Hermes results on 3D imaging of the nucleon

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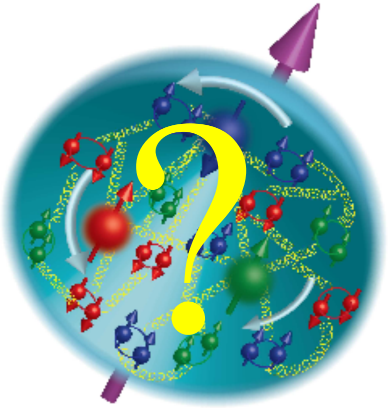
So popular, yet so misterious…

Protons, neutrons:

- Building blocks of ordinary matter
- Account for mass of visible Universe
- Discovered about 100 years ago
- 50 year of DIS experiments
- ...but **internal structure still largely unknown!**
  - contributions from sea quark & gluons spin ?
  - transverse motion of partons ?
  - spin-orbit correlations ?
  - role of OAM ?
  - ...

npQCD, confinement,...



basic properties from first principles?

- **mass**
- **radius**
- **charge**
- **spin**
- **mag. moment**
- **...**

Describing the internal structure of nucleons is one of the most formidable challenges of hadron physics and QCD!

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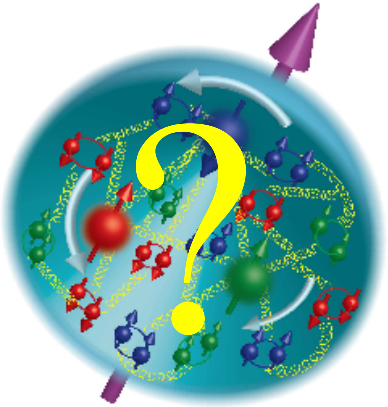

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Describing the internal structure of nucleons is one of the most formidable challenges of hadron physics and QCD!

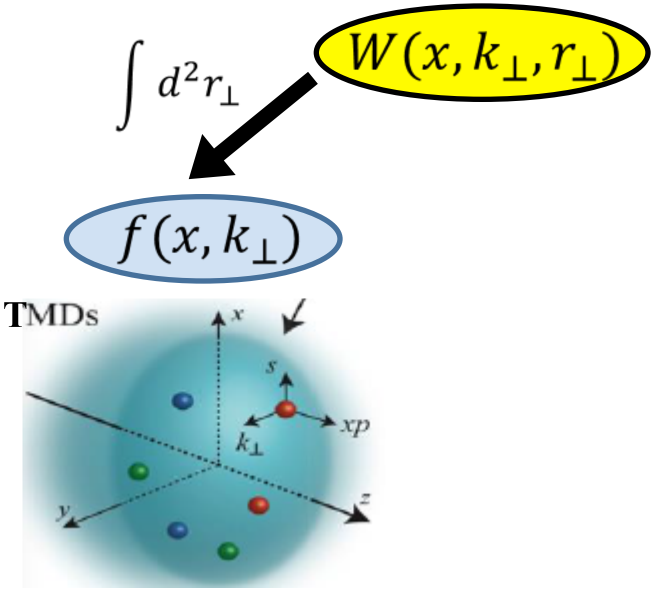
Final goal: understanding the full quantum phase-space distribution of partons

$$\boxed{W(x,k_\perp,r_\perp)}$$

Wigner function

- represents the maximal knowledge of the partonic structure of nucleons
- equivalent to knowing the complete wave function of partons inside the nucleon!
- **…but cannot be measured directly!**

Mapping the phase-space of the nucleon



$W(x, k_\perp, r_\perp)$

$\int d^2 r_\perp$

$f(x, k_\perp)$

TMDs: **3D description in longitudinal (x) and transverse ($k_\perp$) mom.**

Mapping the phase-space of the nucleon

$$\begin{tikzcd}
& W(x,k_\perp,r_\perp) \arrow[dl, "\int d^2r_\perp"'] \arrow[d, "\int d^2k_\perp"] & \\
f(x,k_\perp) & \mathrm{f}(x,r_\perp) \arrow[r, "FT"] & \mathrm{H}(x,\xi,\mathrm{t})
\end{tikzcd}$$

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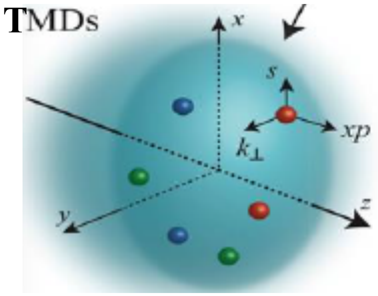

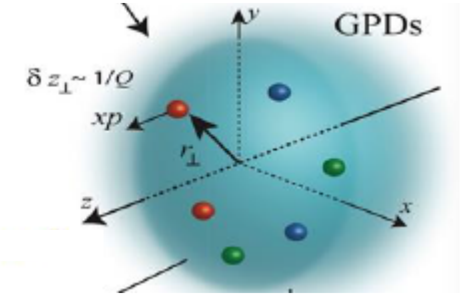

GPDs: **3D description in longit. momentum (x) and transverse location ($r_\perp$)**

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f(x) & & \mathrm{F}(Q^2)
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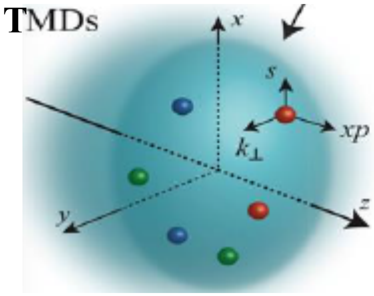
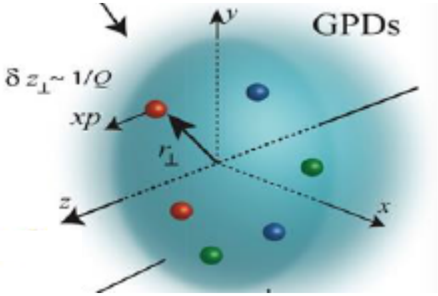


3D



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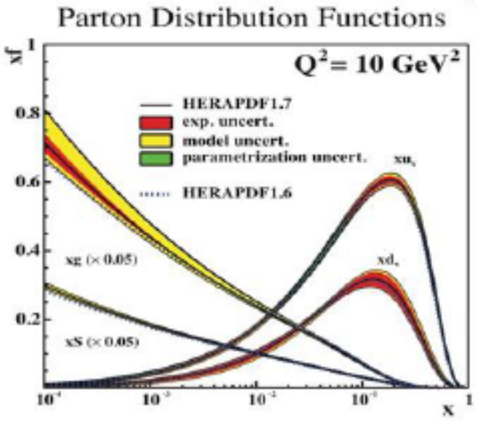
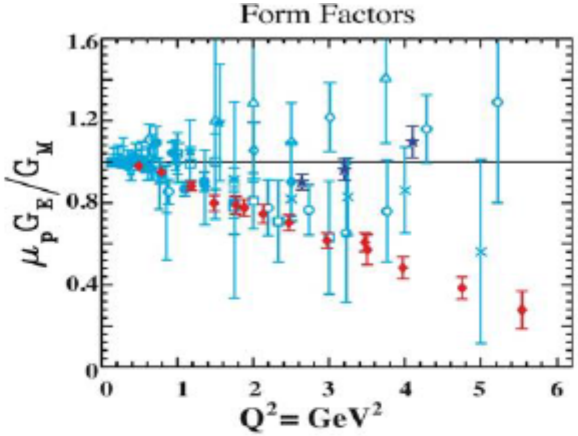
1D





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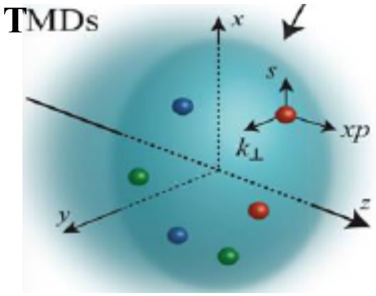

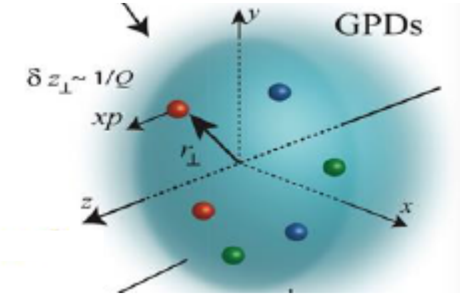

GPDs: 3D description in longit. momentum (x) and transverse location ($r_\perp$)

Transverse degrees of freedom are responsible for a rich phenomenolgy!

Mapping the phase-space of the nucleon

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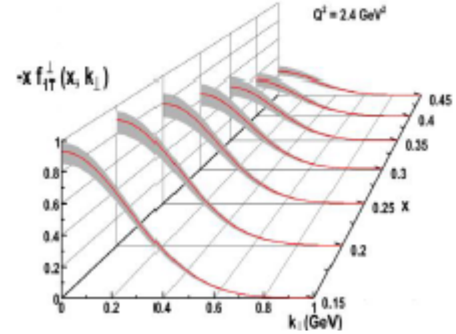

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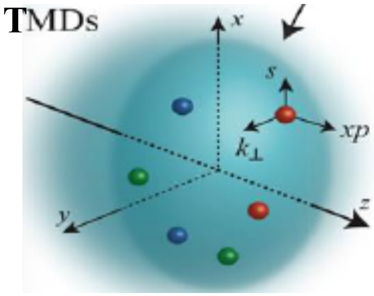

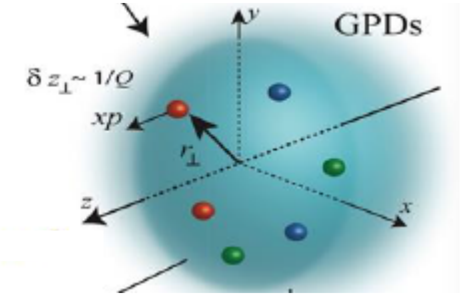

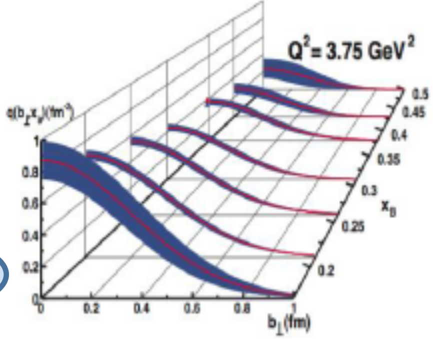

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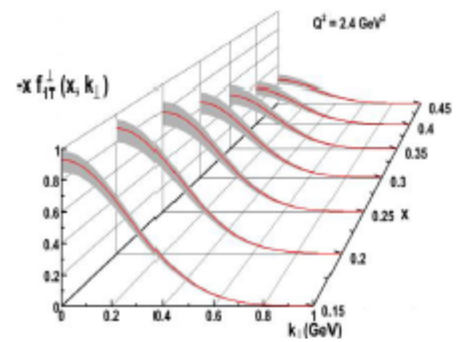
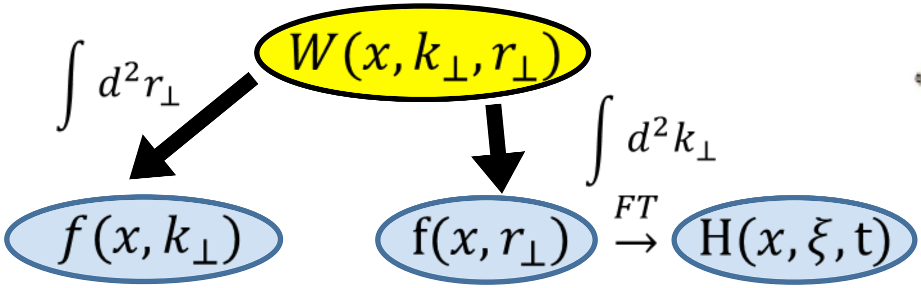
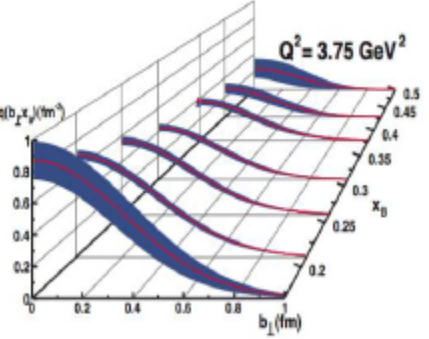
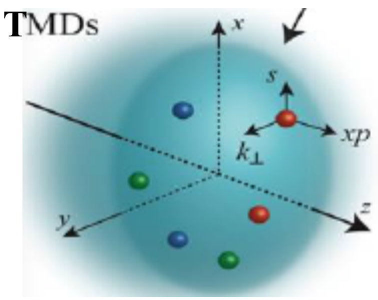


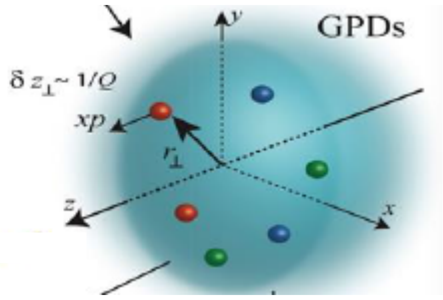


$$\int d^2 r_\perp \qquad W(x, k_\perp, r_\perp) \qquad \int d^2 k_\perp$$

$$f(x, k_\perp) \qquad f(x, r_\perp) \xrightarrow{FT} H(x, \xi, t)$$







TMDs: **3D description in longitudinal (x) and transverse ($k_\perp$) mom.**

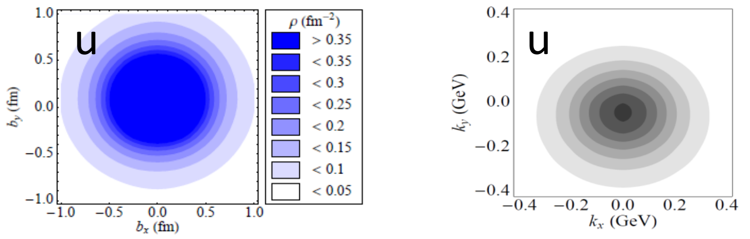
GPDs: **3D description in longit. momentum (x) and transverse location ($r_\perp$)**

Transverse degrees of freedom are responsible for a rich phenomenolgy!

Transverse momentum and transverse location of partons are correlated with:

- The longitudinal momentum
- the spin orientation of the parent hadron

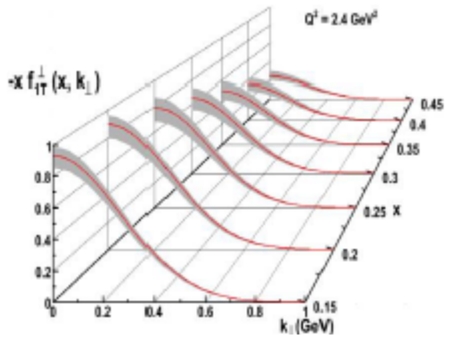
unpolarized quarks in a transversely polarized nucleon (Sivers)



B. Pasquini, C. Lorce arXiv:1304.1479

B. Pasquini, F. Yuan arXiv:1001.5398

Mapping the phase-space of the nucleon



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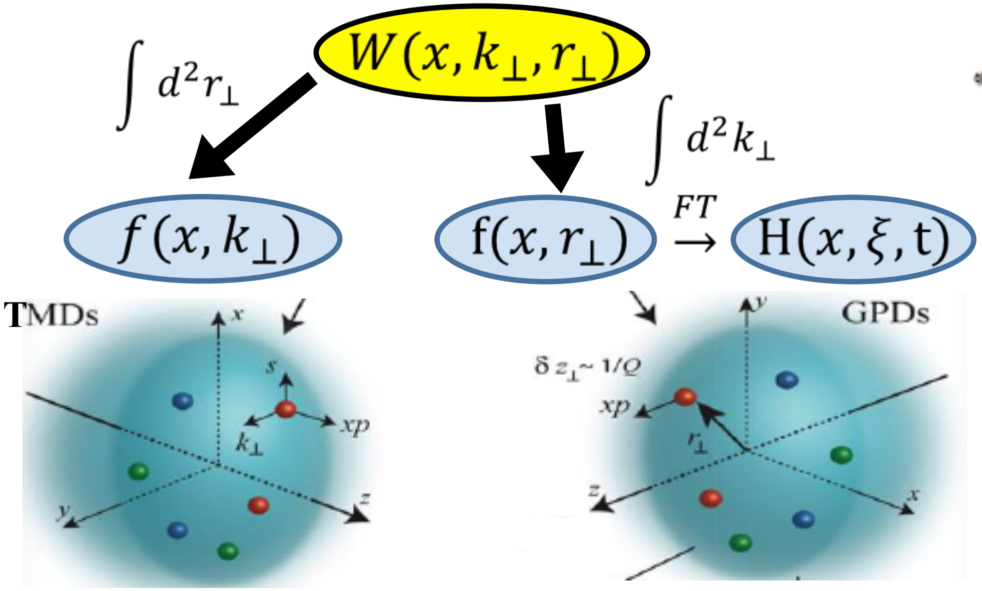

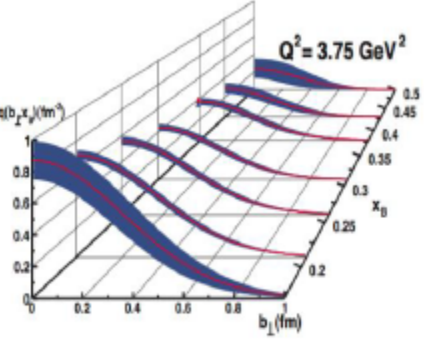

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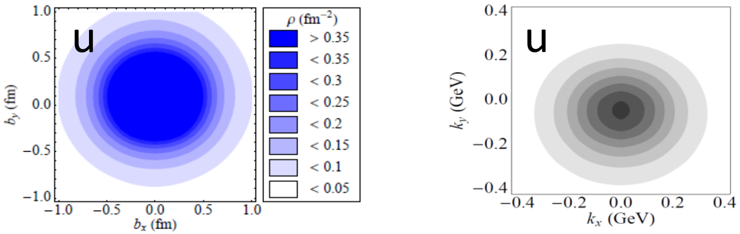
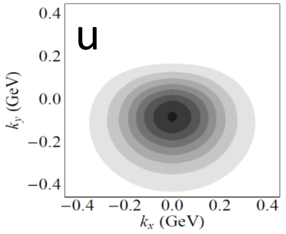


transv. pol. quarks in unpol. nucleon (B-M)



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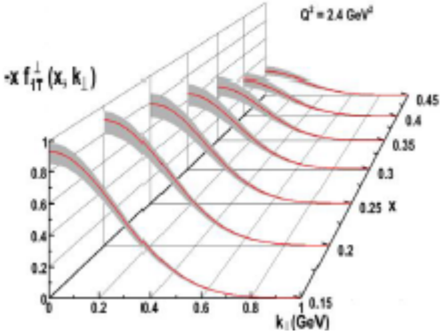

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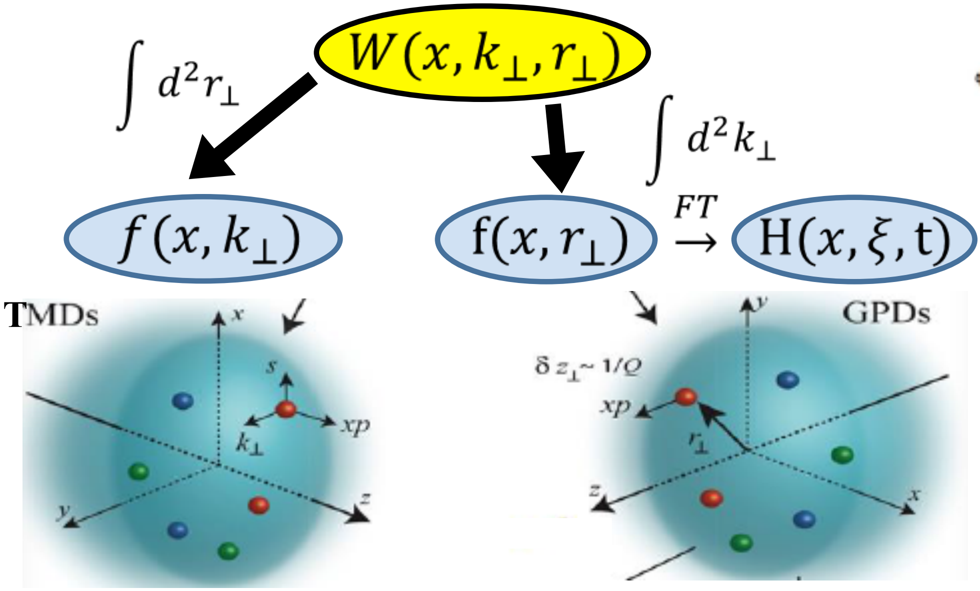

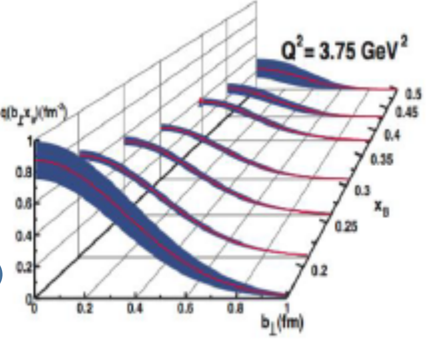

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- and are flavour dependent!

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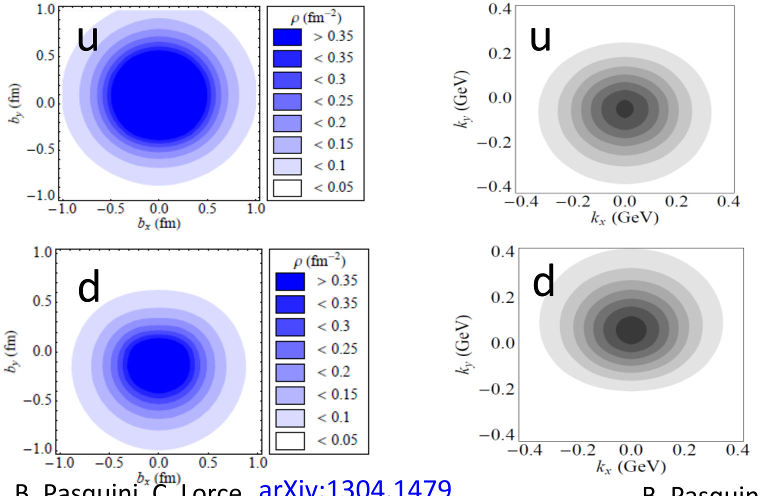

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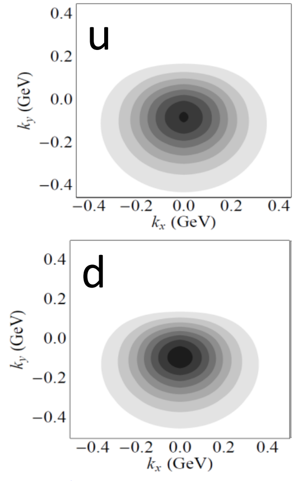

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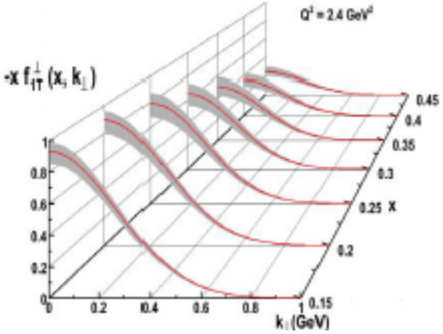

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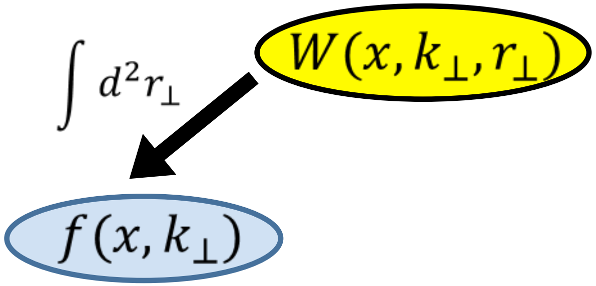

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$W(x, k_\perp, r_\perp)$

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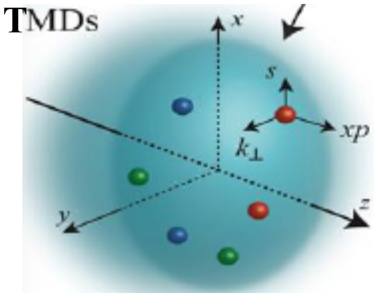
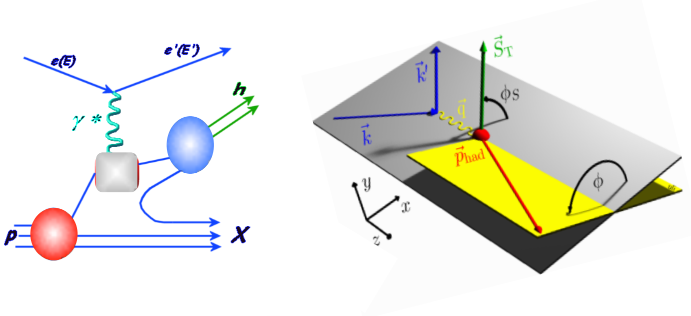


Semi-inclusive processes (SIDIS)



$$
\begin{aligned}
\frac{d\sigma}{dx_B\, dy\, d\psi\, dz_h\, d\phi_h\, dP_{h\perp}^2} &= \frac{\alpha^2}{x_B y Q^2}\, \frac{y^2}{2\,(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x_B}\right) \Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} \\
&+ \quad \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\, \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h} \\
&+ \quad S_\| \left[\sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} \right] \\
&+ \quad S_\| \lambda_e \left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_h\, F_{LL}^{\cos\phi_h} \right] \\
&+ \quad |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) \\
&+ \quad \varepsilon\, \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\, \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&+ \quad \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big] \\
&+ \quad |\boldsymbol{S}_\perp| \lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S} \\
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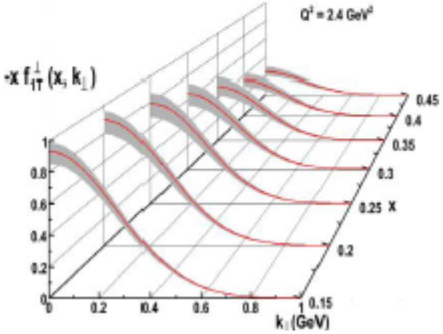
$$

Bacchetta et al JHEP 08

Mapping the phase-space of the nucleon



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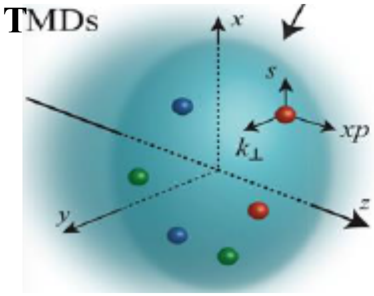

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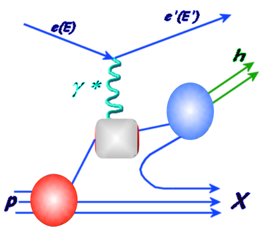

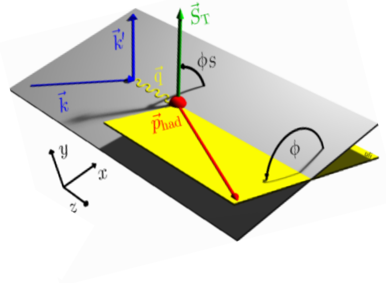

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&+\quad \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\\
&+\quad \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]\\
&+\quad |\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}\\
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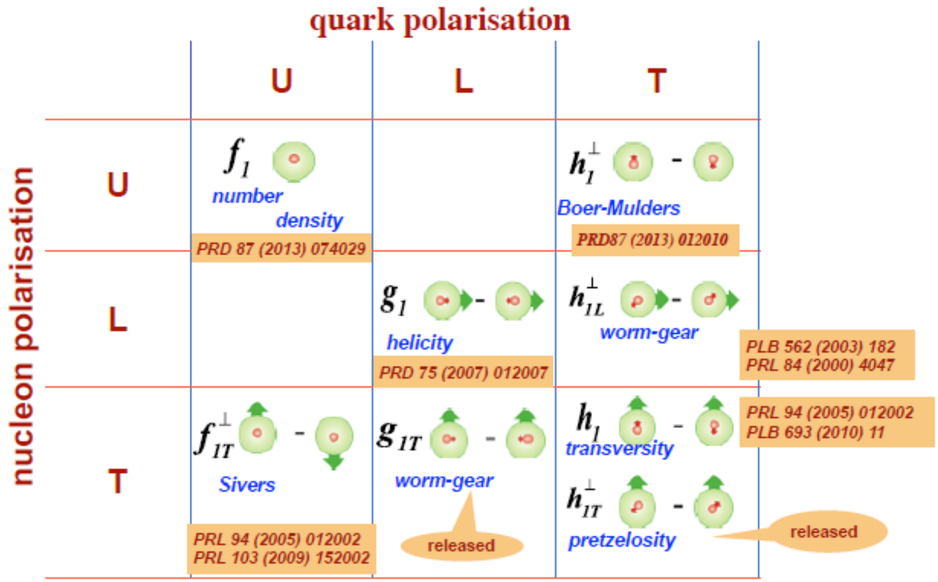
\end{aligned}$$

Bacchetta et al JHEP 08



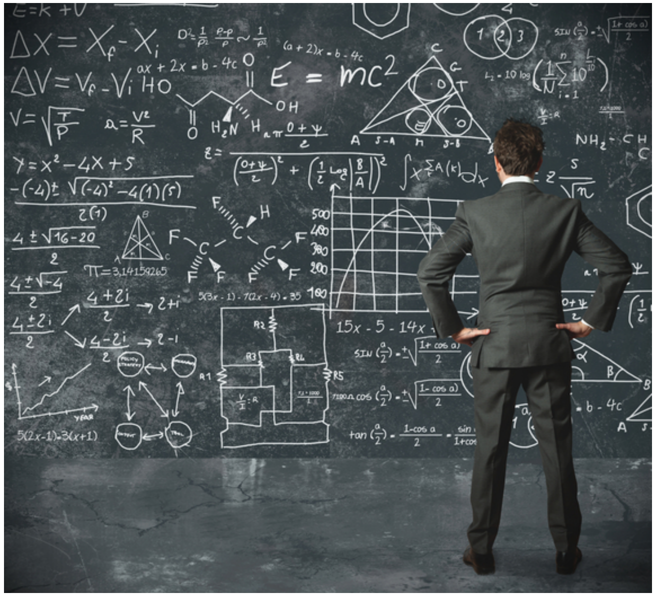
quark polarisation

nucleon polarisation

	U	L	T
U	f_1 - number density PRD 87 (2013) 074029		$h_1^\perp$ - Boer-Mulders PRD87 (2013) 012010
L		g_1 - helicity PRD 75 (2007) 012007	$h_{1L}^\perp$ - worm-gear PLB 562 (2003) 182 PRL 84 (2000) 4047
T	$f_{1T}^\perp$ - Sivers PRL 94 (2005) 012002 PRL 103 (2009) 152002	g_{1T} - worm-gear released	h_1 - transversity PRL 94 (2005) 012002 PLB 693 (2010) 11 $h_{1T}^\perp$ - pretzelosity released

- 8 leading-twist TMDs
- describe **spin-orbit correlations**
- sensitive to quark OAM!
- ...but how can we extract these objects?

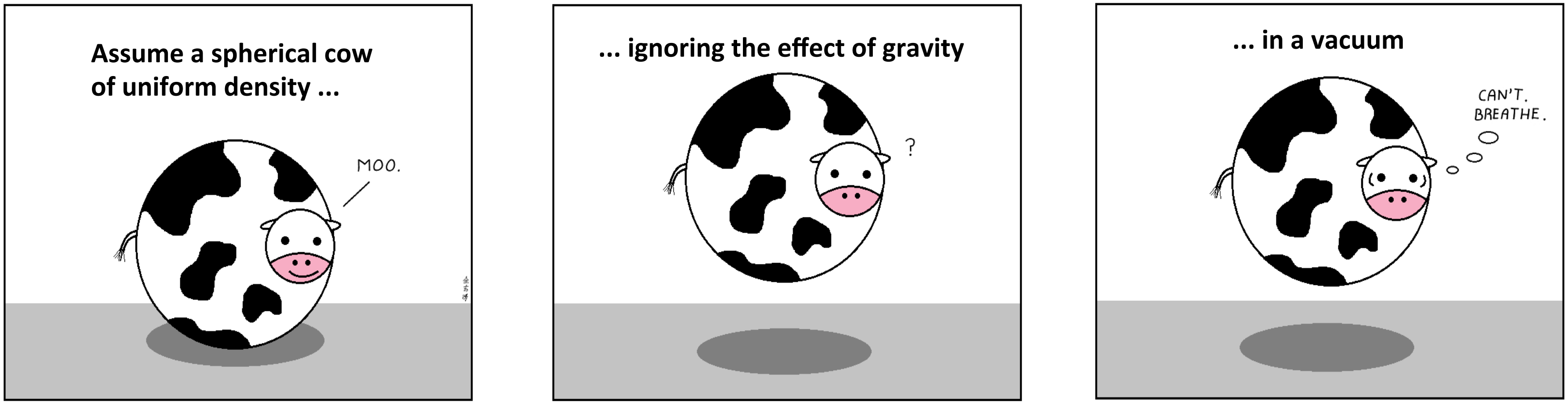
The main ingredients from theory



- **Factorization:** proved for SIDIS & DY (milestone!) → allows interpretation of cross-section
- **Universality:** essential to interpret underlying physics in different processes;
  - can be tested by comparing TMDs from different processes
  - predicted sign change for T-odd TMDs in SIDIS/DY awaits first experimental check!
- **TMD Evolution:** different schemes/implementations now available;
  - Hard to apply to SIDIS data (low energy) where non-perturbative behaviour is dominant
  - can be tested by comparing results from experiments at different energies:

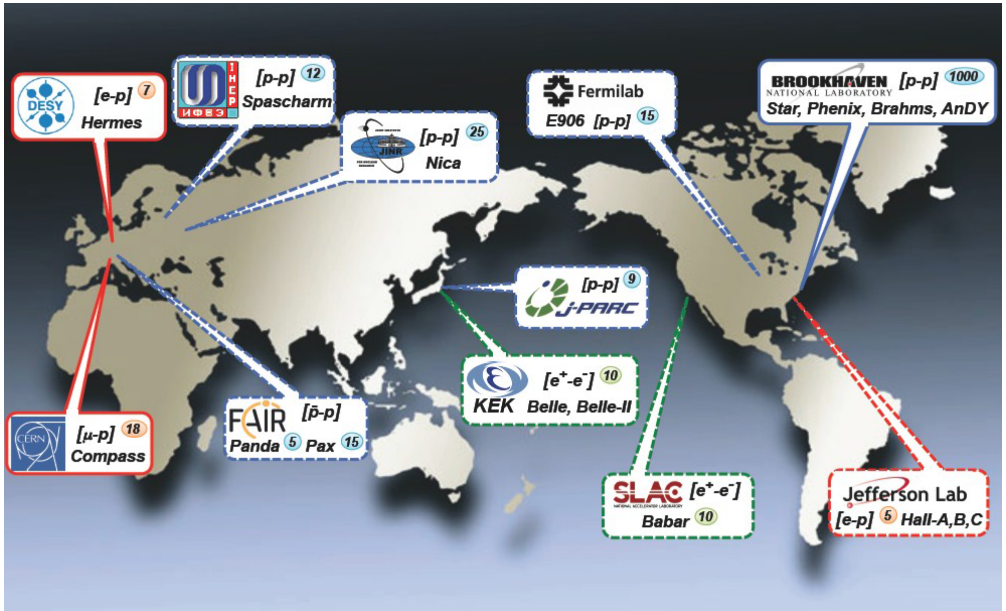
  $$\langle Q^2 \rangle_{Hermes,Compass,JLab12} \sim 2-5\ GeV^2;\ \langle Q^2 \rangle_{BesIII} \sim 15 GeV^2;\ \langle Q^2 \rangle_{Belle\,/Babar} \sim 100 GeV^2$$
- **Lattice QCD**: recent results on Transversirt, Sivers, B-M, worm-gear, tensor charge, etc

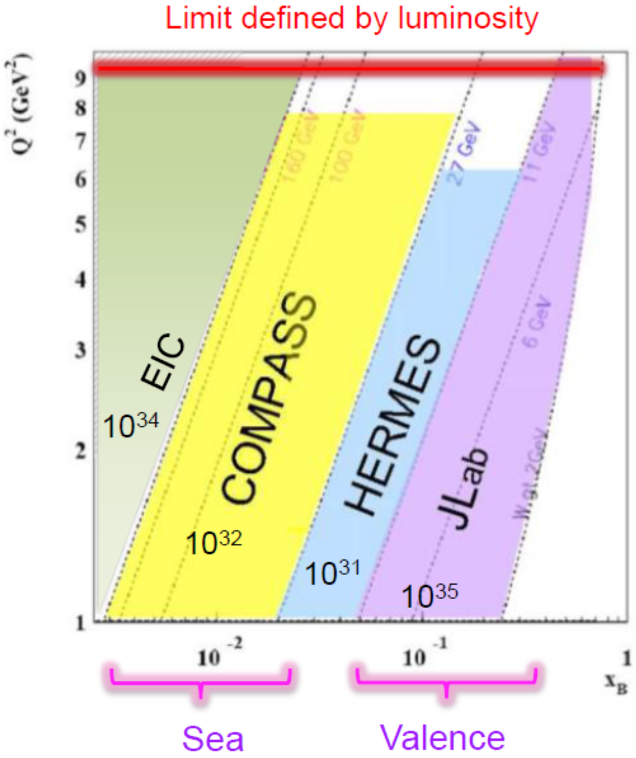
The main ingredients from phenomenology



- **Phenomenological models**: L-C constituent quark models, spectator models, χQSM, etc
- Sofisticated **global analyses** of SIDIS and e^+e^- data (multi-D) based on **TMD-evolution**
- **Careful error propagation and advanced statistical tools**
- **Deconvolution of PDF & FF**: educated guess on $k_\perp$ distribution, $\boldsymbol{P_{h\perp}}$/Bessel-weighting
- **Knowledge of higher-twist** contributions is crucial to interpret leading-twist observables
- Separation between **CFR & TFR** (Fracture Functions, Berger criterion, x_F, ...)

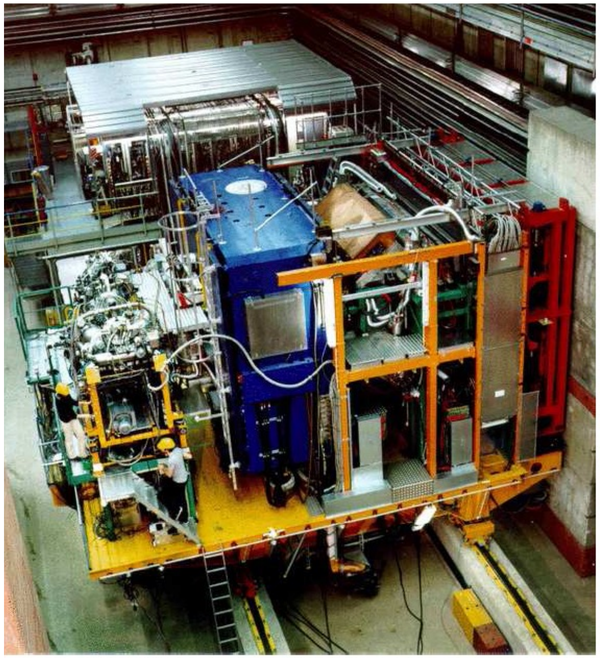
The main ingredients from experiments

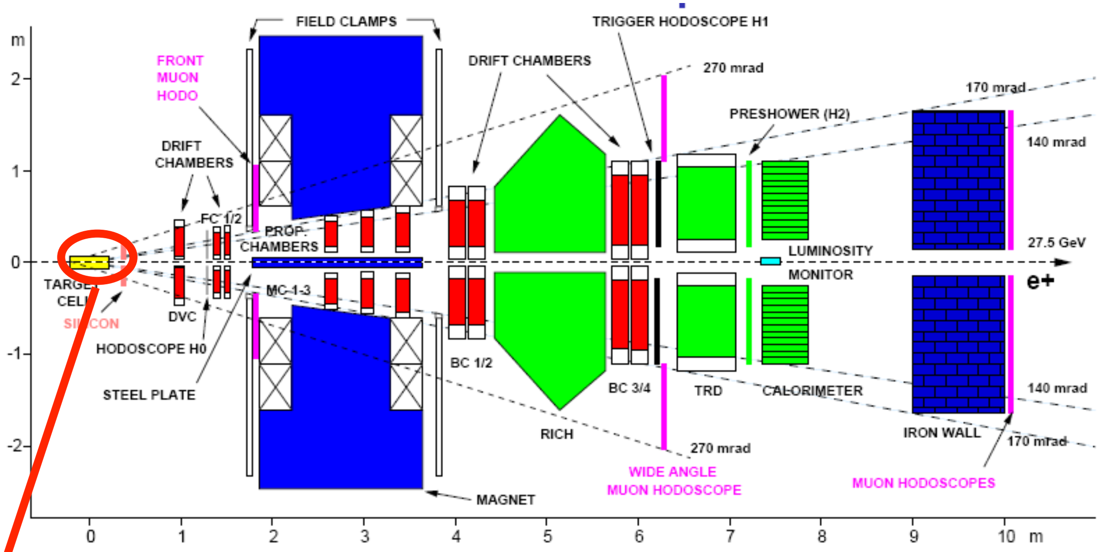




- High luminosity → **high statistical precision → multi-dimensional analysis**
- Large and uniform acceptance → **Wide kinematic coverage, access both CFR and TFR**
- Excellent tracking → **Precision measurement of $P_{h\perp}$ → sensitivity to intrinsic $k_{\perp}$**
- Excellent hadron PID → **quark flavour tagging**
- High beam and target polarization, small target dilution → **large asymmetries**
- Reliable MC → **Systematics well under control**

The HERMES experiment at HERA (1995-2007)



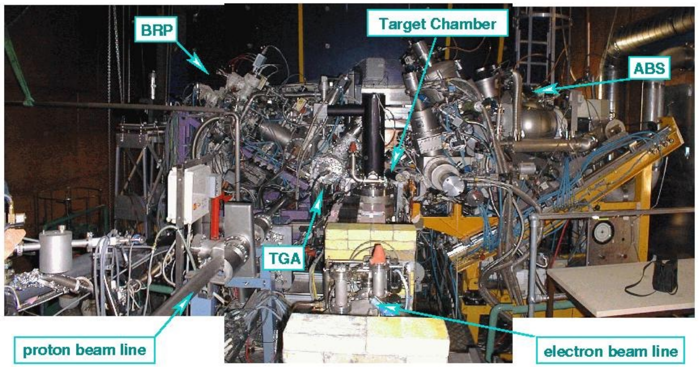


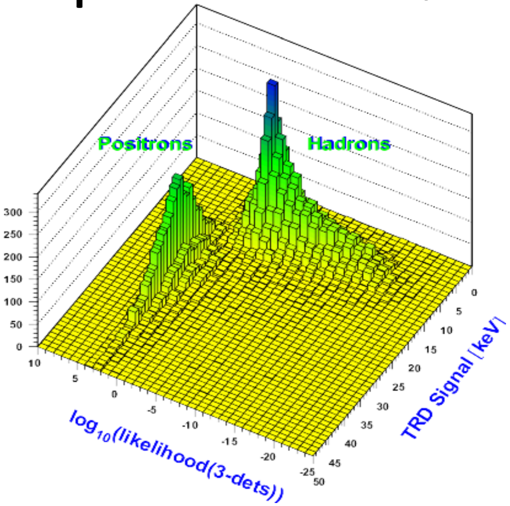
TRD, Calorimeter, preshower, RICH:

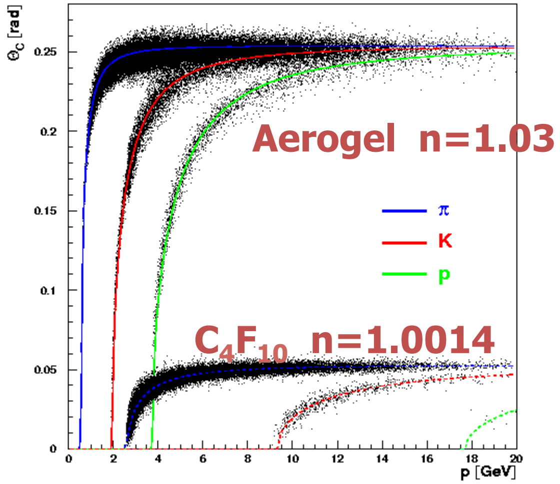
lepton-hadron > 98%

hadron separation

The polarized gas target







π ~ 98%, K ~ 88% , P ~ 85%

Selected TMDs results

Transversity

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

$$\Big\{ \Big[F_{\mathrm{UU,T}}+\epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon\,(1+\epsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+\ \lambda_l\ \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

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

$$+\ S_L\ \lambda_l\ \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

$$+\ S_T\ \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)}+\epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon\,(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

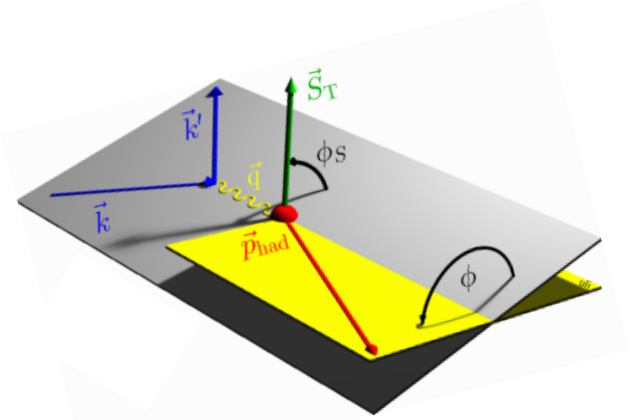
$$+\ S_T\ \lambda_l\ \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

Describes probability to find transversely polarized quarks in a transversely polarized nucleon

Transversity

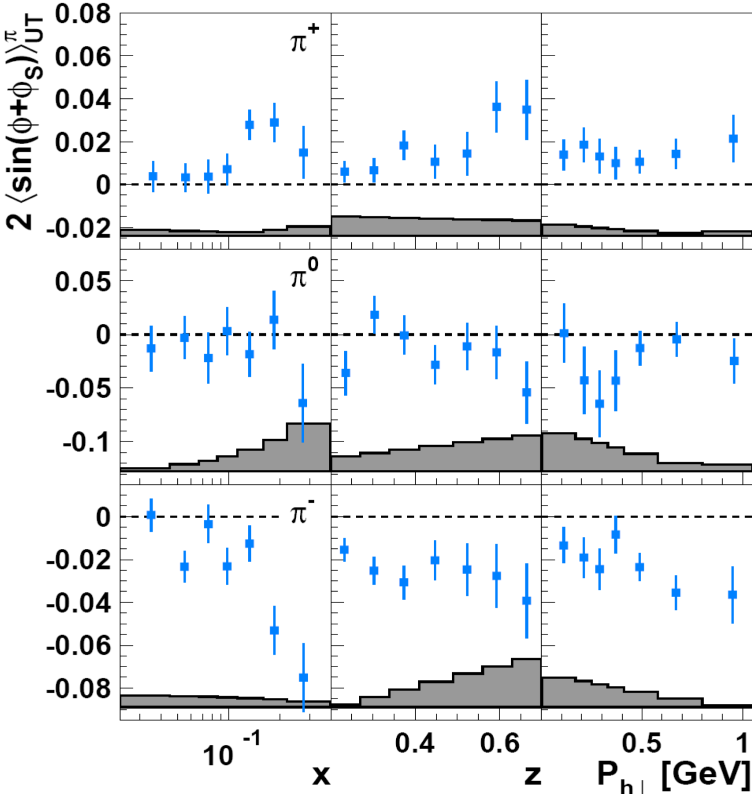
$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}h_1 H_1^{\perp}\right]$$

Collins FF



Collins amplitudes $\propto h_1(x, p_T^2) \otimes H_1^\perp(z, k_T^2)$

Airapetian *et al.*, Phys. Lett. B 693 (2010)



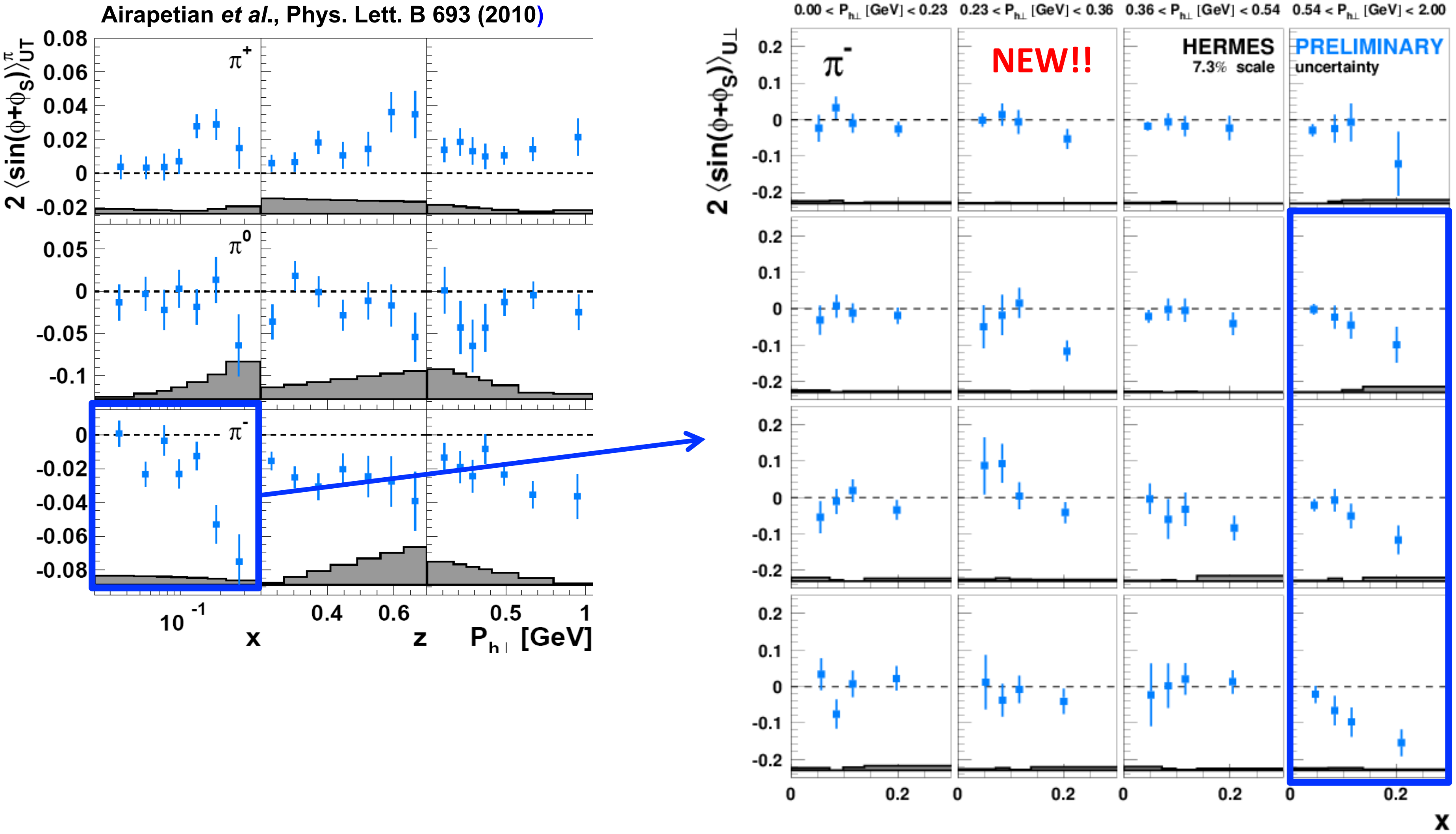
☛ **positive**

☛ **~ zero**

(isospin-symmetry)

☛ **large & negative**

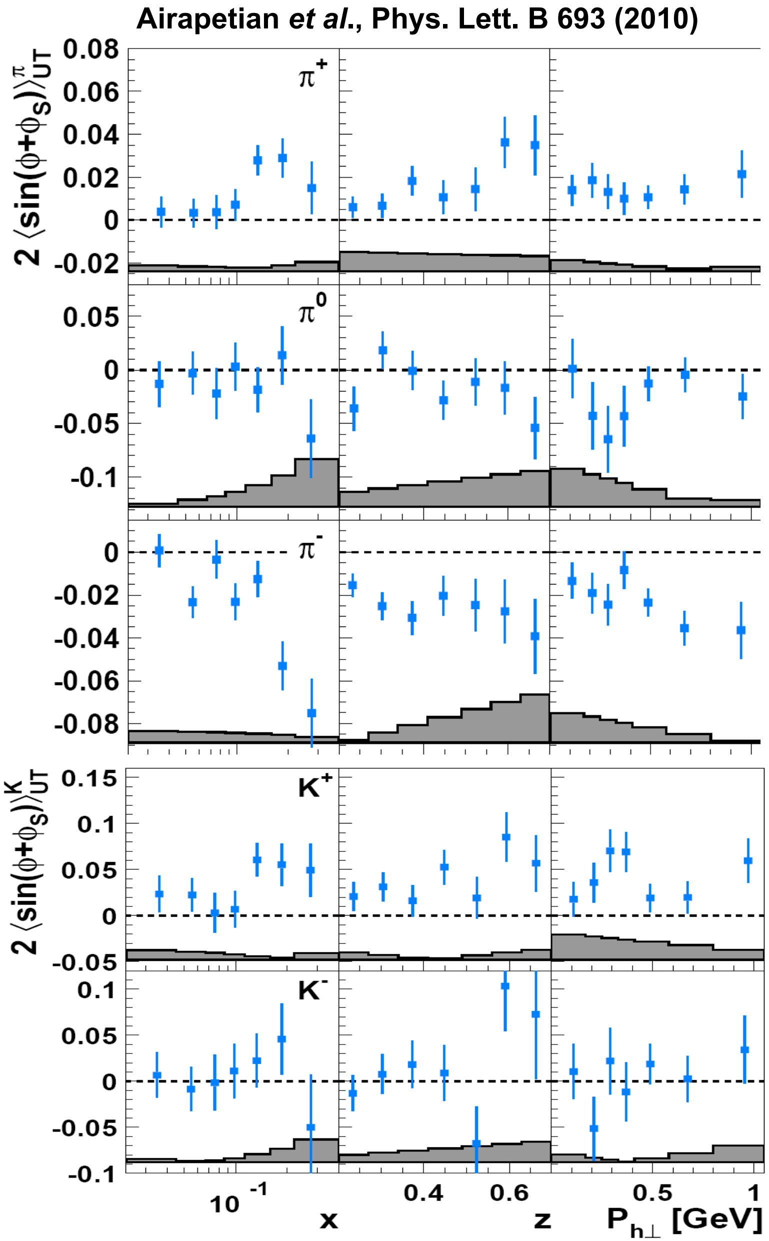
Collins amplitudes $\propto h_1(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$



3D projections allow to constrain global fits in a more profound way!

- also available vs. z (in bins of x and $P_{h\perp}$) and vs. $P_{h\perp}$ (in bins of x and z)
- also availbable for other hadron types

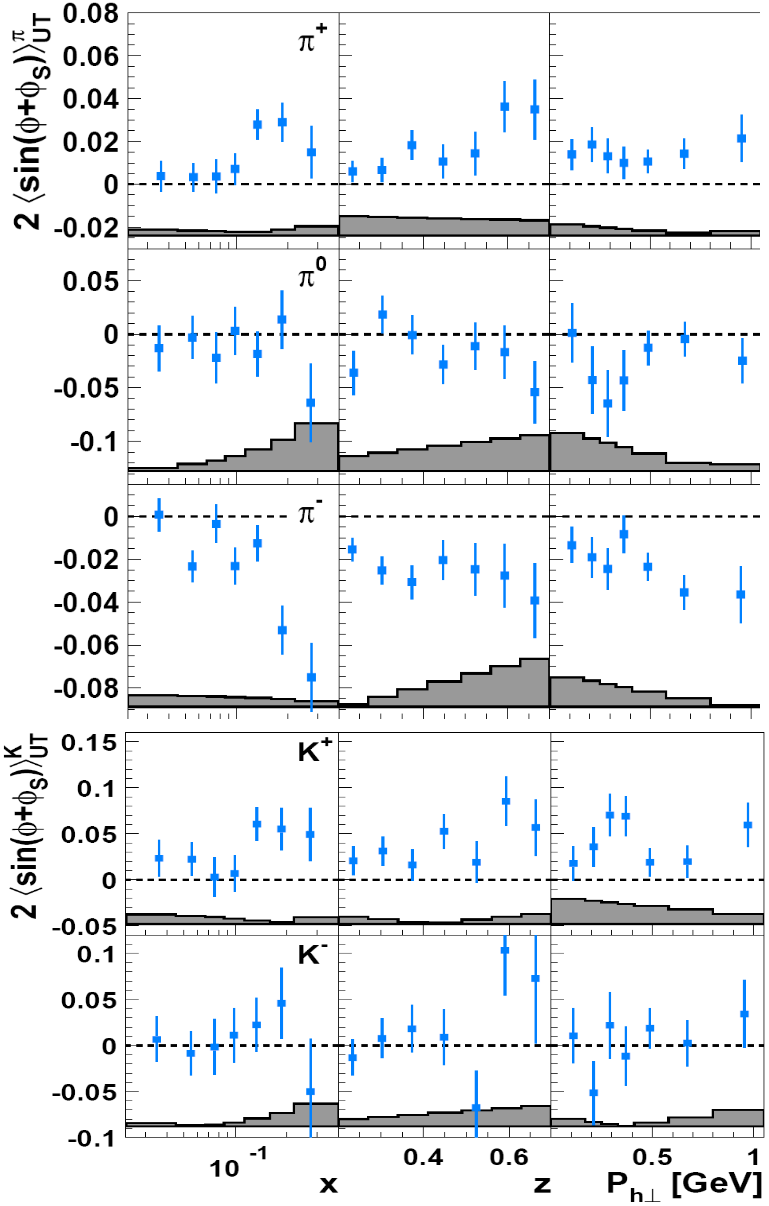
Collins amplitudes $\propto h_1(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$



☛ positive

☛ ~ zero

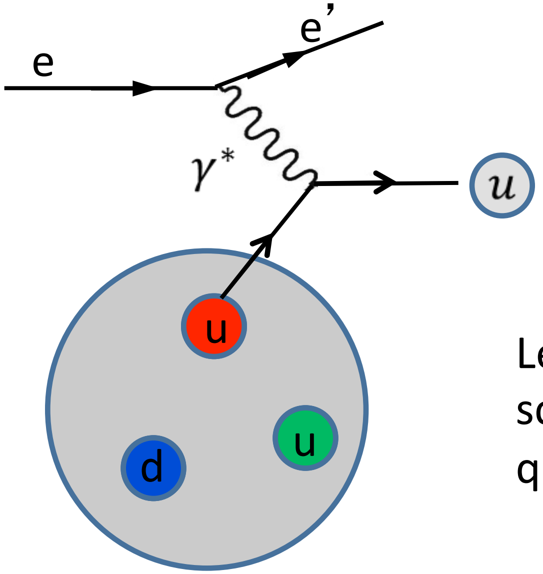
Collins amplitudes $\propto h_1(x,p_T^2)\otimes H_1^\perp(z,k_T^2)$



Airapetian *et al.*, Phys. Lett. B 693 (2010)

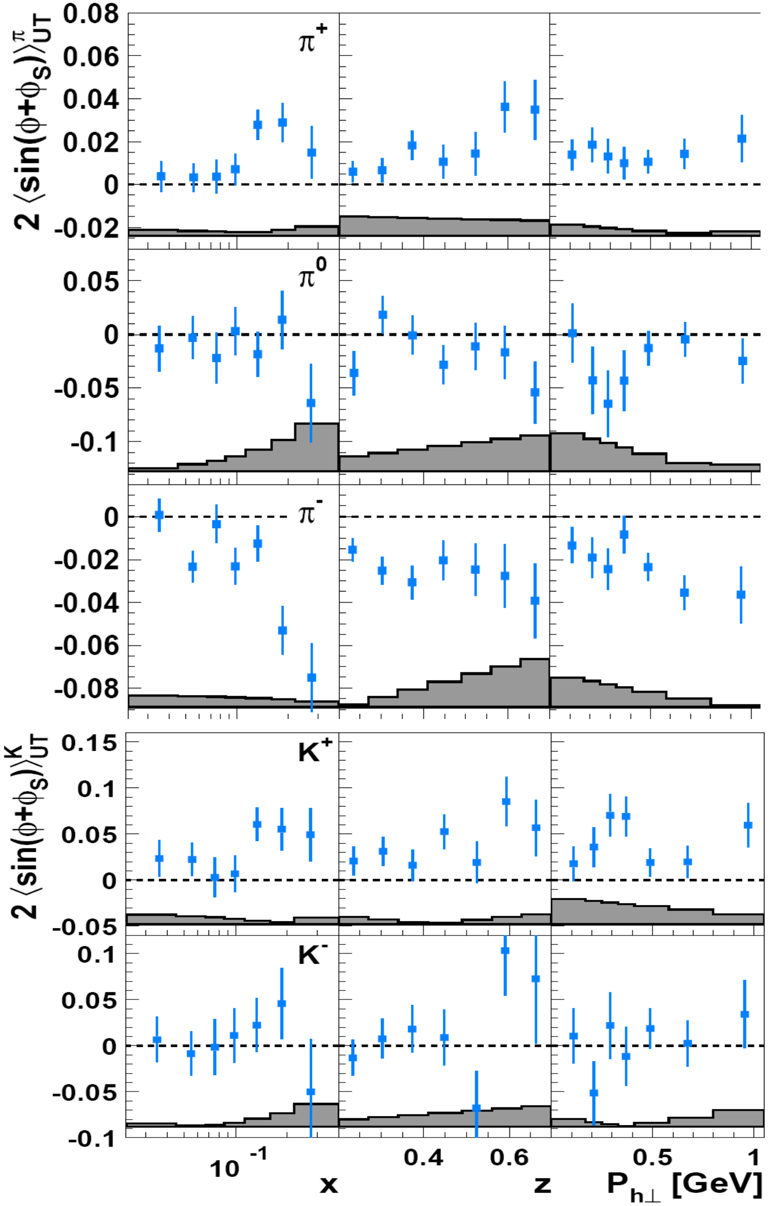
...and what about **proton production in SIDIS**?

A naive fragmentation process that can lead to $p/\bar{p}$:



Let's assume scattering off the up quark

Collins amplitudes $\propto h_1(x,p_T^2)\otimes H_1^\perp(z,k_T^2)$



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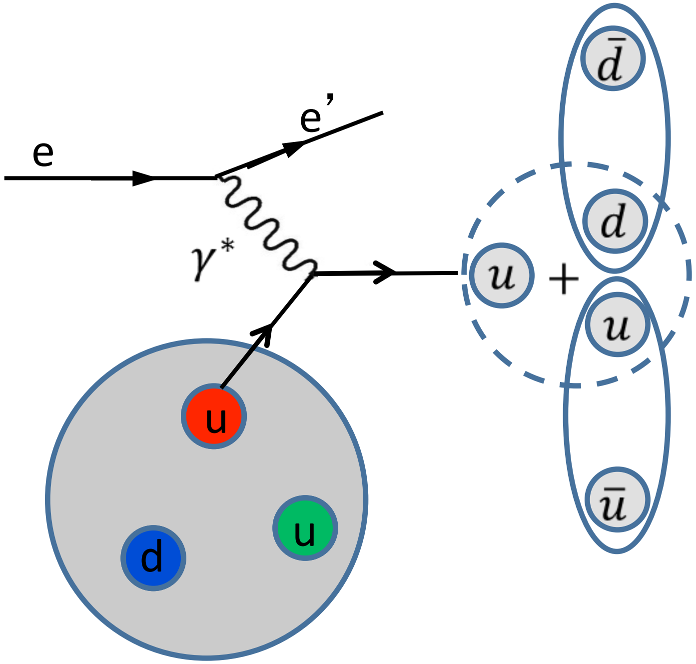
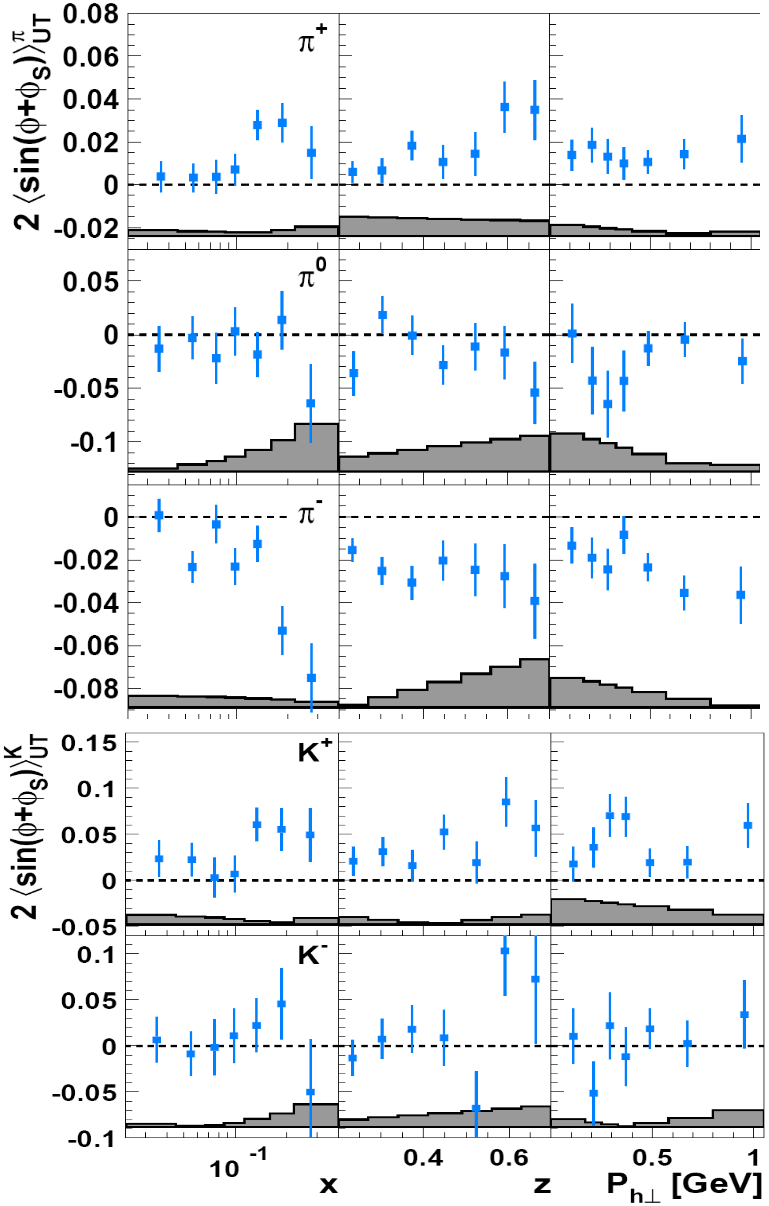


Collins amplitudes $\propto h_1(x,p_T^2)\otimes H_1^{\perp}(z,k_T^2)$

Airapetian *et al.*, Phys. Lett. B 693 (2010)



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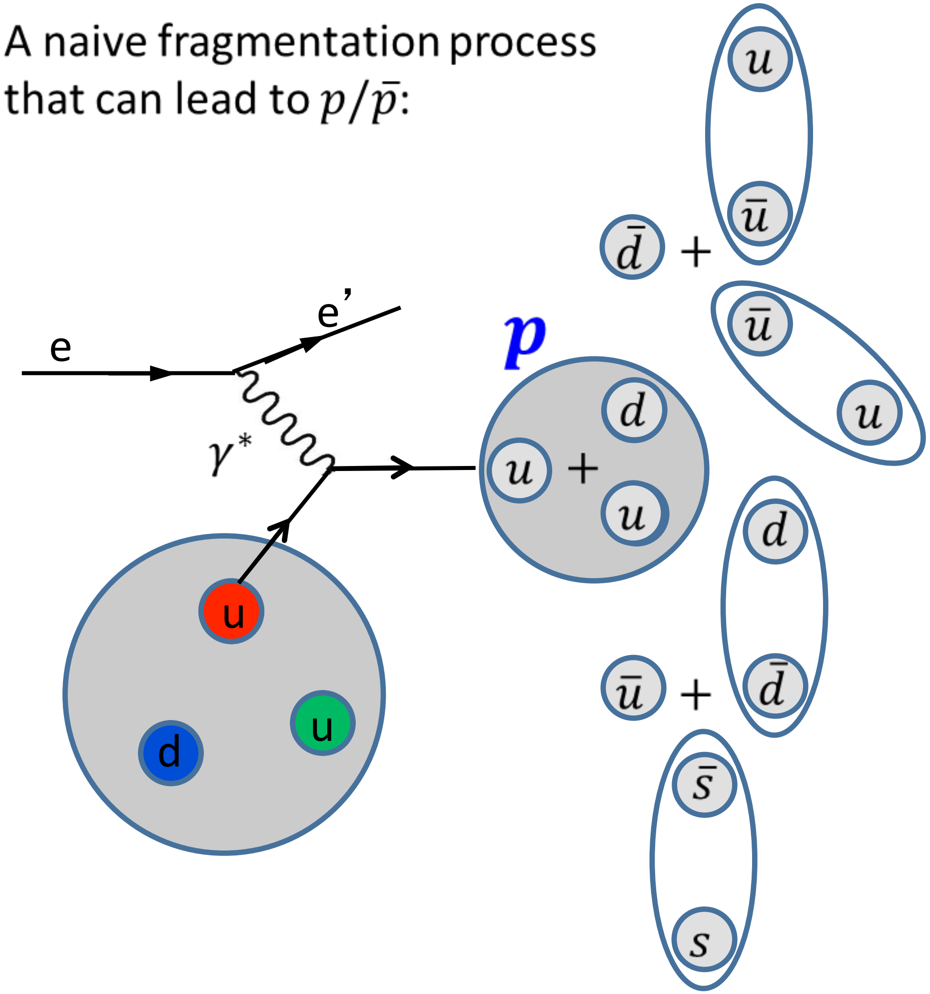

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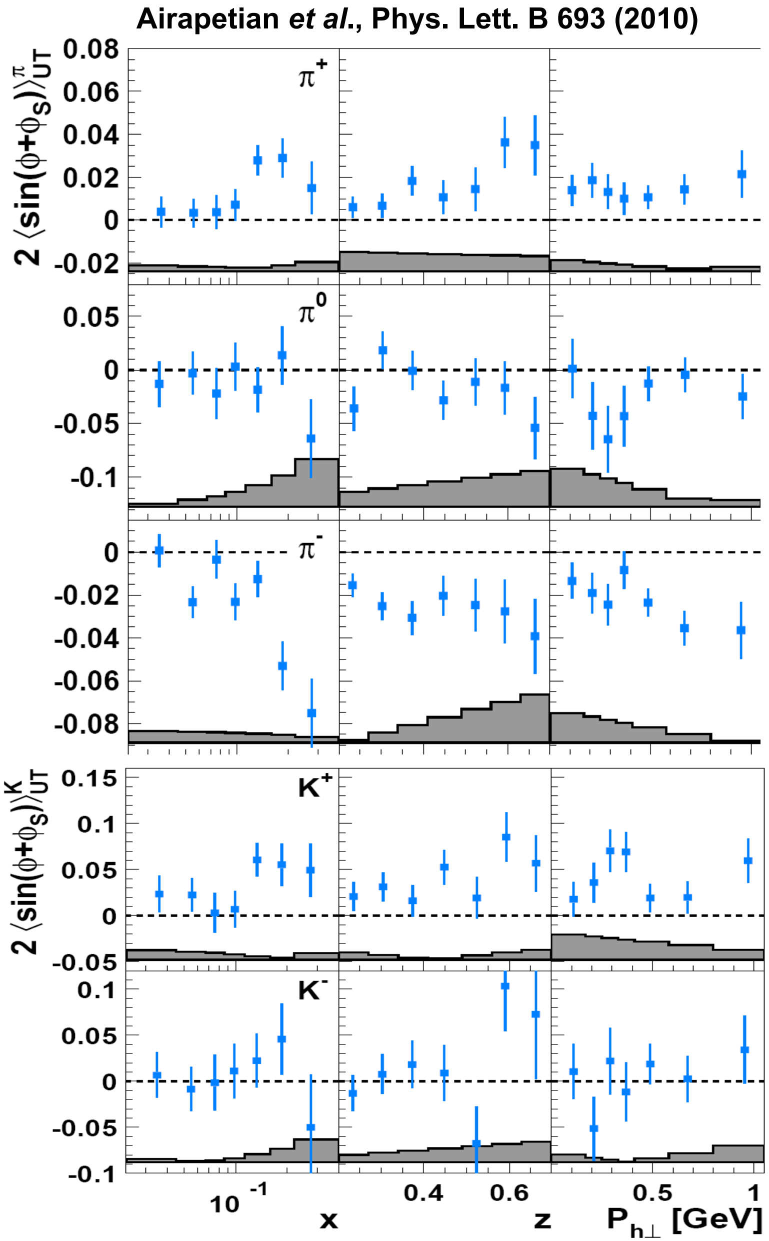

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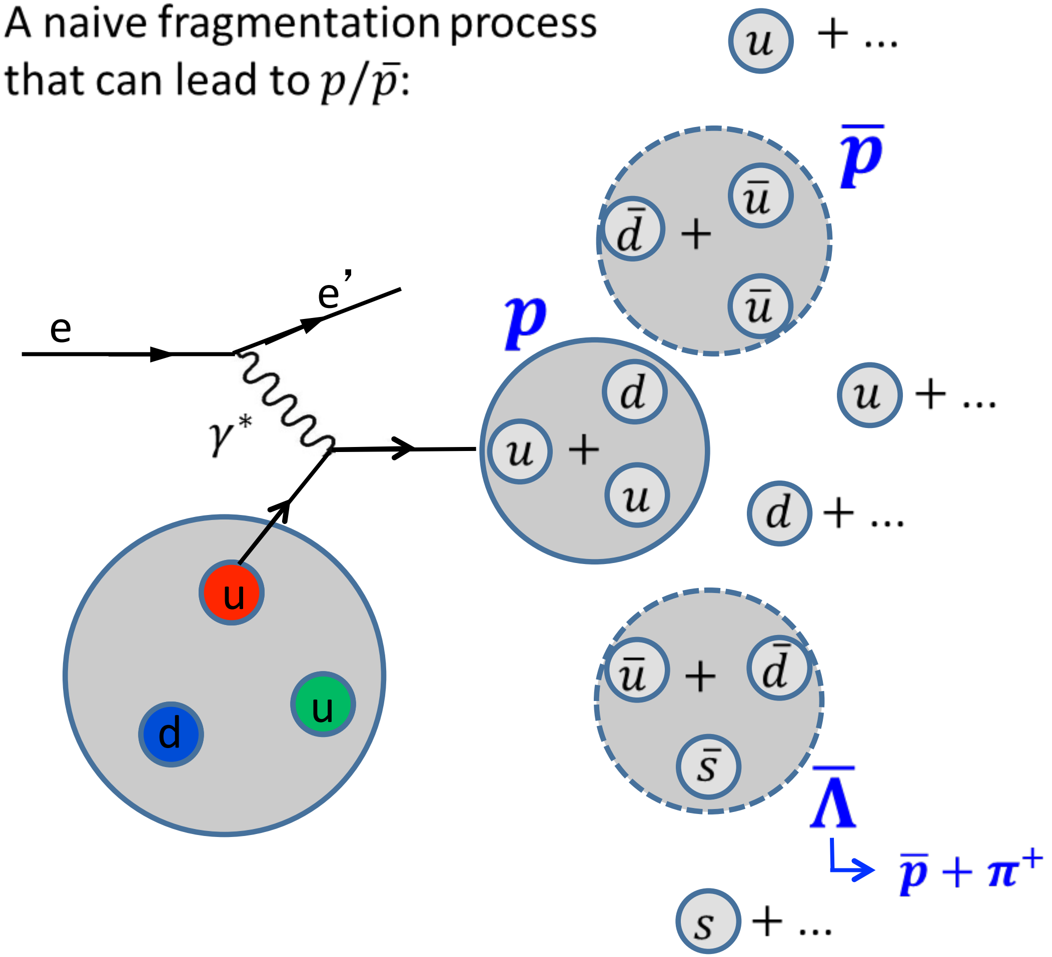

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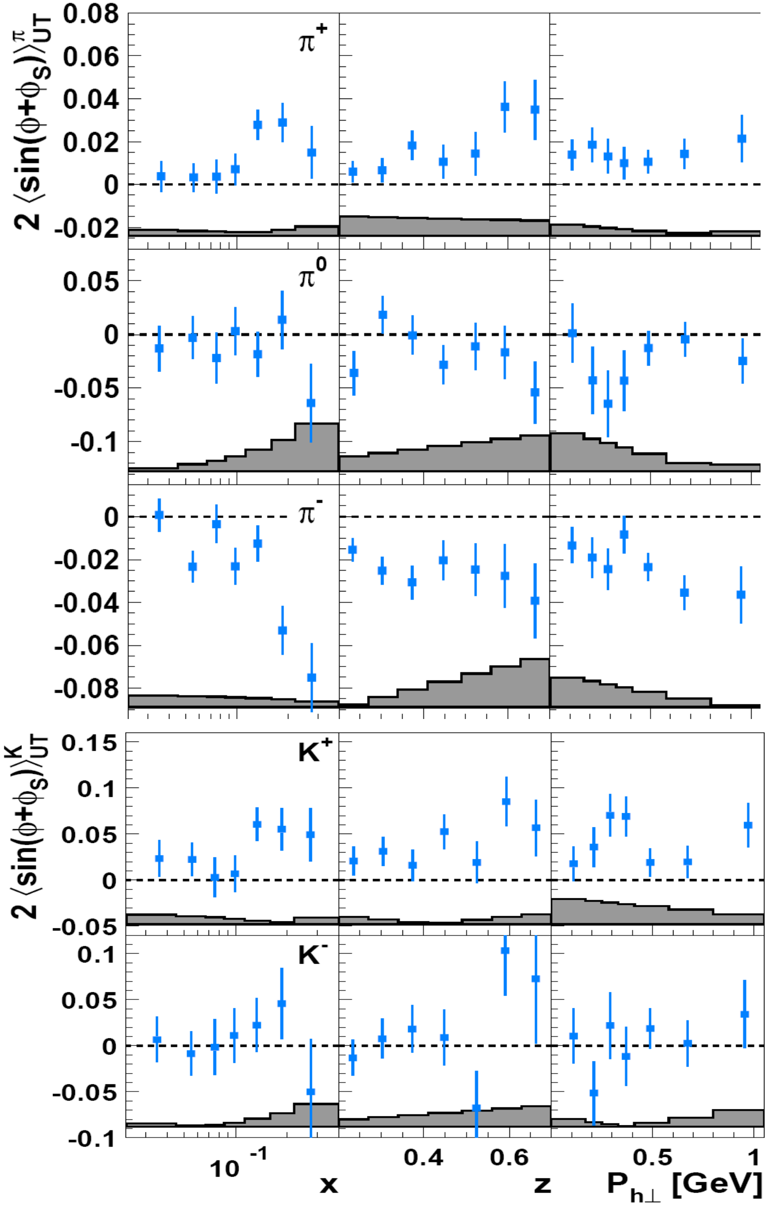

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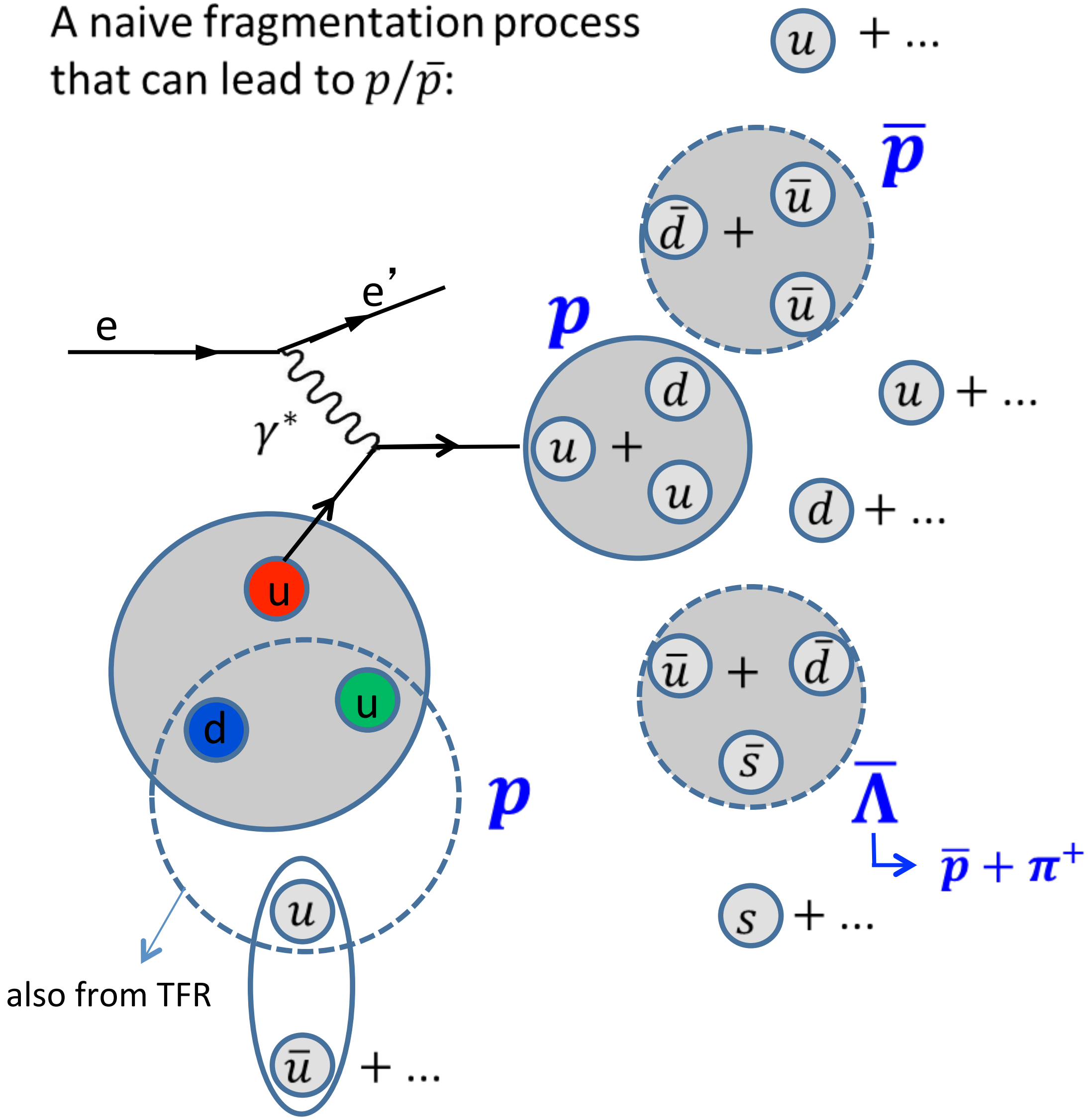

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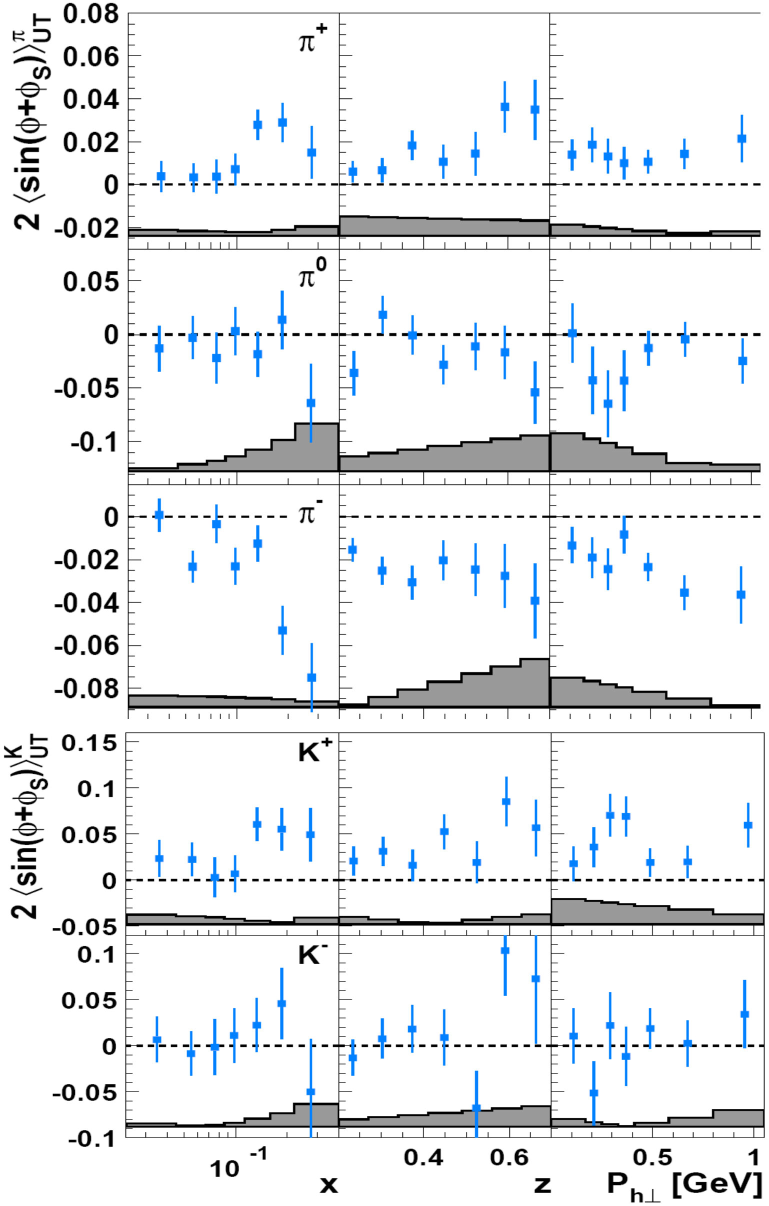

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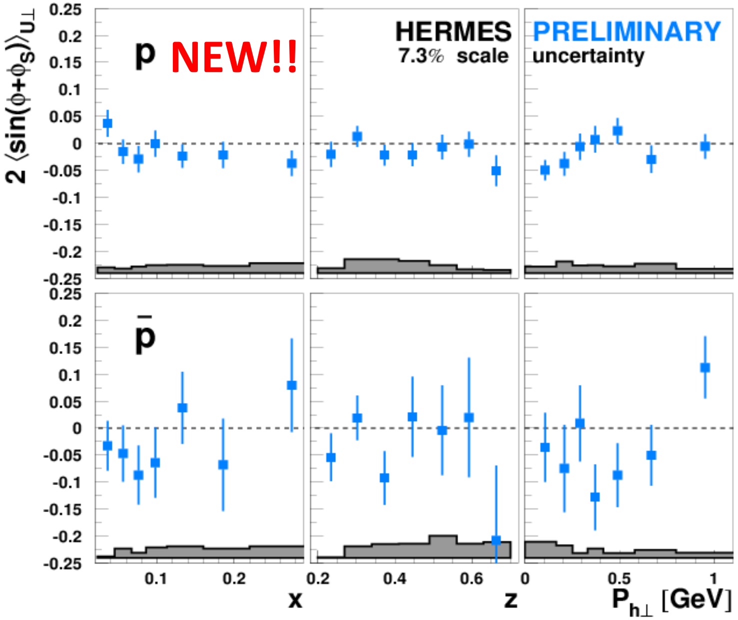


☛ ~ zero

☛ ~ zero

Sivers function

Describes correlation between quark transverse momentum and nucleon transverse polarization

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

$$\Big\{ \Big[F_{\mathrm{UU,T}}+\epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon\,(1+\epsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+\ \lambda_l\ \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

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

$$+\ S_L\ \lambda_l\ \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

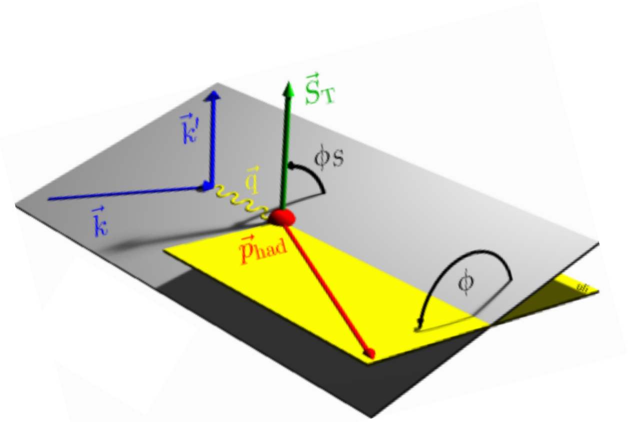
$$+\ S_T\ \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)}+\epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon\,(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

$$+\ S_T\ \lambda_l\ \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

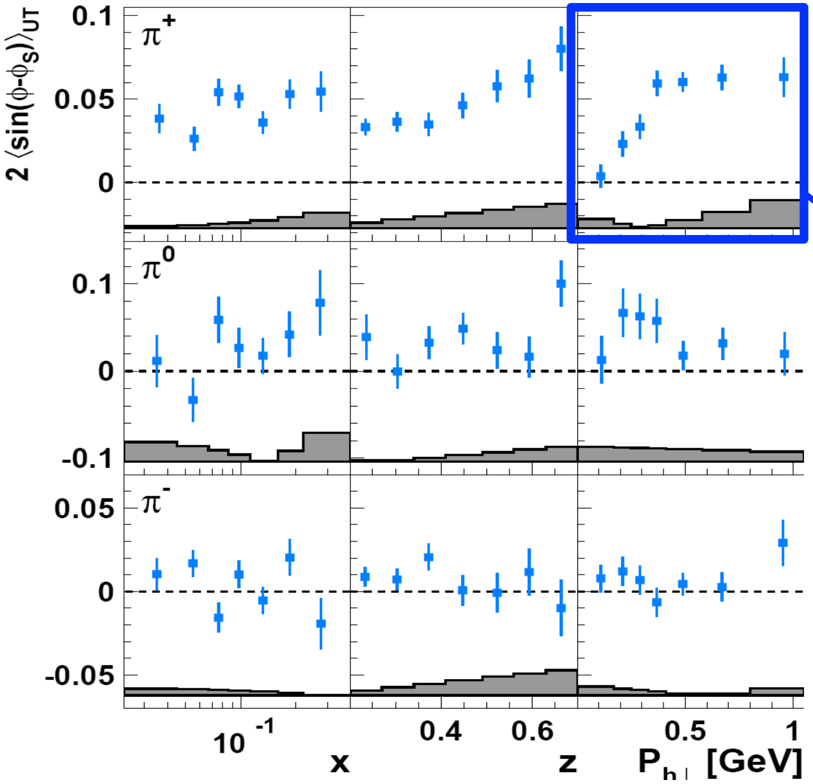
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}f_{1T}^{\perp}D_1\right]$$

Sivers

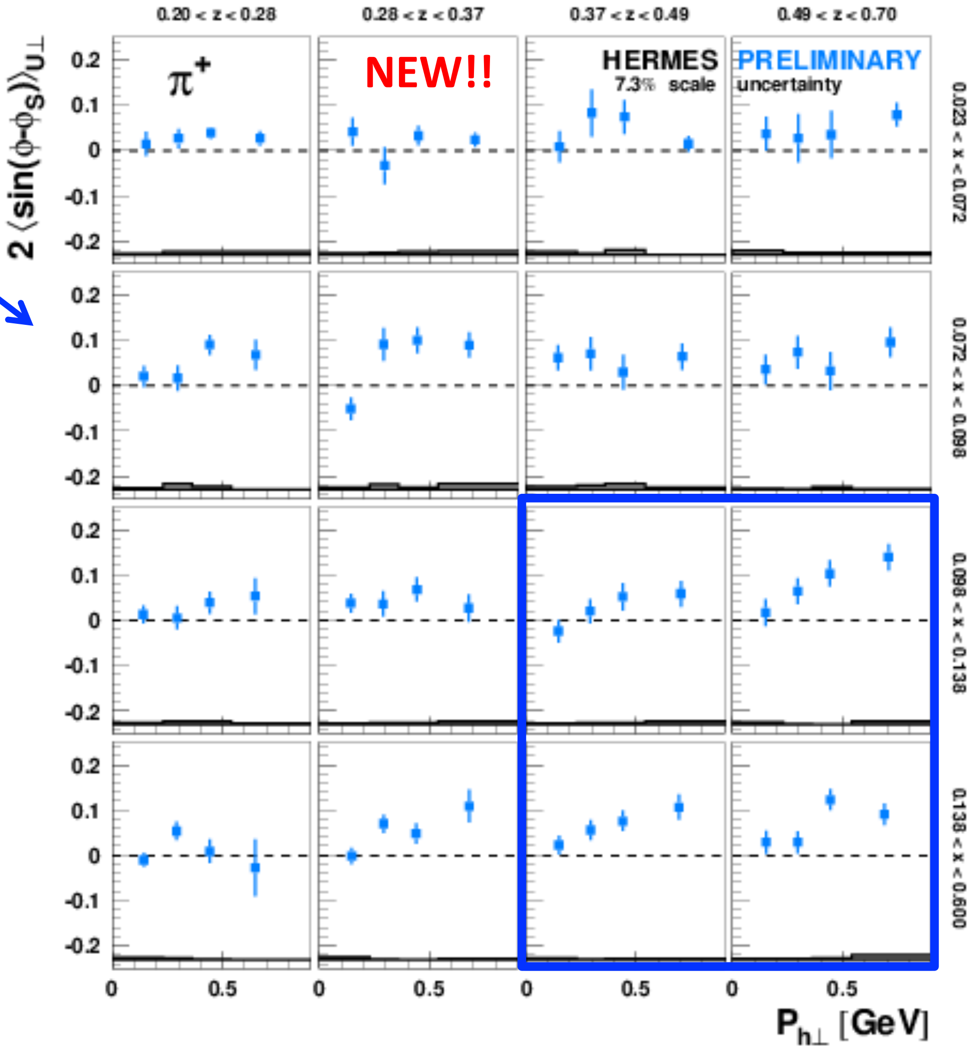
Unpol. FF



Sivers amplitudes $\propto f_{1T}^{\perp}(x,p_T^2)\otimes D_1(z,k_T^2)$



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



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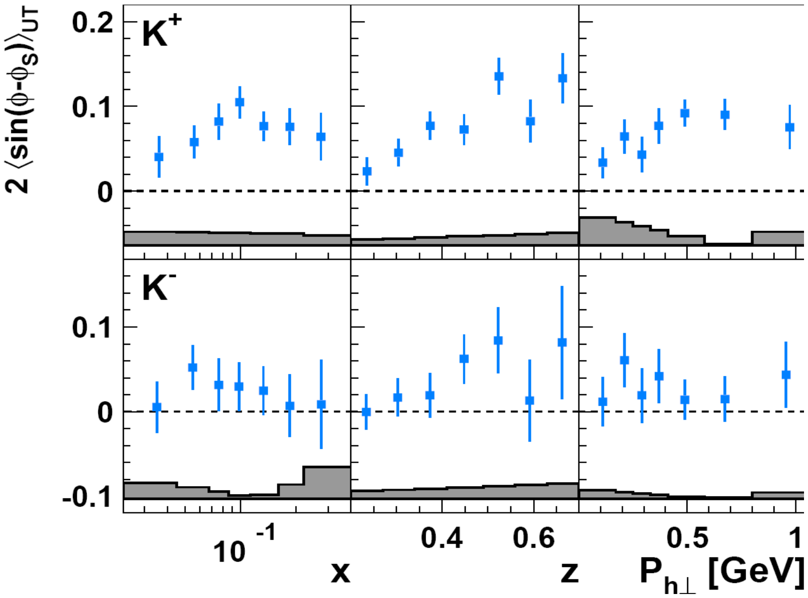
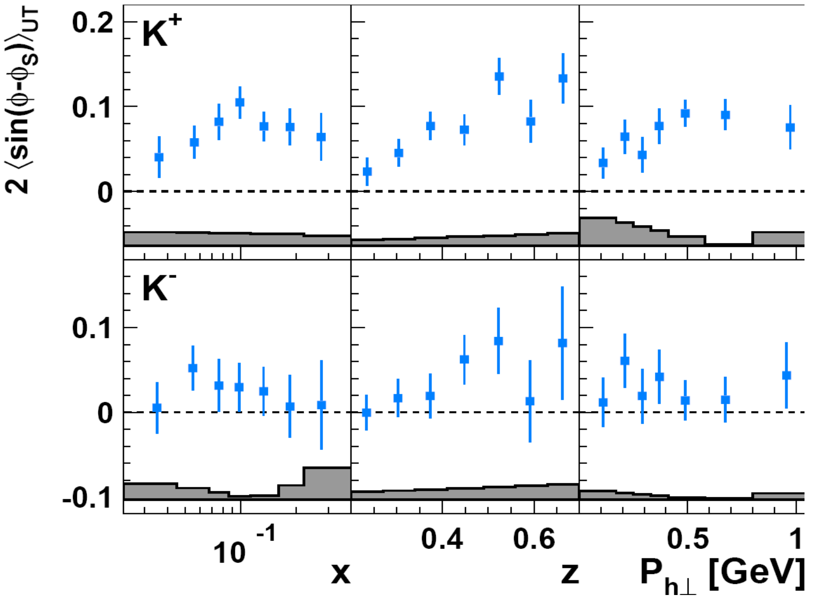
Airapetian *et al.*, Phys. Rev. Lett. 103 (2009)



☛ large & positive

☛ Slightly positive

Sivers amplitudes $\propto f_{1T}^{\perp}(x, p_T^2) \otimes D_1(z, k_T^2)$



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

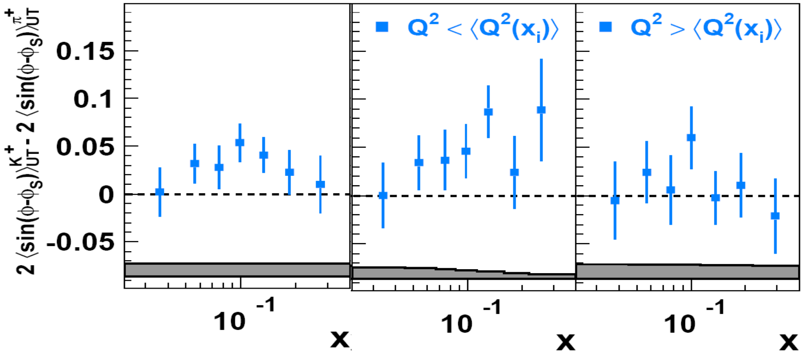
Flavor sensitivity reveals unexpected features:

K^+ amplitude larger than π^+!!

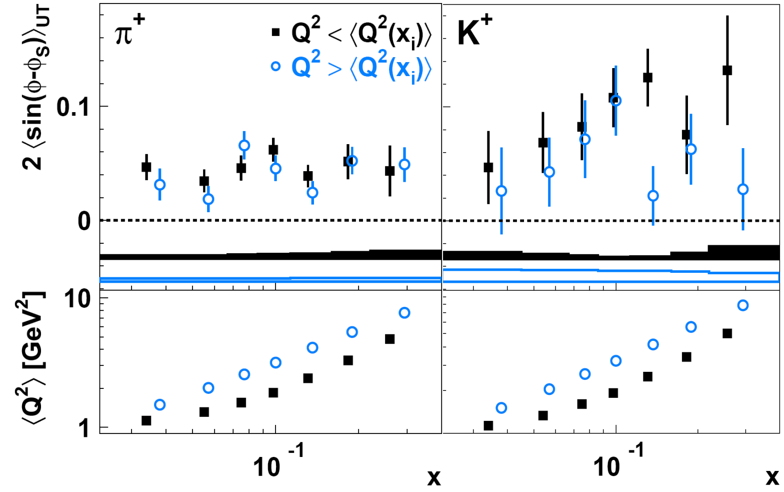
$\pi^+ \equiv |u\bar{d}\rangle, \; K^+ \equiv |u\bar{s}\rangle \;\rightarrow$

different role of sea quarks ?

Higher-twist contrib. for Kaons



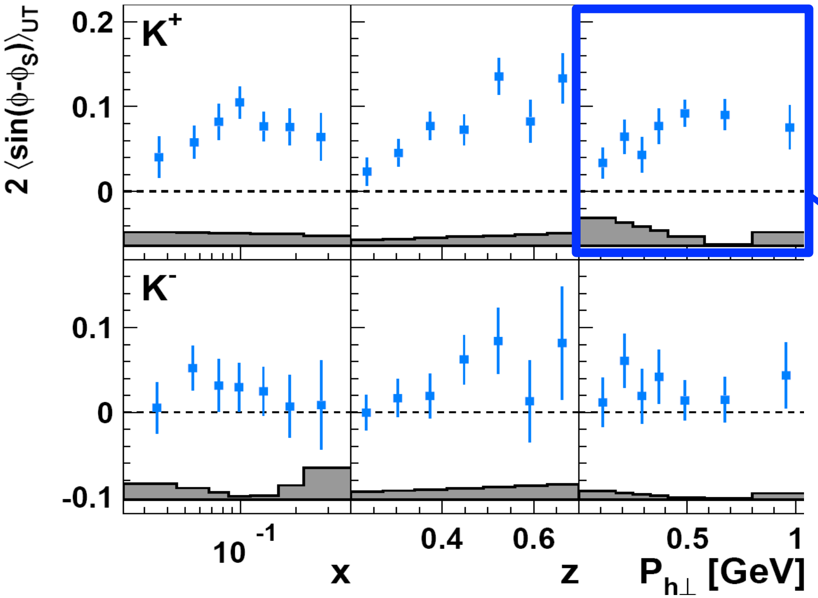
- only in low-Q² region significant (90% C.L.) deviation is observed

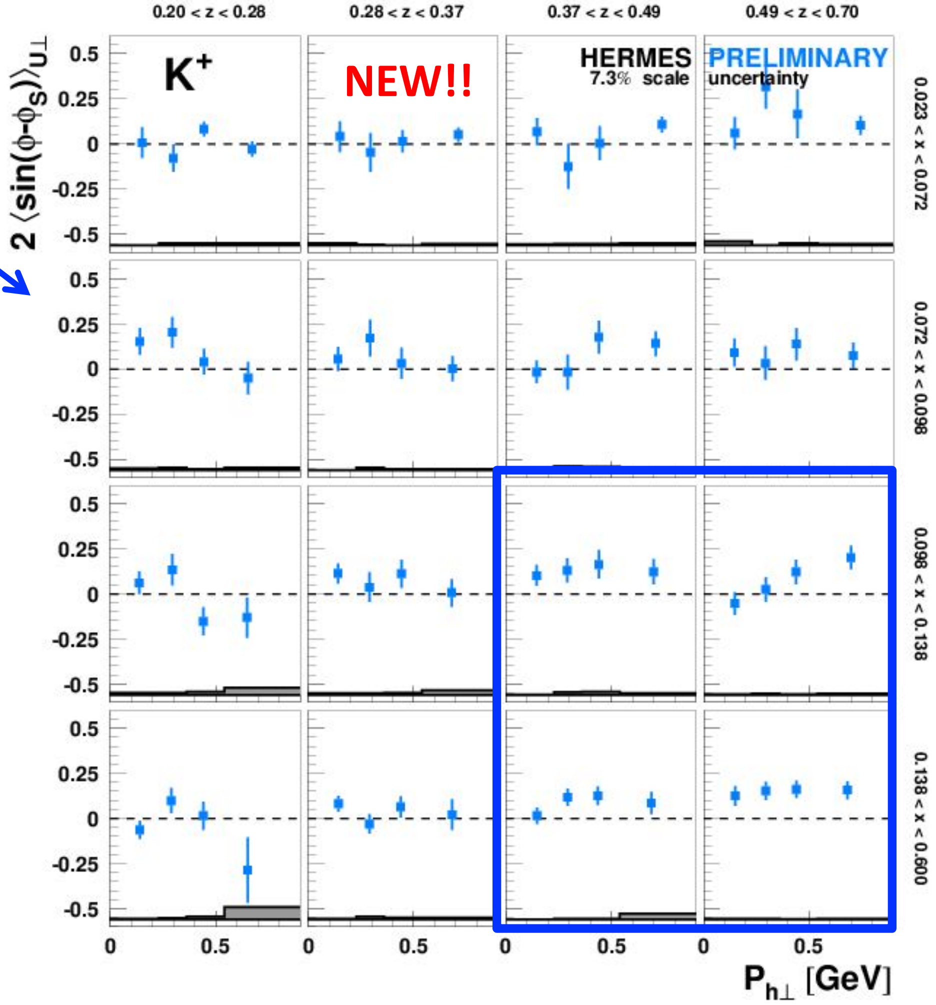


- each x-bin divided into two Q² bins
- no effect for pions, but hint of a systematic shifts for kaons

Sivers amplitudes $\propto f_{1T}^{\perp}(x,p_T^2)\otimes D_1(z,k_T^2)$

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





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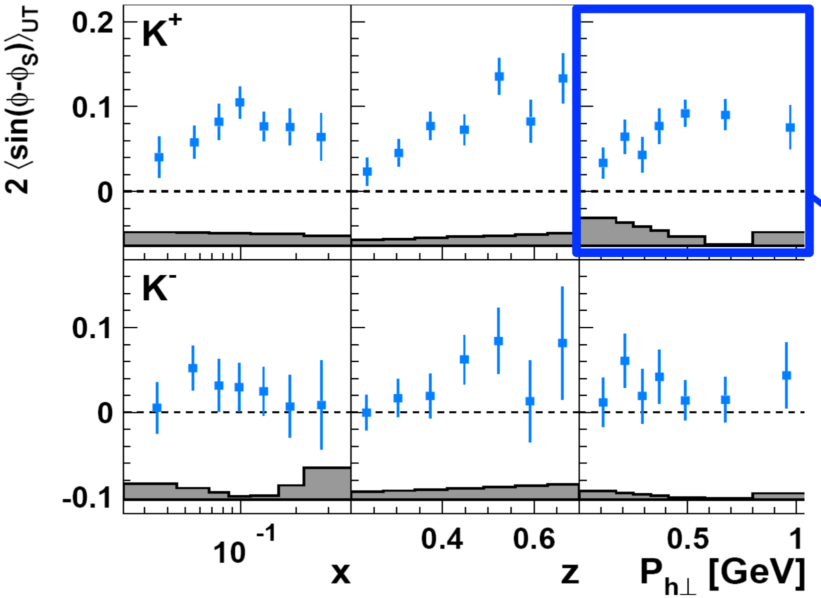
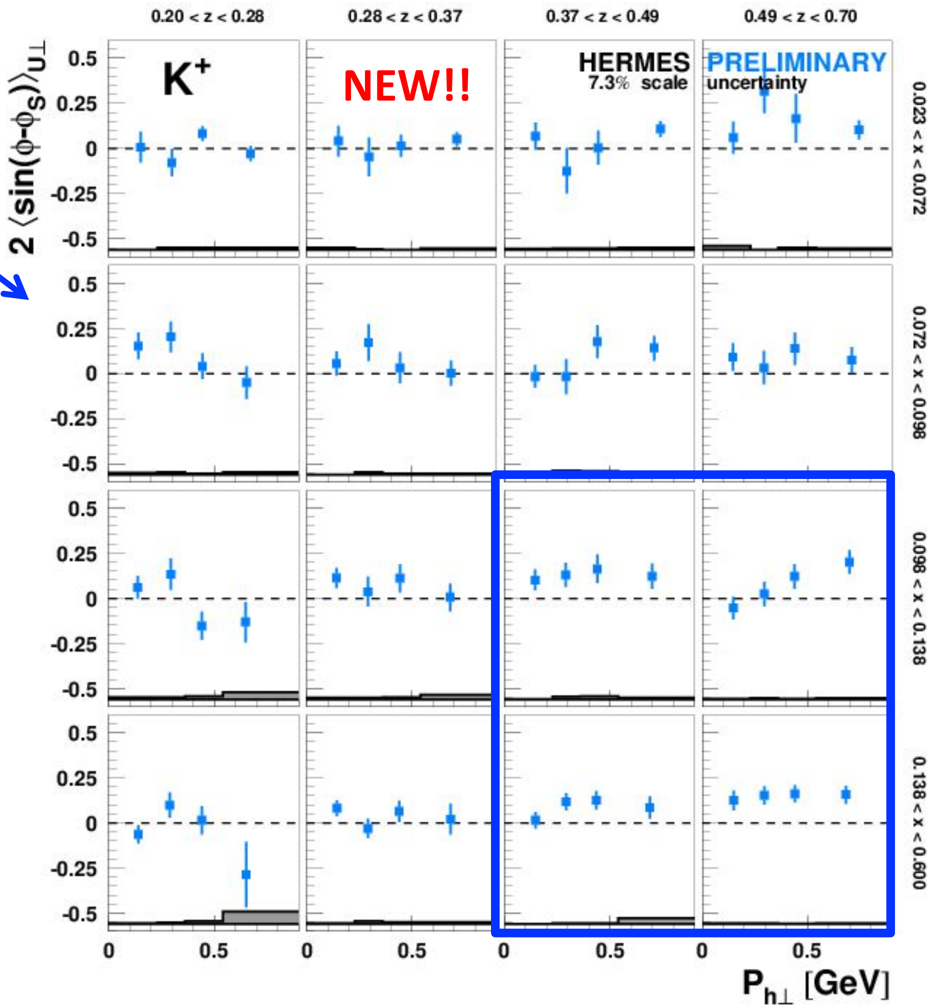
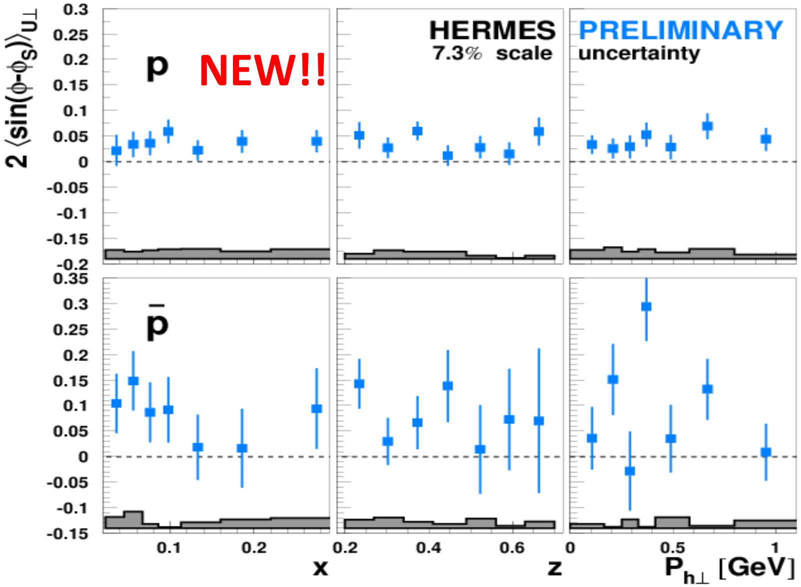
Airapetian *et al.*, Phys. Rev. Lett. 103 (2009)







First evidence of non-zero Sivers amplitudes for SIDIS protons!!

Sub-leading twist terms (1)

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

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

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

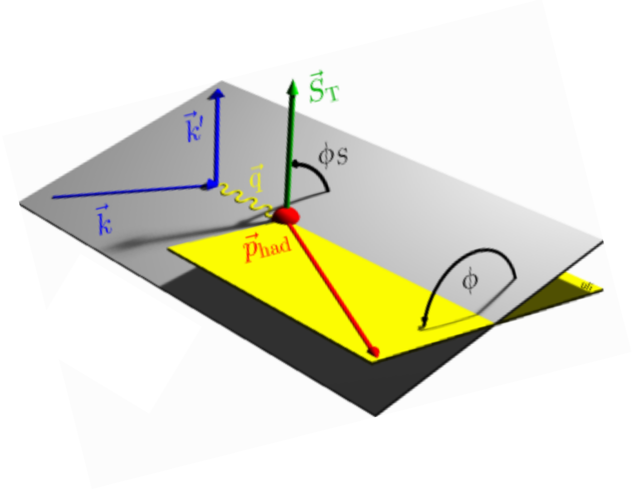
$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

$$\boxed{\begin{aligned} + S_T \Big[& \sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\ & + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\ & + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} \\ & + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \end{aligned}}$$

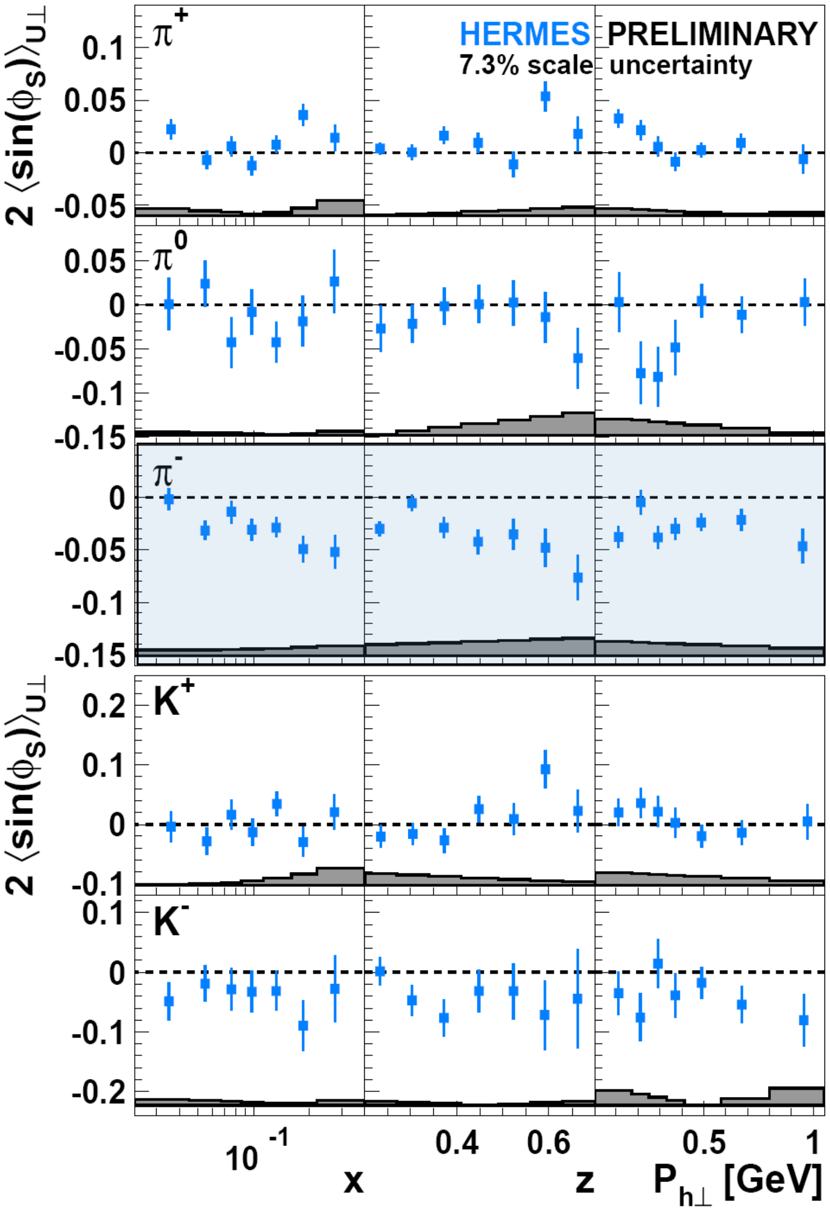
$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

Sensitive to worm-gear $g_{1T}^{\perp}$, sivers, transversity + higher-twist DF and FF

$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q}\,\mathcal{C}\Big\{\left(xf_T D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z}\right) - \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\Big[\left(xh_T H_1^{\perp} + \frac{M_h}{M} g_{1T}\frac{\tilde{G}^{\perp}}{z}\right) - \left(xh_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp}\frac{\tilde{D}^{\perp}}{z}\right)\Big]\Big\}$$

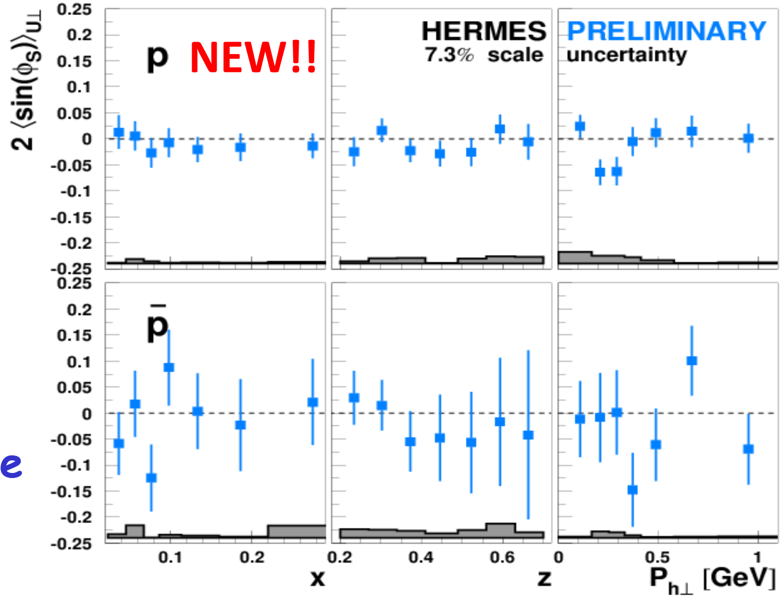


Subleading-twist sin(ϕ_S)

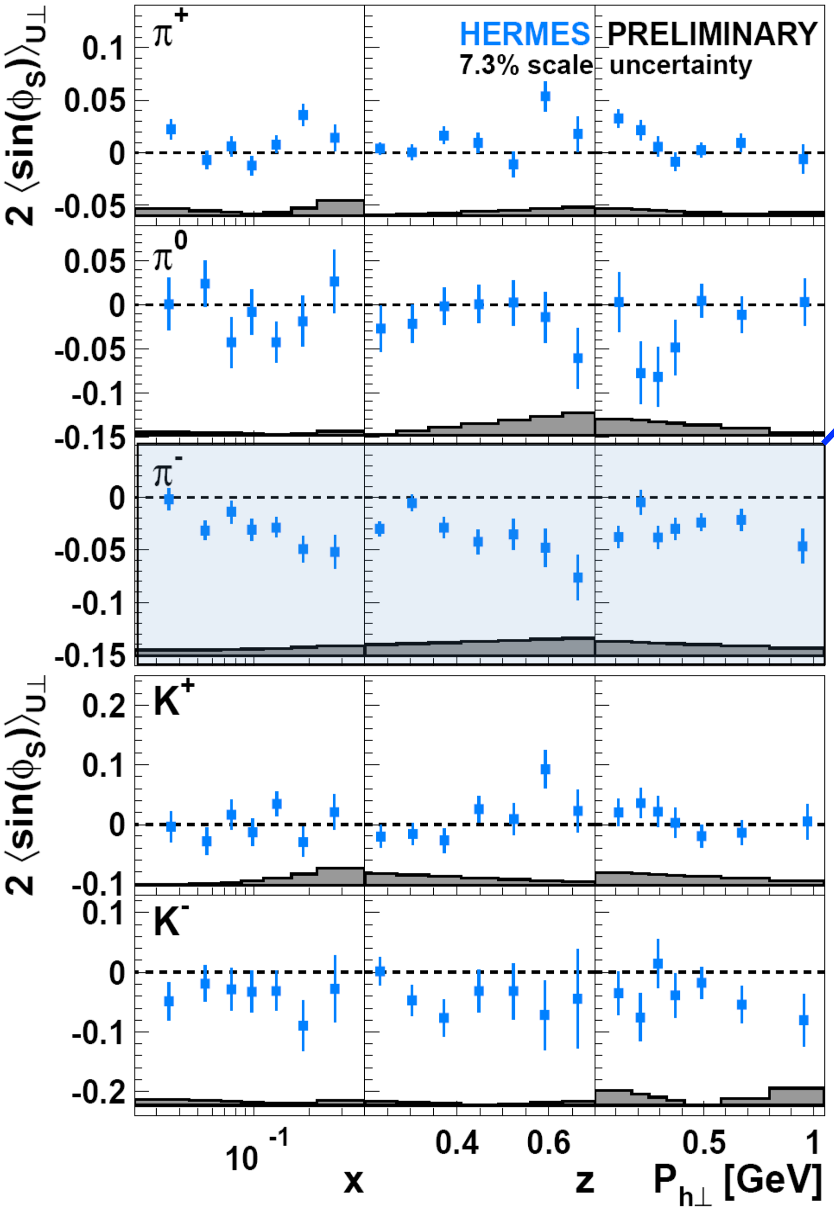


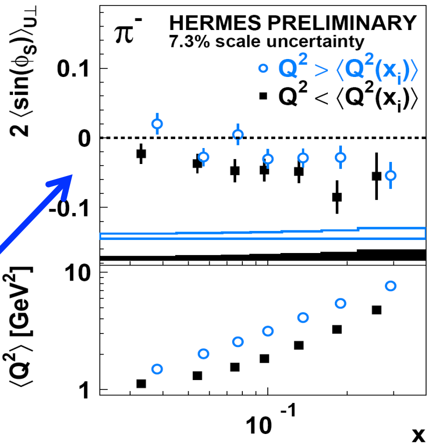
Large and negative

negative



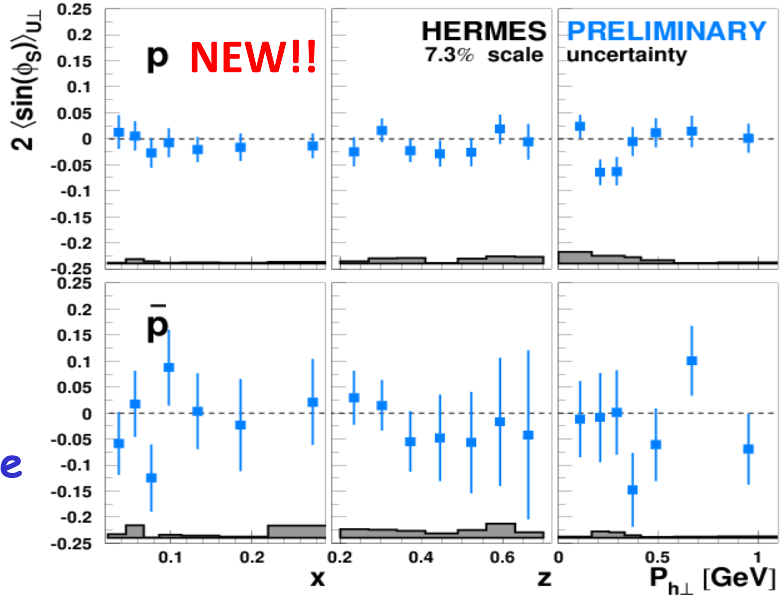
Subleading-twist $\sin(\phi_S)$





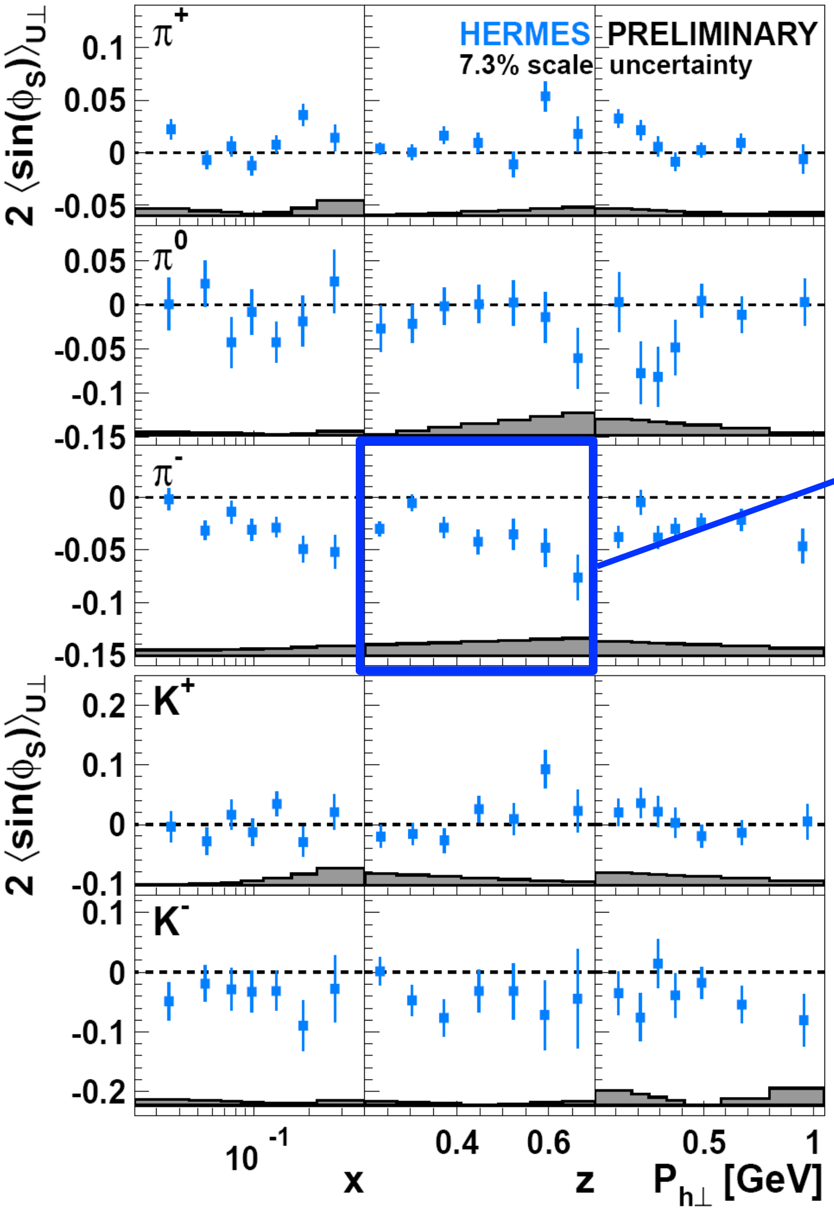
- low-Q^2 amplitude larger
- **hint of Q^2 dep. for π^-**

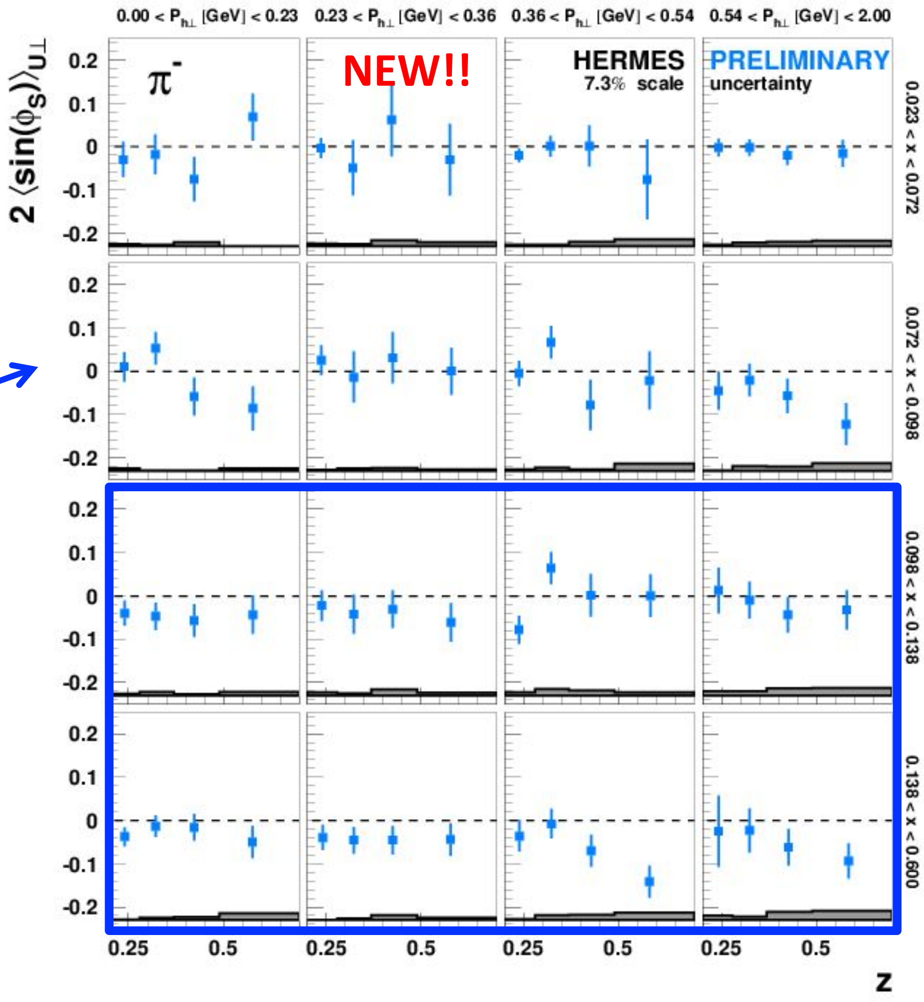
Large and negative



negative

Subleading-twist sin(ϕ_S)





Sub-leading twist terms (2)

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

$$\Big\{ \Big[F_{\rm UU,T} + \epsilon F_{\rm UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{\rm UU}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{\rm UU}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l\Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\rm LU}^{\sin(\phi)}\Big]$$

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

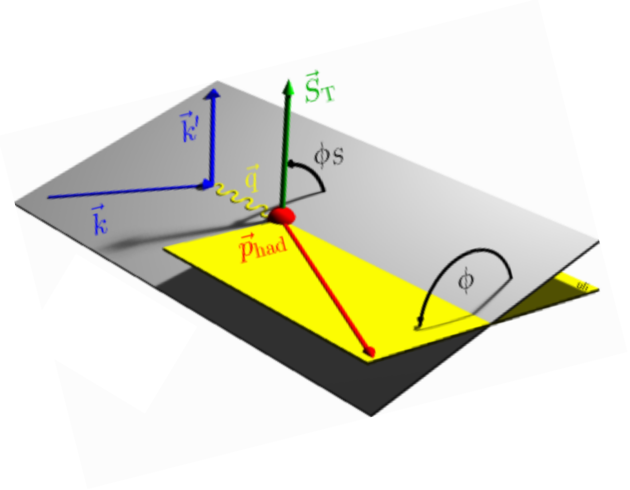
$$+ S_L\,\lambda_l\Big[\sqrt{1-\epsilon^2}F_{\rm LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\rm LL}^{\cos(\phi)}\Big]$$

$$+ S_T\Big[\sin(\phi-\phi_S)\Big(F_{\rm UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{\rm UT,L}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S)F_{\rm UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\rm UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\rm UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\rm UT}^{\sin(2\phi-\phi_S)}\Big]$$

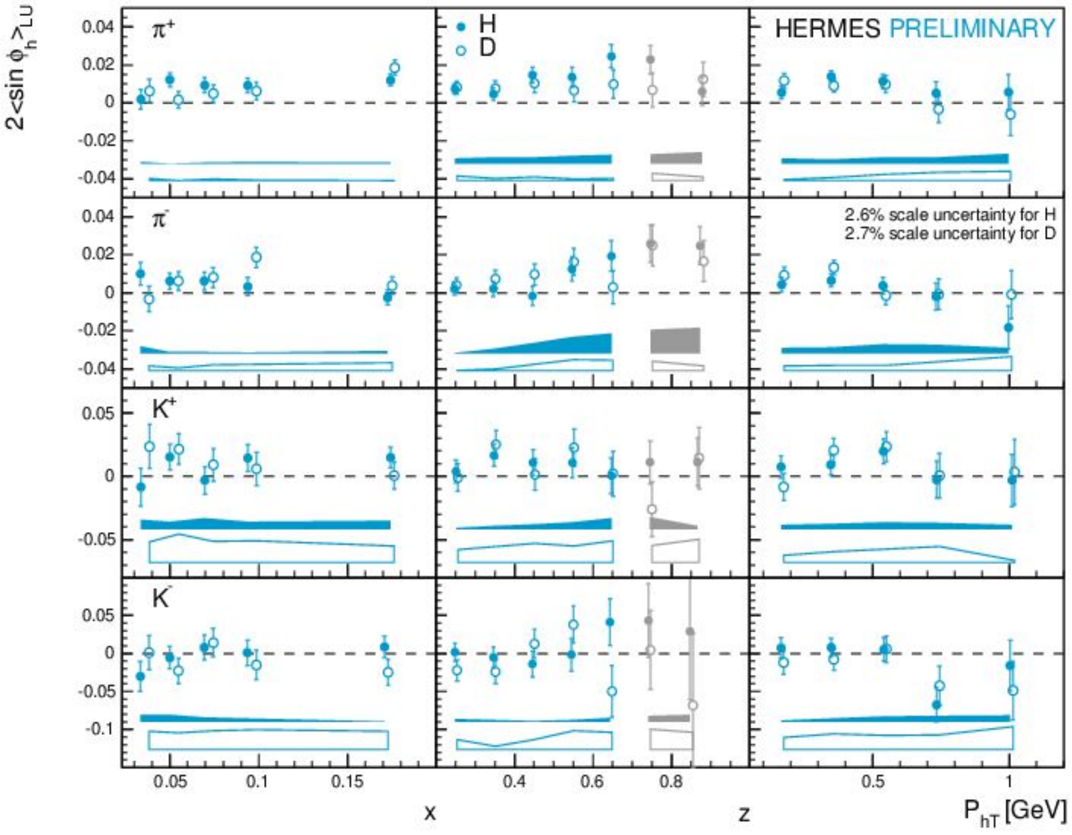
$$+ S_T\,\lambda_l\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\rm LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\rm LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\rm LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

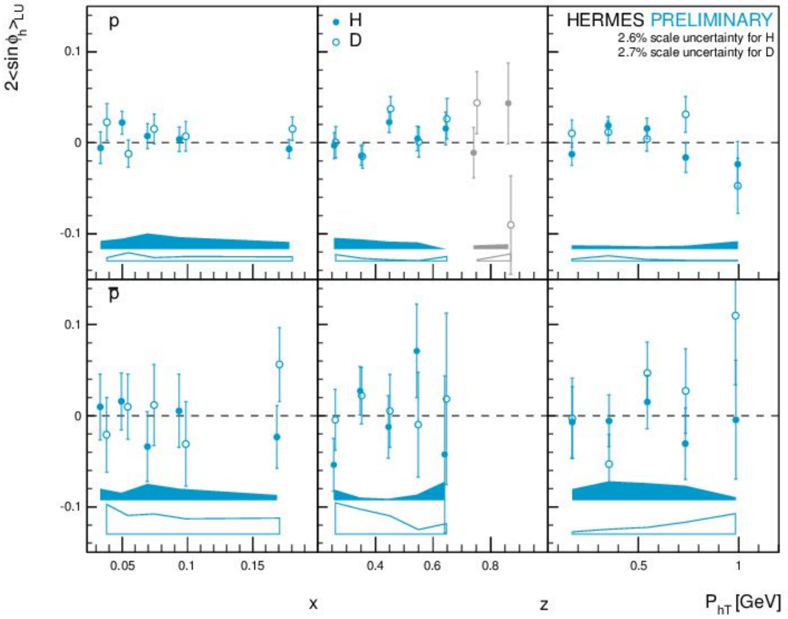
Sensitive to f_1 , Boer-Mulders + higher-twist DF and FF

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$



Subleading-twist sin(ϕ) BSA





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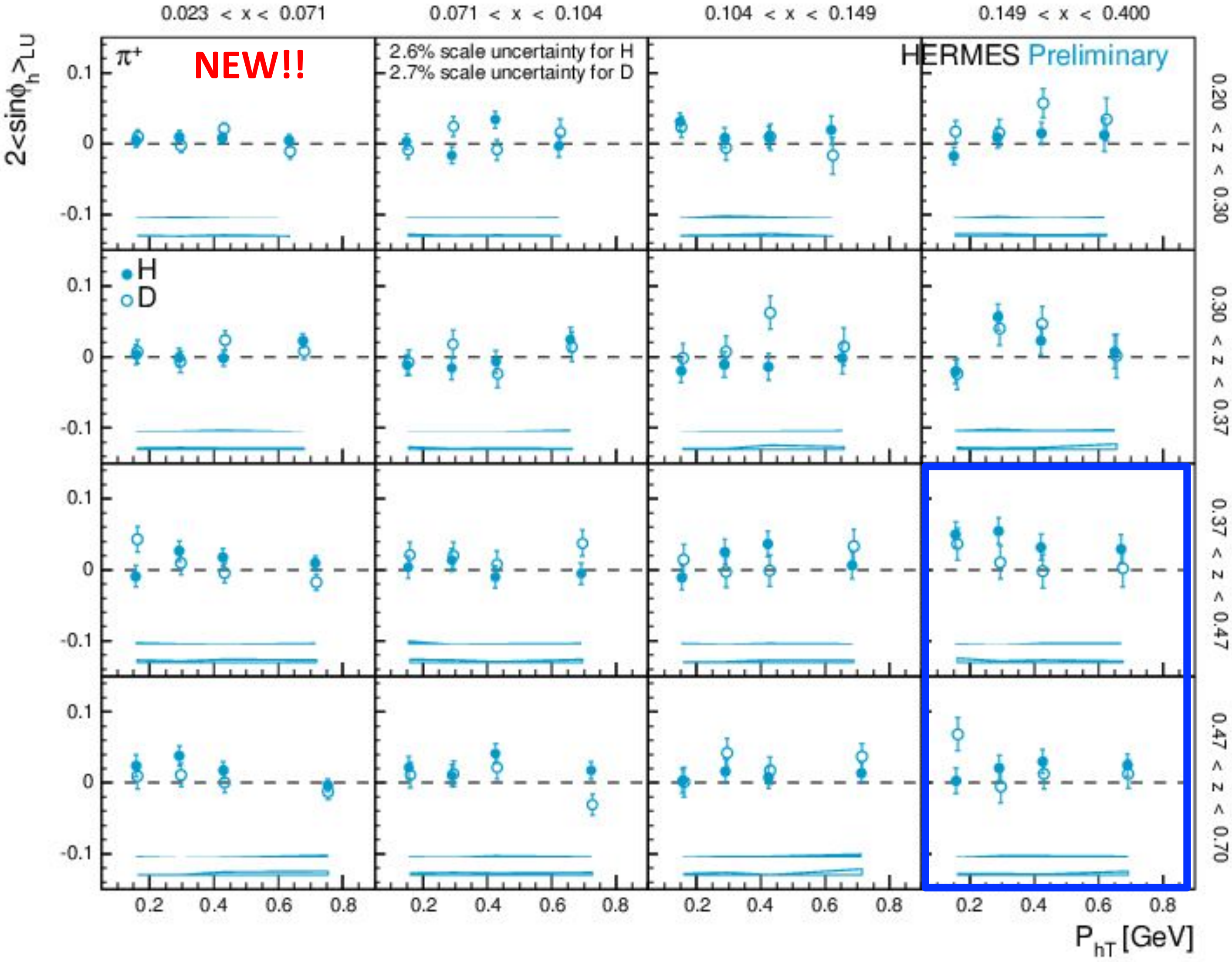

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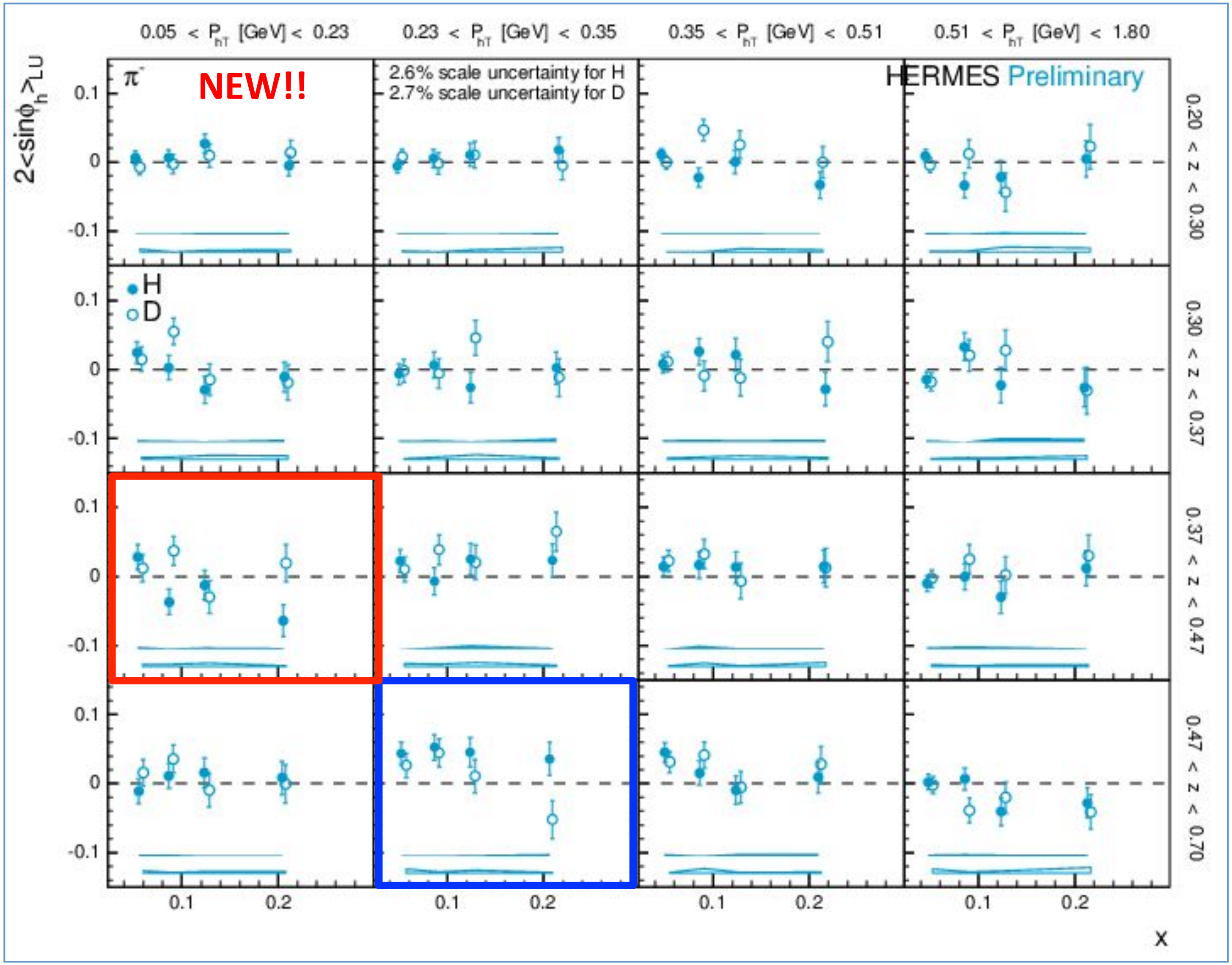
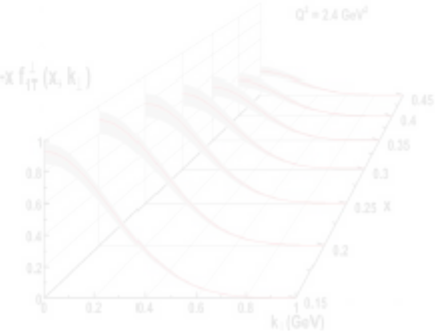
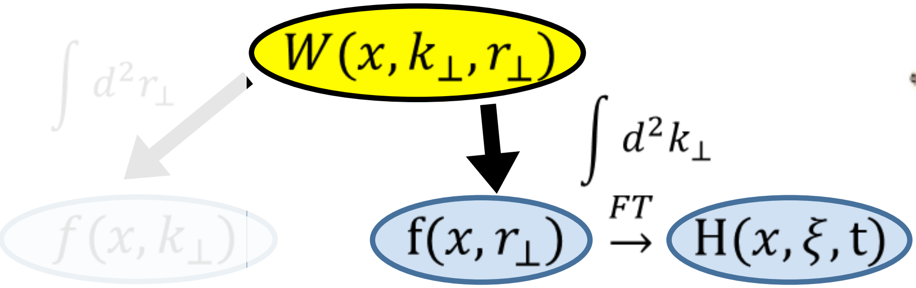


Mapping the phase-space of the nucleon



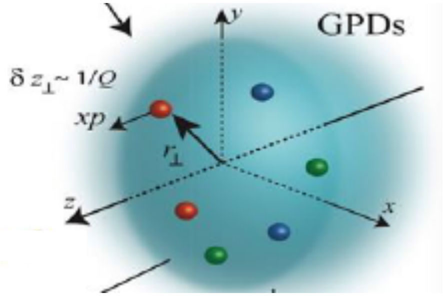
TMDs: 3D description in longitudinal (x) and transverse ($k_\perp$) mom.

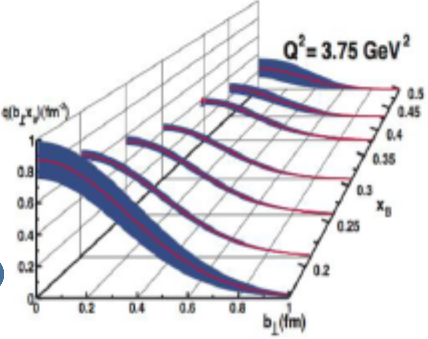


$W(x, k_\perp, r_\perp)$

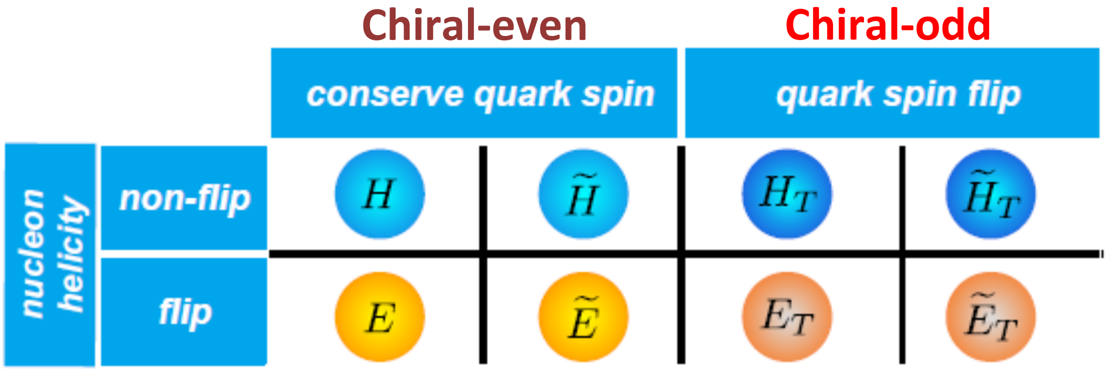
$\int d^2 r_\perp$ $f(x, k_\perp)$

$\int d^2 k_\perp$ $f(x, r_\perp) \xrightarrow{FT} H(x, \xi, t)$



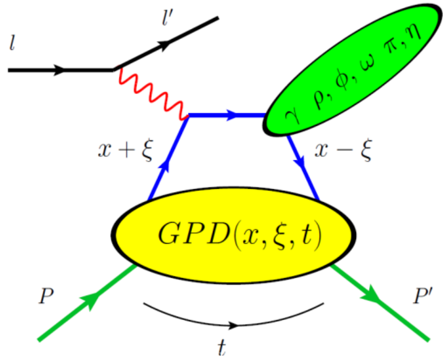


GPDs: 3D description in longit. momentum (x) and transverse location ($r_\perp$)



		Chiral-even		Chiral-odd	
		conserve quark spin		quark spin flip	
nucleon helicity	non-flip	H	$\widetilde{H}$	H_T	$\widetilde{H}_T$
	flip	E	$\widetilde{E}$	E_T	$\widetilde{E}_T$

Exclusive processes (DVCS, DVMP)



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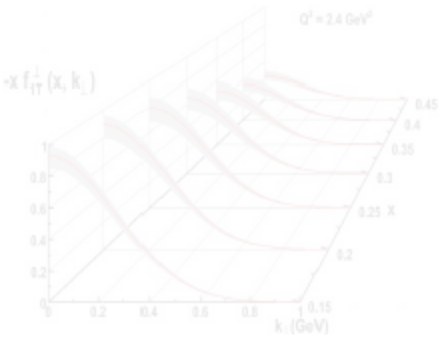

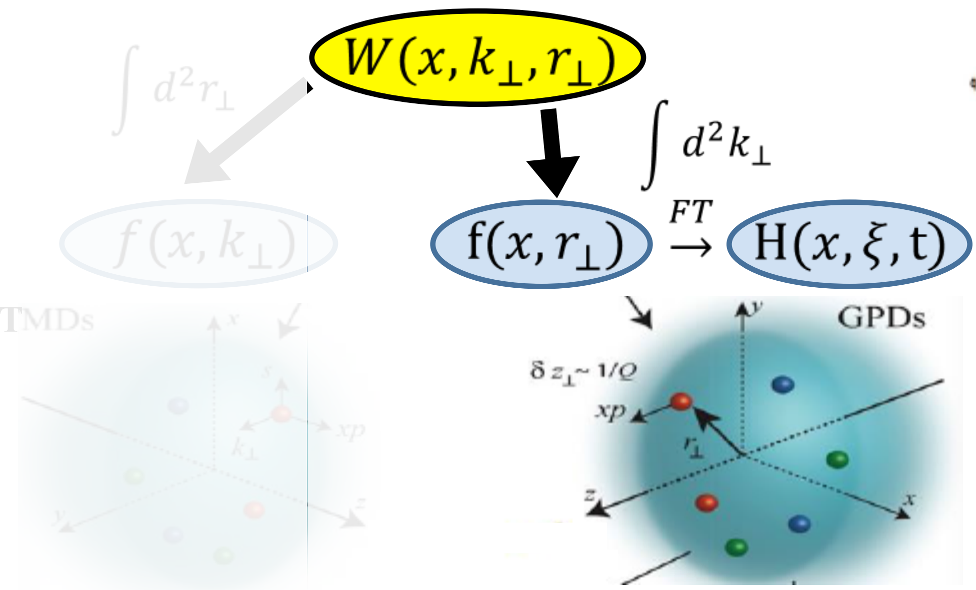

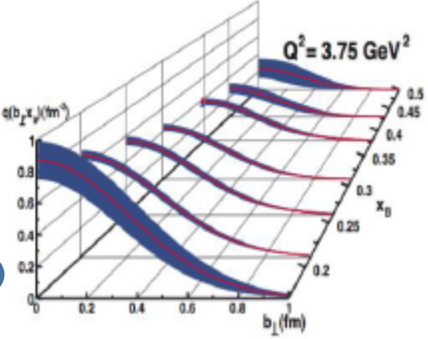

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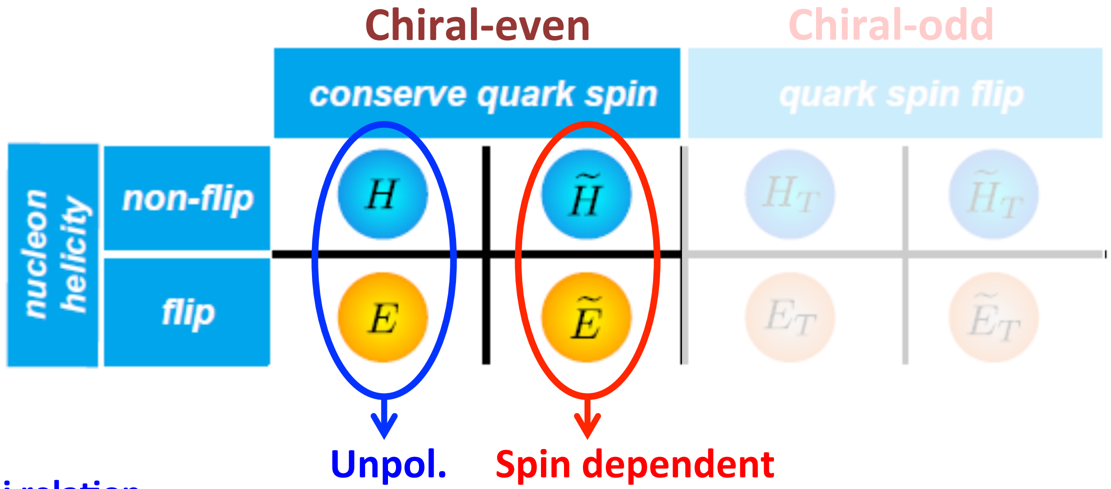

		Chiral-even		Chiral-odd	
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nucleon helicity	non-flip	H	$\tilde{H}$	H_T	$\tilde{H}_T$
	flip	E	$\tilde{E}$	E_T	$\tilde{E}_T$

Unpol. Spin dependent

Ji relation

$$\lim_{t\to 0}\int_0^1 \mathrm{d}x\; x\,(H_q(x,\xi,t)+E_q(x,\xi,t)) = J_q$$

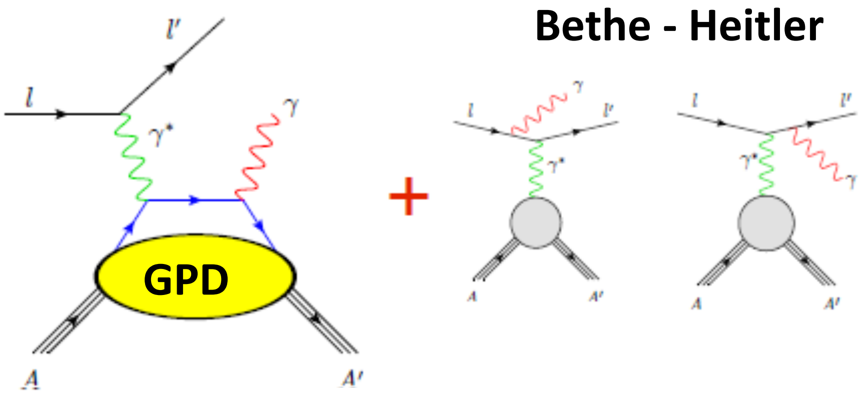
> **DVCS**
- at leading twist:
  H E $\tilde{H}$ $\tilde{E}$

> **vector mesons:**
- at leading twist: H E
- higher twist: $\tilde{H}$ $\tilde{E}$

> **pseudoscalar mesons**
- at leading twist: $\tilde{H}$ $\tilde{E}$
- higher twist: H_T

Deeply Virtual Compton Scattering (DVCS)

- Cleanest probe of GPDs
- Theoretical accuracy at NNLO
- GPDs are accessed through convolution integrals with hard scattering amplitudes (CFFs)
- Experimental observables are: azimuthal asymmetries, cross-secrion



$$\begin{aligned}
d\sigma \sim d\sigma^{BH}_{UU} &+ e_\ell d\sigma^{I}_{UU} + d\sigma^{DVCS}_{UU} \\
&+ e_\ell P_\ell d\sigma^{I}_{LU} + P_\ell d\sigma^{DVCS}_{LU} \\
&+ e_\ell S_L d\sigma^{I}_{UL} + S_L d\sigma^{DVCS}_{UL} \\
&+ e_\ell S_T d\sigma^{I}_{UT} + S_T d\sigma^{DVCS}_{UT} \\
+P_\ell S_L d\sigma^{BH}_{LL} &+ e_\ell P_\ell S_L d\sigma^{I}_{LL} + P_\ell S_L d\sigma^{DVCS}_{LL} \\
+P_\ell S_T d\sigma^{BH}_{LT} &+ e_\ell P_\ell S_T d\sigma^{I}_{LT} + P_\ell S_T d\sigma^{DVCS}_{LT}
\end{aligned}$$

$$\frac{d\sigma}{dx_B dQ^2 d|t| d\phi} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{DVCS}\mathcal{T}^*_{BH} + \mathcal{T}_{BH}\mathcal{T}^*_{DVCS}}_{I}$$

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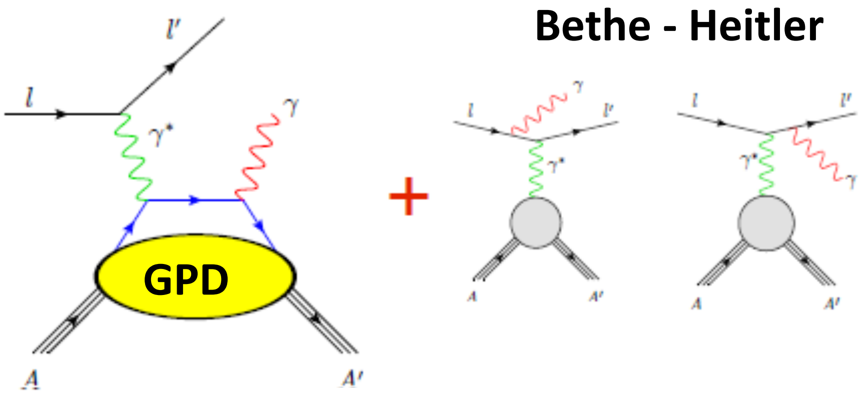

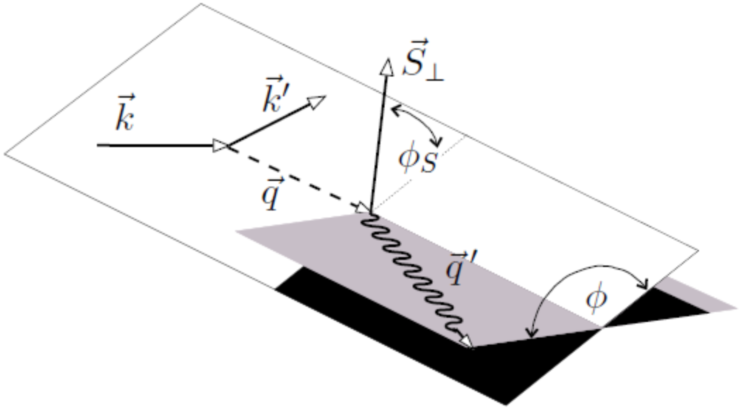

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At Hermes $|T_{DVCS}|^2 \ll |T_{BH}|^2 \Rightarrow$ DVCS amplitudes mainly accessed through Interference terms

- Beam-Charge asymmetry
  $\sigma(e^+,\phi) - \sigma(e^-,\phi) \propto Re[F_1\mathcal{H}]$
- Beam-Spin Asymmetry
  $\sigma(\overrightarrow{e},\phi) - \sigma(\overleftarrow{e},\phi) \propto Im[F_1\mathcal{H}]$
- Longitudinal Target-Spin Asymmetry
  $\sigma(\overset{\Rightarrow}{P},\phi) - \sigma(\overset{\Leftarrow}{P},\phi) \propto Im[F_1\widetilde{\mathcal{H}}]$
- Longitudinal Double-Spin Asymmetry
  $\sigma(\overset{\Rightarrow}{P},\overrightarrow{e},\phi) - \sigma(\overset{\Rightarrow}{P},\overleftarrow{e},\phi) \propto Re[F_1\widetilde{\mathcal{H}}]$
- Transverse Target-Spin Asymmetry
  $\sigma(\phi,\phi_S) - \sigma(\phi,\phi_S+\pi) \propto Im[F_2\mathcal{H} - F_1\mathcal{E}]$
- Transverse Double-Spin Asymmetry
  $\sigma(\overrightarrow{e},\phi,\phi_S) - \sigma(\overleftarrow{e},\phi,\phi_S+\pi) \propto Re[F_2\mathcal{H} - F_1\mathcal{E}]$

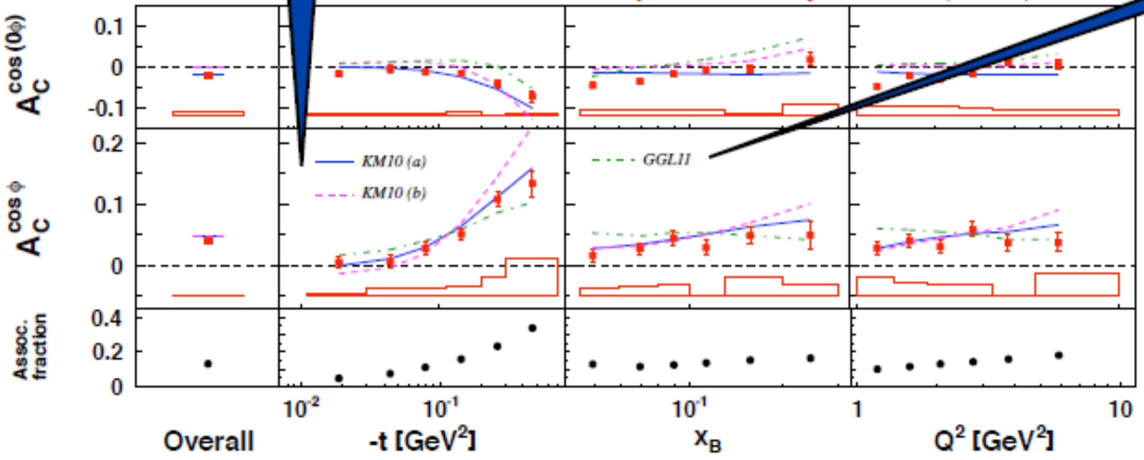
Beam-Charge & Beam-Helicity Asymmetries → H

KM10: Global fit
K. Kumericki, D. Muller
Nucl.Phys.B 841(2010) 1

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

Airapetian el al. JHEP 07 (2012) 032

GGL11: Model calculation
G. Goldstein, S. Liuti,
J. Hernandez
Phys.Rev.D 84 034007 (2011)



Beam-charge asymmetry:

- Non-zero leading amplitude
- Strong $-t$ dependence
- Mild dependence on x_B, Q^2

Fractions of associated process from MC

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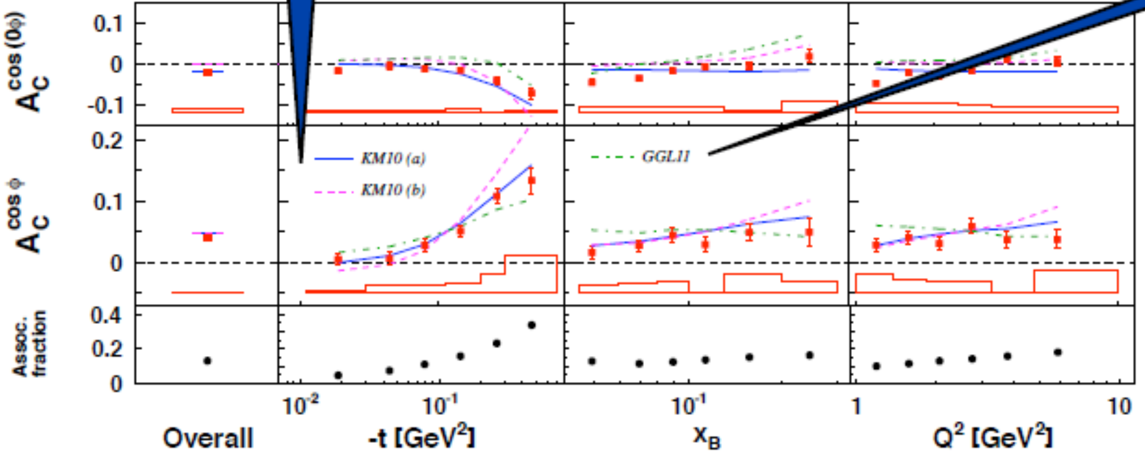

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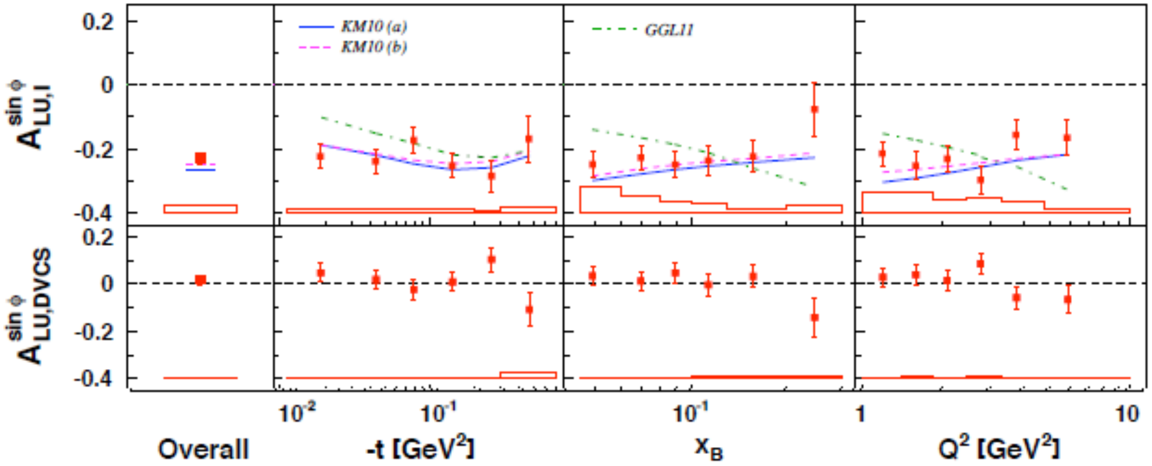


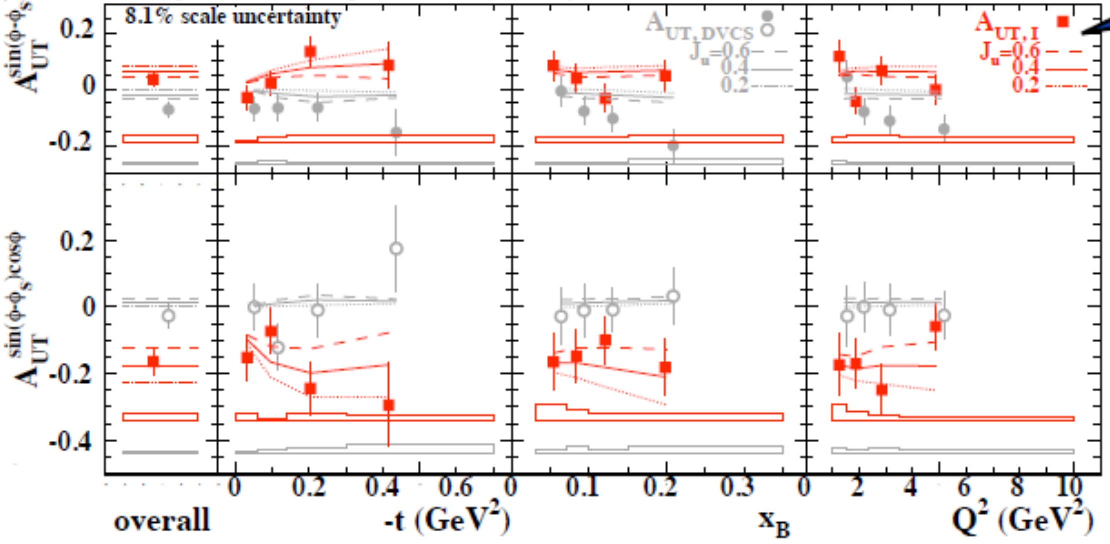
Combined beam-charge and beam-helicity asymmetry

- Leading amplitude large & negative
- Mild dependence of kinematic var.

Transverse Target-Spin Asymmetries → E $\widetilde{H}$ $\widetilde{E}$

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

Airapetian el al. JHEP 06 (2008) 066



VGG: Model calculation
M.Vanderhaeghen, P. Guichon, M. Guidal
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

Combined beam-charge & transverse target spin asymmetry

- Leading amplitude large & negative

Transverse Target-Spin Asymmetries → E $\widetilde{H}$ $\widetilde{E}$

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

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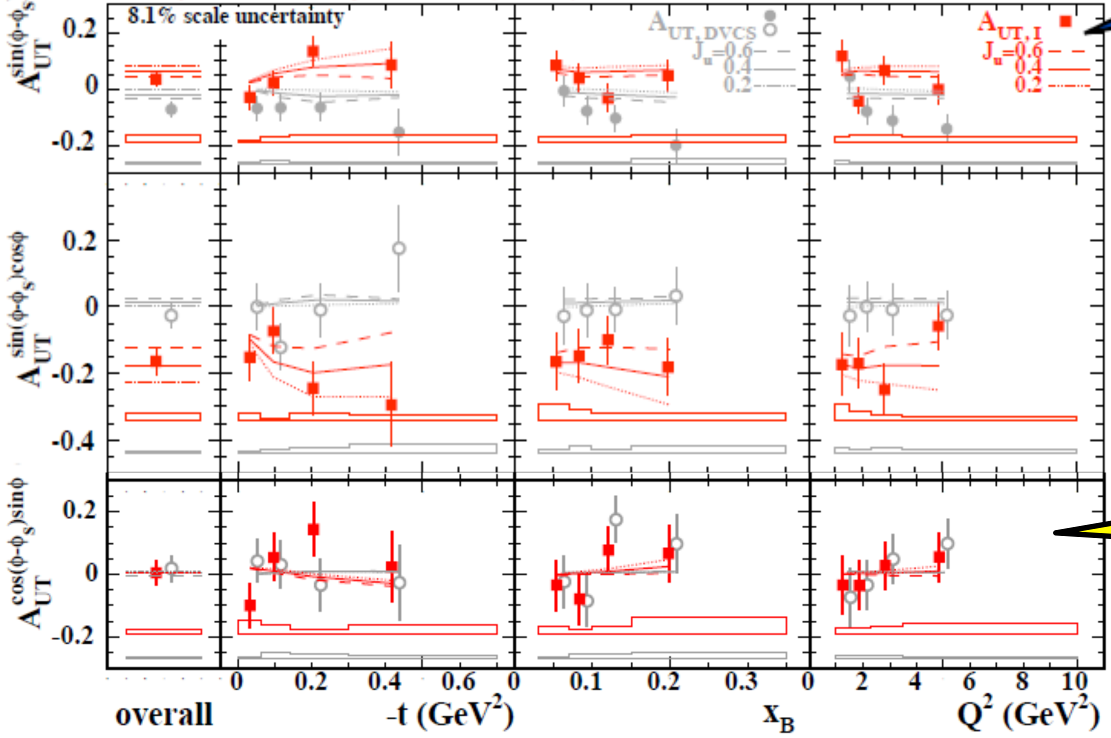

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Combined beam-charge & transverse target spin asymmetry

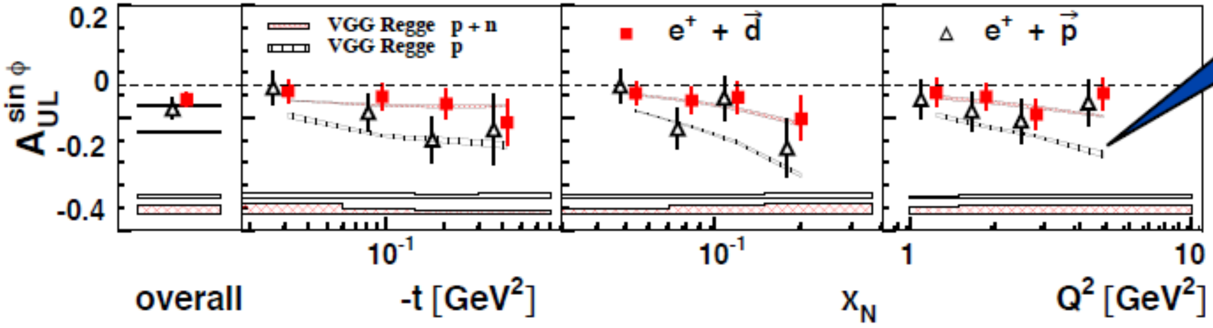
- Leading amplitude large & negative

Sensitive to $\widetilde{H}$ and $\widetilde{E}$ but consistent with zero

Longitudinal Target-Spin Asymmetries → $\widetilde{H}$

Airapetian et. al..Nucl. Phys. B 842 (2011)

$$A_{UL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}$$



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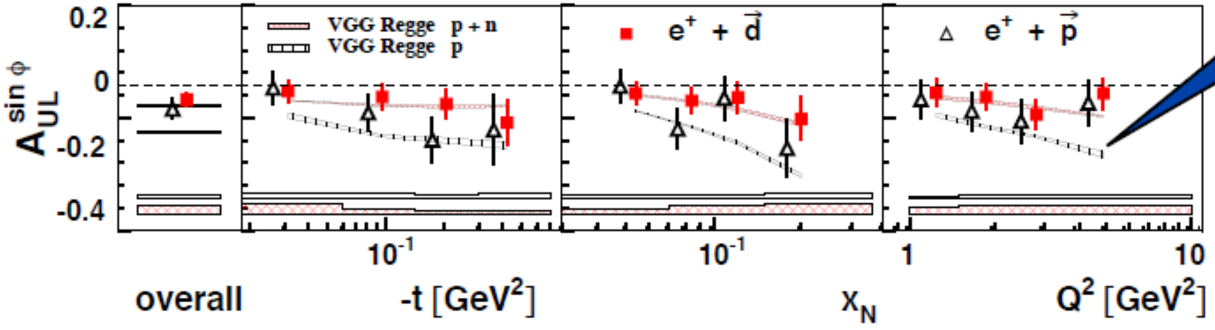
Longitud. target spin asymmetry

- Non-zero sin ϕ amplitude on both H and D targets
- Results on H and D targets compatible within uncertainties
- **Results on deuteron neither support nor disfavor large contribution from the neutron**

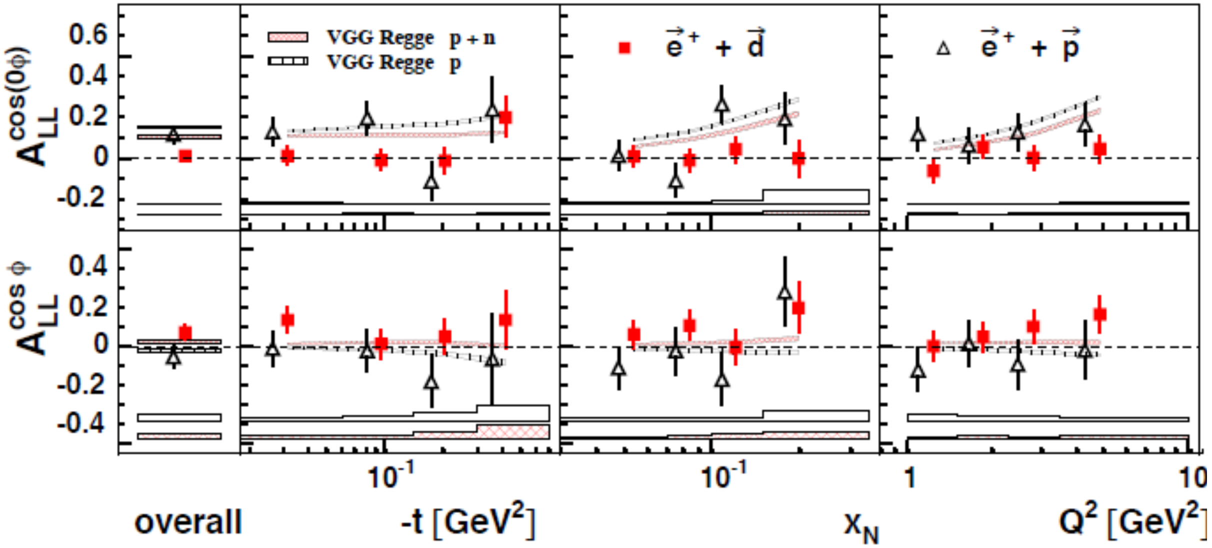
Longitudinal Target-Spin Asymmetries → $\widetilde{H}$

Airapetian et. al..Nucl. Phys. B 842 (2011)

$$A_{UL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}$$



$$A_{LL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Rightarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Rightarrow})}$$



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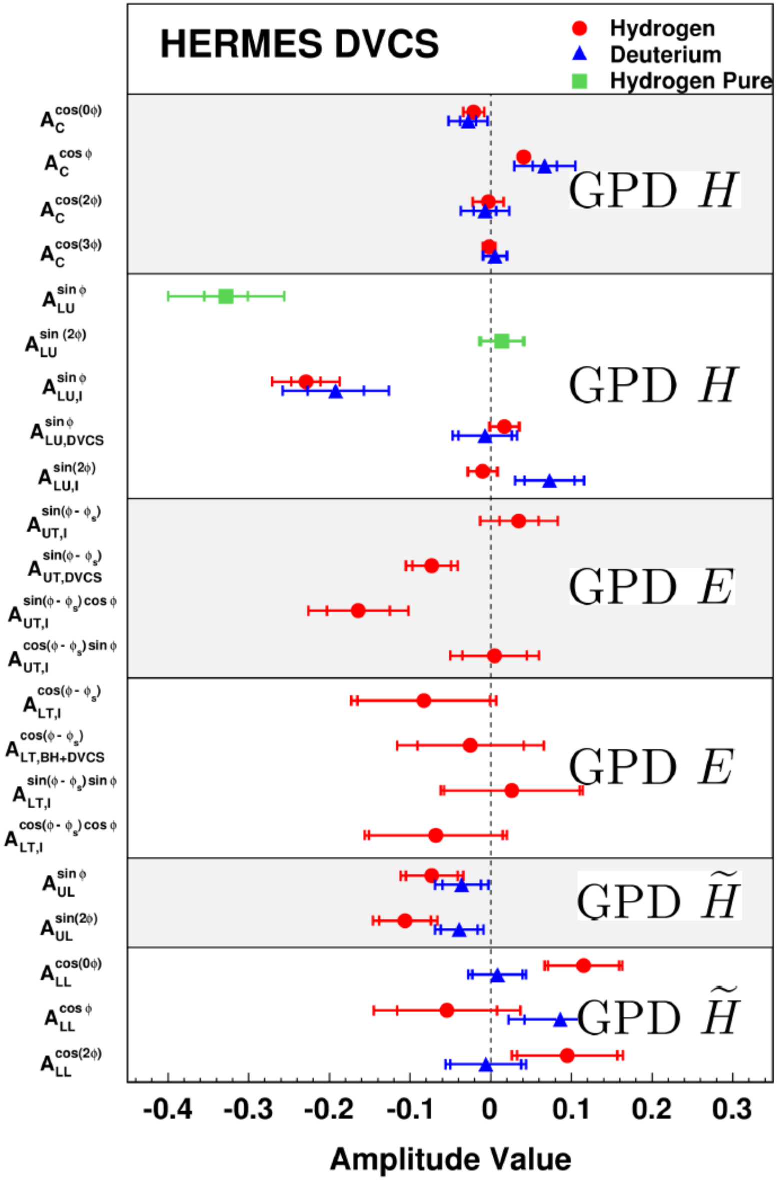
Longitud. double spin asymmetry

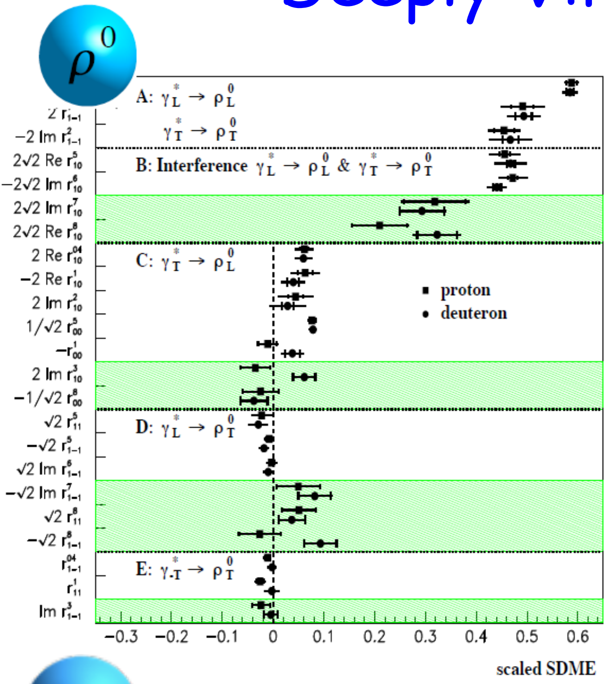
- $\sim 2\sigma$ discrepancy for $\cos(0\phi)$ where D results are ~ 0
- D results slightly positive for $\cos(\phi)$
- **In general no significant evidence of coherent scattering on d**
- **Process dominated by scattering on p**

Deeply Virtual Compton Scattering (DVCS)



- Beam-charge and beam-spin asymmetry
  - *PRL 87 (2001) 182001*
  - *PRD 75 (2007) 011103*
  - *JHEP 11 (2009) 083*
  - *JHEP 07 (2012) 032*, *JHEP 10 (2012) 042*
  - *Nucl. Phys. B 829 (2010) 1*
- Transverse target-spin asymmetry
  - *JHEP 06 (2008) 066*
- Transverse double-spin asymmetry
  - *Phys. Lett. B 704 (2011) 15*
- Longitudinal target spin asymmetry
  - *JHEP 06 (2010) 019*
- Longitudinal target & double spin asymmetry
  - *Nucl. Phys. B 842 (2011) 265*

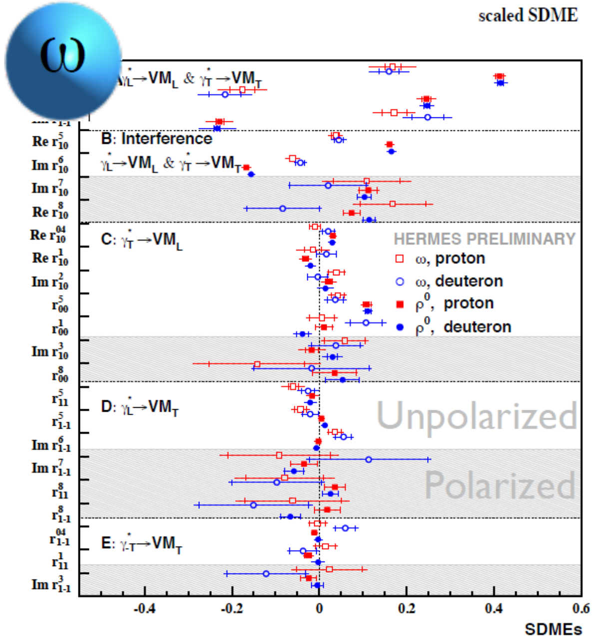
Deeply Virtual Meson Production (DVMP)

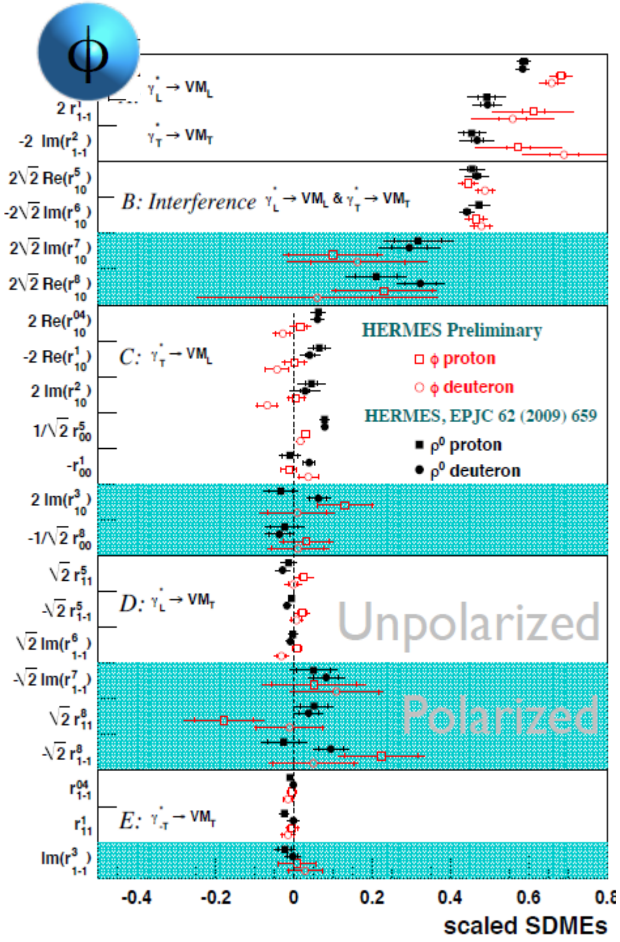


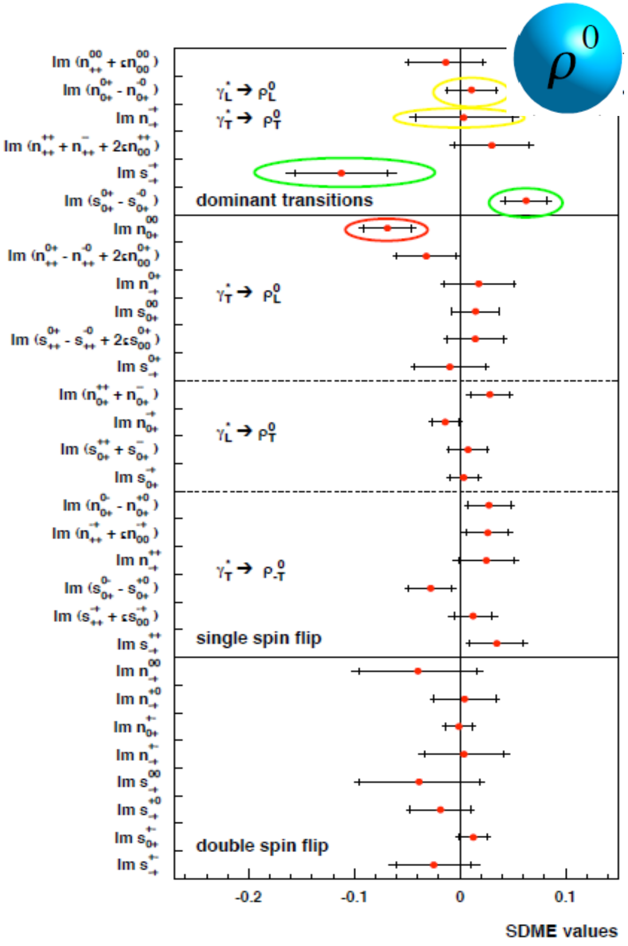
Complete set of SDMEs for ρ^0, ω, ϕ on H and D targets

- 15 SDMEs → unpolarised target
- 8 SDMEs → longitudinally polarised beam
- 30 SMDEs → transversely polarised target

grouped according to the different spin transitions between γ^* and VM







Conclusions

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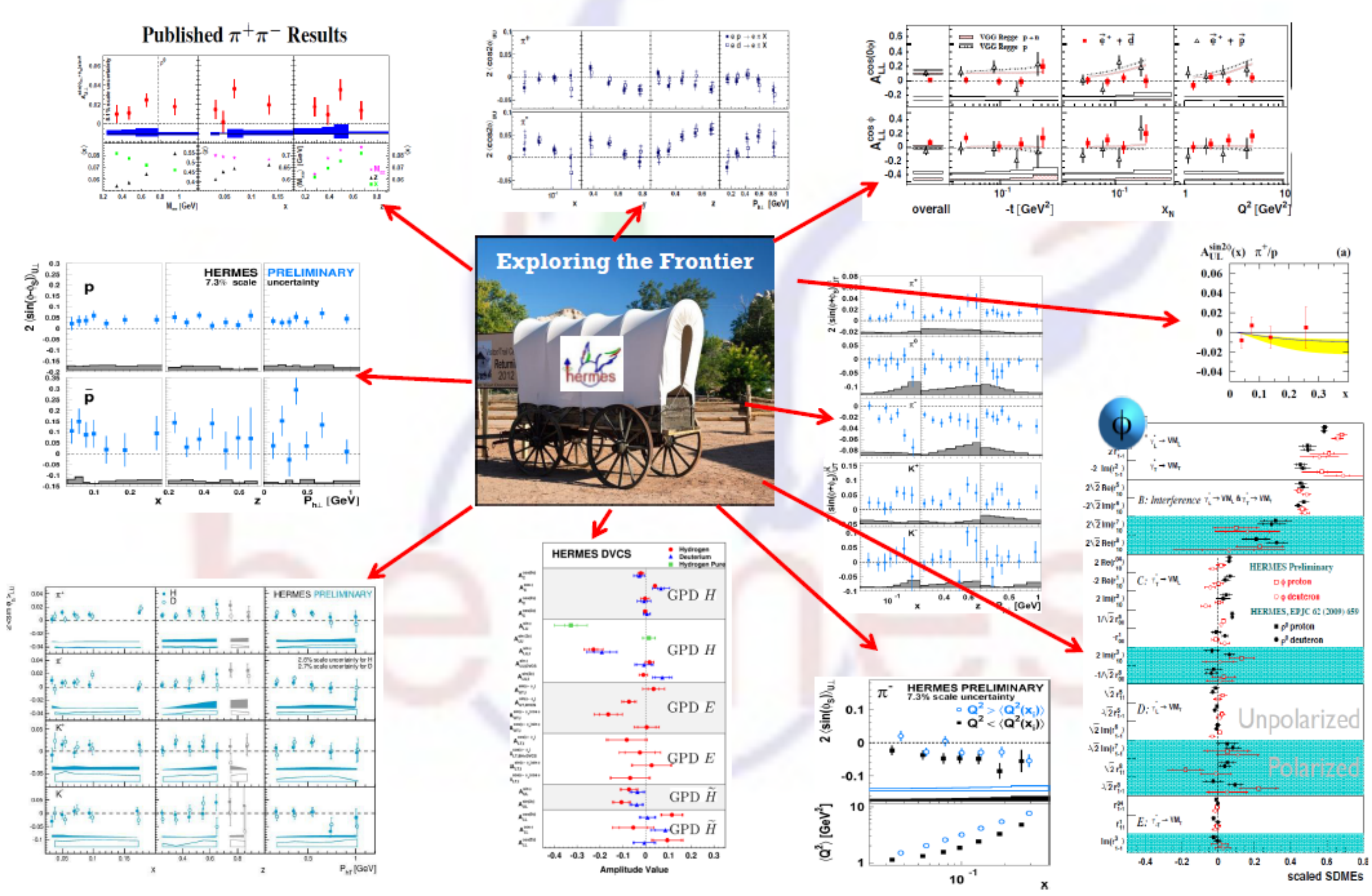
- High-precision data from present and future experiments will allow to push forwards our understanding of the nucleon structure
- HERMES, as a pioneer experiment, has played a key exploratory role in this field!



Back-up

Other TMDs results

Boer-Mulders function

Describes correlation between quark transverse momentum and transverse spin in unpolarized nucleon

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

$$\boxed{\left\{ \quad \left[F_{\mathrm{UU,T}}+\epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F^{\cos(\phi)}_{\mathrm{UU}} + \epsilon\cos(2\phi)F^{\cos(2\phi)}_{\mathrm{UU}}\right]\right.}$$

$$+ \quad \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F^{\sin(\phi)}_{\mathrm{LU}}\right]$$

$$+ \; S_L \quad \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F^{\sin(\phi)}_{\mathrm{UL}} + \epsilon\sin(2\phi)F^{\sin(2\phi)}_{\mathrm{UL}}\right]$$

$$+ \; S_L\;\lambda_l \left[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F^{\cos(\phi)}_{\mathrm{LL}}\right]$$

$$\begin{aligned} + \; S_T \quad & \Big[\sin(\phi-\phi_S)\left(F^{\sin(\phi-\phi_S)}_{\mathrm{UT,T}} + \epsilon F^{\sin(\phi-\phi_S)}_{\mathrm{UT,L}}\right) \\ & + \epsilon\sin(\phi+\phi_S)F^{\sin(\phi+\phi_S)}_{\mathrm{UT}} + \epsilon\sin(3\phi-\phi_S)F^{\sin(3\phi-\phi_S)}_{\mathrm{UT}} \\ & + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F^{\sin(\phi_S)}_{\mathrm{UT}} \\ & + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F^{\sin(2\phi-\phi_S)}_{\mathrm{UT}}\Big] \end{aligned}$$

$$\left.\begin{aligned} + \; S_T\;\lambda_l \; & \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F^{\cos(\phi-\phi_S)}_{\mathrm{LT}} \\ & + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F^{\cos(\phi_S)}_{\mathrm{LT}} \\ & + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F^{\cos(2\phi-\phi_S)}_{\mathrm{LT}}\Big] \end{aligned}\right\}$$

$$F^{\cos(2\phi)}_{UU} \propto \underbrace{h_1^\perp}_{\text{Boer-Mulders}} \otimes \underbrace{H_1^\perp}_{\text{Collins FF}} + \frac{1}{Q^2}\left[f_1\otimes D_1 + \cdots\right]$$

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$$+ \quad \lambda_l \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

$$+ \; S_L \quad \Big[\sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

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$$\begin{aligned} + \; S_T \; \lambda_l \Big[& \sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\ & + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} \\ & + \sqrt{2\epsilon\,(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\} \end{aligned}$$

Cahn effect

$$F_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \frac{1}{Q^2}\left[f_1 \otimes D_1 + \cdots\right]$$

Boer-Mulders

Collins FF

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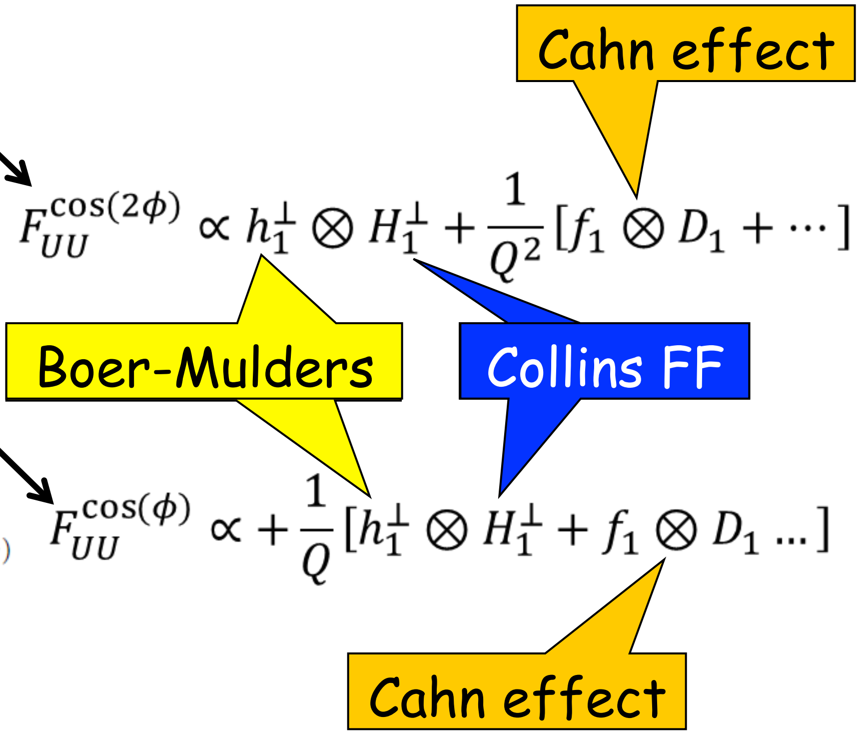
$$\begin{aligned} + \; S_T \; \lambda_l \; & \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\ & + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} \\ & + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big] \Big\} \end{aligned}$$



Cahn effect

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Boer-Mulders

Collins FF

$$F_{UU}^{\cos(\phi)} \propto + \frac{1}{Q}[h_1^{\perp} \otimes H_1^{\perp} + f_1 \otimes D_1 \ldots]$$

Cahn effect

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$$\begin{aligned} + S_T\,\lambda_l \Big[&\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\ &+\sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} \\ &+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\} \end{aligned}$$

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Cahn effect

Boer-Mulders

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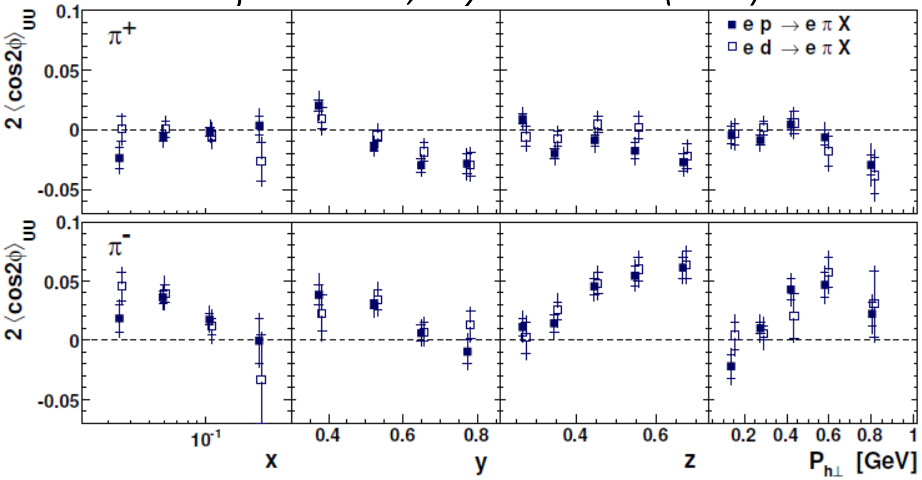
$$F_{UU}^{\cos(\phi)} \propto + \frac{1}{Q}[h_1^\perp \otimes H_1^\perp + f_1 \otimes D_1 \ldots]$$

Cahn effect

Interaction dependent terms

The cos2φ amplitudes $\propto h_1^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

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



☛ **negative**

☛ **positive**

- **Amplitudes are significant**
  → evidence of BM effect
- **similar results for H & D**
  → $h_1^{\perp,u} \approx h_1^{\perp,d}$
- **Opposite sign for π^+/π^-**
  → opposite signs of fav/unfav Collins FF

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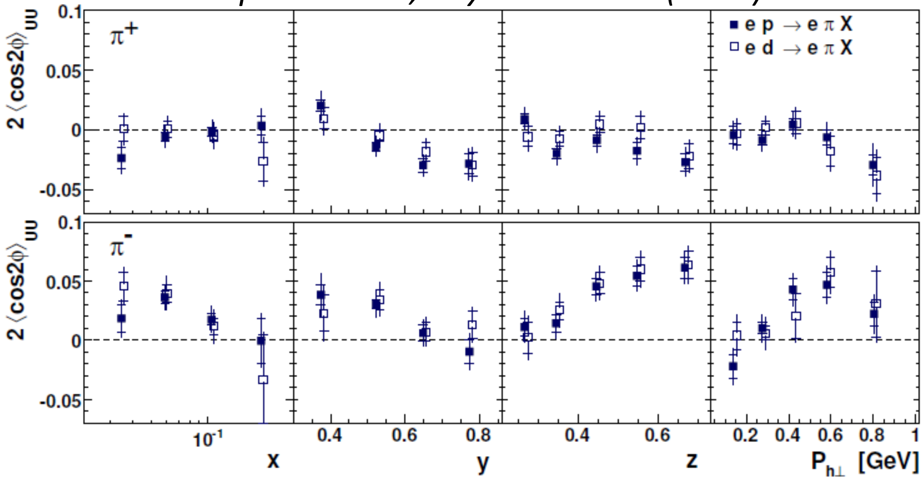

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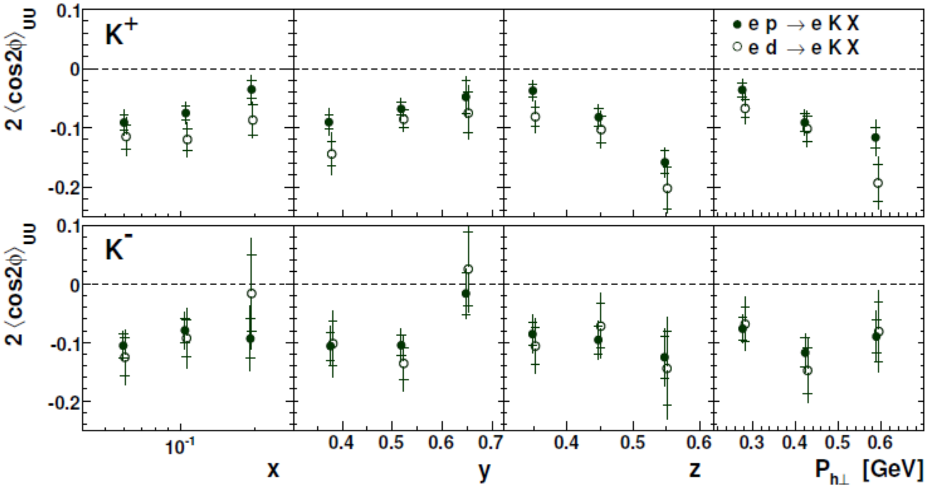


Large and negative

Large and negative

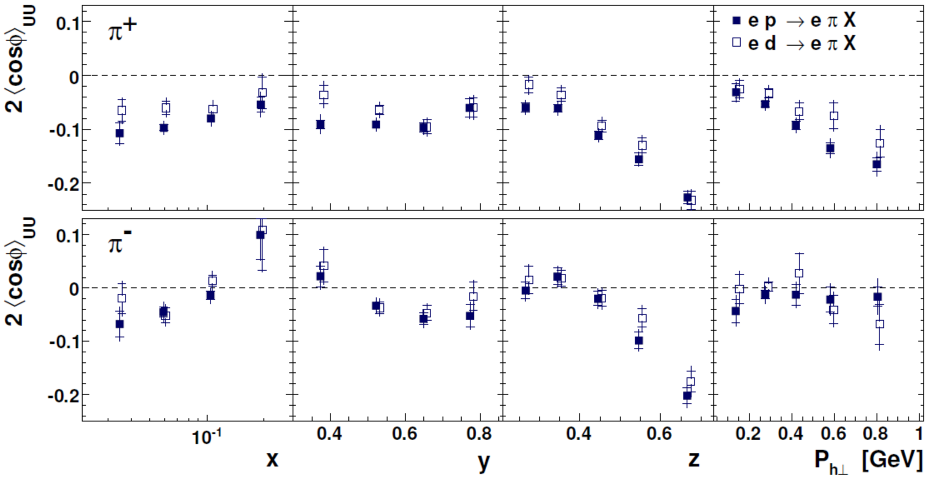
- **K^+/K^- amplitudes larger than for pions , have different kinematic dependencies than pions and have same sign**

→ different role of Collins FF for pions and kaons?

→ significant contribution from scattering off strange quarks?

The cosϕ amplitudes $\propto +\frac{1}{Q}[h_1^\perp \otimes H_1^\perp + f_1 \otimes D_1 \ldots]$

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



☛ **negative**

☛ **negative**

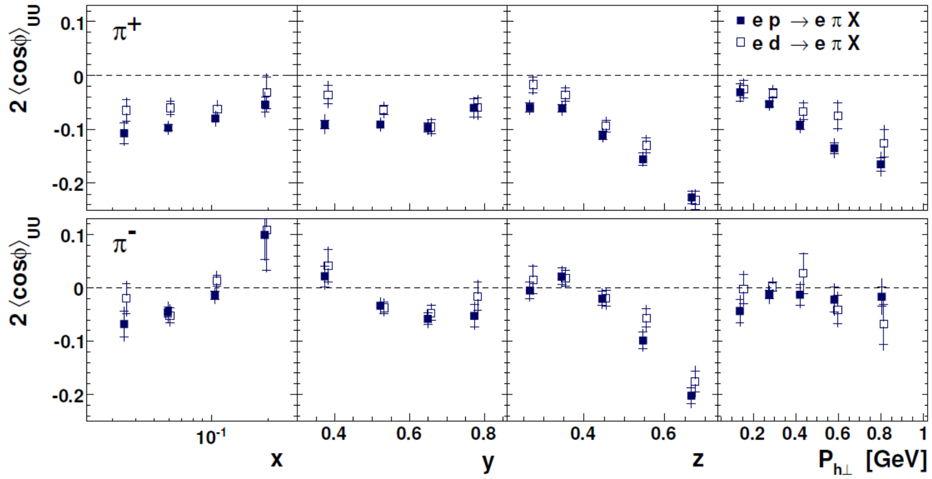
- Significant and of same sign
→ Chan effect weekly flavor dependent?

- Clear rise with z for π^+& π^- and $P_{h\perp}$ for π^+

- Different $P_{h\perp}$ dependence
→ contrib. of flavor dependent effects (e.g. BM) for π^-?

The cosϕ amplitudes $\propto +\frac{1}{Q}[h_1^\perp \otimes H_1^\perp + f_1 \otimes D_1 \dots]$

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



negative

negative

- **Significant and of same sign**
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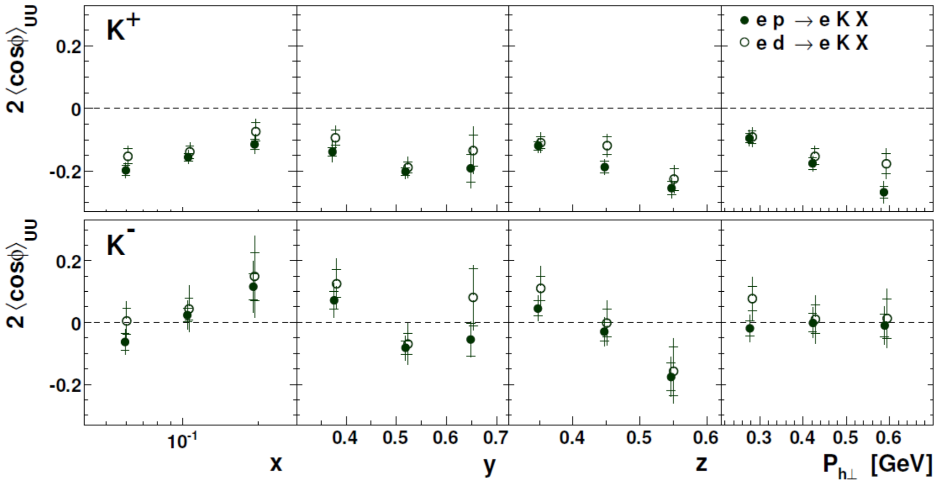
- **Clear rise with z for π^+ & π^- and $P_{h\perp}$ for π^+**
- **Different $P_{h\perp}$ dependence**
  → contrib. of flavor dependent effects (e.g. BM) for π^-?

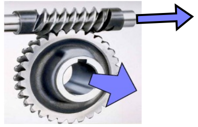


Large and negative

Consist. with 0

- **K^+ amplitudes larger than π^+**
  → different Collins FF for π & K
- **$K^- \approx 0$ different than K^+ (in contrast to $\cos 2\phi$)**
- Significant contrib from interaction dependent terms?

Worm-gear $g^{\perp}{}_{1T}$



$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{h}\cdot p_T}{M} g_{1T} D_1\right]$$

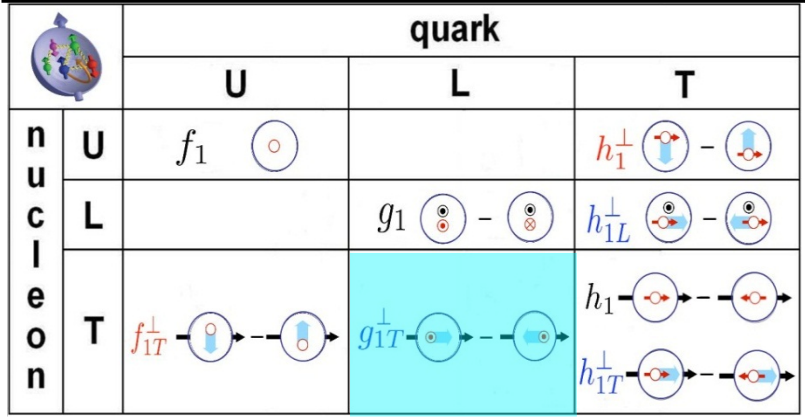
$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\begin{aligned}
\Big\{ \quad & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ \quad \lambda_l \quad & \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ \; S_L \quad & \Big[\sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ \; S_L\ \lambda_l \quad & \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
+ \; S_T \quad & \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon\,(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ \; S_T\ \lambda_l \quad & \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon\,(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}$$

Describes the probability to find longitudinally polarized quarks in a transversely polarized nucleon!

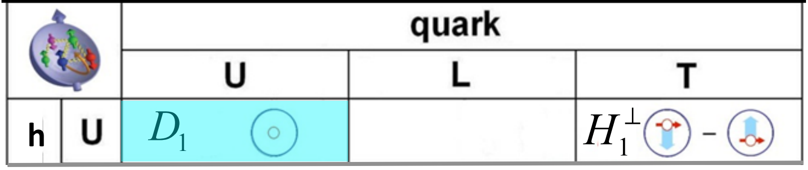
- requires interference between wave funct. components that differ by 1 unit of **OAM**
- Can be accessed in **LT DSAs**

Distribution Functions



		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



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

Probing $g_{1T}^{\perp}$ through Double Spin Asymmetries

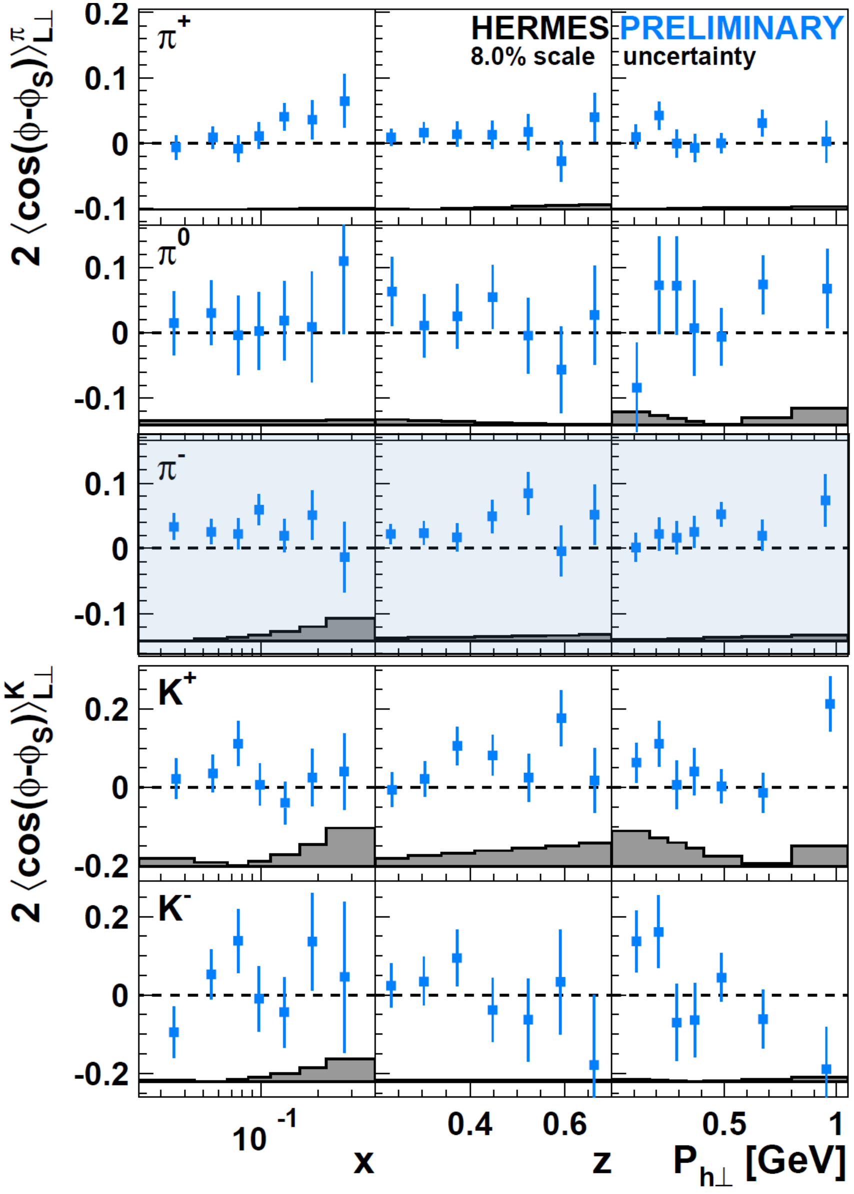
$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\boxed{g_{1T}}D_1\right]$$

$$\begin{aligned}F_{LT}^{\cos\phi_S} = \frac{2M}{Q}\,\mathcal{C}\Bigg\{&-\left(x g_T D_1 + \frac{M_h}{M}\,h_1\frac{\tilde{E}}{z}\right)\\ &+\frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2M\,M_h}\left[\left(x e_T H_1^{\perp} - \frac{M_h}{M}\boxed{g_{1T}}\frac{\tilde{D}^{\perp}}{z}\right) + \left(x e_T^{\perp} H_1^{\perp} + \frac{M_h}{M}\,f_{1T}^{\perp}\frac{\tilde{G}^{\perp}}{z}\right)\right]\Bigg\}\end{aligned}$$

$$\begin{aligned}F_{LT}^{\cos(2\phi_h-\phi_S)} = \frac{2M}{Q}\,\mathcal{C}\Bigg\{&-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{2M^2}\left(x g_T^{\perp} D_1 + \frac{M_h}{M}\,h_{1T}^{\perp}\frac{\tilde{E}}{z}\right)\\ &+\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2M\,M_h}\left[\left(x e_T H_1^{\perp} - \frac{M_h}{M}\boxed{g_{1T}}\frac{\tilde{D}^{\perp}}{z}\right)\right.\\ &\left.-\left(x e_T^{\perp} H_1^{\perp} + \frac{M_h}{M}\,f_{1T}^{\perp}\frac{\tilde{G}^{\perp}}{z}\right)\right]\Bigg\}\end{aligned}$$

The simplest way to probe worm-gear $g_{1T}^{\perp}$ is through the $\cos(\phi-\phi_S)$ Fourier component

The cos(ϕ-ϕ$_S$) amplitudes $\propto g_{1T}^{\perp}(x,p_T^2)\otimes D_1(z,k_T^2)$



☛ slightly positive ?

☛ consistent with zero

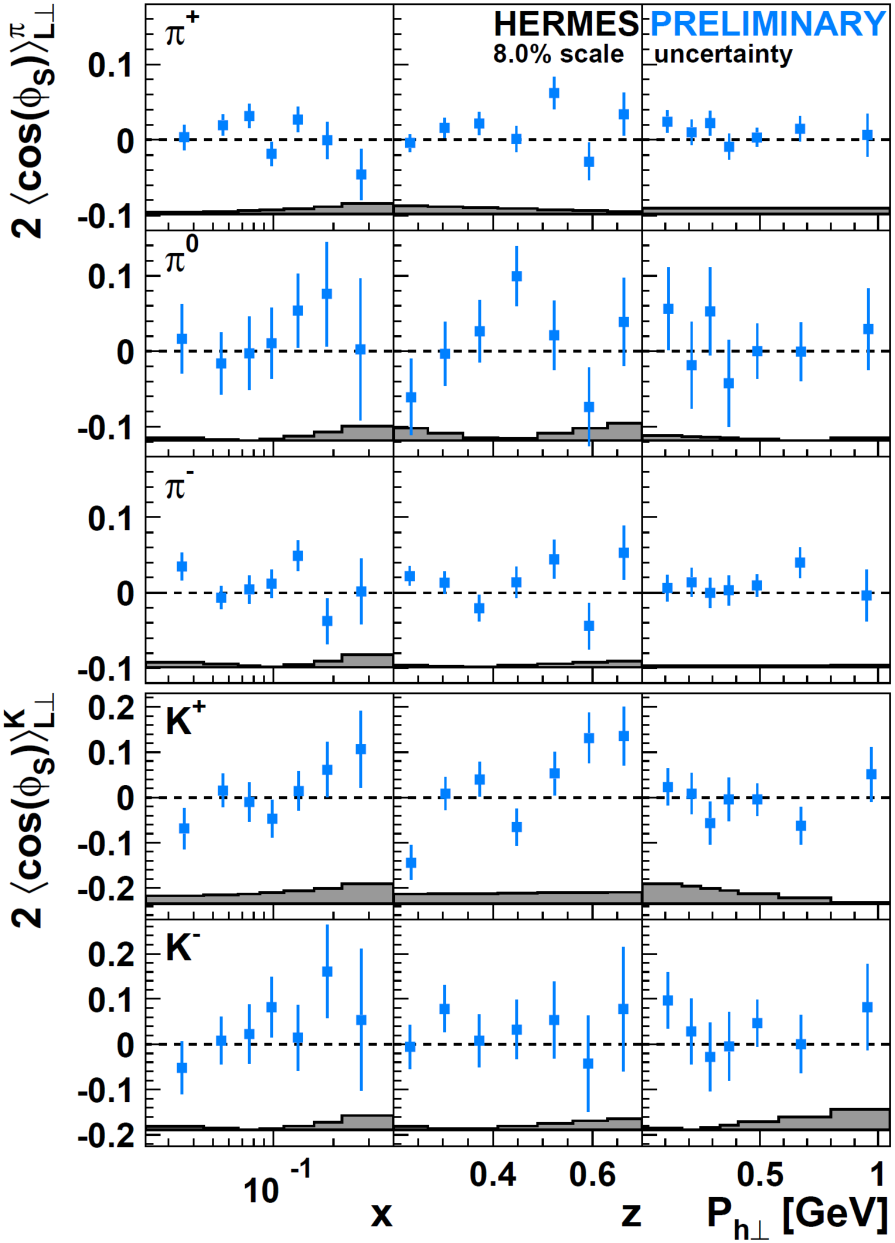
☛ positive!!

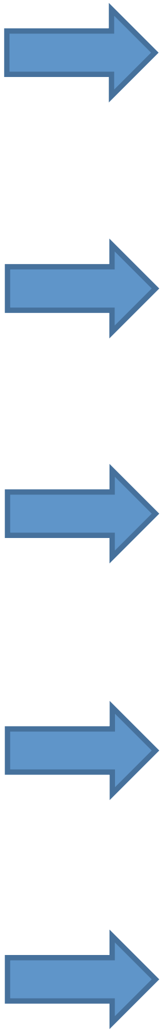
similar observations from Hall-A and COMPASS

☛ slightly positive ?

☛ consistent with zero

The cos(ϕ_S) Fourier component





≈ 0

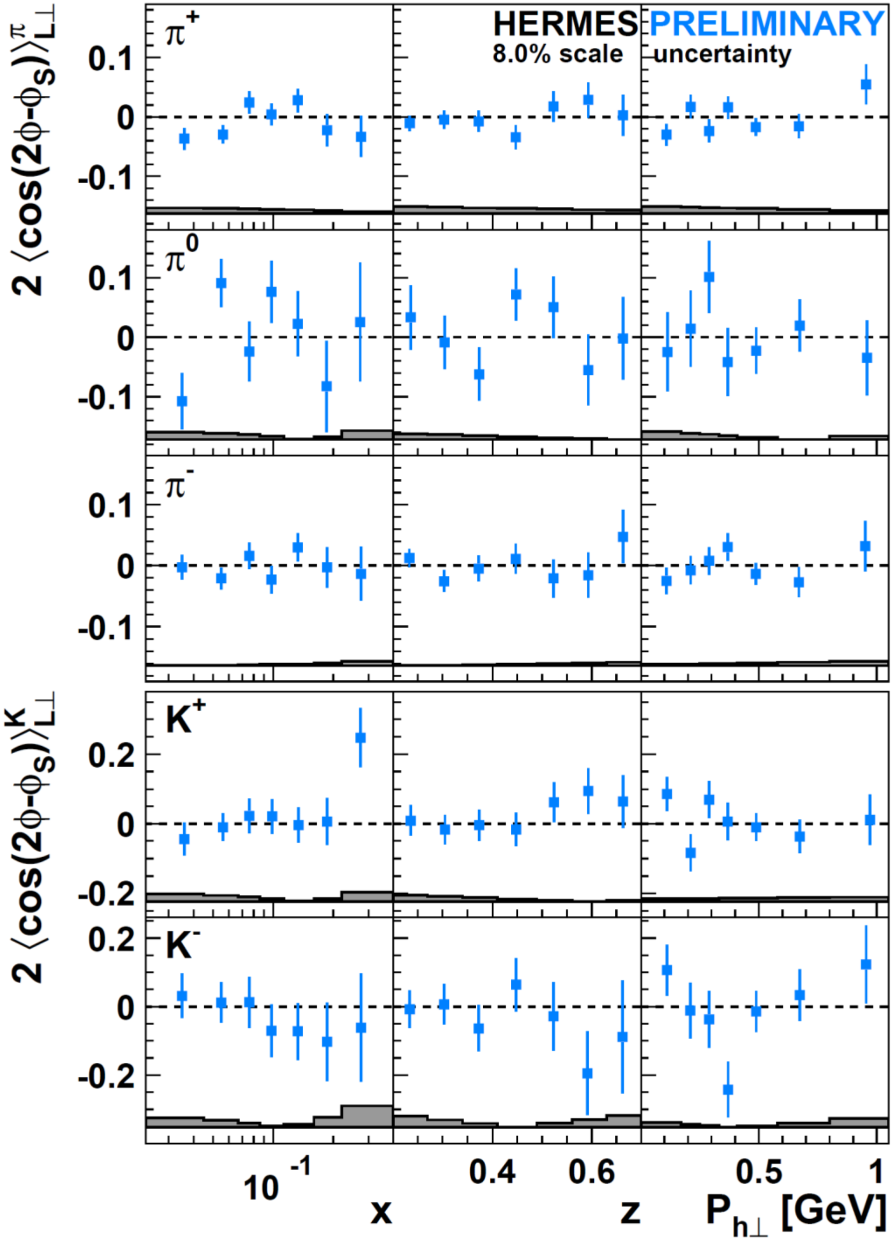
≈ 0

≈ 0

≈ 0
sign change?

≈ 0

The cos(2ϕ-ϕ_S) Fourier component



≈ 0

≈ 0

≈ 0

≈ 0

≈ 0

Pretzelosity

$$F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{C}\left[\frac{2\left(\hat{h}\cdot p_T\right)\left(p_T\cdot k_T\right)+p_T^2\left(\hat{h}\cdot k_T\right)-4\left(\hat{h}\cdot p_T\right)^2\left(\hat{h}\cdot k_T\right)}{2M^2M_h}\, h_{1T}^{\perp} H_1^{\perp}\right]$$

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

$$\Big\{ \left[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\right]$$

$$+ \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\right]$$

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

$$+ S_L\,\lambda_l \left[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\right]$$

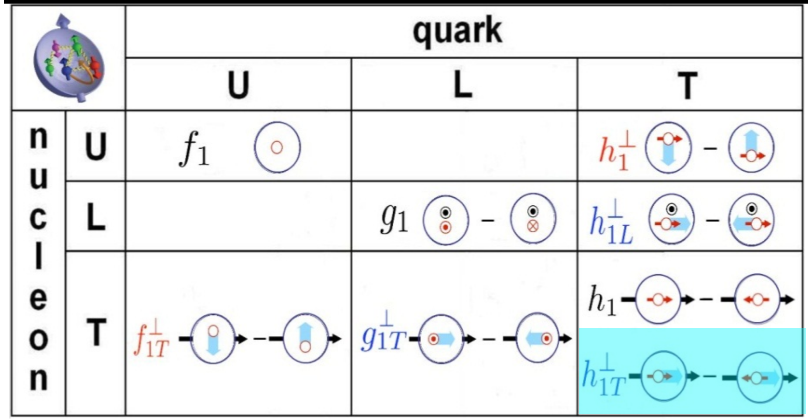
$$+ S_T \left[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\right]$$

$$+ S_T\,\lambda_l \left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\right]\Big\}$$

Describes correlation between quark transverse momentum and transverse spin in a transversely pol. nucleon

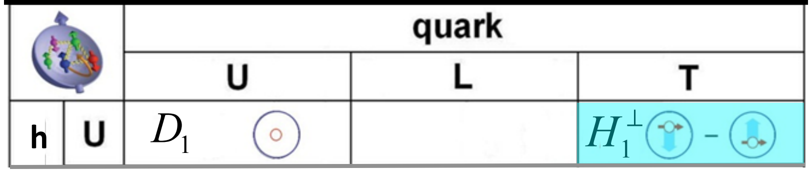
- Sensitive to **non-spherical shape** of the nucleon

Distribution Functions



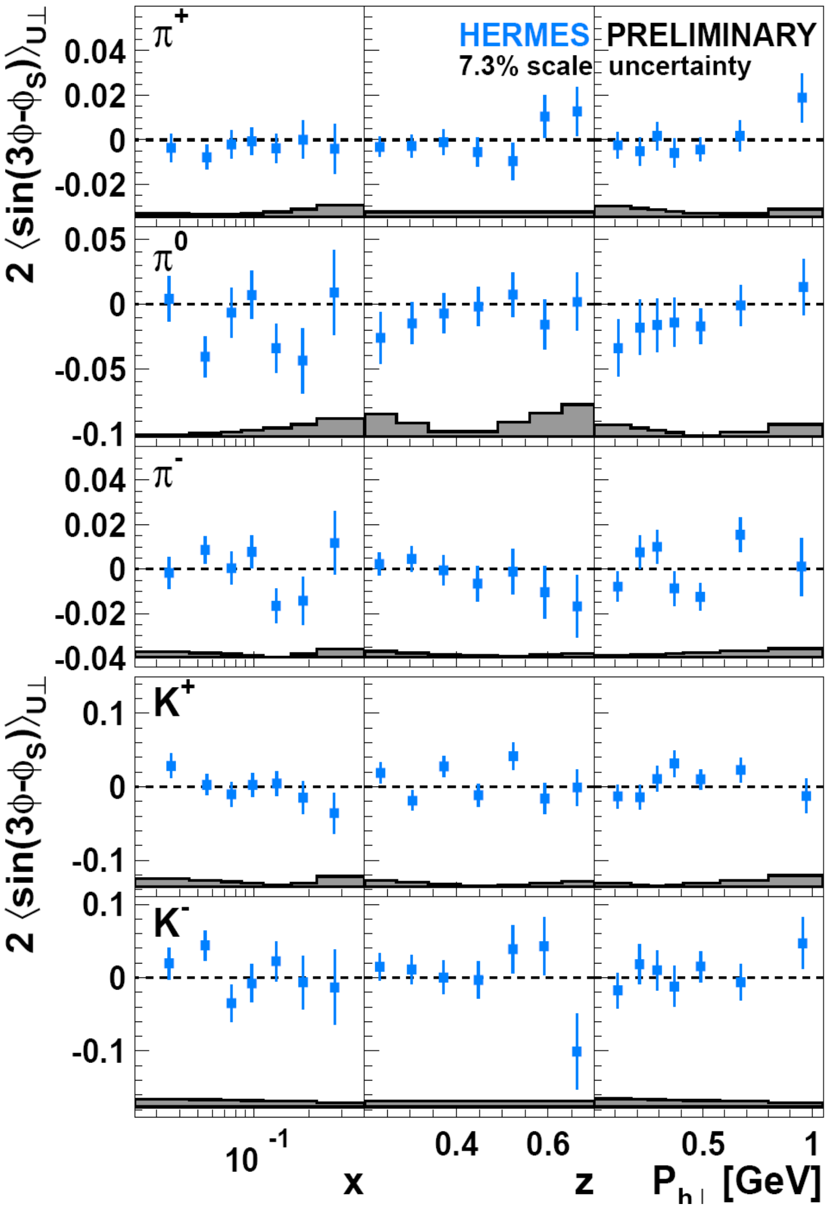
		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Fragmentation Functions



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

The sin(3ϕ-ϕ_s) amplitude $\propto h_{1T}^{\perp}(x,p_T^2)\otimes H_1^{\perp}(z,k_T^2)$



All amplitudes consistent with zero

…suppressed by two powers of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes

Worm-gear $h^{\perp}{}_{1L}$

$$\boxed{F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{h}\cdot k_T\right)\left(\hat{h}\cdot p_T\right) - k_T\cdot p_T}{M M_h} h_{1L}^{\perp} H_1^{\perp}\right]}$$

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

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l\left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\right]$$

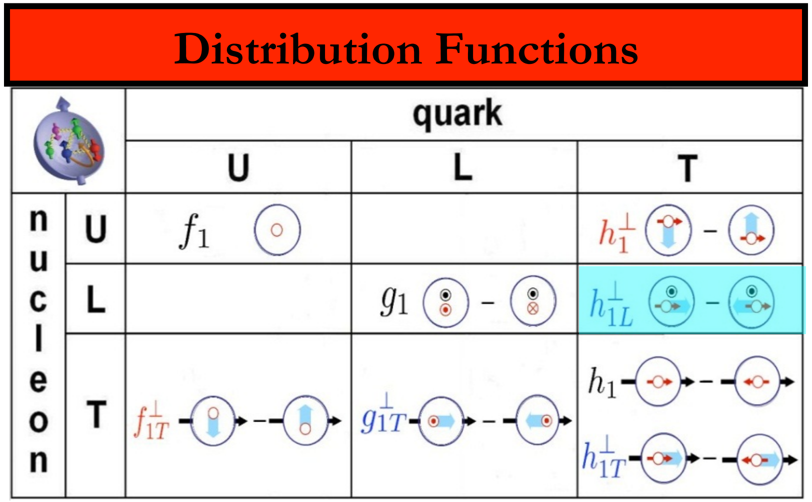
$$+ S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{\mathrm{UL}}^{\sin(2\phi)}\right]$$

$$+ S_L\,\lambda_l\left[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\right]$$

$$+ S_T\Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

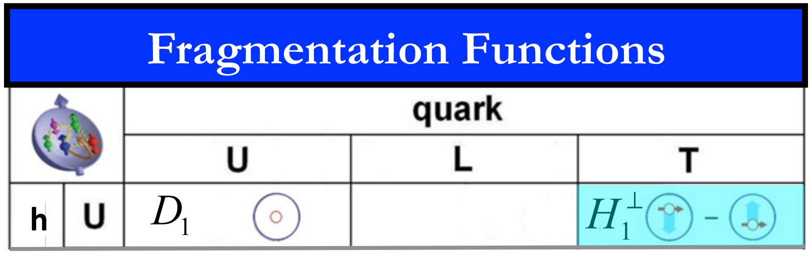
$$+ S_T\,\lambda_l\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

Describes the probability to find transversely polarized quarks in a longitudinally polarized nucleon



Distribution Functions

		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 $h_{1T}^{\perp}$

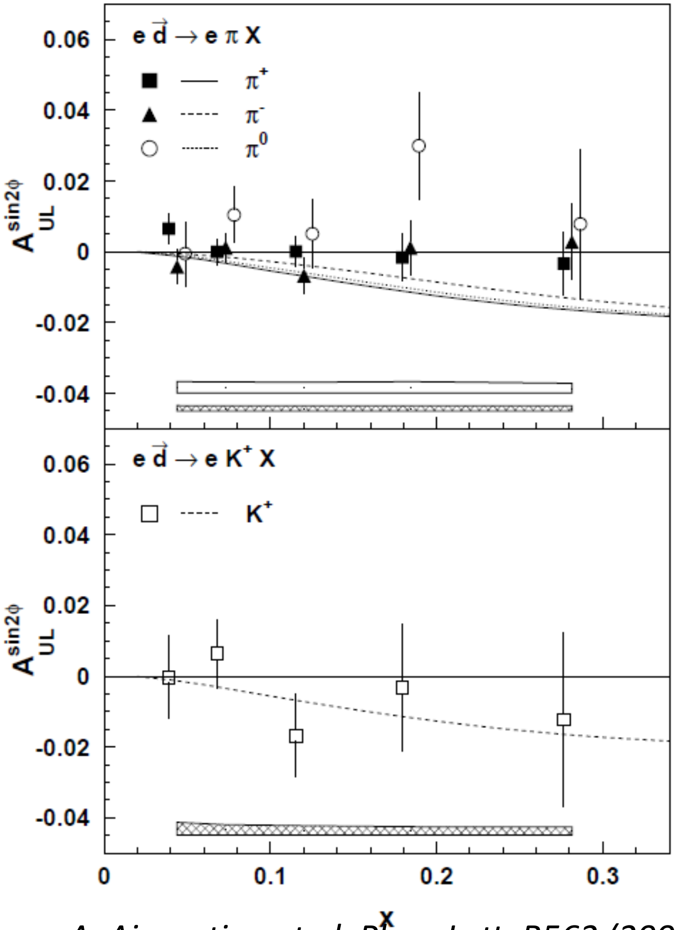


Fragmentation Functions

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

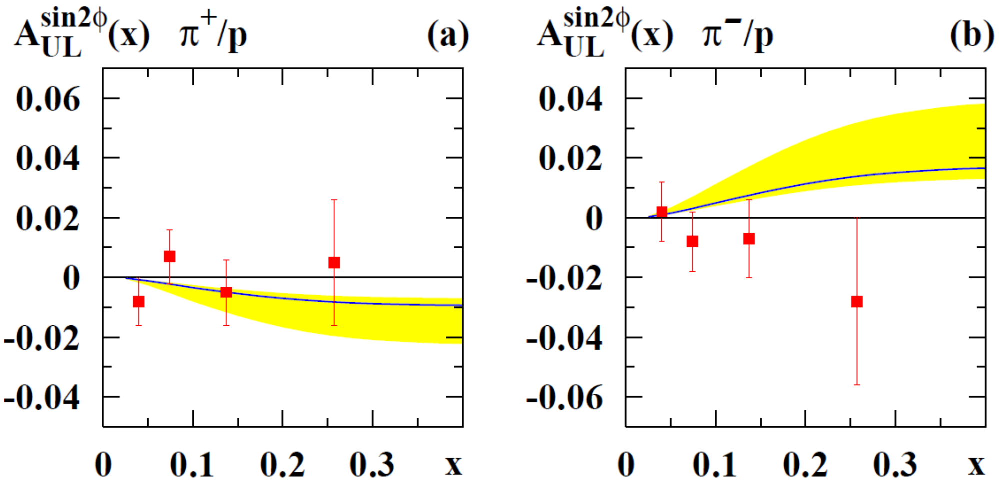
The sin(2ϕ) amplitude $\propto h_{1L}^{\perp}(x,p_T^2)\otimes H_1^{\perp}(z,k_T^2)$

Deuterium target



A. Airapetian et al, Phys. Lett. B562 (2003)

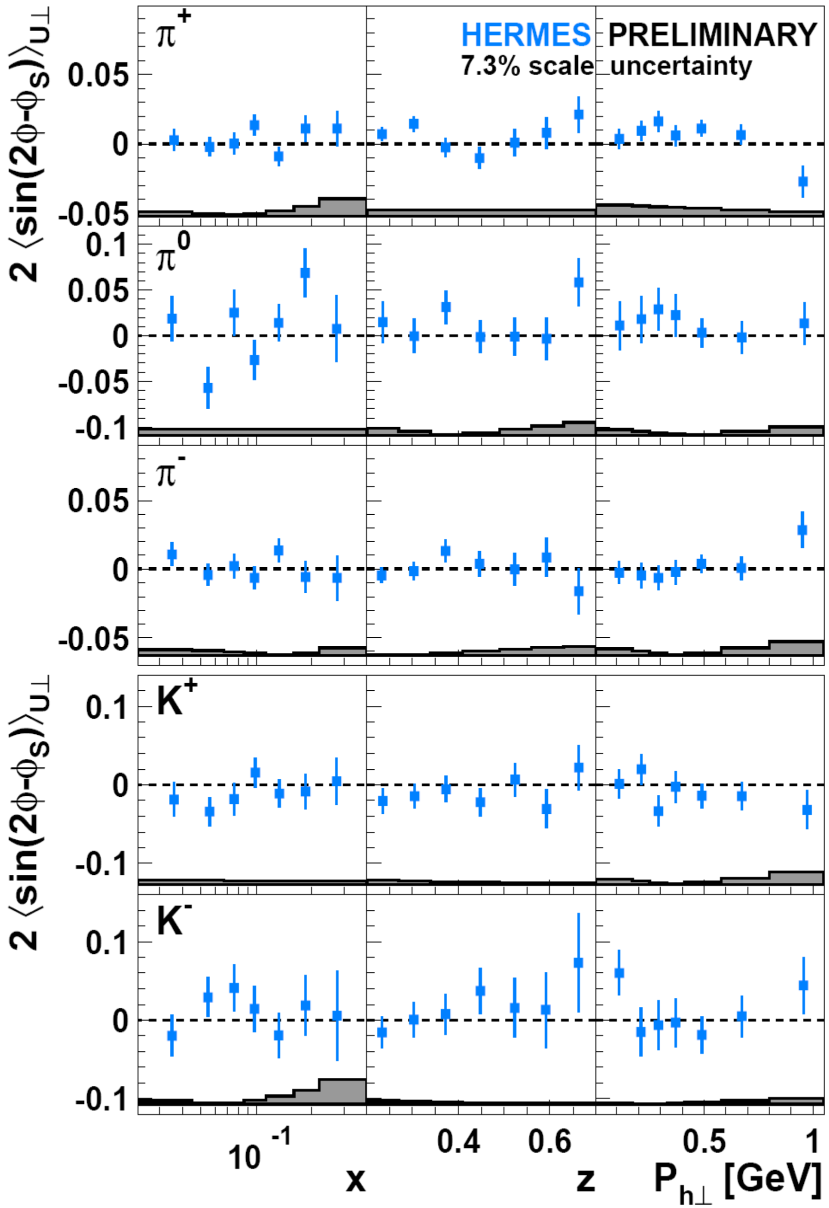
Hydrogen target



A. Airapetian et al, Phys. Rev. Lett. 84 (2000)

Amplitudes consistent with zero for all mesons and for both H and D targets

The subleading-twist sin(2ϕ-ϕ_S) Fourier component



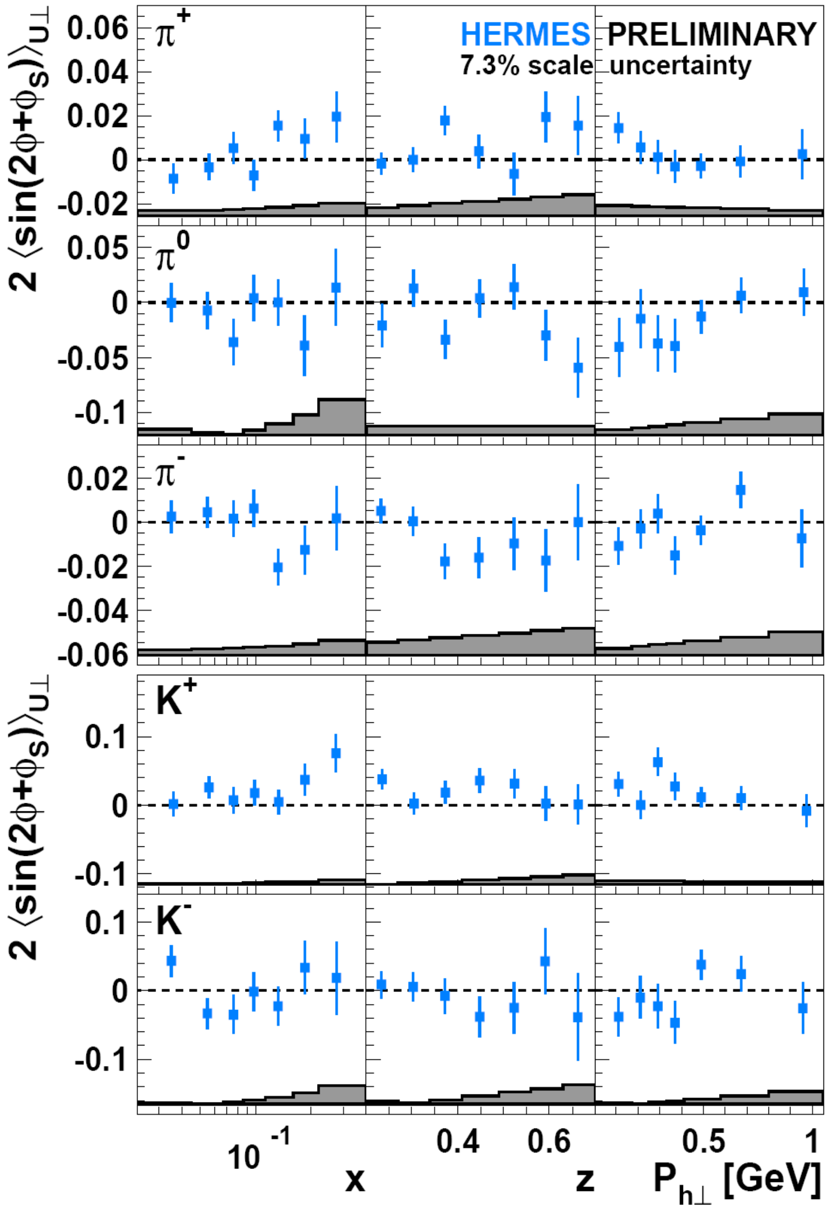
- sensitive to **worm-gear** $g_{1T}^{\perp}$, **Pretzelosity** and **Sivers function**:

$$\propto \mathcal{W}_1(p_T, k_T, P_{h\perp})\left(xf_T^{\perp}D_1 - \frac{M_h}{M}h_{1T}^{\perp}\frac{\tilde{H}}{z}\right)$$
$$- \mathcal{W}_2(p_T, k_T, P_{h\perp})\left[\left(xh_T H_1^{\perp} + \frac{M_h}{M}g_{1T}\frac{\tilde{G}^{\perp}}{z}\right)\right.$$
$$\left. + \left(xh_T^{\perp}H_1^{\perp} - \frac{M_h}{M}f_{1T}^{\perp}\frac{\tilde{D}^{\perp}}{z}\right)\right]$$

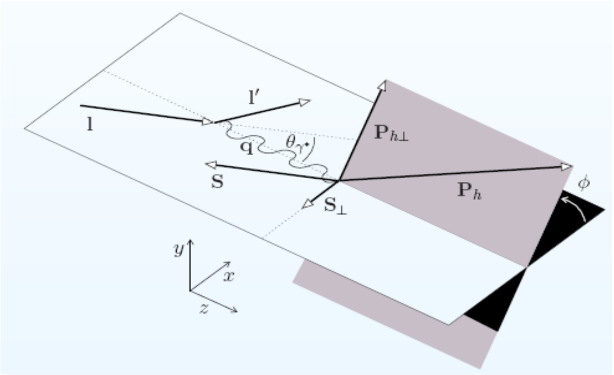
- suppressed by one power of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes

- **no significant non-zero signal observed**

The sin(2ϕ+ϕ_S) Fourier component



- arises solely from longitudinal (w.r.t. virtual photon direction) component of the target spin



- related to $\langle\sin(2\phi)\rangle_{UL}$ Fourier comp:

$$2\left\langle\sin(2\phi+\phi_S)\right\rangle_{UT}^{h} \propto \frac{1}{2}\sin(\vartheta_{l\gamma^*})2\left\langle\sin(2\phi)\right\rangle_{UL}^{h}$$

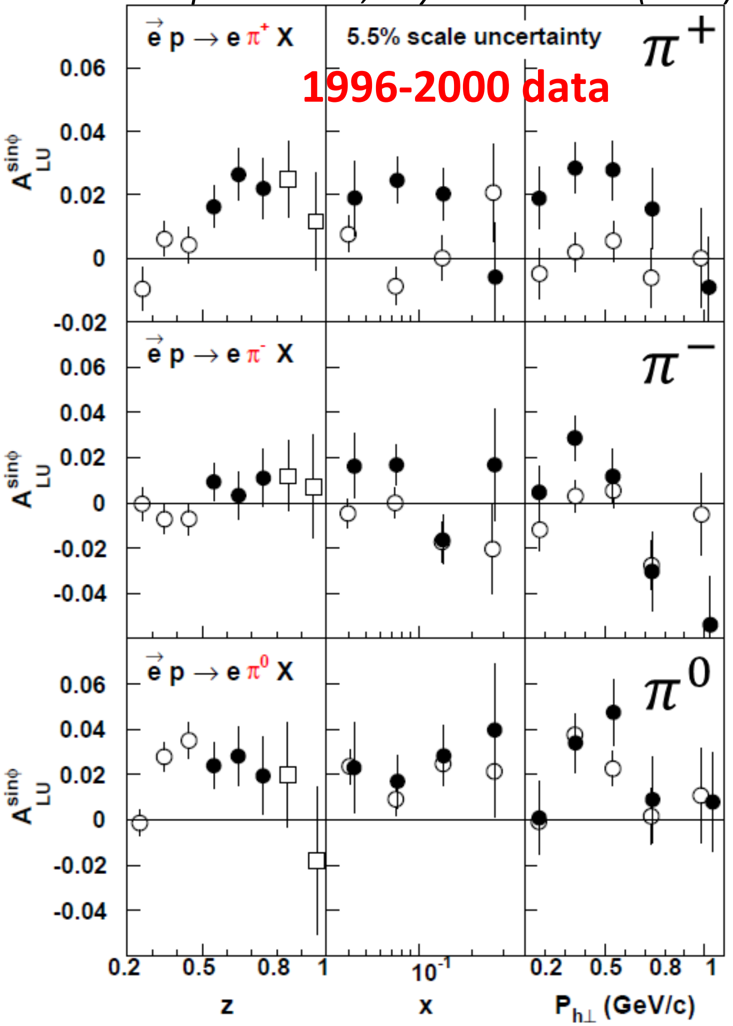
- sensitive to **worm-gear** $h_{1L}^{\perp}$
- suppressed by one power of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes
- **no significant signal observed (except maybe for K+)**

$F_{LU}^{\sin\phi}$

$$\boxed{F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{E}}{z}\right)\right]}$$

$$\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = {} & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
\Big\{ & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ \; & \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\right] \\
+ \; S_L \; & \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{\mathrm{UL}}^{\sin(2\phi)}\right] \\
+ \; S_L\,\lambda_l \; & \left[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\right] \\
+ \; S_T \; & \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& + \epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ \; S_T\,\lambda_l \; & \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}$$

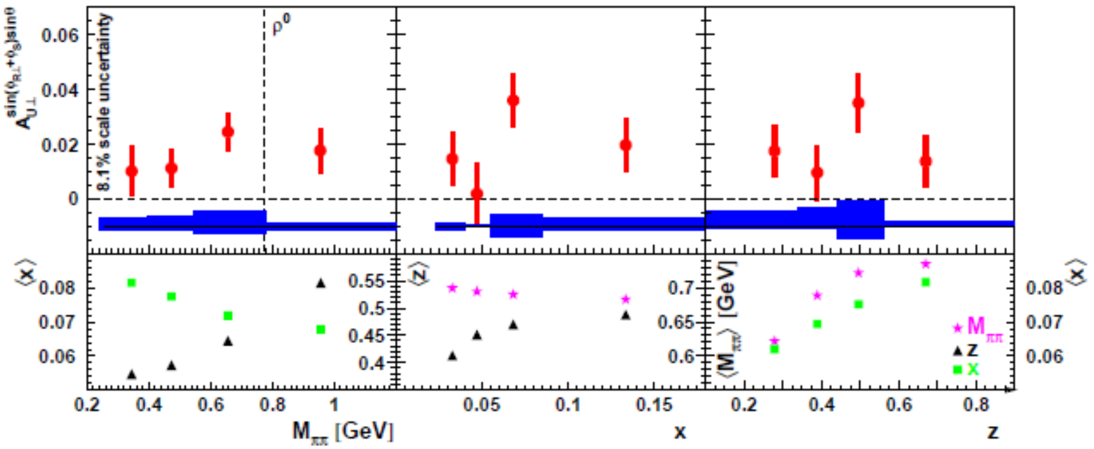
A. Airapetian et al, Phys. Lett. B 648 (2007)



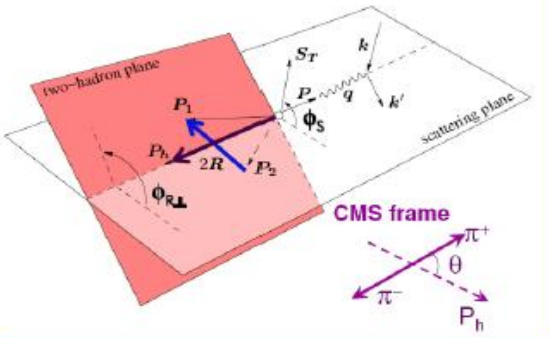
open circles 0.2<z<0.5
full circles 0.5<z<0.8
open squares: 0.8<z<1.0

The di-hadron SIDIS cross-section

Published $\pi^+\pi^-$ Results

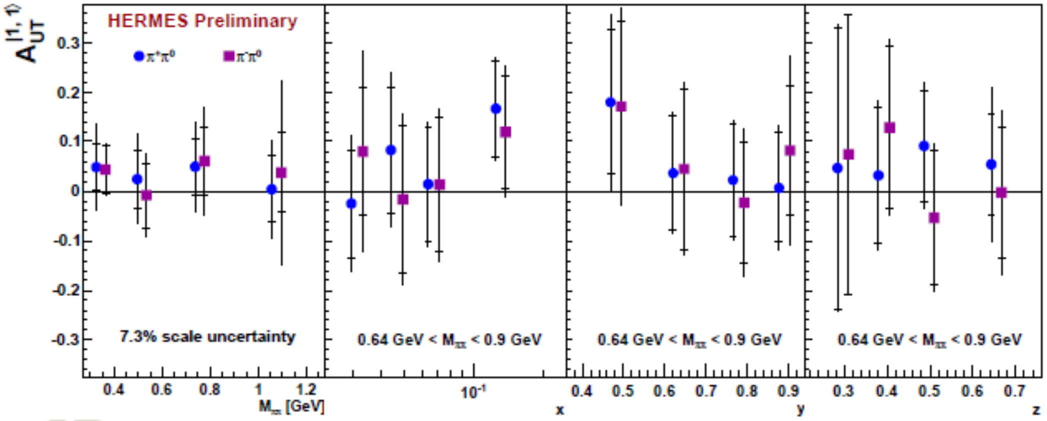


Two-hadron case



$$\sigma_{UT} \propto S_T \sin\theta \sin(\phi_{R\perp}+\phi_S)\sum_q e_q^2\, \delta q\; H_{1,q}^{\sphericalangle}$$

New $\pi^\pm\pi^0$ Results



- New tracking, new PID, use of ϕ_R rather than $\phi_{R\perp}$
- Different fitting procedure and function
- Acceptance correction

- independent way to access transversity
- significantly positive amplitudes
- 1^{st} evidence of non zero dihadron FF
- no convolution integral involved
- limited statistical power (v.r.t. 1 hadron)
- signs are consistent for all $\pi\pi$ species
- statistics much more limited for $\pi^\pm\pi^0$
- despite uncertainties may still help to constrain global fits and may assist in $u-d$ flavor separation

More on DVCs
Exclusive Mesons

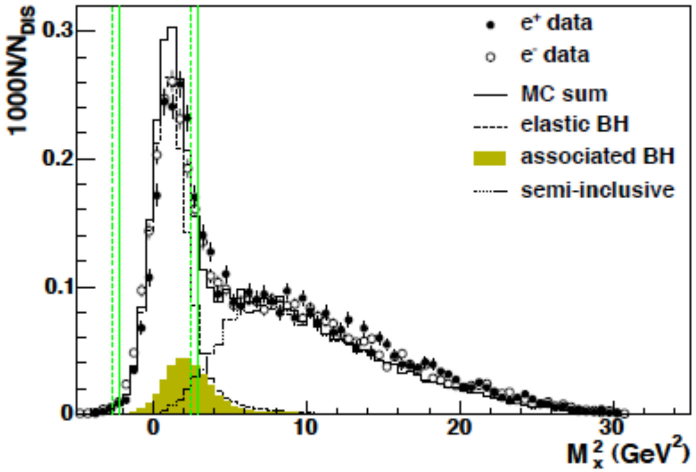
Deeply Virtual Compton Scattering (DVCS)

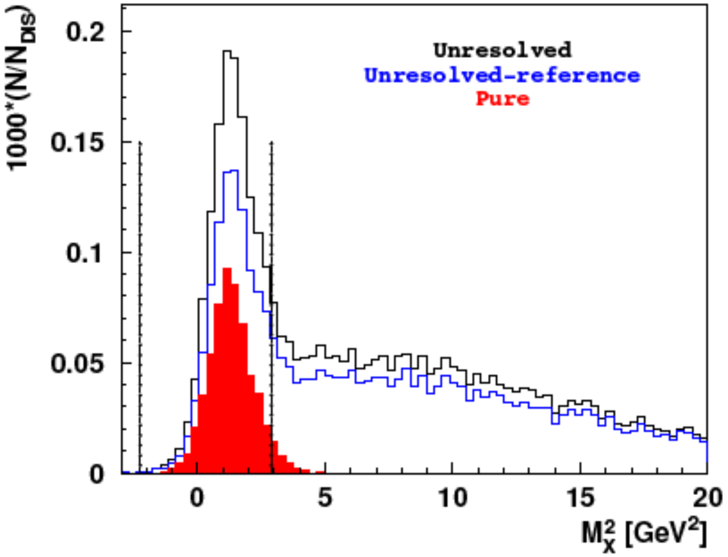
Measurements with Recoil Detection

- Events with one DIS lepton and one trackless cluster in the calorimeter.
- "***Unresolved***" for associated process $ep \rightarrow e\Delta^{+}\gamma$ $\approx 12\ \%$

- "***Unresolved reference***" sample.
- "Hypothetical" proton required in the Recoil Detector acceptance.

- "***Pure Elastic***" sample.
- Kinematic event fitting technique. Allows to achieve purity > 99.9 %





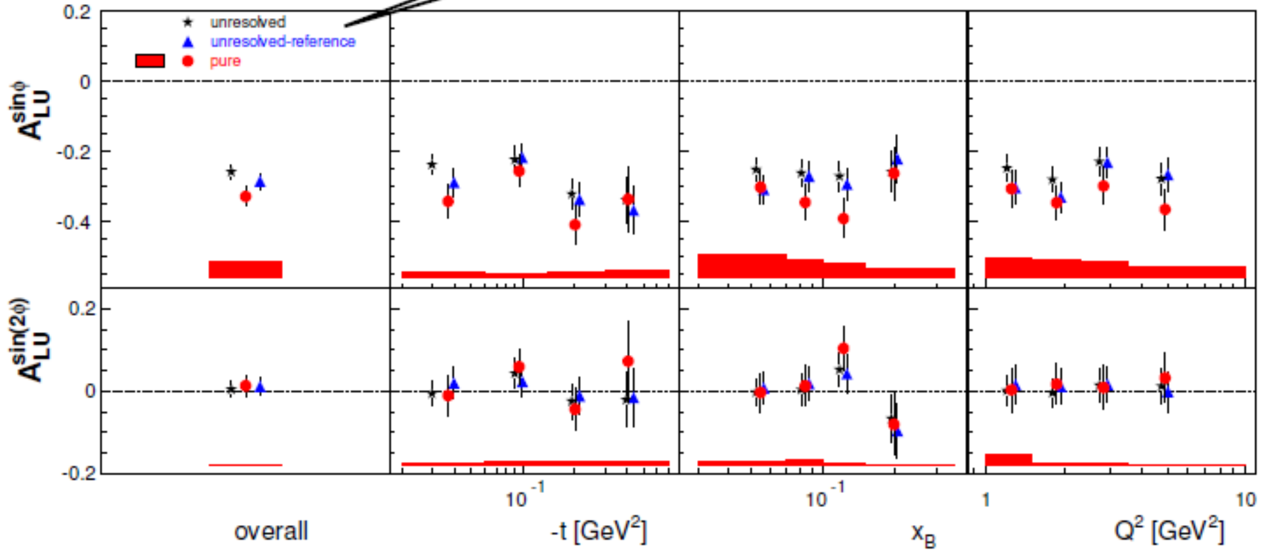
Deeply Virtual Compton Scattering (DVCS)

Beam-Helicity Asymmetry (Recoil Measurement)

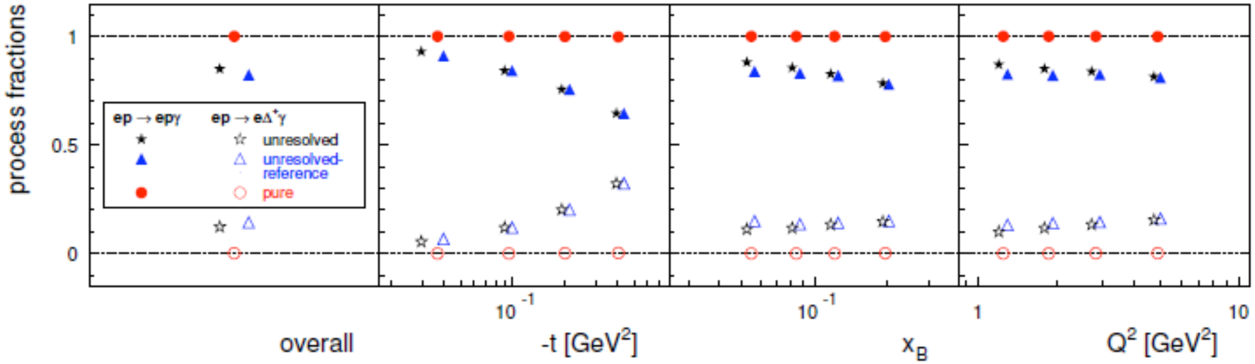
$$\mathcal{A}_{LU}(\phi)=\frac{\sigma^{+\rightarrow}-\sigma^{+\leftarrow}}{\sigma^{+\rightarrow}+\sigma^{+\leftarrow}}$$

Unresolved
Unresolved Reference
Pure Elastic

Airapetian el al. JHEP 10 (2014) 042



Indication of slightly larger magnitude of leading amplitude for pure elastic sample compared with reference sample

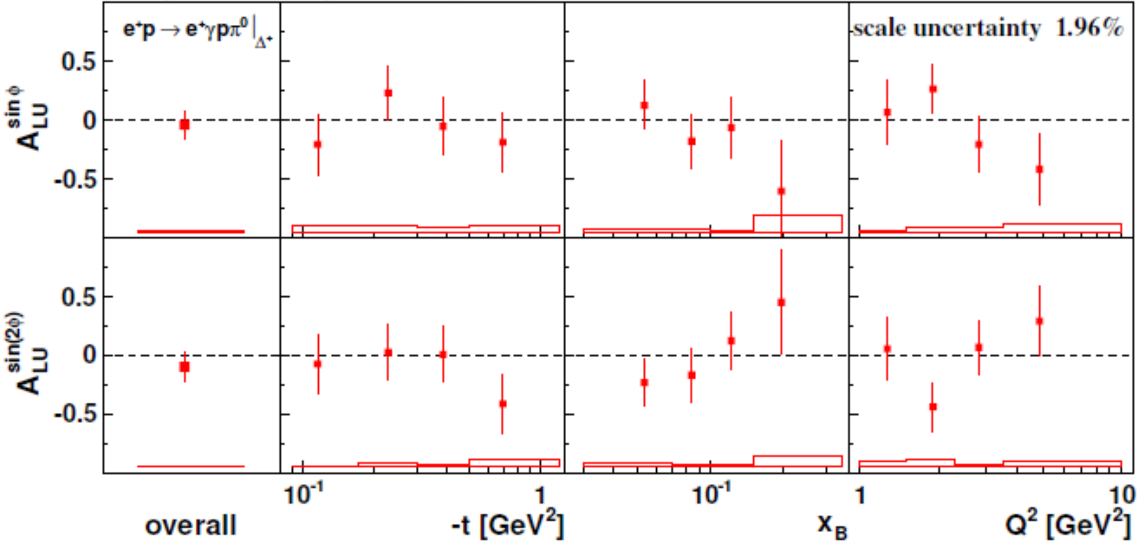


Fractional contributions of elastic and associated processes for different samples

Deeply Virtual Compton Scattering (DVCS)

Associated Process $e^+p \rightarrow e^+\gamma\Delta^+$

Airapetian el al. JHEP 01 (2014) 077



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

$$e^+p \rightarrow e^+\gamma p\pi^0|_{\Delta^+}$$

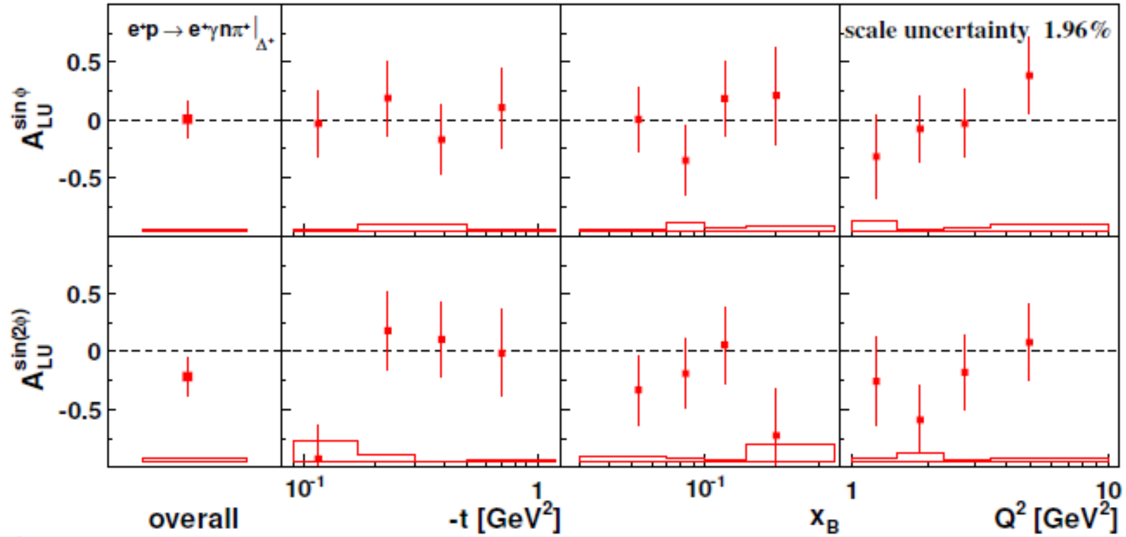
Fractional contributions

Associated DVCS/BH - 85 ± 1%

Elastic DVCS/BH - 4.6 ± 0.1 %

SIDIS - 11 ± 1 %

Asymmetry amplitudes are consistent with zero for both channels.



$$e^+p \rightarrow e^+\gamma n\pi^+|_{\Delta^+}$$

Fractional contributions

Associated DVCS/BH - 77 ± 2%

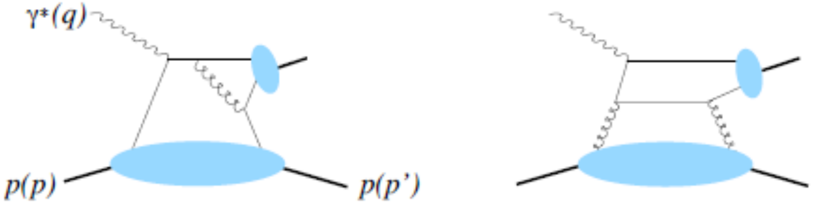
Elastic DVCS/BH - 0.2 ± 0.1 %

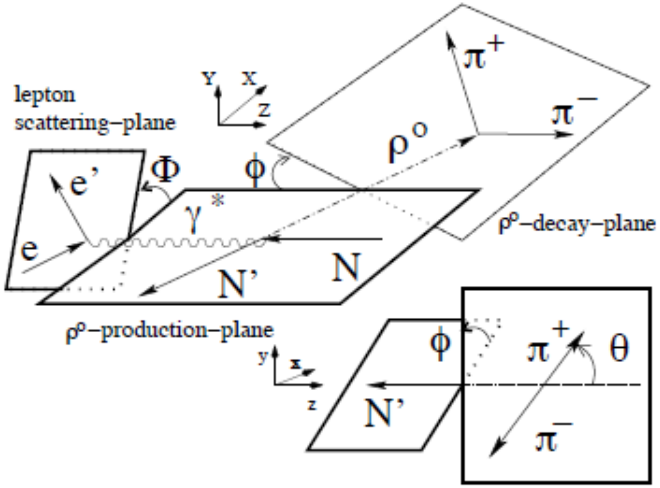
SIDIS - 23 ± 3 %

Exclusive meson production

pQCD description of the process.

I) dissociation of the virtual photon into quark-antiquark pair
II) scattering of a pair on a nucleon
III) formation of the observed vector meson





UPE GPDs $\widetilde{H}, \widetilde{E}$
NPE GPDs H, E

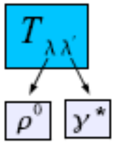
Cross Section

$$\frac{d\sigma}{dx_B dQ^2 dt d\Phi d\cos\theta d\phi} \propto \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \Phi, \cos\theta, \phi)$$

production and decay angular distribution: W decomposition

$$W = W_{UU} + P_\ell W_{LU} + S_L W_{UL} + P_\ell S_L W_{LL} + S_T W_{UT} + P_\ell S_T W_{LT}$$

parameterization in terms of helicity amplitudes

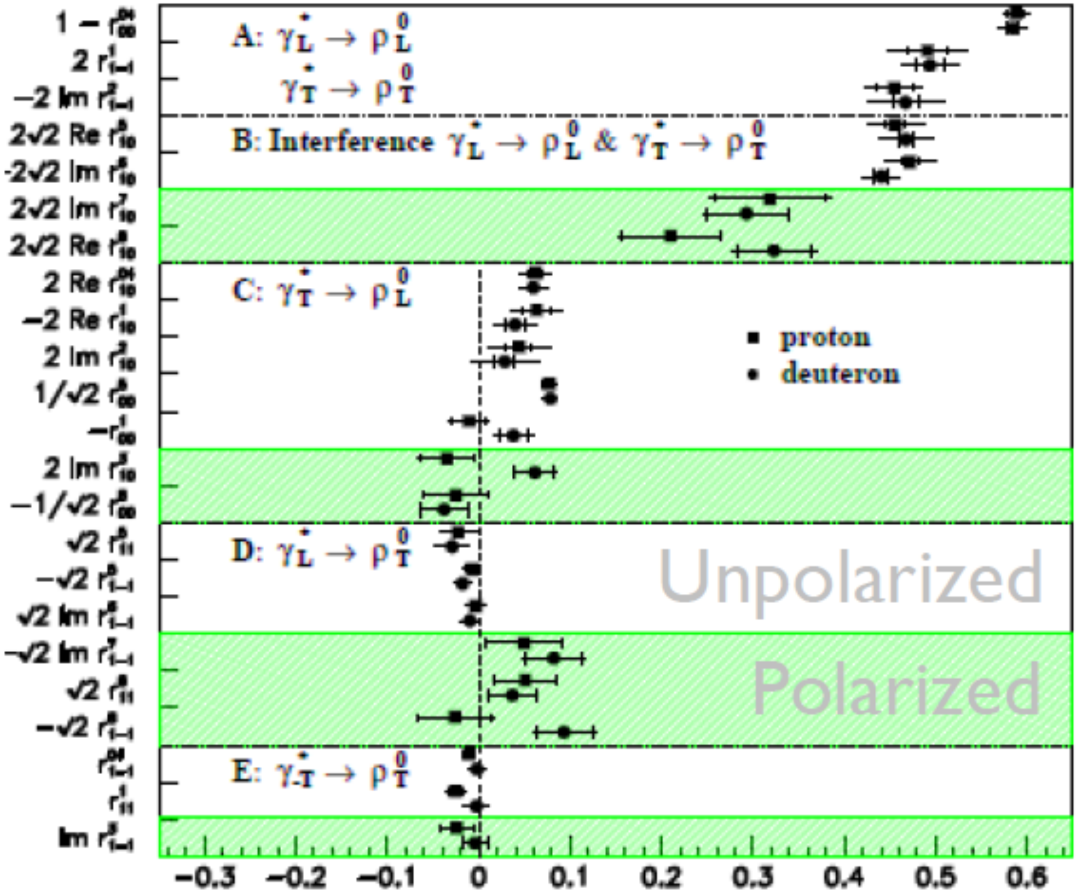


or SDMEs

-Schilling, Wolf (1973)
-Diehl (2007)

SDMEs ρ^0

$$|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \geq |T_{1-1}|$$



- Selected hierarchy of NPE helicity amplitudes is confirmed
- No differences between proton and deuteron

$\gamma^*_L \to V_L$ && $\gamma^*_T \to V_T$ (Class A & B)

- SDMEs are significantly different from zero
- SDMEs of Class B are smaller than SDMEs of Class A

$\gamma^*_T \to V_L$ (Class C)

- some SDMEs are significantly different from zero (up to 10σ)
- Violation from SCHC

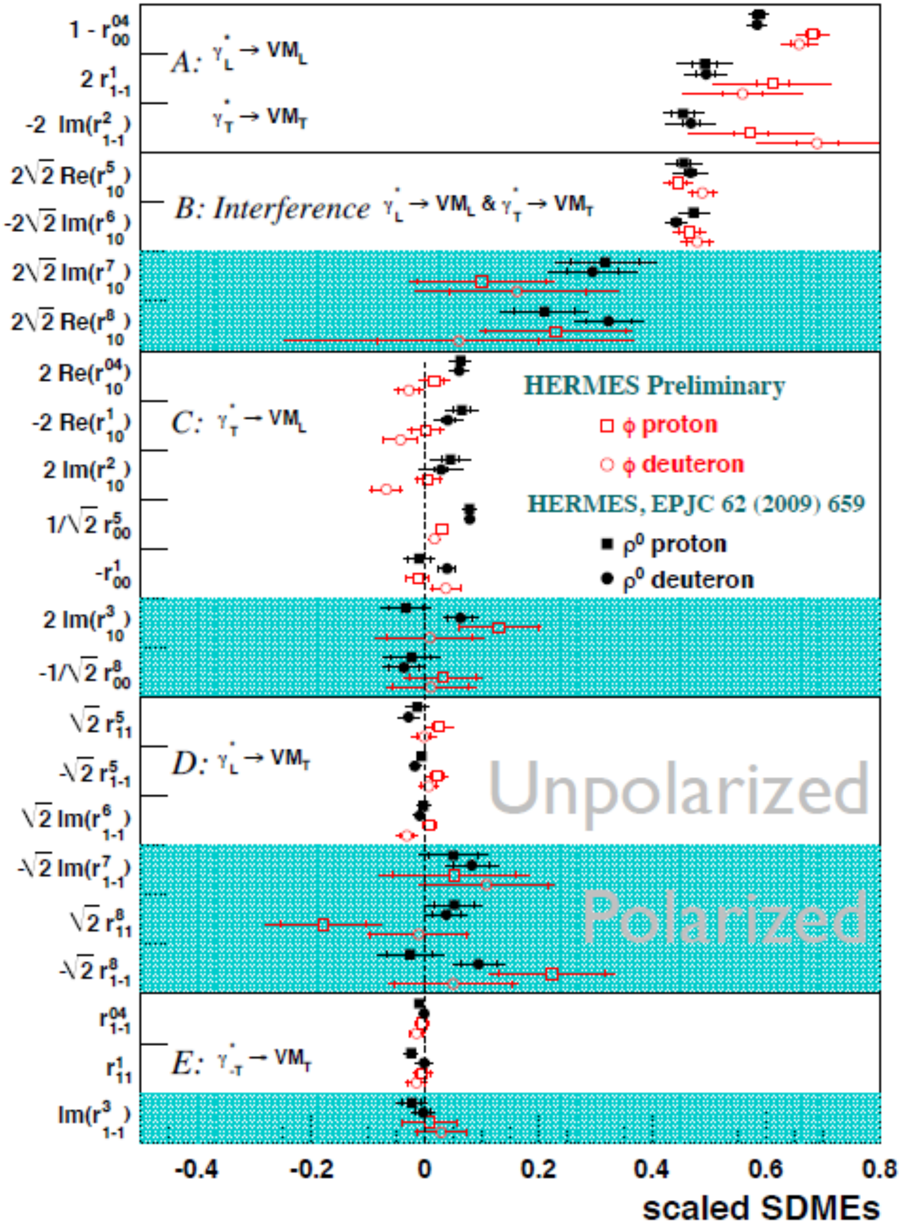
$\gamma^*_L \to V_T$ (Class D)

- Unpolarized SDMEs are slightly negative
- Polarized SDMEs are slightly positive

$\gamma^*_{-T} \to V_T$ (Class E)

- SDMEs on Deuteron are consistent with zero
- Small deviation from zero for SDMEs on hydrogen

SDMEs Φ



- Selected hierarchy of NPE helicity amplitudes is confirmed
- No significant differences between proton and deuteron

$\gamma^*_L \rightarrow V_L$ & $\gamma^*_T \rightarrow V_T$ (Class A & B)

- SDMEs are significantly different from zero
- 10-20% difference between ρ and ϕ SDMEs

$\gamma^*_T \rightarrow V_L$ (Class C)

- SDMEs are consistent with zero
- SDMEs on deuteron are slightly negative
- No strong indication of violation from SCHC

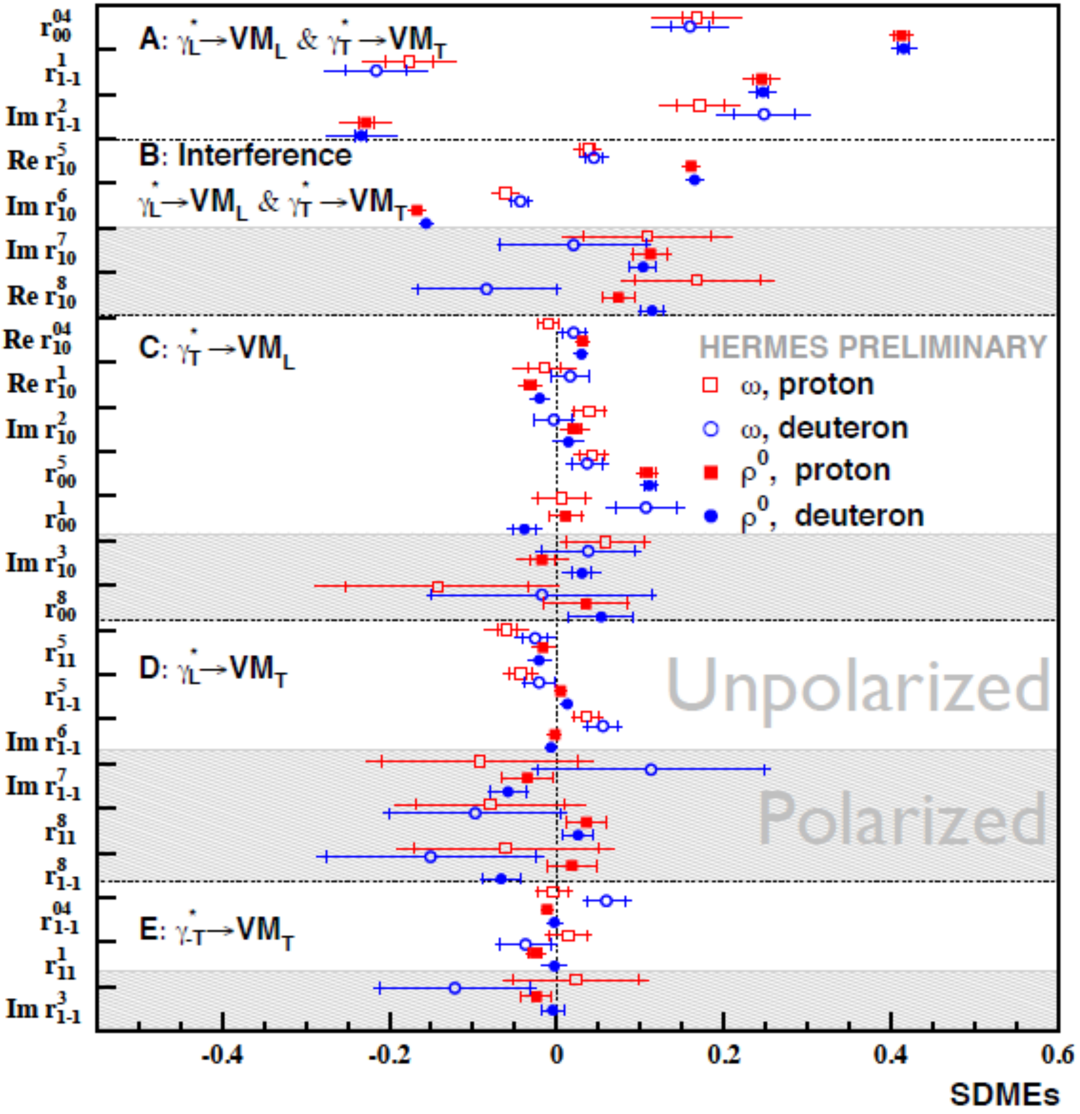
$\gamma^*_L \rightarrow V_T$ (Class D)

- Unpolarized and Polarized SDMEs are consistent with zero for both hydrogen and deuteron

$\gamma^*_{-T} \rightarrow V_T$ (Class E)

- Unpolarized and Polarized SDMEs are consistent with zero for both hydrogen and deuteron

SDMEs ω



- Selected hierarchy of NPE helicity amplitudes is not confirmed
- No differences between proton and deuteron

$\gamma^*_L \to V_L$ & $\gamma^*_T \to V_T$ (Class A & B)

- SDMEs are significantly different from zero
- Significant differences between ρ and ω SDMEs

$\gamma^*_T \to V_L$ (Class C)

- SDMEs are consistent with zero on both targets

$\gamma^*_L \to V_T$ (Class D)

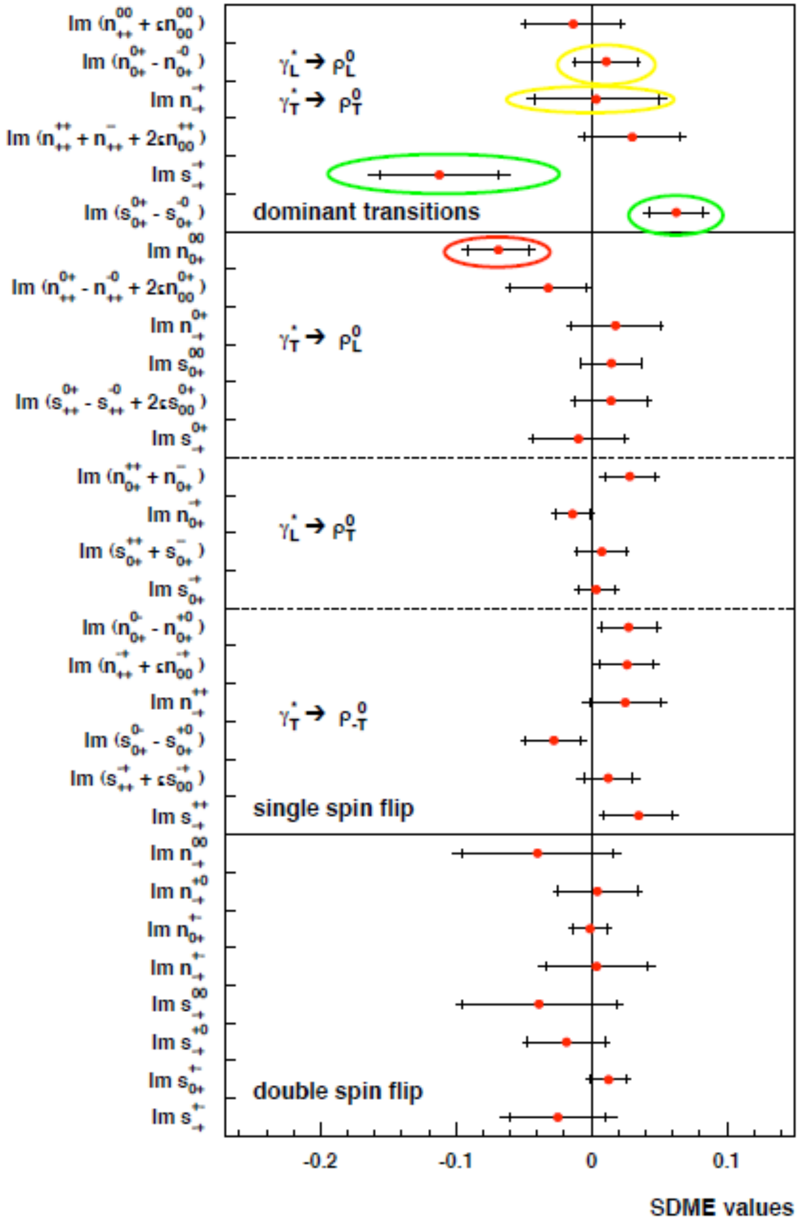
- Unpolarized SDMEs differ from zero
- Small evidence for violation from SCHC

$\gamma^*_{-T} \to V_T$ (Class E)

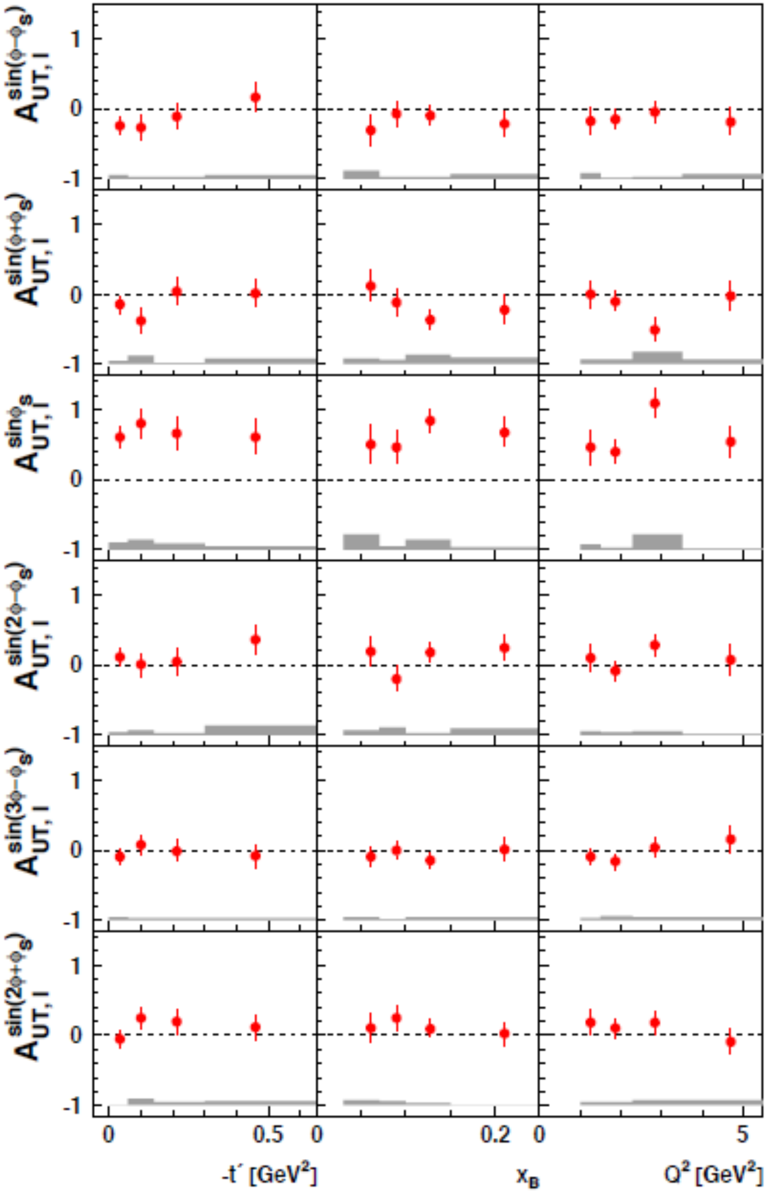
- Unpolarized and Polarized SDMEs are consistent with zero for both hydrogen and deuteron

Transverse SDMEs of ρ^0

- Most of the SDMEs are consistent with zero within 1.5σ
- SDMEs $\mathrm{Im}\,(s^{0+}_{0+} - s^{-0}_{0+})$, $\mathrm{Im}\, s^{-+}_{-+}$ and $\mathrm{Im}\, n^{00}_{0+}$ differ form zero by 2.5σ
- Non - zero value for SDME $\mathrm{Im}\, n^{00}_{0+}$ - violation from SCHC
- In case of NPE - expected $s^{\nu\nu'}_{\mu\mu'} < n^{\nu\nu'}_{\mu\mu'}$
- Non - zero values for SDMEs $\mathrm{Im}\,(s^{0+}_{0+} - s^{-0}_{0+})$ and $\mathrm{Im}\, s^{-+}_{-+}$ indicate a large contribution of UPE



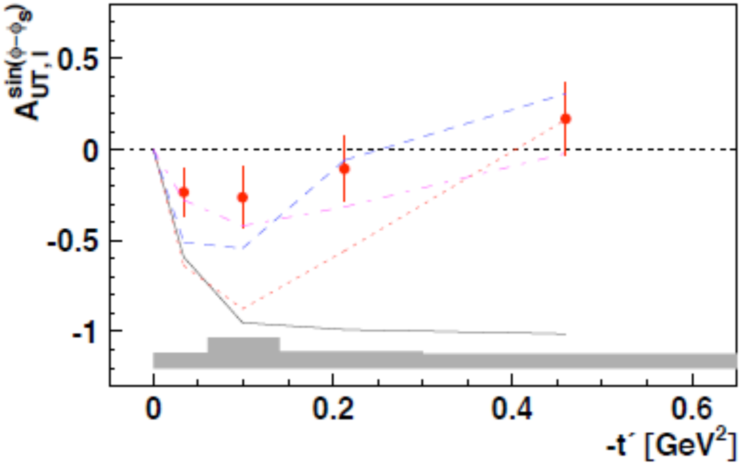
Exclusive π^+ Production



$$A_{UT}(\phi, \phi_S) = \frac{\sigma^{\Uparrow} - \sigma^{\Downarrow}}{\sigma^{\Uparrow} + \sigma^{\Downarrow}}$$

- 6 azimuthal asymmetry amplitudes are measured
- no L/T separation
- small overall value for the leading asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_S)}$
- unexpectedly large value for the asymmetry amplitude $A_{UT}^{\sin(\phi_S)}$
- other amplitudes are consistent with zero
- evidence for contribution from transversally polarized photons

Exclusive π⁺ Production



Leading amplitude $A_{UT}^{\sin(\phi-\phi_S)}$

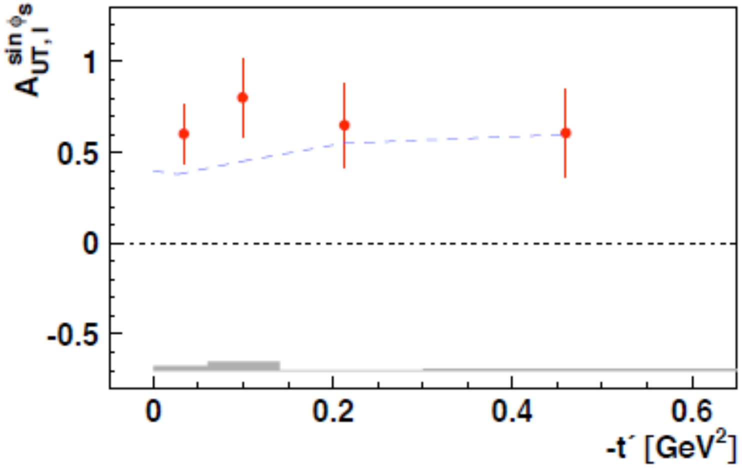
- small asymmetry with possible sign change
- $A_{UT}^{\sin(\phi-\phi_S)} \propto Im(\widetilde{\mathcal{E}} * \widetilde{\mathcal{H}})$
- theoretical expectation:

large negative value *Frankfurt et.al. (2001)*
Belitsky, Muller (2001)

- difference could be due the γ^*_T .

Goloskokov, Kroll (2009)
Bechler, Muller (2009)

-Goloskokov, Kroll (2009)-



amplitude $A_{UT}^{\sin(\phi_S)}$

- large positive value
- mild t' dependence
- does not vanish at -t'=0
- can be explained by a sizable interference between contributions from γ^*_L and γ^*_T.

Transverse target spin asymmetries for exclusive ω

NEW!!

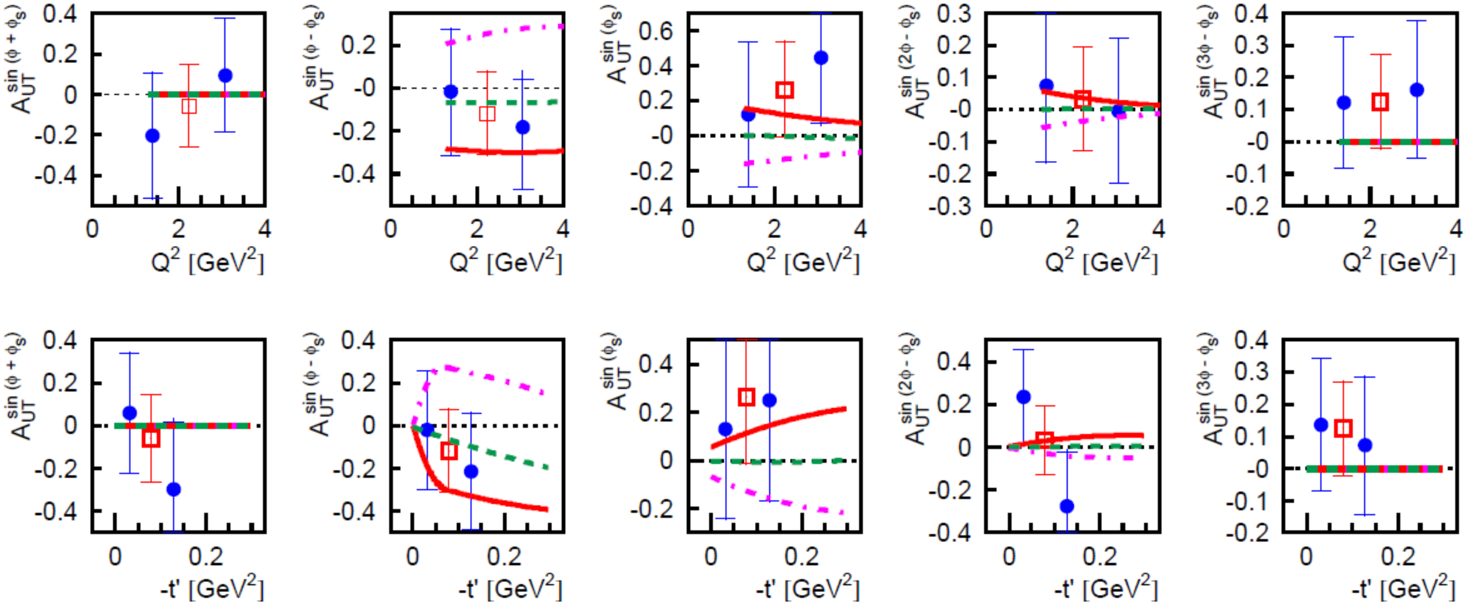


Fig. 5. The five amplitudes describing the strength of the sine modulations of the cross section for hard exclusive ω-meson production. The full circles show the data in two bins of Q^2 or $-t'$. The open squares represent the results obtained for the entire kinematic region. The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature. The results receive an additional 8.2% scale uncertainty corresponding to the target polarization uncertainty. The solid (dash-dotted) lines show the calculation of the GK model [11,21] for a positive (negative) $\pi\omega$ transition form factor, and the dashed lines are the model results without the pion pole.