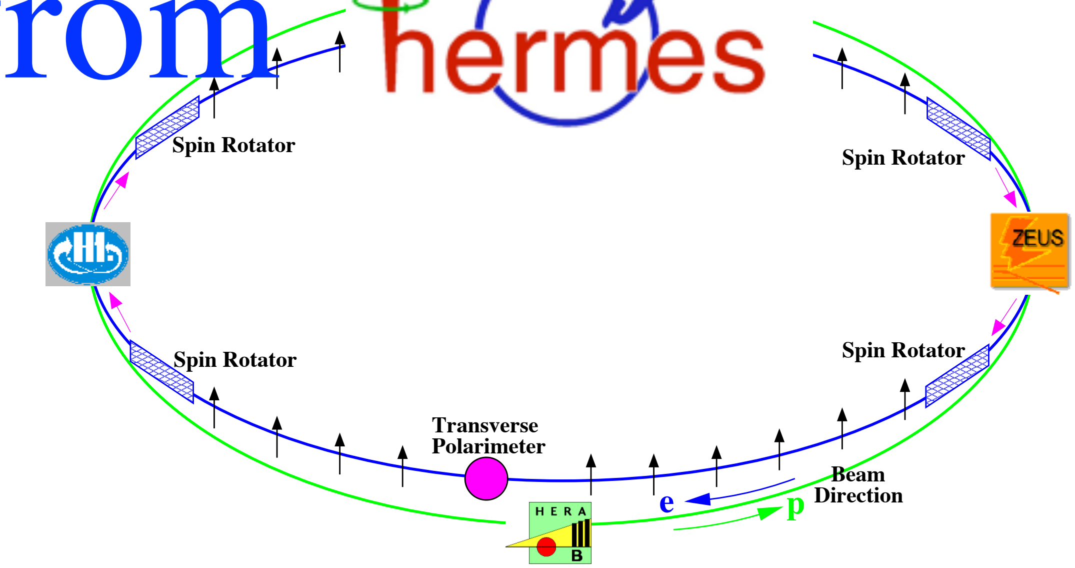
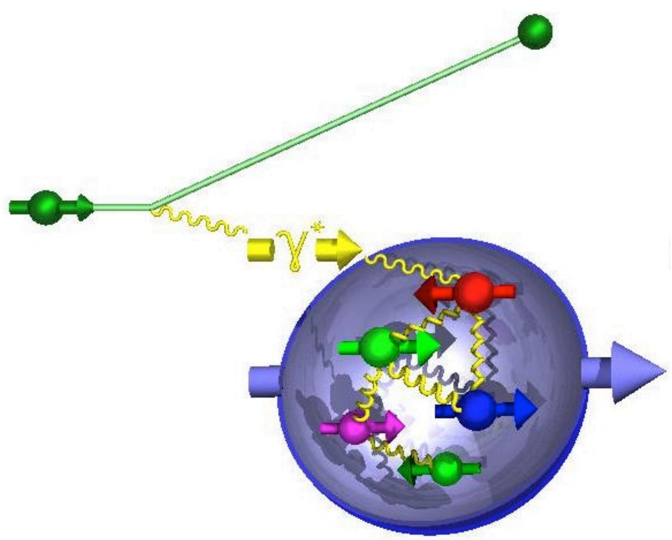
Recent results from hermes



Ami Rostomyan
(for the HERMES collaboration)

spin and hadronization



HERMES main research topics:

- ✓ **origin of nucleon spin**
  - ☛ longitudinal spin/momentum structure
  - ☛ transverse spin/momentum structure
- ✓ **hadronization/fragmentation**

✓ nucleon properties (mass, charge, momentum, magnetic moment, spin...) should be explained by its constituents

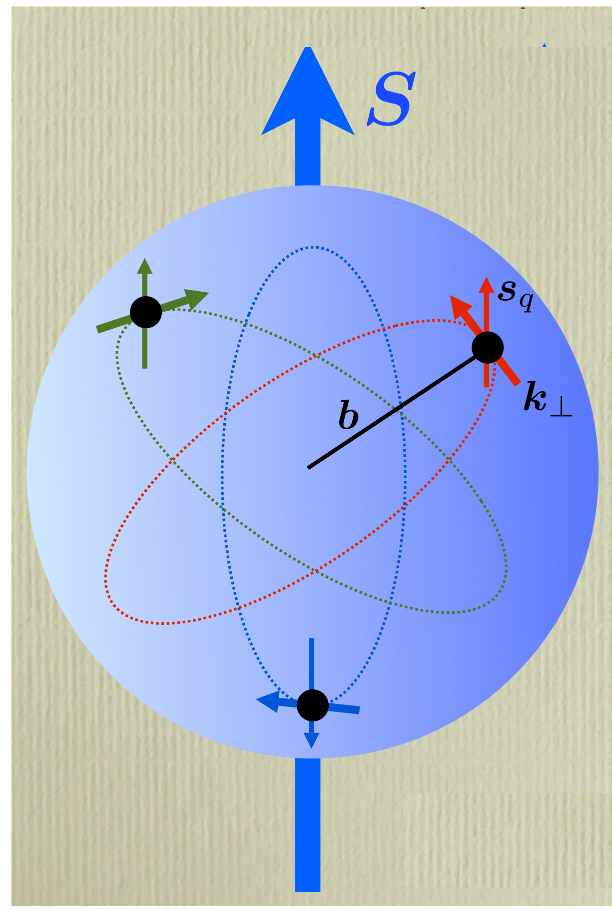
☛ momentum: quarks carry ~ 50 % of the proton momentum

☛ spin: total quark spin contribution only ~30%

quantum phase-space "tomography" of the nucleon

Wigner functions: $W^q(\mathbf{k}, \mathbf{b})$

probability to find a quark in a nucleon with a certain polarization in a position **b** and momentum **k**



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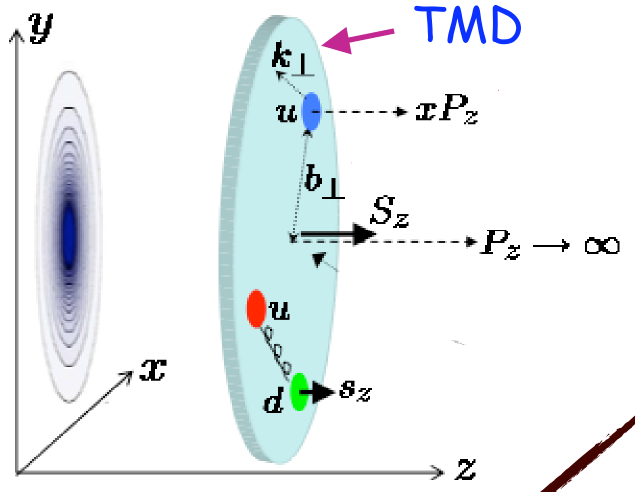
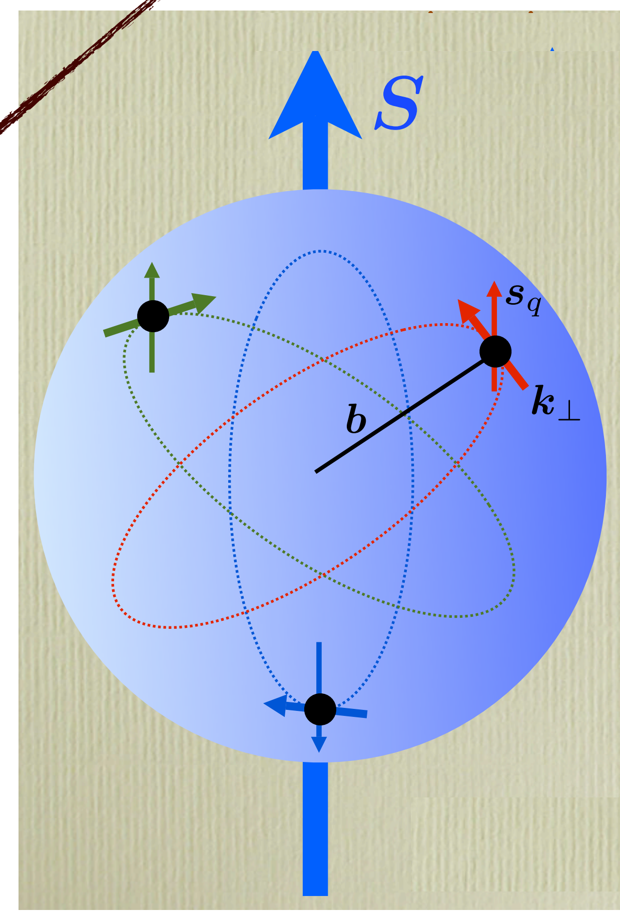


$\int d^3\mathbf{b}$

$q(x, \mathbf{k_T})$

Transverse Momentum Dependent
(**TMDs**) distribution functions (DF)



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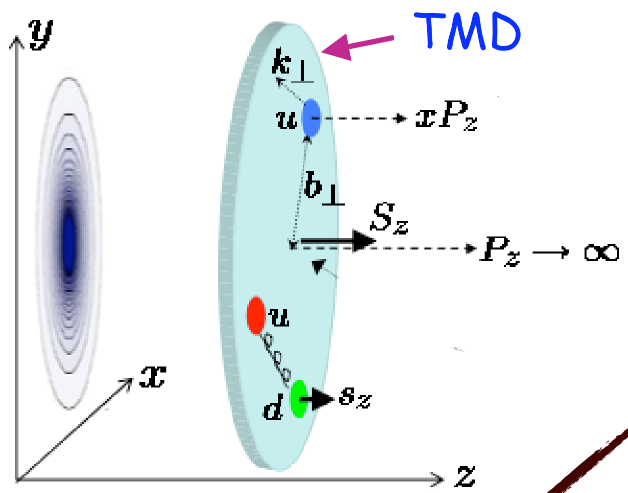

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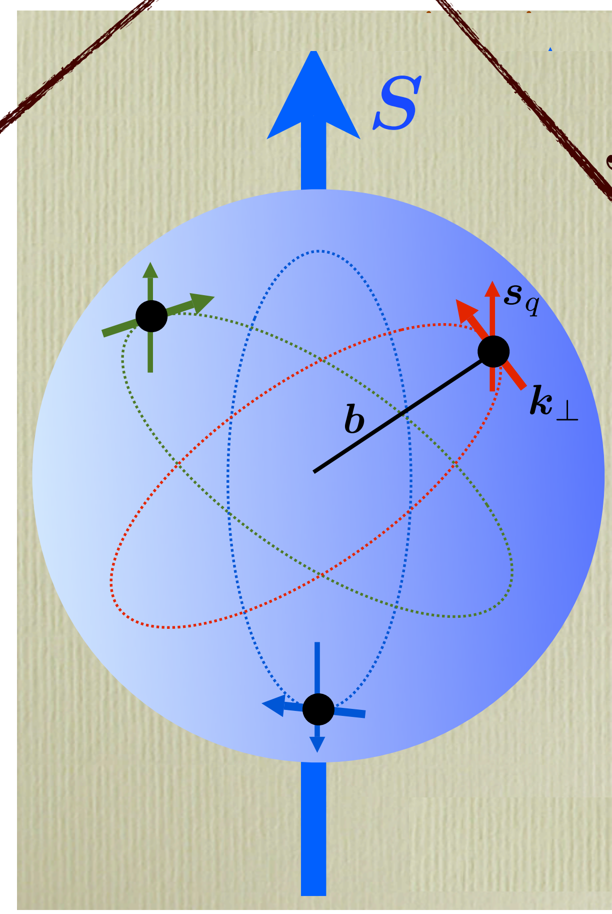
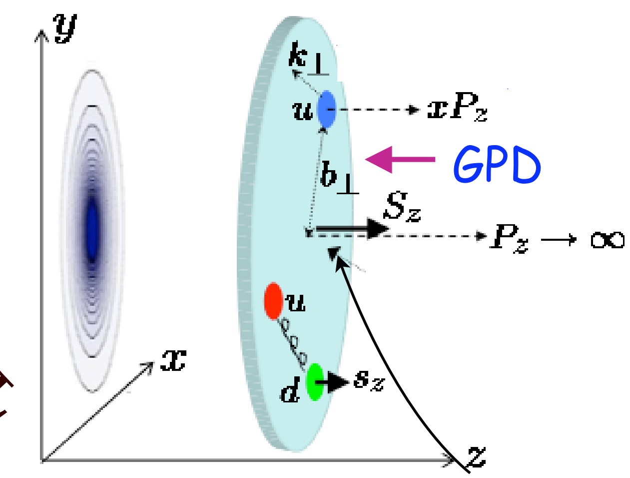


$\int d^2\mathbf{k_T}\, d\mathbf{b_L}$



center of momentum

$R_\perp = \sum x_i r_{\perp_i}$

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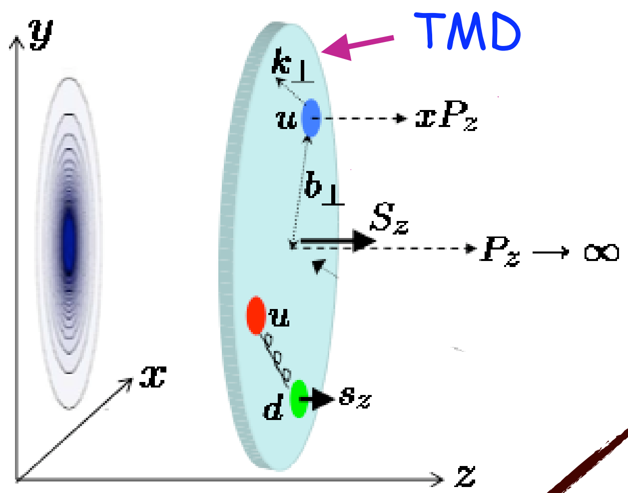

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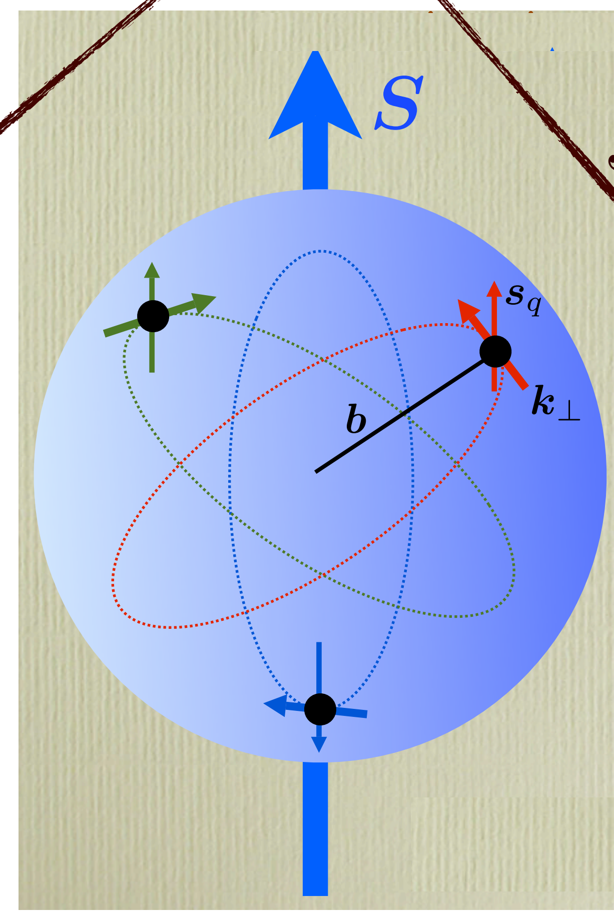

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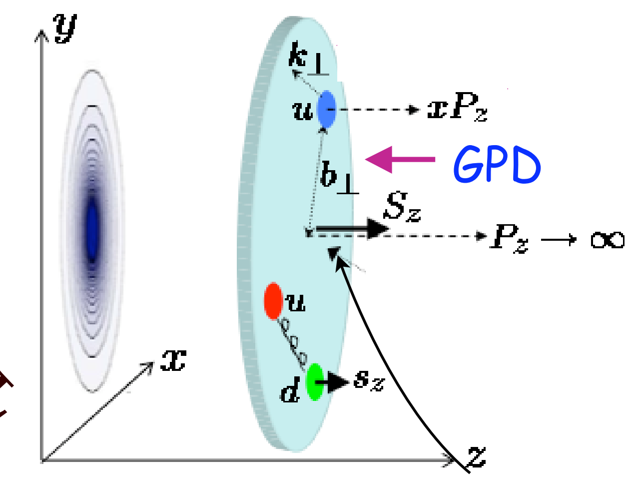

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transverse position dependent distribution functions

FT

$H(x, \xi, t)$

Generalized Parton Distributions **(GPDs)**

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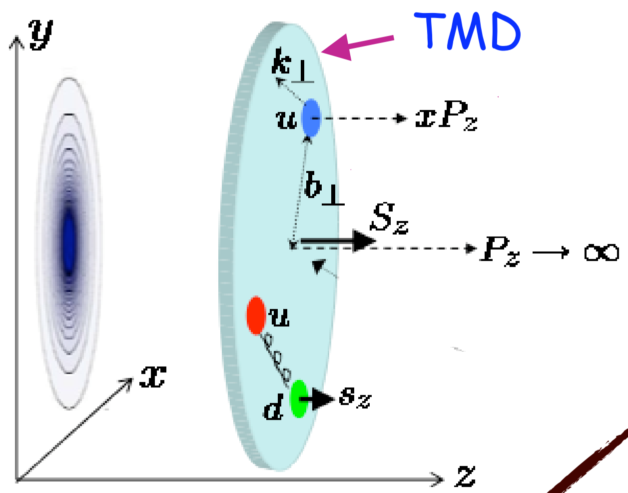

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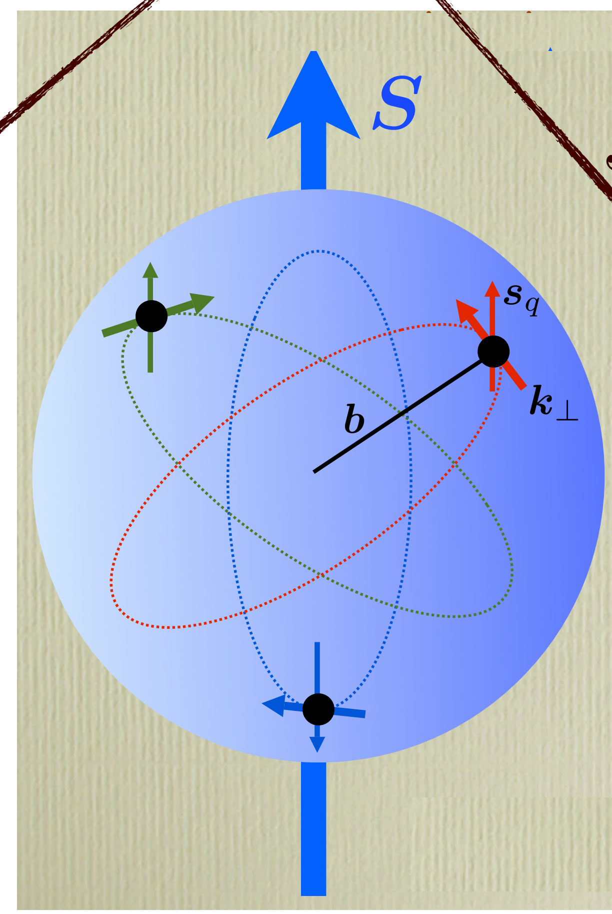

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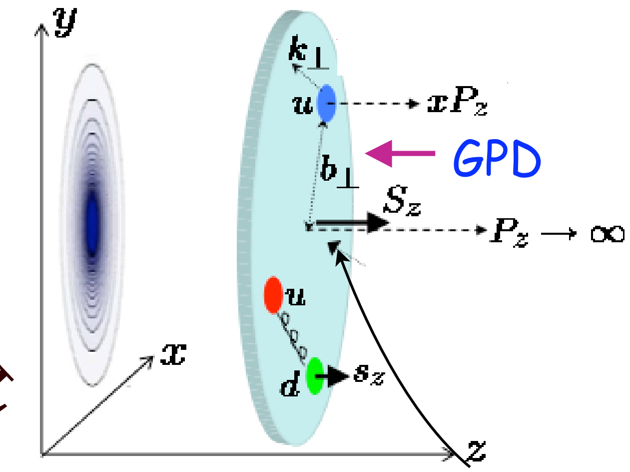

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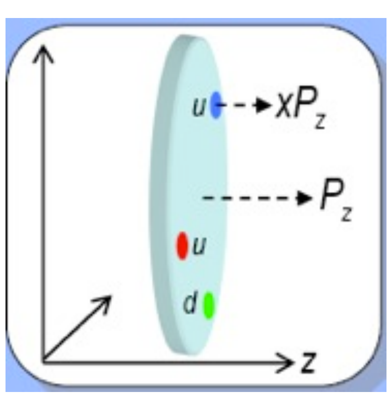
Generalized Parton Distributions (**GPDs**)

$\int d^2\mathbf{k_T}$

$\xi = 0,\ t = 0$

$f^q(x)$



Parton Distribution Functions **(PDFs)**

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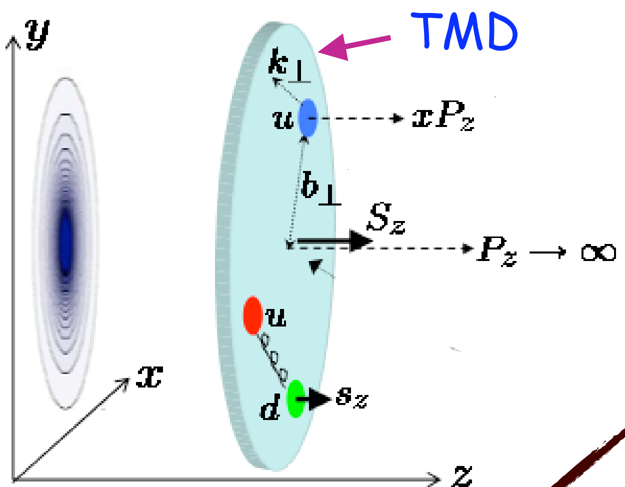

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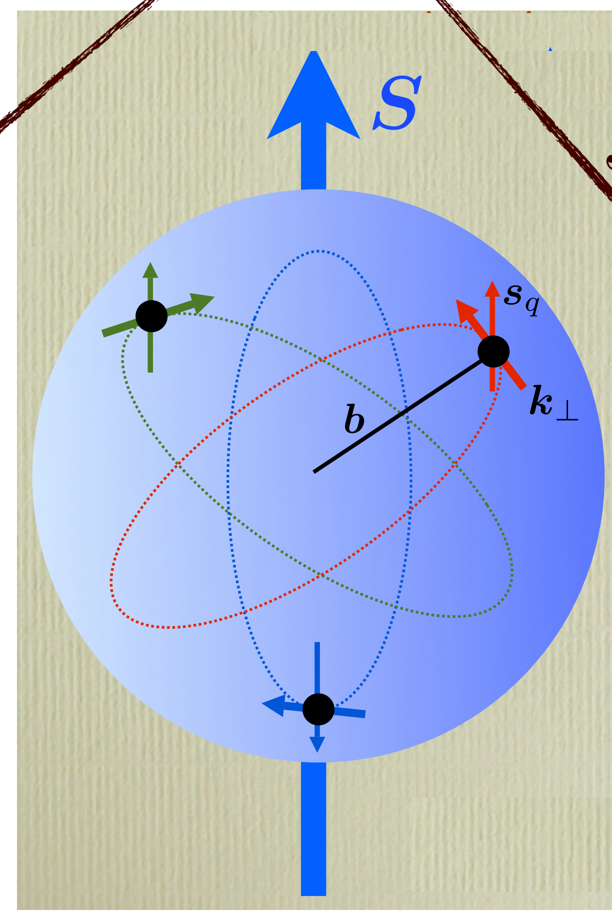

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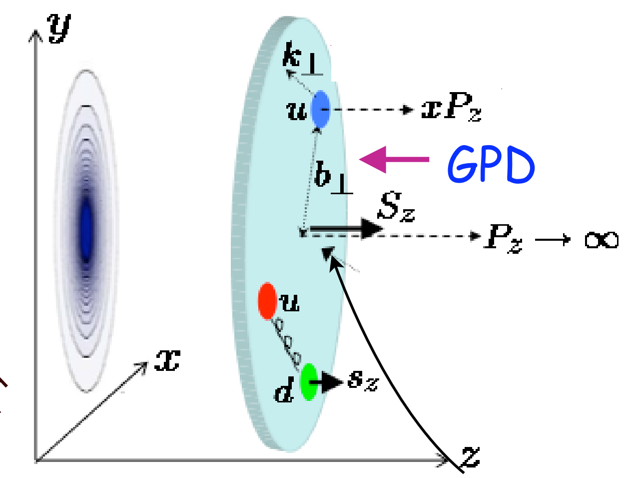

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☛**semi-inclusive measurements**

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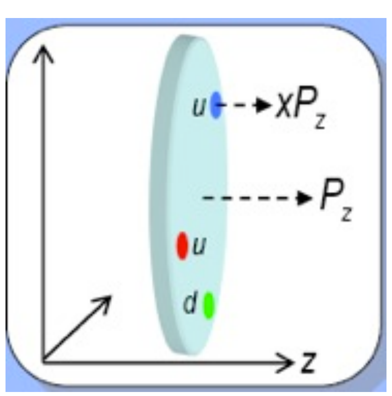

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Parton Distribution Functions (**PDFs**)

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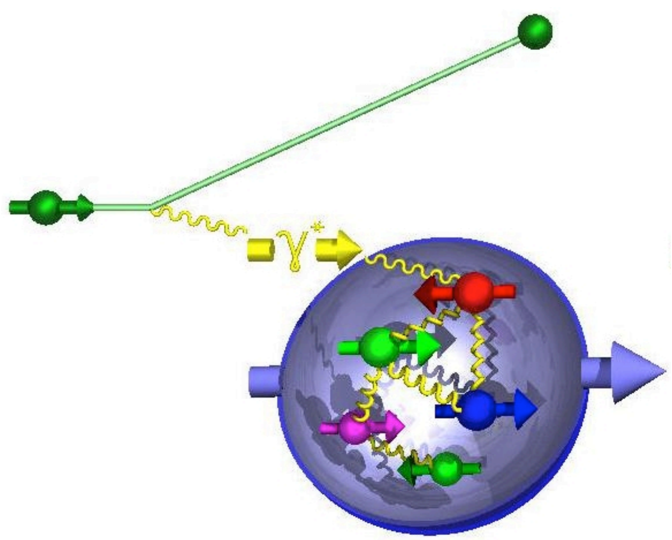
spin and hadronization



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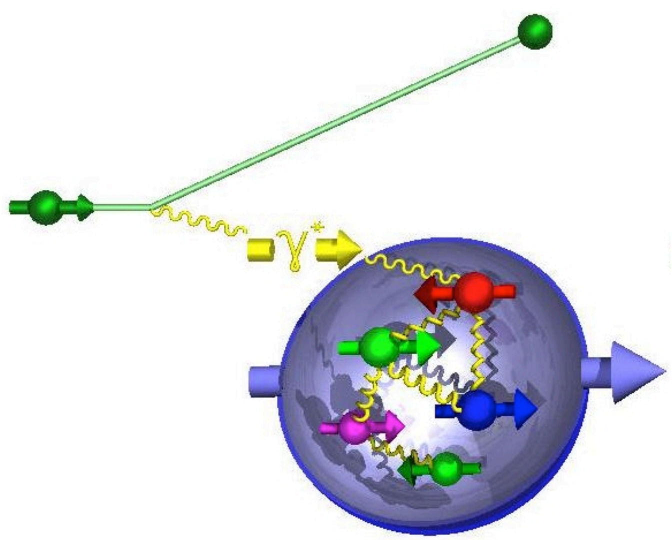

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➡ **study of TMD DFs and GPDs**

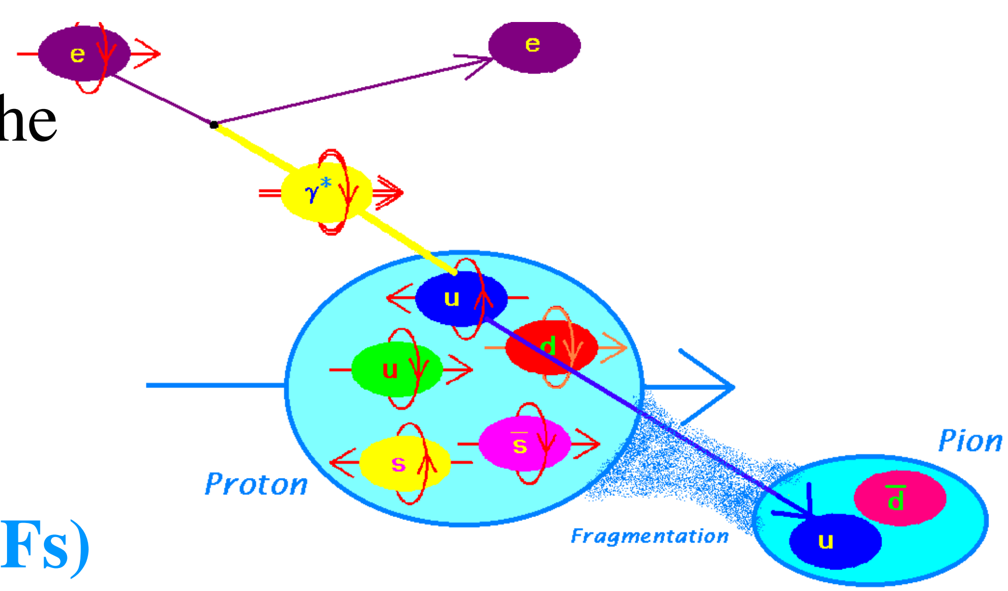
✓ isolated quarks have never been observed in nature

✓ fragmentation functions were introduced to describe the hadronization

☛ non-pQCD objects

☛ universal but not well known functions

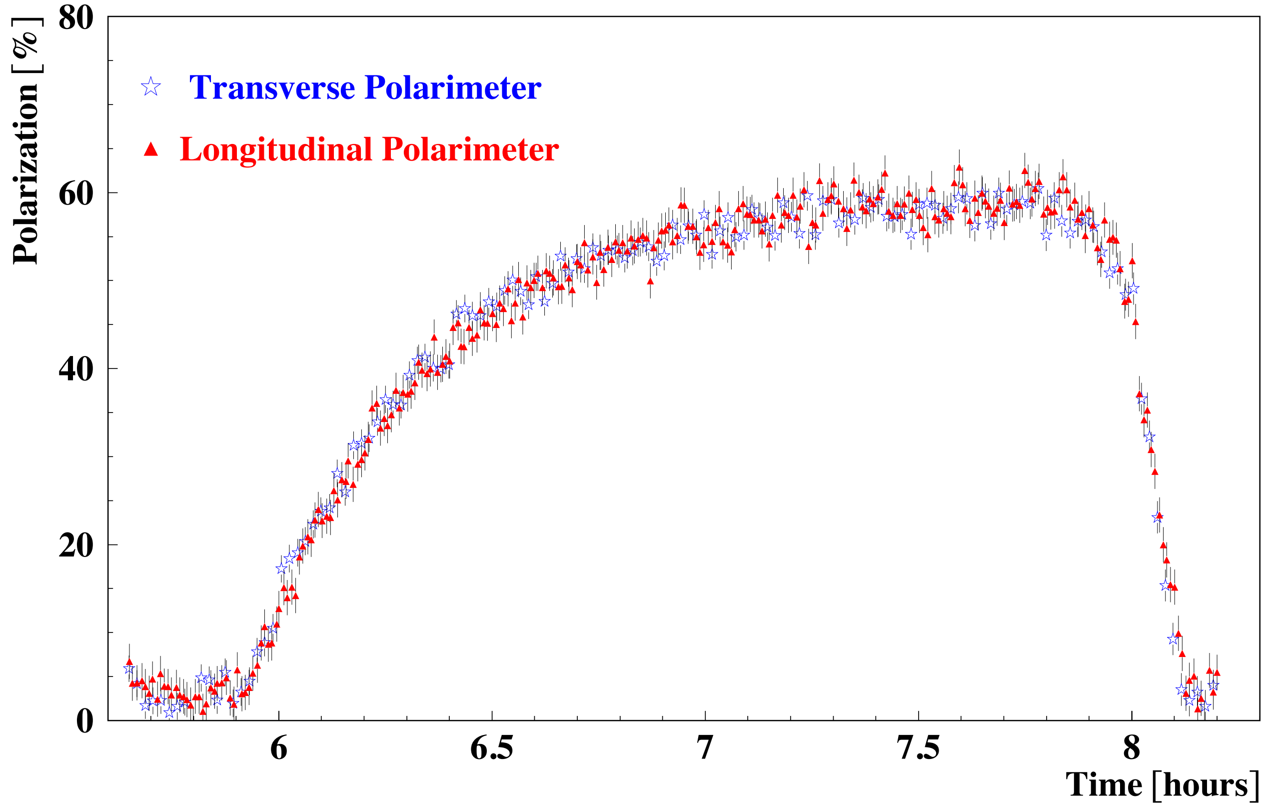
➡ **advantage of lepton-nucleon scattering data → flavour separation of fragmentation functions (FFs)**



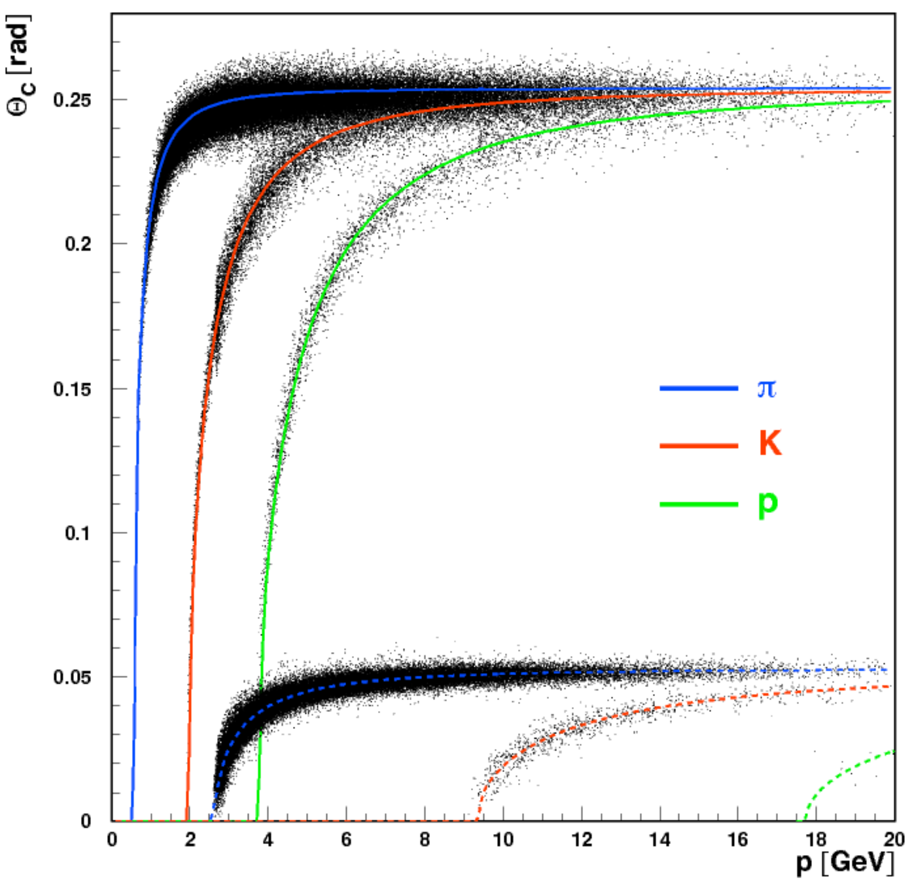
advantages of the experiment

The HERMES experiment, located at HERA, with its pure gas targets and advanced particle identification (π, K, p) is well suited for TMD and GPD measurements.

self-polarized e^+/e^- beam



hadron identification with RICH detector



- **longitudinal** target polarization (H, D, ^{3}He)
- **transverse** target polarization (H)
- **unpolarized** targets: H, D, ^{4}He, ^{14}N, ^{20}Ne, ^{84}Kr, ^{131}Xe
- **unpolarized** H, D targets with **recoil detector**

semi-inclusive measurements (probing TMDs)

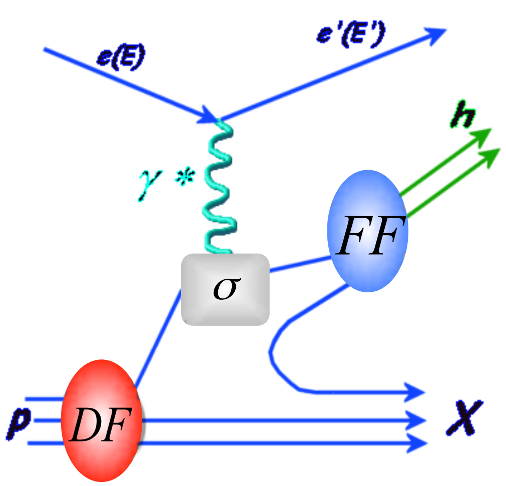
semi-inclusive DIS cross section and TMDs

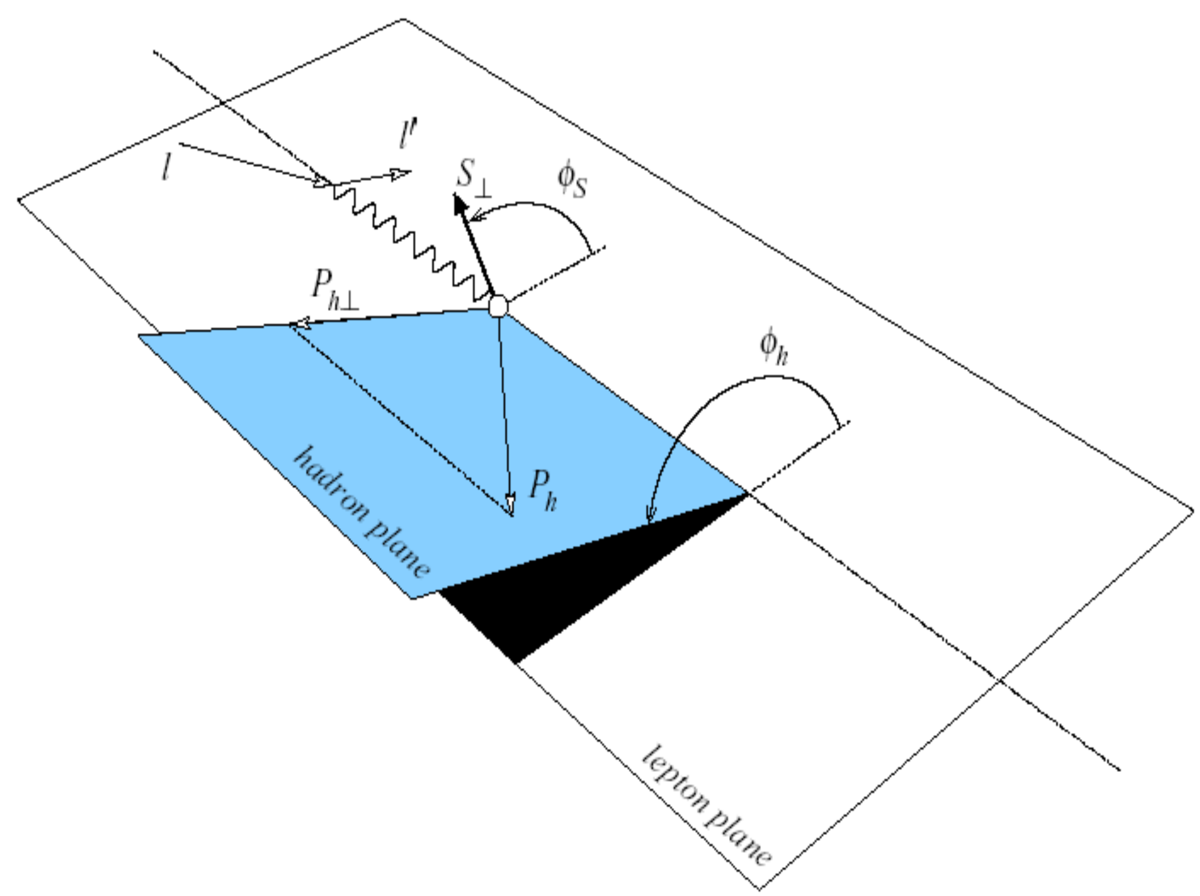
F_{XY}

beam	target
λ_e	$S_\perp, S_{\|\|}$

$$\frac{d^4\sigma}{dx\, dy\, dz\, d\phi_s} \propto F_{UU} + S_{||}\lambda_e\sqrt{1-\epsilon^2}F_{LL} + S_\perp\left\{\ldots\right\}$$

F_{UU}: $f_1 \otimes D_1$





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beam: λ_e — target: $S_\perp, S_{||}$

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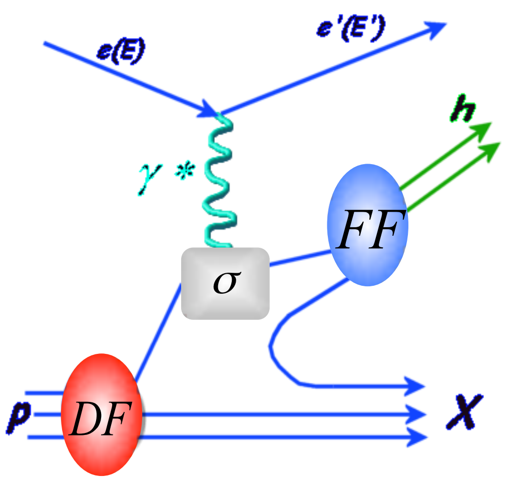
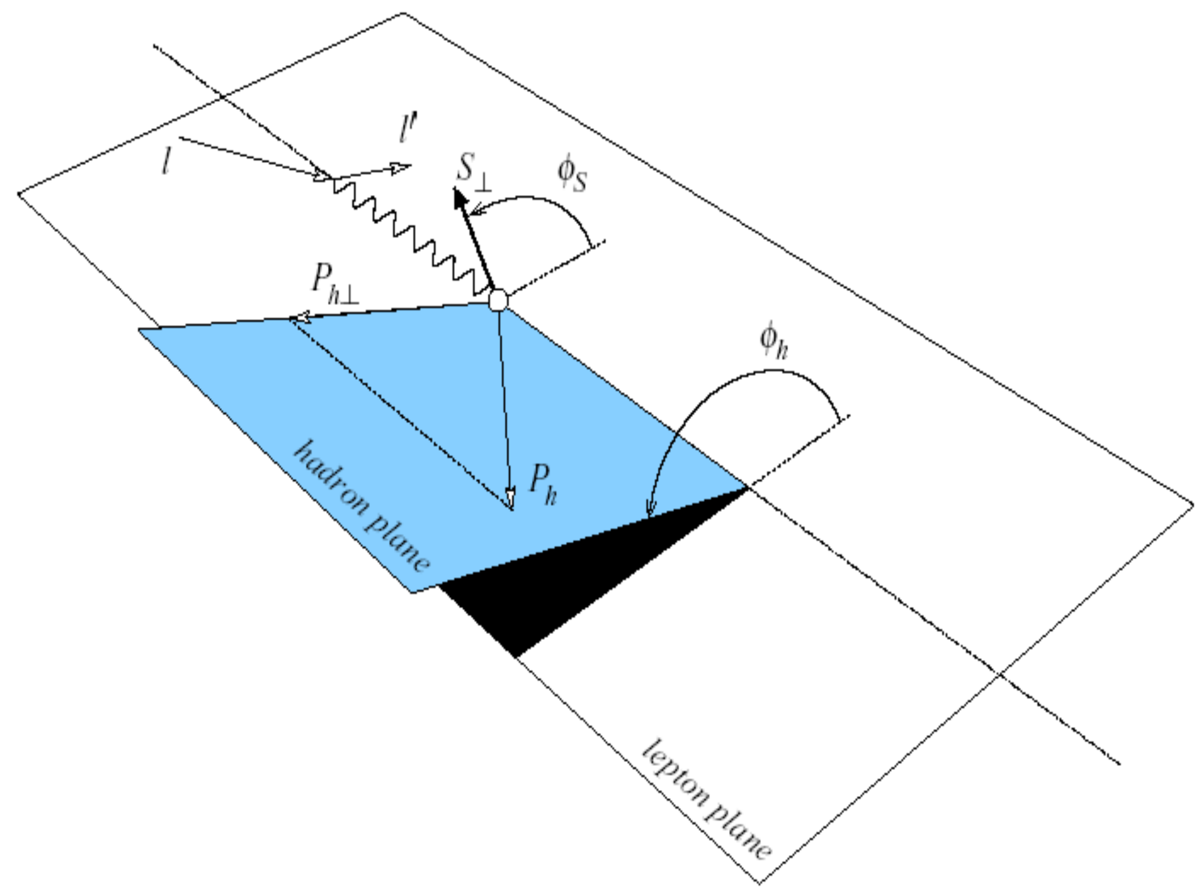
$$\frac{d^6\sigma}{dx\; dy\; dz\; dP^2_{h\perp}\, d\phi\; d\phi_s} \propto \left\{F_{UU} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi}\cos\phi + \epsilon\, F_{UU}^{\cos 2\phi}\cos 2\phi\right\}$$

$$+ \quad \lambda_e\left\{\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi\right\} + S_{||}\left\{\ldots\right\} + S_\perp\left\{\ldots\right\}$$





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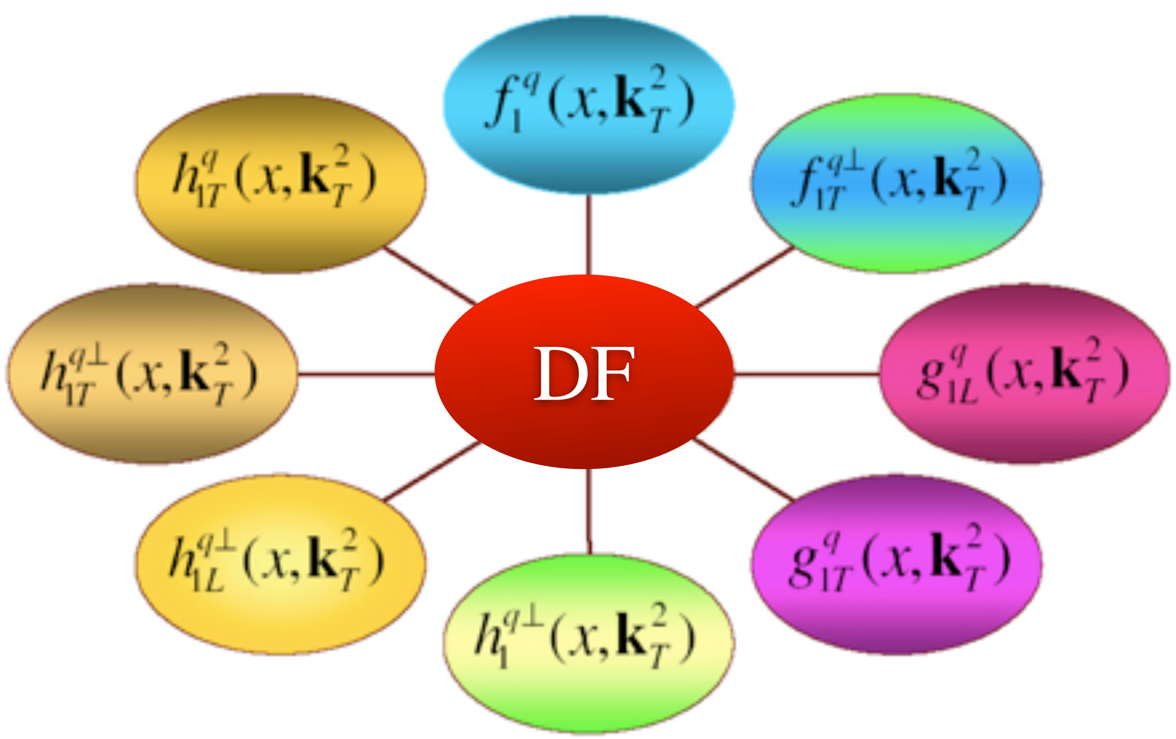
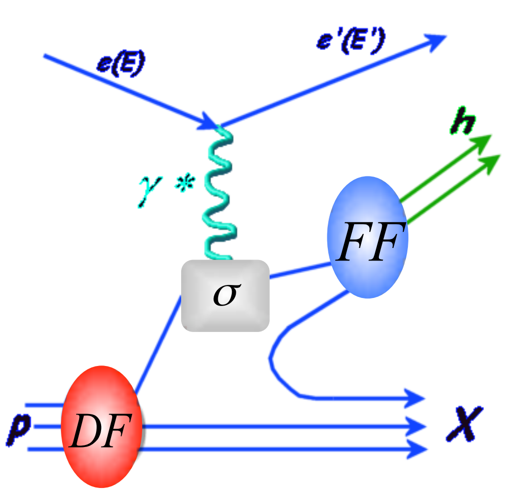
leading twist TMD DF:
parameterize the quark-flavor structure of the nucleon





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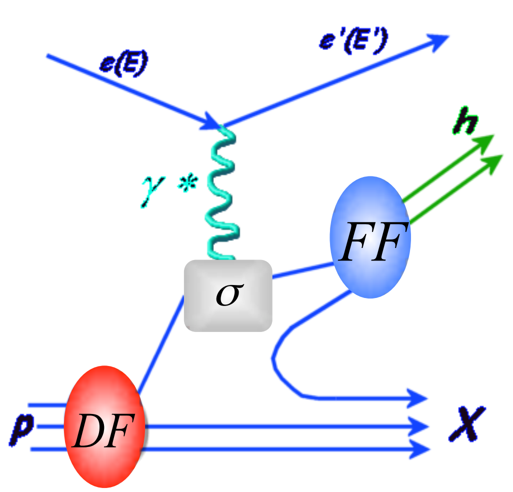
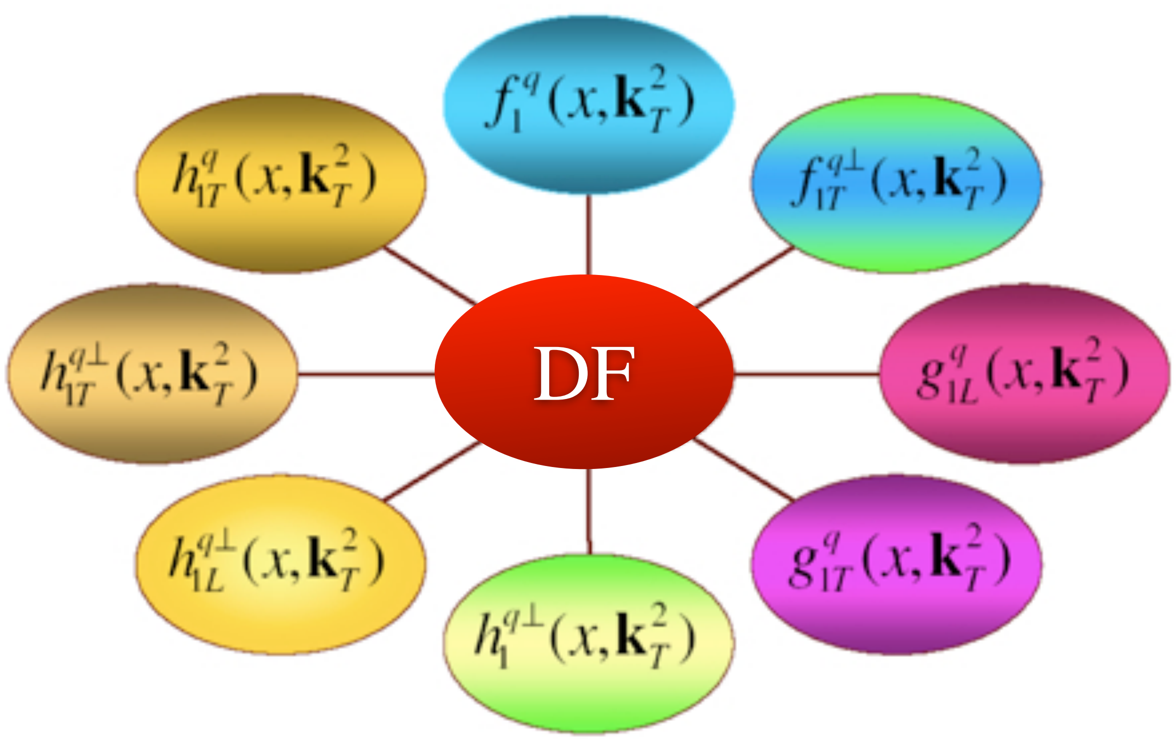
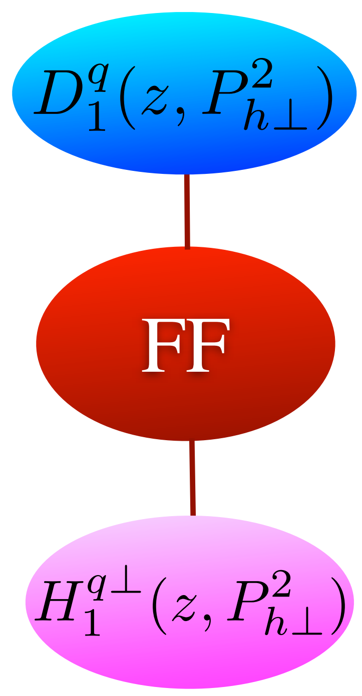
leading twist TMD FF:
number densities for the conversion of a quark of a certain type to a specific hadron







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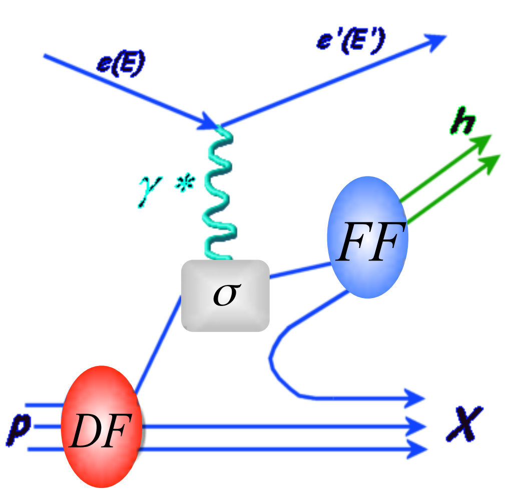

JHEP 05 (2011) 126

PRL 94 (2005) 012002
PLB 693 (2010) 11

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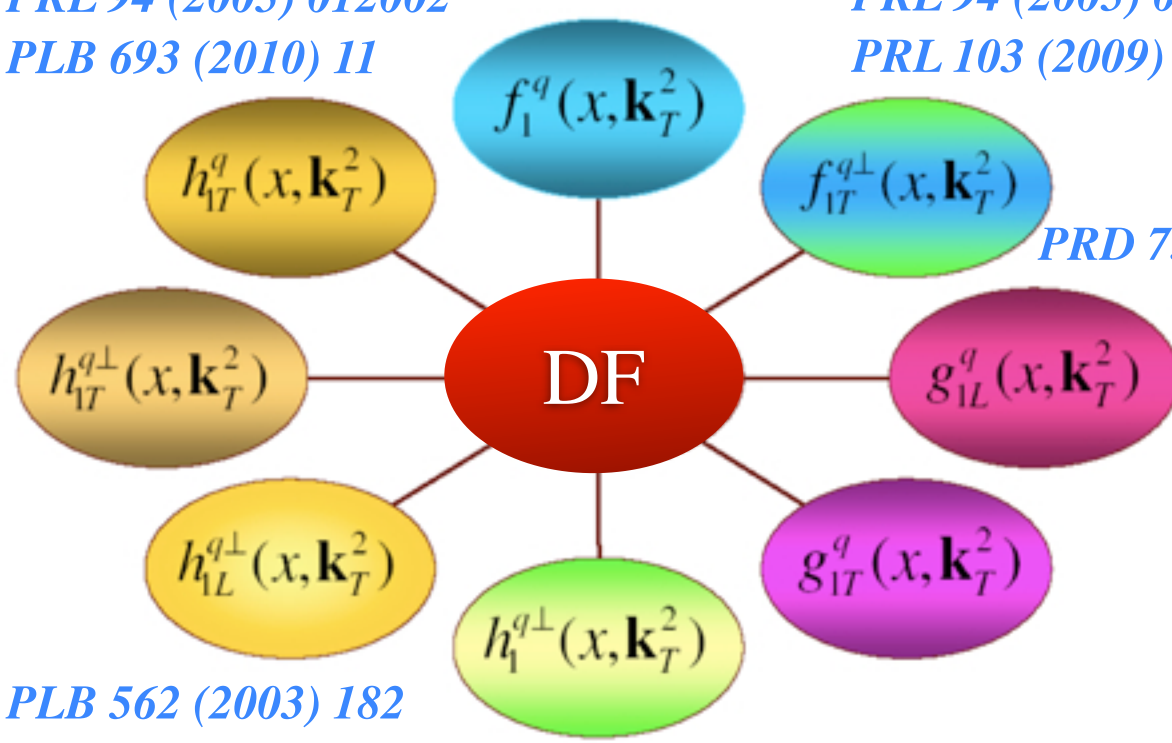
PRL 103 (2009) 152002

PRD 75 (2007) 012007



PLB 562 (2003) 182
PRL 84 (2000) 4047

PRD87 (2013) 012010

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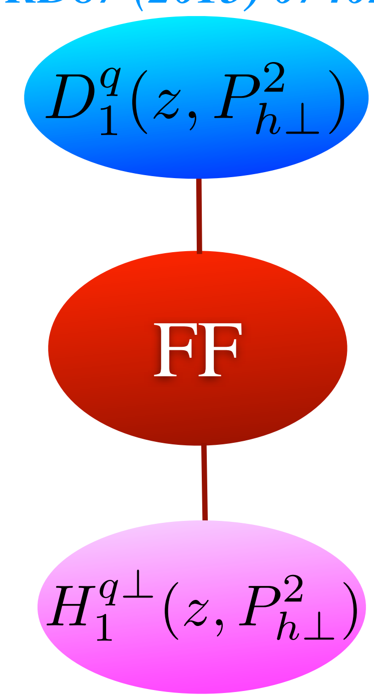

PRD87 (2013) 012010

HERMES: access to all TMDs thanks to the polarized beam and target

semi-inclusive DIS cross section and TMDs

$f_1 \otimes D_1$ twist-3 $h_1^\perp \otimes H_1^\perp$

$$\frac{d^6\sigma}{dx\, dy\, dz\, dP_{h\perp}^2\, d\phi\, d\phi_s} \propto \left\{ F_{UU} + \sqrt{2\epsilon(1+\epsilon)}\, F_{UU}^{\cos\phi} \cos\phi + \epsilon\, F_{UU}^{\cos 2\phi} \cos 2\phi \right\}$$

$$+ \quad \lambda_e \left\{ \sqrt{2\epsilon(1-\epsilon)}\, F_{UL}^{\sin\phi} \sin\phi \right\} + S_{||}\left\{ \dots \right\} + S_\perp \left\{ \dots \right\} + \dots$$

twist-3

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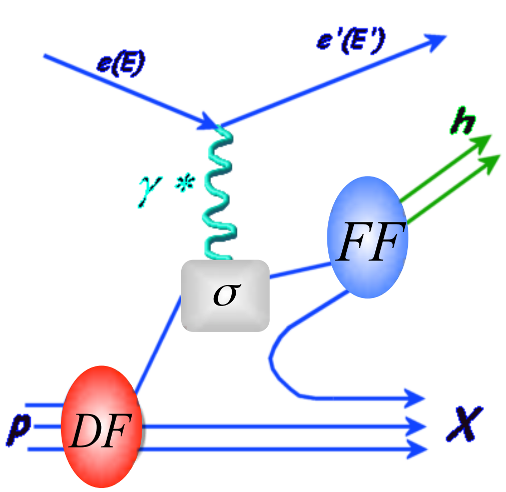

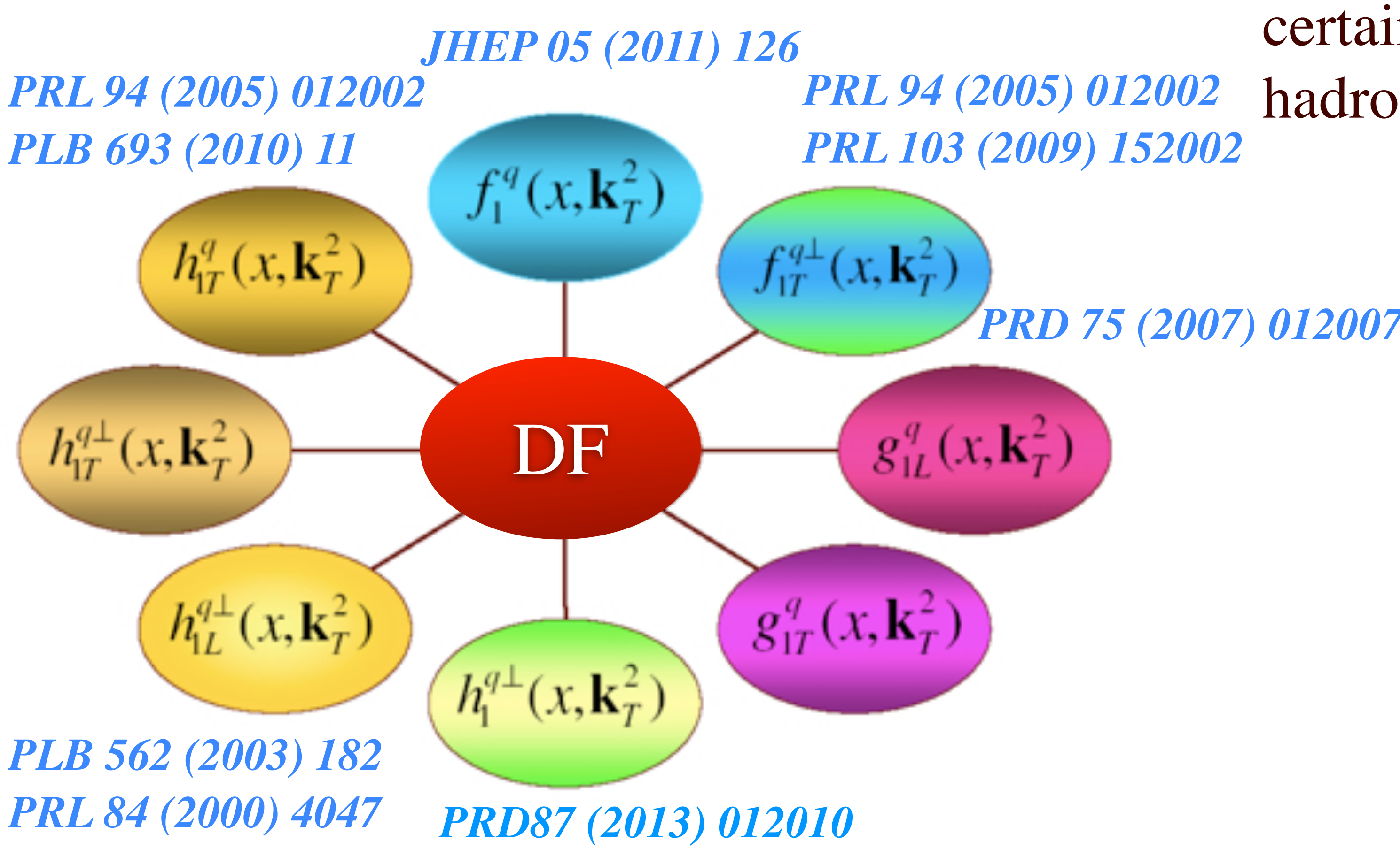

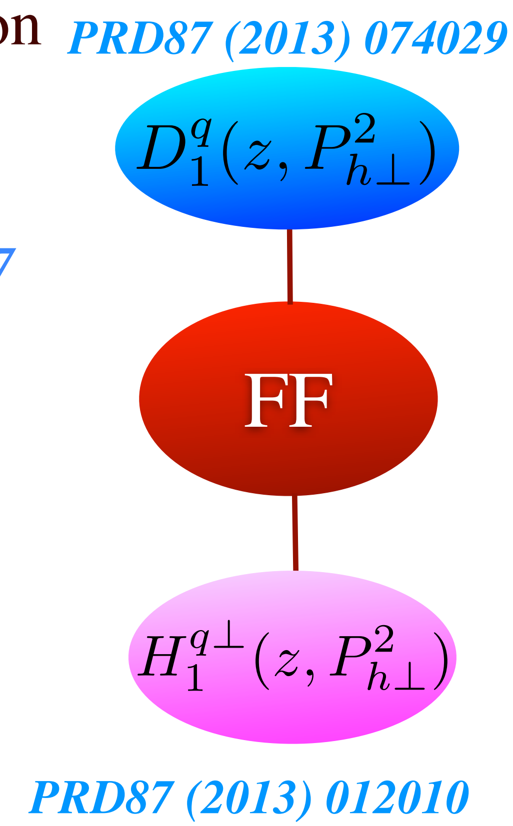

HERMES: access to all TMDs thanks to the polarized beam and target

unpolarized quarks

$$\sigma_{UU} \propto f_1 \otimes D_1$$

$$f_1 =$$ 

unpolarized quarks

$$\sigma_{UU} \propto f_1 \otimes D_1$$

$f_1 =$ 

$$M^h = \frac{d\sigma^h_{SIDIS}(x, Q^2, z, P_{h\perp})}{d\sigma_{DIS}(x, Q^2)}$$

unpolarized quarks

$$\sigma_{UU} \propto f_1 \otimes D_1$$

$$f_1 =$$ 

LO interpretation of multiplicity results (integrated over $\mathbf{P}_{h\perp}$):

$$M^h \propto \frac{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2)}$$

$$M^h = \frac{d\sigma^h_{SIDIS}(x,Q^2,z,P_{h\perp})}{d\sigma_{DIS}(x,Q^2)}$$

✓charge-separated multiplicities of pions and kaons sensitive to the individual quark and antiquark flavours in the fragmentation process

unpolarized quarks

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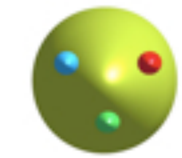
$$f_1 =$$ 

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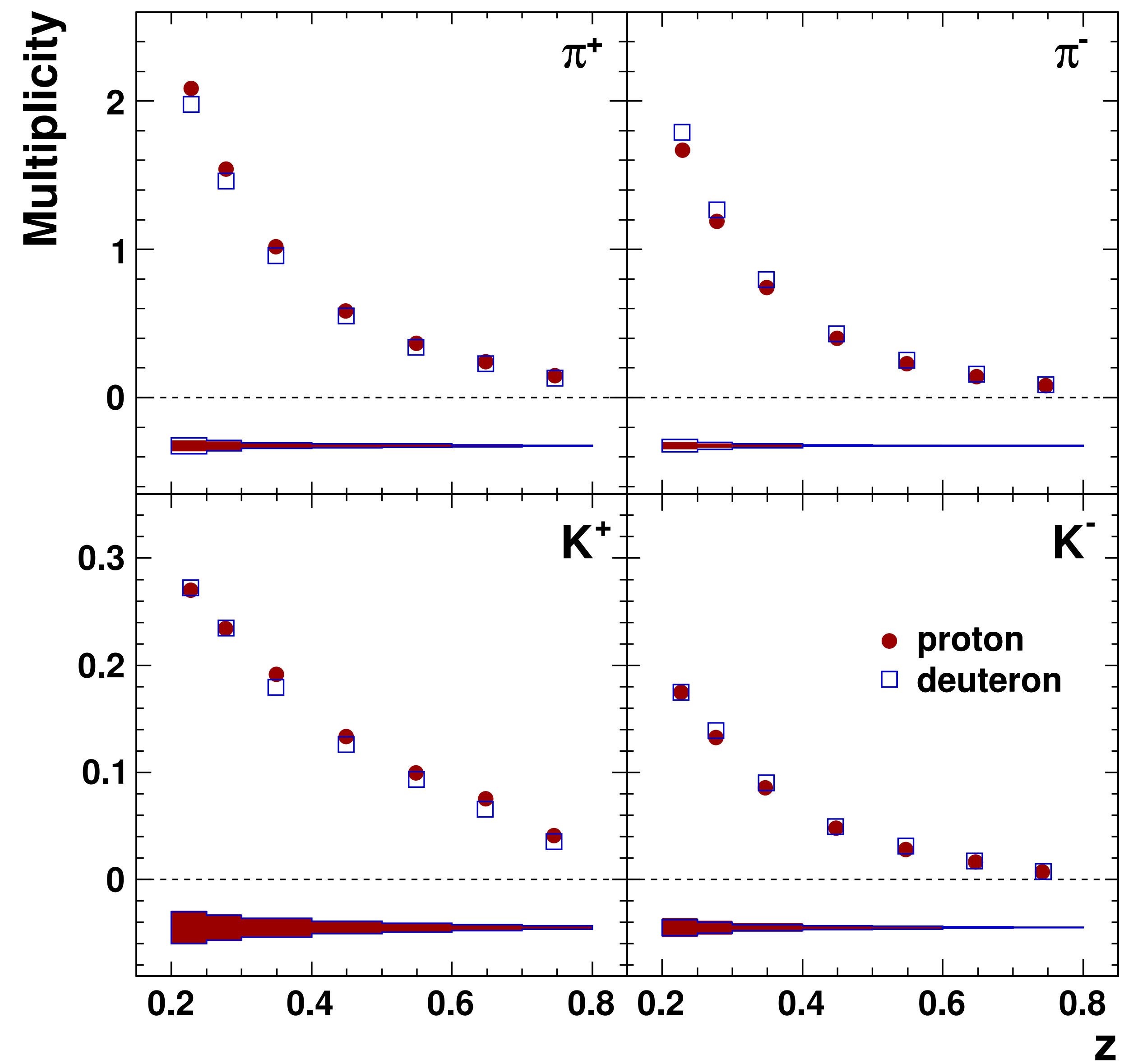
Phys. Rev. D87 (2013) 074029



π+ and K+:

☛ favoured fragmentation on proton

π-:

☛ increased number of d-quarks in D target and favoured fragmentation on neutron

K-:

☛ cannot be produced through favoured fragmentation from the nucleon valence quarks

unpolarized quarks

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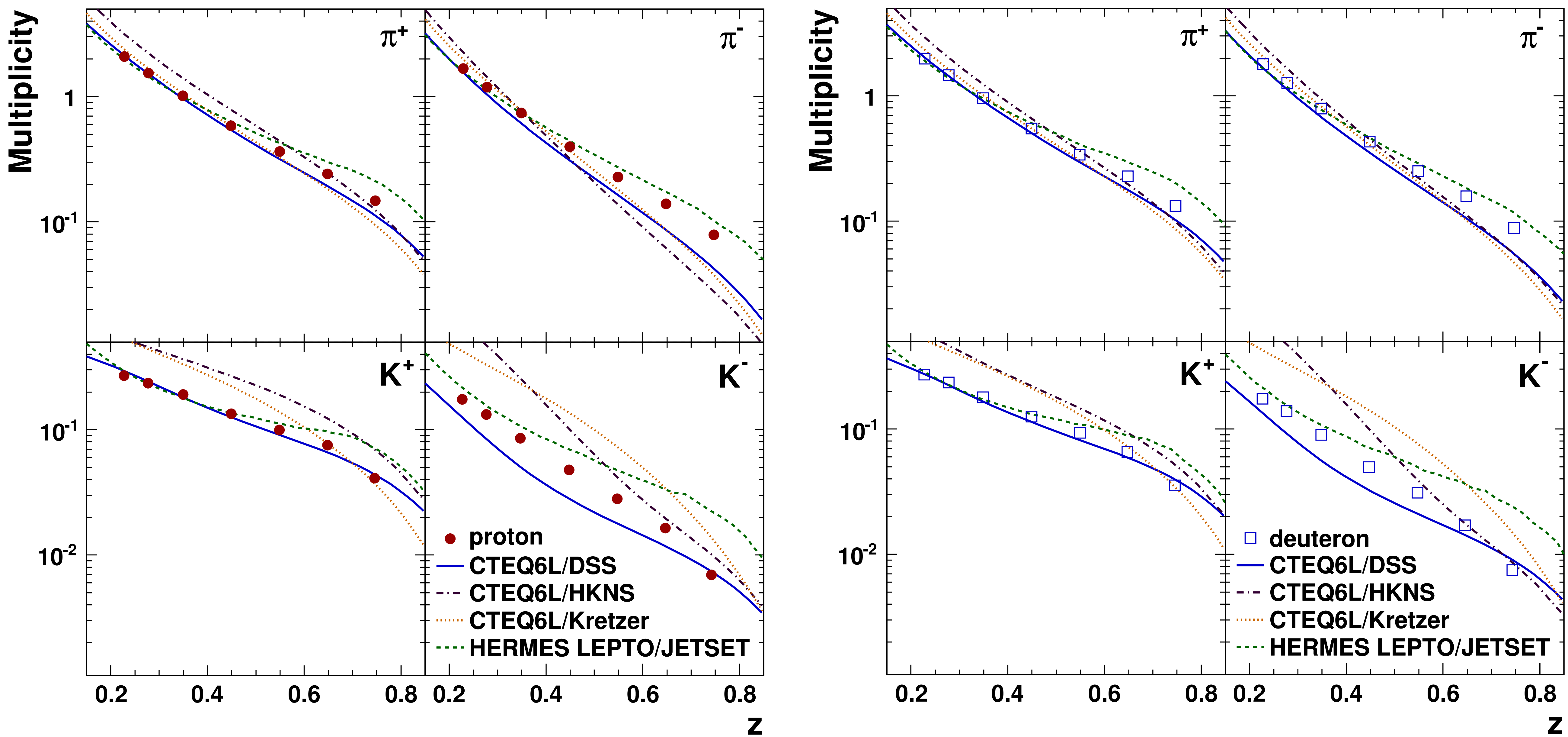
Phys.Rev. D87 (2013) 074029

$$\sigma_{UU} \propto f_1 \otimes D_1$$



✓calculations using DSS, HNKS and Kretzer FF fits together with CTEQ6L PDFs

proton:

- fair agreement for positive hadrons
- disagreement for negative hadrons

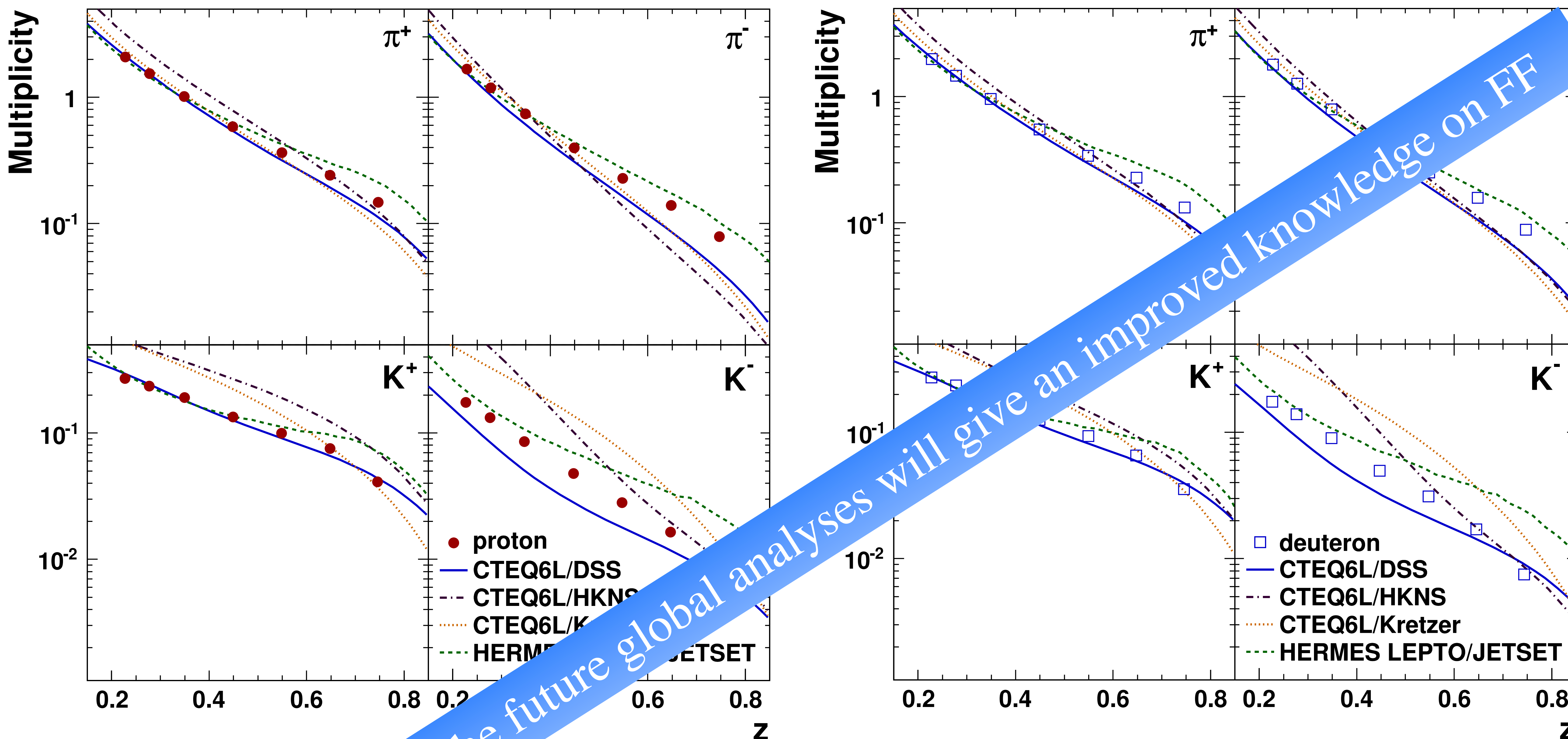
deuteron:

- results are in general in better agreement with the various predictions

unpolarized quarks

- HERMES Collaboration-
Phys.Rev. D87 (2013) 074029

$$\sigma_{UU} \propto f_1 \otimes D_1$$



✓ inclusion of the data in the future global analyses will give an improved knowledge on FF

✓calculations using D... KS and Kretzer FF fits together with CTEQ6L PDFs

proton:

- fai... nt for positive hadrons
- ...ement for negative hadrons

d...

- results are in general in better agreement with the various predictions

evaluation of strange quark PDFs

✓ in the absence of experimental constraints, many global QCD fits of PDFs assume

$$s(x) = \bar{s}(x) = r[\bar{u}(x) + \bar{d}(x)]/2$$

✓ isoscalar extraction of $S(x)\mathcal{D}_{\mathcal{S}}^{\mathcal{K}}$ based on the multiplicity data of K$^+$ and K$^-$ on D

$$S(x)\int \mathcal{D}_S^K(z)dz \simeq Q(x)\left[5\frac{\mathrm{d}^2N^K(x)}{\mathrm{d}^2N^{DIS}(x)} - \int \mathcal{D}_Q^K(z)dz\right]$$

$$\begin{aligned}
S(x) &= s(x) + \bar{s}(x) \\
Q(x) &= u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \\
\mathcal{D}_{\mathcal{S}}^{\mathcal{K}} &= D_1^{s\to K^+} + D_1^{\bar{s}\to K^+} + D_1^{s\to K^-} + D_1^{\bar{s}\to K^-} \\
\mathcal{D}_{\mathcal{Q}}^{\mathcal{K}} &= D_1^{u\to K^+} + D_1^{\bar{u}\to K^+} + D_1^{d\to K^+} + D_1^{\bar{d}\to K^+} + \ldots
\end{aligned}$$

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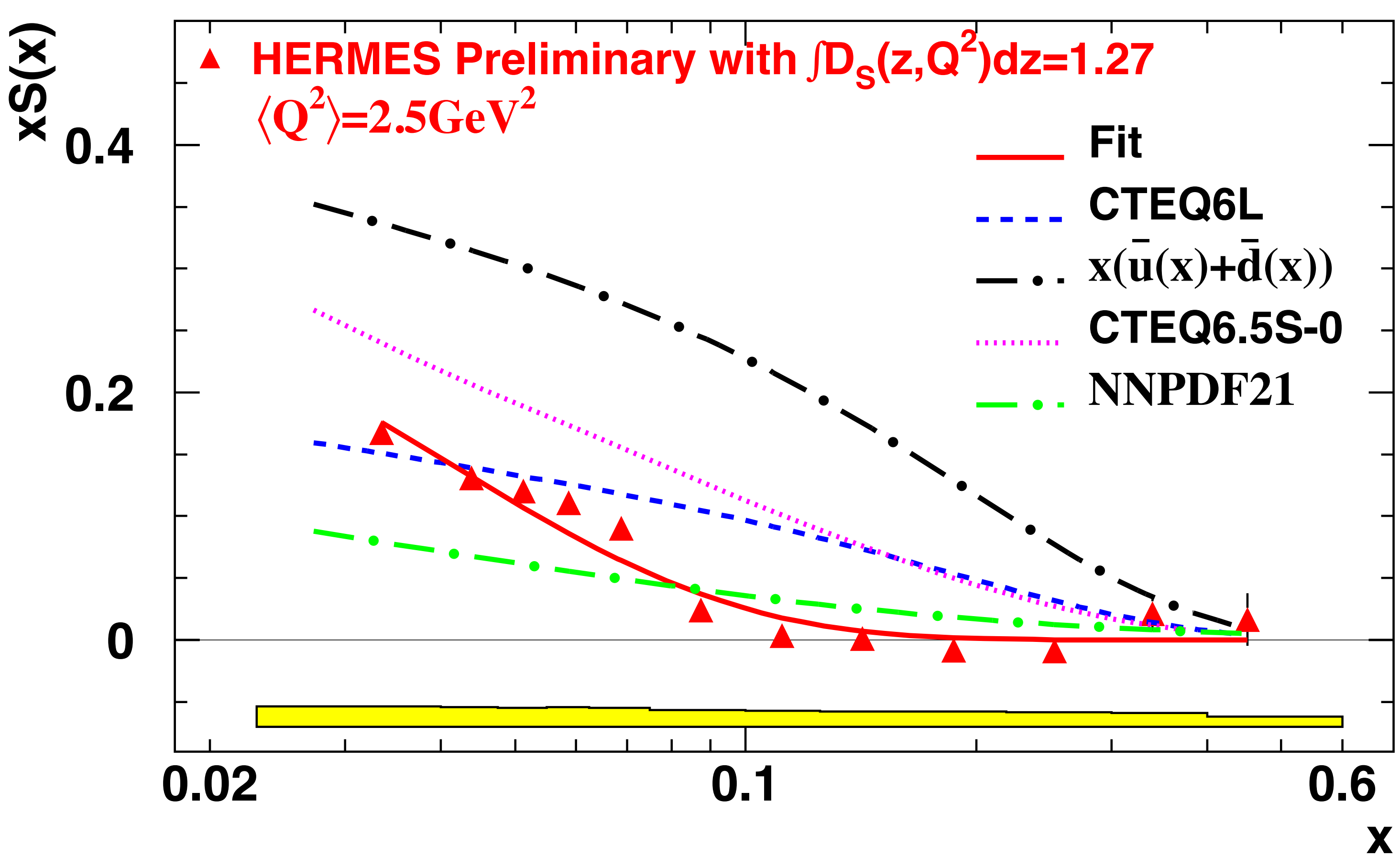
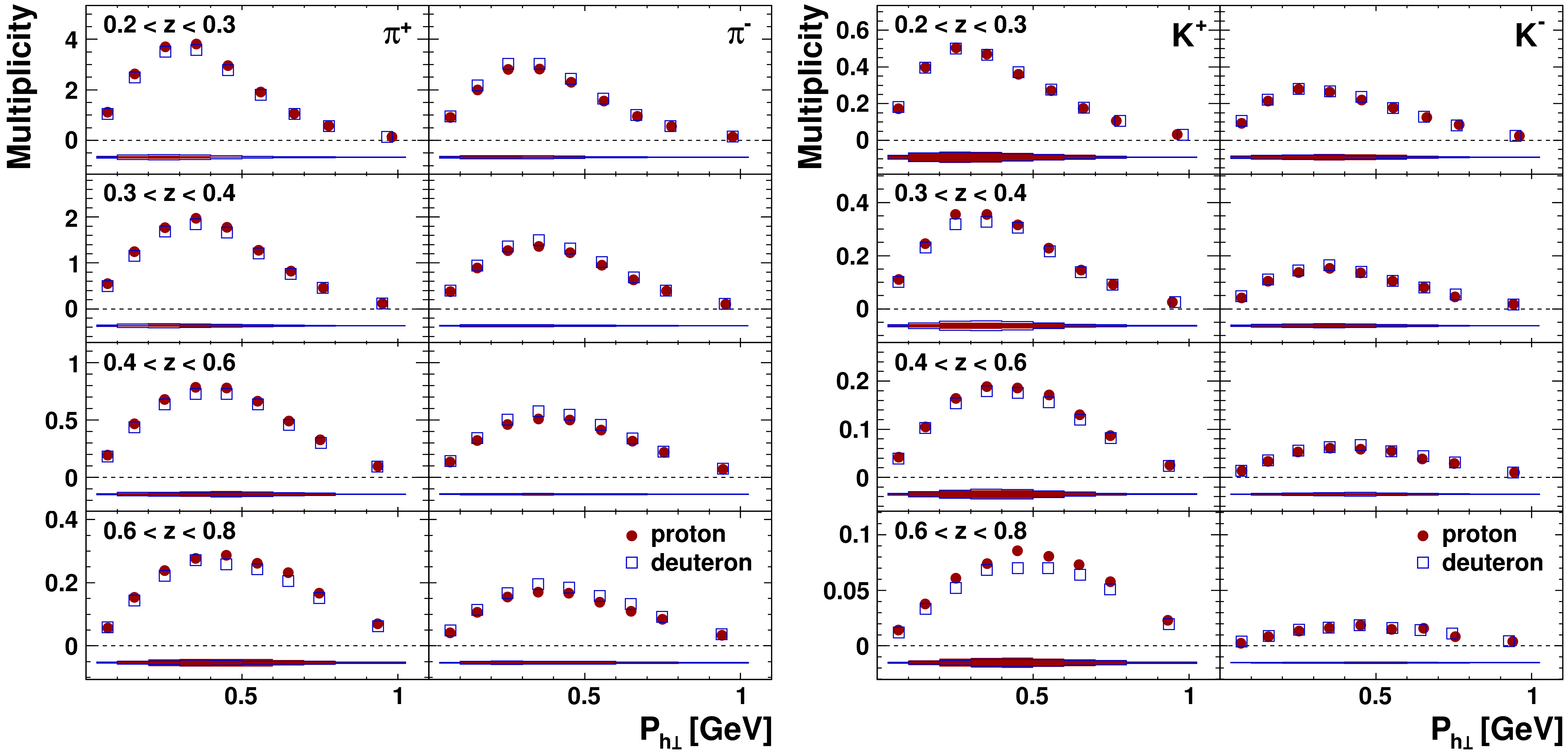
$$\begin{aligned} S(x) &= s(x) + \bar{s}(x) \\ Q(x) &= u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \\ \mathcal{D}_{\mathcal{S}}^{\mathcal{K}} &= D_1^{s\to K^+} + D_1^{\bar{s}\to K^+} + D_1^{s\to K^-} + D_1^{\bar{s}\to K^-} \\ \mathcal{D}_{\mathcal{Q}}^{\mathcal{K}} &= D_1^{u\to K^+} + D_1^{\bar{u}\to K^+} + D_1^{d\to K^+} + D_1^{\bar{d}\to K^+} + \ldots \end{aligned}$$



- the distribution of S(x) is obtained for a certain value of $\mathcal{D}_{\mathcal{S}}^{\mathcal{K}}$
- the normalization of the data is given by that value
- whatever the normalization, the shape is incompatible with the predictions

beyond the collinear factorization

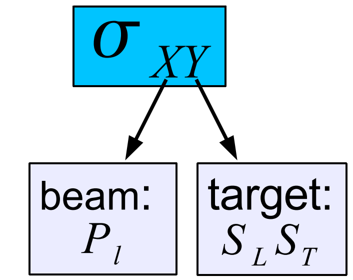
- HERMES Collaboration-
Phys.Rev. D87 (2013) 074029



✓ multi-dimensional analysis allows exploration of new kinematic dependences

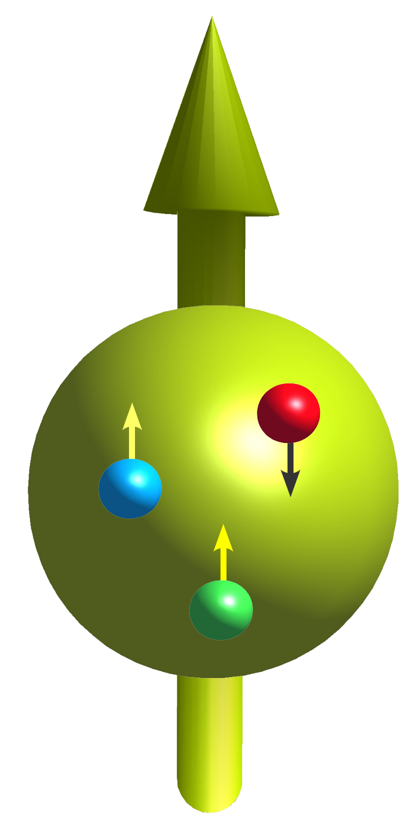
✓ broader $P_{h\perp}$ distribution for K^-

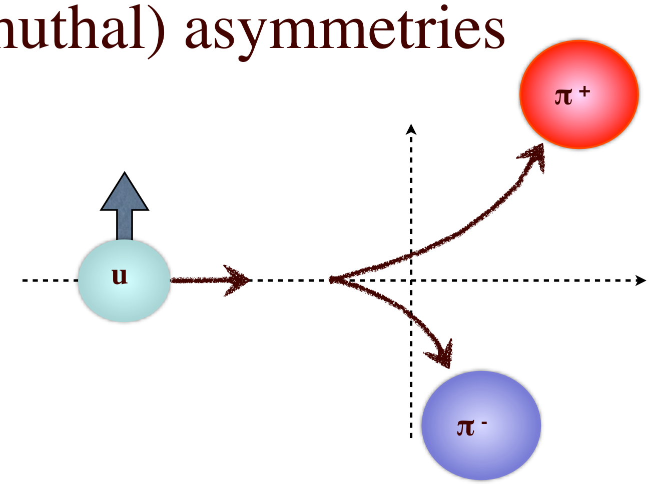
Collins effect



$$
\begin{aligned}
d\sigma \;=\;& d\sigma^0_{UU} + \cos(2\phi) d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi) d\sigma^2_{UU} + P_l \frac{1}{Q}\sin(\phi) d\sigma^3_{LU} \\
+\;& S_L\left[\sin(2\phi) d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi) d\sigma^5_{UL} + P_l\left(d\sigma^6_{LL} + \frac{1}{Q}\cos(\phi) d\sigma^7_{LL}\right)\right] \\
+\;& S_T\left[\sin(\phi-\phi_s) d\sigma^8_{UT} + \sin(\phi+\phi_s) d\sigma^9_{UT} + \sin(3\phi-\phi_s) d\sigma^{10}_{UT} + \frac{1}{Q}\sin(2\phi-\phi_s) d\sigma^{11}_{UT} + \frac{1}{Q}\sin(\phi_s) d\sigma^{12}_{UT}\right. \\
& \left. P_l\left(\cos(\phi-\phi_s) d\sigma^{13}_{LT} + \frac{1}{Q}\cos(\phi_s) d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi-\phi_s) d\sigma^{15}_{LT}\right)\right]
\end{aligned}
$$

- the transversity DF $h_1^q(x)$ is sensitive to the difference of the number densities of transversely polarized quarks aligned along or opposite to the polarization of the nucleon
- "Collins-effect" accounts for the correlation between the transverse spin of the fragmenting quark and the transverse momentum of the produced unpolarized hadron
- generates left-right (azimuthal) asymmetries



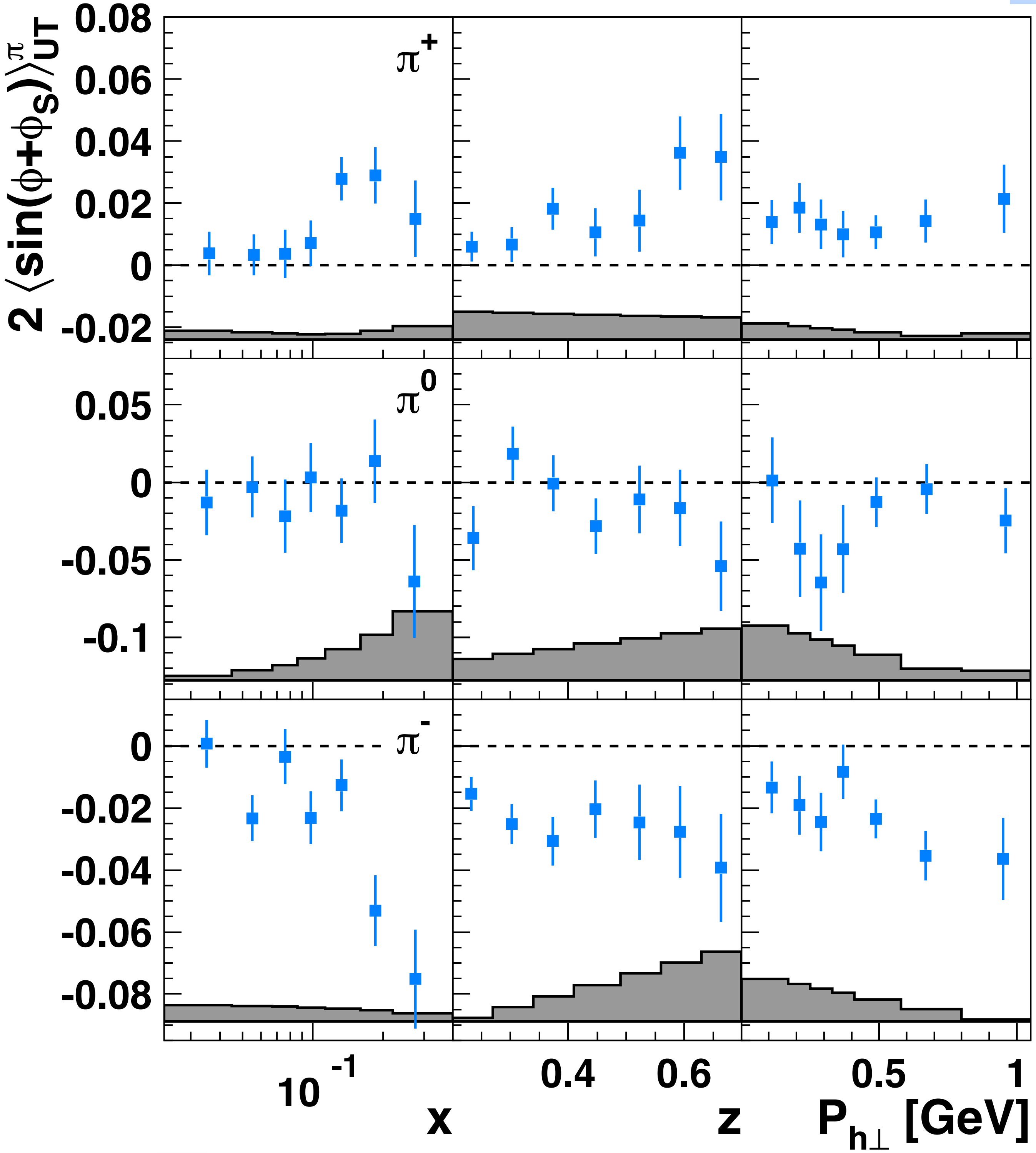


Collins amplitudes for pions

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

- non-zero Collins effect observed!
- both Collins FF and transversity sizeable

$$2\langle\sin(\phi+\phi_s)\rangle_{UT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{k}_{\mathrm{T}}}{M_h}\, h_1^q(x,p_{\mathrm{T}}^2)H_1^{\perp q\to h}(z,k_{\mathrm{T}}^2)\right]}{\mathcal{C}\left[f_1^q(x,p_{\mathrm{T}}^2)D_1^{q\to h}(z,k_{\mathrm{T}}^2)\right]}$$



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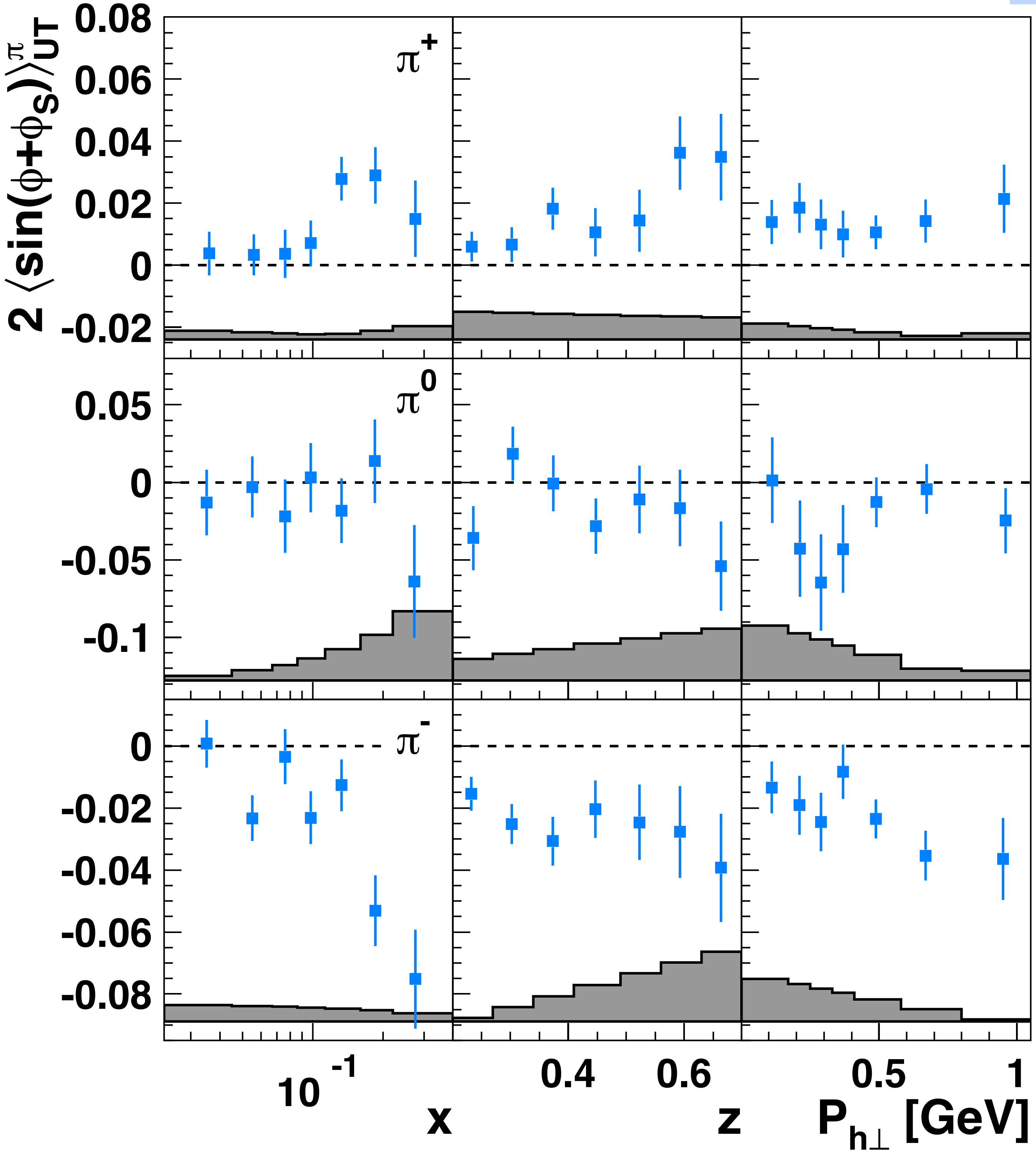

- positive amplitude for π^+
- compatible with zero amplitude for π^0
- large negative amplitude for π^-
- increase in magnitude with x
  - transversity mainly receives contribution from valence quarks
- increase with z
  - in qualitative agreement with BELLE results

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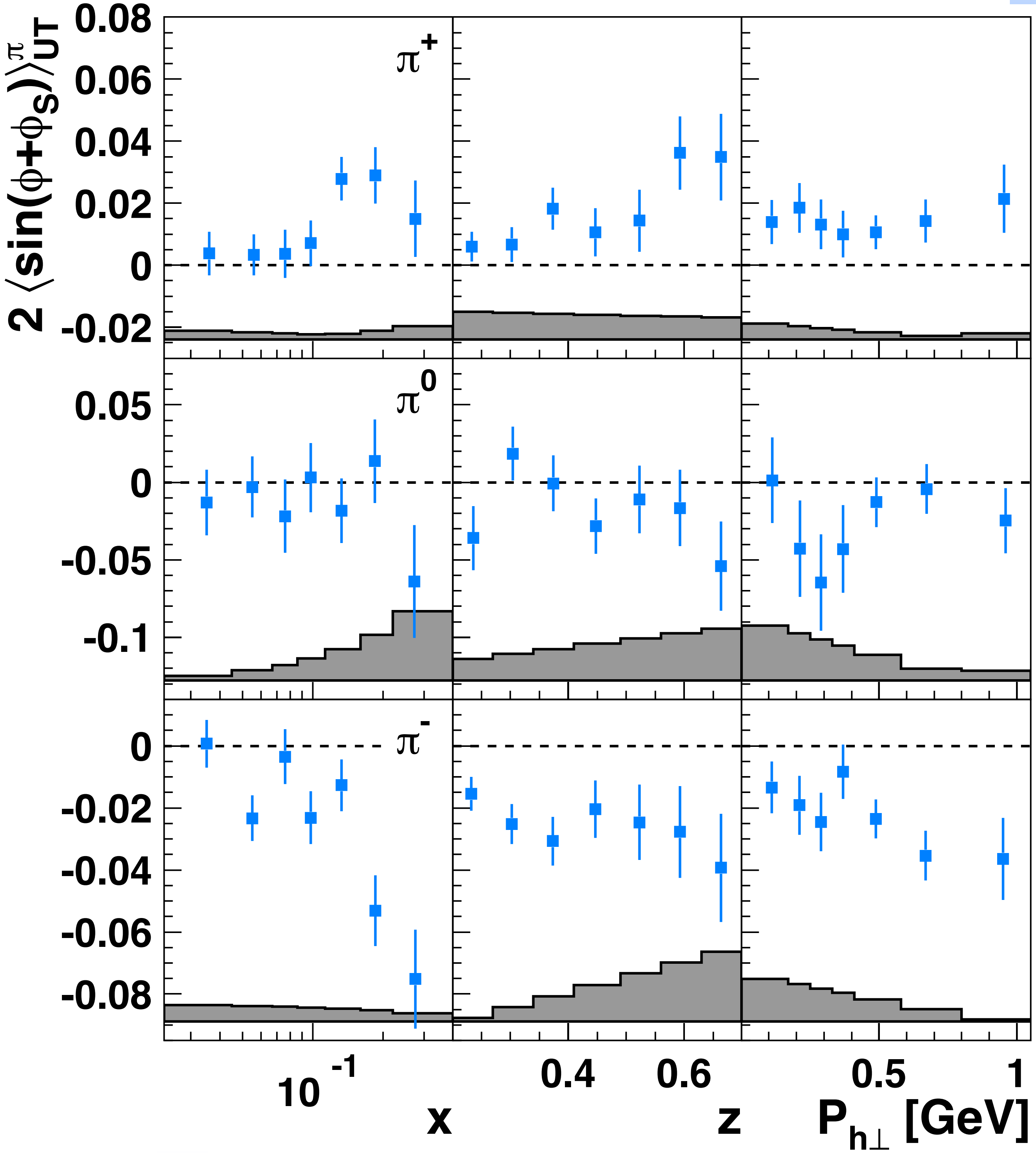

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- increase in magnitude with x
  - transversity mainly receives contribution from valence quarks
- increase with z
  - in qualitative agreement with BELLE results
- positive for π^+ and negative for π^-
  - role of disfavored Collins FF:

$$\mathbf{H_1^{\perp,disfav}} \approx -H_1^{\perp,fav}$$

$$u \Rightarrow \pi^+; \qquad d \Rightarrow \pi^-(fav)$$

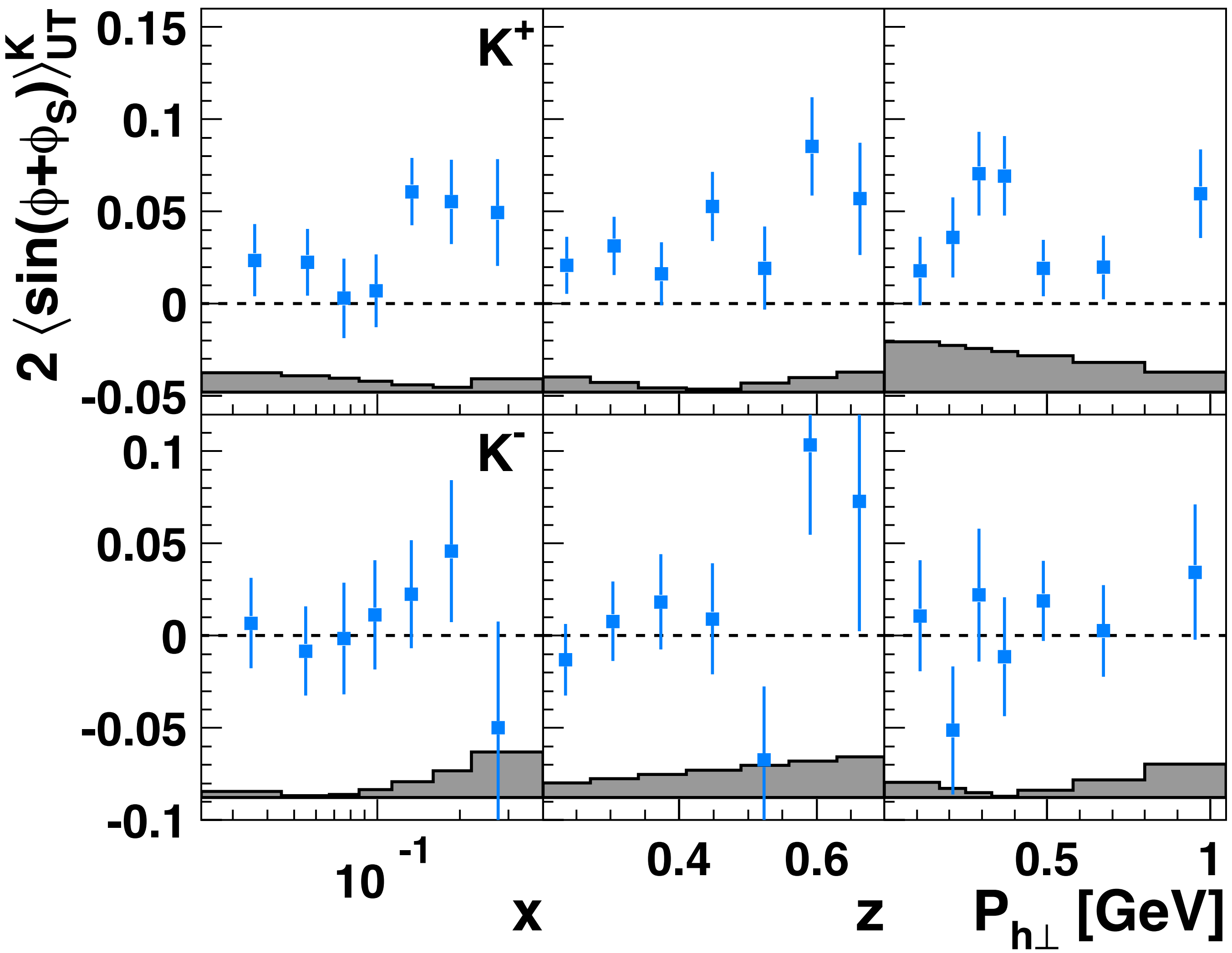
$$u \Rightarrow \pi^-; \qquad d \Rightarrow \pi^+(disfav)$$

$$\mathbf{h_1^u} > 0$$

$$\mathbf{h_1^d} < 0$$

Collins amplitudes for kaons

- HERMES Collaboration-
Phys. Rev. Lett. 103 (2009) 152002



$$2\langle\sin(\phi+\phi_s)\rangle_{UT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{k}_T}{M_h} h_1^q(x,p_T^2) H_1^{\perp q\to h}(z,k_T^2)\right]}{\mathcal{C}\left[f_1^q(x,p_T^2) D_1^{q\to h}(z,k_T^2)\right]}$$

K^+

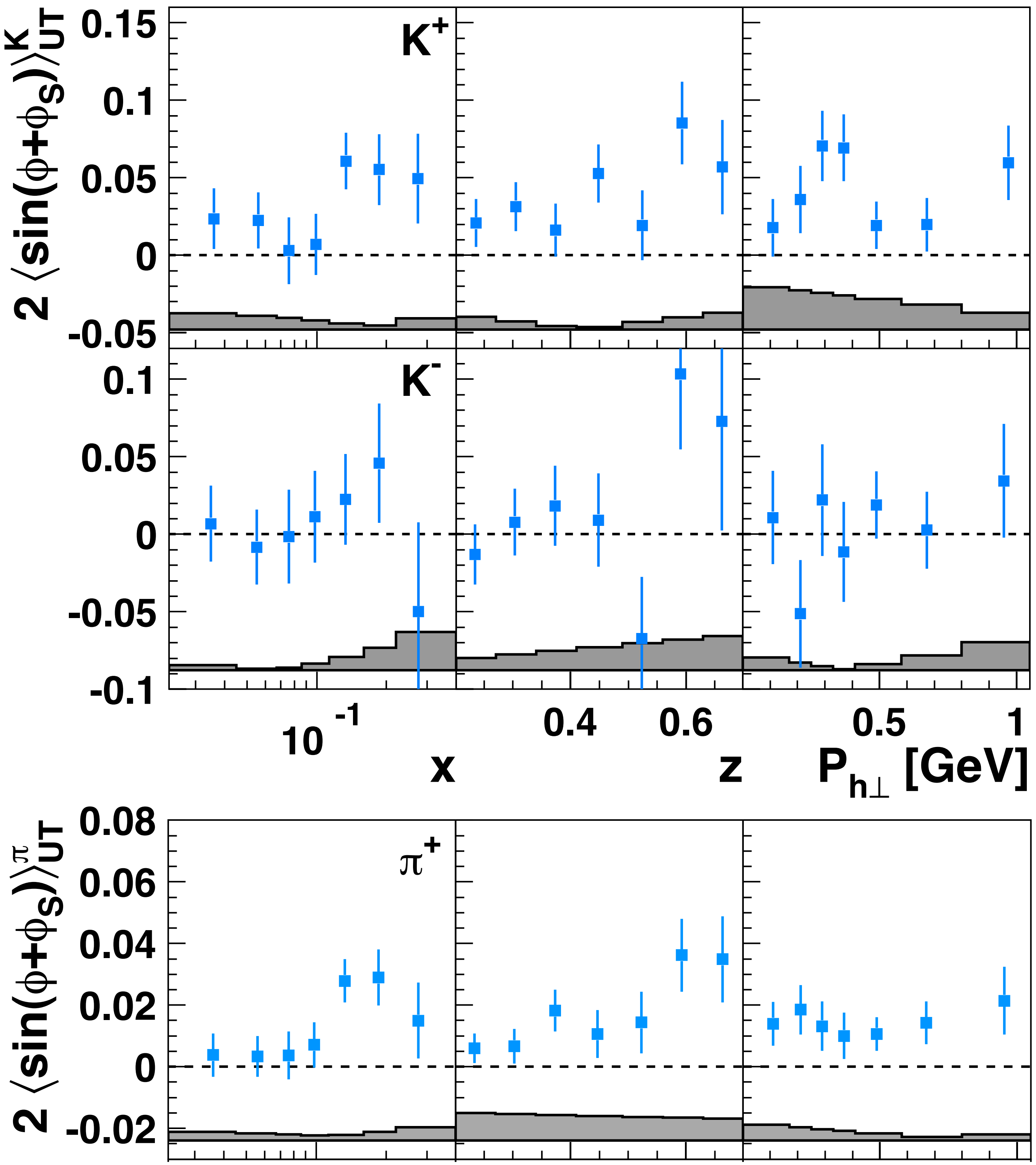
- ☛ K^+ amplitudes are similar to π^+ as expected from the u-quark dominance
- ☛ K^+ are larger than π^+

K^-

- ☛ consistent with zero amplitudes
- ☛ $\mathbf{K}^-(\bar{\mathbf{u}}\mathbf{s})$ is all see object

Collins amplitudes for kaons

- HERMES Collaboration-
Phys. Rev. Lett. 103 (2009) 152002



$$2\langle\sin(\phi+\phi_s)\rangle_{UT} \propto \frac{\mathcal{C}\left[-\frac{\hat{\mathbf{P}}_{h\perp}\cdot\mathbf{k}_T}{M_h} h_1^q(x,p_T^2) H_1^{\perp q\to h}(z,k_T^2)\right]}{\mathcal{C}\left[f_1^q(x,p_T^2) D_1^{q\to h}(z,k_T^2)\right]}$$

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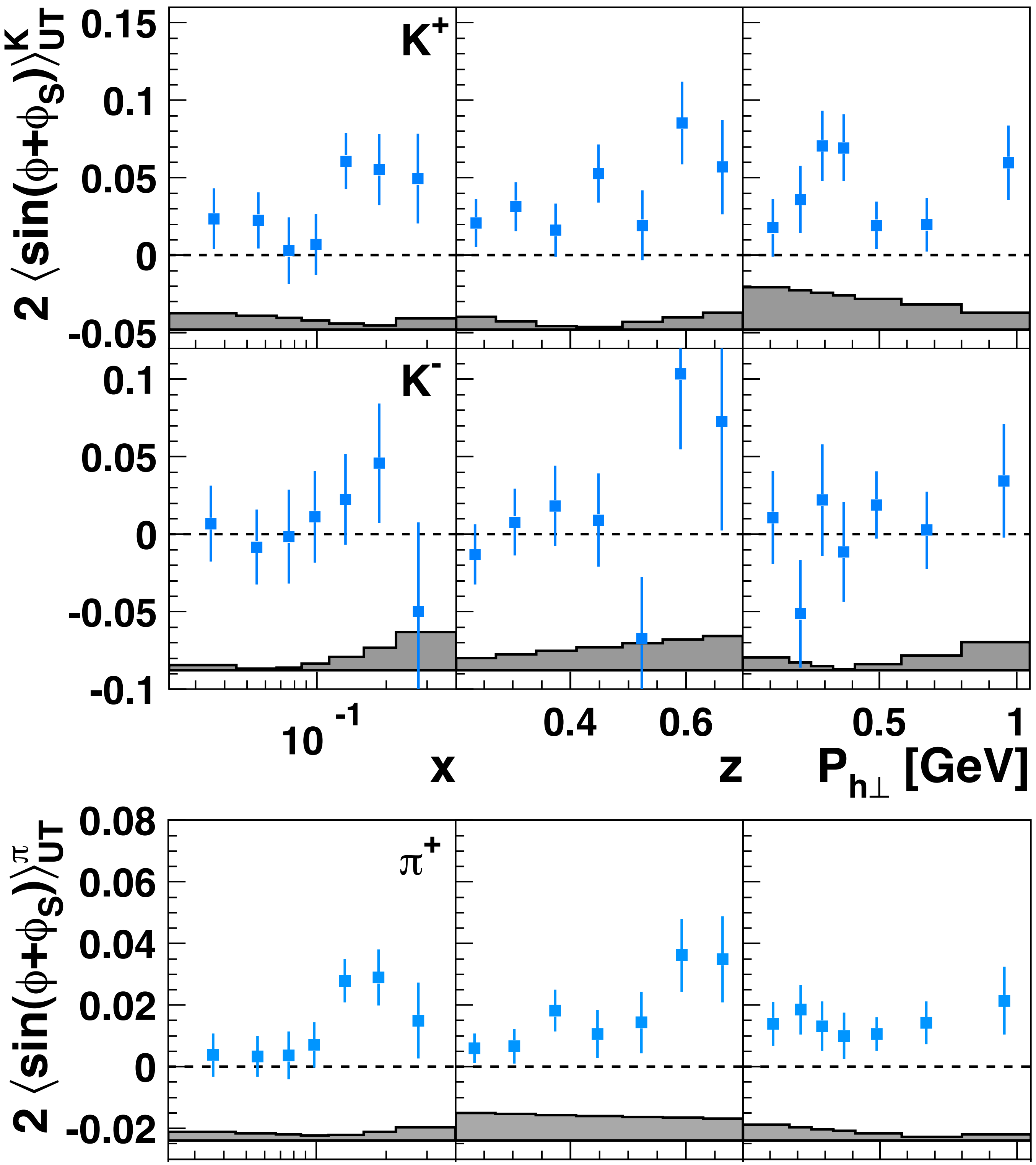
Collins amplitudes for kaons

- HERMES Collaboration-
Phys. Rev. Lett. 103 (2009) 152002



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K^+

- K^+ amplitudes are similar to π^+ as expected from the u-quark dominance
- K^+ are larger than π^+

K^-

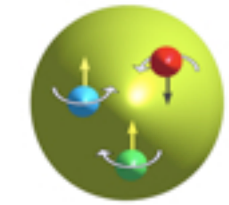
- consistent with zero amplitudes
- $\mathbf{K^-}(\bar{\mathbf{u}}\mathbf{s})$ is all see object

differences between K^+ and π^+ amplitudes

- role of sea quarks in conjunction with possibly large FF
- various contributions from decay of semi-inclusively produced vector-mesons
- the k_T dependences of the fragmentation functions

quark's transverse degrees of freedom

$$\sigma_{UU} \propto h_1^{\perp} \otimes H_1^{\perp}$$

$$h_1^{\perp} =$$ 

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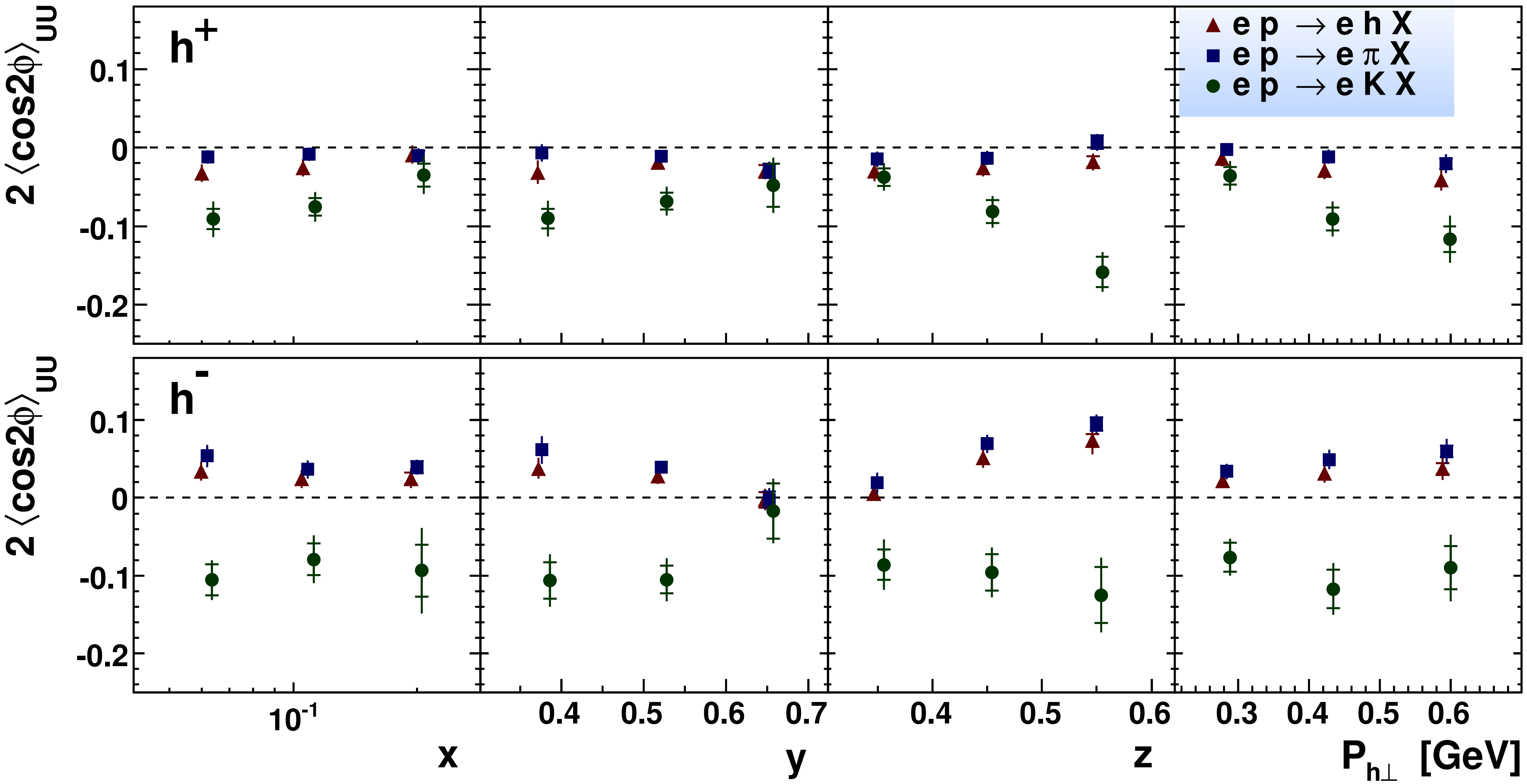
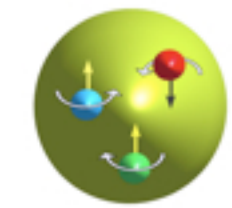
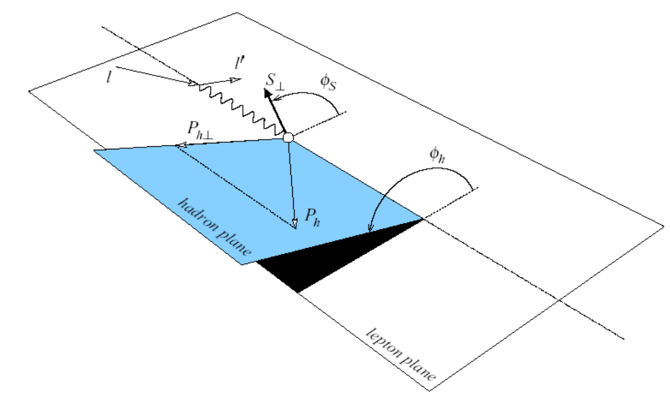


$$h_1^\perp =$$





- HERMES Collaboration-
Phys.Rev. D87 (2013) 012010

✓ negative asymmetry for π^+ and positive for π^-

☛ from previous publications (*PRL 94 (2005) 012002, PLB 693 (2010) 11-16*):

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

☛ **data support Boer-Mulders DF $h_1^\perp$ of same sign for u and d quarks**

✓ K^- and K^+ : striking differences w.r.t. pions

☛ role of the sea in DF and FF

beyond the leading twist

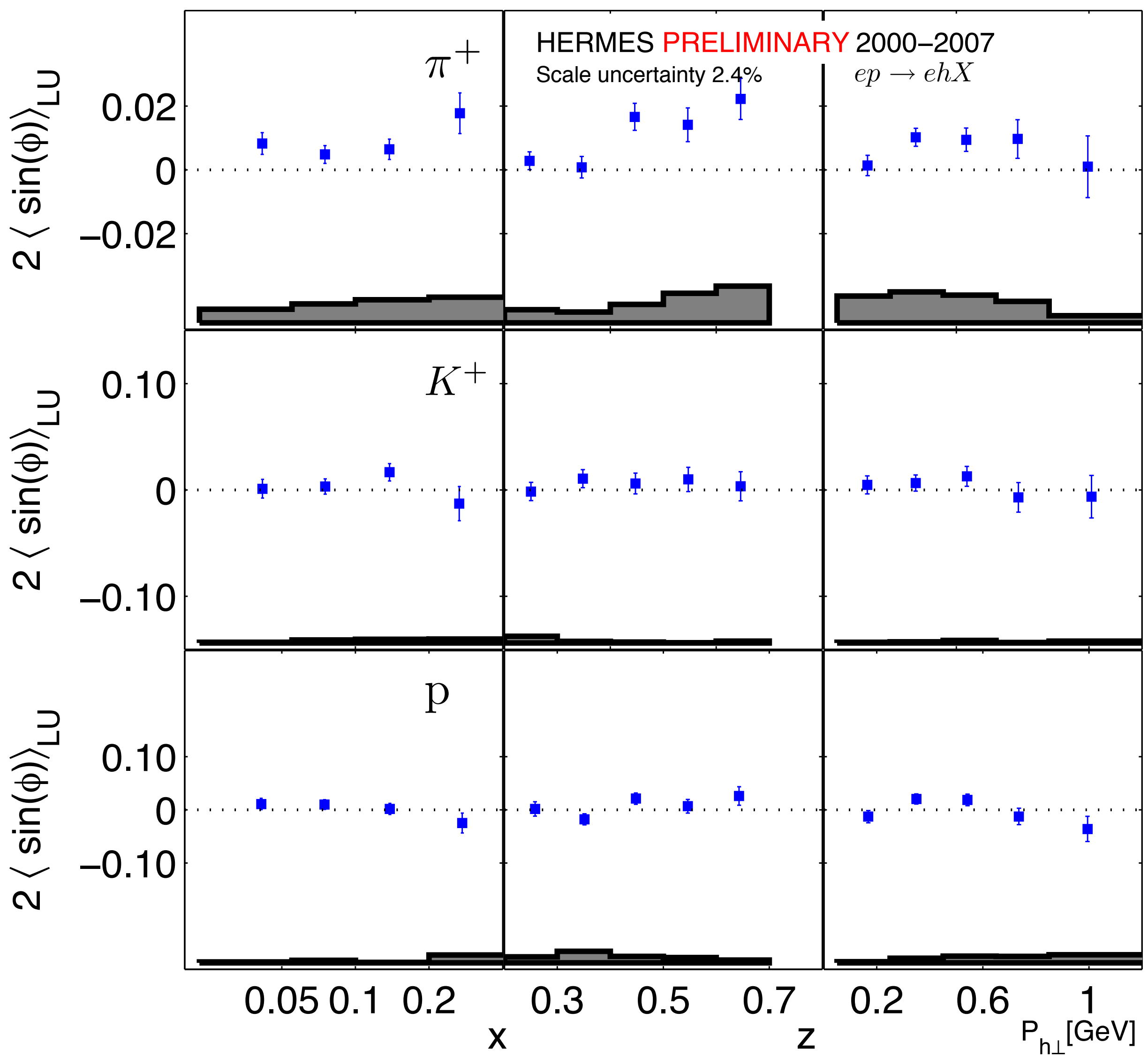
$$\frac{d^6\sigma}{dx\; dy\; dz\; dP^2_{h\perp}\, d\phi\; d\phi_s} \propto \Big\{F_{UU} + \ldots + \lambda_e \Big\{\sqrt{2\epsilon(1-\epsilon)}F^{\sin\phi}_{LU}\sin\phi\Big\} + \ldots$$

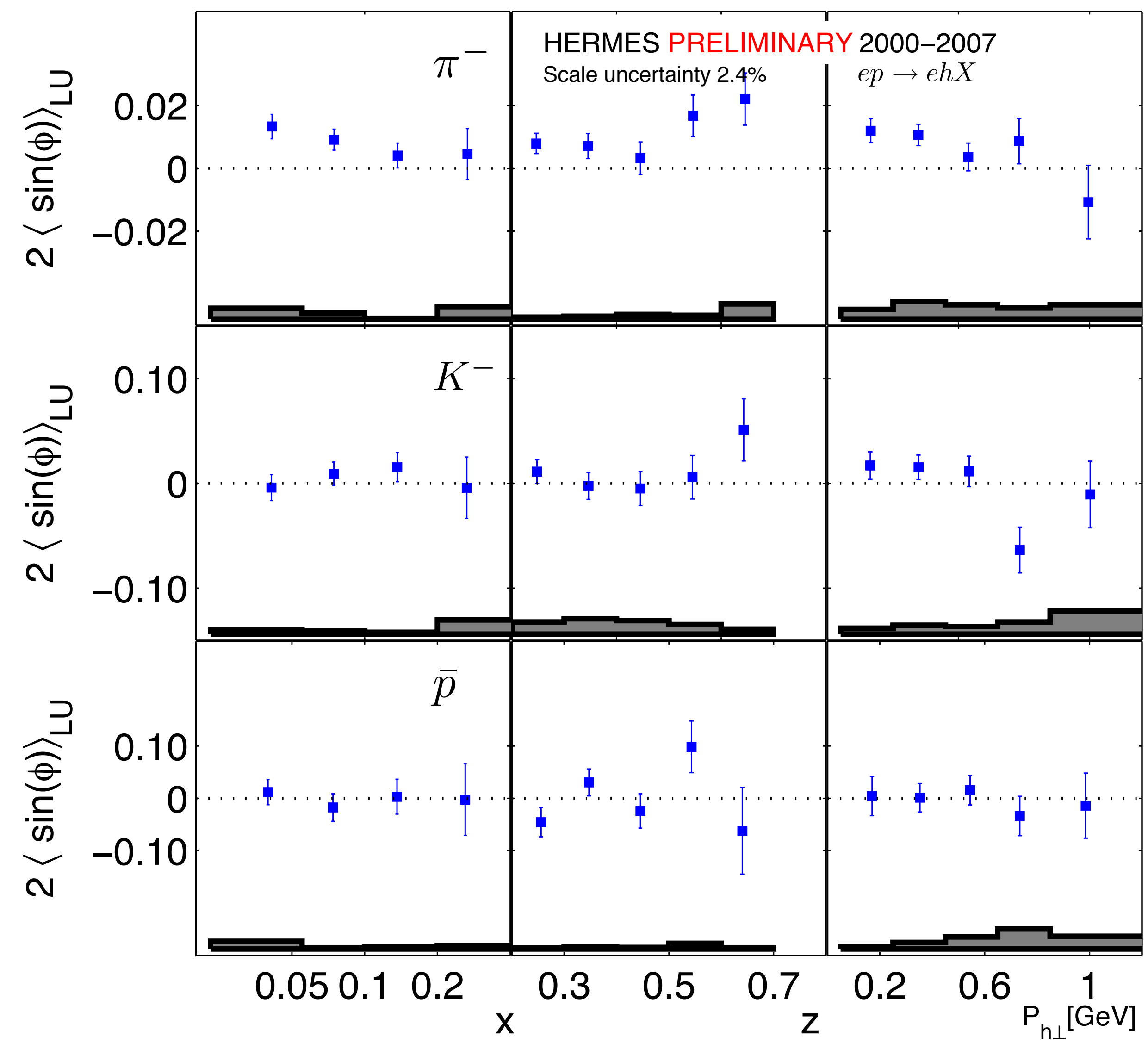
convolutions of twist-2 and twist-3 functions

beyond the leading twist

$$\frac{d^6\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi\,d\phi_s} \propto \left\{F_{UU} + \ldots + \lambda_e\left\{\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi\right\} + \ldots\right.$$

convolutions of twist-2 and twist-3 functions

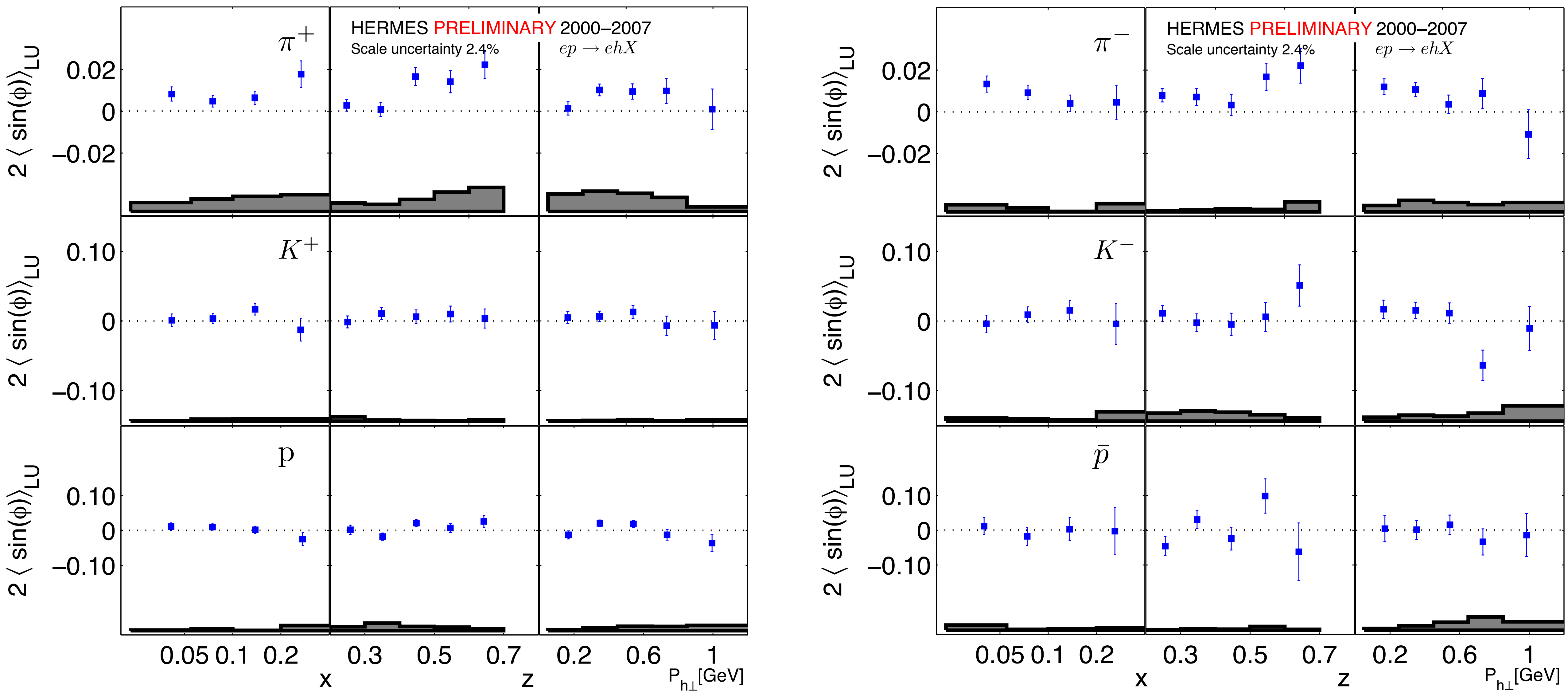




beyond the leading twist

$$\frac{d^6\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi\,d\phi_s} \propto \left\{F_{UU} + \ldots + \lambda_e\left\{\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi\right\} + \ldots\right.$$

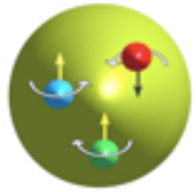
convolutions of twist-2 and twist-3 functions



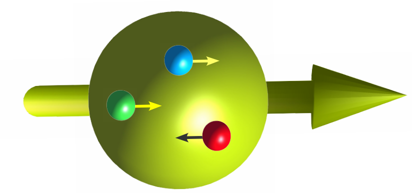
π^+ and π^-

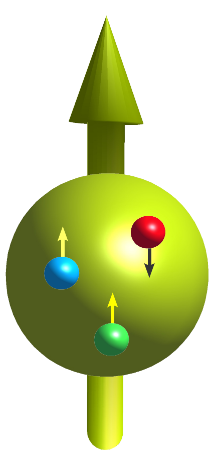
☛ the role of the twist-3 DF or FF is sizeable

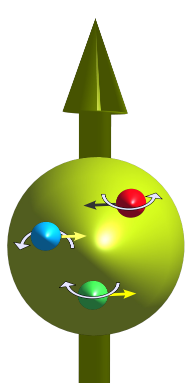
halftime report

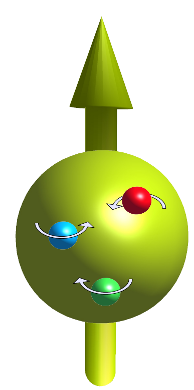


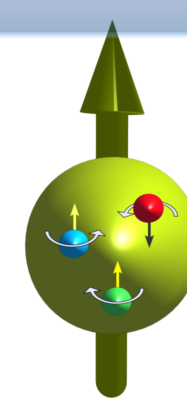
$$d\sigma = d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} + P_l \frac{1}{Q}\sin(\phi)d\sigma^3_{LU}$$
$$+ S_L\left[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} + P_l\left(d\sigma^6_{LL} + \frac{1}{Q}\sin(\phi)d\sigma^7_{LL}\right)\right]$$
$$+ S_T\Bigg[\sin(\phi-\phi_s)d\sigma^8_{UT} + \sin(\phi+\phi_s)d\sigma^9_{UT} + \sin(3\phi-\phi_s)d\sigma^{10}_{UT} + \frac{1}{Q}\sin(2\phi-\phi_s)d\sigma^{11}_{UT} + \frac{1}{Q}\sin(\phi_s)d\sigma^{12}_{UT}$$
$$+ P_l\left(\cos(\phi-\phi_s)d\sigma^{13}_{LT} + \frac{1}{Q}\cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi-\phi_s)d\sigma^{15}_{LT}\right)\Bigg]$$











halftime report

published

published

published

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paper coming out soon

paper coming out soon

$$
\begin{aligned}
d\sigma = \; & d\sigma^0_{UU} + \cos(2\phi) d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi) d\sigma^2_{UU} + P_l \frac{1}{Q}\sin(\phi) d\sigma^3_{LU} \\
& + S_L \left[\sin(2\phi) d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi) d\sigma^5_{UL} + P_l \left(d\sigma^6_{LL} + \frac{1}{Q}\sin(\phi) d\sigma^7_{LL} \right) \right] \\
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& \left. + P_l \left(\cos(\phi - \phi_s) d\sigma^{13}_{LT} + \frac{1}{Q}\cos(\phi_s) d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi - \phi_s) d\sigma^{15}_{LT} \right) \right]
\end{aligned}
$$

published

published

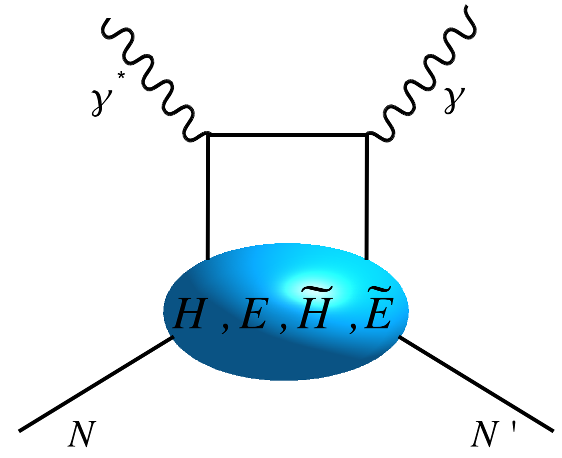
paper coming out soon

exclusive measurements (probing GPDs)

DVCS

☛ theoretically the cleanest probe of GPDs

$$\gamma^* N \to \gamma N : H, E, \widetilde{H}, \widetilde{E}$$



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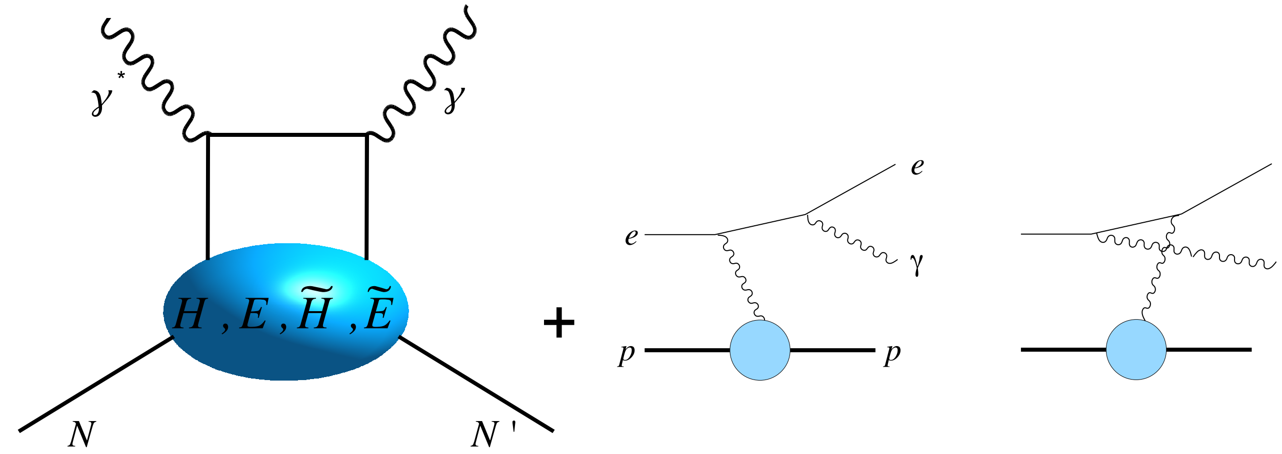
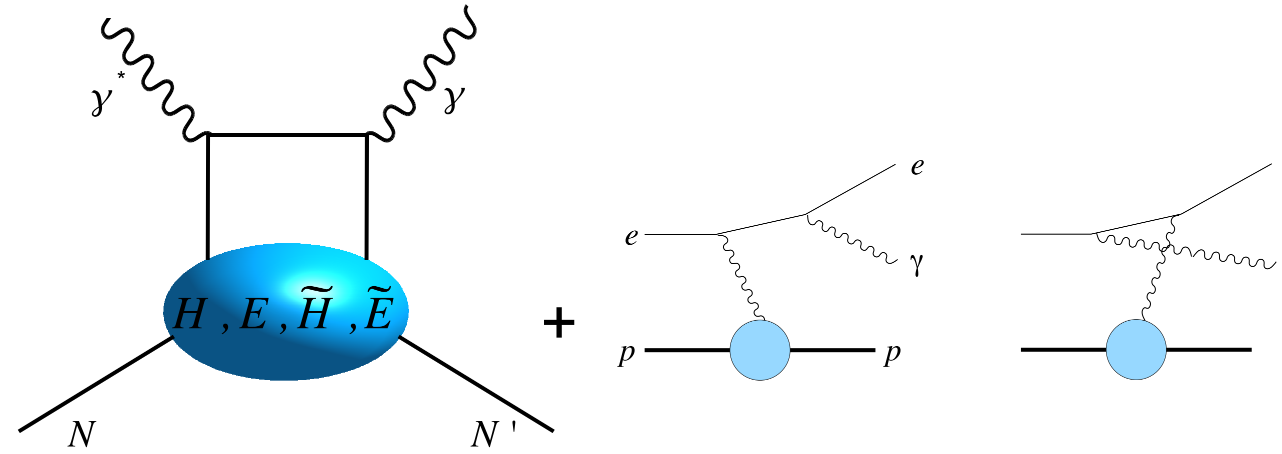


DVCS



☛ theoretically the cleanest probe of GPDs

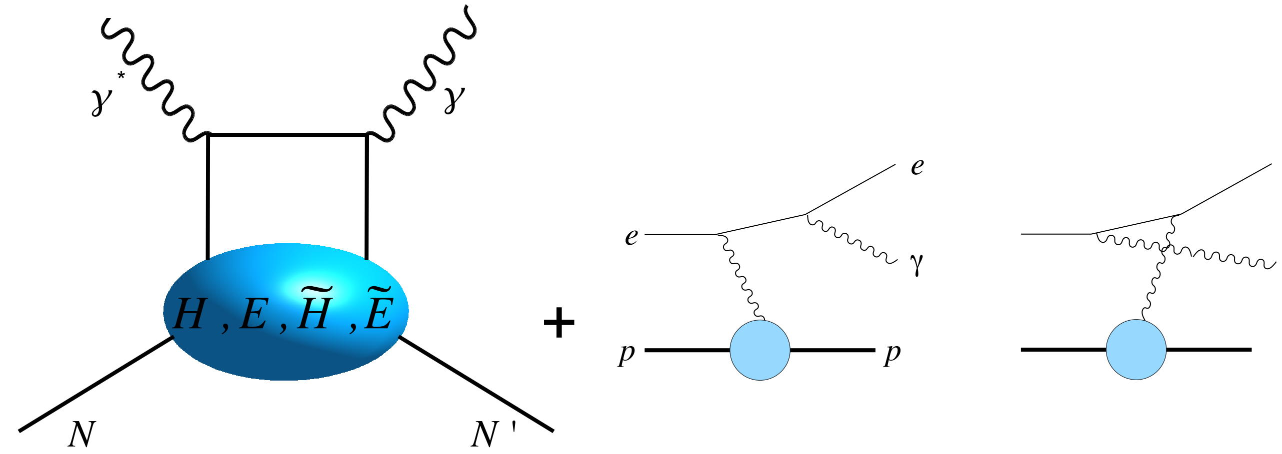
$$\gamma^* N \to \gamma N : H, E, \widetilde{H}, \widetilde{E}$$

σ_{xy} → beam: λ_l ; target: $S_\perp, S_{||}$

Bethe–Heitler | interference | DVCS

$$\begin{array}{llll}
d\sigma \sim d\sigma^{BH}_{UU} & + \; e_\ell d\sigma^I_{UU} & + \; d\sigma^{DVCS}_{UU} \\
& + \; e_\ell \lambda_\ell d\sigma^I_{LU} & + \; \lambda_\ell d\sigma^{DVCS}_{LU} \\
& + \; e_\ell S_{||} d\sigma^I_{UL} & + \; S_{||} d\sigma^{DVCS}_{UL} \\
& + \; e_\ell S_\perp d\sigma^I_{UT} & + \; S_\perp d\sigma^{DVCS}_{UT} \\
+\lambda_\ell S_{||} d\sigma^{BH}_{LL} & + \; e_\ell \lambda_\ell S_{||} d\sigma^I_{LL} & + \; \lambda_\ell S_{||} d\sigma^{DVCS}_{LL} \\
+\lambda_\ell S_\perp d\sigma^{BH}_{LT} & + \; e_\ell \lambda_\ell S_\perp d\sigma^I_{LT} & + \; \lambda_\ell S_\perp d\sigma^{DVCS}_{LT}
\end{array}$$

DVCS



☛ theoretically the cleanest probe of GPDs

$$\gamma^* N \to \gamma N : H, E, \widetilde{H}, \widetilde{E}$$

σ_{xy}

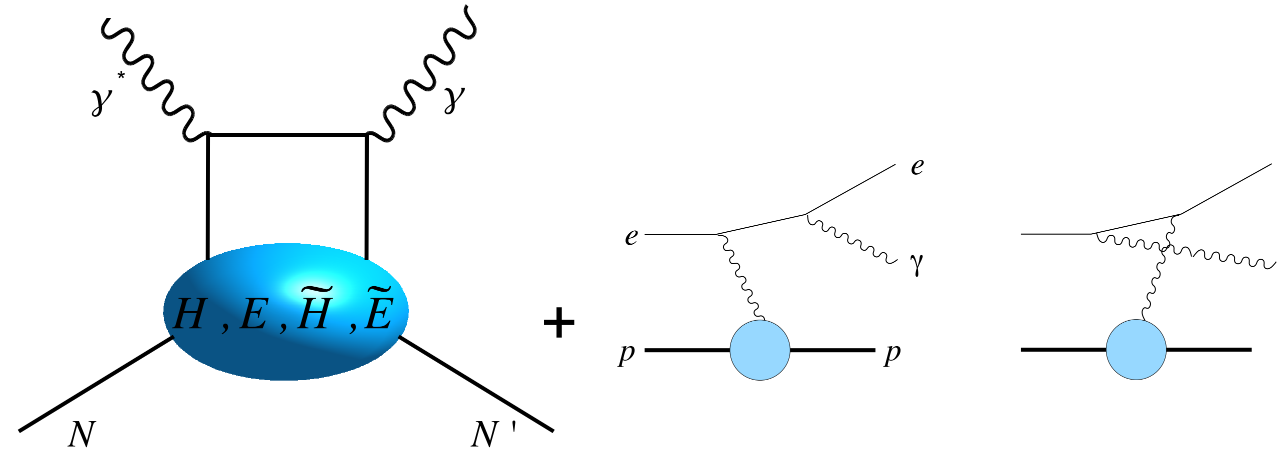
beam: λ_l | target: $S_\perp, S_{||}$

beam charge: e_ℓ

Bethe–Heitler | interference | DVCS

$$
\begin{aligned}
d\sigma \sim d\sigma^{BH}_{UU} &+ e_\ell d\sigma^{I}_{UU} &+ d\sigma^{DVCS}_{UU} \\
&+ e_\ell \lambda_\ell d\sigma^{I}_{LU} &+ \lambda_\ell d\sigma^{DVCS}_{LU} \\
&+ e_\ell S_{||} d\sigma^{I}_{UL} &+ S_{||} d\sigma^{DVCS}_{UL} \\
&+ e_\ell S_\perp d\sigma^{I}_{UT} &+ S_\perp d\sigma^{DVCS}_{UT} \\
+\lambda_\ell S_{||} d\sigma^{BH}_{LL} &+ e_\ell \lambda_\ell S_{||} d\sigma^{I}_{LL} &+ \lambda_\ell S_{||} d\sigma^{DVCS}_{LL} \\
+\lambda_\ell S_\perp d\sigma^{BH}_{LT} &+ e_\ell \lambda_\ell S_\perp d\sigma^{I}_{LT} &+ \lambda_\ell S_\perp d\sigma^{DVCS}_{LT}
\end{aligned}
$$

DVCS



- ☛ theoretically the cleanest probe of GPDs

$$\gamma^* N \to \gamma N : H, E, \widetilde{H}, \widetilde{E}$$

σ_{xy}

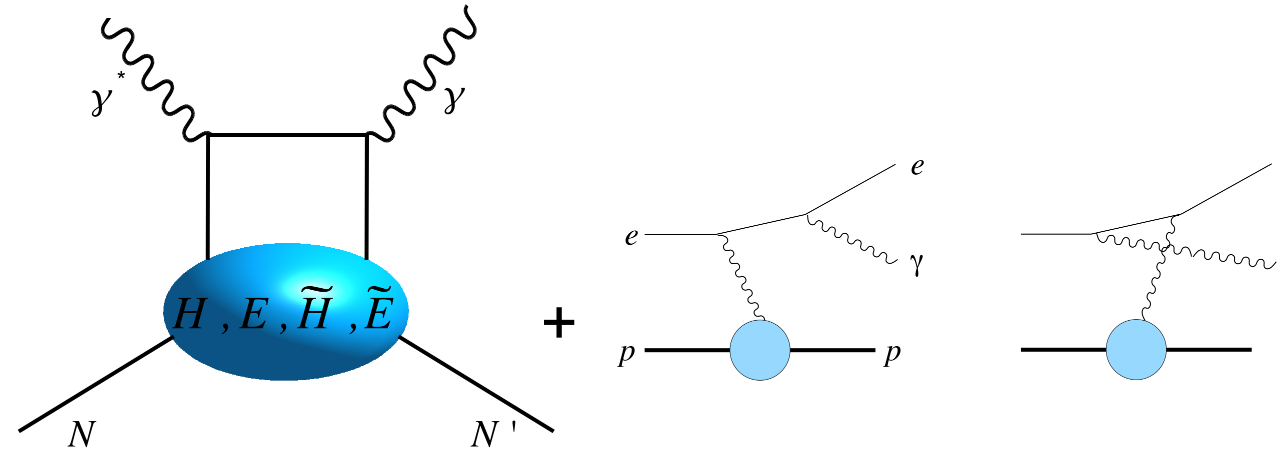
beam: λ_l | target: $S_\perp, S_{||}$

Bethe–Heitler | beam charge: e_ℓ | interference | DVCS

$$
\begin{aligned}
d\sigma \sim d\sigma^{BH}_{UU} &+ e_\ell d\sigma^{I}_{UU} &+ d\sigma^{DVCS}_{UU} \\
&+ e_\ell \lambda_\ell d\sigma^{I}_{LU} &+ \lambda_\ell d\sigma^{DVCS}_{LU} \\
&+ e_\ell S_{||} d\sigma^{I}_{UL} &+ S_{||} d\sigma^{DVCS}_{UL} \\
&+ e_\ell S_\perp d\sigma^{I}_{UT} &+ S_\perp d\sigma^{DVCS}_{UT} \\
+\lambda_\ell S_{||} d\sigma^{BH}_{LL} &+ e_\ell \lambda_\ell S_{||} d\sigma^{I}_{LL} &+ \lambda_\ell S_{||} d\sigma^{DVCS}_{LL} \\
+\lambda_\ell S_\perp d\sigma^{BH}_{LT} &+ e_\ell \lambda_\ell S_\perp d\sigma^{I}_{LT} &+ \lambda_\ell S_\perp d\sigma^{DVCS}_{LT}
\end{aligned}
$$

✓HERMES measured complete set of beam helicity, beam charge and target polarization asymmetries

DVCS



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Bethe–Heitler | beam charge: e_ℓ | interference | DVCS | σ_{xy} → beam: λ_l ; target: $S_\perp, S_{||}$

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&+ \quad e_\ell \lambda_\ell d\sigma^{I}_{LU} \quad &+ \quad \lambda_\ell d\sigma^{DVCS}_{LU} \\
&+ \quad e_\ell S_{||} d\sigma^{I}_{UL} \quad &+ \quad S_{||} d\sigma^{DVCS}_{UL} \\
&+ \quad e_\ell S_\perp d\sigma^{I}_{UT} \quad &+ \quad S_\perp d\sigma^{DVCS}_{UT} \\
+\lambda_\ell S_{||} d\sigma^{BH}_{LL} \quad &+ \quad e_\ell \lambda_\ell S_{||} d\sigma^{I}_{LL} \quad &+ \quad \lambda_\ell S_{||} d\sigma^{DVCS}_{LL} \\
+\lambda_\ell S_\perp d\sigma^{BH}_{LT} \quad &+ \quad e_\ell \lambda_\ell S_\perp d\sigma^{I}_{LT} \quad &+ \quad \lambda_\ell S_\perp d\sigma^{DVCS}_{LT}
\end{aligned}$$

☛ unpolarized target

$$F_1 \mathcal{H} + \frac{x_B}{2 - x_B}(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$$

☛ longitudinally polarized target

$$\frac{x_B}{2 - x_B}(F_1 + F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E})$$
$$+F_1 \widetilde{\mathcal{H}} - \frac{x_B}{2 - x_B}\left(\frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2\right)\widetilde{\mathcal{E}}$$

☛ transversely polarized target

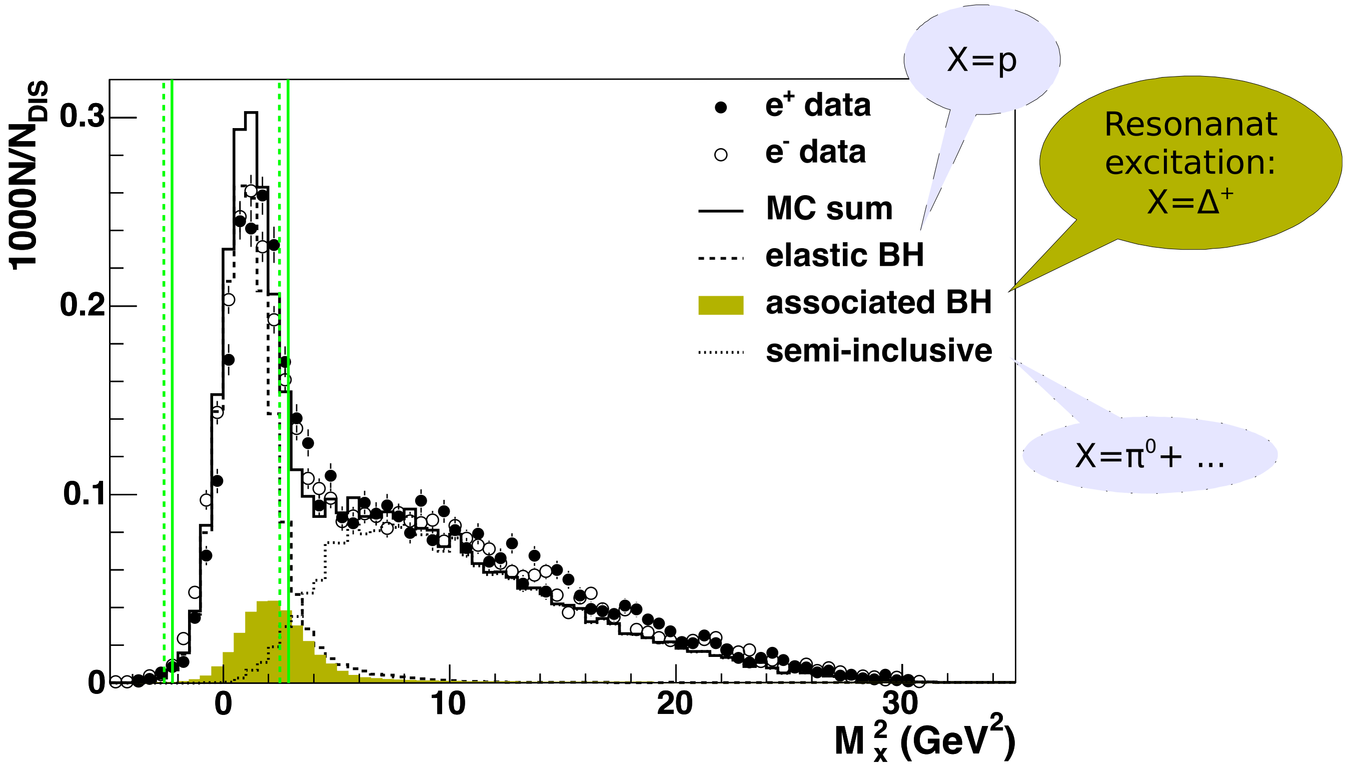
$$\frac{t}{4M^2}\left[(2 - x_B) F_1 \mathcal{E} - 4\frac{1 - x_B}{2 - x_B} F_2 \mathcal{H}\right]$$

✓HERMES measured complete set of beam helicity, beam charge and target polarization asymmetries

$ep \to e'\gamma X$

DVCS measurements

(without recoil detector)



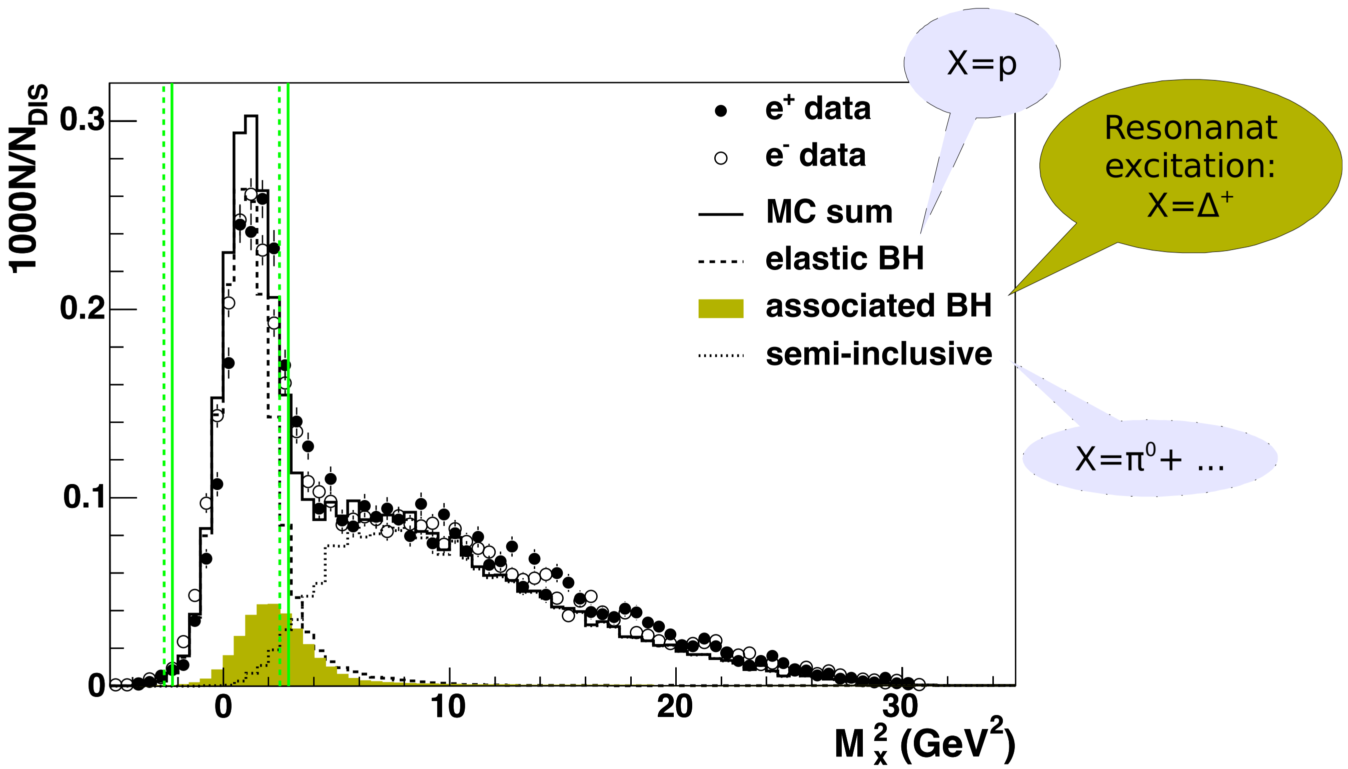
☛ missing mass technique

$$M_X^2 = (p + e - e' - \gamma)^2$$

DVCS measurements

(without recoil detector)

(with recoil detector)



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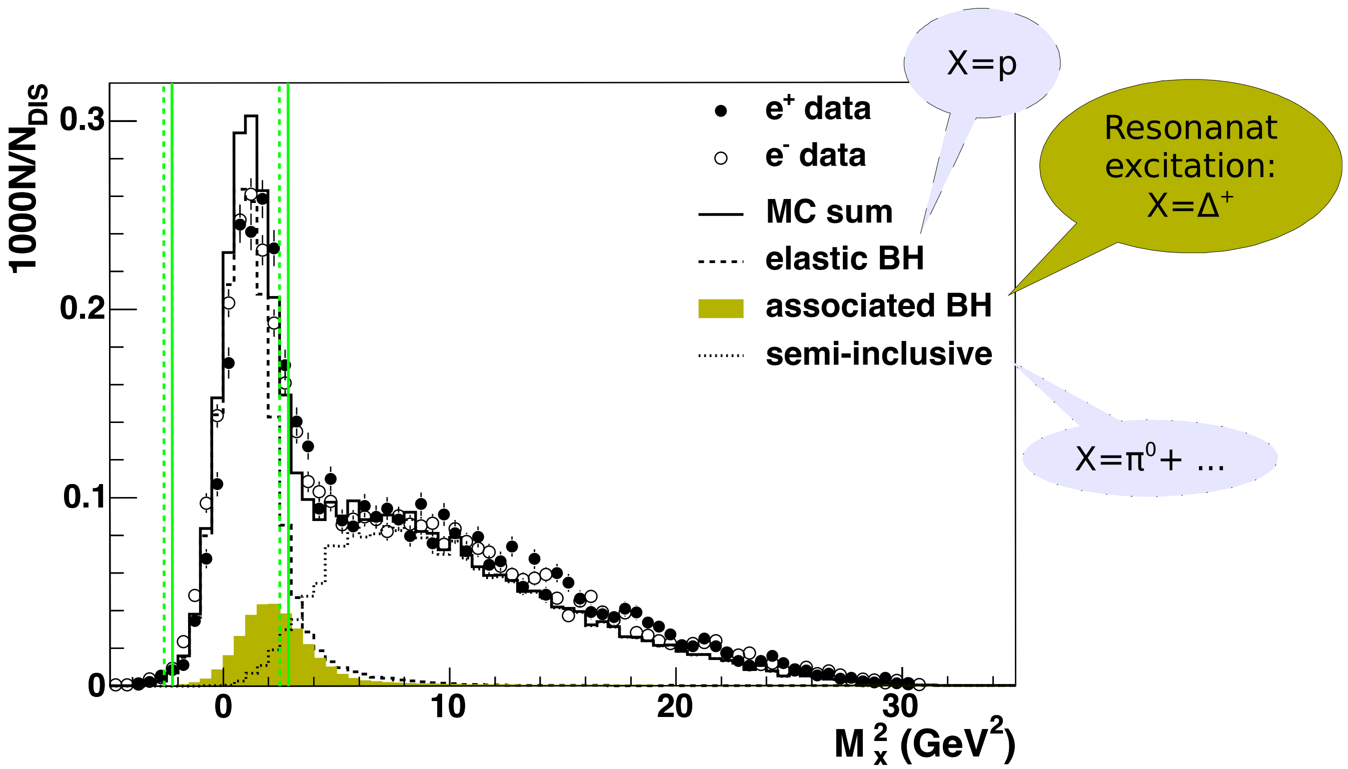
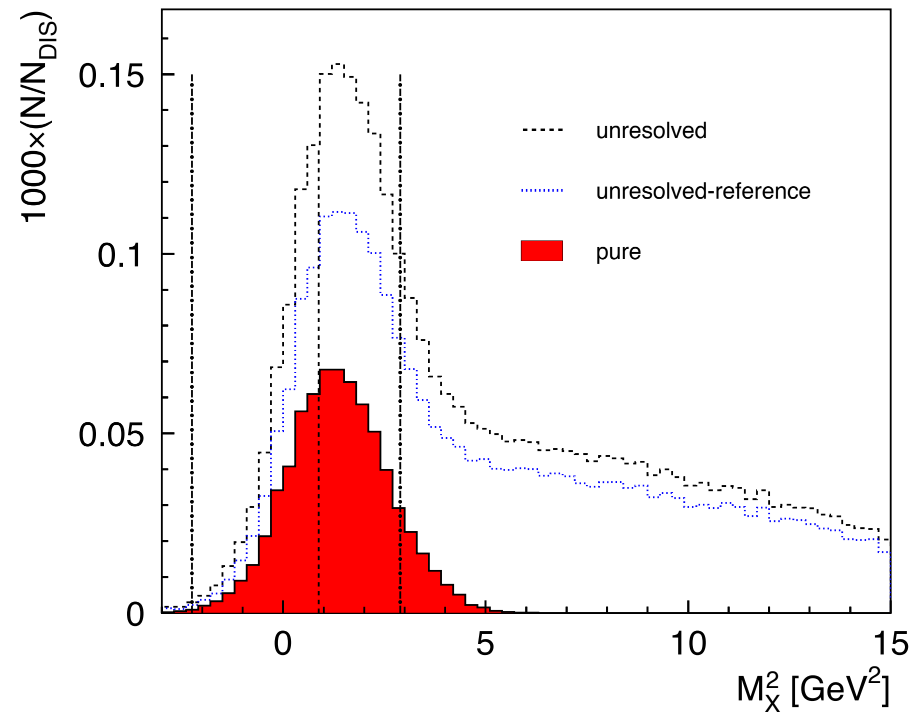
(without recoil detector)

$ep \to e'\gamma p'$

(with recoil detector)





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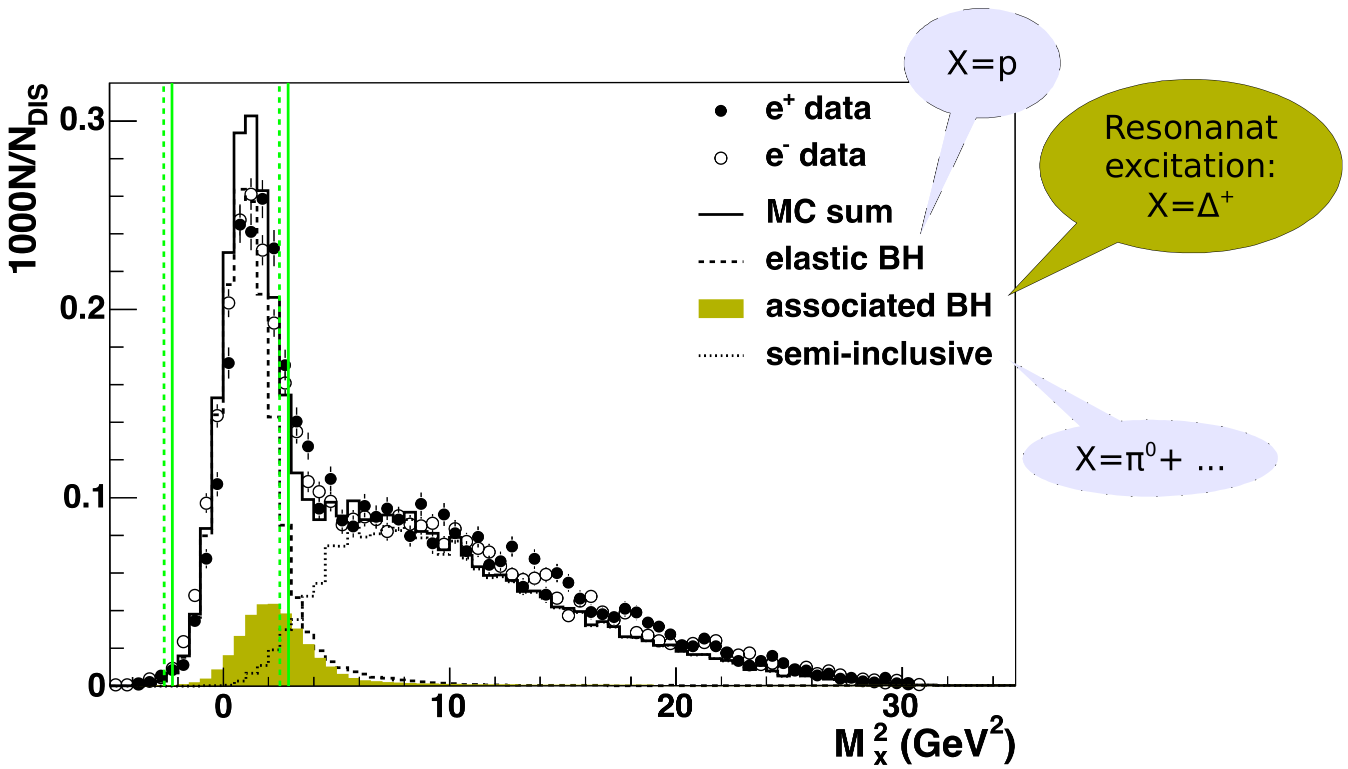
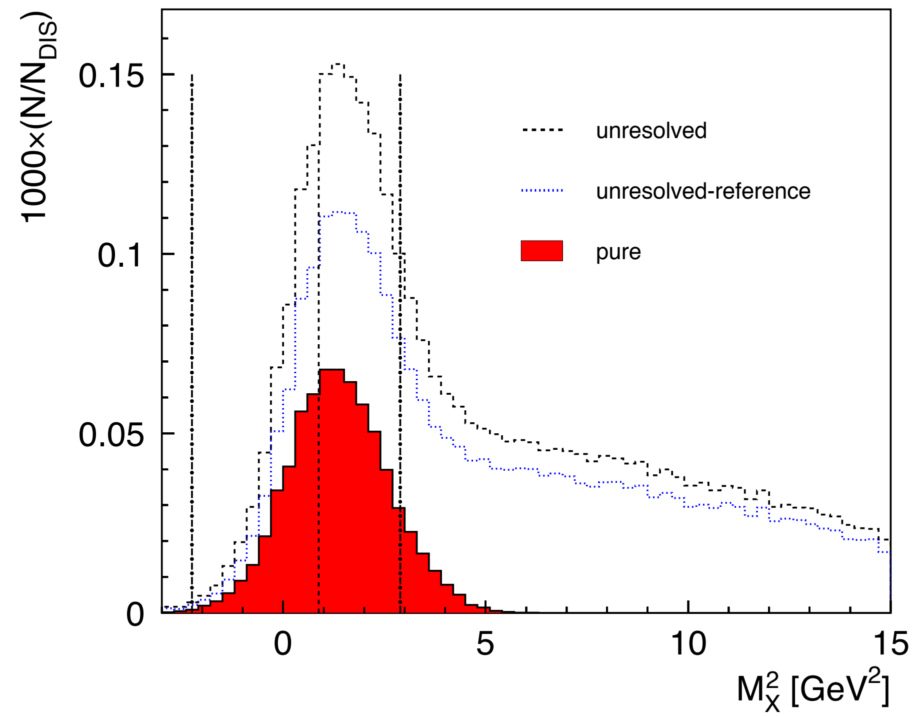




☛ missing mass technique

$M_X^2 = (p + e - e' - \gamma)^2$

✓ unresolved and unresolved-reference samples: $ep \to e'\gamma X$

☛ use missing mass technique

☛ for comparison only

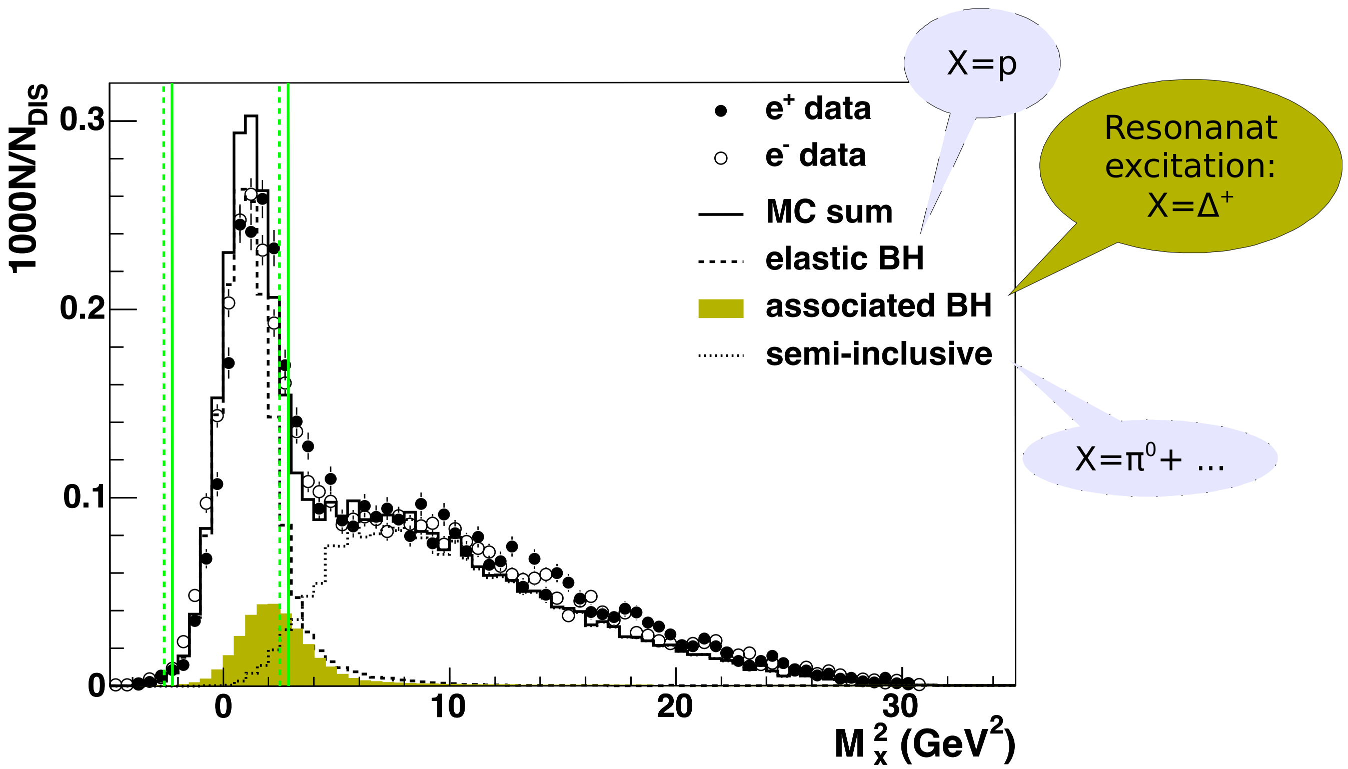
DVCS measurements

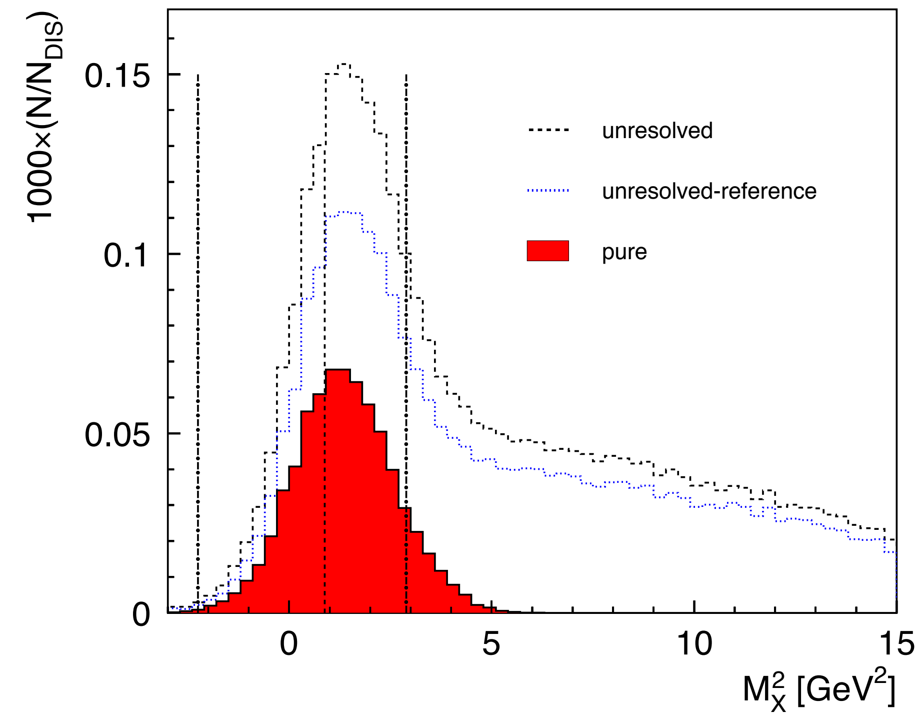
$ep \to e'\gamma X$

(without recoil detector)

$ep \to e'\gamma p'$

(with recoil detector)





☛ missing mass technique

$$M_X^2 = (p + e - e' - \gamma)^2$$

✓ unresolved and unresolved-reference samples: $ep \to e'\gamma X$

- ☛ use missing mass technique
- ☛ for comparison only

✓ pure sample: $ep \to e'\gamma p'$

- ☛ all particles in the final state are detected
- ☛ kinematic event fit
- ☛ BH/DVCS events with 83% efficiency
- ☛ background contamination from semi-inclusive and associated processes less than 0.2%

$ep \to e'\gamma X$
(pre-recoil data)

GPD H: unpolarized hydrogen target

-HERMES Collaboration- : JHEP 11 (2009) 083

$$\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[1 + P_\ell \mathcal{A}_{LU}^{DVCS}(\phi) + e_\ell P_\ell \mathcal{A}_{LU}^{I}(\phi) + e_\ell \mathcal{A}_C(\phi)\right]$$

$$\mathcal{A}_C(\phi) = \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi)$$

$$\mathcal{A}_{LU}^{I}(\phi) = \sum_{n=1}^{2} A_{LU,\mathrm{I}}^{\sin(n\phi)} \sin(n\phi)$$

$ep \to e'\gamma X$
(pre-recoil data)

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-HERMES Collaboration- : JHEP 11 (2009) 083

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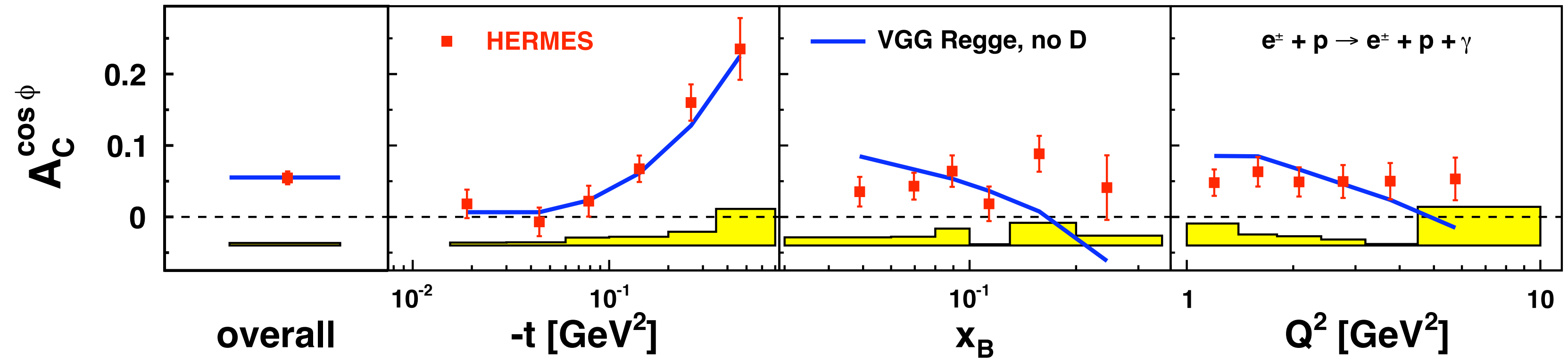
$$\mathcal{A}_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}$$

$$A_C^{\cos\phi} \propto \mathrm{Re}[F_1 \mathcal{H}]$$



beam charge asymmetry

☛ strong t-dependence

☛ no x_B or Q^2 dependences

$ep \to e'\gamma X$
(pre-recoil data)

GPD H: unpolarized hydrogen target

-HERMES Collaboration- : JHEP 11 (2009) 083

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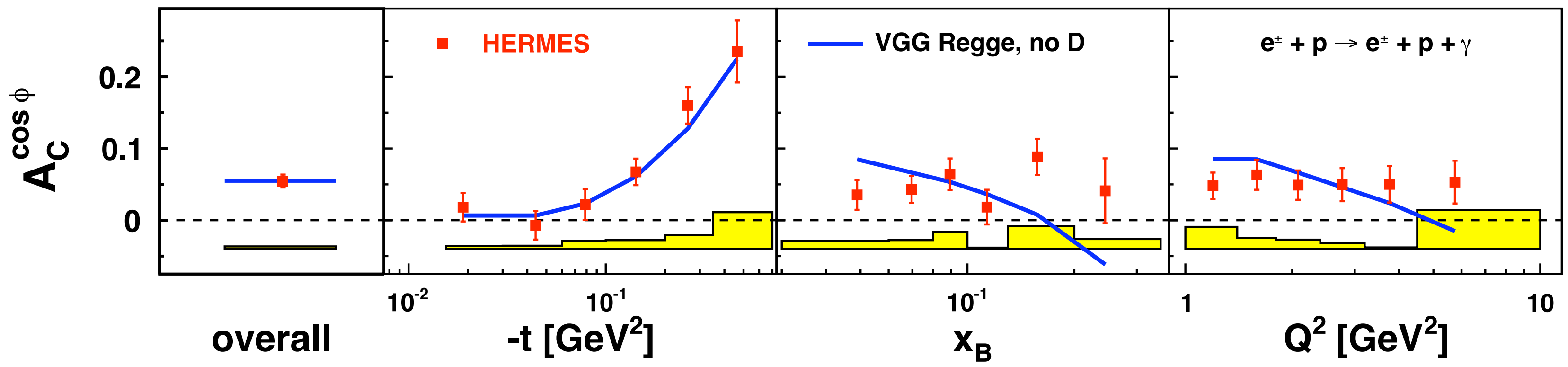


beam charge asymmetry

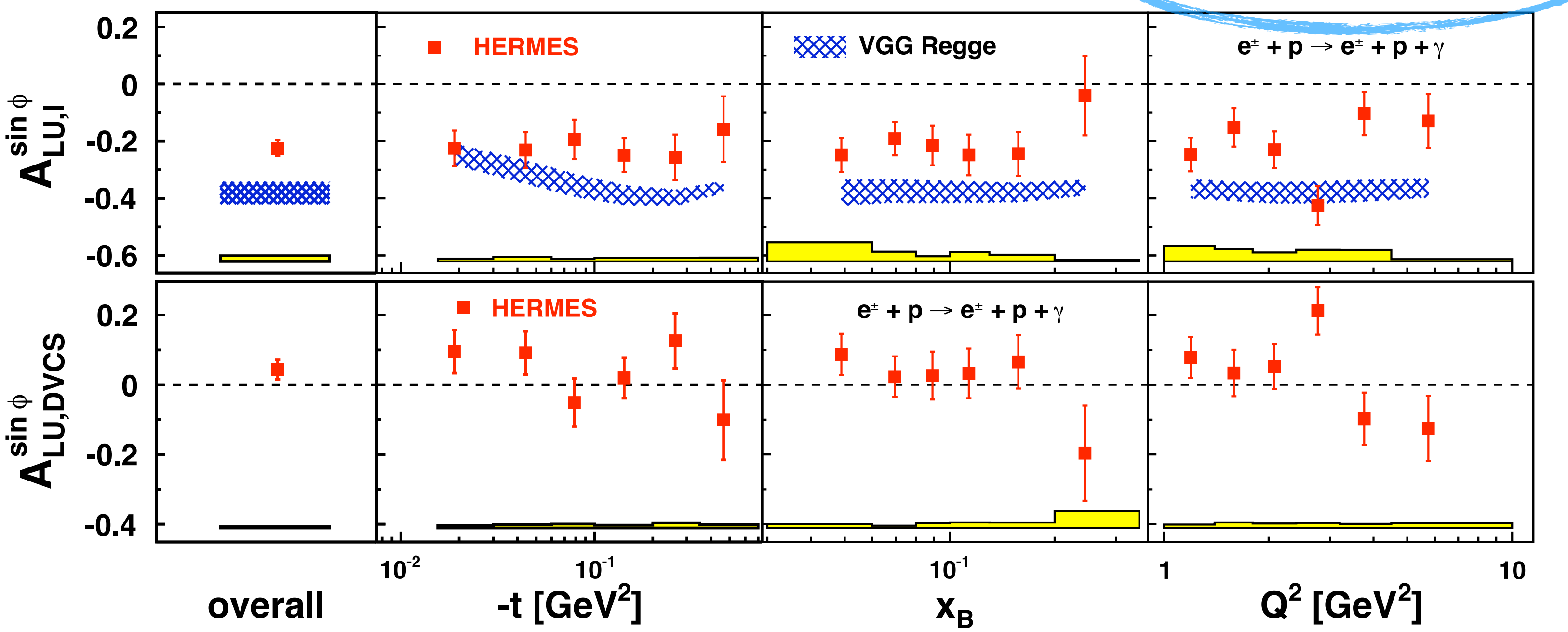
- ☛ strong t-dependence
- ☛ no x_B or Q^2 dependences

$$\mathcal{A}_{LU}^{I,DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) \pm (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})}$$

$$A_{LU,\mathrm{I}}^{\sin\phi} \propto \mathrm{Im}[F_1 \mathcal{H}]$$

charge-difference beam helicity asymmetry

- ☛ large overall value
- ☛ no kin. dependencies



charge-averaged beam helicity asymmetry

- ☛ consistent with zero

$$A_{LU,\mathrm{DVCS}}^{\sin\phi} \propto \mathrm{Im}[\mathcal{H}\mathcal{H}^* - \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*]$$

$ep \to e'\gamma p'$

(recoil data)

GPD H: unpolarized hydrogen target

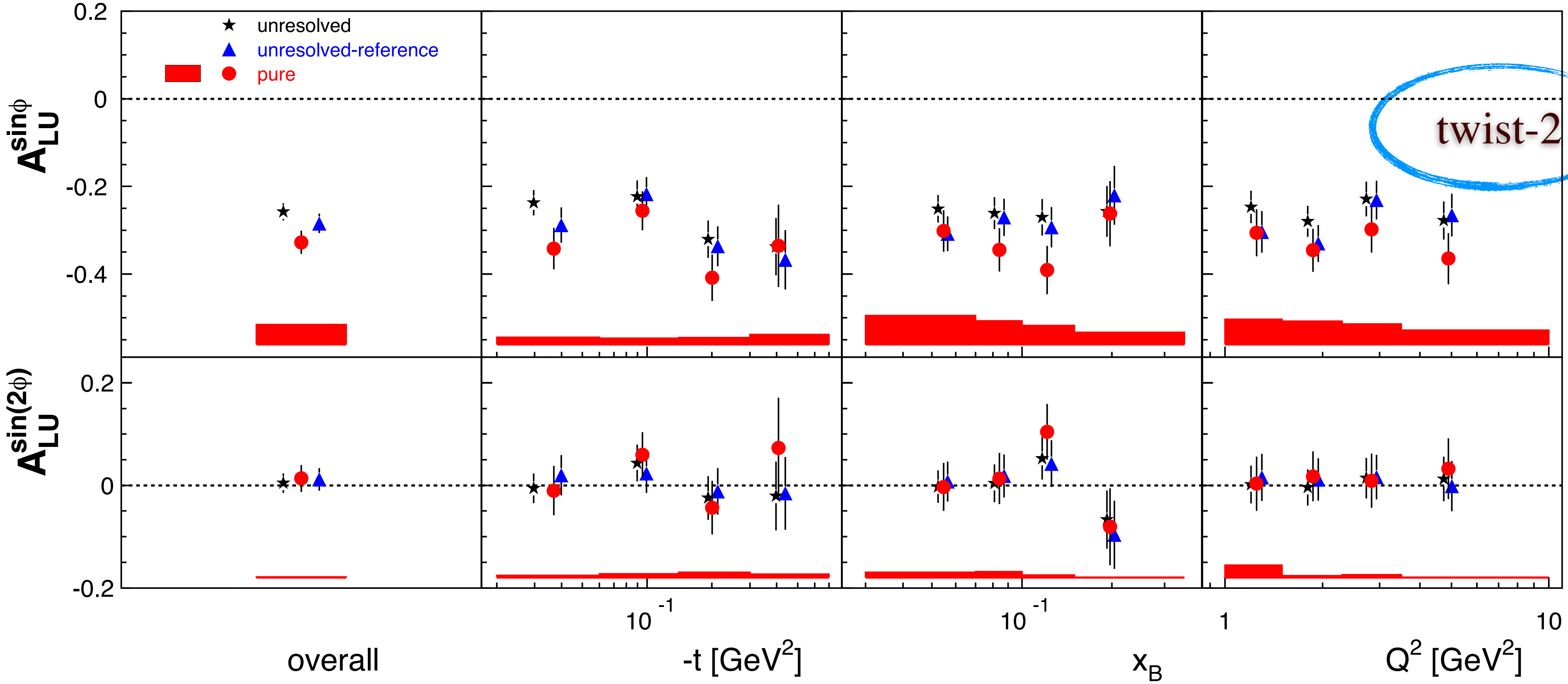
$$\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[1 + P_\ell \mathcal{A}_{LU}^{DVCS}(\phi) + e_\ell P_\ell \mathcal{A}_{LU}^{I}(\phi) + e_\ell \mathcal{A}_C(\phi)\right]$$

$$\mathcal{A}_{\mathrm{LU}}(\phi) \simeq \sum_{n=1}^{2} A_{\mathrm{LU}}^{\sin(n\phi)} \sin(n\phi)$$

- HERMES Collaboration-
JHEP 10 (2012) 042

☛ extraction of single-charge beam-helicity asymmetry amplitudes for elastic (pure) data sample

☛ no separate access to DVCS and interference terms

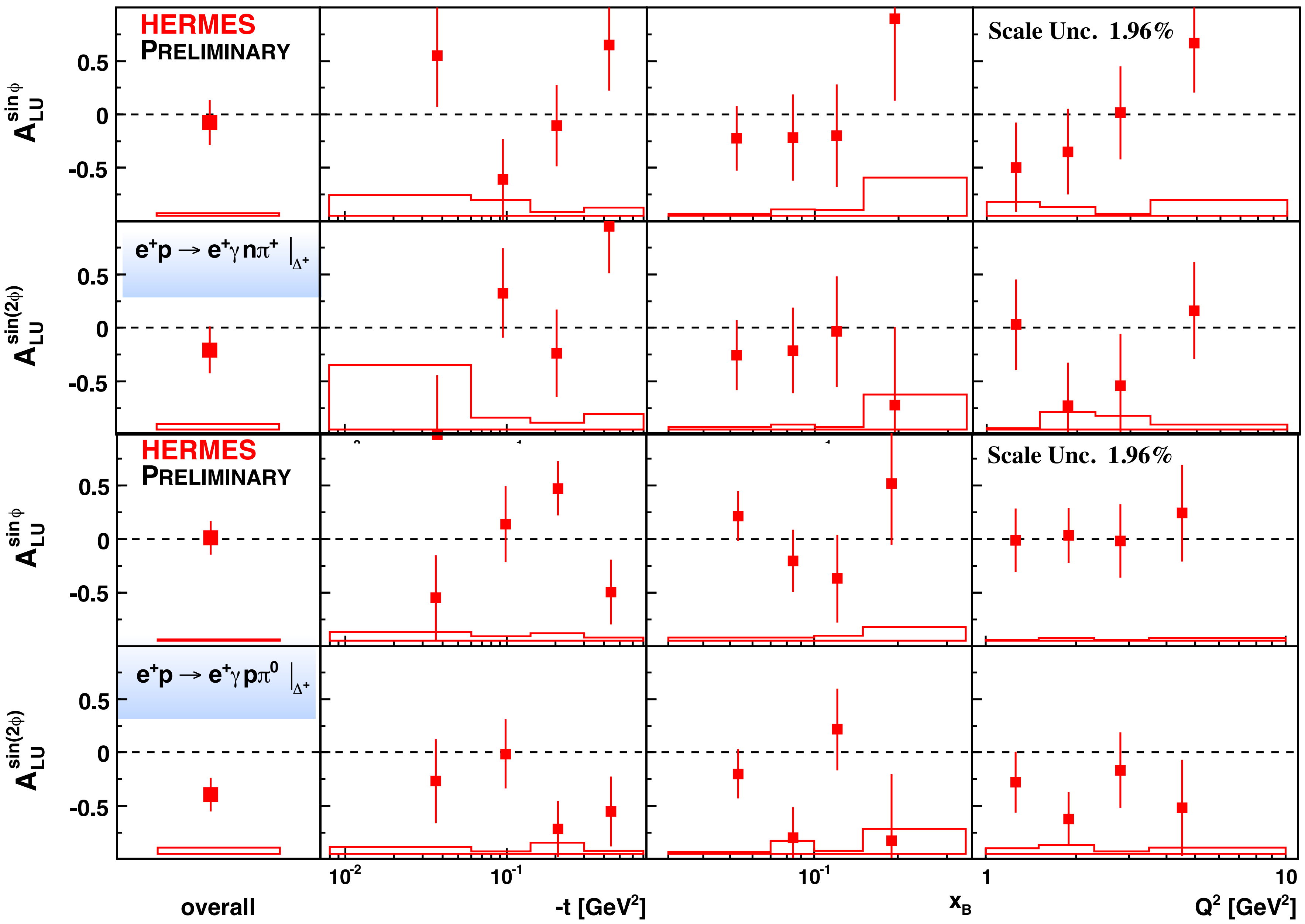


☛ indication for slightly larger magnitude of the leading amplitude for elastic process compared to the one in the recoil detector acceptance (unresolved-reference)

associated DVCS

$ep \to e'\gamma\Delta$

(recoil data)



- consistent with zero result for both channels
- associated DVCS is mainly dilution in the analysis using the missing mass technique
- in agreement with the DVCS results on pure sample

$ep \to e'\gamma X$

(pre-recoil data)

GPD $\widetilde{H}$: longitudinally polarized hydrogen target

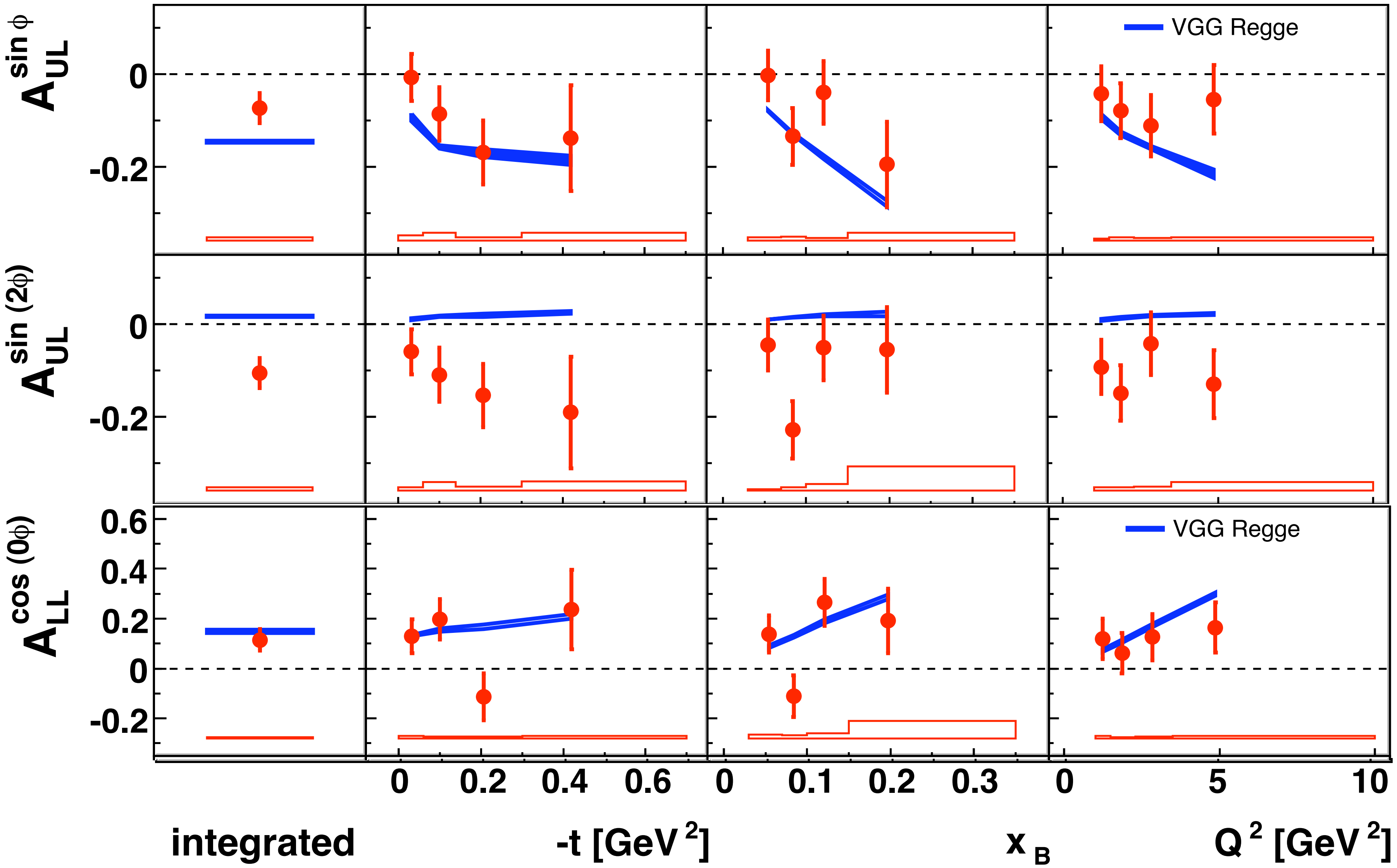
- HERMES Collaboration- Nucl. Phys. B842 (2011) 265

$$\sigma(P_\ell, P_z, \phi, e_\ell) = \sigma_{UU}(\phi, e_\ell)\left[1 + P_z \mathcal{A}_{UL}(\phi) + P_\ell P_z \mathcal{A}_{LL}(\phi) + P_\ell \mathcal{A}_{LU}(\phi)\right]$$

☛ no separate access to DVCS and interference terms

$$\mathcal{A}_{UL}(\phi) \simeq \sum_{n=1}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi)$$

$$\mathcal{A}_{LL}(\phi) = \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \cos(n\phi) .$$



$ep \to e'\gamma X$

(pre-recoil data)

GPD $\widetilde{H}$: longitudinally polarized hydrogen target

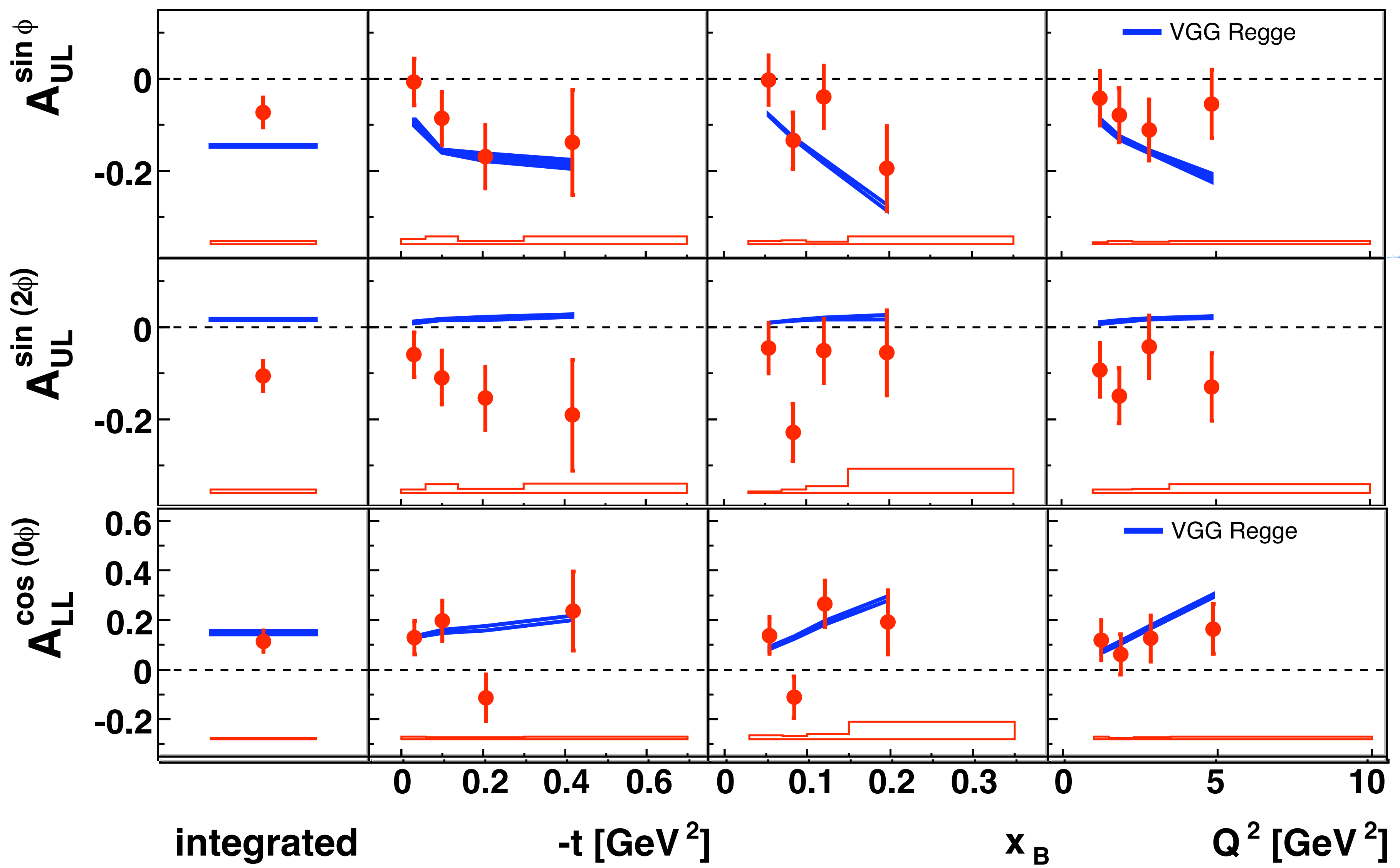
- HERMES Collaboration- Nucl. Phys. B842 (2011) 265

$$\sigma\,(P_\ell,\,P_z,\,\phi,e_\ell) = \sigma_{\rm UU}(\phi,e_\ell)\,[1 + P_z\,\mathcal{A}_{\rm UL}(\phi) + P_\ell\,P_z\,\mathcal{A}_{\rm LL}(\phi) + P_\ell\,\mathcal{A}_{\rm LU}(\phi)]$$

☛ no separate access to DVCS and interference terms

$$\mathcal{A}_{\rm UL}(\phi) \simeq \sum_{n=1}^{3} A_{\rm UL}^{\sin(n\phi)}\,\sin(n\phi)$$

$$\mathcal{A}_{\rm LL}(\phi) = \sum_{n=0}^{2} A_{\rm LL}^{\cos(n\phi)}\,\cos(n\phi)\,.$$



$$A_{UL}^{\sin\phi} \propto \begin{cases} \text{DVCS : twist} - 3 \\ \text{I : twist} - 2 \end{cases}$$

$$A_{UL}^{\sin\phi} \propto F_1 \text{Im}\widetilde{\mathcal{H}}$$

$ep \to e'\gamma X$

(pre-recoil data)

GPD $\widetilde{H}$: longitudinally polarized hydrogen target

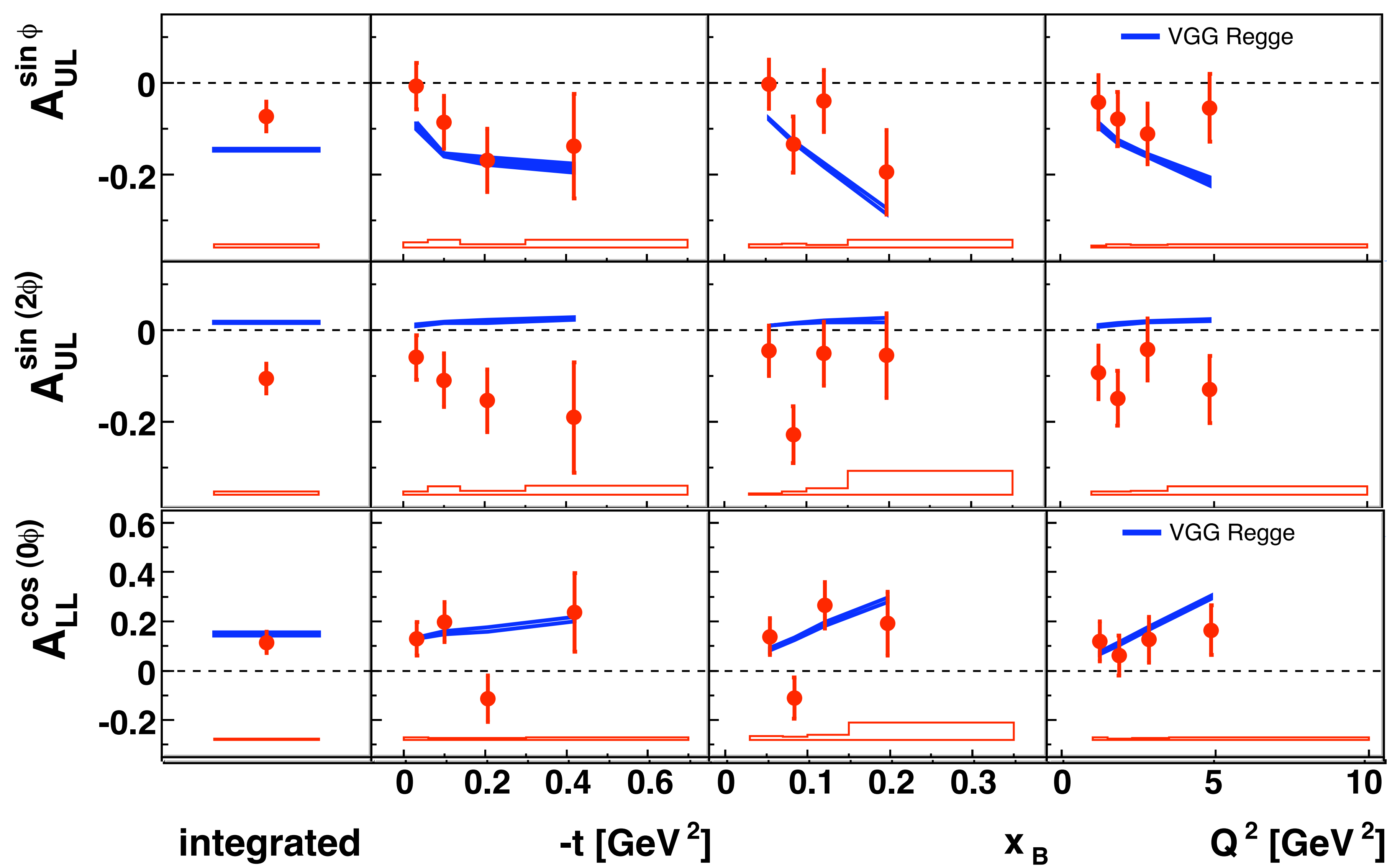
- HERMES Collaboration- Nucl. Phys. B842 (2011) 265

$$\sigma\,(P_\ell,\, P_z,\, \phi, e_\ell) = \sigma_{\rm UU}(\phi, e_\ell)\,[1 + P_z\,\mathcal{A}_{\rm UL}(\phi) + P_\ell\,P_z\,\mathcal{A}_{\rm LL}(\phi) + P_\ell\,\mathcal{A}_{\rm LU}(\phi)]$$

☛ no separate access to DVCS and interference terms

$$\mathcal{A}_{\rm UL}(\phi) \simeq \sum_{n=1}^{3} A_{\rm UL}^{\sin(n\phi)}\,\sin(n\phi)$$

$$\mathcal{A}_{\rm LL}(\phi) = \sum_{n=0}^{2} A_{\rm LL}^{\cos(n\phi)}\,\cos(n\phi)\,.$$



$$A_{UL}^{\sin\phi} \propto \begin{cases} \text{DVCS : twist} - 3 \\ \text{I : twist} - 2 \end{cases}$$

$$A_{UL}^{\sin\phi} \propto F_1 {\rm Im}\widetilde{\mathcal{H}}$$

$$A_{UL}^{\sin 2\phi} \propto \begin{cases} \text{I : quark twist} - 3 \\ \quad \text{or gluon twist} - 2 \\ \text{DVCS : twist} - 4 \end{cases}$$

☛ unexpected large value

$ep \to e'\gamma X$
(pre-recoil data)

GPD $\widetilde{H}$: longitudinally polarized hydrogen target

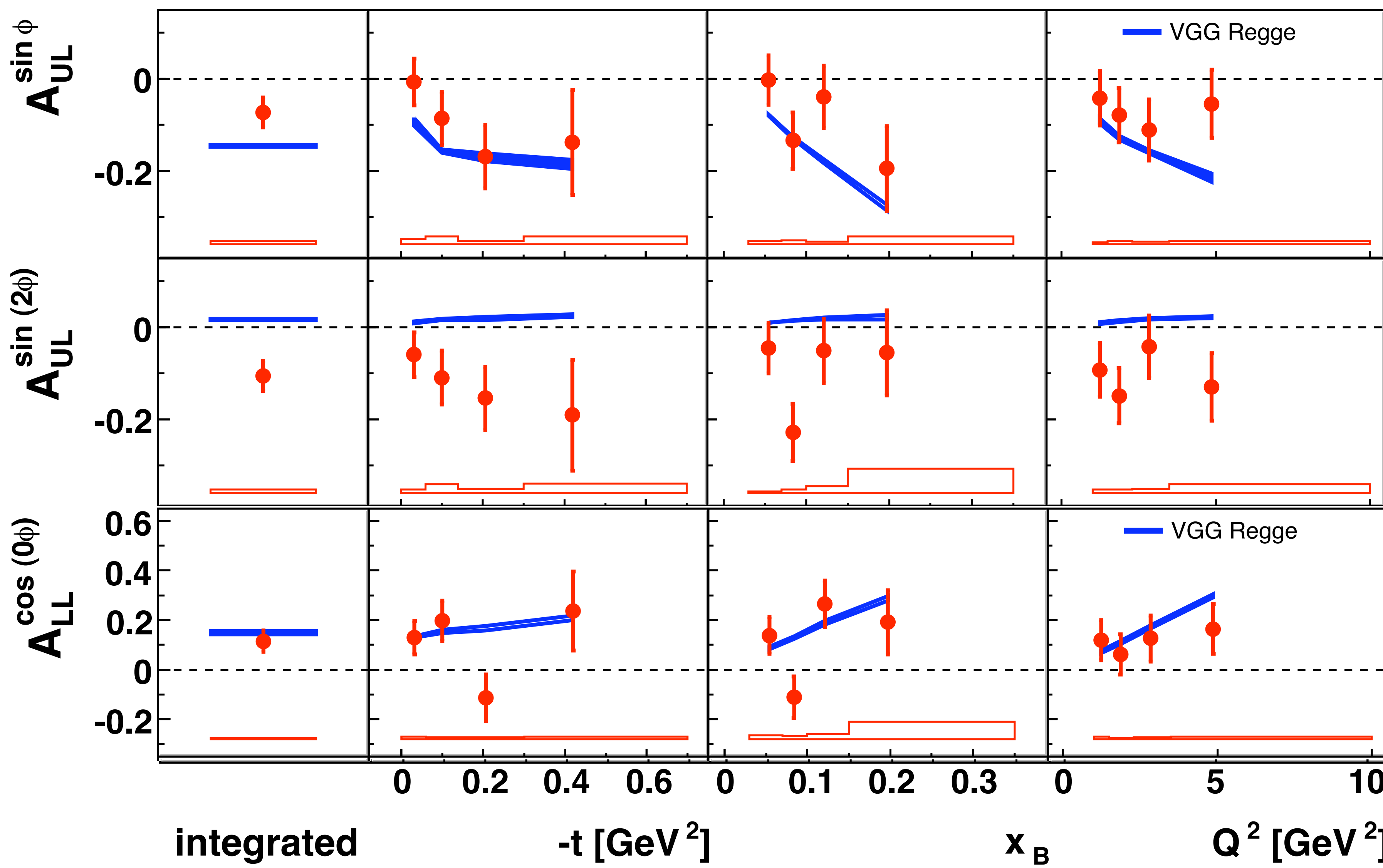
- HERMES Collaboration- Nucl. Phys. B842 (2011) 265

$$\sigma\,(P_\ell,\,P_z,\,\phi,e_\ell) = \sigma_{\mathrm{UU}}(\phi,e_\ell)\,[1 + P_z\,\mathcal{A}_{\mathrm{UL}}(\phi) + P_\ell\,P_z\,\mathcal{A}_{\mathrm{LL}}(\phi) + P_\ell\,\mathcal{A}_{\mathrm{LU}}(\phi)]$$

☛ no separate access to DVCS and interference terms

$$\mathcal{A}_{\mathrm{UL}}(\phi) \simeq \sum_{n=1}^{3} A_{\mathrm{UL}}^{\sin(n\phi)}\,\sin(n\phi)$$

$$\mathcal{A}_{\mathrm{LL}}(\phi) = \sum_{n=0}^{2} A_{\mathrm{LL}}^{\cos(n\phi)}\,\cos(n\phi)\,.$$



$$A_{UL}^{\sin\phi} \propto \begin{cases} \text{DVCS : twist} - 3 \\ \text{I : twist} - 2 \end{cases}$$

$$A_{UL}^{\sin\phi} \propto F_1 \mathrm{Im}\widetilde{\mathcal{H}}$$

$$A_{UL}^{\sin 2\phi} \propto \begin{cases} \text{I : quark twist} - 3 \\ \quad \text{or gluon twist} - 2 \\ \text{DVCS : twist} - 4 \end{cases}$$

☛ unexpected large value

$$A_{LL}^{\cos 0\phi} \propto \begin{cases} \text{DVCS : twist} - 2 \\ \text{I : twist} - 2 \end{cases}$$

$$A_{LL}^{cos0\phi} \propto F_1 \mathrm{Re}\widetilde{\mathcal{H}}$$

$ep \to e'\gamma X$
(pre-recoil data)

GPD E: transversely polarized hydrogen target

- HERMES Collaboration- : JHEP 06 (2008) 066, 24

$$\sigma(\phi, \phi_s, e_\ell, S_\perp, \lambda) = \sigma_{\mathrm{UU}}(\phi)\Big\{1 + e_\ell \mathcal{A}_C(\phi) + \lambda \mathcal{A}_{LU}^{DVCS}(\phi) + e_\ell \lambda \mathcal{A}_{LU}^{I}(\phi)$$
$$+S_\perp \mathcal{A}_{UT}^{DVCS}(\phi, \phi_S) + e_\ell S_\perp \mathcal{A}_{UT}^{I}(\phi, \phi_S)$$
$$+ \lambda S_\perp \mathcal{A}_{LT}^{BH+DVCS}(\phi, \phi_S) + e_\ell \lambda S_\perp \mathcal{A}_{LT}^{I}(\phi, \phi_S)\Big\}$$

$ep \to e'\gamma X$
(pre-recoil data)

GPD E: transversely polarized hydrogen target

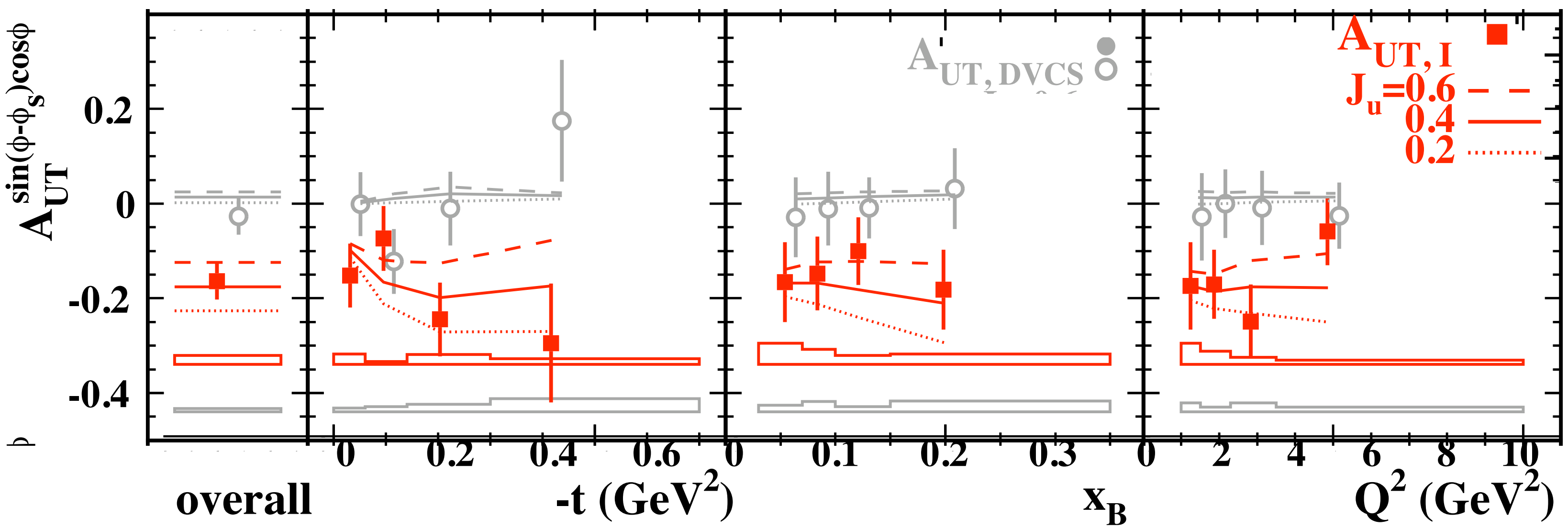
- HERMES Collaboration- : JHEP 06 (2008) 066, 24

$$\sigma(\phi,\phi_s,e_\ell,S_\perp,\lambda) = \sigma_{UU}(\phi)\Big\{1 + e_\ell\mathcal{A}_C(\phi) + \lambda\mathcal{A}_{LU}^{DVCS}(\phi) + e_\ell\lambda\mathcal{A}_{LU}^{I}(\phi) + S_\perp\mathcal{A}_{UT}^{DVCS}(\phi,\phi_S) + e_\ell S_\perp\mathcal{A}_{UT}^{I}(\phi,\phi_S) + \lambda S_\perp\mathcal{A}_{LT}^{BH+DVCS}(\phi,\phi_S) + e_\ell\lambda S_\perp\mathcal{A}_{LT}^{I}(\phi,\phi_S)\Big\}$$

$$\mathcal{A}_{UT}^{I,DVCS}(\phi,\phi_S) = \frac{(\sigma^{+\Uparrow}-\sigma^{+\Downarrow}) \pm (\sigma^{-\Uparrow}-\sigma^{-\Downarrow})}{(\sigma^{+\Uparrow}+\sigma^{+\Downarrow}) + (\sigma^{-\Uparrow}+\sigma^{-\Downarrow})}$$

$\propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]$

$\propto \mathrm{Im}[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* + \xi\widetilde{\mathcal{E}}\widetilde{\mathcal{H}}^* - \widetilde{\mathcal{H}}\xi\widetilde{\mathcal{E}}^*]$



☛ $A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$ found much more sensitive to GPD E than others, and thus to J_u

☛ with a good model, allows a model-dependent constraint

$ep \to e'\gamma X$
(pre-recoil data)

GPD E: transversely polarized hydrogen target

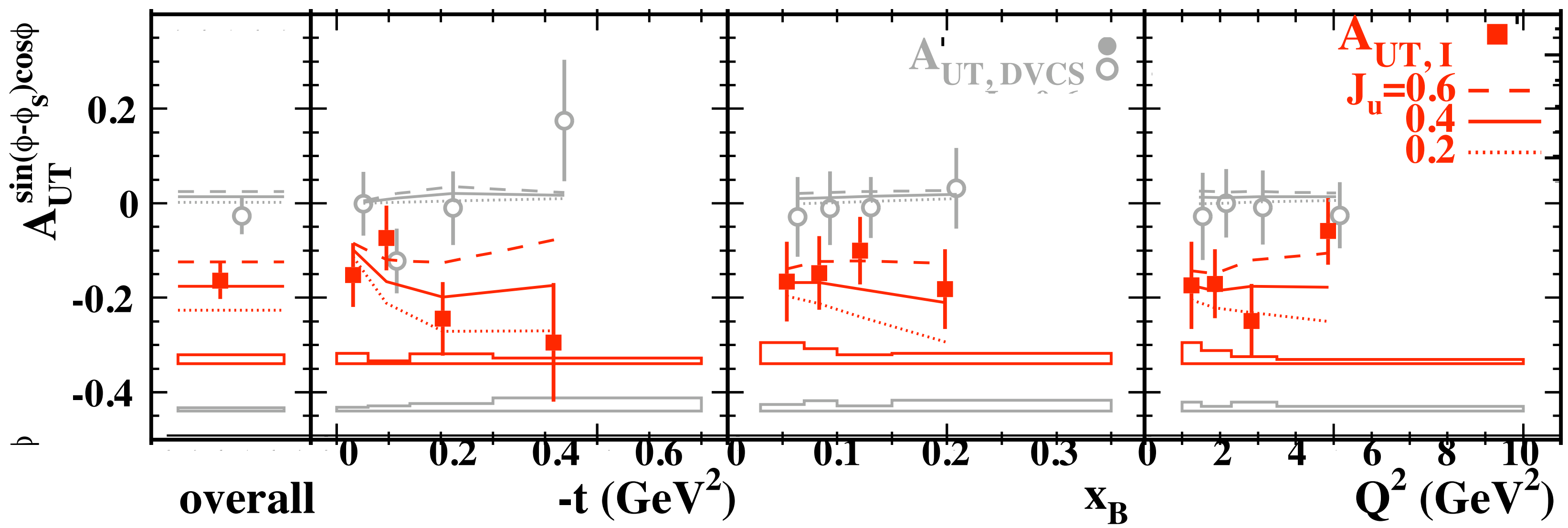
- HERMES Collaboration- : JHEP 06 (2008) 066, 24

$$\sigma(\phi,\phi_s,e_\ell,S_\perp,\lambda) = \sigma_{\rm UU}(\phi)\Big\{1+e_\ell\mathcal{A}_C(\phi)+\lambda\mathcal{A}_{LU}^{DVCS}(\phi)+e_\ell\lambda\mathcal{A}_{LU}^{I}(\phi)$$
$$+S_\perp\mathcal{A}_{UT}^{DVCS}(\phi,\phi_S)+e_\ell S_\perp\mathcal{A}_{UT}^{I}(\phi,\phi_S)$$
$$+\lambda S_\perp\mathcal{A}_{LT}^{BH+DVCS}(\phi,\phi_S)+e_\ell\lambda S_\perp\mathcal{A}_{LT}^{I}(\phi,\phi_S)\Big\}$$

$$\mathcal{A}_{UT}^{I,DVCS}(\phi,\phi_S)=\frac{(\sigma^{+\Uparrow}-\sigma^{+\Downarrow})\pm(\sigma^{-\Uparrow}-\sigma^{-\Downarrow})}{(\sigma^{+\Uparrow}+\sigma^{+\Downarrow})+(\sigma^{-\Uparrow}+\sigma^{-\Downarrow})}$$

$\propto \mathrm{Im}[F_2\mathcal{H}-F_1\mathcal{E}]$

$\propto \mathrm{Im}[\mathcal{H}\mathcal{E}^*-\mathcal{E}\mathcal{H}^*+\xi\widetilde{\mathcal{E}}\,\widetilde{\mathcal{H}}^*-\widetilde{\mathcal{H}}\,\xi\widetilde{\mathcal{E}}^*]$



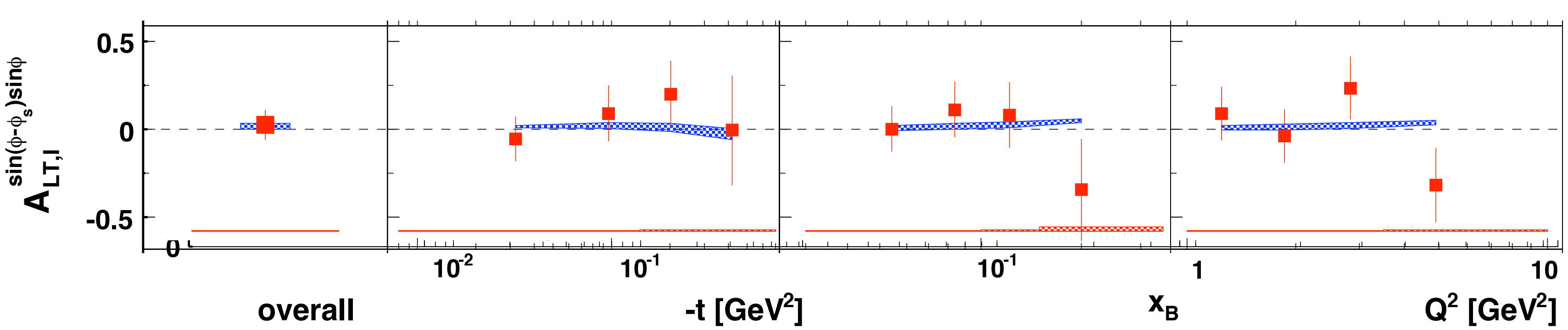
☛ $A_{\rm UT,I}^{\sin(\phi-\phi_s)\cos\phi}$ found much more sensitive to GPD E than others, and thus to J_u

☛ with a good model, allows a model-dependent constraint

- HERMES Collaboration- Phys. Lett. B 704 (2011) 15-23

$\propto \mathrm{Re}[F_2\mathcal{H}-F_1\mathcal{E}]$

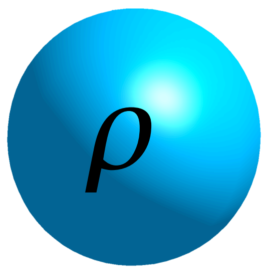
$$\mathcal{A}_{LT}^{I,BH+DVCS}(\phi,\phi_S)=\frac{(\overrightarrow{\sigma}^{+\Uparrow}+\overleftarrow{\sigma}^{+\Downarrow}-\overrightarrow{\sigma}^{+\Downarrow}-\overleftarrow{\sigma}^{+\Uparrow})\pm(\overrightarrow{\sigma}^{-\Uparrow}+\overleftarrow{\sigma}^{-\Downarrow}-\overrightarrow{\sigma}^{-\Downarrow}-\overleftarrow{\sigma}^{-\Uparrow})}{(\overrightarrow{\sigma}^{+\Uparrow}+\overleftarrow{\sigma}^{+\Downarrow}+\overrightarrow{\sigma}^{+\Downarrow}+\overleftarrow{\sigma}^{+\Uparrow})+(\overrightarrow{\sigma}^{+\Uparrow}+\overleftarrow{\sigma}^{+\Downarrow}+\overrightarrow{\sigma}^{+\Downarrow}+\overleftarrow{\sigma}^{+\Uparrow})}$$

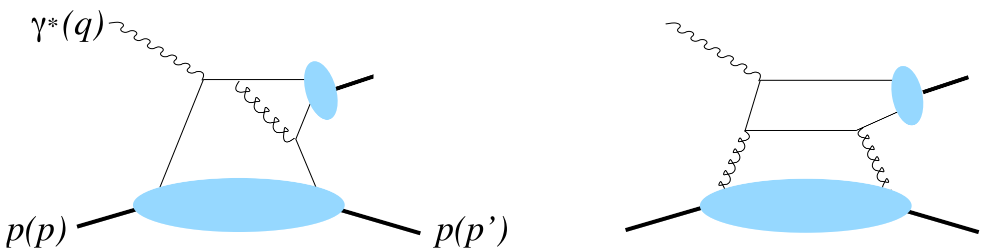


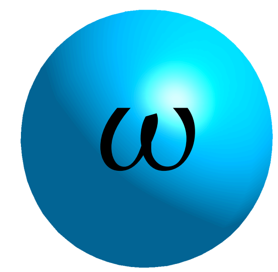
☛ $A_{\rm UT,I}^{\sin(\phi-\phi_s)\sin\phi}$ could provide a similar constraint to the real part

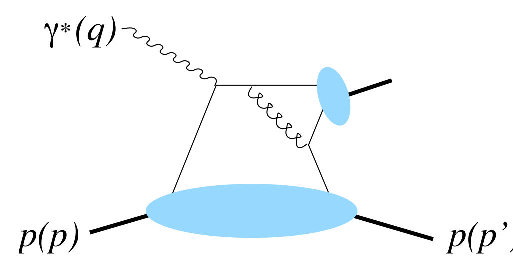
☛ due to different kinematic pre-factors, this amplitude is suppressed

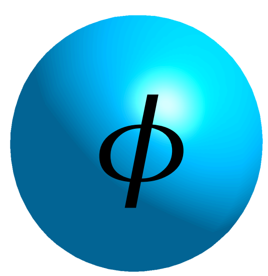
given channel probes specific GPD flavour

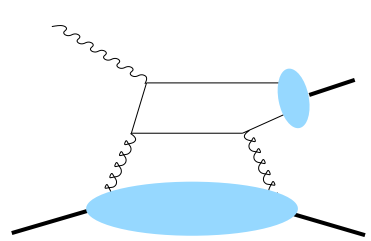


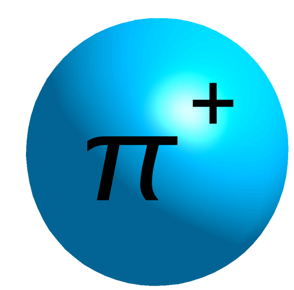




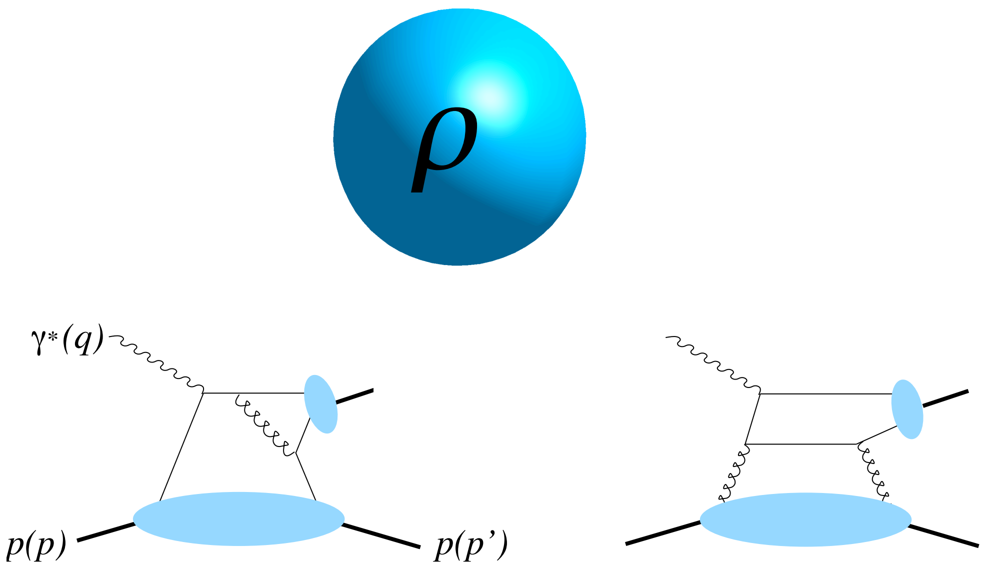


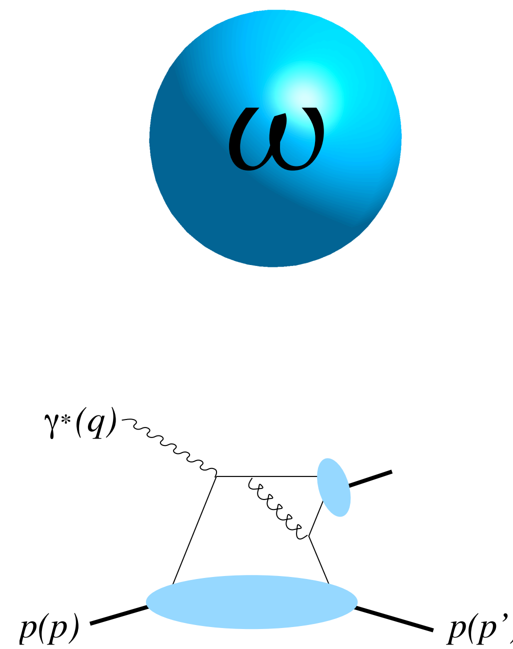


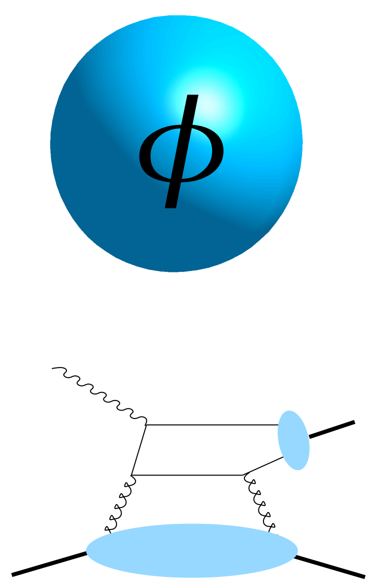


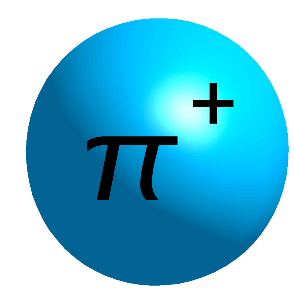


given channel probes specific GPD flavour

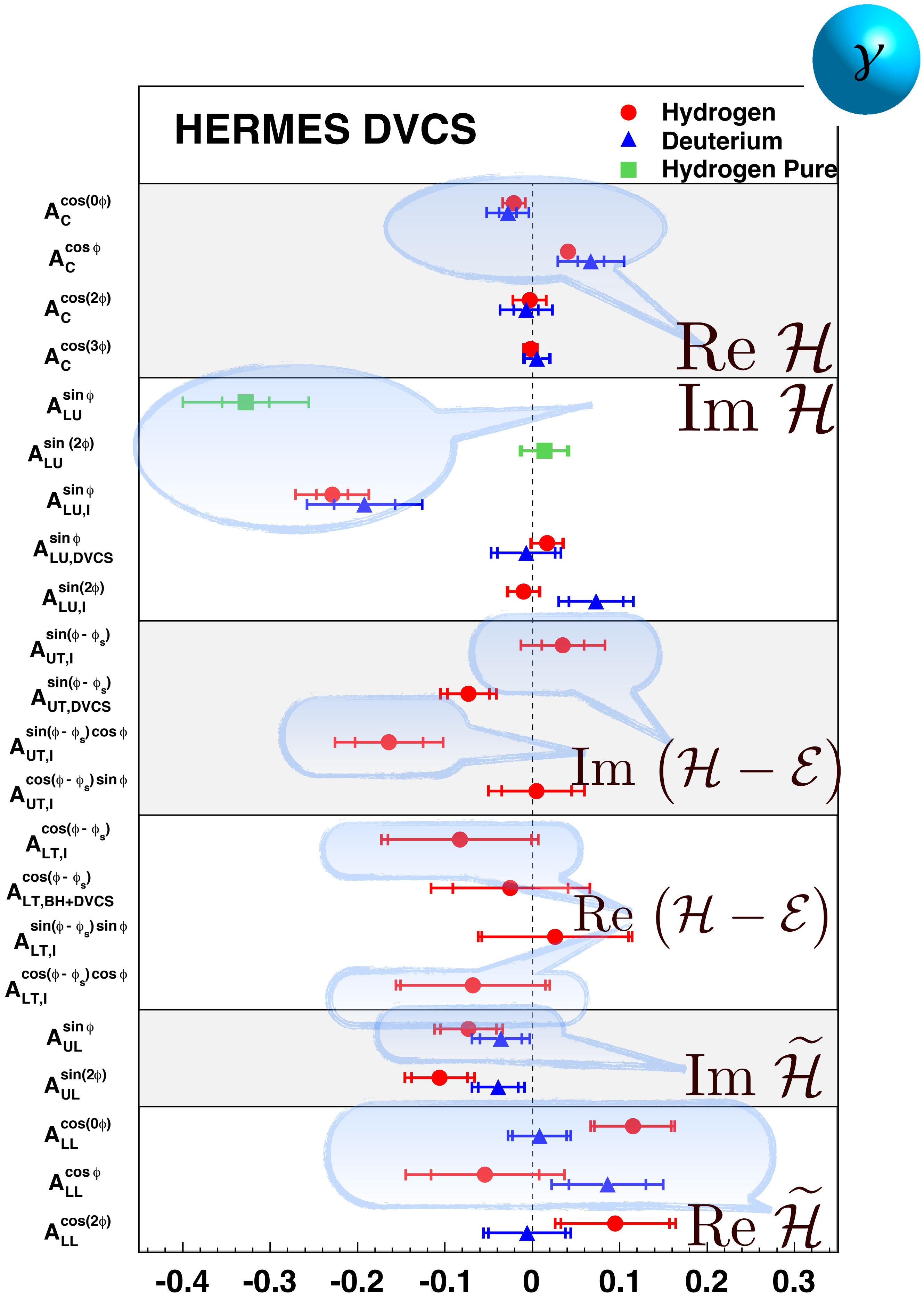


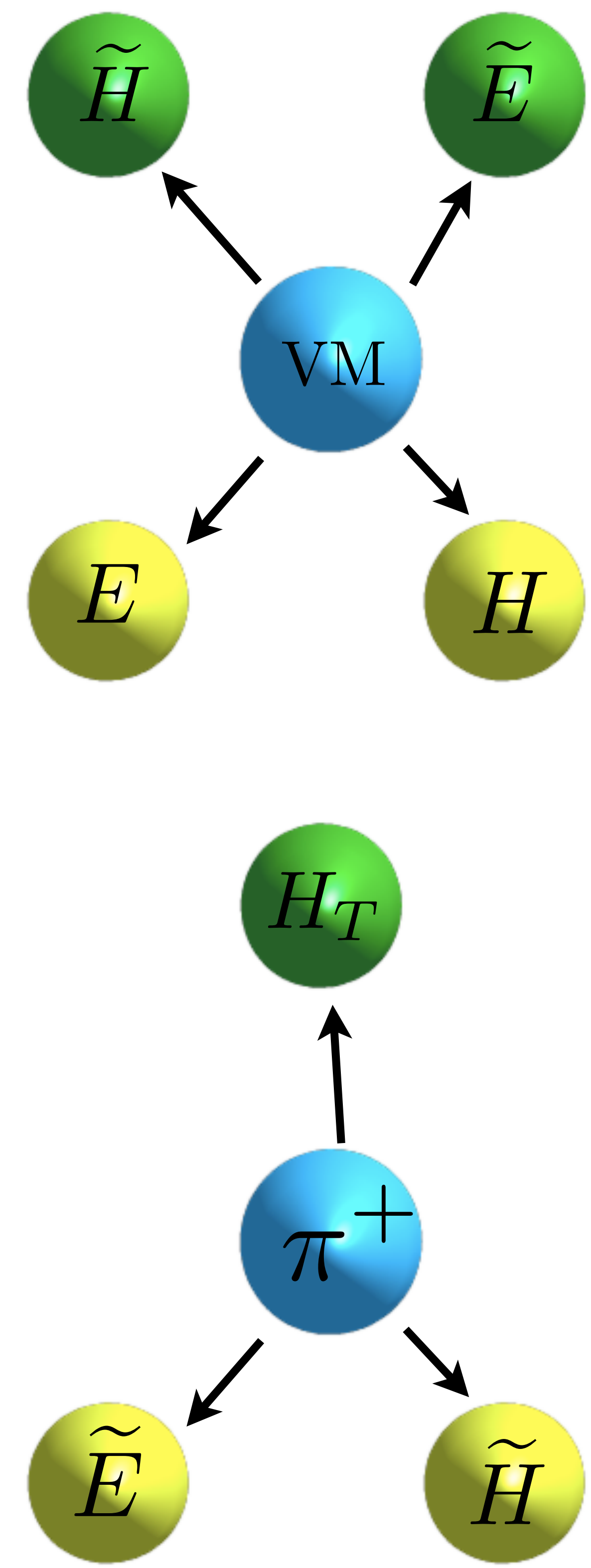






✓ see the talk by W. Augustyniak


HERMES DVCS
Hydrogen
Deuterium
Hydrogen Pure
γ
$A_C^{\cos(0\phi)}$
$A_C^{\cos\phi}$
$A_C^{\cos(2\phi)}$
$A_C^{\cos(3\phi)}$
$A_{LU}^{\sin\phi}$
$A_{LU}^{\sin(2\phi)}$
$A_{LU,I}^{\sin\phi}$
$A_{LU,DVCS}^{\sin\phi}$
$A_{LU,I}^{\sin(2\phi)}$
$A_{UT,I}^{\sin(\phi-\phi_s)}$
$A_{UT,DVCS}^{\sin(\phi-\phi_s)}$
$A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$
$A_{UT,I}^{\cos(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)}$
$A_{LT,BH+DVCS}^{\cos(\phi-\phi_s)}$
$A_{LT,I}^{\sin(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)\cos\phi}$
$A_{UL}^{\sin\phi}$
$A_{UL}^{\sin(2\phi)}$
$A_{LL}^{\cos(0\phi)}$
$A_{LL}^{\cos\phi}$
$A_{LL}^{\cos(2\phi)}$
$\mathrm{Re}\,\mathcal{H}$
$\mathrm{Im}\,\mathcal{H}$
$\mathrm{Im}\,(\mathcal{H}-\mathcal{E})$
$\mathrm{Re}\,(\mathcal{H}-\mathcal{E})$
$\mathrm{Im}\,\widetilde{\mathcal{H}}$
$\mathrm{Re}\,\widetilde{\mathcal{H}}$
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Amplitude Value


$\widetilde{H}$
$\widetilde{E}$
VM
E
H
H_T
π^+
$\widetilde{E}$
$\widetilde{H}$

The Spin Community And The World

- HERMES has been the pioneering collaboration in TMD and GPD fields
- still very important player in the field of nucleon (spin) structure
  - polarized $e^{+/-}$ beams
  - pure gas target
  - good particle identification
  - recoil detector