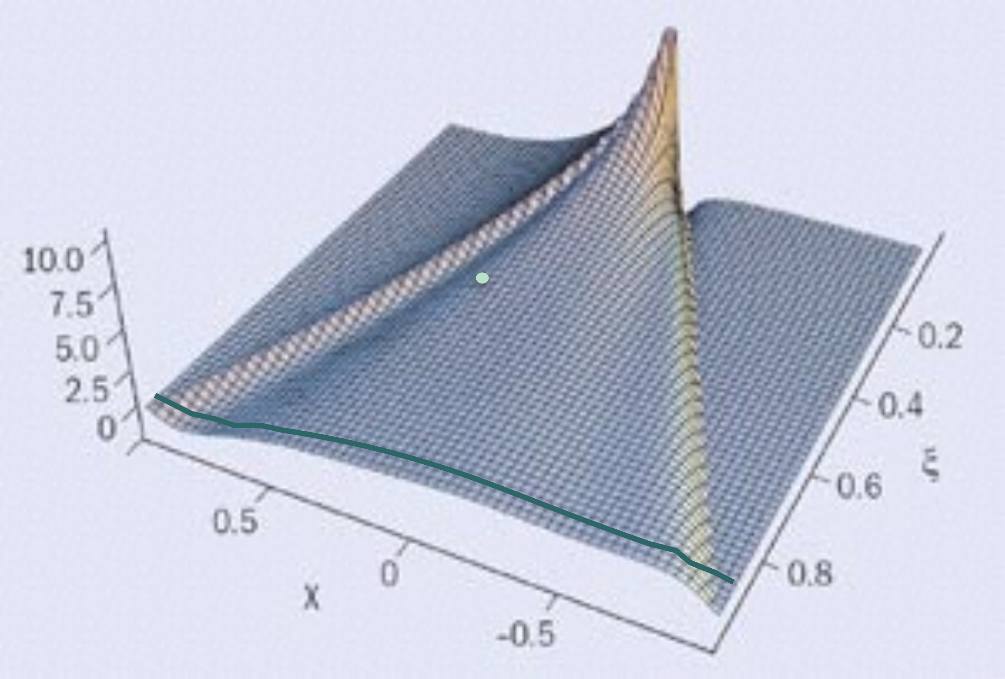
$$M^{1,1} = F_1(t)\,\mathcal{H}(\xi,t) + \frac{x_B}{2-x_B}(F_1(t)+F_2(t))\,\tilde{\mathcal{H}}(\xi,t) - \frac{t}{4M_p^2}\,F_2(t)\mathcal{E}(\xi,t)$$

CFF $\mathcal{H}, \tilde{\mathcal{H}}, \mathcal{E}$ =convolution GPD x hard scattering amplitude

At LO: $\Im$ direct access to GPDs at $x = \pm\xi$

$\Re$ convolution integral over x

+ access to D-term



Beam-charge asymmetry

$$\mathcal{A}_{\mathrm{C}}(\phi) \equiv \frac{d\sigma^{+} - d\sigma^{-}}{d\sigma^{+} + d\sigma^{-}} = \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{3} c_n^{I} \cos(n\phi)}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + \frac{1}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}$$

Beam-charge asymmetry

$$\mathcal{A}_{\mathrm{C}}(\phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{3} c_n^I \cos(n\phi)}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + \frac{1}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}$$

Beam-charge asymmetry

$$\mathcal{A}_{\mathrm{C}}(\phi) \equiv \frac{d\sigma^{+} - d\sigma^{-}}{d\sigma^{+} + d\sigma^{-}} = \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{3} \boxed{c_n^I \cos(n\phi)}}{\boxed{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)} + \boxed{\frac{1}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}}$$

calculable

- c_n^{DVCS} expected small at HERMES
- suppressed as $1/Q^2$

Beam-charge asymmetry

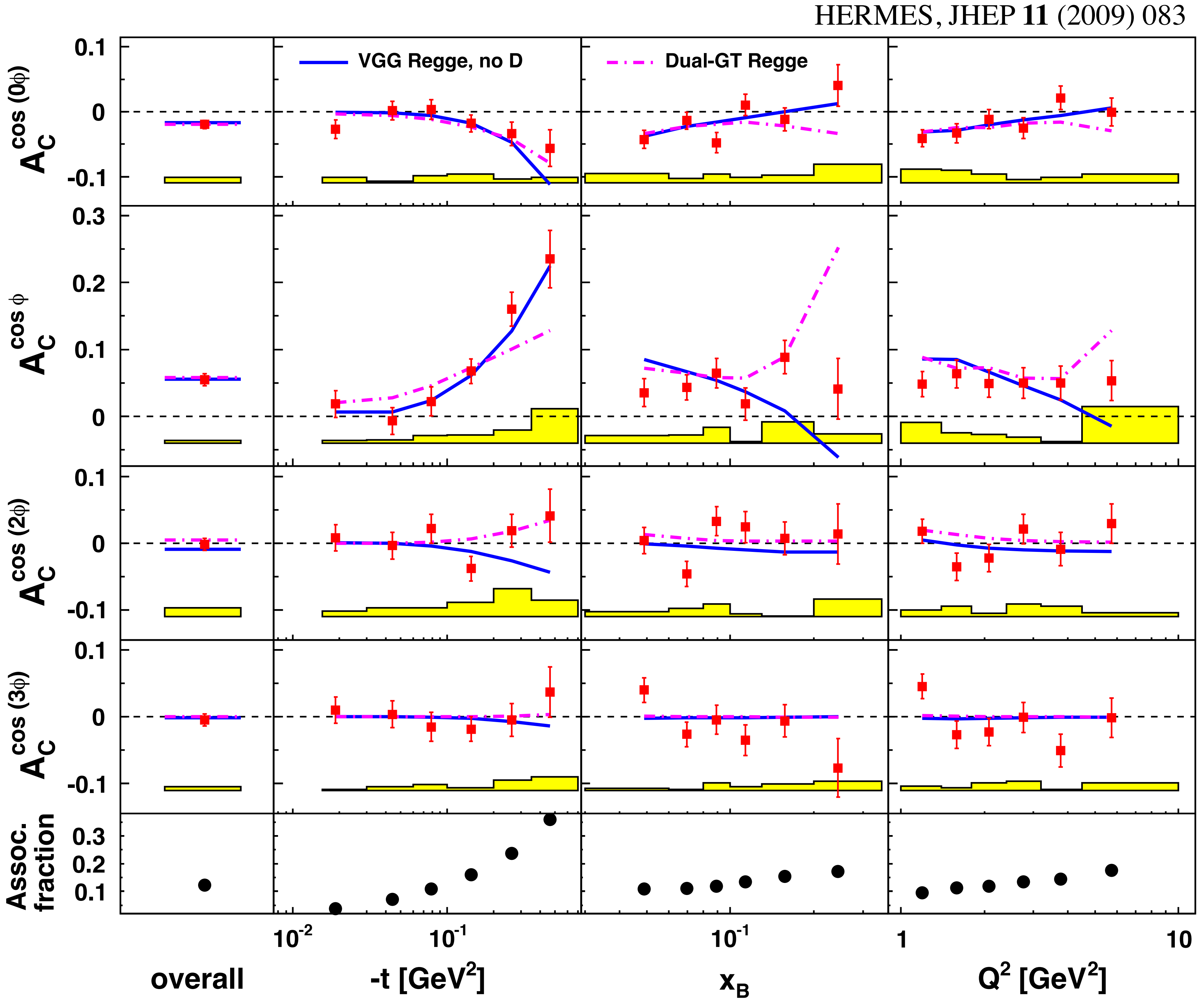
$$\mathcal{A}_{\mathrm{C}}(\phi) \equiv \frac{d\sigma^{+} - d\sigma^{-}}{d\sigma^{+} + d\sigma^{-}} = \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{3} c_n^{I} \cos(n\phi)}{\xcancel{\boxed{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)} + \boxed{\frac{1}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}}}$$

calculable

- c_n^{DVCS} expected small at HERMES
- suppressed as $1/Q^2$

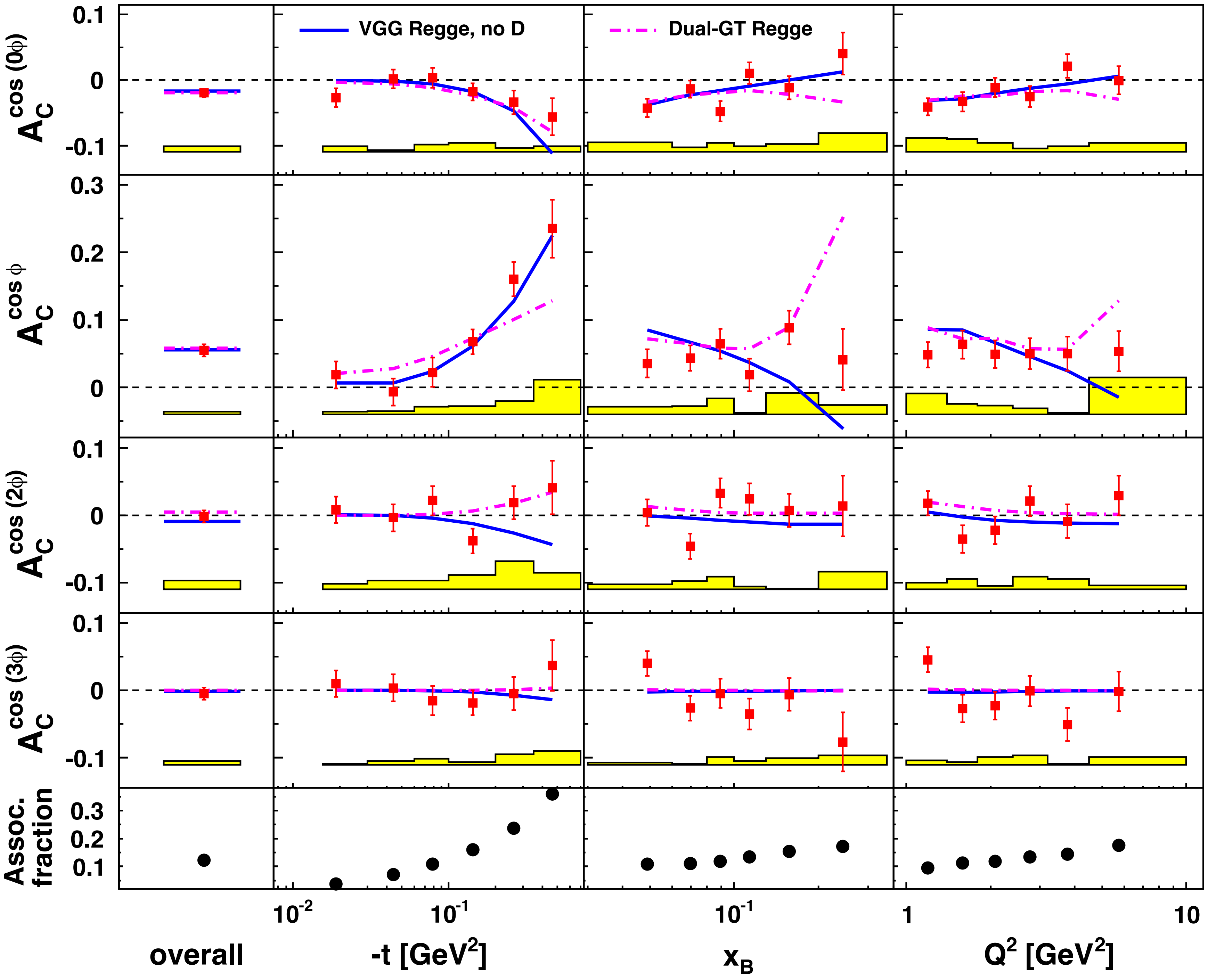
Cross section differences

Beam-charge asymmetry



Beam-charge asymmetry

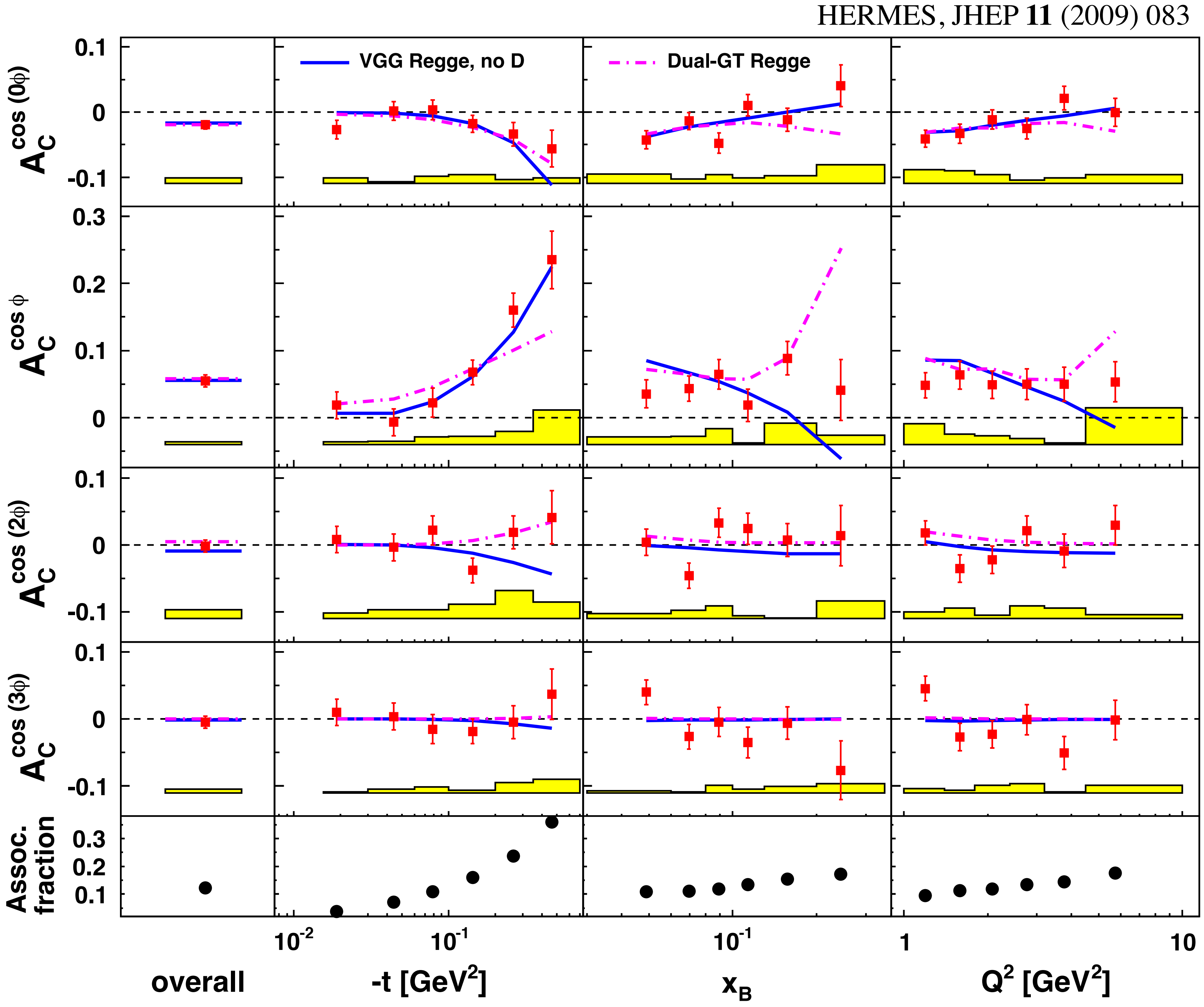
HERMES, JHEP **11** (2009) 083



$\Re M^{1,1}$

twist-2 GPDs

Beam-charge asymmetry

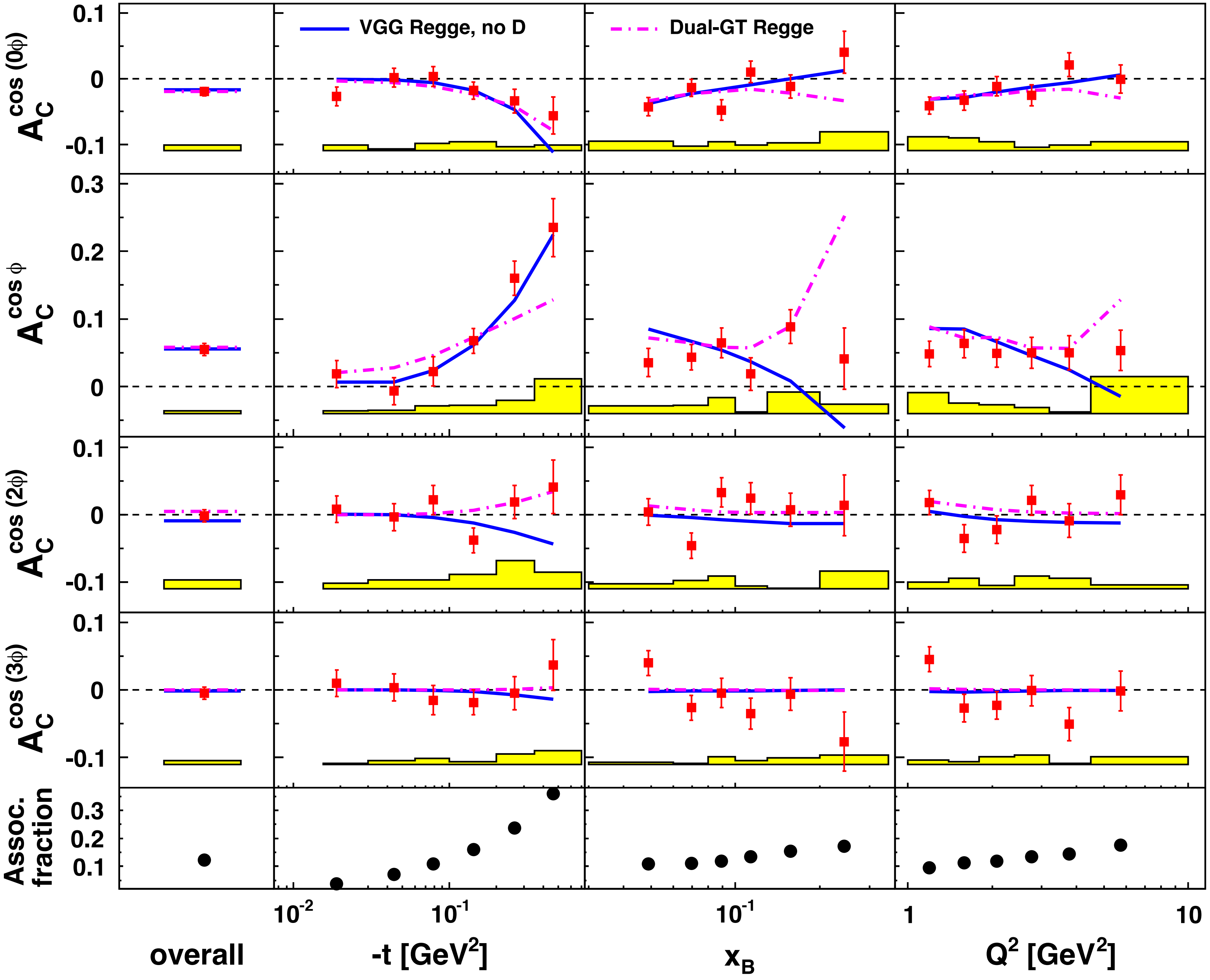


$c_0^{\mathcal{I}} \propto -k\, c_1^{\mathcal{I}}$

$\Re M^{1,1}$

twist-2 GPDs

Beam-charge asymmetry



HERMES, JHEP **11** (2009) 083

$c_0^{\mathcal{I}} \propto -k\, c_1^{\mathcal{I}}$

$\Re M^{1,1}$

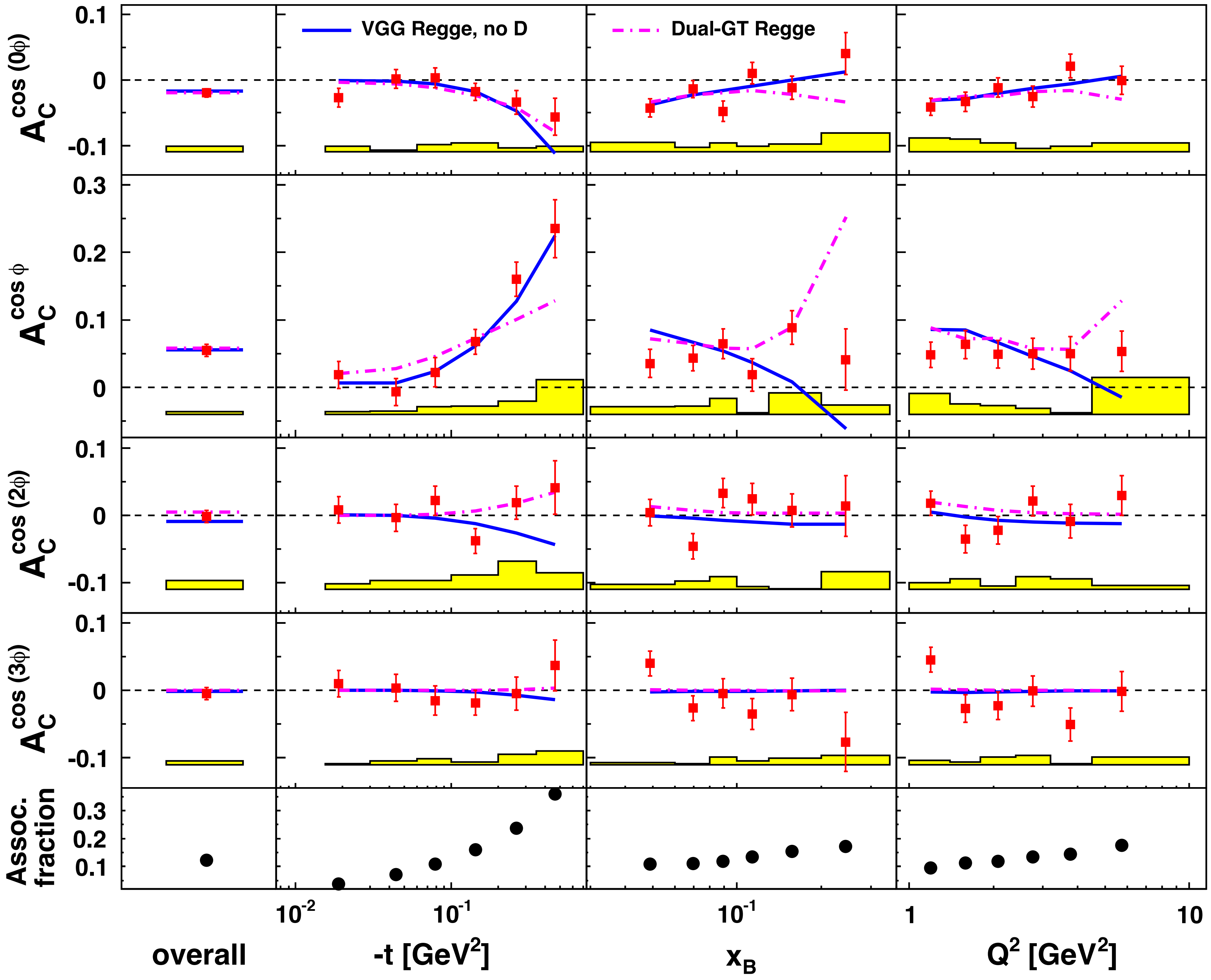
twist-2 GPDs

$\Re M^{0,\pm 1}$:

twist-3 GPDs

Beam-charge asymmetry

HERMES, JHEP **11** (2009) 083



$c_0^{\mathcal{I}} \propto -k\, c_1^{\mathcal{I}}$

$\Re M^{1,1}$

twist-2 GPDs

$\Re M^{0,\pm 1}$:

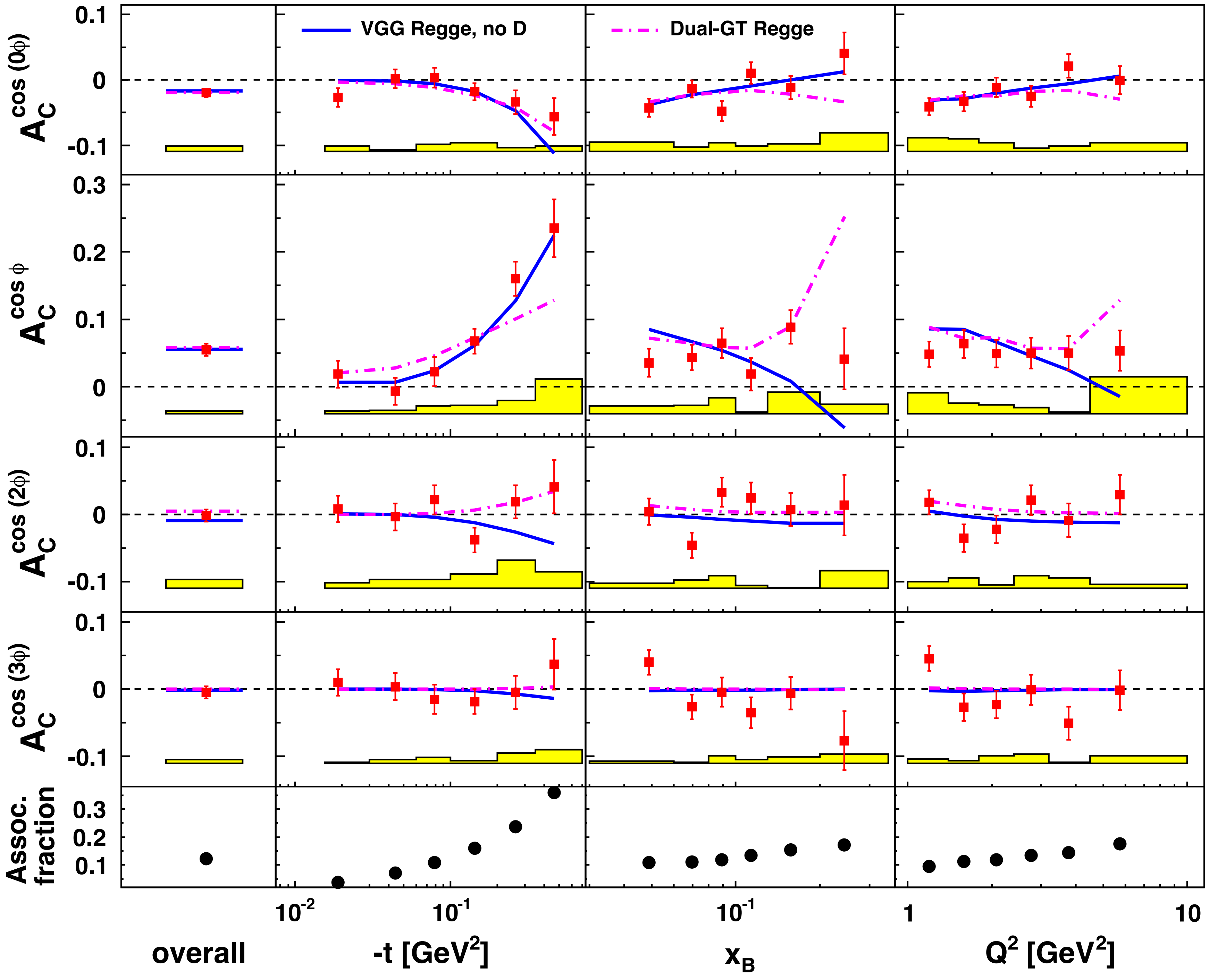
twist-3 GPDs

$\Re M^{\mp 1,\pm 1}$:

twist-2 gluon helicity-flip GPDs

Beam-charge asymmetry

HERMES, JHEP **11** (2009) 083



$c_0^{\mathcal{I}} \propto -k\, c_1^{\mathcal{I}}$

$\Re M^{1,1}$

twist-2 GPDs

$\Re M^{0,\pm 1}$:

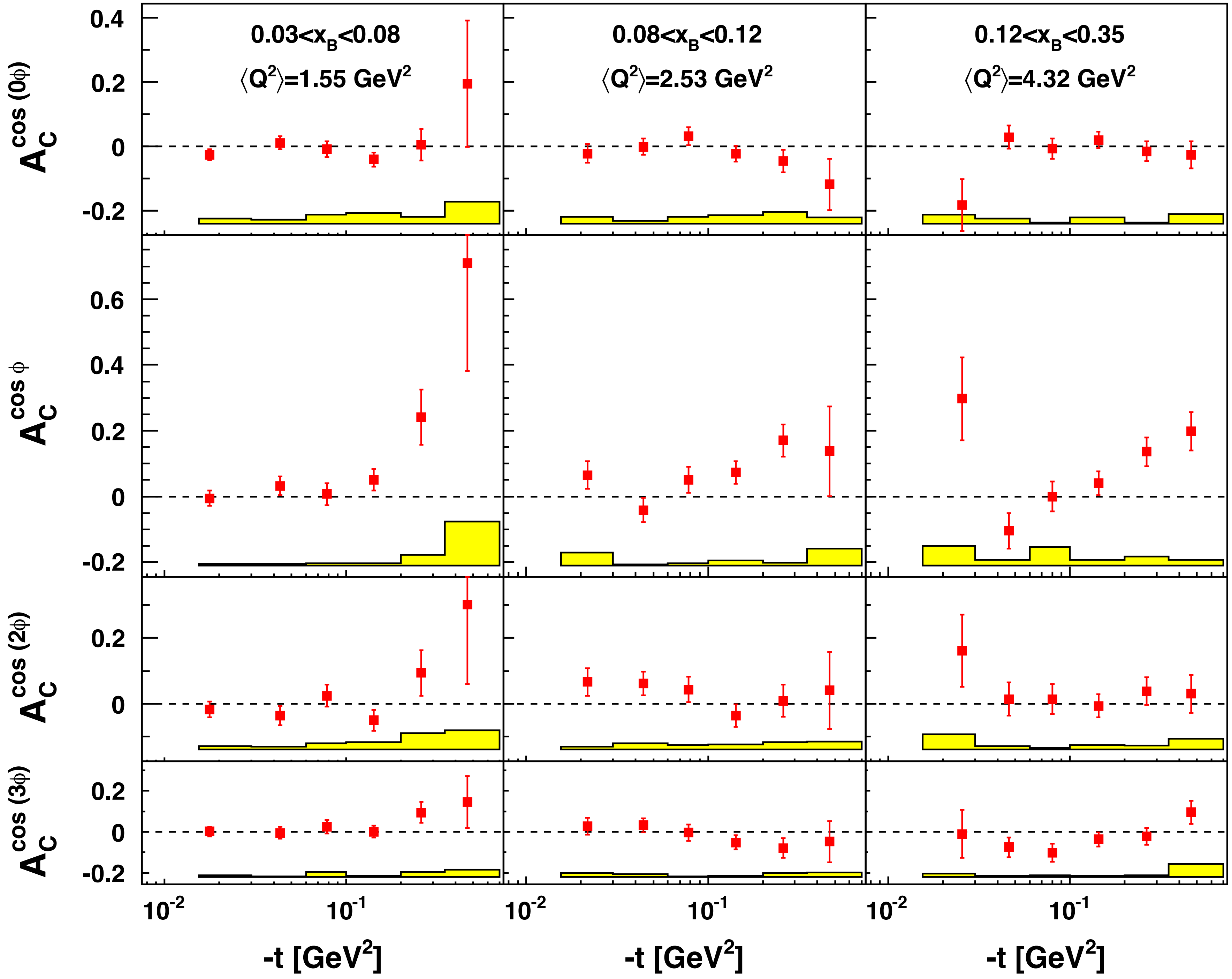
twist-3 GPDs

$\Re M^{\mp 1,\pm 1}$:

twist-2 gluon helicity-flip GPDs

$ep \to e\gamma N\pi$

Beam-charge asymmetry



HERMES, JHEP **11** (2009) 083

$c_0^{\mathcal{I}} \propto -k\, c_1^{\mathcal{I}}$

$\Re M^{1,1}$

twist-2 GPDs

$\Re M^{0,\pm1}$:

twist-3 GPDs

$\Re M^{\mp1,\pm1}$:

twist-2 gluon helicity-flip GPDs

Beam-helicity asymmetry

Beam-helicity asymmetry

Unpolarized nucleon
Longitudinally polarized lepton beam

$$|\tau_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{2} c_n^{BH} \cos(n\phi) \right\}$$

Calculable with knowledge Pauli & Dirac form factors

$$|\tau_{DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + \lambda\, s_1^{DVCS} \sin(\phi) \right\}$$

coefficients: bilinear in GPDs

$$\mathcal{I} = \frac{-e_l\, K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right\}$$

coefficients: linear in GPDs

beam
charge

beam
polarization

Beam-helicity asymmetry

$$\mathcal{A}_{\mathrm{LU}}(\phi, e_\ell) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

$$= \frac{-e_\ell \frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=1}^{2} s_n^{\mathrm{I}} \sin(n\phi)\right] + \frac{1}{Q^2} s_1^{\mathrm{DVCS}} \sin\phi}{\frac{1}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[K_{\mathrm{BH}} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) - e_\ell K_{\mathrm{I}} \sum_{n=0}^{3} c_n^{\mathrm{I}} \cos(n\phi)\right] + \frac{1}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}$$

Beam-helicity asymmetry

$$\mathcal{A}_{\mathrm{LU}}(\phi, e_\ell) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

$$= \frac{-e_\ell \frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=1}^{2} s_n^{\mathrm{I}} \sin(n\phi)\right] + \frac{1}{Q^2} s_1^{\mathrm{DVCS}} \sin\phi}{\frac{1}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[K_{\mathrm{BH}} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) - e_\ell K_{\mathrm{I}} \sum_{n=0}^{3} c_n^{\mathrm{I}} \cos(n\phi)\right] + \frac{1}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}$$

Beam-helicity asymmetry

$$\mathcal{A}_{\mathrm{LU}}(\phi, e_\ell) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

- s_1^{DVCS} twist-3
- suppressed as $1/Q^2$

$$= \frac{-e_\ell \frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=1}^{2} s_n^{\mathrm{I}} \sin(n\phi) \right] + \frac{1}{Q^2} s_1^{\mathrm{DVCS}} \sin\phi}{\frac{1}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[K_{\mathrm{BH}} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) - e_\ell K_{\mathrm{I}} \sum_{n=0}^{3} c_n^{\mathrm{I}} \cos(n\phi) \right] + \frac{1}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}$$

Beam-helicity asymmetry

$$\mathcal{A}_{\mathrm{LU}}(\phi, e_\ell) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

$$= \frac{-e_\ell \frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=1}^{2} s_n^{\mathrm{I}} \sin(n\phi)\right] + \frac{1}{Q^2} s_1^{\mathrm{DVCS}} \sin\phi}{\frac{1}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left[K_{\mathrm{BH}} \sum_{n=0}^{2} \underset{\text{calculable}}{\boxed{c_n^{\mathrm{BH}} \cos(n\phi)}} - e_\ell K_{\mathrm{I}} \sum_{n=0}^{3} c_n^{\mathrm{I}} \cos(n\phi)\right] + \boxed{\frac{1}{Q^2}\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}}$$

- s_1^{DVCS} twist-3
- suppressed as $1/Q^2$

- c_n^{DVCS} expected small at HERMES
- suppressed as $1/Q^2$

Beam-helicity asymmetry

$$\mathcal{A}_{\rm LU}(\phi, e_\ell) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

- $s_1^{\rm DVCS}$ twist-3
- suppressed as $1/Q^2$

$$= \frac{-e_\ell \frac{K_{\rm I}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left[\sum_{n=1}^{2} s_n^{\rm I}\sin(n\phi)\right] + \frac{1}{Q^2}s_1^{\rm DVCS}\sin\phi}{\frac{1}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left[K_{\rm BH}\sum_{n=0}^{2}\boxed{c_n^{\rm BH}\cos(n\phi)} - \boxed{e_\ell K_{\rm I}\sum_{n=0}^{3} c_n^{\rm I}\cos(n\phi)}\right] + \boxed{\frac{1}{Q^2}\sum_{n=0}^{2} c_n^{\rm DVCS}\cos(n\phi)}}$$

calculable

twist-2 $c_0^{\rm I}, c_1^{\rm I} \neq 0$

- $c_n^{\rm DVCS}$ expected small at HERMES
- suppressed as $1/Q^2$

Beam-helicity asymmetries

Charge-difference beam-helicity asymmetry

$$\mathcal{A}_{\mathrm{LU}}^{\mathrm{I}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) - (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

$$= \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=1}^{2} s_n^{\mathrm{I}} \sin(n\phi)\right]}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + \frac{1}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}$$

Beam-helicity asymmetries

Charge-difference beam-helicity asymmetry

linear access to GPDs

$$\mathcal{A}_{\mathrm{LU}}^{\mathrm{I}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) - (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

$$= \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left[\sum_{n=1}^{2} \boxed{s_n^{\mathrm{I}} \sin(n\phi)}\right]}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{2} c_n^{\mathrm{BH}}\cos(n\phi) + \frac{1}{Q^2}\sum_{n=0}^{2} c_n^{\mathrm{DVCS}}\cos(n\phi)}$$

Beam-helicity asymmetries

Charge-difference beam-helicity asymmetry

linear access to GPDs

$$\mathcal{A}^{\mathrm{I}}_{\mathrm{LU}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) - (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

$$= \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left[\sum_{n=1}^{2} s_n^{\mathrm{I}} \sin(n\phi)\right]}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + \frac{1}{Q^2}\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}$$

Charge-averaged beam-helicity asymmetry

$$\mathcal{A}^{\mathrm{DVCS}}_{\mathrm{LU}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

$$= \frac{\frac{1}{Q^2}\, s_1^{\mathrm{DVCS}} \sin\phi}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + \frac{1}{Q^2}\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}$$

Beam-helicity asymmetries

Charge-difference beam-helicity asymmetry

linear access to GPDs

$$\mathcal{A}_{\mathrm{LU}}^{\mathrm{I}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) - (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

$$= \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left[\sum_{n=1}^{2} s_n^{\mathrm{I}} \sin(n\phi)\right]}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{2} c_n^{\mathrm{BH}}\cos(n\phi) + \frac{1}{Q^2}\sum_{n=0}^{2} c_n^{\mathrm{DVCS}}\cos(n\phi)}$$

Charge-averaged beam-helicity asymmetry

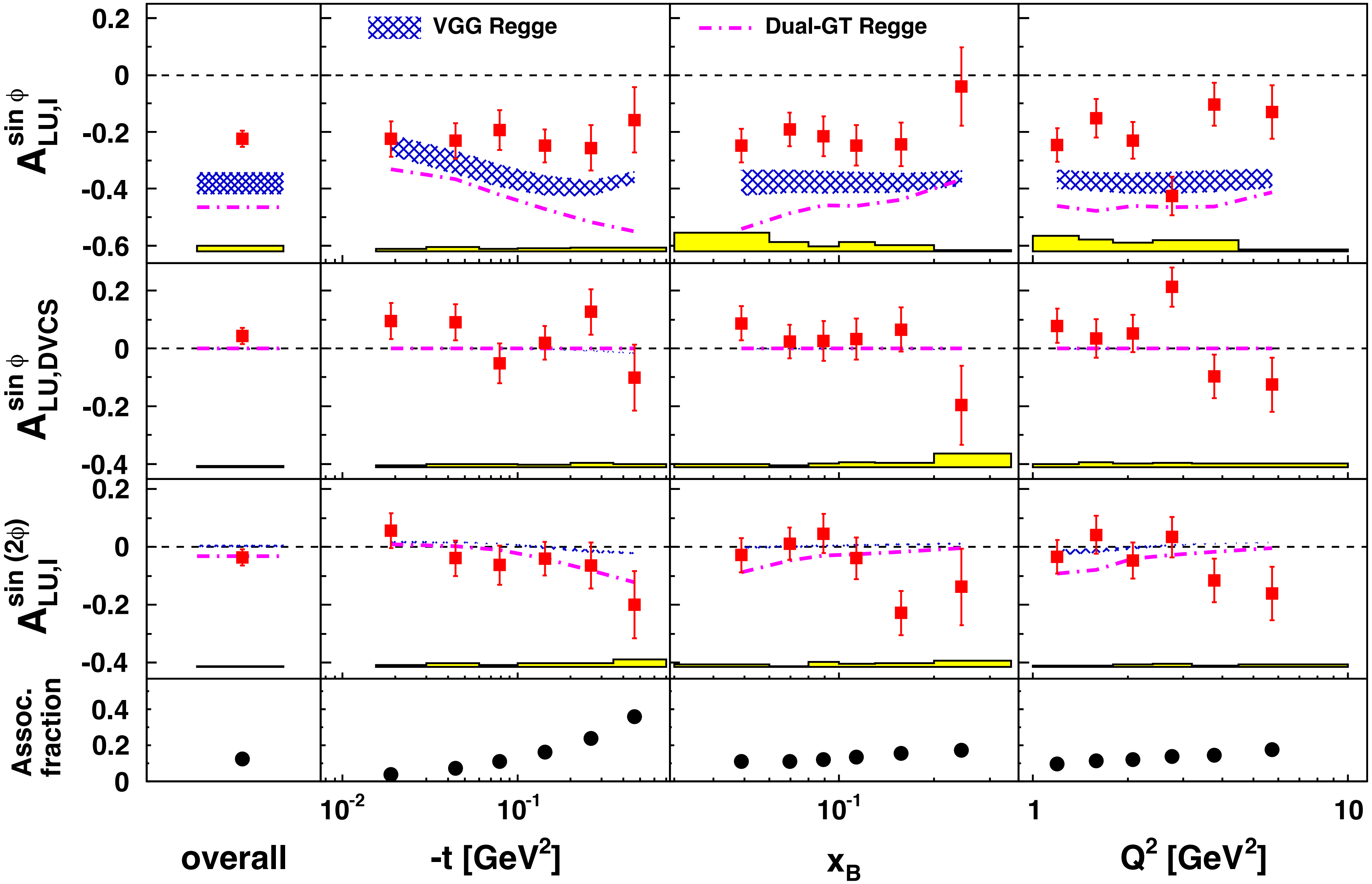
bilinear access to GPDs

$$\mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

$$= \frac{\frac{1}{Q^2}\, s_1^{\mathrm{DVCS}} \sin\phi}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{2} c_n^{\mathrm{BH}}\cos(n\phi) + \frac{1}{Q^2}\sum_{n=0}^{2} c_n^{\mathrm{DVCS}}\cos(n\phi)}$$

Charge-difference and charge-average beam-helicity asymmetry

HERMES, JHEP **11** (2009) 083



$\Im M^{1,1}$

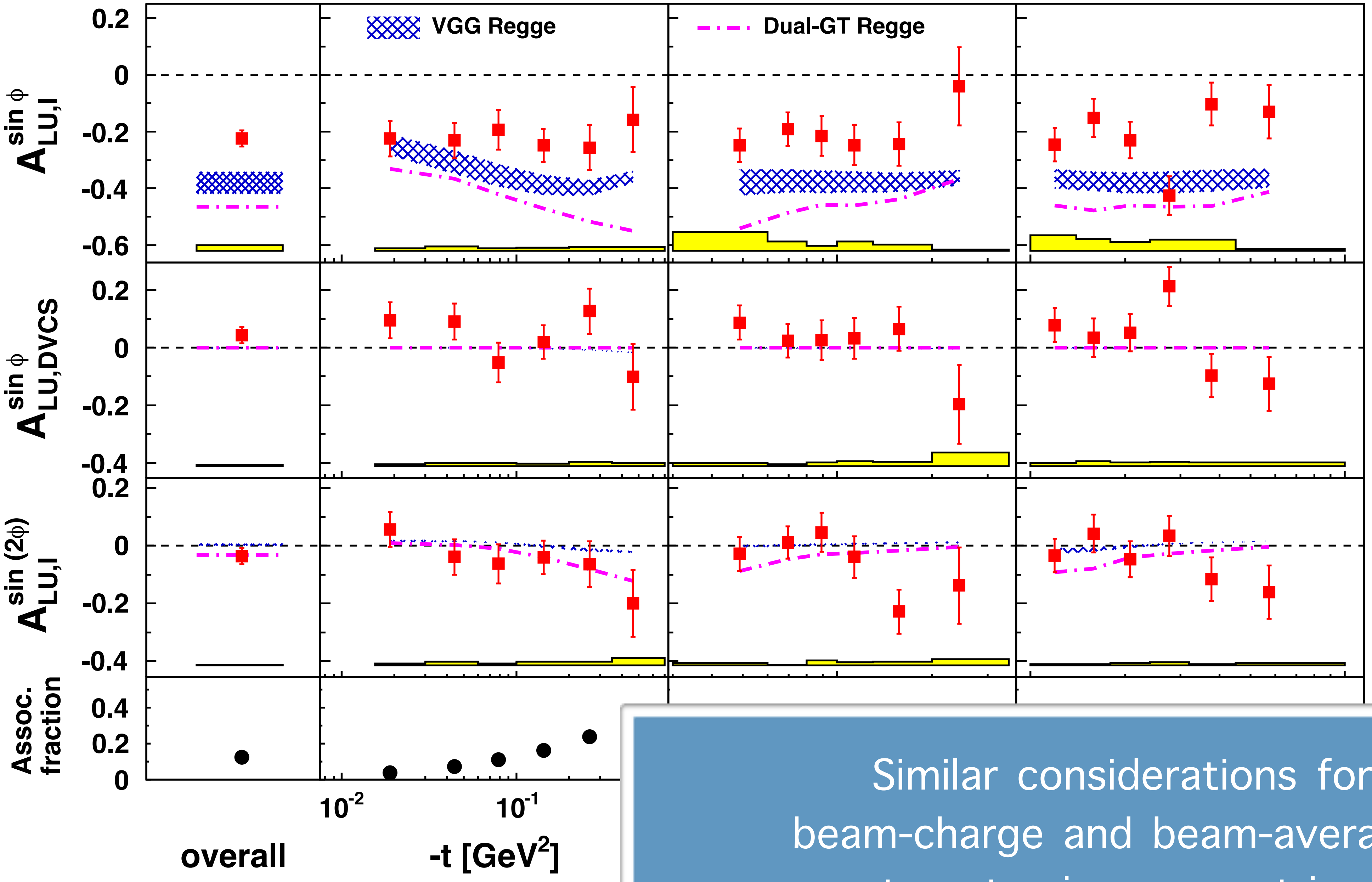
twist-2 GPDs

twist-3 GPDs

$\Im M^{0,\pm 1}$

twist-3 GPDs

Charge-difference and charge-average beam-helicity asymmetry



HERMES, JHEP **11** (2009) 083

$\Im M^{1,1}$
twist-2 GPDs

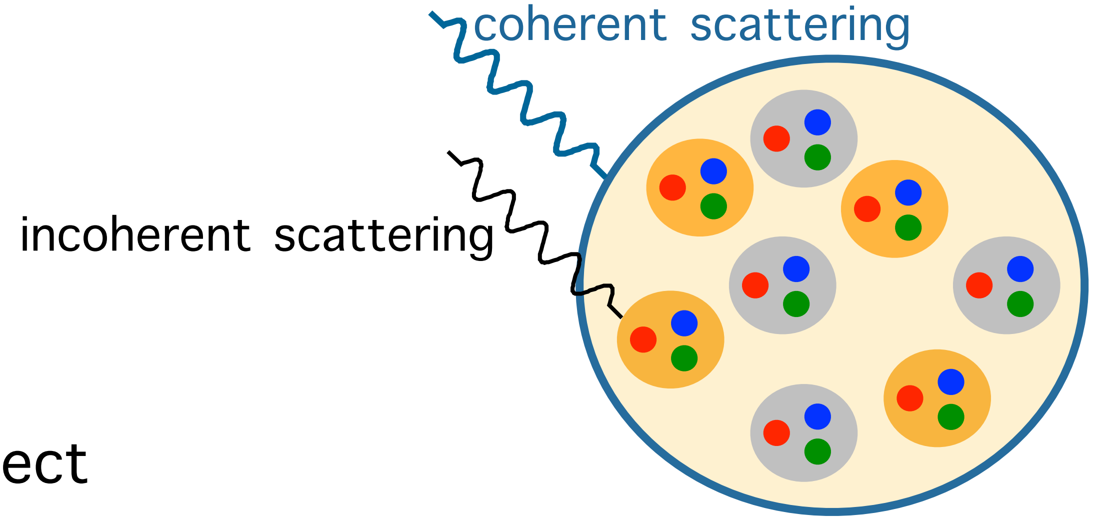
twist-3 GPDs

$\Im M^{0,\pm1}$
twist-3 GPDs

Similar considerations for beam-charge and beam-averaged target-spin asymmetries

(JHEP 06 (2008) 066, Phys. Lett. B 704 (2011) 15-23)

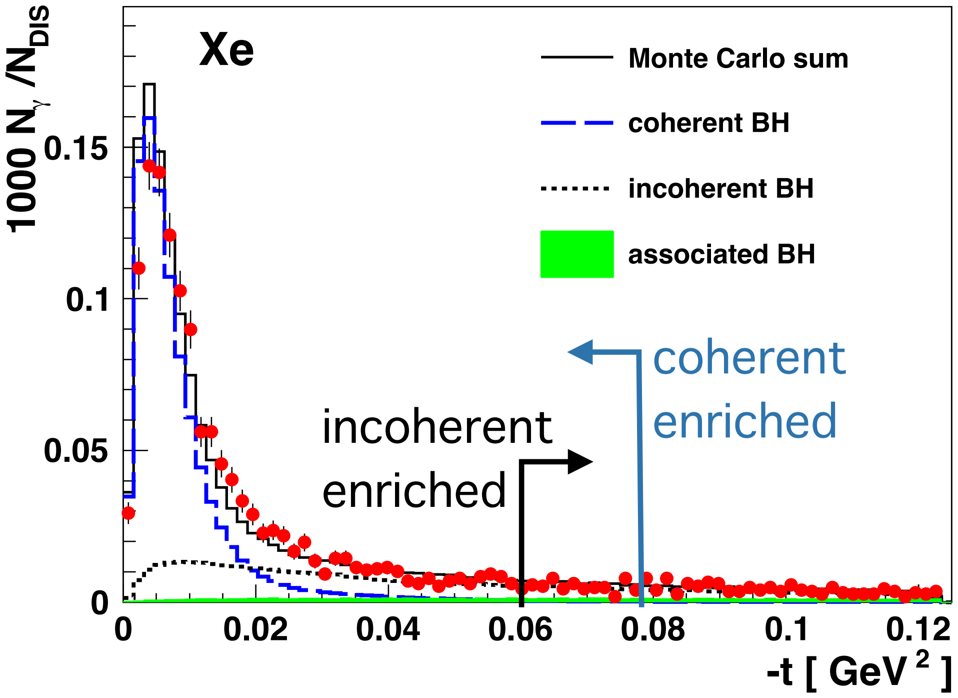
Beam-charge asymmetry on nuclear targets



- Nuclear DVCS: (anti-)shadowing, EMC effect
- New nuclear effect, absent in $\Im$ forward DIS amplitude?
- Coherent scattering: mesonic degrees of freedom:
  - ✦ non-linear A dependence of first moment of D-term
  - ✦ at HERMES, beam-charge asymmetry grows with increasing A: τ_{DVCS} increases. Absence of mesons: asymmetry independent of A.
- Incoherent scattering: similar to proton GPDs

(V. Guzey and M. Siddikov, J. Phys. G 32 (2006) 251)

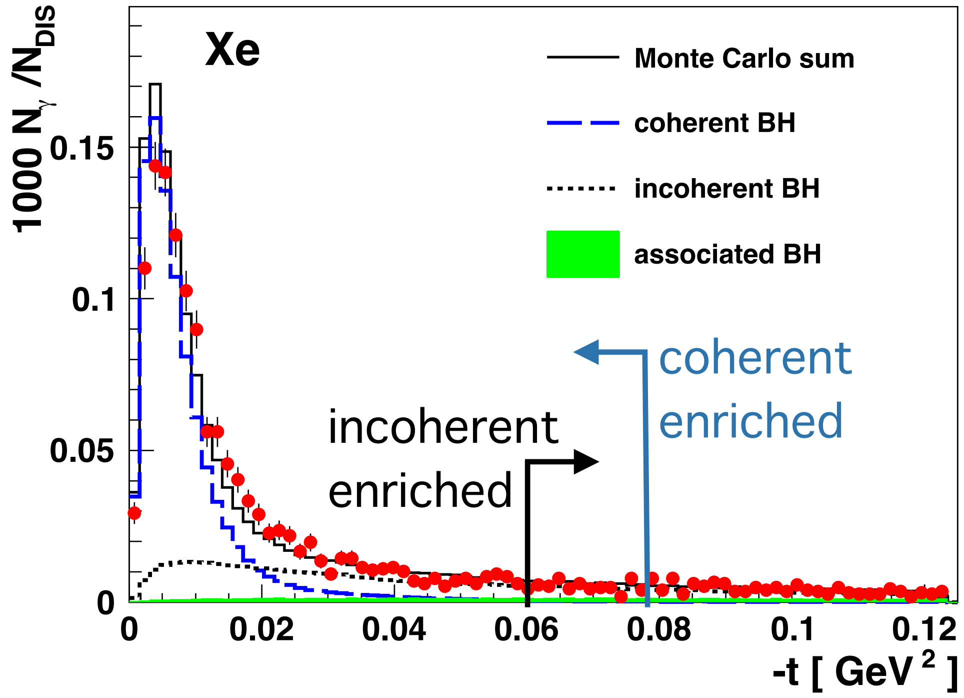
Beam-charge asymmetry on nuclear targets



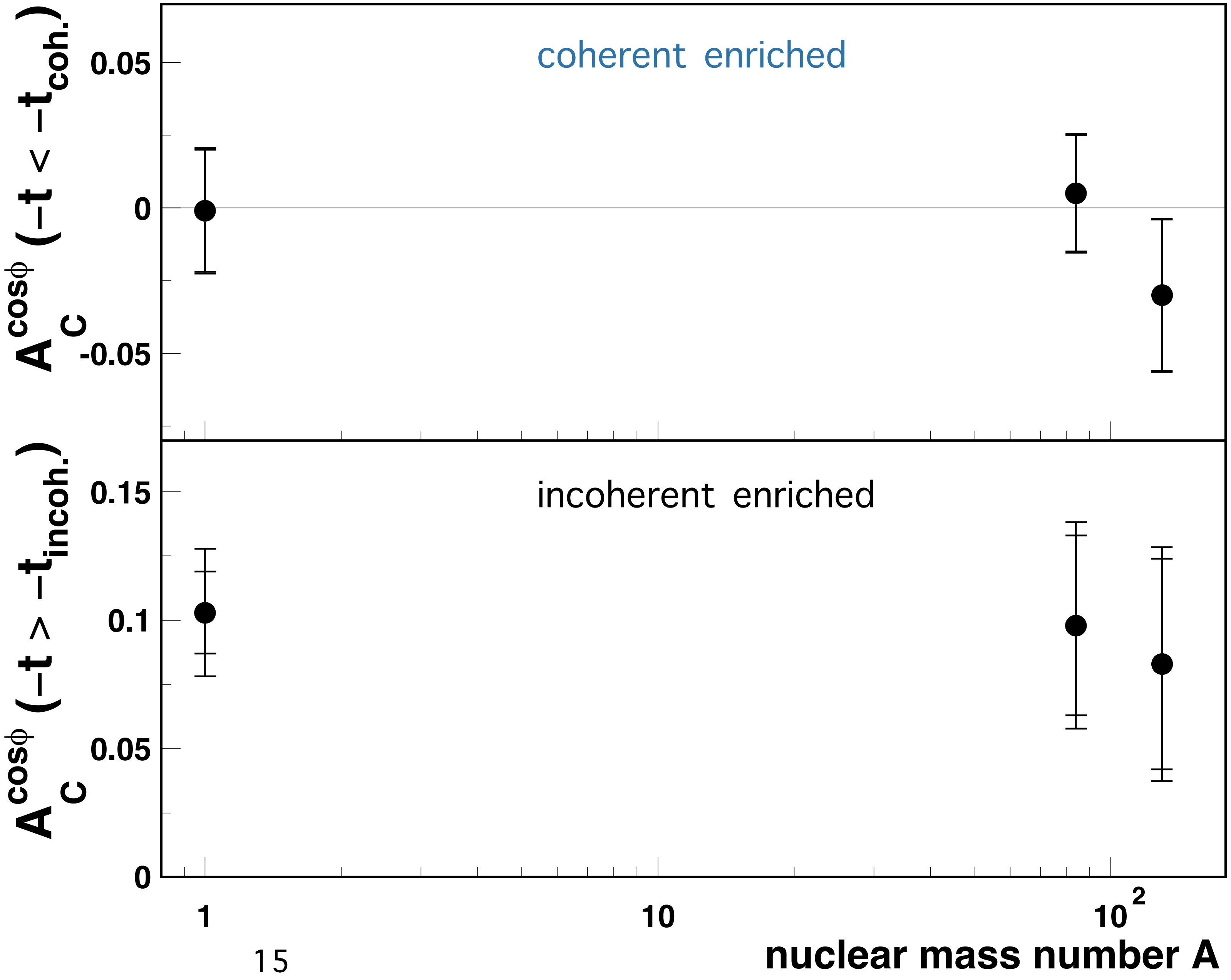
incoherent enriched

coherent enriched

Beam-charge asymmetry on nuclear targets



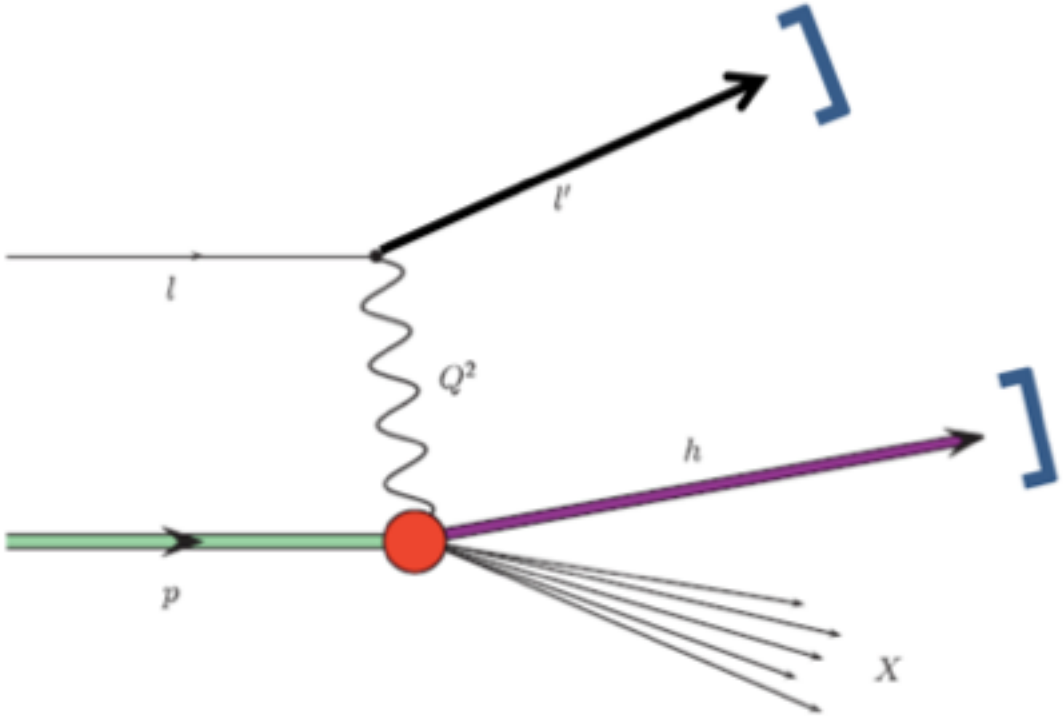
HERMES, Phys. Rev. C 81 (2010) 035202



No dependence on A observed

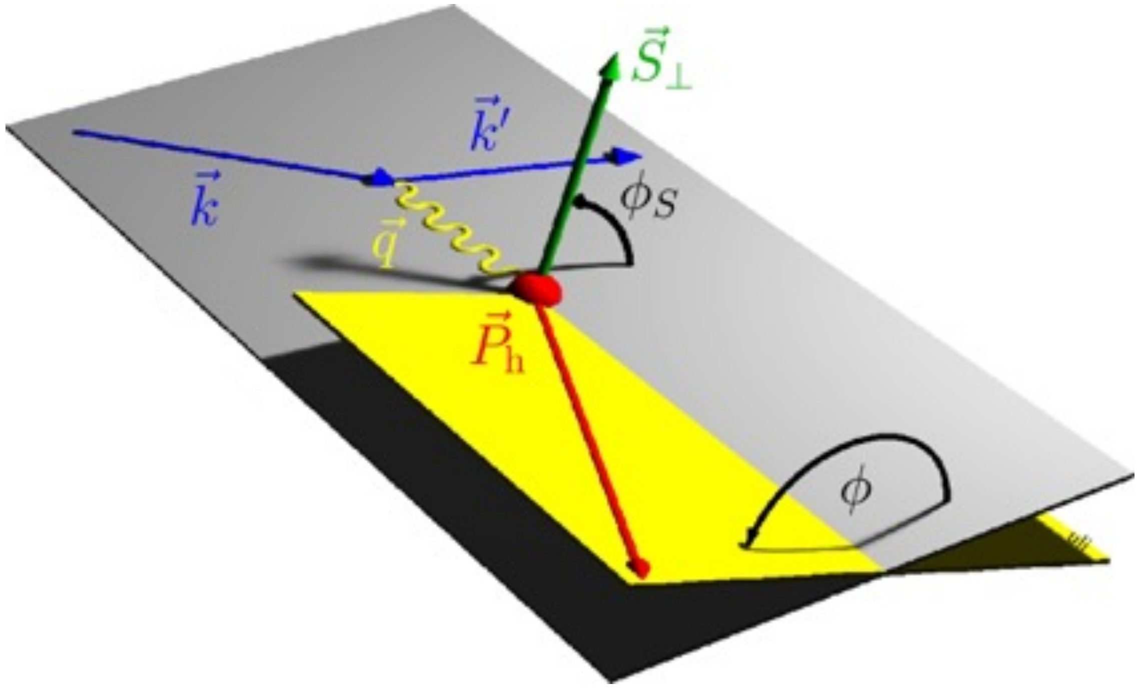
(TMD) PDFs

Semi-inclusive DIS production



Semi-inclusive DIS cross section

$$\begin{aligned}
\sigma^h(\phi,\phi_S) \quad &= \quad \sigma^h_{UU}\Big\{1+2\langle\cos(\phi)\rangle^h_{UU}\,\cos(\phi)+2\langle\cos(2\phi)\rangle^h_{UU}\,\cos(2\phi) \\
&+ \quad \lambda_l\,2\langle\sin(\phi)\rangle^h_{LU}\,\sin(\phi) \\
&+ \quad S_L\Big[2\langle\sin(\phi)\rangle^h_{UL}\,\sin(\phi)+2\langle\sin(2\phi)\rangle^h_{UL}\,\sin(2\phi) \\
&+ \quad \lambda_l\Big(2\langle\cos(0\phi)\rangle^h_{LL}\,\cos(0\phi)+2\langle\cos(\phi)\rangle^h_{LL}\,\cos(\phi)\Big)\Big] \\
&+ \quad S_T\Big[2\langle\sin(\phi-\phi_S)\rangle^h_{UT}\,\sin(\phi-\phi_S)+2\langle\,\sin(\phi+\phi_S)\rangle^h_{UT}\,\sin(\phi+\phi_S) \\
&+ \quad 2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}\,\sin(3\phi-\phi_S)+2\langle\sin(\phi_S)\rangle^h_{UT}\,\sin(\phi_S) \\
&+ \quad 2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\,\sin(2\phi-\phi_S) \\
&+ \quad \lambda_l\Big(2\langle\cos(\phi-\phi_S)\rangle^h_{LT}\,\cos(\phi-\phi_S) \\
&+ \quad 2\langle\cos(\phi_S)\rangle^h_{LT}\,\cos(\phi_S)+2\langle\cos(2\phi-\phi_S)\rangle^h_{LT}\,\cos(2\phi-\phi_S)\Big)\Big]\Big\}
\end{aligned}$$



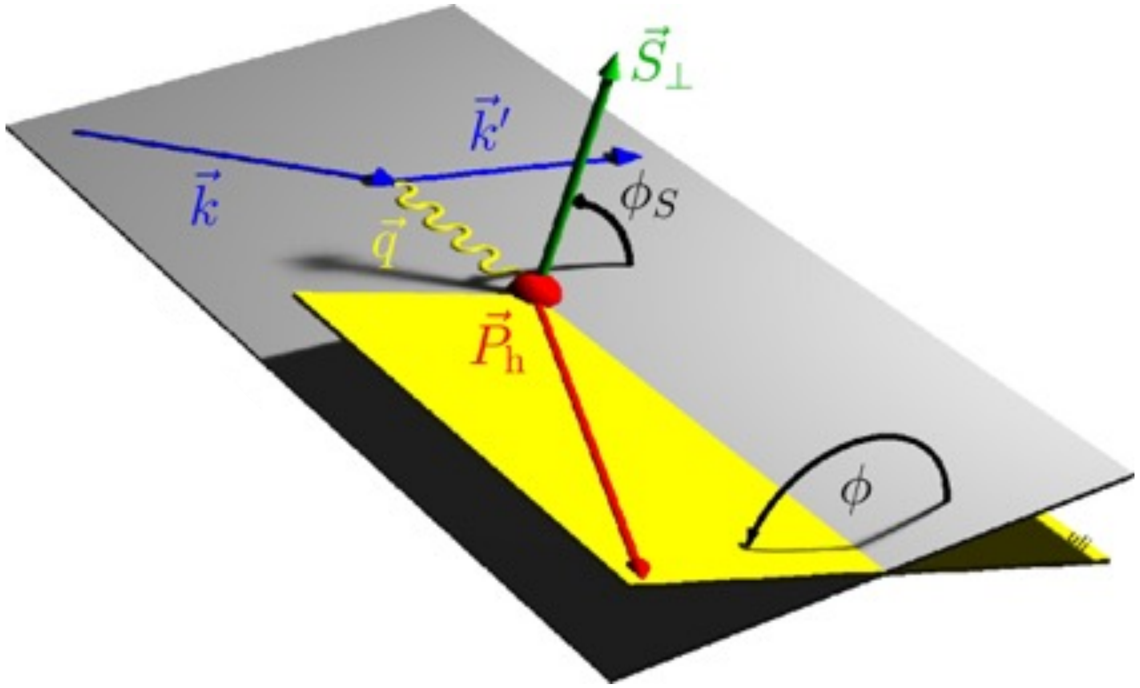
Semi-inclusive DIS cross section

$$
\begin{aligned}
\sigma^h(\phi,\phi_S) \;&=\; \sigma^h_{UU}\Big\{1 + 2\langle\cos(\phi)\rangle^h_{UU}\,\cos(\phi) + 2\langle\cos(2\phi)\rangle^h_{UU}\,\cos(2\phi)\\
&+\; \lambda_l\, 2\langle\sin(\phi)\rangle^h_{LU}\,\sin(\phi)\\
&+\; S_L\Big[2\langle\sin(\phi)\rangle^h_{UL}\,\sin(\phi) + 2\langle\sin(2\phi)\rangle^h_{UL}\,\sin(2\phi)\\
&+\; \lambda_l\Big(2\langle\cos(0\phi)\rangle^h_{LL}\,\cos(0\phi) + 2\langle\cos(\phi)\rangle^h_{LL}\,\cos(\phi)\Big)\Big]\\
&+\; S_T\Big[2\langle\sin(\phi-\phi_S)\rangle^h_{UT}\,\sin(\phi-\phi_S) + 2\langle\,\sin(\phi+\phi_S)\rangle^h_{UT}\,\sin(\phi+\phi_S)\\
&+\; 2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}\,\sin(3\phi-\phi_S) + 2\langle\sin(\phi_S)\rangle^h_{UT}\,\sin(\phi_S)\\
&+\; 2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\,\sin(2\phi-\phi_S)\\
&+\; \lambda_l\Big(2\langle\cos(\phi-\phi_S)\rangle^h_{LT}\,\cos(\phi-\phi_S)\\
&+\; 2\langle\cos(\phi_S)\rangle^h_{LT}\,\cos(\phi_S) + 2\langle\cos(2\phi-\phi_S)\rangle^h_{LT}\,\cos(2\phi-\phi_S)\Big)\Big]\Big\}
\end{aligned}
$$

longitudinal target polarization

transverse target polarization

beam polarization



Semi-inclusive DIS cross section

$$
\begin{aligned}
\sigma^h(\phi,\phi_S) &= \sigma^h_{UU}\Big\{1+2\langle\cos(\phi)\rangle^h_{UU}\cos(\phi)+2\langle\cos(2\phi)\rangle^h_{UU}\cos(2\phi)\\
&+\lambda_l\,2\langle\sin(\phi)\rangle^h_{LU}\sin(\phi)\\
&+S_L\Big[2\langle\sin(\phi)\rangle^h_{UL}\sin(\phi)+2\langle\sin(2\phi)\rangle^h_{UL}\sin(2\phi)\\
&+\lambda_l\Big(2\langle\cos(0\phi)\rangle^h_{LL}\cos(0\phi)+2\langle\cos(\phi)\rangle^h_{LL}\cos(\phi)\Big)\Big]\\
&+S_T\Big[2\langle\sin(\phi-\phi_S)\rangle^h_{UT}\sin(\phi-\phi_S)+2\langle\sin(\phi+\phi_S)\rangle^h_{UT}\sin(\phi+\phi_S)\\
&+2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}\sin(3\phi-\phi_S)+2\langle\sin(\phi_S)\rangle^h_{UT}\sin(\phi_S)\\
&+2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\sin(2\phi-\phi_S)\\
&+\lambda_l\Big(2\langle\cos(\phi-\phi_S)\rangle^h_{LT}\cos(\phi-\phi_S)\\
&+2\langle\cos(\phi_S)\rangle^h_{LT}\cos(\phi_S)+2\langle\cos(2\phi-\phi_S)\rangle^h_{LT}\cos(2\phi-\phi_S)\Big)\Big]\Big\}
\end{aligned}
$$

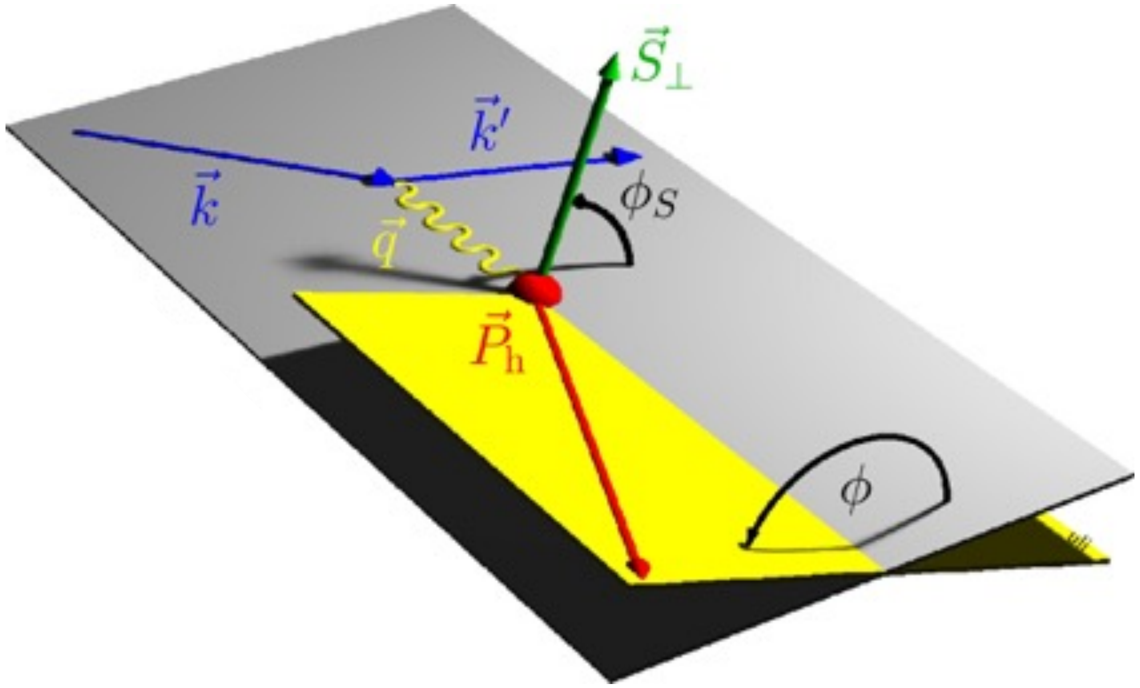
longitudinal target polarization

transverse target polarization

beam polarization

beam polarization

target polarization



Semi-inclusive DIS cross section

$$
\begin{aligned}
\sigma^h(\phi,\phi_S) &= \sigma^h_{UU}\Big\{1+2\langle\cos(\phi)\rangle^h_{UU}\,\cos(\phi)+\boxed{2\langle\cos(2\phi)\rangle^h_{UU}}\,\cos(2\phi)\\
&+\lambda_l\,2\langle\sin(\phi)\rangle^h_{LU}\,\sin(\phi)\\
&+S_L\Big[2\langle\sin(\phi)\rangle^h_{UL}\,\sin(\phi)+\boxed{2\langle\sin(2\phi)\rangle^h_{UL}}\,\sin(2\phi)\\
&+\lambda_l\Big(\boxed{2\langle\cos(0\phi)\rangle^h_{LL}}\,\cos(0\phi)+2\langle\cos(\phi)\rangle^h_{LL}\,\cos(\phi)\Big)\Big]\\
&+S_T\Big[\boxed{2\langle\sin(\phi-\phi_S)\rangle^h_{UT}}\,\sin(\phi-\phi_S)+\boxed{2\langle\sin(\phi+\phi_S)\rangle^h_{UT}}\,\sin(\phi+\phi_S)\\
&+\boxed{2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}}\,\sin(3\phi-\phi_S)+2\langle\sin(\phi_S)\rangle^h_{UT}\,\sin(\phi_S)\\
&+2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\,\sin(2\phi-\phi_S)\\
&+\lambda_l\Big(\boxed{2\langle\cos(\phi-\phi_S)\rangle^h_{LT}}\,\cos(\phi-\phi_S)\\
&+2\langle\cos(\phi_S)\rangle^h_{LT}\,\cos(\phi_S)+2\langle\cos(2\phi-\phi_S)\rangle^h_{LT}\,\cos(2\phi-\phi_S)\Big)\Big]\Big\}
\end{aligned}
$$

longitudinal target polarization

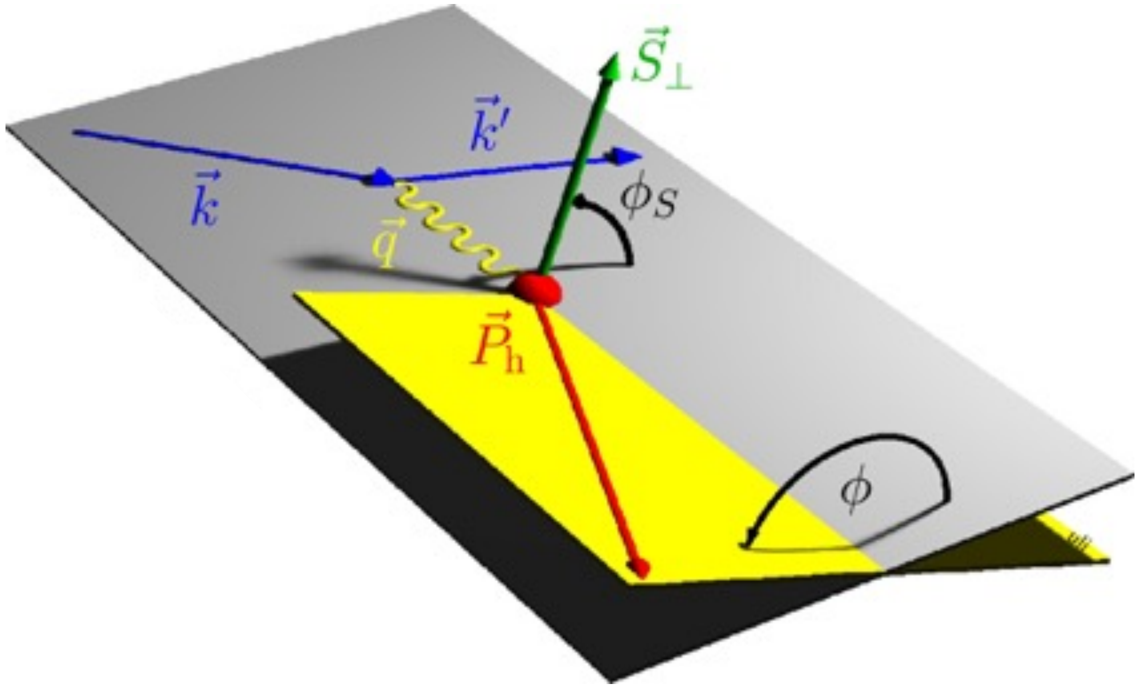
transverse target polarization

beam polarization

beam polarization

target polarization

leading twist



TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY}:

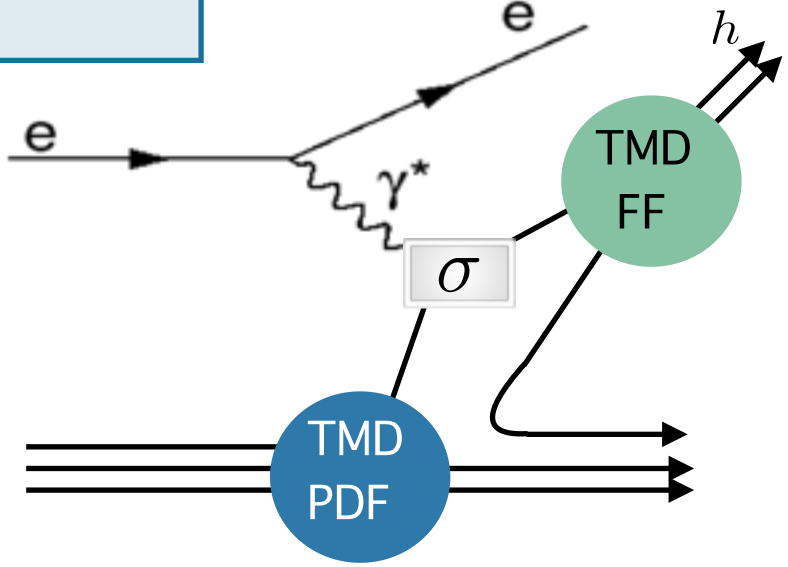
$$2\langle \sin(\phi + \phi_S) \rangle_{UT}^{h} = \epsilon \, F_{UT}^{\sin(\phi+\phi_S)}$$

TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY}:

$$2\langle \sin(\phi + \phi_S) \rangle^h_{UT} = \epsilon \, F_{UT}^{\sin(\phi+\phi_S)}$$

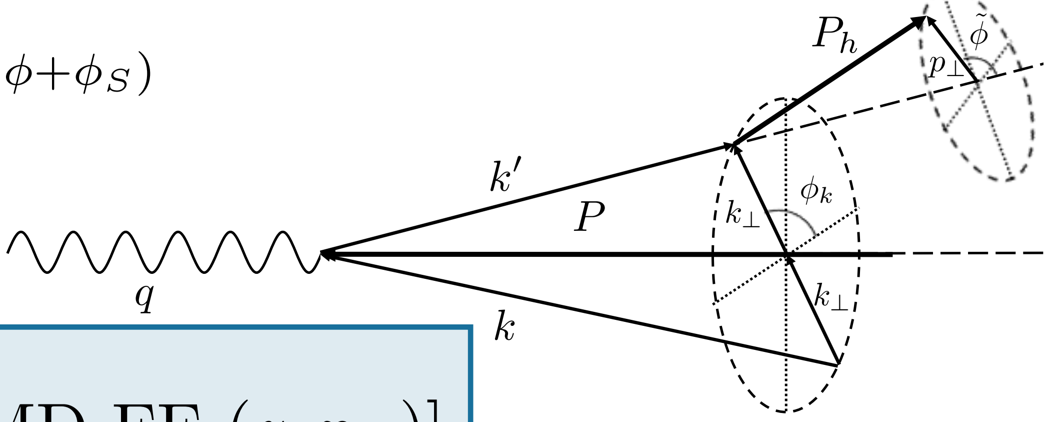
$$\boxed{F_{XY} \propto \mathcal{C}\left[\text{TMD PDF}(x, k_\perp) \times \ \text{TMD FF}\ (z, p_\perp)\right]}$$



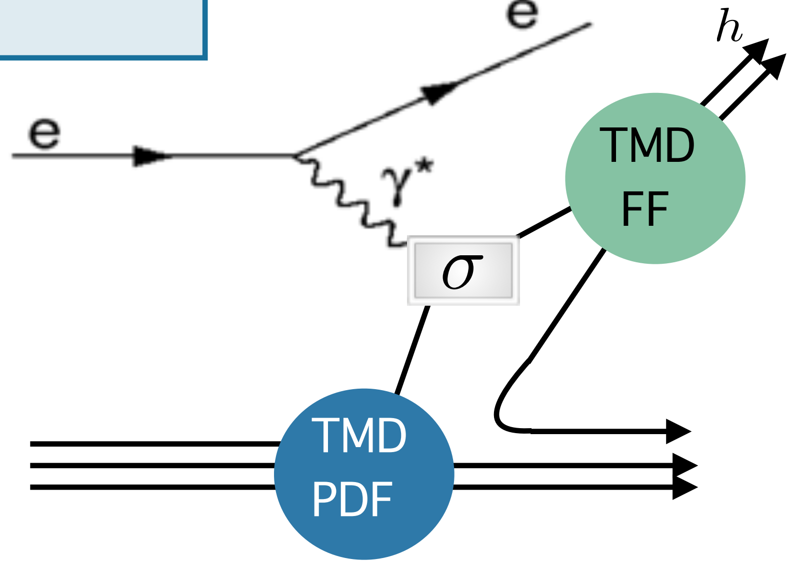
TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY}:

$$2\langle \sin(\phi + \phi_S)\rangle^{h}_{UT} = \epsilon \, F^{\sin(\phi+\phi_S)}_{UT}$$



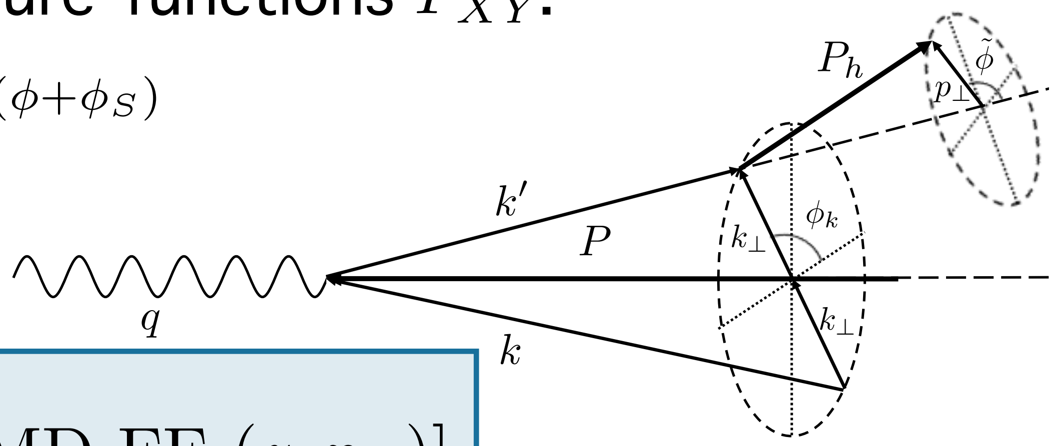
$$\boxed{F_{XY} \propto \mathcal{C}\,[\mathrm{TMD\ PDF}(x, k_\perp) \times \ \mathrm{TMD\ FF}\ (z, p_\perp)]}$$



TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY}:

$$2\langle \sin(\phi+\phi_S)\rangle^{h}_{UT} = \epsilon\, F_{UT}^{\sin(\phi+\phi_S)}$$

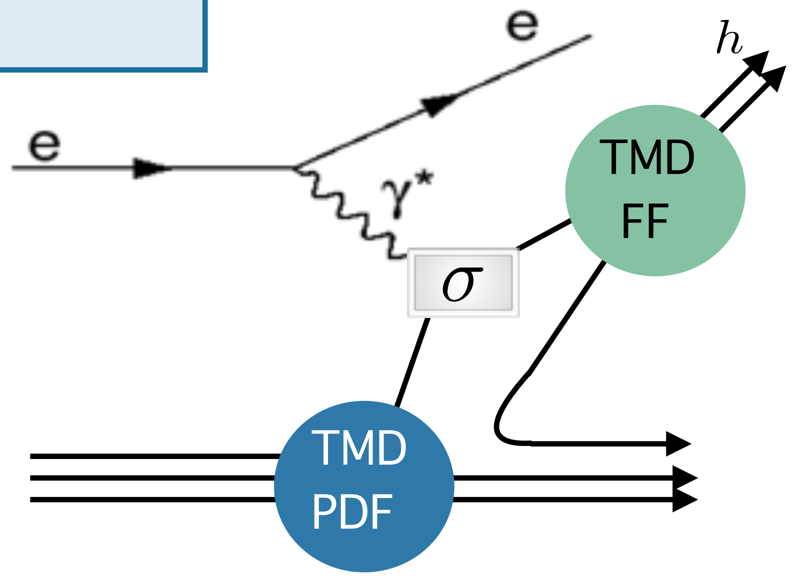


$$\boxed{F_{XY} \propto \mathcal{C}\left[\text{TMD PDF}(x,k_\perp) \times \ \text{TMD FF}\ (z,p_\perp)\right]}$$

quark polarization

nucleon polarization

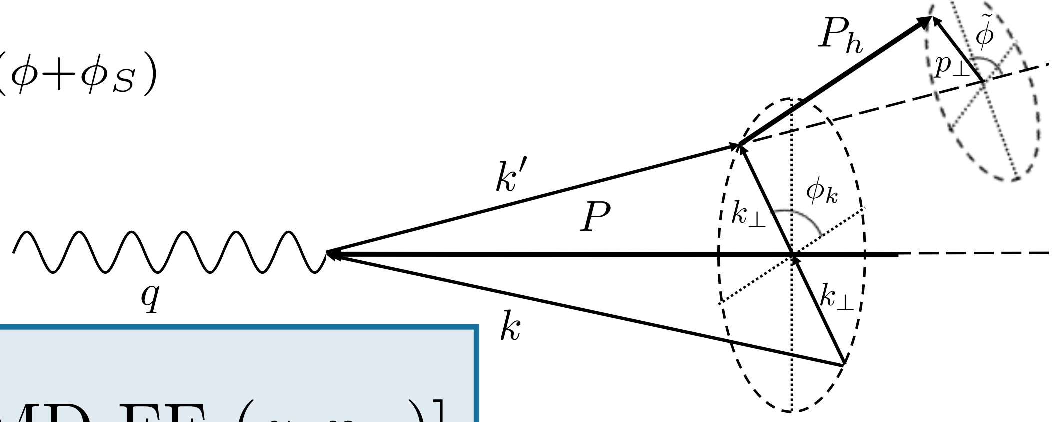
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$



TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY}:

$$2\langle \sin(\phi+\phi_S)\rangle^h_{UT} = \epsilon\, F^{\sin(\phi+\phi_S)}_{UT}$$



$$\boxed{F_{XY} \propto \mathcal{C}\,[\mathrm{TMD\ PDF}(x,k_\perp) \times\ \mathrm{TMD\ FF}\ (z,p_\perp)]}$$

quark polarization

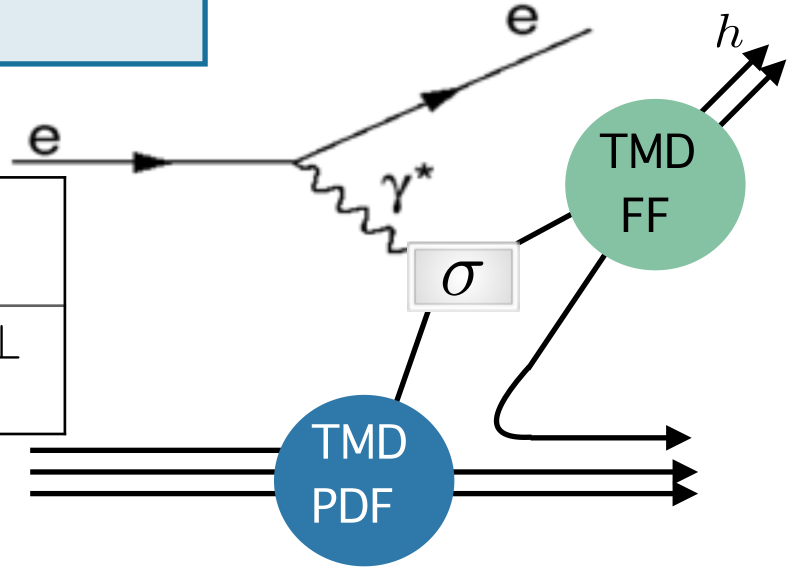
nucleon polarization

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$

quark polarization

hadron polarization

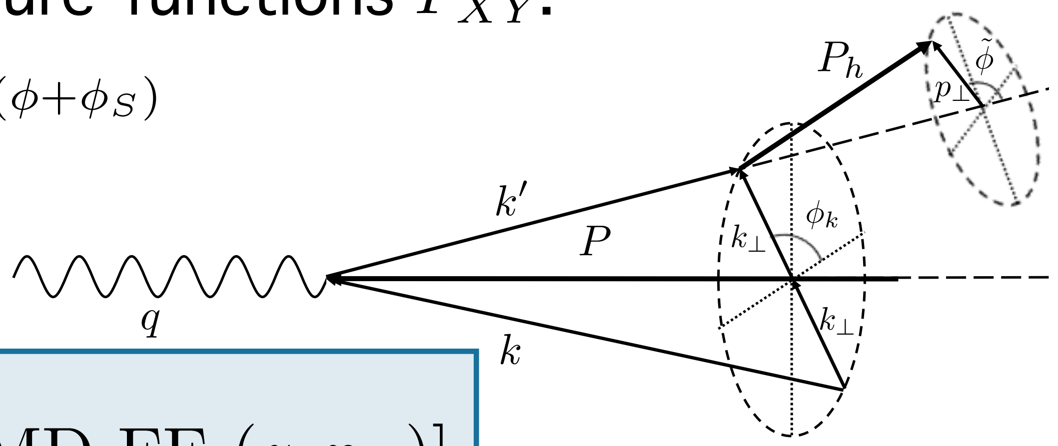
	U	L	T
U	D_1		$H_1^\perp$



TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY}:

$$2\langle \sin(\phi+\phi_S)\rangle^{h}_{UT} = \epsilon\, F_{UT}^{\sin(\phi+\phi_S)}$$



$$F_{XY} \propto \mathcal{C}\,[\text{TMD PDF}(x,k_\perp) \times\ \text{TMD FF}\ (z,p_\perp)]$$

quark polarization

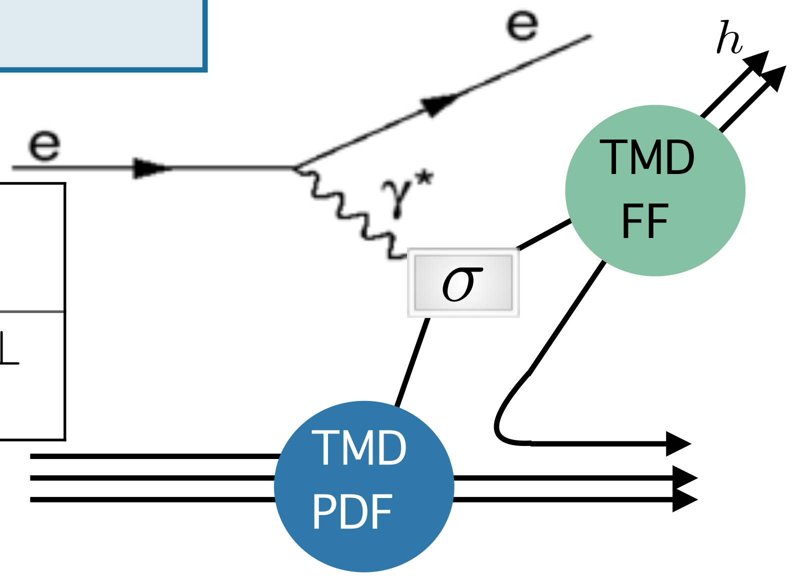
nucleon polarization

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$

quark polarization

hadron polarization

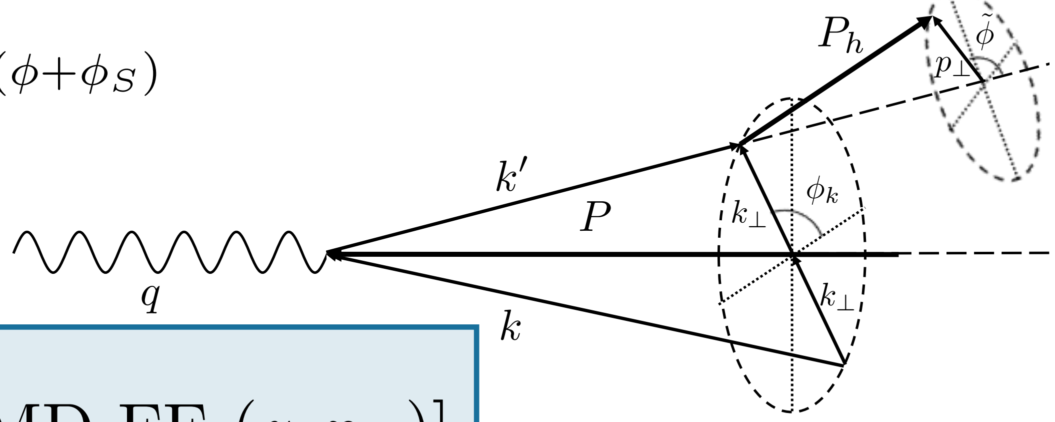
	U	L	T
U	D_1		$H_1^\perp$



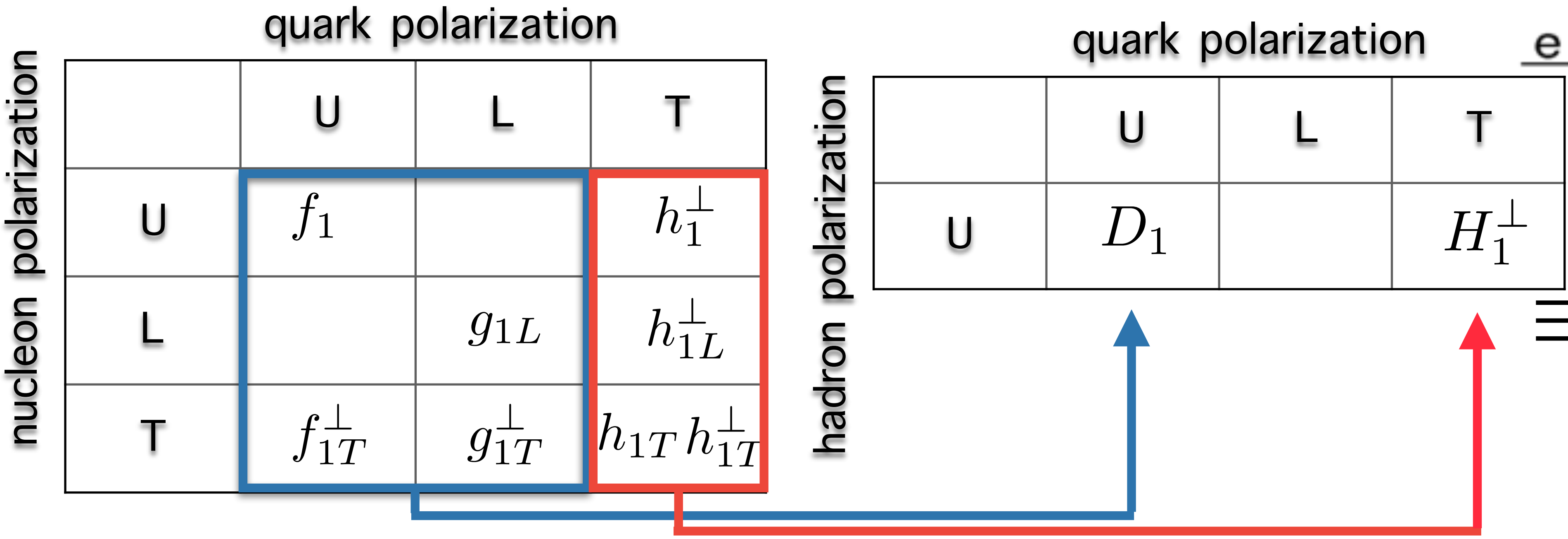
TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY}:

$$2\langle \sin(\phi+\phi_S)\rangle^h_{UT} = \epsilon\, F_{UT}^{\sin(\phi+\phi_S)}$$



$$F_{XY} \propto \mathcal{C}\left[\text{TMD PDF}(x, k_\perp) \times \ \text{TMD FF}\ (z, p_\perp)\right]$$

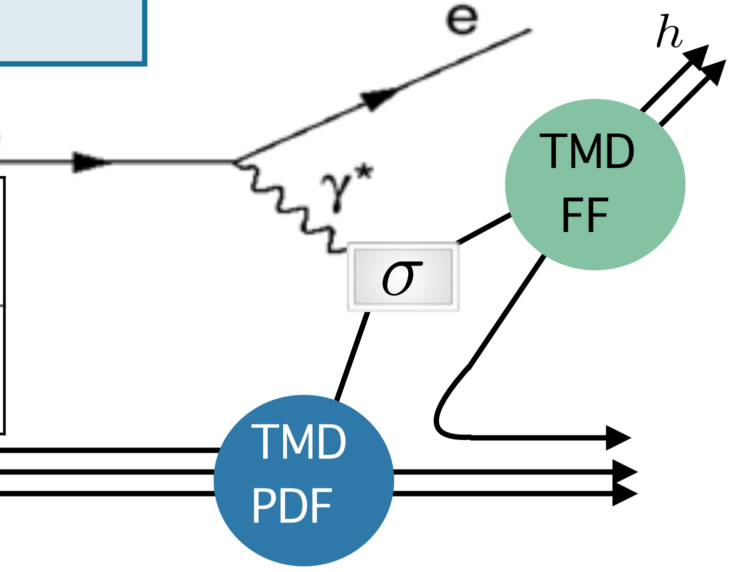


quark polarization

nucleon polarization	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$

quark polarization

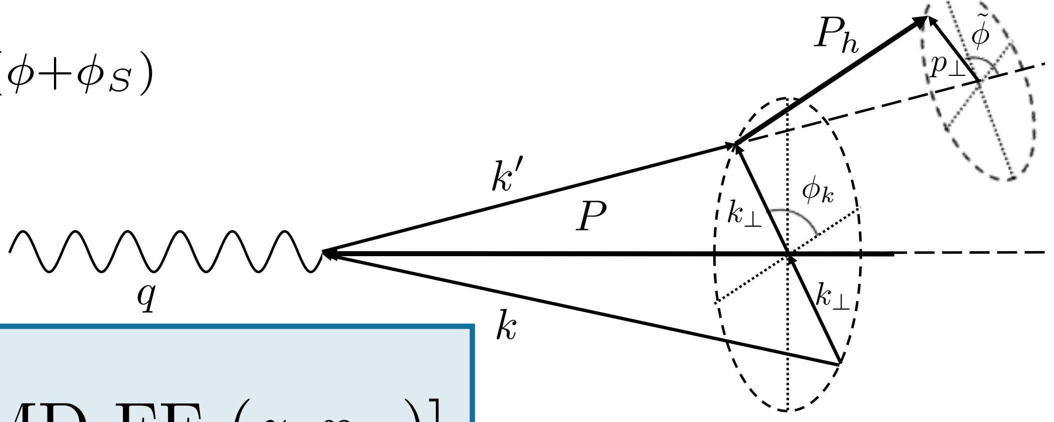
hadron polarization	U	L	T
U	D_1		$H_1^\perp$



TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY}:

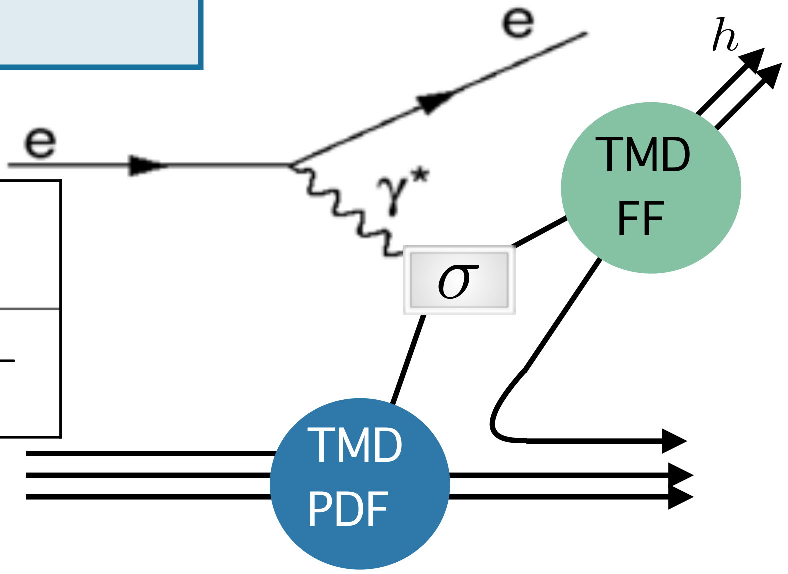
$$2\langle\sin(\phi+\phi_S)\rangle^h_{UT} = \epsilon\, F_{UT}^{\sin(\phi+\phi_S)}$$



$$F_{XY} \propto \mathcal{C}\left[\mathrm{TMD\ PDF}(x,k_\perp) \times \ \mathrm{TMD\ FF}\ (z,p_\perp)\right]$$

	quark polarization		
nucleon polarization	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_{1T} $h_{1T}^\perp$

	quark polarization		
hadron polarization	U	L	T
U	D_1		$H_1^\perp$

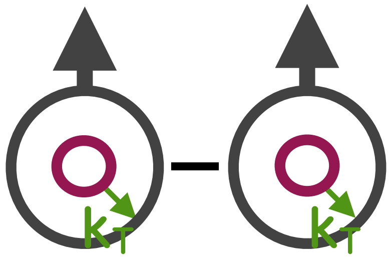


Survive integration over transverse momentum

f_1, g_{1L}: via (semi-)inclusive DIS

h_{1T}: via semi-inclusive DIS

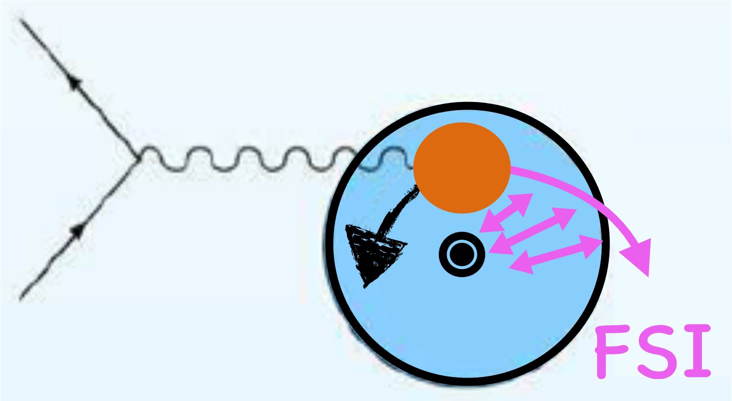
h_{1T}
- convolution via single-hadron semi-inclusive DIS
- direct production via
  - ✦ two-hadron production
  - ✦ $\langle\sin(\phi_S)\rangle$ = twist-3

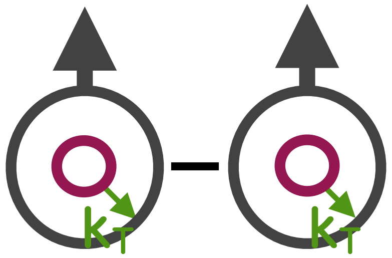


$\mathcal{C}[f_{1T}^{\perp,q} \times D_1^q]$

Sivers amplitudes

- Sivers function:
  - requires non-zero orbital angular momentum (model)
  - naive T-odd
  - final-state-interactions → azimuthal asymmetries

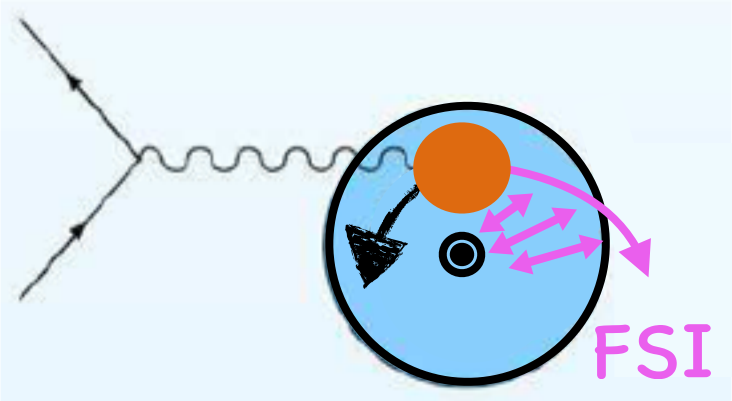




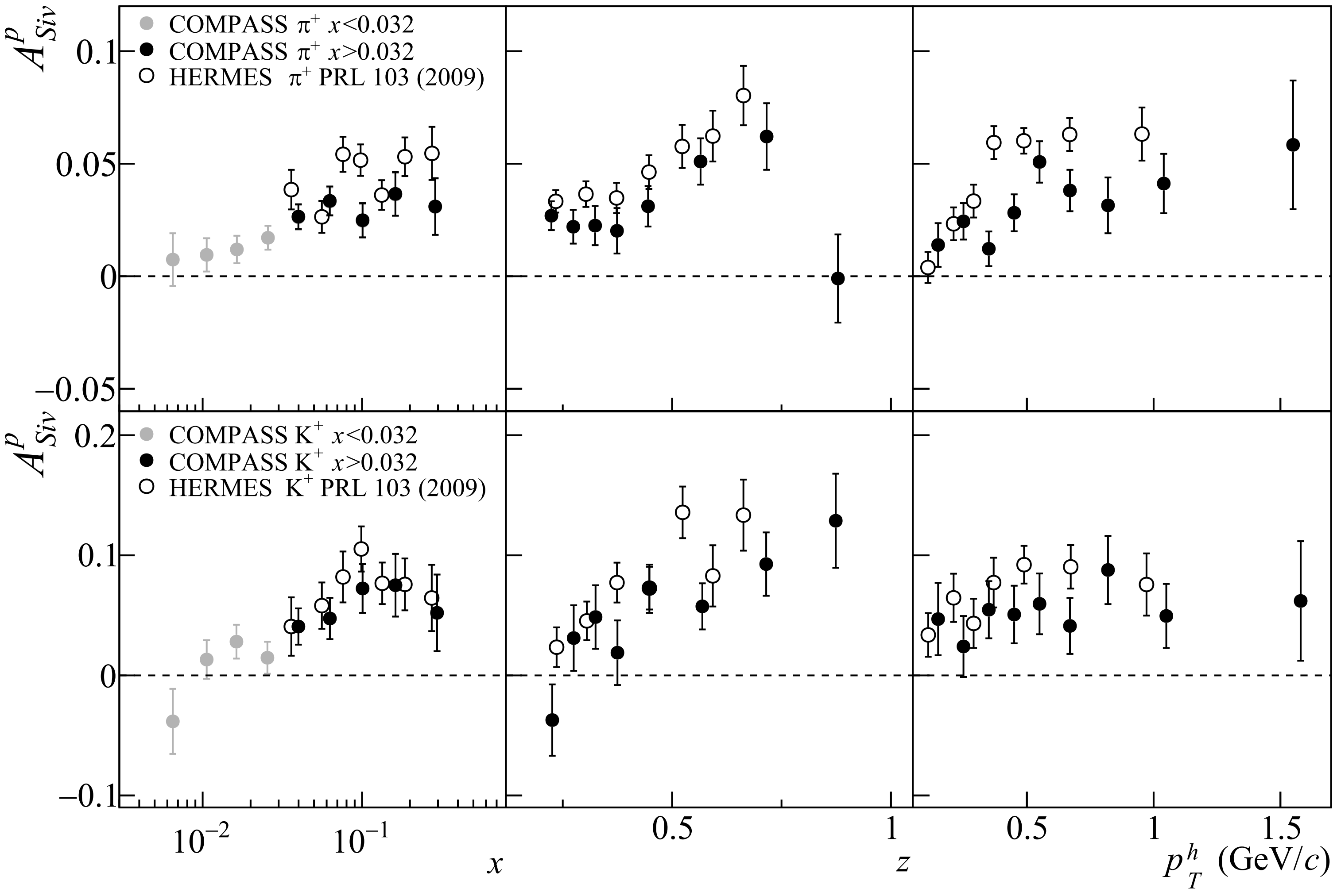
Sivers amplitudes

$$\mathcal{C}[f_{1T}^{\perp,q} \times D_1^q]$$

- Sivers function:
  - requires non-zero orbital angular momentum (model)
  - naive T-odd
  - final-state-interactions → azimuthal asymmetries



HERMES>COMPASS
Q^2 evolution?



Phys. Lett. B 744 (2015) 250

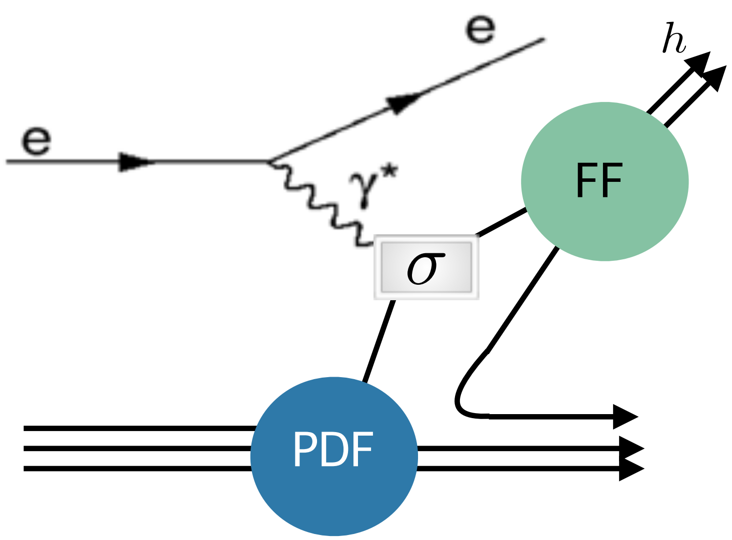
- π^+:
  - positive -> non-zero orbital angular momentum
  - amplitude dominated by u-quark scattering:

$$\approx -\frac{\mathcal{C} f_{1T}^{\perp,u} \times D_1^{u\to\pi^+}}{\mathcal{C} f_{1T}^{u} \times D_1^{u\to\pi^+}} \quad \to f_{1T}^{\perp,u} < 0$$

- π^-:
  - consistent with zero
  - u and d quark cancelation $\to f_{1T}^{\perp,d} > 0$
- K$^+$:
  - larger amplitude than for π^+

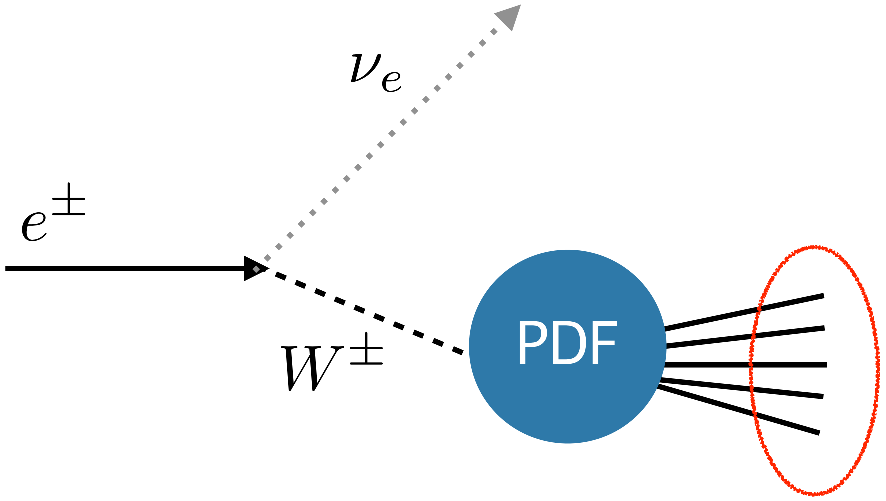
Accessing collinear helicity PDFs: complementary probes to inclusive γ*DIS

Semi-inclusive DIS



- Fragmentation function ⟶ flavour tagging, but additional non-perturbative object
- Reconstruction kinematic variables: initial/scattered lepton
- Longitudinally polarized beam and polarized target needed

Charged-current DIS



- No fragmentation functions
- Probe combinations of flavours different from inclusive γ*DIS
- Reconstruction kinematic variables:

  initial lepton and detected final-state particles

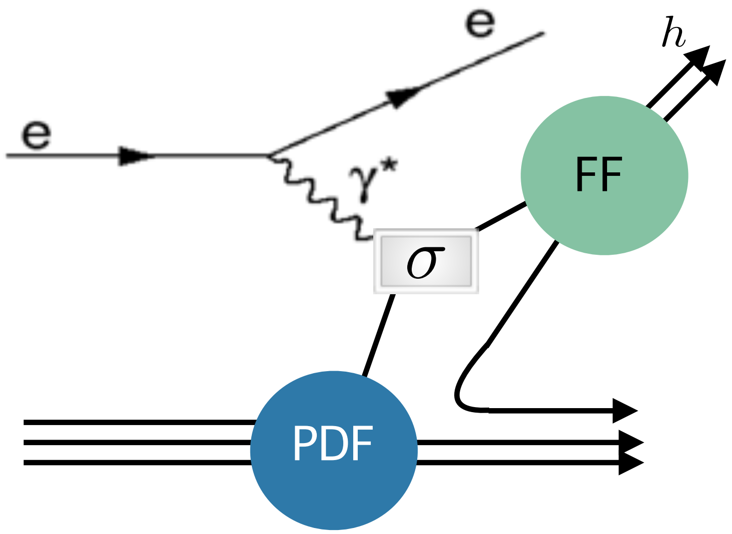
$$y_{JB} = \frac{\sum_i (E_i - p_{z,i})}{2E_e} \qquad Q^2_{JB} = \frac{|\sum_i \vec{p}_{T,i}|^2}{1 - y_{JB}}$$

$\downarrow$ resolution ↘ if more p_T missed

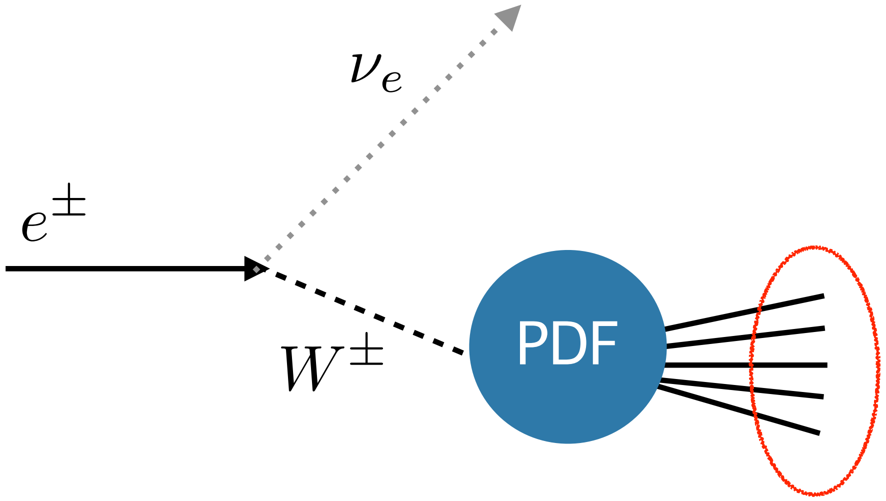
- Longitudinally polarized target needed
- Need high enough Q^2!

Accessing collinear helicity PDFs: complementary probes to inclusive γ*DIS

Semi-inclusive DIS



Charged-current DIS



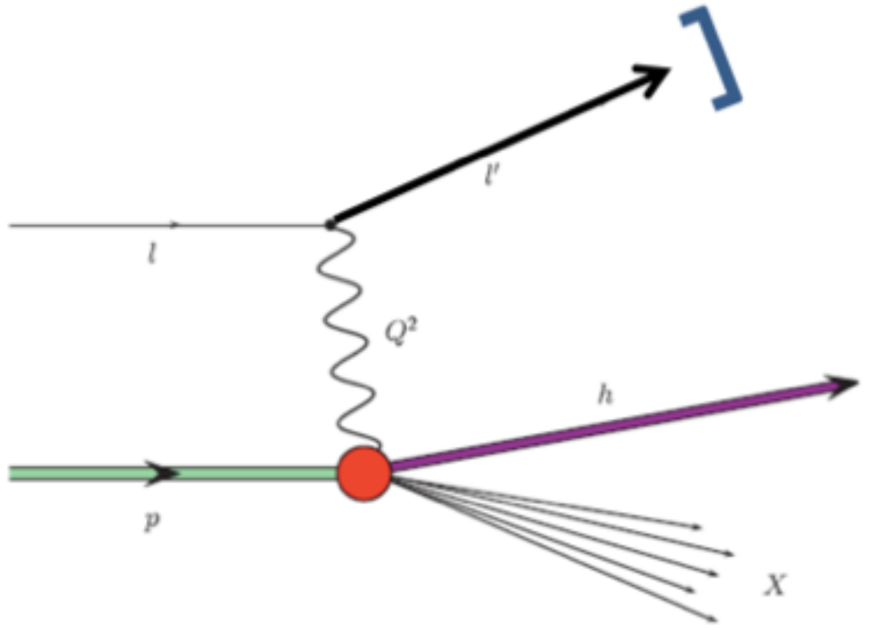
Inclusive DIS, independent of beam charge:

$$g_{1,p}(x) = \frac{1}{2}\sum_q e_q^2\,\Delta q(x)$$

$$e^- \left[\begin{aligned} g_{1,p}^{W^-}(x) &= \Delta u(x) + \Delta\bar{d}(x) + \Delta c(x) + \Delta\bar{s}(x) \\ g_{5,p}^{W^-}(x) &= -\Delta u(x) + \Delta\bar{d}(x) - \Delta c(x) + \Delta\bar{s}(x) \end{aligned}\right.$$

$$e^+ \left[\begin{aligned} g_{1,p}^{W^+}(x) &= \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{c}(x) + \Delta s(x) \\ g_{5,p}^{W^+}(x) &= \Delta\bar{u}(x) - \Delta d(x) + \Delta\bar{c}(x) - \Delta s(x) \end{aligned}\right.$$

Inclusive DIS production



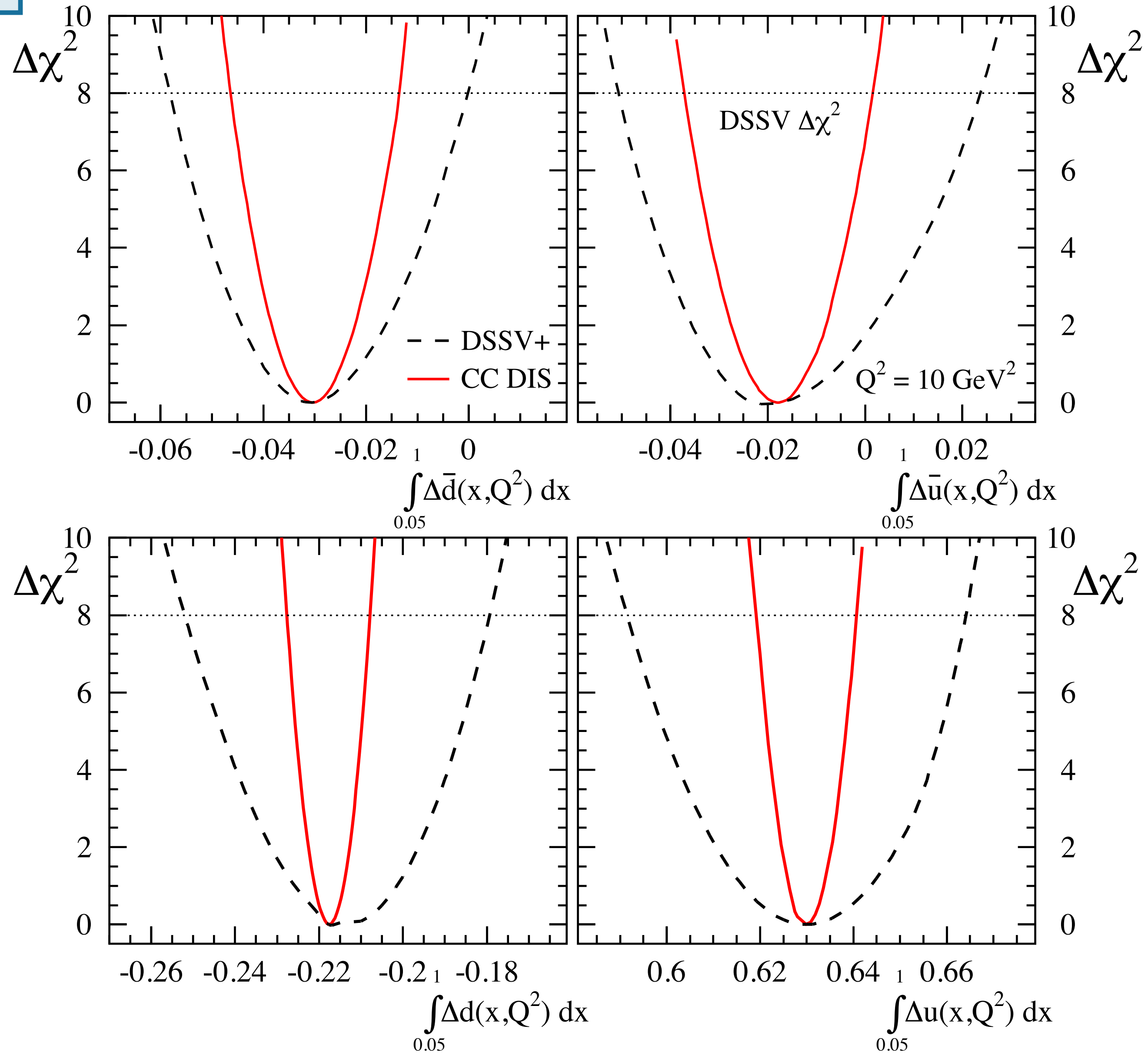
Longitudinal target single-spin asymmetries

- Charged currents @ EIC: PRD 88 (2013) 114025
- DJANGOH
- Detector effects, radiative corrections
- DSSV analysis @ NLO

$$A_p^{W^-} = \frac{2b\, g_{1p}^{W^-} - a\, g_{5p}^{W^-}}{a\, F_{1p}^{W^-} + b\, F_{3p}^{W^-}}$$

$$a,\, b = f(y_{JB})$$

- Charged currents @ EIC: E. Aschenauer et al., PRD 88 (2013) 114025

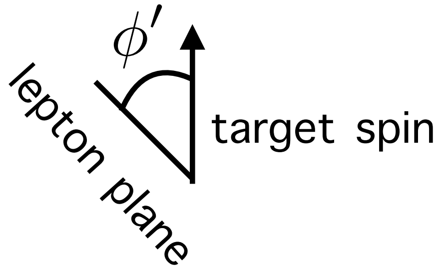


DSSV+: Prog. Part. Nucl. Phys. 67, 251 (2012).

Structure function g_2

- transversely pol. target
- longitudinal spin: beam/boson

- $$\frac{d^3\sigma_{LT}}{dx\,dy\,d\phi'} \propto -\lambda\left[\frac{y}{2}\,g_1(x,Q2)+g_2(x,Q^2)\right]\cos(\phi')$$



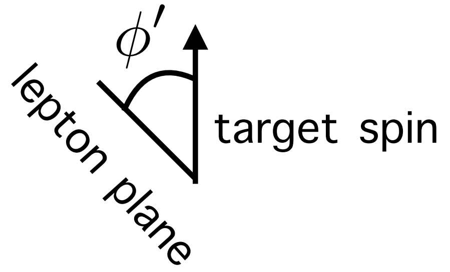
$$\downarrow$$

$$A_{LT}(x,Q^2,\phi') = \lambda\frac{\sigma_{LT}(x,Q^2,\phi')}{\sigma_{UU}(x,Q^2,\phi')} \quad = -A_T\cos(\phi')$$

Count # events with
target spin up - target-spin down

Structure function g_2

- transversely pol. target
- longitudinal spin: beam/boson



- $$\frac{d^3\sigma_{LT}}{dx\,dy\,d\phi'} \propto -\lambda\left[\frac{y}{2}\,g_1(x,Q2)+g_2(x,Q^2)\right]\cos(\phi')$$

$$\downarrow$$

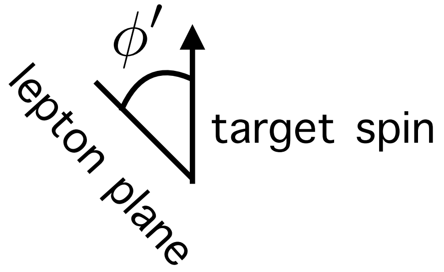
$$A_{LT}(x,Q^2,\phi') = \lambda\frac{\sigma_{LT}(x,Q^2,\phi')}{\sigma_{UU}(x,Q^2,\phi')} \quad = -A_T\cos(\phi')$$

Count # events with
target spin up - target-spin down

- $$g_2(x) = g_2^{WW} + \bar{g}_2(x) \qquad d_2 = 3\int_0^1 dx\,x^2\,\bar{g}_2(x)$$

Structure function g_2

- transversely pol. target
- longitudinal spin: beam/boson



- $$\frac{d^3\sigma_{LT}}{dx\,dy\,d\phi'} \propto -\lambda \left[\frac{y}{2}\,g_1(x,Q2) + g_2(x,Q^2)\right] \cos(\phi')$$

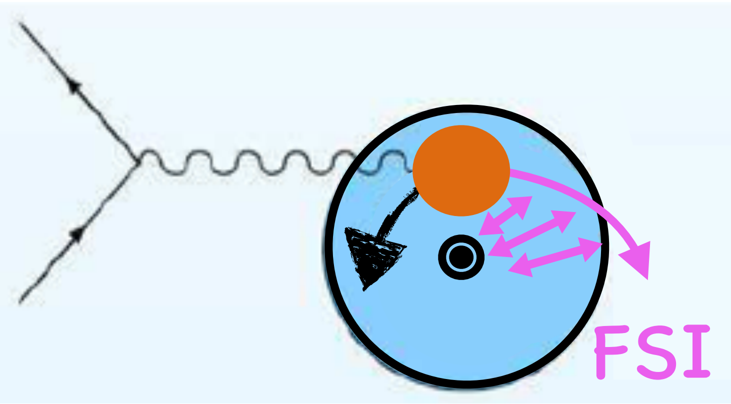
$$\downarrow$$

$$A_{LT}(x,Q^2,\phi') = \lambda \frac{\sigma_{LT}(x,Q^2,\phi')}{\sigma_{UU}(x,Q^2,\phi')} \quad = -A_T \cos(\phi')$$

Count # events with
target spin up - target-spin down

- $g_2(x) = g_2^{WW} + \bar{g}_2(x) \qquad d_2 = 3\int_0^1 dx\, x^2\, \bar{g}_2(x)$

- Sivers effect

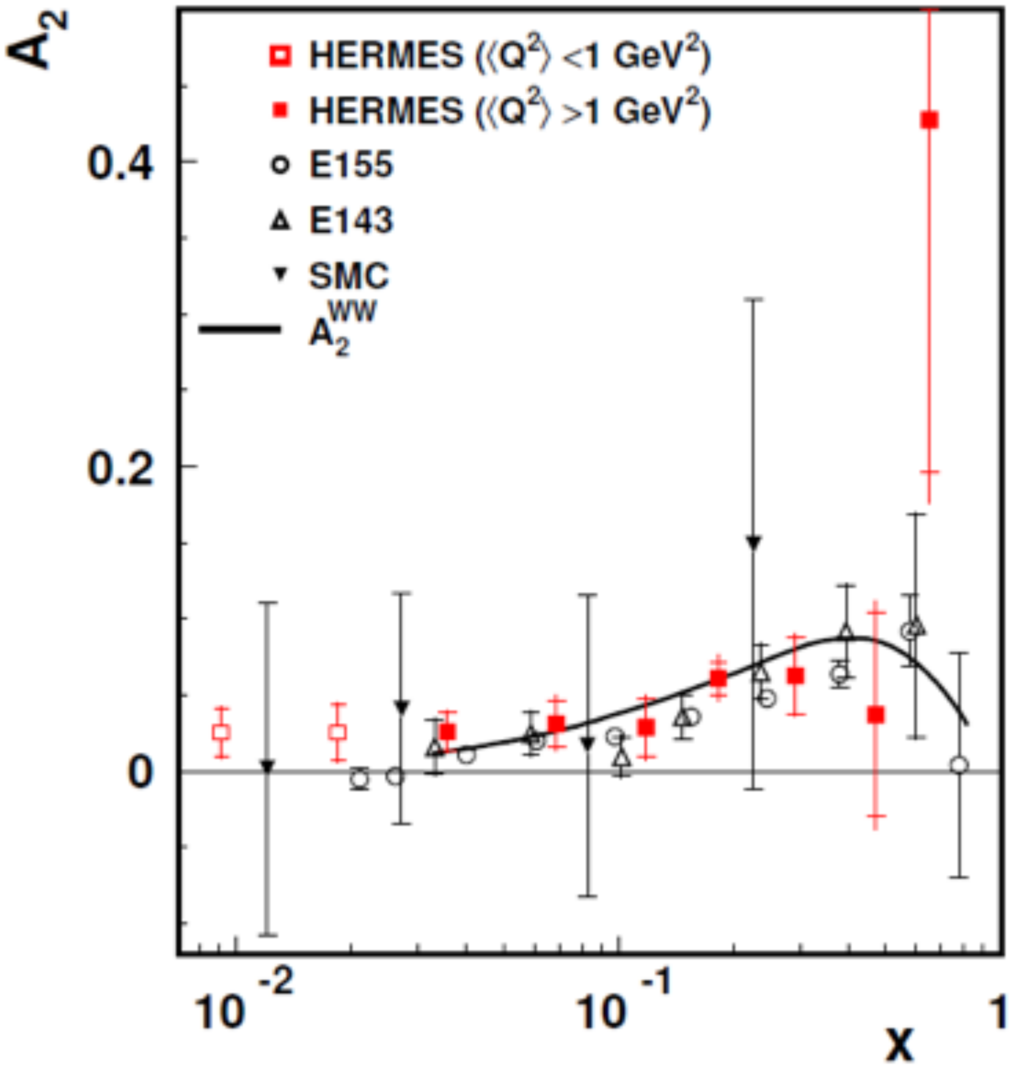


FSI from t=0 $\rightarrow \infty$

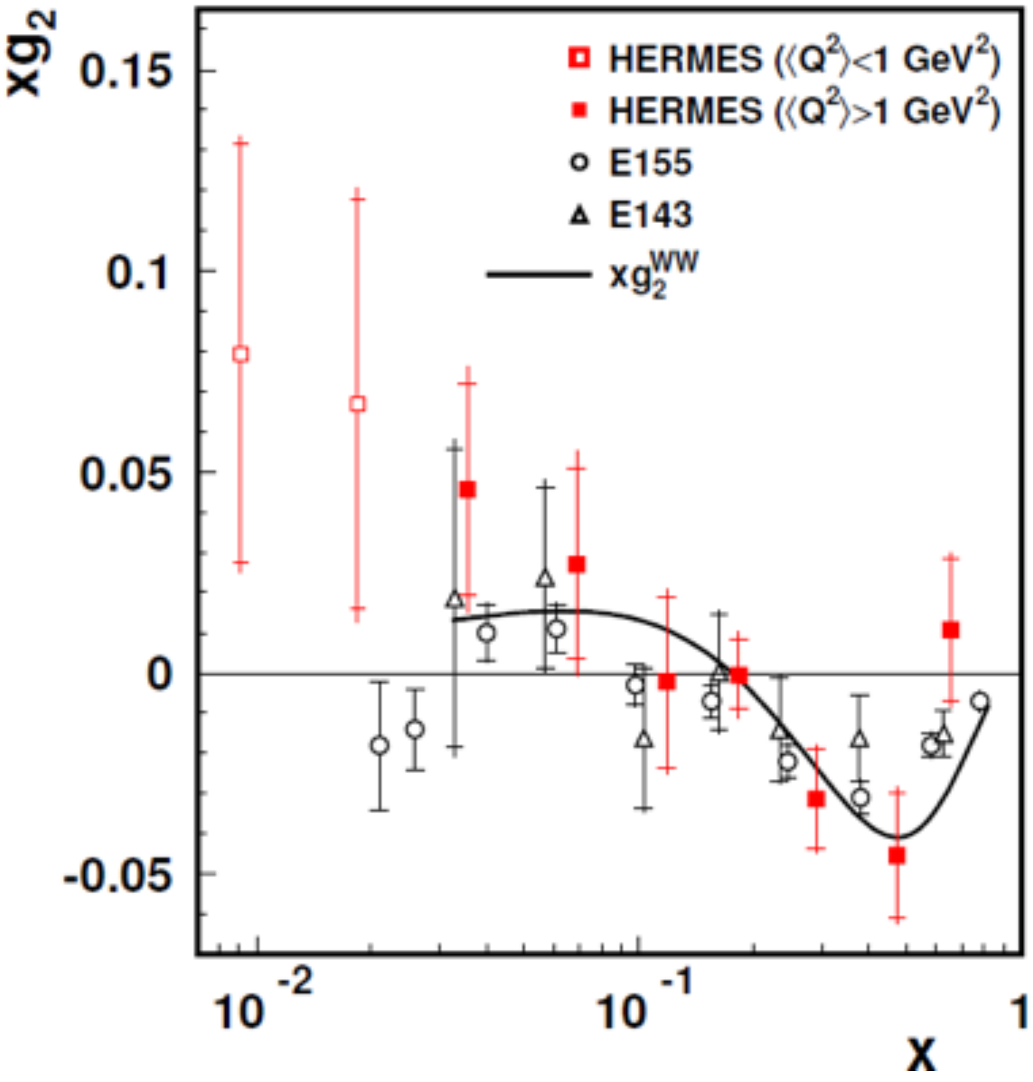
Force on struck quark at t=0 $\propto -d_2$

M. Burkardt arXiv:0810.3589

A_2 and g_2



HERMES, EPJ C 72 (2012) 1921

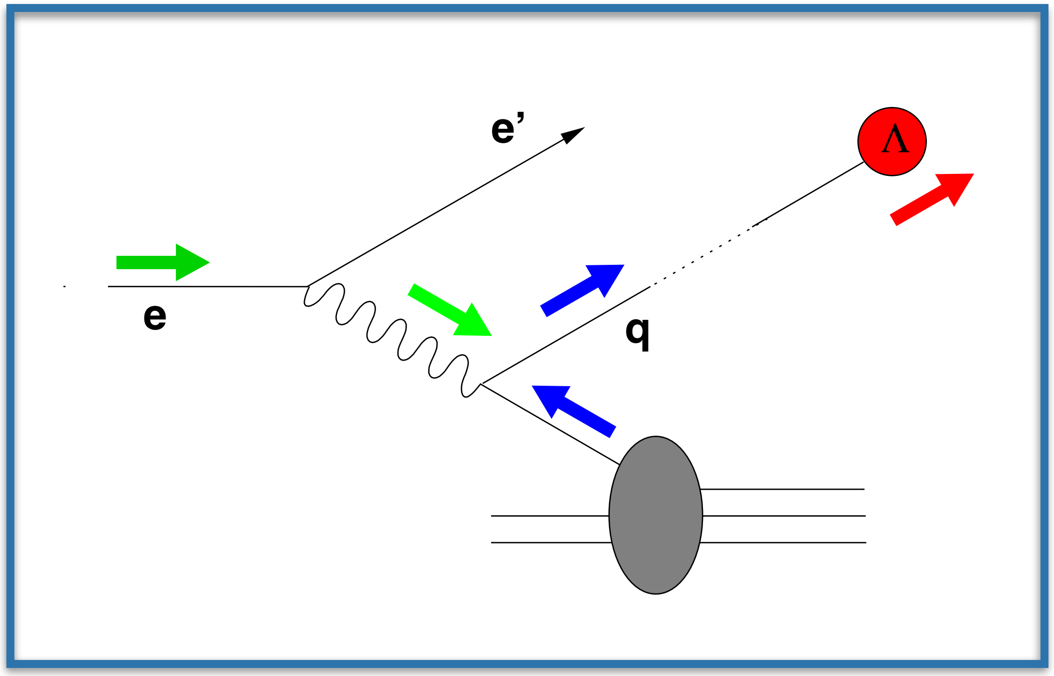


HERMES: $d_2 = 0.0148 \pm 0.0096(\mathrm{stat}) \pm 0.0048(\mathrm{syst})$

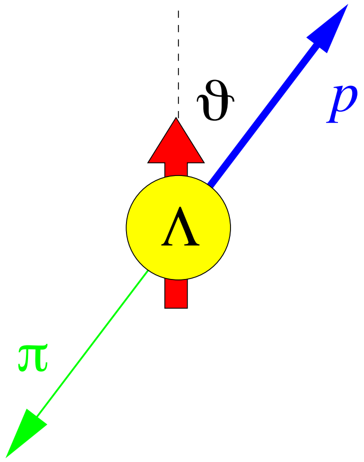
E143+155: $d_2 = 0.0032 \pm 0.0017$

Furthermore…

Spin-dependent fragmentation functions



Probe with longitudinal spin: polarization transfer to quark ⟶ fragmentation to Λ

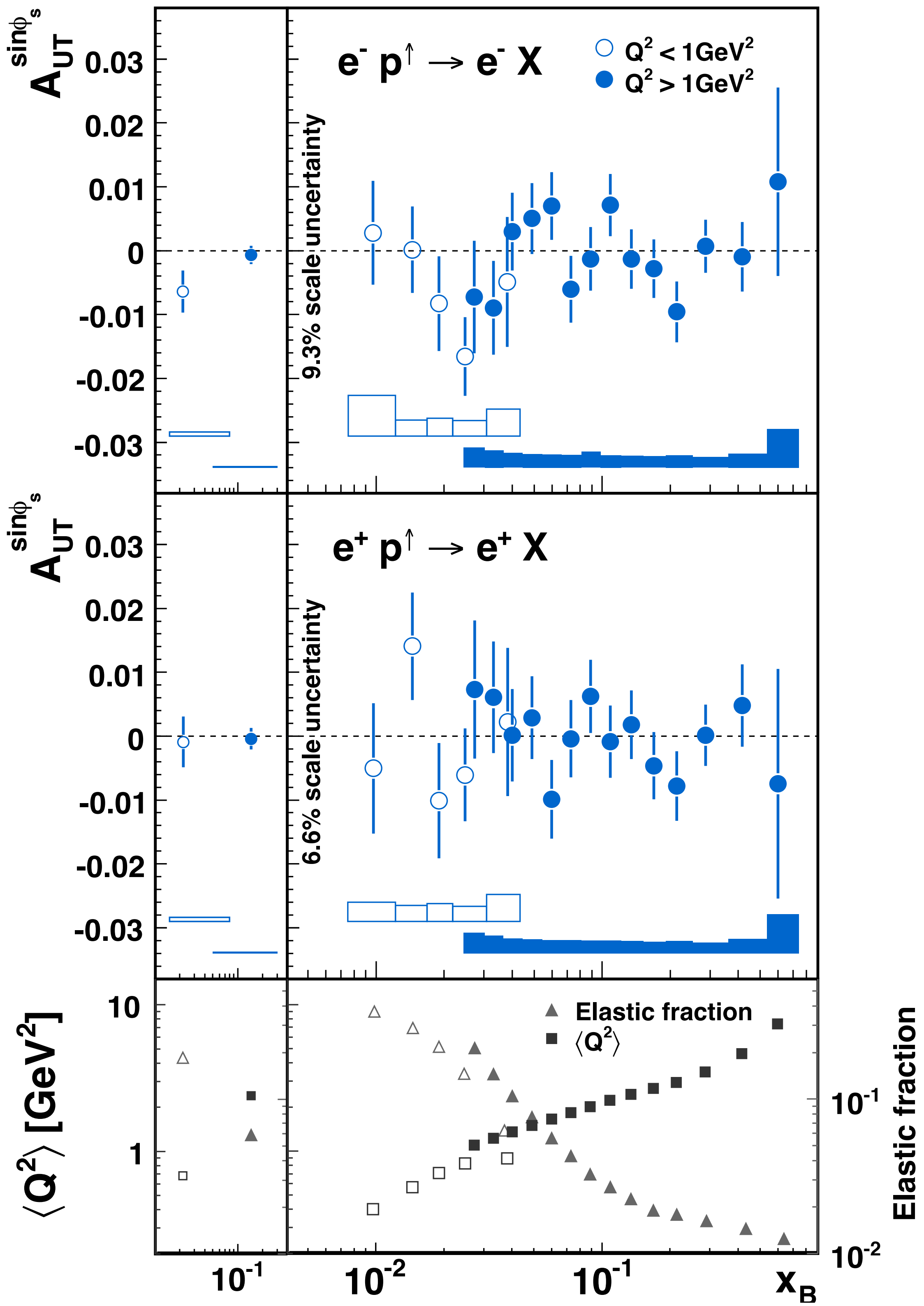


parity-violating weak decay of Λ:
in Λ rest frame, proton preferably emitted along Λ spin direction

Spin-dependent fragmentation functions $G_1,\, H_1,\, \tilde{G}_T$

Two-photon exchange in inclusive DIS

HERMES, Phys. Lett. B 682 (2010) 351-354



- transversely pol. target
- unpolarized beam

beam	$A_{UT}^{\sin\phi_S}$ $\times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(stat.) $\times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(syst.) $\times 10^{-3}$	$\langle x_B \rangle$	$\langle Q^2 \rangle$ [GeV^2]
e^+	-0.61	3.97	0.63	0.02	0.68
e^-	-6.55	3.40	0.63		
e^+	-0.60	1.70	0.29	0.14	2.40
e^-	-0.85	1.50	0.29		

$Q^2 < 1$

$Q^2 > 1$

Summary

Usage of e^+ and e^- beam offers advantages to access

- GPDs in DVCS measurements: beam charge but also spin asymmetries
- helicity distributions (collinear)
- g_2 structure function
- spin-dependent, collinear fragmentation functions
- two-photon exchange in elastic and deep-inelastic scattering

Summary

Usage of e^+ and e^- beam offers advantages to access

- GPDs in DVCS measurements: beam charge but also spin asymmetries
- helicity distributions (collinear)
- g_2 structure function
- spin-dependent, collinear fragmentation functions
- two-photon exchange in elastic and deep-inelastic scattering

Thank you