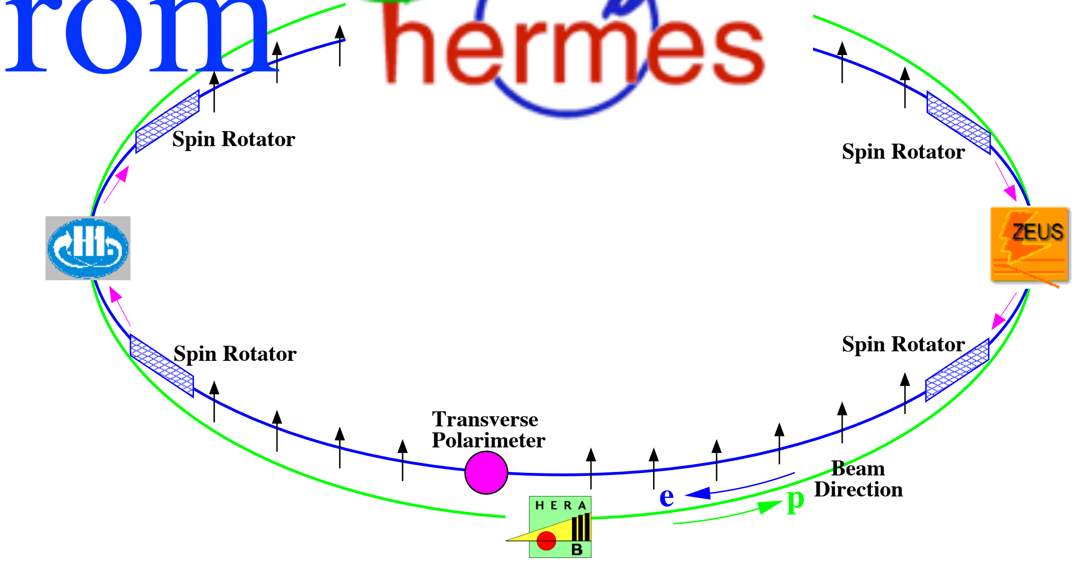
Recent results from hermes

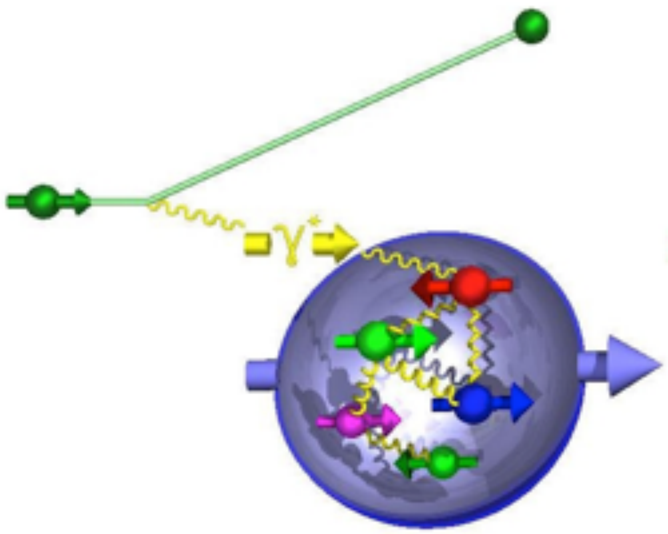


DSPIN 2013

Dubna, Russia, October 8 - 12, 2013

Wolf-Dieter Nowak,
Ami Rostomyan, Charlotte Van Hulse
(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

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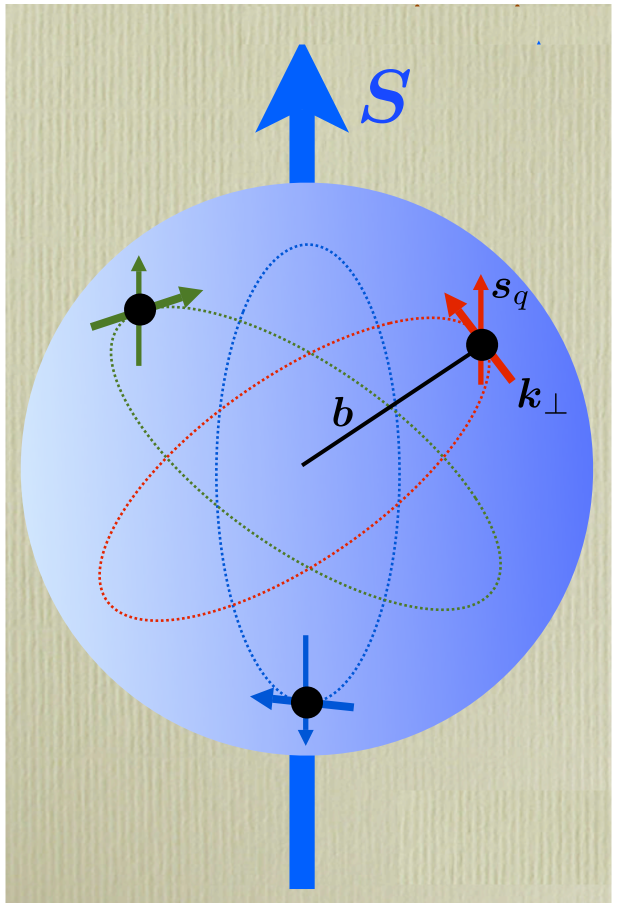
quantum phase-space "tomography" of the nucleon

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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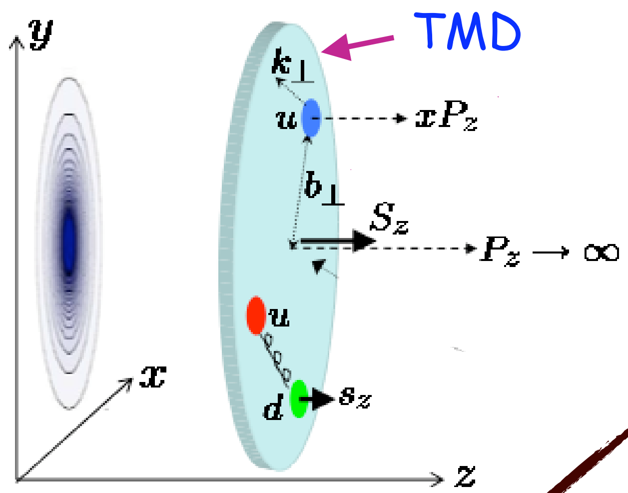
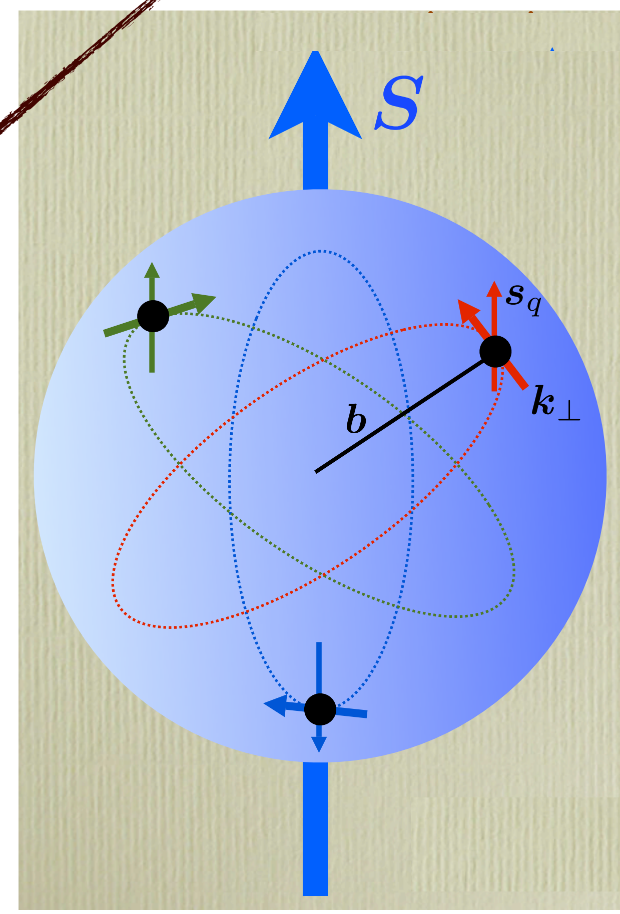


$$\int d^3\mathbf{b}$$

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

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



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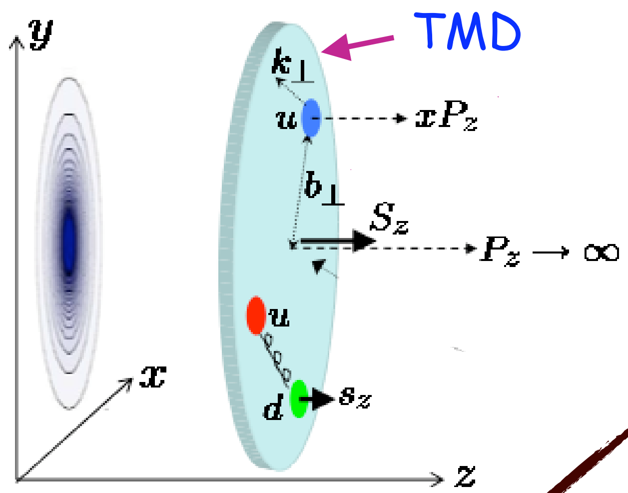

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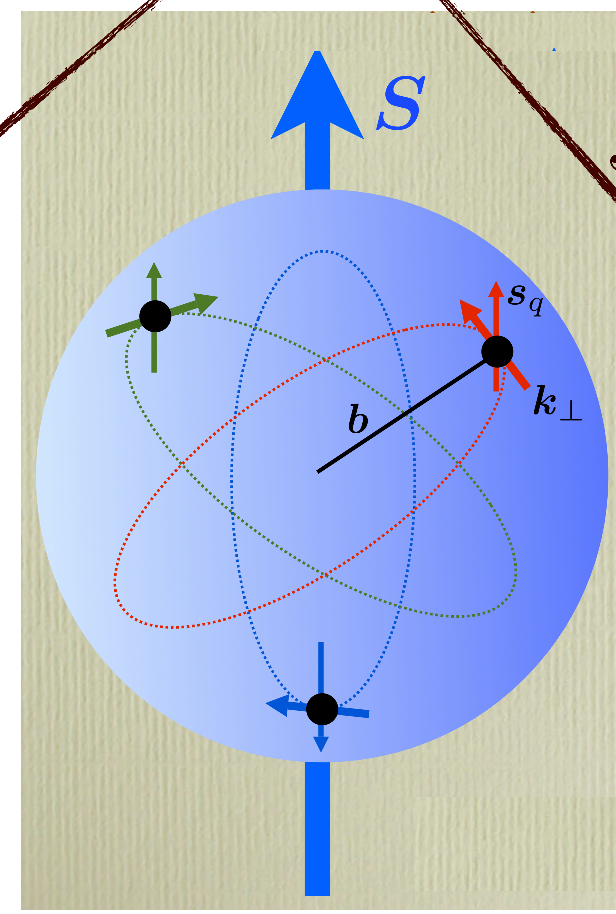
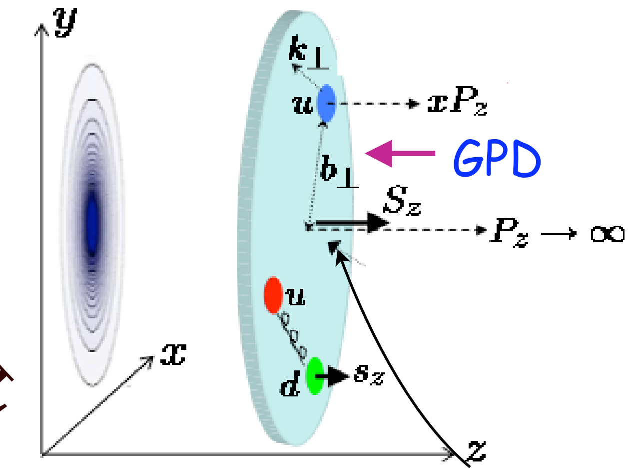


$$\int d^2\mathbf{k_T}\, d\mathbf{b_L}$$



center of momentum

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

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

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

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transverse position dependent distribution functions

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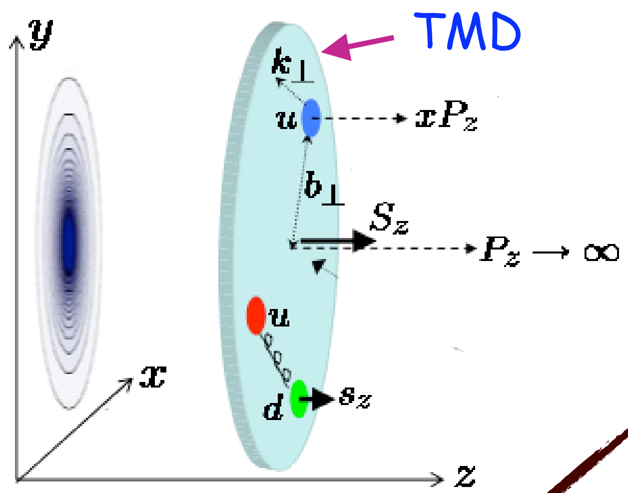

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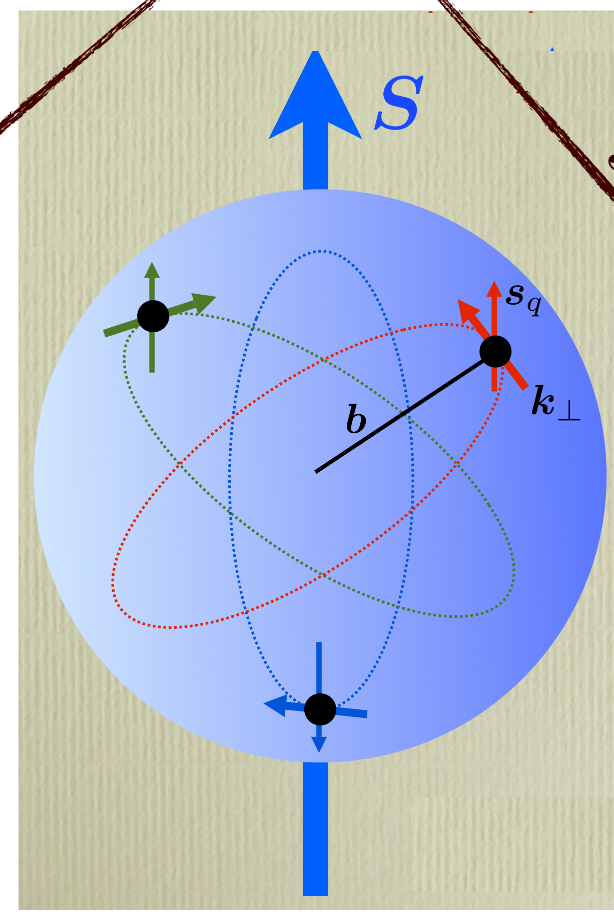

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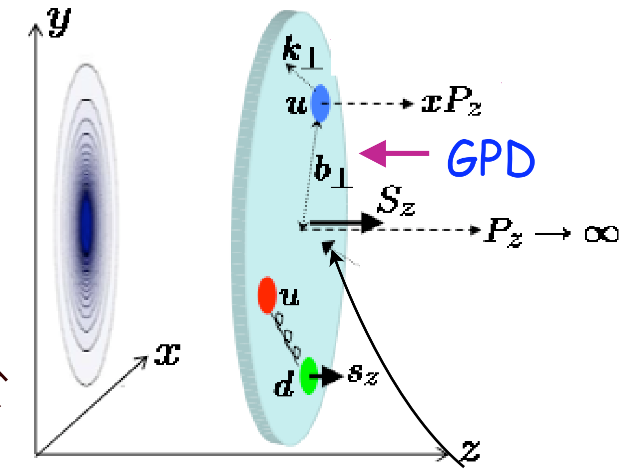

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$q(x, \mathbf{b_T})$

transve[illegible]osition dependent d[illegible]bution functions

FT

$H(x, \xi, t)$

Generalized Parton Distributions **(GPDs)**

quantum phase−space "tomography" of the nucleon

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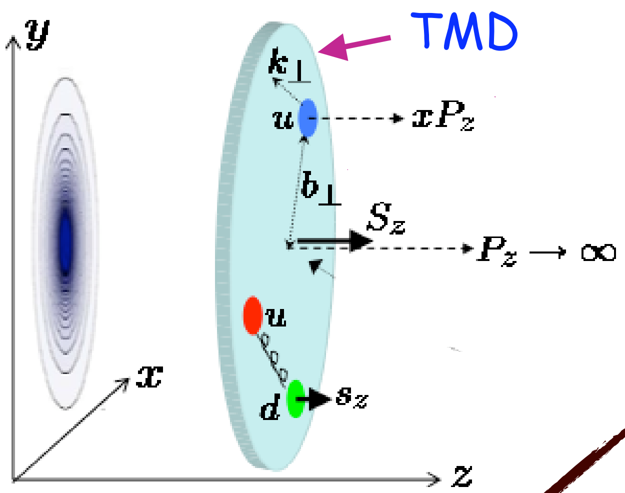

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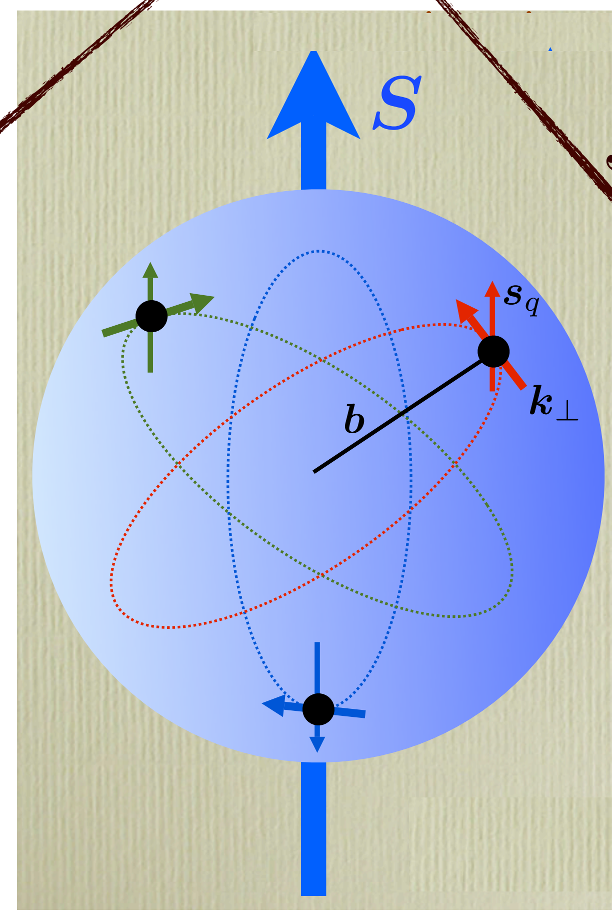

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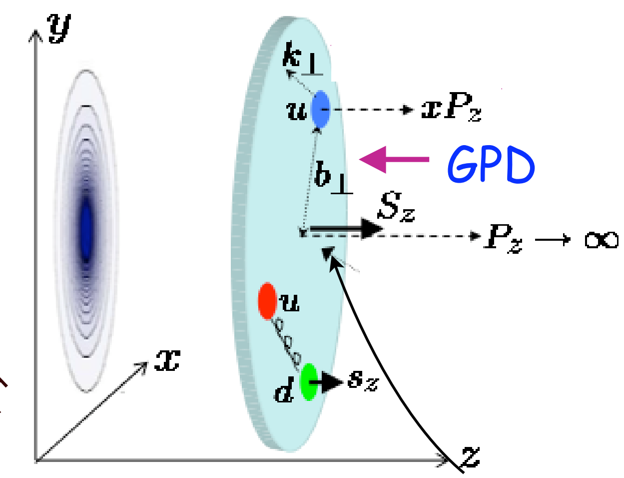

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transverse position dependent distribution functions

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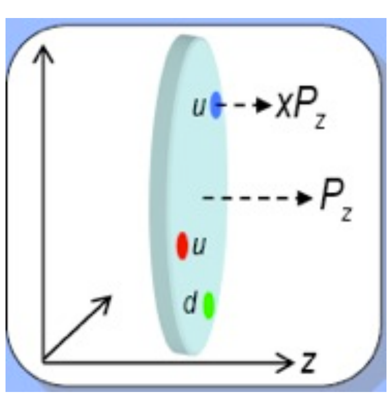
Generalized Parton Distributions (**GPDs**)

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

$\xi = 0,\ t = 0$

$f^q(x)$



Parton Distribution Functions (**PDFs**)

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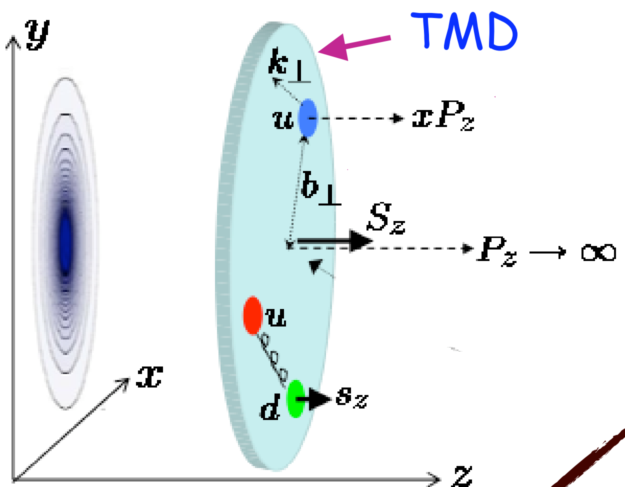

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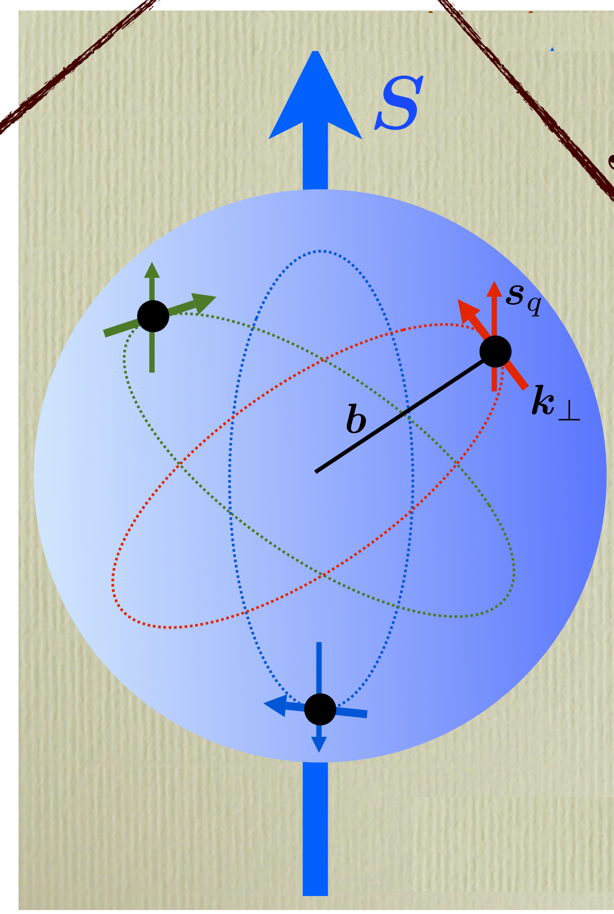

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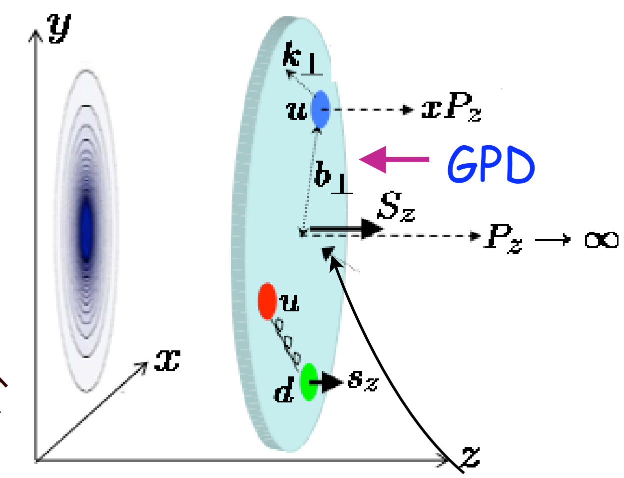

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☛**semi-inclusive measurements**

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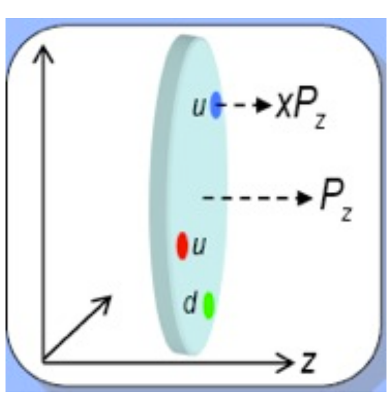
transve osition dependent

d bution functions

FT



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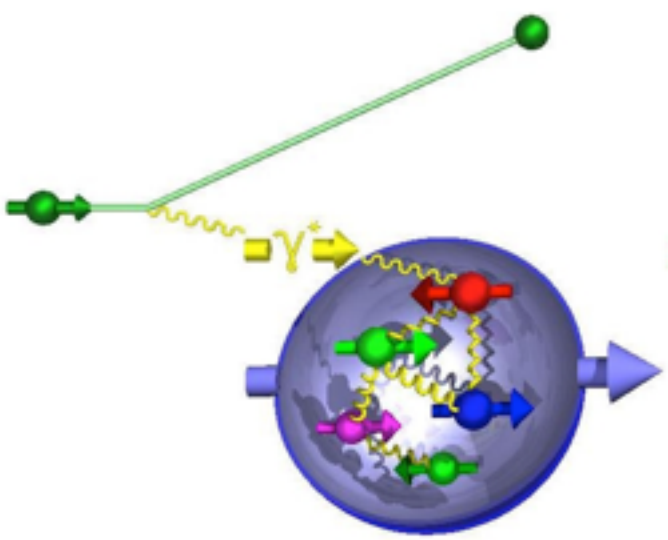
Generalized Parton Distributions (**GPDs**)

☛ **exclusive measurements**

Parton Distribution Functions (**PDFs**)

☛ **inclusive measurements**

spin and hadronization



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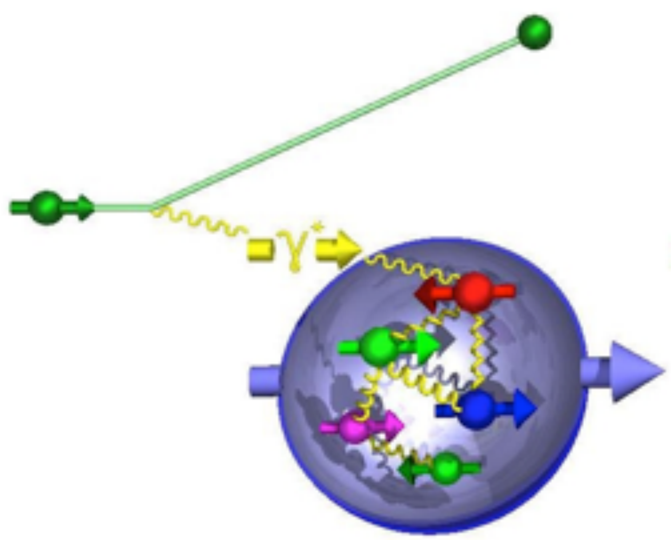

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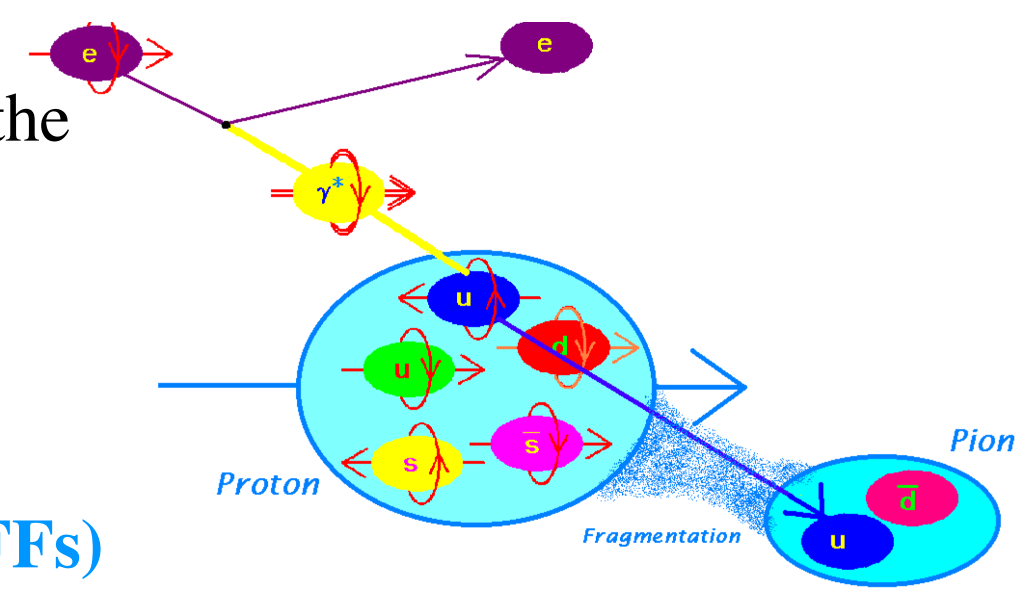
- ☛ momentum: quarks carry ~ 50 % of the proton momentum
- ☛ spin: total quark spin contribution only ~30%
- ➡ **study of TMD DFs and GPDs**

✓ isolated quarks have never been observed in nature

✓ fragmentation functions were introduced to describe the hadronization

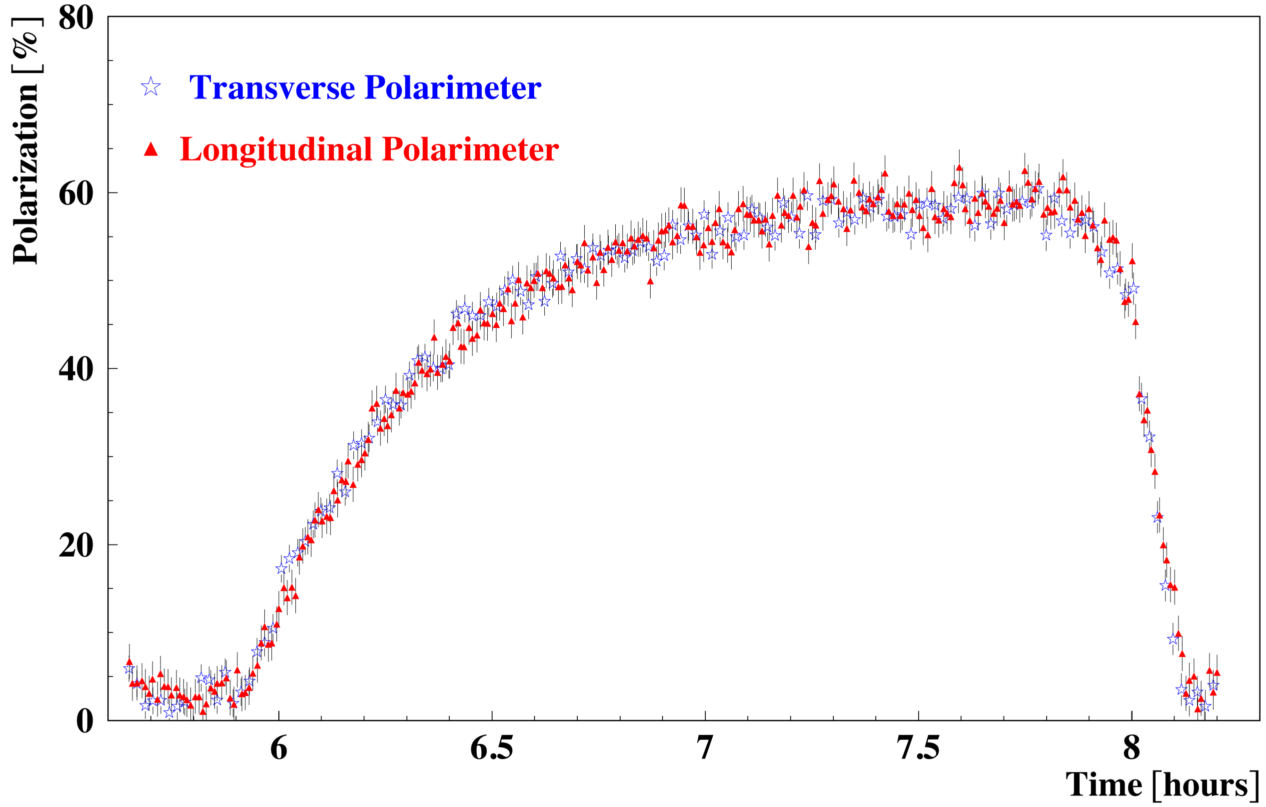
- ☛ non-pQCD objects
- ☛ universal but not well known functions
- ➡ **advantage of lepton-nucleon scattering data → flavour separation of fragmentation functions (FFs)**



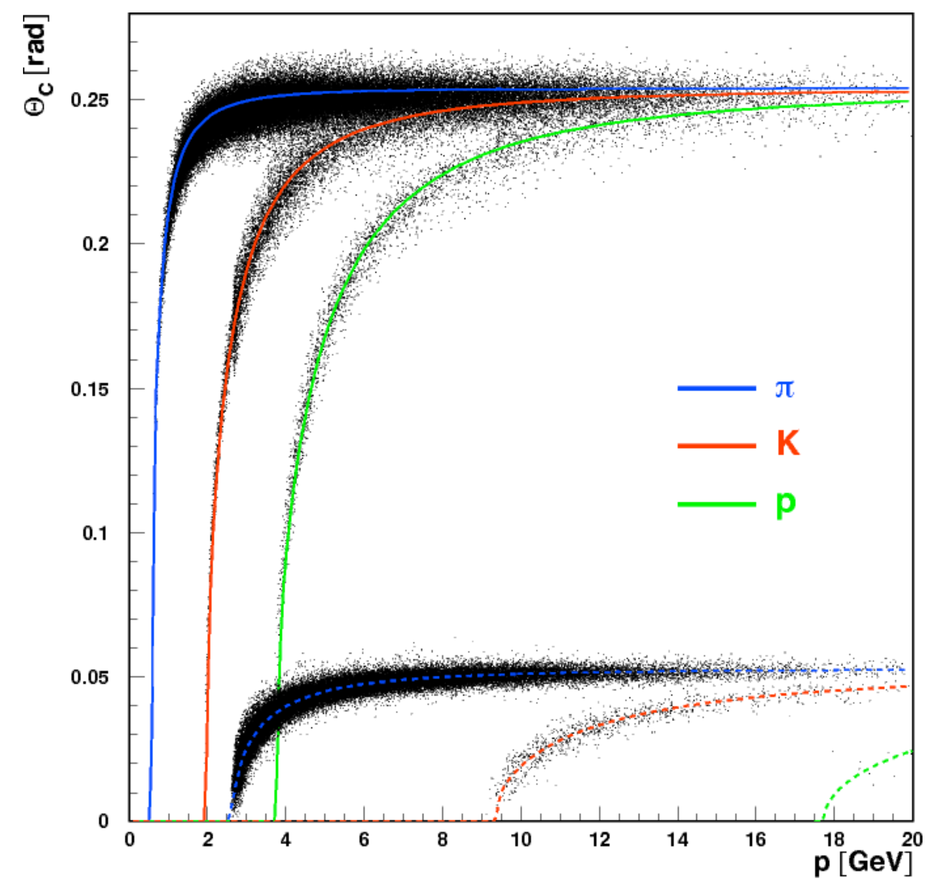
advantages of the experiment

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

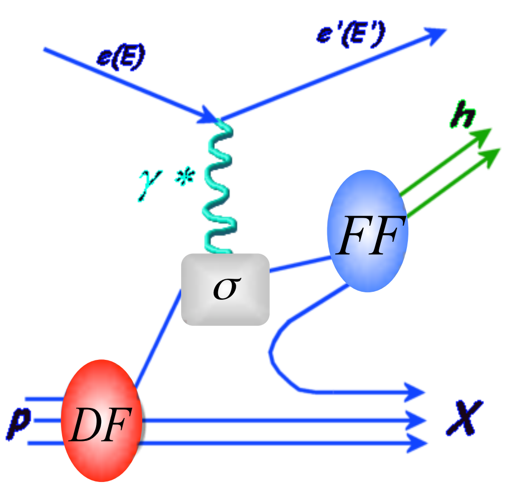
F_{XY}

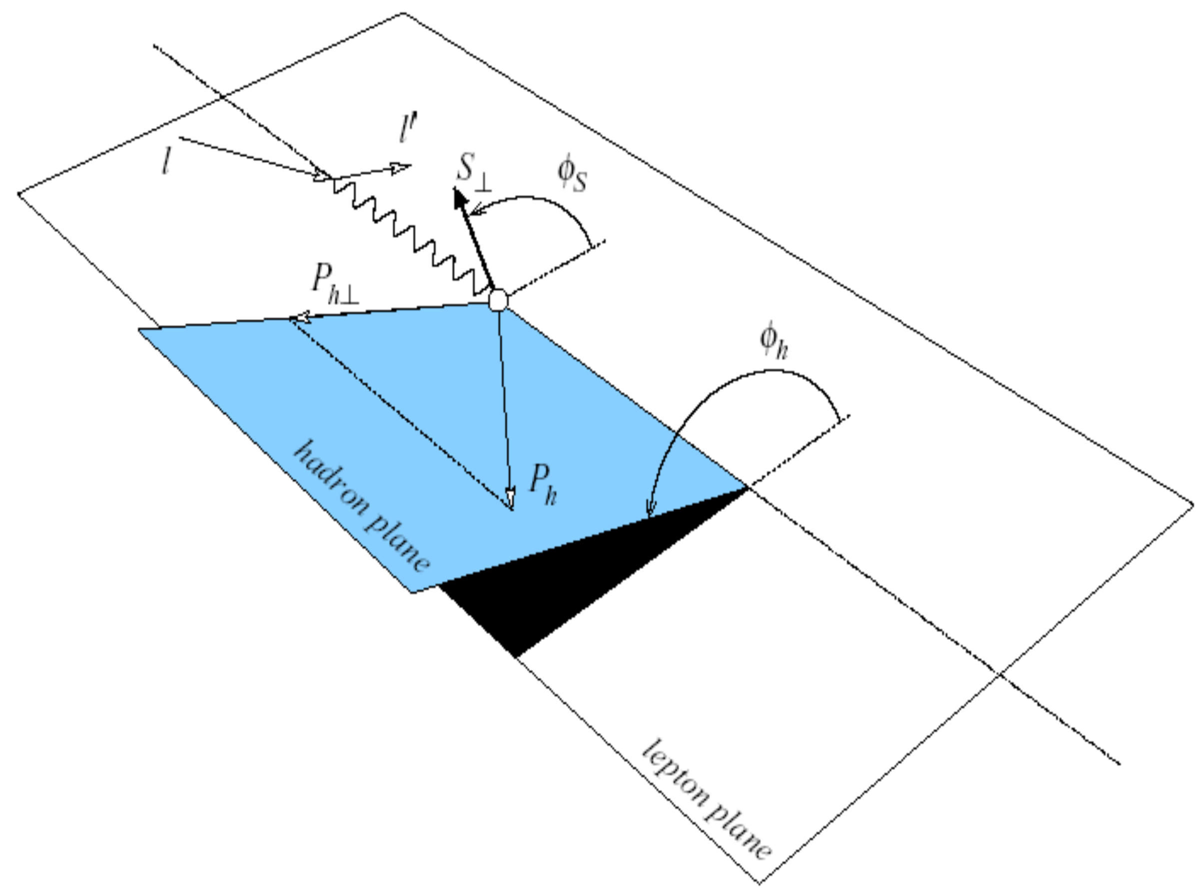
beam: λ_e

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

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

$$f_1 \otimes D_1$$





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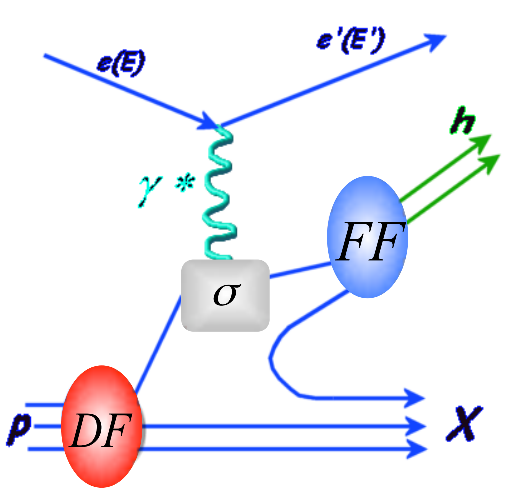
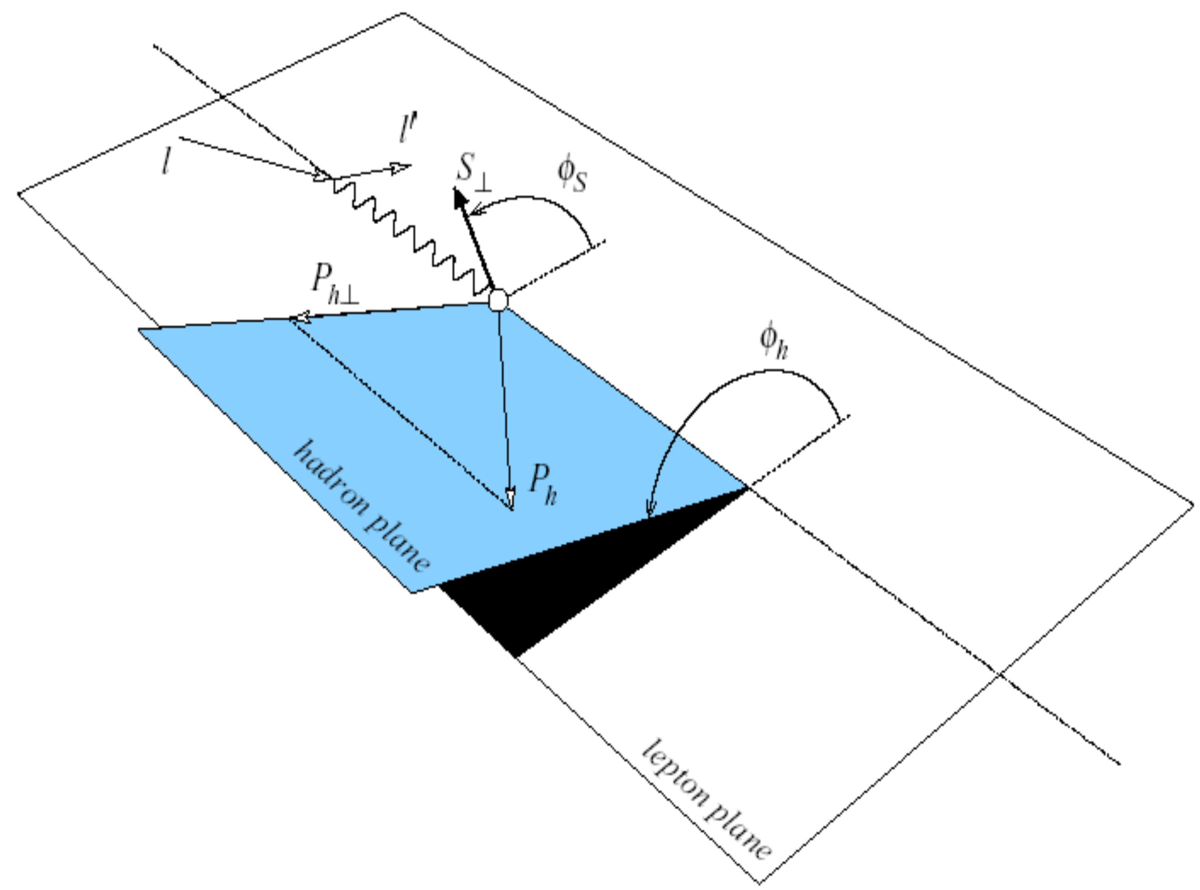
$$+ \quad \lambda_e\left\{\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi\right\} + S_{||}\left\{\ldots\right\} + S_\perp\left\{\ldots\right\}$$





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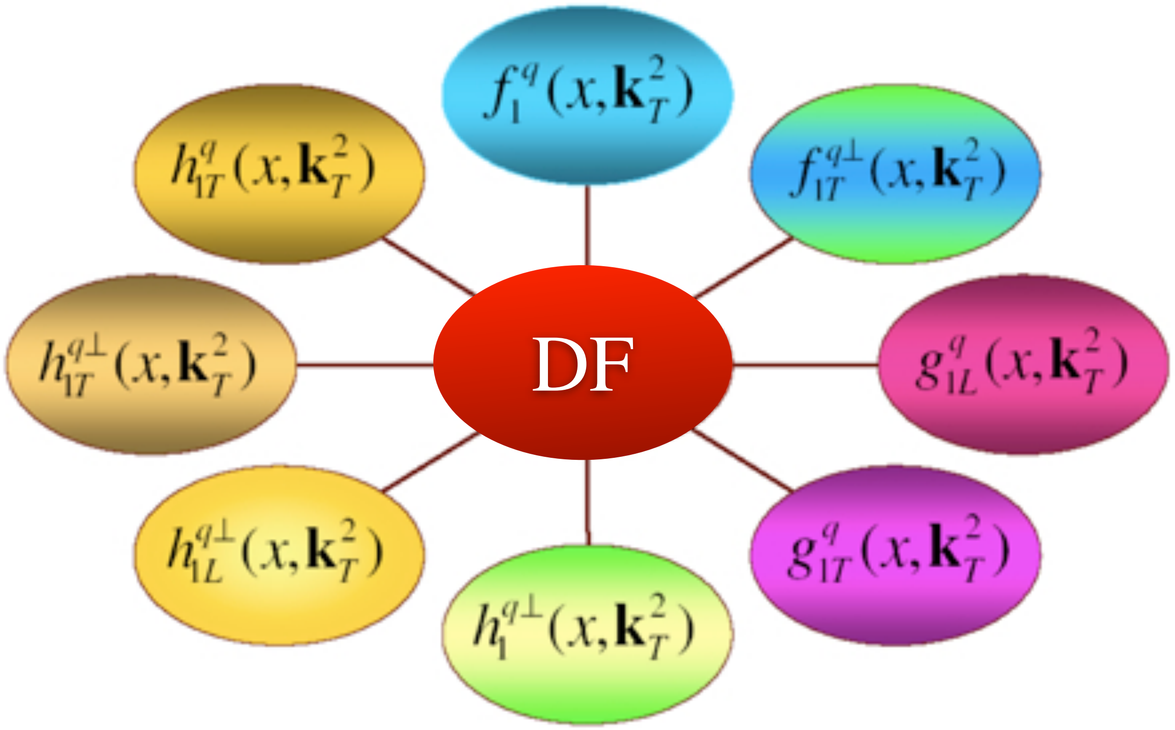
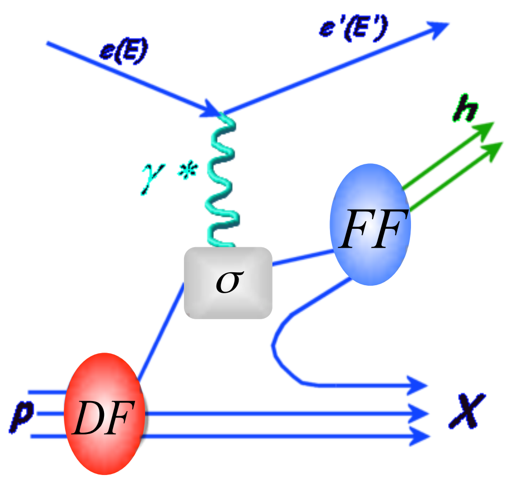
leading twist TMD DF:
parameterize the quark-flavor structure of the nucleon





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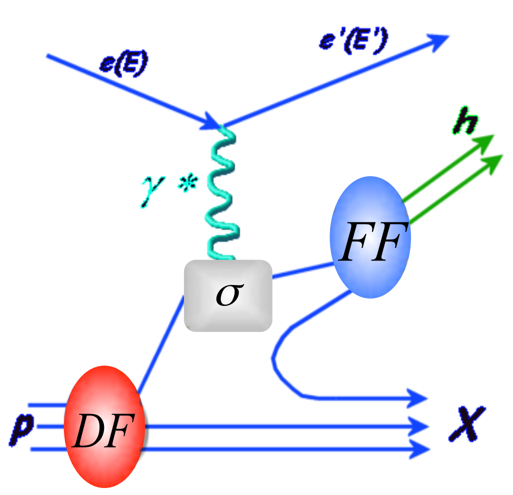
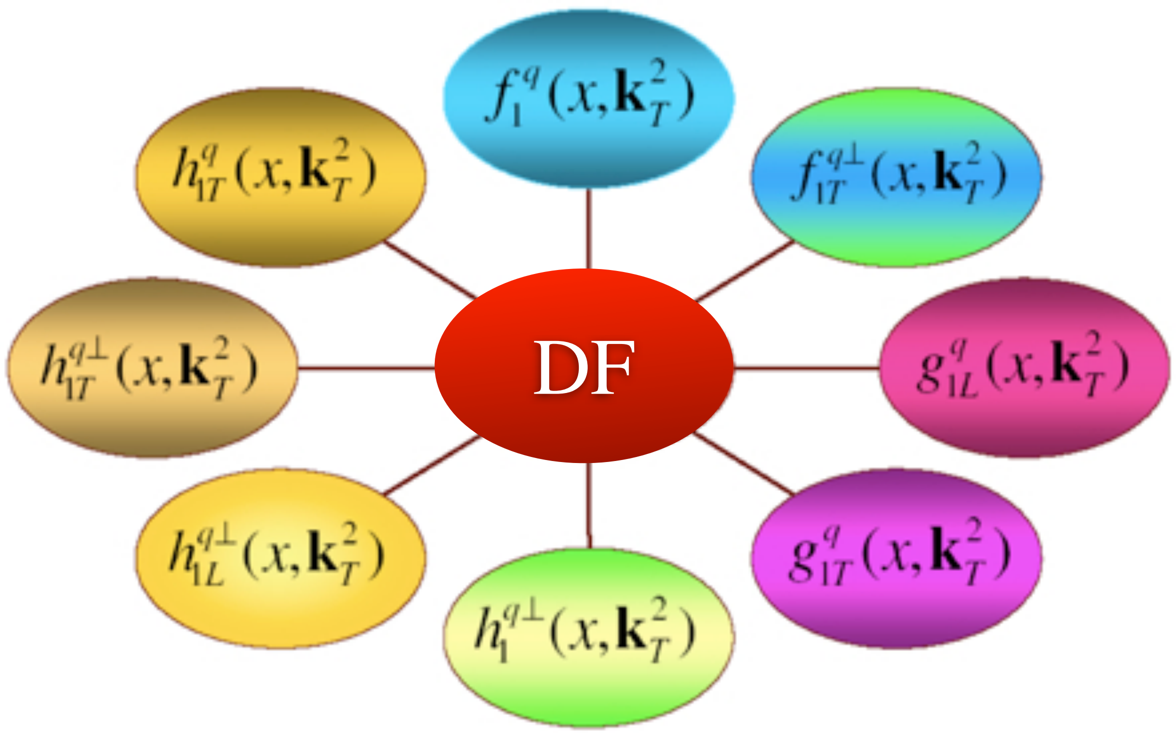
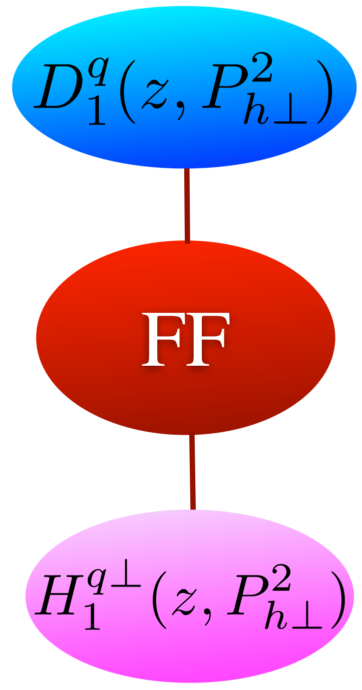
parameterize the quark-flavor structure of the nucleon

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







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PRL 94 (2005) 012002
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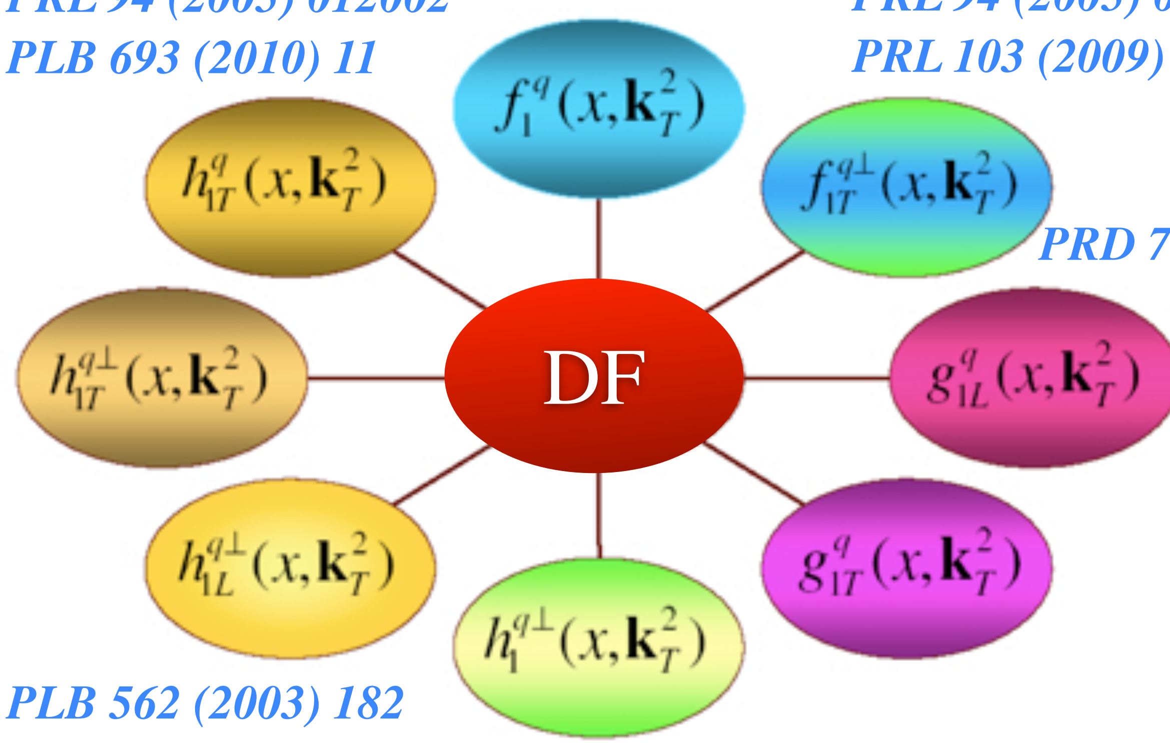

PLB 562 (2003) 182
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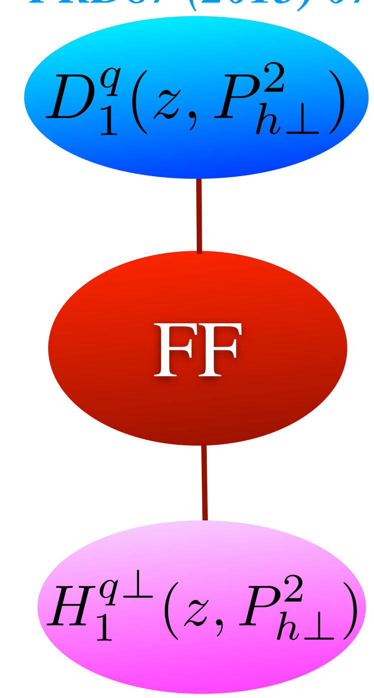

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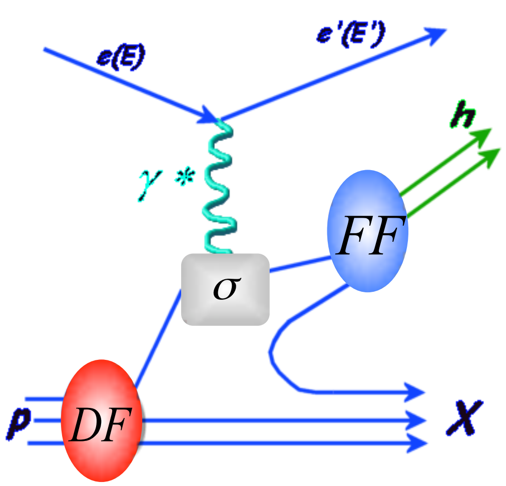

HERMES: access to all TMDs thanks to polarized beam and target

semi-inclusive DIS cross section and TMDs

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

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

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

twist-3

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

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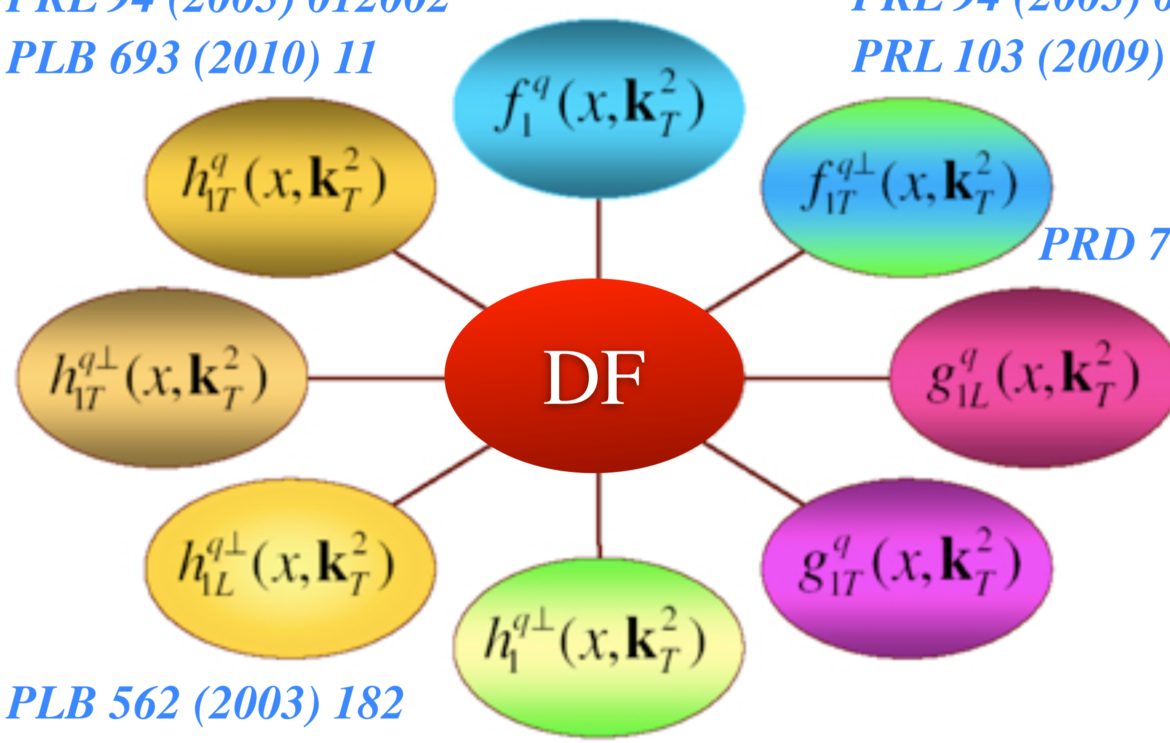

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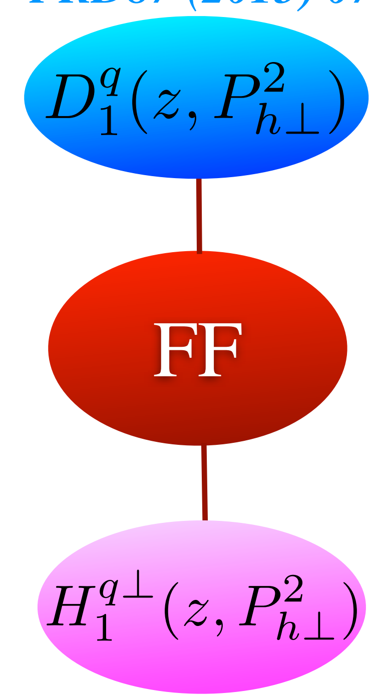

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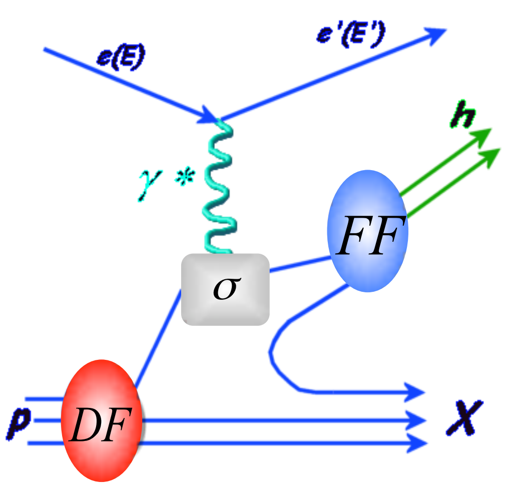

HERMES: access to all TMDs thanks to polarized beam and target

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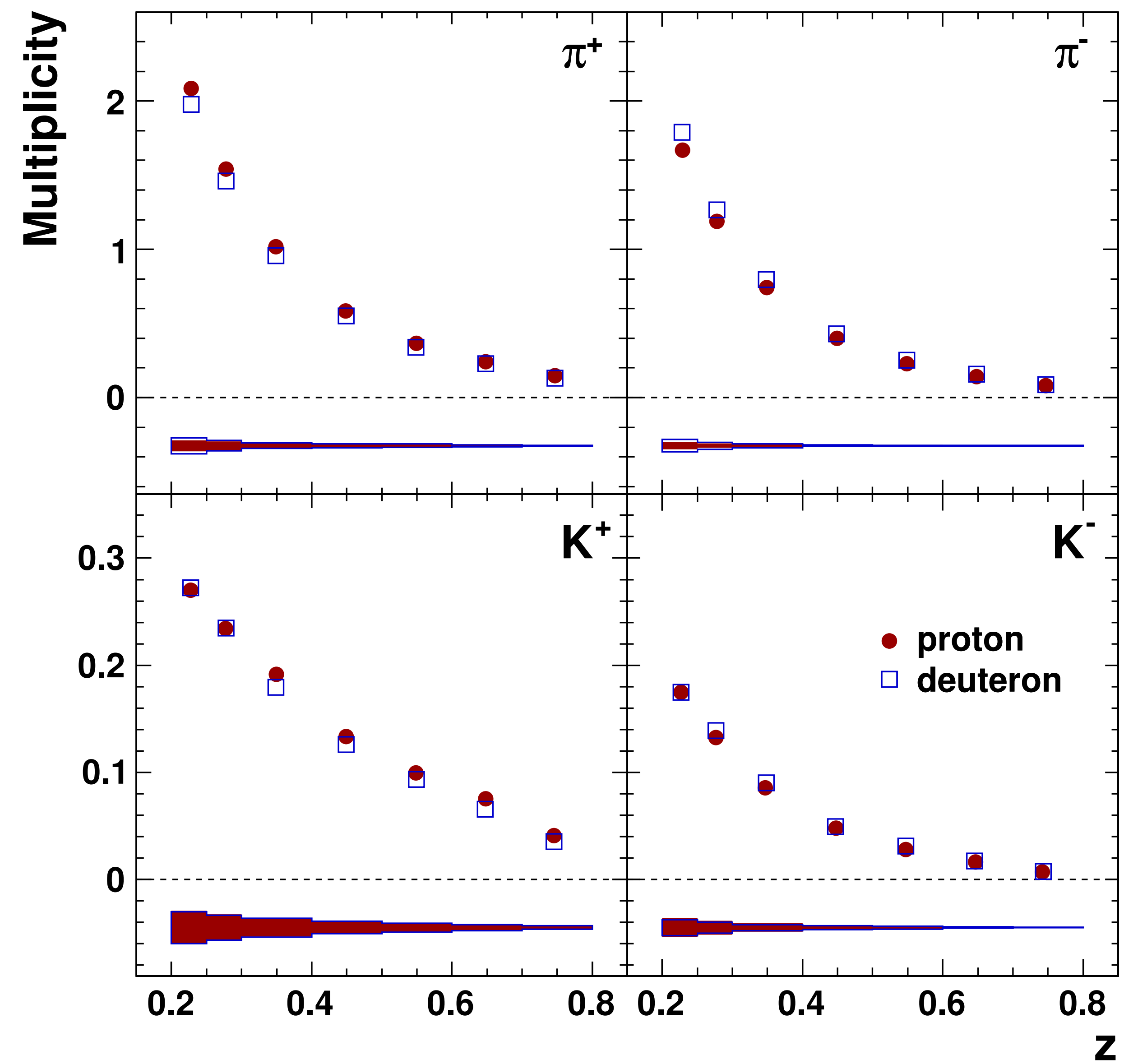
- HERMES Collaboration-
Phys. Rev. D87 (2013) 074029



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

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

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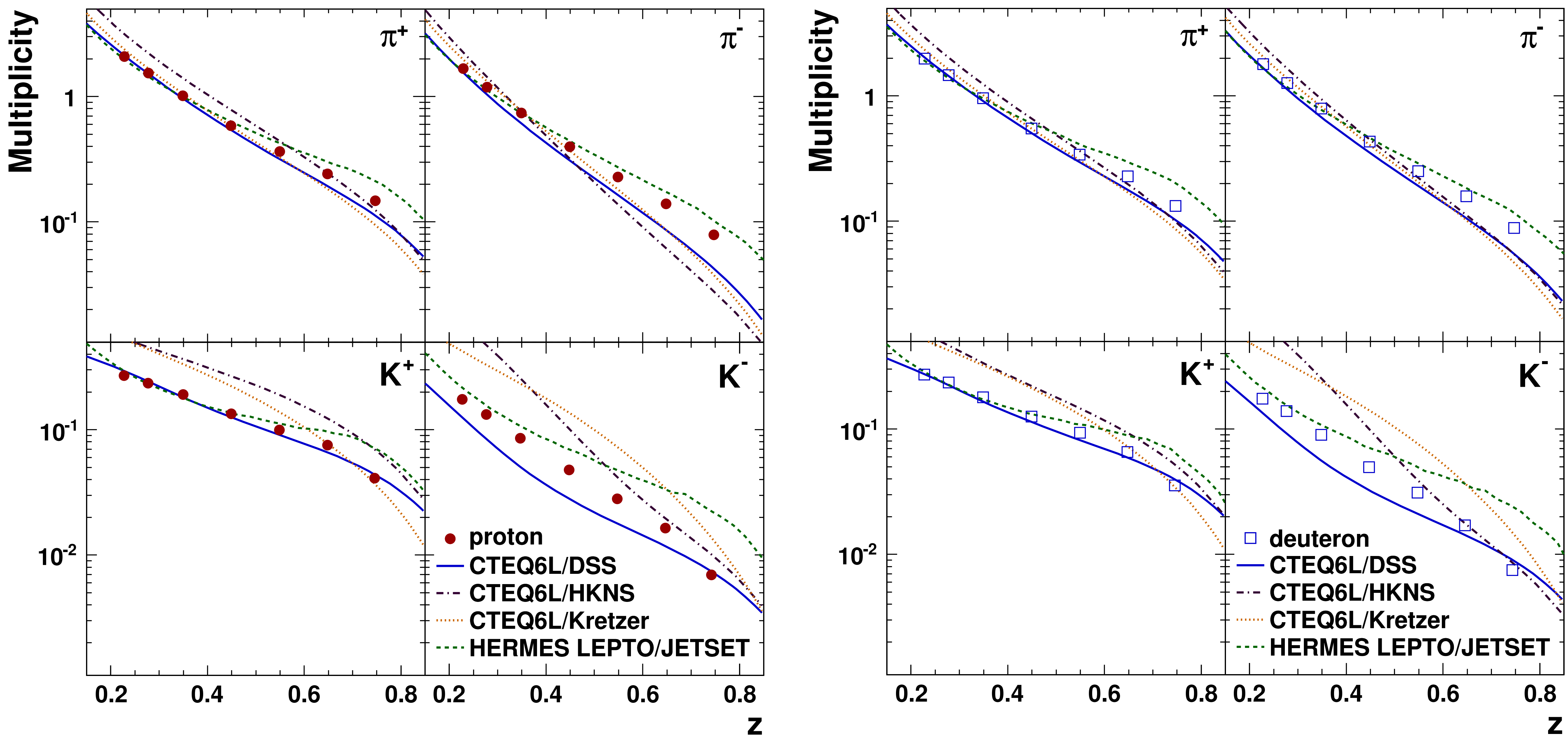

✓ calculations using DSS, HNKS and Kretzer FF fits together with CTEQ6L PDFs

proton:

- ☛ fair agreement for positive hadrons
- ☛ disagreement for negative hadrons

deuteron:

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

unpolarized quarks

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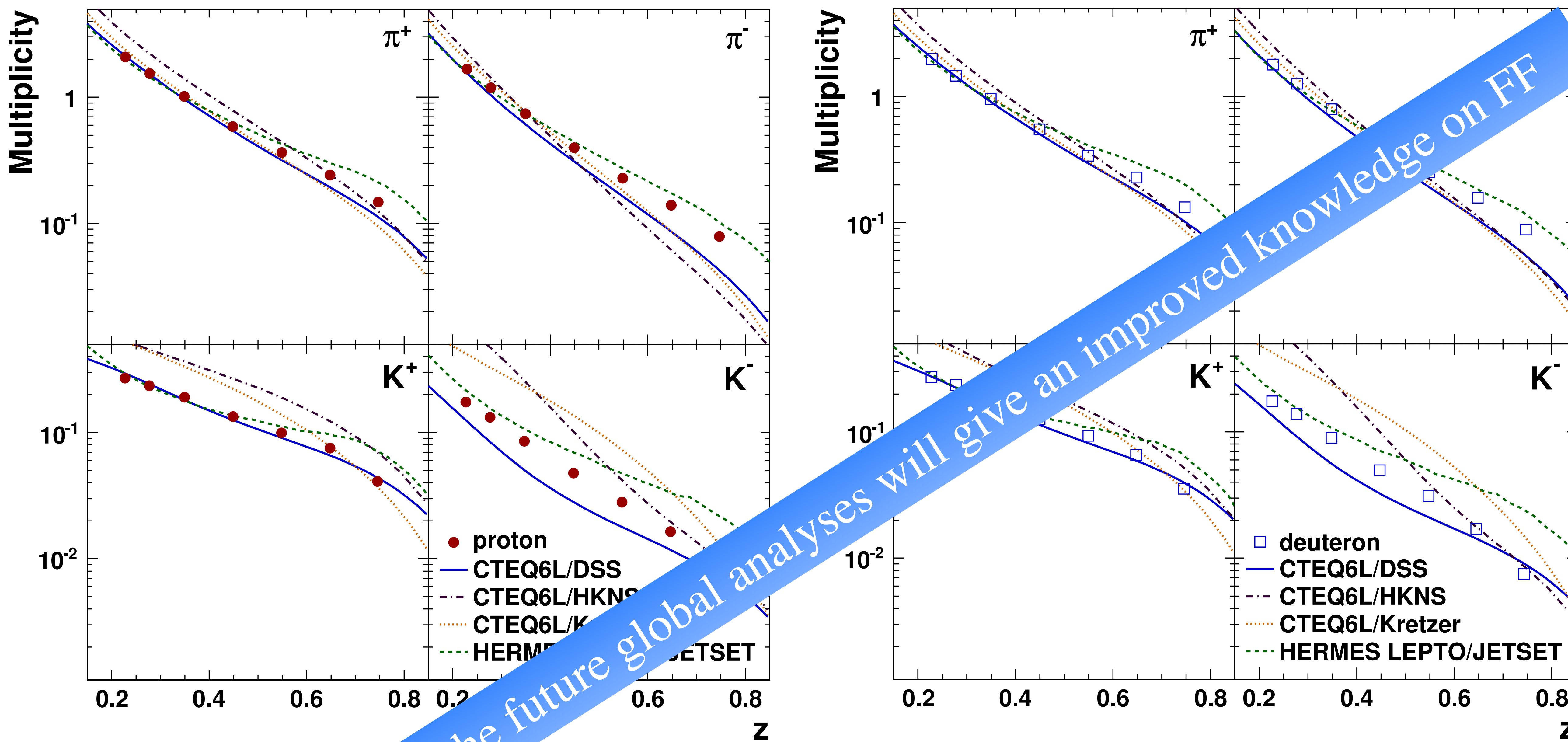
Phys.Rev. D87 (2013) 074029

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



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

proton:

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

d...

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

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

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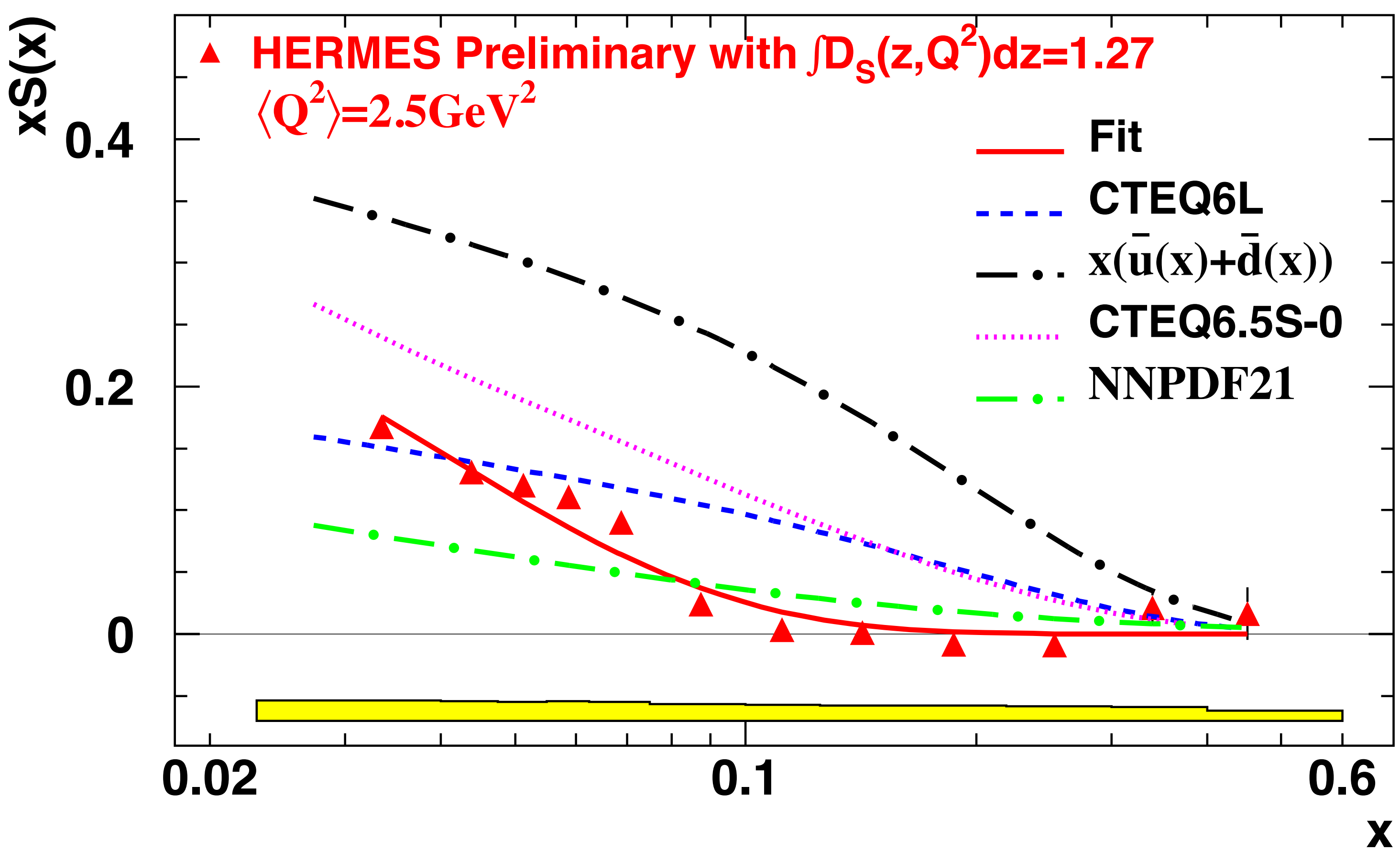
$$\begin{aligned} S(x) &= s(x) + \bar{s}(x) \\ Q(x) &= u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \\ \mathcal{D}_{\mathcal{S}}^{\mathcal{K}} &= D_1^{s\to K^+} + D_1^{\bar{s}\to K^+} + D_1^{s\to K^-} + D_1^{\bar{s}\to K^-} \\ \mathcal{D}_{\mathcal{Q}}^{\mathcal{K}} &= D_1^{u\to K^+} + D_1^{\bar{u}\to K^+}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



✓ 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

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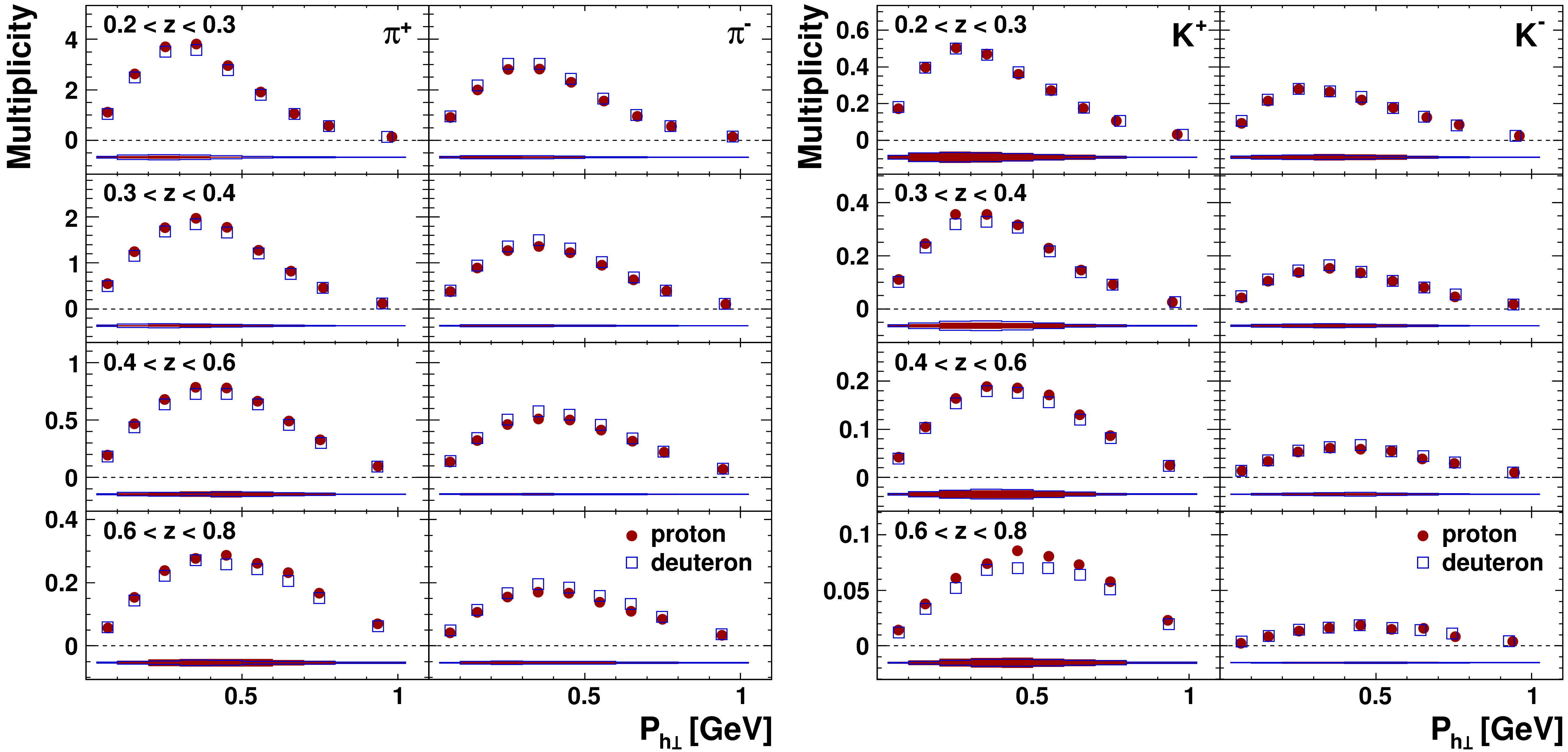
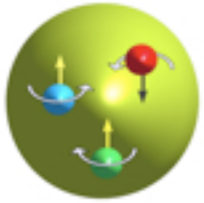


✓ multi-dimensional analysis allows exploration of new kinematic dependences

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

quark's transverse degrees of freedom

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

$h_1^{\perp} =$ 

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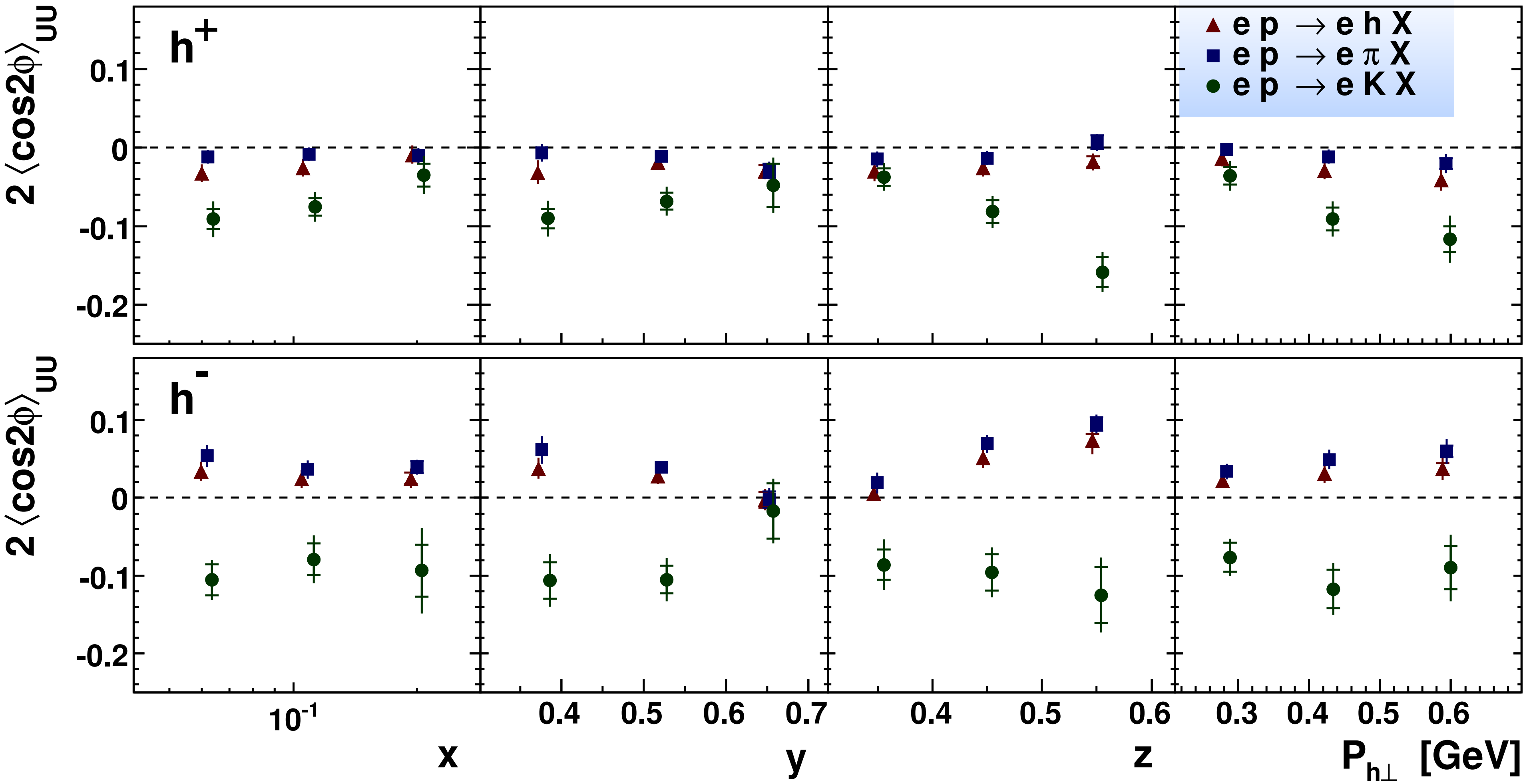
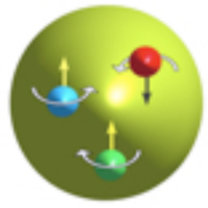
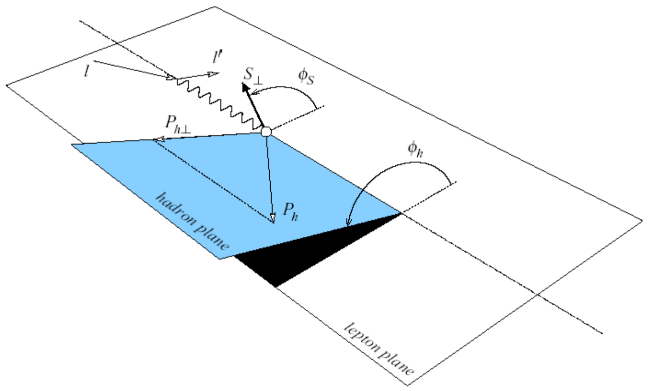


$h_1^\perp =$ 



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

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

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

☛ **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

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

convolutions of twist-2 and twist-3 functions

beyond the leading twist

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

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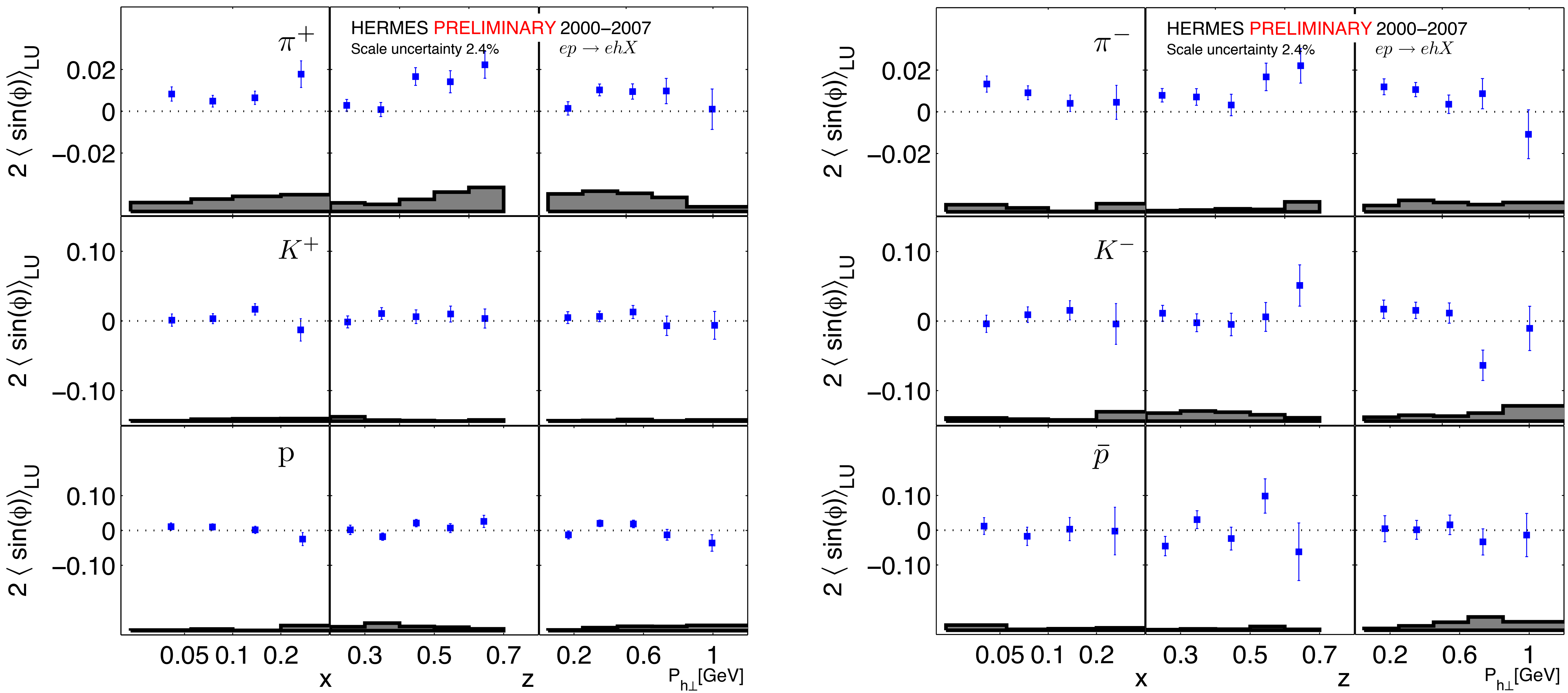

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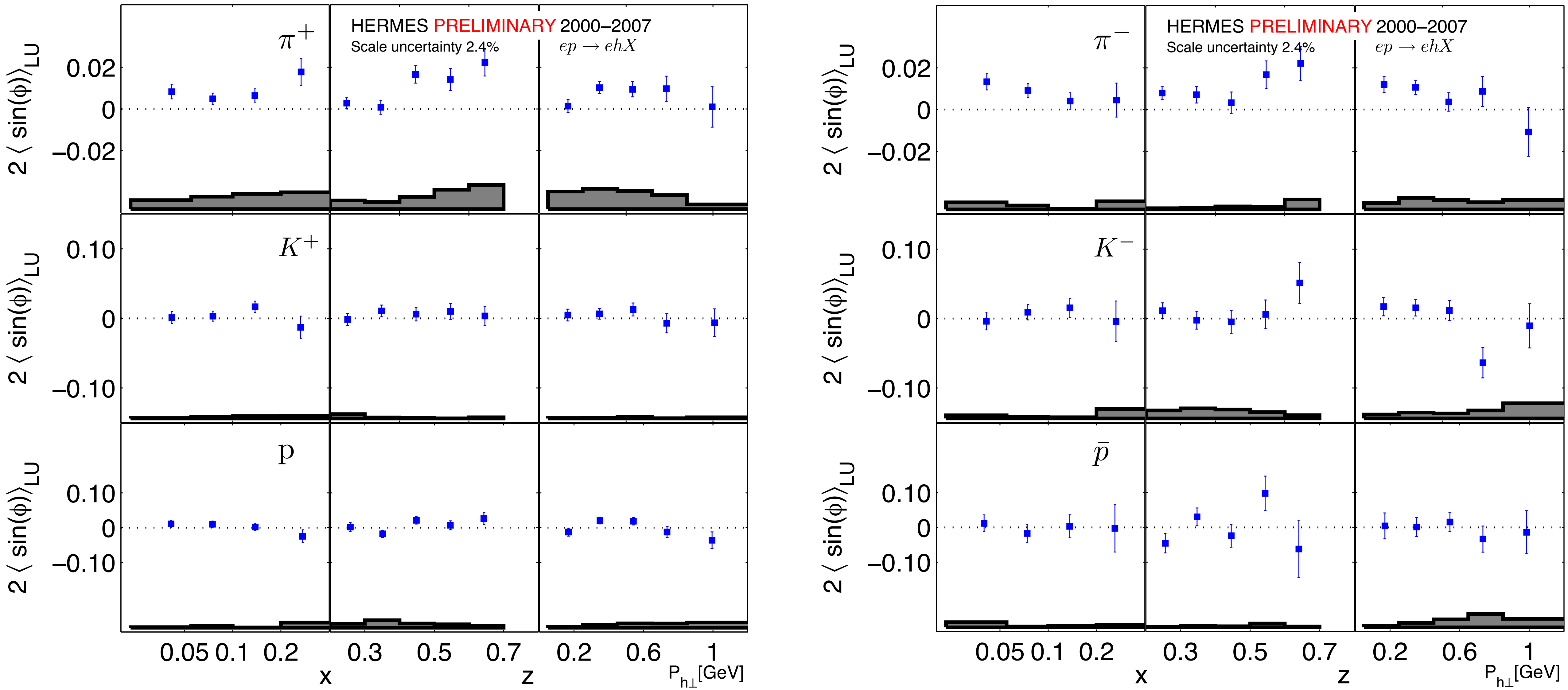
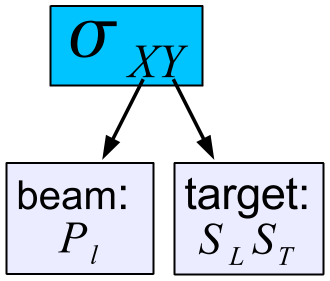


π^+ and π^-

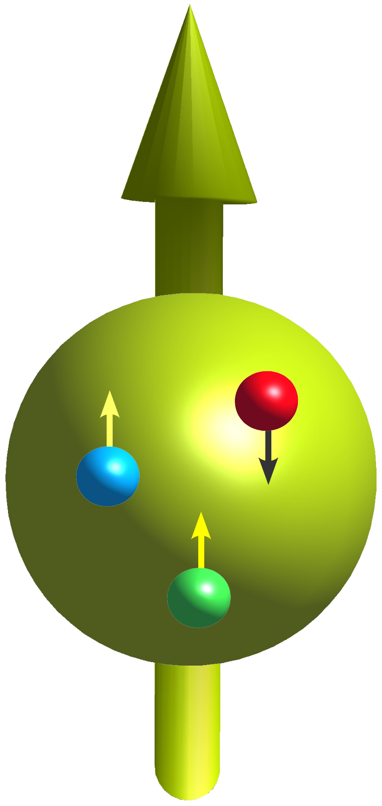
☛ the role of the twist-3 DF or FF is sizeable

Collins effect



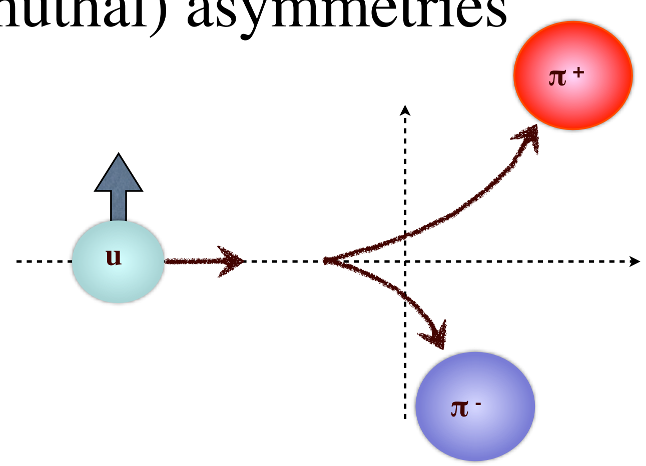
$$
\begin{aligned}
d\sigma = \; & d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} \; + \; P_l \frac{1}{Q}\sin(\phi)d\sigma^3_{LU} \\
+ \; & S_L\left[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} \; + \; P_l\left(d\sigma^6_{LL} + \frac{1}{Q}\cos(\phi)d\sigma^7_{LL}\right)\right]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

☛ 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

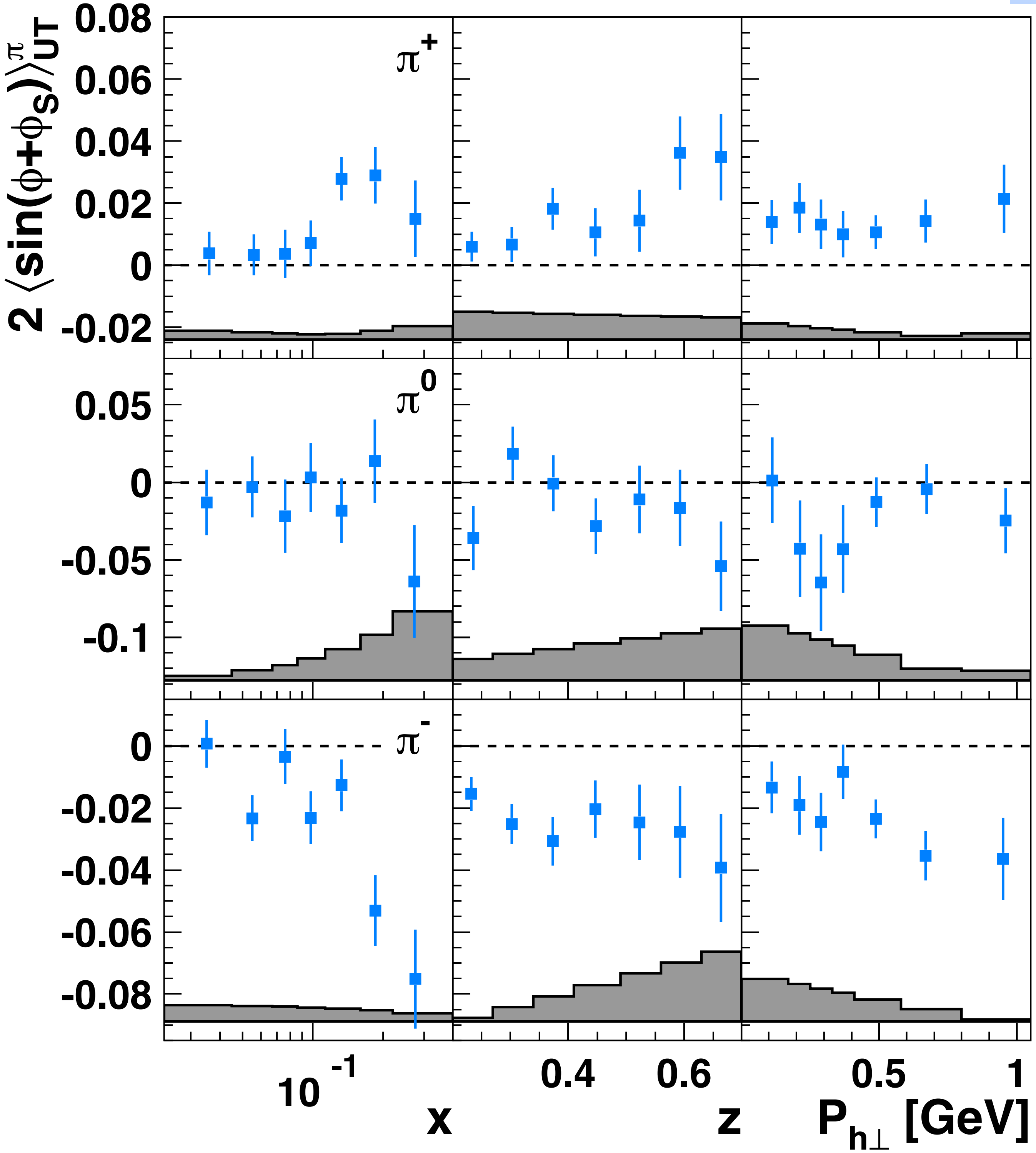


Collins amplitudes for pions

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

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

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



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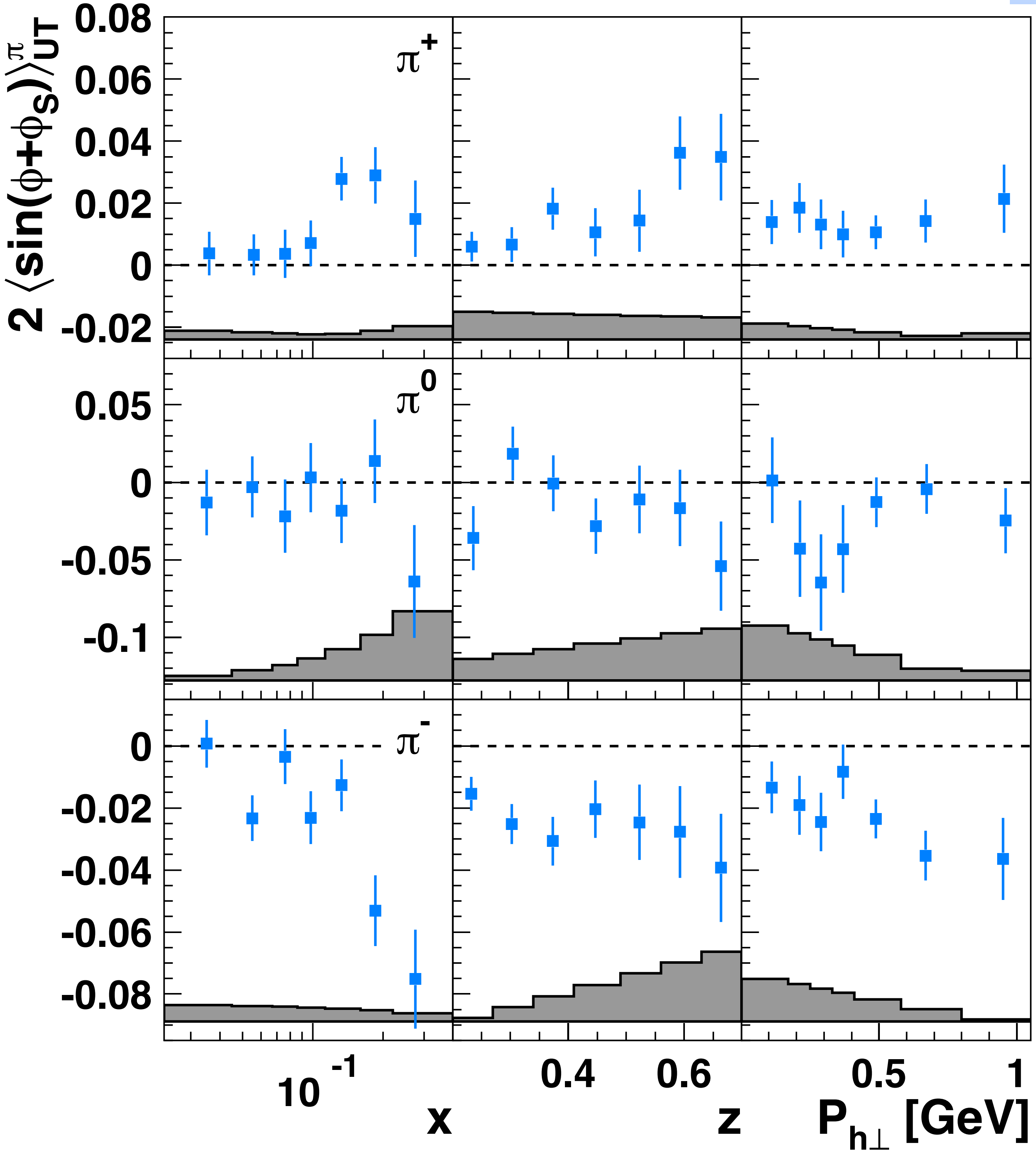

- positive amplitude for π^+
- compatible with zero amplitude for π^0
- large negative amplitude for π^-
- increase in magnitude with x
  - transversity mainly receives contribution from valence quarks
- increase with z
  - in qualitative agreement with BELLE results

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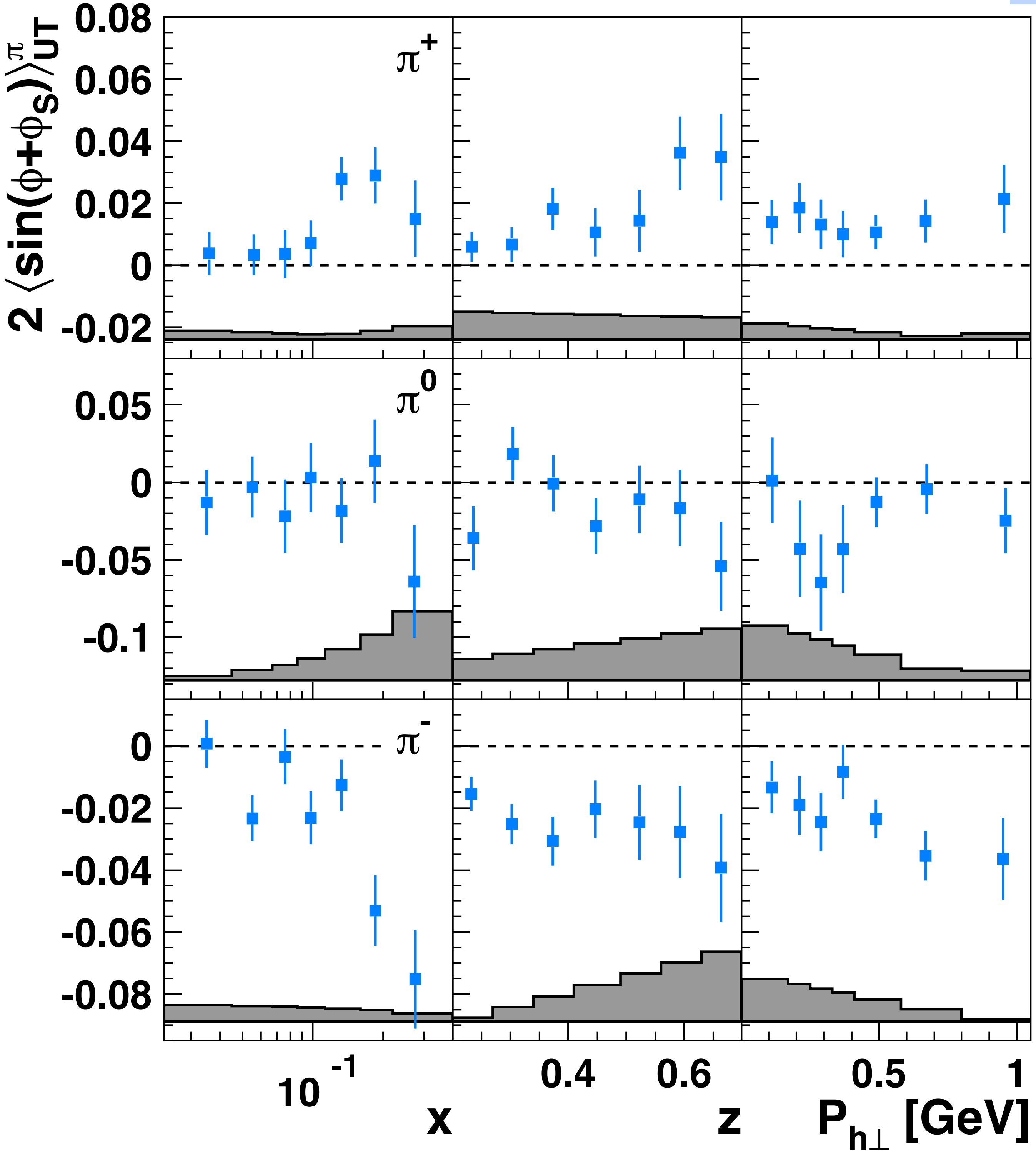

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- large negative amplitude for π^-
- increase in magnitude with x
  - transversity mainly receives contribution from valence quarks
- increase with z
  - in qualitative agreement with BELLE results
- positive for π^+ and negative for π^-
  - role of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

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

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

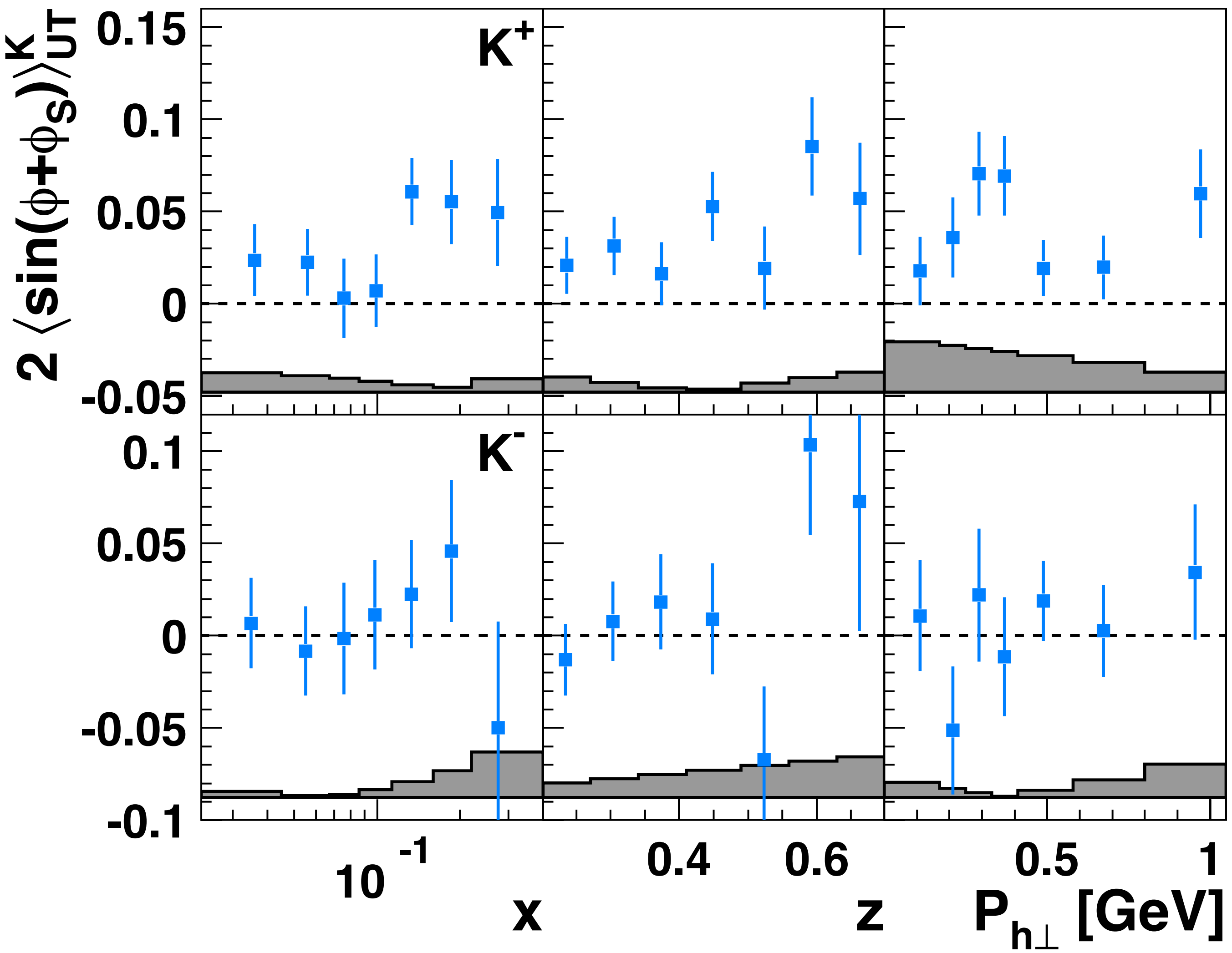
$$u \Rightarrow \pi^-; \qquad d \Rightarrow \pi^+(disfav)$$

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

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

Collins amplitudes for kaons

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



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

K^+

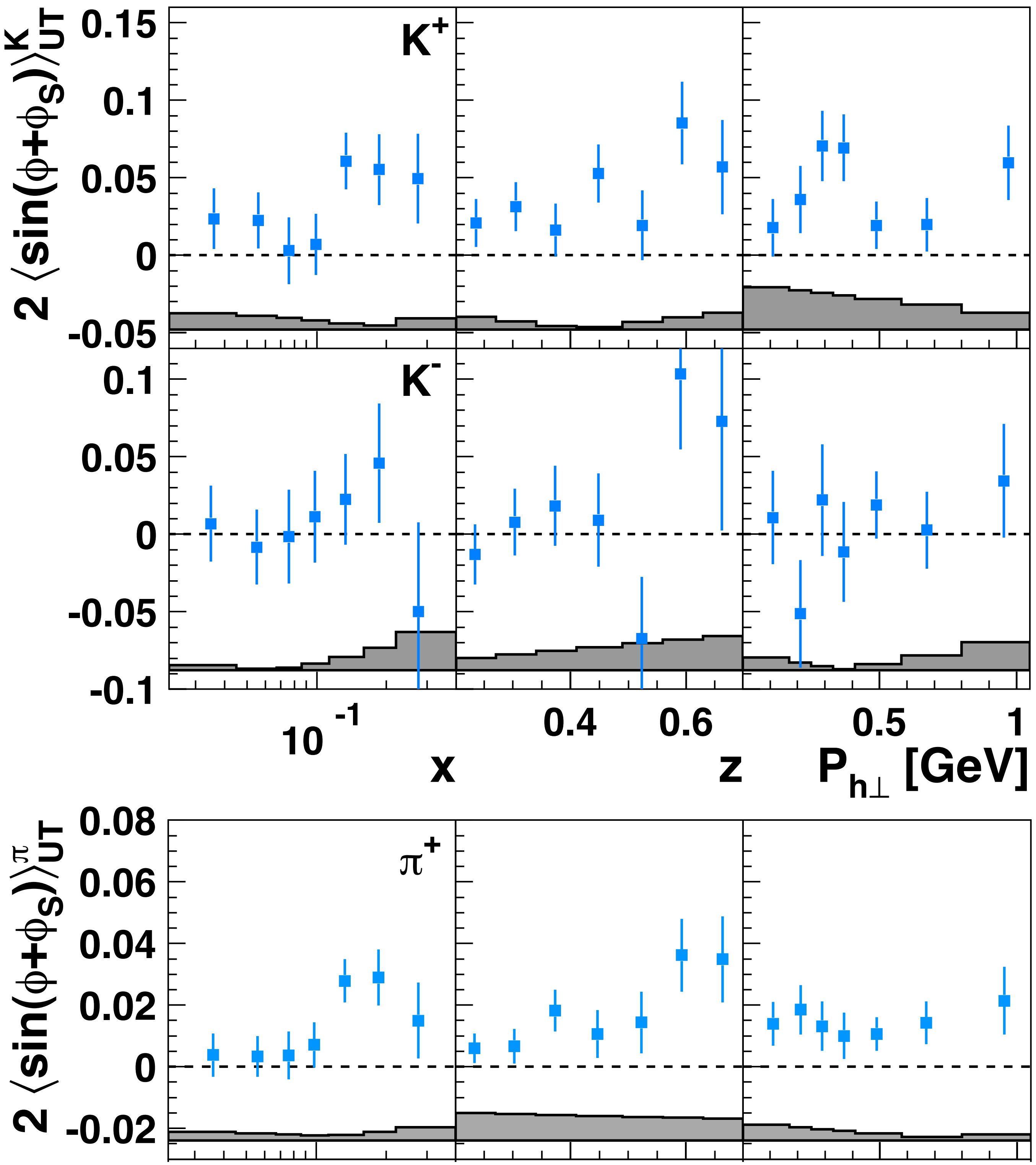
- ☛ K^+ amplitudes are similar to π^+ as expected from the u-quark dominance
- ☛ K^+ are larger than π^+

K^-

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

Collins amplitudes for kaons

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



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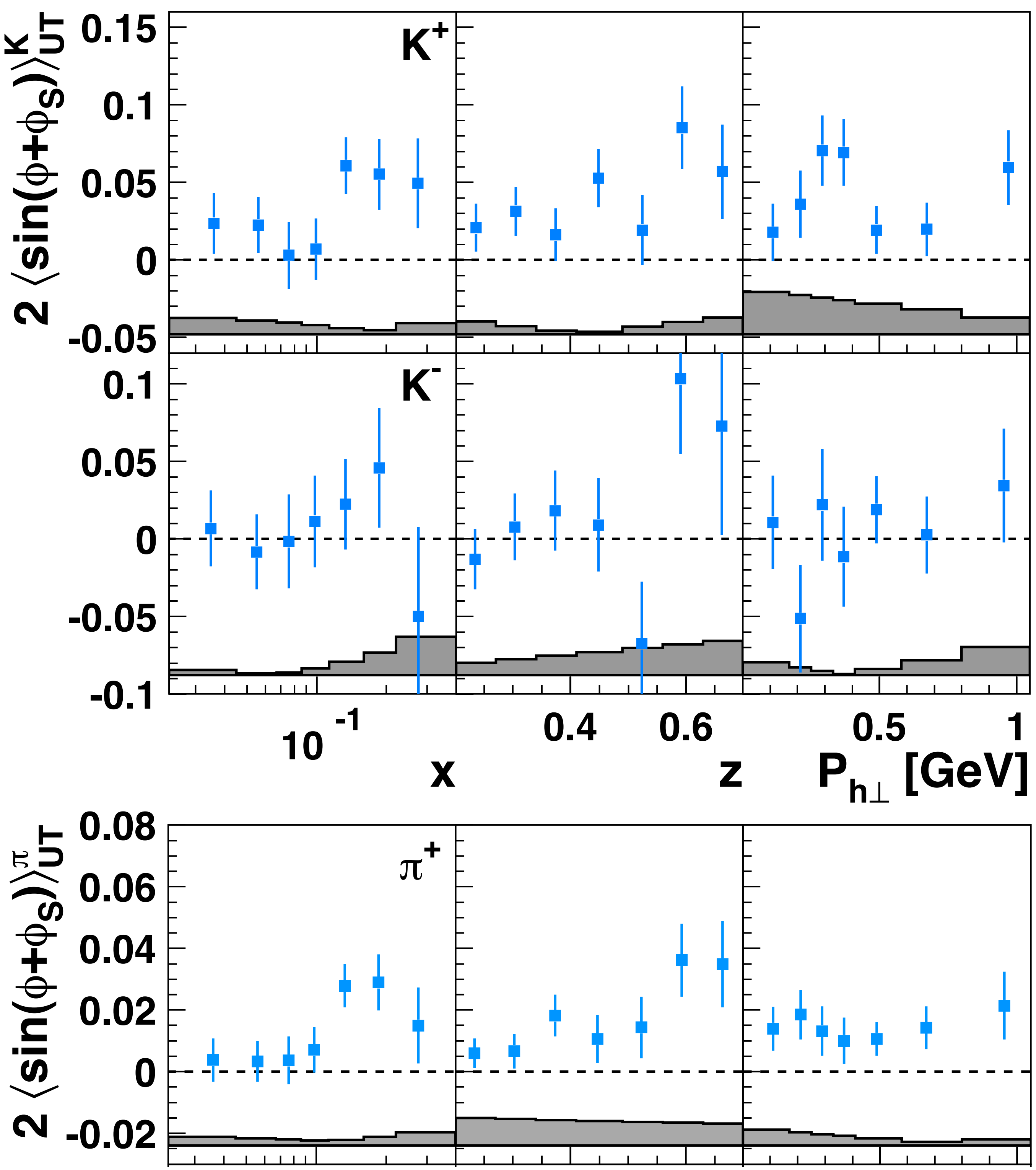

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K^+

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

K^-

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

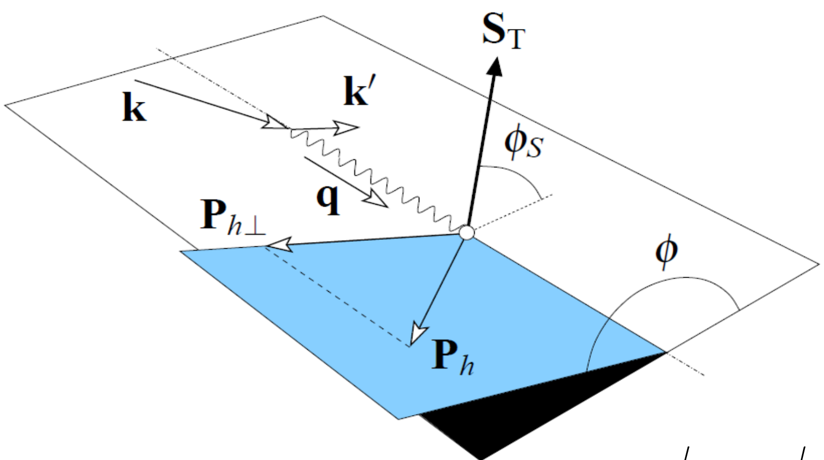
differences between K^+ and π^+ amplitudes

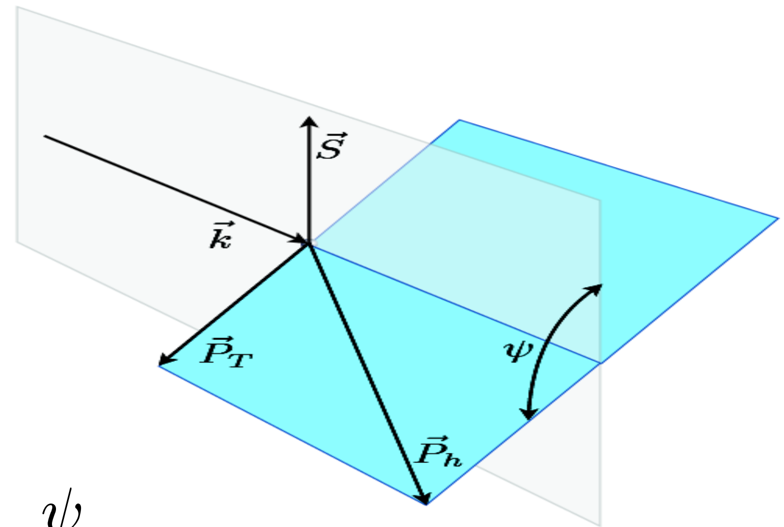
- ☛ role of sea quarks in conjunction with possibly large FF
- ☛ various contributions from decay of semi-inclusively produced vector-mesons
- ☛ the k_T dependences of the fragmentation functions

inclusive hadron measurements

Inclusive transverse target spin asymmetries

semi-inclusive DIS $lp^{\uparrow} \rightarrow l'hX$ → inclusive hadrons $lp^{\uparrow} \rightarrow hX$





$\phi - \phi_S$ - - → ψ

inclusive transverse target spin asymmetry

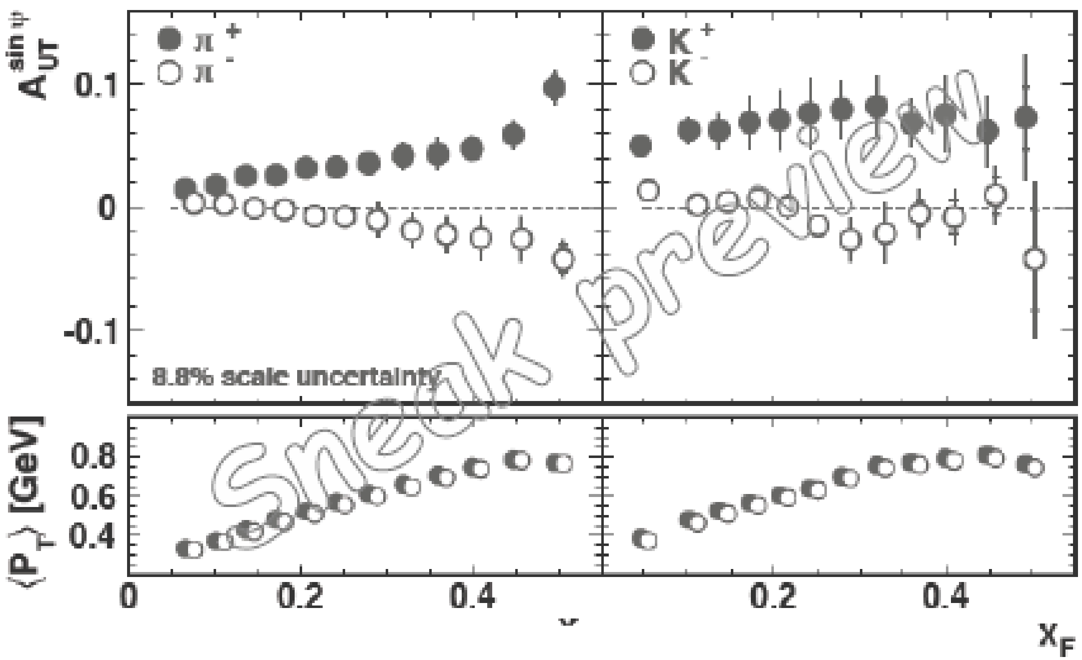
$$d\sigma = d\sigma_{UU}[1 + S_{\perp} A_{UT}^{\sin(\psi)}\, sin(\psi)]$$

- no info on Q^2
- data dominated by $Q^2 \approx 0$

  SIDIS only small subsample

Inclusive transverse target spin asymmetries

- x_F dependence



π^+

- positive, increase nearly linearly with x_F

π^-

- negative, decrease nearly linearly with x_F
- x_F behavior of pions similar to what observed in hadron-hadron collisions

K^+

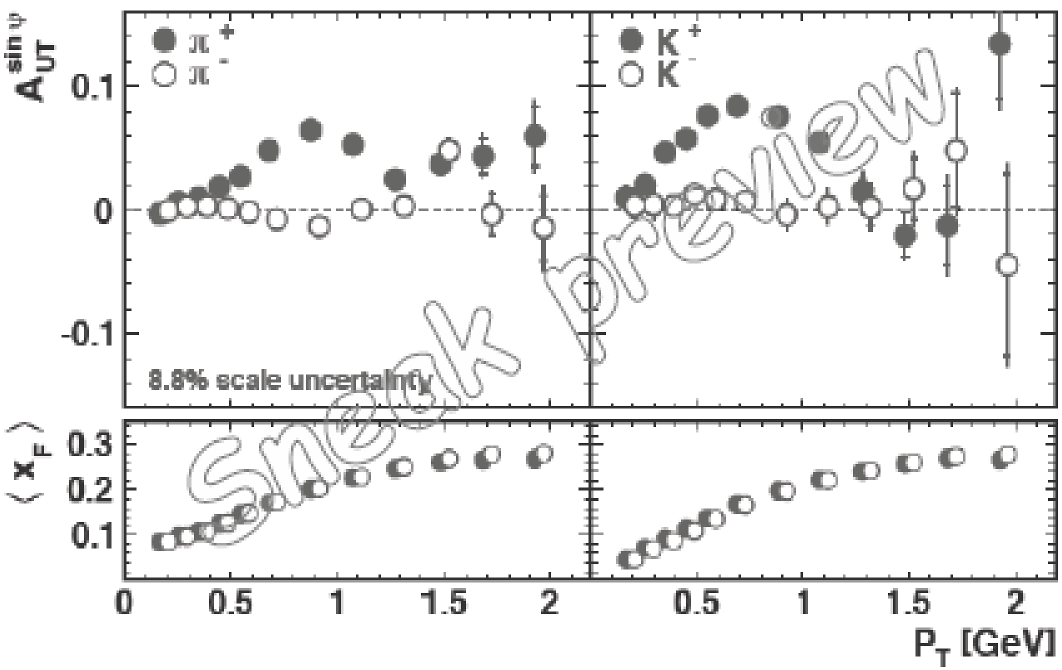
- positive, approximately constant with x_F

K^-

- compatible with zero, with small variation over x_F

Inclusive transverse target spin asymmetries

- p_T dependence



π^+

- positive, increase to approximately 0.06, and then decrease with p_T

π^-

- small, varyingly positive and negative

K^+

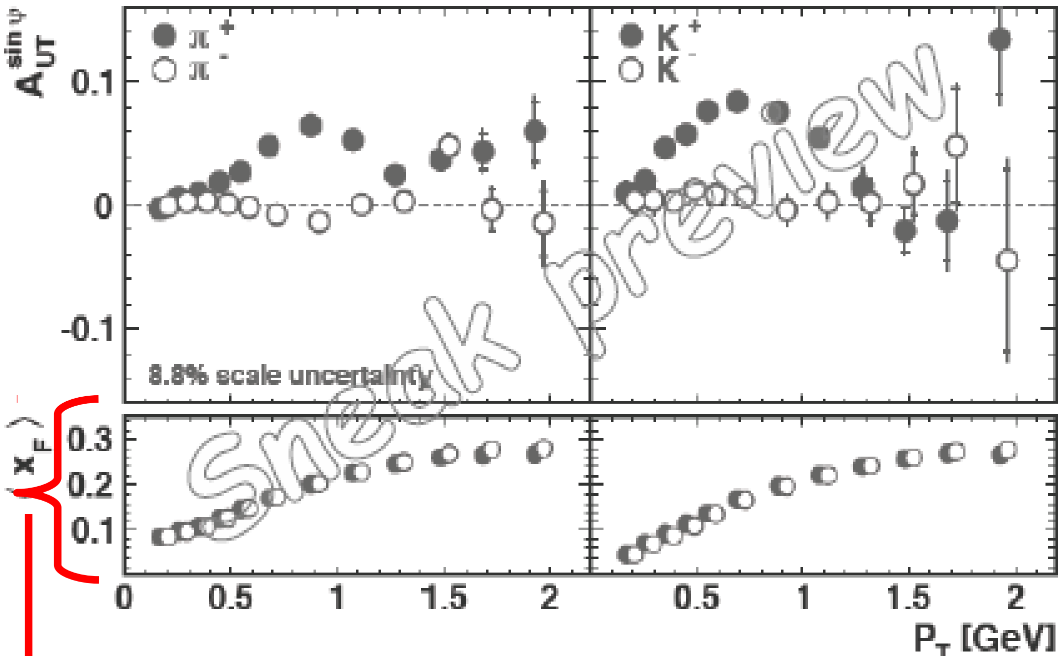
- positive, increase to approximately 0.08, and then decrease with p_T

K^-

- small, positive

Inclusive transverse target spin asymmetries

- p_T dependence



π^+

- positive, increase to approximately 0.06, and then decrease with p_T

π^-

- small, varyingly positive and negative

K^+

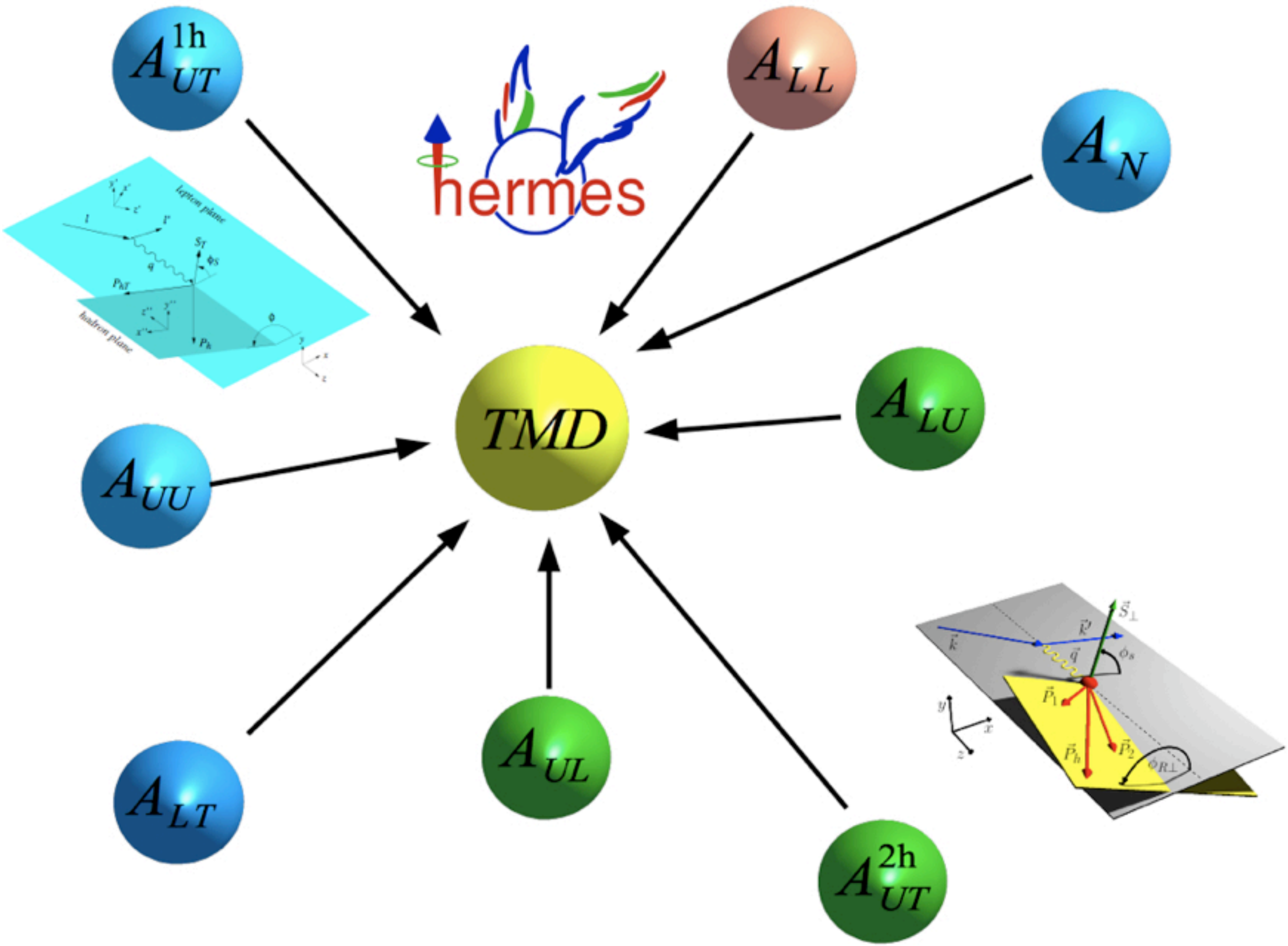
- positive, increase to approximately 0.08, and then decrease with p_T

K^-

- small, positive

- disentangling of x_F - p_T correlation: 2D asymmetries
- disentangling of different data samples:
  with and without scattered-electron tagging, and different kinematic regions

to appear very soon on the arXiv!



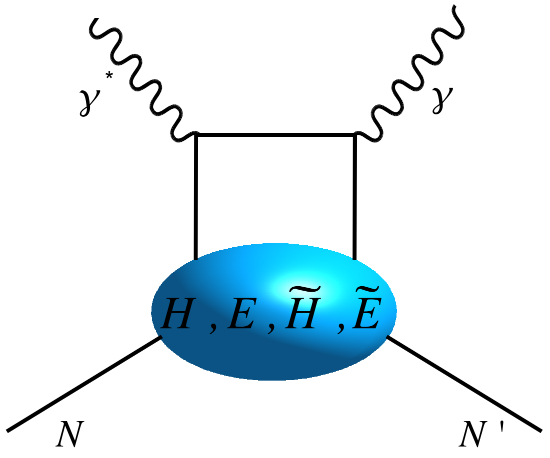
A_{UT}^{1h}
hermes
A_{LL}
A_N
A_{LU}
TMD
A_{UU}
A_{LT}
A_{UL}
A_{UT}^{2h}
lepton plane
hadron plane

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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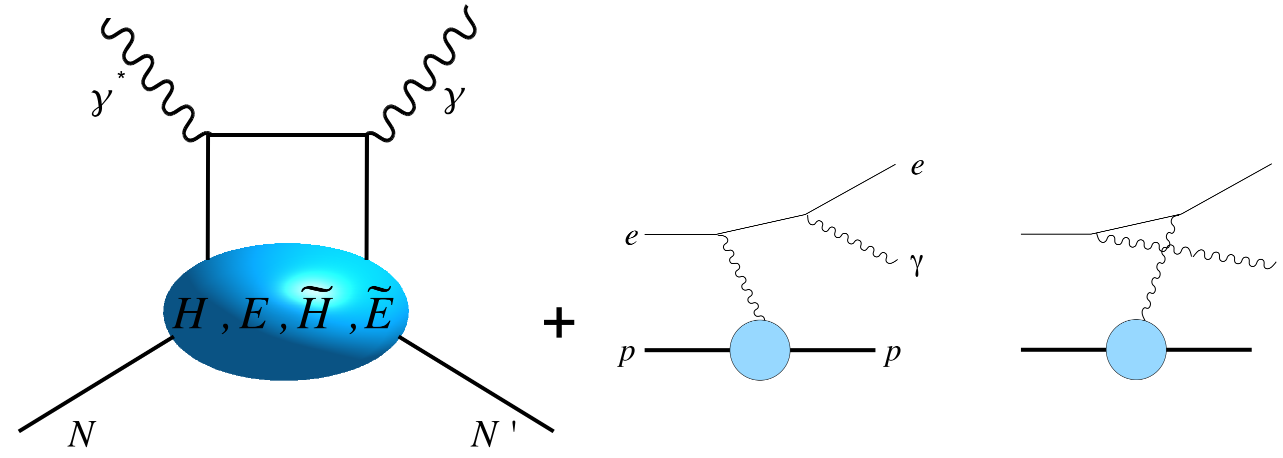

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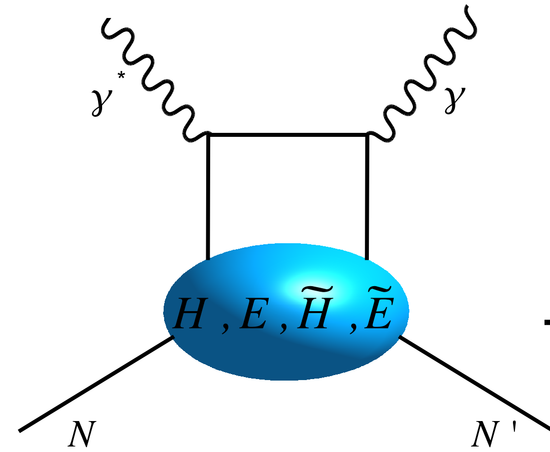
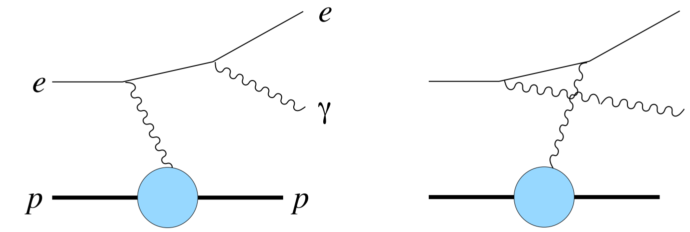


+



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

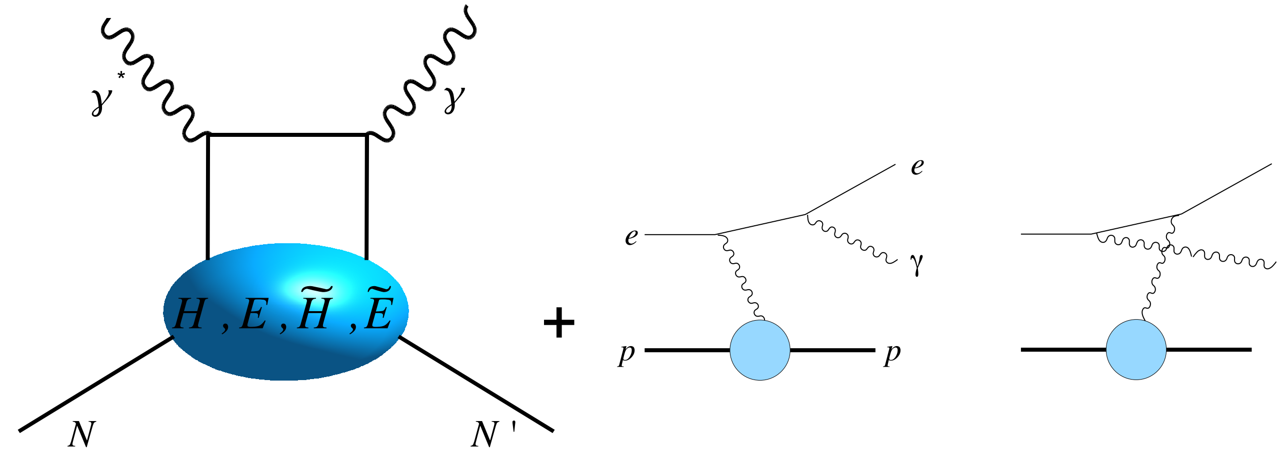
Bethe–Heitler | interference | DVCS

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

DVCS

☛ theoretically the cleanest probe of GPDs

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



σ_{xy}

beam: λ_l

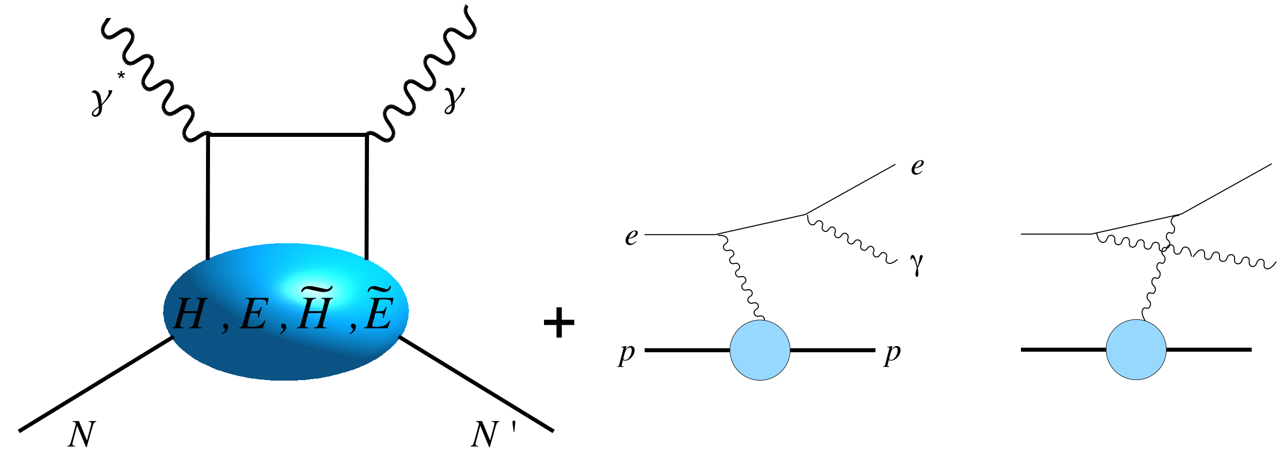
target: $S_\perp, S_{||}$

beam charge: e_ℓ

Bethe–Heitler | interference | DVCS

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

DVCS



☛ theoretically the cleanest probe of GPDs

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

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

Bethe-Heitler | beam charge: e_ℓ → interference | DVCS

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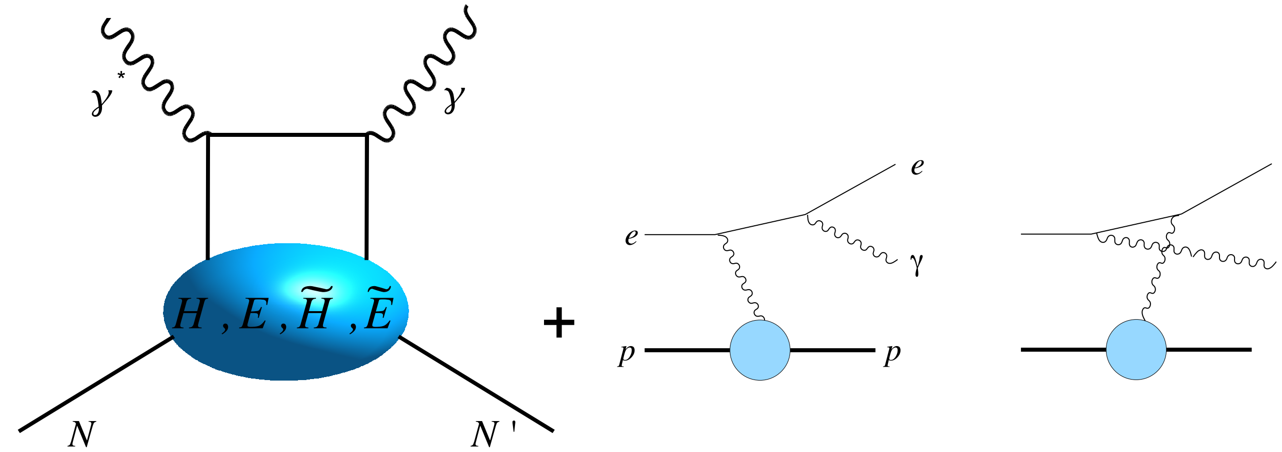
\end{aligned}$$

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

DVCS



- theoretically the cleanest probe of GPDs

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\end{aligned}$$

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

- 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

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

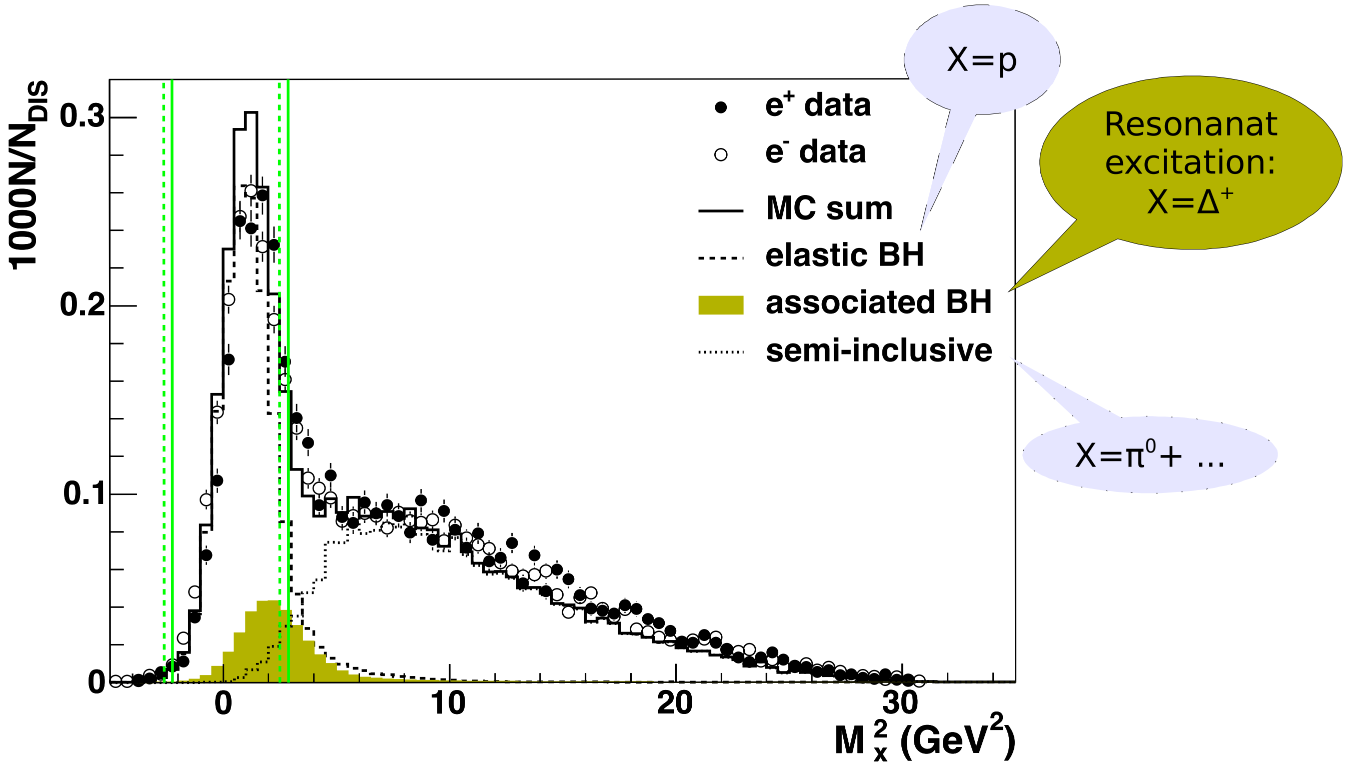
- transversely polarized target

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

$ep \rightarrow e'\gamma X$

DVCS measurements

(without recoil detector)



☛ missing mass technique

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

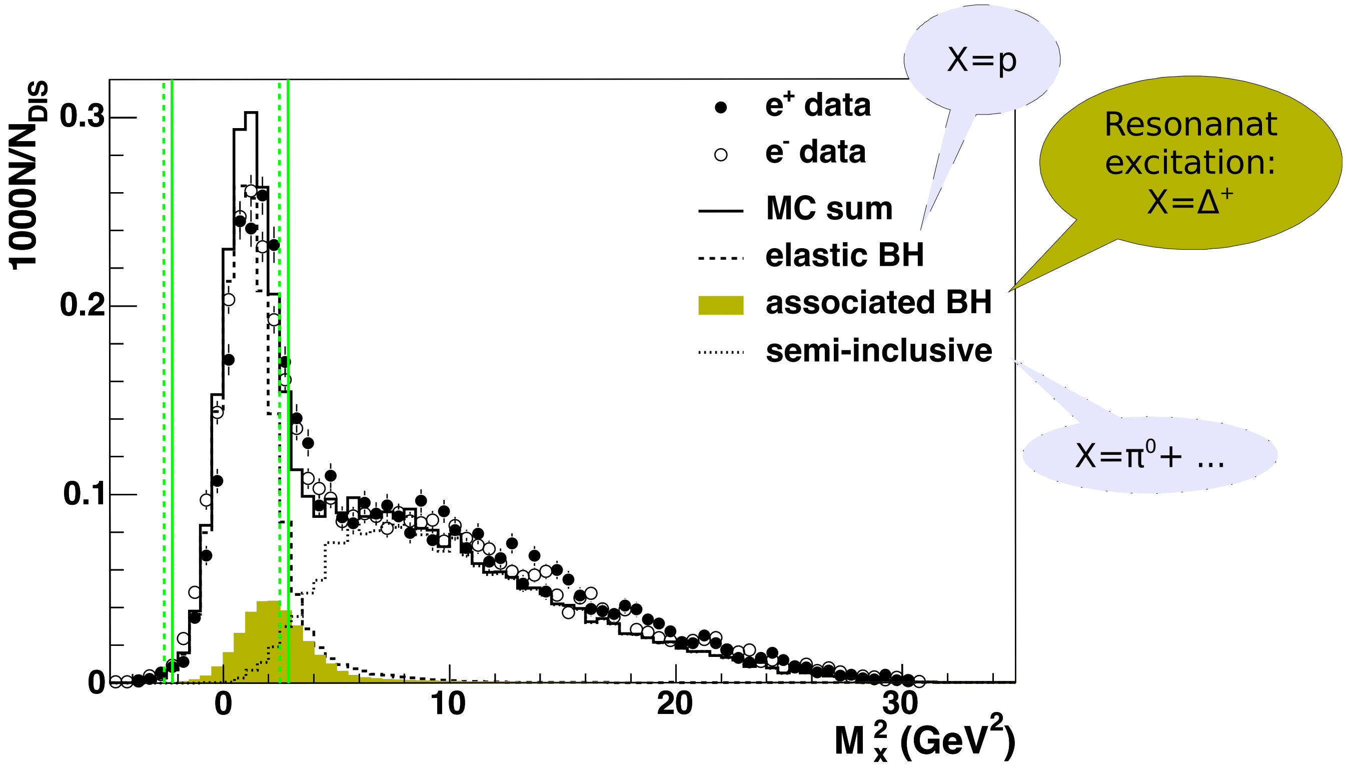
DVCS measurements

$ep \to e'\gamma X$

(without recoil detector)

$ep \to e'\gamma p'$

(with recoil detector)



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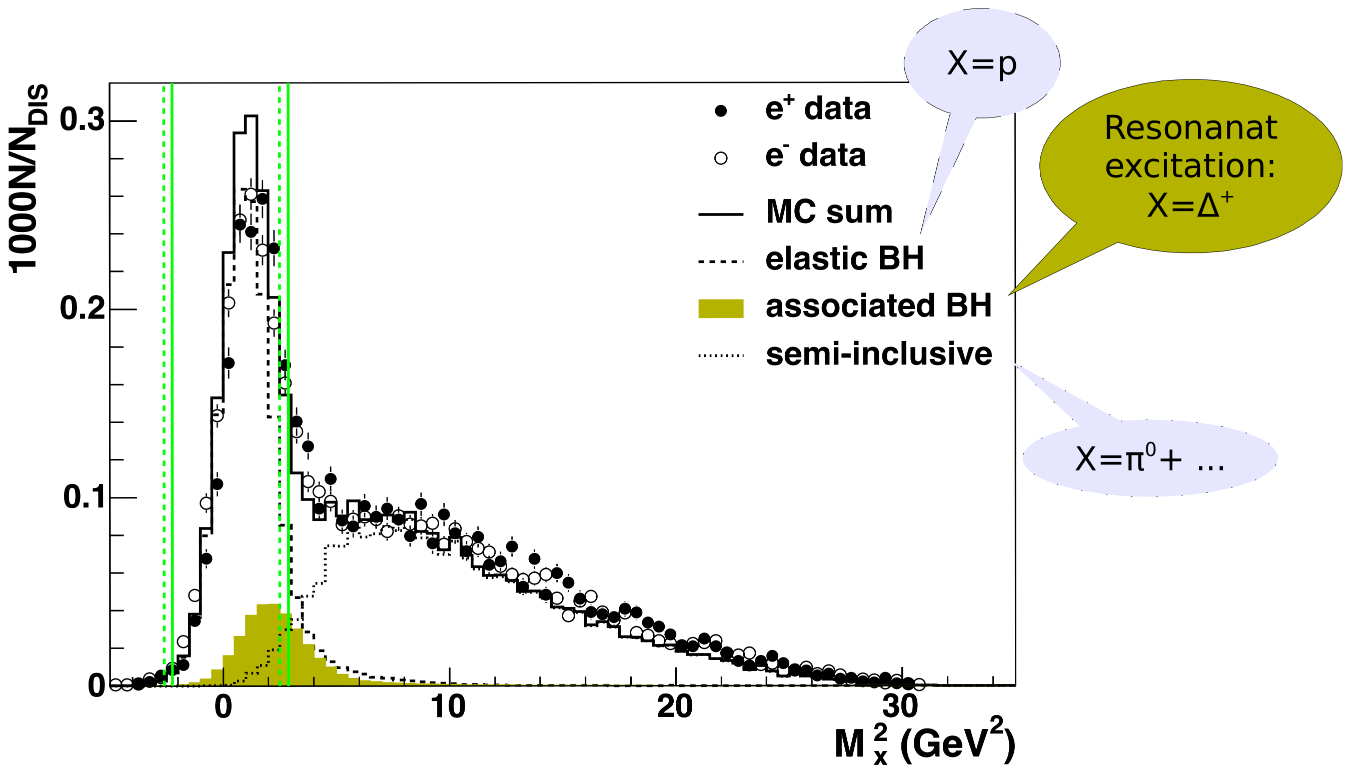

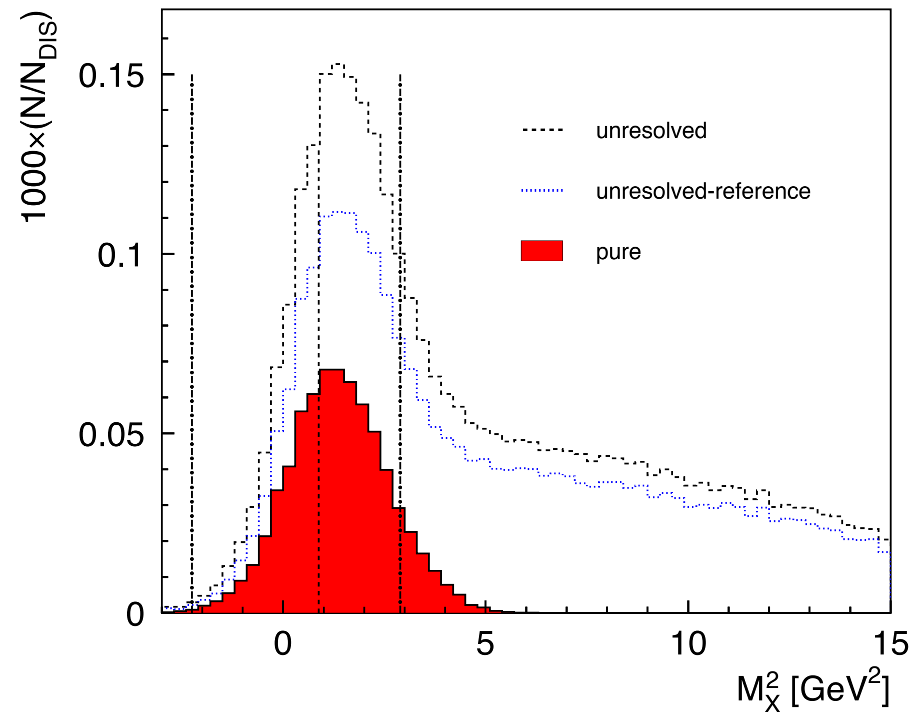

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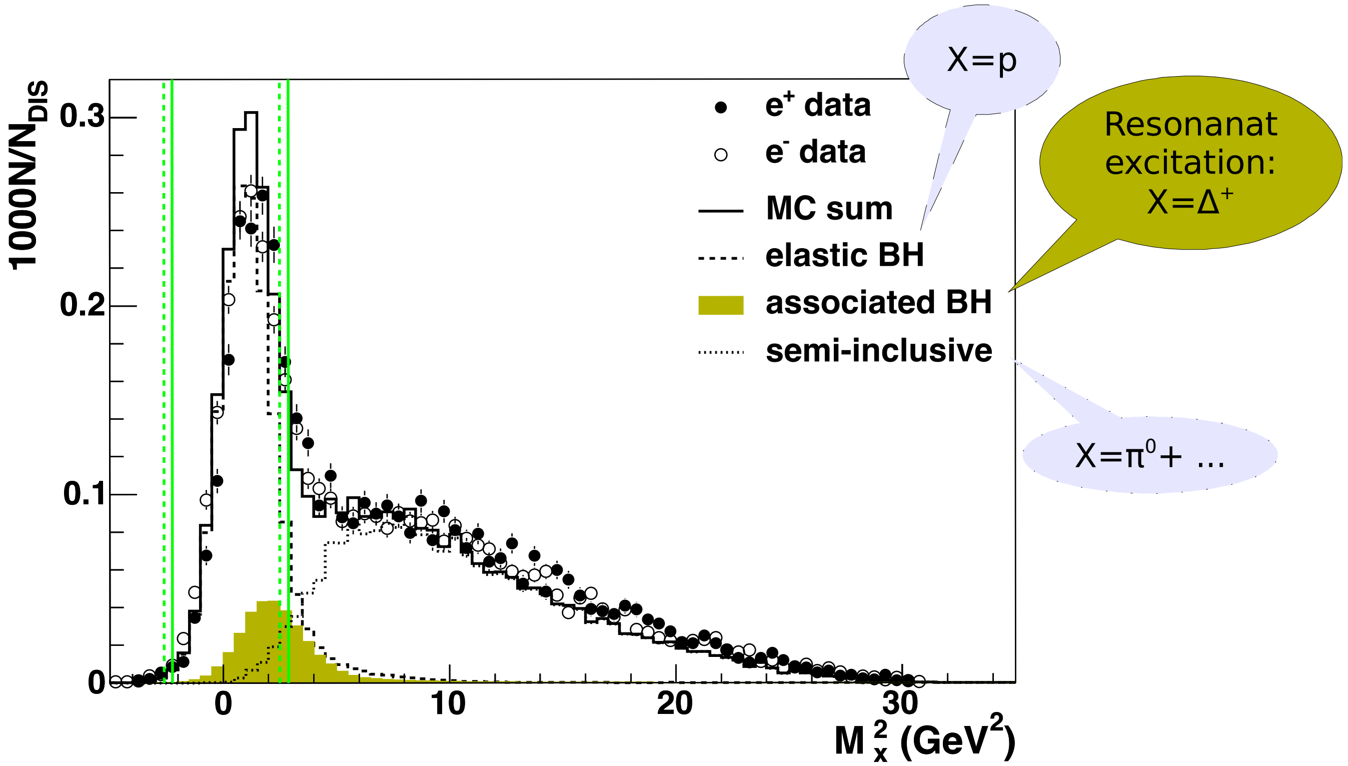
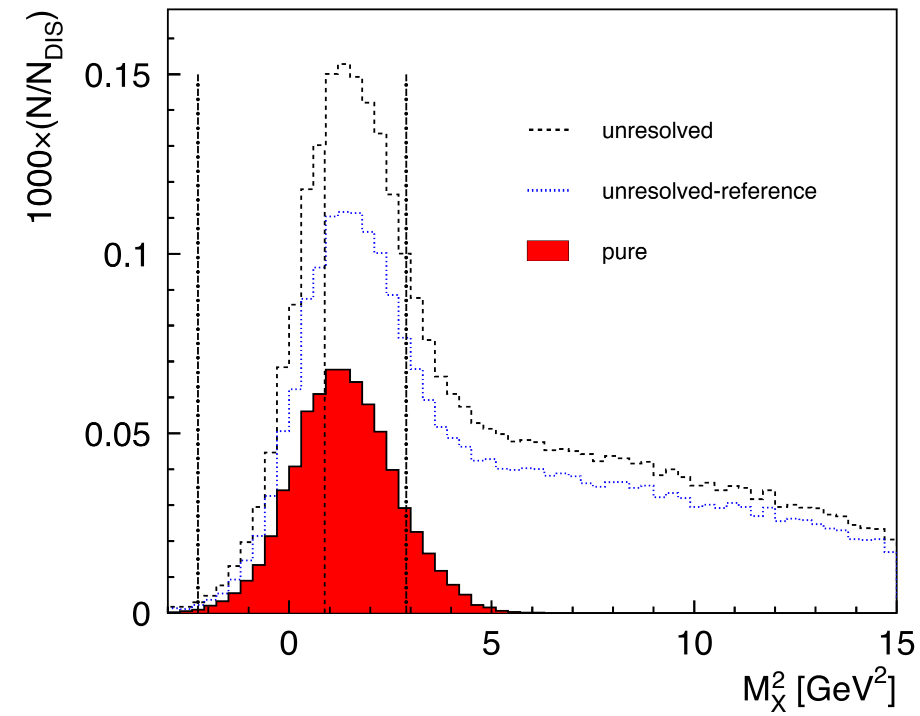




- ☛ missing mass technique

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

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

- ☛ use missing mass technique
- ☛ for comparison only

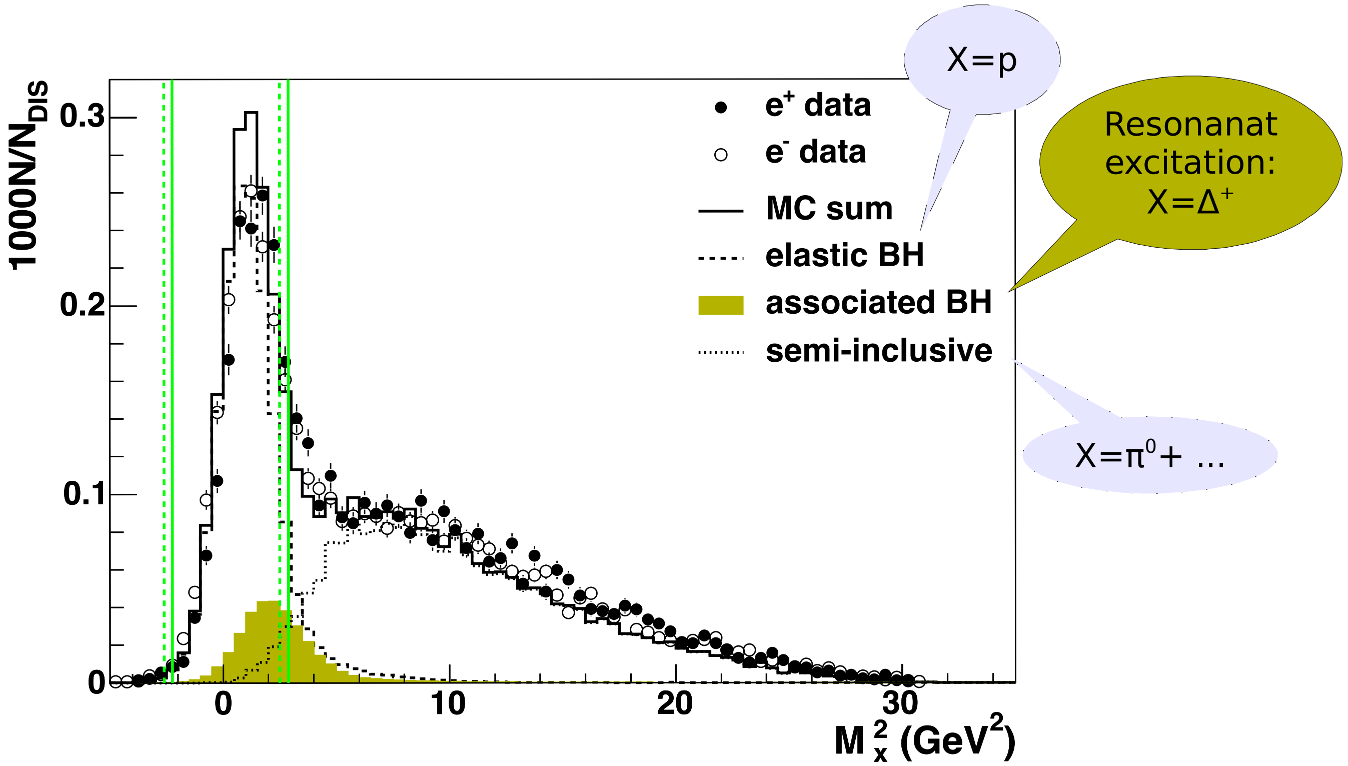
DVCS measurements

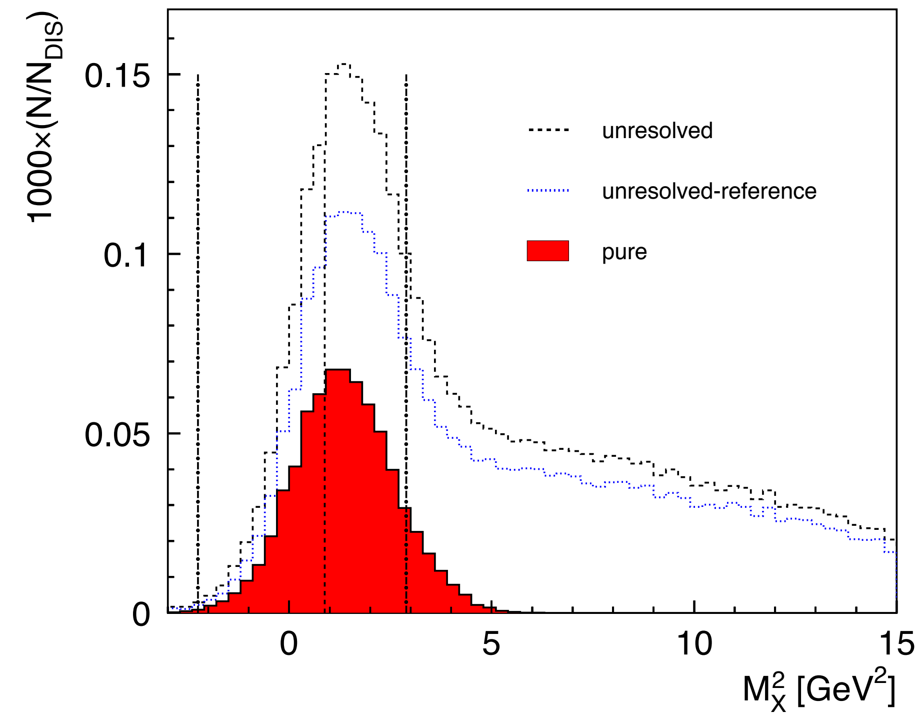
$ep \to e'\gamma X$

(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 07 (2012) 032

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

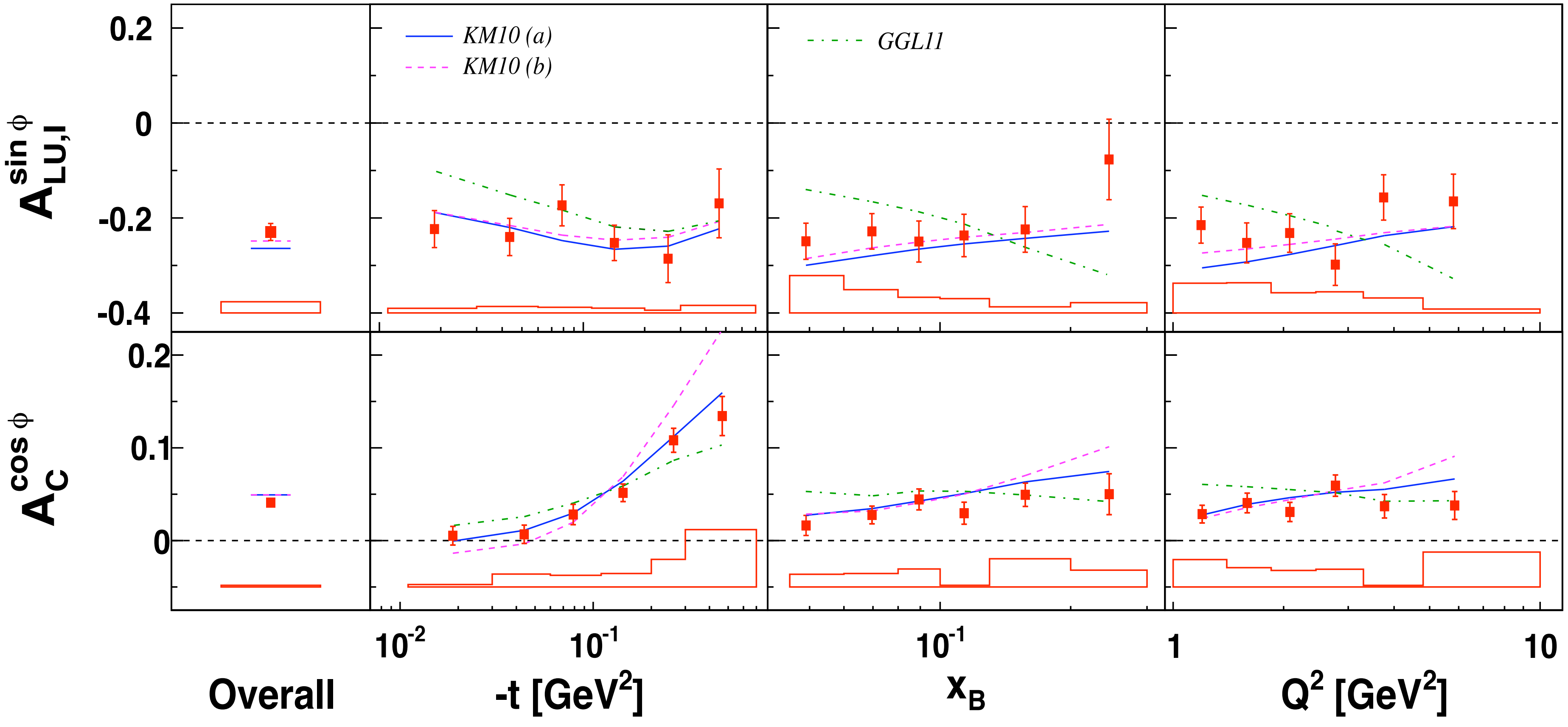
- ✓ full hydrogen dataset used (incl. 2006/2007 data)
- ✓ sensitivity to Re and Im parts of CFF H

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

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

$A_C^{\cos\phi} \propto \mathrm{Re}[\mathrm{F}_1\mathcal{H}]$

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



charge-difference beam helicity asymmetry

- ☛ large overall value
- ☛ no kin. dependencies

beam charge asymmetry

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

$ep \to e'\gamma p'$

(recoil data)

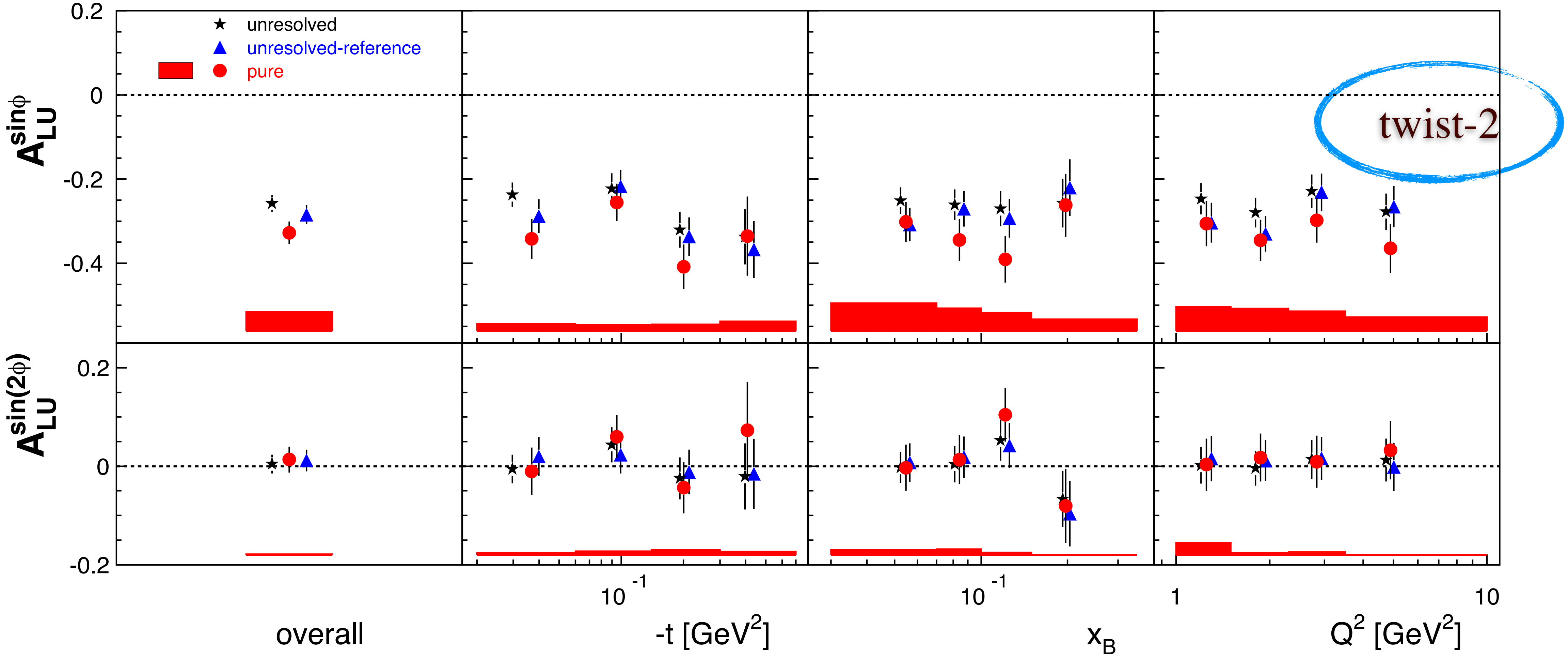
GPD H: unpolarized hydrogen target

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

- HERMES Collaboration-
JHEP 10 (2012) 042

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

- ☛ extraction of single-charge beam-helicity asymmetry amplitudes for elastic (pure) data sample
- ☛ no separate access to DVCS and interference terms

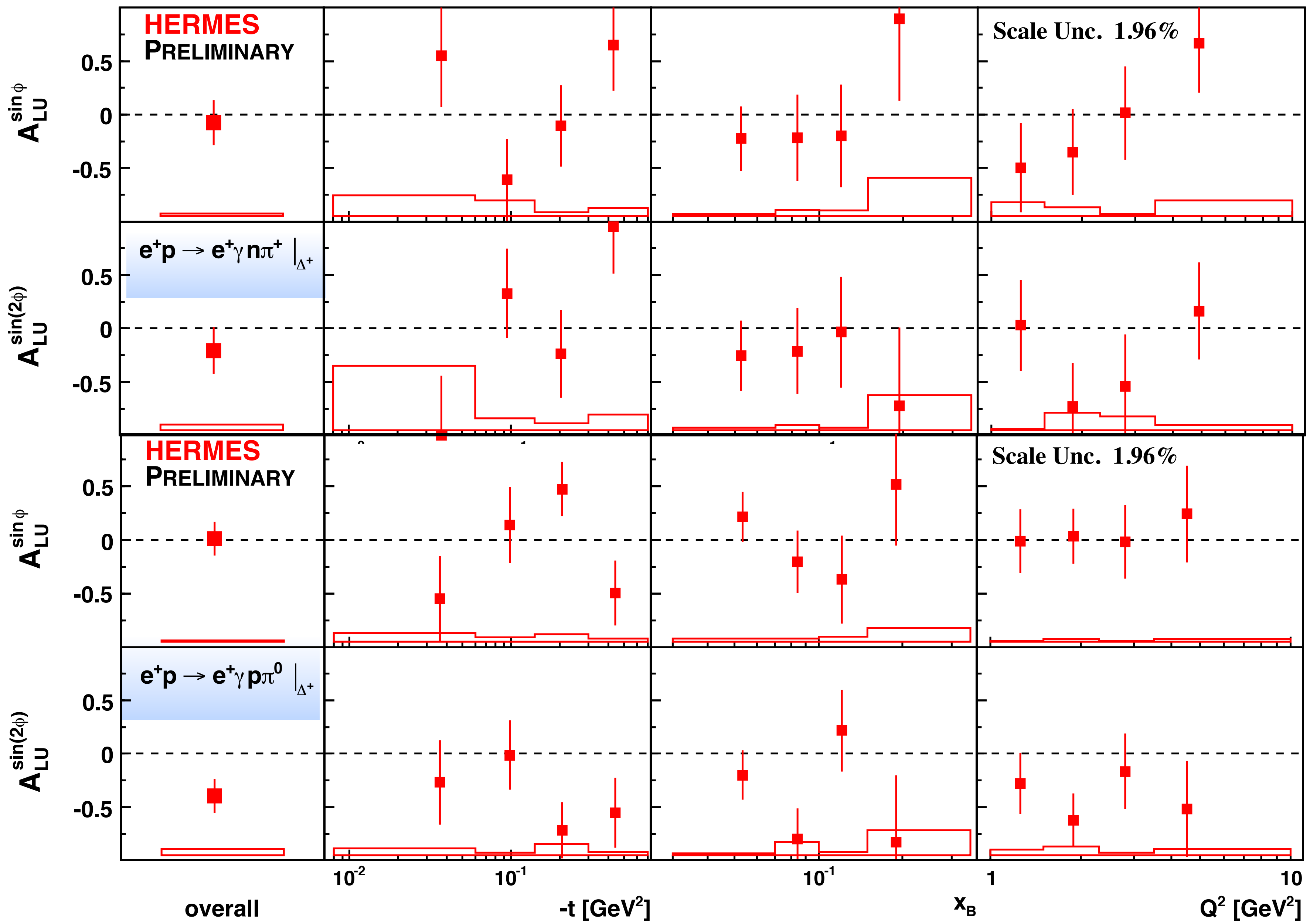


☛ indication for slightly larger magnitude of the leading amplitude for elastic process compared to the one in the recoil detector acceptance (unresolved-reference)

associated DVCS

$ep \to e'\gamma\Delta$

(recoil data)



Fractional purity
Associated: DVCS/BH - 85.7 ± 1.8
Elastic DVCS/BH (ep→eγp): 1.1 ± 0.1
SIDIS: 13.2 ± 1.9

Fractional purity
Associated DVCS/BH: 75.6 ± 2.6
Elastic DVCS/BH (ep→eγp): 0.1 ± 0.1
SIDIS: 24.4 ± 3.4

- 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

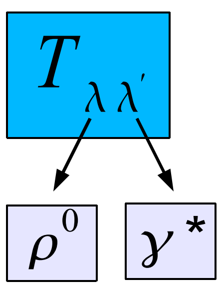
vector meson production

$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_s\, d\phi\, d\cos\vartheta\, d\varphi} \sim \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)$$

☛ production and decay angular distributions W decomposed:

$$W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}$$

☛ parametrized by helicity amplitudes



☛ or alternatively by SDMEs:

-Schilling, Wolf (1973)-

helicity amplitudes or SDMEs describe

☛ the helicity transfer from virtual photon to the vector meson

☛ the parity of the diffractive exchange process

- ☛ natural parity is related to H and E
- ☛ unnatural parity is related to $\widetilde{H}$ and $\widetilde{E}$

SDMEs on unpolarized H and D targets

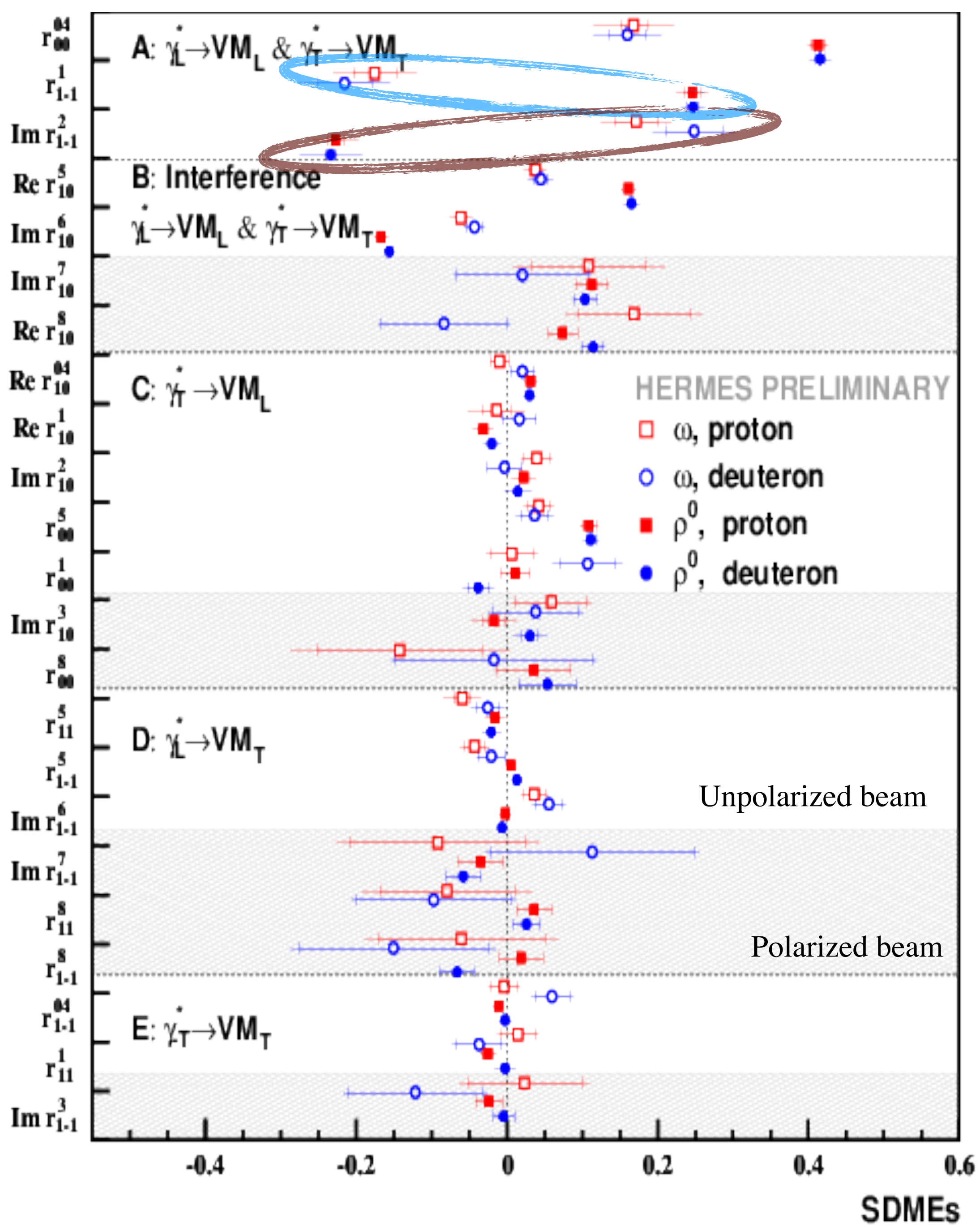
ρ^0 | $ep \to e' \rho^0 p'$

ω | $ep \to e' \omega p'$

-HERMES Collaboration-:
EPJC 62 (2009) 659-694

$T_{\lambda\lambda'}$ → ρ^0, γ^*

$$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$$



23 SDMEs in 5 classes

The SDMEs for hydrogen and deuteron are similar

✓**class A:** different sign of ω leading twist SDMEs compared to ρ^0

- indication of unnatural parity exchange!

$$r^1_{1-1} = \frac{1}{2}\widetilde{\sum}\{|T_{11}|^2 + |T_{1-1}|^2 - |U_{11}|^2 - |U_{1-1}|^2\}/\mathcal{N},$$
$$\mathrm{Im}\,\{r^2_{1-1}\} = \frac{1}{2}\widetilde{\sum}\{-|T_{11}|^2 + |T_{1-1}|^2 + |U_{11}|^2 - |U_{1-1}|^2\}/\mathcal{N}$$

$|U_{11}|^2 + |U_{1-1}|^2 > |T_{11}|^2 + |T_{1-1}|^2$ for ω meson
$|T_{1-1}|^2 + |U_{11}|^2 > |T_{11}|^2 + |U_{1-1}|^2$ for ω meson

Assuming $|T_{1-1}|^2 \approx |U_{1-1}|^2$ we get $|U_{11}|^2 > |T_{11}|^2$ for ω meson

✓**class D:** Some SDMEs indicate SCHC violation

$r^5_{11} + r^5_{1-1} - Im\{r^6_{1-1}\} = -0.14 \pm 0.02 \pm 0.04$ for hydrogen
$r^5_{11} + r^5_{1-1} - Im\{r^6_{1-1}\} = -0.10 \pm 0.03 \pm 0.03$ for deuterium

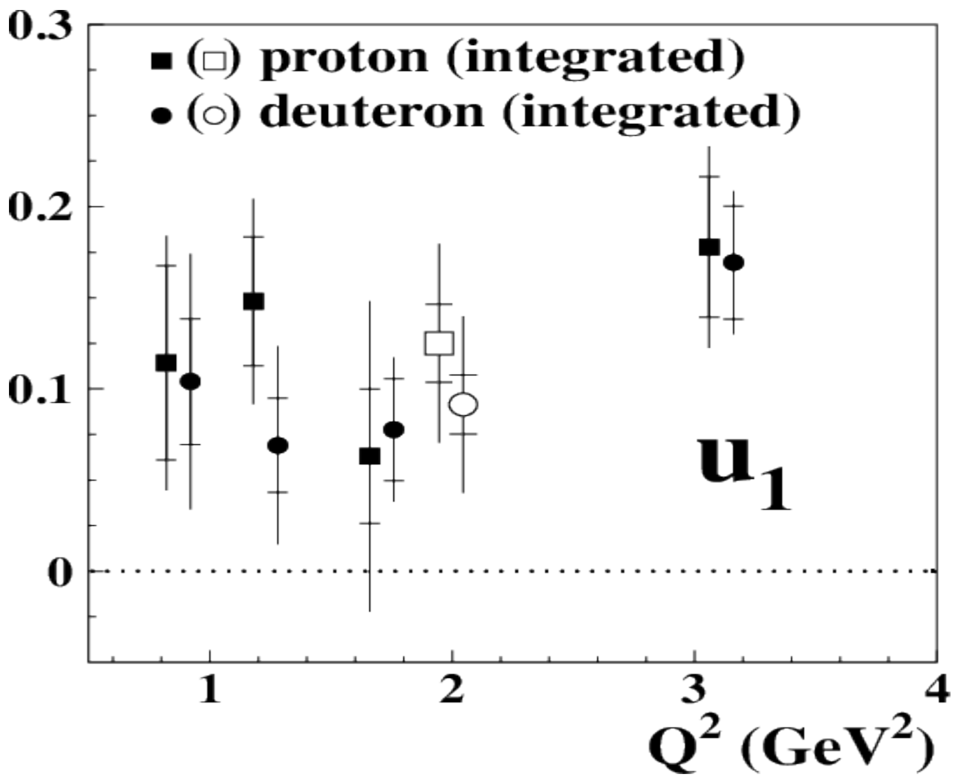
unnatural parity exchange observation

✔At large Q^2 and W the **unnatural** parity exchange should be suppressed by M_v/Q

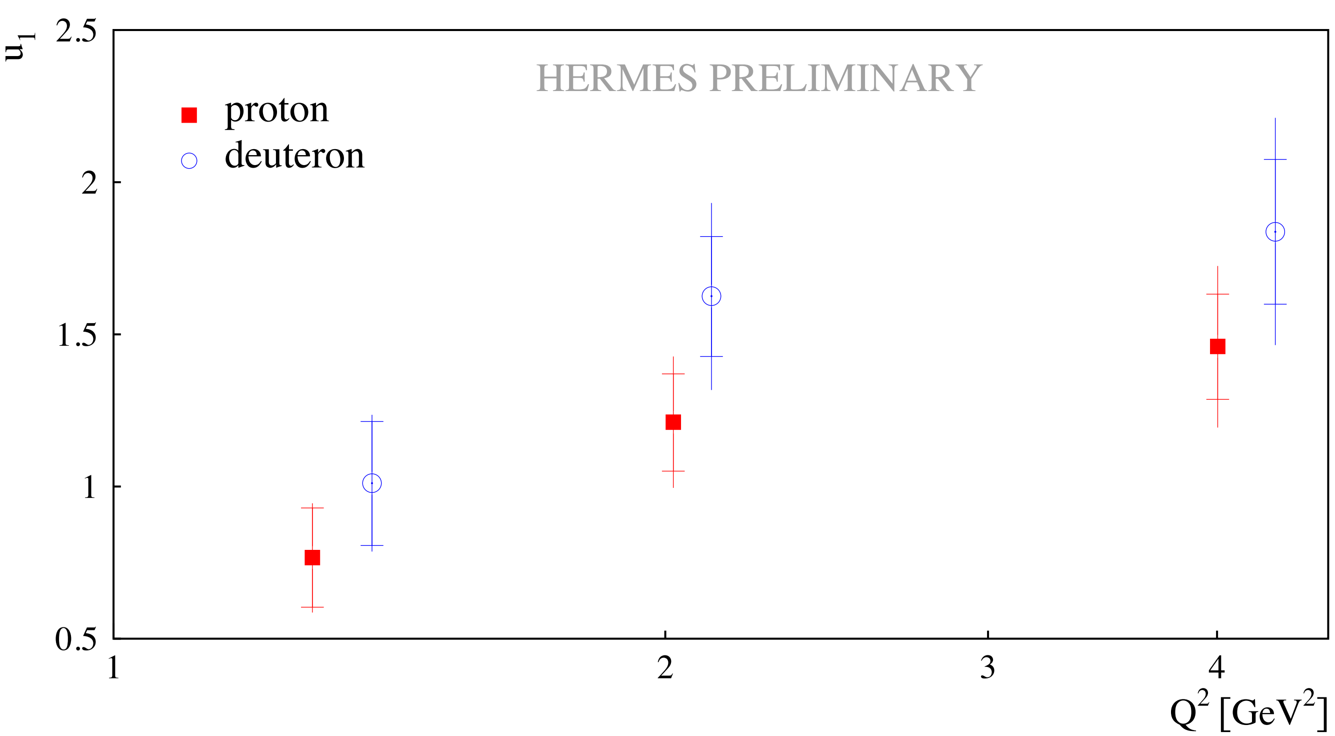
✔The combinations of SDMEs expected to be zero in case of natural parity exchange dominance:

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}$$ $$u_2 = r^{5}_{11} + r^{5}_{1-1}$$ $$u_3 = r^{8}_{11} + r^{8}_{1-1}$$

ρ^0: non-zero UPE signal (3σ)

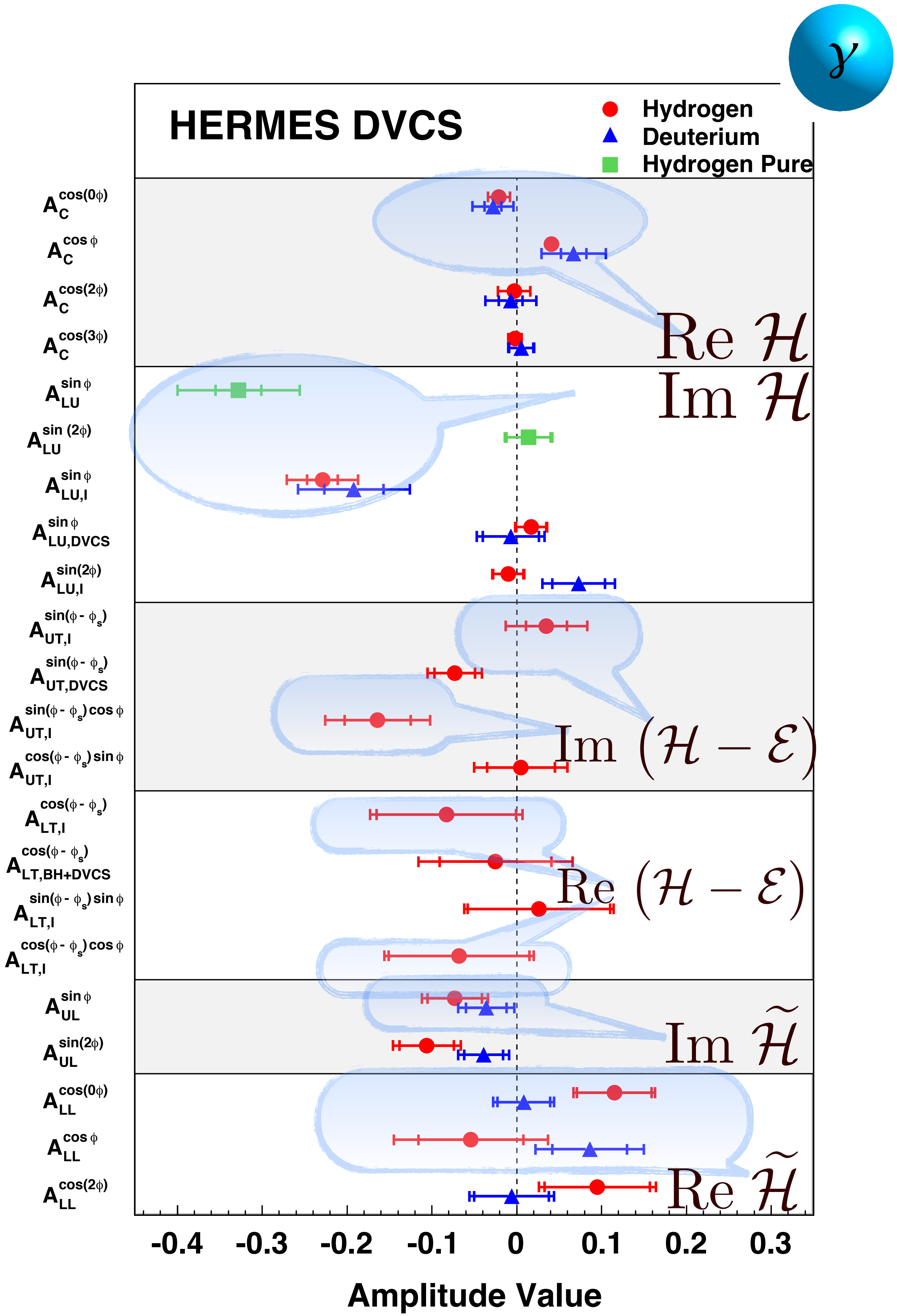


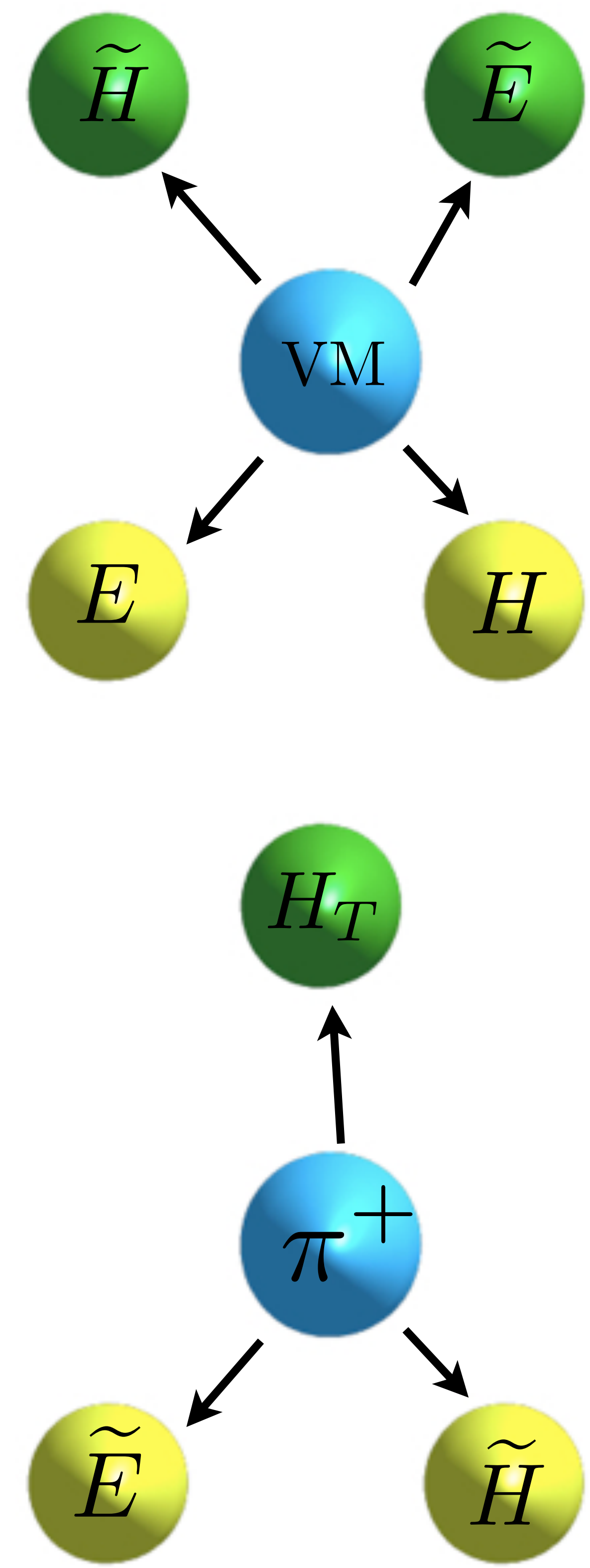
ω: dominant UPE signal!



possible access to GPD $\widetilde{H}$!

2^{nd} halftime report





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