Latest results from the hermes experiment

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ikerbasque
Basque Foundation for Science

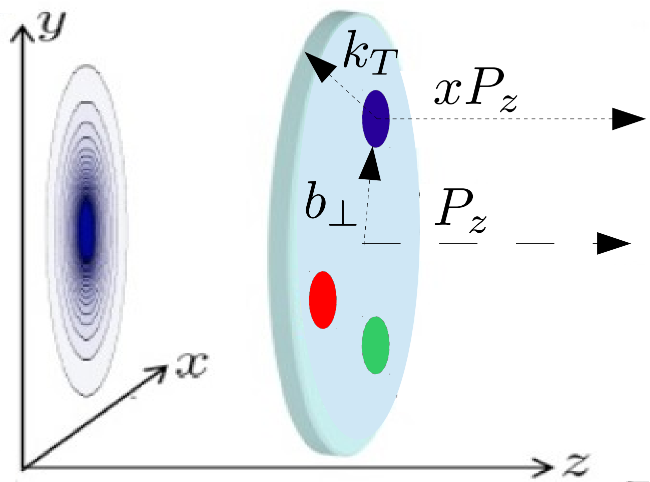
EPSHEP 2013, Stockholm

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

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

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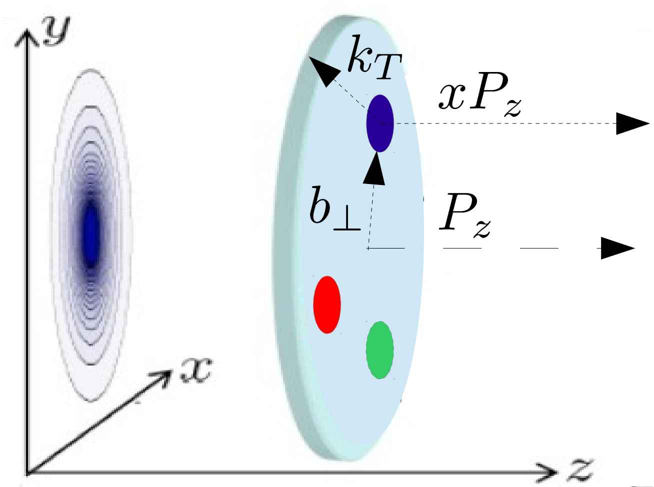

transverse-momentum dependent PDFs (TMDs)

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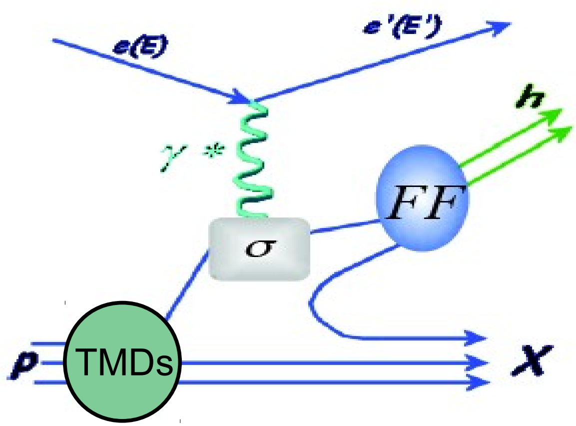
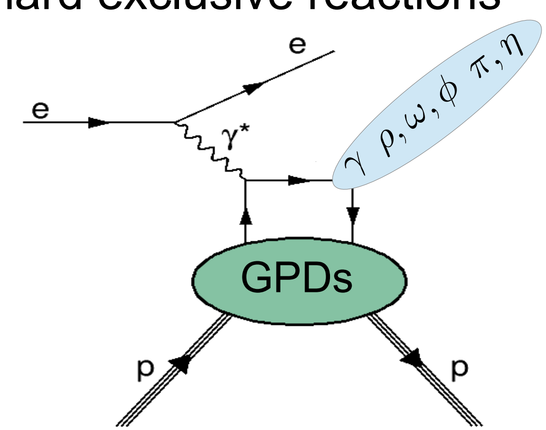
generalized parton distributions (GPDs)

semi-inclusive deep-inelastic scattering (DIS)



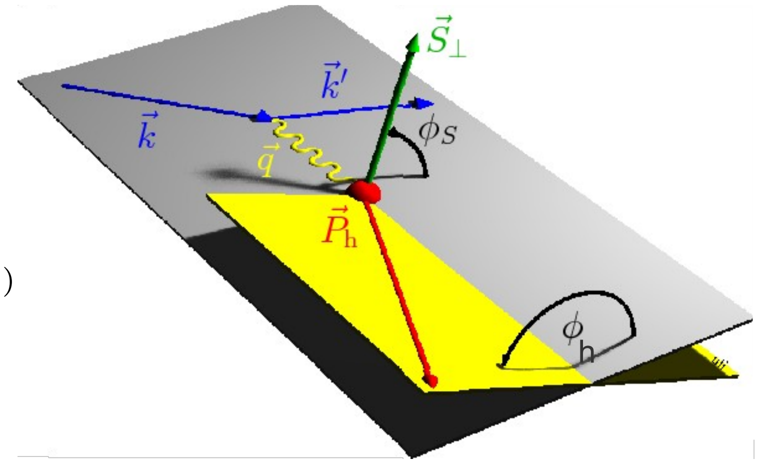
hard exclusive reactions

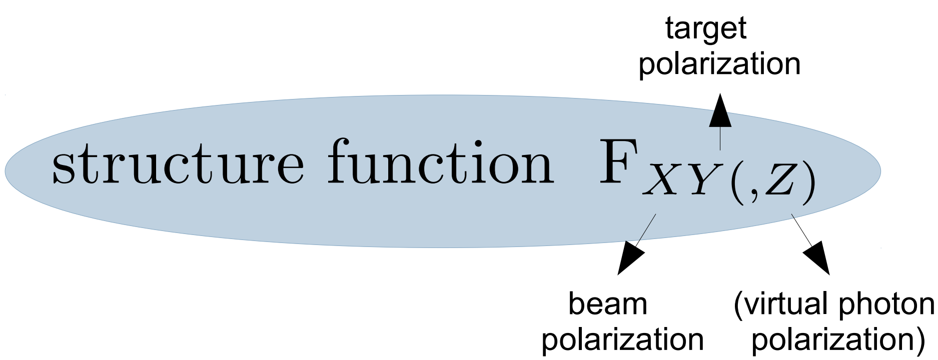


Semi-inclusive DIS cross section

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

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





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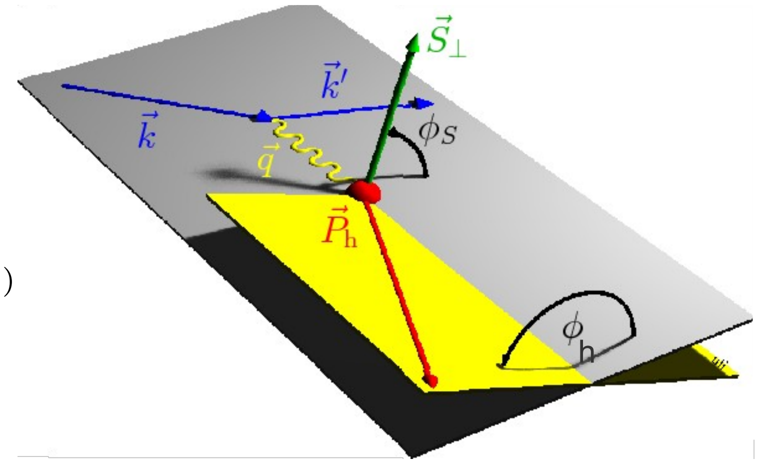

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beam polarization

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

longitudinal target polarization

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

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

transverse target polarization

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

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

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

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

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

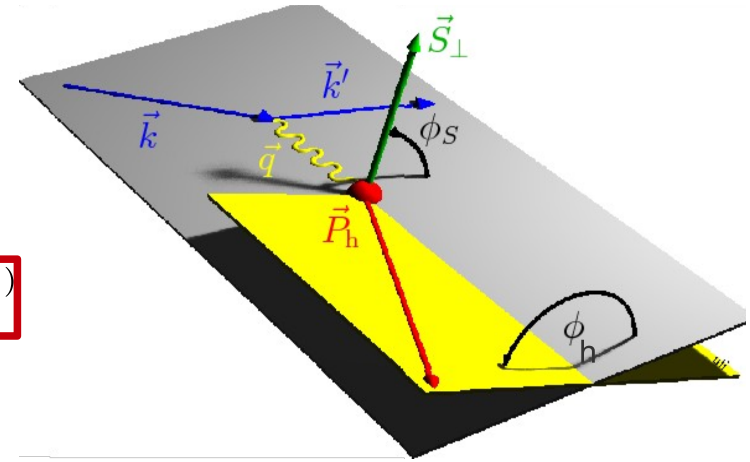
target polarization

structure function $\mathrm{F}_{XY(,Z)}$

beam polarization

(virtual photon polarization)

Semi-inclusive DIS cross section



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

beam polarization

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

transverse target polarization

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

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

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

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

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

target polarization

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

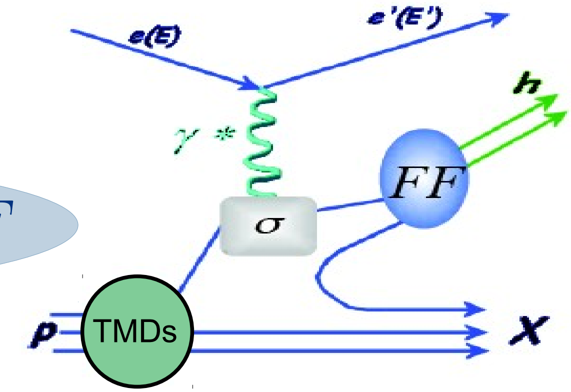
beam polarization

(virtual photon polarization)

leading twist

Semi-inclusive DIS cross section

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



transverse momentum distributions (TMDs)

		quark		
		U	L	T
nucleon	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)

		quark		
		U	L	T
h	U	D_1		$H_1^{\perp}$

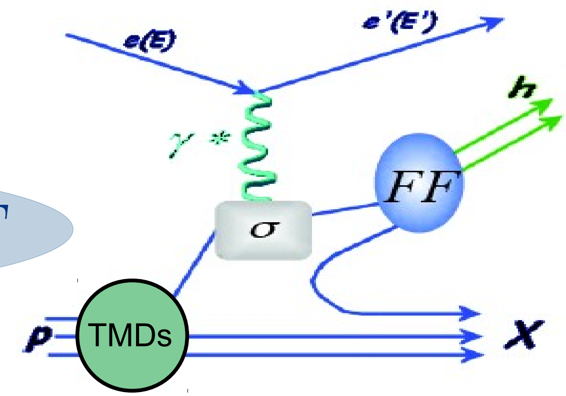
nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Semi-inclusive DIS cross section

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



transverse momentum distributions (TMDs)		quark U	quark L	quark T
nucleon	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)		quark U (spin-independent FF)	quark L (Collins FF)	quark T
h	U	D_1		$H_1^\perp$

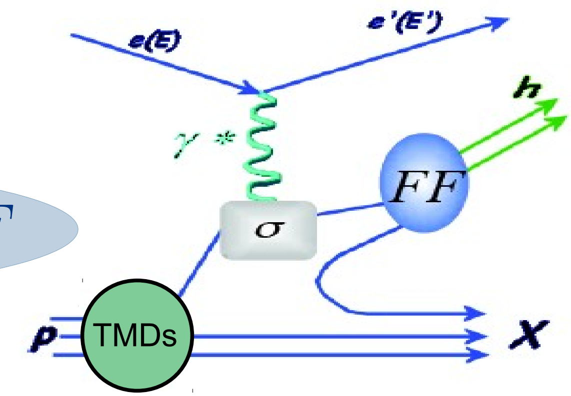
nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Semi-inclusive DIS cross section

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



transverse momentum distributions (TMDs)

nucleon \ quark	U	L	T
U	spin-independent DF f_1		Boer-Mulders DF $h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	Sivers DF $f_{1T}^\perp$	Worm-gear DF $g_{1T}^\perp$	h_1, $h_{1T}^\perp$

fragmentation functions (FFs)

h \ quark	U	L	T
U	spin-independent FF D_1		Collins FF $H_1^\perp$

nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Hadron multiplicities

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2}$$

$$\int d\phi_h$$

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

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

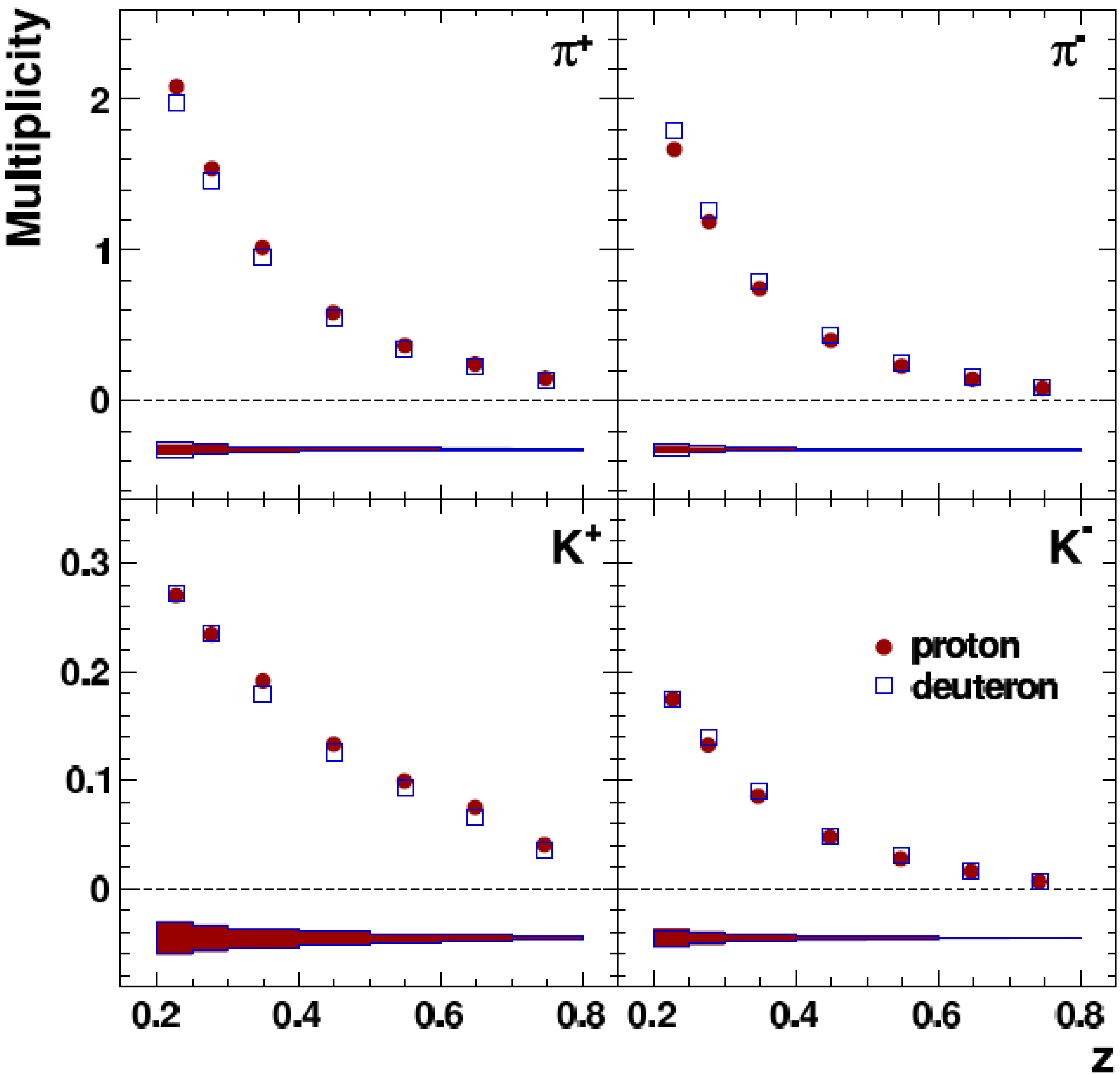
$$\propto \frac{\sum_q e_q^2\, f_1^q(x_B, k_T^2, Q^2) \otimes \mathcal{W}\, D_1^q(z, p_T^2, Q^2)}{\sum_q e_q^2\, f_1^q(x_B, Q^2)}$$

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

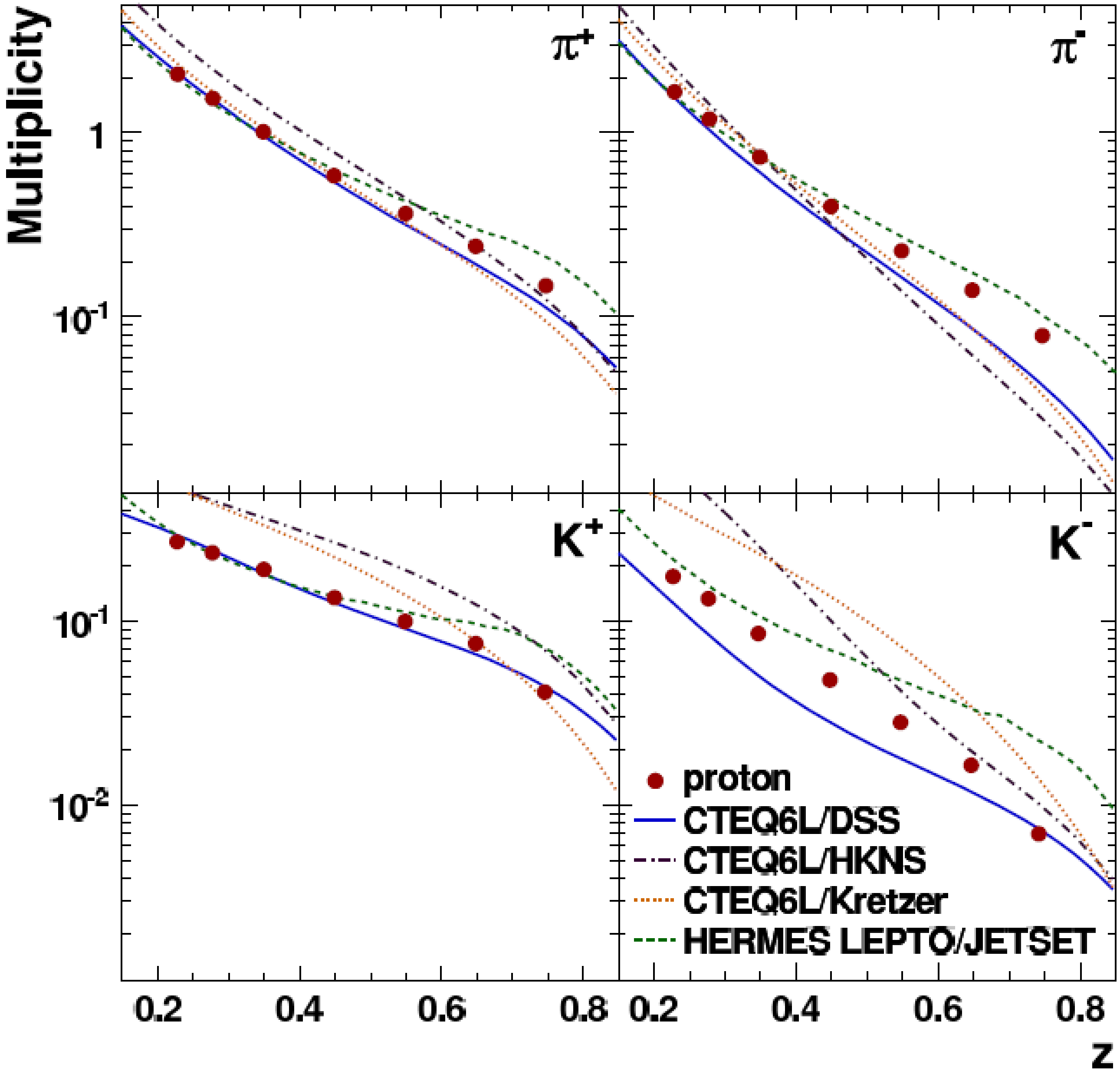


multiplicities reflect

- nucleon valence-quark content (u-dominance)
- favored $\leftrightarrow$ unfavored fragmentation

Comparison to models

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

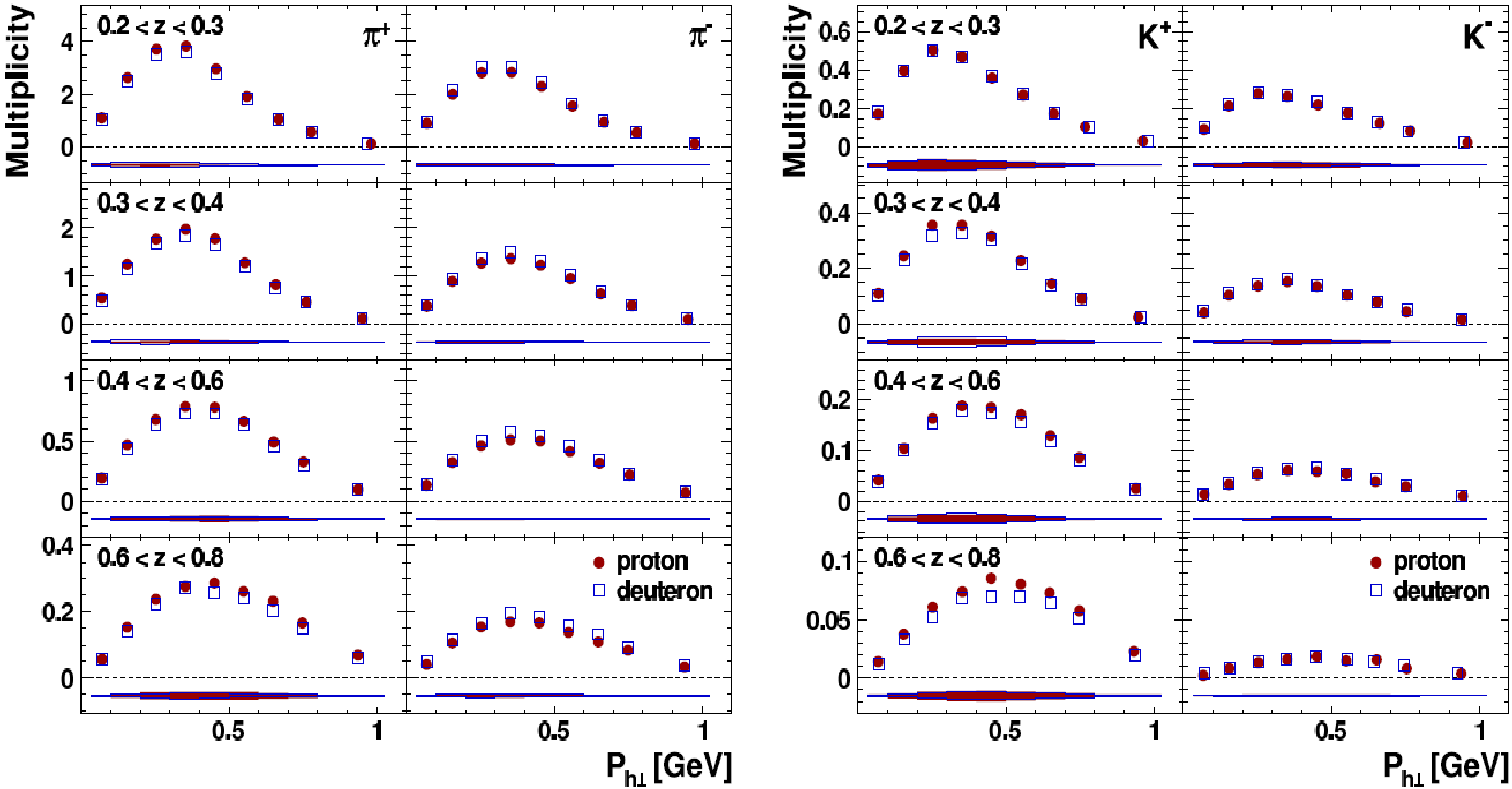


- LO in α_S
- CTEQ6L PDFs JHEP **0602** (2006) 032
- DSS FFs Phys. Rev. D **75** (2007) 114010
- Kretzer FFs Phys. Rev. D **62** (2000) 054001

- fair 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

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

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

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

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

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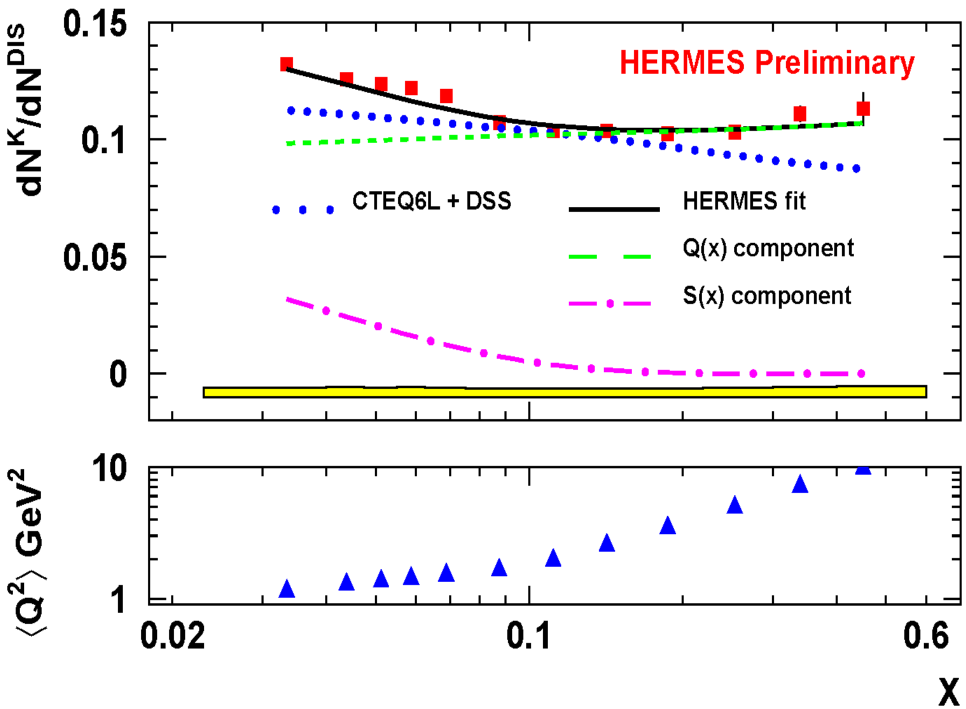
$$Q(x) \equiv u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \qquad \mathcal{D}_Q^K(z) \equiv 4D_u^K(z) + D_d^K(z)$$

$$S(x) \equiv s(x) + \bar{s}(x) \qquad \mathcal{D}_S^K(z) \equiv 2D_s^K(z)$$



S(x)=0 for x>0.15

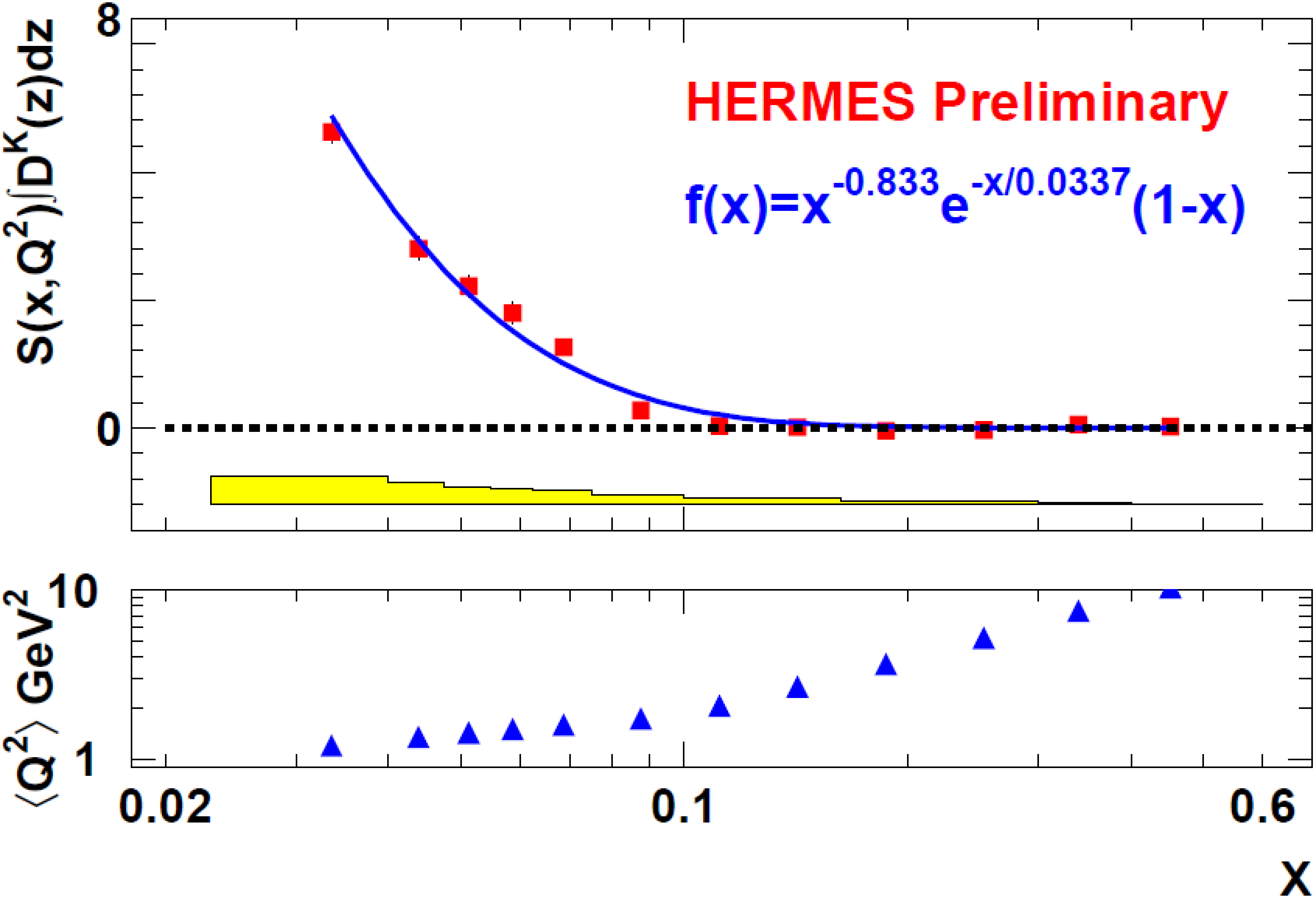
fit

$$f(x) = (0.1020.002) + (0.013 \pm 0.010)\,x$$

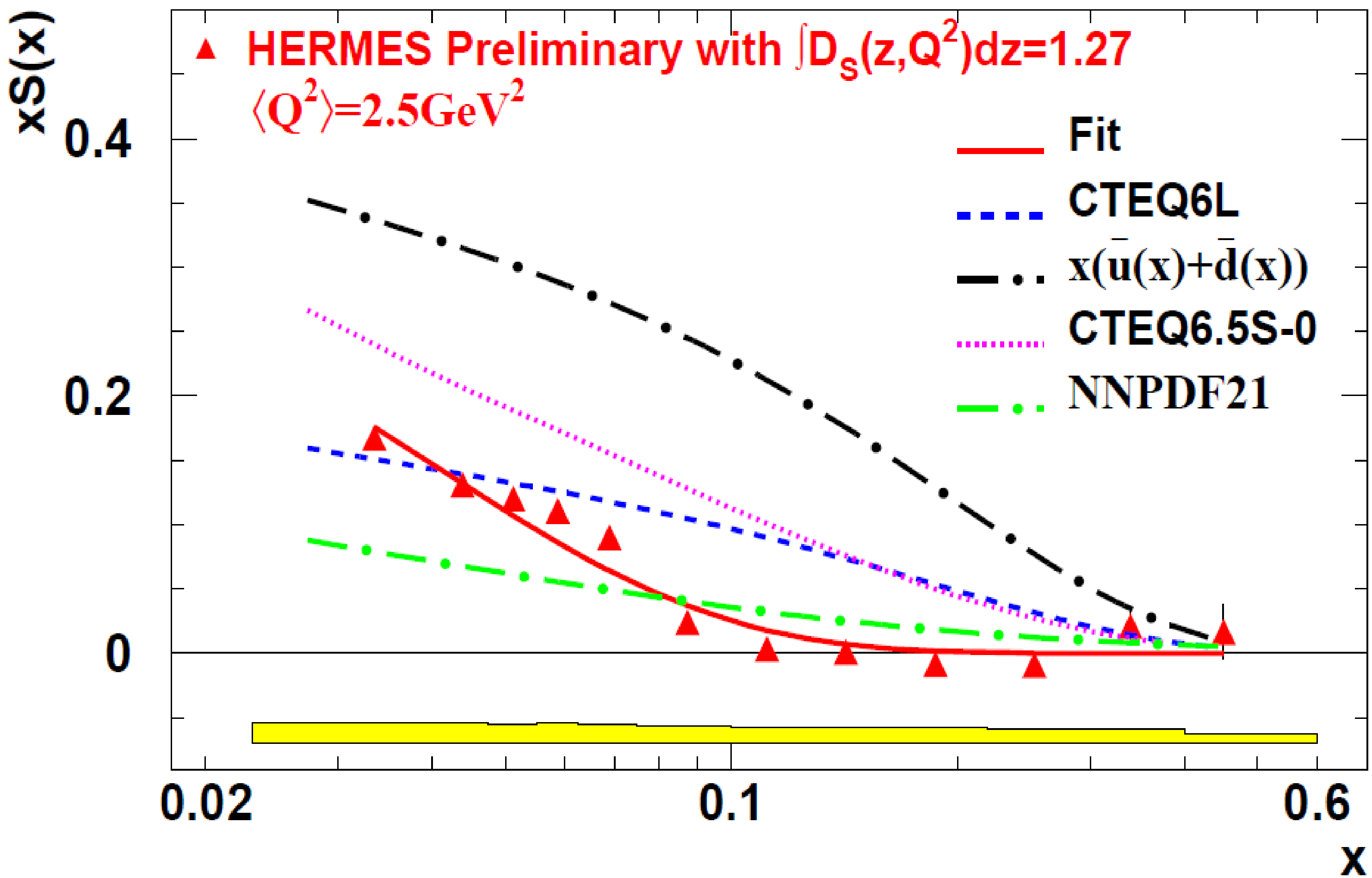
$$\int_{0.2}^{0.8}\mathcal{D}_Q^K(z)dz = 0.398 \pm 0.010$$

Re-evaluation of the strange quark distribution

Q(x) from CTEQ6L



Re-evaluation of the strange quark distribution

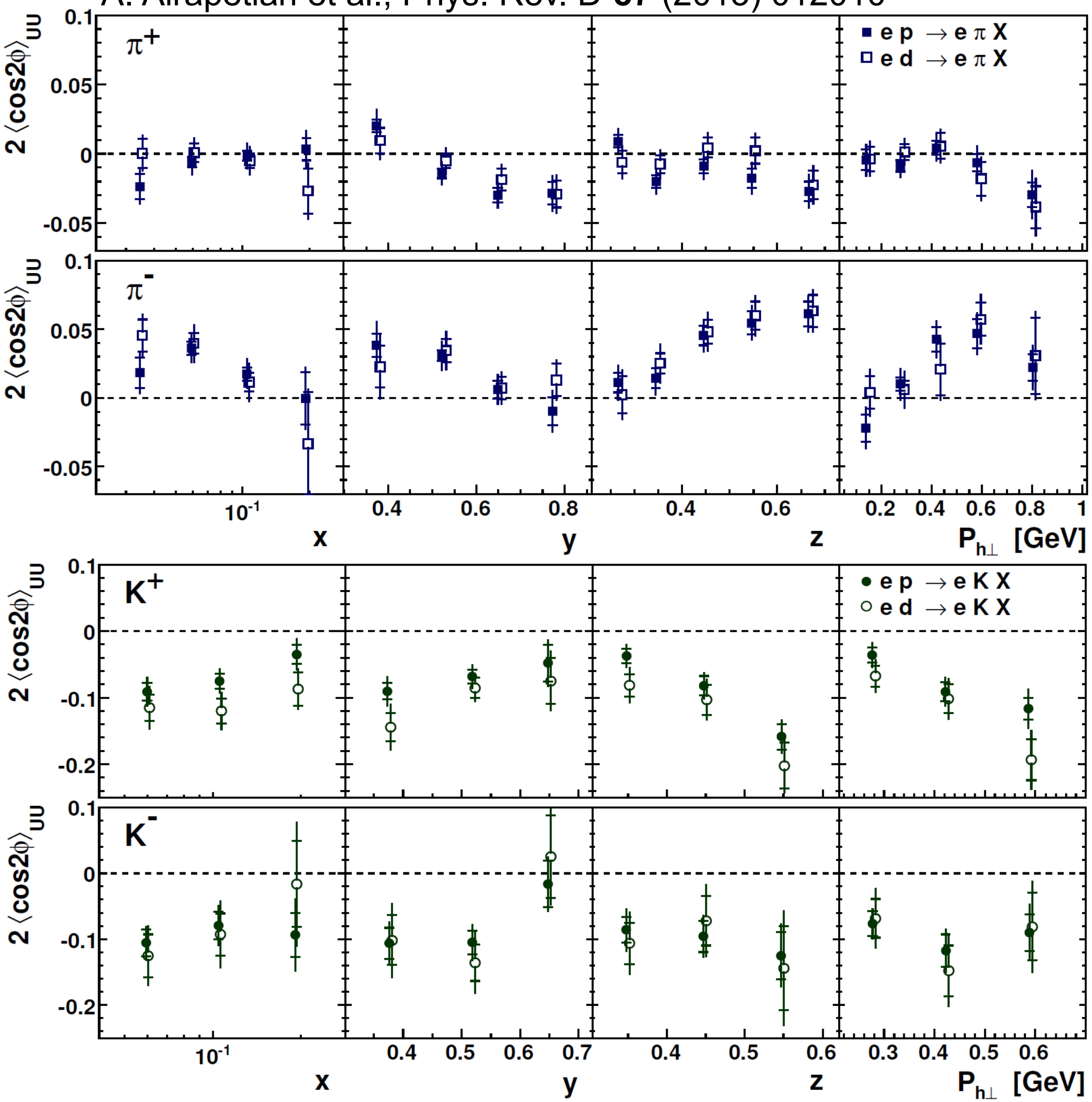


- $xS(x)$ for certain value of $\int \mathcal{D}_S^K(z)dz$
- independent of value, shape of $xS(x)$ incompatible with predictions

Boer-Mulders function $h_1^\perp$

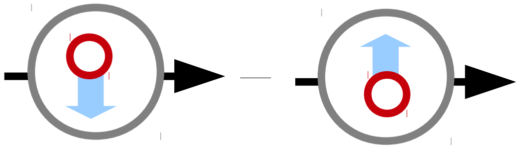
$$F_{UU}^{\cos(2\phi_h)} \propto h_1^\perp \otimes H_1^\perp$$

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



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

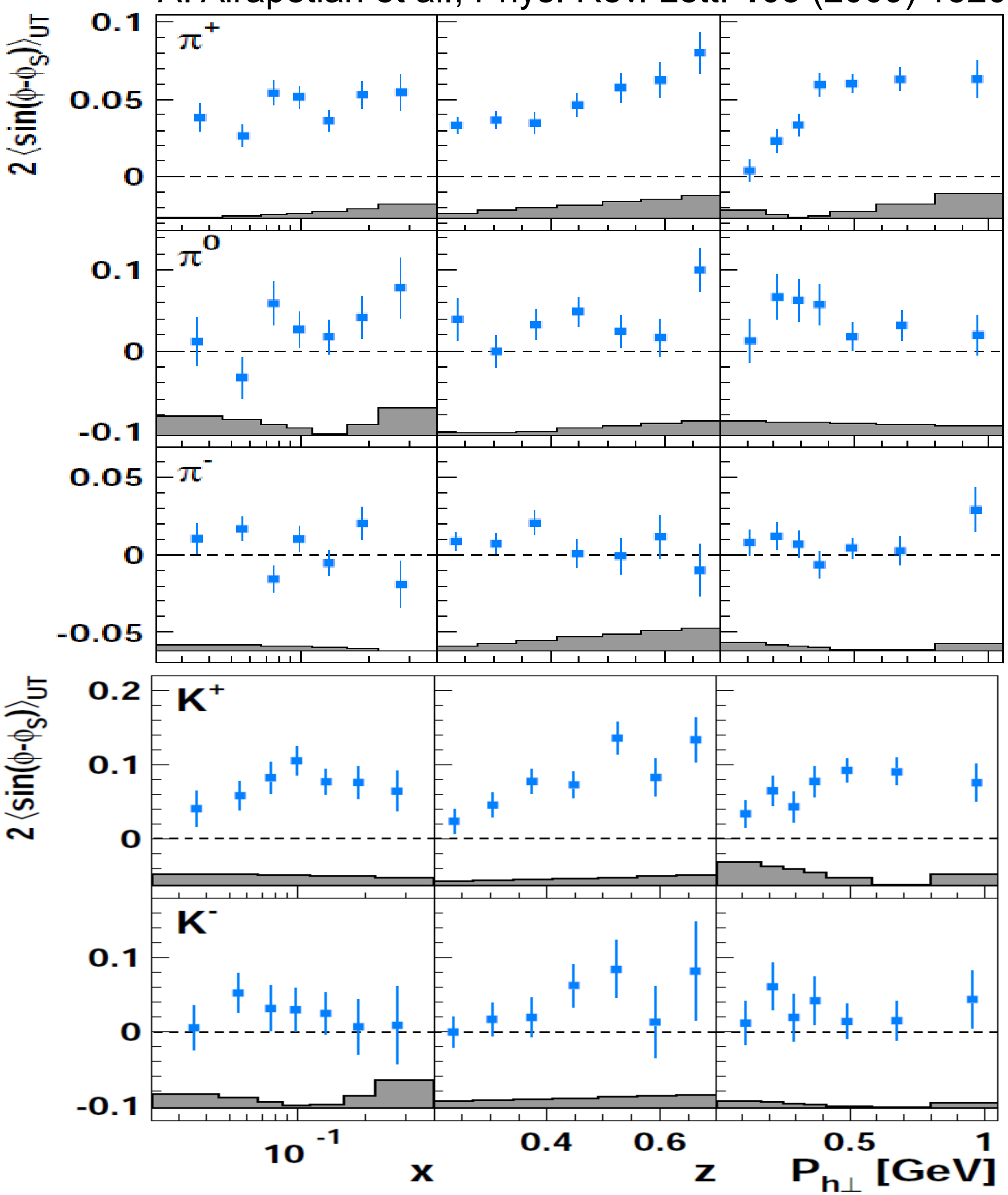
fully differential analysis; more projections via http://www-hermes.desy.de/cosnphi/



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^+/K$^+$: significantly positive

  non-zero orbital angular momentum

- π^-: consistent with zero
- π^0: slightly positive (isospin symmetry)
- K$^-$: slightly positive
- u-quark dominance for π^+ amplitude:

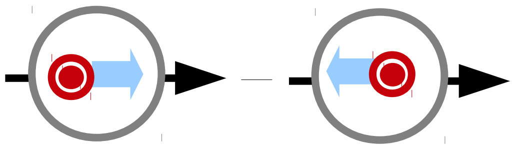
$$\approx -\frac{f_{1T}^{\perp,u}(x,k_T^2) \otimes D_1^{u\to\pi^+}(z,p_T^2)}{f_1^u(x,k_T^2) \otimes D_1^{u\to\pi^+}(z,p_T^2)}$$

$$f_{1T}^{\perp,u}(x,k_T^2) < 0$$

- π^-: u- and d-quark cancellation

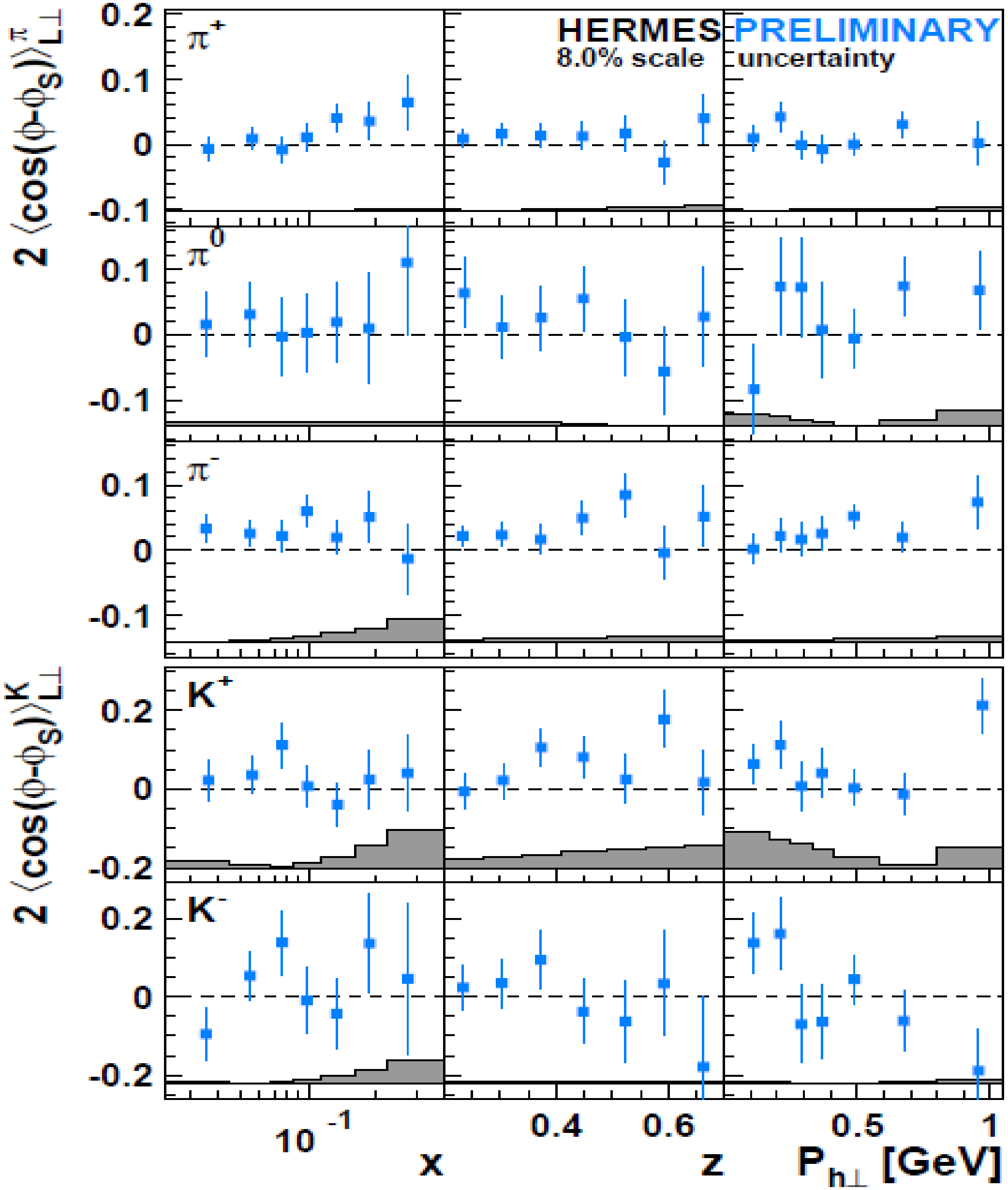
$$f_{1T}^{\perp,d}(x,k_T^2) > 0$$

- K$^+$>π^+



Worm-gear function $g_{1T}^{\perp}$

$$F_{LT}^{\cos(\phi_h - \phi_S)} \propto g_{1T}^{\perp} \otimes D_1$$



- π^+/K^+: slightly positive?
- π^-: positive
  → non-zero orbital angular momentum
- π^0/K^-: consistent with zero

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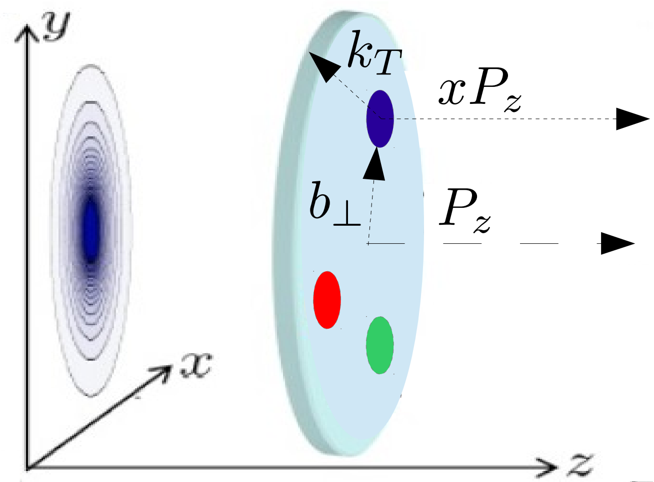
$\int d^2\vec{b}_\perp$

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



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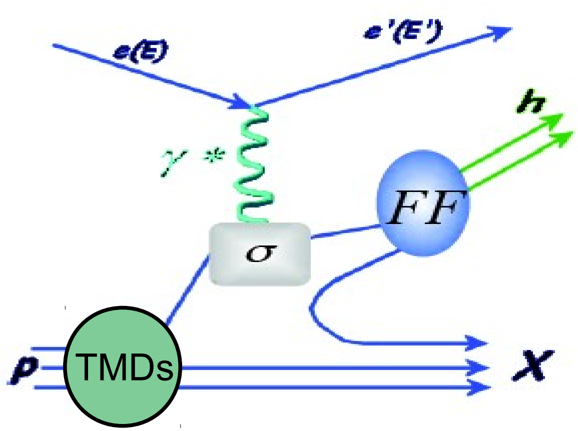
impact-parameter distributions

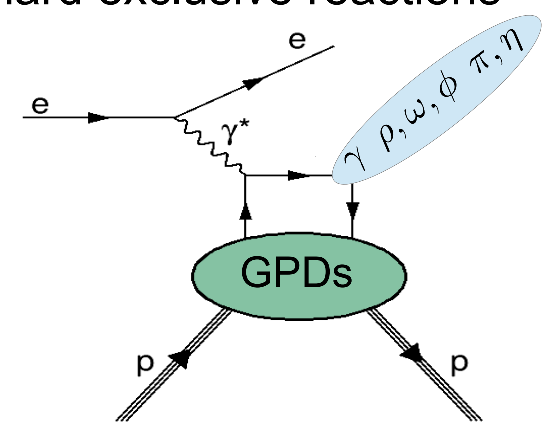
Fourier transform

generalized parton distributions (GPDs)

semi-inclusive deep-inelastic scattering (DIS)



hard exclusive reactions



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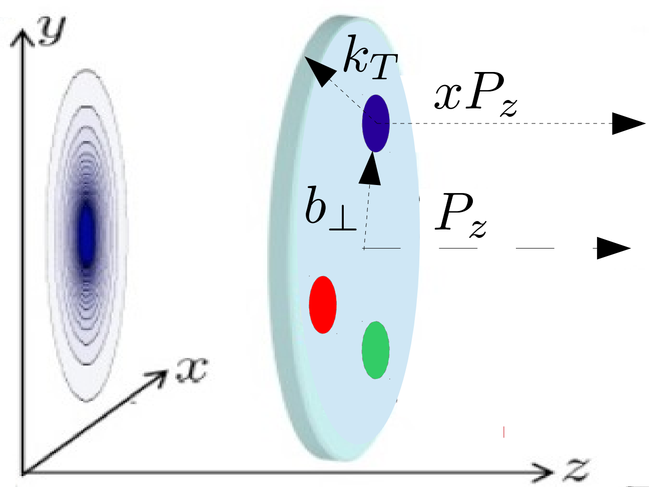

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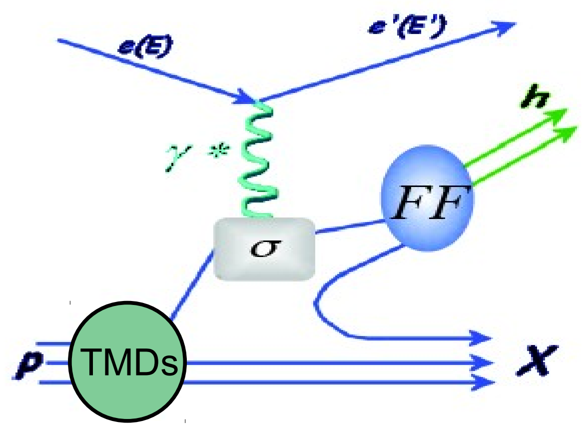

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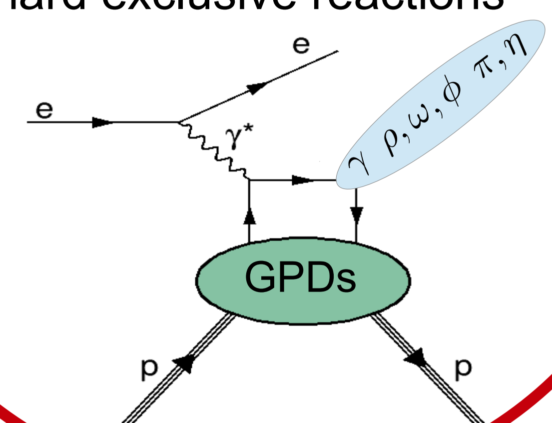

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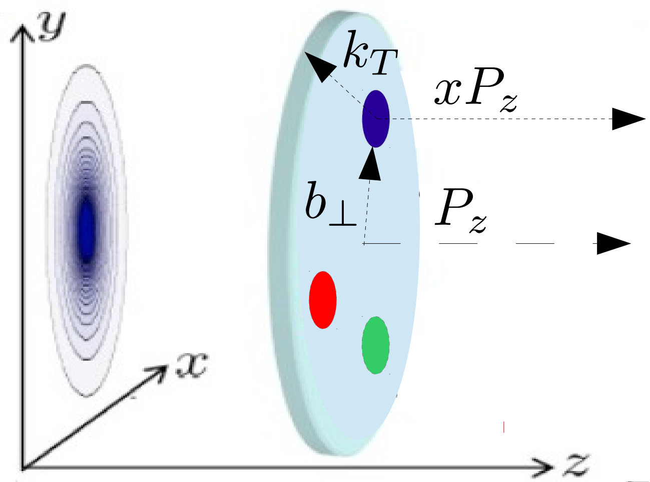


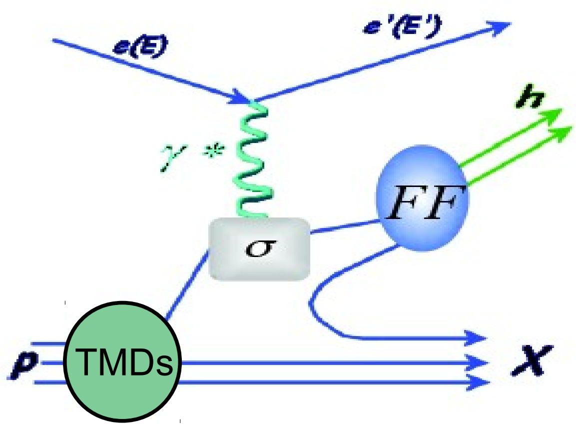
$\int d^2\vec{k}_T$

impact-parameter distributions

Fourier transform

generalized parton distributions (GPDs)

semi-inclusive deep-inelastic scattering (DIS)



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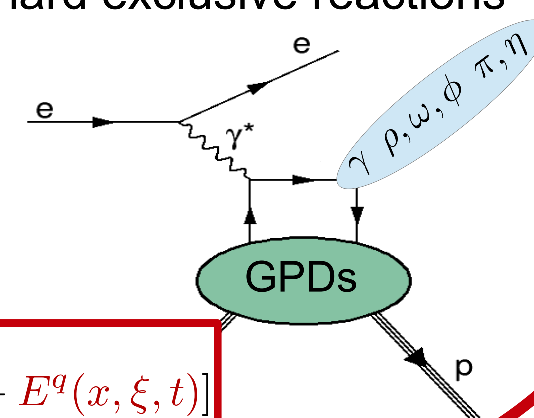
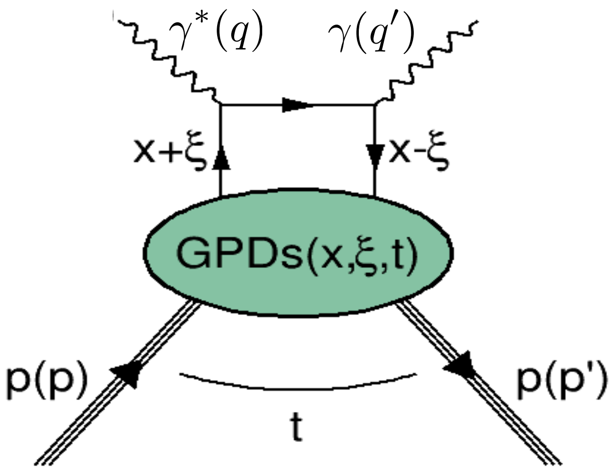


X. Ji, Phys. Rev. Lett. **78** (1997) 610

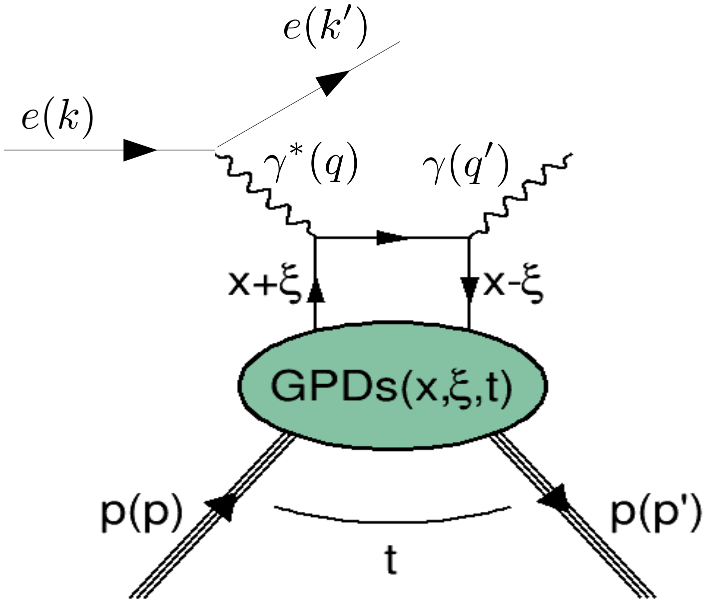
$$\boxed{J^q = \lim_{t\to 0} \frac{1}{2} \int_{-1}^{1} dx\, x [H^q(x,\xi,t) + E^q(x,\xi,t)]}$$

Deeply virtual Compton scattering



DVCS

Deeply virtual Compton scattering



DVCS

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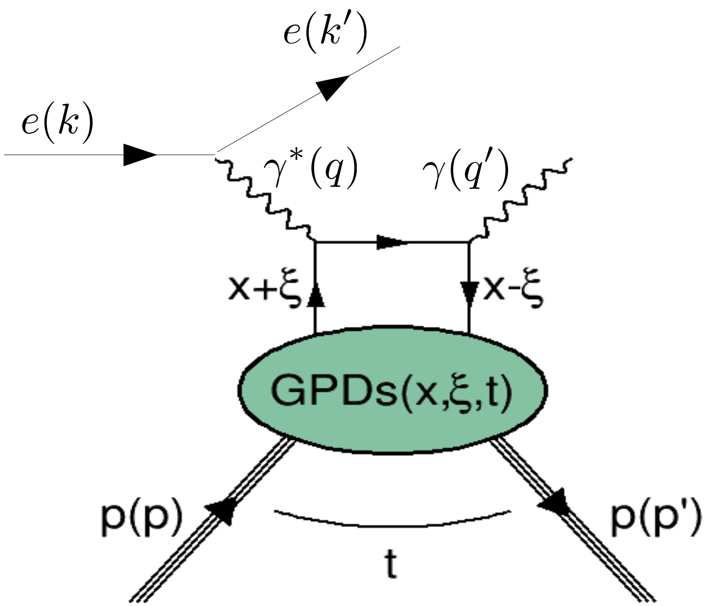
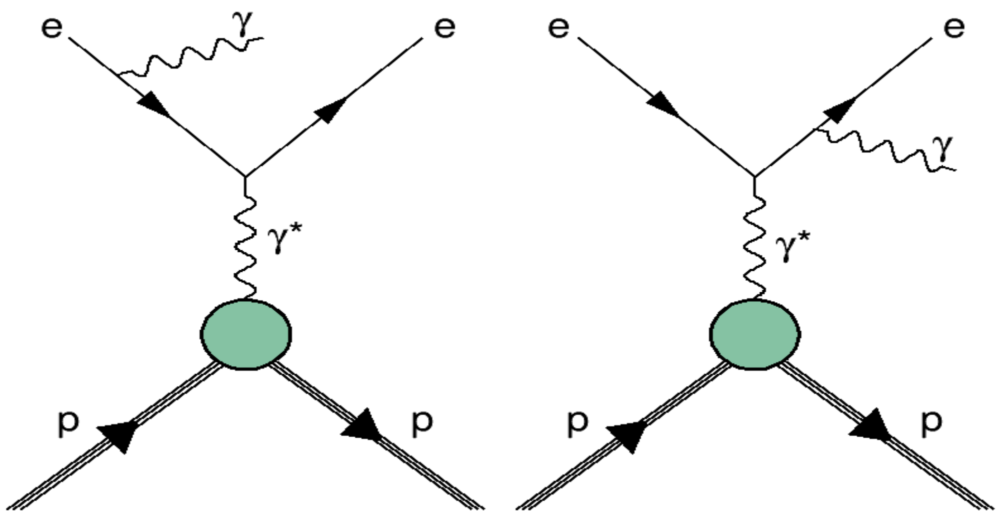
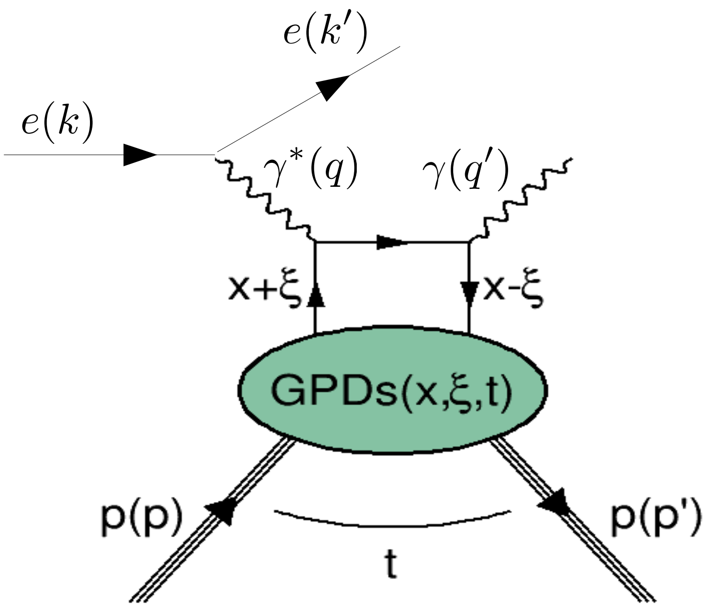


DVCS

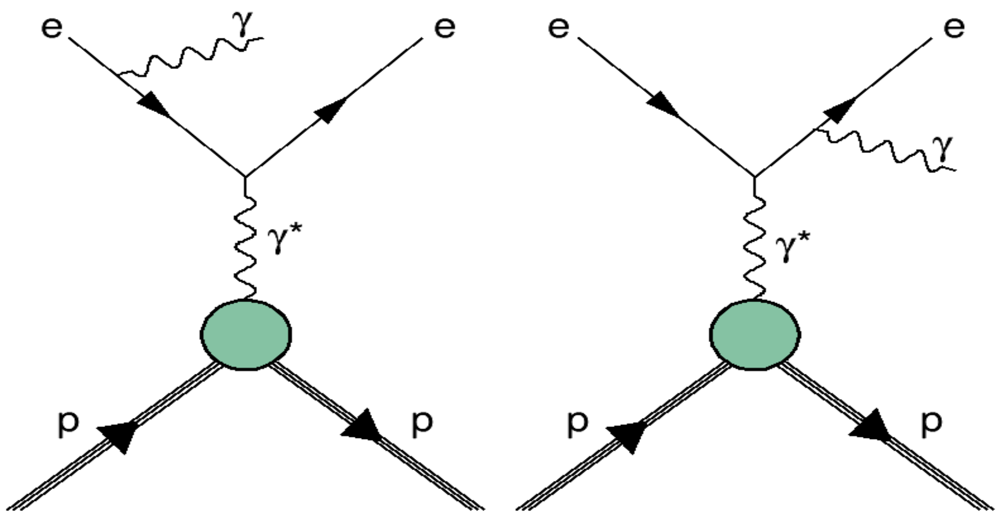


Bethe-Heitler

Deeply virtual Compton scattering



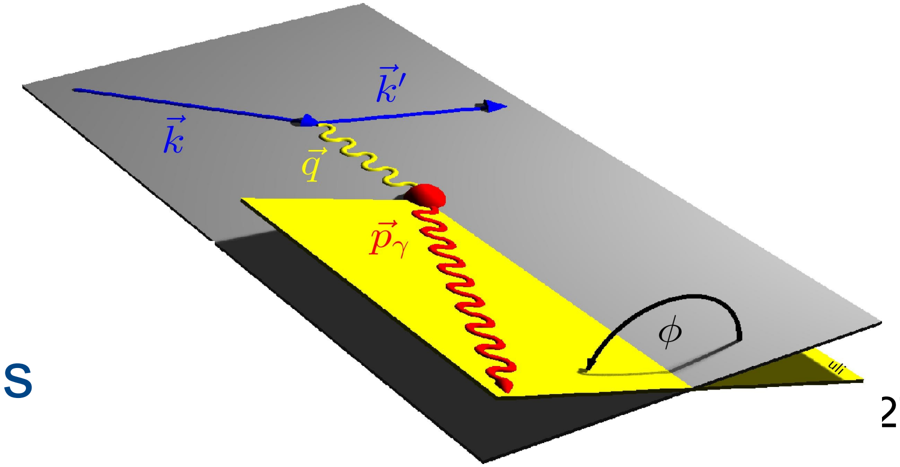
DVCS



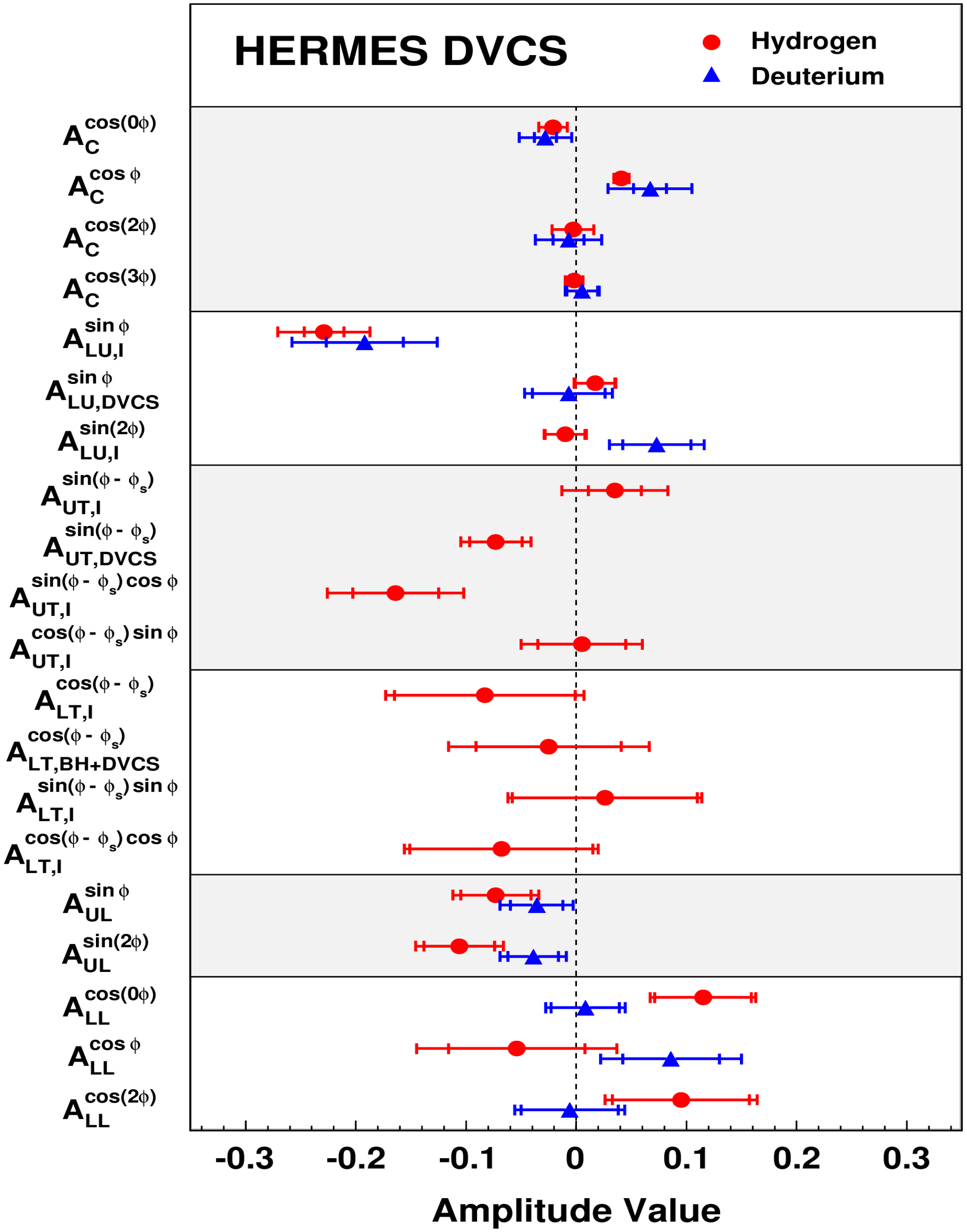
Bethe-Heitler

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

- $|\tau_{BH}|$: calculable (form factors)
- $|\tau_{BH}| \gg |\tau_{DVCS}|$ at HERMES
- interference term: - large at HERMES
  - linear in GPDs
- access through azimuthal asymmetries



DVCS at HERMES



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

GPD H

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

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

GPD E

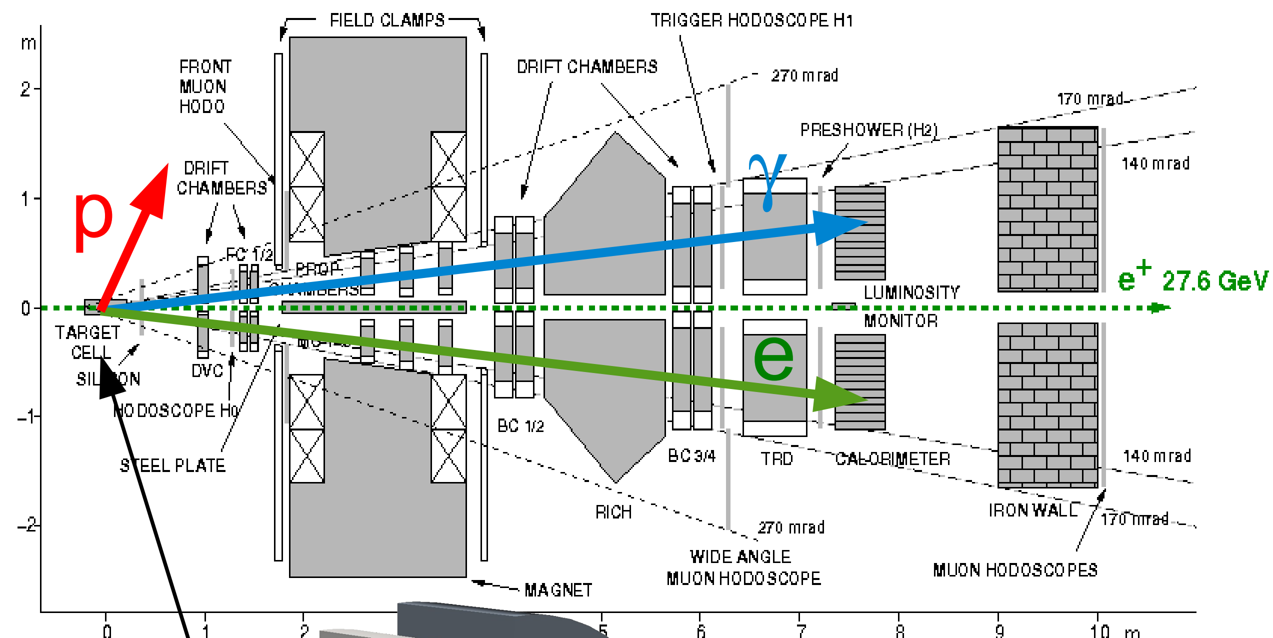
double spin (LT) asymmetry
Phys. Lett. B **704** (2011) 15

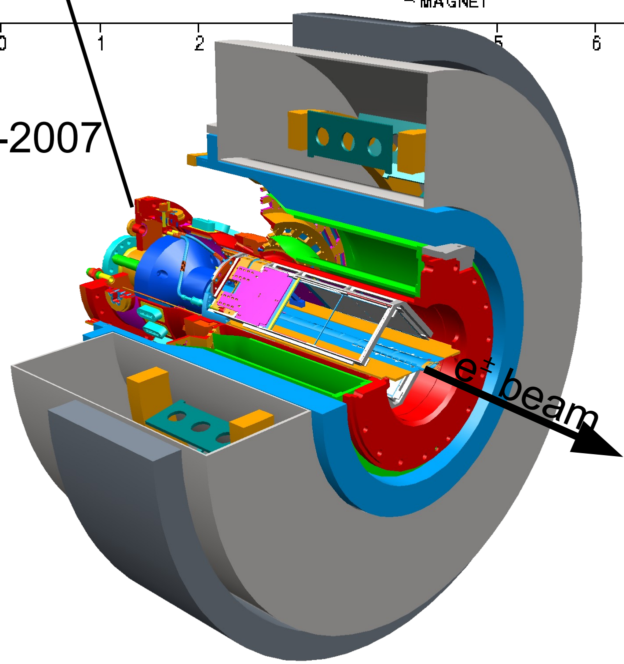
longitudinal target-spin asymmetry
JHEP **06** (2010) 019
Nucl. Phys. B 842 (2011) 265

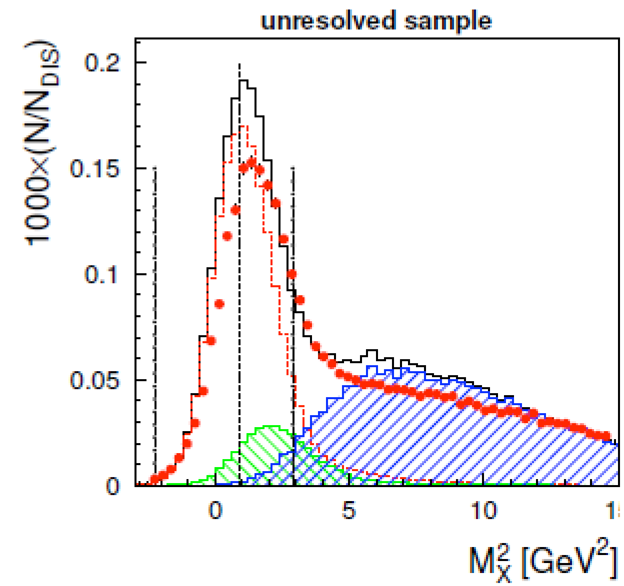
GPD $\tilde{H}$

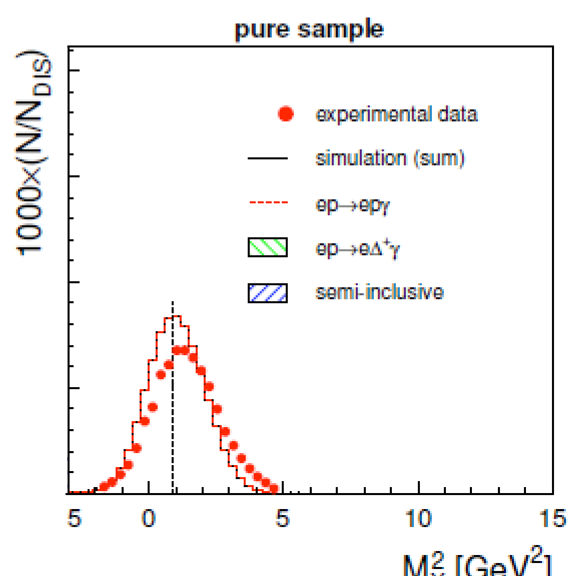
double spin (LL) asymmetry
JHEP **06** (2010) 019
Nucl. Phys. B 842 (2011) 265

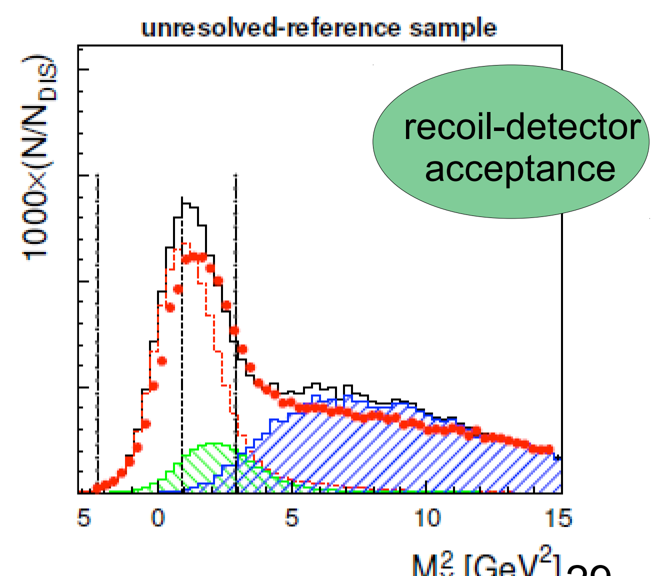
DVCS event selection





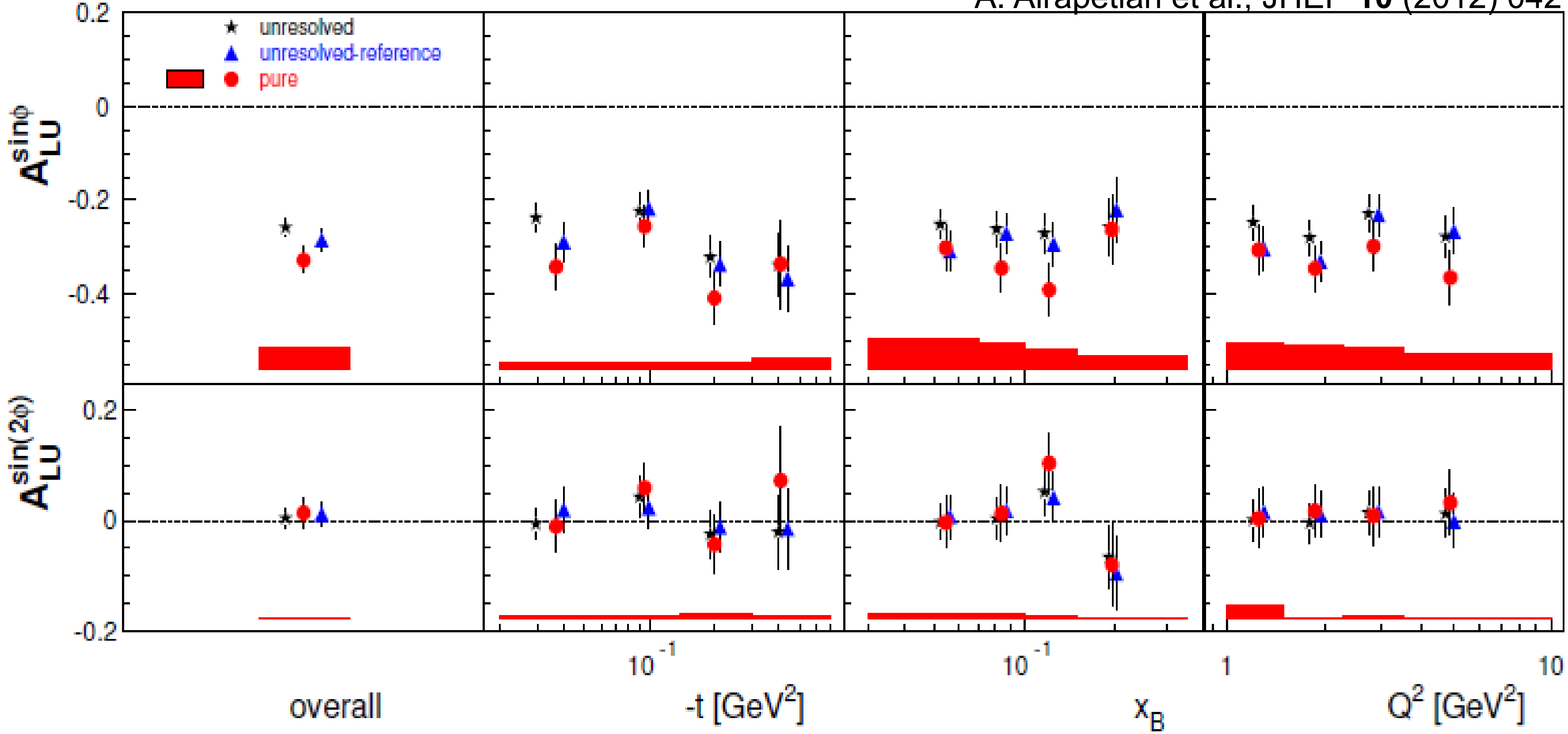






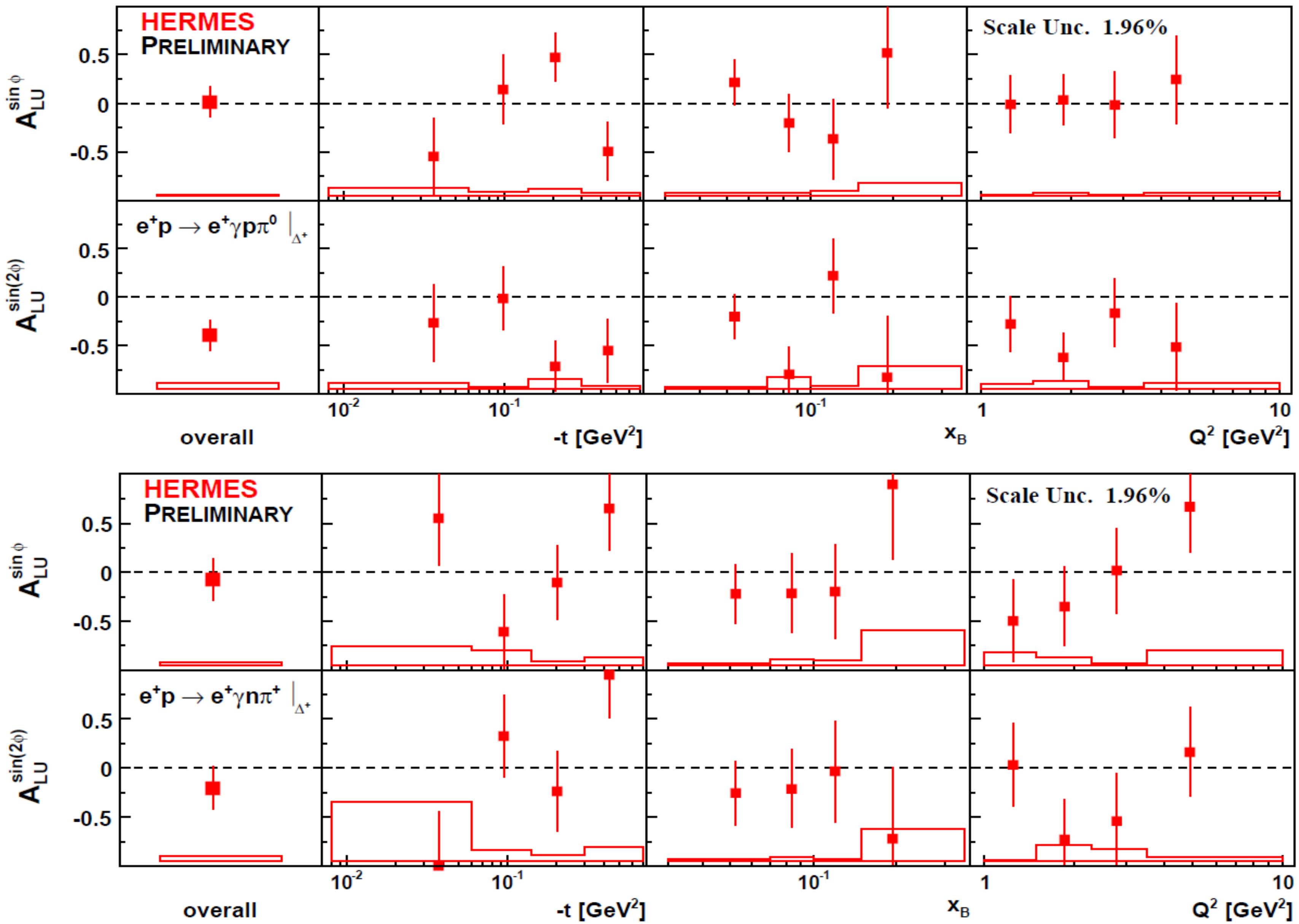
Beam-helicity asymmetry

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



- additional 1.96 % scale uncertainty from beam polarization

Beam-helicity asymmetry for associated DVCS

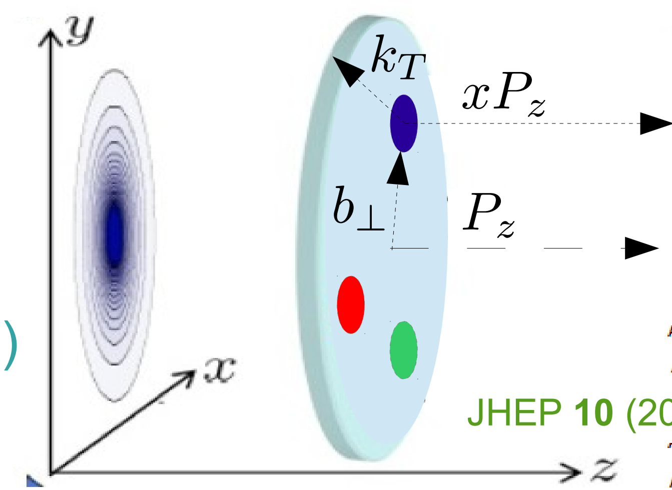


Summary

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

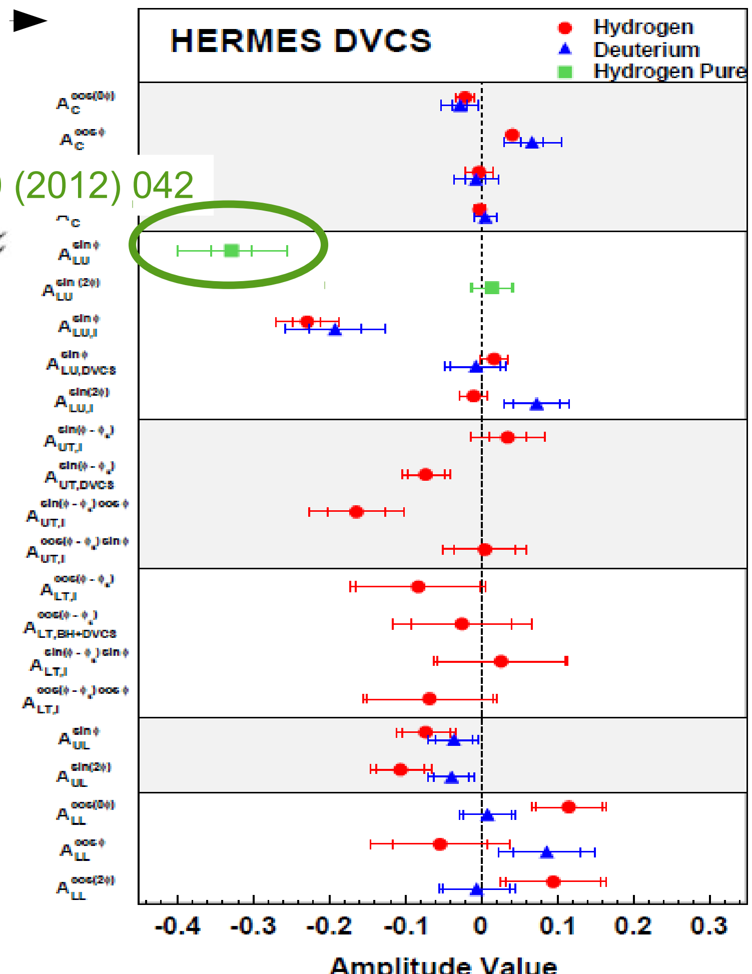
$\int d^2\vec{b}_\perp$

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



transverse-momentum
dependent PDFs (TMDs)

JHEP **10** (2012) 042



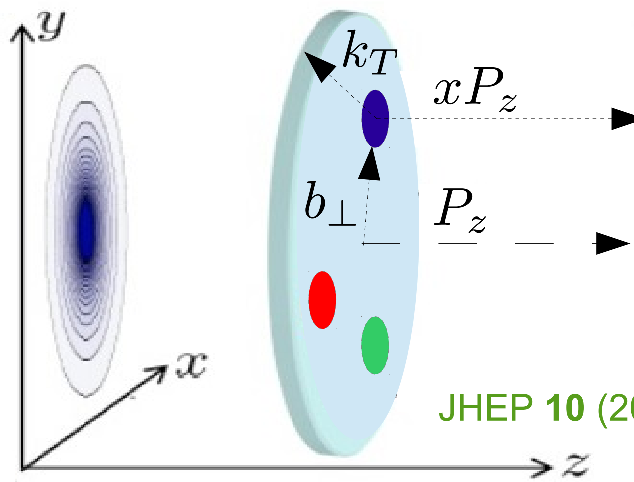
Summary

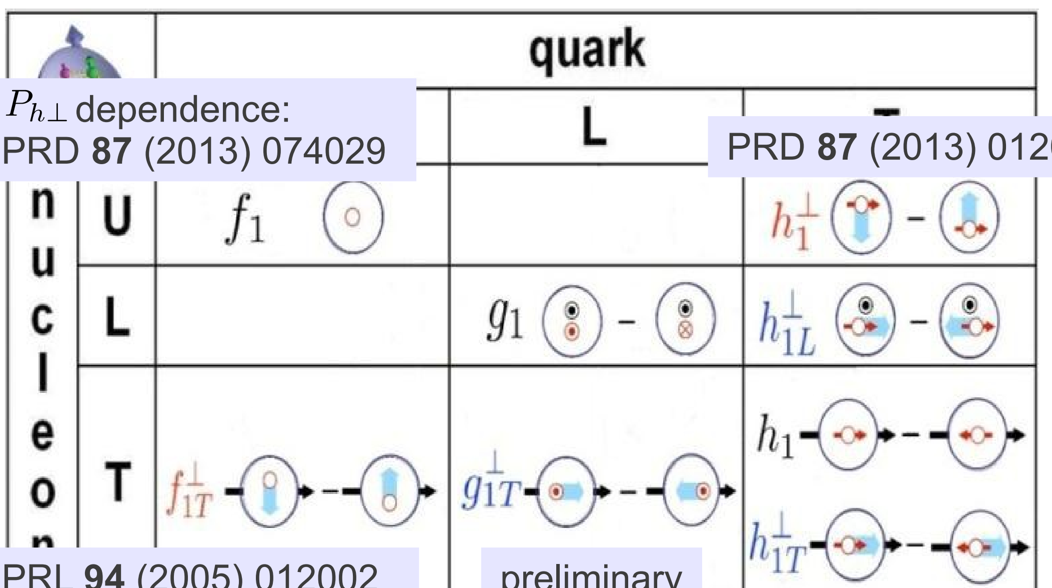
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

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

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

transverse-momentum dependent PDFs (TMDs)





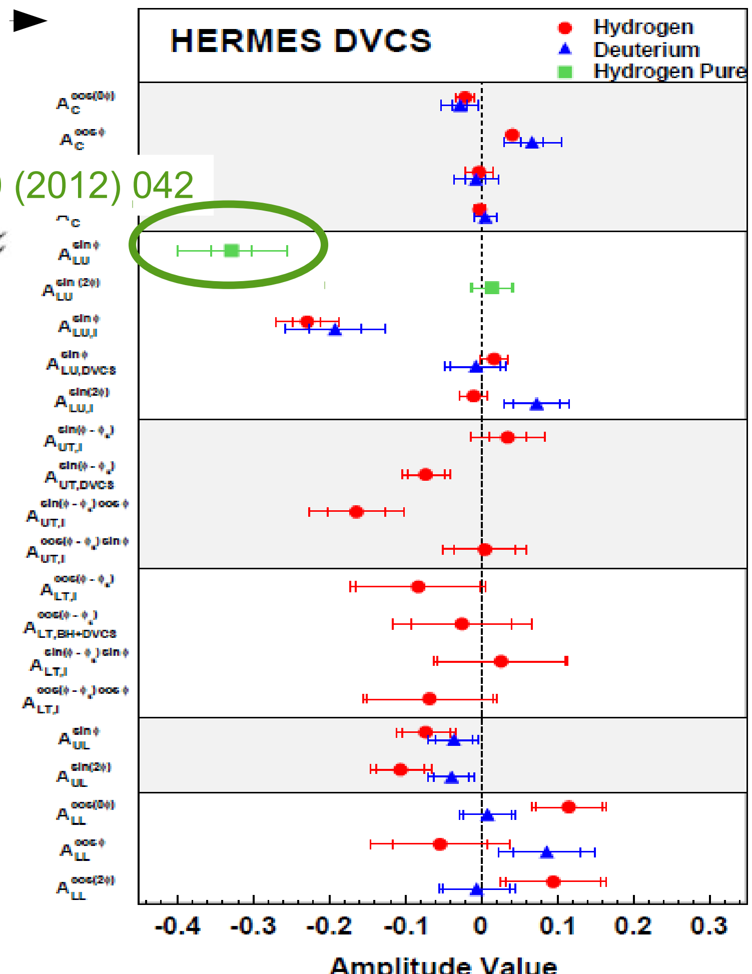
$P_{h\perp}$ dependence:
PRD **87** (2013) 074029

PRD **87** (2013) 012010

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

preliminary results

JHEP **10** (2012) 042



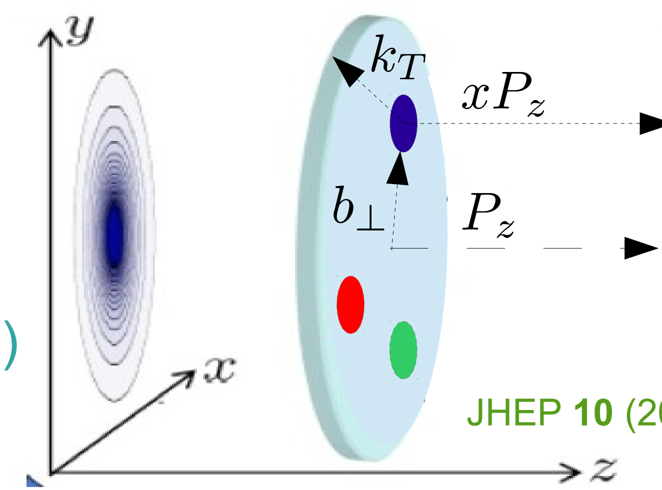
Summary

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

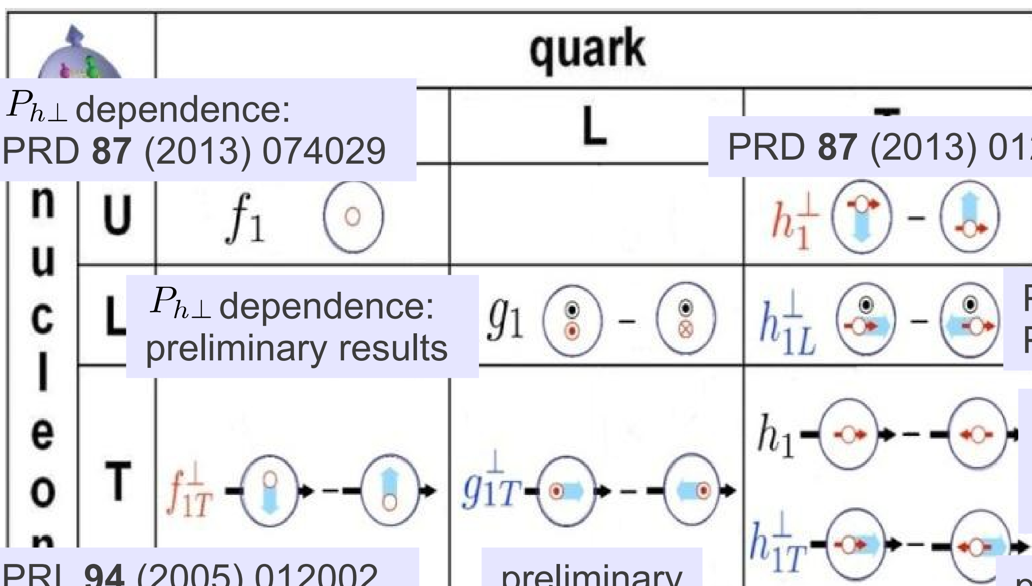
$\int d^2\vec{b}_\perp$

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

transverse-momentum dependent PDFs (TMDs)



JHEP **10** (2012) 042



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

PRD **87** (2013) 012010

$P_{h\perp}$ dependence:
preliminary results

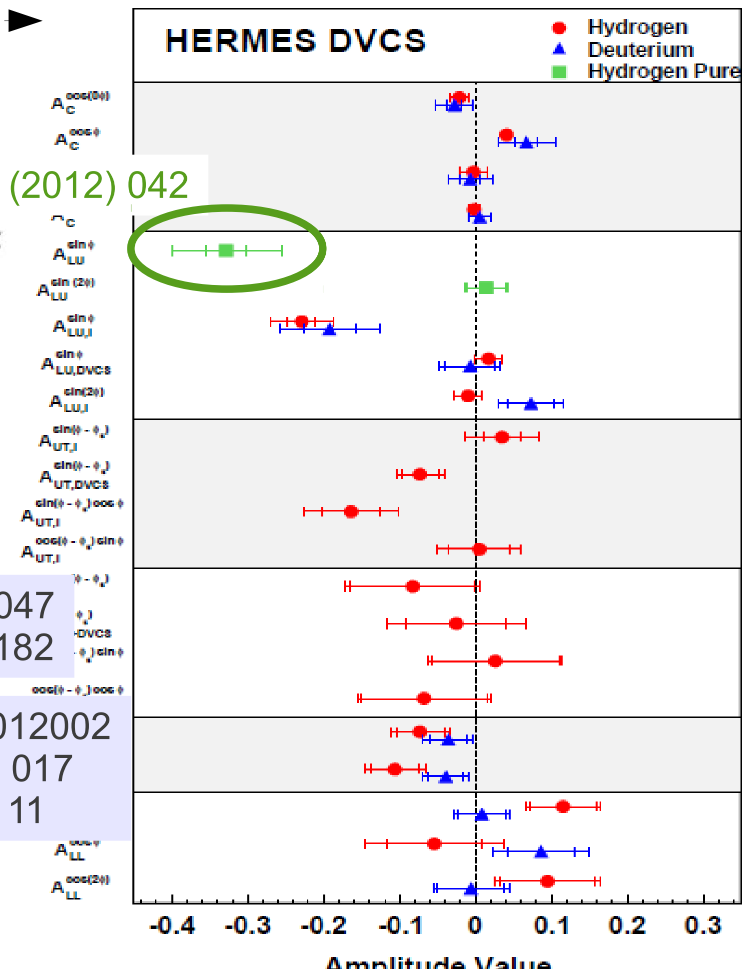
PRL 84 (2000) 4047
PLB **562** (2003) 182

PRL **94** (2005) 012002
JHEP **06** (2008) 017
PLB **693** (2010) 11

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

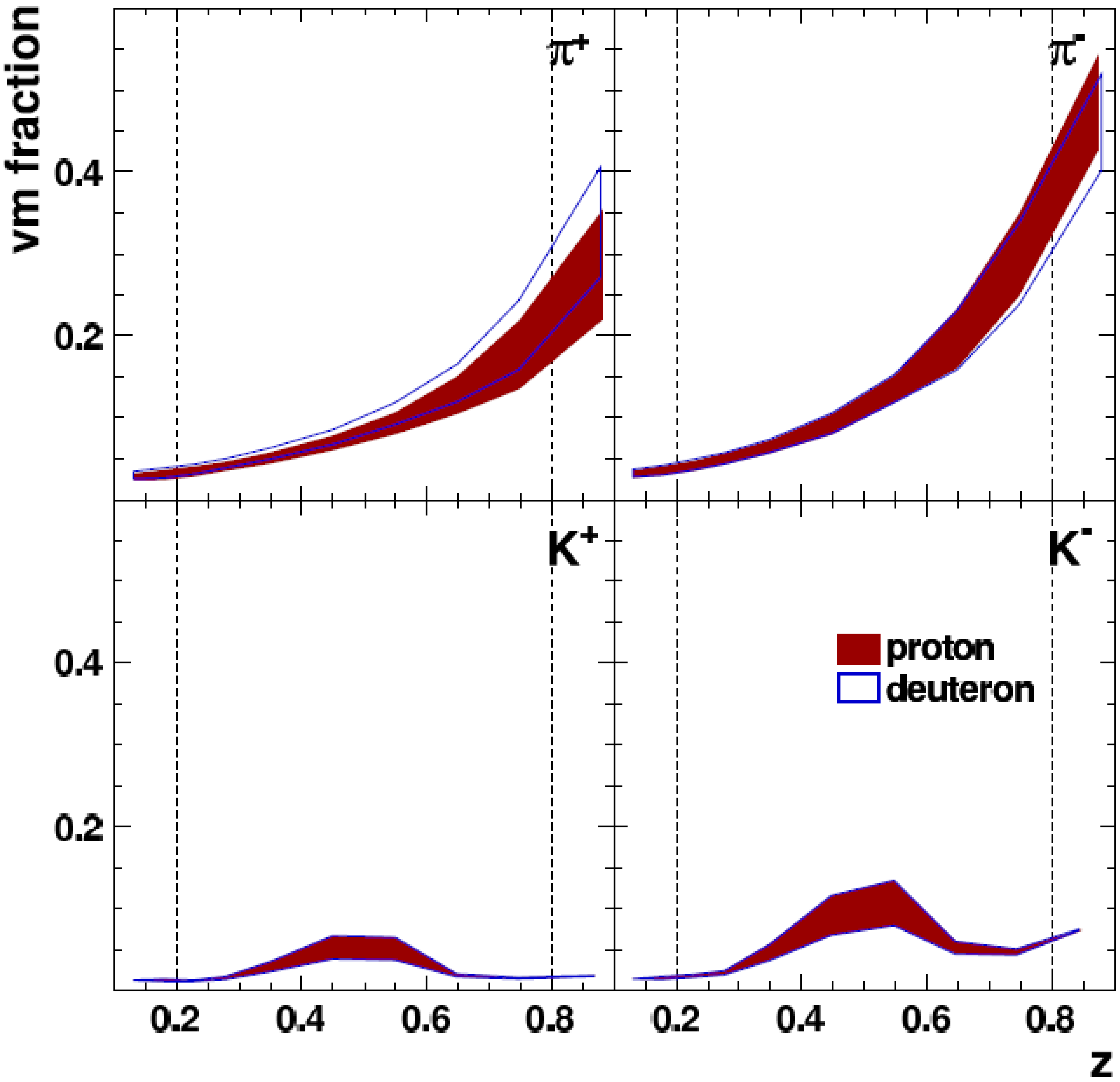
preliminary results

preliminary results

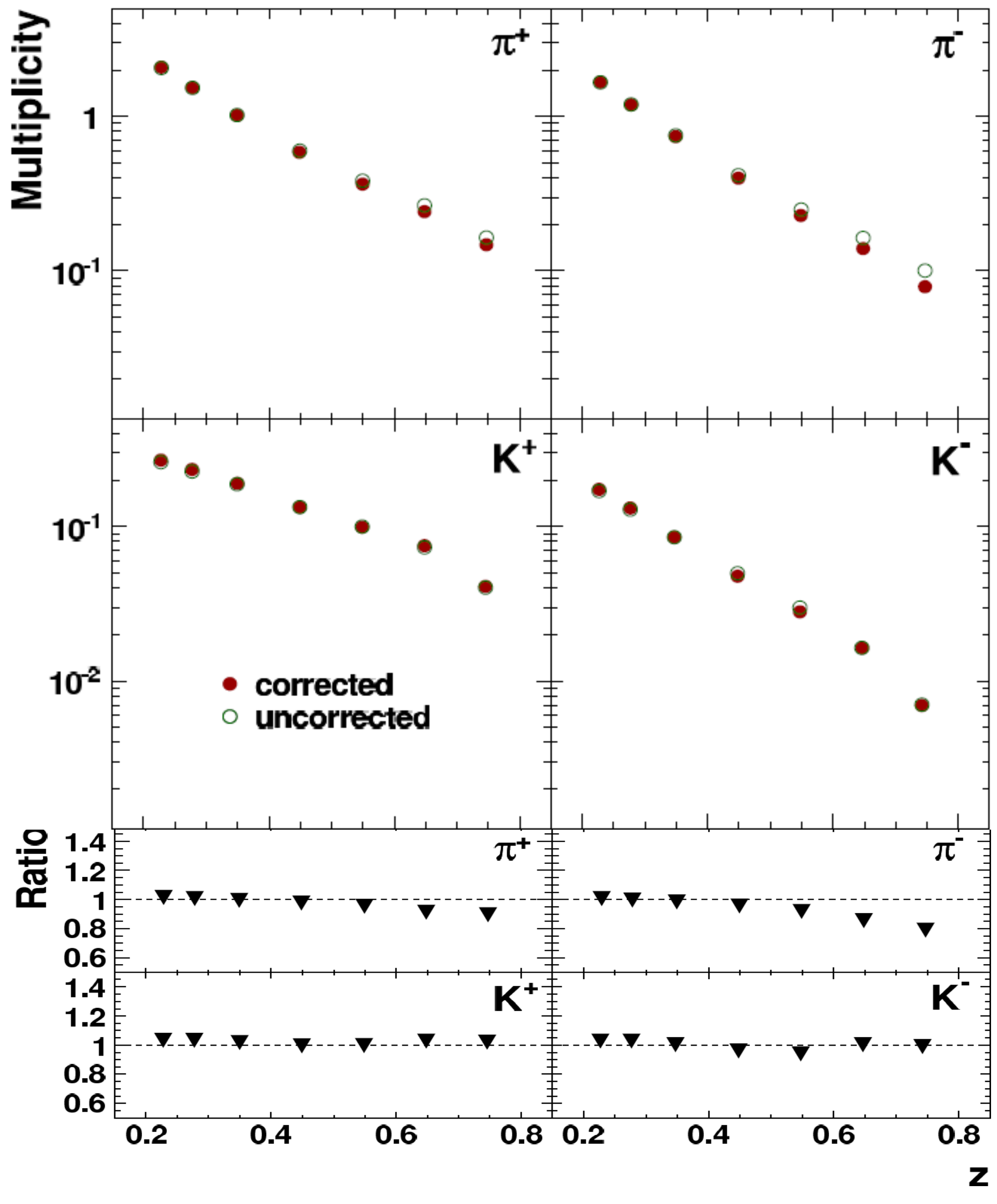


Backup

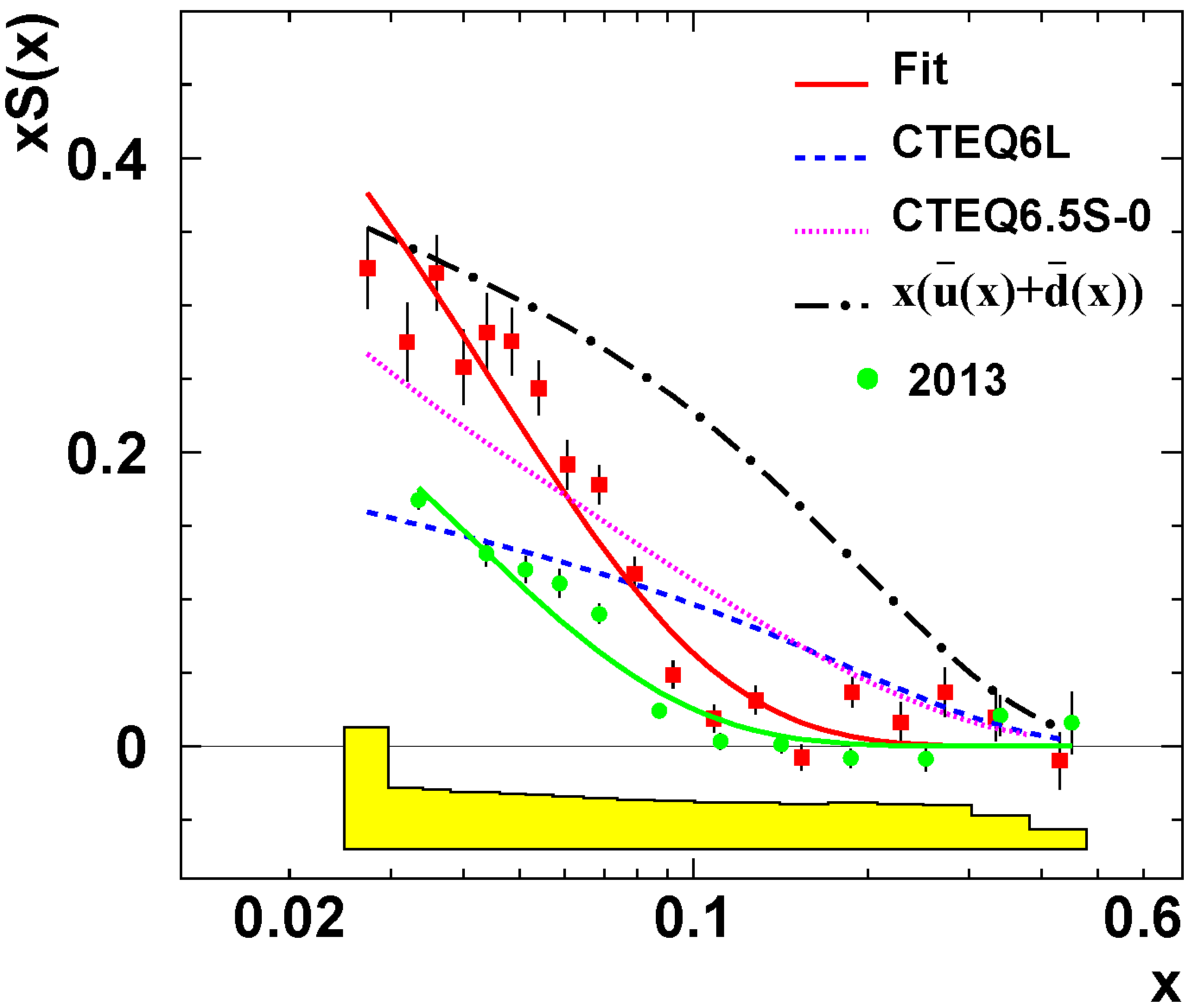
Exclusive vector-meson fraction



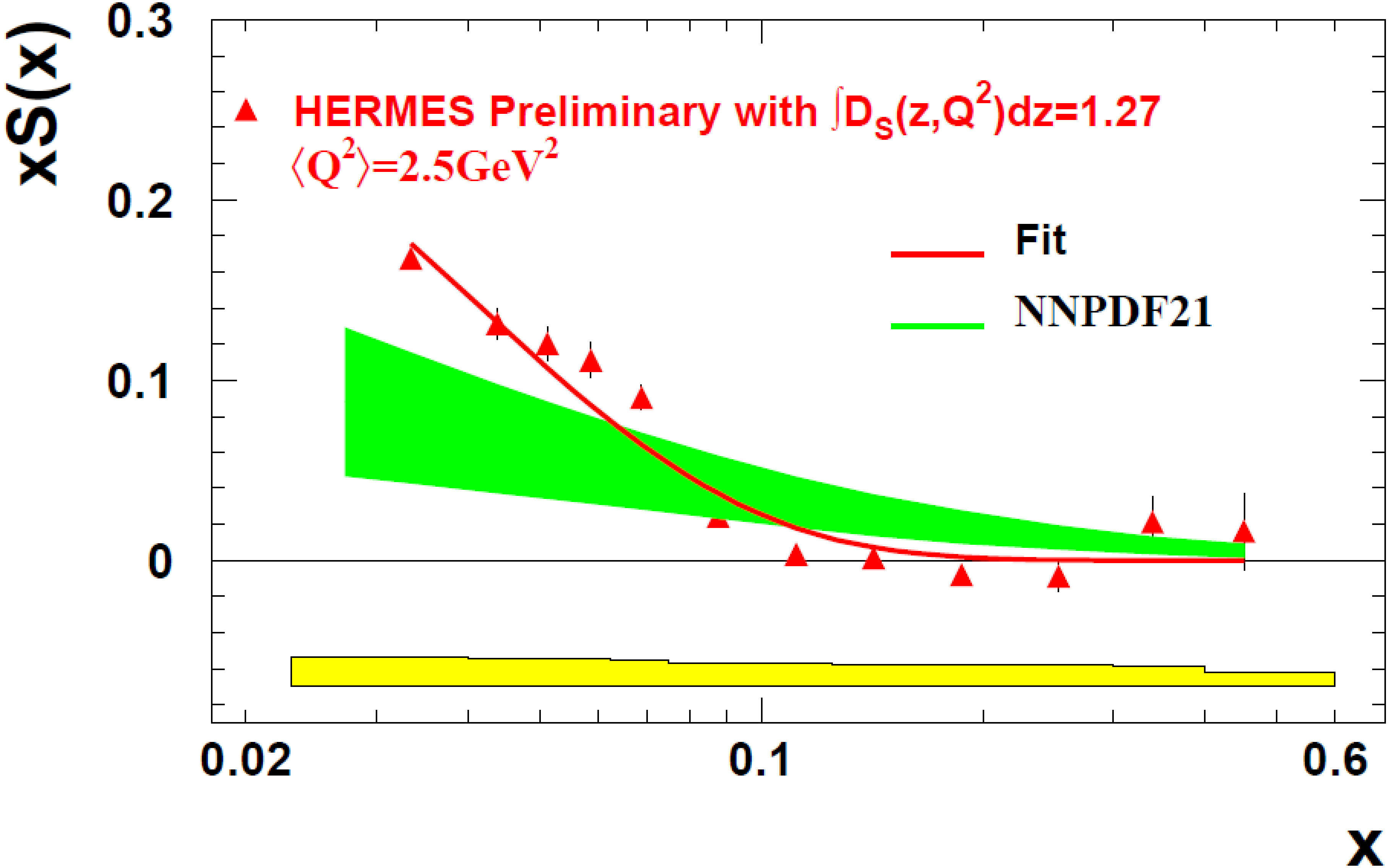
Multiplicities corrected in z: without and with exclusive vector-meson correction



Comparison S(x) PLB and new preliminary results

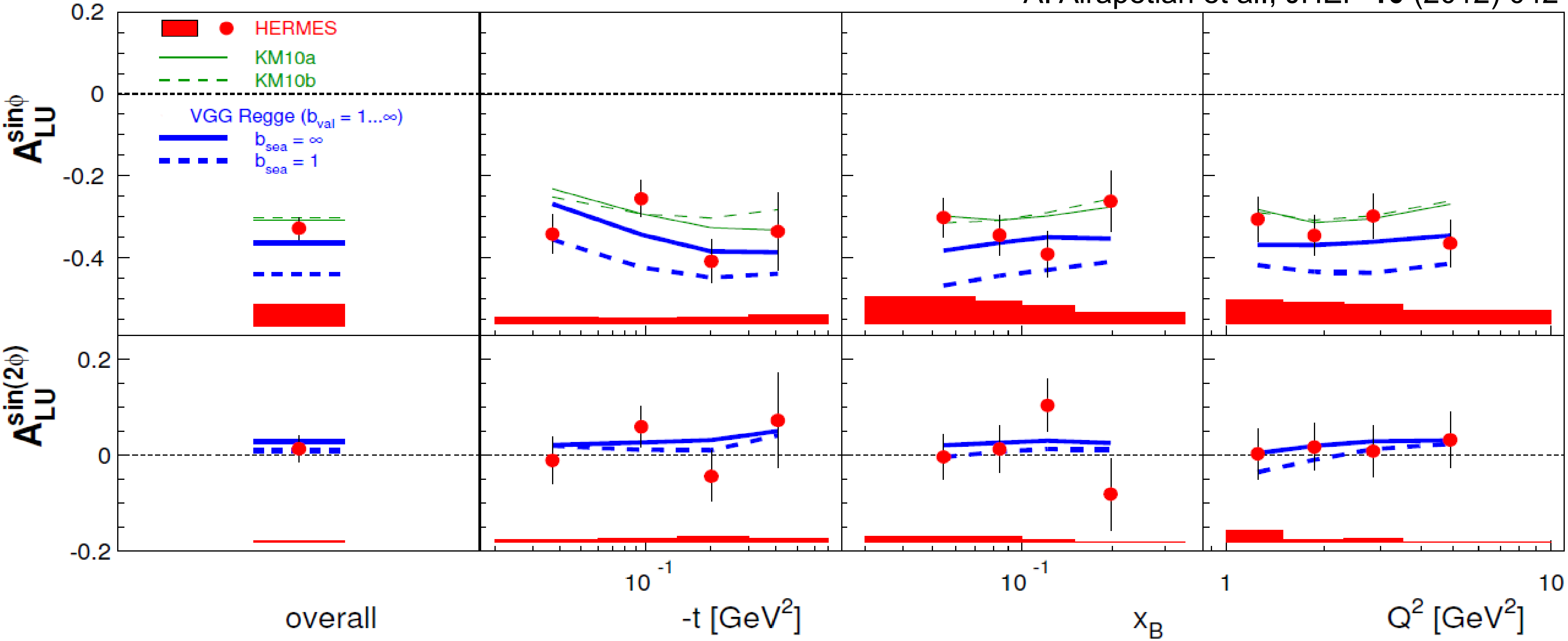


Comparison S(x) with NNPDF21



Beam-helicity asymmetry

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



- additional 1.96 % scale uncertainty from beam polarization