Recent results from the hermes experiment

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ikerbasque
Basque Foundation for Science

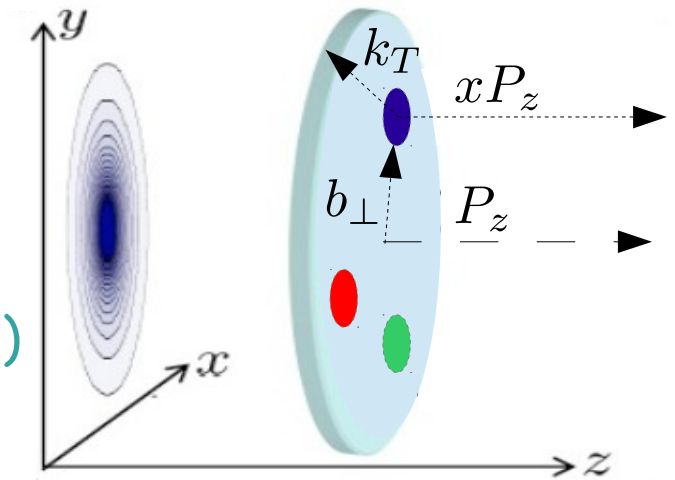
PacSpin 2013, Ji'nan

The nucleon in multiple dimensions

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

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

transverse-momentum dependent PDFs (TMDs)



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

impact-parameter distributions

Fourier transform

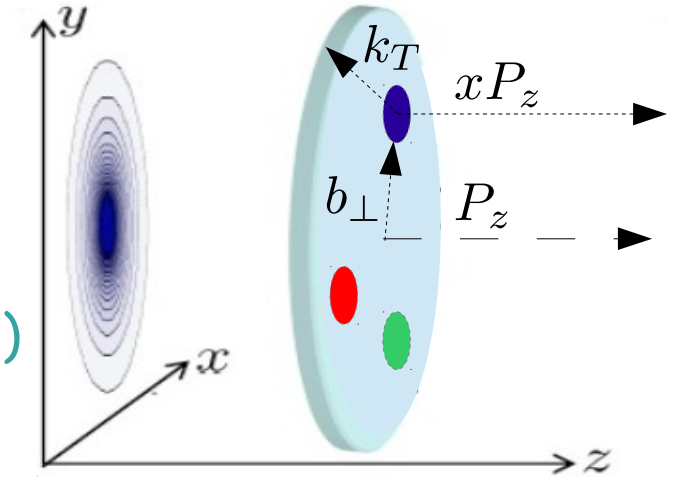
generalized parton distributions (GPDs)

The nucleon in multiple dimensions

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

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

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



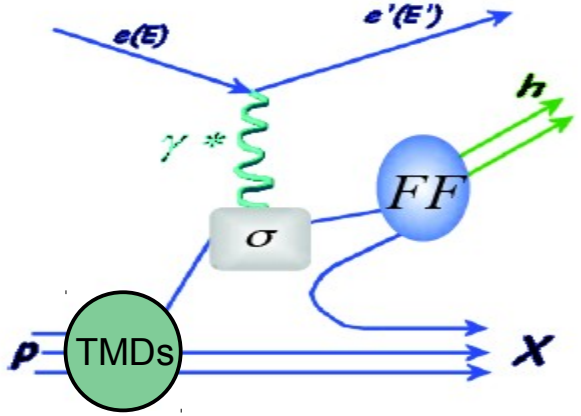
transverse-momentum dependent PDFs (TMDs)

impact-parameter distributions

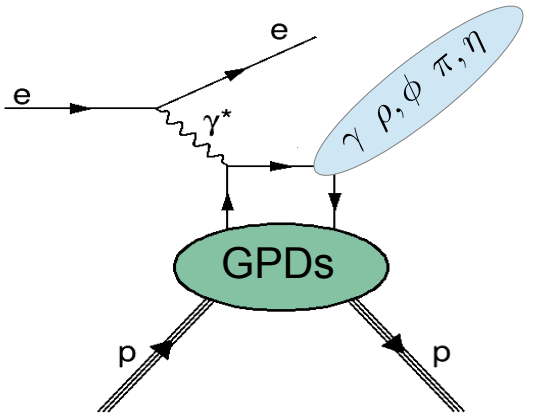
Fourier transform

generalized parton distributions (GPDs)

semi-inclusive deep-inelastic scattering (DIS)



hard exclusive reactions



Semi-inclusive DIS

Semi-inclusive DIS cross section

$$\frac{d\sigma}{dxdydzd\phi_h dP_{h\perp}^2 d\phi_S} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi_h) F_{UU}^{\cos(\phi_h)} + \epsilon\cos(2\phi_h) F_{UU}^{\cos(2\phi_h)}$$

beam polarization

$$+\lambda_e \sqrt{2\epsilon(1-\epsilon)}\sin(\phi_h) F_{LU}^{\sin(\phi_h)}$$

longitudinal target polarization

$$+S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_h) F_{UL}^{\sin(\phi_h)} + \epsilon\sin(2\phi_h) F_{UL}^{\sin(2\phi_h)}\Big]$$

$$+S_L\lambda_e\Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_h) F_{LL}^{\cos(\phi_h)}\Big]$$

transverse target polarization

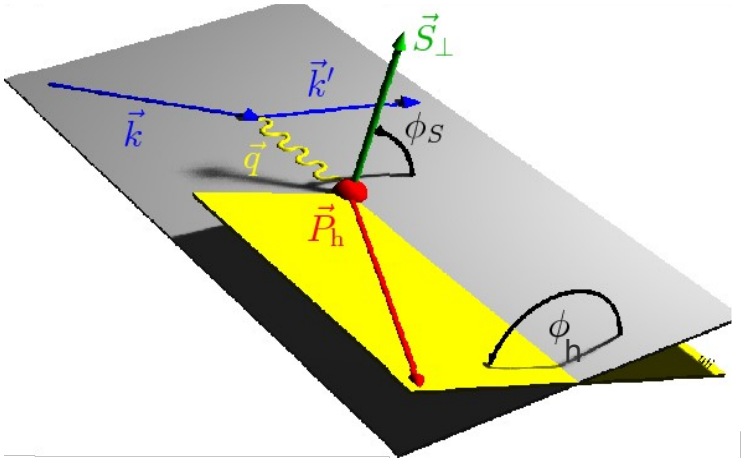
$$+S_T\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+ \quad \epsilon\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \quad \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+S_T\lambda_e\Big[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)}$$

$$+ \quad \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi_h-\phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$



target polarization

structure function $F_{XY(,Z)}$

beam polarization

(virtual photon polarization)

Semi-inclusive DIS cross section

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transverse target polarization

$$+S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

$$+ \epsilon\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

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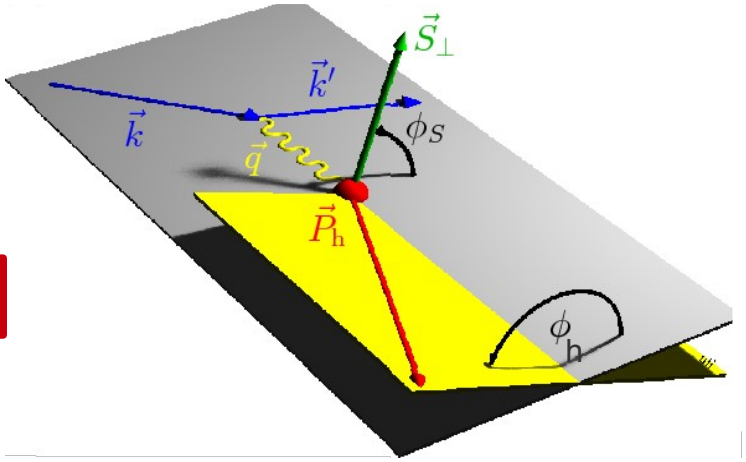
$$+ \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi_h-\phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$



target polarization

structure function $F_{XY(,Z)}$

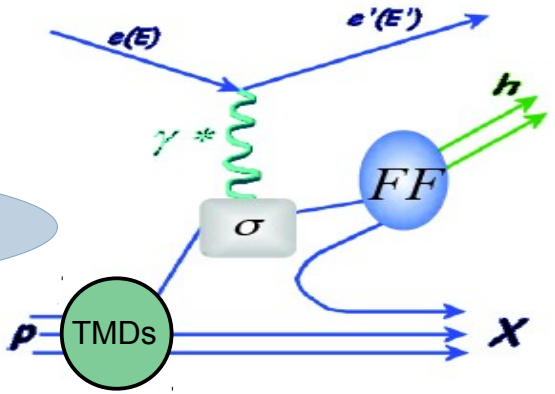
beam polarization

(virtual photon polarization)

leading twist

Semi-inclusive DIS cross section

structure function $F_{XY} \propto TMD \otimes FF$



transverse momentum distributions (TMDs)

nucleon	quark: U	quark: L	quark: T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

fragmentation functions (FFs)

h	quark: U	quark: L	quark: T
U	D_1		$H_1^\perp$

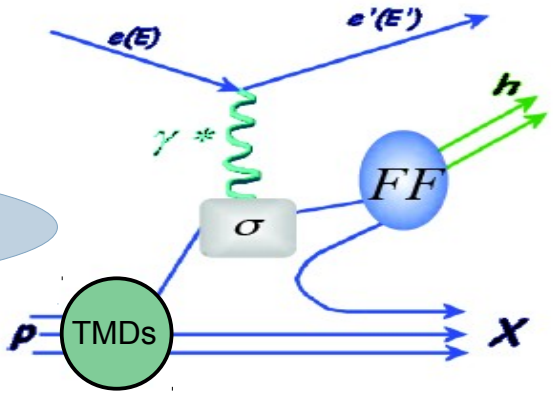
nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Semi-inclusive DIS cross section

structure function $F_{XY} \propto TMD \otimes FF$



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U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

fragmentation functions (FFs)

hadron	quark U	quark T
h	D_1 (spin-independent FF)	$H_1^\perp$ (Collins FF)

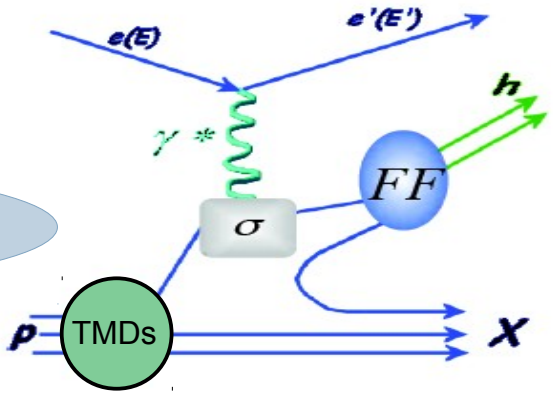
nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Semi-inclusive DIS cross section

structure function $F_{XY} \propto TMD \otimes FF$



transverse momentum distributions (TMDs)

nucleon	quark U	quark L	quark T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

spin-independent DF

Boer-Mulders DF

Sivers DF

fragmentation functions (FFs)

hadron	quark U	quark T
h	D_1	$H_1^\perp$

spin-independent FF

Collins FF

nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Hadron multiplicities

Hadron multiplicities

$$\frac{d\sigma}{dxdydzd\phi_h dP_{h\perp}^2} \Rightarrow \int d\phi_h$$

$$\mathrm{M}^h(x_B, Q^2, z, P_{h\perp}) = \frac{1}{d^2\,N^{DIS}(x_B,Q^2)} \frac{d^4\,N^h(x_B,Q^2,z,P_{h\perp})}{dzdP_{h\perp}}$$

$$\propto \frac{F_{UU,T} + \epsilon F_{UU,L}}{F_T + \epsilon F_L}$$

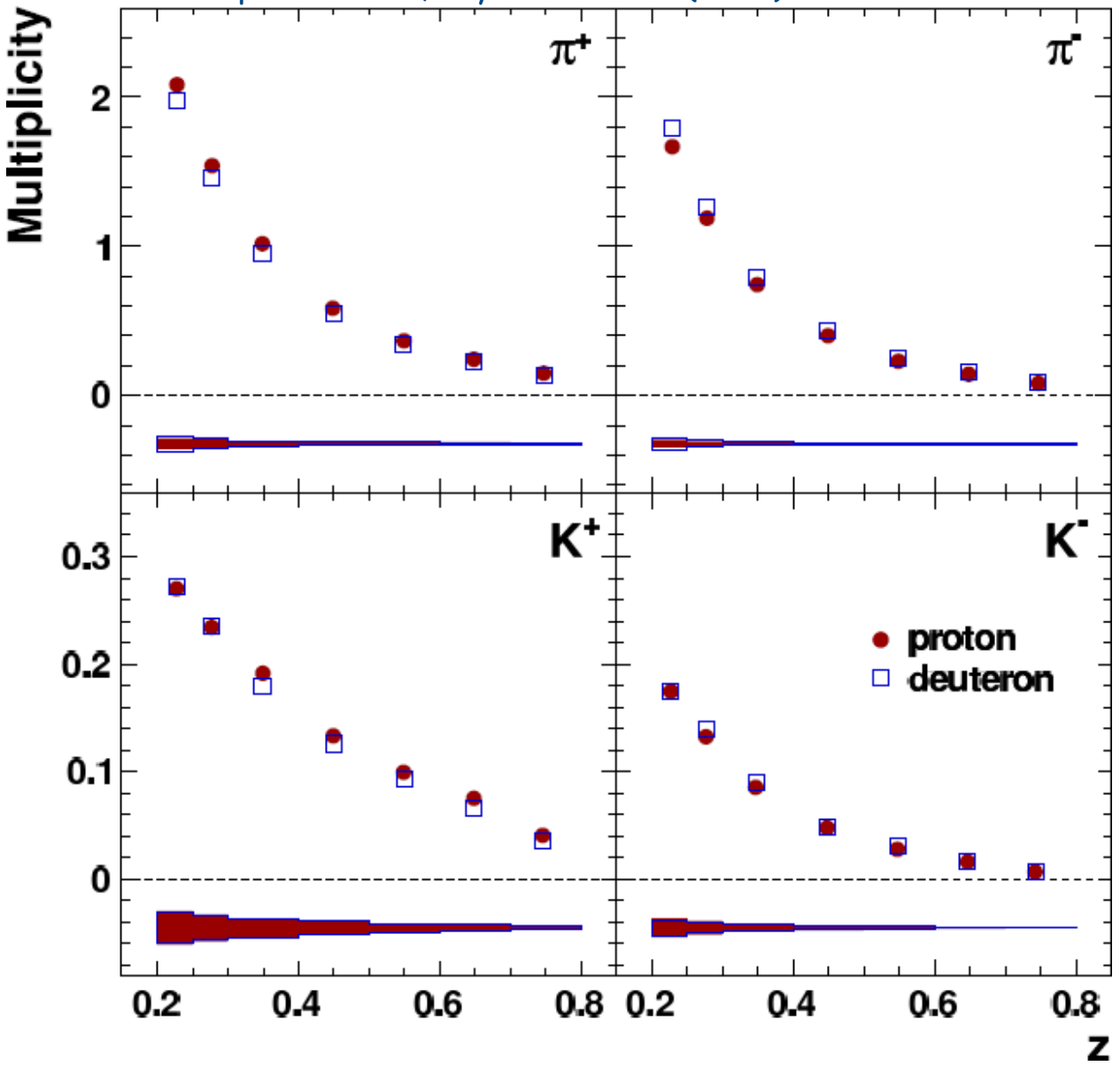
$$\propto \frac{\sum_q e_q^2\, f_1^q(x_B, k_T^2, Q^2) \otimes D_1^q(z, p_T^2, Q^2)}{\sum_q e_q^2\, f_1^q(x_B, Q^2)}$$

k_T : transverse momentum of struck quark

p_T : transverse momentum of fragmenting quark

Results projected in z

A. Airapetian et al., Phys. Rev. D **87** (2013) 074029

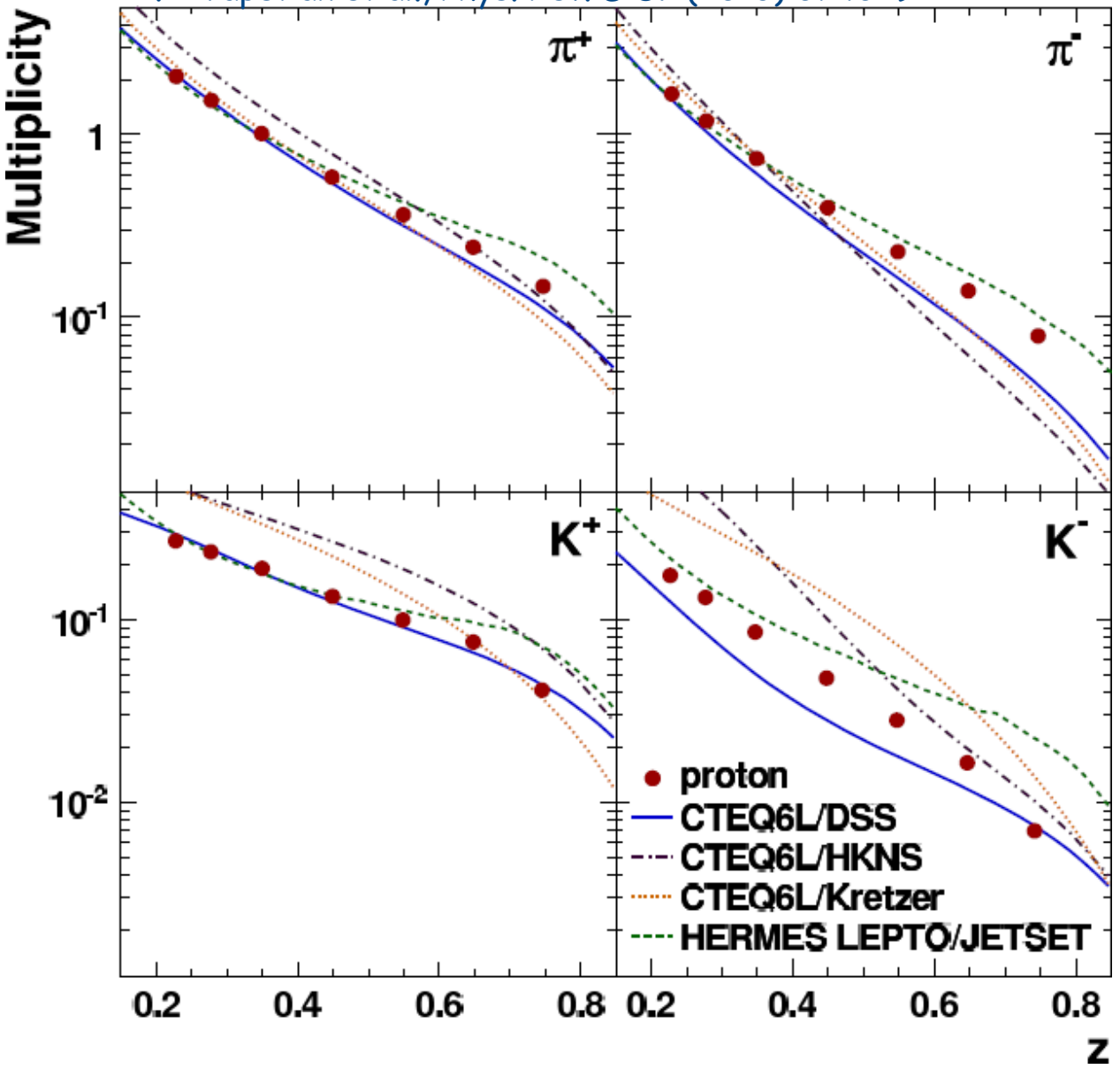


multiplicities reflect

- nucleon valence-quark content (u-dominance)
- favored ↔ unfavored fragmentation

Comparison to models

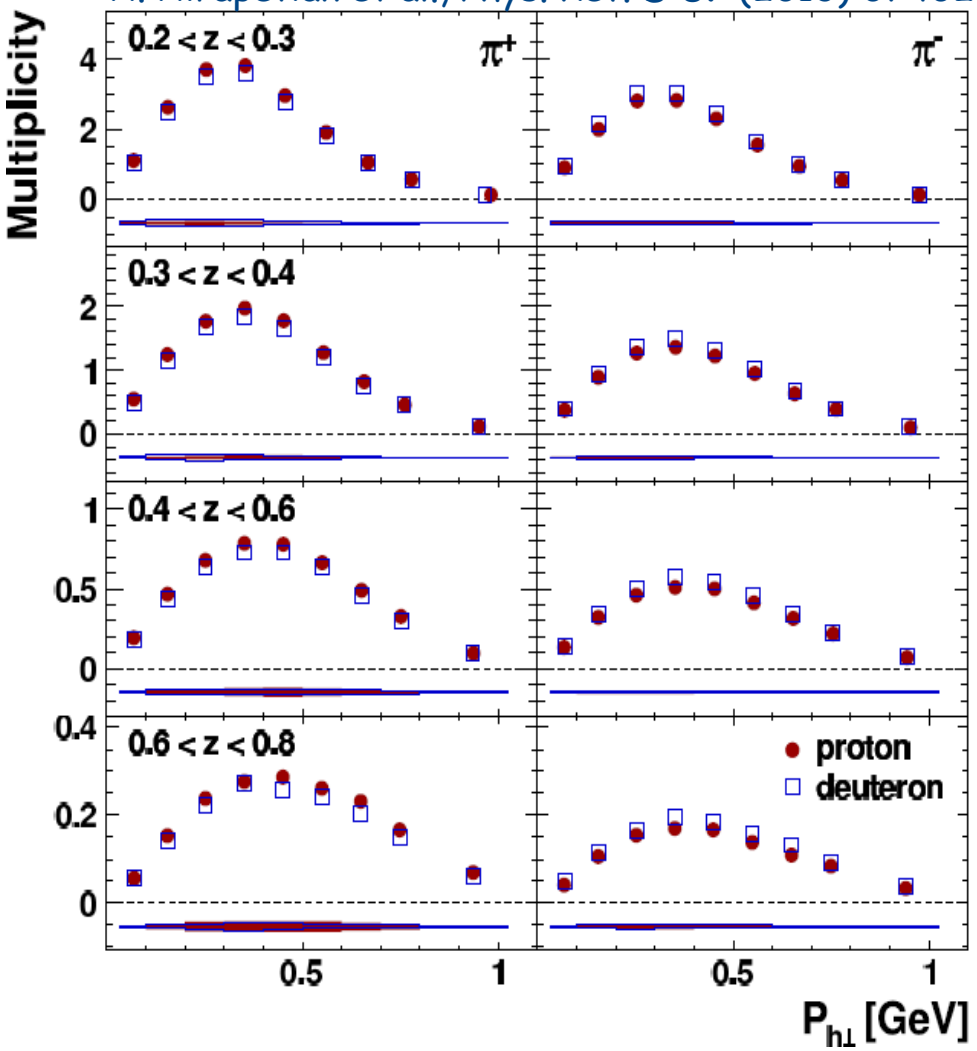
A. Airapetian et al., Phys. Rev. D **87** (2013) 074029

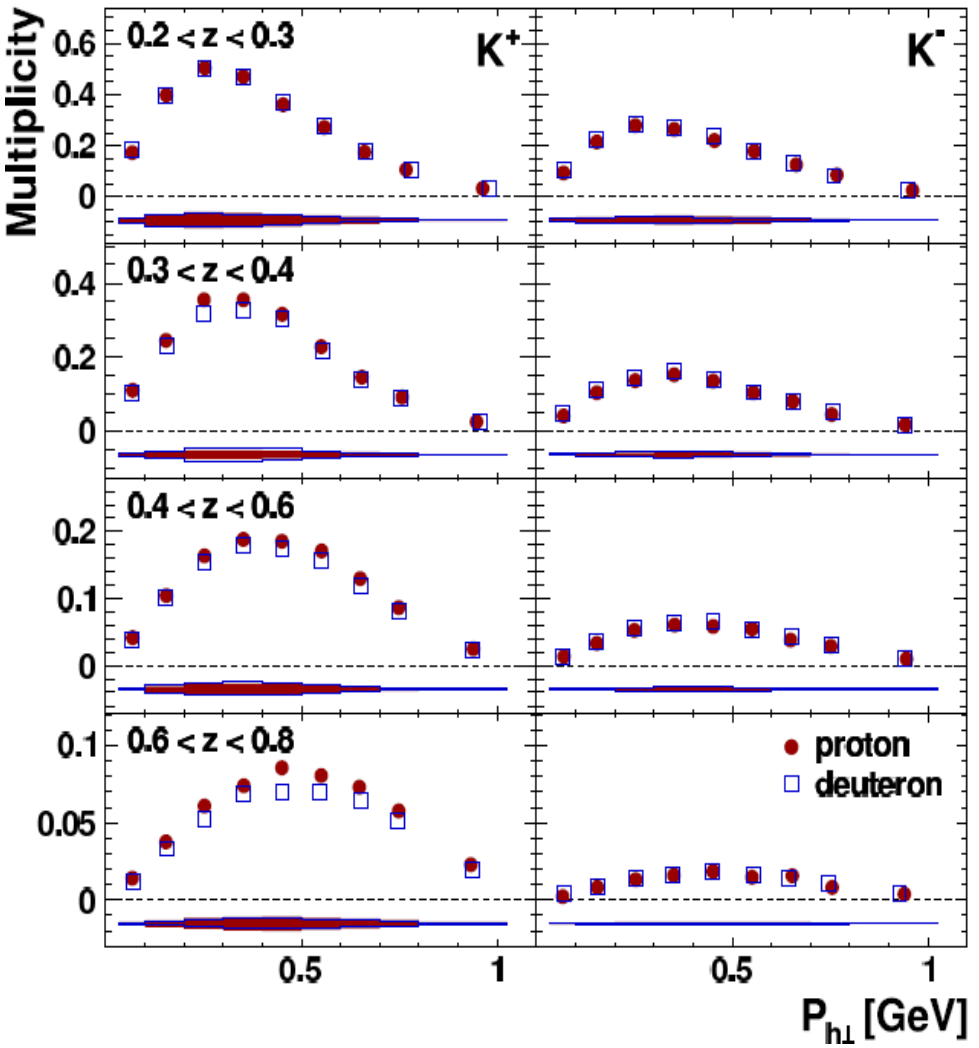


- LO in α_S
- CTEQ6L PDFs
  JHEP **0207** (2002) 012
- DSS FFs
  Phys. Rev. D **75** (2007) 114010
- Kretzer FFs
  Phys. Rev. D **62** (2000) 054001
- reasonable agreement between DSS and positive mesons
- poor agreement for negative mesons

Results projected in z and $P_{h\perp}$

A. Airapetian et al., Phys. Rev. D **87** (2013) 074029





- $P_{h\perp}$: - transverse intrinsic struck-quark momentum
  - transverse momentum from fragmentation process
- K^-: broader distribution

multi-dimensional analysis; more projections via http://www-hermes.desy.de/multiplicities

Re-evaluation of the strange quark distribution

K± multiplicities from unpolarized deuterium

$$\frac{d^2N^K(x)}{d^2N^{DIS}(x)} = \frac{Q(x)\int_{0.2}^{0.8}\mathcal{D}_Q^K(z)dz + S(x)\int_{0.2}^{0.8}\mathcal{D}_S^K(z)dz}{5Q(x)+2S(x)}$$

$$Q(x) \equiv u(x) + \bar{u}(x) + d(x) + \bar{d}(x)$$
$$S(x) \equiv s(x) + \bar{s}(x)$$

$$\mathcal{D}_Q^K(z) \equiv 4D_u^K(z) + D_d^K(z)$$
$$\mathcal{D}_S^K(z) \equiv 2D_s^K(z)$$

Re-evaluation of the strange quark distribution

$K^{\pm}$ multiplicities from unpolarized deuterium

$$\frac{d^2N^K(x)}{d^2N^{DIS}(x)} = \frac{Q(x)\int_{0.2}^{0.8}\mathcal{D}_Q^K(z)dz + S(x)\int_{0.2}^{0.8}\mathcal{D}_S^K(z)dz}{5Q(x)+2S(x)}$$

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$$S(x) \equiv s(x) + \bar{s}(x)$$

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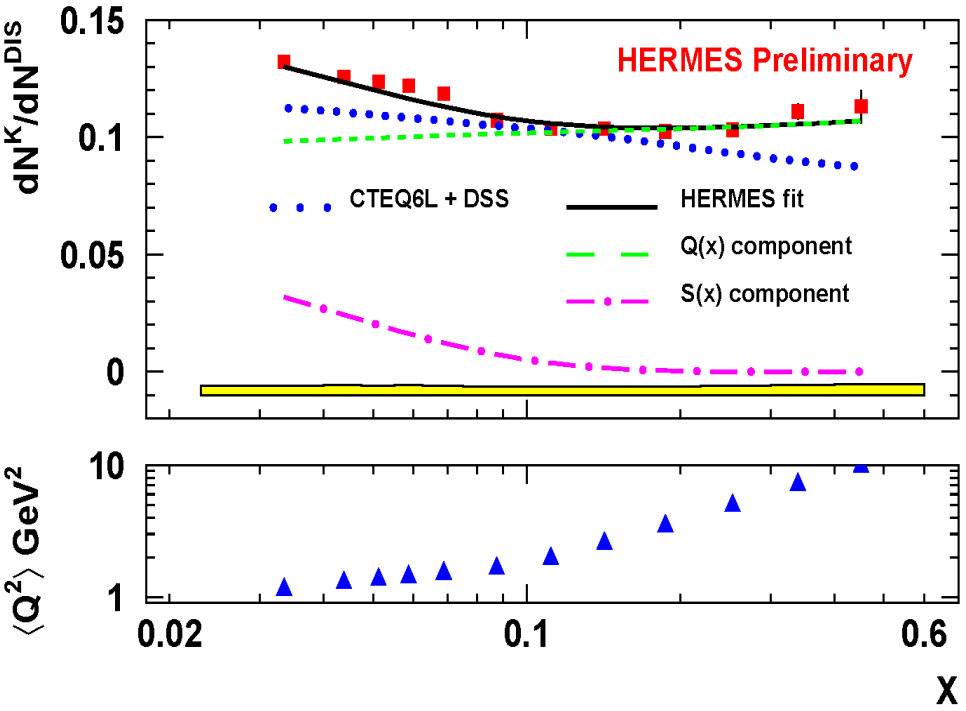
$$\mathcal{D}_S^K(z) \equiv 2D_s^K(z)$$



S(x)≈0 for x>0.1

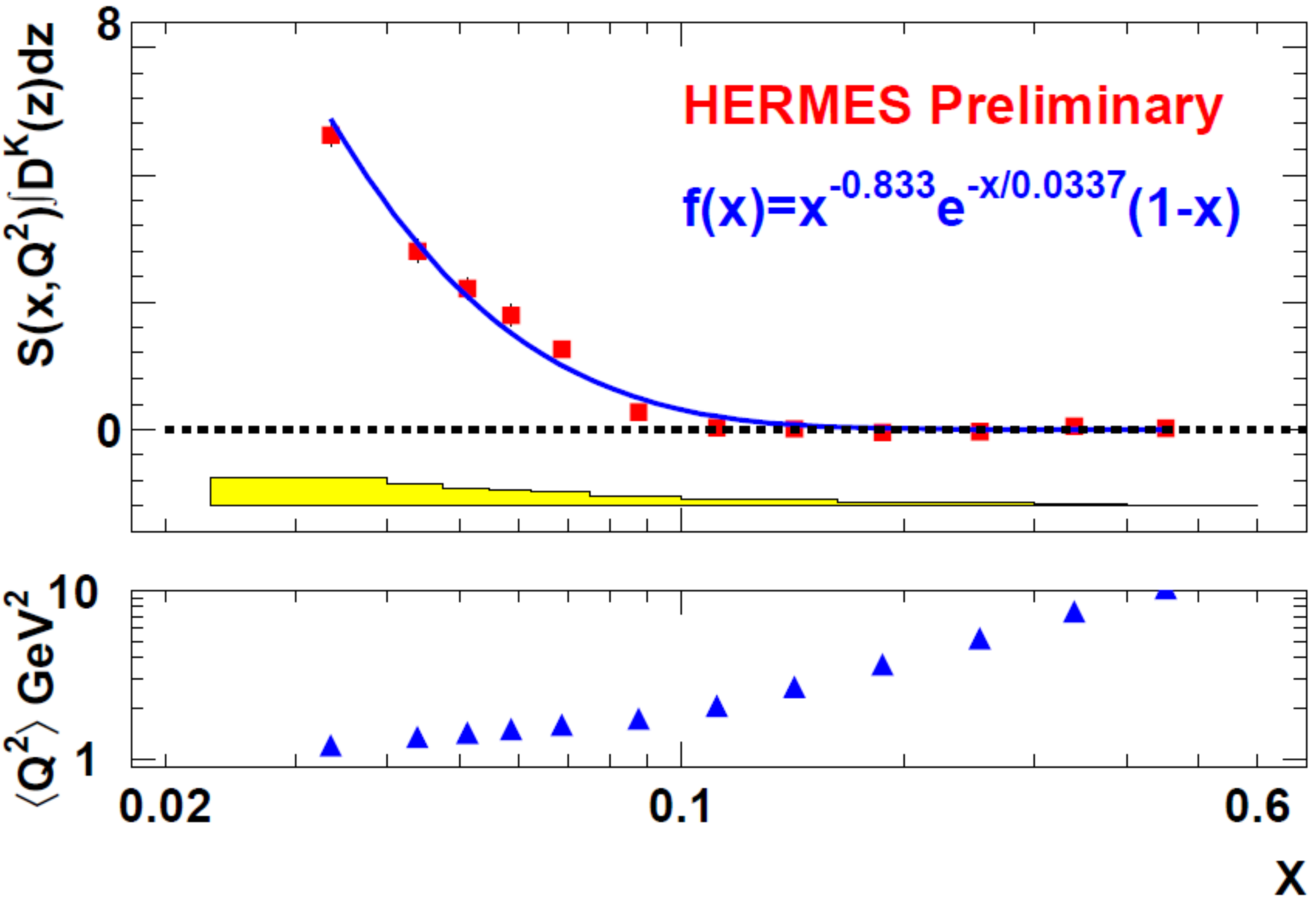
fit

$$f(x) = (0.102 \pm 0.002) + (0.013 \pm 0.010)\,x$$

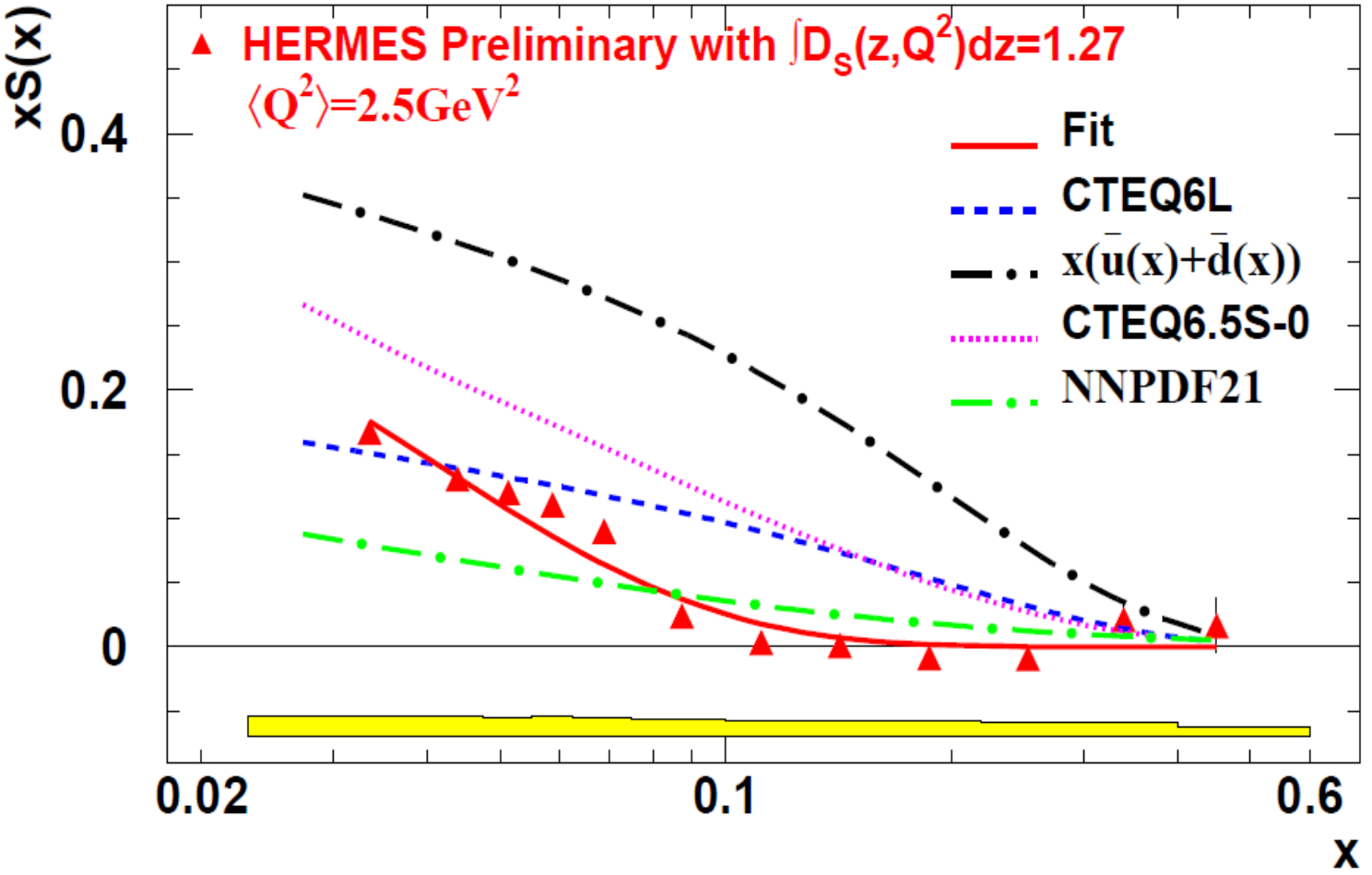
$$\int_{0.2}^{0.8}\mathcal{D}_Q^K(z)dz = 0.398 \pm 0.010$$

Re-evaluation of the strange quark distribution

Q(x) from CTEQ6L



Re-evaluation of the strange quark distribution



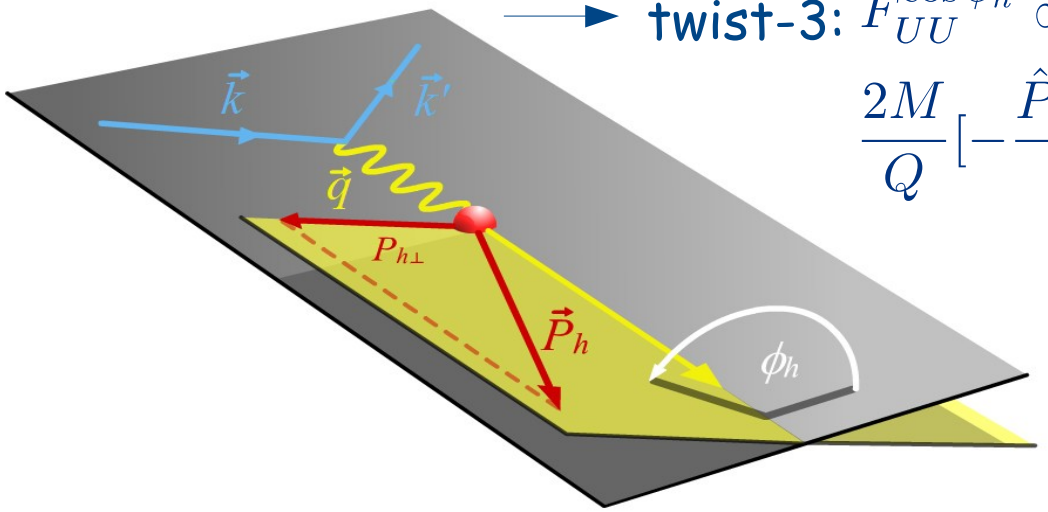
- $xS(x)$ for certain value of $\int \mathcal{D}_S^K(z)dz$
- independent of value, shape of $xS(x)$ incompatible with predictions

non-collinear semi-inclusive DIS

- twist-2: $F_{UU}^{\cos 2\phi_h} \propto h_1^{\perp} \times H_1^{\perp}$
- twist-3: $F_{UU}^{\cos \phi_h} \propto$

$$\frac{2M}{Q}[-\frac{\hat{P}_{h\perp}.\vec{k}_T}{M} f_1 \otimes D_1 - \frac{\hat{P}_{h\perp}.\vec{p}_T}{M_h} \frac{k_T^2}{M^2} h_1^{\perp} \otimes H_1^{\perp} + ...]$$

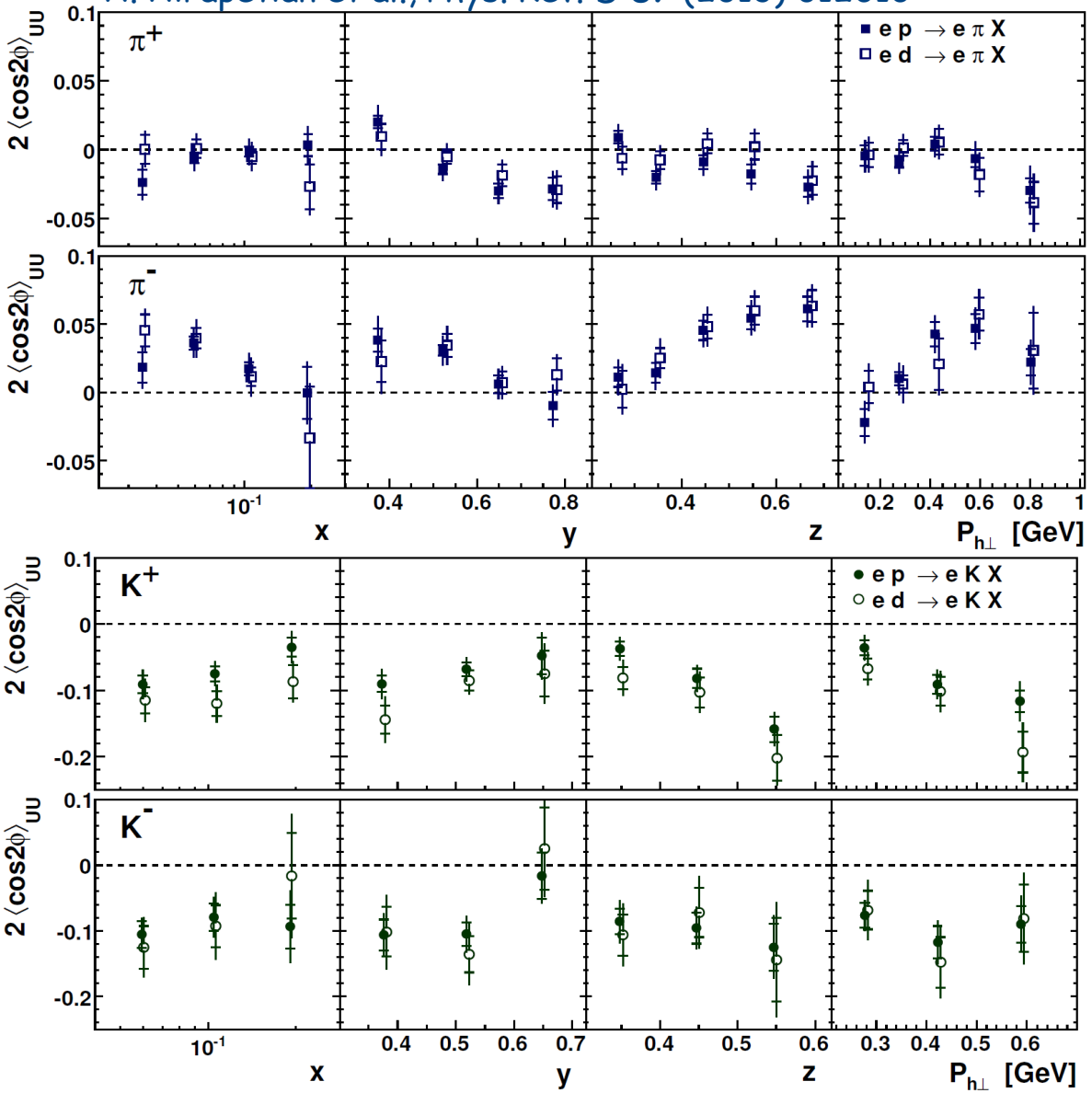
quark-gluon-quark correlations



Boer-Mulders function $h_1^\perp$

$$F_{UU}^{\cos(2\phi_h)} \propto h_1^\perp \otimes H_1^\perp$$

A. Airapetian et al., Phys. Rev. D **87** (2013) 012010



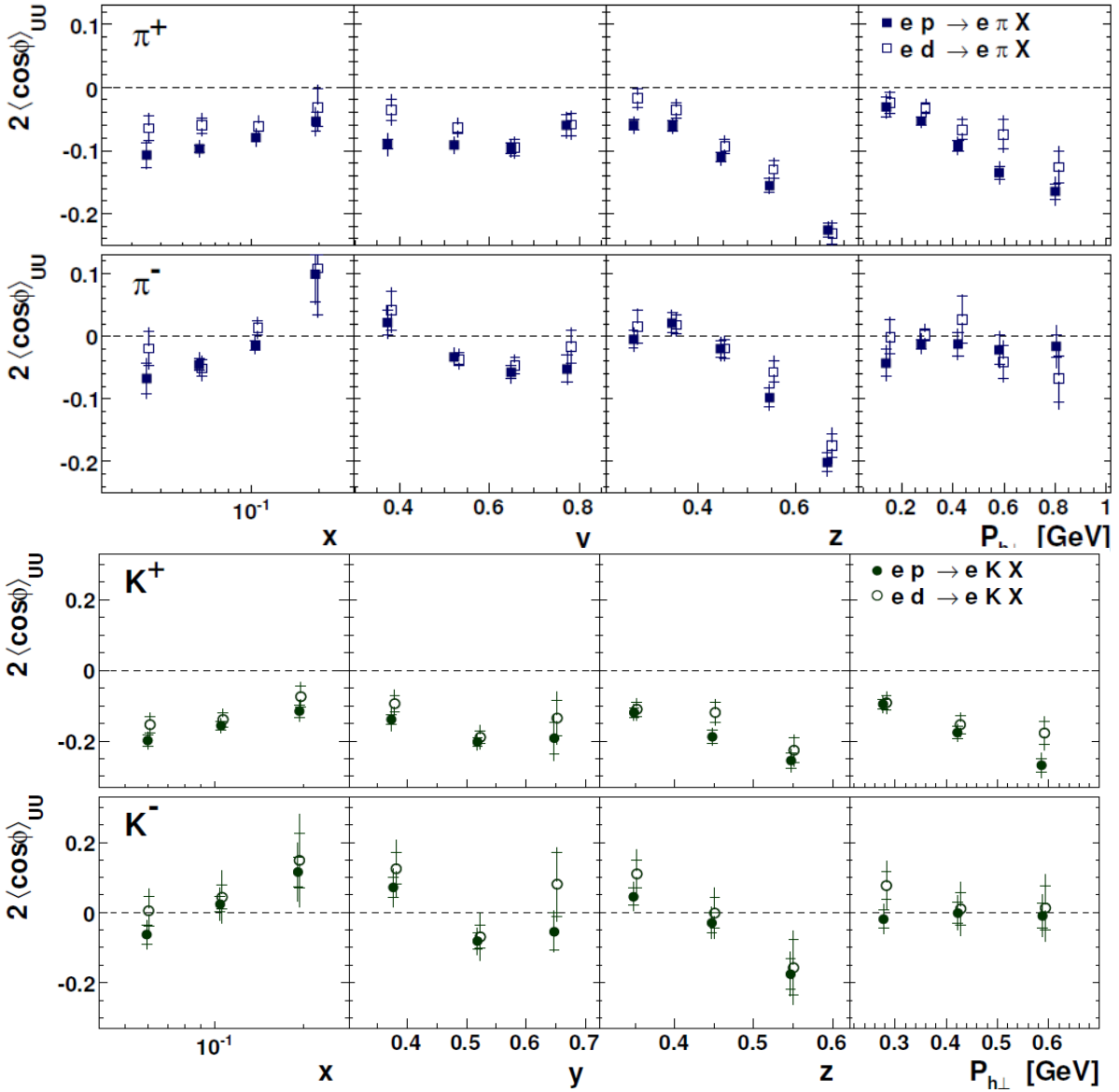
- significant amplitudes ⇒ orbital angular momentum
- H-D comparison: $h_1^{\perp,u} \approx h_1^{\perp,d}$
- $\pi^- > 0$ ◄► $\pi^+ \leqslant 0$, consistent with $H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$
- K^+ & K^-: large negative amplitudes
- $K^- \simeq K^+$
- $K^\pm$ very different from $\pi^\pm$

fully differential analysis; more projections via http://www-hermes.desy.de/cosnphi/

Twist-3: Cahn, Boer-Mulders, ...

$$F_{UU}^{\cos\phi_h} \propto \frac{M}{Q}[f_1 \times D_1,\ h_1^\perp \times H_1^\perp, ...]$$

A. Airapetian et al., Phys. Rev. D **87** (2013) 012010



- H-D comparison: weak flavour dependence
- strong flavour dependence

fully differential analysis; more projections via http://www-hermes.desy.de/cosnphi/

DIS with transversely polarized target

Structure function g_2

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

access via

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

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

Structure function g_2

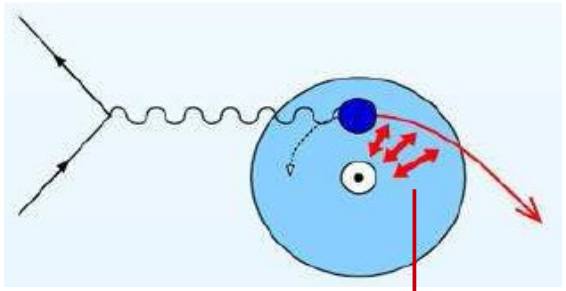
- $$\frac{d^3\sigma_{LT}}{dx\,dy\,d\phi'} \propto -h_k \left(\frac{y}{2} g_1(x,Q^2) + g_2(x,Q^2)\right) \cos(\phi')$$

  access via

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

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

- Sivers effect

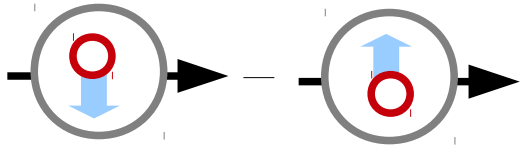


FSI: t=0 $\rightarrow \infty$

force on struck quark at t=0

$\propto -d_2$

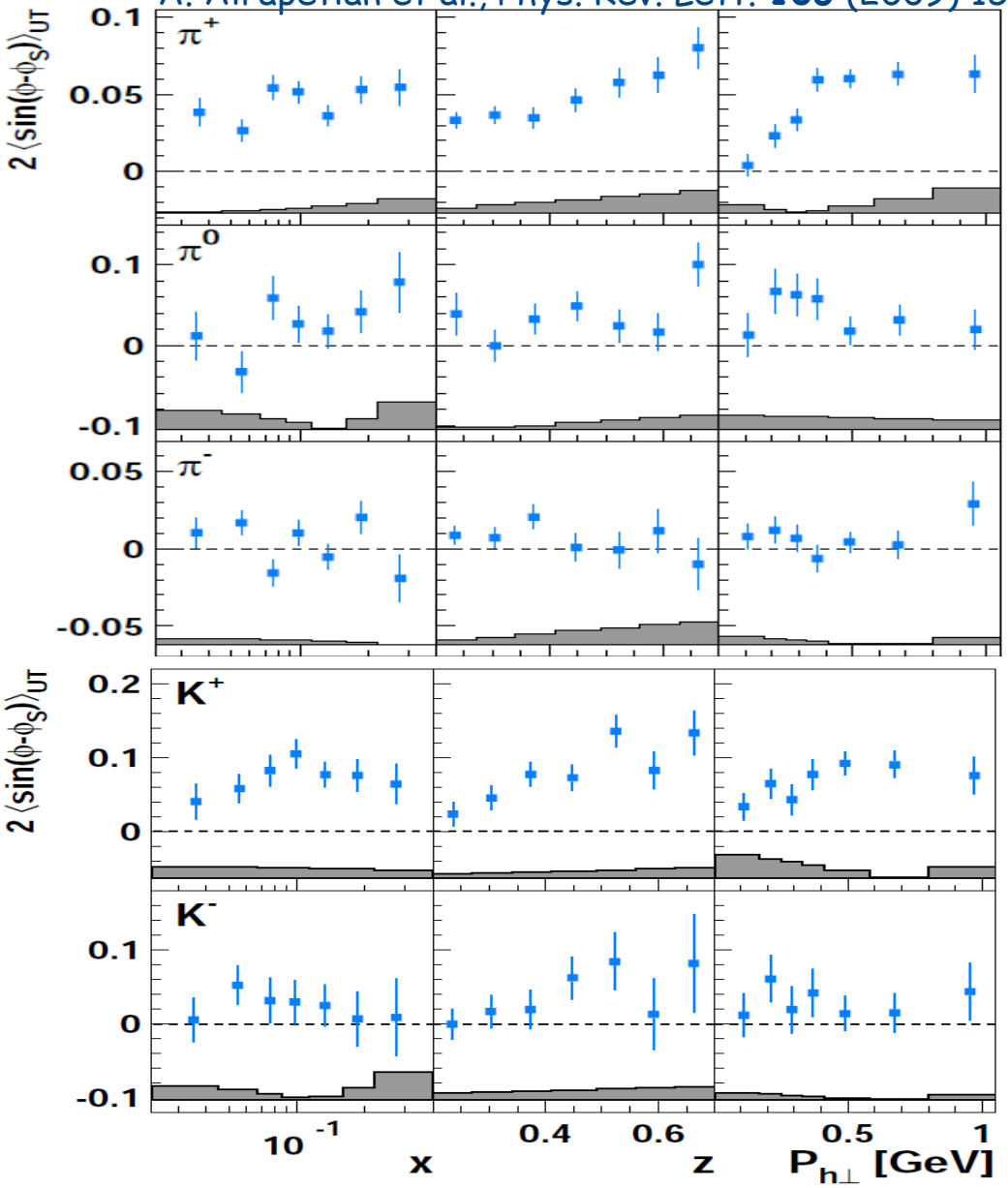
M. Burkardt, arXiv:0810.3589



Sivers function $f_{1T}^{\perp}$

$$F_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002



- π^+: significantly positive

  ⇒ orbital angular momentum

- u-quark dominance for p^+ amplitude:

$$\approx -\frac{f_{1T}^{\perp,u}(x,k_T^2) \otimes D_1^{u\to\pi^+}(z,p_T^2)}{f_1^u(x,k_T^2) \otimes D_1^{u\to\pi^+}(z,p_T^2)}$$

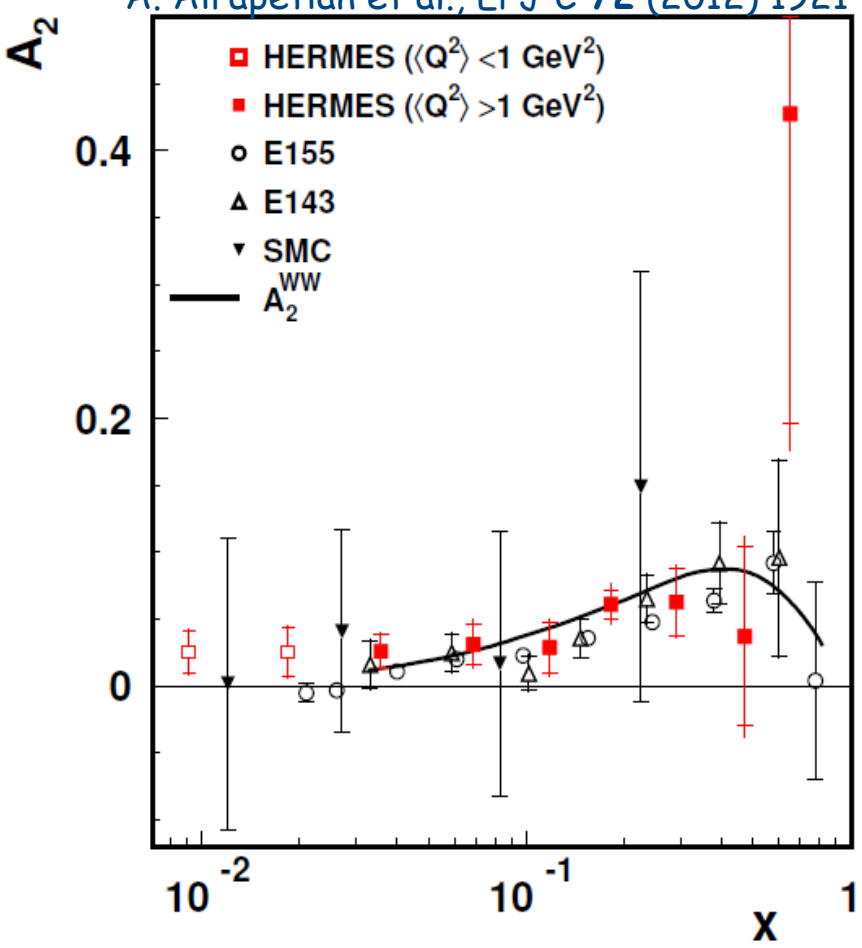
  ⇒ $f_{1T}^{\perp,u}(x,k_T^2) < 0$

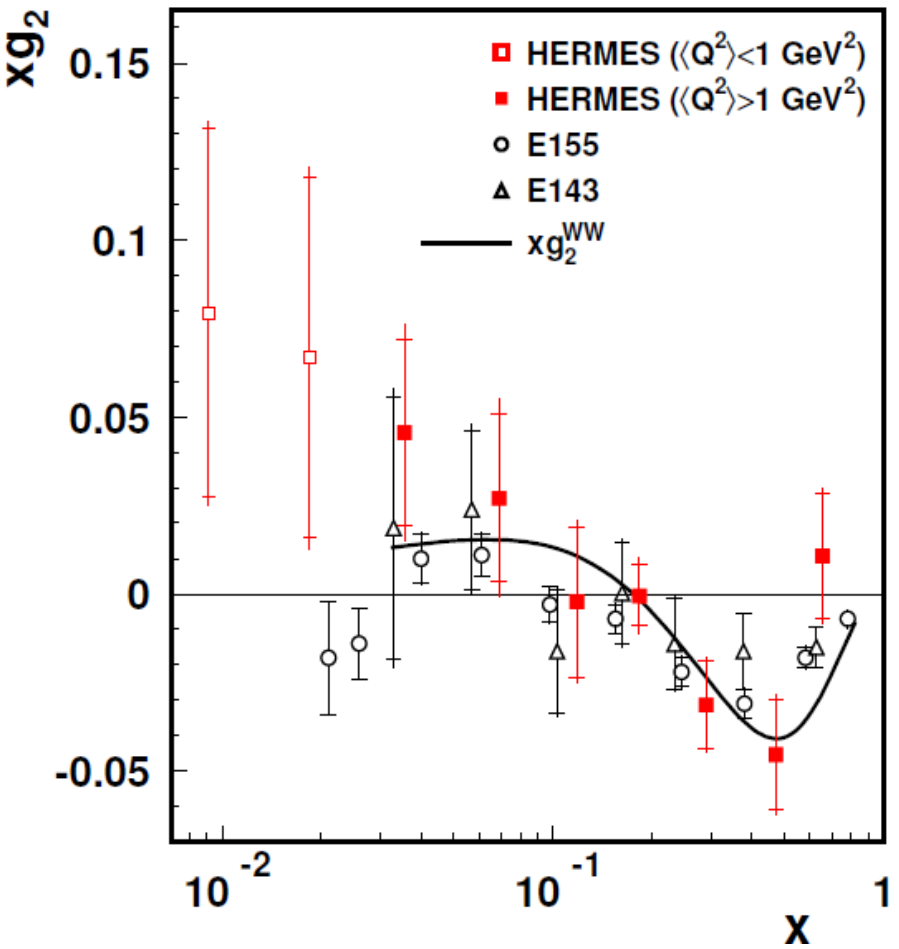
- π^-: u- and d-quark cancellation

  ⇒ $f_{1T}^{\perp,d}(x,k_T^2) > 0$

A_2 and g_2

A. Airapetian et al., EPJ C **72** (2012) 1921





- evaluation of Burkhardt-Cottingham sum rule:

$$\int_{0.023}^{0.9} dx\, g_2(x) = 0.006 \pm 0.024 \pm 0.017$$

E143+E155: $\int_{0.02}^{0.8} dx\, g_2(x) = -0.042 \pm 0.008$

- d_2:

$$d_2 = 0.0148 \pm 0.0096 \pm 0.0048$$

E143+E155:

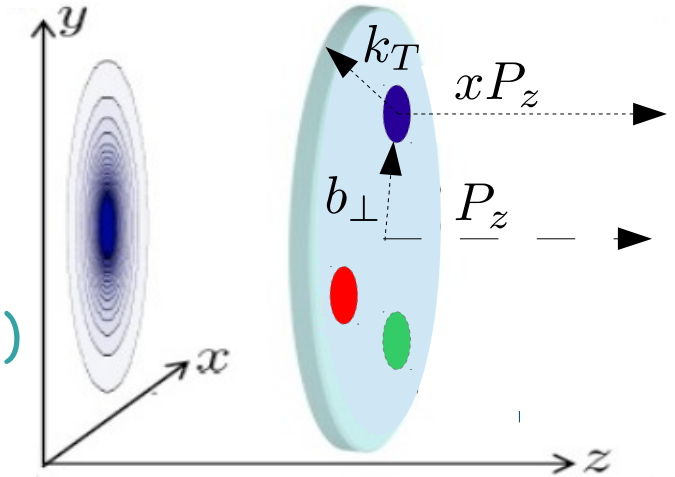
$$d_2 = 0.0032 \pm 0.0017$$

The nucleon in multiple dimensions

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

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

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



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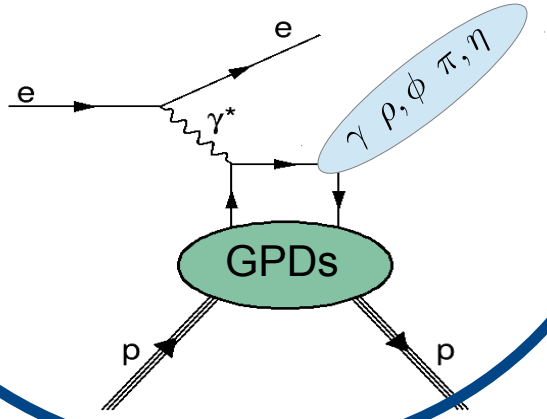
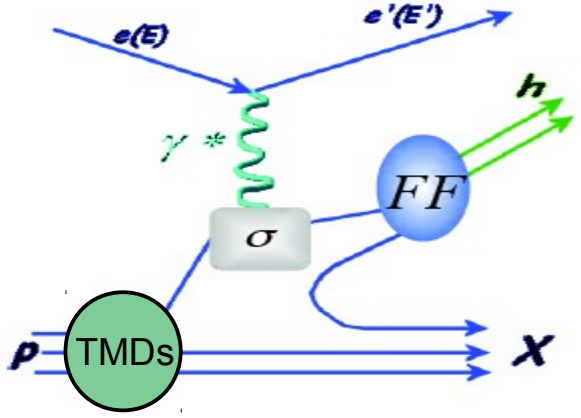
generalized parton distributions (GPDs)

hard exclusive reactions

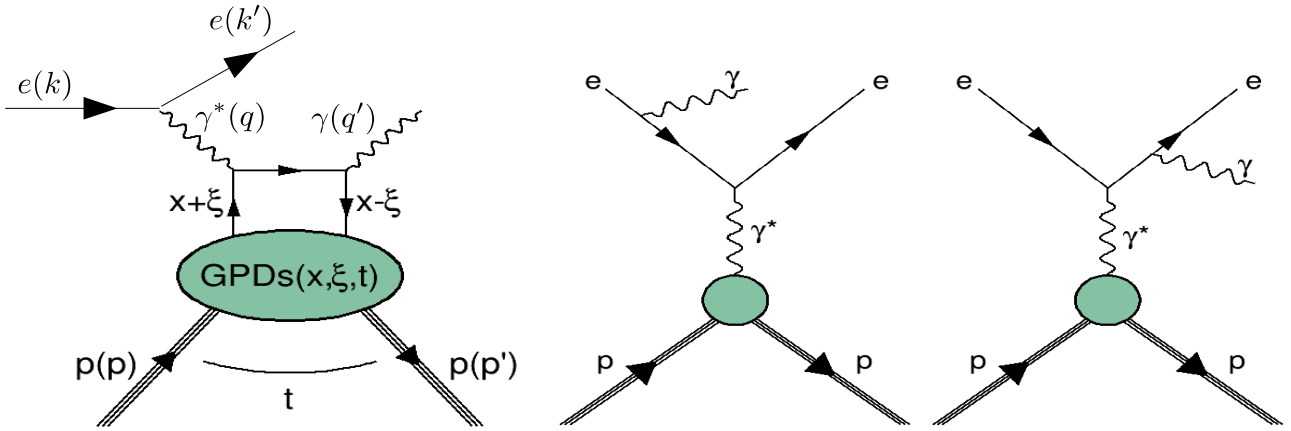


semi-inclusive deep-inelastic scattering (DIS)



Deeply virtual Compton scattering

Exclusive electroproduction of real photons

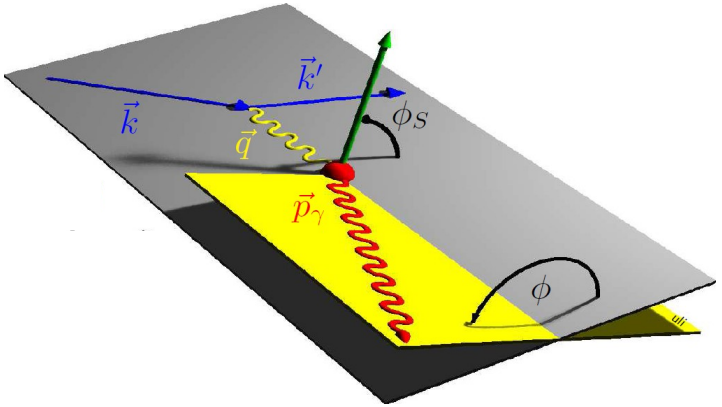


DVCS

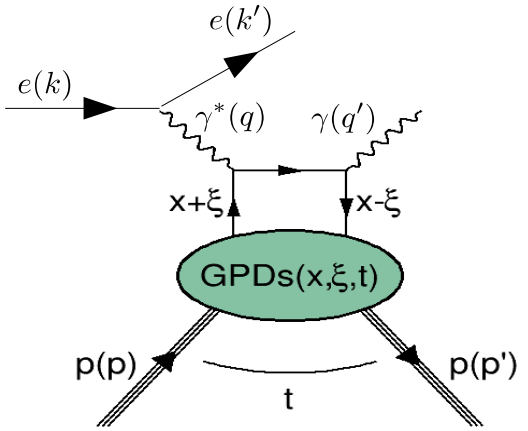
Bethe-Heitler

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

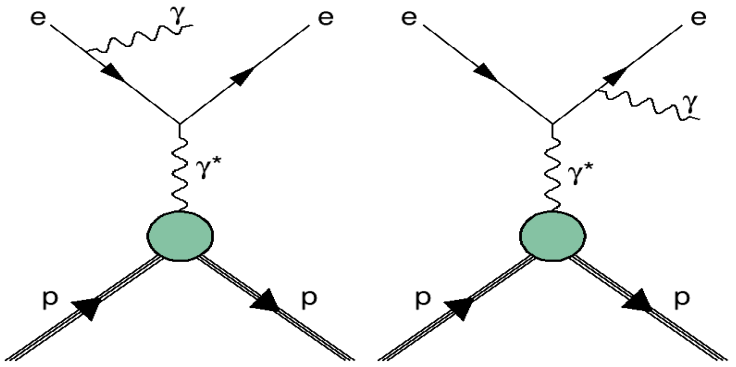
→ access through azimuthal asymmetries



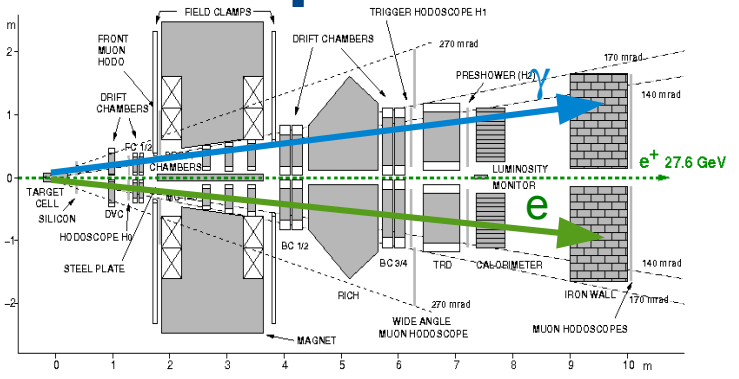
Exclusive electroproduction of real photons



DVCS



Bethe-Heitler

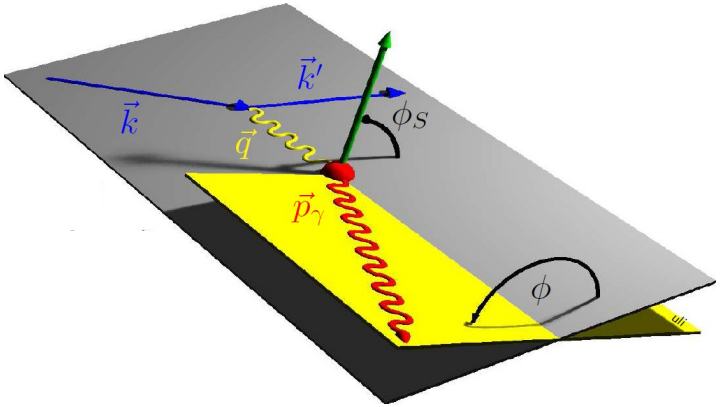


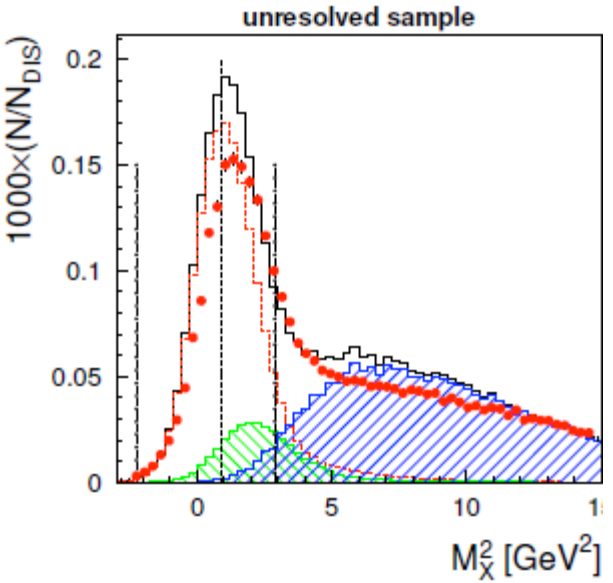
exclusivity

reconstruct proton via missing mass:

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

→ access through azimuthal asymmetries

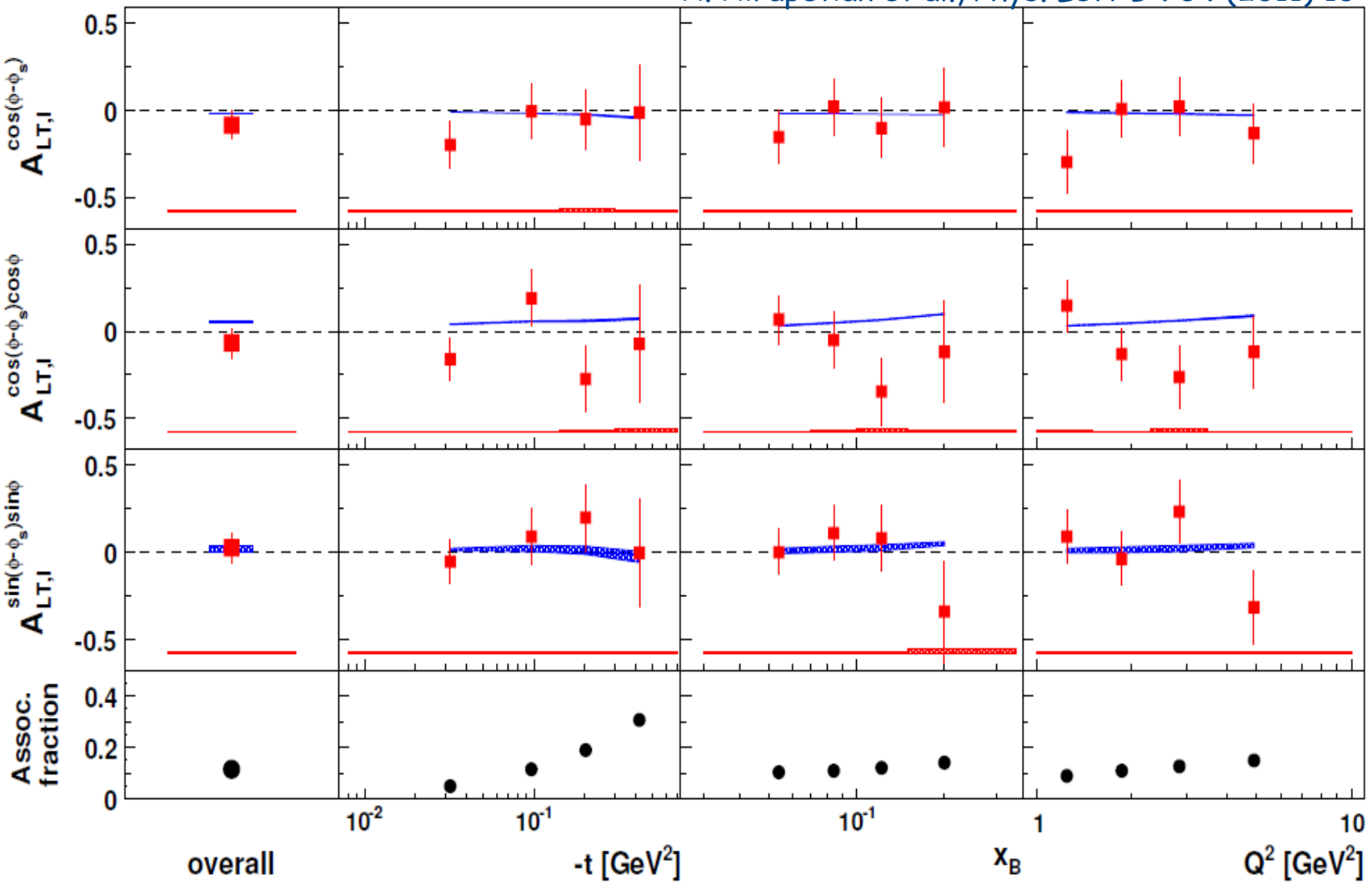




Double spin asymmetries on transversely polarized target

GPD E

A. Airapetian et al., Phys. Lett B **704** (2011) 15



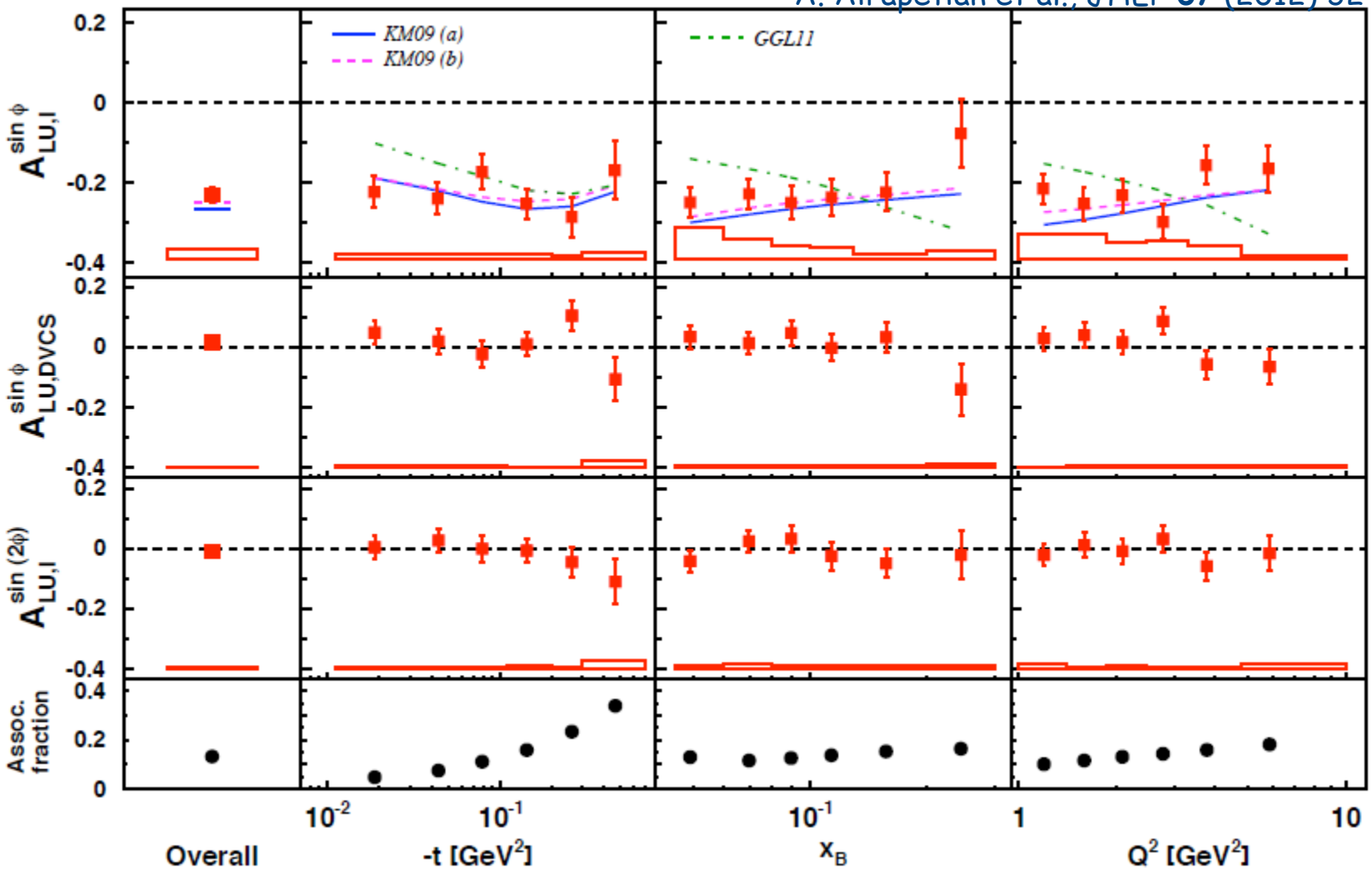
phys. Rev D 60 (1999) 094017 + VGG code:
- double distributions
- Regge t-dependence
- 0.2<Ju<0.6 & Jd=0

- compatible with zero

Charged-separated beam-helicity asymmetry

GPD *H*

A. Airapetian et al., JHEP **07** (2012) 32



KM09: Nucl. Phys. B **841** (2010) 1:
fit to HERMES, ZEUS, H1 data

Fit to HERMES, ZEUS, H1, Jefferson Lab data

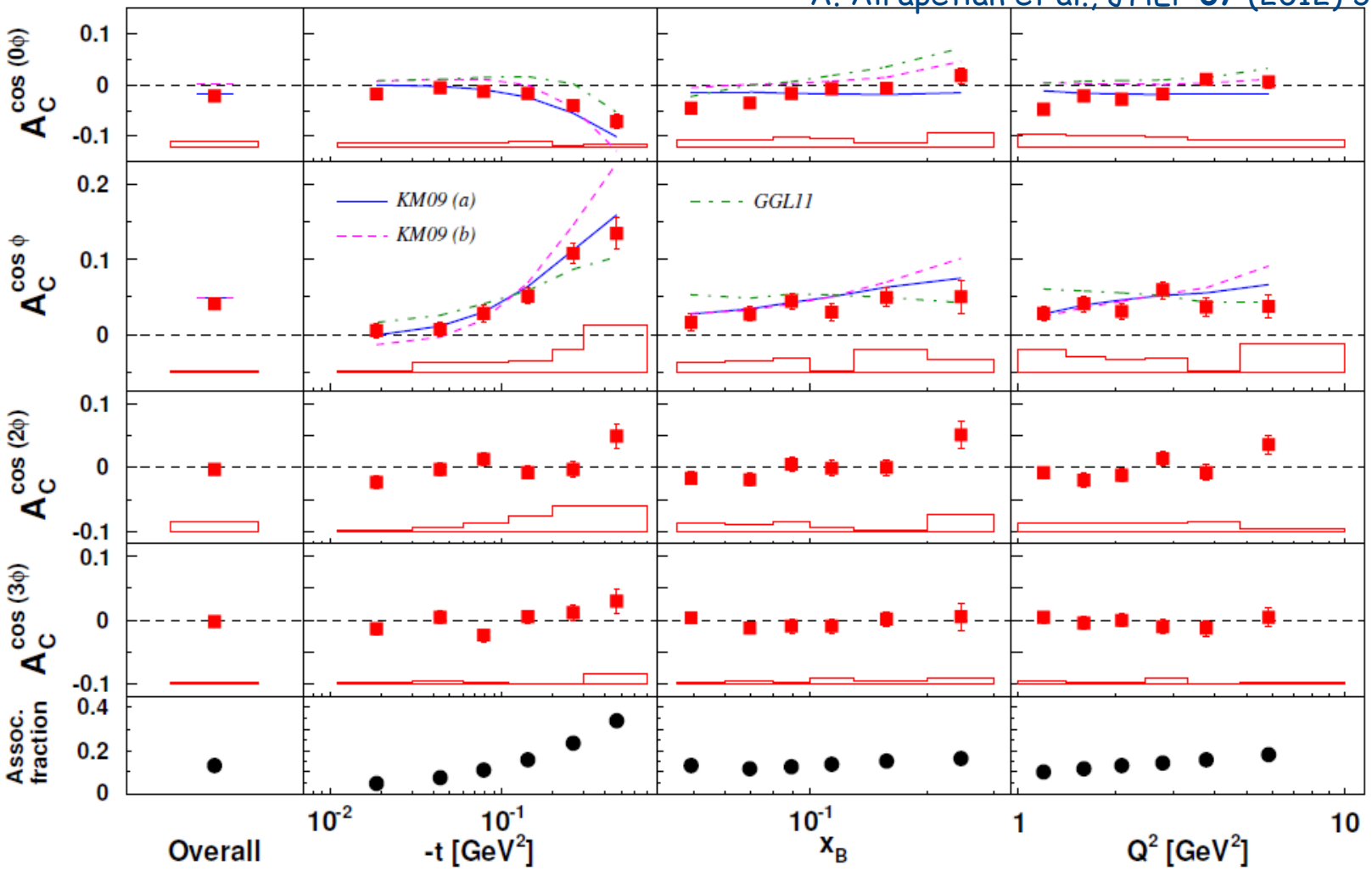
GGL11:Phys. Rev. D **84** (2011) 034007

- data collected from 1996-2007 (74% of data from 2006-2007)
- additional 3.2% scale uncertainty from beam polarization

Beam-charge asymmetry

GPD *H*

A. Airapetian et al., JHEP **07** (2012) 32



KM09: Nucl. Phys. B **841** (2010) 1:
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Fit to HERMES, ZEUS, H1, Jefferson Lab data

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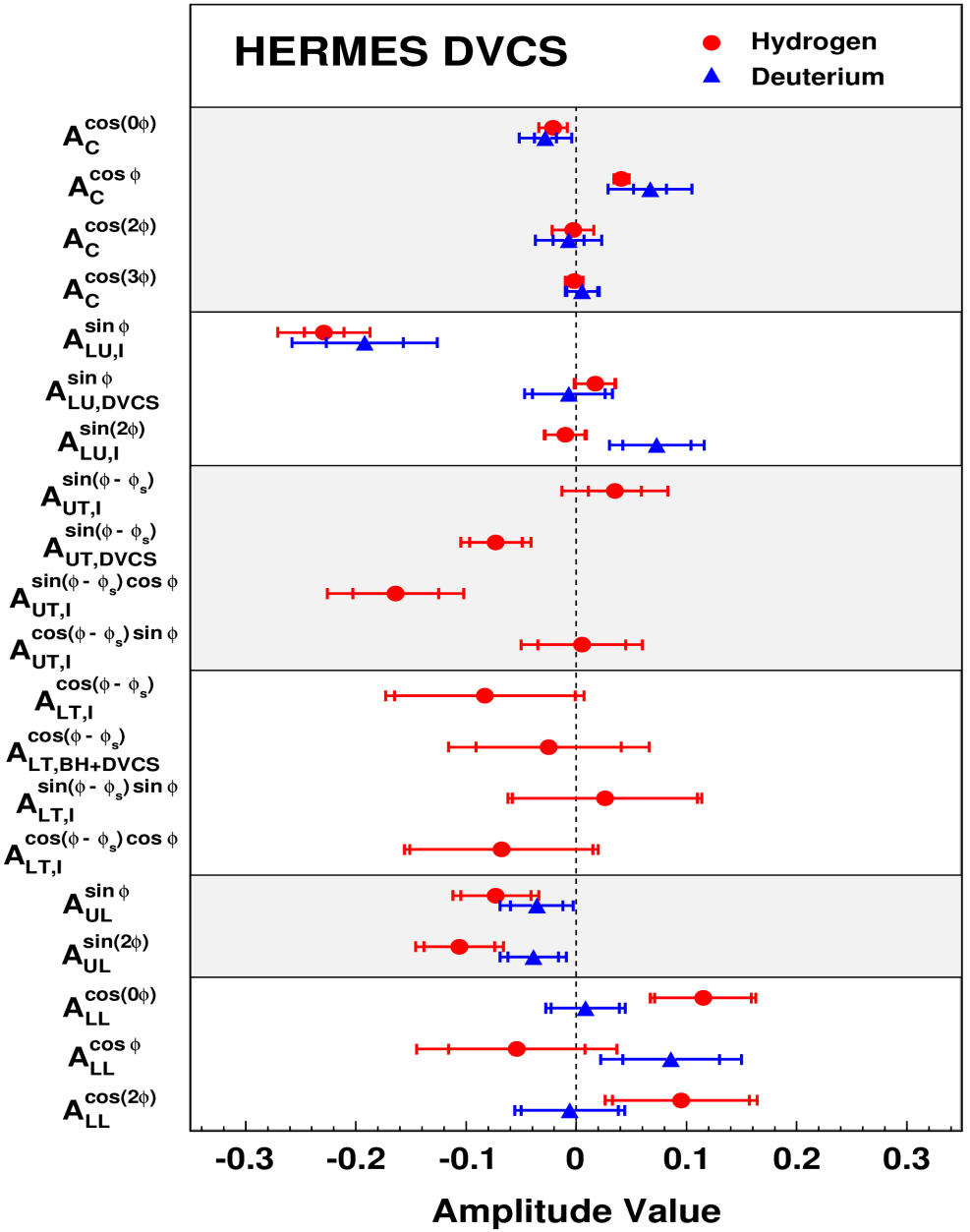
- data collected from 1996-2007 (74% of data from 2006-2007)
- additional 3.2% scale uncertainty from beam polarization

DVCS at HERMES



beam-charge asymmetry
JHEP **07** (2012) 32
Nucl. Phys. B 829 (2010) 1

beam-helicity asymmetry
JEHP **07** (2012) 32
Nucl. Phys. B 829 (2010) 1

GPD H

transverse target-spin asymmetry
JHEP **06** (2008) 066

GPD E

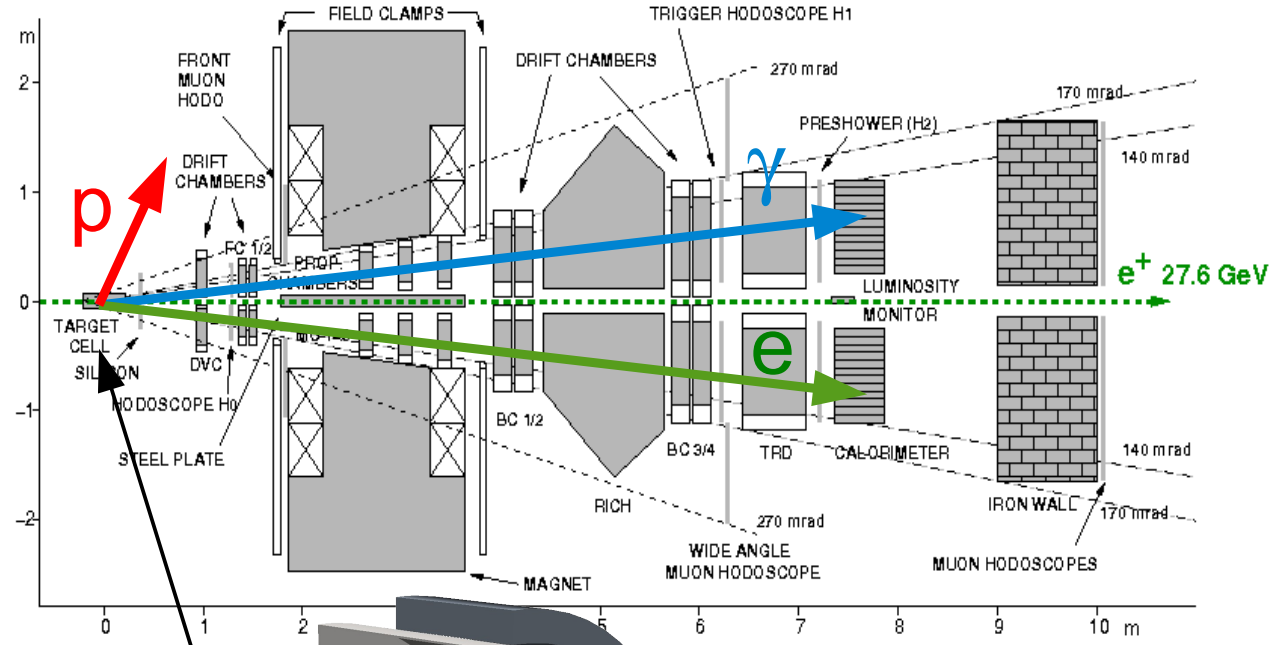
double spin (LT) asymmetry
Phys. Lett. B **704** (2011) 15

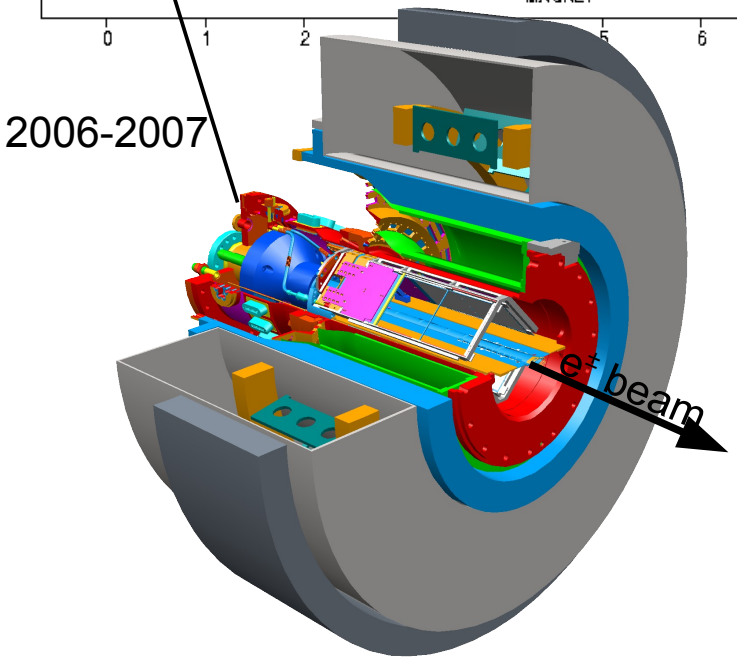
longitudinal target-spin asymmetry
JHEP **06** (2010) 019
Nucl. Phys. B 842 (2011) 265

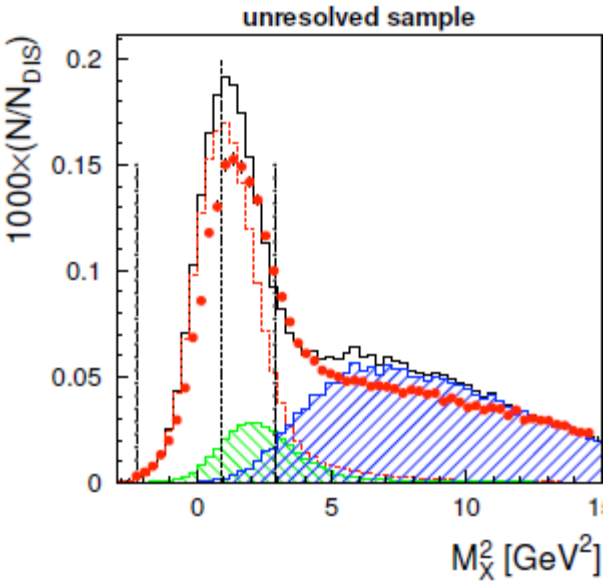
double spin (LL) asymmetry
JHEP **06** (2010) 019
Nucl. Phys. B 842 (2011) 265

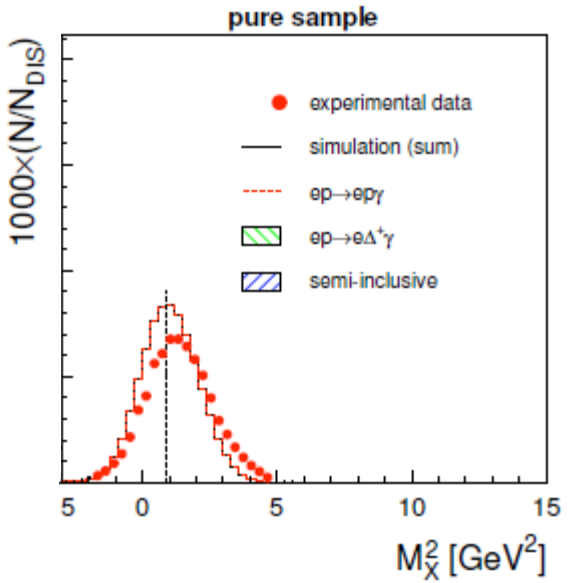
GPD $\tilde{H}$

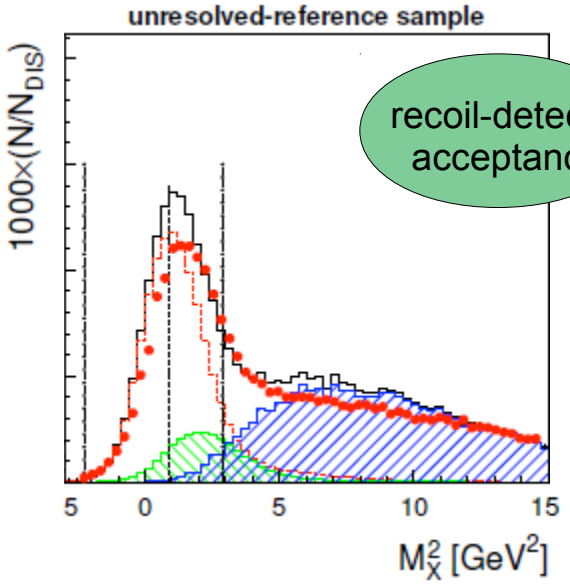
DVCS/BH complete event reconstruction





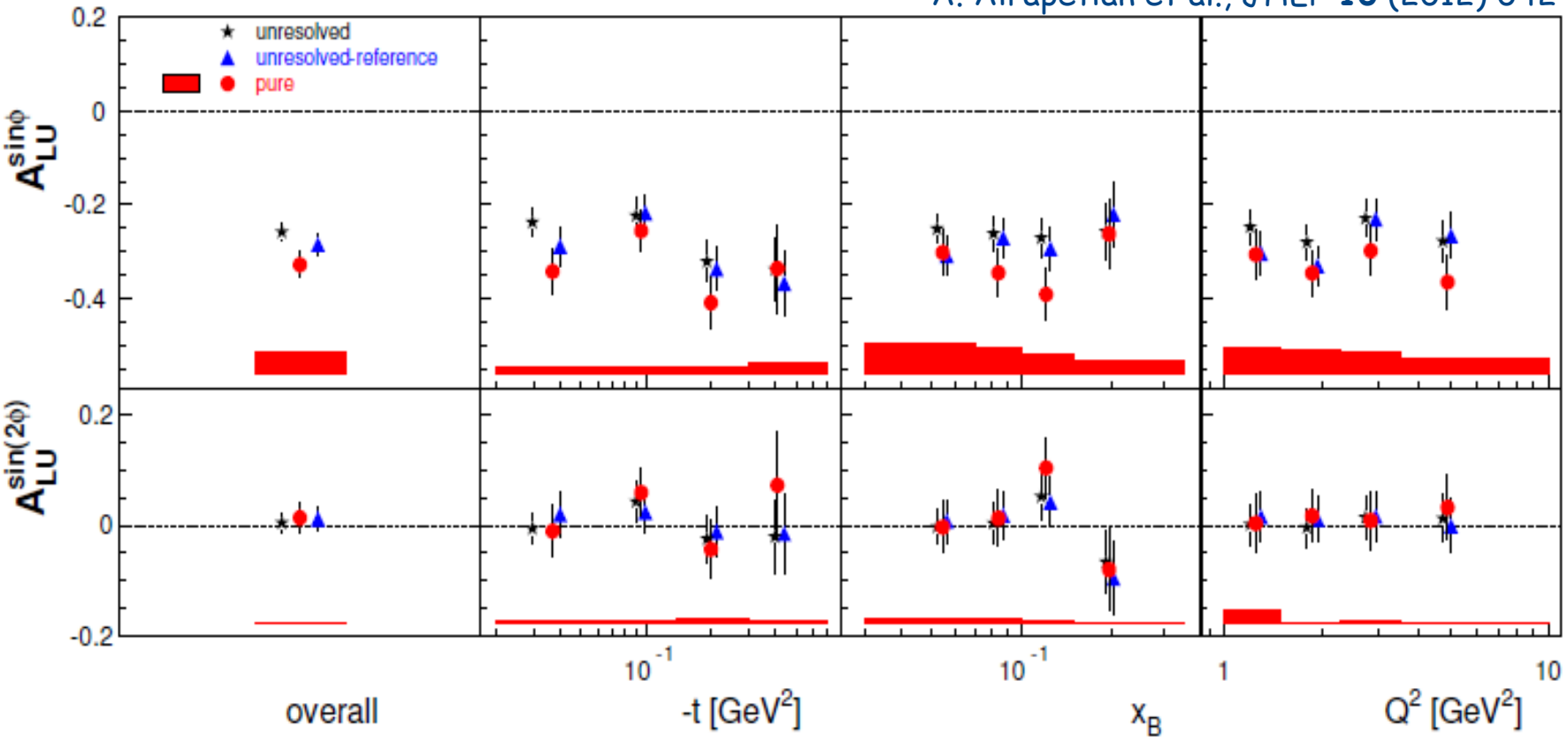






Beam-helicity asymmetry

A. Airapetian et al., JHEP **10** (2012) 042

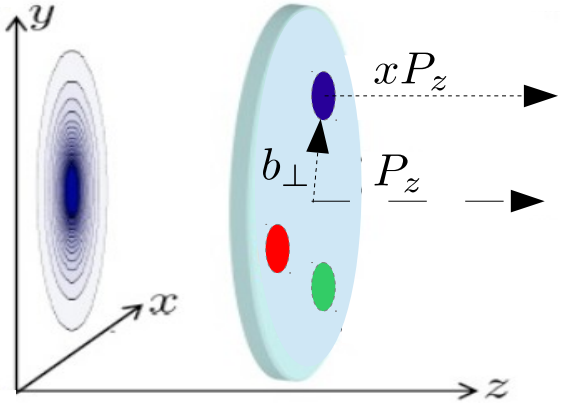


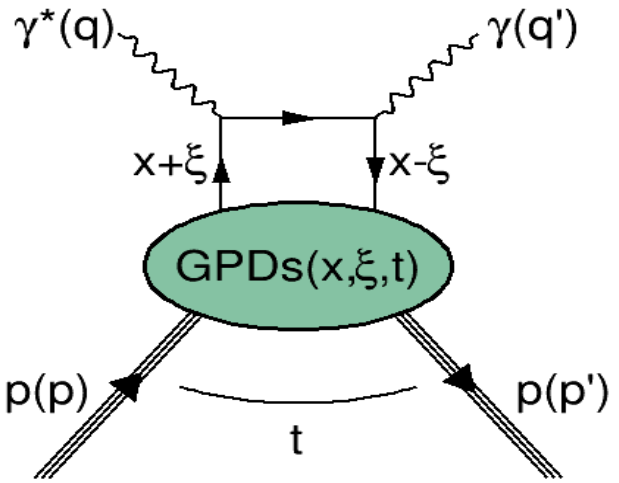
- additional 1.96 % scale uncertainty from beam polarization
- leading asymmetry from pure sample is larger

Beam-helicity asymmetry in $ep \to e\gamma\pi N$ in Δ-resonance region

GPDs

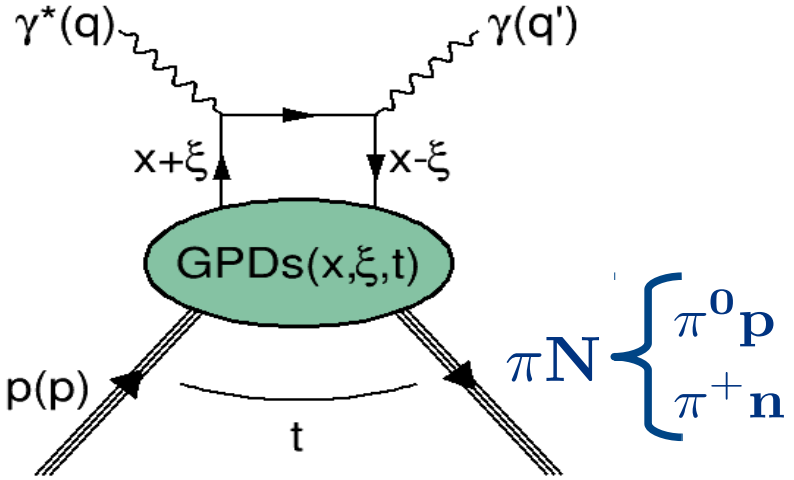
quark distribution in longitudinal-momentum and transverse-position space





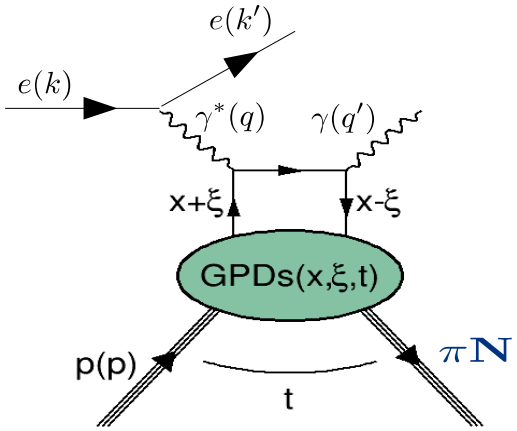
DVCS

transition GPDs p → πN

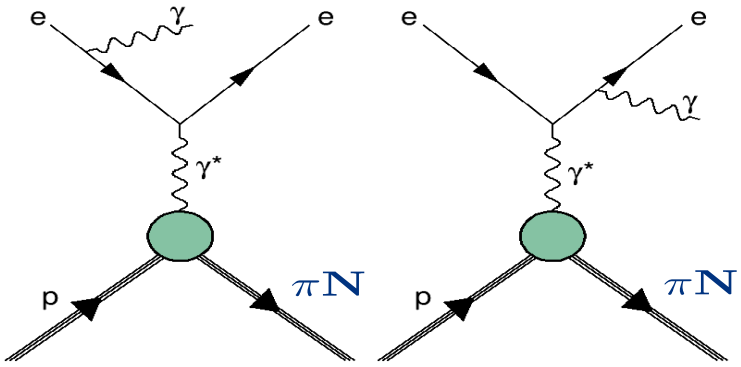


associated DVCS

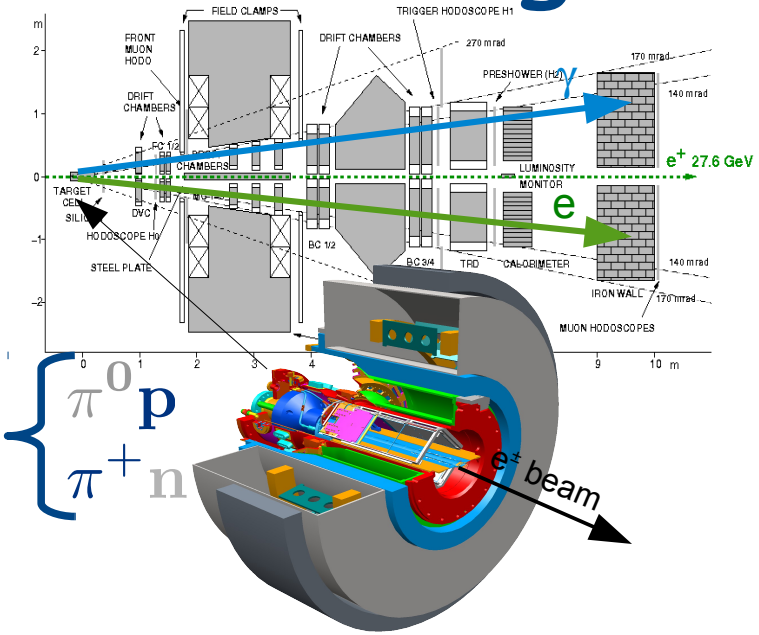
Beam-helicity asymmetry in $ep \to e\gamma\pi N$ in Δ-resonance region



associated DVCS

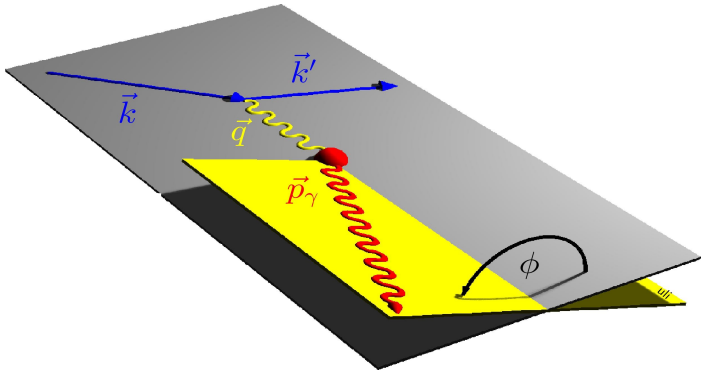


associated Bethe-Heitler



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

→ access through azimuthal asymmetries

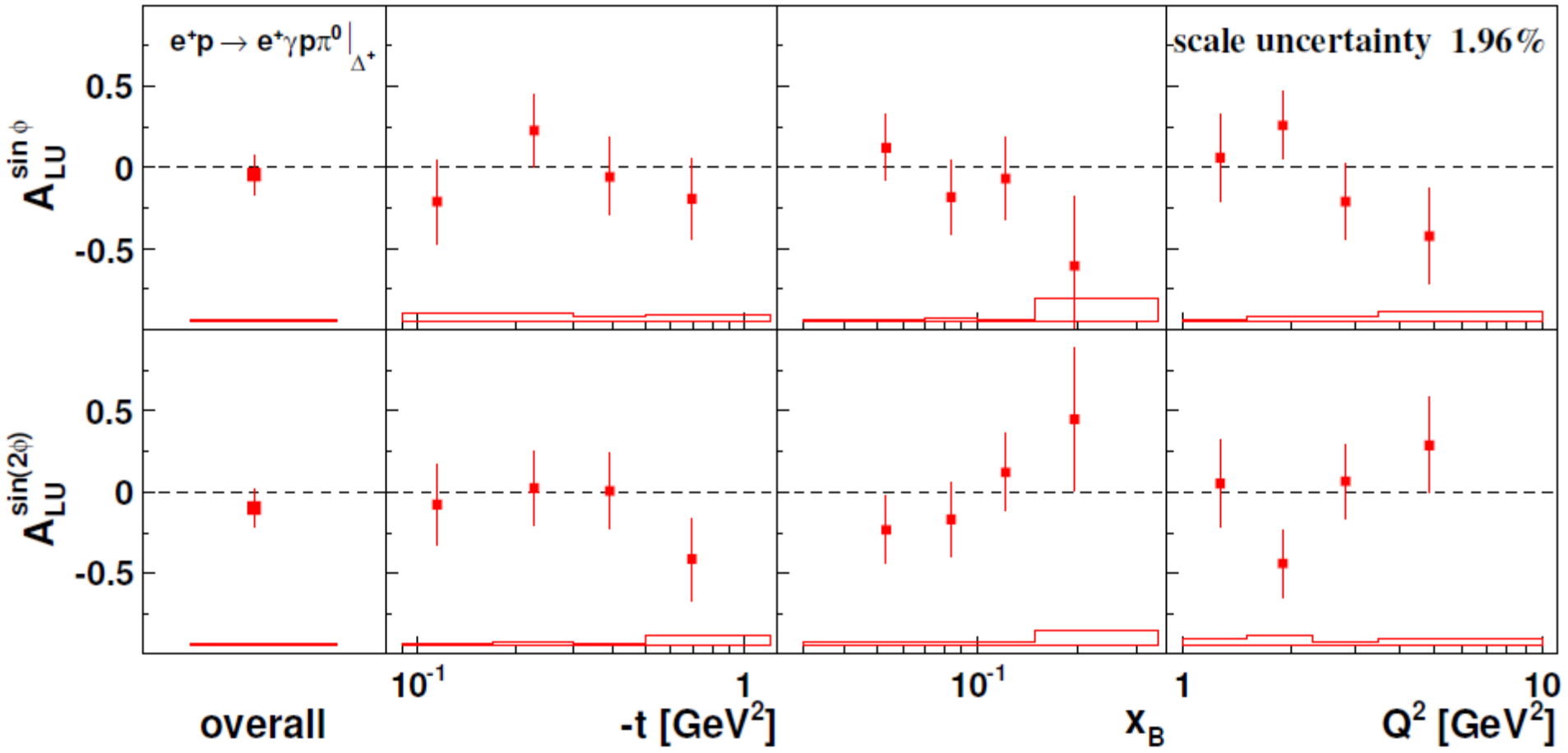


recoil detector

- p and π^+ via PID
- π^0 and n undetected
- kinematic fitting
- select region around Δ-resonance

Beam-helicity asymmetry in $ep \to e\gamma\pi^0 p$ in Δ-resonance region

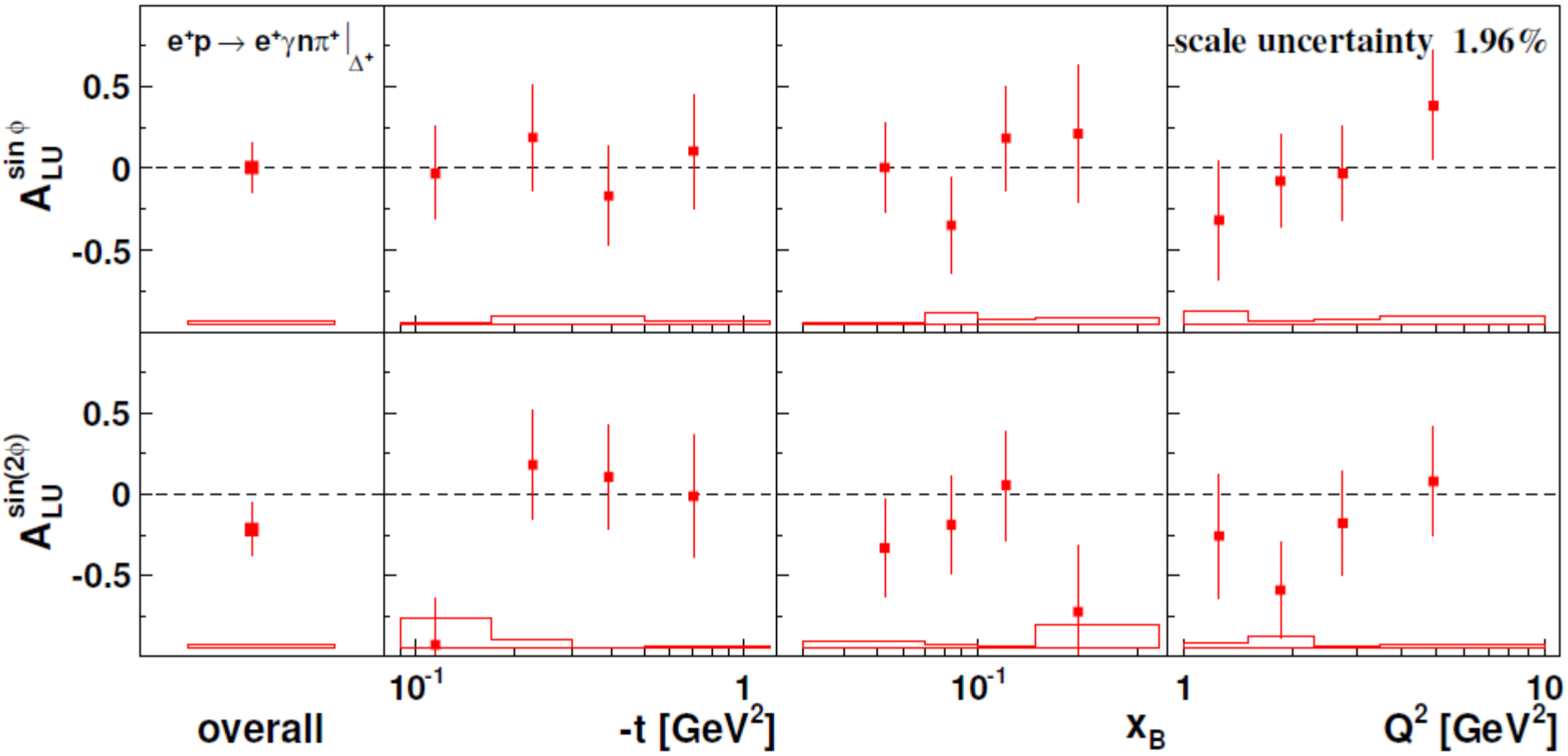
HERMES Collaboration – arXiv:1310.5081



- asymmetry background correction from SIDIS (11%) and $ep \to e\gamma p$ (4.6%)
- leading asymmetry consistent with zero

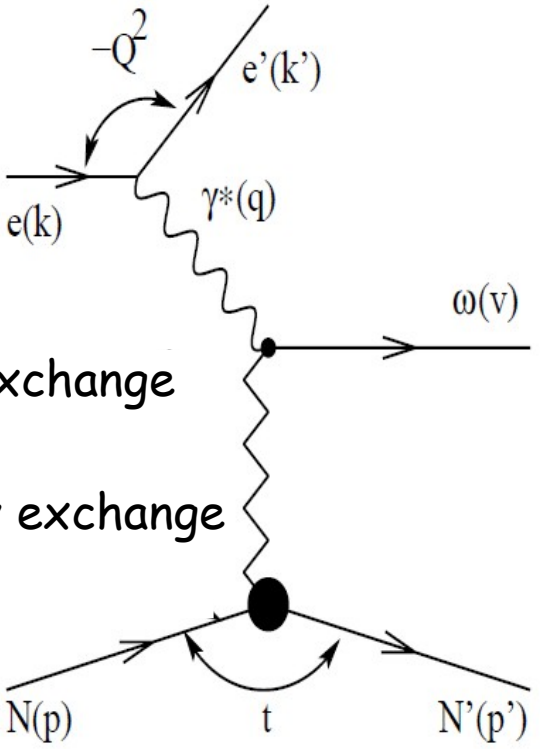
Beam-helicity asymmetry in $ep \to e\gamma\pi^+ n$ in Δ-resonance region

HERMES Collaboration – arXiv:1310.5081



- asymmetry background correction from SIDIS (23%) and $ep \to e\gamma p$ (0.2%)
- leading asymmetry consistent with zero

Exclusive ω production



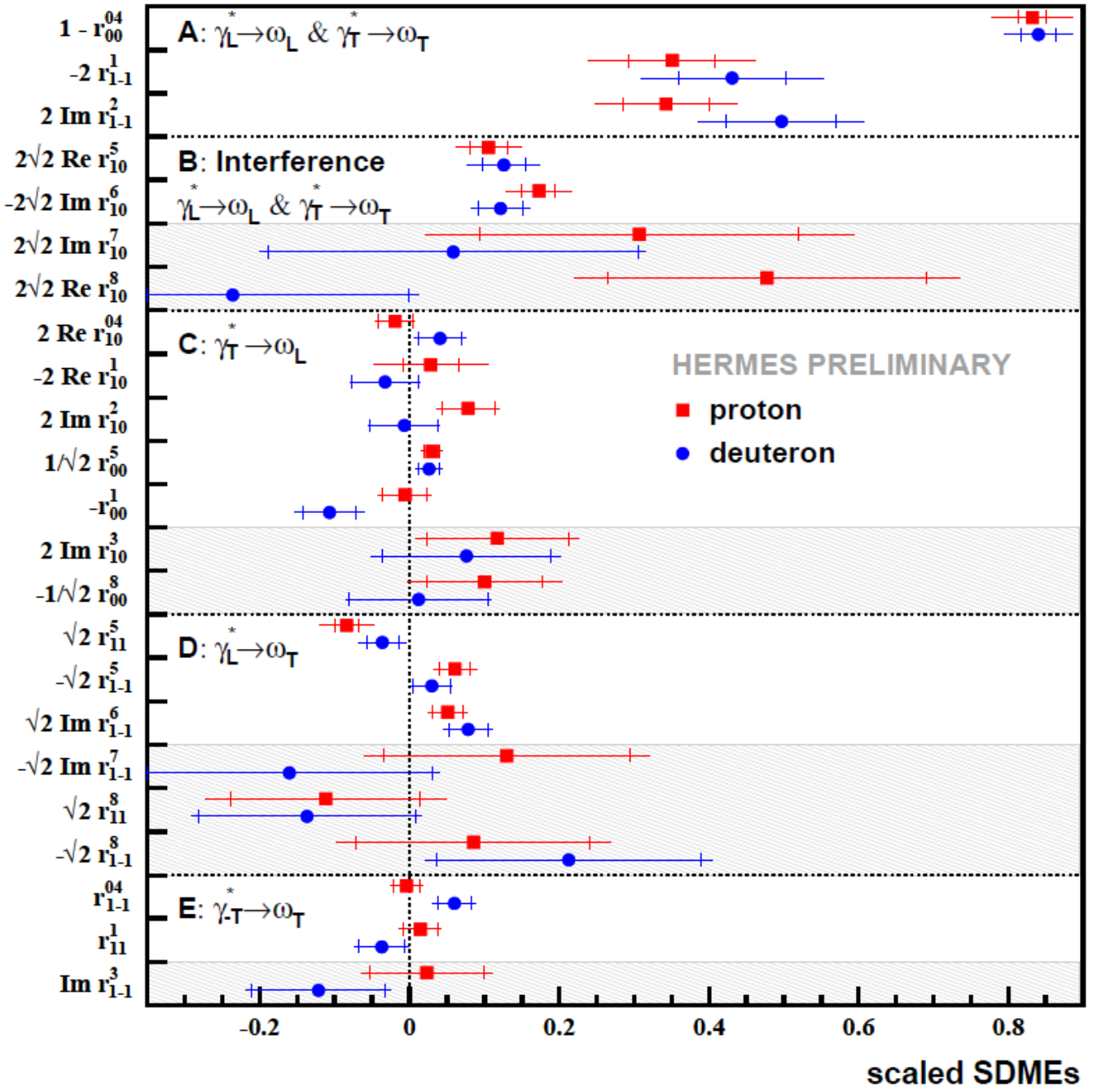
natural parity exchange

$J^P=0^+, 1^-, \ldots$

unnatural parity exchange

$J^P=0^-, 1^+, \ldots$

Exclusive ω production

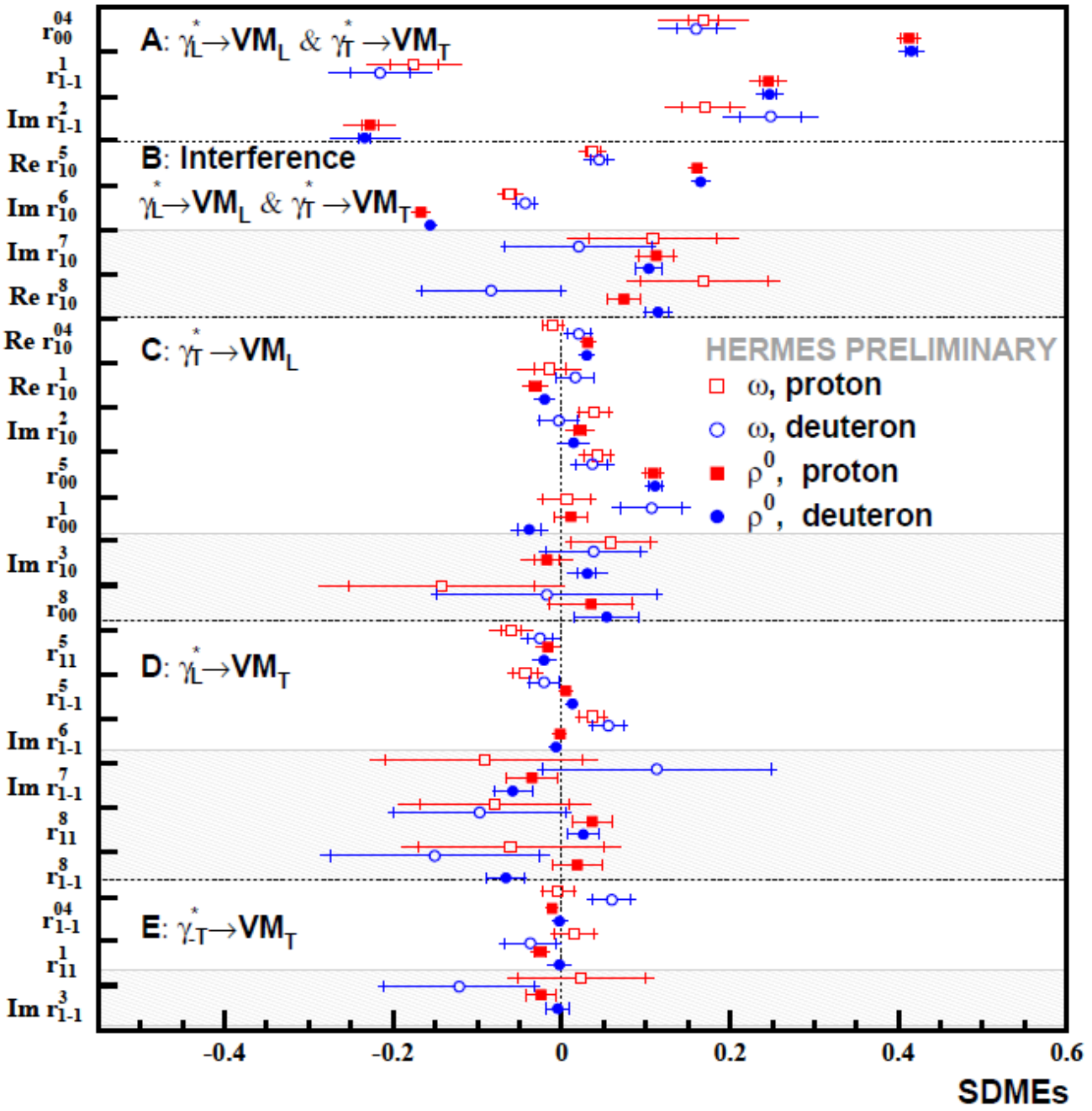


- compatible SDMEs for proton and deuteron

slight violation of s-channel helicity conservation:

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

Exclusive ω production



- ω-ρ^0 comparison:
  - ω: $r^1_{1-1} < 0$
  - ρ^0: $r^1_{1-1} > 0$
  - ω: $\Im\, r^2_{1-1} > 0$
  - ρ^0: $\Im\, r^2_{1-1} < 0$

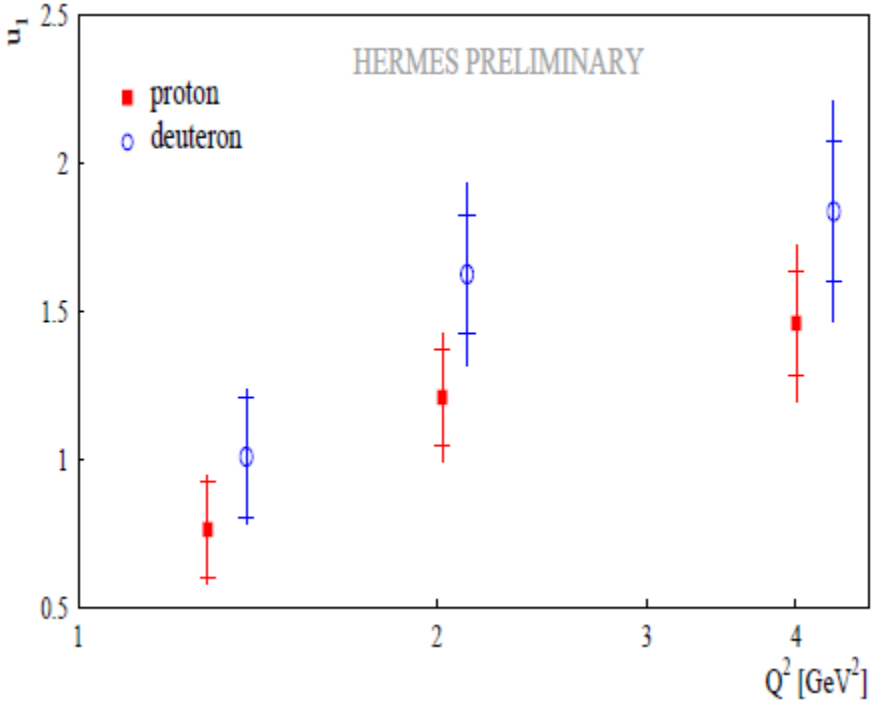
large unnatural parity exchange for ω production

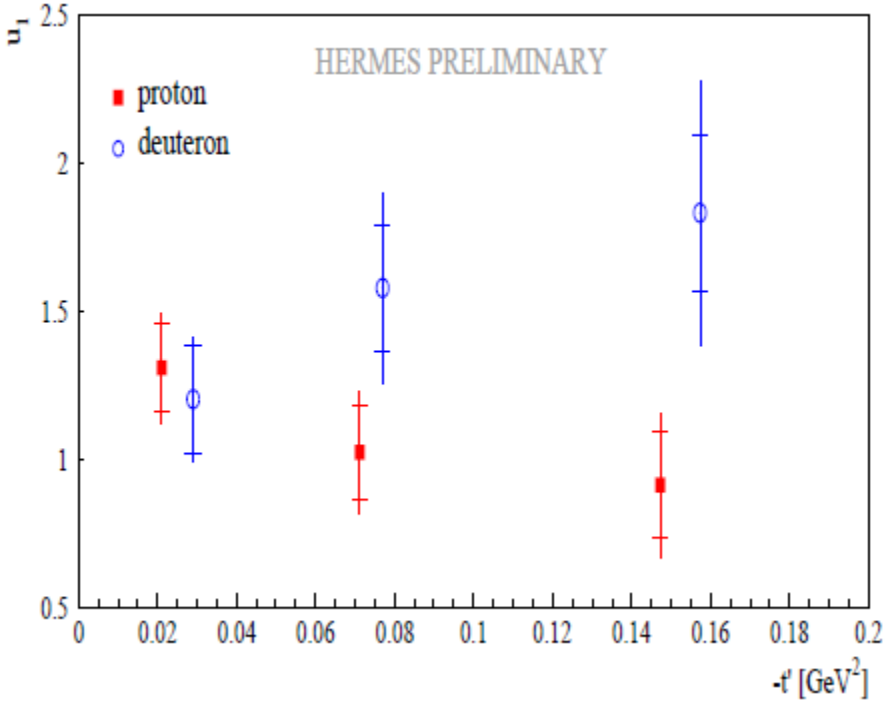
exclusve ρ^0:
A. Airapetian et al., Eur. Phys. J. C **62** (2009) 659

Exclusive ω production

test of unnatural parity exchange:

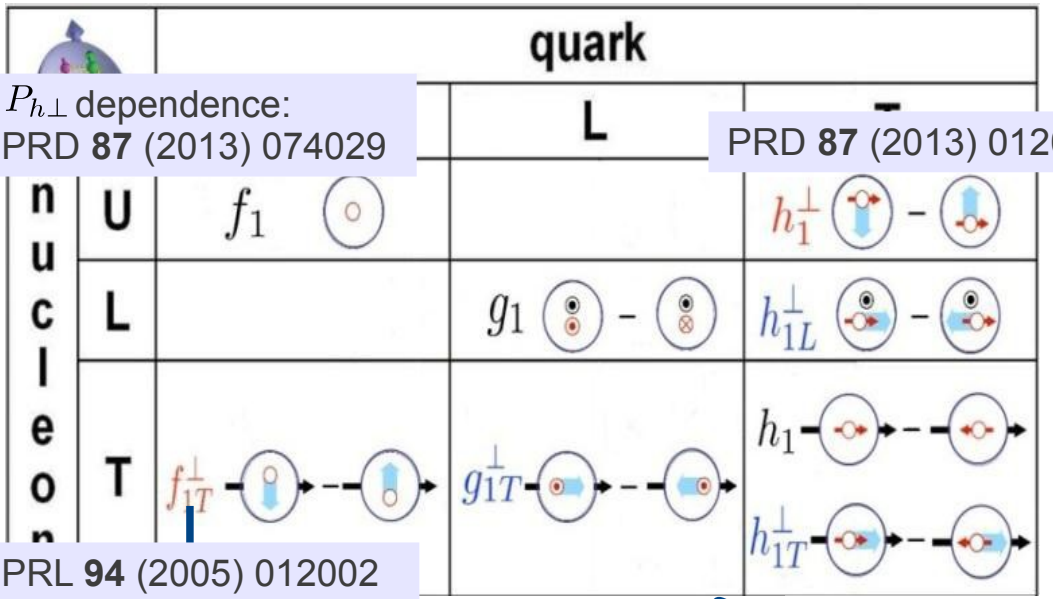
$$\mathbf{u_1 = 1 - r^{04}_{00} + 2\,r^{04}_{1-1} - 2\,r^{1}_{11} - 2\,r^{1}_{1-1}}$$
$$\propto 2\epsilon|U_{10}|^2 + |U_{11} + U_{-11}|^2$$





large unnatural-parity exchange

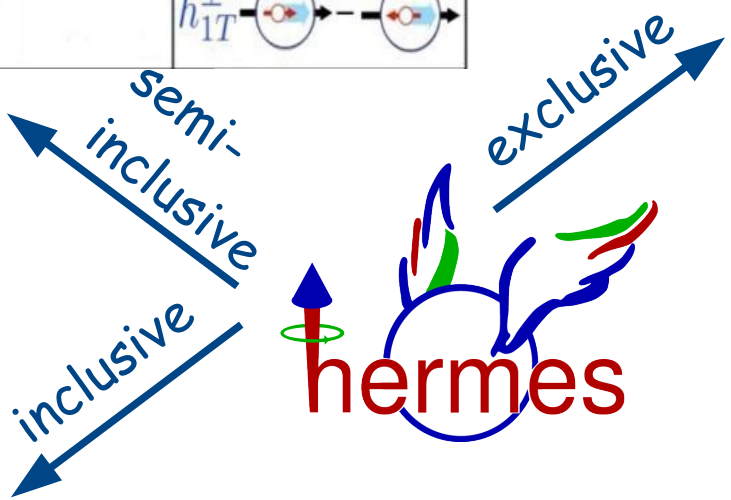
Summary



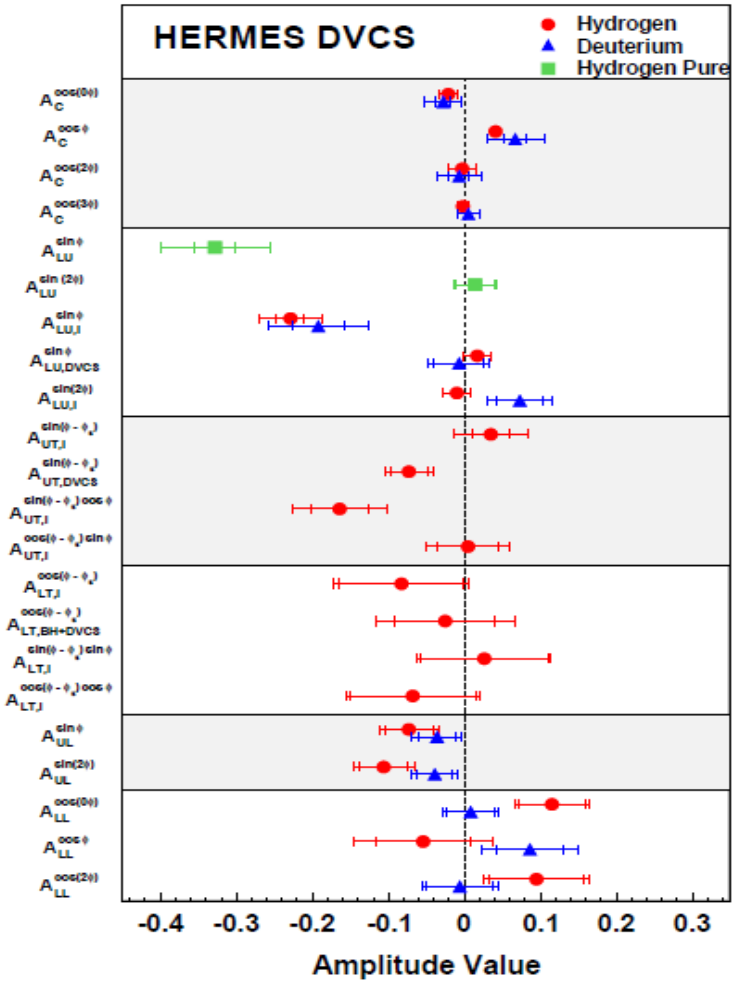
$P_{h\perp}$ dependence:
PRD **87** (2013) 074029

PRD **87** (2013) 012010

PRL **94** (2005) 012002
PRL **103** (2009) 152002



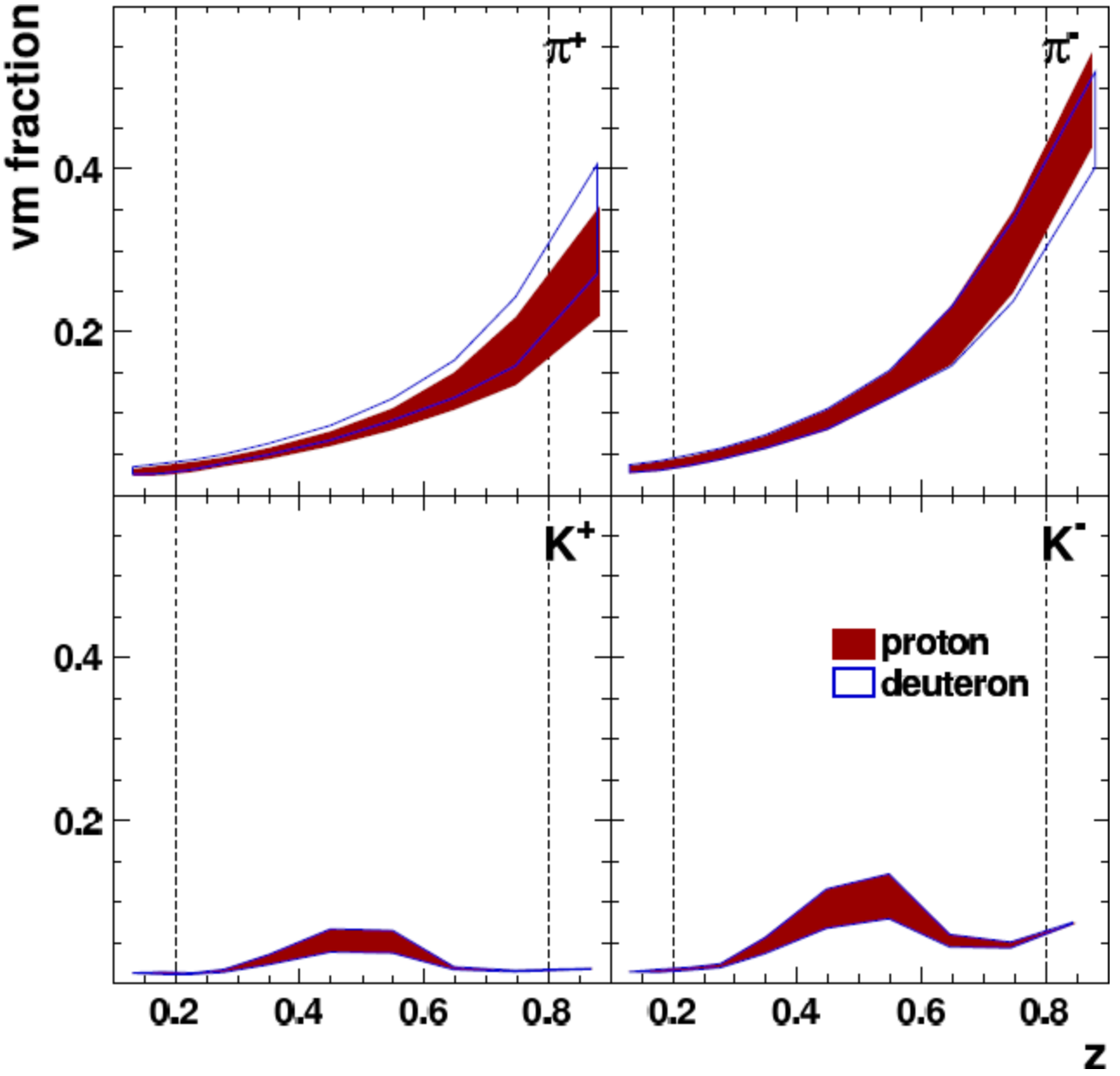
exclusive ω production



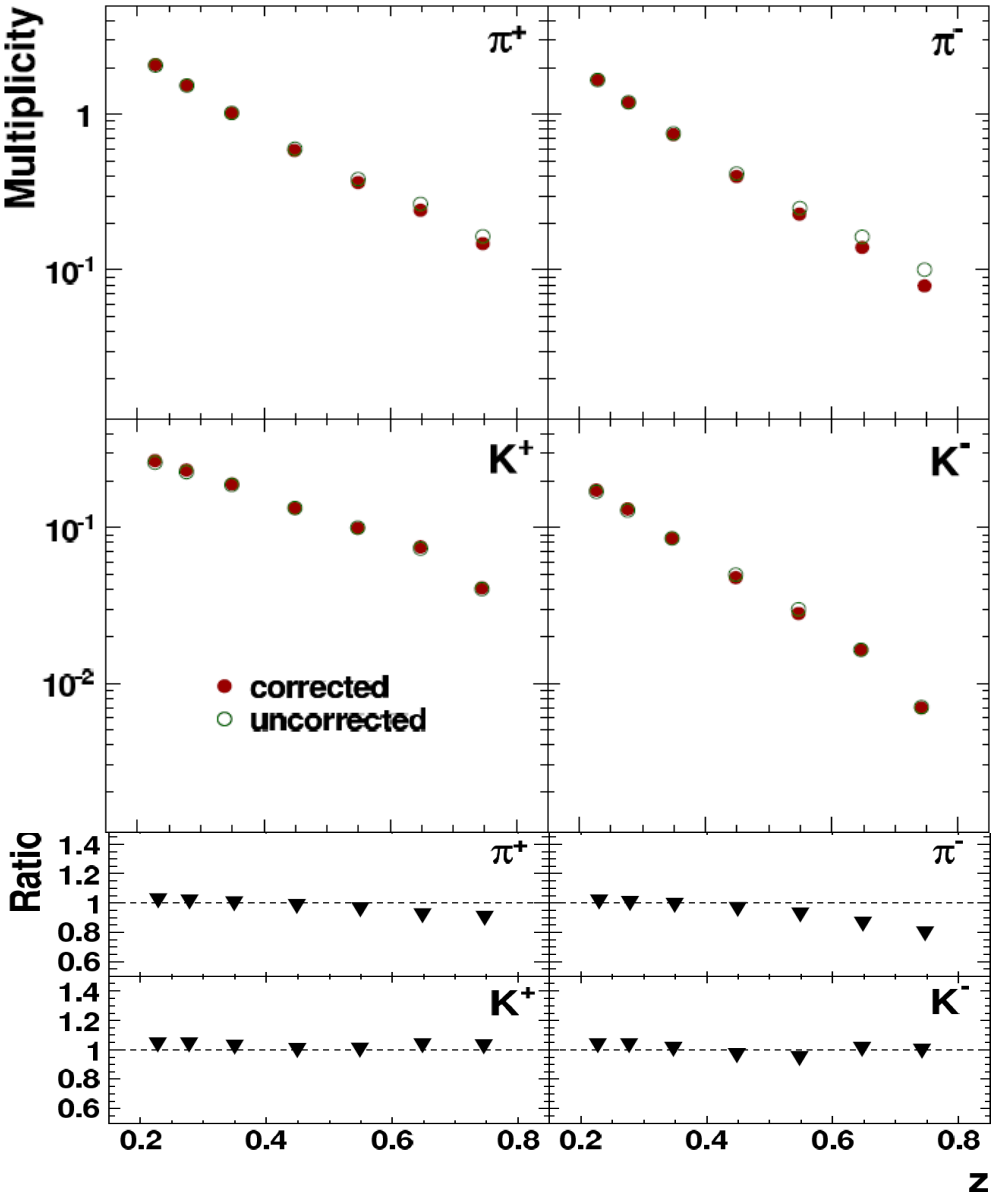
- g2
- A_{UT} in inclusive electroproduction of pions and protons, see talk T. Shibata-san

Backup

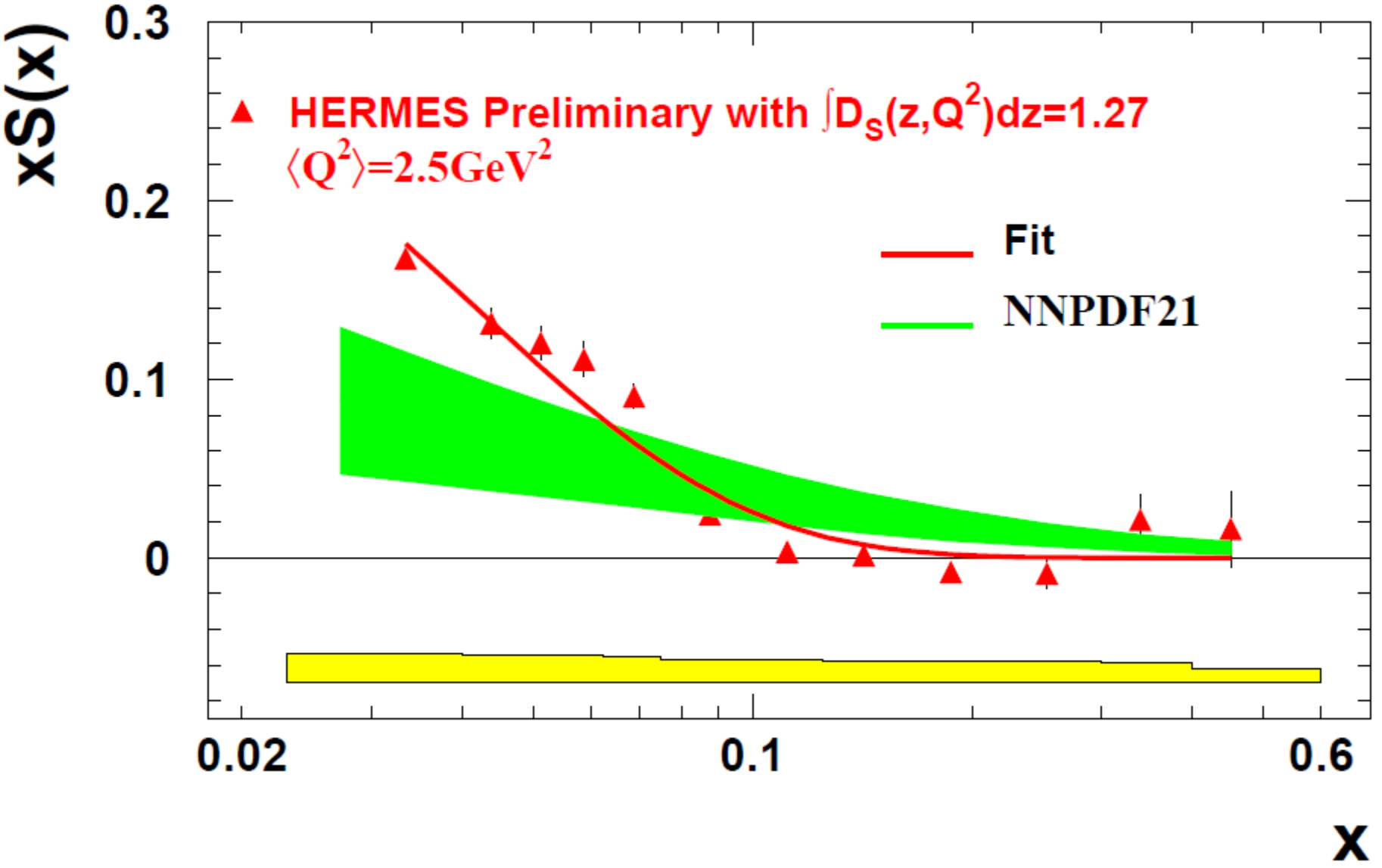
Exclusive vector-meson fraction



Multiplicities corrected in z: without and with exclusive vector-meson correction

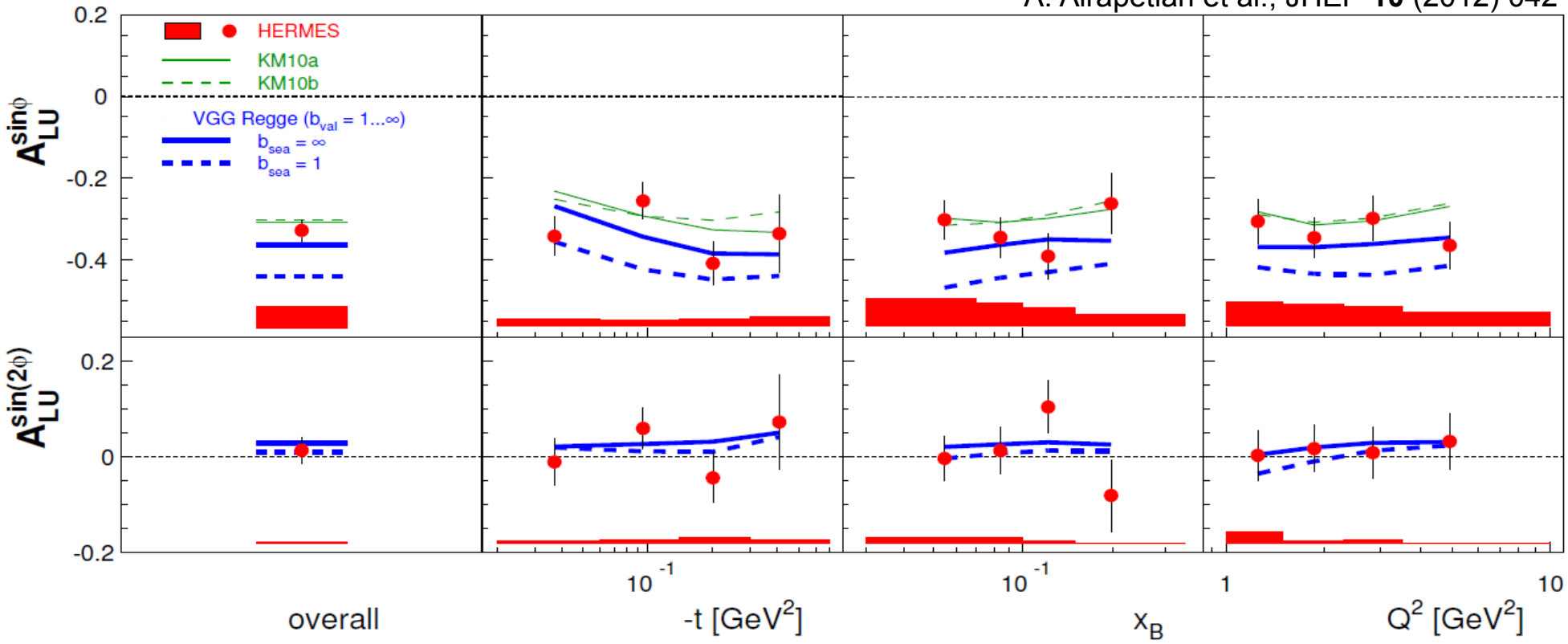


Comparison S(x) with NNPDF21



Beam-helicity asymmetry

A. Airapetian et al., JHEP **10** (2012) 042

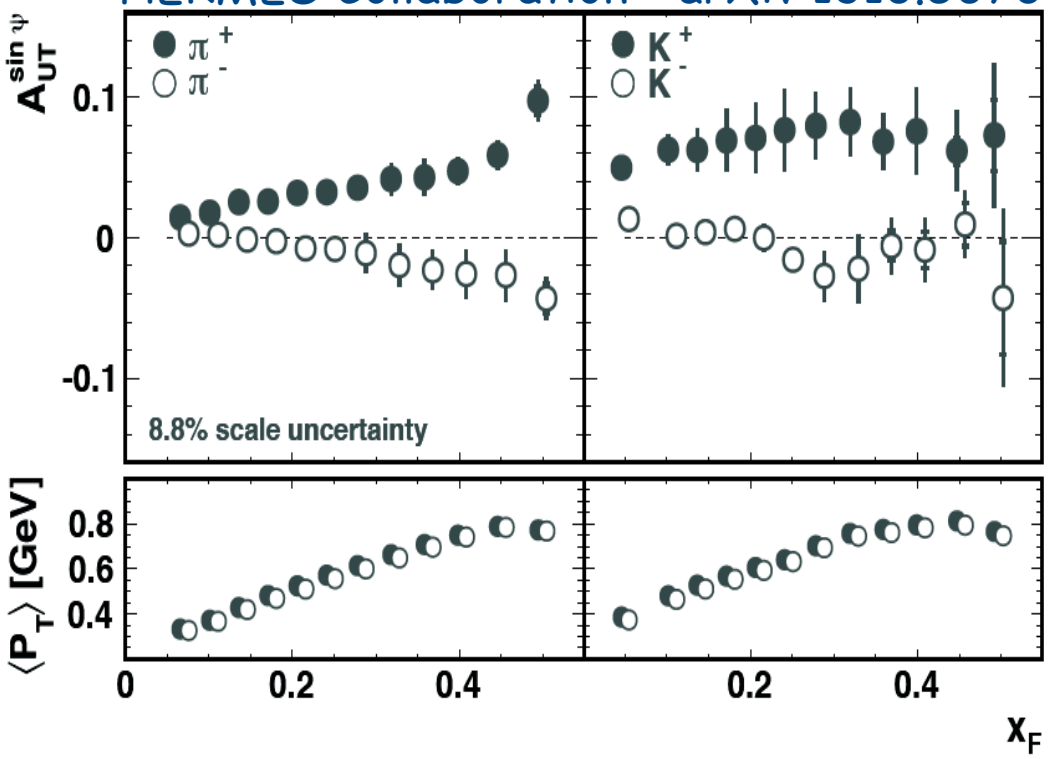


- additional 1.96 % scale uncertainty from beam polarization

Transverse target single-spin asymmetry in inclusive electroproduction of pions and kaons

$x_F = 2P_L/\sqrt{s}$ dependence

HERMES Collaboration – arXiv:1310.5070



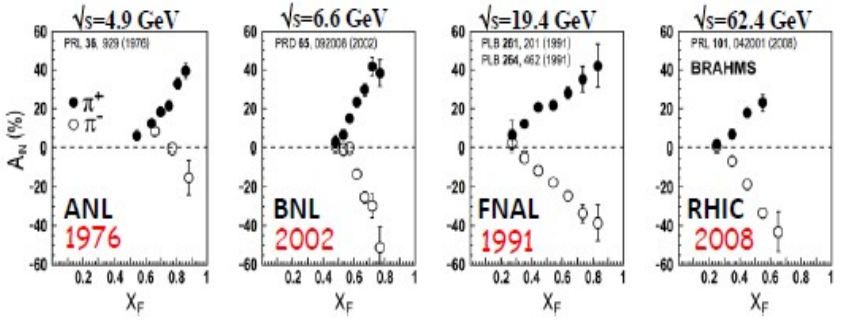
π^+

- positive, increase linearly with x_F

π^-

- negative, decrease linearly with x_F

x_F behavior of pions similar to what observed in hadron-hadron collisions



K^+

- positive, ~constant with x_F

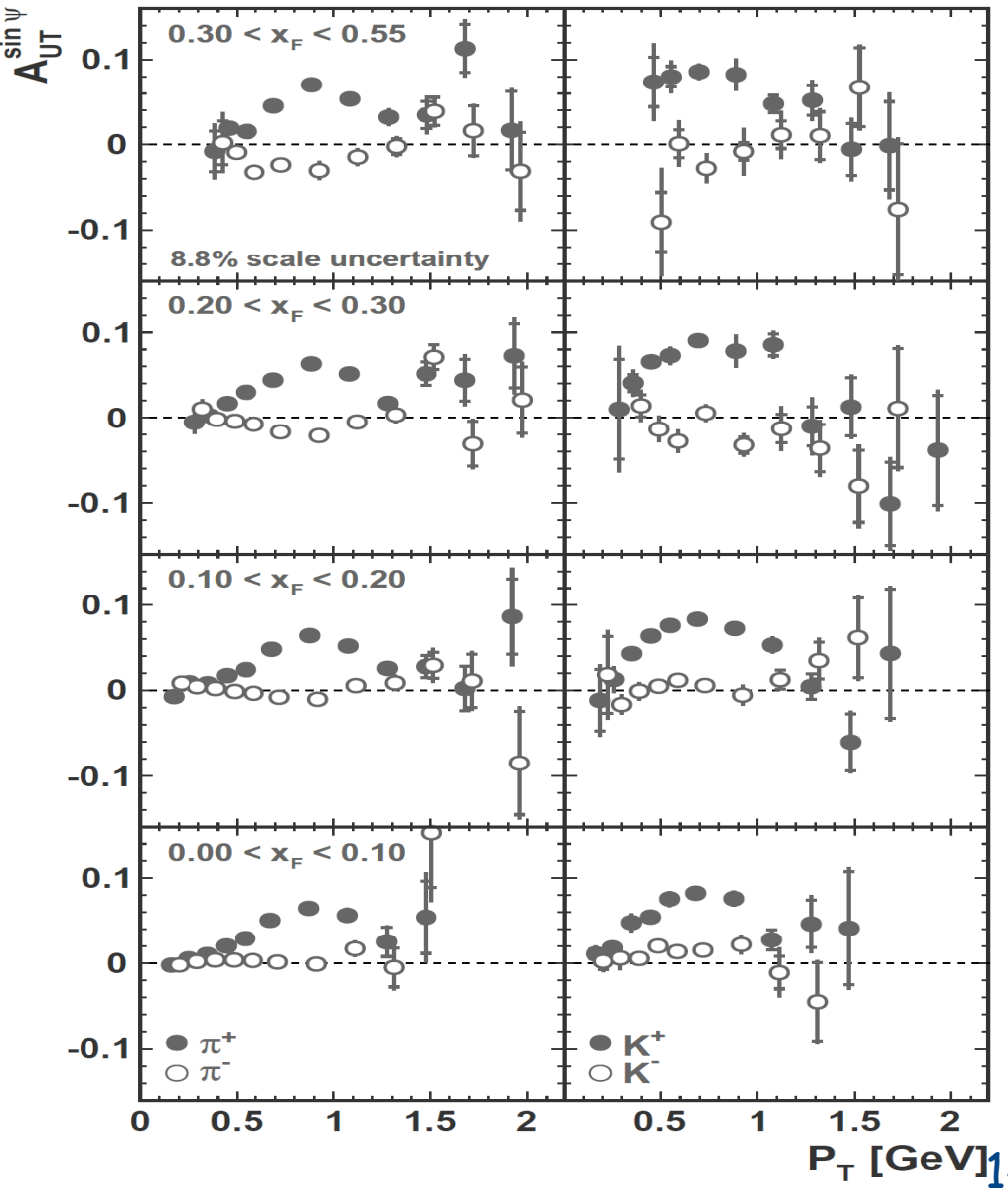
K^-

- compatible with zero, with small variation over x_F

Transverse target single-spin asymmetry in inclusive electroproduction of pions and kaons

disentangle x_F and P_T dependence

HERMES Collaboration – arXiv:1310.5070



π^+

- increase with P_T up to $P_T \approx 0.8$ GeV
- P_T dependence independent of x_F
  → x_F increase from P_T dependence

π^-

- small amplitudes, varyingly positive and negative with P_T
- decrease with increasing x_F

K^+

- increase with P_T up to $P_T \approx 0.8$ GeV
- increase with increasing x_F

K^-

- small amplitudes
- decrease with increasing x_F