The structure of the proton from the hermes point of view

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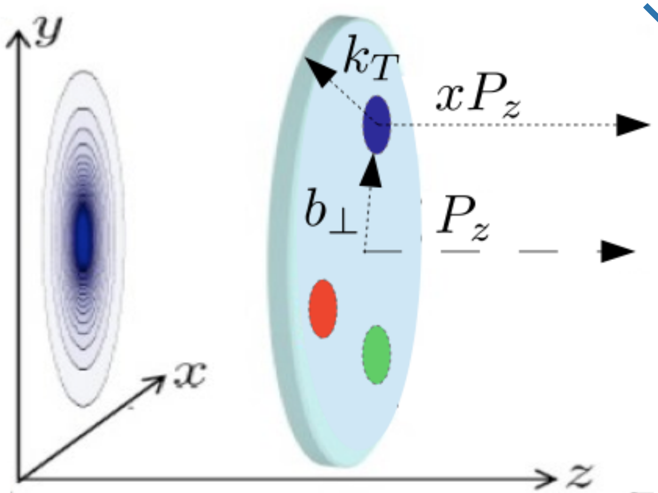
GRC - Photonuclear reactions
Holderness NH - Aug 10-15, 2014

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)

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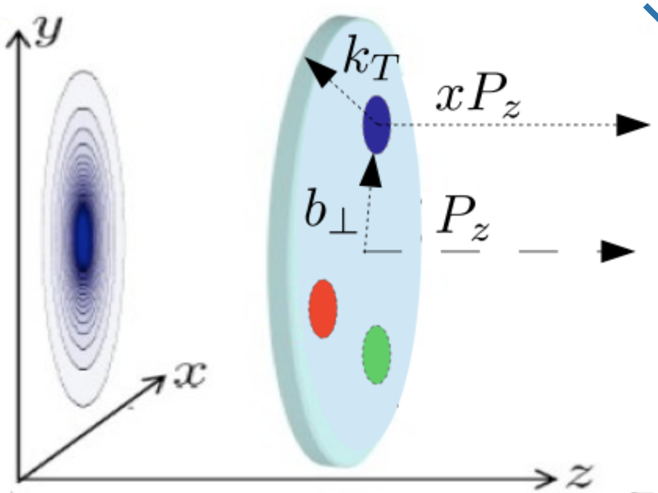

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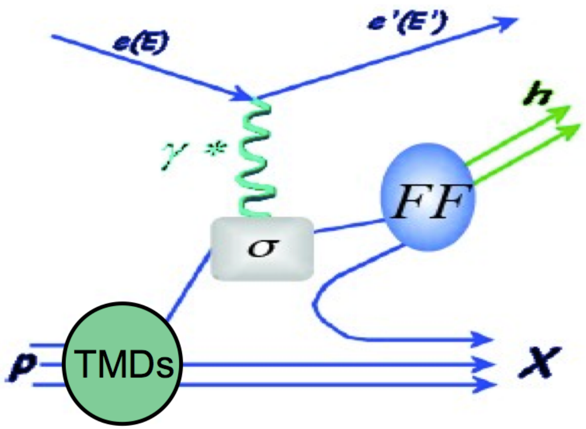
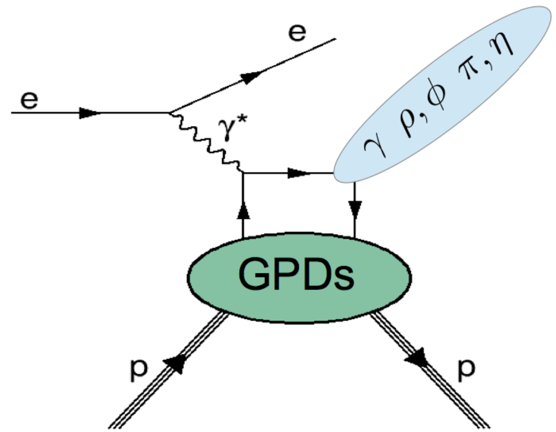
generalized parton distributions (GPDs)

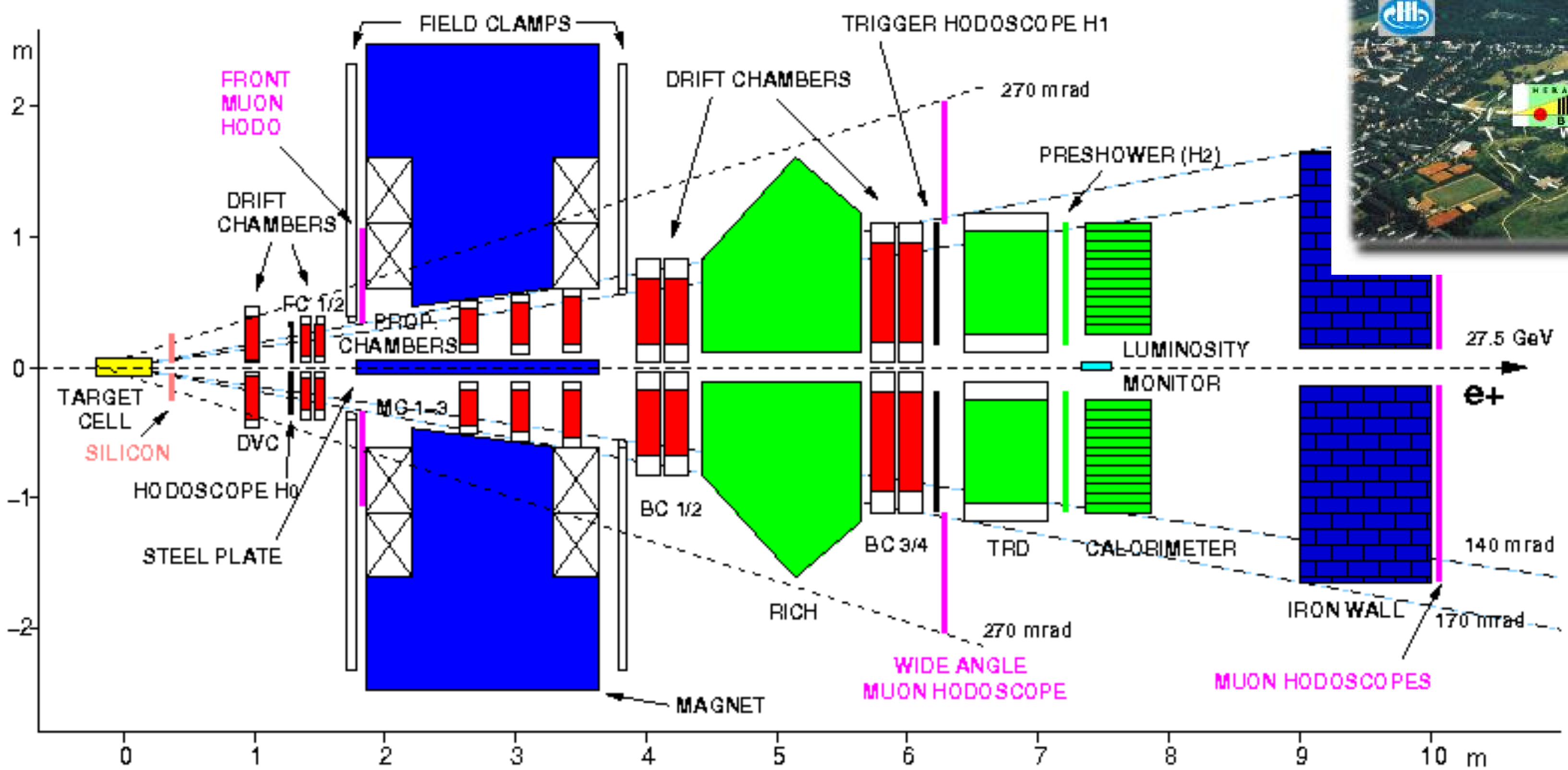
semi-inclusive deep-inelastic scattering (DIS)



hard exclusive reactions



The HERMES experiment



data taking from 1995 until 2007

Beam

longitudinally polarised e+ & e-

E=27.6 GeV

Gaseous internal target

transversely polarised H

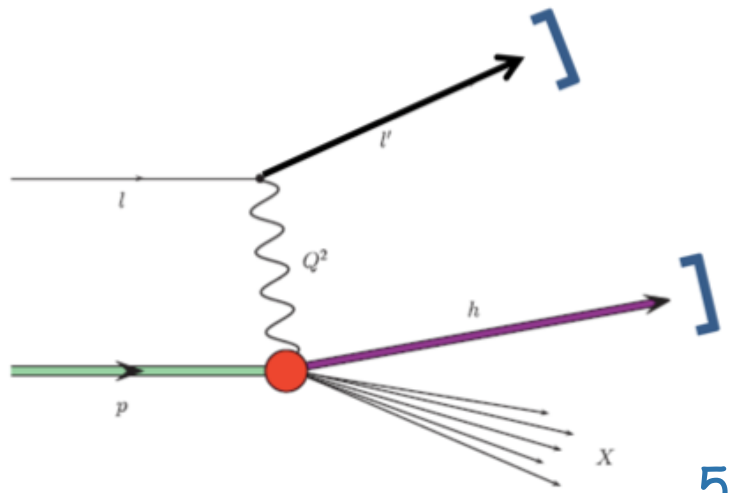
longitudinally polarised H,De,He

unpolarised H,De,He,Ne,Kr,Xe

Particle identification

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

Semi-inclusive DIS



Semi-inclusive DIS cross section

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

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

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

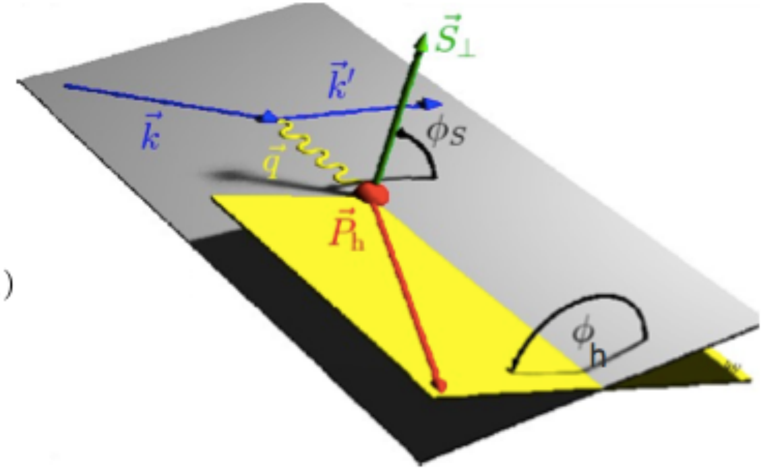
$$+S_T\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

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

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

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

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



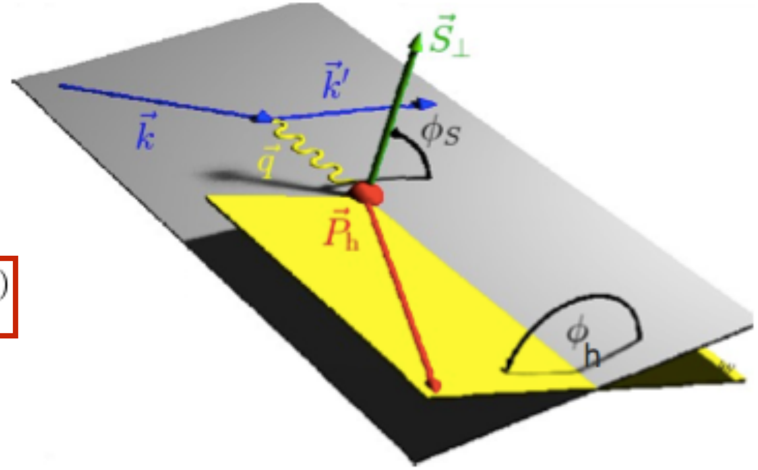
target polarization

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

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

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

longitudinal target polarization

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

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

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

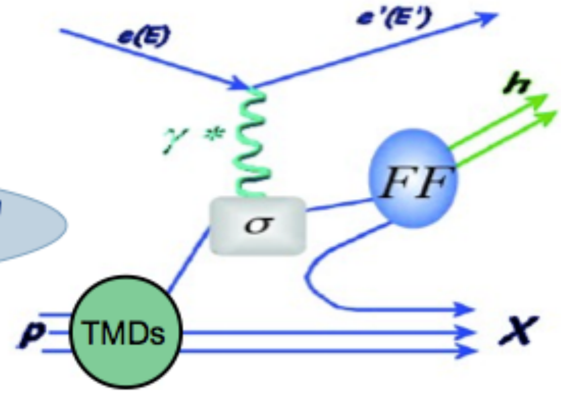
beam polarization

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

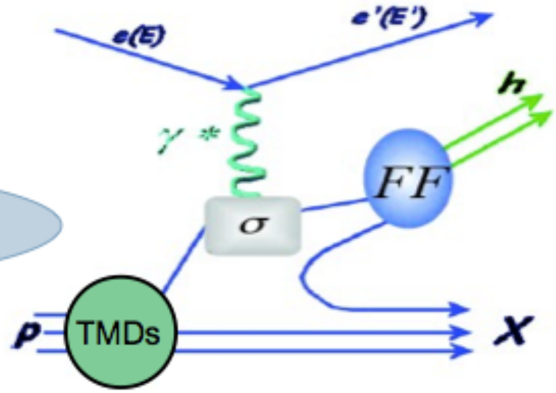
nucleon with transverse/longitudinal spin

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	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		$H_1^\perp$

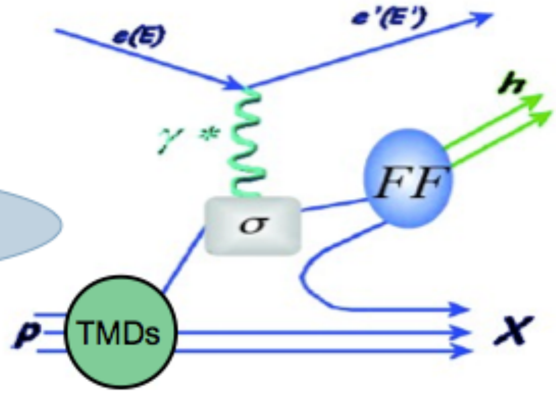
nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Semi-inclusive DIS cross section

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



spin-independent DF

Sivers DF

transverse momentum distributions (TMDs)

nucleon \ quark	U	L	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 FF

fragmentation functions (FFs)

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

nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Hadron multiplicities

unpolarized target

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

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

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

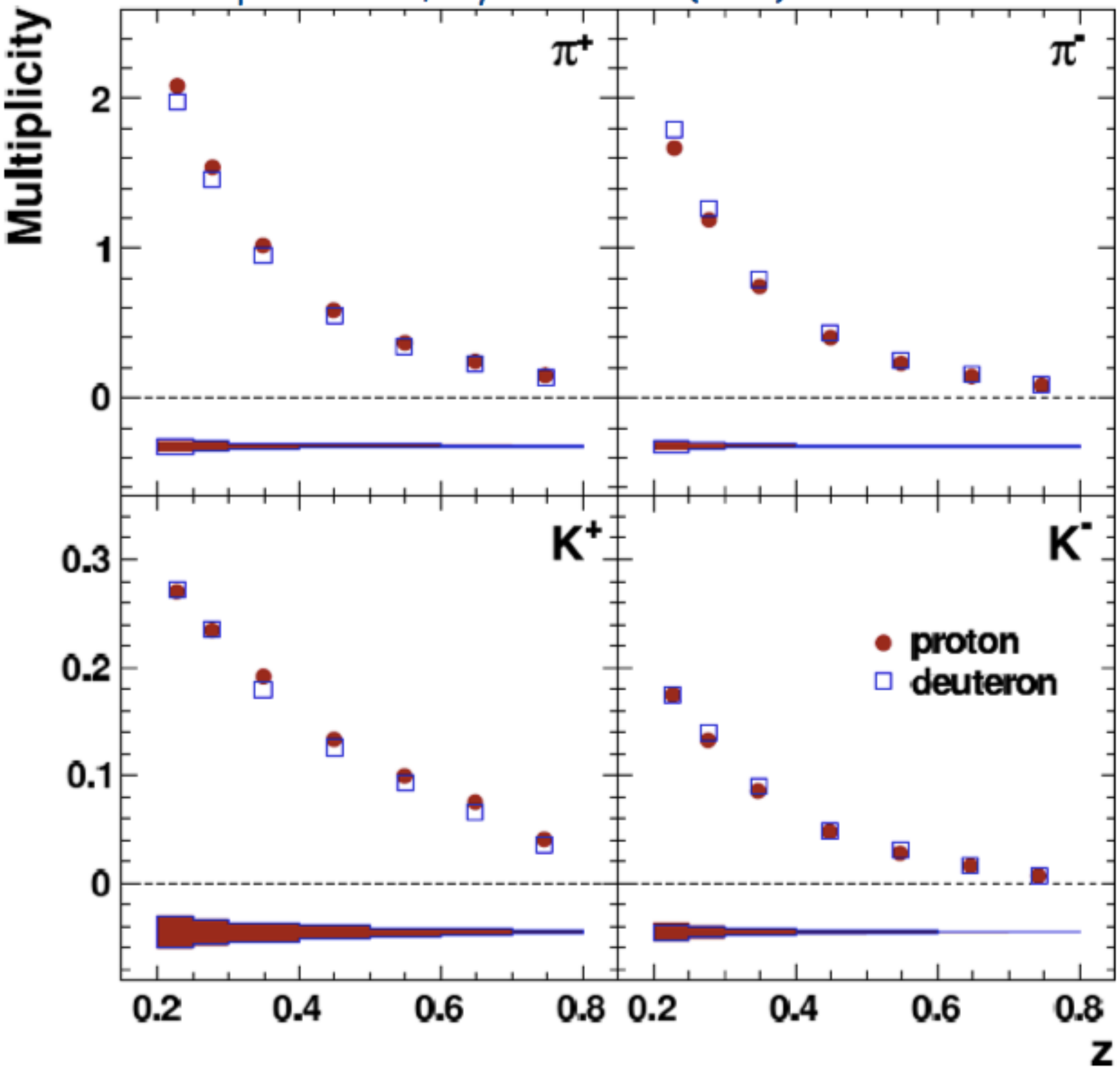
$$\propto \frac{\sum_q e_q^2\, f_1^q(x_B, k_T^2, Q^2) \otimes D_1^q(z, p_T^2, Q^2)}{\sum_q e_q^2\, f_1^q(x_B, Q^2)}$$

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

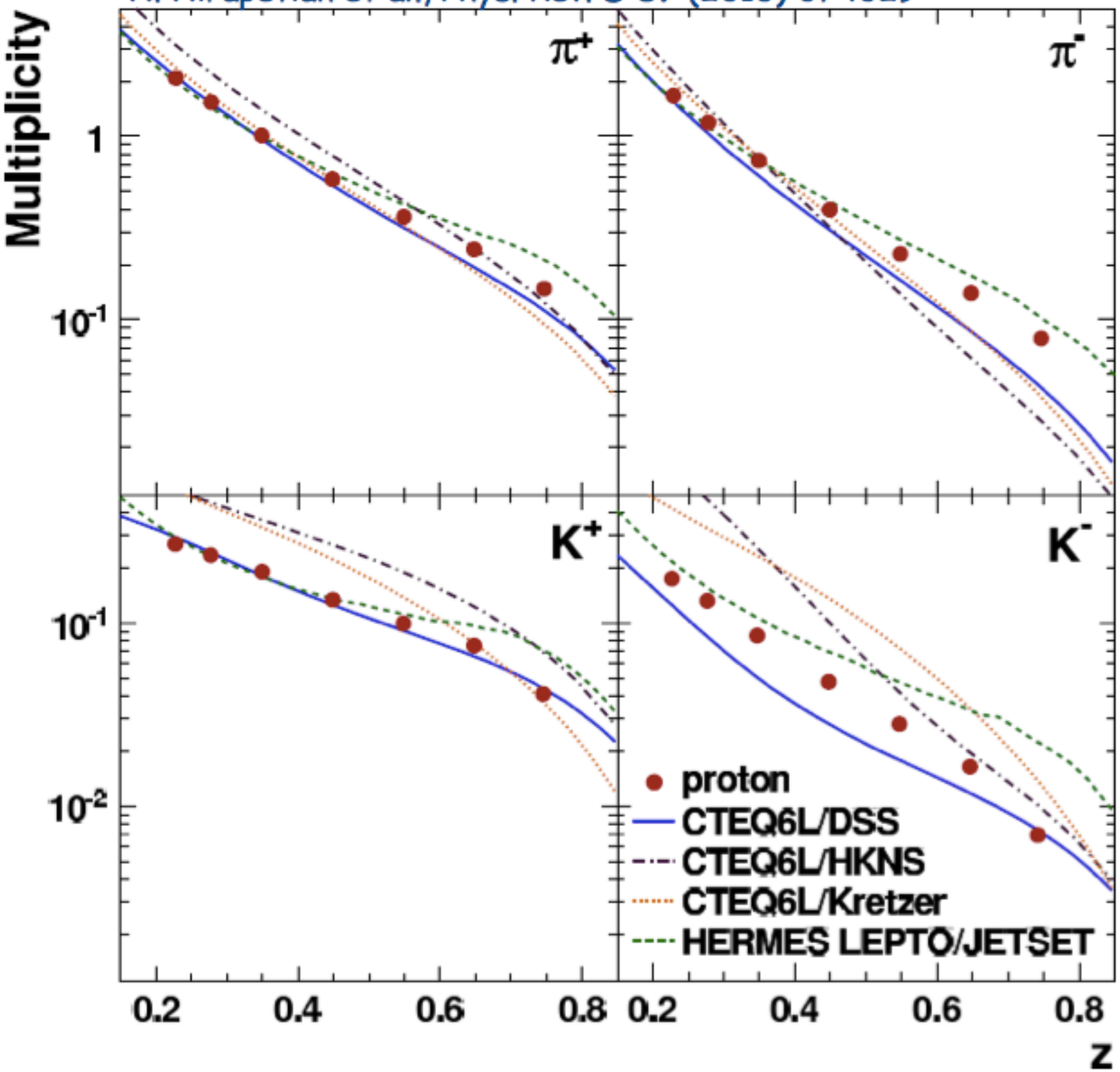


multiplicities reflect

- nucleon valence-quark content
- favored ↔ unfavored fragmentation

Comparison to models

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

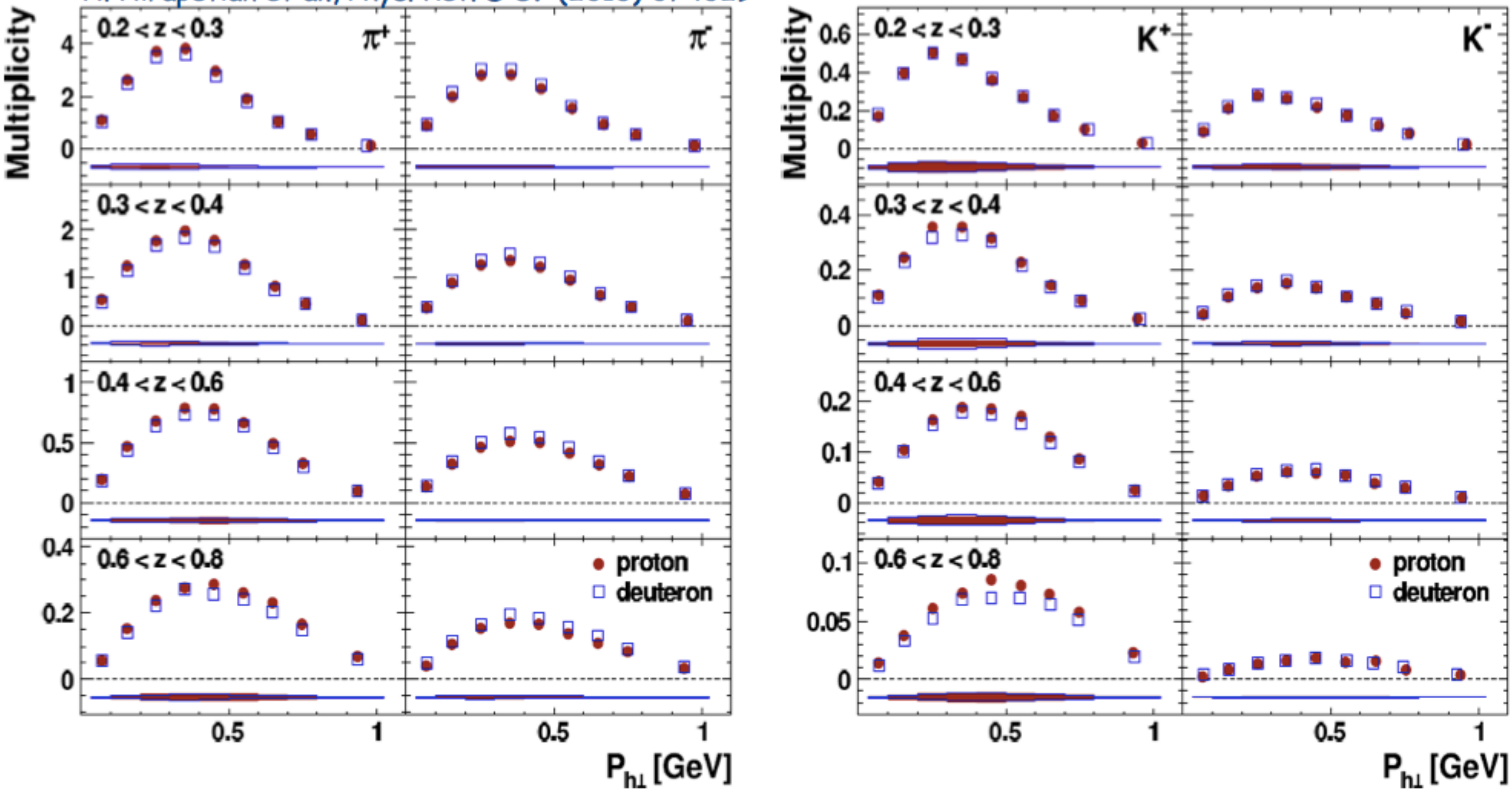


- leading order in α_S
- CTEQ6L PDFs
  JHEP **0207** (2002) 012
- DSS FFs
  Phys. Rev. D **75** (2007) 114010
- Kretzer FFs
  Phys. Fev. D **62** (2000) 054001

- reasonable agreement between DSS and positive mesons
- poor agreement for negative mesons

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

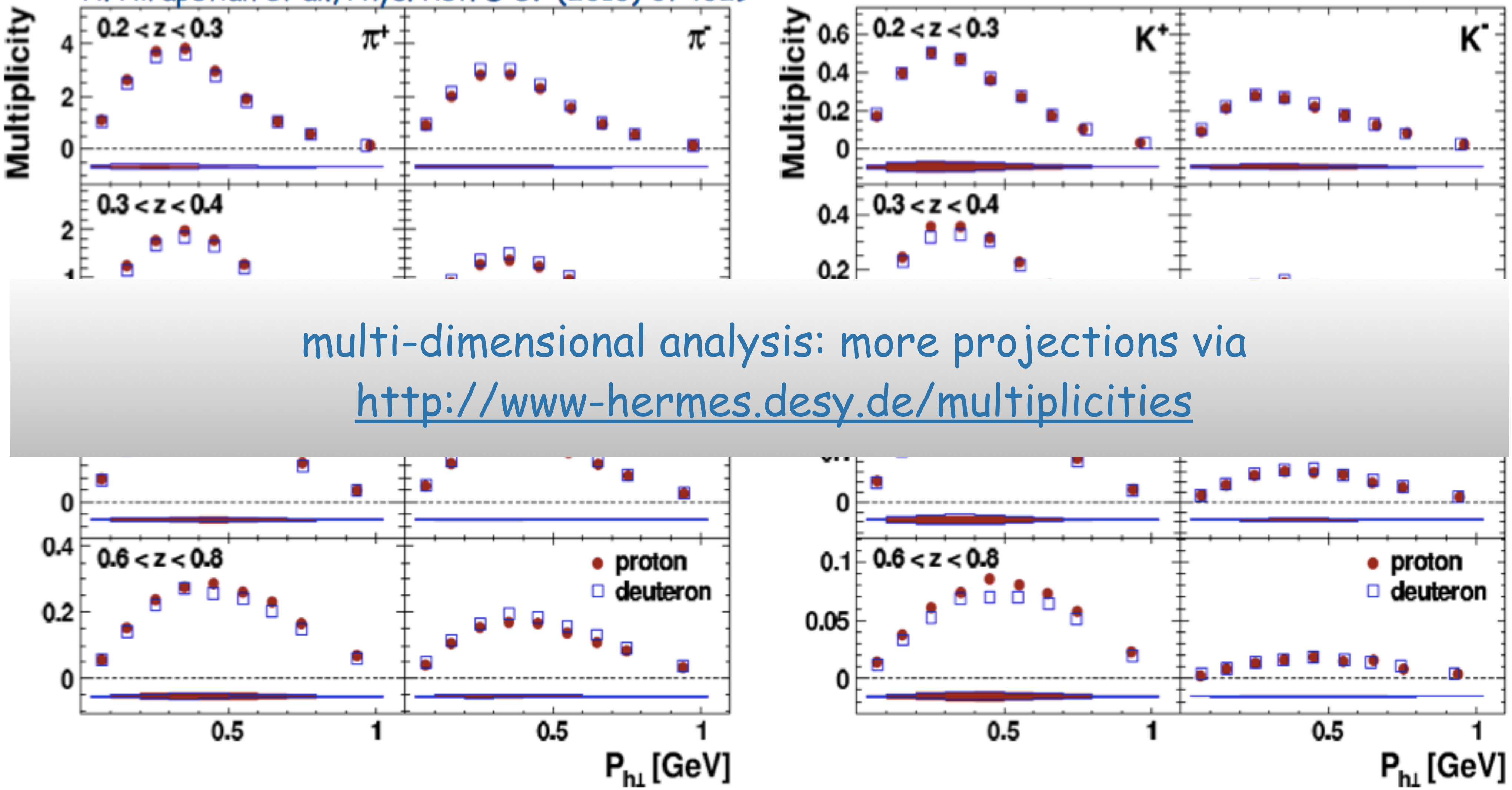
A. Airapetian et al., Phys. Rev. D **87** (2013) 074029



- $P_{h\perp}$ distribution reflects transverse intrinsic struck-quark momentum & transverse momentum acquired in fragmentation process
- K^- displays broader distribution

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

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



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

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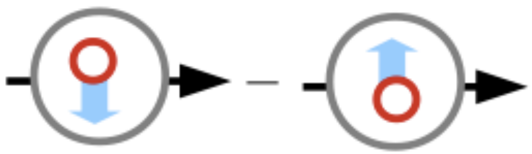
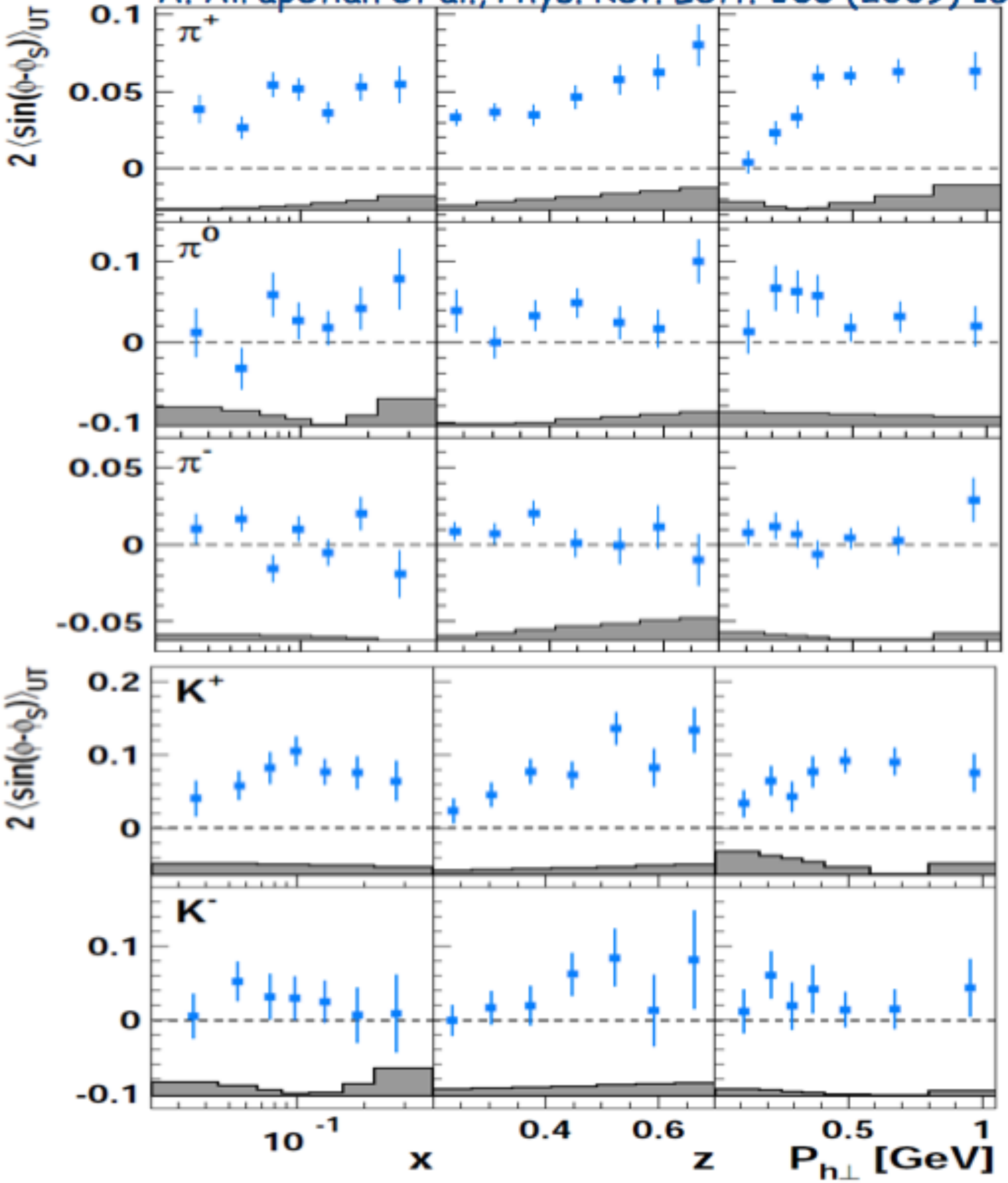


Sivers amplitude

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

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



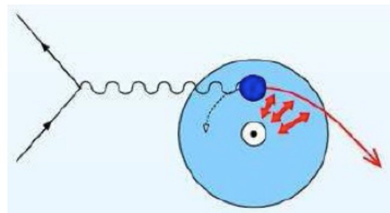
- π^+ significantly positive

  $\longrightarrow$ orbital angular momentum

- u-quark dominance for π^+ amplitude

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

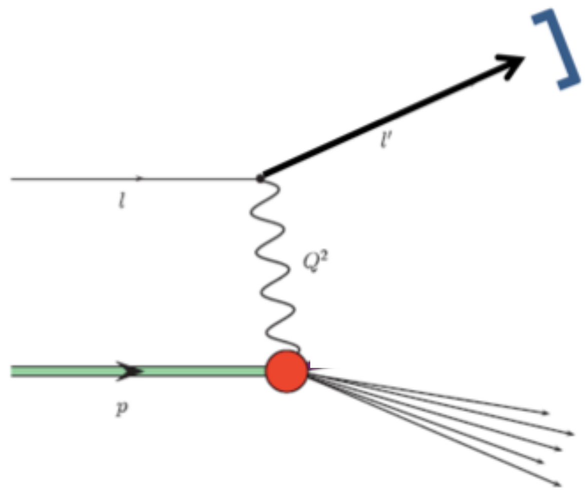
$$\longrightarrow f_{1T}^{\perp,u}(x,k_T^2) < 0$$



- π^-: u- and d-quark cancelation

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

A_{LT} inclusive DIS



Structure function g_2

transversely polarized target

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

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

transversely polarized target

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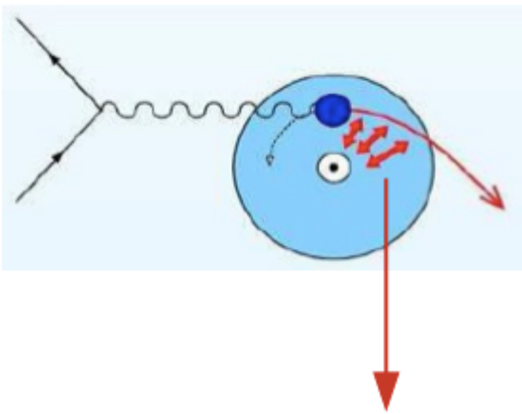
- $g_2(x) = g_2^{WW} + \bar{g}_2(x)$ $\qquad d_2 = 3\int_0^1 dx\, x^2\, \bar{g}_2(x)$

- Sivers effect



FSI from t=0 $\longrightarrow \infty$

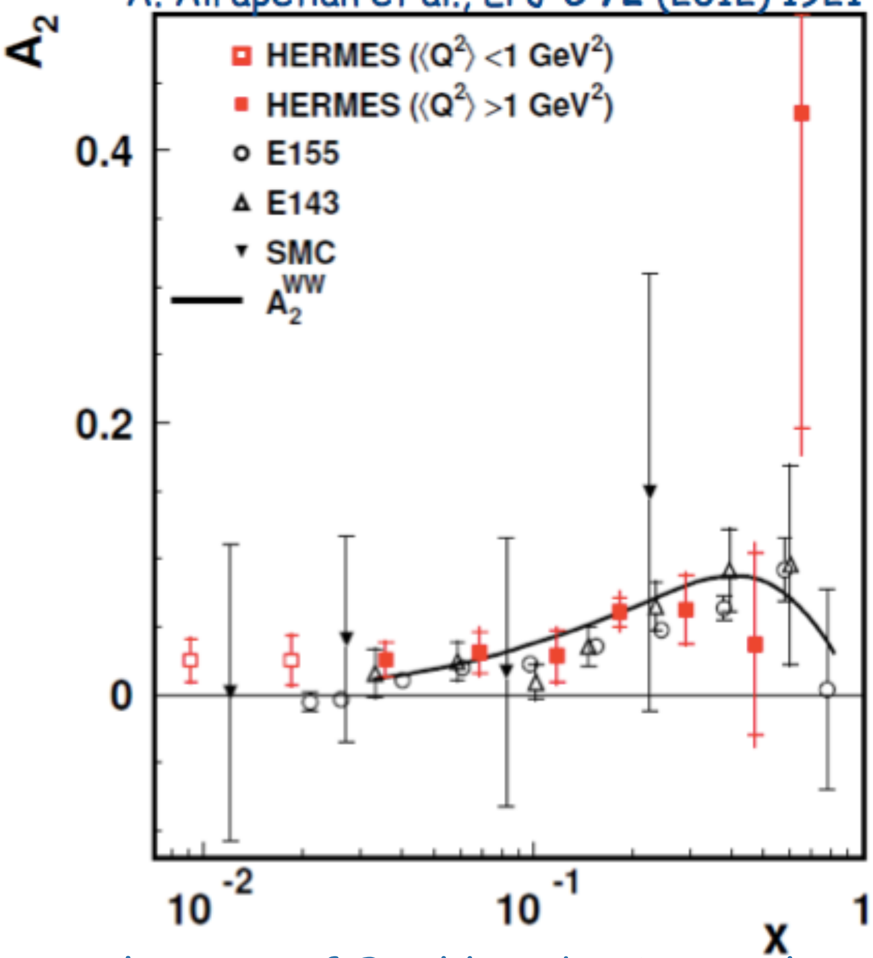
force on struck quark at t=0

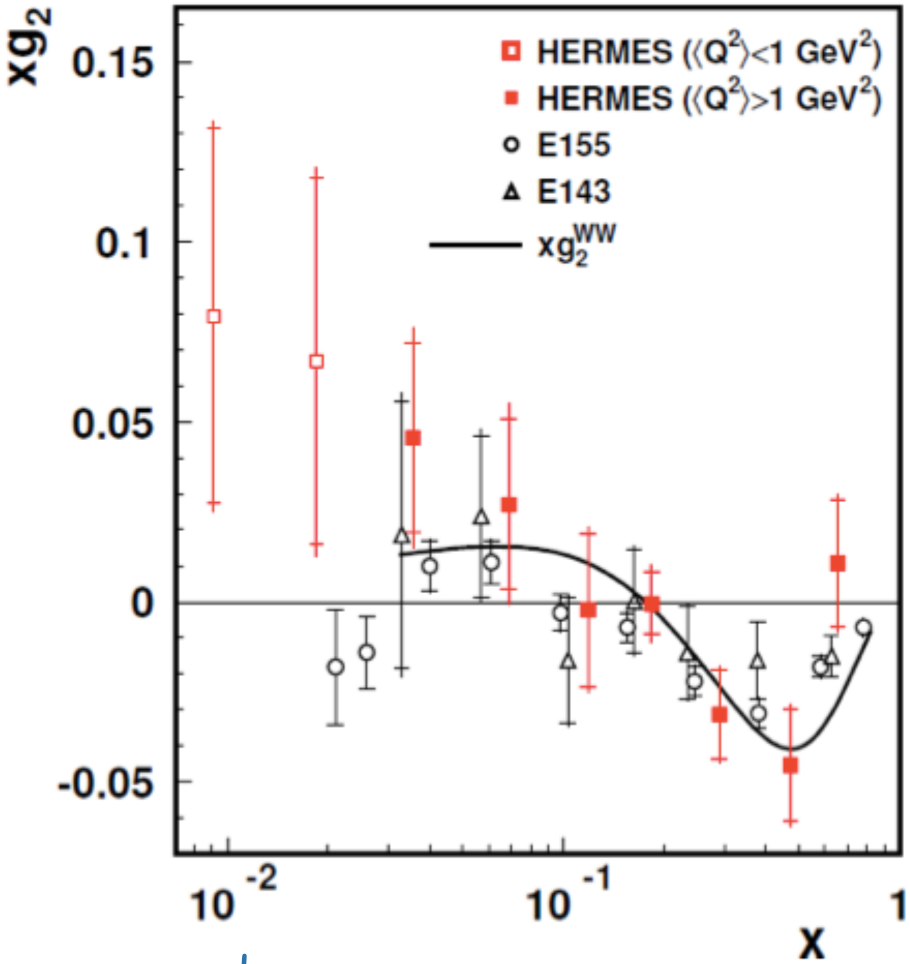
$\propto -d_2$

M. Burkardt arXiv:0810.3589

A_2 and g_2

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





- evaluation of Burkhardt-Cottingham sum rule

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

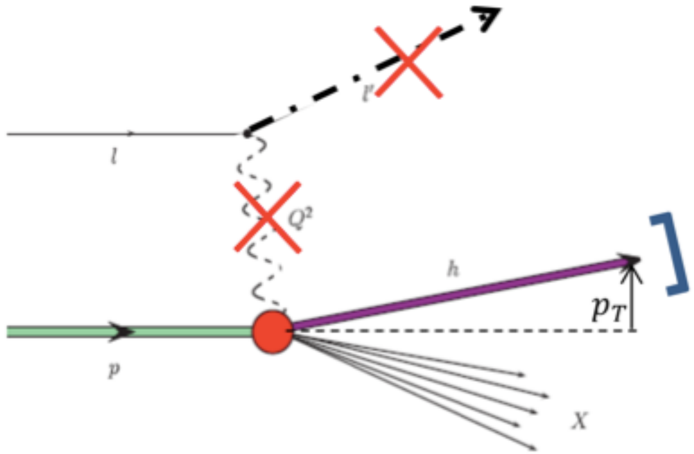
E143+E155: $\int_{0.02}^{0.8} dx\, g_2(x) = -0.042 \pm 0.008$

- d_2

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

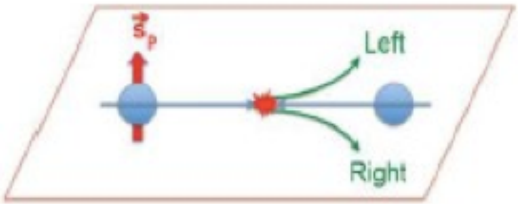
E143+E155: $d_2 = 0.0032 \pm 0.0017$

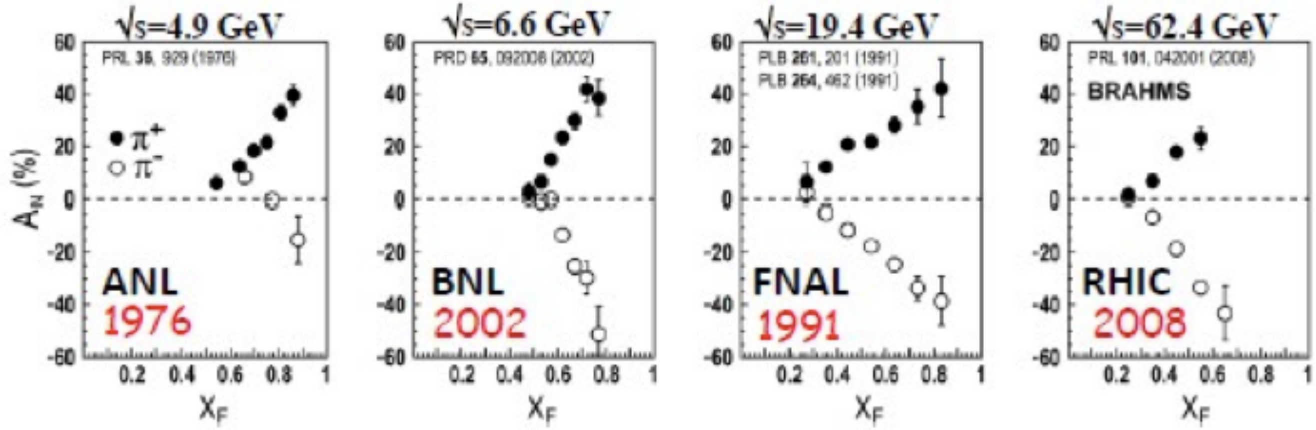
A_{UT} inclusive



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

- various polarized pp scattering experiments consistently observe since 35 years large A_N asymmetries, with $\sqrt{s}$ from 5 to 200 GeV





- not interpretable in leading-twist based on collinear factorisation

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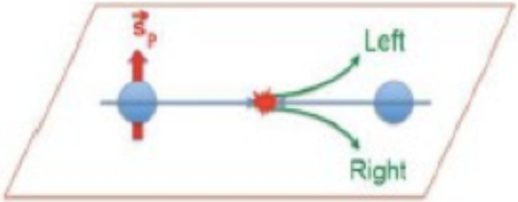
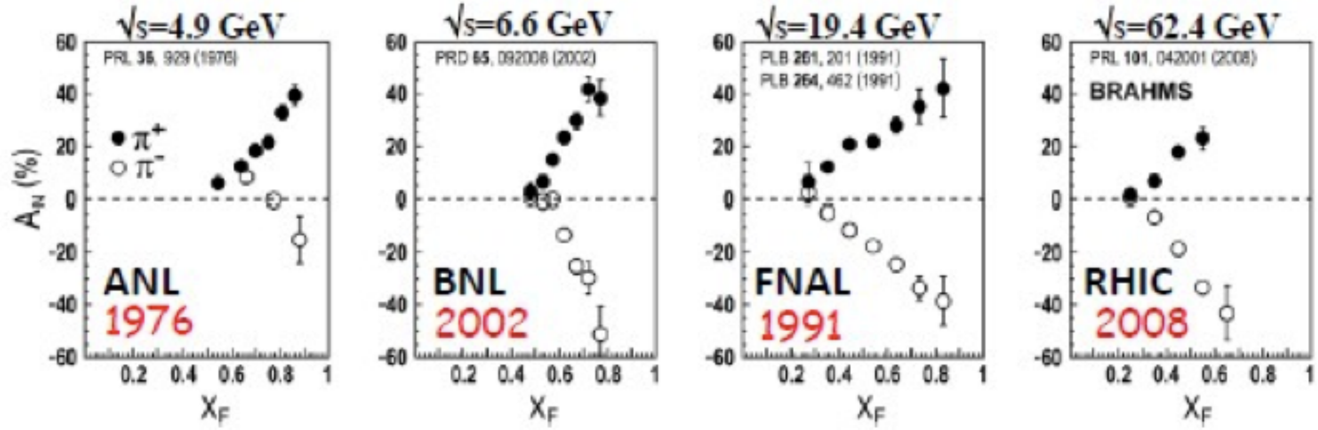
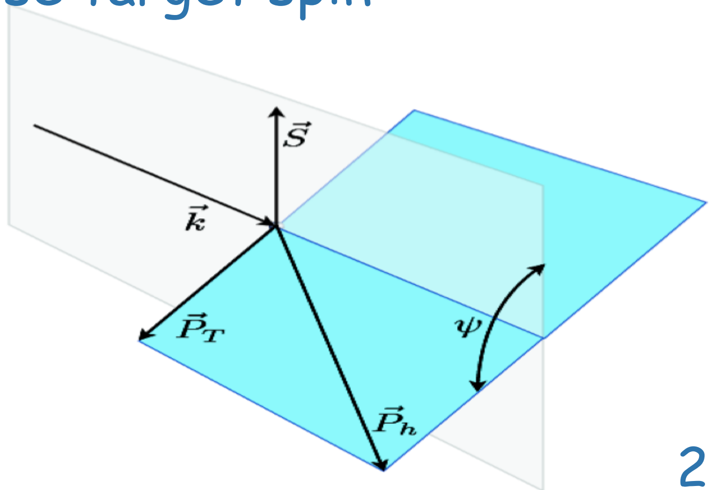




- not interpretable in leading-twist based on collinear factorisation
- HERMES measurement of inclusive transverse target spin asymmetry $A_{UT}^{\sin(\psi)}$:

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

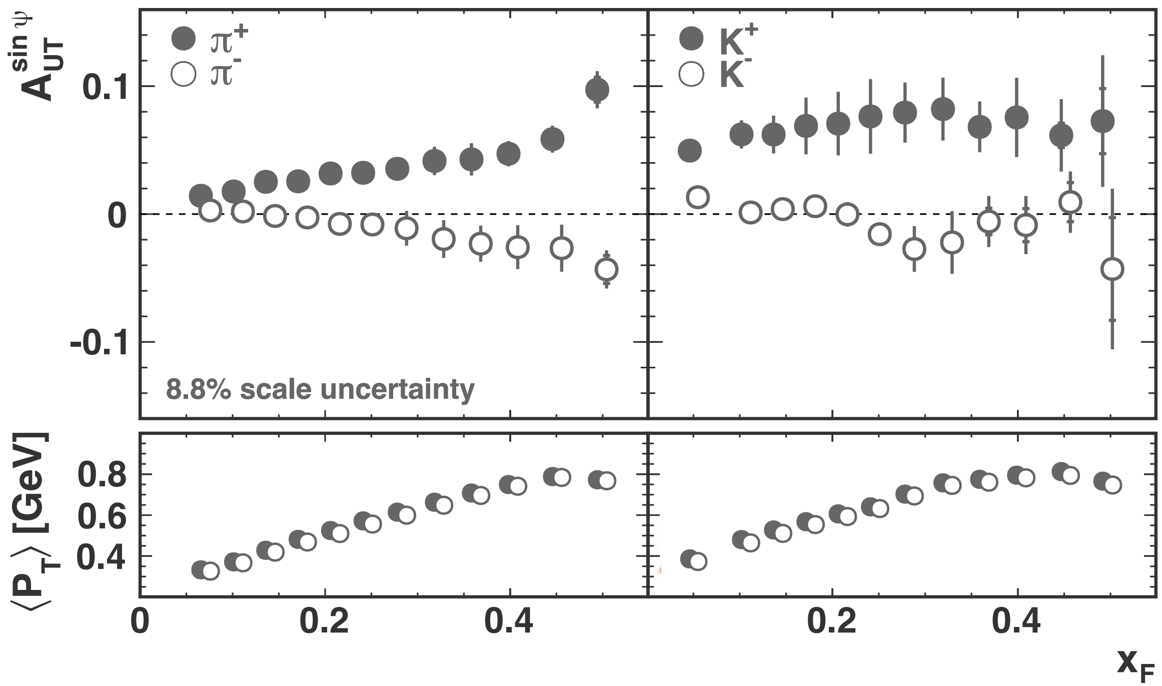
- $A_{UT}^{\sin(\psi)} = \frac{\pi}{2} A_N$
- at HERMES: $\sin(\psi) \sim \sin(\phi - \phi_S)$



Results: x_F dependence

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

A. Airapetian et al, Phys. Lett. B **728** (2014) 183-190



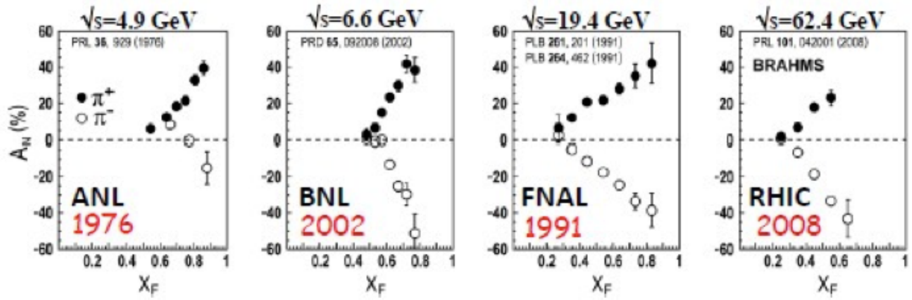
π^+

- 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^+

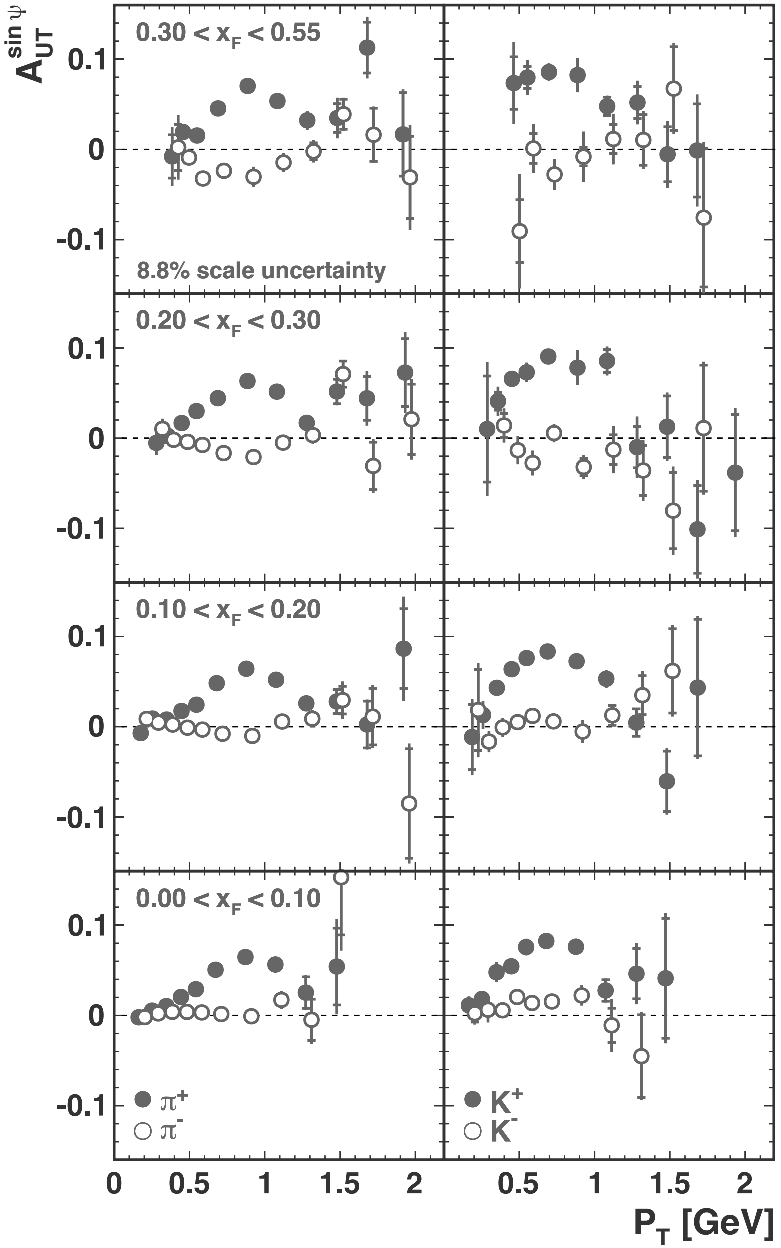
- positive, ~constant with x_F

K^-

- compatible with zero, with small variations over x_F

Results: disentangle x_F and P_T dependence

A. Airapetian et al, Phys. Lett. B **728** (2014) 183-190



π^+

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

$\rightarrow$ x_F increase from P_T dependence

π^-

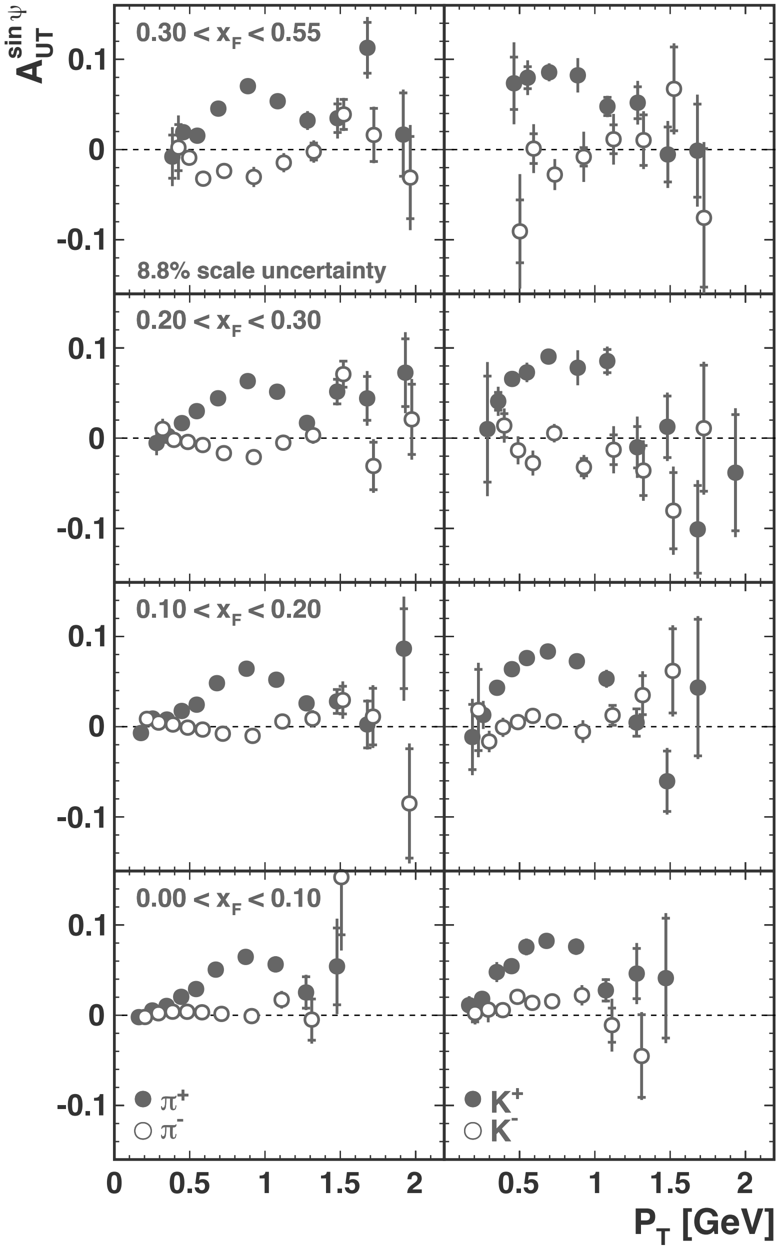
- small amplitudes,

  varyingly positive and negative with P_T

- decrease with increasing x_F

Results: disentangle x_F and P_T dependence

A. Airapetian et al, Phys. Lett. B **728** (2014) 183-190



K^+

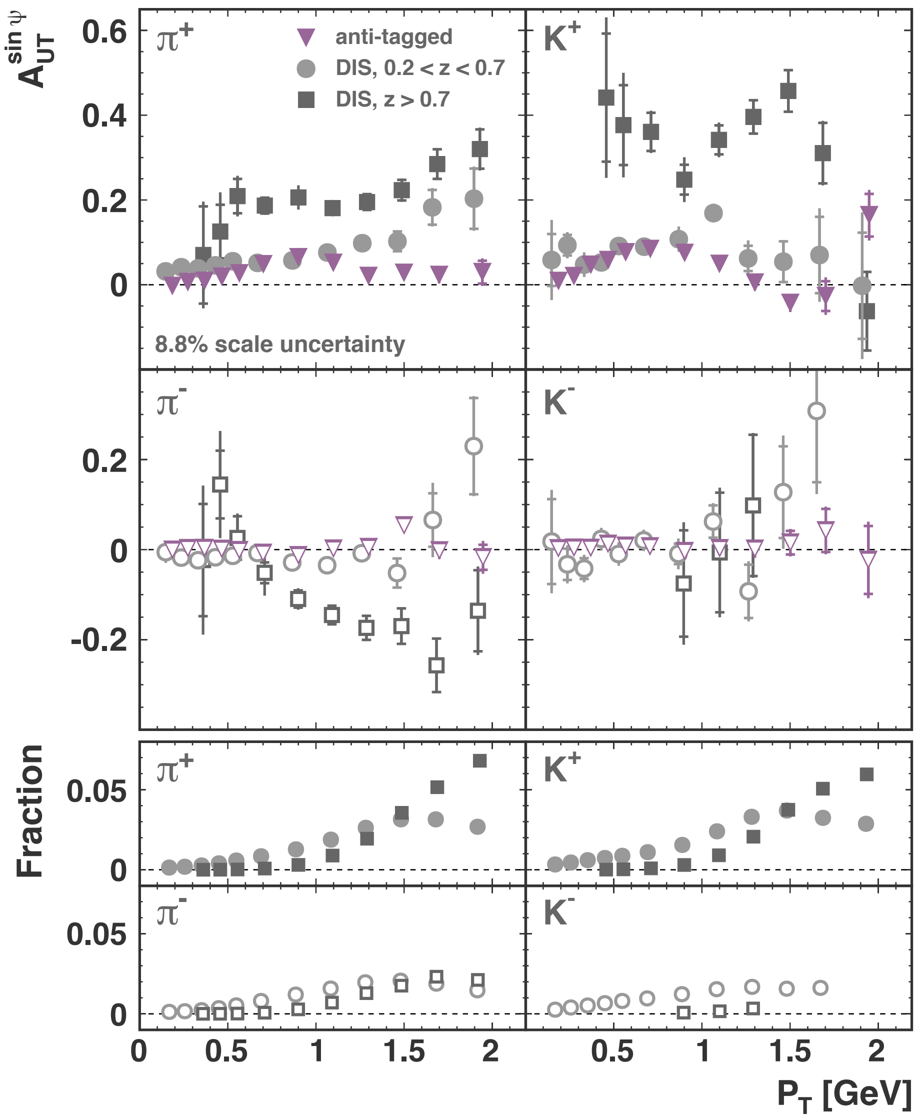
- increase with P_T up to $P_T \approx 0.8$ GeV
- increase with increasing x_F

K^-

- small amplitudes
- decrease with increasing x_F

Contribution of various subsamples

A. Airapetian et al, Phys. Lett. B **728** (2014) 183-190



3 subsamples:

- anti-tagged: no $e^{\pm}$ detected (mostly $Q^2 \approx 0$)
- DIS with 0.2<z<0.7
- DIS with z>0.7

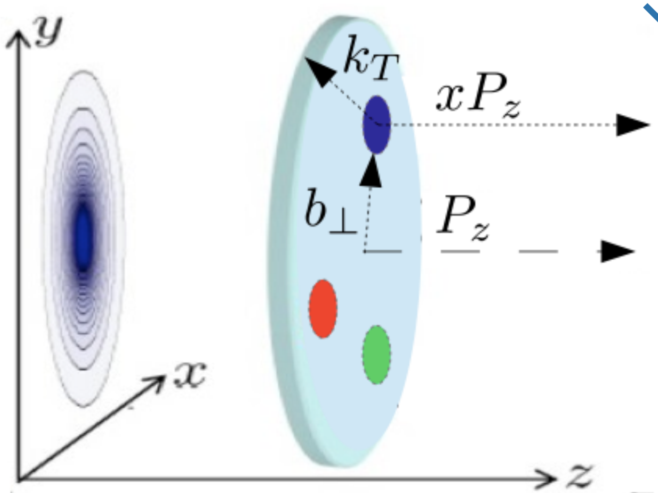
- anti-tagged results ~ overall results, majority of statistics
- 0.2<z<0.7 results: similar to Sivers amplitudes
- z>0.7 results: large asymmetries

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)



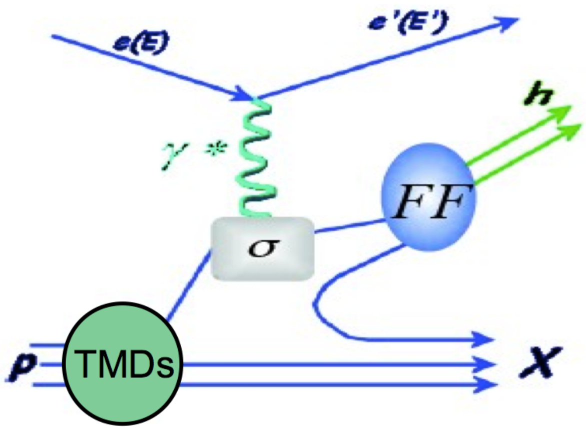
$\int d^2\vec{k}_T$

impact-parameter distributions

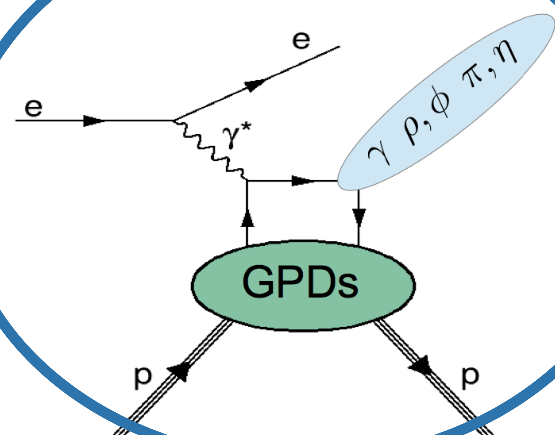
Fourier transform

generalized parton distributions (GPDs)

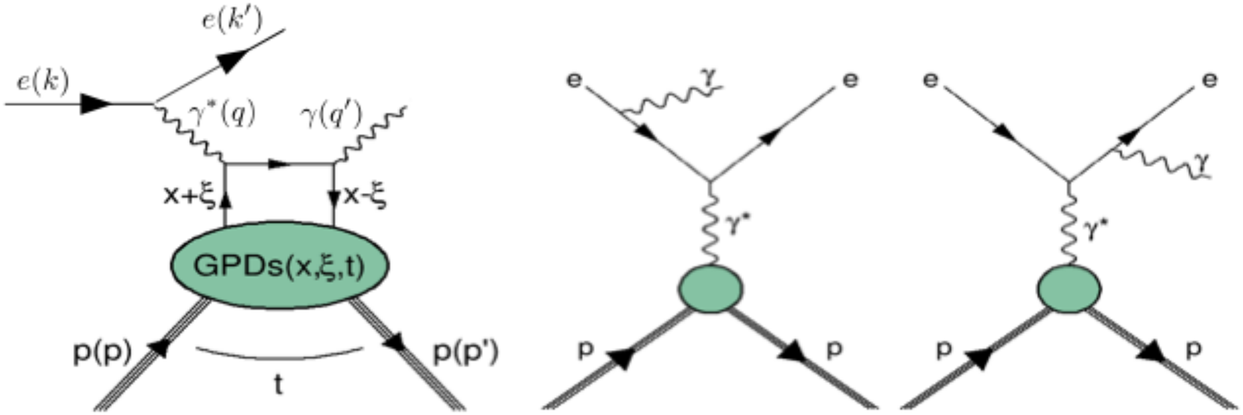
semi-inclusive deep-inelastic scattering (DIS)



hard exclusive reactions



Exclusive production of real photons

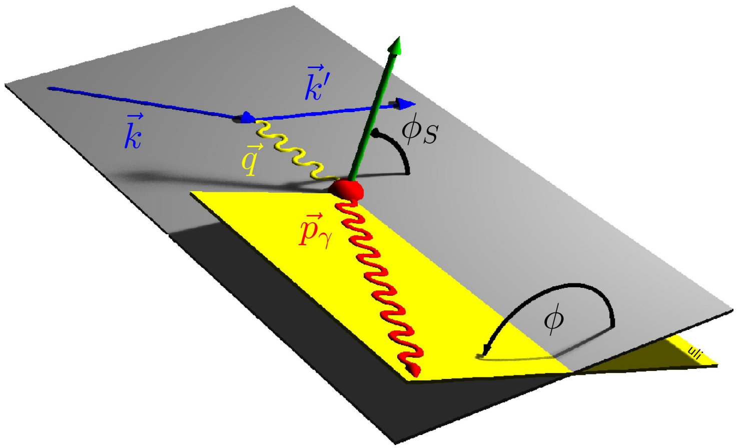


DVCS

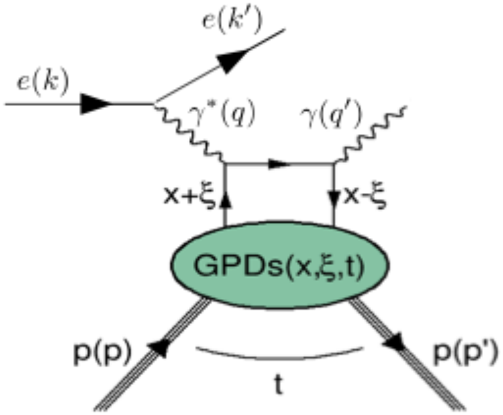
Bethe-Heitler

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

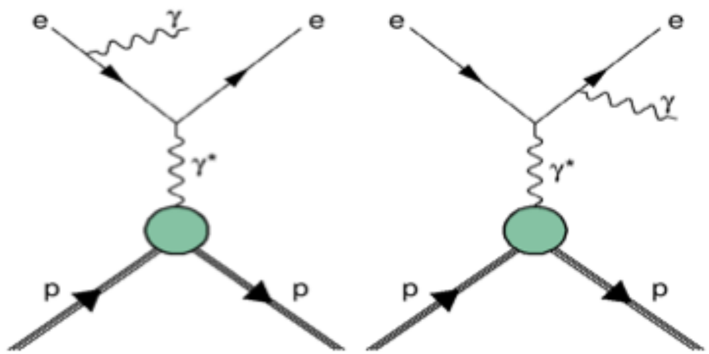
access through azimuthal asymmetries



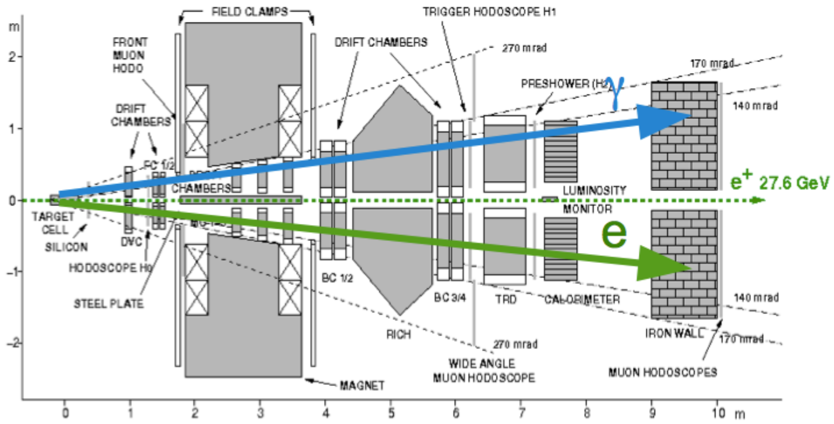
Exclusive production of real photons



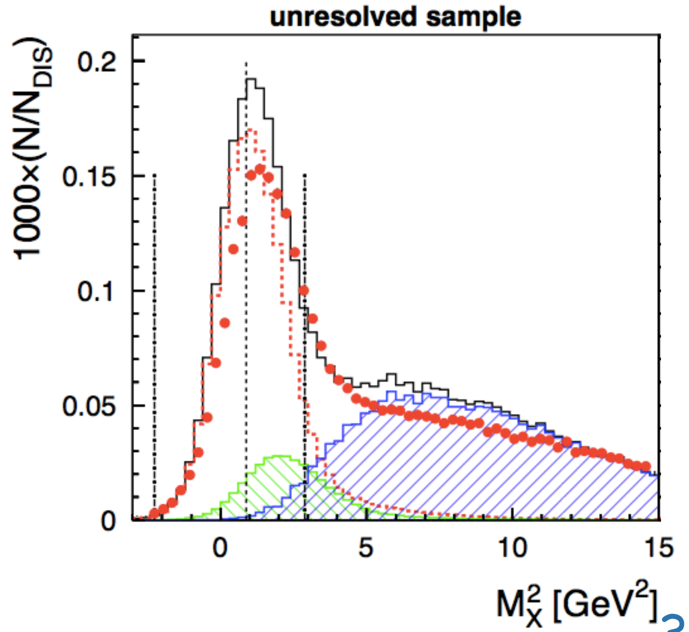
DVCS



Bethe-Heitler

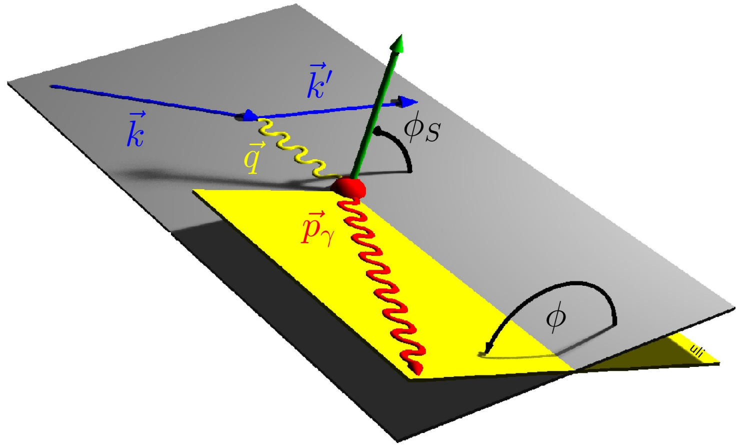


exclusivity: reconstruct proton via missing mass:

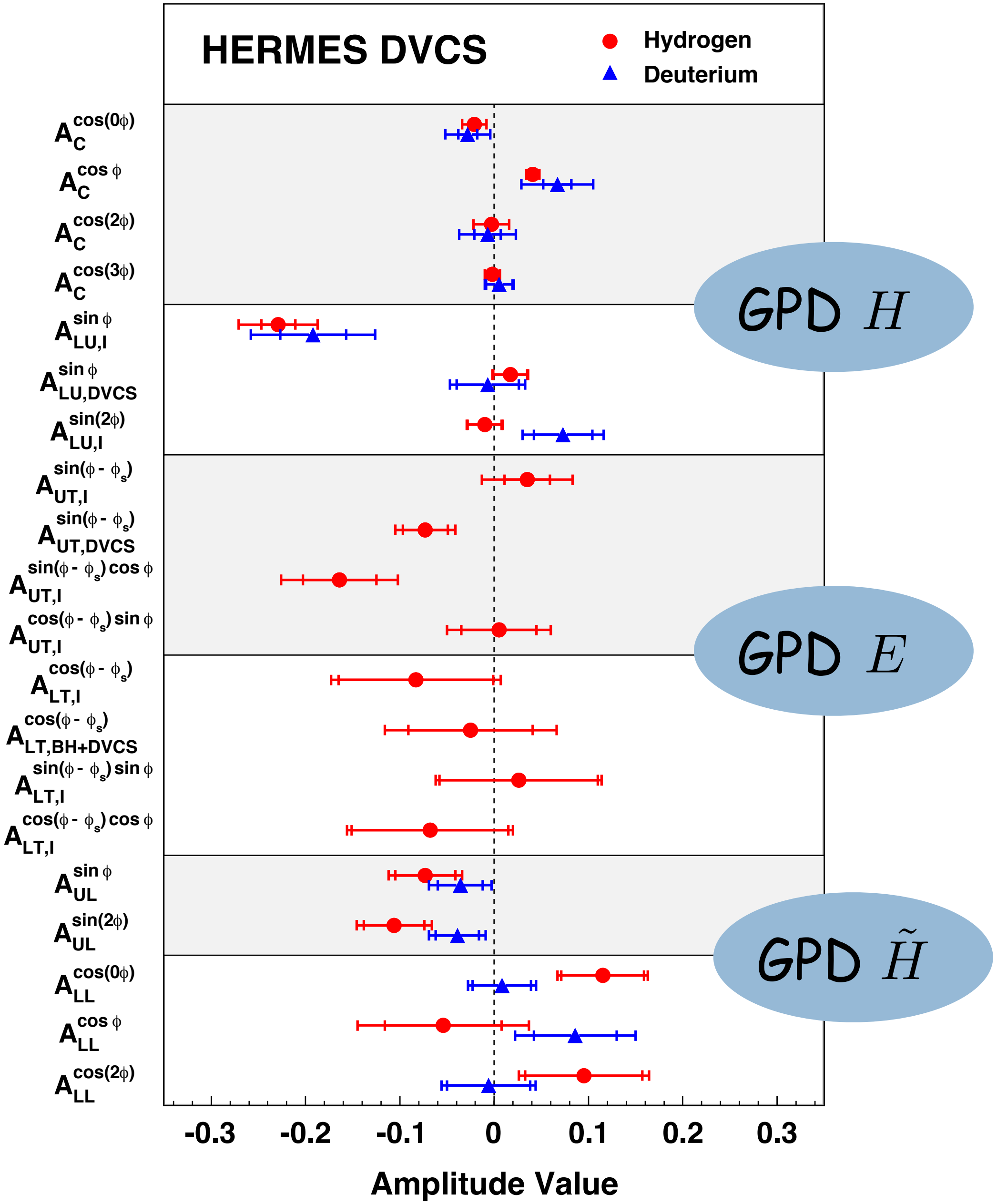


$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{BH}\tau^*_{DVCS} + \tau_{DVCS}\tau^*_{BH}$$

access through azimuthal asymmetries



DVCS at HERMES



beam-charge asymmetry

JHEP **07** (2012) 32

Nucl. Phys. B **829** (2010) 1

beam-helicity asymmetry

JHEP **07** (2012) 32

Nucl. Phys. B **829** (2010) 1

transverse target-spin asymmetry

JHEP **06** (2008) 066

double spin (LT) asymmetry

Phys. Lett. B **704** (2011) 15

longitudinal target-spin asymmetry

JHEP **06** (2010) 019

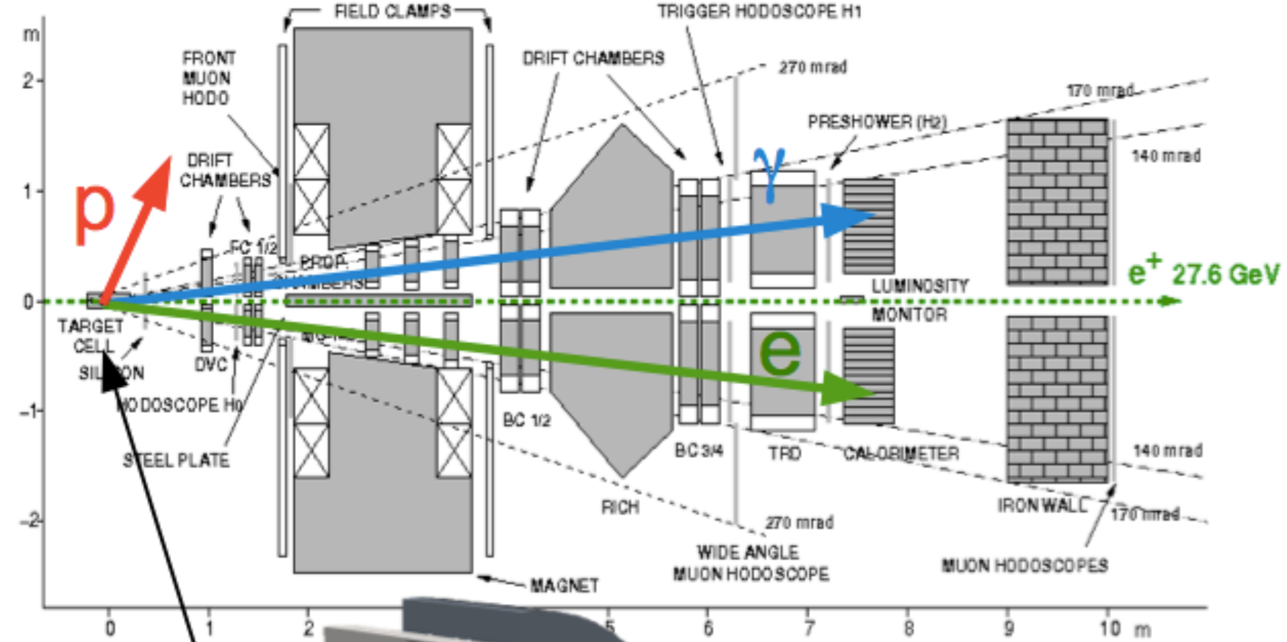
Nucl. Phys. B **842** (2011) 265

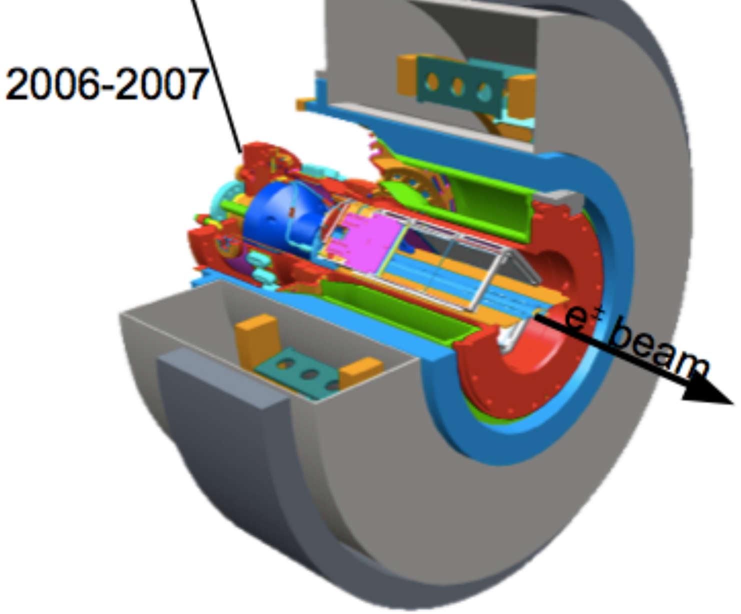
double spin (LL) asymmetry

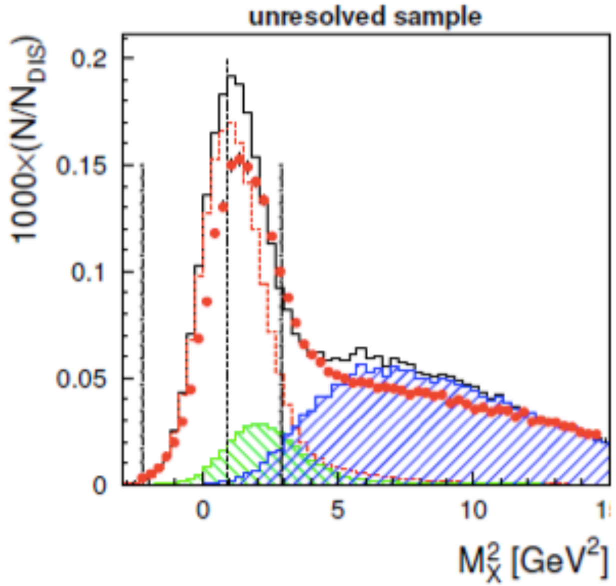
JHEP **06** (2010) 019

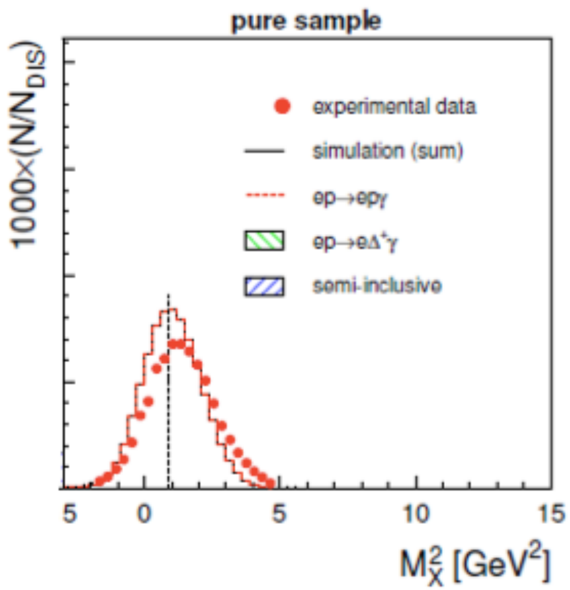
Nucl. Phys. B **842** (2011) 265

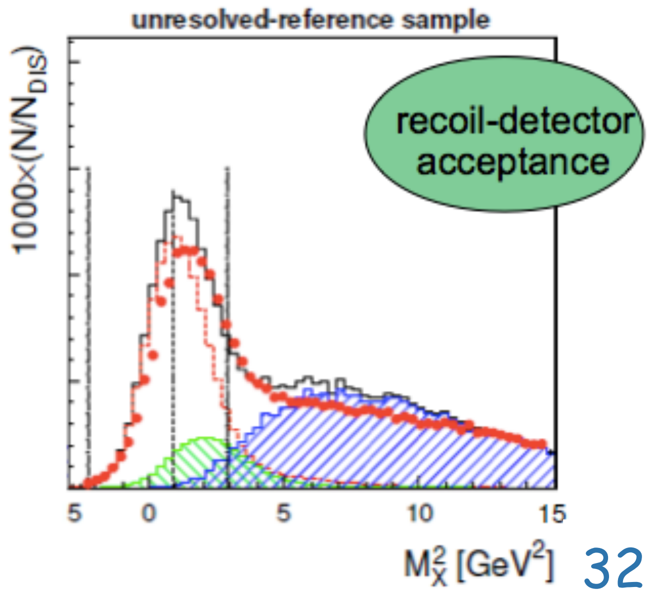
DVCS/BH complete event reconstruction





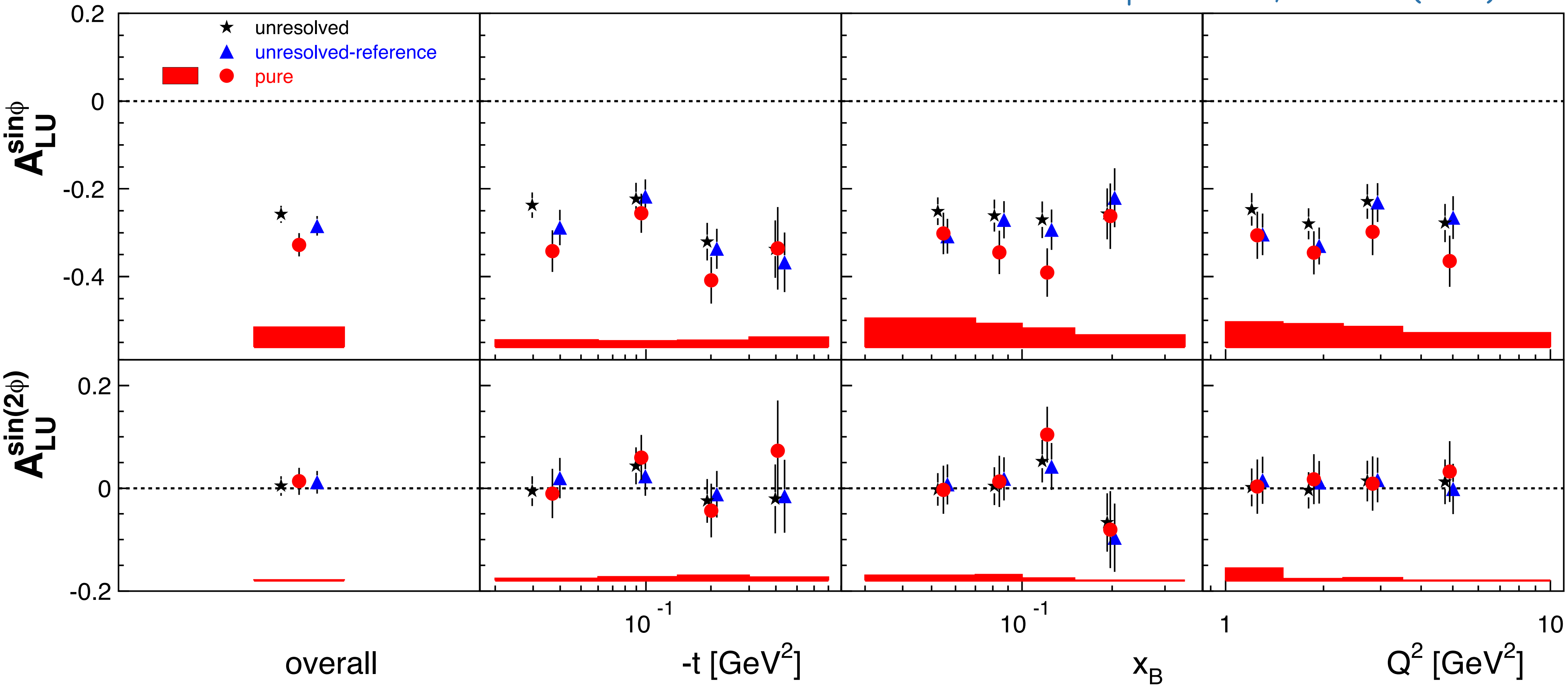






Beam-helicity asymmetry

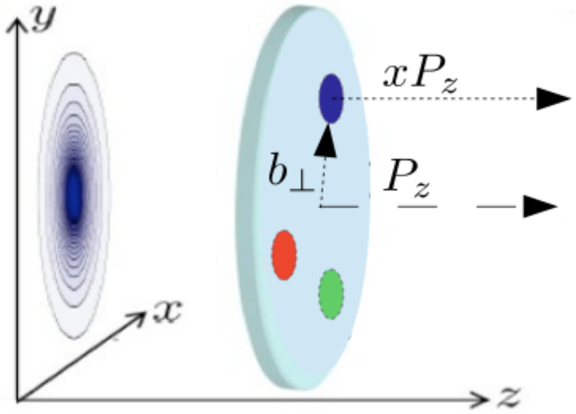
A. Airapetian et al, JHEP **10** (2012) 042

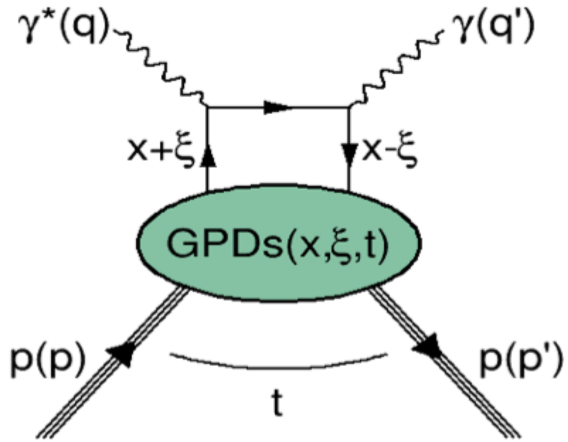


- additional 1.96% scale uncertainty from beam polarization
- leading asymmetry from pure sample is larger

Beam-helicity asymmetry in ep→eγπN in Δ-resonance region

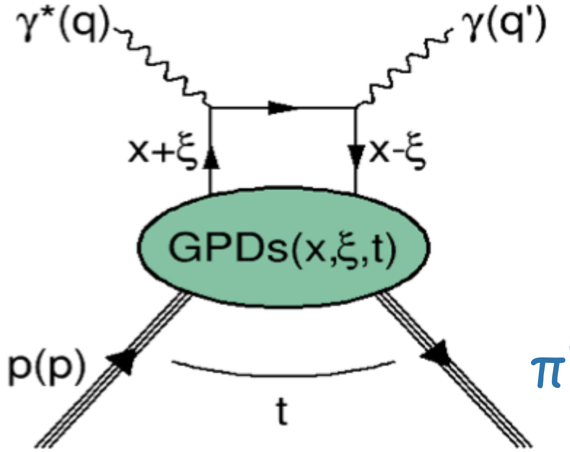
GPDs: quark distribution in longitudinal-momentum and transverse-position space





DVCS

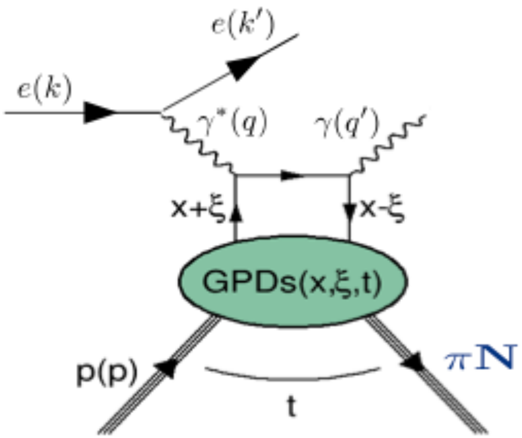
transition GPDs p→πN



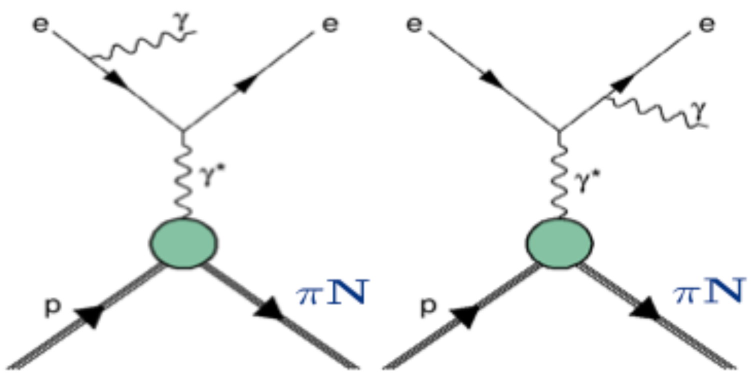
$\pi N \begin{cases} \pi^0 p \\ \pi^+ n \end{cases}$

associated DVCS

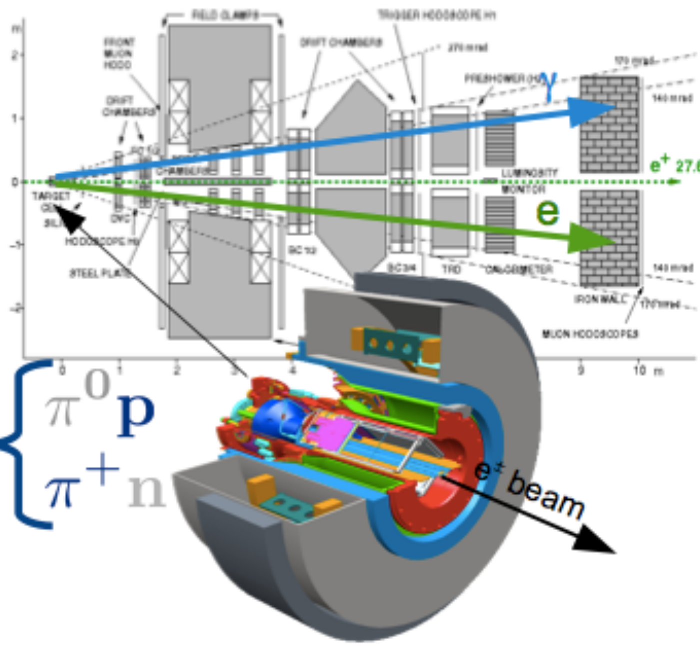
Beam-helicity asymmetry in ep→eγπN in Δ-resonance region



associated DVCS

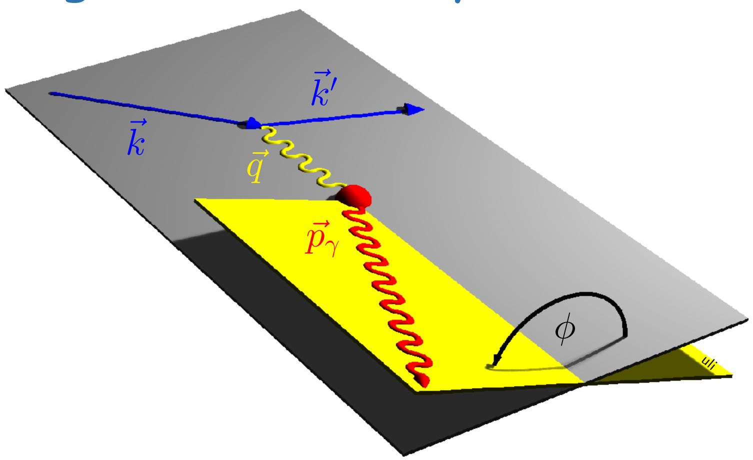


associated Bethe-Heitler



recoil detector

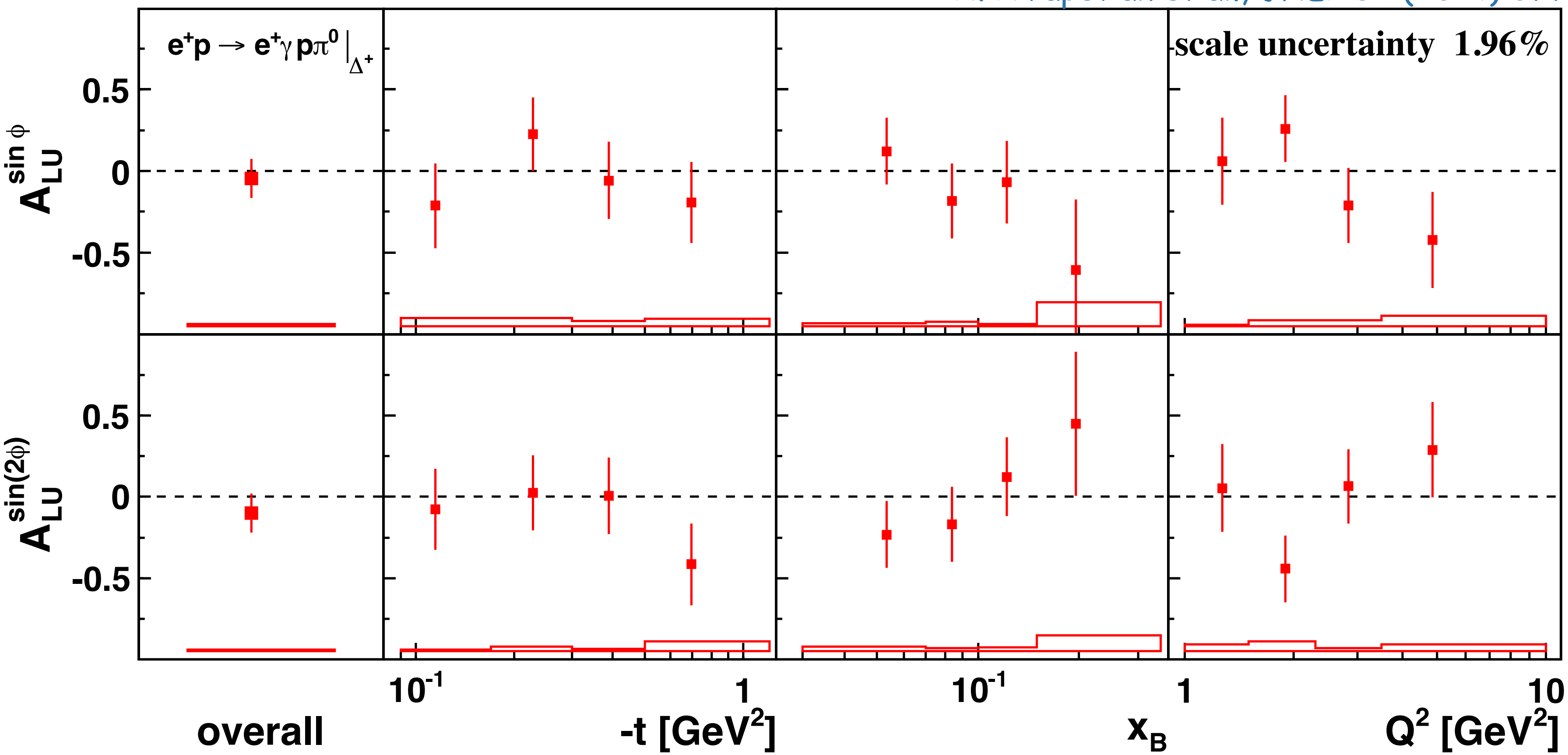
access through azimuthal asymmetries



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

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

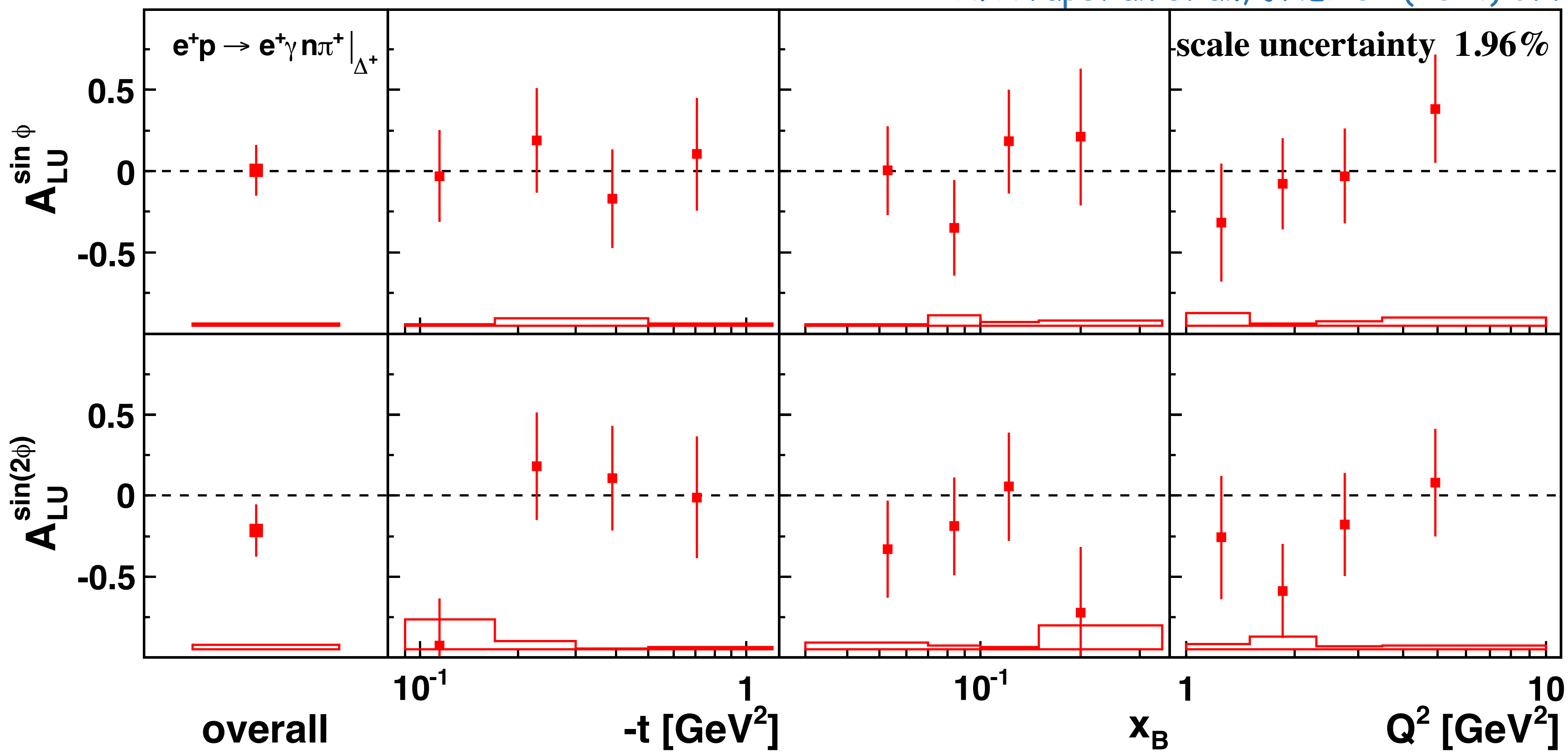
A. Airapetian et al., JHEP **01** (2014) 077



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

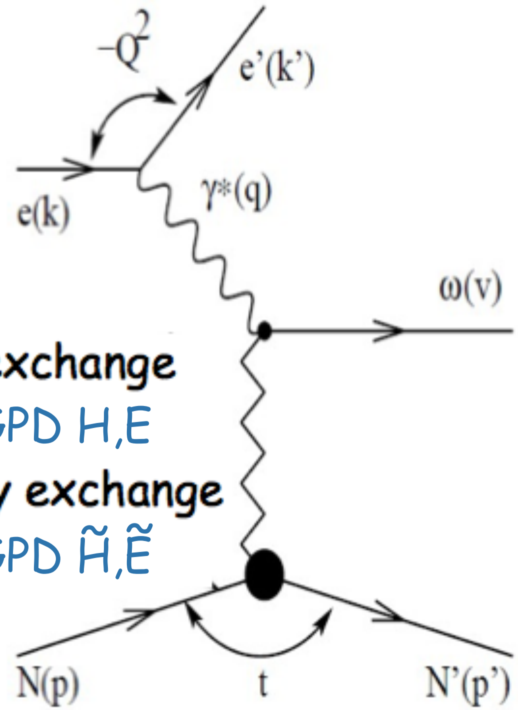
Beam-helicity asymmetry in $ep \to e\gamma\pi^+ n$ in Δ-resonance region

A. Airapetian et al., JHEP **01** (2014) 077



- 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

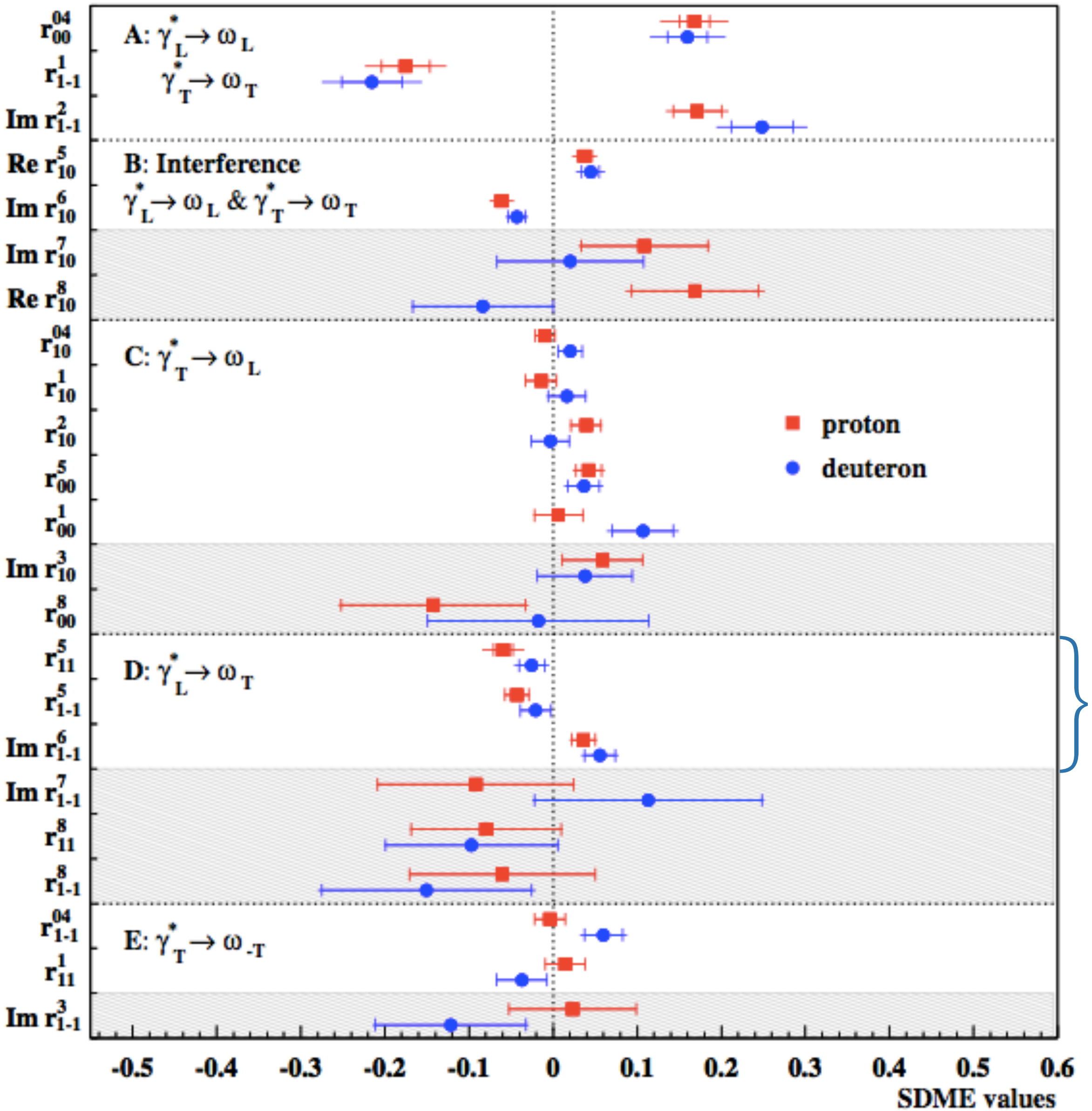
$J^P=0^+, 1^-, \ldots$ ➡ GPD H,E

unnatural parity exchange

$J^P=0^-, 1^+, \ldots$ ➡ GPD $\tilde{H},\tilde{E}$

Exclusive ω production

A. Airapetian et al., arXiv:1407.2119



- SDMEs compatible for proton and deuteron

- slight violation of s-channel helicity conservation

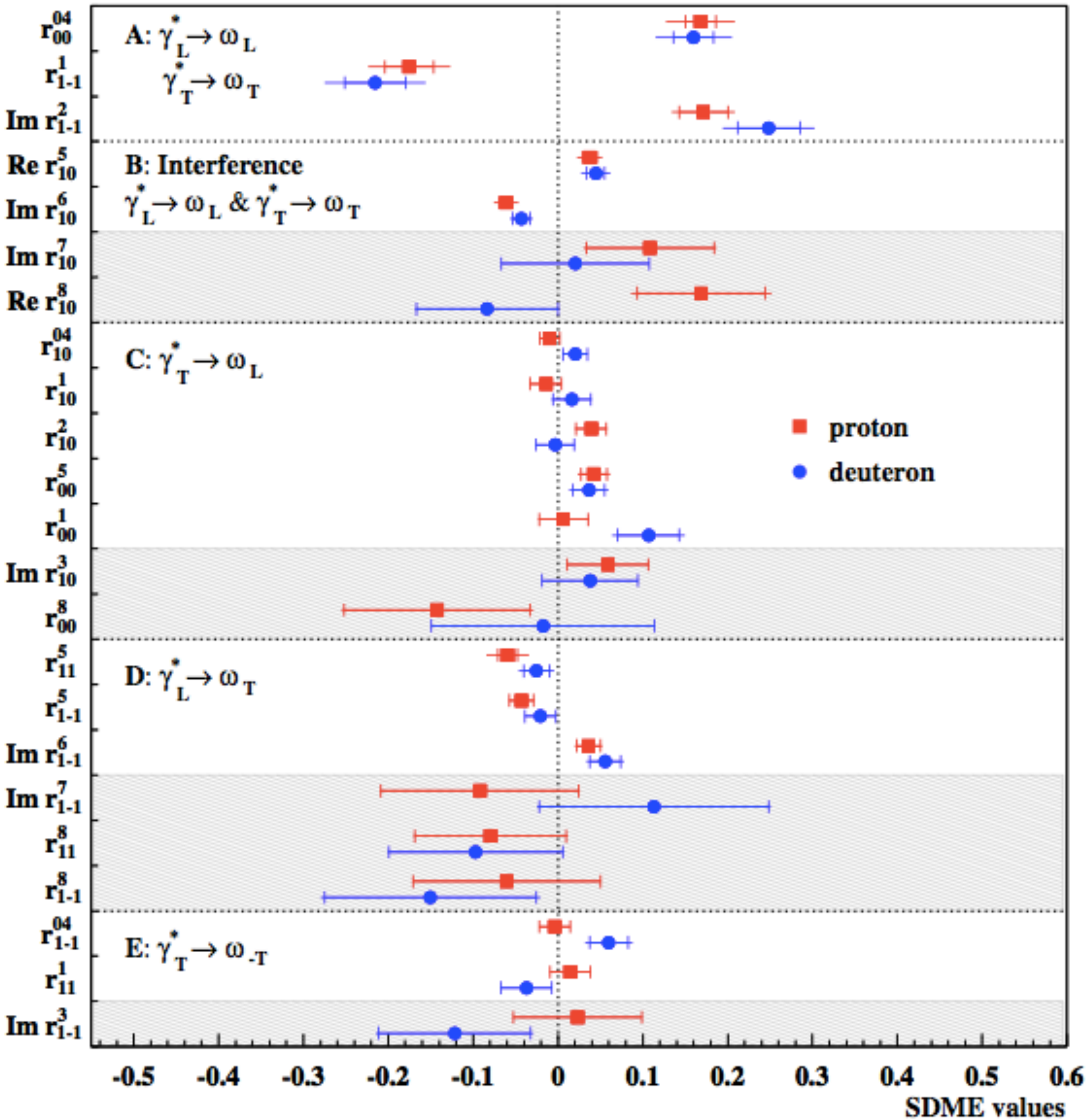
$$r^5_{11} + r^5_{1-1} - \Im r^6_{1-1}$$

$$= -0.14 \pm 0.02 \pm 0.04$$

$$= -0.10 \pm 0.03 \pm 0.03$$

Exclusive ω production

A. Airapetian et al., arXiv:1407.2119



- 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

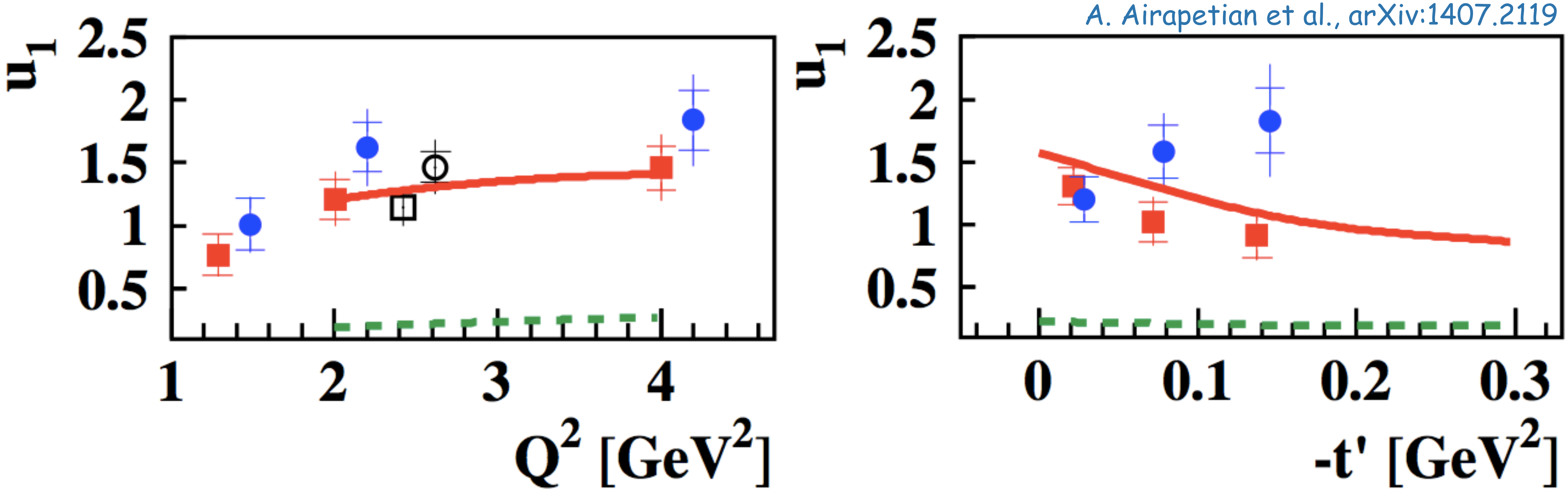
Exclusive ω production

- test of unnatural parity exchange:

$$u_1 = 1 - r^{04}_{00} + 2\, r^{04}_{1-1} - 2\, r^1_{11} - 2\, r^1_{1-1}$$

$$\propto 2\,\epsilon |U_{10}|^2 + |U_{11} + U_{-11}|^2$$

A. Airapetian et al., arXiv:1407.2119

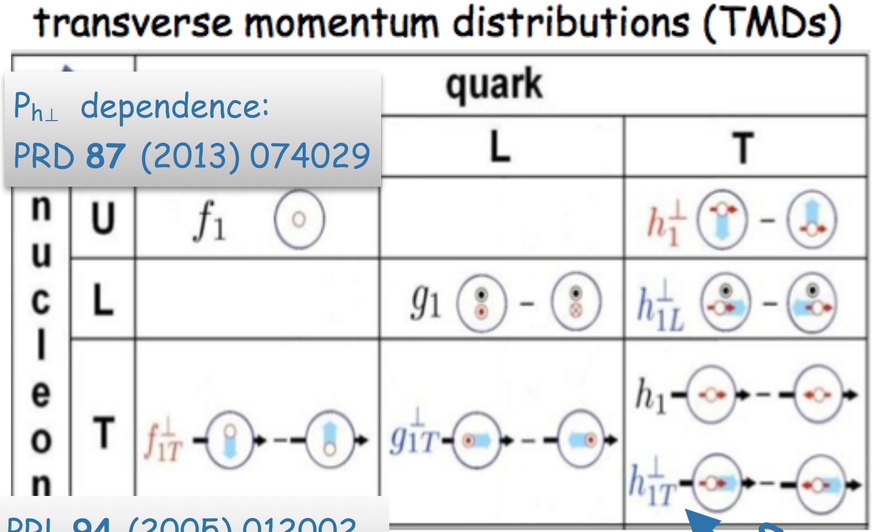


- large unnatural parity exchange
- model for protons - S. Goloskokov and P. Kroll, arXiv. 1407.1141:

  without pion-pole contribution

  with pion-pole contribution

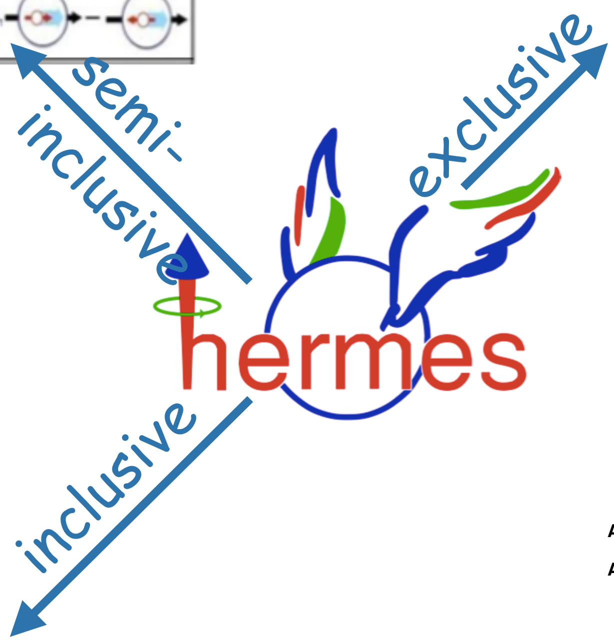
Summary



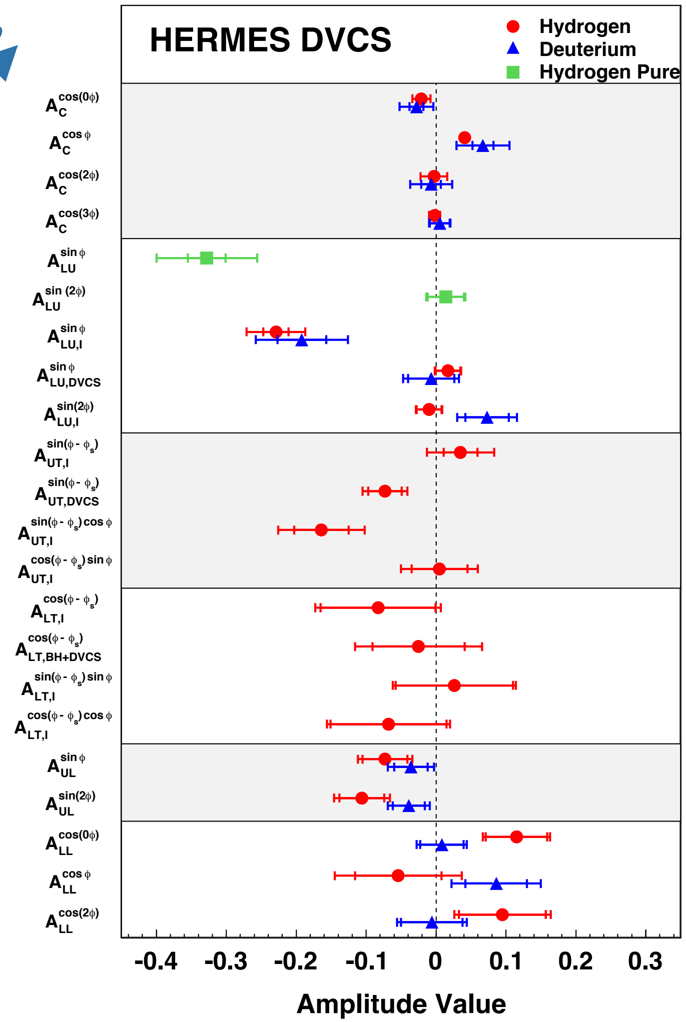
$P_{h\perp}$ dependence:
PRD **87** (2013) 074029

PRL **94** (2005) 012002

PRL **103** (2009) 152002



exclusive ω production
arXiv:1407.2119



g_2 - EPJ C 72 (2012) 1921

A_{UT} - Phys. Lett. B **728** (2014) 183-190

Back up

Hadron multiplicities: VM fractions