Highlights from the HERMES experiment

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UTFSM
Valparaiso
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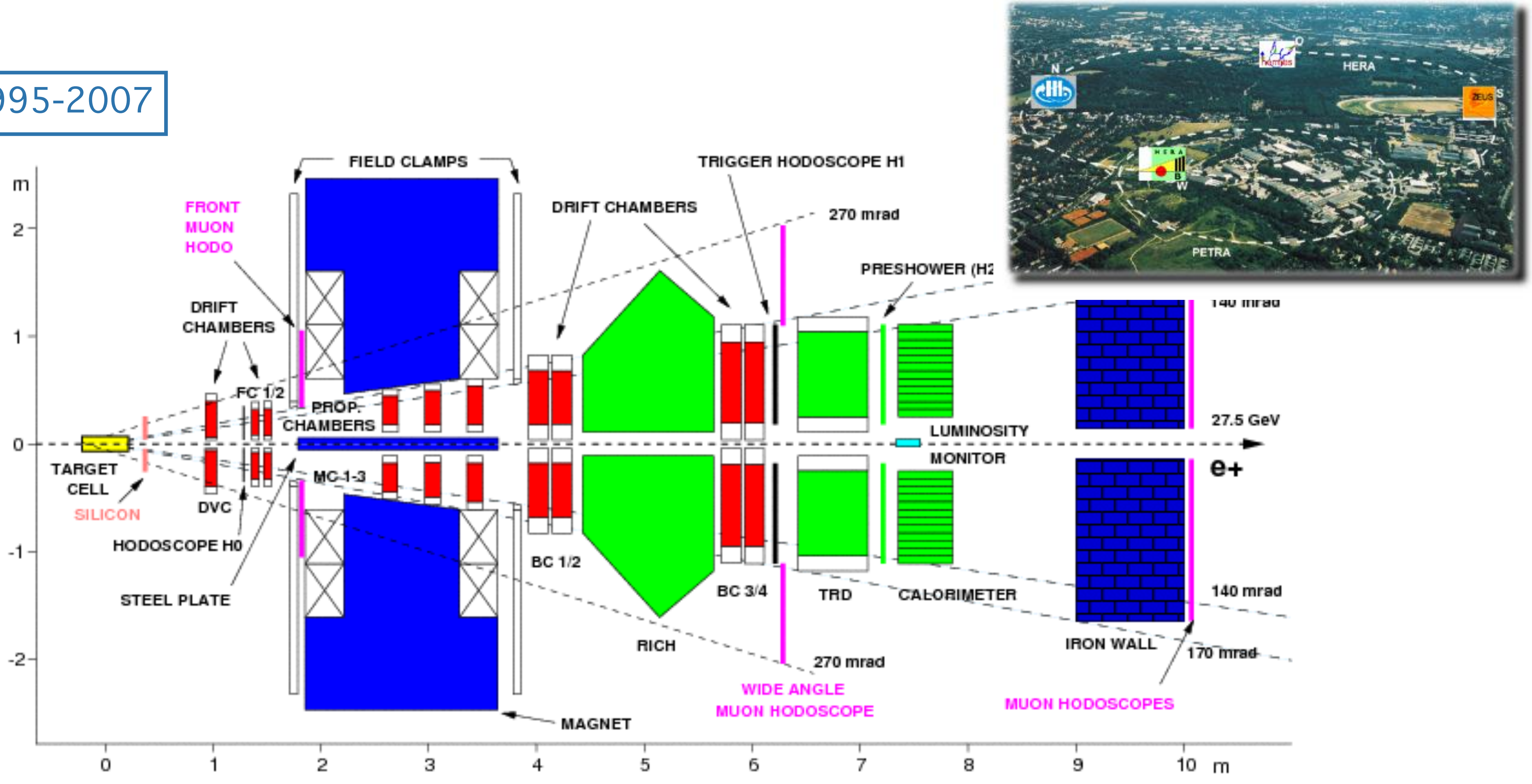
HERMES: HERA MEasurement of Spin

The HERMES experiment

data taking 1995-2007

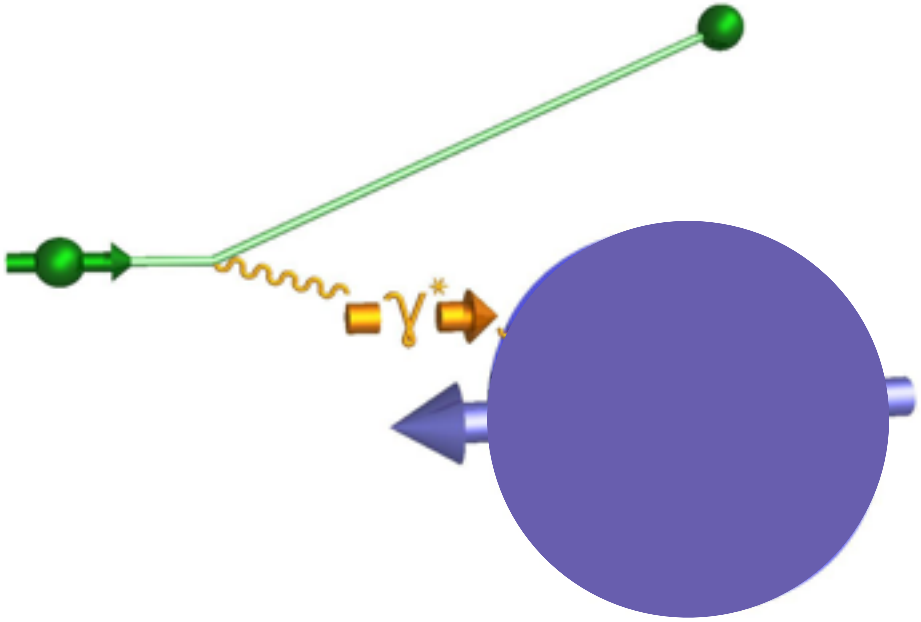


<u>Beam</u>
longitudinally pol. e^+ & e^-
E=27.6 GeV

<u>Gaseous internal target</u>
transversely pol. H
longitudinally pol. H, D, He
unpol. H, D, He, Ne, Kr, Xe

- lepton-hadron PID:
  - high efficiency (>98%)
  - low contamination (<1%)
- hadron PID: RICH 2-15 GeV

Measurement of quark spin contribution



- longitudinally polarised proton, deuteron, …
- longitudinally polarised e±, μ± beam

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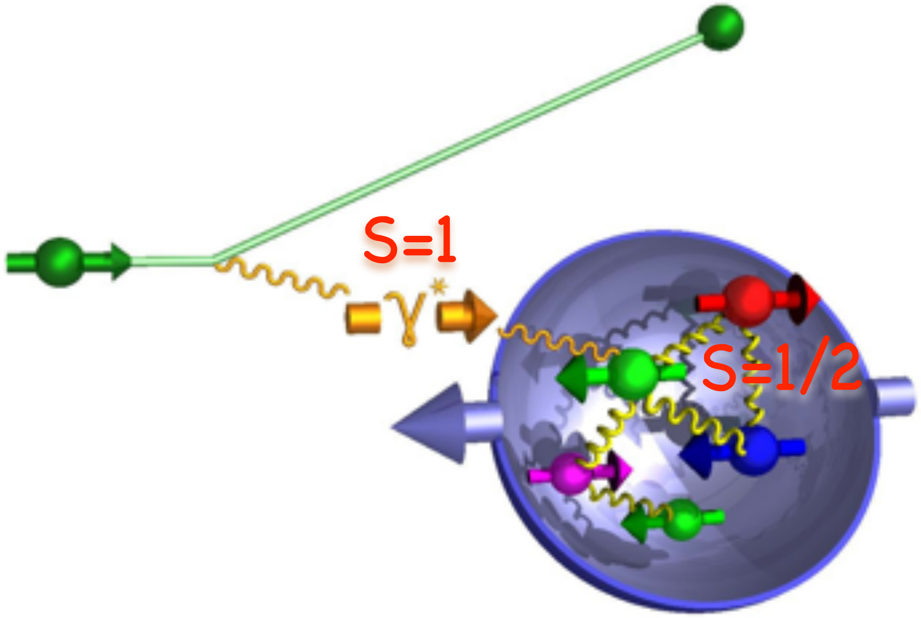

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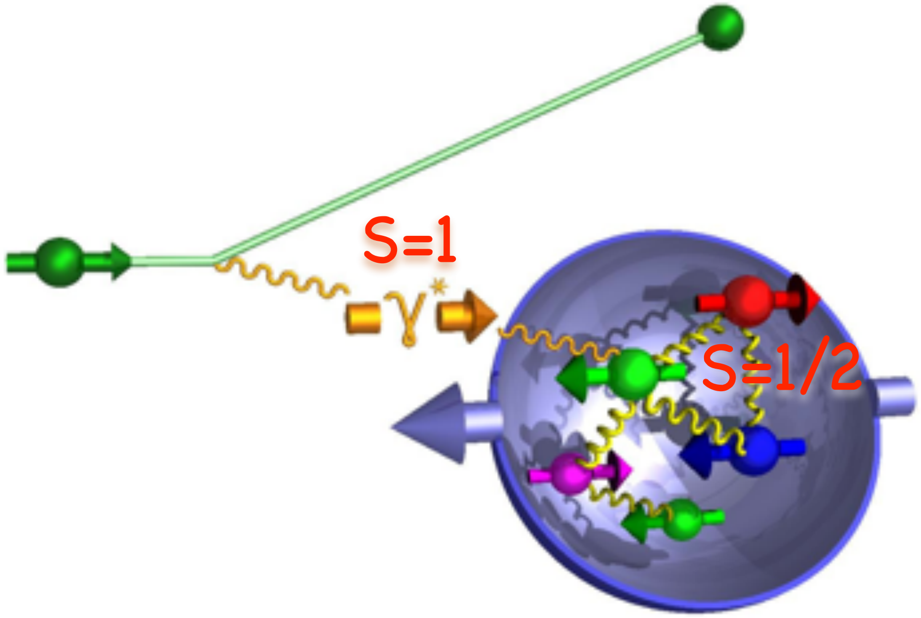

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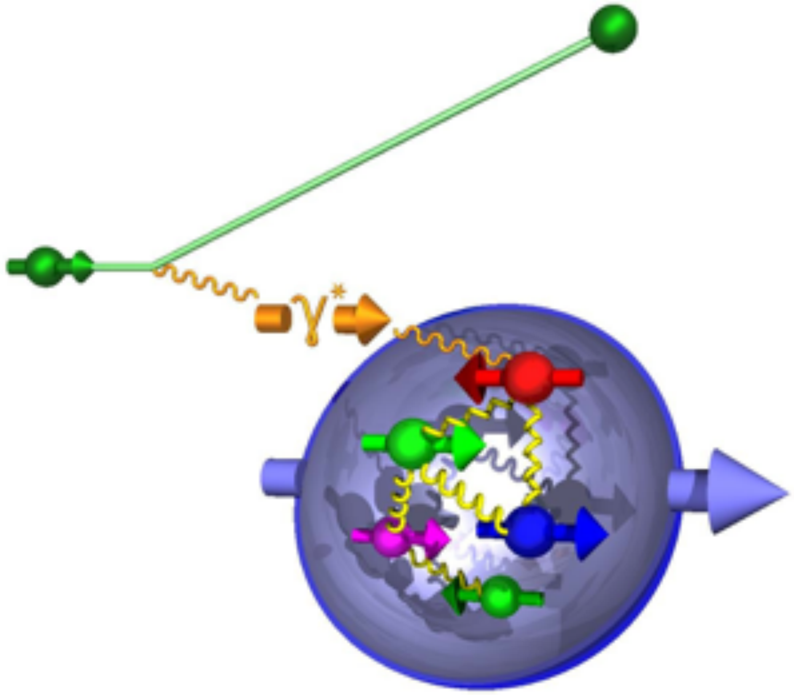
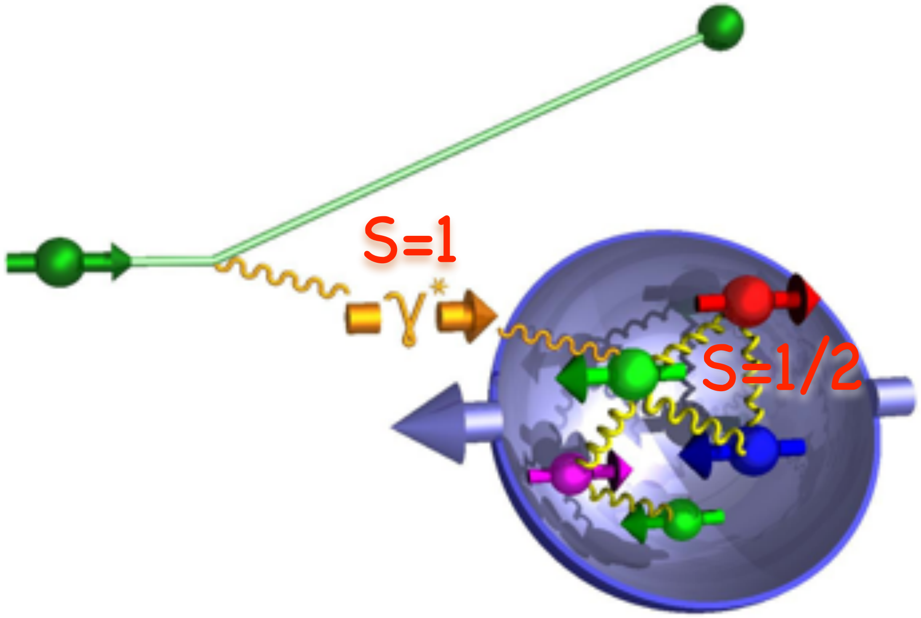
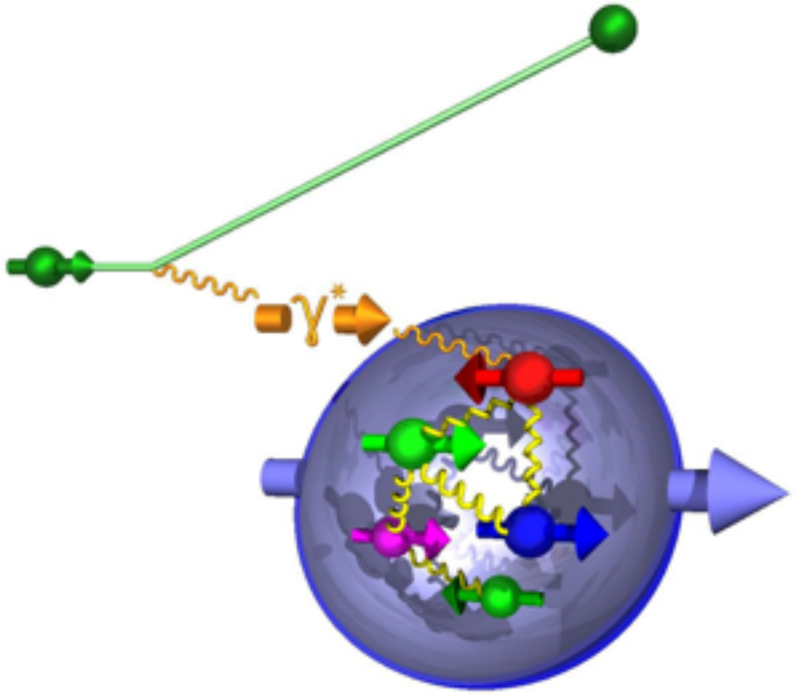


flip spin

Measurement of quark spin contribution





- longitudinally polarised proton, deuteron, …
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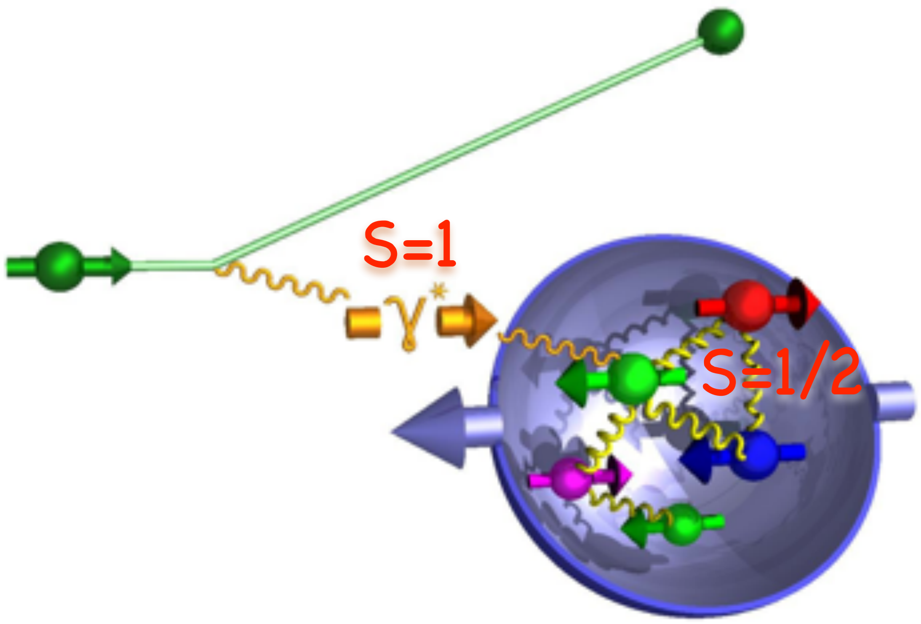
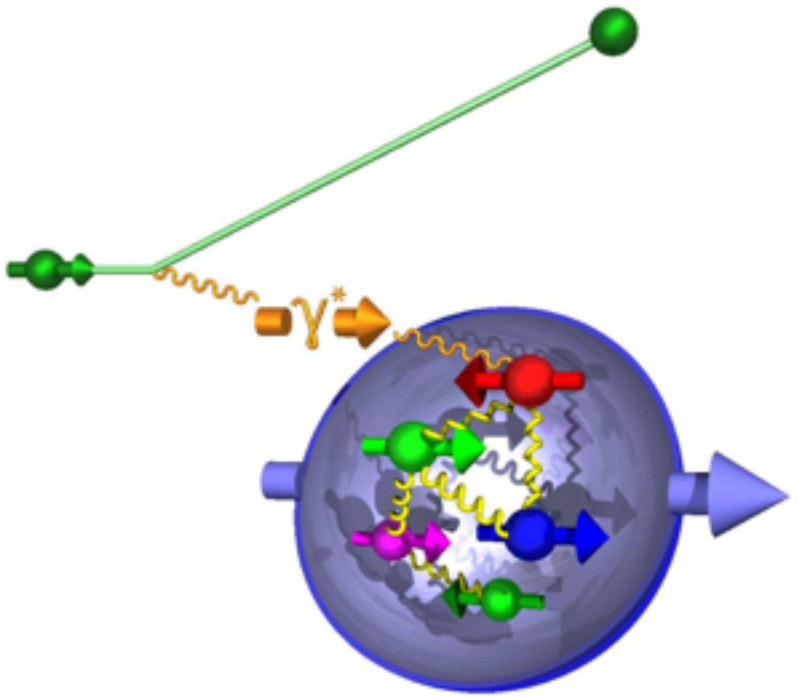
flip spin

number of quarks with spin aligned - anti-aligned with proton spin

$$\overset{\Leftarrow}{\overset{\rightarrow}{\sigma}} - \overset{\Rightarrow}{\overset{\rightarrow}{\sigma}}$$

Measurement of quark spin contribution





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$$\frac{\overset{\Leftarrow}{\overset{\rightarrow}{\sigma}} - \overset{\Rightarrow}{\overset{\rightarrow}{\sigma}}}{\overset{\Leftarrow}{\overset{\rightarrow}{\sigma}} + \overset{\Rightarrow}{\overset{\rightarrow}{\sigma}}}$$

Measurement of quark spin contribution

$$\frac{\overset{\Leftarrow}{\overset{\rightarrow}{\sigma}} - \overset{\Rightarrow}{\overset{\rightarrow}{\sigma}}}{\overset{\Leftarrow}{\overset{\rightarrow}{\sigma}} + \overset{\Rightarrow}{\overset{\rightarrow}{\sigma}}} \propto g_1^p(x) = \frac{1}{2}\sum_q e_q^2\,\Delta q(x) = \frac{1}{2}\sum_q e_q^2 \left(\overset{\Leftarrow}{\overset{\leftarrow}{q}}\,(x) - \overset{\Leftarrow}{\vec{q}}\,(x) \right)$$

parton fractional
longitudinal momentum

Measurement of quark spin contribution

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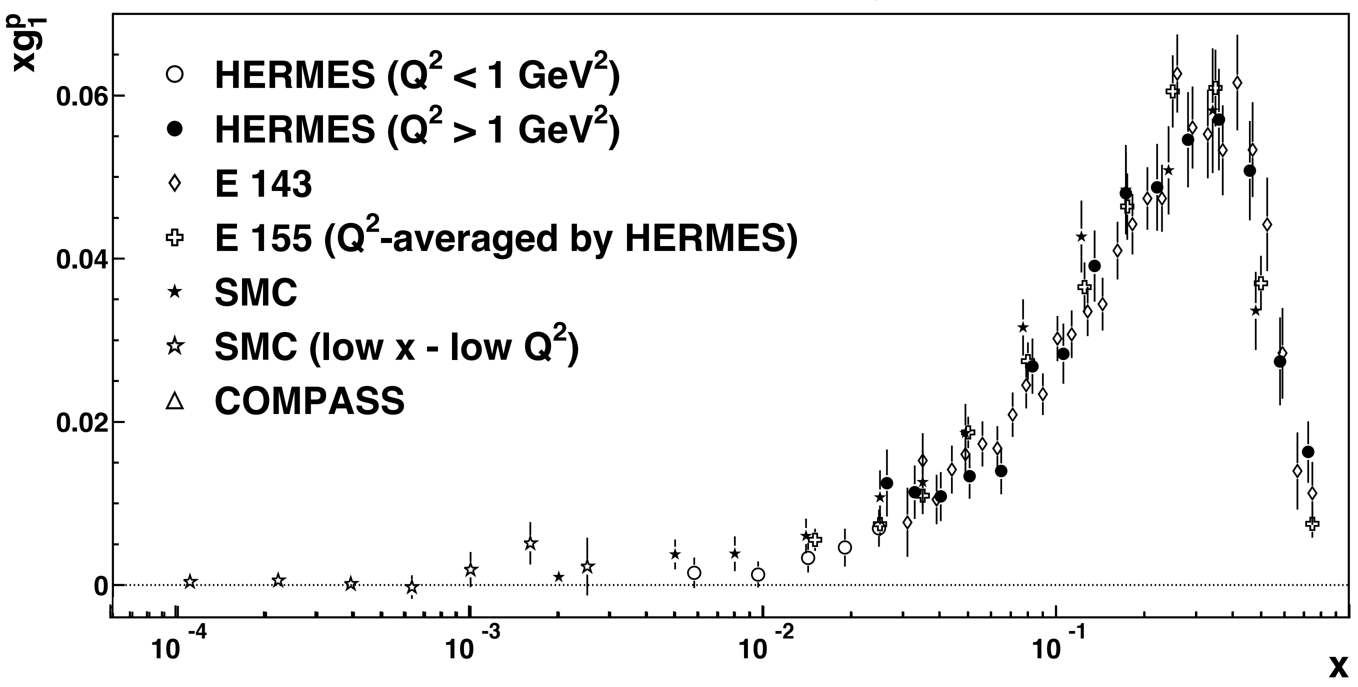
parton fractional longitudinal momentum

Phys. Rev. D 75 (2007) 012007



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parton fractional longitudinal momentum

$$\Big\downarrow \int dx$$

neutron β decay: $\Delta u - \Delta d$

hyperon β decay: $\Delta u + \Delta d - 2\Delta s$

$$\Big\downarrow$$

$$\boxed{\Delta\Sigma = \Delta u + \Delta d + \Delta s}$$

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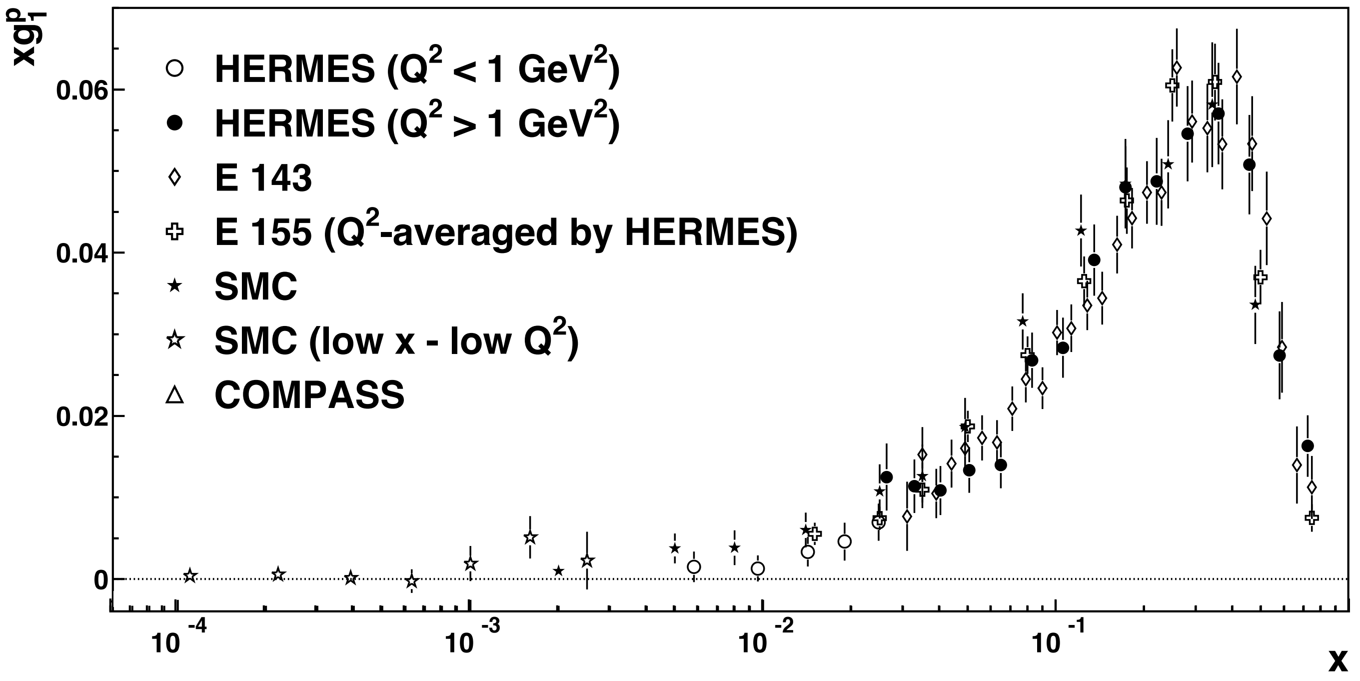

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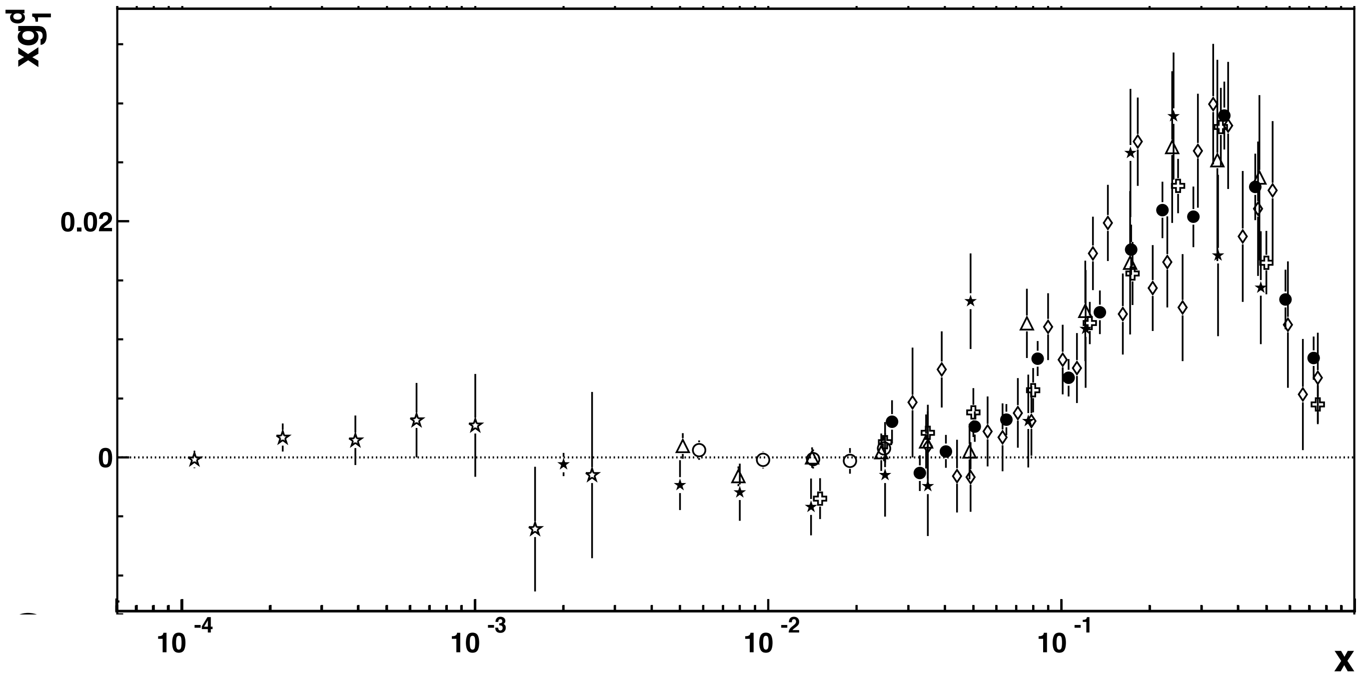
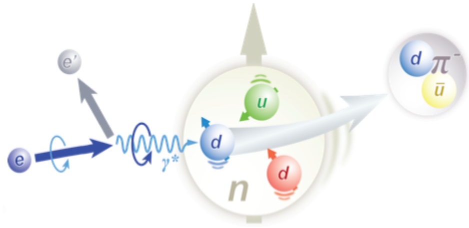
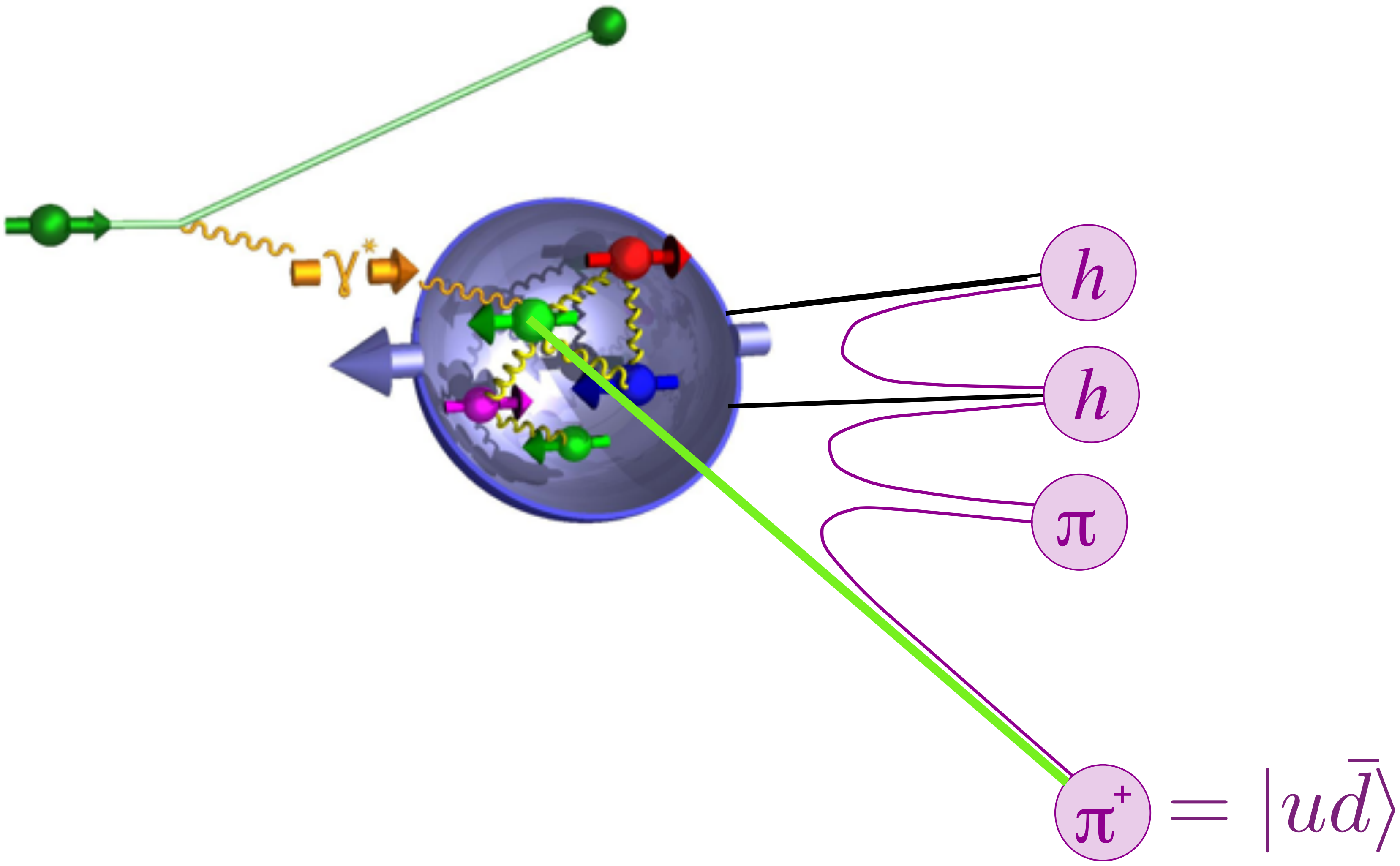


From deuterium data:

$$\Delta\Sigma(Q^2 = 5\ \mathrm{GeV}^2) = 0.330 \pm 0.011(\mathrm{theo.}) \pm 0.025(\mathrm{exp.}) \pm 0.028(\mathrm{evol.})$$

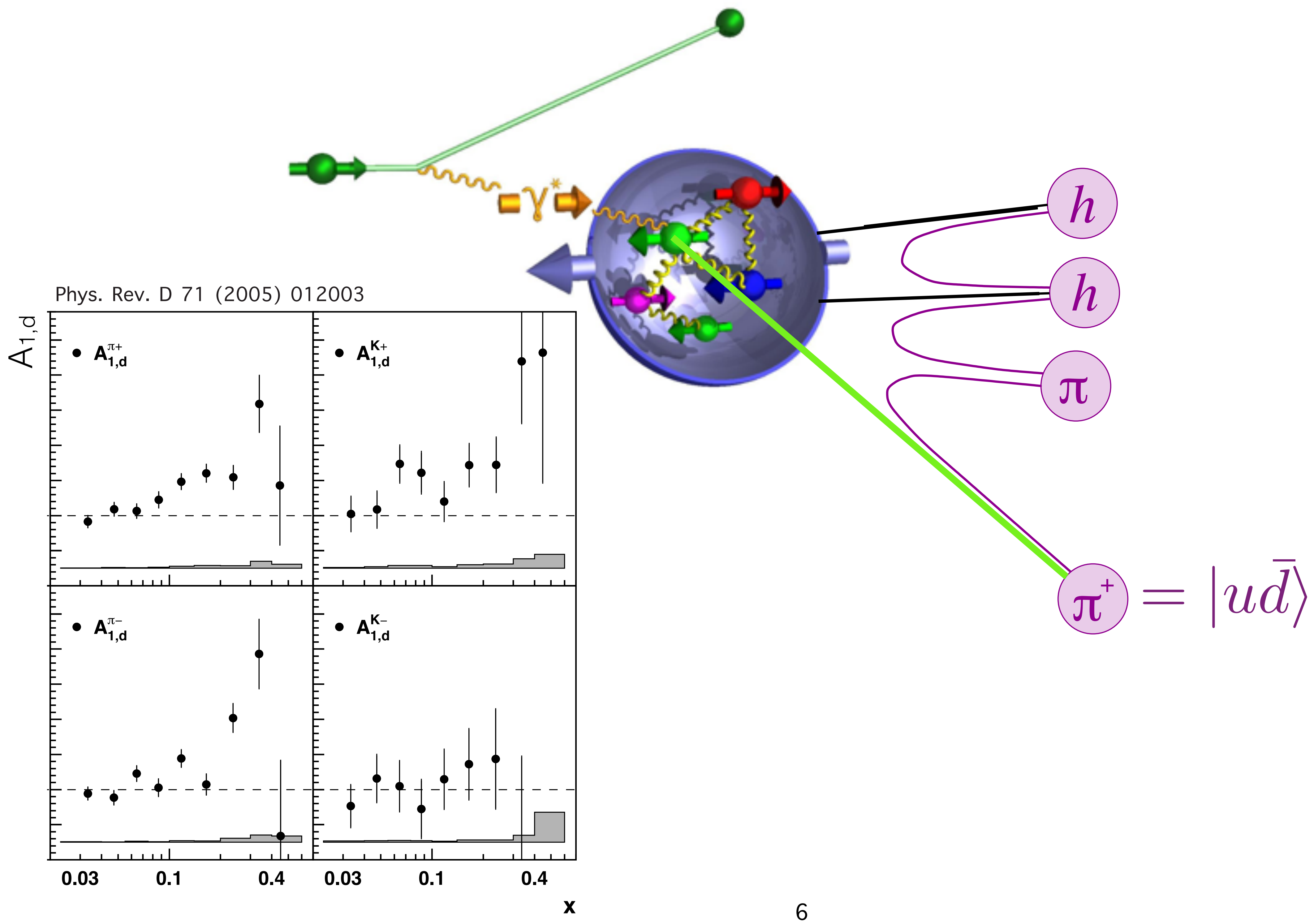


Disentangling quark flavours

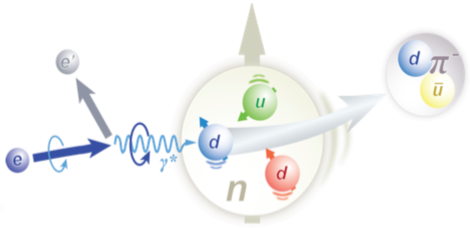


$= |u\bar{d}\rangle$

Disentangling quark flavours



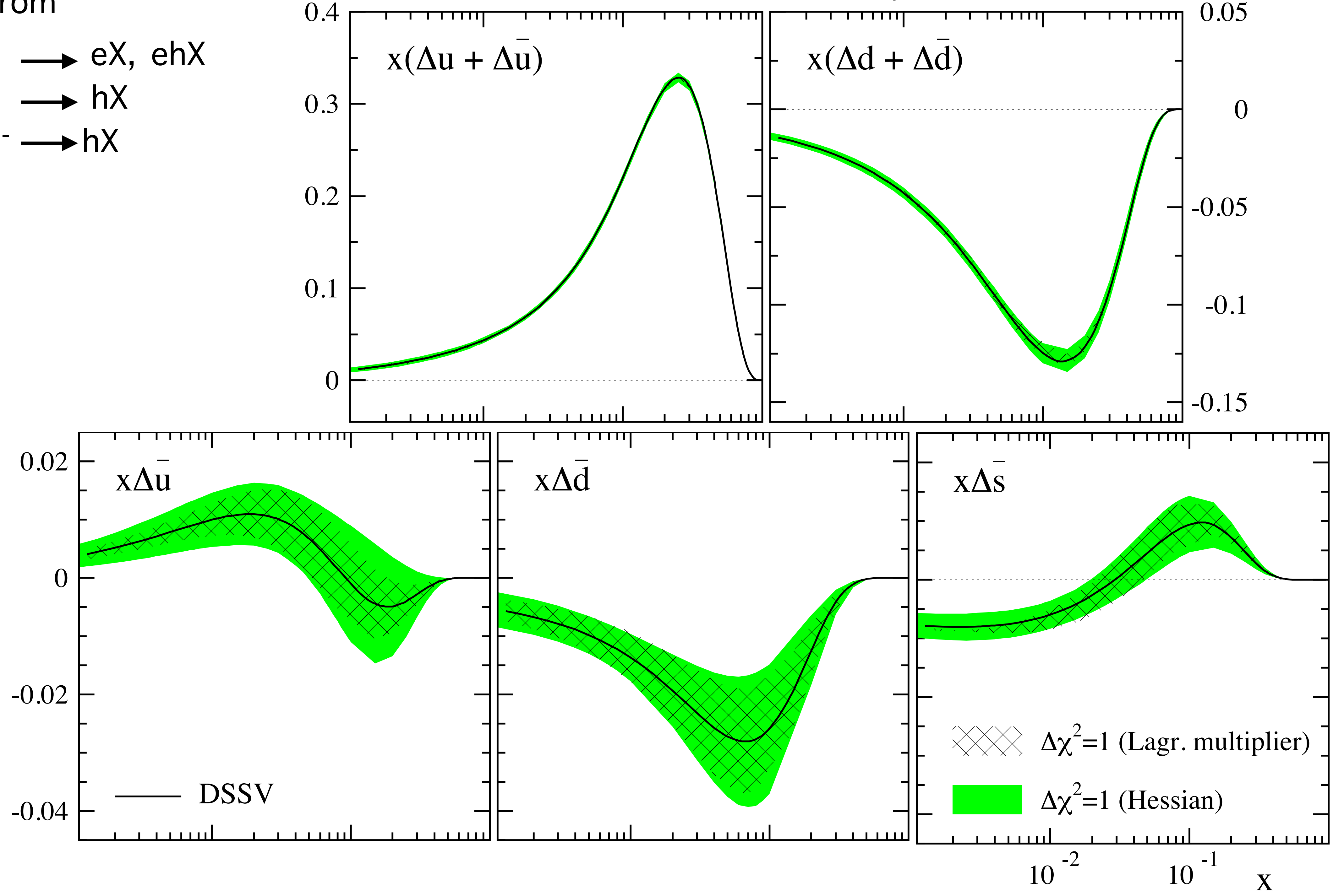
Phys. Rev. D 71 (2005) 012003



Disentangling quark flavours

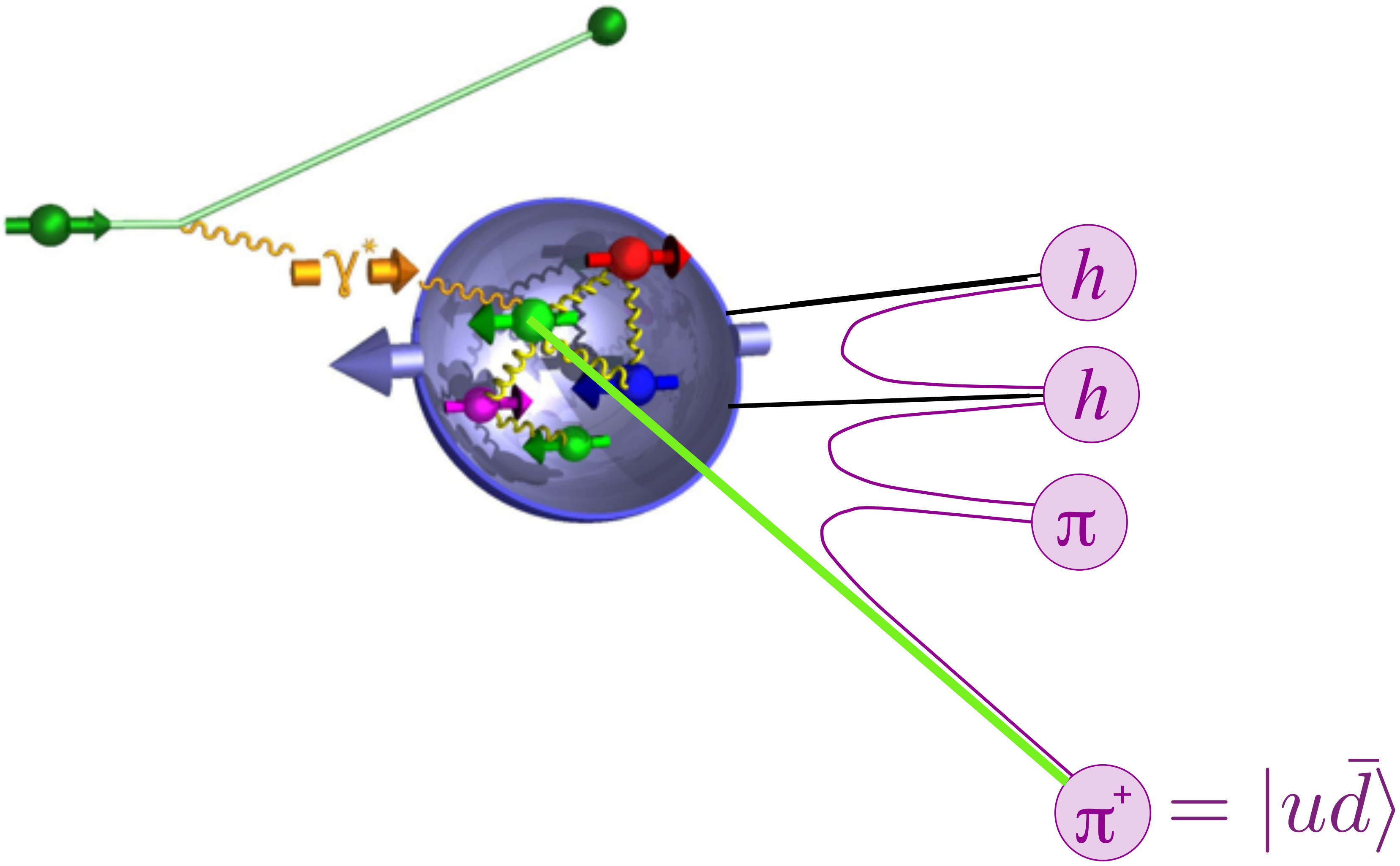
Data from

- ep $\longrightarrow$ eX, ehX
- pp $\longrightarrow$ hX
- e^+e^- $\longrightarrow$ hX



Phys.Rev. D 80 (2009) 034030

Transverse momentum dependent semi-inclusive DIS



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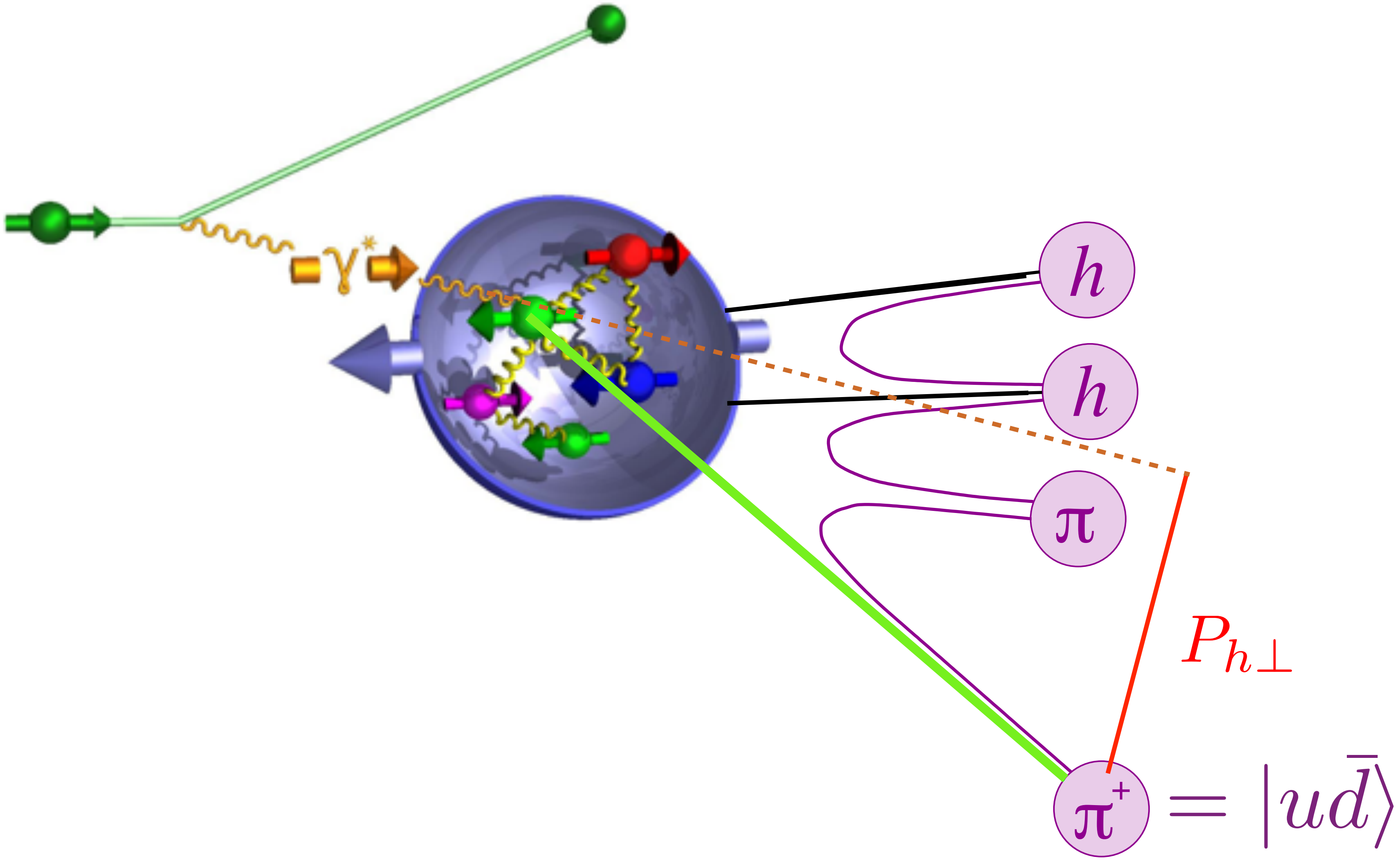
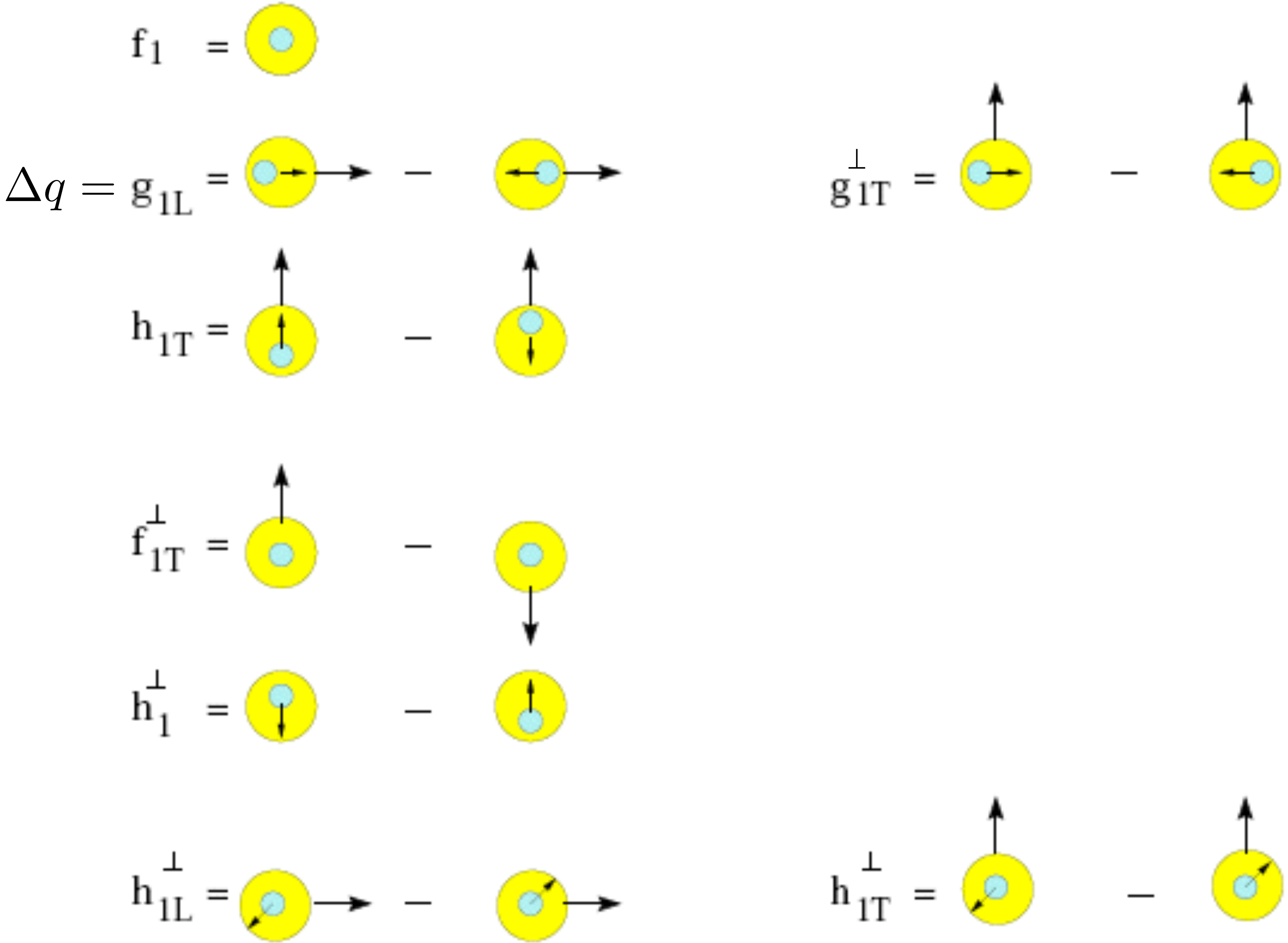
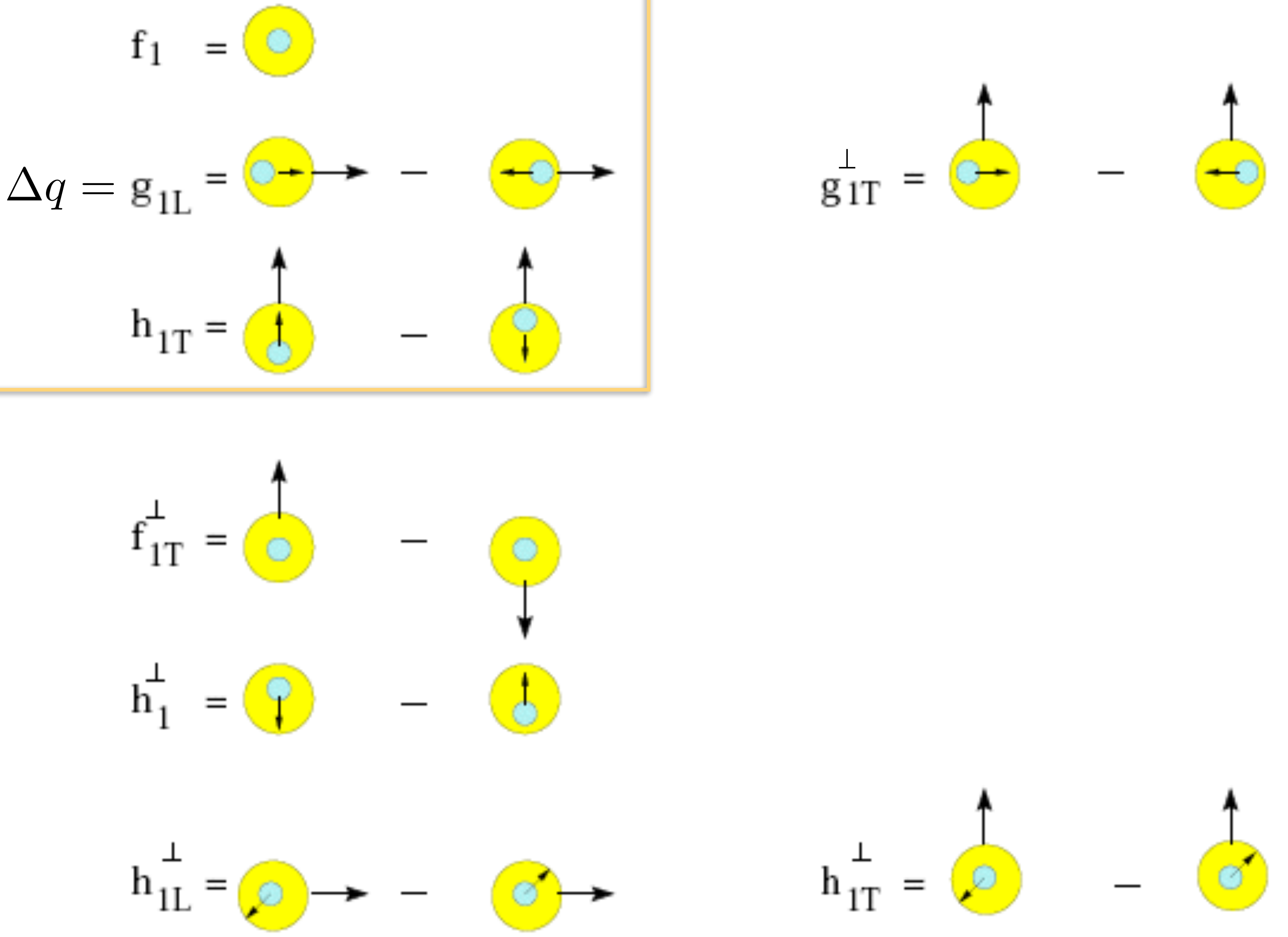


Transverse-momentum-dependent (TMD) PDFs

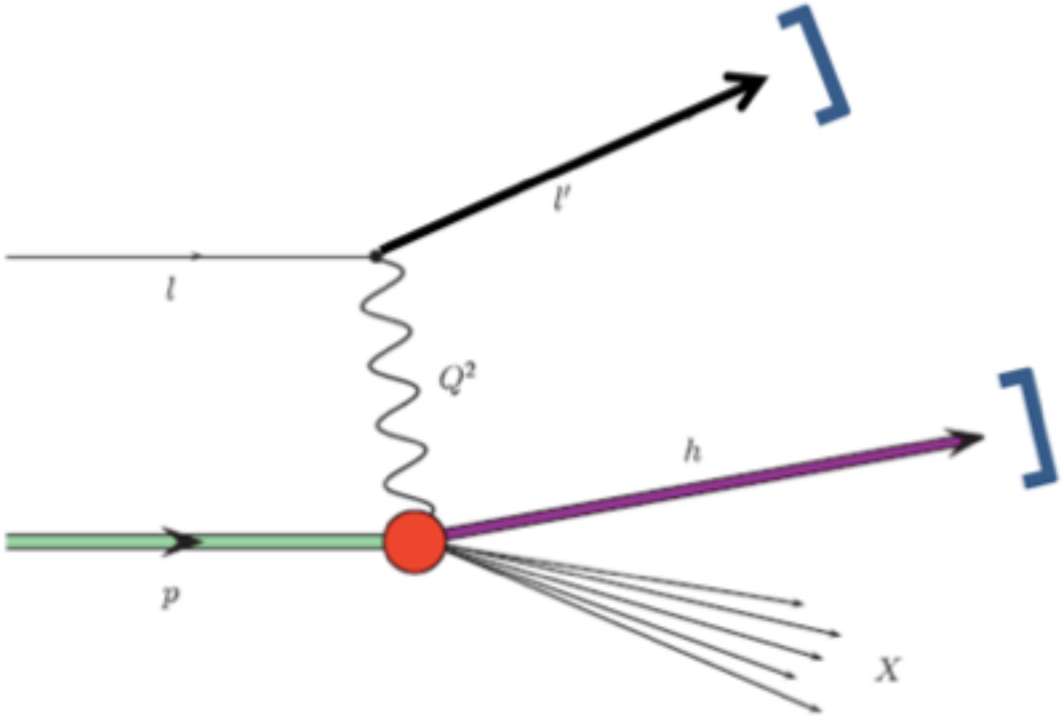


Transverse-momentum-dependent (TMD) PDFs

Only PDFs to survive integration over transverse momentum

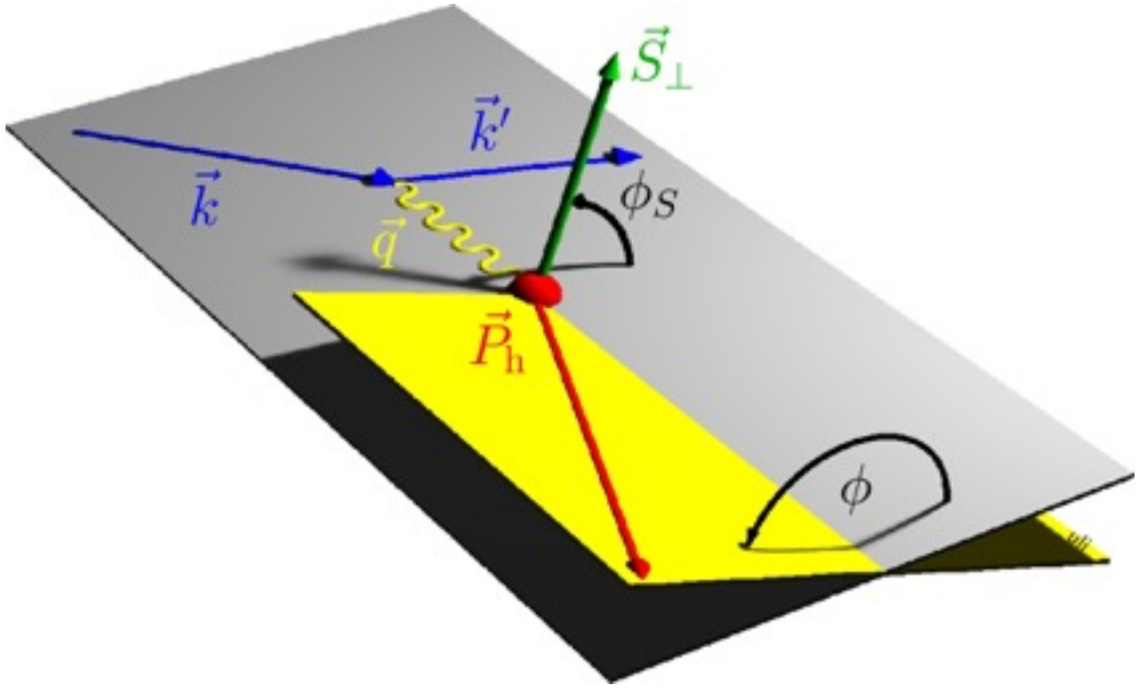


Semi-inclusive DIS
single-hadron production



Semi-inclusive DIS cross section

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



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&+\ \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)\\
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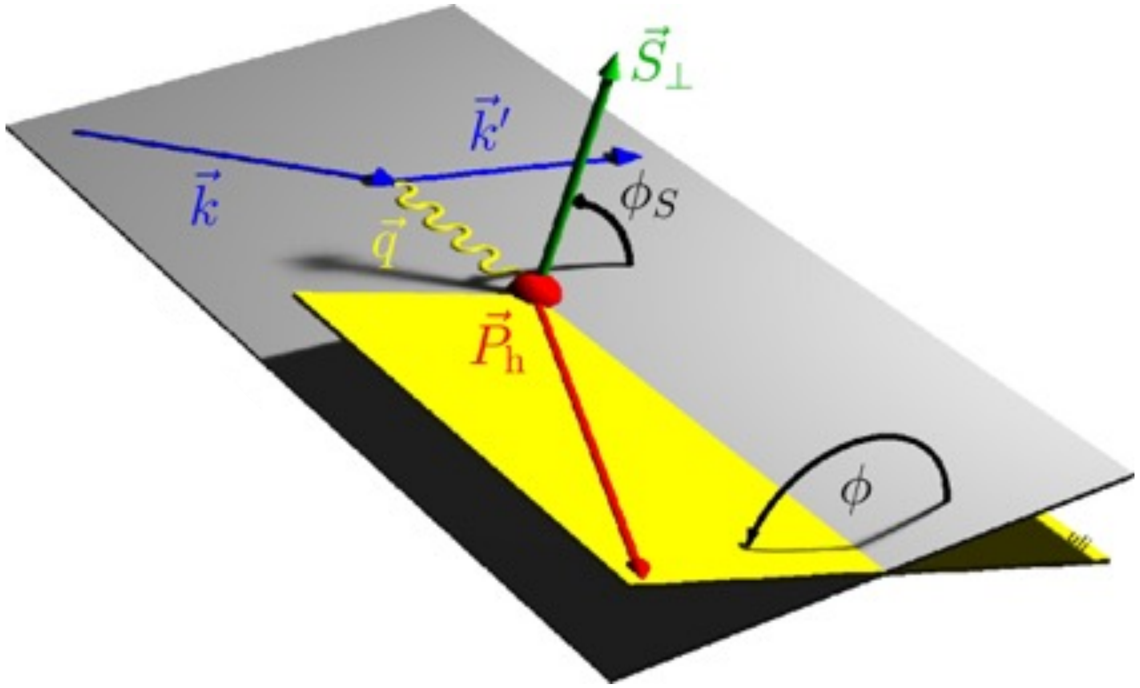
\end{aligned}
$$

longitudinal target polarization

transverse target polarization

beam polarization



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&+ \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) \\
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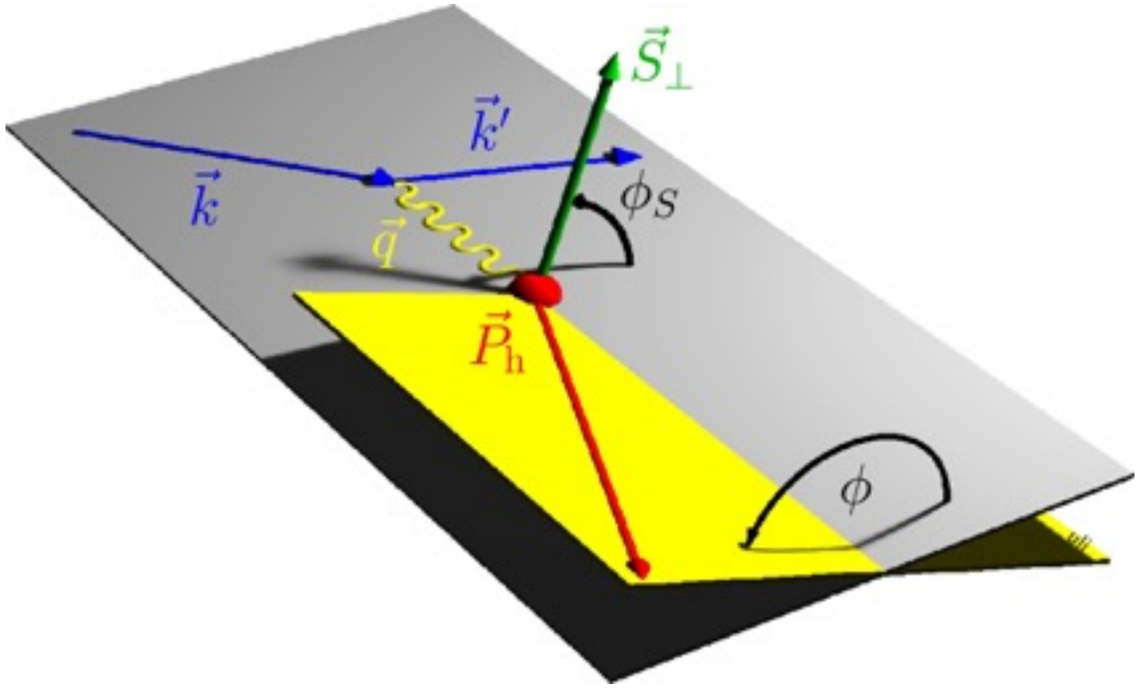
longitudinal target polarization

transverse target polarization

beam polarization

beam polarization

target polarization



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\end{aligned}$$

longitudinal target polarization

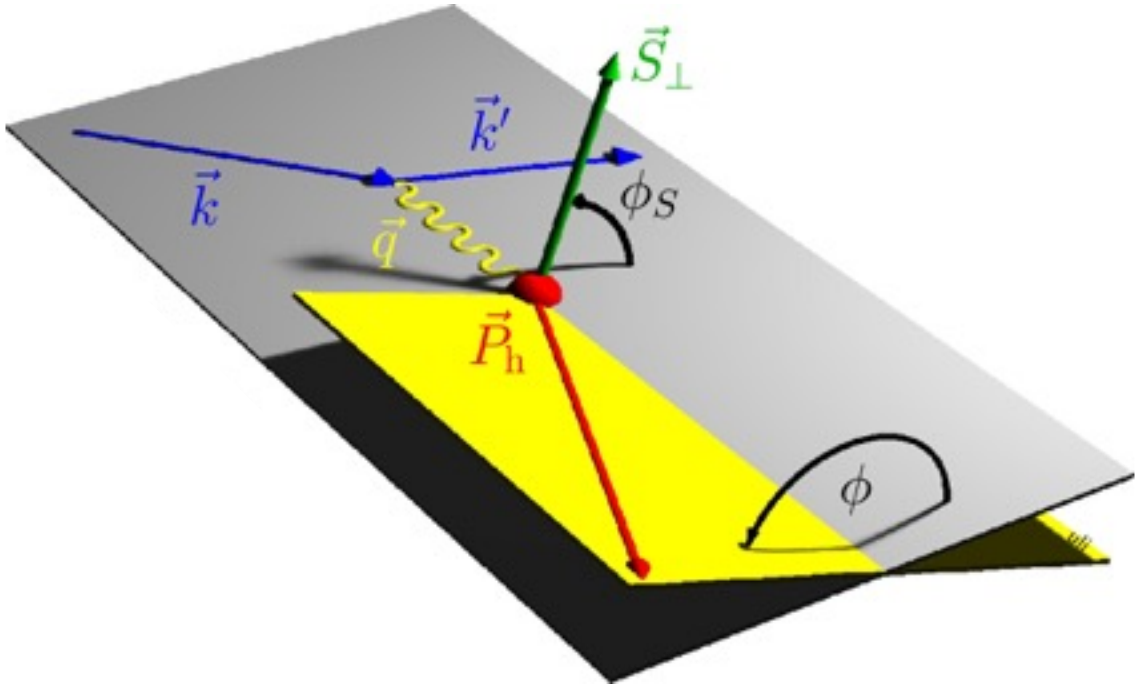
transverse target polarization

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)

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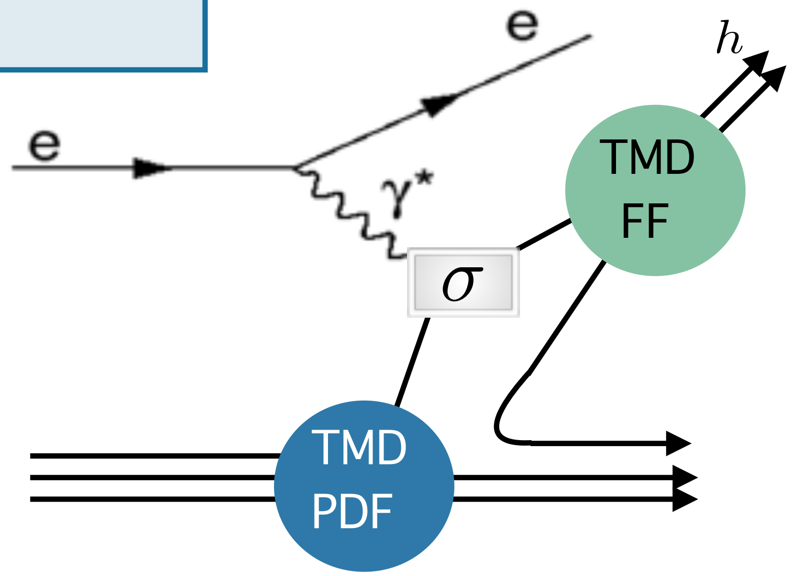

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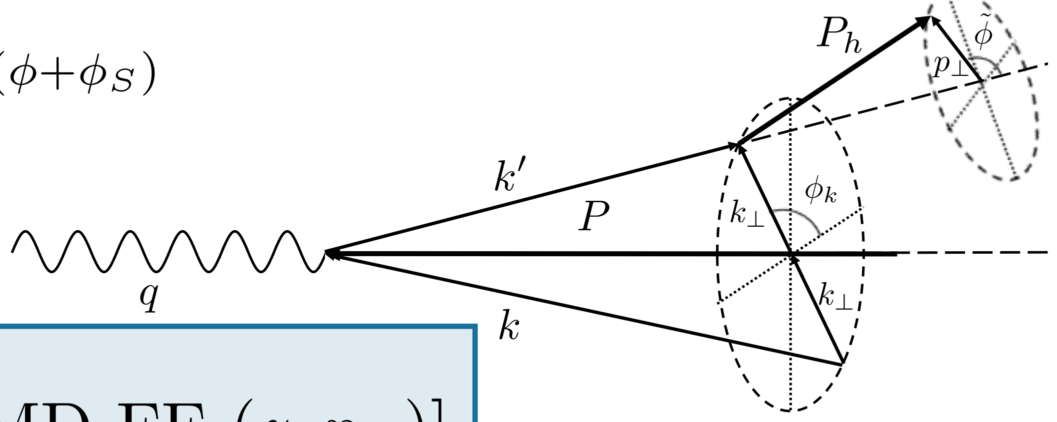

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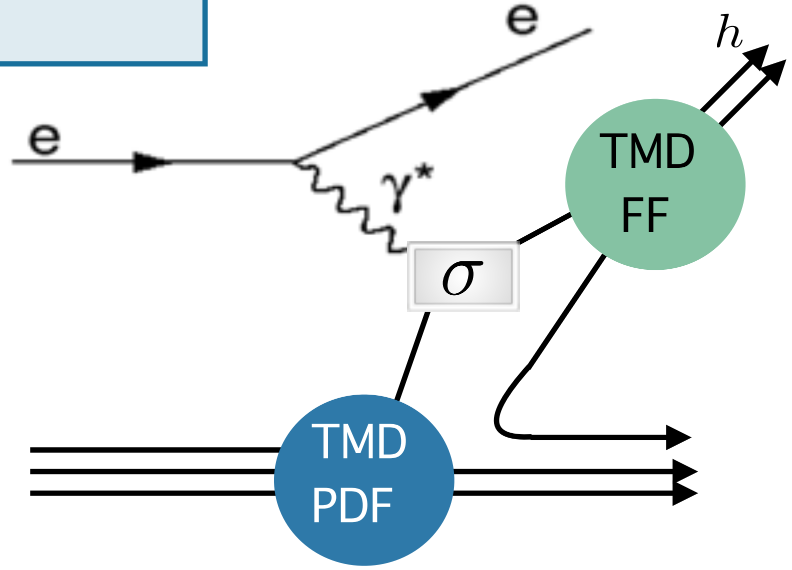

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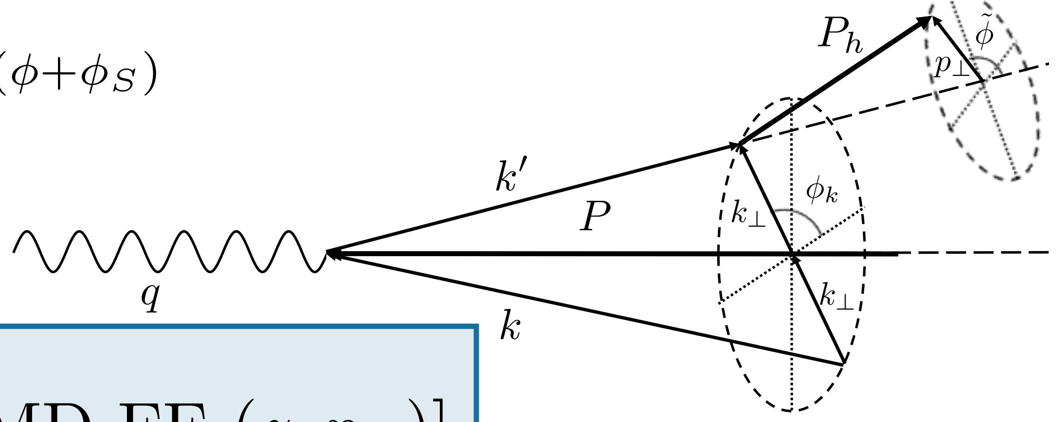

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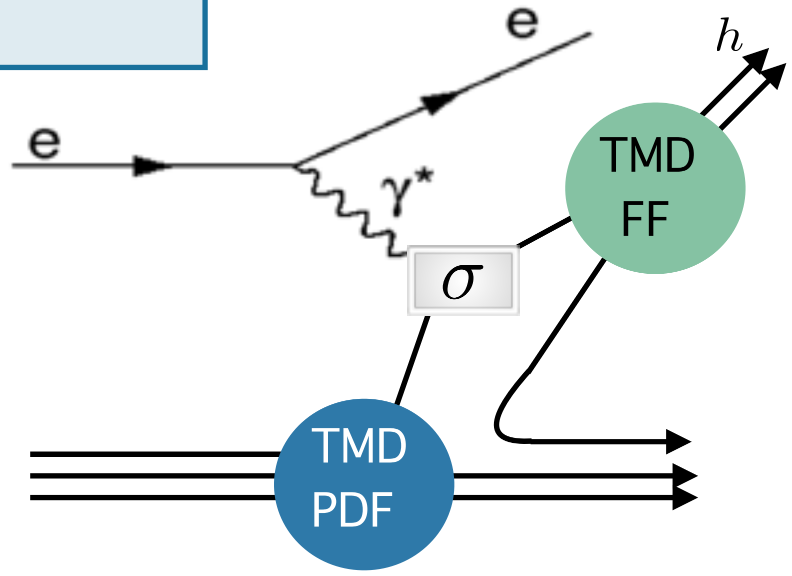

quark polarization

nucleon polarization

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

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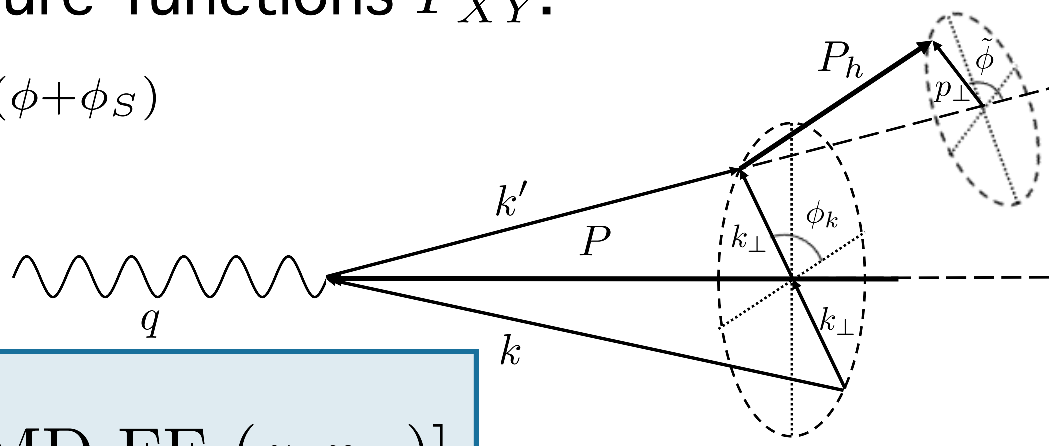

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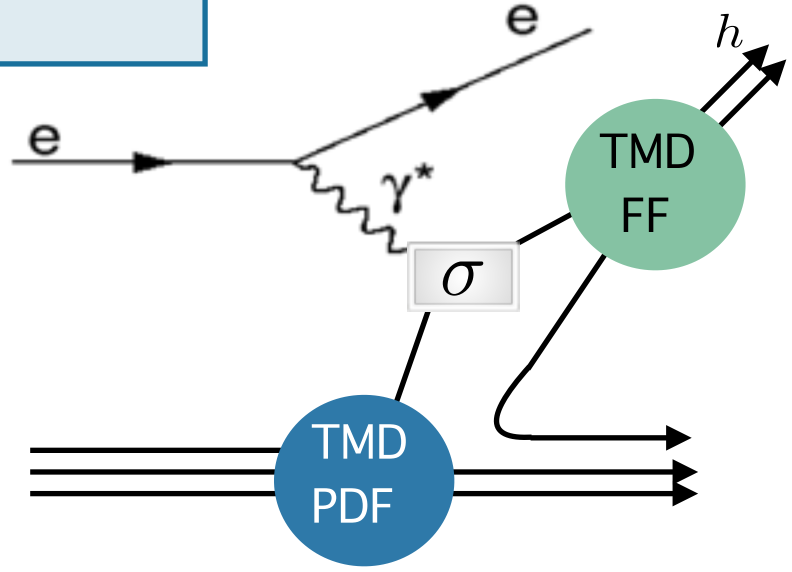

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L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\,h_{1T}^\perp$

quark polarization

hadron polarization

	U	L	T
U	D_1		$H_1^\perp$

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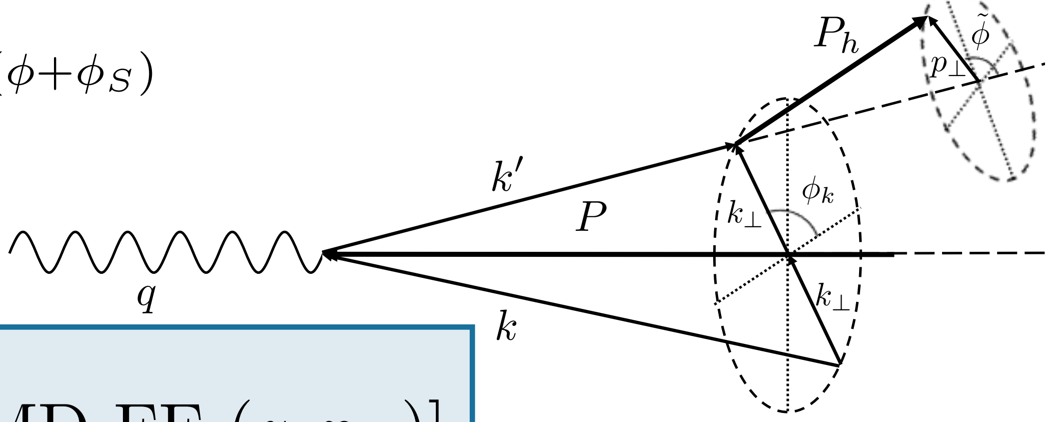

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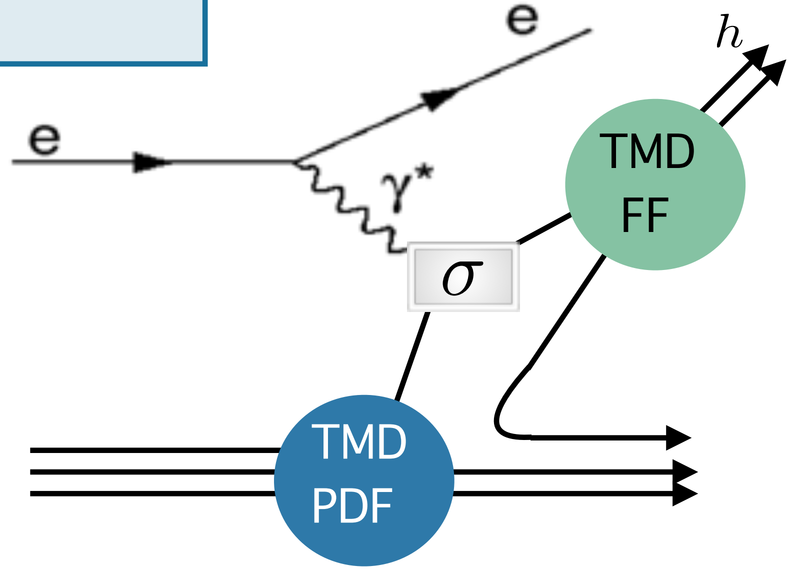


quark polarization

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

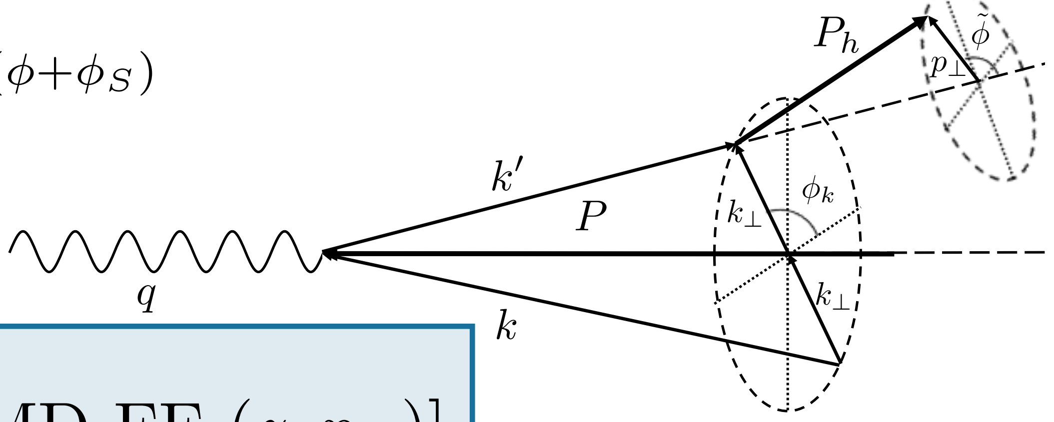
hadron polarization

	U	L	T
U	D_1		$H_1^\perp$

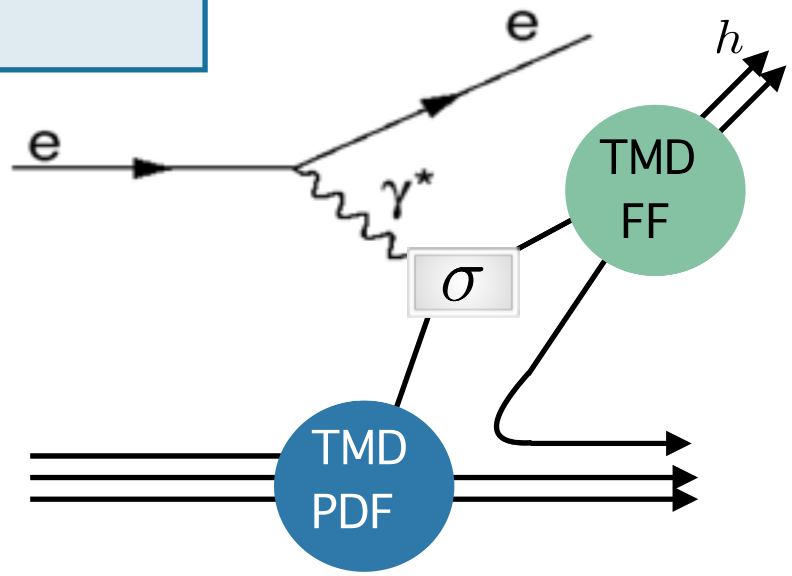
TMD PDFs and fragmentation functions (FFs)

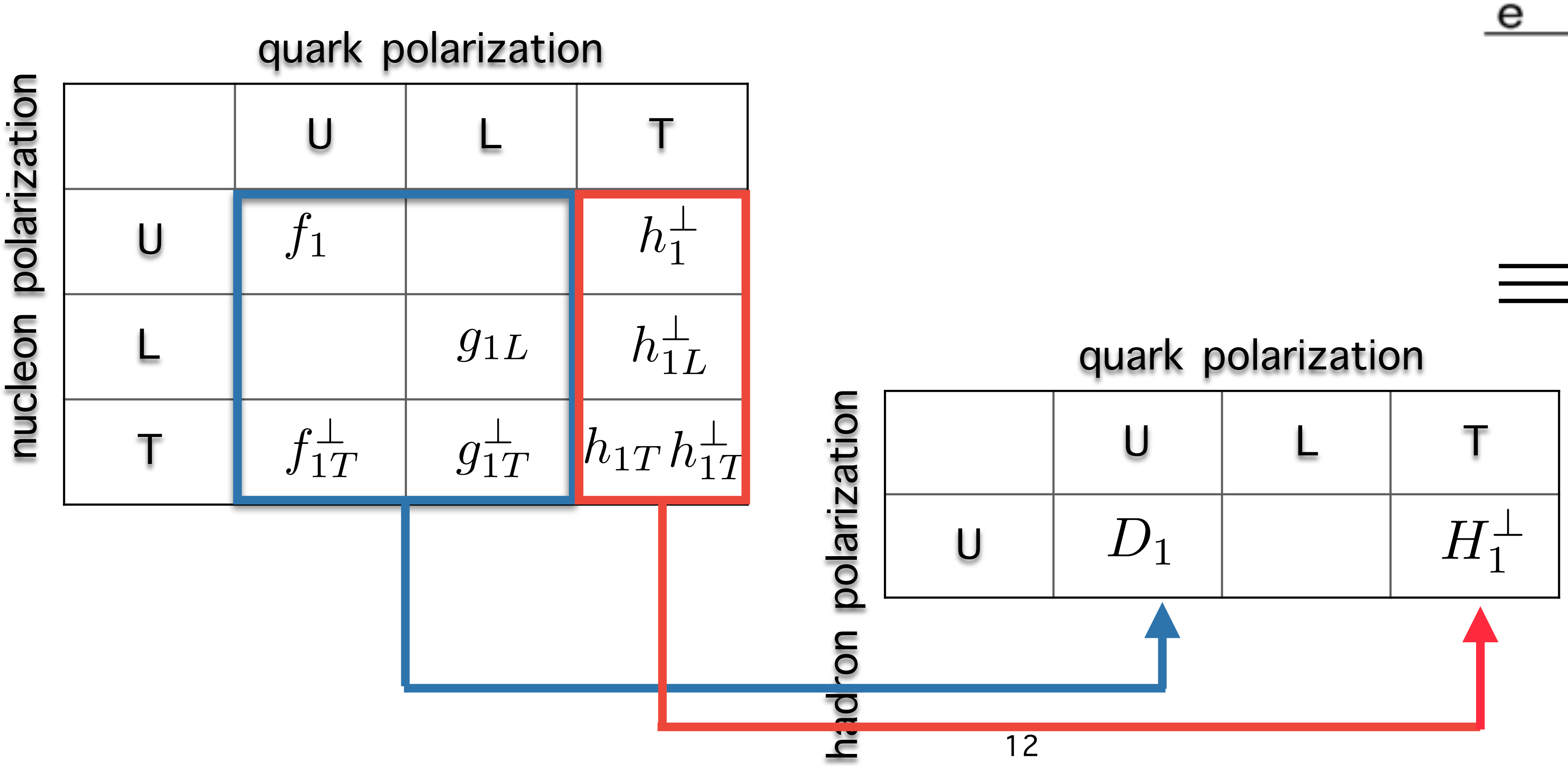
Azimuthal amplitudes related to structure functions F_{XY}:

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



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





quark polarization

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

quark polarization

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

Semi-inclusive DIS cross section

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

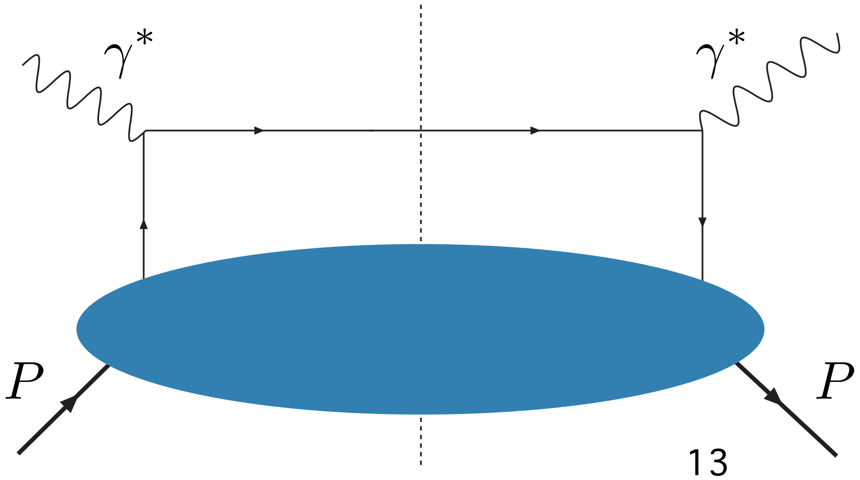
longitudinal target polarization ← S_L

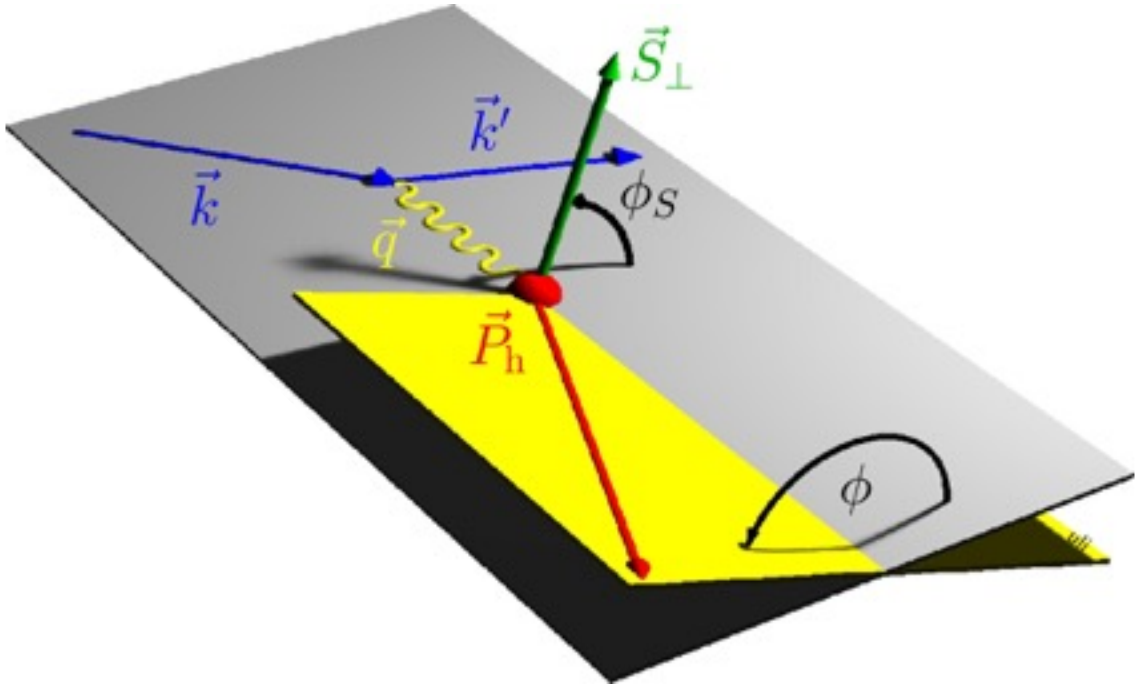
transverse target polarization ← S_T

beam polarization ← λ_l

LT: beam polarization, target polarization

leading twist





Semi-inclusive DIS cross section

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

longitudinal target polarization

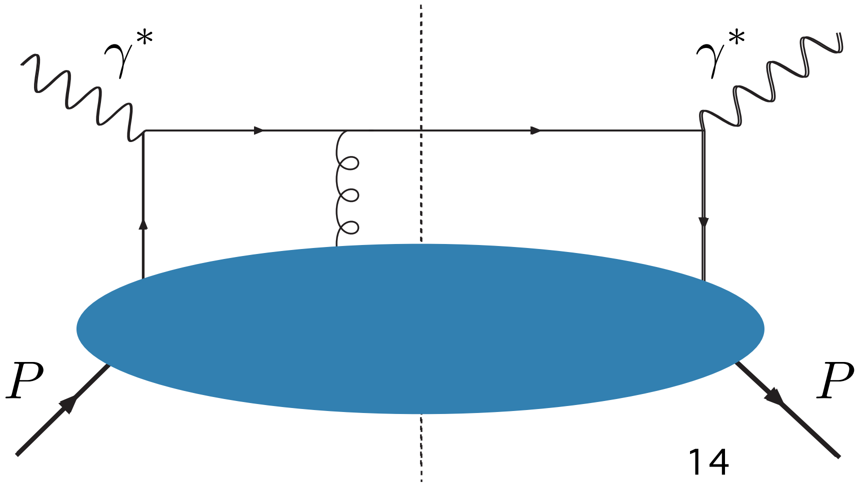
transverse target polarization

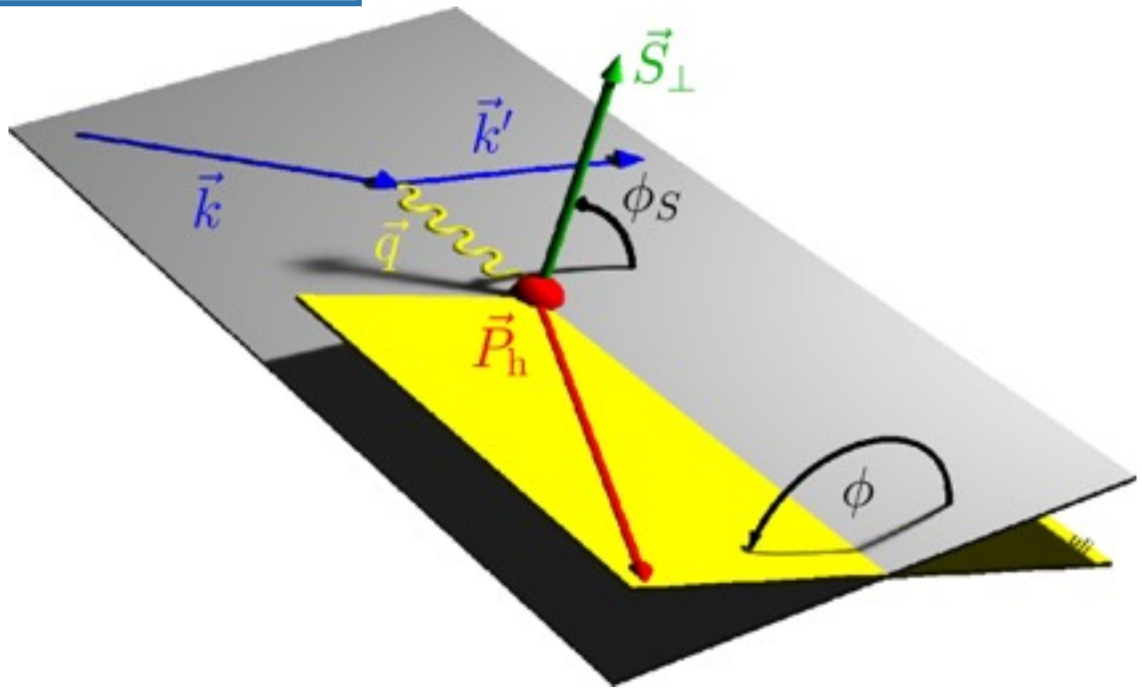
beam polarization

beam polarization

target polarization

sub-leading twist





Presented amplitudes

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

🟦 Presented here

$Q^2 > 1\ \mathrm{GeV}^2$
$W^2 > 10\ \mathrm{GeV}^2$
$0.023 < x < 0.6$

Presented amplitudes

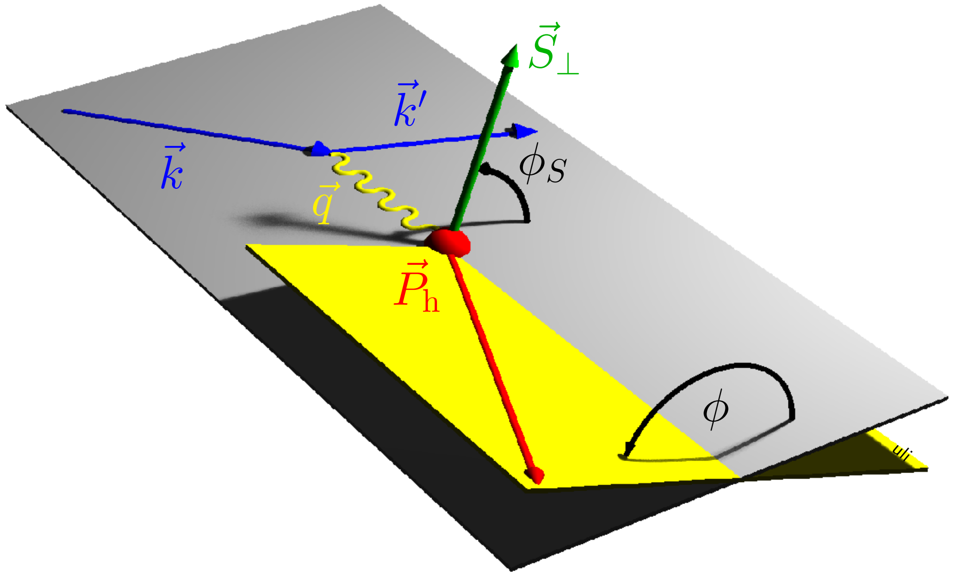
- Unpolarized and longitudinally polarized e+/e- beam
- Transversely polarized H target: fit all amplitudes simultaneously

→ Results for charged pions, kaons, (anti-)protons, neutral pions

$$\begin{aligned}
&+ \quad S_T \Big[2\langle\sin(\phi-\phi_S)\rangle^h_{UT}\sin(\phi-\phi_S)+\boxed{2\langle\sin(\phi+\phi_S)\rangle^h_{UT}}\sin(\phi+\phi_S)\\
&+ \quad \boxed{2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}}\sin(3\phi-\phi_S)+\boxed{2\langle\sin(\phi_S)\rangle^h_{UT}}\sin(\phi_S)\\
&+ \quad 2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\sin(2\phi-\phi_S)\\
&+ \quad \lambda_l\Big(2\langle\cos(\phi-\phi_S)\rangle^h_{LT}\cos(\phi-\phi_S)\\
&+ \quad 2\langle\cos(\phi_S)\rangle^h_{LT}\cos(\phi_S)+2\langle\cos(2\phi-\phi_S)\rangle^h_{LT}\cos(2\phi-\phi_S)\Big)\Big]\Big\}
\end{aligned}$$

Presented here

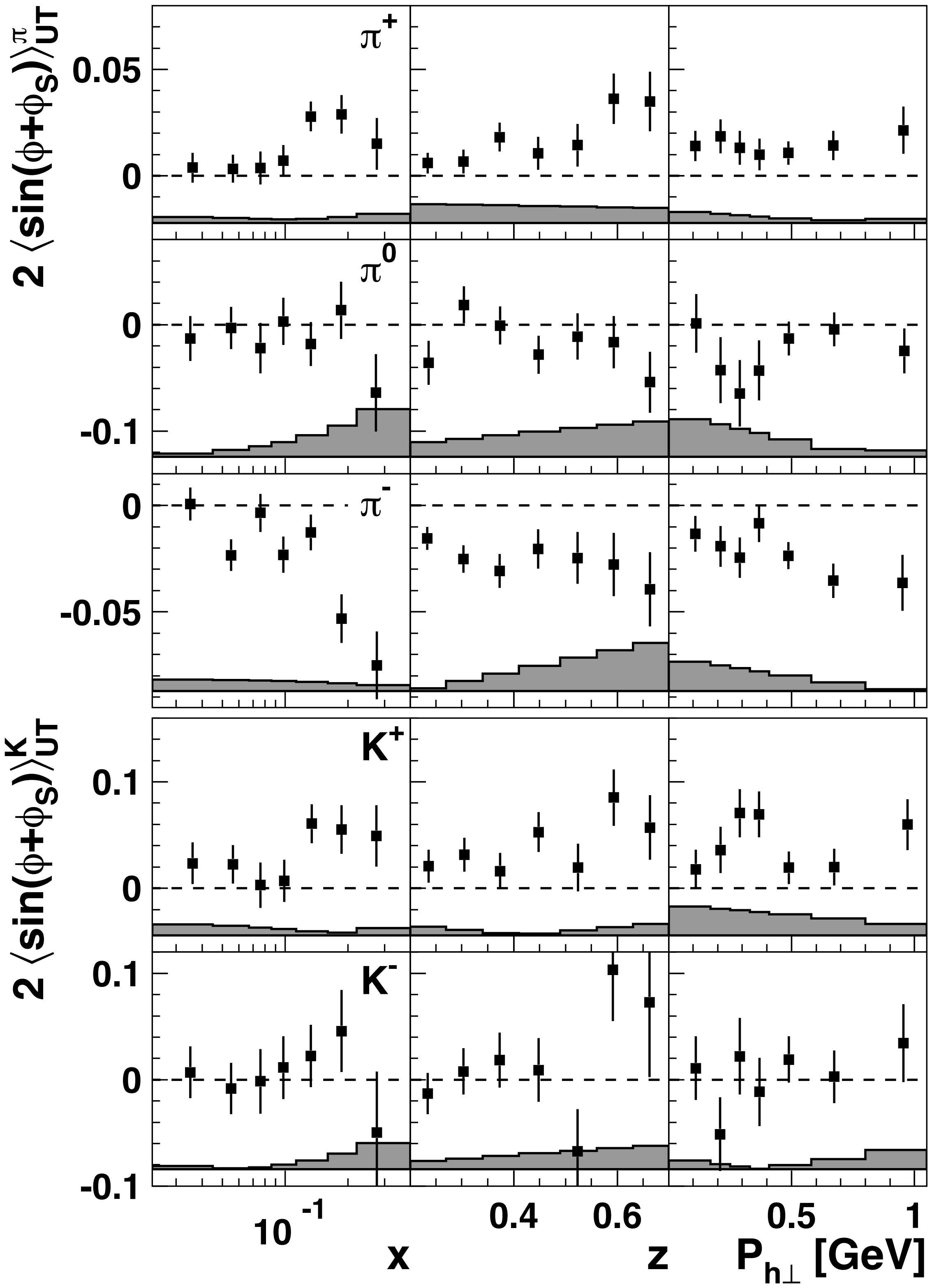
$$Q^2 > 1\ \mathrm{GeV}^2$$
$$W^2 > 10\ \mathrm{GeV}^2$$
$$0.023 < x < 0.6$$



Collins amplitudes

$$\mathcal{C}[h_{1T}^{q} \times H_1^{\perp,q}]$$

Phys. Lett. B 693 (2010) 11-16



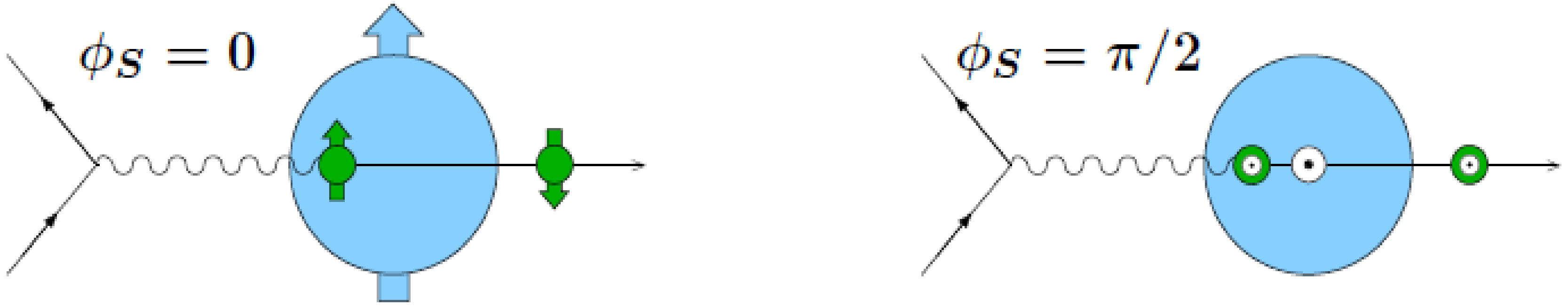
- Positive amplitudes for π⁺, negative amplitudes for π⁻:

$$H_1^{\perp,u\to\pi^+} \approx -H_1^{\perp,u\to\pi^-}$$

Artru model

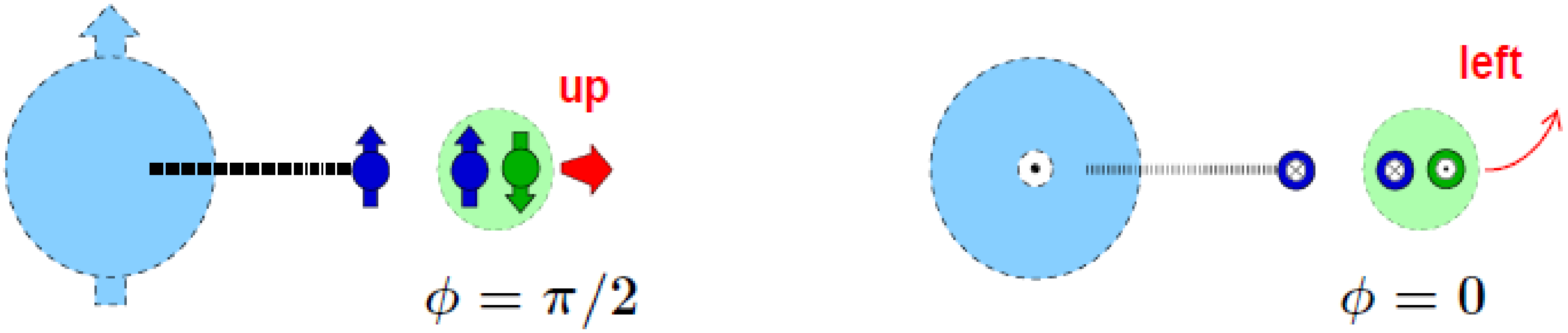
X. Artru et al., Z. Phys. C73 (1997) 527

polarisation component in lepton scattering plane reversed by photoabsorption:



string break, quark-antiquark pair with vacuum numbers:

orbital angular momentum creates transverse momentum:

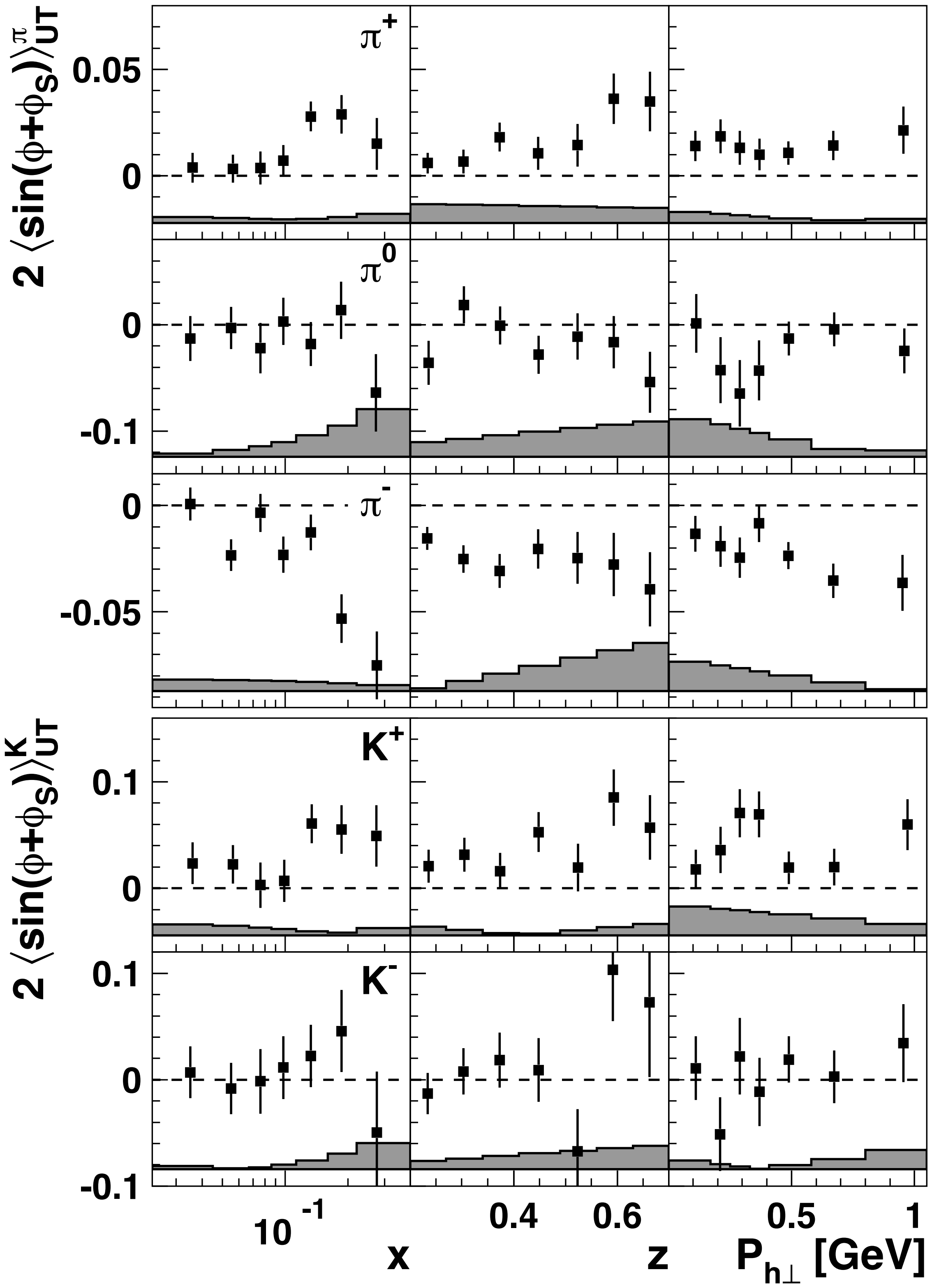


Courtesy U. Elschenbroich

Collins amplitudes

$$\mathcal{C}[h_{1T}^{q} \times H_1^{\perp,q}]$$

Phys. Lett. B 693 (2010) 11-16

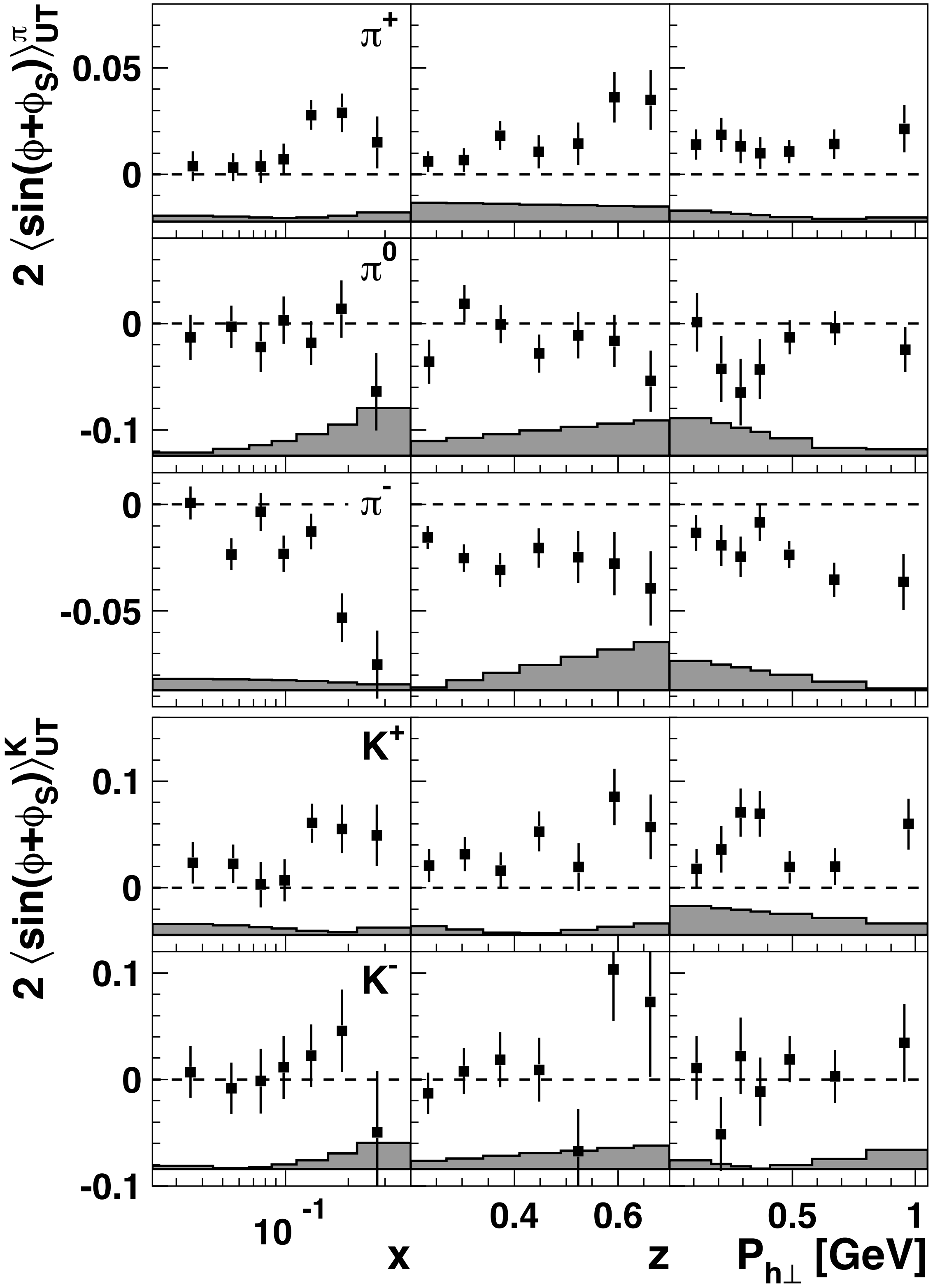


- Positive amplitudes for π^+, negative amplitudes for π^-:

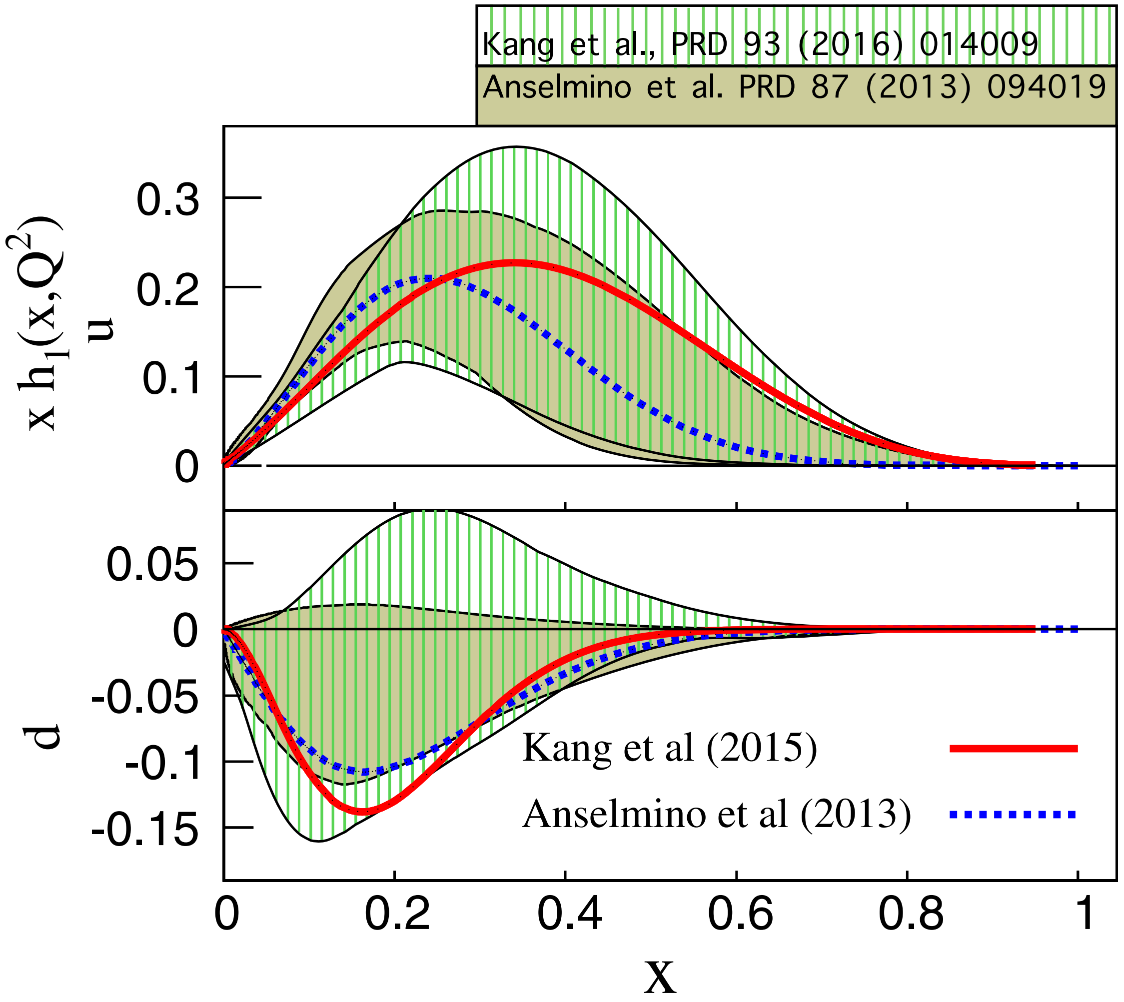
$$H_1^{\perp,u\rightarrow\pi^+} \approx -H_1^{\perp,u\rightarrow\pi^-}$$

Collins amplitudes

$$\mathcal{C}[h_{1T}^q \times H_1^{\perp,q}]$$



Phys. Lett. B 693 (2010) 11-16

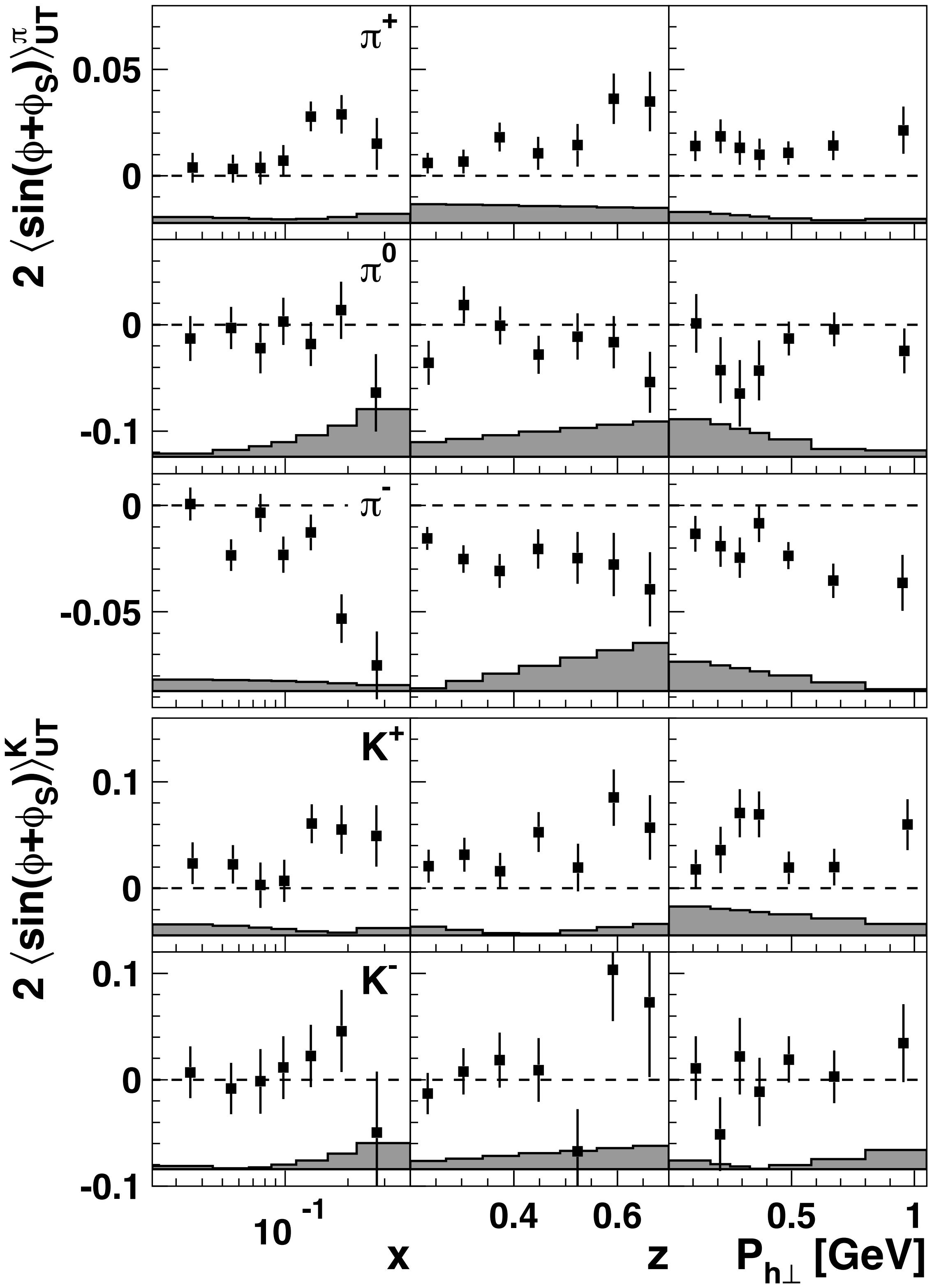


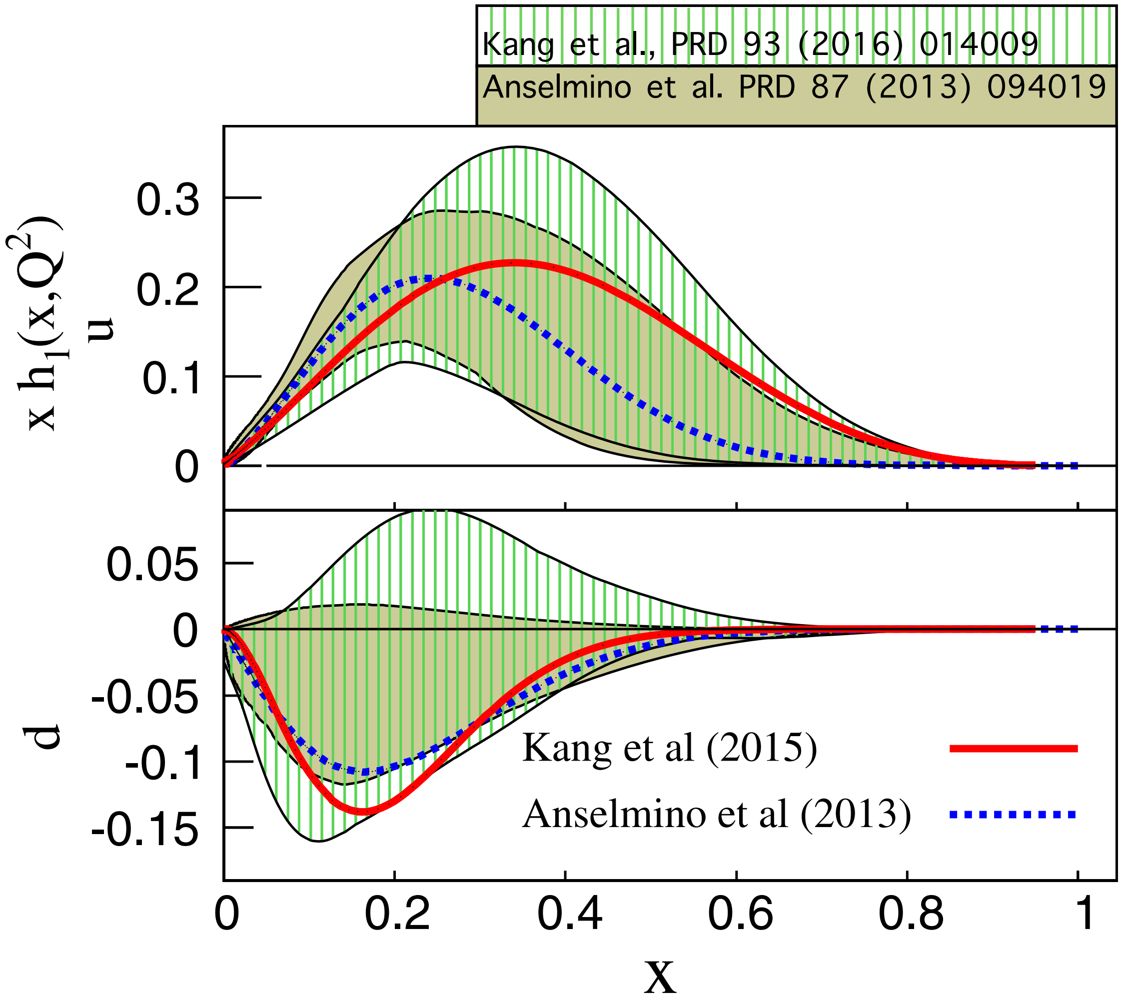
data from Belle, Babar, COMPASS, HERMES, Jefferson Lab Hall A

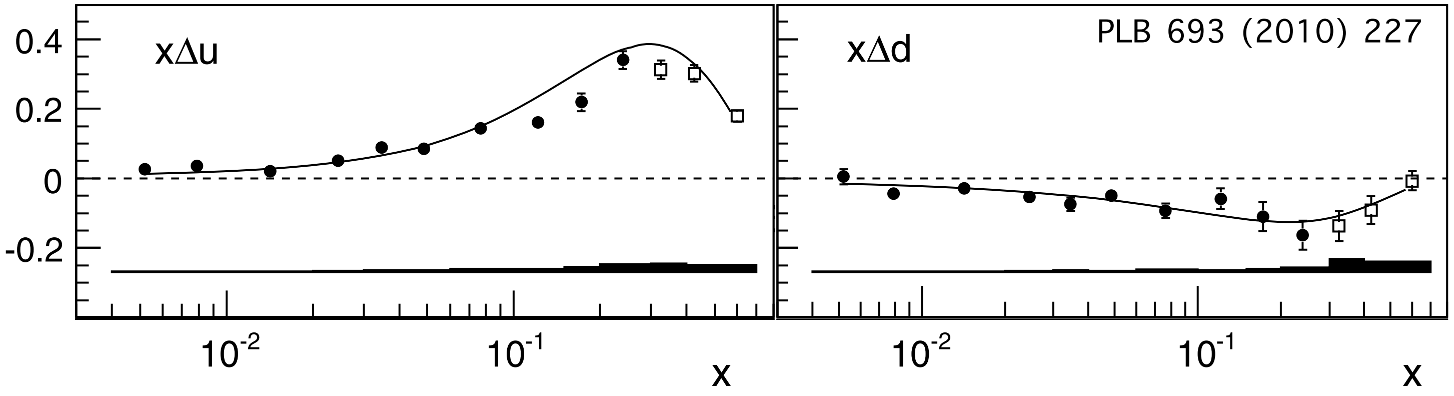
Collins amplitudes

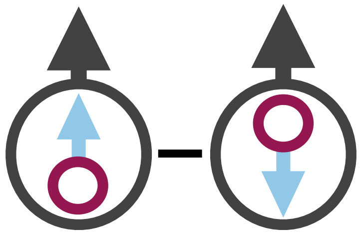
$$\mathcal{C}[h_{1T}^q \times H_1^{\perp,q}]$$

Phys. Lett. B 693 (2010) 11-16





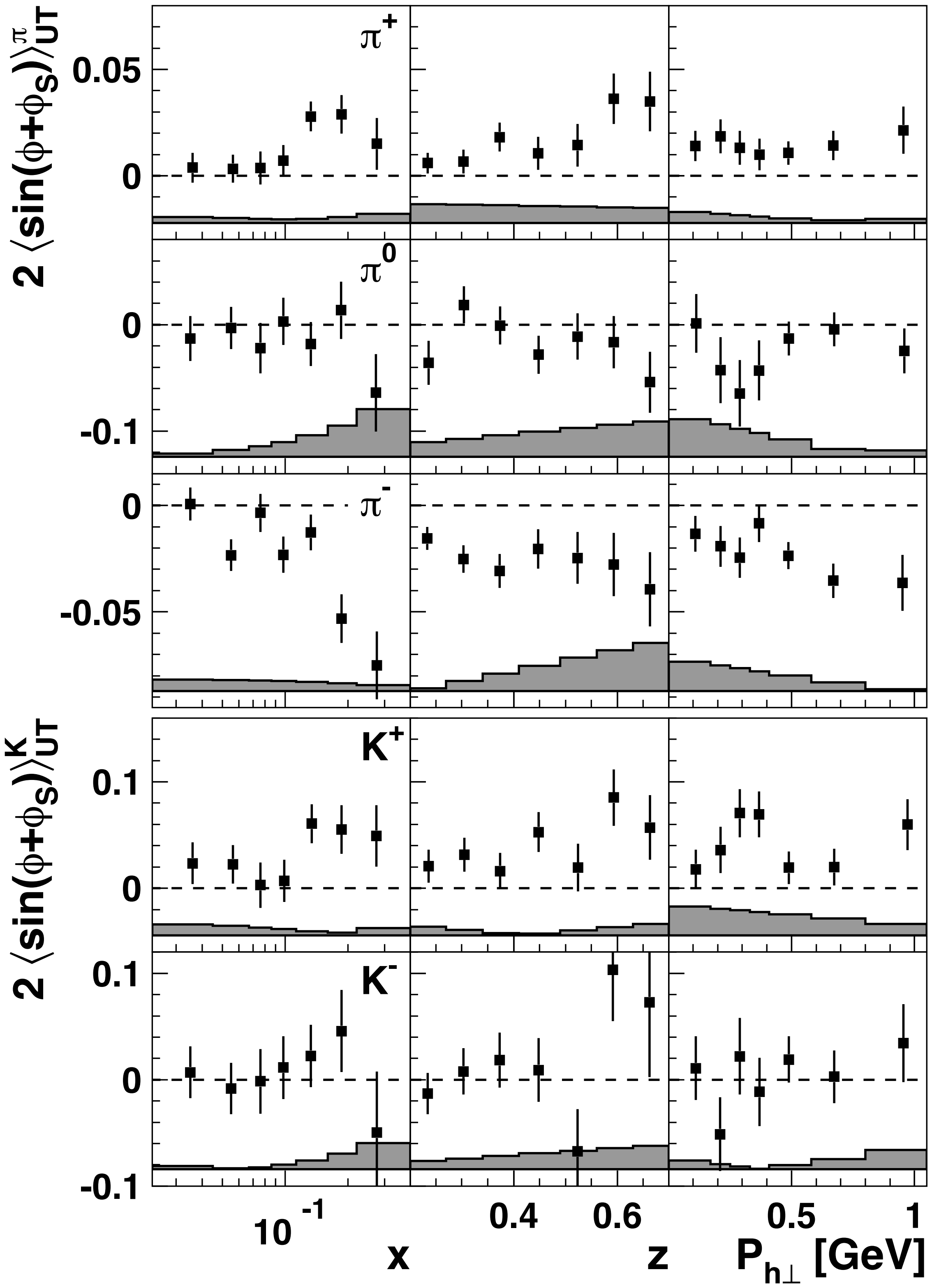


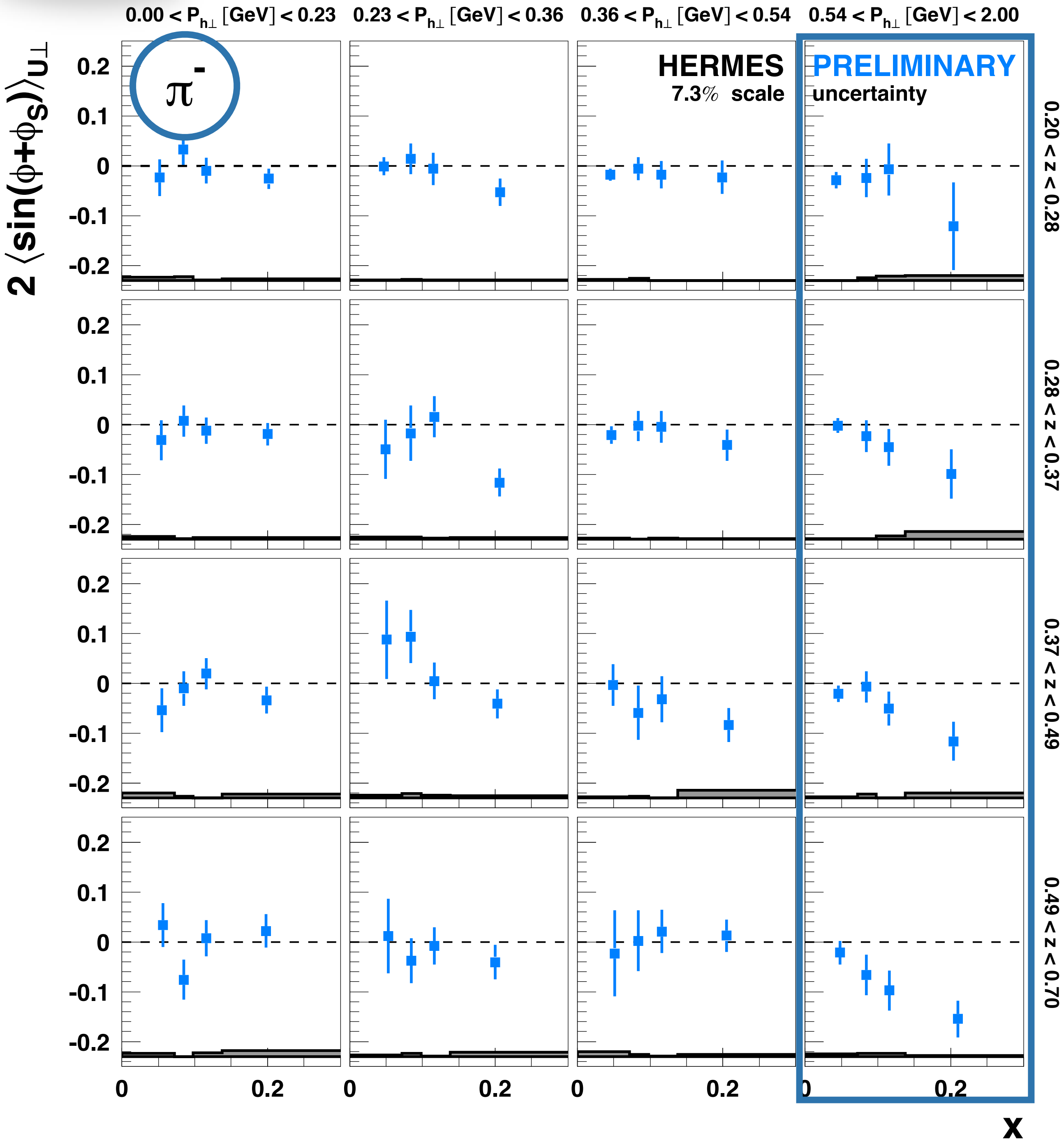


Collins amplitudes

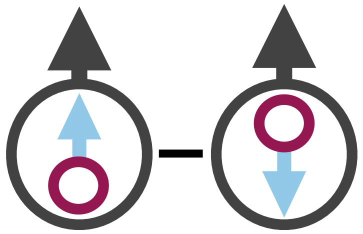
$$\mathcal{C}[h_{1T}^{q} \times H_1^{\perp,q}]$$

Phys. Lett. B 693 (2010) 11-16





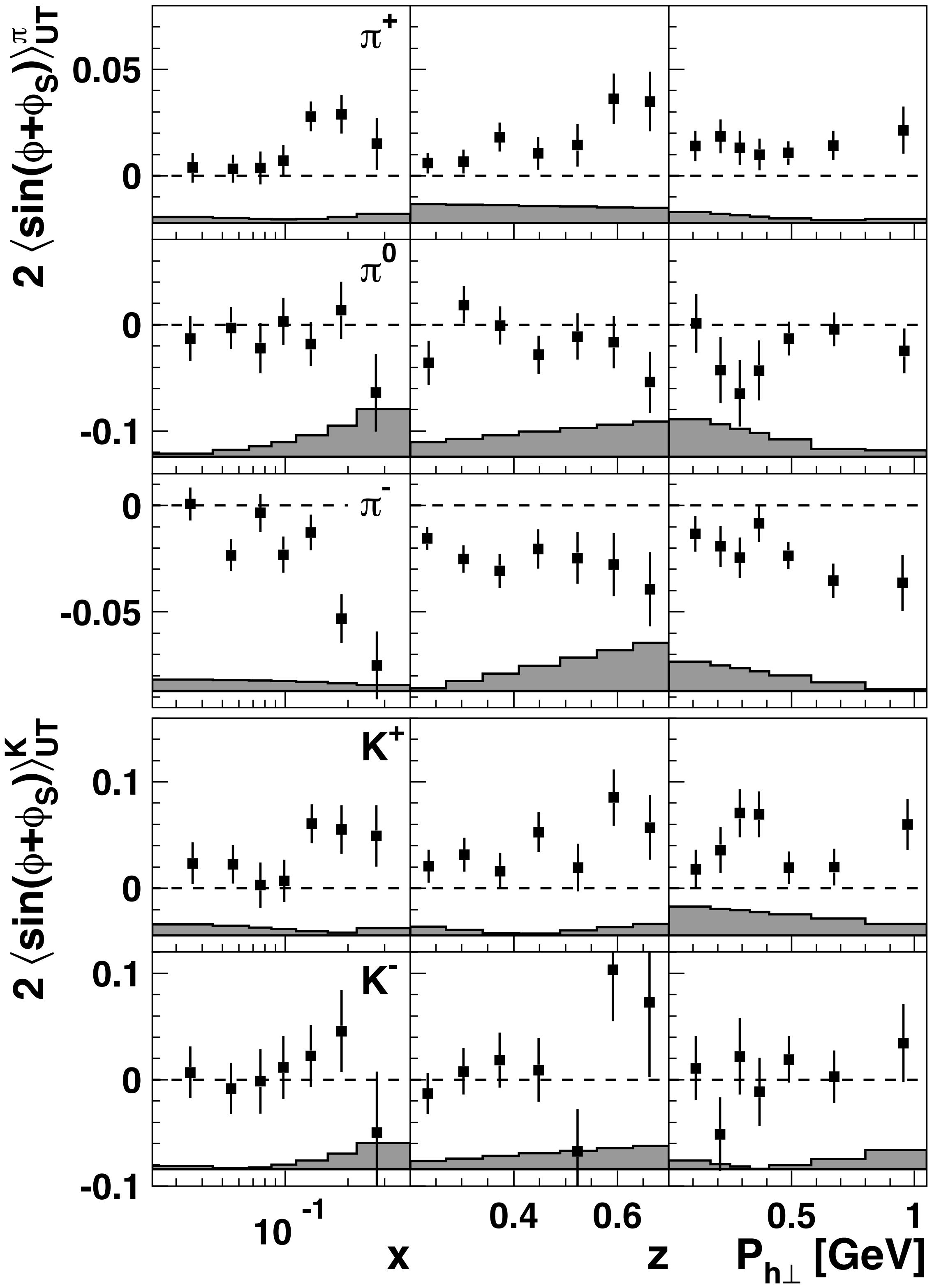
π^- amplitudes increasing with x at large $P_{h\perp}$, increasing with z.

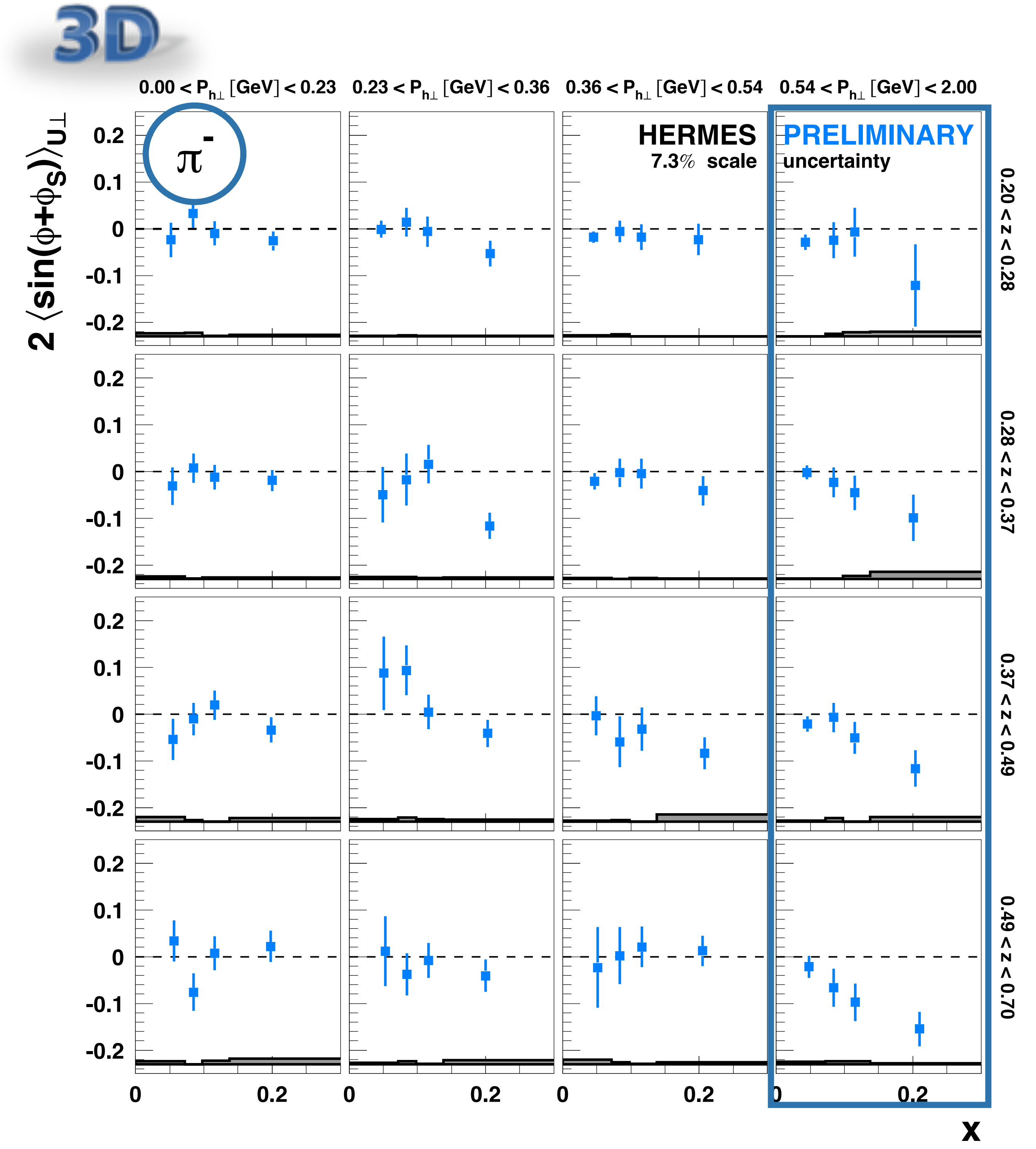


Collins amplitudes

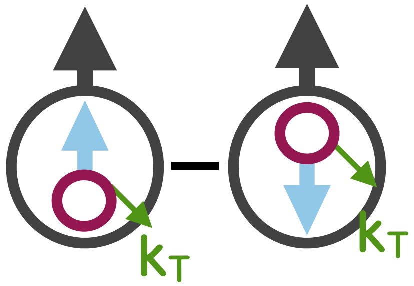
$\mathcal{C}[h_{1T}^q \times H_1^{\perp,q}]$

Phys. Lett. B 693 (2010) 11-16





- Other hadrons, no clear kinematic dependencies in 3D
- No 3D for antiprotons



Pretzelosity amplitudes

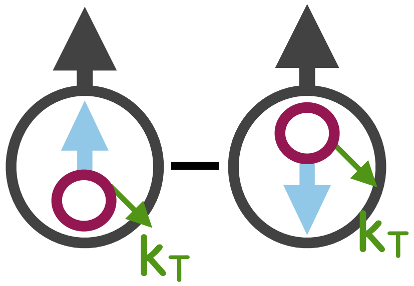
$\mathcal{C}[h_{1T}^{\perp,q} \times H_1^{\perp,q}]$

- Pretzelosity
  - requires non-zero orbital angular momentum
  - models:

$$h_{1T}^{\perp(1),q}(x) = g_{1L}^q(x) - h_{1T}^q(x)$$

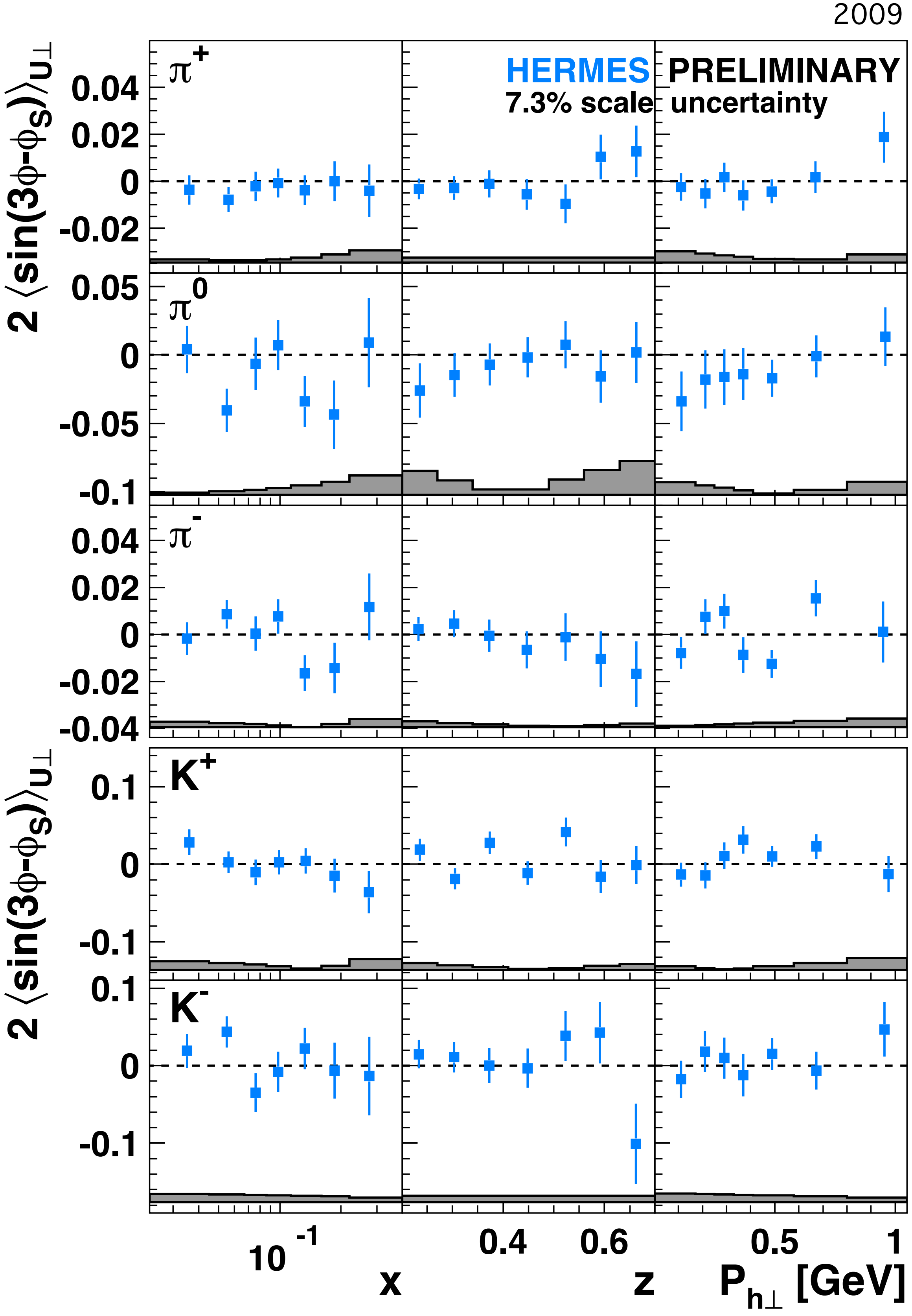
$\longrightarrow$ measure for relativistic effects

  - suppressed as $P_{h\perp}^2$ compared to Collins amplitude



Pretzelosity amplitudes

$$\mathcal{C}[h_{1T}^{\perp,q} \times H_1^{\perp,q}]$$



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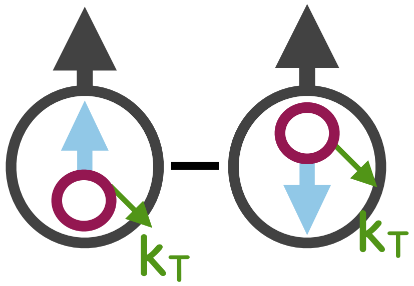

Pretzelosity amplitudes

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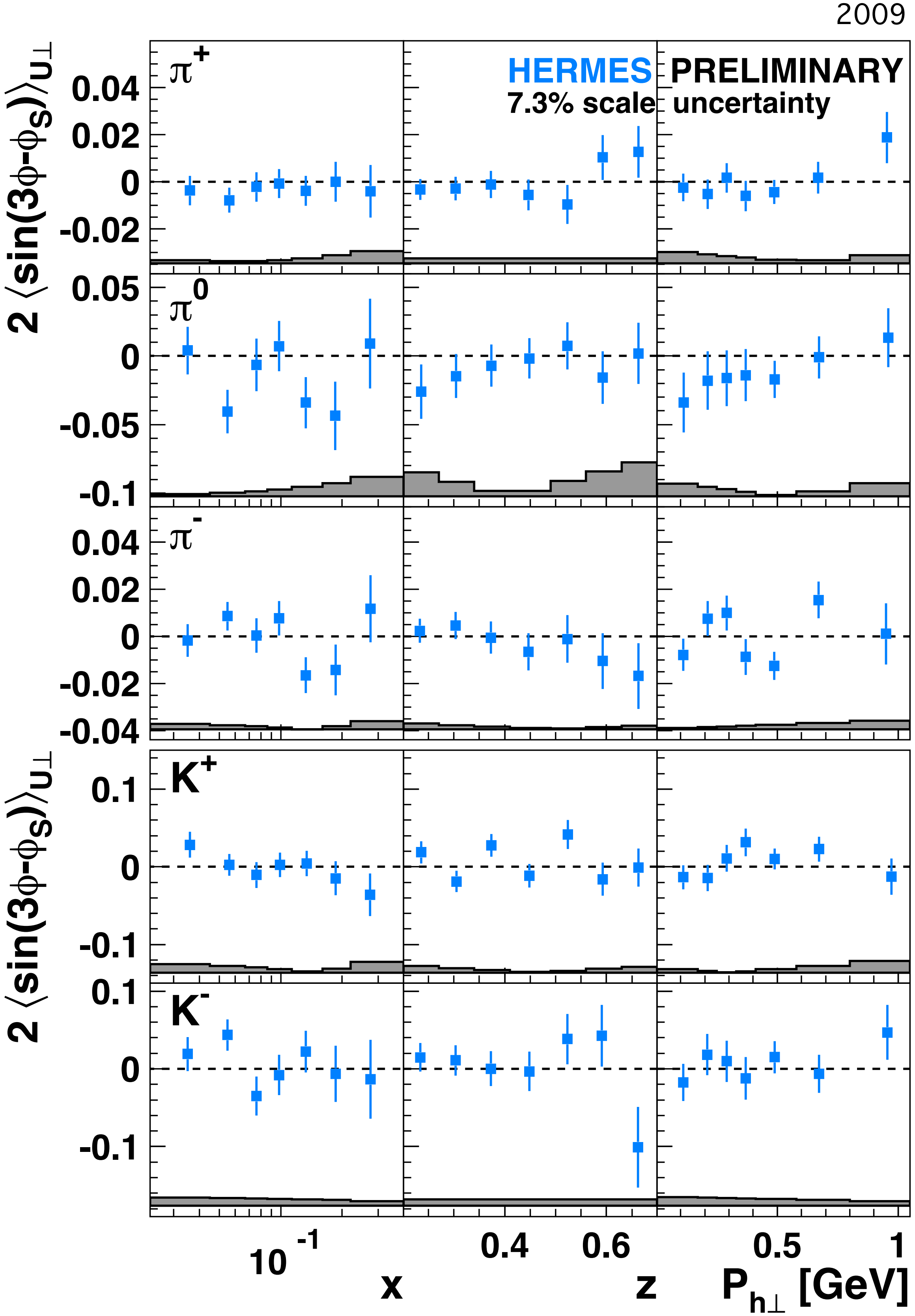

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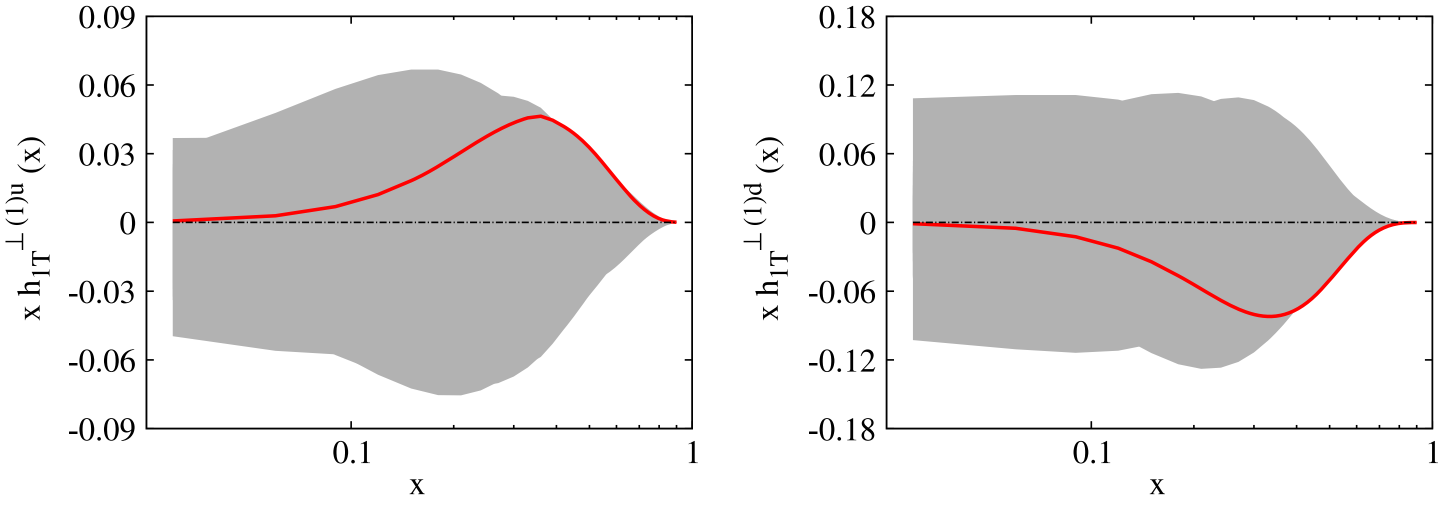
$\longrightarrow$ measure for relativistic effects

  - suppressed as $P_{h\perp}^2$ compared to Collins amplitude

C. Lefky and A. Prokudin, PRD 91 (2015) 034010



data from Jefferson Lab Hall A
preliminary data from COMPASS, HERMES

Twist-3: $\langle \sin(\phi_S) \rangle_{UT}$

$$\langle \sin(\phi_S) \rangle_{UT}$$

$$\propto \mathcal{C}[\boxed{f_T^q} \times D_1^q, h_{1T}^q \times \boxed{\tilde{H}^q}, \boxed{h_T^q} \times H_1^{\perp,q}, g_{1T}^{\perp,q} \times \boxed{\tilde{G}^{\perp,q}}, \boxed{h_T^{\perp,q}} \times H_1^{\perp,q}, f_{1T}^{\perp,q} \times \boxed{\tilde{D}^{\perp,q}}]$$

twist-3

Twist-3: $\langle\sin(\phi_S)\rangle_{UT}$

$$\langle\sin(\phi_S)\rangle_{UT}$$

$$\propto \mathcal{C}[\boxed{f_T^q} \times D_1^q, h_{1T}^q \times \boxed{\tilde{H}^q}, \boxed{h_T^q} \times H_1^{\perp,q}, g_{1T}^{\perp,q} \times \boxed{\tilde{G}^{\perp,q}}, \boxed{h_T^{\perp,q}} \times H_1^{\perp,q}, f_{1T}^{\perp,q} \times \boxed{\tilde{D}^{\perp,q}}]$$

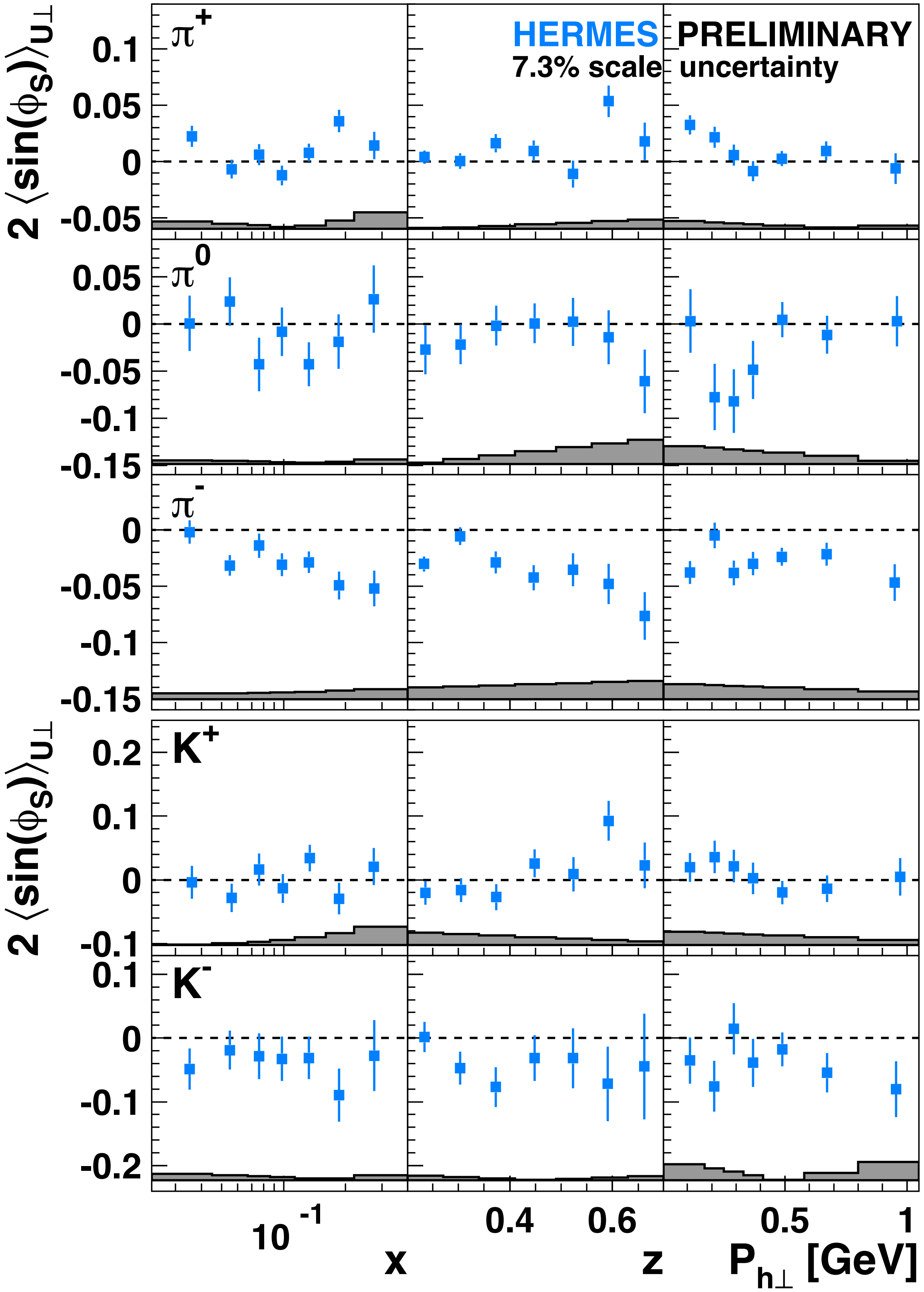
twist-3

$\downarrow$ integrate over hadron transverse momentum $P_{h\perp}$

$$\boxed{\langle\sin(\phi_S)\rangle_{UT} = -x\frac{2M_h}{Q}\sum_q e_q^2 h_{1T}^q \frac{\tilde{H}^q}{z}}$$

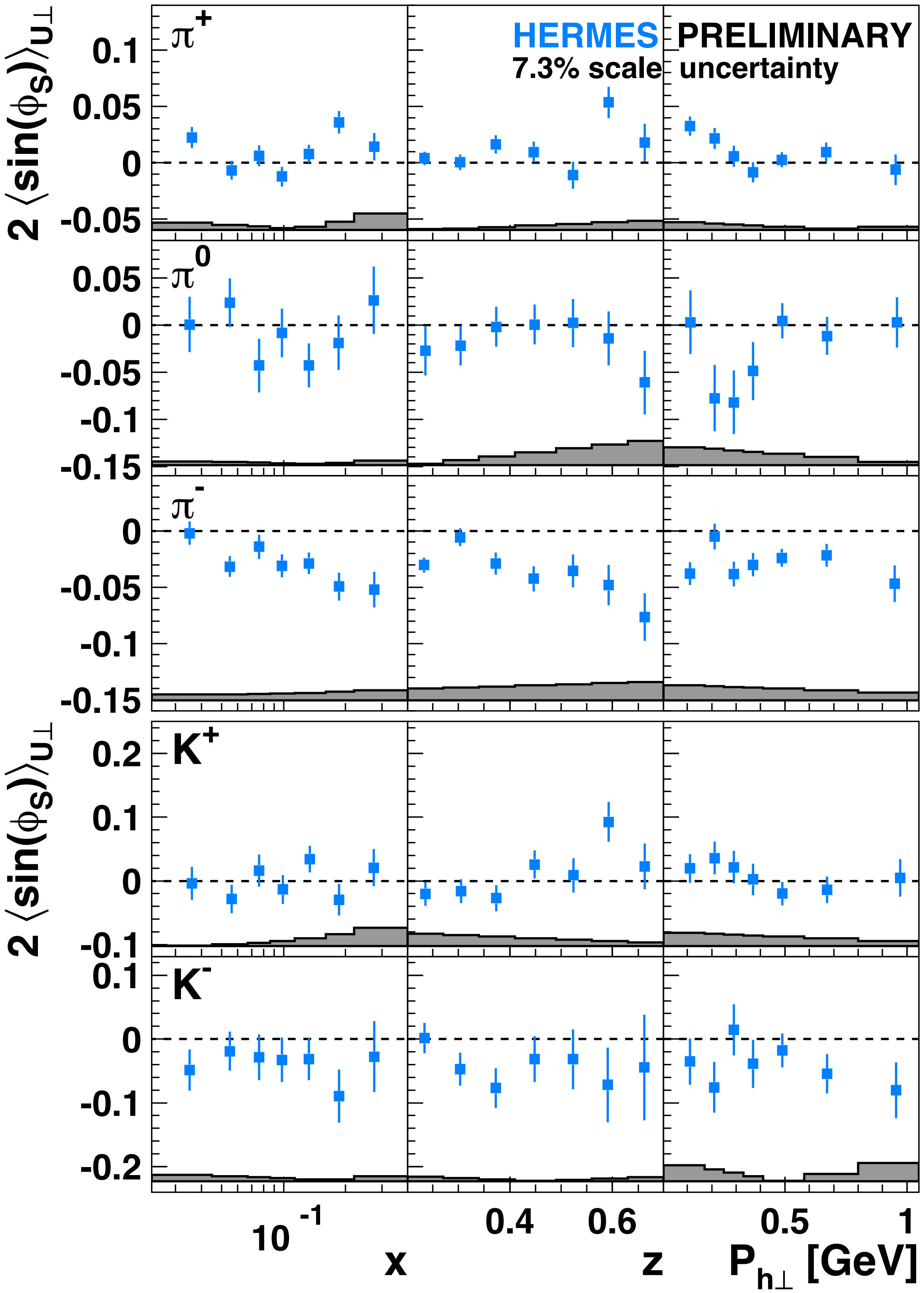
no convolution

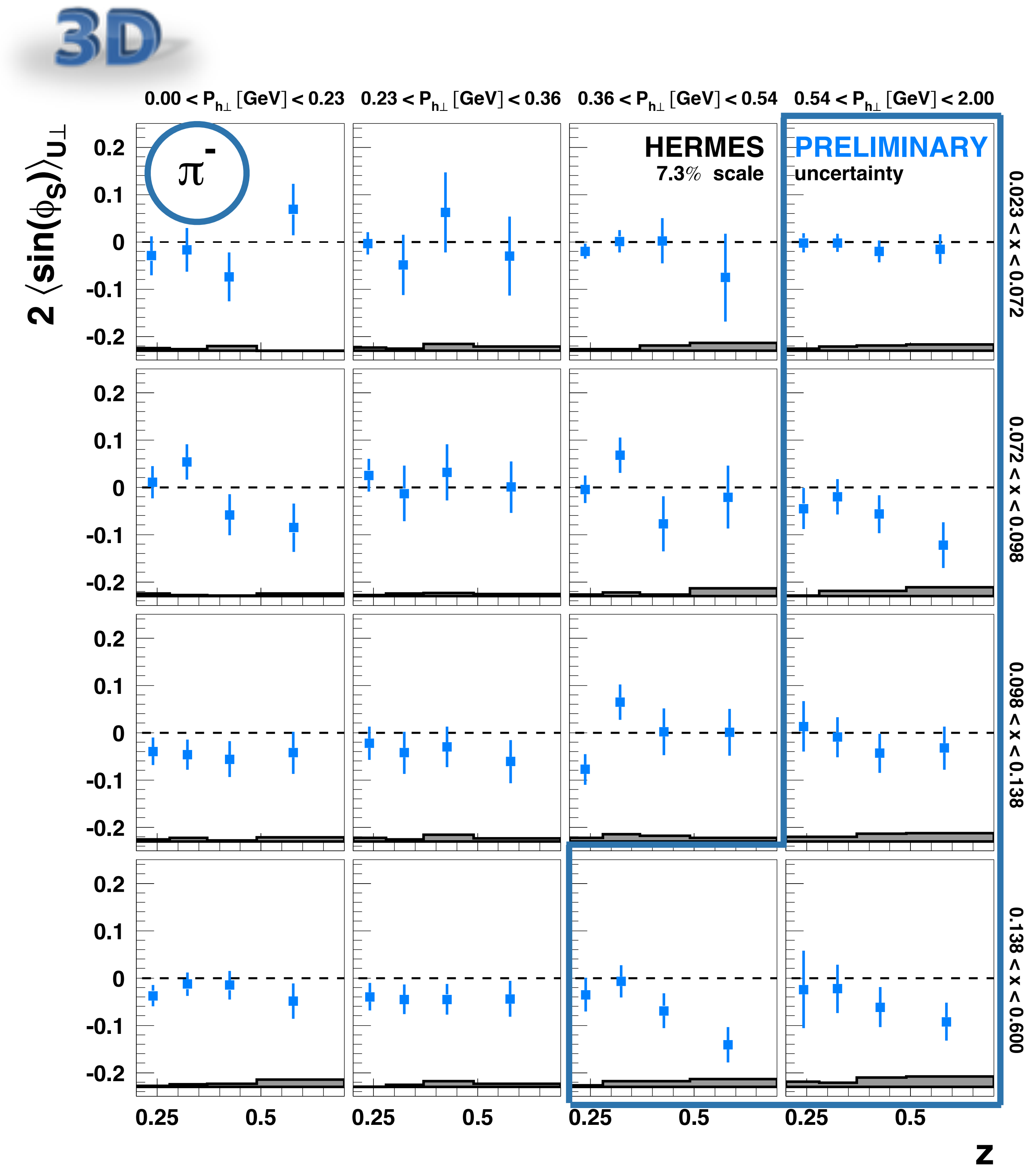
Twist-3: $\langle \sin(\phi_S) \rangle_{UT}$



- Significant non-zero signal for π^-, increasing with x, z

Twist-3: $\langle\sin(\phi_S)\rangle_{UT}$

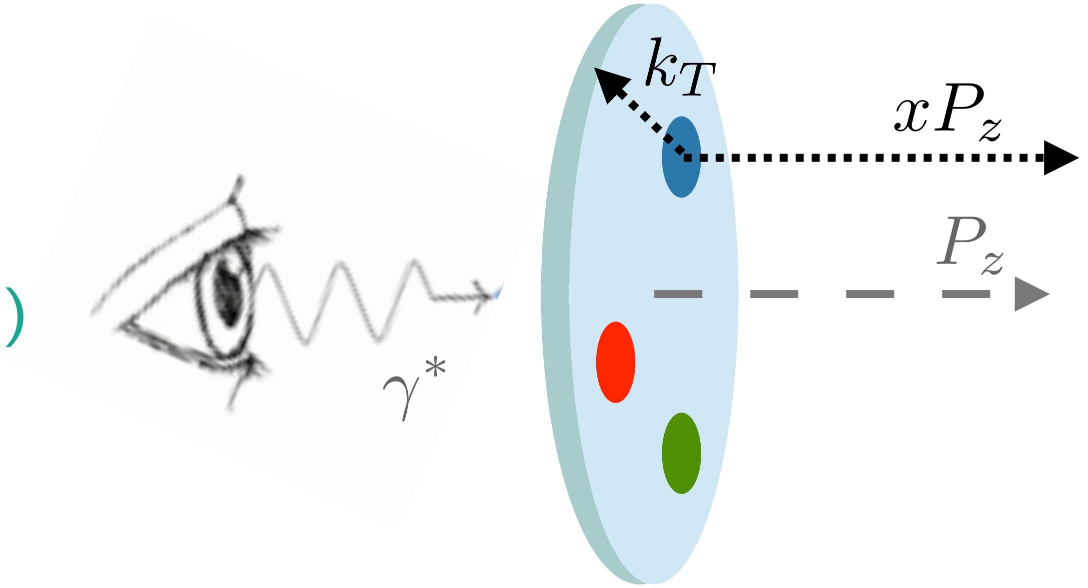




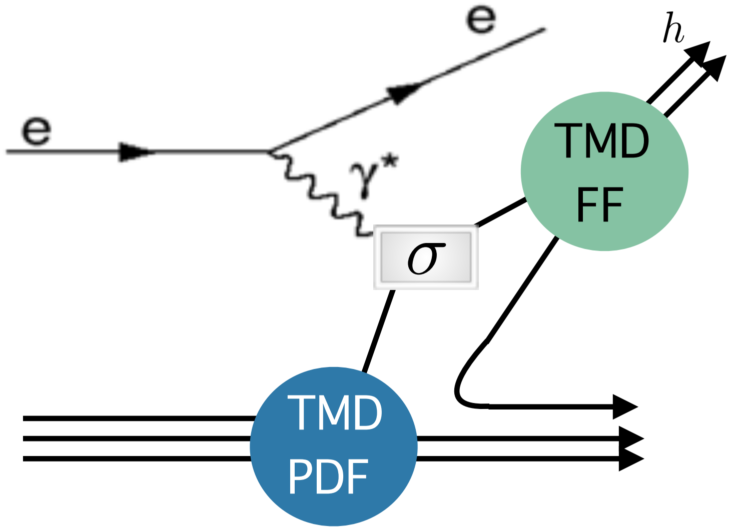
Increase with z, rather at larger x and $P_{h\perp}$

Structure of the nucleon

transverse-momentum dependent PDFs (TMDs)



semi-inclusive deep-inelastic scattering (DIS)

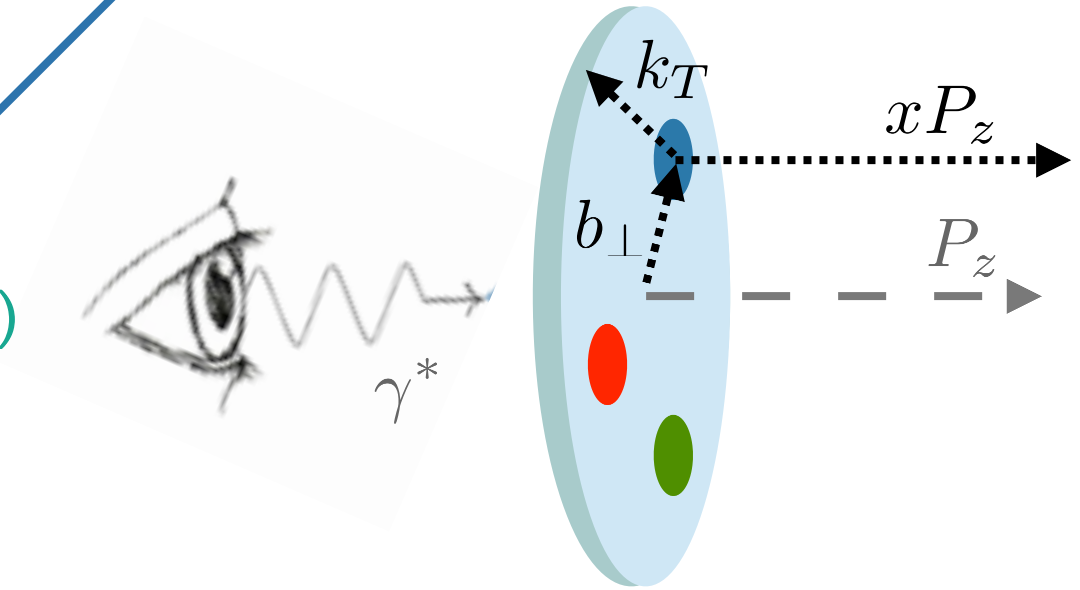


Structure of the nucleon

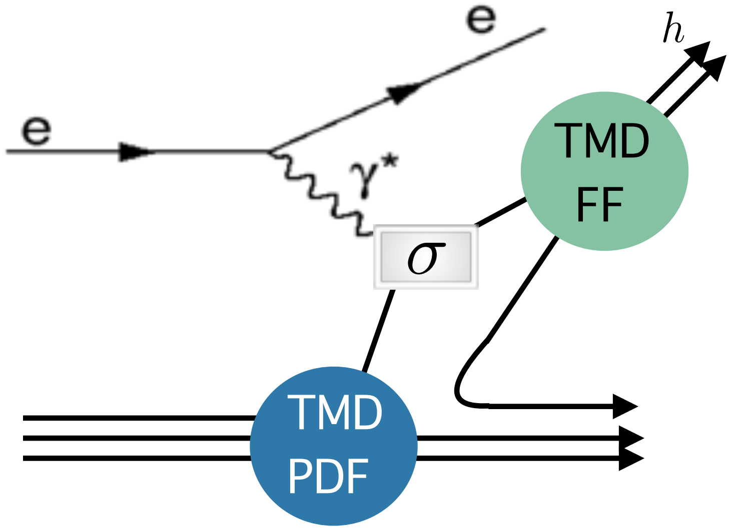
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

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

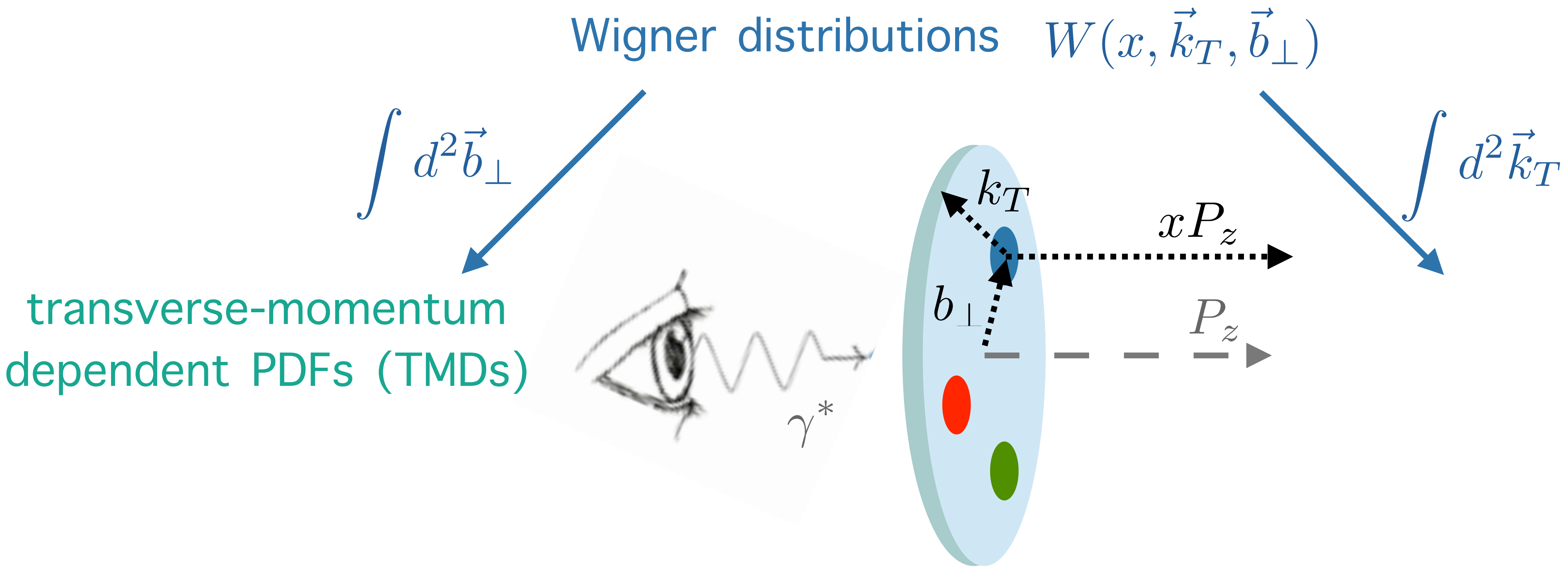
transverse-momentum dependent PDFs (TMDs)



semi-inclusive deep-inelastic scattering (DIS)



Structure of the nucleon



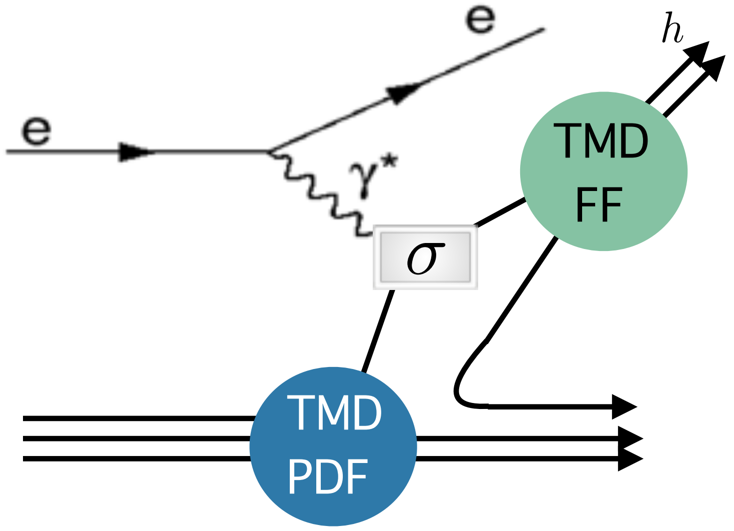
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

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

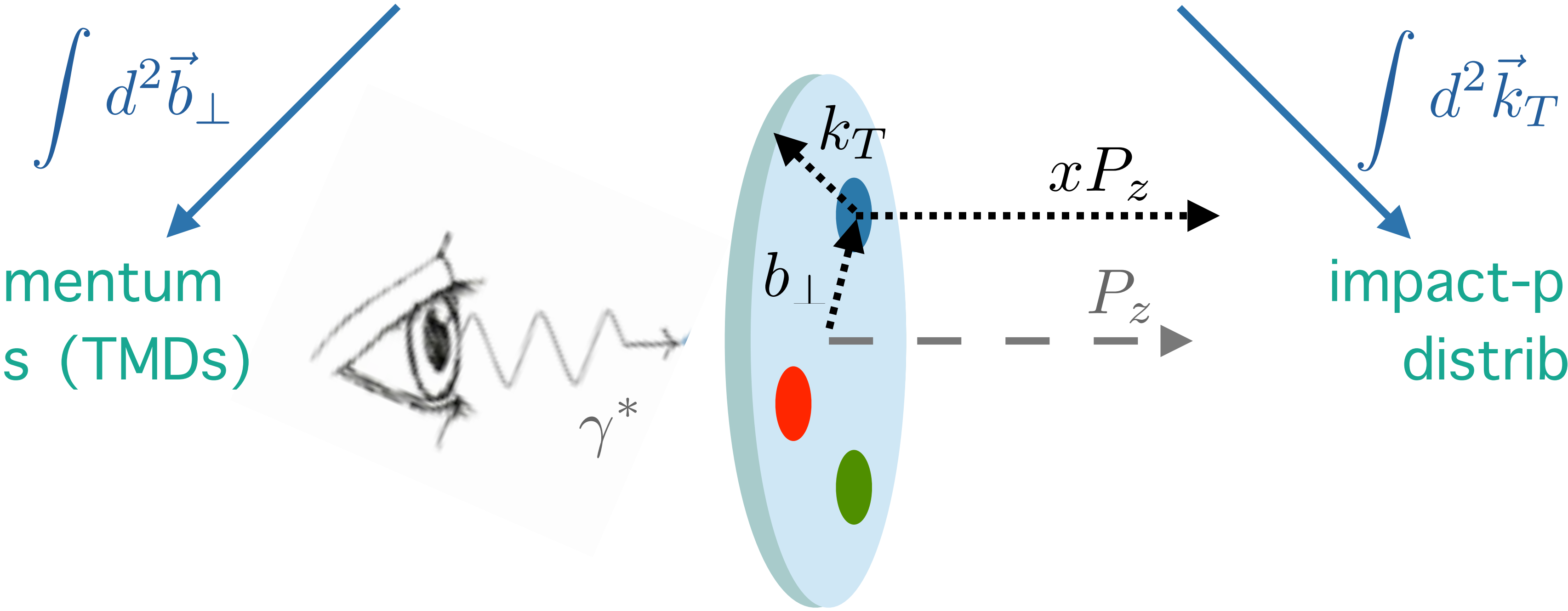
$\int d^2\vec{k}_T$

transverse-momentum dependent PDFs (TMDs)

semi-inclusive deep-inelastic scattering (DIS)



Structure of the nucleon



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

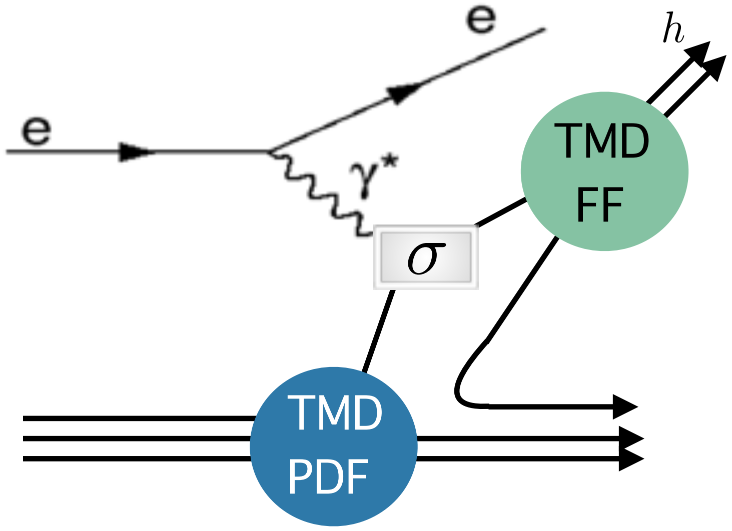
$\int d^2\vec{b}_\perp$

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

transverse-momentum dependent PDFs (TMDs)

impact-parameter distributions

semi-inclusive deep-inelastic scattering (DIS)



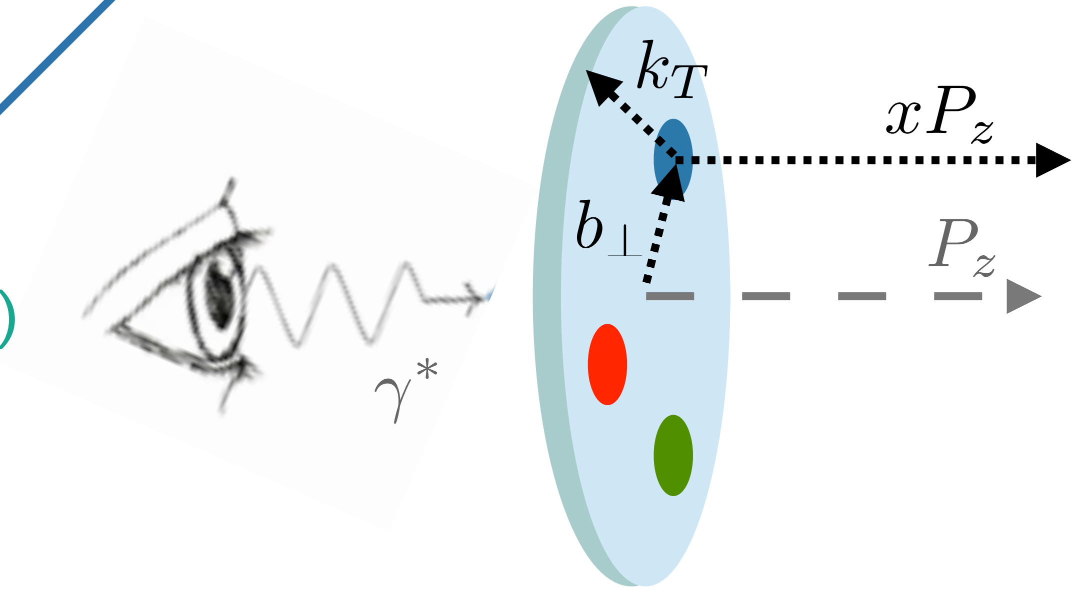
Structure of the nucleon

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

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

transverse-momentum dependent PDFs (TMDs)

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

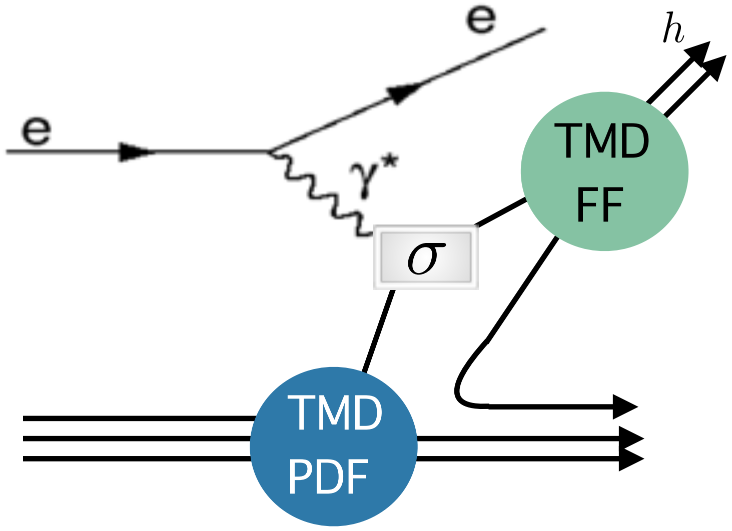


impact-parameter distributions

Fourier transform

generalized parton distributions (GPDs)

semi-inclusive deep-inelastic scattering (DIS)



Structure of the nucleon

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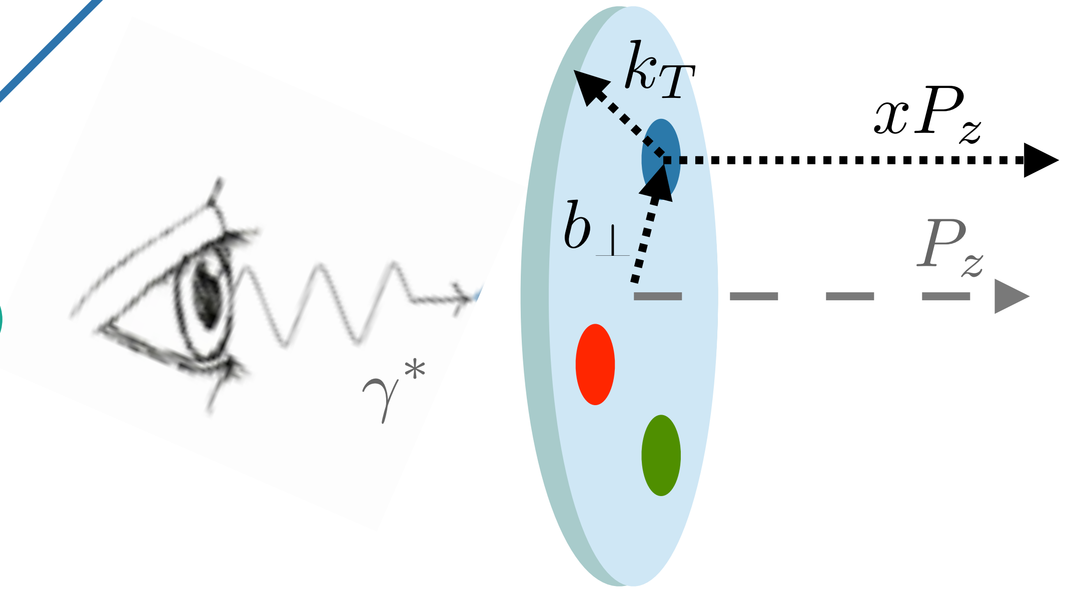

$\int d^2\vec{k}_T$

impact-parameter distributions

Fourier transform

generalized parton distributions (GPDs)

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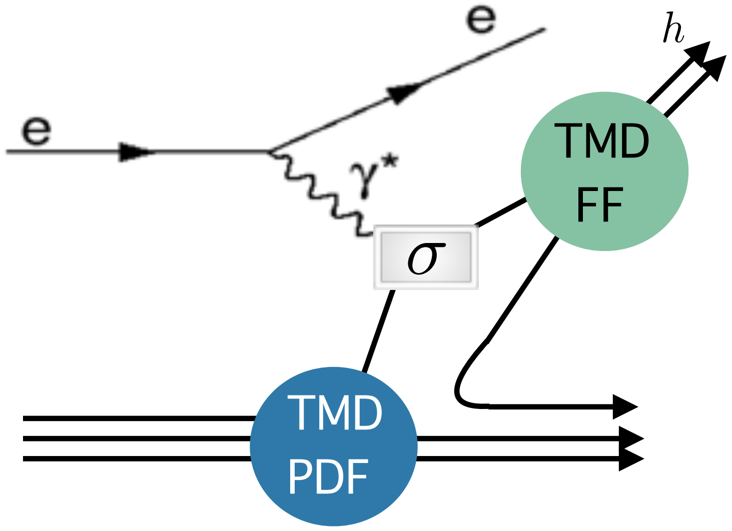
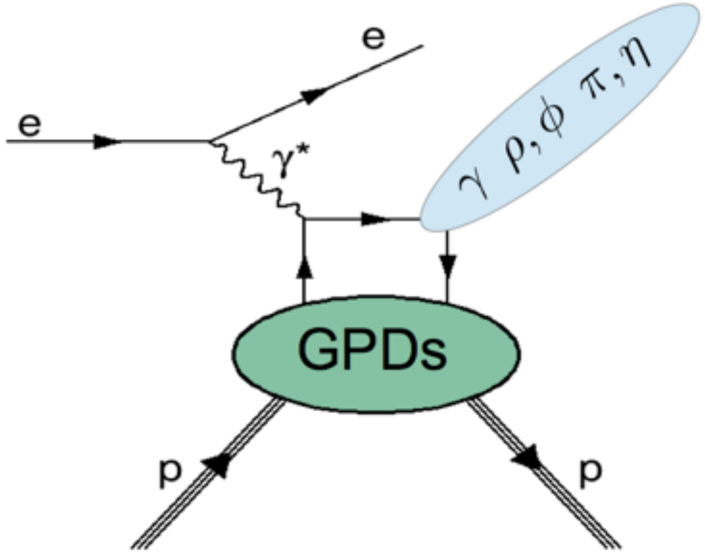
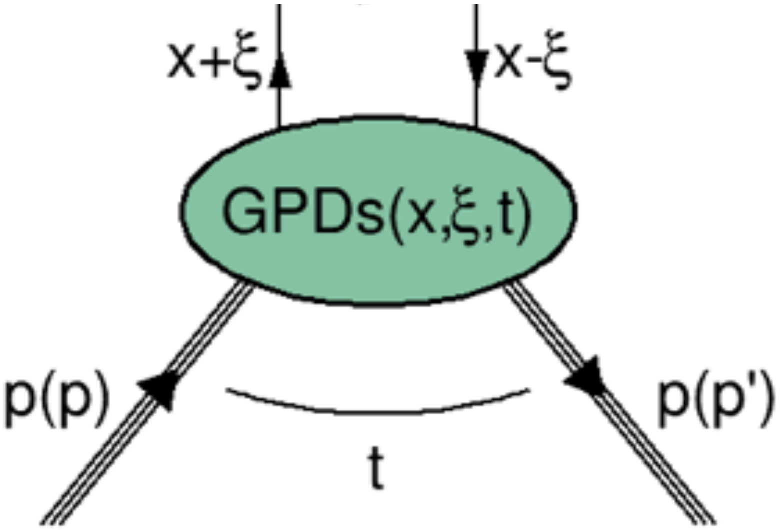


hard exclusive reactions

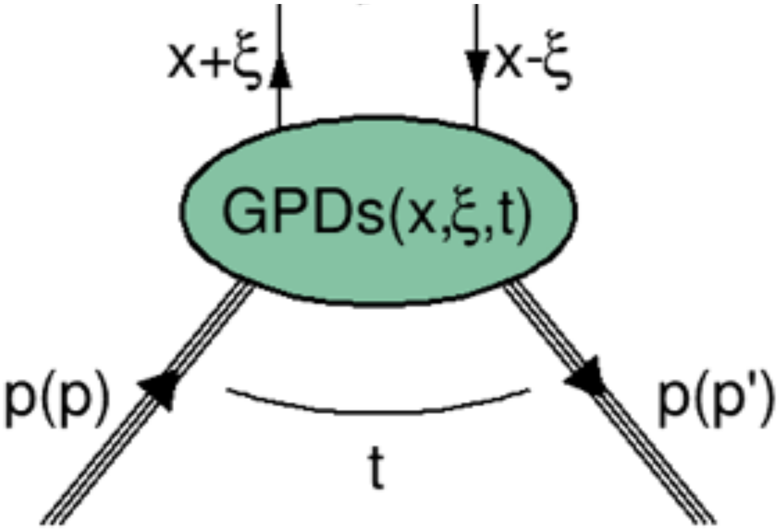


Generalized parton distributions (GPDs)



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

Generalized parton distributions (GPDs)



- x=average longitudinal momentum fraction
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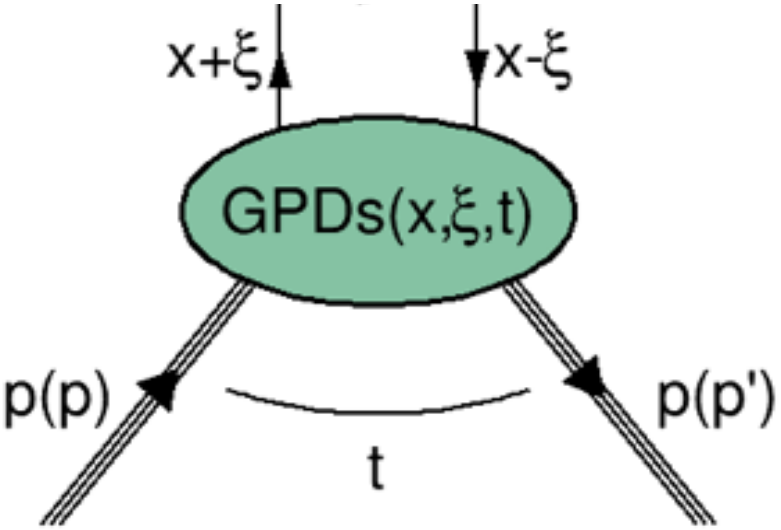
Four quark helicity-conserving twist-2 GPDs

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

Generalized parton distributions (GPDs)



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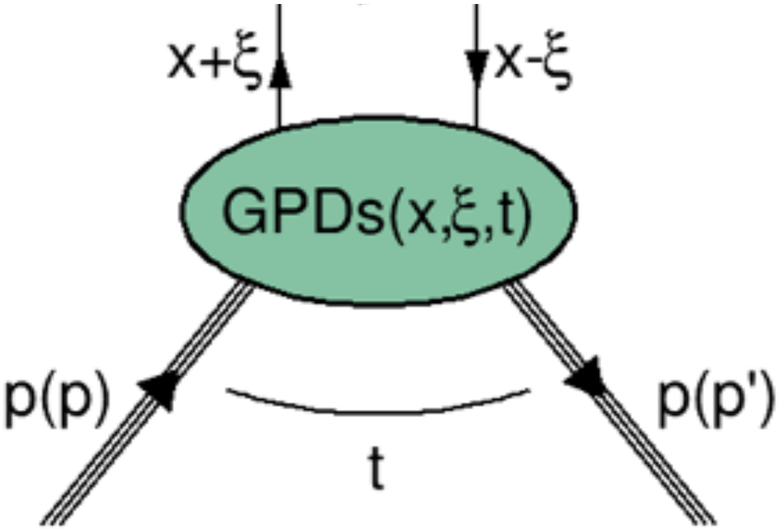
proton helicity non flip	proton helicity flip	

Four quark helicity-flip twist-2 GPDs

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

Generalized parton distributions (GPDs)



- x=average longitudinal momentum fraction
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Four quark helicity-conserving twist-2 GPDs

$H(x,\xi,t)$	$E(x,\xi,t)$	spin independent
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proton helicity non flip	proton helicity flip	

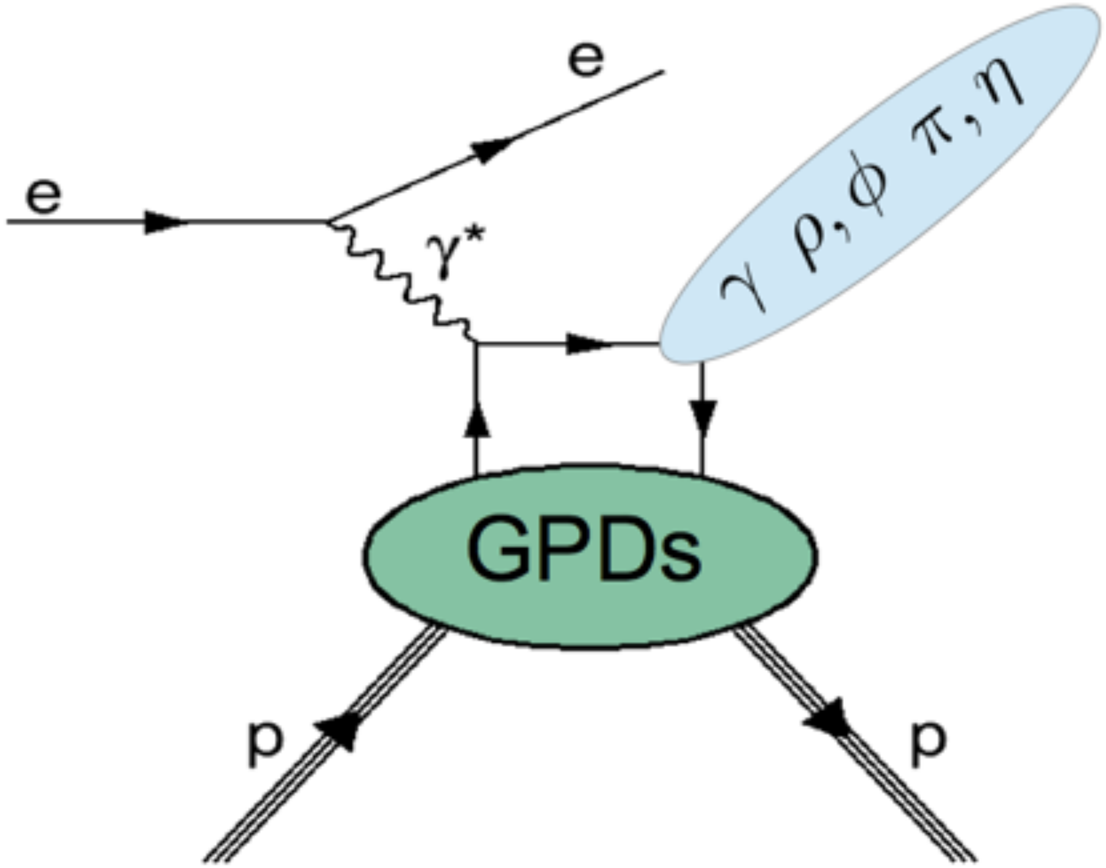
Four quark helicity-flip twist-2 GPDs

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

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

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

Hard exclusive processes

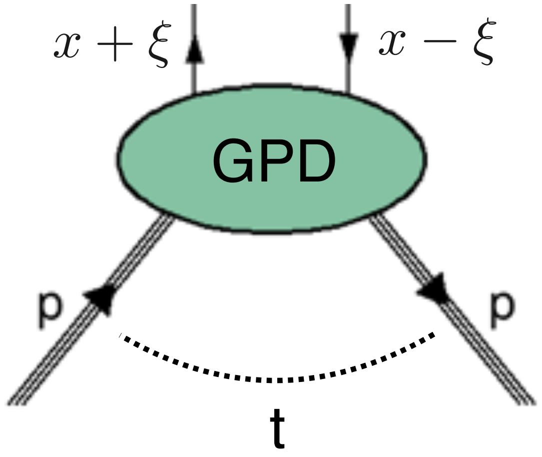


- Deeply virtual Compton scattering (DVCS): theoretically cleanest probe

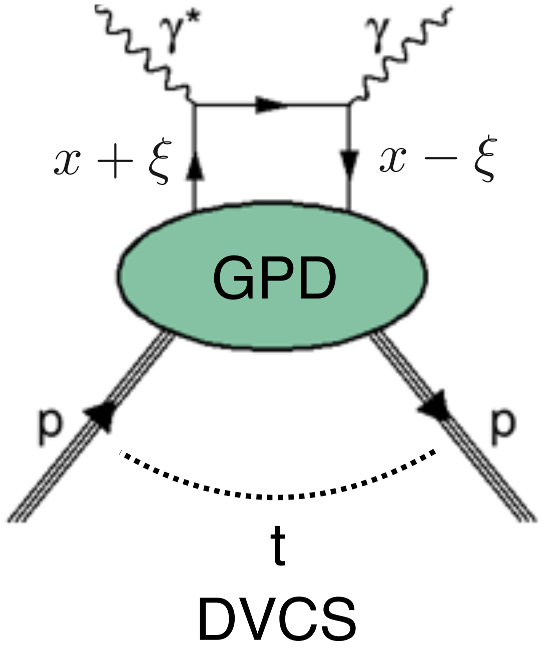
- Exclusive meson production
  - probe various types of GPDs with different sensitivity and different flavour combinations: also access to quark-helicity-flip GPDs
  - complementary to DVCS

- Target polarization state: access to different GPDs

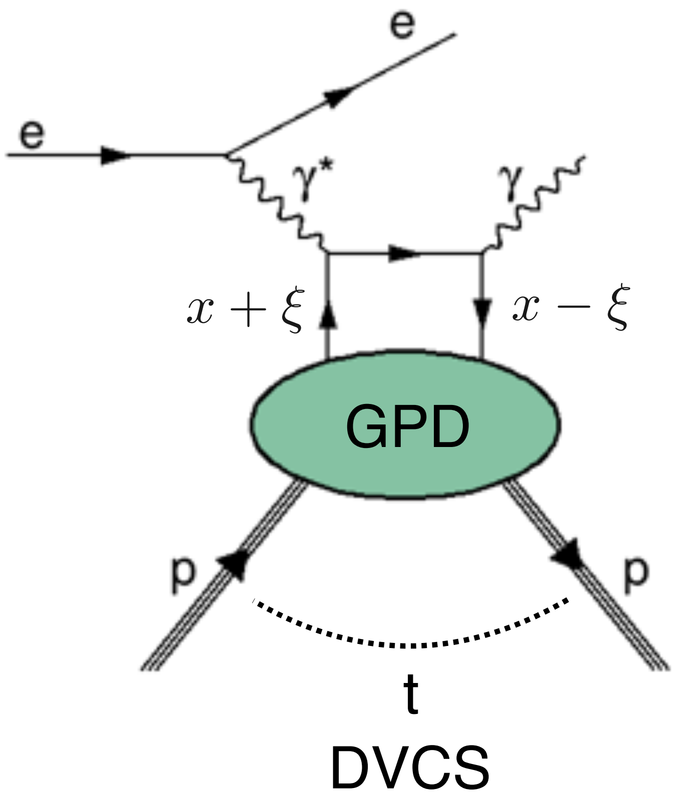
GPDs and DVCS



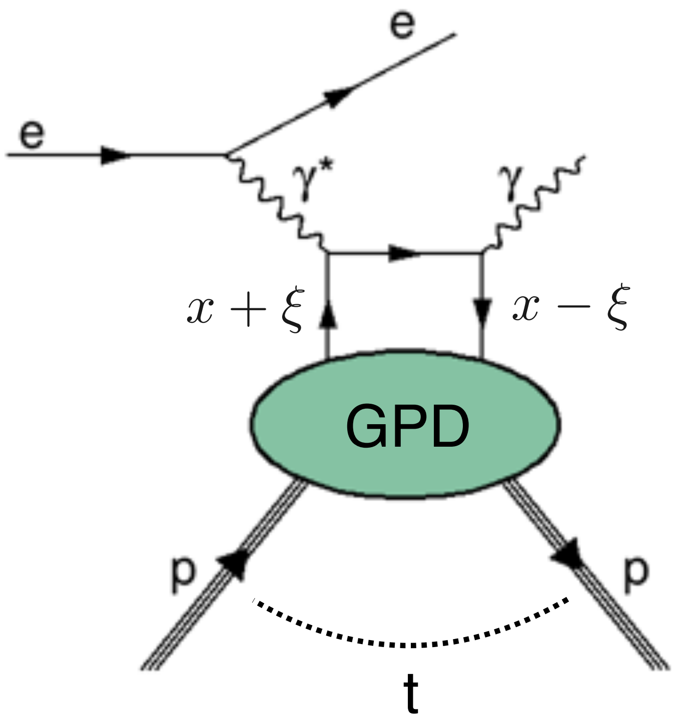
GPDs and DVCS



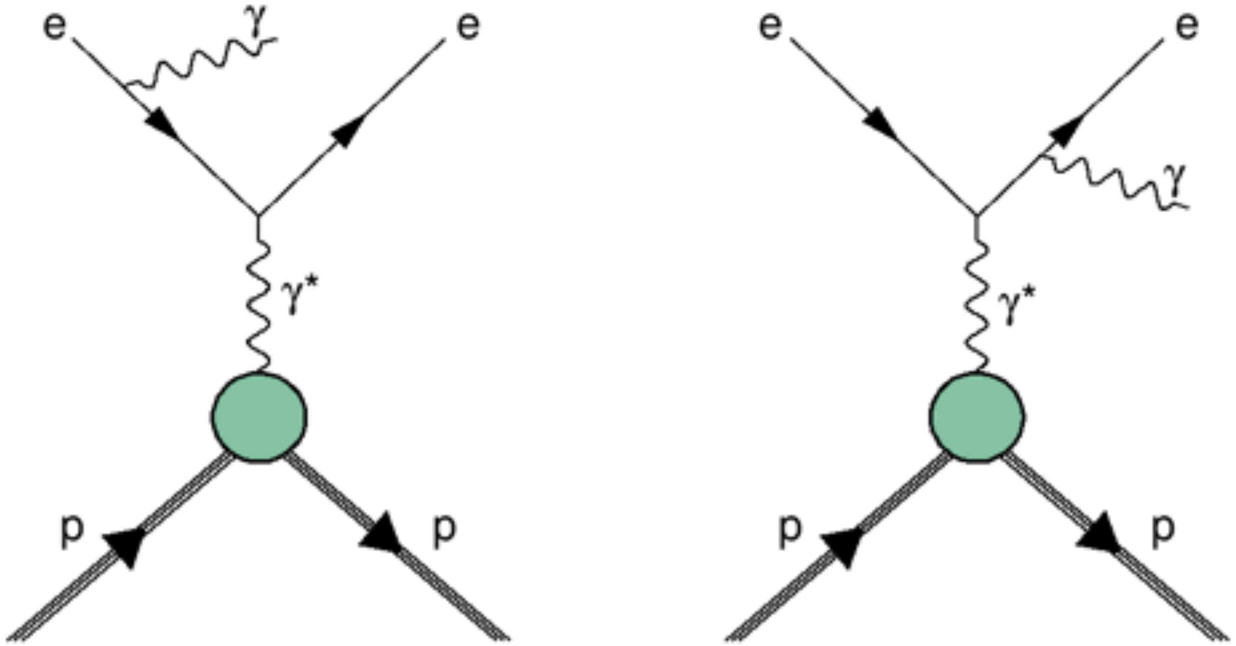
GPDs and DVCS



GPDs and DVCS

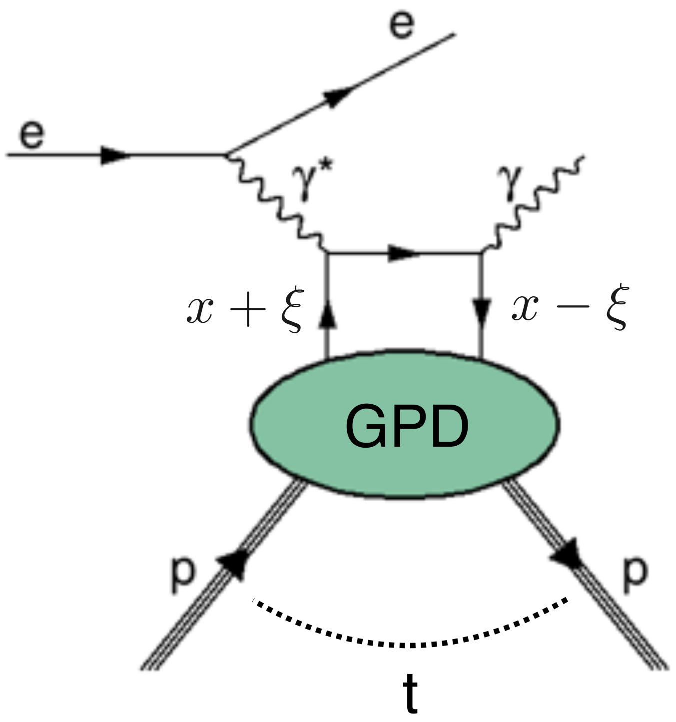


DVCS

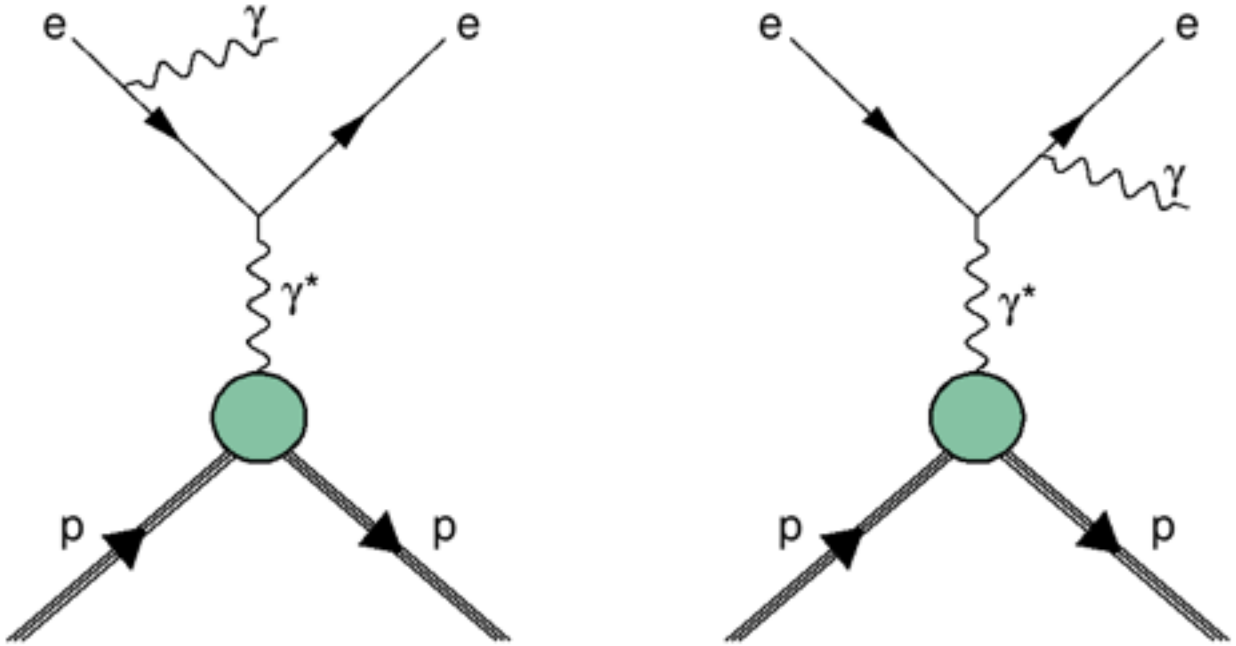


Bethe-Heitler

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

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

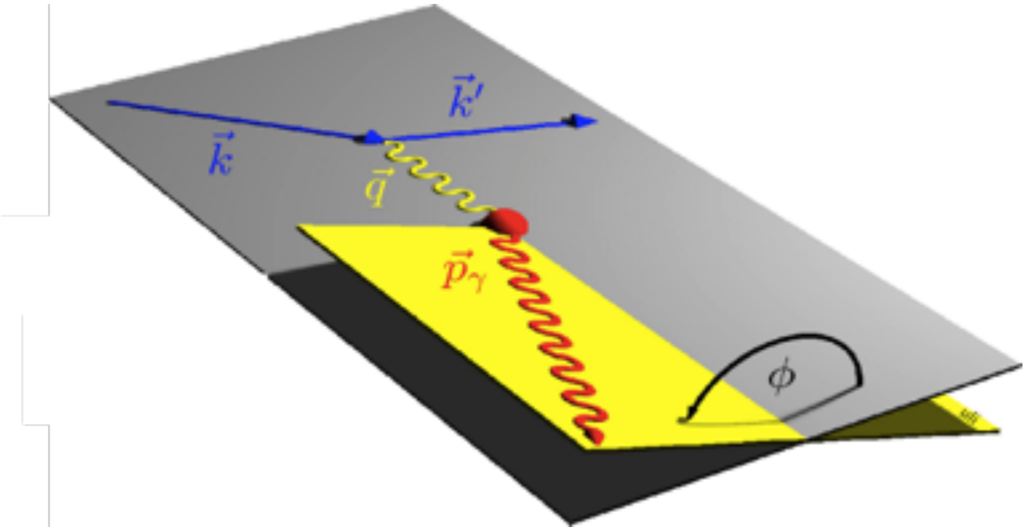
calculable with knowledge Pauli & Dirac form factors

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

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

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

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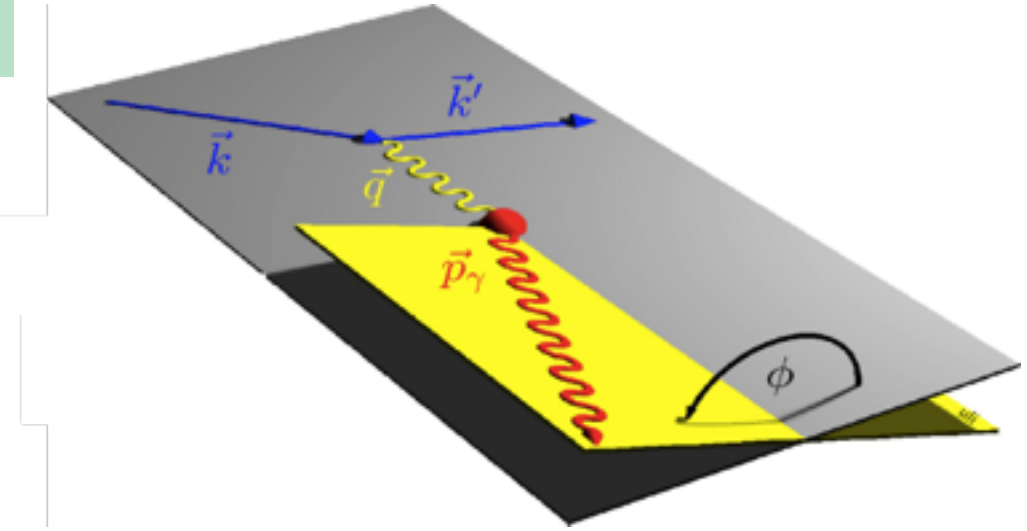
coefficients: linear in GPDs

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

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

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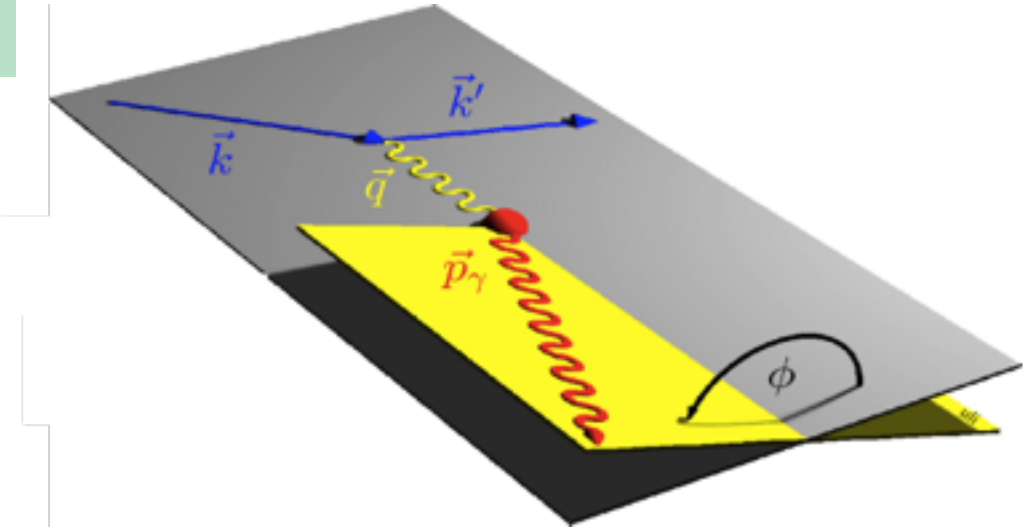
$$\mathcal{I} = \frac{-e_l K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right\}$$

coefficients: linear in GPDs

beam
charge

beam
polarization



DVCS cross section

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

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

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

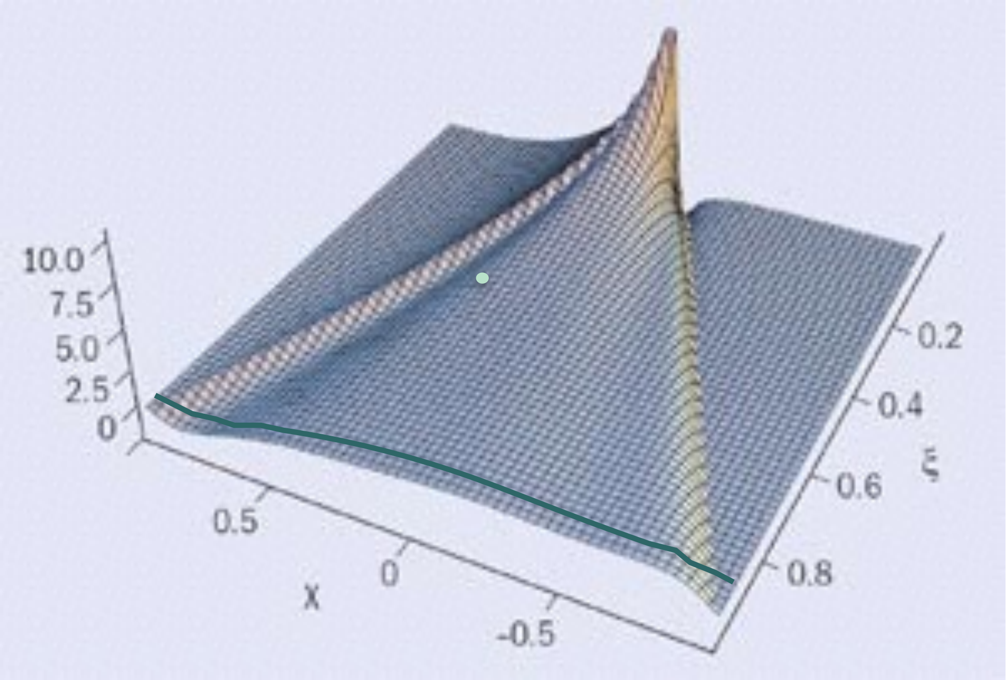
$$M^{1,1} = F_1(t)\,\mathcal{H}(\xi,t) + \frac{x_B}{2-x_B}(F_1(t)+F_2(t))\,\tilde{\mathcal{H}}(\xi,t) - \frac{t}{4M_p^2}\,F_2(t)\mathcal{E}(\xi,t)$$

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

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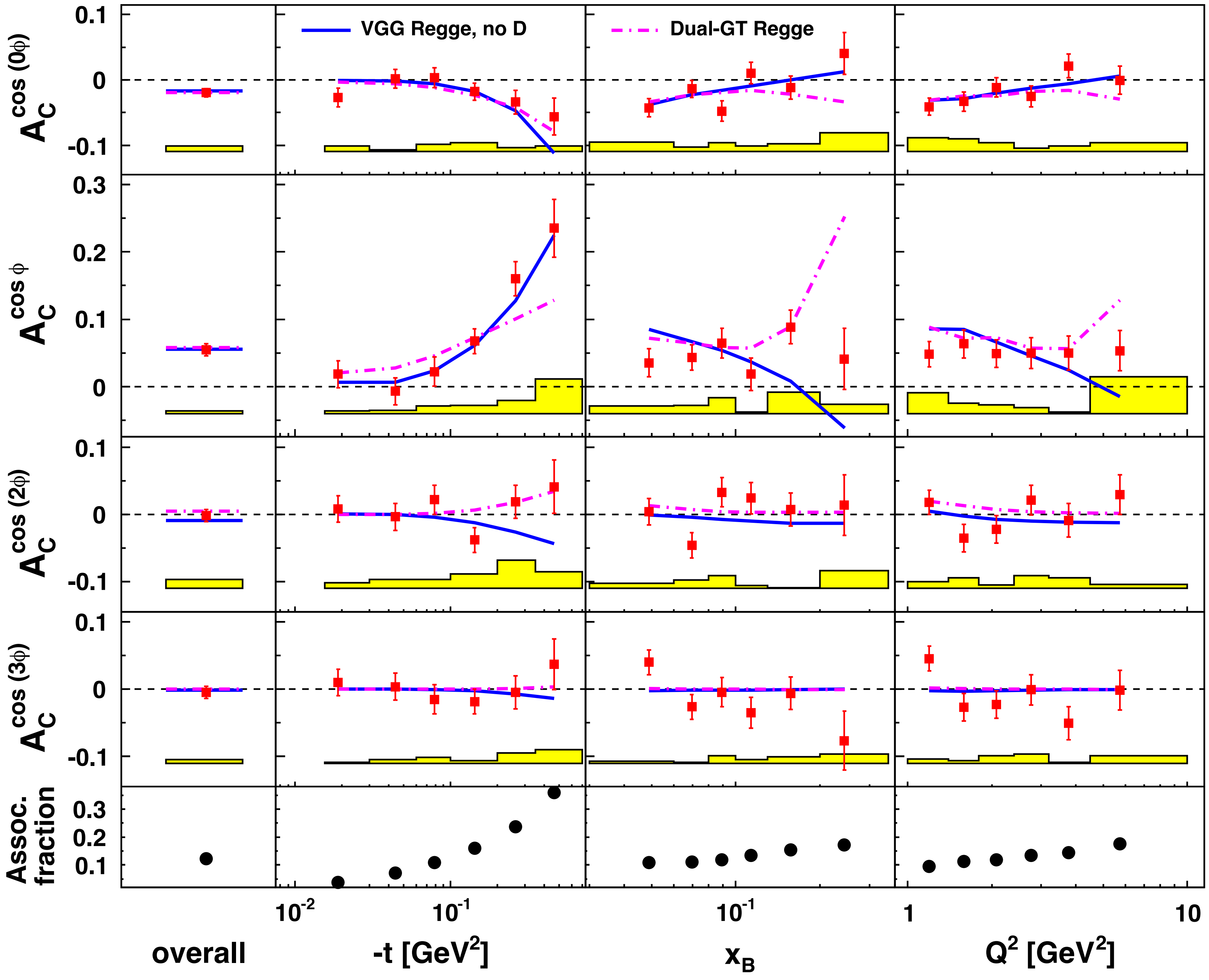
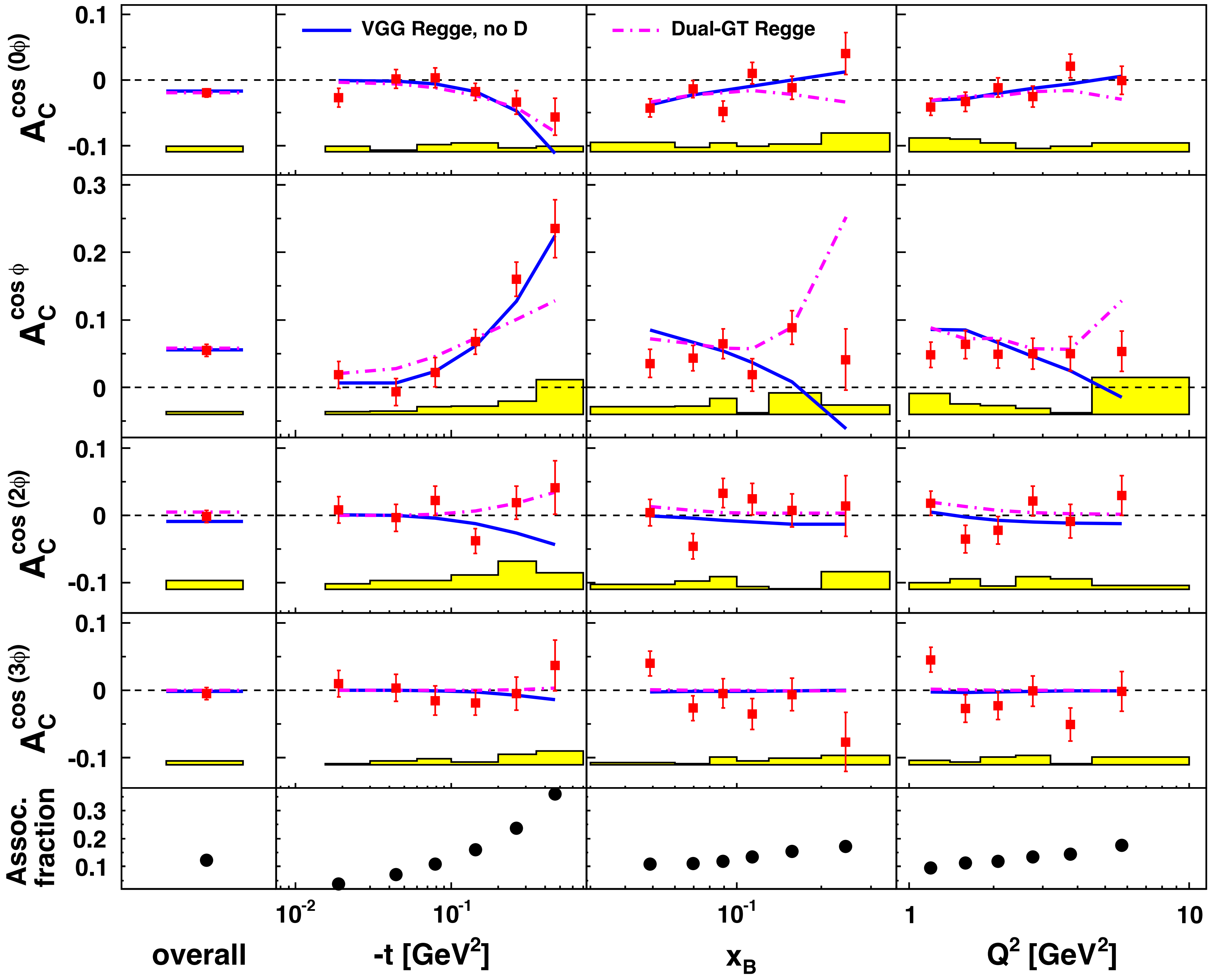
Beam-charge asymmetry

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



Beam-charge asymmetry

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

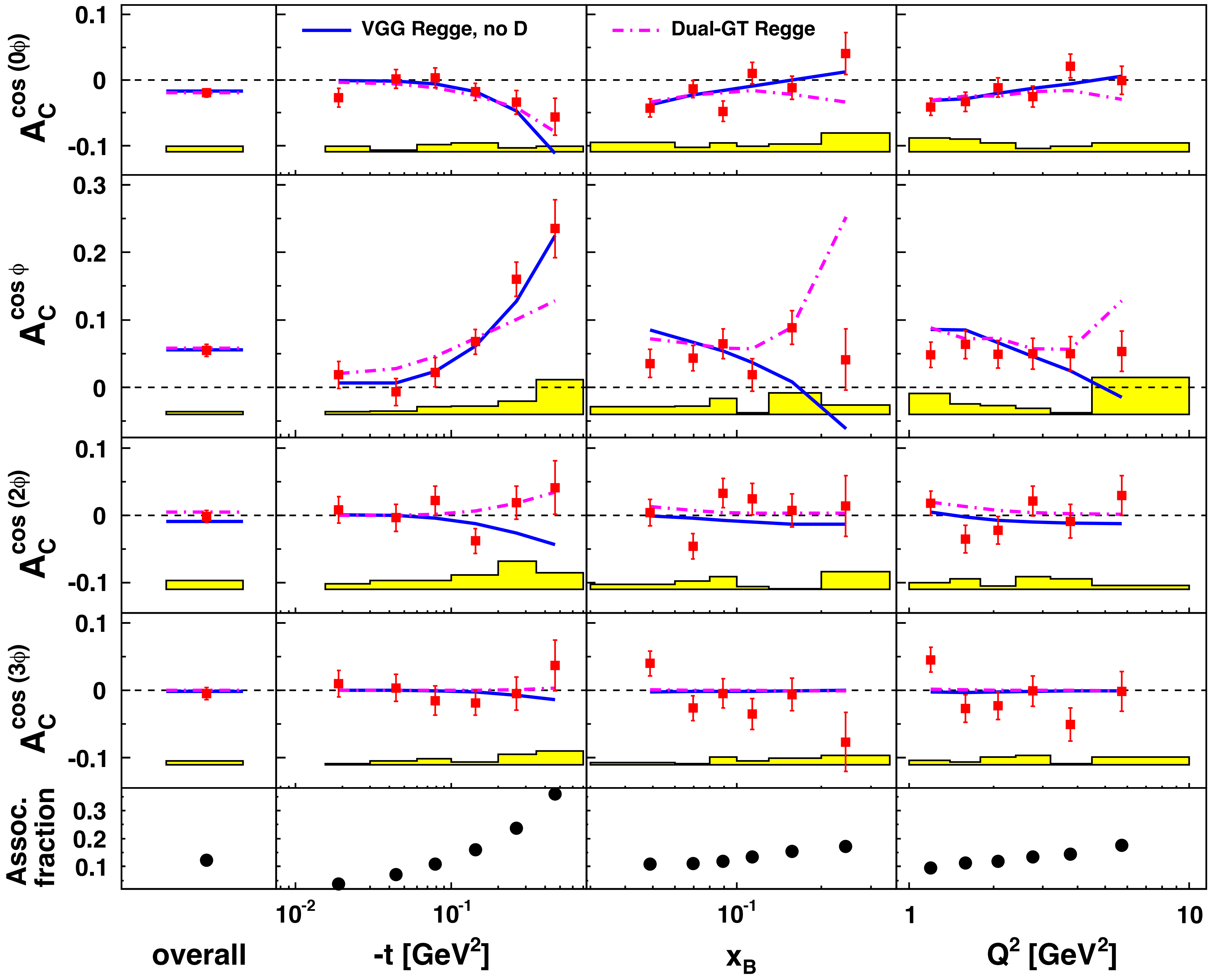


$\Re M^{1,1}$

twist-2 GPDs

Beam-charge asymmetry

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



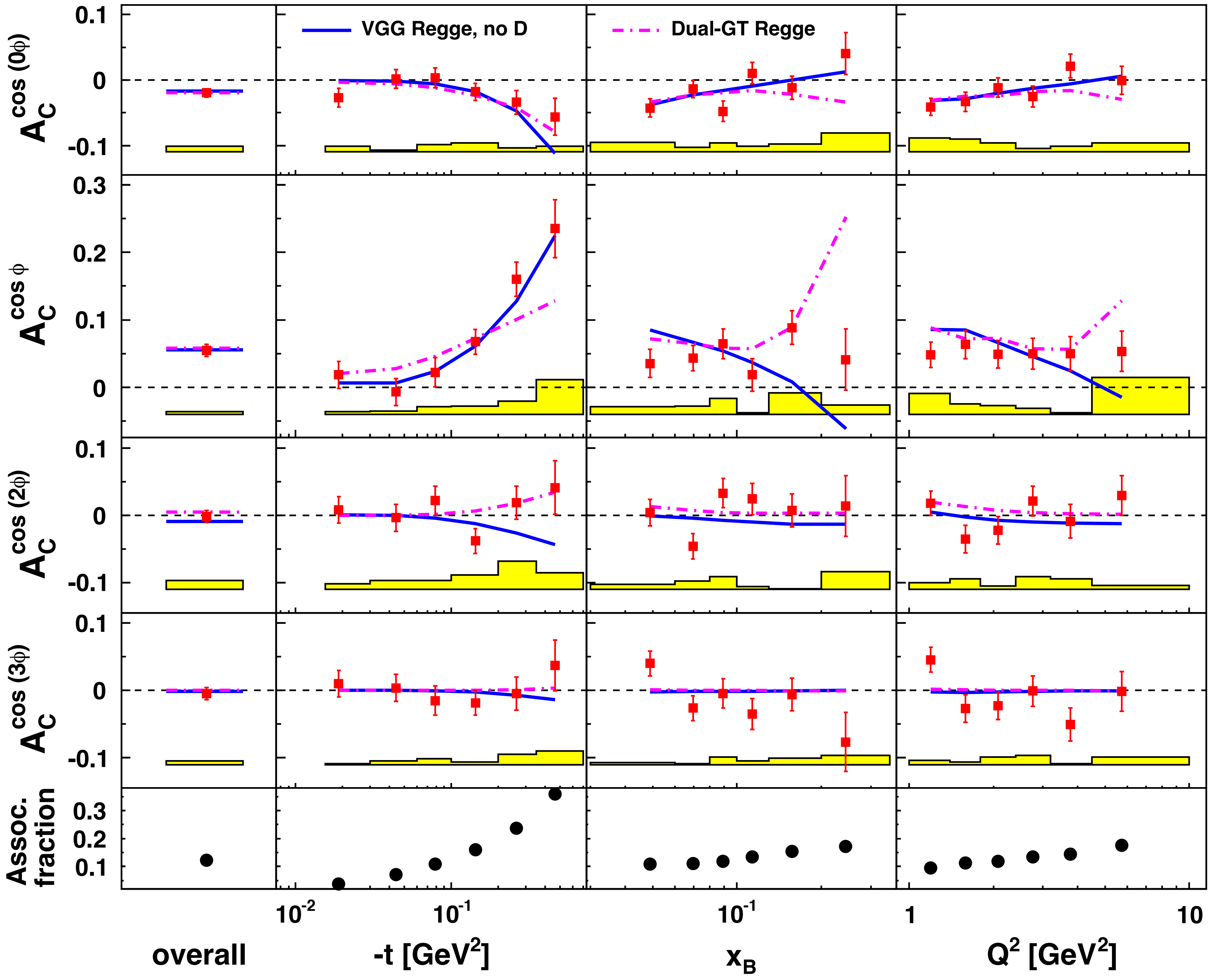
$c_0^{\mathcal{I}} \propto -k\, c_1^{\mathcal{I}}$

$\Re M^{1,1}$

twist-2 GPDs

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

$ep \to e\gamma N\pi$

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 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

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

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

Charge-averaged beam-helicity asymmetry

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

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

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

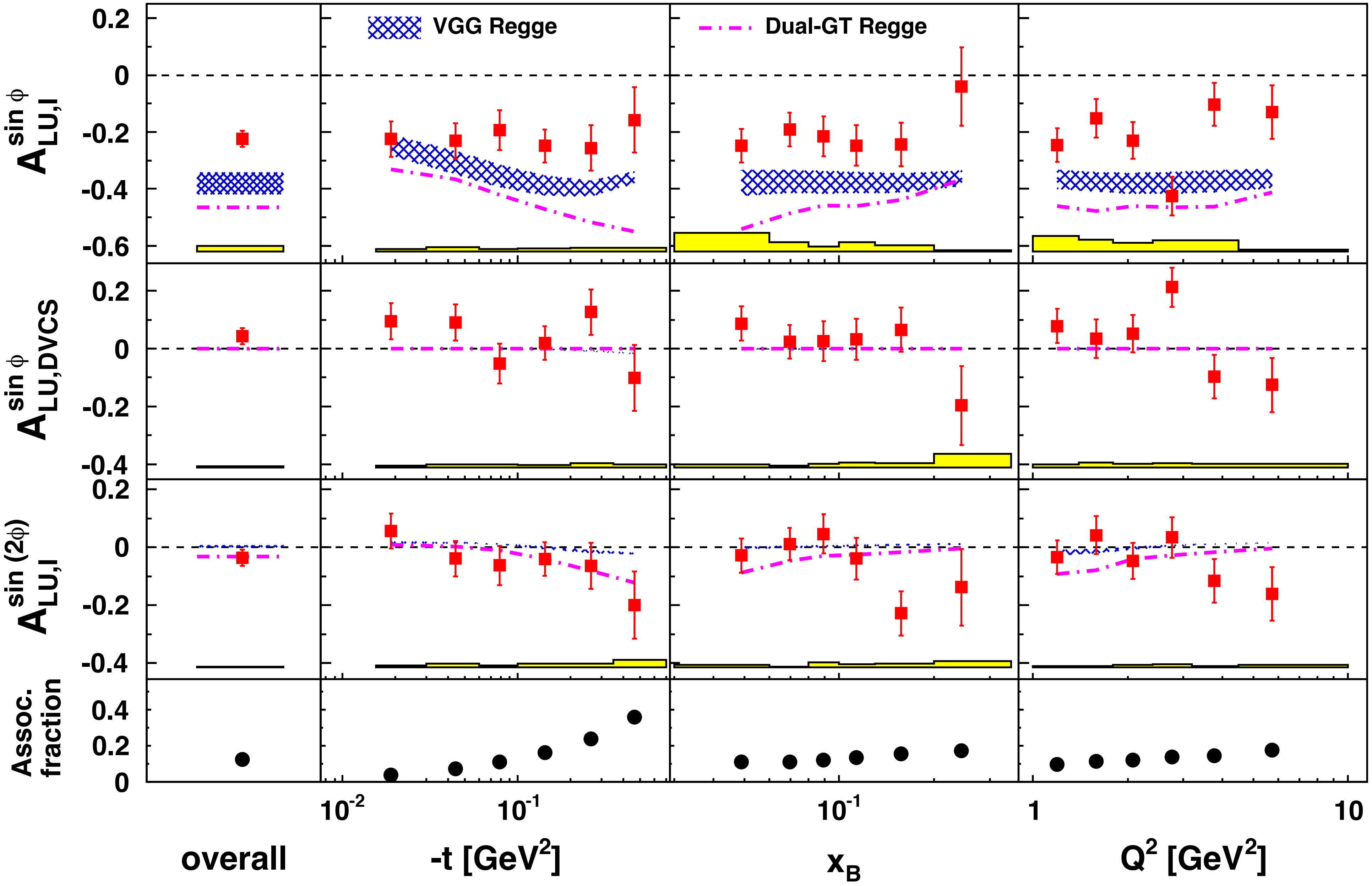
bilinear access to GPDs

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

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

Charge-difference and charge-average beam-helicity asymmetry

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



$\Im M^{1,1}$

twist-2 GPDs

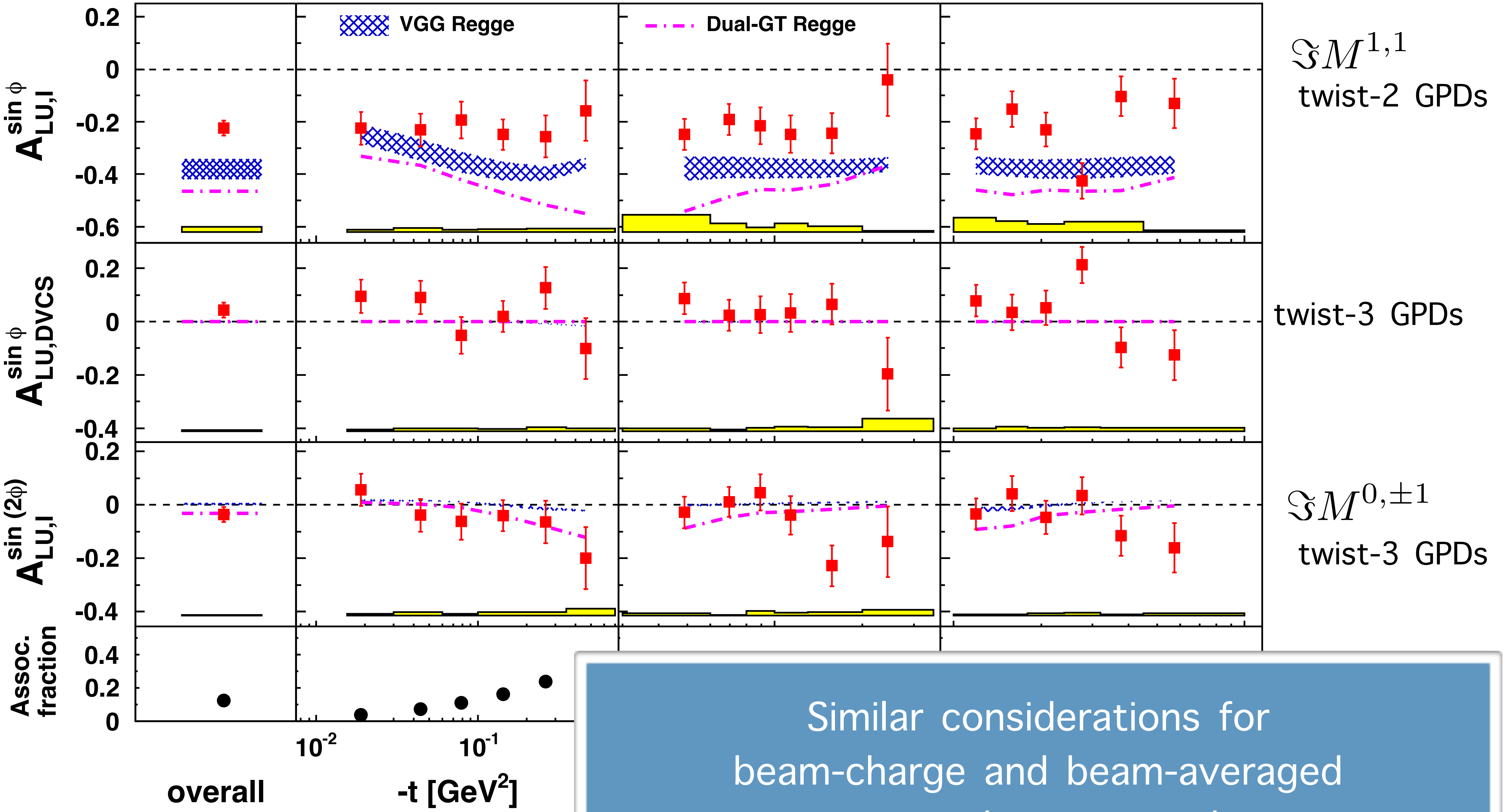
twist-3 GPDs

$\Im M^{0,\pm1}$

twist-3 GPDs

Charge-difference and charge-average beam-helicity asymmetry

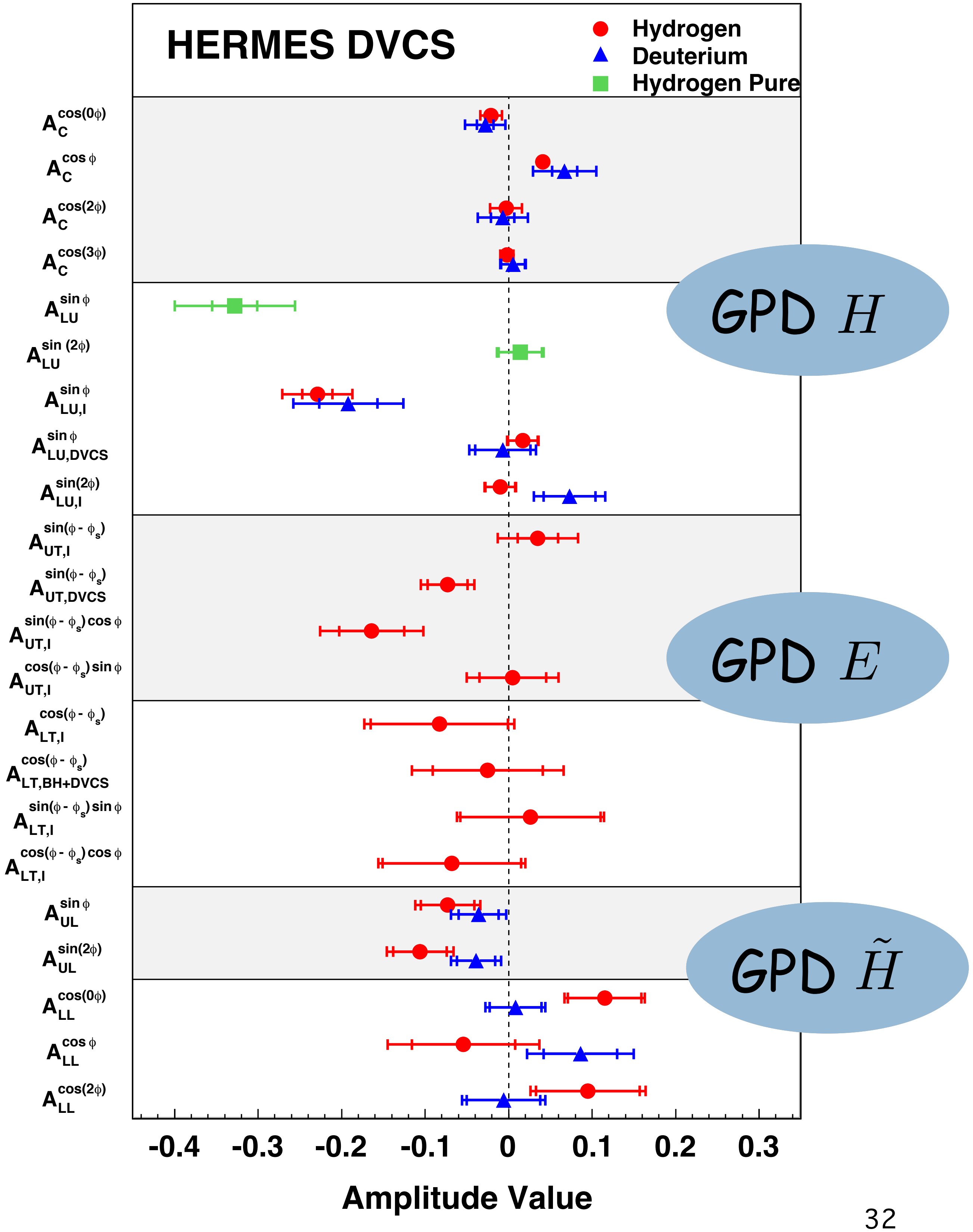
HERMES, JHEP **11** (2009) 083



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

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

DVCS at HERMES



beam-charge asymmetry

JHEP 07 (2012) 32
Nucl. Phys. B 829 (2010) 1

beam-helicity asymmetry

JHEP 07 (2012) 32
Nucl. Phys. B 829 (2010) 1
JHEP10(2012)042

transverse target-spin asymmetry

JHEP 06 (2008) 066

double spin (LT) asymmetry

Phys. Lett. B 704 (2011) 15

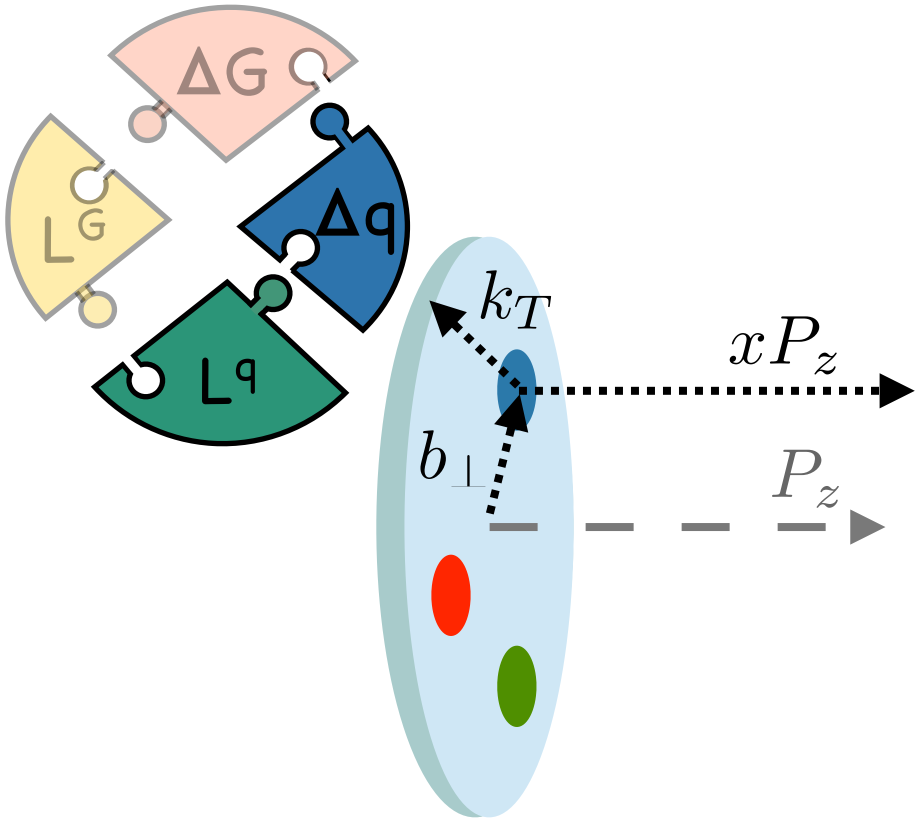
longitudinal target-spin asymmetry

JHEP 06 (2010) 019
Nucl. Phys. B 842 (2011) 265

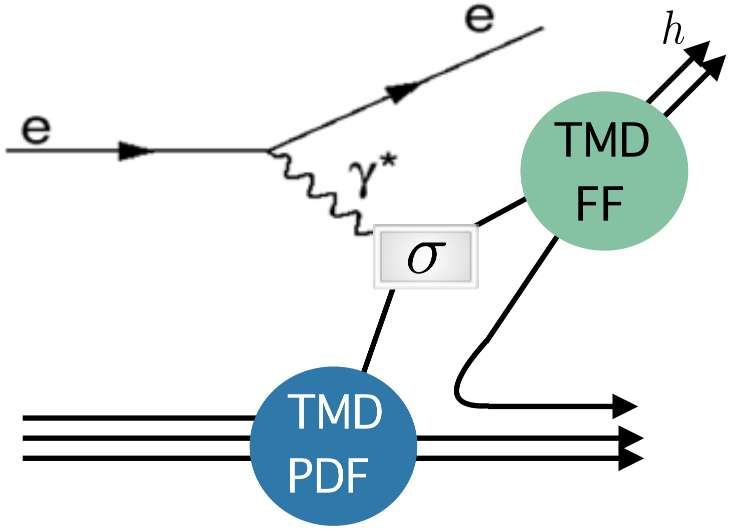
double spin (LL) asymmetry

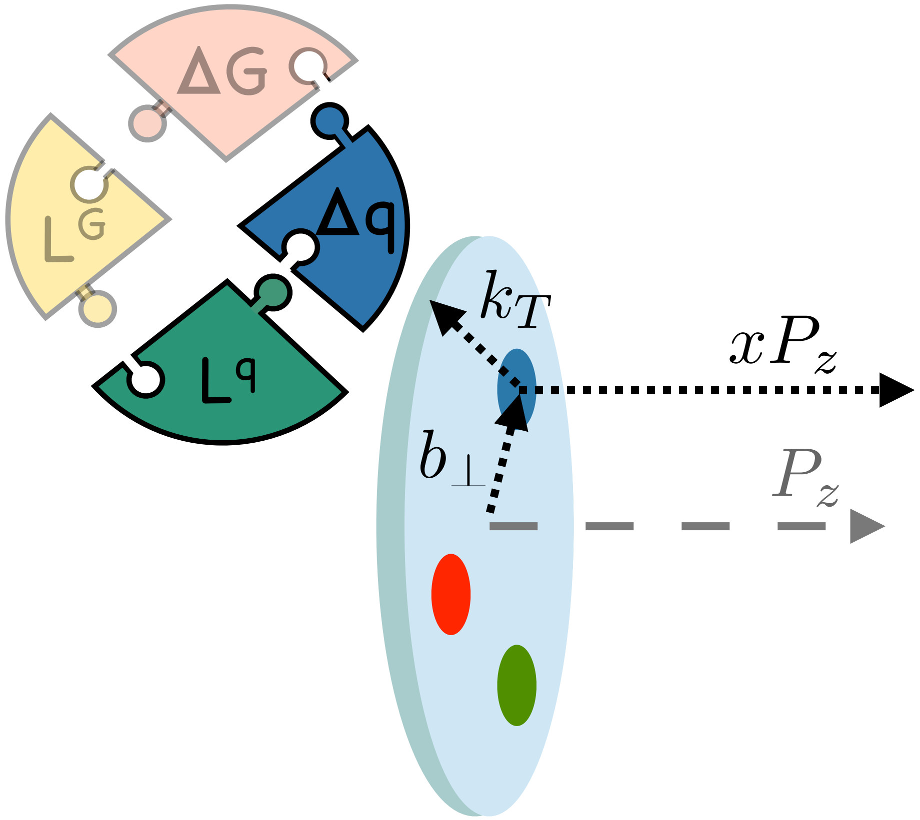
JHEP 06 (2010) 019
Nucl. Phys. B 842 (2011) 265

Summary



Summary





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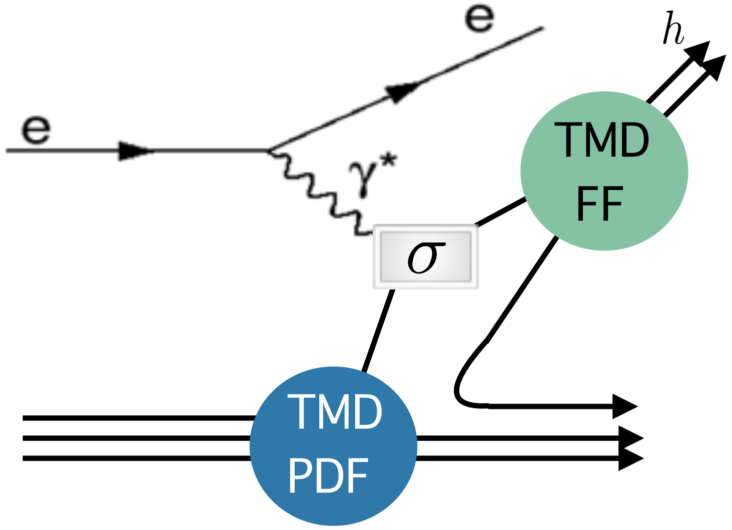
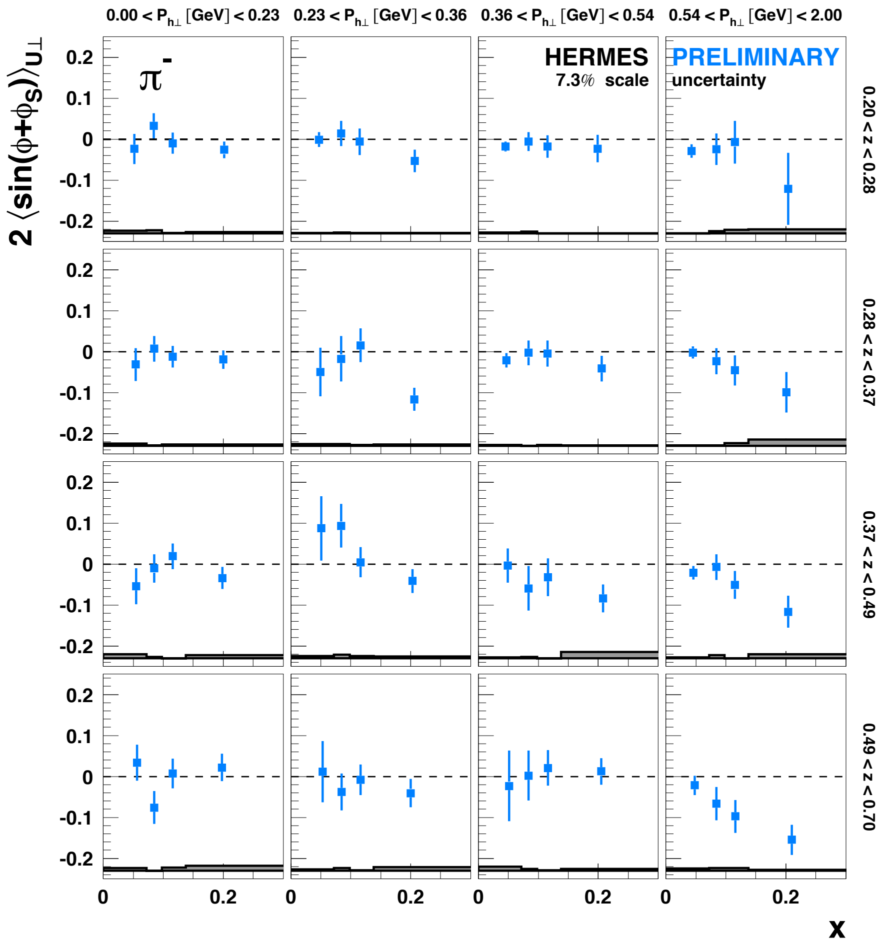
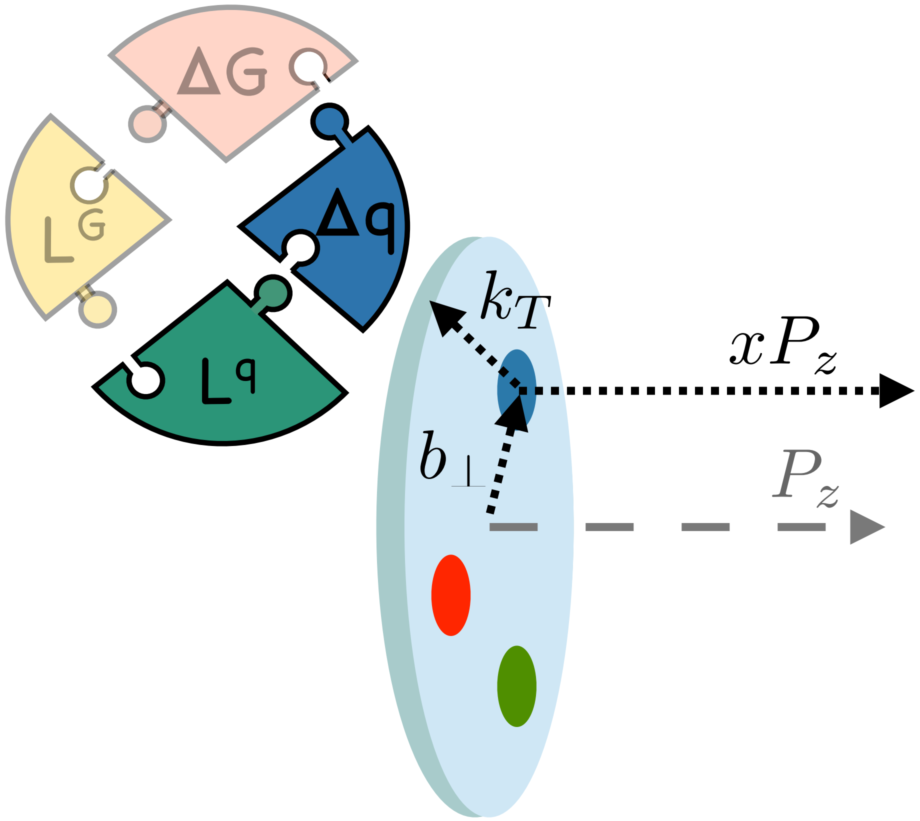
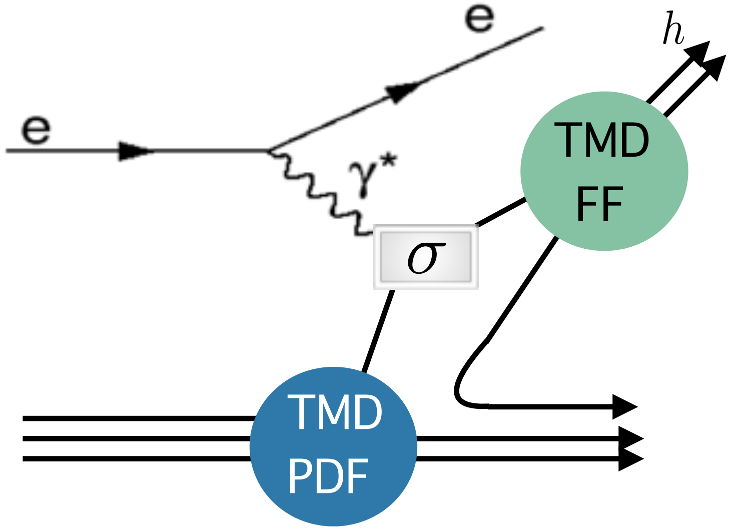
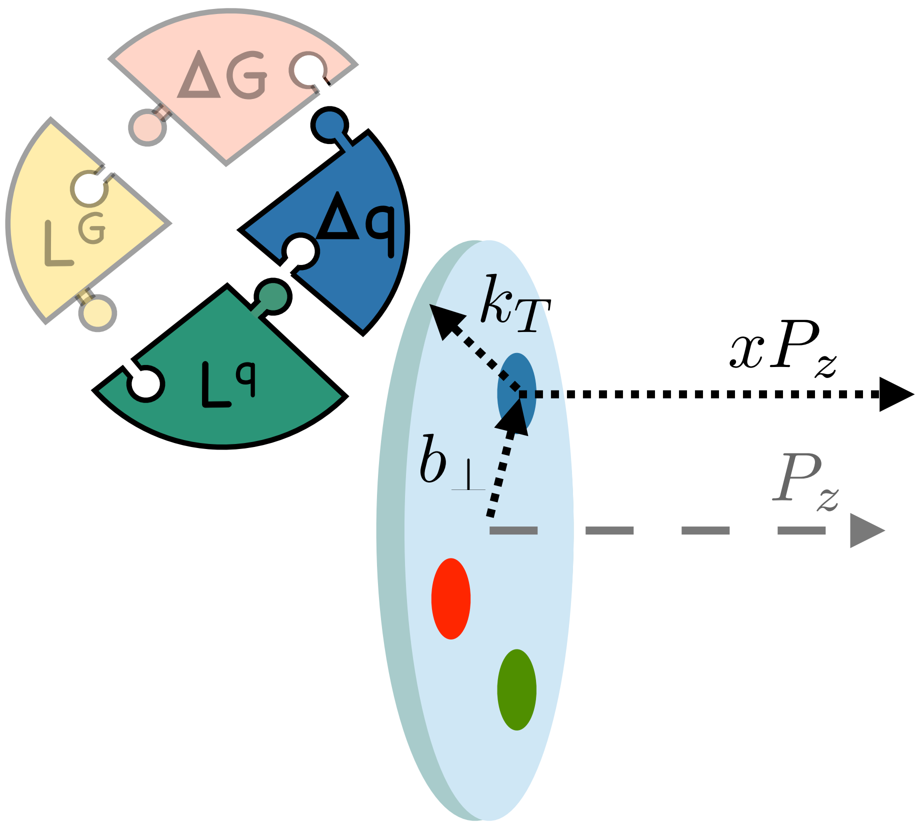

e
e
h
γ^*
σ
TMD FF
TMD PDF

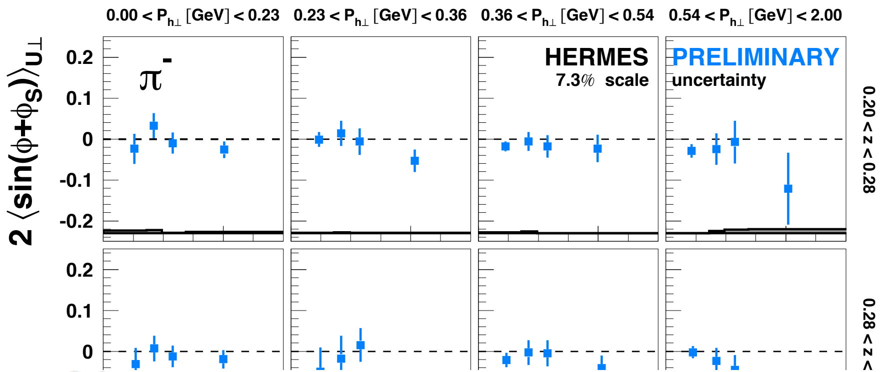

0.00 < $P_{h\perp}$ [GeV] < 0.23
0.23 < $P_{h\perp}$ [GeV] < 0.36
0.36 < $P_{h\perp}$ [GeV] < 0.54
0.54 < $P_{h\perp}$ [GeV] < 2.00
$2\langle\sin(\phi+\phi_S)\rangle_{U\perp}$
π^-
HERMES
PRELIMINARY
7.3% scale uncertainty
0.20 < z < 0.28
0.28 < z < 0.37
0.37 < z < 0.49
0.49 < z < 0.70
0.2
0.1
0
-0.1
-0.2
x

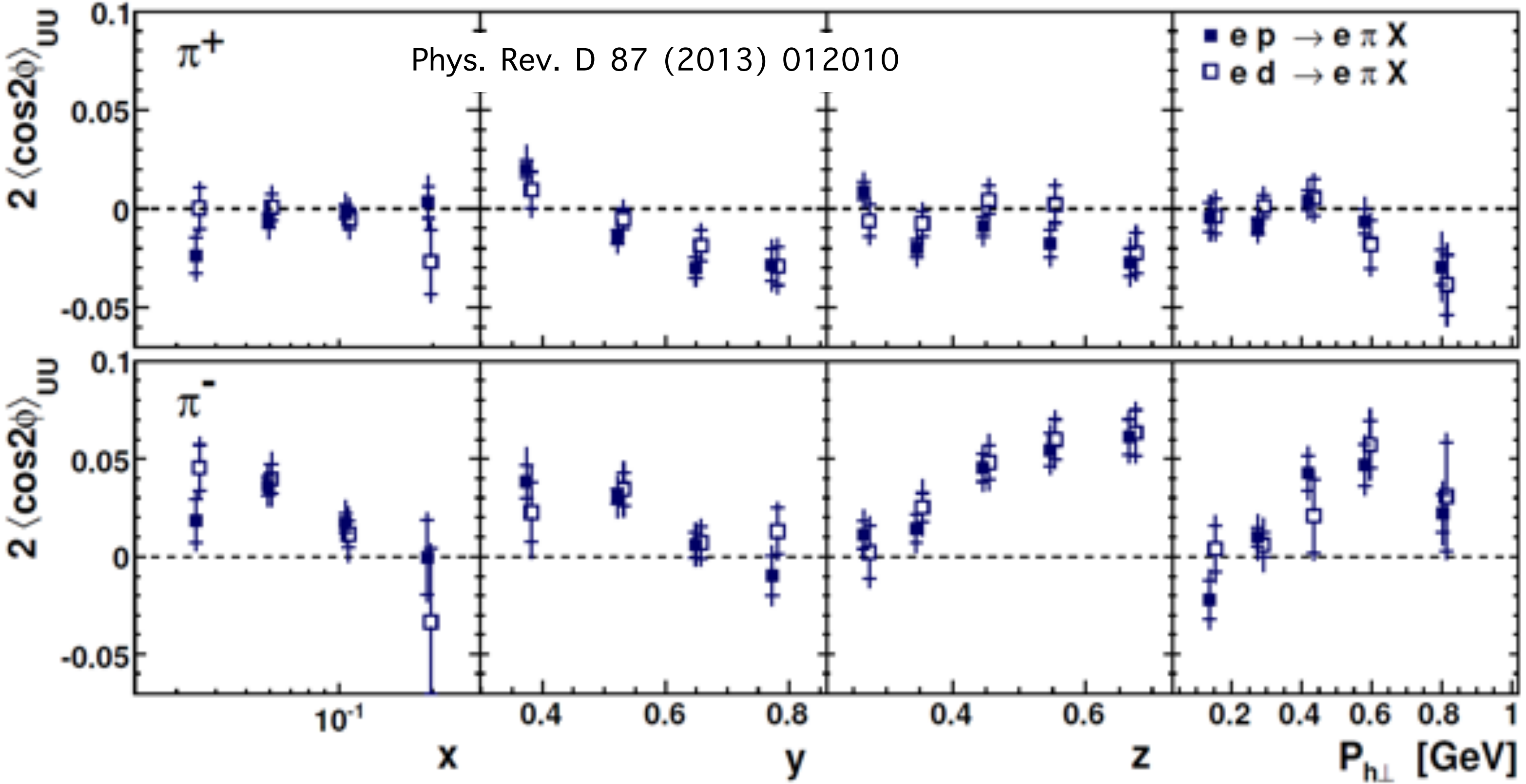

ΔG
L^G
Δq
L^q
k_T
xP_z
$b_\perp$
P_z

Summary


e
e
h
γ*
σ
TMD
FF
TMD
PDF


ΔG
L^G
Δq
L^q
k_T
xP_z
$b_\perp$
P_z


0.00 < P_h⊥ [GeV] < 0.23
0.23 < P_h⊥ [GeV] < 0.36
0.36 < P_h⊥ [GeV] < 0.54
0.54 < P_h⊥ [GeV] < 2.00
2 ⟨sin(φ+φS)⟩U⊥
π⁻
HERMES
7.3% scale
PRELIMINARY
uncertainty
0.2
0.1
0
-0.1
-0.2
0.20 < z < 0.28
0.28 < z <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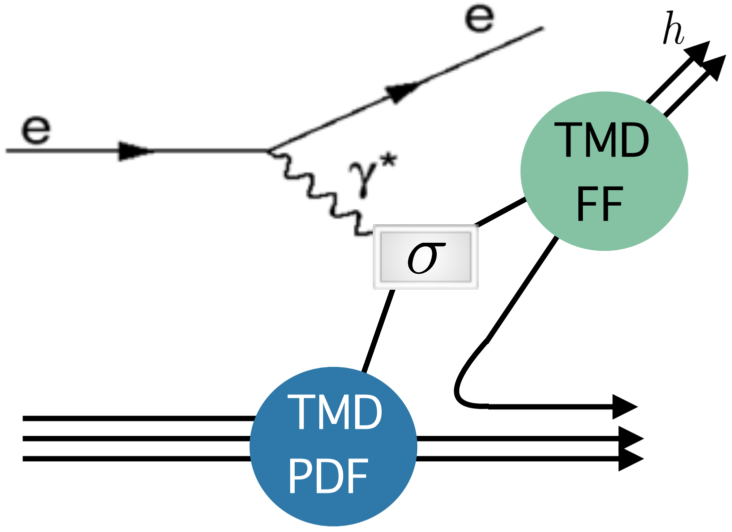
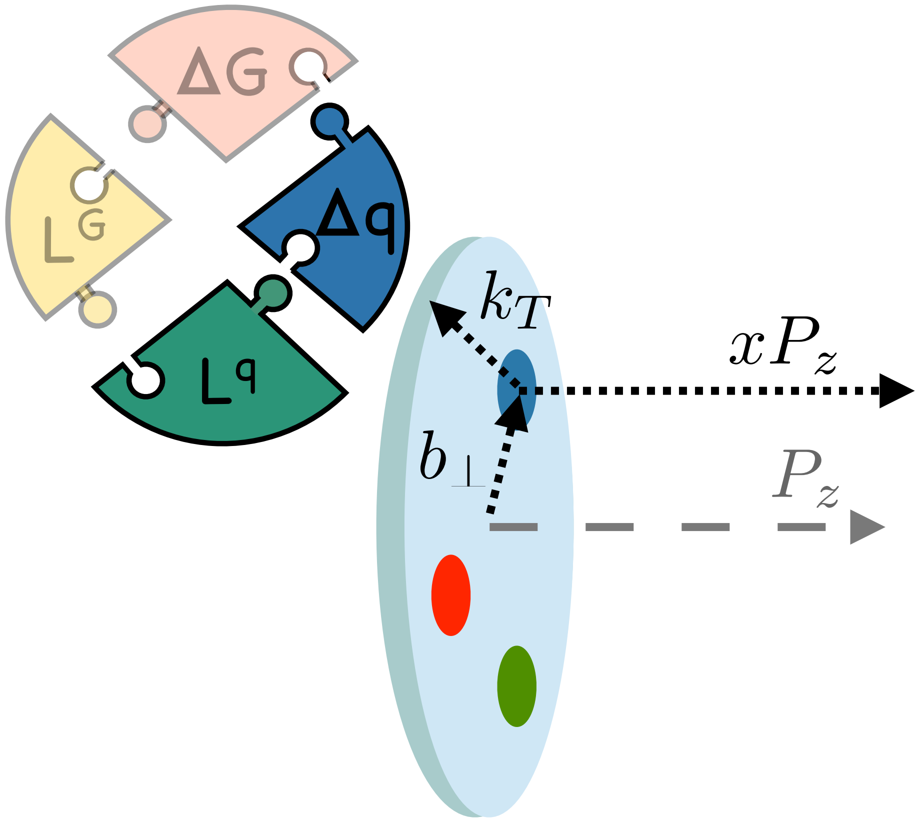
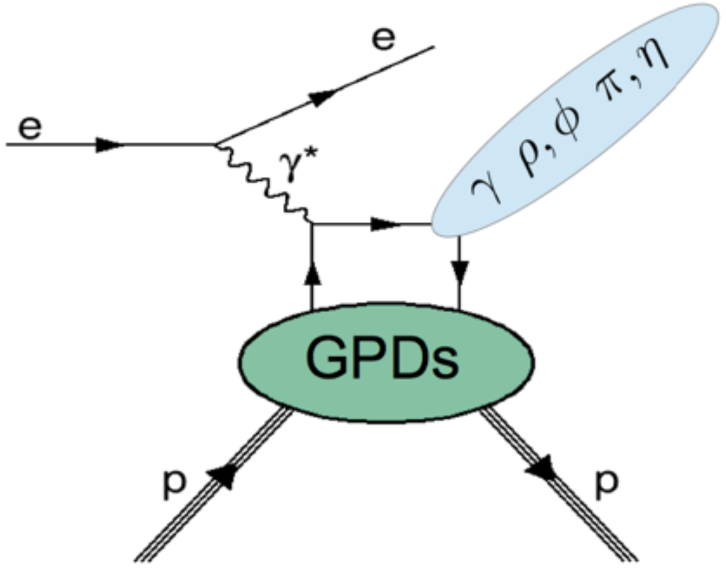
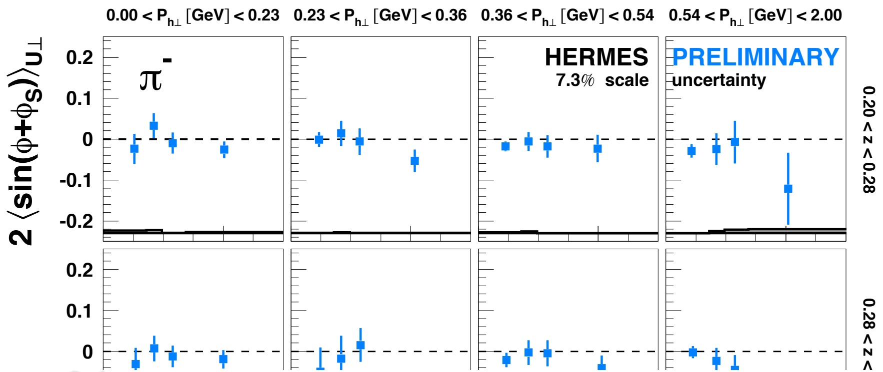
π⁺
π⁻
■ e p → e π X
□ e d → e π X
2 ⟨cos2φ⟩UU
0.1
0.05
0
-0.05
10⁻¹
x
0.4
0.6
0.8
y
0.4
0.6
z
0.2
0.4
0.6
0.8
1
P_h⊥ [GeV]

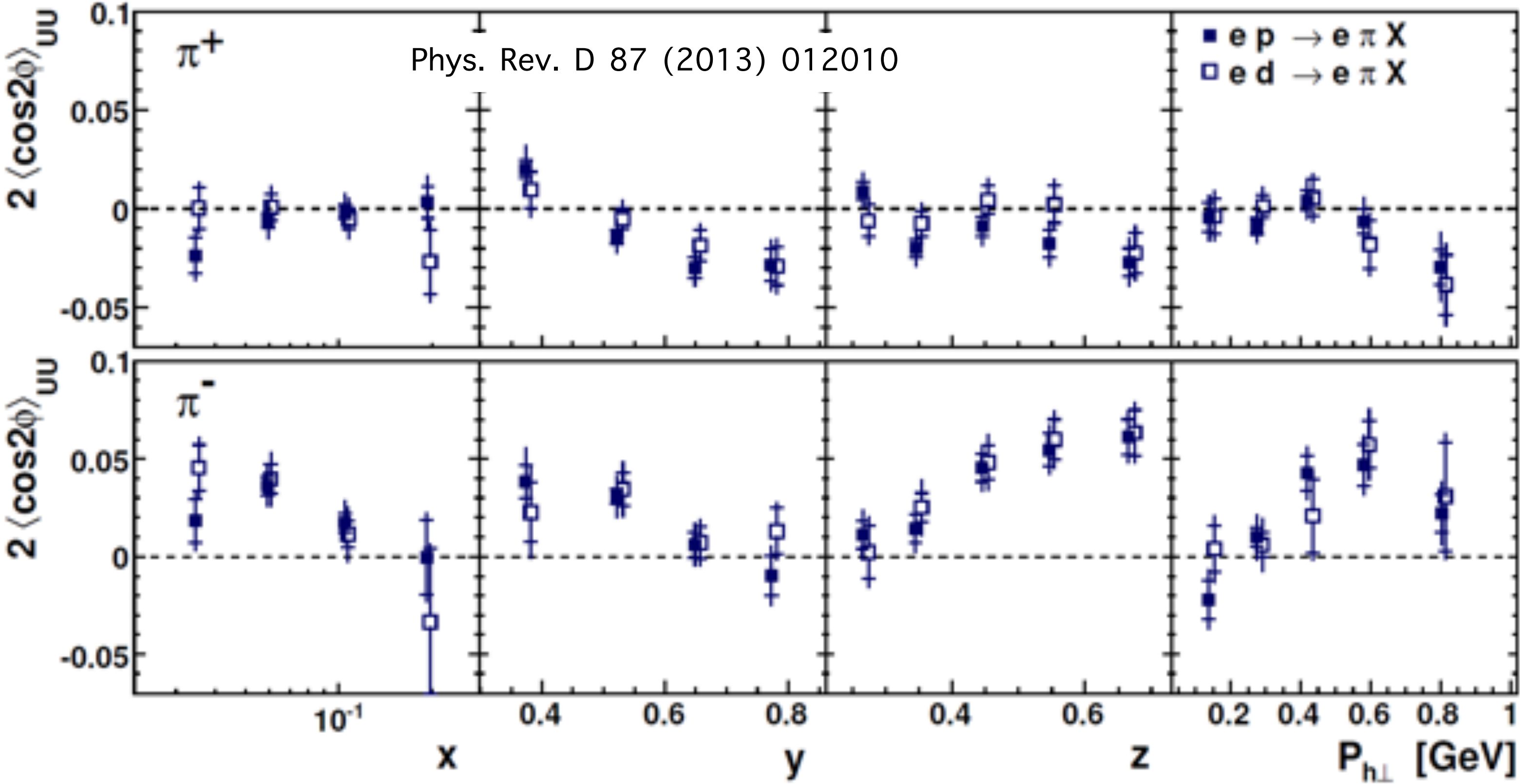
Summary







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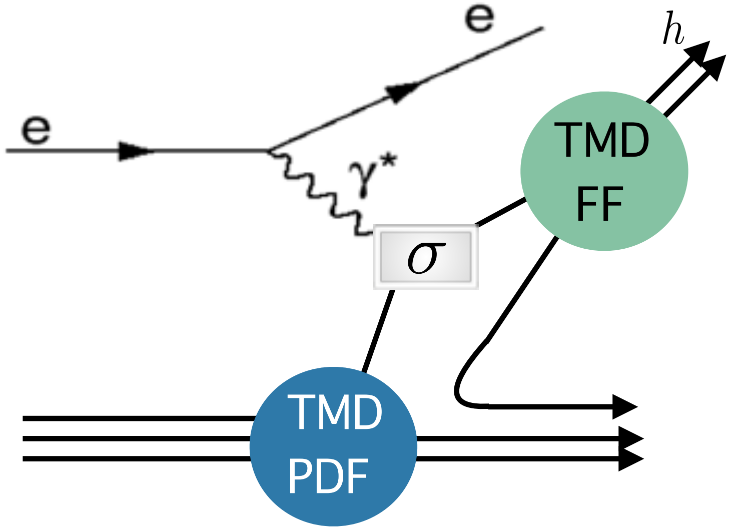
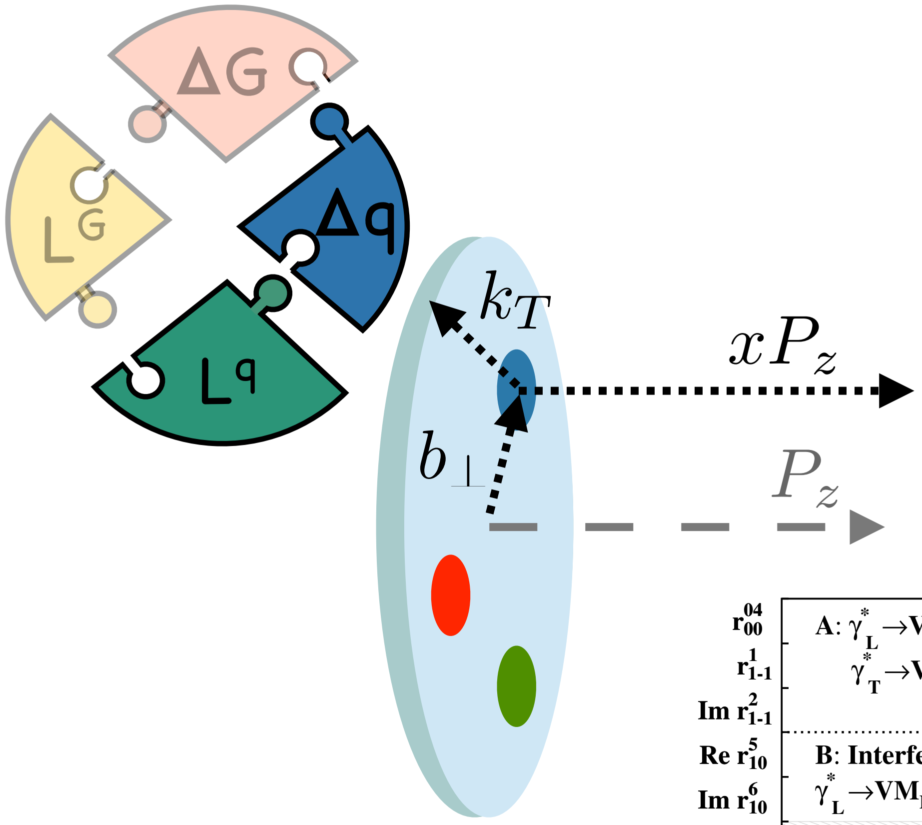
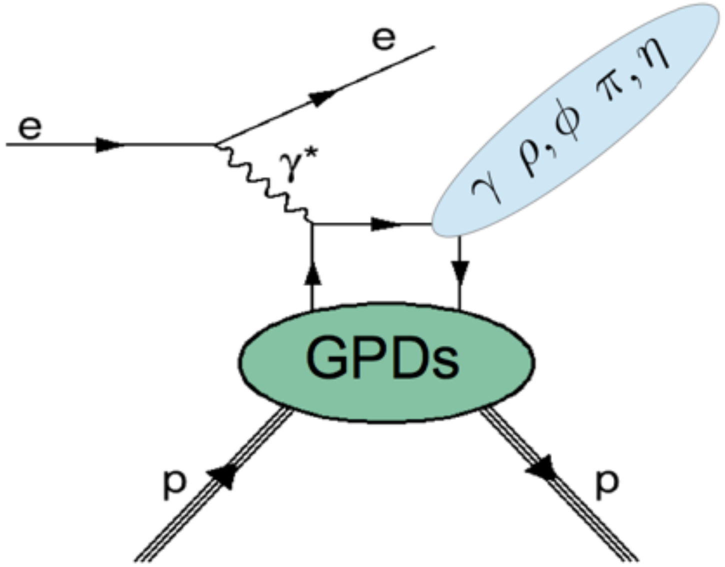
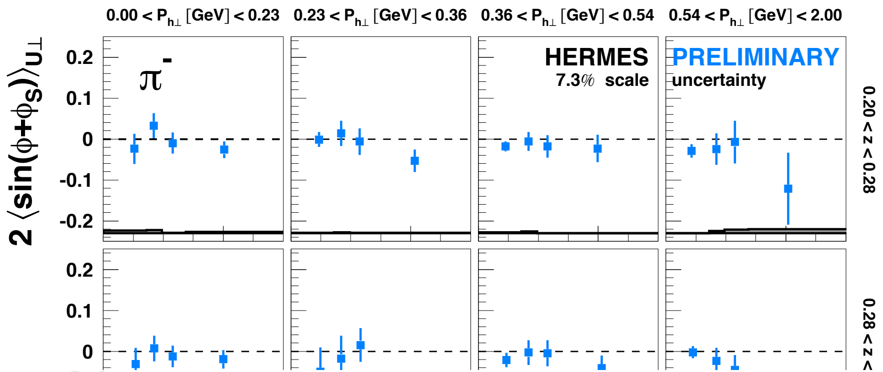
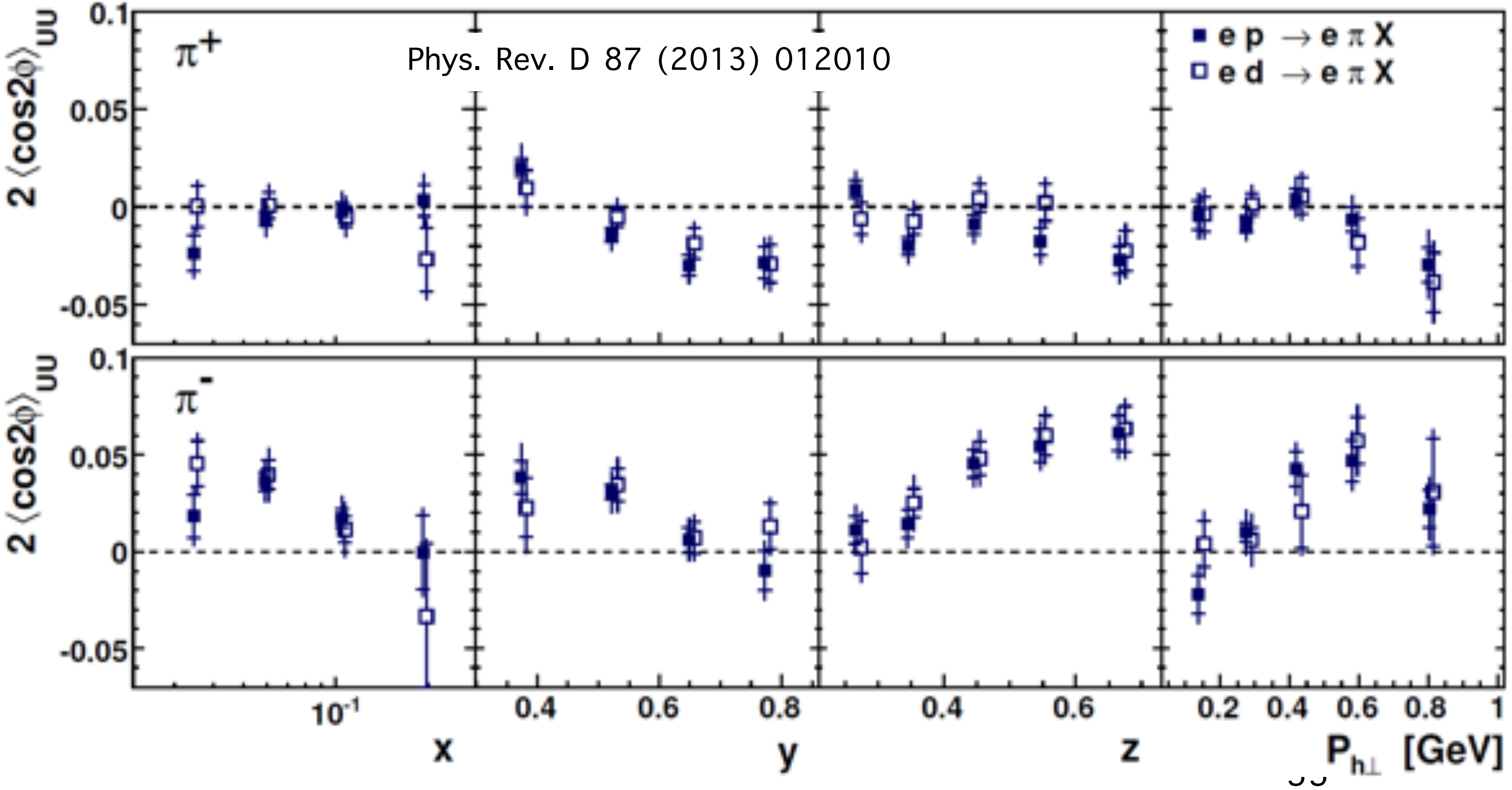
Summary











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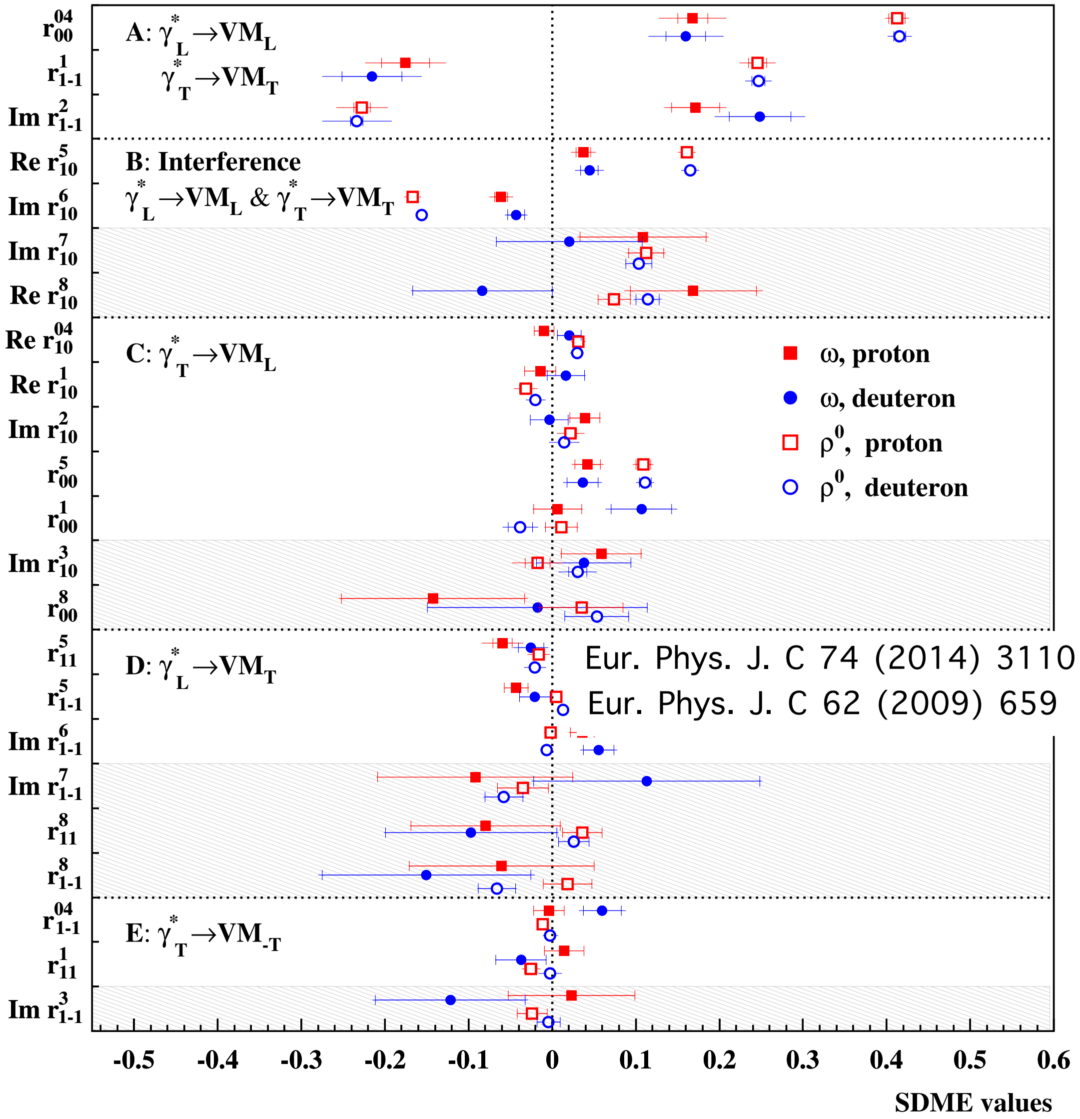
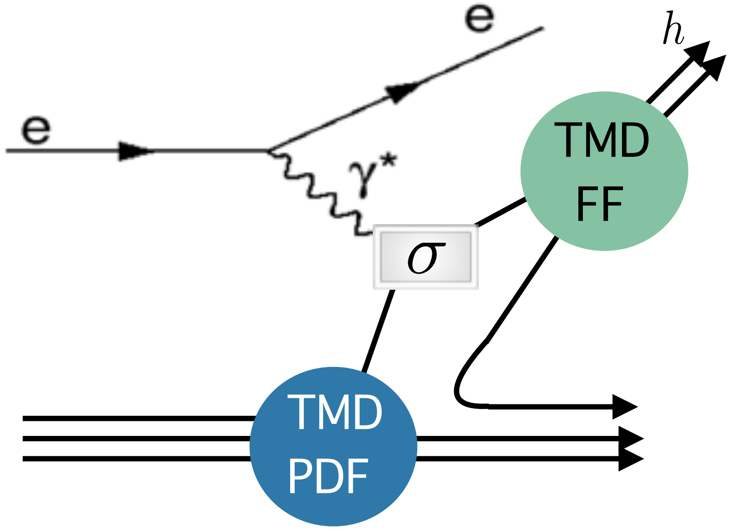
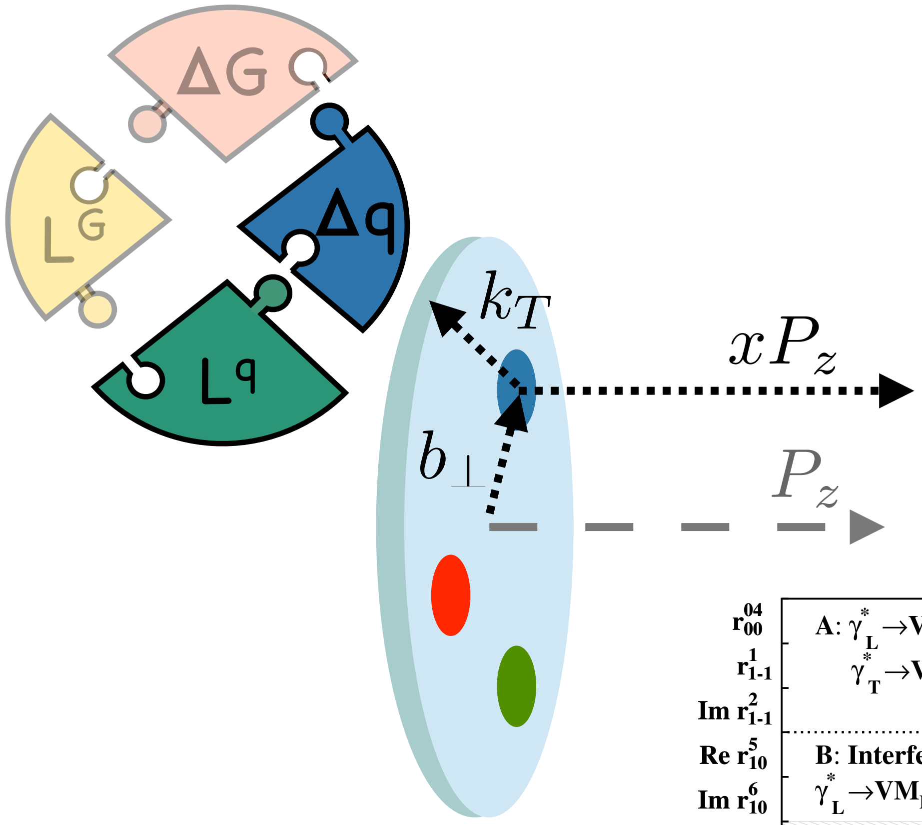
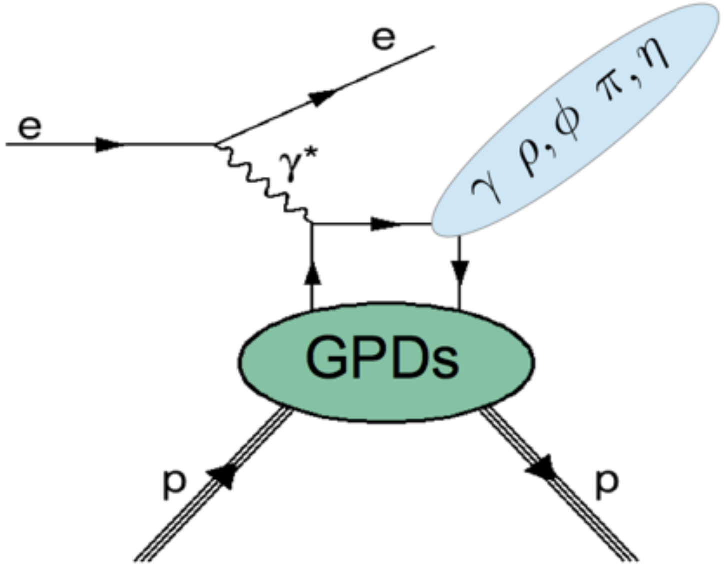


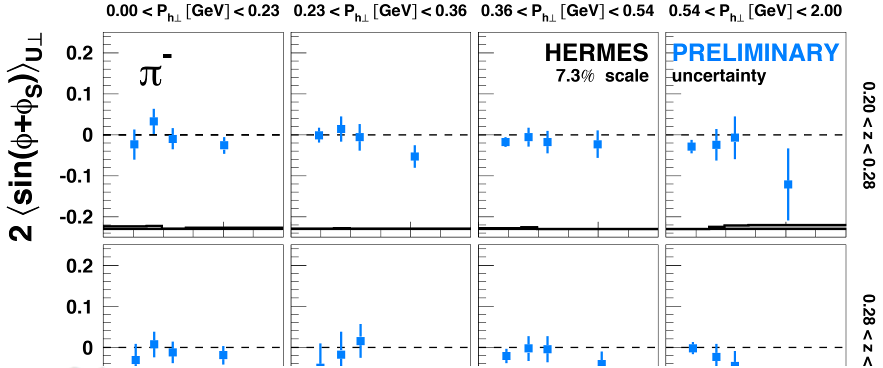
Eur. Phys. J. C 74 (2014) 3110
Eur. Phys. J. C 62 (2009) 659

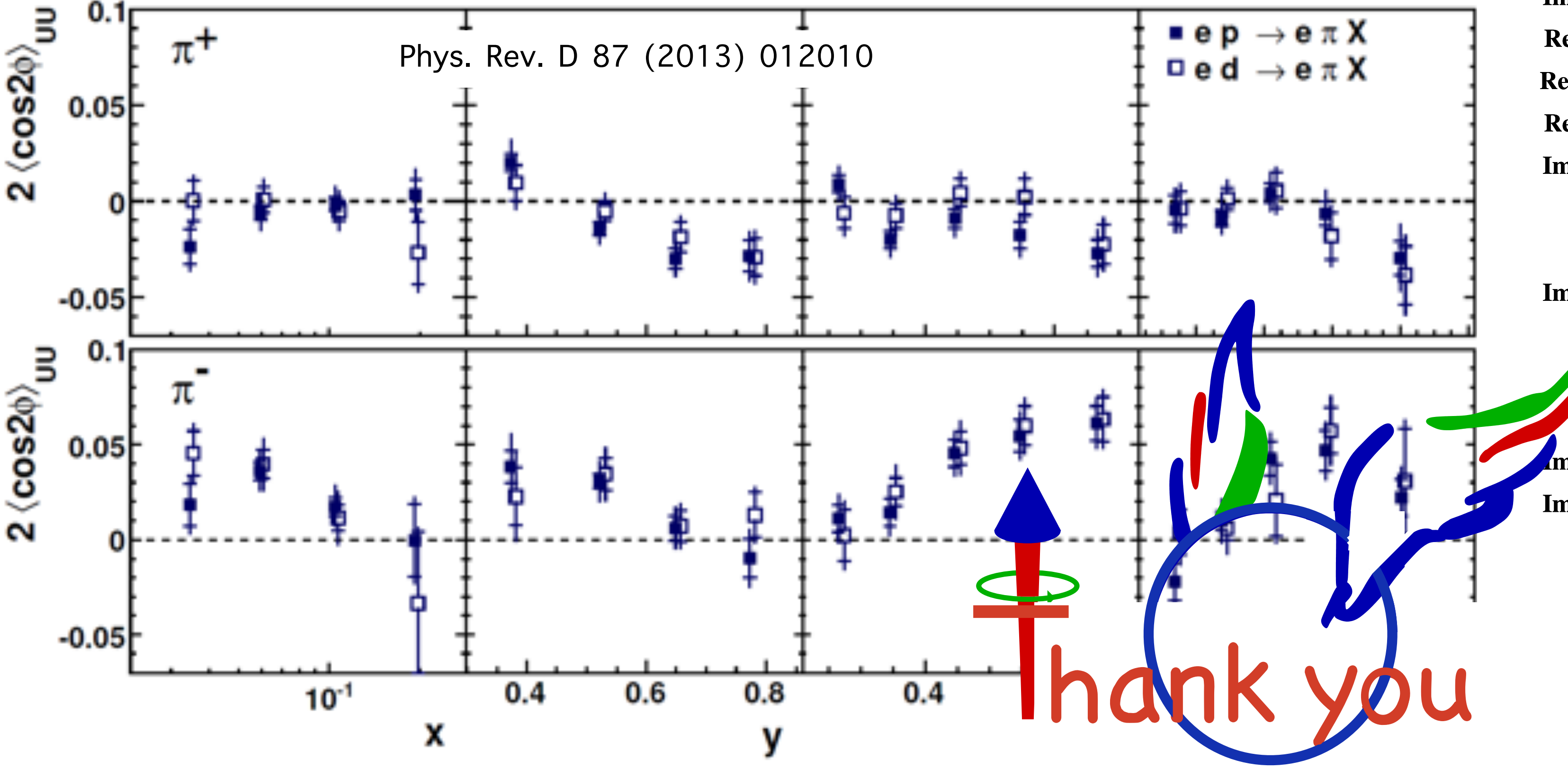
Summary











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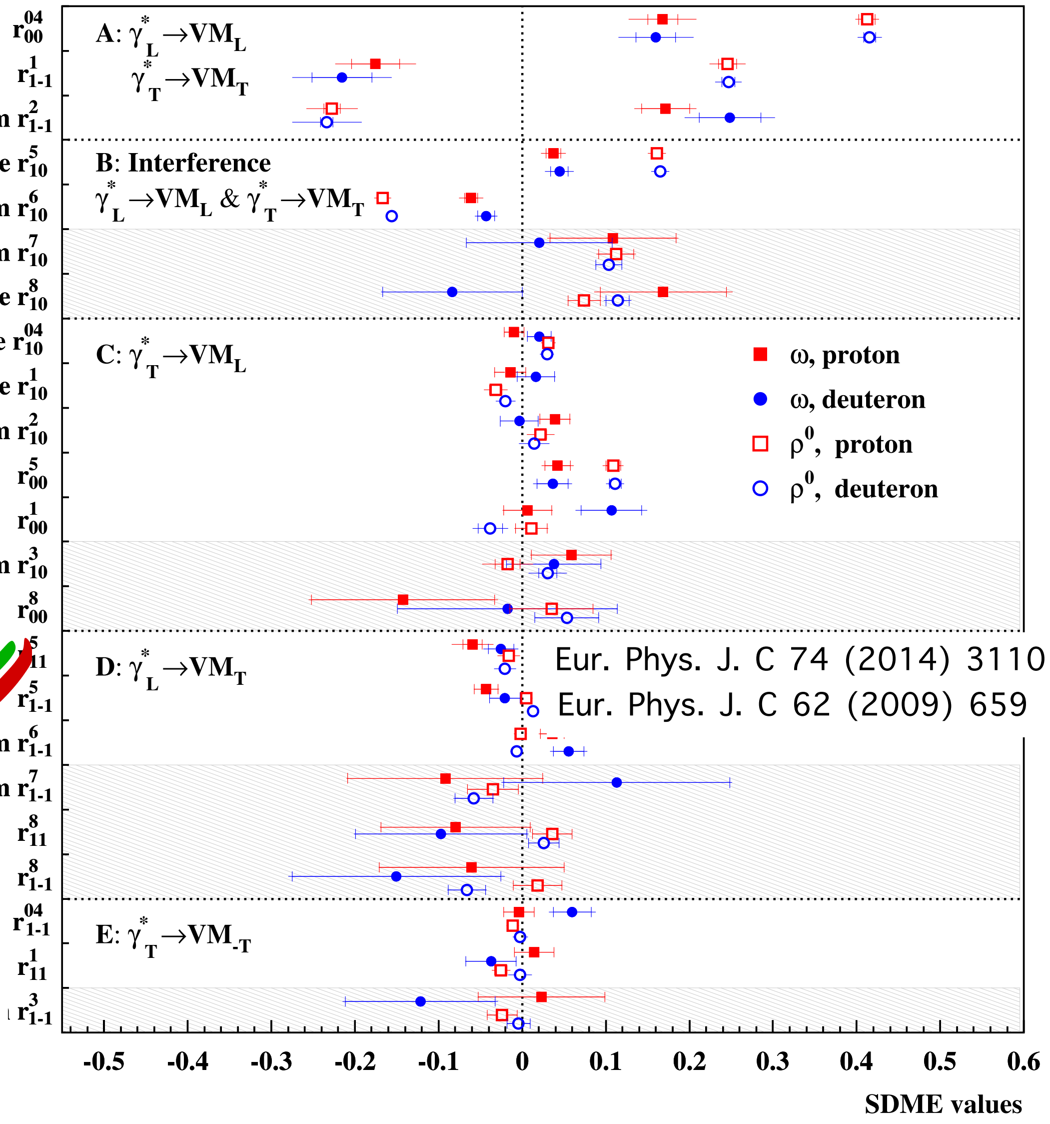

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Eur. Phys. J. C 62 (2009) 659