Transversity and Beyond at HERMES

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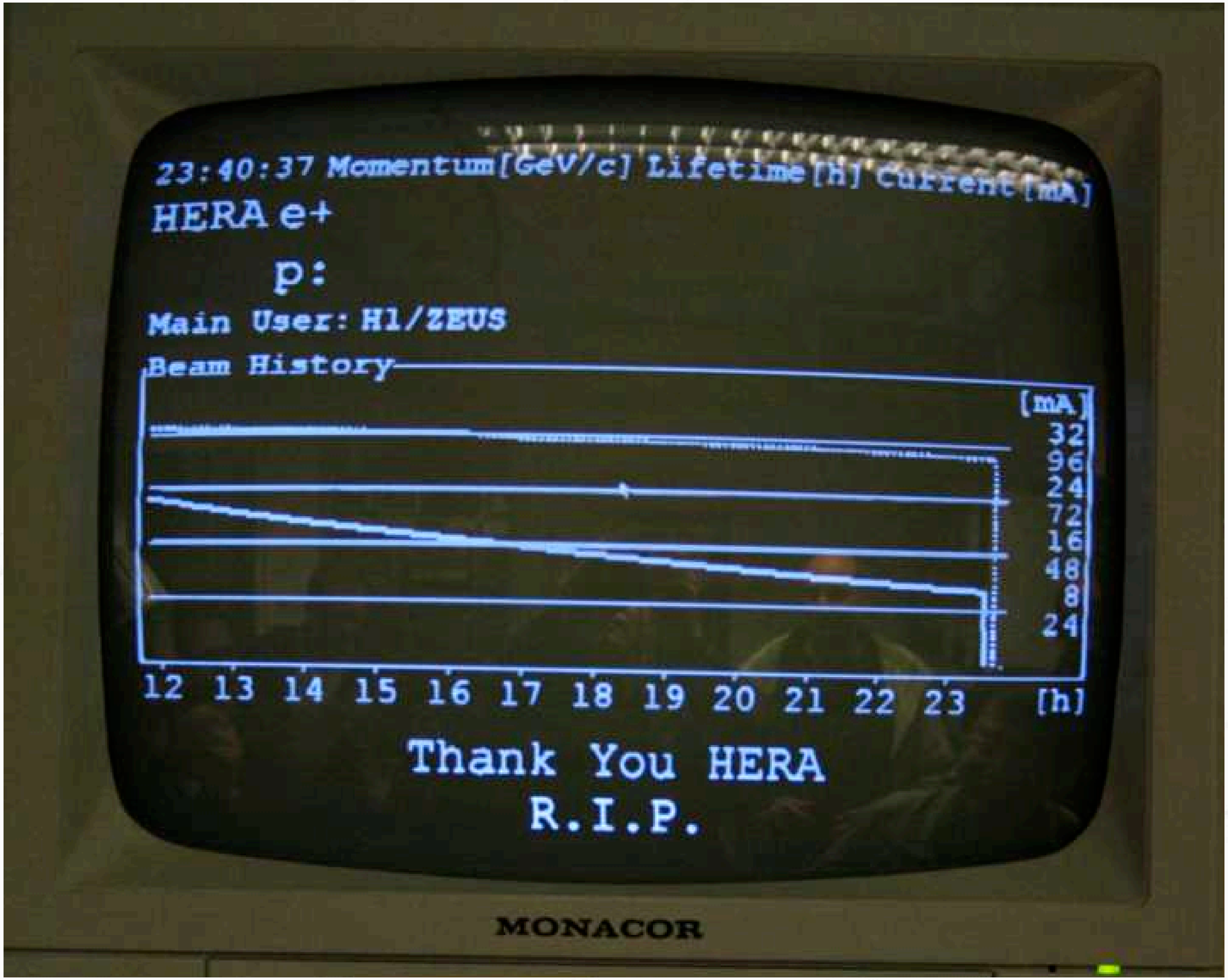
Transversity 2008
Ferrara, May 31st 2008

June 30th, 2007 (around midnight)



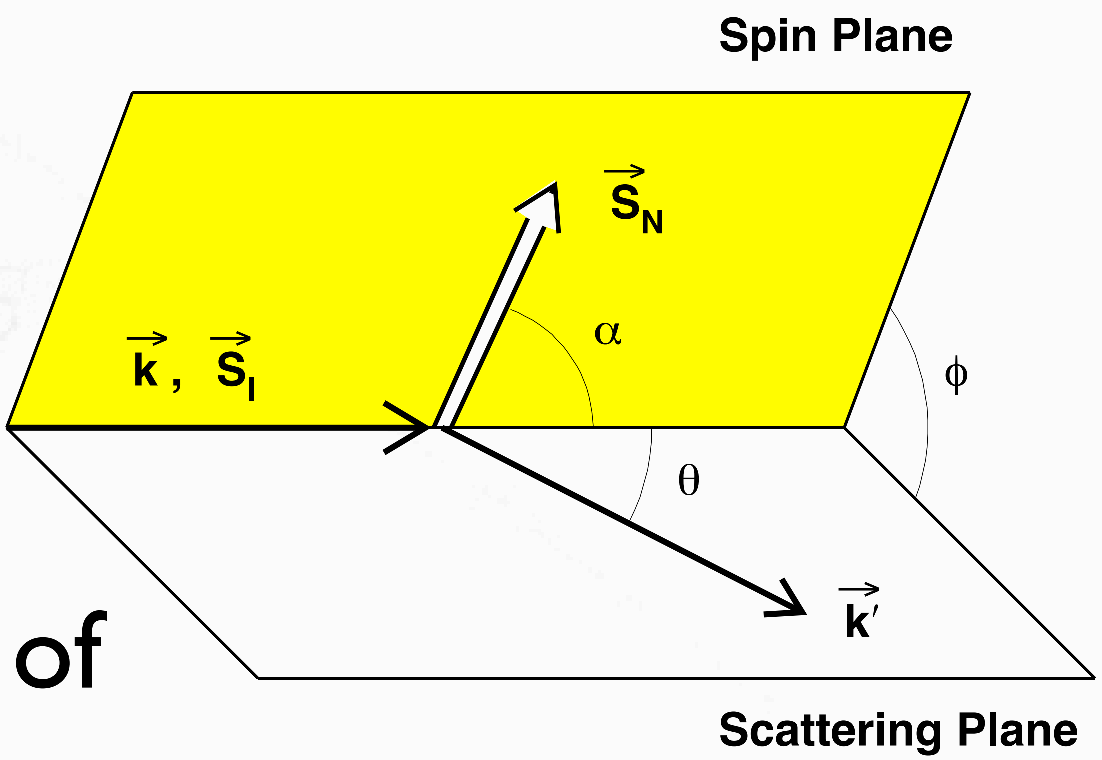
Data taking is over,
but data analysis by far not!

Inclusive DIS

$$\frac{\mathrm{d}^2\sigma(s,S)}{\mathrm{d}x\ \mathrm{d}Q^2} = \frac{2\pi\alpha^2 y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$

Lepton Tensor

Hadron Tensor



parametrized in terms of

Structure Functions

$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}F_1(x,Q^2) + \frac{1-y-\gamma^2y^2/4}{2xy}F_2(x,Q^2)$$

$$-P_l P_T \cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)g_1(x,Q^2) - \frac{\gamma^2 y}{2}g_2(x,Q^2)\right]$$

$$+P_l P_T \sin\alpha\cos\phi\,\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right)$$

Parton-Model Interpretation of Structure Functions

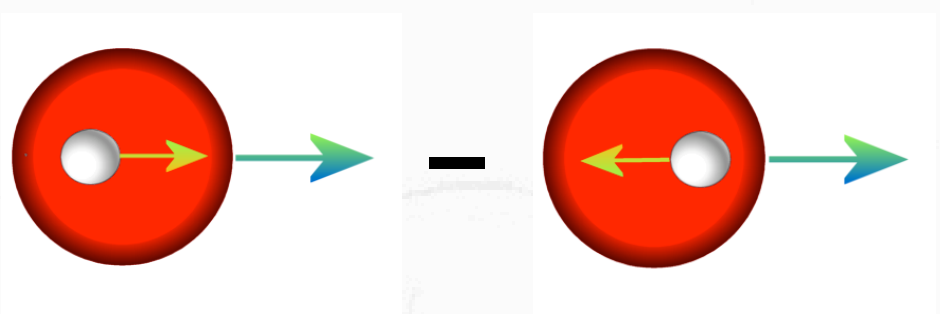
$$F_1(x) = \frac{1}{2} \sum_q e_q^2 f_1^q(x)$$

$$F_2(x) = x \sum_q e_q^2 f_1^q(x)$$

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 g_1^q(x)$$

$$g_2(x) = 0$$

$f_1^q =$ 

$g_1^q =$ 

quark-spin constribution to nucleon helicity

Closer Look at g_2

- **higher-twist, thus**
  - **no probabilistic interpretation**
  - **probes parton correlations**
- **at LO:** $g_2 = \frac{1}{2} \sum e_q^2 \, g_T(x)$
- $$\int_0^1 dx x g_2(x, Q^2) = \frac{1}{3}\left(-a_2(Q^2) + d_2(Q^2)\right)$$

second moment of g_1

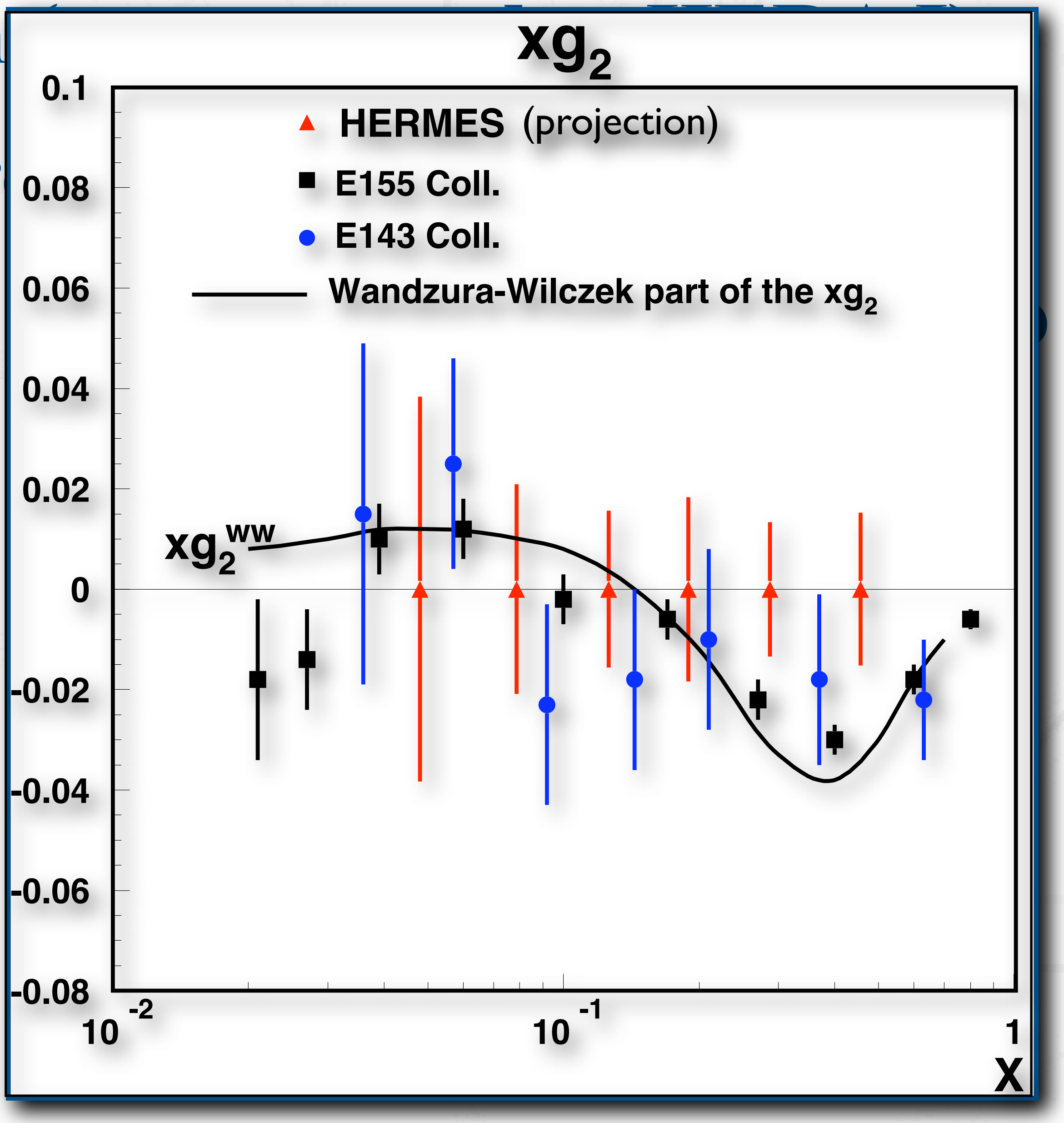
sensitive to a quark *and* a gluon amplitude

What HERMES can do for g_2

- **unfortunately, HERA II with no or only low beam polarization (as compared to HERA I)**
  ➠ low figure of merit
  ➠ expected precision not comparable to E155

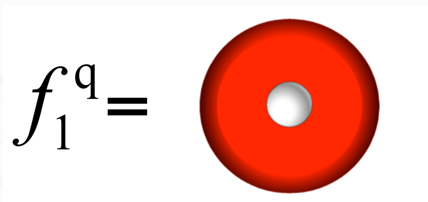
What HERMES can do for g_2

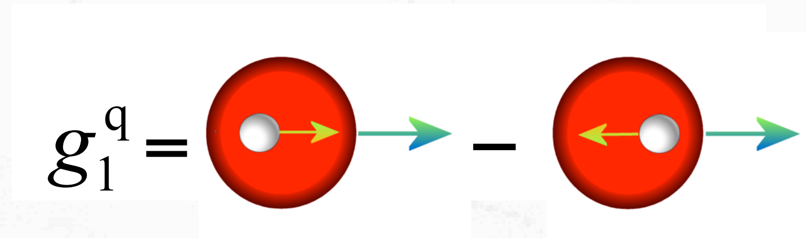
- unfortunately, HERA II with no or only low beam polarization
  - ➡ low figur
  - ➡ expected E155

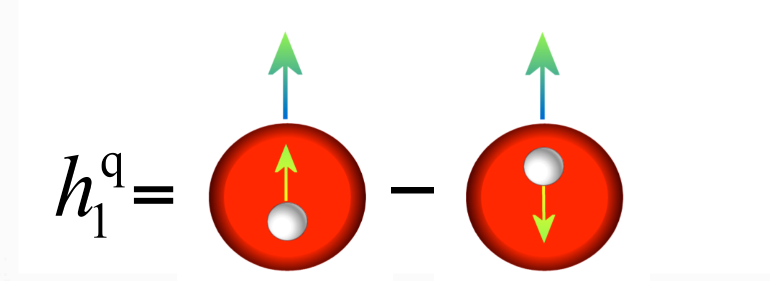


... back to parton distributions ...

Quark Structure of the Nucleon







$\Downarrow$ $\Downarrow$ $\Downarrow$

Unpolarized quarks and nucleons

Longitudinally polarized quarks and nucleons

Transversely polarized quarks and nucleons

$f_1^q(x)$: spin averaged (well known)

$g_1^q(x)$: helicity difference (known)

$h_1^q(x)$: transversity (~~hardly~~ known!)

$\Rightarrow$ Vector Charge **Alexei & Co., THANKS!!** ...sor Charge

$\langle PS|\bar{\Psi}\gamma^{\mu}\Psi|PS\rangle = \int dx(f_1^q(x) - f_1^{\bar{q}}(x))$

$\langle PS|\bar{\Psi}\gamma^{\mu}\gamma_5\Psi|PS\rangle = \int dx(g_1^q(x) + g_1^{\bar{q}}(x))$

$\langle PS|\bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi|PS\rangle = \int dx(h_1^q(x) - h_1^{\bar{q}}(x))$

SSAs in One-Hadron Production

$$A_{UT}(\phi,\phi_S) = \frac{1}{\langle|S_\perp|\rangle}\frac{N_h^\uparrow(\phi,\phi_S)-N_h^\downarrow(\phi,\phi_S)}{N_h^\uparrow(\phi,\phi_S)+N_h^\downarrow(\phi,\phi_S)}$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{k_T}\hat{\boldsymbol{P}}_{h\ldots}}{\ldots}\ldots p_T^2)\,H_1^{\perp,q}(z,k_T^2)\right]$$

$$+ \sin(\phi-\phi_S)\ldots\left[\frac{\ldots\boldsymbol{T}\hat{\boldsymbol{P}}_{h\perp}}{M}f_{1T}^{\perp,q}(x,p_T^2)\,D_1^q(z,k_T^2)\right]$$

$$+ \ldots$$

cf. L. Pappalardo's talk for results

$\mathcal{I}[\ldots]$: **convolution integral over initial (p_T) and final (k_T) quark transverse momenta**

$\Rightarrow$ 2D Max.Likelihd. fit to get Collins and Sivers amplitudes:

$$PDF(2\langle\sin(\phi\pm\phi_S)\rangle_{UT},\ldots,\phi,\phi_S) = \tfrac{1}{2}\{1+P_T(2\langle\sin(\phi\pm\phi_S)\rangle_{UT}\,\sin(\phi\pm\phi_s)+\ldots)\}$$

Resolving the Convolution Integral

Weight with transverse hadron momentum $P_{h\perp}$ to resolve convolution:

$$\tilde{A}_{UT}(\phi,\phi_S) = \frac{1}{\langle S_\perp \rangle} \frac{\sum_{i=1}^{N^+} P_{h\perp,i} - \sum_{i=1}^{N^-} P_{h\perp,i}}{N^+ + N^-}$$

$$\sim \sin(\phi+\phi_S) \cdot \sum_q e_q^2 \, h_1^q(x) \; z \, H_1^{\perp(1),q}(z)$$

$$- \sin(\phi-\phi_S) \cdot \sum_q e_q^2 \, f_{1T}^{\perp(1),q}(x) \; z \, D_1^q(z)$$

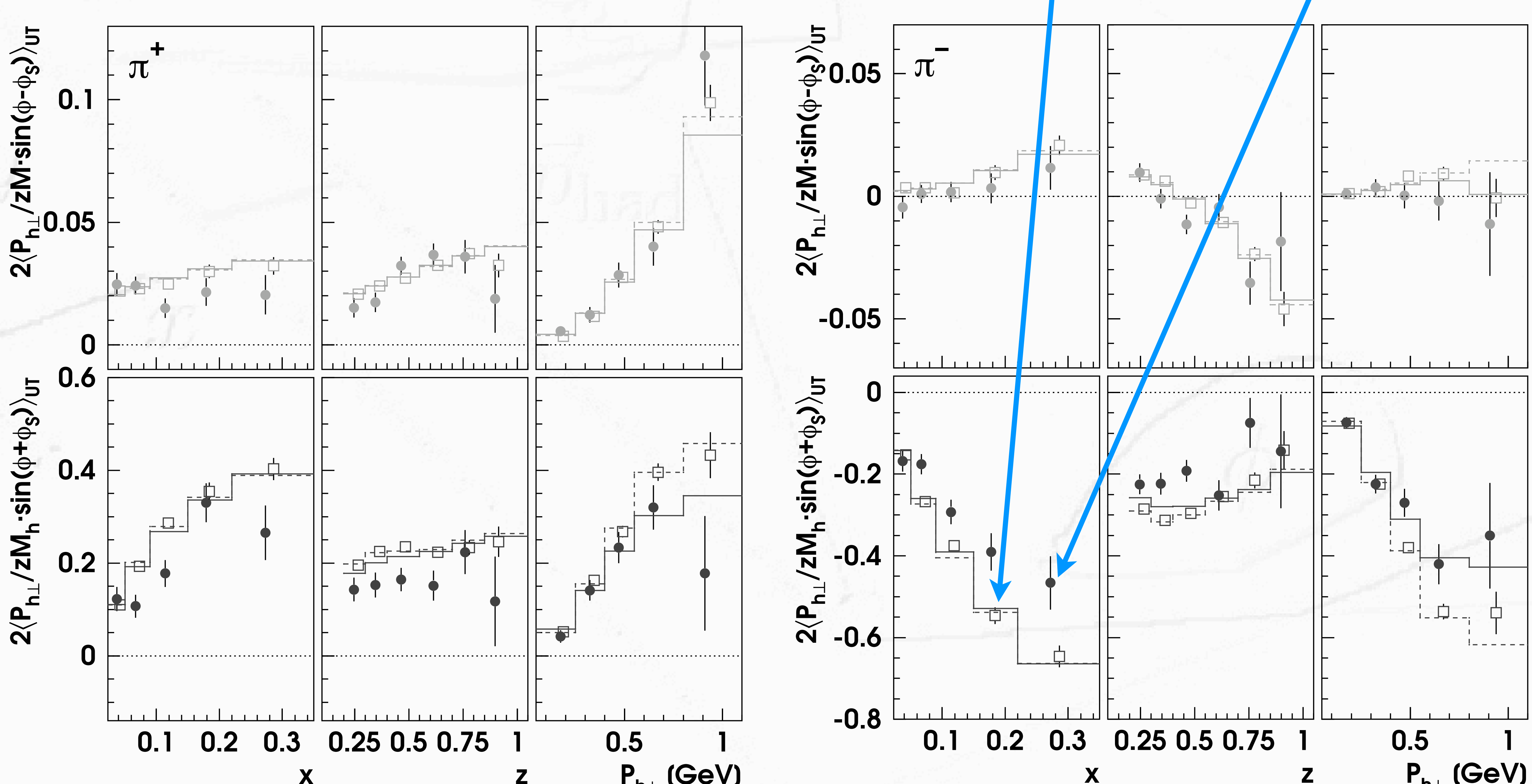
$$+ \ \ldots$$

(1): p_T^2-/k_T^2-moment of distribution / fragmentation function

- **idea goes back to Kotzinian & Mulders [Phys. Rev. D 54 (1996) 1229]**
- **factorized expressions**
- **Q^2 evolution under control**
- **model-independent analysis of DFs and FFs possible**

What about Integration over Transverse Momentum?

Large acceptance effects observed when comparing reconstructed *weighted* amplitudes in **4π** vs. **acceptance**



Extracting full kinematic dependence

1. The full kinematic dependence of the Collins and Sivers moments on $\bar{x} \equiv (x, Q^2, z, P_{h\perp})$ is evaluated from the real data through a fit of the full set of SIDIS events based on a Taylor expansion on $\bar{x}$:

$$f(\bar{x}, P_t; c) = 1 + P_t \cdot [A_{Collins}(\bar{x}; c_i) \cdot \sin(\phi + \phi_S) + A_{Sivers}(\bar{x}; c_i) \cdot \sin(\phi - \phi_S)]$$

e.g.: $A_{Collins}(\bar{x}, c) = c_0 + c_1 \cdot x + c_2 \cdot z + c_3 \cdot Q^2 + c_4 \cdot P_{h\perp} + c_5 \cdot x^2 + \ldots + c_{22} \cdot x^2 \cdot z \cdot P_{h\perp}$

2. The extracted azimuthal moments $A_{Collins}(\bar{x}; c_i)$ and $A_{Sivers}(\bar{x}; c_i)$ are folded with the spin-independent cross section (known!) in 4π ($\sigma_{UU}^{4\pi}$) and within the HERMES acceptance ($\sigma_{UU}^{acc.}$) :

$$\left\langle \frac{P_{h\perp}}{zM} \sin(\phi \pm \phi_S) \right\rangle_{UT}^{acc,4\pi} (x) = \frac{\int P_{h\perp}/(zM)\ \sigma_{UU}^{acc,4\pi}(\bar{x})\ A_{Collins,Sivers}(\bar{x}; c_i)}{\int \sigma_{UU}^{acc,4\pi}(\bar{x})}$$

L. Pappalardo's talk at Transversity'08

From SSA amplitudes to TMDs

Leading-Twist TMDs

		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$
	L		Δq	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	δq $h_{1T}^\perp$

Sivers function

Using *Purities* to extract PDFs

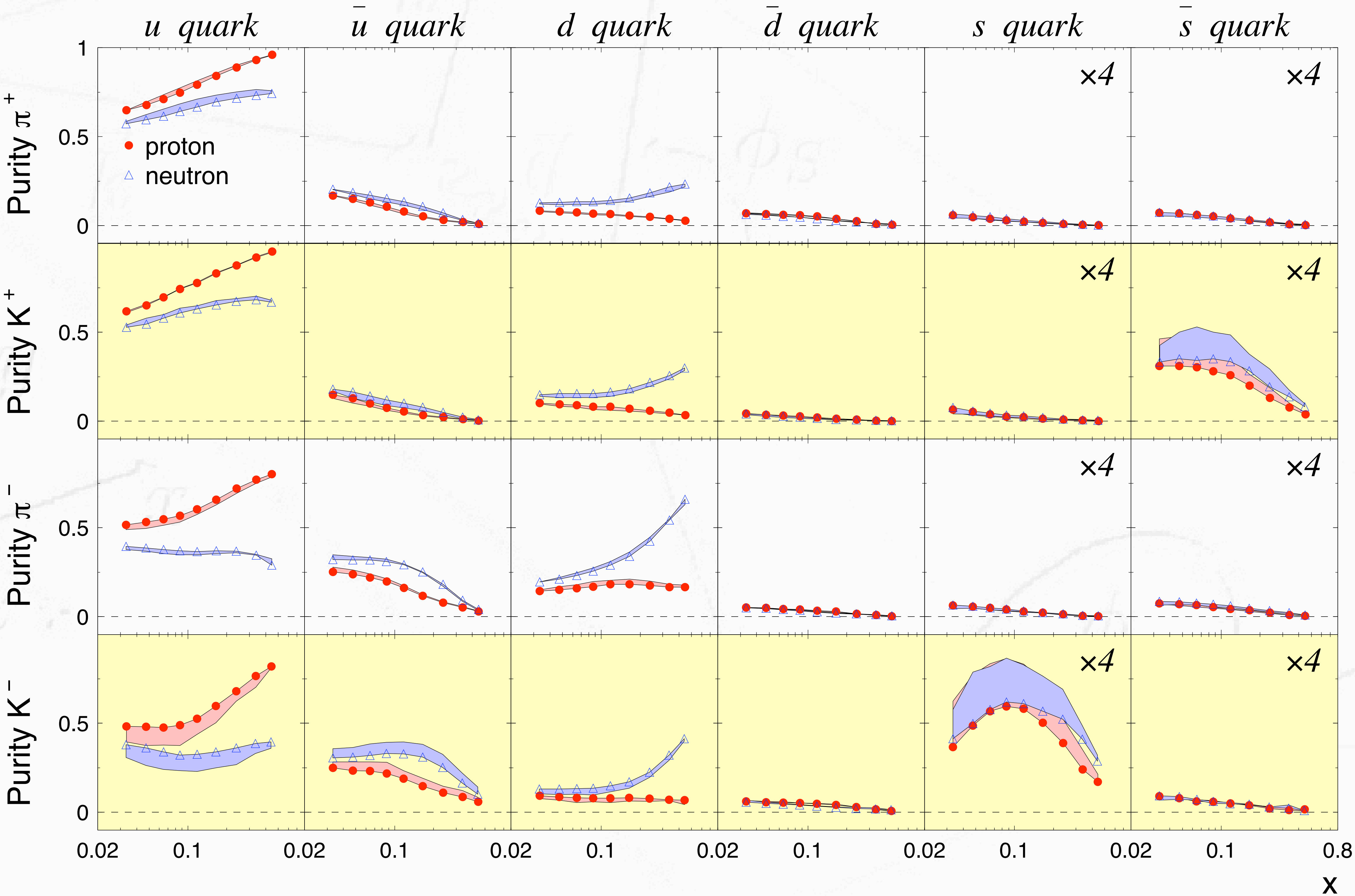
$$\tilde{A}_{UT}^{\sin(\phi-\phi_S),h}(x) = \mathcal{C} \cdot \frac{\sum_q e_q^2\, f_{1T}^{\perp(1),q}(x) \int dz\, D_1^{q,h}(z) \mathcal{A}(x,z)}{\sum_{q'} e_{q'}^2\, f_1^{q'}(x) \int dz\, D_1^{q',h}(z) \mathcal{A}(x,z)}$$

$$= \mathcal{C} \cdot \sum_q \frac{e_q^2\, f_1^q(x)\, \mathcal{D}_1^{q,h}(x)}{\sum_{q'} e_{q'}^2\, f_1^{q'}(x)\, \mathcal{D}_1^{q',h}(x)} \cdot \frac{f_{1T}^{\perp(1),q}}{f_1^q}(x)$$

$$= \mathcal{C} \cdot \sum_q \mathcal{P}_q^h(x) \cdot \frac{f_{1T}^{\perp(1),q}}{f_1^q}(x)$$

- **when using weighted asymmetries, model-independent extraction of PDFs (e.g., Sivers) possible**
- **used successfully in HERMES helicity-DF analysis**
- **purities are completely unpolarized objects ➥ present MC can be used**
- **Sivers case: easy as the only FF that appears is D_1**

Purities at HERMES



Using *Purities* to extract PDFs

$$\tilde{A}_{UT}^{\sin(\phi+\phi_S),h}(x) = \mathcal{C} \cdot \frac{\sum_q e_q^2\, h_1^q(x) \int dz\, H_1^{\perp(1),q,h}(z) \mathcal{A}(x,z)}{\sum_{q'} e_{q'}^2\, f_1^{q'}(x) \int dz\, D_1^{q',h}(z) \mathcal{A}(x,z)}$$

$$= \mathcal{C} \cdot \sum_q \frac{e_q^2\, f_1^q(x)\, \mathcal{H}_1^{\perp(1),q,h}(x)}{\sum_{q'} e_{q'}^2\, f_1^{q'}(x)\, \mathcal{D}_1^{q',h}(x)} \cdot \frac{h_1^q}{f_1^q}(x)$$

$$= \mathcal{C} \cdot \sum_q \mathcal{P}_q^h(x) \cdot \frac{h_1^q}{f_1^q}(x)$$

- **when using weighted asymmetries, model-independent extraction of PDFs (e.g., Sivers) possible**
- **used successfully in HERMES helicity-DF analysis**
- **purities are completely unpolarized objects ➥ present MC can be used**
- **Collins case: need to consider Collins FF**

Valence-Quark Sivers DF

- **look at difference in charged-pion yields: $\Delta N = N^{\pi^+} - N^{\pi^-}$:**

$$A_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) \equiv \frac{1}{S_T}\frac{\Delta N^{\uparrow}(\phi,\phi_S) - \Delta N^{\downarrow}(\phi,\phi_S)}{\Delta N^{\uparrow}(\phi,\phi_S) + \Delta N^{\downarrow}(\phi,\phi_S)}$$

- **simple interpretation in terms of valence distributions:**

$$\langle \sin(\phi-\phi_S)\rangle_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) = -\frac{4f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

at least for *weighted* asymmetries, but also for unweighted case convolutions simplify

Leading-Twist TMDs

		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$
	L		Δq	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	δq $h_{1T}^\perp$

"Pretzelosity"

Leading-Twist TMDs

		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$
	L		Δq	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	δq $h_{1T}^\perp$

the "weird/boost" distributions

1-Hadron Production (ep→ehX)

$$d\sigma = d\sigma^0_{UU} + \cos 2\phi\, d\sigma^1_{UU} + \frac{1}{Q}\cos\phi\, d\sigma^2_{UU} + \lambda_e \frac{1}{Q}\sin\phi\, d\sigma^3_{LU}$$

$$+S_L \left\{ \sin 2\phi\, d\sigma^4_{UL} + \frac{1}{Q}\sin\phi\, d\sigma^5_{UL} + \lambda_e \left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^7_{LL} \right] \right\}$$

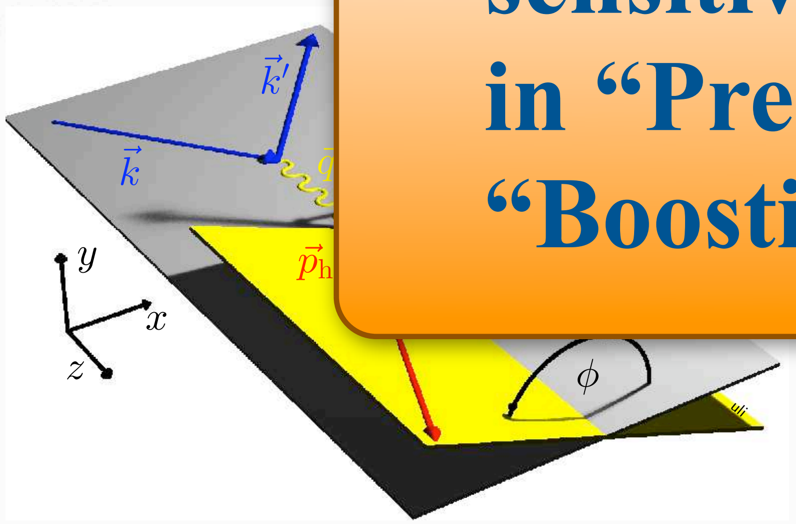
$$+S_T \left\{ \sin(\phi-\phi_S)\, d\sigma^8_{UT} + \sin(\phi+\phi_S)\, d\sigma^9_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{10}_{UT} \right.$$

$$+\frac{1}{Q}\left(\sin(2\phi-\phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma^{12}_{UT}\right)$$

$$\left. \ldots \phi_S)\, d\sigma^{15}_{LT}) \right] \Big\}$$

σ_{XY}

Beam Target Polarization



Collins Effect:

sensitive to quark transverse spin in "Pretzelocity" distribution or "Boostisity" $h_{1L}^{\perp}$

... (1996) 197

...780

...9

Bacchetta et al., JHEP 0702 (2007) 093

"Trento Conventions", Phys. Rev. D 70 (2004) 117504

1-Hadron Production (ep → ehX)

$$d\sigma = d\sigma^0_{UU} + \cos 2\phi \, d\sigma^1_{UU} + \frac{1}{Q} \cos\phi \, d\sigma^2_{UU} + \lambda_e \frac{1}{Q} \sin\phi \, d\sigma^3_{LU}$$

$$+S_L \left\{ \sin 2\phi \, d\sigma^4_{UL} + \ldots \right\}$$

$$+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \ldots \right.$$

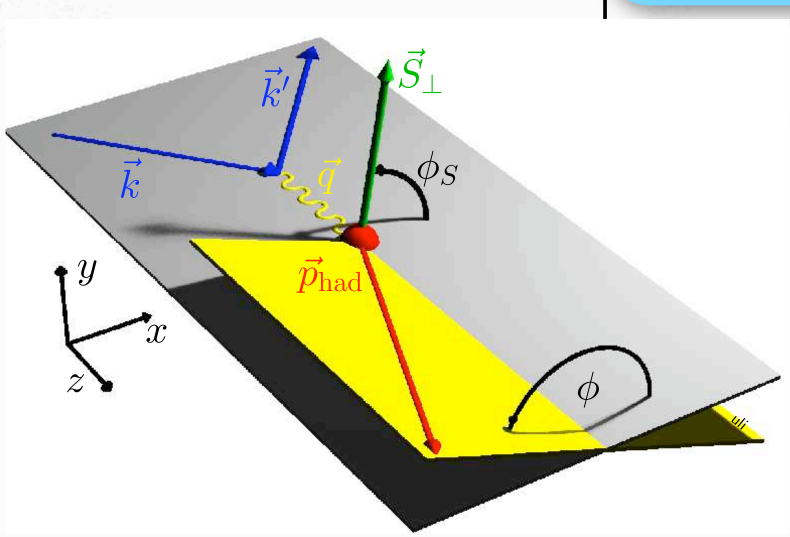
$$\left. + \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right) \right.$$

$$\left. + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q} \left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}$$

DSA involving spin-independent FF and "Boostisity" $g_{1T}^{\perp}$

σ_{XY}

Beam Target Polarization



Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197

Boer and Mulders, Phys. Rev. D 57 (1998) 5780

Bacchetta et al., Phys. Lett. B 595 (2004) 309

Bacchetta et al., JHEP 0702 (2007) 093

"Trento Conventions", Phys. Rev. D 70 (2004) 117504

... more twist-3 ...

1-Hadron Production (ep→ehX)

$$d\sigma = d\sigma^0_{UU} + \cos 2\phi \, d\sigma^1_{UU} + \frac{1}{Q} \cos\phi \, d\sigma^2_{UU} + \lambda_e \frac{1}{Q} \sin\phi \, d\sigma^3_{LU}$$

$$+ S_L \left\{ \sin 2\phi \, d\sigma^4_{UL} + \frac{1}{Q} \sin\phi \, d\sigma^5_{UL} + \lambda_e \left[d\sigma^6_{LL} + \frac{1}{Q} \cos\phi \, d\sigma^7_{LL} \right] \right\}$$

$$+ S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right.$$

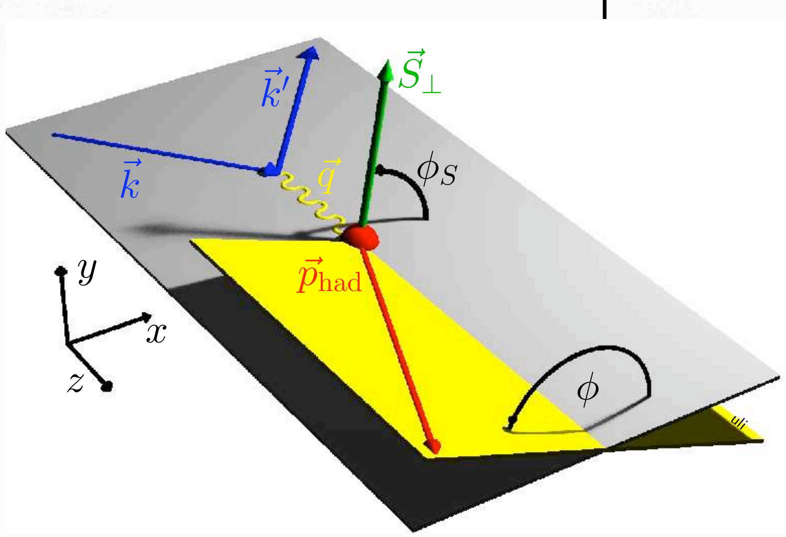
$$\ldots d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \Big)$$

$$\left. + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q} \left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}$$

sensitivity to or needed for transversity

σ_{XY}: X = **Beam**, Y = **Target**

Polarization



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$\sin\phi_S$ - term in A_{UT}

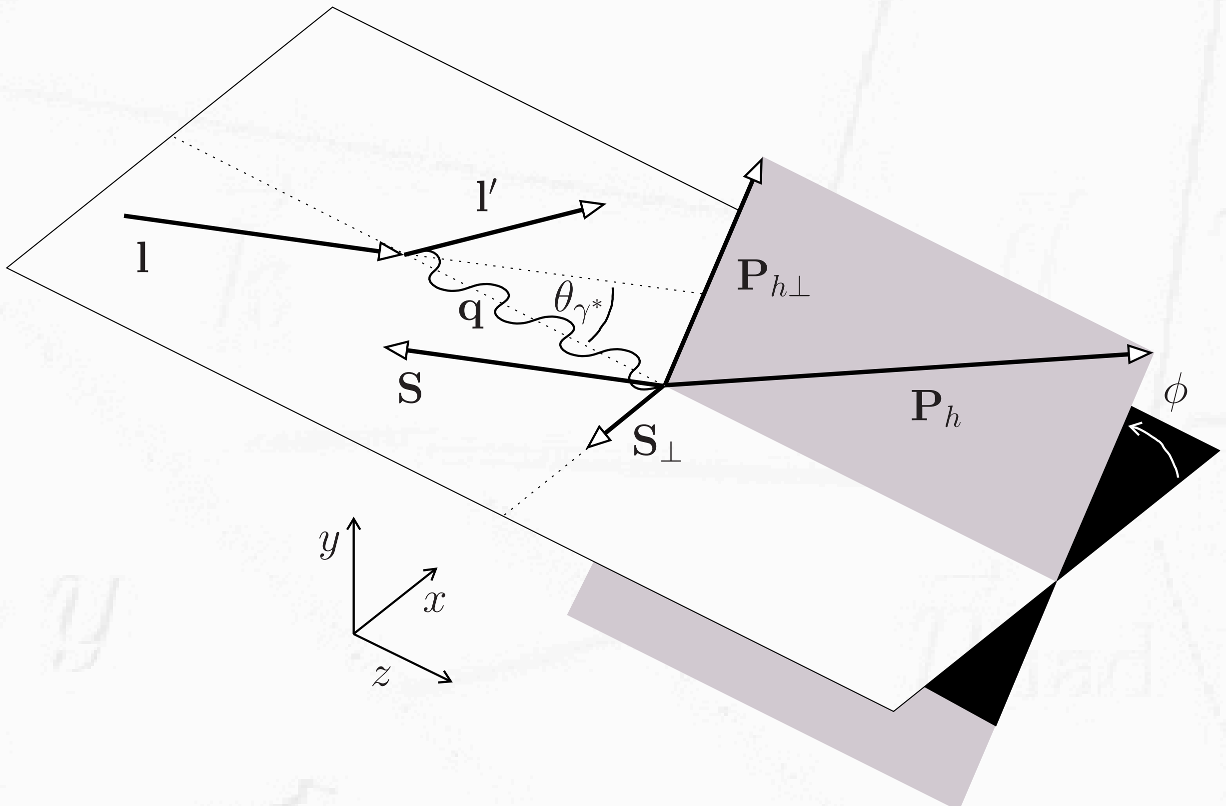
$$-\mathcal{I}\left[\frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left(xh_T H_1^\perp - xh_T^\perp H_1^\perp - \frac{M_h}{M}g_{1T}\frac{\tilde{G}^\perp}{z} + \frac{M_h}{M}f_{1T}^\perp\frac{\tilde{D}^\perp}{z}\right)\right]$$

$$-h_1 + \tilde{h}_T - \frac{p_T^2}{2M^2x}h_{1T}^\perp$$

$$h_1 - \tilde{h}_T^\perp - \frac{p_T^2}{2M^2x}h_{1T}^\perp$$

$$-2h_1 + (\tilde{h}_T + \tilde{h}_T^\perp)$$

A_{UL} & Mixing of Azimuthal Moments



Experiment: Target Polarization w.r.t. Beam Direction (l)!

Theory: Polarization along virtual photon direction (q)

⇒ mixing of "experimental" and "theory" asymmetries via:

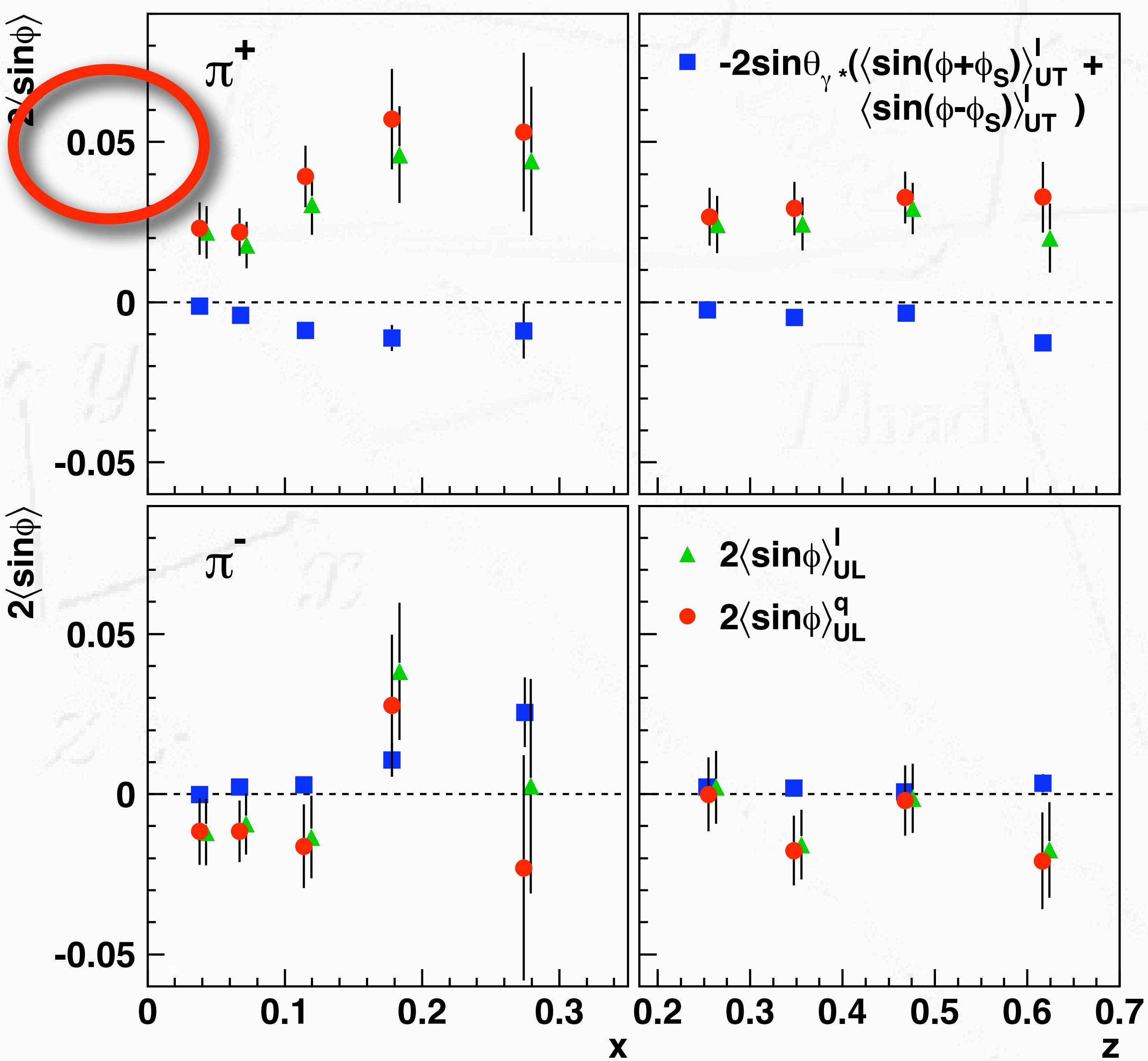
[Diehl and Sapeta, Eur. Phys. J. C41 (2005)]

$$\begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{l} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\ \frac{1}{2}\sin\theta_{\gamma^*} & \cos\theta_{\gamma^*} & 0 \\ \frac{1}{2}\sin\theta_{\gamma^*} & 0 & \cos\theta_{\gamma^*} \end{pmatrix} \begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{q} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{q} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{q} \end{pmatrix}$$

($\cos\theta_{\gamma^*} \simeq 1$, $\sin\theta_{\gamma^*}$ up to 15% at HERMES energies)

Twist-3 at HERMES

$$\left\langle \sin\phi \right\rangle_{UL}^{q} = \left\langle \sin\phi \right\rangle_{UL}^{l} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} + \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \right)$$



- twist-3 dominates measured asymmetries on longitudinally polarized targets!
- significantly positive for π^+
- consistent with zero for π^-
- twist-3 not necessarily small

Airapetian et al., Phys. Lett. B 622 (2005) 14

Another Longitudinal SSA: A_{LU}

longitudinally pol. beam & unpol. target ⇒ subleading-twist

$$\langle \sin\phi \rangle_{LU} \propto \lambda_e \frac{M}{Q} \, \mathcal{I}\left[x e(x) H_1^{\perp}(z) - \frac{M_h}{zM} h_1^{\perp}(x) E(z) \right]$$

⇒ for long time candidate to access $e(x)$

($h_1^{\perp}(x)$ **contribution either assumed to be zero (T-odd!) or small(??)**)

Another Longitudinal SSA: A_{LU}

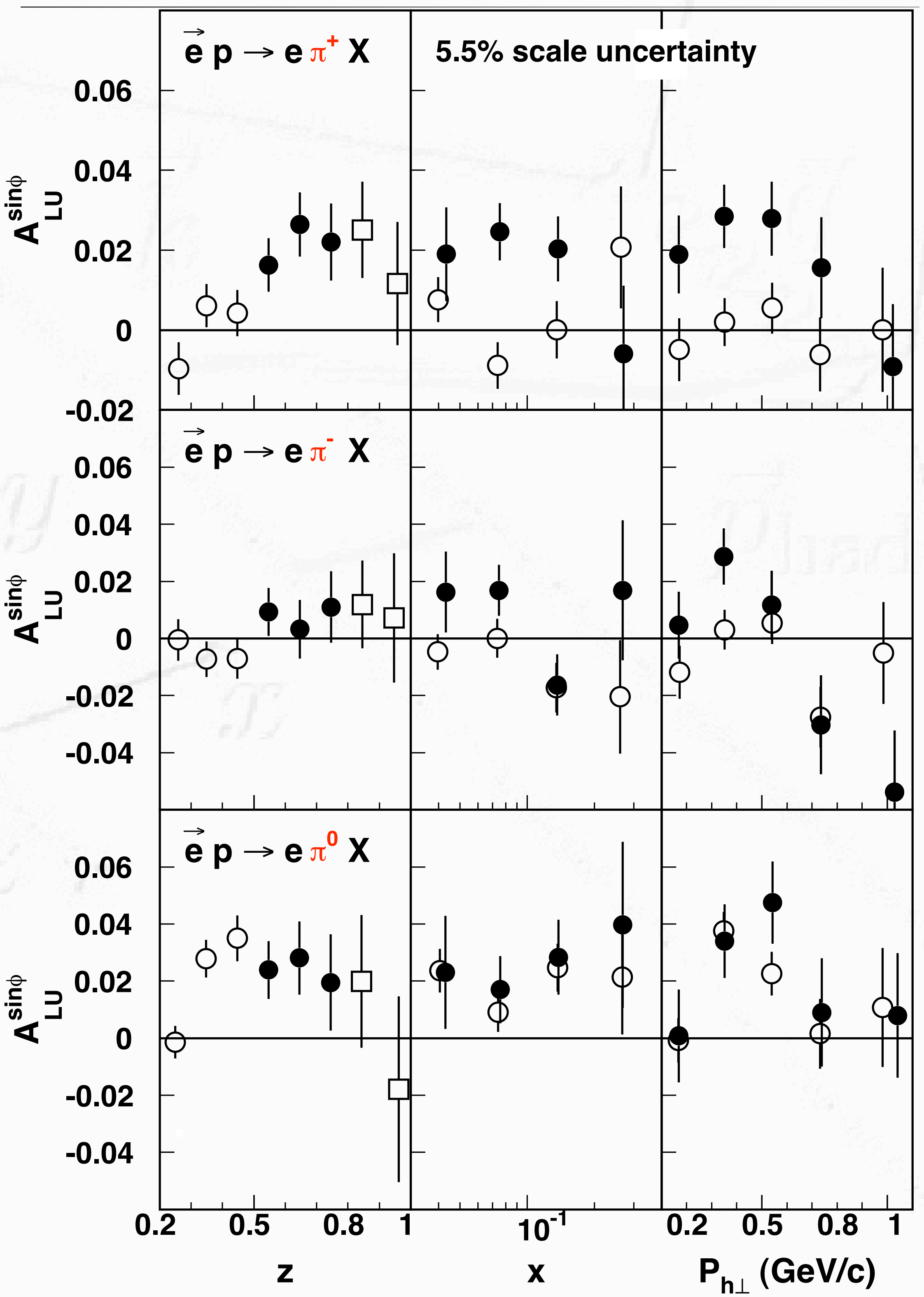
longitudinally pol. beam & unpol. target ⇒ subleading-twist

$$\left\langle \sin\phi \right\rangle_{LU} \propto \lambda_e \frac{M}{Q}\, \mathcal{I}\Big[x e(x) H_1^\perp(z) - \frac{M_h}{zM} h_1^\perp(x) E(z) + \frac{M_h}{zM} f_1(x) G^\perp(z) - x g^\perp(x) D_1(z) + \frac{m_q}{M} h_1^\perp(x) D_1(z) - \frac{m_q}{M} f_1(x) H_1^\perp(z) \Big]$$

quark-mass suppressed ⇒ (last line)

Bacchetta et al., Phys. Lett. B 595 (2004) 309

Longit. Beam-Spin Asymmetries



- **Significantly positive amplitudes for neutral and positive pions**
- **much more data on tape:**
  - **in total factor 7 for H**
  - **factor 3 for D**
  - **mostly with RICH detector, thus kaon amplitudes possible**

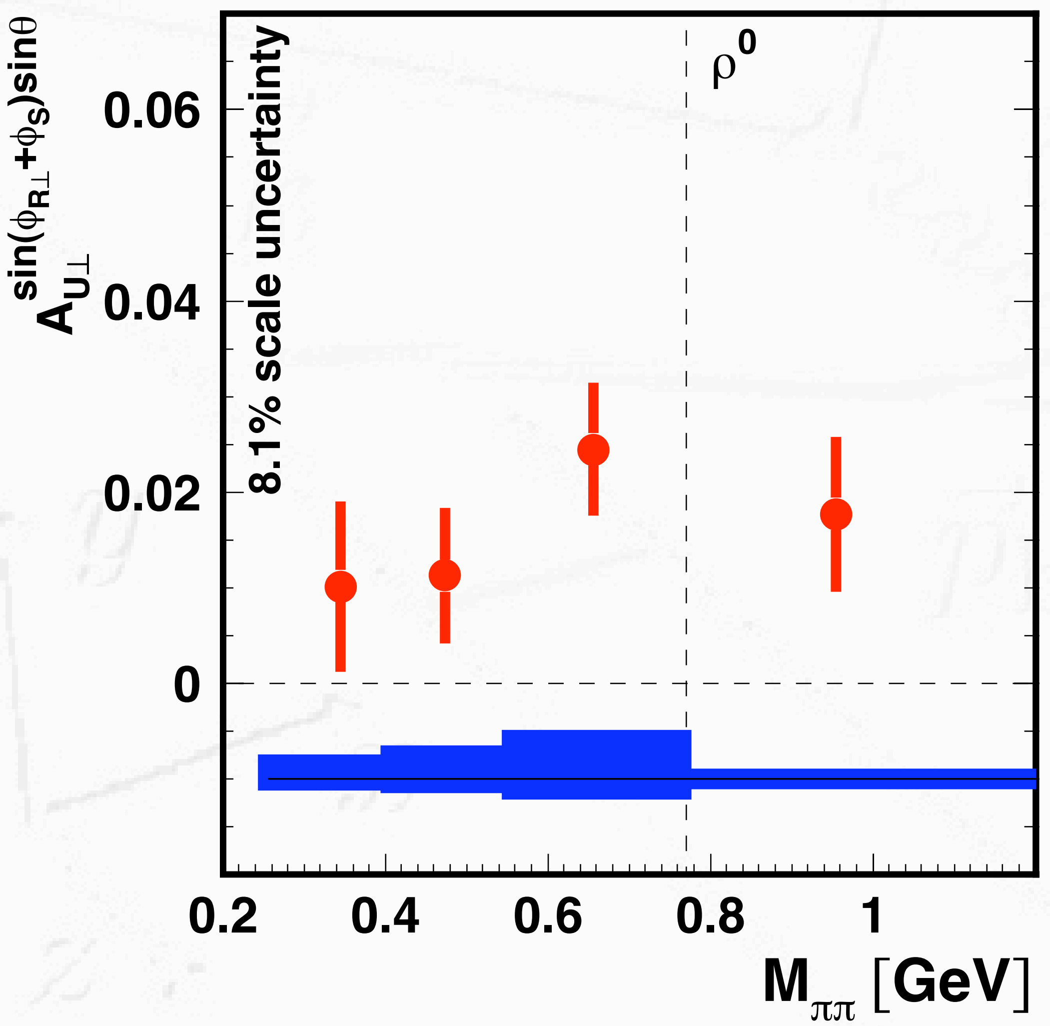
What can we learn from A_{UL}?

$$\langle \sin\phi \rangle_{LU} \propto \lambda_e \frac{M}{Q} \mathcal{I}\Big[x e(x) H_1^{\perp}(z) - \frac{M_h}{zM} h_1^{\perp}(x) E(z) - x g^{\perp}(x) D_1(z) + \frac{M_h}{zM} f_1(x) G^{\perp}(z) \Big]$$

- **any help from other observables to separate contributions?**
  - ***jet* SIDIS ⇒ only g$^{\perp}$-term survives**
  - **2-hadron produc** **nonzero! (cf. R. Fabbri's talk)**

$$\sigma_{LU} \propto \sin\phi_{R\perp} \left[x e(x) H_1^{\sphericalangle}(z,\zeta,M_h^2) + \frac{1}{z} f_1(x) \tilde{G}^{\sphericalangle}(z,\zeta,M_h^2) \right]$$

2-Hadron Fragmentation



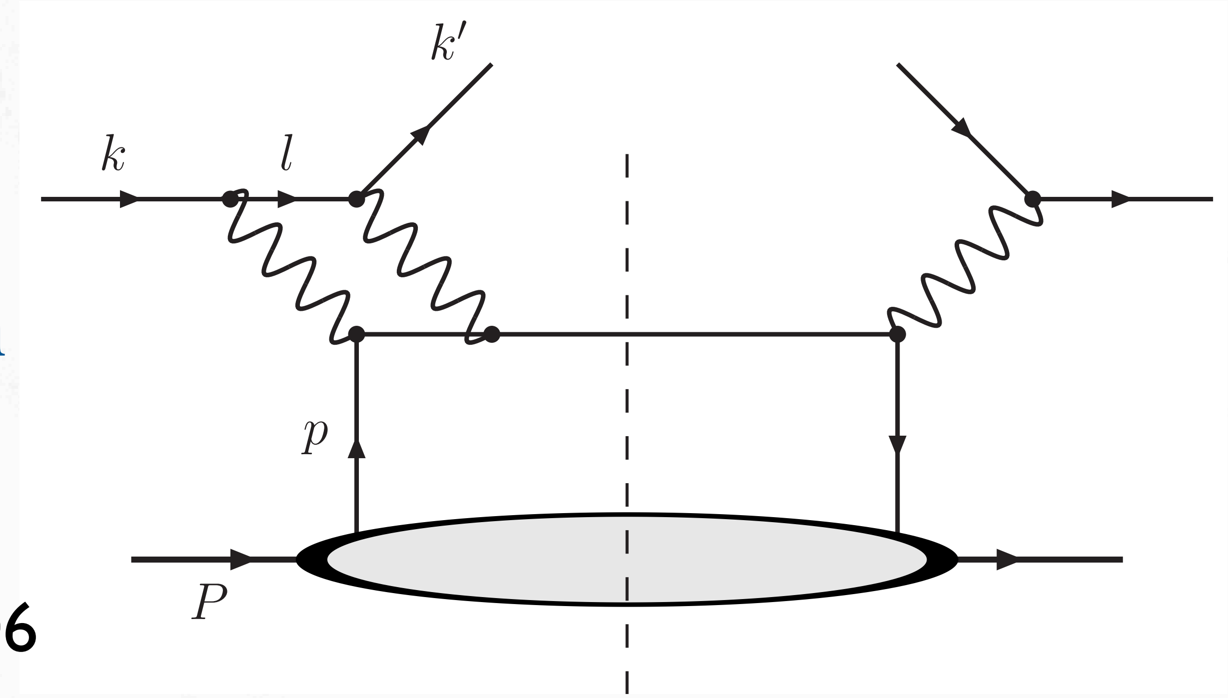
$$H_1^{\sphericalangle,sp} \neq 0$$

- so far: sp interference
  ➠ look at pp interference
- πK, KK pair production
- spin-1 fragmentation (ρ^0)
- ...
- for A_{UT} and A_{LU} (the latter also on D target)

now something completely different

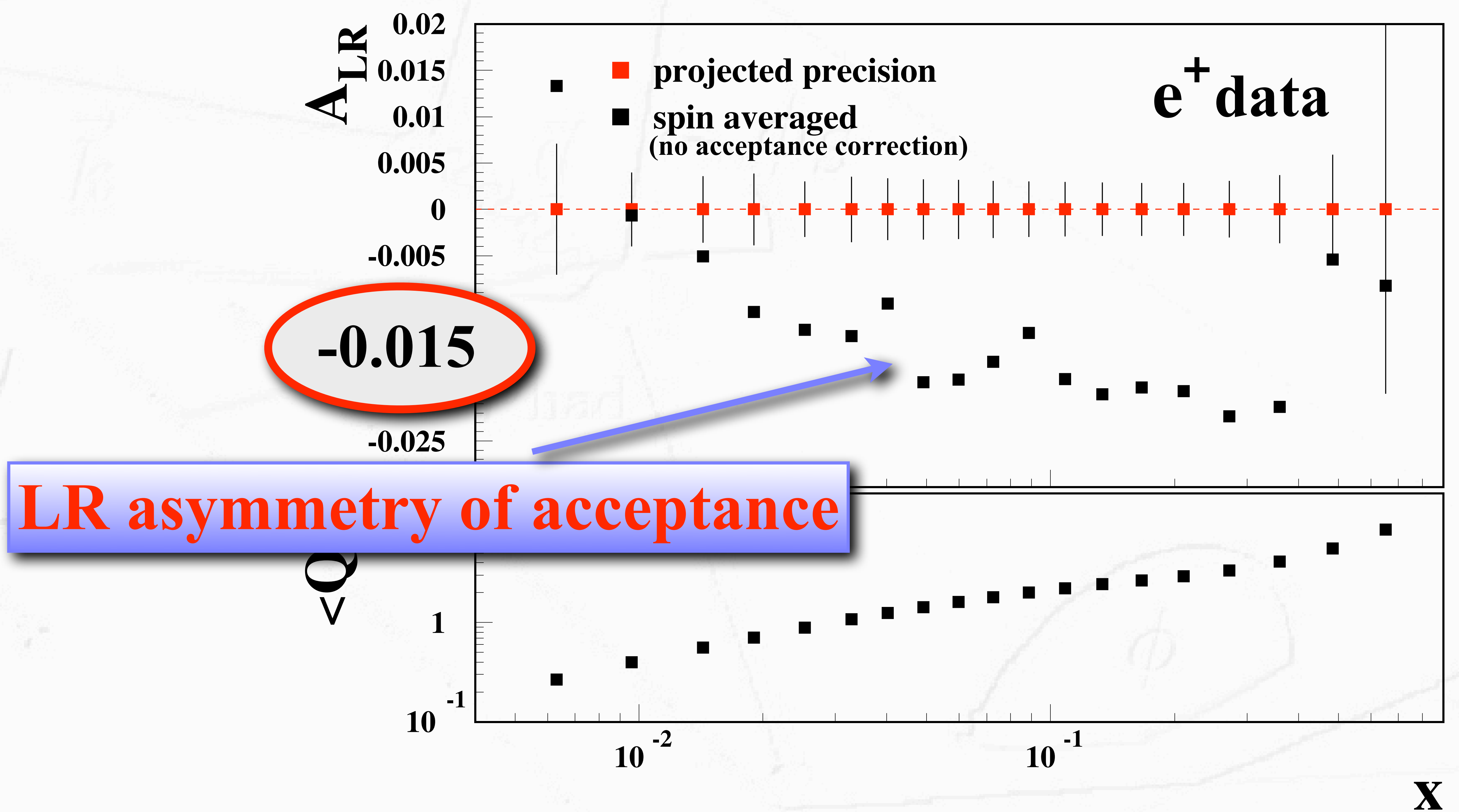
SSA in inclusive DIS

- transverse SSA require <u>interference</u> of amplitudes with different <u>phases</u>
- achievable via loop diagrams, e.g.
  - Sivers DF includes gauge link (soft gluon exchange)
- How about inclusive DIS?
- 2-photon exchange could provide such mechanism in inclusive DIS



A. Metz et al., Phys.Lett.B643:319-324,2006

2γ-exchange sensitivity @ HERMES



even more e- data available!

The other inclusive SSA

- instead of inclusive DIS, look at inclusive hadron production (a la E704 etc., but photo-production)
- plenty of data available
- can they be related to Sivers effect in any way?
- or what is the physics of Left-Right asymmetries in photo-production?

Conclusions

- **plenty of projects**
  - **inclusive DIS (g_2, 2-photon exchange)**
  - **inclusive hadron left-right asymmetries**
  - **SSA and DSA in semi-inclusive DIS ➠ access to various TMDs like Sivers, Pretzelosity and the “weird ones”**
  - **flavor decomposition of Sivers function via purity analysis and pion-yield difference asymmetries**
  - **2-hadron fragmentation: sp-&pp-interference etc., in A_{LU} and A_{UT}**
- **“only the sky*) is the limit”**

***) sky = manpower**